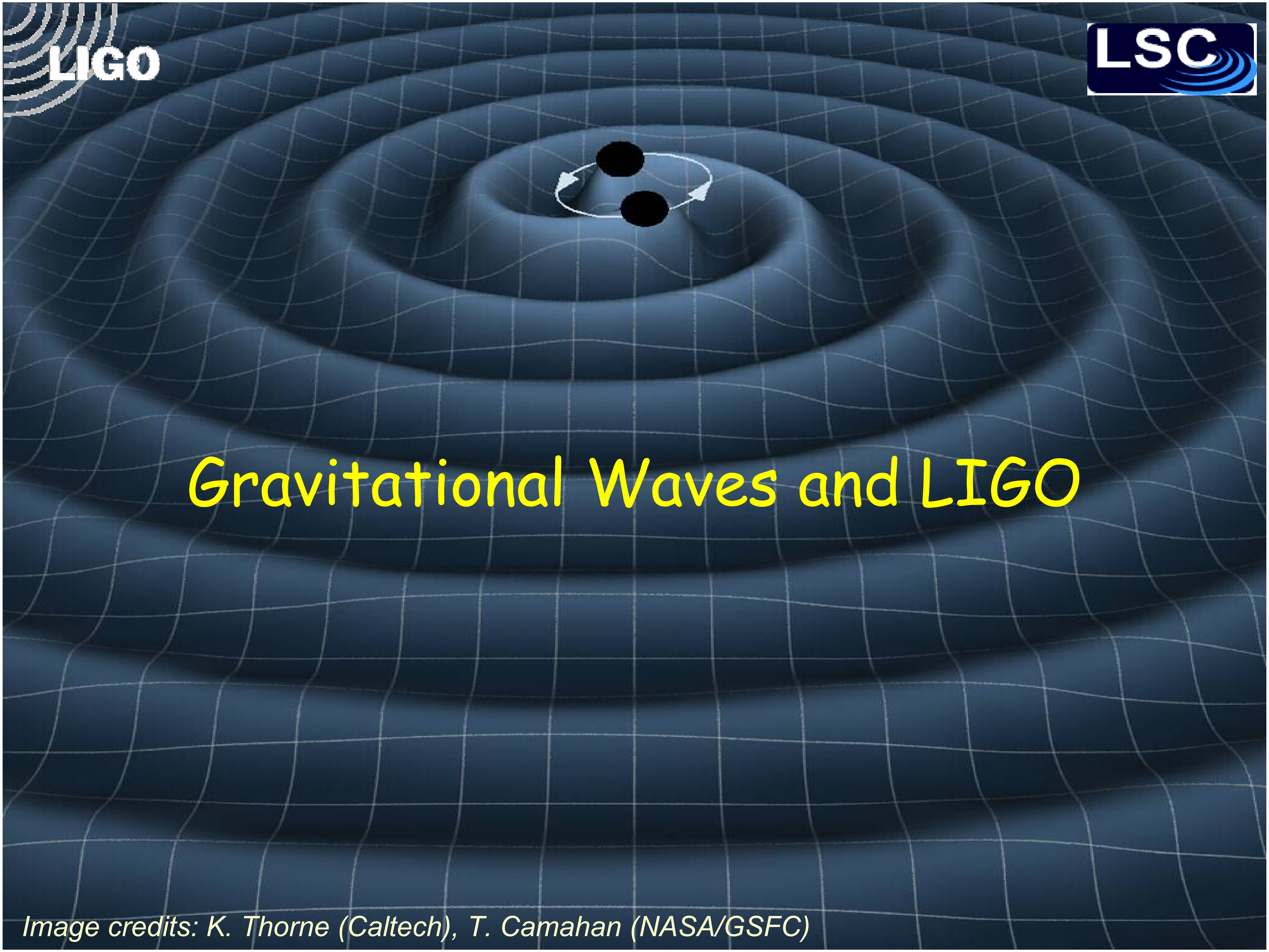
# Status of the search for gravitational waves with LIGO

Laura Cadonati
Massachusetts Institute of Technology
LIGO Scientific Collaboration

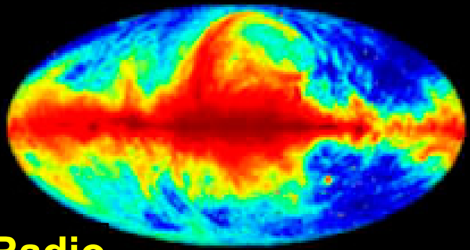
Legnaro, July 4 2007

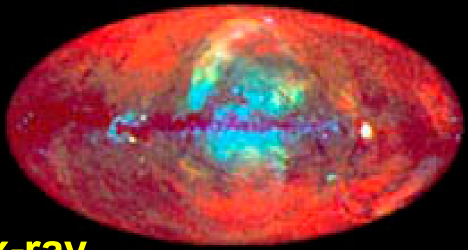


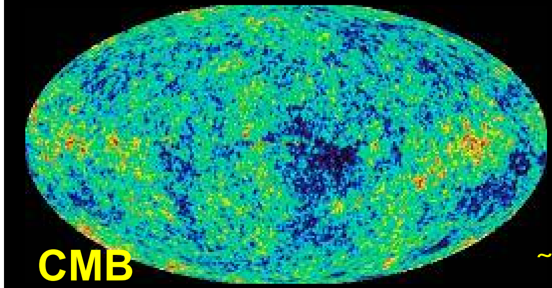
# Gravitational Waves and LIGO

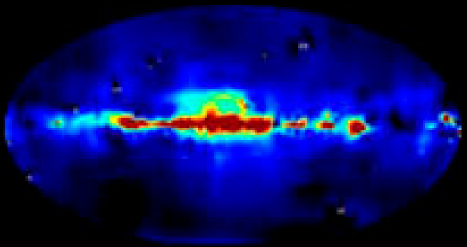
*Image credits: K. Thorne (Caltech), T. Camahan (NASA/GSFC)*

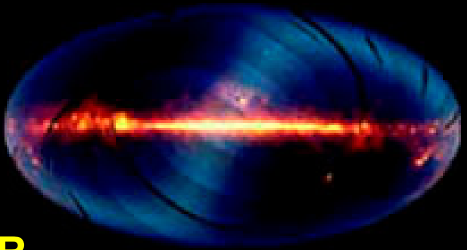
# A New Probe into the Universe

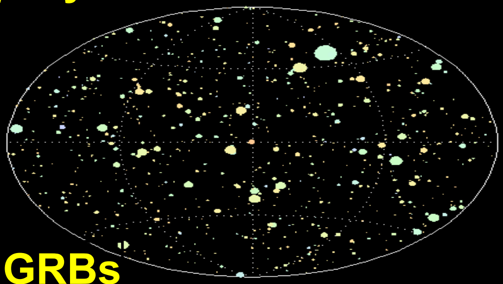

**Radio**


**x-ray**


**CMB**


**$\gamma$-ray**


**IR**


**GRBs**


**GW sky??**

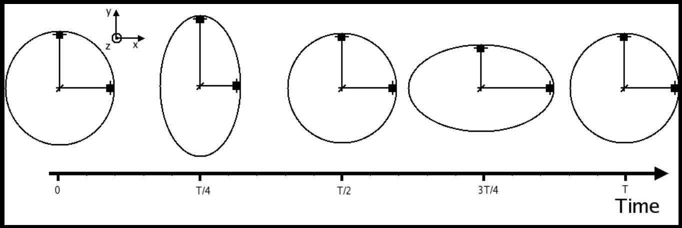
Gravitational Waves will give us a different, non electromagnetic view of the universe, and open a new spectrum for observation.

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

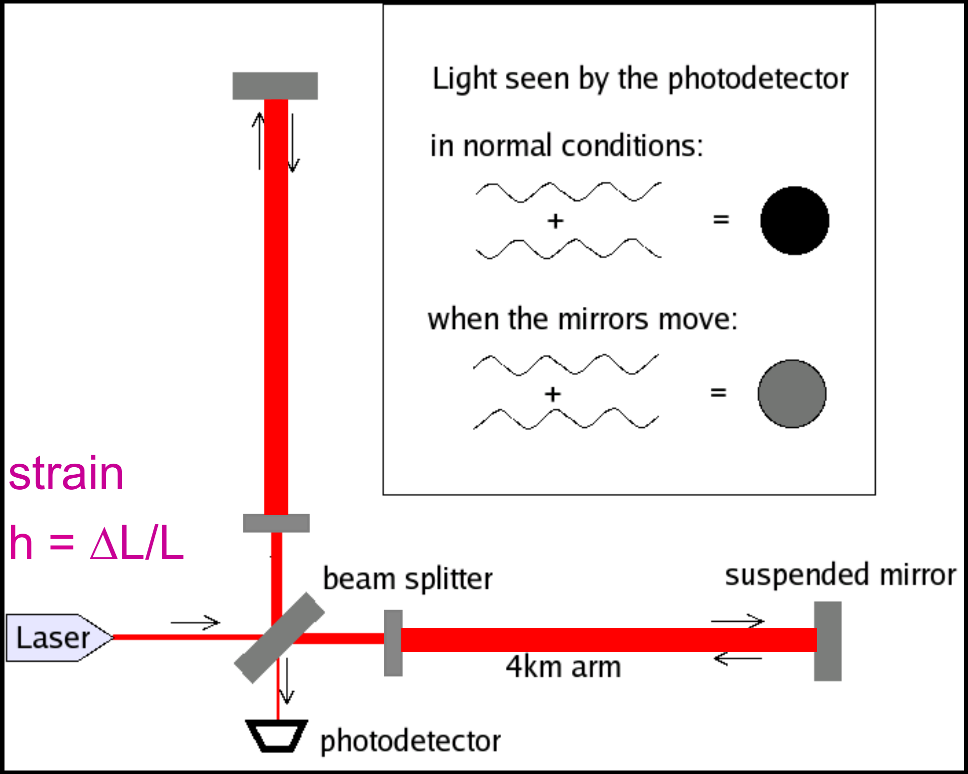
***EXPECT THE UNEXPECTED!***

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.

# The LIGO Observatory

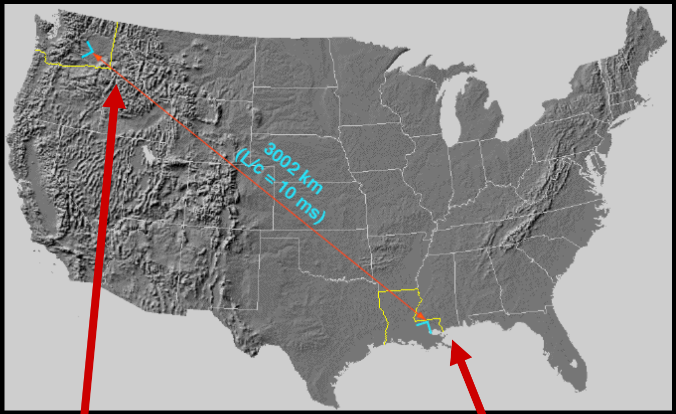


Initial goal: measure difference in length to one part in $10^{21}$, or $10^{-18}$ m



strain

$h = \Delta L/L$



Hanford Observatory
4 km and 2 km interferometers
H1 and H2

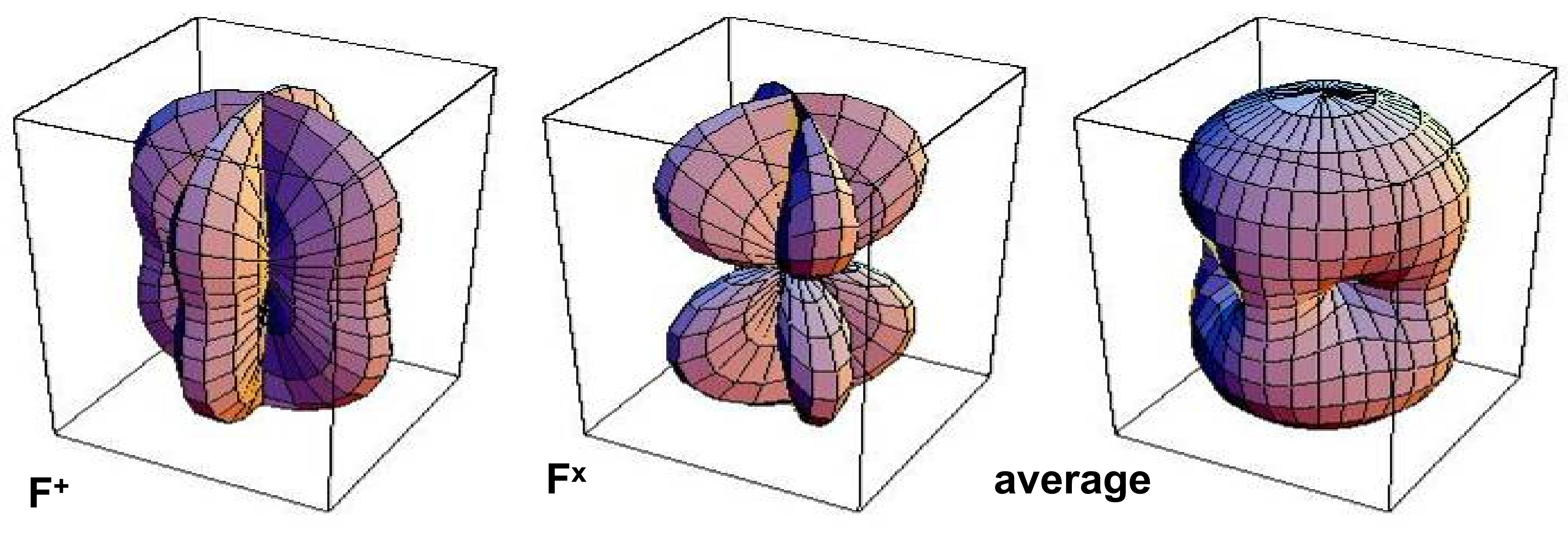
Livingston Observatory
4 km interferometer
L1

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

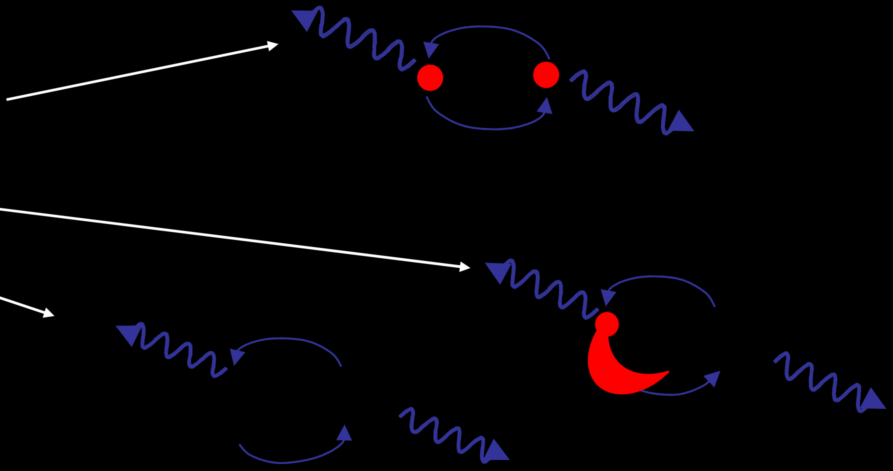
Beam patterns:

$F^+, F^x$ : [-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

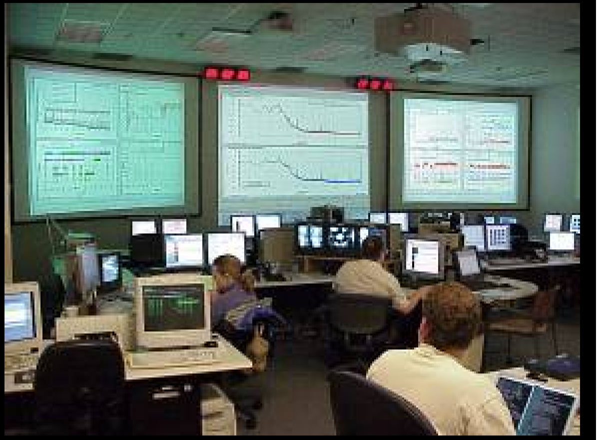


- Binary systems
  - Neutron star – Neutron star
  - Black hole – Neutron star
  - Black hole – Black hole
- “Burst” Sources
  - Supernovae
    - Gamma ray bursts

- Residual Gravitational Radiation from the Big Bang

- Periodic Sources
  - Rotating pulsars

- ?????



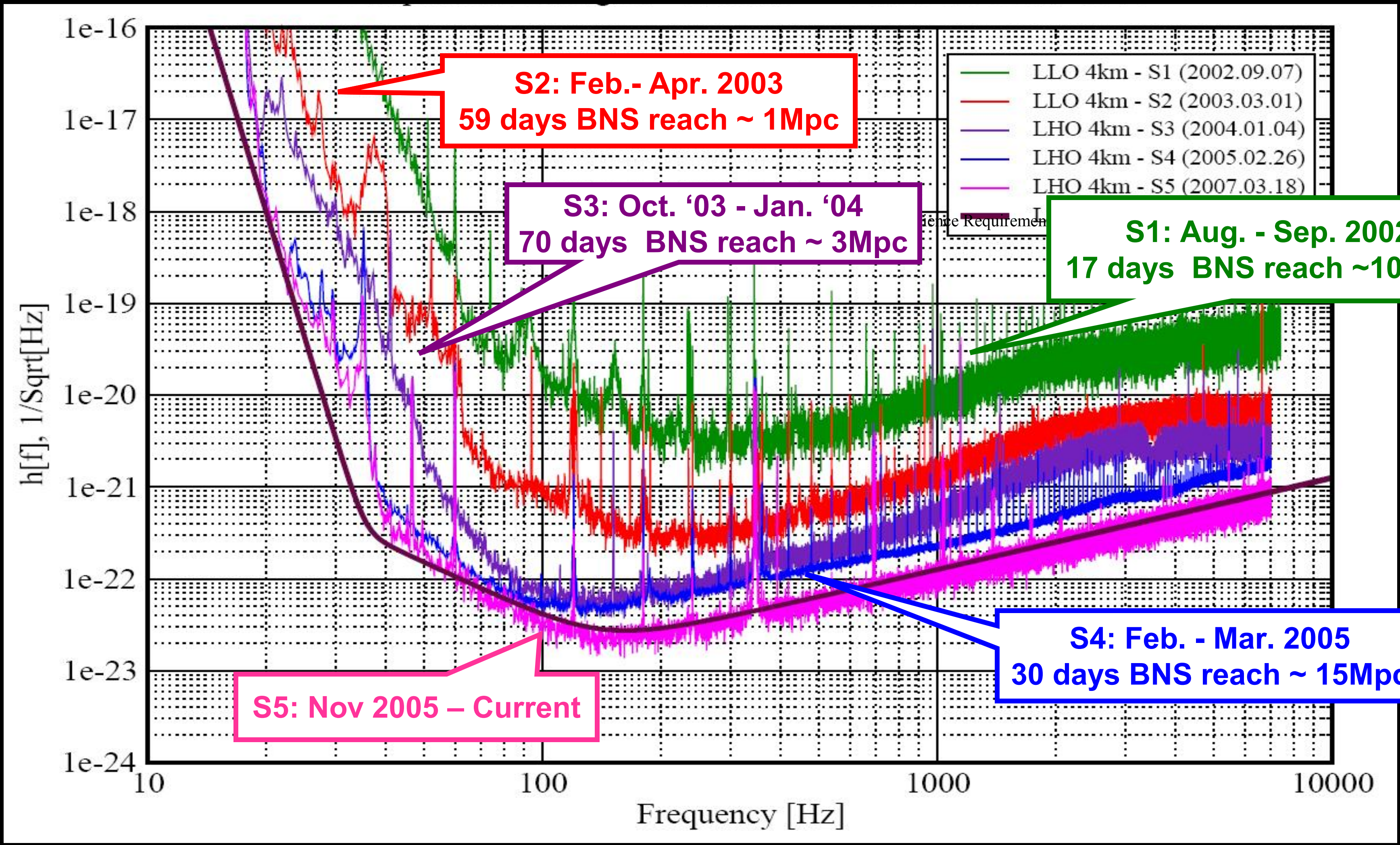
# The LIGO Scientific Collaboration

- Australian Consortium for Interferometric Gravitational Astronomy
- The Univ. of Adelaide
- Andrews University
- The Australian National Univ.
- The University of Birmingham
- California Inst. of Technology
- Cardiff University
- Carleton College
- Charles Stuart Univ.
- Columbia University
- Embry Riddle Aeronautical Univ.
- Eötvös Loránd University
- University of Florida
- German/British Collaboration for the Detection of Gravitational Waves
- University of Glasgow
- Goddard Space Flight Center
- Leibniz Universität Hannover
- Hobart & William Smith Colleges
- Inst. of Applied Physics of the Russian Academy of Sciences
- Polish Academy of Sciences
- India Inter-University Centre for Astronomy and Astrophysics
- Louisiana State University
- Louisiana Tech University
- Loyola University New Orleans
- University of Maryland

- Max Planck Institute for Gravitational Physics
- University of Michigan
- Massachusetts Inst. of Technology
- Monash University
- Montana State University
- Moscow State University
- National Astronomical Observatory of Japan
- Northwestern University
- University of Oregon
- Pennsylvania State University
- Rochester Inst. of Technology
- Rutherford Appleton Lab
- University of Rochester
- San Jose State University
- Univ. of Sannio at Benevento, and Univ. of Salerno
- University of Sheffield
- University of Southampton
- Southeastern Louisiana Univ.
- Southern Univ. and A&M College
- Stanford University
- University of Strathclyde
- Syracuse University
- Univ. of Texas at Austin
- Univ. of Texas at Brownsville
- Trinity University
- Universitat de les Illes Balears
- Univ. of Massachusetts Amherst
- University of Western Australia
- Univ. of Wisconsin-Milwaukee
- Washington State University
- University of Washington

# 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**

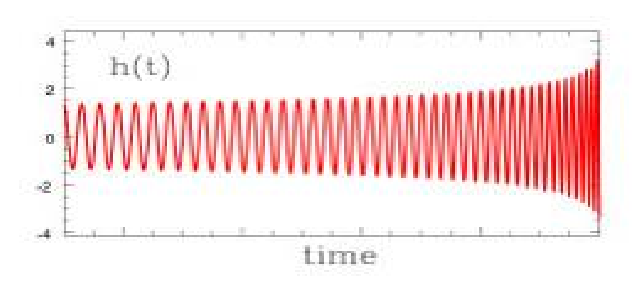
**S3: Oct. ‘03 - Jan. ‘04**
**70 days BNS reach ~ 3Mpc**

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

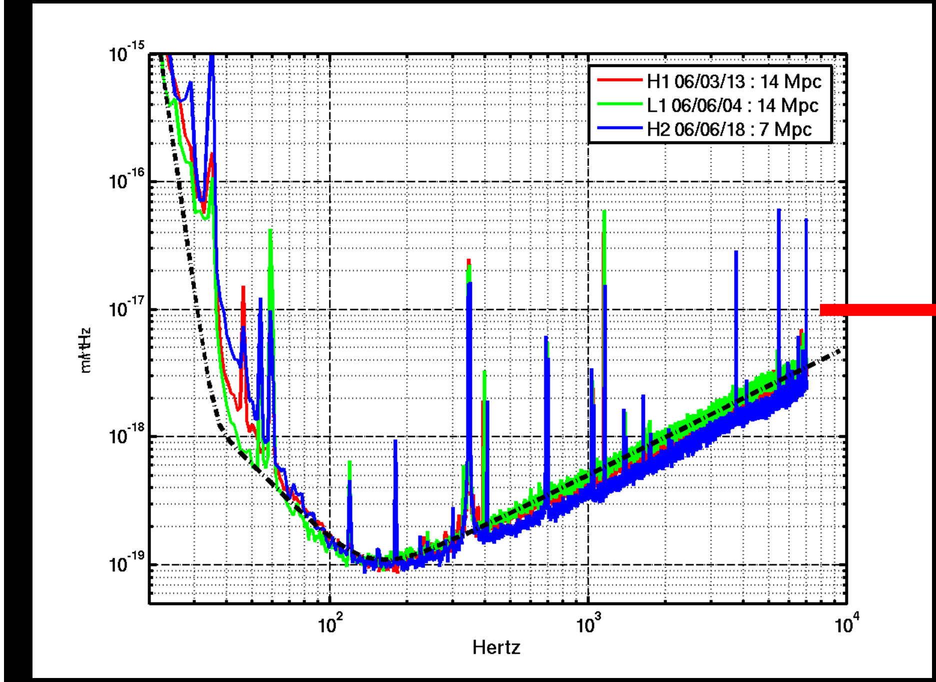
**S4: Feb. - Mar. 2005**
**30 days BNS reach ~ 15Mpc**

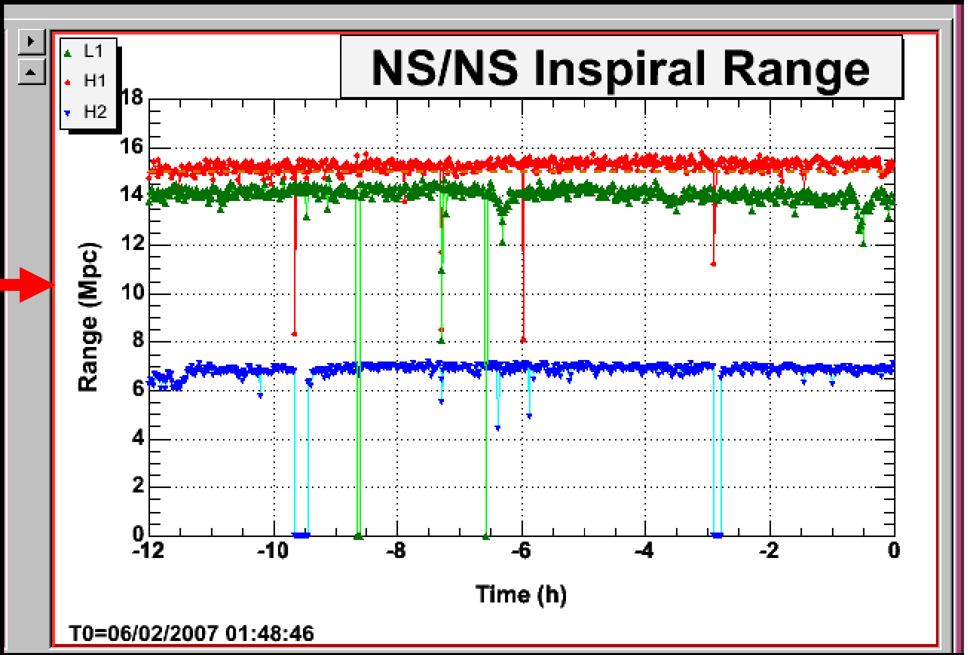
**S5: Nov 2005 – Current**

# 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.

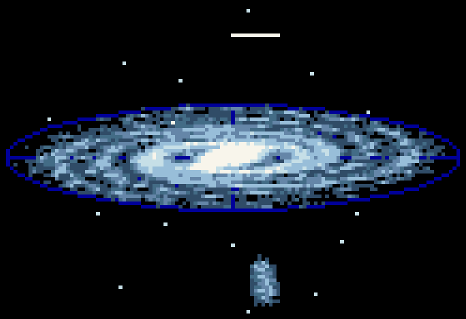




Range: distance of a 1.4-1.4 M binary, averaged over orientation/polarization
Predicted rate for S5: 1/3year (most optimistic), 1/100years (most likely)

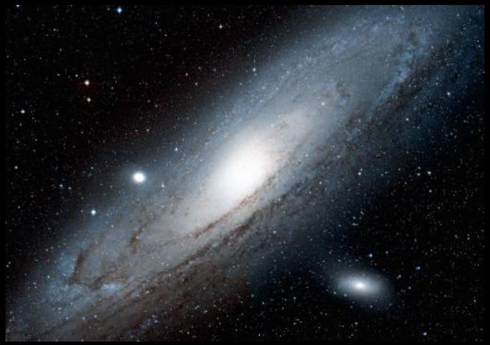
# Progress in Sensitivity

Average distance for detecting a coalescing neutron-star binary:



Milky Way
(8.5 kpc)

Sept 2002
[ ~1 galaxy ]



Andromeda
(700 kpc)

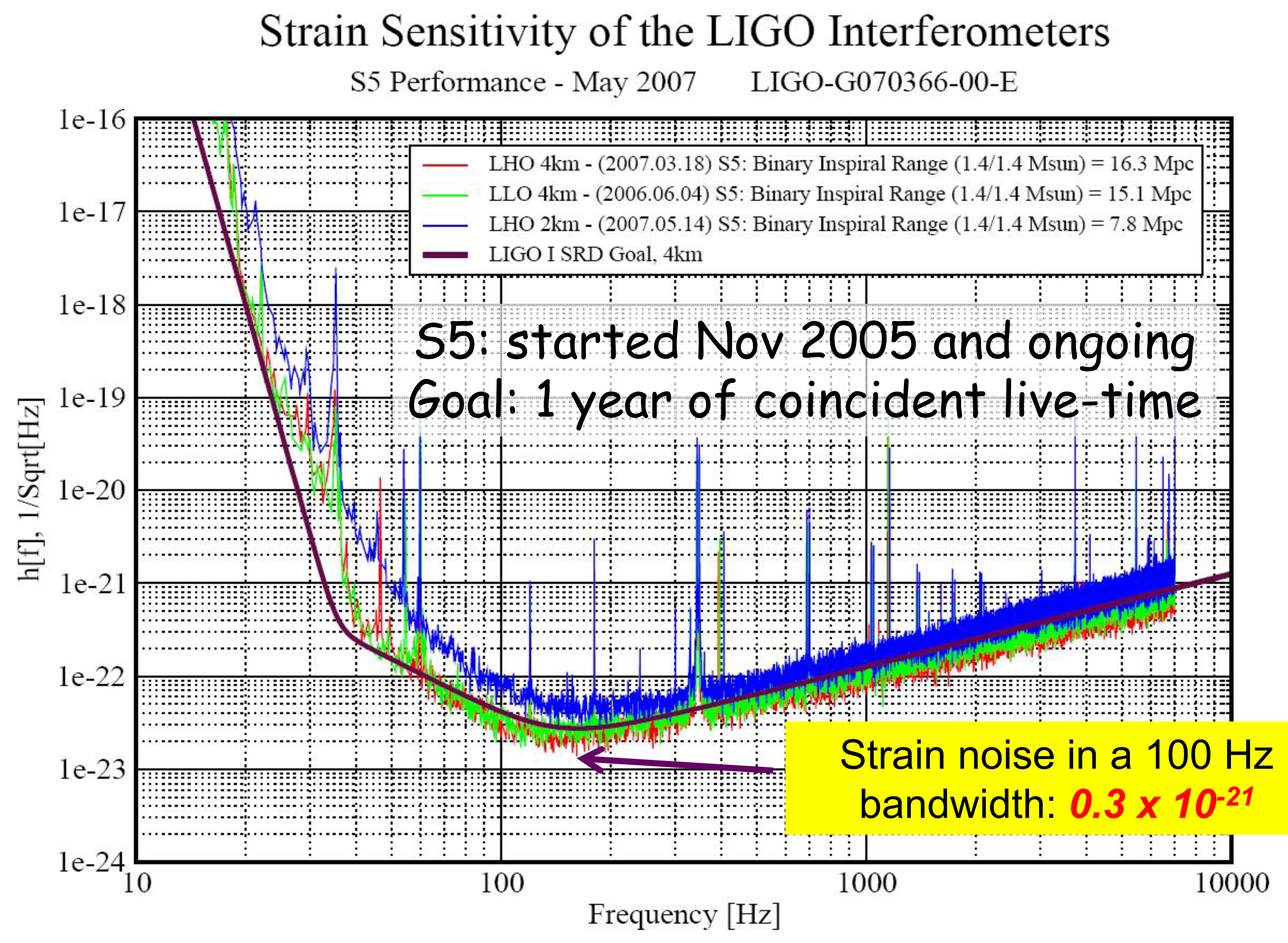
March 2003
[ ~2 galaxies ]

Virgo Cluster
(15 Mpc)

now
[ ~$10^3$ galaxies ]

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

# Science Run 5

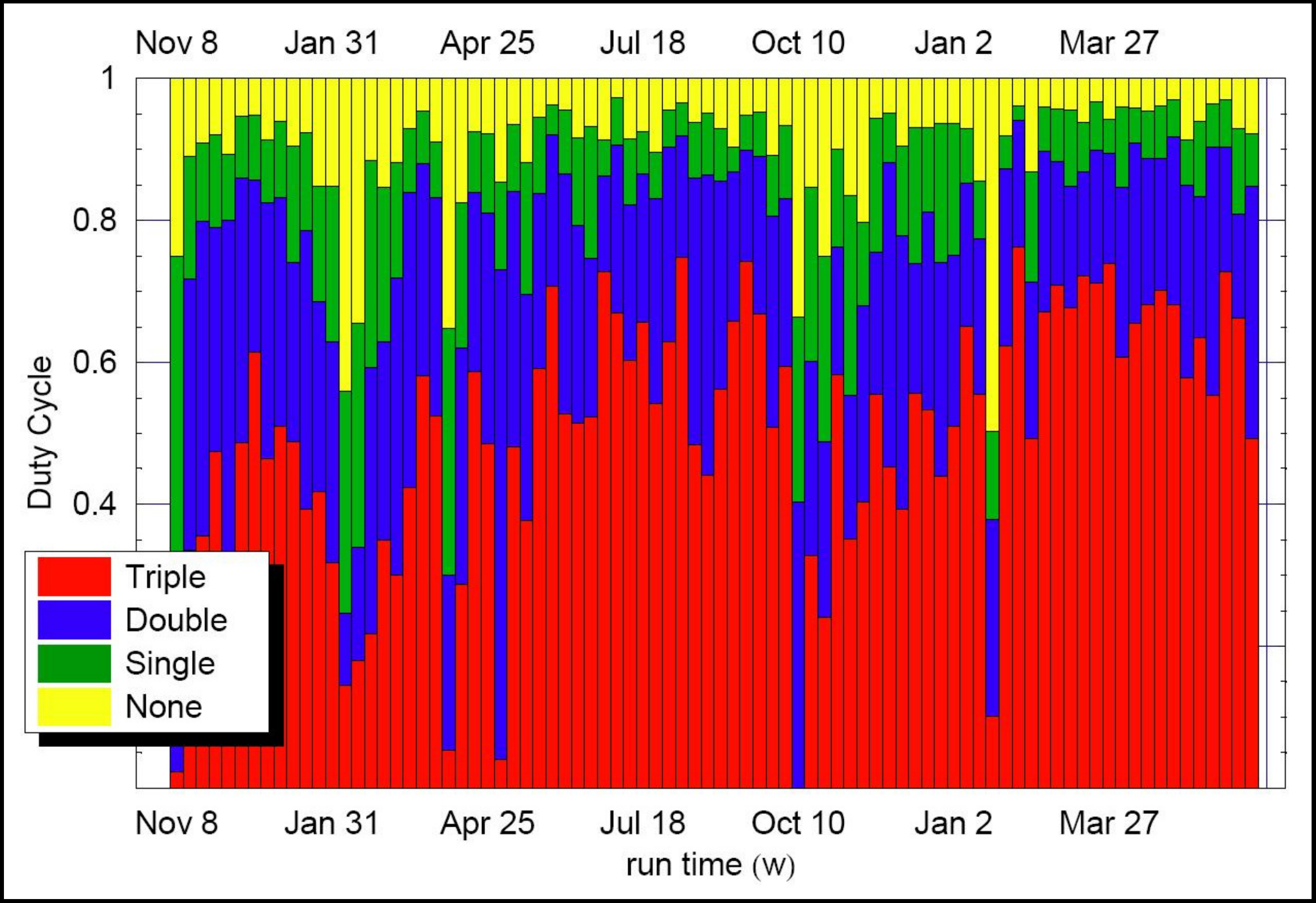


S5: started Nov 2005 and ongoing

Goal: 1 year of coincident live-time

Strain noise in a 100 Hz bandwidth: ***$0.3 \times 10^{-21}$***

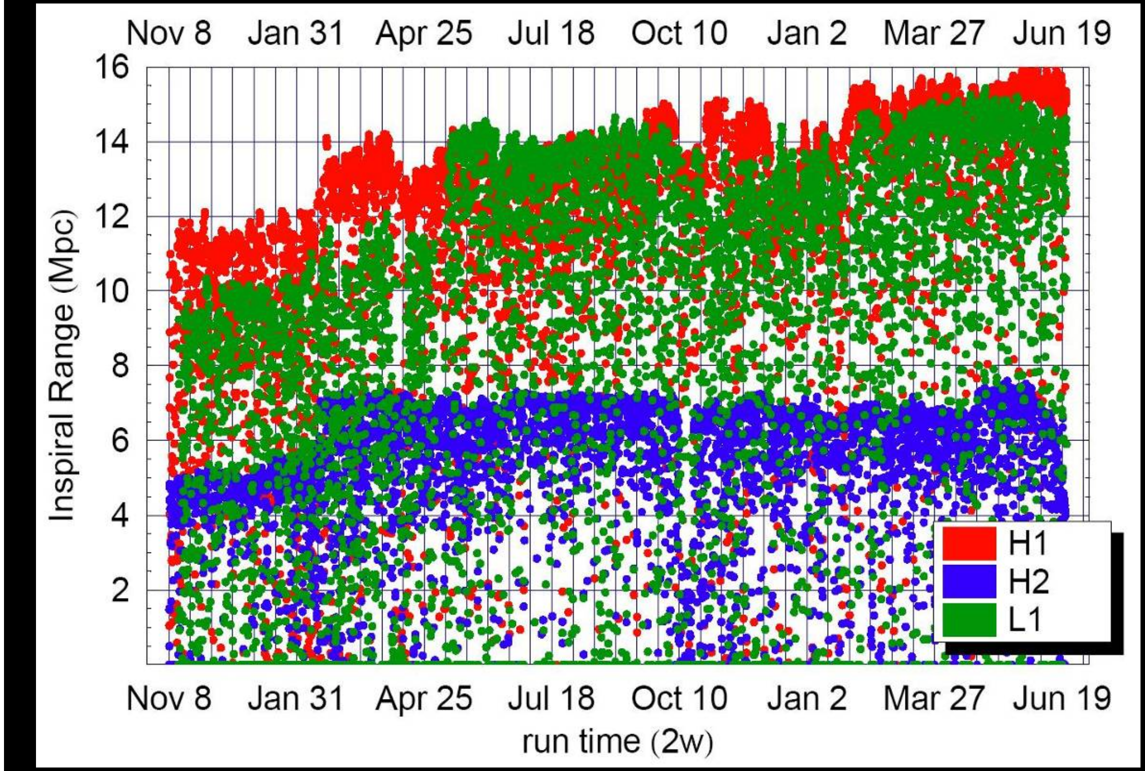
# The 5th Science Run

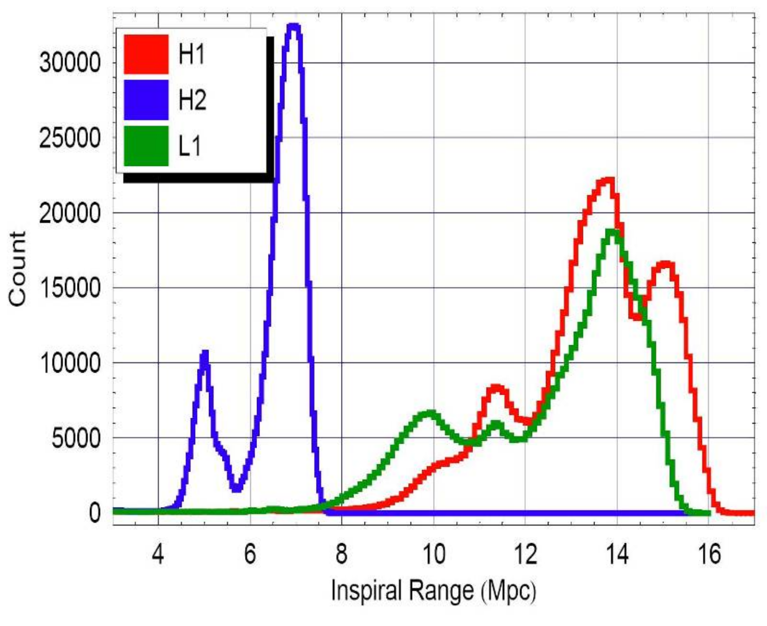


- Dates: Start: Nov ’05 Stop: ~Oct ‘07
- Duty cycle: H1: 76% H2: 78% L1: 64%

3-coinc.: 51% HL-coinc.: 59%

# Range during S5

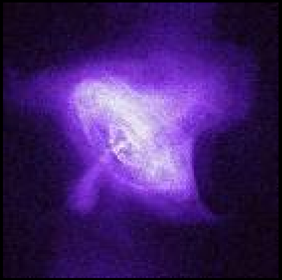
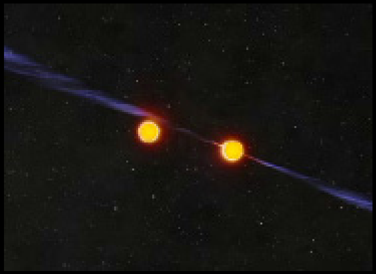
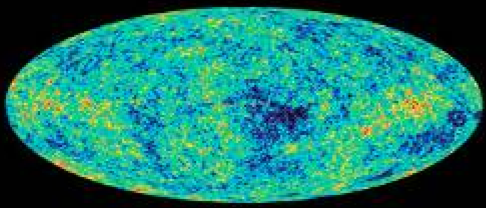
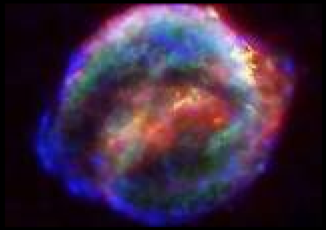




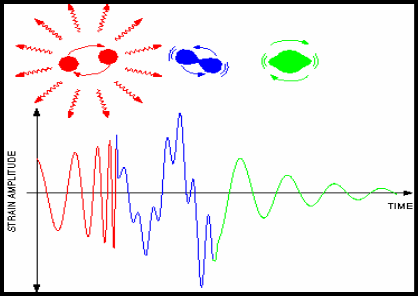
# Astrophysical Searches

Image Courtesy: Library of Congress

# Sources And Methods

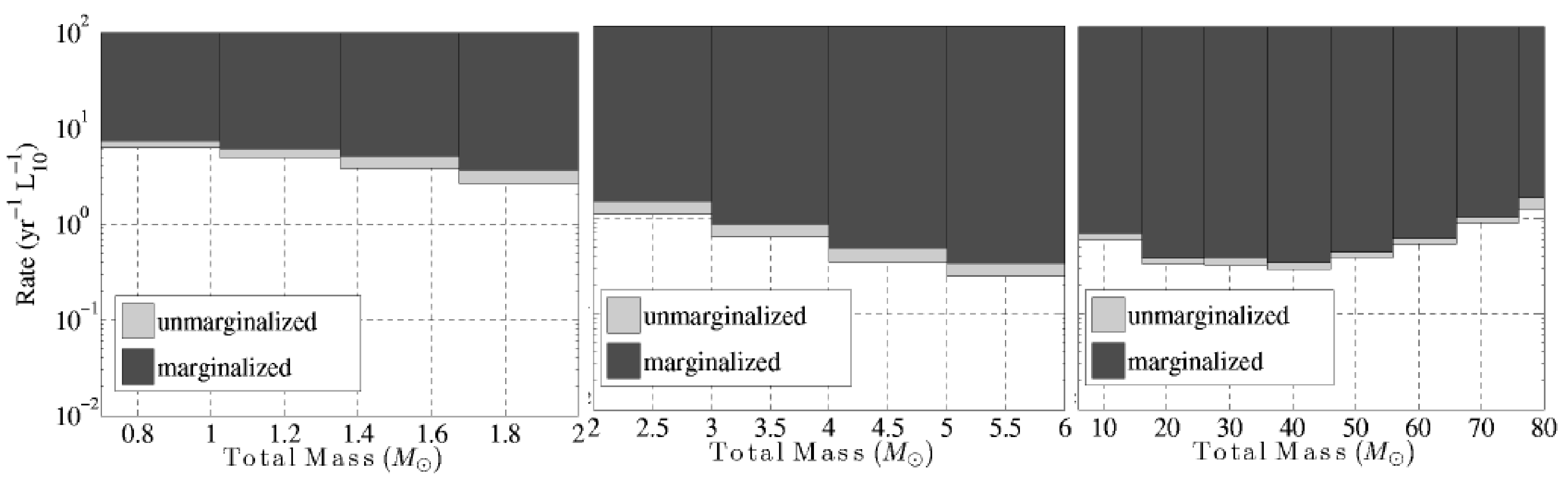
| | Long duration | Short duration |
|---|---|---|
| Matched filter | <br>Pulsars | <br>Compact Binary Inspirals |
| Template-less methods | <br>Stochastic Background | <br>Bursts |

# S4 Upper Limits for Binary Coalescences



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

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



arXiv:074-3368

# Horizon in S5

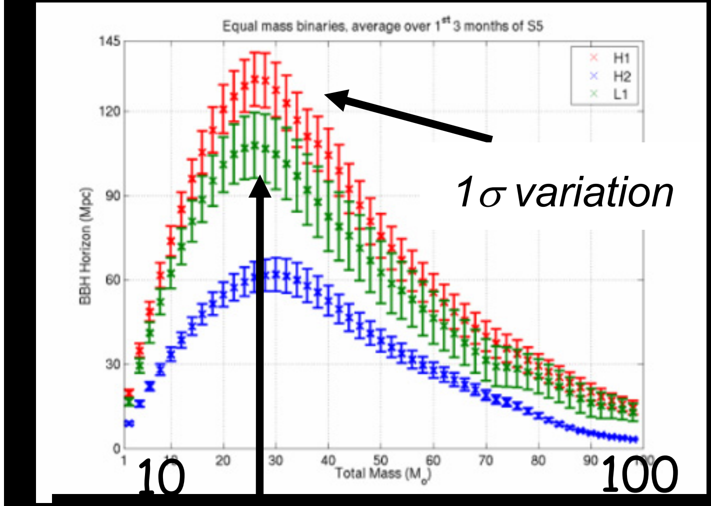
distance at which an optimally oriented and located binary system can be seen with signal-to-noise ratio $\rho=8$

For 1.4-1.4 $M_o$ binaries:

~ 200 MWEGs in range

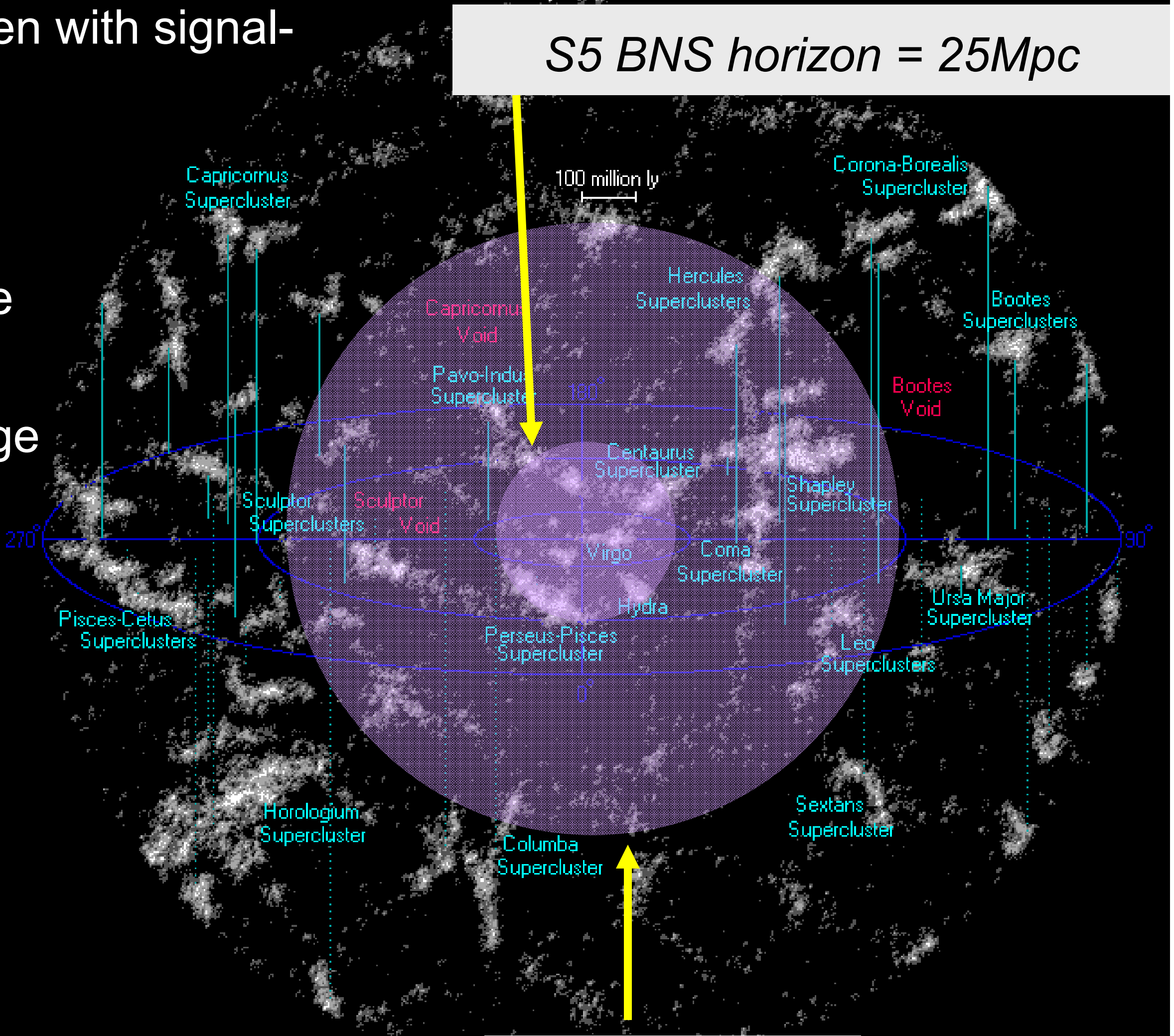
For 5-5 $M_o$ binaries:

~ 1000 MWEGs in range



$1\sigma$ variation

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

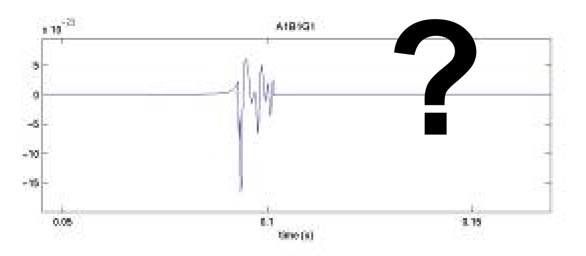


*S5 BNS horizon = 25Mpc*

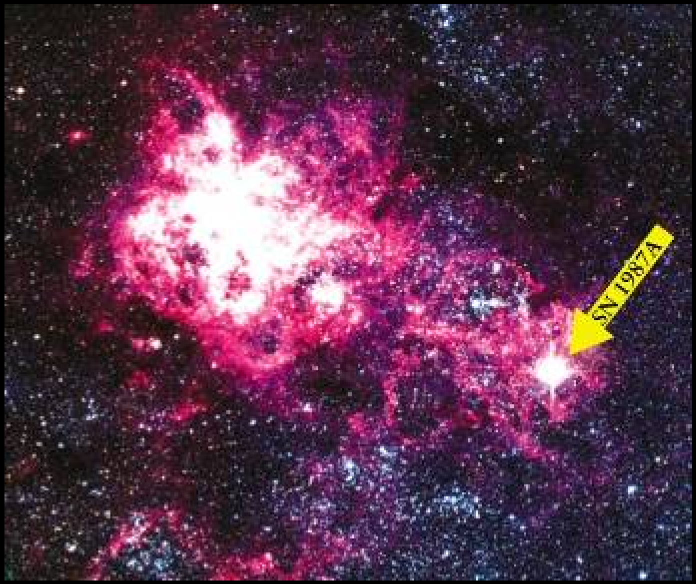
*S5 BBH horizon*

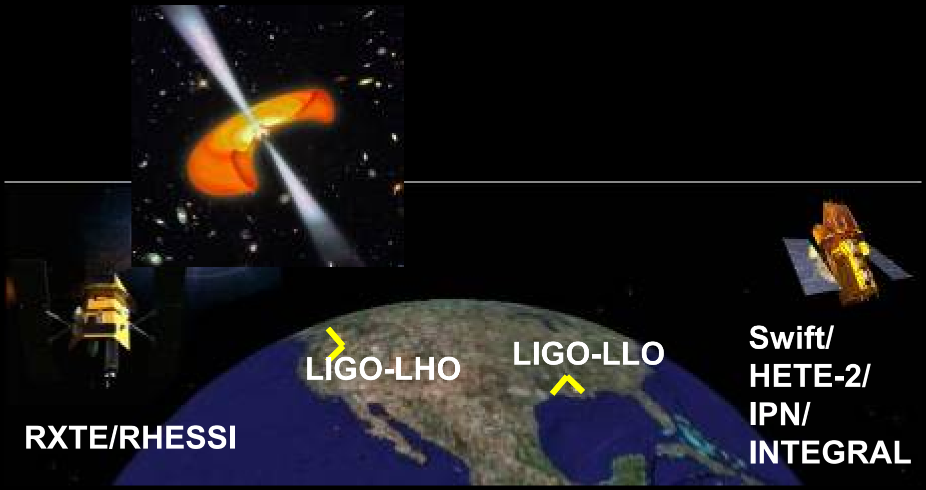
Image: R. Powell

# Astrophysical Sources: Bursts

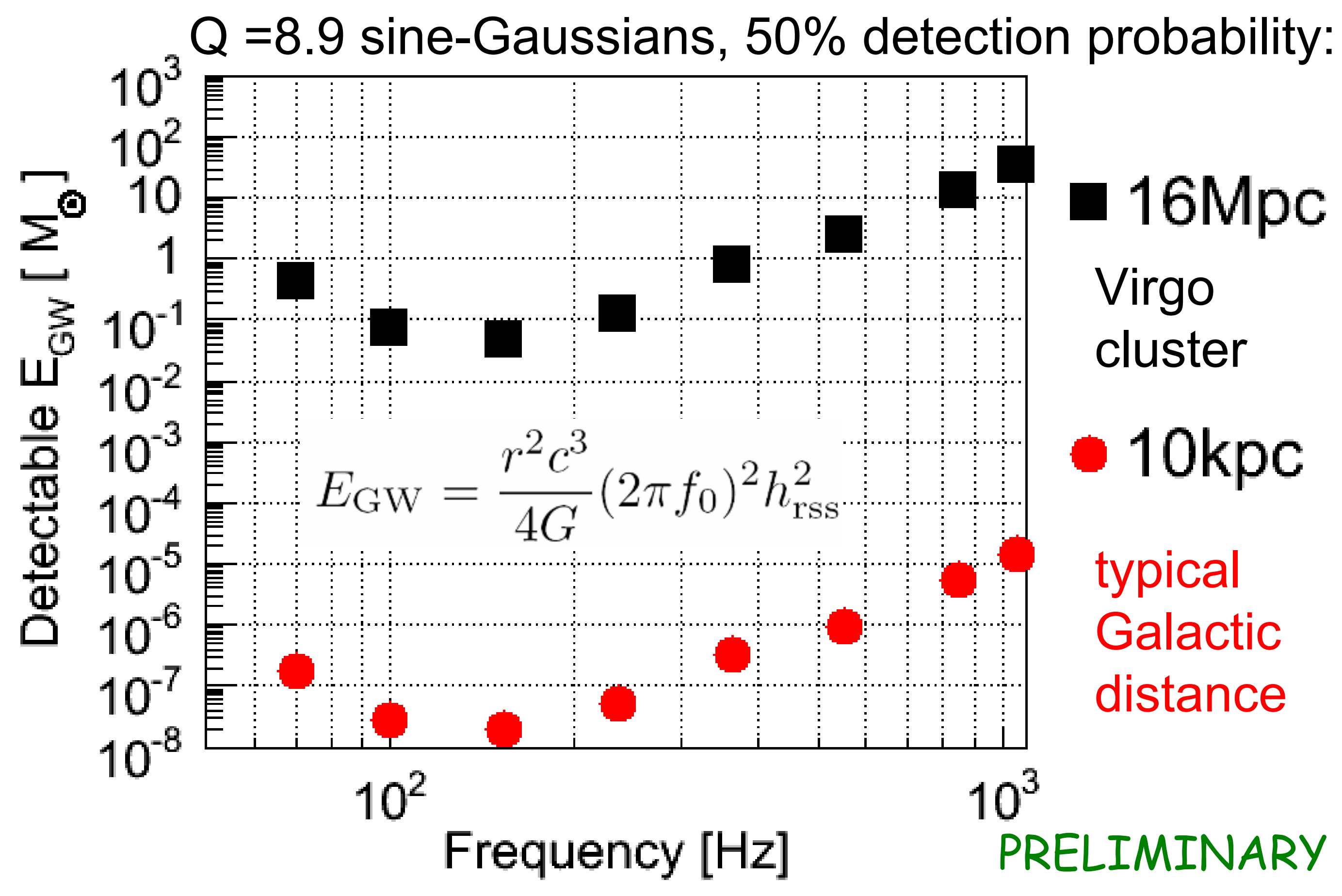


Uncertainty of waveforms complicates the detection ⇒ minimal assumptions, open to the unexpected





# Burst Range in S5



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

~ 2 × $10^{-8}$ $M_\odot c^2$ 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)

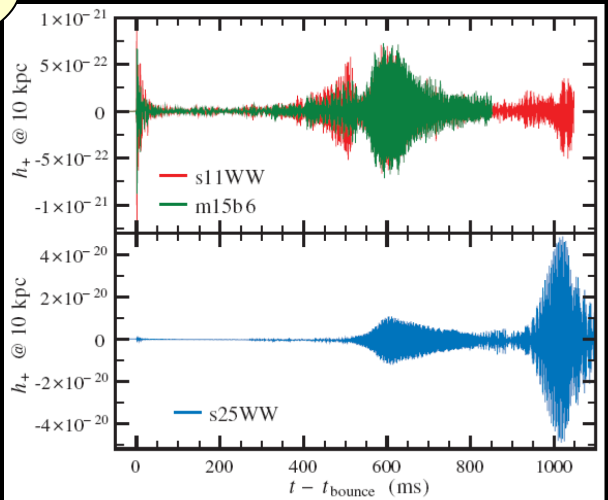
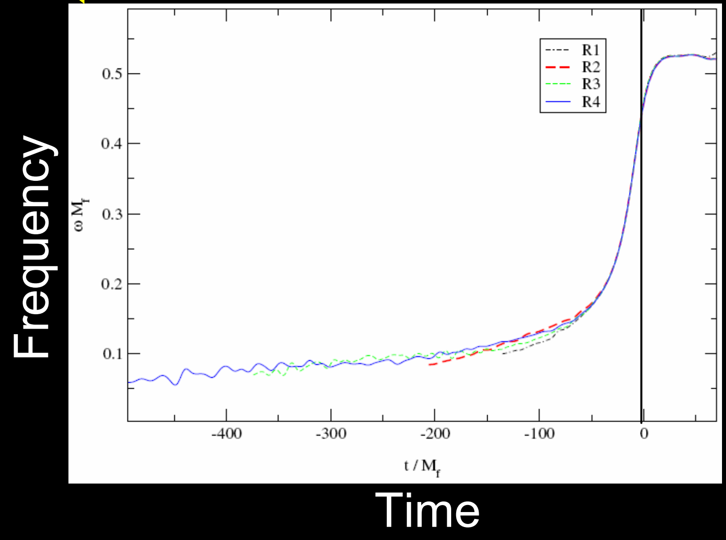


TABLE I. MODEL SUMMARY.

| Model | $\Delta t^{a}$ (ms) | $\lvert h_{+,\mathrm{max}}\rvert^{b}$ ($10^{-21}$) | $h_{\mathrm{char,max}}{}^{b,c}$ ($10^{-21}$) | $f(h_{\mathrm{char,max}})$ (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)
$\Rightarrow$ reach ≈ 0.4 kpc
25 $M_{\odot}$ progenitor (s25WW model)
$\Rightarrow$ reach ≈ 16 kpc

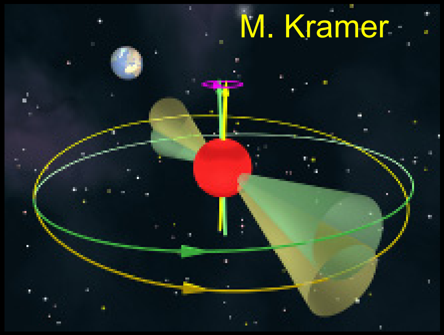


$$f_{\mathrm{peak}} \approx \frac{0.46}{2\pi M_f} \approx \frac{15\ \mathrm{kHz}}{(M_f/M_{\odot})}$$

Baker et al, PRD 73, 104002 (2006)

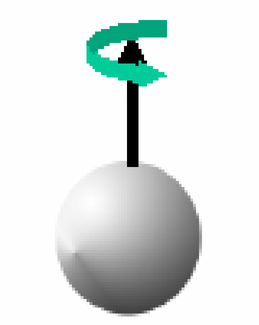
Assuming ~3.5% mass radiates in the merger:
10+10 $M_{\odot}$ binary $\Rightarrow$ reach ≈ 3 Mpc
50+50 $M_{\odot}$ binary $\Rightarrow$ reach ≈ 100 Mpc

# Continuous Waves


M. Kramer

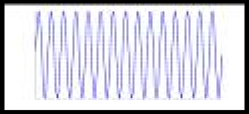
Wobbling neutron stars

J. Creighton


Pulsars with mountains

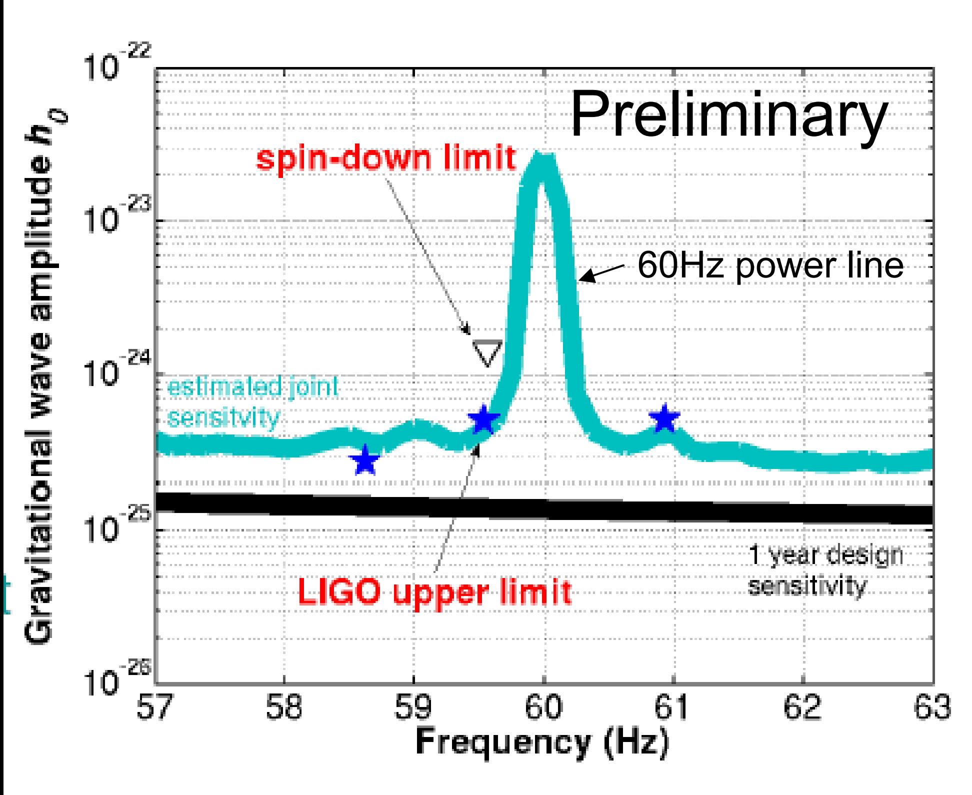

Dana Berry/NASA

Accreting neutron stars



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

S5: beat spin-down limit on Crab pulsar
13 months of data



# GW Searches: Known pulsars

Joint 95% upper limits from first ~13 months of S5 using H1, H2 and L1 (for 97 known pulsars). Results are overlaid on the median estimated sensitivity

For 32 pulsars (green stars) we only give *expected* upper limits due to uncertainties in the pulsar parameters

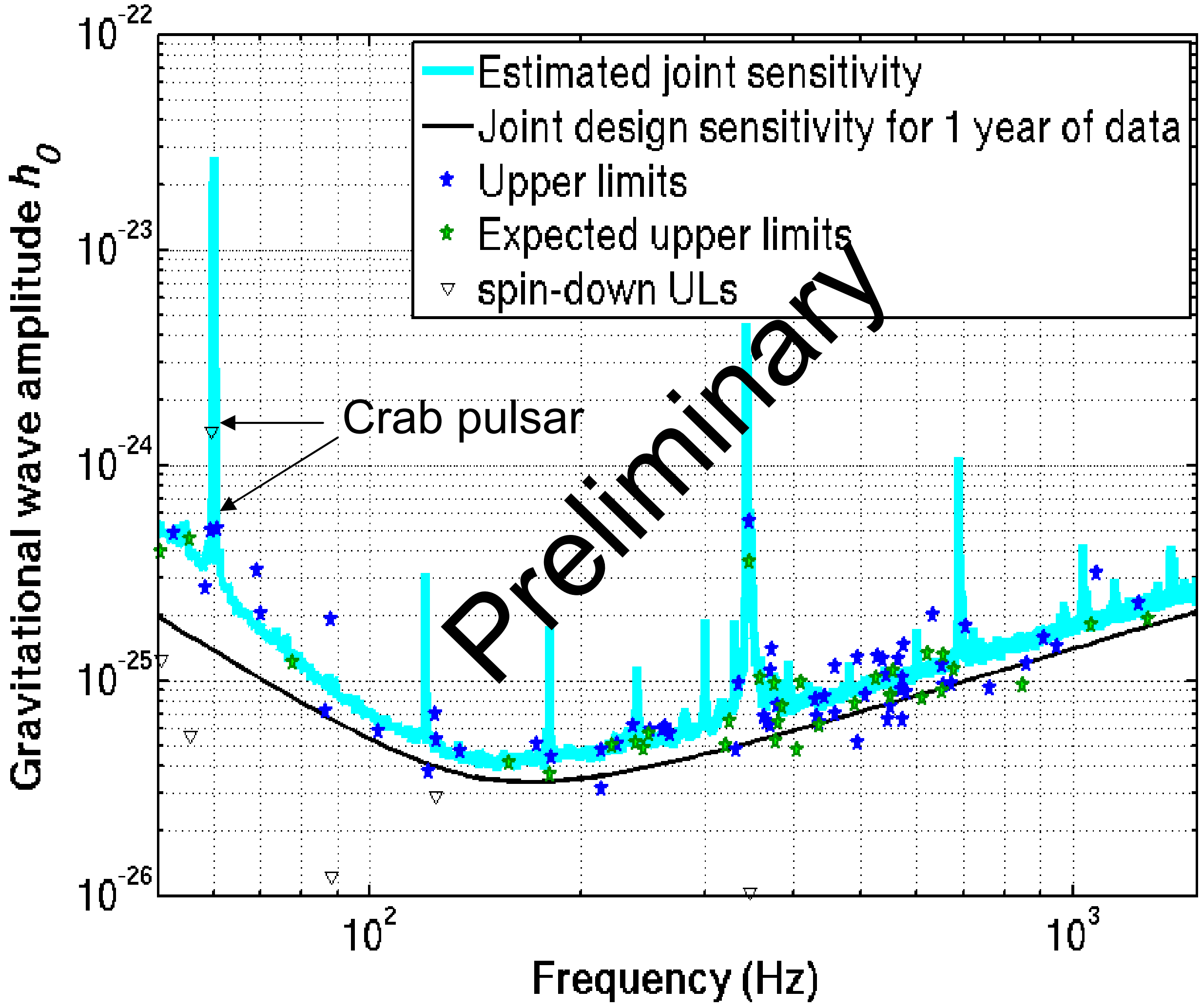
**Lowest $h_0$ upper limit:**

PSR J1623-2631 ($\nu_{gw}$ = 180.6 Hz) $h_0 = 3.4\text{x}10^{-26}$

**Lowest ellipticity upper limit:**

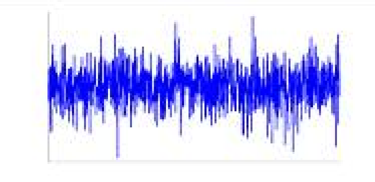
PSR J2124-3358 ($\nu_{gw}$ = 405.6 Hz) $\varepsilon = 7.3\text{x}10^{-8}$

Crab pulsar ***beats*** the spin-down upper limit by a factor of 2.9 – we can constrain the power radiated by GWs to less than 10% of the total available from spin-down

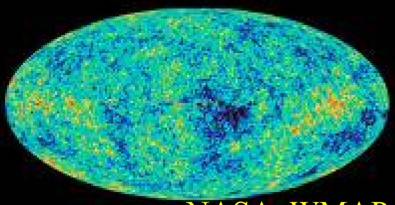


# Astrophysical Sources: Stochastic Background

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

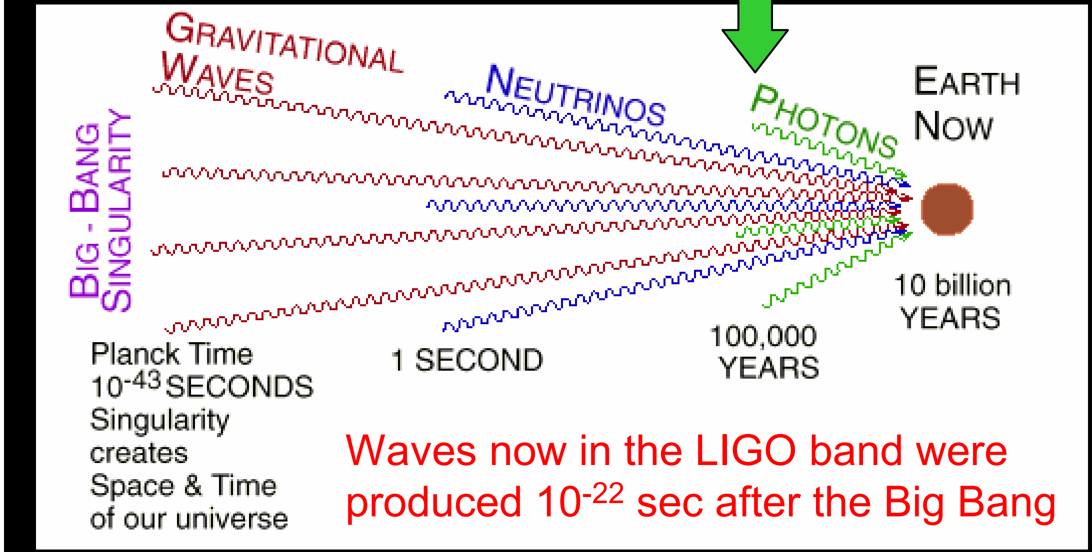


cosmic GW background



NASA, WMAP

CMB ($10^{+12}$ s)



Waves now in the LIGO band were produced $10^{-22}$ sec after the Big Bang

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

**LIGO S4: $\Omega_0 < 6.5 \times 10^{-5}$**

S5 sensitivity:

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

# 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.

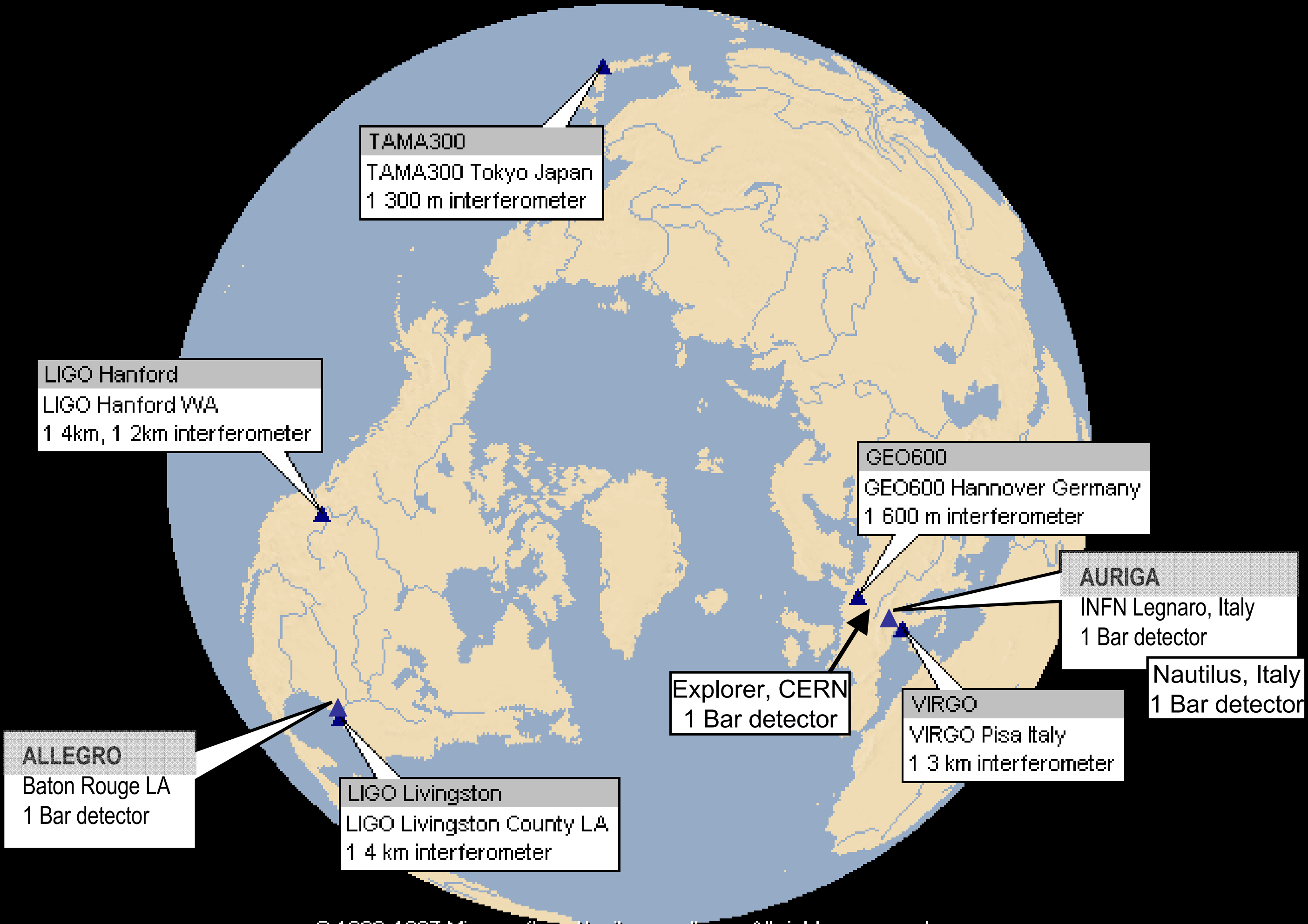
### Use environmental monitors as vetos

- 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 International Quest: Ground-Based Detectors



TAMA300
TAMA300 Tokyo Japan
1 300 m interferometer

LIGO Hanford
LIGO Hanford WA
1 4km, 1 2km interferometer

GEO600
GEO600 Hannover Germany
1 600 m interferometer

AURIGA
INFN Legnaro, Italy
1 Bar detector

Nautilus, Italy
1 Bar detector

Explorer, CERN
1 Bar detector

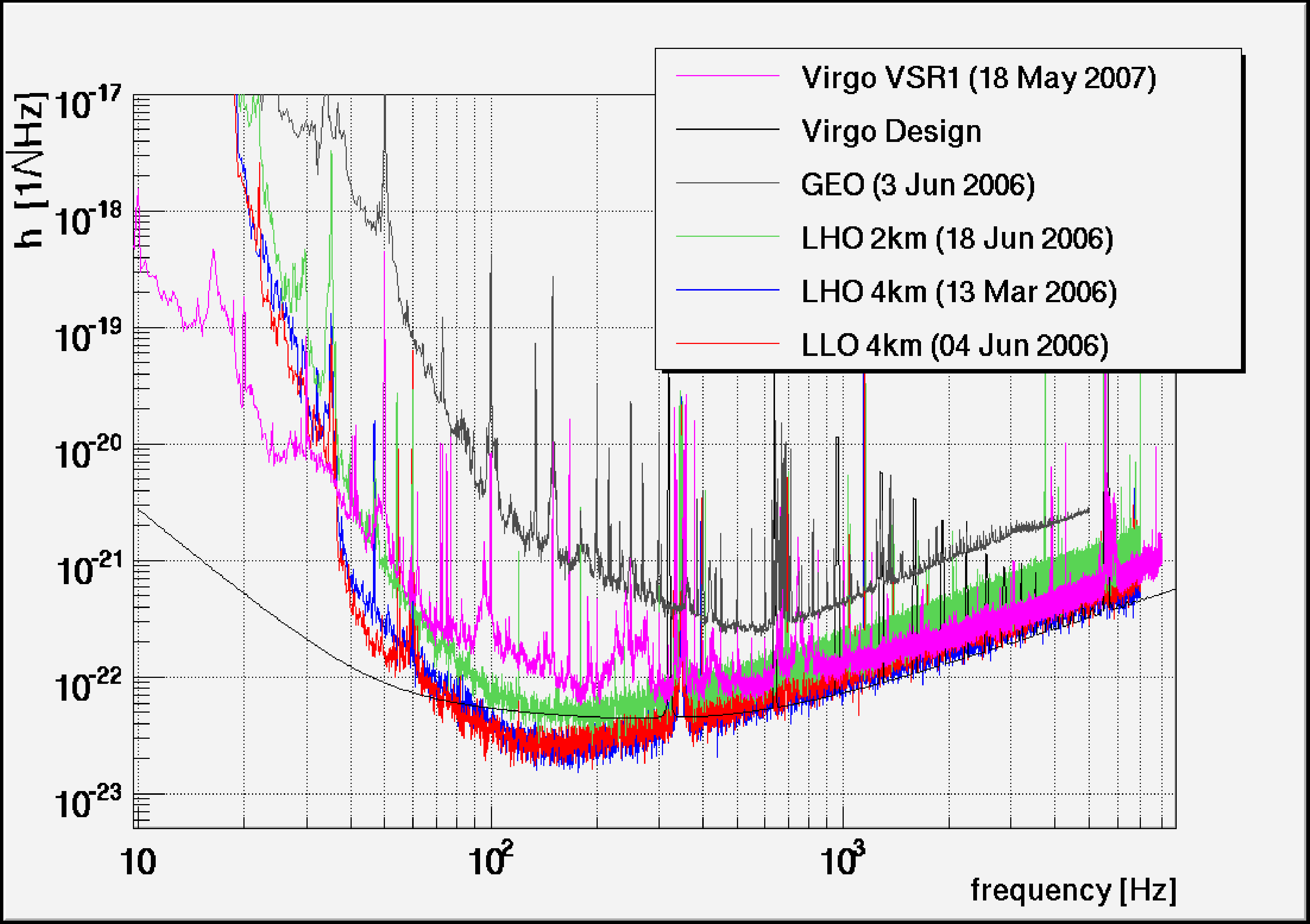
VIRGO
VIRGO Pisa Italy
1 3 km interferometer

ALLEGRO
Baton Rouge LA
1 Bar detector

LIGO Livingston
LIGO Livingston County LA
1 4 km interferometer

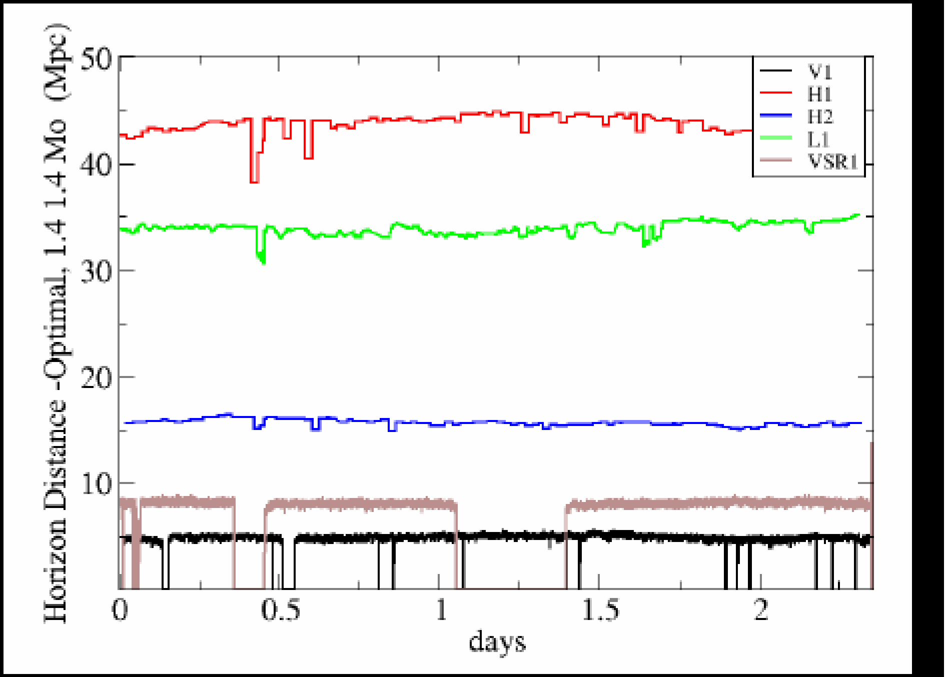
Interferometers
And Resonant Bars

# LIGO, Virgo & GEO sensitivities



# LSC-Virgo joint data analysis

- Recognizing the benefits of joint data analysis, the LIGO Scientific and Virgo collaborations have entered into an agreement to jointly analyze data from the GEO, LIGO, and Virgo detectors
- Sharing of data started in May 2007 when Virgo commenced its first long science run in coordination with LIGO’s fifth science run
- A joint run plan committee is coordinating detector operation and commissioning schedules to improve the prospects for detection
- Joint data analysis meetings are already taking place
- Joint data analysis exercises with simulated and small amounts of real data have already been performed for the inspiral, burst, and stochastic analysis



Inspiral range during Project 2B:
3 days of non-coincident data Sept 06

# The Road Ahead

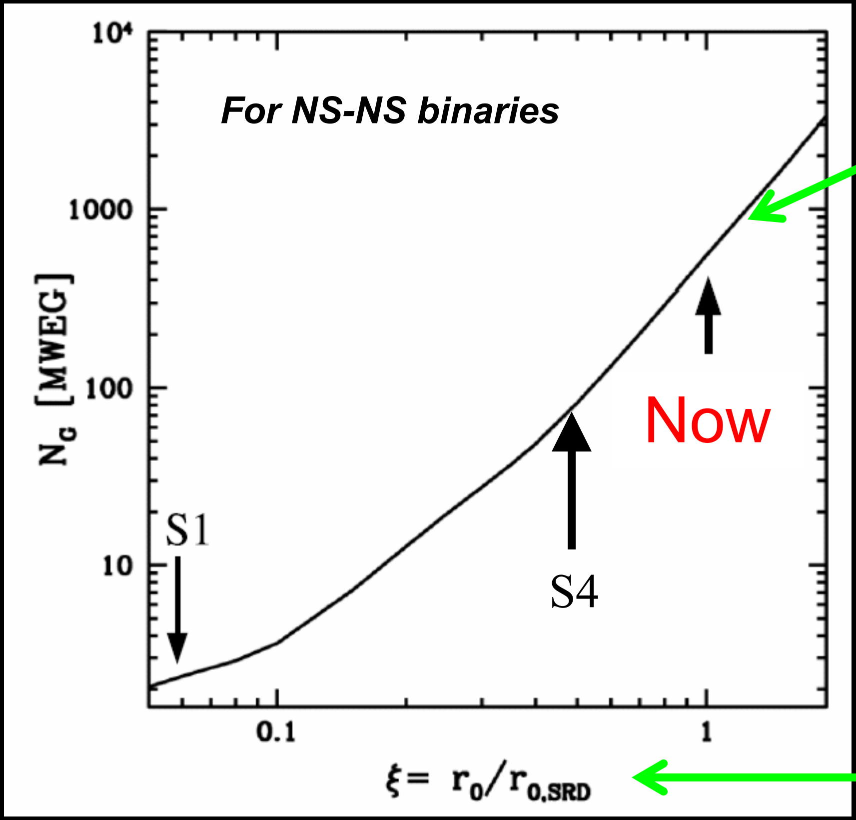
Enhanced LIGO
~2009

LIGO today

Advanced LIGO
~2014

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

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



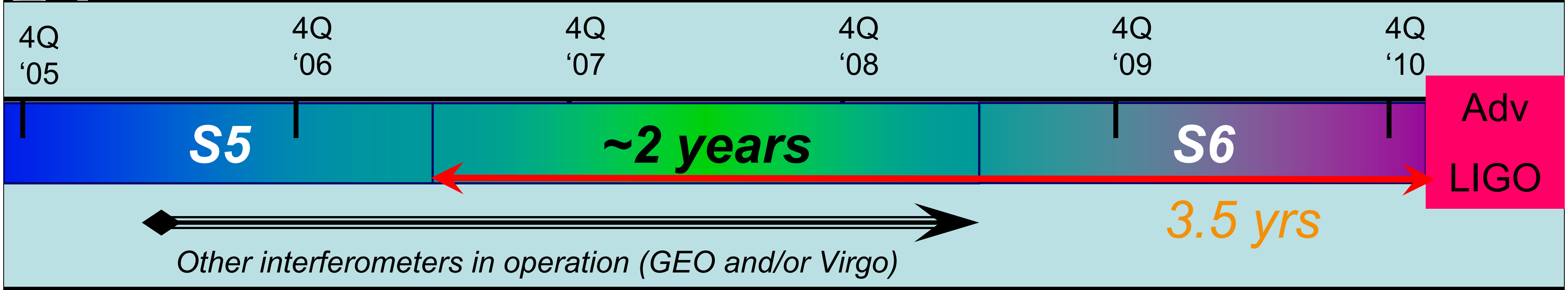
Power law: 2.7

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

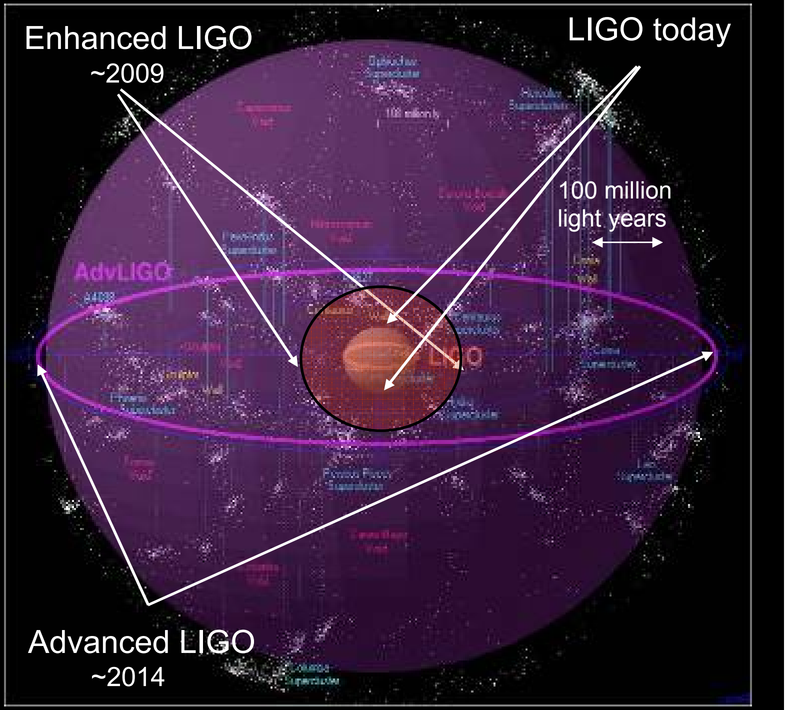
⇨scientific program for Enhanced LIGO (post S5)

Proportional to inspiral range

# LIGO timeline



- 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



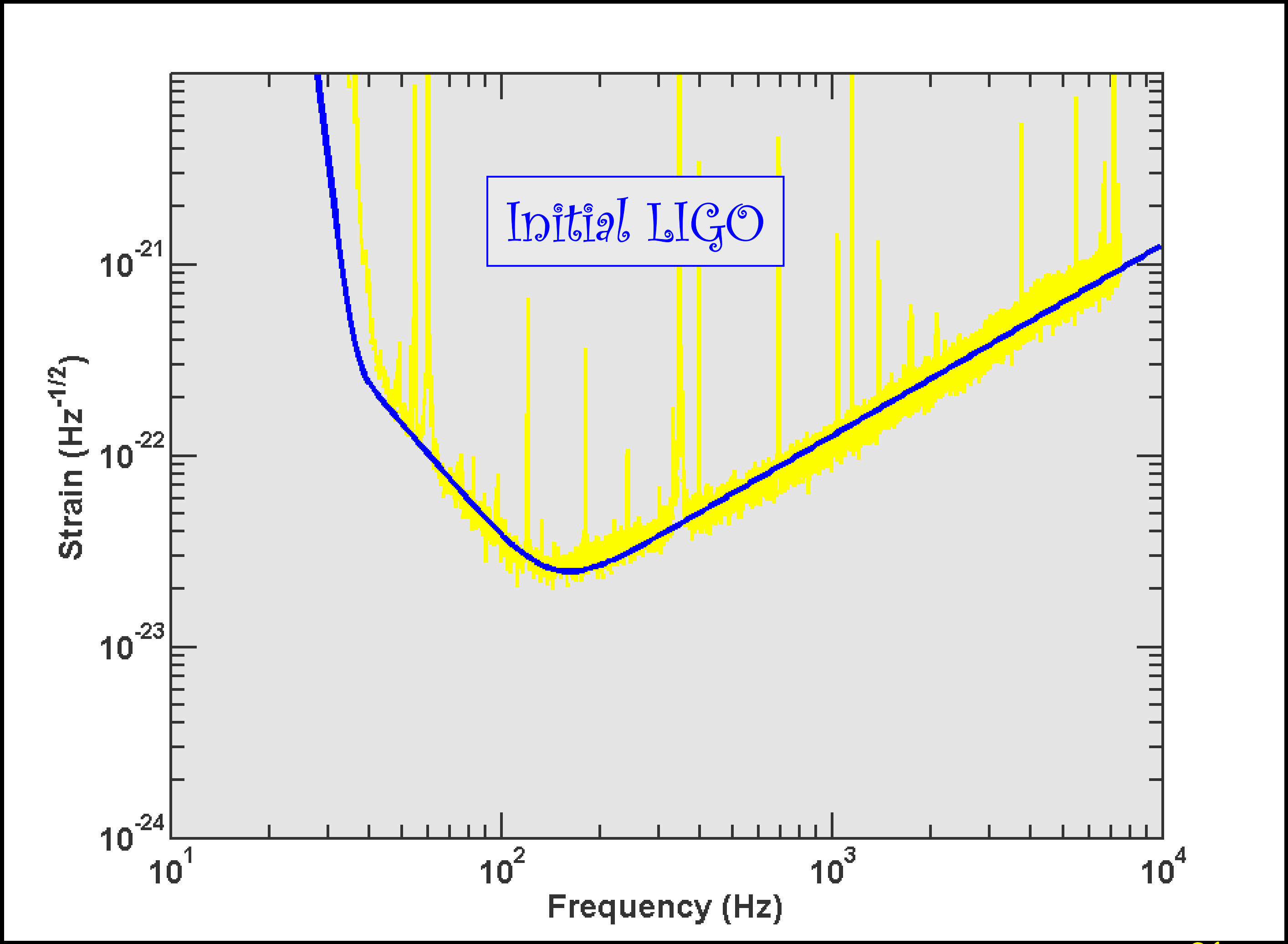
*The science from the first 3 hours of Advanced LIGO should be comparable to 1 year of initial LIGO*

# Initial LIGO - Sept 15 2006

Input laser power
~ 6 W

Circulating power
~ 20 kW

Mirror mass
10 kg

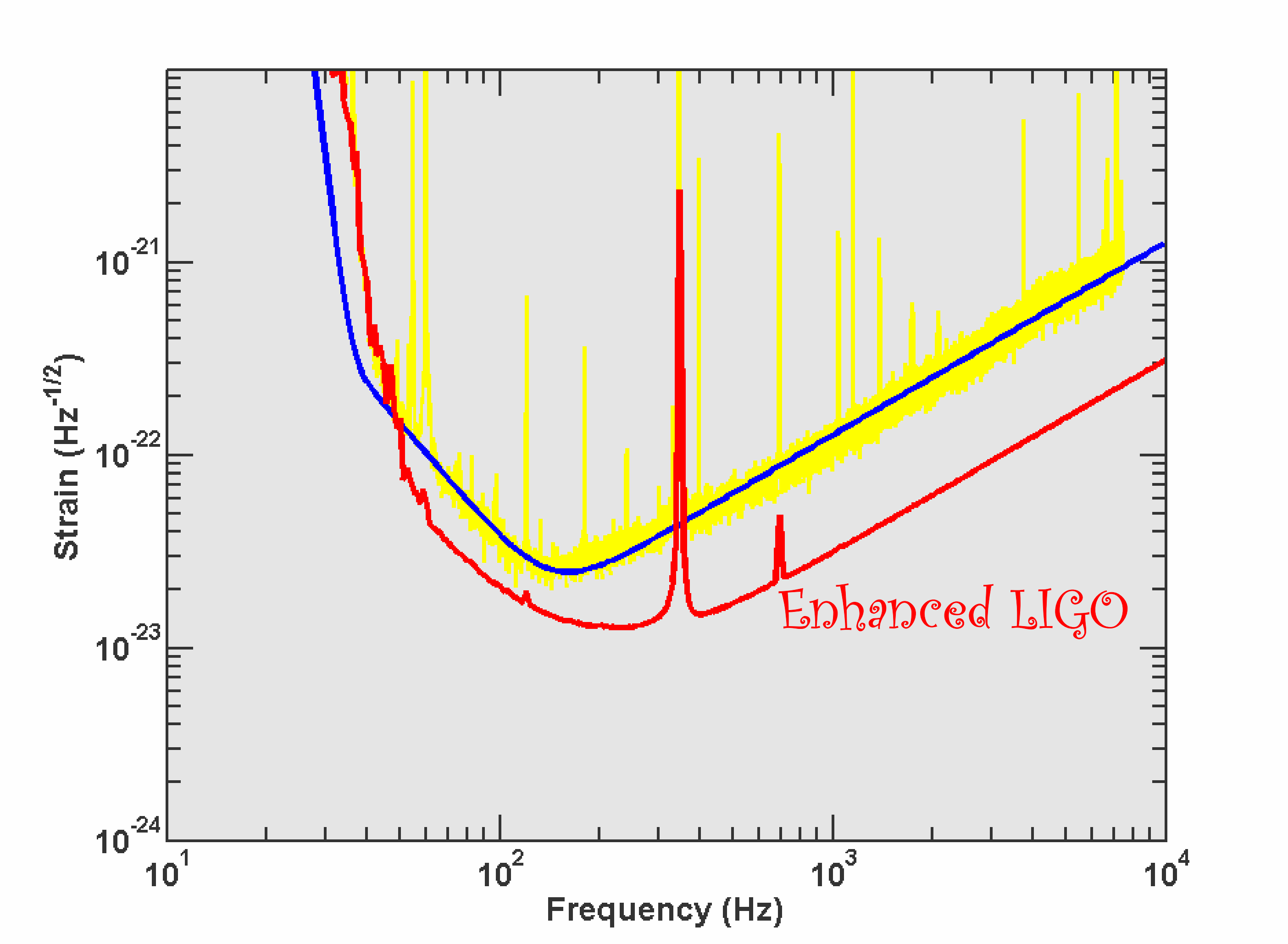


# Enhanced LIGO

Input laser power
~ 30 W

Circulating power
~ 100 kW

Mirror mass
10 kg

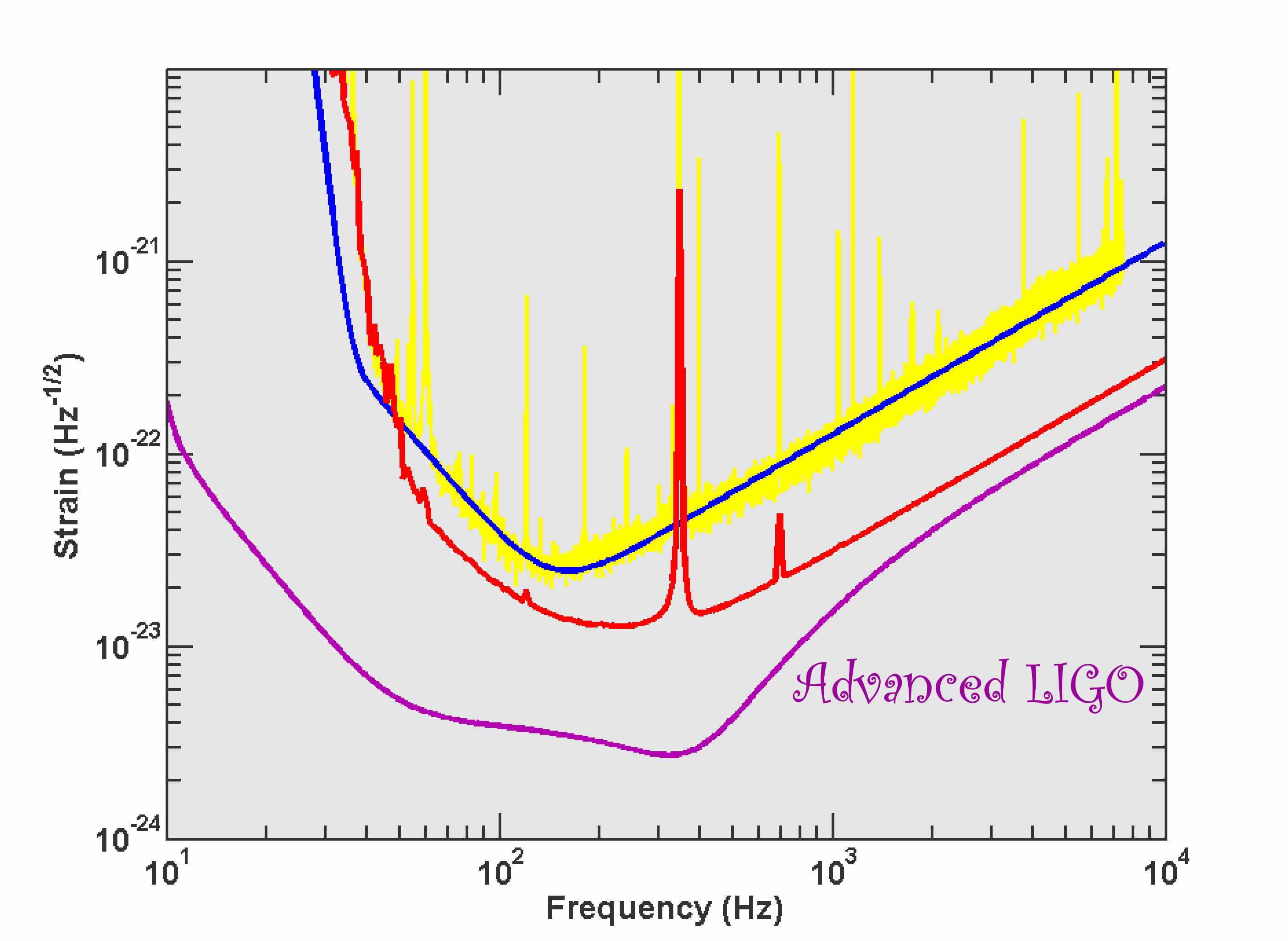


# Advanced LIGO

Input laser power
> 100 W

Circulating power
> 0.5 MW

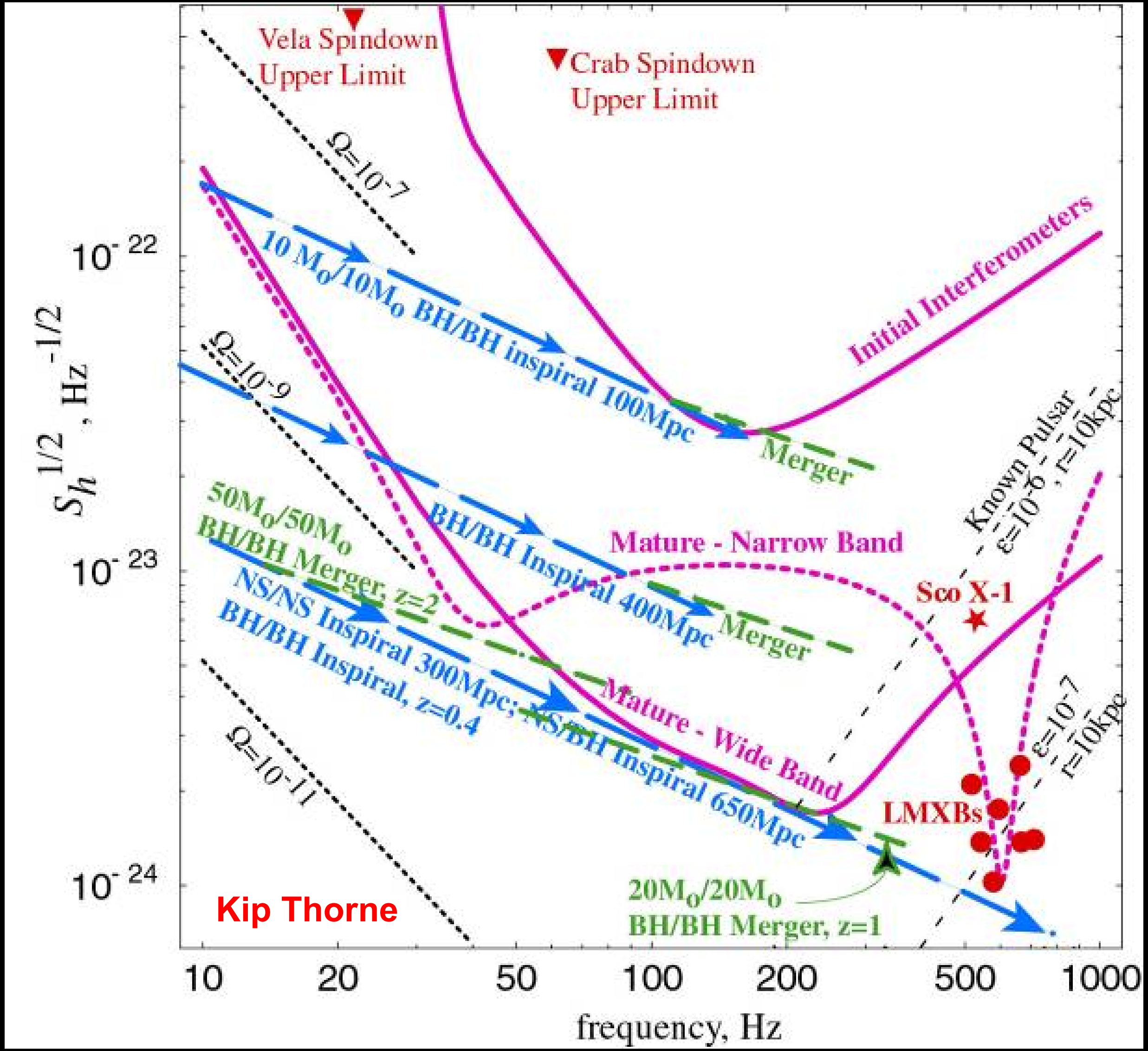
Mirror mass
40 kg



# How will we get there?

- Seismic noise
  - Active isolation system
  - Mirrors suspended as fourth (!!) stage of quadruple pendulums
- Thermal noise
  - Suspension ➔ fused silica fibers
  - Test mass ➔ more massive; better coatings
- Optical noise
  - Laser power ➔ increase to ~200 W
  - Optimize interferometer response<br>➔ signal recycling

# 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 $\varepsilon = 3\text{x}10^{-6}$ to $2\text{x}10^{-8}$

*Stochastic background:*

From $\Omega_{GW}$ ~$3\text{x}10^{-6}$ to ~$3\text{x}10^{-9}$

# 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

## 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!