LIGO: a journey towards gravitational wave astronomy

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Princeton Plasma Physics Laboratory, April 23, 2008

LIGO-G080252-00

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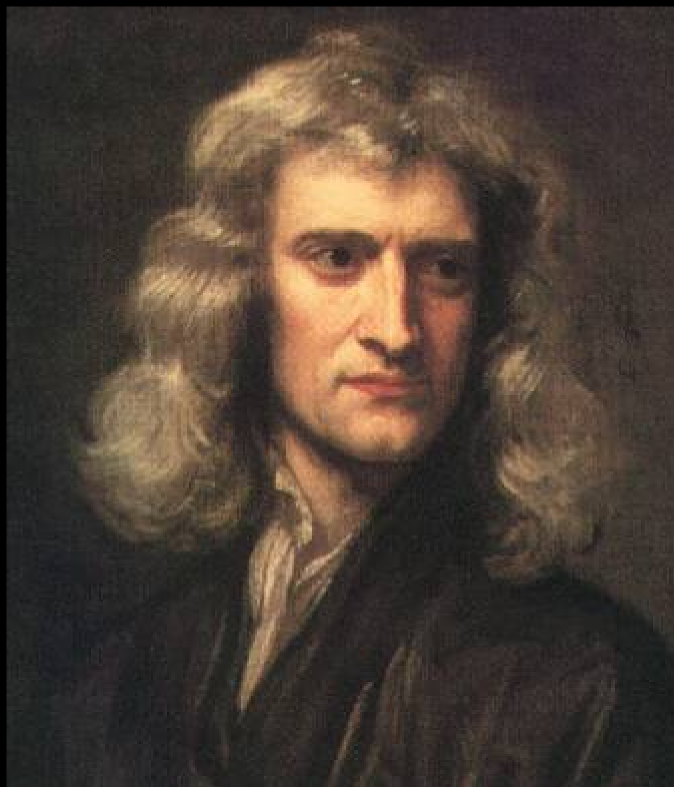
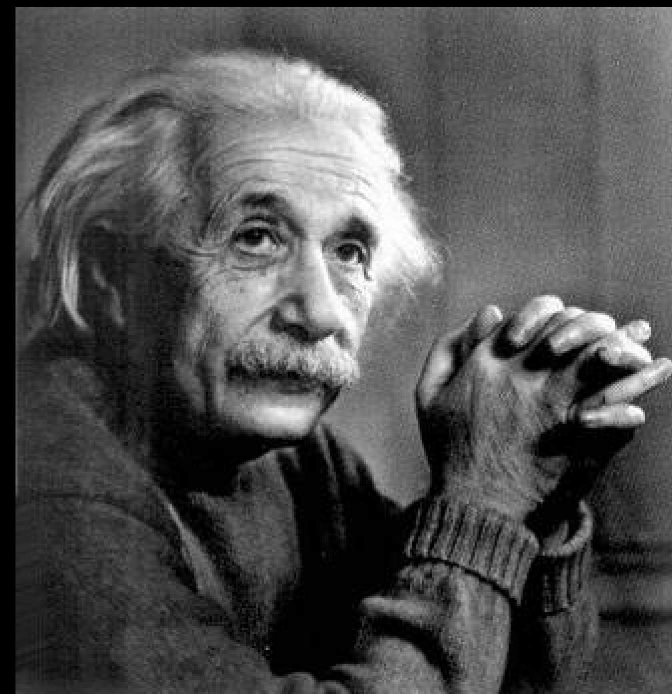
- Gravitational Waves
- LIGO and its performance
- The world-wide picture
- Science with LIGO
- The Road Ahead

Newton's Universal Gravitation

action at a distance

$$G_{\mu\nu} = 8\pi T_{\mu\nu}$$



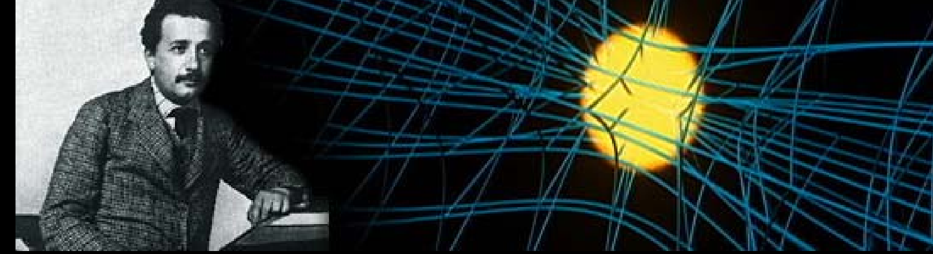


$$F = G\frac{m_1 m_2}{d^2}$$

Einstein's General Relativity

information is carried by a gravitational wave traveling at the speed of light

Gravitational Waves: ripples in spacetime



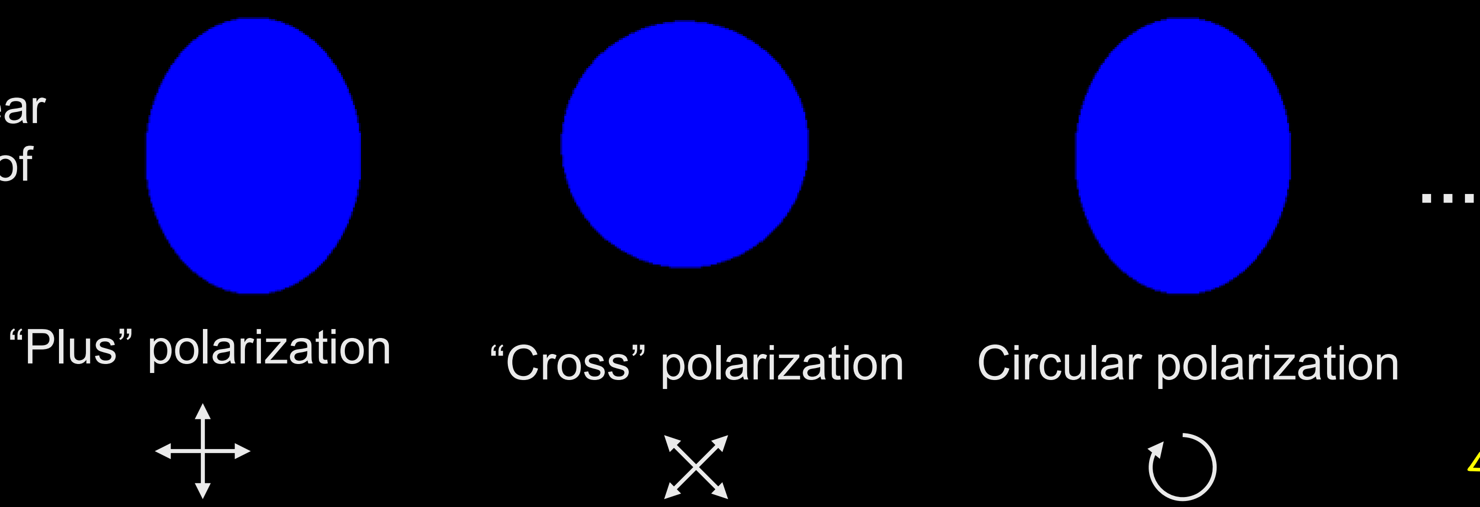
American Museum of Natural History GW project

- Perturbations of the spacetime metric: "stretch and squeeze" space

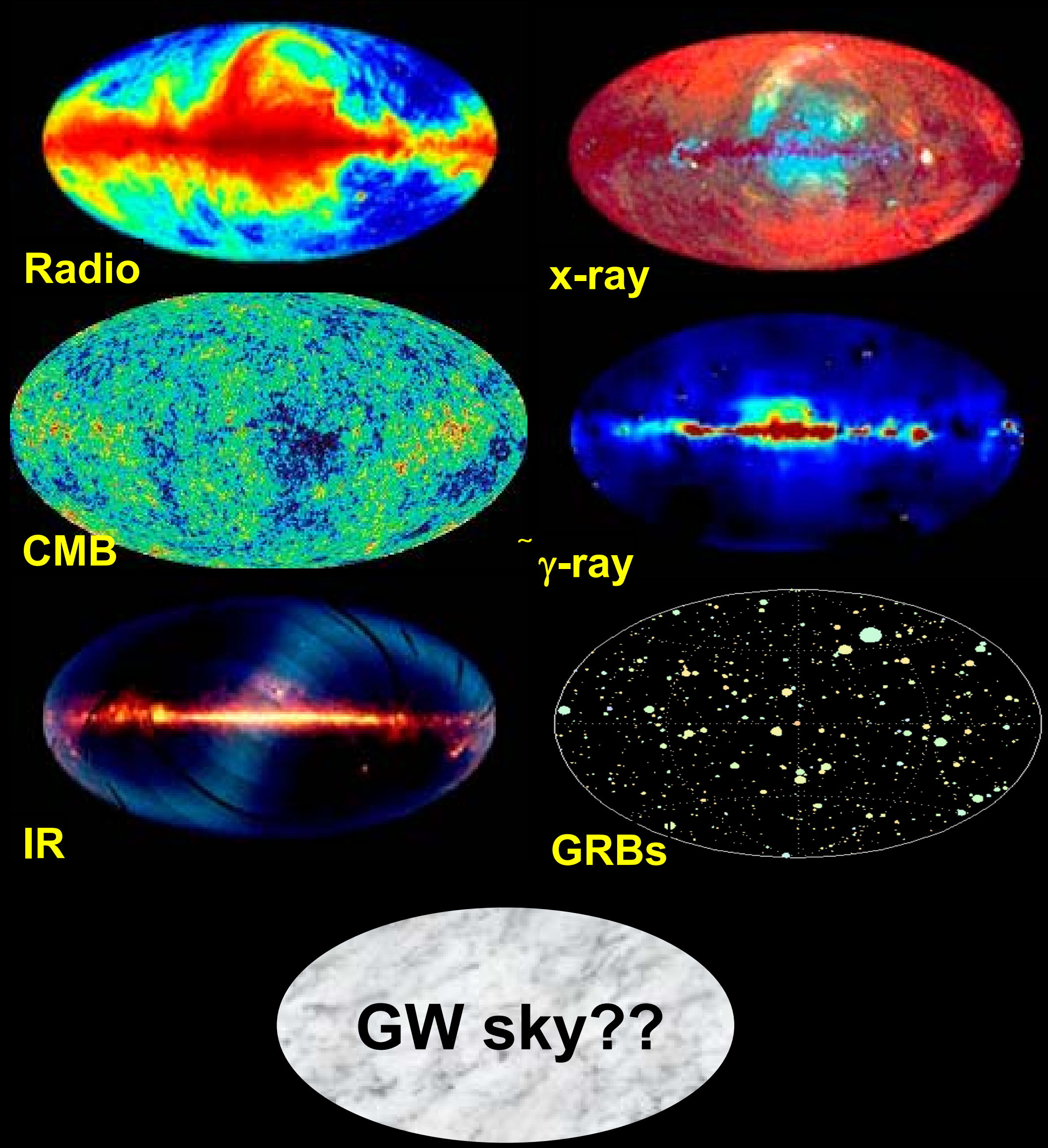
$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

- Generated when massive objects rapidly change shape or orientation
- Expected to propagate at the speed of light
- Dimensionless strain with amplitude inversely proportional to distance
- Strength and polarization depend on direction relative to source

Can be a linear combination of polarization components



A New Probe into the Universe



Gravitational Waves will give us a different, non electromagnetic view of the universe, and open a new spectrum for observation.

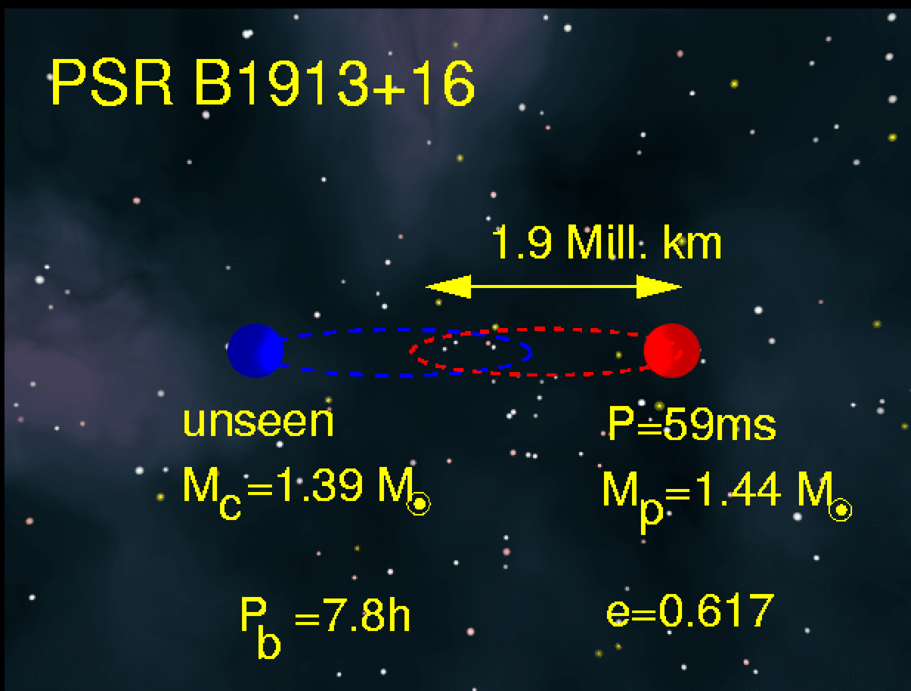
This will be complementary information, as different from what we know as *hearing* is from *seeing*.

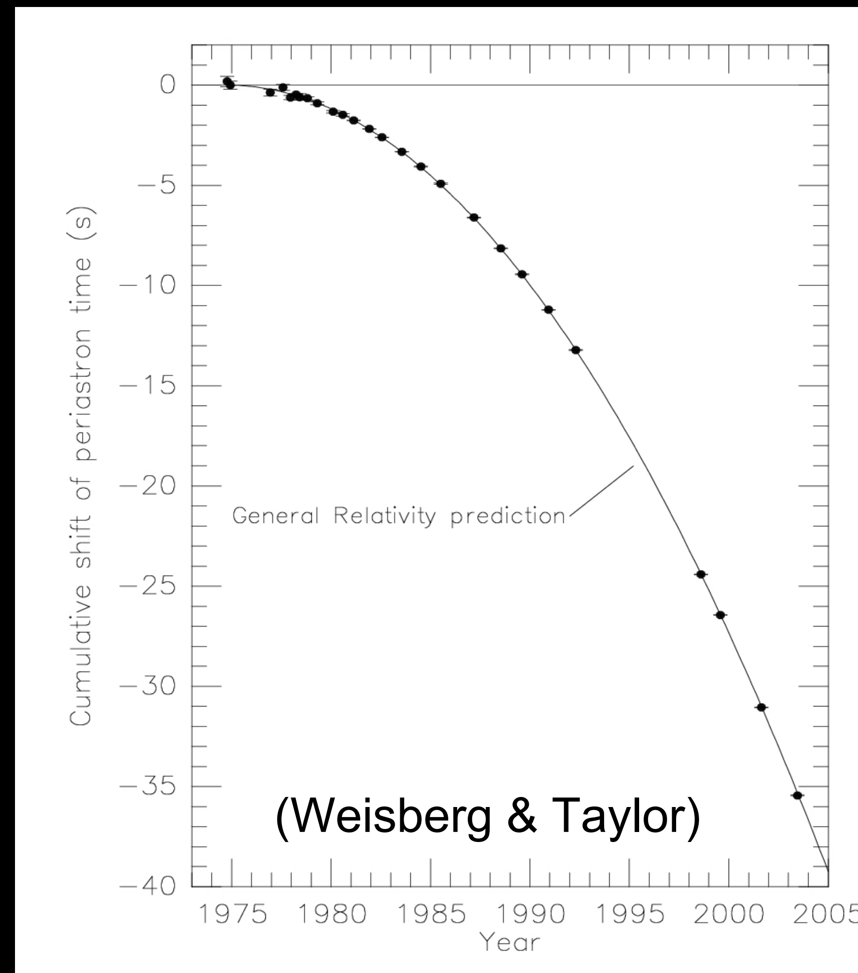
EXPECT THE UNEXPECTED!

Gravitational Waves carry information from the bulk motion of matter.
With them we can learn the physics of black holes, spinning neutron stars, colliding massive bodies, and gain further insights in the early universe.

Indirect Evidence

Pulsar System PSR 1913 + 16 (R.A. Hulse, J.H. Taylor Jr, 1975)





Orbit will continue to decay over the next ~300 million years, until coalescence

Gravitational wave emission will be strongest near the end

The Challenge: Space-Time is Stiff!

Einstein's equations are similar to equations of elasticity

$c^4/8\pi G \sim 10^{42}$N is the space-time "stiffness" (energy density/unit curvature)

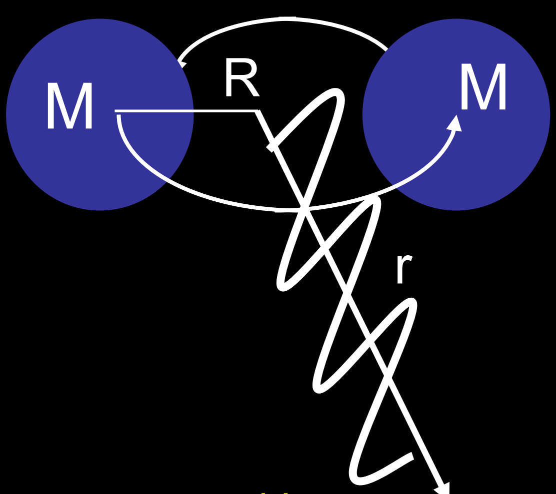
The wave can carry huge energy with miniscule amplitude: $h \sim (G/c^4)(E/r)$

Sources expected to be rare $\Rightarrow$ Need to search a large volume of space, large r

For colliding $1.4M_\odot$ neutron stars in the Virgo Cluster:

$$h_{\mu\nu} = \frac{2G}{c^4 r}\ddot{I}_{\mu\nu} \Rightarrow h \approx \frac{4\pi^2 GMR^2 f_{orb}^2}{c^4 r}$$

I = quadrupole mass distribution of source



$M \approx 10^{30}$ kg

$R \approx 20$ km

$F \approx 400$ Hz

$r \approx 10^{23}$ m

$\Rightarrow$ $h \sim 10^{-21}$

Stretches the diameter of the Earth by ~ 10^{-14} m (about the size of an atomic nucleus)

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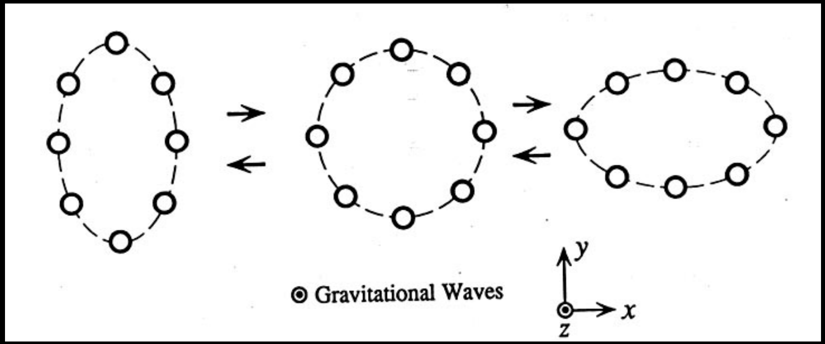
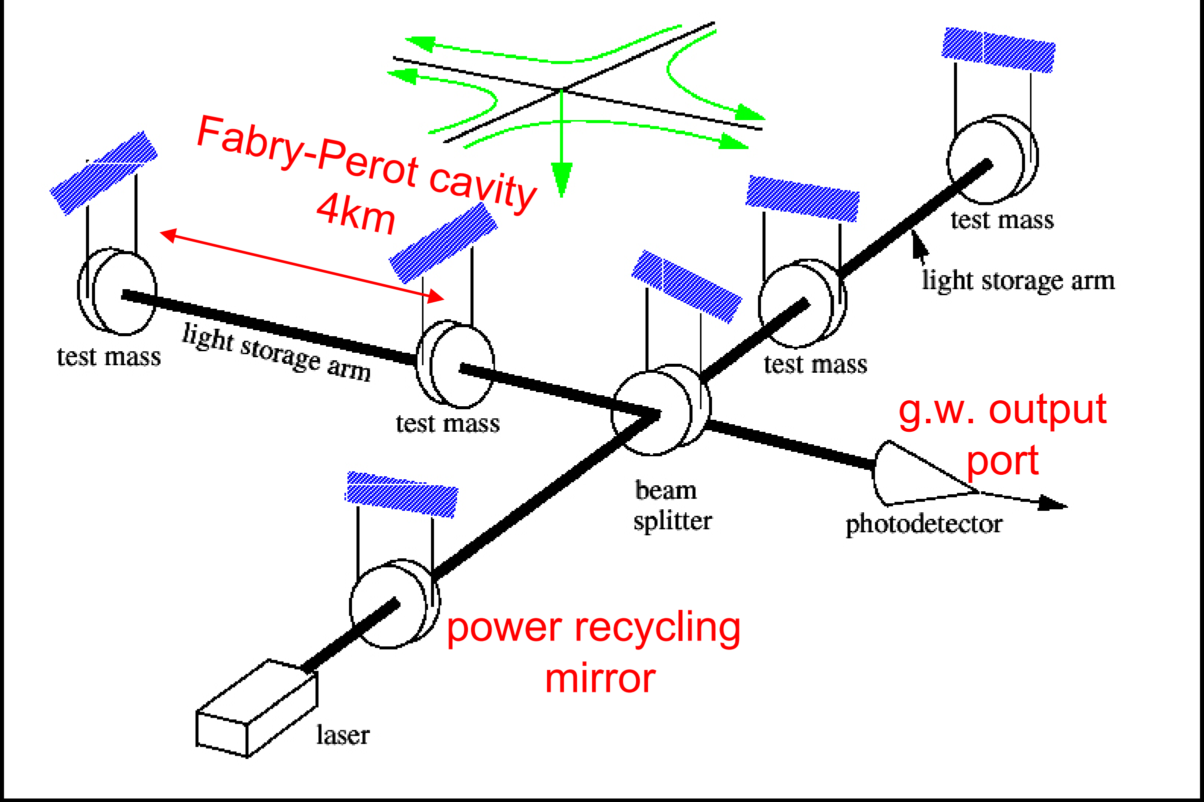
Interferometer

Ring of test masses responding to wave propagating along z

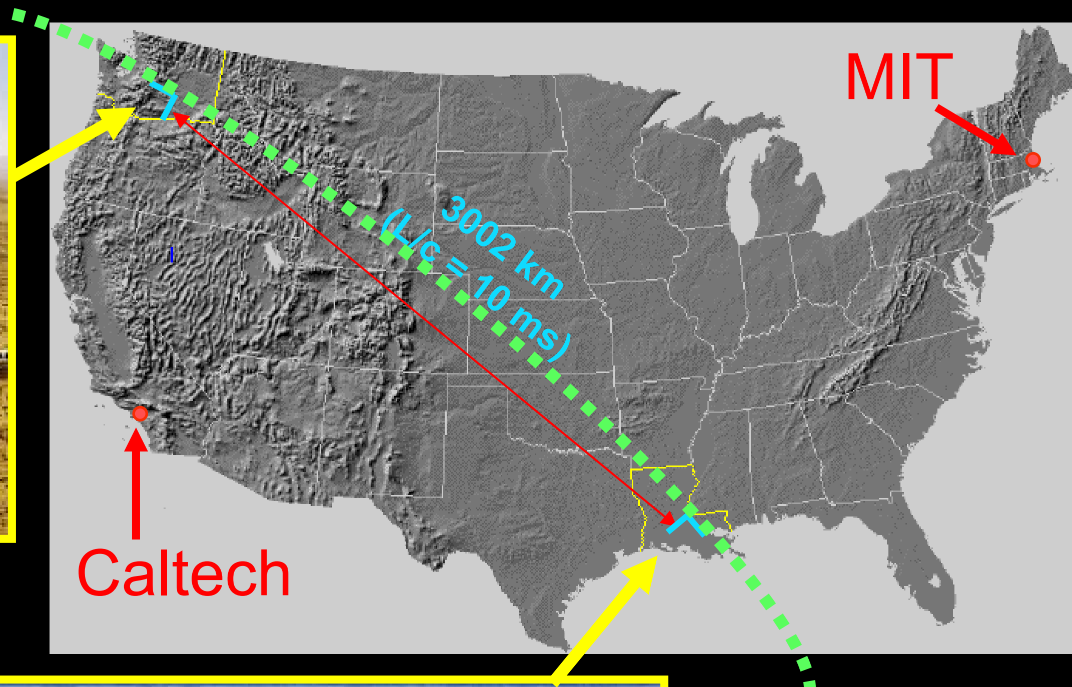


- Suspended mirrors in "free-fall"
- Michelson interferometer "natural" GW detector
- Broad-band response ~50 Hz to few kHz
- Waveform information e.g., chirp reconstruction



- Arms in LIGO are 4km
- Goal: measure difference in length to one part in 10^{21}, or 10^{-18} meters

Laser Interferometer Gravitational-wave Observatory



- Managed and operated by Caltech & MIT with funding from NSF
- Ground breaking 1995
- 1st interferometer lock 2000
- LIGO Scientific collaboration: 45 institutions, world-wide

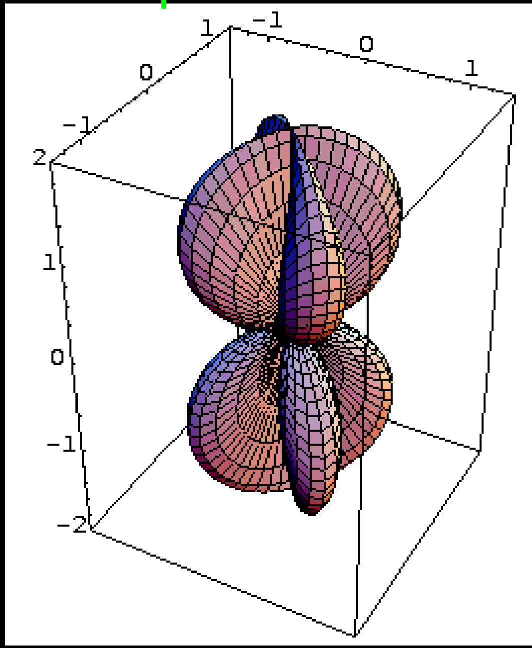
Giant "Ears"
Listen to the Vibrations of the Universe

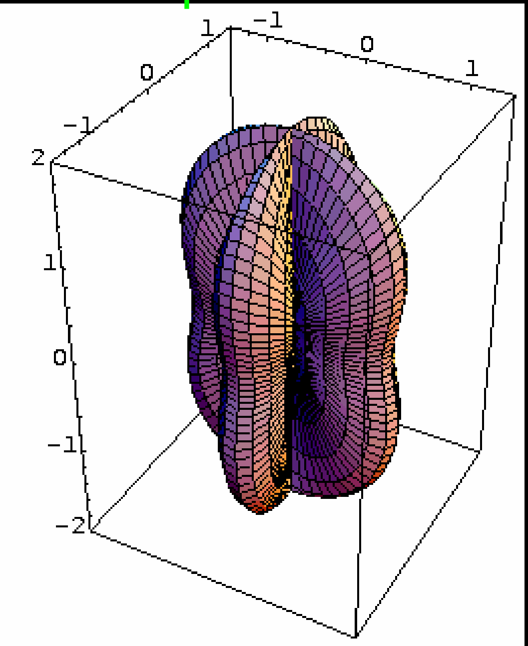
$$\frac{\delta L(t)}{L} = h(t) = F^{+} h_{+}(t) + F^{\times} h_{\times}(t)$$

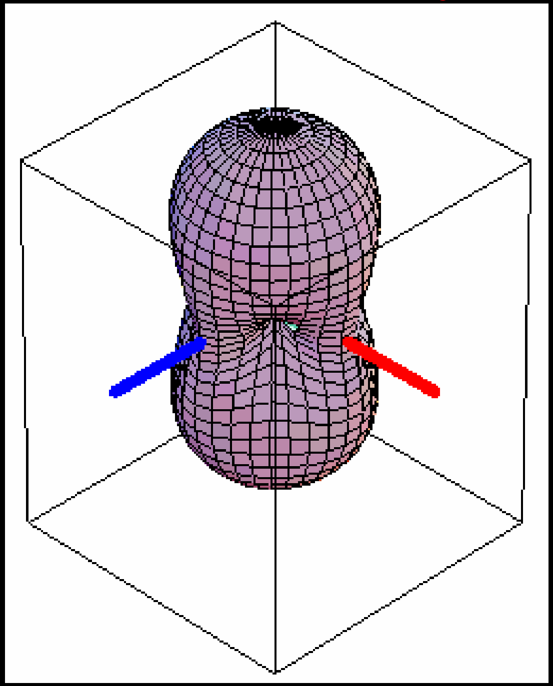
"×" polarization

"+" polarization

RMS sensitivity

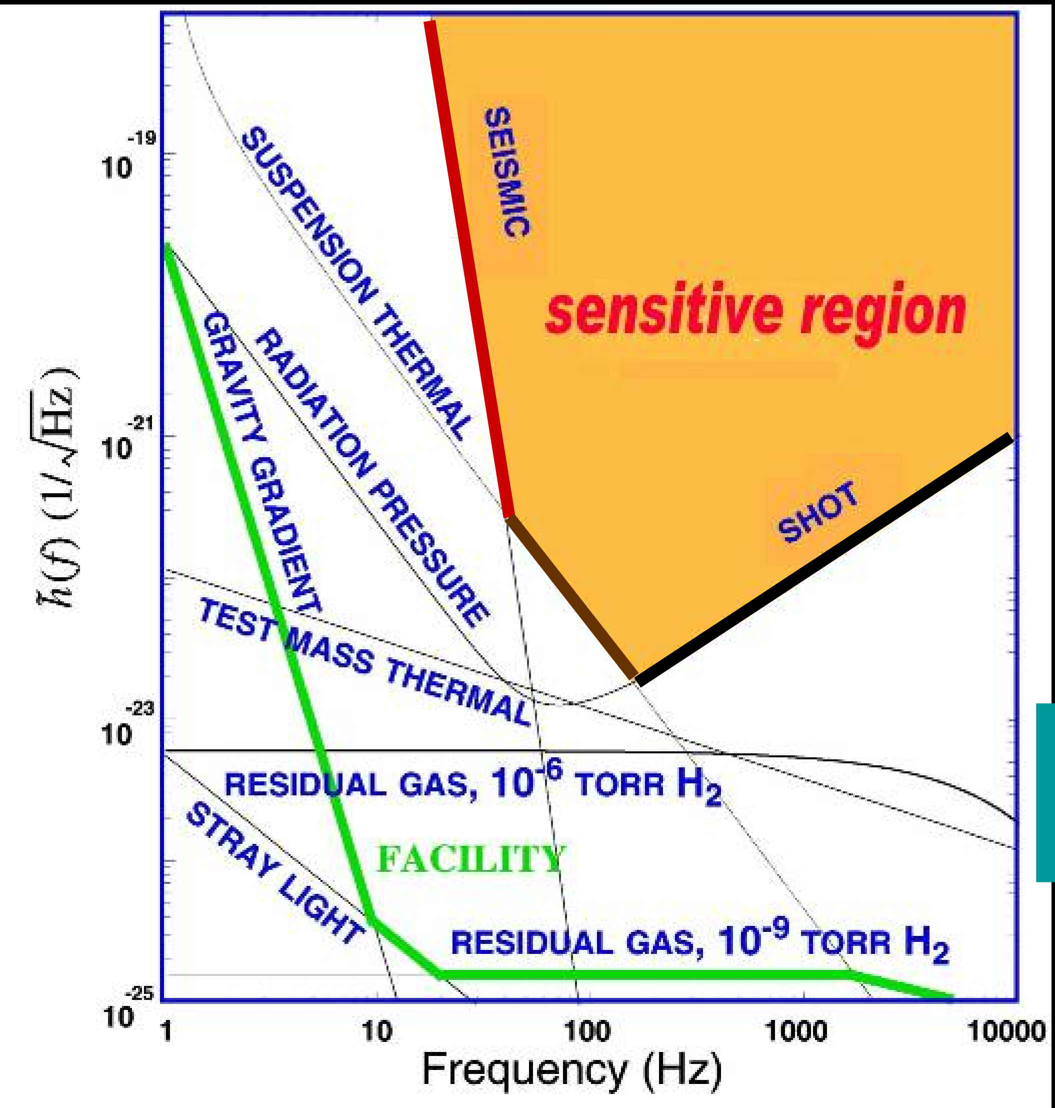


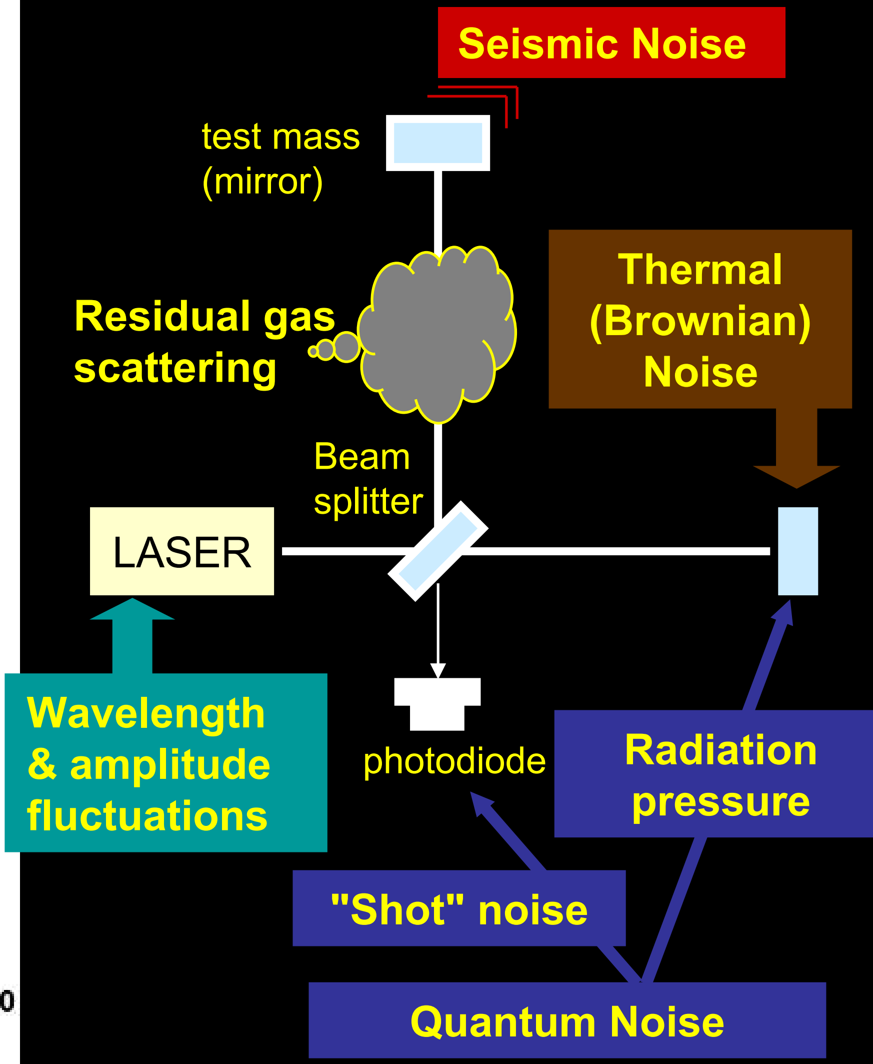




Beam patterns: $F^{+}, F^{\times}$: [-1, 1] depend on time, direction

Initial LIGO Sensitivity Limits





- LIGO beam tube (1998)
- 1.2 m diameter - 3mm stainless steel
- 50 km of weld

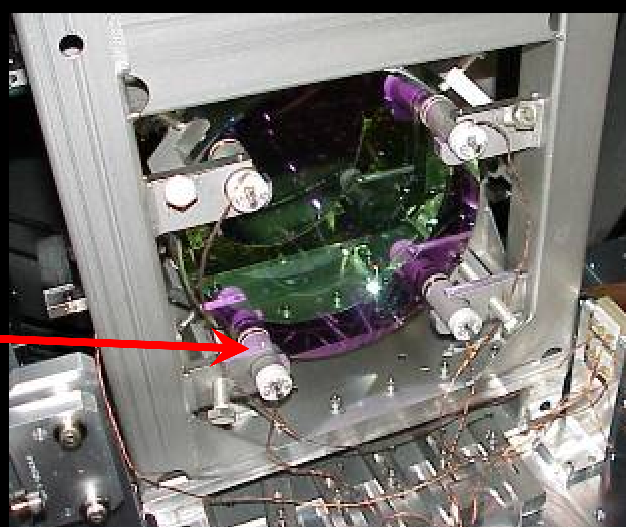
20,000 m^3 @ 10^{-8} torr

Corner Station

Suspended Mirrors

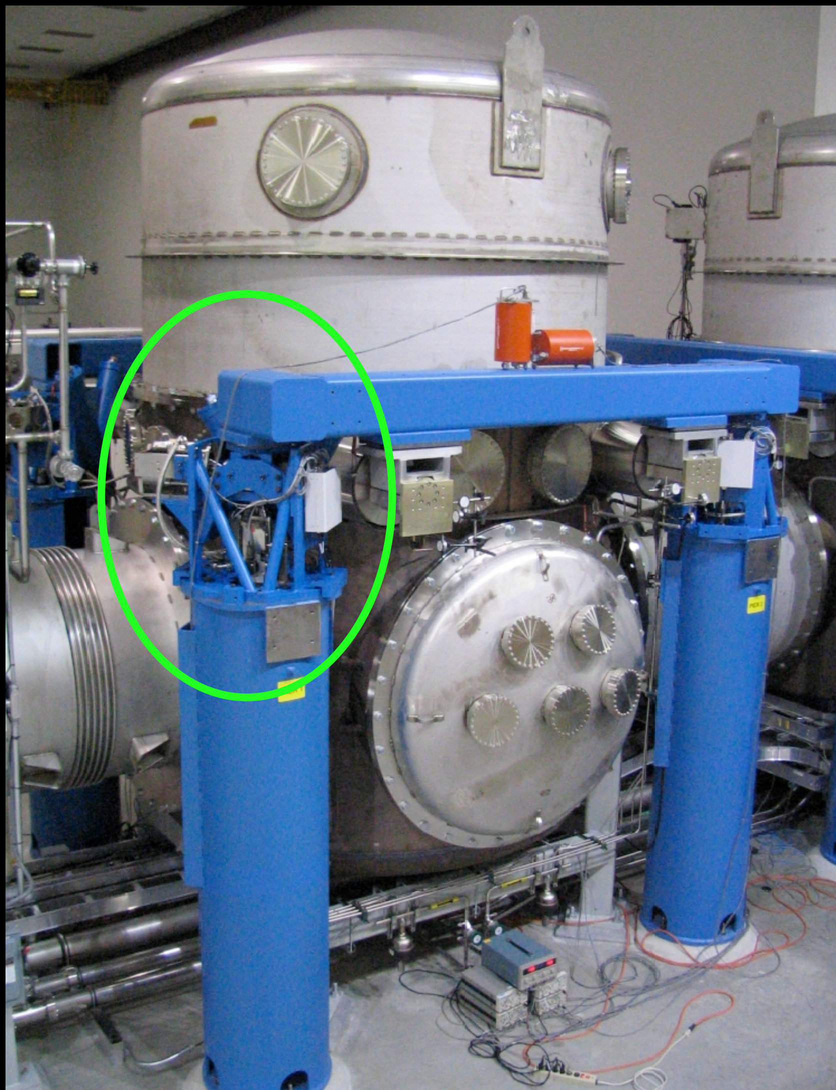
10 kg Fused Silica, 25 cm diameter and 10 cm thick

0.3mm steel wire



Local sensors/actuators for damping and control forces

Active Seismic Isolation in Louisiana

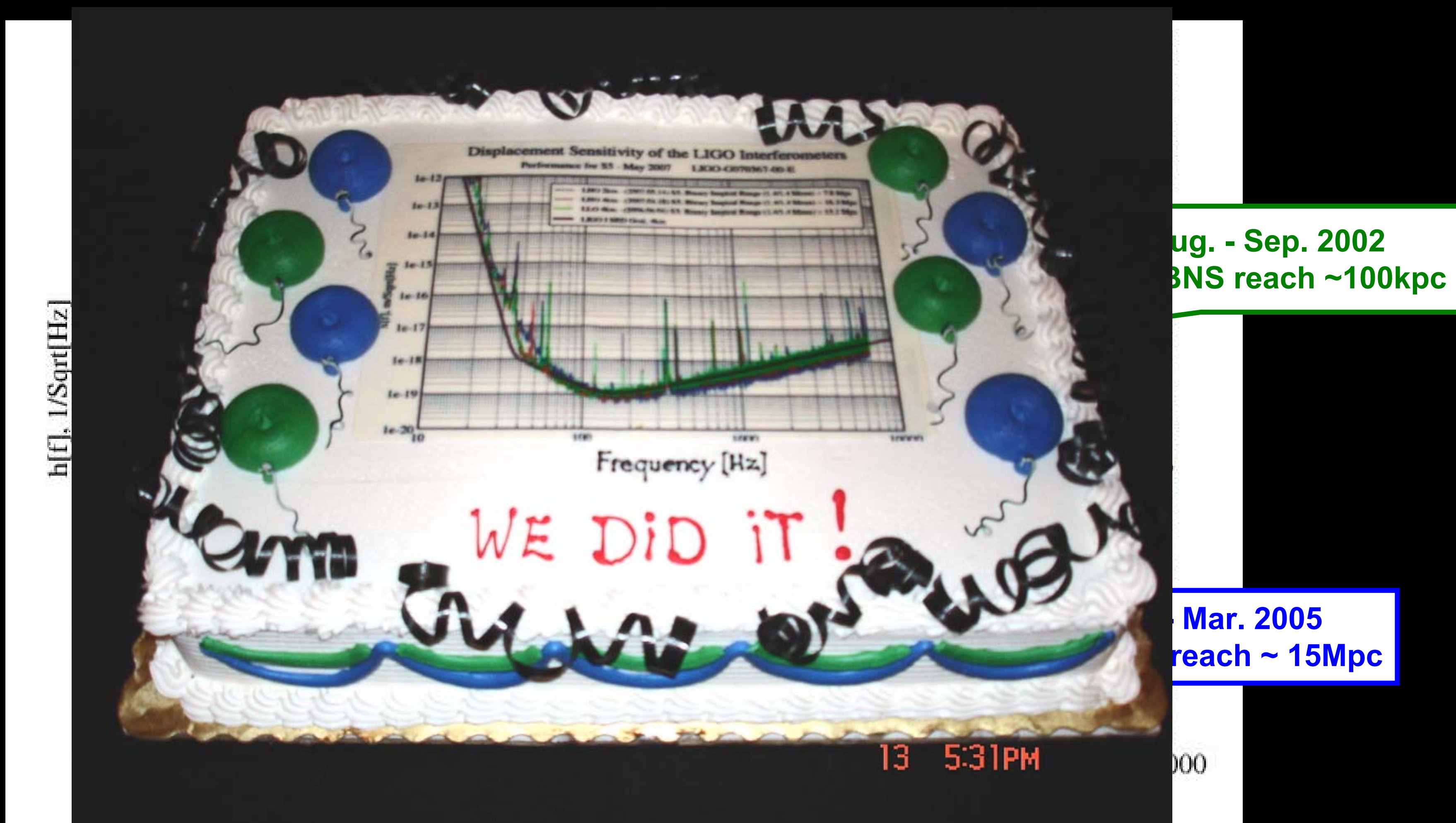


- Hydraulic external pre-isolator (HEPI)
- Signals from sensors on ground and cross-beam are blended and fed into hydraulic actuators
- Provides much-needed immunity against normal daytime ground motion at LLO

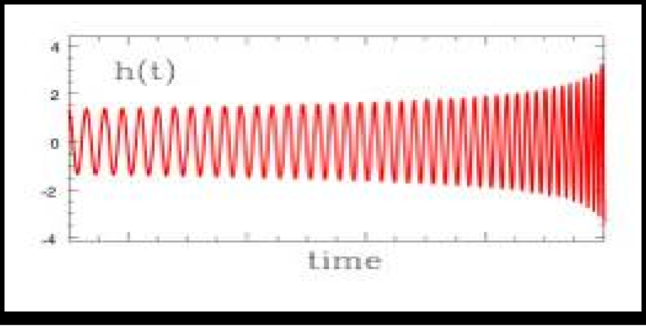
Despite some obstacles along the way…

…LIGO has met its experimental challenges

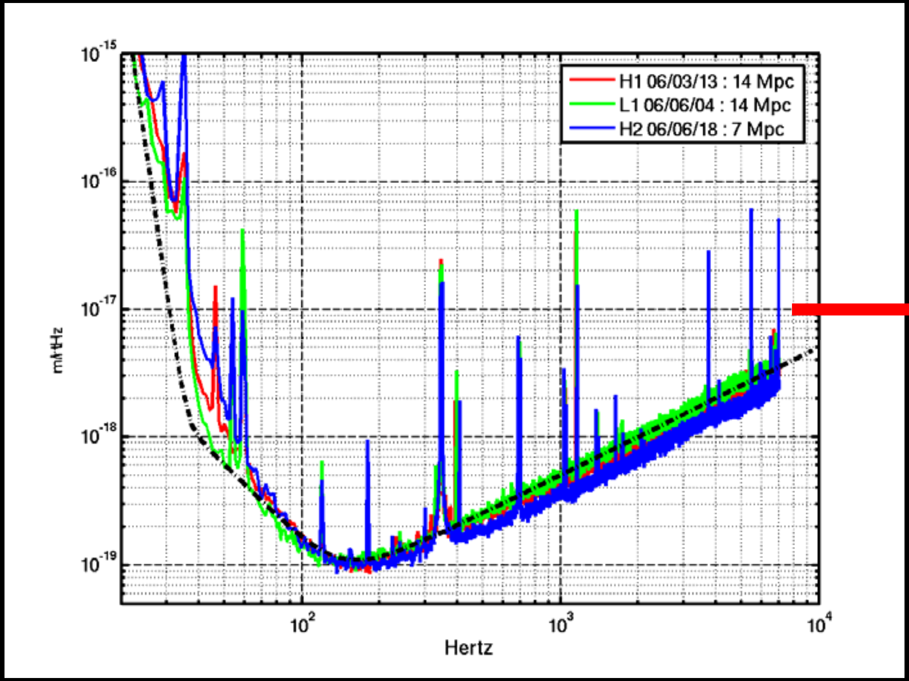
the design sensitivity predicted in the 1995 LIGO Science Requirements Document was reached in 2005

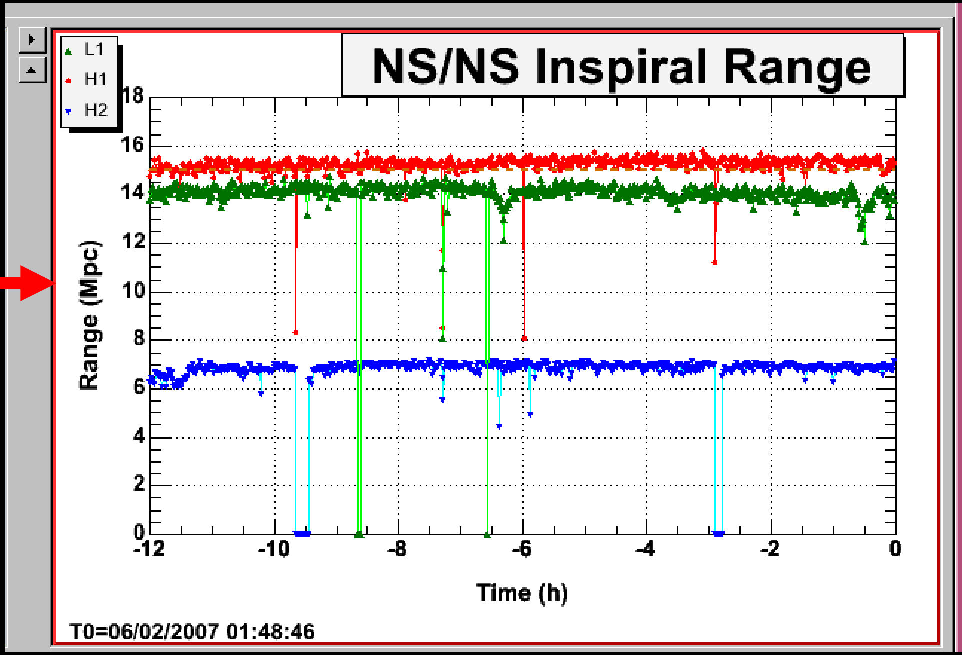


Binary Neutron Stars (BNS): a Measure of Performance



The inspiral waveform for BNS is known analytically from post-Newtonian approximations. We can translate strain amplitude into (effective) distance.

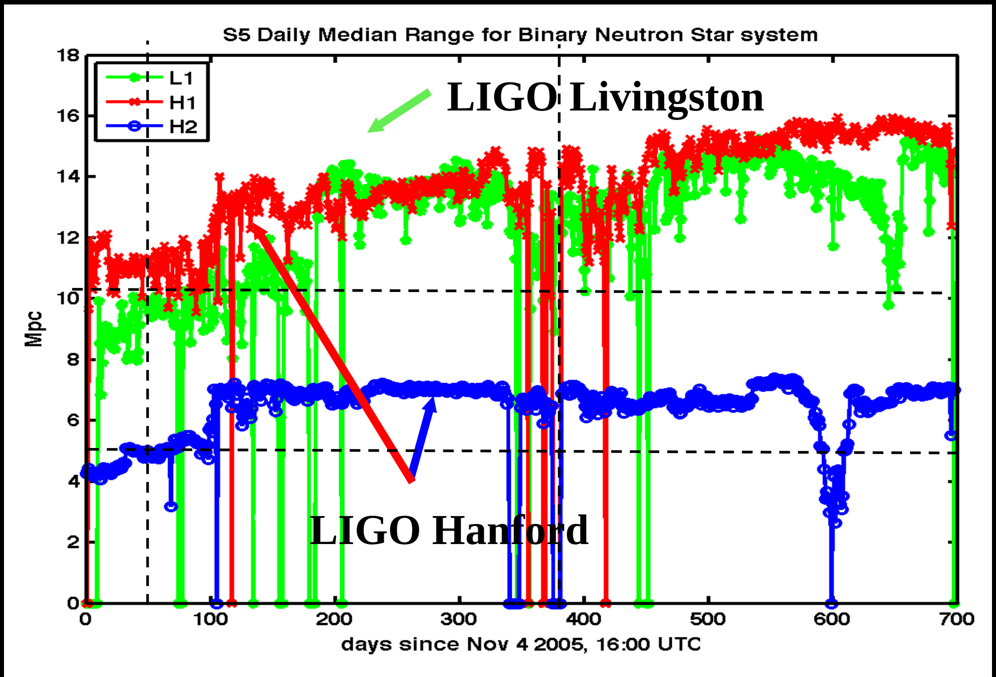


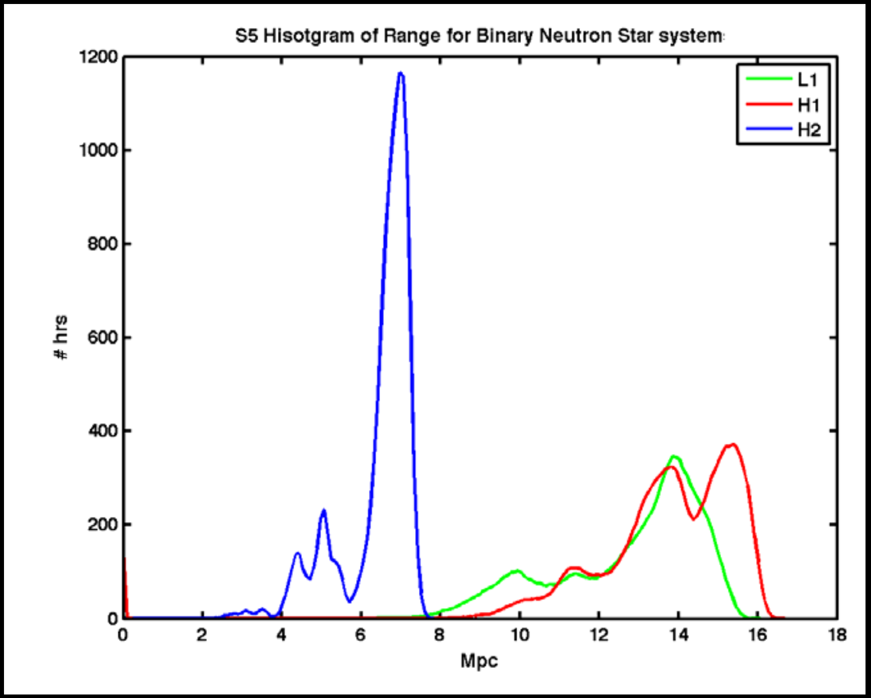


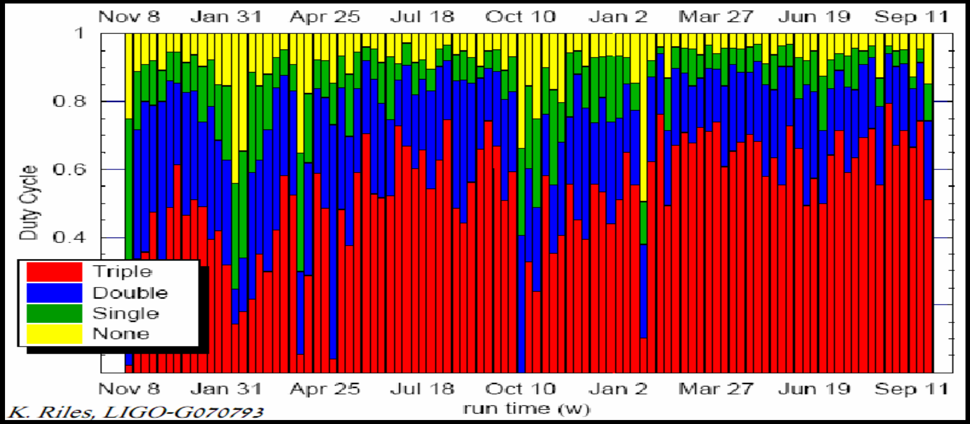
Range: distance of a 1.4-1.4 M binary, averaged over orientation/polarization

Predicted rate for S5: 1/3 years (most optimistic), 1/100 years (most likely)

The S5 run







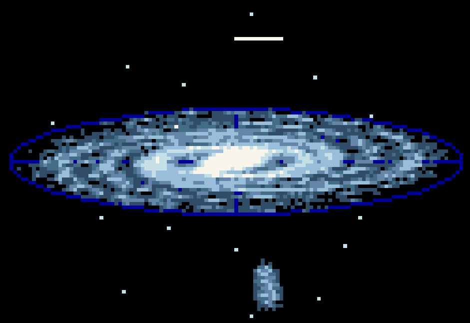
S5 started in Nov 2005 and ended Oct 2007

LIGO collected 1 year of triple coincidence data

Duty cycle: ~75% per IFO, 53% triple coincidence

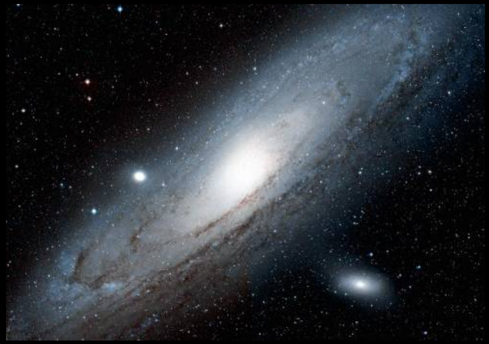
Progress in Sensitivity

Average distance for detecting a coalescing neutron-star binary:



Milky Way
(8.5 kpc)

Sept 2002
[~1 galaxy]



Andromeda
(700 kpc)

March 2003
[~2 galaxies]

Virgo Cluster
(15 Mpc)

now
[~10^3 galaxies]

1 light year = 9.5×10^{12} km
1 pc = 30.8×10^{12} km = 3.26 light years

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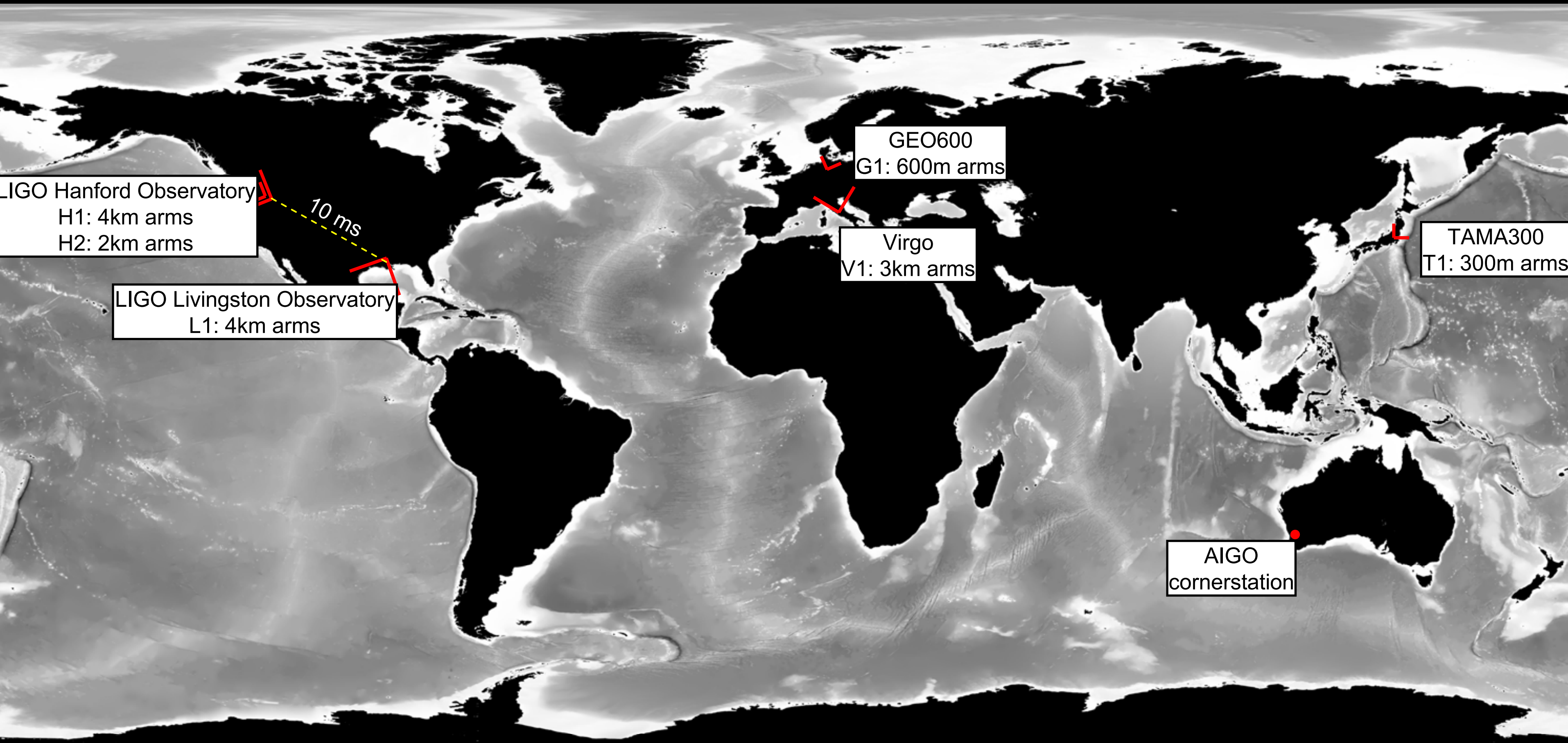
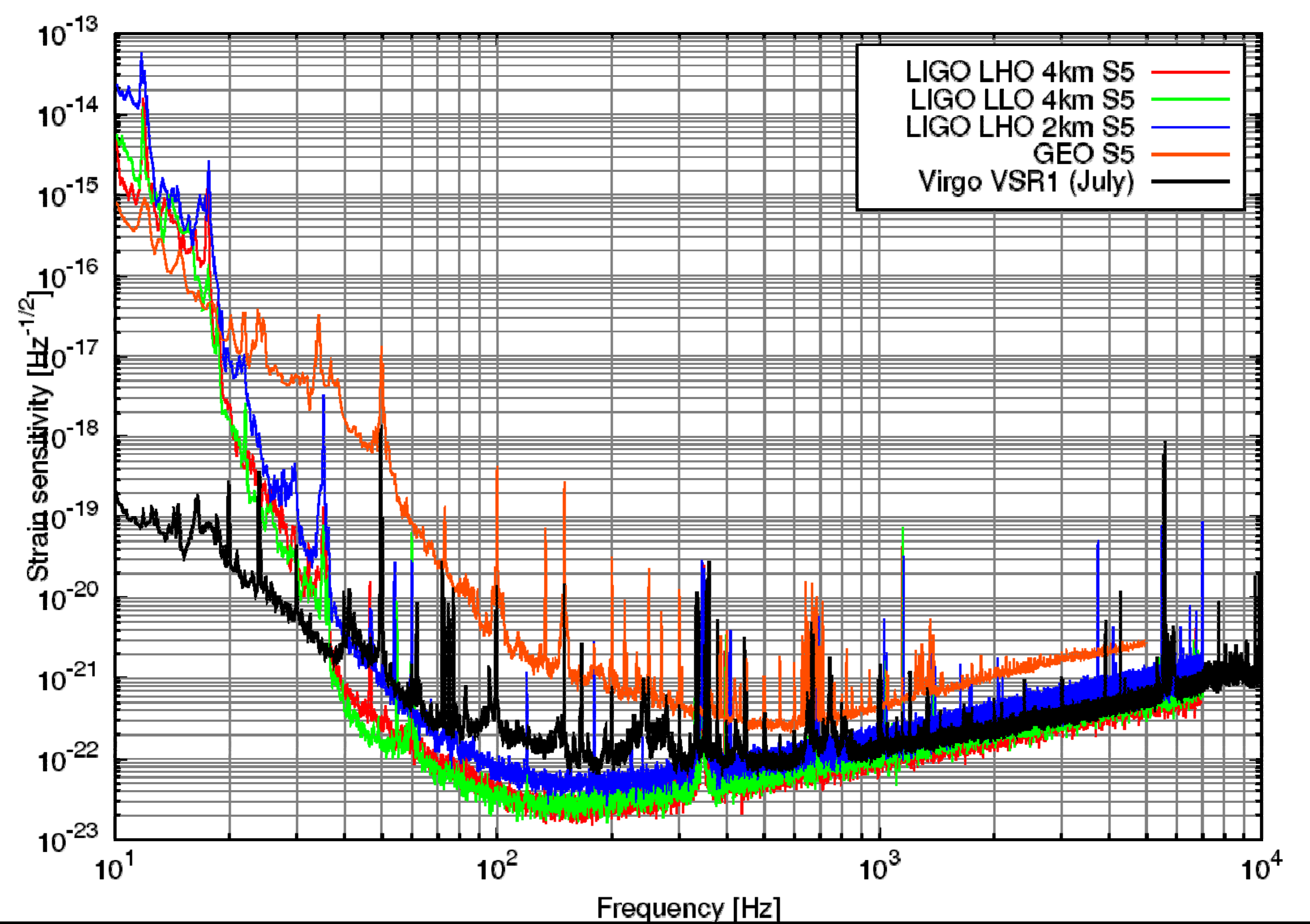
An International Quest: Ground-Based Interferometers



Credit: NASA's Earth Observatory

Also: Resonant Bars, LISA

Summer 2007 Performance of the Large Interferometers



Organization of the Projects

Scientific users

Cooperative agreement for data exchange and joint data analysis for last 5 months of S5 (Virgo VSR1)

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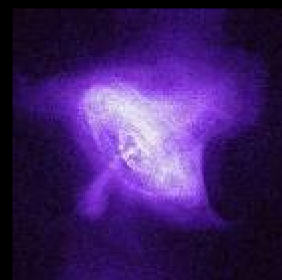
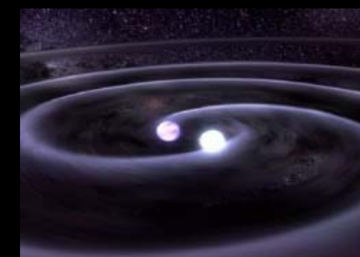
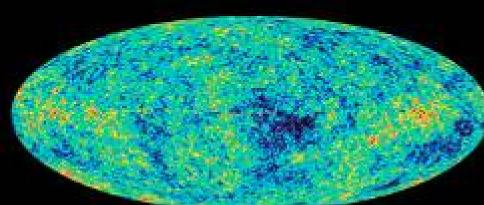
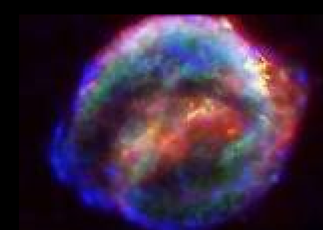
NASA

Sources And Methods

	Long duration	Short duration
Matched filter	 Pulsars	 Compact Binary Inspirals
Template-less methods	 Stochastic Background	 Bursts

Binary Systems

We know gravitational waves emitted from *compact binary systems* exist:

PSR1913+16 Hulse-Taylor

Inspiral chirp: Amplitude and duration depend on the masses and spins.

D_{eff} effective distance, depends on the physical distance r and on orientation of the binary system; $D_{eff}>r$

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

Method: matched filtering with thousands of templates.

Results from the S3+S4 science runs [Preprint arXiv:0704.3368]

- No GW signals identified
- Binary neutron star signal out to ~17 Mpc (optimal case)
- Binary black hole signals out to tens of Mpc
- Place limits on binary coalescence rate for certain population models

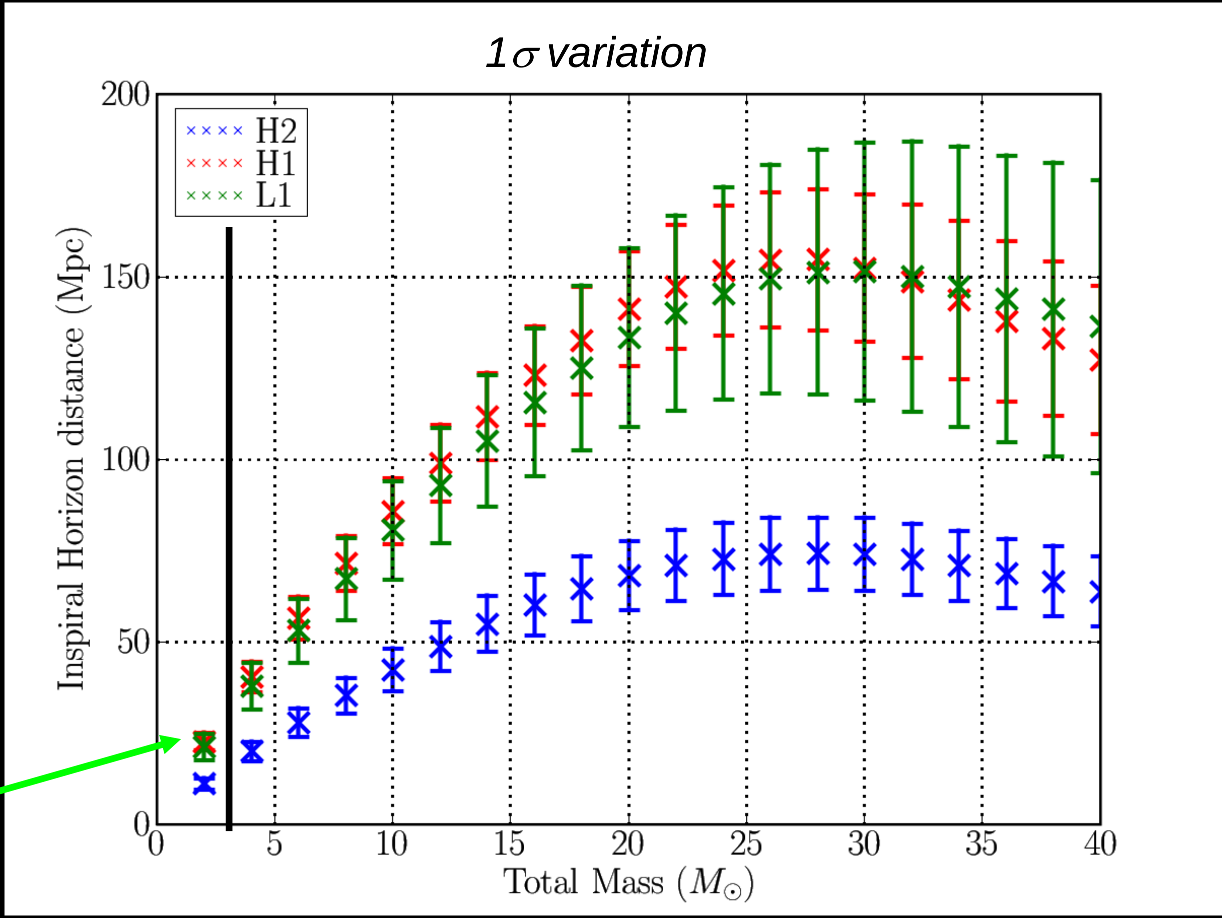
Horizon in S5

distance at which an optimally oriented and located binary system can be seen with signal-to-noise ratio $\rho=8$

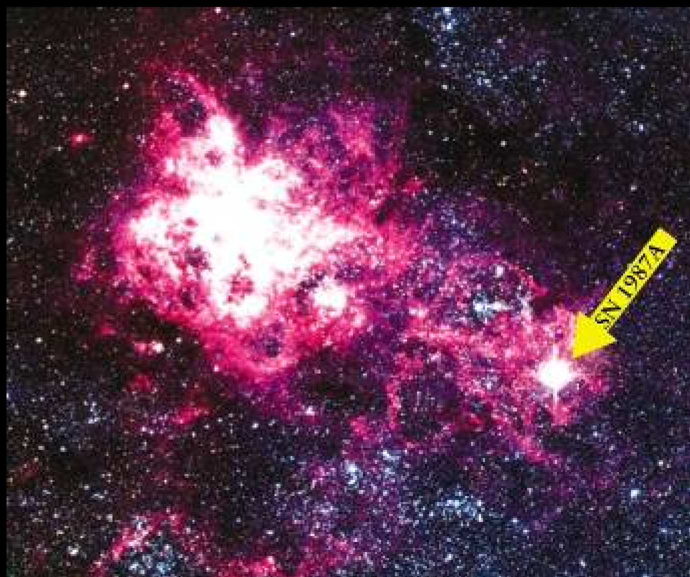
For 1.4-1.4 M_o binaries:
~ 200 MWEGs in range

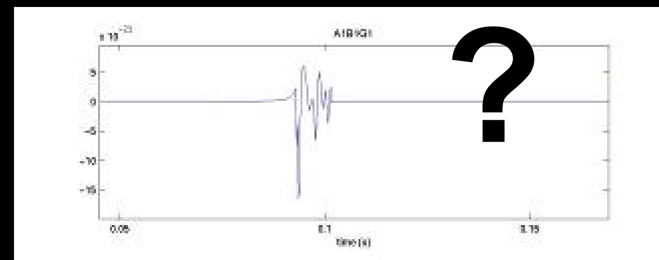
For 5-5 M_o binaries:
~ 1000 MWEGs in range

Binary Neutron Stars



Bursts





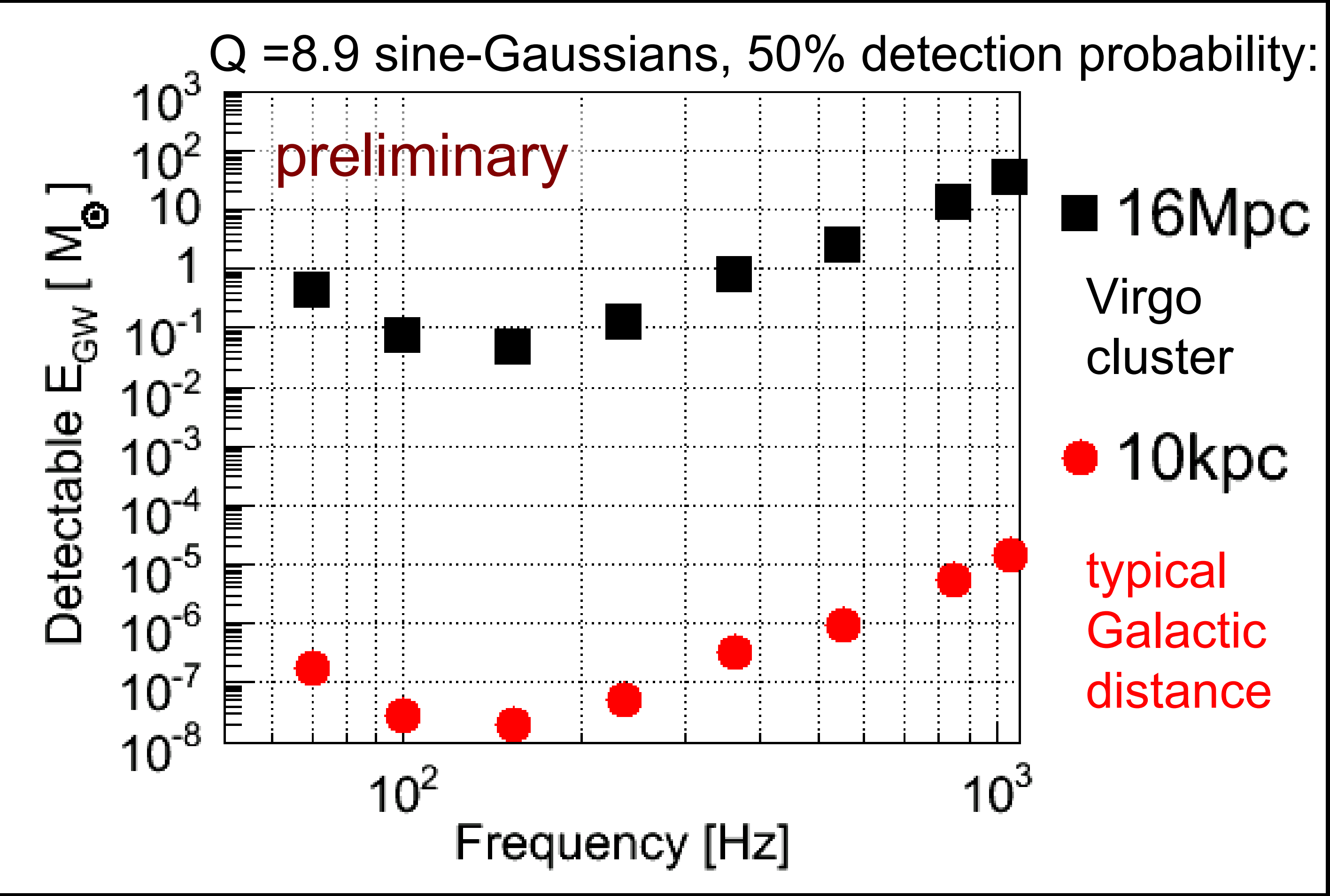
Uncertainty of waveforms complicates the detection ⇒ minimal assumptions, open to the unexpected

Method:
Coincident excess power in time-frequency plane or cross-correlation
Data quality/vetoes

Example: S4 general all-sky burst search

[Class Quant Grav 24, 5343 (2007)]

Detection Efficiency / Range



For a 153 Hz, *Q* =8.9 sine-Gaussian, the S5 search can see with 50% probability:

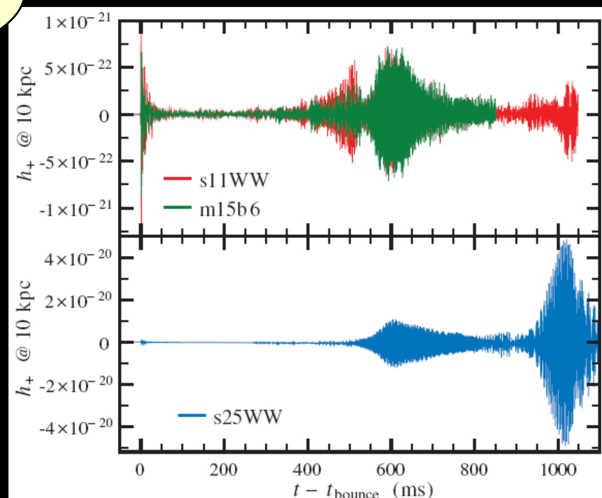
$\sim 2 \times 10^{-8}\ M_\odot c^2$ at 10 kpc (typical Galactic distance)

$\sim 0.05\ M_\odot c^2$ at 16 Mpc (Virgo cluster)

Order of Magnitude Range Estimate for Supernovae and BH Mergers

Model dependent!

Ott, Burrows, Dessart and Livne, PRL 96, 201102 (2006)



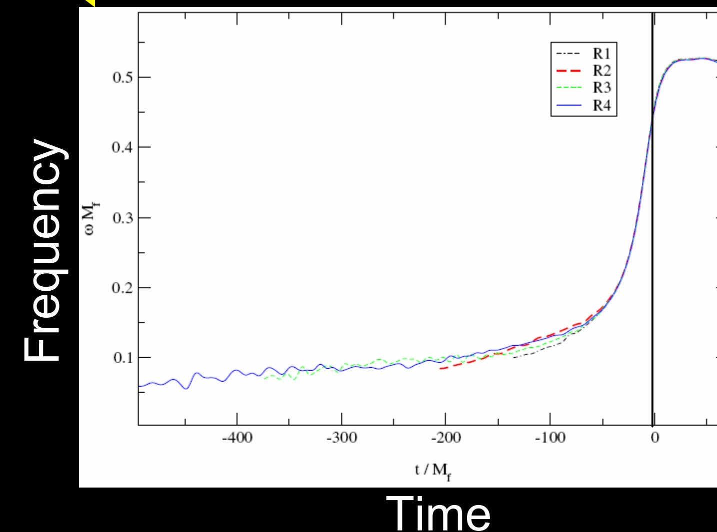


TABLE I. MODEL SUMMARY.

Model	Δt[a] (ms)	$\lvert h_{+,max}\rvert$[b] (10^{-21})	$h_{char,max}$[b,c] (10^{-21})	$f(h_{char,max})$ (Hz)	E_{GW}[d] $(10^{-7} M_\odot c^2)$
s11WW	1045	1.3	22.8	654	0.16
s25WW	1110	50.0	2514.3	937	824.28
m15b6	927.2	1.2	19.3	660	0.14

$$f_{peak} \approx \frac{0.46}{2\pi M_f} \approx \frac{15\ \mathrm{kHz}}{(M_f/M_\odot)}$$

Baker et al, PRD 73, 104002 (2006)

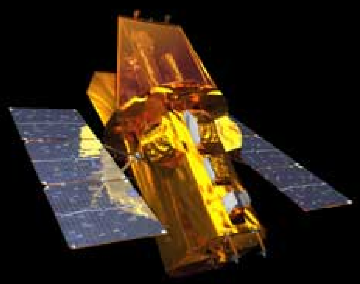
11 $M_\odot$ progenitor (s11WW model)
$\Rightarrow$ reach ~ 0.4 kpc
25 $M_\odot$ progenitor (s25WW model)
$\Rightarrow$ reach ~ 16 kpc

Assuming ~3.5% mass radiates in the merger:
10+10 $M_\odot$ binary $\Rightarrow$ reach ~ 3 Mpc
50+50 $M_\odot$ binary $\Rightarrow$ reach ~ 100 Mpc

Externally Triggered Searches

Search for gravitational wave inspirals or bursts associated with GRBs or other observed astrophysical events

- Known time allows use of lower detection threshold
- Known sky position fixes relative time of arrival at detectors



Swift

Analyzed 39 GRBs during runs S2+S3+S4 ***[Preprint arXiv:0709.0766]***

Looked for quasiperiodic GW signals in tail of SGR 1806–20 hyperflare of Dec. 2004 ***[PRD** 76**, 062003 (2007)]***

During S5: over 200 GRBs, many SGR flares, etc.

- Doing or developing searches for GW signals associated with these

GRB 070201

- Feb 1, 2007: short hard γ burst (T_{90}=0.15 s)
- Observed by five spacecraft
- Location consistent with M31spiral arms (0.77 Mpc)
- At the time of the event, both Hanford instruments were recording data (H1, H2), while others were not (L1, V1, G1)
- Short GRB: could be inspiral of compact binary system (NS/BH), or perhaps soft gamma repeater

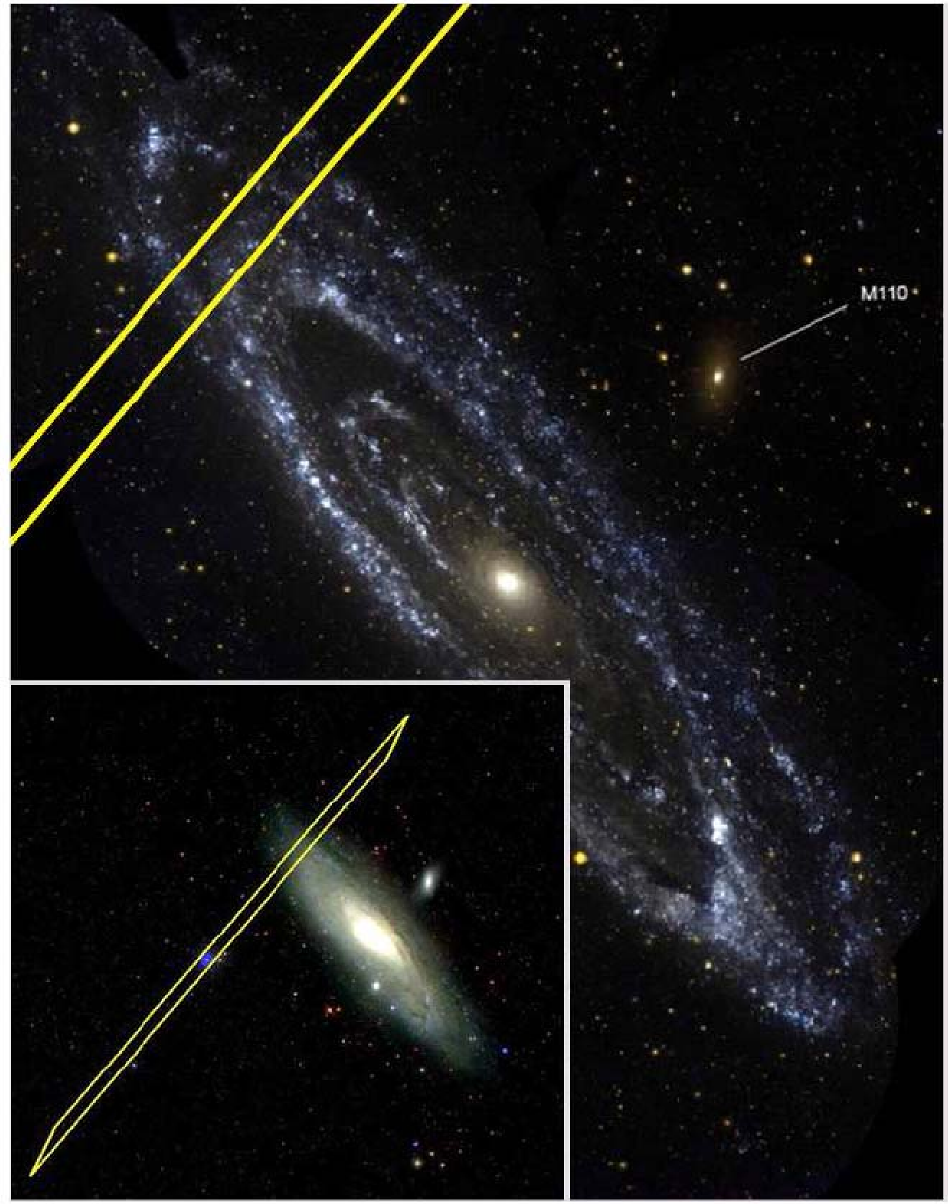


FIG. 1.— The IPN3 (IPN3 2007) (γ-ray) error box overlaps with the spiral arms of the Andromeda galaxy (M31). The inset image shows the full error box superimposed on an SDSS (SDSS 2007) image of M31. The main figure shows the overlap of the error box and the spiral arms of M31 in UV light (Thilker et al. 2005).

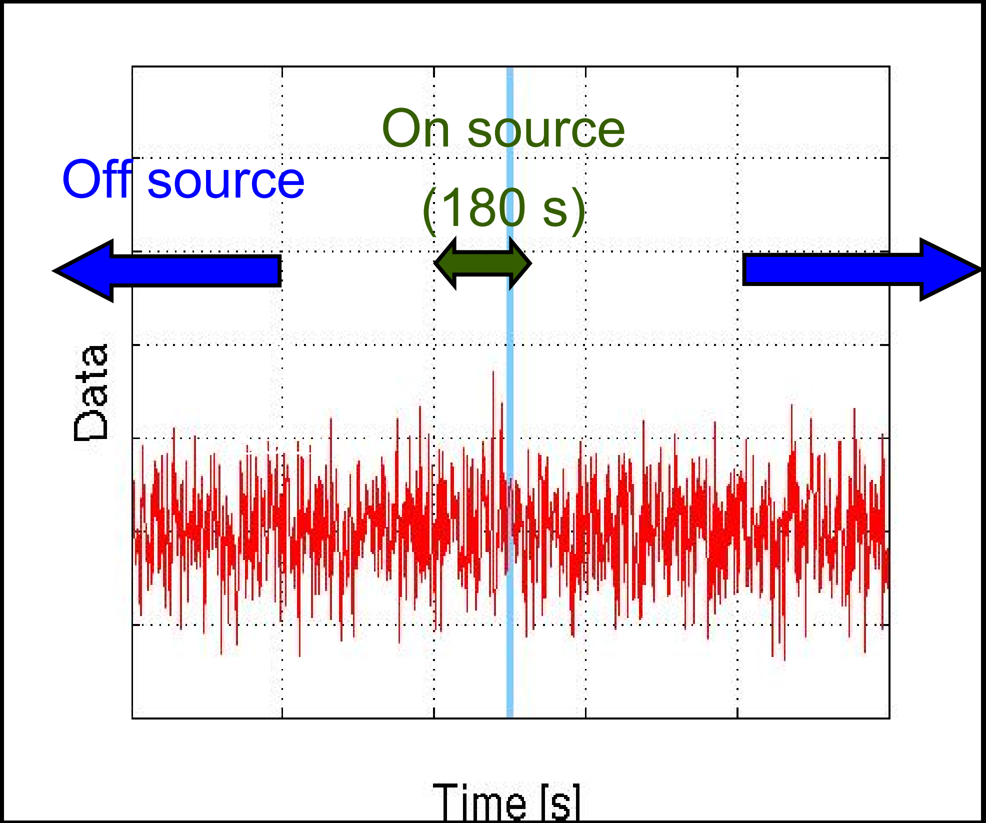
Inspiral (model-dependent) and burst (model-independent) analyses

On source data: 180s around GRB

Off source, for background estimate
- inspiral: -14h, +8h
- burst: -1.5h, +1.5h

Some (.9%) off source data excluded, based on data quality cuts obtained from *playground* studies (e.g. excess seismic noise, digital overflows, hardware injections of fake signals)

Assume gravitational waves travel at the speed of light



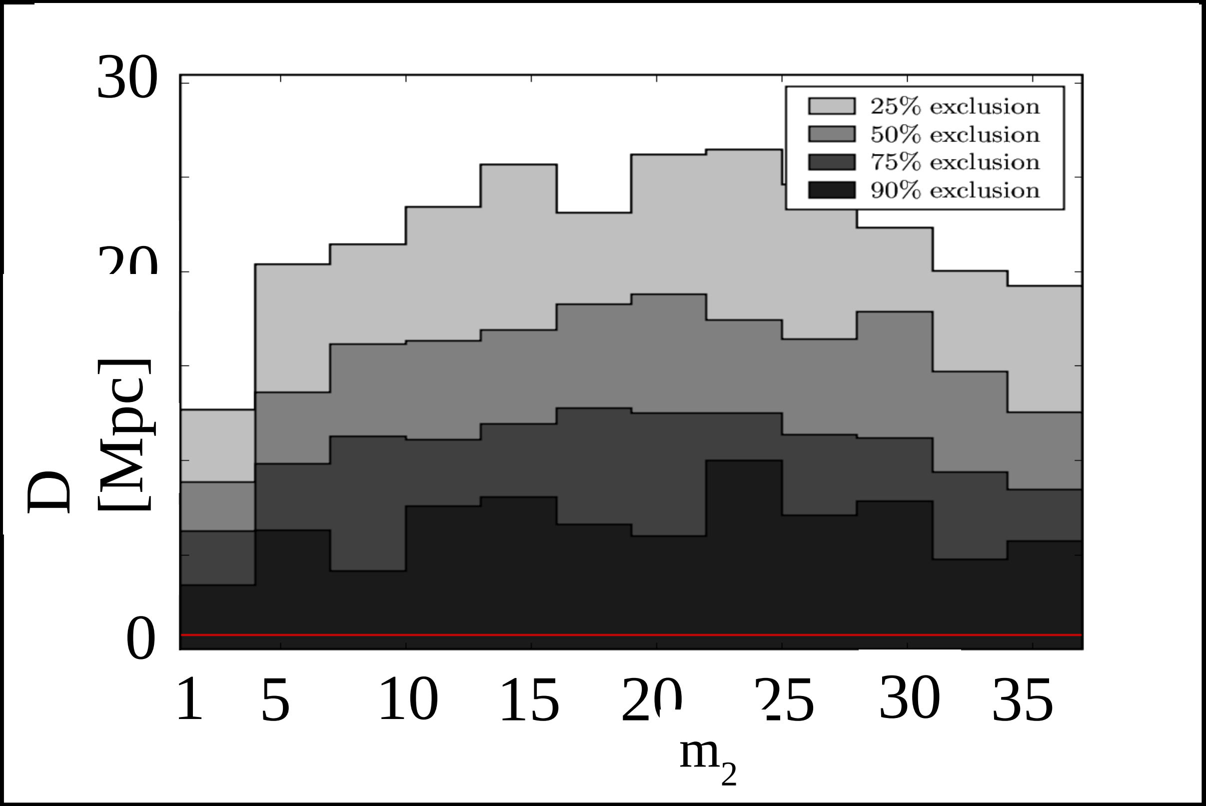
Inspiral search - GRB 070201

- Matched template analysis, $1M_\odot < m_1 < 3M_\odot$, $1M_\odot < m_2 < 40M_\odot$
- H1 ~ 7200 templates, H2 ~ 5400 templates, obtain filter SNR
- Require consistent timing and mass parameters between H1, H2
- Additional signal-based vetos

arXiv:0711.1163

No gravitational wave candidates found

Compact binary in M31 with
$1M_\odot < m_1 < 3M_\odot$
$1M_\odot < m_2 < 40M_\odot$
excluded at 99% confidence



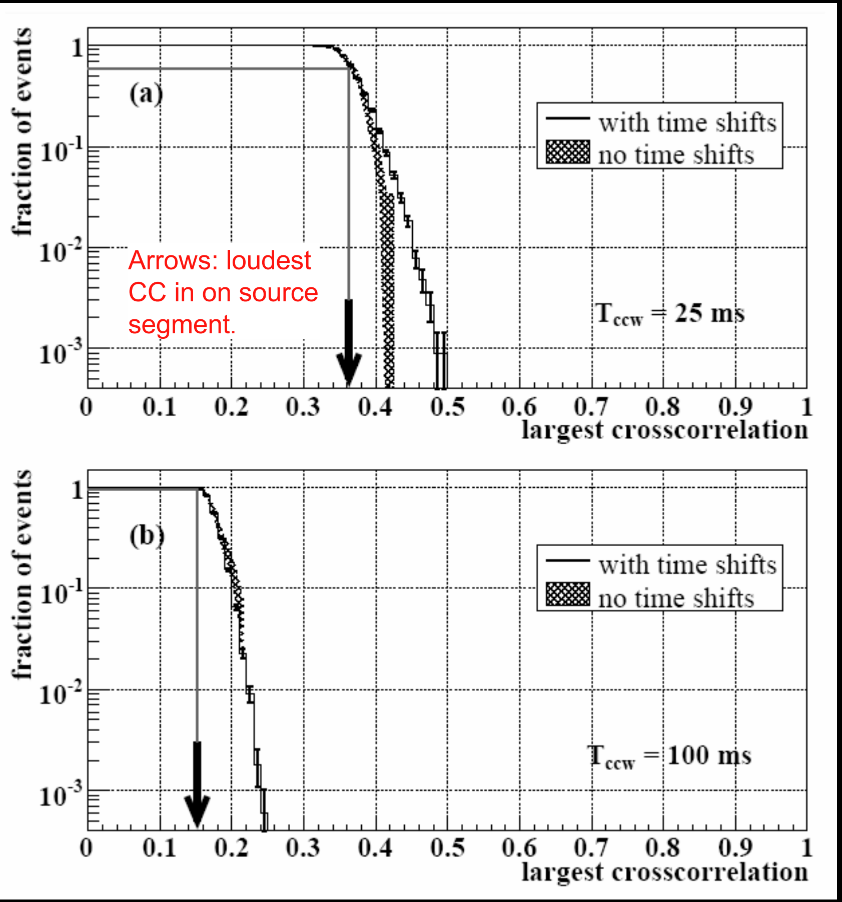
Triggered burst search GRB 070201

$$cc = \frac{\sum_{i=1}^{n}[s_1(i)-\mu_1][s_2(i)-\mu_2]}{\sqrt{\sum_{j=1}^{n}[s_1(j)-\mu_1]^2}\sqrt{\sum_{k=1}^{n}[s_2(k)-\mu_2]^2}}$$

No assumption on waveform
Cross-correlate (CC) detector data streams, on and off source
Use two windows, 25ms and 100ms
No candidates found

GRB emitted < $4.4\times10^{-4}\ M_{O}c^2$ in GW in <100ms, if source in M31, isotropic, and peaked at ~150Hz

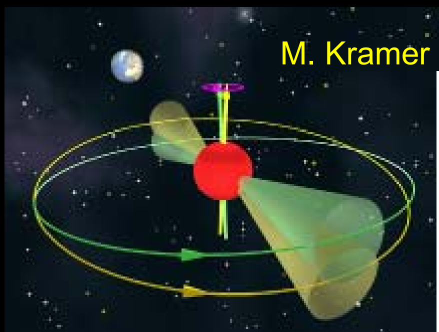
Limits on GW energy release from GRB 070201 cannot exclude an SGR in M31



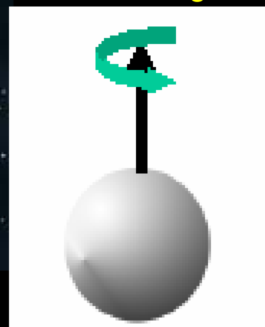
arXiv:0711.1163

Continuous Waves

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.



J. Creighton



Wobbling neutron stars

Pulsars with mountains

Accreting neutron stars

$$\epsilon = (I_{xx} - I_{yy})/I_{zz}$$

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

Best limits on known pulsars ellipticities at few x10^{-7}

Beat spin-down limit on Crab pulsar:

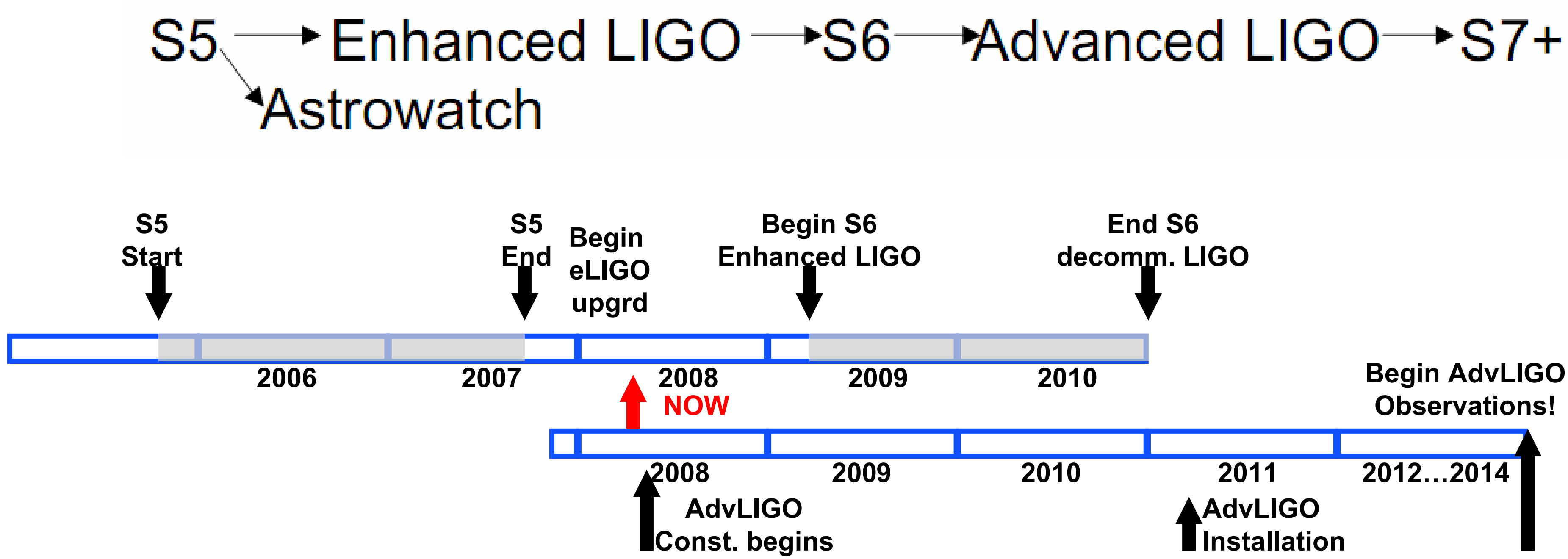
PRELIMINARY 3.4x10^{-25}, 4.2 lower than spindown

Ellipticity < 1.8x10^{-4}

- Gravitational Waves
- LIGO and its performance
- The world-wide picture
- Science with LIGO
- **The Road Ahead**

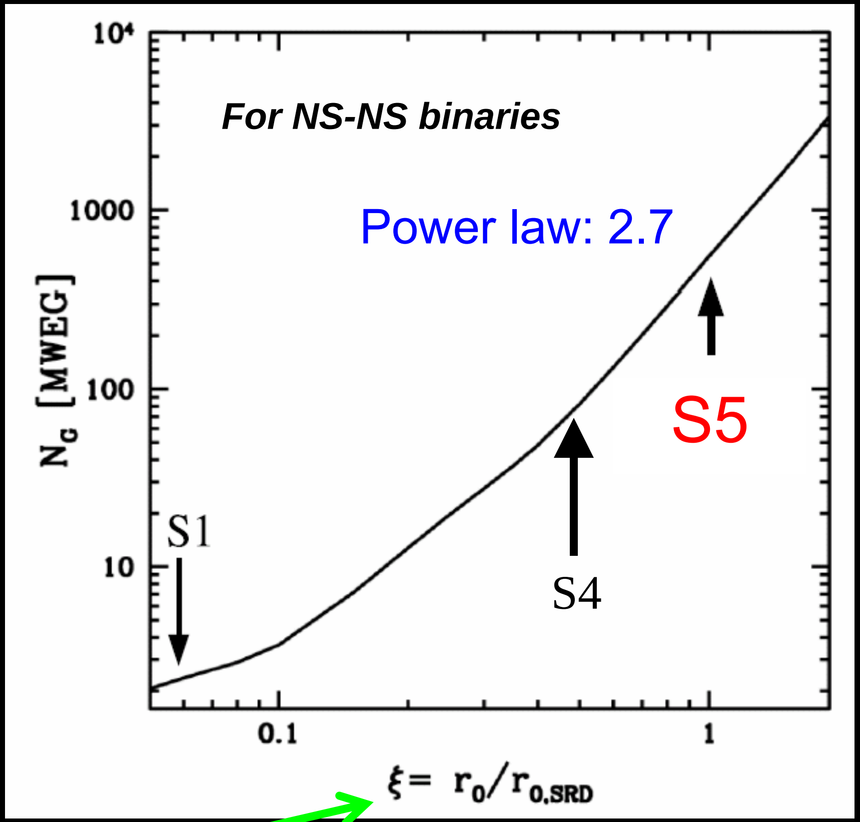
NASA

LIGO → eLIGO → AdvLIGO



How does the Number of Surveyed Galaxies Increase as the Sensitivity is Improved?

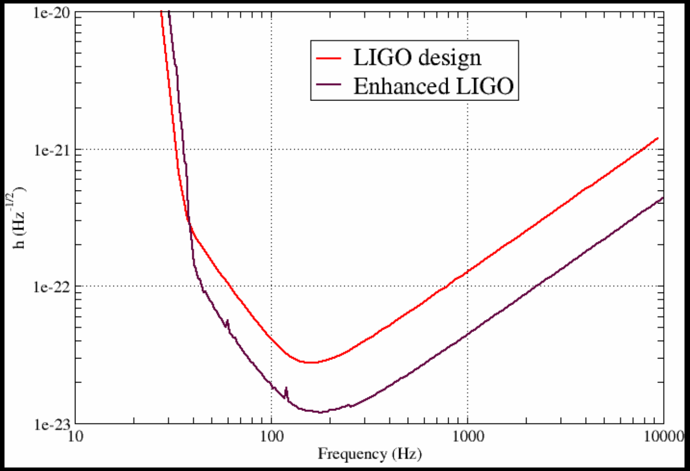
From astro-ph/0402091, Nutzman et al.



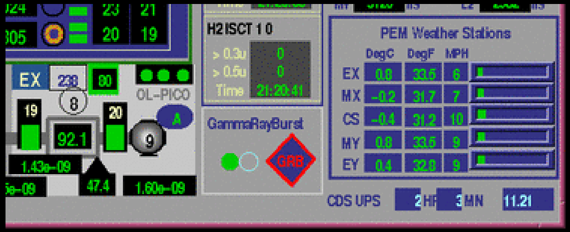
Proportional to inspiral range

So if we push the strain noise down by a factor of 2, we have a factor 6.5 increase in the number of surveyed galaxies

⇨scientific program for Enhanced LIGO (post S5)

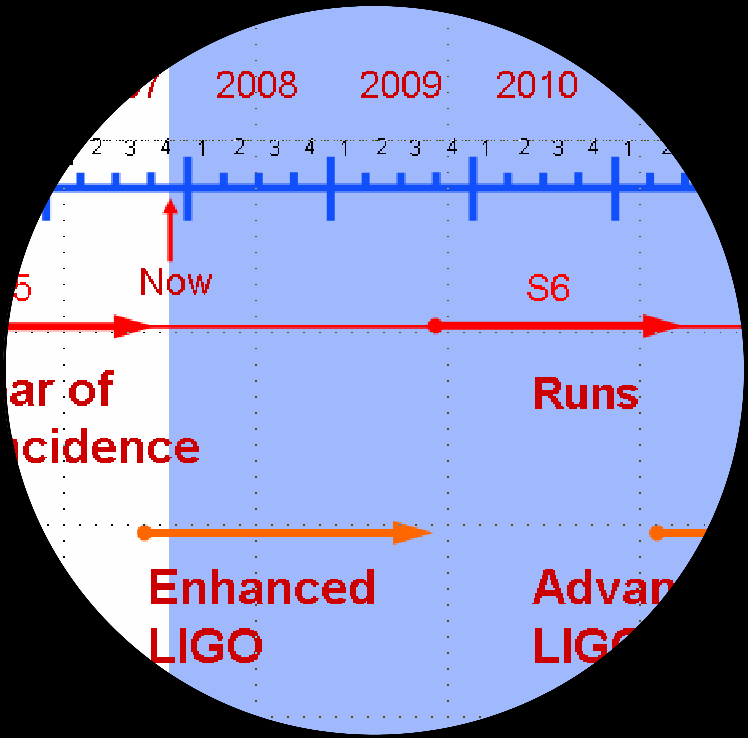


Astrowatch



- Galactic supernova rate ~ 1/50 years
- GRBs routinely observed by IPN et al.
- Resonant mass detectors off during SN1987A
- LIGO and Virgo down for enhancements in 2008 : potential to miss interesting triggers
- Astrowatch! H2-G1 coincidence, manned by graduate students

Recall timeline:



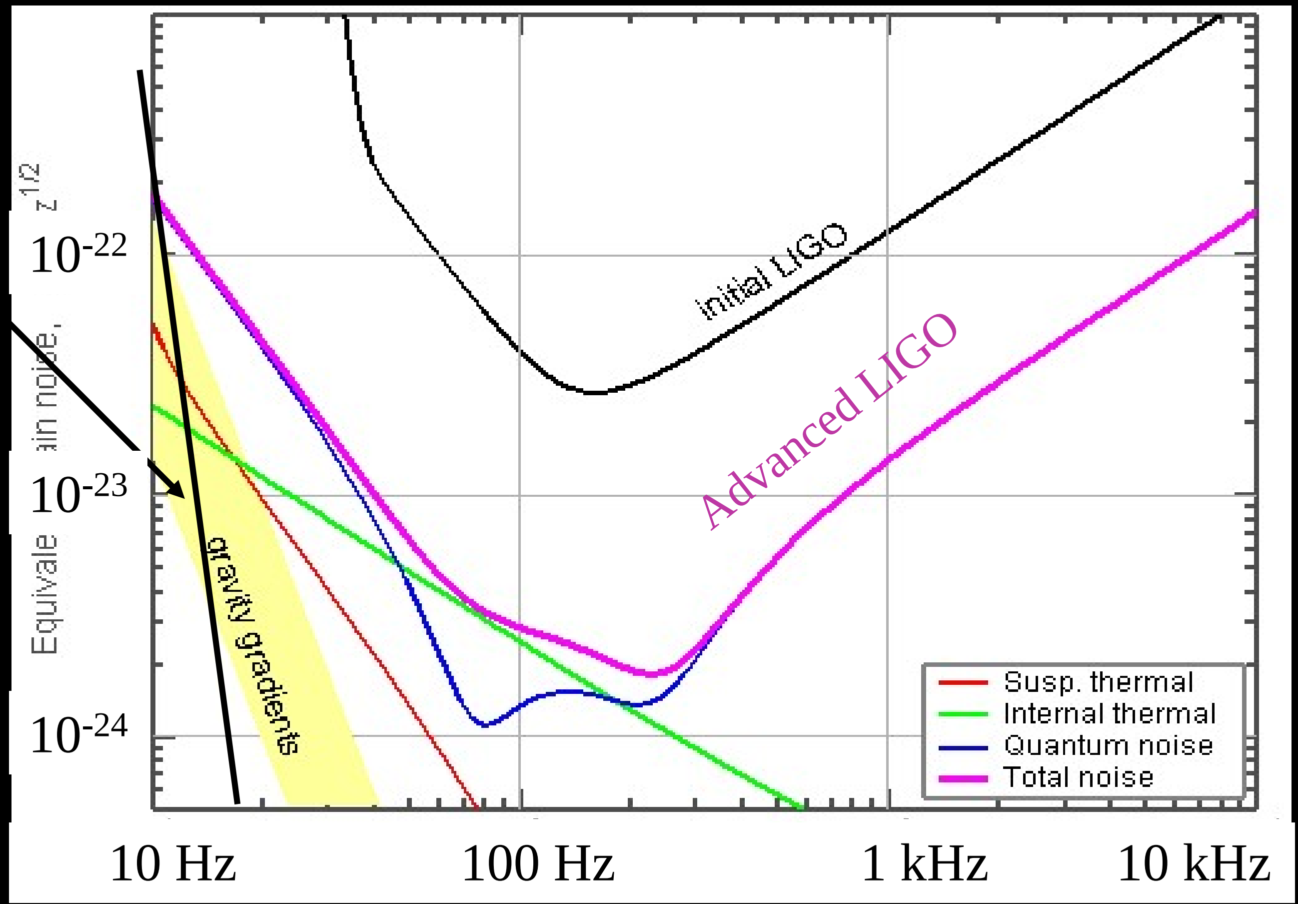
LHO 2km

GEO600

Advanced LIGO

Seismic 'cutoff' at 10 Hz

Quantum noise
(shot noise + radiation pressure) dominates at most frequencies



Factor of ~10 better than current LIGO ⇒ factor of ~1000 in volume
Also extends sensitive band to lower frequencies

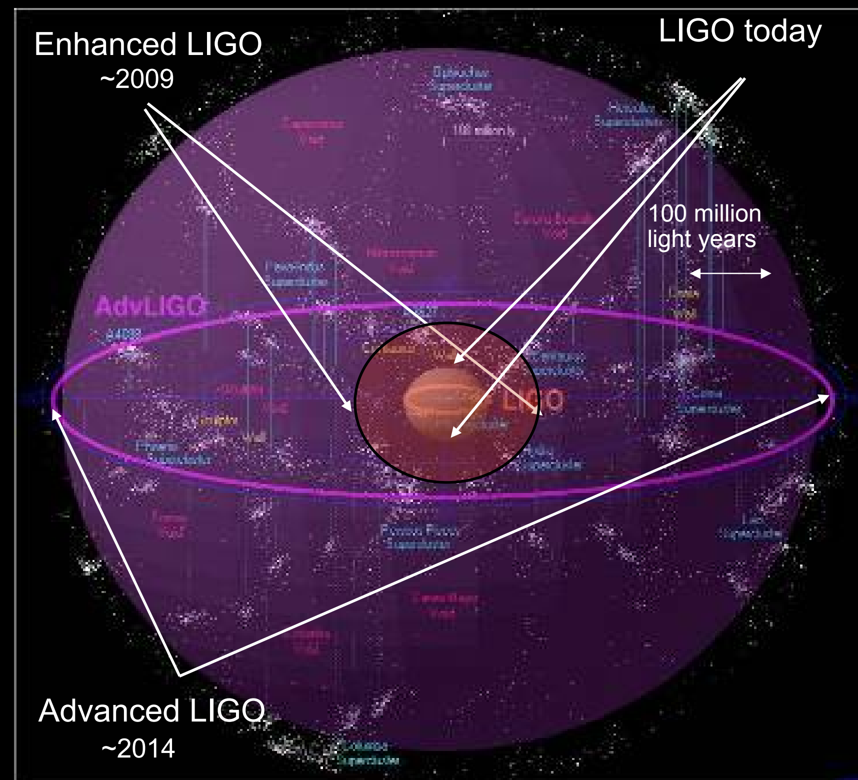
03/27/08 NSB APPROVED FUNDING!

Science with Advanced LIGO

- *Binary neutron stars: from ~20 Mpc to ~350 Mpc*
  - Estimated: 0.015/y (Ini LIGO), 0.15/y (Enh LIGO), 20/y (Adv LIGO)
  - Plausibly as high as: 0.15/y (Ini LIGO), 1.5/y (Enh LIGO), 200/y (Adv LIGO)
- *Binary black holes: from ~100 Mpc to z=2*
  - Estimated: 0.01/y (Ini LIGO), 0.11/y (Enh LIGO), 16/y (Adv LIGO)
  - Plausibly as high as: 1.7/y (Ini LIGO), 18/y (Enh LIGO), 2700/y (Adv LIGO)
- *Known pulsars:*
  - From $\varepsilon = 3\times10^{-6}$ to 2×10^{-8}
- *Stochastic background:*
  - From $\Omega_{GW} \sim 3\times10^{-6}$ to $\sim 3\times10^{-9}$

Summary

- Initial LIGO
  - All interferometers at design sensitivity
  - S5 run, one year of triple-coincidence, complete and under analysis
  - Preliminary null results astrophysically interesting
- Enhanced LIGO
  - Short-term gain of X2 in sensitivity, plus, retire Advanced LIGO risk
  - While commissioning: Astrowatch with LHO 2km and GEO600
- Experiments in the coming decade will transition field to observational astronomy
  - Advanced LIGO
  - LISA



We should be detecting gravitational waves regularly within the next 6 years!