Exploring the Gravitational Wave Sky with LIGO

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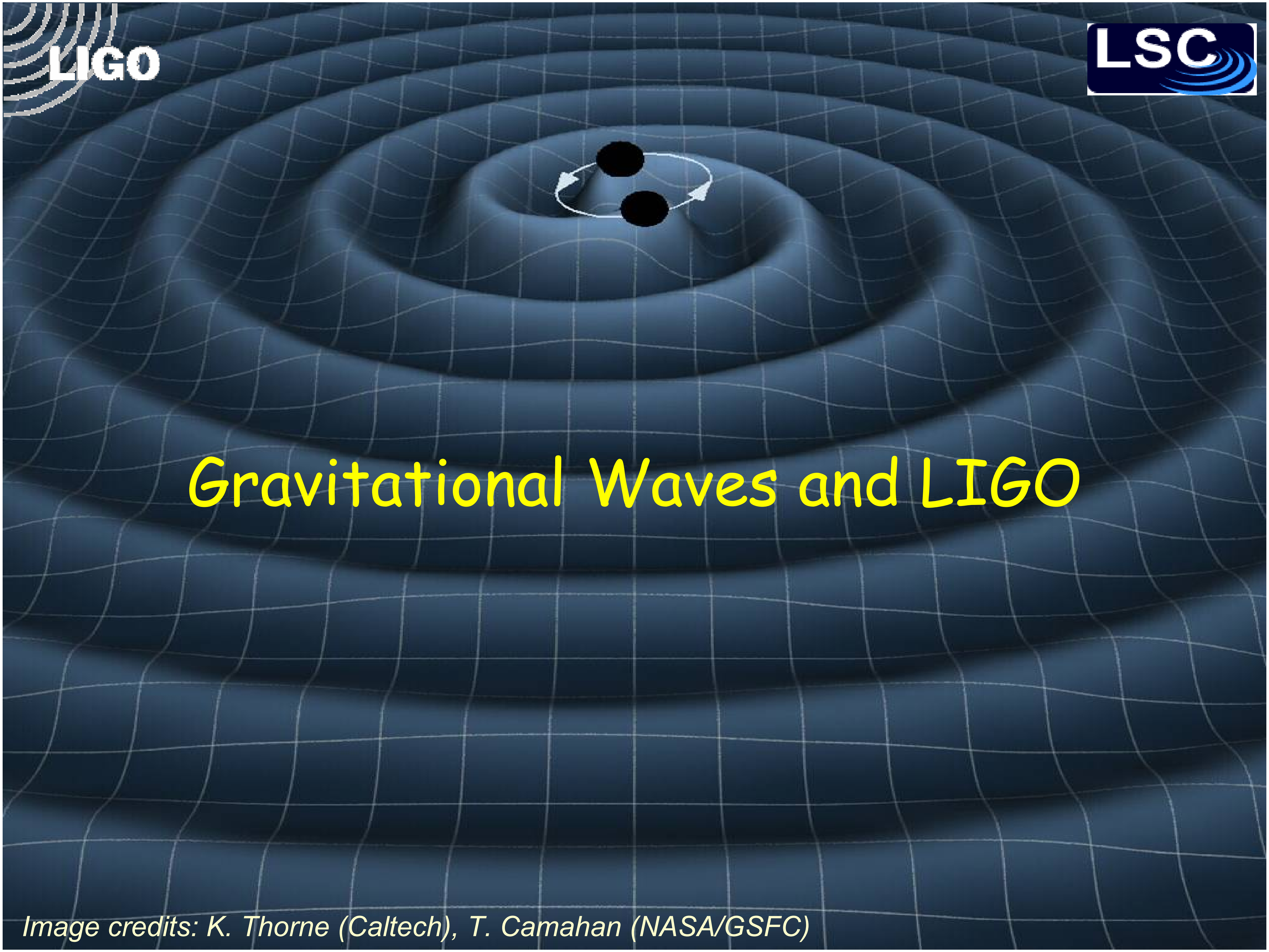
Massachusetts Institute of Technology
LIGO Scientific Collaboration

IUCF Bloomington IN, April 27 2007

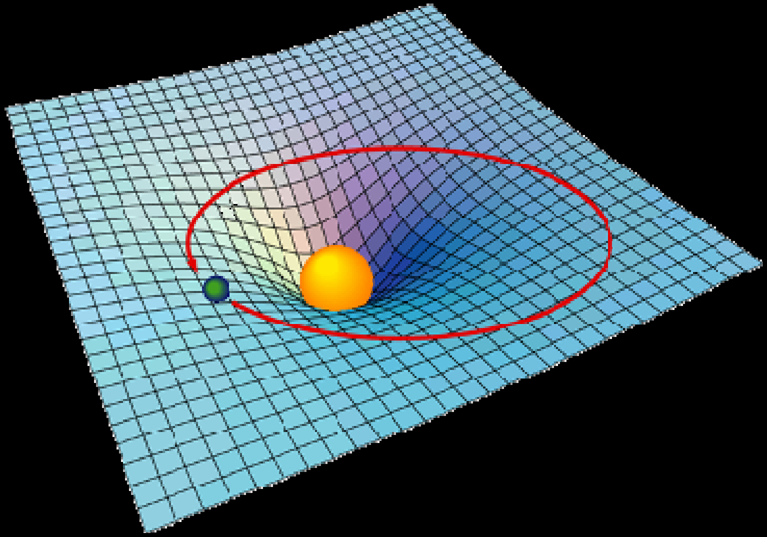
LIGO-G070251-00



Gravitational Waves and LIGO

Image credits: K. Thorne (Caltech), T. Camahan (NASA/GSFC)

Einstein's Vision: General Relativity (1916)



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

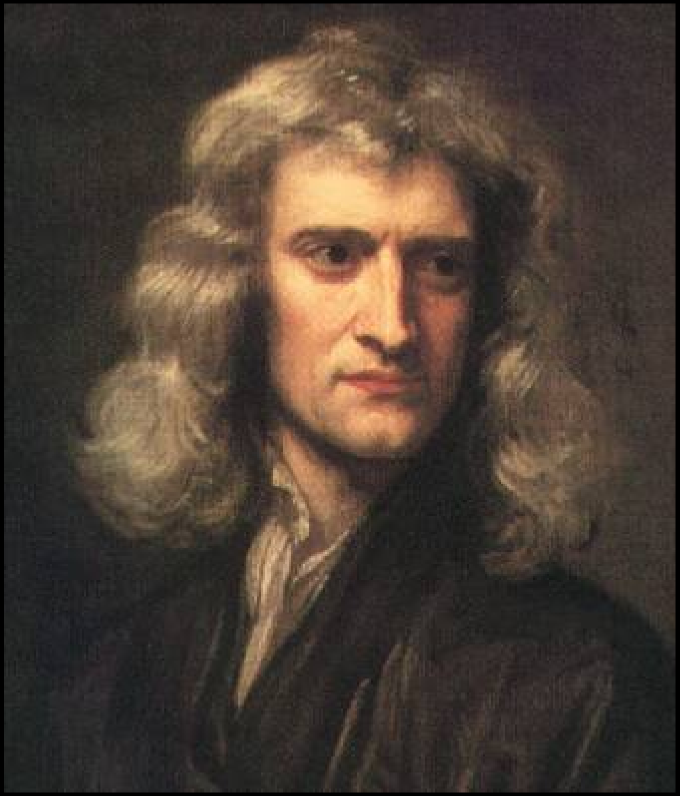
*"Mass tells space-time how to curve,
and space-time tells mass how to move."
John Archibald Wheeler*

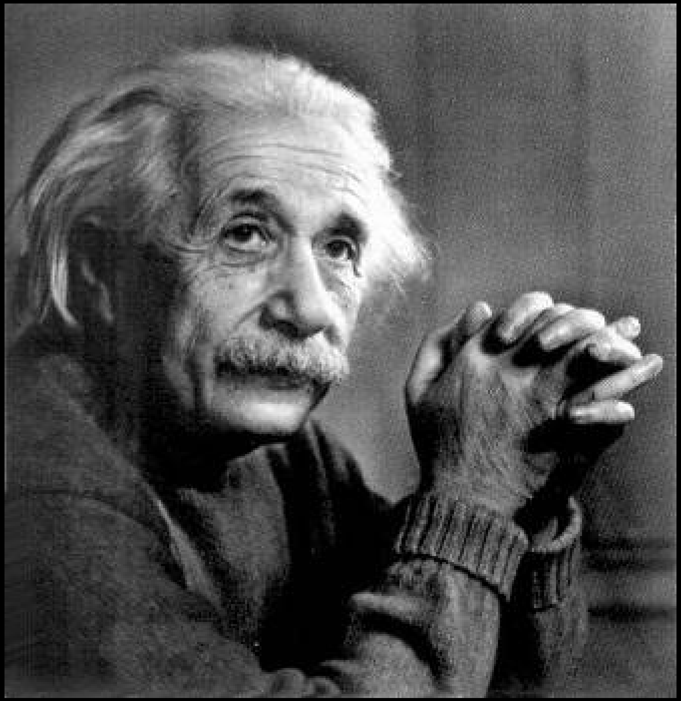
Einstein's Equations:

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

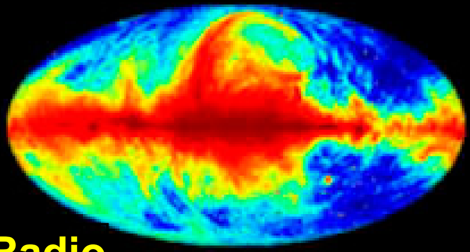




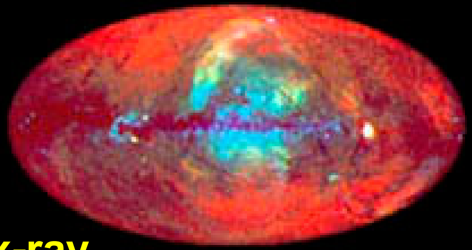
Einstein's General Relativity

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

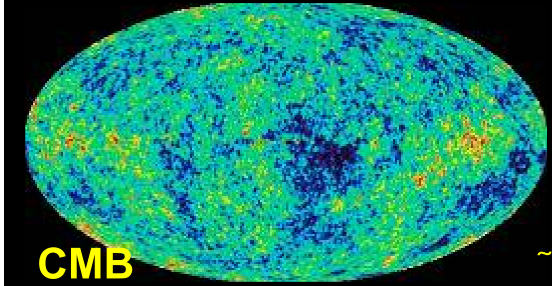
A New Probe into the Universe



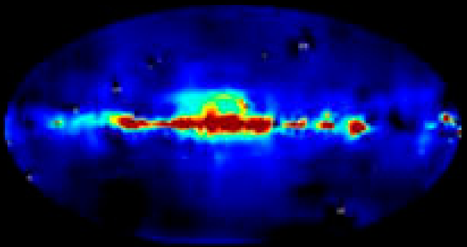
Radio



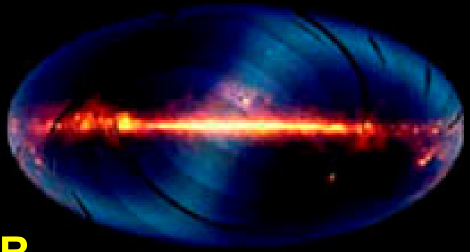
x-ray



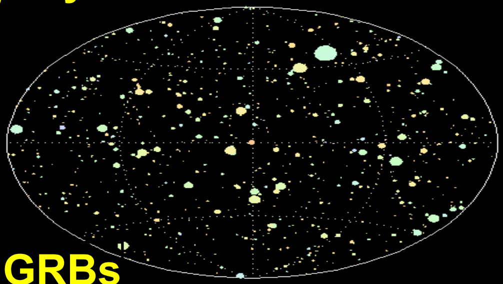
CMB



γ-ray



IR



GRBs

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

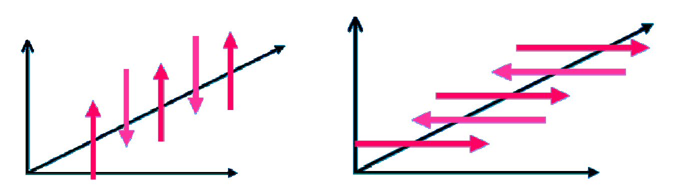
This will be complementary information, as different from what we know as *hearing* is from *seeing*.

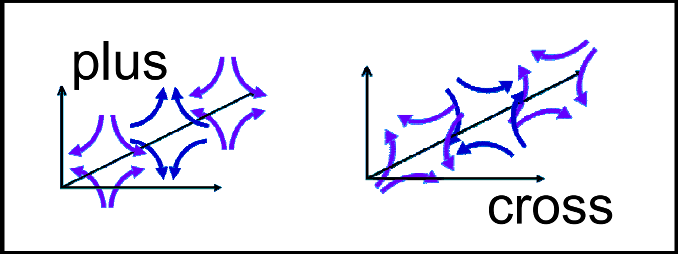
EXPECT THE UNEXPECTED!

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.

Astrophysics with E&M vs Gravitational Waves

E&M	GW
Accelerating charge	Accelerating aspherical mass
Wavelength small compared to sources ➔ images	Wavelength large compared to sources ➔ no spatial resolution
Absorbed, scattered, dispersed by matter	Very small interaction; 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

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 hearth 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 $h=\Delta L/L$

GWs are Hard to Find:
Space-Time is Stiff!

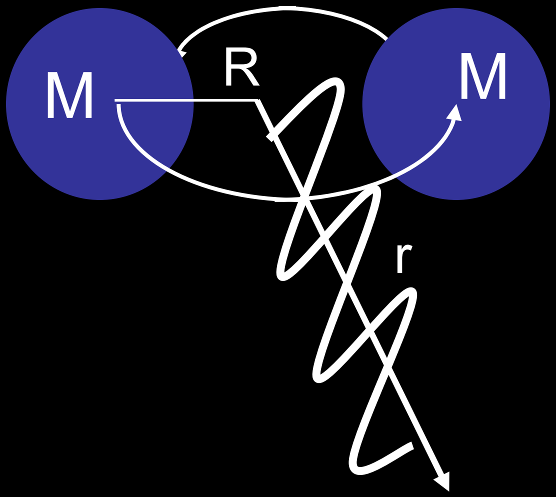
Einstein’s equations are similar to equations of elasticity: $T = (c^4/8\pi G)\,h$

$c^4/8\pi G \sim 10^{42}$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:

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



I =quadrupole mass distribution of source

$M \approx 10^{30}$ kg
$R \approx 20$ km
$F \approx 400$ Hz
$r \approx 10^{23}$ m

→ $h \sim 10^{-21}$

LIGO

LSC

The LIGO Scientific Collaboration

NAOJ 国立天文台

GEO 600

UTB TSC

Syracuse University Founded AD 1870
Suos Cultores Scientia Coronat

Montana State University

California Institute of Technology 1891

Washington State University

Northwestern University

UF University of Florida

LSU

University of Wisconsin UW Milwaukee

University of Maryland 1856

Universitat de les Illes Balears

University of Massachusetts Amherst 1863

Southern University Agricultural & Mechanical College

Hobart College

William Smith College

The University of Adelaide Australia

San José State University

PAH

Cardiff University

Andrews University
Seek Knowledge. Affirm Faith. Change the World.

Carleton College Northfield, Minn. A.D. 1866

Michigan

Loyola University New Orleans

Southeastern Louisiana University

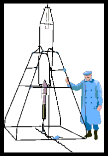
Universität Hannover

Rochester Institute of Technology R·I·T 1829

IGR

PennState 1855

The University of Western Australia

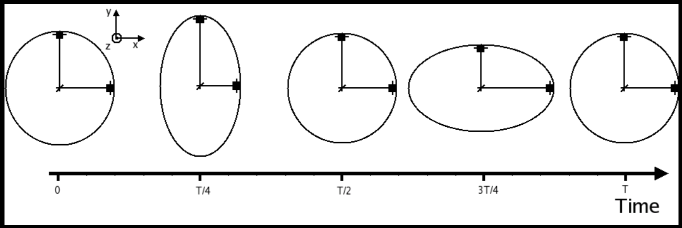


Leland Stanford Junior University Organized 1891

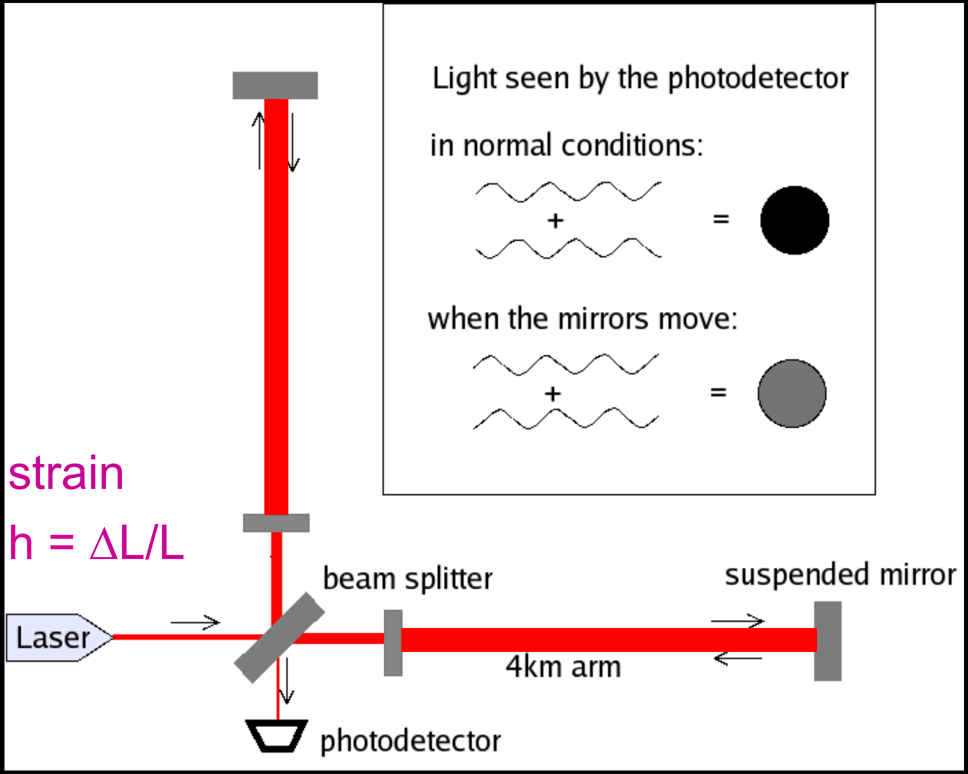
Columbia University in the City of New York

Massachusetts Institute of Technology

The LIGO Observatory

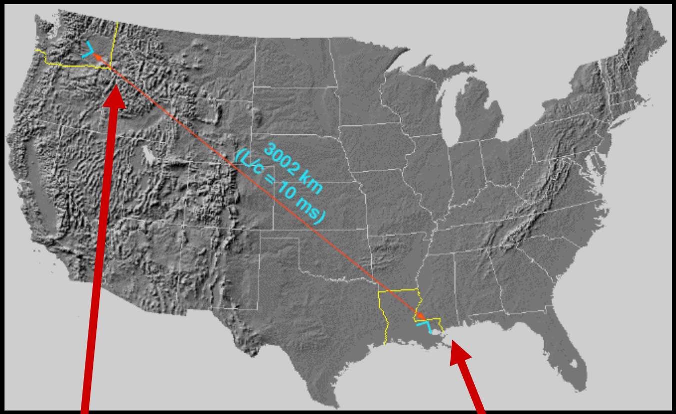


Initial goal: measure difference in length to one part in 10^{21}, or 10^{-18} m



strain

$h = \Delta L/L$



Hanford Observatory
4 km and 2 km interferometers
H1 and H2

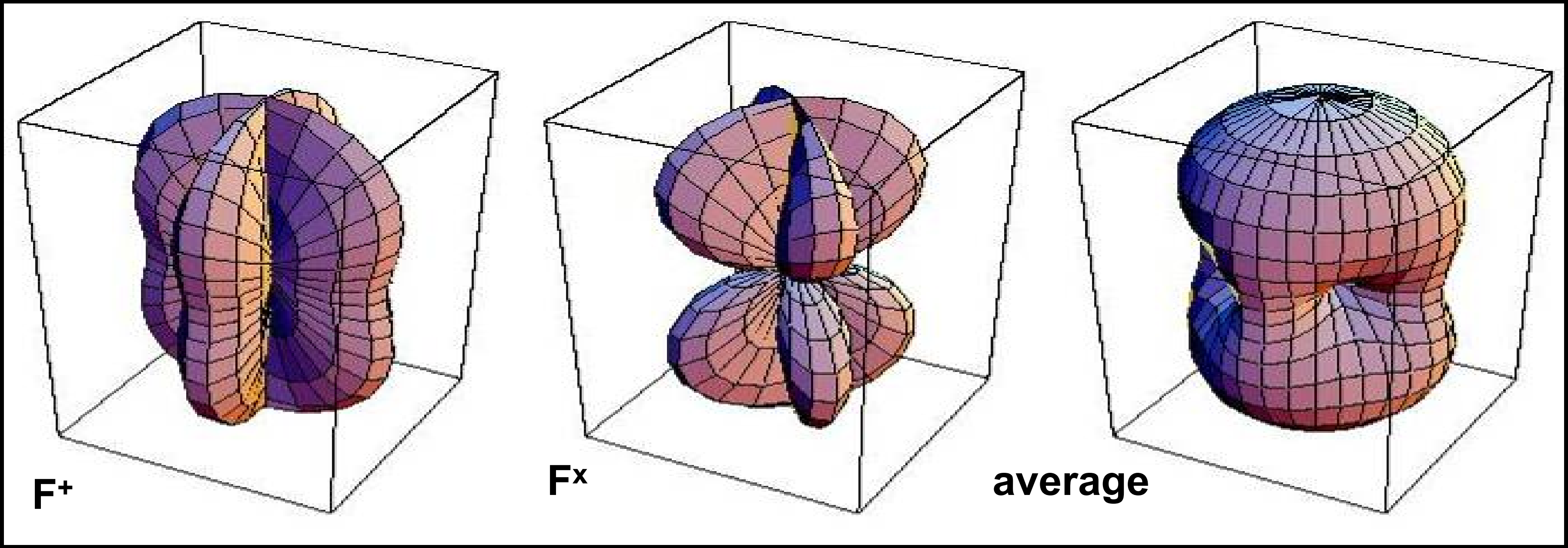
Livingston Observatory
4 km interferometer
L1

Giant "Ears"
Listen to the Vibrations of the Universe

Beam patterns:

$F^{+}, F^{\times}$: [-1, 1] $F = F(t; \alpha, \delta)$

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



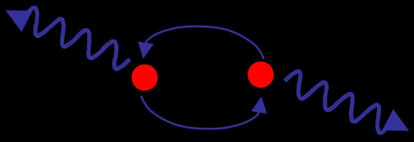
Science with LIGO: Sources Lurking in the Dark

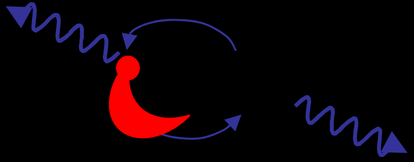
- Binary systems
  - Neutron star – Neutron star
  - Black hole – Neutron star
  - Black hole – Black hole
- “Burst” Sources
  - Supernovae
    - Gamma ray bursts

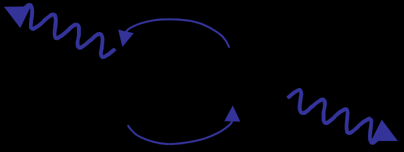
- Residual Gravitational Radiation from the Big Bang

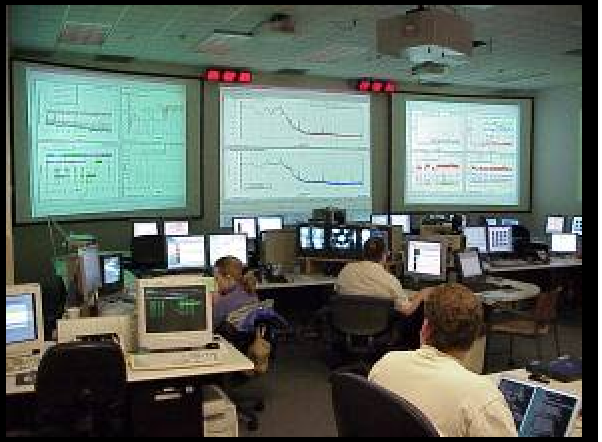
- Periodic Sources
  - Rotating pulsars

- ?????

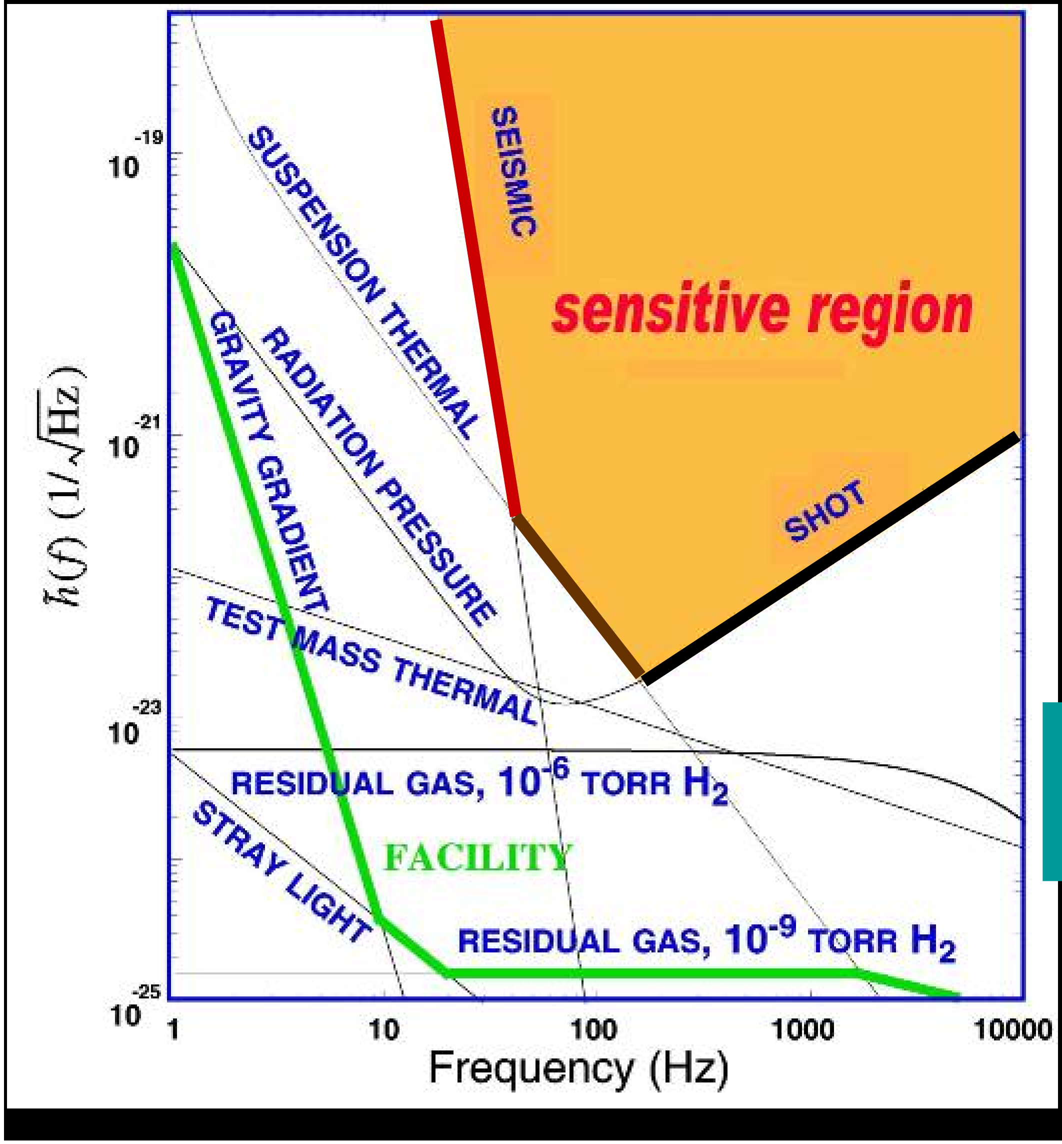


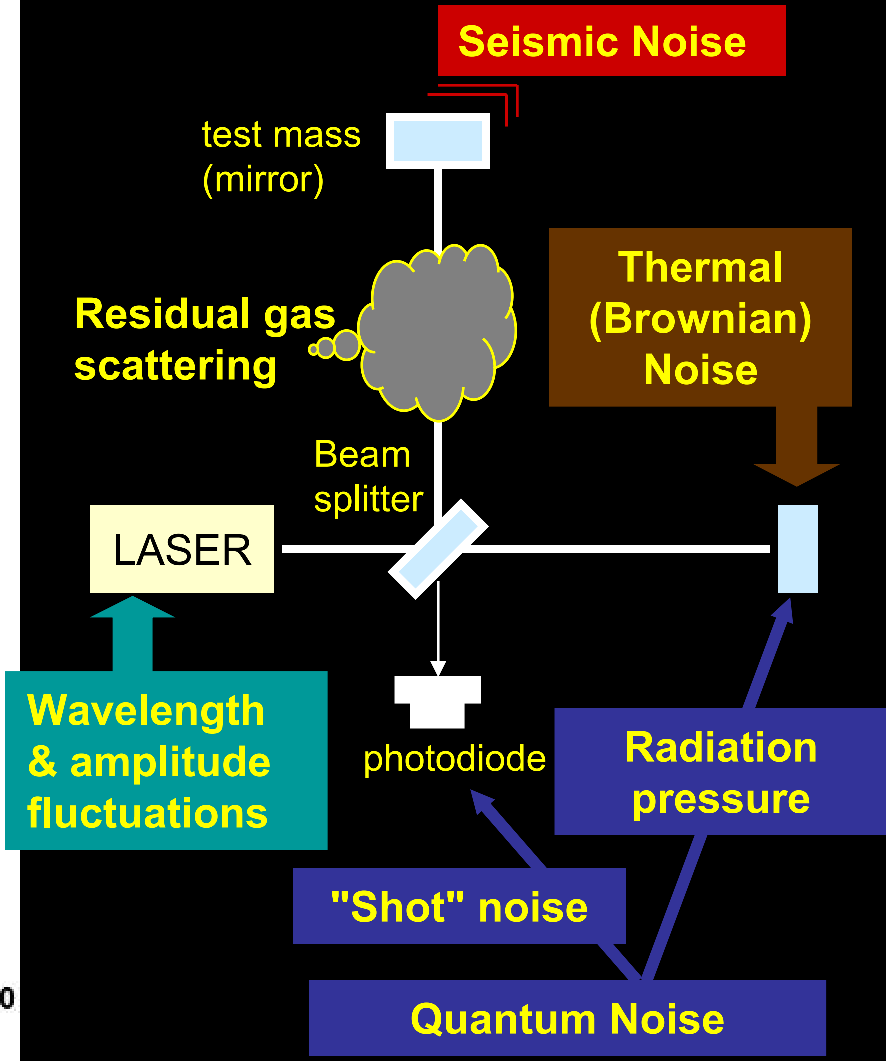






Initial LIGO Sensitivity Limits





Seismic Noise

test mass (mirror)

Residual gas scattering

Thermal (Brownian) Noise

Beam splitter

LASER

photodiode

Wavelength & amplitude fluctuations

Radiation pressure

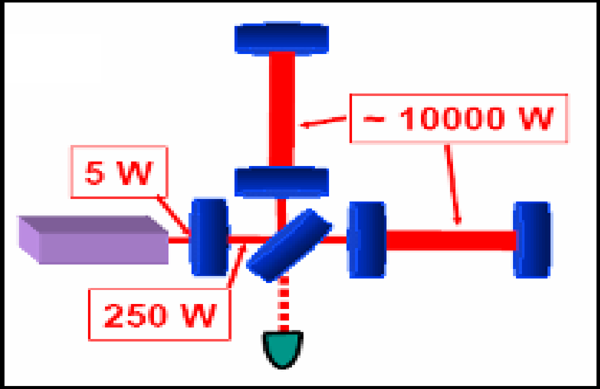
"Shot" noise

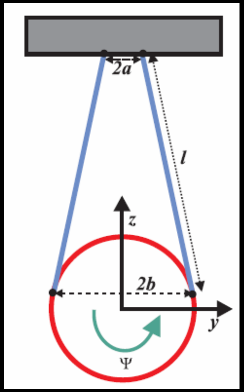
Quantum Noise

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:

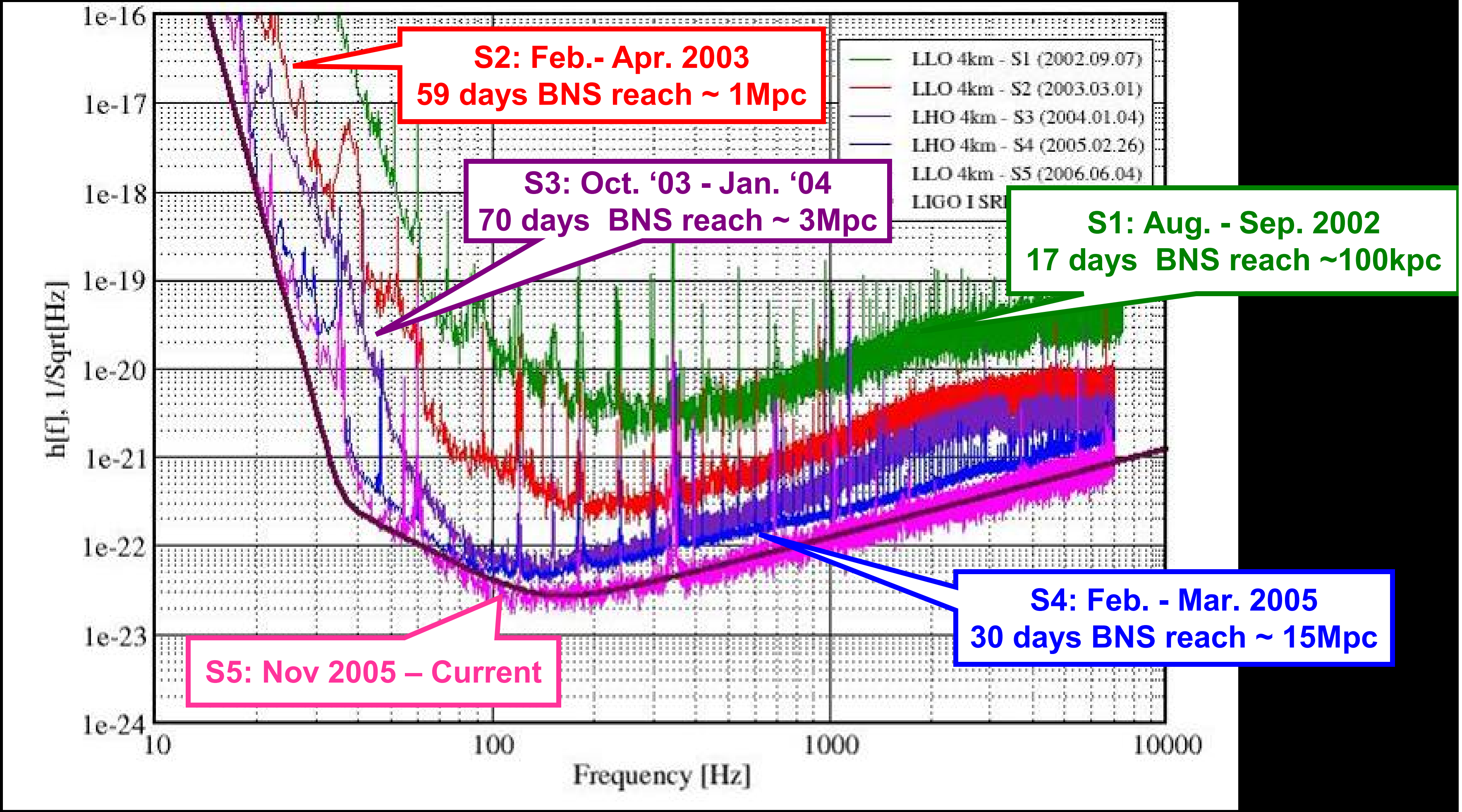
Passive isolation stacks
Pendulum suspension
Active isolation at LLO

All under vacuum

Despite some obstacles along the way...

…LIGO meets its experimental challenges

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



S2: Feb.- Apr. 2003
59 days BNS reach ~ 1Mpc

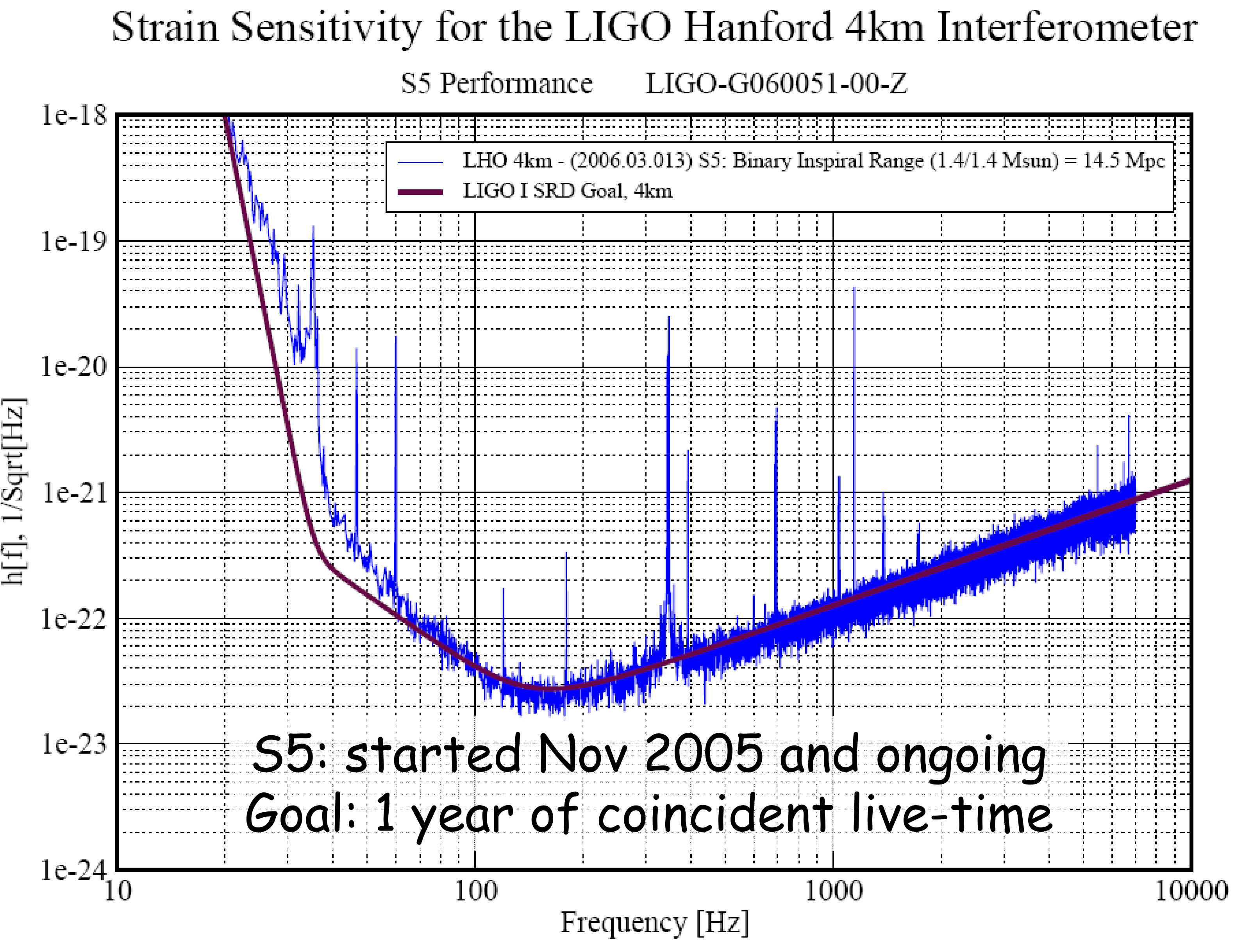
S3: Oct. '03 - Jan. '04
70 days BNS reach ~ 3Mpc

S1: Aug. - Sep. 2002
17 days BNS reach ~100kpc

S4: Feb. - Mar. 2005
30 days BNS reach ~ 15Mpc

S5: Nov 2005 – Current

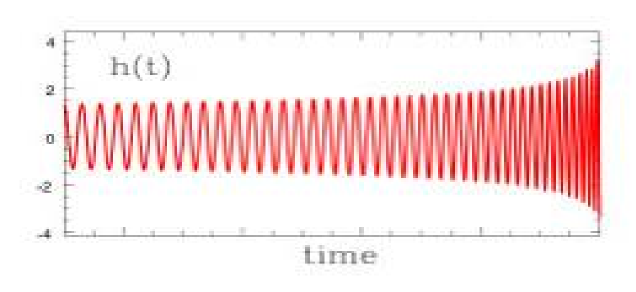
Science Run 5



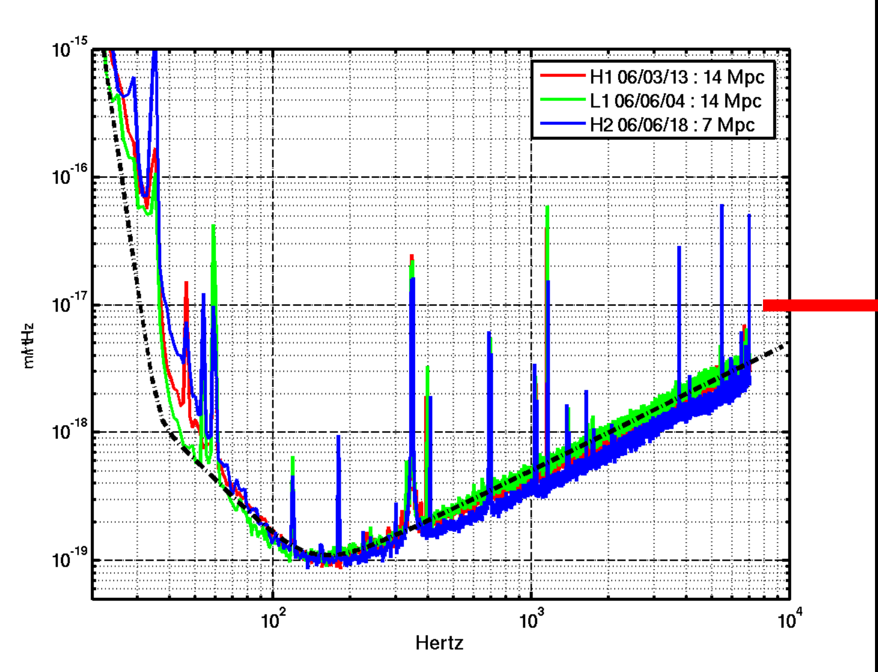
S5: started Nov 2005 and ongoing

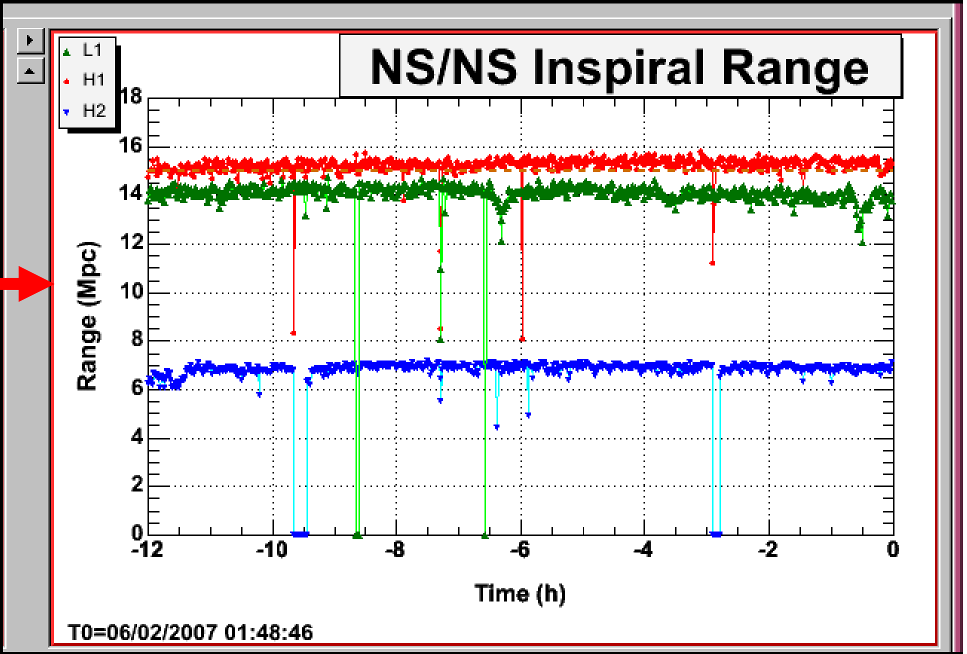
Goal: 1 year of coincident live-time

Binary Neutron Stars: a Measure of Performance



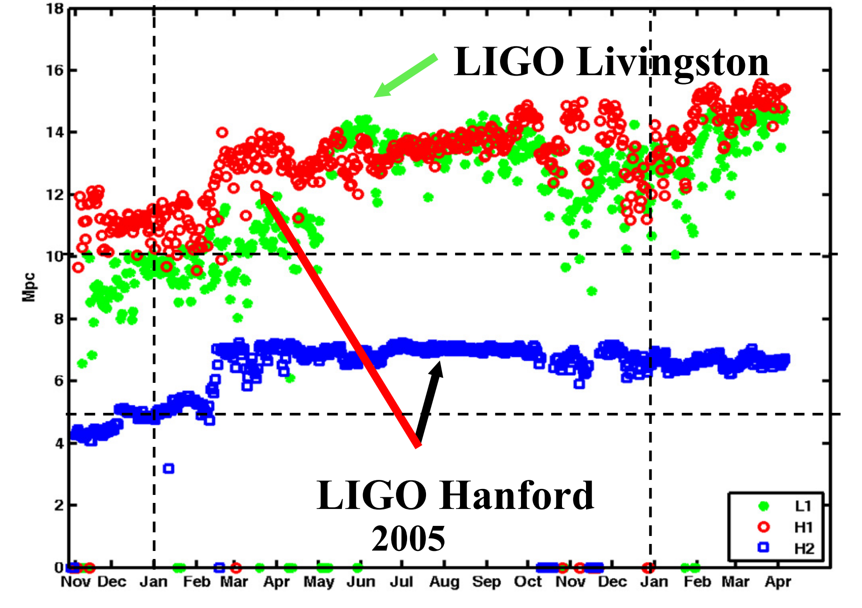
The inspiral waveform for BNS is known analytically from post-Newtonian approximations. We can translate strain amplitude into (effective) distance.





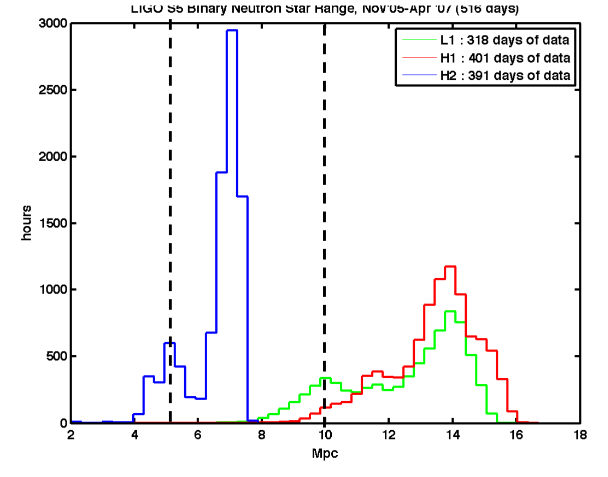
Range: distance of a 1.4-1.4 M binary, averaged over orientation/polarization
Predicted rate for S5: 1/3year (most optimistic), 1/100years (most likely)

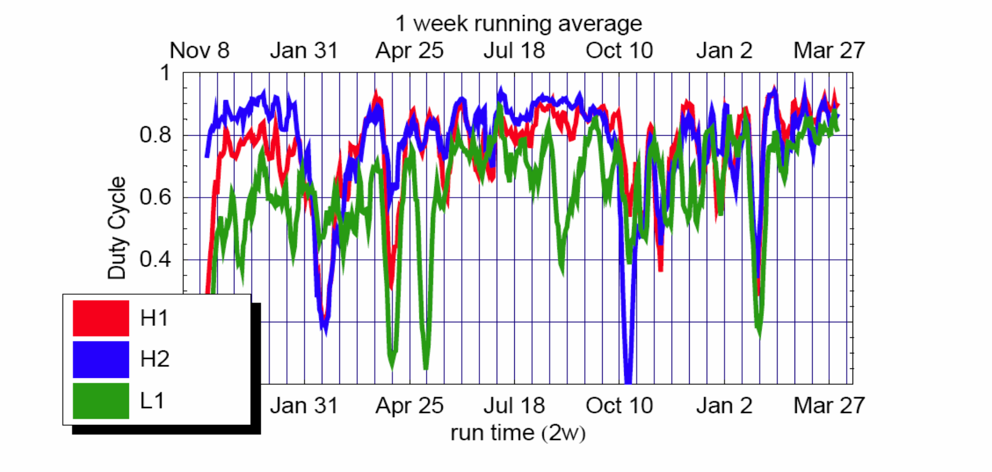
S5 so far…



Science-mode statistics for S5 run
Up to Apr 08 2007 19:21:05 UTC
Elapsed run time = 12483.4 hours = 520 days
------------------------ Whole run so far ---------------

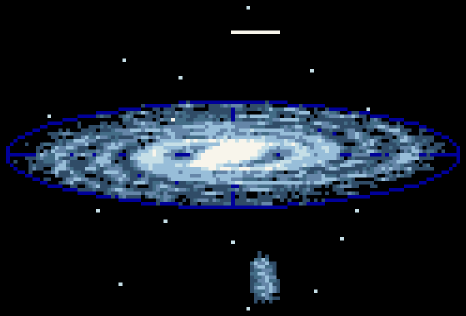
Sample	**Hours**	**Duty factor**
H1	9340.1	74.8 since Nov 4, 2005
H2	9644.3	77.3 since Nov 4, 2005
L1	7784.5	63.6 since Nov 14, 2005
H1+H2+L1	6108.4	49.9 since Nov 14, 2005
(H1orH2)+L1	7054.2	56.5 since Nov 4, 2005
One or more LIGO	11124.5	89.1 since Nov 4, 2005
One or more LSC	11841.6	94.9 since Nov 4, 2005

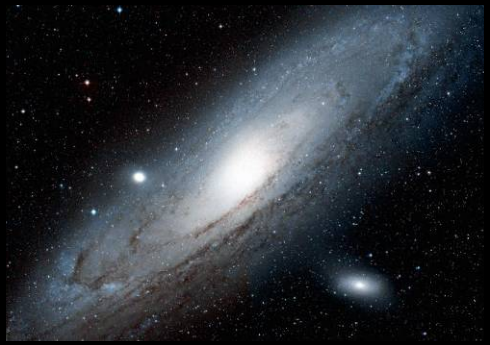




Progress in Sensitivity

Average distance for detecting a coalescing neutron-star binary:





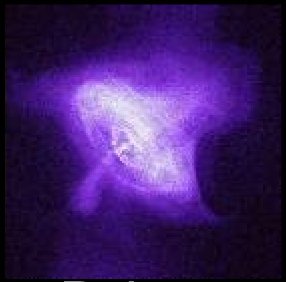
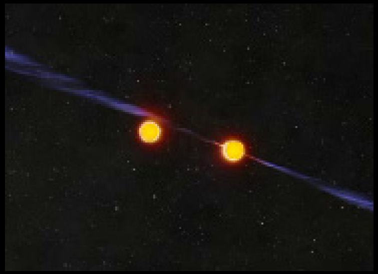
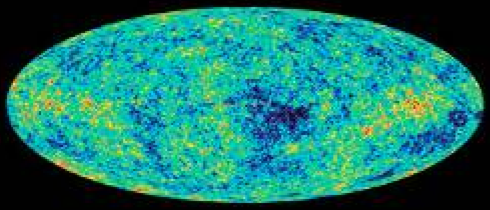
Milky Way (8.5 kpc)	Andromeda (700 kpc)	Virgo Cluster (15 Mpc)
Sept 2002 [~1 galaxy]	March 2003 [~2 galaxies]	now [~10^3 galaxies]

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

Astrophysical Searches

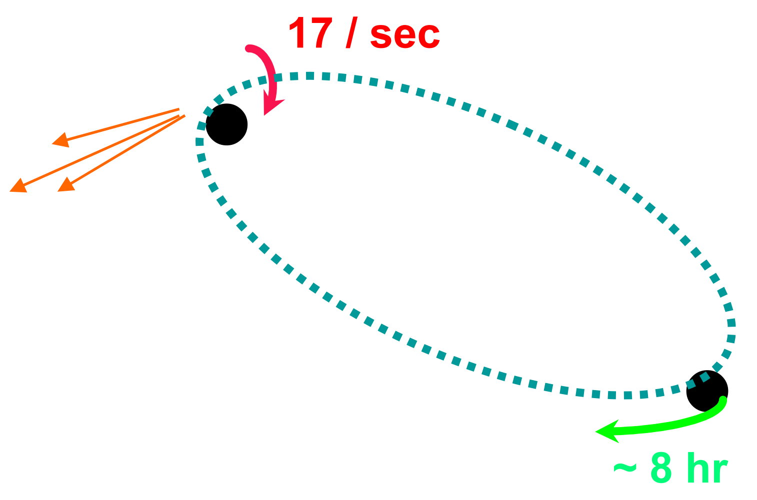
Image Courtesy: Library of Congress

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

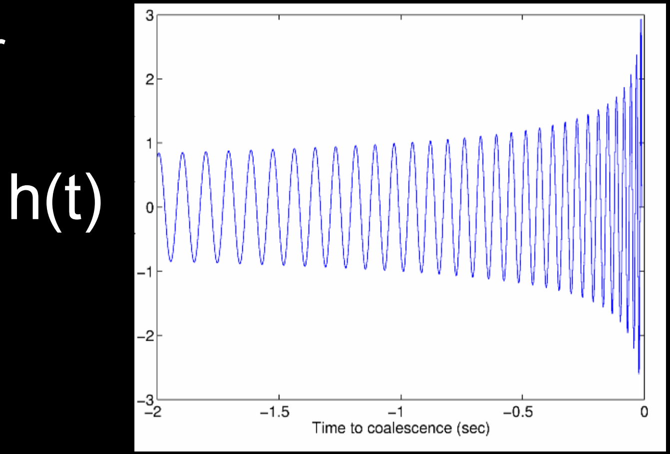
Neutron Star Binary System

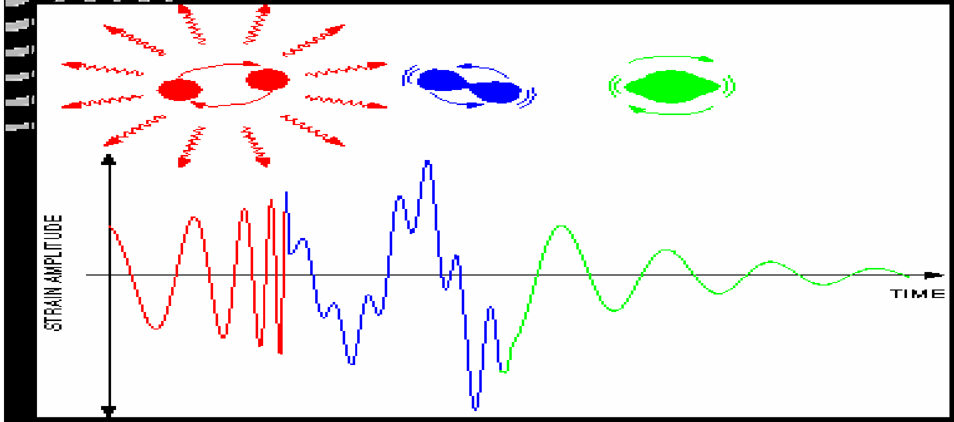
- separated by 10^6 miles
- $m_1 = 1.4M_\odot$ $m_2 = 1.36M_\odot$

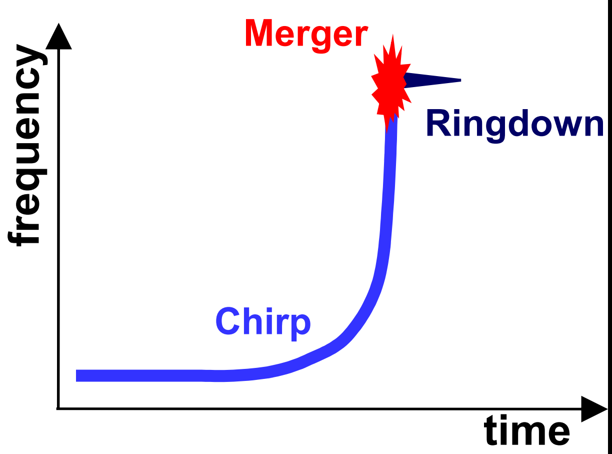
Exact match to general relativity

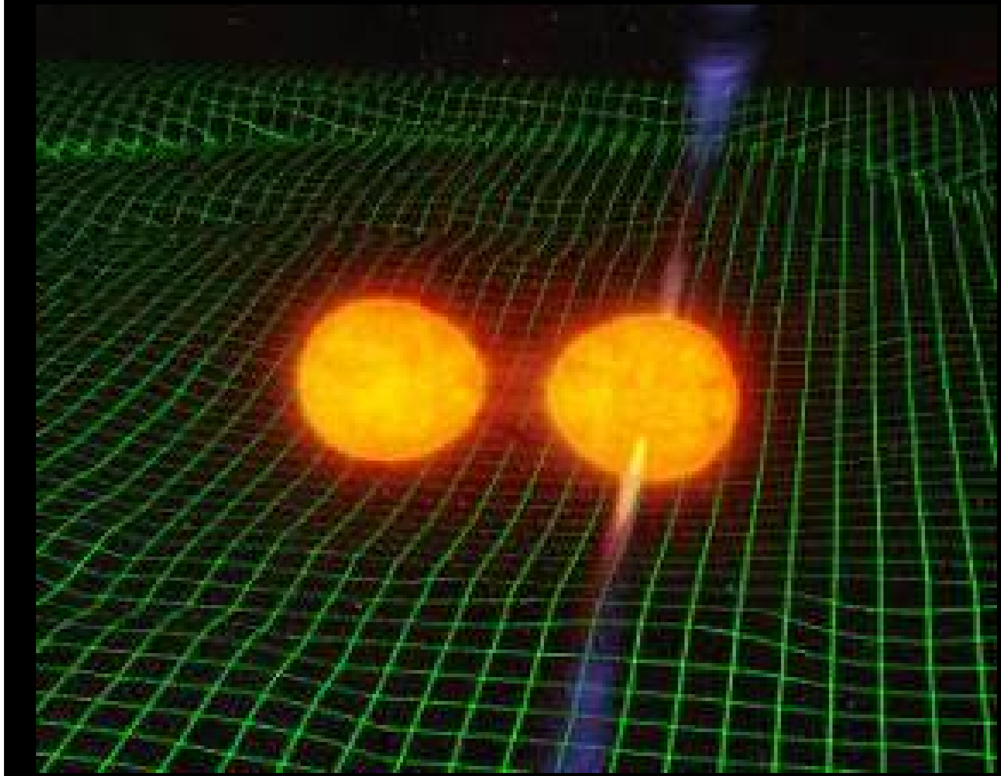
- spiral in by 3 mm/orbit
- shortening of orbital period

- 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









Credits: John Rowe Animation

Inspiral chirp:

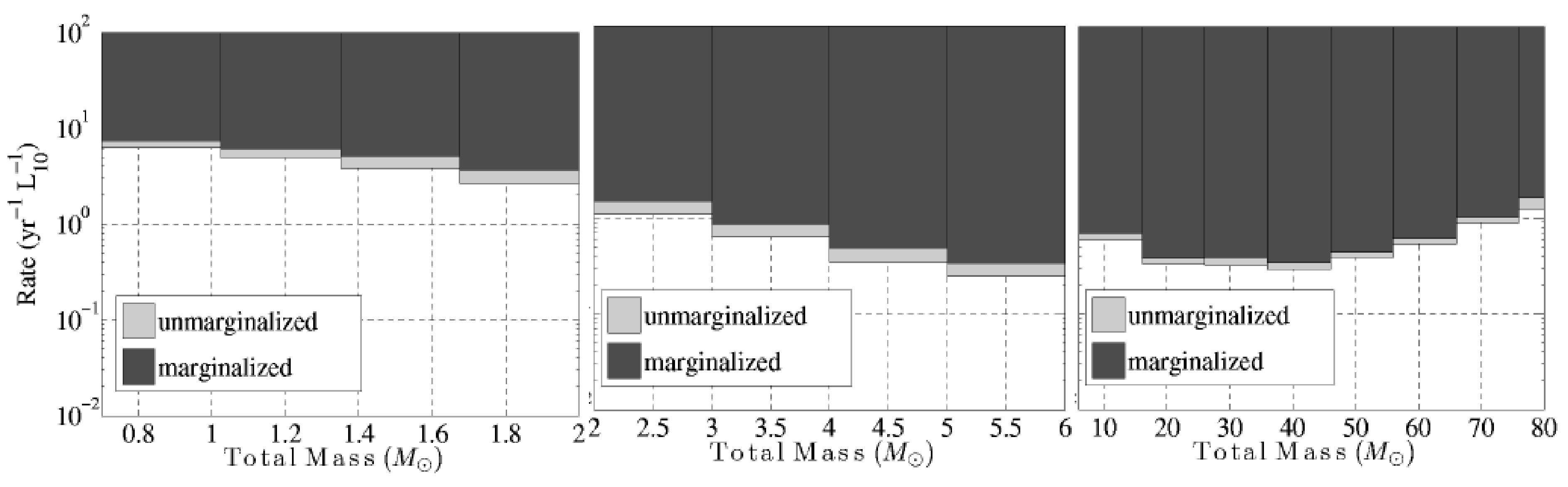
- Amplitude and duration only depend on the masses m_1 and m_2 and the lower cutoff frequency.
- Neglect spin for now
- D_{eff} effective distance, depends on the physical distance r and on orientation of the binary system; $D_{eff}>r$

Method: matched filter,
coincidence between detectors, vetoes

S4 Upper Limits for Binary Coalescences

- Rate/L_{10} vs. binary total mass

  $L_{10} = 10^{10}\ L_{sun,B}$ (1 Milky Way = 1.7 L_{10})
- Dark region excluded at 90% confidence



arXiv:074-3368

Horizon in S5

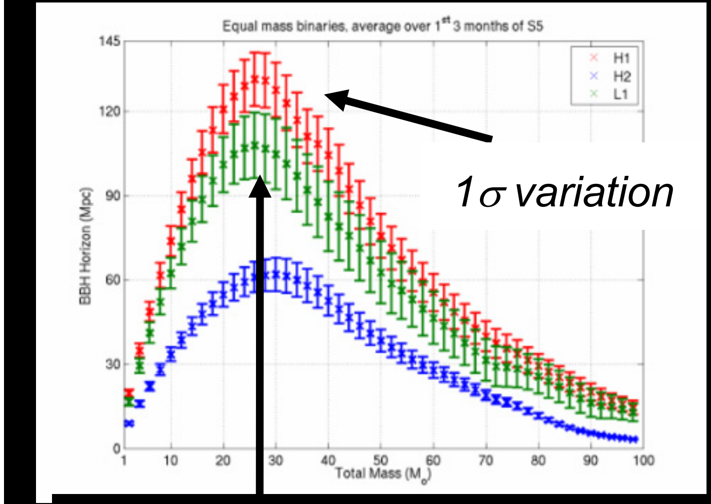
distance at which an optimally oriented and located binary system can be seen with signal-to-noise ratio $\rho=8$

For 1.4-1.4 M_o binaries:

~ 200 MWEGs in range

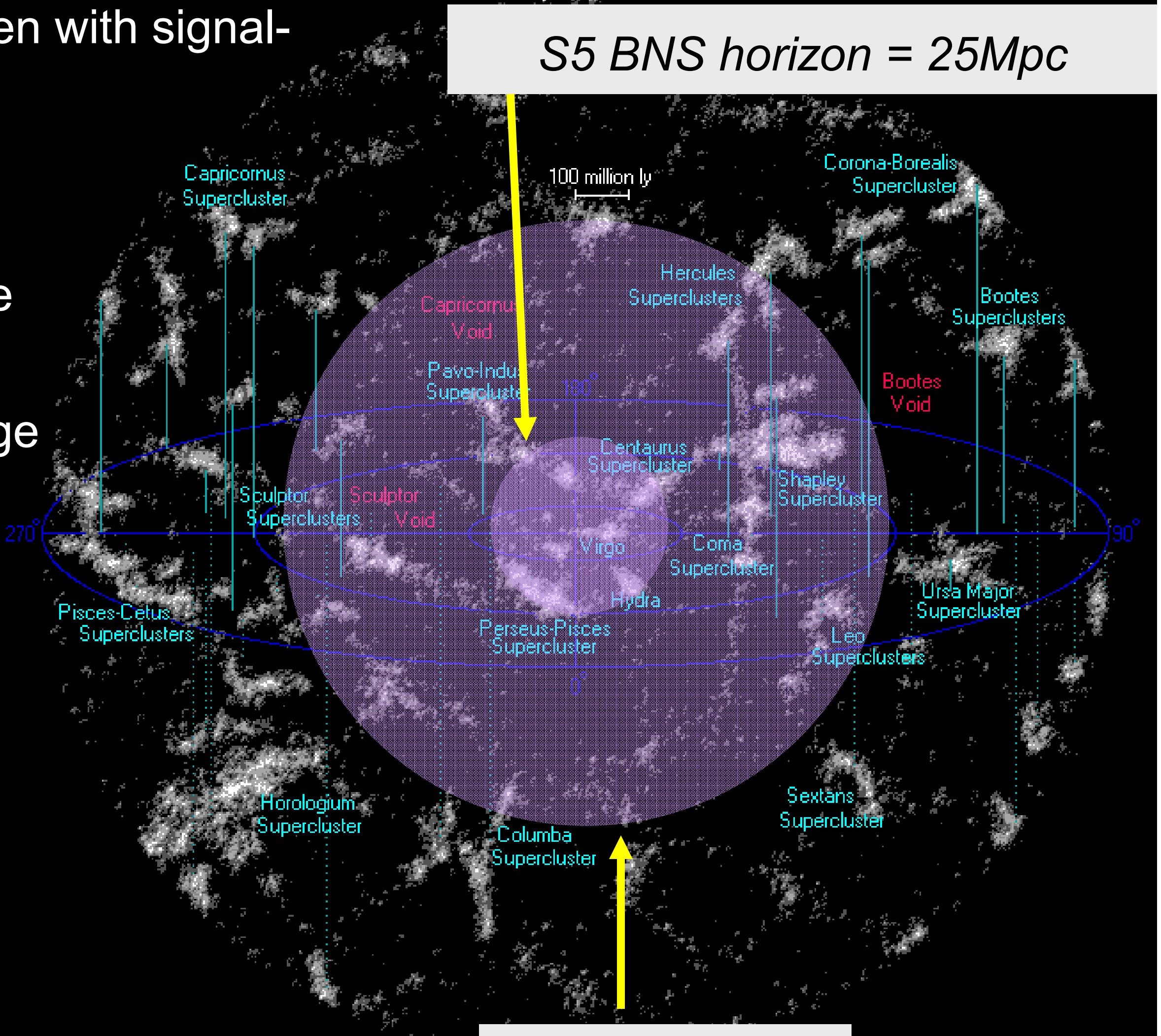
For 5-5 M_o binaries:

~ 1000 MWEGs in range



1σ variation

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

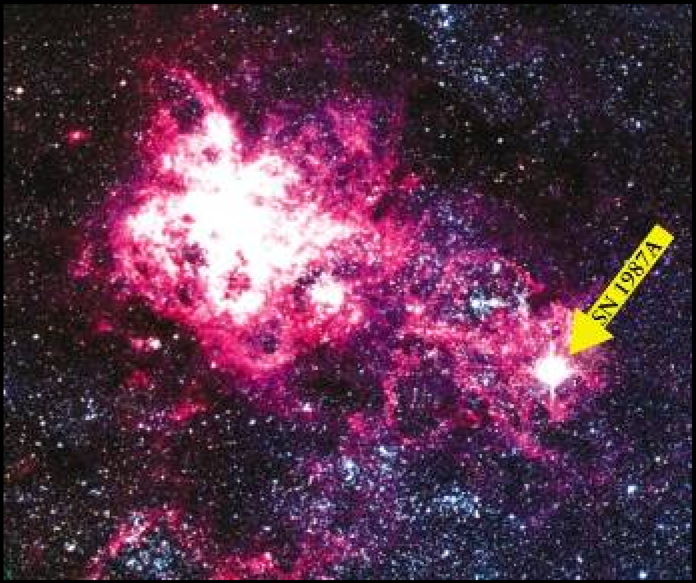


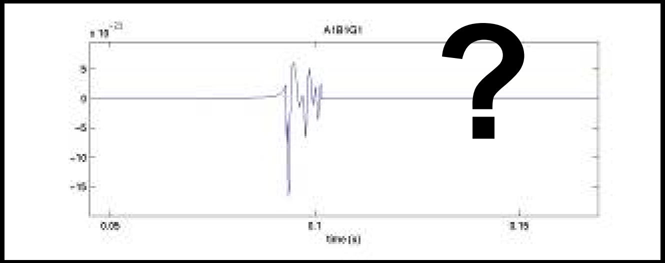
S5 BNS horizon = 25Mpc

S5 BBH horizon

Image: R. Powell

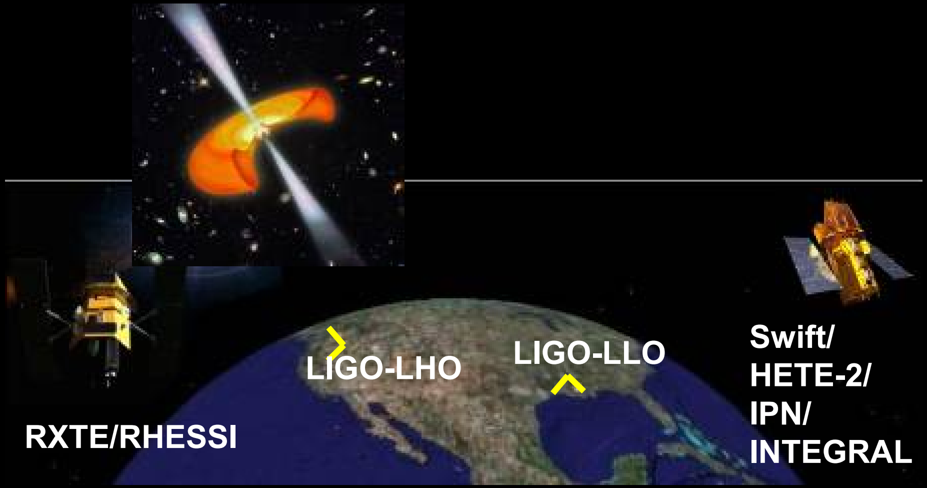
Astrophysical Sources: Bursts



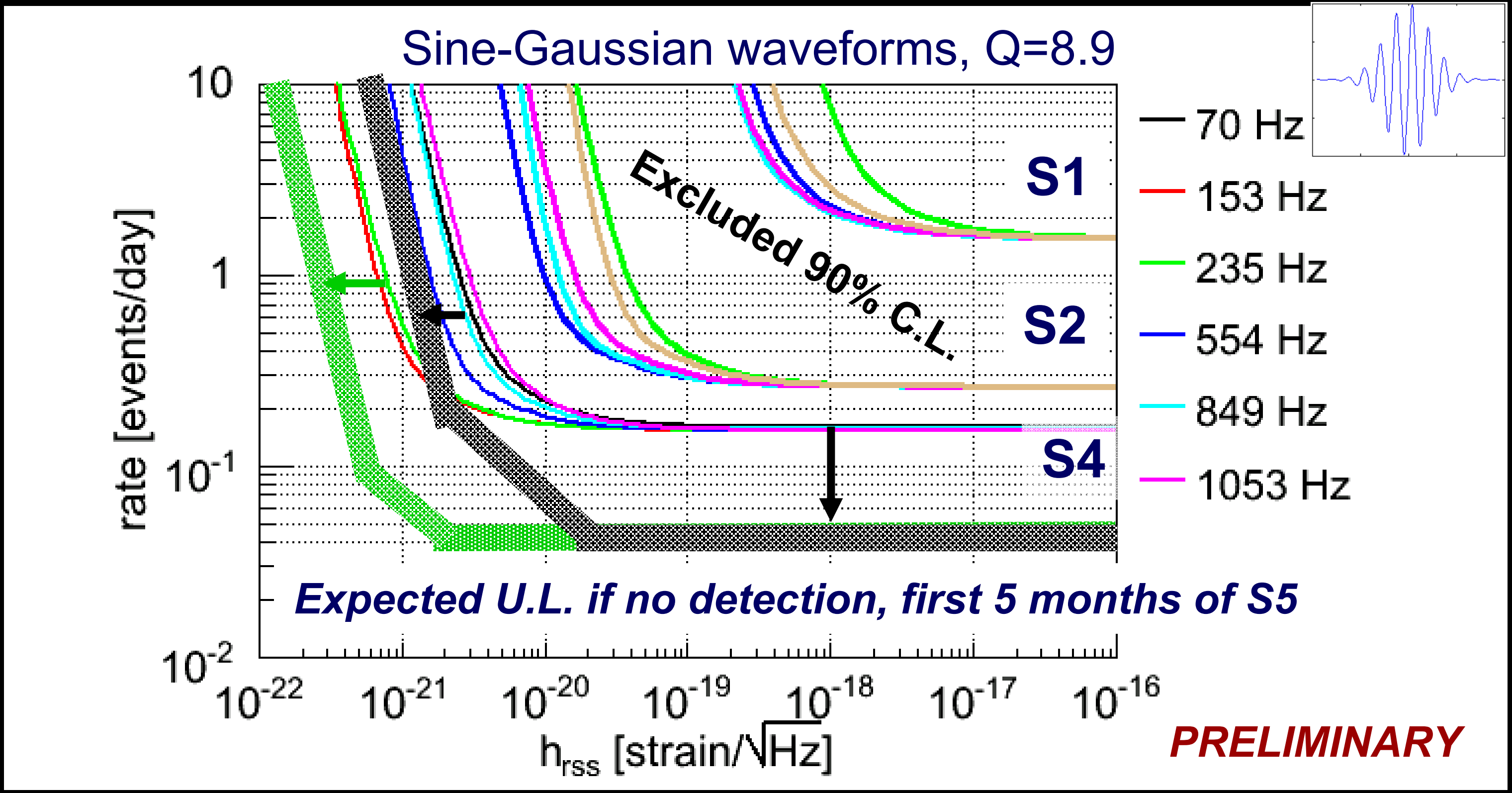


Uncertainty of waveforms complicates the detection ⇒ minimal assumptions, open to the unexpected

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



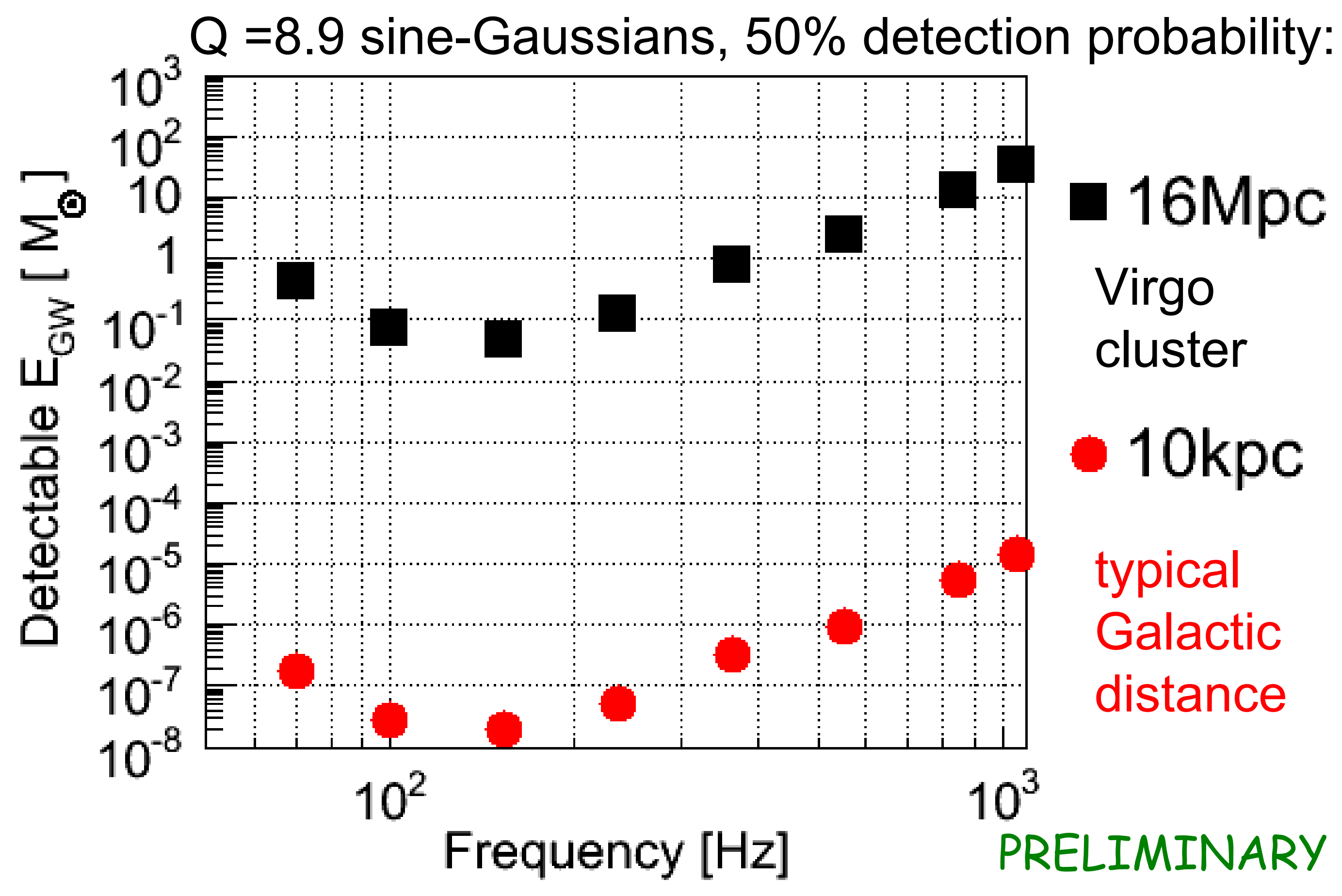
Exclusion Curves from S1 to S5



$$h_{\mathrm{rss}} \equiv \sqrt{\int \left(|h_+(t)|^2 + |h_\times(t)|^2 \right) dt}$$

- Detection algorithms
  tuned for 64–1600 Hz, duration << 1 sec
- Veto thresholds pre-established before looking at data (blind analysis)

S5 Detection Efficiency / Range

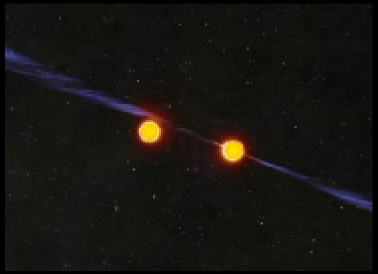
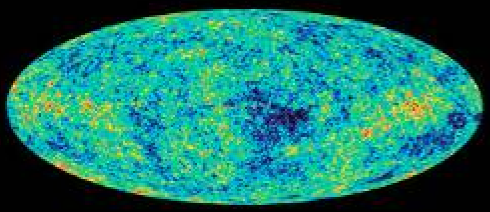
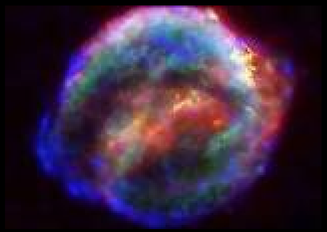


For a 153 Hz, Q =8.9 sine-Gaussian, the S5 search can see with 50% probability:

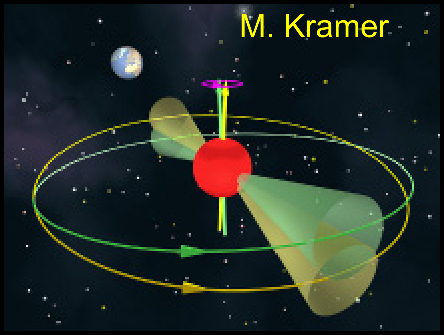
~ $2 \times 10^{-8}\ M_{\odot} c^2$ at 10 kpc (typical Galactic distance)

~ $0.05\ M_{\odot} c^2$ at 16 Mpc (Virgo cluster)

Sources And Methods

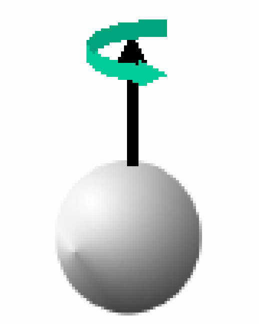
	Long duration	Short duration
Matched filter	 Pulsars	 Compact Binary Inspirals
Template-less methods	 Stochastic Background	 Bursts

Continuous Waves


M. Kramer

Wobbling neutron stars

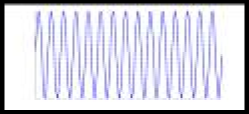
J. Creighton



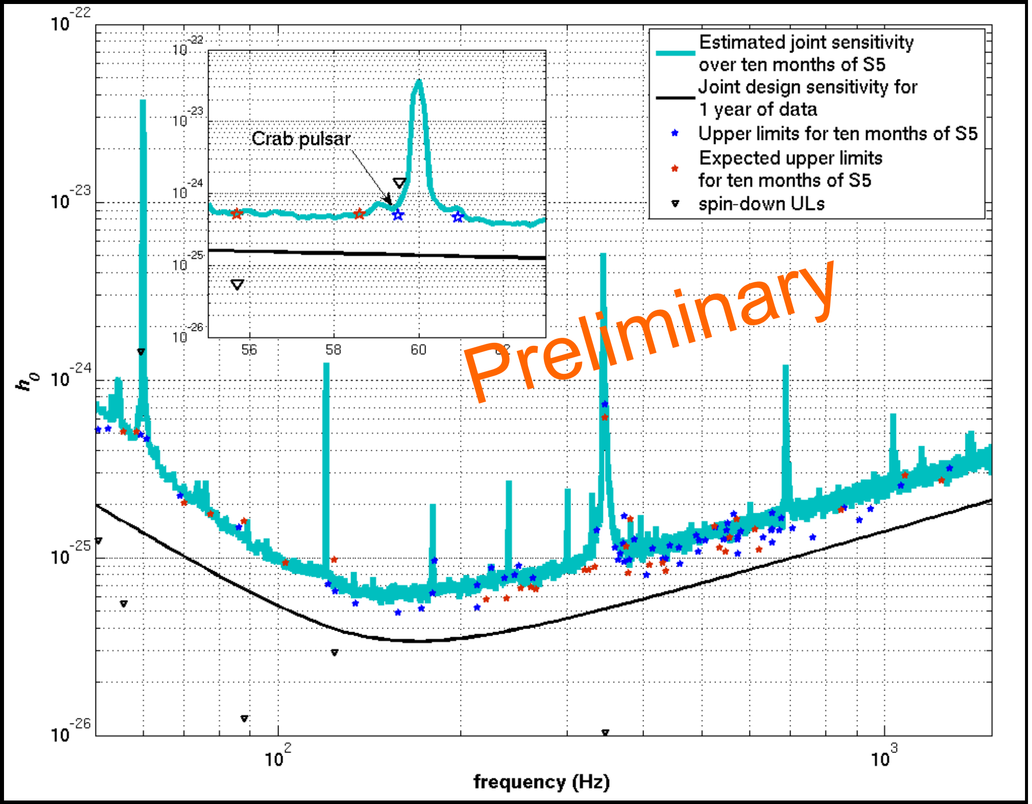
Pulsars with mountains

Dana Berry/NASA

Accreting neutron stars



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



S5 expectations:

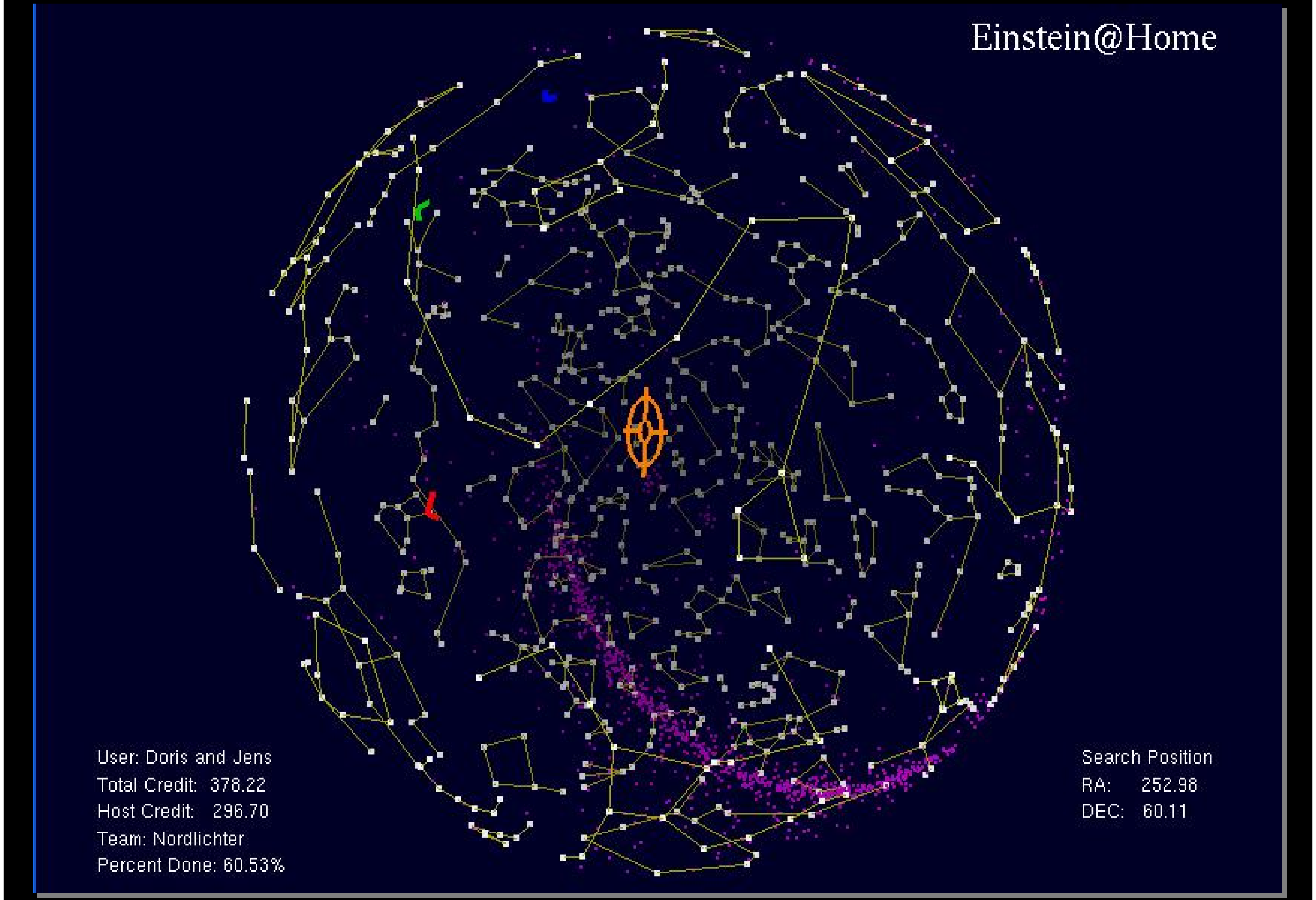
Best limits on known pulsars ellipticities at few x10^{-7}

Beat spin-down limit on Crab pulsar

Hierarchical all-sky/all-frequency search

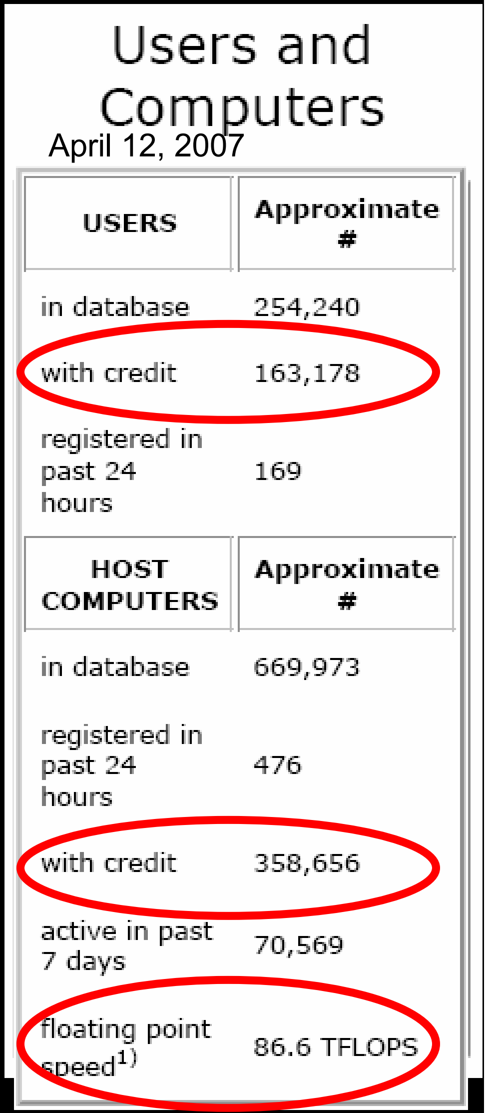
The Einstein@home Project

http://www.einsteinathome.org/



User: Doris and Jens
Total Credit: 378.22
Host Credit: 296.70
Team: Nordlichter
Percent Done: 60.53%

Search Position
RA: 252.98
DEC: 60.11



Users and Computers

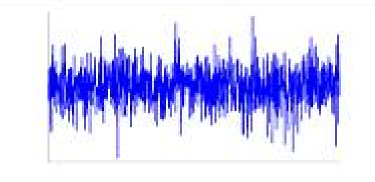
April 12, 2007

USERS	Approximate #
in database	254,240
with credit	163,178
registered in past 24 hours	169

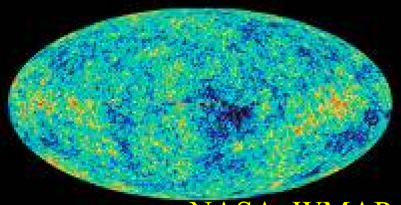
HOST COMPUTERS	Approximate #
in database	669,973
registered in past 24 hours	476
with credit	358,656
active in past 7 days	70,569
floating point speed$^{1)}$	86.6 TFLOPS

Astrophysical Sources: Stochastic Background

Cosmological background: Big Bang and early universe
Astrophysical background: unresolved bursts

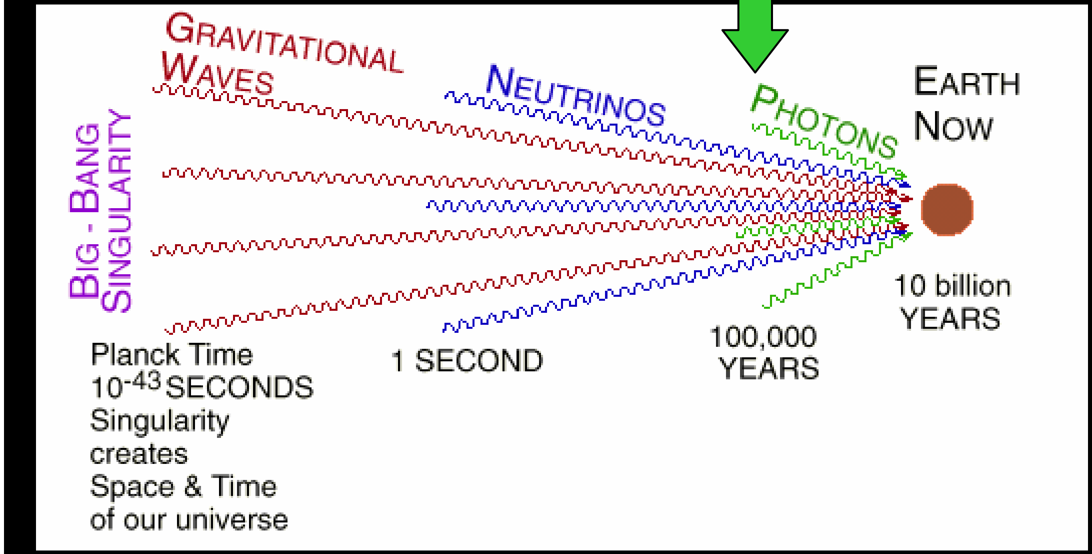


cosmic GW background



NASA, WMAP

CMB (10^{+12} s)

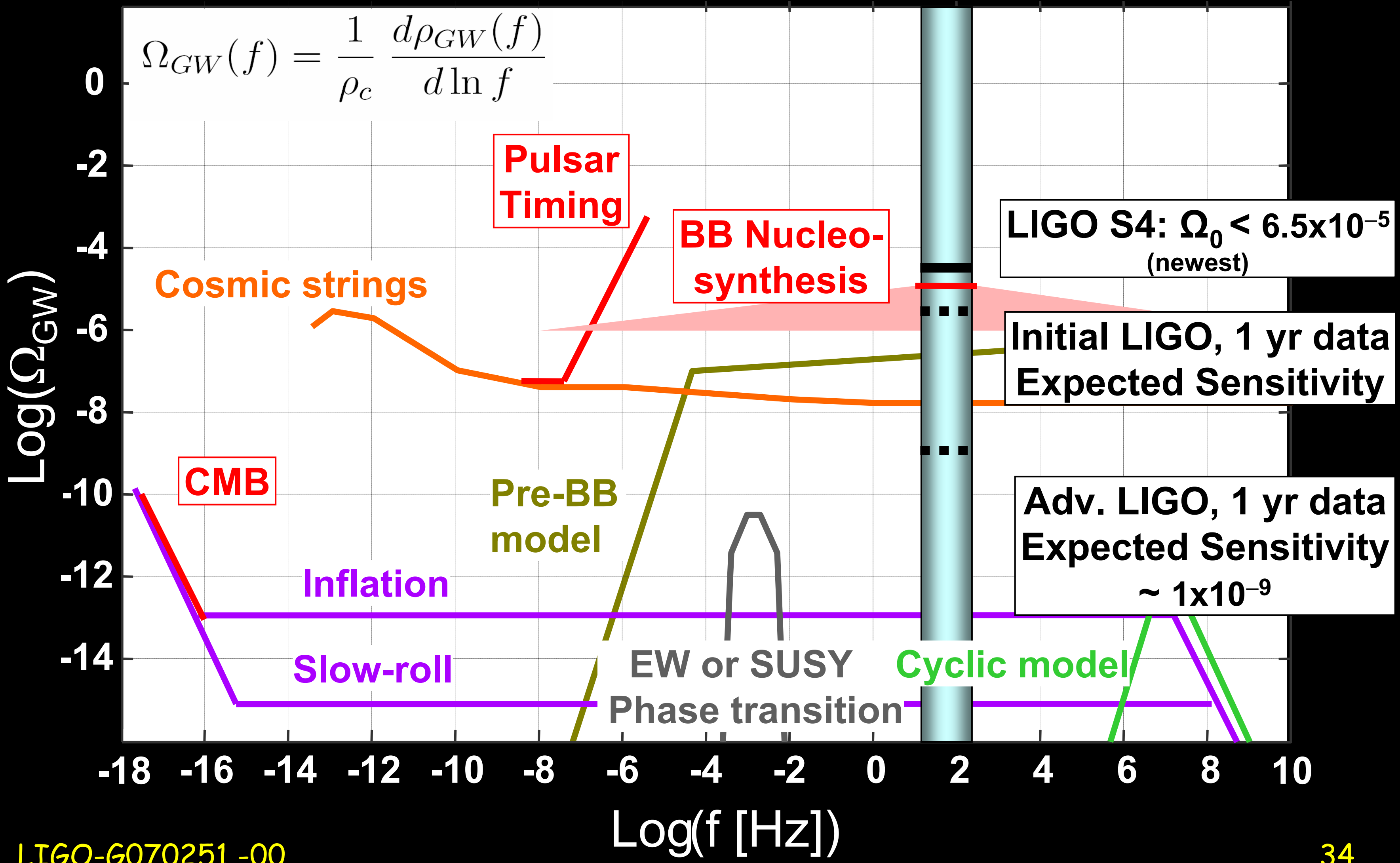


$$\Omega_{GW}(f) = \frac{1}{\rho_c}\frac{d\rho_{GW}(f)}{d\ln f}$$

S5 sensitivity:

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

Landscape



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

LIGO S4: $\Omega_0 < 6.5\text{x}10^{-5}$
(newest)

Initial LIGO, 1 yr data
Expected Sensitivity

Adv. LIGO, 1 yr data
Expected Sensitivity
~ $1\text{x}10^{-9}$

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

The Road Ahead

Enhanced LIGO
~2009

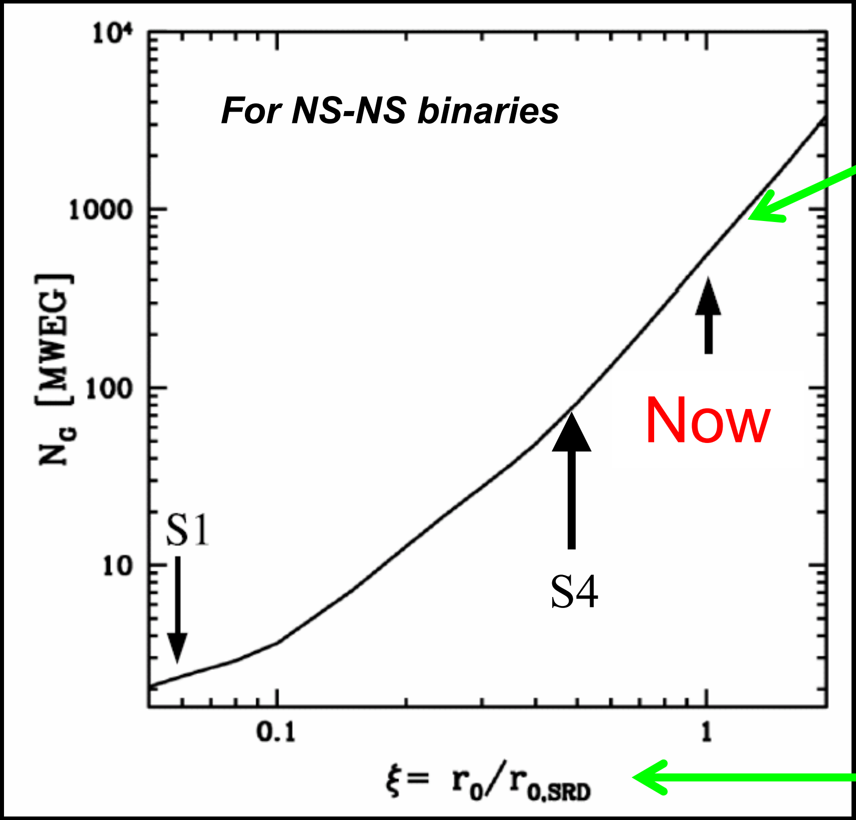
LIGO today

100 million
light years

Advanced LIGO
~2014

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

From astro-ph/0402091, Nutzman et al.



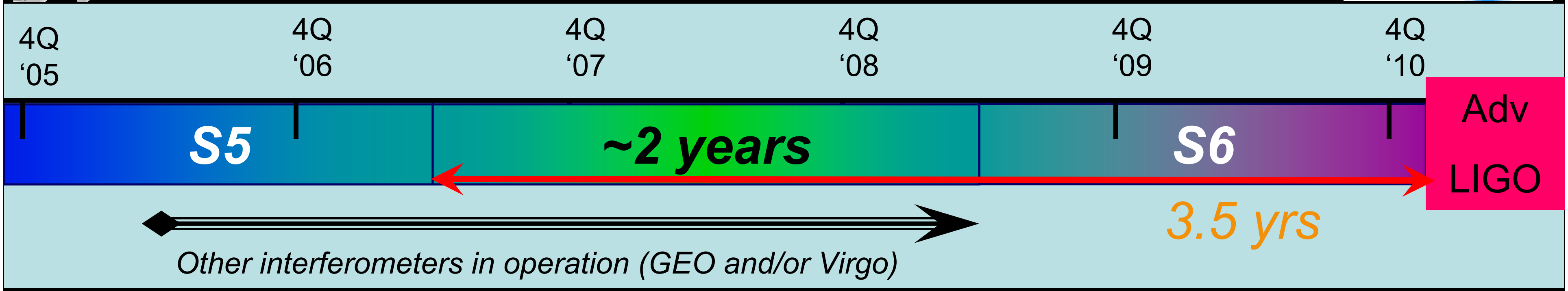
Power law: 2.7

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)

Proportional to inspiral range

LIGO timeline



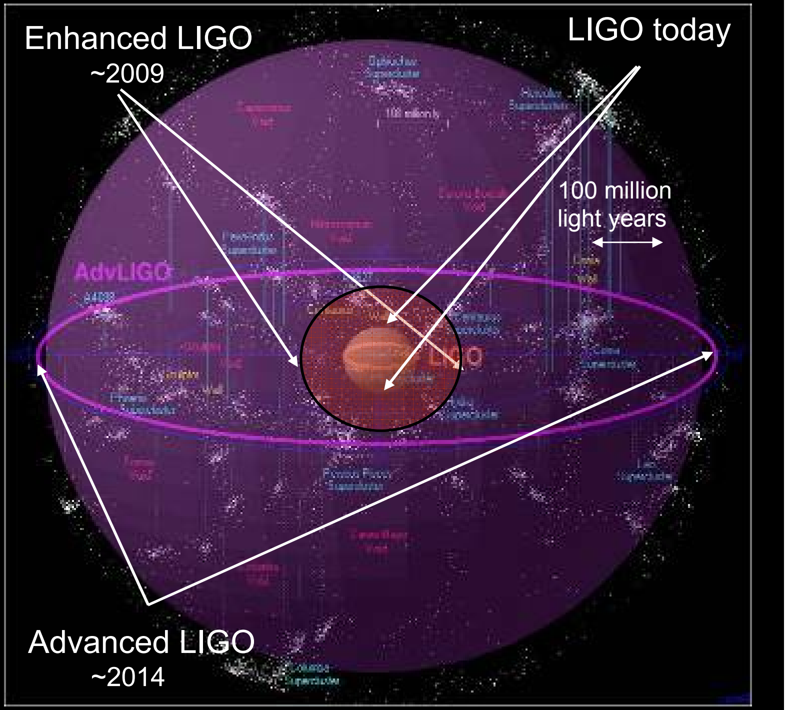
4Q ‘05
4Q ‘06
4Q ‘07
4Q ‘08
4Q ‘09
4Q ‘10

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* is in progress
  - Hundreds of galaxies now 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
  - ~10^3 times more galaxies in range
  - Most probable BNS rate 40/year in ~2014



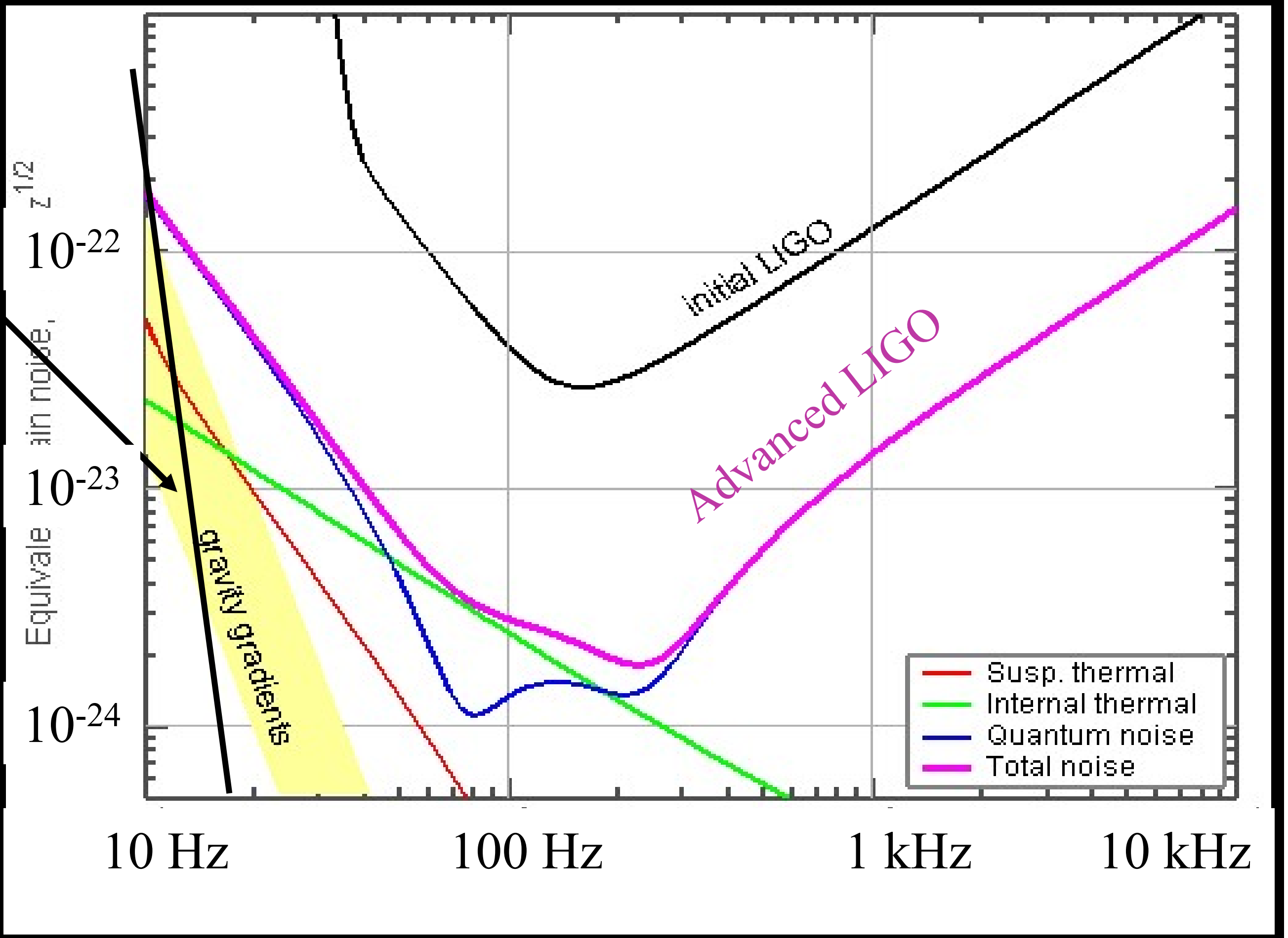
The science from the first 3 hours of Advanced LIGO should be comparable to 1 year of initial LIGO

Advanced LIGO: President Requests FY2008 Construction Start

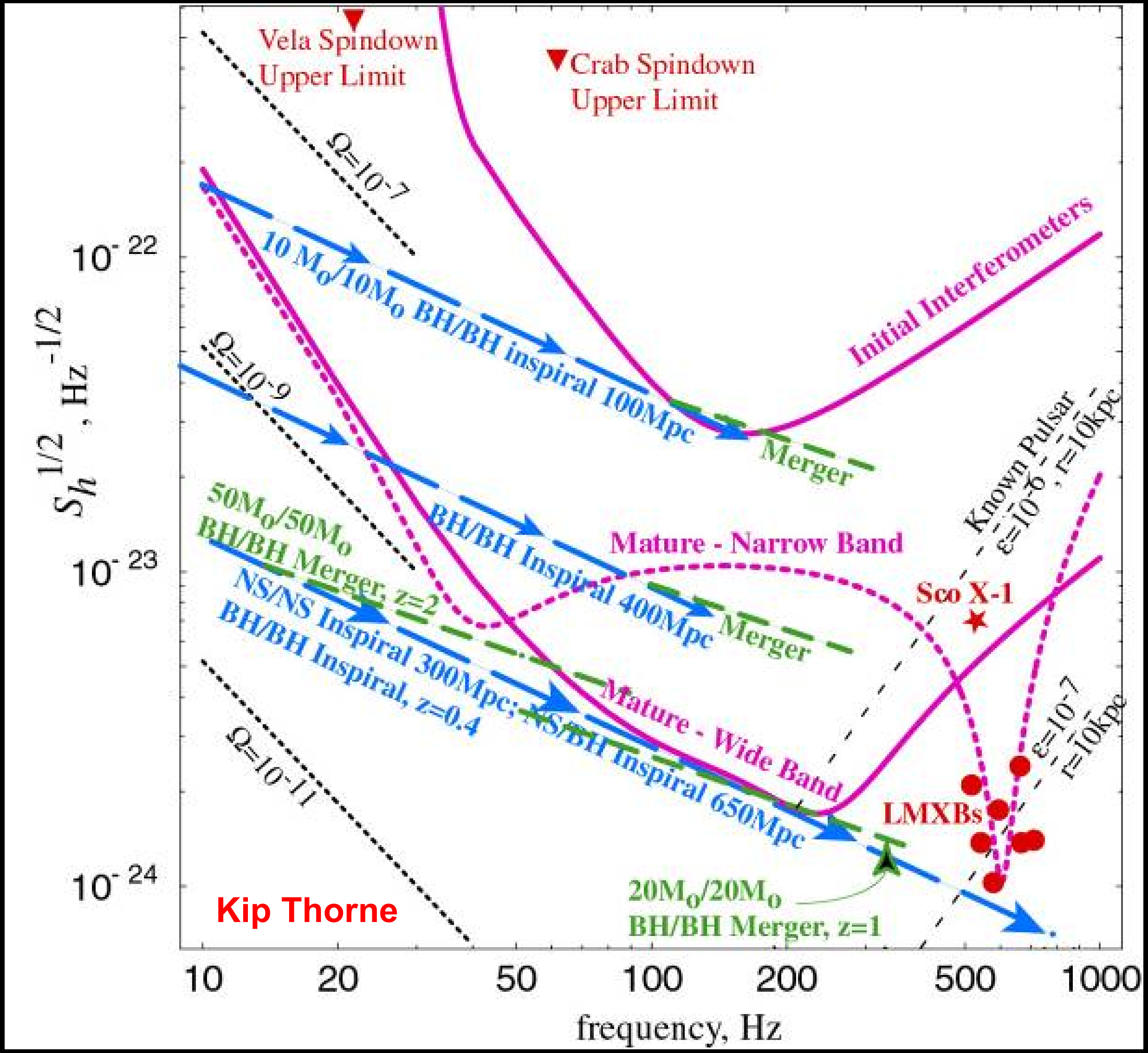
Seismic ‘cutoff’ at 10 Hz

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

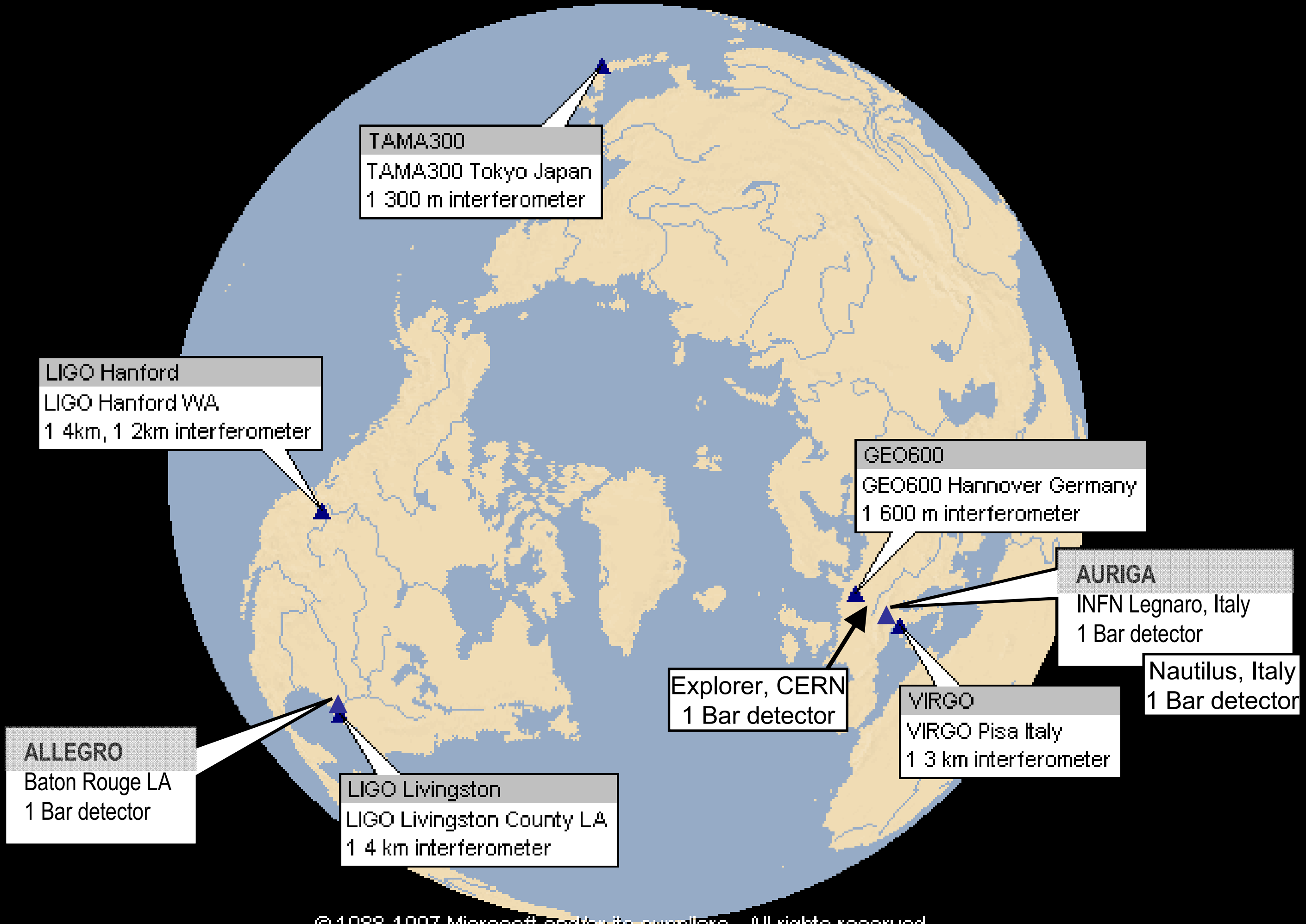
Known pulsars:

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

Stochastic background:

From Ω_{GW} ~3×10^{-6} to ~3×10^{-9}

An International Quest: Ground-Based Detectors



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Interferometers
And Resonant Bars

These are exciting times!

We are searching for GWs at unprecedented sensitivity.

Early implementation of Advanced LIGO techniques helped achieve goals:
HEPI for duty-cycle boost
Thermal compensation of mirrors for high-power operation
Detection is possible, but not assured for initial LIGO detector

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

Advanced LIGO will reach the low-frequency limit of detectors on Earth's surface given by fluctuations in gravity at surface

Direct observation: Not If, but When

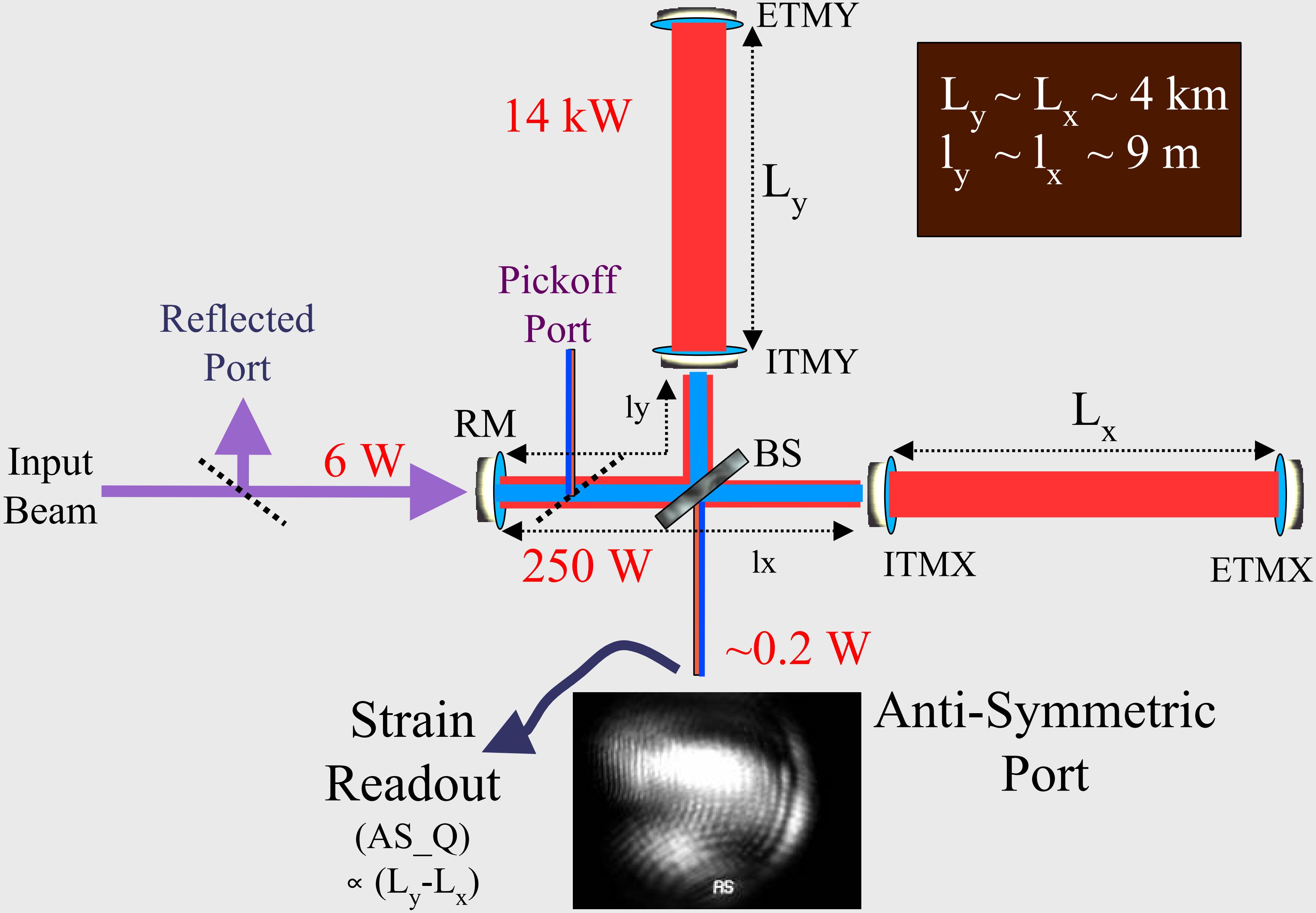
LIGO detectors and their siblings will open a new window to the Universe: what's out there?

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

Stay Tuned!

Extra Slides

Interferometry



$L_y \sim L_x \sim 4$ km
$l_y \sim l_x \sim 9$ m

Strain Readout
(AS_Q)
$\propto (L_y - L_x)$

Anti-Symmetric Port

Vacuum for a Clear Light Path

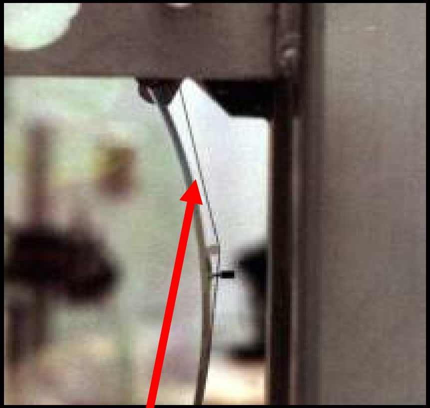
- LIGO beam tube (1998)
- 1.2 m diameter - 3mm stainless steel
- 50 km of weld

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

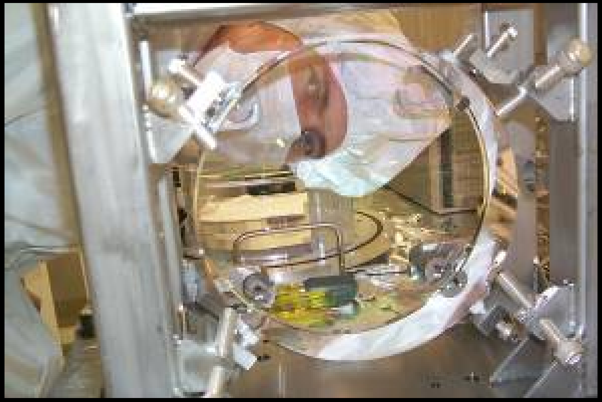
Corner Station

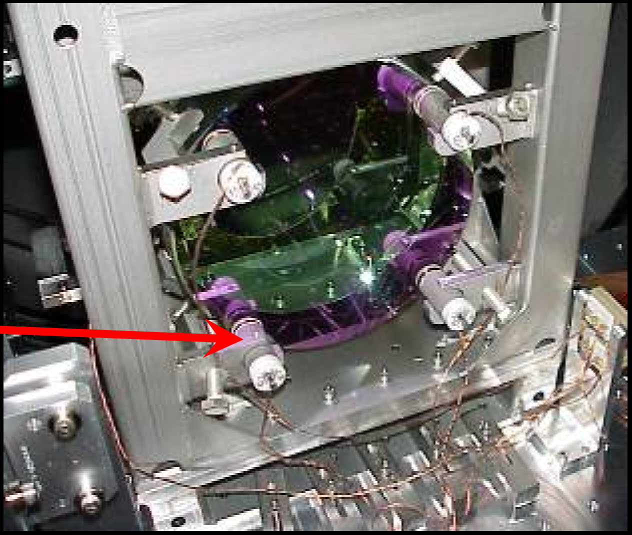
Suspended Mirrors

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



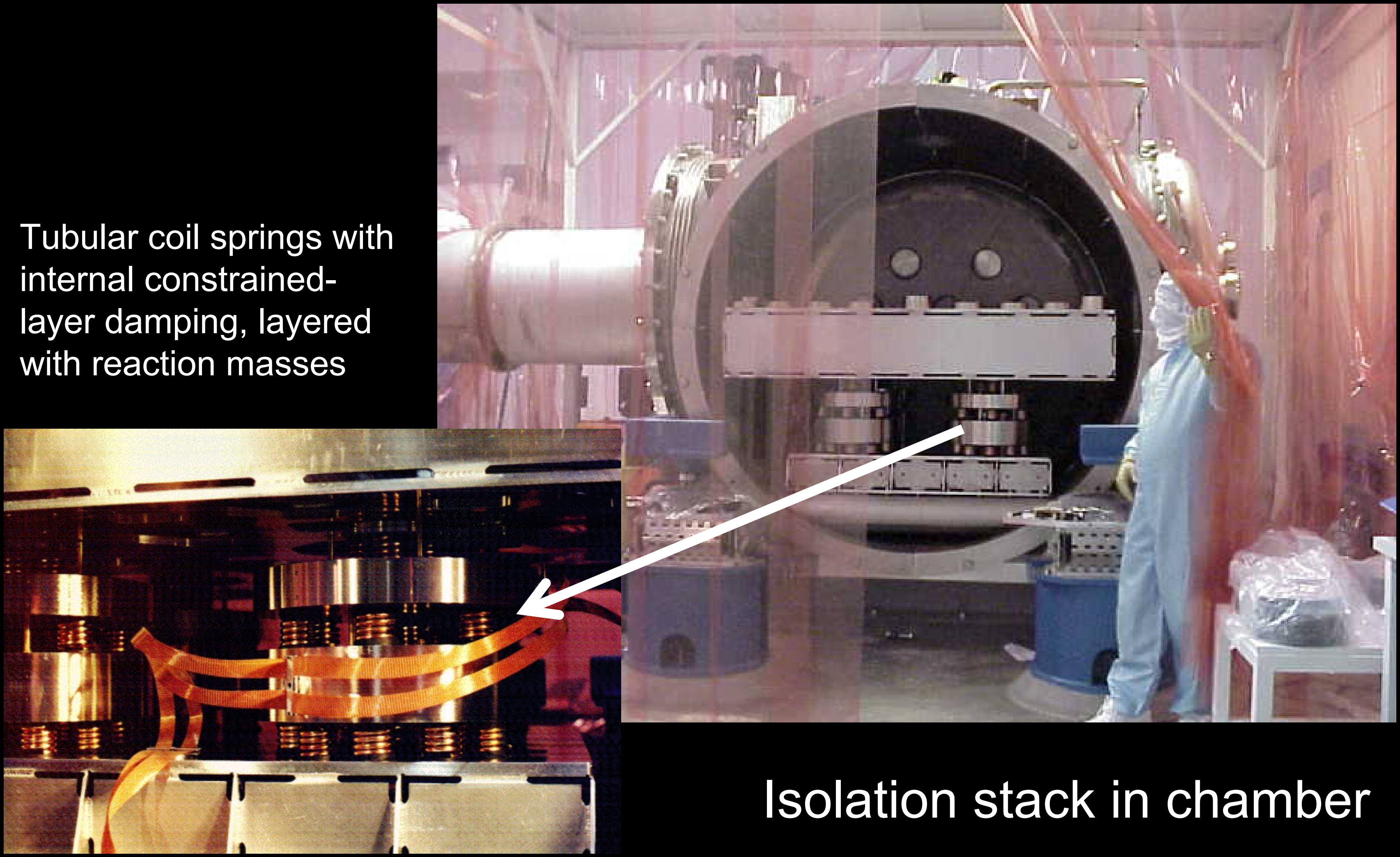
0.3mm steel wire





Local sensors/actuators for damping and control forces

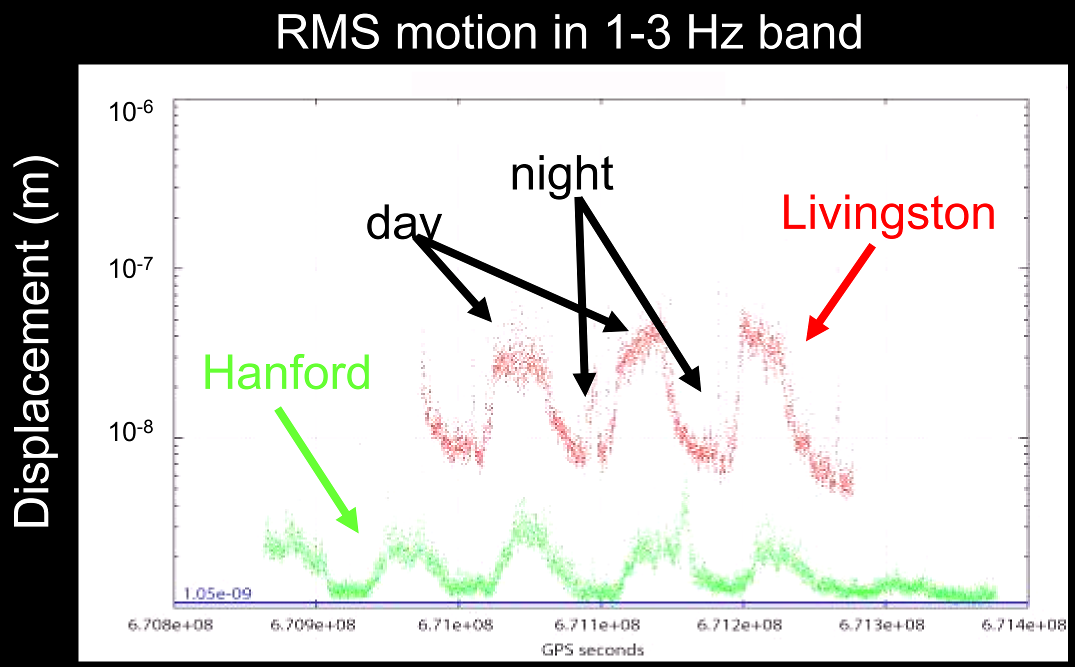
Passive Seismic Isolation System



Tubular coil springs with internal constrained-layer damping, layered with reaction masses

Isolation stack in chamber

Active Seismic Pre-Isolation for a Special Livingston Problem: Logging



The Livingston Observatory is located in a pine forest popular with pulp wood cutters

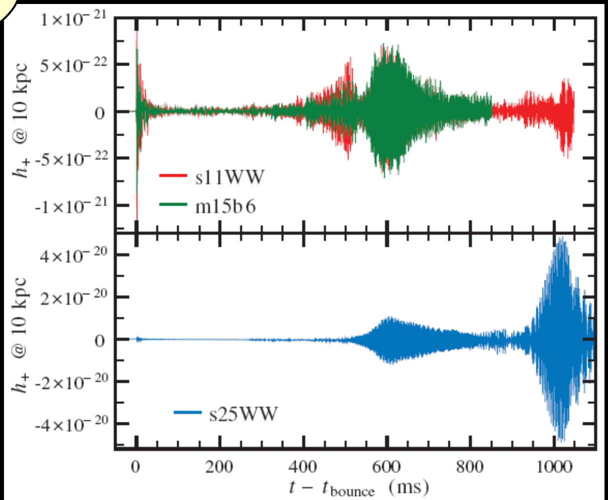
Spiky noise (e.g. falling trees) in 1-3 Hz band creates dynamic range problem for arm cavity control

The installation of HEPI (Hydraulic External Pre-Isolator), for active feed-forward isolation (Advanced LIGO technology) has sensibly improved the stability of Livingston: can lock in day time!

Order of Magnitude Range Estimate for Supernovae and BH Mergers

Model dependent!

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



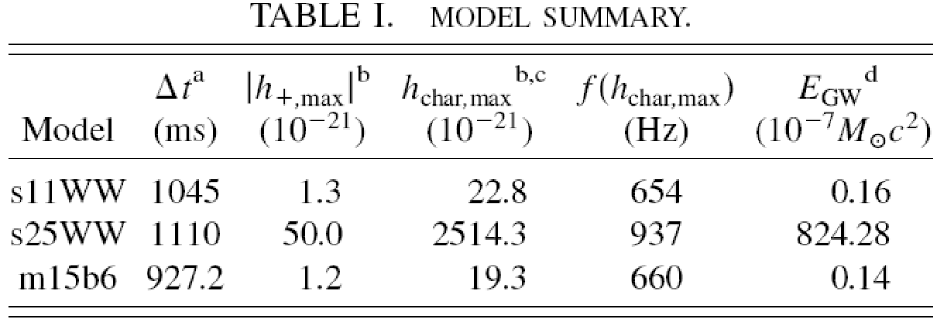


TABLE I. MODEL SUMMARY.

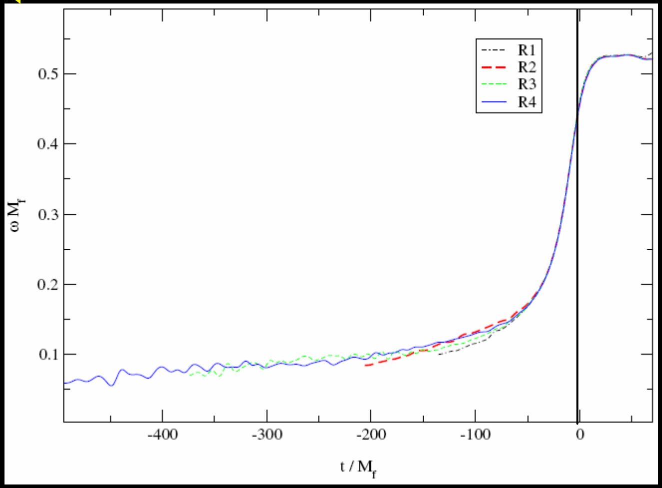
Model	Δt^{a} (ms)	$\lvert h_{+,\mathrm{max}}\rvert^{b}$ (10^{-21})	$h_{\mathrm{char,max}}{}^{b,c}$ (10^{-21})	$f(h_{\mathrm{char,max}})$ (Hz)	$E_{\mathrm{GW}}{}^{d}$ ($10^{-7} M_{\odot} c^2$)
s11WW	1045	1.3	22.8	654	0.16
s25WW	1110	50.0	2514.3	937	824.28
m15b6	927.2	1.2	19.3	660	0.14

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

⇒ reach ≈ 0.4 kpc

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

⇒ 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 ⇒ reach ≈ 3 Mpc

50+50 $M_{\odot}$ binary ⇒ reach ≈ 100 Mpc