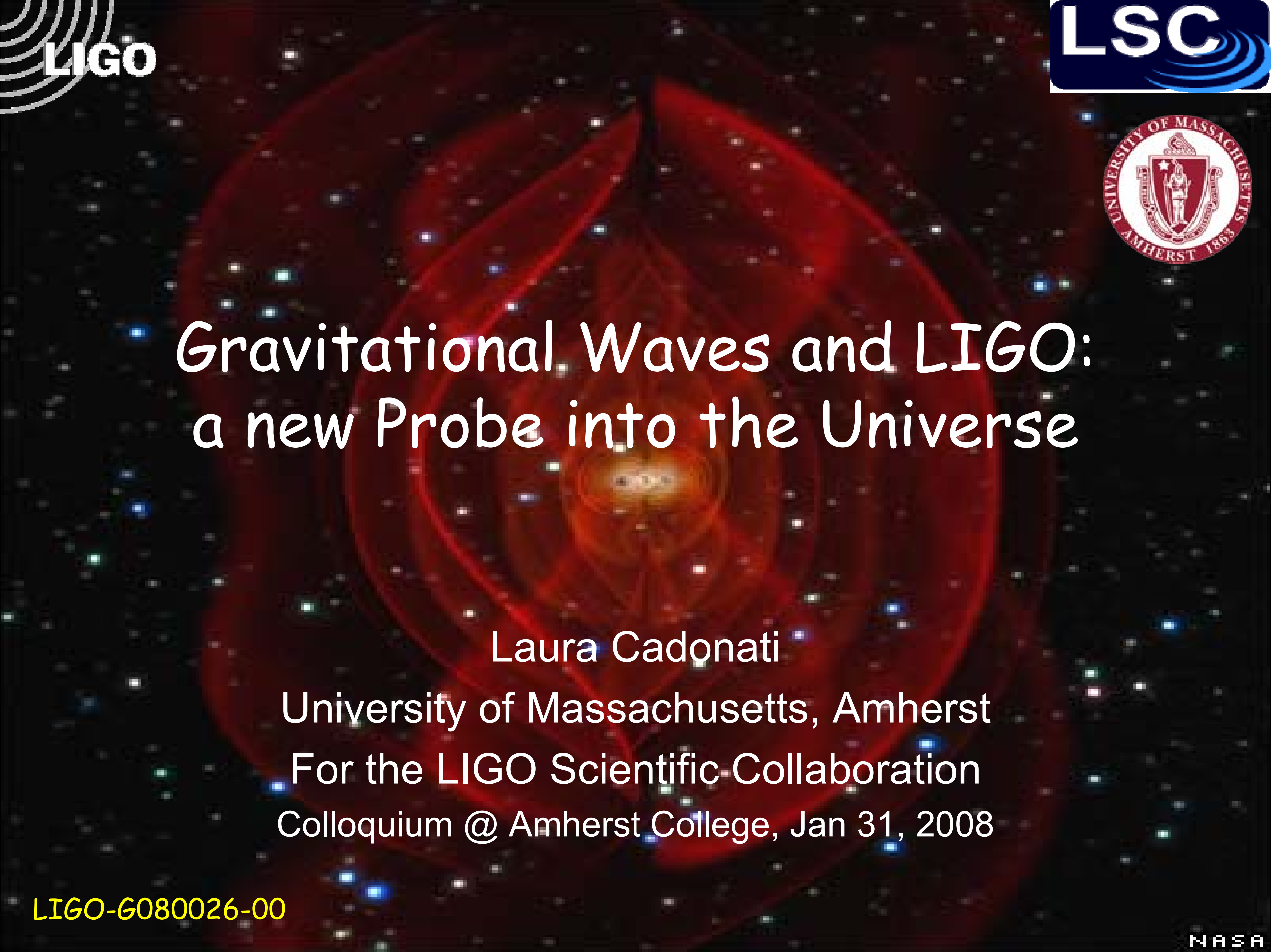
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Gravitational Waves and LIGO: a new Probe into the Universe

Laura Cadonati
University of Massachusetts, Amherst
For the LIGO Scientific Collaboration

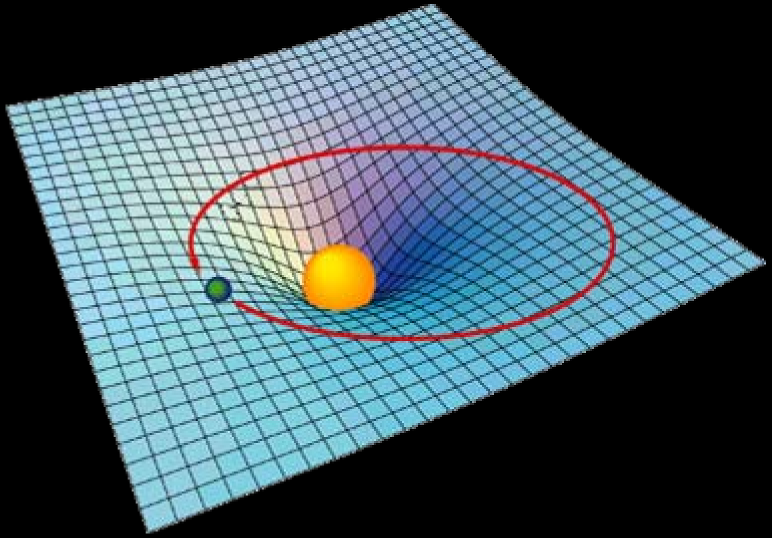
Colloquium @ Amherst College, Jan 31, 2008

LIGO-G080026-00

- Gravitational Waves
- LIGO
- Science with LIGO
- The Road Ahead

NASA

Einstein's Vision:
General Relativity (1916)



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

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

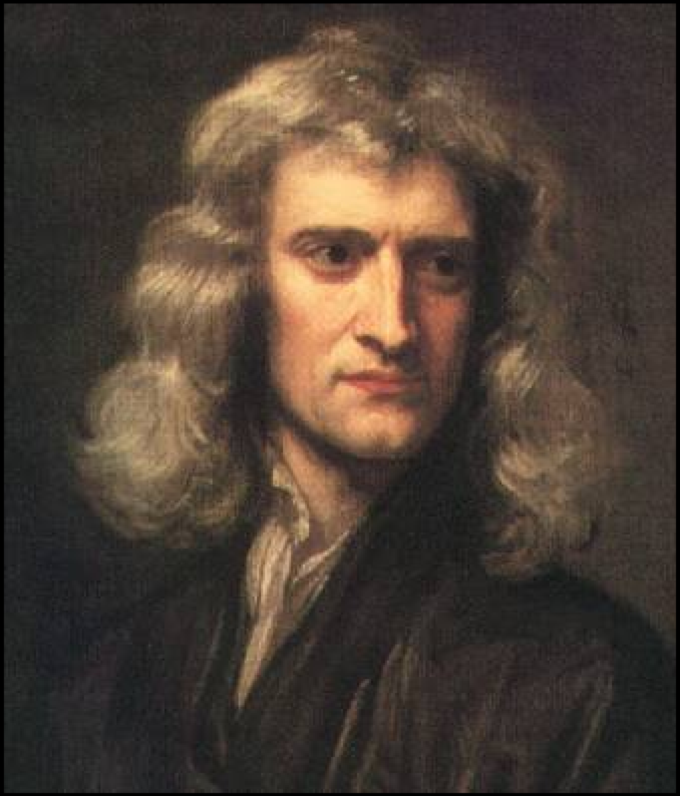
Einstein's Equations:

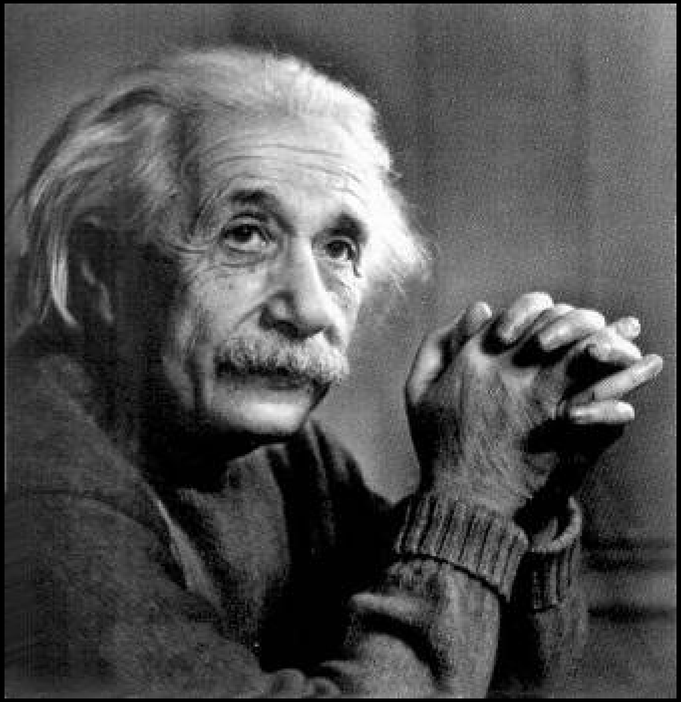
When matter moves, or changes its configuration, its gravitational field changes. This change propagates outward as a *ripple in the curvature of space-time*: a gravitational wave.

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

When a GW Passes Through Us…

…we “stretch and squash” in perpendicular directions at the frequency of the GW:

Leonardo da Vinci’s Vitruvian man

The effect is greatly exaggerated!!
If the Vitruvian man were 4.5 light years tall with feet on earth and head touching the nearest star, he would grow by only a ‘hairs width’

To directly measure gravitational waves, we need an instrument able to measure tiny relative changes in length, or strain $h=\Delta L/L$

Space-Time is Stiff!

Einstein's equations are similar to equations of elasticity: $T = (c^4/8\pi G)h$

T = stress, G = curvature, h=strain

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

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

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

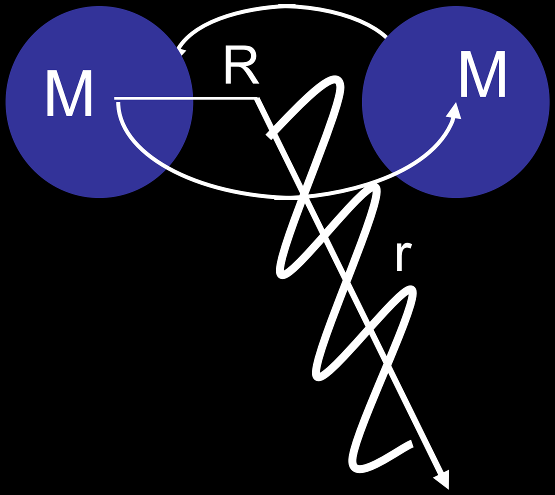
$M \approx 10^{30}$ kg

$R \approx 20$ km

$F \approx 400$ Hz

$r \approx 10^{23}$ m

➡ $h \sim 10^{-21}$



Setting the Scale

- Strongest signal produced by relativistic motion of massive objects at distance d:

$$h \lesssim \frac{1}{d}\frac{2GM}{c^2} \lesssim 10^{-19}\left(\frac{M}{M_\odot}\right)\left(\frac{d}{\mathrm{Mpc}}\right)^{-1}$$

- A tiny effect, and these assumptions are very optimistic (all rest mass emitted as GW):

$$\frac{d^2 I_{\mu\nu}}{dt^2} \sim Mc^2$$

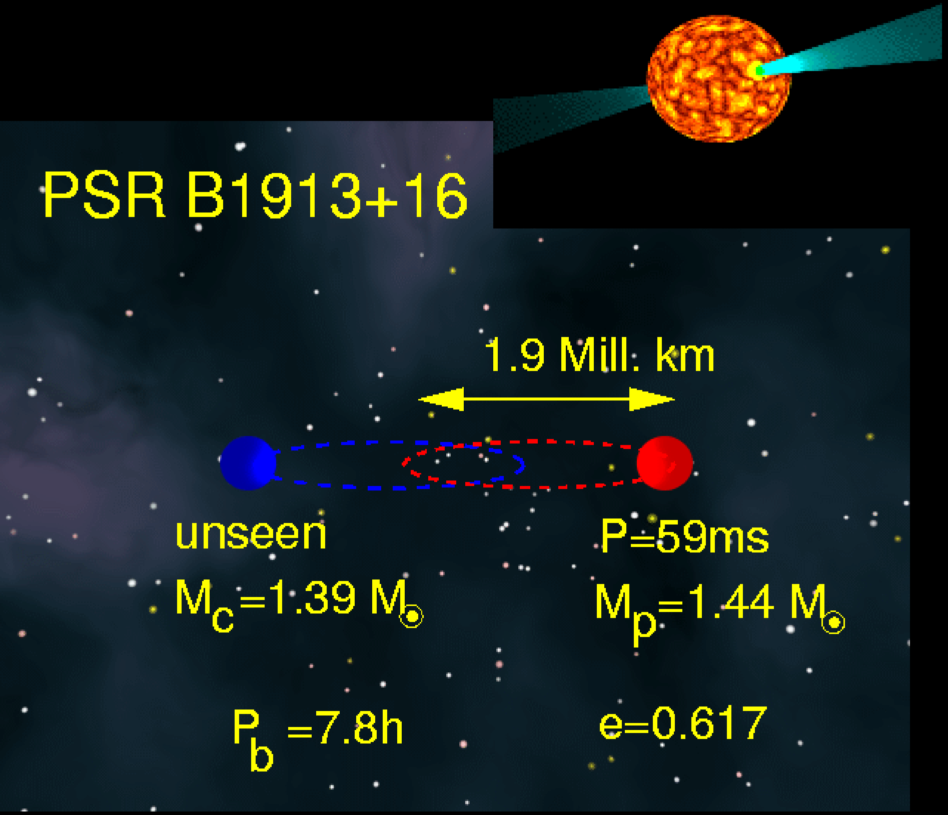
Sources need to be astrophysical!

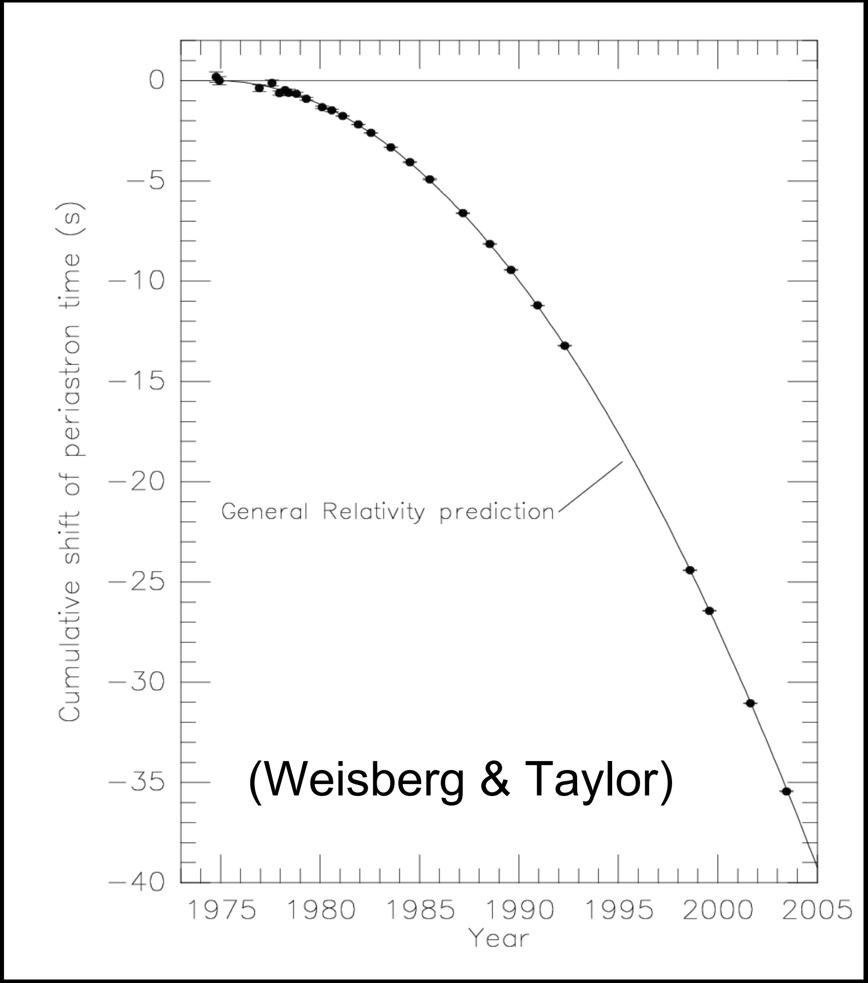
- Maximum oscillation frequency of the source is limited by the round trip light travel time across its extent, limited by the Schwarzschild radius ($2GM/c^2$):

$$f \lesssim \frac{c^3}{4\pi GM} \sim 16\left(\frac{M}{M_\odot}\right)^{-1} \quad \mathrm{kHz}$$

We have Indirect Proof of the Existence of GWs:

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





(Weisberg & Taylor)

From stars living in galaxies…

Where do gravitational waves come from?

From stars living in galaxies…

Supernova explosions

Where do gravitational waves come from?

Credits: Animation: NASA/CXC/D.Berry & A.Hobart

From stars living in galaxies…

Supernova explosions

Rotating stars (pulsars)

Where do gravitational waves come from?

Credit: NASA/CXC/ASU/J.Hester et al.

From stars living in galaxies…

Supernova explosions

Rotating stars (pulsars)

Where do gravitational waves come from?

Binary systems
(black holes, neutron stars)

Credit: John Rowe

From stars living in galaxies…

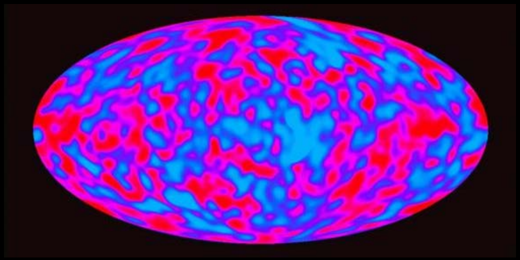
Supernova explosions

Rotating stars (pulsars)

Where do gravitational waves come from?

Binary systems
(black holes, neutron stars)

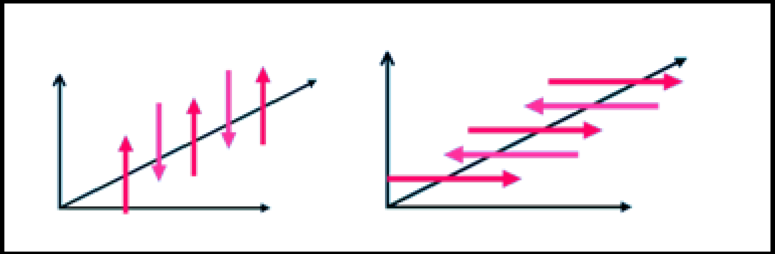
..and from the beginning
of the Universe!

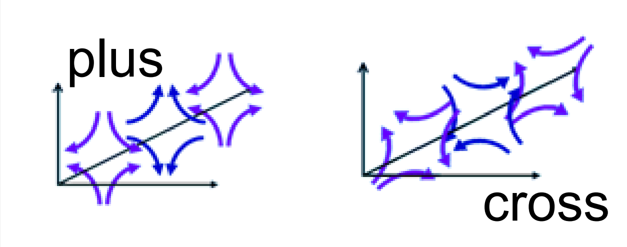


Credit: NASA/COBE

Astrophysics with
E&M vs Gravitational Waves

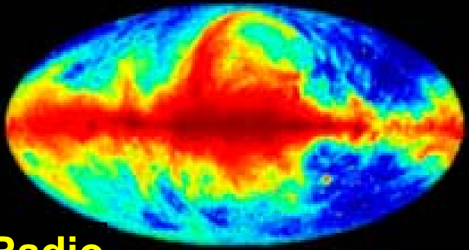
E&M	GW
Accelerating charge	Accelerating mass
Wavelength small compared to sources ➔ images	Wavelength large compared to sources ➔ no spatial resolution
Absorbed, scattered, dispersed by matter	matter is transparent
Frequency > 10 MHz and up	Frequency < 10 kHz
Dipole Radiation, 2 polarizations (up-down and left-right)	Quadrupole Radiation, 2 polarizations (plus and cross)



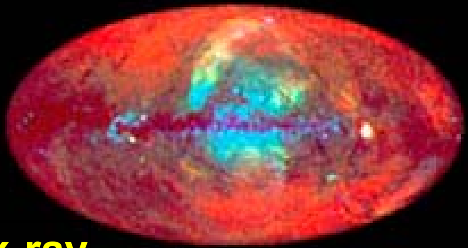


Very different information, mostly mutually exclusive

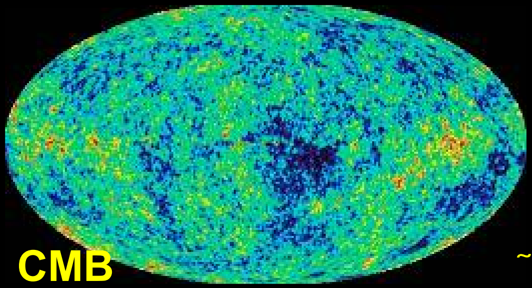
A New Probe into the Universe



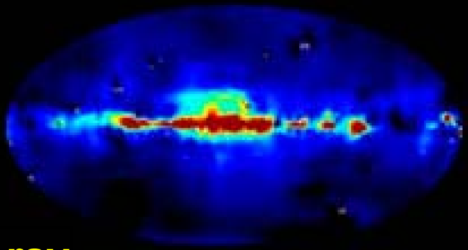
Radio



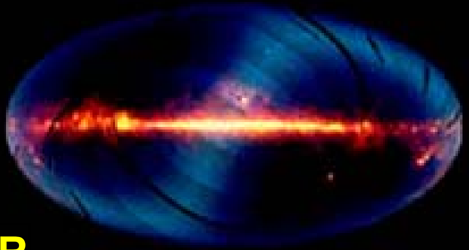
x-ray



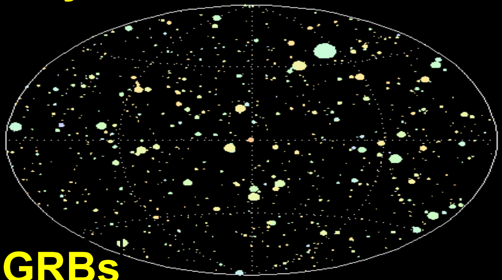
CMB



γ-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*.

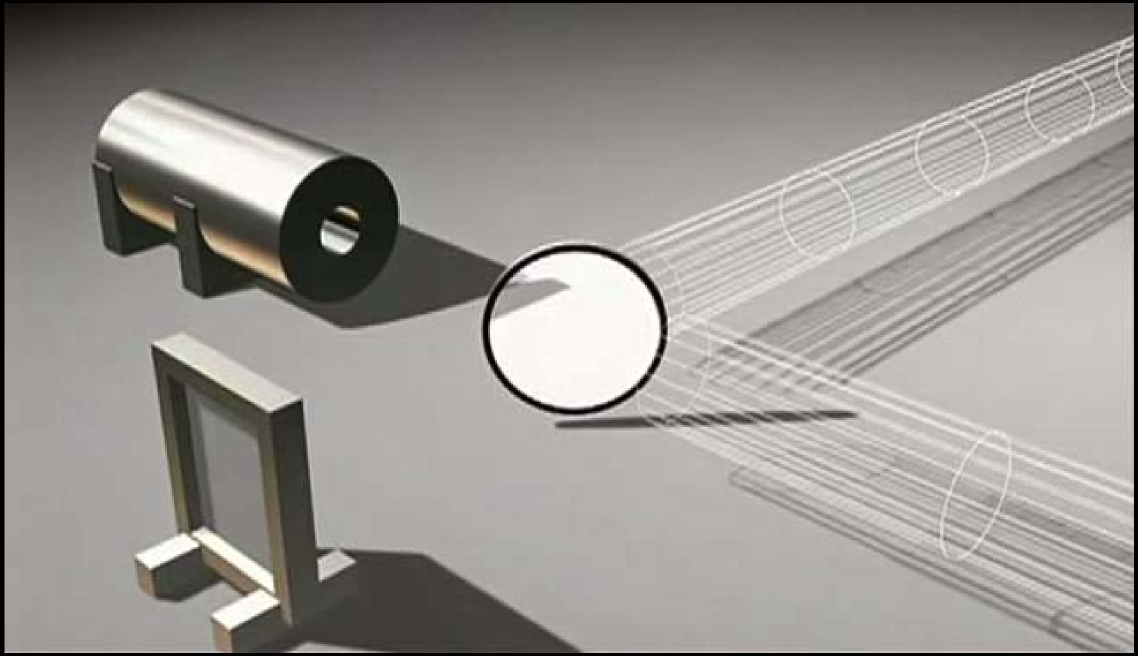
EXPECT THE UNEXPECTED!

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.

NASA

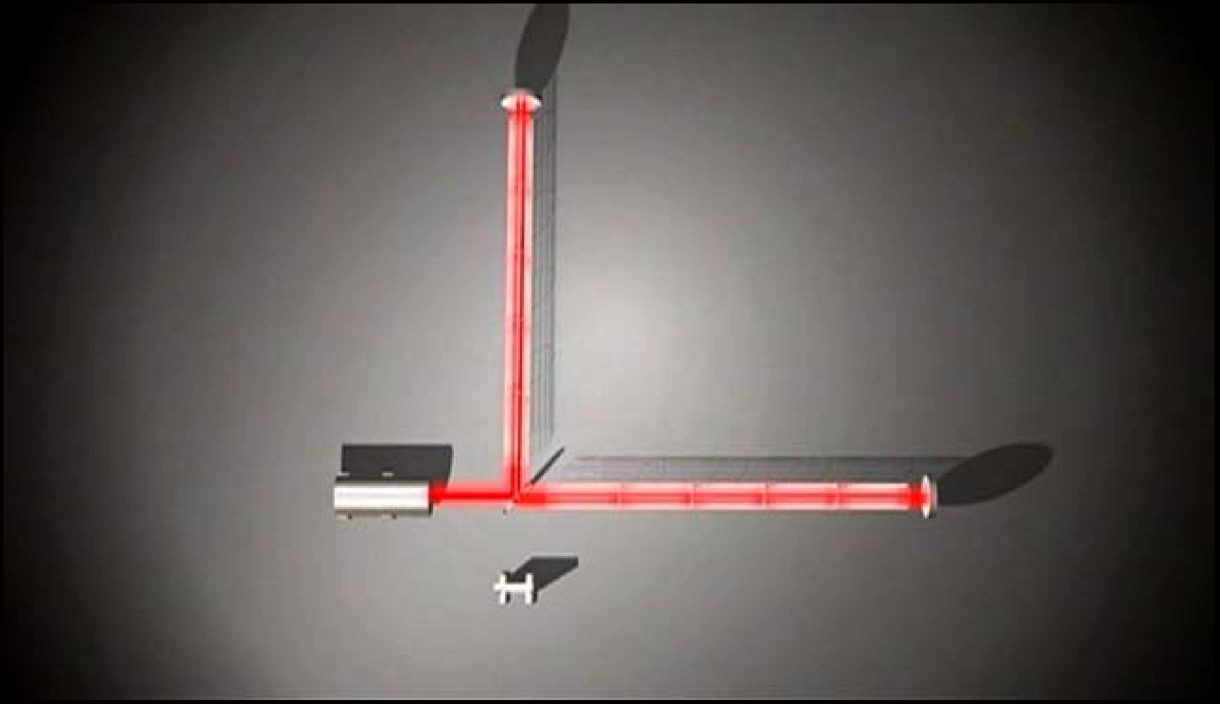
- Gravitational Waves
- LIGO
- Science with LIGO
- The road ahead

How to detect gravitational waves



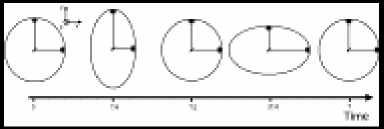
Einstein’s messengers,
National Science Foundation video

How to detect gravitational waves



Einstein’s messengers,
National Science Foundation video

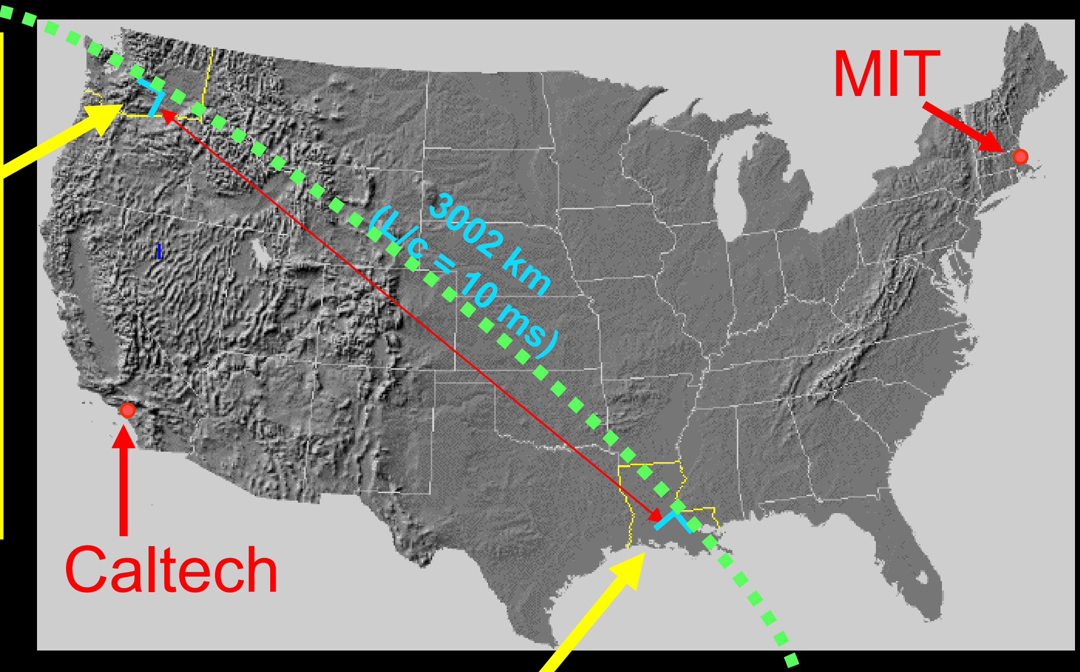
Suspended Mirrors as Free Test Masses



Initial LIGO goal: measure difference in length to one part in 10^{21}, or 10^{-18} m over km-scale distances

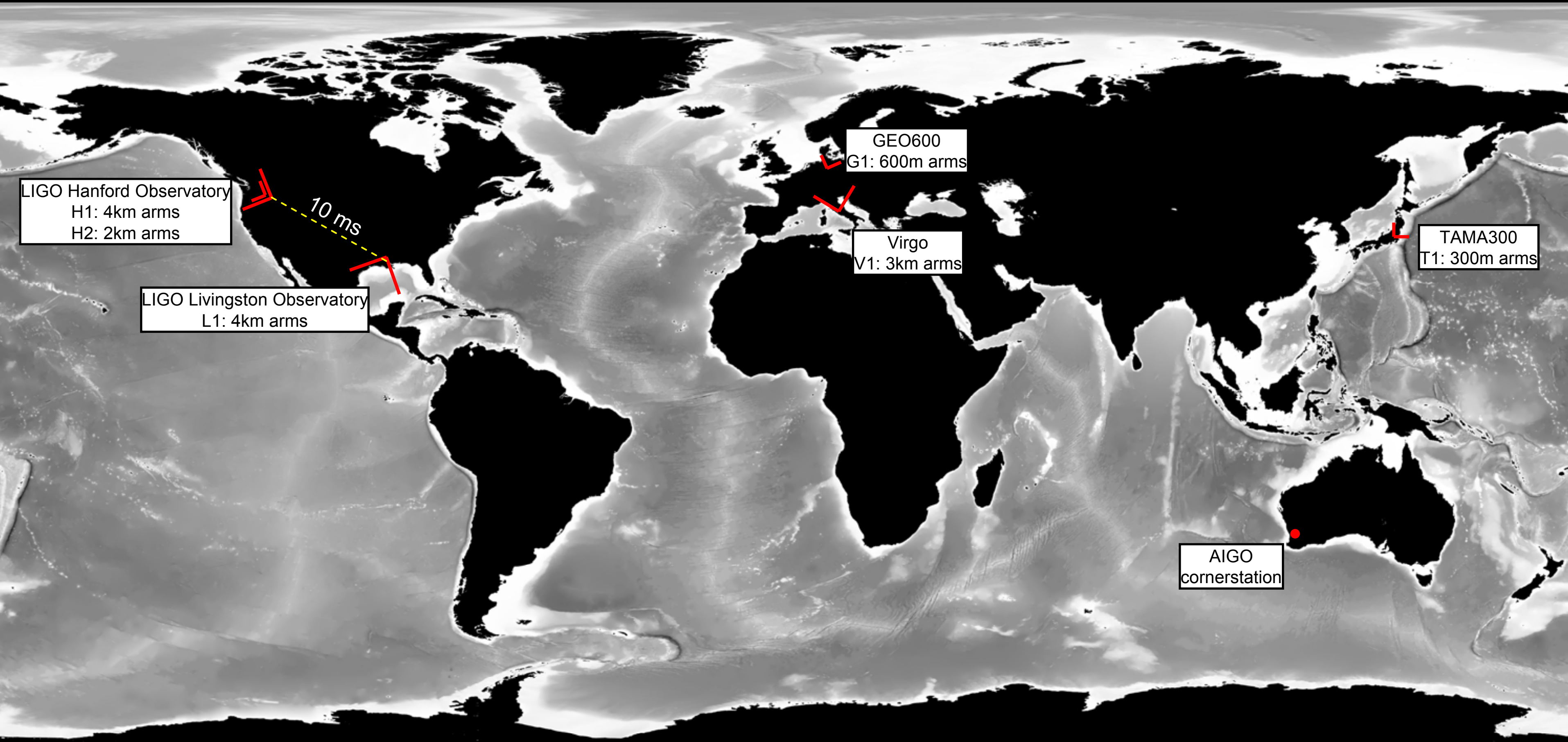
sciencebulletins.amnh.org

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

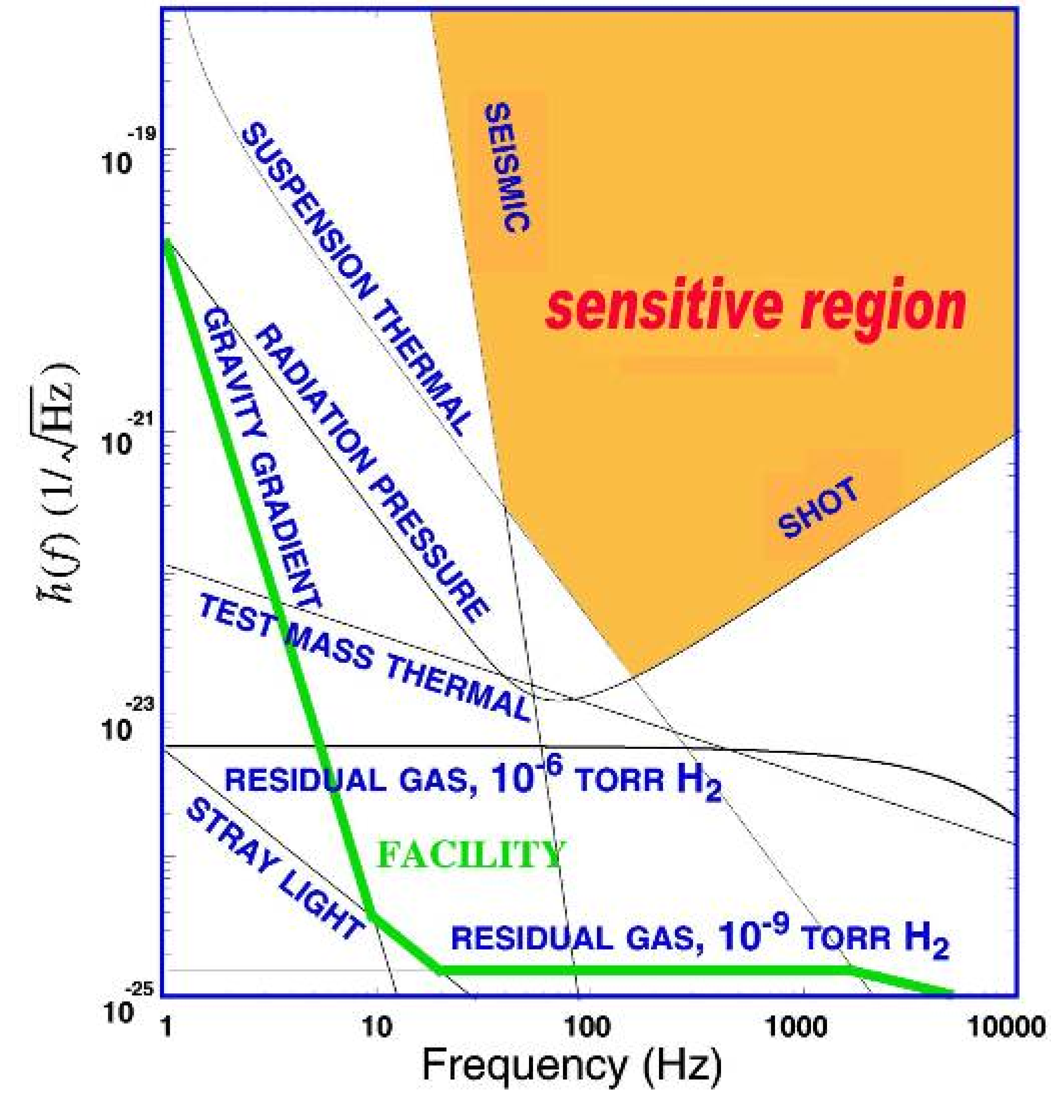
An International Quest:
Ground-Based Interferometers

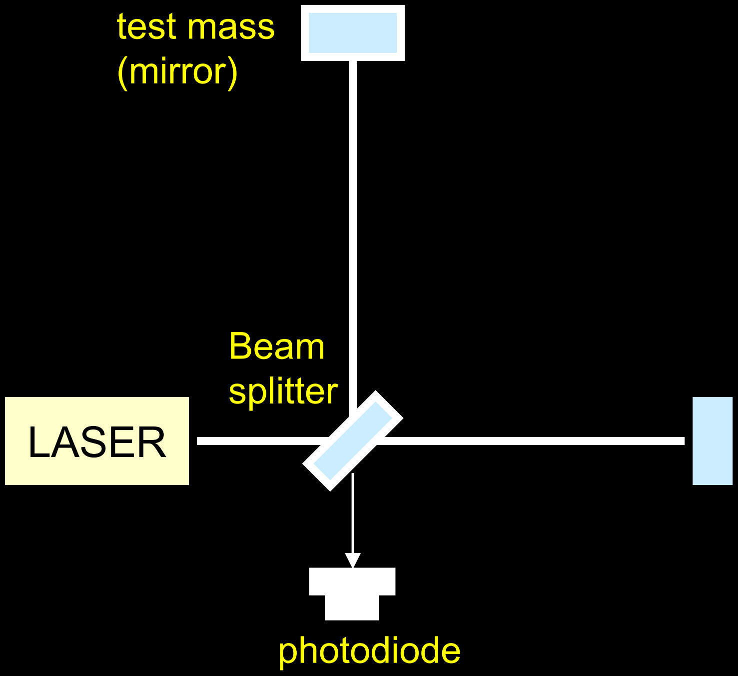


Credit: NASA’s Earth Observatory

Also: Resonant Bars, LISA

Initial LIGO Sensitivity Limits





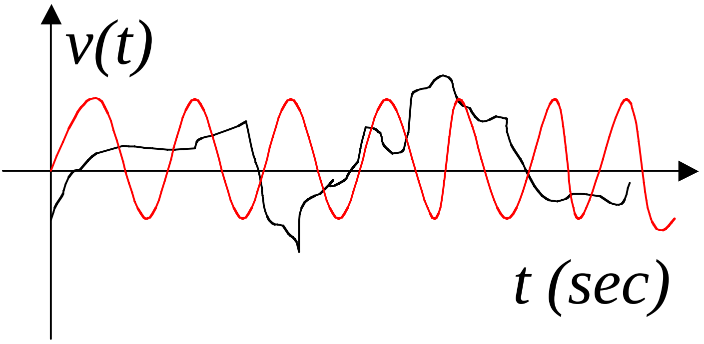
test mass
(mirror)

Beam
splitter

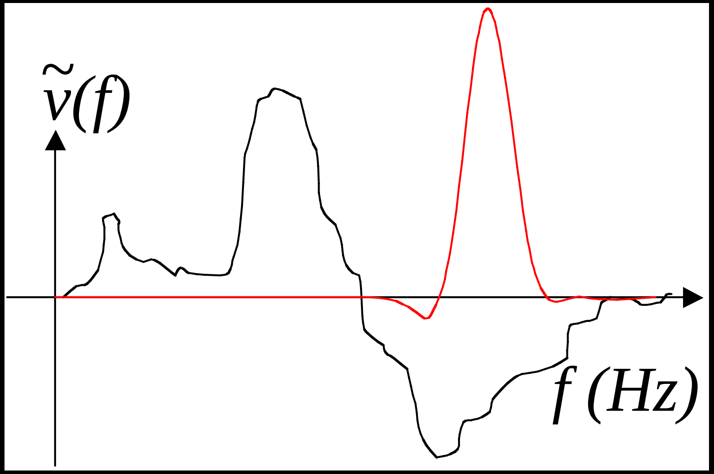
LASER

photodiode

What's on the vertical axis



Fourier transform



Energy ~ $<v^2> \Delta t$

Power ~ $<v^2>$

(energy per unit time)

$$v_{RMS} = \sqrt{< v^2(t) >}$$

$S_v(f)$= Power Spectral Density

(energy per unit frequency interval)

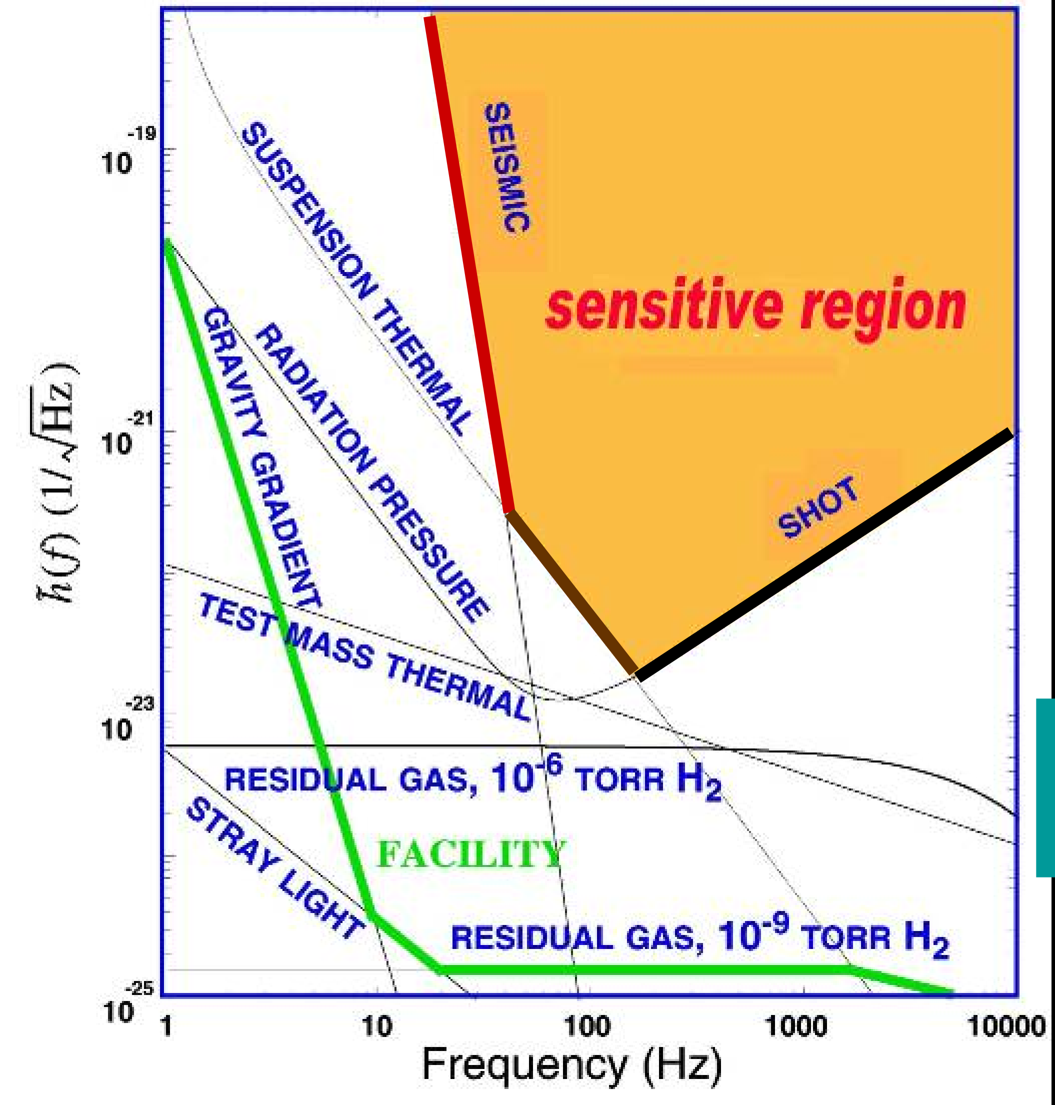
$$\int_0^\infty df\, S_v(f) = \int_0^\infty dt\, v^2(t)$$

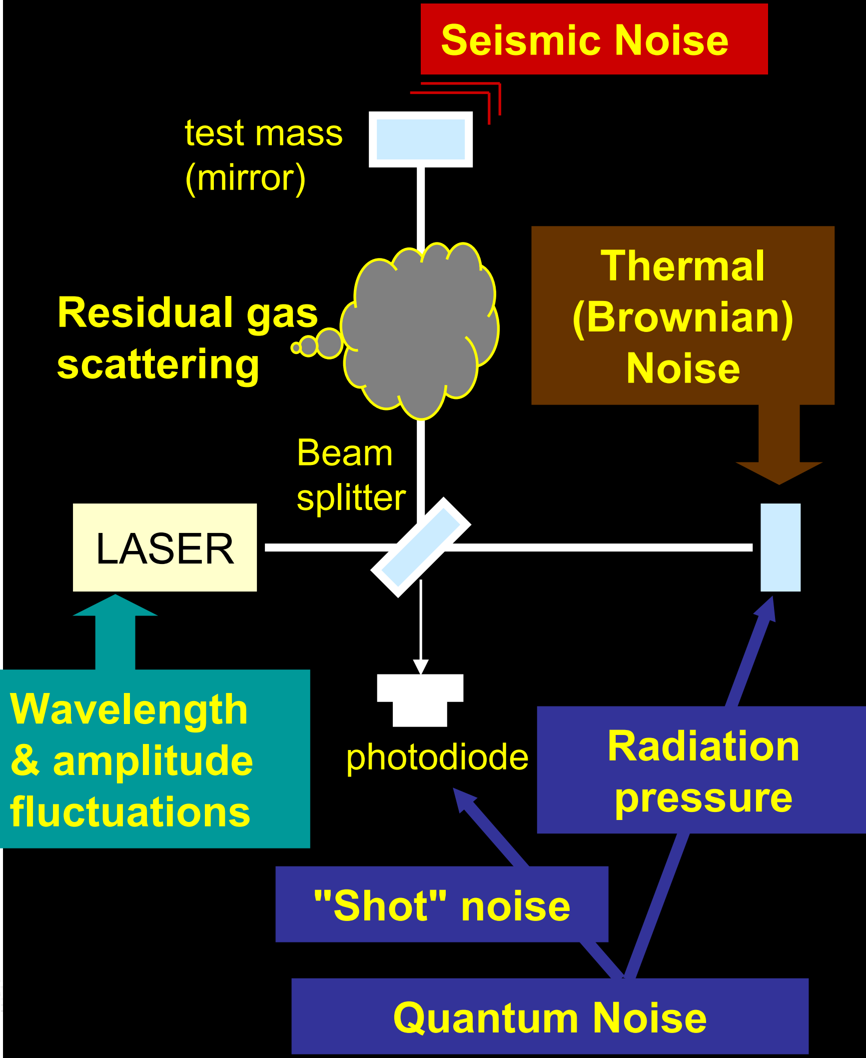
Amplitude Spectral Density:

$$\hat{v}(f) = \sqrt{S_v(f)}$$

in units of: $\frac{[v]}{\sqrt{\mathrm{Hz}}}$

Initial LIGO Sensitivity Limits





Seismic Noise

test mass (mirror)

Residual gas scattering

Thermal (Brownian) Noise

Beam splitter

LASER

Wavelength & amplitude fluctuations

photodiode

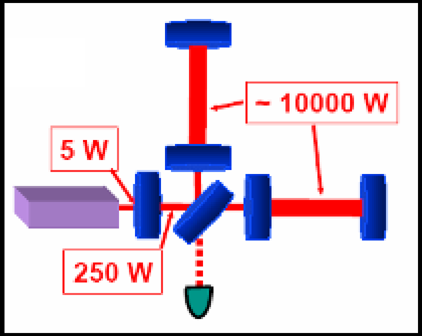
Radiation pressure

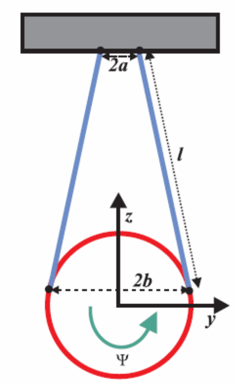
"Shot" noise

Quantum Noise

Mitigation of Noise Sources

Photon Shot Noise:
10W Nd-YAG laser
Fabry Perot Cavities
Power Recycling





Thermal noise:
Use low loss materials
Work away from resonances
Thin suspension wires

Seismic noise:
Passive Isolation Stacks
Pendulum suspension
Active isolation

All under vacuum

Vacuum for a Clear Light Path

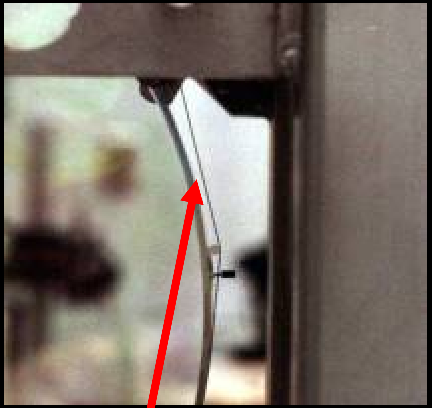
- LIGO beam tube (1998)
- 1.2 m diameter - 3mm stainless steel
- 50 km of weld

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

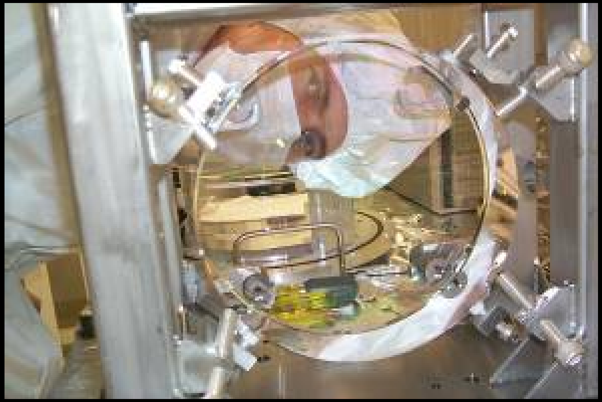
Corner Station

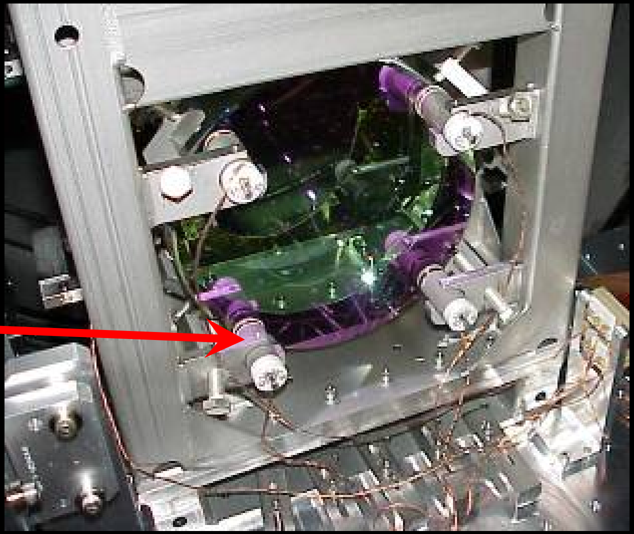
Suspended Mirrors

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



0.3mm steel wire



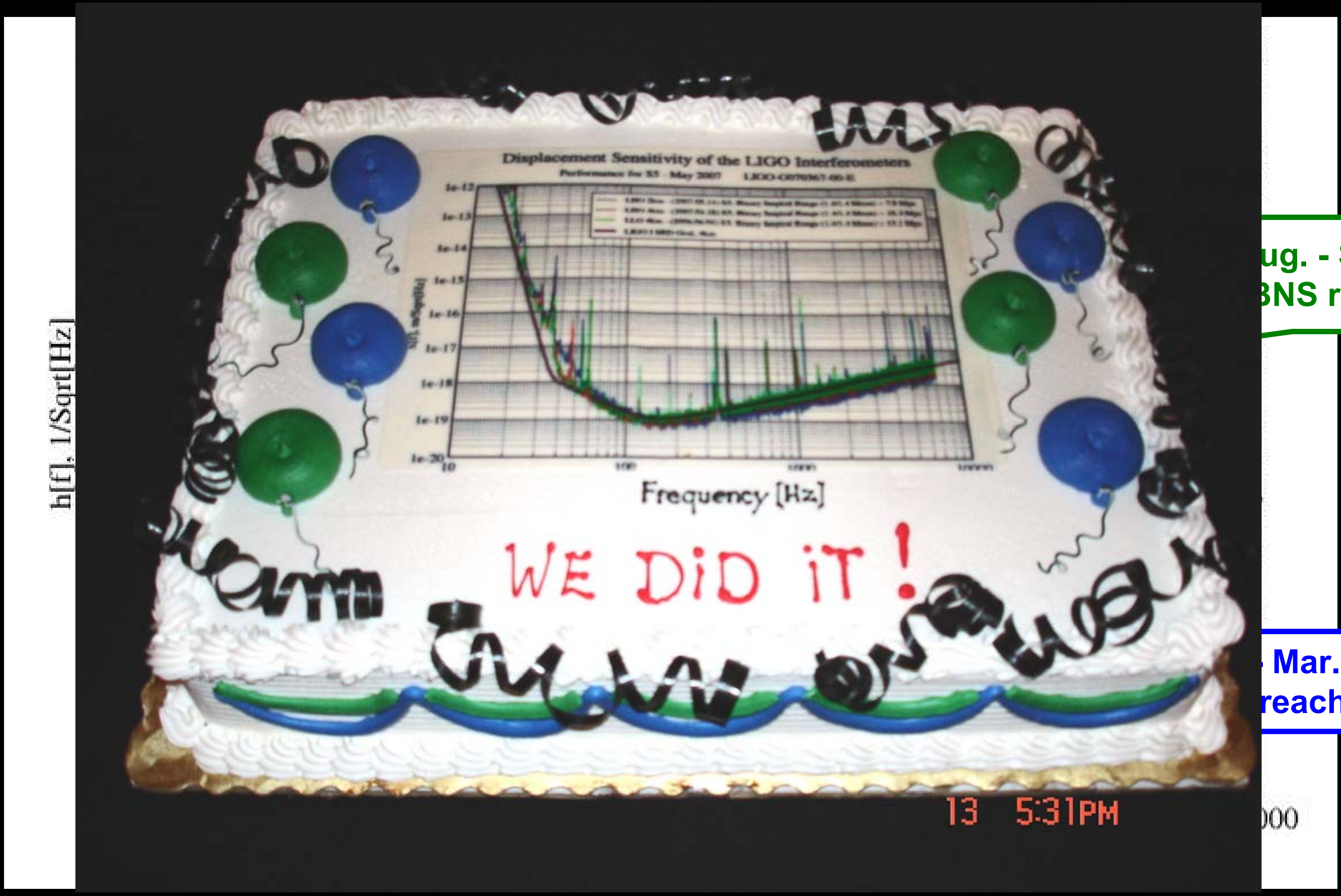


Local sensors/actuators for damping and control forces

Despite some obstacles along the way…

…LIGO has met its experimental challenges

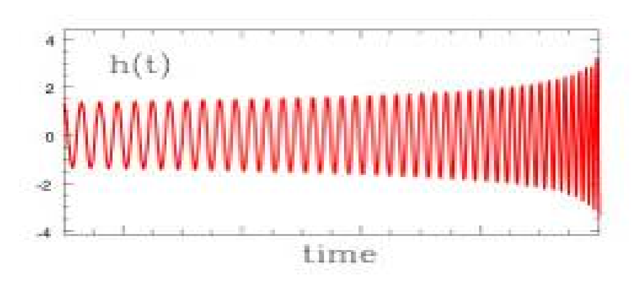
the design sensitivity predicted in the 1995 LIGO Science Requirements Document was reached in 2005



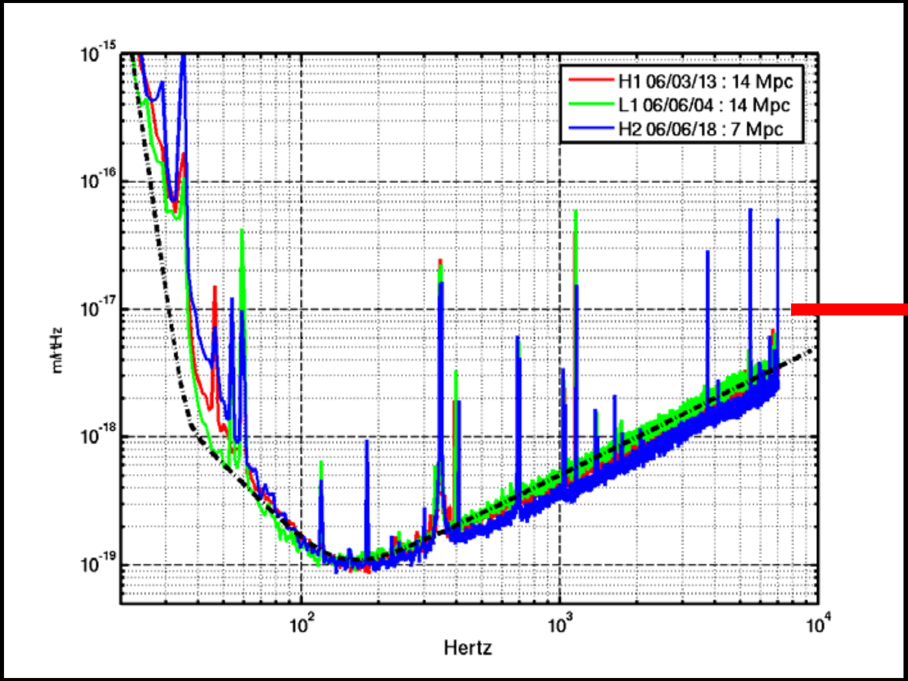
ug. - Sep. 2002
3NS reach ~100kpc

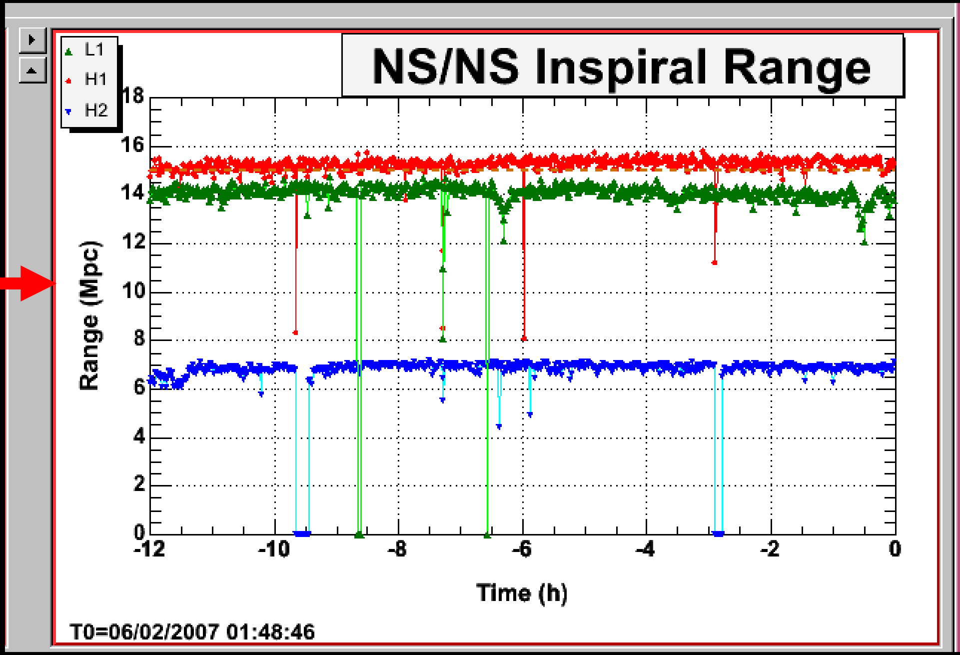
- Mar. 2005
reach ~ 15Mpc

Binary Neutron Stars: a Measure of Performance



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

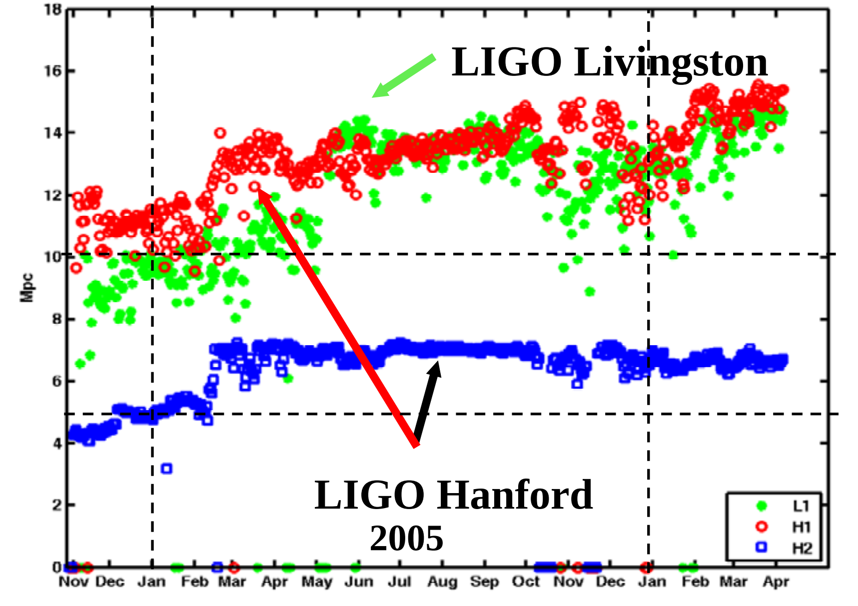


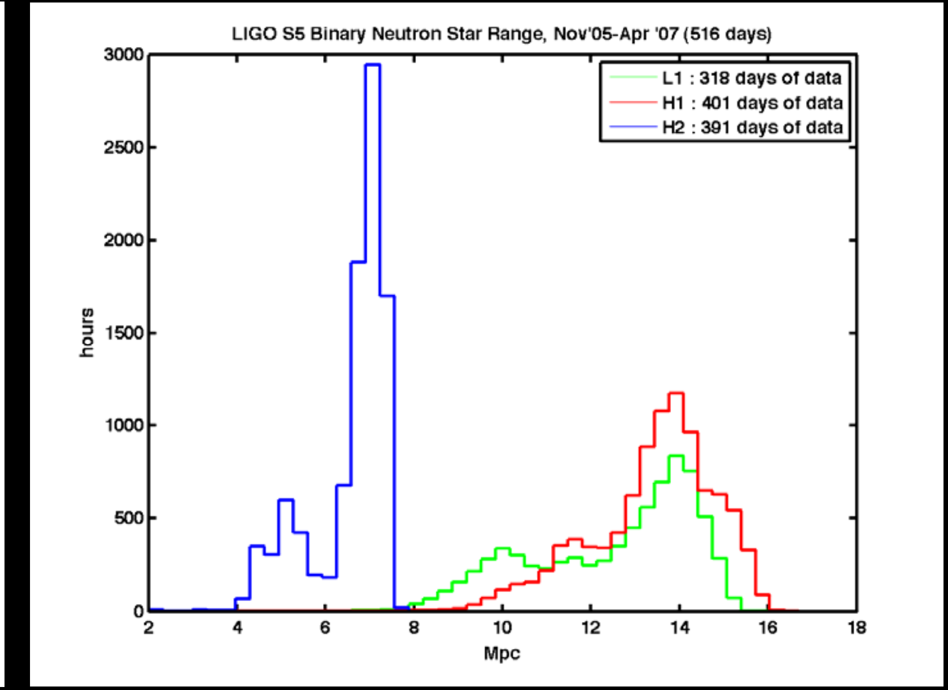


Range: distance of a 1.4-1.4 M binary, averaged over orientation/polarization

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

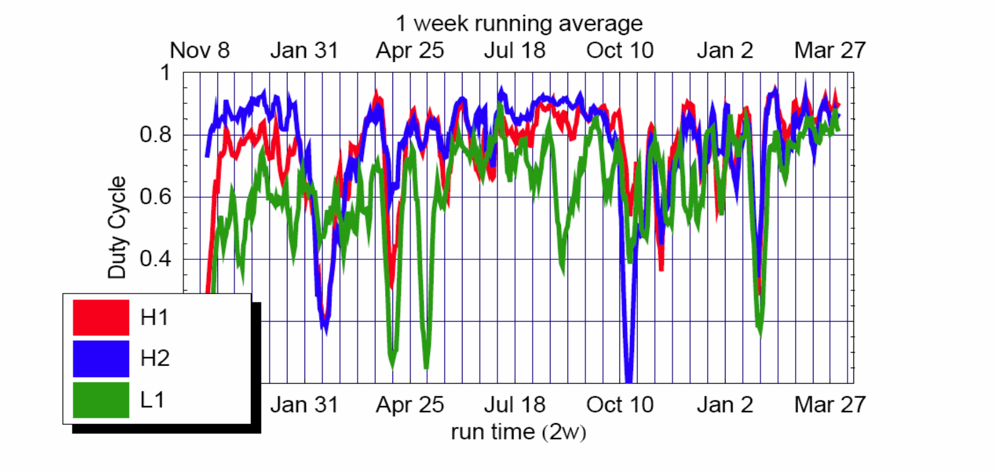
The S5 run


LIGO S5 Binary Neutron Star Daily Median Range, Nov'05-Apr '07


LIGO S5 Binary Neutron Star Range, Nov'05-Apr '07 (516 days)

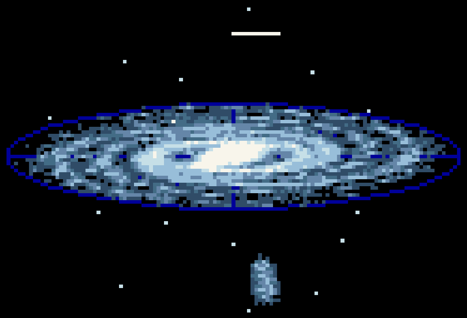
S5 started in Nov 2005 and ended Oct 2007

- LIGO collected 1 year of triple coincidence data
- Duty cycle: ~75% per IFO, 53% triple coincidence


1 week running average

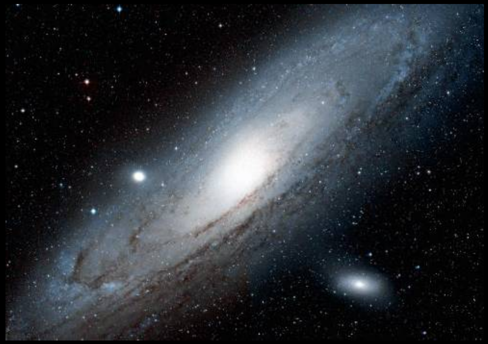
Progress in Sensitivity

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 = $9.5\text{x}10^{12}$ km
1 pc = $30.8\text{x}10^{12}$ km = 3.26 light years


NASA

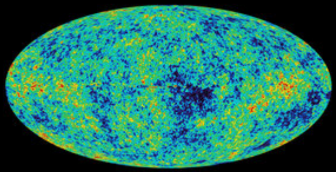
- Gravitational Waves
- LIGO
- Science with LIGO
- The road ahead

When will we see something?

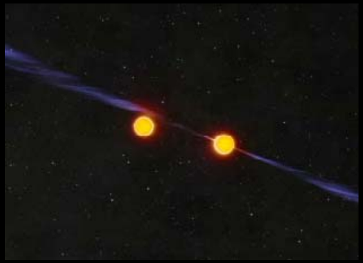
Predictions are difficult… many unknowns!

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

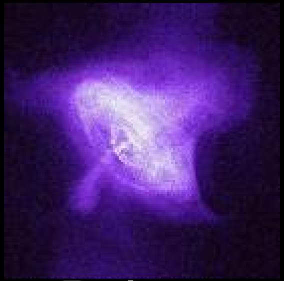
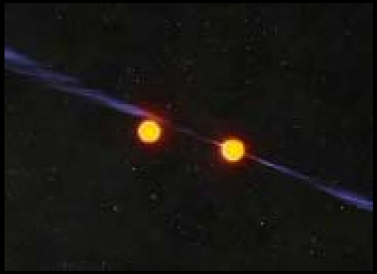
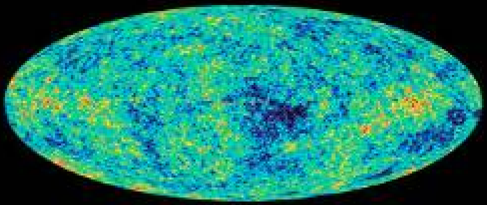
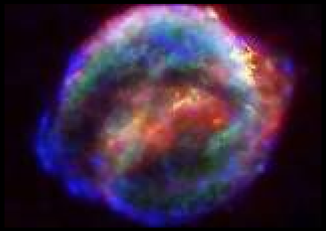
- Cosmological background:
  how did the Universe evolve?



- 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 100 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!



Sources And Methods

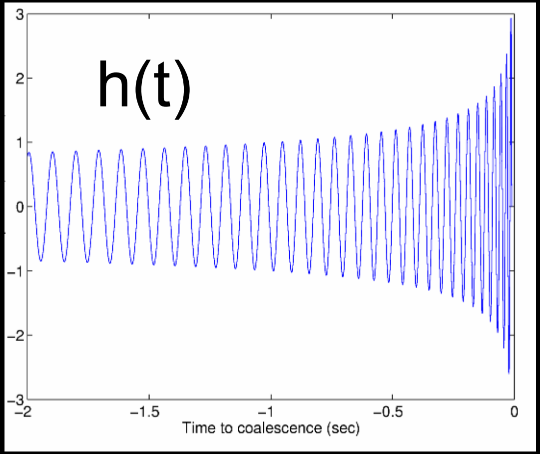
	Long duration	Short duration
Matched filter	 Pulsars	 Compact Binary Inspirals
Template-less methods	 Stochastic Background	 Bursts

Binary Systems

PSR1913+16
Hulse-Taylor

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

- Gravitational waves carry away energy and angular momentum. Orbit will continue to decay
- In ~300 million years, the "inspiral" will accelerate, and the neutron stars coalesce. Gravitational wave emission will be strongest near the end



Inspiral chirp:

- Amplitude and duration only depend on the masses m_1 and m_2 and the lower cutoff frequency. Neglect spin for now.
- 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.

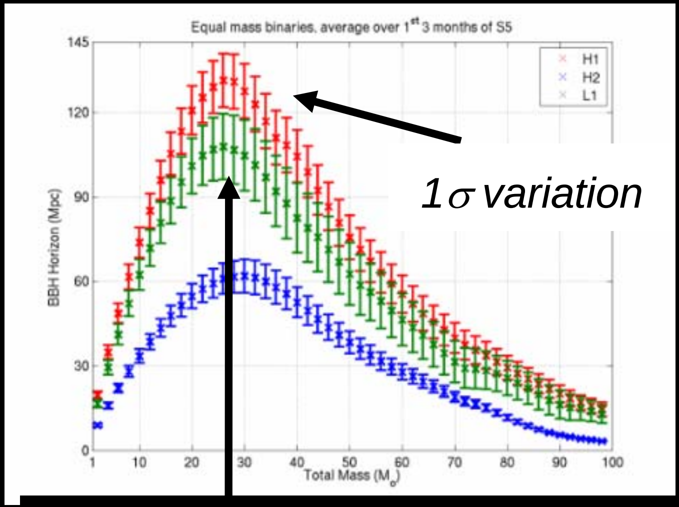
- Results from the S3+S4 science runs [Preprint arXiv:0704.3368]
  - No GW signals identified
  - Binary neutron star signal out to ~17 Mpc (optimal case)
  - Binary black hole signals out to tens of Mpc
  - Place limits on binary coalescence rate for certain population models

Horizon in S5

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

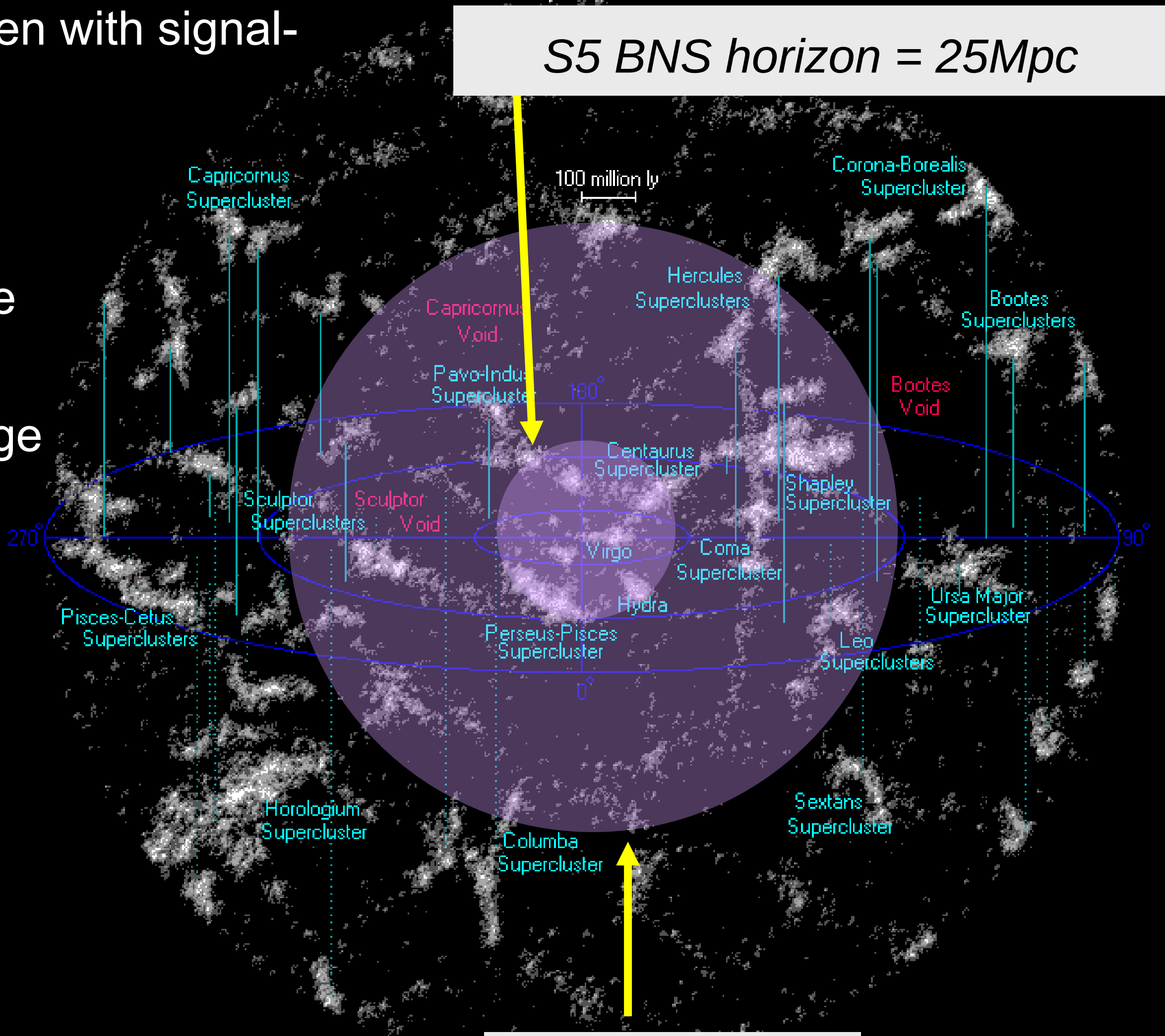
For 1.4-1.4 M_o binaries:
~ 200 MWEGs in range

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



1σ variation

Peak 130Mpc at total mass ~ $25M_{sun}$

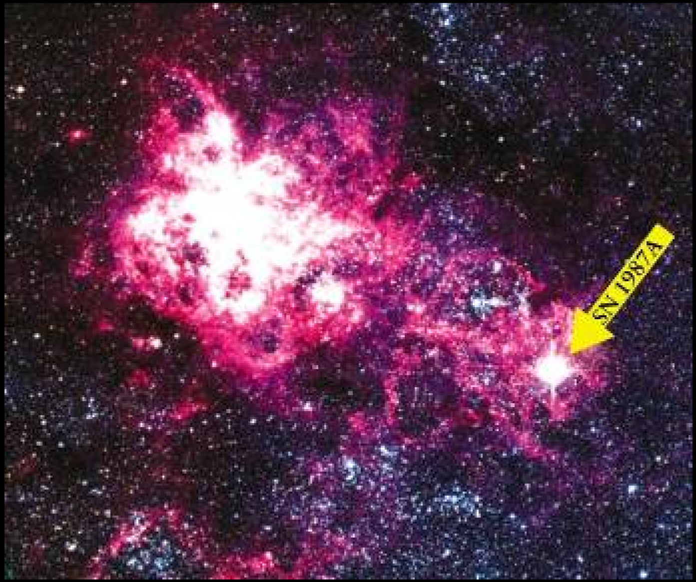


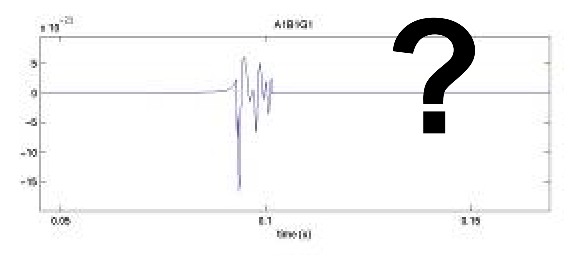
S5 BNS horizon = 25Mpc

S5 BBH horizon

Image: R. Powell

Astrophysical Sources: Bursts





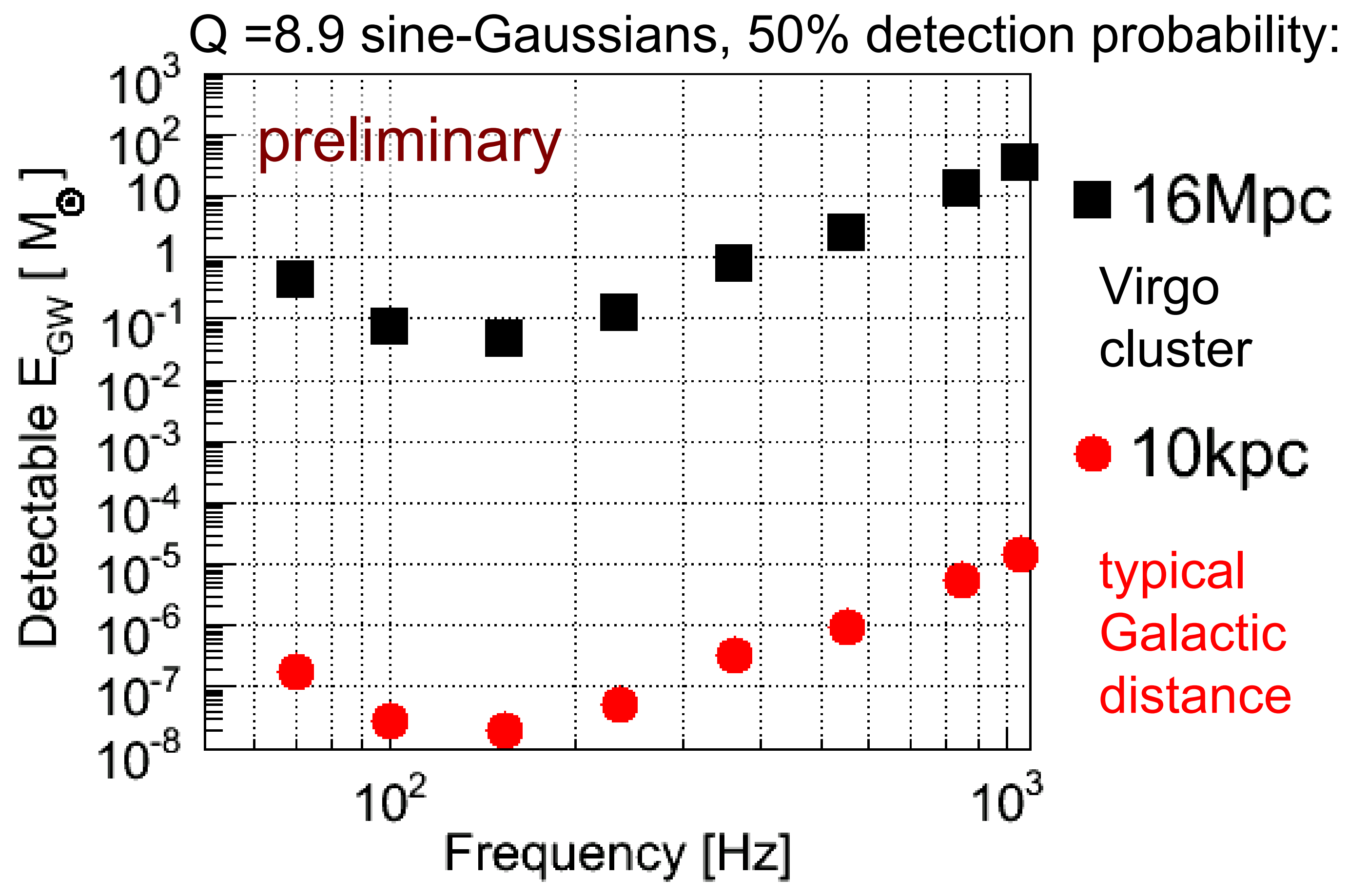
Uncertainty of waveforms complicates the detection ⇒ minimal assumptions, open to the unexpected

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:

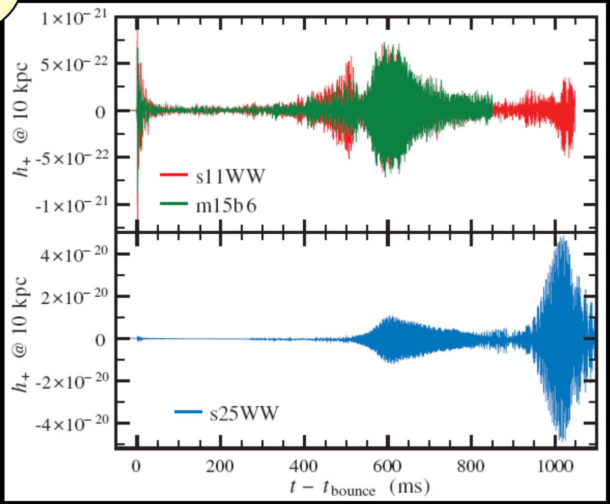
$\sim 2 \times 10^{-8}\ M_{\odot} c^2$ at 10 kpc (typical Galactic distance)

$\sim 0.05\ M_{\odot} c^2$ 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)



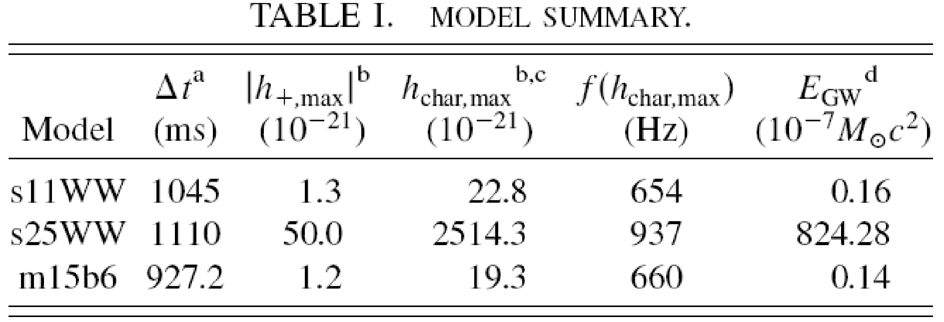


TABLE I. MODEL SUMMARY.

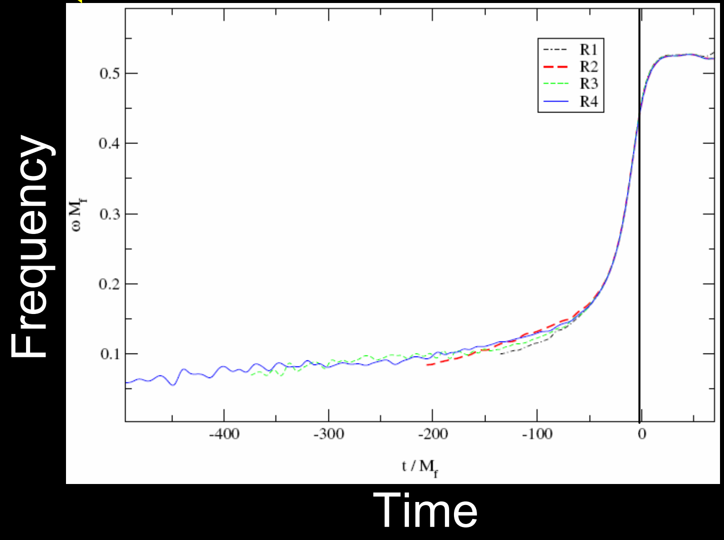
Model	Δt^{a} (ms)	$\lvert h_{+,\max}\rvert^{b}$ (10^{-21})	$h_{\mathrm{char,max}}{}^{b,c}$ (10^{-21})	$f(h_{\mathrm{char,max}})$ (Hz)	$E_{\mathrm{GW}}{}^{d}$ $(10^{-7}M_{\odot}c^{2})$
s11WW	1045	1.3	22.8	654	0.16
s25WW	1110	50.0	2514.3	937	824.28
m15b6	927.2	1.2	19.3	660	0.14

11 $M_{\odot}$ progenitor (s11WW model)

$\Rightarrow$ reach ~ 0.4 kpc

25 $M_{\odot}$ progenitor (s25WW model)

$\Rightarrow$ reach ~ 16 kpc



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

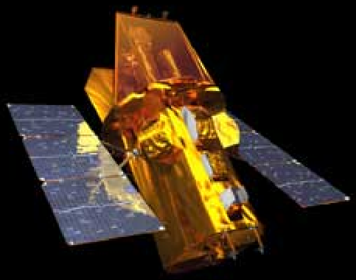
Baker et al, PRD 73, 104002 (2006)

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



Swift

- 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

- 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

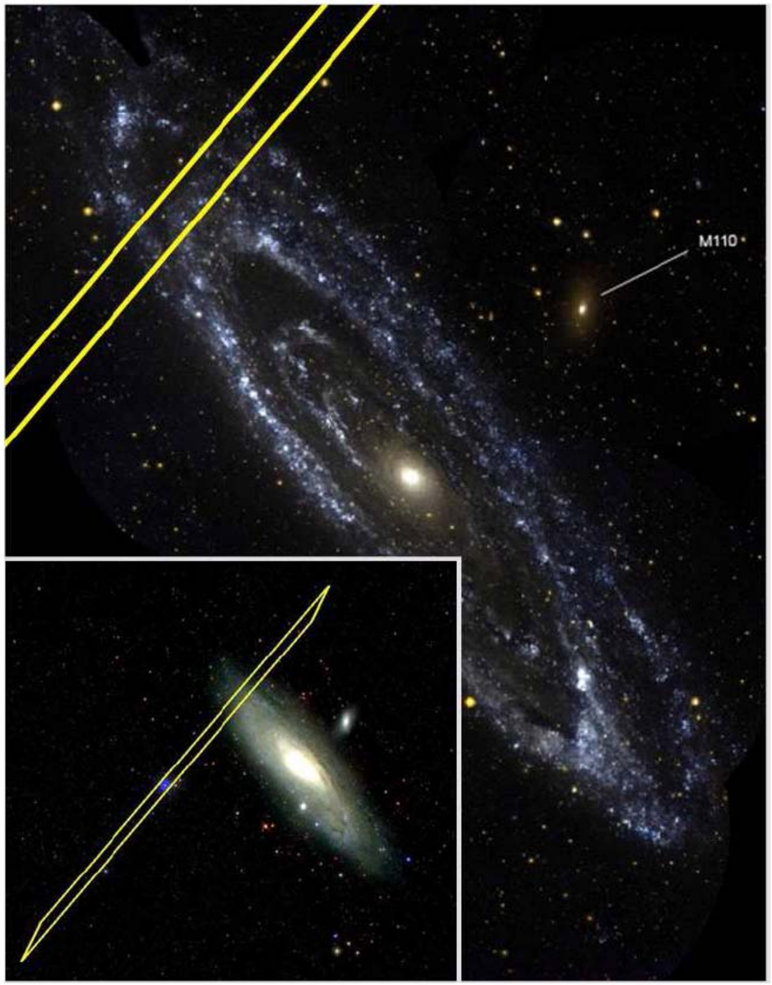
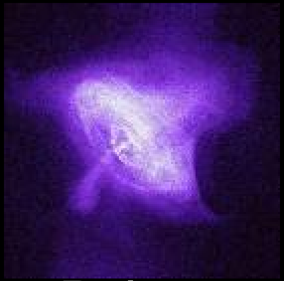
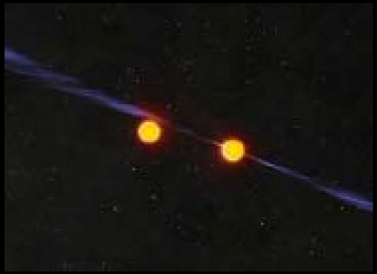
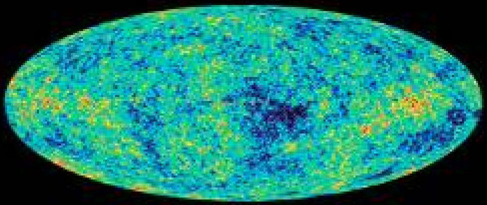
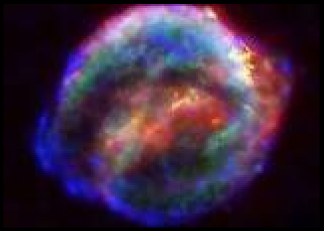


Fig. 1.— The IPN3 (IPN3 2007) (γ-ray) error box overlaps with the spiral arms of the Andromeda galaxy (M31). The inset image shows the full error box superimposed on an SDSS (SDSS 2007) image of M31. The main figure shows the overlap of the error box and the spiral arms of M31 in UV light (Thilker et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

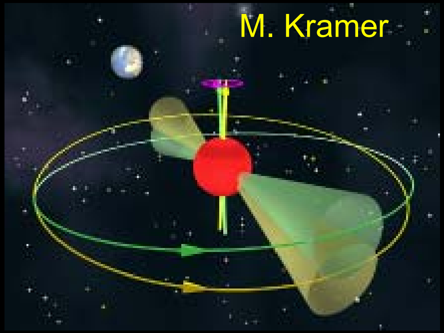
- Short, hard gamma-ray burst
  - A leading model for short GRBs: binary merger involving a neutron star
- Position (from IPN) is consistent with being in M31

- LIGO H1 and H2 were operating
- Result from LIGO data analysis: No plausible GW signal found; therefore very unlikely to be from a binary merger in M31
- *[Preprint arXiv:0711.1163]*

Sources And Methods

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

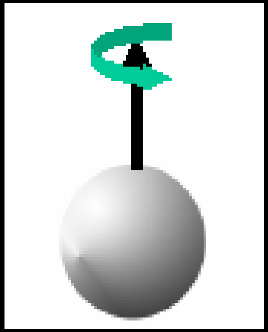
Continuous Waves



M. Kramer

Wobbling neutron stars

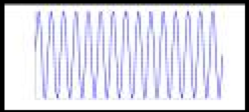
J. Creighton



Pulsars with mountains

Dana Berry/NASA

Accreting neutron stars



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

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

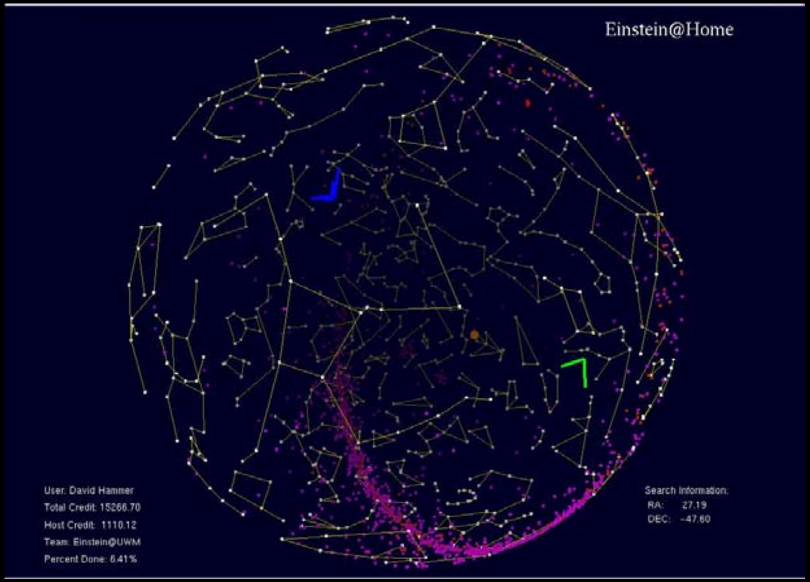
Beat spin-down limit on Crab pulsar:

(PRELIMINARY from 13 months of data:

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

Wide-parameter searches for periodic systems
The Einstein@home Project

- All-sky coherent search for *unknown* isolated periodic signals
  - Computationally very expensive!
  - S4 search using semi-coherent methods: *[PRD in press, preprint arXiv:0708.3818]* placed upper limits on strain amplitude as low as 4 × 10^{-24}
- Doing S5 search with a “hierarchical” approach
  - Semi-coherent and coherent stages
  - Main processing power provided by *Einstein@Home*


Einstein@Home

User: David Hammer
Total Credit: 15266.70
Host Credit: 1110.12
Team: Einstein@UWM
Percent Done: 6.41%

Search Information:
RA: 27.19
DEC: -47.60

http://www.einsteinathome.org/

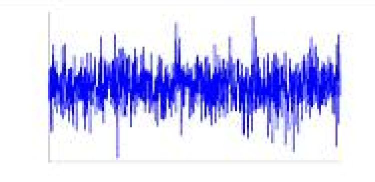
~180,000 users

Astrophysical Sources: Stochastic Background

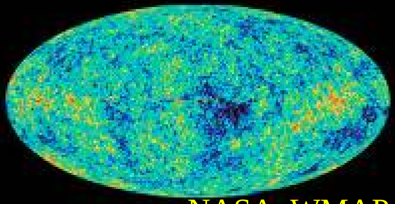
Weak, random gravitational waves could be bathing the Earth

Cosmological background: Big Bang and early universe

Astrophysical background: unresolved bursts



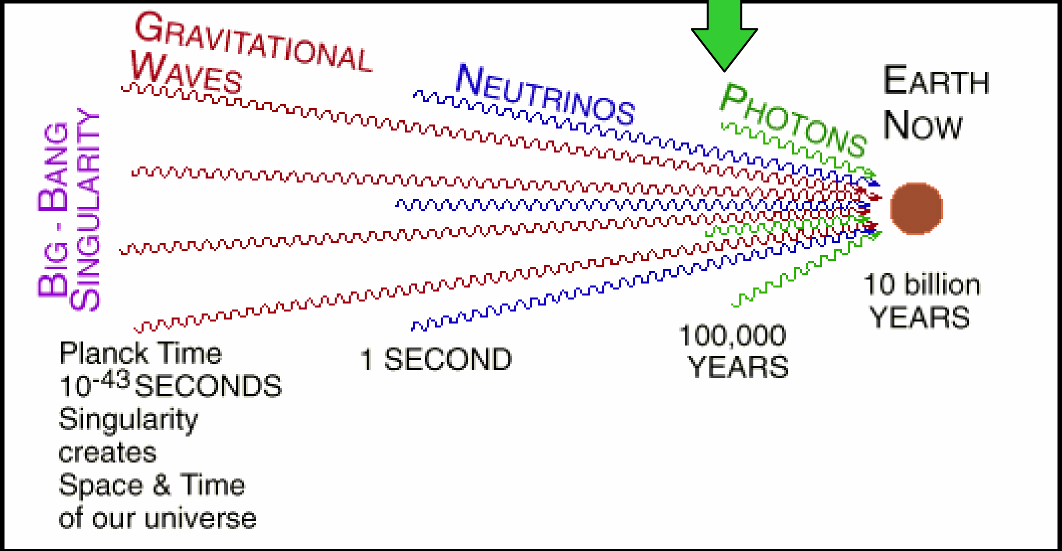
cosmic GW background (10^{-22} s)



NASA, WMAP

CMB (10^{+12} s)

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



S5 sensitivity:

Cosmic GW background limits expected to be near Ω_{GW}~10^{-5} below the BBN limit

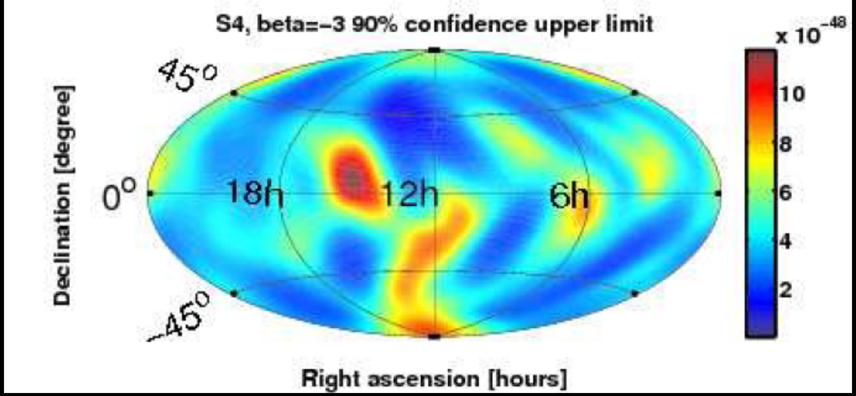
Astrophysical Sources: Stochastic Background

- Search by cross-correlating data streams (4km Hanford-Livingston)
- S4 result *[**Astrophys. J.** 659, **918 (2007)**]*
  - Searched for isotropic stochastic signal with power-law spectrum
  - For flat spectrum, set upper limit on energy density in GW:

    $\Omega_0 < 6.5 \times 10^{-5}$
  - Or look for anisotropic signal:

    none found

    *[**PRD** 76, **082003 (2007)**]*



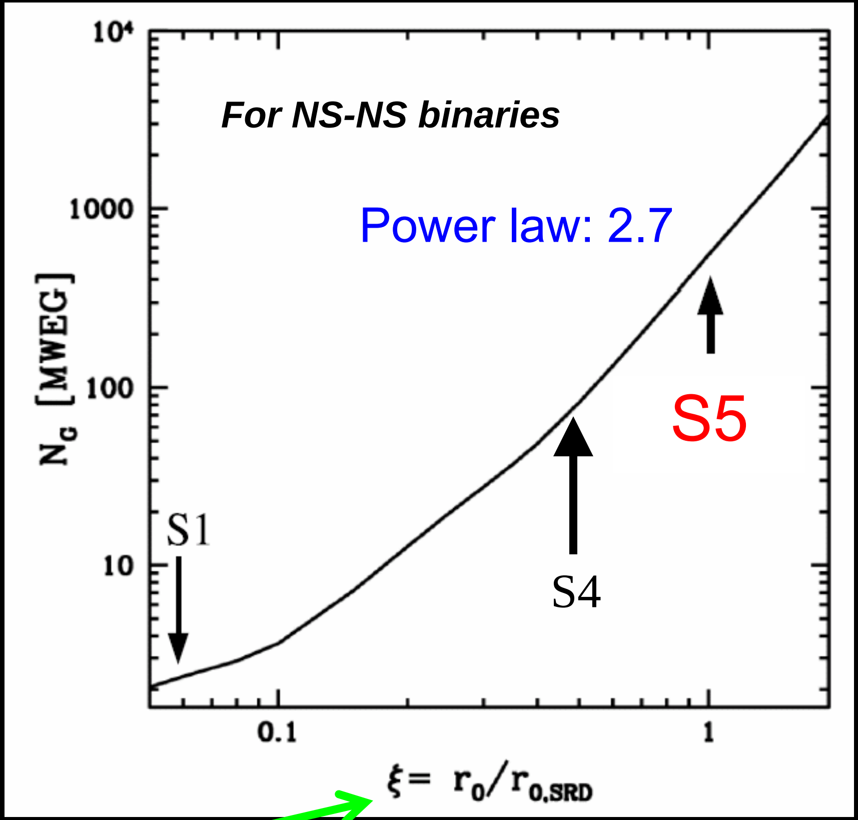
S5 analysis in progress
PRELIMINARY result
from partial run
(expect 1.7 sensitivity
improvement for full run)

- Gravitational Waves
- LIGO
- Science with LIGO
- The road ahead

NASA

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

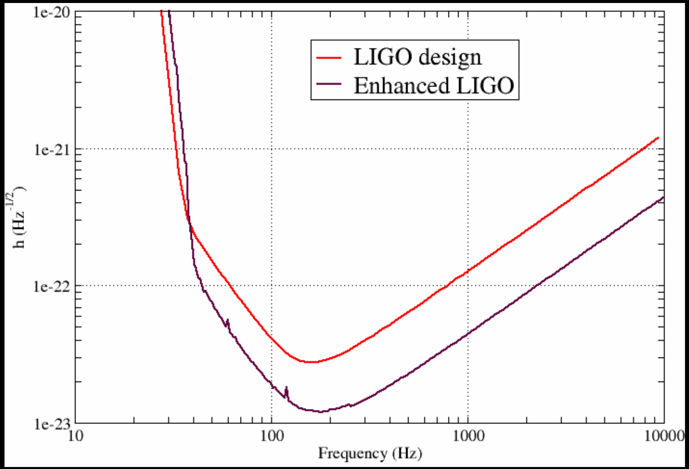
From astro-ph/0402091, Nutzman et al.



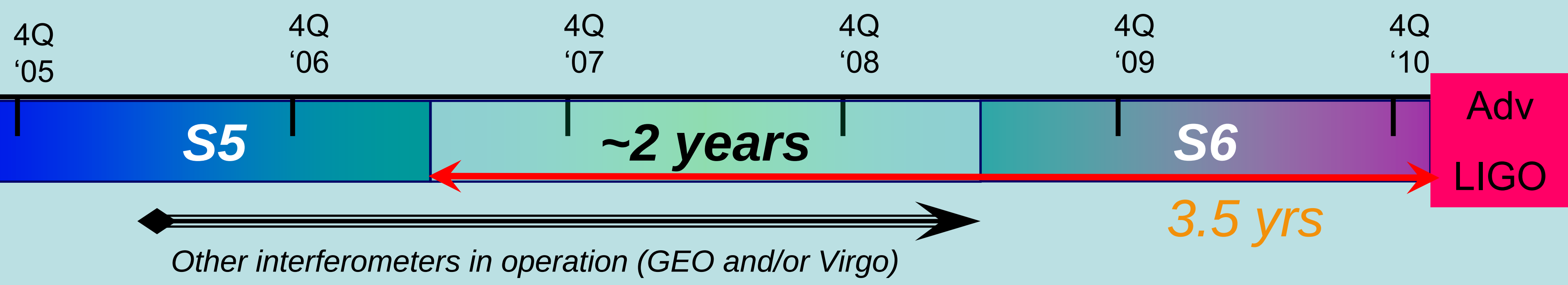
Proportional to inspiral range

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)



LIGO timeline



4Q ‘05
4Q ‘06
4Q ‘07
4Q ‘08
4Q ‘09
4Q ‘10

S5

~2 years

S6

Adv LIGO

3.5 yrs

Other interferometers in operation (GEO and/or Virgo)

- The first science run of LIGO *at design sensitivity* ended 10/01/2007
  - Hundreds of galaxies in range for $1.4\ M_{\odot}$ neutron star binary coalescences
- Enhancement program
  - In 2009 ~6.5 times more galaxies in range
- Advanced LIGO
  - Construction start expected in FY08
  - $\sim 10^3$ times more galaxies in range
  - Most probable BNS rate 40/year in ~2014

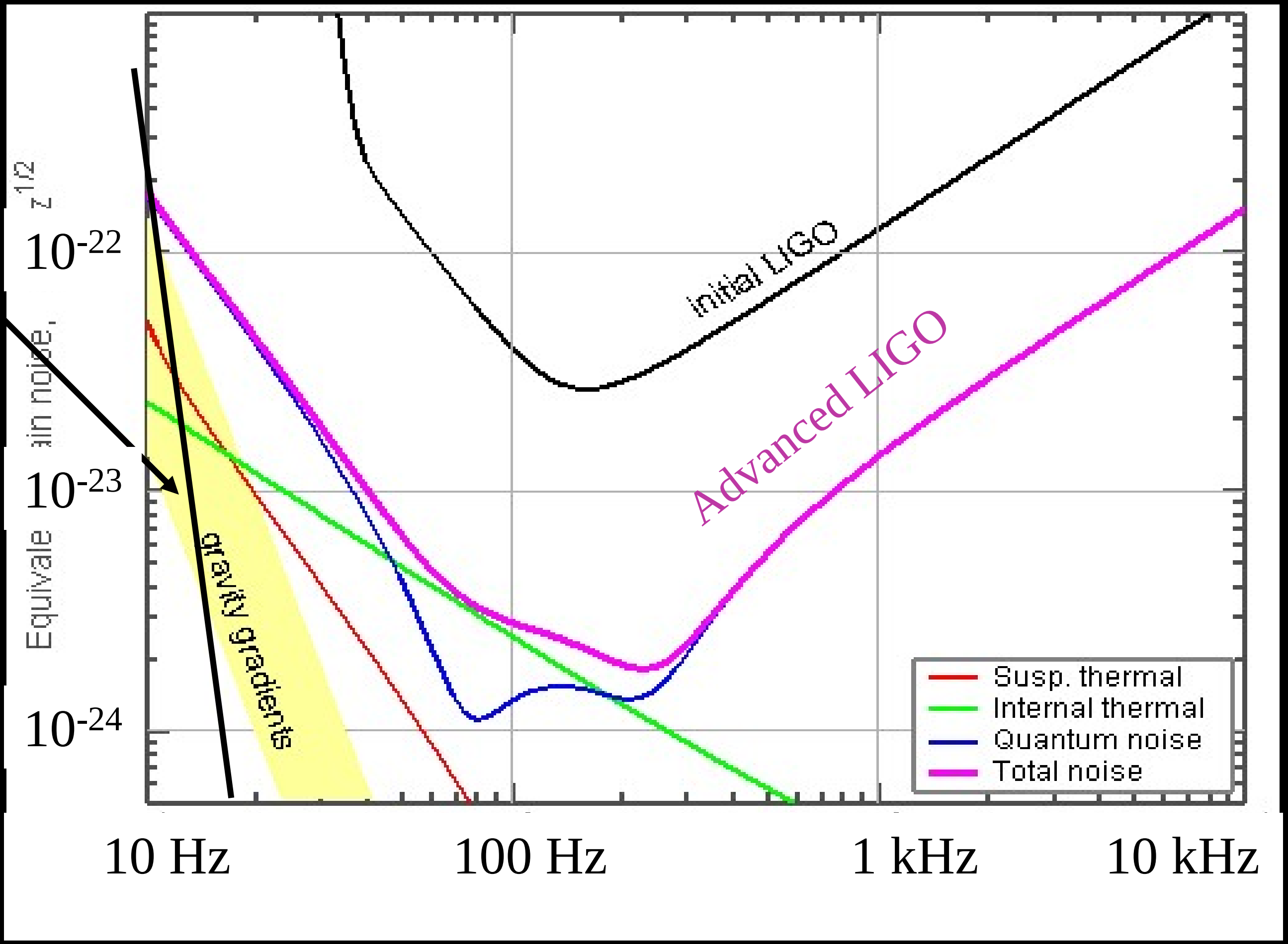
The science from the first 3 hours of Advanced LIGO should be comparable to 1 year of initial LIGO

Advanced LIGO: Approved for FY2008 Construction Start

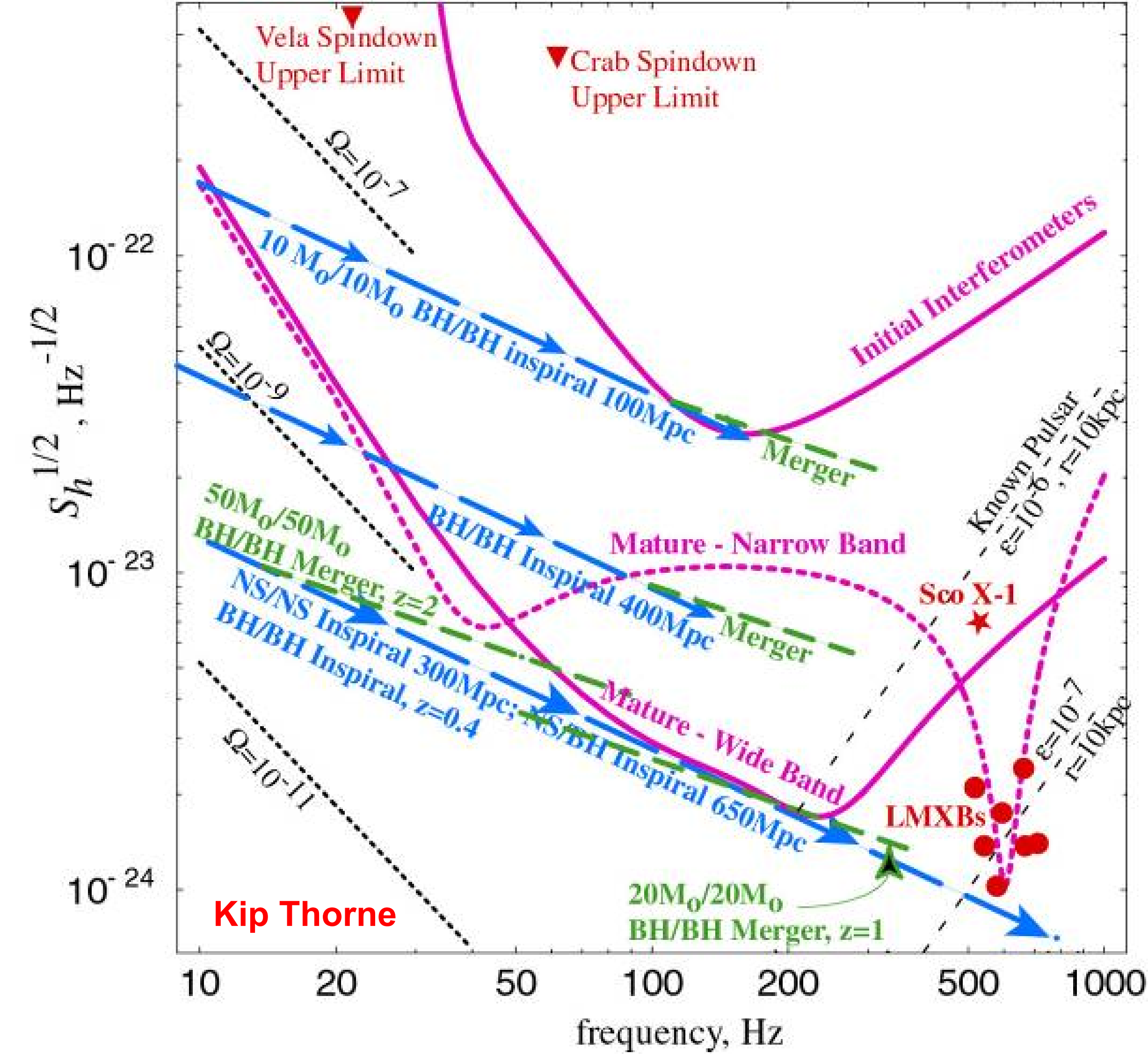
Seismic ‘cutoff’ at 10 Hz

Quantum noise

(shot noise + radiation pressure) dominates at most frequencies



Science Potential of Advanced LIGO



Kip Thorne

Binary neutron stars:

From ~20 Mpc to ~350 Mpc

From 1/100y(<1/3y) to 40/y(<5/d)

Binary black holes:

From ~100Mpc to z=2

Known pulsars:

From $\varepsilon = 3\times10^{-6}$ to 2×10^{-8}

Stochastic background:

From $\Omega_{GW} \sim 3\times10^{-6}$ to $\sim 3\times10^{-9}$

On the path to GW astronomy

We are searching for GWs at unprecedented sensitivity.

Initial LIGO completed a 2-year run at design sensitivity: we are analyzing data, detection is possible but not assured.

We are getting ready for Advanced LIGO

Sensitivity/range will be increased by ~ 2 in 2009 and another factor of 10 in ~2014 with Advanced LIGO

We are collaborating with other interferometers in a world wide effort

Virgo and LIGO are syncronizing their activities

Direct observation: Not If, but When

LIGO detectors and their siblings will open a new window to the Universe: what’s out there?

www.ligo.caltech.edu
www.ligo.org