LIGO e la Sfida delle Inafferrabili Onde Gravitazionali

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LIGO Scientific Collaboration
Trento, 21 Febbraio 2007

LIGO-G070030-00

Newton's Law of Universal Gravitation (1686)

Mechanics [F=ma] and the Universal law of gravitation [centripetal acceleration $a=GM/d^2$] explained various puzzles of the time:

- Why things fall
- Orbit of planets and comets
- Tides
- Perturbation of the moon's motion due to the gravitational attraction of the sun

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

BUT:

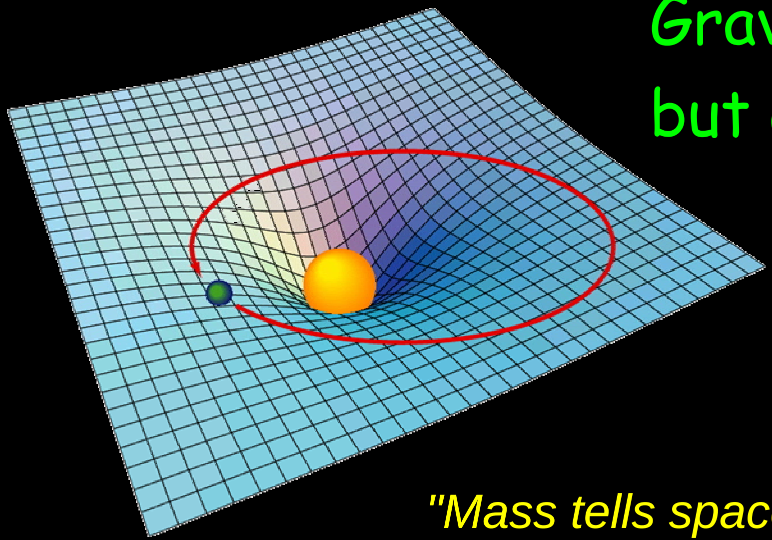
The gravitational field is static

The attraction between two masses is instantaneous action at a distance

what mechanism produces the mysterious force of attraction in Newton's theory?

LIGO-G070030-00

Einstein's Vision: General Relativity (1916)



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

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

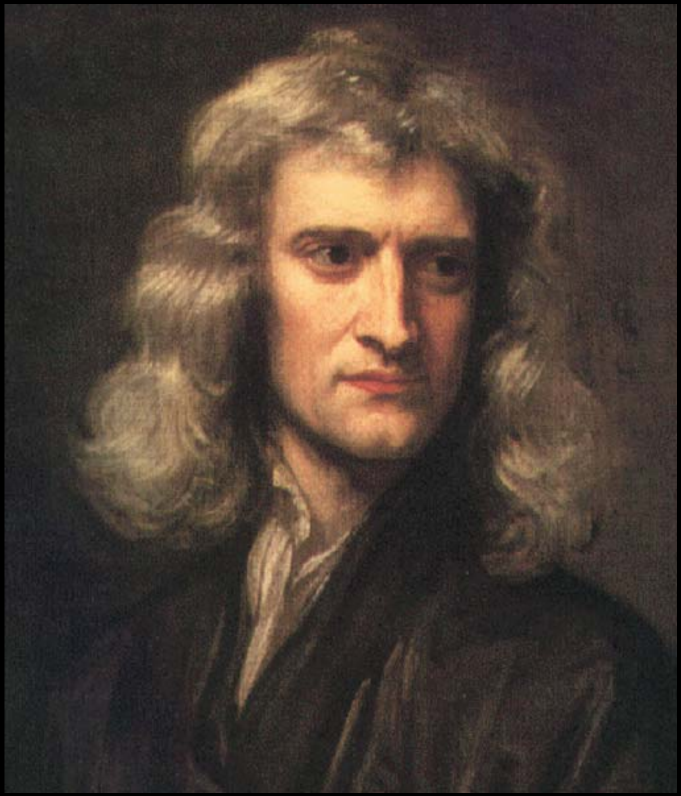
Einstein's Equations:

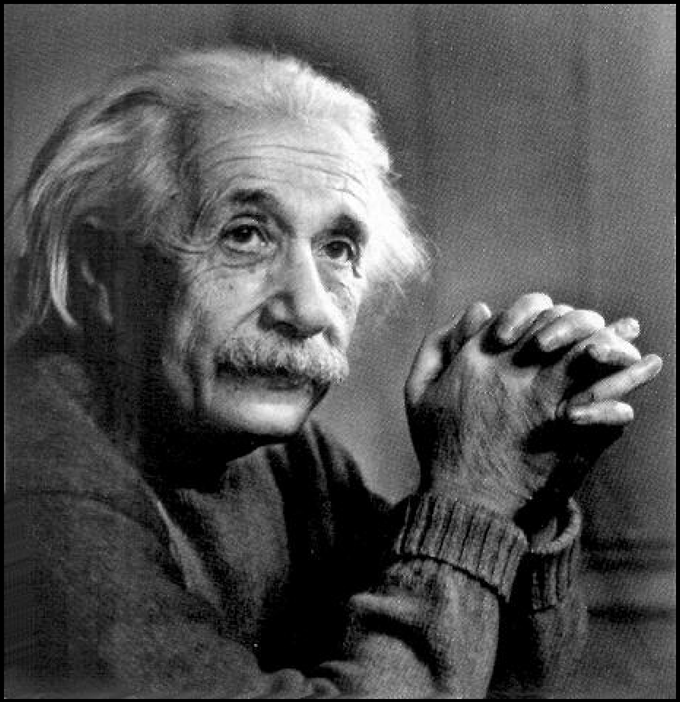
When matter moves, or changes its configuration, its gravitational field changes. This change propagates outward as

a ripple in the curvature of space-time: a gravitational wave.

Newton's Universal Gravitation

action at a distance

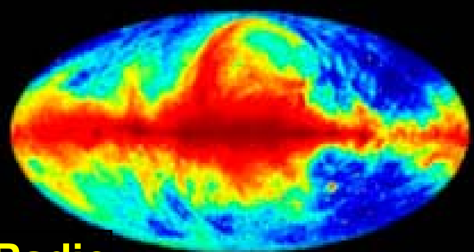




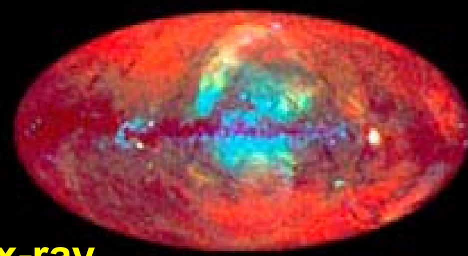
Einstein's General Relativity

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

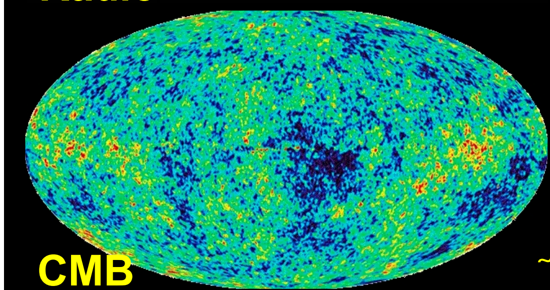
A New Probe into the Universe



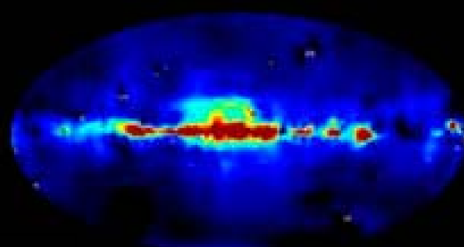
Radio



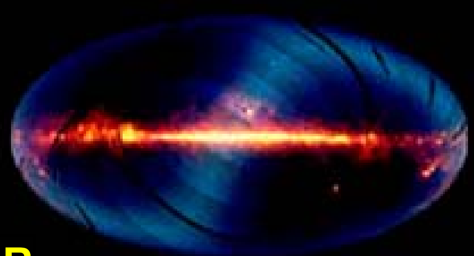
x-ray



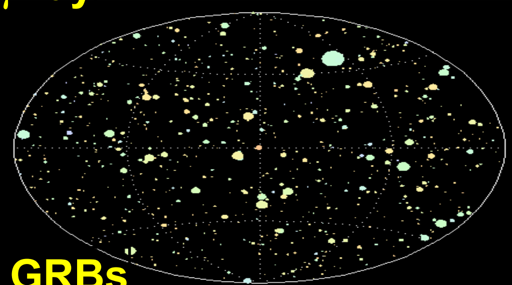
CMB



$\tilde{\gamma}$-ray



IR



GRBs

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

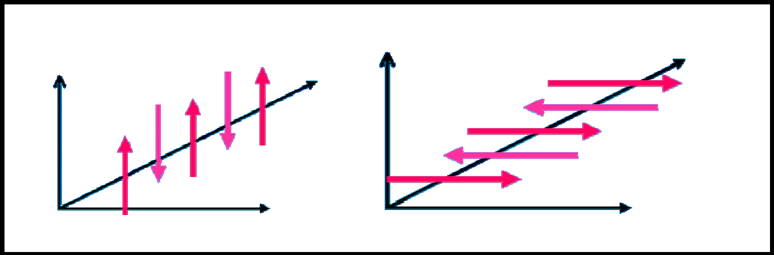
This will be complementary information, as different from what we know as *hearing* is from *seeing*.

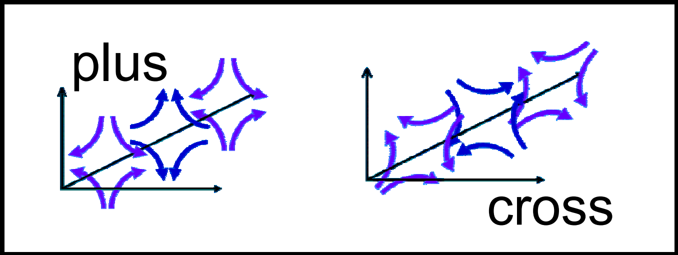
EXPECT THE UNEXPECTED!

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.

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)

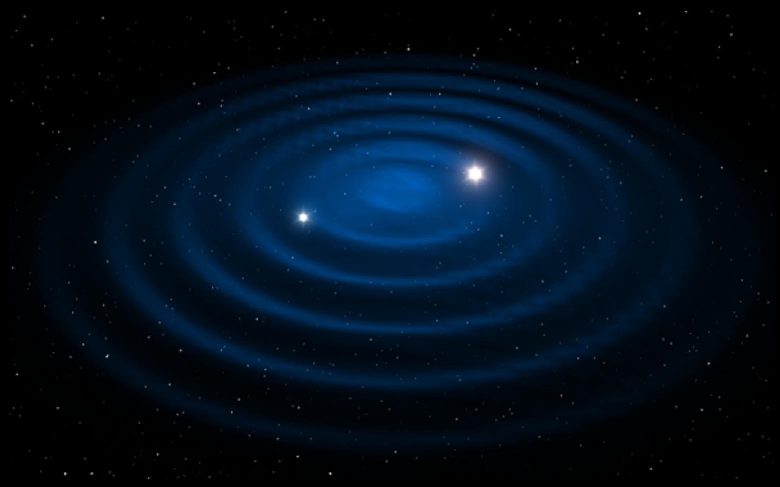




Very different information, mostly mutually exclusive

We have Indirect Proof of the Existence of GWs:

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



Source: www.NSF.gov

A 17/sec pulsar (neutron star in rapid rotation, emanating periodic pulses of electromagnetic radiation) orbits around a neutron star with period = 8 hours
Only 7kpc away

General Relativity prediction:
the orbital radius diminishes 3mm/orbit;
a collision is expected in 300 million years

The rotation period diminished 14 sec in 1975-94; energy loss

Optimum agreement with the predictions of general relativity: the energy is carried away by gravitational waves!

…But They are Hard to Find: Space-Time is Stiff!

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

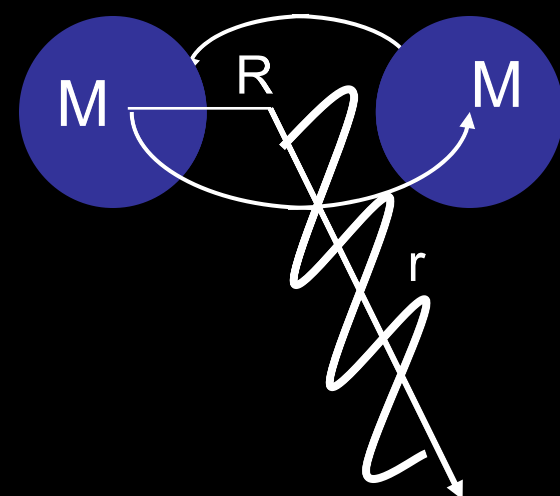
T = stress tensor, G = Curvature tensor

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

⇒ $h \sim 10^{-21}$

When a GW Passes Through Us…

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

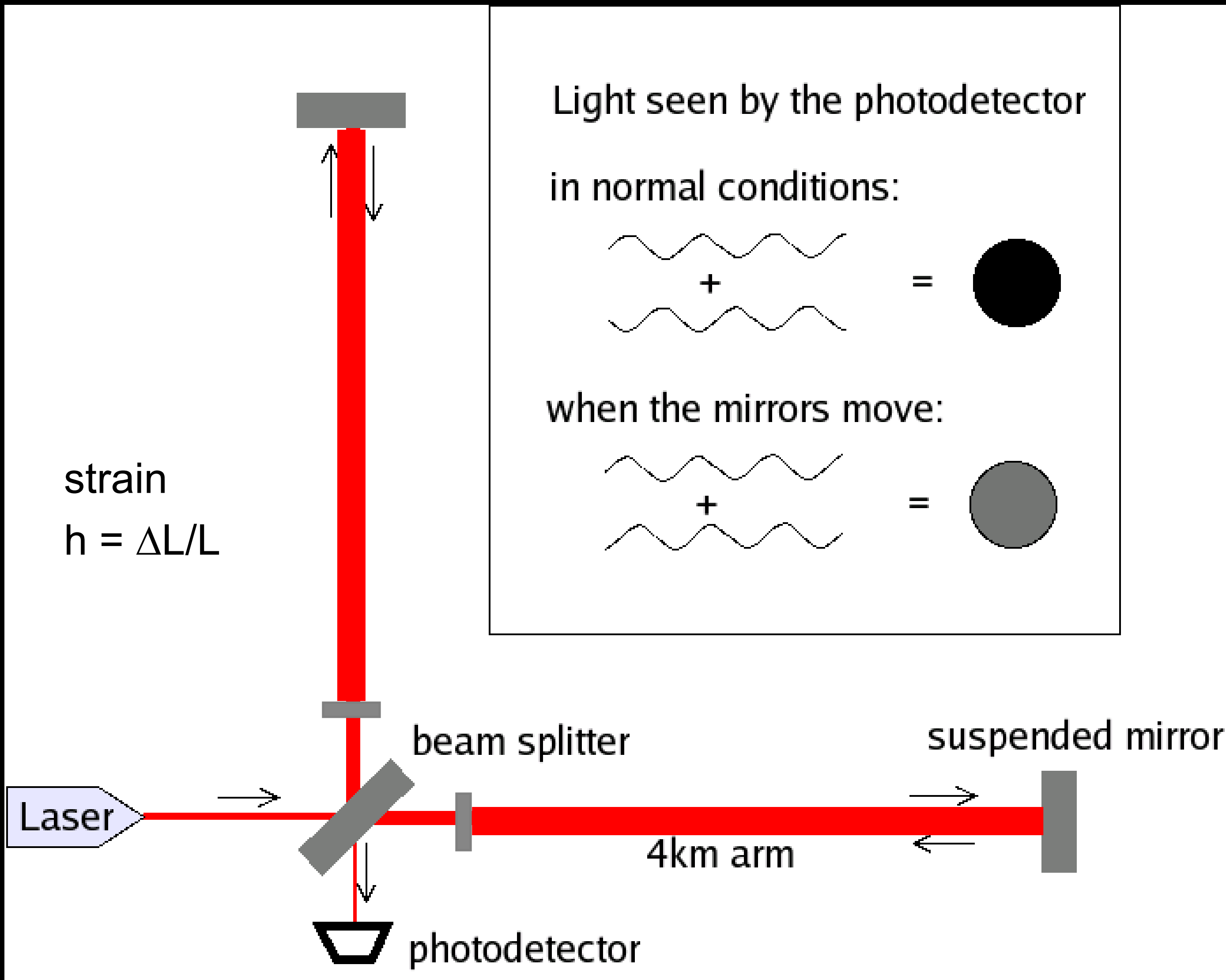
Leonardo da Vinci's Vitruvian man

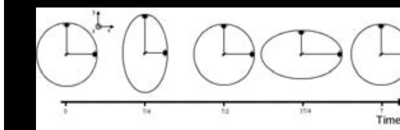
The effect is greatly exaggerated!!

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 $h=\Delta L/L$

Interferometers: Suspended Mirrors as Free Masses





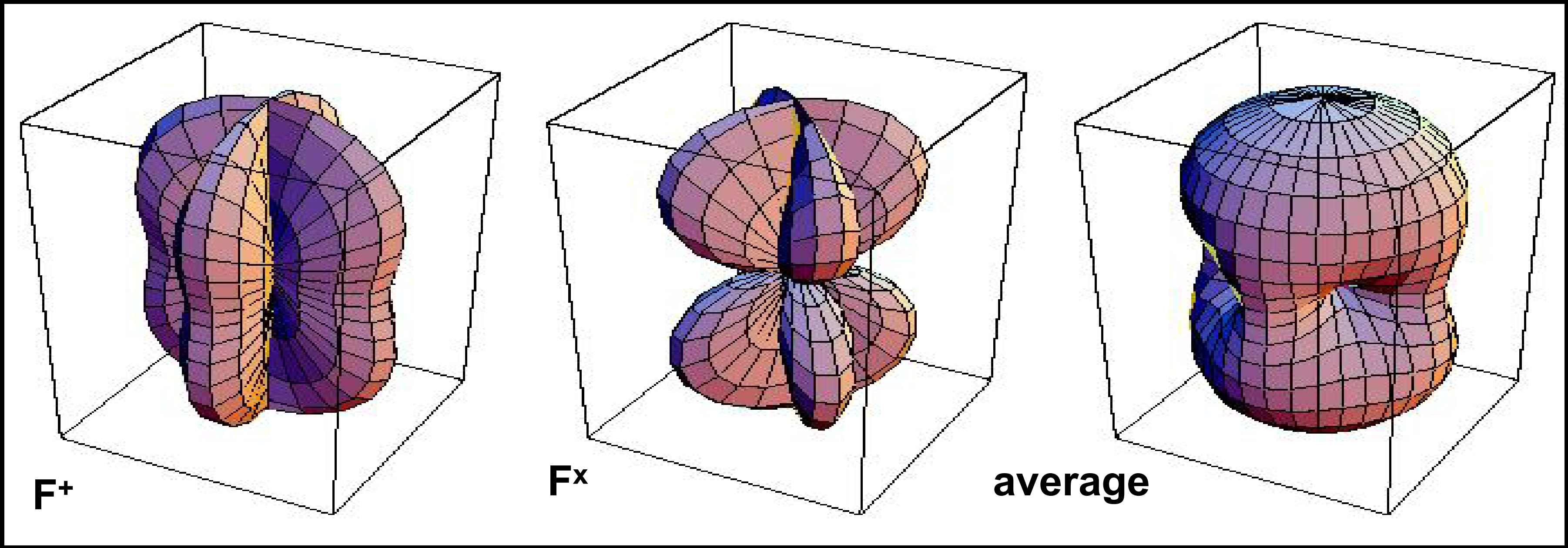
Initial LIGO goal: measure difference in length to one part in 10^{21}, or 10^{-18} m

Giant "Ears"
Listen to the Vibrations of the Universe

Beam patterns:

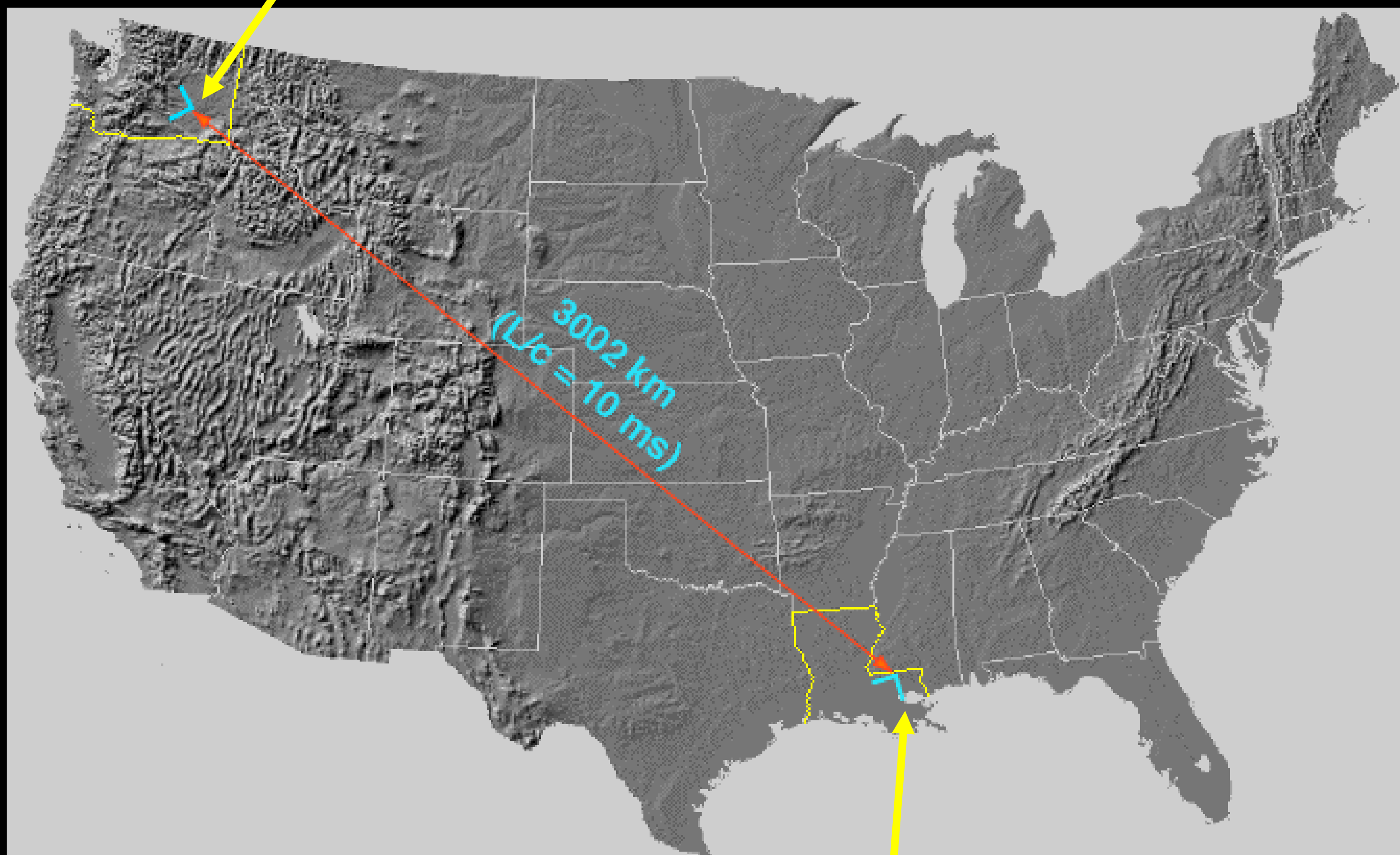
$F^+, F^\times$: [-1, 1] F = F(t; α, δ)

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



The LIGO Observatory

Hanford (WA)
4 km + 2 km interferometers



Livingston (LA)
4 km interferometer


Hanford, Washington
4 km
2 km

4 km

The LIGO Scientific Collaboration

LIGO

LSC

NSF

UTB TSC

Southeastern Louisiana University

Loyola University New Orleans

LSU

GEO 600

University of Maryland

Universitat de les Illes Balears

Northwestern University

University of Florida

Southern University

William Smith College

The University of Adelaide Australia

NAOJ 国立天文台

UWMilwaukee

Columbia University

The University of Birmingham

Massachusetts Institute of Technology

The University of Texas at Austin

Syracuse University

IGR

Universität Hannover

Washington State University

Embry-Riddle Aeronautical University

Cardiff University

The University of Western Australia

Michigan

The Physics of the Universe PPARC

PAH

PennState

University of Glasgow

Andrews University

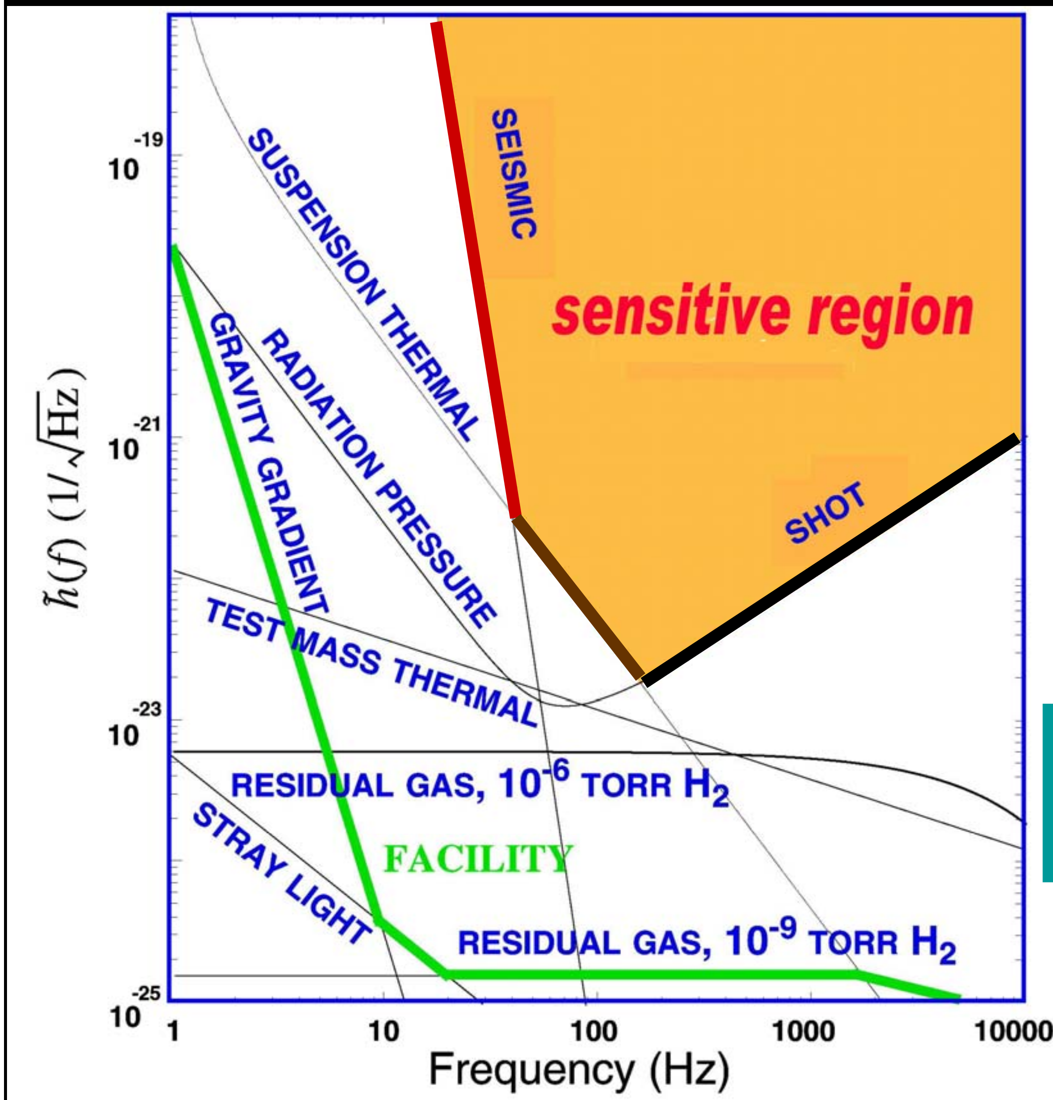
San José State University

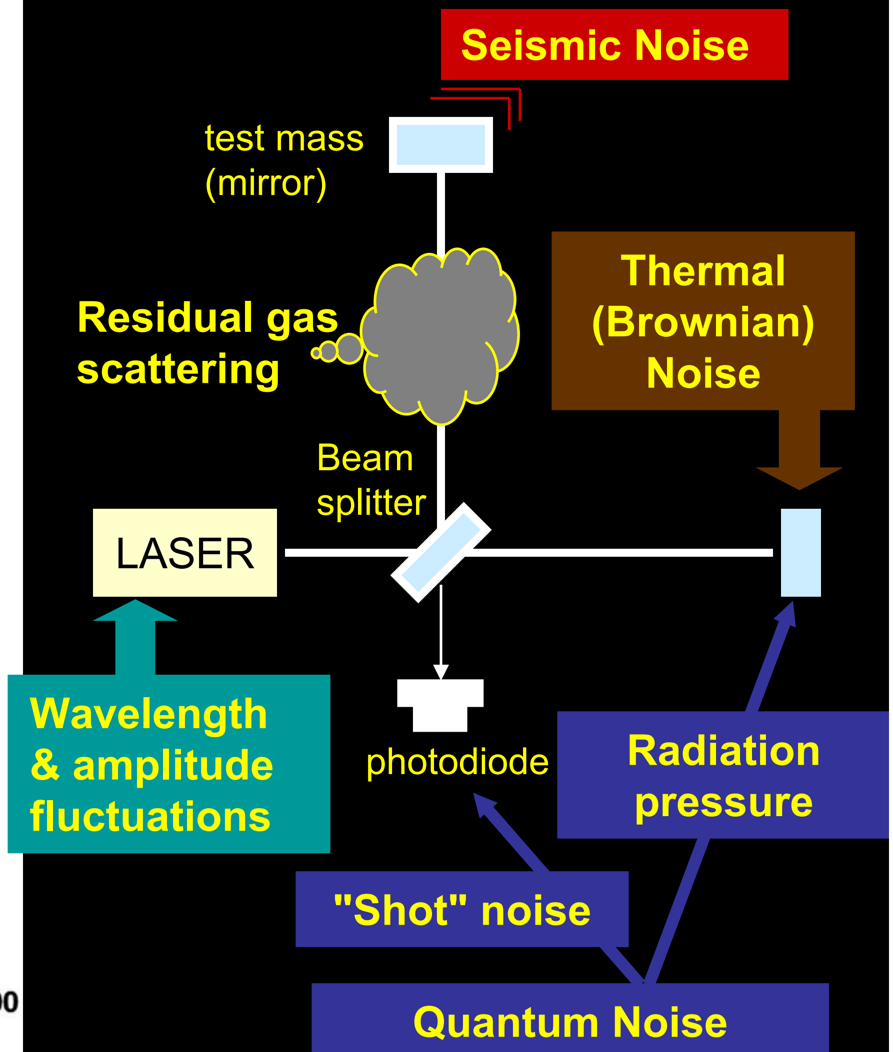
R·I·T

An International Quest: Ground-Based Detectors

Interferometers
And Resonant Bars

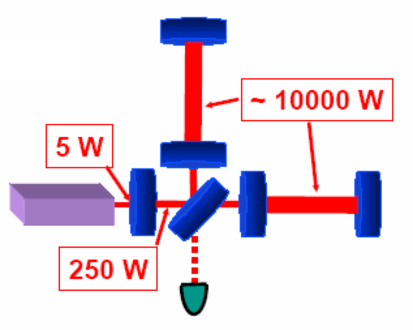
Initial LIGO Sensitivity Limits

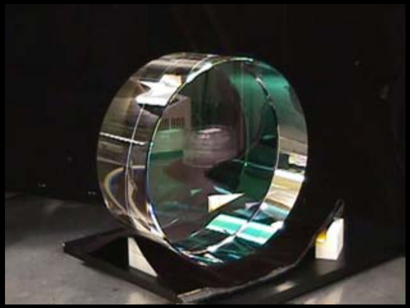


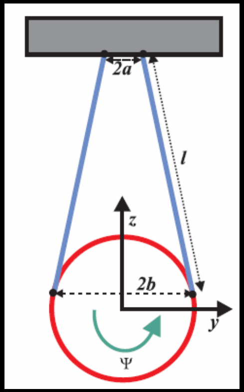


Mitigation of Noise Sources

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





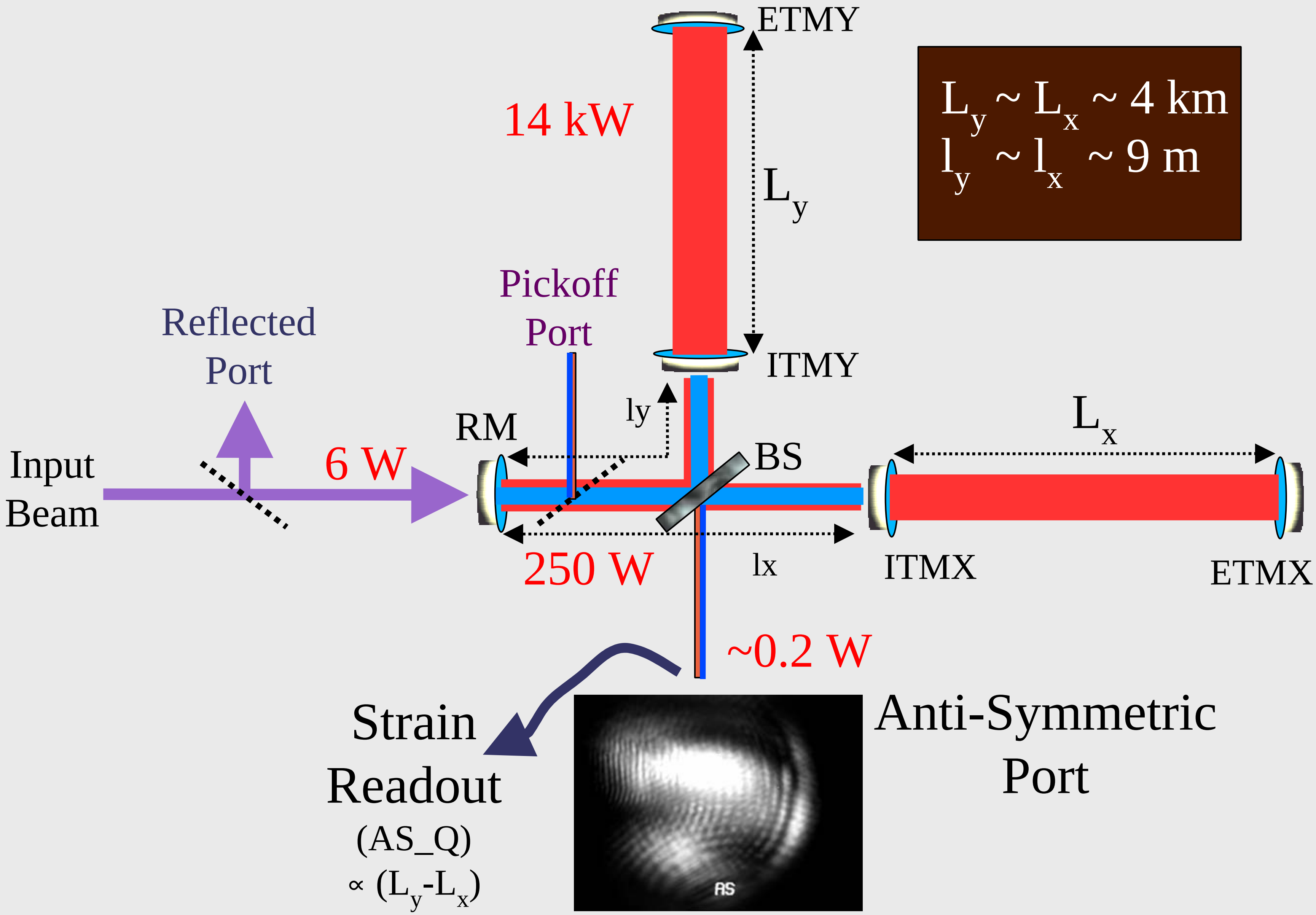


Thermal noise:
Use low loss materials
Work away from resonances
Thin suspension wires

Seismic noise:
Passive Isolation Stacks
Pendulum suspension

All under vacuum

Interferometry



Vacuum for a Clear Light Path

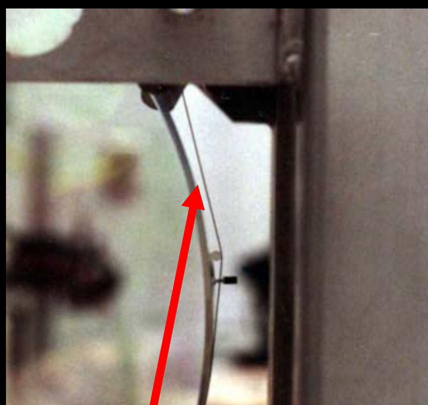
- LIGO beam tube (1998)
- 1.2 m diameter - 3mm stainless steel
- 50 km of weld

Corner Station

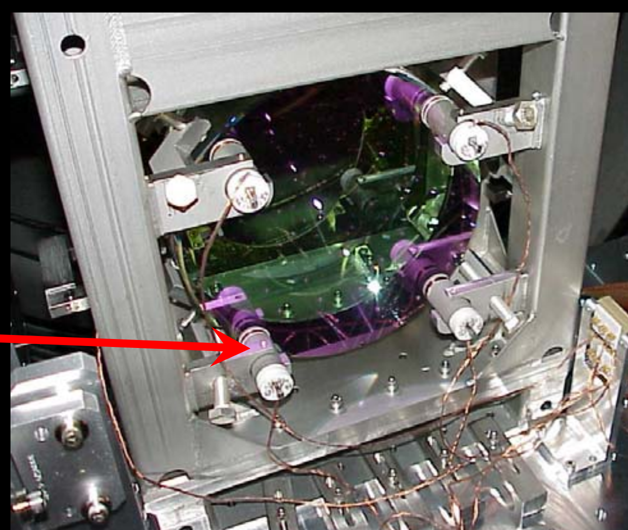
20,000 m^3 @ 10^{-8} torr; earth's largest high vacuum system

Suspended Mirrors

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



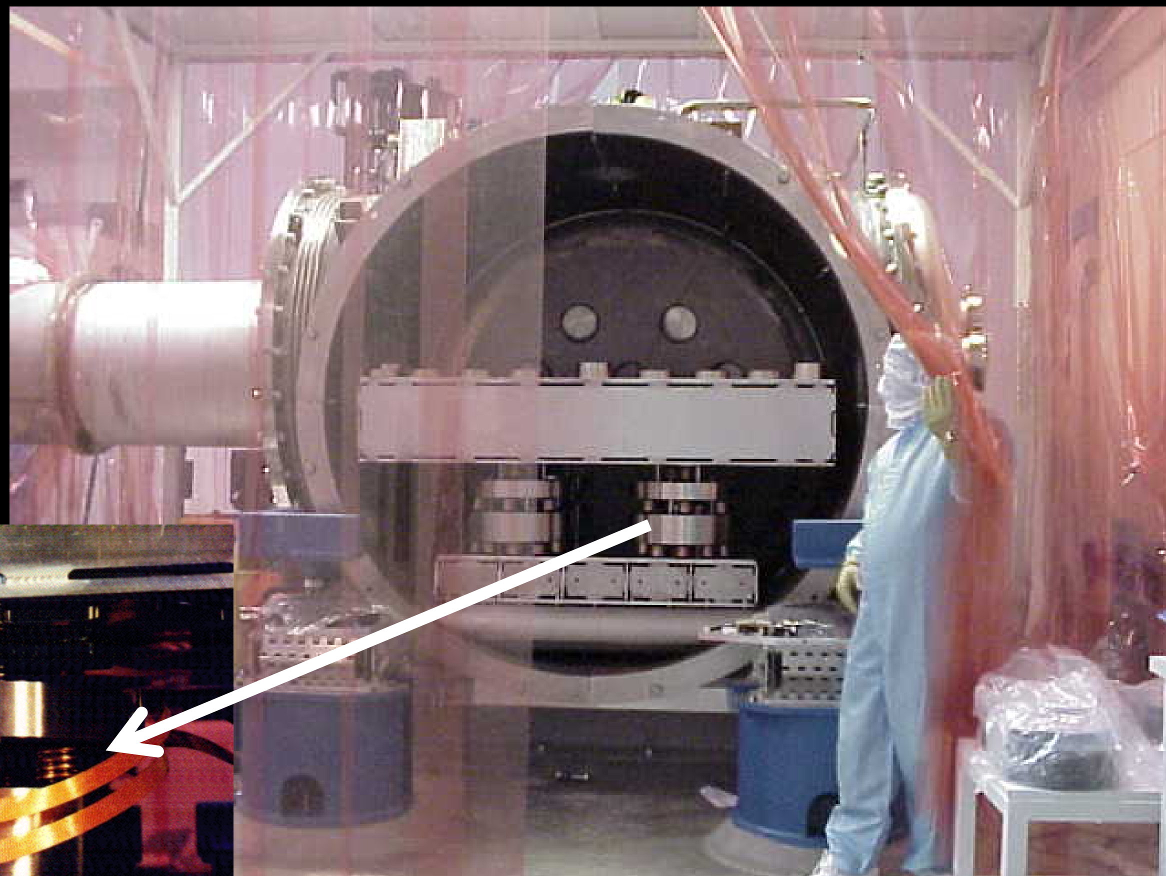
0.3mm steel wire

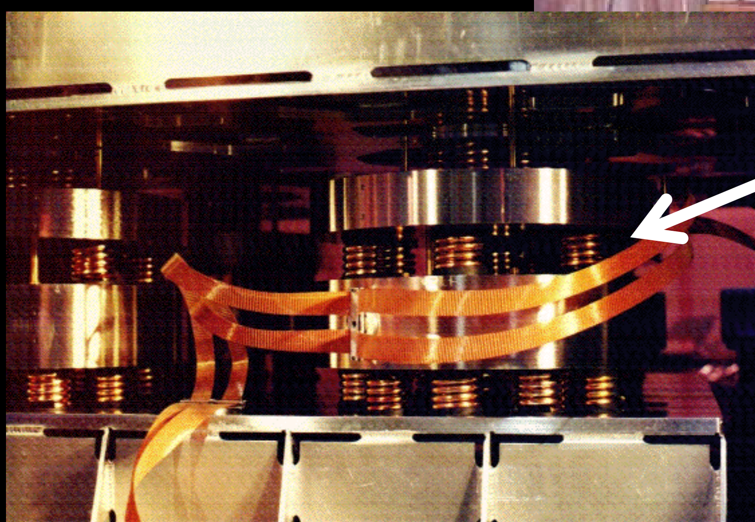


Local sensors/actuators for damping and control forces

Passive Seismic Isolation System

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

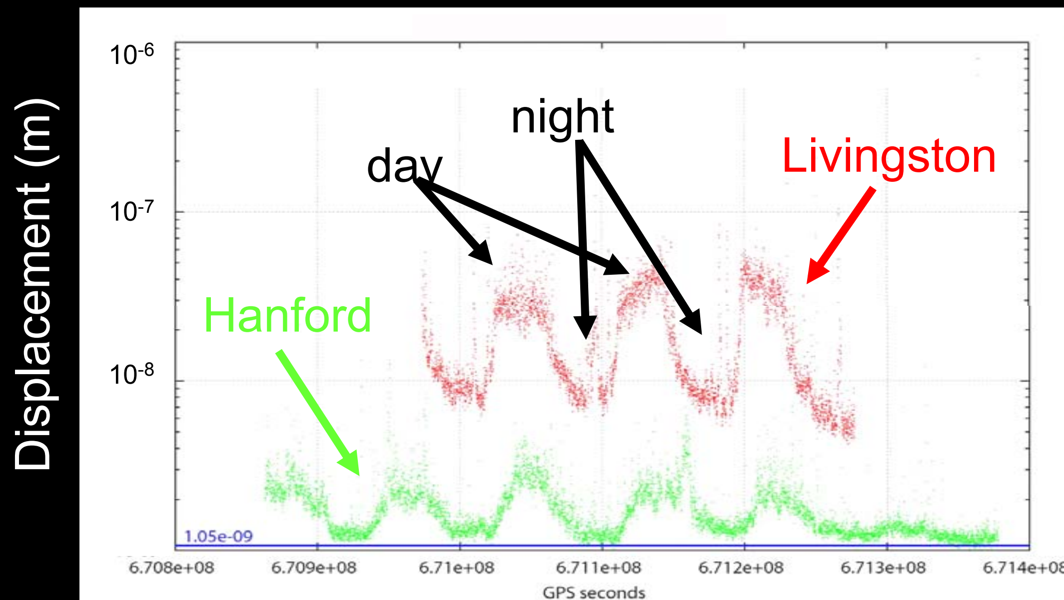




Isolation stack in chamber

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

RMS motion in 1-3 Hz band



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

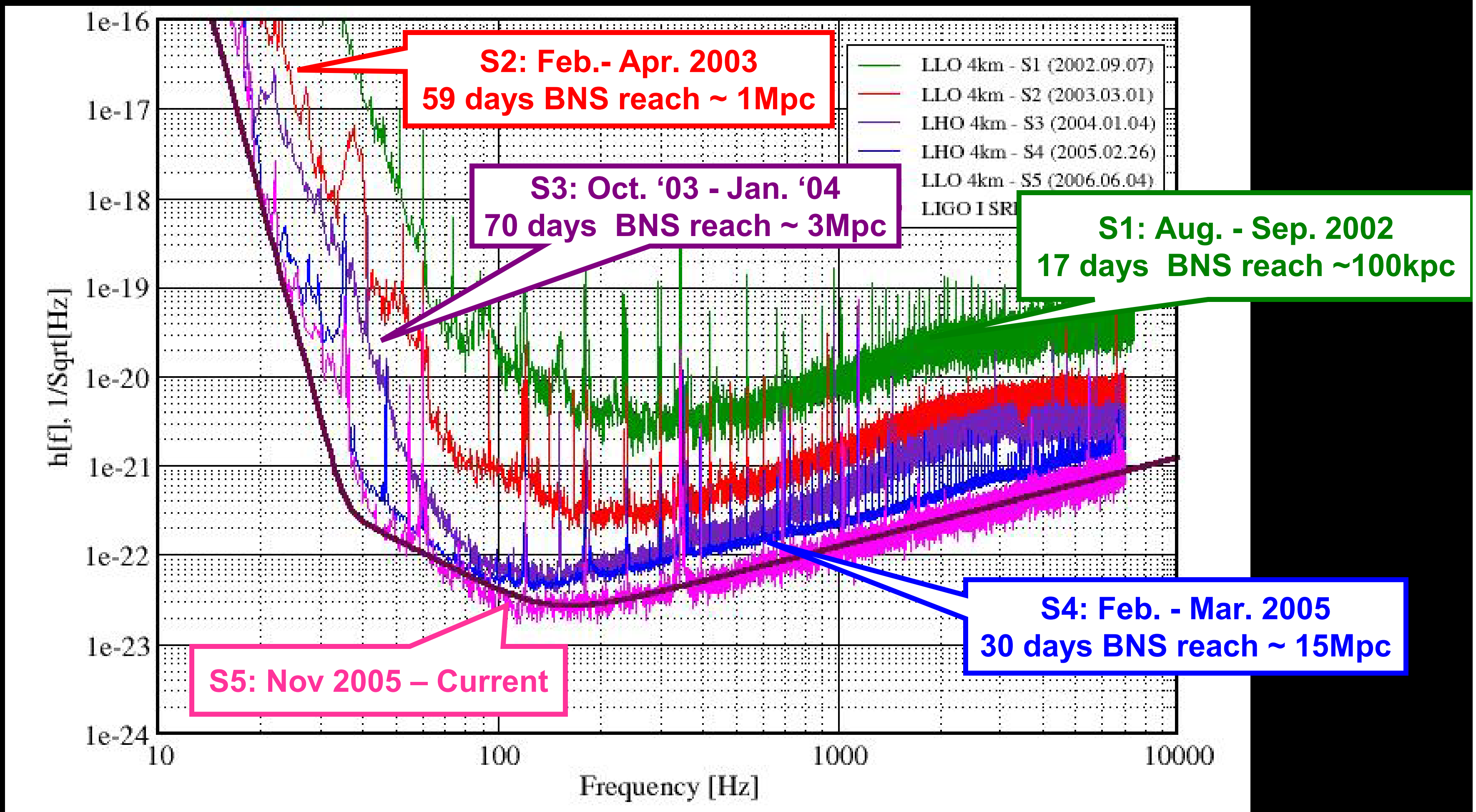
Spiky noise (e.g. falling trees) in 1-3 Hz band creates dynamic range problem for arm cavity control

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!

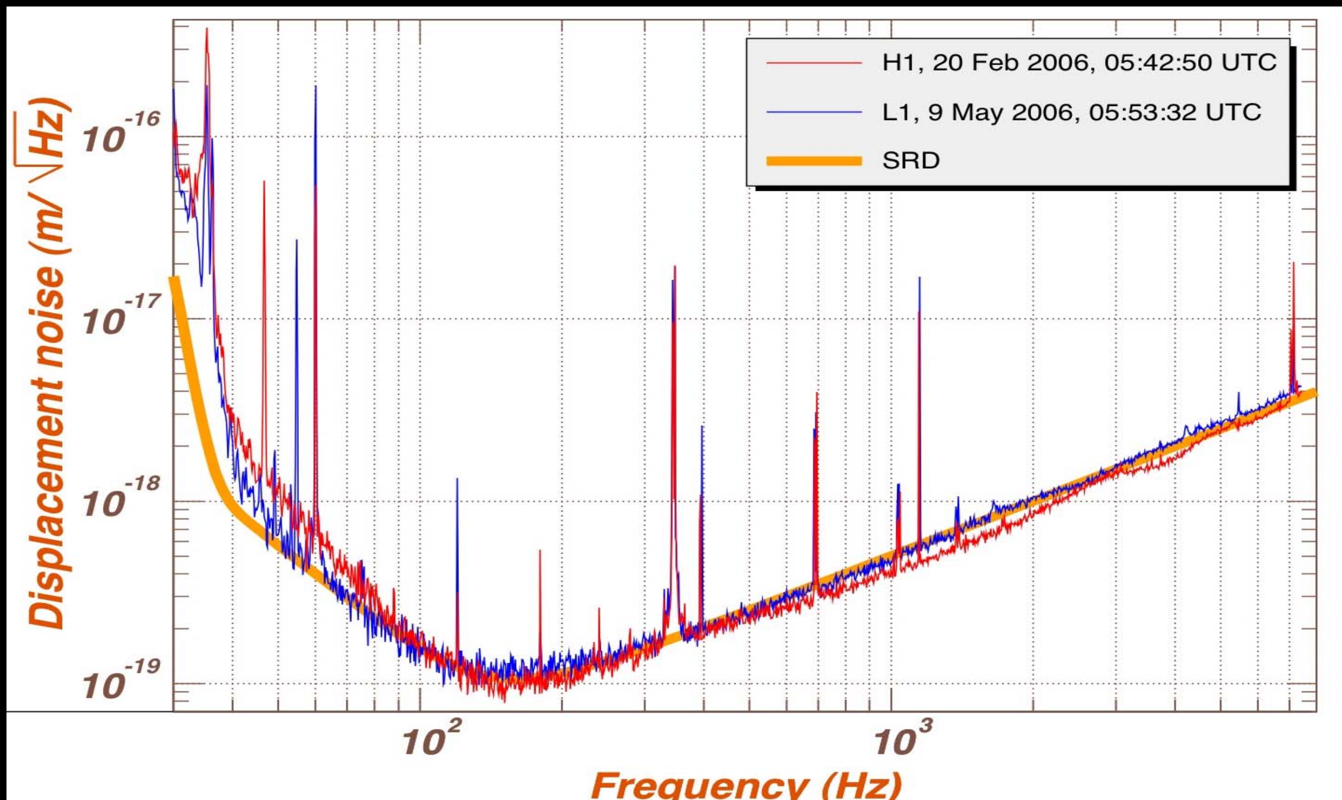
Despite some obstacles along the way…

…LIGO meets its experimental challenges

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



Science Run 5

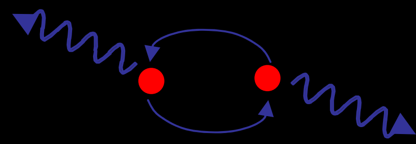


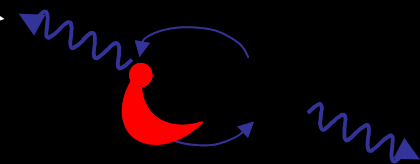
S5: started Nov 2005 and ongoing

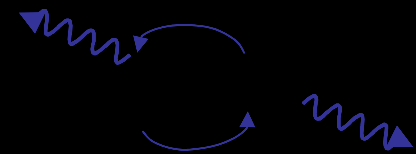
Goal: 1 year of coincident live-time

Science with LIGO: Sources Lurking in the Dark

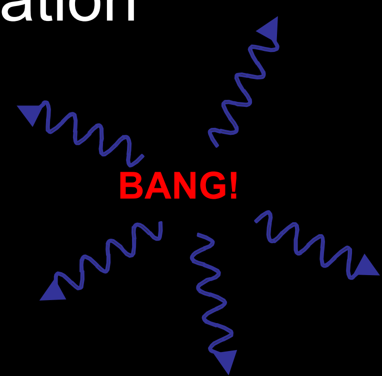
- Binary systems
  – Neutron star – Neutron star
  – Black hole – Neutron star
  – Black hole – Black hole



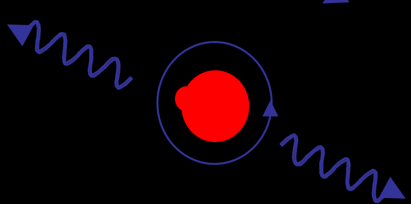




- "Burst" Sources
  – Supernovae
    - Gamma ray bursts
- Residual Gravitational Radiation from the Big Bang
  – Cosmic Strings

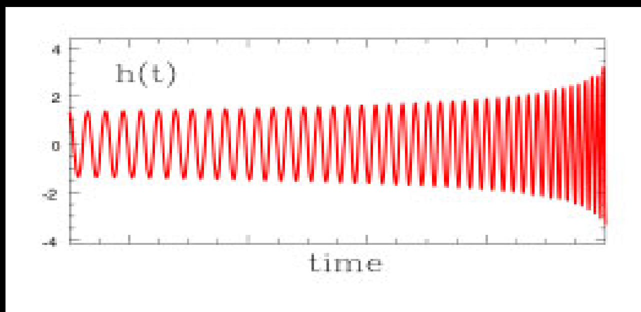


- Periodic Sources
  – Rotating pulsars

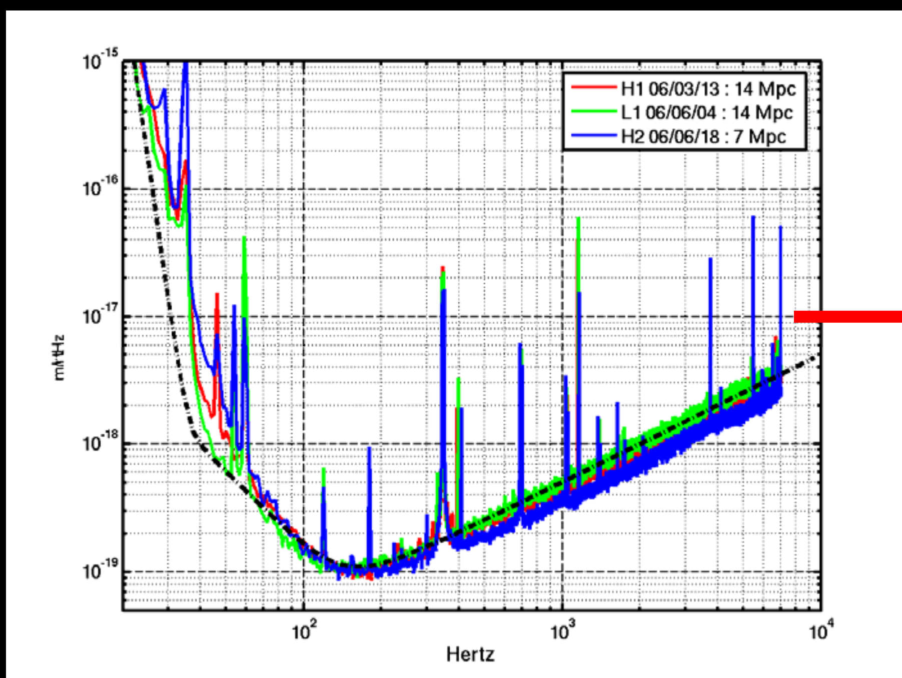


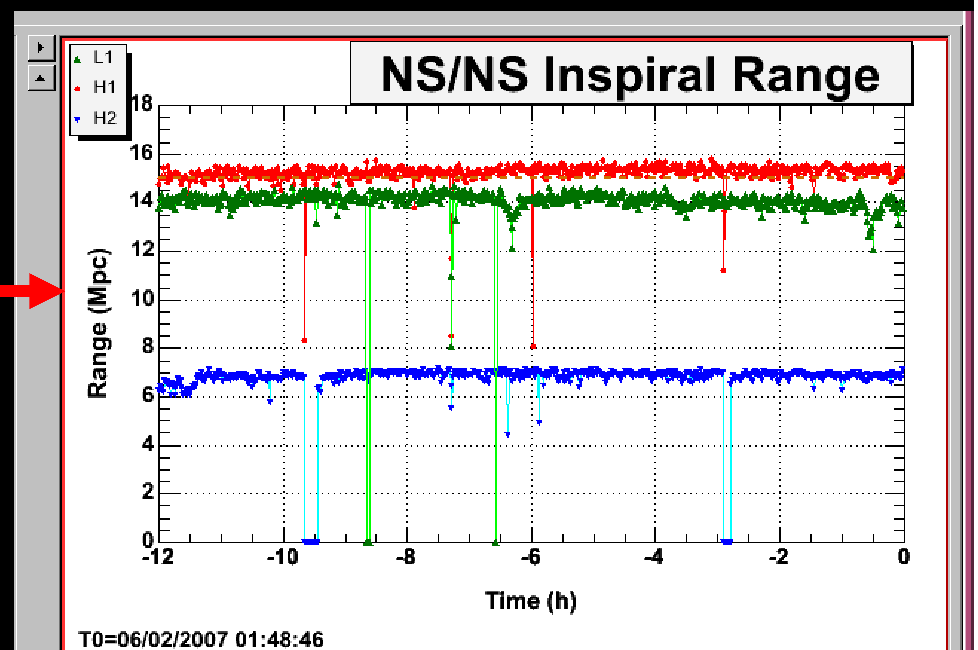
- ?????

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.

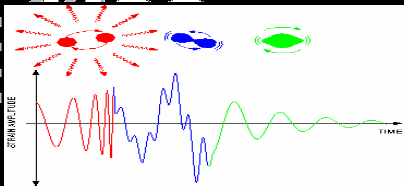


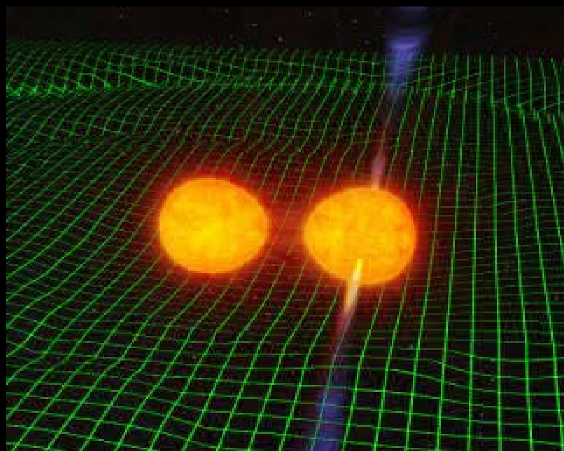


Range: distance of a 1.4-1.4 M binary, averaged over orientation/polarization

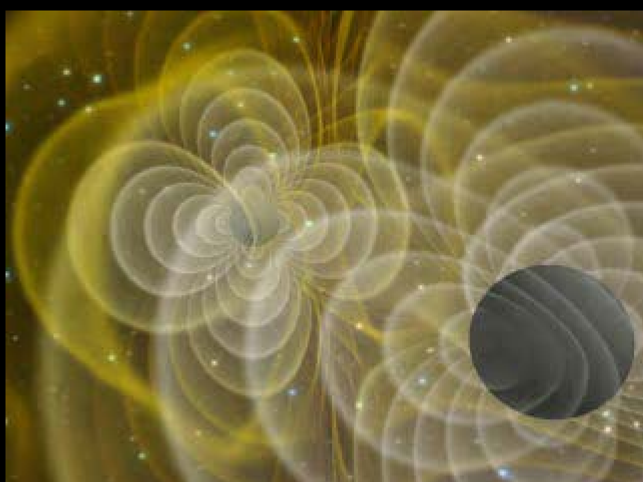
Predicted rate for S5: 1/3year (most optimistic), 1/30years (most likely)

Astrophysical Sources: Binary Inspirals



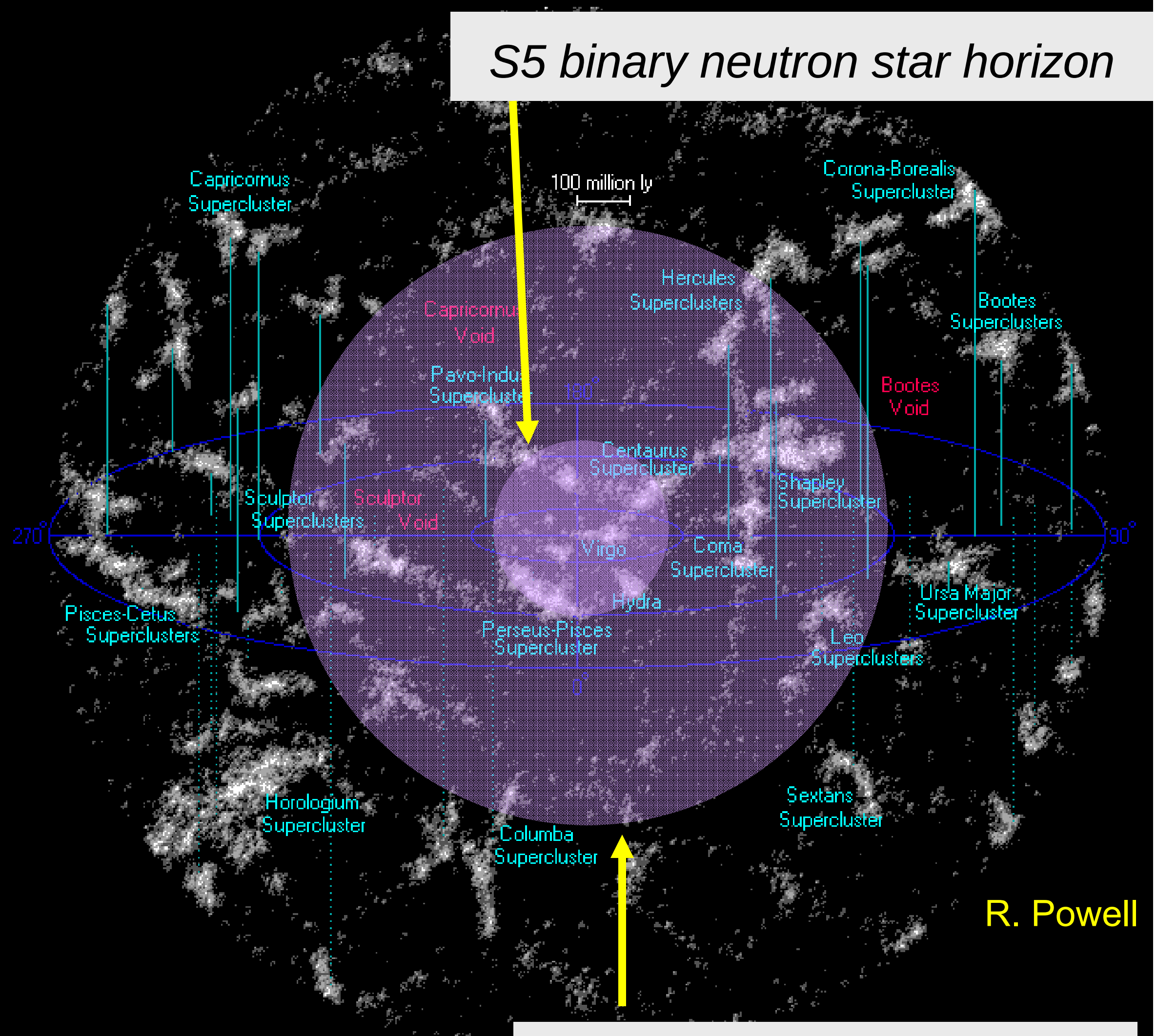


Credits: John Rowe Animation



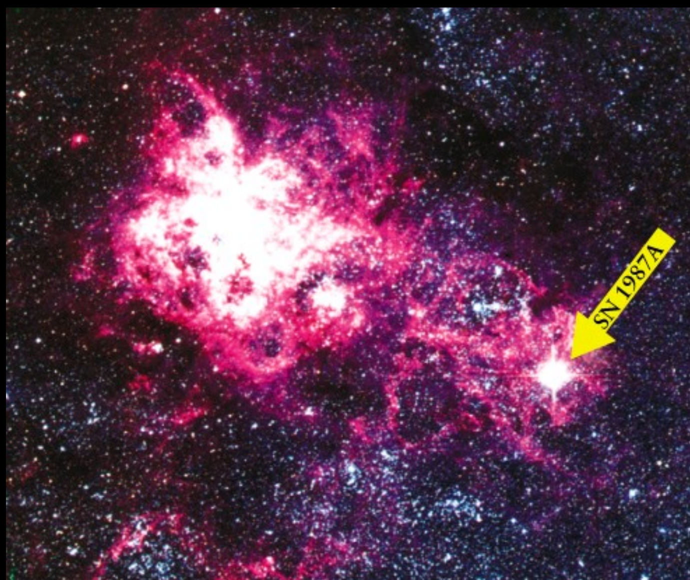
Simulation of gravitational waves produced by colliding black holes. Credit:Henze, NASA

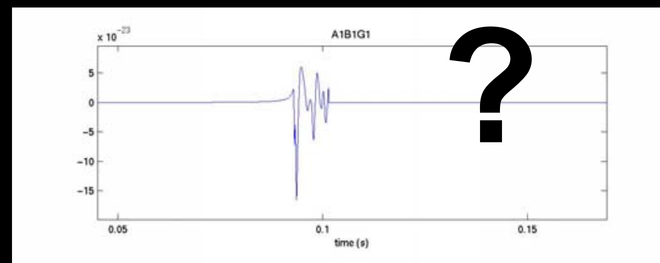
S5 binary neutron star horizon



S5 binary black hole horizon

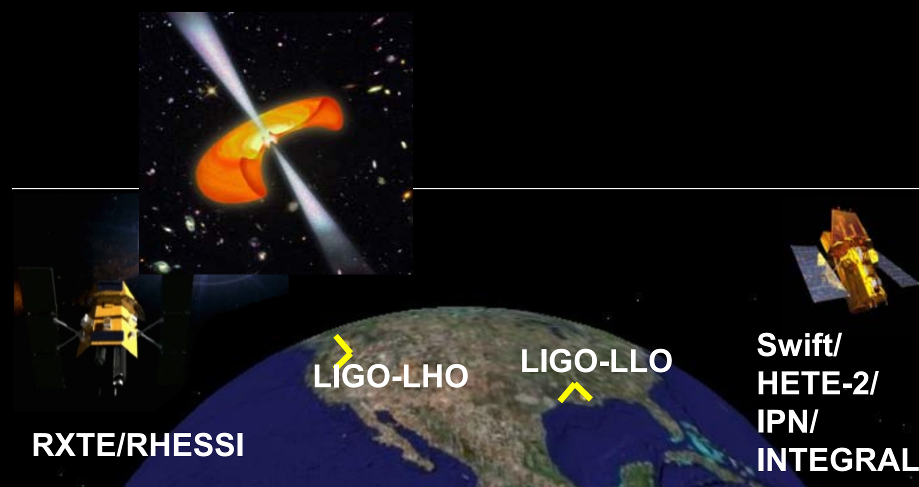
Astrophysical Sources: Bursts





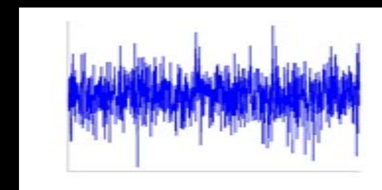
Uncertainty of waveforms complicates the detection ⇒ minimal assumptions, open to the unexpected

S5 sensitivity:
~$0.1M_{\odot}$ from 20MPc at 153 Hz



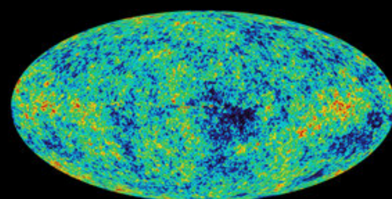
Astrophysical Sources: Stochastic Background

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



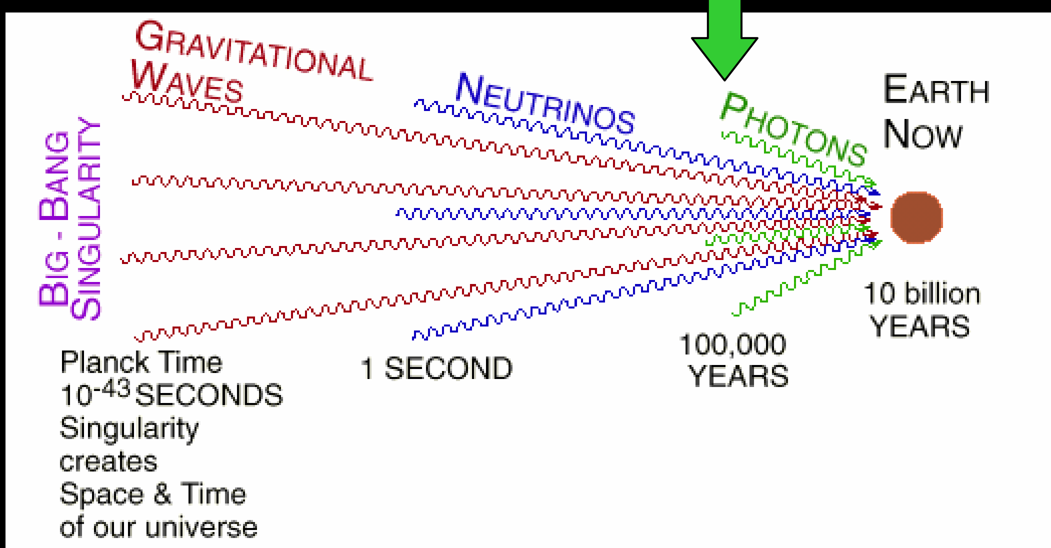
$$\Omega_{GW}(f) = \frac{1}{\rho_c} \frac{d\rho_{GW}(f)}{d \ln f}$$

cosmic GW background



NASA, WMAP

CMB (10^{+12} s)

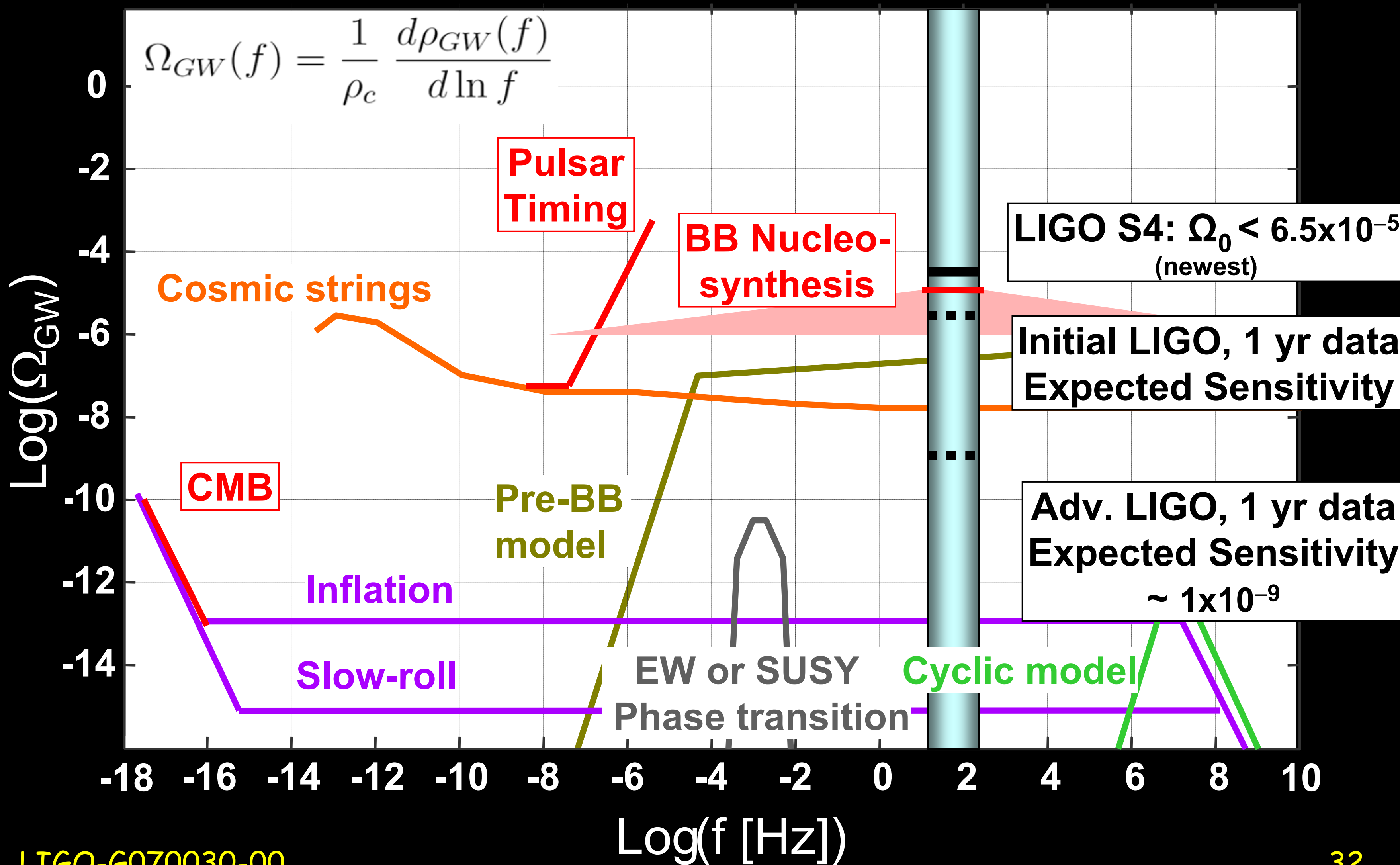


S5 sensitivity:

Cosmic GW background limits expected to be near $\Omega_{GW} \sim 10^{-5}$

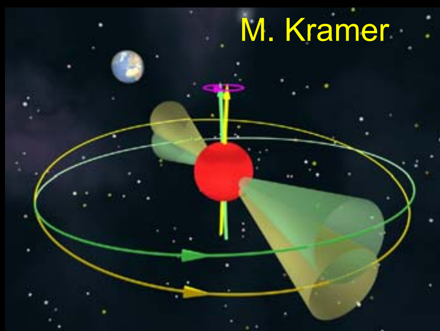
below the BBN limit!

Landscape



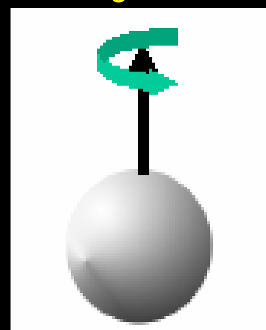
$\Omega_{GW}(f) = \frac{1}{\rho_c} \frac{d\rho_{GW}(f)}{d \ln f}$
Pulsar Timing
BB Nucleo-synthesis
LIGO S4: $\Omega_0 < 6.5\times10^{-5}$
(newest)
Cosmic strings
Initial LIGO, 1 yr data Expected Sensitivity
CMB
Pre-BB model
Adv. LIGO, 1 yr data Expected Sensitivity
$\sim 1\times10^{-9}$
Inflation
Slow-roll
EW or SUSY Phase transition
Cyclic model
Log(Ω_{GW})
0
-2
-4
-6
-8
-10
-12
-14
-18
-16
-14
-12
-10
-8
-6
-4
-2
0
2
4
6
8
10
Log(f [Hz])

Continuous Waves



Wobbling neutron stars

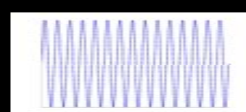
J. Creighton

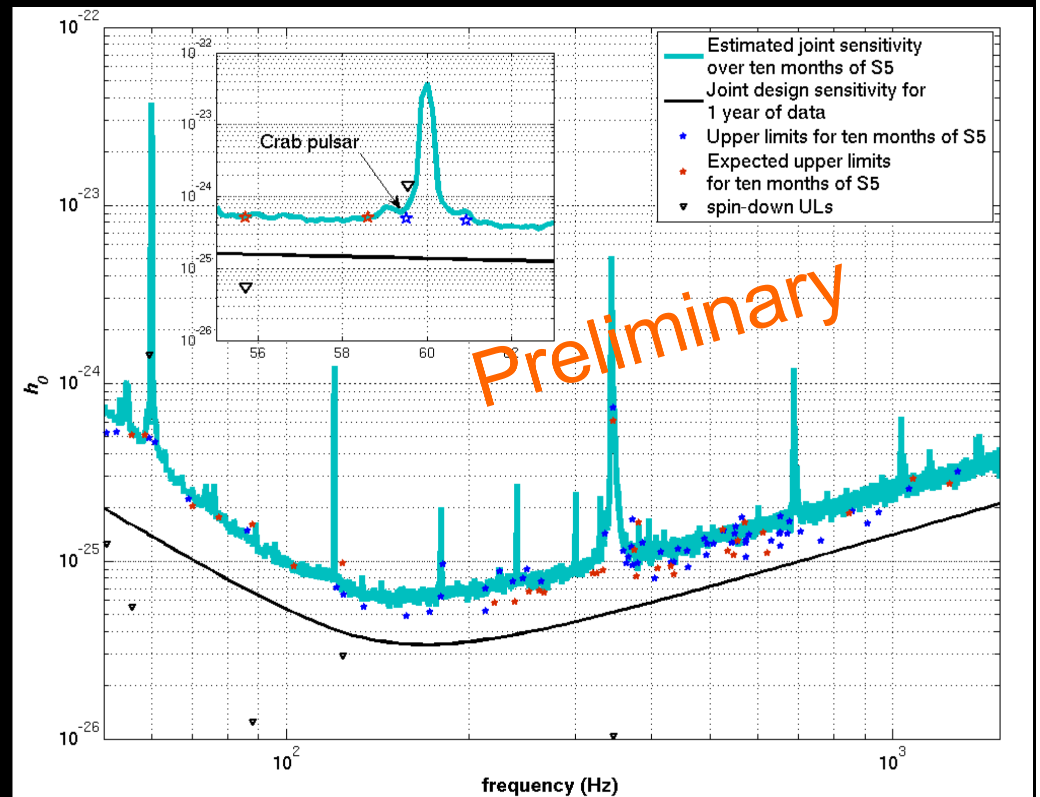


Pulsars with mountains

Dana Berry/NASA

Accreting neutron stars





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

S5 expectations:

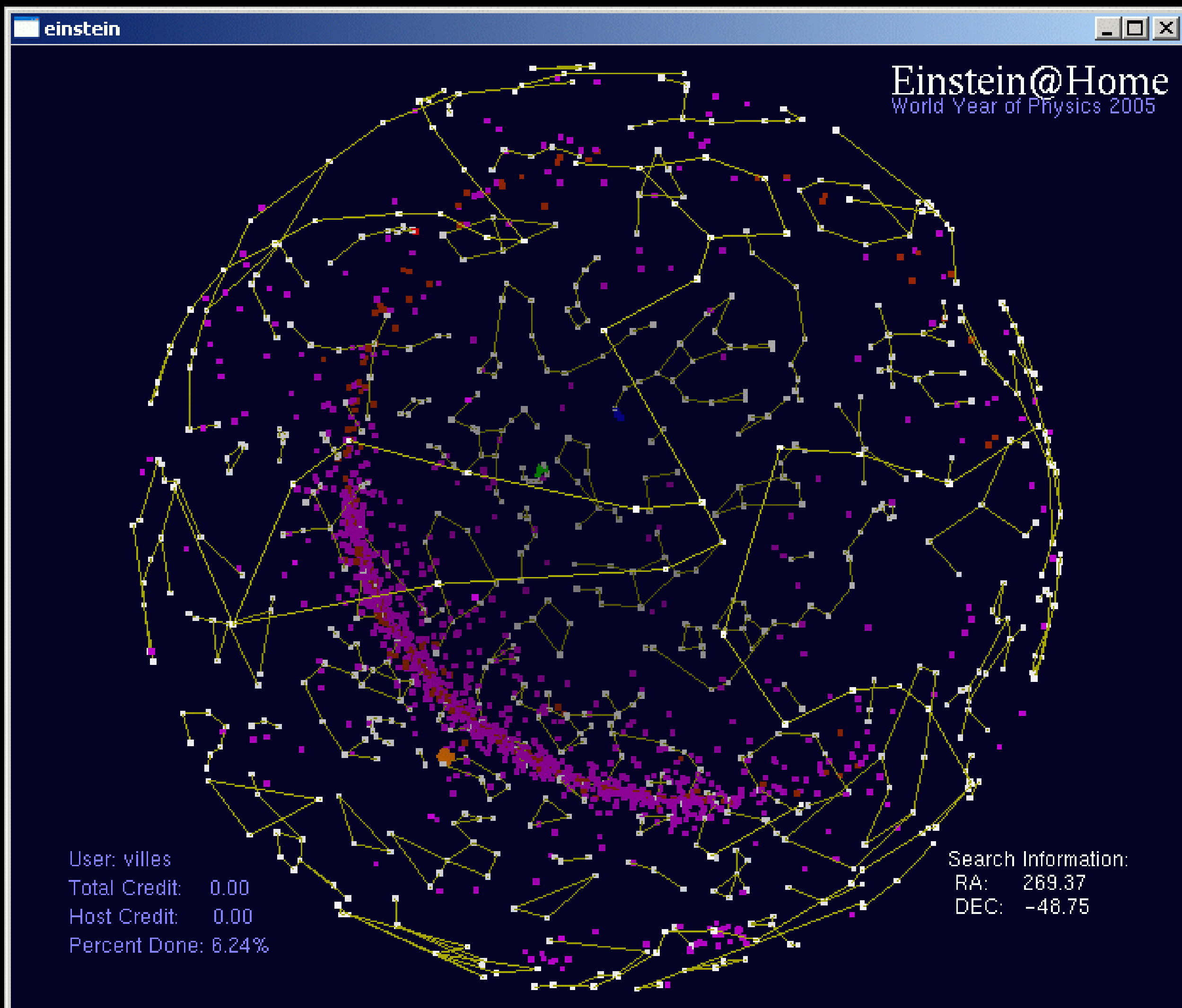
Best limits on known pulsars ellipticities at few x10^{-7}

Beat spin-down limit on Crab pulsar

Hierarchical all-sky/all-frequency search

The Einstein@home Project

http://www.physics2005.org



Users and Computers

Thur Nov 9 2006 15:14 UTC

USERS	Approximate #
in database	229,674
with credit	145,882
registered in past 24 hours	197
HOST COMPUTERS	**Approximate #**
in database	552,155
registered in past 24 hours	939
with credit	300,421
active in past 7 days	76,857
floating point speed[1)]	81.6 TFLOPS

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.

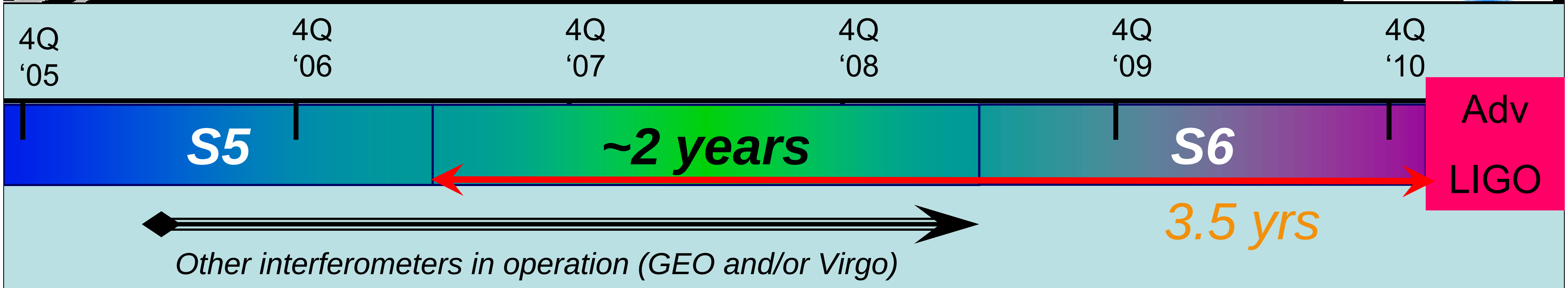
Use environmental monitors as vetos

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

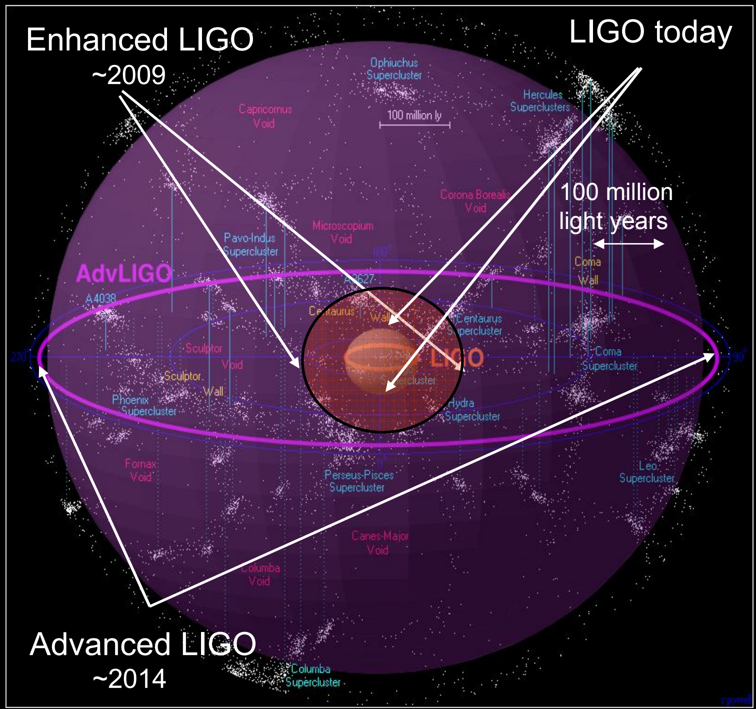
Understand the detector response:

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

LIGO timeline



- 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 ~8 times more galaxies in range
- Advanced LIGO
  - Construction start expected in FY08
  - 1000 times more galaxies in range
  - Expect ~1 signal/day - 1/week in ~2014



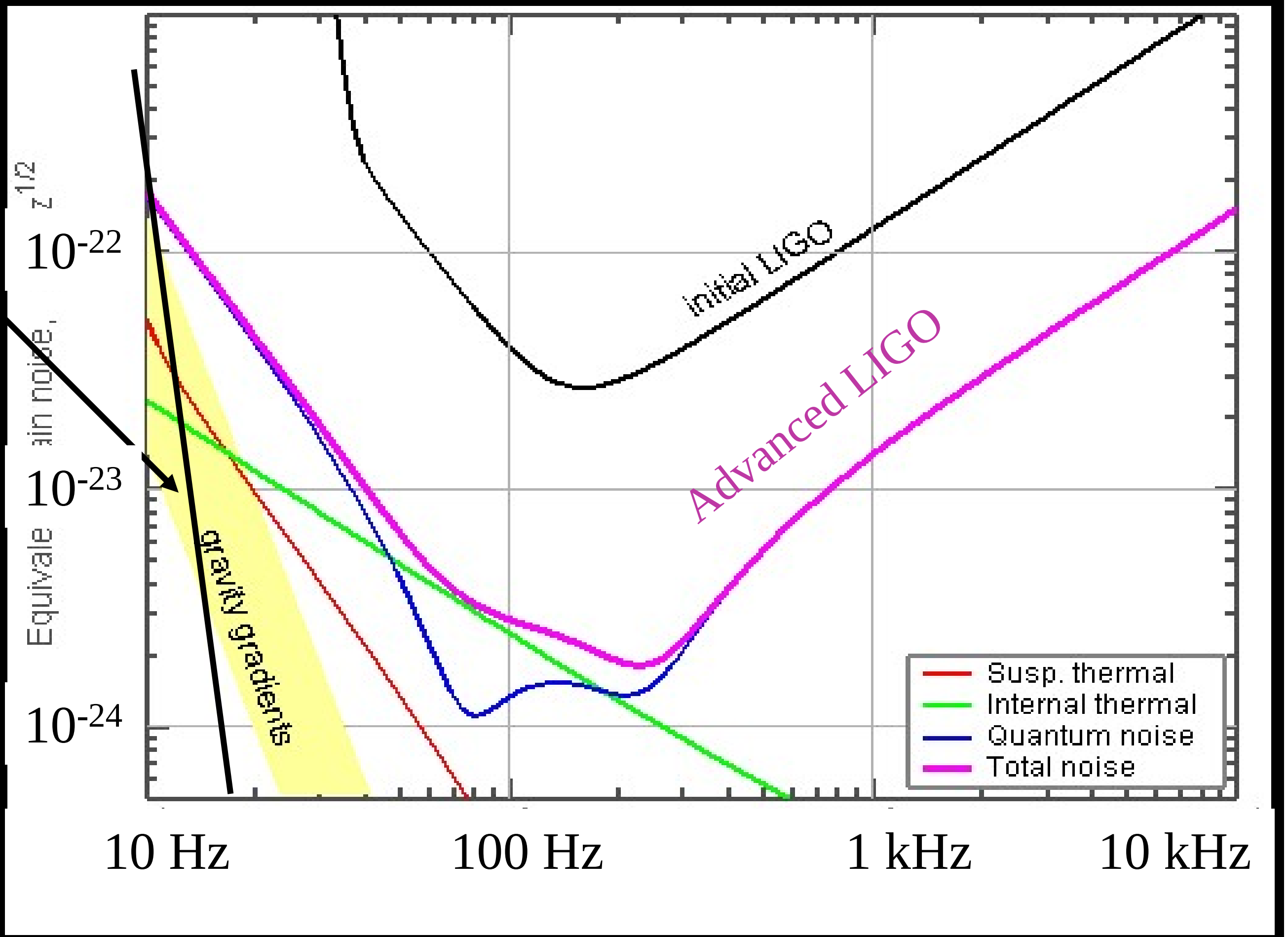
The science from the first 3 hours of Advanced LIGO should be comparable to 1 year of initial LIGO

Advanced LIGO: President Requests FY2008 Construction Start

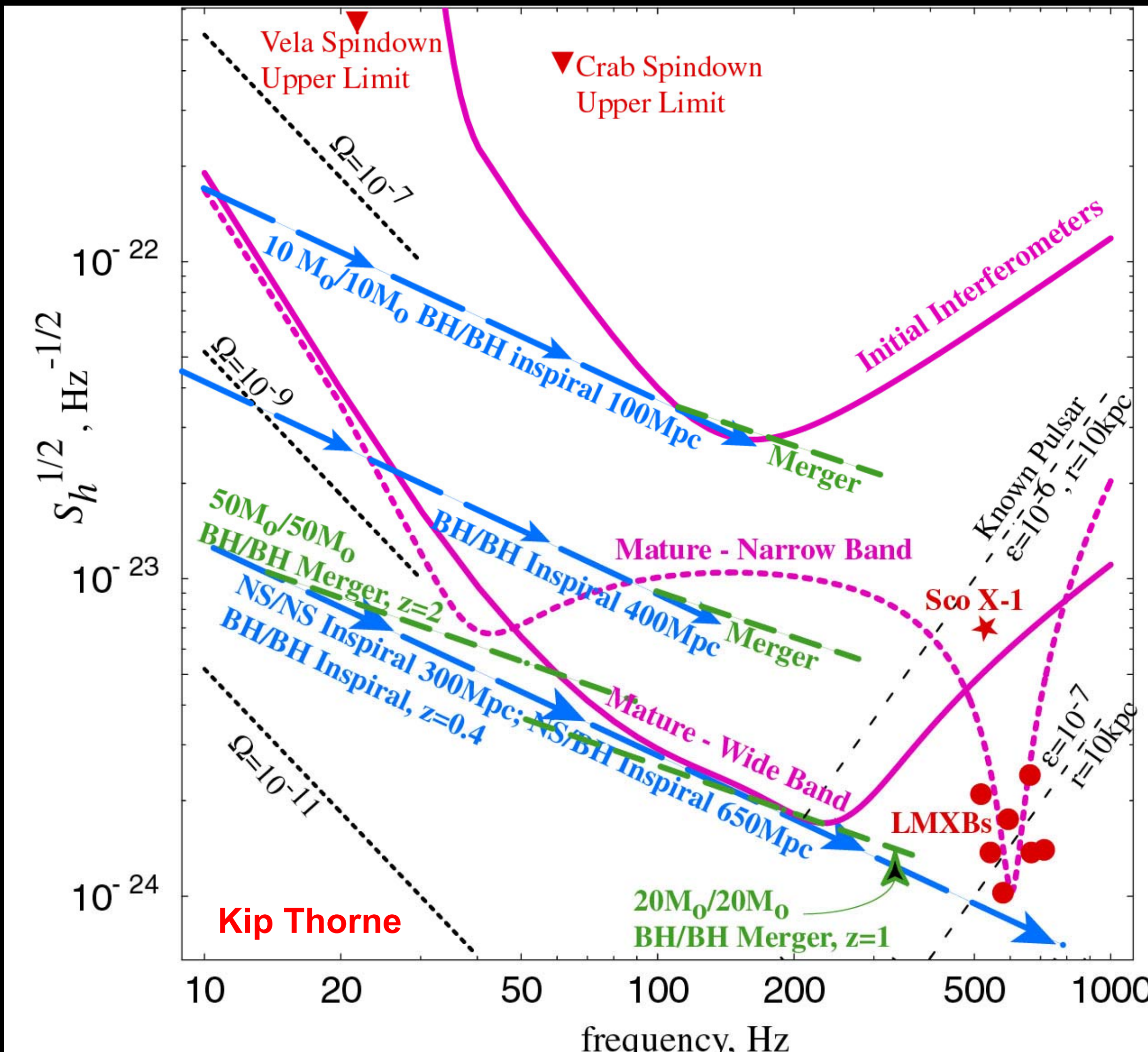
Seismic 'cutoff' at 10 Hz

Quantum noise

(shot noise +
radiation pressure)
dominates at
most frequencies



Science Potential of Advanced LIGO



Binary neutron stars:

From ~20 Mpc to ~350 Mpc

From 1/30y(<1/3y) to 1/2d(<5/d)

Binary black holes:

From ~100Mpc to z=2

Known pulsars:

From ε = 3×10^{-6} to 2×10^{-8}

Stochastic background:

From Ω_{GW} ~3×10^{-6} to ~3×10^{-9}

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