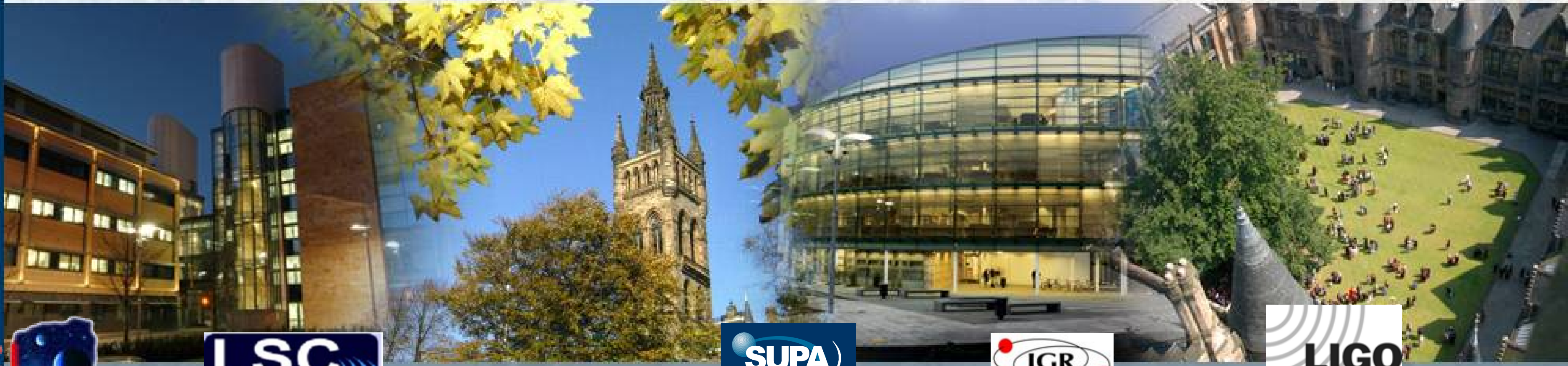
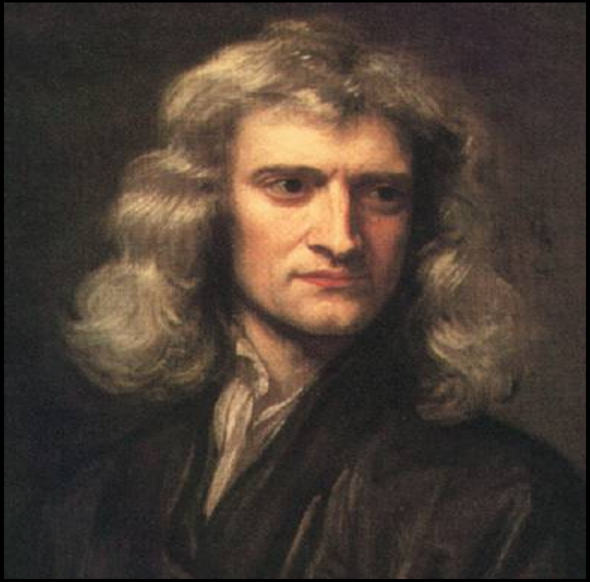
The Search for Gravitational Waves

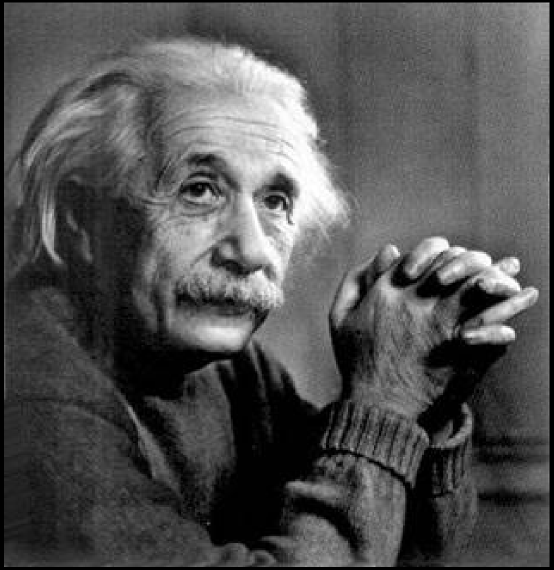
Prof.Jim Hough
Kelvin Professor of Natural Philosophy
University of Glasgow

Erice - September 2010



Gravitation





Newton's Theory

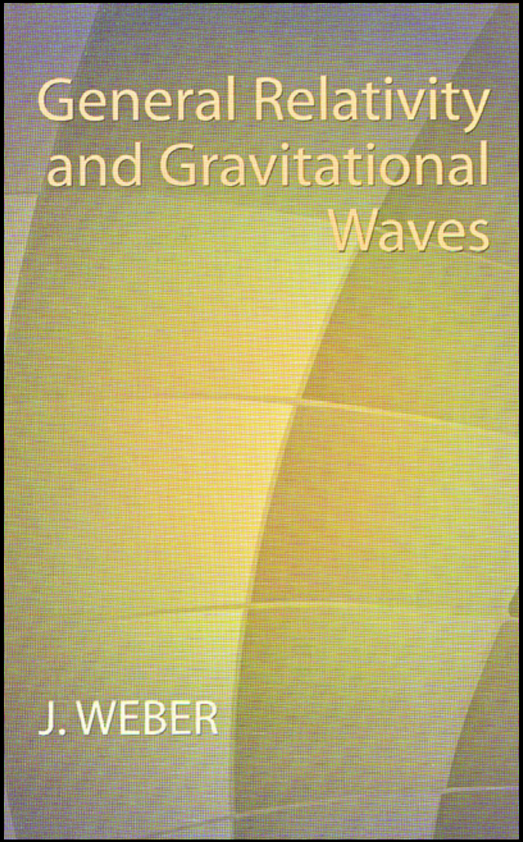
"instantaneous action at a distance"

Einstein's Theory

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

University of Glasgow

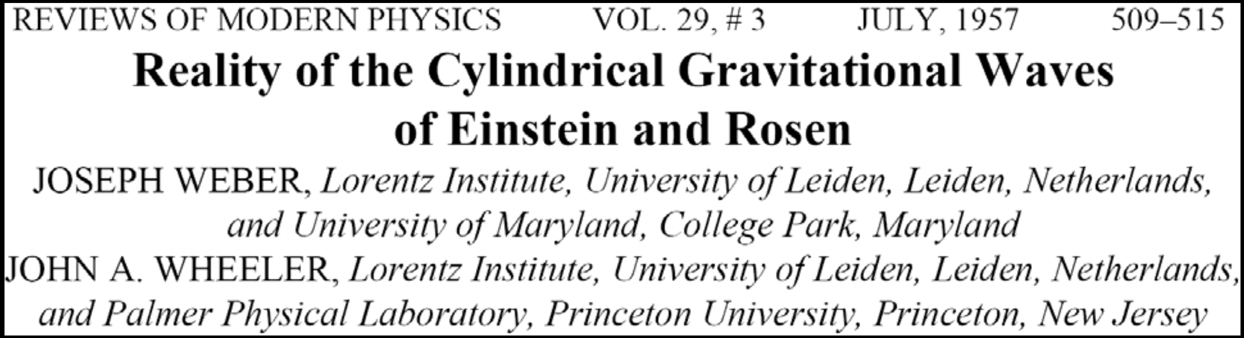
GW a prediction of General Relativity (1916)



General Relativity and Gravitational Waves

J. WEBER

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

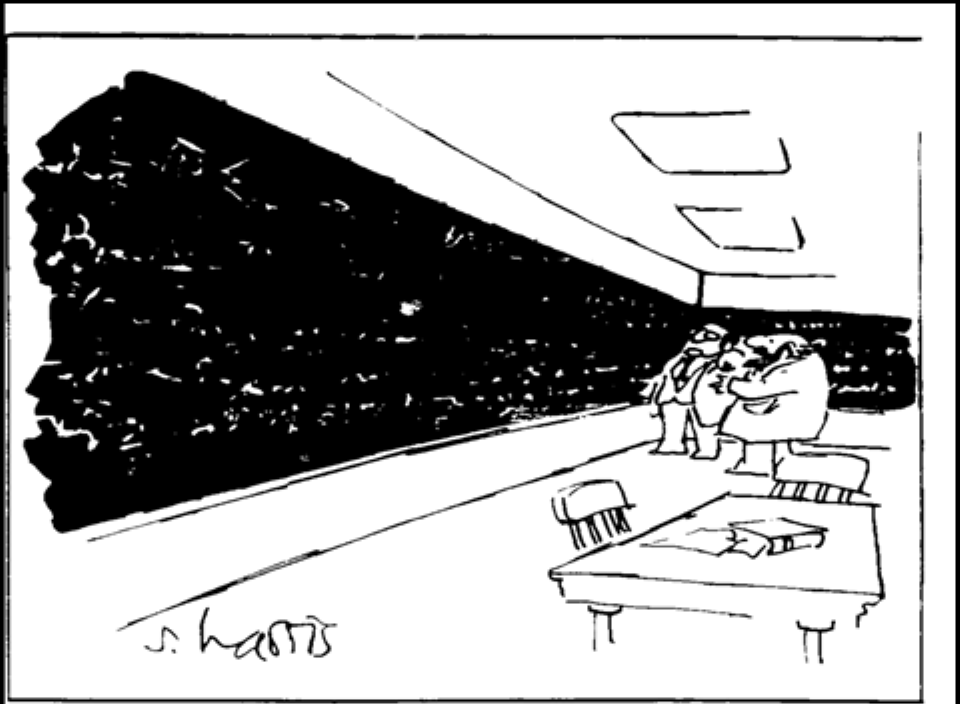
JOSEPH WEBER, *Lorentz Institute, University of Leiden, Leiden, Netherlands, and University of Maryland, College Park, Maryland*

JOHN A. WHEELER, *Lorentz Institute, University of Leiden, Leiden, Netherlands, and Palmer Physical Laboratory, Princeton University, Princeton, New Jersey*

(1961)

LSC SUPA IGR LIGO

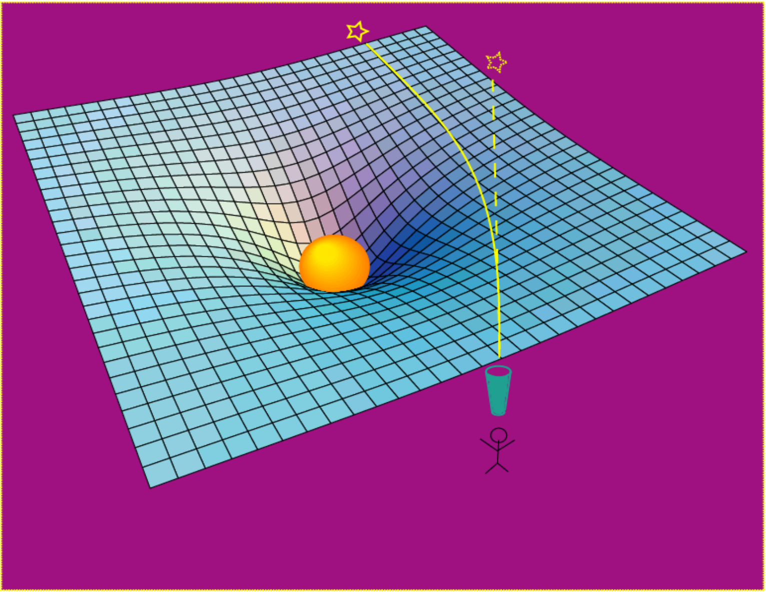
‘Gravitational Waves – the experimentalist’s view’



"But this is just a simplistic way of looking at the problem".
© 1989 by Sidney Harris

- **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 ~ ΔL/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

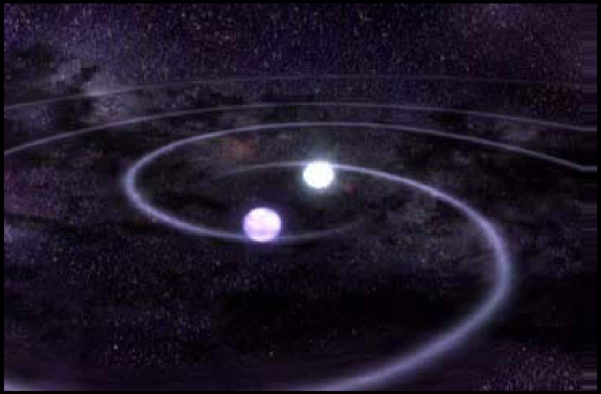
  Low mass X-ray binaries (e.g. SCO X1)

  Modes and Instabilities of Neutron Stars

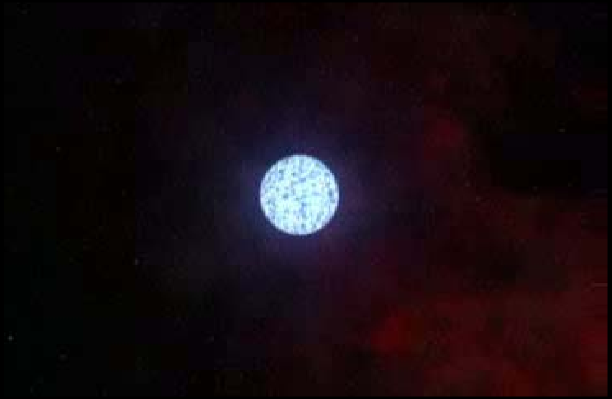
- **Stochastic**

  Inflation

  Cosmic Strings



Binary stars coalescing



Supernova

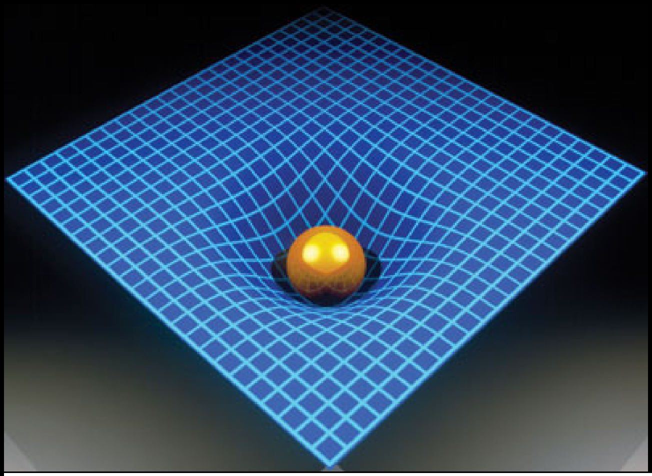
Science questions to be answered

Fundamental physics and general relativity

- *What are the properties of gravitational waves?*
- *Is general relativity the correct theory of gravity?*
- *Is general relativity still valid under strong-gravity conditions?*
- *Are Nature's black holes the black holes of general relativity?*
- *How does matter behave under extremes of density and pressure?*

Cosmology

- *What is the history of the accelerating expansion of the Universe?*
- *Were there phase transitions in the early Universe?*



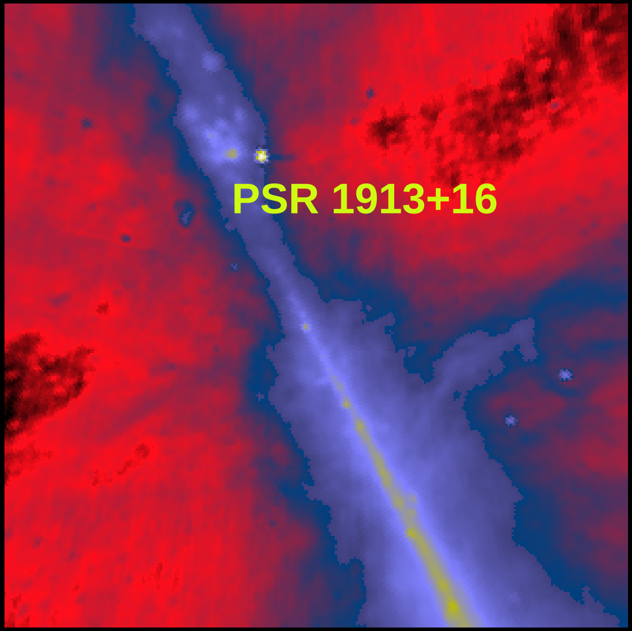
Science questions to be answered

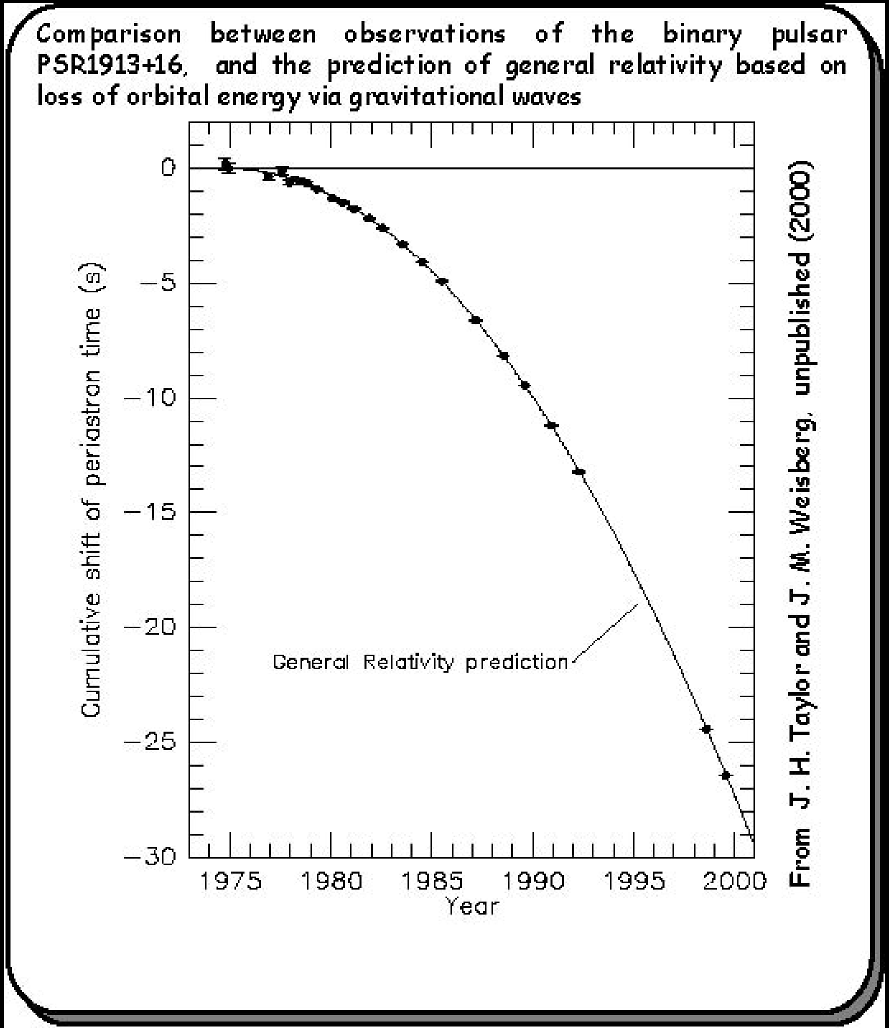
Astronomy and astrophysics

- *How abundant are stellar-mass black holes?*
- *What is the central engine behind gamma-ray bursts?*
- *Do intermediate mass black holes exist?*
- *Where and when do massive black holes form and how are they connected to the formation of galaxies?*
- *What happens when a massive star collapses?*
- *Do spinning neutron stars emit gravitational waves?*
- *What is the distribution of white dwarf and neutron star binaries in the galaxy?*
- *How massive can a neutron star be?*

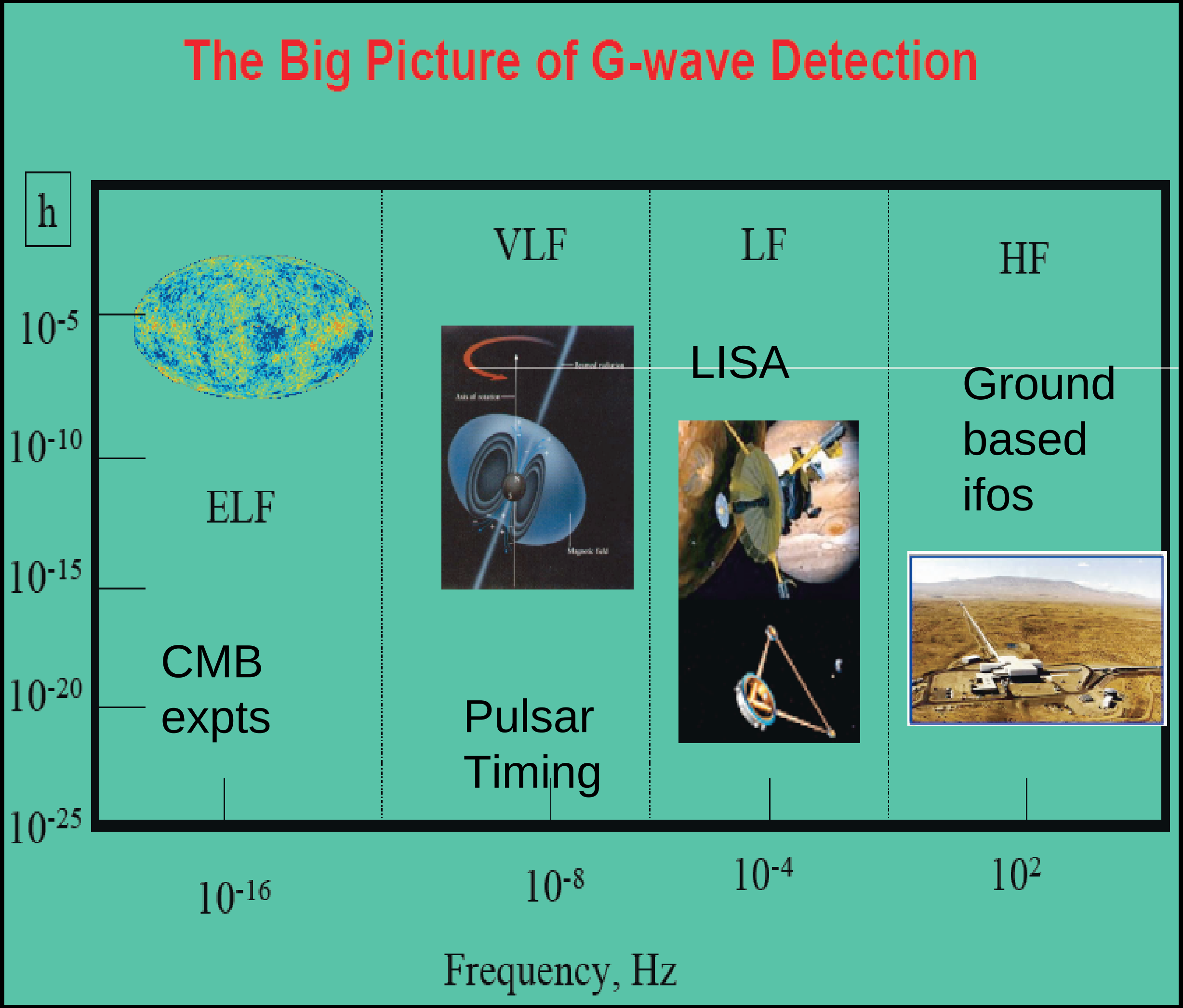
Evidence for gravitational waves

**“Indirect”
detection
of gravitational waves**

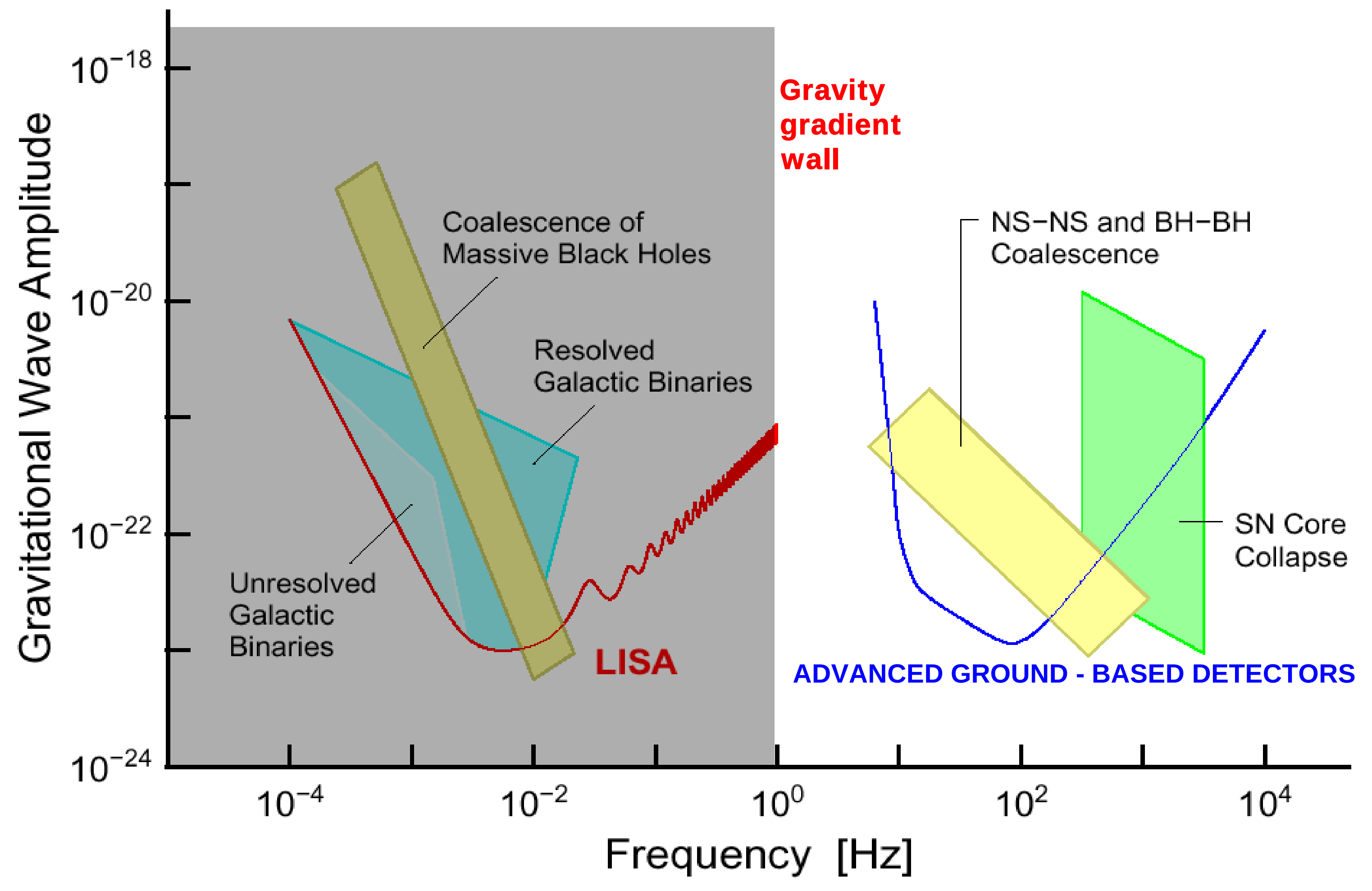



Comparison between observations of the binary pulsar PSR1913+16, and the prediction of general relativity based on loss of orbital energy via gravitational waves

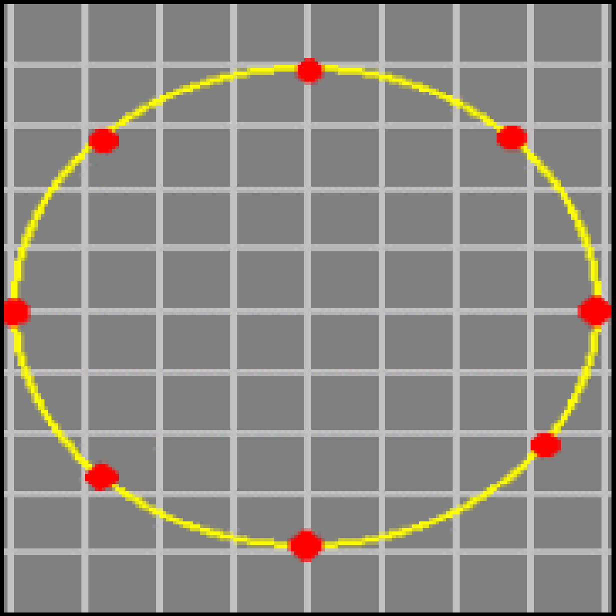
The Gravitational Wave Spectrum



Sources – the gravitational wave spectrum

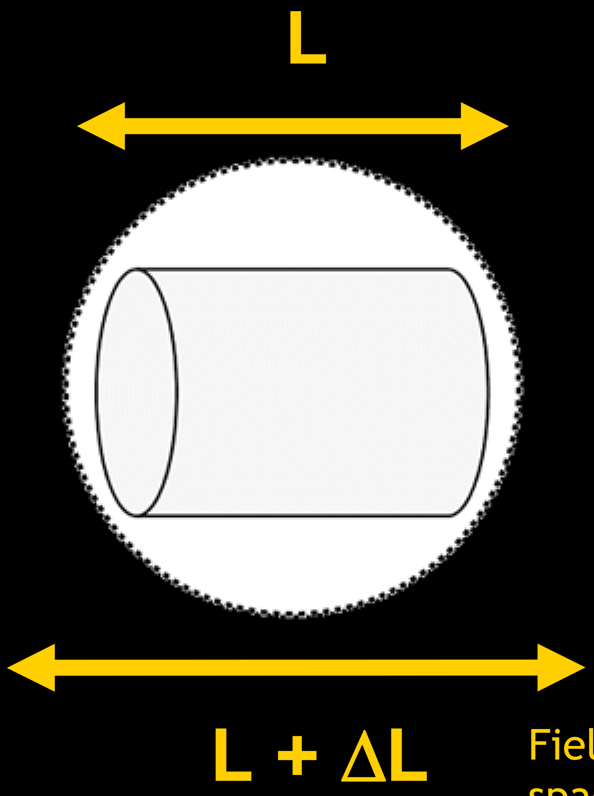


The Effect of Gravitational Waves

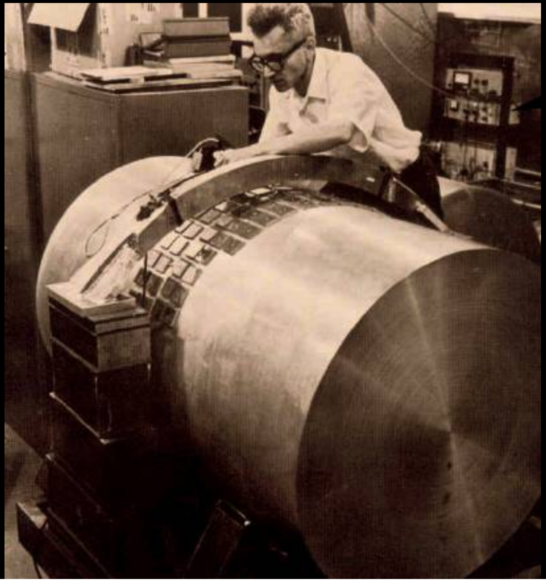


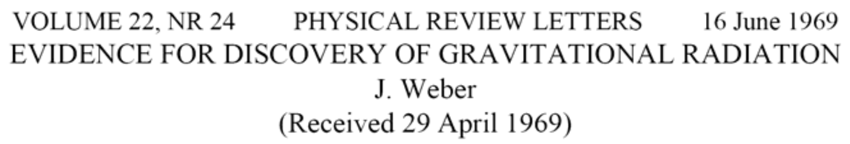
How can we detect them?

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



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)

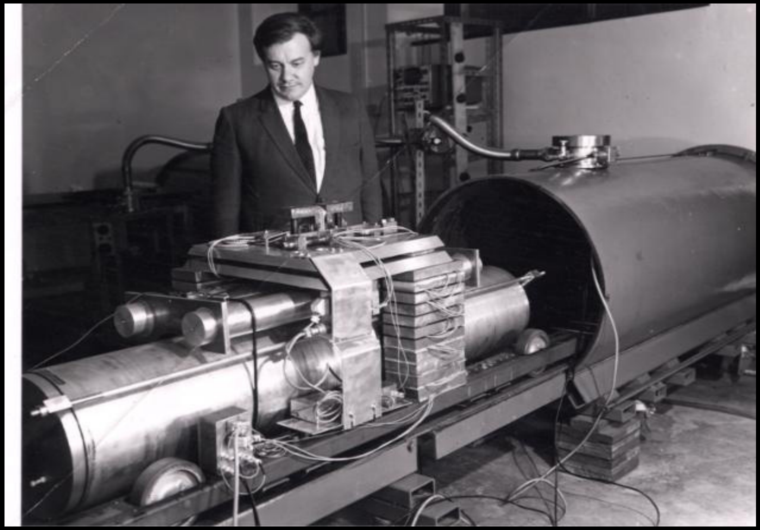
Field originated with J. Weber looking for the effect of strains in space on aluminium bars at room temperature

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

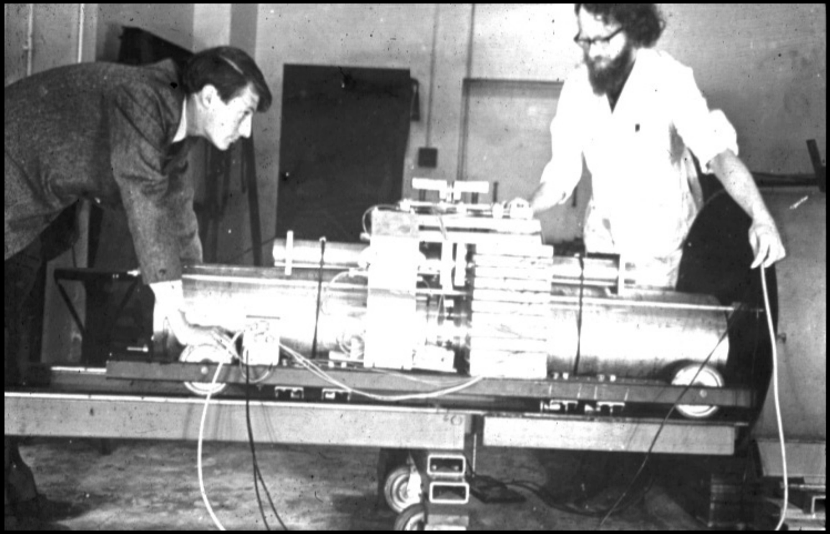
University of Glasgow

Detection Techniques

- Joined by other groups in Germany, Italy,UK and USA
- No believable evidence for existence of GW



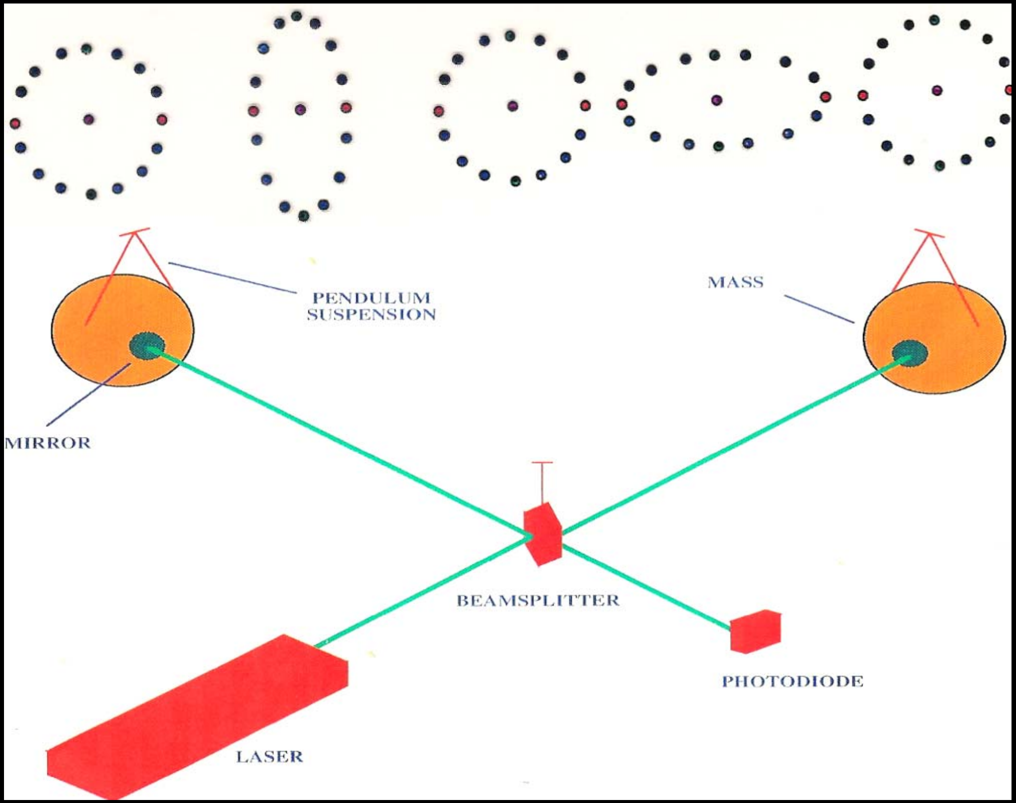
R. Drever et al, Glasgow



J. Hough and S. Cherry, Glasgow

Detection of Gravitational Waves

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



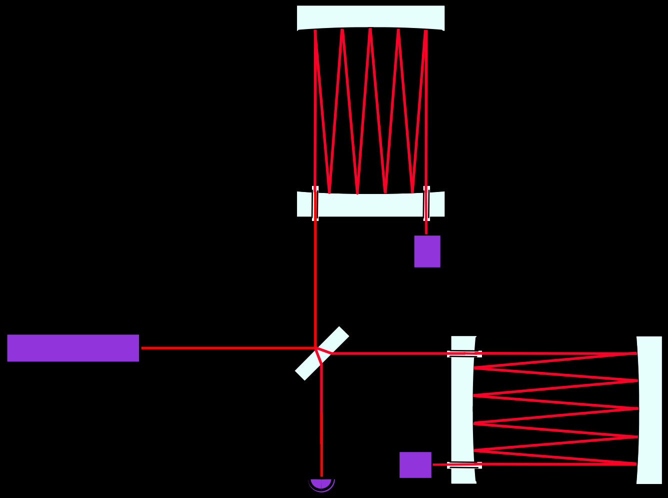
One cycle

Michelson Interferometer

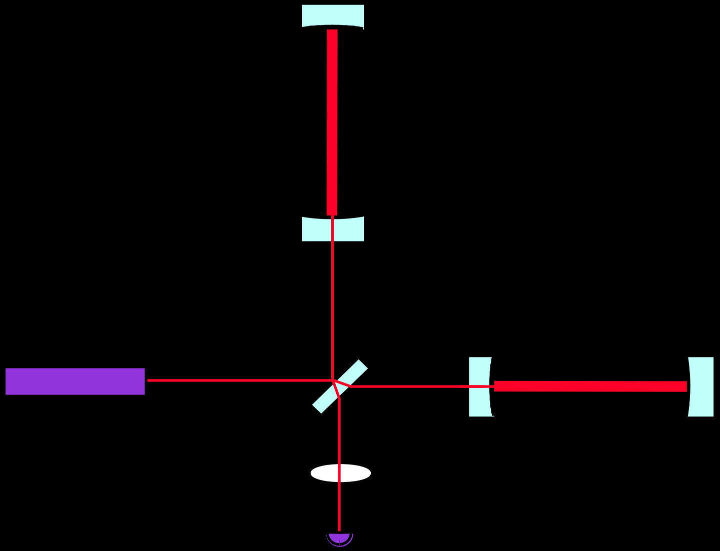
Gravitational waves have very weak effect: Expect movements of less than 10^{-18} m over 4km

Laser Interferometer

- For best performance want arm length ~ λ/4
  - i.e. for 1kHz signals, length = 75 km !
- Such lengths not really possible on earth, but optical path can be folded



MIT and Garching

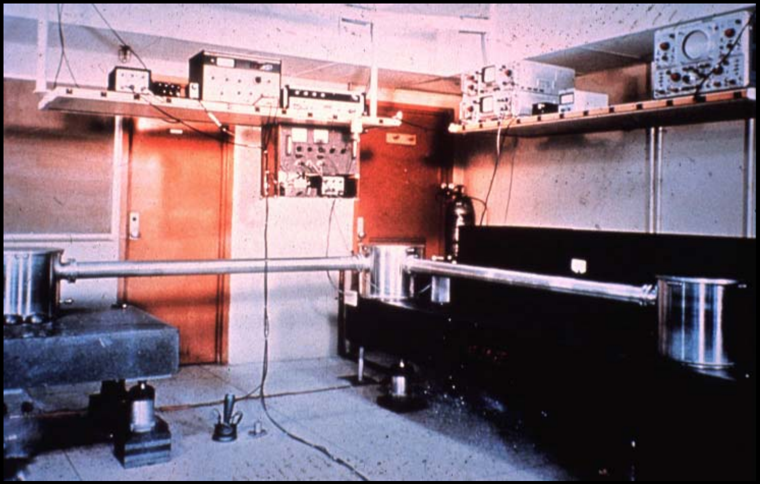


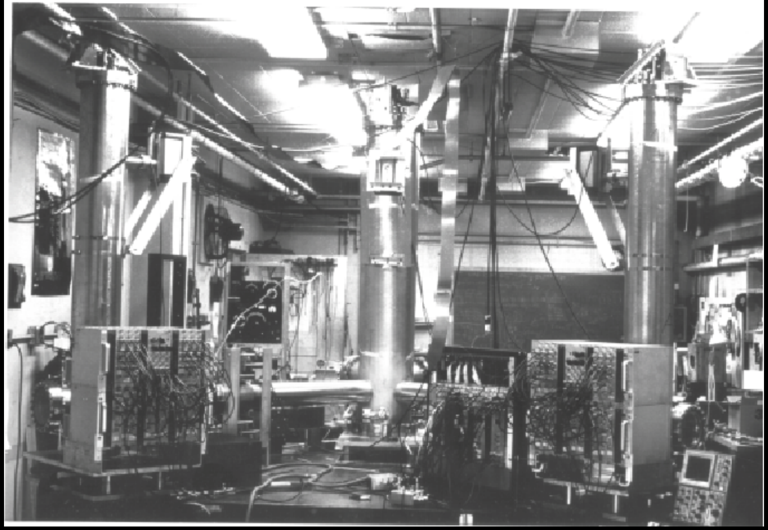
Glasgow and Caltech

- Much longer arm lengths are possible in space

Early Interferometer prototypes

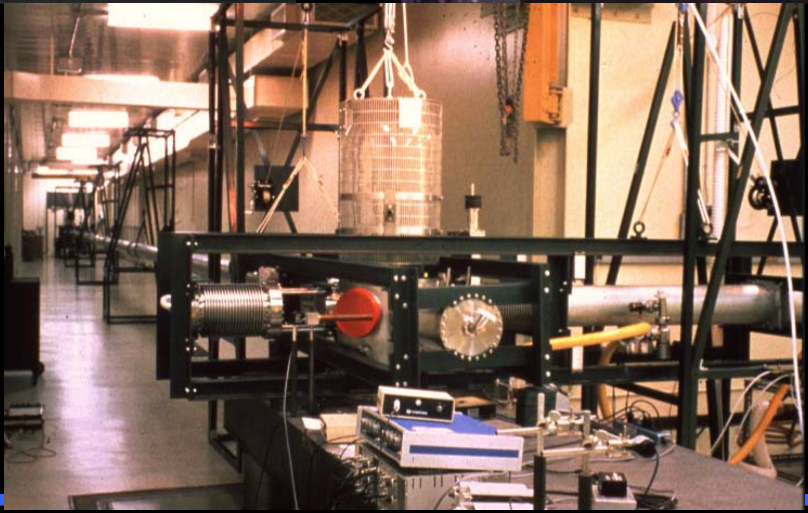
Simple Michelson
-R. Forward





Delay line prototype
- R. Weiss MIT

Garching 30m, Glasgow 10m, Caltech 40m



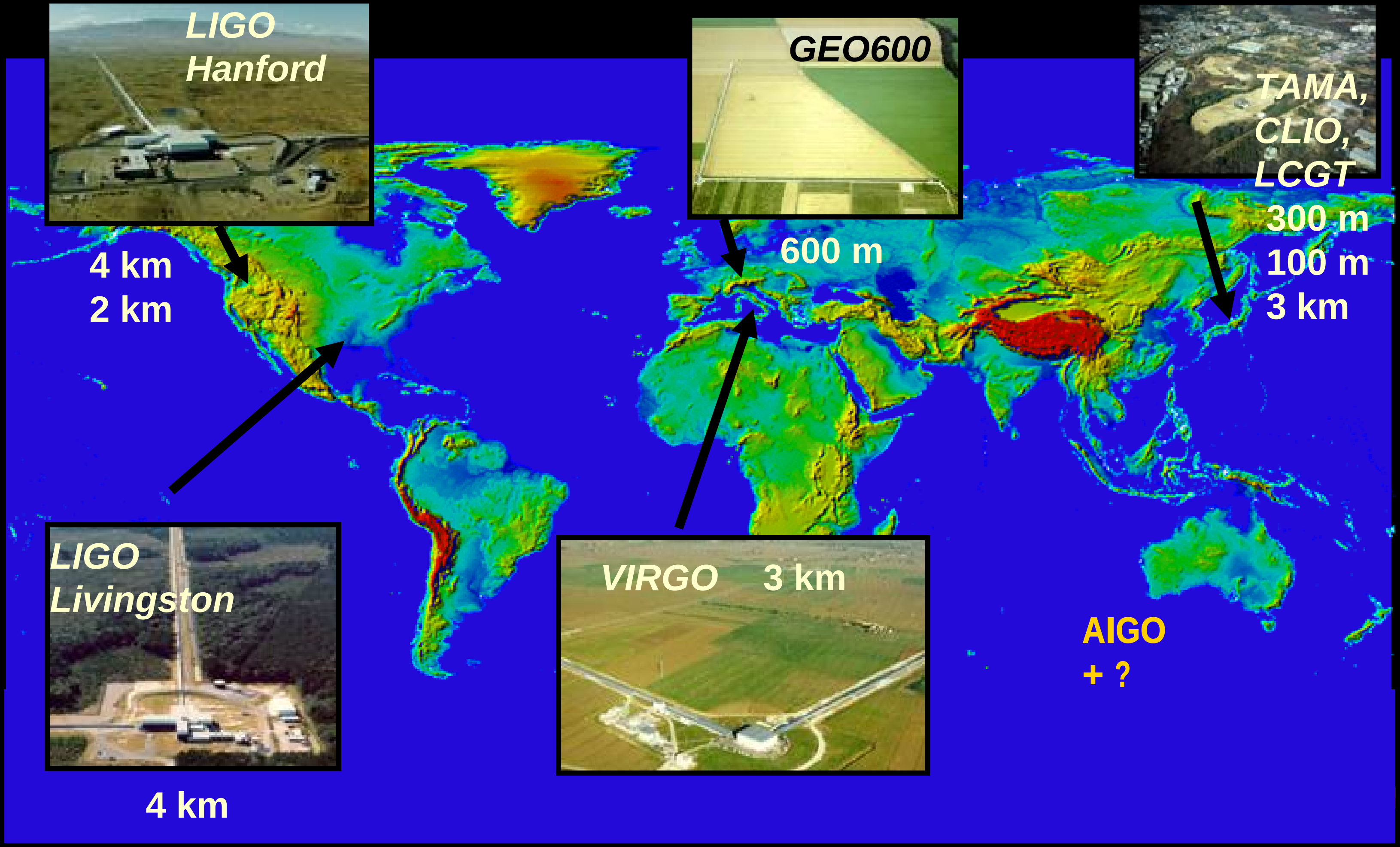
Principal limitations to sensitivity ground based detectors

- 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/thermo-elastically induced motion of test masses and suspensions) – need materials of ultra-low mechanical loss

All point to long arm lengths being desirable and projects were planned and built in the US (LIGO), Europe (Virgo and GEO 600) and Japan (TAMA 300)

Worldwide Network of Interferometers

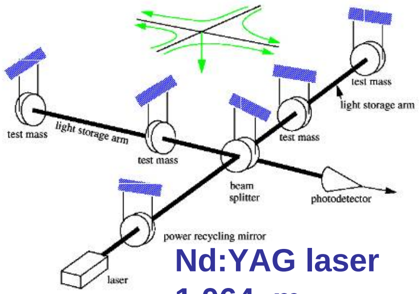


Initial LIGO detectors

LIGO project (USA)

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

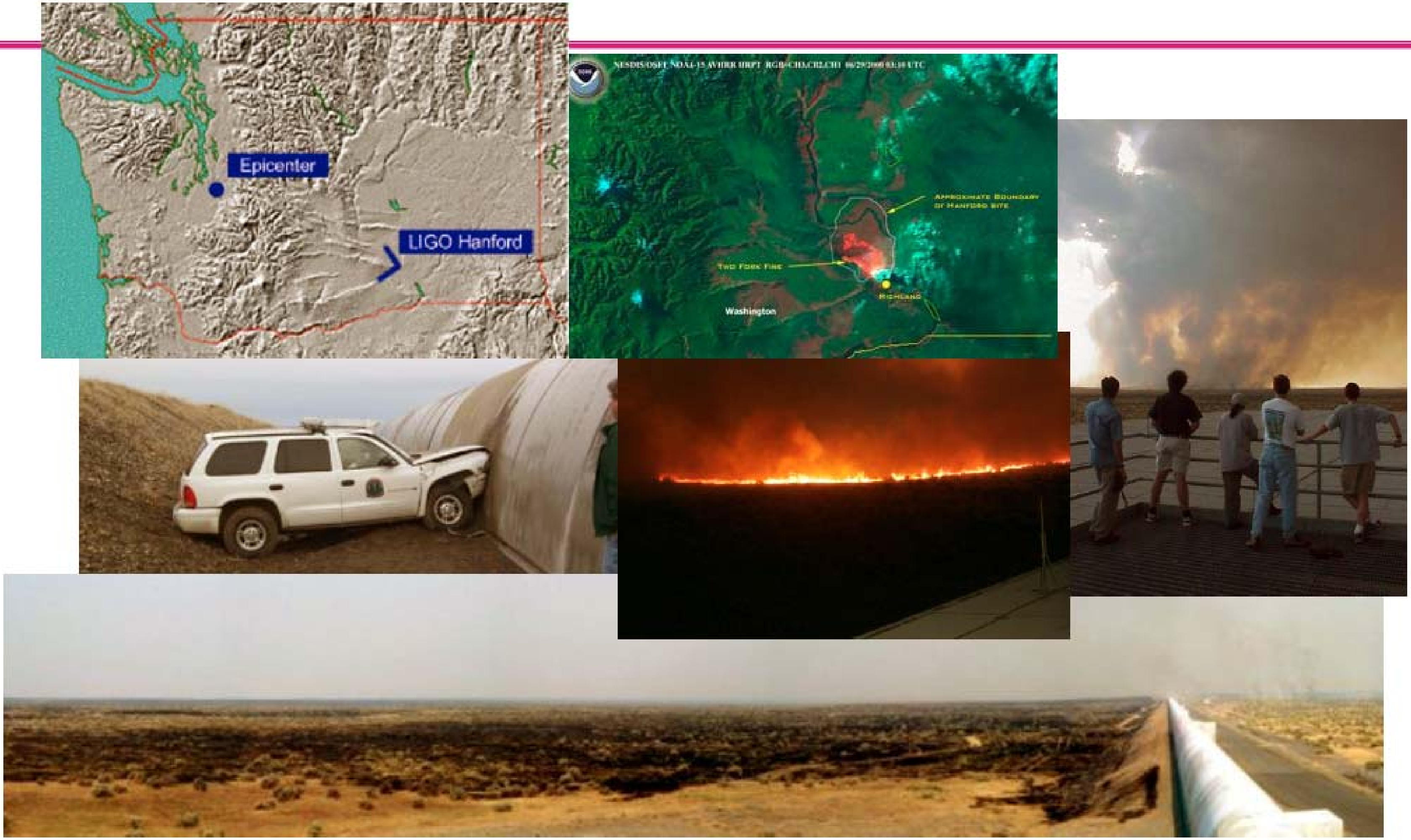
Each detector is based on a ‘Fabry-Perot – Michelson’



Nd:YAG laser 1.064μm

LIGO

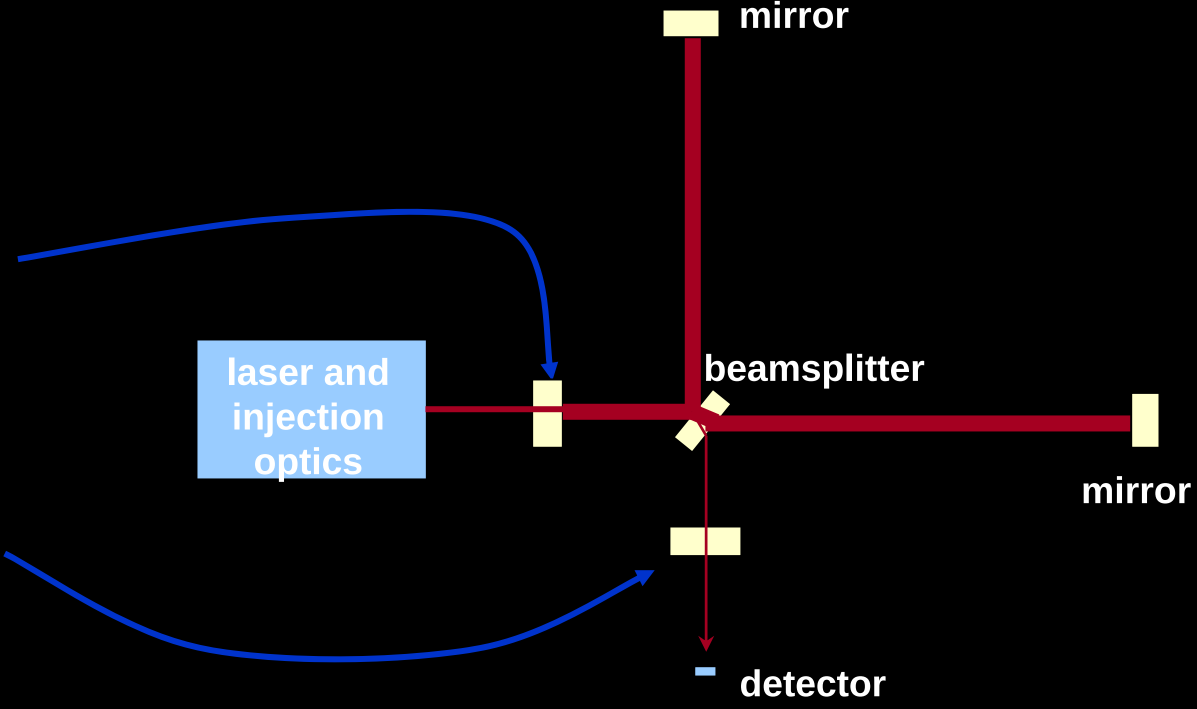
It’s never as easy as it looks…



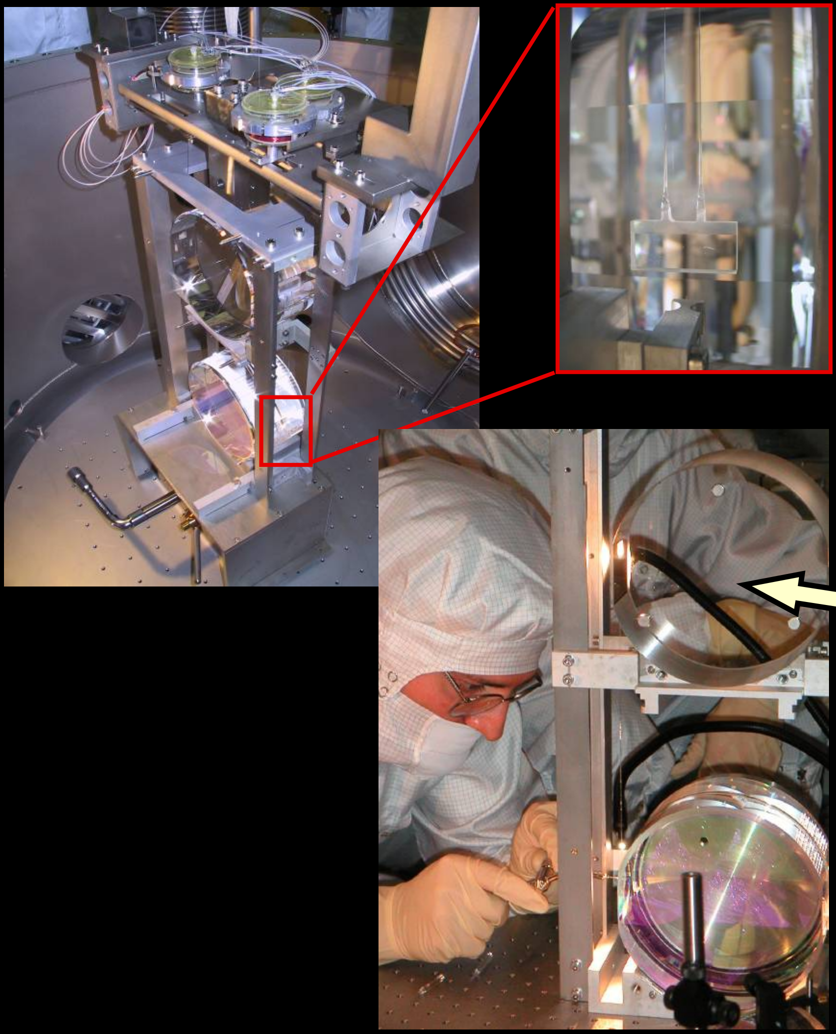
GEO 600

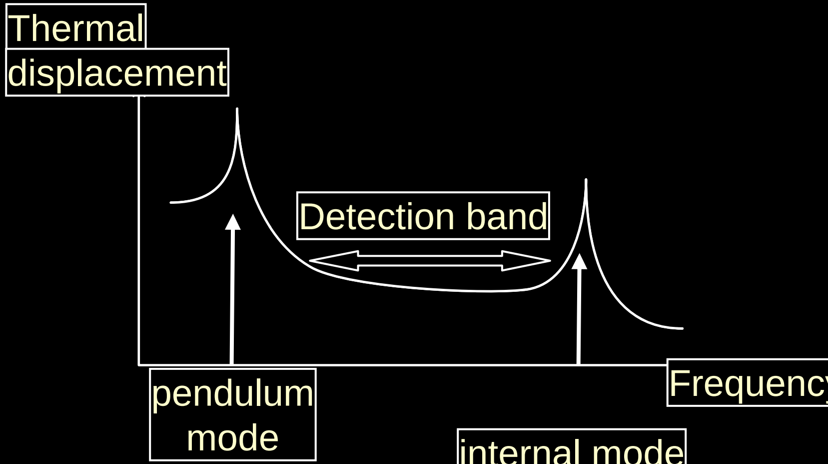
Unique GEO Technology 1 - Advanced Interferometry

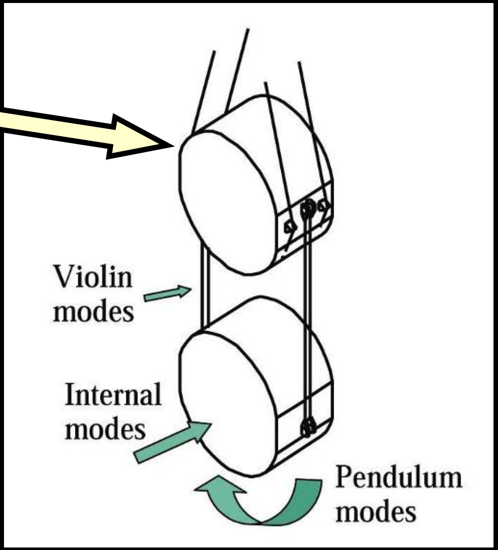
- One of the fundamental limits to interferometer sensitivity is photon shot noise
- Power recycling effectively increases the laser power
- Signal recycling – a GEO invention – trades bandwidth for improved sensitivity



Unique GEO Technology 2 - Monolithic Silica Suspension



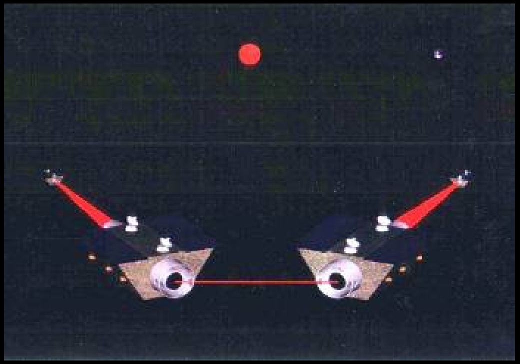




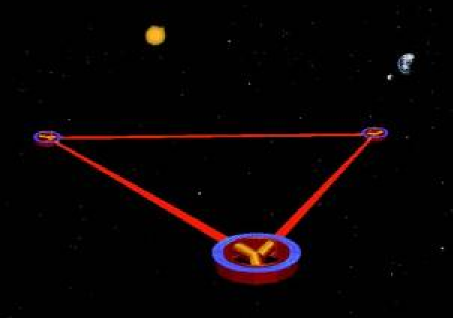
Ultra-low mechanical loss suspension at the heart of the interferometer

Detectors in Space - LISA

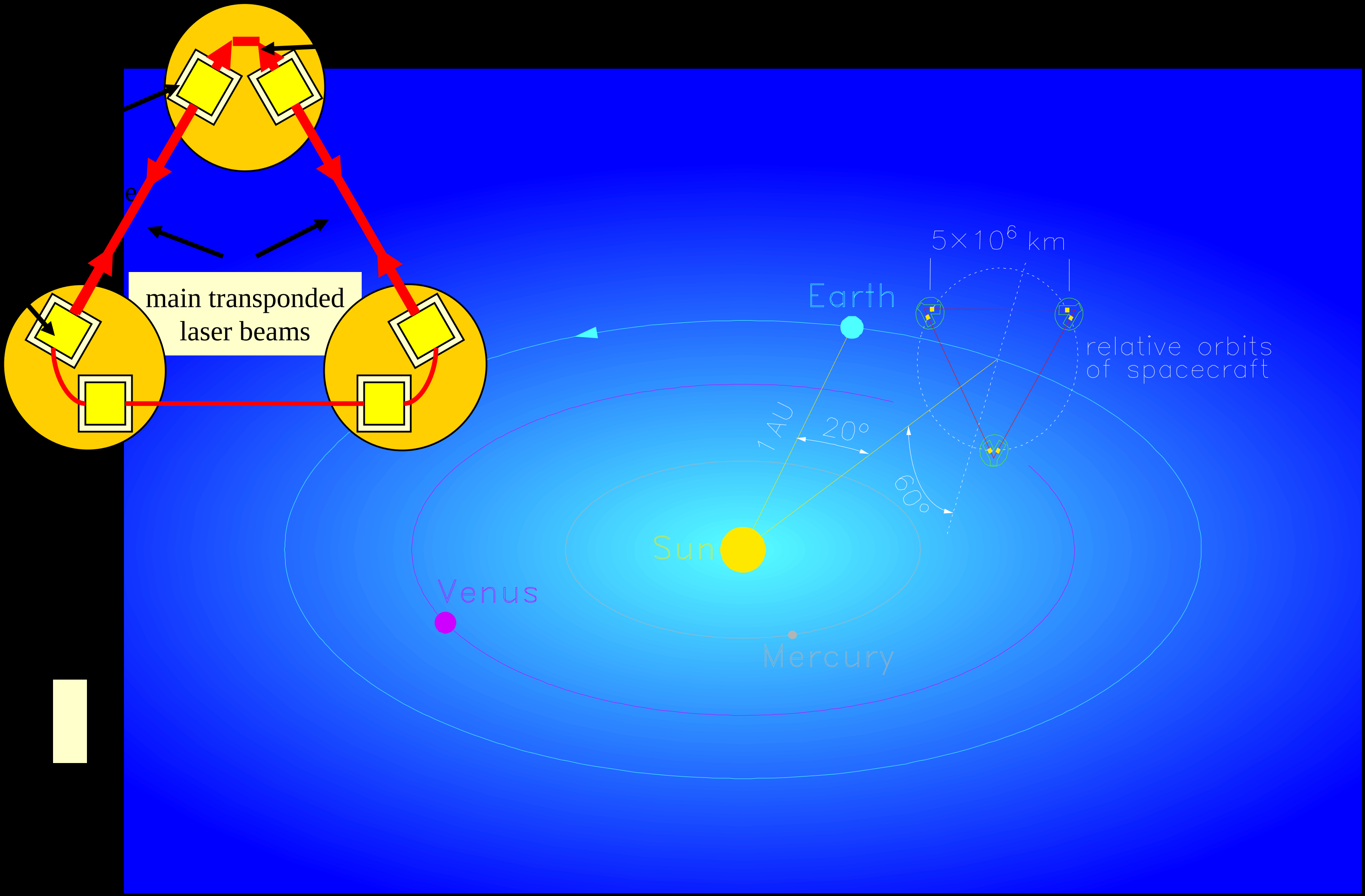
LISA – a joint ESA/NASA Mission to study Black hole physics and more, in the frequency range 10^{-4} Hz -10^{-1} Hz



- After first studies in 1980s, M3 proposal for 4 S/C ESA/NASA collaborative mission in 1993
- LISA selected as ESA Cornerstone in 1995
- *3 S/C NASA/ESA LISA appears in 1997*
- **Baseline concept unchanged ever since!**



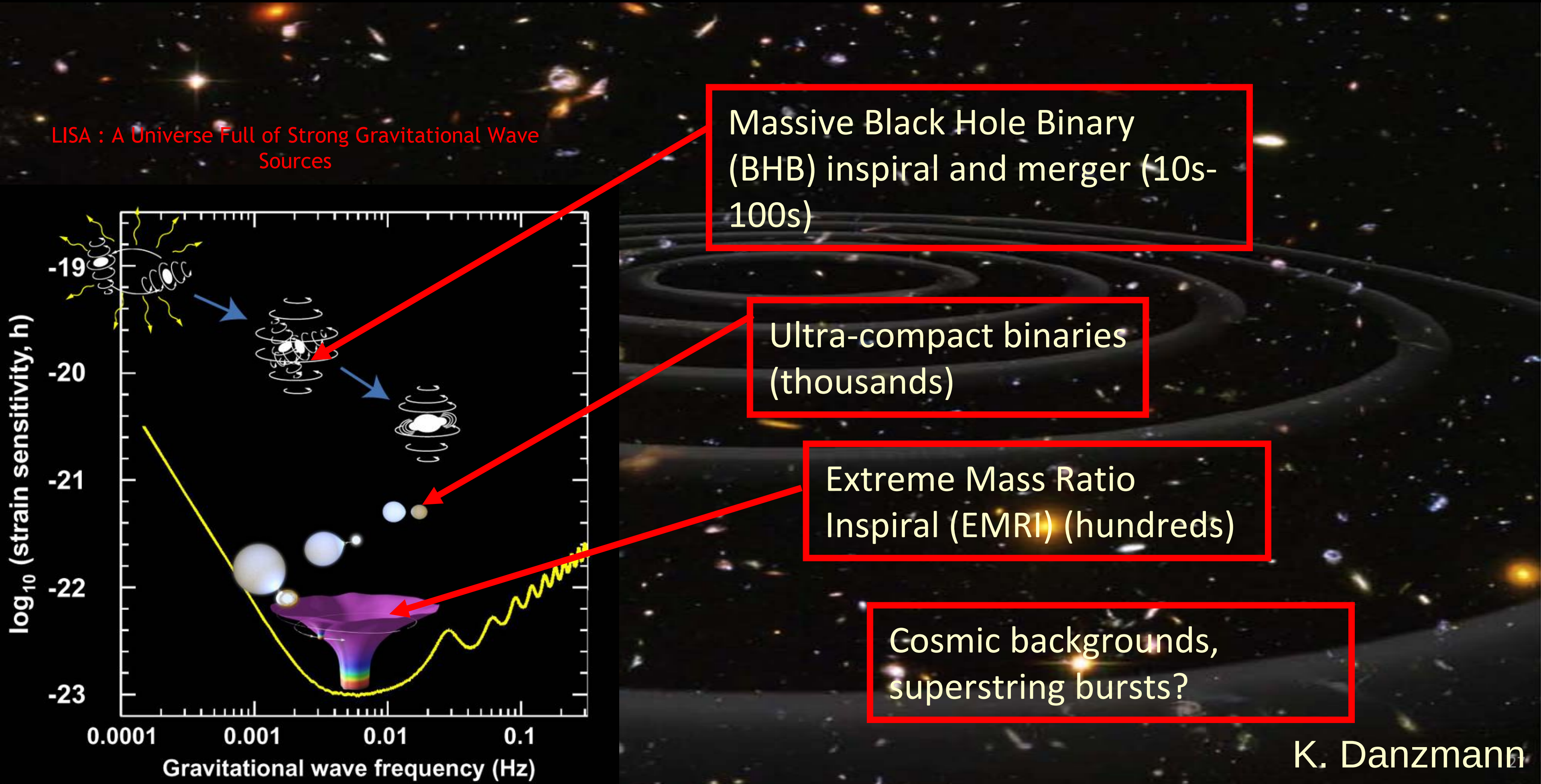
LISA -Cluster of 3 sp'craft in heliocentric orbit at 1 AU



LISA Science

LISA (Laser Interferometer Space Antenna)

10^{-4} Hz – 10^{-1} Hz First space based GW mission (2020+)



LISA : A Universe Full of Strong Gravitational Wave Sources

Massive Black Hole Binary (BHB) inspiral and merger (10s-100s)

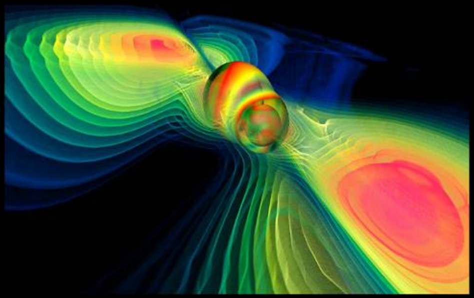
Ultra-compact binaries (thousands)

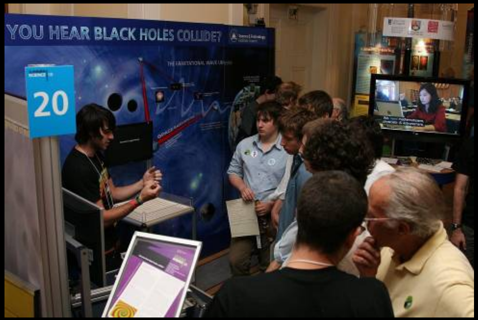
Extreme Mass Ratio Inspiral (EMRI) (hundreds)

Cosmic backgrounds, superstring bursts?

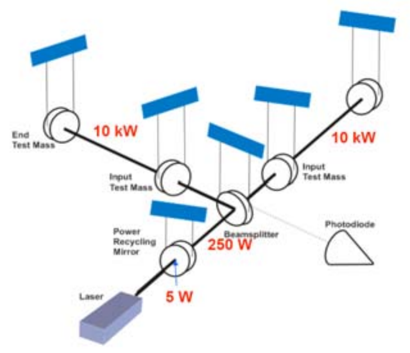
K. Danzmann

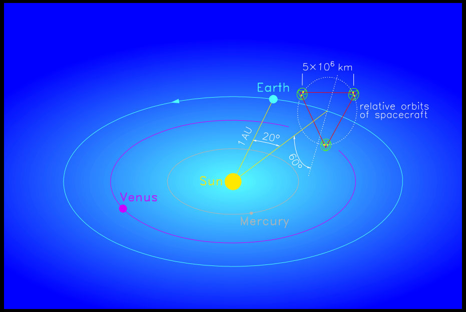
Real Progress in field over last few years

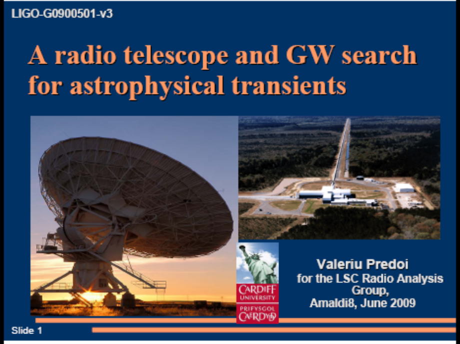




- Operation of six ground based interferometers (in addition to three cryogenic bar detectors)
- Waveform Predictions from Numerical Relativity
- Significant advances in Space Borne Detectors – Pathfinder for LISA due to launch in 2012
- Pulsar Timing coming to the fore
- Importance of Multi-messenger Astronomy







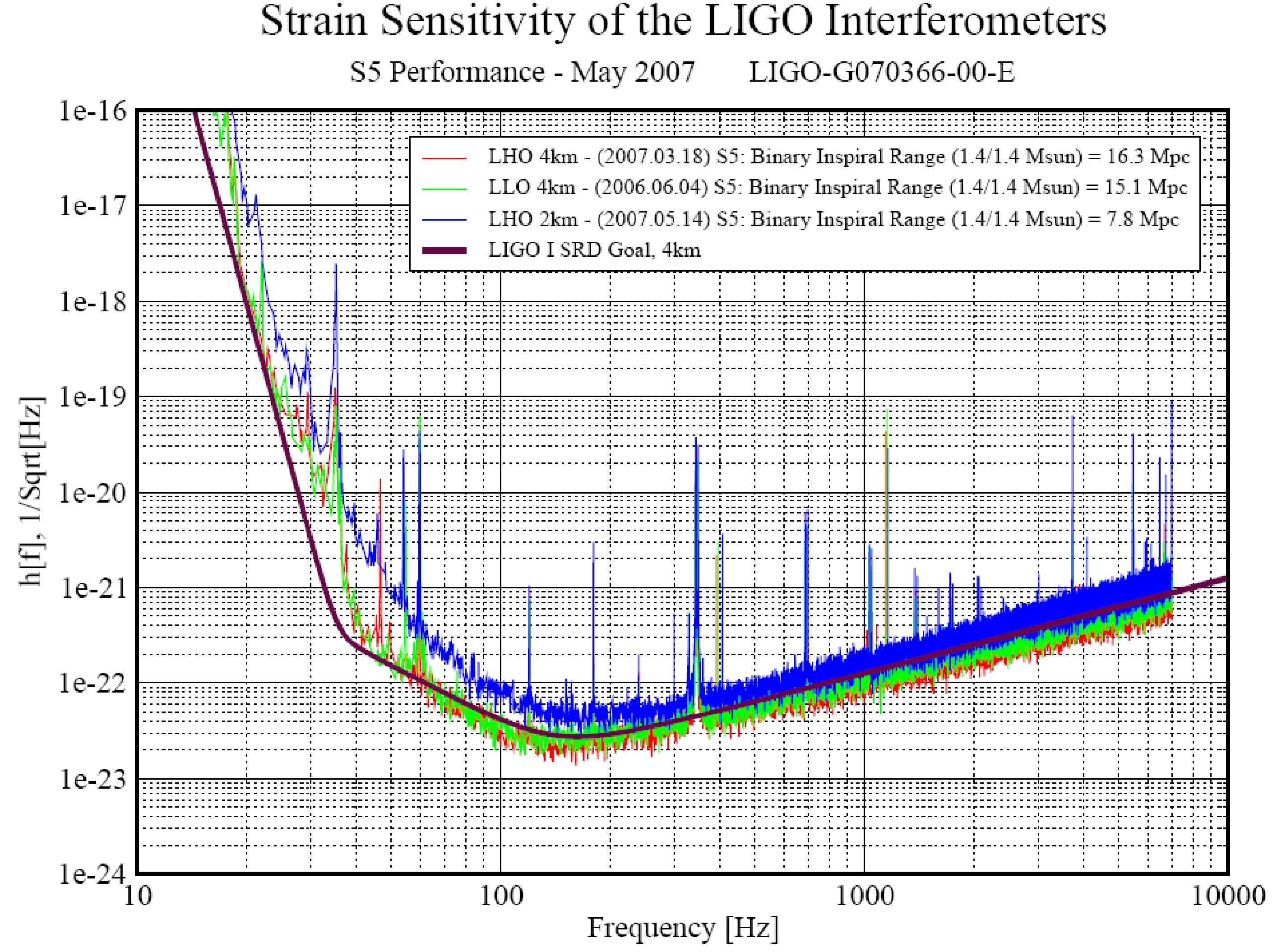
LIGO-G0900501-v3

A radio telescope and GW search for astrophysical transients

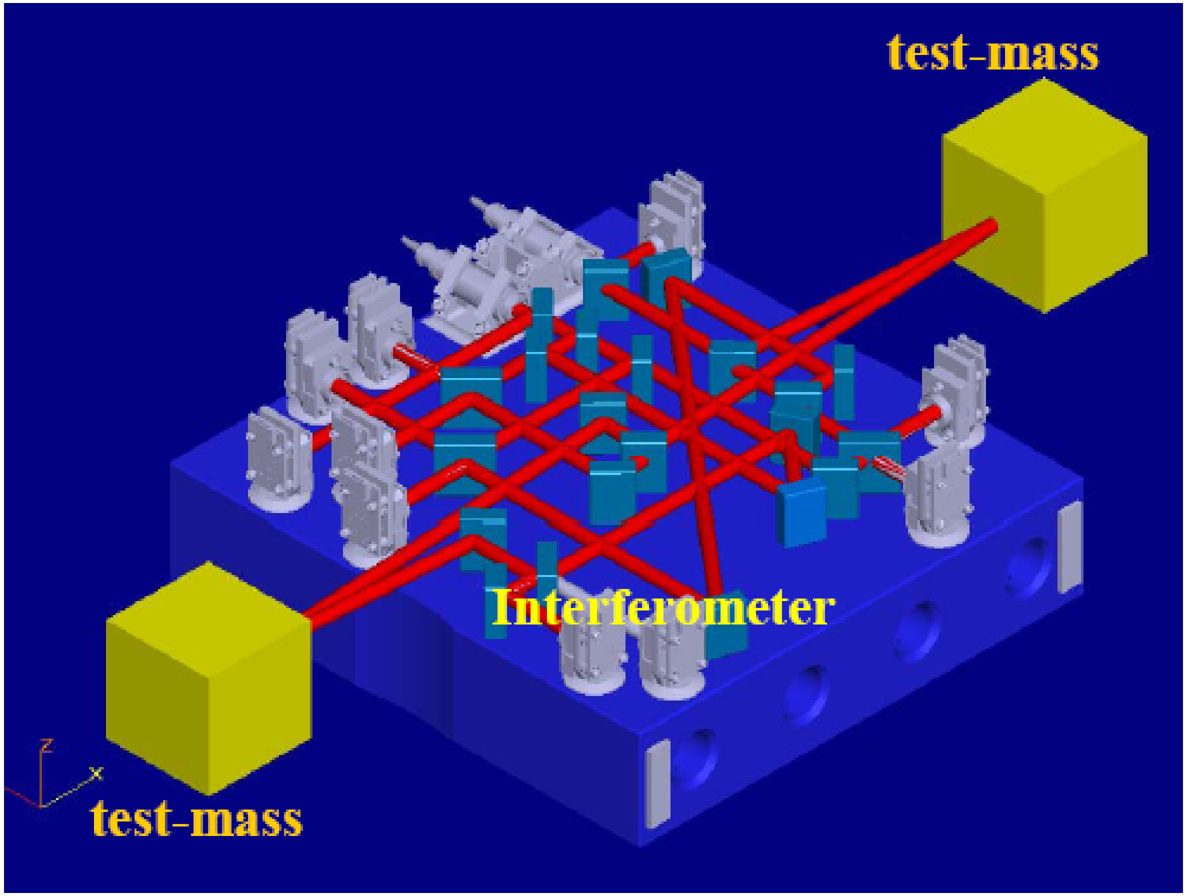
Valeriu Predoi
for the LSC Radio Analysis Group,
Amaldi8, June 2009

Slide 1

Current Status 1 -LIGO reached design sensitivity

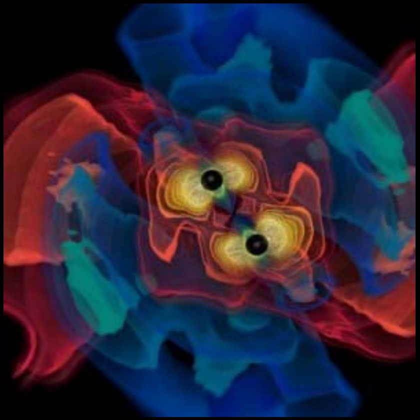


LISA Pathfinder Concept
– Technology demonstrator for launch in 2012



Current status 2

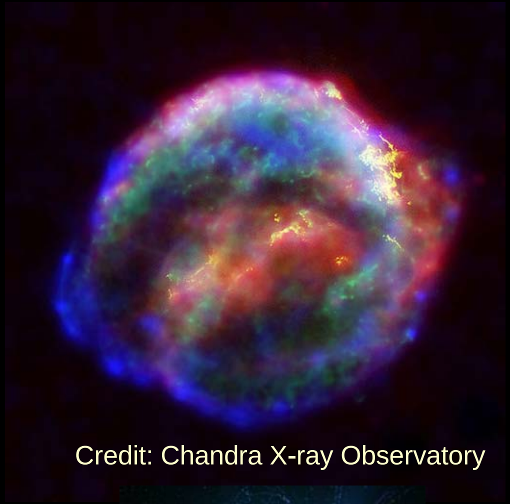
- Initial Science Runs Complete (LIGO, Virgo, GEO 600, TAMA)
- Upper Limits set on a range of sources (no detections as yet)



Credit: AEI, CCT, LSU

Coalescing Binary Systems

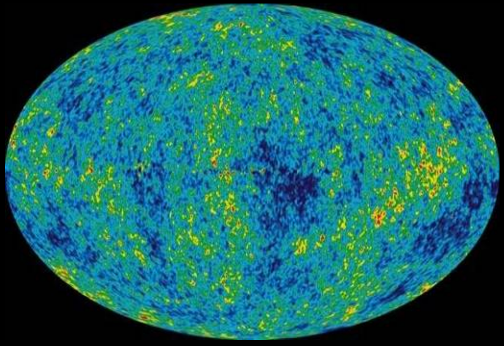
- Neutron stars, low mass black holes, and NS/BS systems



Credit: Chandra X-ray Observatory

Bursts'

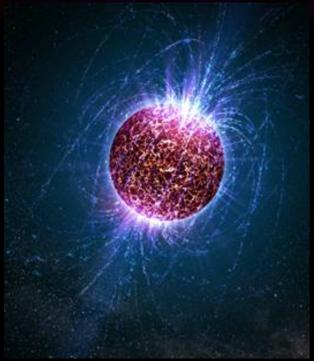
- galactic asymmetric core collapse supernovae
- cosmic strings
- ???



NASA/WMAP Science Team

Cosmic GW background

- stochastic, incoherent background
- unlikely to detect, but can bound in the 10-10000 Hz range



Casey Reed, Penn State

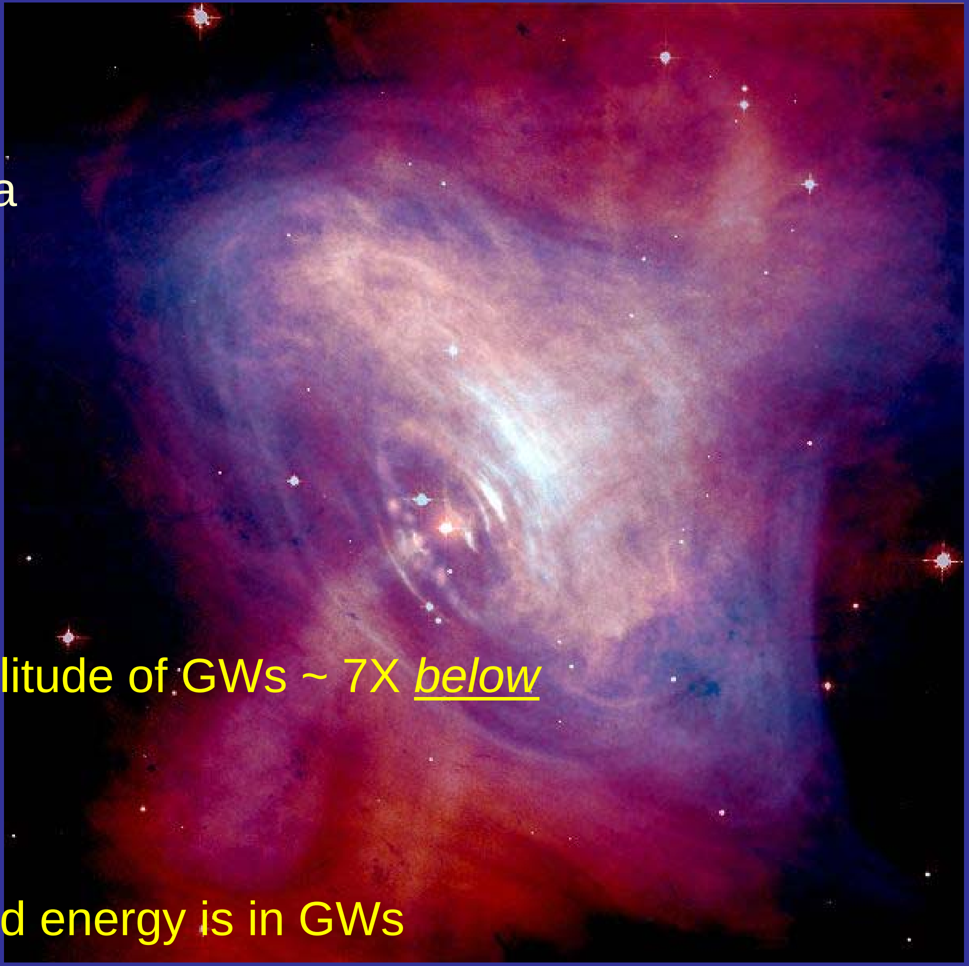
Continuous Sources

- Spinning neutron stars
- probe crustal deformations, 'quarki-ness'

An example

The Crab Pulsar: *Beating the Spin Down Limit – Glasgow*

Abbott, et al., *"Beating the spin-down limit on gravitational wave emission from the Crab pulsar,"* Ap. J. Lett. **683**, L45-L49, (2008).



- Remnant from supernova in year 1054
- Spin frequency ν_{EM} = 29.8 Hz

  → $\nu_{gw} = 2\ \nu_{EM}$ = 59.6 Hz
- observed luminosity of the Crab nebula

accounts for < 1/2 spin down power

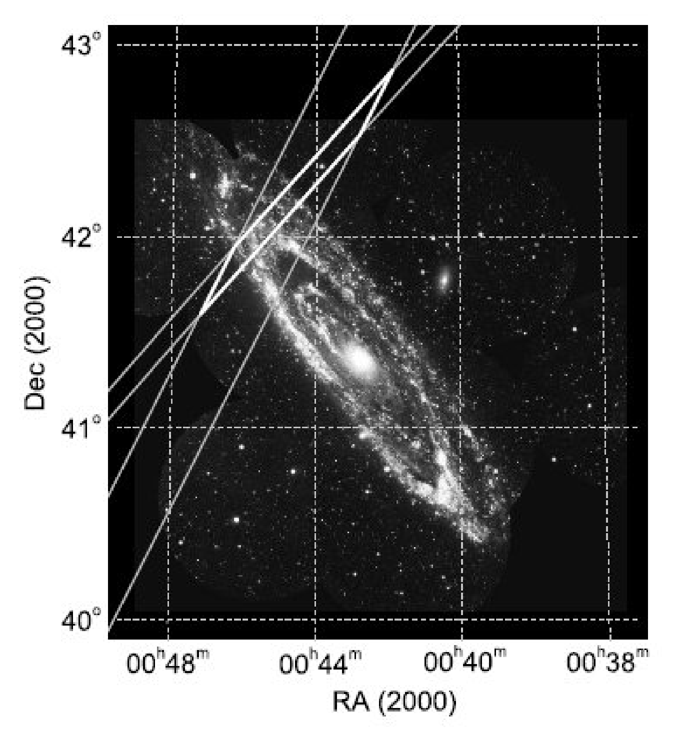
- spin down due to:
  - electromagnetic braking
  - particle acceleration
  - *GW emission?*
- LIGO S5 result: $h < 3.9 \times 10^{-25}$ → Amplitude of GWs ~ 7X *below*

  the spin down limit
- ellipticity upper limit: $\varepsilon < 1.1 \times 10^{-4}$
- GW energy upper limit < 2% of radiated energy is in GWs

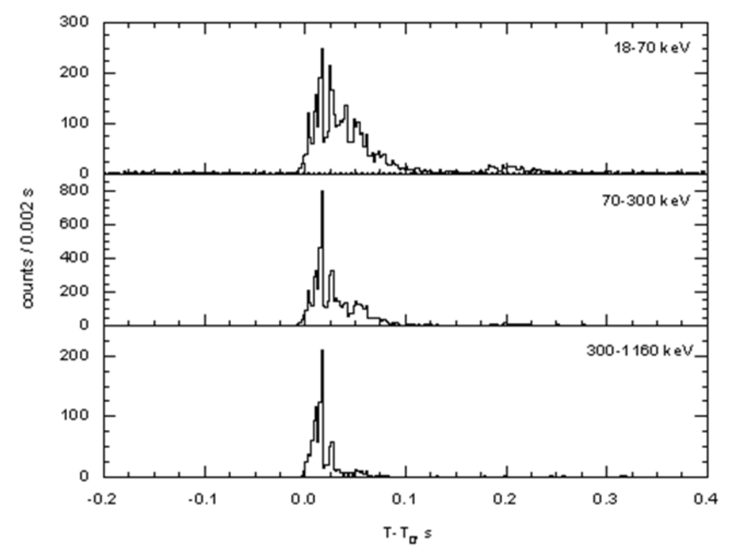
Example 2

GRB 070201

Refs:
GCN: http://gcn.gsfc.nasa.gov/gcn3/6103.gcn3



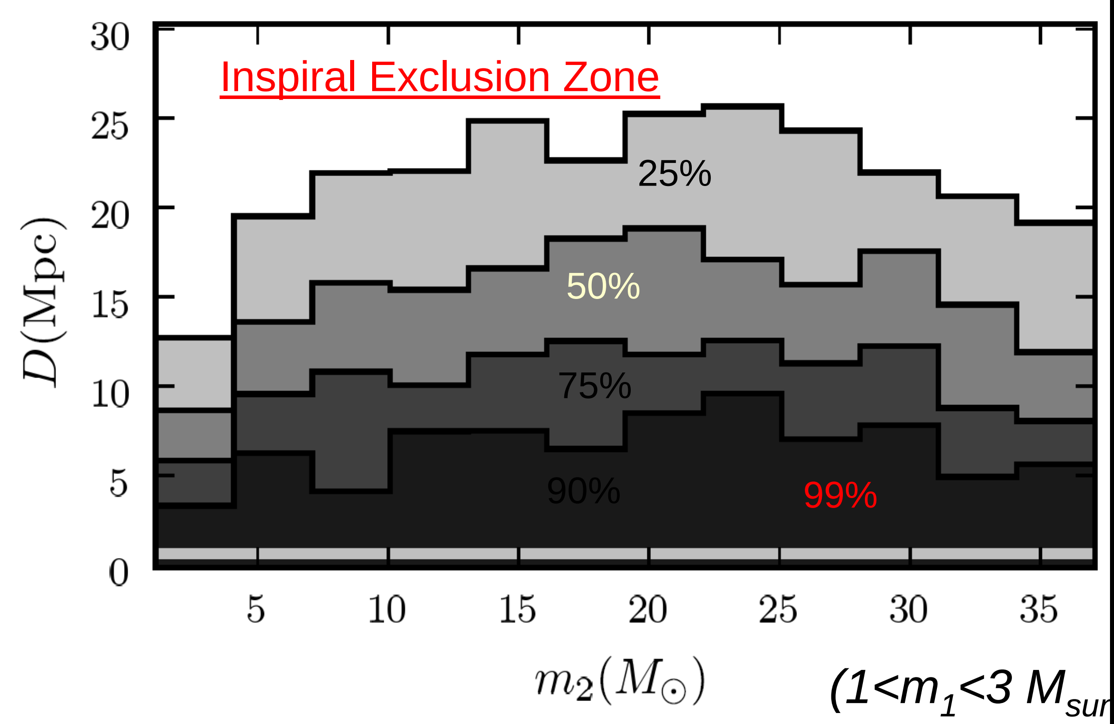
X-ray emission curves (IPN)



GRB070201: *Not a Binary Merger in M31, maybe a soft gamma ray repeater (sgr)*

- Inspiral (matched filter search:
  - Binary merger in M31 scenario excluded at >99% level
  - Exclusion of merger at larger distances

Abbott, et al. "Implications for the Origin of GRB 070201 from LIGO Observations", Ap. J., 681:1419–1430 (2008).



$(1<m_1<3\ M_{sun}$

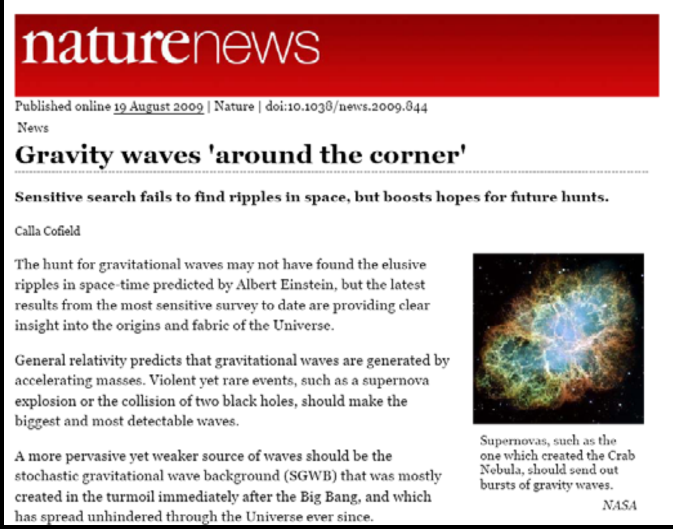
- **Burst search:**
  - **Cannot exclude an SGR in M31**
    - **SGR in M31 is the current best explanation for this emission**
  - **Upper limit: 8×10^{50} ergs ($4\times10^{-4}\ M_\odot c^2$) (emitted within 100 ms for isotropic emission of energy in GW at M31 distance)**

Example 3

The Stochastic GW Background

- **An isotropic stochastic GW background could come from:**
  - **Primordial universe (inflation)**
  - **Incoherent sum of point emitters isotropically distributed over the sky**
- *Preliminary* **LIGO/Virgo result, 90% C.L. limit:**

$$\boxed{\Omega_{0,\,\mathrm{LIGO}} < 9.0 \times 10^{-6}}$$



naturenews

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News

Gravity waves 'around the corner'

Sensitive search fails to find ripples in space, but boosts hopes for future hunts.

Calla Cofield

The hunt for gravitational waves may not have found the elusive ripples in space-time predicted by Albert Einstein, but the latest results from the most sensitive survey to date are providing clear insight into the origins and fabric of the Universe.

General relativity predicts that gravitational waves are generated by accelerating masses. Violent yet rare events, such as a supernova explosion or the collision of two black holes, should make the biggest and most detectable waves.

A more pervasive yet weaker source of waves should be the stochastic gravitational wave background (SGWB) that was mostly created in the turmoil immediately after the Big Bang, and which has spread unhindered through the Universe ever since.

Supernovas, such as the one which created the Crab Nebula, should send out bursts of gravity waves.

NASA

D. Reitze

Current status 3

- **Enhancements** to LIGO and Virgo at end of commissioning
  - aimed at a factor of two improvement in sensitivity -
  - meanwhile GEO, LIGO and cryogenic bar detectors have maintained 'astrowatch'
- Further science runs started (July 7th 2009)
- 2nd generation
  - Advanced LIGO fully funded (x10 to 15 improved sensitivity, operational ~2014)
  - Advanced Virgo approved
  - GEO conversion and upgrade starting

For Comparison:

- <u>Neutron Star Binaries:</u>
  - Initial LIGO (S5): ~15 Mpc → rate ~1/50yr
  - Adv LIGO: ~ 200 Mpc → rate ~ 40/year

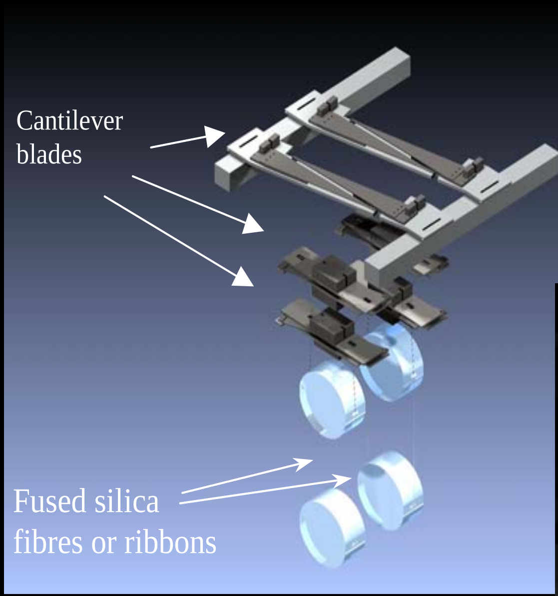
- <u>Black Hole Binaries (Less Certain)</u>:
  - Initial LIGO (S5): ~100 Mpc → rate ~1/100yr
  - Adv LIGO: ~ 1 Gpc → rate ~ 20/year

Advanced LIGO – major GEO involvement

Achieve x10 to x15 sensitivity improvement:

GEO technology being applied to LIGO

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

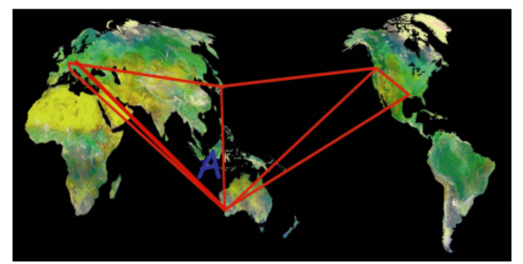


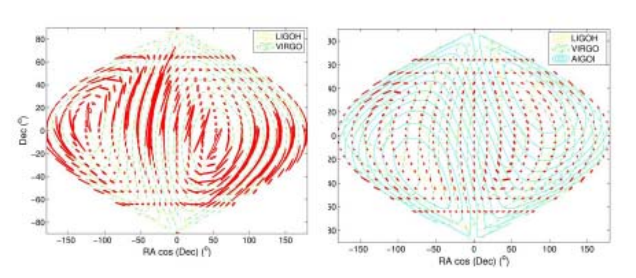
Plus active isolation, high power optics and other input from US groups

RAL, University of Birmingham and University of Glasgow play essential roles in this work

The future of the field in response to anticipated scientific opportunities – on the ground

Need a network of detectors for good source location and improve overall sensitivity





Second Generation Network

Advanced LIGO/Advanced Virgo/Geo-HF/LCGT/AIGO

- **LCGT recently approved for initial phase (proposed cryo, underground interferometer in Kamioka mine)**
- **AIGO plans progressing (real possibility of ALIGO detector being situated in Australia)**

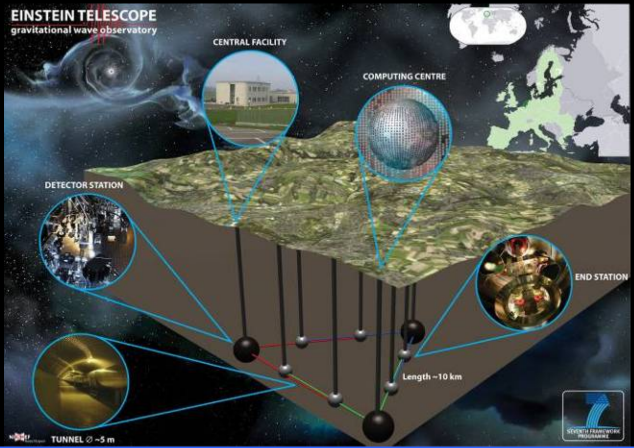
The future of the field in response to anticipated scientific opportunities – on the ground

Third Generation Network — Incorporating Lower Frequ. Detectors

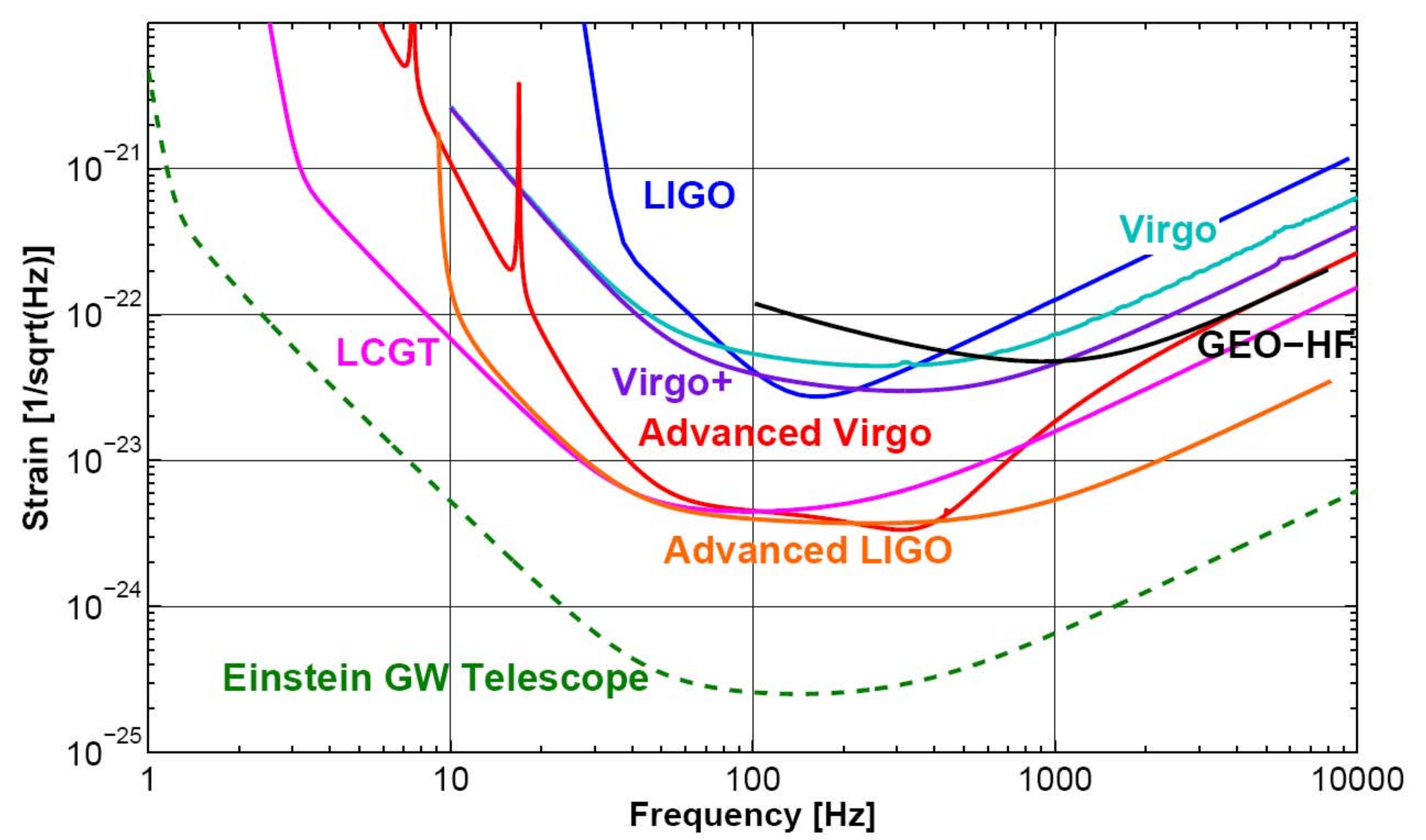
- *Third-generation underground facilities are aimed at having excellent sensitivity from ~1 Hz to ~10^4 Hz.*
- *As such, they will greatly expand the new frontier of gravitational wave astronomy and astrophysics.*

But as "Large increases in cost with questionable increases in performance can be tolerated only in race horses …. " (Lord Kelvin) So we need to approach with great care. Thus -

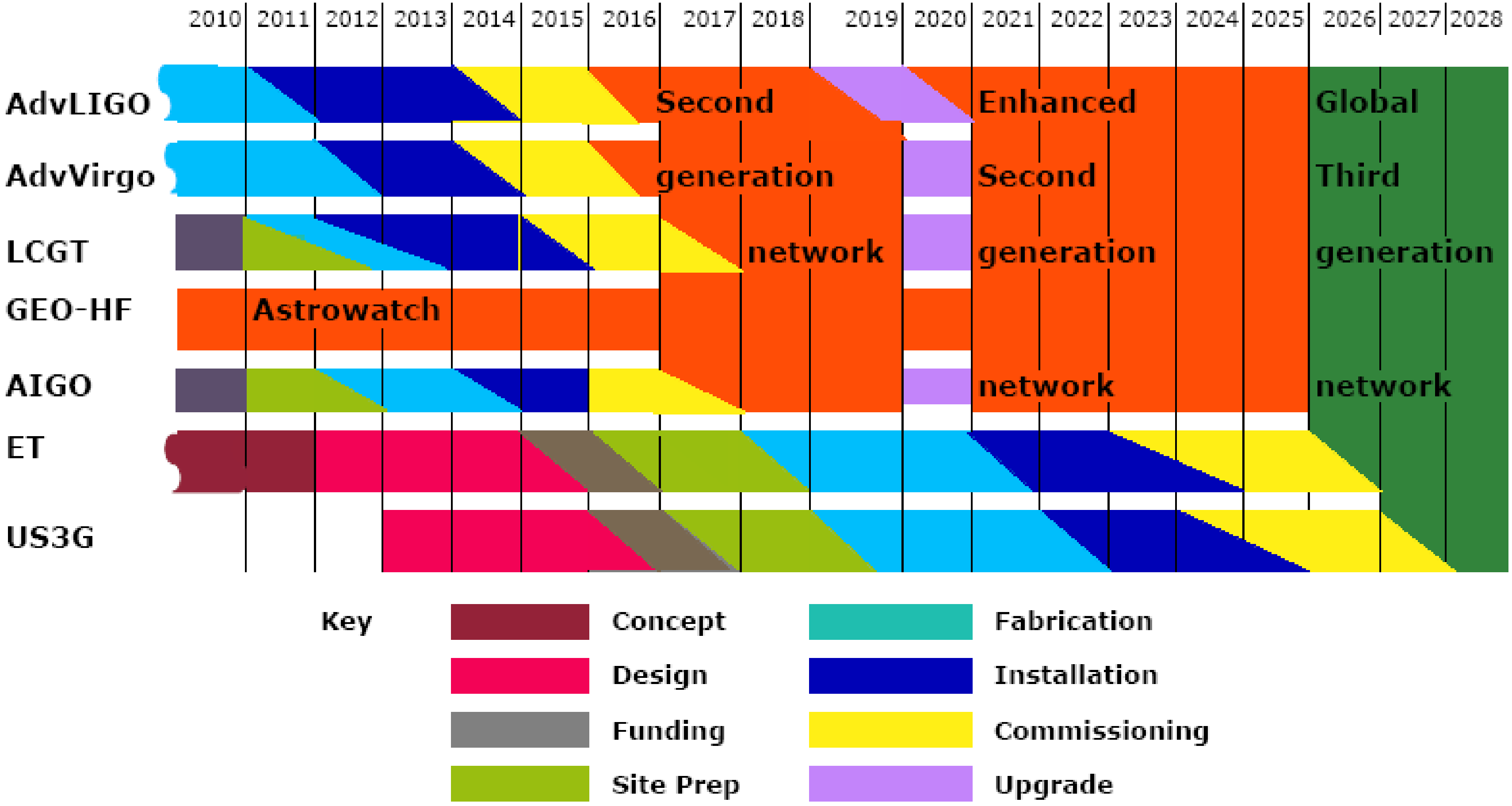
In Europe, a three year-long design study for a third-generation gravitational wave facility, the Einstein Telescope (ET), has recently begun with funding from the European Union. Goal: 100 times better sensitivity than first generation instruments.



The current and planned GW network



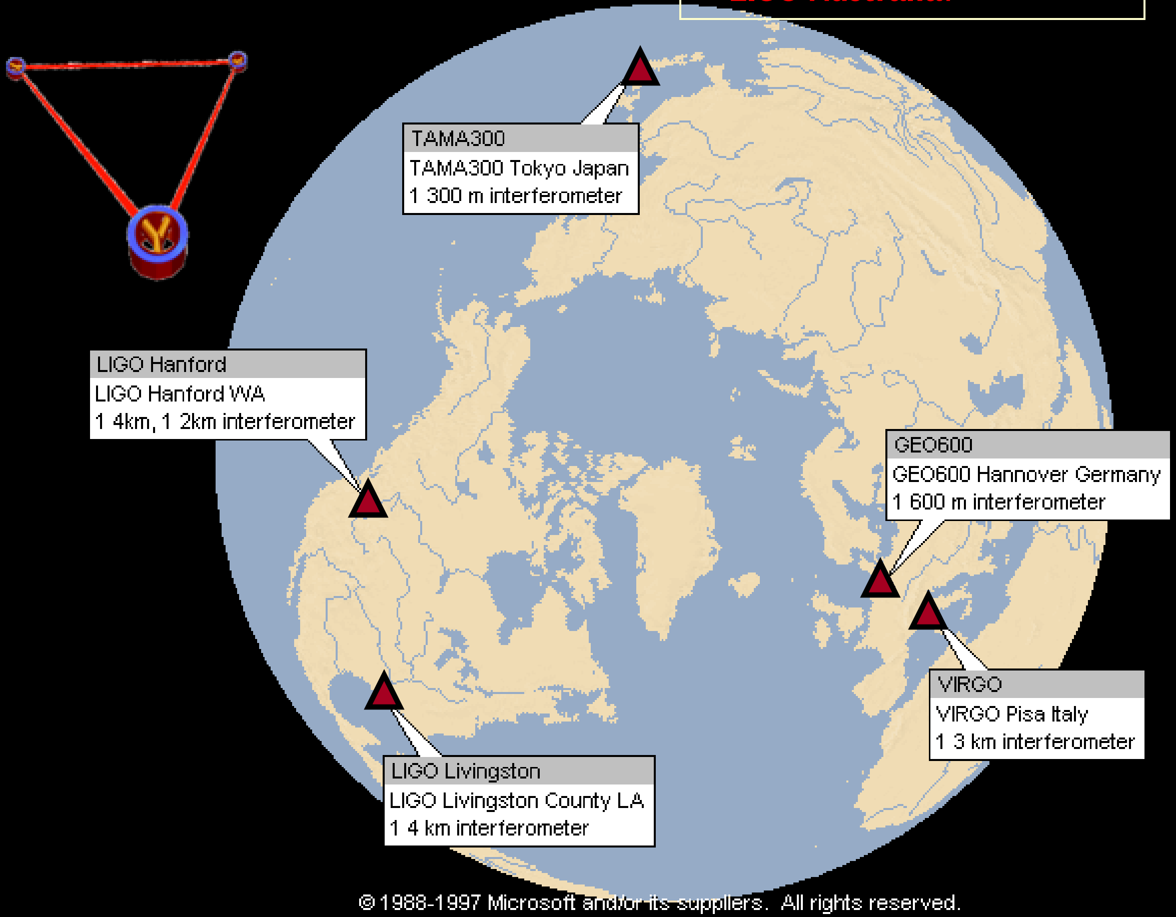
Important Timescales



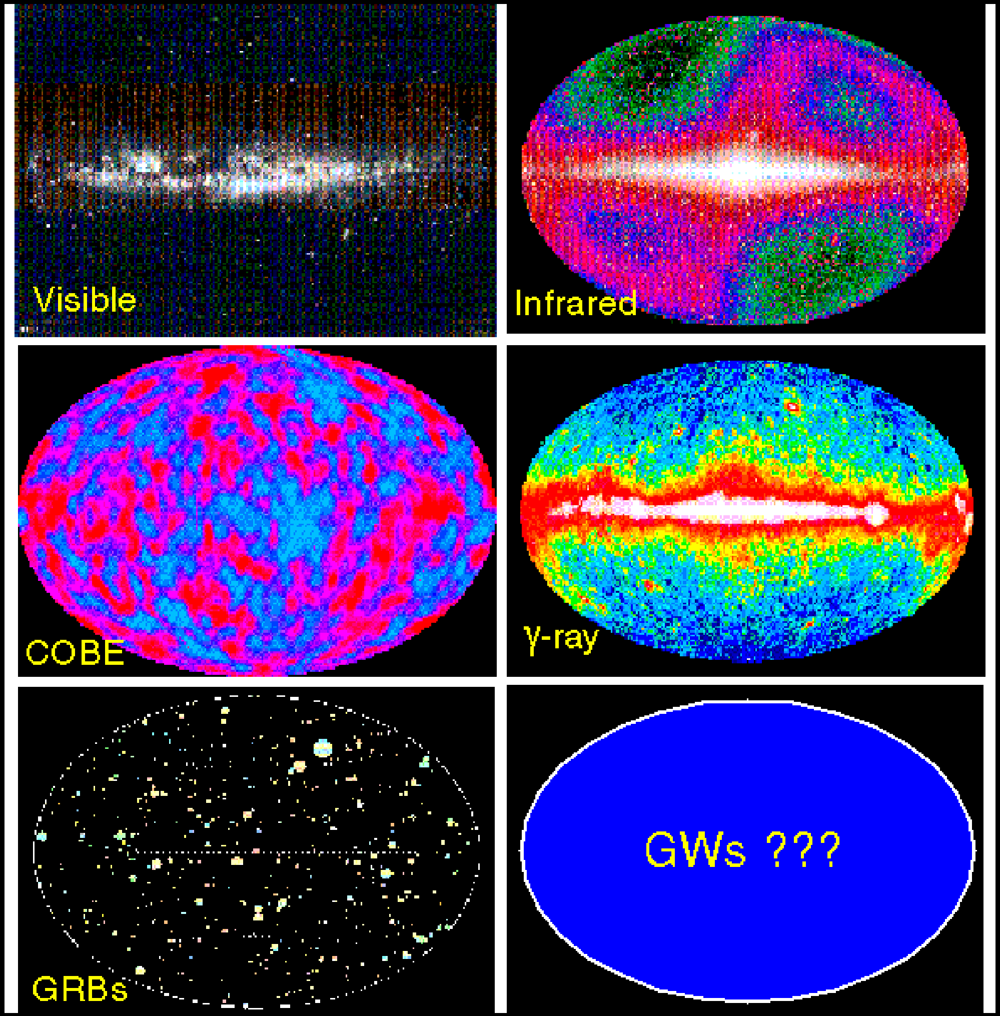
Worldwide Interferometer Network

+ LCGT

+ LIGO Australia?



Gravitational Wave Astronomy



"When you are face to face with a difficulty, you are up against a discovery." **(Lord Kelvin)**

A new way to observe the Universe

Important timescales