Gravitational Wave Detection - Current Status

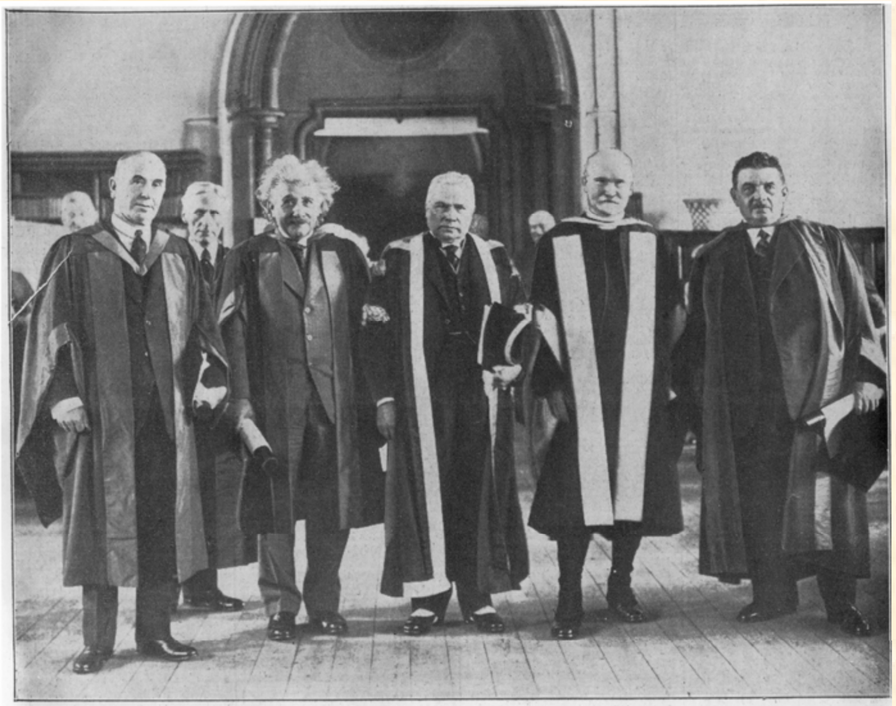
Sheila Rowan
Institute for Gravitational Research
University of Glasgow

NPPD 2007

Max-Planck-Institut
für Gravitationsphysik
(Albert-Einstein-Institut)

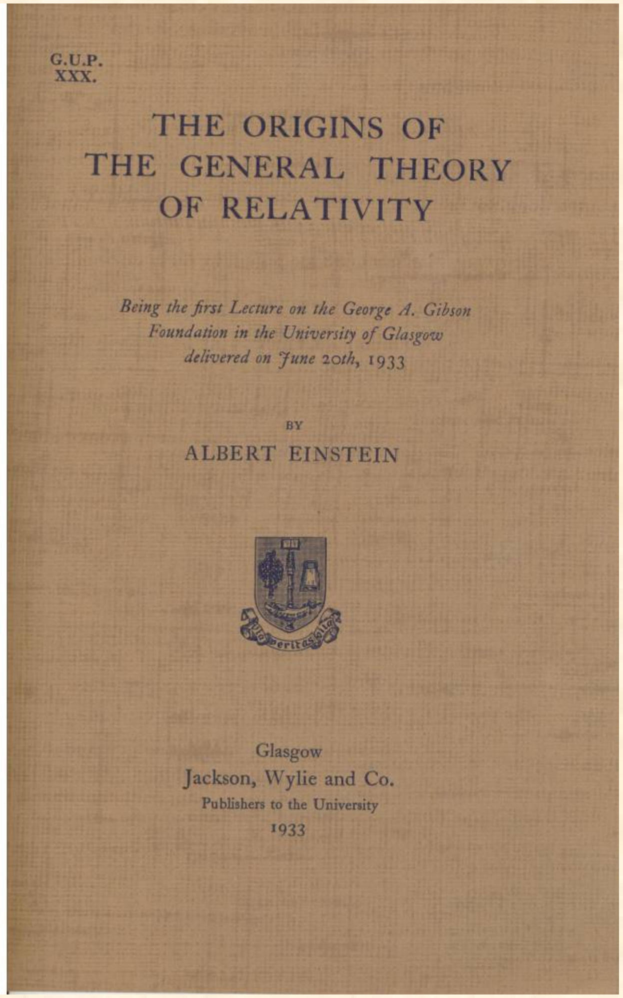
G070214-00-R

GW a consequence of General Relativity (1916)



A group of some of the honorary graduates taken after the ceremony in the Bute Hall of Glasgow University yesterday. Left to right—The Right Hon. Sir Robert S. Horne; Emeritus Professor William Blair-Bell, University of Liverpool; Professor Albert Einstein; Principal Sir Robert S. Rait; the Archbishop of Armagh and Primate of All Ireland; and M. Edouard Herriot, former Prime Minister of France.

Einstein in Glasgow 1933



G.U.P.
XXX.

THE ORIGINS OF
THE GENERAL THEORY
OF RELATIVITY

Being the first Lecture on the George A. Gibson Foundation in the University of Glasgow delivered on June 20th, 1933

BY

ALBERT EINSTEIN

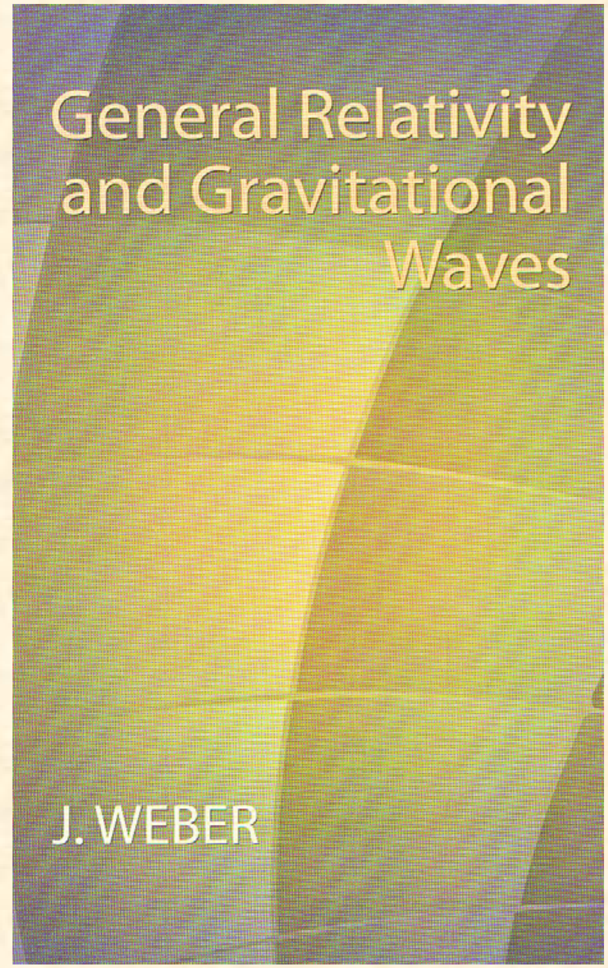
Glasgow
Jackson, Wylie and Co.
Publishers to the University
1933

GW ‘rediscovered’ by Joseph Weber

REVIEWS OF MODERN PHYSICS VOL. 29, # 3 JULY, 1957 509–515

Reality of the Cylindrical Gravitational Waves of Einstein and Rosen

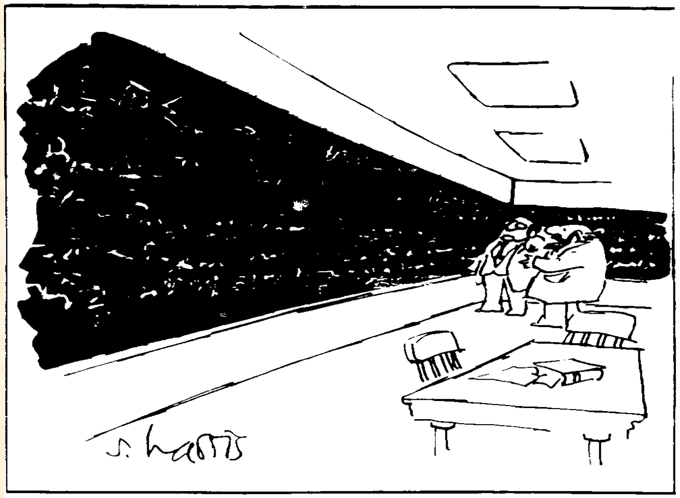
JOSEPH WEBER, *Lorentz Institute, University of Leiden, Leiden, Netherlands, and University of Maryland, College Park, Maryland*
JOHN A. WHEELER, *Lorentz Institute, University of Leiden, Leiden, Netherlands, and Palmer Physical Laboratory, Princeton University, Princeton, New Jersey*



1961

‘Gravitational Waves’

- Produced by violent acceleration of mass in:
  - neutron star binary coalescences
  - black hole formation and interactions
  - cosmic string vibrations in the early universe



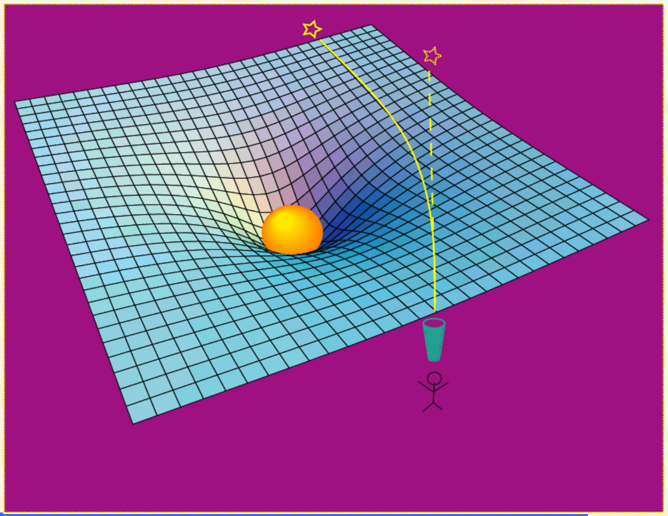
'But this is just a simplistic way of looking at the problem".

- and in less violent events:
  - pulsars
  - binary stars

- **Gravitational waves**

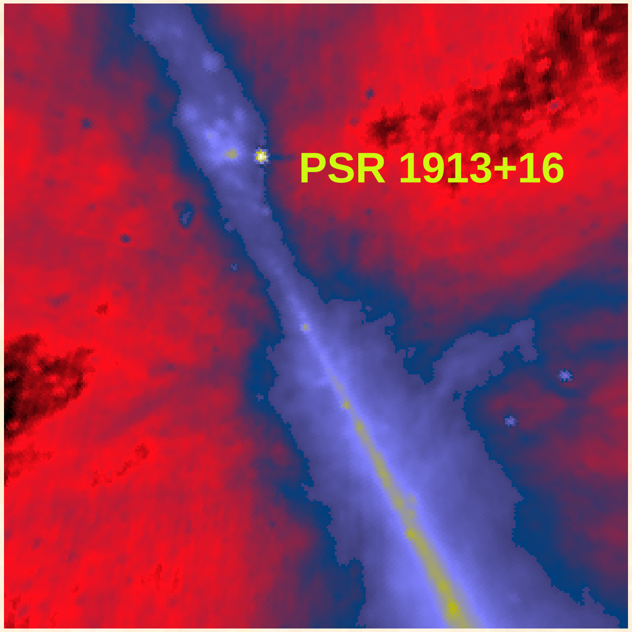
  ‘ripples in the curvature of spacetime’ that carry information about changing gravitational fields – or fluctuating strains in space of amplitude *h* where

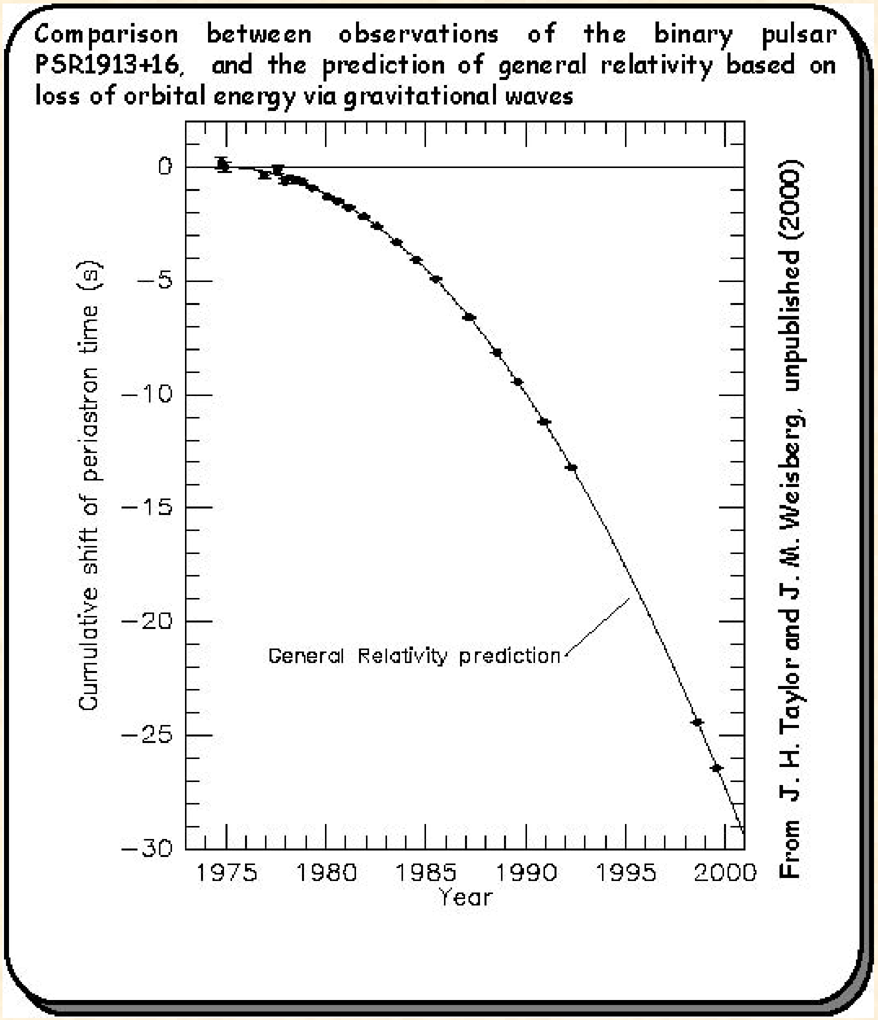
$$h \sim \frac{\Delta L}{L}$$



The evidence for gravitational waves

"Indirect" detection of gravitational waves





‘Gravitational Waves’- possible sources

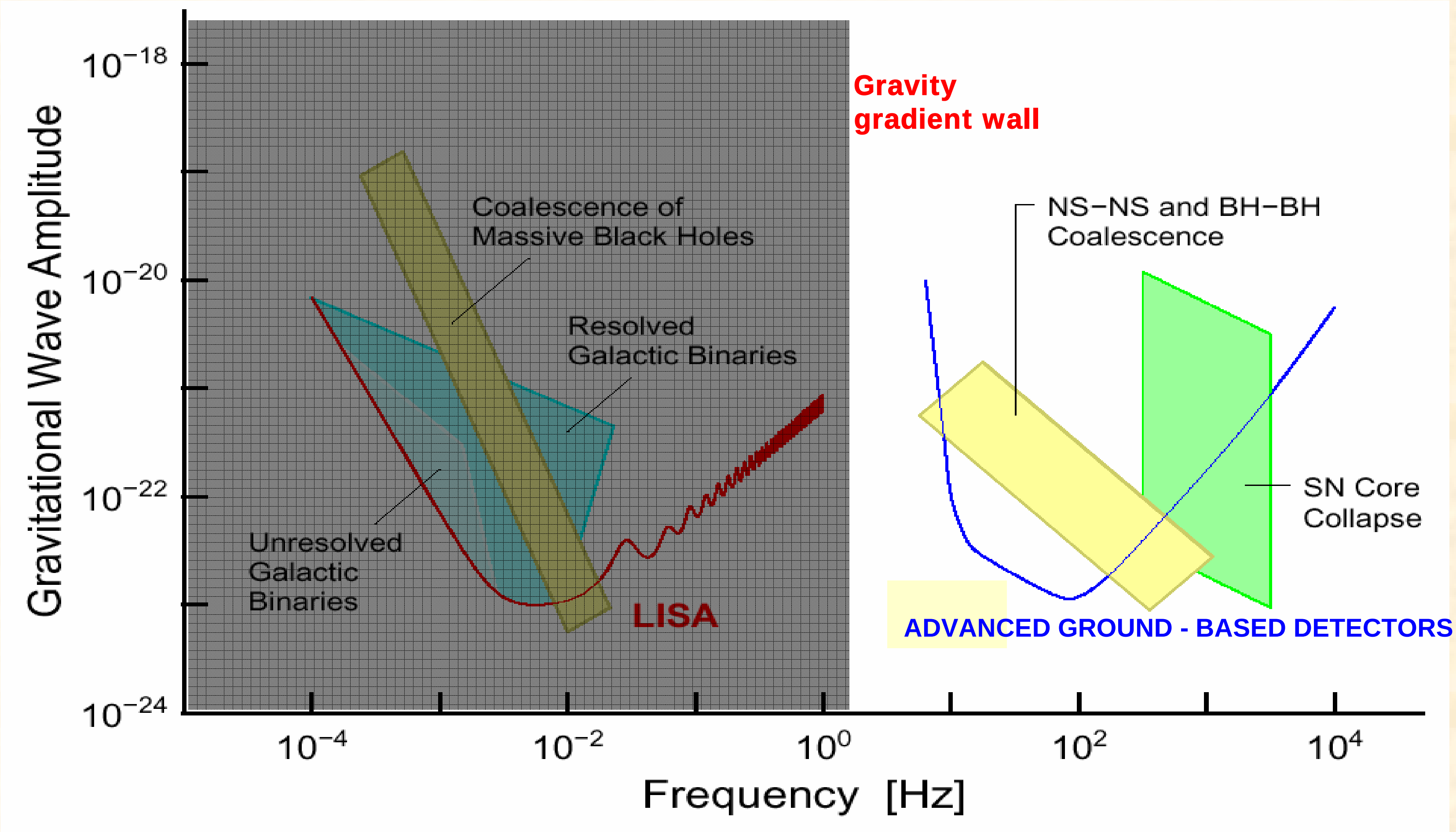
- **Pulsed**
  Compact Binary Coalescences
  NS/NS; NS/BH; BH/BH
  Stellar Collapse (asymmetric) to NS or BH
- **Continuous Wave**
  Pulsars
  Low mass X-ray binaries (e.g. SCO X1)
  Modes and Instabilities of Neutron Stars
- **Stochastic**
  Inflation
  Cosmic Strings

Detection of Gravitational waves – sources and science

- **WHY?** - obtain information about astrophysical events obtainable in no other way
- Fundamental Physics
  - test Einstein's quadrupole formula in the strong field regime using binary inspirals
  - test Einstein's theory from network measurements of polarisation
  - confirm the speed of gravitational waves with coincident EM/GW observations
- Astrophysics: (Advanced interferometers)
  - provide links to γ-ray bursts by detecting NS-NS, NS-BH binaries
  - take a census of BHs by detecting 100's of BBH from cosmological distances
  - detect radiation from LMXB's
  - Measure NS normal modes; probe glitches in pulsars
- Cosmology and Fundamental Physics (Advanced detectors +)
  - Inform studies of dark energy
    - obtain accurate luminosity-distance Vs. red-shift relationship from inspirals at $z \sim 1$ from GW/EM observations
  - Detect possible GW background at $\Omega \sim 10^{-9}$
- New Sources and Science:
  - Intermediate Mass Binary Black Holes?
  - Burst of radiation from cosmic strings?
  - Backgrounds predicted by Brane-world scenarios?

Sources

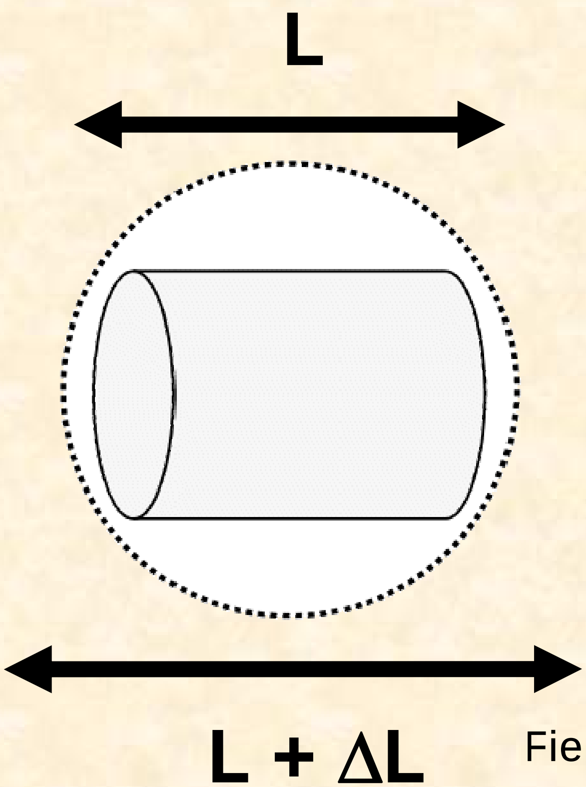
– Amplitudes from expected sources are tiny



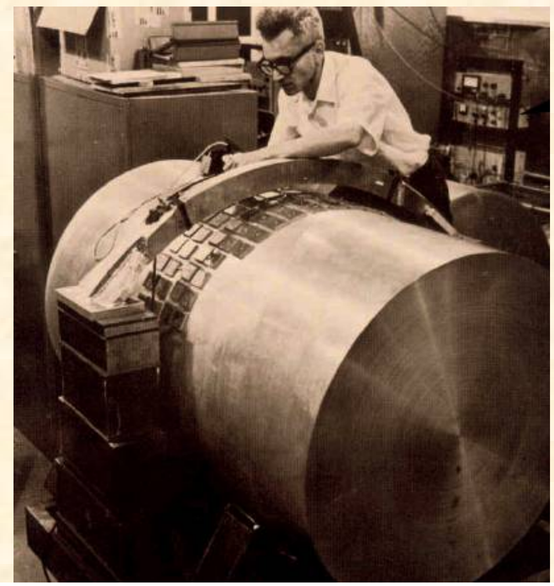
Detectors are split into space-based and ground based systems

How can we detect them?

- Gravitational wave amplitude $h \sim \frac{\Delta L}{L}$



Sensing the induced excitations of a large bar is one way to measure this



VOLUME 22, NR 24 PHYSICAL REVIEW LETTERS 16 June 1969
EVIDENCE FOR DISCOVERY OF GRAVITATIONAL RADIATION
J. Weber
(Received 29 April 1969)

Field originated with J. Weber looking for the effect of strains in space on aluminium bars at room temperature

Coincident events between detectors at Argonne Lab and Maryland

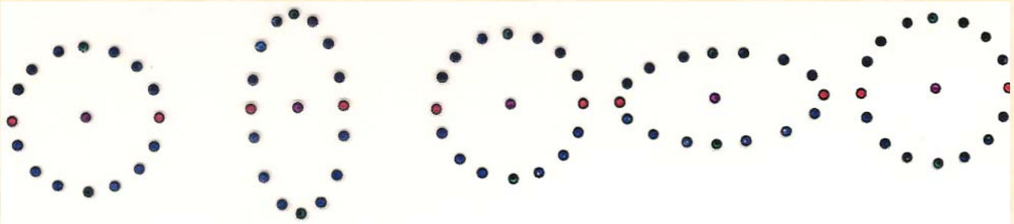
Resonant detectors around the world

Now operating at cryogenic temperature

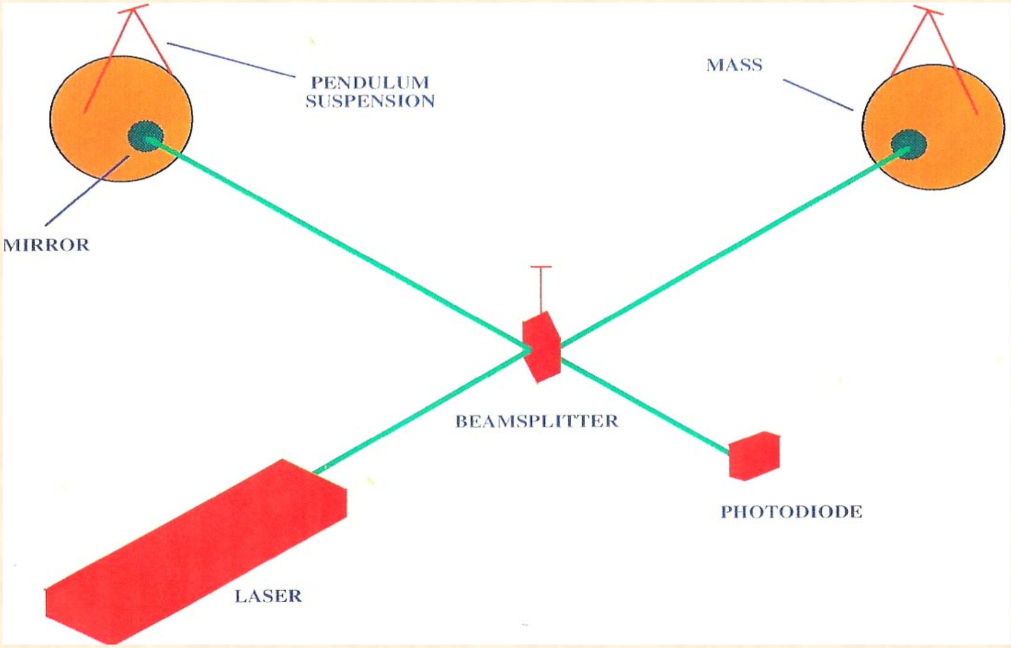
They are reliable and have excellent duty cycle.

Detection of Gravitational Waves

Consider the effect of a wave on a ring of particles :

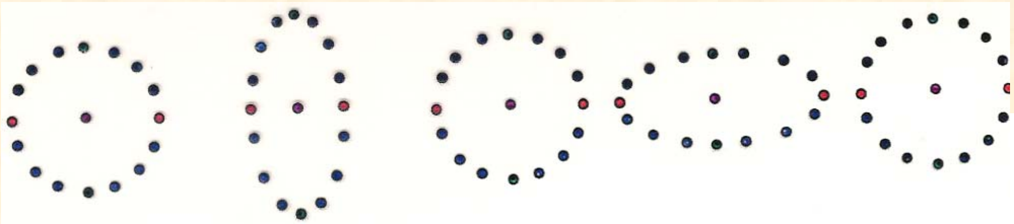


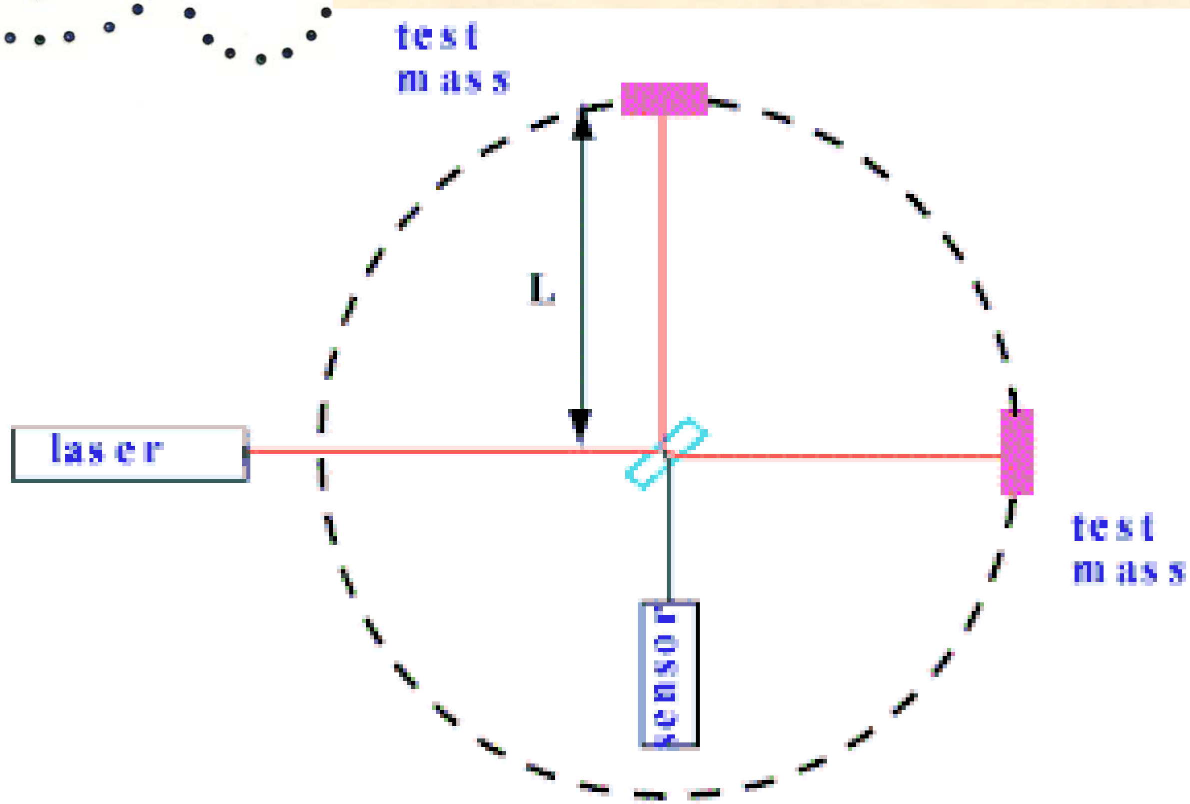
One cycle



Michelson Interferometer

Detection again





Interferometer

Gravitational waves have very weak effect:

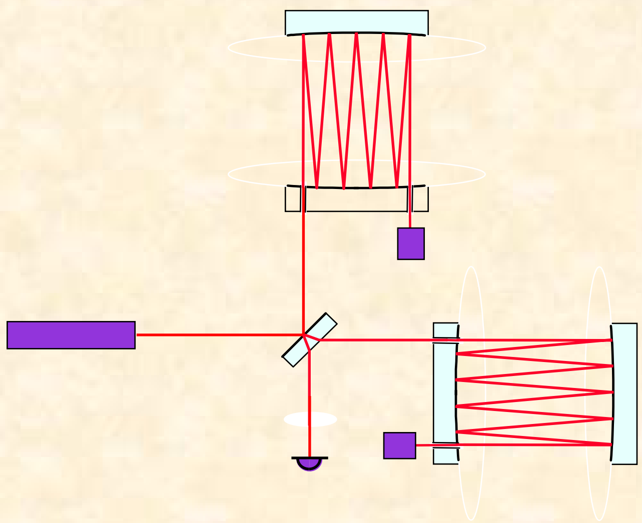
expect movements of less than 10^{-18} m over 4km

Laser Interferometric detectors

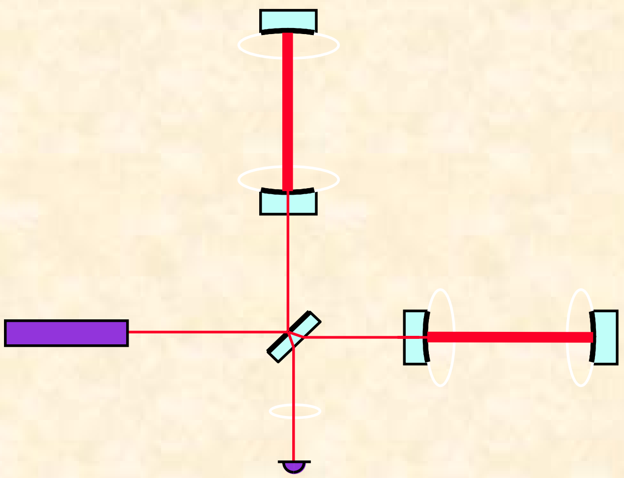
- For best performance want arm length $\sim \lambda/4$

  i.e. for 1kHz signals, length = 75 km

- Such lengths not really possible on earth, but optical path can be folded



Delay lines



Fabry Perot Cavities

- Much longer arm lengths are possible in space

Principal limitations to sensitivity – ground based detectors

- Photon shot noise (improves with increasing laser power) and radiation pressure (becomes worse with increasing laser power)

  There is an optimum light power which gives the same limitation expected by application of the Heisenberg Uncertainty Principle – the 'Standard Quantum limit'

- Seismic noise (relatively easy to isolate against – use suspended test masses)
- Gravitational gradient noise, – particularly important at frequencies below ~10 Hz
- Thermal noise – (Brownian motion of test masses and suspensions)

• **All point to long arm lengths being desirable**

- **Several long baseline interferometers are now operating**

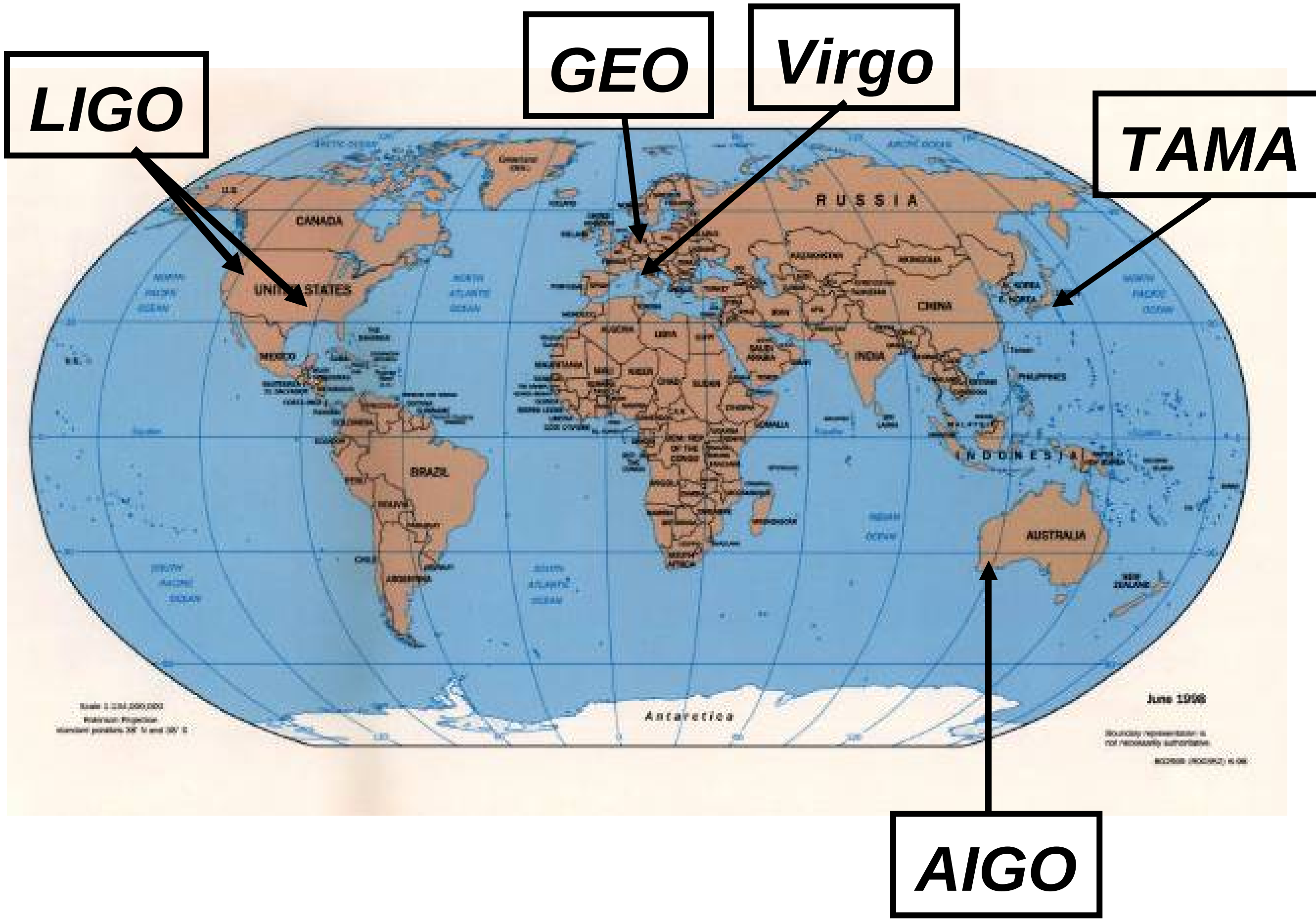
Gravitational Wave Detectors

5 detector systems approved/now being developed:

LIGO (USA) –	2 detectors of 4km arm length
	+ 1 detector of 2km arm length – WA and LA
VIRGO (Italy/France) –	1 detector of 3km arm length – Pisa
GEO 600 (UK/Germany) –	*1 detector of 600m arm length – Hannover*
TAMA 300 (Japan) –	1 detector of 300m arm length – Tokyo
LISA (NASA/ESA) –	*Spaceborne detector of 5 x 10^6km arm length*

Interferometers - *international network*

'Simultaneously' detect signal (within msec)



detection confidence

locate the sources

decompose the polarization of gravitational waves

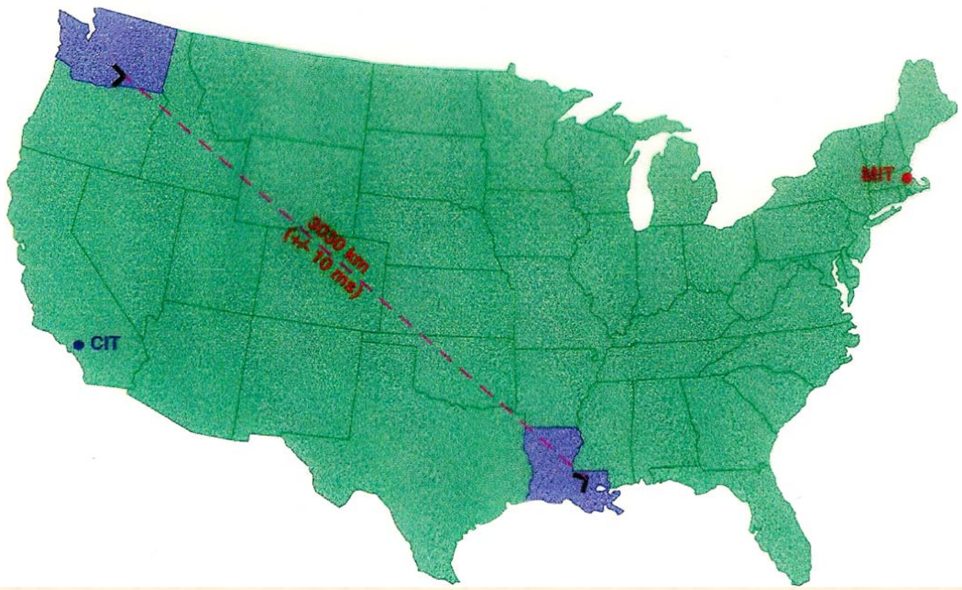
LIGO USA

Hanford, WA

- located on DOE reservation
- treeless, semi-arid high desert
- 25 km from Richland, WA

Livingston, LA

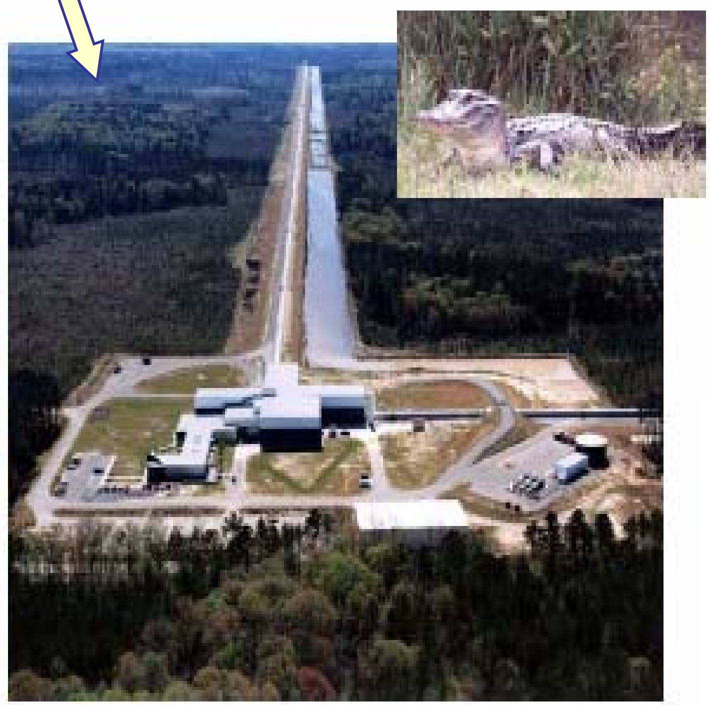
- located in forested, rural area
- commercial logging, wet climate
- 50km from Baton Rouge, LA



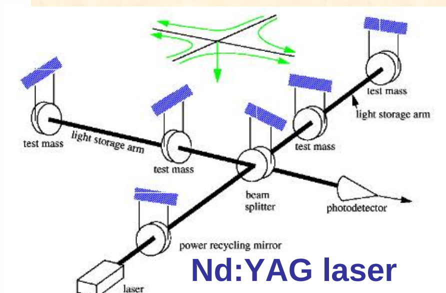
Initial LIGO detectors

LIGO project (USA)

- 2 detectors of 4km arm length + 1 detector of 2km arm length
- Washington State and Louisiana

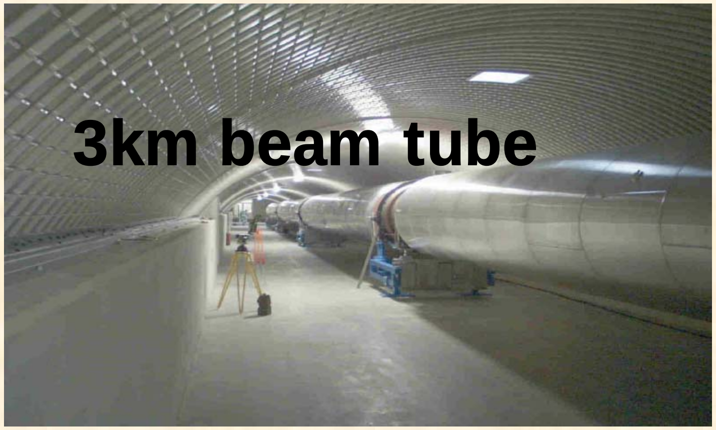


Each detector is based on a 'Fabry-Perot – Michelson'

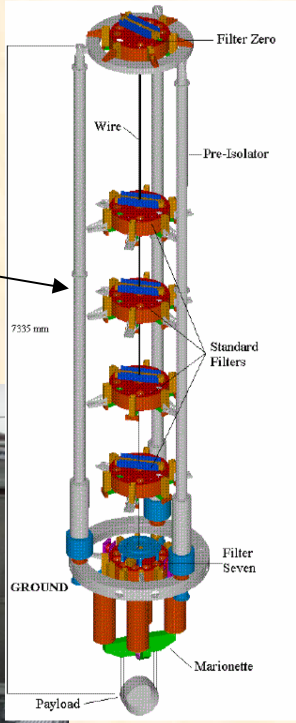


Nd:YAG laser $1.064\mu m$

VIRGO: The French-Italian Project 3 km armlength at Cascina near Pisa



The ‘Super Attenuator’ filters the seismic noise above 4 Hz



VIRGO

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Other Detectors and Developments – TAMA 300 and AIGO

TAMA 300 Tokyo
300 m arms

AIGO Gingin, WA
80 m arm test facility

GEO 600

UK-German collaboration:

- Univ. of Glasgow:
  - Hough, Strain, Robertson, Rowan, Ward, Woan, Cagnoli, Heng and colleagues
- Cardiff Univ.
  - Sathyaprakash, Romano, Schutz, Grishchuk and colleagues
- Univ. of Birmingham
  - Cruise, Vecchio, Freise and colleagues
- AEI Hannover and Golm
  - Danzmann, Schutz and colleagues

- Colleagues here in Univ. de les Illes Balears

GEO 600

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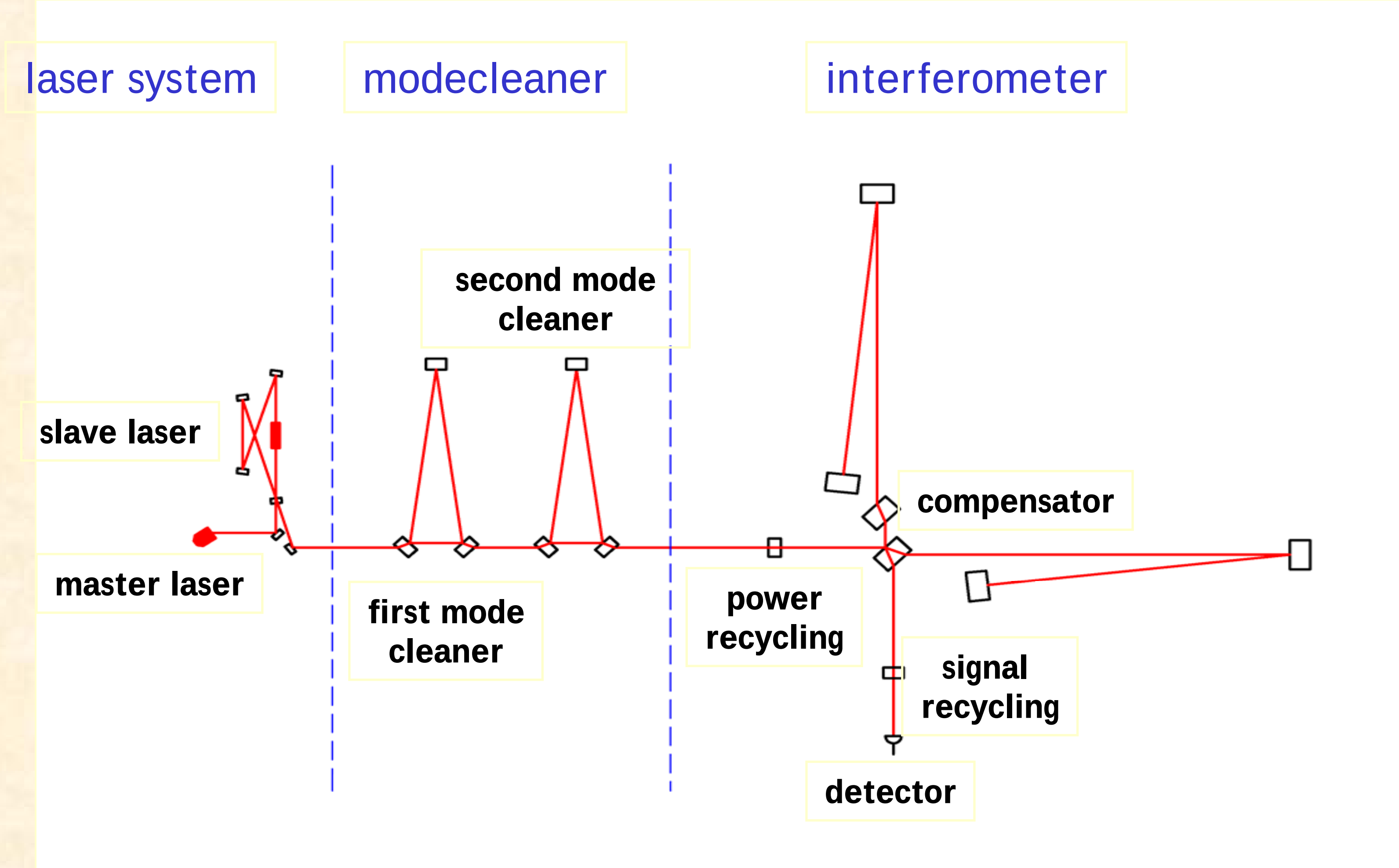
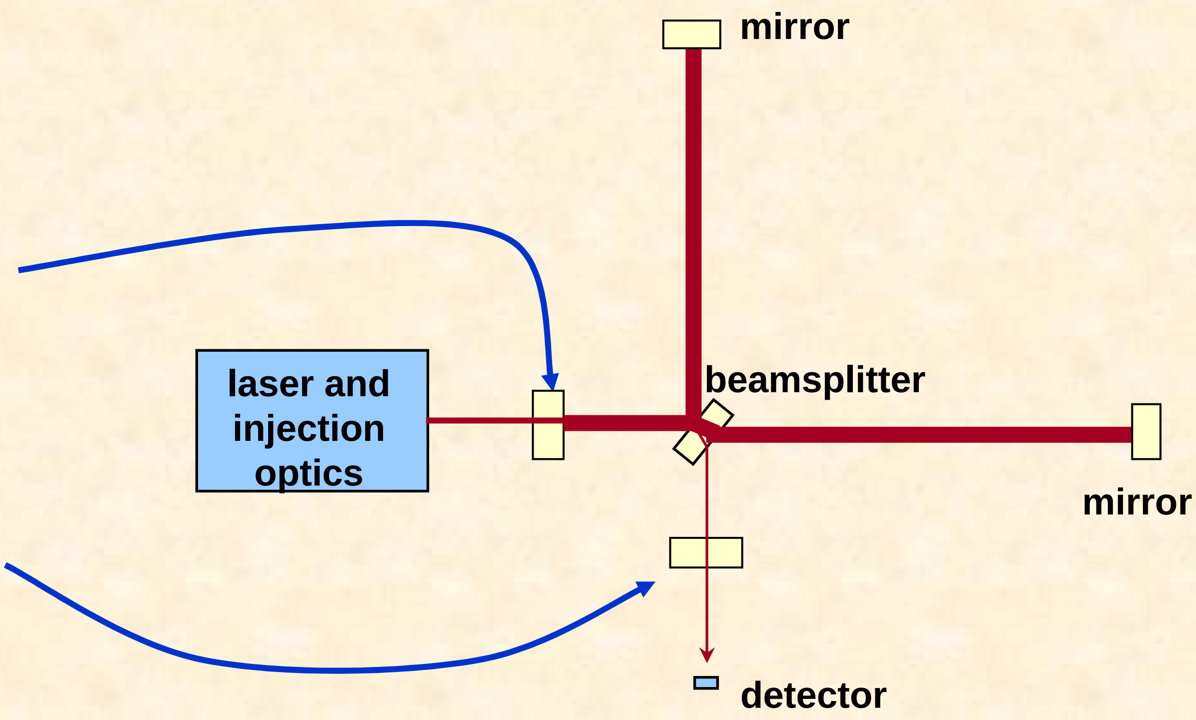
GEO600 – optical layout

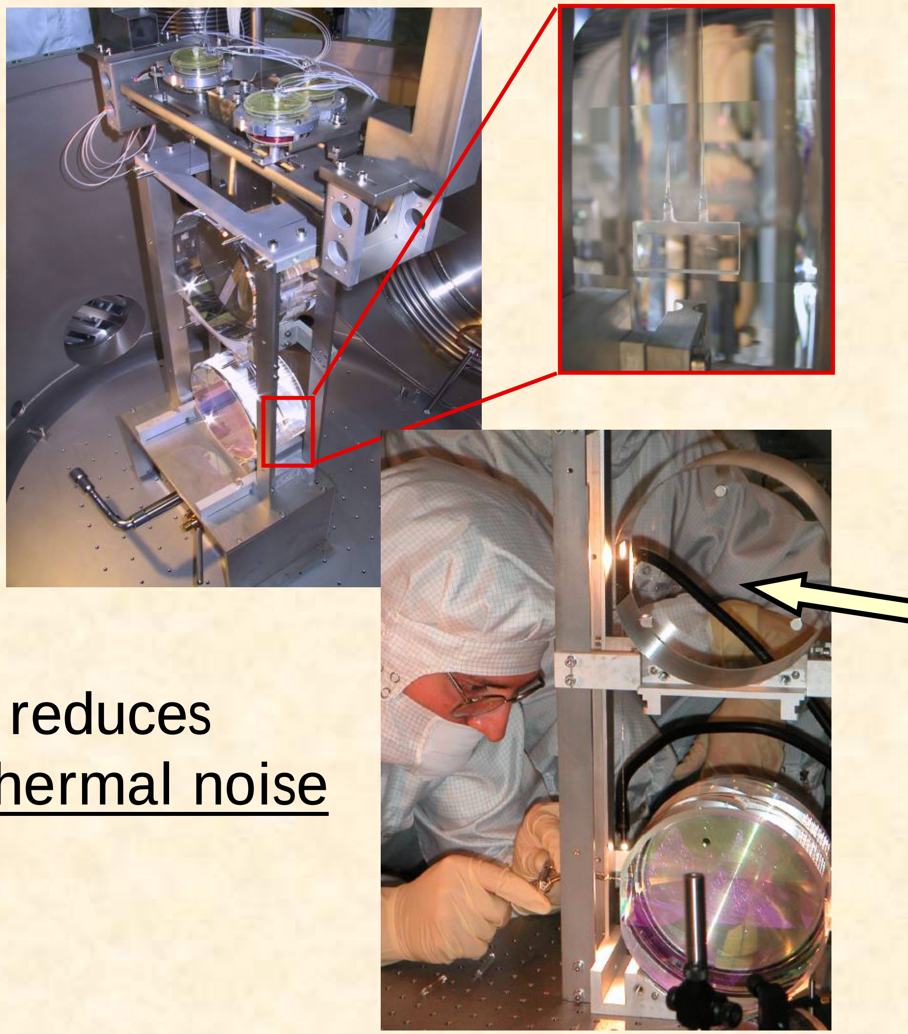


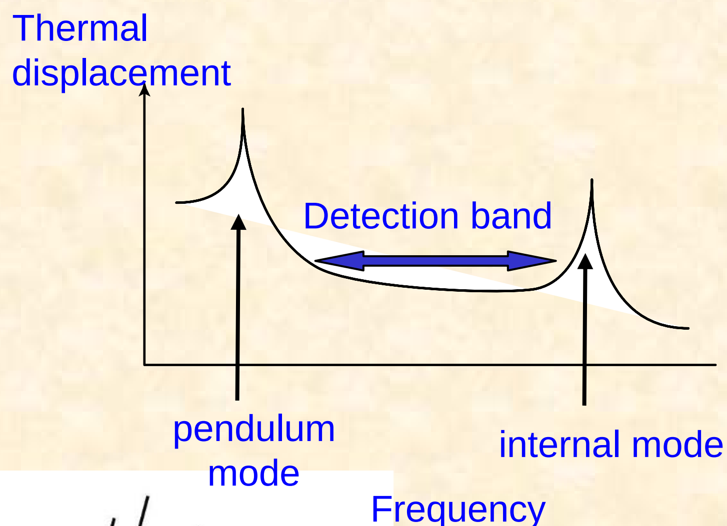
Unique GEO Technology 1 - Advanced Interferometry

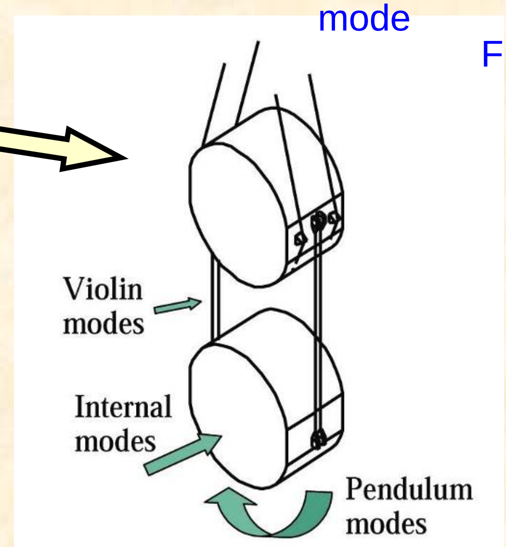
- One of the fundamental limits to interferometer sensitivity is photon shot noise
- Power recycling effectively increases the laser power
- Signal recycling – a GEO invention – trades bandwidth for improved sensitivity



Unique GEO Technology 2 - Monolithic Silica Suspension







– reduces <u>thermal noise</u>

Ultra-low mechanical loss suspension at the heart of the interferometer

Science data runs to date

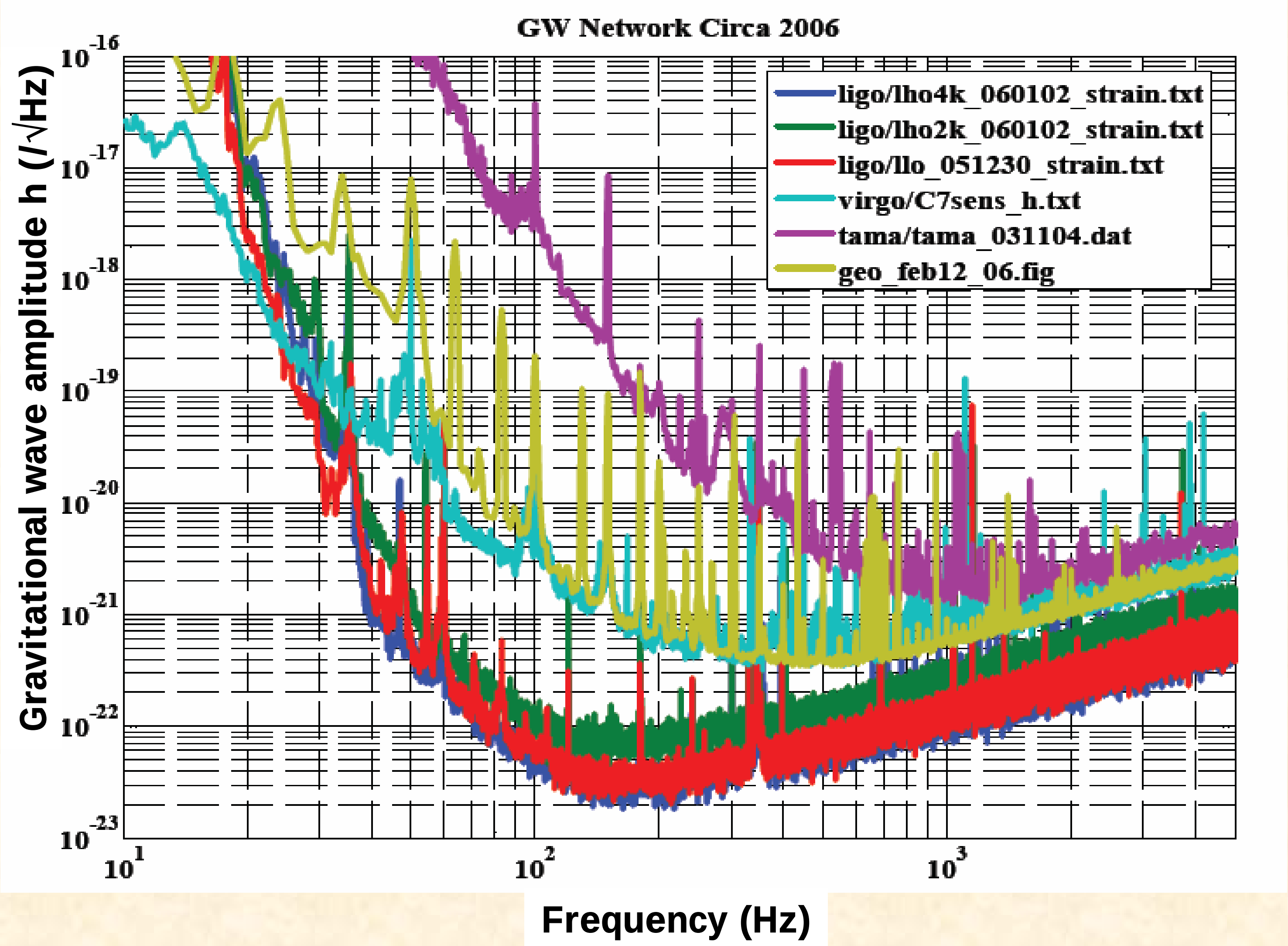
- Since Autumn 2001 GEO and LIGO have completed 4 science ('S') runs
  - Some runs done in coincidence with TAMA and bars (Allegro)
  - LIGO now at design sensitivity
- 'Upper Limits' have been set for a range of signals
  - Coalescing binaries
  - Pulsars
  - Bursts
  - Stochastic background
- **>19 major papers published or in press since 2004**
  (work from a collaboration (LSC) of more than 400 scientists)

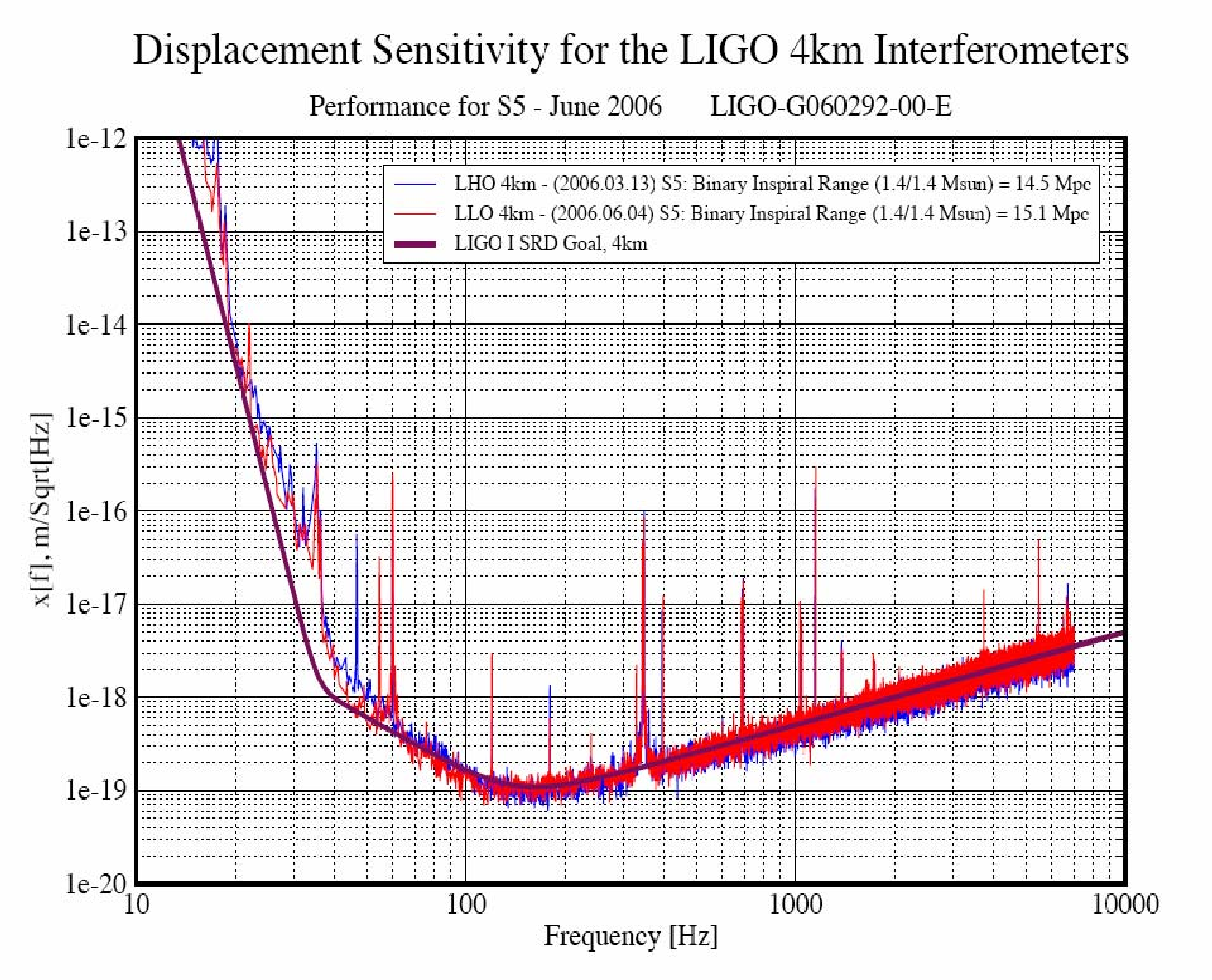
S5: started on 4th Nov. 2005 at Hanford (LLO a few weeks later)

GEO joined initially for overnight data taking in Jan 06, then 24/7 till Oct 06 then interleaved with commissioning

Virgo joined May 18th 2007

Gravitational wave network sensitivity





Displacement Sensitivity for the LIGO 4km Interferometers
Performance for S5 - June 2006 LIGO-G060292-00-E
LHO 4km - (2006.03.13) S5: Binary Inspiral Range (1.4/1.4 Msun) = 14.5 Mpc
LLO 4km - (2006.06.04) S5: Binary Inspiral Range (1.4/1.4 Msun) = 15.1 Mpc
LIGO I SRD Goal, 4km
x[f], m/Sqrt[Hz]
1e-12
1e-13
1e-14
1e-15
1e-16
1e-17
1e-18
1e-19
1e-20
10
100
1000
10000
Frequency [Hz]

Plans for Advanced detectors : 2008-

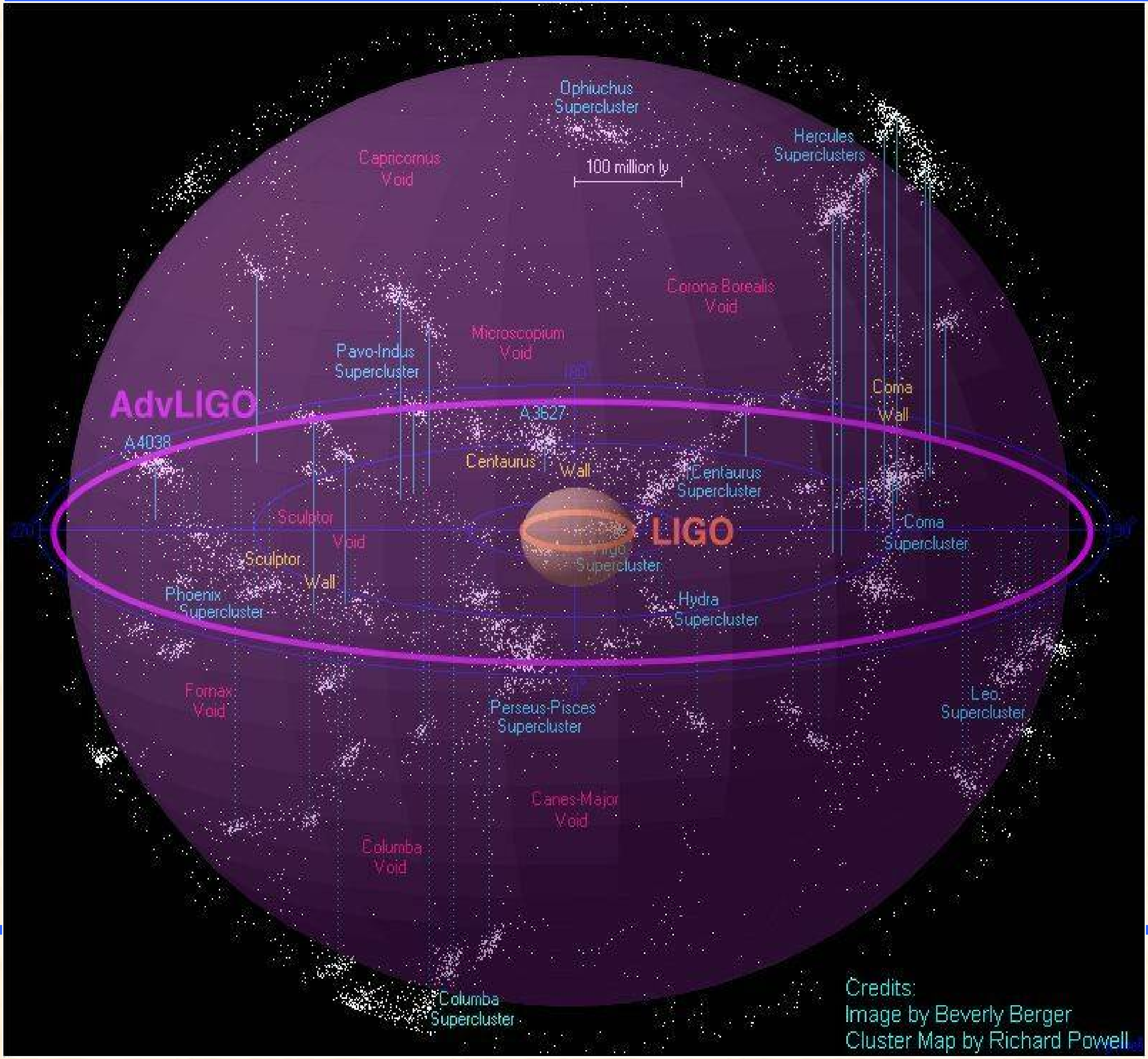
To move from detection to astronomy the current detector network will upgrade to a series of 'Advanced' instruments

- 'Advanced LIGO' will comprise a set of significant hardware upgrades to the US LIGO detectors
- 'Advanced Virgo' will be built on the same time scale as Advanced LIGO, and will achieve comparable sensitivity
- Japan's Large Cryogenic Gravitational Telescope (LCGT) will pioneer cryogenics and underground installation
- GEO-HF will improve the sensitivity beyond GEO600's, mainly at high frequency
- Acoustic DUAL technology could equal that of interferometers at high frequencies

What is Advanced LIGO

- Project to increase sensitivity (range) of LIGO by factor of ten
  - Uses existing sites, infrastructure
  - Implements higher power laser, new optics and monolithic suspensions, improved seismic isolation and other improvements
  - Increases number of GW emitting sources in range by factor of 1000
  - Will enable study of significant number of astrophysical sources of gravity waves
- Advanced LIGO will pioneer the new field of GW astronomy and astrophysics

Range of Advanced LIGO for 1.4 M_o binary neutron star inspirals



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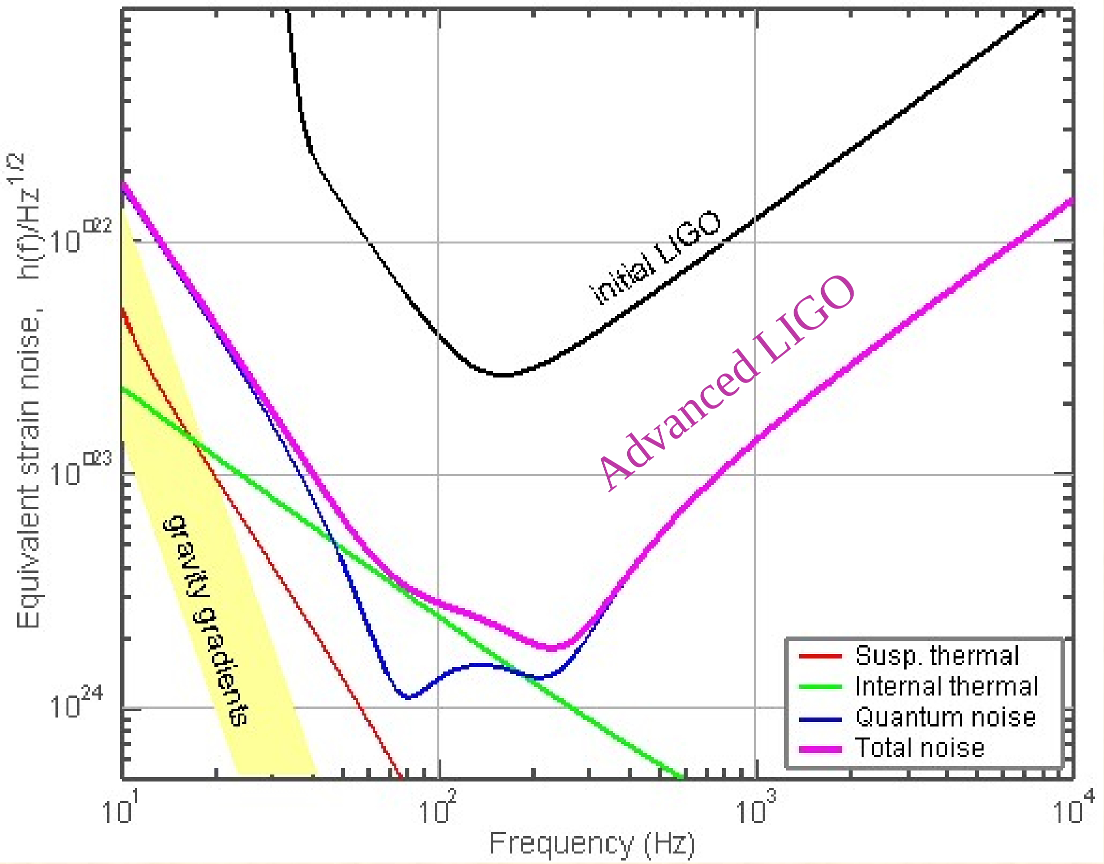
Astronomy & astrophysics with Advanced LIGO

- **Neutron Star Binaries:**
  Initial LIGO: ~10-20 Mpc →
  Advanced LIGO: ~200-350 Mpc
- **Black hole Binaries:**
  Up to 10 M_o, at ~ 100 Mpc
  → up to 50 M_o, in most of the observable Universe
- **Stochastic Background:**
  - Initial LIGO: ~3e-6
  - Adv LIGO ~3e-9
- **x10 better amplitude sensitivity**
  - ⇒ x1000 rate=(reach)^3
  - ⇒ 1 year of Initial LIGO < 1 day of Advanced LIGO



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Status of Advanced LIGO

- Fully peer reviewed
- Approved by National Science Board in the USA
- Expect start of US construction funds in 2008
  - UK, German contributions already funded
- 6 year construction schedule; ~$200M cost
- Funded from NSF account for big projects (MREFC) with operations to be supported by NSF Gravity Program (not from NSF Astronomy Program)
- Initial operations expected in 2014

Advanced VIRGO

- Planned sensitivity improvement is a factor of 10 over VIRGO sensitivity
- Implementation will start 2011
- Hardware upgrades (laser power, optics, coatings, suspensions and others) will be installed
- Re-commissioning period will be 2012-2013
- Operation on same timescale as Advanced LIGO

Large **Cryogenic** Gravitational Telescope (LCGT) (Japan)

Planned for construction in the Kamioka mine in Japan

Will use sapphire mirrors cooled to 40K

Proposal for funding submitted - currently under consideration by Ministry of Education

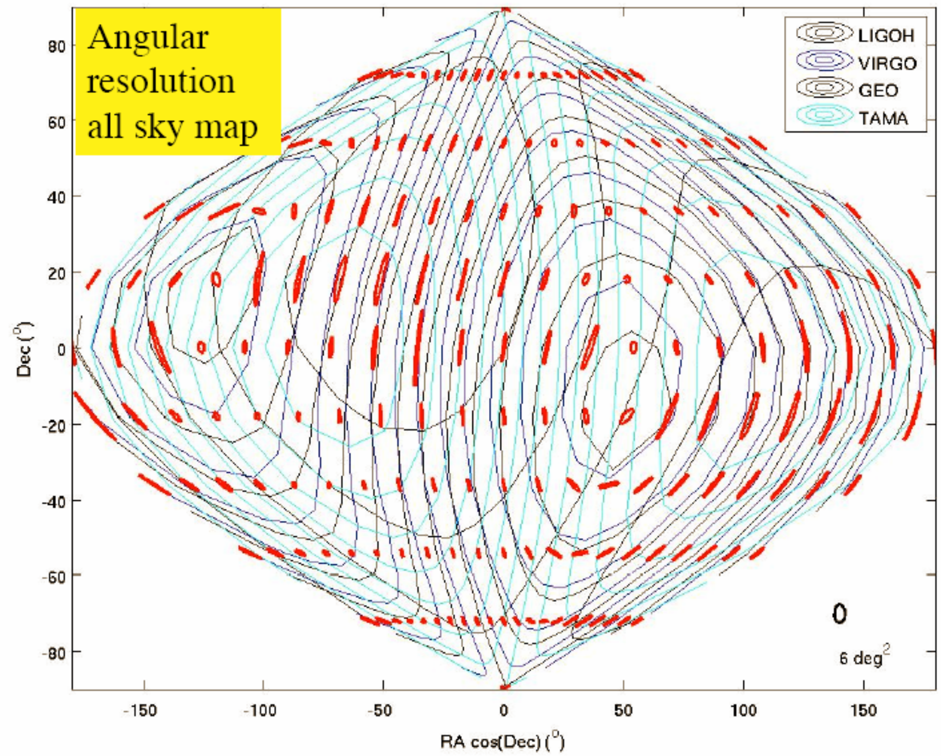
Sensitivity goals very similar to Advanced LIGO and Advanced VIRGO

GEO -HF

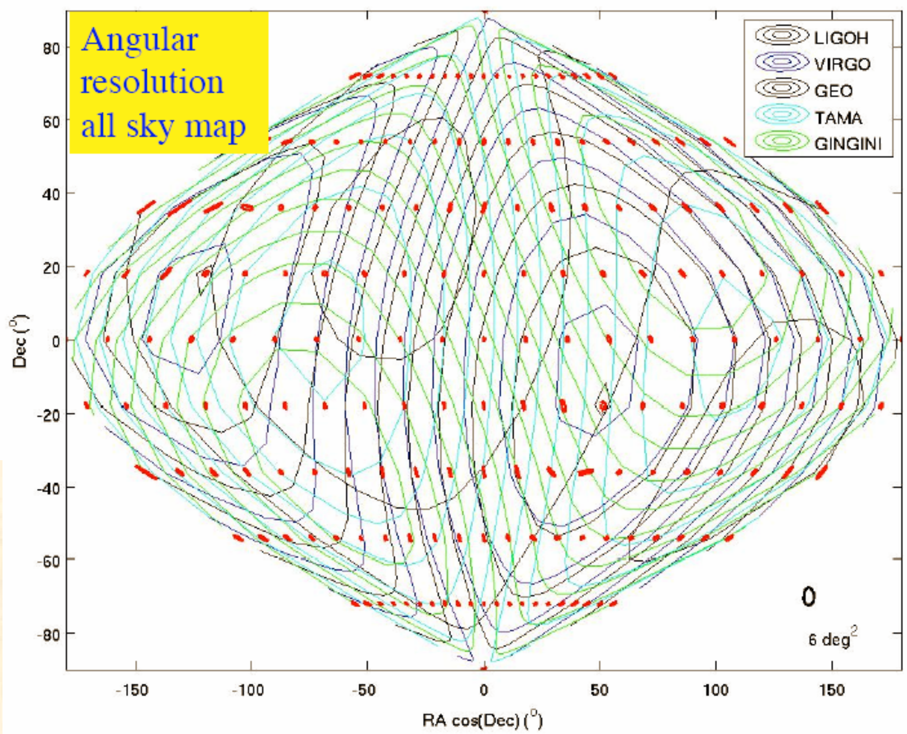
- Provide scientifically interesting data with the GEO instrument until 2014
  - optimized at low frequencies for network analysis or
  - optimized for high frequency sources
- Perform incremental upgrades and tests towards ‘third generation’ detectors
  - technologies, materials and optical schemes
- Timeline: starting upgrading after extended data taking 2007/2008

AIGO – possible detector in Australia

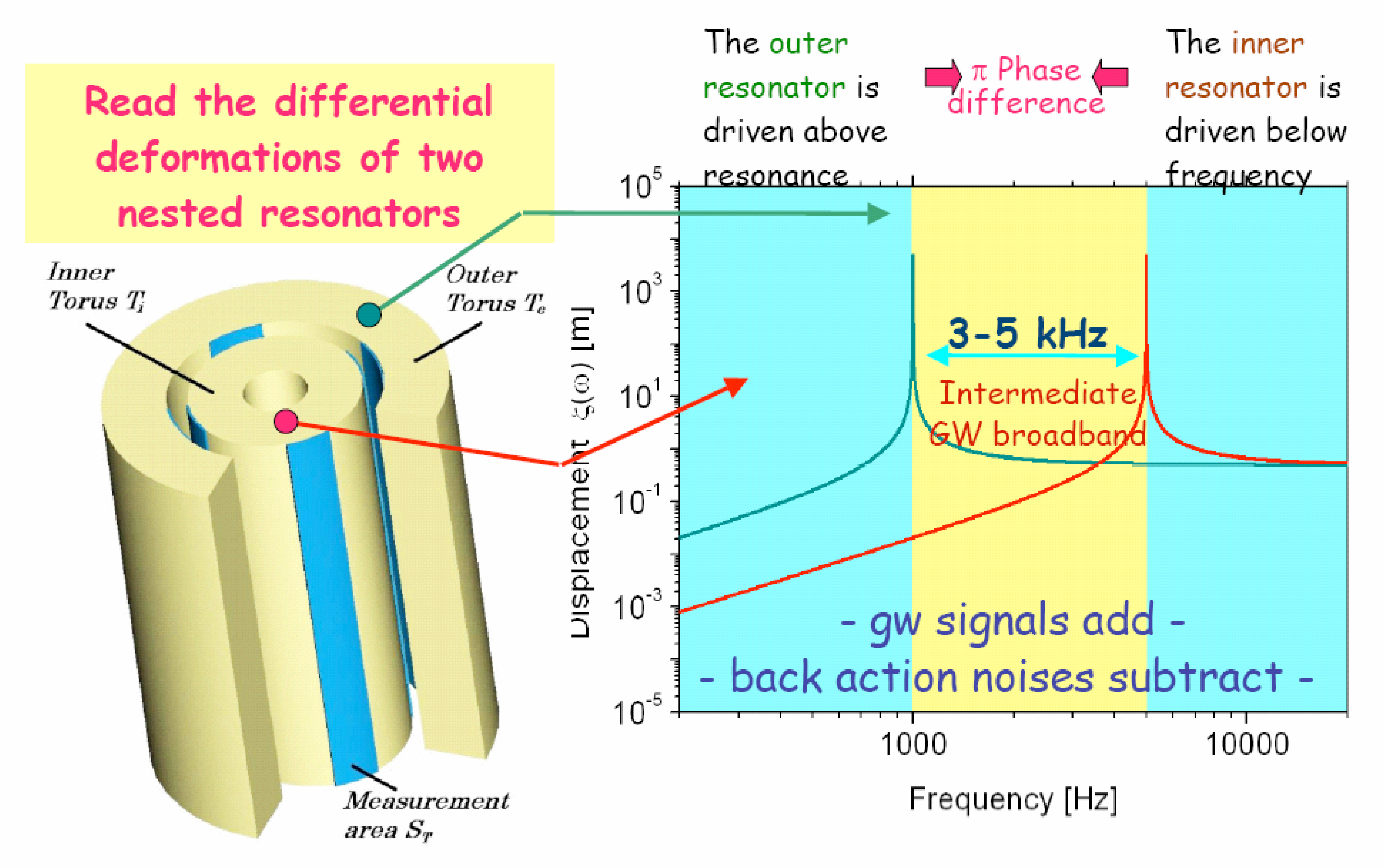
Linqing Wen: Null stream network analysis: without AIGO



Linqing Wen: Null stream network analysis: ***with*** AIGO

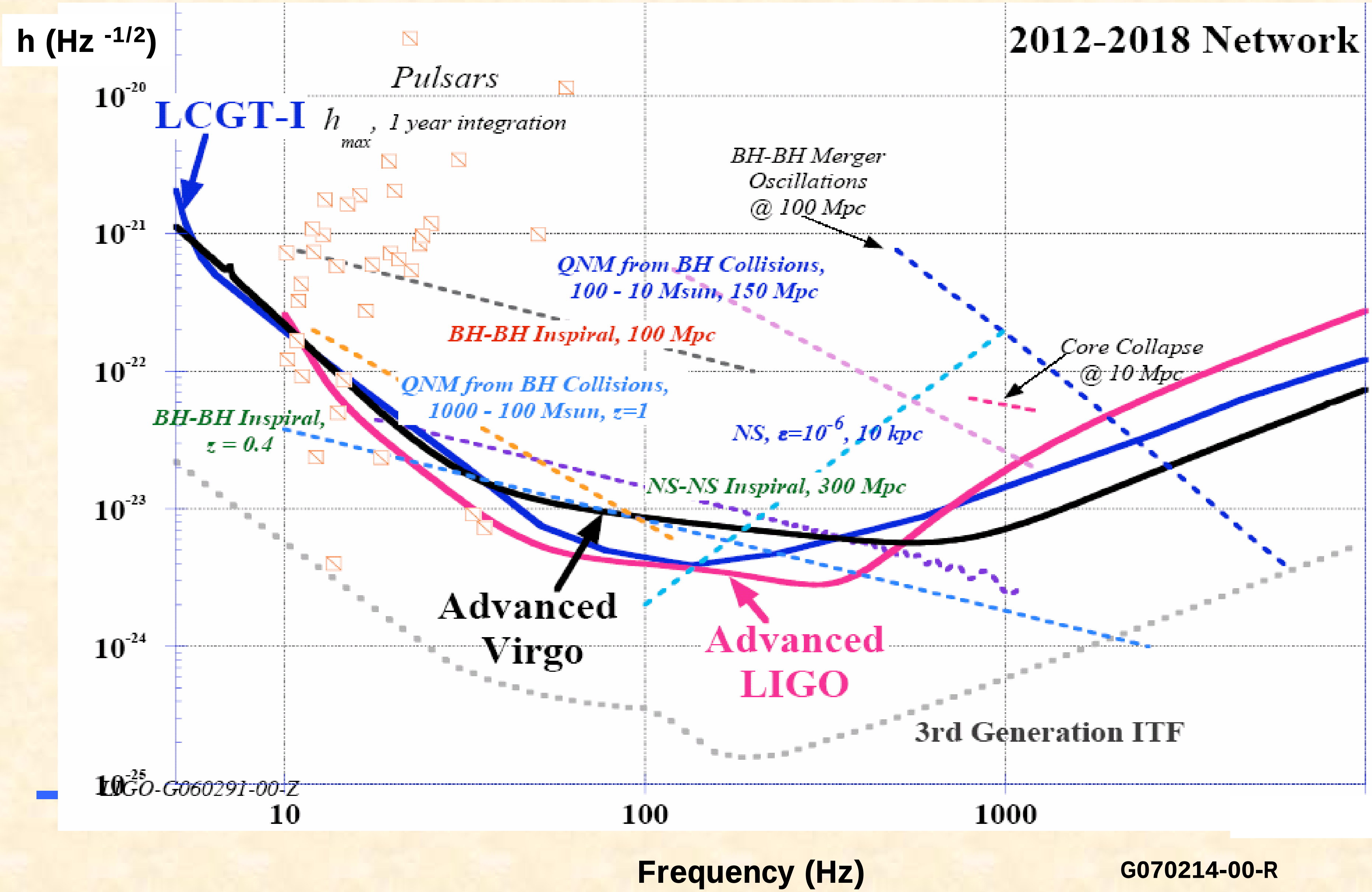


Advanced Bar detectors – the 'Dual' concept



At kHz frequencies, sensitivity expected to be comparable with the interferometric detectors

Advanced detector network



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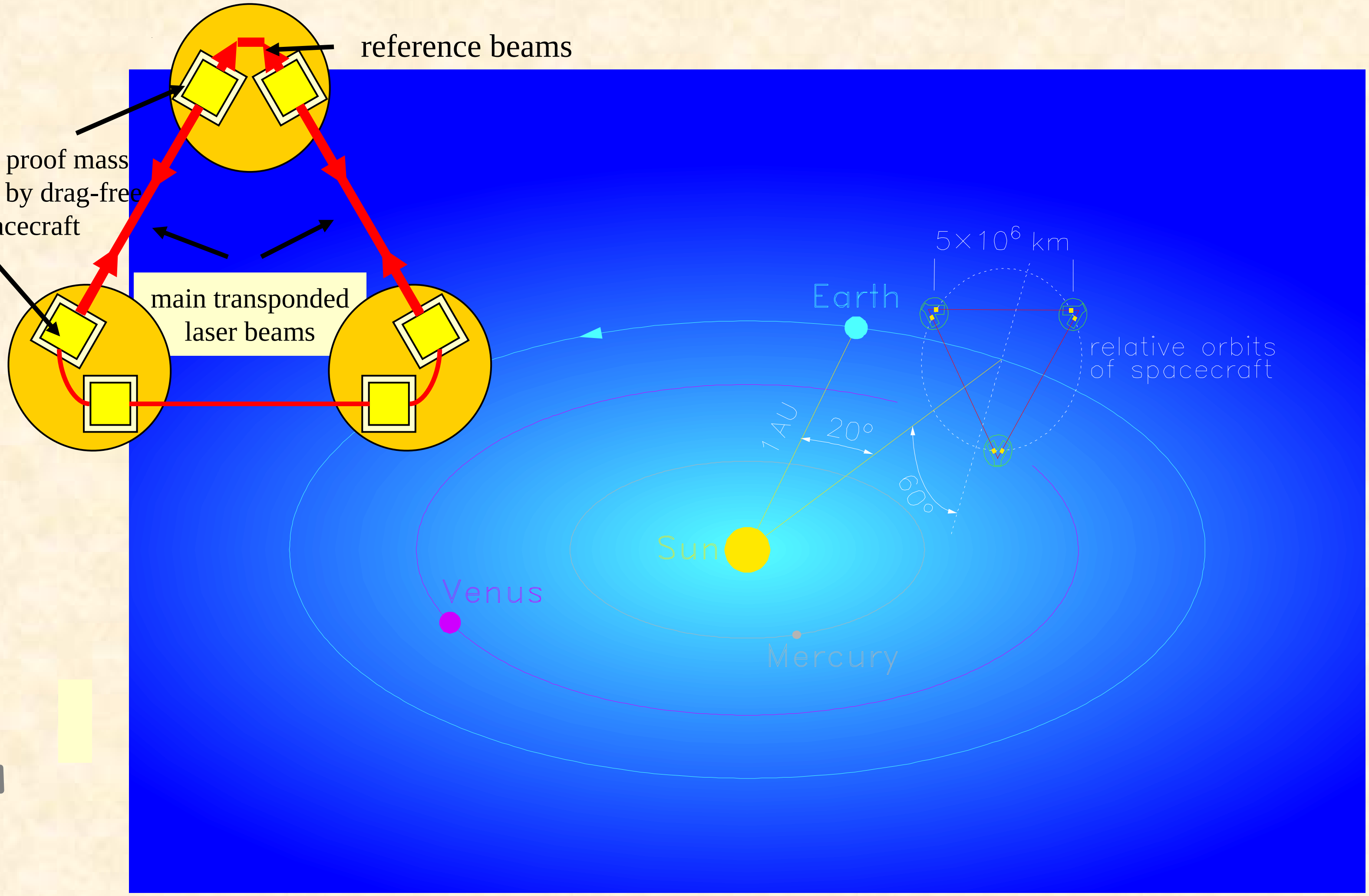
The Future of Detectors on Earth

- 3rd generation 2015-20,
  - **Design proposal for future pan-European instrument**
    - Possibly built underground, optimised for low frequency sources, with mirrors at liquid helium temperature, using quantum-non-demolition techniques?
    - Aim for another factor of 10 improvement in sensitivity over advanced detectors
    - Lab research ongoing on necessary instrumentation
    - European groups propose a design study for the concept of a 3rd generation interferometric detector for the FP7 call
  - **Lab research towards technically advanced concepts also ongoing in the US and elsewhere**

LISA -Cluster of 3 spacecraft in heliocentric orbit at 1 AU

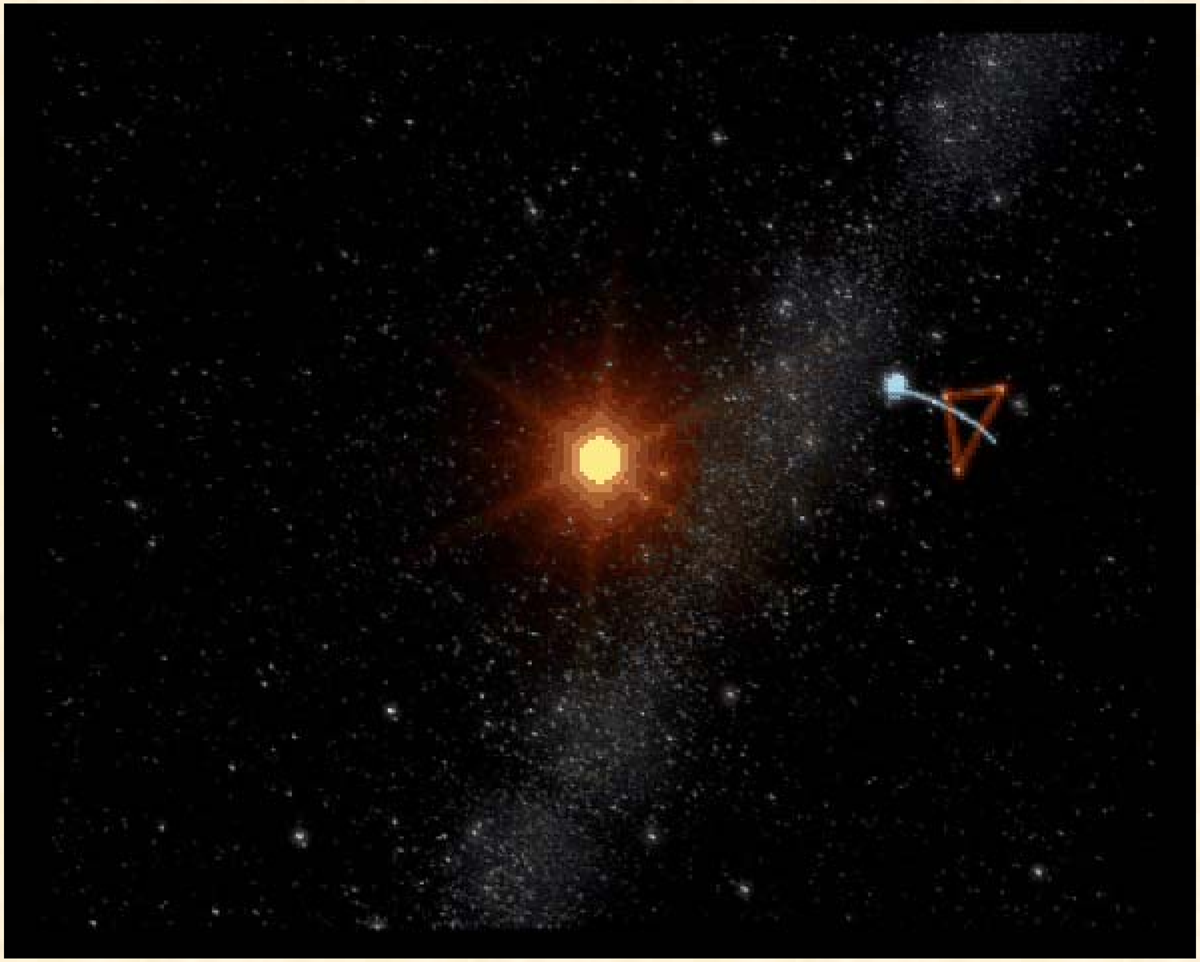


LISA

NASA

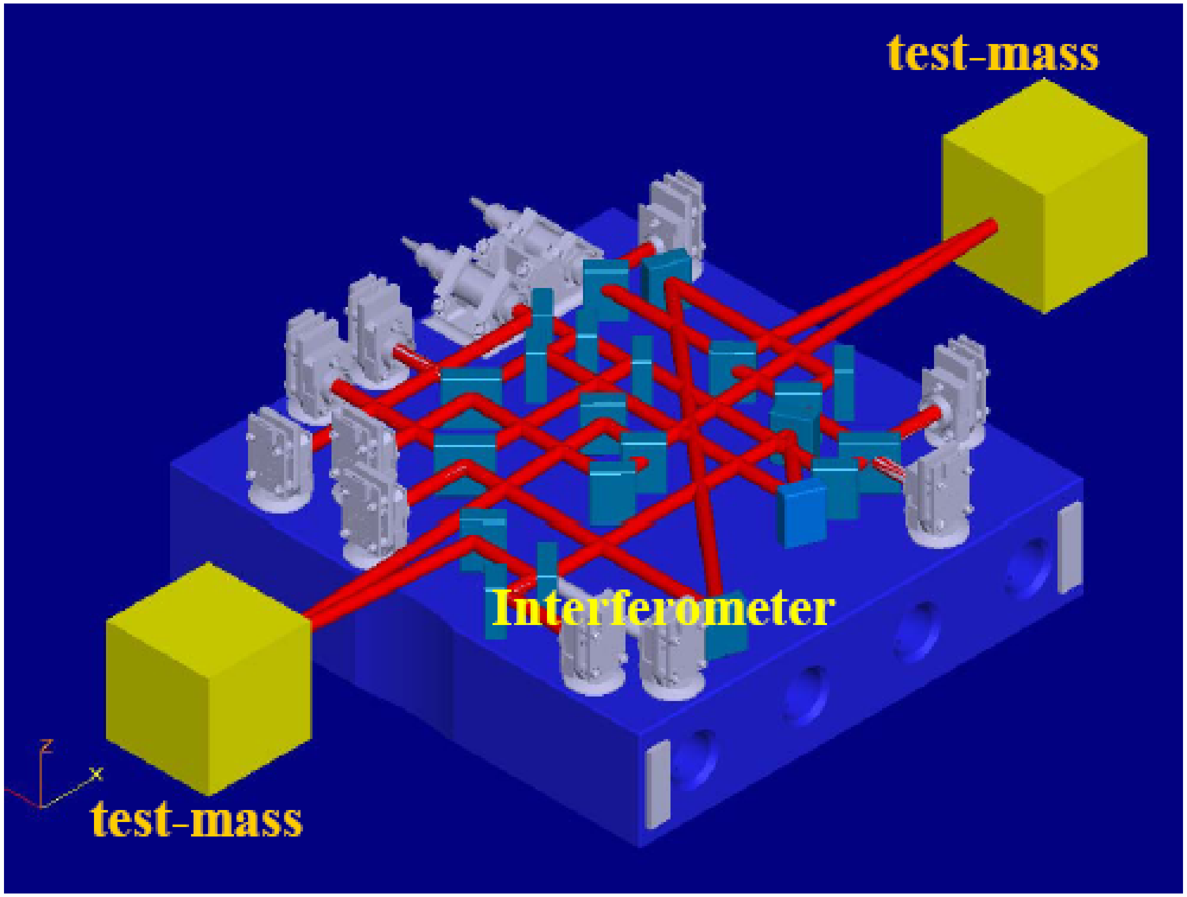
esa

LISA ORBIT



LISA Pathfinder Concept
– Technology demonstrator for launch in 2009

Demonstration of inertial sensing and ‘drag free’ control



Mission status

- LISA and demonstrator mission 'LISA Pathfinder' approved joint ESA-NASA missions
- Pathfinder – mission in phase of building hardware
- Launch –late 2009

- US budget requirements necessitate Beyond Einstein missions be sequential rather than parallel efforts
- One of 3 will go first: LISA, Con-X, JDEM
- Already substantial investment made towards LISA (~200MEuro)
- Final decision in the US to be made over ~ next 6 months

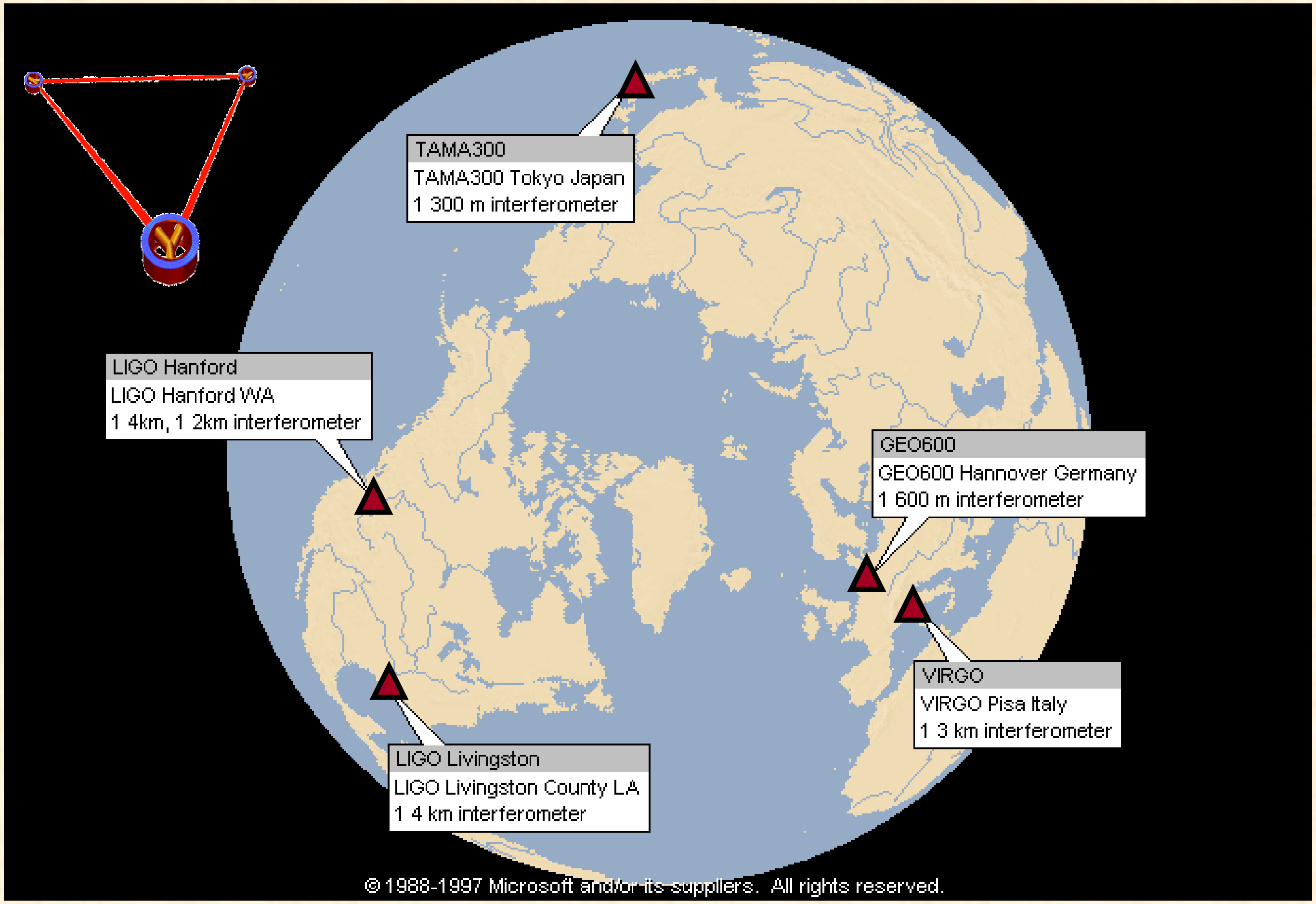
- On the ESA side, final commitment to LISA's implementation will be influenced strongly by the success of LPF
- However work underway before LPF launch to define the LISA mission and prepare the invitation to tender for the implementation phase.

With NASA's selection in FY2007 and ESA's final commitment, LISA expected to enter the implementation phase in 2011, and launch in the post-2015 timeframe.

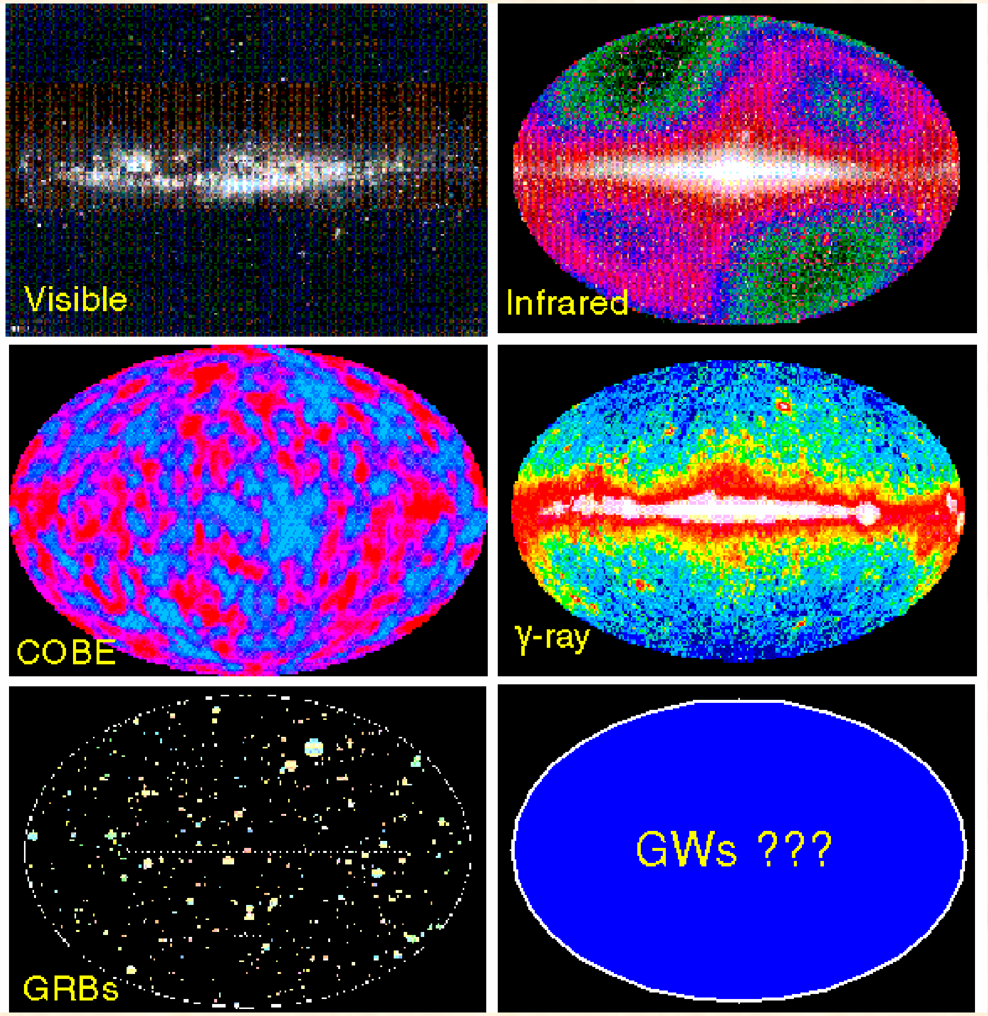
The Network of Gravitational Wave Facilities

- 1st generation on ground are operating and taking data
- 2nd generation follows 2010-14, designs mature,
  - Advanced LIGO (USA/GEO Group/LSC)
  - Advanced VIRGO (Italy/France +GEO Group?)
  - Large Cryogenic Gravitational Telescope (LCGT) (Japan)
  - GEO-HF (GEO/LSC)
  - DUAL – acoustic detector concept
- 3rd generation
  - Lab research underway around the globe
  - Plans for a design proposal under FP7 framework for a 3rd generation detector in Europe
- LISA – spaced based detector
  - Planned for launch not before 2015

Worldwide Interferometer Network



Gravitational Wave Astronomy



A new way to observe the Universe