The Search for Gravitational Waves

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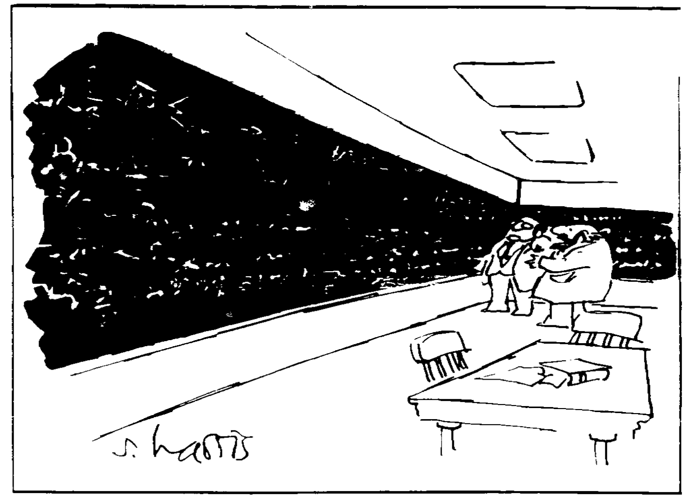
21st August 2007

LIGO-G070603-00-R

‘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 (?)

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

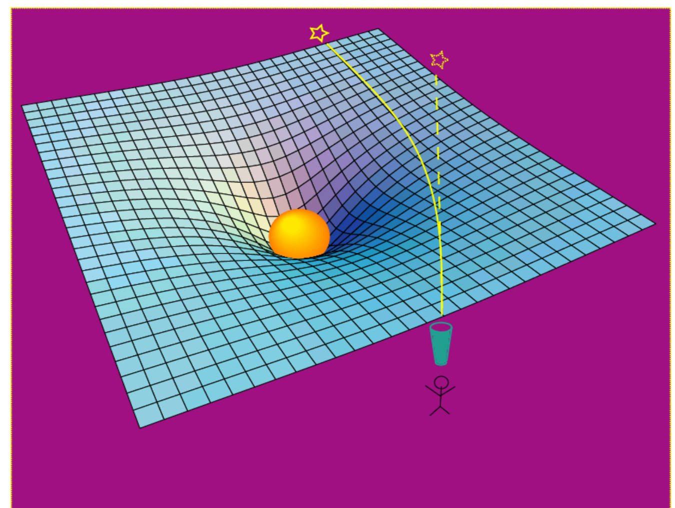


'But this is just a simplistic way of looking at the problem".

- **Gravitational waves**

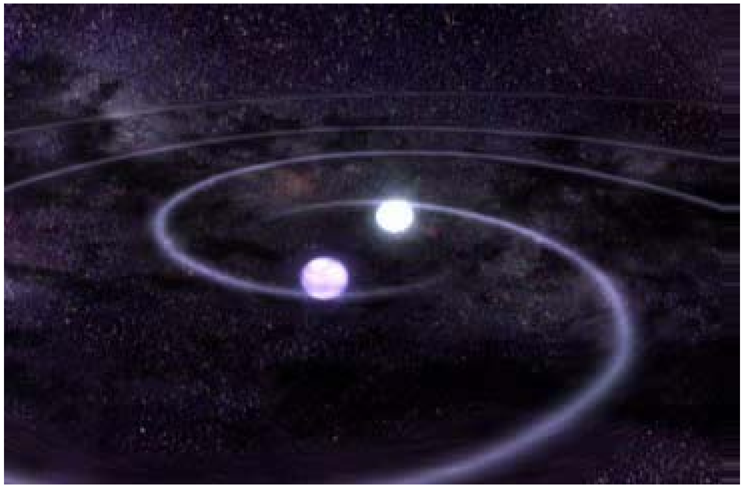
  ‘ripples in the curvature of spacetime’ that carry information about changing gravitational fields – or fluctuating strains in space of amplitude *h* where:

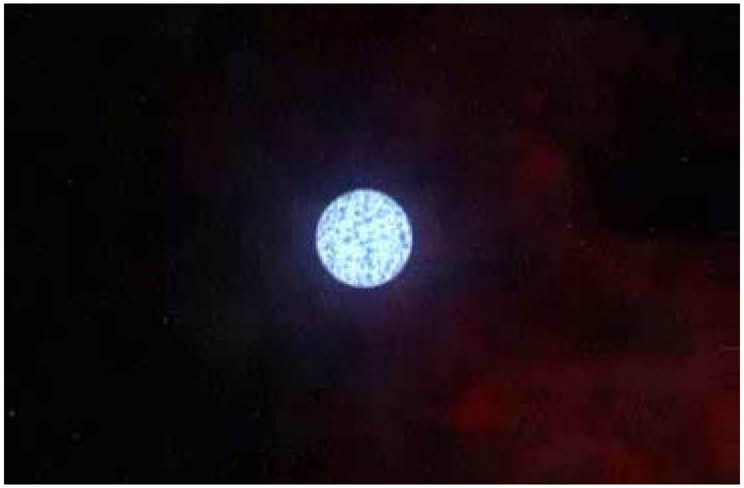
$$h \sim \frac{\Delta L}{L}$$



‘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



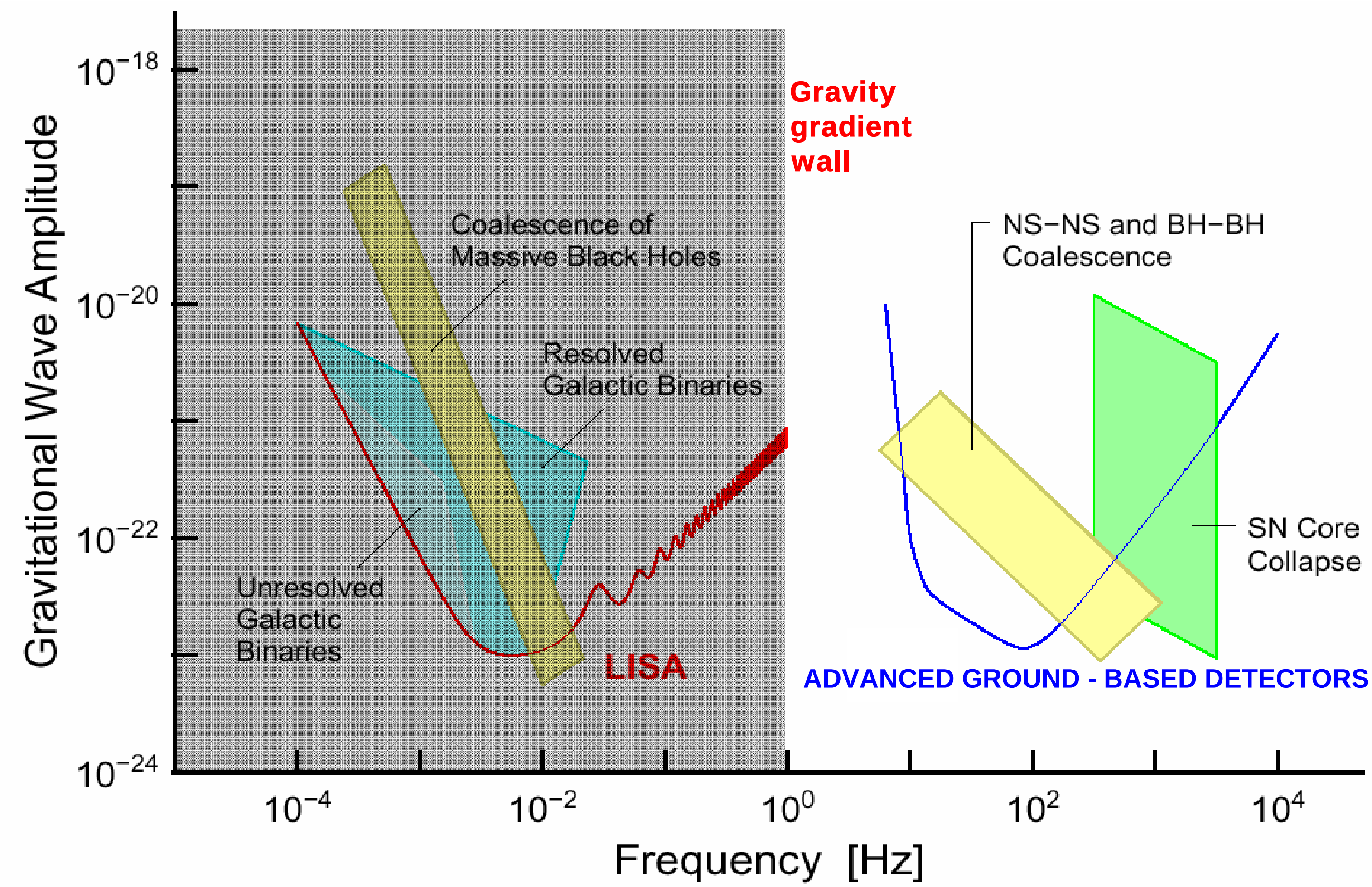


Detection of Gravitational waves – sources and science

- **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?

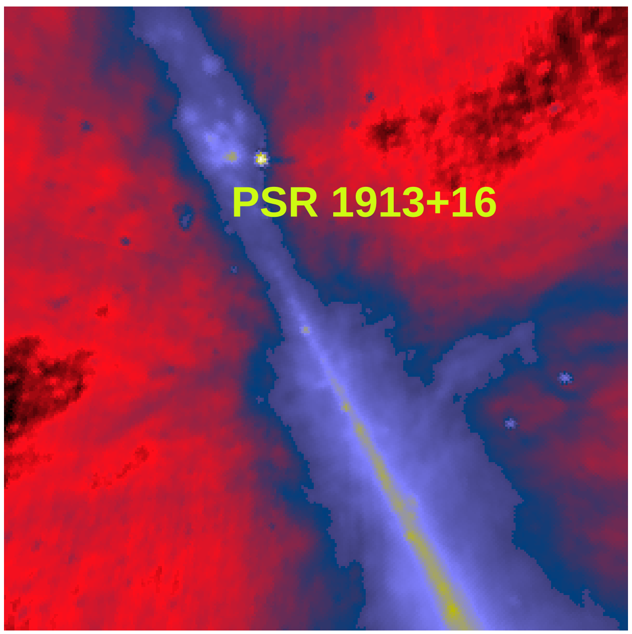
B. Sathyaprakash, 2006

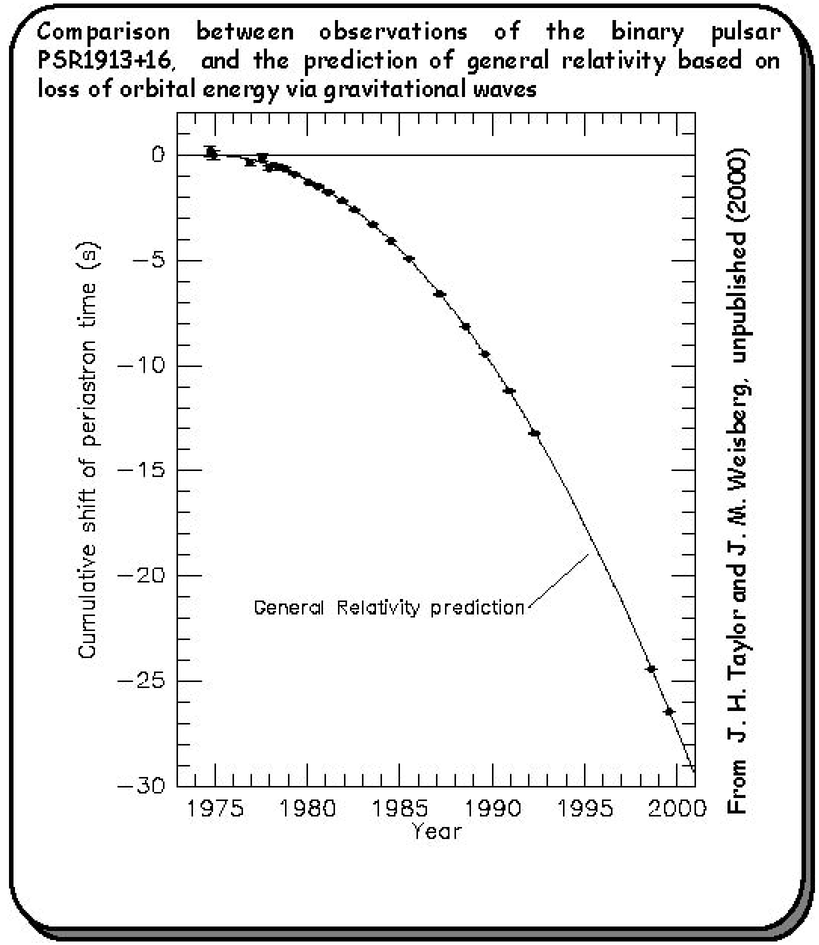
Sources – the gravitational wave spectrum



Evidence for gravitational waves

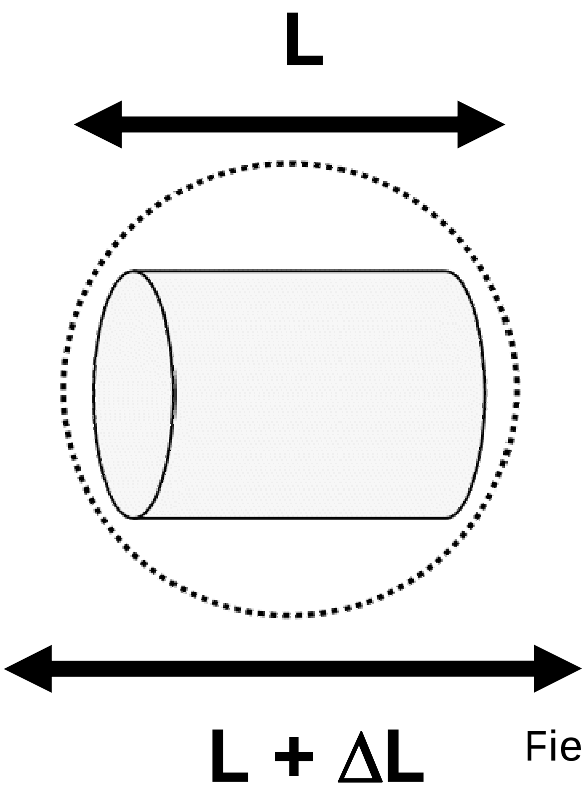
“Indirect” detection of gravitational waves





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

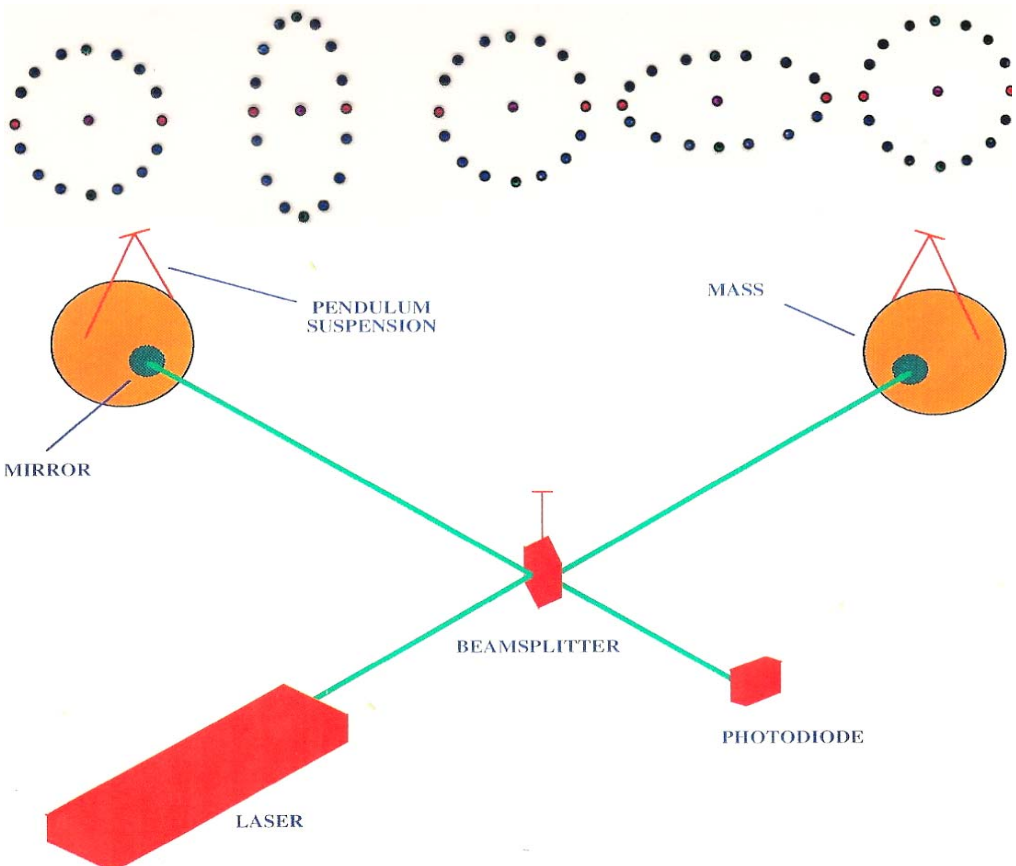
(Received 29 April 1969)

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

Claim of coincident events between detectors at Argonne Lab and Maryland – subsequently shown to be false

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 a trillionth of the wavelength of light (10^{-18} m) over 4km

Principal limitations to sensitivity – ground based detectors

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

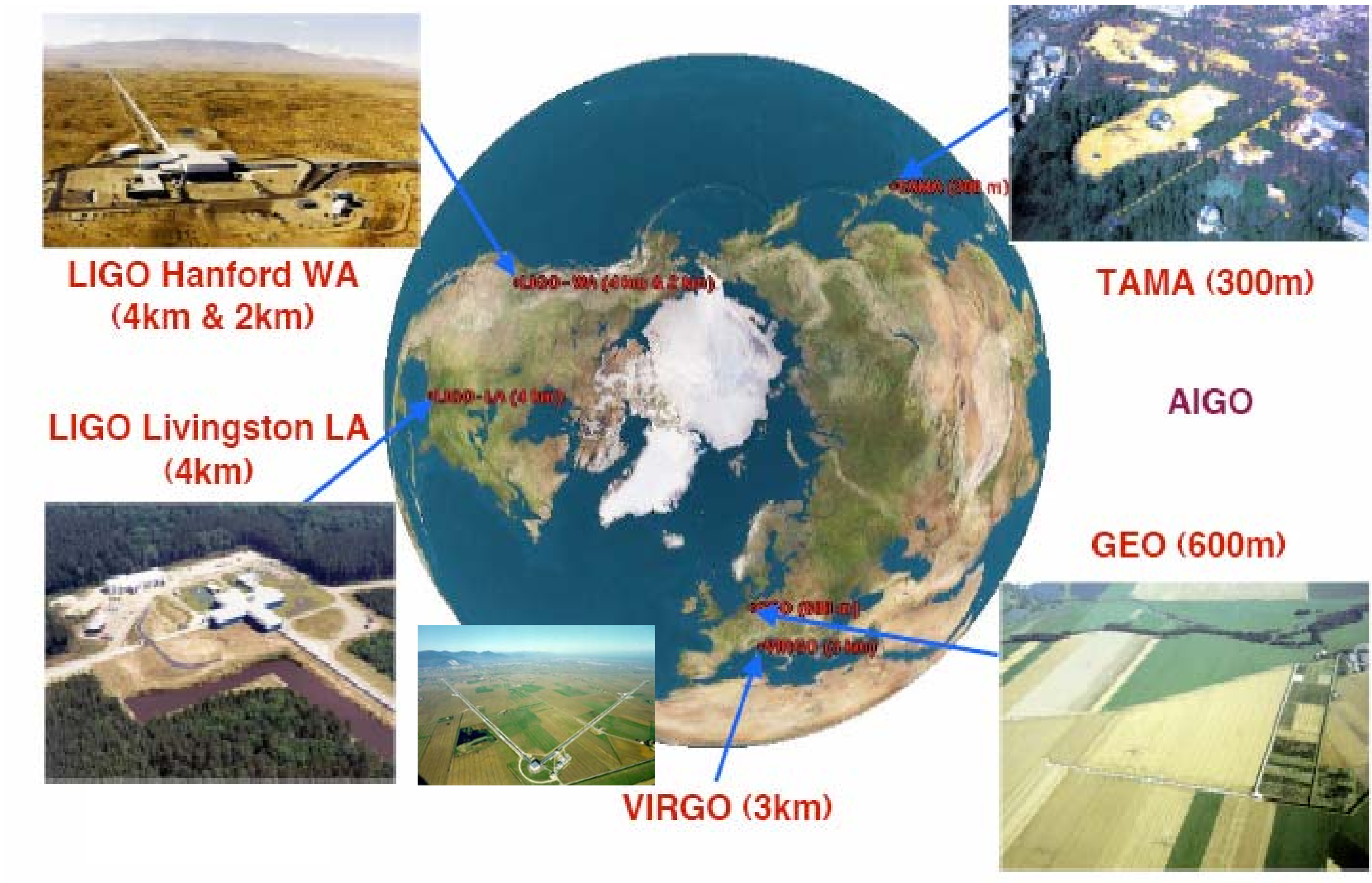
  There is an optimum light power which gives the same limitation expected by application of the Heisenberg Uncertainty Principle - the 'Standard Quantum limit'

- 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**

GW detector network



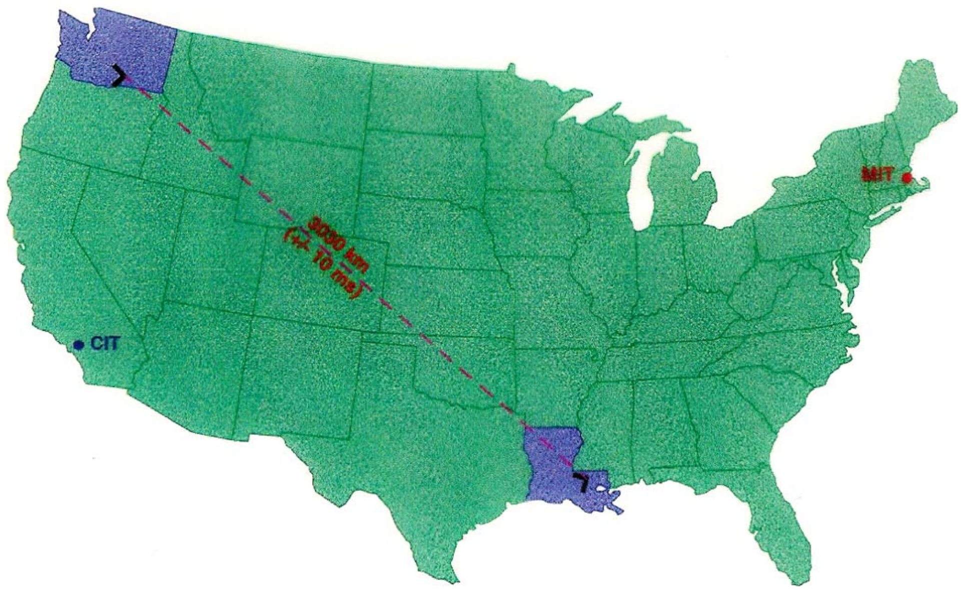
LIGO USA

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

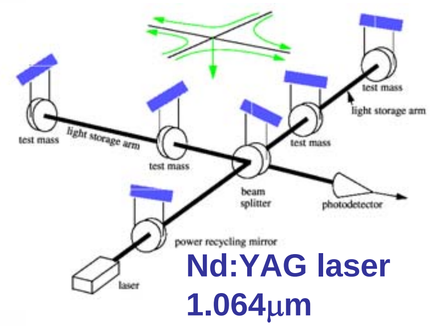


Initial LIGO detectors

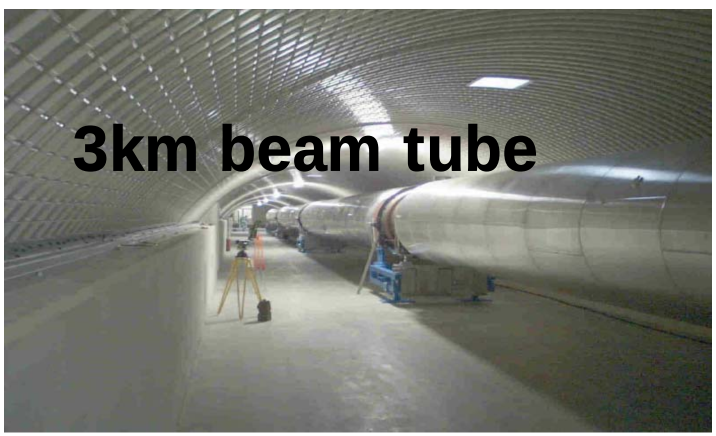
LIGO project (USA)

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

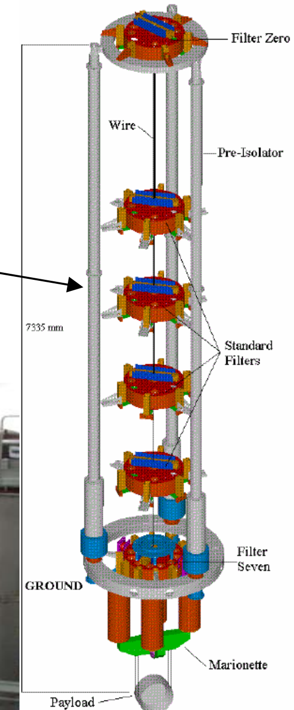
Each detector is based on a 'Fabry-Perot – Michelson'



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

UK-German collaboration:

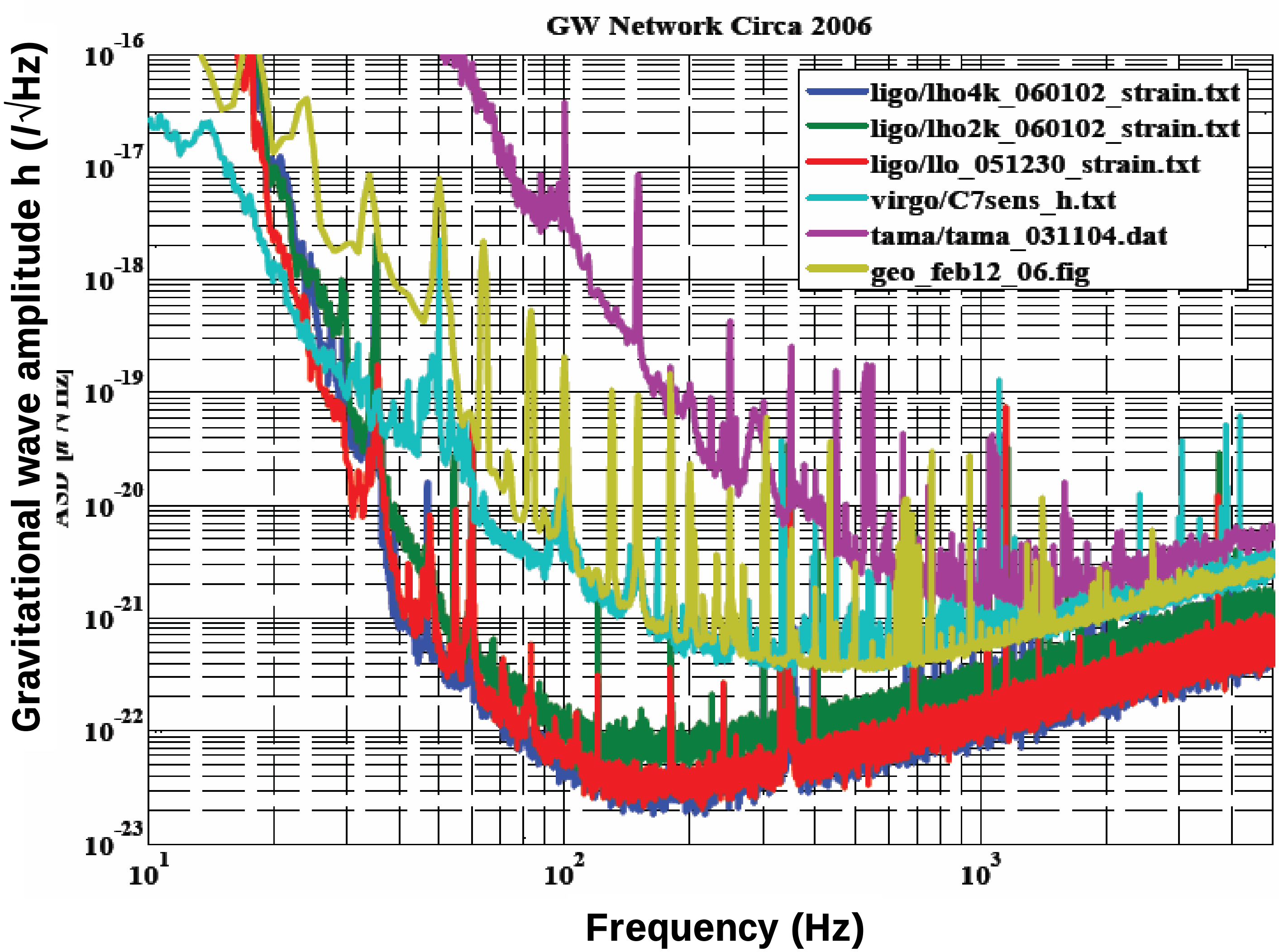
- Univ. of Glasgow:
  - Hough, Rowan, Strain, Ward, Woan, Cagnoli, Heng, Robertson and colleagues
- Cardiff Univ.
  - Sathyaprakash, Schutz, Grishchuk and colleagues
- Univ. of Birmingham
  - Cruise, Vecchio, Freise and colleagues
- AEI Hannover and Golm
  - Danzmann, Schutz,Allen and colleagues

- Colleagues here in Univ. de les Illes Balears

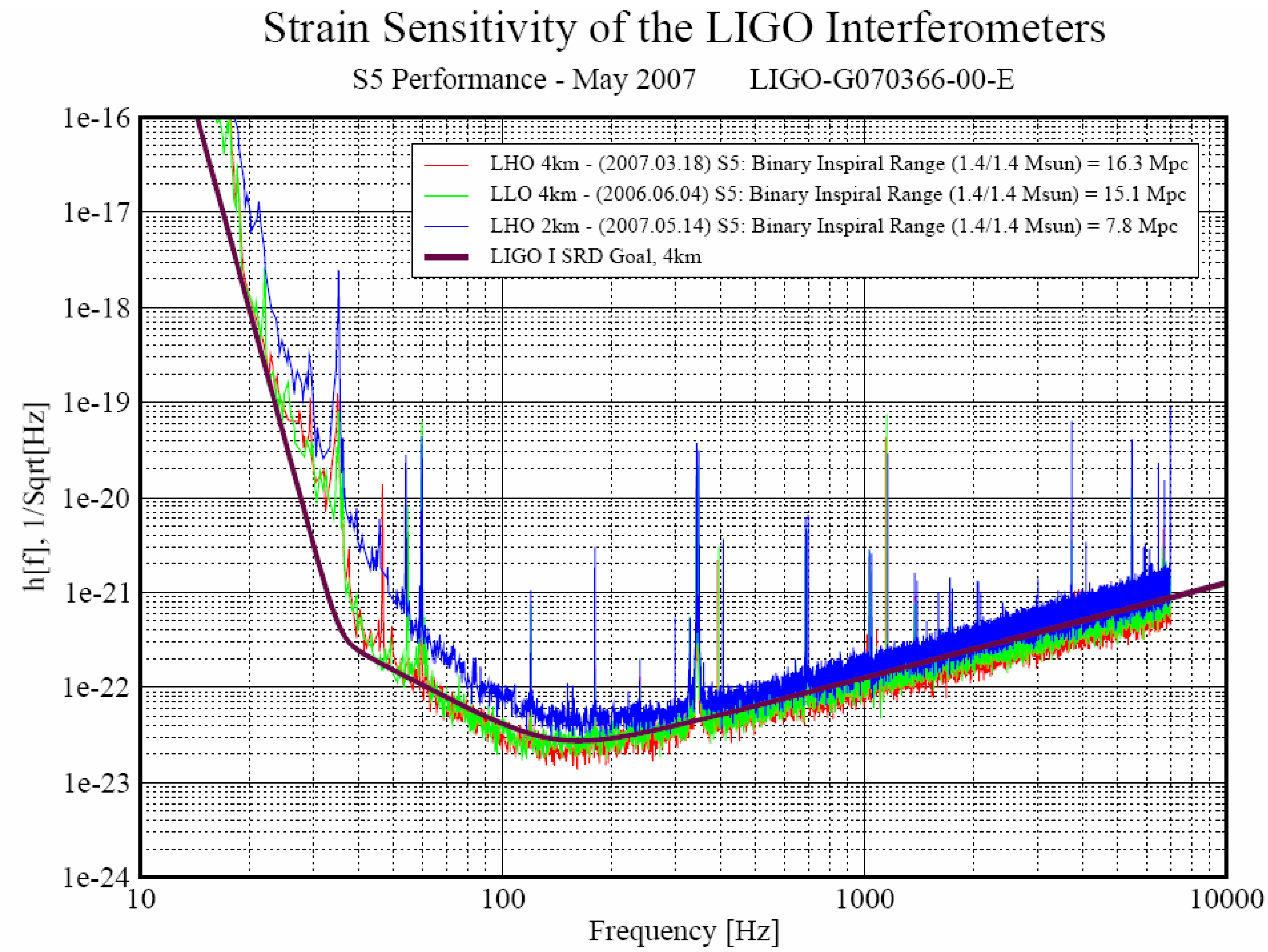
GEO 600

Novel technologies make GEO unique and allow it to run in coincidence with the larger LIGO (and Virgo) instruments

Gravitational wave network sensitivity



LIGO now at design sensitivity



The LIGO Scientific Collaboration (LSC)

- 55 institutions and > 500 people
- The LSC carries out a scientific program of instrument science and data analysis.
- The 3 LIGO interferometers and the GEO600 instrument are analysed as one data set
- LSC & Virgo signed a 'Memorandam of Understanding'
  - Joint data analysis
  - Increased science potential
- Joint run plan
  - Goal of observation of the gravitational sky over the next decade

LIGO Scientific Collaboration

- Australian Consortium for Interferometric Gravitational Astronomy
- The Univ. of Adelaide
- Andrews University
- The Australian National Univ.
- The University of Birmingham
- California Inst. of Technology
- Cardiff University
- Carleton College
- Charles Stuart Univ.
- Columbia University
- Embry Riddle Aeronautical Univ.
- Eötvös Loránd University
- University of Florida
- German/British Collaboration for the Detection of Gravitational Waves
- University of Glasgow
- Goddard Space Flight Center
- Leibniz Universität Hannover
- Hobart & William Smith Colleges
- Inst. of Applied Physics of the Russian Academy of Sciences
- Polish Academy of Sciences
- India Inter-University Centre for Astronomy and Astrophysics
- Louisiana State University
- Louisiana Tech University
- Loyola University New Orleans
- University of Maryland
- Max Planck Institute for Gravitational Physics
- University of Michigan
- Massachusetts Inst. of Technology
- Monash University
- Montana State University
- Moscow State University
- National Astronomical Observatory of Japan
- Northwestern University
- University of Oregon
- Pennsylvania State University
- Rochester Inst. of Technology
- Rutherford Appleton Lab
- University of Rochester
- San Jose State University
- Univ. of Sannio at Benevento, and Univ. of Salerno
- University of Sheffield
- University of Southampton
- Southeastern Louisiana Univ.
- Southern Univ. and A&M College
- Stanford University
- University of Strathclyde
- Syracuse University
- Univ. of Texas at Austin
- Univ. of Texas at Brownsville
- Trinity University
- Universitat de les Illes Balears
- Univ. of Massachusetts Amherst
- University of Western Australia
- Univ. of Wisconsin-Milwaukee
- Washington State University
- University of Washington

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 (including GRBs)
  - Stochastic background
- **>19 major papers published or in press since 2004**
  (work from a collaboration (LSC) of more than 500 scientists)

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

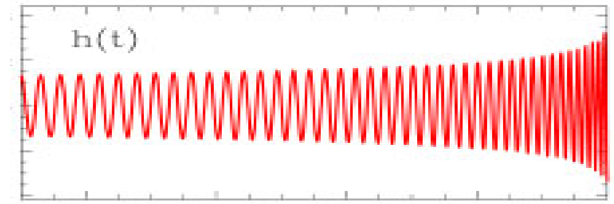
GEO joined initially for overnight data taking in Jan 06, then 24/7 till Oct 06, then interleaved with commissioning

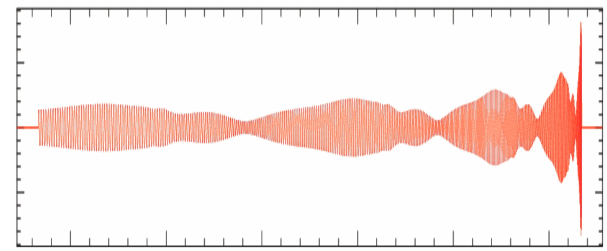
Virgo joined May 18th 2007

GW searches: binary systems

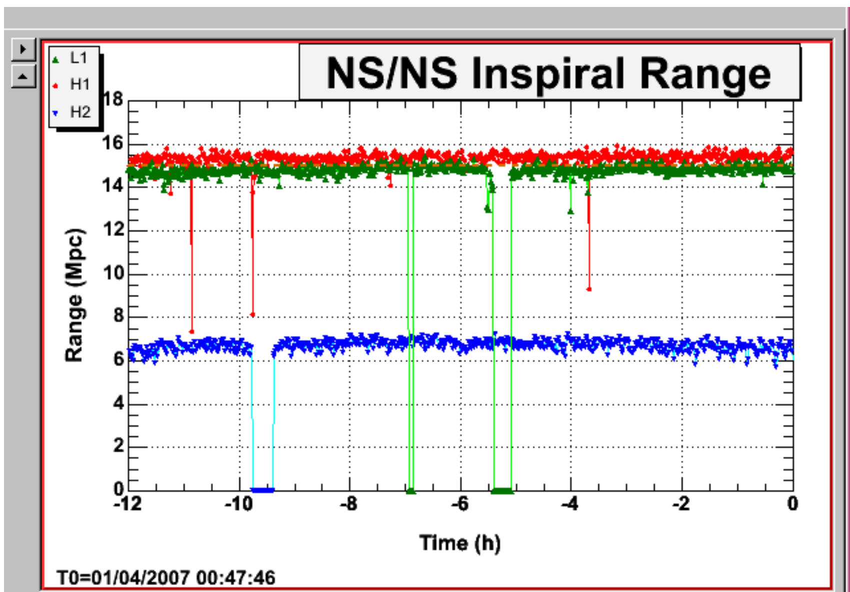
Use calculated templates for inspiral phase ("chirp") with optimal filtering.

Waveform parameters:
distance, orientation, position,
m_1, m_2, t_0, ϕ (+ spin, ending cycles …)





We can translate the "noise" into distances surveyed.
We monitor this in the control room for *binary neutron stars*:

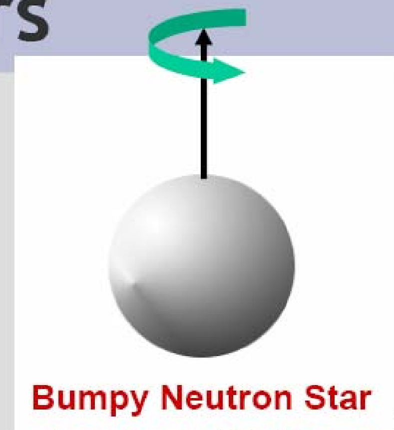


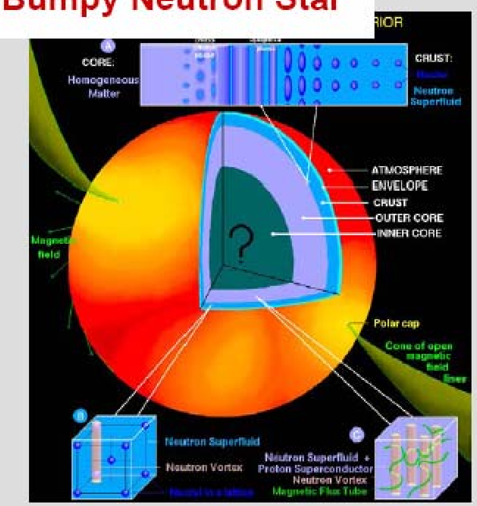
If system is optimally located and oriented, we can see even further: we are surveying hundreds of galaxies

GW Searches: Pulsars

Gravitational waves from neutron stars

- Rapidly spinning neutron stars provide a potential source of continuous gravitational waves
- To emit gravitational waves they must have some degree of non-axisymmetry
  - Triaxial deformation due to elastic stresses or magnetic fields
  - Free precession about axis
  - Fluid modes e.g. r-modes
- Size of distortions can reveal information about the neutron star equation of state





www.astroscu.unam.mx/neutrones/NS-Picture/NStar/NStar_lS.gif

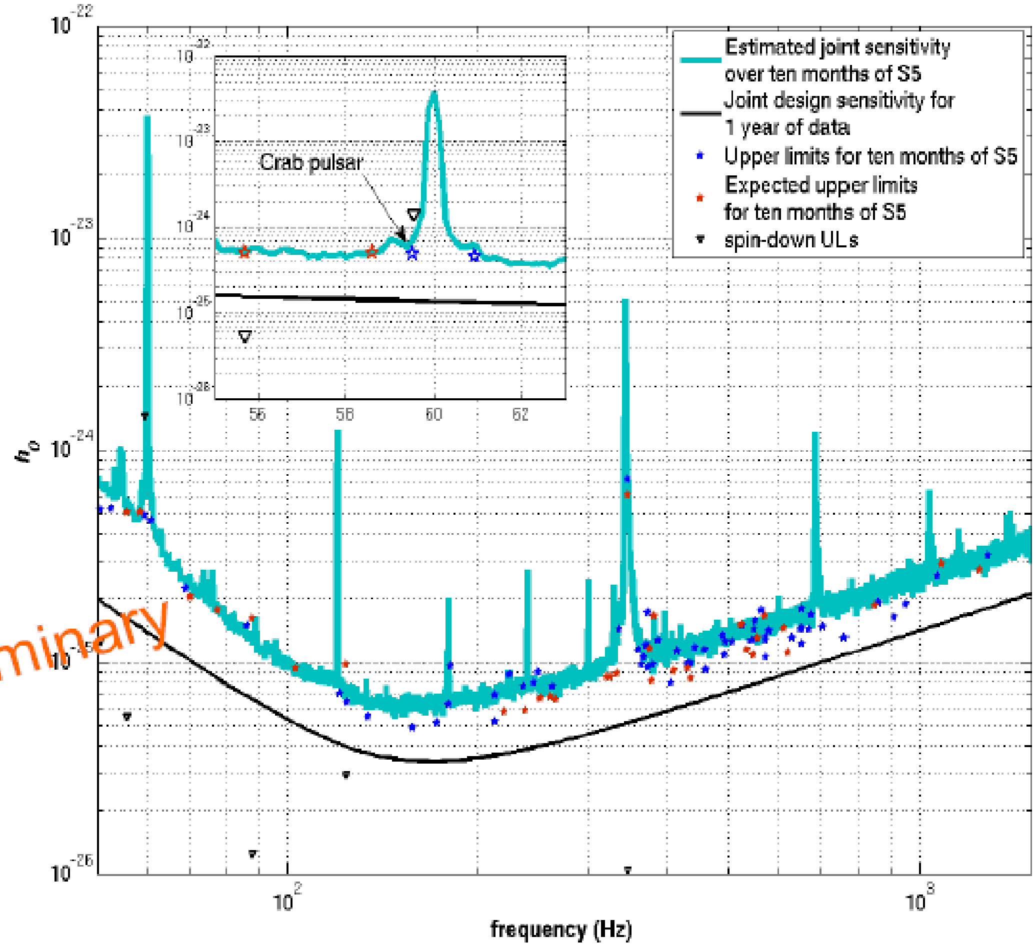
Search for known pulsars- preliminary

- Joint 95% upper limits for 97 pulsars using ~10 months of the LIGO S5 run. Results are overlaid on the estimated median sensitivity of this search.

For 32 of the pulsars we give the *expected* sensitivity upper limit (red stars) due to uncertainties in the pulsar parameters .

Pulsar timings provided by the Jodrell Bank pulsar group

Lowest GW strain upper limit: **PSR J1802-2124** (f_{gw} = 158.1 Hz, r = 3.3 kpc) $\mathbf{h_0 < 4.9\times10^{-26}}$ Lowest ellipticity upper limit: **PSR J2124-3358** (f_{gw} = 405.6 Hz, r = 0.25 kpc) $\varepsilon < \mathbf{1.1\times10^{-7}}$



Planned detector evolution

- Detection with the initial instruments is possible but –not- guaranteed

- Thus plans for improving the sensitivity are in place
  - ‘Enhanced’ then ‘Advanced’ LIGO
  - ‘Virgo +’ then ‘Advanced’ Virgo
  - GEO-HF

- These upgrades will be interleaved with periods of data taking

- Sensitivity improvements are broadly aimed at reducing
  - Photoelectron shot noise
  - Thermal noise
  - Seismic noise

For the near future :

- LIGO and Virgo plan
  - 2007 - 2009 incremental detector enhancements

    Enhanced LIGO:

    higher laser power, better optical readout, higher power optics -> x 2 enhancement in sensitivity

    VIRGO +

    higher laser power, and silica suspensions (?) to reduce thermal noise, better optical readout -> x ? improvement

    Advanced LIGO

  - 2009 - 2011 subsequent science operation

LIGO

Plans for Advanced detectors

To move from detection to astronomy the current detector network will upgrade to a series of 'Advanced' instruments with sensitivity improvements of 10 to 15 allowing potential BH-BH coalescence rates of up to 500 per year to be observed.

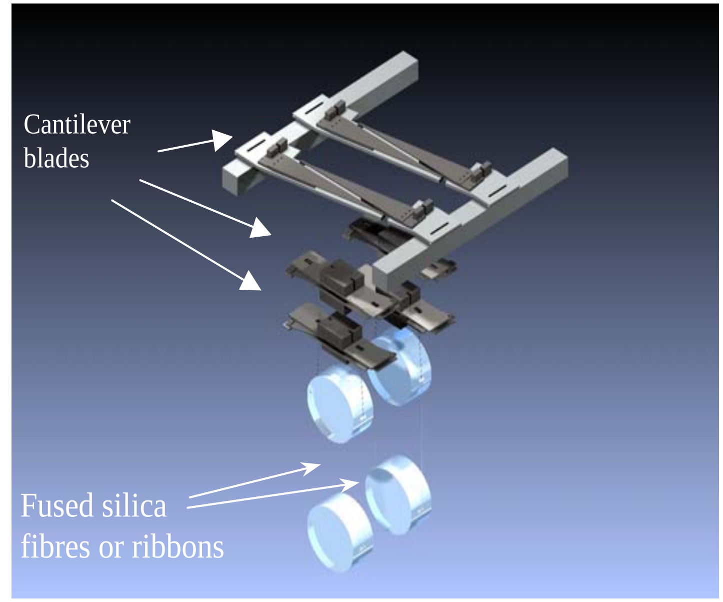
- Advanced LIGO
- Advanced Virgo
- GEO-HF
- Large Cryogenic Gravitational Telescope (LCGT)

Advanced LIGO

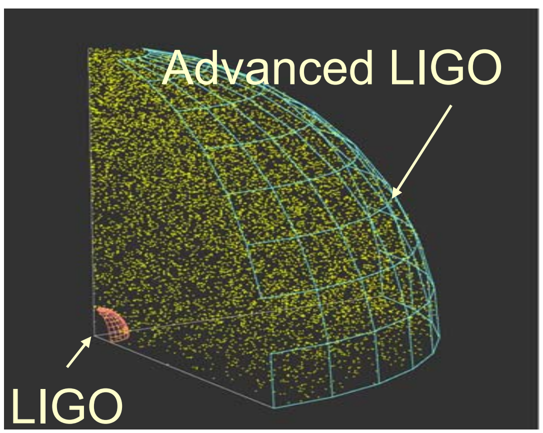
Achieve x10 to x15 sensitivity improvement:

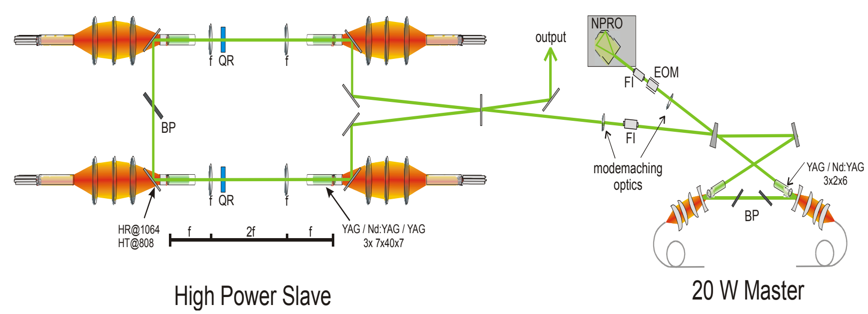
GEO technology being applied to LIGO

- silica suspensions
- more sophisticated interferometry
- more powerful lasers from our colleagues in Hannover



Plus active isolation, high power optics from US groups





Status of Advanced LIGO

- R&D funded in US, UK and Germany
- Capital contributions funded in UK and Germany (~ £8M from PPARC/STFC and an equivalent amount from MPG)
- Advanced LIGO in President's budget for 2008 to allow re-construction on site starting 2011
- Full installation and initial operation of 3 interferometers by 2014

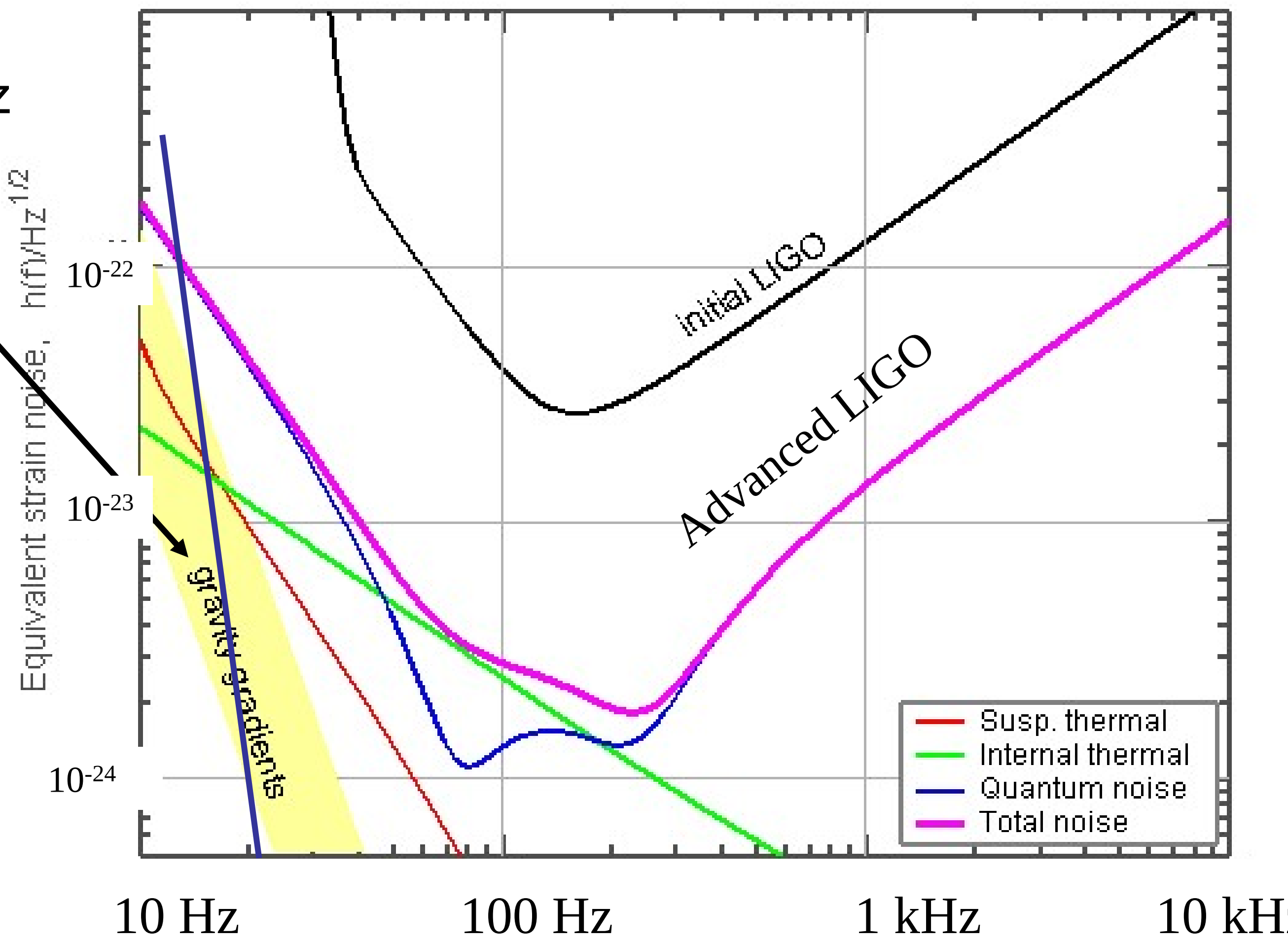
Advanced LIGO is making excellent progress

Advanced LIGO: President Requests FY2008 Construction Start

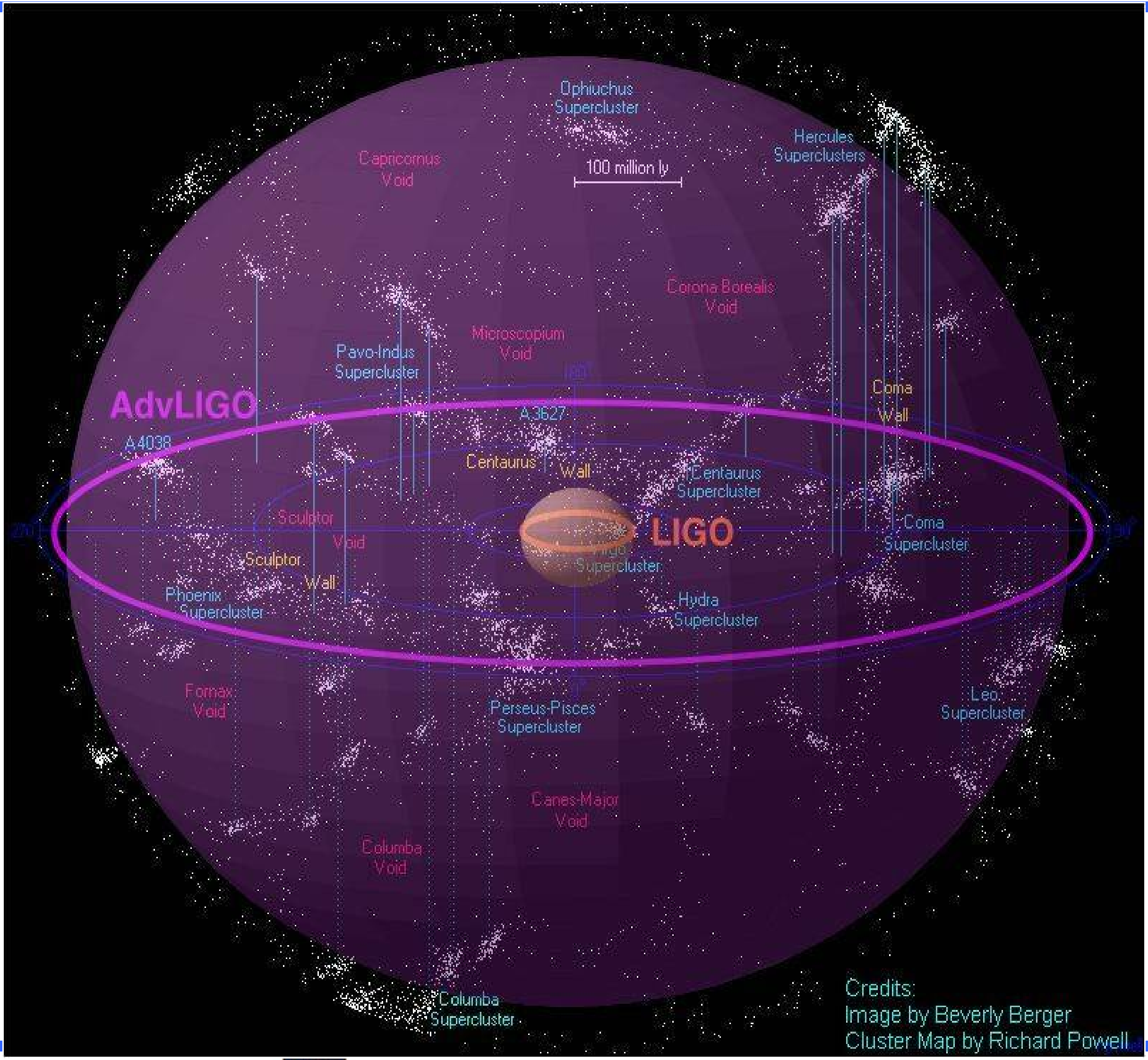
Seismic ‘cutoff’ at 10 Hz

Quantum noise

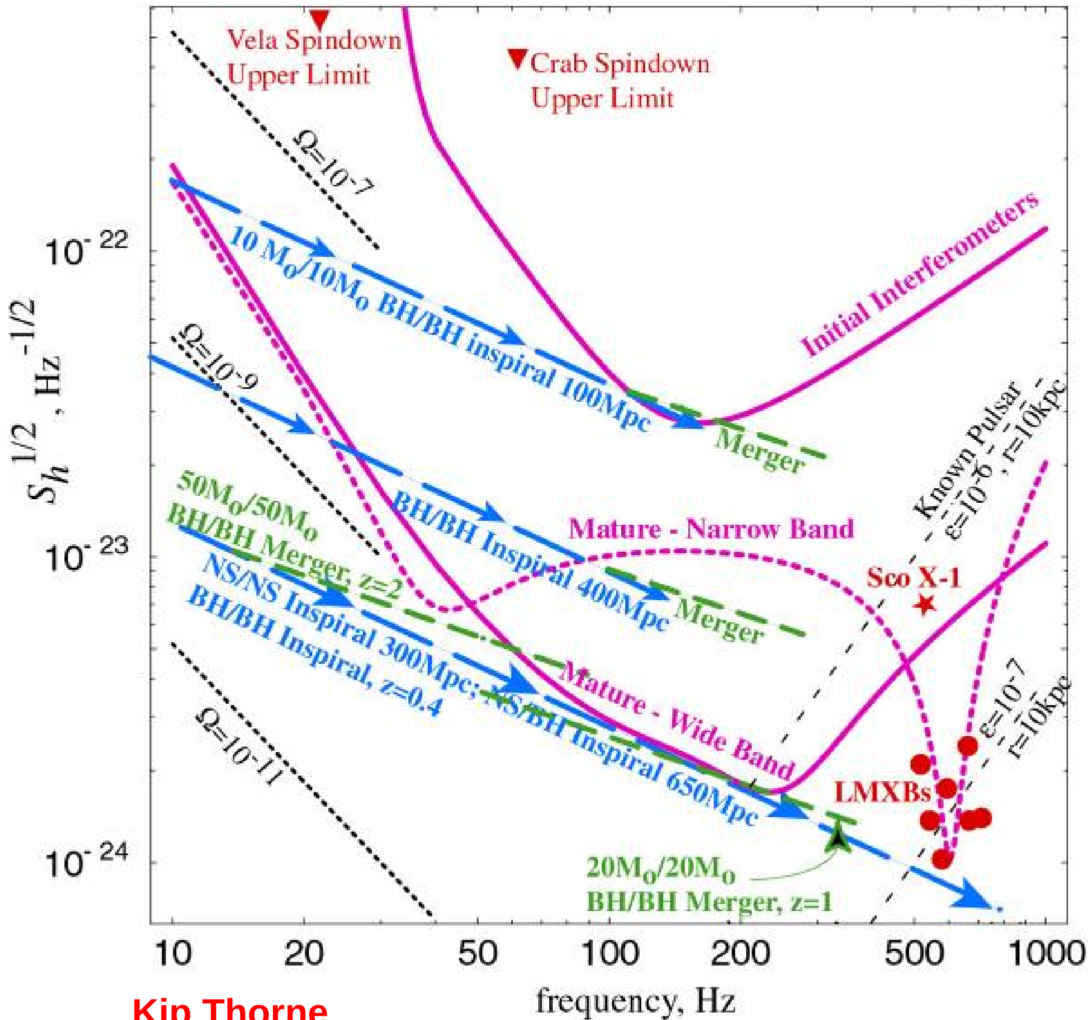
(shot noise + radiation pressure) dominates at most frequencies



Range of Advanced LIGO for 1.4 M_{o} binary neutron star inspirals



Science Potential of Advanced LIGO



Kip Thorne

Binary neutron stars:

From ~20 Mpc to ~350 Mpc

From 1/100y(<1/3y) to 40/y(<5/d)

Binary black holes:

From ~100Mpc to z=2

Known pulsars:

From $\varepsilon = 3\times10^{-6}$ to 2×10^{-8}

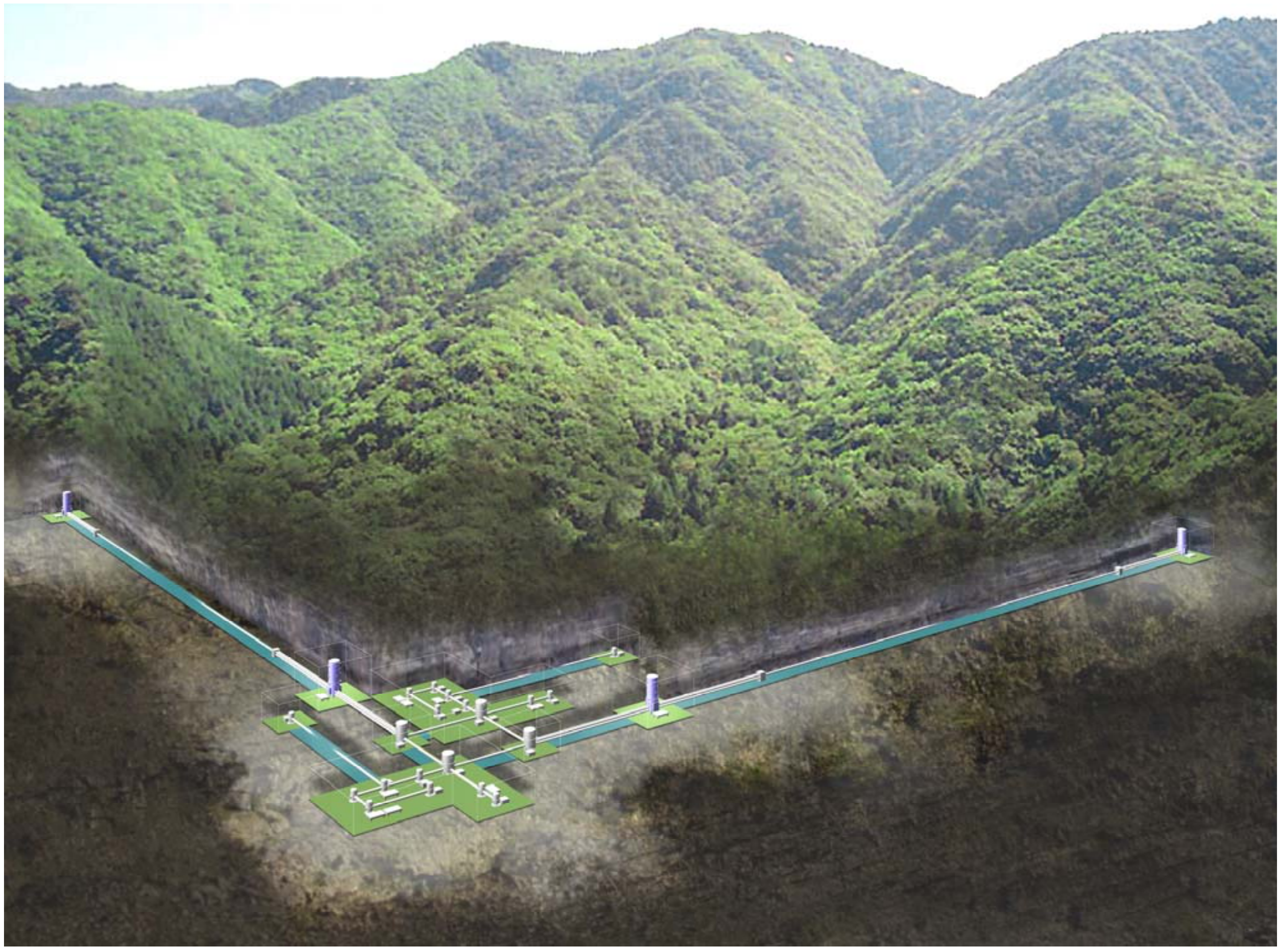
Stochastic background:

From Ω_{GW} ~3×10^{-6} to ~3×10^{-9}

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

Not yet funded – proposal still being developed

Sensitivity goals very similar to Advanced LIGO and Advanced VIRGO

GEO-HF

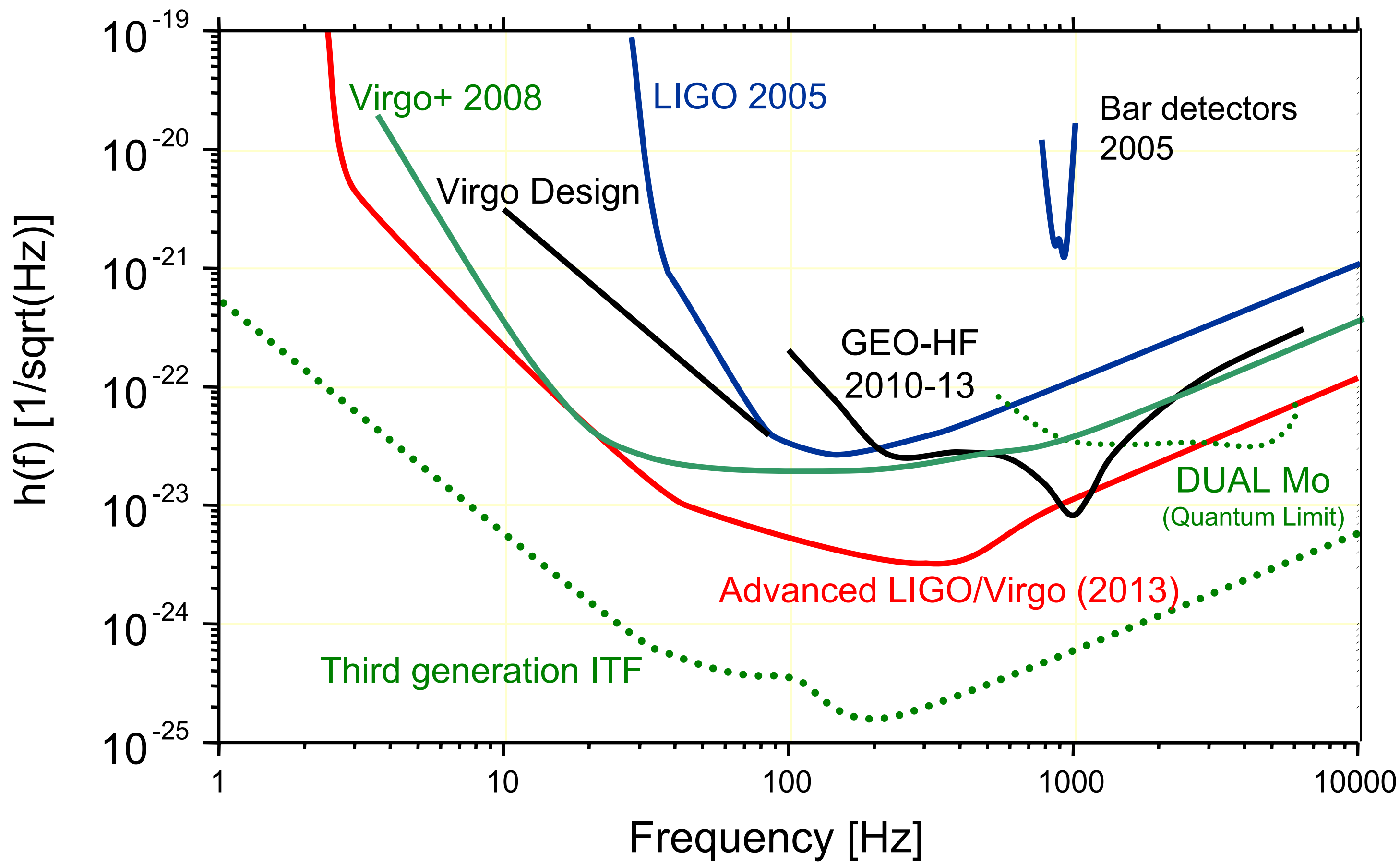
- Provide scientifically interesting data with the GEO instrument until 2014, providing coverage when other detectors are offline for major upgrading
  - optimised at low frequencies for network analysis or
  - optimised for high frequency sources
- Perform incremental upgrades and tests towards 'third generation' detectors
  - technologies, materials and optical schemes
- Timeline: starting upgrading after extended data taking 2007/2009

Challenges of the field for 3rd Generation

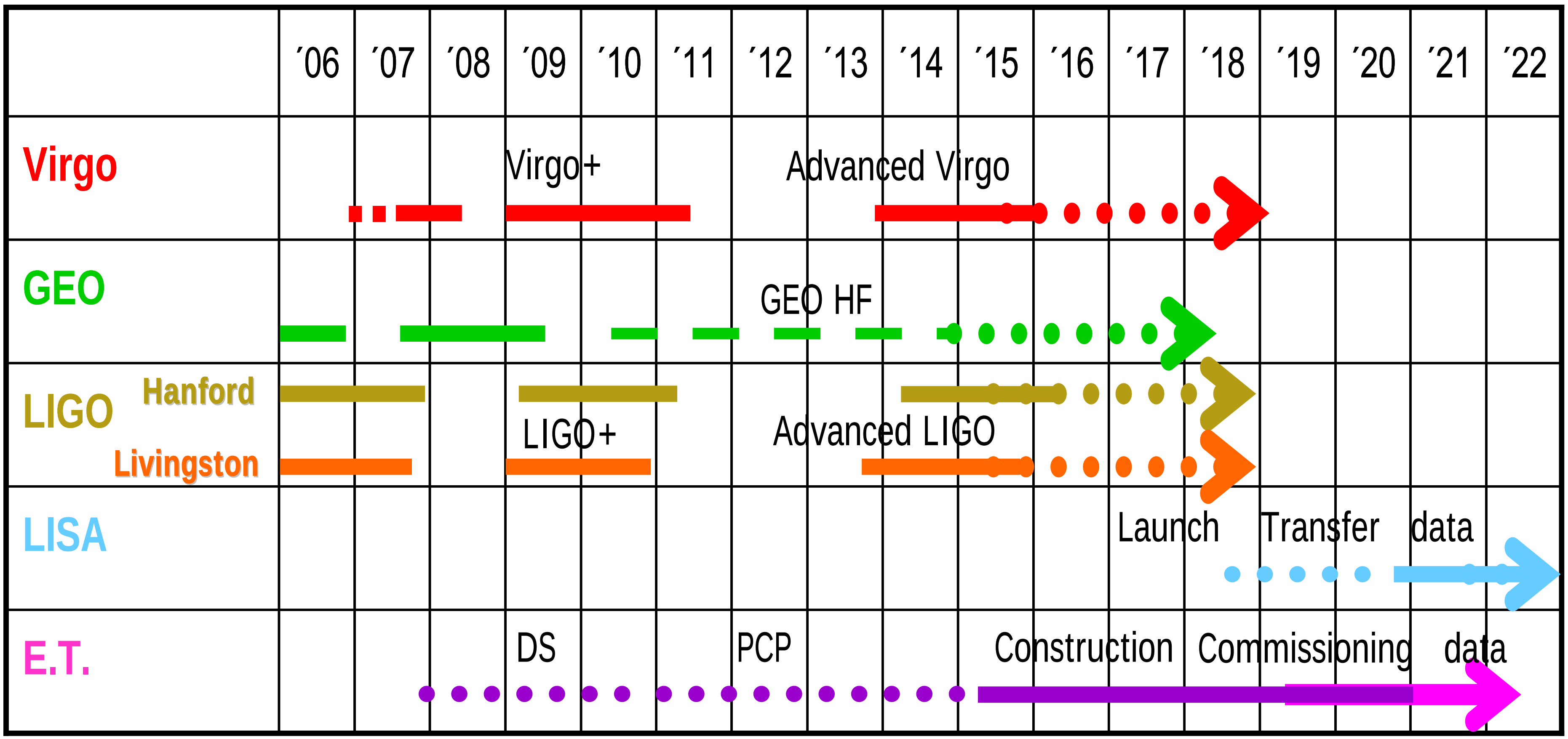
- For a further factor of ten sensitivity improvement we need to
  - fully understand and further reduce seismic and thermal noise from mirrors and suspensions
  - improve interferometric techniques to reduce the significance of quantum noise in the optical system
  - refine data analysis techniques

- A design study for such a detector [the Einstein gravitational-wave Telescope – 'ET'] is currently the subject of an EC FP7 proposal

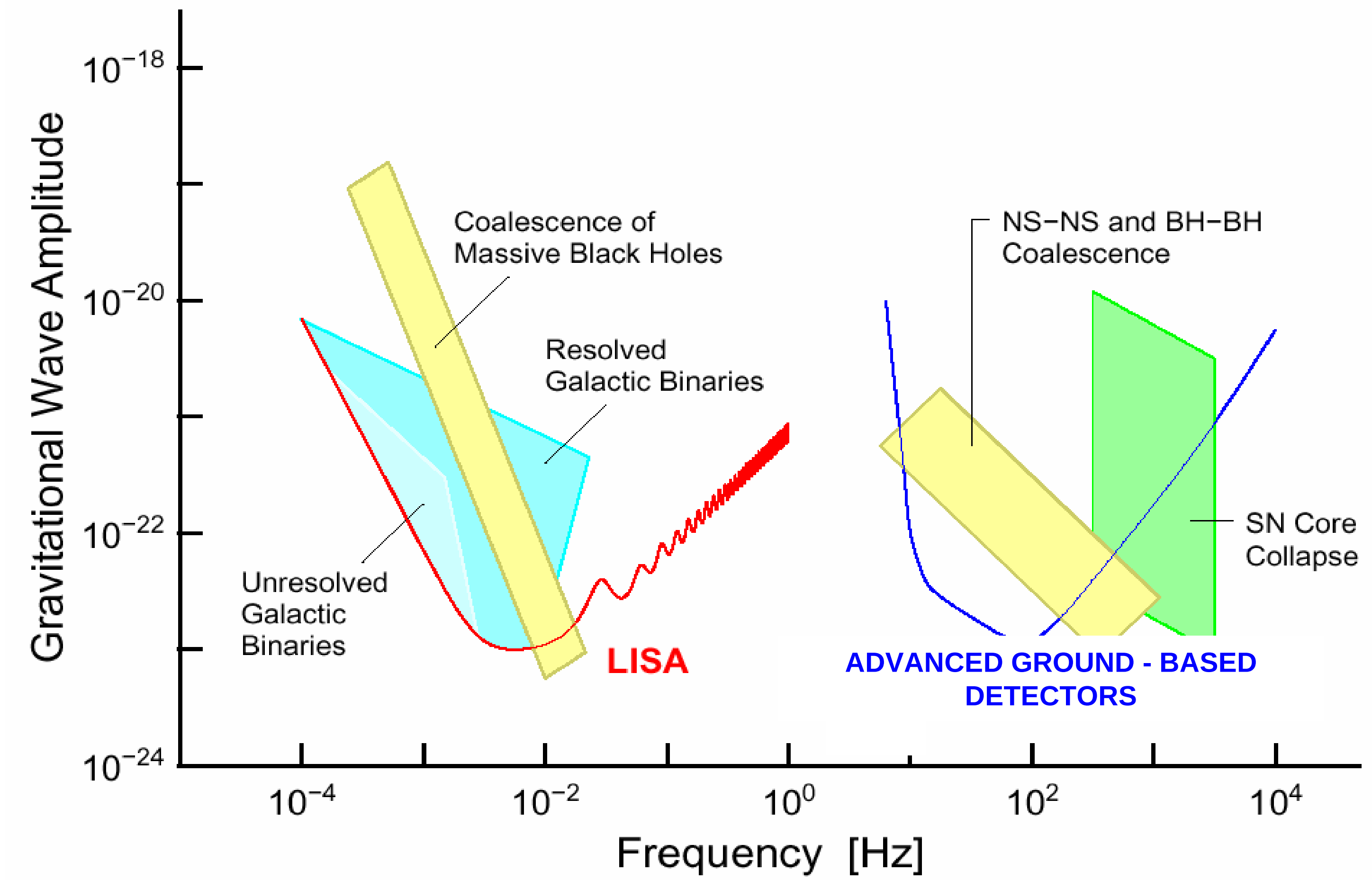
Advanced detector network



Future detectors and data taking plans

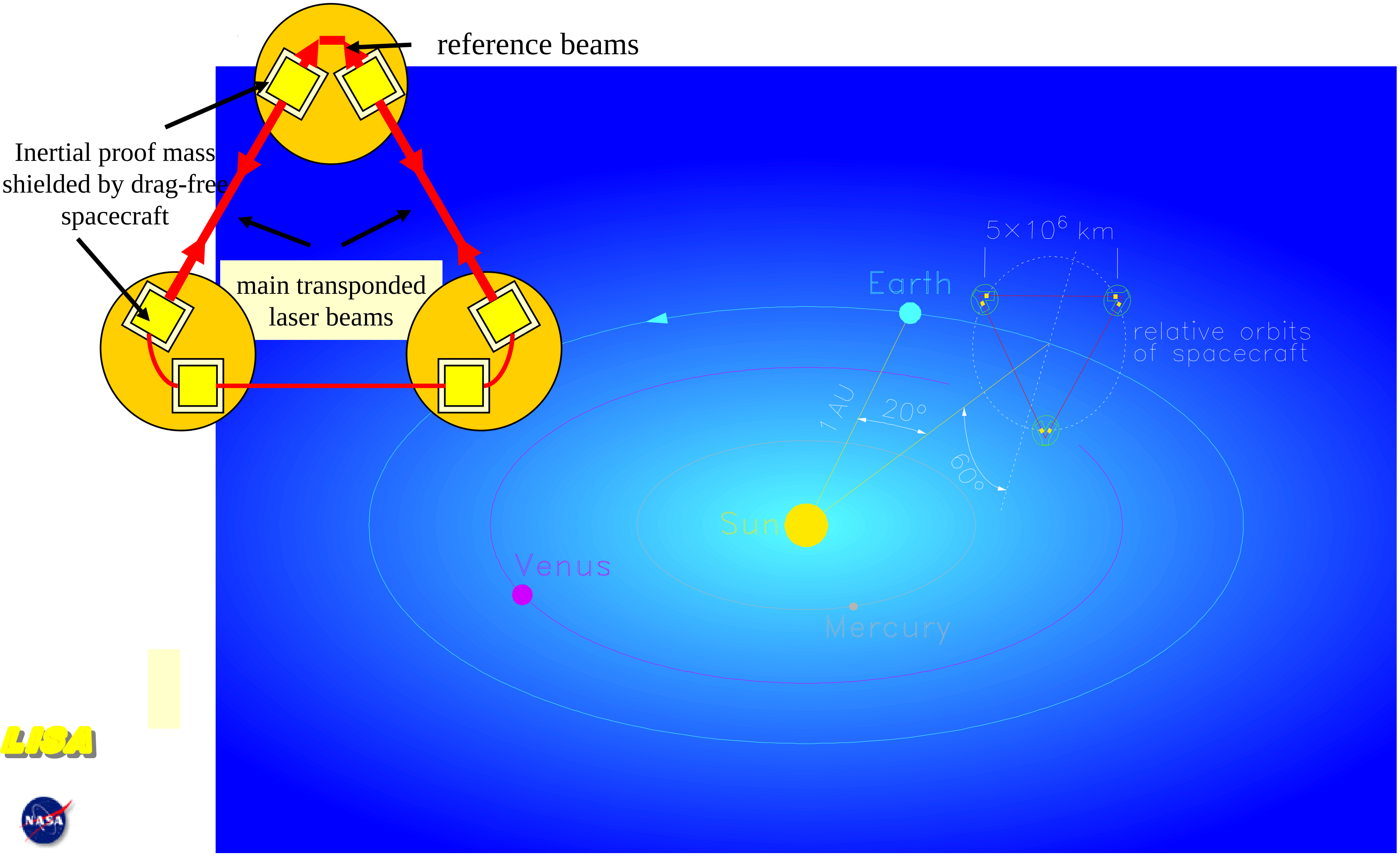


Sources - reminder

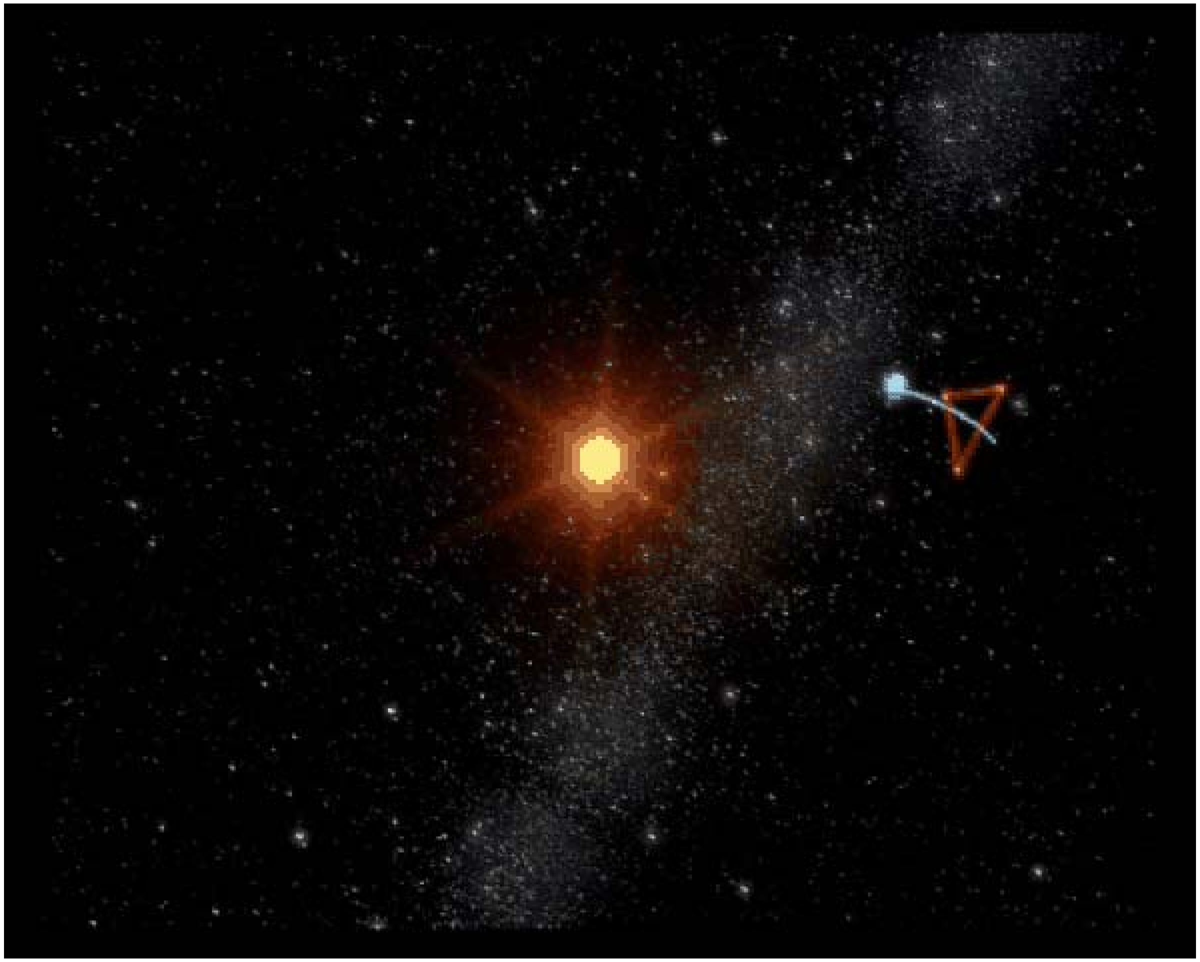


- To see sources at low frequencies – <u>need detector in space</u>

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

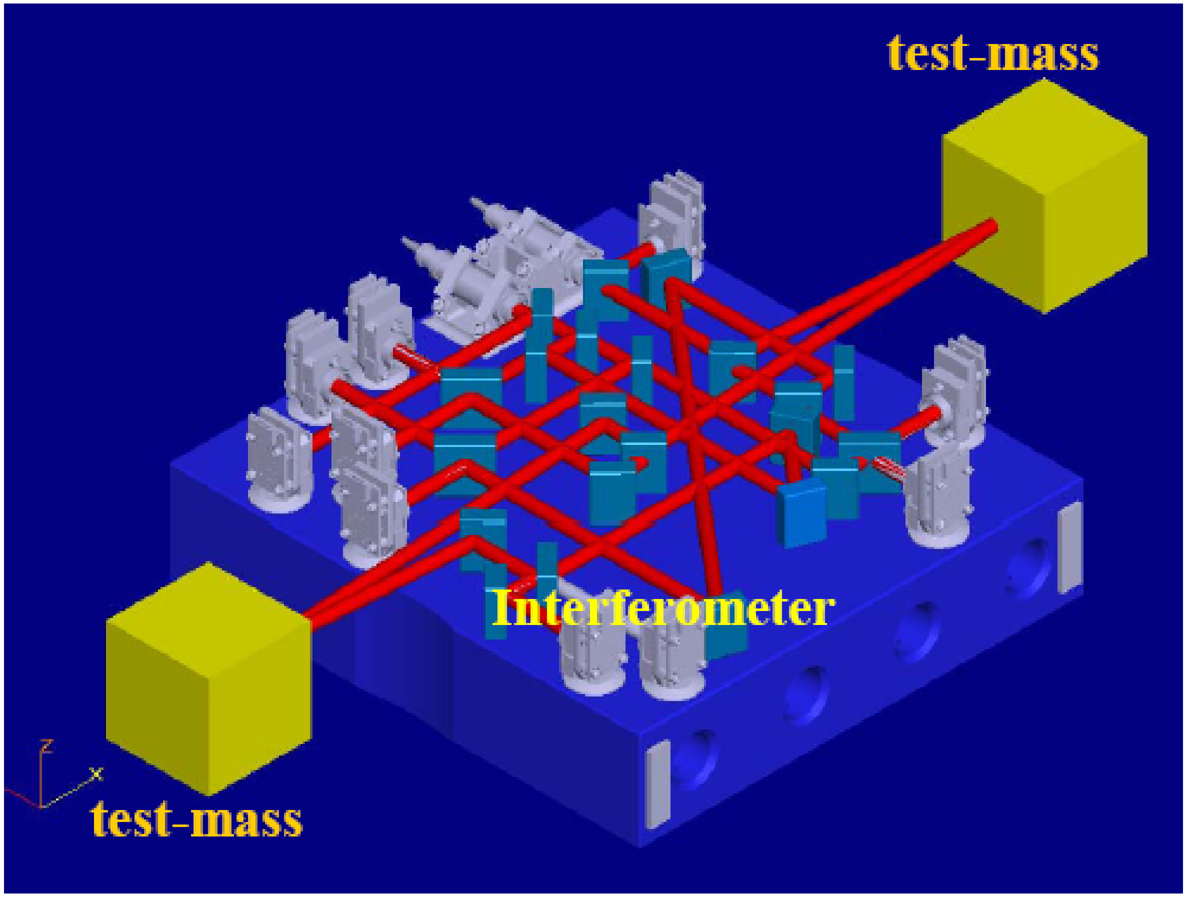


LISA ORBIT



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 with report due early September

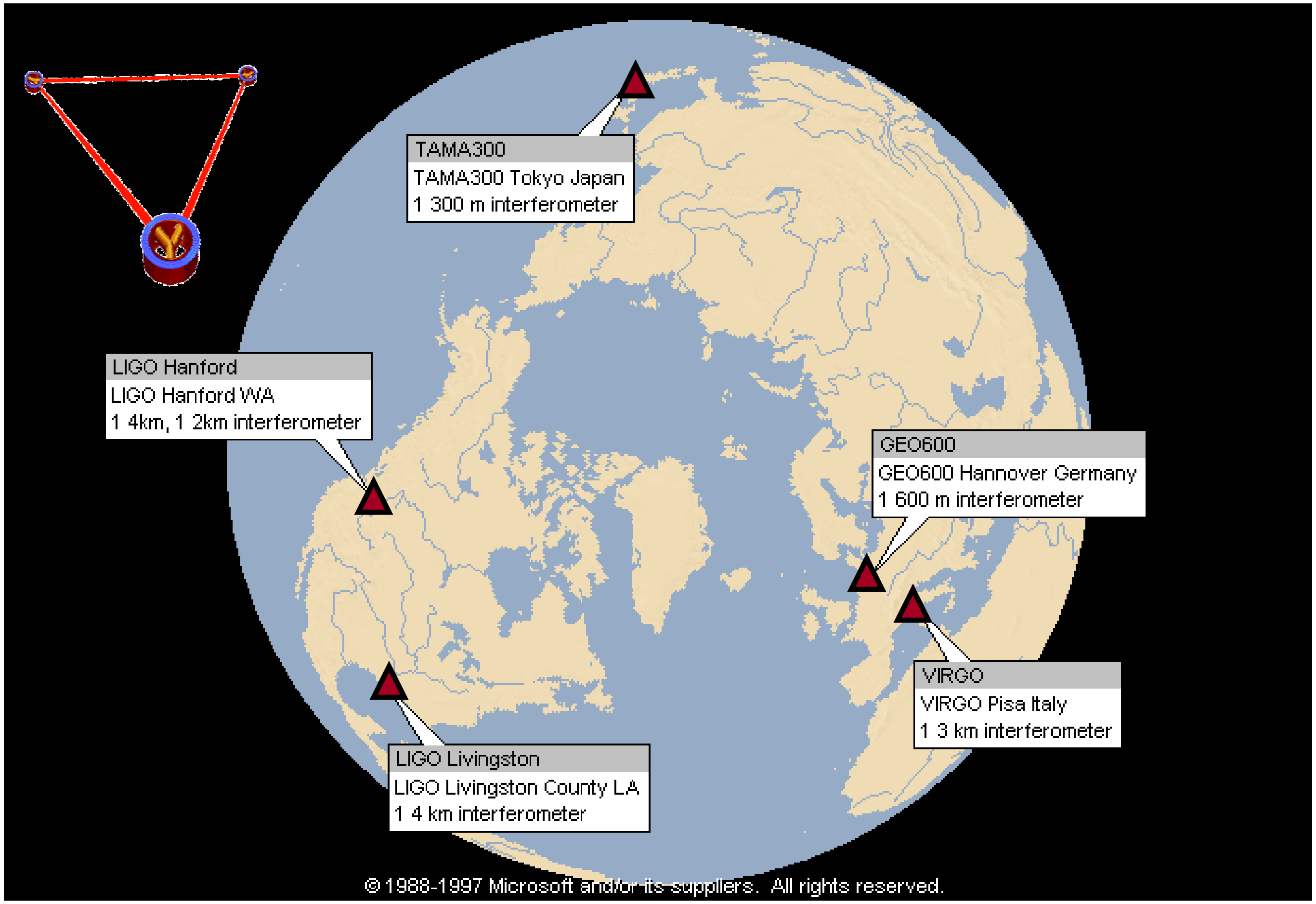
- On the ESA side, final commitment to LISA's implementation will be influenced strongly by the success of LPF
- However work underway before LPF launch to define the LISA mission and prepare the invitation to tender for the implementation phase.

With NASA's selection in FY2007 and ESA's final commitment, LISA expected to enter the implementation phase in 2011, and launch in the 2018 timeframe.

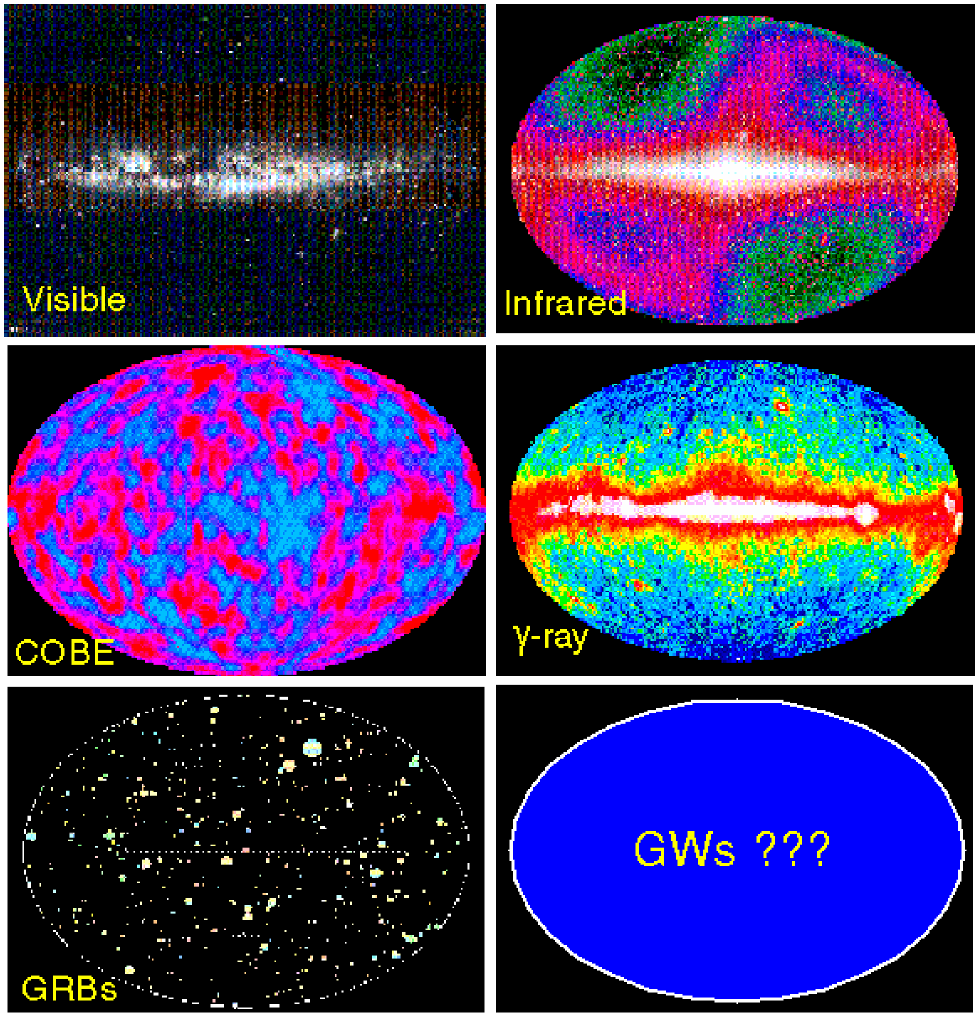
The Network of Gravitational Wave Facilities

- 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 2018

Worldwide Interferometer Network



Gravitational Wave Astronomy



GW detector systems now reaching levels where they may see signals associated with gamma ray bursts within the next few years.

The essentially guaranteed detection of compact binary systems by the advanced detectors early in the next decade is likely lead to further understanding of the nature of the gamma ray bursts.

A new way to observe the Universe