Gravitational wave detection: recent progress

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for the LIGO Scientific Collaboration

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The LIGO Scientific Collaboration

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R·I·T
1829

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1855

COLUMBIA UNIVERSITY
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THE UNIVERSITY OF
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ORGANIZED 1891

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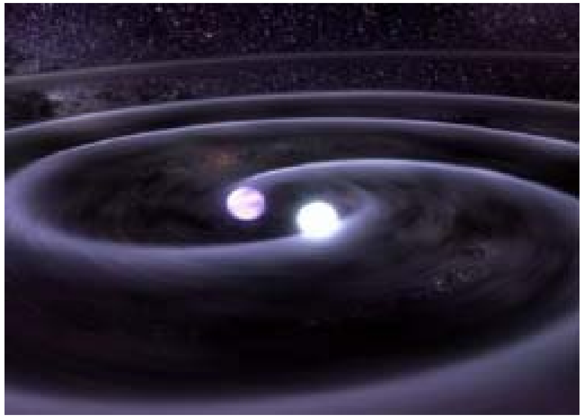
Outline

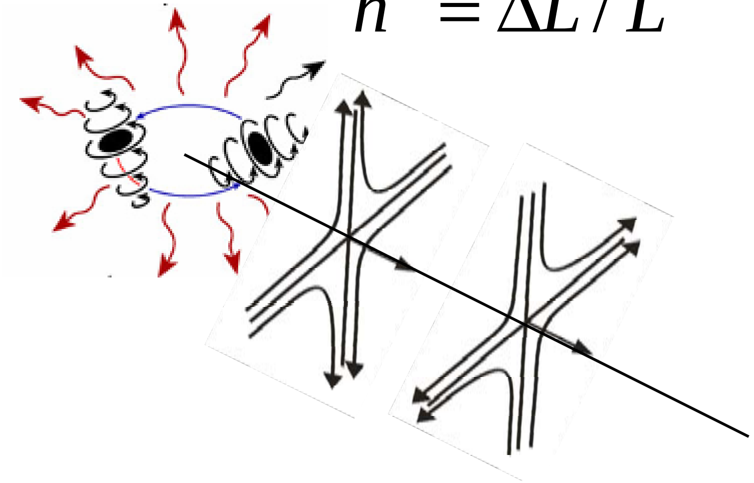
- Review of GW physics
- The Worldwide detector network
  - GEO600: example 1st Generation detector
  - Operational performance
- Example results from the network
- Future detectors
  - Advanced LIGO: 2nd generation detector
  - Science and Technology
  - Other future detectors

Gravitational Waves

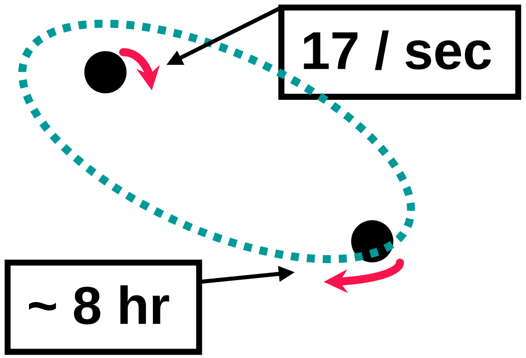
- Einstein (in 1916 and 1918) recognized gravitational waves in his theory of General Relativity
  - necessary consequence of Special Relativity with its finite speed for information transfer
- Time-dependent distortions of space-time created by the acceleration of masses
  - propagate at the speed of light
  - transverse waves
  - characterised by strain-amplitude h



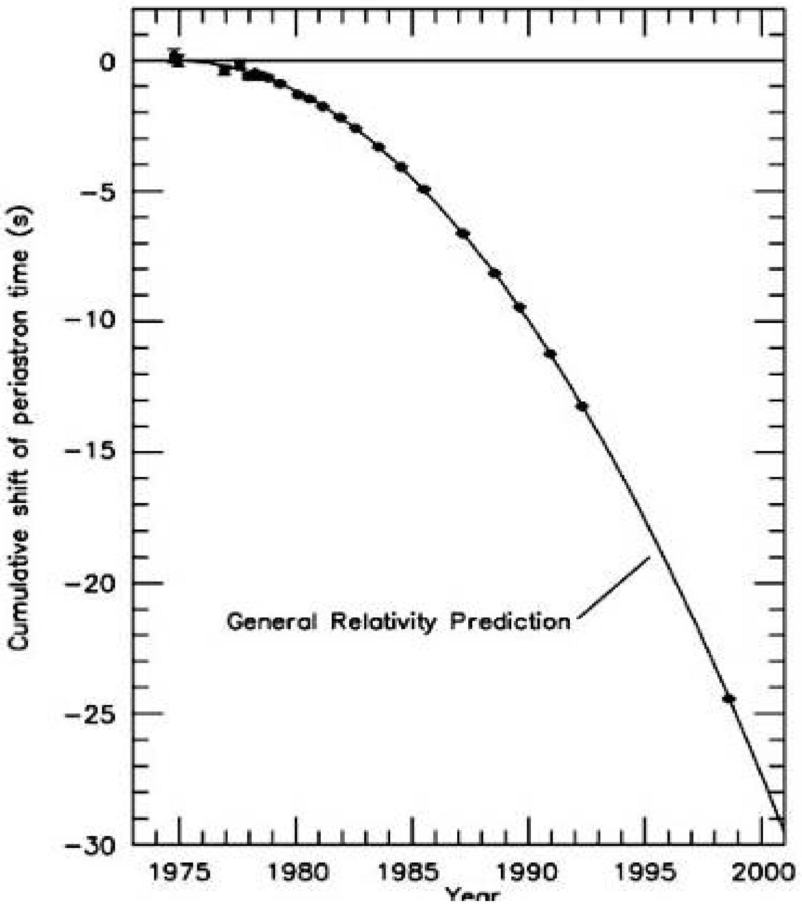
$$h = \Delta L / L$$



Evidence for GWs - binary pulsar



- PSR1913+16
- Hulse and Taylor
- observed from 1975
- extremely stable pulsar
- good “laboratory” to study strong gravitational fields



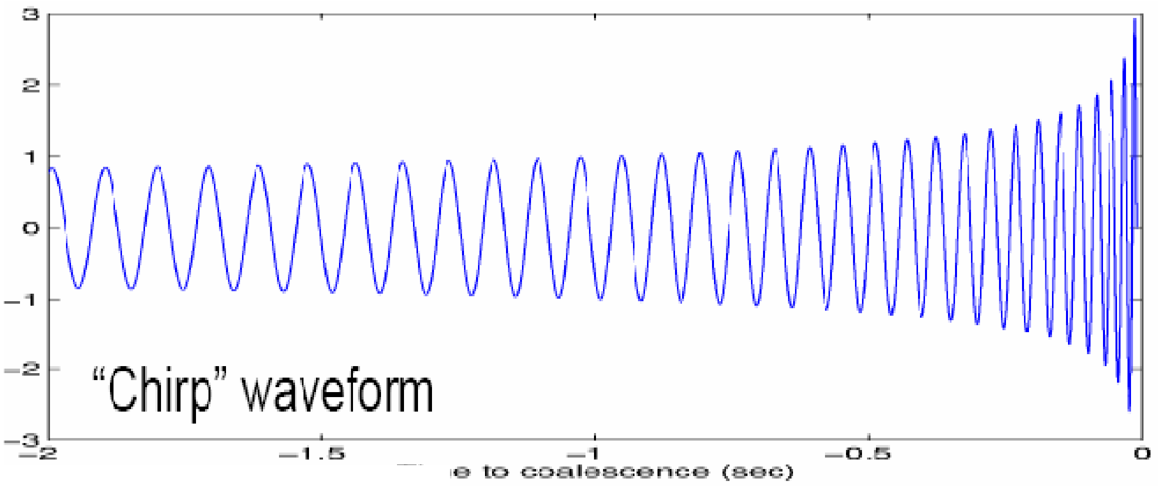
- observe loss of orbital energy implying emission of GWs

Astrophysical sources

- Signals are classified according to waveform
  - **burst** – unmodelled or poorly modelled short duration event
    - typically several cycles of 100~1000Hz for ground-based searches
    - example: supernova core-collapse and subsequent Neutron Star or Black Hole formation
  - **inspiral** – well modelled evolution of final stages of orbital decay of a compact binary system
    - allows a coherent template search over 10s or 100s of cycles
  - **continuous** – quasi-continuous, modulated sinusoidal wave e.g. from non-axisymmetric neutron star (a “mountain” on a pulsar)
  - **stochastic** – combination of many faint sources, or the cosmological background from the Big Bang

Example: Binary Inspiral “Chirp” signal

Neutron Star Merger



Chirp parameters give:

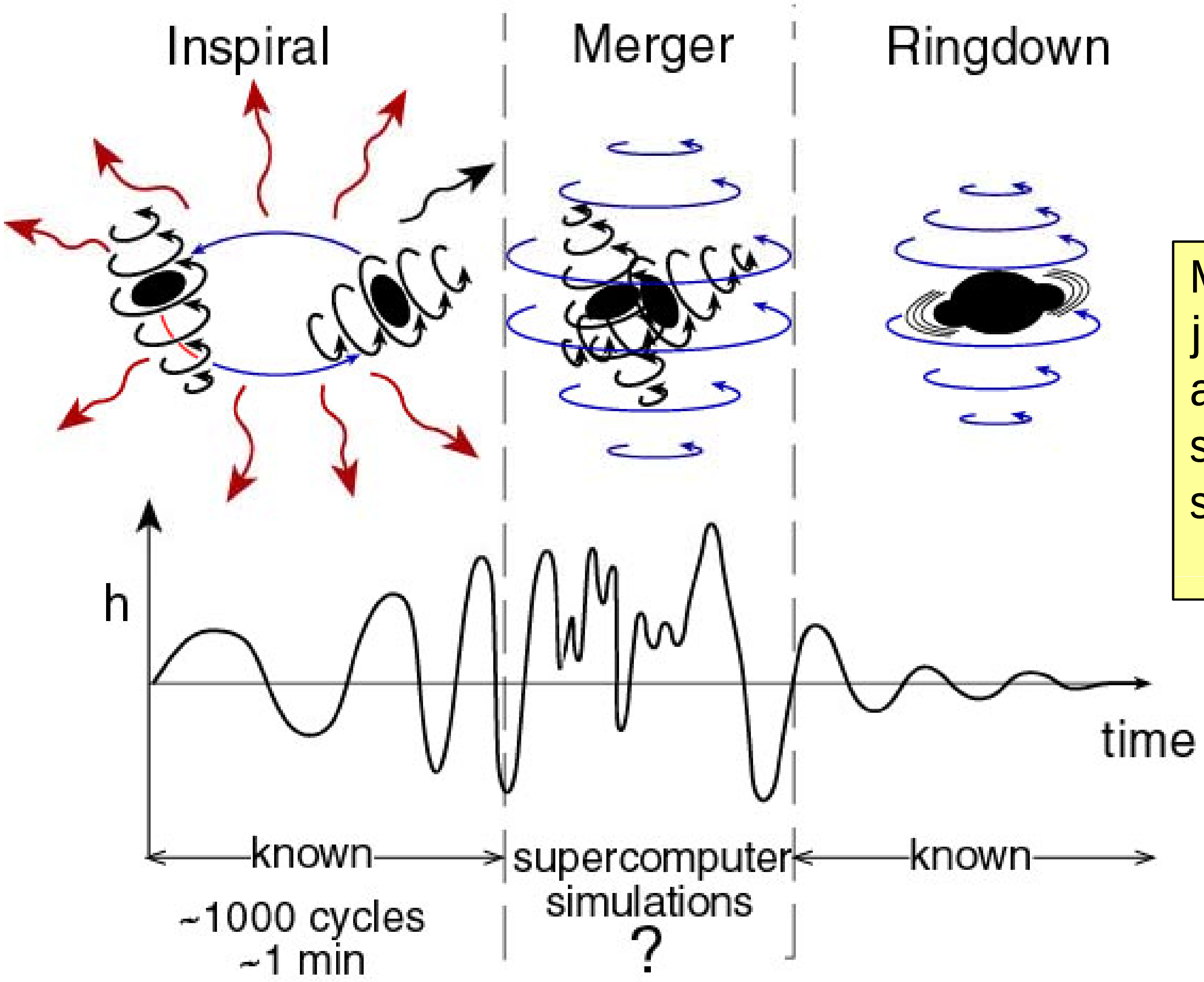
- masses of the two bodies (NS or BH)
- distance from Earth (not redshift)
- orientation of orbit

Optical observations may also give redshift

Search by passing data through bank of templates spanning parameter range accessible to detectors. Demand high SNR for detection (8 or more) and so have quite good parameter estimation

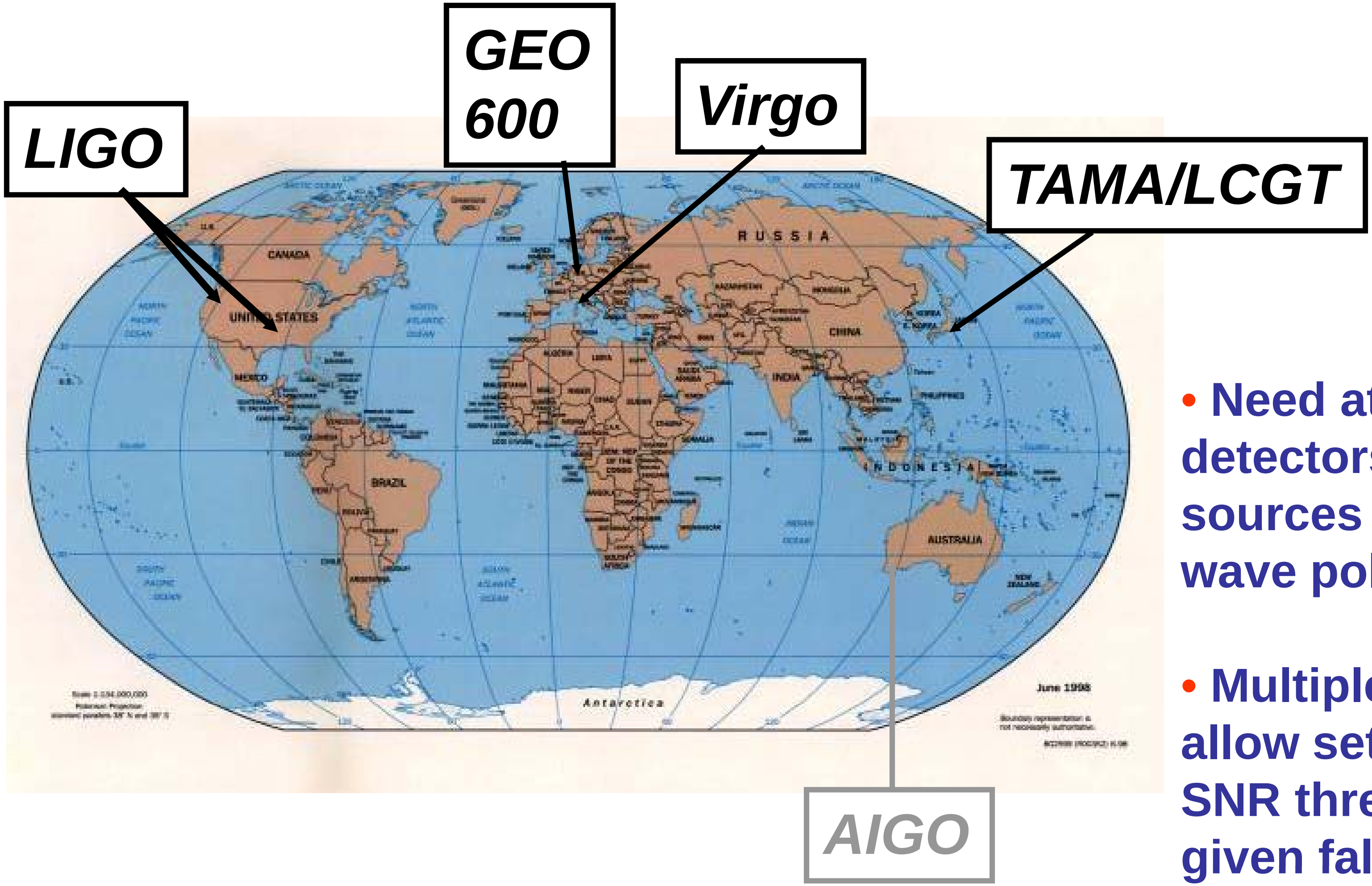
Gamma/X-ray observations may also link with GRB (some GRBs are associated with compact binary mergers – SWIFT observations)

Exploring warped space-time
BH:BH mergers



Merger phase is just now becoming accessible to supercomputer simulation

The Global Network of GW Detectors

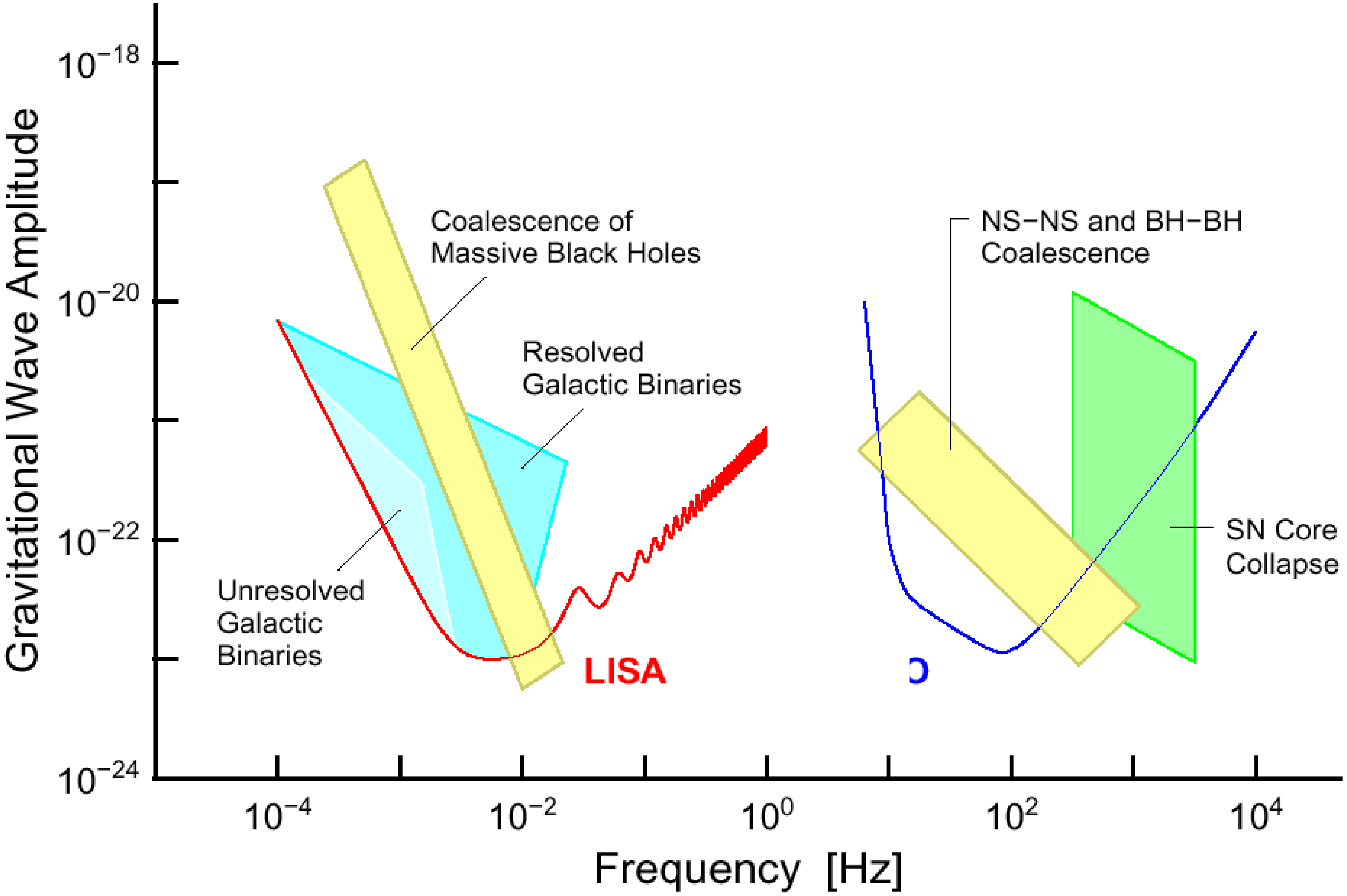


- Need at least 4 detectors to locate sources and determine wave polarisation

- Multiple detectors allow setting lower SNR thresholds for a given false alarm rate

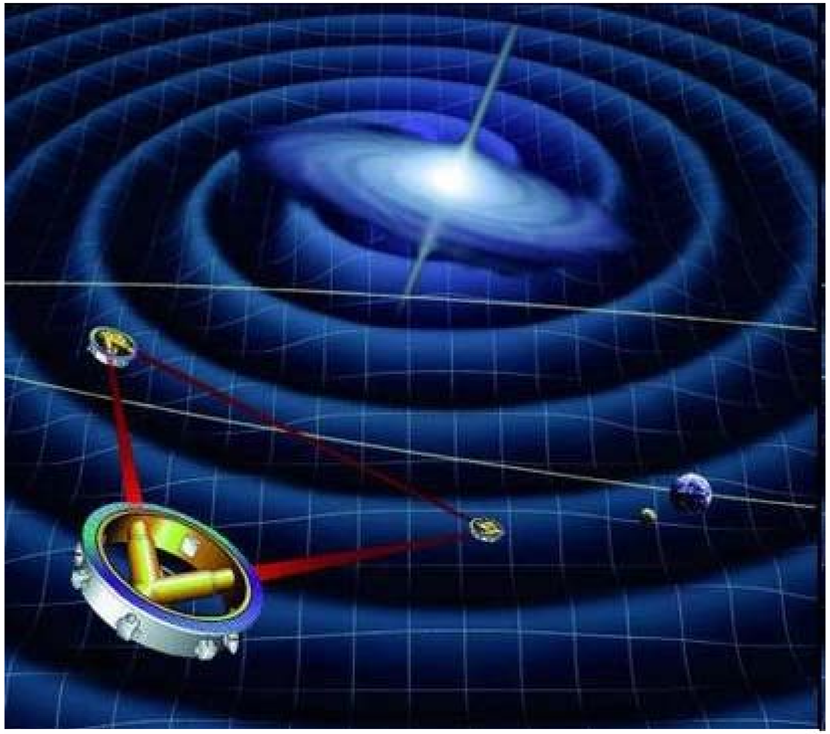
Frequency bands

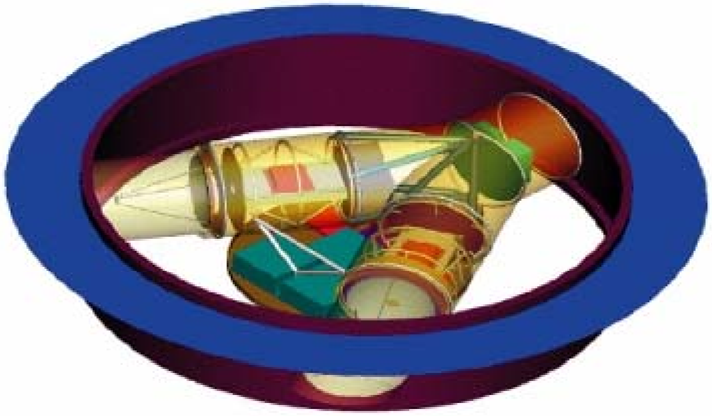
- space-based detectors are required for lower frequency observations due to fluctuating local gravitational fields on Earth (clouds, rabbits etc.)



LISA – a planned detector in space

- To cover the sub-Hz frequency band inaccessible on the ground
  - ESA/NASA mission
  - 3 spacecraft in solar orbit (1.5tonne launch mass)
  - "laser-transponder" style interferometry over 5Gm arms
  - drag-free control to shield proof masses, and micro-N thrusters with 5 year mission life
  - planned for 2018 launch
  - guaranteed "calibration" sources such as galactic binaries
  - GW "noise" at low frequency





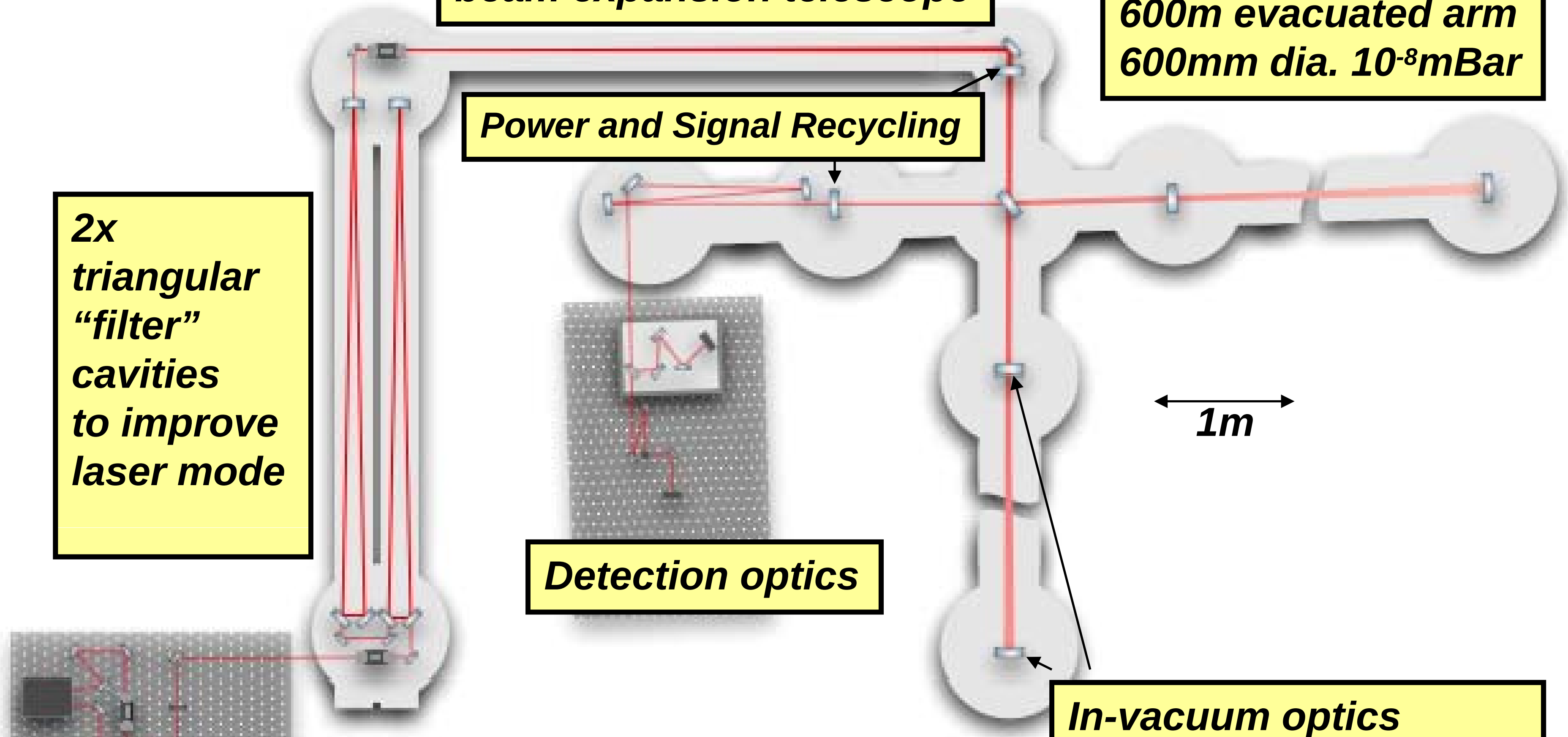
Ground-based detectors: test masses

- Need a set of masses with relative motion less than of order 0.001 fm in 10ms
  - choose frequency band (10 Hz to few kHz on ground)
  - exclude resonances from components in that band
  - provide multi-stage compliant supports (springs, pendula) for vibration isolation in all 6 degrees of freedom
  - place in a vacuum
  - use low dissipation materials to reduce thermal noise (the thermal energy is concentrated in high-Q resonances outside the detection band)
  - provide delicate actuation on to mirrors and/or supporting stages in the isolation system (hierarchical control)
  - provide (some hundreds of) control loops to keep everything aligned

Sensing: laser interferometry

- Sense relative length changes of two arms
  - based on Michelson interferometer (multi-bounce or cavity arms)
  - typically shot-noise (photon counting) limited over much of the band (above ~100 Hz)
  - require high power lasers (10W+) and tricks to build up stored light energy in the interferometer (low loss optics, tricks with mirrors) to store >10^{18} photons (~10kW stored for 10 to 100ms)
  - optical absorption leads to heating and distorts the optics, which limits interference contrast
  - scattered light can acquire large phase shifts and tiny amounts destroy sensitivity (in GEO as little as 1aW out of 3 kW would be enough to limit performance in the worse case)

GEO600 Optical Layout



beam expansion telescope

600m evacuated arm
600mm dia. 10^{-8}mBar

Power and Signal Recycling

2x
triangular
“filter”
cavities
to improve
laser mode

Detection optics

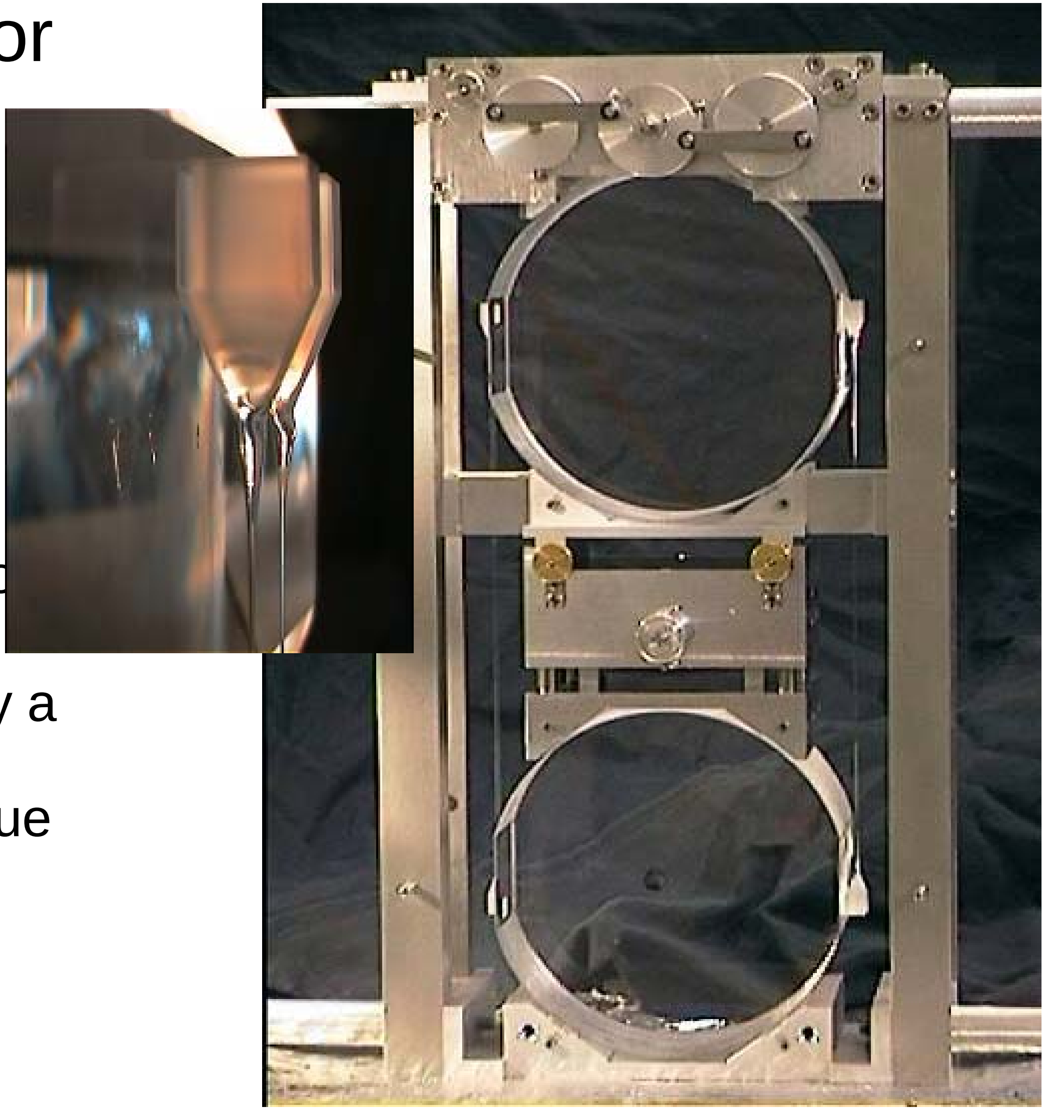
In-vacuum optics
are suspended on
2 or 3 stage pendulum
suspensions

12 W laser (1064nm)
ultra-stable frequency
and amplitude

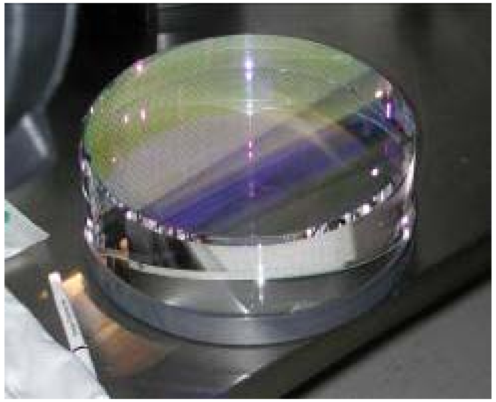
GEO: site during construction

GEO600 quasi-monolithic silica suspension technology

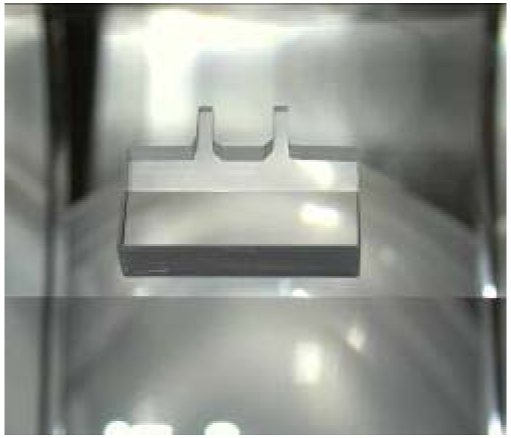
- Thermal noise is a major challenge
  - – arises from finite (i.e. room) temperature heat bath and non-zero dissipation in materials
  - – suspension fibres
    - use fused silica in GEO fo low loss
    - welded to ears bonded by a specially developed “silicate bonding” technique
  - – also require low dissipation silica mirror substrates and coatings



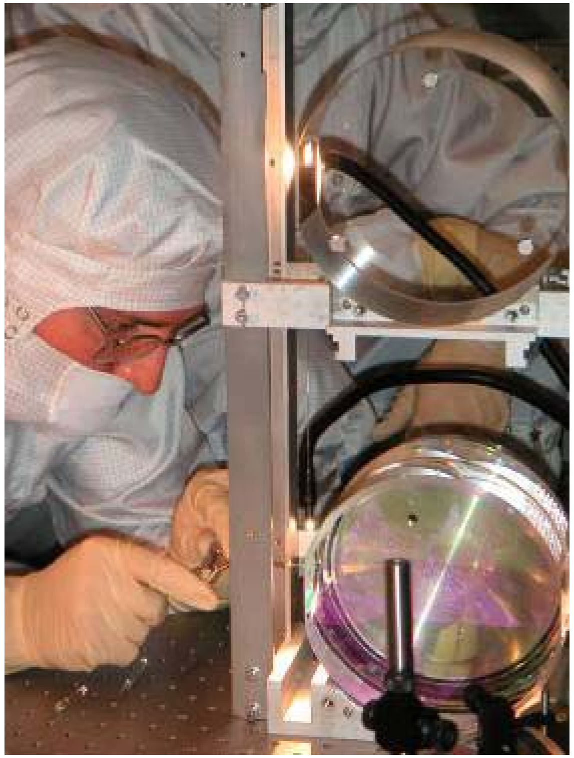
Suspending ~10kg on 4 fine silica fibres



Preparing the optic



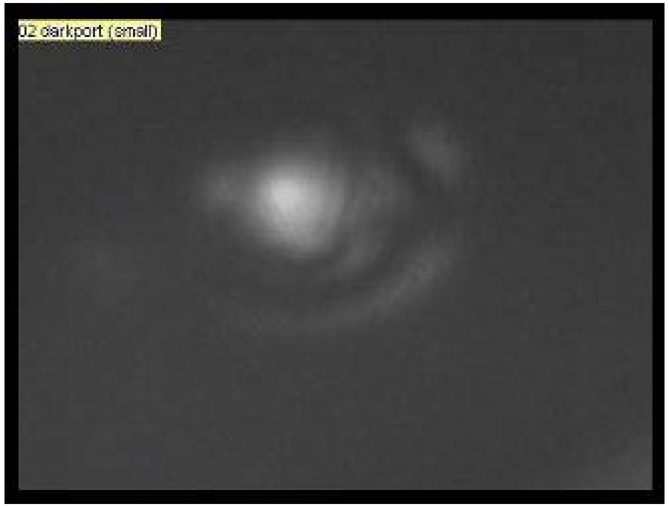
Silica ‘ears’ bonded to masses



Welding fibres to the ears

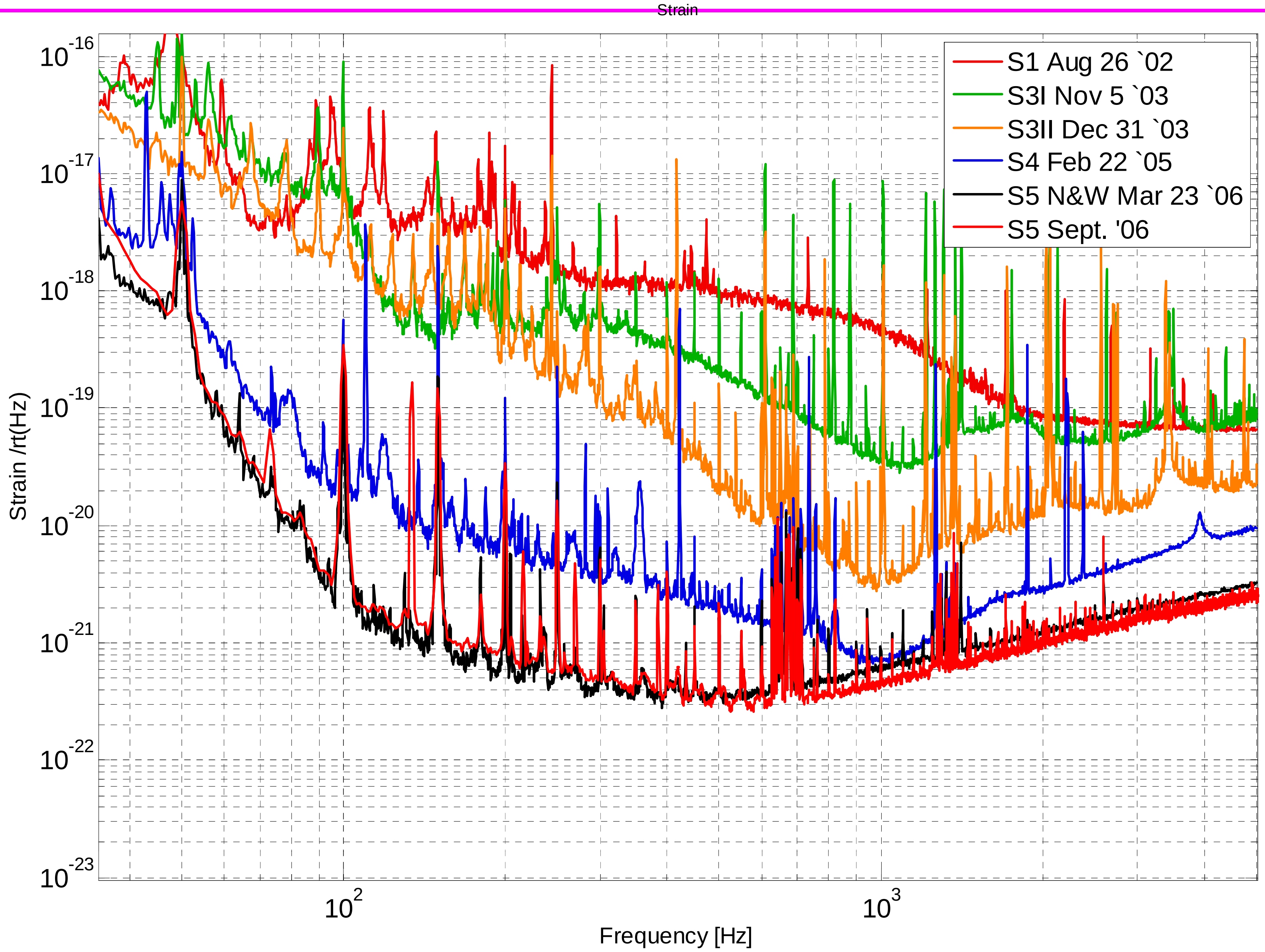
GEO600 – signal recycling

- Signal recycling technique
  - place mirror between interferometer and photo-detector
  - partially transmits signals, but most of the field is re-circulated and builds up on multiple round trips
  - mirror transmission controls bandwidth, its position (phase) controls centre frequency
  - helps GEO 600 approach 4km LIGO detectors in photon-noise limited performance
  - also increases interferometer contrast
    - in GEO 3kW at beamsplitter but <50mW on photodetector (<5mW of unwanted waste light)
    - the effective contrast is ~1,000,000:1



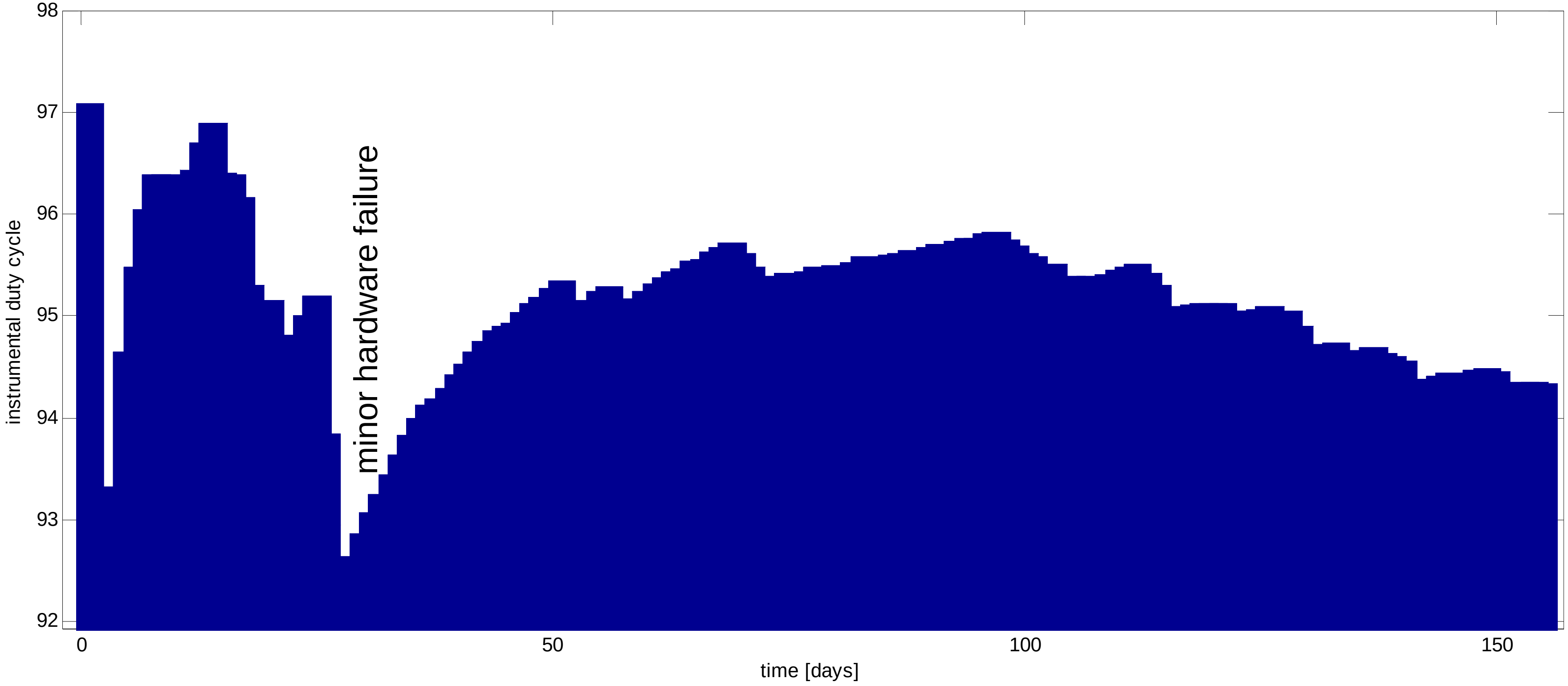
Signal recycling is currently unique to GEO, but will be a key technology for all future detectors

GEO600 Sensitivity in Science Runs



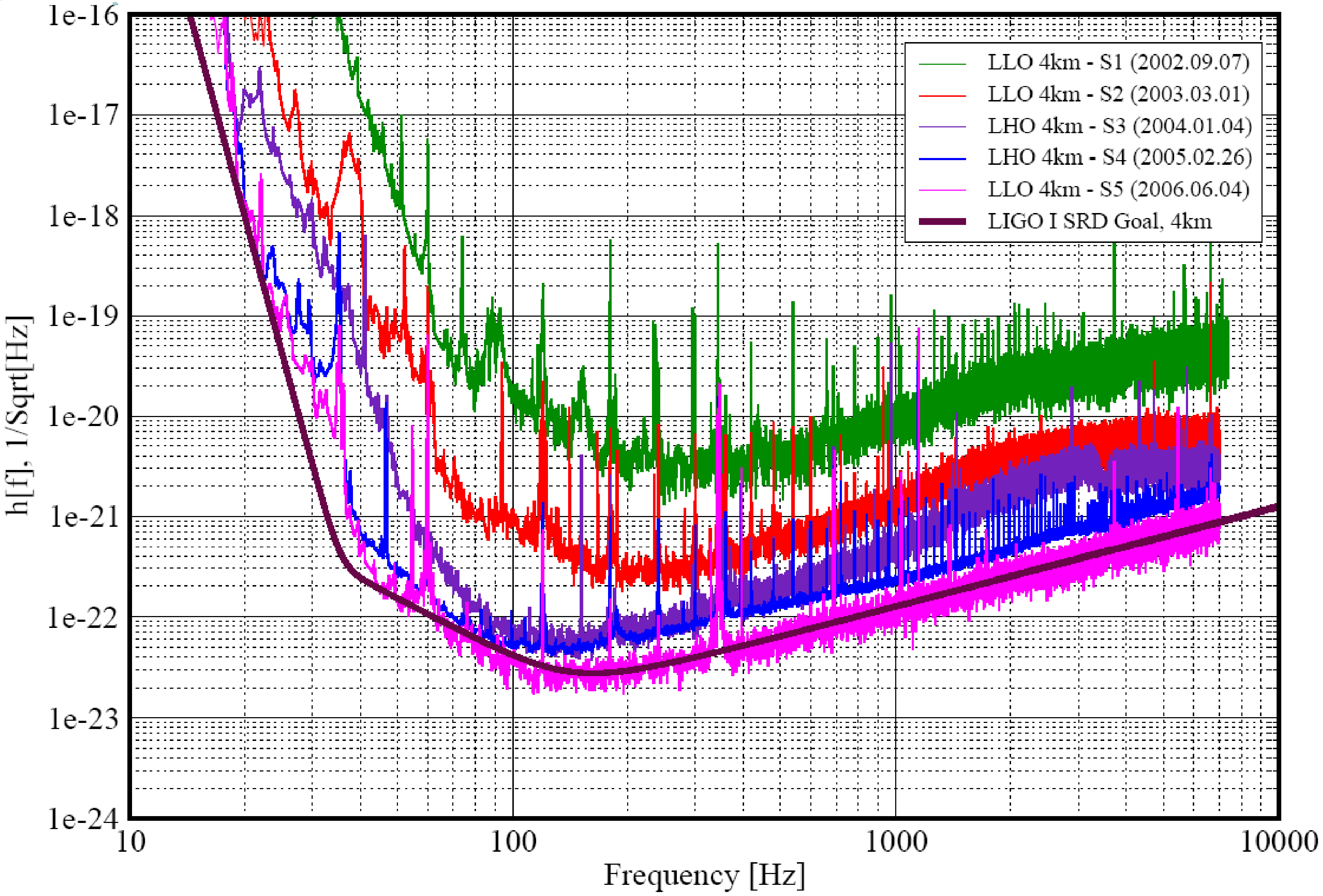
GEO S5: Duty Cycle

- May- October 2006, 157 days
  - Instrumental duty cycle: 94.3 % (1.5.-2.10.)
  - Science time duty cycle: 90.8% (1.5.-4.10.)
- Longest lock: 102 hours (typ. few minutes relock)



Best Strain Sensitivities for the LIGO Interferometers

Comparisons among S1 - S5 Runs LIGO-G060009-02-Z



Science results snapshot

- The LSC has analysed most of the data from the 3 US LIGO detectors and GEO, from 5 science runs
  - papers published covering all search types (burst, inspiral, continuous wave and stochastic)
  - no detections to announce at this stage
  - starting to place astrophysically interesting upper limits in several areas
  - some searches are computing-power limited (hence the use of Einstein@home using the BOINC screensaver to obtain over 80Tflops)
- Example: searching for GW from known pulsars
  - strong involvement by Glasgow scientists
  - close co-operation with radio astronomers

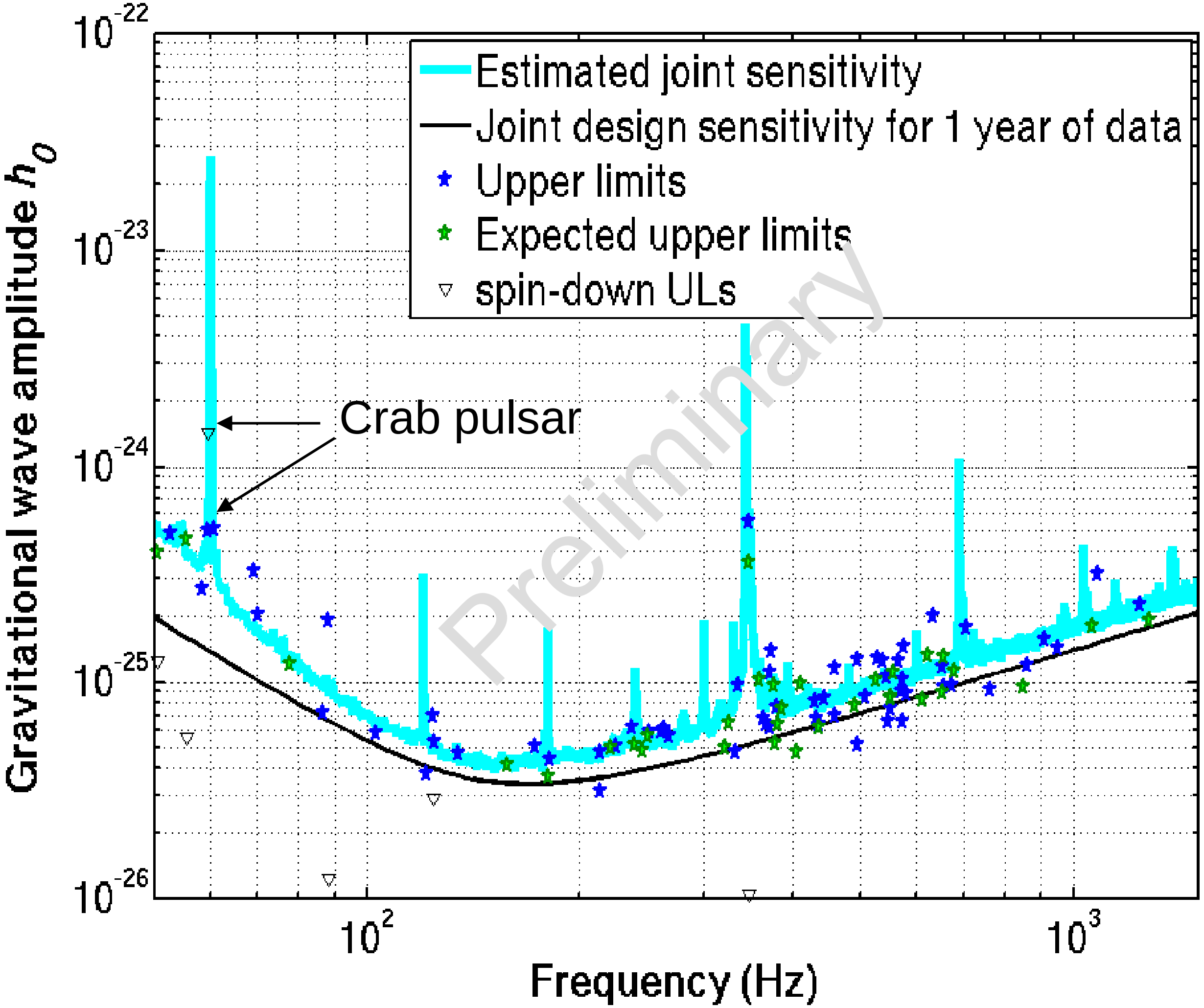
Example results from GW Searches: known pulsars

Joint 95% upper limits from first ~13 months of S5 using H1, H2 and L1 (for 97 known pulsars). Results are overlaid on the median estimated sensitivity

For 32 pulsars (green stars) we only give *expected* upper limits due to uncertainties in the pulsar parameters

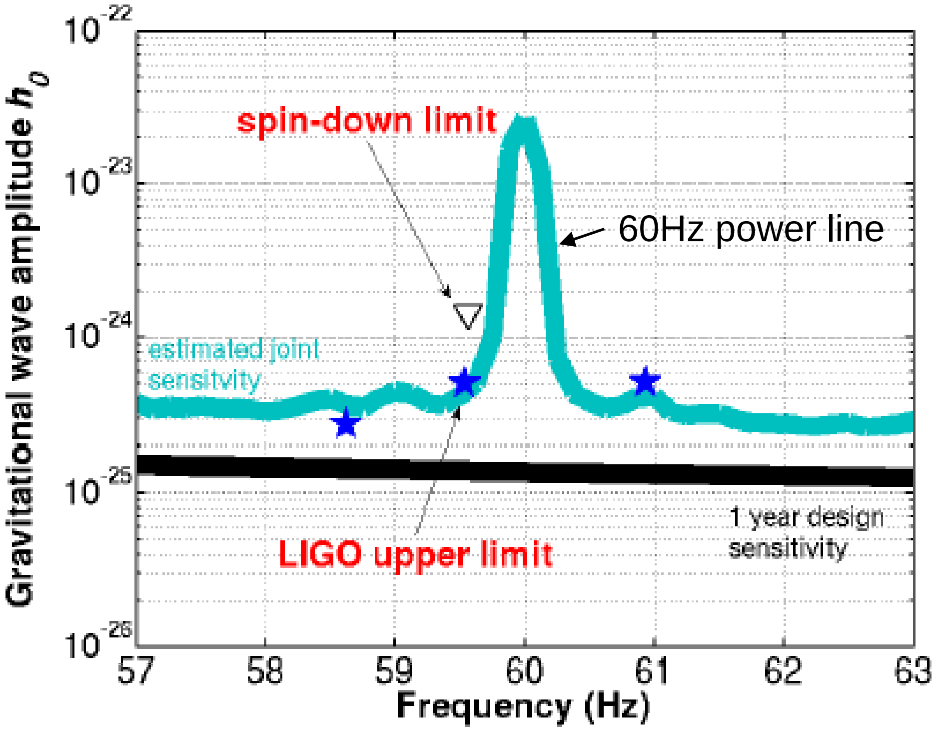
Lowest h_0 upper limit:
PSR J1623-2631 (ν_{gw} = 180.6 Hz) $h_0 = 3.4\text{x}10^{-26}$
Lowest ellipticity upper limit:
PSR J2124-3358 (ν_{gw} = 405.6 Hz) $\varepsilon = 7.3\text{x}10^{-8}$

Crab pulsar ***beats*** the spin-down upper limit by a factor of 2.9 – we can constrain the power radiated by GWs to less than 10% of the total available from spin-down



Crab Pulsar

- Spin-down limit assumes all the pulsar’s rotational energy loss is radiated away by gravitational waves
- Our results for the Crab pulsar give upper limits of $\varepsilon = 2.6\times10^{-4}$ and $h_0 = 5.0\times10^{-25}$
- This ***beats*** the spin-down limit of $h_0 = 1.4\times10^{-24}$ by a factor of **2.9**
- From this we can constrain the amount of power emitted in GWs to less than 10% of power available from spin-down



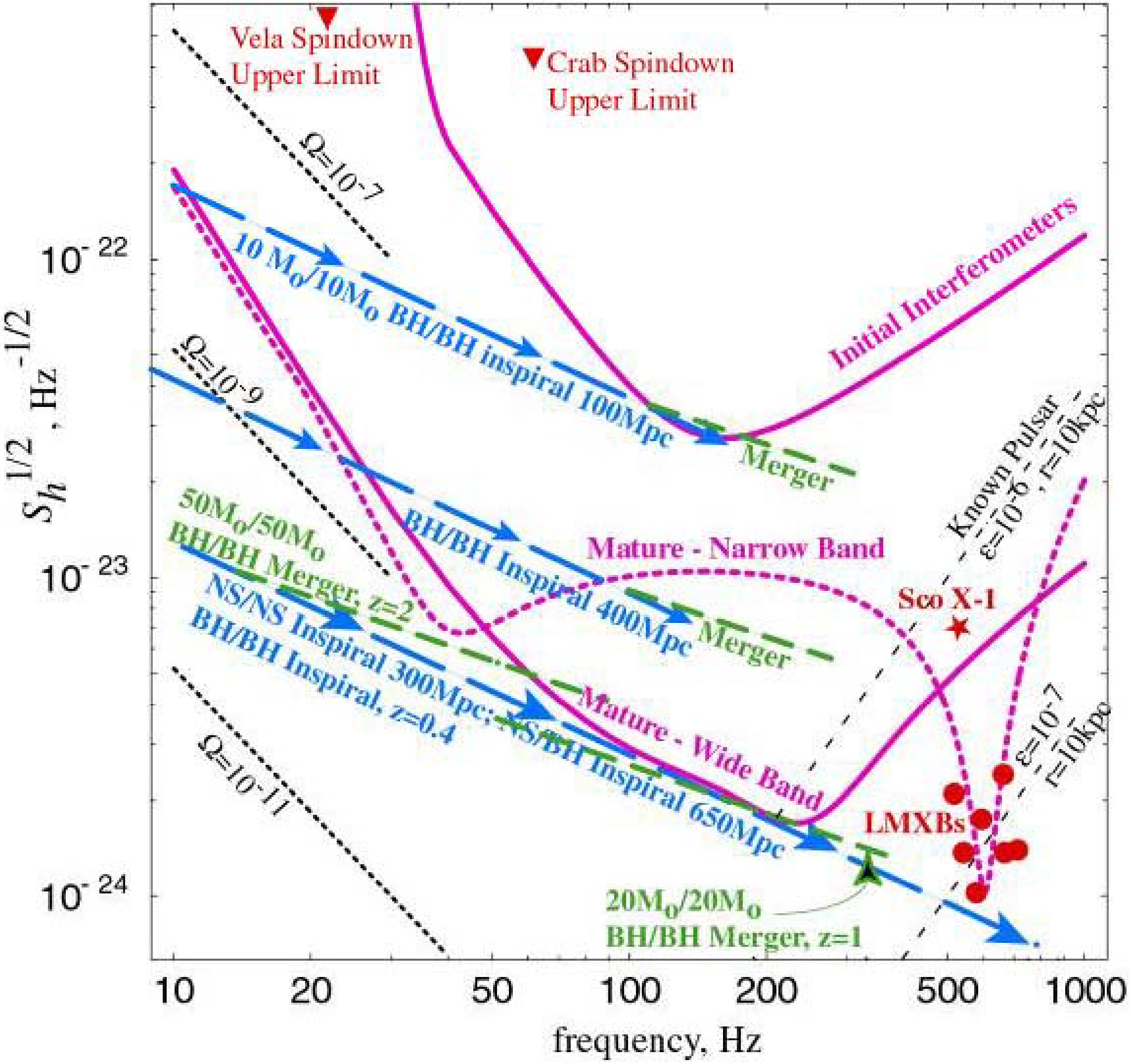
Motivation for Advanced LIGO

Aim for reliable, frequent detections

Requires 10~15x better peak amplitude sensitivity

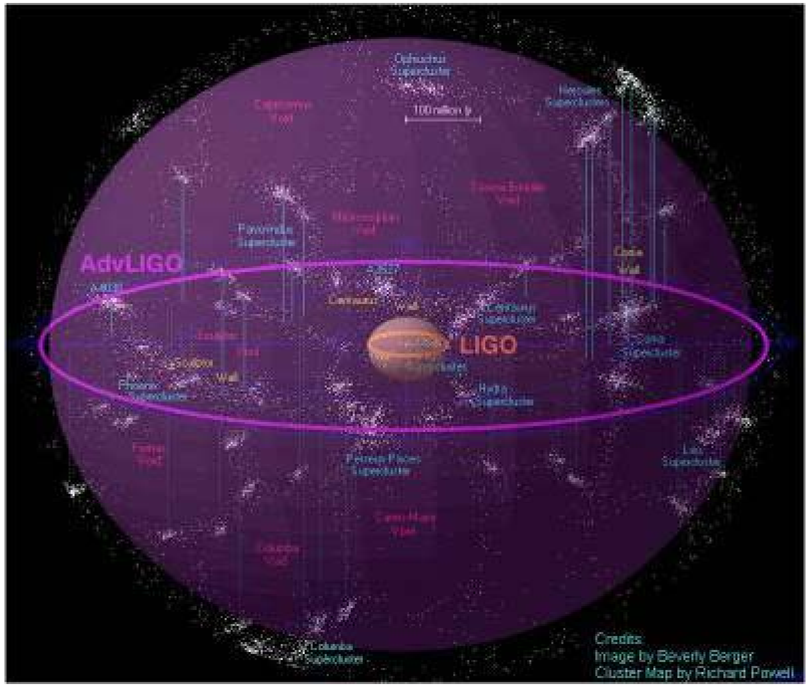
GW detectors measure amplitude so the range is increased by 10~15x

⇒ 1000~3000x rate (number of sources increases approx. as cube of range)



Advanced LIGO

- Incorporate technology from GEO600 and other new ideas to upgrade the LIGO detectors
  - Active anti-seismic system operating to lower frequencies
  - Lower thermal noise suspensions and optics
  - Higher laser power
  - More sensitive and more flexible optical configuration



Credits:
Image by Beverly Berger
Cluster Map by Richard Powell

R&D phase nearly completed

Project ready to start

Installation starts 2011

Planned operation 2014

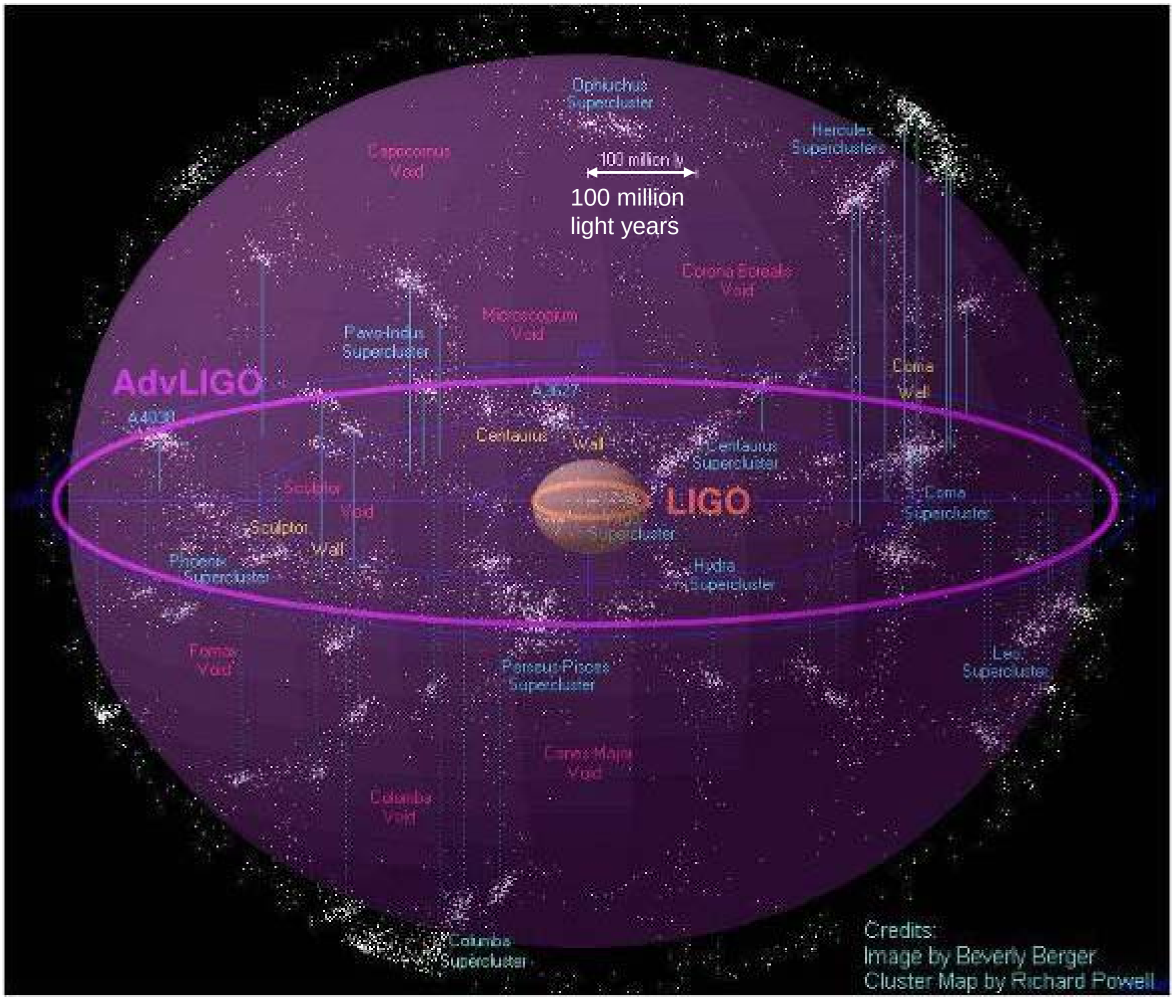
UK funding approved 2004 (PPARC/STFC)

D funding approved 2005 (MPG)

US funding start expected 2007 (NSF)

Advanced LIGO

- Rates for inspirals should increase from of order 1/30 years to of order 30/year (rates have wide spread due to difficulty of observing by other means)



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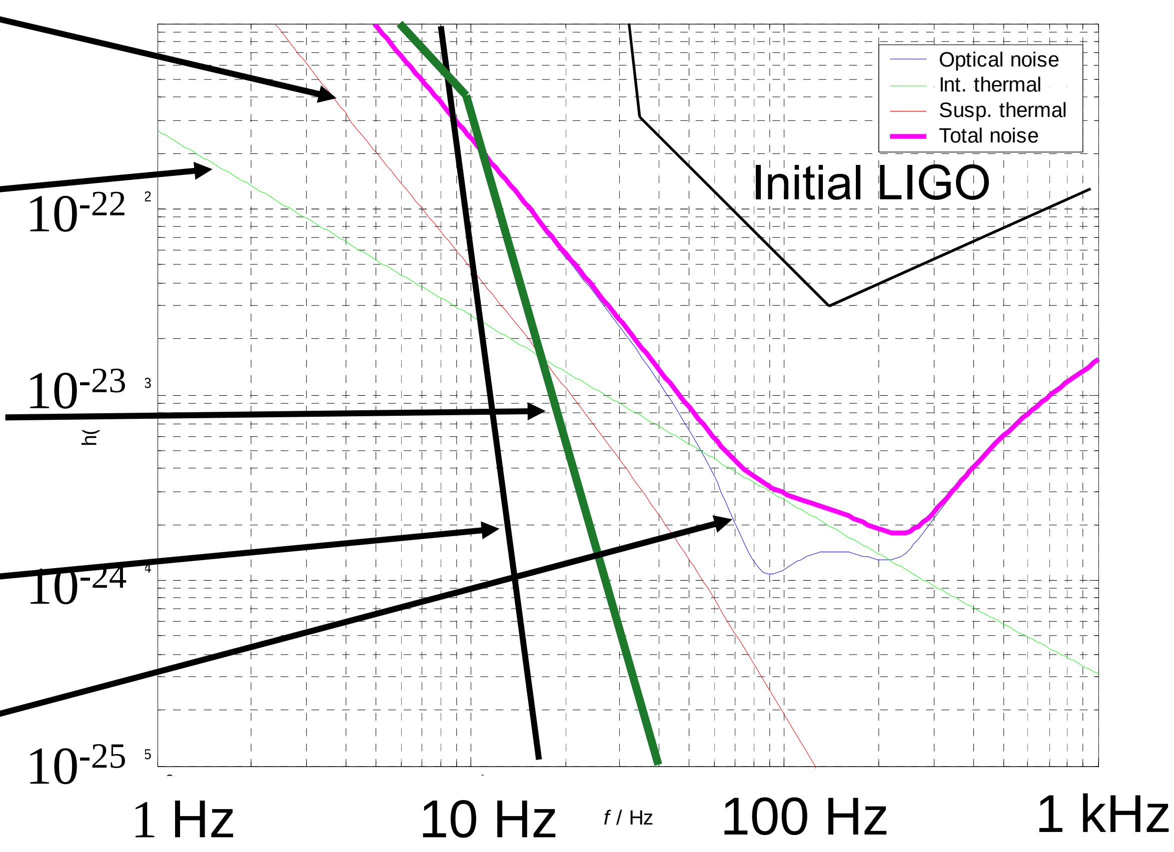
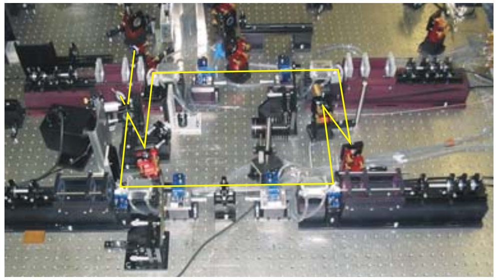
Advanced LIGO Performance

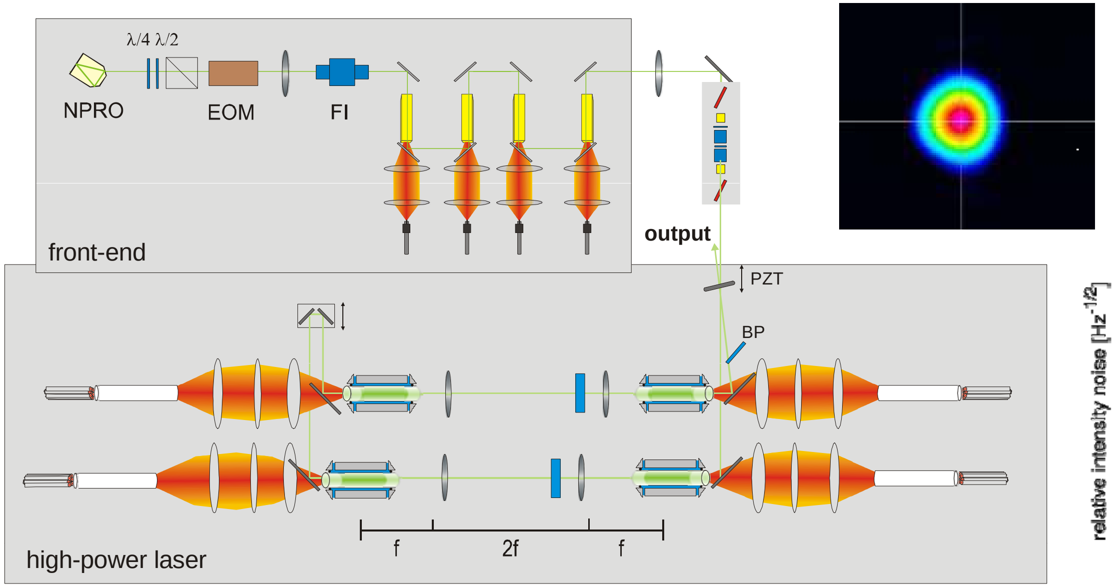


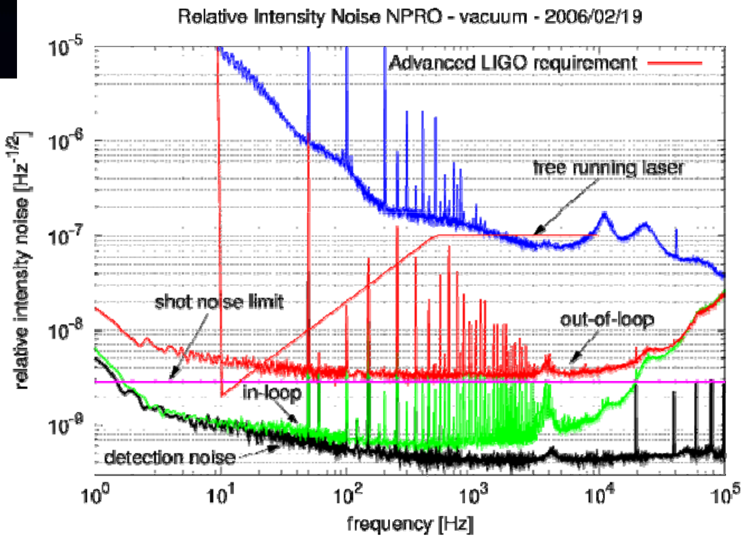
- Suspension thermal noise
- Internal thermal noise
- Newtonian background, estimate for LIGO sites
- Seismic ‘cutoff’ at 10 Hz
- Quantum noise (shot noise + radiation pressure noise) crossing the “Heisenberg Microscope” limit with 40kg “test particles”

Advanced LIGO laser

- 180 W amplitude and frequency stabilized Nd:YAG laser
- Two stage amplification
  - First stage: MOPA (NPRO + single pass amplifier)
  - Second stage: injection-locked ring cavity
- Developed by Laser Zentrum Hannover and MPI at Hannover
- Well along toward meeting performance specs
  - Frequency, intensity, beam jitter noise

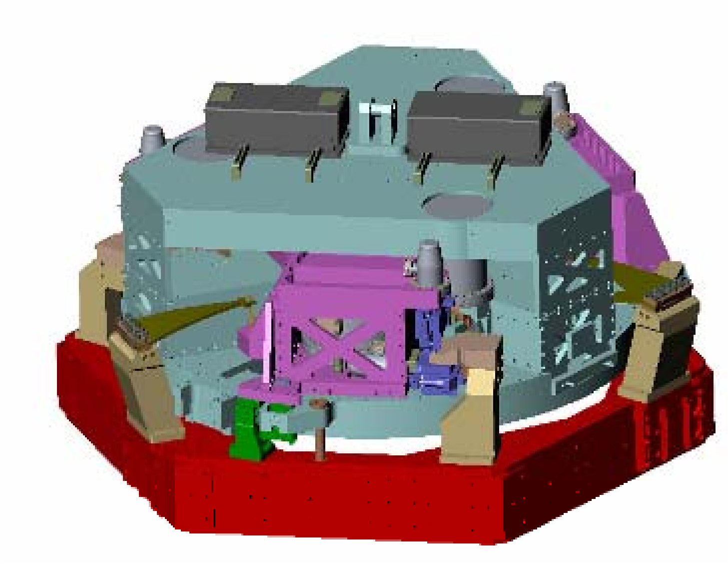


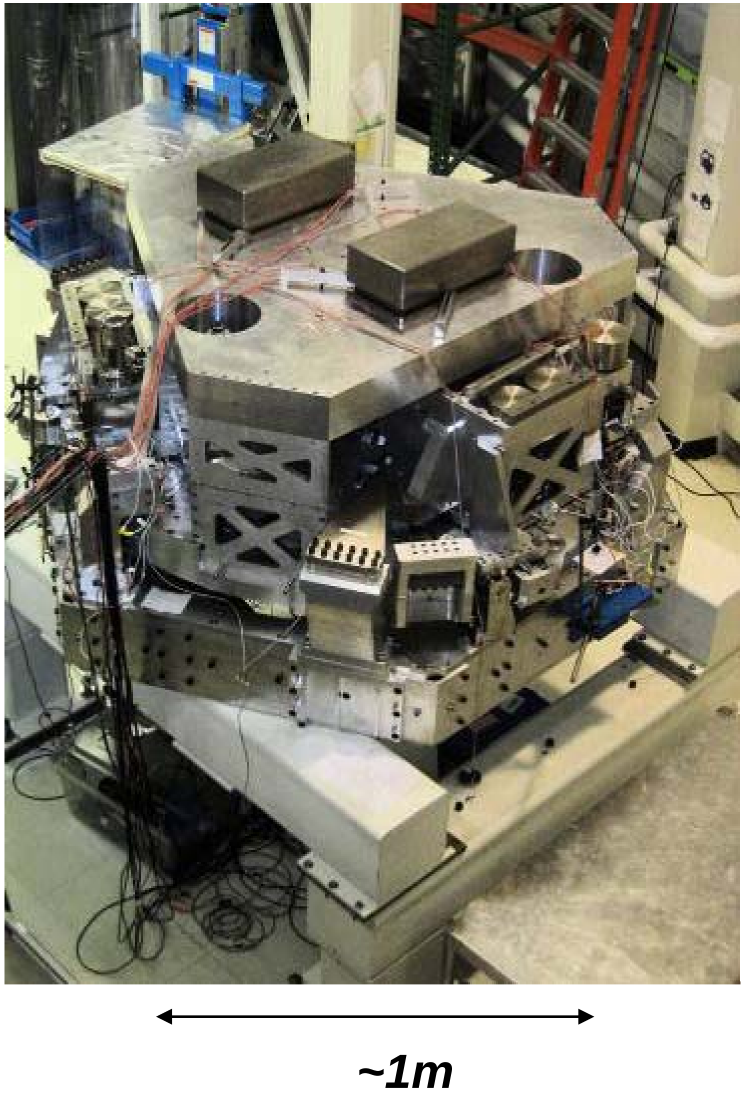




Seismic isolation

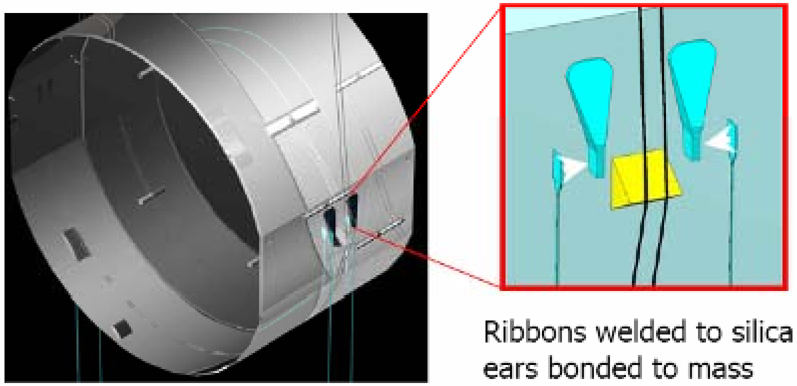
- To push Advanced LIGO performance down to low frequencies requires a completely new seismic isolation system
- Required Isolation
  - 10x @ 1 Hz
  - 3000x @ 10 Hz (sub pm motion)
- This needs a multi-stage active isolation platform





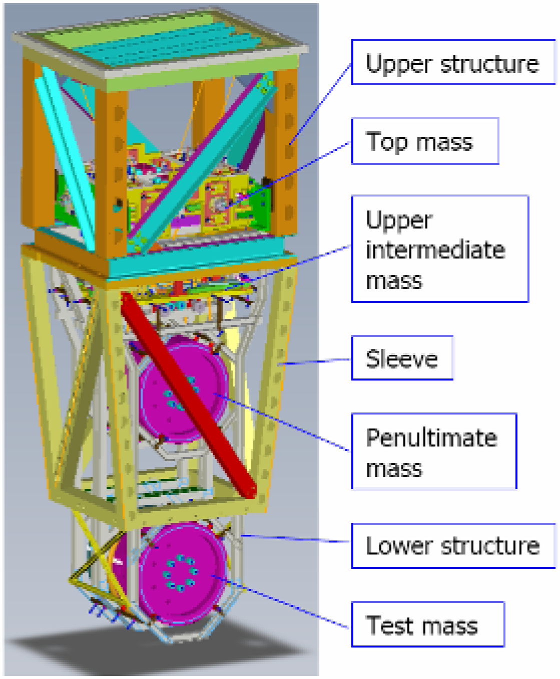
Advanced LIGO suspensions

- 3 and 4 stage suspensions based on GEO600 triple design
- Final prototype currently being assembled at MIT test facility
- Final stages of fabrication-tooling tests underway at Glasgow



Ribbons welded to silica ears bonded to mass

Quad Noise Prototype



Noise Prototype OSEM (Prototype Unit)

Mechanical test assembly at RAL

advancedligo

Advanced LIGO UK

LSC

- PPARC (now STFC) £8.9 M grant to Glasgow and Birmingham, with RAL, Strathclyde and Cardiff as partners
- Main deliverables
  - provide optical substrates and the main suspensions for 3 interferometers, plus associated control electronics
  - all based on tried and tested GEO600 technology
  - scaled up to work with 40kg mirrors in the LIGO vacuum envelopes

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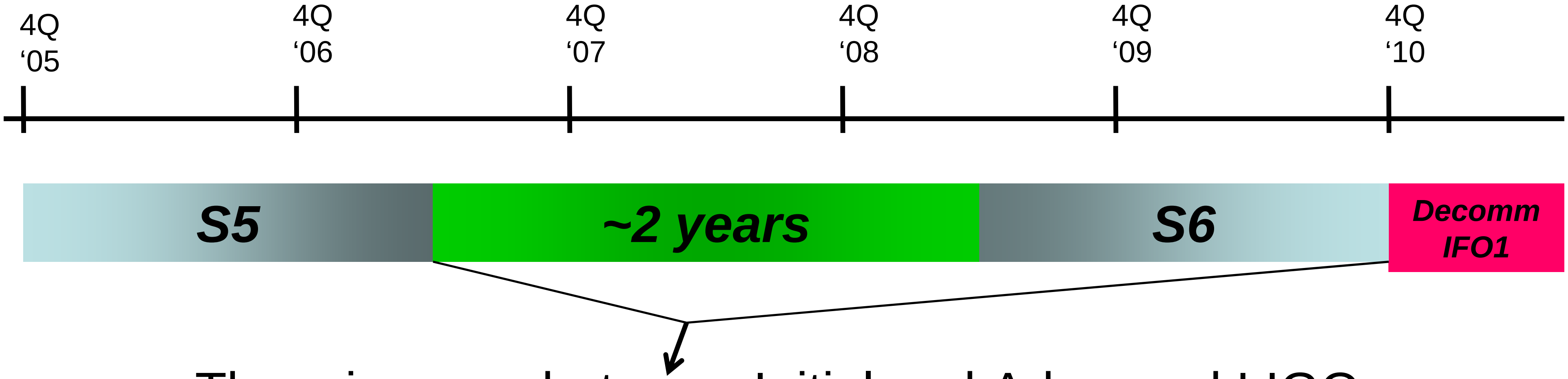
Enhanced LIGO



- There is a gap between Initial and Advanced LIGO
- Enough time for one significant set of enhancements
- Aim for a factor of 2 improvement in sensitivity (factor of 8 in event rate)
- Early tests of some Advanced LIGO hardware and techniques

Beyond Advanced LIGO

- “3rd generation” GW detectors will have to perform beyond the Standard Quantum Limit
  - requires a new approach to read out the GW signal without back-action on the measured variable (Quantum non-demolition measurement)
  - ideas exist based on externally or internally generated non-classical states of light
- To reduce thermal noise detectors may require cryogenic optics and suspensions
- To shield the test masses from the local gravitational background may require placing detectors underground in carefully formed caverns
- GW detection may become really-big-science!

Conclusion

- The next few years will bring the opening of this new field of observational science
  - detections are not guaranteed with the 1st generation detectors, but are certainly possible with the detectors operating at design sensitivity
- Advanced LIGO is approved and ready to start fabrication
  - essentially guaranteed observations and rich science
  - reaches to cosmological distances (approaching 1 Gparsec)
- Space interferometry (LISA) extends the science reach to lower frequencies (0.1 mHz to 0.1 Hz approx.)
  - can probe deep cosmological distances
  - a major source of noise is the GW background!