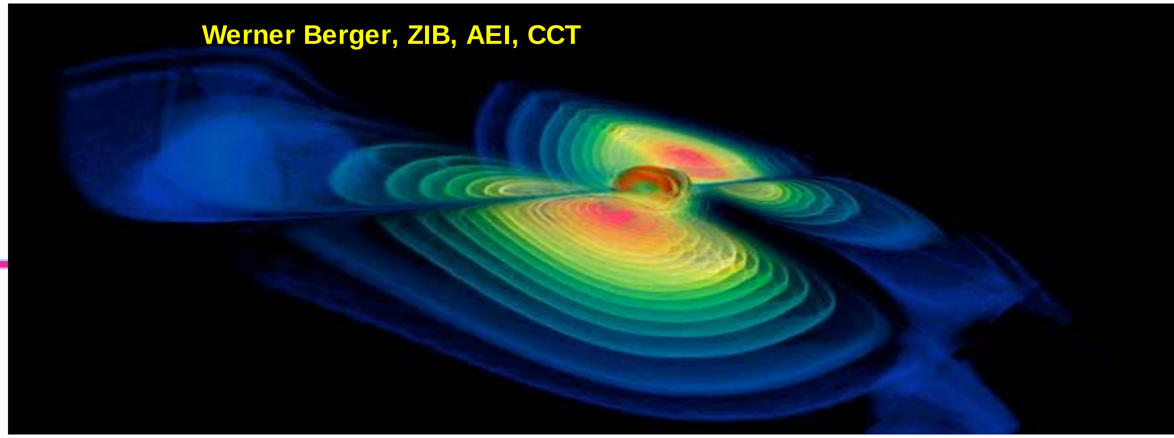
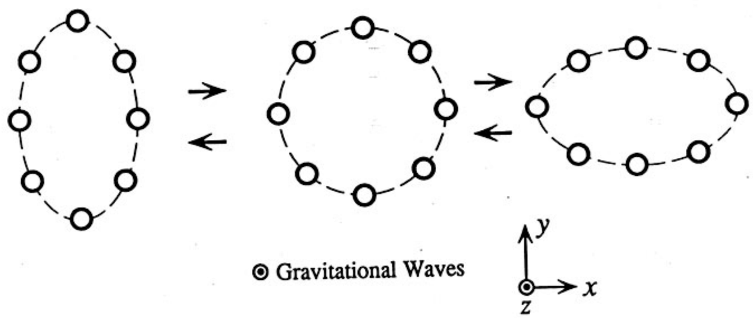


Searching for gravitational waves with LIGO detectors

Gabriela González
Louisiana State University
On behalf of the LIGO Scientific Collaboration

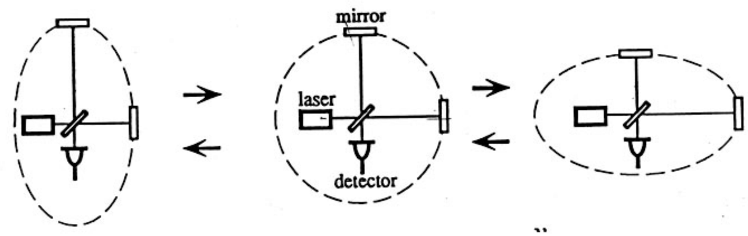
KITP Colloquium, May 30 2007

Gravitational waves

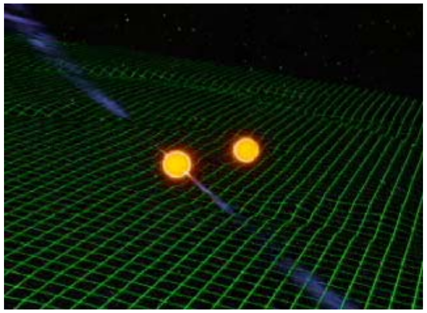


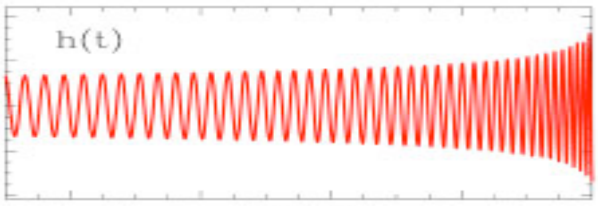
Gravitational waves are quadrupolar distortions of distances between freely falling masses: “ripples in space-time”

Michelson-type interferometers can detect space-time distortions, measured in “strain” h=ΔL/L.



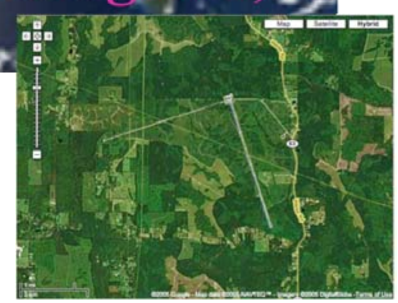
Amplitude of GWs produced by binary neutron star systems in the Virgo cluster have $h=\Delta L/L \sim 10^{-21}$





The LIGO project

Lunch time at LSC Summit

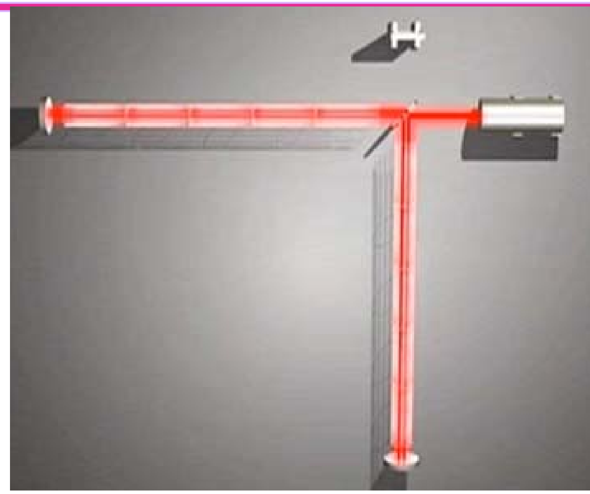


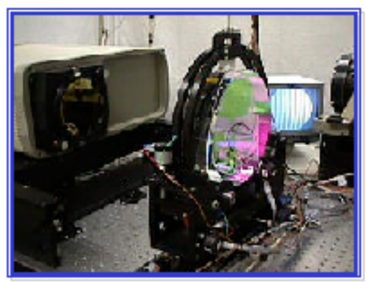
Hundreds of people working on the experiment and looking at the data:

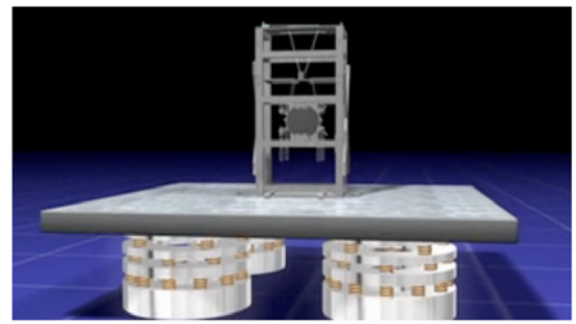
LIGO Scientific Collaboration

www.ligo.org

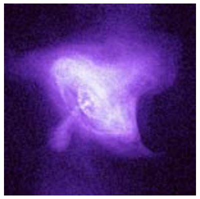
GW Detection:
a difficult and fun experiment



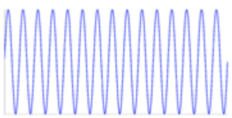


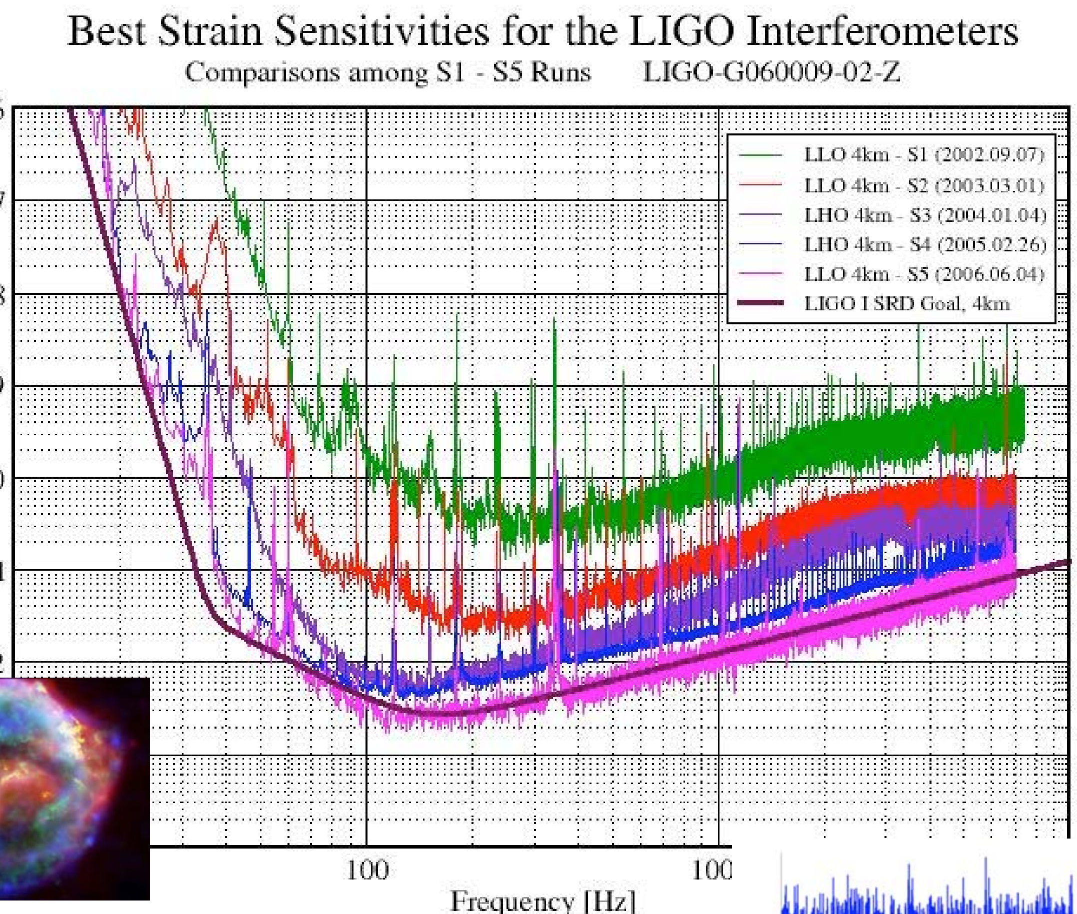


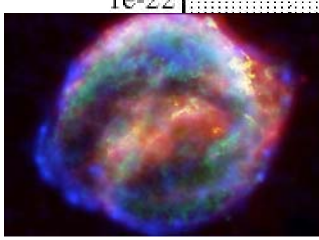
GW sources



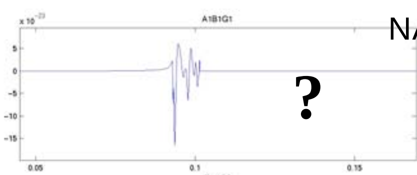
Crab pulsar (NASA, Chandra Observatory)

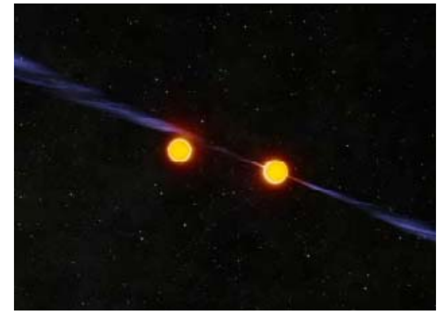




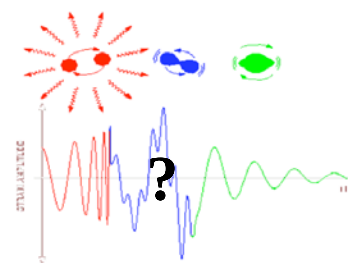


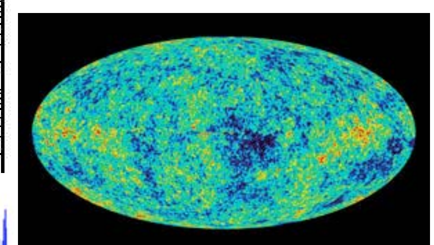
NASA, HEASARC





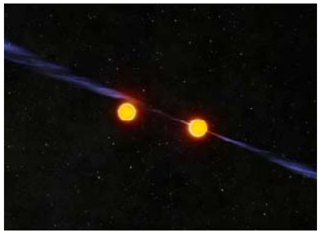
John Rowe, CSIRO





NASA, WMAP

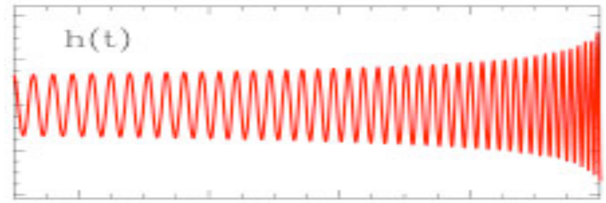
Observational results in www.ligo.org

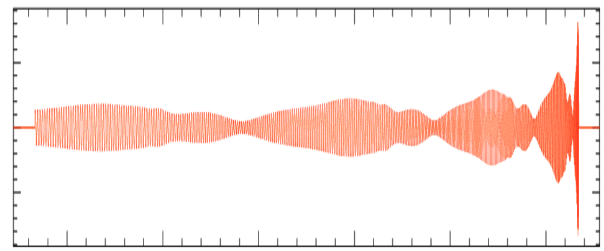


GW searches: binary systems

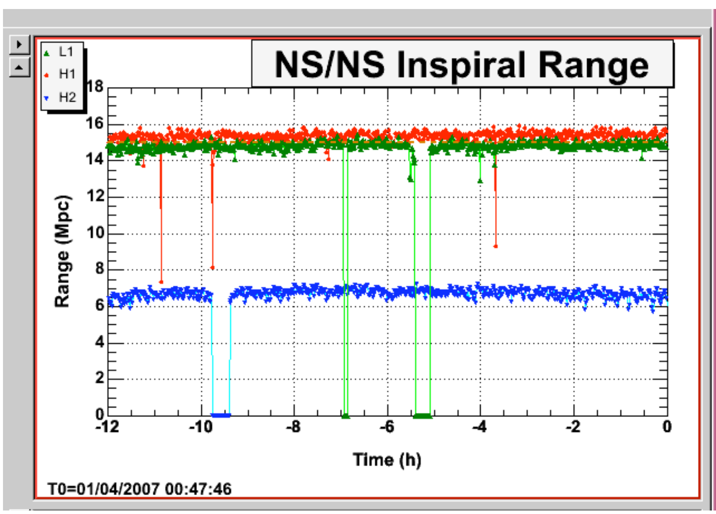
Use calculated templates for inspiral phase ("chirp") with optimal filtering.

Waveform parameters:
distance, orientation, position,
m_1, m_2, t_0, ϕ (+ spin, ending cycles …)





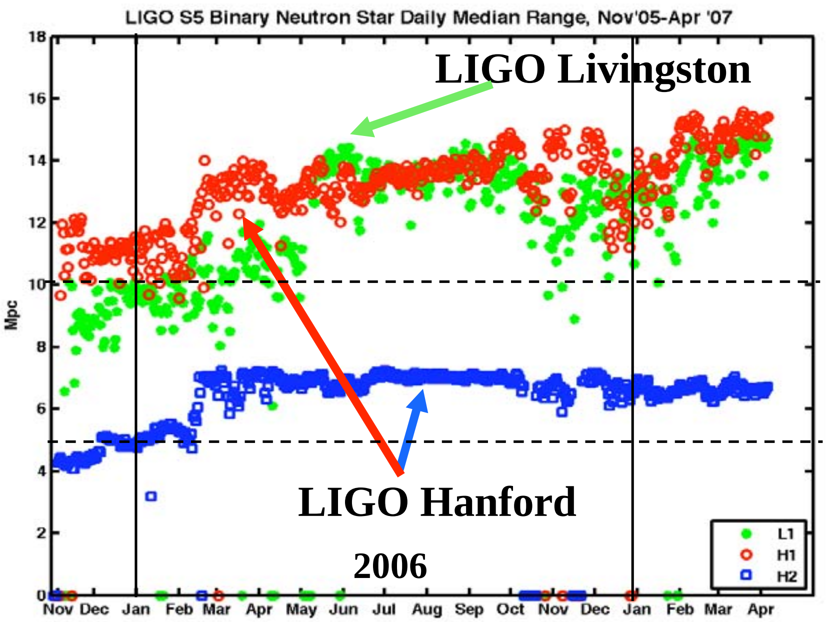
We can translate the "noise" into distances surveyed.
We monitor this in the control room for *binary neutron stars*:

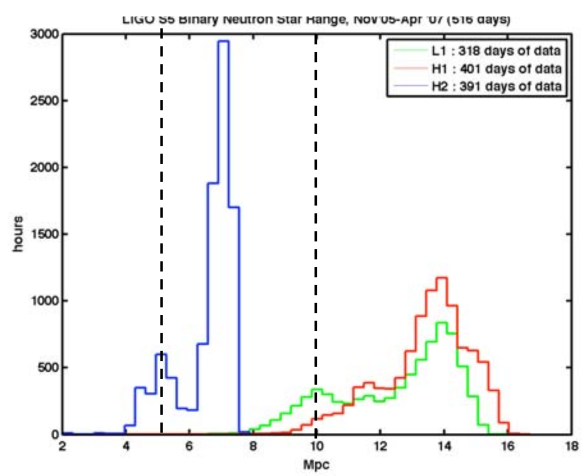


If system is optimally located and oriented, we can see even further: we are surveying hundreds of galaxies!

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

A digression: S5 so far…





Science-mode statistics for S5 run (H1, H2, L1, G1)

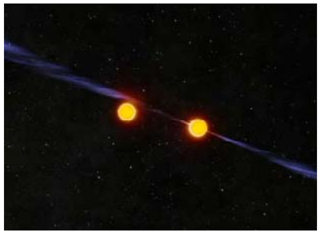
Up to May 30 2007 18:31:04 UTC

Elapsed run time = 13730.5 hours = 573 days

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

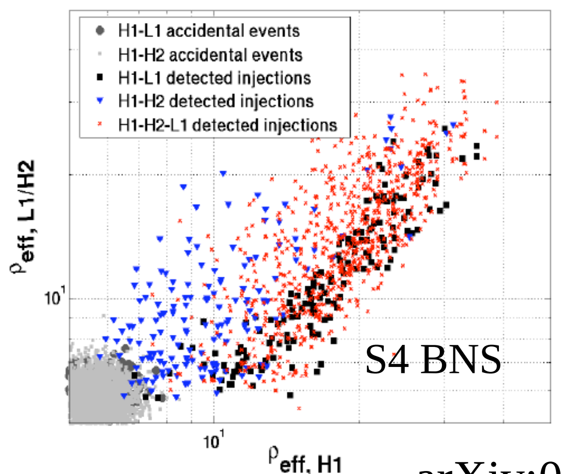
Sample	Hours	Duty factor
H1	10433.8	76.0 since Nov 4, 2005
H2	10673.4	77.7 since Nov 4, 2005
L1	8749.3	64.9 since Nov 14, 2005
H1+H2+L1	6911.8	51.2 since Nov 14, 2005
(H1orH2)+L1	7958.9	58.0 since Nov 4, 2005
One or more LIGO	12312.0	89.7 since Nov 4, 2005
One or more LSC	13029.1	94.9 since Nov 4, 2005

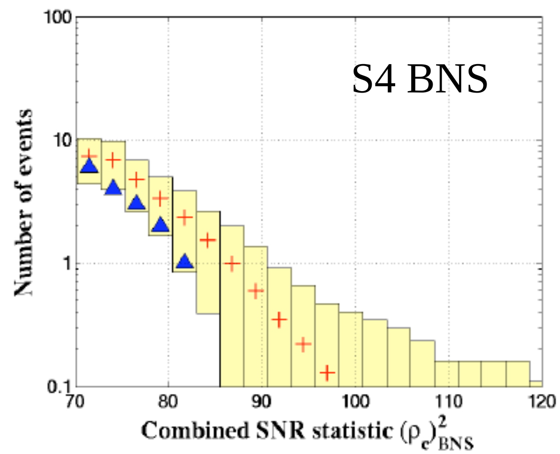
Since May 18, 2007: Joint data taking with Virgo.



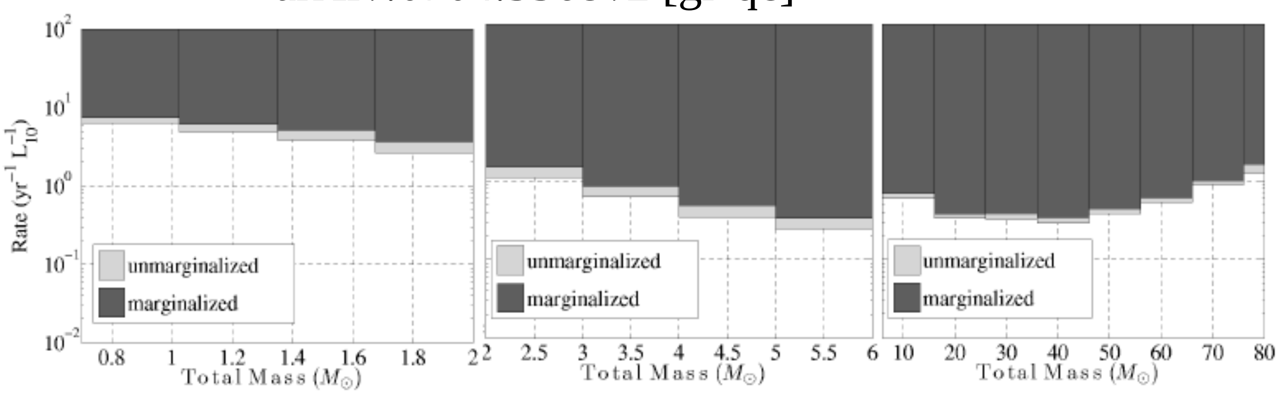
GW searches: binary systems

- 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

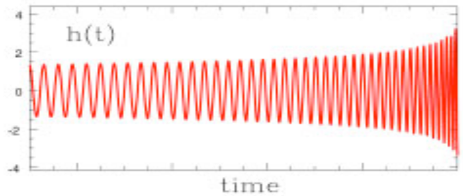




arXiv:0704.3368v2 [gr-qc]

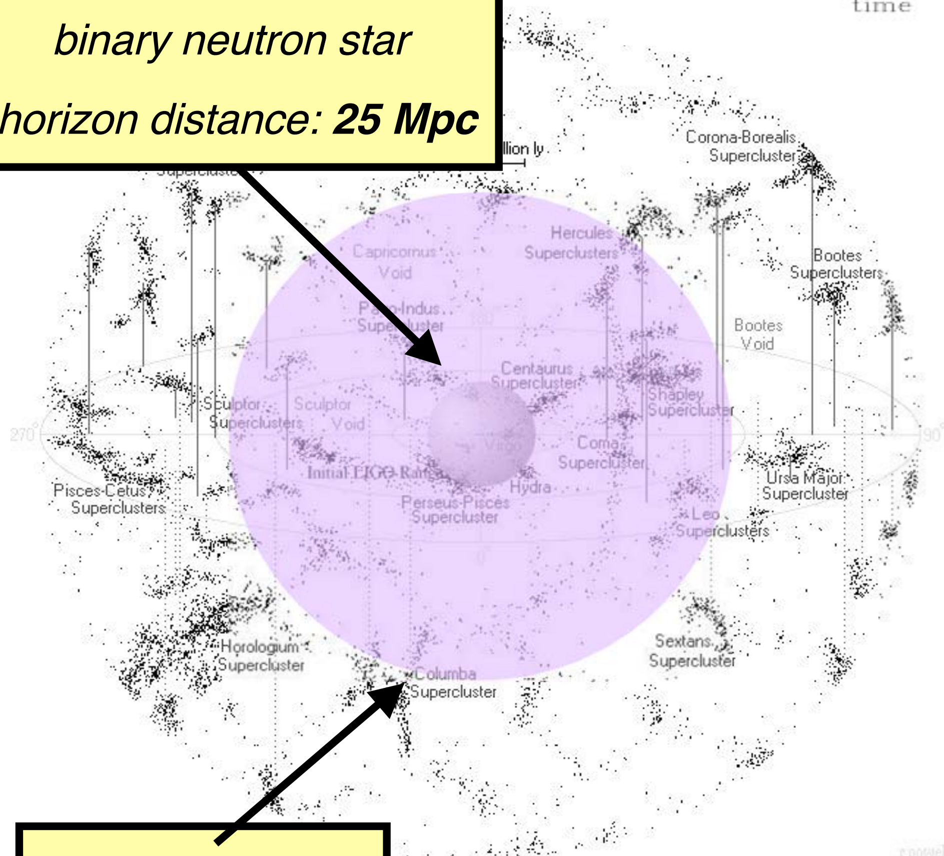


Searches for coalescing compact binary signals in S5



f_{coal}~1/M

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

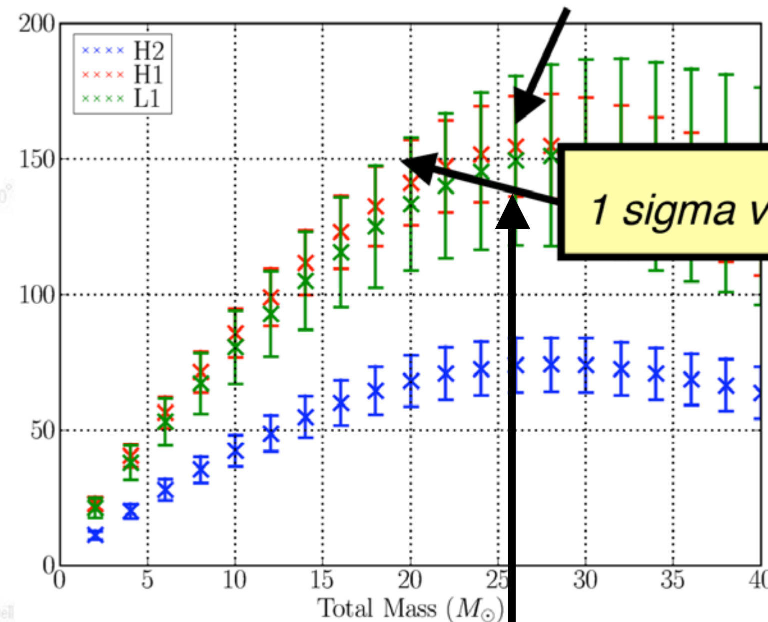


binary black hole horizon distance

Image: R. Powell

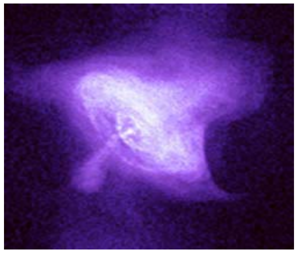
Inspiral Horizon distance vs mass

Average over run ***150 Mpc***



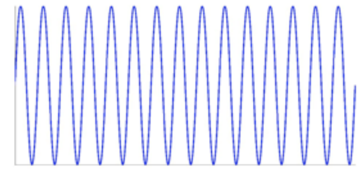
1 sigma variation

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

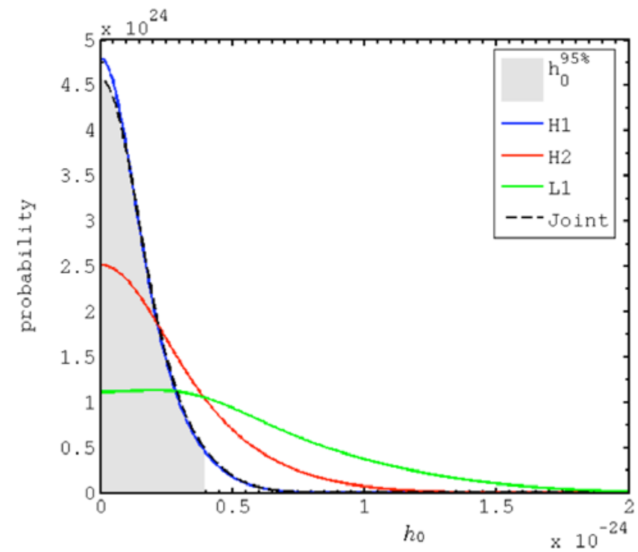


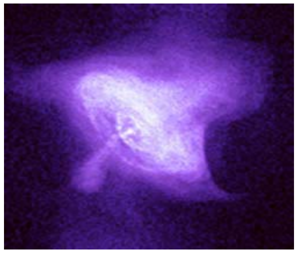
GW searches: spinning compact objects

- Rotating stars produce GWs if they have asymmetries,
  if they wobble or through fluid oscillations.
- There are many known pulsars (rotating stars!) that would produce GWs in the LIGO frequency band (40 Hz-2 kHz).
  - Targeted searches for 97 known (radio and x-ray) systems in S5: isolated pulsars, binary systems, pulsars in globular clusters…
- There are likely to be many non-pulsar rotating stars producing GWs.
  - All-sky, unbiased searches; wide-area searches.
- GWs (or lack thereof) can be used to measure (or set up upper limits on) the ellipticities of the stars.
- Search for a sine wave, modulated by Earth's motion, and possibly spinning down: easy, but computationally expensive!



http://www.einsteinathome.org/





GW searches: pulsars

Lowest GW strain upper limit:

PSR J1623-2631

(f_{gw} = 180.6 Hz, r = 3.8 kpc)

$\mathbf{h_0 < 4.8\times10^{-26}}$

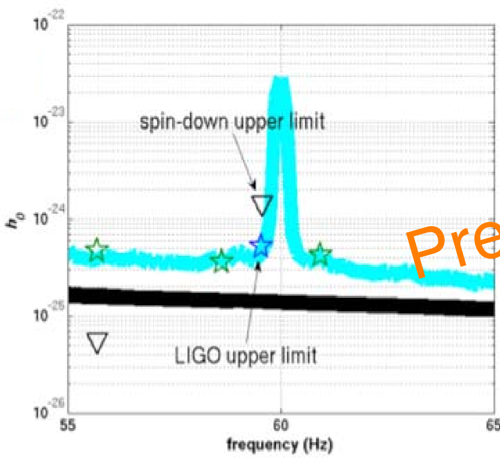
Lowest ellipticity upper limit:

PSR J2124-3358

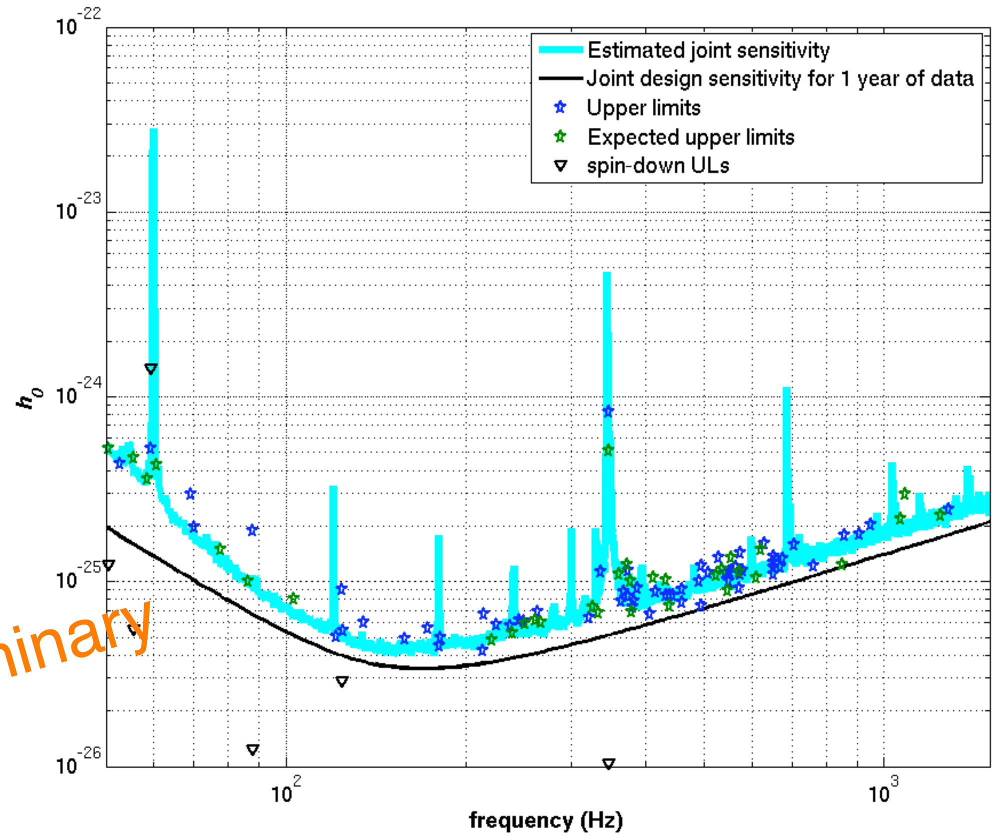
(f_{gw} = 405.6 Hz, r = 0.25 kpc)

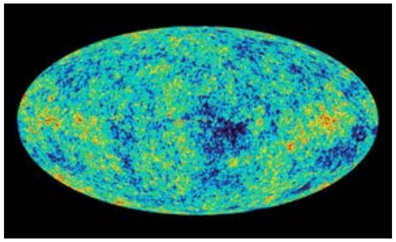
$\boldsymbol{\varepsilon < 1.1\times10^{-7}}$

Upper limits on GWs from targeted pulsars:



Preliminary



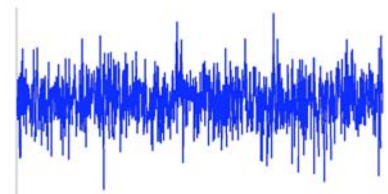


GW searches: Stochastic Background

A primordial GW stochastic background is a prediction from most cosmological theories. It can also result from unresolved astrophysical sources.

Given an energy density spectrum $\Omega_w(f)$, there is a strain power spectrum:

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

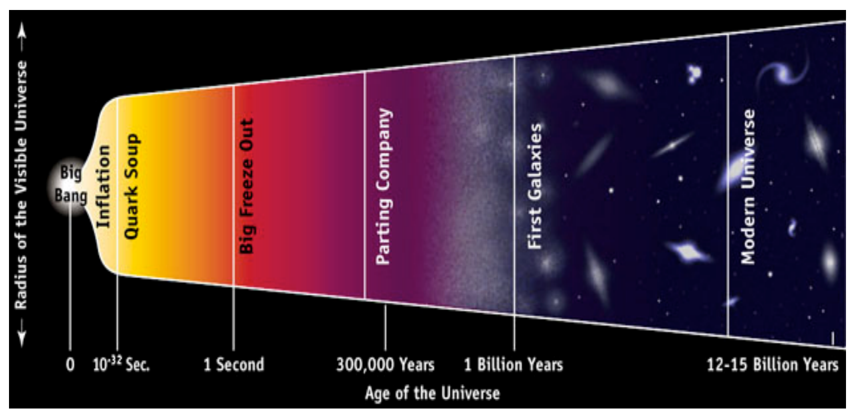


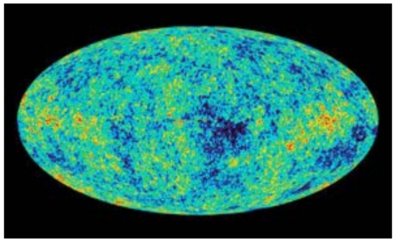
$$S_{\rm gw}(f) = \frac{3H_0^2}{10\pi^2} f^{-3}\Omega_{\rm gw}(f)$$

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

The signal can be searched from *cross-correlations* in different pairs of detectors: L1-H1, H1-H2, L1-ALLEGRO, LIGO-VIRGO… the farther the detectors, the lower the frequencies that can be searched ($\lambda_{GW} \geq 2D$)

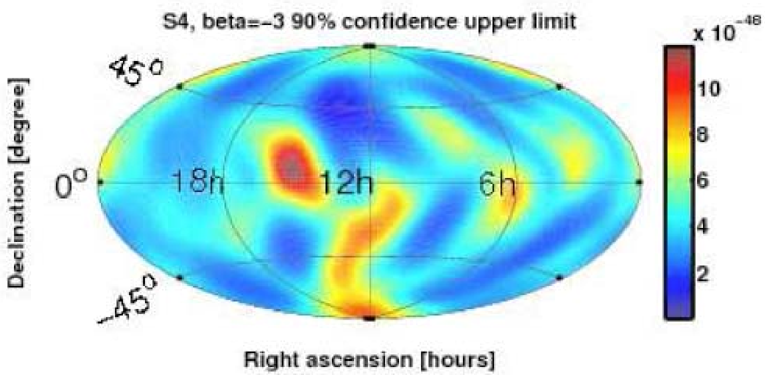
The signal can be searched assuming an isotropic, or using spatial resolution.



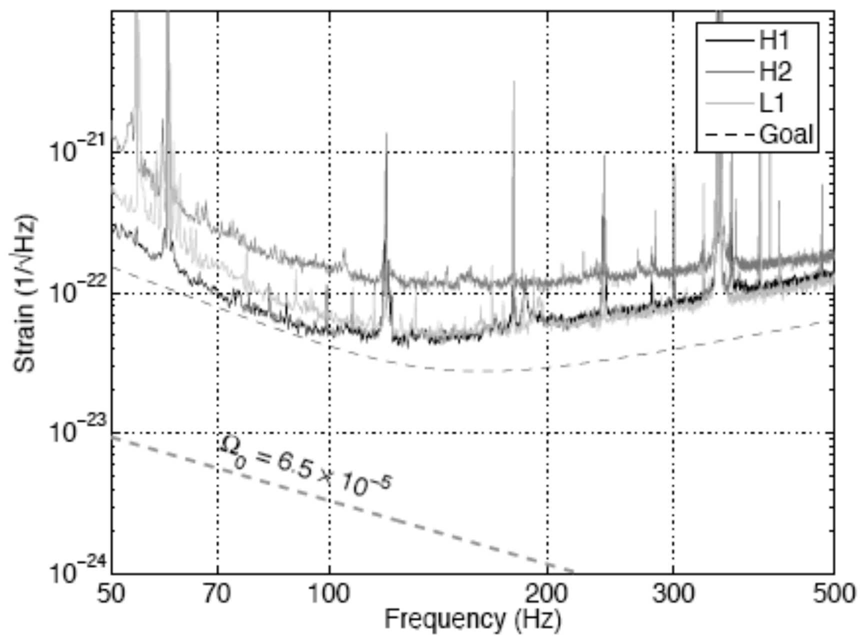


GW searches: Stochastic Background

S4, astro-ph 0703234



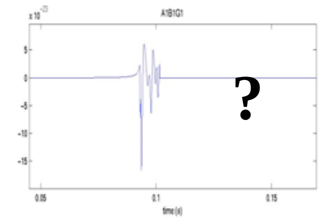
S4 (ApJ **659**, 618, 2007)



S5 result will be 10-100x better than S4
Advanced LIGO can reach $\Omega_0 \sim 10^{-9}$-10^{-10}
Big Bang, CMB Constrains $\Omega_0 < 10^{-5}$

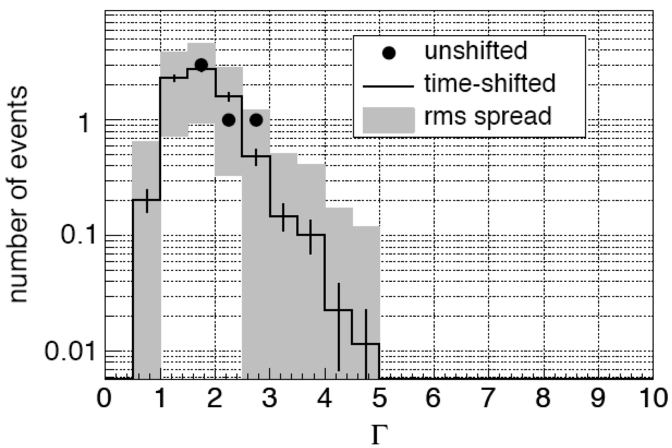
Predictions?
Cosmic strings (?) $\sim 10^{-8}$-10^{-5}
Inflation $\sim 10^{-14}$ --? (10^{-10} in some models with "preheating")

GW searches: bursts

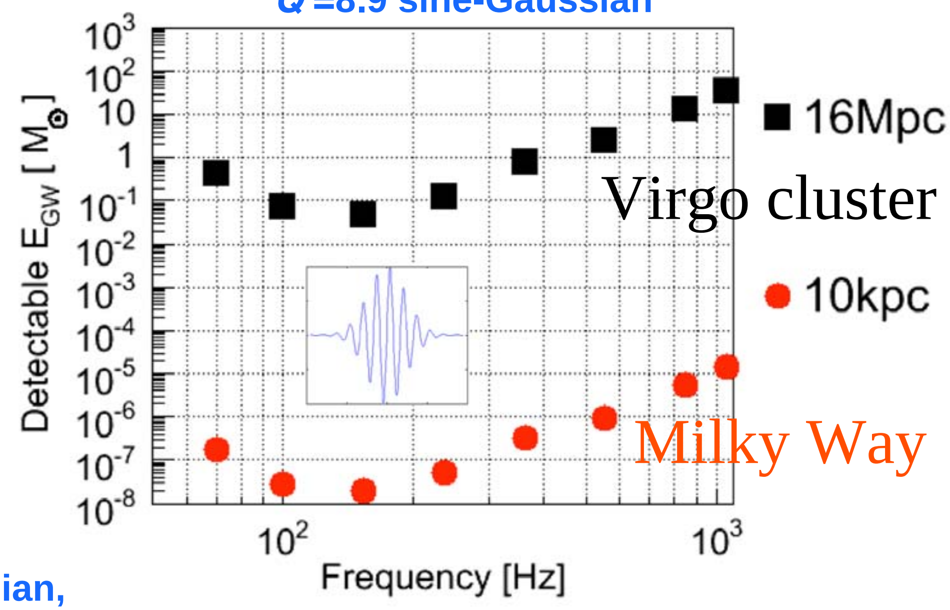


- Search for <u>triple coincident</u> triggers with a wavelet algorithm
- Measure waveform consistency
- Measure <u>false alarm probability</u>
- Compare with efficiency for detecting simple waveforms

S4, arXiv:0704.0943v1 [gr-qc]



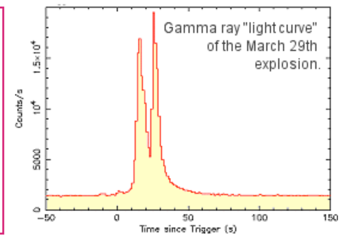
Q =8.9 sine-Gaussian



For a 153 Hz, *Q* =8.9 sine-Gaussian,
S5 can see with 50% probability:
$\sim 2 \times 10^{-8}$ $M_\odot c^2$ at 10 kpc,
~ 0.05 $M_\odot c^2$ at 16 Mpc (Virgo cluster)

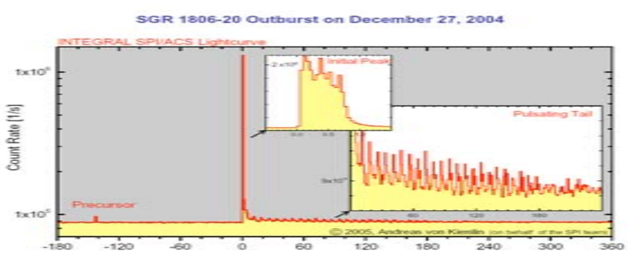
GW searches: triggered bursts

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



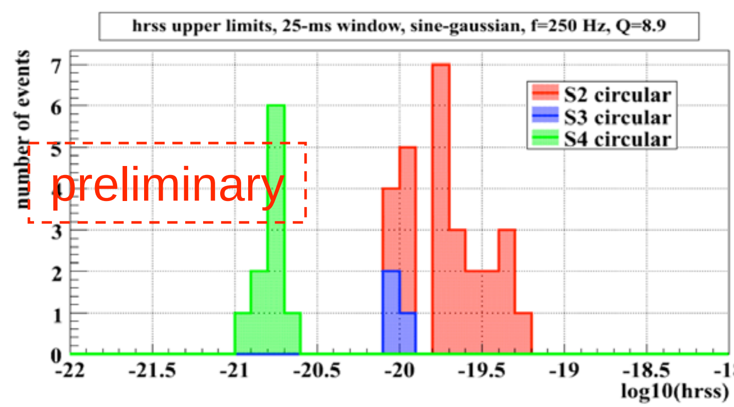
Soft Gamma Repeater 1806-20

- galactic neutron star with intense magnetic field (~10^{15} G)
- Record γ-ray flare on Dec 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
- astro-ph/0703419



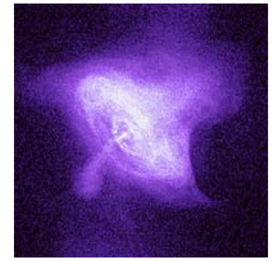
Gamma-Ray Bursts

- 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

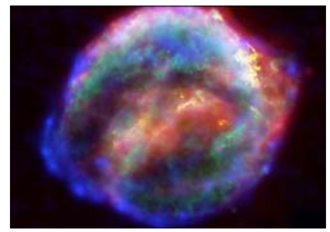


When will we see something?

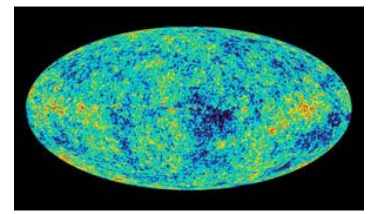
Predictions are difficult… especially about the future (Y. Berra)



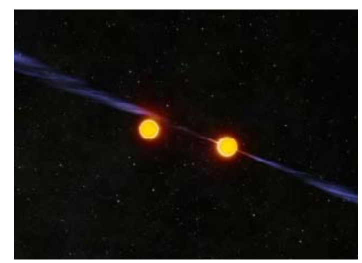
- Rotating stars: we know the rates,
  but not the amplitudes: how lumpy are they?



- Supernovae, gamma ray bursts:
  again rates known, but not amplitudes…



- Cosmological background:
  optimistic predictions are very dependent on model…



- Binary black holes:
  amplitude is known, but rates and populations
  highly unknown… Some estimates promise
  S5 results will be interesting!
- Binary neutron stars:
  amplitude is known, and galactic rates and population can be estimated:
  For R~86/Myr, initial LIGO rate ~1/100 yrs.

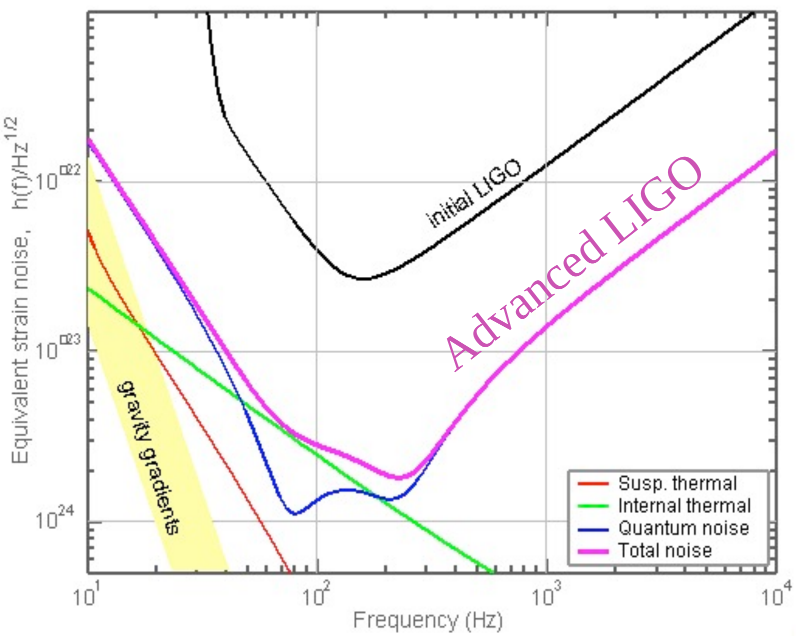
LIGO detectors: future

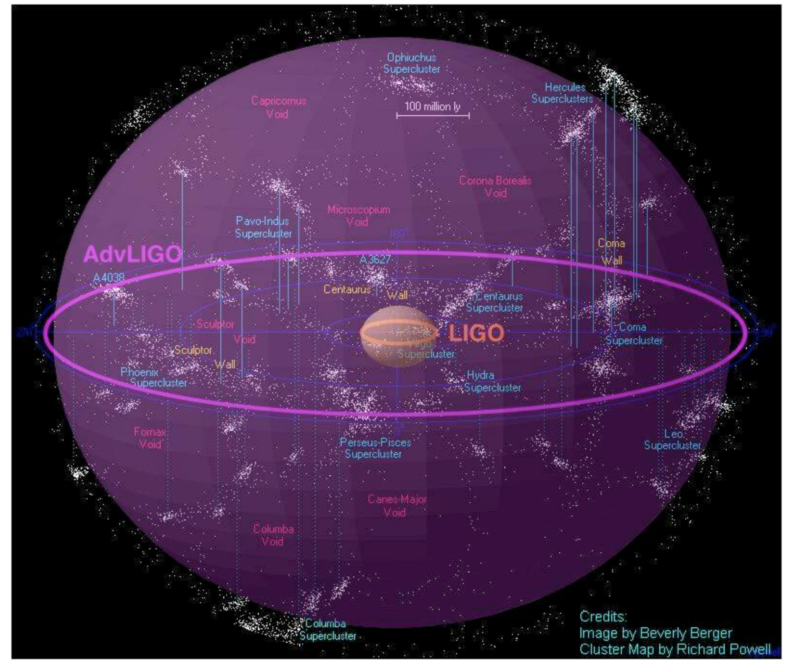
Neutron Star Binaries:

Initial LIGO: ~15 Mpc →

Advanced LIGO: ~200-300 Mpc

Most likely rate ~ 40/year !





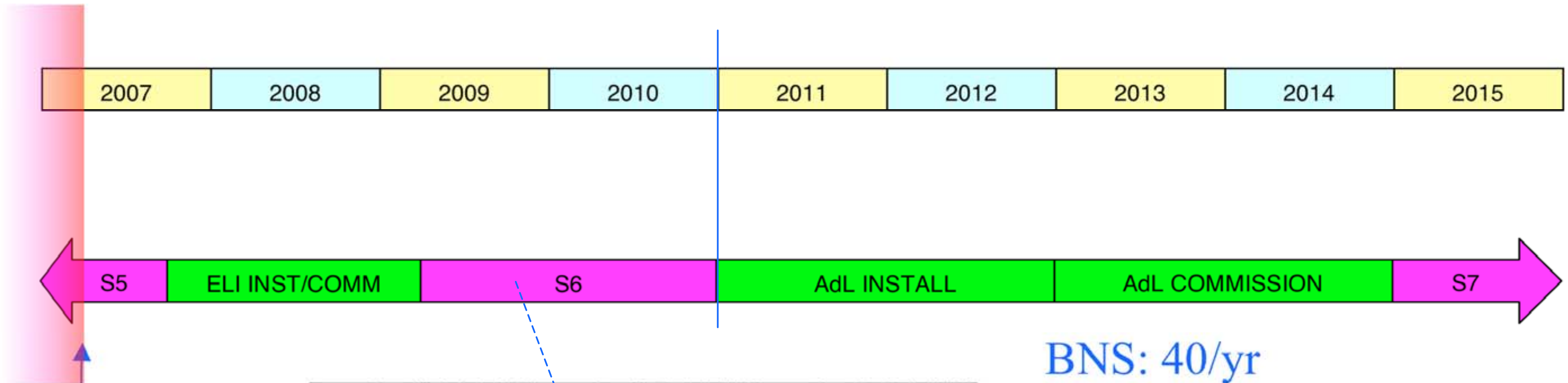
x10 better amplitude sensitivity

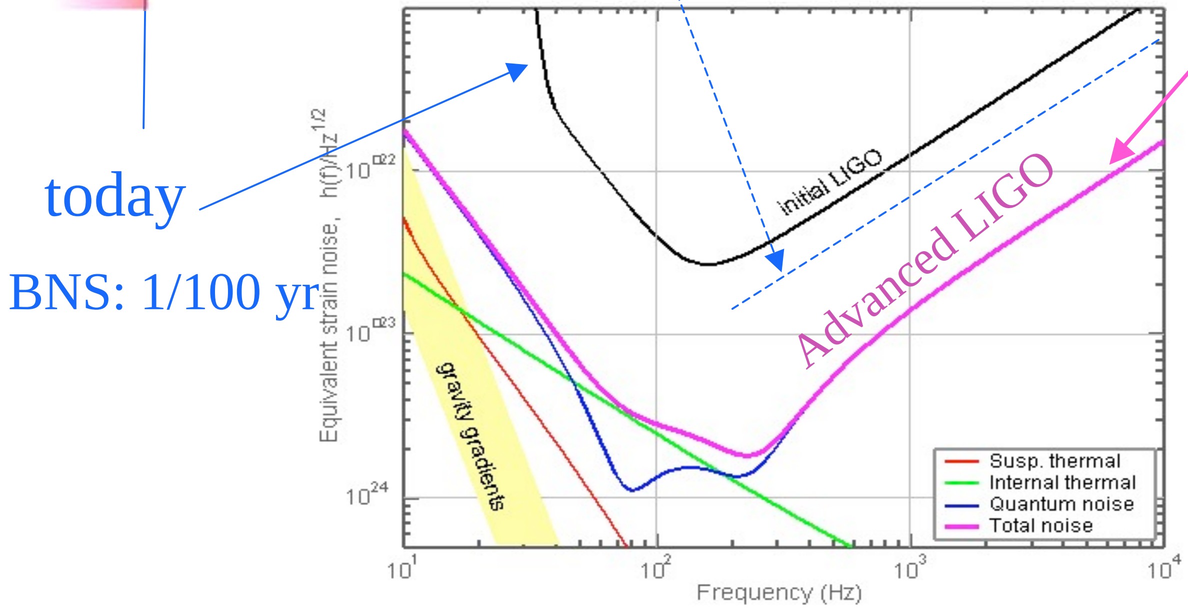
⇒ x1000 rate=(reach)^3

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

NSF Funding in FY'08 presidential budget request.

A possible timeline?

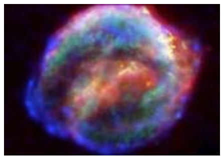


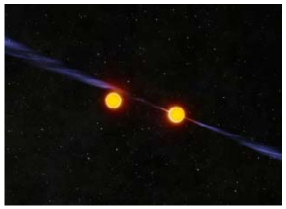


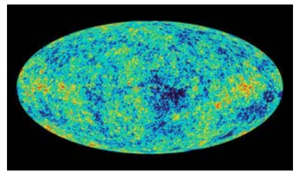
Physics and Astronomy to be done!

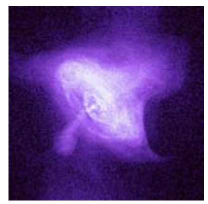
GR strong field tests
NS physics
BH population
….

LIGO detectors: future

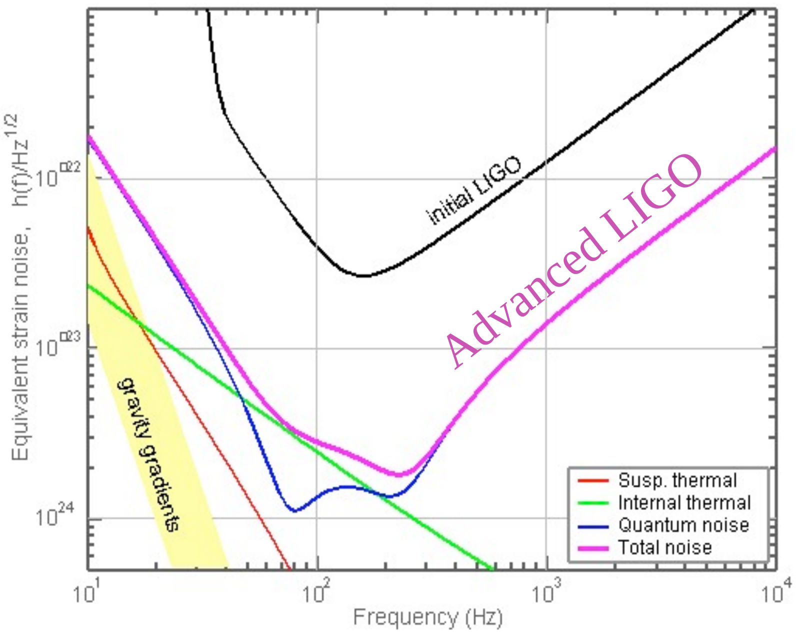


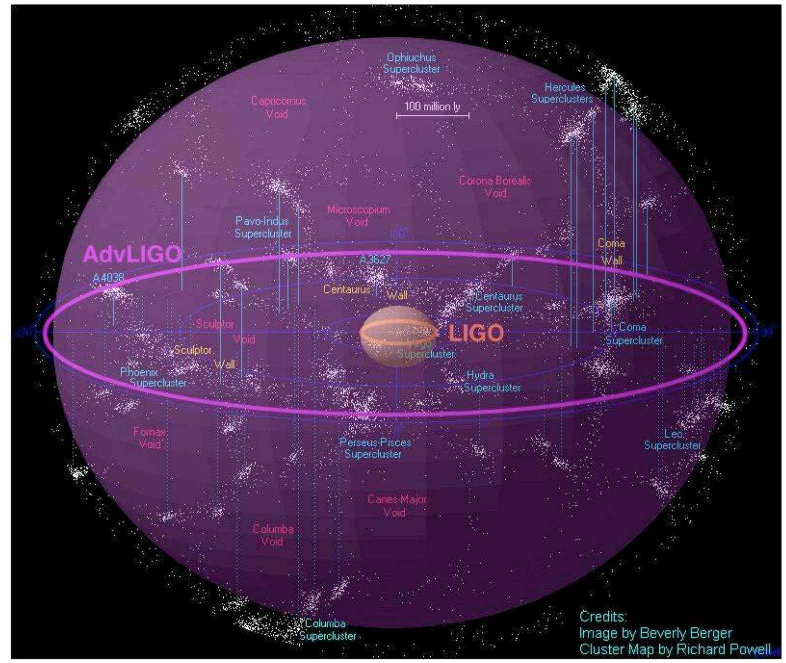






What's out there?





We'll find out!