# Gravitational waves and LIGO: a new probe into the universe

Laura Cadonati
UMass, Amherst
LIGO Scientific Collaboration

Colloquium, UMass, May 7, 2008

LIGO-G080286-00

Image credit:NASA

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

# Newton (1686)

Universal law of gravitation: $F = G\frac{m_1 \times m_2}{d^2}$

A simple formula that explains a lot:

Why things fall

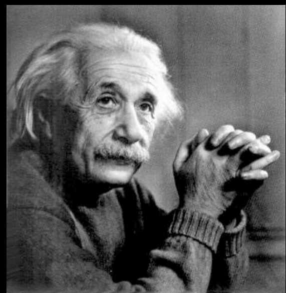
Orbits of planets and comets

Tides

BUT

1) What mechanism produces the force of attraction between masses?

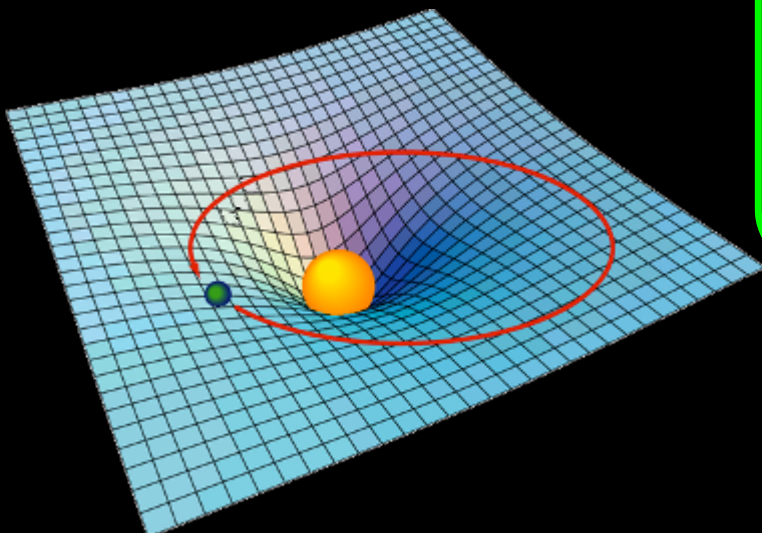
2) The attraction between two masses is instantaneous action at a distance.



# Einstein's Vision: General Relativity (1916)

Gravity is not a force, but a geometrical property of space-time

$$\mathbf{G}_{\mu\nu} = 8\pi\mathbf{T}_{\mu\nu}$$



Smaller masses travel toward larger masses, not because "attracted" by a mysterious force, but because they travel through space that is warped by the larger object.

*"Mass tells space-time how to curve, and space-time tells mass how to move."*
*John Archibald Wheeler*

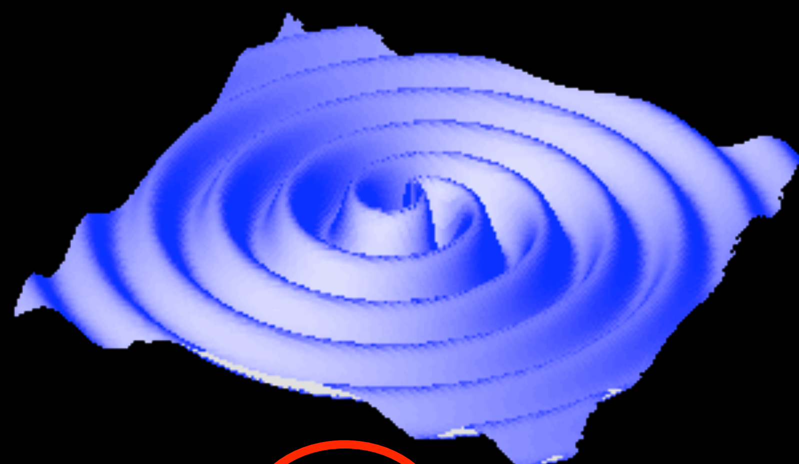
*American Museum of Natural History GW project*

# Einstein's Messengers

When massive objects rapidly change shape or orientation, the curvature of space-time also changes.
This change propagates as a wave, with the speed of light.

These ripples in the fabric of space-time are called

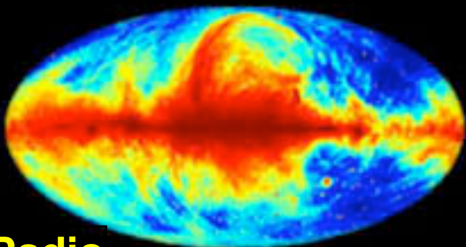
## Gravitational Waves



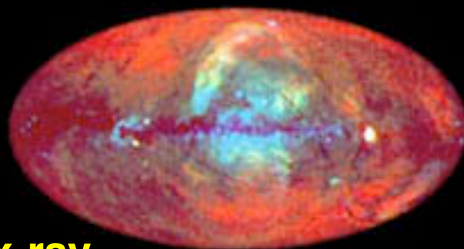
$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

- Dimensionless strain with amplitude inversely proportional to distance
- Strength and polarization depend on direction relative to source

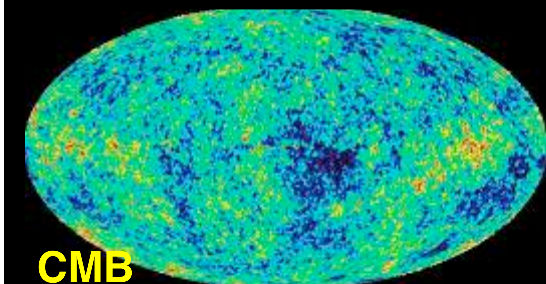
# A New Probe into the Universe



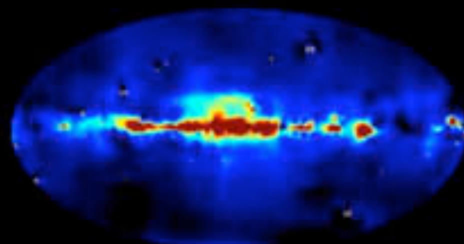
**Radio**



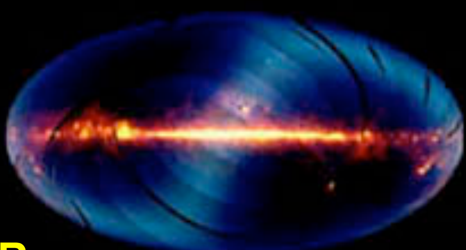
**x-ray**



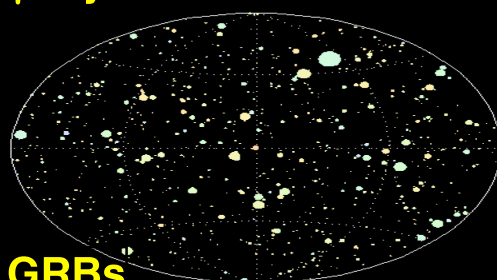
**CMB**



**-$\gamma$-ray**



**IR**



**GRBs**



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

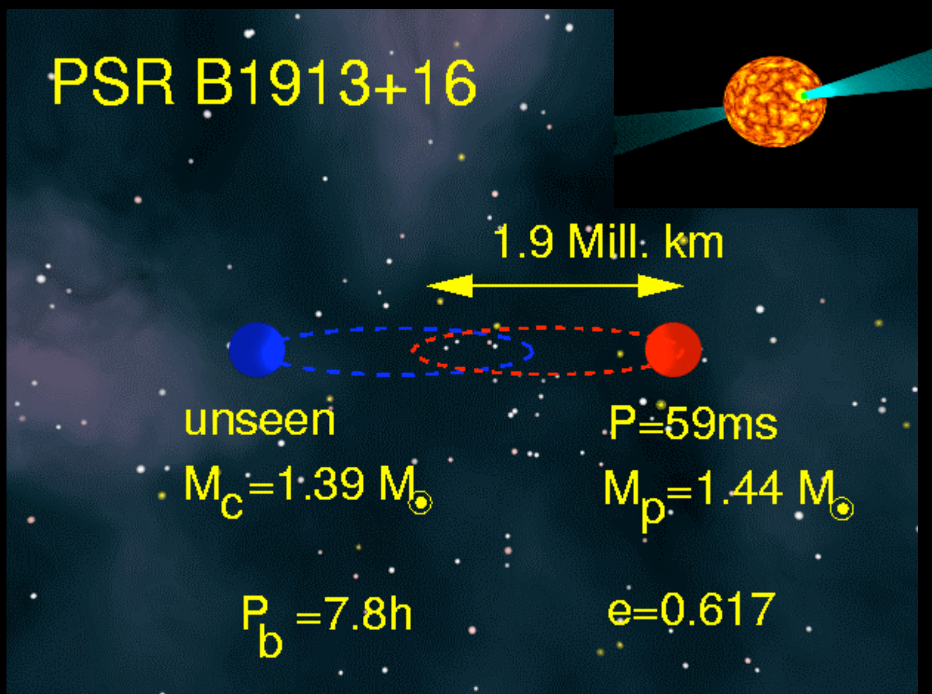
This will be complementary information, as different from what we know as *hearing* is from *seeing*.

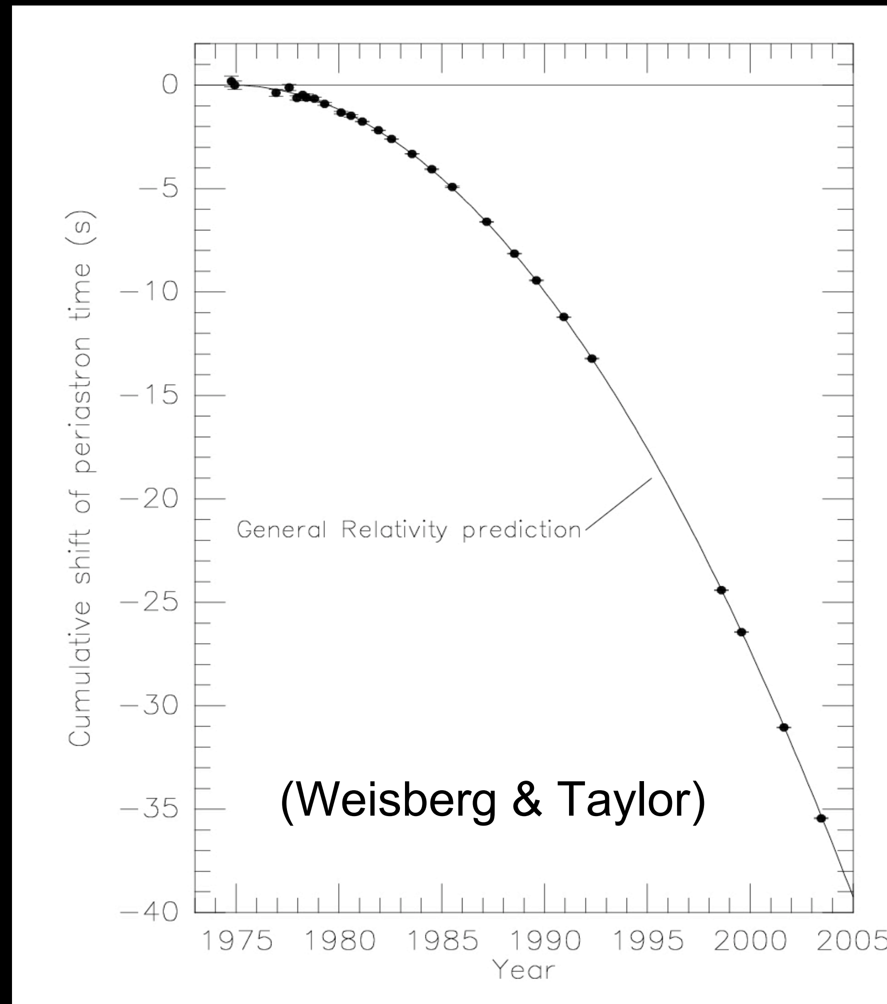
***EXPECT THE UNEXPECTED!***

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)

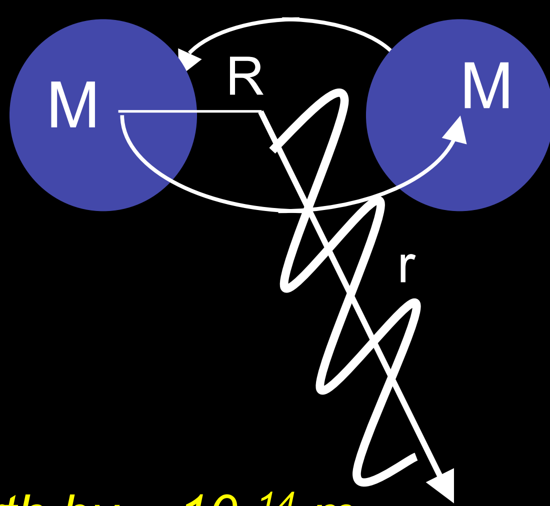
The wave can carry huge energy with miniscule amplitude: $h \sim (G/c^4)\,(E/r)$

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:

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

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)*

- Gravitational Waves
- **LIGO and its performance**
- Science with LIGO
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# Detecting Gravitational Waves

Let's assume two free masses are placed at positions $x1$ and $x2$ ($y = 0$) and a gravitational wave with + polarization is propagating along the $z$-axis.

The free masses will stay fixed at their coordinate positions, but the space in between (and therefore the distance between $x1$ and $x2$) will expand and shrink at the frequency of the gravitational wave. Similarly, along the $y$-axis the separation of two points will decrease and increase with opposite sign.

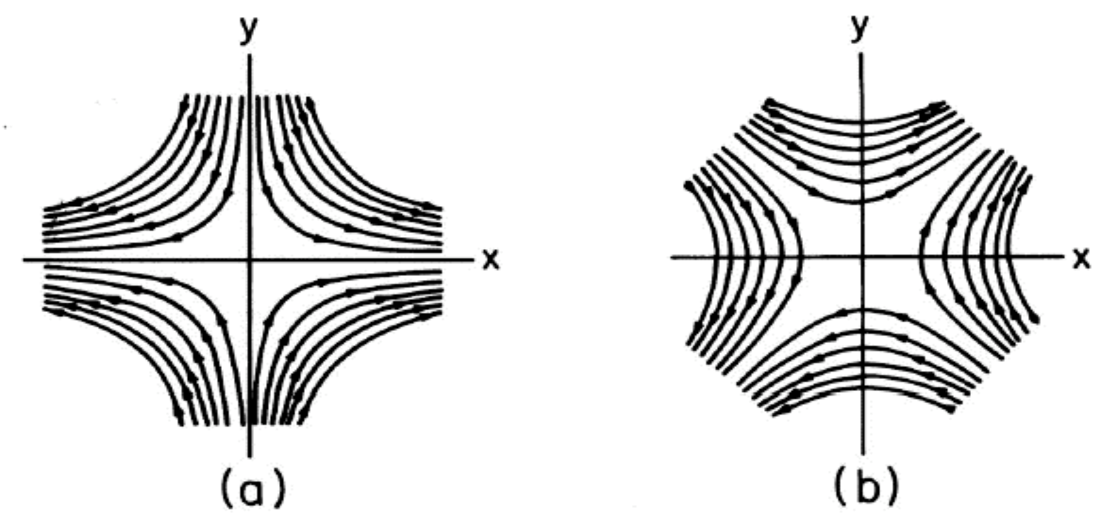



Figure 1. Direction of space deformation for a gravitational wave propagating along the $z$-axis, + polarization (a) and $\times$ polarization (b).

The strength of a gravitational wave is then best expressed as a dimension-less quantity, the strain $h$ which measures the relative length change $\Delta L/L$.

# Detecting Gravitational Waves

LIGO graduate student responding to wave propagating along z (perpendicular to this plane)

The effect is greatly exaggerated!!

If Marcelo were 4.5 light years tall with feet on Earth and head touching Proxima Centauri, the nearest star, he would grow by only a ‘hairs width’

# Detecting Gravitational Waves

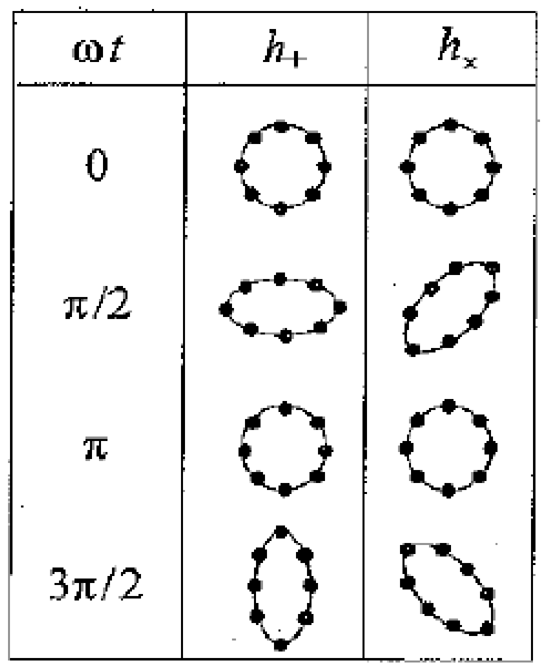
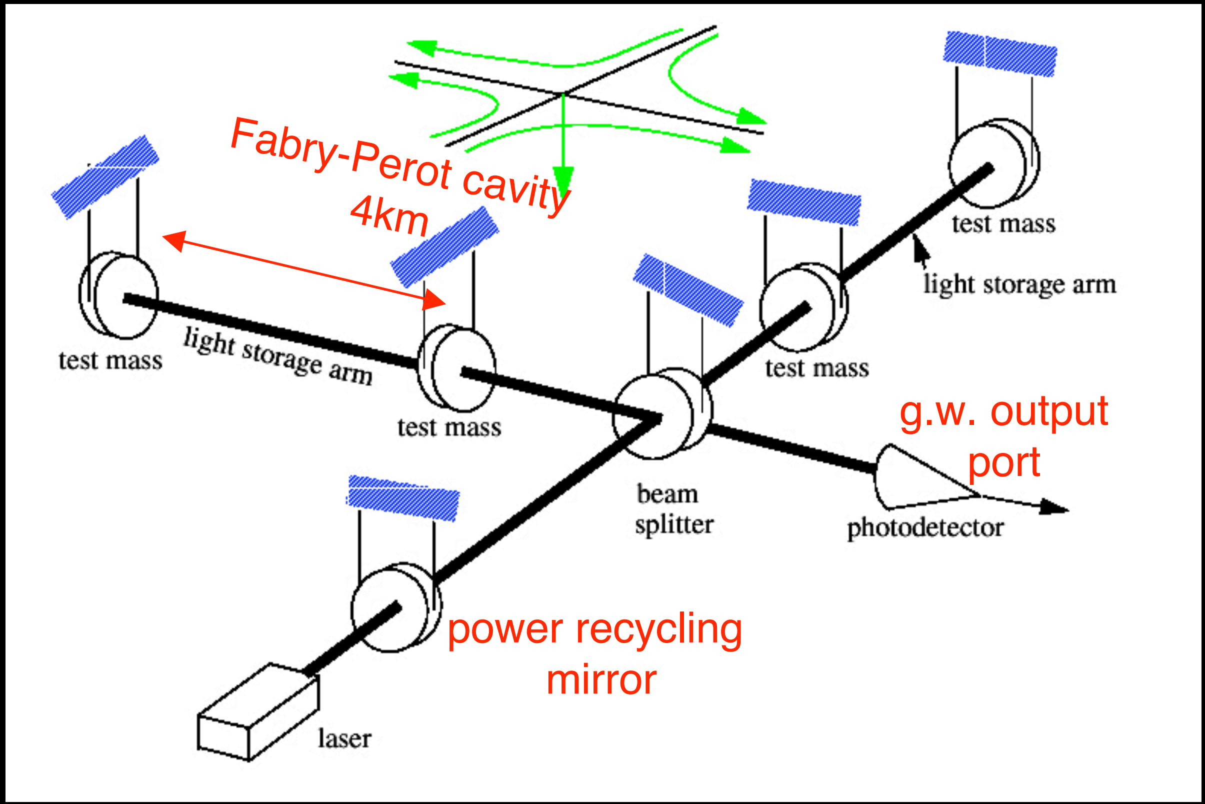



Fig. 1.1 The deformation of a ring of test masses due to the + and × polarization.

Ring of (free) test masses responding to wave propagating along z

# Interferometer

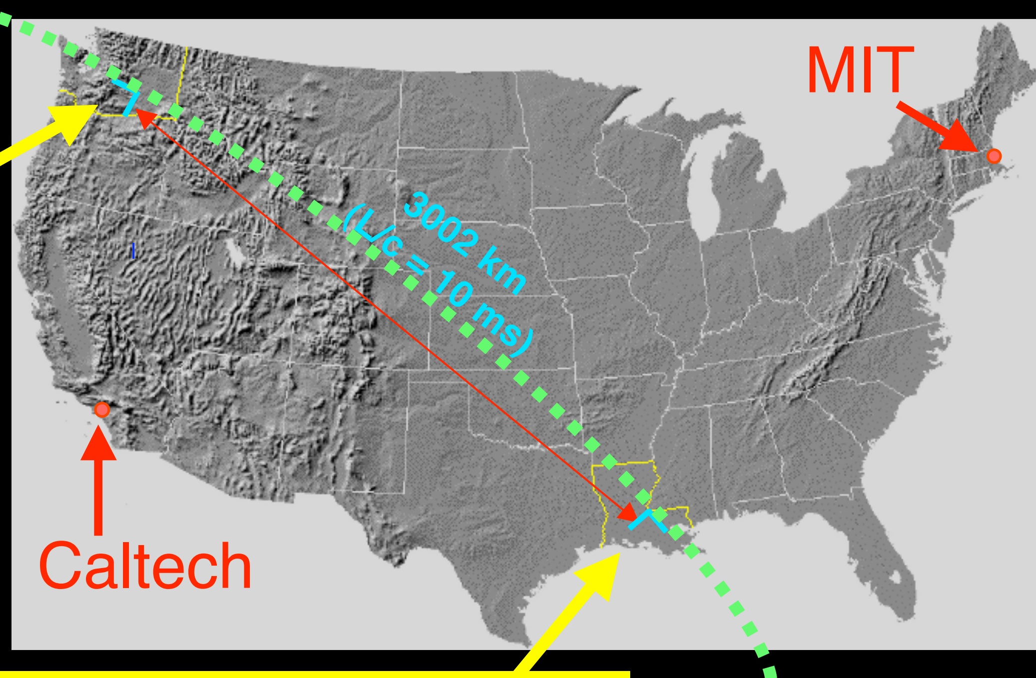
- Suspended mirrors in "free-fall"
- Michelson interferometer "natural" GW detector
- Broad-band response ~50 Hz to few kHz
- Waveform information e.g., chirp reconstruction




Arms in LIGO are 4km long

Goal: measure difference in length to one part in $10^{21}$, or $10^{-18}$ meters

# Laser Interferometer Gravitational-wave Observatory

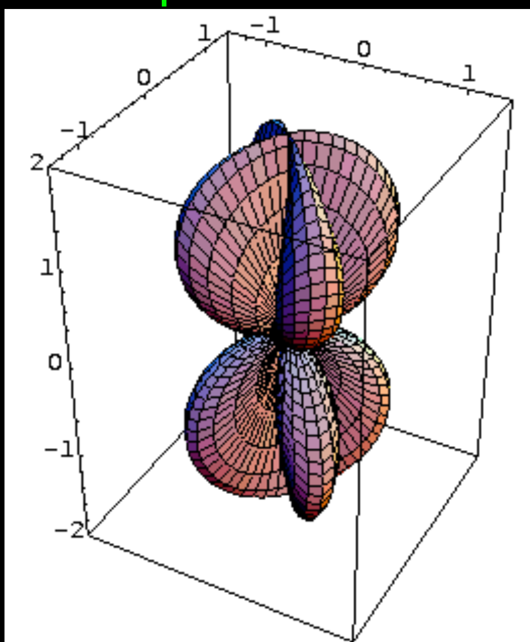


- Managed and operated by Caltech & MIT with funding from NSF
- Ground breaking 1995
- 1st interferometer lock 2000
- LIGO Scientific collaboration: 45 institutions, world-wide

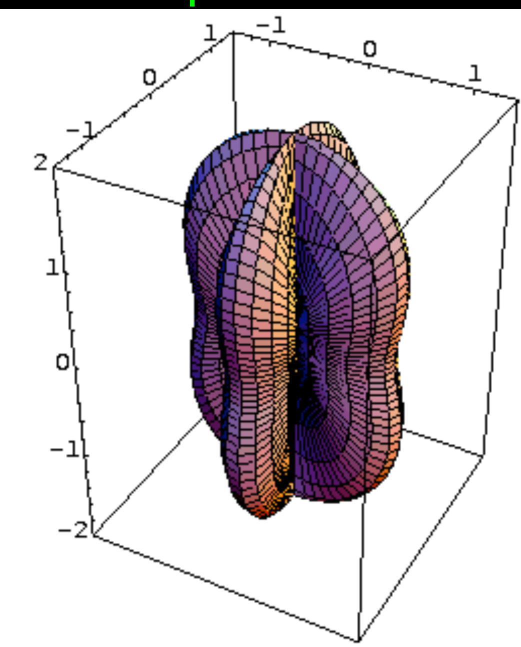
# Giant "Ears"
# Listen to the Vibrations of the Universe

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

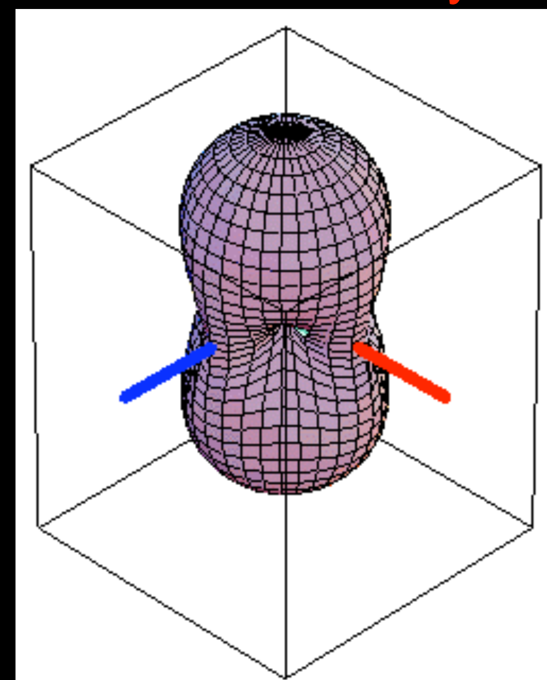
"×" polarization



"+" polarization

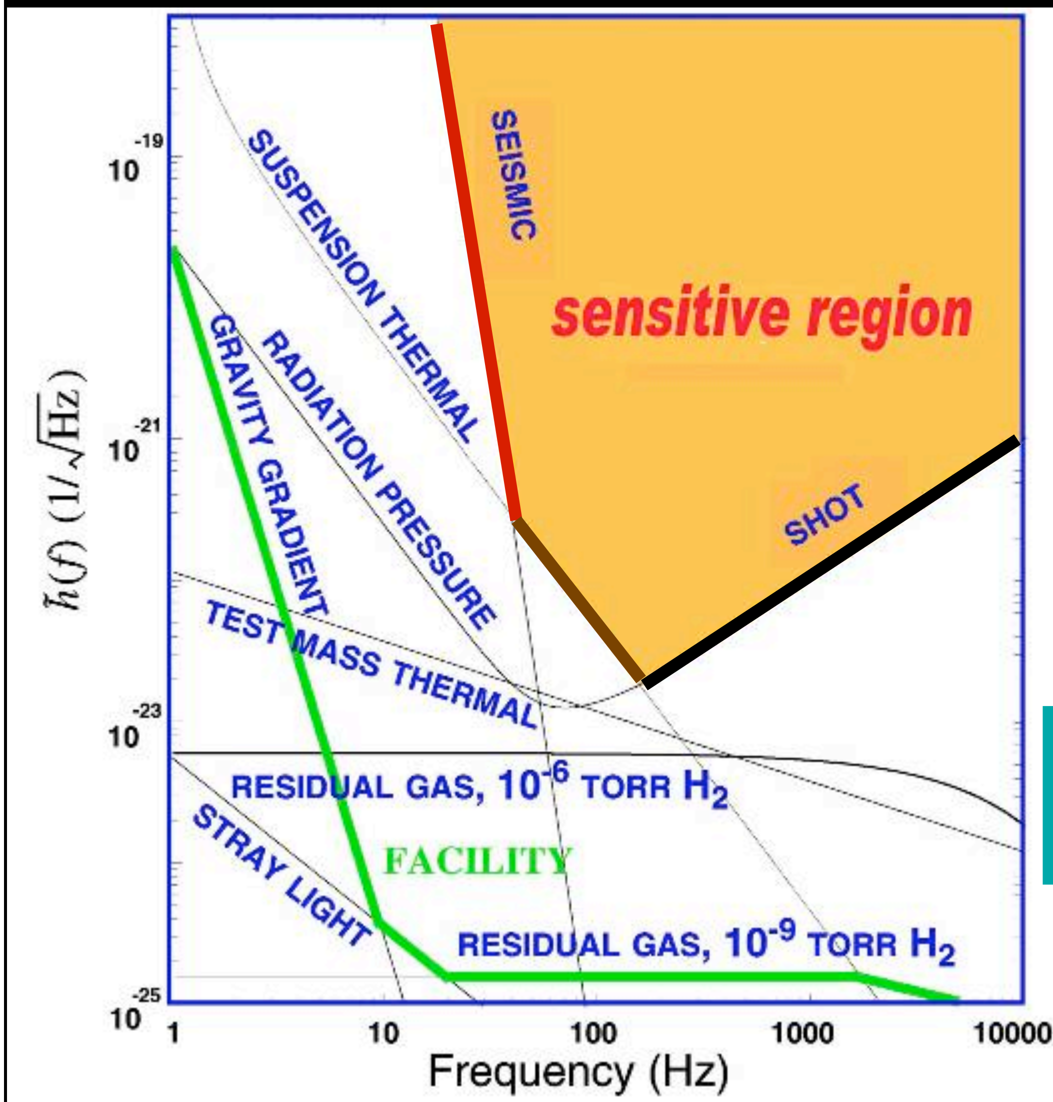


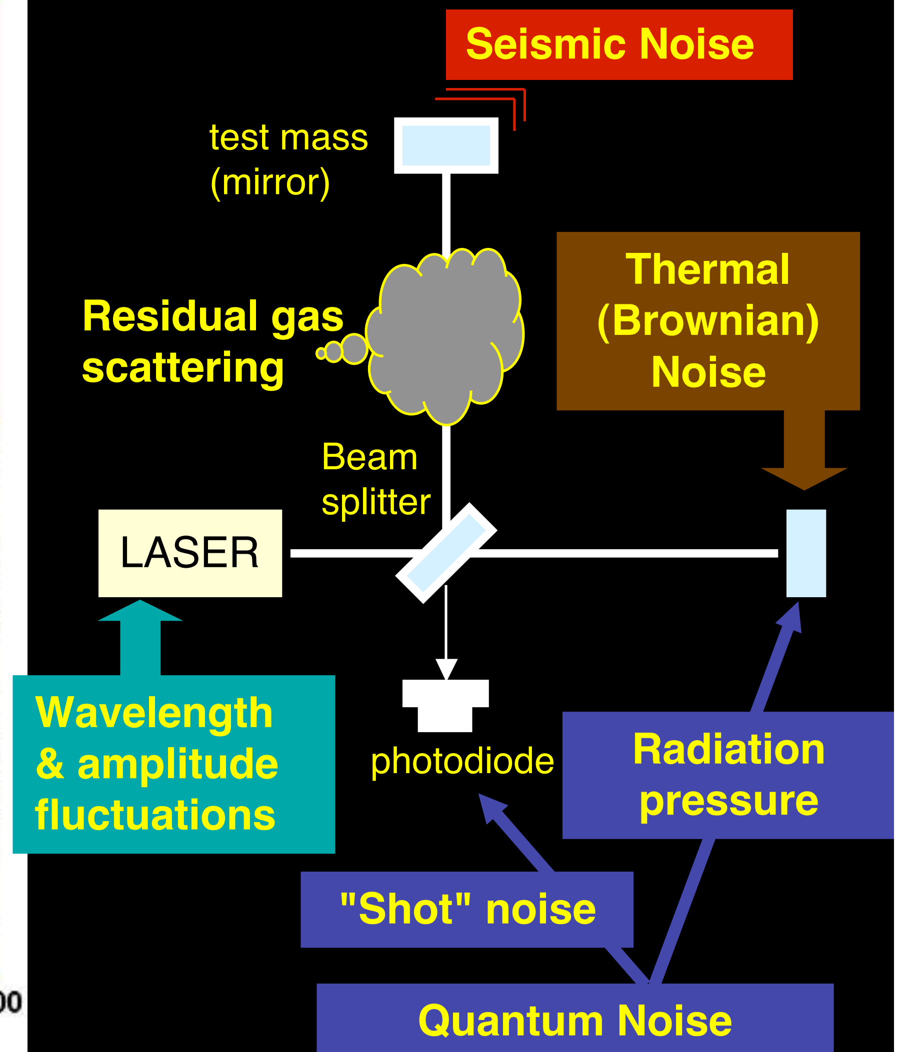
RMS sensitivity



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

# Initial LIGO Sensitivity Limits



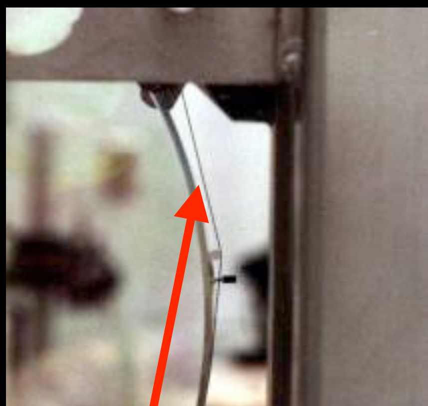
- LIGO beam tube (1998)
- 1.2 m diameter - 3mm stainless steel
- 50 km of weld

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

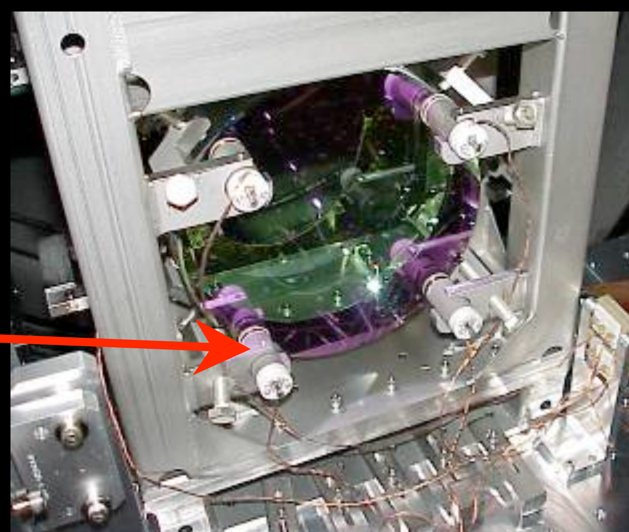
Corner Station

# Suspended Mirrors

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

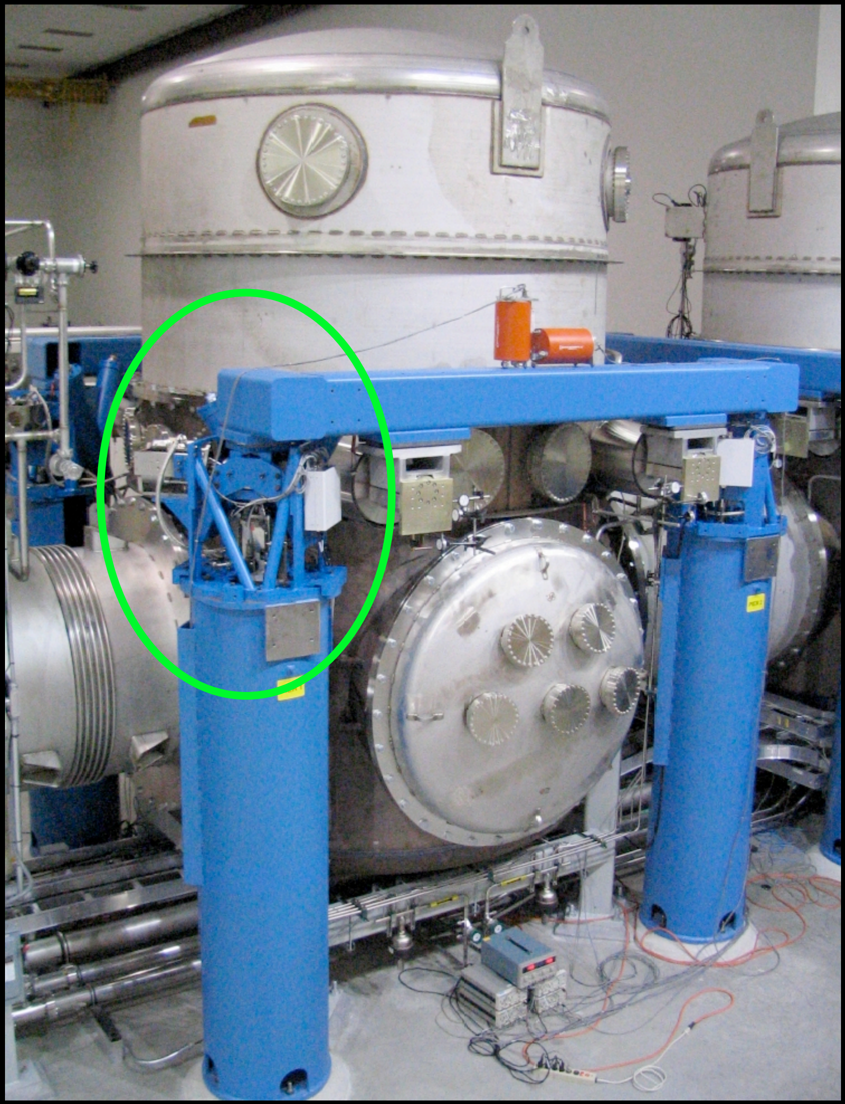


0.3mm steel wire



*Local sensors/actuators for damping and control forces*

# Active Seismic Isolation in Louisiana

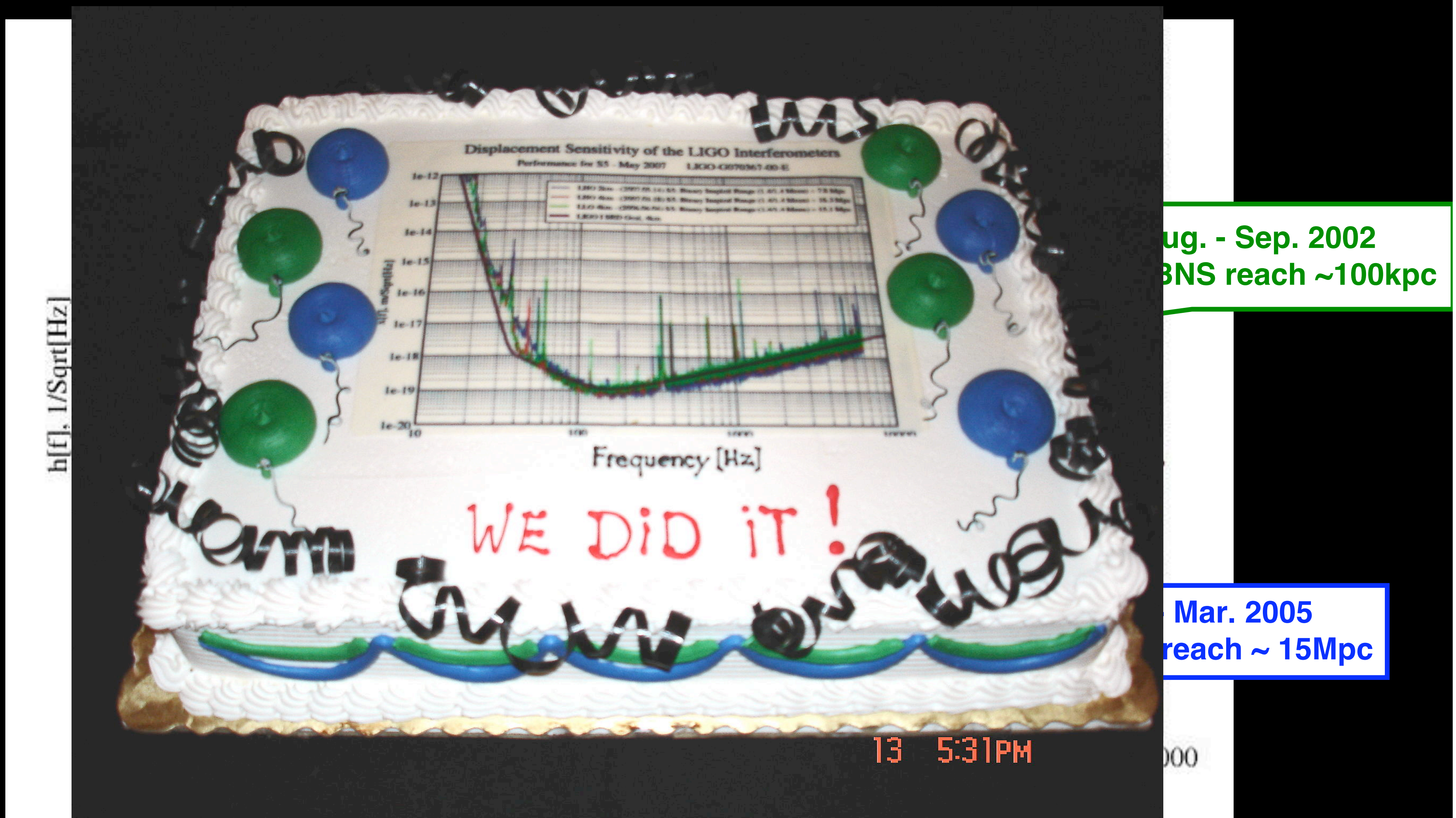


- Hydraulic external pre-isolator (HEPI)
- Signals from sensors on ground and cross-beam are blended and fed into hydraulic actuators
- Provides much-needed immunity against normal daytime ground motion at LLO

# Despite some obstacles along the way…

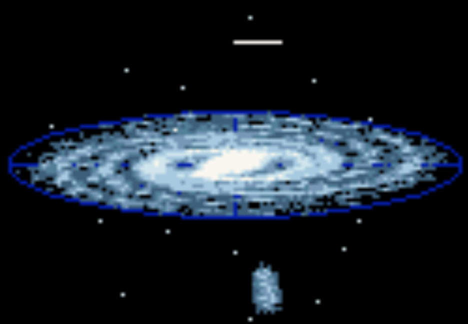
# …LIGO has met its experimental challenges

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



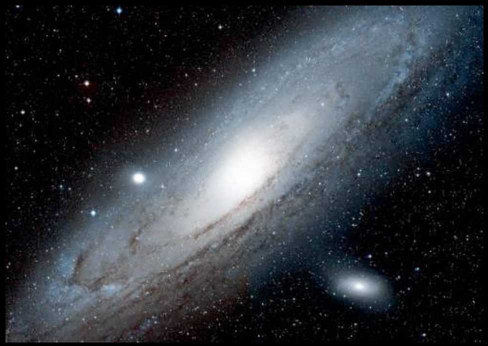
# Progress in Sensitivity

Average distance for detecting a coalescing neutron-star binary:



Milky Way
(8.5 kpc)

Sept 2002
[ ~1 galaxy ]



Andromeda
(700 kpc)

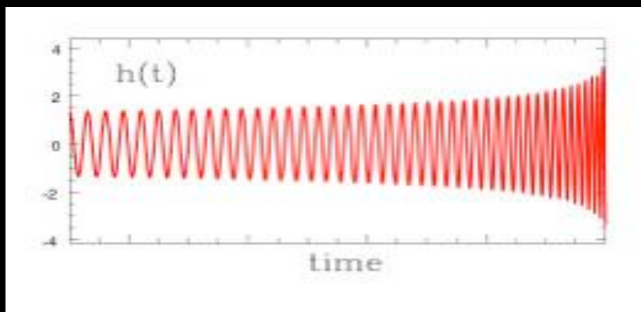
March 2003
[ ~2 galaxies ]

Virgo Cluster
(15 Mpc)

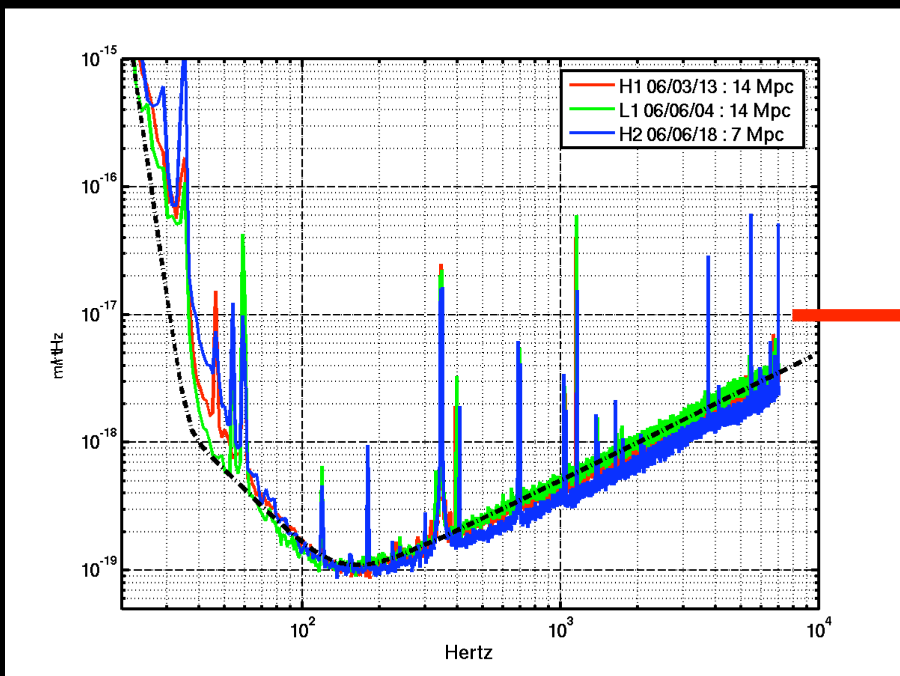
now
[ $\sim 10^3$ galaxies ]

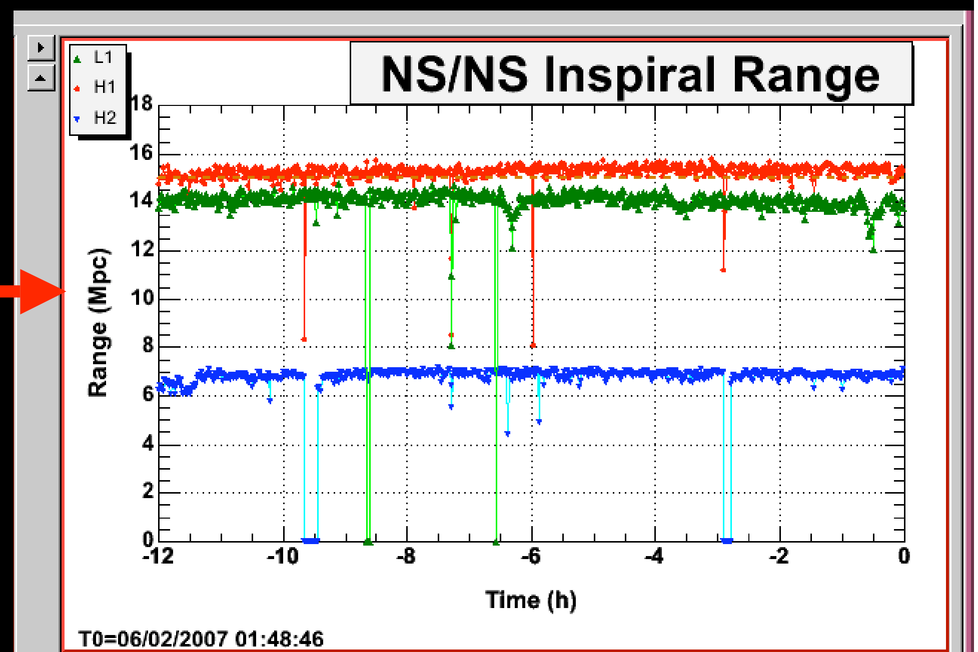
*1 light year = $9.5 \times 10^{12}$ km*
*1 pc = $30.8 \times 10^{12}$ km = 3.26 light years*

# LIGO Binary Neutron Stars (BNS): a Measure of Performance



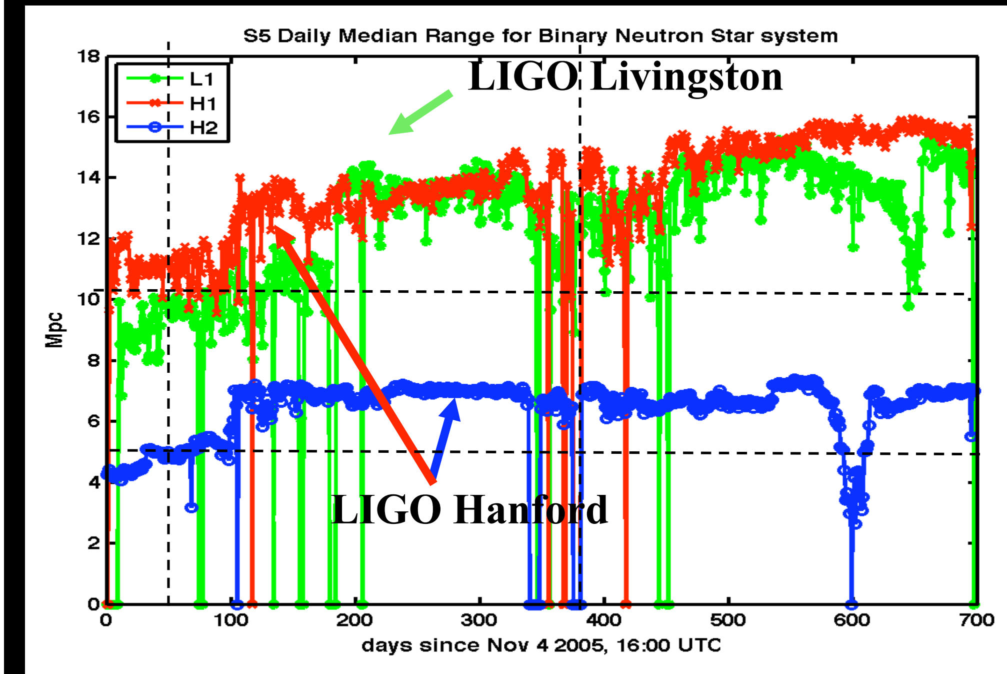

The inspiral waveform for BNS is known analytically from post-Newtonian approximations. We can translate strain amplitude into (effective) distance.

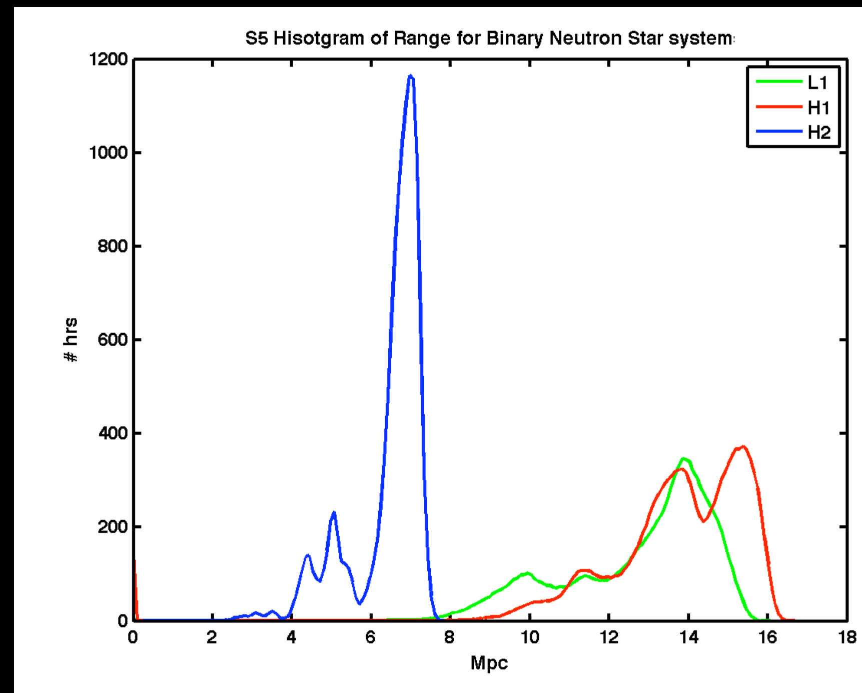


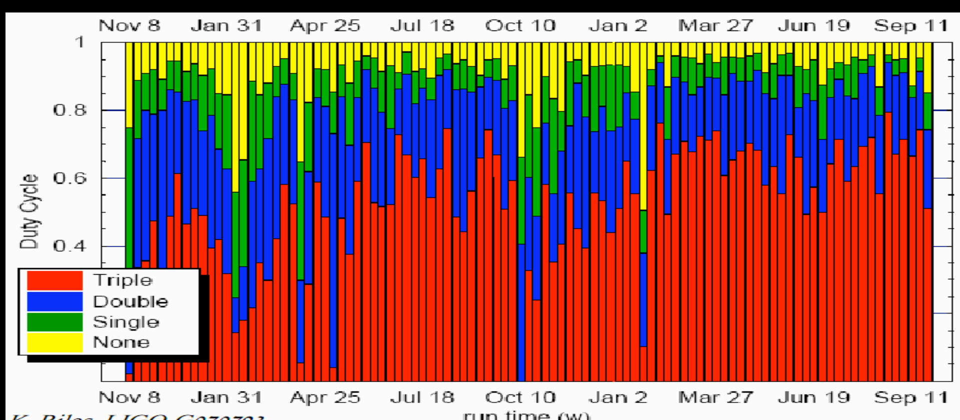




Range: distance of a 1.4-1.4 M binary, averaged over orientation/polarization
Predicted rate for S5: 1/3 years (most optimistic), 1/100 years (most likely)

# The S5 run



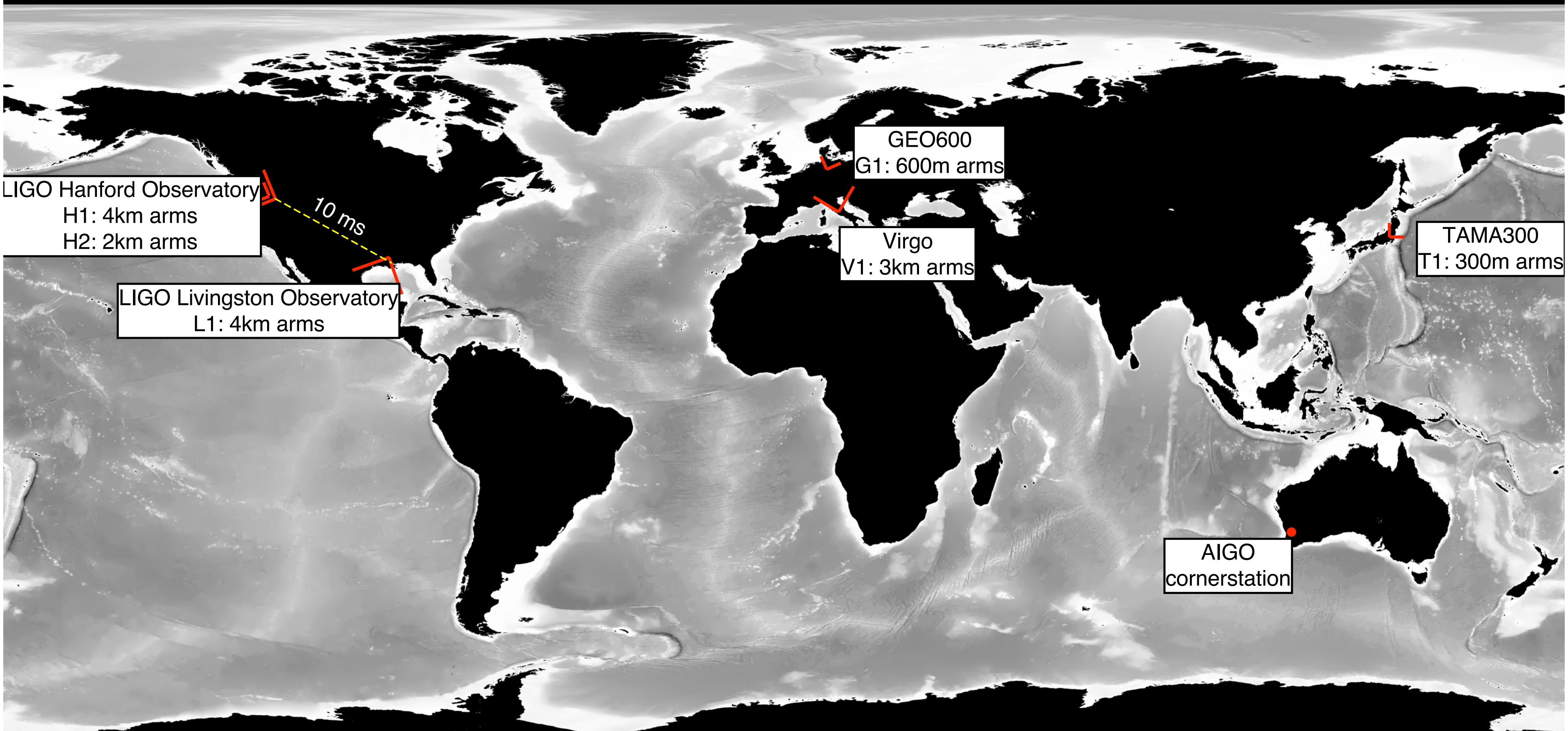




S5 started in Nov 2005 and ended Oct 2007

LIGO collected 1 year of triple coincidence data

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

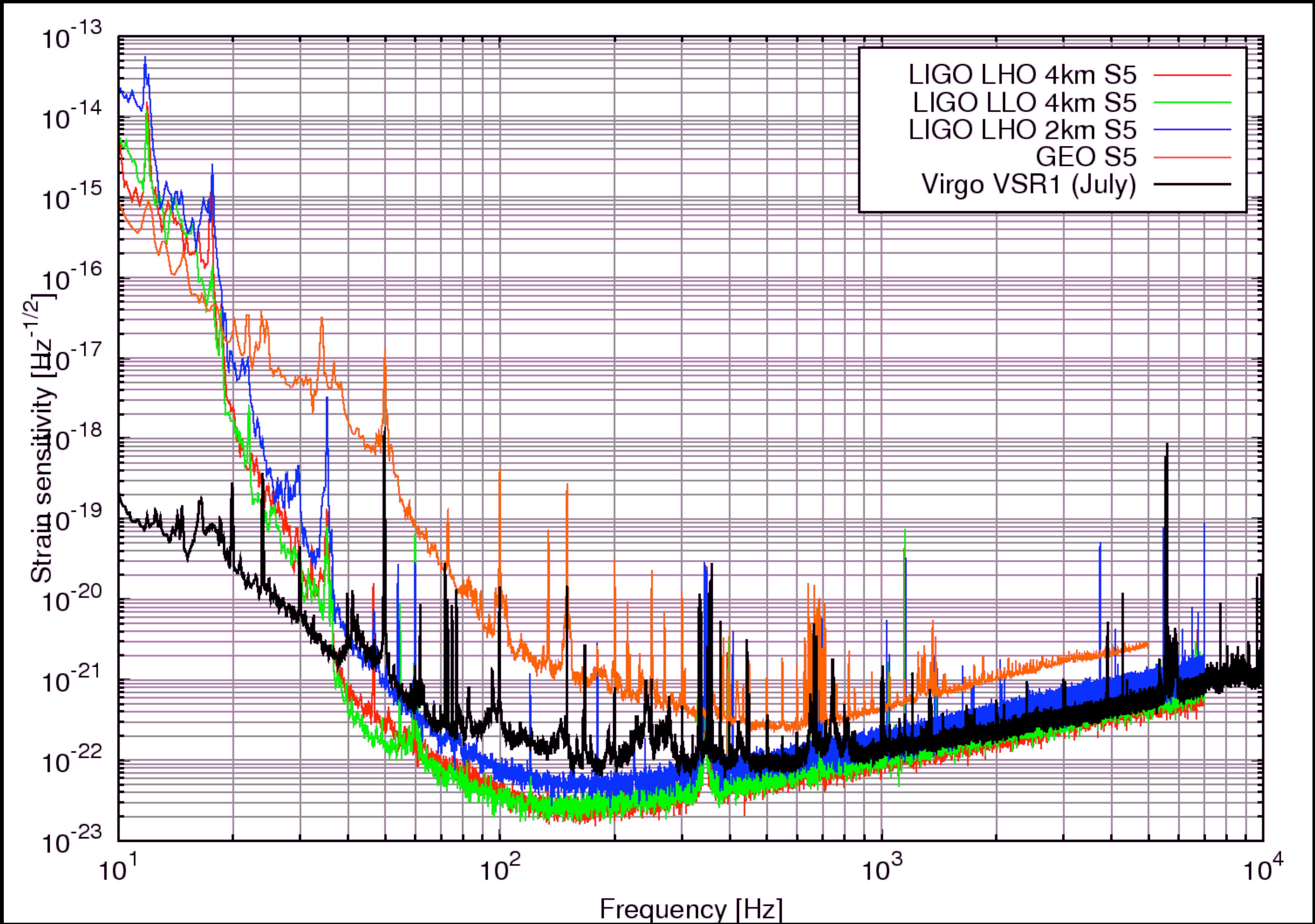
# An International Quest: Ground-Based Interferometers




Credit: NASA's Earth Observatory

Also: Resonant Bars, LISA

# Summer 2007 Performance of the Large Interferometers



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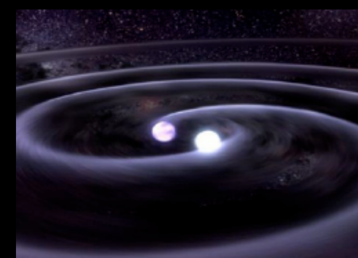
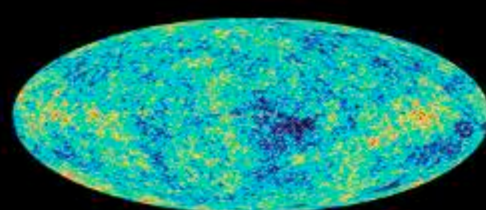
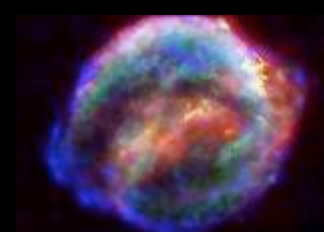
# Sources And Methods

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

# UMass in the LIGO Scientific Collaboration

Laura Cadonati, Satya Mohapatra, Marcelo Dias

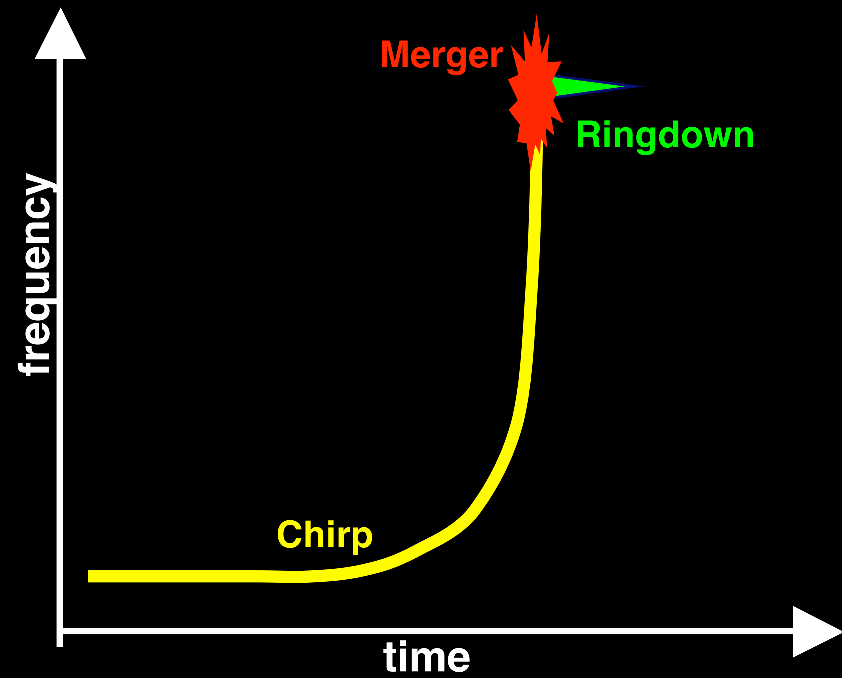
- Bridge Burst and Compact Binary Coalescence analyses with focus on Binary Black Hole Coalescences over a wide parameter space (mass, spin)

- Supernovae / unmodeled bursts, triggered and all-sky


- Event validation / veto

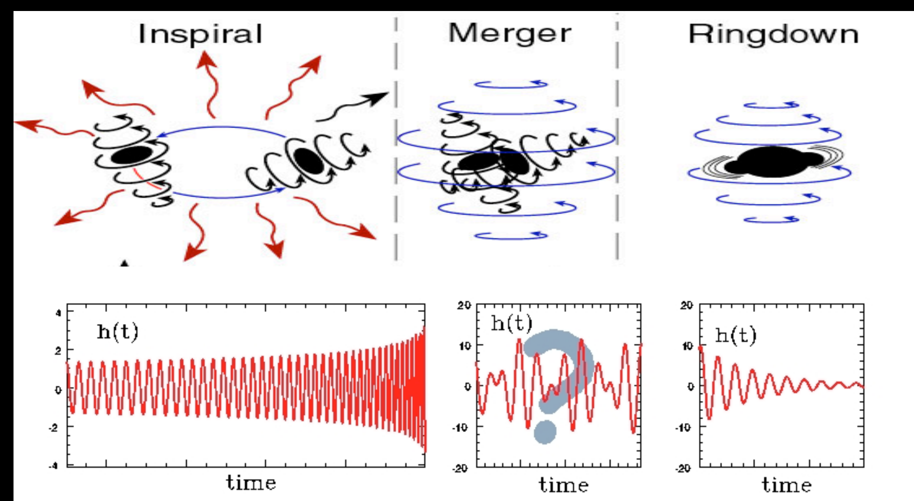
- Detector Characterization

# Compact Binary Coalescences




LIGO is sensitive to gravitational waves from neutron star (BNS) and black hole (BBH) binaries.
Waveforms depend on masses and spins.
Detection would probe internal structure and populations

Credit: NASA




**Matched filter** | **Template-less** | **Matched filter**

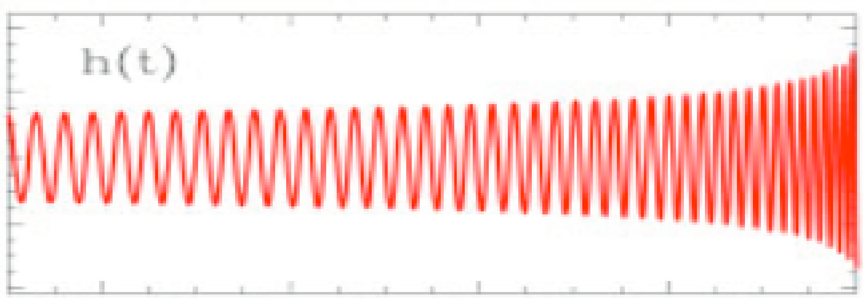
# Binary Systems

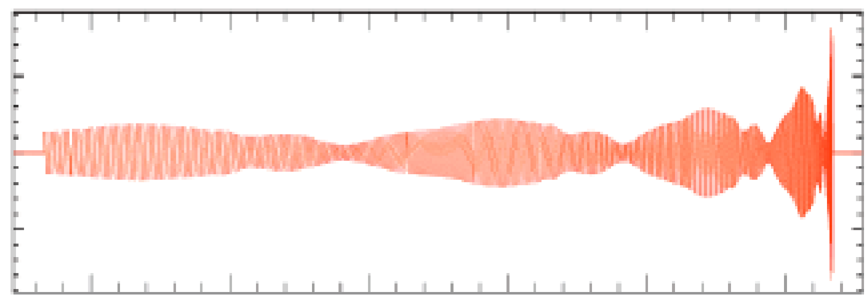
We know gravitational waves emitted from *compact binary systems* exist:

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; $D_{eff}>r$



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

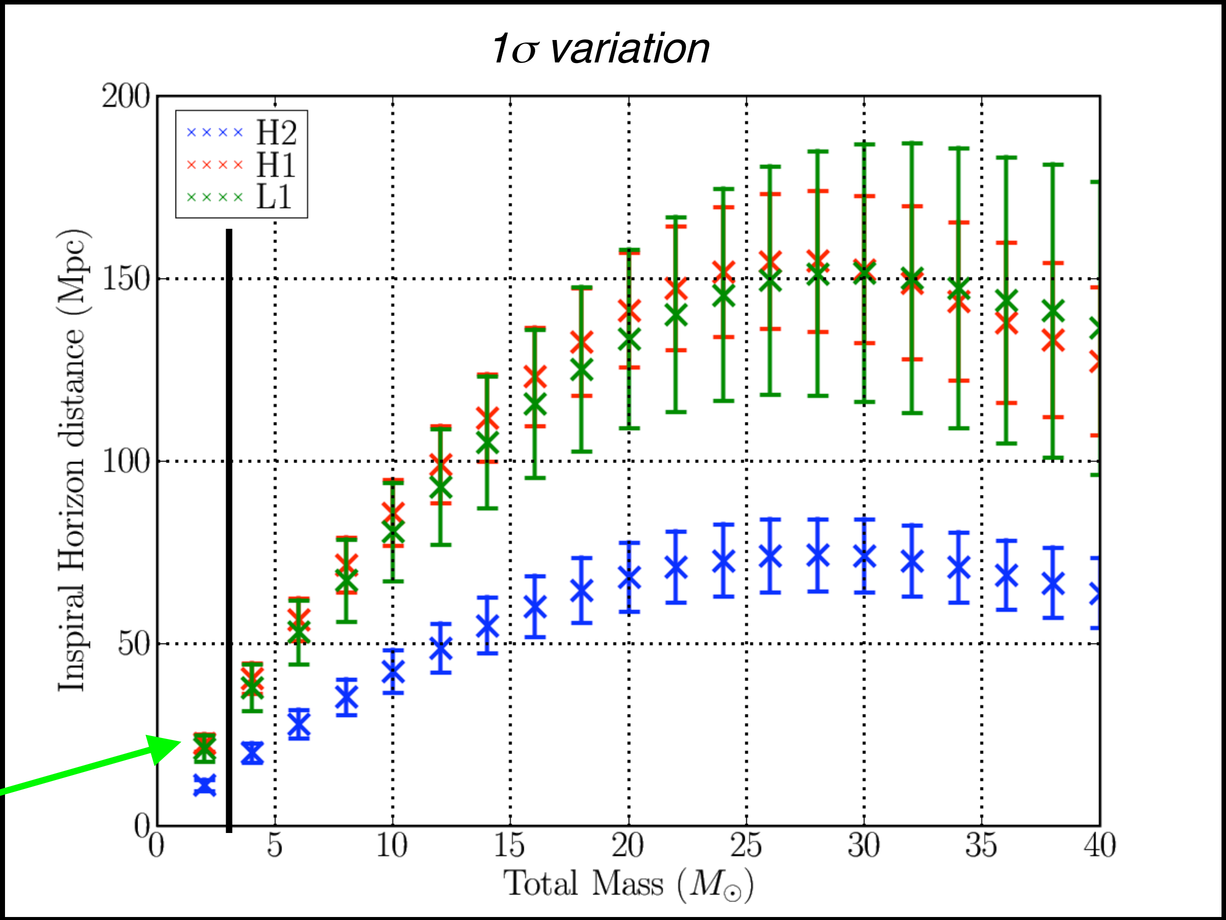
# Horizon in S5

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

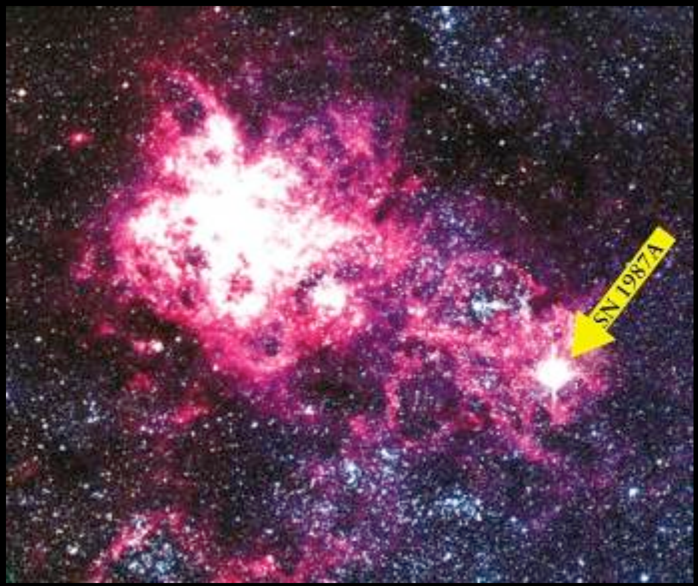
For 1.4-1.4 $M_o$ binaries:
~ 200 MWEGs
in range

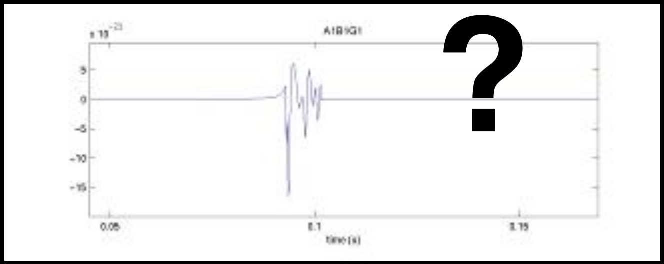
For 5-5 $M_o$ binaries:
~ 1000 MWEGs
in range

Binary Neutron Stars



# Bursts



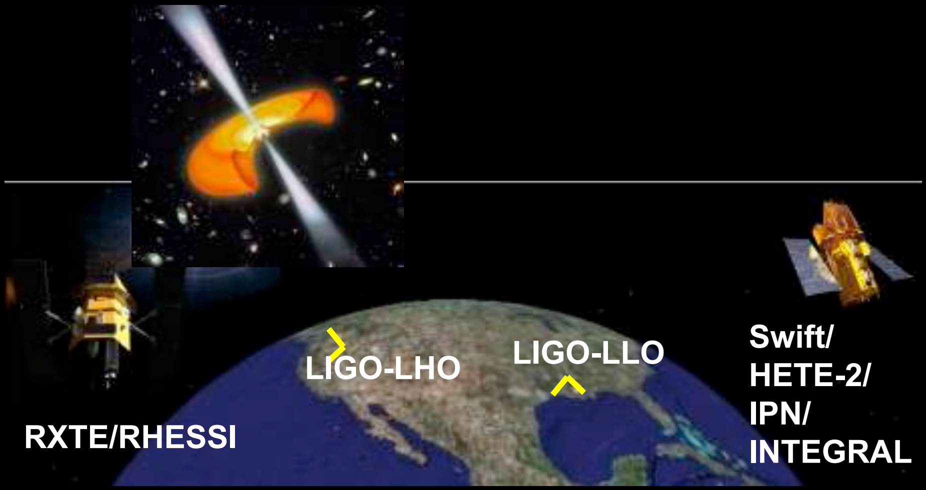




Uncertainty of waveforms complicates the detection $\Rightarrow$ minimal assumptions, open to the unexpected

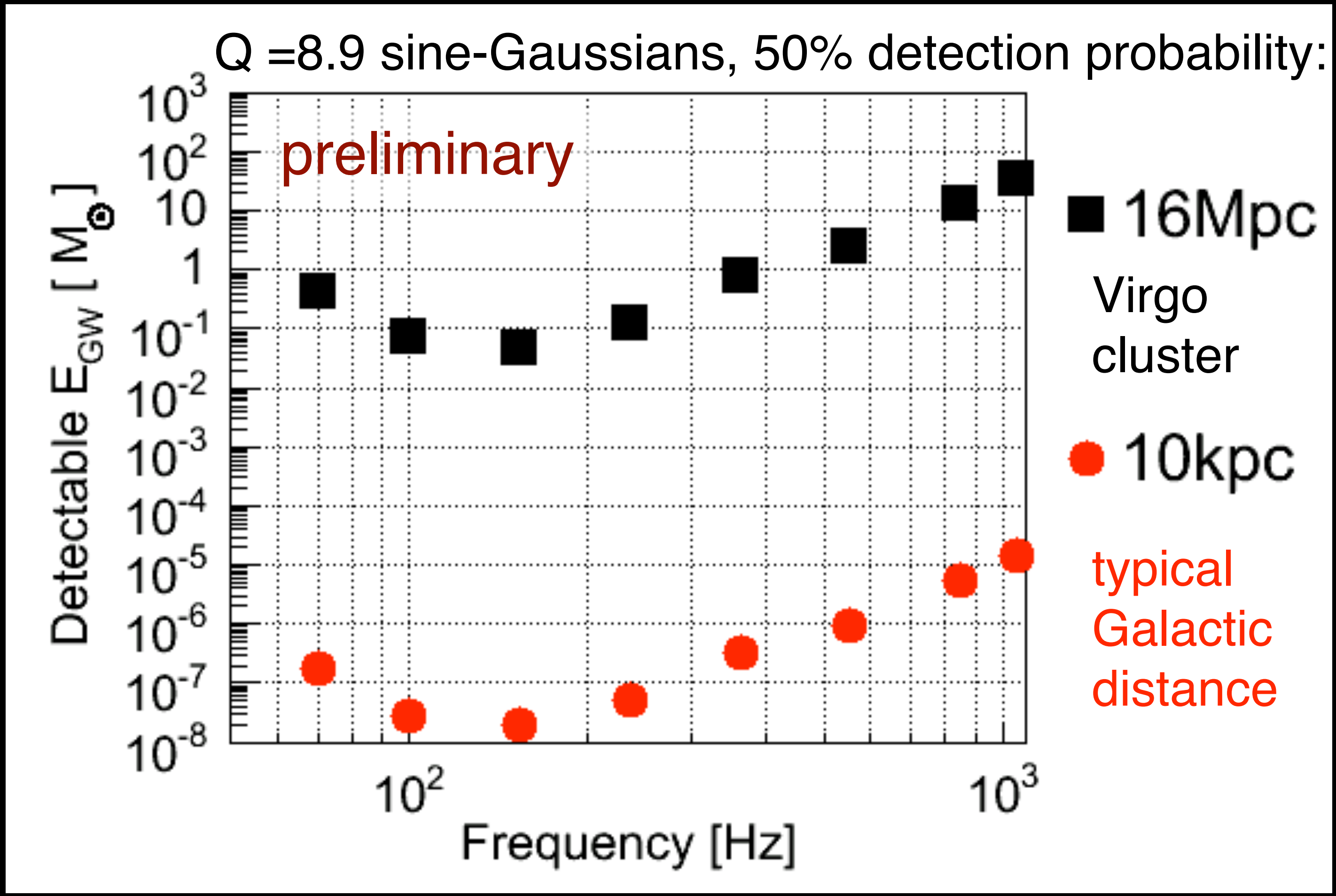
Method:
Coincident excess power in time-frequency plane or cross-correlation
Data quality/vetoes

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:

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

~ 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)

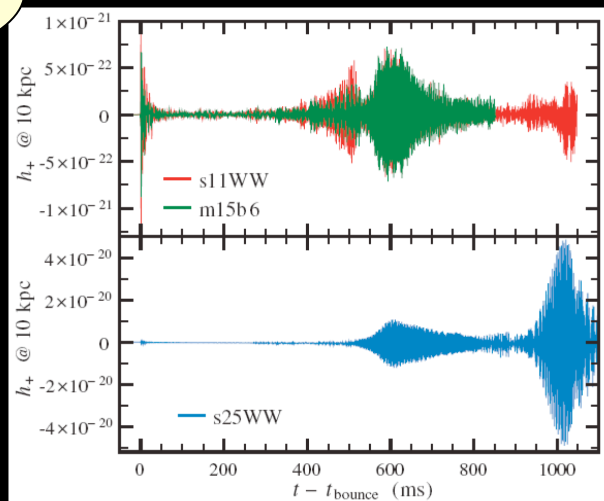
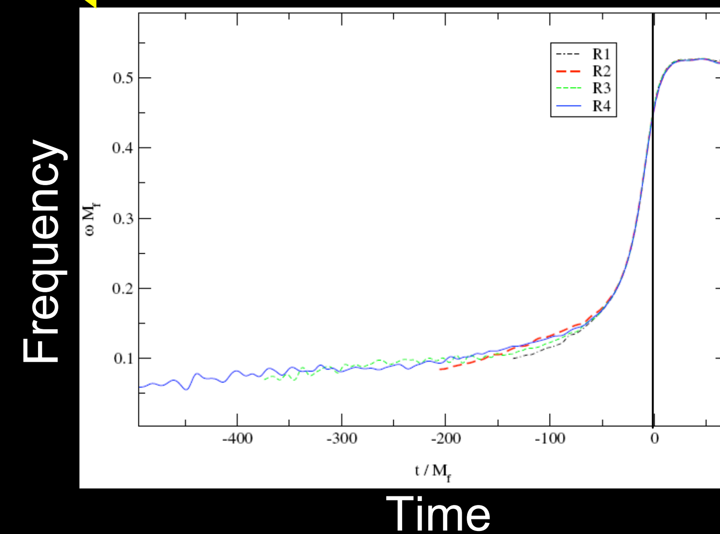



TABLE I. MODEL SUMMARY.

| Model | $\Delta t$[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 |

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




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

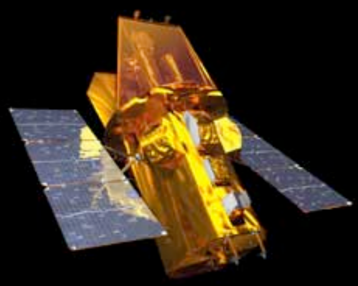
Baker et al, PRD 73, 104002 (2006)

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

# How do we avoid fooling ourselves?

## Seeing a false signal or missing a real one

### Require at least 2 independent signals:

- e.g. coincidence between interferometers at 2 sites for inspiral and burst searches, external trigger for GRB or nearby supernova.

### Apply known constraints:

- Pulsar ephemeris, inspiral waveform, time difference between sites.

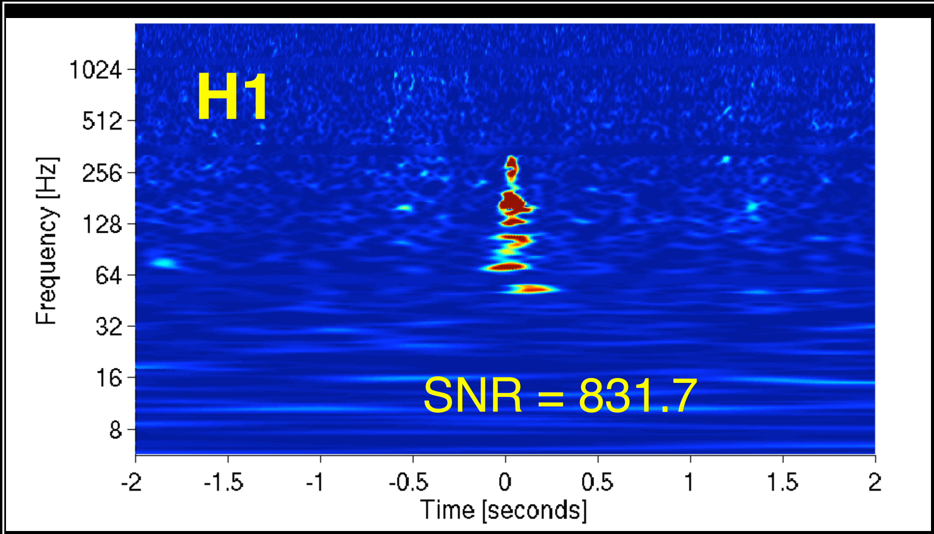
### Use environmental monitors as vetos

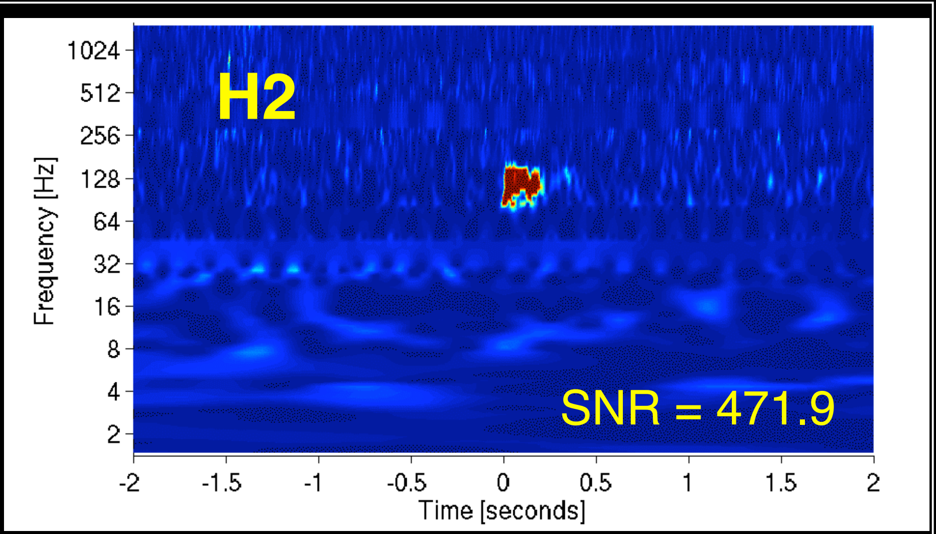
- Seismic/wind: seismometers, accelerometers, wind-monitors
- Sonic/acoustic: microphones
- Magnetic fields: magnetometers
- Line voltage fluctuations: volt meters

### Understand the detector response:

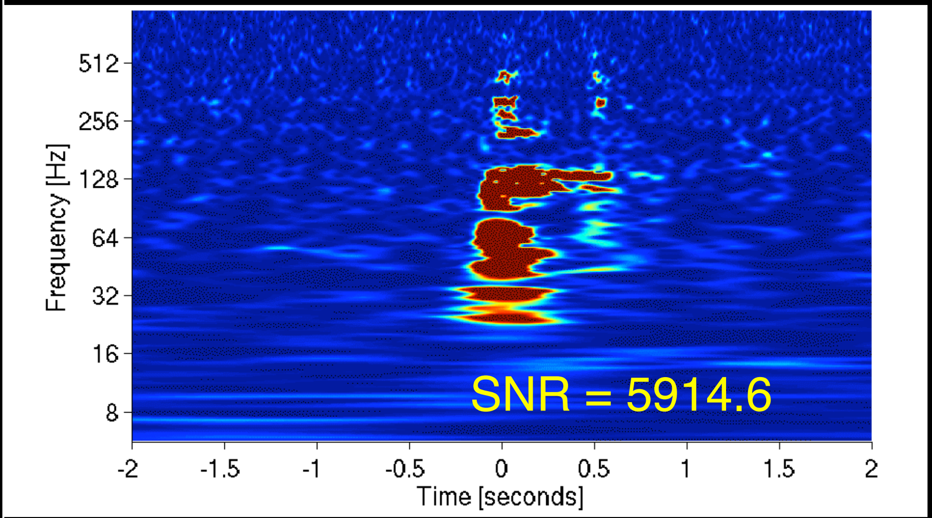
- Hardware injections of pseudo signals (actually move mirrors with actuators)
- Software signal injections

# An example of local seismic disturbances




H0:PEM-ISCT4_ACCZ




# 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

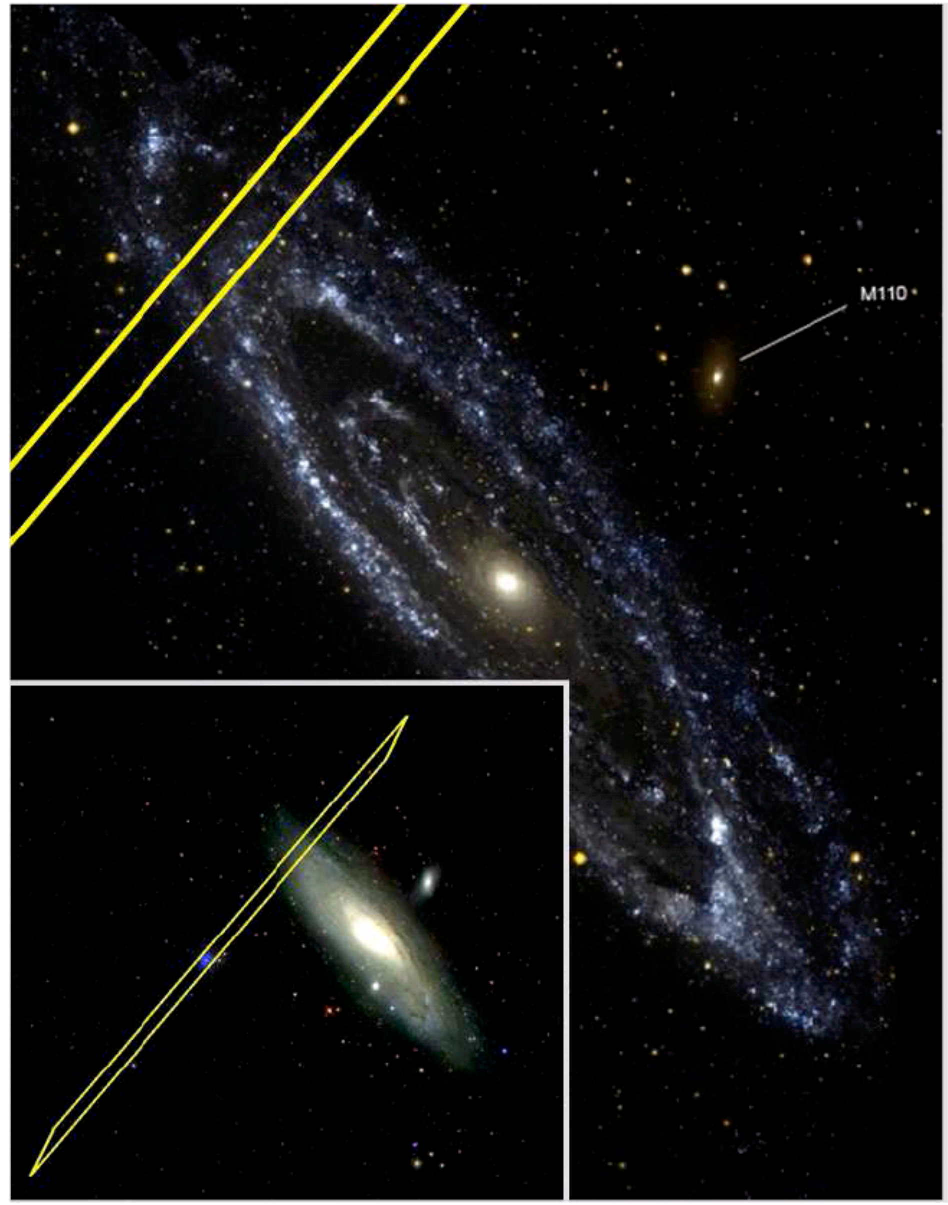



FIG. 1.— The IPN3 (IPN3 2007) (γ-ray) error box overlaps with the spiral arms of the Andromeda galaxy (M31). The inset image shows the full error box superimposed on an SDSS (SDSS 2007) image of M31. The main fi gure shows the overlap of the error box and the spiral arms of M31 in UV light (Thilker et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

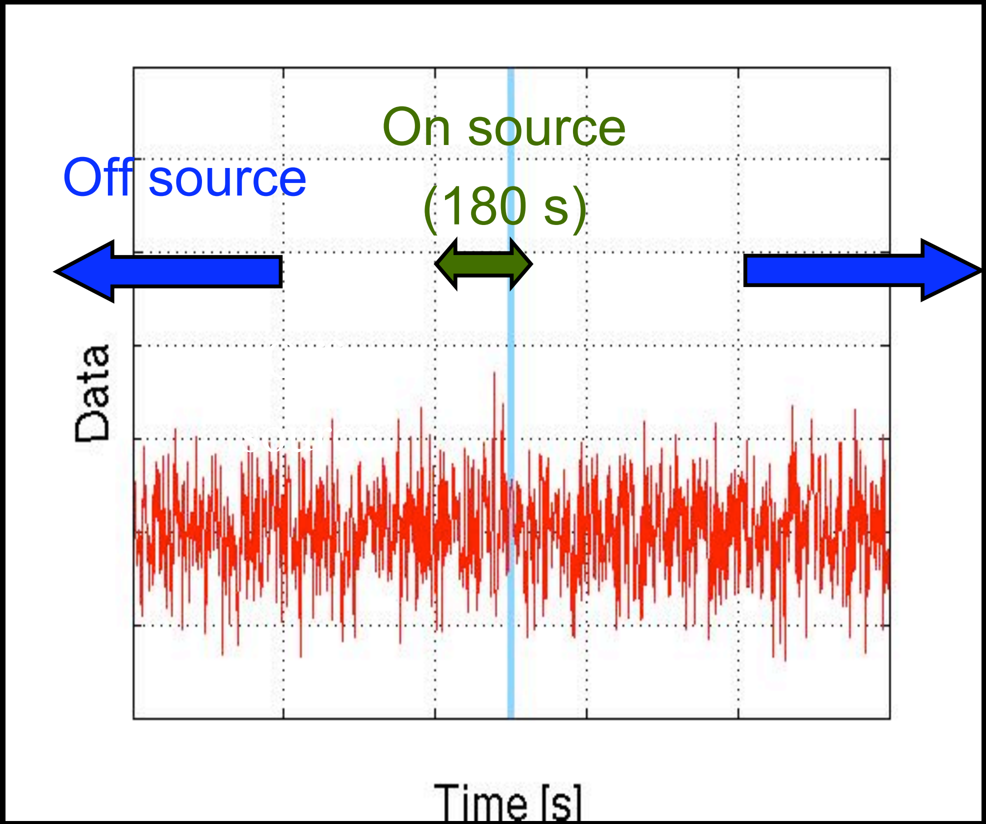
# Inspiral (model-dependent) and burst (model-independent) analyses

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



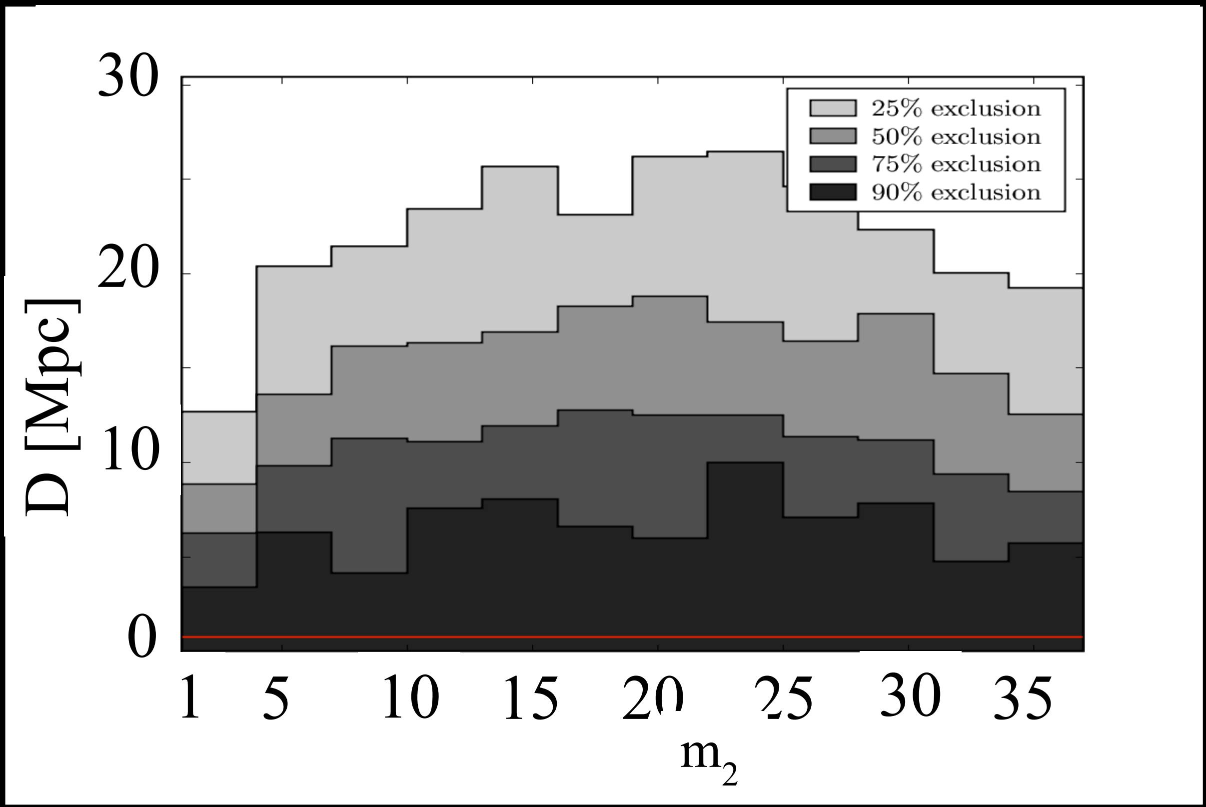
# Inspiral search - GRB 070201

- 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



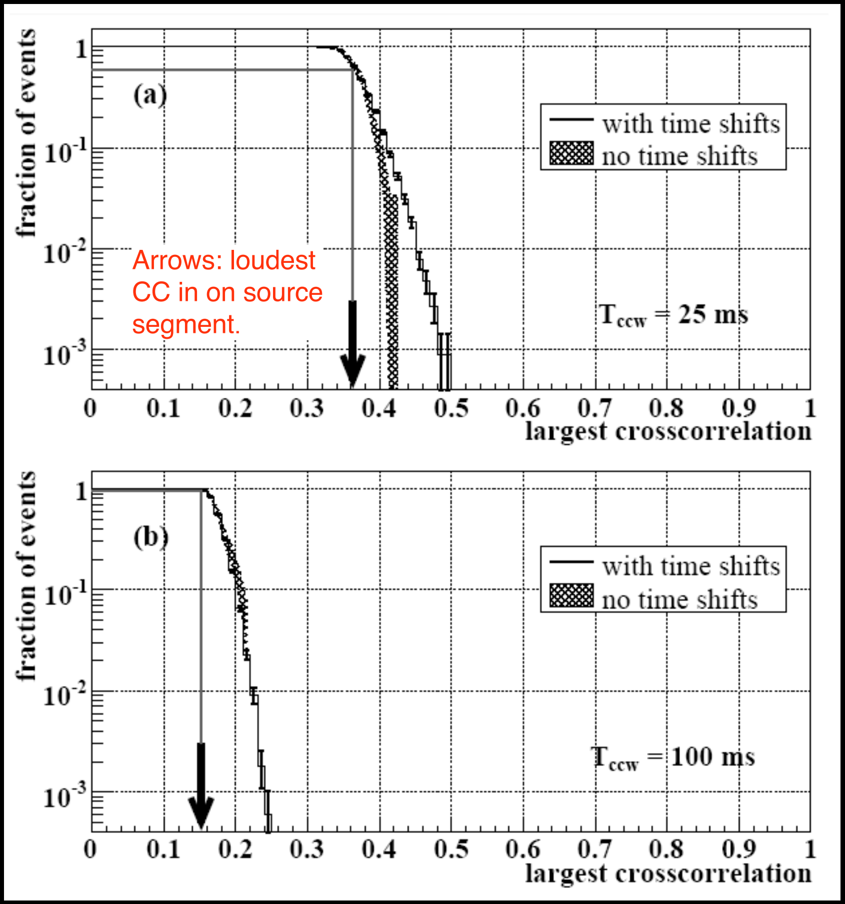
# Triggered burst search GRB 070201

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

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

p = 0.58 for 25-ms cc ; 0.96 for 100-ms cc
Consistent with null hypothesis

GRB emitted < $4.4 \times 10^{-4}\ M_{O}c^2$ in GW in <100ms, if source in M31, isotropic, and peaked at ~150Hz




arXiv:0711.1163

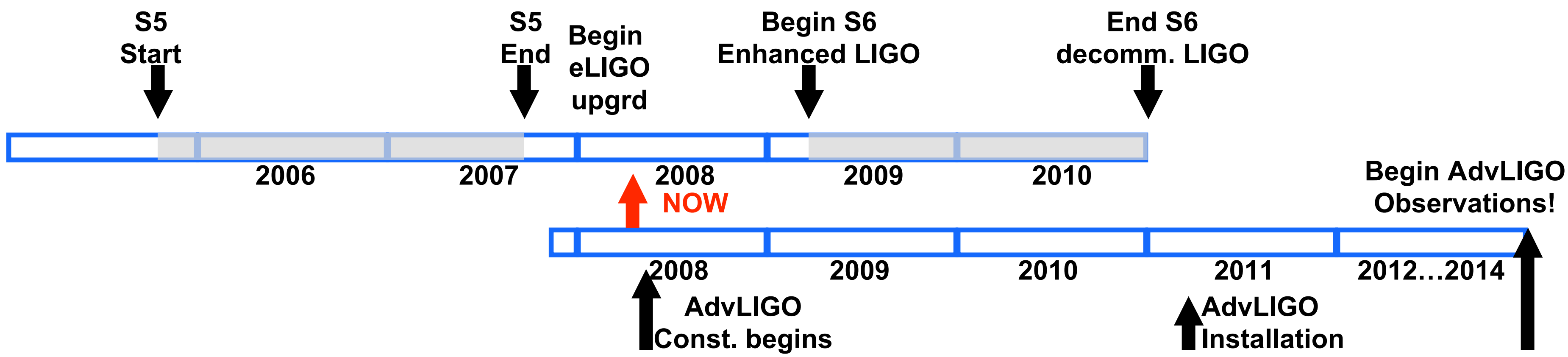
Limits on GW energy release from GRB 070201 cannot exclude an SGR in M31

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

# LIGO → eLIGO → AdvLIGO

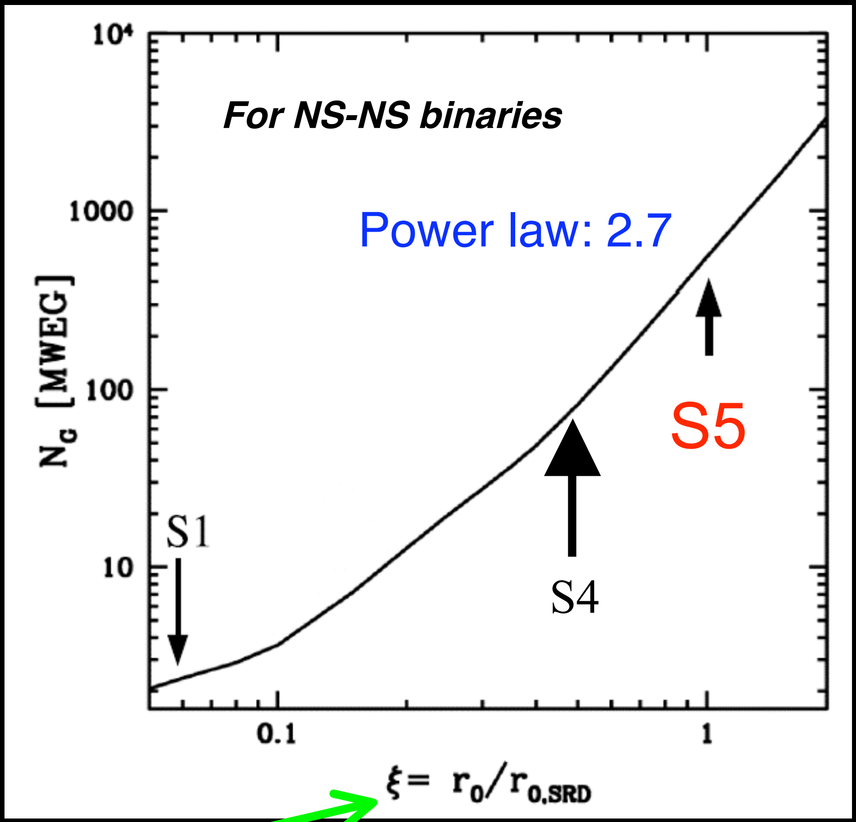
S5 → Enhanced LIGO → S6 → Advanced LIGO → S7+

S5 → Astrowatch



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

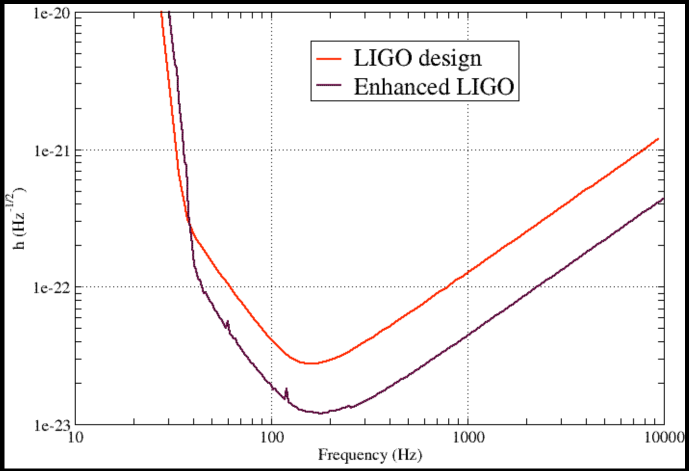
*From astro-ph/0402091, Nutzman et al.*




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

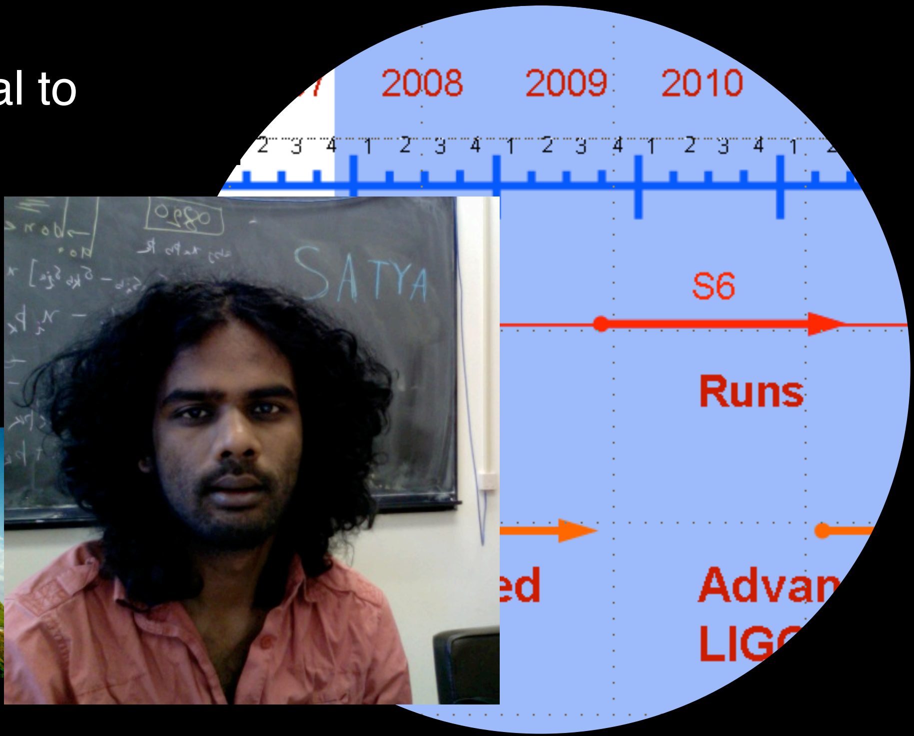
⇨scientific program for Enhanced LIGO (post S5)



# 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:



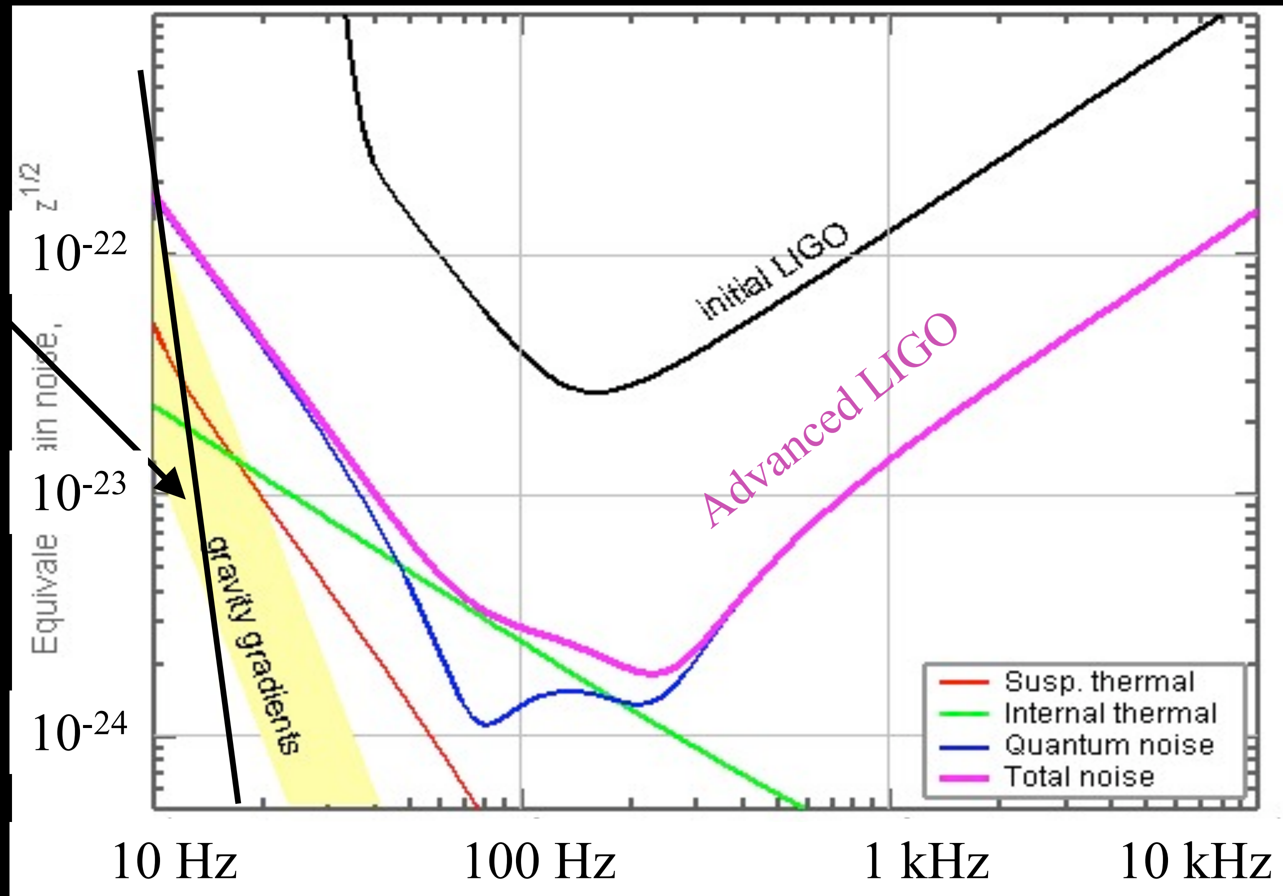

LHO 2km

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 $\varepsilon = 3 \times 10^{-6}$ to $2 \times 10^{-8}$
- *Stochastic background:*
  - From $\Omega_{GW} \sim 3 \times 10^{-6}$ to $\sim 3 \times 10^{-9}$

# 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!

# LIGO Scientific Collaboration

LIGO

LSC

University of Maryland 1856
Michigan
University of Strathclyde
ACIGA
Loyola University New Orleans
Stanford University
Montana State University
University of Washington
Syracuse University, Founded AD 1870
University of Glasgow
Università degli Studi del Sannio
Trinity University
San José State University
University of Wisconsin UW Milwaukee
ANU The Australian National University
NASA Goddard Space Flight Center
LSU
UTB TSC
The University of Western Australia
1754
Andrews University
Massachusetts Institute of Technology
Southeastern Louisiana University
California Institute of Technology 1891
Northwestern University
R·I·T Rochester Institute of Technology 1829
The University of Adelaide Australia
PAN
The University of Texas at Austin
Moscow State University
GEO 600
Embry-Riddle Aeronautical University
University of Massachusetts Amherst 1863
University of Southampton
PennState 1855
Carleton College, Northfield, Minn. A.D. 1866
Cardiff University
Washington State University
UF University of Florida
The University of Mississippi 1848
Charles Sturt University
UIB Universitat de les Illes Balears
University of Rochester
NAOJ
University of Minnesota
Southern University Agricultural & Mechanical College
Hobart College
William Smith College
Science & Technology Facilities Council Rutherford Appleton Laboratory
Universität Hannover