The Search for Gravitational Waves

Jim Hough for the LIGO Scientific Collaboration
SUPA, Institute for Gravitational Research
University of Glasgow

LEOS Montreal 2006

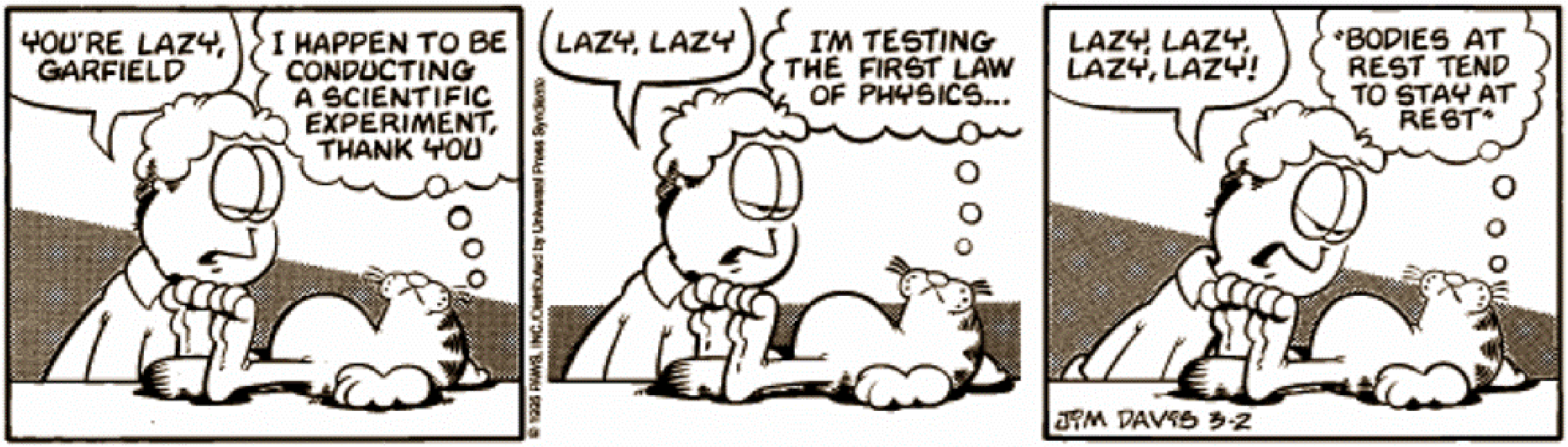
LIGO-G060573-00-K

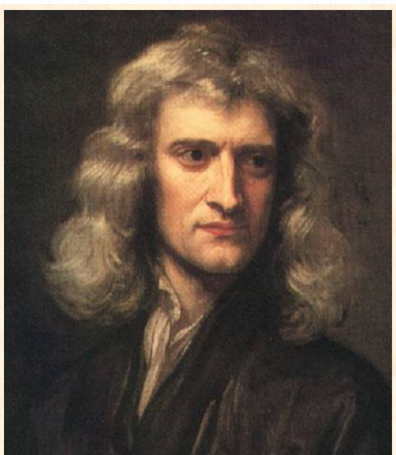
IGR

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

LIGO

Newton’s Laws

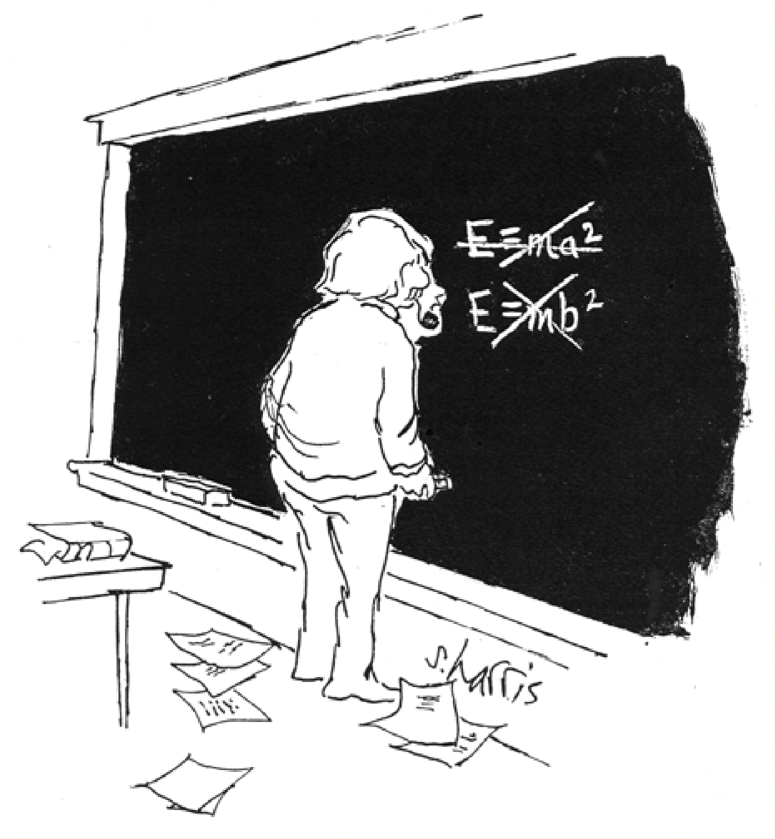


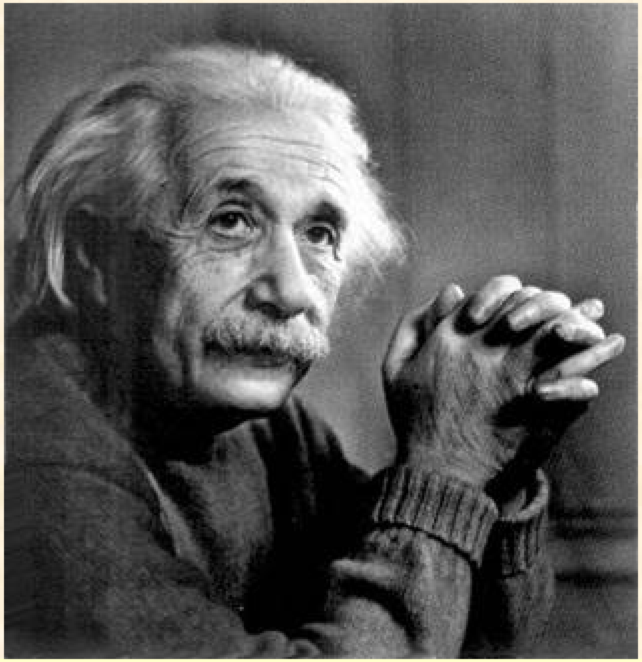


Newton’s Theory

“instantaneous action at a distance”

Einstein's Special Relativity





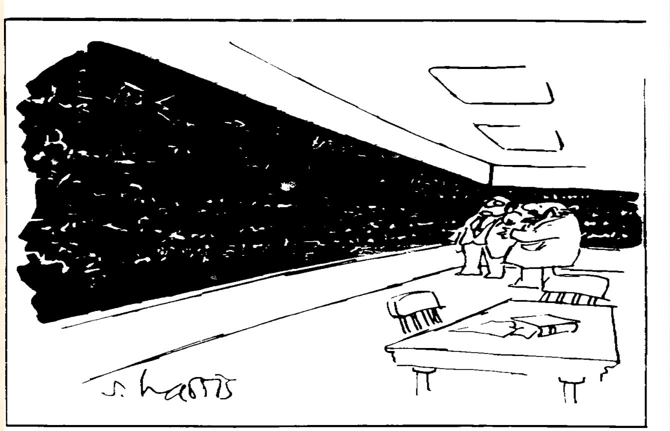
Einstein's Theory

information cannot be carried faster than speed of light – there must be gravitational radiation

'Gravitational Waves' a prediction of General Relativity

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

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

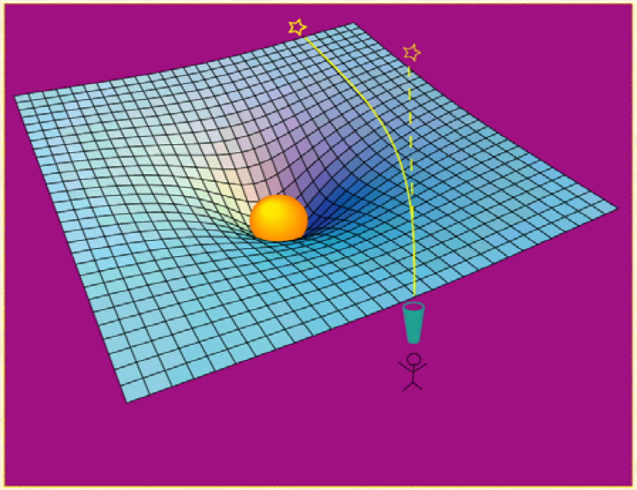


'But this is just a simplistic way of looking at the problem".

- **Gravitational waves**

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

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

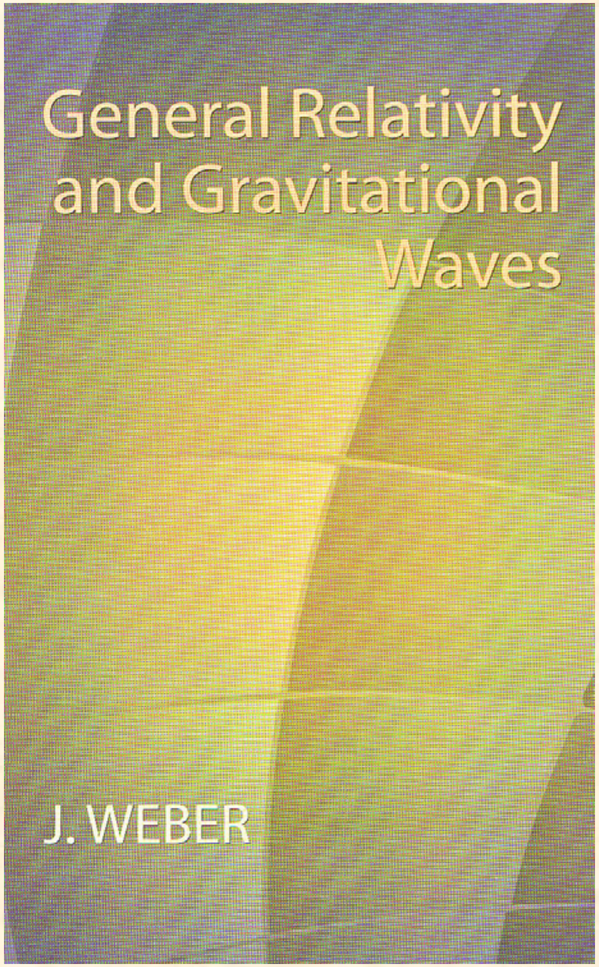


GW ‘rediscovered’ by Joseph Weber

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

Reality of the Cylindrical Gravitational Waves of Einstein and Rosen

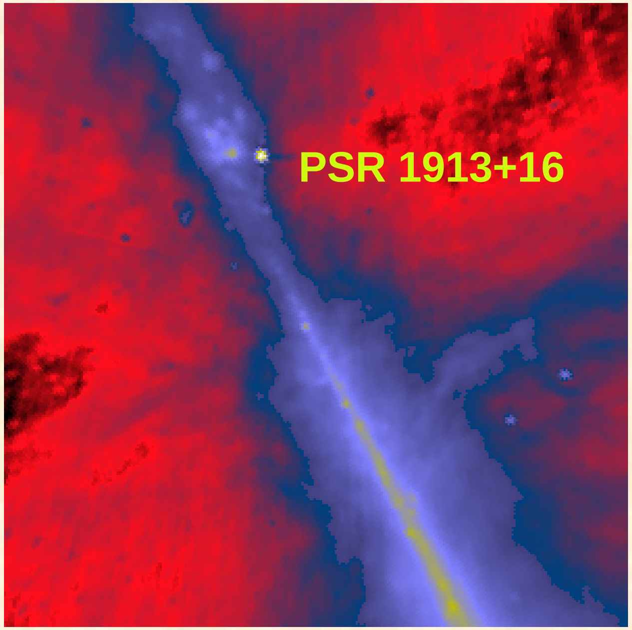
JOSEPH WEBER, *Lorentz Institute, University of Leiden, Leiden, Netherlands, and University of Maryland, College Park, Maryland*
JOHN A. WHEELER, *Lorentz Institute, University of Leiden, Leiden, Netherlands, and Palmer Physical Laboratory, Princeton University, Princeton, New Jersey*

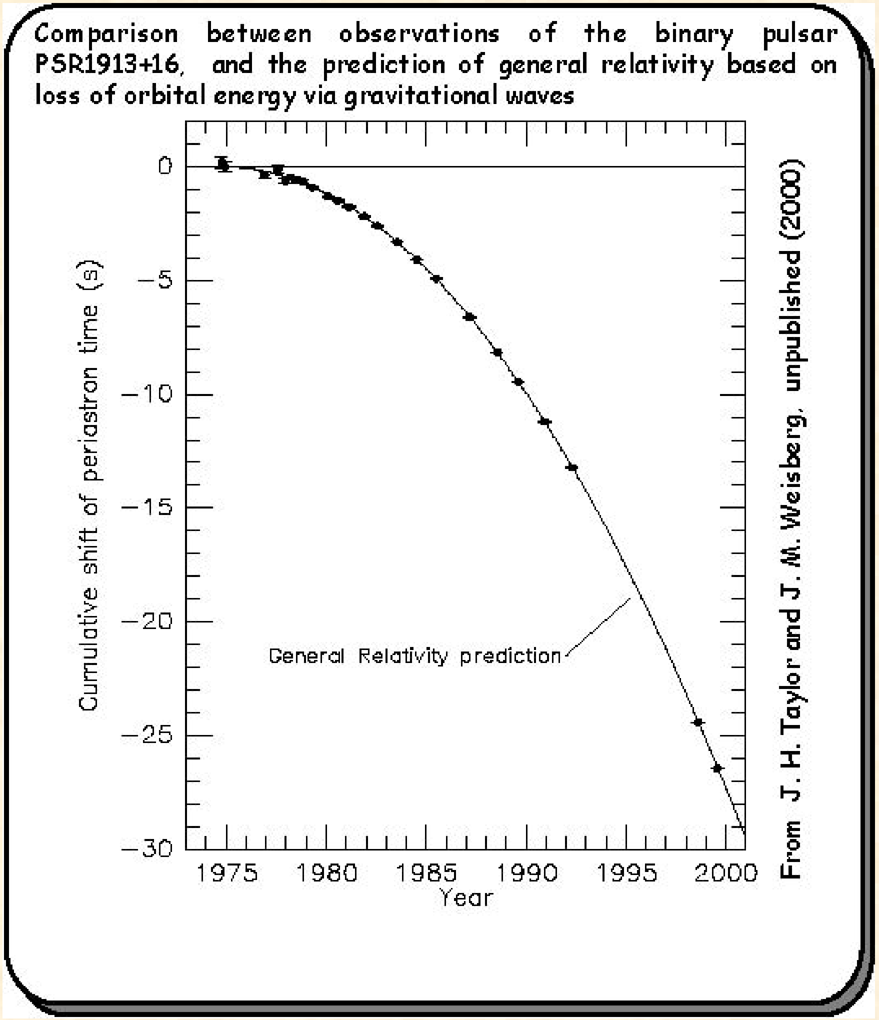


1961

The evidence for gravitational waves

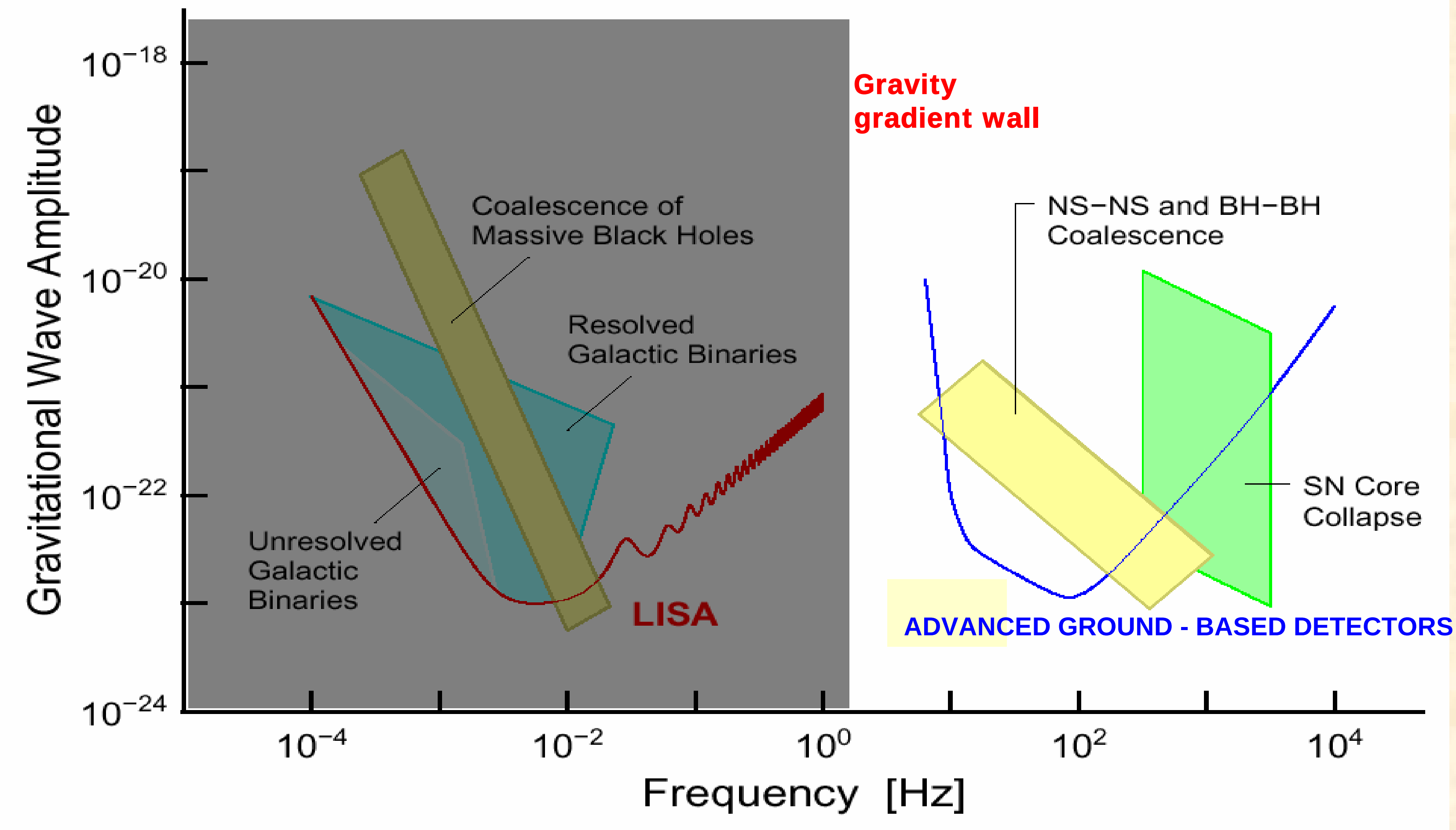
“Indirect” detection of gravitational waves





Sources

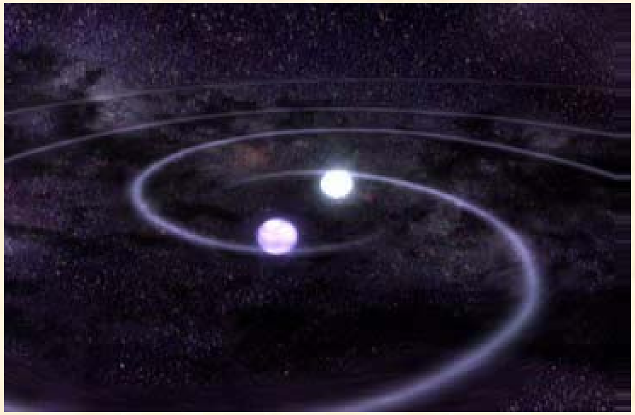
– Amplitudes from expected sources are tiny



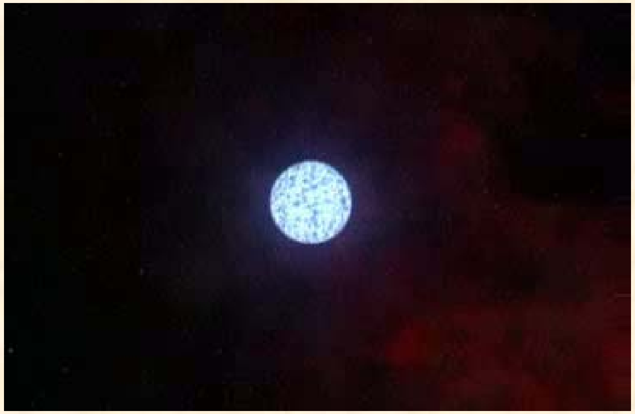
Detectors are split into space-based and ground based systems

‘Gravitational Waves’- possible sources

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

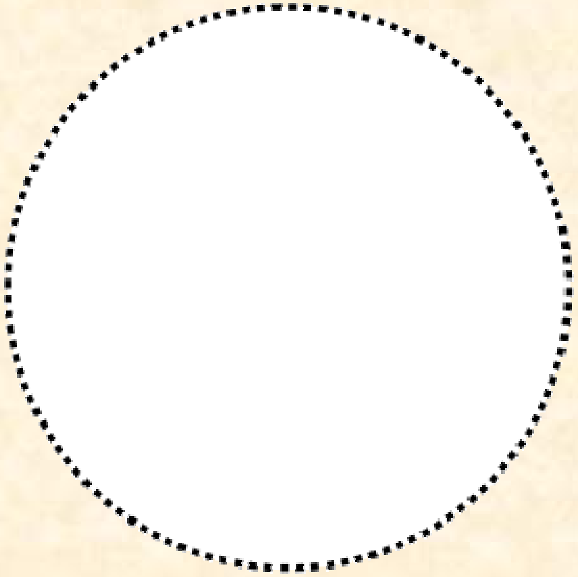


Binary stars coalescing



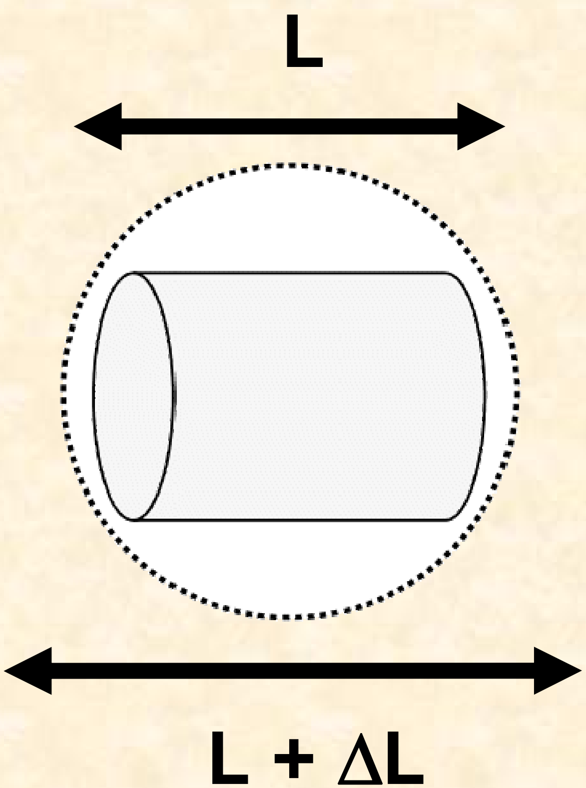
Supernovae

Gravitational Waves : A Strain in Space

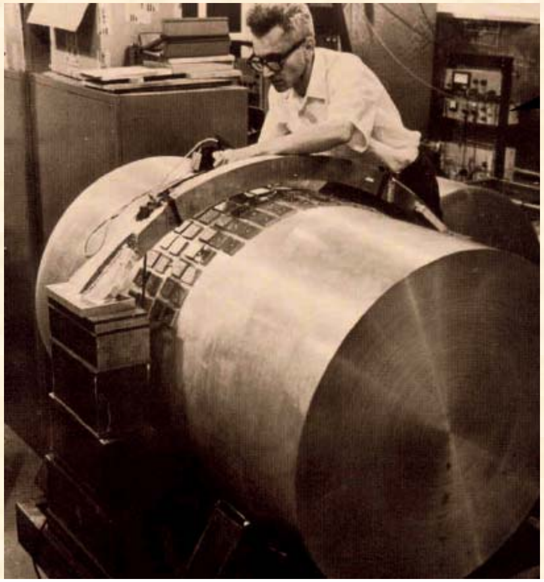


How can we detect them?

- Gravitational wave amplitude h ~ $\dfrac{\Delta L}{L}$



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

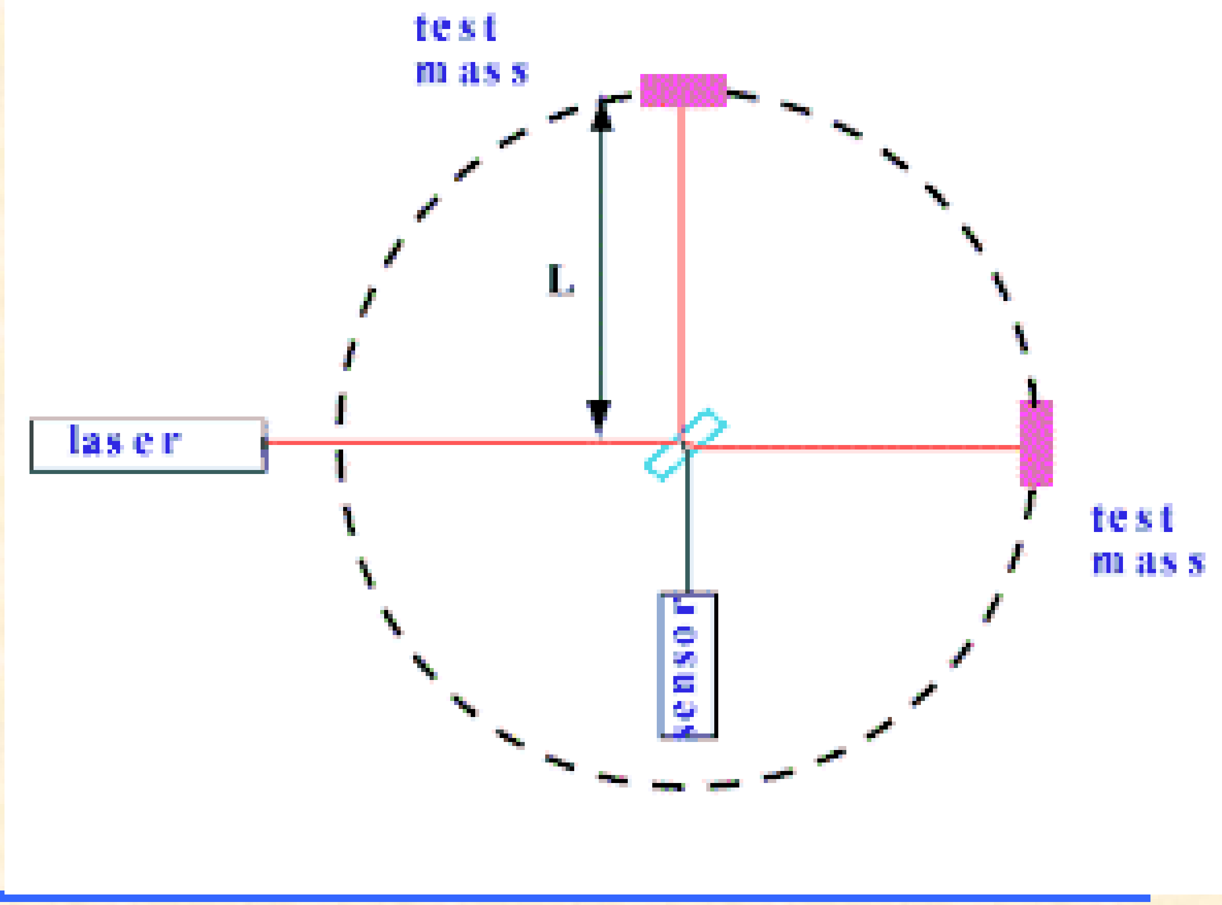
Now operating at cryogenic temperature

Sensitivities of h_{rms} ~10^{-21}

They are reliable and have excellent duty cycle.

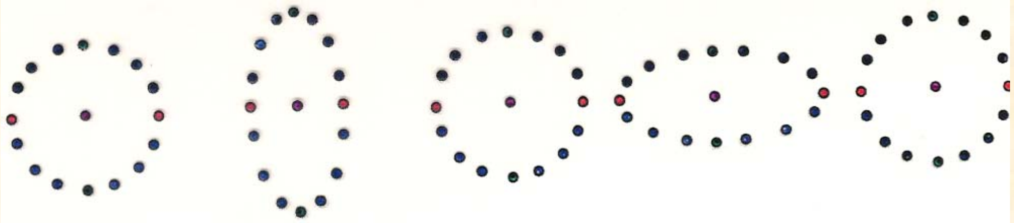
Detection again

Interferometer

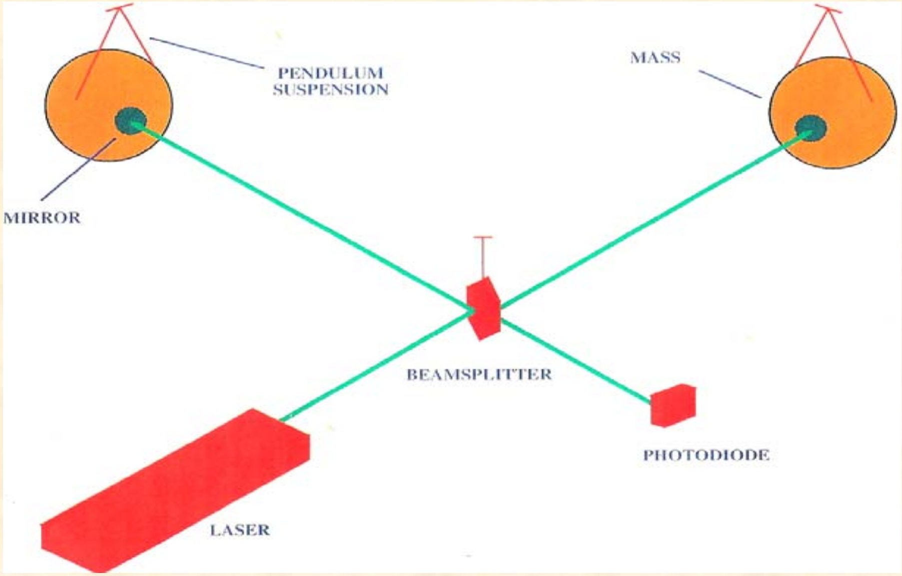


Detection of Gravitational Waves

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



One cycle



Michelson Interferometer

Gravitational waves have very weak effect:

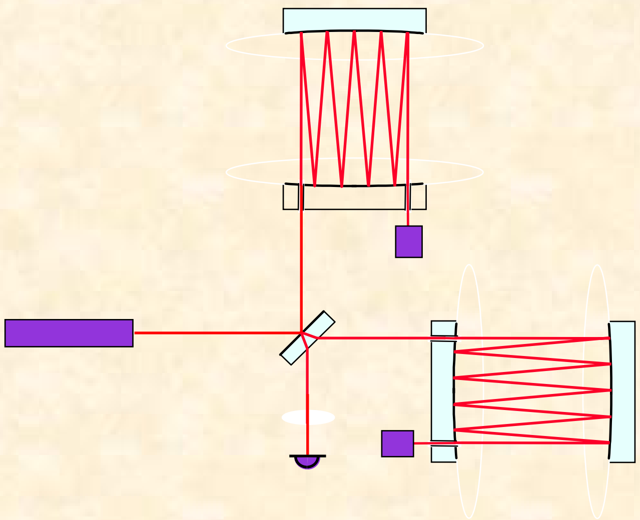
expect movements of less than 10^{-18} m over 4km

Laser Interferometric detectors

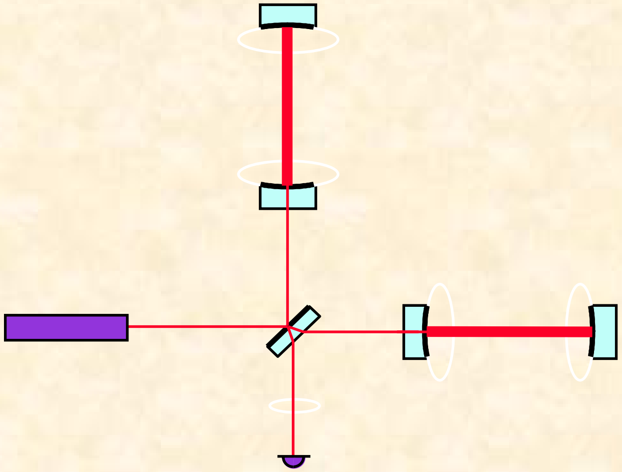
- For best performance want arm length $\sim \lambda/4$

  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 or under development**

Gravitational Wave Detectors

4 detector systems operational:

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

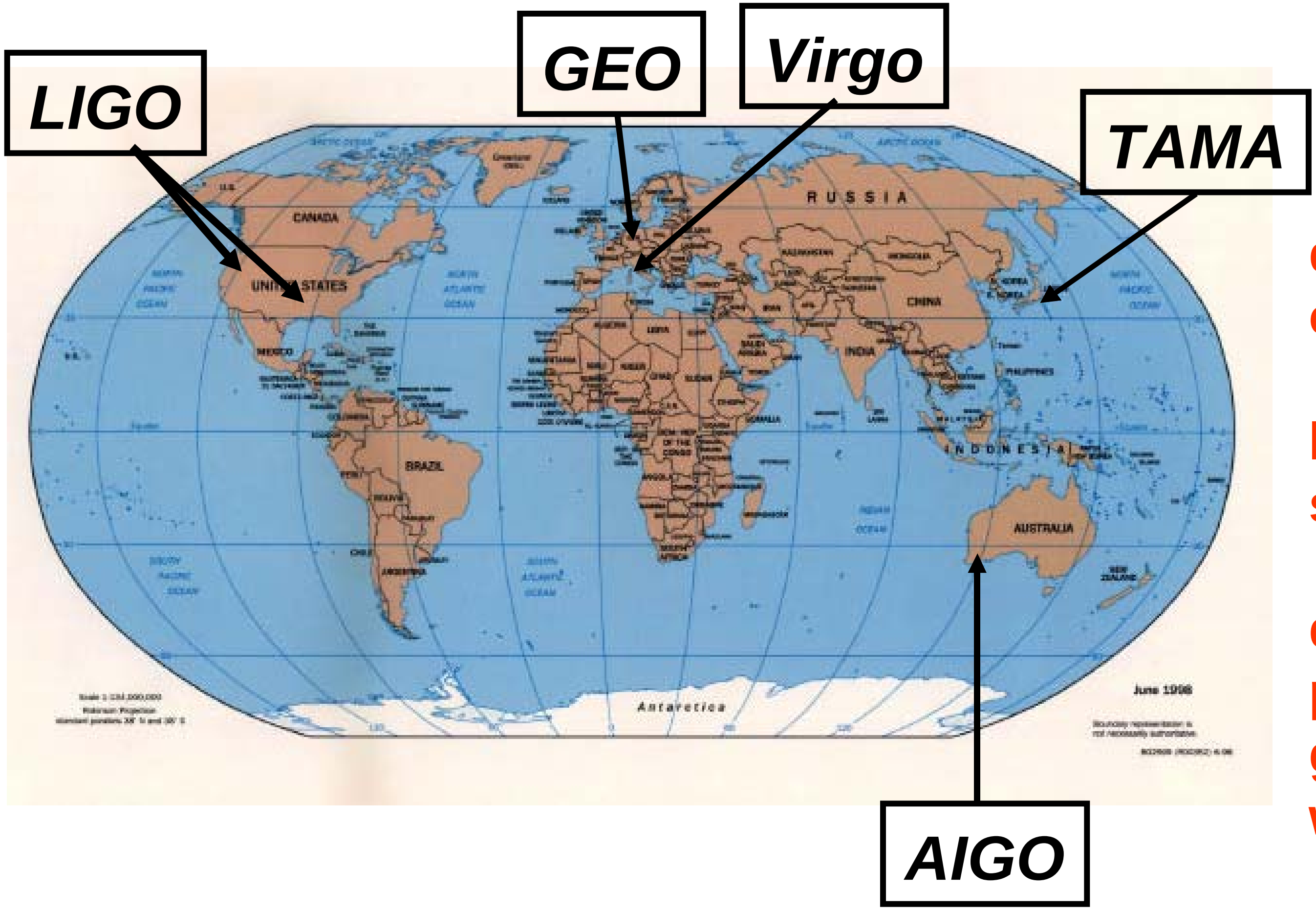
Another under development

LISA (NASA/ESA) –	*Spaceborne detector of 5 x 10^6km arm length*

Test Facility/Potential Detector in Western Australa - AIGO

Interferometers - *international network*

'Simultaneously' detect signal (within msec)



detection confidence

locate the sources

decompose the polarization of gravitational waves

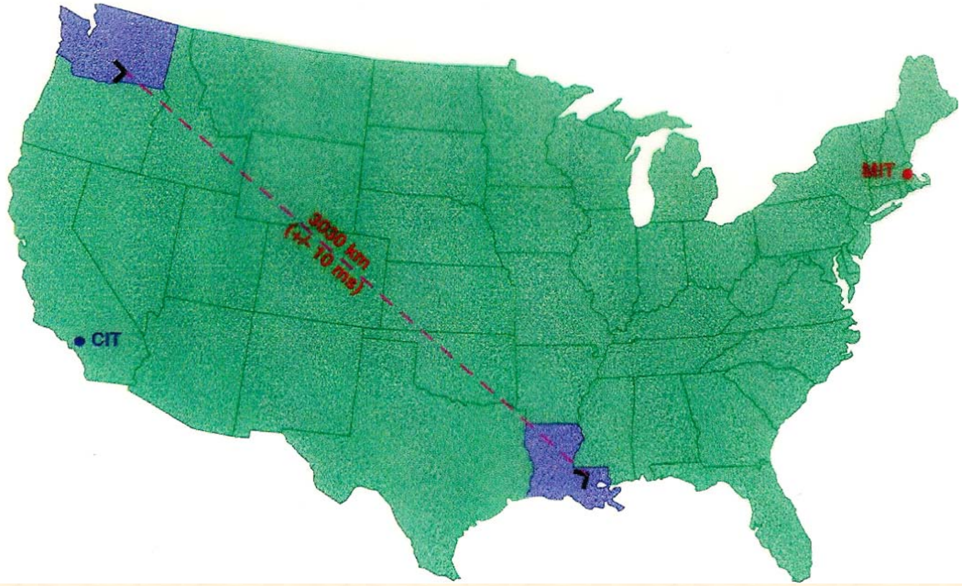
LIGO USA

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

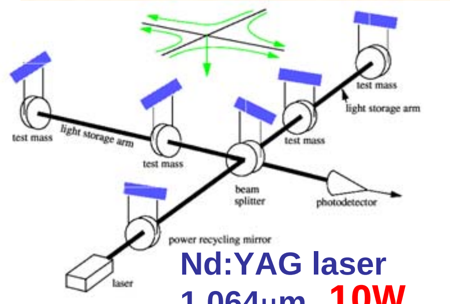


Initial LIGO detectors

LIGO project (USA)

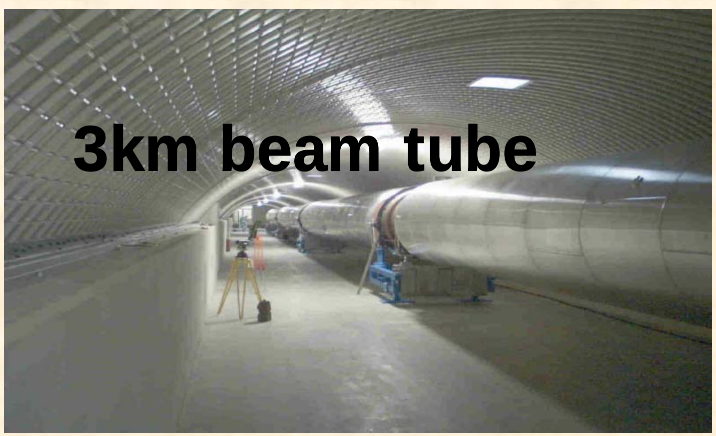
- 2 detectors of 4km arm length + 1 detector of 2km arm length
- Washington State and Louisiana

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

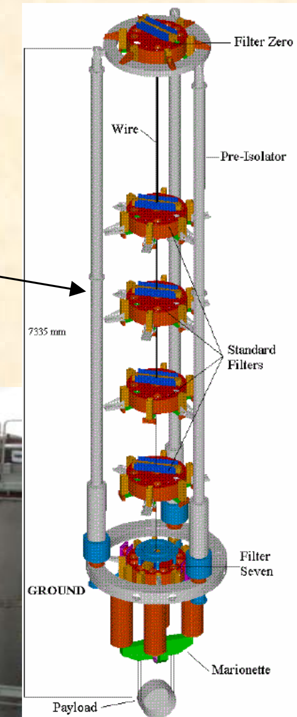


Nd:YAG laser
1.064μm 10W

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



The 'Super Attenuator' filters the seismic noise above 4 Hz



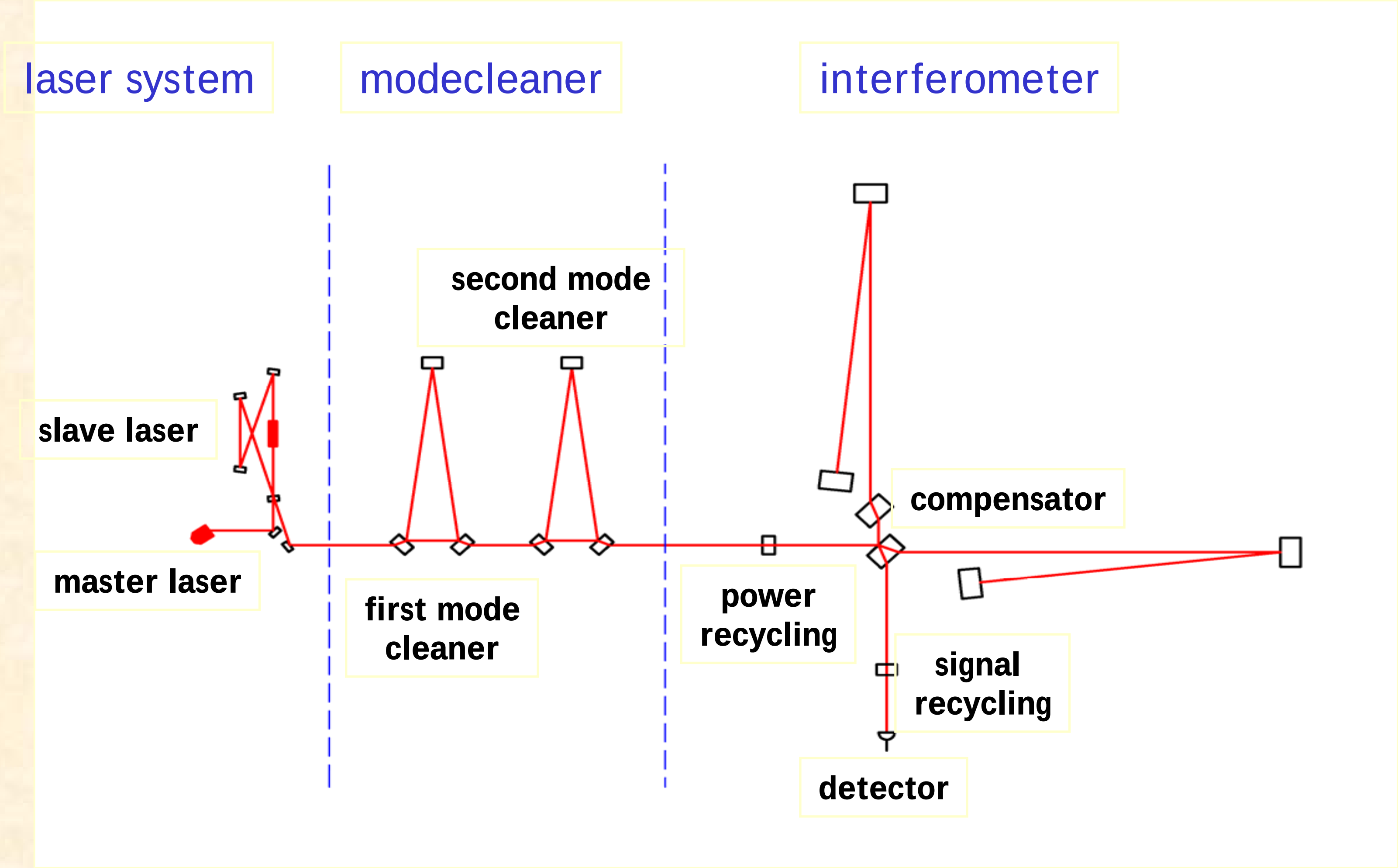
Other Detectors and Developments – TAMA 300 and AIGO

TAMA 300 Tokyo
300 m arms

AIGO Gingin, WA
80 m arm test facility

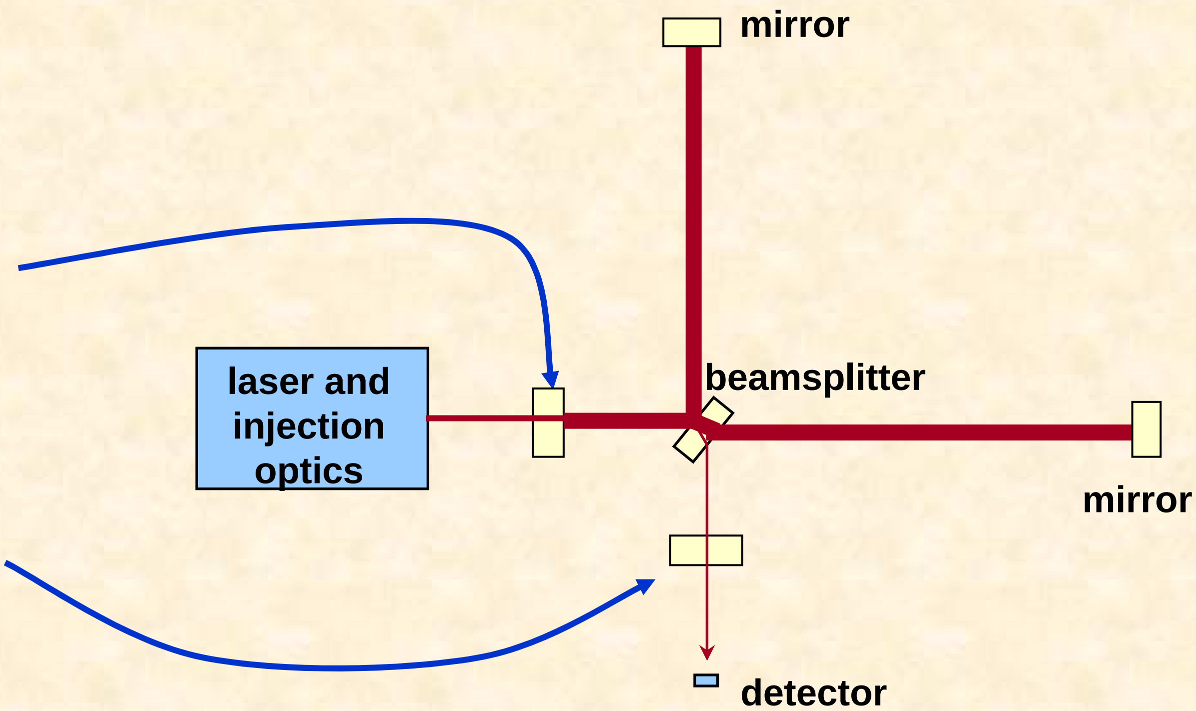
GEO 600

GEO600 – optical layout



Unique GEO Technology 1 - Advanced Interferometry

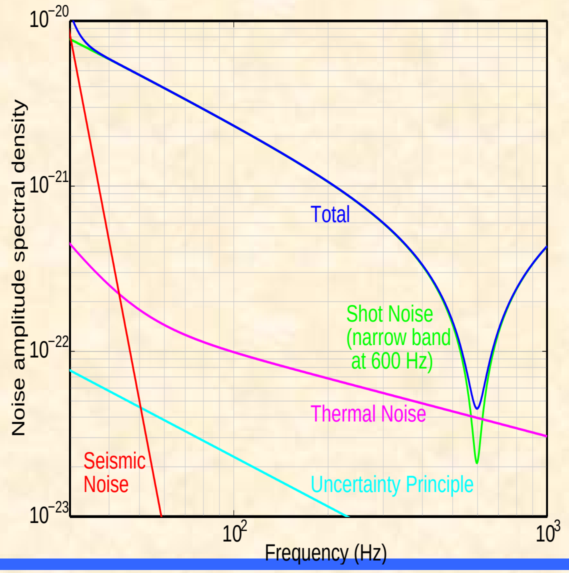
- One of the fundamental limits to interferometer sensitivity is photon shot noise
- Power recycling effectively increases the laser power
- Signal recycling – a GEO invention – trades bandwidth for improved sensitivity

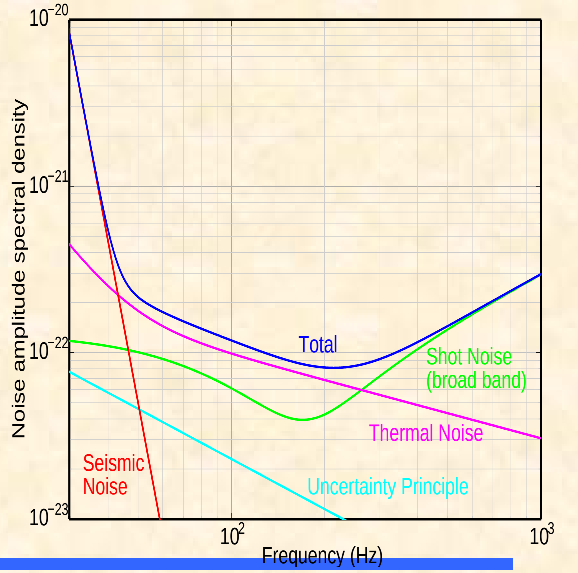


Unique GEO Technology 1 - Advanced Interferometry

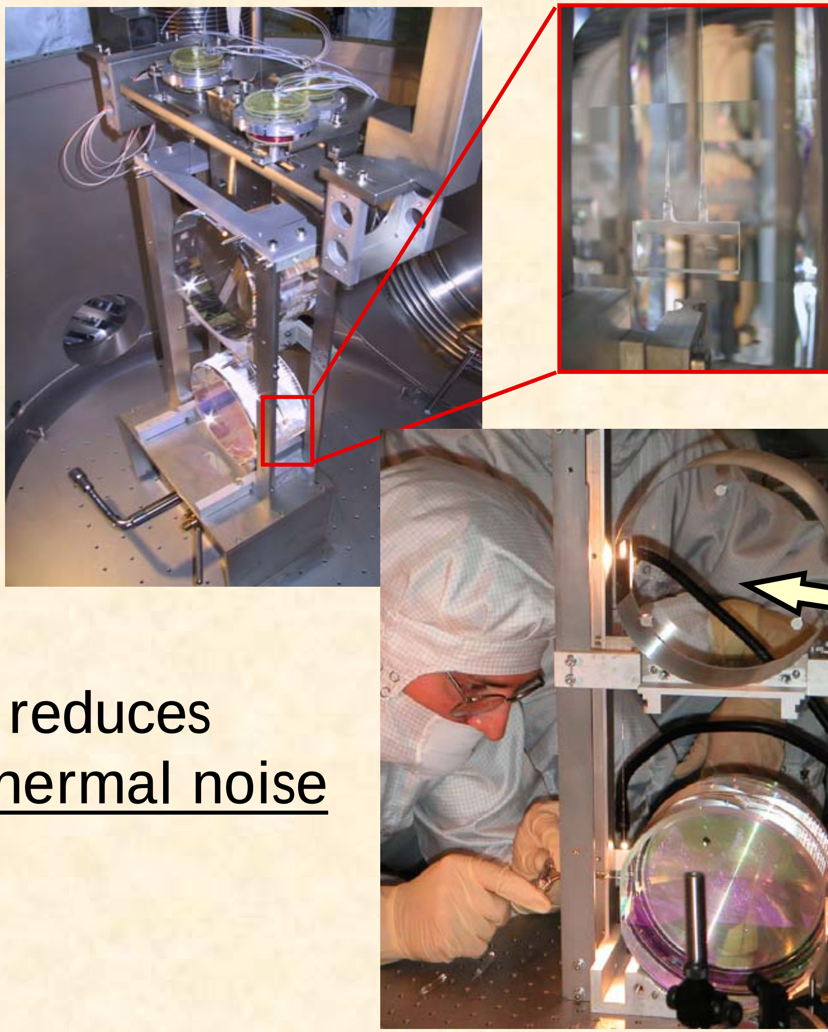
<u>The interferometer is operated with the output port held at an interference minimum</u>

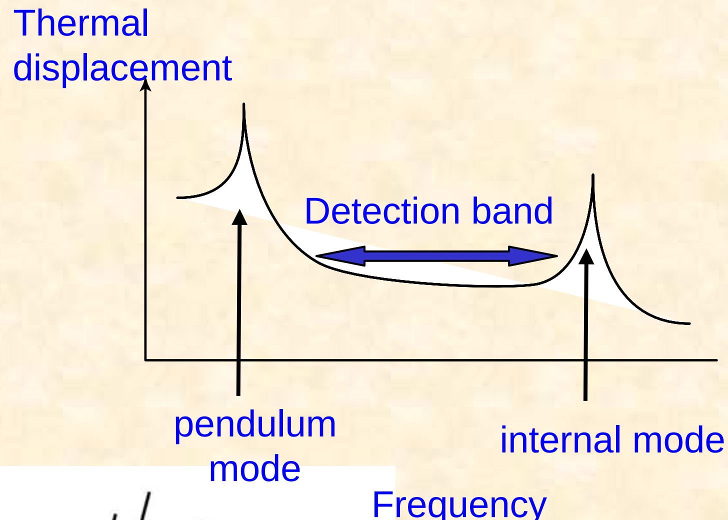
- The only light at the output is (ideally) that containing information about differential length changes of the arms (the gravitational wave signal)
- The SR mirror reflects most of this light back into the interferometer
- The interferometer behaves like optical cavity – in which the gw signal amplitude builds up
- Resonant enhancement of the signal occurs at a Fourier frequency and over a band width determined by the position and transmittance of the SR mirror

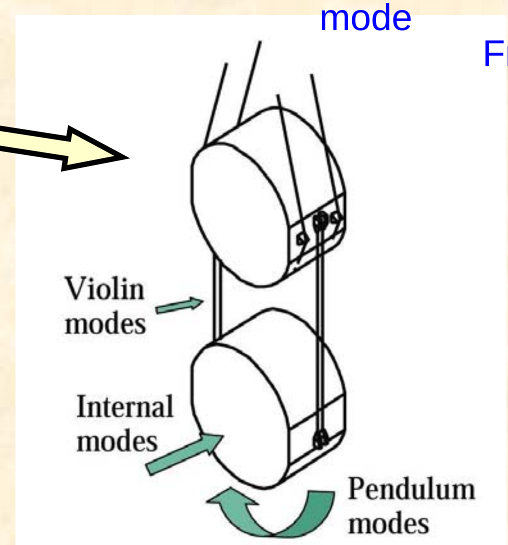




Unique GEO Technology 2 - Monolithic Silica Suspension







- 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 runs
  - Analysis completed for S1/2 and (most) papers published;
  - For S3/4 analysis – 2 papers published and many more in preparation
  - Some runs done in coincidence with TAMA and bars (Allegro)
  - LIGO now at design sensitivity

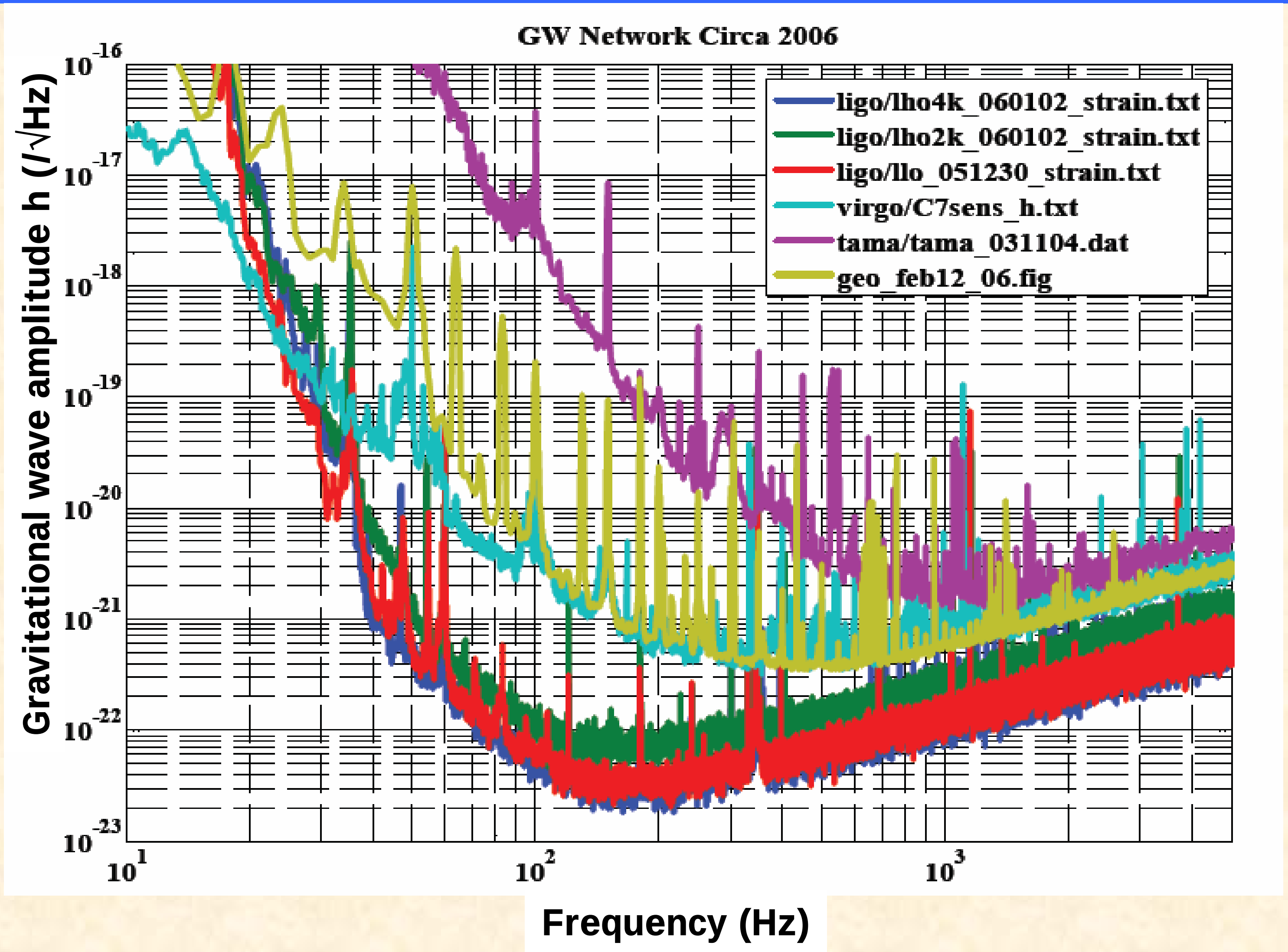
- 'Upper Limits' have been set for a range of signals
  - Coalescing binaries
  - Pulsars
  - Bursts
  - Stochastic background

- **>15 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, then 24/7

- 18 months data taking in coincidence

Gravitational wave network sensitivity

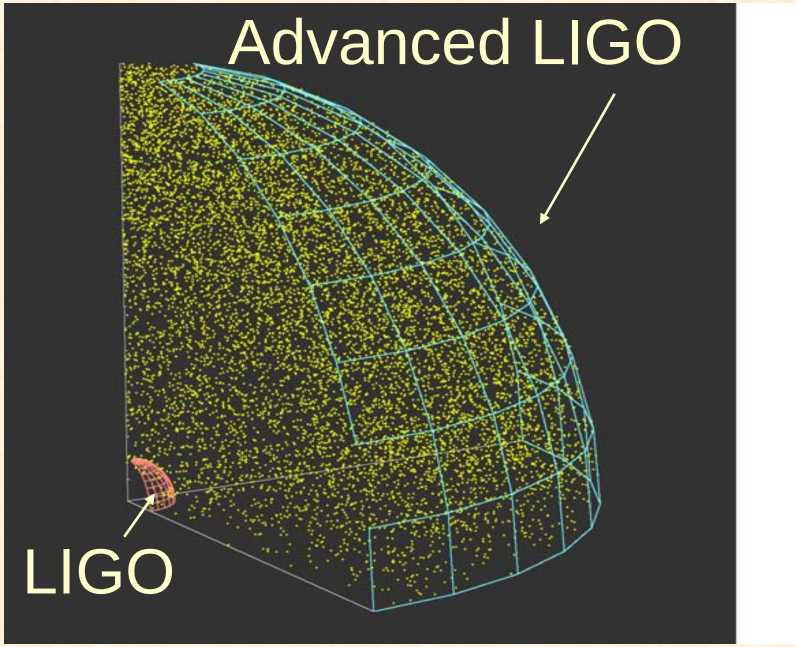


Prospects for Initial LIGO and GEO – eg coalescing compact binaries

- Recent discovery of a unique compact binary system in the galaxy
  - double pulsar J0737-3039 – has improved the statistics for the expected rate of binary coalescences by a significant factor
  - most probable rate of binary neutron star coalescences detectable by the LIGO system ~ 1 per 10 years to 1 per six hundred years
- Thus detection at the sensitivity level of the initial detectors is not guaranteed
  - Need another X 10
  - then most probable rate of detectable binary neutron star coalescences ~ 10 to 500 per year

Plans for Advanced Detectors 2008 -

- **Need** to improve sensitivity:
  - try to reach limits set by the Uncertainty Principle and Gravity Gradient noise
- How?
  - can go a long way towards this goal by applying the GEO technology and its extensions to longer detectors
    - Silica Fibres/Ribbons
    - Signal Recycling and injection locked lasers (100W)

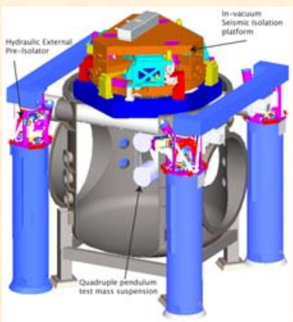


⇒ 'Advanced LIGO', Advanced VIRGO

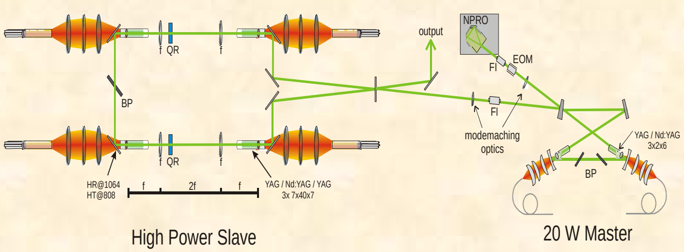
Further proposal to go cryogenic – LCGT (Japan)

Advanced LIGO: how to get where we want to go

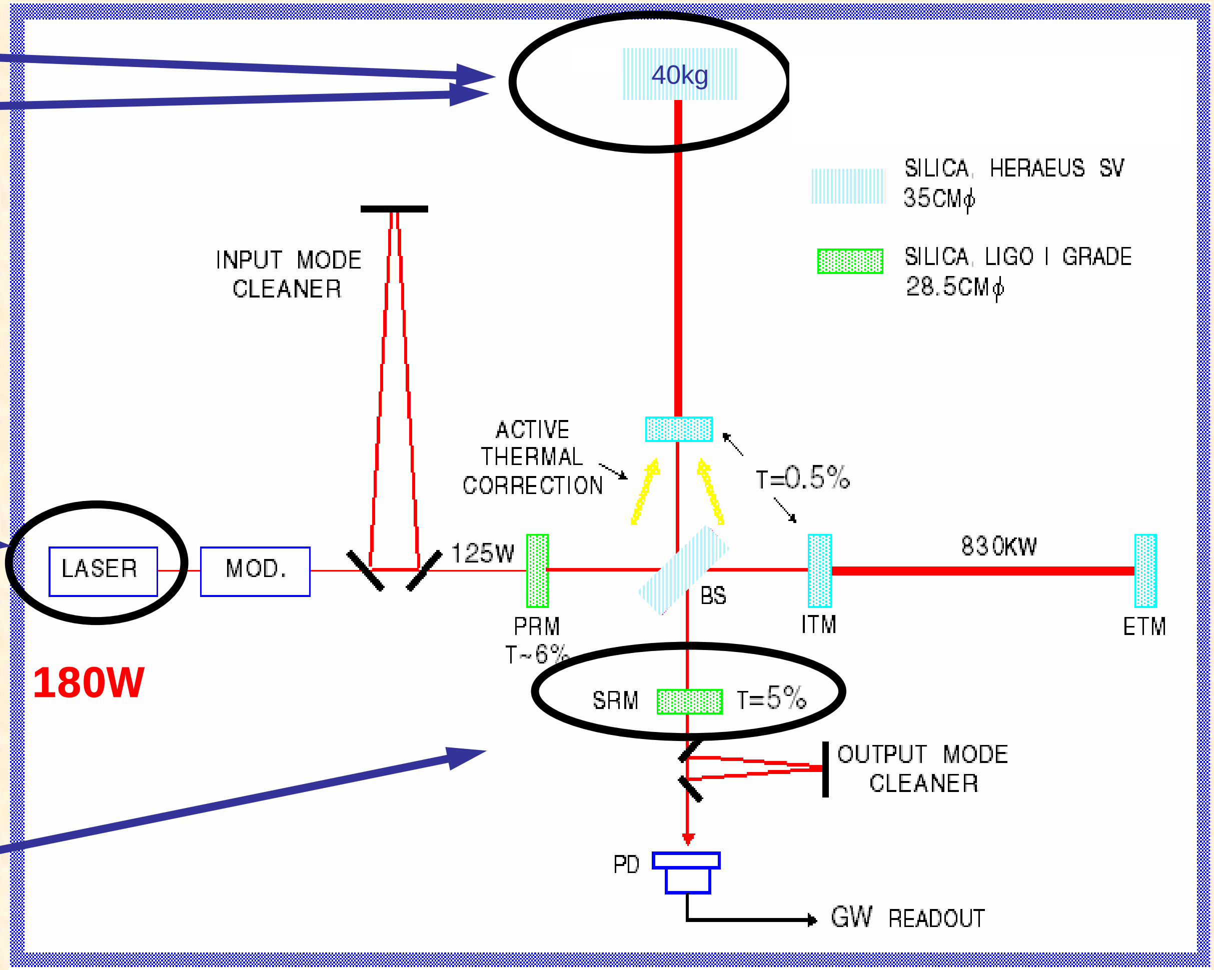
- Make significant improvements in interferometer subsystems including:
  - seismic isolation
  - thermal noise



  - high power lasers

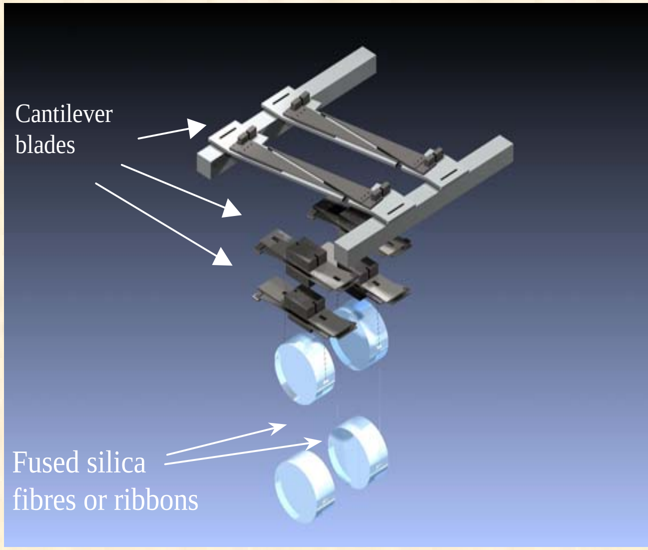


  - tunability of response - signal recycling



Status of Advanced LIGO

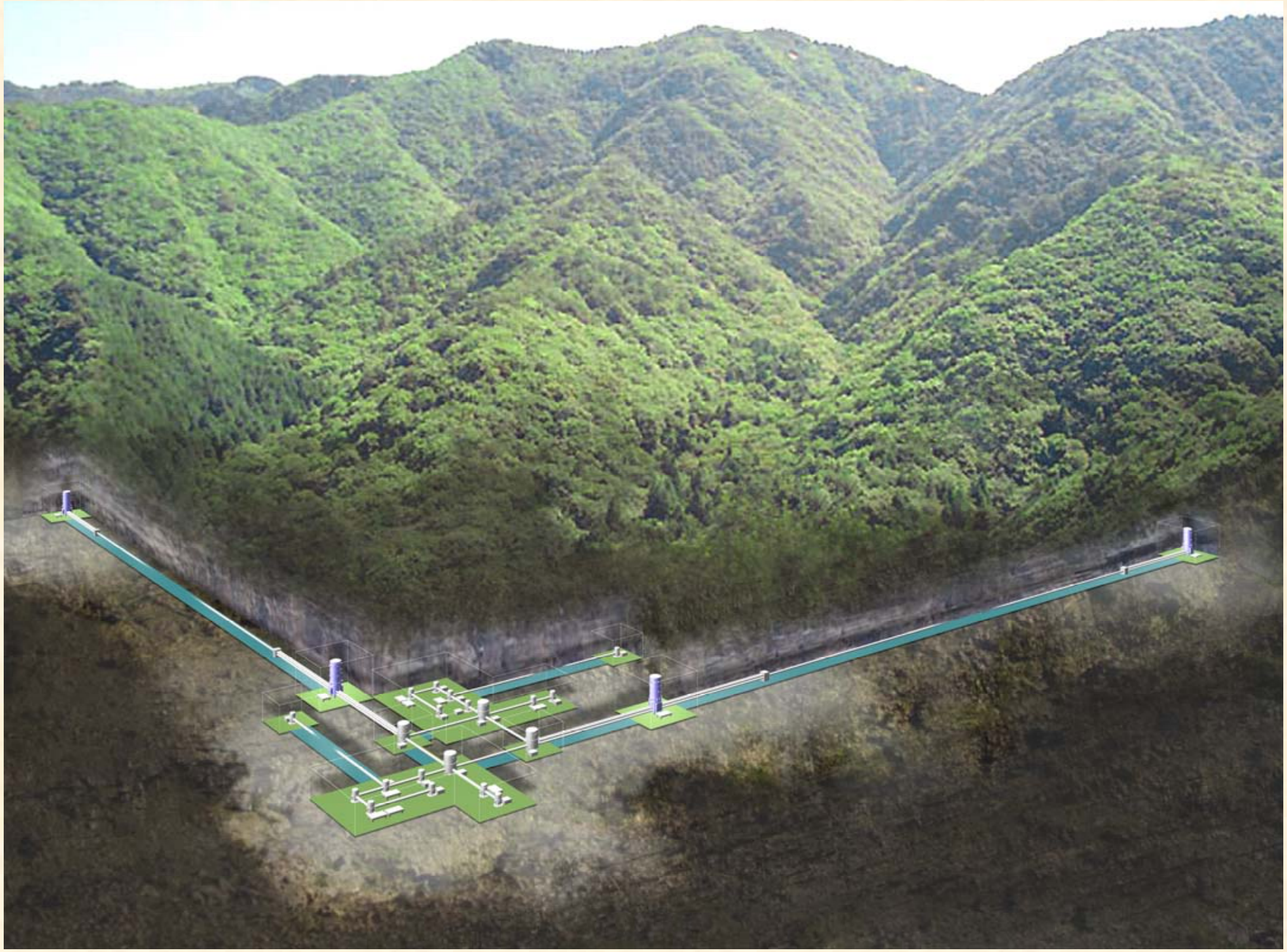
- Fully peer reviewed
- Approved by National Science Board
- Expect start of US construction funds in 2008
  - **UK (PPARC), Germany (MPG) contributions already funded**
- 6 year construction schedule; ~$200M cost
- Funded from NSF account for big projects (MREFC) with operations to be supported by NSF 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

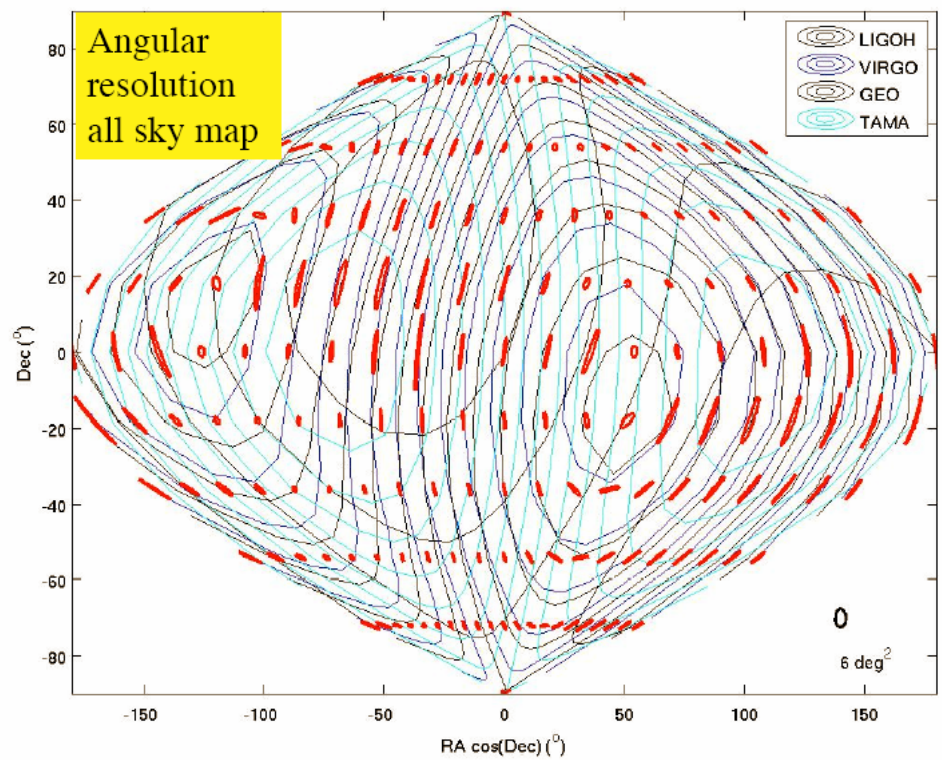
Will use sapphire mirrors cooled to 40K

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

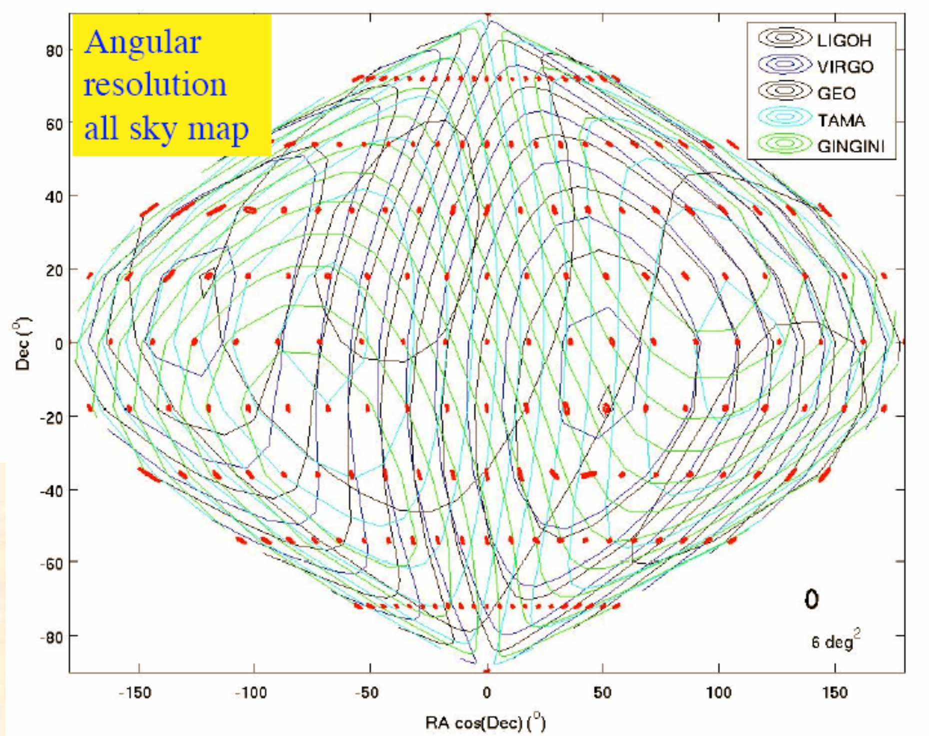
Sensitivity goals very similar to Advanced LIGO and Advanced VIRGO

AIGO – possible detector in Australia

Linqing Wen: Null stream network analysis: without AIGO



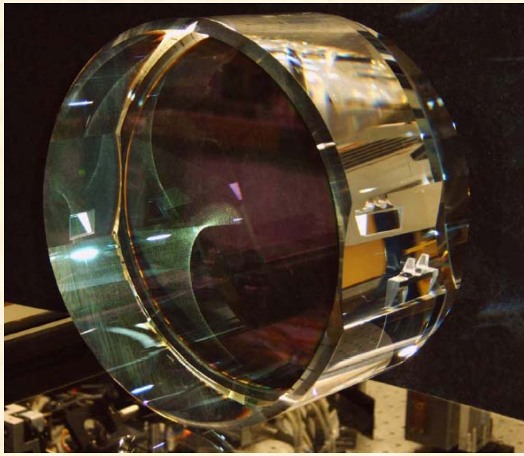
Linqing Wen: Null stream network analysis: ***with*** AIGO



Challenges for Advanced Detectors

- High power lasers
- Seismic Isolation
- Thermal lensing effects in optical components
- Mirror coatings (ultra low optical loss ~0.5 ppm combined with ultra low mechanical loss)
  - Currently multi-layers of tantala and silica are the baseline

Mirror coatings for Advanced Detectors



- thermal noise associated with ultra low loss optical coatings is at a level which is of real significance for the immediate future
- Current research is targeted at reducing coating noise, which is mainly in the Tantala by

•reducing residual mechanical loss of Tantala

or

•finding an alternate high-index material with similar thermo-mechanical properties but lower residual mechanical loss

or

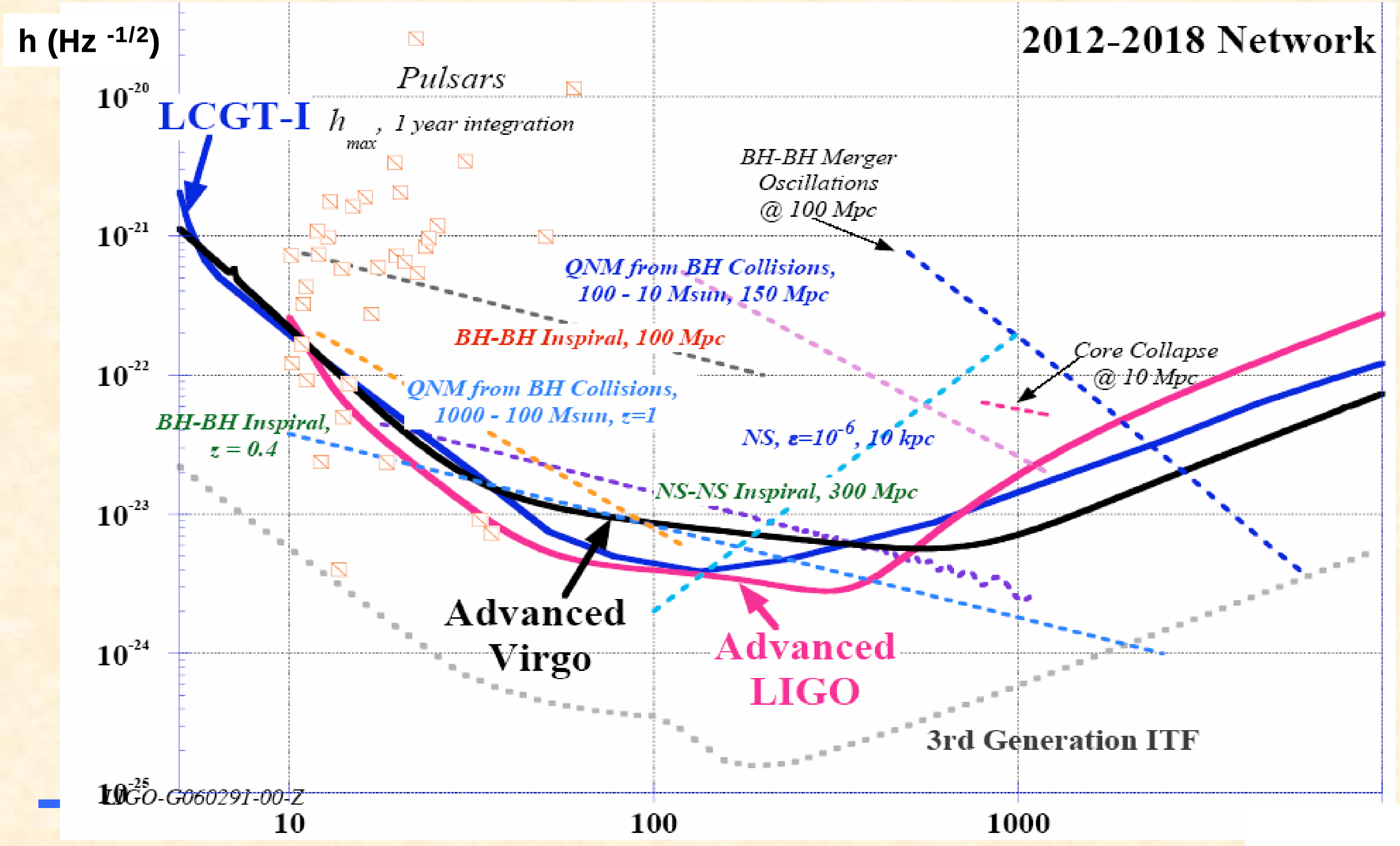
•Modifying multilayer geometry using genetic algorithms (Pinto et al)

and

•Investigating the use of flat-topped beams in the detector cavities thus allowing increased beam size

Our recent work suggests that dissipation in Tantala can be reduced by ~50% by the addition of small amounts of Titania – further research ongoing

Advanced detector network



Frequency (Hz)

The Future of Detectors on Earth

- 3rd generation 2015-20,
  - Possibly built underground, optimised for low frequency sources, with mirrors at liquid helium temperature?
  - Aim for another factor of 10 improvement in sensitivity over advanced detectors
  - Lab research ongoing on necessary instrumentation
  - European groups will propose a design study for the concept of a 3rd generation interferometric detector for the FP7 call of the European Commission

For the Future 1

- Active program of technology research and development for ground based detectors to improve sensitivites:
  - Recognition that Dual recycled interferometers can bypass the Standard Quantum Limit

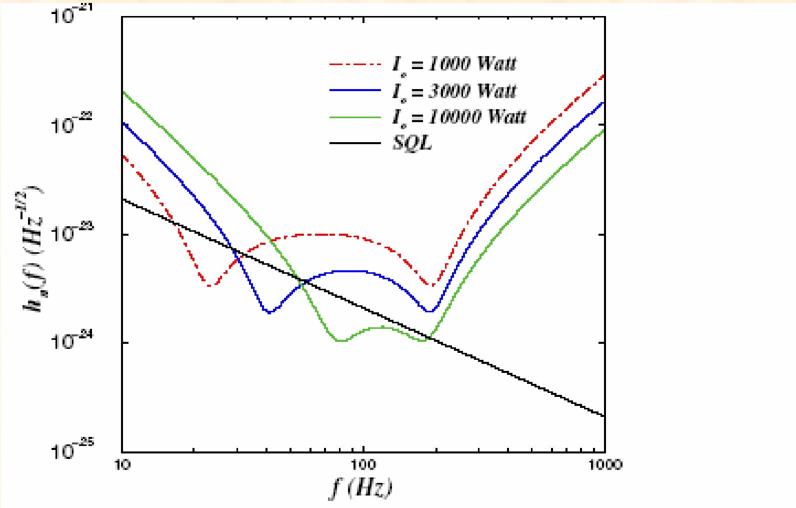


Figure 2. Plot of the square root of the quantum-noise spectral density $h_n \equiv \sqrt{S_h}$ versus frequency, for various choices of the light power at the beamsplitter, having fixed the SR mirror reflectivity and the SR detuning. The SQL line is also shown.

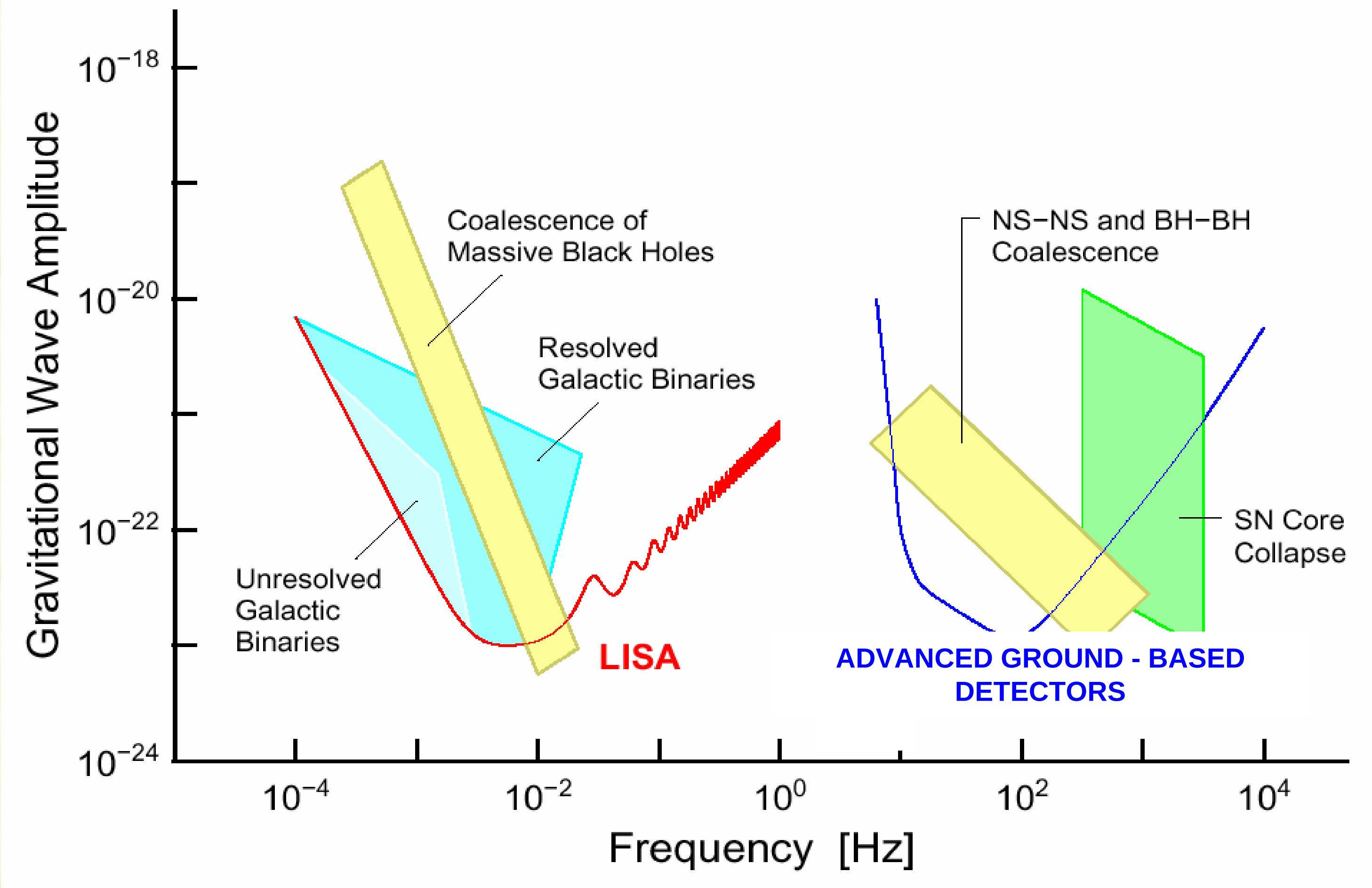
•Use of 'non-classical' light to broaden frequency range

For the Future 2

- Other materials for test masses and suspensions to reduce mechanical loss and help with thermal loading problems
  - Sapphire and silicon both candidates – good thermal conductivity
- All reflective interferometry to further reduce thermal loading
- Heat removal from test mass mirrors at cryogenic temperatures

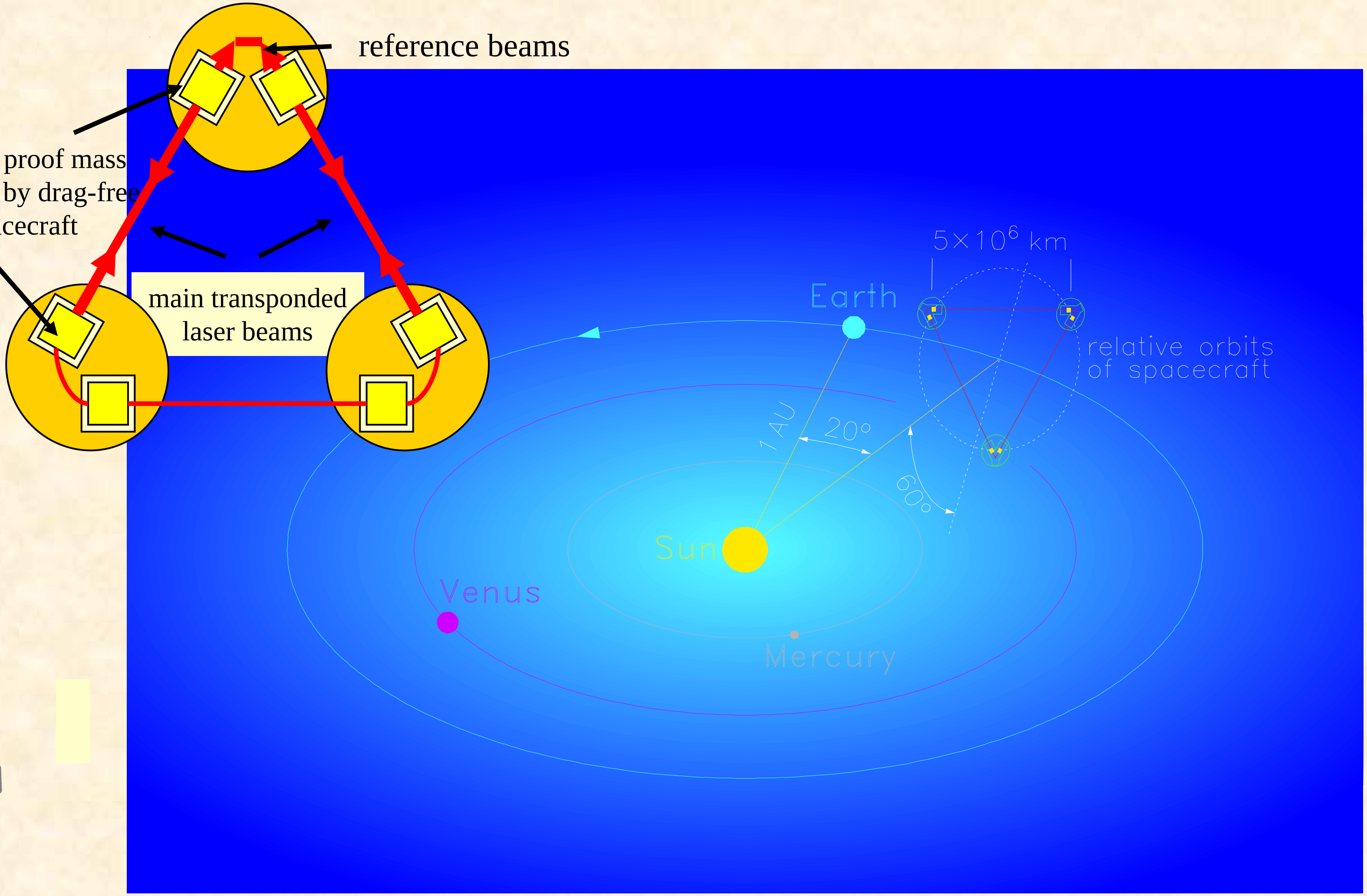
Can we find methods of subtracting gravitational gradient noise?

Sources - reminder



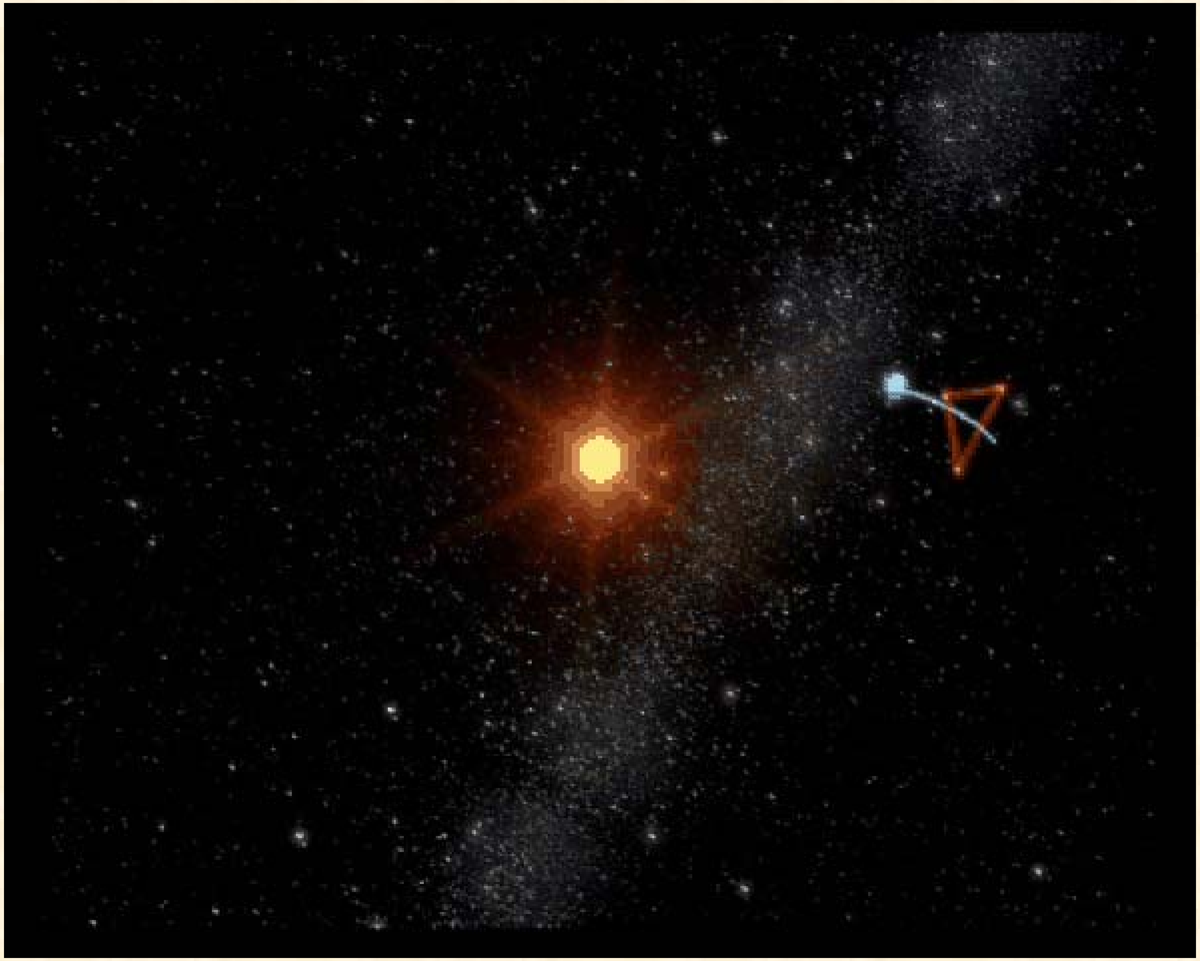
- To see sources at low frequencies – <u>need detector in space</u>

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



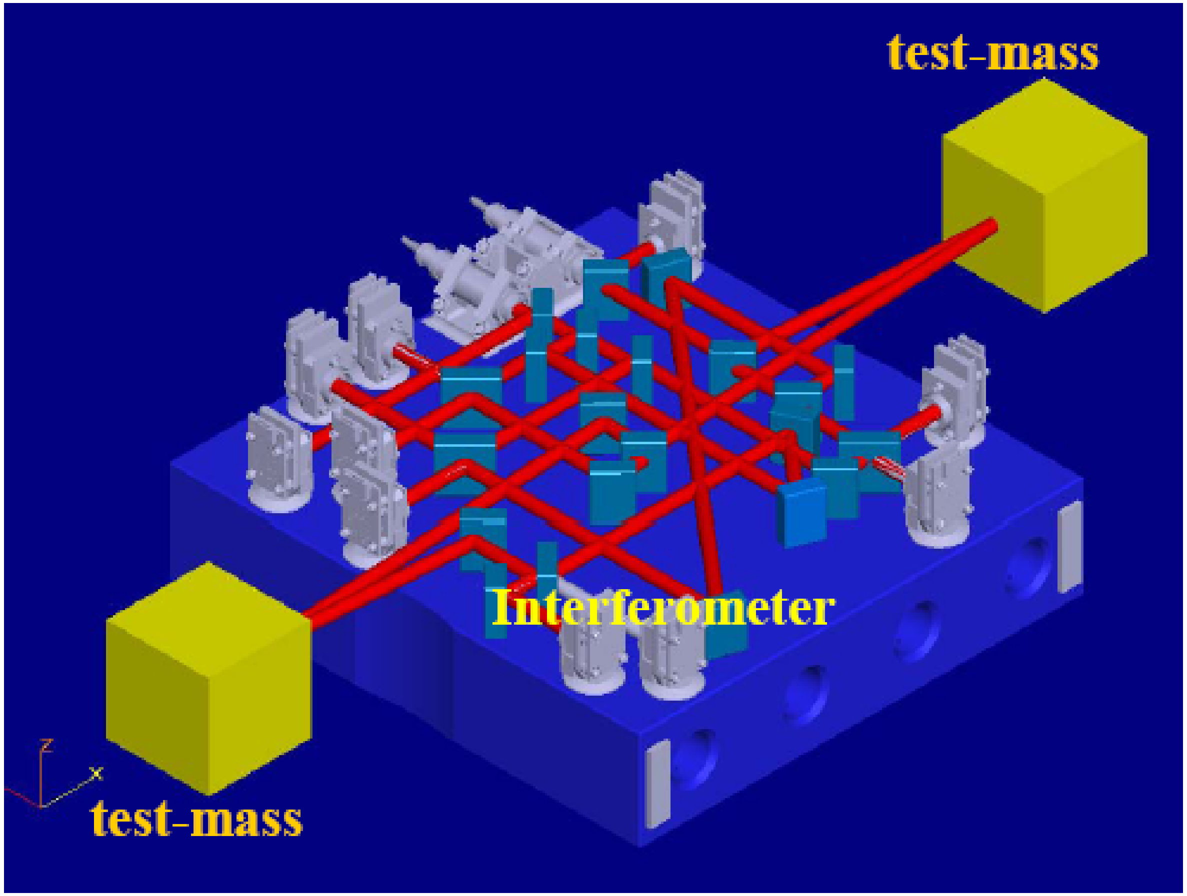
LISA

LISA ORBIT



LISA Pathfinder Concept
– Technology demonstrator for launch in 2009

Demonstration of inertial sensing and 'drag free' control



Mission status

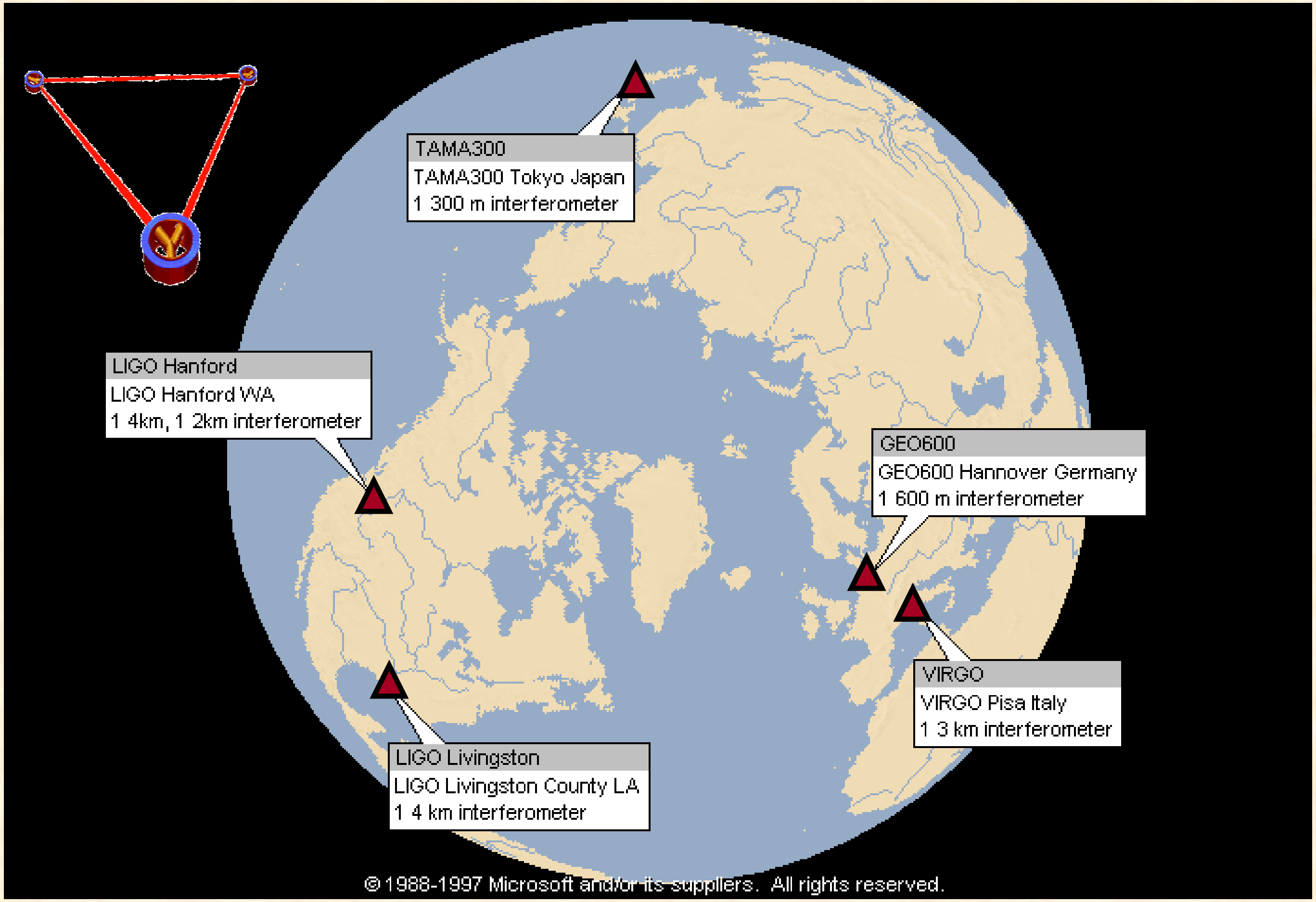
- LISA and demonstrator mission 'LISA Pathfinder' approved joint ESA-NASA missions
- Pathfinder – mission in phase C/D and building hardware
- Launch –late 2009

- 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)
- Decision in the US to be made over ~next year

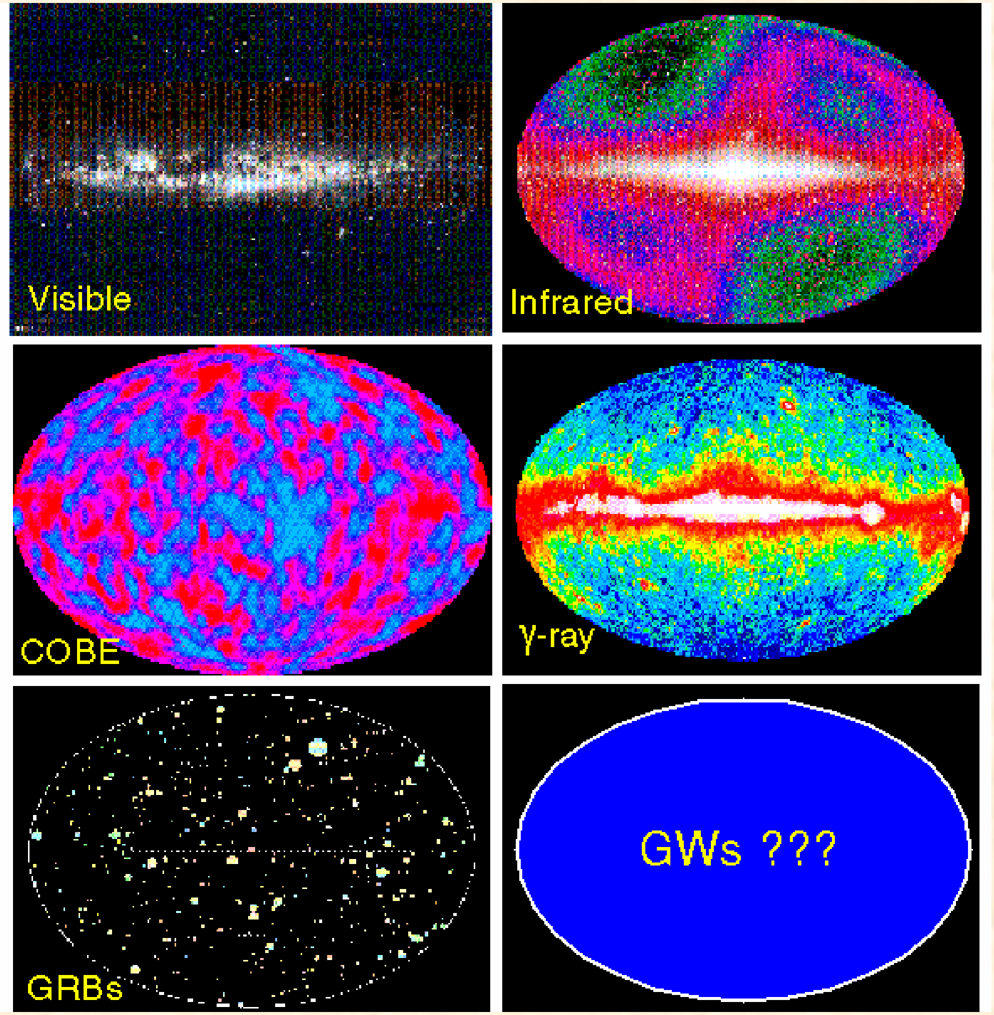
- On the ESA side, final commitment to LISA's implementation will be influenced strongly by the success of LPF
- However work underway before LPF launch to define the LISA mission and prepare the invitation to tender for the implementation phase.

With NASA's selection in FY2007 and ESA's final commitment, LISA expected to enter the implementation phase in 2011, and launch in the 2015–2016 timeframe.

Worldwide Interferometer Network



Gravitational Wave Astronomy



A new way to observe the Universe