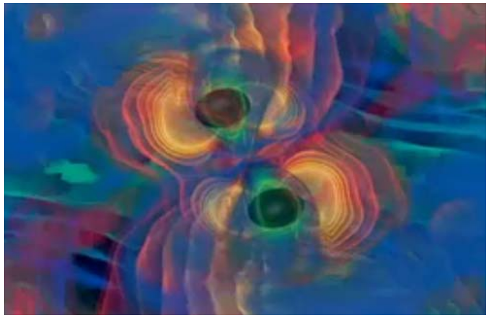


Searching for Gravitational Waves with LIGO

Gabriela González

Physics and Astronomy, Louisiana State University

LIGO Scientific Collaboration

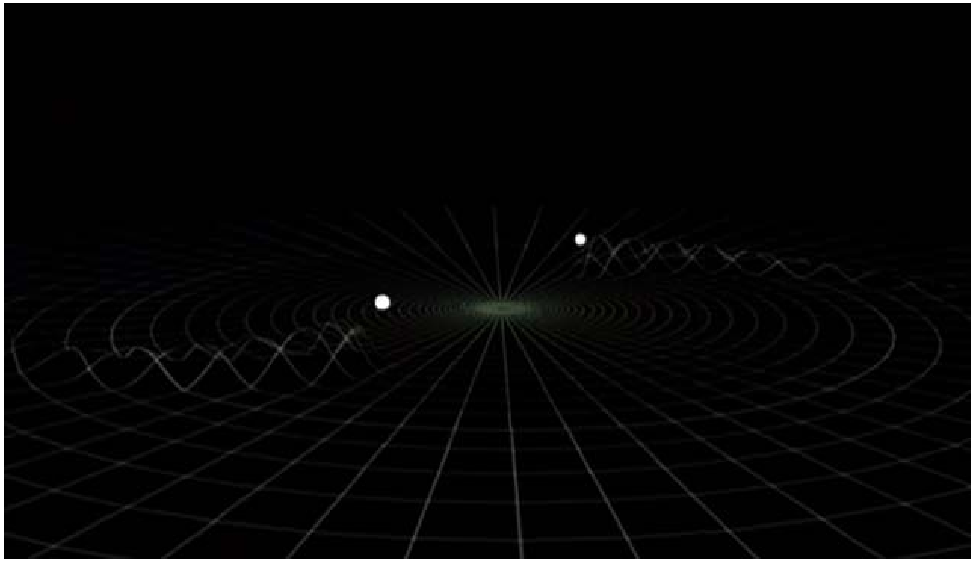
The University of Mississipi

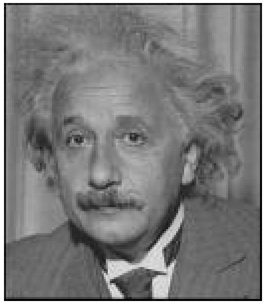
April 3, 2007

G070215-00-Z

Einstein’s gravitation

When masses move, they wrinkle the space time fabric, making other masses move…

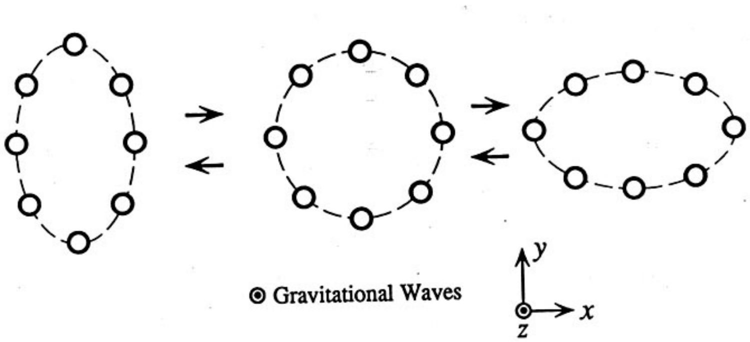




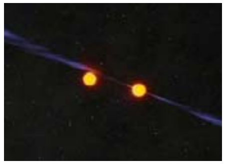
Einstein’s messengers,
National Science Foundation video
www.ligo.caltech.edu

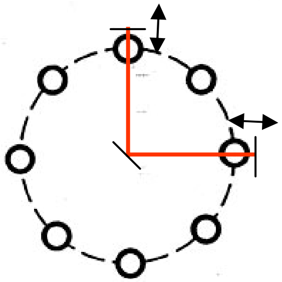
The theory predicts gravitational waves traveling away from moving masses.

Gravitational waves



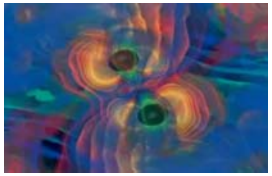
Gravitational waves are quadrupolar distortions of distances between freely falling masses. They are produced by time-varying mass quadrupoles.



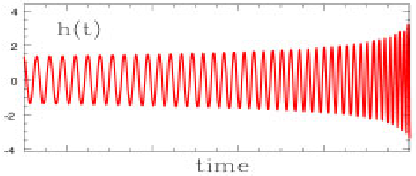


Michelson-type interferometers can detect distance changes in orthogonal directions.

What's measured is **$\Delta L = hL$, or $\Delta\Phi \sim \Delta L/\lambda$**

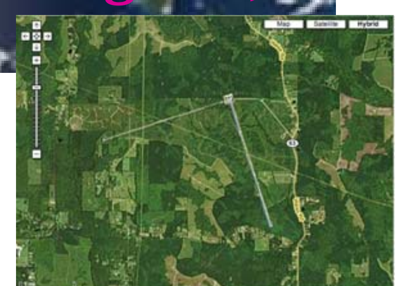


Amplitude of GWs produced by binary neutron star systems in the Virgo cluster have **$h = \Delta L/L \sim 10^{-21}$** and frequencies sweeping up to ~1400 Hz.



The LIGO project

$h=\Delta L/L\sim 10^{-21}$ and $L=4km \Rightarrow \Delta L=hL\sim 10^{-18}$ m !

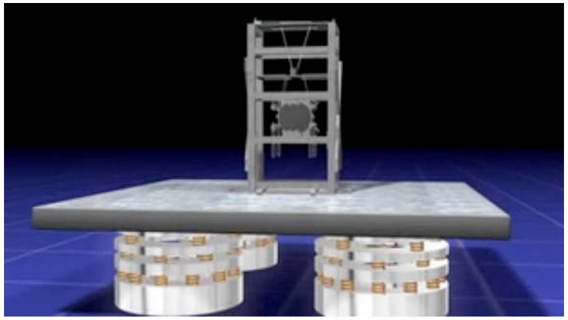


Three LIGO detectors: 4km long in Livingston, LA (L1); 4km and 2km long in Hanford, WA (H1, H2).

Hundreds of people working on the experiment and looking at the data: LIGO Scientific Collaboration

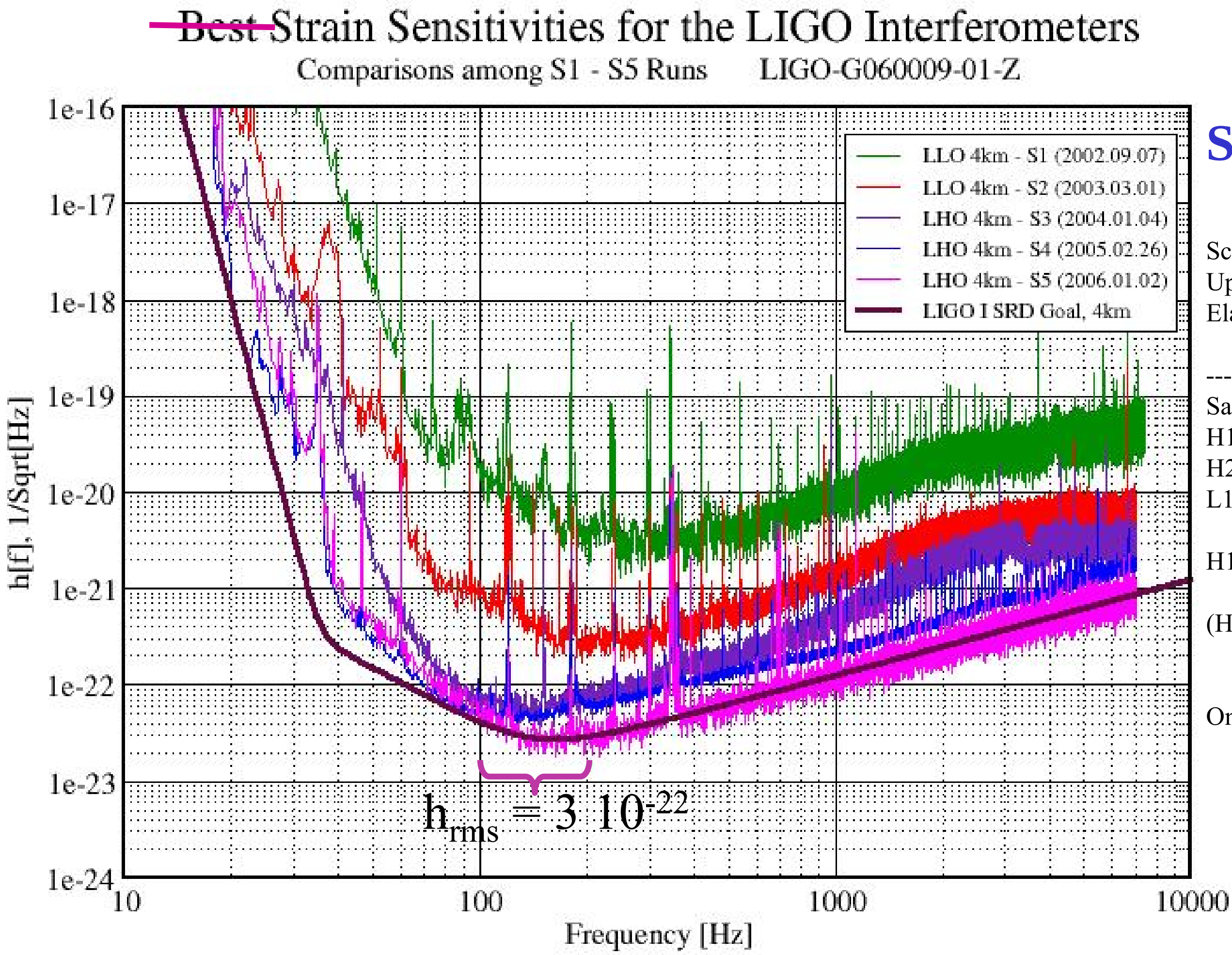
GW Detection: a difficult and fun experiment

QuickTime™ and a
Animation decompressor
are needed to see this picture.



QuickTime™ and a
Animation decompressor
are needed to see this picture.

LIGO: Steady progress



S5 so far:

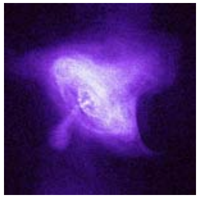
Science-mode statistics for S5 run
Up to Apr 01 2007 16:56:04 UTC
Elapsed run time = 12312.9 hours=513 days

----------------------- Whole run so far -----------------------

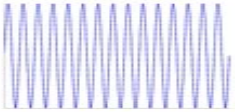
Sample	Hours	Percent	
H1	9193.4	74.7	since Nov 4, 2005
H2	9496.1	77.1	since Nov 4, 2005
L1	7660.2	63.5	since Nov 14, 2005
H1+H2+L1	6000.0	49.7	since Nov 14, 2005
(H1orH2)+L1	6935.4	56.3	since Nov 4, 2005
One or more LIGO	10965.1	89.1	since Nov 4, 2005

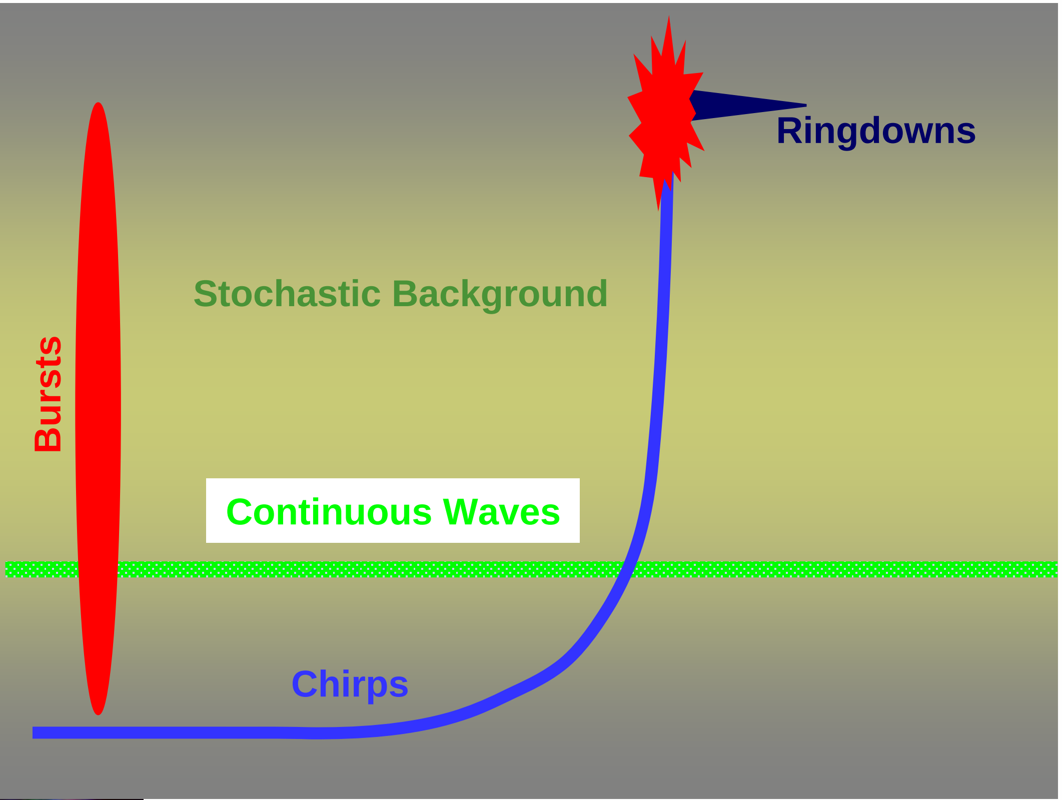
Observational Results

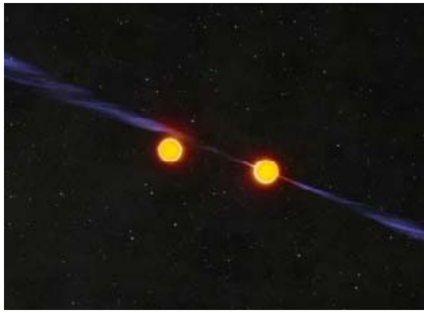
www.ligo.org



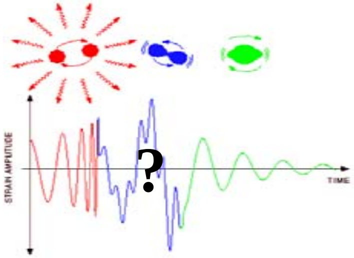
Crab pulsar (NASA, Chandra Observatory)

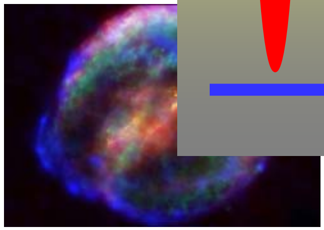




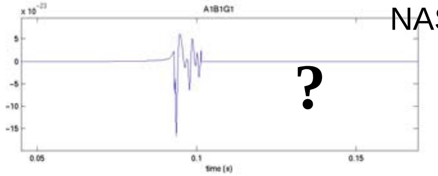


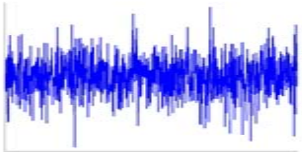
John Rowe, CSIRO

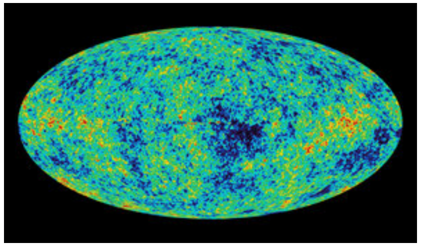




NASA, HEASARC



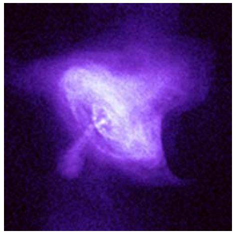




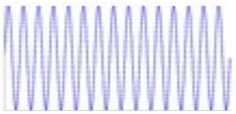
NASA, WMAP

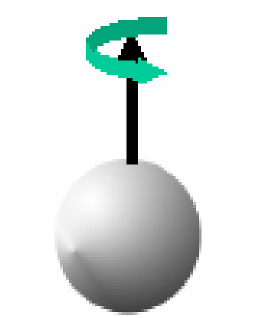
Gravitational wave searches: pulsars

Crab pulsar
(Chandra Telescope)



- Rotating stars produce GWs *if* they have asymmetries or *if* they wobble.
- There are many known pulsars (rotating stars!) that produce GWs
  in the LIGO frequency band (40 Hz-2 kHz
- *Observed* spindown can be used to set strong indirect upper limits on GWs.
- There are likely to be many non-pulsar rotating stars producing GWs.
- Search for a sine wave, modulated by Earth's motion,
  and possibly spinning down: easy, but computationally expensive!
- GWs (or lack thereof) can be used to measure
  (or set up upper limits on) the ellipticities of the stars.





http://www.einsteinathome.org/

Gravitational wave searches: pulsars

Lowest GW strain upper limit:

PSR J1802-2124

(f_{gw} = 158.1 Hz, r = 3.3 kpc)

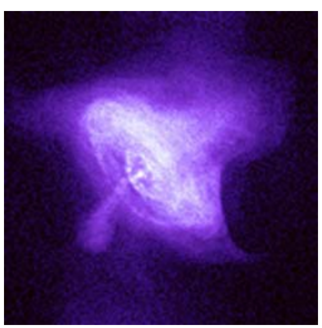
$\mathbf{h_0 < 4.9\times10^{-26}}$

Lowest ellipticity upper limit:

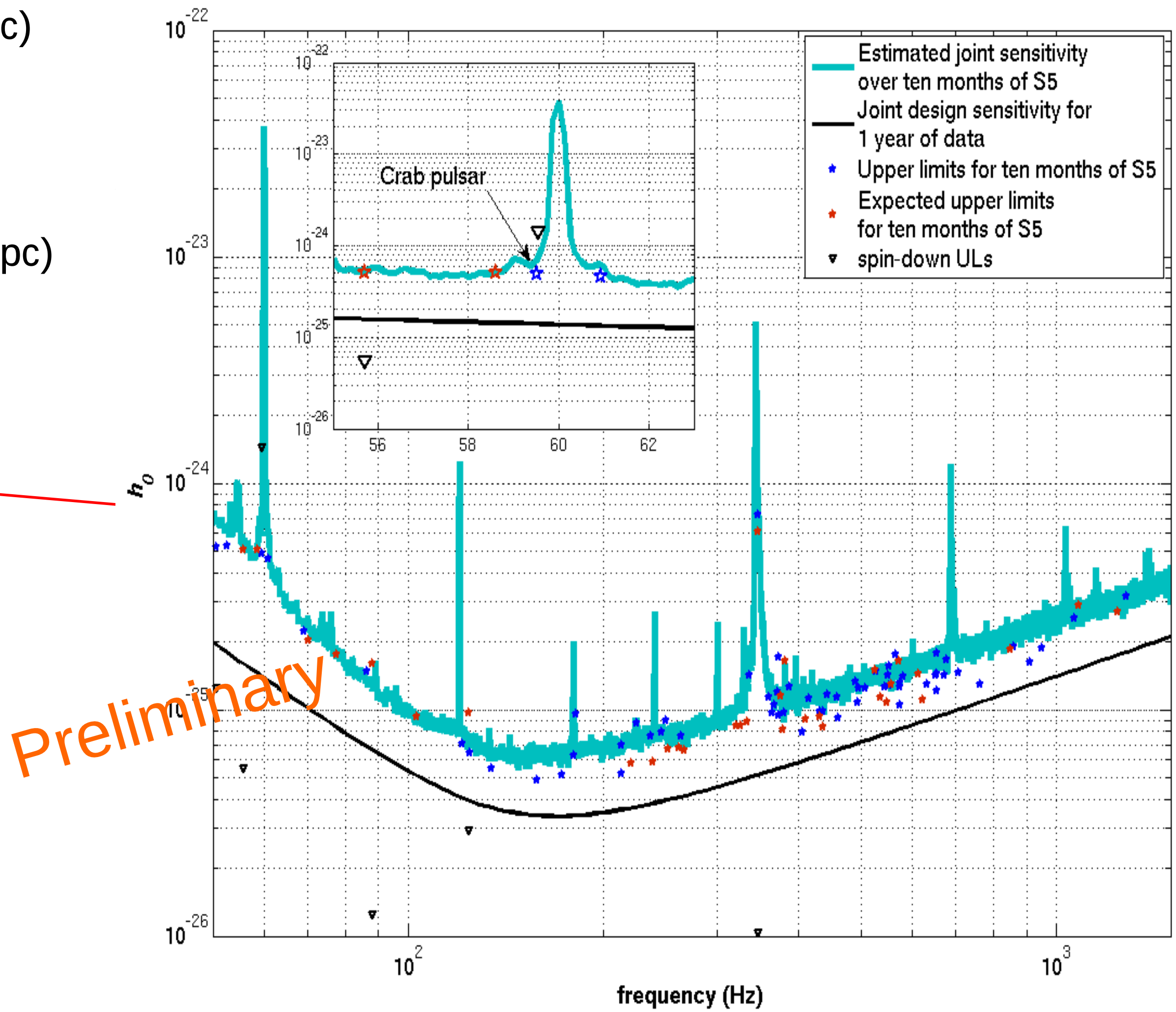
PSR J2124-3358

(f_{gw} = 405.6 Hz, r = 0.25 kpc)

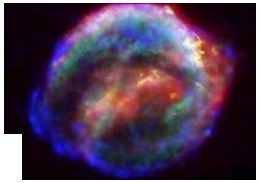
$\boldsymbol{\varepsilon < 1.1\times10^{-7}}$



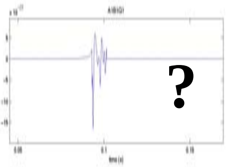
Crab pulsar

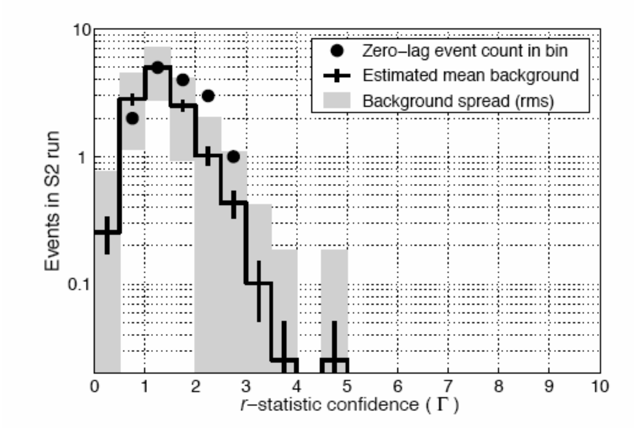


LIGO searches: “burst” sources (untriggered)

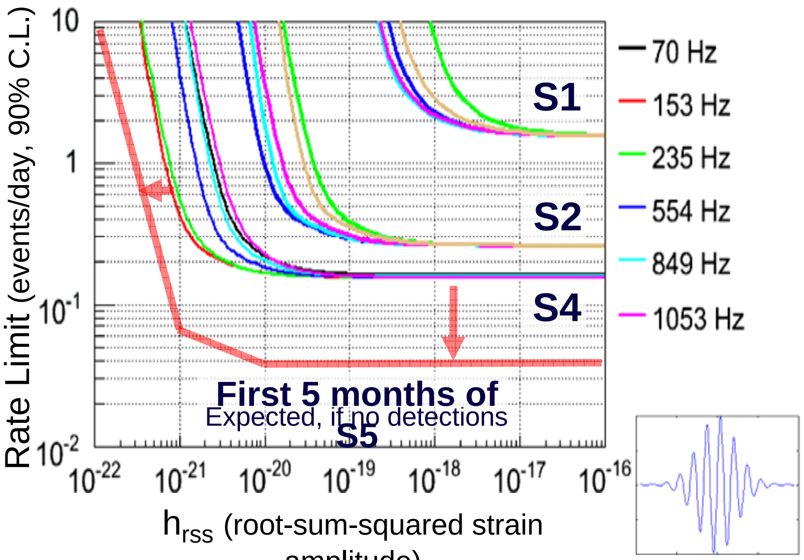


- Search for <u>triple coincident</u> triggers with a wavelet algorithm
- Measure waveform consistency
- Set a threshold for detection for <u>low false alarm probability</u>
- Compare with efficiency for detecting simple waveforms

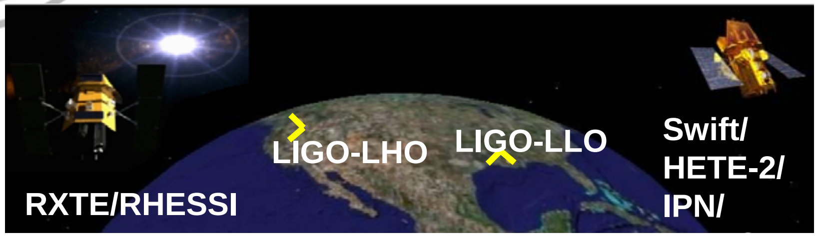




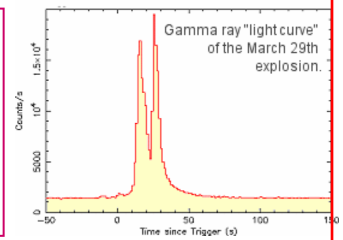
Limit on rate vs. GW signal strength sensitivity



Triggered Searches for GW Bursts



HETE GRB030329 (~800 Mpc SN): during S2, search resulted in no detection (**PRD** 72, 042002, 2005)



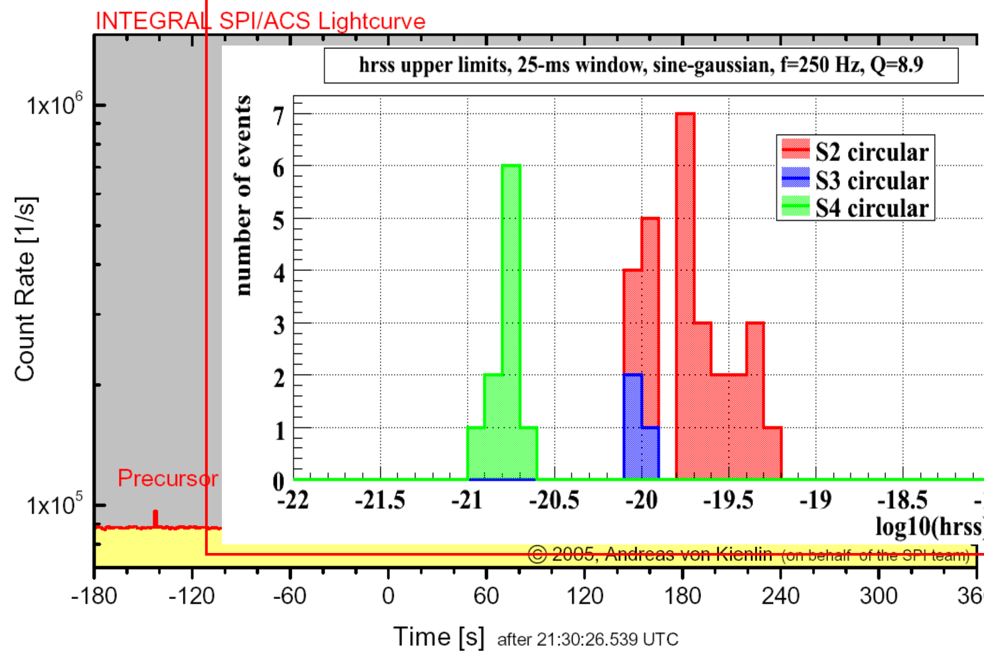
Gamma-Ray Bursts

- search LIGO data surrounding GRB trigger using cross-correlation method
- no GW signal found associated with 39 GRBs in S2, S3, S4 runs
- set limits on GW signal amplitude
- 53 GRB triggers for the first five months of LIGO S5 run

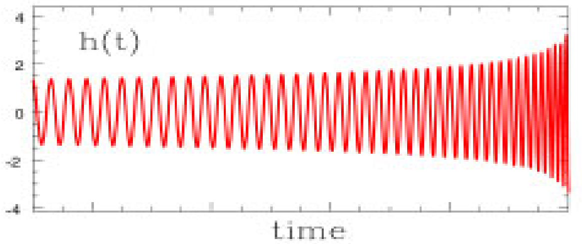
Soft Gamma Repeater 1806-20

- galactic neutron star (10-15 kpc) with intense magnetic field (~10^{15} G)
- source of record gamma-ray flare on December 27, 2004
- quasi-periodic oscillations found in RHESSI and RXTE x-ray data
- search S4 LIGO data for GW signal associated with quasi-periodic oscillations-- no GW signal found
- sensitivity: $E_{GW} \sim 10^{-7}$ to 10^{-8} Msun for the 92.5 Hz QPO
- this is the same order of magnitude as the EM energy emitted in the flare

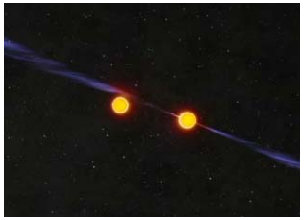
SGR 1806-20 Outburst on December 27, 2004

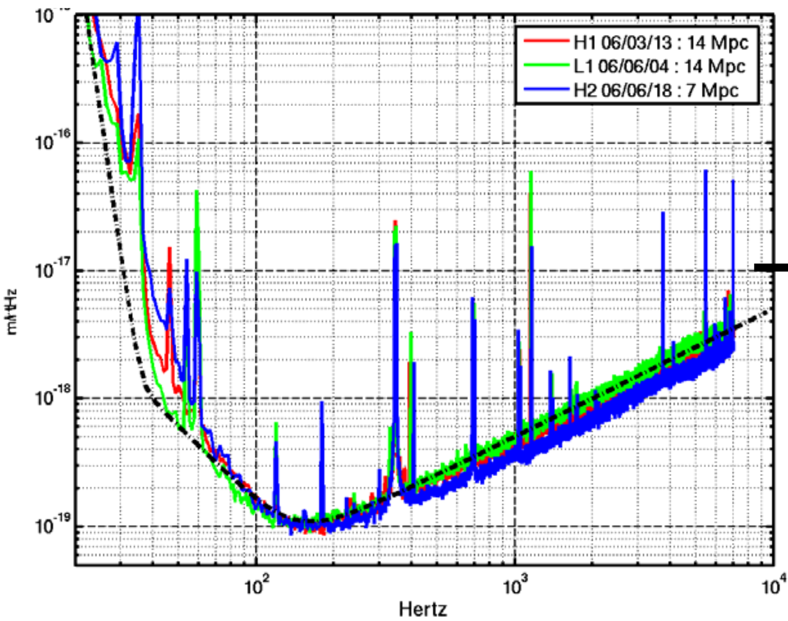


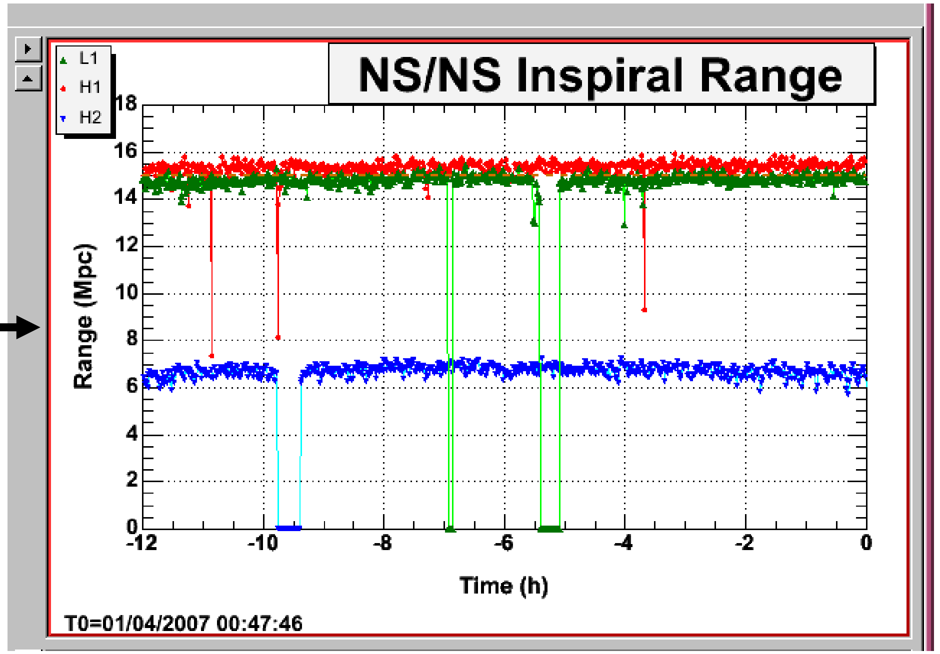
Binary systems: a measure of performance



Can translate strain amplitude into (effective) distance



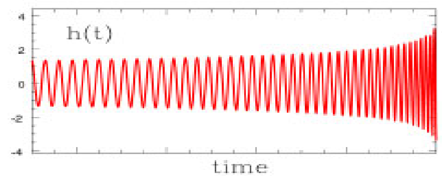




If system is optimally located and oriented, we can see even further: we are surveying <u>hundreds of galaxies</u>!

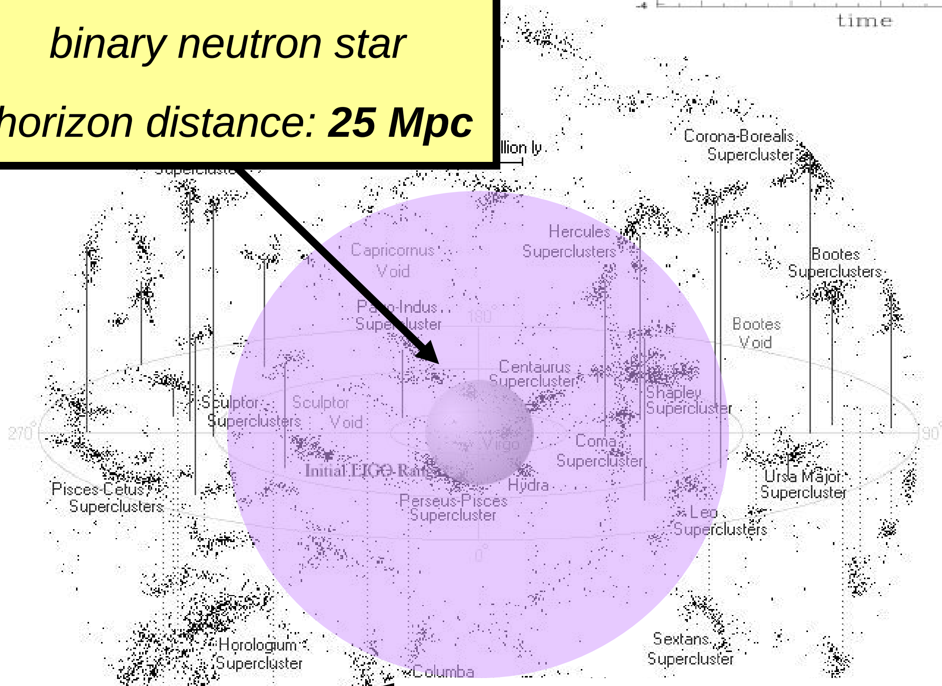
Electronic logs are public!
www.ligo.caltech.edu

Searches for coalescing compact binary signals in S5



$f_{coal} \sim 1/M$

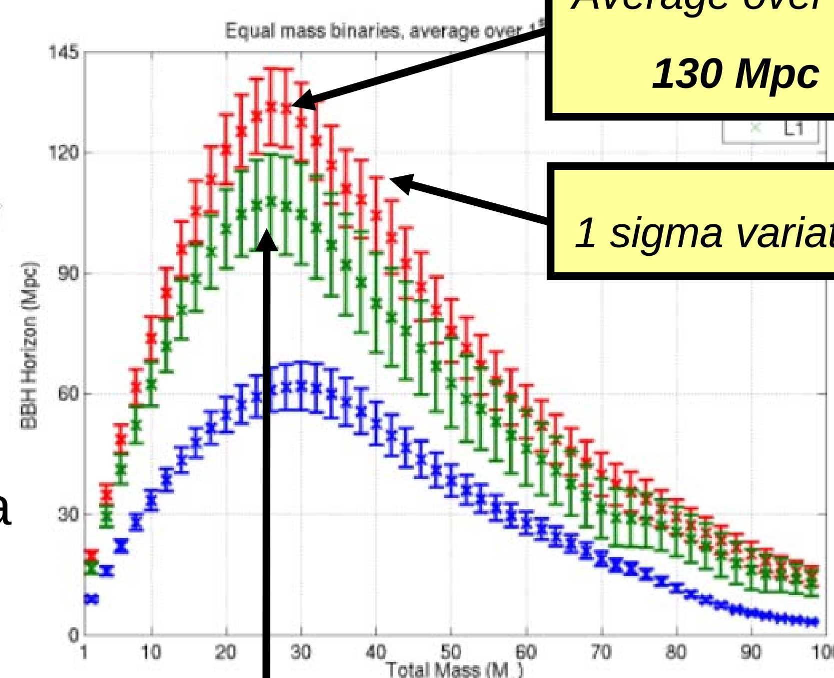
binary neutron star horizon distance: ***25 Mpc***



binary black hole horizon distance

- 3 months of S5 data analyzed
- 1 calendar yr in progress

Inspiral Horizon distance vs mass



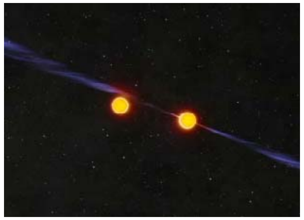
Average over run ***130 Mpc***

1 sigma variation

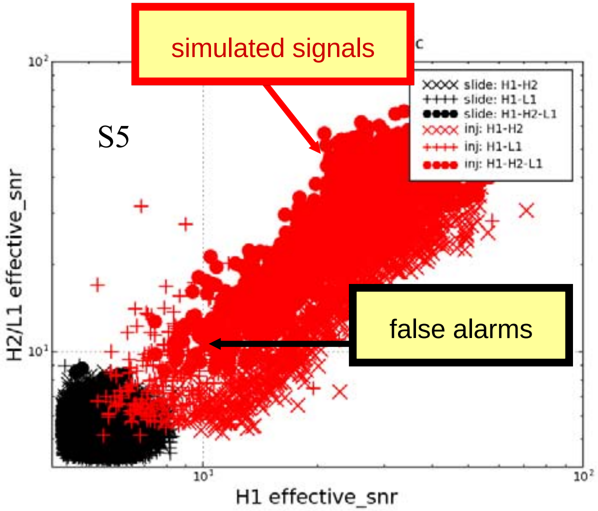
Peak at total mass ~ $25M_{sun}$

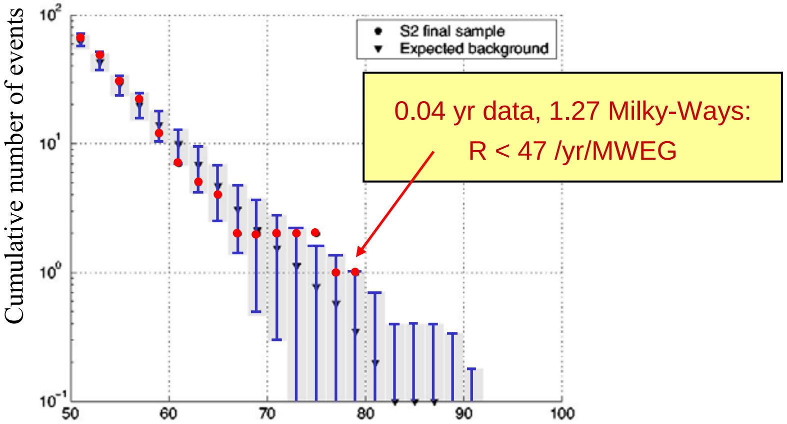
Search for binary systems

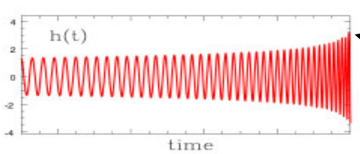
- Use two or more detectors: search for double or triple *coincident* “triggers”
- Can infer masses and “effective” distance.
- Estimate false alarm probability of resulting candidates: detection?
- Compare with expected efficiency of detection and surveyed galaxies: upper limit



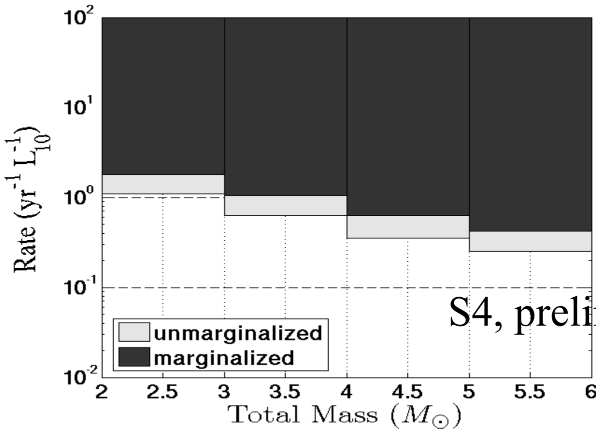
John Rowe, CSIRO





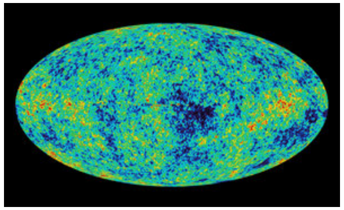


$f_{coal} \sim 1/M$



S4, preliminary result

Gravitational Wave sources: Stochastic Background



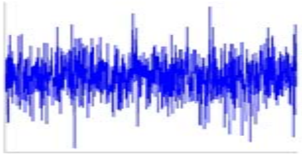
NASA, WMAP

- A primordial GW stochastic background is a prediction from most cosmological theories.
- Given an energy density spectrum $\Omega_w(f)$, there is a strain power spectrum:

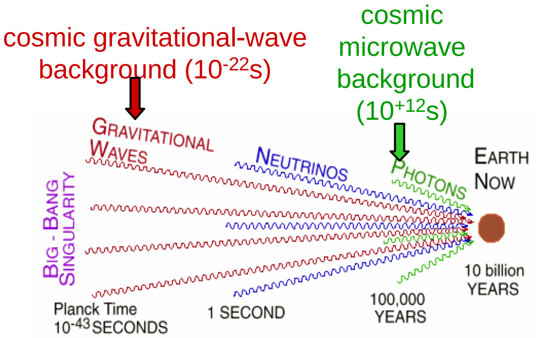
$$\Omega_{GW}(f) = \frac{1}{\rho_c}\frac{d\rho_{GW}(f)}{d\ln f}$$

$$S_{\rm gw}(f) = \frac{3H_0^2}{10\pi^2} f^{-3}\Omega_{\rm gw}(f)$$

$$h(f) = S_{\rm gw}^{1/2}(f) = 5.6\times10^{-22}\, h_{100}\sqrt{\Omega_0}\left(\frac{100\mathrm{Hz}}{f}\right)^{3/2}\mathrm{Hz}^{1/2}$$



- The signal can be searched from cross-correlations in different pairs of detectors: L1-H1, H1-H2, L1-ALLEGRO… the farther the detectors, the lower the frequencies that can be searched.



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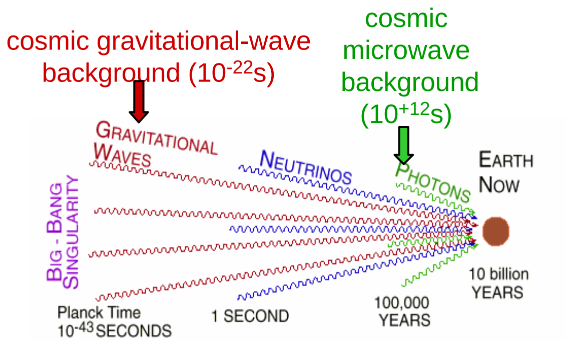
Gravitational Wave sources: Stochastic Background

- Cross-correlate signals between 2 interferometers
- LIGO S1: $\Omega_{GW} < 44$
  PRD 69 122004 (2004)

H_0 = 72 km/s/Mpc

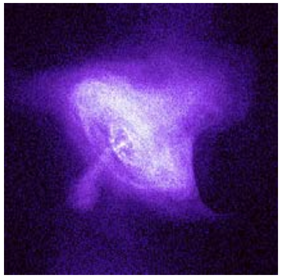
- LIGO S3: $\Omega_{GW} < 8.4 \times 10^{-4}$
  PRL 95 221101 (2005)
- LIGO S4: $\Omega_{GW} < 6.5 \times 10^{-5}$
  ApJ 658, 2007
- Initial LIGO, 1 yr data
  Expected sensitivity ~ 4×10^{-6}
  upper limit from Big Bang nucleosynthesis 10^{-5}; interesting scientific territory
- Advanced LIGO, 1 yr data
  Expected Sensitivity ~1×10^{-9}

Cosmic strings (?) ~10^{-8}
Inflation prediction ~10^{-14}

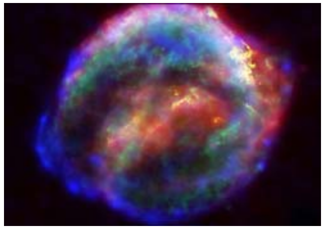


When will we see something?

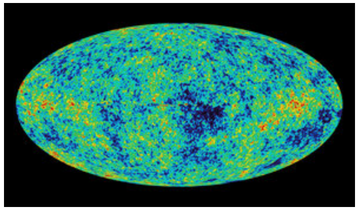
Predictions are difficult… many unknowns!



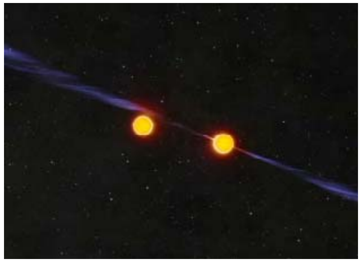
- Rotating stars: how lumpy are they?



- Supernovae, gamma ray bursts: how strong are the waves (and what do they look like)?



- Cosmological background: how did the Universe evolve?



- Binary black holes: how many are there? What masses do they have?
- Binary neutron stars: from observed systems in our galaxy, predictions are up to 1/3yrs, but most likely one per 30 years, at LIGO's present sensitivity.
- From rate of short GRBs, much more optimistic predictions for BNS and BBH rates? Ready to be tested with S5!

LIGO detectors: future

- **Neutron Star Binaries:**

  Initial LIGO: ~10-20 Mpc →

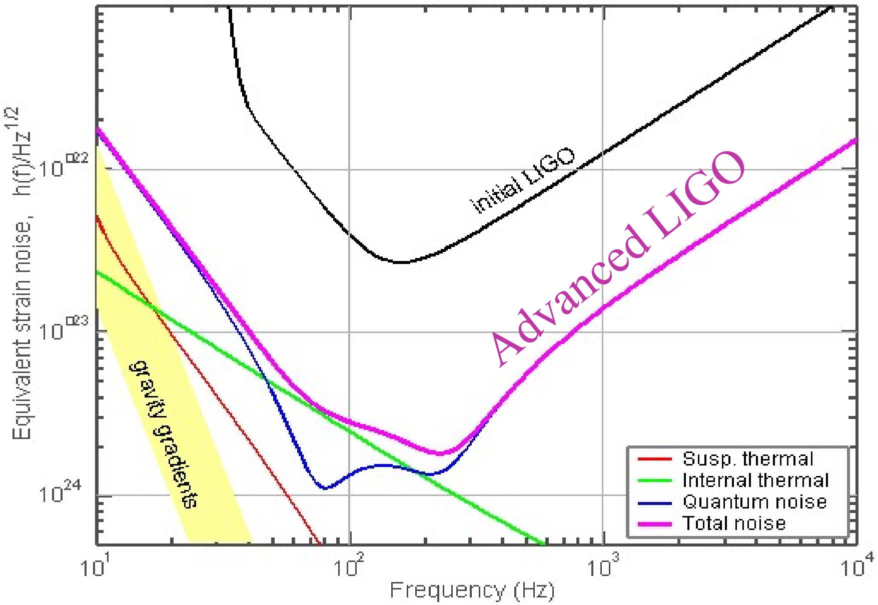
  Advanced LIGO: ~200-350 Mpc

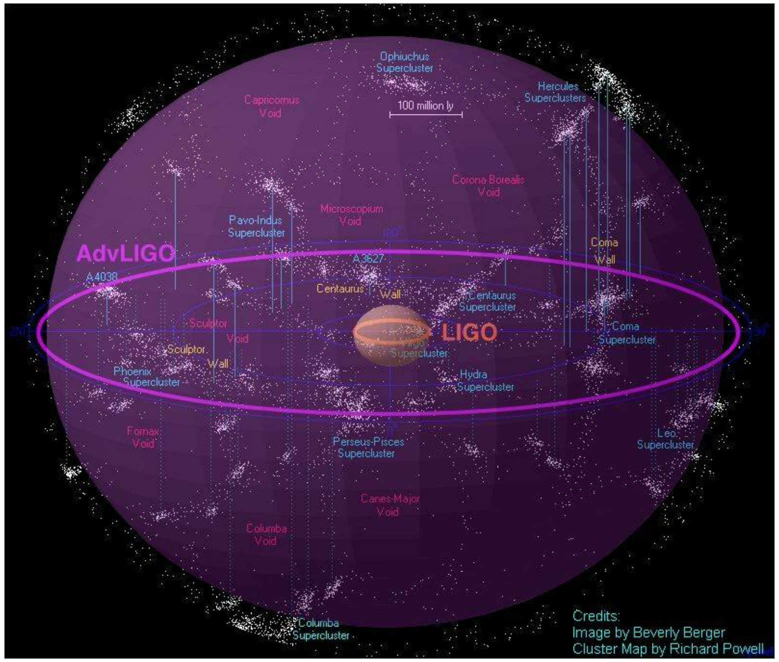
  Most likely rate: 1 every 2 days !

- **Black hole Binaries:**

  Up to 30 M_o, at ~ 100 Mpc

  → up to 50 M_o, in most of the observable Universe!





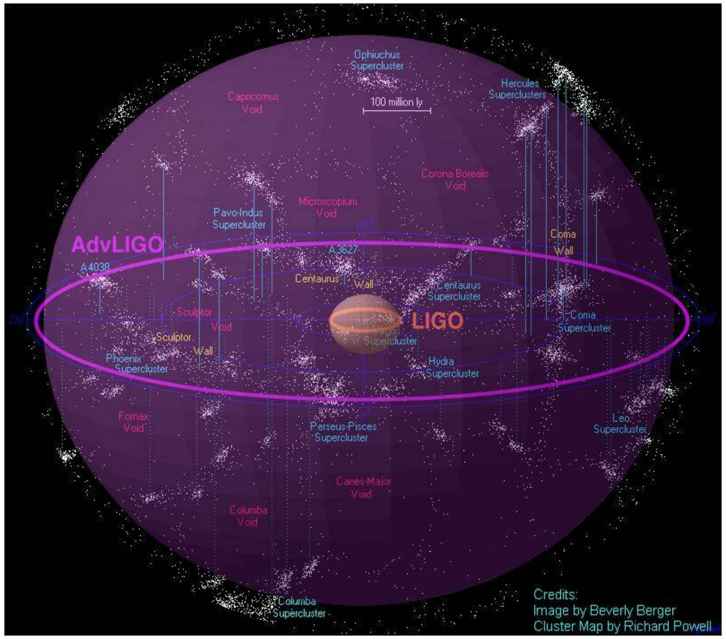
x10 better amplitude sensitivity

⇒ x1000 rate=(reach)^3

⇒ 1 year of Initial LIGO < 1 day of Advanced LIGO !

Planned NSF Funding in FY'08 budget (being discussed right now!).

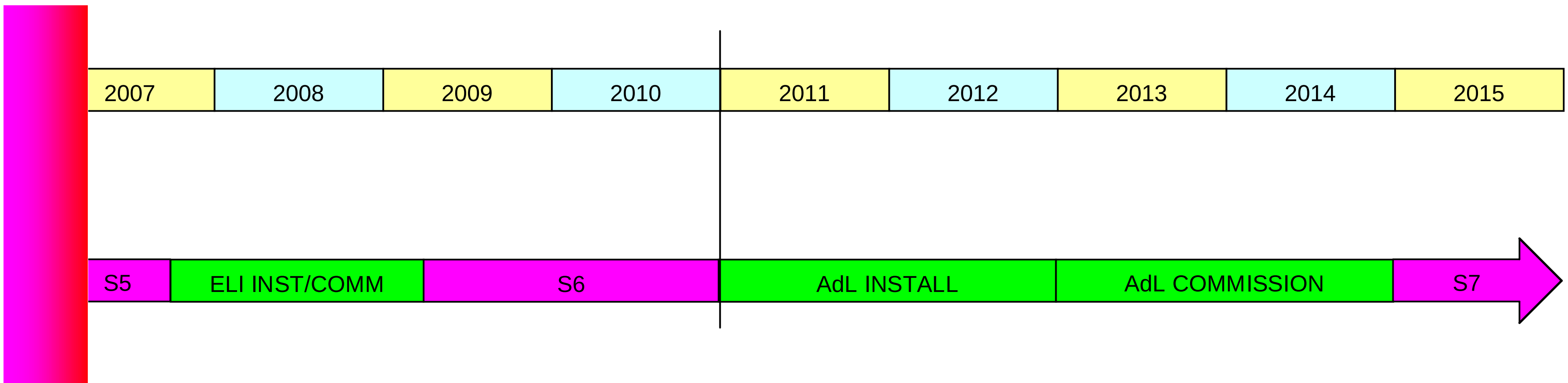
These are exciting times!



- We are taking data at unprecedented sensitivity, and we are searching for gravitational waves.
- We are getting ready for Advanced LIGO.

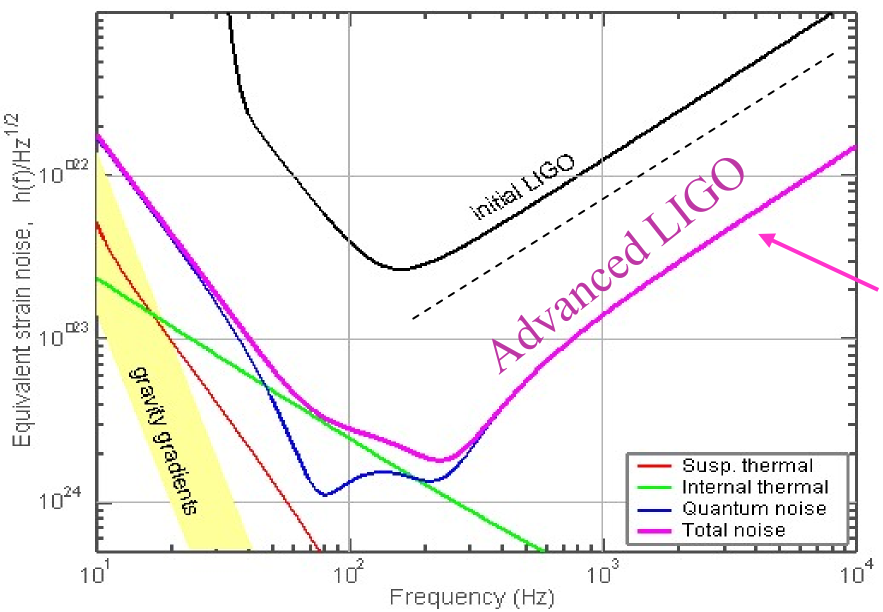
- We are preparing ourselves for a direct observation of gravitational waves:
  not if, but when!
- LIGO detectors and their siblings will open a new window to the Universe: what's out there?

A possible timeline?

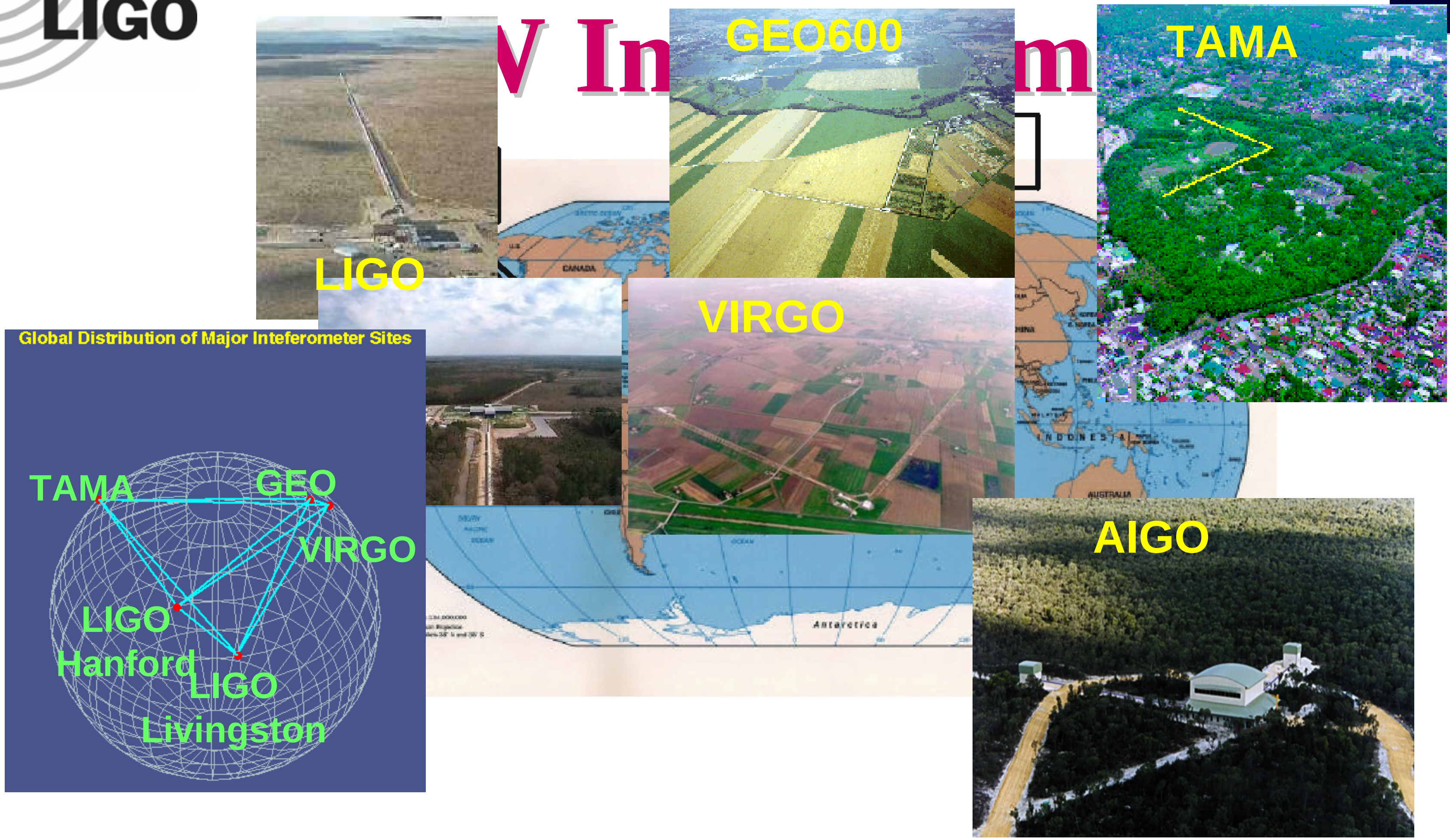


today

BNS: 1/30 yr
BBH: ??



BNS: 1/2days
BBH: we’ll measure it!



- Worldwide Network:
  - GEO and LIGO detectors’ data analyzed by LSC
  - We have coordinated observations and shared data with TAMA
  - We will start data sharing with VIRGO