LIGO-INDIA

PROPOSAL FOR AN INTERFEROMETRIC GRAVITATIONAL-WAVE OBSERVATORY

IndIGO

Indian Initiative in Gravitational-wave Observations

Indian Initiative in Gravitational wave Observations
http://www.gw-indigo.org

Title of the Project

LIGO-INDIA

Proposal of the Consortium for

INDIAN INITIATIVE IN GRAVITATIONAL WAVE OBSERVATIONS

IndIGO

to

Department of Atomic Energy & Department of Science and Technology

Government of India

IndIGO Consortium Institutions

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IISER, Kolkata
IISER, Pune
IISER, Thiruvananthapuram
IIT Madras, Chennai
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10 November 2011

LIGO-India
EXECUTIVE SUMMARY

This proposal by the IndIGO consortium is for the construction and subsequent 10-year operation of an advanced interferometric gravitational wave detector in India called LIGO-India under an international collaboration with Laser Interferometer Gravitational–wave Observatory (LIGO) Laboratory, USA. The detector is a 4-km arm-length Michelson Interferometer with Fabry-Perot enhancement arms, and aims to detect fractional changes in the arm-length smaller than 10^{-23} $\mathrm{Hz}^{-1/2}$. The task of constructing this very sophisticated detector at the limits of present day technology is facilitated by the amazing opportunity offered by the LIGO Laboratory and its international partners to provide the complete design and all the key components required to build the detector as part of the collaboration. Indian scientists will build the detector as well as the entire infrastructure including the ultra-high vacuum vessels and tubes required to house the interferometer at a suitable, gravitationally and seismically quiet site in India. IndIGO and the LIGO Laboratory will work together in realizing the Indian node (LIGO-India) of the international gravitational wave detector network in India.

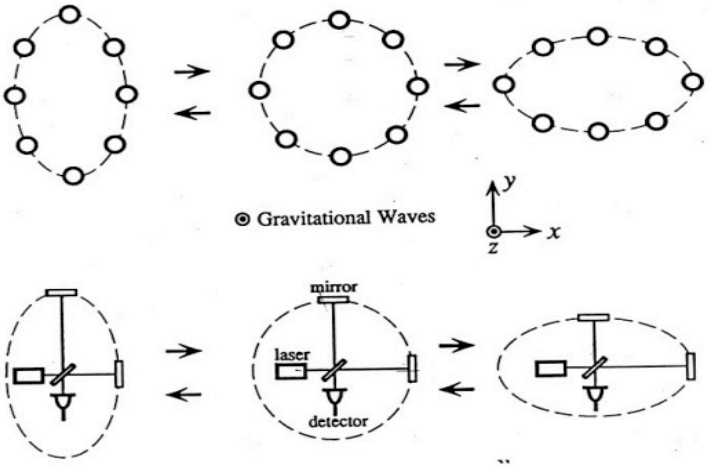
These advanced detectors will be 10 times more sensitive than the first generation initial detectors reaching that level of sensitivity when the first detection of gravitational waves from astrophysical events involving neutron stars or black holes are expected. The proposal to build and operate the Indian detector is timed to be in this exciting decade of the first detection and observations with gravitational waves. Operating as a part of the international network of gravitational wave detectors LIGO-India will be a valuable frontline instrument for GW astronomy. LIGO-India is considered to be an essential element in the global network of detectors to guarantee, with the identical LIGO detectors in USA, improved pointing accuracy and simultaneous observations for Gravitational Wave (GW) astronomy.

Predicted by Einstein’s General Theory of Relativity (GTR) almost a century ago, gravitational waves are yet to be directly detected. Apart from putting GTR on a sound footing, the detection of gravitational waves is of great importance to fundamental physics and would also serve to open a new window for astronomy to study astrophysical phenomena inaccessible to electromagnetic waves, such as the growth of black holes, final phase of in-spiraling and merging binary neutron stars, asymmetric supernova explosions and the stochastic gravitational wave background or the murmurs of the big-bang. Some of the fundamental questions in physics, astronomy, astrophysics and cosmology that will be addressed by this network of detectors are:

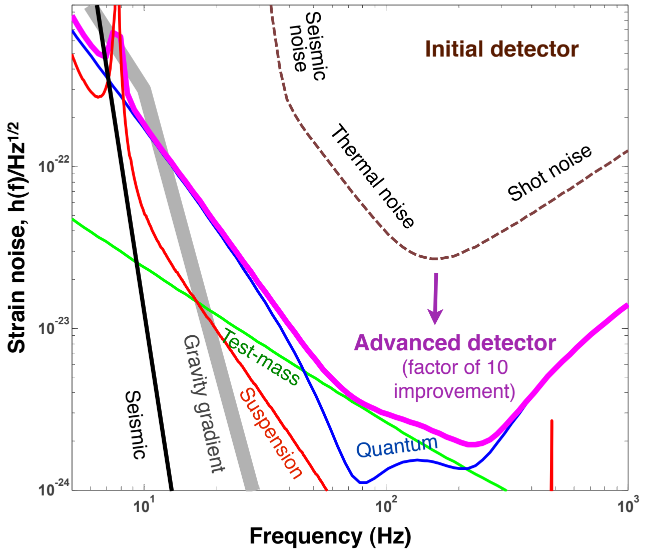
- What is the structure of neutron stars and how do they evolve?
- How common are black holes, and how are they distributed in the universe?
- What is the mechanism that causes a collapsing star to become a supernova?
- What were the physical processes involving matter- energy during the Big Bang?
- Is Einstein’s General Theory of Relativity the correct description of gravity?

The Michelson interferometer is a 'natural' detector of gravitational waves because of the differential changes in the two orthogonal arms induced by the quadruple field of the gravitational waves. The displacement of two mirrors separated by a distance L scales with the distance. For reliable detection from expected astrophysical processes the sensitivity for strain should be below 10^{-23} $\mathrm{Hz}^{-1/2}$ and this translates to sensitivity to relative displacement of 4×10^{-20} $\mathrm{m\text{-}Hz}^{-1/2}$ for interferometer detector with arm length of about 4km. This is the target for ‘Advanced-LIGO’, which will achieve this displacement sensitivity by various techniques like Fabry-Perot resonators inside the

Michelson arms, laser power recycling into the interferometer and signal recycling. One of the early upgrades to further improve the sensitivity for advanced LIGO is expected to employ 'squeezed light' technology. This relies on appropriately decreasing the quantum uncertainty on one of the two quantum conjugate variable, phase and intensity of light, at the expense of the other. This would allow a 'tailored' sensitivity curve over the frequency range gaining up to an order of magnitude in sensitivity at a chosen narrow detector frequency band. This has been demonstrated on the smaller GEO detector in Hanover, Germany.

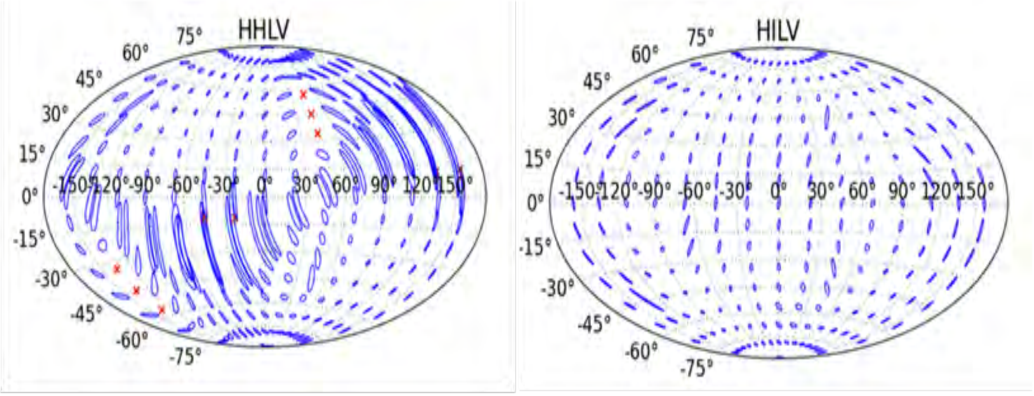


The effect of a passing gravitational wave on a set of masses arranged in a circle and the detection scheme using a Michelson interferometer.



Evolution of detector sensitivity to strain from measurement of the differential displacement of two mirrors. The advanced detectors under construction as well as LIGO-India will reach a sensitivity better than 10^{-23} $Hz^{-1/2}$. Also shown are the different noise sources contributing to the noise budget of advanced detectors.

The Gravitational Wave International Committee (GWIC) has identified the expansion of the global network of gravitational wave interferometers as a high priority for maximizing the scientific potential of gravitational wave observations in the coming three decades. Among the first questions that must be answered about each gravitational wave observed is where it originates from on the sky. The international GW detector network answers this question by comparing the signals at widely separated detectors. This will enable gravitational wave sources to be studied using the tools of multi-messenger astronomy such as optical telescopes, the Square Kilometer Array (SKA) radio telescope, or x-ray detectors. The addition of LIGO-India to the international network offers a very significant improvement in establishing the sky location of gravitational wave sources.



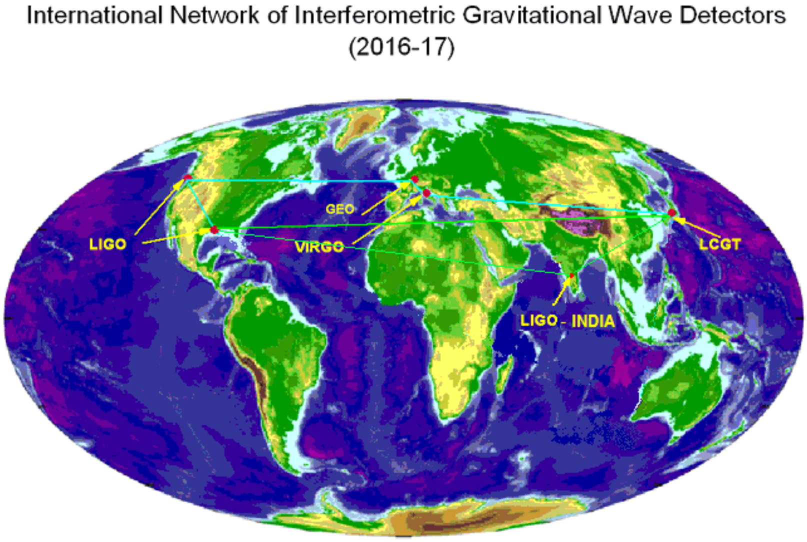
Original plan
2 +1 LIGO USA+ Virgo

LIGO-India plan
1+1 LIGO USA+ Virgo+ LIGO India

Maps of the sky comparing how accurately the positions of compact binary coalescence sources can be located without (left) and with LIGO-India (right).

The development of this critical element of a global array of gravitational wave detectors will place India among the nations leading the scientific exploration of this new window to the universe. This project is a timely opportunity to enter the field of Gravitational Wave Detection and Astronomy without the gestation period required for the component development and at a time when the detector sensitivity has reached the threshold for gravitational wave detection. The advanced interferometer detector located and operated in India will be transformational and rejuvenating for Indian astronomy and gravity research, bringing together the best engineering and physics groups, fostering very importantly the research-industry partnership for advanced scientific instrument building and initiating the much needed development of expertise and human resource in many fields relevant to the next generation technology, physics and computation. **In July 2011, the IndIGO Consortium became a member of the Gravitational Wave International Committee (GWIC) and in September of the LIGO Scientific Collaboration (LSC). LSC membership gives the IndIGO scientists access to detector data of LIGO-USA and the opportunity to be part of the potential first detection of GW.**

The challenges of making measurements to detect GW requires the most sophisticated technologies in lasers, optics, vibration isolation, electronics, high speed and high volume computing, data handling and network communications, and engineering. The LIGO-India project will be highly multi-disciplinary and will bring together scientists and engineers from these different fields. The technology for these detectors are at the limits of current capabilities and would push the current technologies to new levels, motivating new R&D in these fields. Spin-offs to other science, engineering and industrial applications will provide unprecedented commercial opportunities for Indian industries and businesses in collaboration with research institutions and universities. These have the potential to seed technological spin-offs in several areas that include ultra-stable and high-power lasers, high-tech optics, sensors and vibration isolation platforms, multi-channel control systems, large volume data storage, retrieval, computing and fast network communications and quantum technologies for communication. LIGO-India will be transformational for Indian physics, technology and astronomy and will drive accelerated growth in these areas over decades. The partnership with LIGO moves the gravitational wave detector project to a state of readiness that would normally take decades to achieve. Though a collaborative project with an international partner, unlike other similar collaborative projects the LIGO-India detector will be installed in India and the major part of the project money will be spent in India with several components (e.g, vacuum envelopes) sourced from Indian industries.


International Network of Interferometric Gravitational Wave Detectors
(2016-17)

The international network of interferometric gravitational-wave detectors in circa 2016-2017, including the proposed LIGO-India detector.

Data storage, retrieval and analysis constitute one of the most important components of the operation of a gravitational wave detector. The IndIGO Data Center proposed to be set up in IUCAA, Pune is envisaged to be the core facility for data analysis of integrated astronomy of the future with gravitational wave astronomy as one major activity, apart from the analysis of data from Astrosat, CMB, Pulsar survey and general astronomy. It is planned to be set up as a Tier-2 data analysis centre with several tens of Teraflops in computational resources along with several hundred Terabytes of storage for data archival. The centre will serve as a data archival facility for LIGO-India as well as for the other detectors in the international network.

For the LIGO-India project the contribution from the US and its international partners (UK, Germany and Australia) will be in kind, consisting of complete design and hardware of the detector worth \$140M (Rs 650 Crores). The hardware includes: The Detector (Laser Interferometer) consisting of a high power CW laser, core optics, mode cleaning cavities, thermal compensation system; Vibration isolation system consisting of three-stage isolation; a hydraulic external pre-isolator, a four stage passive isolation system with a monolithic fused silica suspension for the mirrors and beam splitters; Control Systems and Electronics; Data analysis algorithms and protocols, as used in the LIGO detectors; Installation tooling and fixturing.

Apart from a cost saving of about 50% in terms of the detector cost, this unprecedented opportunity makes it possible to jump start and develop gravitational wave astronomy in India synchronous with its anticipated global beginnings. The actual cost benefits is much more because of the continued creation of human resources with special expertise and advancement of high technology and spin-offs within the country.

The major funding in the XII Plan is Rs. 650 Crores for the construction of the Civil infrastructure and installation of the detector. During the XIII 5-year Plan (2017-22) the expected expenditure is Rs. 380 Crores, out of which Rs 280 Crores is for completing the construction and installation of the detector and the remaining Rs 100 Crores for continuous operation and maintenance. The XIV Plan will see mature gravitational wave astronomy with the LIGO-India detector and projected operation cost for continuous operation and maintenance during this period (2022-27) is Rs. 230 Crores. Thus the total projected expenditure for 15 years spanning three plan periods from 2012 to 2027 is Rs. 1260 Crores.

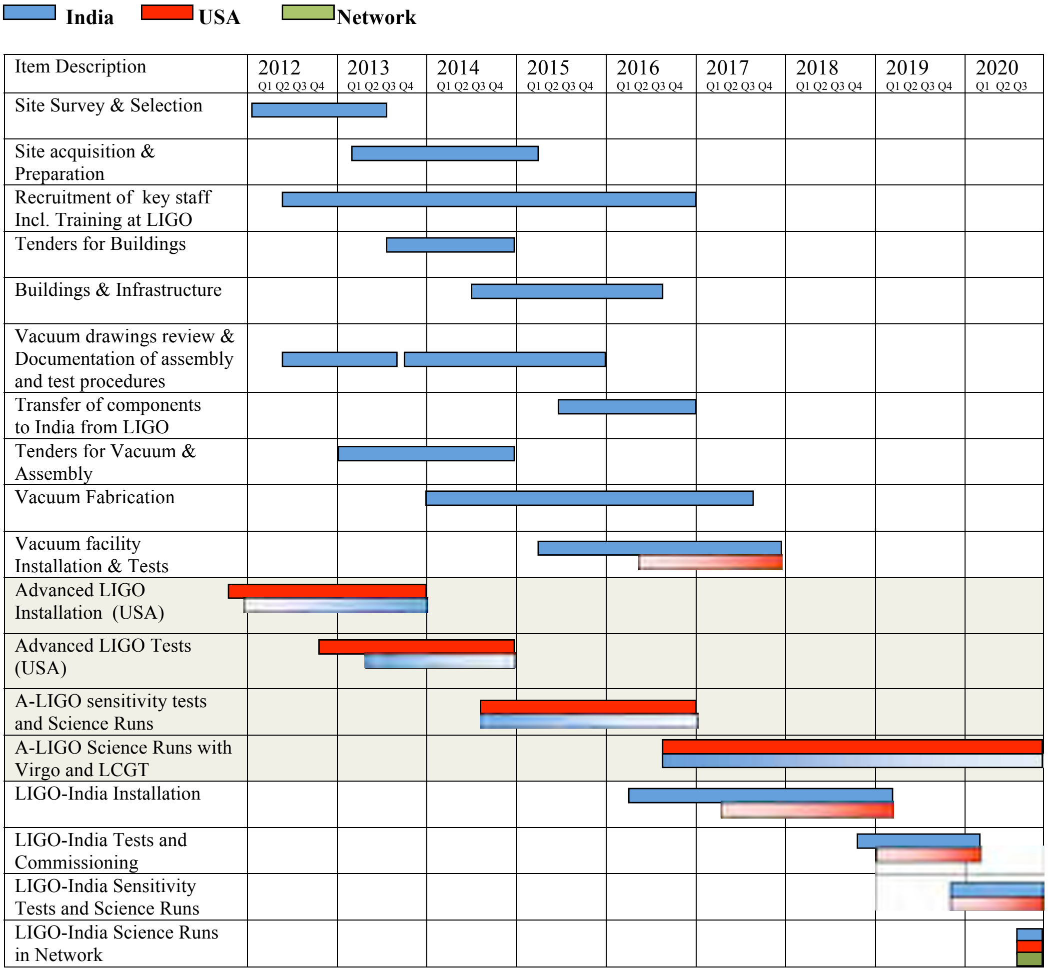
Project Schedule:

IndIGO and LIGO will work together to closely implement LIGO-India in the planned time-frame such that the detector can be part of the international network not later than 2020. IndIGO members will also actively participate in the science runs of the LIGO detector starting 2015, since IndIGO is already part of the LIGO Scientific collaboration (LSC).

LIGO-India Timeline

2012 - 2013	Site survey, measurements, validation, selection and acquisition
2014 - 2015	Site preparation, Design and Drawings for Buildings, Tendering for Civil infrastructure, construction of Central and End stations.
2012 - 2015	On site training and participation at LIGO-USA during initial phases of LIGO-USA assembly and tests.
2012- 2013	Update and finalization of drawings for UHV systems, Preparation of infrastructure for fabrication & tests, Establishing protocols and processes for fabrication.
2014 - 2017	Fabrication of spiral welded tubes and main UHV End stations.
2015 - 2016	Shipping of LIGO components from LIGO-USA.
2016	Start of LIGO-India interferometer assembly.
2016 - 2018	LIGO-India integration, tests and validation.
2018 - 2019	Locked operation of the detector and tuning to aimed sensitivity.
2019 - 2020	**Science Runs and regular Operation of LIGO-India.**
2020 -	**Network runs and GW astronomy with LIGO-India.**

LIGO-India schedule



🟦 India 🟥 USA 🟩 Network

Item Description	2012 Q1 Q2 Q3 Q4	2013 Q1 Q2 Q3 Q4	2014 Q1 Q2 Q3 Q4	2015 Q1 Q2 Q3 Q4	2016 Q1 Q2 Q3 Q4	2017 Q1 Q2 Q3 Q4	2018 Q1 Q2 Q3 Q4	2019 Q1 Q2 Q3 Q4	2020 Q1 Q2 Q3
Site Survey & Selection	🟦	🟦							
Site acquisition & Preparation		🟦	🟦	🟦					
Recruitment of key staff Incl. Training at LIGO	🟦	🟦	🟦	🟦	🟦				
Tenders for Buildings		🟦	🟦						
Buildings & Infrastructure			🟦	🟦	🟦				
Vacuum drawings review & Documentation of assembly and test procedures	🟦	🟦	🟦	🟦					
Transfer of components to India from LIGO				🟦	🟦				
Tenders for Vacuum & Assembly		🟦	🟦						
Vacuum Fabrication			🟦	🟦	🟦	🟦			
Vacuum facility Installation & Tests				🟦	🟦 🟥	🟦 🟥			
Advanced LIGO Installation (USA)	🟥 🟦	🟥 🟦							
Advanced LIGO Tests (USA)	🟥	🟥 🟦	🟥 🟦						
A-LIGO sensitivity tests and Science Runs			🟥 🟦	🟥 🟦	🟥 🟦				
A-LIGO Science Runs with Virgo and LCGT					🟥 🟦	🟥 🟦	🟥 🟦	🟥 🟦	🟥 🟦
LIGO-India Installation					🟦	🟦 🟥	🟦 🟥	🟦 🟥	
LIGO-India Tests and Commissioning							🟦	🟦 🟥	🟦 🟥
LIGO-India Sensitivity Tests and Science Runs								🟦 🟥	🟦 🟥
LIGO-India Science Runs in Network									🟦 🟥 🟩

Note: The installation and commissioning of the LIGO-USA detector will be complete by about 2016 and some LIGO scientists and engineers who are experienced on the assembly and tests of the detector (post-doctoral associates and engineers) will be able to join the LIGO-India effort for short durations from few months to a year or two. This will accelerate the LIGO-India schedule, as indicated in this table. The red stripes along with the blue one indicate some LIGO-USA involvement, with cost management from LIGO-India.

LIGO-India

AN OVERVIEW AND SUMMARY

1. Opportunity:

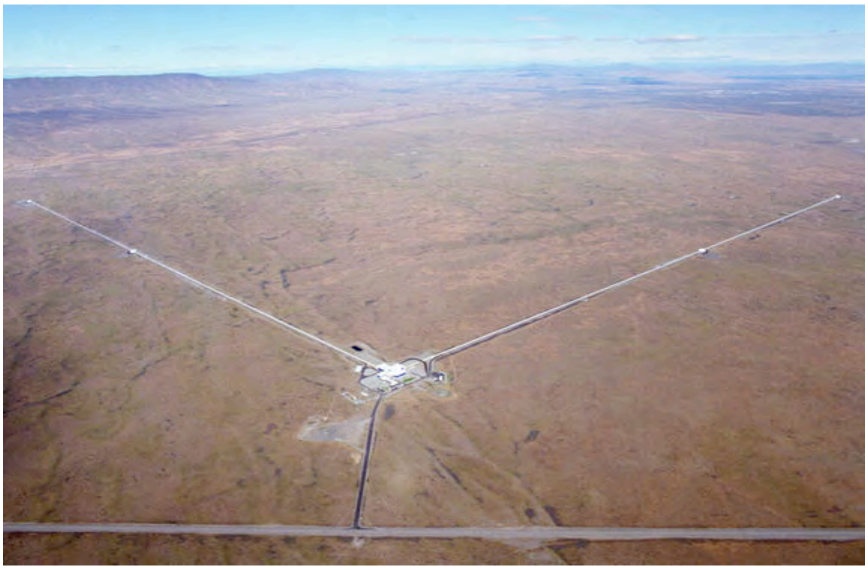


Fig. 1: LIGO facility in Hanford, Washington

The opening of a new window to the Universe through gravitational waves (GWs) is imminent**.** This proposal by the IndIGO consortium is for participation in the construction and operation of LIGO-India, an advanced gravitational wave observatory in an international collaboration involving the LIGO-USA. The detector is a 4-km arm-length Michelson Interferometer with Fabry-Perot enhancements that aims to detect fractional changes in the arm-length better than 10^{-23} $Hz^{-1/2}$. The US-LIGO project is the largest and most advanced of the international gravitational wave detector efforts in the world. The LIGO lab has embarked on an ambitious program to upgrade its US detectors incorporating advanced technologies (high power precision lasers, ultra-precise optics, low-noise vibration isolating platforms, grid-based supercomputing) developed over the past decade by an international team. The 'Advanced LIGO' detectors will be a factor of 10 more sensitive than the pioneering first generation detectors and is expected to transform the field from one of gravitational wave detection to one of gravitational wave astrophysics. LIGO is funded to build three Advanced LIGO detectors in the US. Its original plan (developed nearly a decade ago) was to install one detector at its site in Louisiana and two detectors in its facility in Washington State. To enhance the baseline for coincidence detection and to maximize the science output from these detectors, the LIGO laboratory is offering to provide all the key components of one of the Advanced-LIGO detectors to be installed in India as ‘LIGO-India’. The addition of LIGO-India to the existing international detector network offers a significant improvement in establishing the sky location of gravitational wave sources. Depending on signal to noise and the location on the sky, the accuracy of the position of a source can be 5 to 10 times better with LIGO-India, approaching 1 square degree in many places in the sky enabling identification by optical and radio telescopes. This will enable gravitational wave sources to be studied using radio and optical telescopes and other proposed tools of multi-messenger astronomy such as the Square Kilometer Array (SKA) radio telescopes, or Astrosat.

The development of such detector systems have been pushing the envelope of technology on a number of important experimental fields globally. Besides the enormous fundamental science goals, Indian collaboration in this area would have far-reaching consequences for the development of cutting-edge technology and experimental expertise.

2. Science Goals:

Predicted by Einstein almost a century ago as a consequence of his General Theory of Relativity and the most characteristic departure from Newtonian gravity, the ubiquitous yet elusive gravitational waves carry large amount of energy and yet produce only infinitesimally small effects as they pass through space at the speed of light. There is unequivocal indirect evidence for existence of GW emitted by massive compact binary systems in the sky, from the study of pulsar timing of binary neutron stars. However, they are yet to be detected directly. They are of great importance to fundamental physics and an emerging window for astronomy as a means to study astrophysical phenomena beyond the reach of electromagnetic waves.

In the coming decade, an international network of multi-kilometer scale gravitational wave observatories with enhanced sensitivity will come into operation in the US, Europe and Japan. Working together, these ultra-sensitive detectors based on laser interferometry will begin to throw light on the astrophysics of gravitational wave sources, have implications for cosmology, probe the quantum limits to measurement and eventually unravel the mysteries of gravity as a fundamental force. Fundamental questions that will be addressed using such detectors that operate at their quantum mechanical sensitivity limits are:

- Is Einstein's General Theory of Relativity the correct description of gravity, or does it have other modes of expression (in regimes beyond binary pulsar tests) with additional fields as some theories suggest?
- How common are black holes, and how are they distributed in the universe? What is the structure of neutron stars and how do they evolve?
- What is the final phase of evolution of binary neutron stars and black holes as they merge due to loss of energy emitted in gravitational waves?
- What is the mechanism that causes a collapsing star to become supernova?
- What was the gravitational evolution of the very early Universe immediately after the big-bang?
- What is the late-time expansion evolution of the Universe? (using compact binary sources as standard sirens of GW emission for cosmology).
- How do the laws of quantum mechanics apply to the macroscopic objects?

3. Current Status:

The partnership with LIGO moves the gravitational wave detector project to a state of readiness that would normally take years to achieve. Through this collaborative project, India will gain a major and early entry in experimental gravitational astronomy at a fraction of the total cost of independently developing and establishing a fully-equipped observatory. Advanced LIGO detectors have undergone years of research and design, and the LIGO Laboratory and its partners (UK, Germany, Australia) have begun fabricating the components for the three Advanced LIGO detectors. The US National Science Foundation (Advanced LIGO's main sponsor) has already given approval to study the feasibility for LIGO-India. The facility needed is well-defined based on the LIGO model, and construction could be underway after a brief period to adapt the designs to Indian standards and methods of construction. A preliminary cost estimate for the Indian component has been made by IndIGO and is being reviewed by LIGO for completeness and accuracy. The recent faculty hiring of researchers associated with gravitational wave research in a number of institutes and universities in India ensure long-term commitment for the use of the LIGO-India detector for astronomy and gravity research in India. It is clearly a great opportunity for a timely surge and boost in Indian gravity research and astronomy, along with other major projects like INO, TMT, LHC, SKA etc. and the Indian program on space-based astronomy like Astrosat. In short, the scientists are ready to begin work in earnest as soon as project approval can be secured.

4. Challenge:

The field of gravitational wave astronomy is evolving rapidly and quick action will be required to bring LIGO-India into existence on a timely scale. In the last two years, the Northern Hemisphere portion of the international network has been filled in with the beginning of Advanced LIGO funding (2008), approval of Europe's Advanced Virgo (2009), and the initial funding for the Large Cryogenic Gravitational-wave Telescope (LCGT, Japan, 2010). To join this network will require immediate and decisive action by India. LIGO has offered a complete Advanced LIGO detector (one of two originally planned for LIGO's Washington State site), but this offer comes with a sharp deadline. This detector is scheduled to begin installation in its US facility near the end of 2011. **If India, as the major partner and the host country, cannot make a commitment to build the facility to house it by March 31, 2012, LIGO will be forced to withdraw this offer and to install the detector at Washington State site as originally planned.** If India can make this commitment and start on the operational aspects as soon as possible after funding assurances, LIGO-India can be operational by 2019/20, and can join in the excitement of early detections only a short time after the US Advanced-LIGO detectors come into operation. It is clearly a great opportunity, but due to pre-existing time frames, it has a very sharp deadline which if not met, **will close on 31 March 2012.**

5. Objectives:

In collaboration with the world-leading Laser Interferometer Gravitational–wave Observatory (LIGO) and its International collaborators, the IndIGO Consortium proposes to establish at a suitable site in India the crucial Indian node of the international gravitational wave observatory network. This involves setting up a 4km long advanced interferometric gravitational wave detector in India with a spatial strain measurement sensitivity of 10^{-23} Hz $^{-1/2}$ (displacement sensitivity of 4×10^{-20} m Hz$^{-1/2}$) and operate it in coincident and/or coherent mode for a period of 10 years with the international network of gravitational wave detectors. The detector 'LIGO-India' will be operated as front-line instrument for gravitational wave astronomy involving observations of various astrophysical phenomena through the gravitational waves they emit. The IndIGO consortium seeks funding from DAE and DST for LIGO-India.

Budget: **2011-13 : Rs. 10.3 Crores (Seed Funding)**
2012-17: Rs. 650 Crores
2017-22: Rs. 380 Crores
2022-27: Rs. 230 Crores

Time frame: Site and Detector Construction: 2012-2019
Commissioning and Science Runs: 2019
Network Operation: 2020

6. LIGO-India Project: Science and Technology

Large scale optical interferometer technology has been tailored and improved for the specific purpose of the detection of gravitational waves during the past two decades and has now reached a displacement sensitivity of 10^{-19} m-Hz$^{-1/2}$. For a 4 km arm length interferometer this translates to a strain sensitivity of $3\text{x}10^{-23}$ Hz$^{-1/2}$. This figure, amazing as it may be, is still not adequate for a practical rate of detection with terrestrial detectors. Improvement by a factor of 10, amounting to an improvement in the number of detectable sources by a factor of 1000, will however ensure several detections per month. This will usher in the new astronomy with gravitational waves. Advanced LIGO and the proposed LIGO-India are detectors of the same design and hardware and operational specifications with several technological feats incorporated to achieve the required strain sensitivity of $h < 3 \text{ x } 10^{-24}$ Hz$^{-1/2}$.

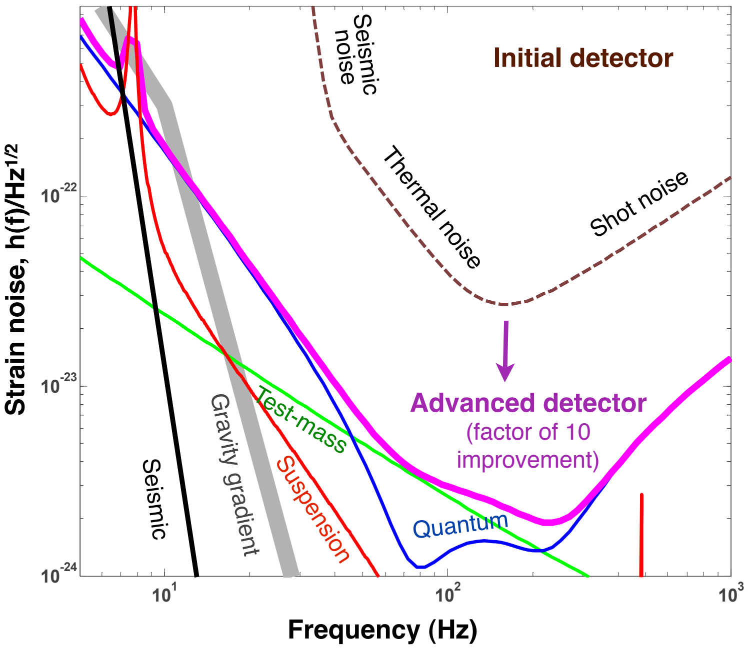


Fig. 2: Evolution of detector sensitivity to strain from measurement of the differential displacement of two mirrors. The advanced detectors under construction as well as LIGO-India will reach a sensitivity better than 10^{-23} Hz$^{-1/2}$. Also shown are the different noise sources contributing to the noise budget of advanced detectors.

7. The detector, Signal and Noise

The LIGO-India detector is a Michelson Interferometer with full length Fabry-Perot cavities inserted into the 4-km long arms. The signals from an astrophysical source (mass scale M, velocity v, at a distance R from the detector) follow the Einstein quadrupole radiation formula, according to which the strain ΔL generated on free masses on earth, separated by a distance L is

$$h = \frac{\Delta L}{L} = \frac{GM}{c^2 R}\,\frac{v^2}{c^2}$$

Since the velocities of neutron stars as they spiral in for merger in a binary system can be about 10% of the speed of light, this amounts to about 10^{-19} for $R \sim 10$ kpc, or galactic distances, and only about 3 x 10^{-24} for a distance of 250 Mpc, covering several local super-clusters of galaxies. With the arm-length L of the order of 4 km, the displacement sensitivity needed to observe a large number of events for gravitational wave astronomy is about 10^{-20} m-$\mathrm{Hz}^{-1/2}$. This defines the goal sensitivity of the advanced detectors like LIGO-USA and LIGO-India.

Since the quantum limit from photon shot noise for measuring the shift of a fringe in an interferometer operating with light at wavelength λ is at best $\lambda(N)^{-1/2}$ where N is the number of photons, even with 100 W of power, the achievable sensitivity at 1000 nm wavelength is limited to 3 x 10^{-17} m. The Fabry-Perot cavities increase the effective length by the number of passages of the beam, at the slight cost of introducing a time-constant for response, reducing high frequency sensitivity. With an enhancement factor of 100, the displacement sensitivity becomes 3 x 10^{-19} m-$\mathrm{Hz}^{-1/2}$. Further increase if effected by power recycling - since the interferometer is operated at a dark fringe with special modulation techniques for the first order detection of the fringe shift, all the light reflects back into the laser and that is recycled back into the interferometer using an additional mirror outside that forms a second Fabry-Perot cavity with the entire Michelson interferometer acting like a mirror. With a power recycling factor of 50 or so, one gets a further shot-noise-limited enhancement of factor $50^{1/2,}$, about 4 x 10^{-20} m-$\mathrm{Hz}^{-1/2}$. It is possible to enhance this further with additional recycling schemes in a more complex interferometer. Also, it is possible to reduce the shot-noise barrier using quantum squeezed light, by factor between 2 and 5 today.

The signal frequency is in the audio-band, practically from about 30Hz to a few 1000 Hz, which represents the maximum spiral frequency before merger of a binary neutron system.

8. Details of equipment, hardware and design transfer from LIGO-USA to LIGO-India

[Some of the material in this proposal describing the features of Advanced LIGO relevant to LIGO-India (e.g. parts of Sections 8, 9, II) are adapted from the text of a proposal submitted by the Australian consortium ACIGA, prepared by a team that included members of IndIGO. We acknowledge and thank members of ACIGA who helped in the preparation of this text.]

The LIGO-India detector will have the same detailed design as the advanced LIGO-USA detectors. This means that, except for deviations specific to Indian standards of hardware (metric measure for example, wherever possible) and Indian conditions of work implementation the details will be exactly similar. Except for the infrastructure to be provided by India, including the key infrastructure of the ultra-high vacuum environment for the operation of the detector, all the hardware required to build the advanced detector will be provided to India free of cost by the LIGO laboratory.

a) Detector (Laser Interferometer):

It consists of a high power continuous wave (CW) laser, core optics, mode cleaning cavities, thermal compensation system etc. The laser is a 180 W narrow line width pre-stabilized and amplified solid state laser with an intensity stability of 10^{-9} $(\mathrm{Hz})^{-1/2}$ and a frequency stability of 10^{-7} $\mathrm{Hz}/(\mathrm{Hz})^{1/2}$. It consists of a stable master oscillator laser, a 35 W amplifier followed by a high power injection locked oscillator. It also includes a pre-mode cleaner, a high power mode cleaner and control and diagnostics systems for the laser. This laser system was developed over more than a decade of research, by the Lazer Zentrum, Hannover and the Max Planck Institute as the German contribution to Advanced LIGO. The requirements on extreme stability of intensity and frequency and the demand on purity of the fundamental mode makes this one of the most advanced high power CW laser system ever developed.

The core optics consist of the four 40kg fused silica test masses, the suspended beam splitter, the recycling mirrors (power and signal) and the thermal compensation plates. The test masses and the beam splitter have very stringent requirements on optical homogeneity, surface figures, coatings and bulk absorption. Typical precision for surface figure is < 1nm (λ/1000) and coating losses (scattering and absorption) are typically $10^{-5} - 10^{-6}$).

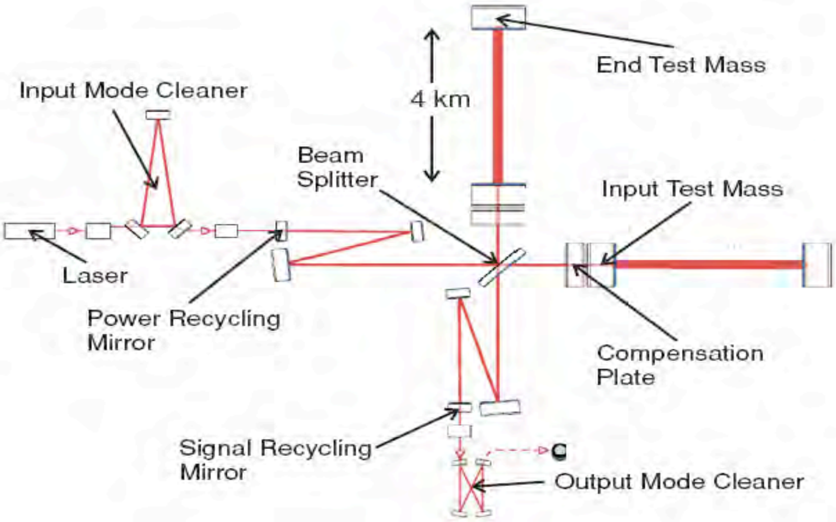


Fig. 3: Advanced LIGO and LIGO-India optical layout. The entire system is housed in UHV chambers.

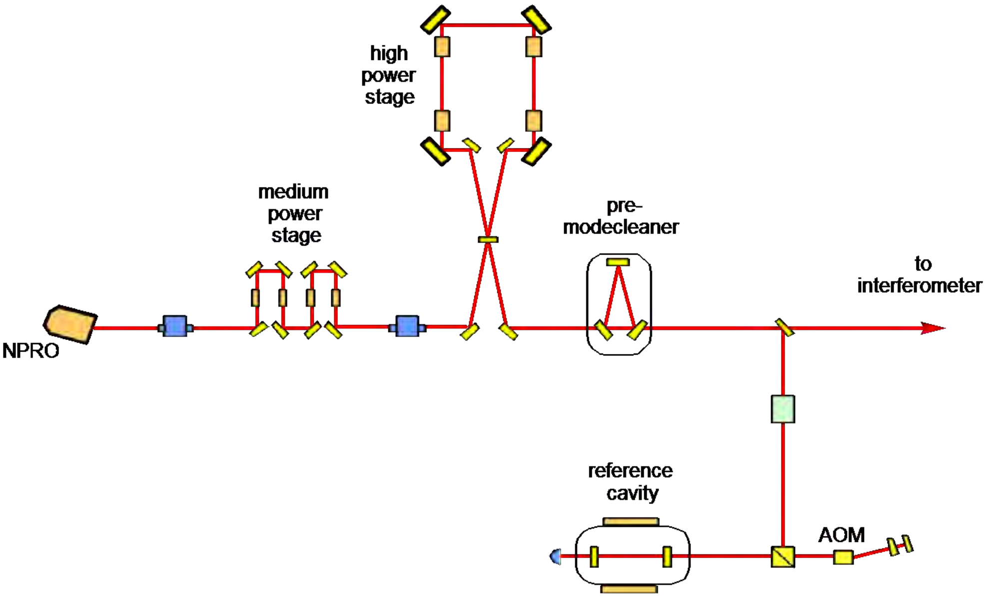


Fig. 4: Pre-stabilized laser will be upgraded to 180 W.

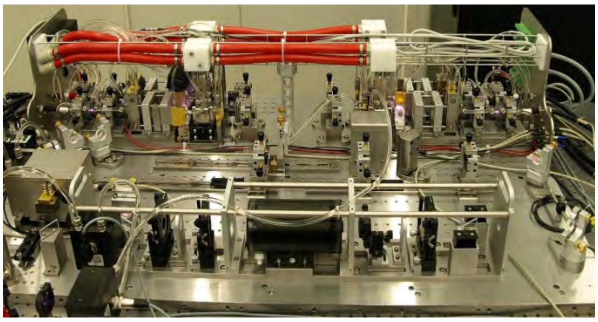


Fig. 5: 180 W narrow line width pre-stabilized and amplified solid state laser developed by LazerZentrum, Hannover and the Max Planck Institute.

Mass	**40Kg**
Dimensions	340mm x 200mm
Surface figure (deviation from sphere over central 15 cm)	< 0.7 nm RMS
Micro-roughness	< 0.2 nm RMS
Optical homogeneity (in transmission through 15 cm thick substrate, over central 8 cm)	< 2 nm RMS
Bulk absorption	< 3 ppm/cm
Bulk mechanical loss	$< 3\ 10^{-9}$
Optical coating absorption	0.5 ppm (required) 0.2 ppm (goal)
Optical coating scatter	10 ppm (required) 1 ppm (goal)
Optical coating mechanical loss	$2\ 10^{-4}$ (required) 3×10^{-5} (goal)

Fig. 6: Specifications for interferometer mirrors that will be provided to LIGO-India from LIGO-USA

The set consists of 10 interferometer core optics (test masses, folding mirrors, beam splitter, recycling mirrors), Input condition optics, including electro-optic modulators, Faraday isolators, a suspended mode-cleaner (12-m long mode-defining cavity), and suspended mode-matching telescope optics. Baffles and beam dumps for controlling scattering and stray radiation are also included. The mirrors are suspended from fused silica fibres that are bonded to the mirror using a specially developed silicate bonding technique designed and supplied by the group at Glasgow, UK as their contribution to Advanced LIGO.

- The interferometer mirrors are suspended in an *all-silica quadruple suspension system*. This was developed by the UK GW group and supplied to LIGO under STFC (UK funding body) funding. Optical distortion monitors and thermal control/compensation system for large optics: In spite of the stringent demands on the optical coatings, thermal distortions of the optics in the presence of the high circulating powers in the arms are more than that can be tolerated. To compensate for these distortions, an active system which monitors the surface figure using a set of Hartmann wavefront sensors, gives real time correction by feed-back to the mirrors using ring heaters, thermal compensation plates and CO_2 laser heater system.

b) Vibration isolation system:

With the displacement sensitivity of the detector pegged at 3×10^{-20} m-$\mathrm{Hz}^{-1/2}$, the vibrations that reach the suspended optical components like the mirrors and beam splitter of the interferometer should be reduced well below this level in the frequency range 30 Hz to a few 1000 Hz. This is accomplished by multi-stage active and passive vibration isolation stacks. By suspending the elements on a spring system with resonant frequency f_0, one gets an ideal attenuation factor of $(f_0/f)^2$ at frequency f. The LIGO vibration isolation system consists of three-stage isolation (the last passive stage consisting itself of 4 stages): a hydraulic external pre-isolator, an active internal isolation system and a four-stage passive isolation system with a monolithic fused silica suspension for the mirrors and beam splitters. Total attenuation of ground vibrations is by more than a factor of 10^{12} in the relevant frequency range. This demands that the ground vibrations themselves should only be about a nm at 10 Hz or so, decreasing rapidly as the frequency increases. This requirement defines one of the criteria for site selection.

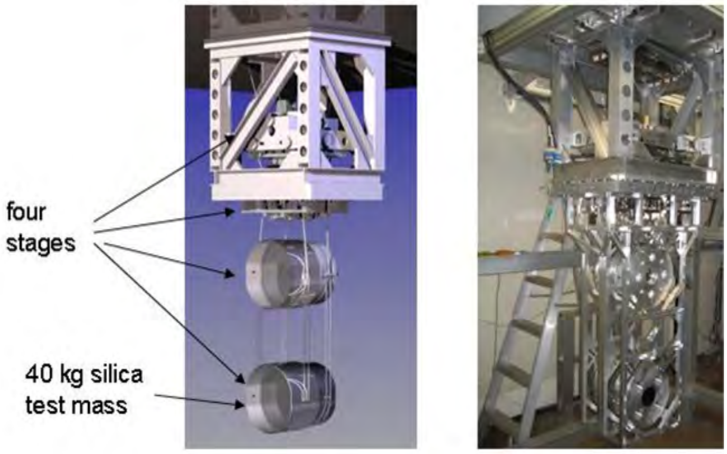


Fig. 7: The test masses will be suspended from a four stage passive isolator.

The hydraulic external pre-isolator provides large actuation range and low frequency isolation. An active internal isolation system uses seismometers and geophones to provide six-degree-of-freedom isolation over a broad frequency. The different stages have been developed to optimize the overall isolation of the test masses from the environment, and the final system represents the state of the art in isolation today. The full set has 5 "BSC chamber" seismic isolation systems (two stage, six degree of freedom, active isolation stages capable of ~200 kg payloads), 6 "HAM Chamber" seismic isolation systems (one stage, six degree of freedom, active isolation stages capable of ~200 kg payloads) 11 Hydraulic External Pre-Isolation systems, Five quadruple stage large optics suspensions systems and the triple stage suspensions for remaining suspended optics.

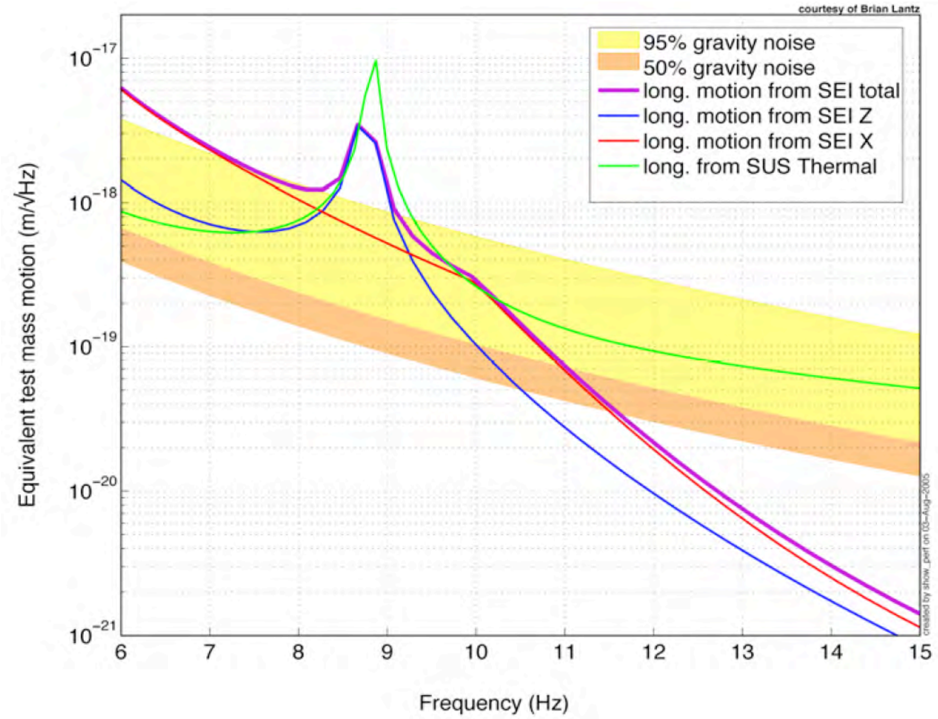


Fig. 8: Expected vibration noise at a seismically excellent site with Advanced LIGO design for vibration isolation. Filtered seismic noise is below the sensitivity goal above 12 Hz. The green curve represents suspension thermal noise and dominates above 10 Hz or so. So is the gravity noise from ground motion (changes in the gravitational field due to small motions of ground).

c) Control Systems and Electronics:

A large number of proximity sensors and force actuators are part of the suspended optics of the interferometer to precisely measure and control, in feedback loops, the positions and angles of the suspended elements, to 'lock' the interferometer for operation. This set includes photo-detectors, conditioning electronics, actuation electronics and conditioning as well as control software. Over 5000 channels of data streams are involved in the control and operation.

d) Data analysis algorithms and protocols, as used in the LIGO detectors:

The LIGO-India detector may initially work in the coincidence mode with the other LIGO-US detectors and for this the same data analysis strategies will be used. Since LIGO-India will be part of the global network, multi-detector data analysis strategies which have been developed and being incorporated into the data analysis pipelines in the global effort will be used eventually. The data rate will be about 20 MB/s without including mirrored data from other interferometers in the network. The algorithms rely heavily on FFTs and GPU based strategies are being experimented with, to handle the intense computing requirements. The actual computing requirements for the single detector can exceed several Teraflops. The initiative at IUCAA to start the data centre right away provides the ideal setting for handling these exceptional requirements.

e) Installation tooling and fixturing:

The assembly of the interferometer with the delicate and matched components require special installation fixtures and this set is part of the hardware available from LIGO.

9. Details of infrastructure development required from the Indian side:

a) Ultra-high vacuum vessels and tubes along with the pumping system and diagnostic tools:

This will be fabricated by the IndIGO team with designs from LIGO, with suitable modifications agreed upon by the LIGO laboratory to suit Indian manufacturing conditions and protocols. The Vacuum system consists of 8 kilometers of beam tubes of 1.2 meter diameter and very large corner/end stations. The total volume of the vacuum system is about 10000 m^3 and must be evacuated to an ultra high vacuum of 10^{-9} mbar. Many important technological developments will be implemented in the field of material processing, mobile fabrication, spiral welding tube fabrication, UHV compatible leak testing of large vessels, establishment of field facilities like clean rooms, mobile welding stations etc. All these developments will be implemented on scale unprecedented in India, such as the processing of about 1000 tons of UHV grade nonmagnetic stainless steel sheets required for the fabrication of beam tubes. In addition to this, procedures and protocols will be evolved to complete the jobs flawlessly, reliably and in the given time frame.

Subsystem and Parameters	**Advanced LIGO Reference Design**
Comparison With initial LIGO Top Level Parameters	
Observatory instrument lengths; LHO = Hanford, LLO = Livingston	LHO: 4km, 4km; LLO: 4km
Anticipated Minimum Instrument Strain Noise [rms, 100 Hz band]	$< 4 \times 10^{-23}$
Displacement sensitivity at 150 Hz	$\sim 1 \times 10^{-20}$ m/√Hz
Fabry-Perot Arm Length	4000 m
Vacuum Level in Beam Tube, Vacuum Chambers	$< 10^{-7}$ torr
Laser Wavelength	1064 nm
Optical Power at Laser Output	180 W
Optical Power at Interferometer Input	125 W
Optical power on Test Masses	800 kW
Input Mirror Transmission	1.4%
End Mirror Transmission	5-10 ppm
Arm Cavity Beam size (1/e^2 intensity radius)	5.3 cm on ITM 6.2 cm on ETM
Light Storage Time in Arms	1.7 ms
Test Masses	Fused Silica, 40 kg
Mirror Diameter	34 cm
Suspension fibers	Fused Silica Fibers
Seismic/Suspension Isolation System	3 stage active, 4 stage passive
Seismic/Suspension System Horizontal Attenuation	$\geq 10^{-10}$ (10 Hz)

Fig. 9. Advanced LIGO reference design summary (from Adv. LIGO document LIGO-M060056 v2). Vacuum and seismic attenuation exceed parameters specified here, improving reliability.

Major tasks involved are :

1. Fabrication of tubes:
    - Development and proofing of fabrication process for beam tubes.
    - Development of jigs and fixtures for automated tube fabrication.
    - Production of 20 m long, 1.2 m diameter Spiral welded SS tubes for UHV applications.
    - Cleaning of tubes
    - Welding of stiffeners and dampers.
    - Butt welding of expansion bellows
    - Machining of alignment monuments on each tube.
    - Leak testing of each 20 m tube to less than 10-10 mbar- l/s leak rate.
    - Butt welding of 20 m tubes together in the field to form 2 km long sections
    - Welding of flanges for gate valves of 1 m aperture at ends of each of the 2 km section.
2. Fabrication of Optics tanks to house the end mirrors and beam splitter/power and signal recycling optics vacuum pumps etc.
3. Development of baking equipment for the facility.
4. Development of fixed and guided supports for the beam tubes.
5. Development/procurement of large bellows to serve as expansion joints.
6. UHV qualification of prototype beam tubes up to full scale testing and development of related infrastructure (at least 10 UHV testing stations each having large Turbo Molecular Pump (TMP), Sputter Ion Pump (SMP), Leak Detector (LD), Residual Gas Analyzer (RGA) and vacuum gauges), so that the UHV qualification of each of the component may be completed in two years time.
7. Development of UHV laboratory at the site, to qualify each component of the facility, which is exposed to vacuum.

Primary responsibility for installing and running the vacuum system will be shared between RRCAT & IPR. All commercially available vacuum components such as flanges, gate-valves, pumps, residual gas analyzers and leak detectors will be purchased from standard UHV component and pump manufacturers under global tender. Fabrication of the beam tubes and optics stations will be done by a collaborative group of Indian companies such as L&T, Fillunger, Hindhivac, Godrej etc, under supervision of experts from RRCAT & IPR. The strategy is to combine the large volume manufacturing capabilities of companies like L&T and Godrej with UHV expertise of other smaller companies, under quality control and supervision of experts from national laboratories. However, during the development of UHV system many teams of four to five trained persons will be needed for the UHV qualification of the system.

b) Clean rooms:

Movable tent type clean rooms will be required during the welding of the beam tubes and assembly of the system and the final building will have to have to be a clean room with air conditioning (AC) and pressurization modules to keep dust out. SAC, ISRO can help with this part, as these are the type of facilities in which satellites are assembled and tested.

c) Site Selection & Civil Constructions:

BARC's Seismology Division can provide data regarding the seismic noise at various DAE sites. This data can be used to do initial selection of sites and then one or two sites can be narrowed down based on other considerations such as accessibility and remoteness from road traffic etc. DAE also has a Directorate of Construction, Services and Estate Management (DCSEM) which can co-ordinate the design and construction of the required civil structures required for the interferometer. The actual construction would be contracted to a private construction firm under the supervision of DCSEM with with technical assistance and guidance from LIGO.

10. Advanced Prototype Detector at TIFR:

A serious program of observational gravitational wave astronomy requires development of national facilities that match the technology and performance of global programs in the long run. Crucial to this is the progressive and systematic development of expertise in all relevant areas. With this in mind and with a definite proposal to conduct novel physics studies that involve extremely small forces and displacements, like short range gravity and Casimir force, a prototype interferometric detector is funded in TIFR, at the level of Rs. 260 lacs. The work to implement this high precision detector in about 3 years, with most technologies of the large scale detectors incorporated, is underway. This will be the IndIGO platform for research and development of the relevant technologies as well as the training platform for graduate student expertise required for the next generation upgrades.

11. Justification: LIGO-India- the unique scientific opportunity:

The scientific benefit of LIGO-India is transformational. The advanced interferometer detector located and operated in India will be transformational and rejuvenating for Indian astronomy and gravity research, bringing together the best of gravitational theory, astronomical source modeling, data analysis and computational strategy, precision instrumentation, high performance and high-throughput computing, and very importantly research-industry partnership for advanced scientific instrument building. It will also initiate the much needed development of expertise and human resource for the entire field of next generation astronomy.

Astronomy with gravitational waves requires that the sources that emit these waves are located and identified with precision. Among the first questions that must be answered about each gravitational wave observed is where it originates from on the sky. Since the interferometer detector by itself is not a telescope with such capability, the source has to be located by a network of three or more detectors with intercontinental baseline with capability of precision timing of the arrival of the signals. This, of course, is well established successfully in radio astronomy with global VLBI radio telescope networks. The international GW detector network answers this question by comparing the signals at widely separated detectors. The addition of LIGO-India to the international network offers a significant improvement in establishing the sky location of gravitational wave sources. Depending on signal to noise and the location on the sky, the accuracy of the position of a source can be 5 to 10 times better with LIGO-India than without it. In many places on the sky, using reasonable signal to noise, the uncertainty in position approaches 1 square degree; sufficiently small to enable electromagnetic astronomical identification of the source. This will enable gravitational wave sources to be studied using the tools of multi-messenger astronomy such as the Square Kilometer Array (SKA) radio telescope or optical telescopes.

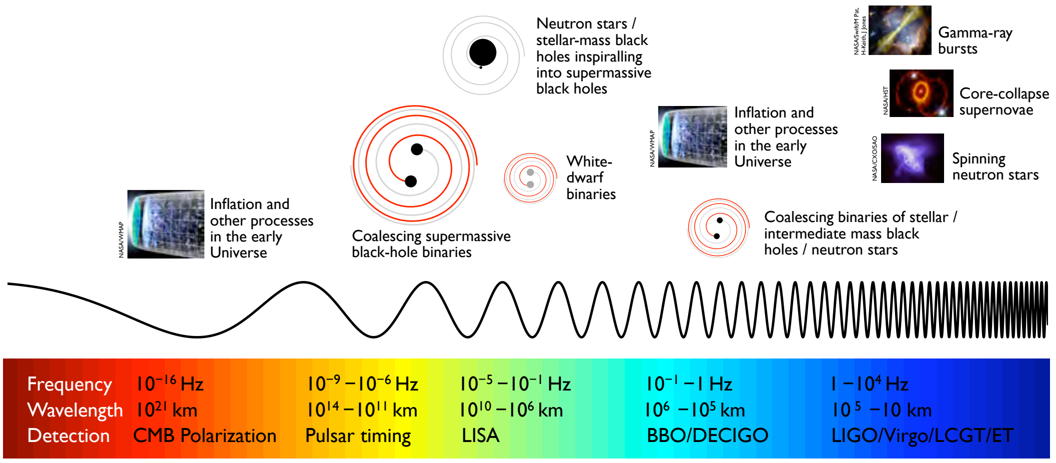


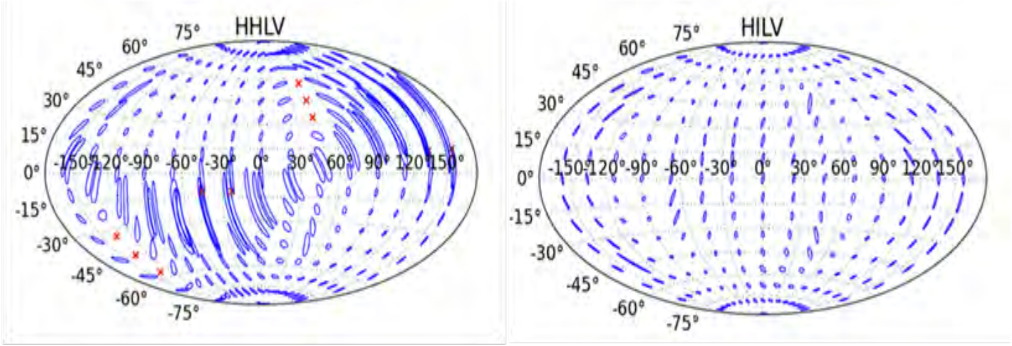
Fig. 10: The gravitational wave spectrum spans over 18 orders of magnitude in frequency.

The unique location of LIGO-India will give it high visibility and importance as a member of the international network. By leading this project, India would be a primary partner and a focal point in the field of gravitational wave astronomy, with its own state-of-the-art detector. Secondly, the sheer physical proportions of the experiment consisting of two 4 km arms at right angles with the most advanced and sophisticated technology in several fields will serve to landmark and motivate high technology based astronomy and physics research & development in India for the next two to three decades. The challenges of making such measurements requires the most sophisticated technologies in lasers, optics, vibration isolation, electronics, high speed and high volume computing, data handling and network communications, and engineering. Spin-offs to other science, engineering and industrial applications will provide unprecedented commercial opportunities for Indian industries and businesses in collaboration with research institutions and universities. These have the potential to seed technological spin-offs and justify the investment in the project, and to give the opportunity for Indian technology industry to be a global player.

12. Scope:

- Identifying and acquiring a seismically and gravitationally quite site, constructing of civil infrastructure and vacuum system needed to house the LIGO-India detector, and the required support systems to operate the detector for a period of 10 years.
- The LIGO-India detector will be one of the three Advanced LIGO interferometers currently in fabrication, and will be provided by the LIGO Laboratory to LIGO-India as part of the project.
- India will be responsible for relocating, installing and commissioning the components for the LIGO-India detector in India at no added cost to the LIGO Laboratory.
- Operation of the LIGO-India facility for ‘Science Runs’ over a minimum period of 10 years after initial commissioning for gravitational wave astronomy.
- Conduct workshops and meets during the construction phase (6 years) and the science run phase (10 years) of the project to draw and generate manpower for the project and fresh talent into science.

- Creation of an outreach centre at the detector site and at the associated University centres focusing on gravitational physics and on the physics and astronomy with gravitational waves.



Original plan
2 +1 LIGO USA+ Virgo

LIGO-India plan
1+1 LIGO USA+ Virgo+ LIGO India

Fig. 11: Maps of the sky comparing how accurately the positions of sources can be located without (left) and with LIGO-India (right)

13. Salient Scientific/Technical features of the Project:

The project aims to build a laser interferometer based gravitational wave detector with a displacement sensitivity of 4x10^{-20} m-Hz$^{-1/2}$ which should be able to detect gravitational waves emanating from astrophysical source with an event rate of 3 orders of magnitude better than the previous generation LIGO detectors. This greatly increases the probability of direct detection of gravitational waves. The technology for these detectors are at the limits of current capabilities and would push the current technologies of lasers, optics, electronics, vibration isolation, vacuum and instumenattion to new levels, motivating new R&D in these fields. Though a collaborative project with an international partner, unlike other similar collabolative projects the LIGO-India detector will be installed in India and a major part of the project money will be spent in India with components sourced from Indian industries. The LIGO Laboratory will contribute one set of LIGO components (Laser, optics, electronics etc as per Sec. 8) in lieu for the detector data during the science runs. This project also gives the Indian scientist access to detector data of LIGO-USA as part of the collaboration. This project is a timely opportunity to enter the field of Gravitational Wave Detection and Astronomy without the gestation period required for the component development and at a time when the detector sensitivity has reached the threshold for gravitational wave detection.

14. National Status:

Over the last two decades, India has contributed significantly to the international effort for detecting GWs on two fronts-- by making seminal contributions to source modeling at RRI under Bala Iyer and to GW data analysis at IUCAA under Sanjeev Dhurandhar. The group at RRI was part of an Indo- French collaboration for two decades to compute high accuracy waveforms for in-spiraling compact binaries from which the GW templates used in LIGO and Virgo are constructed. Designing efficient data analysis algorithms involving sophisticated mathematics has been the hallmark of IUCAA's efforts. Notable contributions include the search for binary in-spirals, hierarchical methods, coherent search with a network of detectors and the radiometric search for stochastic gravitational waves. Dhurandhar has collaborated with most international GW detector groups and has been a member of the LIGO

Science Collaboration. Tarun Souradeep, who has significant expertise in the analysis of Cosmic Microwave Background (CMB) data, has worked to create a bridge between CMB and GW analysis challenges. Most importantly, a generation of young GW researchers with post-doc experience at the LIGO, Virgo, GEO600, have returned to India in the past three years -- a couple more from Caltech are waiting in the wings. In particular, A. Gopakumar (TIFR) and K. G. Arun (CMI) have expertise in post-Newtonian modeling, dynamics of compact binaries and studying the astrophysical and cosmological implications of parameter estimation. R. Nayak (IISER-Kolkata), A. Pai (IISER-TVM), A. Sengupta (DU), and Sanjit Mitra (IUCAA) have extensive experience on single as well as multi-detector detection, parameter estimation strategies for LIGO-Virgo and LISA, time-frequency methods, hierarchical techniques, noise characterization schemes, veto techniques for GW transients, bursts, continuous as well as stochastic sources. Though not directly in GW experiments, C. S. Unnikrishnan (TIFR) has been involved in high precision measurements and tests related to gravitation. He and his collaborators have been involved in the study of weak forces especially gravity and the short range modifications of gravity using some of the most sensitive torsional balances and optical sensors. Several techniques related to precision laser spectroscopy have been implemented in his laboratory, including various electronic locking and stabilization techniques. G. Rajalakshmi (TIFR) and Suresh Doravari (LIGO-Caltech, at present) have multiple expertise: implementing experiments with torsion balances, atomic beams and optical systems to interfacing and programming for experimental control. A number of leaders in GW research internationally have emerged from IUCAA: B.S. Sathyaprakash (Cardiff), Sukanta Bose (WSU), S. Mohanty (UTB). We have close interaction with them and with other persons working on GW: Rana Adhikari at Caltech, USA and Badri Krishnan at AEI, Germany. Over the last three years significant steps have been taken in India to go beyond the contributions to theoretical signal predictions and data analysis methodology and jump start GW experimental activity in India. Prompted by the DST funded IASTC project, "*Establishing India-Australia collaboration in GW Astronomy*", five meetings were held at Kochi (January, 2009), IUCAA (August, 2009), Shanghai (October, 2009), Perth (February, 2010) and Delhi (February, 2011). Each had strong participation from international partners, besides Australia and India. The IndIGO consortium was conceived and launched in August 2009. The International Advisory Committee for the IndIGO consortium (see Annexure V) that consists of top representation from existing GW observatories was formed in November 2010. A document *"IndIGO: An Indian Initiative in GW Observations"* outlining a possible IndIGO road-map for GW astronomy was prepared and circulated to Directors of major research institutions and universities, IISER's and IIT's, and leaders of Indian science community. Unnikrishnan's group at TIFR was funded to build a laboratory scale (3 m) prototype with advanced technical features implemented in the large scale interferometric detectors, to help seed the experimental activity in GW and to take it forward to the point of meaningful collaborations. In 2010, with the Science Case study for LIGO-Australia and the NSF approval for it, a sharp deadline for ACIGA on LIGO-Australia emerged. Thanks to the Indo-Australian collaboration road-map that was already being explored and the strong GWIC endorsement for IndIGO's plans, a MOU was signed between IndIGO (on behalf of seven Indian Institutions) and ACIGA (on behalf of five Australian Universities) to seek funding from their respective governments towards LIGO-Australia. In the February, 2011 Indo-Australia meeting at Delhi on the Indian road-map for gravitational wave astronomy under the DST project, expert scientists from leading laboratories participated and after discussions passed a resolution to recommend Indian participation in LIGO-Australia. To this end in march 2011 IndIGO submitted a project outline for IndIGO participation in LIGO-Australia to DAE and DST with 15% contribution. In parallel, a LIGO-Australia proposal was submitted by the Australian consortium, ACIGA to the Australian Science Minister. While recognizing the scientific value of the proposal, due to funding limitations, it was perceived that LIGO-Australia was in danger of not being funded. At this juncture scientists in the LIGO Lab and IndIGO council began jointly exploring the possibility of a collaborative project in India.

On June 1 2011, the LIGO Laboratory USA offered (proviso NSF approval) to transfer to India a set of the advanced LIGO-interferometer components, as part of a direct Indo-US collaboration, providing the opportunity to leap-start gravitational wave research and astronomy in India. (Letter and Requirement Document to Dr. Kasturirangan with copies to Dr. S. Banerjee, Dr. T. Ramasami and Dr. Bala Iyer). The proposal envisages that IndIGO would identify and put together a technical team from Indian laboratories and identify industries for the construction and commissioning of the entire infrastructure including the ultra-high vacuum vessels and tubes required to house the interferometer at a suitable, gravitationally and seismically quiet site in India. A core team of 10-15 Indian scientists with allied expertise will spend significant time at the US LIGO sites working actively on different subsystems during the advanced LIGO installation and commissioning during 2012-2016, prior to the assembly of the LIGO-India detector. They will also create on the longer time scale sufficient manpower to operate LIGO-India as part of the global network of detectors for gravitational wave astronomy during the next two decades. On October 7, the LIGO Laboratory presented to a panel constituted by NSF the case for LIGO-India. In addition to six presentations from the LIGO-Lab there was a presentation on behalf of IndIGO by Prof Ajit Kembhavi, Director, IUCAA and member IndIGO National Steering committee.

In its close out statement the panel said *"The panel believes that the science case for LIGO-India is compelling, and reason enough to move forward in the near term with the understanding that there are a number of outstanding issues with funding, site selection, and selection of institutional leadership, top management and technical leadership that must be resolved before making a deeper commitment. We note that LIGO-India is the only option actively under consideration by the LIGO Laboratory."* Subsequently, on Oct 10, 2011, the Indian funding agency chiefs of DAE and DST received a letter from the Director of LIGO Laboratory that said **"The purpose of our letter is to inform you that as of October 1, 2011, the LIGO Laboratory is no longer pursuing Australia as a host country. LIGO-India is currently the only candidate for an overseas detector being evaluated by the LIGO Laboratory.....To avoid negative impact on Advanced LIGO, we have identified March 31, 2012 as the date by which we must make our final decision on LIGO-India."**

To assess the technical capability, staffing needs and scientific interest and enthusiasm for the LIGO-India project, there has been visits to the primary potential Indian Institutions (IUCAA, TIFR, RRCAT, IPR) in August 2011 under IUSSTF by Caltech Professor Rana Adhikari and also in October 2011 by a senior LIGO-Lab team consisting of Deputy Director Albert Lazzarini, Chief Scientist Stan Whitcomb, LIGO Hanford Site Head Fred Raab, and University of Syracuse professor Stefan Ballmer representing the LIGO Scientific Collaboration (LSC).

In parallel, on other important fronts IndIGO gained international acceptance and recognition. In July 2011, at its meeting during Amaldi9, the application of IndIGO for Membership of Gravitational Wave International Committee

(GWIC) was accepted and approved. In September 2011, the IndIGO proposal for membership of the LIGO Scientific Collaboration was unanimously approved.

15. Mode of Execution:

Work-plan for the LIGO-IndIGO collaboration

1) Nodal Centre: One government laboratory or university in India, which will serve as the lead institute, with overall responsibility for the execution of the project from the Indian side. An MOU between this organization and the LIGO Laboratory will be established, addressing the requirements from both sides for the collaboration. There may be a parallel agreement between the NSF (or other appropriate US government agency) and a corresponding Indian government agency. The primary governing agreement will be between the US and India only. Addition of other international participants at the scientific and technical level is possible and encouraged. They will require joint US/Indian approval. The proposed facility, henceforth referred to as LIGO-India (the Project), will be managed jointly by the IndIGO and the LIGO laboratory as an integrated part of the international LIGO network.

2) Staffing requirements: India will provide a complete team for the installation, testing and commissioning of the LIGO-India detector. The LIGO Laboratory will endeavor to help realize the instrument and to bring it to operation through advice and visits. LIGO-India personnel will participate in the installation, testing and commissioning of Advanced LIGO at USA in order to build the needed level of experience and expertise of the Indian team. The team will consist of a) LIGO-India Director, b) Project manager, c) Detector leader, d) Project system engineer and e) detector sub-systems leaders (about 10). Apart from these, the team in the detector wing of the project during 2012-14 will consist of about 10 Physics and Engineering post-doctoral researchers with expertise specific to different tasks, 12 engineers, 10 Ph. D students and 12-15 technicians. There will be additional expert engineers from the industrial partner for tasks in the infrastructure development. The number of post-doctoral researchers and Ph. D students will increase by a factor of 2 by 2018. The team for data analysis and computing will consists of 8 faculty level physicists, 12 post-doctoral researchers and 20 students by the time the detector becomes operational. Staff responsible for detector installation and commissioning will spend sufficient time at the US LIGO sites during Advanced LIGO installation and commissioning to become adequately familiar with the Advanced LIGO design to be able to complete installation and commissioning of LIGO-India with minimal assistance from LIGO Laboratory.

3**) Governance and Operational plan:** In order that LIGO-India contribute most effectively as a key element of the global array of ground-based interferometers, LIGO-India must operate seamlessly as a third LIGO observatory, subject to overall programmatic direction and oversight by the LIGO Laboratory Directorate in consultation with the LIGO-India Director, exactly in same way as are LHO and LLO, the US LIGO observatory sites. This operating mode will be carried out in full consultation with Indian host institute management and will recognize any local constraints in the same way that is done in operation of the US sites. The day-to-day operations of LIGO-India will be under the direction of the LIGO-India director. One member nominated by IndIGO and/or the LIGO-India lead institute will be appointed to the LIGO Program Advisory Committee (PAC). The PAC is the highest-level advisory body for the LIGO Directorate, and meets twice per year to provide advice over a range of scientific and programmatic topics. LIGO-India will have full representation in LIGO Laboratory management structures, equivalent to that the US LIGO observatory sites, to facilitate communications and decision-making. LIGO-India data will be fully part of the data utilized and accessed by the LIGO Scientific Collaboration (LSC). The scientific, engineering and operating staff from IndIGO will be LSC members, and will have full access rights to all data that are accessible to LSC members.

Early embedding of LIGO-India in a suitable national laboratory is identified as essential so that the LIGO-India Director and key project and operations staff can be recruited and/or hired and given appropriate authority and so the necessary business, employment, administrative functions, etc. can be provided for the project.

Fig. 12: The LIGO Laboratory comprises designated groups of scientists, engineers, and staff at the California Institute of Technology (Caltech), the Massachusetts Institute of Technology (MIT), and the two LIGO Observatories. The total staff of the LIGO Laboratory consists of approximately 180 scientists students, post-docs, engineers and technicians. Caltech and MIT share prime responsibility for the operation of the LIGO Laboratory and for the design and construction of upgrades, under the terms of a Cooperative Agreement between Caltech and the United States National Science Foundation (NSF).

16. Data Centre and data handling and analysis:

Data storage, retrieval and analysis constitute one of the most important components of the operation of the gravitational wave detector. IUCAA and RRI have contributed at the forefront to the international effort in gravitational wave research. While computing post-Newtonian corrections to the in-spiraling binary waveform has been the thrust of the effort at RRI, IUCAA has mainly focused on the data analysis aspects of the experiment. Source specific algorithms and data analysis strategies developed are in use in all gravitational wave detectors around the world and will form a major contribution from India to the future network as well. These efforts have developed skilled manpower in data analysis of about 20 people who hold responsible key positions in India and abroad. It is important to mention that for the past ten years until 2010, IUCAA has been part of the LIGO Scientific Collaboration (LSC) which consists of about 800 researchers world wide.

An IndIGO Data Center proposed to be set up in IUCAA, Pune is envisaged to be the core facility for data analysis of integrated astronomy of the future with gravitational wave astronomy as one major activity, apart from the analysis of data from Astrosat, CMB, Pulsar survey and general astronomy. It is planned to be set up as a Tier-2 data analysis centre of the LSC with several tens of Teraflops in computational resources along with several hundred Terabytes of storage for data archival. The centre will host the LIGO-India data as well as mirrored network data from other detectors. It will also test and implement GW search algorithms and routinely analyze the data from the worldwide GW detector network. The currently envisaged focus activities of the IndIGO data analysis groups include tests of general relativity, multi-detector coherent vetoes for transient GW searches, radiometer searches for stochastic GWs etc. Sections VIII and IX contains the details of the nature of sources and the data, as well as the details for the plans for the data centre respectively.

17. IndIGO participation in LIGO Scientific Collaboration (LSC)

Sanjeev Dhurandhar's decade long participation in LSC via IUCAA has been consolidated by the broader LSC participation by younger scientists in the IndIGO consortium with data analysis experience like Anand Sengupta, Rajesh Nayak, Archana Pai and K.G. Arun (See Annexure VI). Radiometric search for burst sources, implementation of the radiometric search for periodic sources, development of a veto for non-Gaussian noise in the coherent search for inspirals with a network of detectors and tests of Einstein's theory of gravity by GW observations are some of the projects to be undertaken. In addition a *Tier 2 GW Data Centre* is also being proposed as an IndIGO resource for LSC and in particular LIGO-India.

The IndIGO participation has been broadened to include experimental groups involved in the 3 m prototype (C.S. Unnikrishnan and G. Rajalakshmi) and planned R&D activities in technologies allied to GW experiments at RRCAT (Sendhil Raja). These activities are expected to lead to IndIGO participation in the future large scale 3G detector called Einstein telescope and in the space-based GW detector project LISA providing the Indian research community in gravitational research and the next generation of researchers enthusiastic about participation in the adventure of GW astronomy many opportunities over the coming decades.

18. Benefits:

- Direct detection of the elusive gravitational waves using these detectors would put GTR on a sound footing and would also serve as a new window for astronomy to study astrophysical phenomena well beyond the reach of electromagnetic waves.
- LIGO-India can be expected to be a focal point for gravitational wave detection in the Asian-Pacific region, involving many participating scientists, engineers and students from other countries.
- The LIGO-India project will be highly multi-disciplinary and will bring together scientists and engineers from different fields like optics, lasers, gravitational physics, astronomy and astrophysics, cosmology, computational science, mathematics, mechanical, electrical, electronics and civil engineering, vacuum engineering and surface physics etc.
- LIGO-India should also spur research in allied high technology fronts facilitating participation of the IndIGO consortium in different technological and scientific aspects of the third generation (3G) GW detector like the Einstein Telescope and later space detector like eLISA.

19. Human resource development:

- A project of this scale and long-term active life necessarily has a significant human resource development. For the LIGO-India initiative IndIGO has already taken steps to ensure country wide enthusiasm among young researchers and students.
- The IndIGO consortium will run a graduate school for training of Ph. D. students, a post-doctoral exchange program with LIGO and other detector

groups, to ensure engagement with new technology at expert level, and regular basic and advanced schools and workshops in GW detection and astronomy.

- It will actively seek to bring in experts as well as fresh researchers to this field by internationally visible involvement in the development of the LIGO-India detector.
- We expect that the IndIGO consortium will grow to over 100 active members including faculty, post-doctoral fellows, and research students by 2017, with 40% of them active in experimental areas. In addition, there will be about 20 technical staff with varied expertise in electronics and control systems, optics, ultra-high vacuum and project management. First detection and subsequent developments will increase this body with cutting edge technical and scientific expertise two-fold in another 5 years.

20. Spin-Offs in technology:

- The advanced gravitational wave detector is a power- and signal- recycled Michelson interferometer with internal Fabry-Perot cavities and operates at the quantum mechanical limit of displacement detection in its sensitive bandwidth. Hence it uses the ultimate in the technology of high power and yet ultra-stable lasers, ultra-polished optics with ultra-low scattering losses and absorption, ultra-high vacuum over unprecedented volumes and lengths with minimal pumping speeds, sophisticated steel welding and fabrication techniques, futuristic vibration isolation and precision control of position and angles below sub-nuclear dimensions.
- The possibilities for technology spin-offs are enormous as has been already demonstrated e.g., in the development of high power stabilized lasers, for the initial and Advanced LIGO detectors and their European counterparts.
- Future technologies that will be developed involve compact vibration isolation platforms, fiber based super-stable lasers, special optical coatings, novel computing configurations, etc.
- The possibility to use quantum technologies based on nonlinear optics and quantum correlations that are expected to be implemented in the upgrade to the advanced detectors brings a new dimension to light based detection techniques.

21. Financial outlay:

In terms of actual cost of the construction and operation of the detector in the context of the LIGO offer, this is a unique opportunity. An advanced LIGO-like detector and the associated facility are estimated to cost approximately $290 million in the site acquisition, construction, tests and commissioning. For LIGO-India, the US contribution will be in kind worth $140 M, comprising the full detector design and hardware of the detector. This is approximately half of the total cost, leaving the required funding in India for the construction and commissioning of the detector at about $150M, over the period 2012-2020 (Rs. 750 Crores). Operating costs of the detector facility as part of the network after the completion of facility construction are estimated at $6M (Rs. 30 Crores) per year, including the maintenance of the Indian data analysis network and multi-messenger astronomy initiative and IndIGO's science education and outreach initiatives which would be expected to continue for at least 10 years (Rs. 300 Crores). Thus the total project expenditure works out to be Rs. 1260 Crores, spread out over the next decade and half (2012-2027).

Thus with an expenditure of less than $252 million (Rs. 1260 Crores) over the next decade and half, India will have the opportunity to build and operate its advanced gravitational wave detector before 2020, which would have required about $350 million (Rs. 1750 Crores) in cost and further more several more years in terms of time for realization if constructed without the LIGO offer. The actual cost benefits is much more because of the continued creation of human resources with special expertise and advancement of high technology and spin-offs within the country.

The major funding in the XII Plan is Rs. 650 Crores for the construction of the Civil infrastructure and installation of the detector. During the XIII 5-year Plan (2017-22) the expected expenditure is Rs. 380 Crores, out of which Rs 280 Crores is for completing the construction and installation of the detector and the remaining Rs 100 Crores for continuous operation and maintenance. The XIV Plan will see mature gravitational wave astronomy with the LIGO-India detector. The projected operation cost for continuous operation and maintenance during this period (2022-27) is Rs. 230 Crores. Thus the total projected expenditure for 15 years spanning three plan periods from 2012 to 2027 is Rs. 1260 Crores.

For more information, see:

- GWIC: http://gwic.ligo.org/
- LIGO: http://www.ligo.caltech.edu/
- Virgo: http://www.Virgo.infn.it/
- IndIGO : http://www.gw-indigo.org/
- LIGO-Australia: http://www.aigo.org.au/
- LISA : http://sci.esa.int/lisa
- R.A. Hulse, and J.H. Taylor, *Discovery of a Pulsar in a Binary System*, Astrophysical Journal, 196, L51 (1975).
- C.M. Will, C. M., 2006, *The Confrontation between General Relativity and Experiment, Living Revs*. Relativity, 9, 3 (2006).
- B. Abbott et al., *LIGO: the Laser Interferometer Gravitational-Wave Observatory*, Rep. Prog. Phys. 72 , 076901 (2009); arXiv:0711.3041.
- M. Pitkin, S. Reid, S. Rowan and J. Hough, *Gravitational Wave Detection by Interferometry (Ground and Space)*, Living Revs. Relativity, 14, 5 (2011).
- B.F. Schutz, *Determining the Hubble Constant from Gravitational Wave Observation*s, Nature, 323, 310 (1986).
- B.S. Sathyaprakash and B. Schutz, *Physics, Astrophysics and Cosmology with Gravitational Waves*, Living Revs. Relativity, 12, 2 (2009).
- A. Freise and K. Strain, *Interferometer Techniques for Gravitational-Wave Detection*, Living Revs. Relativity, 13, 1 (2010).
- P. Jaranowski and A. Krolak, *Gravitational-Wave Data Analysis. Formalism and Sample Applications: The Gaussian Case*, Living Revs. Relativity, 8, 3 (2005).
- L. Blanchet, *Gravitational Radiation from Post-Newtonian Sources and Inspiralling Compact Binaries*, Living Revs. Relativity, 9, 4 (2006).
- M. Sasaki and H. Tagoshi, *Analytic Black Hole Perturbation Approach to Gravitational Radiation*, Living Revs. Relativity, 6, 6 (2003)
- F. Pretorius, *Binary Black Hole Coalescence*, in "Relativistic Objects in Compact Binaries: From Birth to Coalescence", edited by: Colpi et al., Springer Verlag, Canopus Publishing Limited (2007).
- M. Maggiore, *Gravitational Wave Experiments and Early Universe Cosmology*, Physics Reports, 331, 6 (2000)
- S. Fairhurst, *Source localization with an advanced gravitational wave detector network*, arXiv:1010.6192.

LIGO-India
THE PROJECT DETAILS

I. The Objective:

In collaboration with the world-leading Laser Interferometer Gravitational–wave Observatory (LIGO) and its International collaborators, the IndIGO Consortium proposes to establish at a suitable site in India the crucial Indian and the southern-most node of the International Gravitational wave observatory network. This involves setting up a 4 km x 4 km advanced interferometric gravitational wave detector in India with a spatial strain measurement sensitivity of 10^{-23} Hz$^{-1/2}$ (displacement sensitivity of 4 x10^{-20} m-Hz$^{-1/2}$) and operate it in coincident and/or coherent mode for a period of 10 years with the international network of gravitational wave detectors. The detector 'LIGO-India' will be operated as frontline instrument for gravitational wave astronomy involving observations of various astro-physical phenomena through the gravitational waves they emit. The IndIGO consortium seeks National Mega Project status and funding from DAE and DST for LIGO-India.

II. The challenge of gravitational wave detection

Just as Maxwell's equations predict electromagnetic waves, any theory of gravity consistent with special relativity like general relativity (GR) predicts gravitational waves, In general relativity, like electromagnetic waves, these time-varying distortions of space-time propagate through space at the speed of light[2], are purely transverse and have two polarizations (Fig II.1). Due to conservation laws of linear and angular momentum, dipole radiation of GW are forbidden in GR. Hence, in GR, gravitational waves are quadrupole waves: they arise from time varying mass quadrupole moments. Gravitational waves are produced by essentially all accelerating masses, at leading order through the change in the mass quadrupole. However, because of the weakness of the gravitational force (compared with other fundamental forces) producing a detectable gravitational wave requires huge masses, of the order of our sun or larger, and accelerations capable of producing very large velocities, approaching a significant fraction of the speed of light. In practical terms, these occur only for compact astrophysical objects including black holes and neutron stars, or cataclysmic events such as supernovae and even the Big Bang. In spite of carrying large energies, even the strongest predicted gravitational waves for LIGO-India create infinitesimal strains in space, at most 10^{-21}.

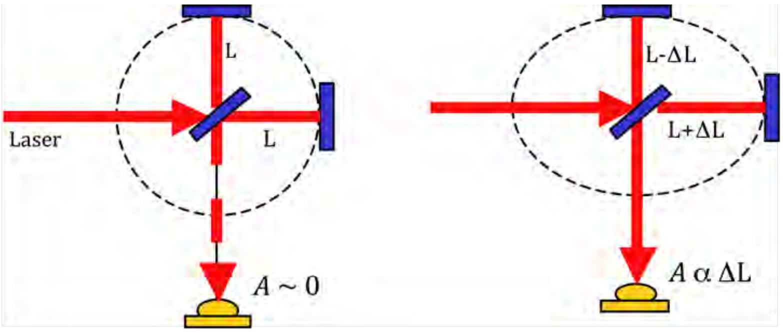


Fig. II.1: Laser Interferometers can detect Gravitational waves by probing the distortion of space. The optics of a Michelson interferometer plays the role of test masses, leading to a change in the length of the interferometer arms. The change in length results in change in the transmitted light at A.

We can detect a gravitational wave by measuring the change in separation of free masses it produces along the two polarization axes. The strength of a gravitational wave is given by its amplitude *h*, which is the fractional distortion of space which it produces, related to the change in separation of two test masses caused by the wave divided by their initial separation, $h = \Delta L / 2L$. While the gravitational wave shown schematically in Fig. II.1 has an amplitude $h \approx 0.2$, an actual gravitational wave might produce a strain in the detector's arms (the fractional change in length of the arm) of just 10^{-22}, or 1 part in 10,000,000,000,000,000,000,000! The corresponding absolute change in arm length caused by a gravitational wave will be on the order of 10^{-19} meters, or 1/10,000 the diameter of a proton[3].

The most promising technique for direct detection of gravitational waves is long baseline laser interferometry[4]. A Michelson interferometer has an ideal geometry to compare the strains along the two axes perpendicular to the direction of travel of the wave (Fig II.2), and offers the high sensitivity associated with an interferometric measurement. Moreover, one can make the arms long to increase the motion of the mirrors relative to one another and thus increase the sensitivity to h. Even so, with kilometer scale arms and a typical laser wavelength of 1 μm, the required sensitivity corresponding to a change in arm length of better than 10^{-19} meters is less than 10^{-13} of the wavelength of the laser. Moreover, we must protect the mirrors from any spurious (non-gravitational wave) sources of motion at the level of less than 10^{-19} m. This is the challenge of gravitational wave detection, one which has been driving precision measurement science for more than three decades.

To achieve the required sensitivity, the LIGO-India interferometer will be a sophisticated elaboration on the basic Michelson interferometer shown in Fig. II 2.

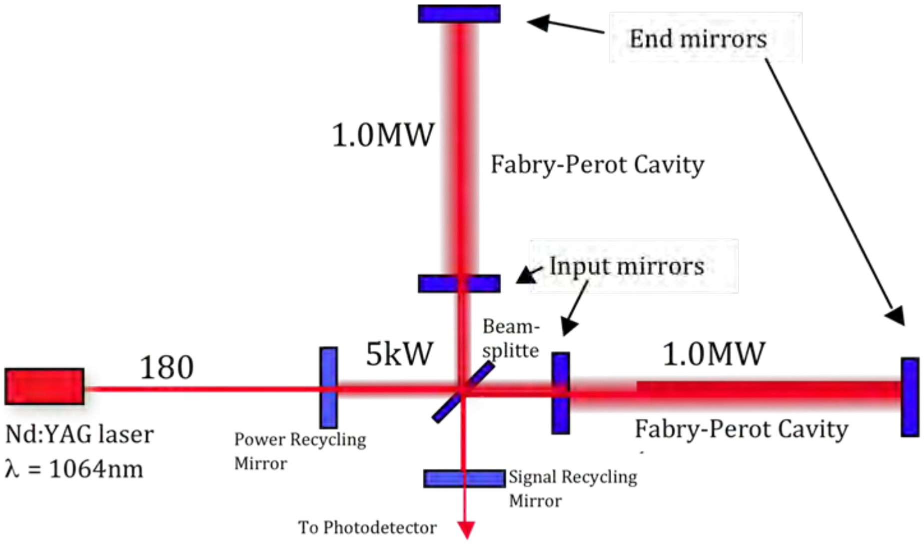


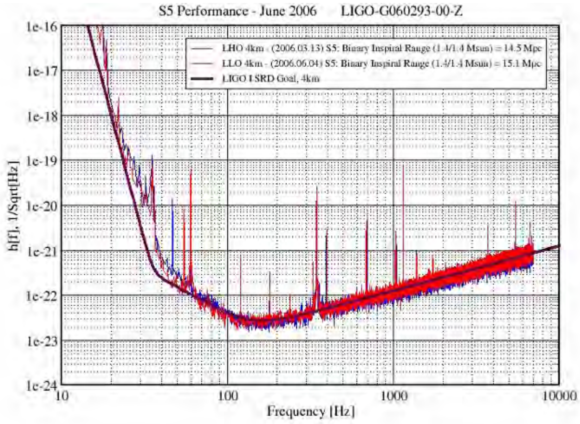
Fig. II.2: Schematic optical design of Advanced LIGO and LIGO-India detectors. Design features include the dual recycled configuration with Fabry-Perot arm cavities, a power recycling mirror, a signal recycling mirror and high power laser. The best sensitivity occurs when optical power on photo-detector is minimum and this allows power recycling of laser to reach optical power levels of 1 MW. All these improvements are needed for the sensitivity to reach $\Delta L/L=10^{-22}$.

It starts with the highest power laser that can be stabilized to the required level. Optical cavities in each arm reflect light back and forth between mirrors, building up the light intensity and increasing the phase shift for a given physical change in arm length. The interferometer achieves its best sensitivity when the phase of the light returning to the beam-splitter is such that the light on the photo-diode is near a minimum. This results in the majority of the light returning toward the laser.

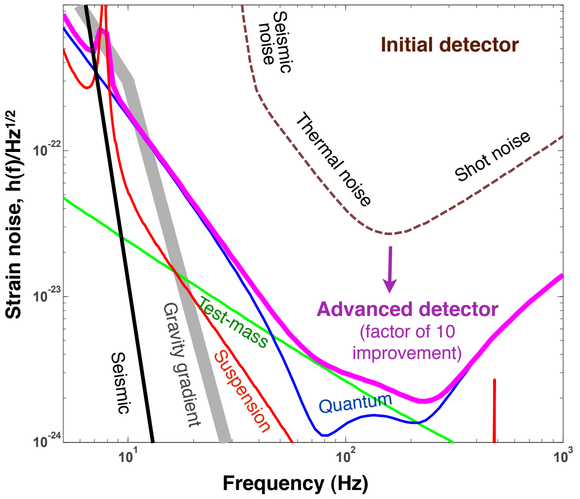
Another partially transmitting mirror, called the power recycling mirror, is positioned between the laser and the beam-splitter creating yet another optical cavity and further increasing the power in the interferometer. When a gravitational wave passes through the detector a tiny fraction of light from the arms is directed out toward the photo-detector Further, it has been shown that it is possible to improve the sensitivity of the detector by placing a suitably-chosen partially-reflective mirror (the signal recycling mirror) between the beam-splitter and the photo-detector This forms a resonant cavity for the signal light, and increases the signal build-up. Finally, the light leaking through the signal recycling mirror strikes the photo-detector, where it is recorded and processed by computer. To maintain optimal operation, all interferometer optics must be accurately aligned and located, in some cases with a precision of better than 10^{-13} m. Sophisticated digital servo control systems are used to maintain correct alignment and positions without introducing extraneous noise. This configuration is called a dual recycled interferometer[5].

Fig II.3 Initial LIGO has been a great success., and has shown that it is feasible to reach the sensitivity required.

Initial LIGO reached its design sensitivity of $h = \Delta L/L = 3 \times 10^{-23}\ \mathrm{Hz}^{-1/2}$.



The parameters influencing the sensitivity are fully understood, and the improvements in sensitivity of Advanced LIGO are directly traceable to known technology. The improvements required in each subsystem are indicated, resulting in the overall sensitivity of Advanced LIGO (solid pink line) compared to the achieved sensitivity of Initial LIGO (black dotted line).



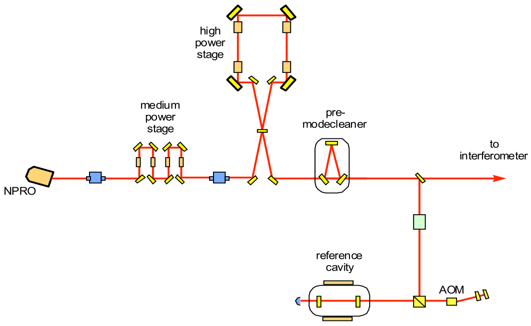
The 4 km initial LIGO detector, based on a simplified version of the above design, in 2005 reached its design sensitivity goal (set 15 years earlier) as shown in Fig II.3.. Having demonstrated this technological feat, the next step is to upgrade the detector to the Advanced LIGO[6], with a ten times better sensitivity leading to near-certain detection of frequent gravitational wave events. With new high power lasers, improved test mass material and coatings, advanced vibration isolation systems, and new detector configurations, such sensitivity is now attainable and the upgrade is in progress: the advanced LIGO detectors are now under construction, and LIGO-India will be such a detector. The improved predicted design sensitivity is shown in Fig II.3.

Needless to say, the extreme sensitivity of this interferometer places extraordinary demands on system components, including:

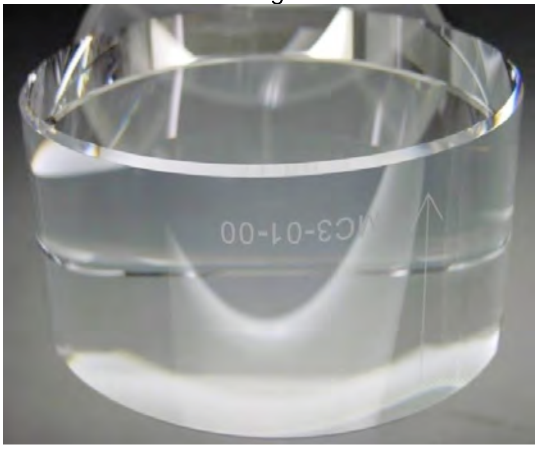
Pre-stabilized laser: The laser must have high output power, extremely low frequency and intensity noise, and be able to operate stably for long periods of time. This will contribute to the increase in stored optical power and hence the indicated reduction by a factor of ten in shot noise at high frequencies. The state-of-the-art laser system, developed and provided by LZH[7] and the Max-Planck Institute[8,9] as the German contribution to Advanced LIGO, produces 180W of power (Fig. II.4) It consists of a stable NPRO master oscillator laser, a 35 W amplifier followed by a high power injection locked oscillator. It also includes the pre-mode-cleaner, the high power mode cleaner and the control and diagnostics systems for the laser. It is stabilized to a level of $10^{-9}/\sqrt{\text{Hz}}$ in intensity and to 10^{-7} Hz/$\sqrt{\text{Hz}}$ in frequency.

Fig. II.4 The improved sensitivity of Advanced LIGO will be reached by improvements in many subsystems:

Pre-stabilized laser will be upgraded to 180W



The core optics will be ultra-pure 40kg fused silica polished to extreme precision and coated with ultra-low loss coatings.



A thermal compensation system will be included to correct for distortions of the core optics due to the high optical power. *Continued…*

Core Optics: The core optics consist of the four 40kg fused silica test masses, the suspended beam splitter, the recycling mirrors (power and signal) and the thermal compensation plates. The test masses and the beam splitter have very stringent requirements on optical homogeneity, surface figures, coatings and bulk absorption. Typical precision for surface figure is < 1nm (that is λ/1000, about 100 times better than required in most conventional high quality optics) and coating losses (scattering and absorption) must be correspondingly low (typically 10^{-5} – 10^{-6}). Some Advanced LIGO optics are coated at CSIRO[10], Australia.

Thermal compensation system: In spite of the stringent demands on the optical coatings, thermal distortions of the optics in the presence of the high circulating powers in the arms are expected to be too large to accommodate. To compensate for these distortions, an active system which monitors the surface figure using a set of Hartmann[11] wavefront sensors, will give real time correction by feed-back to the mirrors using ring heaters, thermal compensation plates and CO2 laser heater systems.

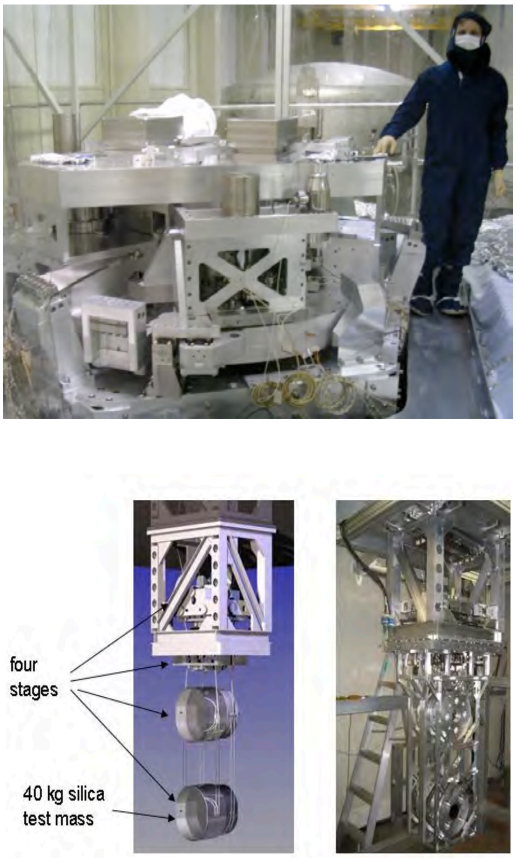
Another challenge in gravitational wave detection using laser interferometry is to prevent any non-gravitational source from moving the surface of the mirror. These include acoustic and seismic vibrations, electric and magnetic fields, and even thermal vibrations of the mirror and its suspension. This is achieved by enclosing the entire detector in a vacuum system, and by suspending the most sensitive optics on vibration isolators, designed to absorb all vibrations that could otherwise reach the mirrors. The vibration isolators developed for gravitational wave detection are the most advanced in the world and have many wider applications.

Vibration Isolation system: Three separate systems contribute to the vibration isolation[12,13]. A hydraulic external pre-isolator provides large actuation range and low frequency isolation. An active internal isolation system uses seismometers and geophones to provide six-degree-of-freedom isolation over a broad frequency range.

The final system is a four stage passive isolation system carefully designed with a monolithic fused silica suspension to minimize thermal noise. The fused silica suspensions systems have been designed and supplied by the UK as their contribution to Advanced LIGO. The different stages have been developed to optimize the overall isolation of the test masses from the environment, and the final system represents the state of the art in isolation today.

III. The LIGO-India facility

Fig. II.4 Continued: The improved sensitivity of Advanced LIGO will be reached by improvements in many subsystems:
The new vibration isolation system will be comprised of three stages: a hydraulic pre-isolator, an active internal isolator, and a final four stage passive isolator.



To house and operate this detector requires a facility meeting stringent and specialized requirements. The actual construction will in itself be a substantial engineering project, building Indian capability in the latest developments in large vacuum system engineering, welding techniques and technology.

The vacuum system: This is by far the largest and most critical single component. Without an excellent vacuum system the interferometer cannot work, and this system also forms the visual envelope and backbone of the instrument. The LIGO vacuum systems are amongst the largest in the world, with a pumped volume of 10000 m^3 (10 Mega-liters), evacuated to an ultra high vacuum**[14]** of 10^{-9} Torr. Building the vacuum system will include manufacturing the beam tubes, the tanks and all the essential vacuum components and pumps as well as the subsequent assembly, baking, leak checking and testing of the completed system.

The large beam tubes will be manufactured on site to avoid complicated and expensive transportation. The magnitude of this task can be appreciated by studying Fig.III.1, showing part of the spiral weld machines which must be constructed on the site and some of the tubes and tanks produced for LIGO.

A total of about 1000 tons of specially processed 304L stainless steel is required, delivered in 3 mm thick, 0.75 m wide coils. These will be formed into a helix and spiral welded into tubes, 1.2m in diameter. Each 20 m length will be fitted with stiffening rings on the outside and optical baffles inside. The total weld length for the whole system is about 50km, and it must be completely free of any leaks. The 20 m tube length from the mill must be fitted with expansion bellows and then installed on site. Sections will be joined by butt welding with ports at 250 m spacing for residual gas analysis (leak checking). Large flanges each 2 km, to accommodate large 1m gate valves, are required to isolate sections for bake-out and for installation of the tanks. In addition, the large optics tanks, vacuum pumps, gate valves and much peripheral vacuum system components and leak checking equipment must be procured and installed. The task will require real time quality control by experienced engineers and physicists, including vacuum leak checking, residual gas analysis and baking of the sealed system.

Site buildings: The detector is housed in three main buildings—a very large corner station and two smaller end stations. These buildings are high quality, clean and temperature regulated buildings to house the instrument. The corner station has approximately 1800 m^2 of high bay space covered by overhead cranes with a hook height of more than 8 m. Strict temperature control and cleanliness are essential. The functional requirements and floor plans are based on the LIGO buildings, but must be adapted to the site and to Indian building standards. The designs for the foundations, floors and body must minimize noise and vibrations, both from the air conditioning fans and outside wind.

In addition we require tube covers for the long vacuum arms to complete the instrument enclosure. The LIGO approach used concrete arches (Fig. III.1) We will explore alternative options appropriate to Indian site requirements. The beam tube foundations must be ready early on to receive the finished tube sections as they come off the mill. The rest of the buildings will be built mostly in parallel with the construction of the vacuum system, so that they are ready once the vacuum tanks and remaining system are ready for installation.

Cleanliness is one of the over-arching concerns for optics in high vacuum systems. The optics must remain ultra clean from any hydrocarbon contamination and free of dust which can act as scattering or absorption centers in the high power laser beam. To accomplish this we use a system of successively cleaner embedded spaces. The overall interferometer building is built with a special air-conditioning system using HEPA filters to remove nearly all dust particles. Whenever the vacuum system is opened, portable clean rooms are erected around all openings. The vacuum system itself is supplied with ultra-clean air and is over-pressurized to prevent any remaining dust particles form entering. Such techniques are applicable to many other areas, such as semiconductor manufacturing, space hardware preparation, etc.

Additional buildings house the control room, the computers, the personnel offices, and general support. (There will also be a need to build a large, temporary beam-

Fig. III .1. Producing the vacuum system will develop new capability in India.

A special beam-tube mill will be built on site to produce the two 4km, 1.2m diameter beam tubes, shown here producing a section of the tube. The finished vacuum system will be the largest in the region.

Tanks containing core optics

Spiral welded beam tubes, LIGO covers

tube manufacturing shed). These buildings are built to conventional office, laboratory or workshop standards, as appropriate.

IV. The LIGO-India Site Requirements

The minimum size requirement for the detector is a *L*-shaped site of arms 4 km and width 150 m. This is about 300 acres. The area should be seismically quiet and free of anthropogenic noise but close enough to reasonable infrastructure for facilitating national and international collaboration.

The gravitational wave detector involves the most accurate measurement of displacements of the order of 10^{-20} m (10 million times smaller than size of an atomic nucleus). The experiment needs to isolate itself from ground vibrations in 0.01-10Hz range --- generated through natural processes as well man made. Hence a few important points to be kept in mind while selecting the site are:

- No sustained heavy equipment, mining, blasting activity in the vicinity (30km) ongoing, or likely to start in the nominal 10-15 year life span of the experiment. Reciprocating power-plant machinery, rock crushers and heavy machinery should not be located within 16 km from the site, with a preferred distance of at least 40 km. Non-reciprocating power-plant machinery and balanced industrial machinery should not be located within 7 km from the site, with a preferred distance of at least 16 km.
- More than 10 km (preferably 16 km) away from any busy railway track active at present, or, possible in the next 15 year.
- More than 4-6 km from any major busy motor highway.
- More than 60 km from any major airport. More than 20 km from a not-so-busy (less than 5 flights/day) airport.
- The site should be at least 100 km (> 200 km preferred) away from the sea-coast.
- Involves cutting edge technology and would need to be readily serviced by highly trained technologists worldwide. Hence, the site should be within few hours drive from an international airport and preferably close to a major science and technology hub.

Fig. III.2. The detector will be housed in high quality clean and temperature regulated buildings, similar to those at the LIGO observatories:
A large central building, comparable to the LIGO building shown (but utilizing many sustainable energy features: see section 4.4) will contain detector, assembly areas and control room.

The detector must be assembled under ultra-clean conditions:

V. Operational Phase:

Following the completion of the LIGO-India commissioning in about 2019 continuous operation of the instrument will begin, with LIGO-India forming a critical southern most component of the world-wide gravitational wave observatory. Detector run planning will be done jointly with the other LIGO sites and Virgo[15]. Data will be collected and consolidated into a single dataset, distributed to computational centers around the world (including centres in India) for processing and analysis. Detector enhancements and upgrades will be researched and developed through the LIGO scientific Collaboration[16] (of which IndIGO and the LIGO Laboratory are members), and implemented in a coordinated fashion to optimize the scientific returns.

Based on actual experience from LIGO, and bearing in mind that this facility will operate around the clock, a dedicated team of operators, and resident scientists and engineers numbering about (50) full time people (including an Observatory Head) will be needed to maintain robust operation. Many of these staff members will be recruited from the local communities and trained to perform the specialized tasks necessary. In addition there will be numerous visiting scientists, and students, both from India and from abroad.

VI. Collaborator responsibilities:

The LIGO-India project is a joint effort by India and the US. Each partner has well-defined responsibilities.

- The LIGO Laboratory will provide all the components required to make one complete Advanced LIGO detector (including those already supplied by Germany, UK and Australia), except for a small set of items that had been planned to be shared between the two LIGO-Hanford detectors. In addition, LIGO will provide advice and past experience with the facilities design, training for LIGO-India staff who will be engaged in the detector installation and commissioning, and assistance in the event problems are encountered. LIGO site civil and vacuum designs will be provided to be replicated to the extent possible except for site-specific alterations and optimizations agreed to by the LIGO Laboratory. A joint committee consisting of members from LIGO-India and the LIGO Laboratory will review and approve the final designs for the vacuum system and the site buildings. This review is to ensure that all facilities meet the requirements to properly house and operate a sensitive Advanced LIGO detector.
- India would be responsible for providing all the required facilities to assemble, build, house and operate the interferometer, including highly specialized, modern buildings, the entire vacuum system, all laboratory components and equipment, utilities and accommodations for computers and staff. India would also be responsible for implementing and enforcing a QA / QC, contamination control, safety program at the site consistent with what is in place at LIGO-USA. This is a major high tech engineering and construction project and it must be built on schedule and subject to approval by a joint committee consisting of members from LIGO-India and the LIGO Laboratory. India will also be responsible for the assembly and installation of the LIGO-India detector, its commissioning, and subsequent operations. This will require a team of long term dedicated scientists and engineers, and very close collaboration with LIGO Laboratory for training and long term advice, as well as very close scientific collaboration.

A close collaboration between the LIGO Laboratory and the Indian gravitational wave community will help ensure that all aspects of the project will be well-coordinated and effectively carried out.

VII. The Science case for LIGO-India[17]

The primary scientific objectives of the LIGO-Virgo collaboration are the following:

- **Make a direct detection of gravitational waves:** Binary neutron stars are the most likely sources for a first direction of gravitational waves. The expected nominal rate of coalescences within the horizon of Advanced LIGO is about 40 events per year. The rate is highly uncertain due to unknown parameters in modeling these systems; it could be smaller or larger by about an order-of-magnitude. Even if the real rates are at the lower end of the predicted rates, advanced detectors are very likely to make detection within a few years of observation.

- **Constrain models of compact binary formation and evolution:** The current uncertainty in rate (some 3 orders-of-magnitude) will be greatly diminished by advanced detectors. In addition to making the first detection, advanced detectors will measure the rate to within a factor of a few in the local (i.e., <500 Mpc) Universe. This should then constrain models of the formation and evolution of compact binaries.

- **Detect binary black holes and neutron star-black hole binaries:** Advanced detectors could make the first ever detection of binaries containing a black hole. The merger rate of such systems is highly uncertain. Nevertheless, such systems will be a new population of astronomical sources and they have a great potential for a better understanding of cosmology and astrophysics.

- **Verify GRB-GW Association:** Advanced detectors will provide the opportunity to check if compact binaries, in which at least one of the companions is a neutron star, are progenitors of short hard gamma-ray bursts. Advanced detector networks will have a horizon of z ~0.25 to such inspirals and it is possible that a (small) fraction of the detected events are in coincidence with gamma-ray bursts. Short hard bursts are not seen at very low red-shifts and so it is possible that the LIGO-Virgo network will not observe any mergers in coincidence with GRBs. However, if their location on the sky could be measured accurately then it might be possible to identify afterglows in X-ray, optical or radio part of the electromagnetic (EM) spectrum.

- **Measure Hubble parameter to within 5%:** Compact binary inspirals are self-calibrating standard sirens. Gravitational wave observations can measure both the absolute luminosity of the source (which is determined by the binary's chirp-mass and the apparent luminosity (which is the strain measured by our detectors). Thus, we will be able to infer the luminosity distance to a source. To be useful as standard candles, it is necessary to identify the host and measure its redshift. Therefore, localizing the source on the sky is an extremely important prerequisite for advanced detectors in order to take advantage of the fact that we can measure the luminosity distance very accurately.

LIGO-India can positively impact each of these science objectives. In the rest of this section we discuss how improved signal/source reconstruction with LIGO-India can be achieved.

VII. A. Detector Networks

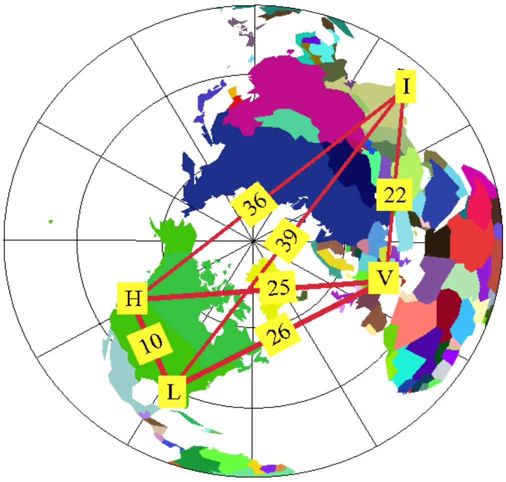


Fig. VII.1: Projected globe shows the available networks and their baselines. HHLV network has one 3-site network. HILV has four 3 site networks with a baseline that is 1.5 times longer than the longest HHLV baseline.The light-travel time (in milliseconds) of each baseline is also shown.

According to current plans, it is expected that by 2015 we will have an advanced detector network consisting of three LIGO detectors at two sites (two at Hanford and one at Livingston) and Virgo (see Fig. VII.1). We shall call this network HHLV. It is essentially a 3-site network and requires all four detectors to be operating in order to triangulate an event on the sky[1]. The baseline consists of arms that are (in light travel time) 10 ms for HL, 25 ms for HV and 26 ms for HL. By moving one of the Hanford detectors to India, creates a 4-site network HILV that consists of four separate 3-site networks with a far larger baseline, owing to arms with the Indian detector being 36 ms for HI, 39 ms for LI and 22 ms for VI. We shall designate this new detector HILV. Previously, we had also considered the benefit of moving one of the Hanford detectors to Australia. The baseline with the Australian detectors with each of HLV is very large: 40 ms for AH, 42 ms for AL and 37 ms for AV. We shall call the network formed by Australia and HLV as AHLV. Australia being in the southern hemisphere and antipodal to LIGO Livingston, creates the longest possible baseline with LIGO detectors.

In what follows we shall consider two 4-detector networks HHLV and HILV and four 3-detector networks, HIL, HIV, HLV, ILV, and study their ability to measure parameters of a source. We will also compare some of our results for the 4-detector networks with AHLV.

VII. B. Sources considered in the study

Binary neutron stars are the most promising sources for a first direct detection by the advanced detector network. We shall, therefore, consider a population of binary neutron stars all placed at a luminosity distance of D_L = 200 Mpc, which is the distance reach of advanced LIGO averaged over binary orientation with respect to the line-of-sight and sky position. We take 1000 binaries, each consisting of a pair of neutron stars of mass $m_1 = m_2 = 1.4\ M_\odot$ (total mass $M = 2.8\ M_\odot$ and symmetric mass ratio $\nu = m_1\, m_2/M^2 = 1/4$), in a quasi-circular inspiraling orbit. We place them at random locations on the sky uniformly distributed over the sky, with random polarization angles and inclination angles of the binary orbit with the line-of-sight.

For each source and different networks we then compute the signal-to-noise ratio ϱ as well as measurement accuracies of the chirp-mass $Mc = M\,\nu^{3/5}$ (which happens to be the best-measured binary parameter), the symmetric mass-ratio, the luminosity distance, the sky resolution, the inclination angle, the polarization angle, the time-of-coalescence and the phase of the waveform at that epoch. Thus, our Fisher matrix is a 9 x 9 matrix and care should be taken in computing its various elements and in inverting it to obtain the covariance matrix. Our comparison of different networks is largely based on the results from the computation of the covariance matrix.

The Fisher matrix analysis is a local analysis, which is valid only in the limit of large signal-to-noise ratio. Moreover, it does not capture parameter degeneracies and other complexities that might be present in the likelihood surface. We have, therefore, used a Bayesian parameter estimation method to compute posterior distribution of the same nine parameters but over a smaller portion of the parameter space. This allows us to make a qualitative study of the different networks.

Since the angular resolution of the detector networks is very critical for advanced LIGO science we have also used the time-of-arrival information to compute the angular resolution. This latter method is fully analytical and hence complements our Fisher matrix and Bayesian parameter estimation results. Let us begin by looking at the results of our study for sky localization.

VII.C. Relative merits of HHLV and HILV for measurement

We will now consider the relative merits of the various detector networks in measuring the parameters of a source.

(a) Angular resolution of the networks: The diffraction limited angular resolution of a detector of baseline L, using radiation of wavelength λ, is $\Delta\theta = 1.22\,(\lambda/L)$ radians. This is can be thought of as a 1-sigma error in one of the angles to triangulate a source that produces a signal-to-noise ratio of 1 in our detector. Starting from this, one can make a rough estimate of the 90%-confidence angular sky area to be $(\Delta\theta)2 \sim 10$ sq deg., taking the minimum SNR of a detected event to be 10, the wavelength of radiation to be 300 km and the baseline to be 14,000 km. More detailed calculations show this to be roughly correct. A minimum of 3 detectors is required to resolve a source on the sky and as expected the resolution gets better both because of longer baselines and greater number of sites. Fig. VII. 2. plots the 90%-confidence regions in estimating the position of a source as a function of the source location on the sky for the 4-detector networks HHLV, HILV and AHLV. In Fig. VII.3. we also plot the cumulative histogram of the 90%-confidence sky areas (in square degrees) computed using Fisher matrix analysis for four 4-detector networks and four 3-detector networks. It is obvious that due to its short baseline, HHLV has a very poor localization of sources, sometimes the 90% confidence region being hundreds of square degrees. This is especially so for sources lying close to the plane of the three sites. Even the best survey telescopes might not be able to follow-up on identifying the host galaxy within the 90% confidence region in a significant portion over the sky. A fourth site that is not in the plane formed by the three LIGO and Virgo sites, and far away from all of them, greatly improves source localization ability. We see that HILV could resolve the sources by an order of magnitude or more in certain regions of the sky as does AHLV. For 50% of the sources, the 90% confidence region is 5 square degrees for AHLV and 8 square degrees for HILV, as opposed to about 30 square degrees for HHLV.

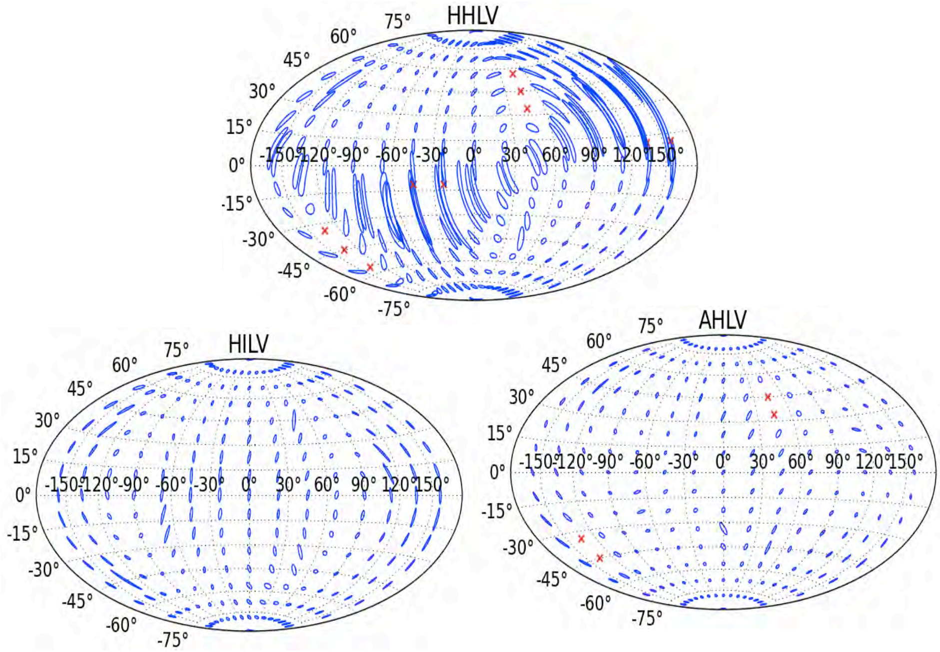


Fig. VII.2. Angular resolution of various networks depicted in terms of error ellipses on the sky within which the source has a 90% likelihood of being found for HHLV, HILV, AHLV.

In addition to providing a better localization of sources, HILV (and also AHLV, but not shown here) resolves degeneracies in parameter estimation. An example of this is shown in Fig.VII.4. where we plot the likelihood surfaces for the joint distribution of RA and DEC. The likelihood is bimodal for the three-site network of HHLV when the source happens to lie in a certain region of the sky, as in this example. The sky position is strictly bimodal in the case of a 3-site network, if only timing information is used to triangulate the source. This is because, for a source with certain time-delays in a 3-site-network, there is a source that is antipodal to it with respect to the detector plane that causes exactly the same time delays and hence indistinguishable. However, additional information (the difference in antenna pattern and polarization) in the waveform, that depends on the source position on the sky, breaks this degeneracy even in a 3-site network over a large fraction of the sky, but the degeneracy remains over a significant region. This degeneracy is completely resolved when a fourth site is included. Luminosity distance and orbital inclination with respect to the line-of-sight are two other parameters for which degeneracies are resolved in a 4-site network, which impacts key science objectives of the advanced detector networks.

(b) Why is sky localization such a big deal?[18]

Detection Majority of the science goals rely on good angular resolution of the source. For instance, accurately locating the source position on the sky helps in identification of the host galaxy, which impact confirming first detections of not only gravitational radiation but also binary black holes, but also mixed binaries consisting of neutron stars and black holes: Association of a specific galaxy with first events greatly enhances detection confidence. Moreover, binary black holes will be a new type of source; it is important to know where they form, what their environment is, etc.

Cosmology Host galaxy identification is critical for cosmology. It is well known that compact binaries are standard candles and can measure the luminosity distance but they are not able to measure the redshift. Host galaxy gives the source's redshift and hence one will be able to measure the Hubble parameter and, with future detectors, other cosmological parameters.

Astrophysics In astrophysics, host identification helps verify that binary neutron star mergers are progenitors of short hard gamma ray bursts. With good source position, one should be able to carry out follow-up observations to hunt for afterglows associated with GW emission in x-ray, optical and radio. Galaxy type and environment and their relation to binary mergers will be very important for testing models of compact binary formation and evolution. Once the host is identified, can use that as prior information to improve measurement accuracies of other parameters. For instance, estimation of distance gets better, as also the source orientation and polarization angle. Finally, tighter constraints on the parameters will help test GR to a greater degree of depth.

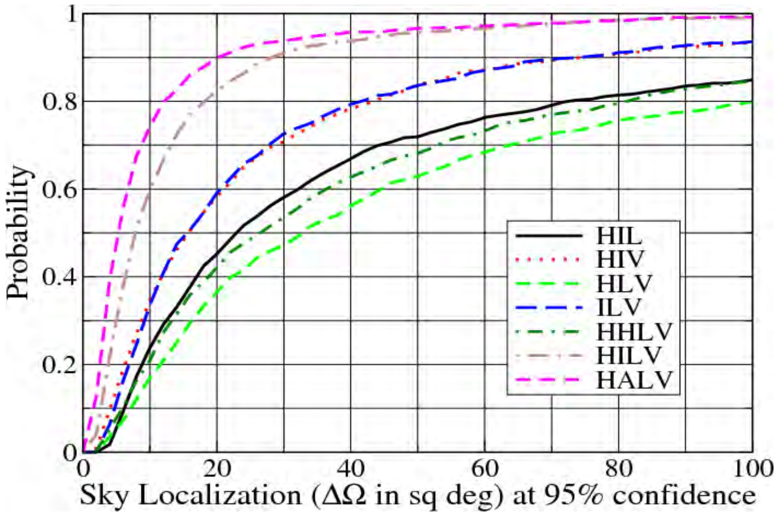


Fig. VII.3: Cumulative probability-density of 90% confidence region within which the source is localized. There is a 50% chance that the source that is randomly selected from the catalogue is localized to within 5 sq.deg in AHLV, 8 sq. deg. In HILV, and 30 sq.deg. In HHLV.

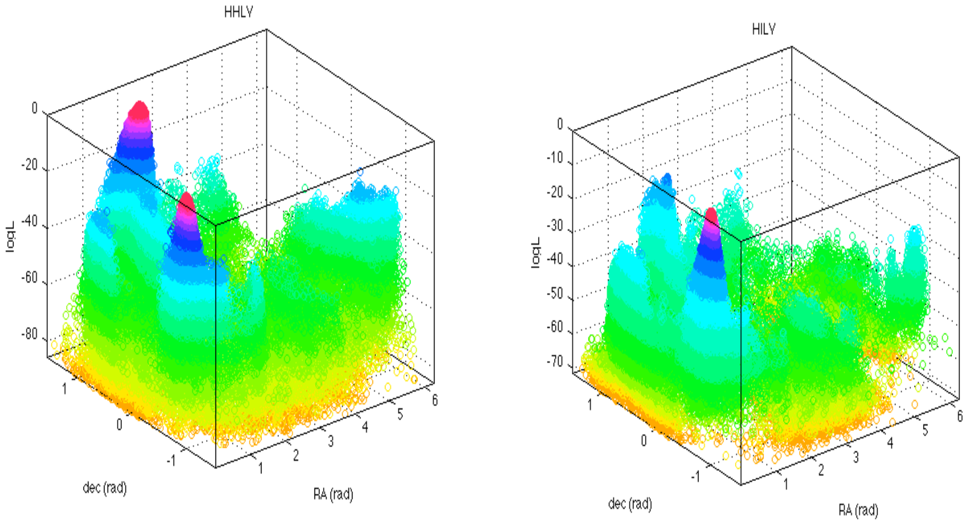


Fig. VII.4: Degeneracy in sky localization in HHLV (left) is broken when a fourth site is available in the network (right) as shown by the likelihood of the source location estimated by a Bayesian MCMC simulation.

(c) Network visibility

Fig. VII.5. (Left) plots the cumulative distribution of the signal-to-noise ratio (SNR) for different networks, namely the probability that the SNR is larger than the value on the horizontal axis. We have assumed that the analysis is carried out by coherently combining the data from different detectors and have shown coherent SNR for different detector networks.

The key result is that on average the 4-detector networks of HHLV and HILV both have the same signal visibility, the SNR being 14.0 or more for 50% of the sources. 80% of the sources will have an SNR of larger than 10.0. Just as 4-detector networks, all 3-detector networks also have the same visibility, the SNR being 12.4 or more for 50% of the sources; this is a fraction 0.9 of that for 4-detector network and hence 3-detector networks will have a volume coverage that is 70% that of 4-detector networks.

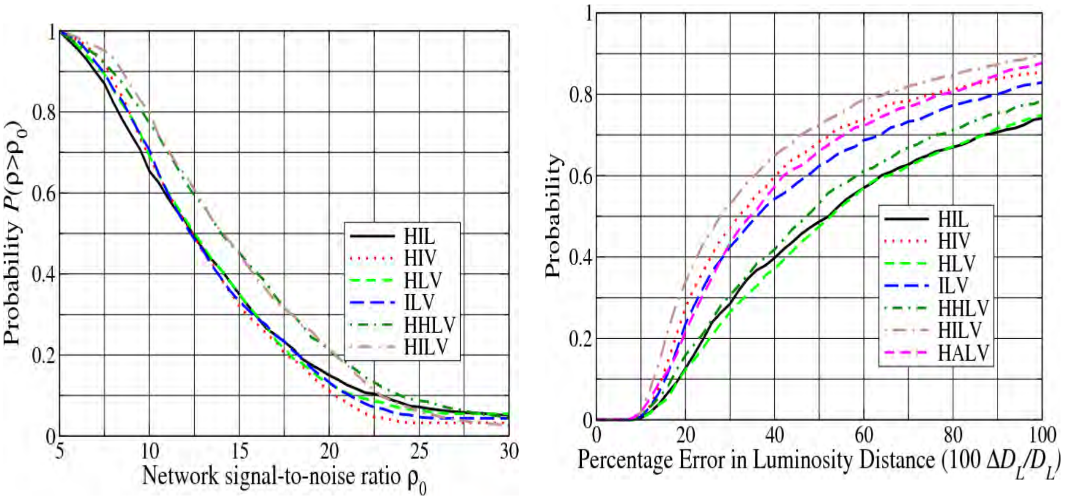


Fig. VII.5. Cumulative distribution of signal-to-noise (snr) ratios for various networks (left panel) and measurement of luminosity distance to the binary neutron star source (right panel). The 4-detector networks both have the same snr as do the 3-detector networks.

(d) Measurement of the luminosity distance

Measuring the distance to a source is tricky in astronomy but gravitational radiation from an inspiraling binary is a standard candle and our detectors measure both the source's absolute luminosity, which depends on the rate at which the system's frequency increases, and apparent luminosity, which is the strain caused by the radiation in our detectors. Thus, one can infer the luminosity distance to a source. Fig. VII.5. (Right) plots the measurement accuracies of the distance for various detector networks. We see that there is considerable improvement in detectors with long baselines. This is true irrespective of whether the network consists of 3 sites or 4. As expected, HILV can measure distances to binary neutron star sources to a fraction accuracy of 30% for an arbitrary source.

What is remarkable is that the three-site network of HIV can also have a similar accuracy, followed by ILV. The most significant factor for the improvement is that a longer baseline not only helps in improving the angular resolution, it also facilitates, as we shall see below, in a better measurement of the binary's orbital orientation with respect to the line-of-sight. Since the luminosity distance and orbital inclination are strongly correlated, breaking that degeneracy helps in a more accurate measurement of both parameters.

(e) Binary Orientation and Polarization Angle

Fig. VII.6. plots the cumulative distribution of the error in the inclination angle (left panel) and the polarization angle (right panel). These two angles together define the orientation of the binary with respect to the detector coordinate system: ι is the angle between the radial vector connecting the detector to the binary and binary's orbital angular momentum; Ψ gives the orientation of the semi-major axis of the binary's circular orbit, projected onto a plane perpendicular to the line-of-sight. An accurate measurement of these two angles is necessary to fully reconstruct the source.

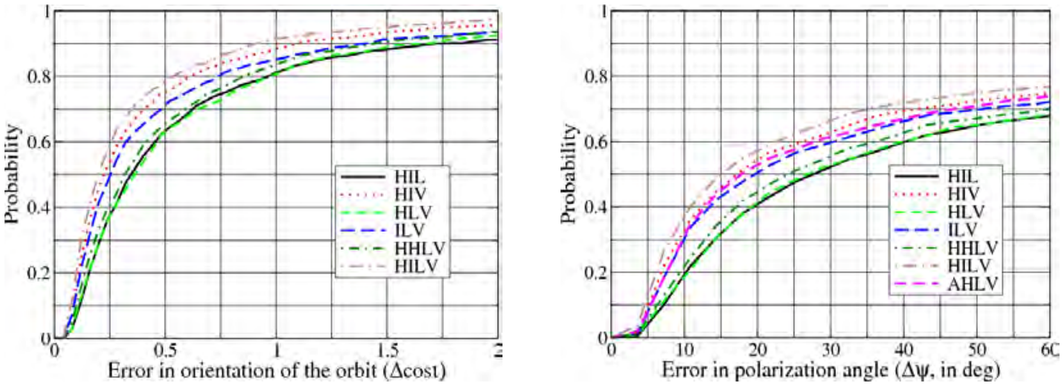


Fig. VII.6. The cumulative probability density for measurement accuracy of orbit orientation (left) and polarization angle (right).

The 4-site network improves the determination of the orientation by a factor of 2. Since orbital inclination is considerably degenerate with the luminosity distance, the superior performance of HILV also helps in determining the luminosity distance slightly better. Moreover, measuring the inclination of the orbit to a higher precision can be helpful for testing gamma ray burst models: binaries with gamma-ray counterparts should be observed to be face-on systems.

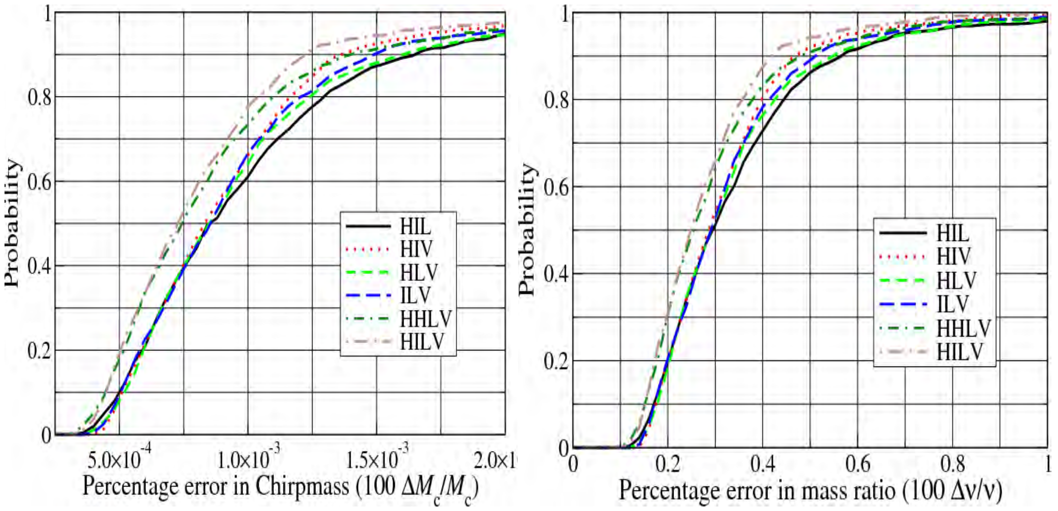


Fig. VII.7. The cumulative probability density for measurement accuracy of chirp-mass (left) and symmetric mass ratio (right).

(f) Measurement accuracy of mass parameters

Fig. VII.7. plots the cumulative distribution of the percentage error in the chirp-mass (left panel) and the symmetric mass ratio (right panel). More specifically, the plots give the probability that the error is smaller than the value on the horizontal axis.
At 50% probability, the errors for 4-detector networks are about 15% smaller than they are for 3-detector networks. This is almost entirely due to the larger SNRs of the 4-detector networks. The HILV network has slightly better parameter accuracies than the HHLV network, since a 4-site network breaks degeneracies between the binary masses and the luminosity distance that is present in a 3-site network.

Accurate measurement of the binary masses helps in testing general relativity in different ways. For instance, from the results obtained, one can deduce that the total mass can be typically measured to better than 2 parts in 1000. In comparison, the mass lost by the system to gravitational radiation could be as high as 3% of its total mass, far larger than the accuracy with which we can measure the total mass of the binary before merger. Thus, it might be possible to observe the effects of mass loss during an inspiral. Preserving such measurement accuracies is an important science goal in any planned alteration of the network. We conclude that there is essentially no improvement or any deterioration in the ability to measure intrinsic parameters when one of the Hanford detectors is moved to India.

(g) Duty cycle

If we assume that each detector has a duty cycle of 80%, and that the duty cycles of the two Hanford detectors are not independent, then the duty cycles of networks consisting of 1, 2, 3 and 4 sites is given in Fig. VII.8. A minimum of 3-site is required to triangulate a source on the sky. The HHLV network consists at most of a 3-site network and its duty cycle for this configuration is 0.51.

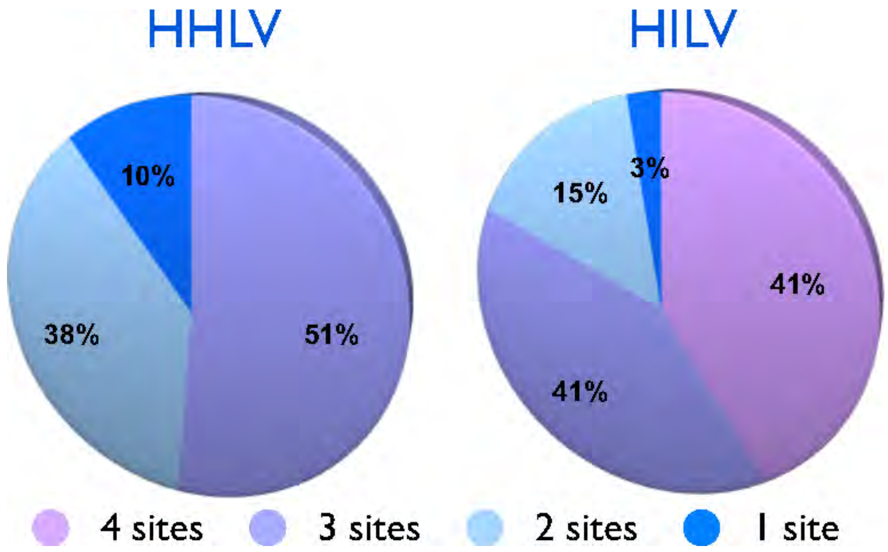


Fig. VII 8. Comparison of duty cycles of networks with 1, 2, 3, 4 sites.

HILV, on the other hand, is a 4-site network and so consists of one 4-site configuration with a duty cycle of 41% and four 3-site configurations with a duty cycle of 41%. Thus, the duty cycle for HILV with three or more sites is 82% as opposed to 51% of HHLV.

Improvement in the operation of the two Hanford detectors may allow future analyses to include data from one of the detectors when the other is not in lock. It is then possible to treat the duty cycles of the two detectors to be completely independent. In this case, the joint duty cycle of 3-site networks in HHLV rises to 61%, still 25% less than the HILV's joint 3- and 4-site duty cycle.

From a purely detection point of view, we should be able to identify events in coincidence in two or more detectors at different sites. The common environmental noise makes it very difficult to be confident about an event that occurs only in the two Hanford detectors. The duty cycle for detection then is nearly 90% in HHLV and 97% in HILV.

A similar simulation has been performed for unmodeled burst sources to investigate the network antenna pattern (network efficiency to capture the signal and uniformity across the sky) and network alignment factor (ability to detect both GW polarization states). Accuracy of source localization of various networks has also been studied[19]. The results are indicated in the following set of figures (Figs. VII.9.-VII.12.) results which also include the Japanese detector LCGT.

Recently, Bernard Schutz[20] carried out a detailed study of detector networks based on certain figures-of-merit (FOMs). The Table VII.1 summarizes his results. The various quantities defined in the Table have the following meaning: The *mean horizon distance* is the maximum detection distance, scaled to the mean horizon distance (maximum range) of a single detector observing at the same threshold. *Detection volume* is the volume inside the antenna pattern, on the same scale. *Volume filling factor* is the ratio between the detection volume in column 3 and the volume of a sphere with radius equal to the maximum range in column 2. The remaining columns are the FOMs: *Triple detection rate* measures the overall detection rate and is given for two different values of the duty cycle: 80% to represent a likely figure at the start of operations, and 95% to represent a reasonable long-term operation goal. The values of triple detection rate are smaller than the detection volume by factors representing the loss of 3-site observing time to duty cycle downtime. *Sky coverage* measures how isotropic the network antenna pattern is. *Directional precision* reflects angular accuracy: the typical solid angle uncertainty is inversely proportional to directional precision, so that larger values denote more accurate networks. The first row of the table is for a single detector, to facilitate comparisons.

Network	Mean Horizon Distance	Detection volume	Volume Filling Factor	Triple Detection Rate (at 80%)	Triple Detection Rate (at 95%)	Sky Coverage	Directional Precision
L	1	1.23	29.00%	-	-	33.60%	-
HLV	1.43	5.76	47.00%	2.95	4.94	71.80%	0.68
HHLV	1.74	8.98	41.00%	4.86	7.81	47.30%	0.66
AHLV	1.69	8.93	44.00%	6.06	8.28	53.50%	3.01
HHJLV	1.82	12.1	48.00%	8.37	11.25	73.50%	2.57
HILV	1.57	8.77	54.00%	5.95	8.13	79.00%	2.02
AHJLV	1.76	12.1	53.00%	8.71	11.25	85.00%	4.24
HIJLV	1.63	12	66.00%	8.64	11.1	100.00%	3.02
AHIJLV	1.85	15.8	60.00%	11.5	14.69	94.50%	4.88

Table VII.1. Mean horizon distance, detection volume, volume filling factor, triple detection rate, sky coverage and directional precision for different networks.

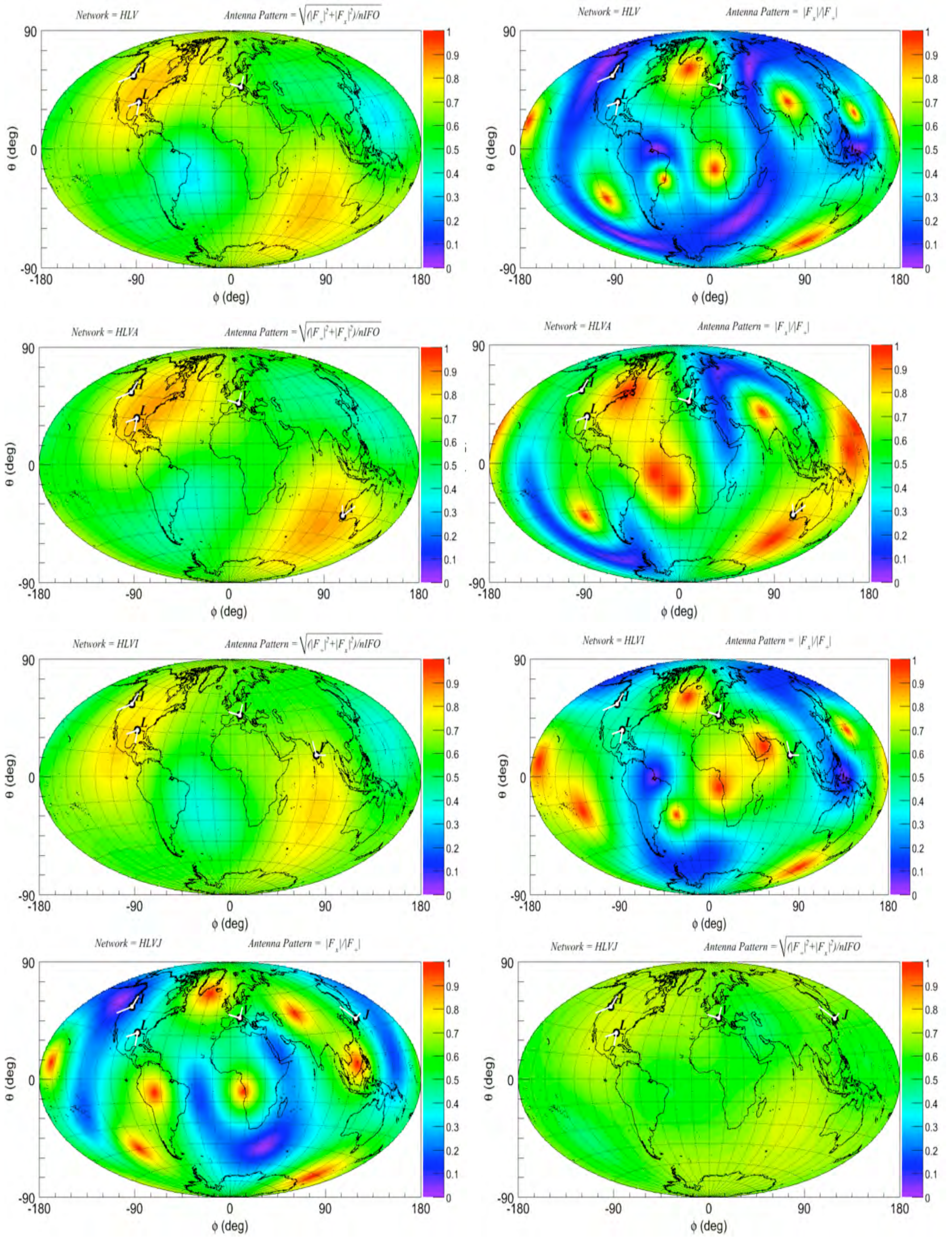


Fig. VII.9. Network sensitivity (network efficiency to capture the signal and uniformity across the sky) and alignment factor (ability to detect both GW polarization states) for detector networks HLV, HLVA, HLVI and HLVJ.

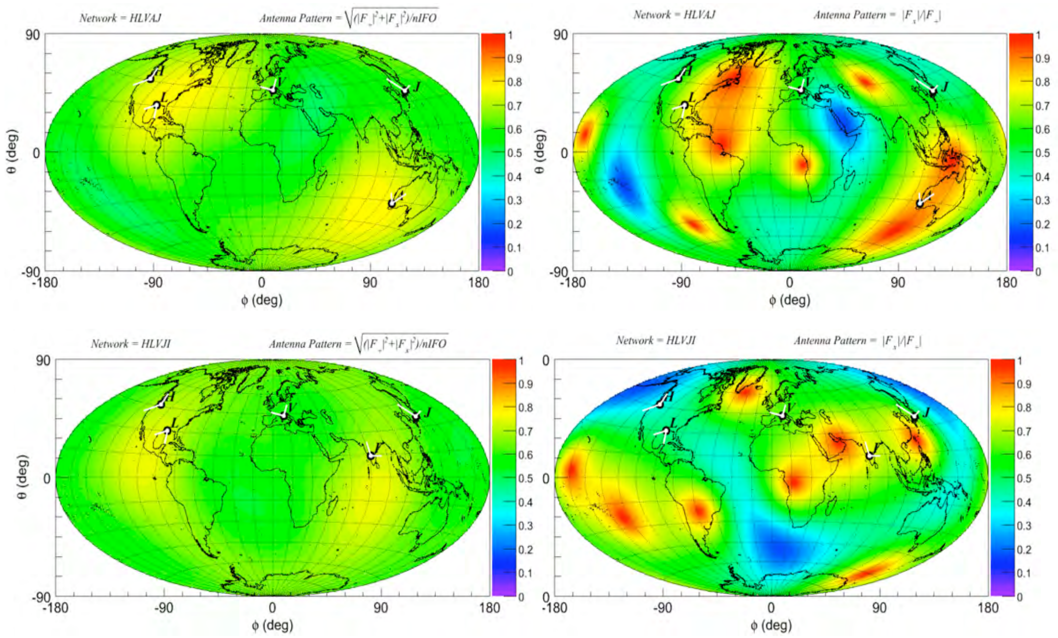


Fig. VII.10. Network sensitivity and alignment factor for detector networks HLVAJ, HLVIJ.

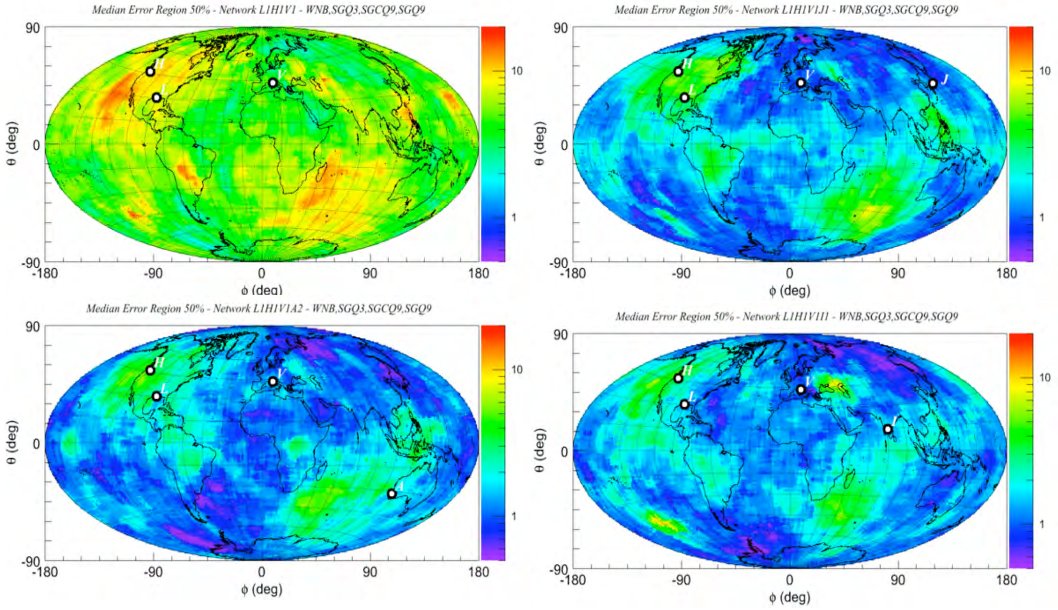


Fig. VII.11. Distribution of median error angle (color scale in degrees) across the sky for networks HLV, HLVJ, HLVI and HLVA.

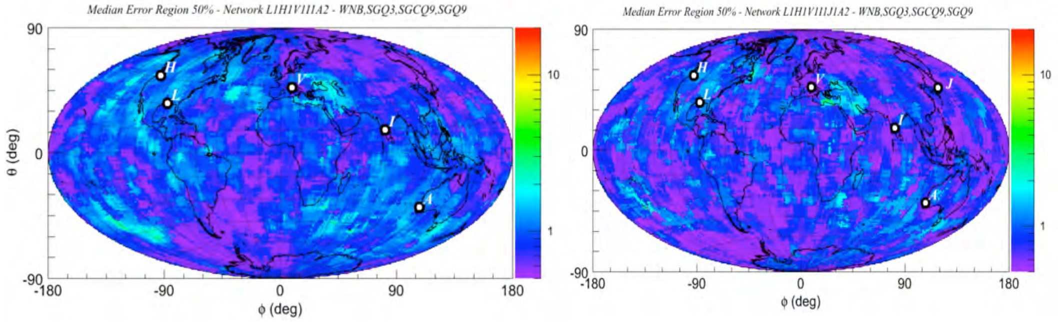


Fig. VII.12. Distribution of median error angle (color scale in degrees) across the sky for networks HLVAJ and HLVIJ.

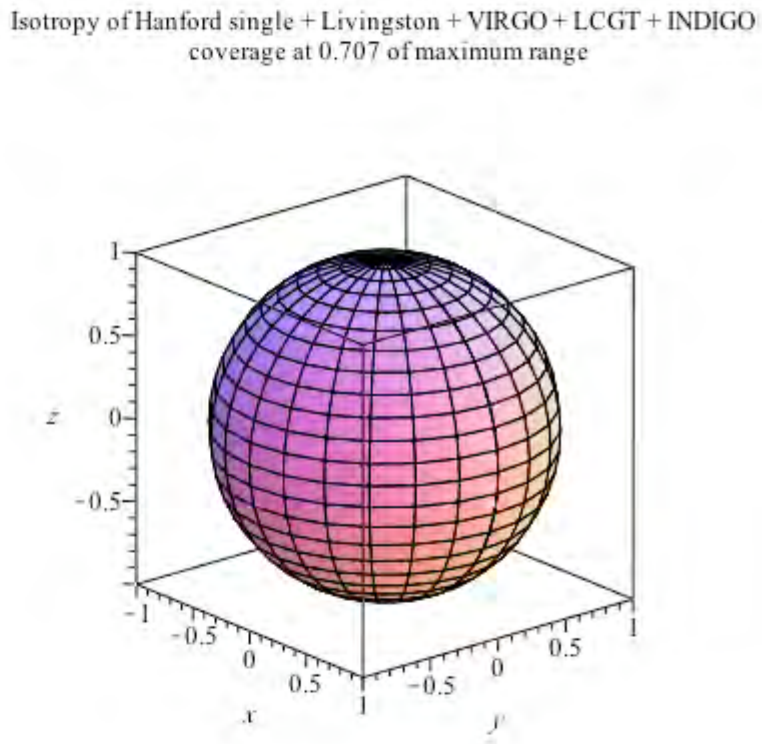


Fig. VII.13. With a five detector network HLVIJ the sky coverage is isotropic .

In conclusion, moving one of the Hanford detectors to southern India has significant advantages in achieving the key science objectives of advanced detectors by providing a factor of 3.5 improvement in sky localization of sources, as also a better estimation of the luminosity distance and orbital inclination. Once the 4-site network begins to operate, the nominal joint duty cycle of 3- and 4-site networks will be 82%, compared to the 51% of the 3-site network in HHLV.

VIII. Gravitational wave sources and astronomy

VIII. A. Expected sources of gravitational waves:

A number of astrophysical/cosmological sources are expected to produce gravitational waves (GWs) that are detectable using ground-based interferometric GW detectors. These include (i) *transient* astrophysical sources such as collapse of massive stars resulting in supernovae, coalescence of compact-object (black holes or neutron stars) binaries etc. (ii) *continuous* astrophysical sources such as rapidly rotating non-axisymmetric neutron stars (iii) *stochastic* backgrounds of radiation of either cosmological or astrophysical origin. The signals are expected to lie well below the mean noise level in the advanced ground-based detectors. This makes the data analysis all the more vital -- firstly in detecting the source, and secondly and more importantly in extracting astrophysical information about it. Expected sources of GWs observable to Earth-based detectors include the following:

(a) Coalescing compact binary systems:

Compact binary systems consisting of neutron stars or black holes can be produced in a variety of astrophysical scenarios, which can be broadly classified into two main classes: 1) Isolated binary evolution in which two massive stars constituting a binary undergo successive supernova explosions without disrupting the binary orbit, leaving behind a binary of compact objects 2) Dynamical formation scenarios in which two compact objects form a bound orbit due to dynamical interactions in dense stellar environments. Once formed, the binary loses orbital energy and angular momentum through GW emission and starts to inspiral and finally the binary components merge with each other. The late-time evolution of compact binaries is conventionally split into three stages: inspiral, merger and ring down. In the inspiral stage, the two compact objects, driven by radiation reaction, move in quasi-circular orbits. Eventually approaching the ultra-relativistic regime, the two bodies merge to form a single excited Kerr black hole. In the ring-down stage, the excited black hole loses its energy by gravitational-wave (GW) emission and settles into a Kerr black hole.

Around ten binary neutron stars have been observed using electromagnetic telescopes[21]. Radio observations from at least a few of these binaries have shown that their orbital periods are changing exactly as predicted by general relativity due to GW emission. Observations of these binaries have also helped to constrain the expected coalescence rates of compact binaries observable to GW detectors. On the other hand, although there are observational evidences of stellar-mass- ($\sim$5–20 $M_\odot$) and super-massive ($\sim 10^6$–$10^{9.5}$ $M_\odot$) black holes[22], currently there are no evidences supporting the existence of compact object binaries containing stellar-mass black holes. Nevertheless, several astrophysical mechanisms to produce black-hole-black-hole binaries and black-hole-neutron-star binaries have been proposed. Additionally, there are evidences supporting the existence of super massive black-hole binaries[23].

Coalescing binaries have been considered highly promising sources not only because of the enormous GW energy they emit in their final stage (of the order of 10^{46} J), but also because they are 'clean' systems to model. The *inspiral* part of the expected signal can be computed accurately to several post-Newtonian orders, adequate for optimal signal extraction and parameter estimation. Since the phase of the waveform, apart from the amplitude, can be computed accurately by post-Newtonian methods, the optimal extraction technique of *matched filtering* is used. More recently, numerical relativity has been successful in computing waveforms for the late inspiral, merger and ring-down. The current searches for high-mass black-hole binaries employ these inspiral-merger-ringdown waveform templates with resulting increase in the signal to noise ratio. RRI has strongly contributed to the computation of inspiral waveforms using post-Newtonian methods. IUCAA has been at the forefront in the international research in the design, validation and implementation of search algorithms for coalescing binaries.

(b) Burst sources:

Astronomical sources like core-collapse supernovae, long-gamma-ray bursts and soft gamma-ray repeaters are expected to be associated with astrophysical phenomena (such as collapse of massive stellar cores, excitations of non-radial modes in neutron stars etc.) producing bursts of GW signals – signals lasting for a time much shorter than the typical observation time (between a few milliseconds and a few minutes). For many of such sources, it is difficult to reliably compute the waveforms because complex physical processes involved. This limits the accurate prediction of the waveform and consequently optimal signal extraction and parameter estimation. These transient sources are typically searched for by using time-frequency 'excess-power' techniques. Recently, numerical-relativity simulations of sources such as core-collapse supernovae (considering a significant amount of the complex physics involved) have been increasingly successful. Work has already started in the community to employ the results of these simulations in the detection of such signals and to distinguish different core-collapse models.

(c) Continuous wave sources:

A rapidly rotating non-axisymmetric neutron star is a source of continuous GWs. These objects may generate GWs through a variety of mechanisms, including non-axisymmetric distortions of the solid part of the star, velocity perturbations in the star's fluid (*r*-modes), and free precession. The emitted signal is a quasi-periodic wave whose frequency changes slowly during the observation time due to energy loss through GW and electromagnetic emission, and possibly other mechanisms such as accretion. There are several spinning neutron stars known from electromagnetic observations (both isolated neutron stars as well as accreting neutron stars in low-mass X-ray binaries), which might be promising sources of continuous GWs. Such searches for known isolated neutron stars are not computationally intensive since they target known sky positions, frequency and spin-down rate. On the other hand, blind all-sky and broadband searches for previously unknown neutron stars are a different matter altogether. Long integration times, typically of the order of a few months or years are needed to build up sufficient signal power in the inherently weak signals.

(d) Stochastic backgrounds of GWs:

Apart from the deterministic astrophysical sources discussed above, a stochastic background of GWs is also expected to be present. This background can be of either cosmological or astrophysical origin. The cosmological background can have its origin in the amplification of vacuum fluctuations during inflation, phase transitions in the early Universe, cosmic strings etc. Alternatively, many deterministic signals from a number of astrophysical sources (such as spinning neutron stars, compact binaries, supernovae or low-mass X-ray binaries) can add up to form a stochastic background. Stochastic signals can be characterized only in terms of its statistical properties. To detect stochastic background one needs a network of detectors – ideally two detectors identically oriented and close to one another. The signal is extracted by cross-correlating the outputs of the detectors. Two kinds of data-analysis methods have been proposed (i) a full-sky search - but this method drastically limits the bandwidth, (ii) a radiometric search in which the sky is scanned pixel by pixel - since a small part of the sky is searched at a time, it allows for larger bandwidth, and more importantly includes the bandwidth in which the current detectors are most sensitive, thus potentially leading to a large signal-to-noise ratio. Moreover, with this method a detailed map of the sky is obtained.

VIII.B. Summary of the expected event rates

(a) Compact binary coalescences:

The best understood astrophysical sources of GWs are compact-binary coalescences. Even for this class of sources, the expected astrophysical event rates depend on a number of assumptions and unknown model parameters, and have large uncertainties. The most confident among these estimates are the rate predictions for coalescing binary neutron stars, which are based on extrapolations from observed binary pulsars in our galaxy. Event-rate predictions for these sources have been made using population-synthesis methods also. On the other hand, since neutron-star-black-hole binaries and black-hole-black-hole binaries have not been observed electromagnetically, their event rates are estimated only using population-synthesis methods. Advanced GW detectors are expected to observe several tens of compact-binary-coalescence events during their operation. A summary of the expected event rates for the case of some archetypal compact binaries is given in Table VIII.1.

Interferometer	**Sources and assumed masses**	**Pessimistic rate (yr −1)**	**Realistic rate (yr −1)**	**Optimistic rate (yr −1)**	**Rate upper limit (yr −1)**
Initial detectors	NS-NS (1.4 $M_\odot$-1.4 $M_\odot$)	2×10^{-4}	0.02	0.2	0.6
	NS-BH (1.4 $M_\odot$-10 $M_\odot$)	7×10^{-5}	0.004	0.1	
	BH-BH (10 $M_\odot$-10 $M_\odot$)	2×10^{-4}	0.007	0.5	
Advanced detectors	NS-NS (1.4 $M_\odot$-1.4 $M_\odot$)	0.4	40	400	1000
	NS-BH (1.4 $M_\odot$-10 $M_\odot$)	0.2	10	300	
	BH-BH (10 $M_\odot$-10 $M_\odot$)	0.4	20	1000	

Table VIII.1. Expected coalescence rates of compact binaries observable to Initial (first-generation) and advanced (second-generation) interferometric GW detectors, assuming a signal-to-noise ratio threshold of 8 for detections. Rate estimates of binaries involving intermediate-mass black holes have not shown here. For a complete list, see Abadie et al (2010)[24].

(b) Core-collapse supernovae

The intrinsic GW luminosity of core-collapse supernovae is quite small, as compared to compact binary coalescences. Hence, the first-generation GW detectors are unable to detect GW signals from core-collapse supernovae outside the Milky Way. Galactic core-collapse supernovae are quite rare events, occurring at a rate of one in a few decades. Second-generation detectors may be able to see most core-collapse supernovae throughout the local group of galaxies ($D \approx 1$ Mpc). This, however, would increase the observable event rate by not more than a factor of two. Third generation GW observatories reaching out to at least 3–5 Mpc will be necessary for GW astronomy of core-collapse supernovae to become possible; but second-generation detectors could put significant upper limits on the GW emission strength for such events[25].

(c) Continuous GW sources

The strength of GW emission from neutron stars depend on the amount of quadrupole deformation (expressed in terms of the ellipticity ϵ), which is not a well constrained by current observations. For the optimistic (but not unrealistic) assumption of $\epsilon \sim 10^{-7}$, estimates suggest that Advanced LIGO might be able to detect one among the known millisecond pulsars[26]. However, since only around 2000 of the 10^8 – 10^9 expected isolated neutron stars in the Galaxy have been observed electromagnetically, there is a chance that advanced GW detectors will discover some of the hitherto undetected ones. This requires an all-sky 'blind search'. Since searches for unknown pulsars are computationally limited, most of the searches are performed with the aid of distributed computing facilities such as Einstein@Home[27]. Additionally a few of the persistently bright neutron stars accreting at rates near the Eddington limit are detectable by advanced detectors, provided they are emitting GWs at a rate matching the torque from accretion[28]. A larger fraction of the known population is detectable if the spin and orbital parameters are known in advance (for e.g., from X-ray timing observations).

(d) Stochastic GW sources

The stochastic GW spectrum predicted by the standard inflationary cosmology is expected to be too weak to be detectable by the second-generation ground-based detectors. However, cosmological mechanisms to produce primordial GW spectra detectable by the second-generation detectors have been predicted by several 'pre-Big Bang' cosmological models based on string theory, and cosmic-strings[29]. Also, recent studies have pointed that second-generation detectors will be able to detect an astrophysical GW background produced by coalescing compact binaries if the event rates are consistent with the 'optimistic' or 'realistic' predictions discussed in Table VIII.1[30].

VIII.C. Modeling of GW sources

(a) Compact binary coalescences

The evolution of compact binaries is conventionally split into three stages: *inspiral*, *merger* and *ring-down*. The expected GW signals form the inspiral stage can be computed using the post-Newtonian approximation to general relativity, while those from the ring-down stage can be computed using black-hole perturbation theory. On the other hand, modeling of the merger stage requires exact solutions of Einstein's equations, which can be computed only using large-scale numerical simulations. Post-Newtonian calculations have been performed to a very high order $(v/c)^7$, in which the Indian community has made significant contributions[31]. The recent breakthrough in numerical relativity[32] has enabled us to model also the non-perturbative merger phase of the coalescence of binary black holes. Significant progress has been made recently on constructing GW templates describing the inspiral, merger and ring-down of binary black holes combining analytical- and numerical-relativity results, and using them in GW searches.

Numerical-relativity simulations of binaries involving neutron stars encounter harder challenges: since this requires consideration of the complex (magneto) hydrodynamics also, apart from general relativity. Recently, merger simulations considering all the relevant complexity are becoming increasingly successful[33] . Numerical-relativity simulations have also been employed to explore the connection between compact binary coalescences and short-hard gamma-ray bursts[34], model the possible electromagnetic counterparts of compact binary mergers[35] etc. Collaborative platforms to link the numerical-relativity community with analytical-relativity community as well as GW data-analysis community have been emerged recently, which will immensely aid the first detection of GWs as well as the extraction of astrophysical information from GW observations[36] .

(b) Core-collapse supernovae and other 'burst' sources

Modeling of core-collapse supernovae requires consideration of the complex micro-physics, apart from the relativistic gravity and (magneto) hydrodynamics, and hence is much more complicated. In a core-collapse supernova, the gravitational collapse of a massive star eventually results in a 'core bounce', which launches a shock wave propagating outwards. The shock quickly stalls, owing to the loss of its energy into neutrinos. The shock must be revived in order to create a successful supernova explosion. Supernova simulations have suggested three different models for the revival of the shock -- heating of the post-shock region by neutrinos, magnetic field amplifications, and acoustic mechanism[37]. Constraining the supernova mechanism by electromagnetic observations will be difficult. But GWs predicted by these different mechanisms have different signatures, and can be used to distinguish between the different models. Although the theoretical understanding of other 'burst' sources is in a much less sophisticated stage, at least some of the long gamma-ray bursts are also thought to be associated with core-collapse events[38].

VIII.D. Physics, Astrophysics and Cosmology using advanced GW detectors

(a) Fundamental physics using gravitational waves

- **Black hole spectroscopy and testing 'no-hair' theorem:** It is known from black hole perturbation theory that an excited Kerr black hole relaxes to its axisymmetric state by radiating the energy in the distortion as GWs. The emitted GW signals consist of a superposition of quasi-normal modes, whose frequency and damping time depend uniquely on the mass and spin angular momentum of the parent black hole (the 'no-hair' theorem) and not on the nature of the external perturbation. Observation of the spectrum of quasi-normal modes from a perturbed black hole would enable tests of no-hair theorem[18] .
- **Testing deviations from general relativity:** Although general relativity has passed all the observational tests with flying colors, there are reasons to expect that the true theory of gravity could deviate from general relativity in strong-gravity regime or at large scales. For example, the observed expansion rate of the Universe is inconsistent with the prediction of general relativity based upon the mass-energy content of the Universe inferred from electromagnetic observations. This means that either general relativity needs to be modified at large scales or that the Universe contains enormous amount of mass-energy that is not visible in electromagnetic observations, termed 'dark energy'. Gravitational-wave observations will also facilitate unique precision tests of general relativity. Deviations from General Relativity can be parameterized, and constraints can be placed on such parameters from the observed GW signal. Some of the proposed tests include test of the no-hair theorem, naked singularities, massive graviton, presence of additional polarizations, extra loss of energy/angular-momentum, and parameterized tests of post-Newtonian theory.
- **Speed of gravitational interactions:** In general relativity, GWs propagate at the speed of light. Unique identification of a GW event with an electromagnetic source would allow us to measure the propagation velocity of gravity with unprecedented accuracies. The best sources for this measurement are extra-galactic gamma-ray bursts. For instance, a delay of one day in the arrival time from a source at a distance of one Giga light-year would determine the relative speeds to better than 10^{-11}. If GWs propagates with speeds less than that of light, this would indicate that the graviton has an effective non-zero mass, which would have other observable effects. By observing GWs from coalescing compact binaries, one can put stringent bounds on the mass of the graviton.
- **Number of GW polarization states:** General relativity predicts two independent polarization states for GWs. But there are competing theories, such as scalar-tensor theories, which predict more than two GW polarizations. Using a network of GW detectors, it would be possible to constrain the strength of various polarization states in different theories.

(b) Astrophysics with Gravitational Waves

GW observations will enable us to measure the individual masses and spins of the black holes or neutron stars in a binary very accurately. This mass measurement will be the first *direct* determination of black-hole masses and spins. Since compact binaries are 'clean' systems well modeled by general relativity, the systematic errors will be much less as compared to other astronomical measurements.

- **Neutron-star physics and astrophysics**: In a neutron star, matter takes exotic forms, which is a major puzzle for modern nuclear physics. Observation of compact binary signals involving neutron stars will enable us to extract information regarding the equation of state of the neutron star, providing unique information concerning the composition of the neutron-star core and the physics of such a highly dense state. Neutron stars have a rich spectrum of non-radial normal modes; the details of their GW spectra (produced by perturbed neutron stars) would be a sensitive probe of their structure, in much the same way that helio-seismology probes the interior of the sun. Observations of continuous-wave signals from neutron stars could enhance our knowledge about various mechanisms driving instabilities in neutron stars such as accretion, spin misalignment etc.
- **Black-hole physics and astrophysics:** Black holes are relativity in extreme. Observing GWs from them, individually or in binaries, helps to test some of the predictions of general relativity in the strongly nonlinear regime, such as the 'tails' of GWs, spin-induced precession etc. Ground-based GW detectors will be sensitive to the signals from intermediate mass (~100 - 1000 M_{sun}) black-hole binary coalescences. These binaries are observable up to distances of the order of a few Giga parsecs. Though there are suggestive evidences of the existence of intermediate-mass black holes (through Ultra Luminous X-ray sources), estimation of the mass of the black hole from GW observations could prove their existence beyond doubt. GW observations of these binaries could give valuable insights about black-hole formation scenarios.
- **Central engine of gamma-ray bursts:** At least some of the short gamma-ray bursts are hypothesized to be powered by compact binary mergers involving neutron stars. The observational evidences for this hypothesis are all indirect. The most unambiguous confirmation could be from a GW signal that is uniquely associated with a short gamma-ray burst. If advanced detectors observe many such signals, the statistics may give important clues about the progenitors of short gamma-ray bursts.
- **Probing the interior of core-collapse supernovae:** In core-collapse supernovae, different models predict different mechanisms to revive the hydrodynamic shock after it stalls. It is the shock revival that makes the supernova explosion possible; and different mechanisms predict different GW signatures. Advanced GW detectors will be sensitive to core-collapse supernovae inside and near our galaxy. Although galactic supernova rates very low, GW signals from a galactic supernova will enable us to understand the internal processes of the supernova.

(c) Cosmology using gravitational waves

- **Estimating cosmological parameters:** GW observations of coalescing compact binaries will be able to provide an absolute measure of the luminosity distance to the source. If the binary coalescence is associated with an electromagnetic counterpart (e.g. a short gamma-ray burst and associated afterglows), the redshift at the source also can be estimated. The observed distance-redshift relation from a collection of events will allow us to constrain various cosmological parameters. The advanced detector network could be capable of measuring the Hubble constant to better than 5% accuracy, depending up on the number of such sources detected[36] . For measuring luminosity distance with ground based GW detectors, it is imperative to have a geographically separated network of detectors.

- **Constraining theories of early Universe:** The cosmological GW background is expected to be produced by processes in the very early Universe, in particular, the epoch of inflation. The observation of this stochastic background can provide a picture of the Universe very shortly ($\sim 10^{-21}$ s) after the big bang. Unfortunately, the expected strength of the GW background from inflation is too low for the advanced ground-based detectors to detect. But these detectors can put interesting upper-limits on the strength of other sources of cosmic GW backgrounds arising in a number of interesting high-energy physics scenarios (such as cosmic strings). Thus we can test current speculations about the very early Universe and begin to probe, or constrain, theories of physics at ultra-high energy.

VIII.E. Some Astrophysical results from current observations

Even in the pre-detection phase, GW observatories have started making significant contribution to Astrophysics. A number of important astrophysical results have been obtained from the data of the LIGO and Virgo detectors. A few of them are listed below:

- Upper limits on the strength of the cosmological stochastic background of GWs have been obtained from the fifth science run of LIGO detectors, which improve the previously obtained limits from big bang nucleo-synthesis and the cosmic microwave background. These results rule out several of the big bang scenarios based on string theory[41] .
- The Crab pulsar is a radio pulsar spinning down at a rate of $\sim -3.7 \times 10^{-10}$ Hz/sec, which gives a strain amplitude $h \sim 1.4 \times 10^{-24}$ if the spin down was all due to GW emission. But the analysis of the data from the S5 run of the LIGO detectors have shown that, since no GW signal was observed even at $h \sim 2\times10^{-25}$, less than 2% of the energy loss can be due to GW (corresponding to an ellipticity limit of $\epsilon < 10^{-4}$).
- A search for periodic GWs from the neutron star in the supernova remnant Cassiopeia A (the youngest known neutron star) was performed using the data from the fifth science run of LIGO. An upper limit of $0.7–1.2 \times 10^{-24}$ was placed on the strength of GW strain, $0.4–4 \times 10^{-4}$ on the equatorial ellipticity and 0.005–0.14 on the amplitude of r-mode oscillations of the neutron star.
- Possible progenitors of short gamma-ray bursts include mergers of black-hole neutron-star binaries or double neutron-star binaries, or soft gamma-ray repeater flares. Analysis of LIGO data has placed constraints on the physical mechanism of GRB 070201. Absence of GW signal during the GRB 070201 excluded a compact binary progenitor located in M31 galaxy. If the GRB 070201 progenitor was not in M31, then it excludes a binary NS merger progenitor with distance less than 3.5 Mpc.
- GW data has also been used to place limits on ultra-high energy physics. In particular, data from the S4 run has been used to place strong limits on the presence of GW bursts from cosmic (super) strings.
- Stringent upper limits on the GW strengths associated with soft-gamma-ray repeater (SGRs) were possible by using the GW data of the S5 run of the LIGO detectors. For three distinct SGR events, GW observations could put excellent upper limits on the GW strengths, though they are still within the theoretical predictions of different SGR models. For one of the SGRs, the energy upper limit was better by an order of magnitude compared to previously published

results and overlaps with a range of electromagnetic energies emitted in SGR flares.

IX. Gravitational Wave Data Analysis

IX.A. Data analysis challenges for advanced detectors

Although the GW community is engaged in the analysis of the data from interferometric GW detectors over a decade, the advanced detector era presents a number of formidable data-analysis challenges. Listed below are a few of such challenges. The list is not meant to be exhaustive.

- **Developing low-latency on-line analyses:** Detection of GW signals with potential electromagnetic counterparts requires a very low-latency analysis of GW data, and broadcasting the relevant information (such as the sky location of the source) to electromagnetic telescopes. The increased low-frequency sensitivity of advanced detectors cause the CBC signals to last for several minutes in the detector's frequency band, which sets a minimum latency for the standard data-analysis methods. Several data-analysis methods/pipelines are being developed for low-latency GW data analysis.
- **Computational challenges:** All-sky searches for spinning neutron stars and multi-detector coherent search for CBCs are computationally limited even in the initial-detector era. The advanced detector era pose more computational challenges: for example, in the search for CBCs, the requirement of employing minute-long templates, along with the need of considering spins, higher harmonics, matter effects in neutron-star binaries, parameter estimation etc. significantly increase the computational cost. Addressing this challenge has taken different dimensions, such as developing computationally efficient search methods, developing distributed computing facilities such as Einstein@Home, making use of emerging technologies such as GPUs, etc.
- **Separating 'signal' and 'background':** Since interferometric detectors are highly complex instruments, the data often contains a large number of non-Gaussian noise transients that mimic potential signals. The complexity of the instruments will only increase in the advanced detector era. Several methods are being developed to robustly separate 'signal' and 'background', such as signal-based vetoes (making use of our understanding of the signals), instrumental vetoes (making use of our understanding of individual detectors) and multi-detector vetoes (making use of our understanding of the response of a multi-detector network to a signal). Robustly evaluating the significance of the first detections, evaluating very small false-alarm rates etc. also pose significant challenges.
- **GW source modeling:** Waveform templates for compact binaries based on analytical- and numerical- relativity has to be further improved considering all the relevant physical effects such as spins, higher harmonics, matter effects in neutron stars and possibly eccentricity. Inclusion of many of these effects is important for detection, and is indispensable for accurate parameter estimation. Additionally, although it is unlikely that reliable GW templates can be developed for the case of more complex 'burst' sources, information such as the frequency content and time-frequency behavior of the expected signals, energetics etc. are quite useful in the search for such sources.
- **Interpreting GW observations:** Interpretation of GW observations requires detailed understanding of the statistical and systematic errors (due to

imperfect modeling of the source as well as the detector) and various selection effects in the observations. Also, work has to be done in preparing source catalogues, sky-maps of transient sources as well as the stochastic background, public release of GW data, electromagnetic follow-up of GW triggers etc.

IX.B. GW astronomy as part of the multi-messenger astronomy

In the advanced detector era, GW astronomy can be seen only as a part of the multi-messenger astronomy. Exchanging information with electromagnetic and neutrino communities is imperative for making full use of the potential of multi-messenger astronomy. For example, poor pointing accuracy is an intrinsic limitation of GW antennas. Even with a wide-baseline ground-based detector network, the source-localization accuracy of GW antennas is significantly inferior to that of electromagnetic telescopes. On the other hand, GW observations enable us to estimate the absolute luminosity distance to the source with remarkable accuracy – something the electromagnetic telescopes are incapable of doing. Coincident GW-electromagnetic observations are essential for certain aspects of GW astronomy; such as in determining the central engine of gamma-ray bursts, in estimating the cosmological parameters etc. Additionally, identifying electromagnetic/ neutrino counterparts also contribute to improving the significance of GW detections, thus enabling more marginal detections and improving the population statistics of the sources.

LSC-Virgo collaboration has already have established close connections with several electromagnetic telescopes and neutrino detectors around the globe. Several LIGO-Virgo-GEO searches for GW signatures from gamma-ray bursts, soft gamma-ray repeaters, core-collapse supernovae, spinning neutron stars etc. have made use of information provided by electromagnetic telescopes. Also, several candidate GW triggers were followed up using electromagnetic telescopes during the last LIGO-Virgo joint science run (no detection were made).

The advanced GW detector network can join forces with several Indian astronomy projects in this aspect. Potential collaborators include the Astrosat project (getting x-ray timing data for searching GWs from spinning neutron stars, electromagnetic follow-up of GW triggers), future upgrades of the India-based Neutrino Observatory (neutrino-GW coincidences for supernova searches), optical/radio telescopes such as the Hanle 2m Telescope, IUCAA 2m Telescope and the Giant Metrewave Radio Telescope (electromagnetic follow-up for GW triggers).

IX.C. Indian contribution to GW data analysis

(a) Past achievements:

IUCAA and RRI have contributed at the forefront to the international effort in GW research. While computing post-Newtonian corrections to the inspiraling binary waveforms has been the thrust of the effort at RRI, IUCAA has mainly focused on the data-analysis aspects of the experiment. Under CEFIPRA, at RRI, Bala Iyer has been part of an Indo-French collaboration involved in the computation of high-accuracy gravitational waveform from inspiraling compact binaries of neutron stars and black holes. These waveforms underlie the construction of the templates used by LIGO and Virgo for detection of GWs and their characterization. They are also crucial for validating and characterizing the numerical-relativity simulations of compact binaries. His group, in collaboration with GW groups at IHES, France and Cardiff University has also been involved in the comparison of various template families, use of re-summation methods and effective-one-body methods to extend the post-Newtonian inspiral waveforms, parameter estimation using post-Newtonian templates and their astrophysical and cosmological implications and in the tests of theories of gravity.

Designing efficient data analysis algorithms involving sophisticated mathematics has been the hallmark of IUCAA's efforts. Notable work involves the search for binary inspirals, hierarchical methods, coherent search with a network of detectors, the radiometric search for stochastic gravitational waves and a fast transform for periodic sources based on group theory. IUCAA has contributed to the inspiral, stochastic and the continuous wave groups under the data-analysis working group of the LSC. IUCAA students have taken part in the several science runs of the LIGO detectors. Sanjeev Dhurandhar at IUCAA has had three Indo-French collaborative projects under CEFIPRA, two Indo-US projects and Indo-Japanese program since 2001. Also there have been informal collaborations with Max Planck Institute, Germany, Cardiff University and University of Western Australia. IUCAA has been part of the LIGO Scientific Collaboration (LSC) for the past ten years. These efforts have developed skilled manpower in data analysis of about 20 people who are involved in contributing crucially to research in GW data analysis in India and abroad.

(b) Planned contribution to LIGO Scientific Collaboration

The IndIGO consortium has joined the LIGO Scientific Collaboration (LSC)[16] as a member research group. LSC is an international collaboration of scientists working on the GW-observation program, and is responsible for analyzing the data collected by the LIGO observatories in the USA and the GEO 600 observatory in Germany. The Virgo observatory in Italy has a data-sharing agreement with the LSC. LSC is made up of more than 800 scientists belonging to over 60 institutions from 13 different nations worldwide. The IndIGO consortium consists of scientists of diverse skills such as data analysis and search algorithm development (Pai, Sengupta, Mitra, Nayak, Dhurandhar) and waveform modeling (Arun, Gopakumar, Iyer, Mishra). In the coming years, we expect the IndIGO consortium to grow with the increase in the number of faculty, postdoctoral fellows and graduate students. The IndIGO consortium plans to contribute towards LIGO Scientific Collaboration in two major ways: (a) Hardware: hosting the IndIGO Data Centre that will be installed by early 2012, (b) Pipeline development: test and implement GW search algorithms in specific areas addressed above, namely; tests of GR and multi-detector coherent veto.

- **IndIGO data center:** A high-throughput computation and gravitational wave data archival facility, called the ‘IndIGO Data Centre’, is in the process of construction. It is planned to be set up as a Tier-2 data analysis centre with around 20 Teraflops in computational resources along with several hundred Terabytes of storage for data archival. This is expected to provide a fundamental infrastructure for consolidating GW data analysis activities within the member institutions of the IndIGO consortium, and to train graduate students and post-docs. An effort will be made to build the data center along the lines of existing LIGO data analysis facilities. This centre will also be used for developing a GW user community in Indian institutes and Universities and for providing web services and collaborative tools to the members of IndIGO collaboration.

  The plans for setting up the data centre will be executed in two phases: the first phase costing about USD 2 million in equipment, will provide 20 Teraflops of computation power and is expected to be installed by early 2012 and will be ready for use by June 2012. The funds for this phase of the data centre have already been secured. The second phase is the upgrading of the facility by a factor of five (from 20 to 100 Teraflops) and is expected to cost USD 10 million in equipments and manpower. The second phase is expected to be completed by 2015, in time for the science runs of Advanced LIGO.

The first phase of the IndIGO Data Centre will cater to the wider Astronomy community apart from the data analysis requirements of the members of the IndIGO consortium. These include the Astrosat group, cosmic microwave background research, Pulsar survey, general astronomy users etc. The second phase is envisaged to be exclusively available for the GW data-analysis community from India and the members of the LSC-Virgo collaboration.

- **Develop multi-detector coherent vetoes:** The multi-detector searches for GWs from compact coalescing binaries can be classified into two: (i) Coincidence search -- signals in individual detectors are compared for consistency of parameters, such as the component masses, times of arrival etc. (ii) Coherent search -- the multi-detector data is combined phase coherently and the network of detectors is treated like a single detector (aperture synthesis) and a single search statistic is computed from the network data which is compared against a threshold. The coincidence search is easy to perform; but ignores the phase information because the detectors are treated in isolation. The coherent search however makes use of the phase information by combining the multi-detector data, thus yielding higher signal-to-noise ratio and is expected to outperform the coincidence search under the assumption of stationary Gaussian noise. However, the actual detector noise is neither Gaussian nor stationary. Thus additional signal-consistency checks must be employed to remove spurious triggers arising from non-Gaussian noise transients. The coincidence search, by its very nature, serves as a powerful ‘veto’ and is therefore preferred over the coherent method in the ongoing GW searches. However, we might be able to develop powerful signal consistency checks (vetoes) from coherent search also. One proposed activity of the IndIGO members within LSC is to develop powerful signal-consistency checks for multi-detector coherent searches for coalescing compact binaries. The idea would be to develop a ‘chi-square’ test along the lines of the single-detector chi-square test. An Indo-Japanese project has also been funded which addresses similar problems.

- **Tests of GR and alternative theories of gravity:** Testing general relativity and alternative theories of gravity is one of the important goals of GW observations. There have been many proposals in the literature to test specific classes of gravity theories (such as Brans-Dicke theory, massive-graviton theories etc.) using GW observations of in-spiraling compact binaries. The basic idea is to measure at least three of the seven GW phasing coefficients calculated for non-spinning compact binaries. Since only two are sufficient for estimating the masses of the binary components, the measurement of the third parameter yields a consistency test in the component-mass plane. In such a formalism, specific theories such as Brans-Dicke theory, massive-graviton theory are regarded as special cases. In collaboration with the LSC-Virgo parameter-estimation group, the IndIGO members plan to use the Bayesian model selection approach to the GW parameter estimation and implement this in the LSC-Virgo parameter estimation pipelines.

- **Stochastic GW background analysis:** The filter functions used in any long-duration stochastic search have a symmetry - they have a period of one sidereal day. This symmetry remained unnoticed for a long time. One can use this symmetry to 'fold' cross-correlated data from each day on top of each frequency bin of each sidereal time segment. That way effectively one has to analyze only one-sidereal-day-long data, as compared to few hundreds to a thousand days of data over a science run. Thus, the technique of data folding will make GW background searches faster by two to three orders of magnitude. Moreover, the data volume is so compressed (1GB, as compared to the original size of 1TB), that the whole data can be loaded in a notebook computer's memory and would comfortably fit in a DVD. Folded data will allow us to do many analysis experiments, as computation cost will be low. Also, new analysis methods can be easily tested on real (folded) data. Since the data volume is low, one would not require to develop a complicated software to test a method which is at its initial stage. IndIGO members plan to formulate and implement such a search in collaboration with the stochastic search group of the LSC-Virgo.

X. Linkages to Indian National Science and Technology Priorities and Initiatives

The national science policy has always emphasized self reliance and the key role of technology as an important element of national development. It was also realized, and emphasized in the national science policy documents that major experimental facilities, even in several areas of basic research, require very large material, human and intellectual resources. Retraining, mobility of scientists and engineers across fields and institutions etc. are important for keeping up pace with developments in science and technology. The importance of creating opportunities of high-end research within India in pure sciences to attract and bring back talent that is abroad has also been realized in all circles of science policy discussion.

LIGO-India provides an ideal platform for realizing many of these goals. There are several ways in which the LIGO-India project links to national priorities and vision for research and development in the next decades. The level of special technologies used in the detector is at the limits of what is practically feasible given the current knowledge and technology base and manufacturing possibilities, with realistic cost limits. Many of these technologies were developed in a strong collaboration from LIGO laboratories, Universities in the LSC and industry partners. They span the fields of optics, vibration isolation, feedback control systems, Ultra-high vacuum, data acquisition, storage and computation etc.. Therefore, the LIGO-India project covers many areas of the national priorities and vision for research and development projected in the vision documents of the SERC and DST. Since the LIGO Scientific Collaboration consists of several hundred scientists and engineers from a large number of universities and national laboratories from around the world, it is also a role model for inclusive human resource development and management, which will reflect directly in the refinement of higher education as well as in expert human resource development in India.

X.A. LIGO-India and National research and development vision documents:

The vision documents of the DST had defined broad thrust areas, and gravitational wave research and astronomy is one of them. The guidelines that motivated the preparation of the document included the need to encourage research areas where there is a large quantum of activity elsewhere in the world and the possibility of training a large number of people with a variety of high level expertise in areas at the cutting edge of modern technology. The LIGO-India project forms an ideal platform for such high level training and human resource development. As mentioned in the vision document there is an immediate need to revitalize the culture of experimentation, materials development and instrumentation, which is dying in the country. With linkages to materials research, coating and glass technologies, high energy physics, nonlinear dynamics, laser physics and astronomy, the LIGO-India project covers several of the identified thrust areas. In the areas defined in the section on mathematics, the project has strong link to deterministic control theory, stochastic process modeling, spectral and inverse spectral theory, and wavelet analysis. Since the project relies on several technologies, the linkages to topics in advanced engineering covers a wide spectrum. Some areas of relevance are sensors, digital systems design, optical communications and time transfer, several areas of signal processing, control systems and parallel computing.

X.B. Interfaces:

a) Physics:

The detection of gravitational waves with a quantum noise limited interferometer detector touches several aspects of physics including general theory of relativity and physics of space-time, fundamental quantum physics, quantum optics, nonlinear dynamics and even some quantum gravitational aspects of space and time. Apart from those essential aspects that go into the design of the detector, this multi-spectral reach to physics will attract a large number of talented and motivated young researchers and students to the program, as it has done in other countries. The detector and the facility will serve as a national symbol for advanced physics in the country.

Associated with the LIGO-India project is research and development of next generation detector ideas and technologies. This will include explorations of optical and matter wave interferometers in new configurations, space-based detectors, quantum technologies based on quantum and nonlinear optics, and sensitive gravity gradiometers. The rich possibilities for new physics research and instrumentation are enormous and very attractive.

b) Engineering:

The gravitational wave detector and observatory incorporates certain extremes scales of ultra-high vacuum, optical engineering, laboratory cleanliness, vibration isolation, multi-channel high dynamic range control engineering and data storage and computing technologies. It will no doubt serve as an attractor for bring engineering graduates to work at the interface of physics and engineering, offering a unique and challenging environment that is ideal for gaining high level technical expertise.

c) Astronomy:

The proposed gravitational wave observatory based on LIGO-India will be rejuvenating for Indian Astronomy and will supplement excellently in this task the other projects under development like the Astrosat, TMT and SKA, along with the already existing facilities for optical and radio astronomy. It is likely that the only space-based X-ray observatory that is operational when the gravitational wave detectors come on-line is India's Astrosat, and therefore it is considered an important instrument for joint astronomy with GW detectors. The overall synergy with other Indian astronomy projects is excellent and will boost astronomy and astrophysics in India to unprecedented levels. In particular the project will aid in motivating and starting specialized courses in these topics with integrated multi-spectral astronomy as the backdrop. It is important to realize that the positive influence is long term, with a sustaining life of two decades or so, by which time next generation detectors will take over. It is expected that a working detector of this importance and visibility in Indian soil will naturally motivate more direct involvement in ground based and space-based astronomy in the country.

d) Geophysics:

The gravitational wave detector with displacement sensitivity below 10^{-19} m at its mirrors and graded displacement sensors at its various stages is more sensitive to ground vibrations than any imaginable seismometer even though a large part of it is filtered out in the passive stages of suspension systems. In addition, its active vibration isolation systems use conventional seismometers and geophones for sensing and controlling ground vibrations. Thus the entire 3-station L shaped interferometer detector is also a large scale seismic sensor network. Combined with the relatively quiet environment created for the operation of the detector, the detector can detect earth quakes and other disturbances from far away with sensitivity better than conventional stations. This will be of some importance for monitoring seismic disturbances and in the quest for developing techniques for earth quake prediction.

e) Higher Education:

There are very few internationally competitive physics and astronomy instruments operating within India. The lack of accessible and visible facilities for research that involves high technology and high finesse instrumentation directly affects the interest and motivation for choosing experimental physics and engineering physics as a career, especially in areas that requires a long term commitment and field work. The LIGO-India project will dramatically change this situation and a large number of tested remedial steps will built into the operation of the detector for continued engagement with undergraduate and post-graduate students in physics, astronomy and engineering. This will include introductory and advanced schools, hands-on laboratories at site as well as in associate centres at universities, IISERs and IITs, summer training programs at associated laboratories in India and abroad for selected motivated students, special LIGO-India fellowships for specialized training etc.

f) Social Sciences:

The LIGO-India project will be set up in a remote enough location, away from large towns and heavy human activity to fulfill the need for isolation from ground vibration noise and gravitational noise. However, the project size is large enough with 50-100 people at site during construction and perhaps about 50 scientists, engineers and students during operation for a decade afterwards. This naturally implies interfacing with the local communities with opportunity and ability to help in some of the local aspects like education, management of environment, power and water harvesting and management etc. This will be of great interest to social scientists interested in studying and helping such societal interfaces with advanced science and high technology and their practitioners and users on one side and the rural community with their own priorities and prejudices on the other, coming together on a project of national interest.

g) Industry:

From infrastructure development in the initial stages to the commissioning of the detector, strong industry participation is required for the success of the LIGO-India project. Particularly important is the creation of ultra-clean laboratory environment and ultra-clean ultra-high vacuum. Innovative vacuum engineering concepts will be tested during prototyping of the UHV systems to reduce cost and improve reliability and the knowledge created will be passed on to the industry partners in the project who will build the 8000 m long beam tubes and the main vacuum systems. We will be interacting strongly also with the electronics and computer industrial sources and a mutually beneficial long term partnership is envisaged. When the detector is operational a large amount of computing in the cloud environment is expected and it is natural that that the project will contribute to the development in distributed computing in India.

The detector components, contributed by LIGO-USA define several goals for technology achievements within the country for optical components, sensor technologies, feed-back control systems, mechanical fabrication etc. Our interaction with the industry in the context of ideas and hardware for next generation detectors will help to realize some of these goals with benefits of global exposure and market for relevant specialized industries.

h) Distributed Expertise Access:

LIGO-India project envisages the creation of a network of expert personnel who can be accessed for high level problem solving and advise throughout the project execution and operation. There is large pool of experts in several areas relevant for the detector project who may not be able to directly get involved in the project. However, their level of expertise is sufficient to offer quickly solutions to technical issues that will arise in such a project and by accessing the network over Internet based video and audio conferencing we will be able to significantly augment our technical problem solving abilities. This larger involvement will also help in linking LIGO-India to other national projects, increasing the scope for human resource development.

X.C. LIGO-India and Human Resource Development:

Fast and efficient human resource development is both a mission and necessity of the LIGO-India project. Starting in about 2015, after the initial activity of preparation of site, infrastructure and interfacing with industry for the fabrication of the vacuum hardware, the project needs a pool of experienced and skilled scientists and engineers to realize the precision assembly, testing and commissioning of the detector. The project leaders for each technical aspects will come from the existing team in India and the Indian post-doctoral researchers currently at the LIGO laboratory, who will augment their familiarity with the task by participating directly in the assembly and commissioning of the LIGO detectors in the USA. A larger team of experts will have to be identified and trained in the coming 4-6 years for completing the task on schedule and the plan for this training is a very important aspect of the project plan. The hands on training centres will be the prototype detector being built in TIFR (Mumbai), the LIGO (US) and GEO (Germany) detectors of the LIGO Science Collaboration, and their partner in the international network Virgo (Italy).The Data Centre at IUCAA will serve as the training centre for data handling and analysis techniques and for gravitational wave astronomy. A regular GW-specific graduate school program is planned to be an integral part of the project. We expect that about 10 Ph. D students and 5 post-doctoral researchers being engaged with LIGO-India every year starting 2018 growing to a pool of 50-60 young researchers associated with the mature LIGO-India.

Apart from direct training with the aim of generating the human resource for the project execution, the project will reach out to undergraduate and post-graduate students in no less than 25 universities, IISERs and IITs with regular programs of lectures and laboratory sessions for teaching in experimental physics, astronomy and engineering physics. Some of these details are already mentioned in the 'Interfaces' section.

X.D. LIGO-India Collaborations:

There are two streams of collaborations that are envisaged in the GW initiative by the IndIGO consortium and LIGO-India. One is specific to gravitational wave research and this is naturally and automatically facilitated through the LIGO Science Collaboration (LSC) in which the IndIGO consortium is a member now. We expect that more university researchers will enter into the consortium and the involvement of IUCAA helps in coordinating this activity. There are also collaborations with the SAARC regional members possible, given the scope of the GW research and astronomy in the near future. National policies on such collaborations can be accommodated with mutual agreements and by agreement with the LIGO collaboration.

The other line of collaboration is with other national initiatives in astronomy research in optical, radio and X-ray, gamma-ray and neutrino astronomy. There are large projects coming up in the near future, some within and some outside the country, like TMT (optical), SKA (radio), Astrosat (UV/X-ray), HAGAR/MACE (gamma-ray), INO (neutrino) etc. Multi-wavelength astronomy in India will be in a state of completeness of coverage when spanned by the non-electromagnetic astro-messengers of neutrinos and gravitational waves.

X.E. LIGO-India Public Outreach:

The LIGO-Indian detector will be one of the very few research facilities in India of this scale, international relevance and technological innovation to which the general public and students can have access through an interface centre located not far from to the actual detector. It has the additional fascination as an instrument for astronomy of the neutron stars and black holes in distant galaxies. Creation and operation of a public outreach centre where key technologies and physical principle that make the detector will be on display, some of which for hands-on access, is an integral part of the project. This will also serve, through direct interaction and through web-based services, as a centre for continuing education on these topics. The observatory will also host field trips for students, tours for the general public, interactions with scientists and engineers etc. Subsidiary centres of a similar nature will also be set up in the associate centres of the IndIGO consortium for wider reach, especially to school students. We will also tie up with national planetariums in different cities in India for programs on gravitational wave astronomy and teacher training in related areas.

The LIGO observatories in the USA (in particular, the LIGO Livingston Observatory) have excellent outreach programs targeted towards school children and teachers. Drawing its motivation from the highly successful ‘Research Experience for Teachers’ program of the LIGO-USA, the LIGO-India project envisages to set up a short-term research and training program for school teachers. This will be a two-month long paid summer internship program to offer selected teachers the opportunity to experience working in a scientific research environment on topics of mutual interest with LIGO-India. The goals for the internship would include professional development and broadening real-world science experience. The proposed activities include develop classroom educational materials, create science exhibits, conduct investigations leading to physical demonstration devices that can be used by students, etc. The observatory will also organize training programs and workshops for teachers of local public schools making use of the audio-visual facilities, science exhibits, auditorium and lab space etc.

The home computer based 'Einstein@home' program for data analysis for continuous wave sources that is currently running as part of the gravitational wave detection global activity will add to the public outreach program. It is not inconceivable that with the enthusiasm among students in India to get involved in such projects this program will touch a 1 million user mark and 1000 Teraflops peak.

X.F. LIGO-India and Environment:

The LIGO-India project is at the outset sensitive to environmental preservation and improvement. Isolation of the site will also imply its preservation that is essential for the success of the project. The project requires stable and uninterrupted power which will be a combination of solar-cell based power in a local power farm at site and the power from the national grid. Requirements of power on air-conditioning and clean room facilities will be minimized using ideas borrowed from the experiments by the Australian consortium on geothermal methods. Water harvesting will be an integral part of the site engineering. Plantation and low-height forestation that do not generate additional vibration noise will be explored and implemented when possible.

X.G. Summary of Interdisciplinary Linkages

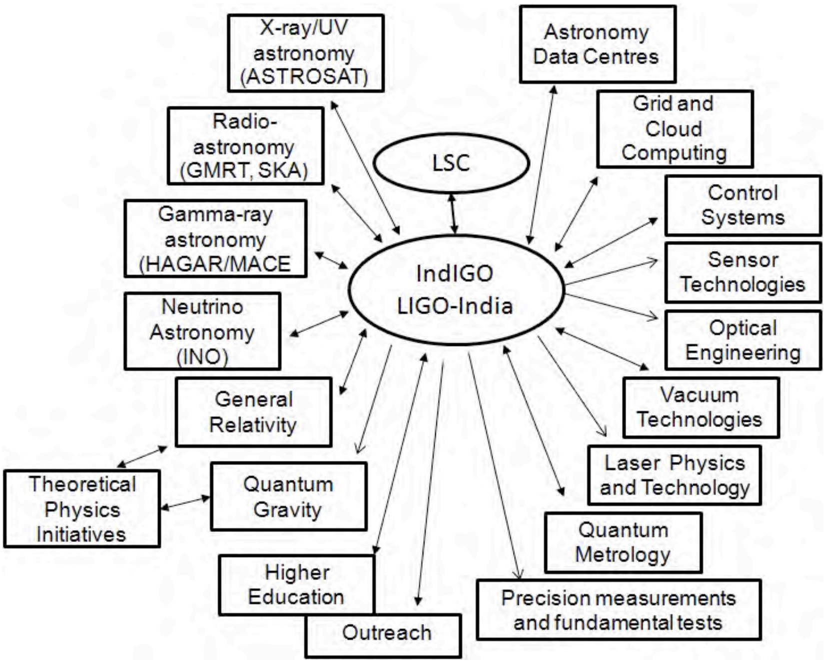


Fig. X.1. LIGO-India is a multi-institutional and multi-disclipinary proposal pushing the envelope on many different fields of science, technology, engineering and human resource generation.

XI. Management Structure and Work Structure

The Governance of the project has two layers. One is related to the management of IndIGO consortium and the other relatively independent one is specifically the management of the LIGO-India detector project. While IndIGO is the initiating organizational body for the project, it is a consortium that coordinates gravitational wave research in general and does not control the LIGO-India detector management, which will be governed by its own structure working for a collaboration with the LIGO laboratories and LSC. The detector construction, commissioning and operation will governed by a structure that is supervised by a Governing Council with representation from IndIGO, LIGO, funding agencies, government representatives, and scientists. The primary responsibility for coordination is with the LIGO-India director, and experimental scientist with broad overview and experience in the science and instrumentation as well as industry parameters. A project Manager and several project science and engineering leaders will form the core team, along with the director, that will realize the LIGO-India detector. The tentative structure is shown in the diagram, Fig. XI.1.

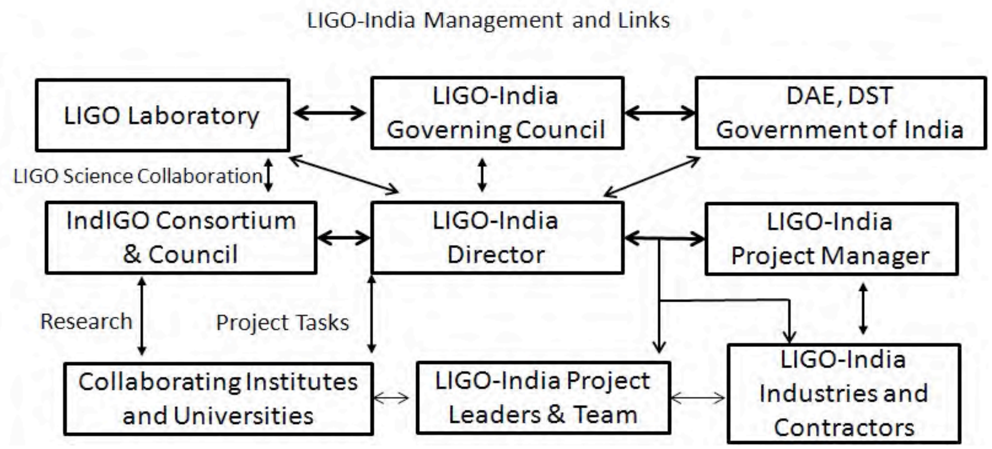


Fig. XI.1. The governing structure for LIGO-India would need to take into account the funding agencies, the science drivers and the institutions involved both on the Indian and the American sides.

The structure is preliminary and would need to be discussed in more detail formally by the funding agencies on both sides and the science stake-holders in the future.

The work structure and planning for the LIGO-India project is projected to follow closely the work breakdown structure (WBS) of the LIGO project itself to have maximum compatibility and familiarity in the collaborative execution of the project. However, there are LIGO-India specific changes and requirements. This structure defines the human resource structure as well with various task specific expertise, as explicitly indicated in the detector section. It also facilitates detailed item wise costing, schedule and the estimates for demands on infrastructure like office and laboratory space. Several of these tasks can run in parallel.

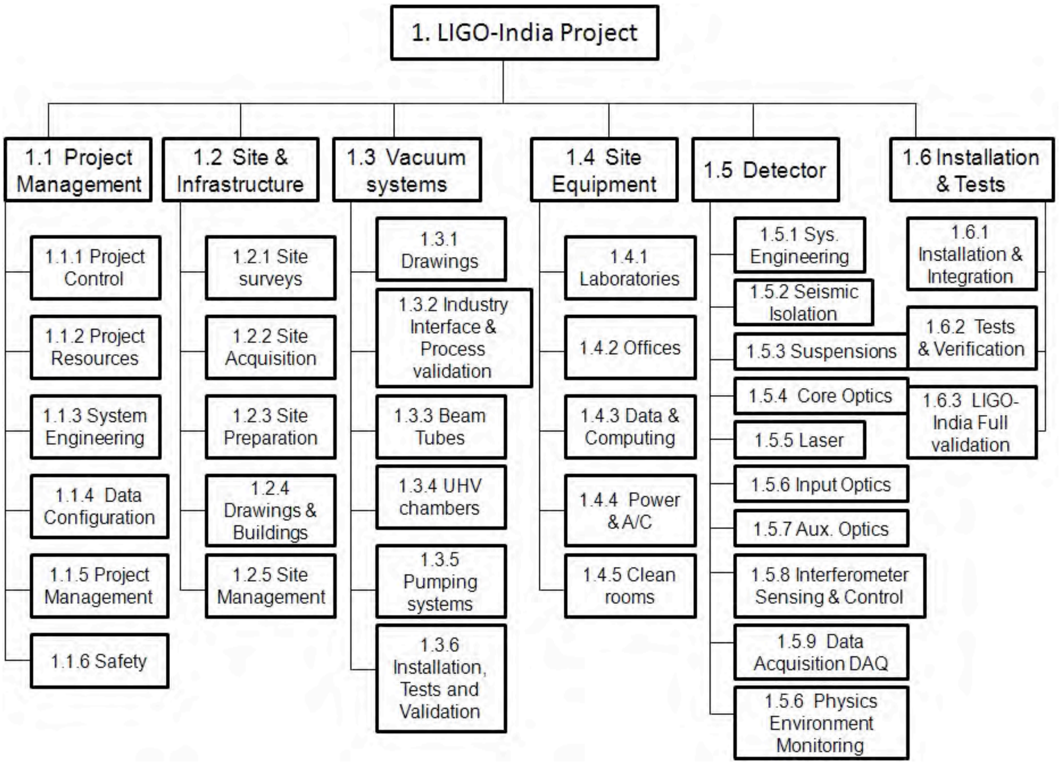


Fig. XI.2. Preliminary Work Breakdown Structure (WBS) for LIGO-India.

The Staffing requirements will approximately follow the WBS. Several facility related requirements can be managed by private contracts and only minimal project staff is projected.

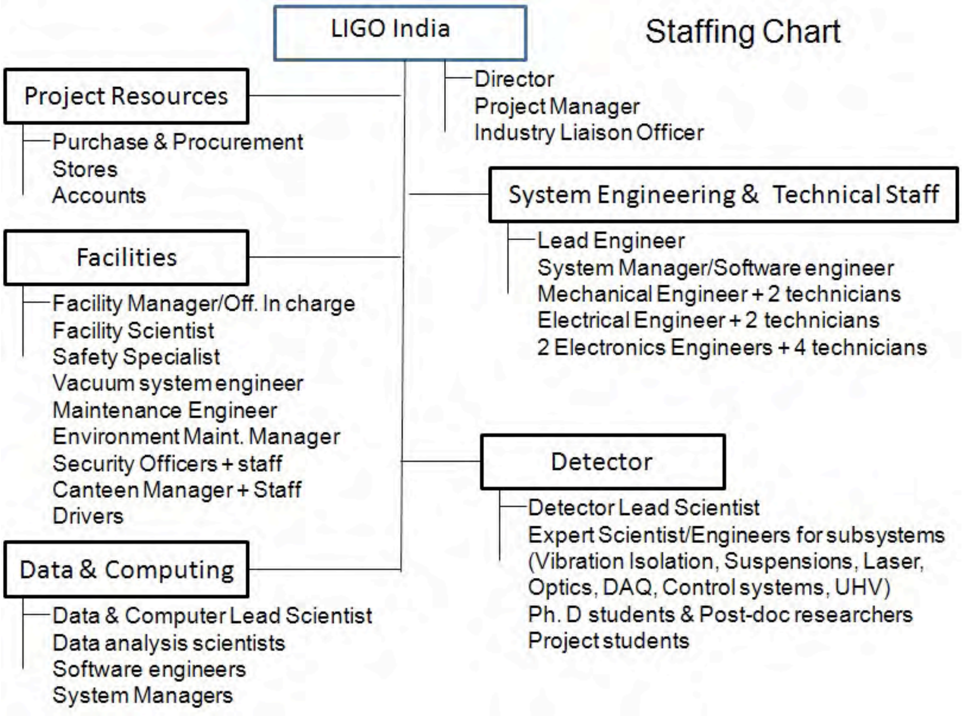


Fig. XI.3. Staffing Requirements for LIGO-India.

XII. Project Feasibility

The interferometric gravitation wave detector pushes the limits of technology on many fronts. To meet the sensitivity requirement, the detectors must operate at the fundamental limits of physical measurement. All parts of the detector such as the laser system, optics, suspension system, control electronics etc, must meet their stringent design specification. Each one of these components represents decades of technology development to achieve the required performance, precision engineering to make it reproducible and reliable, and careful procurement management and quality assurance to ensure that the hardware delivered for the detector meets all requirements.

By allying ourselves with LIGO lab, the largest and best-resourced gravitational wave detector project in the world, we are able to draw on their experience and resources to ensure the technical success of LIGO-India. By using the components shared by the LIGO Laboratory to construct the LIGO-India detector, we are assured of achieving their design sensitivity, and can take advantage of their experience in installing and commissioning the detector to complete LIGO-India much faster than could be done with an untested design.

The remaining challenges are still substantial, but are achievable. The site buildings will need to be designed and built to demanding standards for cleanliness and low vibration. They must provide a stable environment for the detector, including controlled temperature and humidity, quiet acoustic conditions and low electromagnetic noise. The experimental halls will be built with clean-room materials and practices, and HEPA filters will remove dust from the air.

The vacuum system is also a technical and engineering challenge. The LIGO design for the vacuum system relies on two main technical achievements that needs to be replicated for LIGO-India. (1) the welds must be completely free of leaks (10^{-10} Torr-liter/sec) and, (2) the out-gassing of the metal which forms the beam-tubes must be reduced by at least an order of magnitude below the conventional level (10^{-13} Torr-liter/sec). This enables the vacuum system to be pumped only with large ion pumps (2 x 2500 liter/sec) and coaxial liquid nitrogen traps at the end stations during the detector runs.

For reasons of manufacture the fabrication of the LIGO-India beam-tubes will use spiral mill technology commonly used for making pipes for other engineering and industrial applications (a technology available with L&T and Godrej). The vendor capable of spiral mill fabrication of the beam tubes may not be conversant with fabrication of tubes for vacuum applications and will have to be partnered with a vacuum company (such as Hindhivac and Fillunger) to ensure reliable fabrication of leak-free vacuum beam tubes and end stations. LIGO Lab USA pioneered the technology for achieving a 10-fold reduction in out gassing rate in 304L stainless steel (the type proposed for use in LIGO-India), through an inexpensive heat treatment process, prior to the spiral mill forming. The steel sheets for the beam tubes are air baked at 450° C for 36 hours, this removes the hydrogen from the steel and also adds an oxide layer for passivation that reduces out-gassing. Using the process specification from LIGO with careful management and technical assistance by the LIGO-India team to the vacuum system contractor, we are confident that the results achieved by LIGO can be reproduced in India.

In short, although the project is challenging, we know that it is achievable, and by partnering with LIGO, we will have access to the specialized expertise needed to achieve success. Careful management and close attention by the LIGO-India project team will ensure that all technical specifications are properly interpreted and implemented in the designs. Furthermore, hand-holding from the LIGO lab would be available to make the project a success.

References

1. http://www.aigo.org.au/aigo_web_docs/LIGO-AustraliaProposal.pdf
2. A. Einstein, Preuss. Akad. Wiss. Berlin, Sitzungsberichte der Physikalisch mathematischen Klasse, Preuss. Akad. Wiss. Berlin, Sitzungsberichte der Physikalischmathematischen Klasse (1916).
3. A. Abramovici, et al., "LIGO: the Laser Interferometer Gravitational-Wave Observatory, Science (USA), **256**, 325, (1992).
4. M.E. Gertsenshtein, and V.I. Pustovoit, "On the detection of low frequency gravitational waves", Soviet Physics – JETP, **16**, 433, (1962).
5. B.J. Meers, "Recycling in laser-interferometric gravitational-wave detectors", Physics Review D, 38, 2317, (1988).
6. G.M. Harry (for the LIGO Scientific Collaboration), "Advanced LIGO: the next generation of gravitational wave detector", Classical and Quantum Gravity, **27**, 084006, (2010).
7. http://www.aei.mpg.de/hannover-en/66-contemporaryIssues/home/index.html
8. http://www.aei.mpg.de/english/research/teams/laserInterferometry/index.html
9. B. Willke, *Stabilized lasers for advanced gravitational wave detectors,* Laser and Photonics Reviews, **4**, 780, (2010).
10. http://www.acpo.csiro.au/
11. A. F. Brooks, Thu-Lan Kelly, P. J. Veitch, and J. Munch, *Ultra-sensitive wavefront measurement using a Hartmann sensor*, Opt. Express **15**, 10370 (2007)
12. N.A. Robertson, et al, "Seismic isolation and suspension systems for Advanced LIGO". Page 81 of: Hough, J, and Sanders, G (eds), Gravitational Wave and Particle Astrophysics Detectors. Proc. SPIE, **5500,** (2004)
13. R. Abbott et al., 2002, *Seismic isolation for Advanced LIGO*, Classical and Quantum Gravity, **19**, 1591 (2002).
14. M.E. Zucker, and S.E. Whitcomb, "Measurement of Optical Path Fluctuations due to Residual Gas in the LIGO 40 Meter Interferometer". Pages 1434 of: Proceedings of the Seventh Marcel Grossman Meeting on recent developments in theoretical and experimental general relativity, gravitation, and relativistic field theories, (1996).
15. http://wwwcascina.virgo.infn.it/
16. http://www.ligo.org/
17. B.S. Sathyaprakash, S. Fairhurst, B. Schutz, J. Veitch, et al, *Scientific benefits of moving one of LIGO Hanford detectors to India,* (2011).
18. B.S. Sathyaprakash and B. Schutz, Physics, *Astrophysics and Cosmology with Gravitational Waves,* Living Revs. Relativity, **12,** 2 (2009).
19. S. Klimenko and G.Vedavato, *Source localization with the IndIGO detector,* Technical Note LIGO-T1100280-v1 (2011).
20. B. Schutz, *Networks of gravitational wave detectors and three figures of merit,* Class. Quantum Grav. **28,** 125023, (2011).
21. J. Lattimer and M. Prakash (2010), arXiv:1012.3208.
22. R. Narayan, New J. Phys. **7** 199 (2005).
23. S. Komossa, Memorie della Società Astronomica Italiana **77**, 733 (2006).
24. J. Abadie et al, Class. Quantum Grav. 27 173001 (2010).
25. C. D. Ott, Class. Quantum Grav. **26** 063001 (2009).
26. N. Anderson *et al,* Gen Relativ Gravit **43** 409 (2011).
27. http://einstein.phys.uwm.edu/
28. A. Watts *et al,* MNRAS **389** 839 (2008).

29. B. P. Abbott *et al*, Nature **460** 990 (2009).
30. C. Wu, V. Mandic, T. Rejimbau, To be published (2011). LIGO-P1100132-v1
31. See L. Blanchet *et al,* Phys. Rev. Lett. **93** 091101 (2004), and references therein.
32. F. Pretorius, Phys. Rev. Lett. **95** 121101 (2005).
33. See, e.g., Y. Sekiguchi *et al,* Phys. Rev. Lett. **107** 051102 (2011).
34. L. Rezzolla *et al,* Astrophys. J. Lett. **732** L6 (2011).
35. C. Palenzuela *et al,* Science **329** 927 (2010).
36. https://www.ninja-project.org/
37. C. D. Ott, Class. Quantum Grav. **26** 063001 (2009).
38. S. E. Woosley and J. S. Bloom, Annu. Rev. Astron. Astrophys. **44** 507 (2006).
39. S. Nissanke *et al*, Astrophys. J. **725** 496 (2010).
40. B. P. Abbott *et al*, Nature **460**, 990 (2009).

ANNEXURE I
Seed funding for LIGO-India

Seed funding is sought for four areas of initial development that require urgent action towards taking up the LIGO-India project:

- Site selection and validation,
- Vacuum infrastructure development,
- Human Resource development,
- Pre-project start planning and interfacing with LIGO.

a) Site selection and validation: The gravitational wave detector is a ultra-sensitive optical interferometer with projected sensitivity of 10^{-19}m for displacement of its mirrors. This is achieved with careful isolation from seismic and environmental disturbances, vibrations and gravity gradients. This naturally implies very careful site selection and preparation. The nearest railway lines and heavy traffic should be several kilometers away from the central laboratory station and the end stations of the L-shaped 4 km x 4km interferometer. Seismically quiet sites in the Deccan plateau are a good possibility. The central laboratory station will require an isolated area of 400 m x 400 m (40 acres). Ideally, the end stations should also be well isolated, and could be on area of 200 m x 100 m (2x 5 acres). Each of the 4 km arm will need a minimum isolated area of about 4 km x 50 m (2x 50 acres). Hence the total land required is about 150 acres, with good isolation from large disturbances. It is also important to locate the central laboratory site not too far away from air (100-200 km) and good national road (<10 km) access. Careful selection, measurements for validation of noise immunity etc. will have to be done at potential sites during 2011-12 and procedures for site acquisition will have to be initiated and concluded by 2013. Instruments for measurements of vibration, weather monitoring etc. will have to be procured and deployed. The measurements and validation will be done in collaboration and consultation with the LIGO laboratory and help from specialized industry partners may be taken. The estimated expenditure for essential equipment, initial surveys and measurements, visits of experts from LIGO laboratory, associated travel to potential sites, hiring of professional help etc. is Rs. 90 lakhs, during December 2011- March 2013.

b) Vacuum infrastructure development: The most important and sophisticated of the infrastructure facility is the ultra-high vacuum environment to be created to house the mirrors and beams splitters of the interferometer on their vibration isolation suspensions, as well as the 2x4 km long UHV tubes that form the arms of the interferometer. While the technology for producing such vacuum chambers that can maintain UHV of 10^{-9} mbar is standard when considered in terms of modular assembly, the scale of the volume to be handled calls for fresh trials in Indian conditions of work and industrial facilities. This will be done in collaboration with industry partners like Hindhivac, Fillunger and Co., Godrej, Larson &Toubro etc. Tests of low cost surface treatment of steel for UHV, tests of welding technologies, methods of support and thermal isolation of the UHV interferometer beam-lines etc. will be conducted in parallel with the site selection and preparation. Since the cost of creating the UHV infrastructure amounts to almost 40% of the total budget, it will be of great importance to prove out the fabrication techniques and quality control processes, and to implement any cost-saving strategies identified. RRCAT, Indore and IPR Ahmedabad will be the nodal points for these tests, with industry participation. Being the most important pre-installation activity, every effort has to be made to quickly validate the relevant technologies and processes. The estimated expenditure during 2011-13 is Rs. 8 Crores

c) Human Resource development: The team of scientists and engineers needed for the LIGO-India project will have to be expanded within the short time scale of 2 years and this requires several discussion meetings coordinating expertise from several research institutes, universities, IISERs and IITs. Manpower training and detector familiarization at all levels by on site presence and work at the LIGO-USA detectors during 2012-13, is a major strategy point in the implementation of the LIGO-India detector. The required fund for this is Rs. 80 lakhs during 2011-13.

d) Pre-project start planning and interfacing with LIGO: A fund for the efficient working of the IndIGO consortium within the context of LIGO-India will be required during the first two years for its council members and advisory committee members to meet, develop strategies and plan schedule etc. and also for attending the LIGO-India international meetings and GWIC meetings. Offices will be set up in nodal institutions with sufficient networking and dedicated computer and communication facilities. The funds required for this is Rs. 60 lakhs.

IndIGO seeks Rs. 10.3 Crores during December 2011 to March 2013 as the seed funding to facilitate these essential components of preparation for the LIGO-India.

ANNEXURE II

Ultra-High Vacuum (UHV) System for LIGO-IndIGO

To keep the light scattering and phase fluctuations from density fluctuations of the gaseous environment in the interferometer low enough to reach the projected sensitivity of the advanced LIGO detector, the entire optical arrangement and their vibration isolation suspensions require ultrahigh vacuum (UHV) environment with vacuum close to 10^{-9} mbar, limited by the partial pressure of Hydrogen in the system. The partial pressures of heavy hydrocarbons needs to be 3-4 orders lower. This is also important in keeping the mirror surfaces clean, avoiding excessive adsorption of contaminants that will result in unacceptable levels of optical loss. The strain noise from phase fluctuations scale as $Ap^{1/2}$ where p is the pressure, and the coefficient A that depends on the mass of the gas molecule can be 150-200 times larger for heavy hydrocarbons compared the Hydrogen. Advanced LIGO is designed to keep the equivalent strain noise at the level of $2 \times 10^{-25}/(\mathrm{Hz})^{1/2}$, about a 10th below the projected sensitivity.

Realizing the UHV infrastructure for LIGO-India with the required specifications is the most important task in the project and therefore, several technical details are discussed here. The UHV system will consist of 8 kilometers of beam tubes of 1.2 meter diameter and large corner / end stations, with a total volume of about 10000 m^3 . In addition there are various manifolds, large and small gate valves, various types of vacuum pumps, vacuum gauges, controls etc. This UHV system will be the largest outside the USA. The LIGO-India UHV design will maintain the basic design and well-tested and successful protocols of the advanced LIGO systems in USA. Compatibility of the design and fabrication process with the facilities and work methods of Indian vacuum industries will be ensured with a goal to reduce the overall cost while meeting or exceeding the specifications. However, testing of new developments in UHV technology will be explored in parallel for possible use in LIGO-India, if they can be demonstrated as cost-effective and reliable. Various techniques for low cost surface treatment of stainless steel, in situ welding, support and thermal isolation of the UHV interferometer beam lines etc. will be developed in parallel with the site selection and preparation. Being the most important pre-installation activity, every effort has to be made to quickly validate the relevant technologies and processes to UHV enclosure.

The UHV system for Advanced LIGO in USA, installed for the initial LIGO a decade ago, exceeds the requirement specifications due to a simple design that depended on careful preparation of the raw materials with high temperature baking for hydrogen outgassing from steel, clean and reliable welding technology, cleaning and baking. Pumped by only two ion pumps (2500 l/s) at the end stations, vacuum close to 10^{-9} mbar is maintained in each of the 4 km long beam tubes. Water vapor contamination is avoided by operating liquid nitrogen cryo-pumps at the interface of central station chambers and the beam tubes. Thus the technology for pumping is well within the local expertise in India.

Fig. A.II.1 shows main components of the vacuum system for LIGO detector. The details of the vacuum components are as follows.

1. Main Chambers for Beam Splitter and Mirrors

Five large chambers at the places shown in Fig. A.II.1 will house the core optical components like the beam splitter and test masses, and are generally called beam splitter chamber (BSC). It consists of a cylinder of 265 cm inside diameter and upper major access section approximately 154 cm long. It is made up of a 304L stainless steel shell, stiffened by means of a rolled stainless steel angle. The top head is an ASME flanged with dished (F&D) section having lifting lugs. The bottom section of the BSC is also a 265 cm inside diameter shell with a bottom ASME F & D head. This bottom section of shell consists of many port openings for laser beam access, up port beams, electrical feedthorughs etc. The vessel will be on steel supports, anchored to the concrete floor slab. For the upper section of the BSC vessel, a stainless steel external stiffener has been added to the shell to reinforce the vessel.

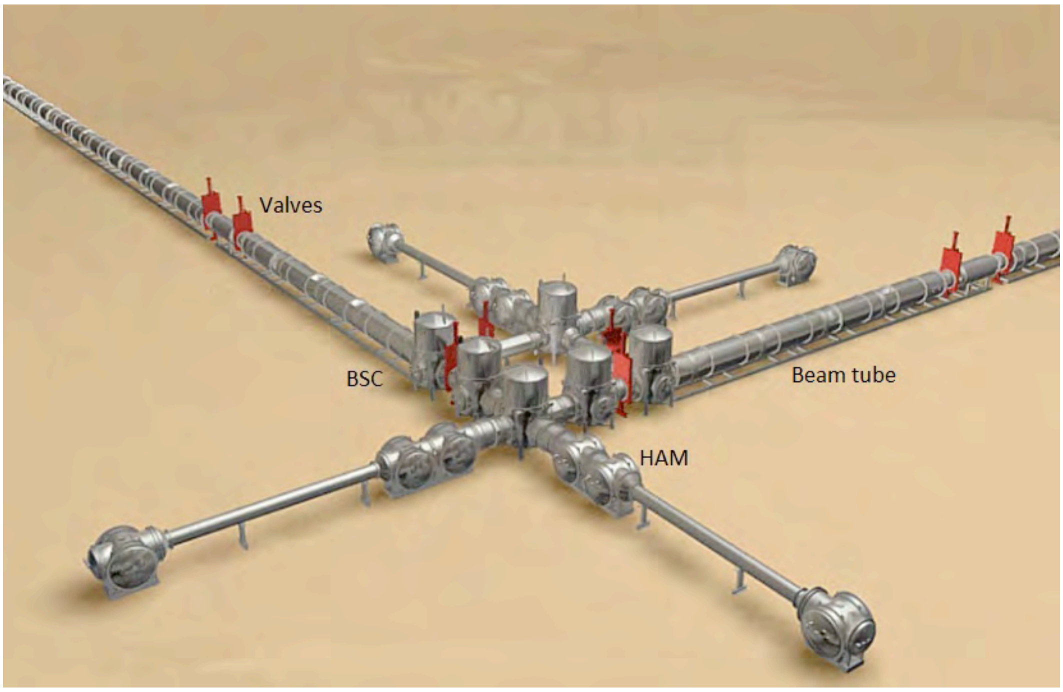


Fig. A.II.1 showing the main components of the vacuum system for the LIGO detector.

2. Horizontal Access Module

The Horizontal Access Modules (HAM) which house rest of the support optics like the power recycling mirror is a 213 cm I. D. horizontal vacuum vessel. They have ASME F&D heads with bolted flanges and 10-20 cm nozzles for observation ports. The shell section is type 304/304L stainless steel stiffened in two areas by means of stainless steel angles to bring stress levels to within ASME Sect.VI is allowable. Lifting Lugs are attached to stiffeners located on the top section of the shell and positioned to allow the vessel to hang vertically when lifted. One Laser Beam nozzle is supplied with a bellow type expansion joint to provide flexibility for thermal movements and to allow O-ring maintenance. The guide rods, attached to the bellows, will carry out the bellow expansion/ compression.

3. Beam Tube Manifolds/Adapter Spools

Beam tube manifolds consist of 183 cm inside diameter, rolled sections of varying length with SS stiffening angles. Flanges for beam tube sections have been located to provide space for future components. Flanges have also been designed to act as vacuum stiffeners. A flexible support will allow thermal expansion, but it will support the weight of the manifold and restrain it against lateral seismic acceleration. The bellows expansion joint allows free thermal motion during bake-out.

4. Mode Cleaner Tubes

Mode cleaner tubes consist of rolled sections of varying length. Supports for the cleaner tubes will be similar to the beam tubes. The flexible supports and bellows allow thermal expansion during bakeout. The design includes flanges featuring dual Viton O-rings and a pumped annulus space.

5. Bellows

Bellow expansion joints are placed between components and between the axial restraints of beam tube manifolds and mode cleaner tubes to allow unrestrained thermal expansion during the bakeout condition.

6. UHV preparation

The vacuum enclosure will be fabricated using flanges with dual Viton o-ring seals and an annular pump out channel. This design will provide the best performance for an operational consideration and also allows us to utilize the best alternatives for fabrication shipping, maintenance. Bolt spacing for the flanges will be selected on the basis of structural considerations of the gasket vendors for optimum performance, and also ease and speed of opening of access ports, dome section, etc.

Movable tent type clean rooms will be required during the welding of the beam tubes and assembly of the system and the final building will have to have to be a clean room with AC and pressurization modules to keep dust out. All the HAM and BSC vacuum chambers will have to be in class 1000 clean room, which mean all the laboratory space has to be of this standard.

The long baselines will be fabricated from pre-treated, air-baked 304L grade stainless steel. The SS 304L, while in the form of a roll, will undergo a baking at 450 °C for 36 h to reduce the outgassing rate of hydrogen. A low temperature vacuum baking after fabricating the roll into a tube will reduce the outgassing rate of hydrogen significantly. After installation, a low temperature (150° C) bake of the chamber in vacuum will be sufficient to remove species such as H_2O, CO, and CO_2. The pipe will be fabricated in long lengths on-site, from rolls that have been pre-treated. The rolls will be spiral welded to form the beam tube. Gaskets used at joints or blanks meant for the interface with vacuum pumps will be made of copper. After fabrication and installation, it will be necessary to apply standard vacuum baking techniques at about 150° C to reduce water vapour and hydrocarbon contamination.

The baffles, designed to minimize the scattering of light within the tube, will also undergo baking and will be installed along with the tube fabrication. 100 baffles will be distributed along the tube length. The stiffening rings will be used at regular intervals to prevent the collapse of the tube under atmospheric pressure. The tube will be supported on concrete footings along the length and will be surveyed to ensure linearity within 5 mm. Vacuum monitoring and control will be performed by a general-purpose automation controller system that will have the facility to remotely monitor and control the vacuum components through a computer network, as well as via the internet.

The axial restraints are designed for full vacuum load where a gate valve is attached to a tube or component. Flexible supports are attached to tubes and adapters to facilitate thermal expansion. These are designed for combined loads resulting from axial thermal expansion of tubes, downward component weight load and lateral seismic forces.

7. Pumps

The gases in the enclosure in vacuum condition are mainly hydrogen, water vapour, hydrocarbon etc. To achieve ultra high vacuum, the partial pressure of hydrogen must be reduced to $1\text{x}10^{-9}$ mbar. The partial pressures of the other species must be still lower. For example, water, N_2, CO, CO_2, and CH_4 are to be less than $5\text{x}10^{-11}$ mbar. The strategy for keeping very low hydrocarbon is to maintain a rigorously hydrocarbon-free system at all stages of manufacture. Of all the other species, hydrogen is the critical one because it is continually outgassed from stainless steel. Pre-baking at 450° C in dry air of the stainless steel sheets used for the fabrication of the UHV tubes will significantly reduce hydrogen degassing in UHV conditions.

- **Pump-down From atmospheric pressure to 0.1 mbar**: Initially, appropriate rough pumping system is used to obtain 10^{-1} mbar in less than few hours, for crossover to Turbo molecular pumping (TMP). The rough pumping system, comprised of a roots blower, backed by a multistage dry pump, pump down from atmospheric pressure to 10^{-2} mbar in few hours for the largest isolatable volume of the chamber in the corner station. For the chambers of mid and end stations, that do not have separate roughing pumps, the pump down will be on the order of 12 to 16 hours.

- **Pump-down From 0.1 mbar to 10^{-6} mbar:** For a clean, dry system, medium-size TMPs with a few 1000l/s net pumping speed is adequate for pump down of the isolatable section in 24 hours. In the presence of some moisture in the chamber, because of improper bake-out, or purging with less dry air, it is straightforward to provide larger pumping speeds with additional larger capacity TMP connected at the roughing port.

- **Pump-down From 10^{-6} mbar to 10^{-9} mbar:** Using the 80K cryo-pump and Ion pumps, reaching the desired ultimate partial pressures within 100 hours of pumping will be dictated by the out-gassing rates and is dependent on proper cleaning and bake-out of the surfaces. To achieve the required partial pressures the out-gassing rate for water, after 100 hours, needs to about 5×10^{-11} mbar-liter/sec-cm^2. The out-gassing rate for hydrogen needs to be about $1\text{x}10^{-11}$ mbar-liter/sec-cm^2, and the total out-gassing rate for the other gases needs to about 1×10^{-12} mbar-liter/sec-cm^2.

The system for continuous pumping consists of only the ion pumps (2x2500 liter/sec for each arm) and the LN2 cryopump, with possible addition of some NEG pumps, all of which are vibration free. Attaining the final vacuum near 10^{-9} mbar may take several days of pumping after baking.

8. Bake out Capability

Degassing of the vacuum chamber walls requires a bake-out temperature of 150° C. The requirements and design criteria for the bake-out blanket system are dictated by bake-out temperature, warm-up time, maximum allowable surface temperature, practical blanket thickness and available space for installation, insulation be, cost effective design and end effects such as gate valves gate and vacuum envelope supports etc.

To be able to reach a temperature of 150° C, insulation blankets are required. To maintain a reasonable cost of the blanket system and manageability of the blankets 5 cm fiberglass insulation is preferable.

9. Leak test

Leak checking and ensuring 'no-leak' situation to the required level for the large chambers and the 8km beam tubes requires a standardized and efficient protocol with strict quality control. Leak checking of the large BSC and HAM chambers will follow leak test with standard Helium mass spectrometer leak detectors and the procedure for that is already familiar in the context of several large scale experimental UHV chambers at IPR and RRCAT in India. The beam tubes will be He leak tested in 20 m sections, 400 of them individually to the level
10^{-10} mbar-l/s, after thorough checks and necessary fine repairs on the welding. This will be done after machining the tube sections, in preparation of the final butt welding, using specially fabricated clampable flanges with a butt seal and another viton seal with pumped annular region. Dry (oil free) pumps will be used for the leak tests as well. The final leak test on each chamber and tube section will be carried out after baking at 150° C. Residual Gas Analyzer (RGA) can also be used for quantitative partial pressures estimates for different species.

ANNEXURE III
Quantum Squeezed Light for Noise Reduction in GW detectors

Use of quantum squeezed light for sub-shot noise metrology is a new frontier in gravitational wave detectors, even though the theoretical proposals existed for more than two decades. The basic idea is that instead of using coherent state of light containing photons with Poisson statistics (shot noise) and symmetric amplitude-phase uncertainties, use light that is modified such that the phase quadrature, relevant for interferometry, is 'squeezed' in uncertainty while allowing correspondingly more uncertainty in the amplitude, with the product of uncertainties respecting the usual Heisenberg bound. One can also tune the quadrature to be squeezed, depending on whether the dominant noise contribution is from the radiation pressure or from the shot noise. This needs to be done in the frequency band relevant for the GW detector, from about 10 Hz to 10 kHz or so. This is an essential and necessary technique for the next generation gravitational detectors that are projected to be capable of frequent detections with a reliable signal to noise factor, suitable for gravitational wave astronomy. Since vibration isolation techniques have managed to shield vibration noise to levels lower than 10^{-20} m-Hz$^{-1/2}$, the residual noise in the advanced detectors is determined by the radiation pressure noise at low frequencies and the quantum shot noise at higher frequencies. The former is proportional to the square root of the photon number or laser power, being caused by fluctuations in intensity, and the latter is proportional to the inverse of the square root of photon number. Therefore, at any given frequency there is an optimum power that gives the best displacement sensitivity, known as the Standard Quantum Limit (SQL), given by

$$d_{\mathrm{sql}} = (\pi f)^{-1}\ (\hbar/m)^{1/2,}$$

where f is the frequency of mirror motion, and m is the mass of the mirror.

The goal using squeezed light is to beat the SQL by a factor up to 10. The technique is to inject quantum-squeezed light into the signal port of the interferometer. The idea is that the quantum vacuum state, with equal uncertainty in phase and amplitude, which usually enters the interferometer from the beam-splitter output port, is now replaced with a special state of light with less fluctuation in phase, and this reflects in a better definition of the phase difference between the two arms, below the usual shot noise limit. Going a factor of F below shot noise with this technique is equivalent to increasing the laser power by a factor F^2, with resultant increase of the radiation pressure noise by a factor F due to the increase in the uncertainty in the amplitude quadrature. However, radiation pressure noise is significant only in the low frequency regime, and in general one can get very useful enhancement of sensitivity in the bandwidth relevant for gravitational wave detection by tuning the squeezing in a frequency dependent way. Using squeezed light is fully compatible with power recycling when operated on the dark fringe at output.

Squeezed light is generated phase coherently with the input laser light to the interferometer by frequency doubling a derived beam in a nonlinear crystal and then down-converting it to the base frequency in another nonlinear crystal using optical parametric generation. This allows homodyne detection of the signal by mixing the signal with the seed laser as the local oscillator.

It is important in this scheme that there is minimal loss of squeezed light in the optical component, detector etc. In practice there is always some loss, and the advantage is quickly lost completely when there is significant optical loss. The use and optimization of these techniques are topics of current research. There are new issues that need to investigated, while trying to combine the advantageous aspects of different techniques like power recycling, DC readout, signal recycling, use of squeezed light etc. in a single system, all working together. However, Advanced LIGO-like detectors are already trying to incorporate this very important quantum detection scheme to improve the sensitivity and it is expected that LIGO-India detector will incorporate these technological advance when mature.

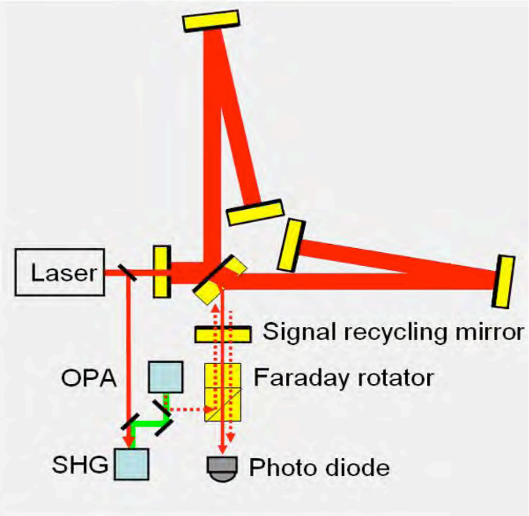


Fig. A.III.1. Scheme for using quantum squeezed light in the GEO600 GW detector (Albert Einstein Institute, Hannover).

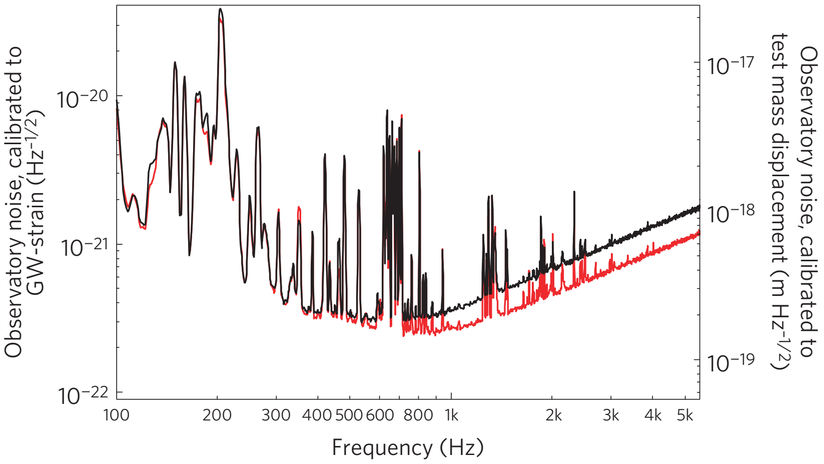


Fig. A.III.2. The demonstration of sensitivity improvement in the GEO600 detector using squeezed light injection [Abadie *et al* 2011]. This detector is shot noise limited above 700 Hz, and the improvement is visible for higher frequencies.

The spin-offs from developing and using this technology will directly benefit low noise and robust telecommunications, quantum cryptographic communication, precision metrology and the development of light sources with built-in quantum noise reduction. The robust correlation in the generated squeezed light can be used for transmission of weaker signals at better signal to noise ratio and for quantum key distribution.

References

- A. Buonanno, and Y. Chen, *Quantum noise in second generation, signal-recycled laser interferometric gravitational-wave detectors,* Physics Reviews D, **64**, 042006 (2001).
- K. McKenzie, N. Grosse, W. Bowen, S.E. Whitcomb, M.B. Gray, D.E. McClelland and P.K. Lam, *Squeezing in the audio gravitational-wave detection band*, Physical Review Letters, **93**, 161105 (2004).
- H. Vahlbruch, H. et al., 2006, *Coherent Control of Vacuum Squeezing in the Gravitational-Wave Detection Band*, Physical Reviews Letters **97**, 011101 (2006).
- Abadie et al (LIGO Scientific Collaboration), *A gravitational wave observatory operating beyond the quantum limit: Squeezed light in application*, Nature Physics (2011) doi:10.1038/nphys2083.

ANNEXURE IV
IndIGO Consortium

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+Soumya Mohanty	University Texas, Brownsville
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Experimenters +Data Analysts Theorists

ANNEXURE V
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ANNEXURE VI

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ANNEXURE VII

List of Acronyms

- **IndIGO:** Indian Initiative in Gravitational-wave Observations
- **LIGO:** Laser Interferometer Gravitational-wave Observatory
- **ACIGA:** Australian Consortium for Interferometric Gravitational Astronomy
- **LCGT:** Large-scale Cryogenic Gravitational-wave Telescope
- **INO:** Indian Neutrino Observatory
- **TMT:** Thirty Meter Telescope
- **LHC:** Large Hadron Collider
- **SKA:** Square Kilometer Array
- **GW:** Gravitational Wave(s)
- **GWIC:** Gravitational Wave International Committee
- **LSC:** LIGO Scientific Collaboration
- **VLBI:** Very Large Baseline Interferometry
- **SKA:** Square Kilometer Array
- **MOU:** Memorandum Of Understanding
- **LISA:** Laser Interferometer Space Antenna
- **LCGT**: Large-scale Cryogenic Gravitational wave Telescope
- **ET:** Einstein Telescope
- **EGO:** European Gravitational Observatory
- **UHV:** Ultra-High Vacuum
