Hunting Black Holes with LIGO in India

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Outline

- Big questions
- Basic ideas:
  - » Special relativity
  - » Special relativity requires gravitational waves
  - » General relativity gives prediction of gravitational-wave strength, confirmed by binary neutron star orbital mechanics
- Some numbers
- What do detectors look like and how do they work?
- Kilometer-scale terrestrial detectors:
  - » First generation: Initial LIGO detectors & the worldwide network
  - » Second generation: Advanced LIGO & LIGO India

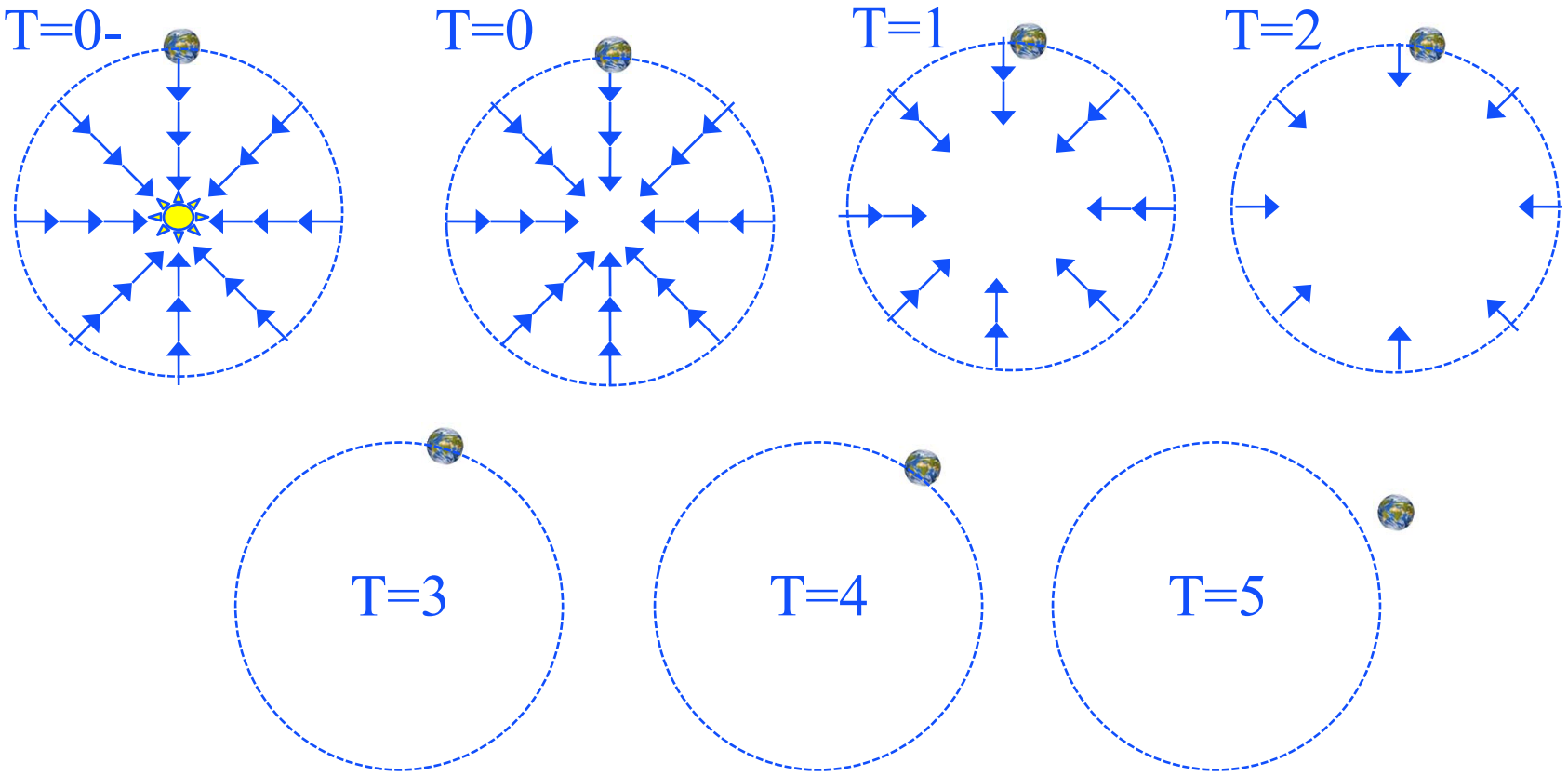
Big questions

- When we look out into the universe, do we see what is really there or do we see how we look at it?
- What is the nature of space and time?
- How did the universe come into being?
- What gives rise to the structure of our universe?
- How did the universe evolve from origins to the present day?

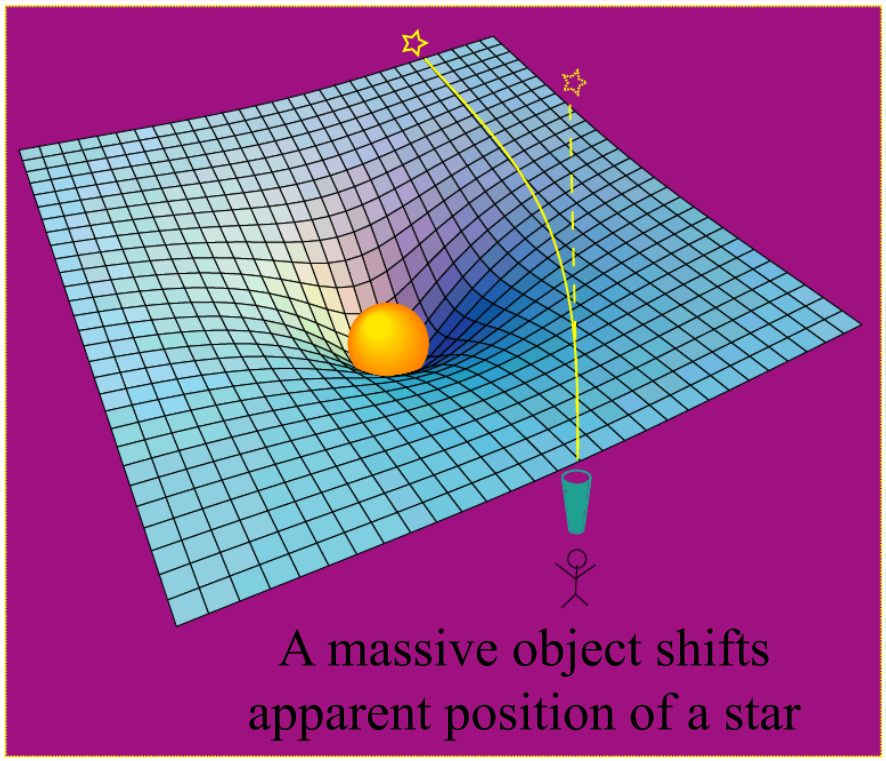
Elevator treatment of special relativity

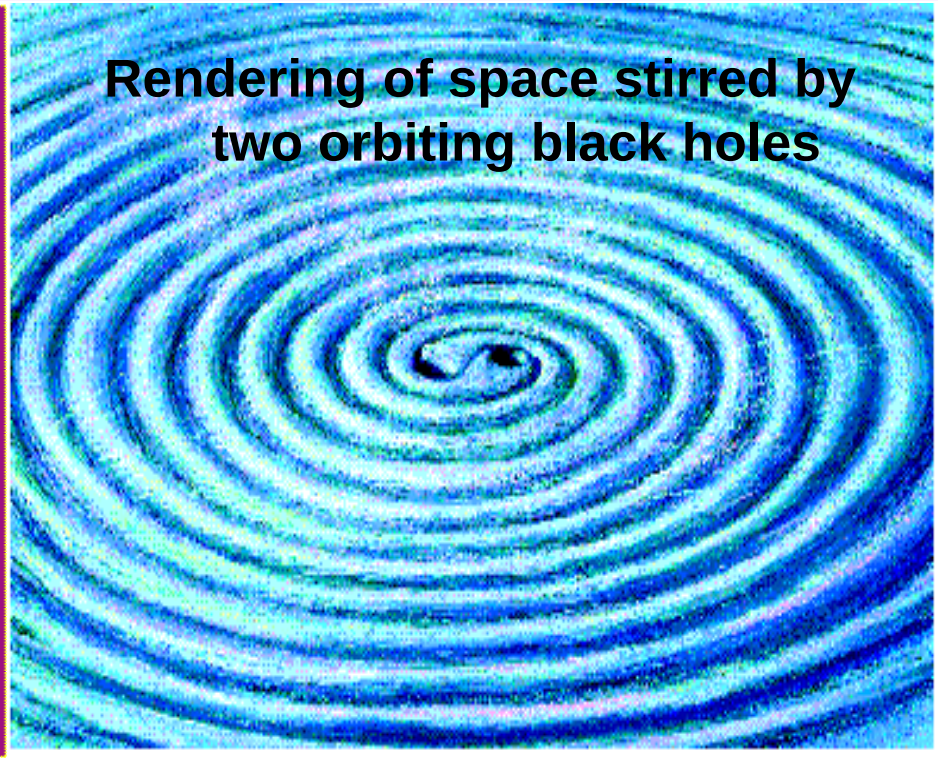
- Special relativity (1905) was Einstein's first attempt to unify Maxwell's electromagnetism and Newton's mechanics
- Galileo had realized that motion through space was not absolute, but relative to the observer
- Einstein further realized that the flow of time was not absolute, but relative to the observer
- Special relativity rules:
  - » Only the speed of light is absolute
  - » Speed of light is the maximum speed for information
  - » Time, space and motion are relative
  - » Moving observers all observe the same laws of physics, but will describe spatial and temporal events differently
  - » Matter & energy related; a bit like ice and water

Special Relativity and the Case of the Missing Sun



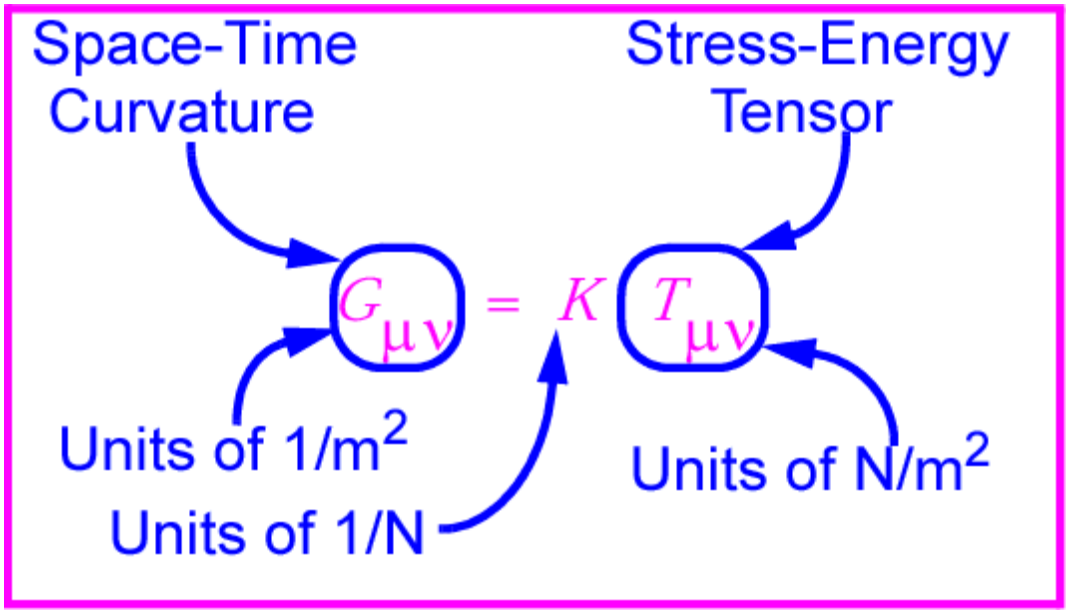
Einstein's General Relativity re-wrote the rules of space and time





Empty space and time are things, with real physical properties. Space has a shape, a stiffness and a maximum speed for information transfer.

Gravitational waves: hard to find because space-time is stiff!



- $K \sim [G/c^4]$ is lowest order combination of G, c with units of 1/N

$$K \sim 10^{-44}\ N^{-1}$$

⇒ Wave can carry huge energy with miniscule amplitude!

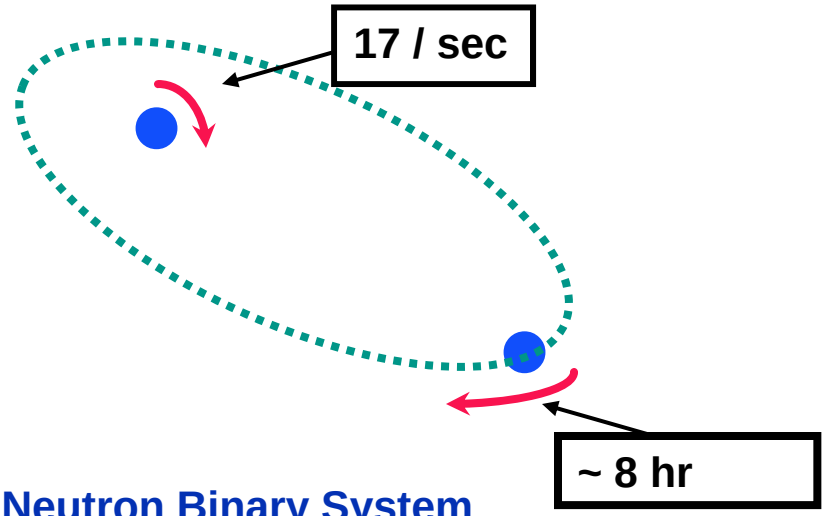
Gravitational Waves

known to exist, just hard to find

Emission of gravitational waves

Neutron Binary System – Hulse & Taylor

PSR 1913 + 16 -- Timing of pulsars

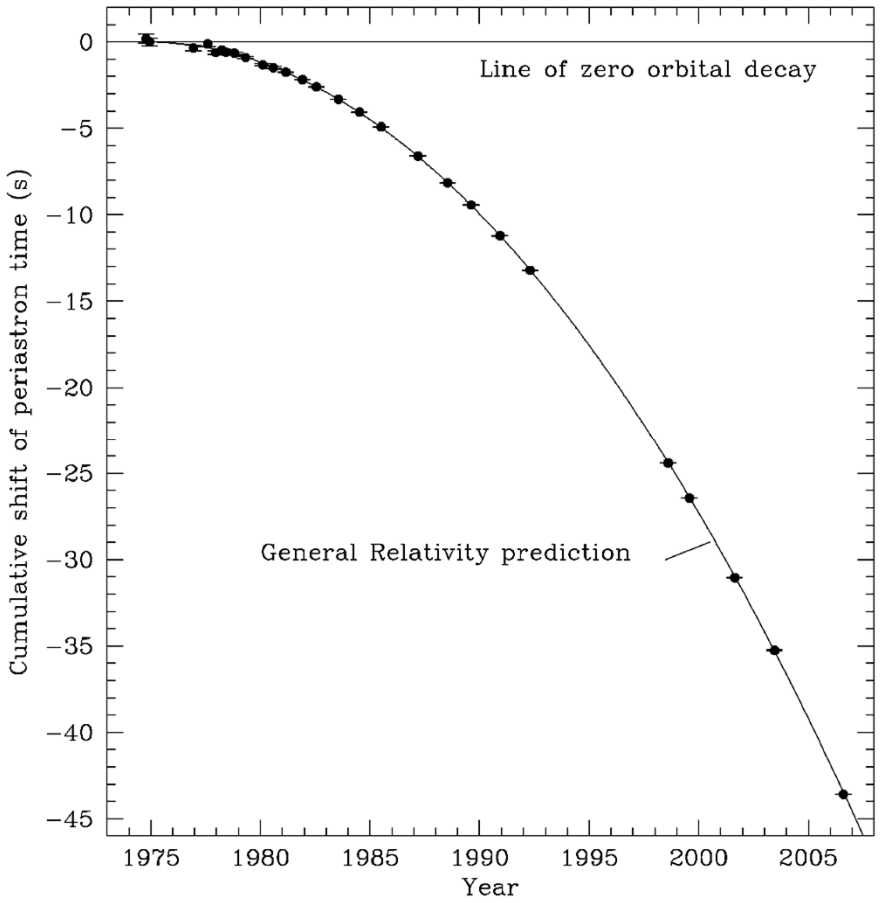


Neutron Binary System

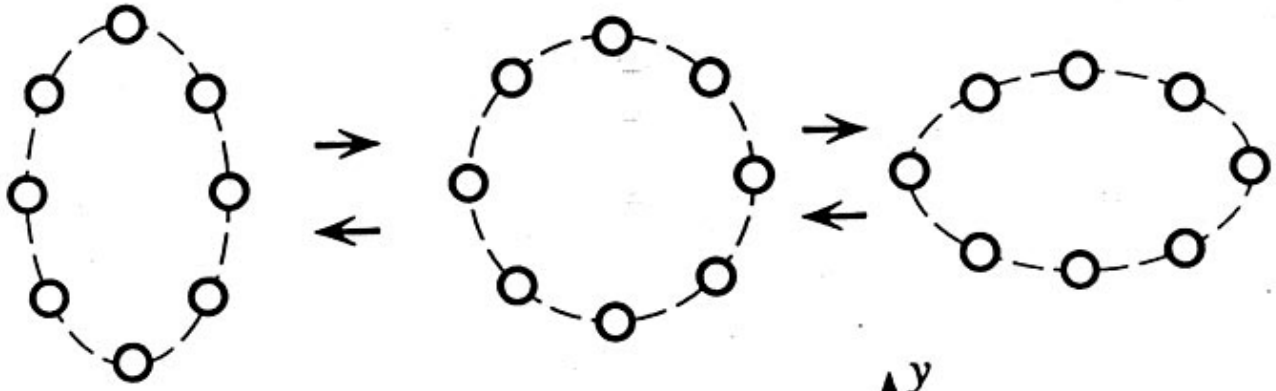
- **separated by 10^6 miles**
- **$m_1 = 1.4m_\odot$; $m_2 = 1.36m_\odot$; $\varepsilon = 0.617$**

Prediction from general relativity

- **spiral in by 3 mm/orbit**
- **rate of change orbital period**

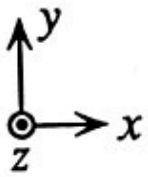


Basic idea for a laser interferometer GW detector

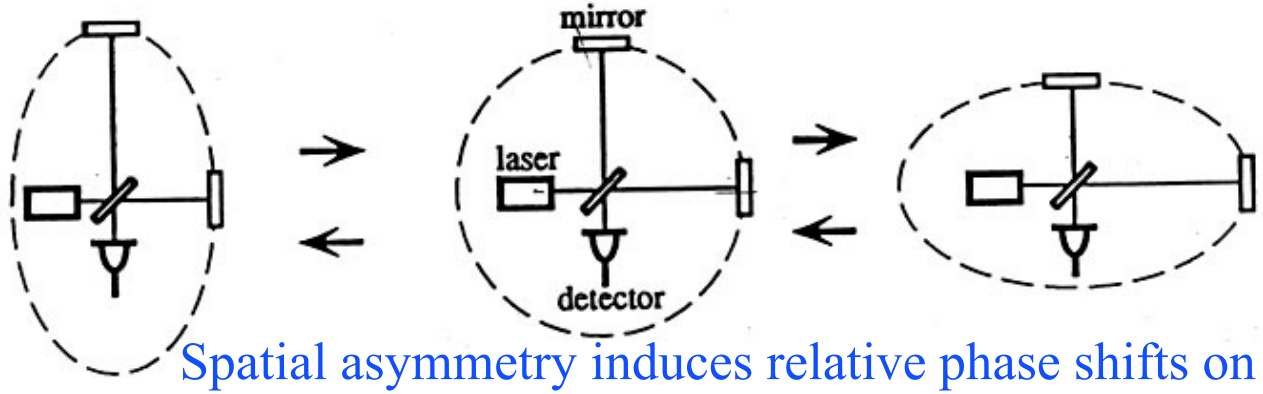


For R=4km, expect
$R_x - R_y \approx 10^{-19}$ m

⊙ Gravitational Waves



GW amplitude h
$= (R_x - R_y)/R$



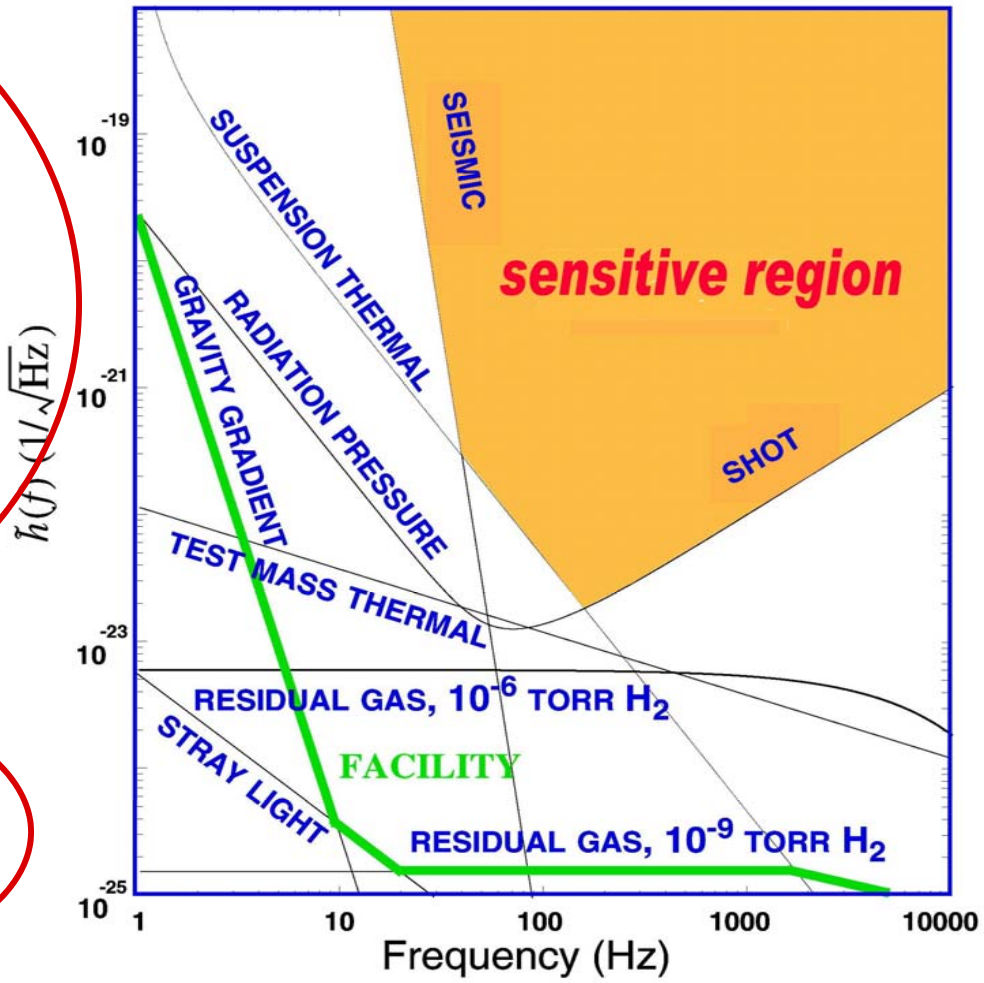
Spatial asymmetry induces relative phase shifts on light in arms

What Limits Sensitivity of Interferometers?

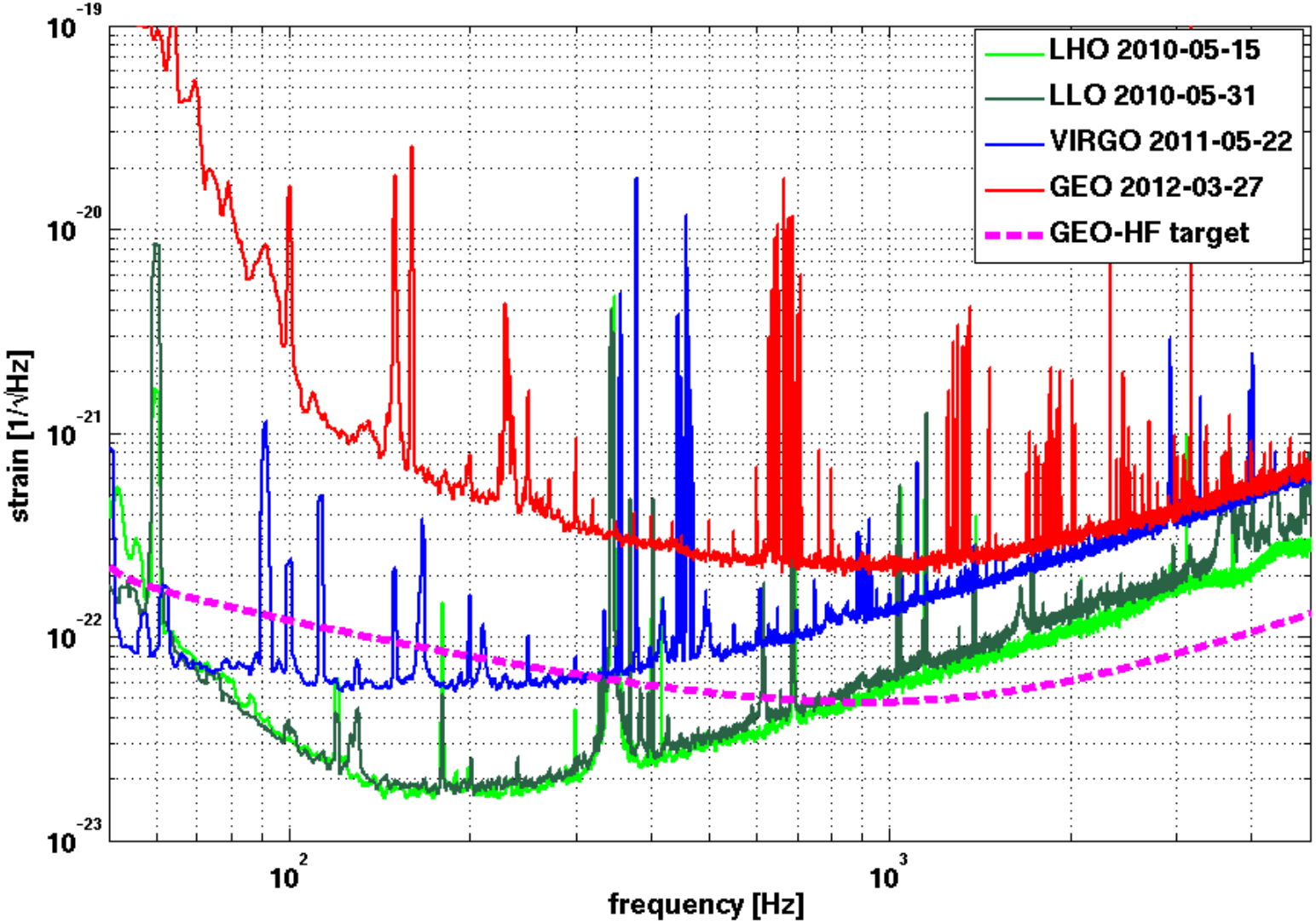
DESIGN

- Seismic noise & vibration limit at low frequencies
- Atomic vibrations (Thermal Noise) inside components limit at mid frequencies
- Quantum nature of light (Shot Noise) limits at high frequencies
- Myriad details of the lasers, electronics, etc., can make problems above these levels

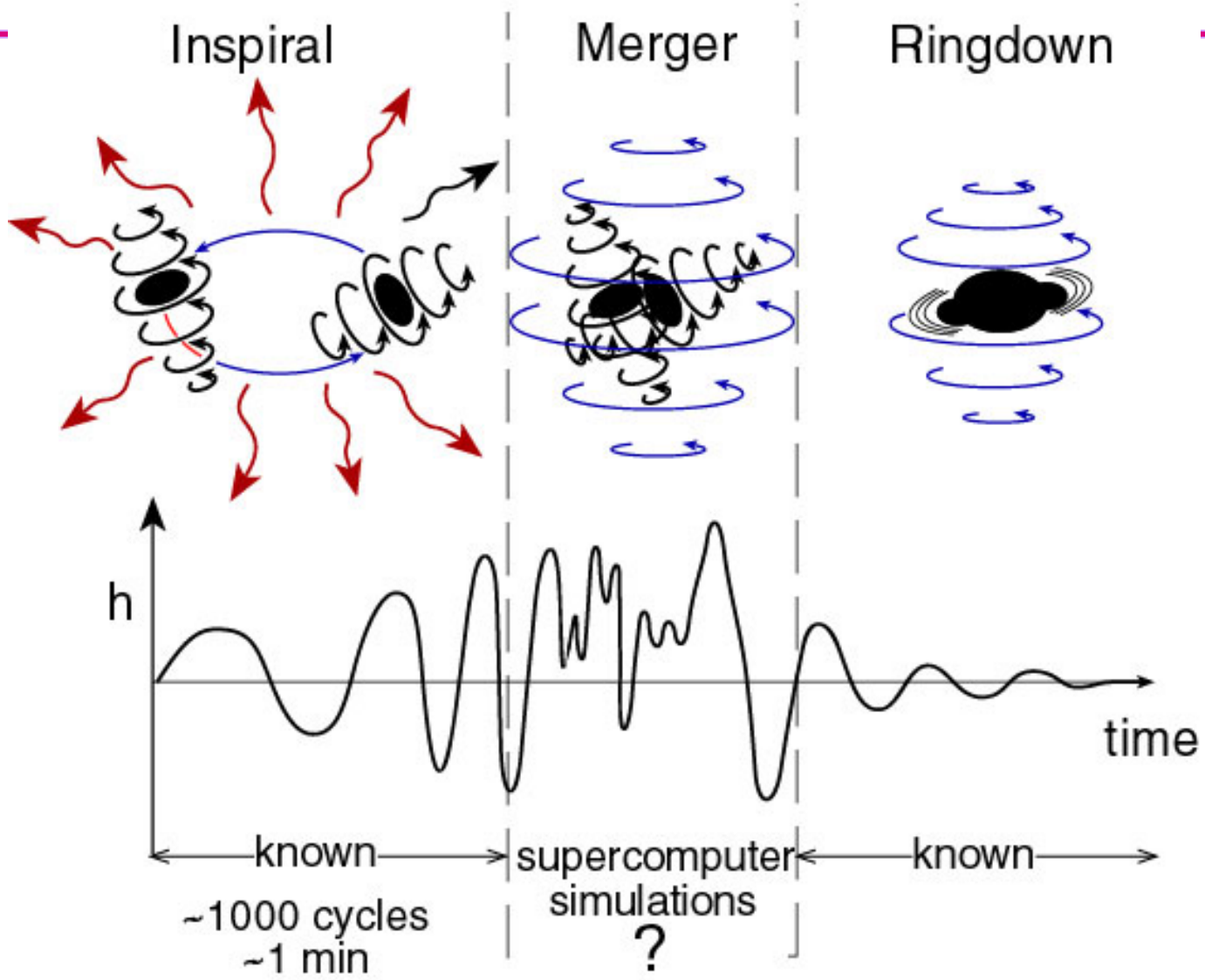
COMMISSIONING



Sensitivity of Initial Generation Detectors

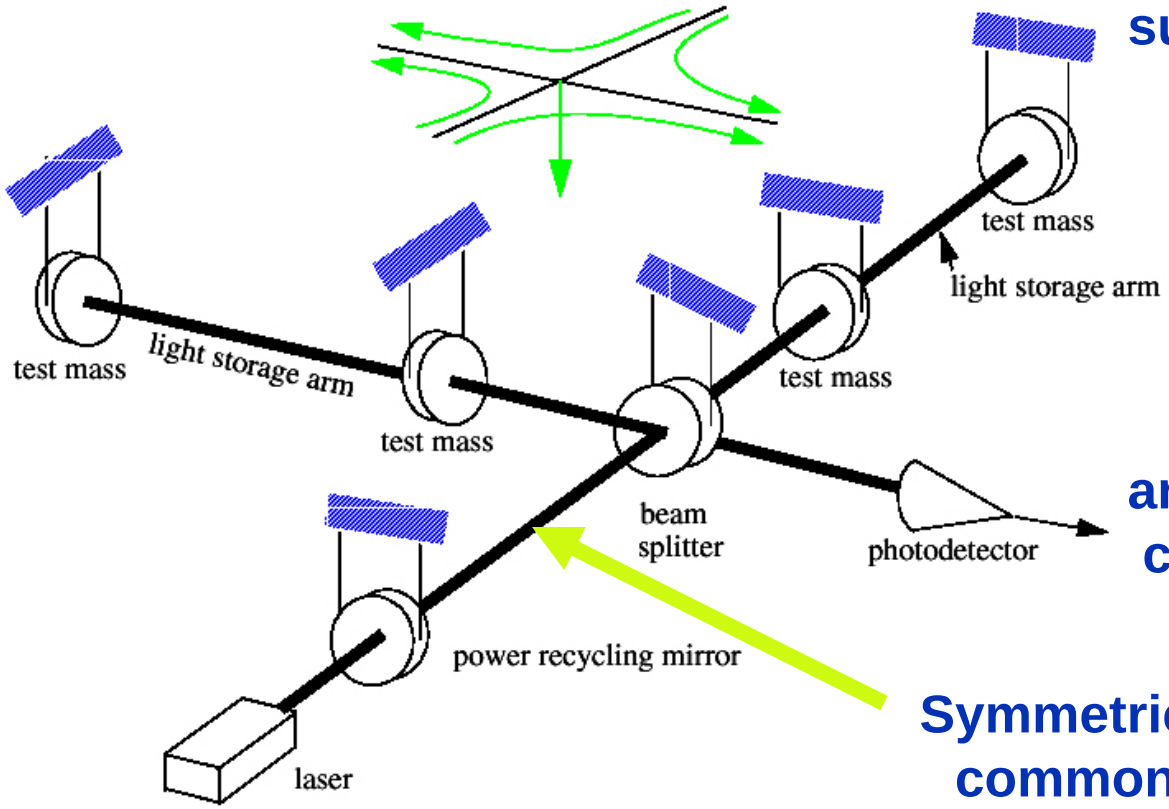


Catching Waves From Black Holes



Sketches courtesy of Kip Thorne

Initial LIGO: Power-recycled Fabry-Perot-Michelson



suspended mirrors mark inertial frames

Once the world's most sensitive machine

antisymmetric port carries GW signal

Symmetric port carries common-mode info

Intrinsically broad band and size-limited by speed of light.

The Laser Interferometer Gravitational-Wave Observatory

LIGO (Washington)

LIGO (Louisiana)

Owned by the US National Science Foundation; operated by Caltech and MIT; the research focus for 850 LIGO Scientific Collaboration members covering 5 continents. Now engaged in joint operations with Virgo Collaboration.

Interferometers in Europe

GEO 600 (Germany)
600-m

Operated by GEO, member of LIGO Scientific Collaboration

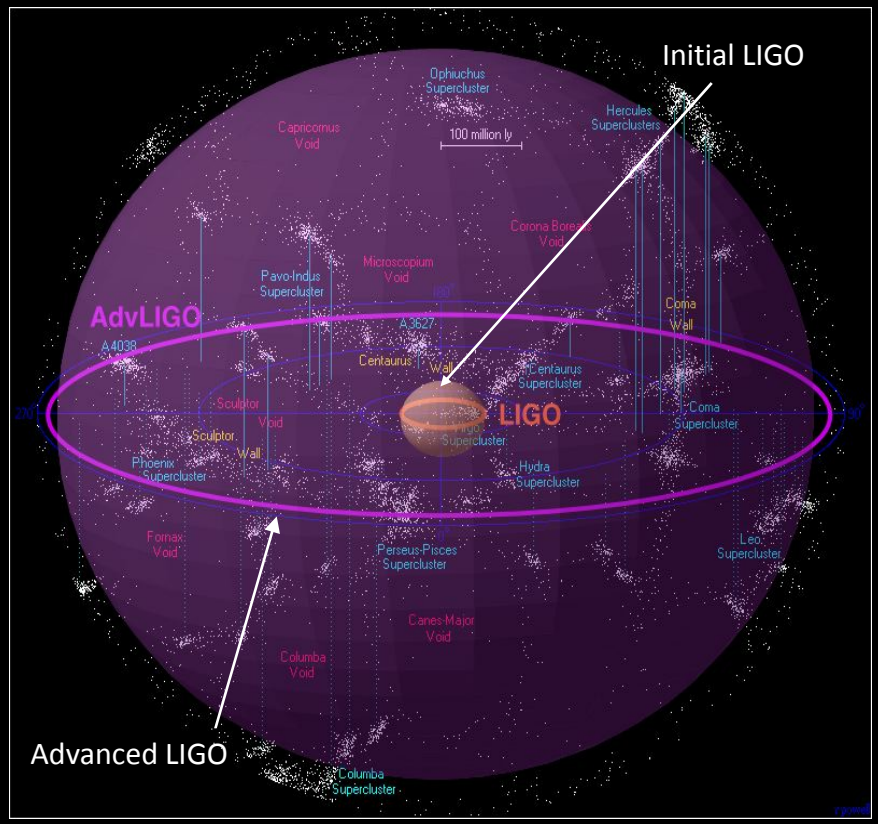
Virgo (Italy)
3-km

CNRS/INFN collaboration; has joint operating agreement w/ LIGO

2-Step Approach, From Discovery to Astronomy

1st generation: iLIGO, pathfinder that pays the billion-fold cost of admission; no guarantee of a home run

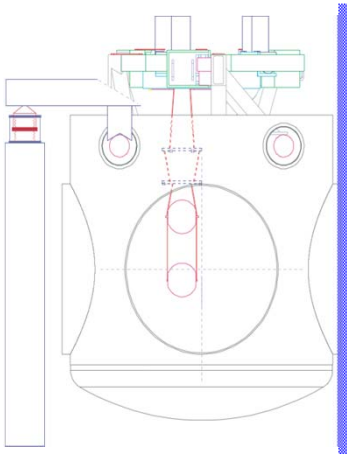
2nd generation: aLIGO, the trillion-fold home-run king



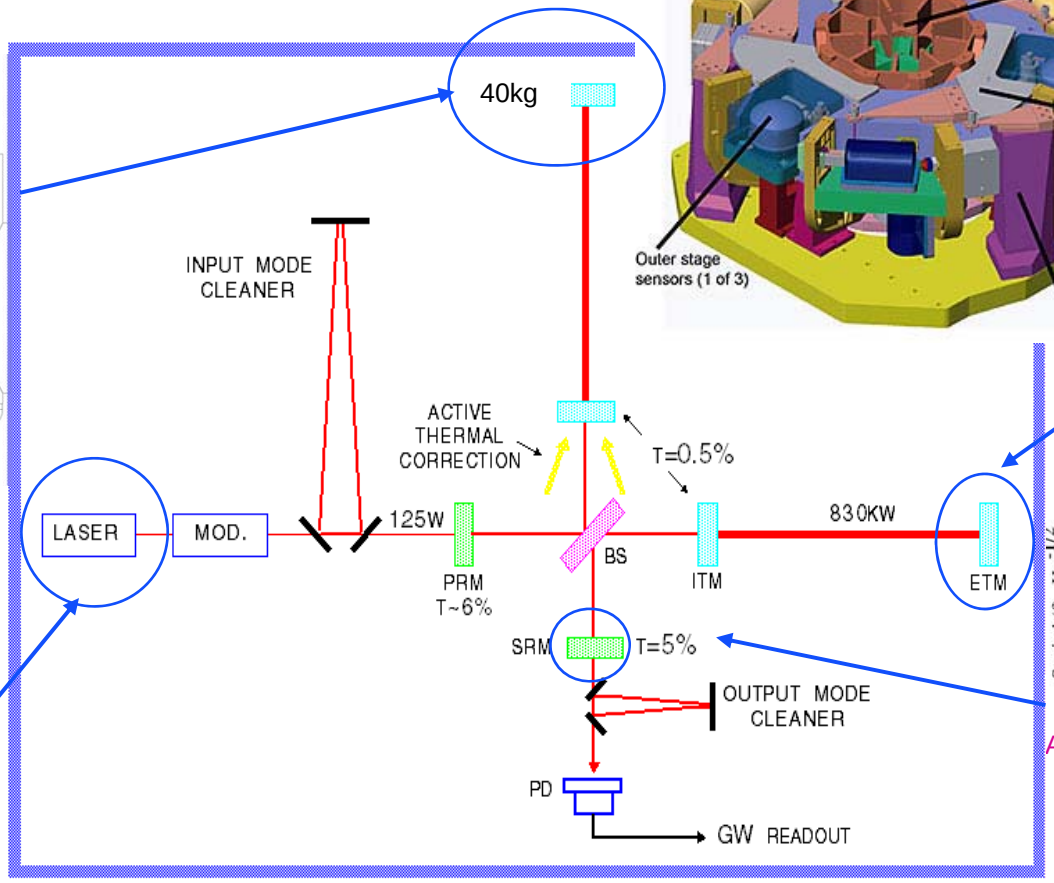
Credit: R.Powell, B.Berger

Advanced LIGO construction (aLIGO) started 1Apr2008

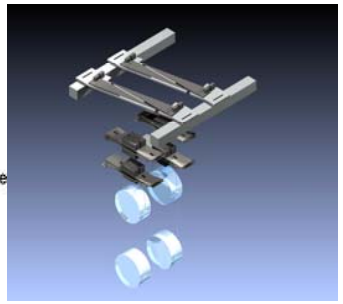
Major technological differences between LIGO and Advanced LIGO



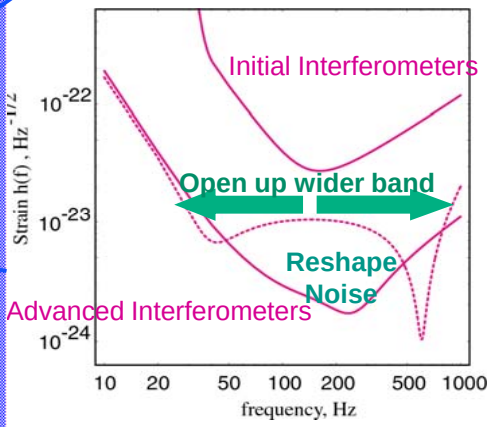
Active vibration isolation systems



High power laser (180W)



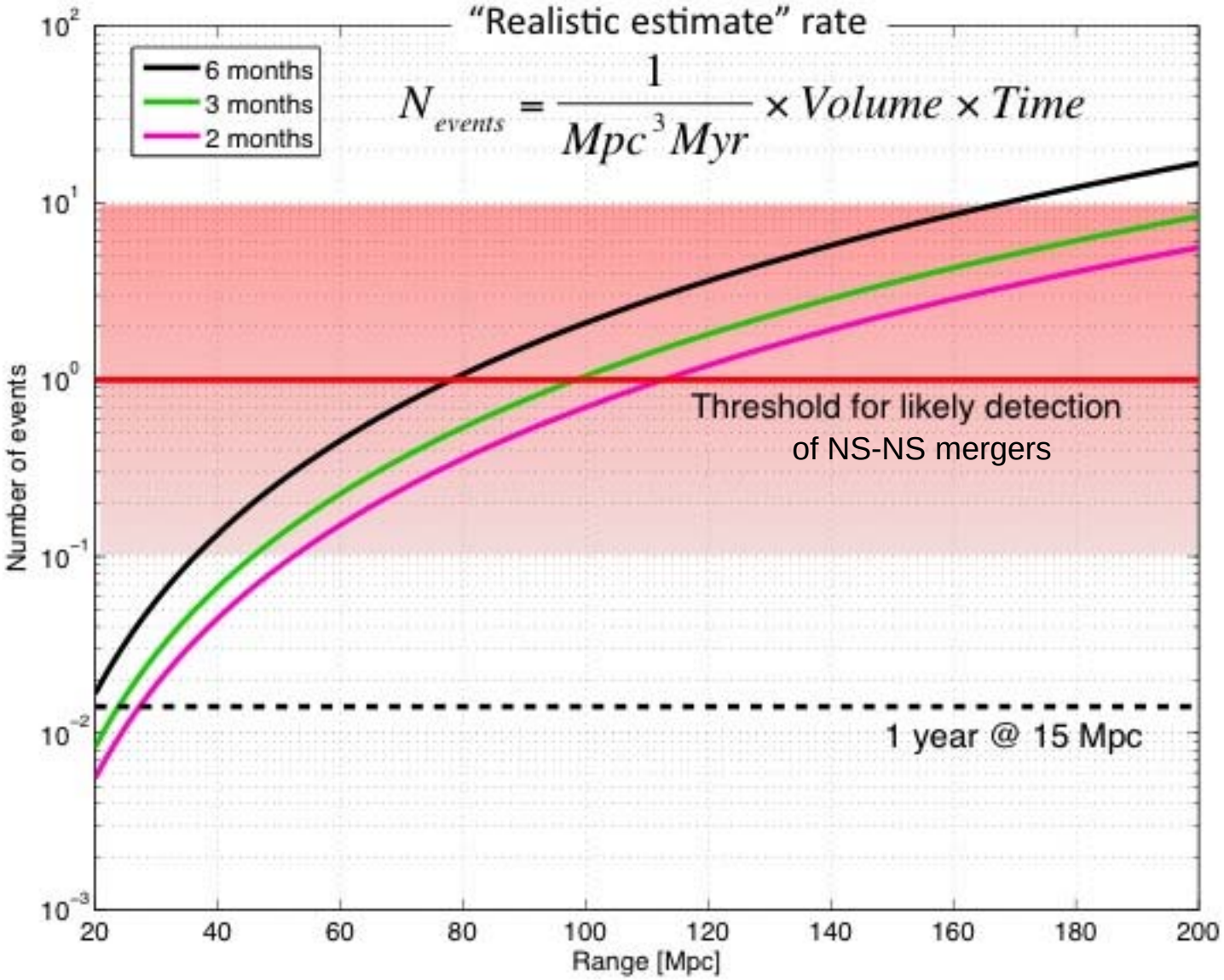
Quadruple pendulum: Silica optics, welded to silica suspension fibers



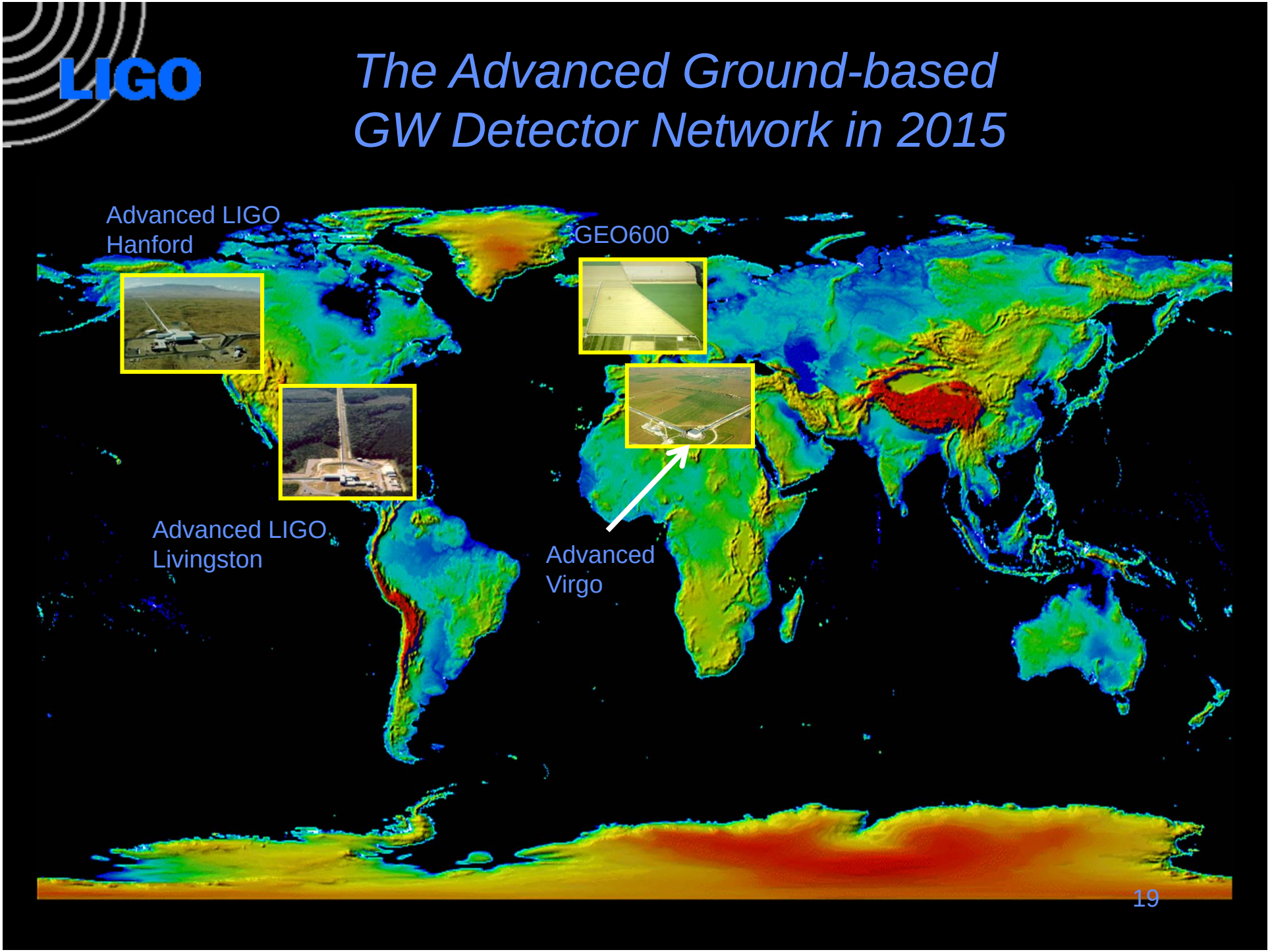
Advanced interferometry Signal recycling

Raab: Hunting for Black Holes with LIGO in India

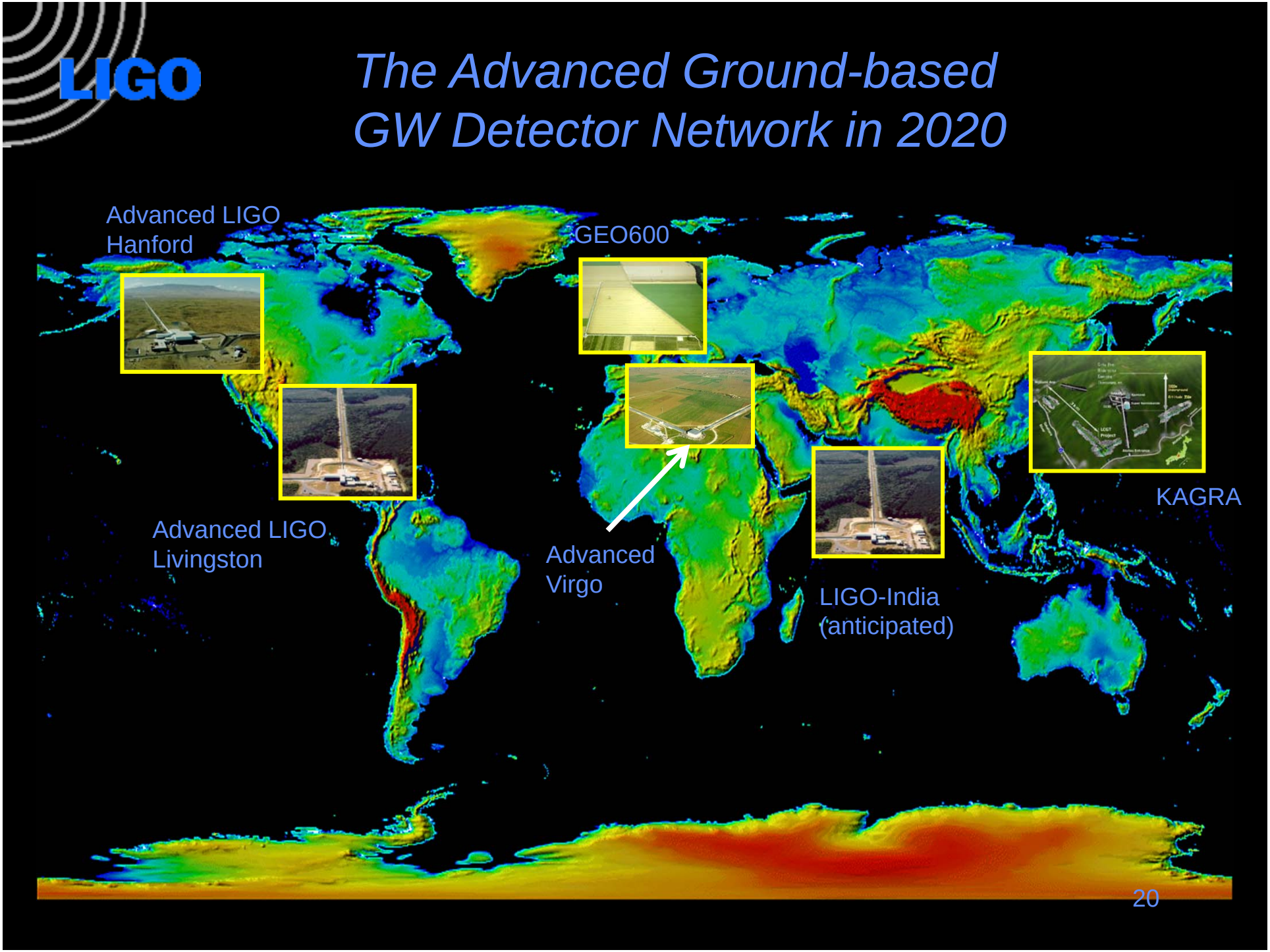
Criteria for early science runs



The Advanced Ground-based GW Detector Network in 2015



The Advanced Ground-based GW Detector Network in 2020

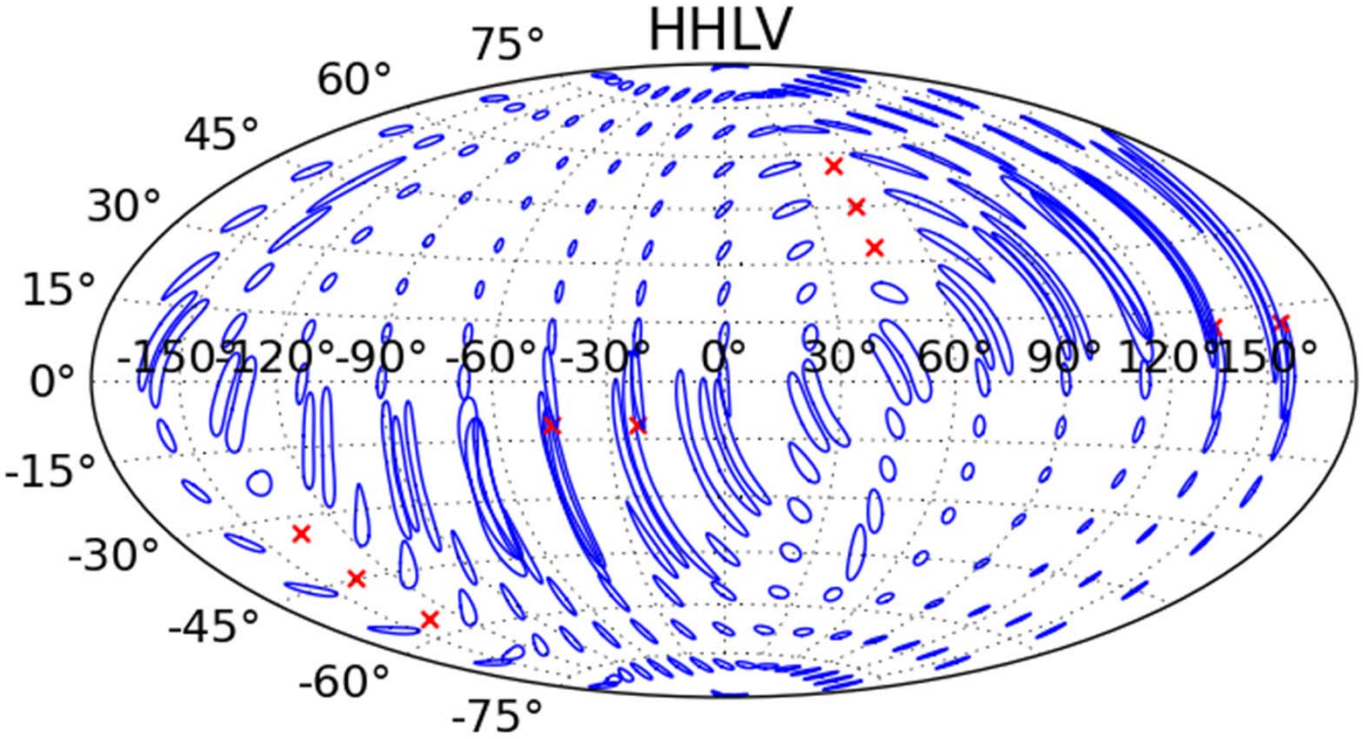


What impact can India have on Gravitational Wave Astronomy?

- India has a history of theoretical contributions to GW
- INDigo, a group of Indian institutes, has joined the LIGO Scientific Collaboration
- LIGO-India is a joint project between scientists in the US and India to construct a GW observatory in India that will become a critical component of the international network of GW observatories
  - » India will build facilities in India to house one of the three aLIGO detectors constructed by the US
- Although LIGO can make discoveries of gravitational waves using its two US observatory facilities, adding LIGO-India will be a ***game-changer*** for the astrophysics that can be derived from these discoveries

Binary Neutron Star Merger Localization: Hanford-Livingston-Virgo

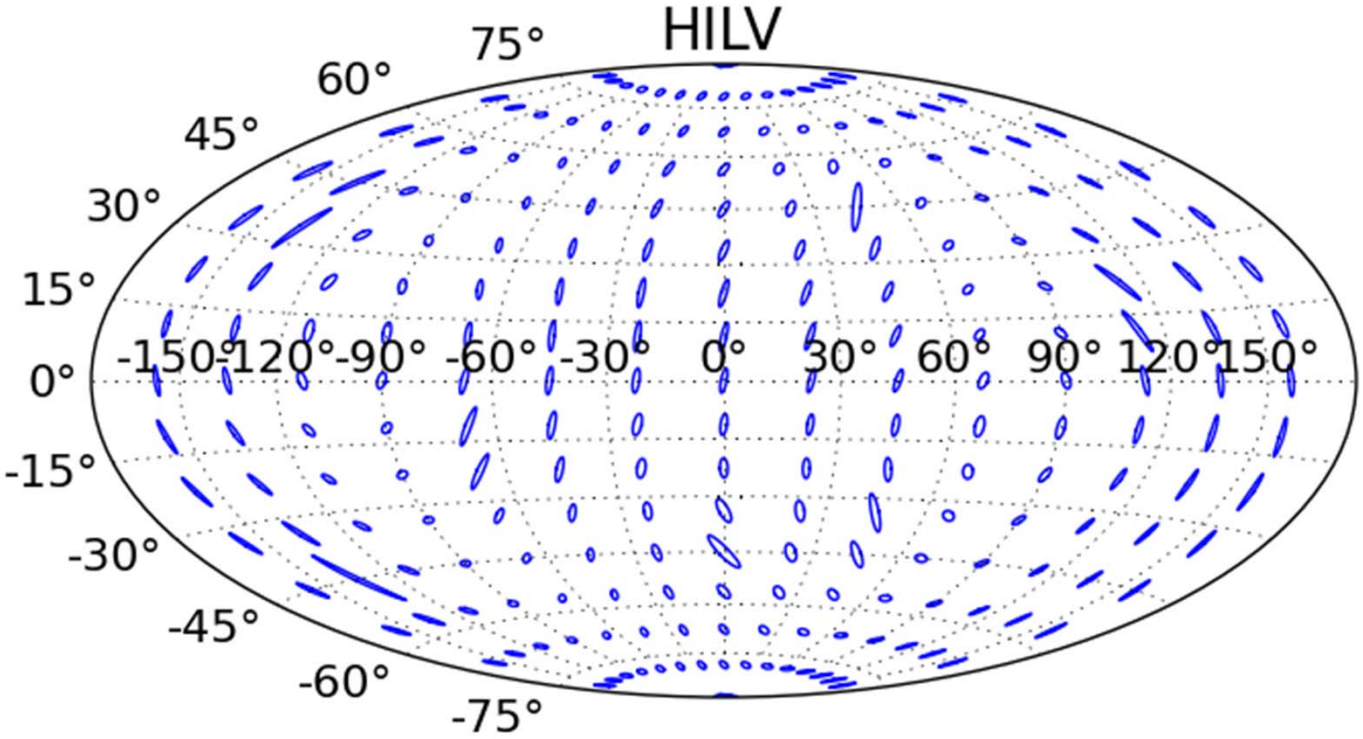
3 site network
x denotes blind spots



S. Fairhurst, "*Improved source localization with LIGO India*", arXiv:1205.6611v1

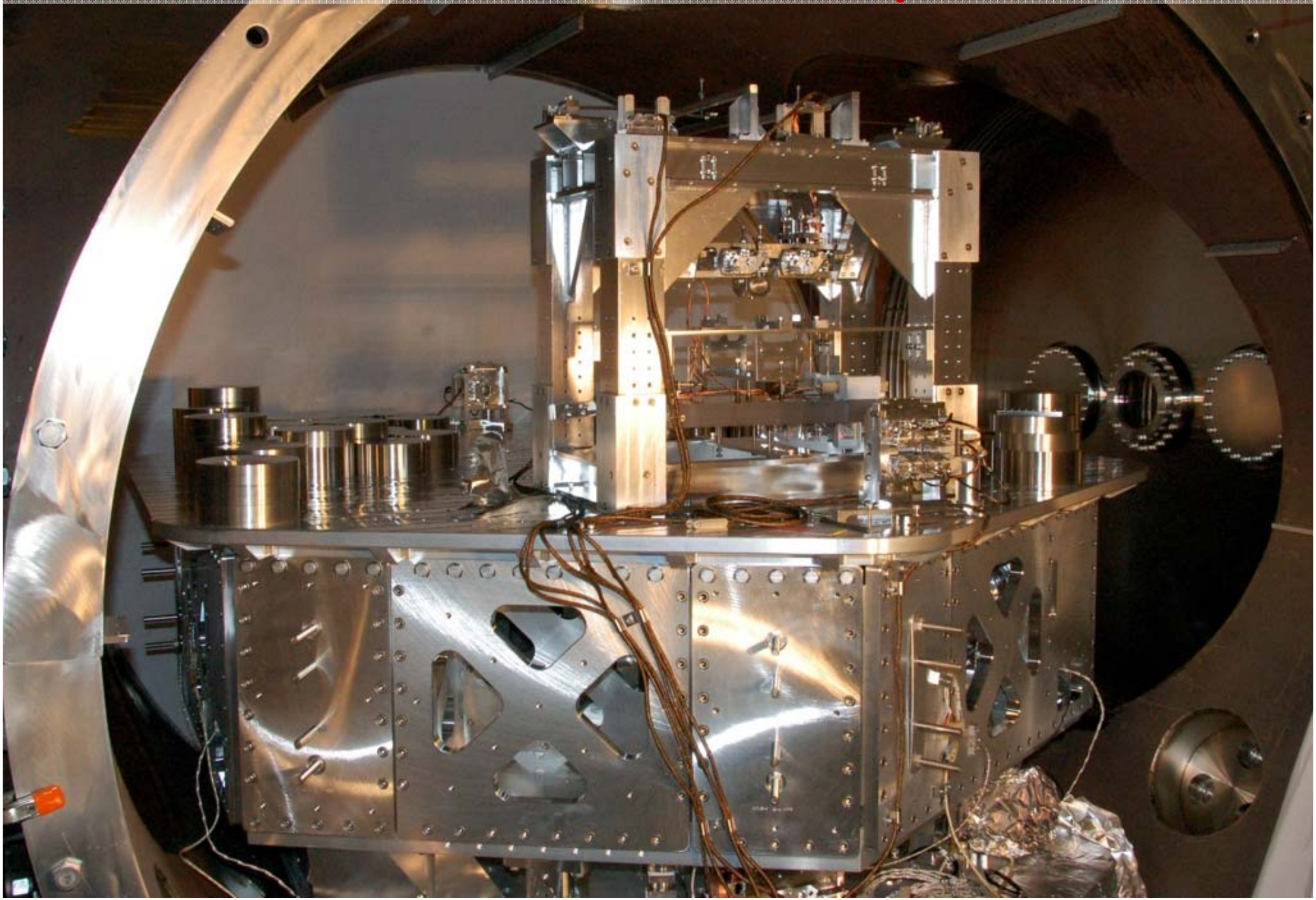
Binary Neutron Star Merger Localization: Hanford-Livingston-Virgo-India

4 site network

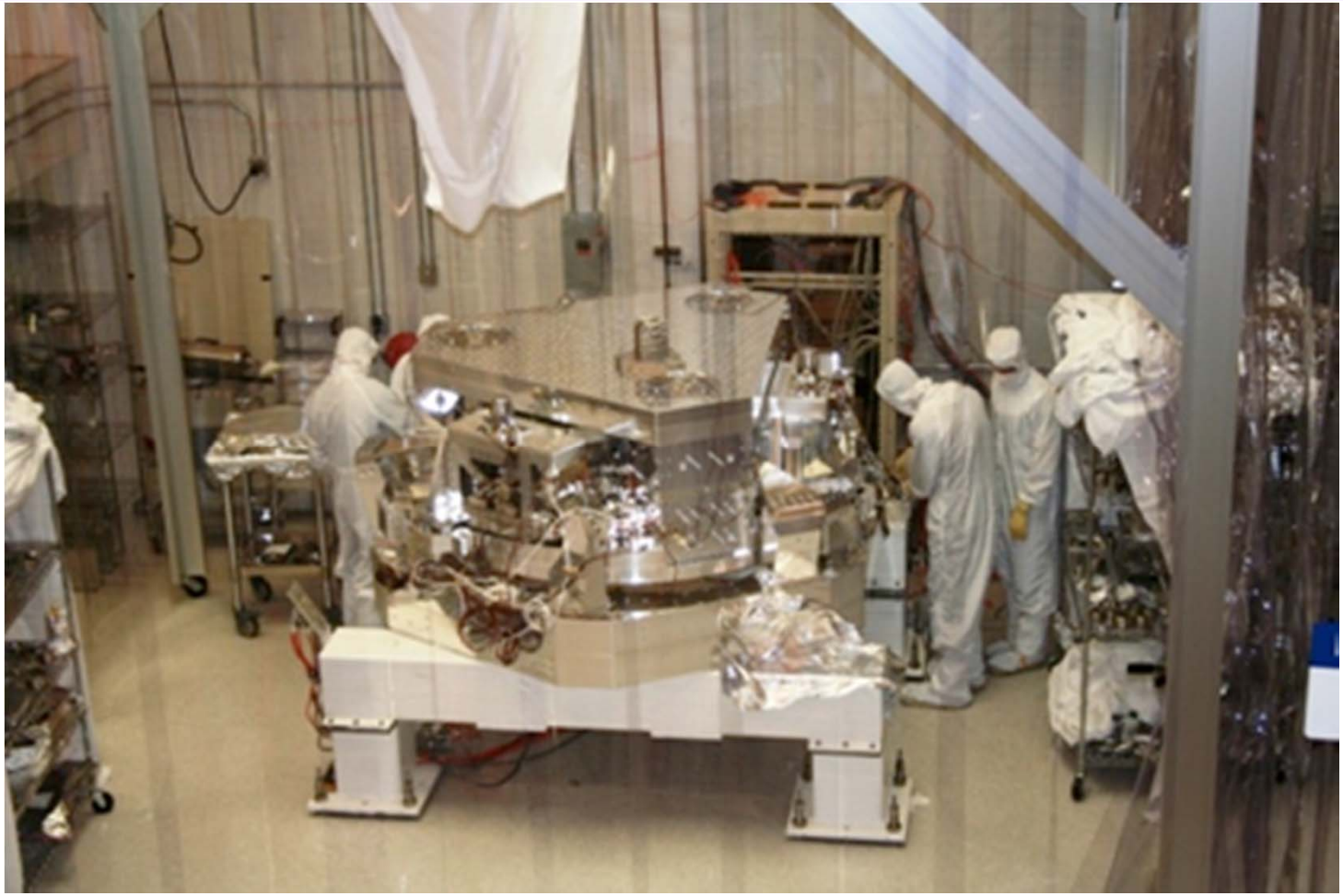


S. Fairhurst, "*Improved source locali*
LIGO India", arXiv:1205.6611v1

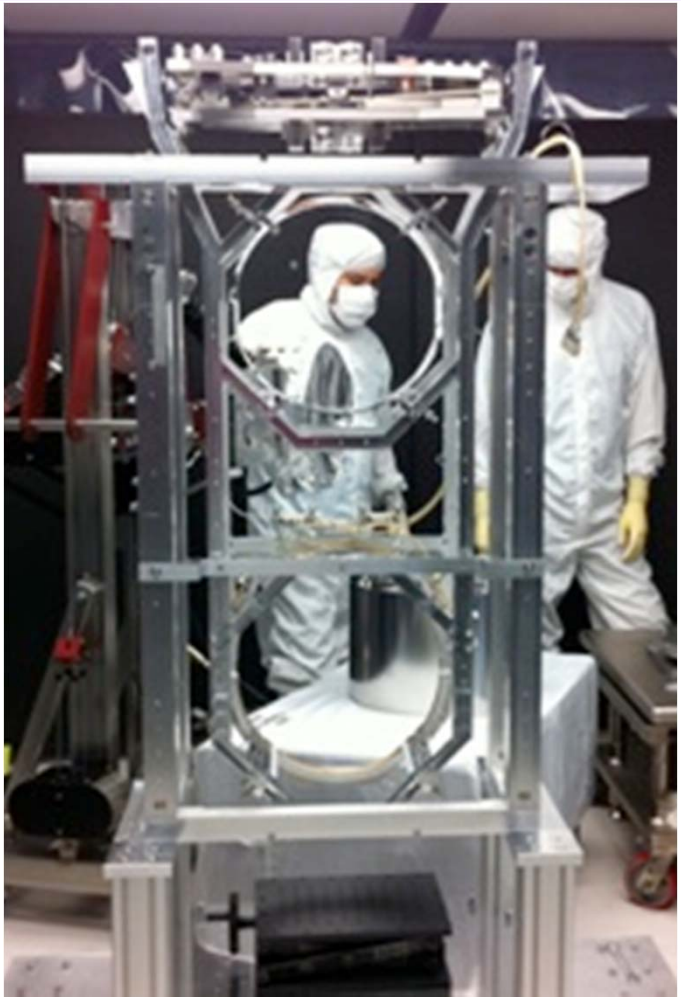
OMC Seismic Isolation platform

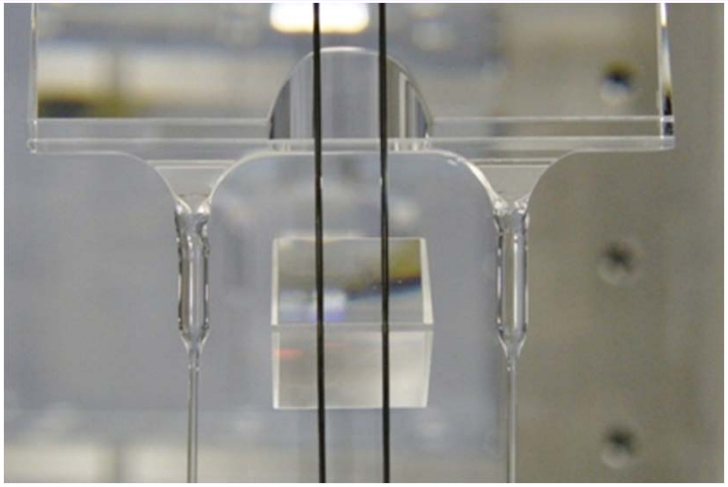


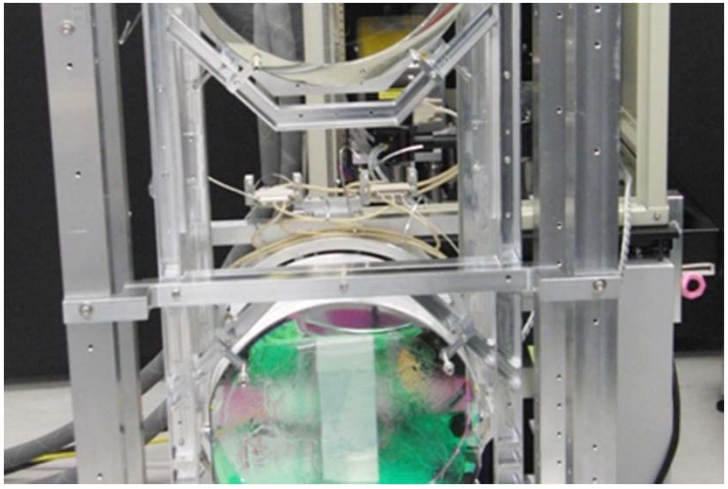
BSC Internal Seismic Isolator



Adv. LIGO Monolithic Suspension

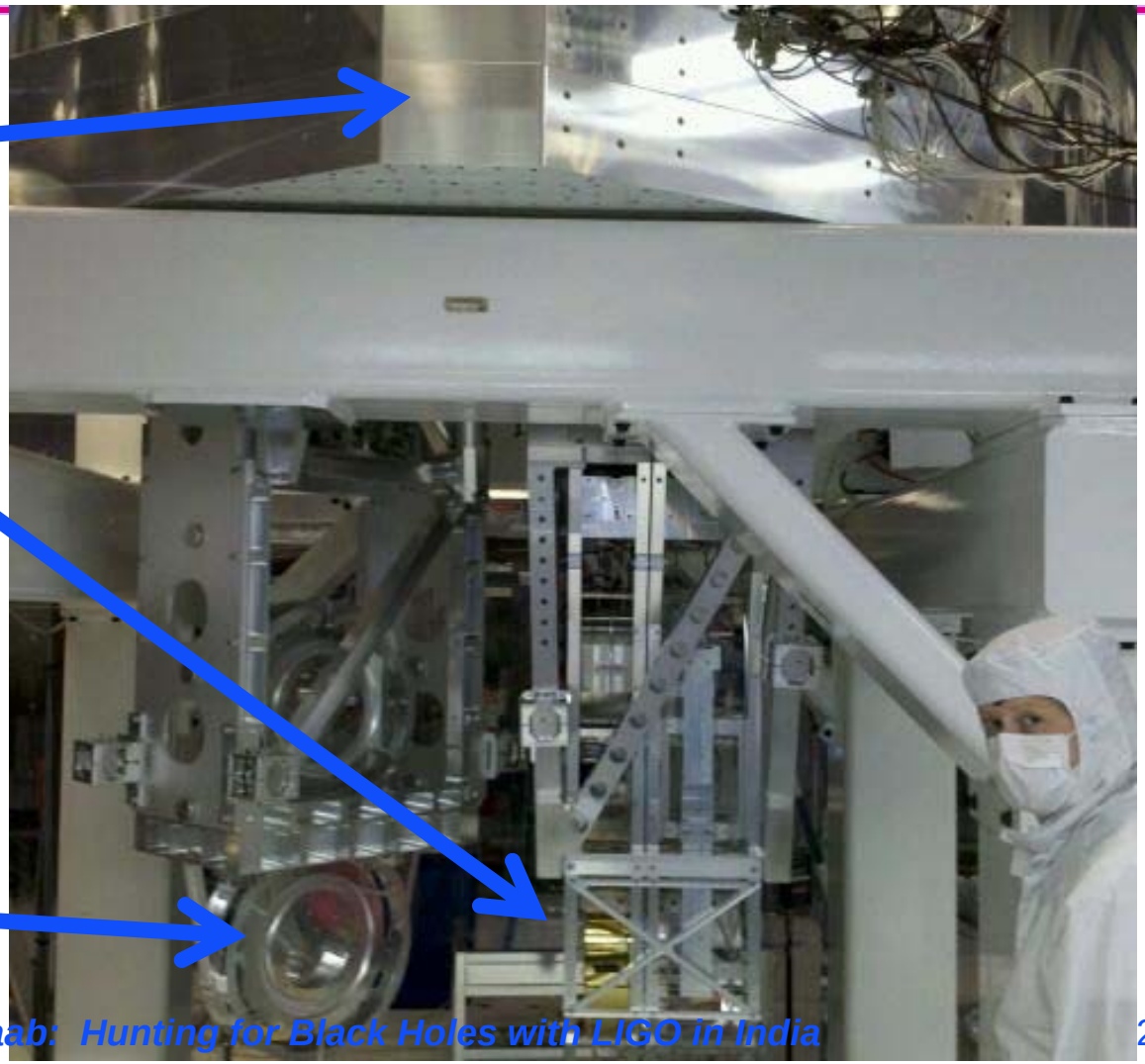




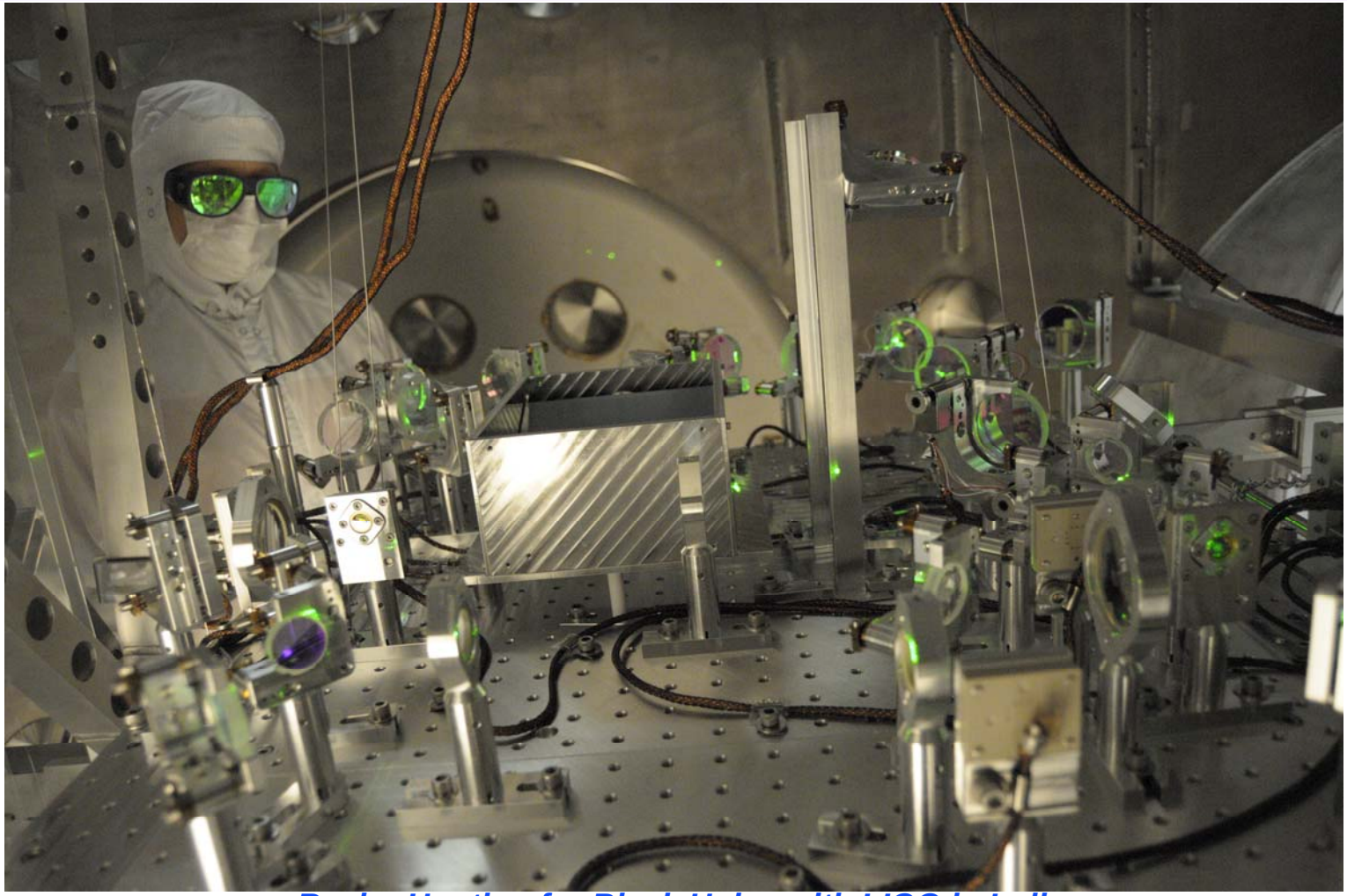


aLIGO installation in progress

Putting it together: Seismic & Suspension & Optics



Lock Acquisition: Arm Locking Subsystem



aLIGO Pre-stabilized laser

What is it like to work in a big science project or operation?

- More like a beehive than a few lone tigers
- Science and engineering skills are broad and multidisciplinary; subjects are OK for classes, but the real world is multidisciplinary; you'll need a broad technical vocabulary
- One has access to an incredible amount of intellectual power and expertise in a broad collaboration
- Controlling and coordinating that intellectual power requires strong communication, coordination and social networking
  - » Think of an cruise ship. It's hard to stop, but not so easy to turn. Every action you take can affect dozens to hundreds of colleagues
- You'll wish you took more college courses in psychology and sociology!

What will be the legacy of LIGO discoveries?

- Attempts in the 19th century to explain why the sky is blue, sunsets red and clouds white led to the 20th century economy:
  - » Atomic and nuclear physics and modern materials
  - » Modern chemical and pharmaceutical industries
  - » Modern electronics and computer industries
  - » Unraveling the structure of DNA and other bio-molecules, leading to modern biochemistry and gene therapy
  - » Development of almost all medical diagnostic machines
  - » Also a new phrase, “Blue-sky research”
- LIGO discoveries likely will revolutionize our understanding of space, time, matter and energy, as well as redefine what people can imagine and build