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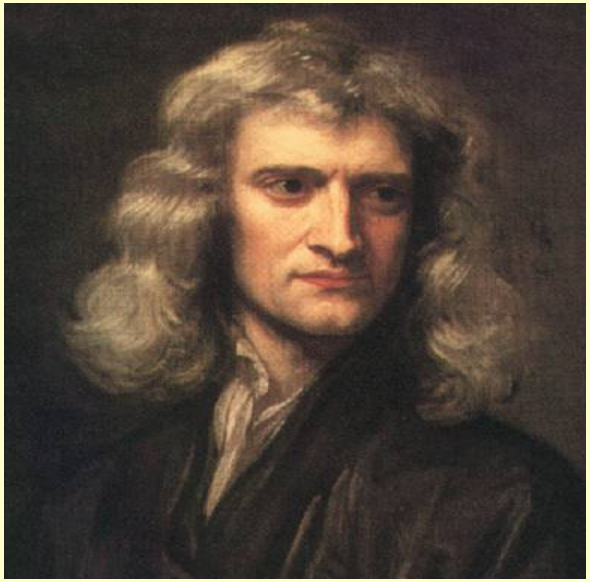
The Search for Gravitational Waves

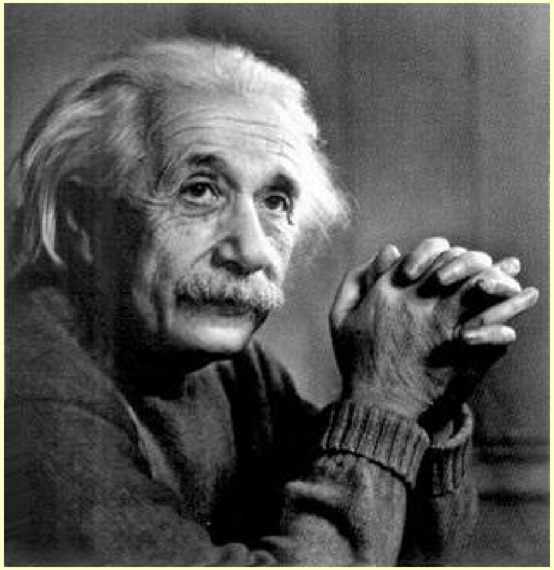
Higgs Maxwell Particle Physics Workshop

Edinburgh February 2010

James Hough, Chair, Gravitational Wave International Committee (GWIC)

Gravitation



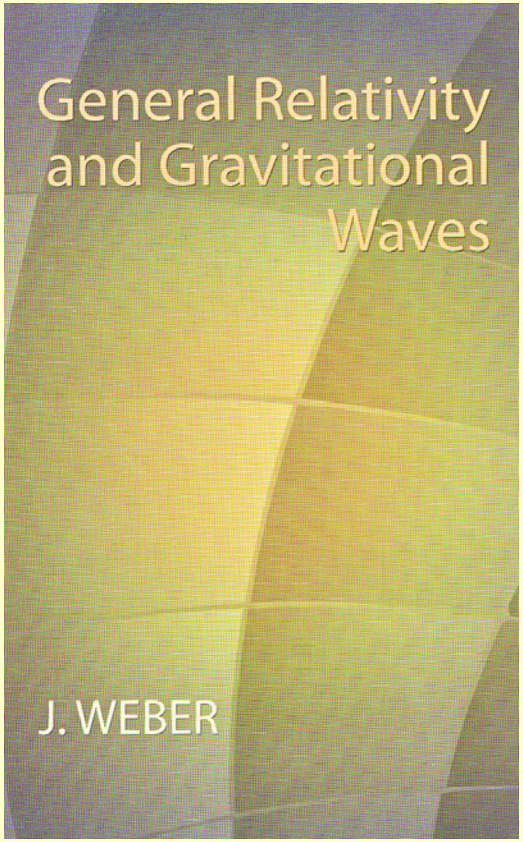


Newton's Theory

"instantaneous action at a distance"

Einstein's Theory

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



GW a prediction of General Relativity (1916)

GW ‘rediscovered’ by Joseph Weber

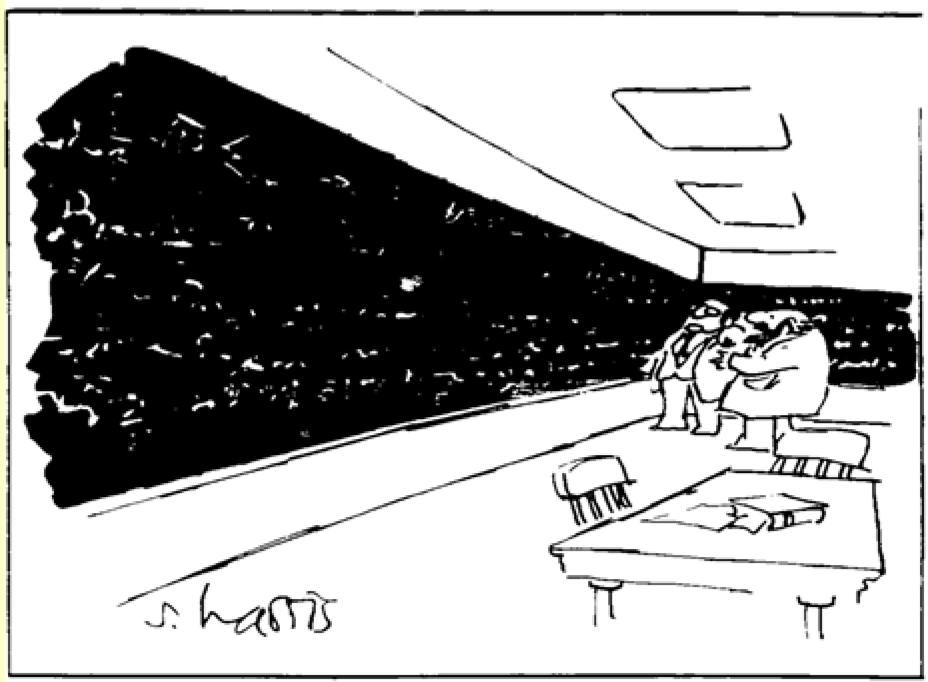
REVIEWS OF MODERN PHYSICS VOL. 29, # 3 JULY, 1957 509–515

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*

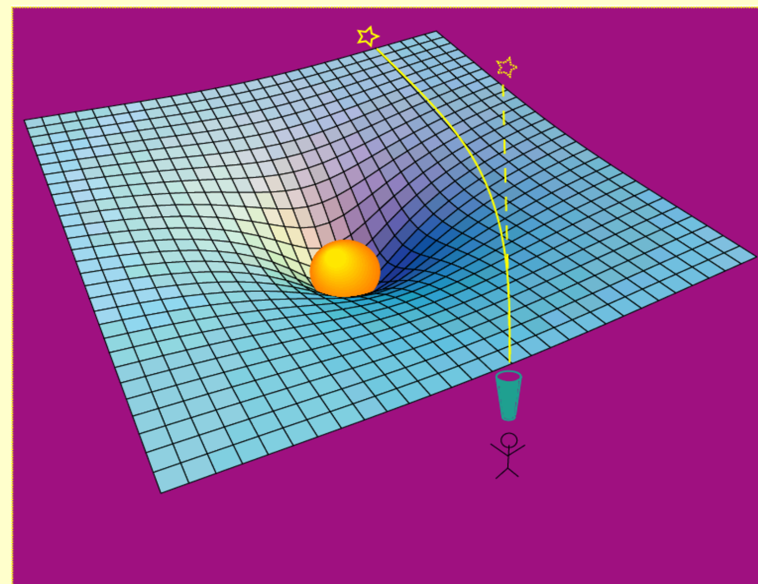
(1961)

Gravitational Waves – what are they?



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

'ripples in the curvature of spacetime' that carry information about changing gravitational fields – or fluctuating strains in space of amplitude *h* where: $h \sim \Delta L/L$



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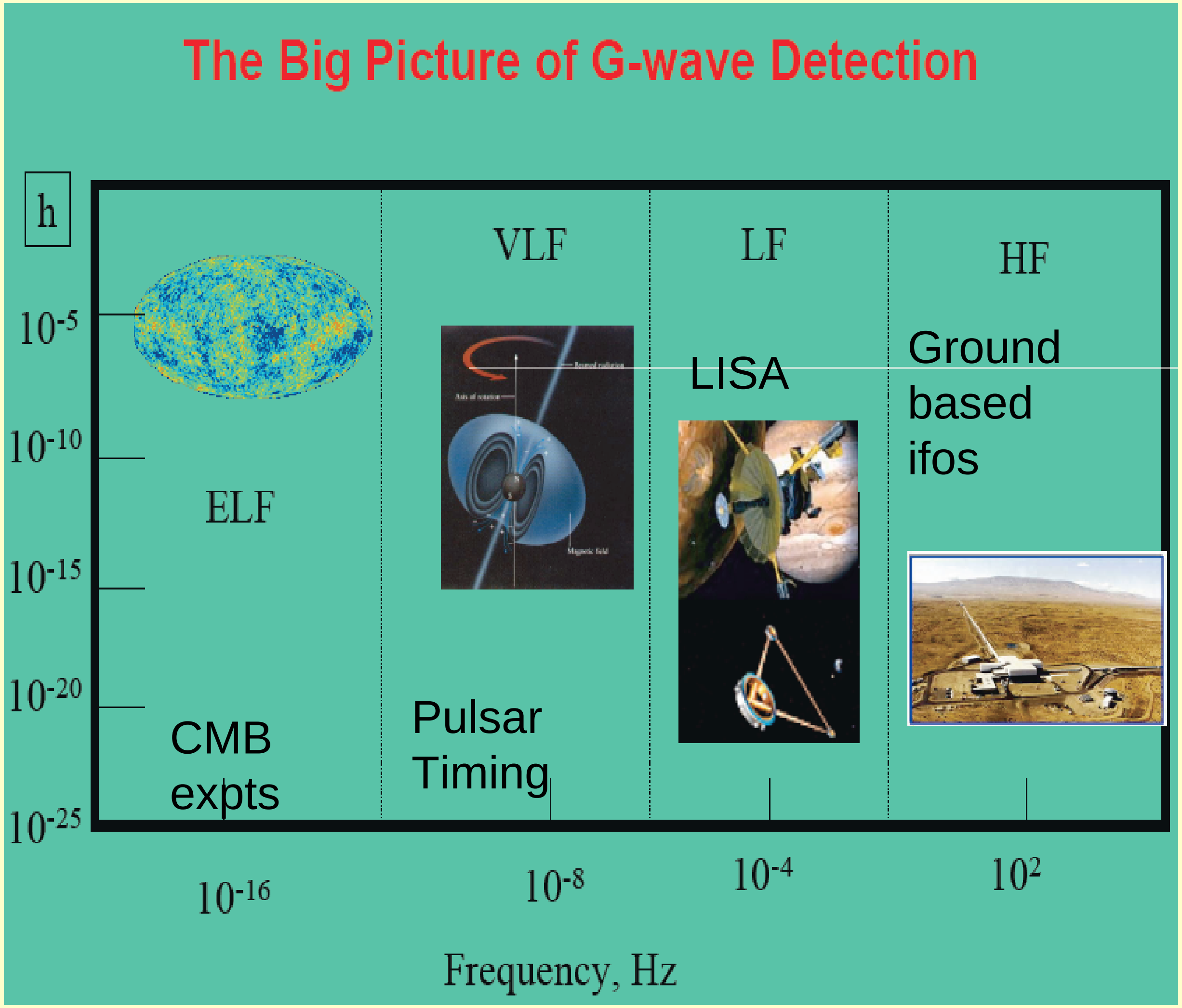
The Gravitational Wave Spectrum



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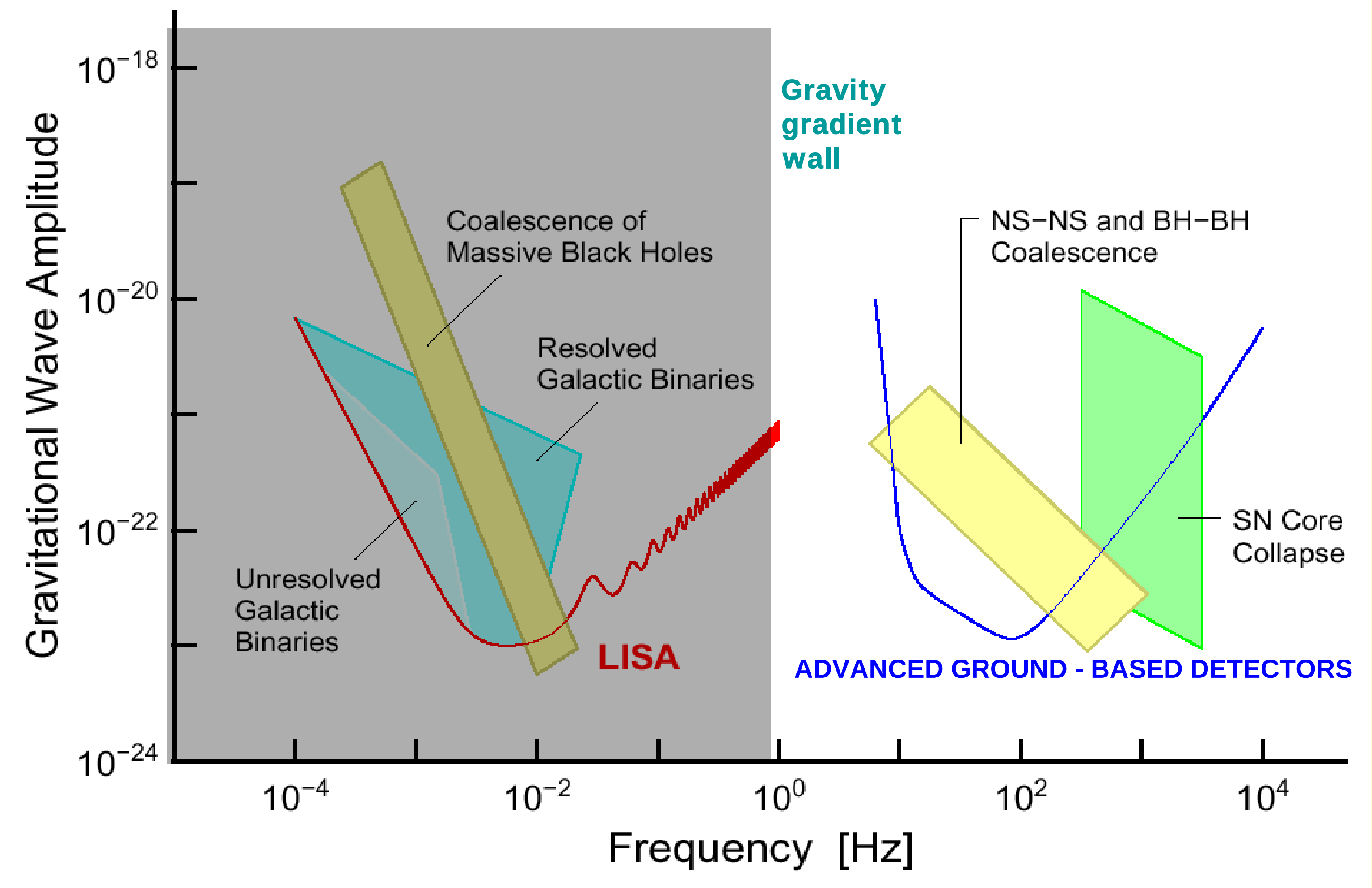
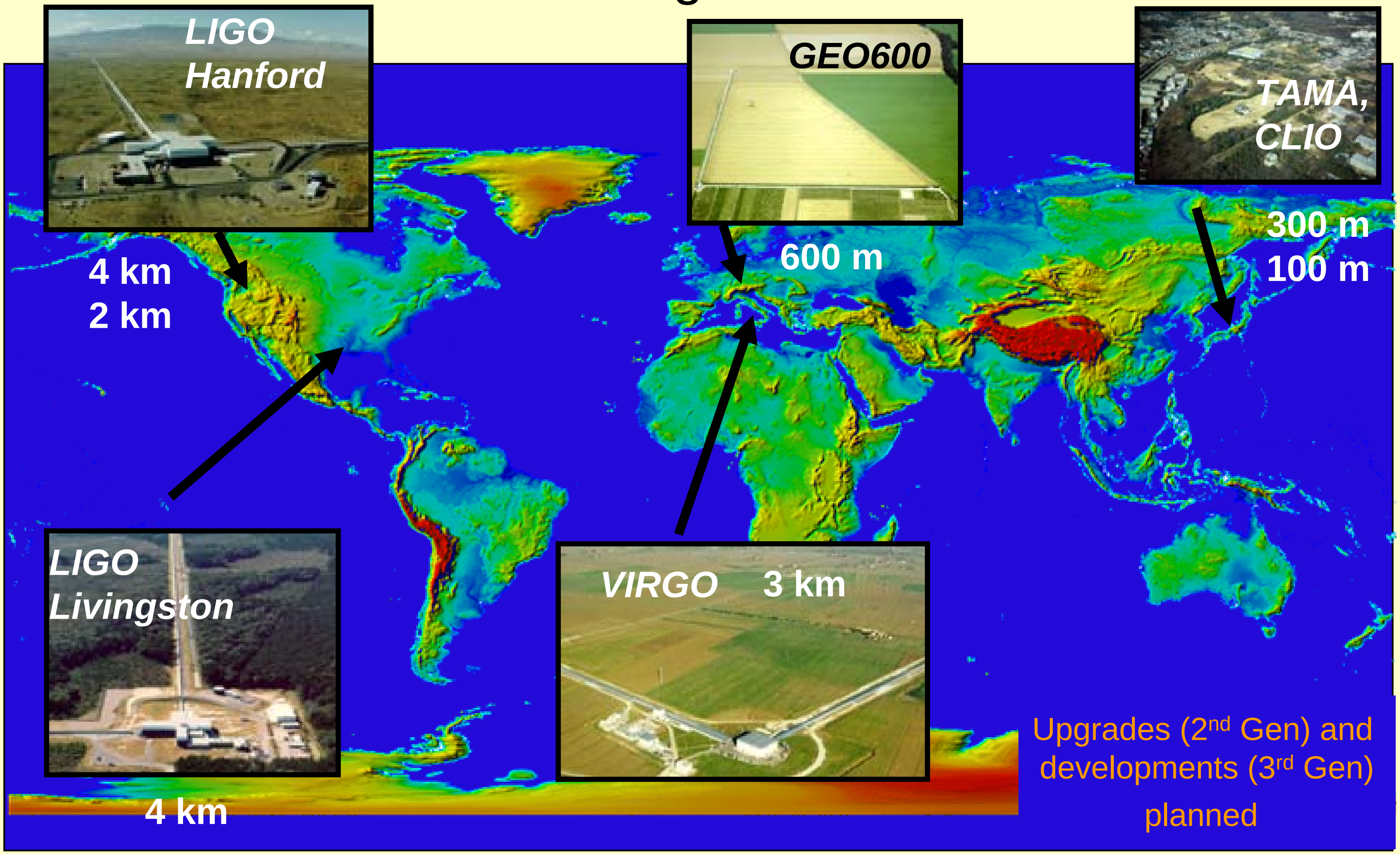


Current worldwide network of ground-based interferometers

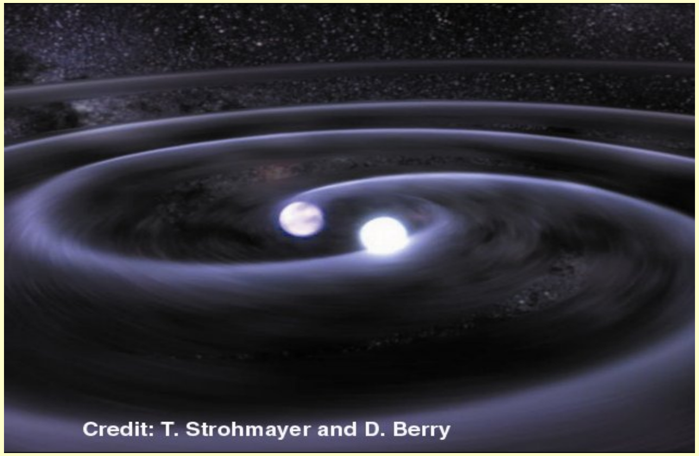


Why?

- Advanced Detectors (LIGO, VIRGO +) will initiate gravitational wave astronomy through the detection of the most luminous sources - compact binary mergers.

- Observation of low frequency gravitational wave with LISA will probe the role of super-massive black holes in galaxy formation and evolution

- Third Generation Detectors (ET and others) will expand detection horizons and provide new tools for extending knowledge of fundamental physics, cosmology and relativistic astrophysics.



Credit: T. Strohmayer and D. Berry

Why? in more detail

- Observations can shed light on many questions:
  - Is the nature of GW as predicted by GR?
  - Are BH space-times uniquely given by Kerr geometry?
  - Do event horizons always form around gravitationally collapsing matter?
  - How did BHs at galactic nuclei form?
  - What were the physical conditions in the early universe?
  - What is the nature of quantum gravity and what is the origin of space and time?
  - Are there really ten to eleven spatial dimensions?
  - The expansion rate of the Universe, relevant to dark energy studies

Real progress over last few years

- Ground based detector operation
- Waveform Predictions from Numerical Relativity
- Space Borne Detectors – LISA and DECIGO
- Pulsar Timing
- Multi-messenger Astronomy – LSC/Virgo MoUs with optical, radio, X & gamma ray, and neutrino astronomy groups

Current status

- Initial Science Runs Complete (LIGO, Virgo, GEO 600)
- Upper Limits set on a variety of sources
- Enhancements to LIGO and Virgo carried out – during down time GEO, LIGO H2 and cryogenic bar detectors have maintained ‘astrowatch’
- New science runs underway at improved sensitivity

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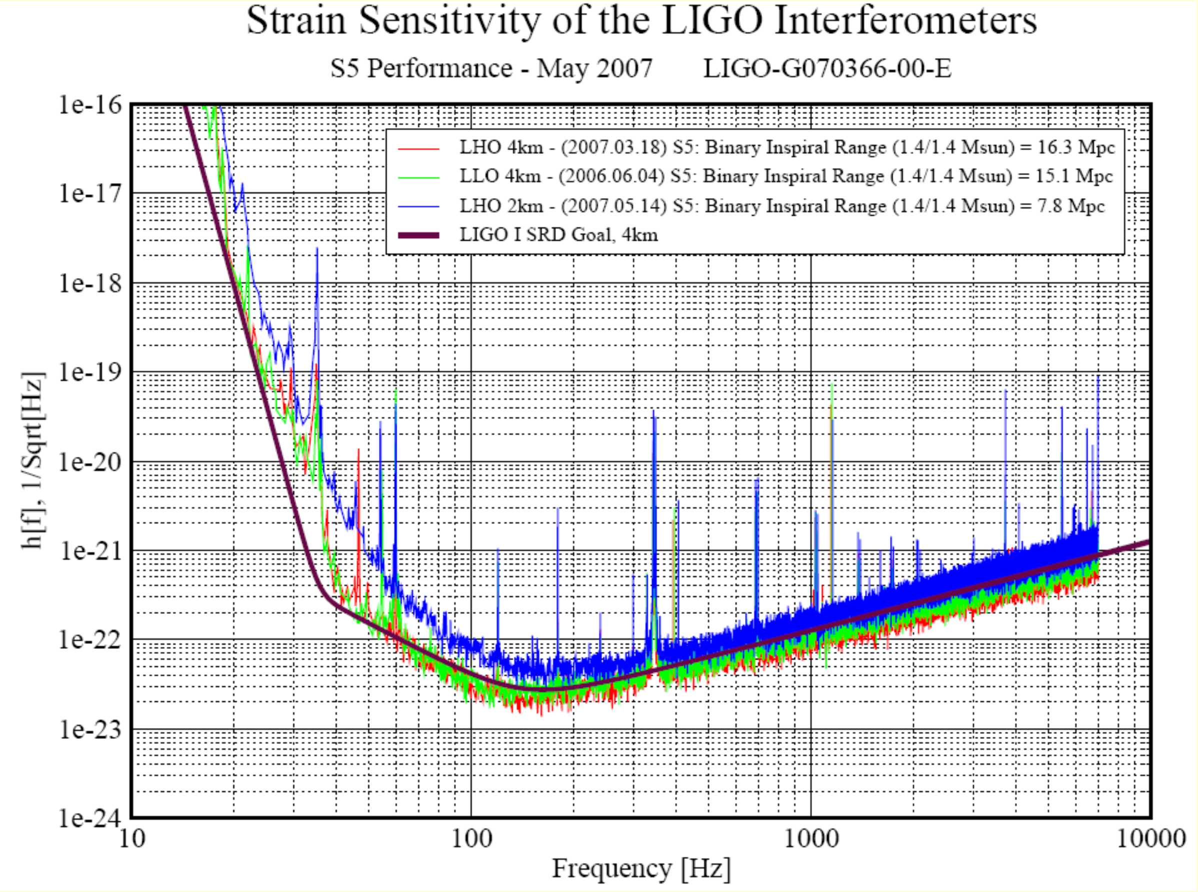
LIGO Sensitivity



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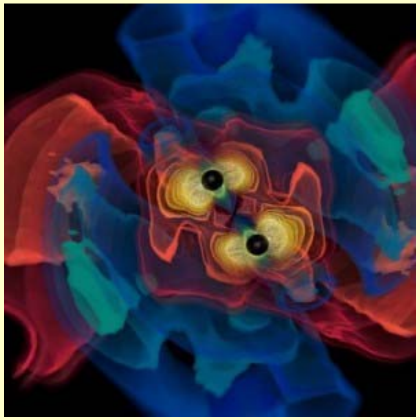
Initial Science Runs Complete (LIGO, Virgo, GEO 600, TAMA)

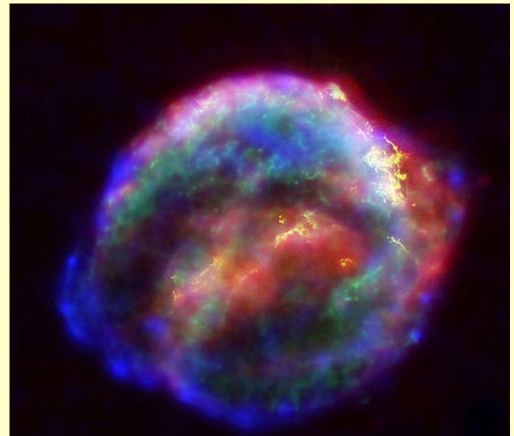
- Upper Limits set on a range of sources (no detections as yet)



Credit: AEI, CCT, LSU

Coalescing Binary Systems

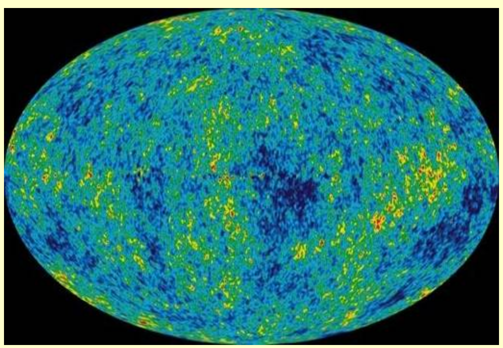
- Neutron stars, low mass black holes, and NS/BS systems



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

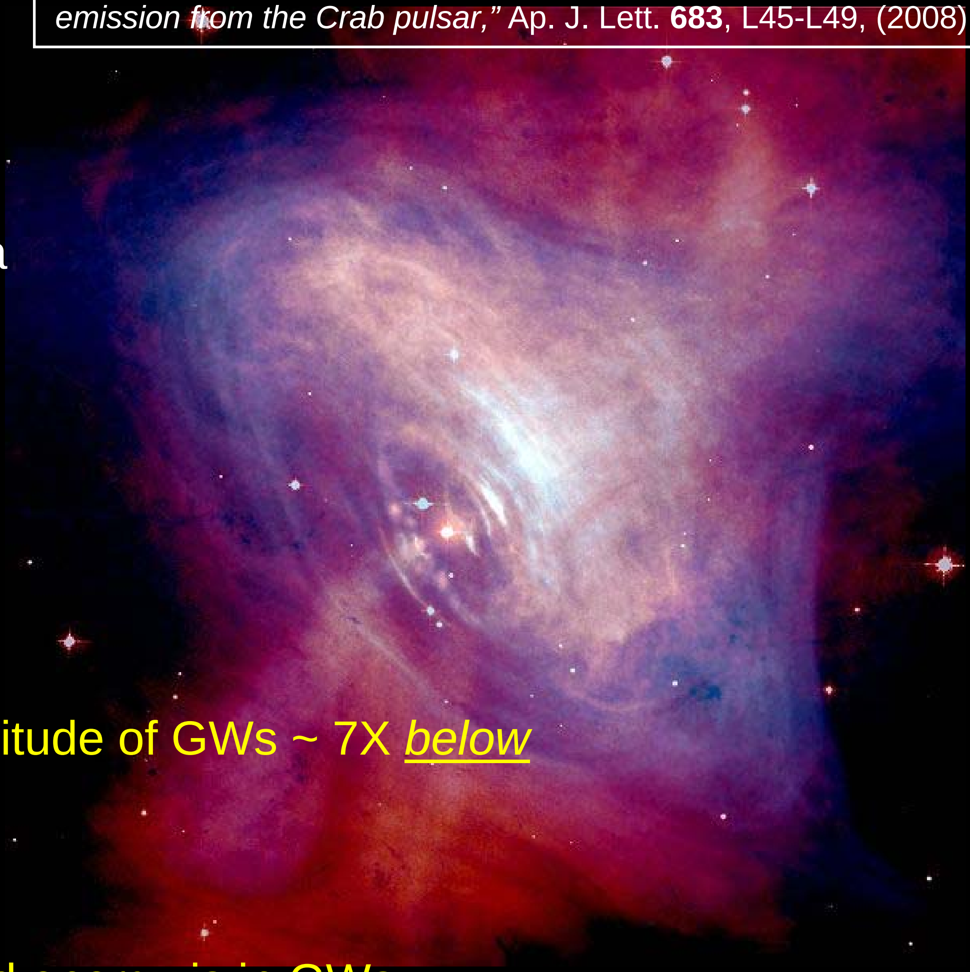
Casey Reed, Penn State

Continuous Sources

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

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

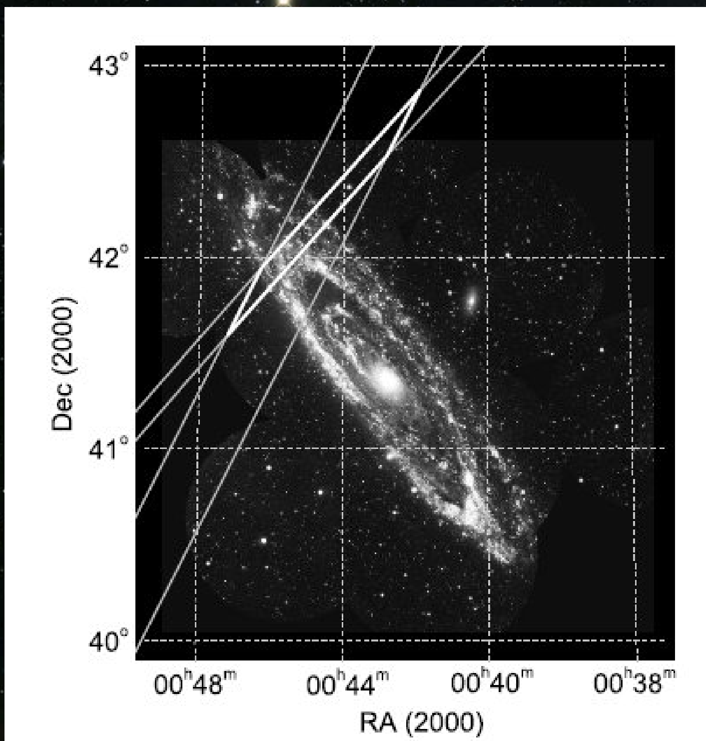
  → $\nu_{gw} = 2\ \nu_{EM}$ = 59.6 Hz
- observed luminosity of the Crab nebula accounts for < 1/2 spin down power
- spin down due to:
  - electromagnetic braking
  - particle acceleration
  - *GW emission?*

- 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

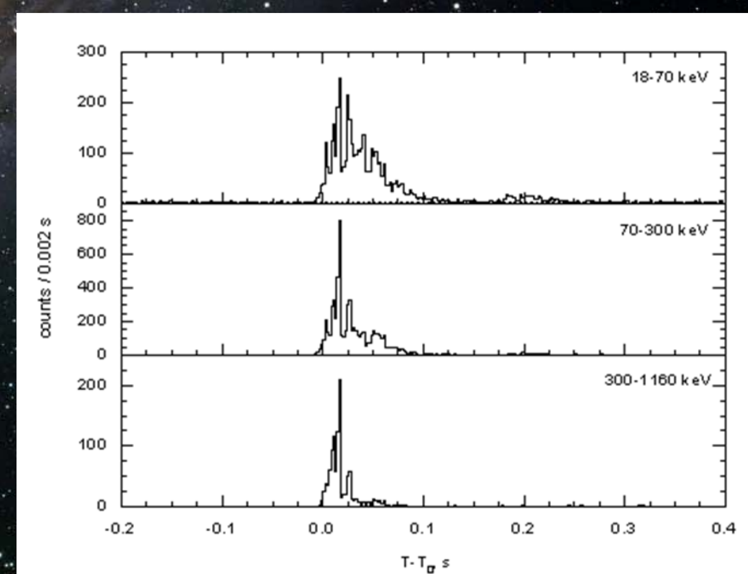
Example 2

GRB 070201

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



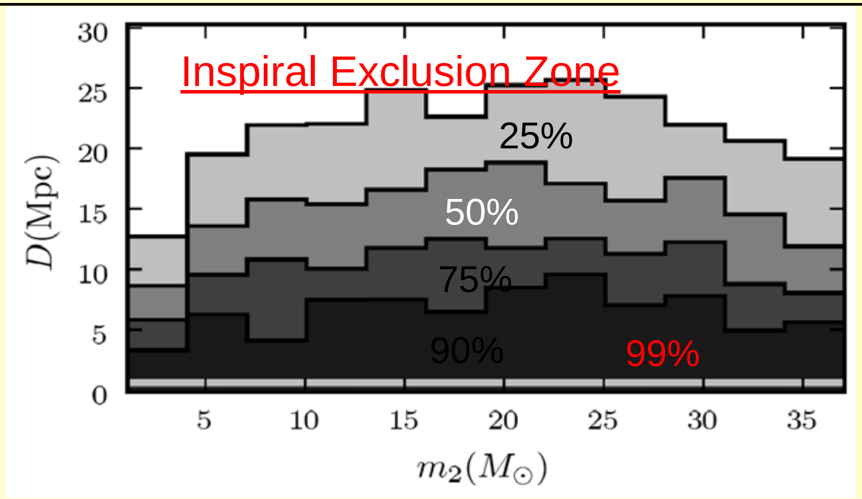
X-ray emission curves (IPN)



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

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

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



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

- **Burst search:**
  - **Cannot exclude an SGR in M31**
    - **SGR in M31 is the current best explanation for this emission**
  - **Upper limit: $8x10^{50}$ ergs ($4x10^{-4}\ M_\bullet c^2$) (emitted within 100 ms for isotropic emission of energy in GW at M31 distance)**

D. Reitze

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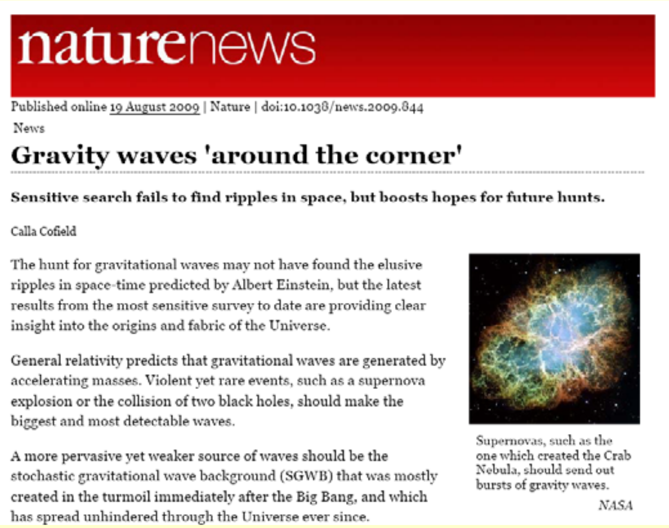
Example 3

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**


naturenews

Published online 19 August 2009 | Nature | doi:10.1038/news.2009.844

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

- ***Preliminary*** **LIGO/Virgo result, 90% C.L.**

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

D. Reitze

Current situation 1: 2nd generation detectors

- Advanced LIGO fully funded (x 10 to 15 improved sensitivity, to be operational ~2014)
- Advanced Virgo approved (as per aLIGO)
- GEO HF conversion starting
- LCGT funding being sought (proposed cryo, underground interferometer in Kamioka mine)

Current situation 2 – Source Rates

For Comparison:

- **Neutron Star Binaries:**
  - **Initial LIGO (S5): ~15 Mpc → rate ~1/50yr**
  - **aLIGO: ~ 200 Mpc → rate ~ 40/year**

- **Black Hole Binaries (Less Certain):**
  - **Initial LIGO (S5): ~100 Mpc → rate ~1/100yr**
  - **aLIGO: ~ 1 Gpc → rate ~ 20/year**

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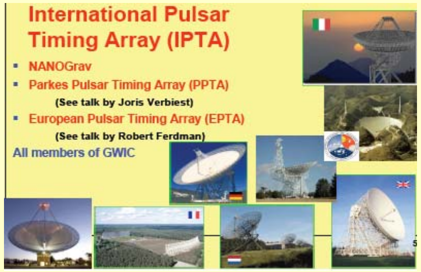
Current situation 3

- AIGO plans progressing (proposed interferometer in Western Australia)
- INDIGO group formed (aiming towards potential detector in India)
- Research towards 2.5/3 generation well under way
- LISA Pathfinder heading to launch in 2012
- International Pulsar Timing Array group (formed from Nanograv (North America), Parkes PTA (Australia) and EPTA (Europe)).



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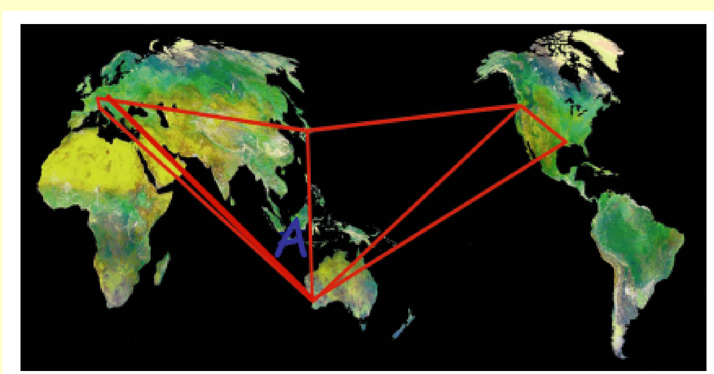
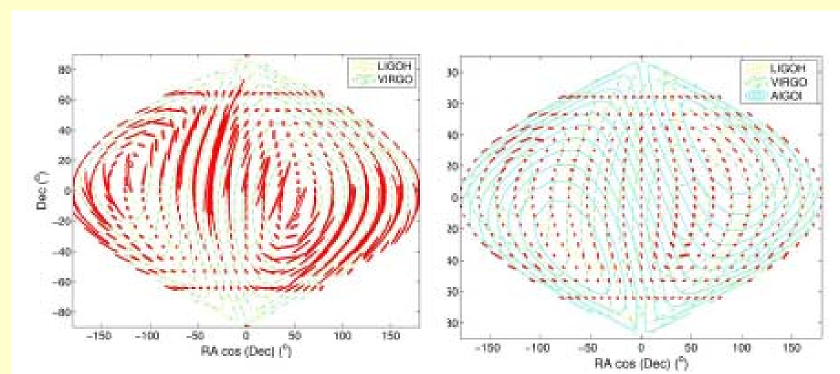
What Needs to be Done? 1

- Make a first detection of gravitational waves – possibly from a coalescing compact binary
- Set up a worldwide ground-based network of appropriate geometry to give accurate source location and distance





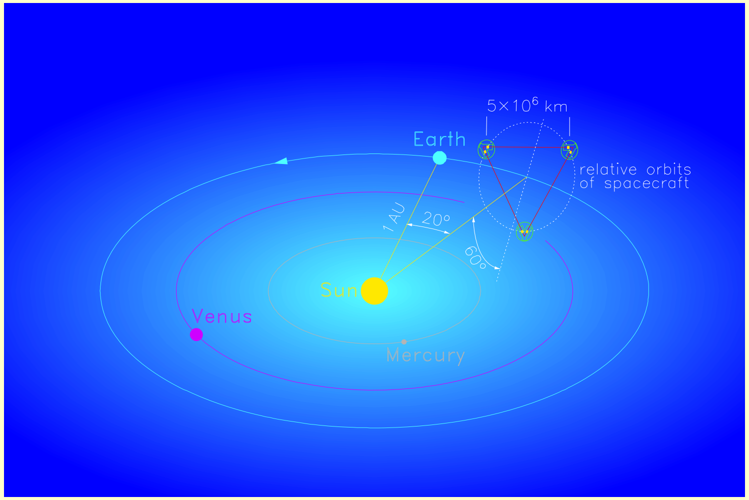
A Global Network

Gives:

- Improved Sky Coverage
  - Non-overlapping antenna pattern $\Rightarrow$ sky coverage
- Improved angular resolution/localisation
  - Longer baselines lead to greater time-delays and thus improved resolution
- Improved distance reach
  - For detectors with overlapping antenna patterns, significant inprovement in distance reach
- Improved 3-way duty cycle
  - With 3 detectors 3 way duty cycle~50%, with 5 detectors 94%

What Needs to be Done? 2

- Fly LISA to explore a wealth of black hole physics at low frequency



- Increase pulsar observing time (dedicated radio-telescope?). Will not discuss further here.

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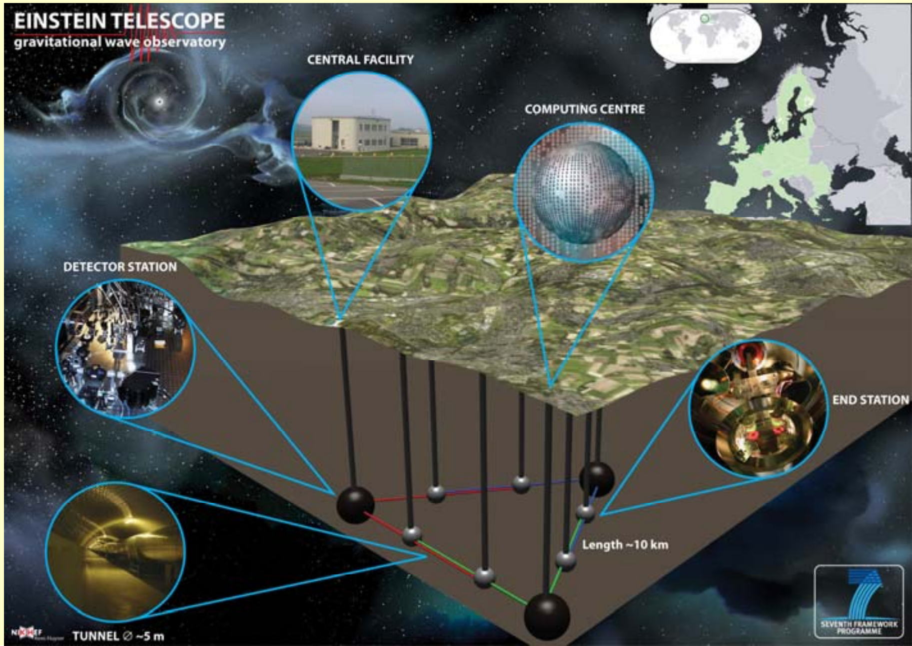
What Needs to be Done? 3

- Increase sensitivity of ground-based detector systems by a further factor of 10 – 3rd generation instruments.
- Ongoing European FP7-funded design study for a 3rd generation detector:

the Einstein Telescope (ET)



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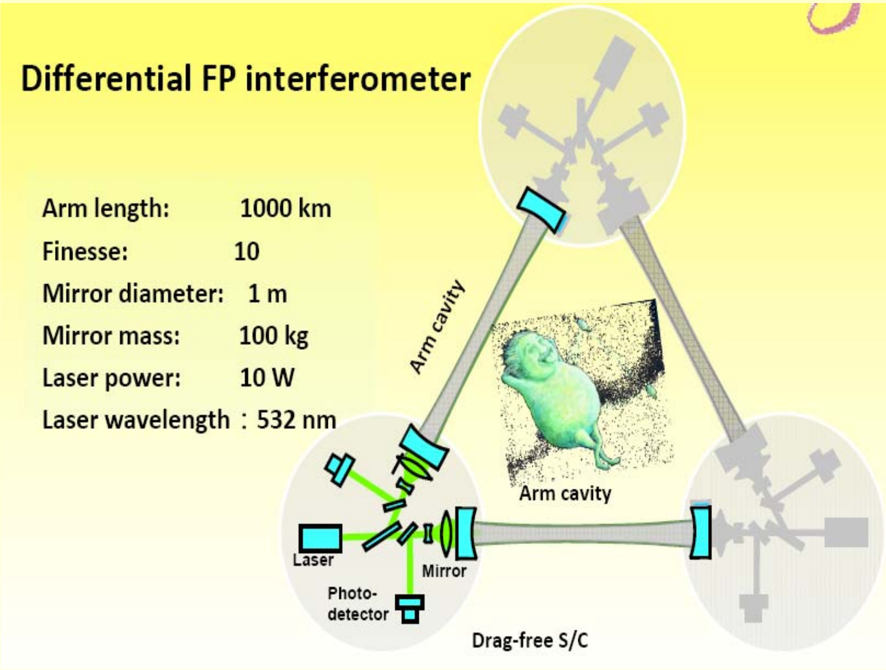
What Needs to be Done? 4

- Fly a LISA follow-on mission operating in the frequency range between LISA and ground-based instruments.

DECIGO - Japanese proposed mission



How?

- First stages
  - Strong international support for timely completion of global network of Advanced Detectors
    - Construction of LCGT in Japan
    - Construction of AIGO in Australia
    - Possibilities in India (INDIGO)
  - Successful launch and operation of LISA Pathfinder to allow LISA to launch in the 2020 timeframe
- And in parallel
  - R&D towards upgrades to Advanced Detectors sharing main technology with third generation detectors to be built underground;
  - Preparatory studies for a third generation detector (ET) in Europe and in the USA (in DUSEL in Homestake mine)

Where?

- Advanced
  - Japan – Kamioka mine
  - Australia – Gingin
  - India – strong interest from ‘INDIGO’ grouping?
- LISA in heliocentric orbit
- 3rd generation
  - Europe – site to be selected – various possibilities
  - USA – DUSEL in Homestake mine
  - Japan – Kamioka?
  - Australia?

Who should build 3G GW Observatories?

- Requires worldwide co-operation in technology and fund raising. GW community already significant (close to 1000 scientists) and continuing to grow.
- Ideally one in Europe, one in USA, one in Southern Hemisphere and one in Far East.
- Strong underpinning framework provided by the LIGO Laboratory and the EGO organisation in Europe.

When? And Cost?

- Start of building of 3 G likely to be dependent on detection by Advanced Detectors
- A cost estimate for European 3G (ET) will be one of the outcomes of the current FP7 funded design study.
- However based on building costs of other detectors we are looking at multi-hundred MEuro per observatory

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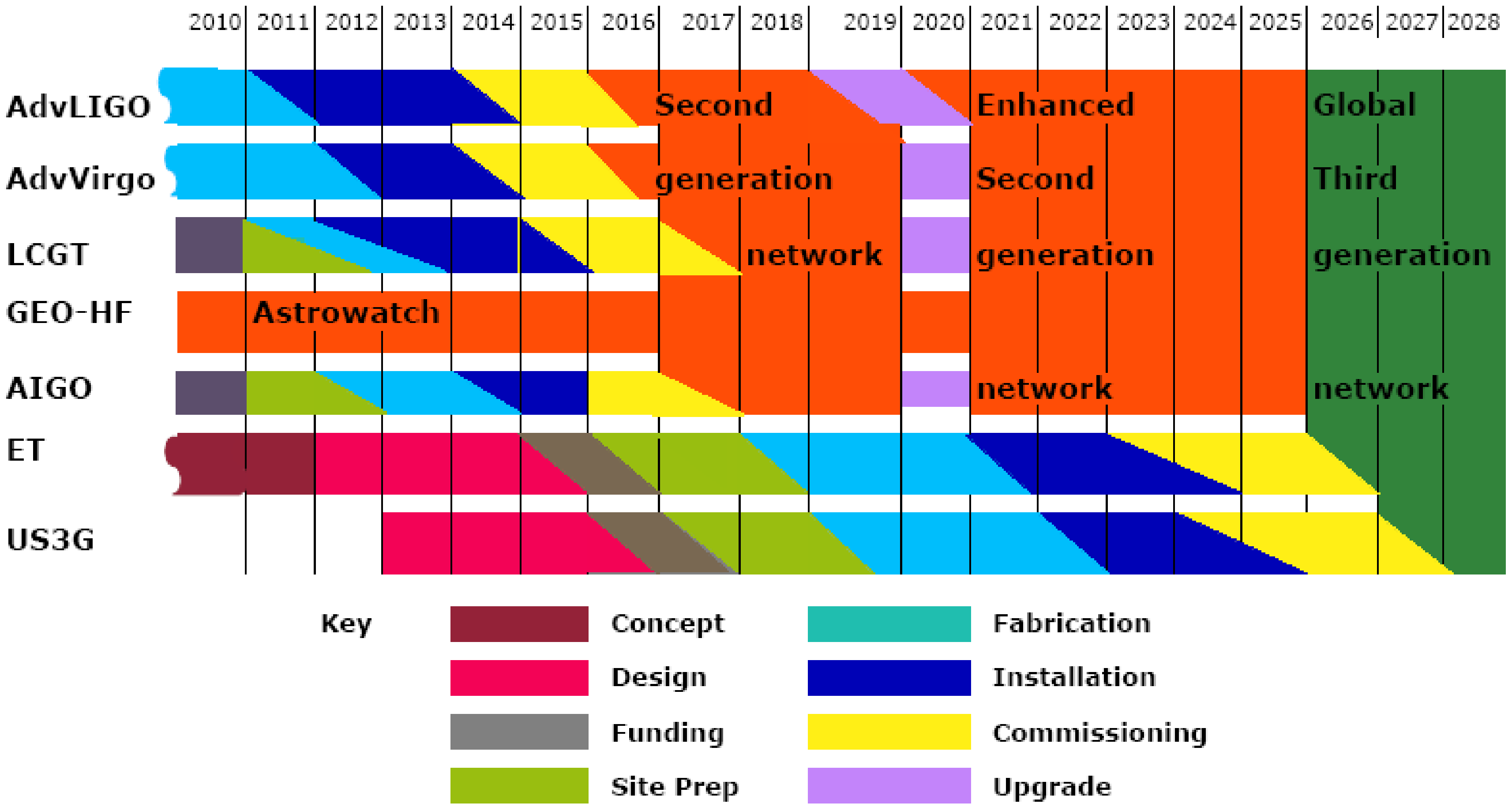
When? And Cost?

- Important Timescales



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Summary of sensitivities (ground based)