The search for gravitational waves

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No – we’ve not found any…

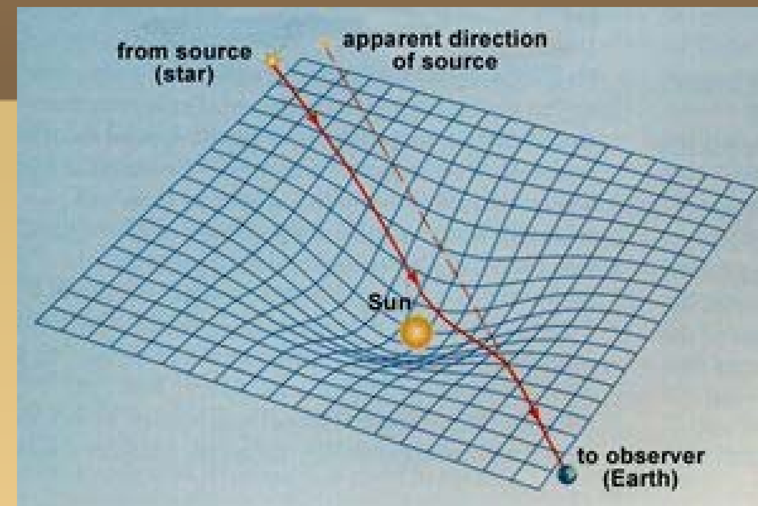
…yet!

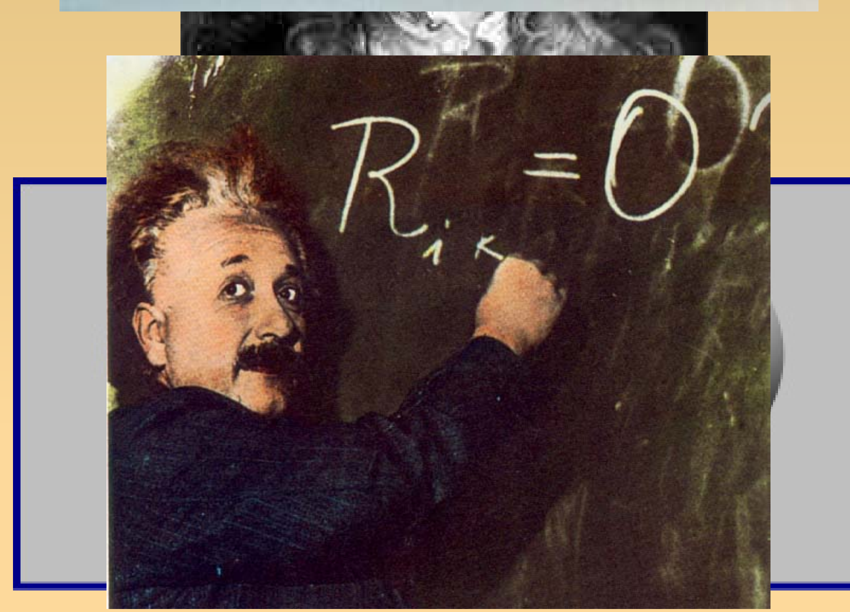
Overview

- Gravitational wave basics
- Detecting gravitational waves
- Sources of gravitational waves
- Searches for gravitational waves
- Future of gravitational wave astronomy

The start...

- In 1686 Sir Isaac Newton pubished the first theory of gravity (Principia Mathematica)
- Massive objects exert a force on other massive objects and the force acts instantaneously
- In 1915 Einstein overturned this view with a new theory explaining gravity as a property of a curved space-time – the General Theory of Relativity

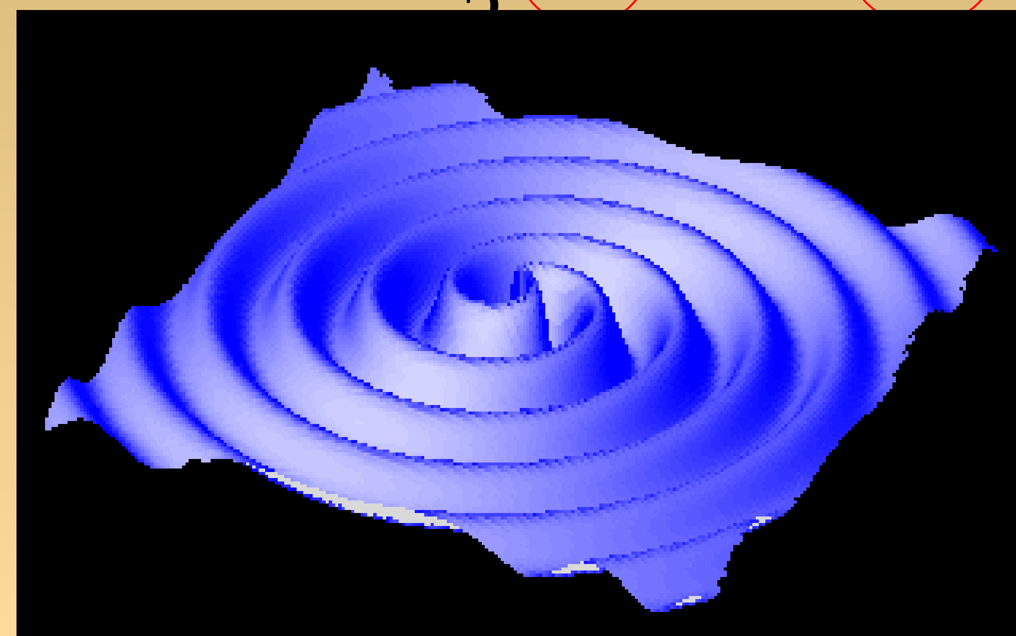




Gravitational wave basics

- Underlying GR is the Einstein field equation showing how mass curves space-time via the stress-energy tensor
- Weak field approximation with a small perturbation on a flat background in free space, gives rise to 3D wave equation

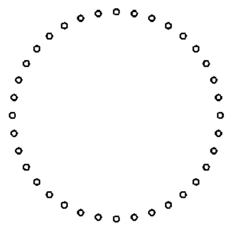
$$G^{\alpha\beta} \equiv R^{\alpha\beta} - \frac{1}{2} g^{\alpha\beta} R = 8\pi T^{\alpha\beta}$$

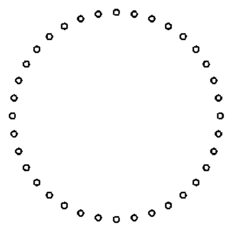


Free space $T^{\alpha\beta} = 0$

Gravitational wave basics – propagation

- Waves will push and pull freely floating objects apart and together as they pass
- Stretch and squeezing of space
  - *transverse* to the direction of propagation
  - equal and opposite along orthogonal axes *(traceless)*
  - invariant under 180º rotation *(spin-2 graviton)*
- Two polarisation axes 'plus' + and 'cross' x rotated at 45*º to each other*





Gravitational wave basics – generation

- Need a time varying mass quadrupole moment
- Make some assumptions
  - $T^{\alpha\beta}$ varies sinusoidally with angular frequency Ω
  - Source is small compared to radiation wavelength, $\varepsilon \ll 2\pi/\Omega$
  - Source motion is slow, $v \ll c$

Mass density = T^{00}

$$I^{lm} \equiv \int \rho x^l x^m \mathrm{d}^3 x$$

$$\bar{h}_{jk} = -2\ddot{I}_{jk}/r = -2\Omega^2 I_{jk} e^{i\Omega r}/r$$

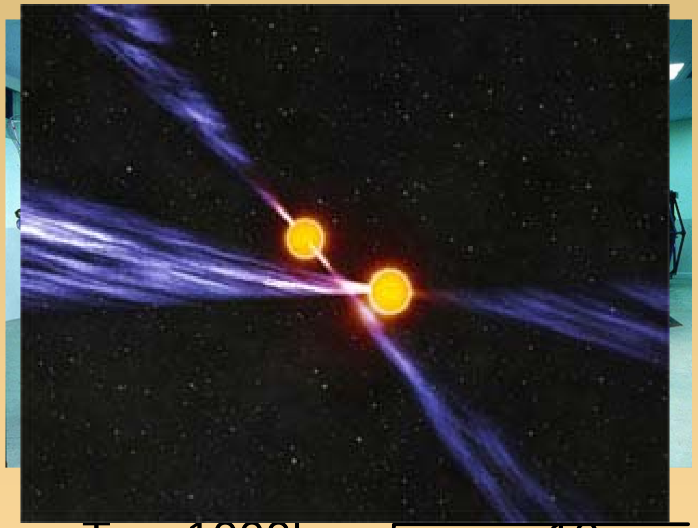
1/*r* fall off in amplitude

Frequency squared increase in amplitude

Gravitational wave basics – strength

- Non-spherical motions will have $d^2I/dt^2 \sim Mv^2$
  - v^2 is non-spherical components velocity
- Frequency is often related to source motion (e.g. binary orbit or spin-frequency), but can be related to the frequency of a self gravitating body
- Main point - very weak!

$$h \sim 2GMv^2 / c^4 r$$



$$f \approx (1/2\pi)\sqrt{GM/R^3}$$

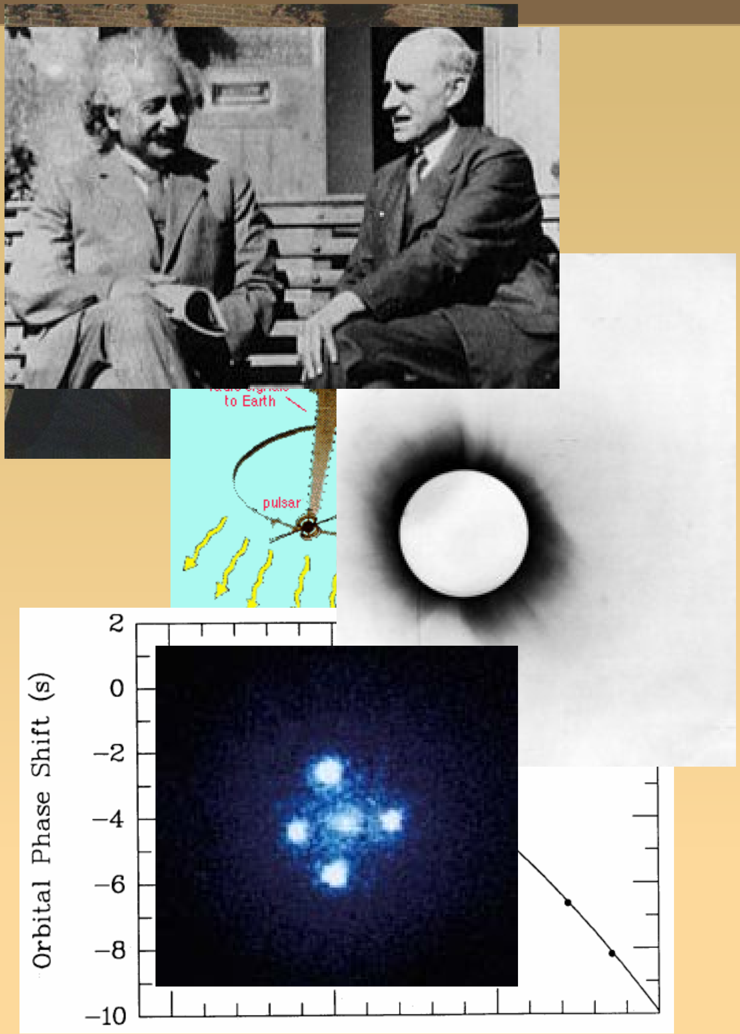
Two 1000kg masses, 10 m apart rotating at 10 Hz, generate GWs at 20 Hz with $h \sim 10^{-43}$ at $r = 1.5\times10^7$ m (e.g. one wavelength away)

Two 1.4 solar mass neutron stars, with a period of 1 s, at a distance of 10 Mpc generate GWs with $h \sim 10^{-22}$

Ringing 5 solar mass black-hole $f \sim 2300$ Hz

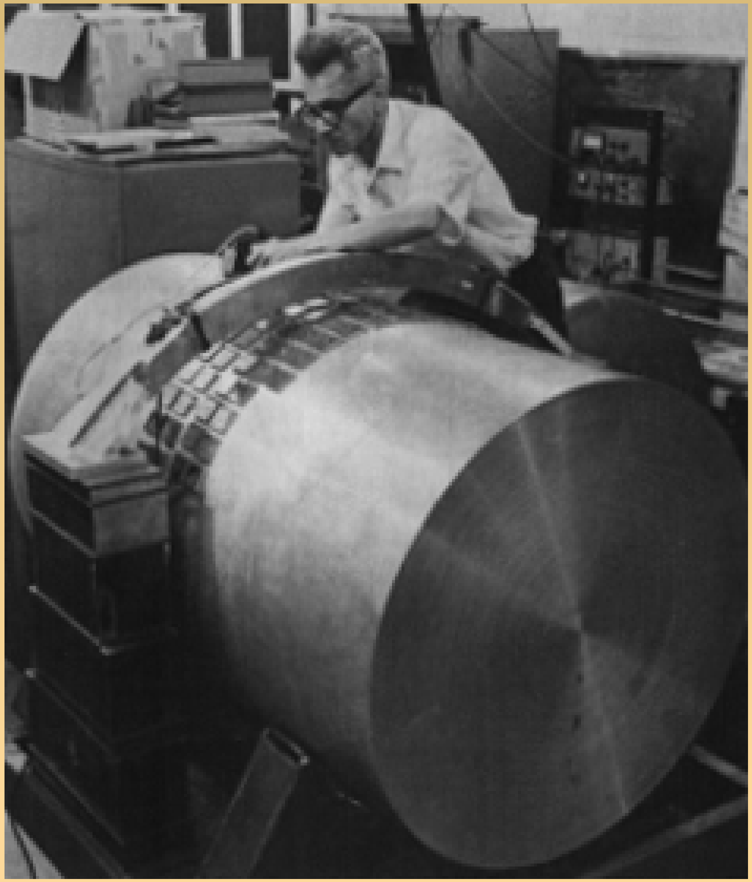
Evidence for gravitational waves

- They are a direct prediction of GR – has correctly predicted observed effects:
  - Perihelion advance of Mercury
  - Gravitational lensing
- Binary neutron star systems are seen to lose energy at exactly the rate predicted by emission of Gws
  - Hulse and Taylor got the 1993 Nobel prize for this observation



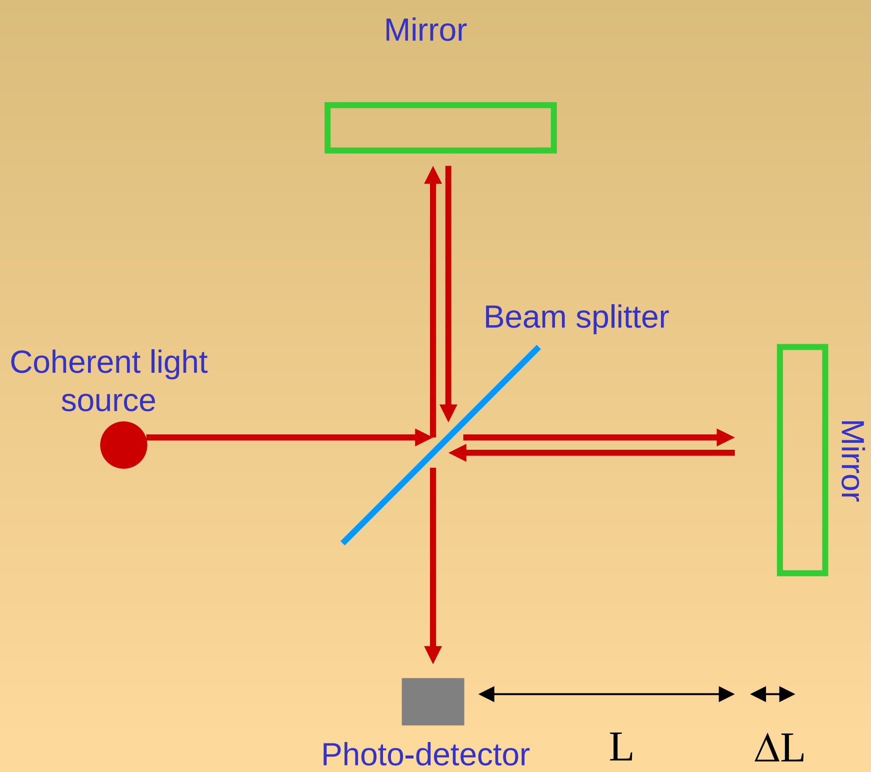
Detection of gravitational waves

- In late 1960s Joseph Weber was the first person to try and directly detect gravitational wave
  - Use resonant mass/bar detector
  - Large cylinder of aluminium with transducers placed around it
  - Gravitational waves with frequencies near the bars resonant frequency would excite its mode
    - Narrow band
- In the 1970s Rai Weiss at MIT pioneered work with interferometers
  - Subsequenctly taken up by other groups: Glasgow, Caltech, Garching



Interferometric detectors

- Basic set-up for gravitational wave detectors is the Michelson interferometer
- Can use laser to measure the displacement of test end mirrors – or difference in speed of light down the arms.
- Split the light down the two paths and recombine it
- Differences between the two paths will show up as changes in the interference pattern at the output

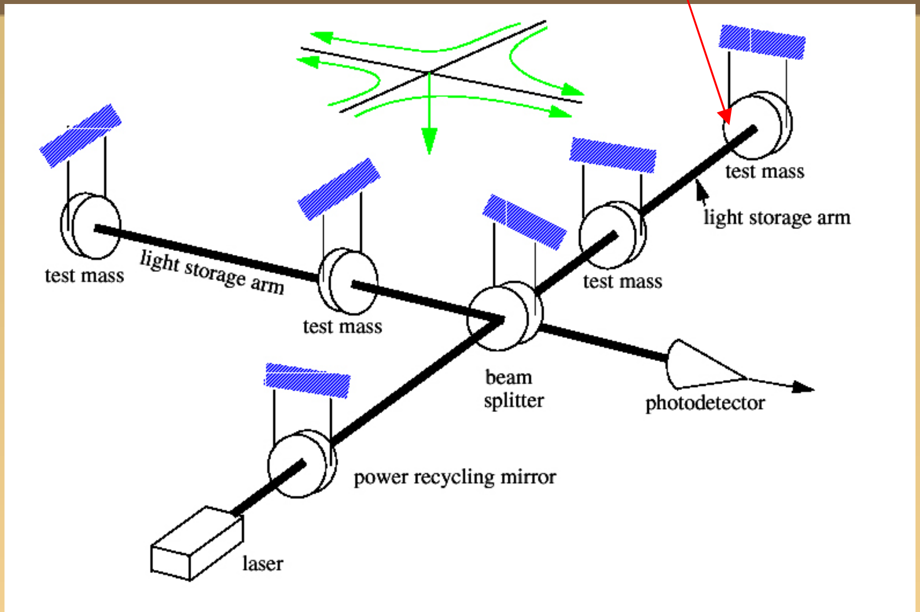


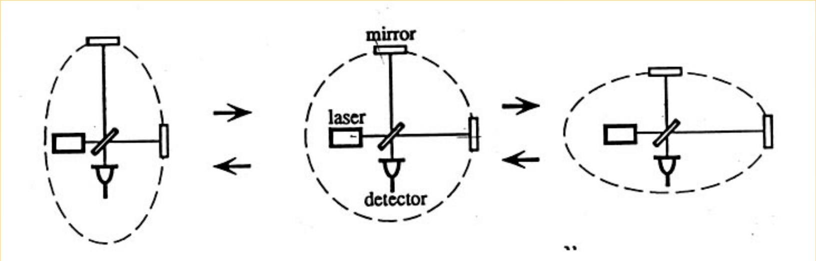
$$\text{strain} = \frac{\Delta L}{L}$$

Interferometers as gravitational wave detectors

- Suspended test mass is “freely falling” in 1D along arm axis
- GW wavelength far longer than detector arms, so need cavity to keep light in arms as the GW passes – Fabry-Perot cavity or signal recycling mirror
  - 100Hz GW has λ~3x10^{6}m, if arm length ~4km need to keep light in arms for of order 1000 round trips
- Keep interferometer on dark fringe via feedback to mirrors and measure required motions

“freely falling” test mass

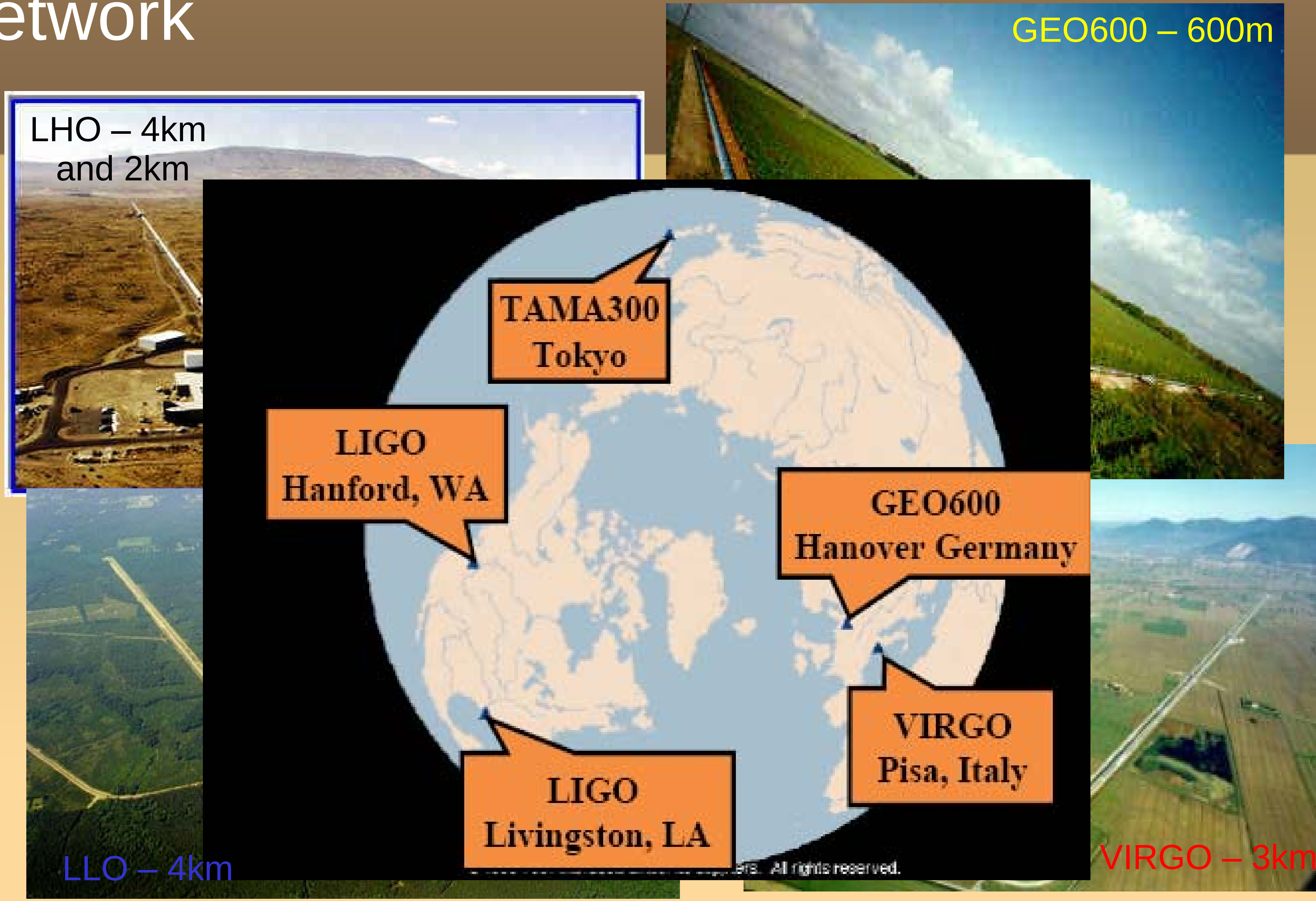




$h=\Delta L/L \sim 10^{-21}$ and

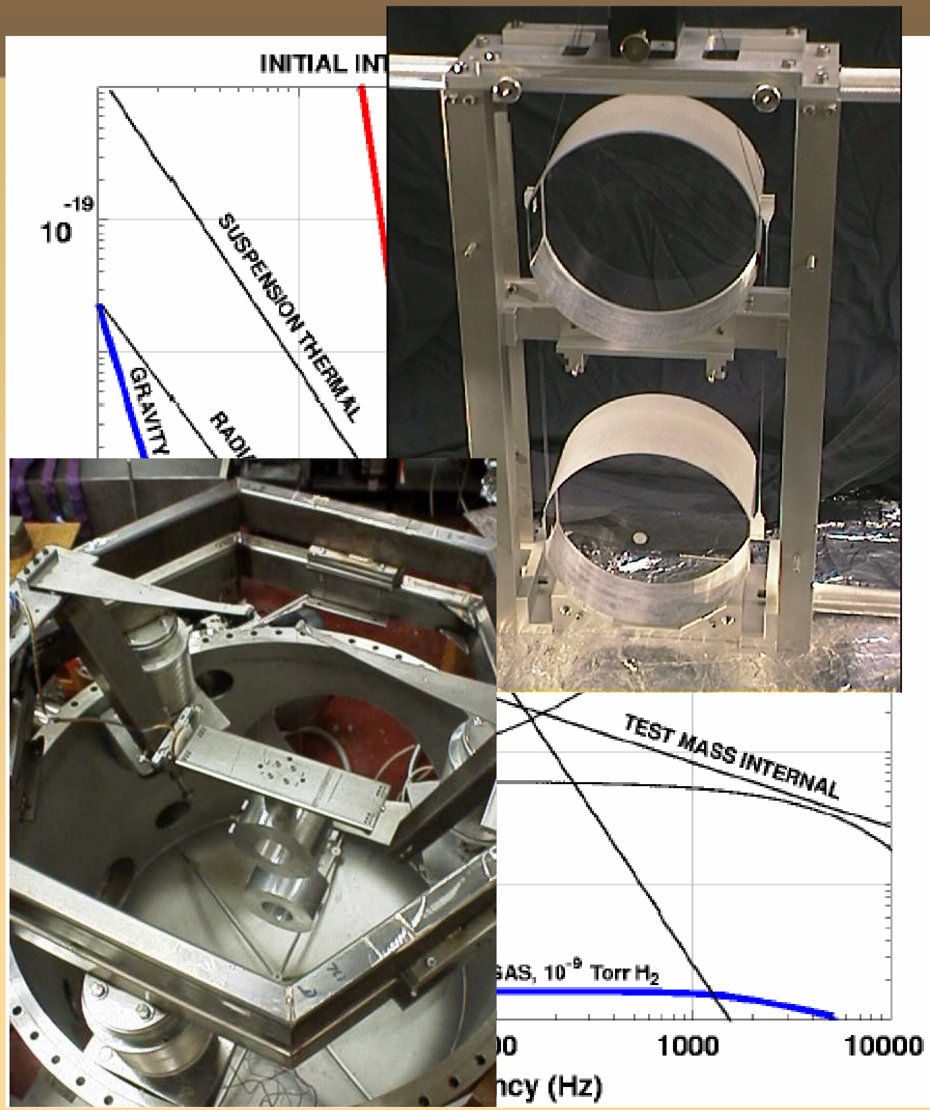
$L=4km \Rightarrow \Delta L = hL \sim 10^{-18}$ m

Interferometric gravitational wave detector network

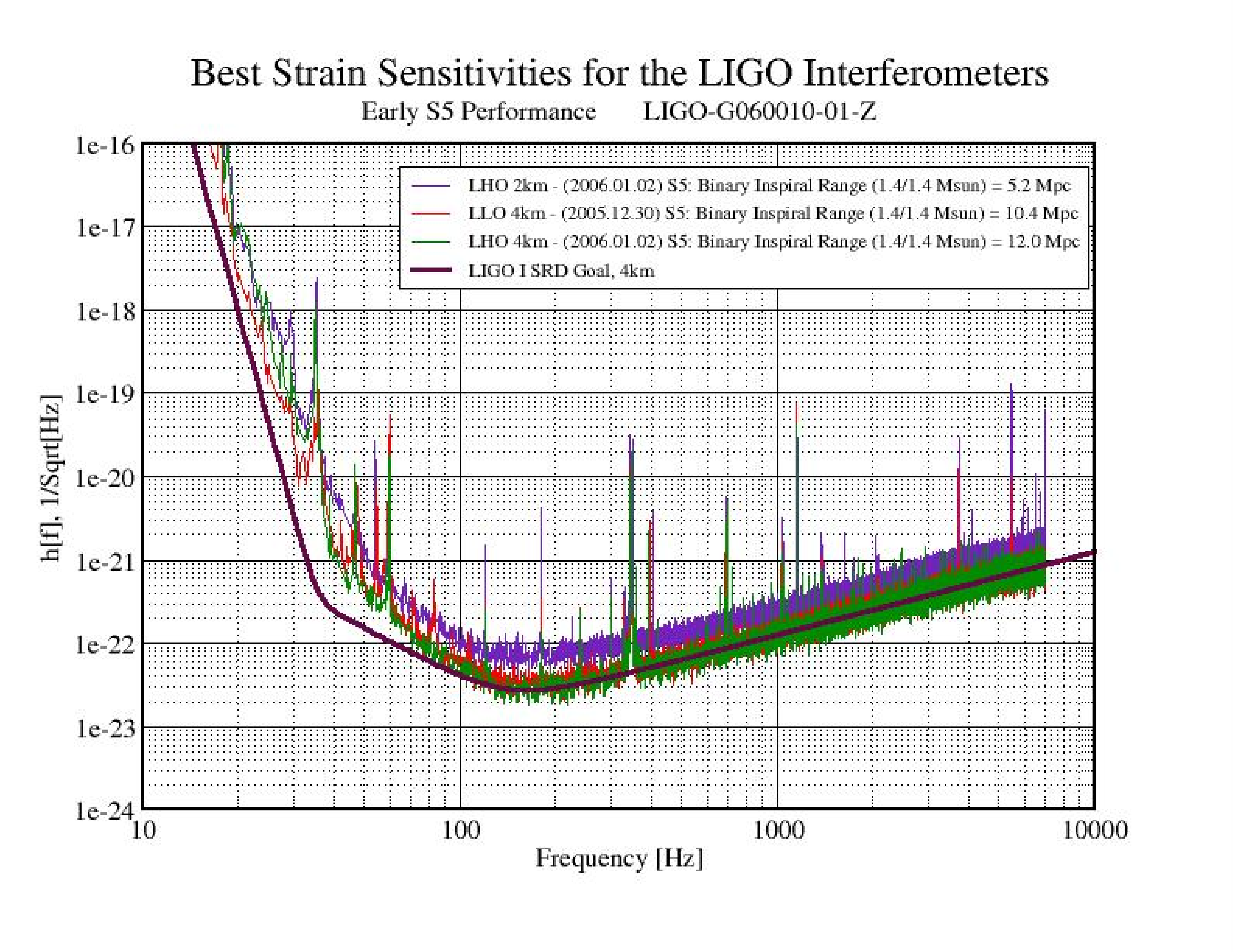


Noise sources

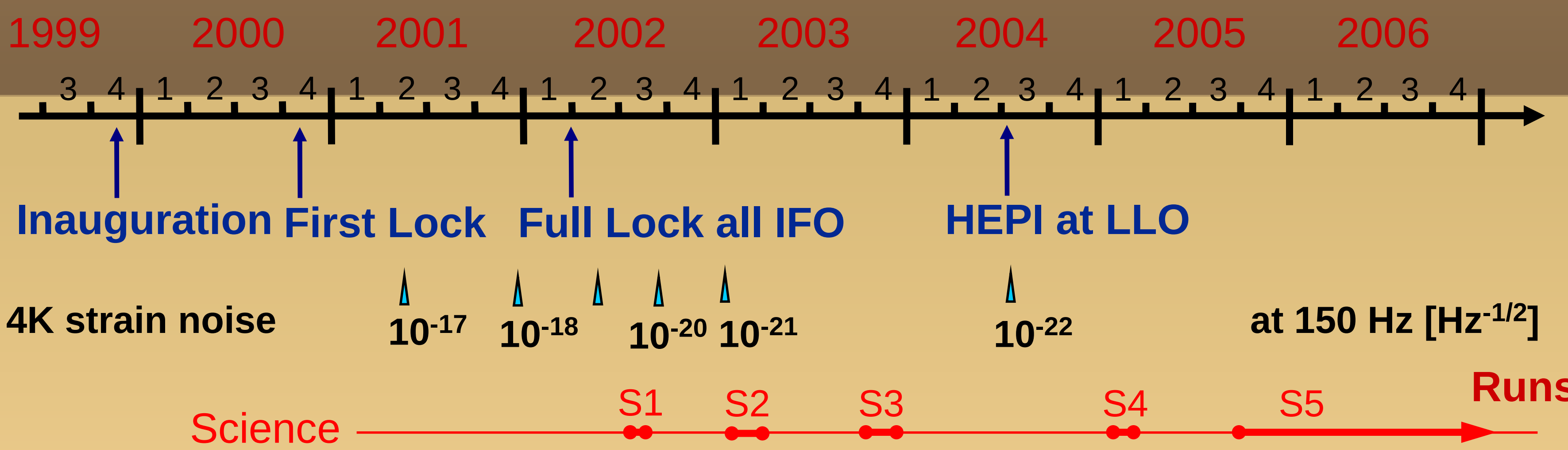
- Thermal noise (mid-range frequency)
  - test mass/suspension vibration
- Seismic noise (low frequency)
  - ground vibrations coupling into test mass
- Shot noise (high frequency)
  - quantum fluctuations in laser power
- Gravity gradient noise (low frequency)
  - gravitational field variations
  - Noise wall for ground based observations (e.g 0.1 kg bird flying 50 m from 10kg test mass causes it to move ~ 10^{-13} cm over 1 sec cf. 10^{-16} cm for GW) – low frequency (<1 Hz))



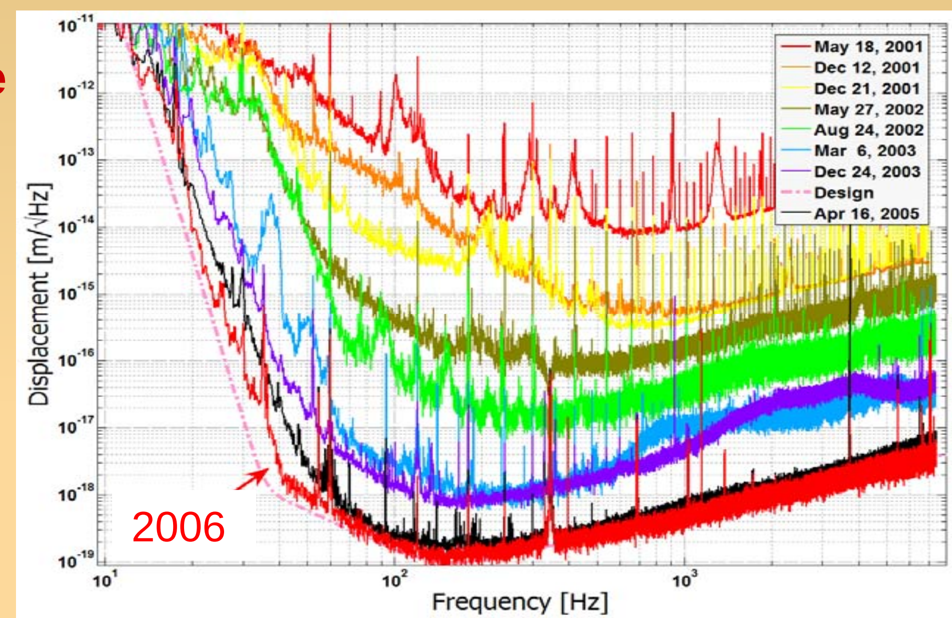
Noise curves



LIGO and GEO600 science runs



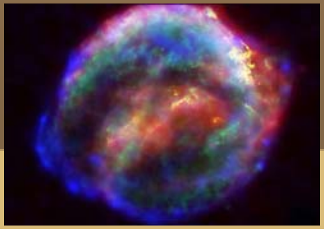
- LIGO and GEO600 detectors/scientists /engineers/technicians are part of the LIGO Scientific Collaboration (LSC)
- Undertaken five “science runs” where commissioning has be suspended and data taken
- Currently on science run 5 (S5) which started in Nov 2005.

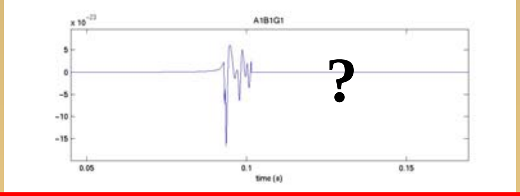


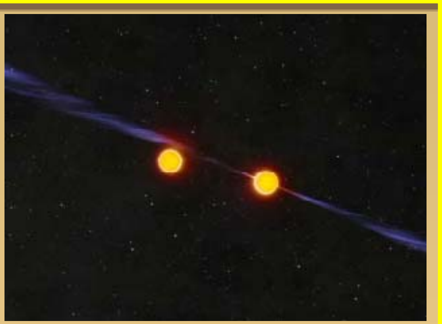
Sources of gravitational waves

- Because GWs are so weak, detectable sources have to be the most violent and energetic objects / events in the universe
- Generally group sources into certain categories depending on the waveform
  - Bursts
    - unmodelled
    - inspirals
    - Ring-downs
  - Continuous waves
    - quasi-periodic sources
  - Stochastic
    - source confusion background
    - primordial background

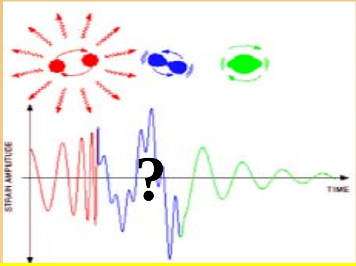
NASA, HEASARC



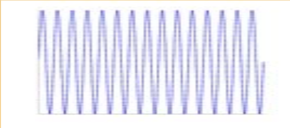


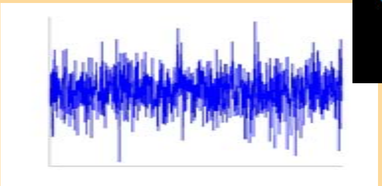


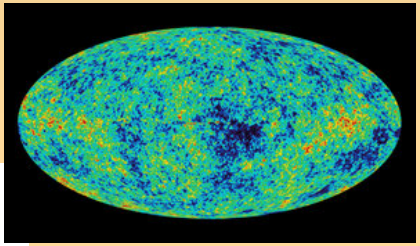
John Rowe, CSIRO



Crab pulsar (NASA, Chandra Observatory)



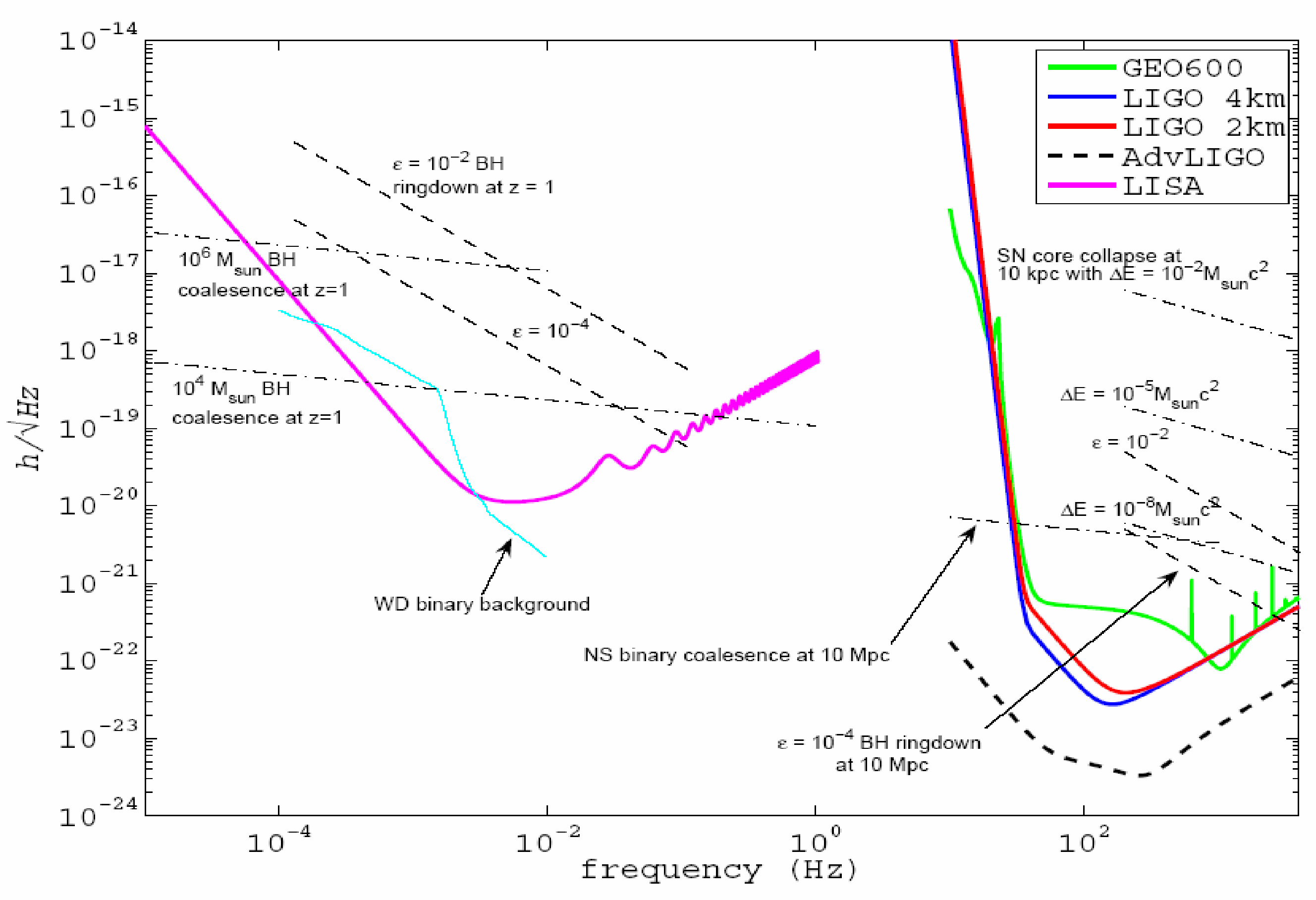




NASA, WMAP

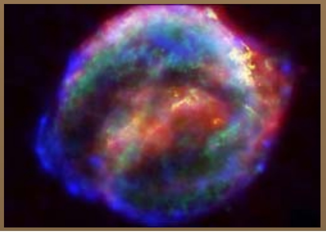
Sources

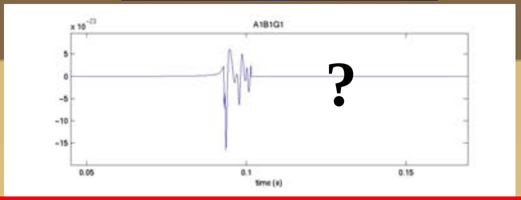
- Expected sources have a range of frequencies and amplitudes



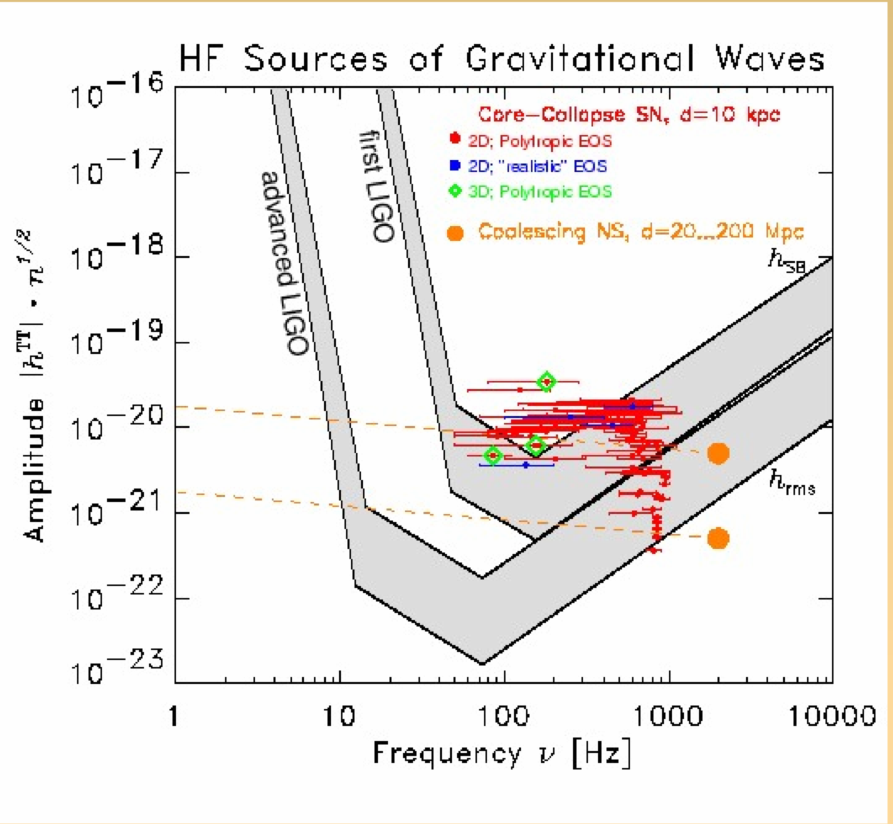
Unmodelled burst sources

NASA, HEASARC





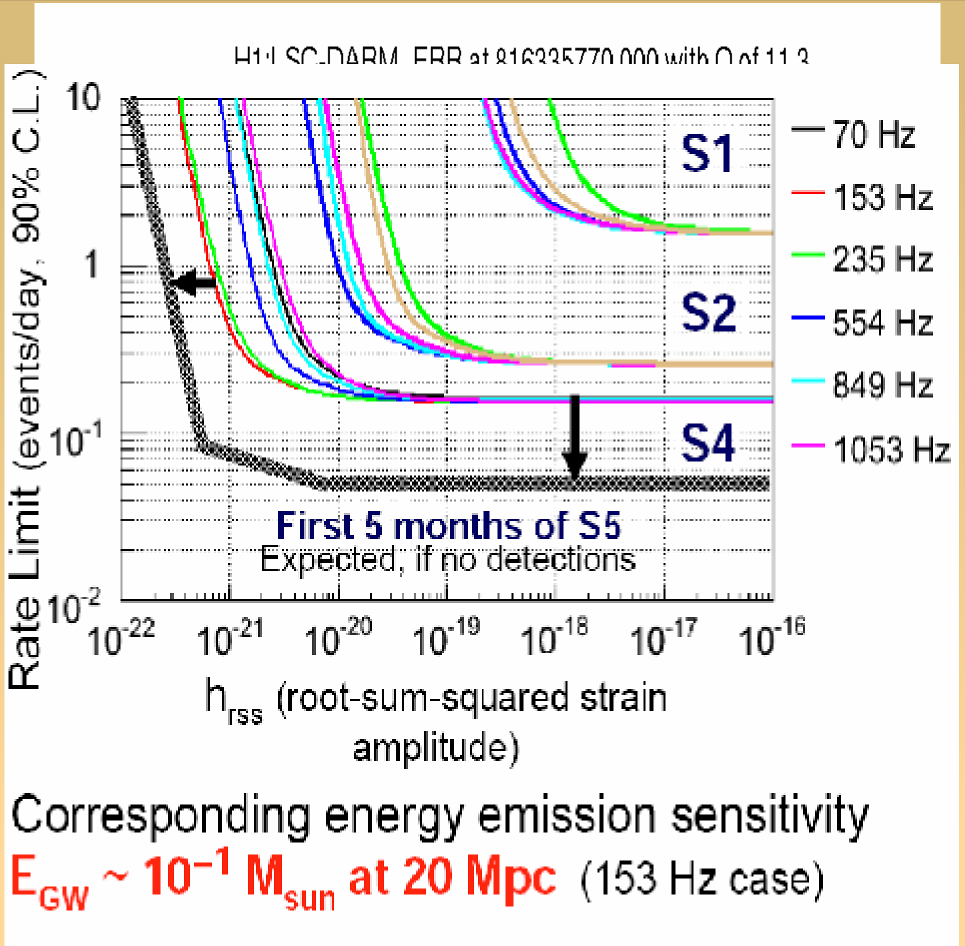
- Supernova core collapse
  - rebound, bar modes, fluid modes
- Core-collapse GRBs
- Core collapse must be non-axisymmetric
  - badly constrained by numerical simulations – mainly 1D and 2D
  - Expected weak emission, but should be visible within local group
- Can learn dynamics of neutron star/black hole formation
  - neutron star structure



Chris Fryer

Unmodelled burst searches

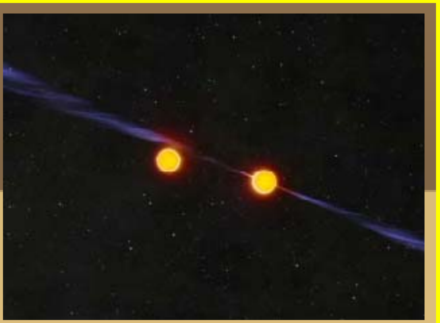
- Look for excess power in time-frequency plane
  - spectrograms
  - wavelets
  - data statistics/change point analysis
- Create candidate lists
  - Perform waveform consistency and time coincidence tests between multiple detectors
    - Would allow positional and polarisation information to be extracted
- Set upper limits on event rates and calculate sensitivity to various waveforms e.g. sine-Gaussians
- **No** detection yet!



Modelled burst sources - inspirals

- Binary system inspirals
  - NS-NS, NS-BH, BH-BH (~solar mass BHs) inspiral and merger within LIGO frequency range (10-1000Hz)
    - Sweep through the frequency range as they approach coalescence – chirp waveform
  - EMRIs and SMBH mergers in LISA frequency range (~0.1mHz – 0.1Hz)
- Test GR in strong field regime
- Test no-hair theorem for Kerr black hole

$$h \sim \frac{(GM)^{5/3}\Omega^{2/3}}{c^4 r}$$



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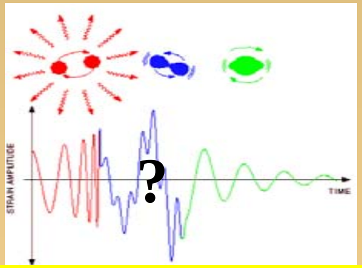
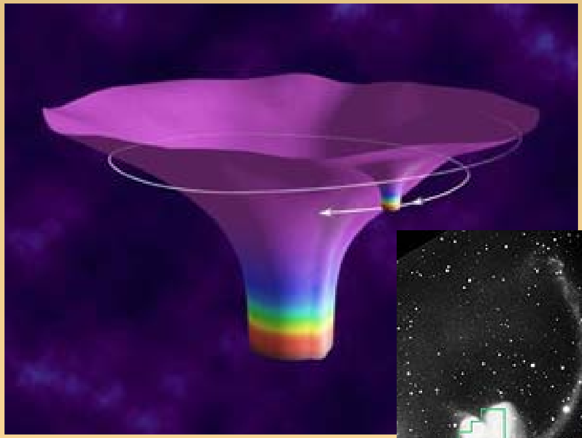
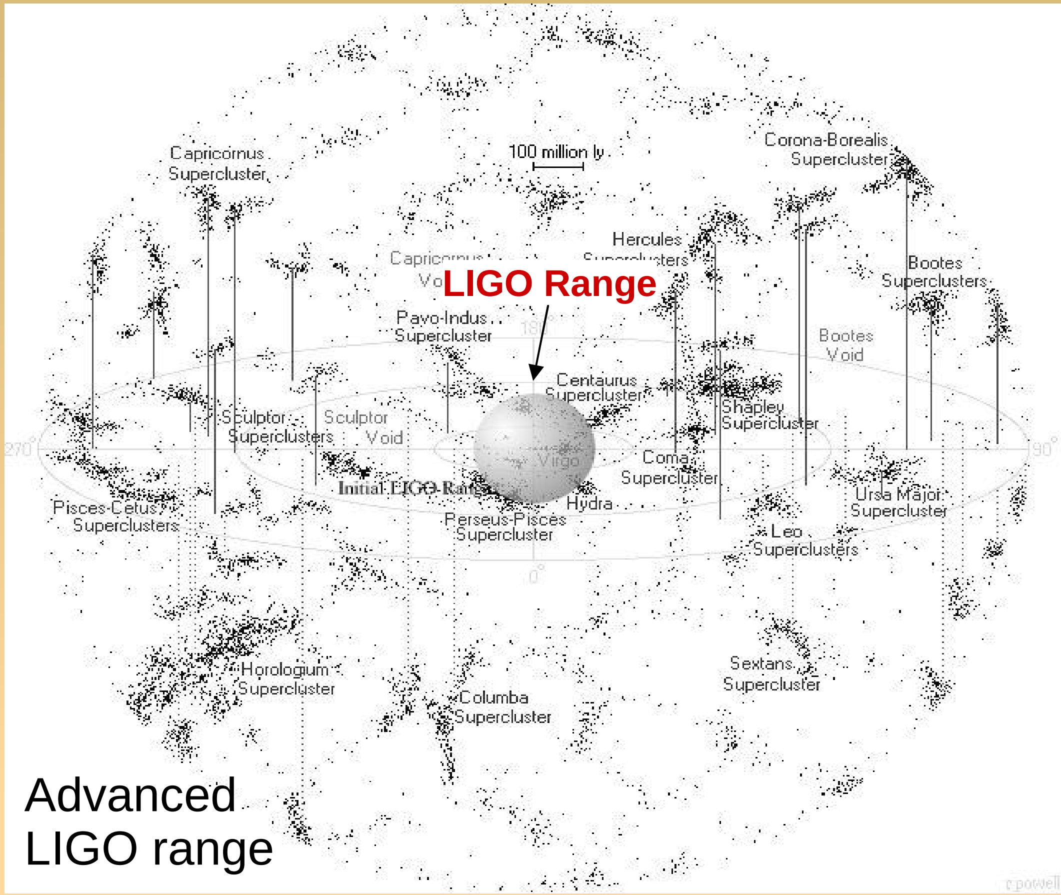




http://rst.gsfc.nasa.gov/Sect20/A4.html

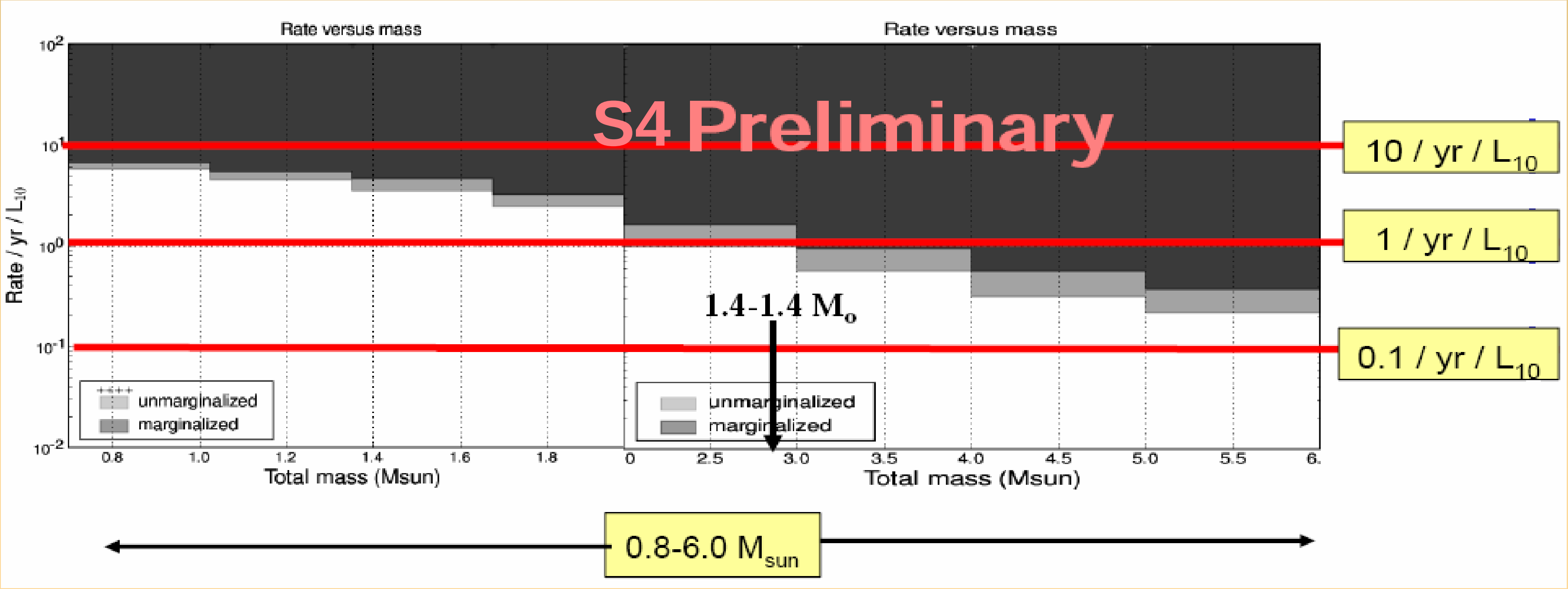
Inspiral range

- We can think of LIGO sensitivity in terms of a distance reach
  - amplitude goes as 1/r
- Using a source model we can say how far away we could see a 1.4 solar mass NS-NS binary at SNR 8
- Current LIGO range is about 15 Mpc (out to Virgo cluster)
  - Advanced LIGO 10 times more sensitive than LIGO, 10 times the reach, but 1000 times the volume covered
- Population estimates optimistically predict ~0.35 events per year visible with LIGO, ~190 per year with Advanced LIGO

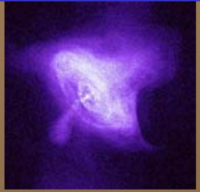


Inspiral searches

- Signal model is very well known until close to merger
  - Matched filtering using templates of signals
  - Set threshold SNR for trigger on background – time slide data
    - Perform coincidence/waveform consistency analysis between detectors
  - No GW triggers yet!



Continous wave sources



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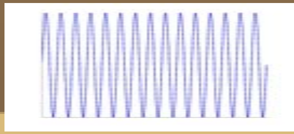
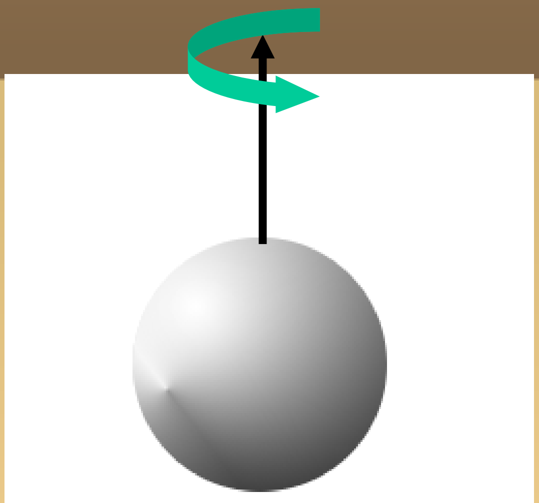
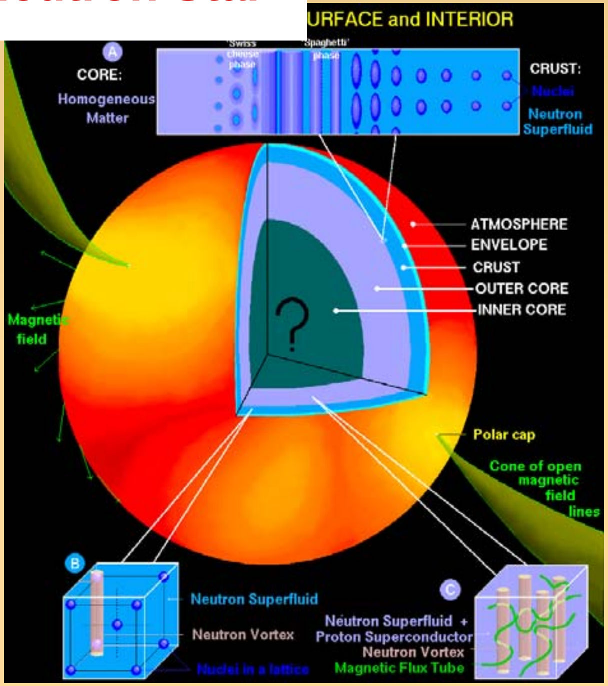


- All binary systems will produce periodic gravitational waves
  - generally very low frequency e.g. α and β Centauri system has h_0~6x10^{-23} at Earth, but f=4x10^{-10} Hz
- Rapidly spinning neutron stars provide a potential source of continuous gravitational waves for LIGO (10-1000Hz)
- To emit gravitational 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



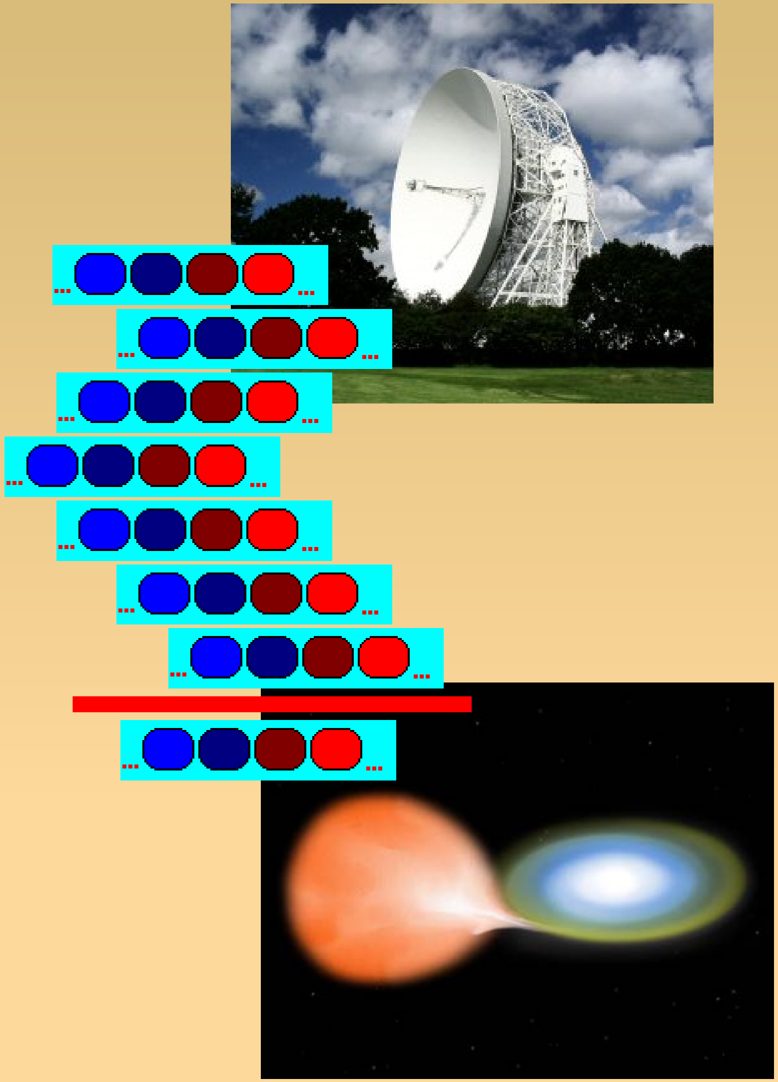
Bumpy Neutron Star



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

Pulsar searches

- Current searches for periodic gravitational waves include:
  - Known pulsar searches
    - Targeting all pulsars within the frequency band (ν_{gw}>50Hz) including pulsars in binary systems using radio inferred phase evolution
  - Semi-coherent searches for excess monochromatic power
    - Hough
    - Stack-slide
    - Power flux
  - Coherent searches over large parameter spaces
    - All sky broadband search and targeted LMXB searches
    - Einstein@home



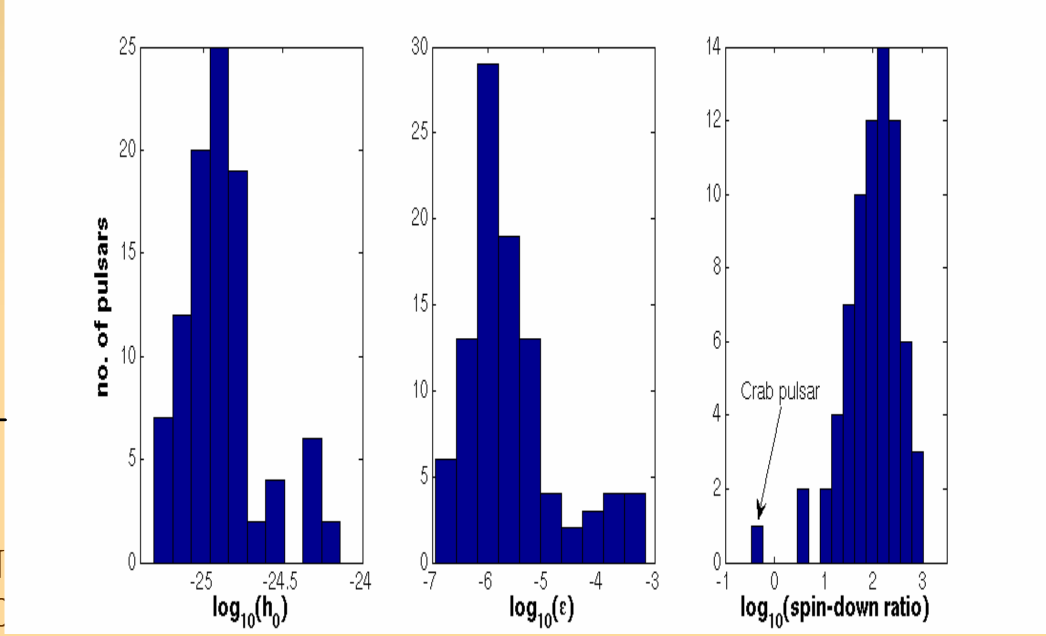
Preliminary S5 search results

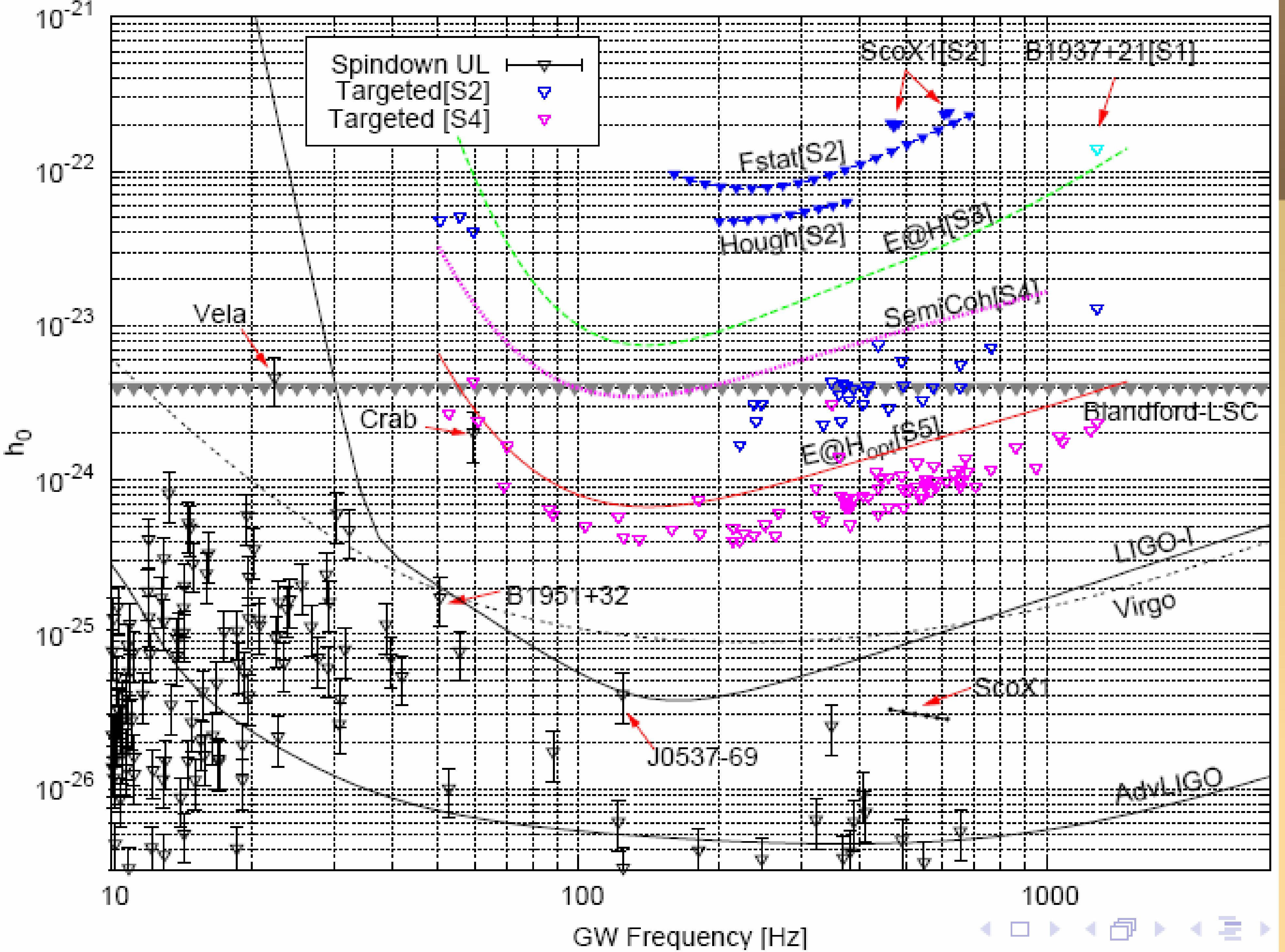
- Obtain pulsar parameter information from pulsar group at Jodrell Bank and the ATNF pulsar catalogue
- Have *preliminary* results – joint 95% h_0 upper limits - using timings for 97 pulsars using H1, H2 and L1 data from first 10 months of S5 data – 1^{st} Nov 05 – 17^{th} Sep 06
  - many will require to timing over the period of the run to be sure of phase coherence

Lowest h_0 upper limit:
PSR J1623-2631 (ν_{gw} = 180.6 Hz, r = 3.8 kpc) h_0 = 4.8x10^{-26}
Lowest ellipticity upper limit:
PSR J2124-3358 (ν_{gw} = 405.6Hz, r = 0.25 kpc) ε = 1.1x10^{-7}

$$\varepsilon = 0.237 \frac{h_0}{10^{-24}} \frac{d}{1\text{kpc}} \frac{1\text{Hz}^2}{\nu_r^2} \frac{10^{38}\,\text{kgm}^2}{I}$$

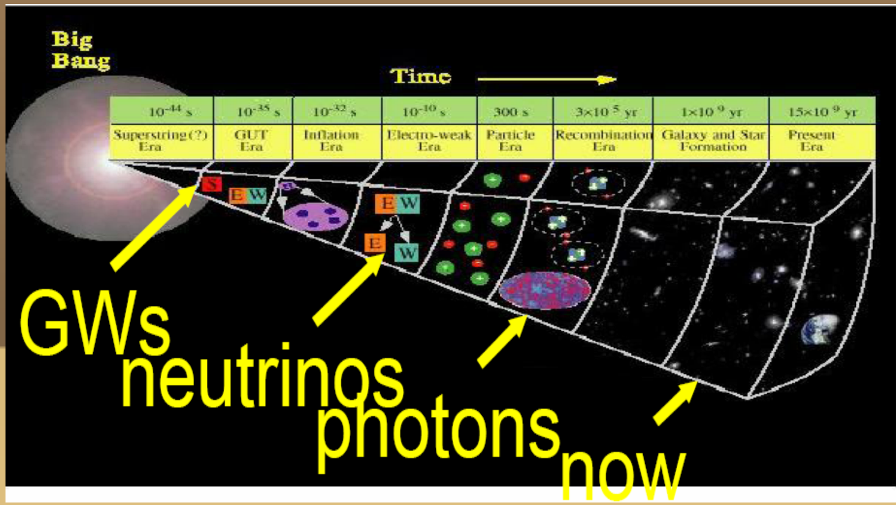
$$h_0^{\text{spin-down}} = \left(\frac{5}{2}\frac{GI\dot{\nu}}{c^3 d_r^2 \nu_r}\right)^{\frac{1}{2}}$$





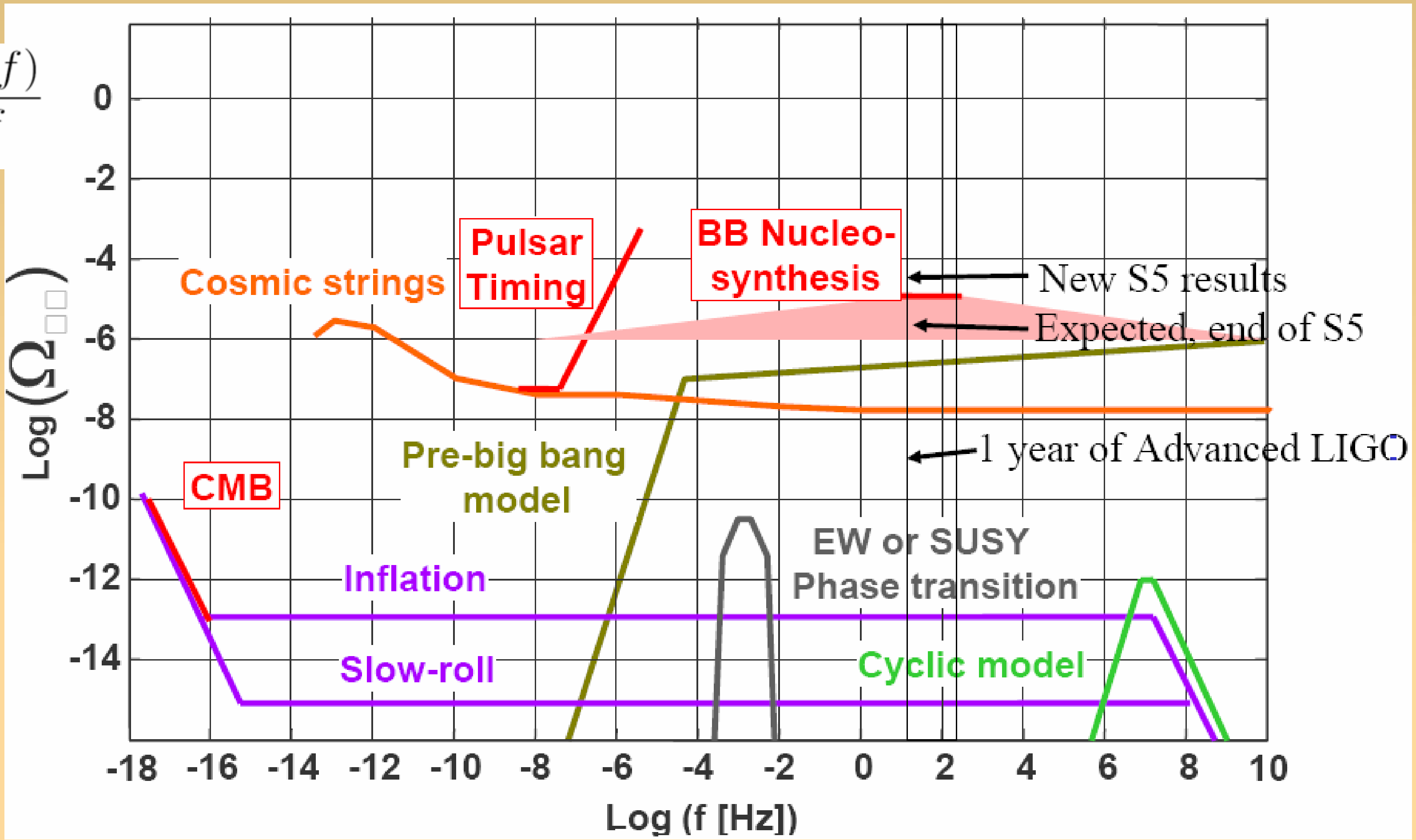
Spindown UL
Targeted[S2]
Targeted [S4]
ScoX1[S2]
B1937+21[S1]
Fstat[S2]
Hough[S2]
E@H[S3]
SemiCoh[S4]
Vela
Crab
E@H$_{opt}$[S5]
Blandford-LSC
LIGO-I
Virgo
B1951+32
ScoX1
J0537-69
AdvLIGO
h_0
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10
100
1000
GW Frequency [Hz]

Stochastic background



- Cross-correlate data from two detectors e.g. use one as matched filter for other

$$\Omega_{GW}(f) = \frac{1}{\rho_c}\frac{d\rho_{GW}(f)}{d\ln f}$$

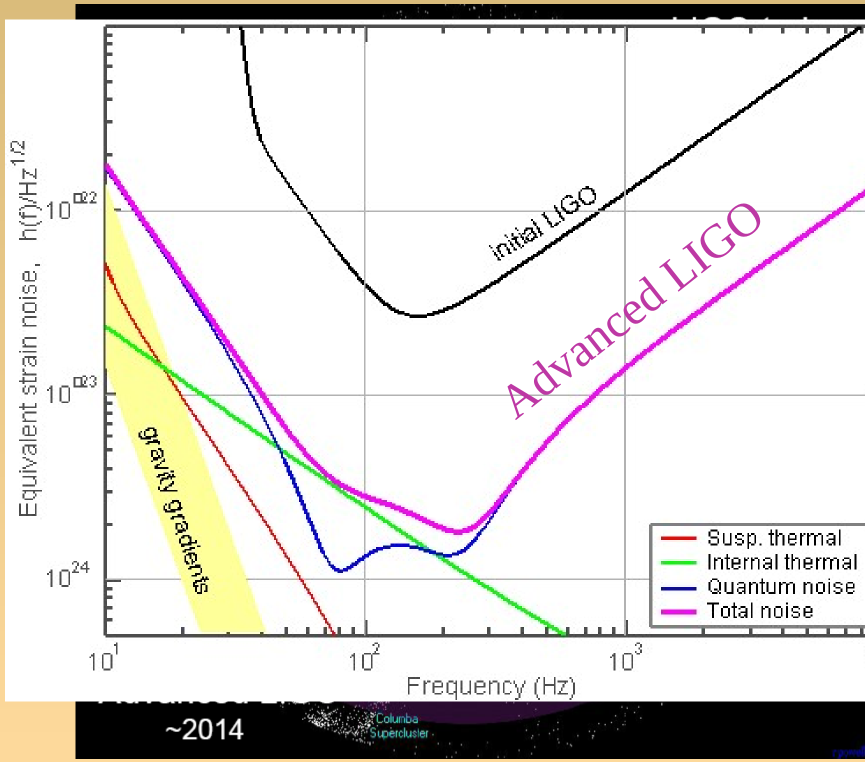


Present status of GW searches

- LIGO operating at design sensitivity.
- Have undertaken observation runs in the last four years, with the current run having been observing for over a year.
- VIRGO will joining data taking soon.
- Several bar detectors also running and being upgraded.

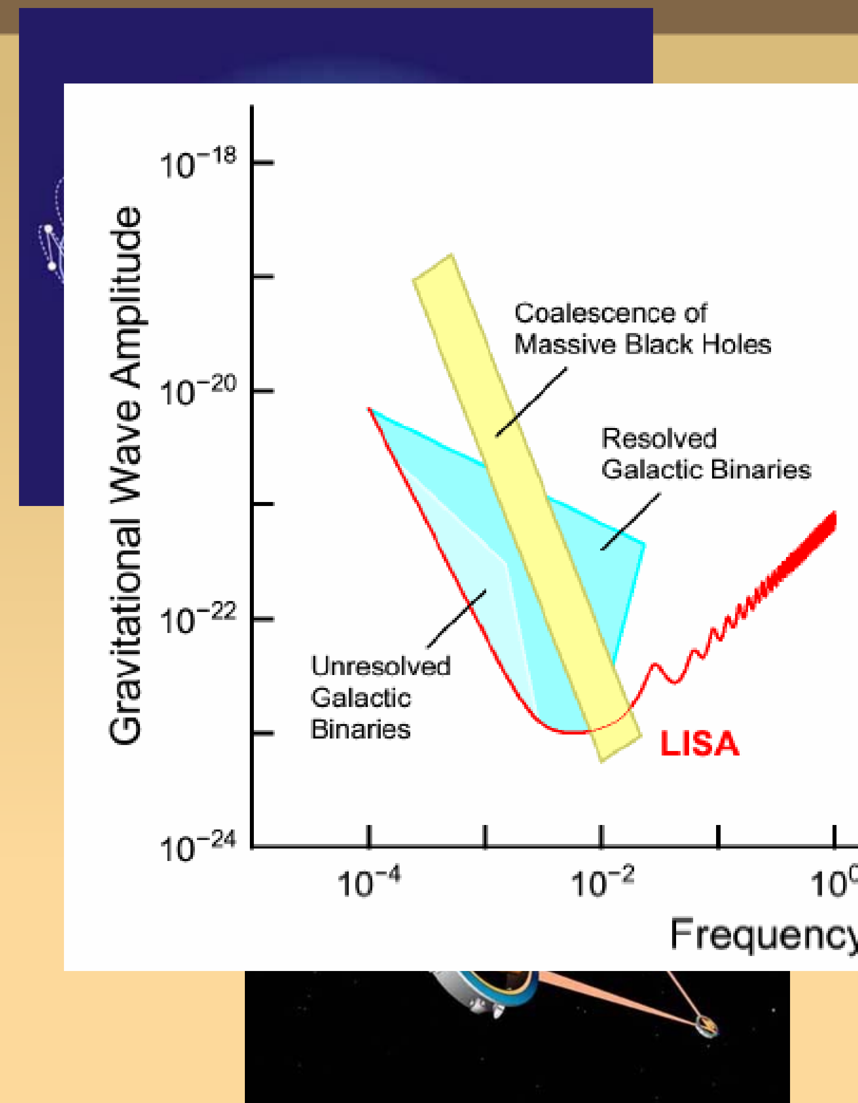
Future - interferometers

- In ~2007/8 LIGO will be upgraded (Enhanced LIGO), and again in 2013 to Advanced LIGO with new technologies (pioneered in GEO600) to improve sensitivity.
  - factor of 10 sensitivity improvement equals factor of 1000 in volume seen
  - expect to see few events per week!
- European (EGO, GEOHF), Japanese (LCGT) and Australian (ACIGA) collaborations are also looking into future detectors covering a range of frequencies.



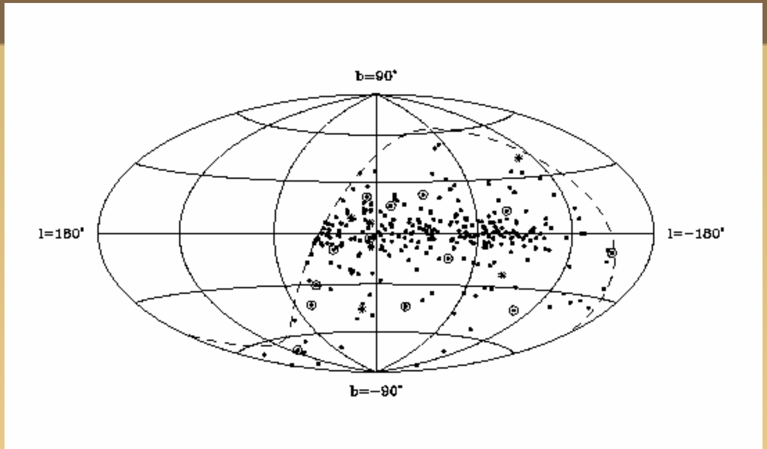
Future - space-based detector

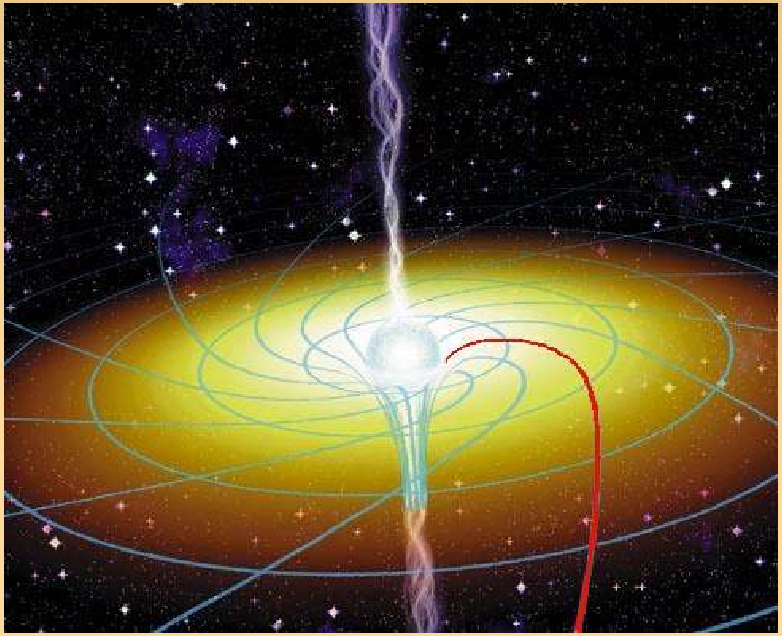
- Laser interferometer space antenna (LISA) is a joint NASA/ESA project for a space based GW detector planned for a 2015 launch.
- LISA has 5 million km arms.
- Will be able to look at low freqs > mHz – not limited by gravity gradient noise



LISA sources

- Sources it will see will be:
  - compact object binary systems – gives us a census of these types of system
  - infall into supermassive black holes – enables us to map space-time in very strong gravity regimes
  - Black hole mergers



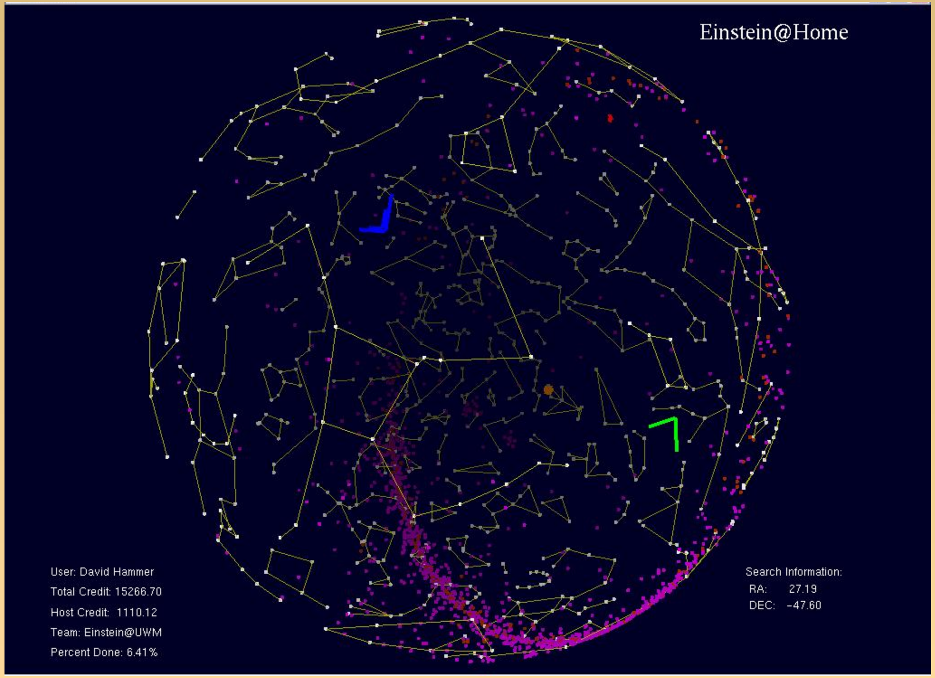


Conclusions

- Currently have near continuous operation of LIGO
  - Produced upper limits from many sources
- Good chance of detecting something – even you can help!
- Detector upgrades and LISA should give opportunity to start GW astronomy for real.
- Exciting times for GW astronomy!

Can I help

- Yes!
- Einstein@home (a SETI@home like screensaver) has been developed for the general public to contribute to searching for gravitational waves from neutron stars using actual data from LIGO and GEO
  - Currently analysing S5 data



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