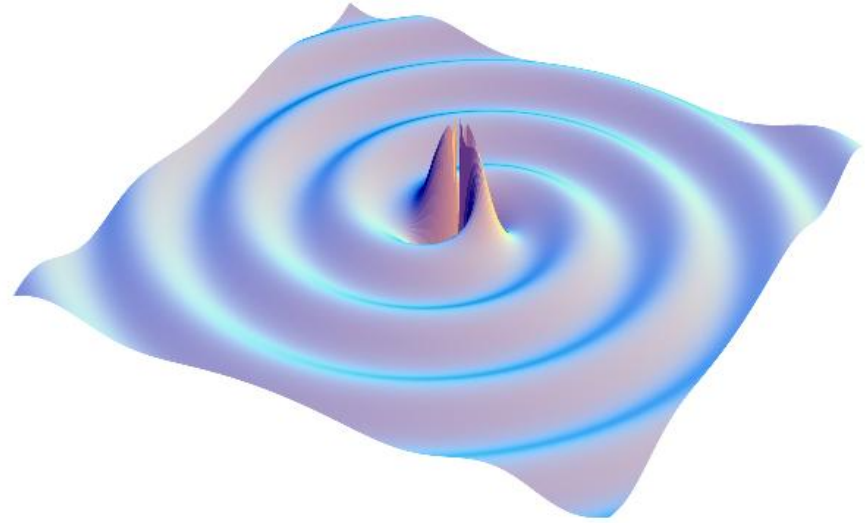


# The Hunt for Gravitational Waves

## Latest Results from LIGO

Keith Riles  
University of Michigan



Physics Colloquium  
Andrews University  
February 22, 2008

LIGO-G080008



# Outline

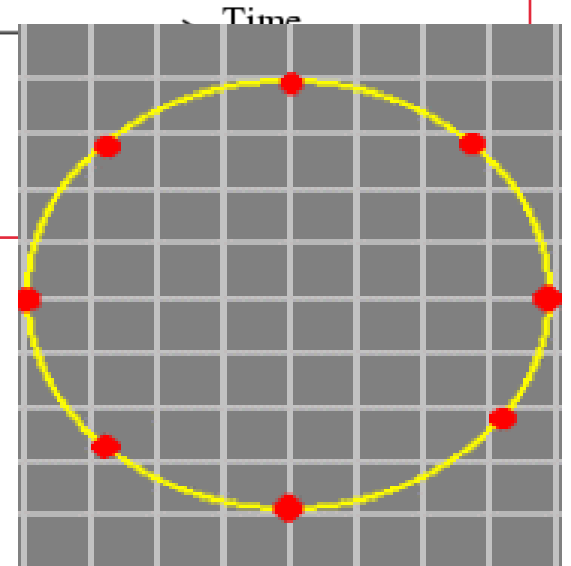
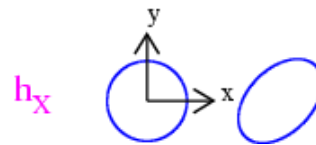
- ❑ **Nature & Generation of Gravitational Waves**
- ❑ **Detecting Gravitational Waves with the LIGO Detector**
- ❑ **Data Runs and Results to Date**
- ❑ **Looking Ahead – Advanced LIGO**

# Nature of Gravitational Waves

- Gravitational Waves = “Ripples in space-time”
- Perturbation propagation similar to light (obeys same wave equation!)
  - ◆ Propagation speed =  $c$
  - ◆ Two transverse polarizations - quadrupolar:  $+$  and  $\times$

Example:

Ring of test masses  
responding to wave  
propagating along  $z$

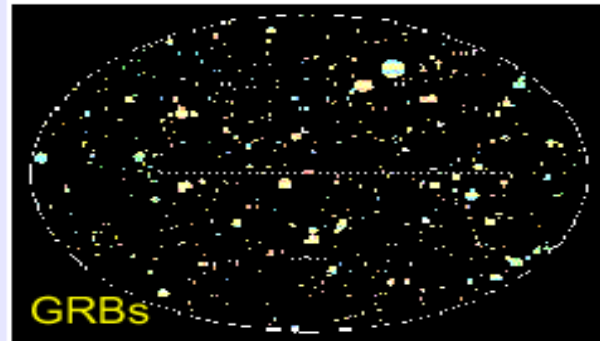
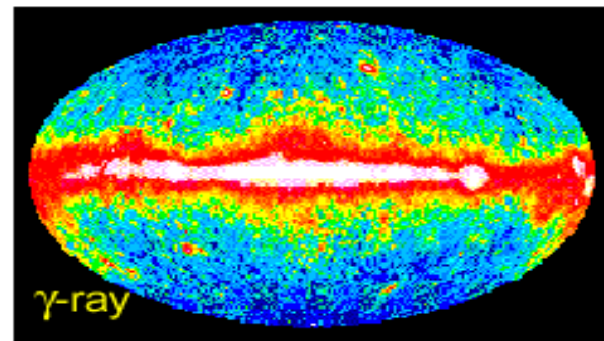
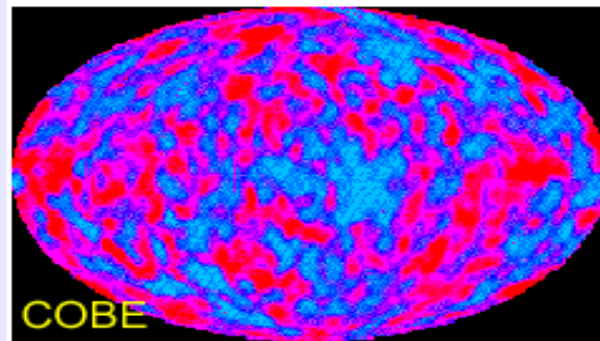
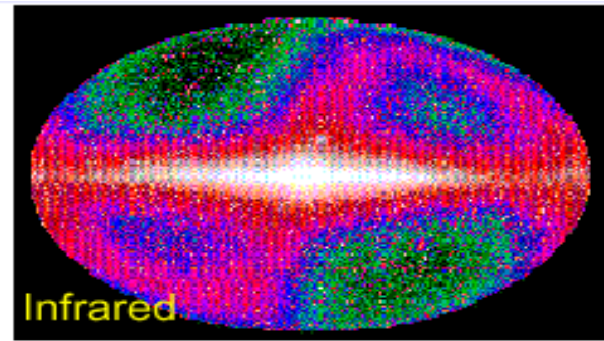
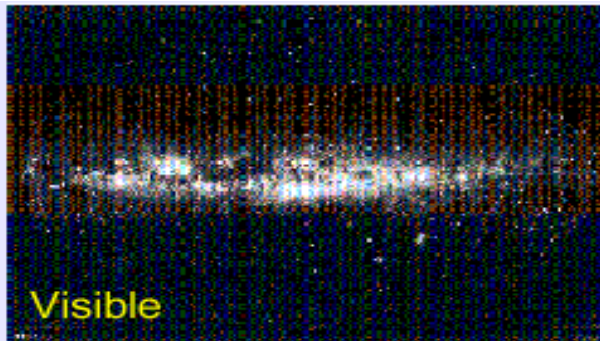


- Amplitude parameterized by (tiny)  
dimensionless strain  $h$ :  $\Delta L \sim h(t) \times L$

# Why look for Gravitational Radiation?

- ❑ Because it's there! (presumably)
  
- ❑ Test General Relativity:
  - ◆ Quadrupolar radiation? Travels at speed of light?
  - ◆ Unique probe of strong-field gravity
  
- ❑ Gain different view of Universe:
  - ◆ Sources cannot be obscured by dust
  - ◆ Detectable sources some of the most interesting, least understood in the Universe
  - ◆ Opens up entirely new non-electromagnetic spectrum

# What will the sky look like?



# Generation of Gravitational Waves

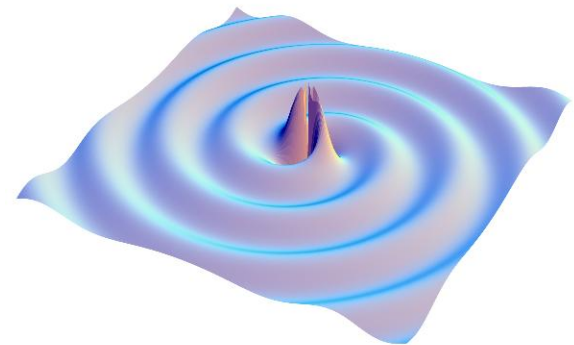
- Radiation generated by quadrupolar mass movements:

$$h_{\mu\nu} = \frac{2G}{rc^4} \frac{d^2}{dt^2} (I_{\mu\nu})$$

(with  $I_{\mu\nu}$  = quadrupole tensor,  $r$  = source distance)

- Example: Pair of  $1.4 M_{\text{solar}}$  neutron stars in circular orbit of radius 20 km (imminent coalescence) at orbital frequency 400 Hz gives 800 Hz radiation of amplitude:

$$h \approx \frac{10^{-21}}{(r/15\text{Mpc})}$$



# Generation of Gravitational Waves

Major expected sources in 10-1000 Hz “terrestrial” band:

- ❑ Coalescences of binary compact star systems  
(NS-NS, NS-BH, BH-BH)
- ❑ Supernovae  
(requires asymmetry in explosion)
- ❑ Spinning neutron stars, e.g., pulsars  
(requires axial asymmetry or wobbling spin axis)

Also expected (but probably exceedingly weak):

- ❑ Stochastic background – Big Bang remnant

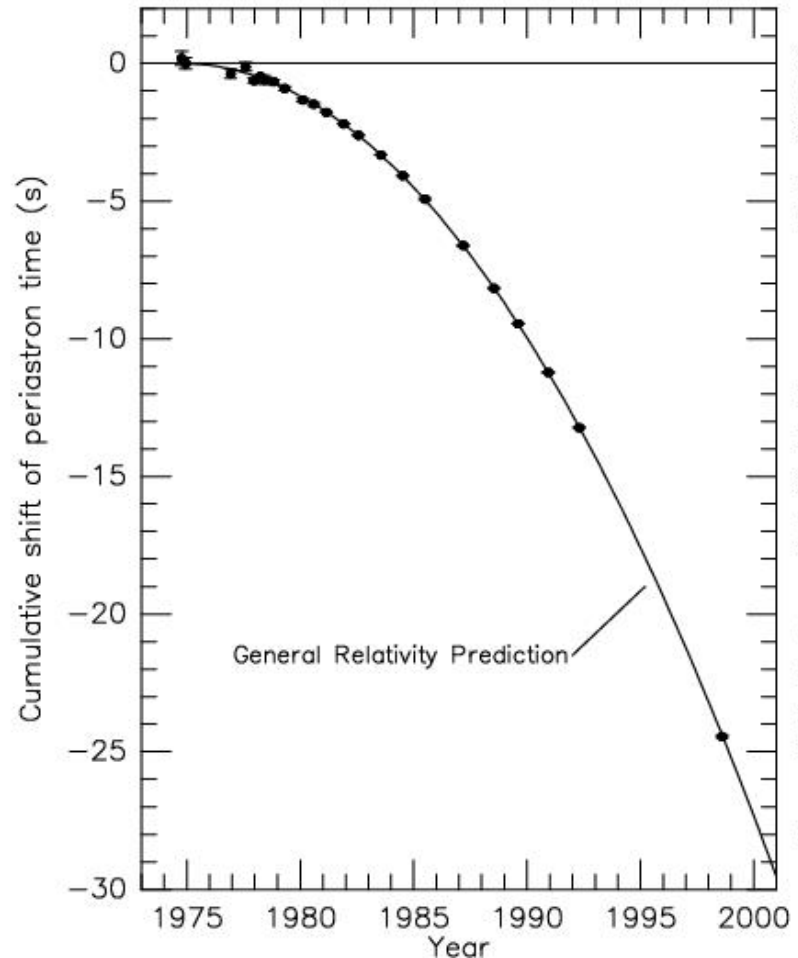
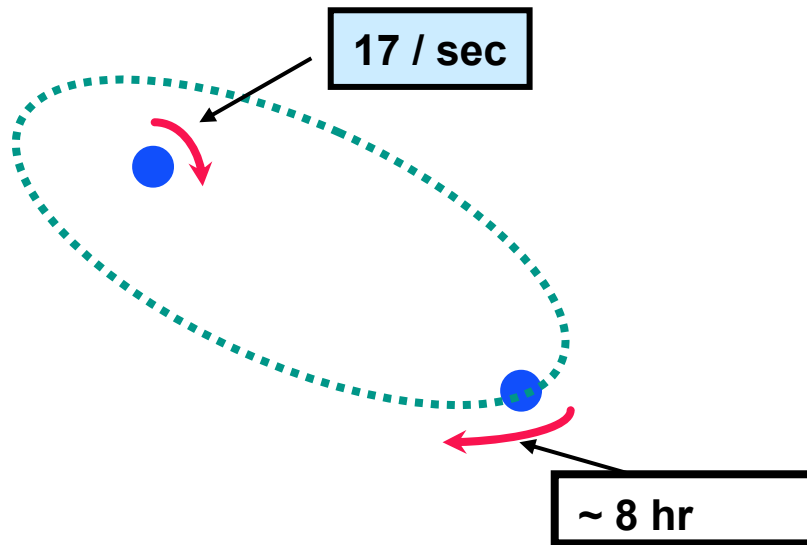
**Or from Cosmic Strings?**

# Generation of Gravitational Waves

- Strong indirect evidence for GW generation:

## Taylor-Hulse Pulsar System (PSR1913+16)

- ◆ Two neutron stars (one=pulsar)  
in elliptical 8-hour orbit
- ◆ Measured periastron advance  
quadratic in time in agreement with  
absolute GR prediction
- Orbital decay due to energy loss



From J. H. Taylor and J. M. Weisberg, unpublished (1998)

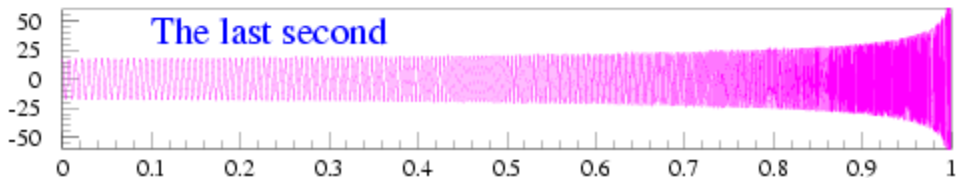
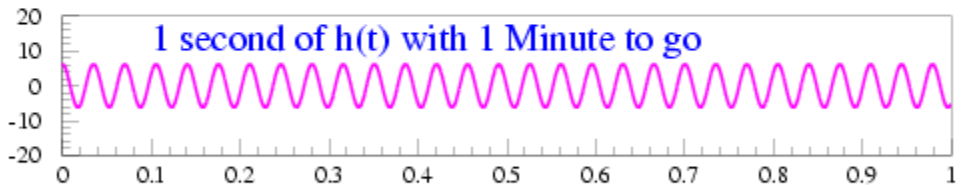
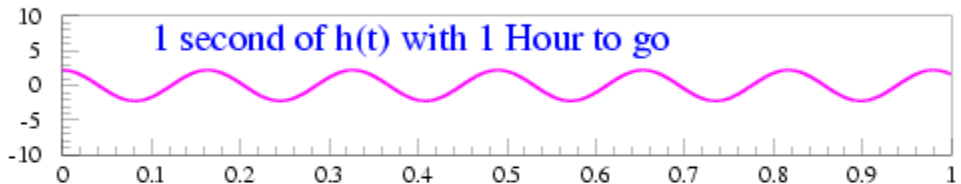
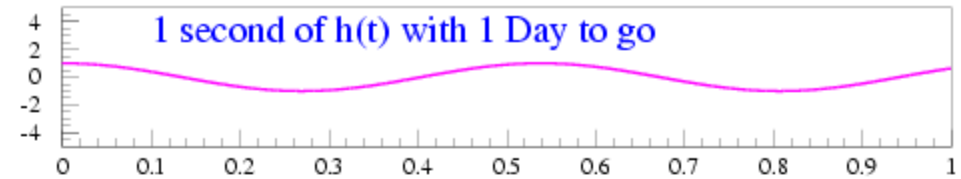


# Generation of Gravitational Waves

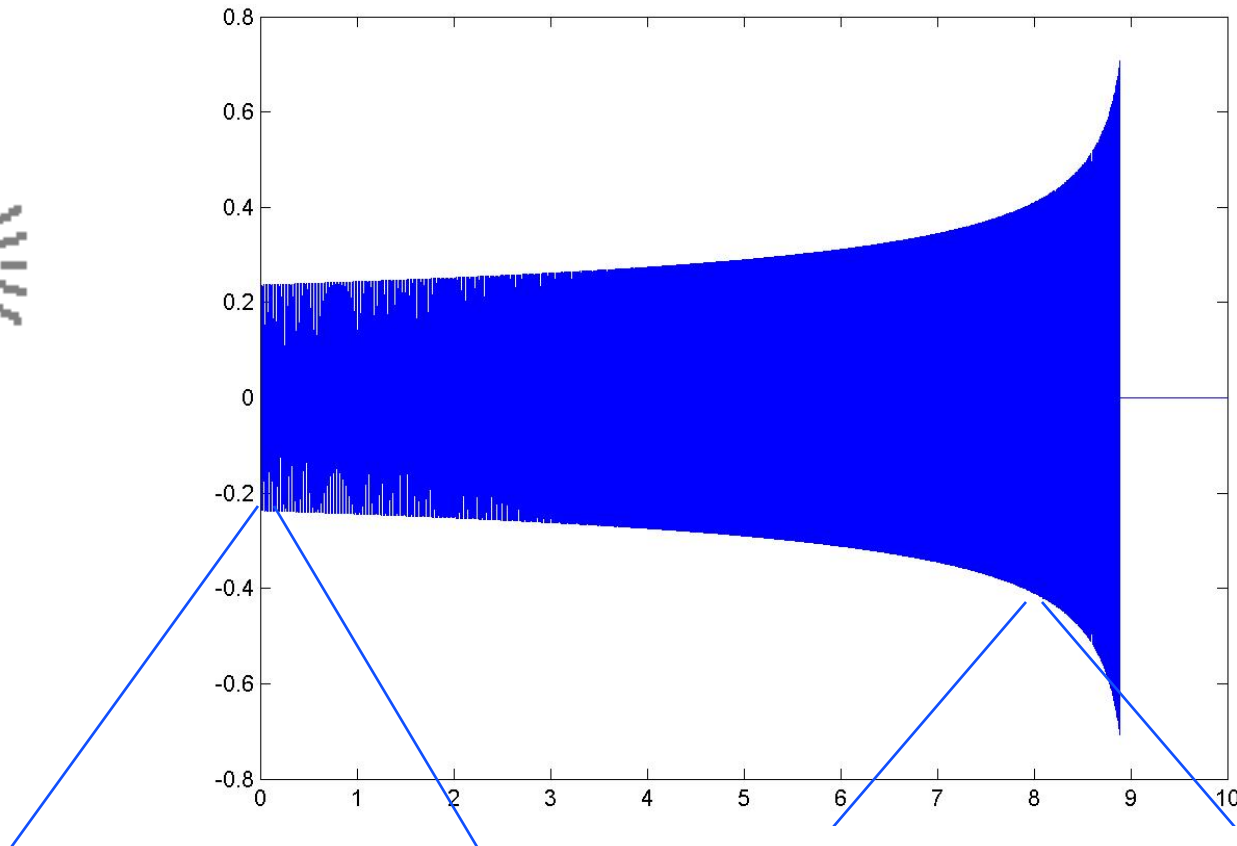
Can we detect this radiation directly?

**NO** - freq too low

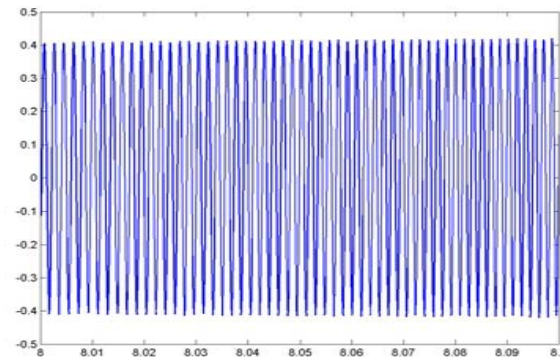
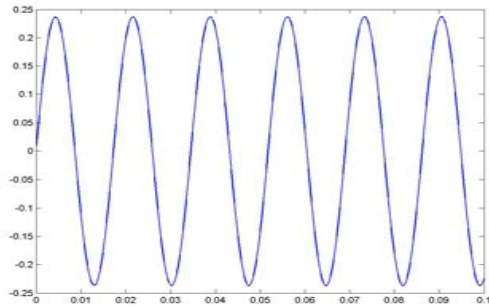
Must wait  $\sim 300$  My for characteristic “chirp”:



# Generation of Gravitational Waves



Last nine  
seconds  
of inspiral



# Generation of Gravitational Waves

Coalescence rate estimates based on two methods:

- Use known NS/NS binaries in our galaxy (three!)
- *A priori* calculation from stellar and binary system evolution

→ Large uncertainties!

For initial LIGO design “seeing distance” (~15 Mpc):

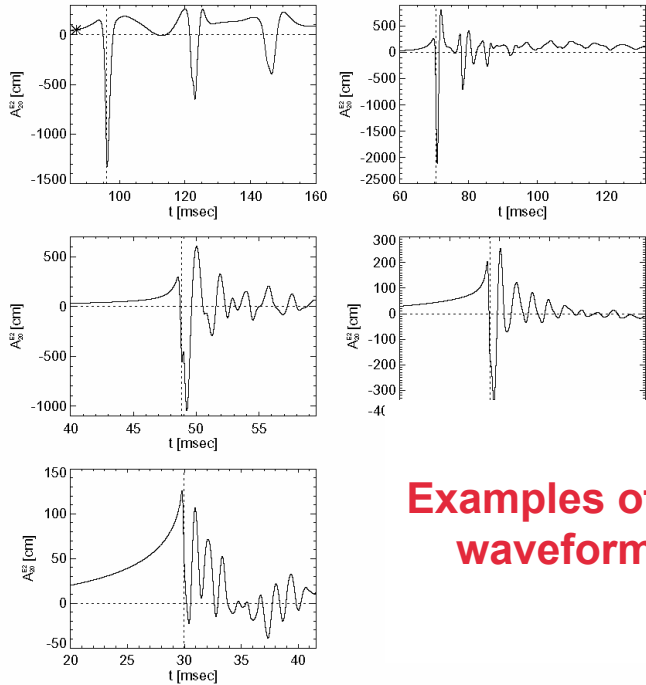
Expect 1/(70 y) to 1/(4 y)

→ Will need Advanced LIGO to ensure detection

# Generation of Gravitational Waves

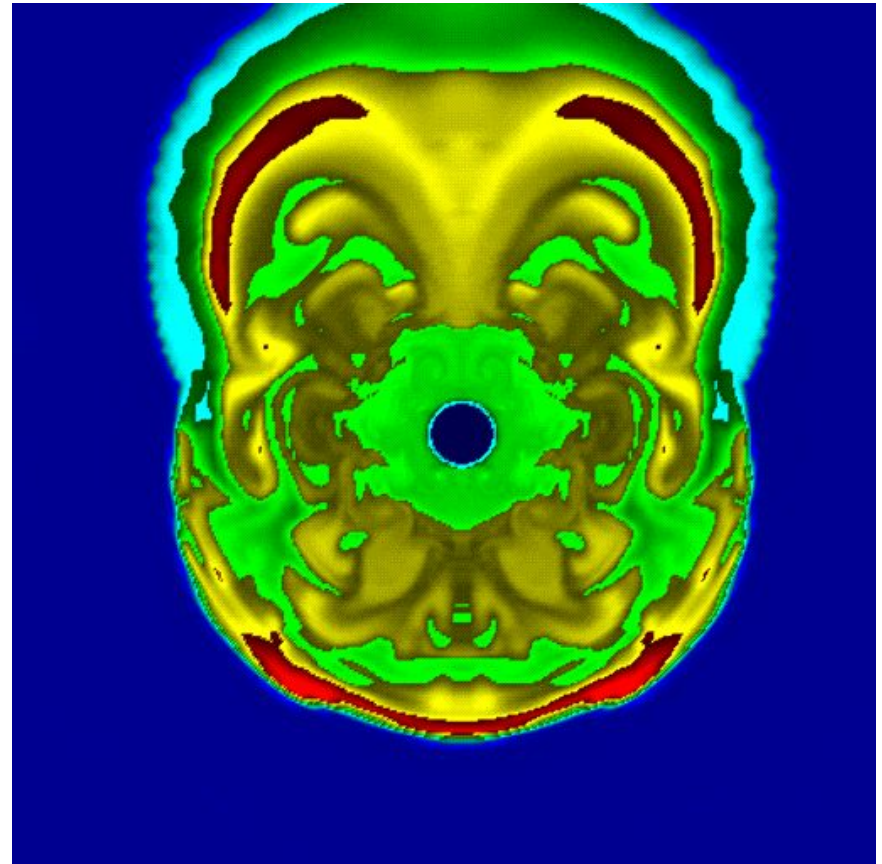
## Super-novae

(requires asymmetry in explosions)



Examples of SN waveforms

May not know exactly what to look for – must be open-minded with diverse algorithms



# Generation of Gravitational Waves

Most promising periodic source: Rotating Neutron Stars (e.g., pulsar)

But axisymmetric object rotating about symmetry axis  
Generates NO radiation

Need an asymmetry or perturbation:

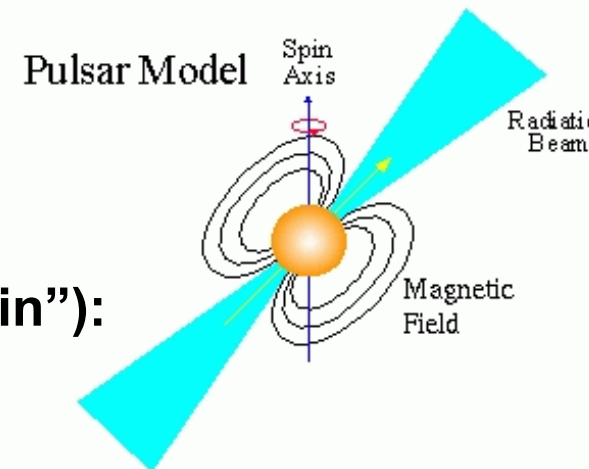
- Equatorial ellipticity (e.g., – mm-high “mountain”):

$$h \propto \epsilon_{\text{equat}}$$

- Poloidal ellipticity (natural) + wobble angle (precessing star):

$$h \propto \epsilon_{\text{pol}} \times \Theta_{\text{wobble}}$$

(precession due to different  $L$  and  $\Omega$  axes)



# Periodic Sources

**Serious technical difficulty: Doppler frequency shifts**

- ◆ Frequency modulation from earth's rotation ( $v/c \sim 10^{-6}$ )
- ◆ Frequency modulation from earth's orbital motion ( $v/c \sim 10^{-4}$ )

**Additional, related complications:**

- ◆ Daily amplitude modulation of antenna pattern
- ◆ Spin-down of source
- ◆ Orbital motion of sources in binary systems

**Modulations / drifts complicate analysis enormously:**

- ◆ Simple Fourier transform inadequate
- ◆ Every sky direction requires different demodulation  
→ All-sky survey at full sensitivity = **Formidable challenge**

# Periodic Sources of GW

## But two substantial benefits from modulations:

- ◆ Reality of signal confirmed by need for corrections
- ◆ Corrections give precise direction of source

## □ Difficult to detect spinning neutron stars!

## □ But search is nonetheless intriguing:

- ◆ Unknown number of electromagnetically quiet, undiscovered neutron stars in our galactic neighborhood
- ◆ Realistic values for  $\epsilon$  unknown
- ◆ A nearby source could be buried in the data, waiting for just the right algorithm to tease it into view

# Outline

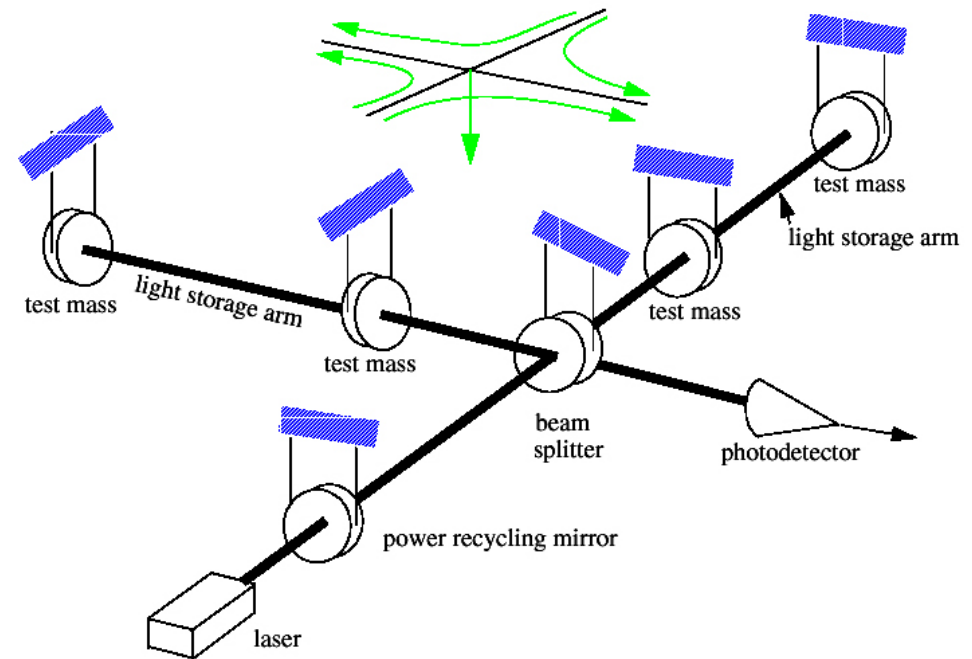
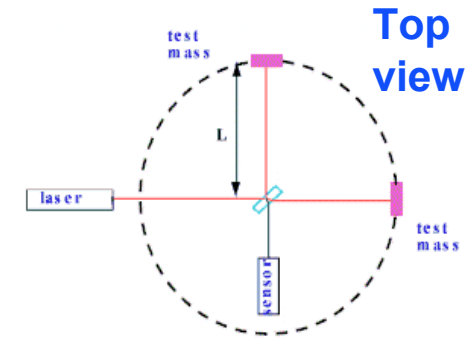
- ❑ **Nature & Generation of Gravitational Waves**
- ❑ **Detecting Gravitational Waves with the LIGO Detector**
- ❑ **Data Runs and Results to Date**
- ❑ **Preparing for Advanced LIGO**



# Gravitational Wave Detection

## □ Suspended Interferometers (IFO's)

- ◆ Suspended mirrors in “free-fall”
- ◆ Michelson IFO is “natural” GW detector
- ◆ Broad-band response (~50 Hz to few kHz)
- ◆ → Waveform information (e.g., chirp reconstruction)



# Gravitational Wave Detection

## Major Interferometers world-wide

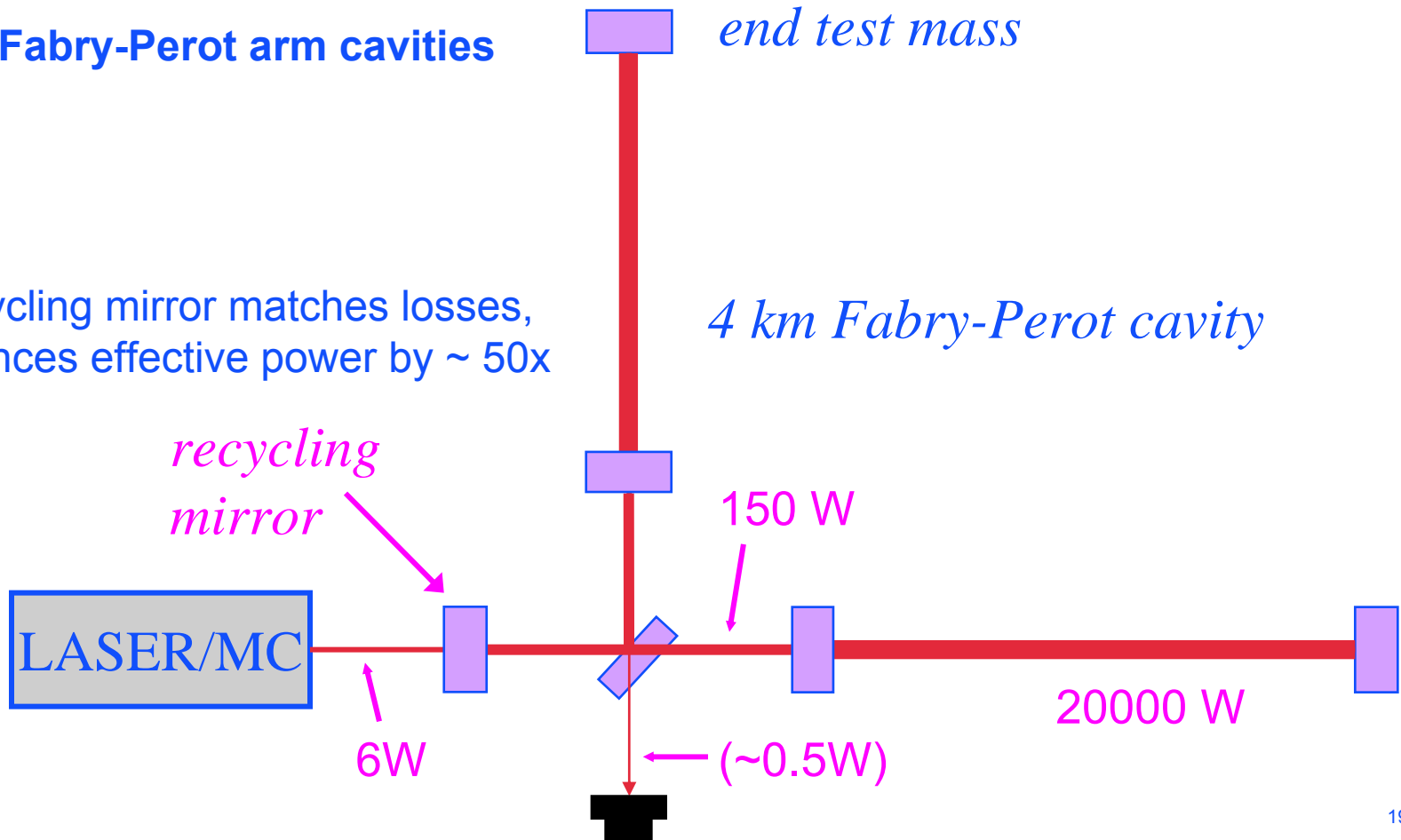
<b>LIGO (NSF-\$300M)</b> Livingston, Louisiana & Hanford, Washington	2 x 4000-m 1 x 2000-m	Completed 2-year data run at design sensitivity – “enhancement” begun
<b>VIRGO</b> Near Pisa, Italy	1 x 3000-m	Took ~4 months coincident data with LIGO – approaching design sensitivity
<b>GEO</b> Near Hannover, Germany	1 x 600-m	Resuming data taking to cover LIGO/Virgo downtime
<b>TAMA</b> Tokyo, Japan	1 x 300-m	Upgrade underway, resuming data taking soon

# LIGO Interferometer Optical Scheme

Michelson interferometer

With Fabry-Perot arm cavities

• Recycling mirror matches losses, enhances effective power by ~ 50x



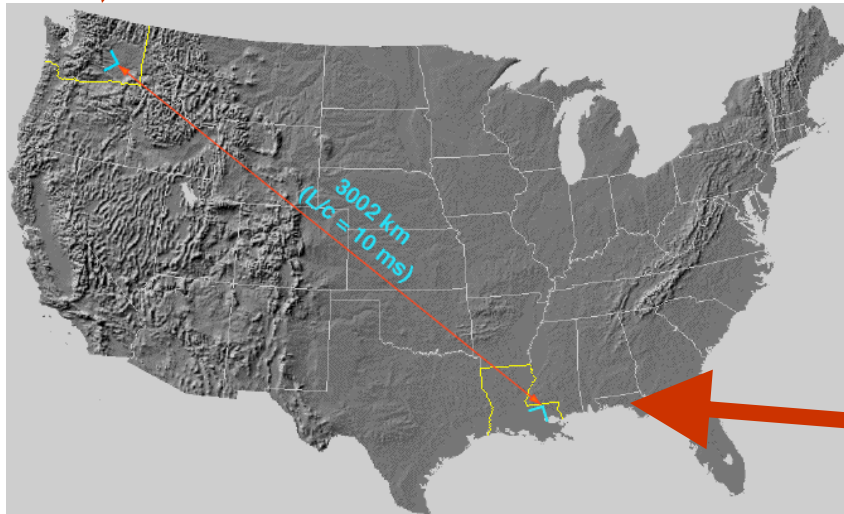
# LIGO Observatories

Hanford

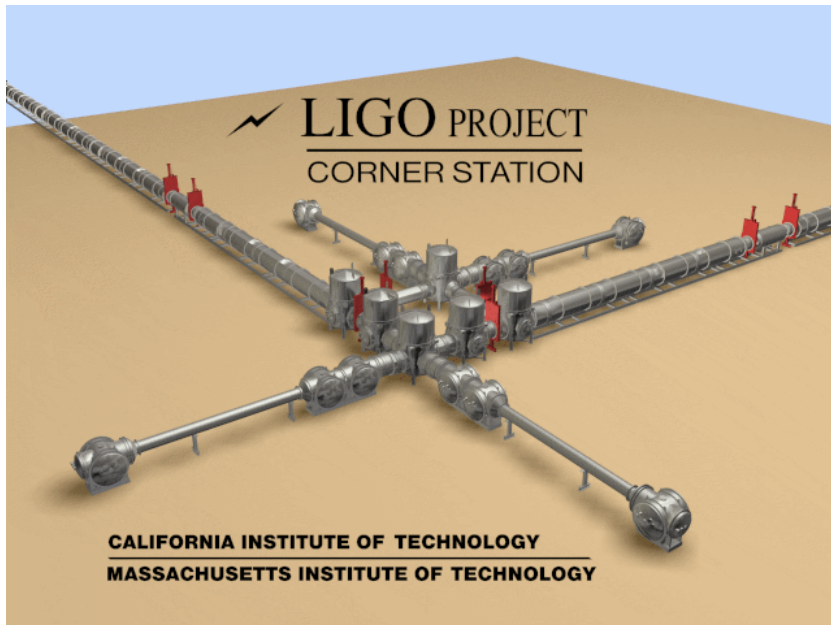


Observation of nearly simultaneous signals 3000 km apart rules out terrestrial artifacts

Livingston



# LIGO Detector Facilities



- Stainless-steel tubes  
(1.24 m diameter,  $\sim 10^{-8}$  torr)
- Gate valves for optics isolation
- Protected by concrete enclosure

## Vacuum System





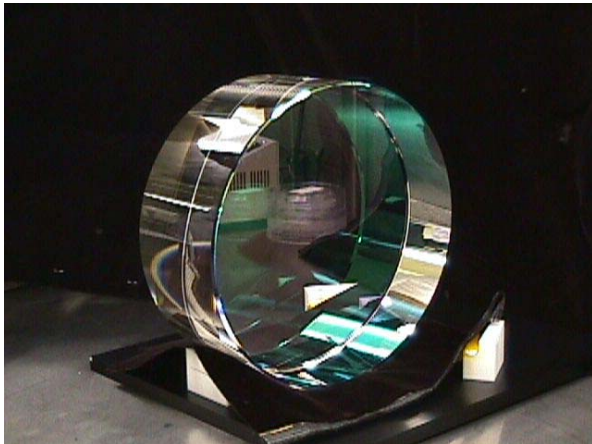
# LIGO Detector Facilities

## LASER

- ❑ Infrared (1064 nm, 10-W) Nd-YAG laser from Lightwave (now commercial product!)
- ❑ Elaborate intensity & frequency stabilization system, including feedback from main interferometer

## Optics

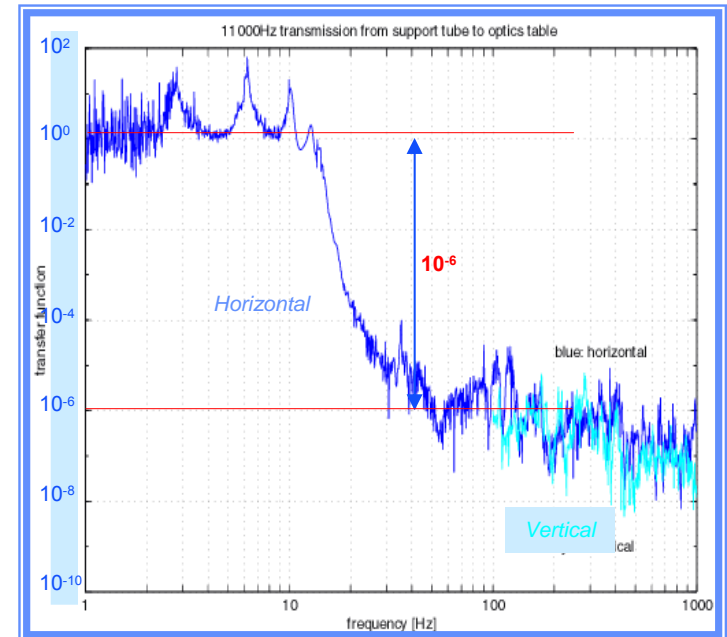
- ❑ Fused silica (high-Q, low-absorption, 1 nm surface rms, 25-cm diameter)
- ❑ Suspended by single steel wire
- ❑ Actuation of alignment / position via magnets & coils



# LIGO Detector Facilities

## Seismic Isolation

- ❑ Multi-stage (mass & springs) optical table support gives  $10^6$  suppression
- ❑ Pendulum suspension gives additional  $1 / f^2$  suppression above  $\sim 1$  Hz

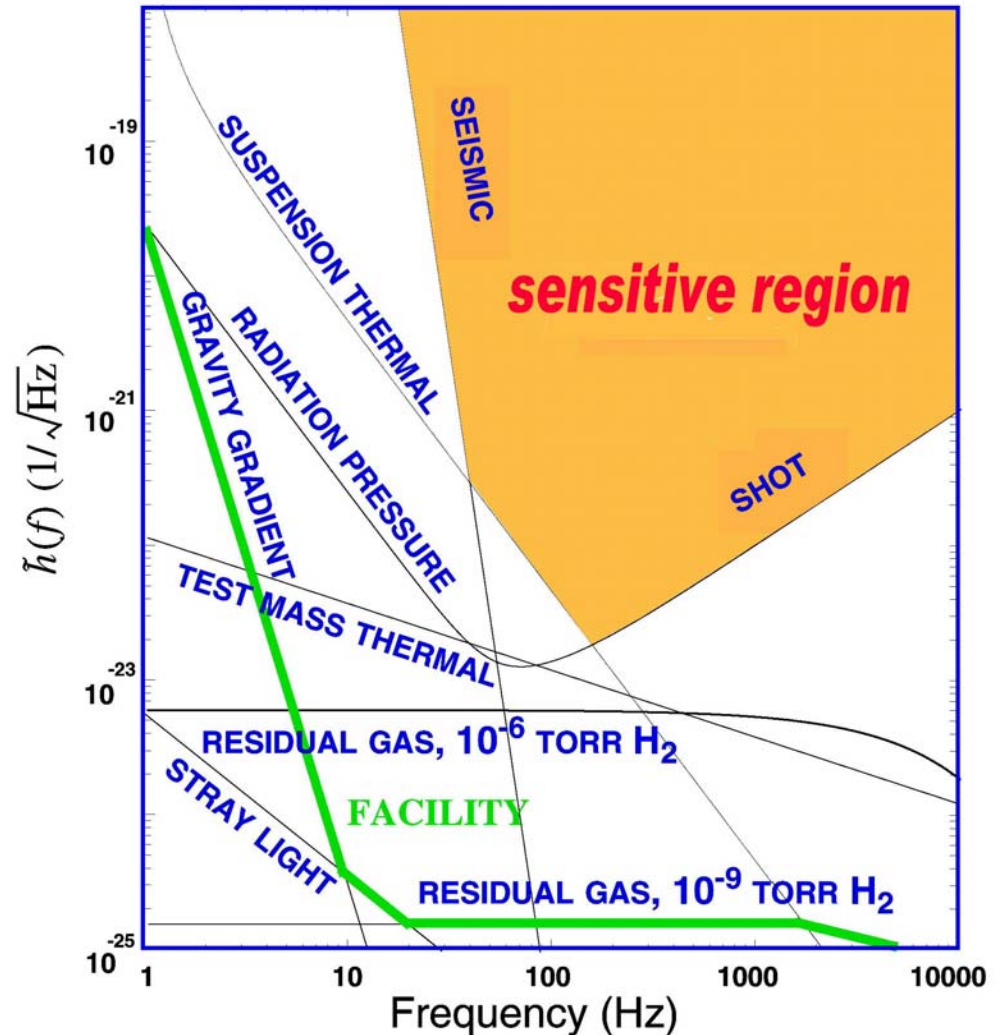


# What Limits the Sensitivity of the Interferometers?

- Seismic noise & vibration limit at low frequencies
- Atomic vibrations (Thermal Noise) inside components limit at mid frequencies
- Quantum nature of light (Shot Noise) limits at high frequencies
- Myriad details of the lasers, electronics, etc., can make problems above these levels

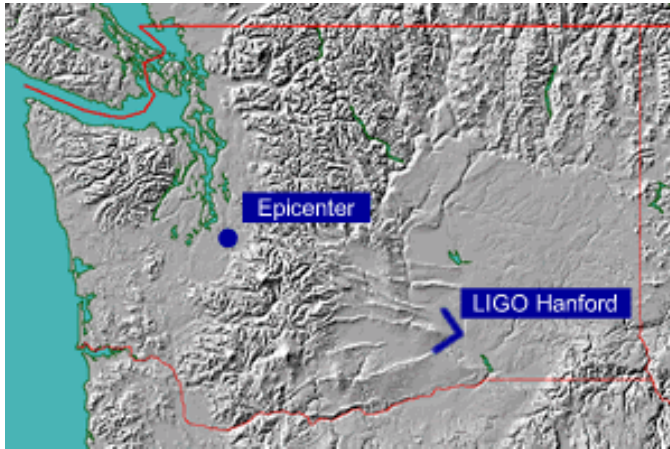
achieved  
~~Best design sensitivity:~~

$\sim 3 \times 10^{-23} \text{ Hz}^{-1/2} @ 150 \text{ Hz}$





# The road to design sensitivity at Hanford...



# Harder road at Livingston...



Livingston Observatory  
located in pine forest popular  
with pulp wood cutters

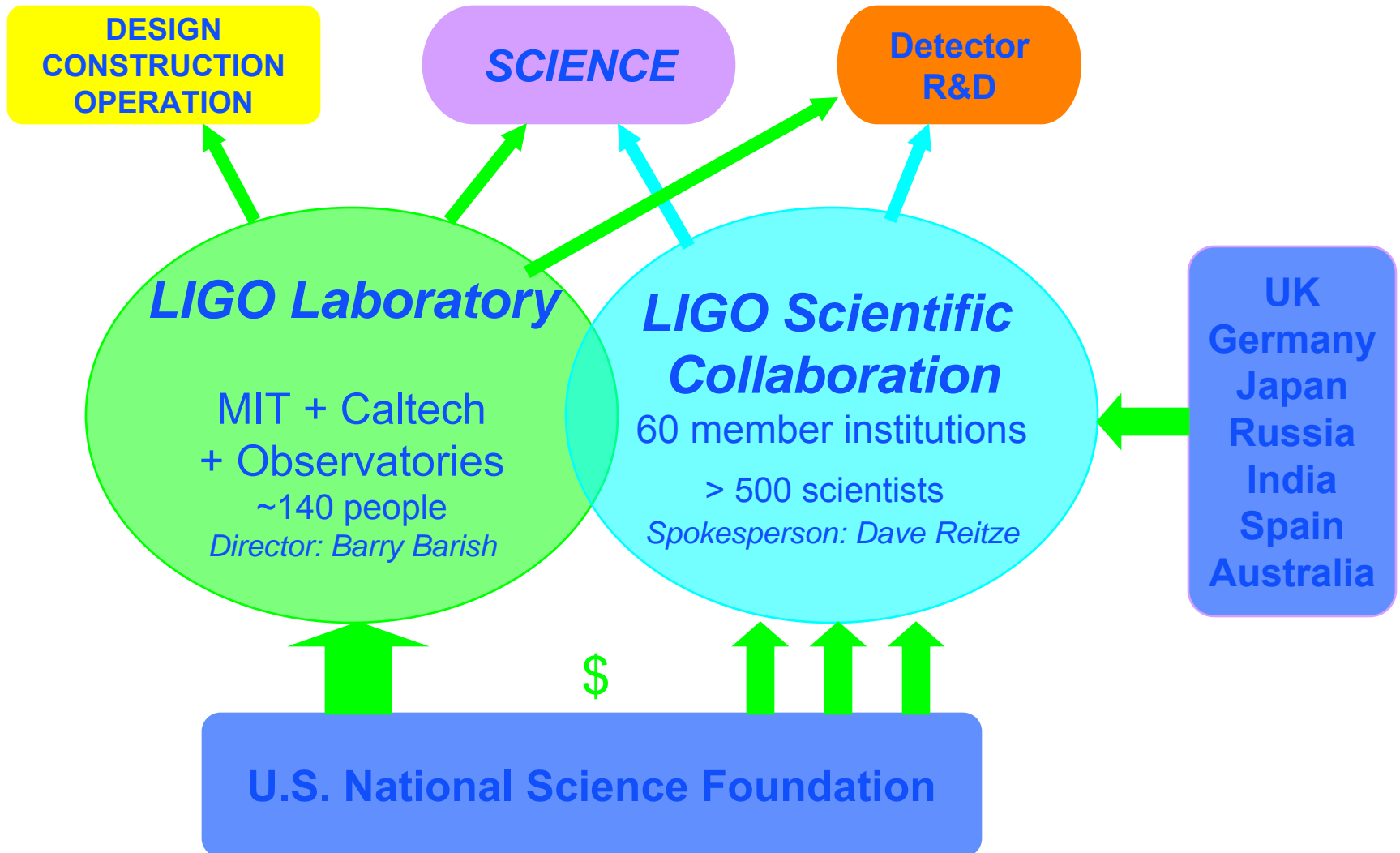
Spiky noise (e.g. falling trees) in  
1-3 Hz band creates dynamic  
range problem for arm cavity  
control

→ **40% livetime**

**Solution:** Retrofit with active feed-forward isolation system  
(using technology developed for Advanced LIGO)

→ Fixed in 2004

# LIGO Organization & Support





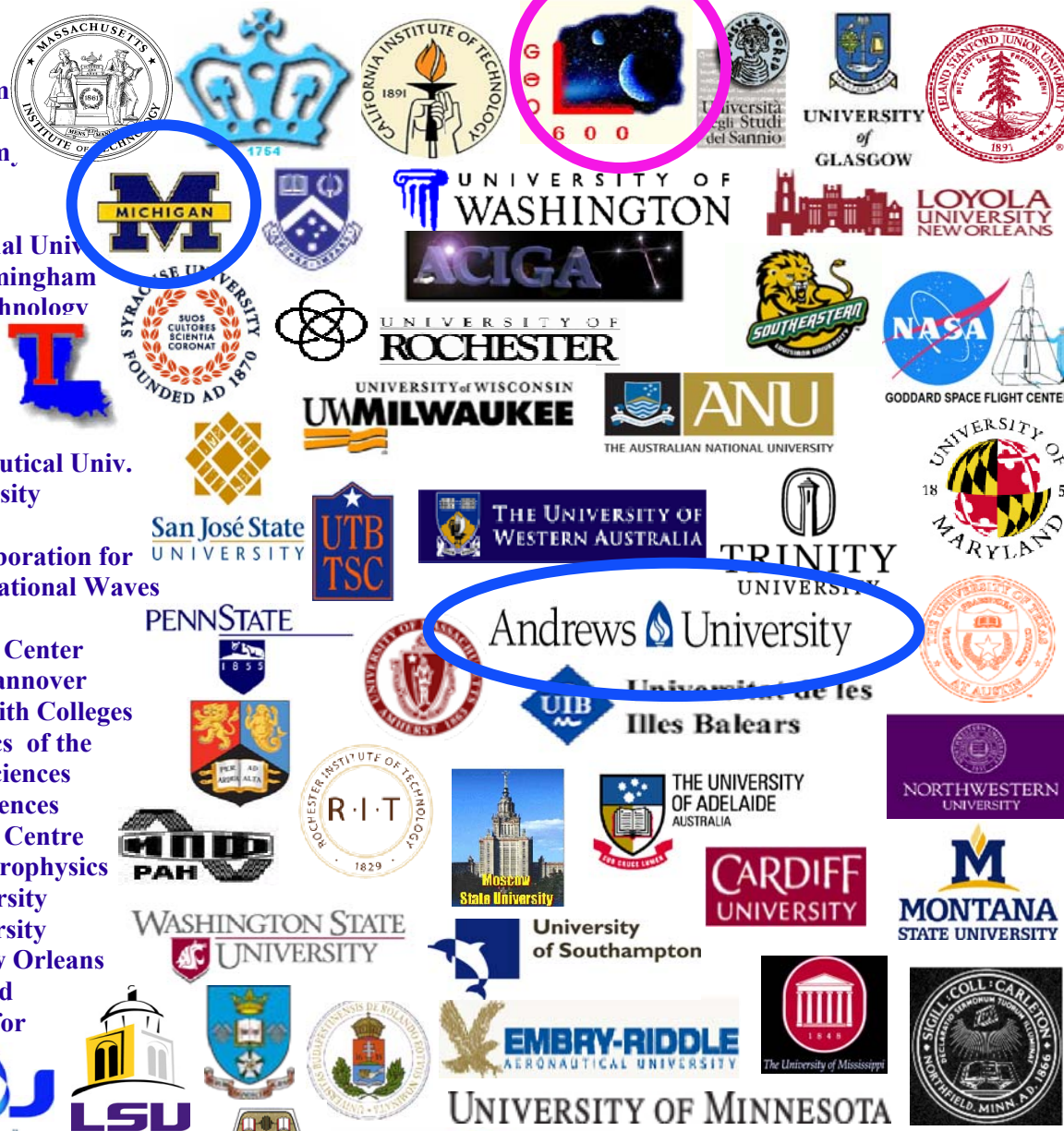
# LIGO

# LIGO Scientific Collaboration



- Australian Consortium for Interferometric Gravitational Astronomy
- The Univ. of Adelaide
- Andrews University
- The Australian National University
- The University of Birmingham
- California Inst. of Technology
- Cardiff University
- Carleton College
- Charles Sturt 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
- University of Minnesota
- The University of Mississippi
- 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



# ***GEO600***

**Work closely with the GEO600 Experiment (Germany / UK / Spain)**

- **Arrange coincidence data runs when commissioning schedules permit**
- **GEO members are full members of the LIGO Scientific Collaboration**
- **Data exchange and strong collaboration in analysis now routine**
- **Major partners in proposed Advanced LIGO upgrade**



**600-meter Michelson Interferometer  
just outside Hannover, Germany**



# Virgo

**Have begun collaborating with Virgo colleagues (Italy/France)**

**Took data in coincidence for last ~4 months of latest science run**

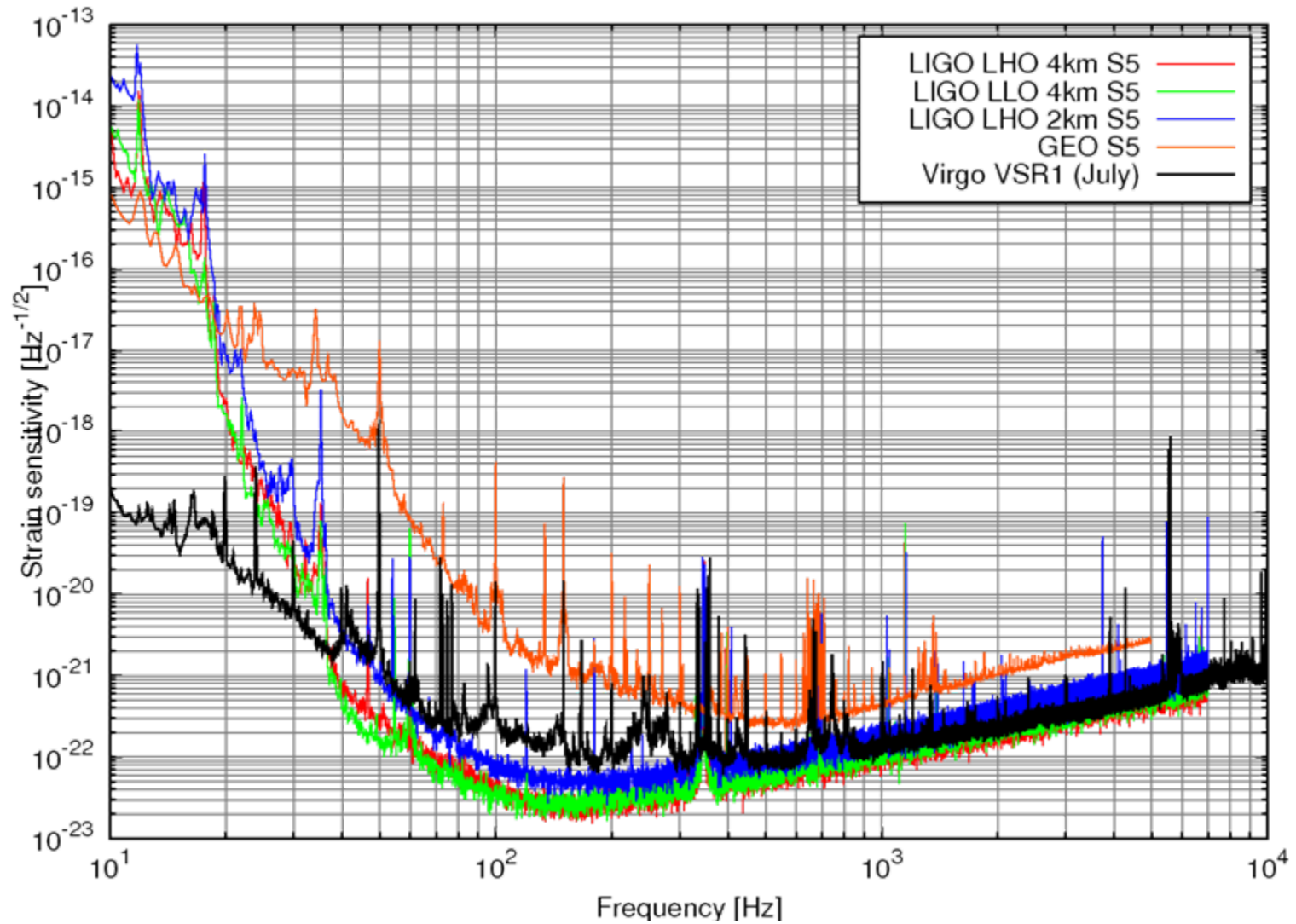
**Data exchange and joint analysis underway**

**Will coordinate closely on detector upgrades and future data taking**

**3-km Michelson  
Interferometer just  
outside Pisa, Italy**



# Sensitivities of the Large Interferometers



# Outline

- ❑ **Nature & Generation of Gravitational Waves**
- ❑ **Detecting Gravitational Waves with the LIGO Detector**
- ❑ **Data Runs and Results to Date**
- ❑ **Looking Ahead – Advanced LIGO**



# Data Runs

Have carried out a series of Engineering Runs (E1–E12) and Science Runs (S1--S5) interspersed with commissioning

## S1 run:

17 days (Aug / Sept 2002) – Rough but good practice

## S2 run:

59 days (Feb—April 2003) – Many good results

## S3 run:

70 days (Oct 2003 – Jan 2004) -- Ragged

## S4 run:

30 days (Feb—March 2005) – Another good run

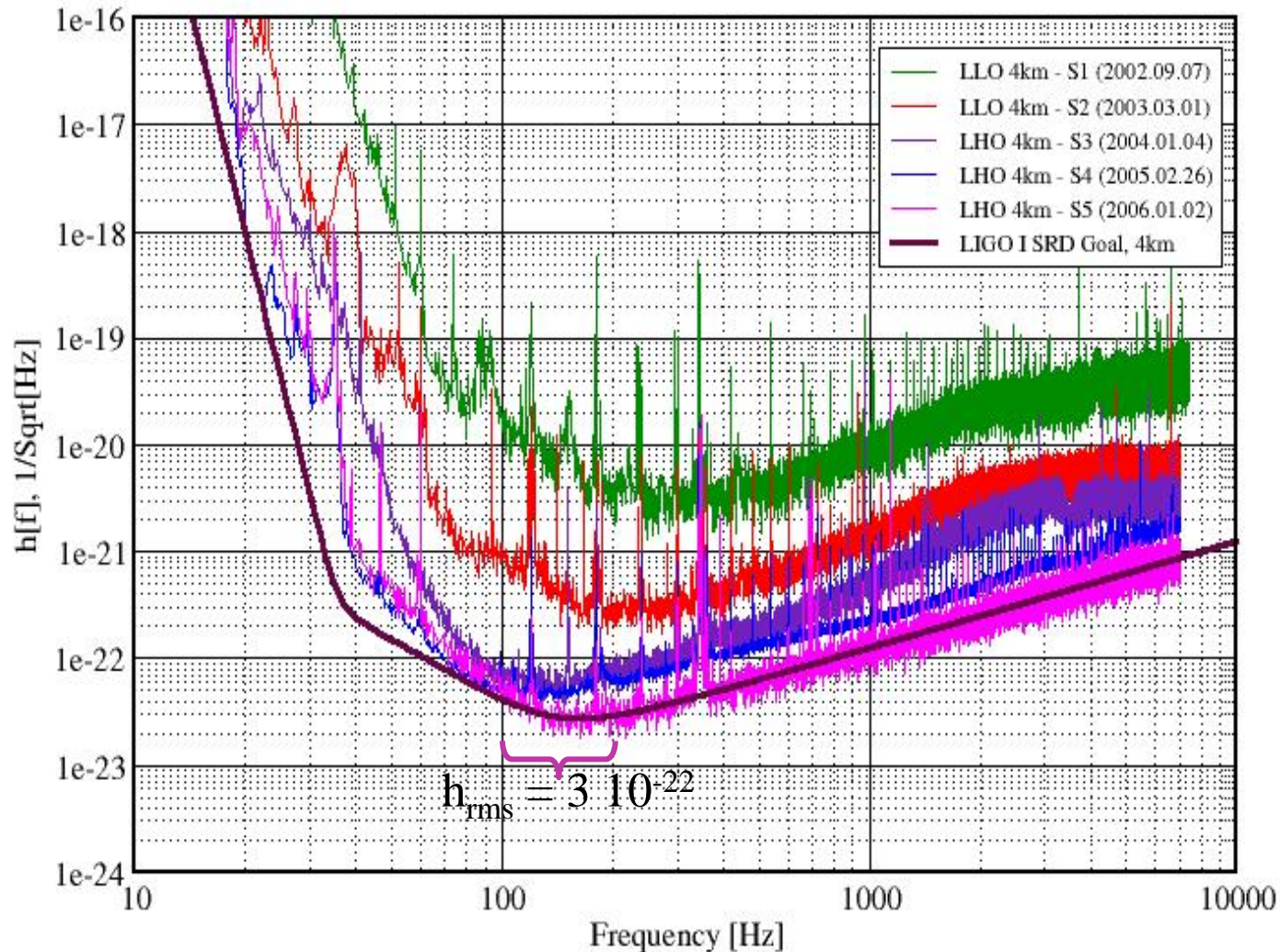
## S5 run:

23 months (Nov 2005 – Sept 2007) – Great!

# S1 → S5 Sensitivities

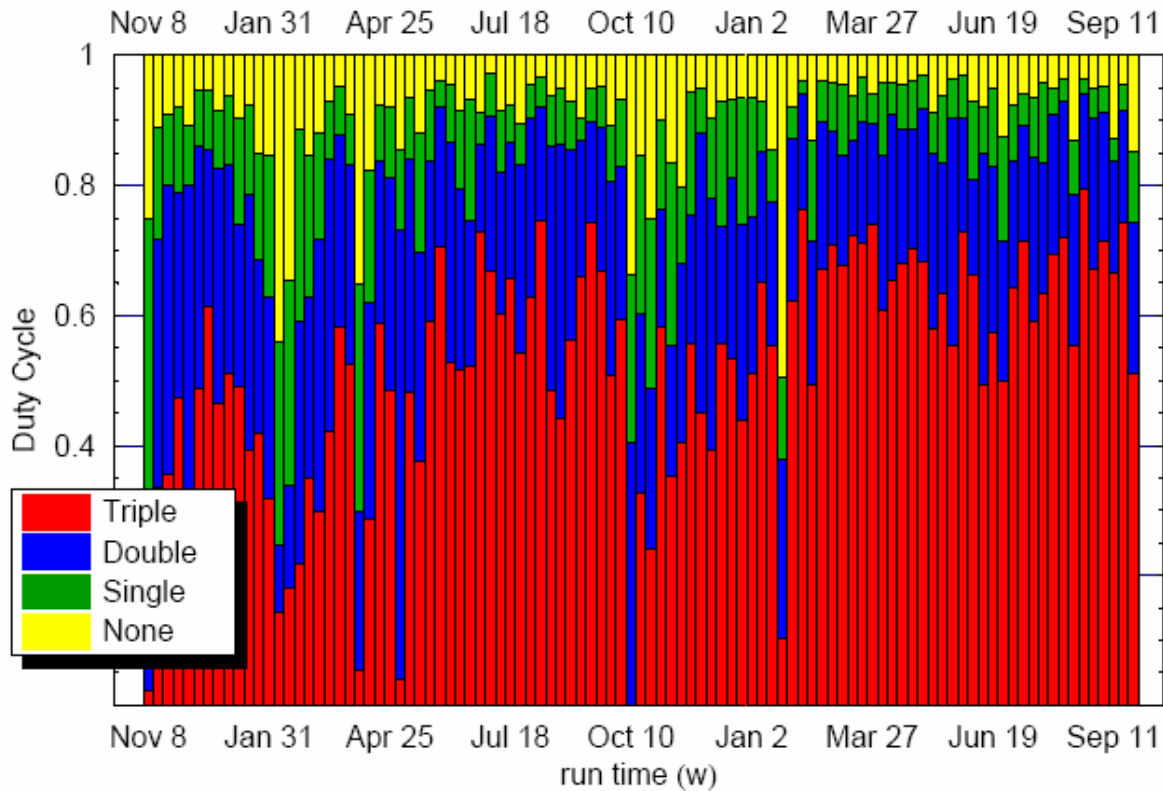
## Best Strain Sensitivities for the LIGO Interferometers

Comparisons among S1 - S5 Runs LIGO-G060009-01-Z



# The S5 science run

- Started Nov 2005 – Ended Sep 30, 2007
- Completion of one year of triple coincidence data between the 3 LIGO interferometers



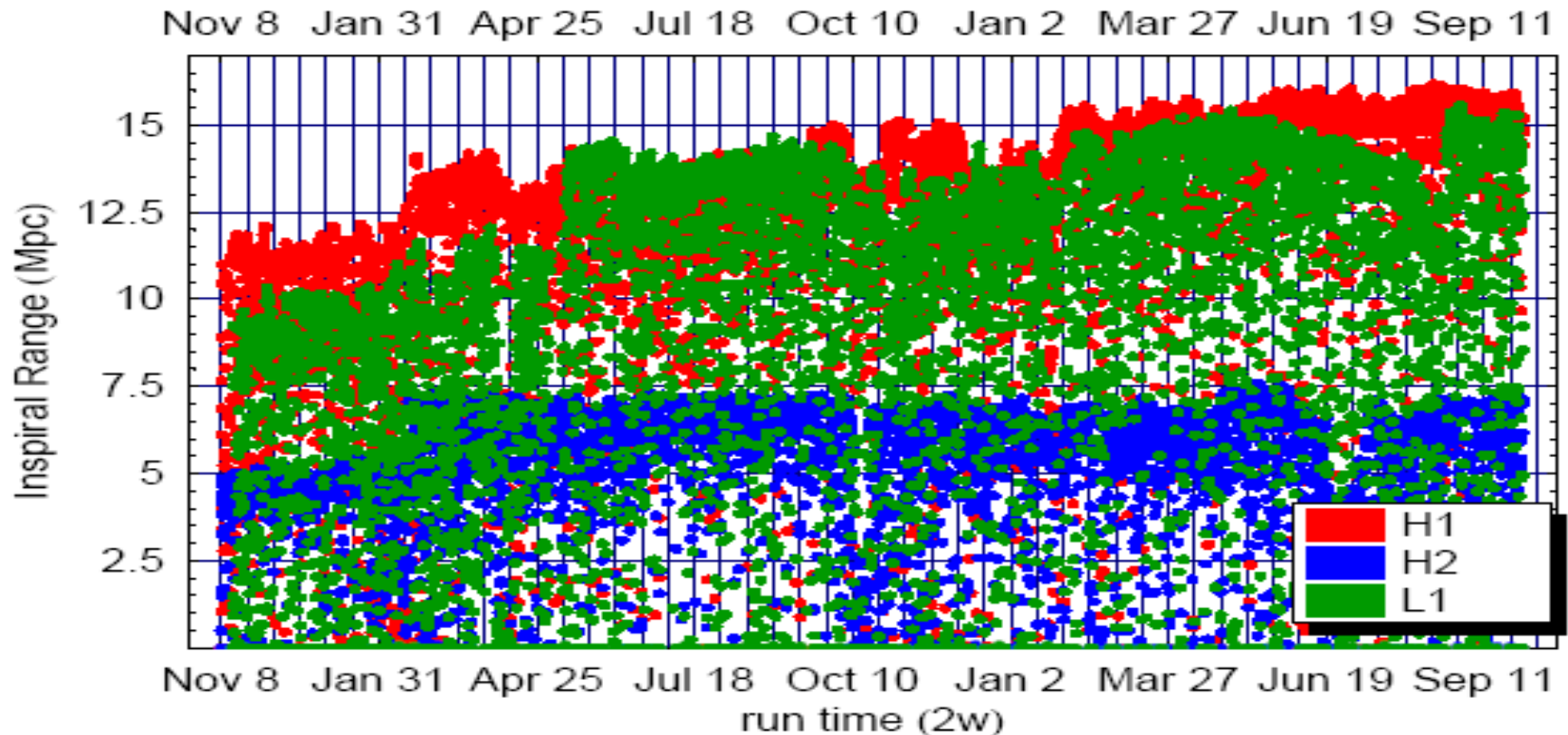
## S5 duty cycles:

- 52.8 % in triple coincidence
- 57.0 % in H1L1 coincidence
- Total for H1: 77.7 %
- Total for H2: 78.2 %
- Total for L1: 65.7 %
- H1H2L1V1: 11.3 %

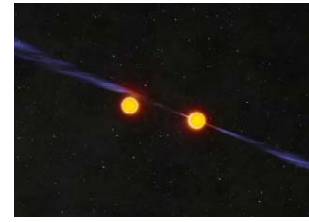
# Range (=averaged horizon) during S5

The sensitivity can be translated into distances surveyed.

Range definition: *distance to which an interferometer can detect an inspiral, averaged over all sky positions and orientations*  
(for a 1.4/1.4 solar mass system, with  $\text{snr} = 8$ )



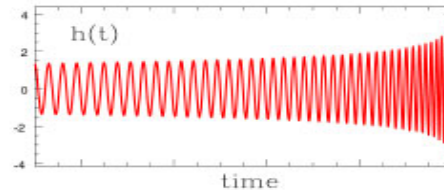
# Search for binary systems



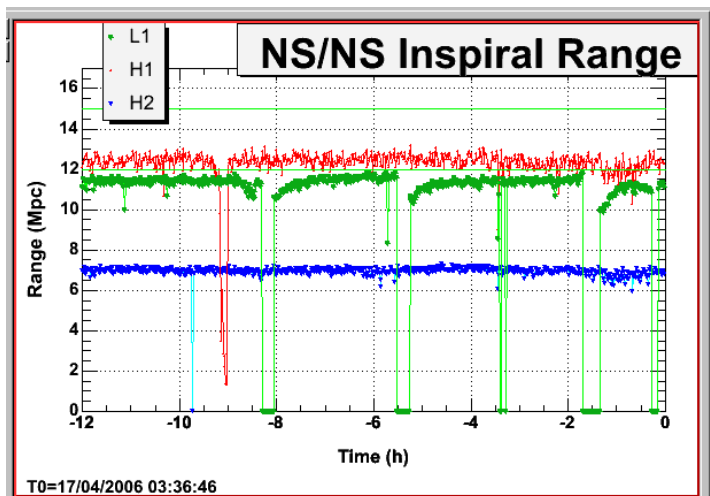
Use calculated templates for inspiral phase (“chirp”) with optimal filtering.

Search for systems with different masses:

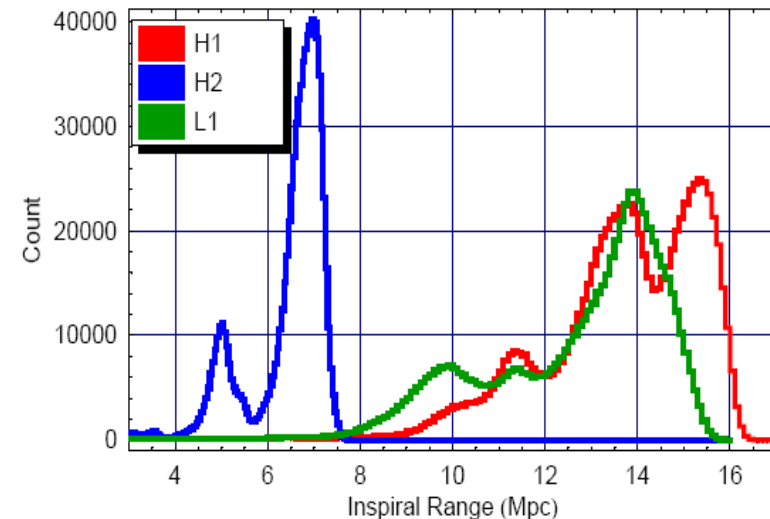
- ◆ Binary neutron stars (~1-3 solar masses): ~15 sec templates, 1400 Hz end freq
- ◆ Binary black holes (< ~30 solar masses): shorter templates, lower end freq
- ◆ Primordial black holes (<1 solar mass): longer templates, higher end freq



“Typical” 12-hour history:



S5 range histograms:



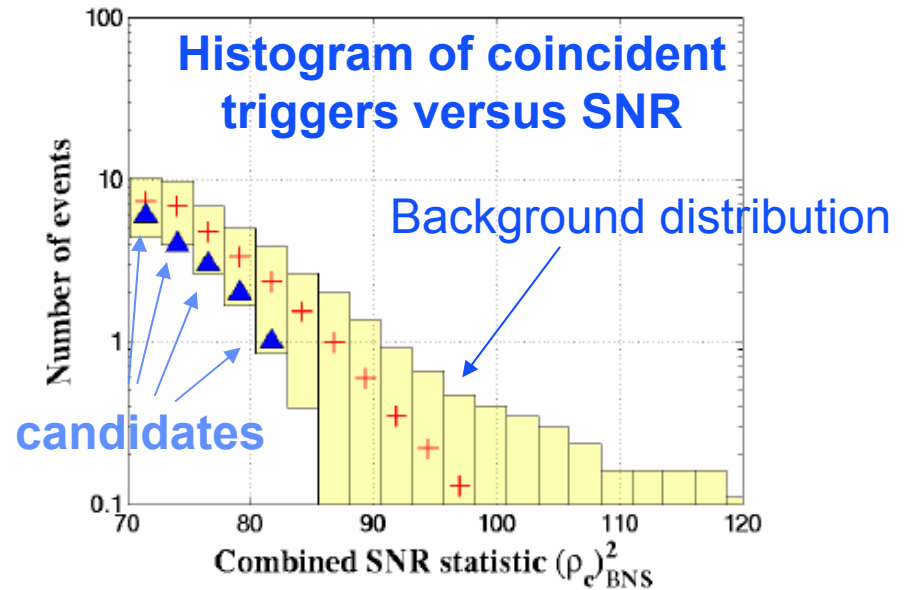
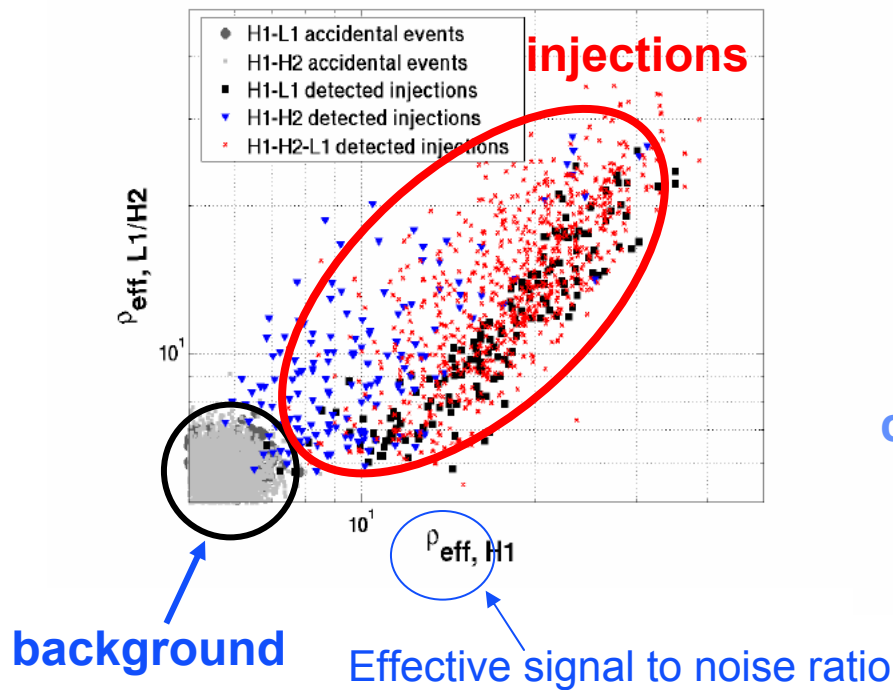
If system is optimally located and oriented, we can see even further: we are surveying hundreds of galaxies!

Estimate the false alarm probability

⇒ **compare candidate to expected background**

→ background estimated by applying time-slides before coincidence

Ex: S4 Binary Neutron Star search [*Preprint arXiv:0704.3368*]



**If candidates consistent with background ⇒ no detection**

**Else ?**



# Compact Binary Inspirals

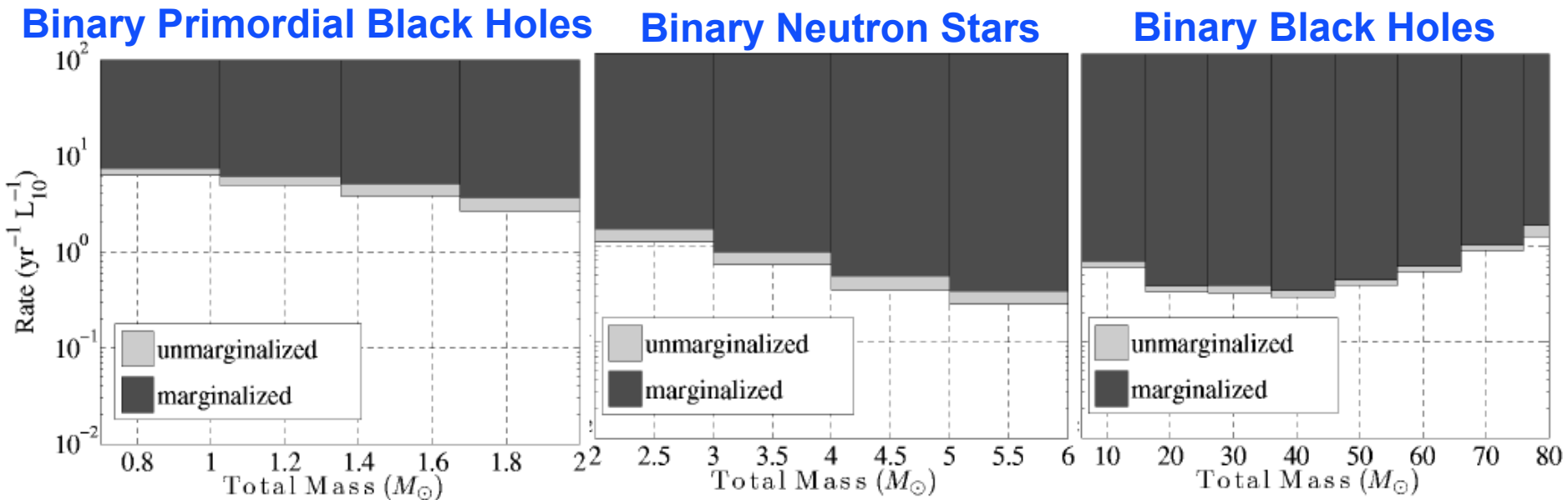
- **S3/S4 runs:** [ *Preprint arXiv:0704.3368* ]

No GW signals identified

Binary neutron star signals could be detected 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



- Rate/L<sub>10</sub> vs. binary total mass  
L<sub>10</sub> = 10<sup>10</sup> L<sub>⊙,B</sub> (1 Milky Way = 1.7 L<sub>10</sub>)
- Dark region excluded at 90% confidence

# Compact Binary Inspirals: S5 prospects

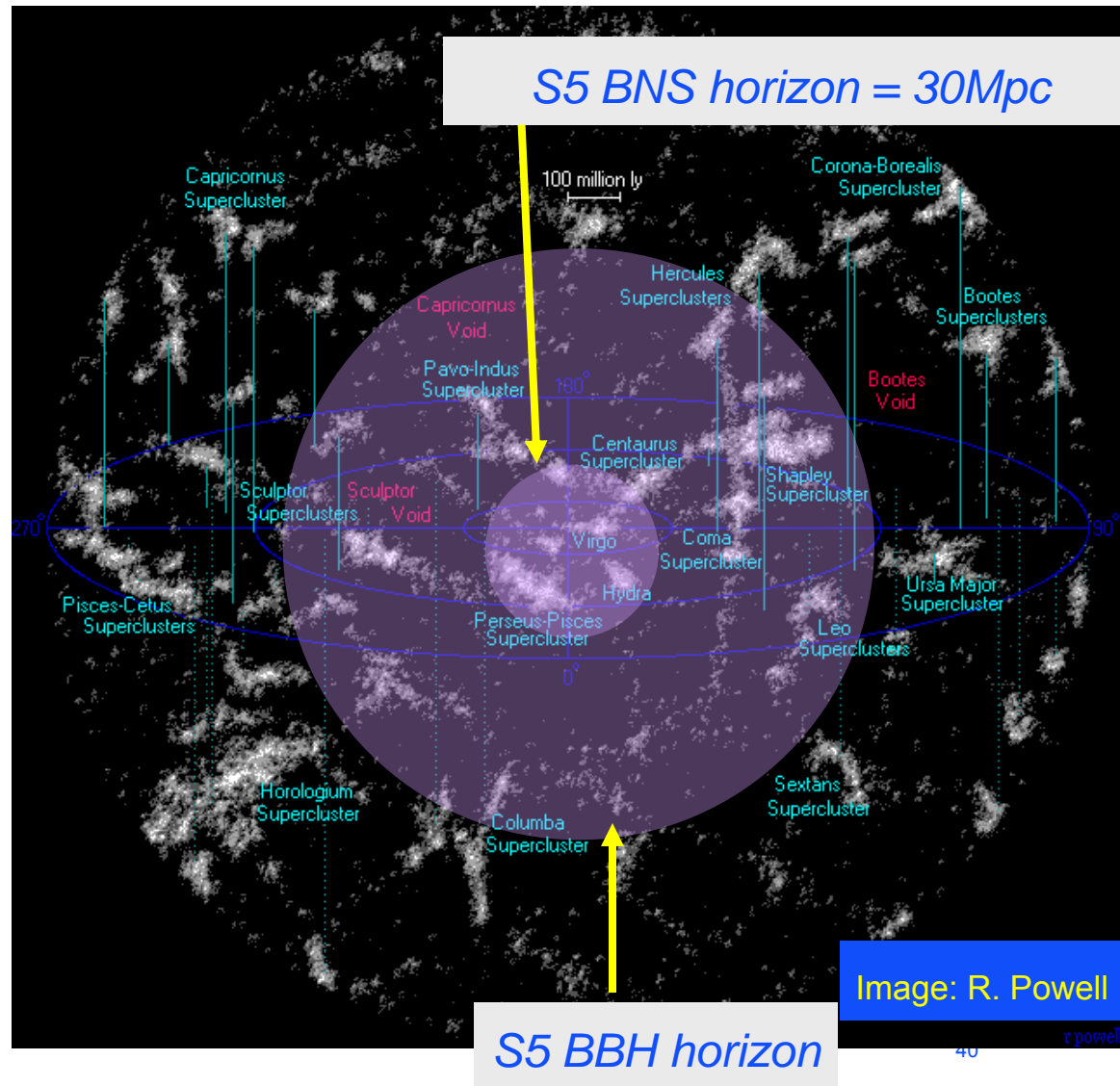
Horizon (optimal) = distance at which an **optimally oriented and located** binary system can be seen with signal-to-noise ratio  $\rho=8$

Expected rate for Binary Neutron Star:

~ 1/100 yrs

⇒ **Detection unlikely** ☹️

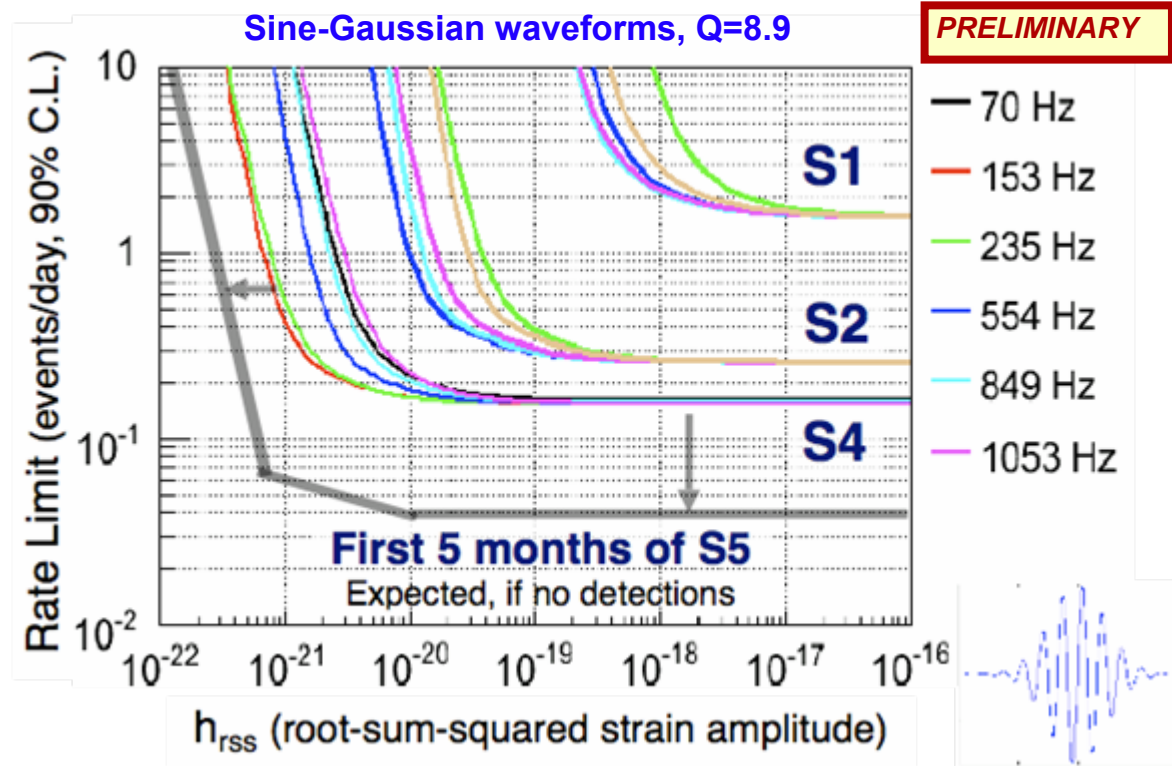
Carried out some **blind injections** to test detection efficiency – Perhaps!





# All-Sky Burst Search from S1 to S5

- Tuned for 64–1600 Hz, duration  $\ll 1$  sec No GW bursts signals seen in S1/S2/S3/S4
- Ad-hoc waveforms (Sine-Gaussian, Gaussian, etc.) used to determine detection sensitivity
- Convert to corresponding energy emission sensitivity (assuming isotropic,  $h_+$  only polarization)

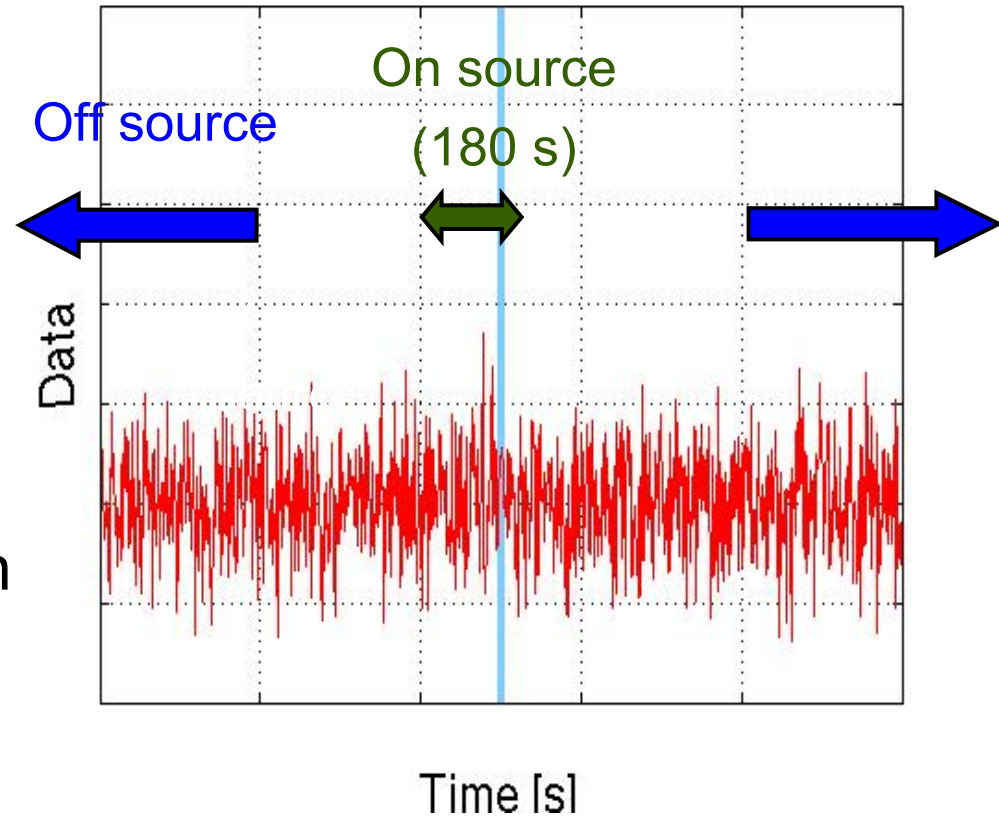


$$h_{\text{rss}} \equiv \sqrt{\int (|h_+(t)|^2 + |h_\times(t)|^2) dt}$$

**LIGO is sensitive to  $E_{\text{GW}} \sim 0.1 M_{\text{SUN}}c^2$  at 20 Mpc @153 Hz**

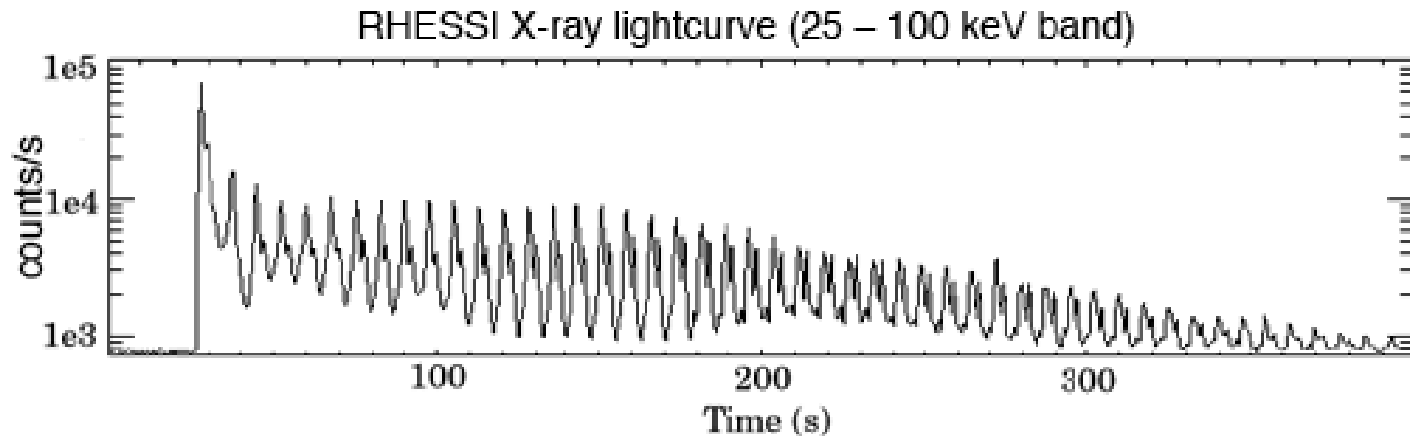
# Triggered burst searches

- Triggered search:
  - GRB gives time and sky location
  - Gives geometrical time-delay between different detectors
  - ▶ The GRB triggered search can probe deeper into the data



# SGR 1806-20 Result

- Record flare from Soft Gamma-Ray Repeater SGR 1806-20 on December 27, 2004
- > Quasi-periodic oscillations (QPO) in RHESSSE, RXTE x-ray data



- Only one LIGO detector (H1) was observing
- Band-limited excess-power search for quasi-periodic GW signal
- No evidence for GW signal found
- Sensitivity for 92.5Hz QPO  $E_{\text{GW}} \sim 10^{-7}$  to  $10^{-8} M_{\text{SUN}}$  at 5-10 kpc (this is comparable to electro-magnetic energy in flare)

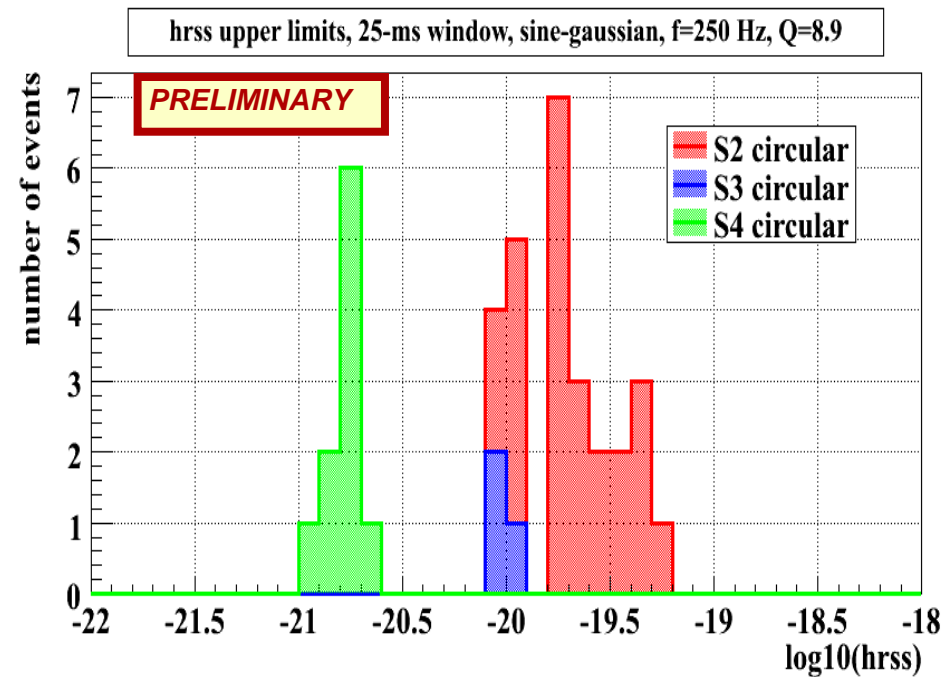
# GRB Search Results

- Search for short-duration gravitational-wave bursts (GWBs) coincident with GRBs using S2, S3 and S4 data from LIGO
- Analysis based on pair-wise cross-correlation of two interferometers
  - ▶ --> Increased observation time over triple-coincidence
- Target GWB durations:  $\sim 1$  ms to  $\sim 100$  ms; Bandwidth: 40-2000 Hz

• No GW signal found associated with 39 GRBs in S2,S3,S4 runs

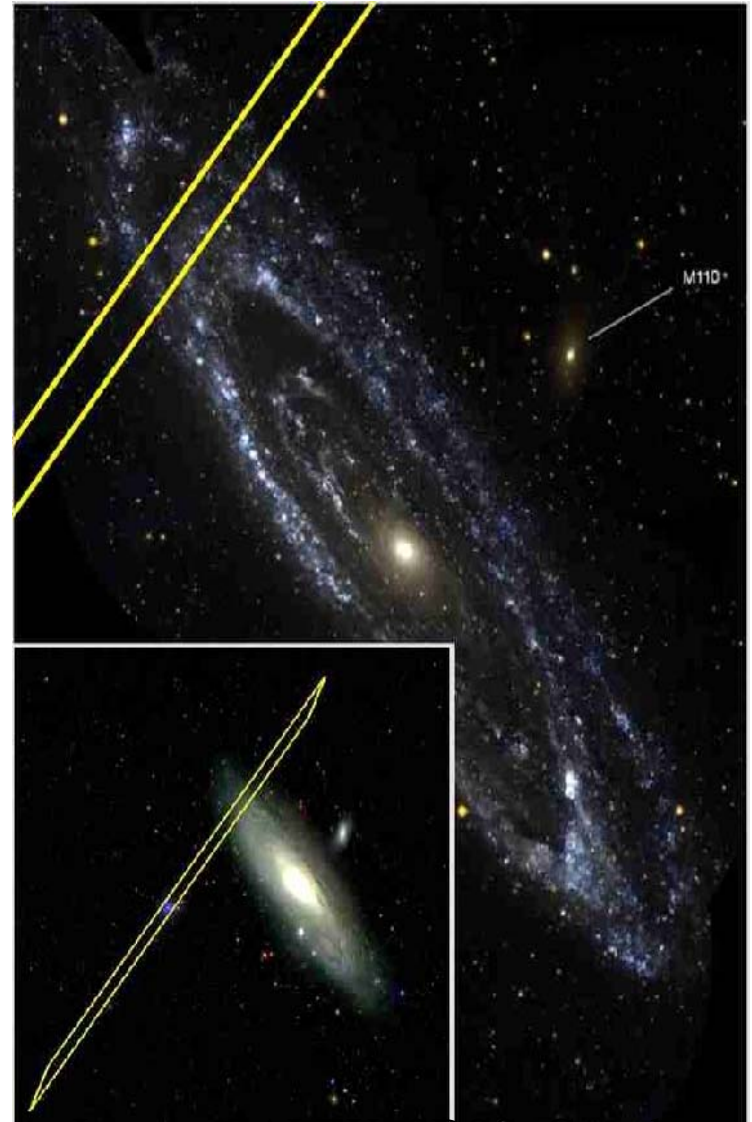
(Sensitivity similar to untriggered search)

• About 10 GRBs/month during the S5 run



# GRB 070201

- Short GRB ( $T_{90}=0.15$  s)
- Possible compact binary merger (NS/BH)
- Possible SGR
- Error-box of location overlay M31 (770 kpc away)



9 November 2007

GRB 2007

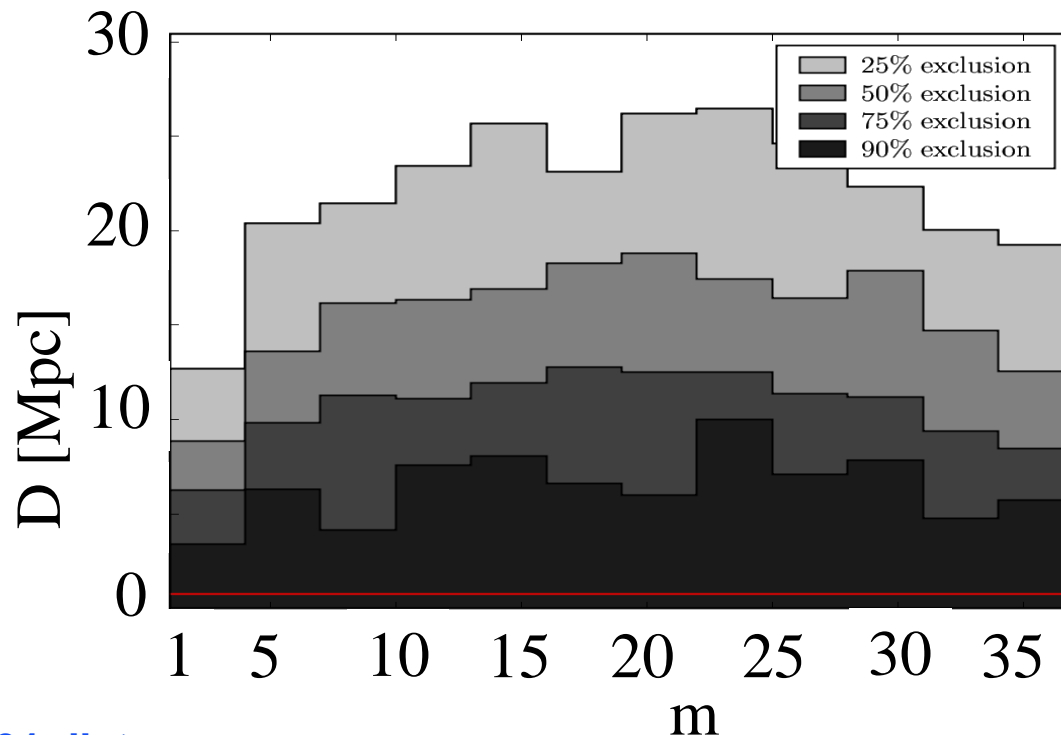
Image: GALEX, SDSS, Google Sky

# Results GRB070201

No gravitational wave detected

## Inspiral search:

- Binary merger in M31 scenario excluded at >99% level
- Exclusion of merger at larger distances: see plot



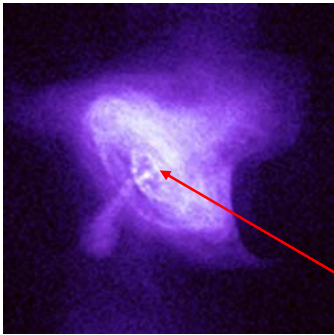
## Burst search:

- Cannot exclude a SGR at M31 distance
- Upper limit:  $8 \times 10^{50}$  ergs ( $4 \times 10^{-4} M_{\odot} c^2$ ) (emitted within 100 ms for isotropic emission of energy in GW at M31 distance)

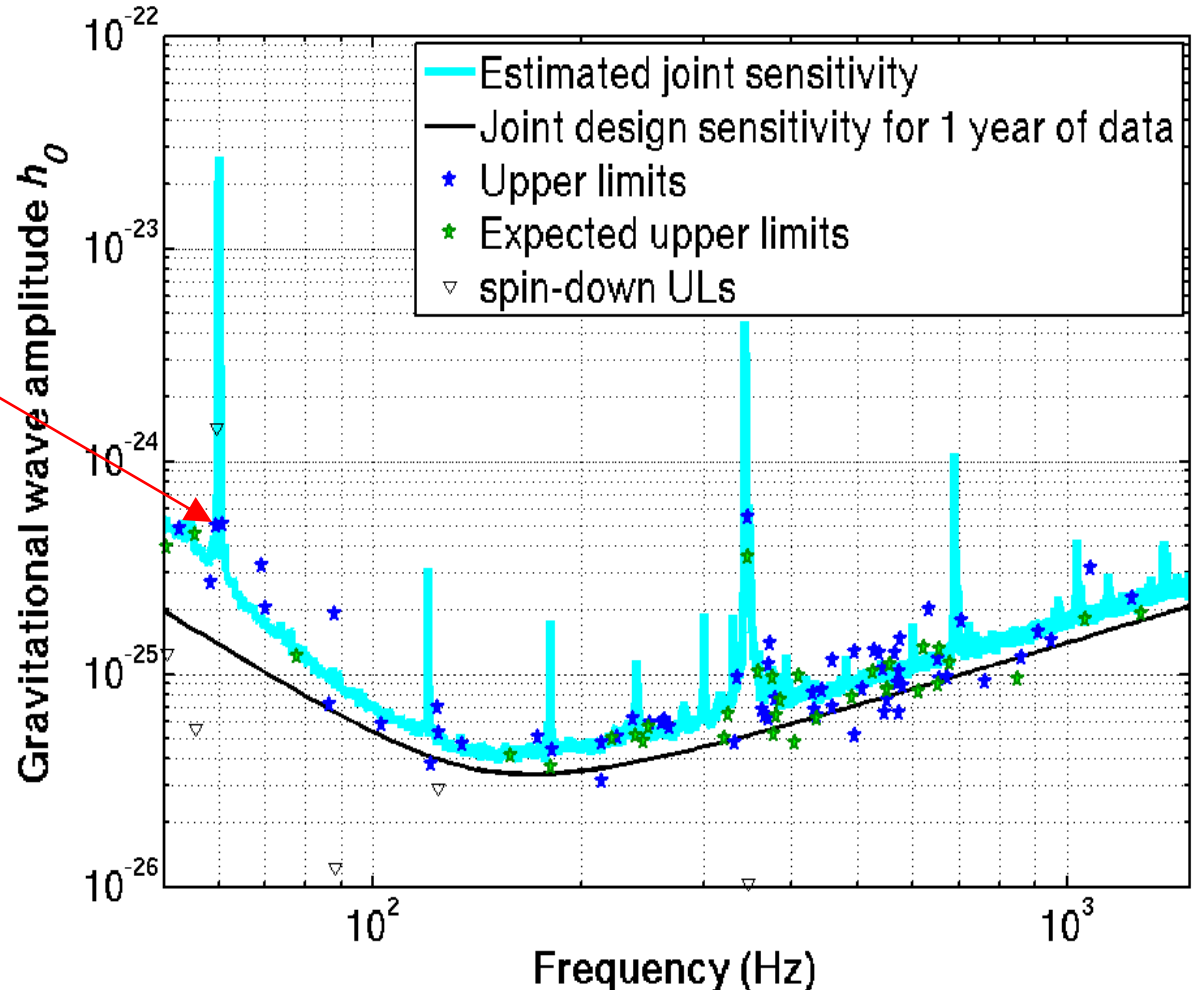
# Searches for Pulsars

Targeted searches for 97 known (radio and x-ray) systems in S4: isolated pulsars, binary systems, pulsars in globular clusters...

Crab pulsar



Upper limits on GWs from targeted pulsars:



Will beat  
spindown  
limit for  
Crab from  
S5 data

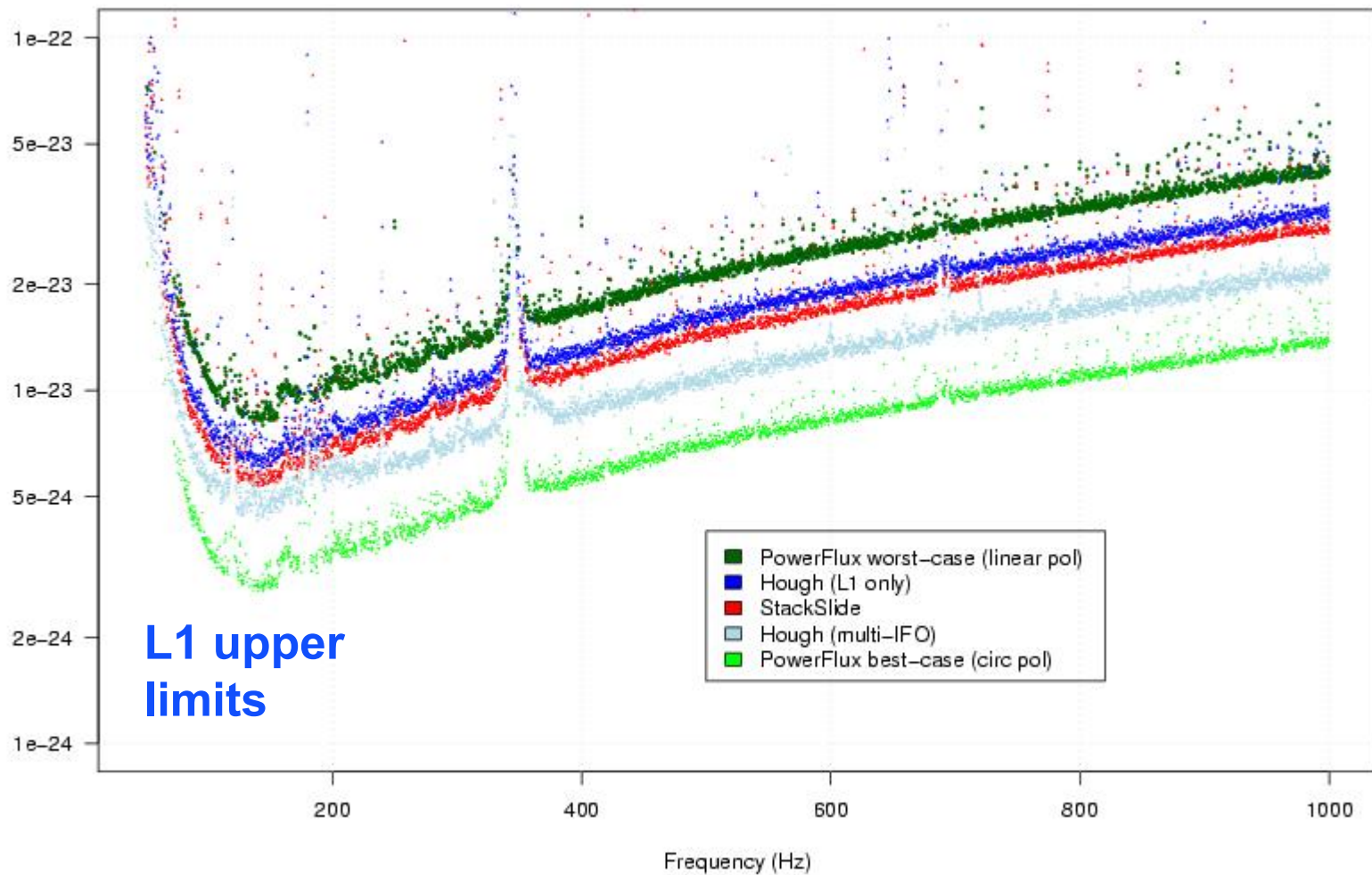
Preliminary



# Searches for Pulsars

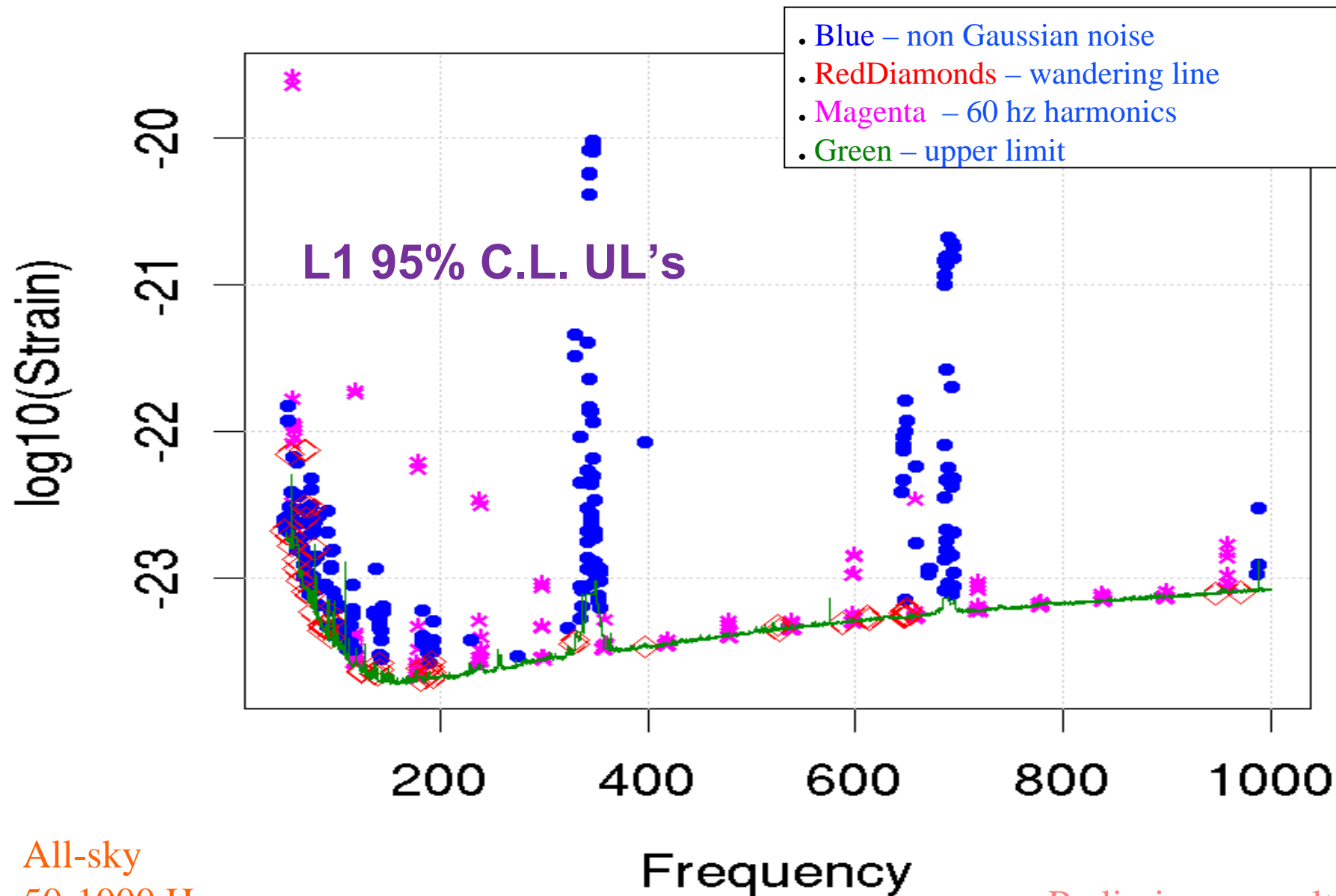
Broadband, untargeted, all-sky search (S4 data) – [arXiv:0708.3818](https://arxiv.org/abs/0708.3818)

- Sacrifice sensitivity for coverage, given computational resources
- Could saturate Earth's computers easily with coherent searches





# Preliminary S5 results – no spindown

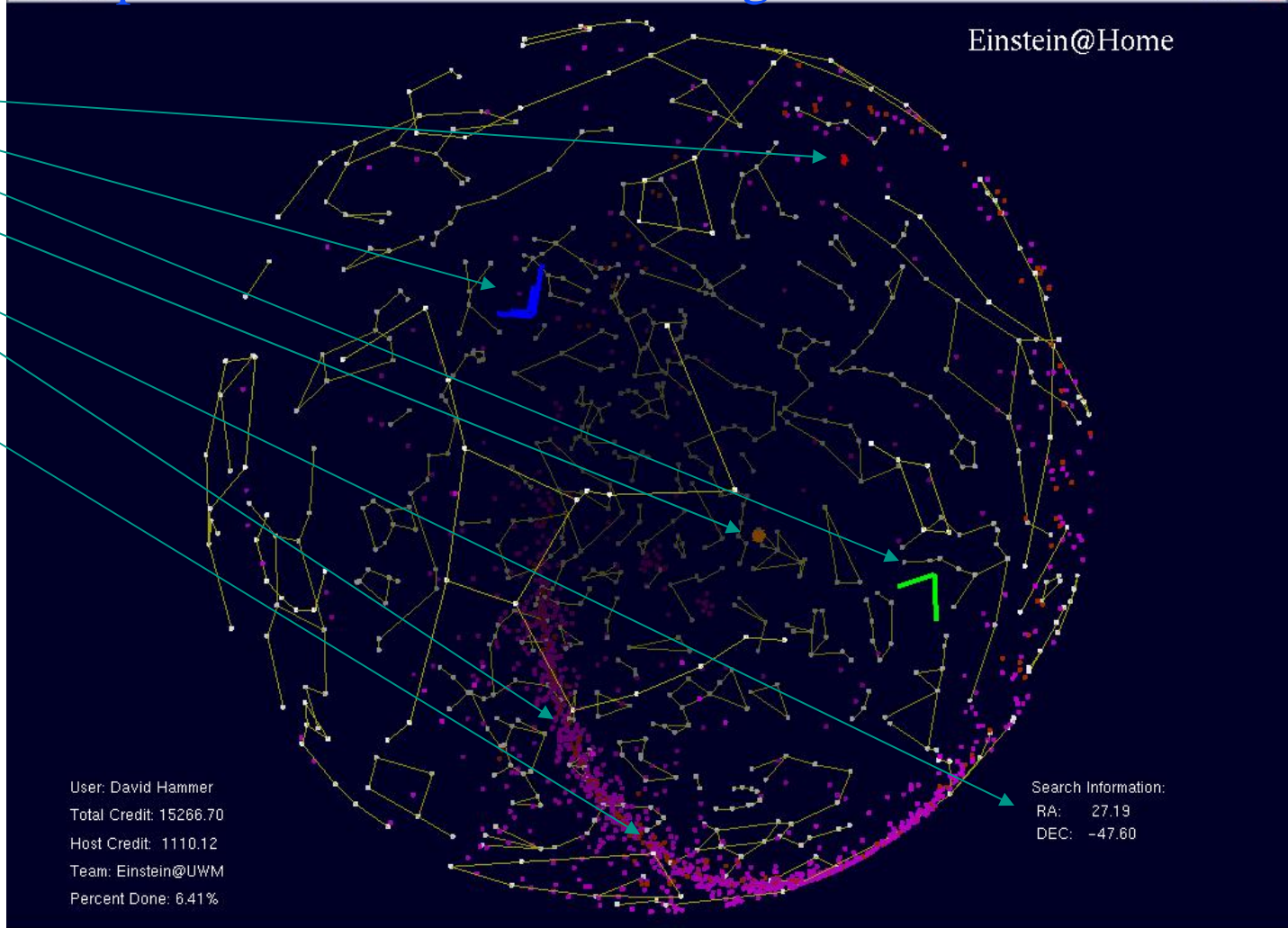


Preliminary results

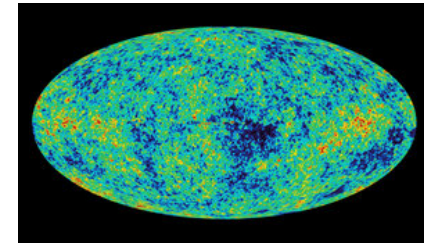


<http://www.einsteinathome.org/>

- GEO-600 Hannover
- LIGO Hanford
- LIGO Livingston
- Current search point
- Current search coordinates
- Known pulsars
- Known supernovae remnants



# Stochastic Background

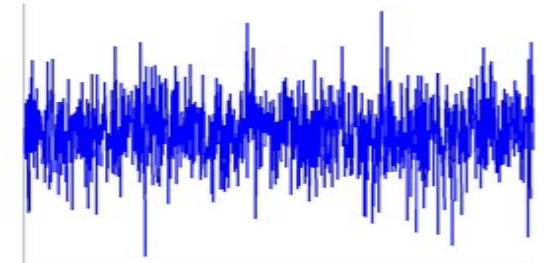


NASA, WMAP

- A primordial GW stochastic background is a prediction from most cosmological theories.
- Given an energy density spectrum  $\Omega_{\text{gw}}(f)$ , there is a strain power spectrum:

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

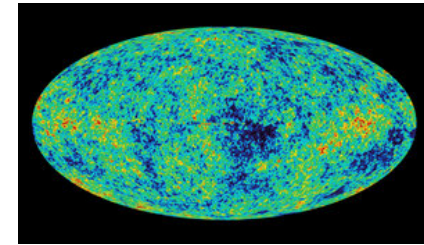
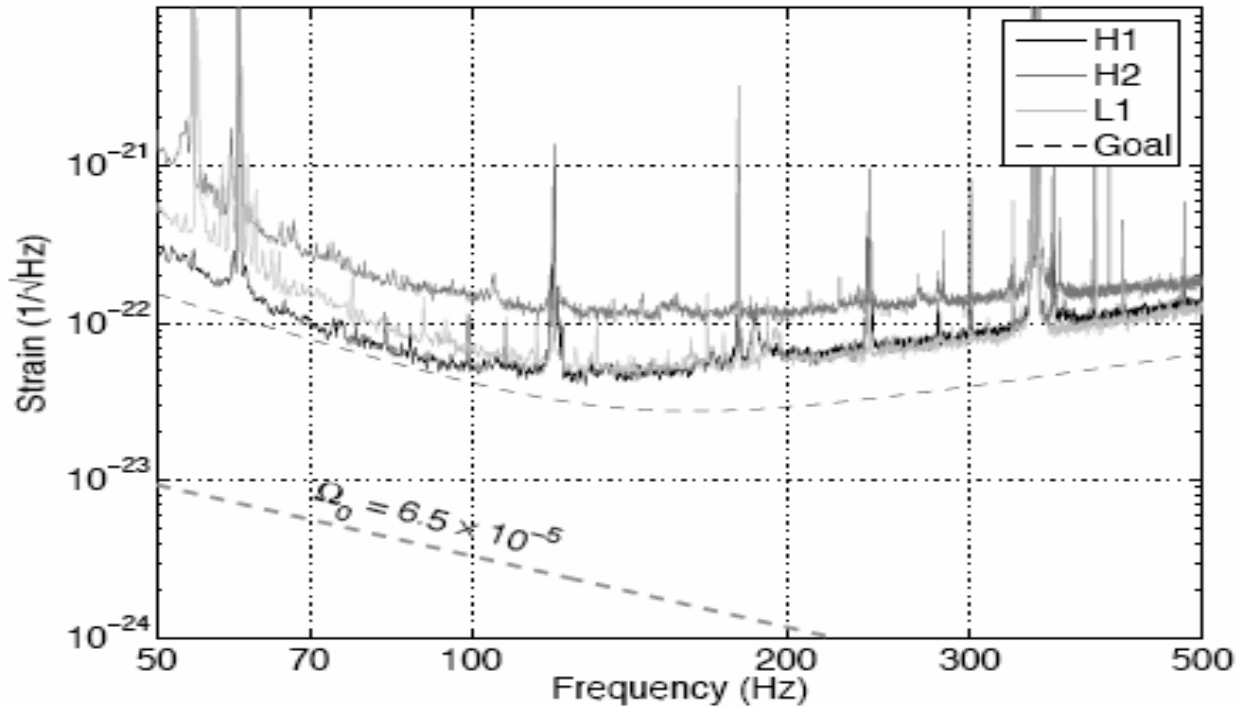
$$S_{\text{gw}}(f) = \frac{3H_0^2}{10\pi^2} f^{-3} \Omega_{\text{gw}}(f)$$



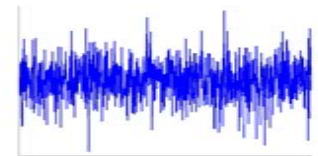
$$h(f) = S_{\text{gw}}^{1/2}(f) = 5.6 \times 10^{-22} h_{100} \sqrt{\Omega_0} \left( \frac{100\text{Hz}}{f} \right)^{3/2} \text{Hz}^{1/2}$$

- The signal can be searched from cross-correlations in different pairs of detectors: L1-H1, H1-H2. The farther the detectors, the lower the frequencies that can be searched.

# Stochastic Background



NASA, WMAP



- S4 H1-L1 and H2-L1 Bayesian 90% UL:  $\Omega_{90\%} = 6.5 \times 10^{-5}$  (51-150 Hz)
- Expect 1-2 orders of magnitude improvement from S5 run

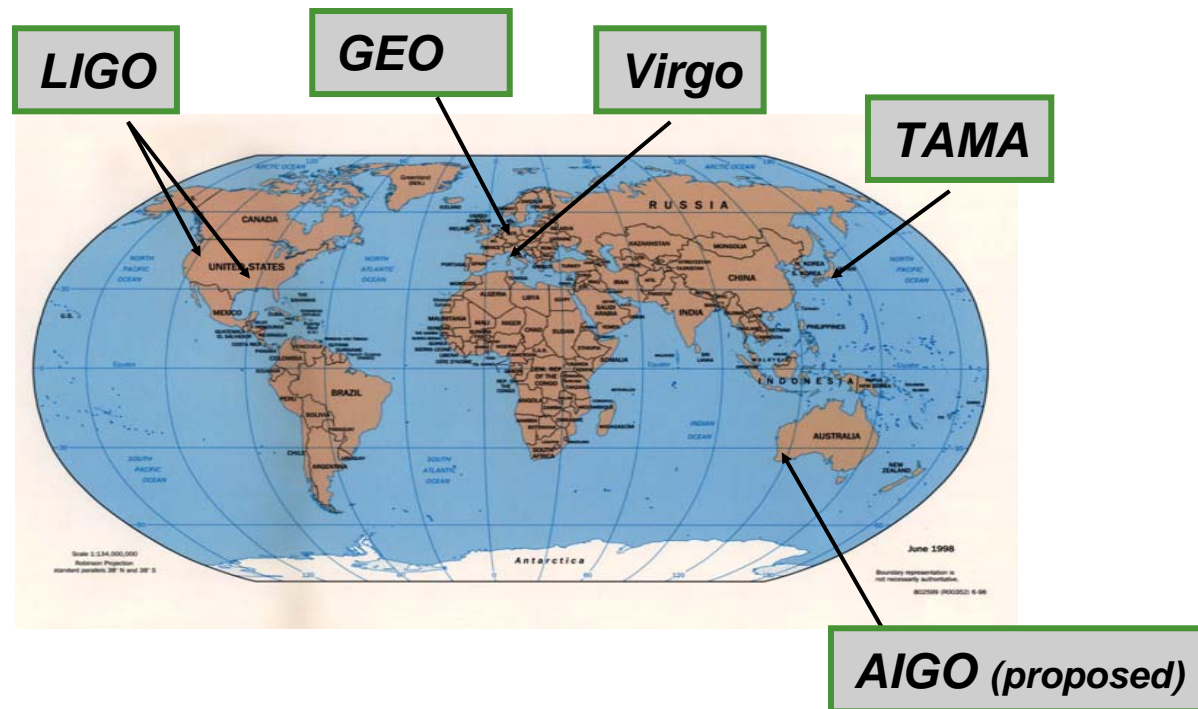
# Outline

- ❑ **Nature & Generation of Gravitational Waves**
- ❑ **Detecting Gravitational Waves with the LIGO Detector**
- ❑ **Data Runs and Results to Date**
- ❑ **Looking Ahead – Advanced LIGO**

# Looking Ahead

The three LIGO and the GEO interferometers are part of a forming **Global Network**.

Multiple signal detections will increase detection confidence and provide better precision on source locations and wave polarizations



## *Looking Further Ahead*

Despite their immense technical challenges, the initial LIGO IFO's were designed conservatively, based on “tabletop” prototypes, but with expected sensitivity gain of ~1000.

Given the expected low rate of detectable GW events, it was always planned that in engineering, building and commissioning initial LIGO, one would learn how reliably to build Advanced LIGO with another factor of ~10 improved sensitivity.

Because LIGO measures GW amplitude, an increase in sensitivity by 10 gives an increase in sampling volume, i.e, rate by ~1000

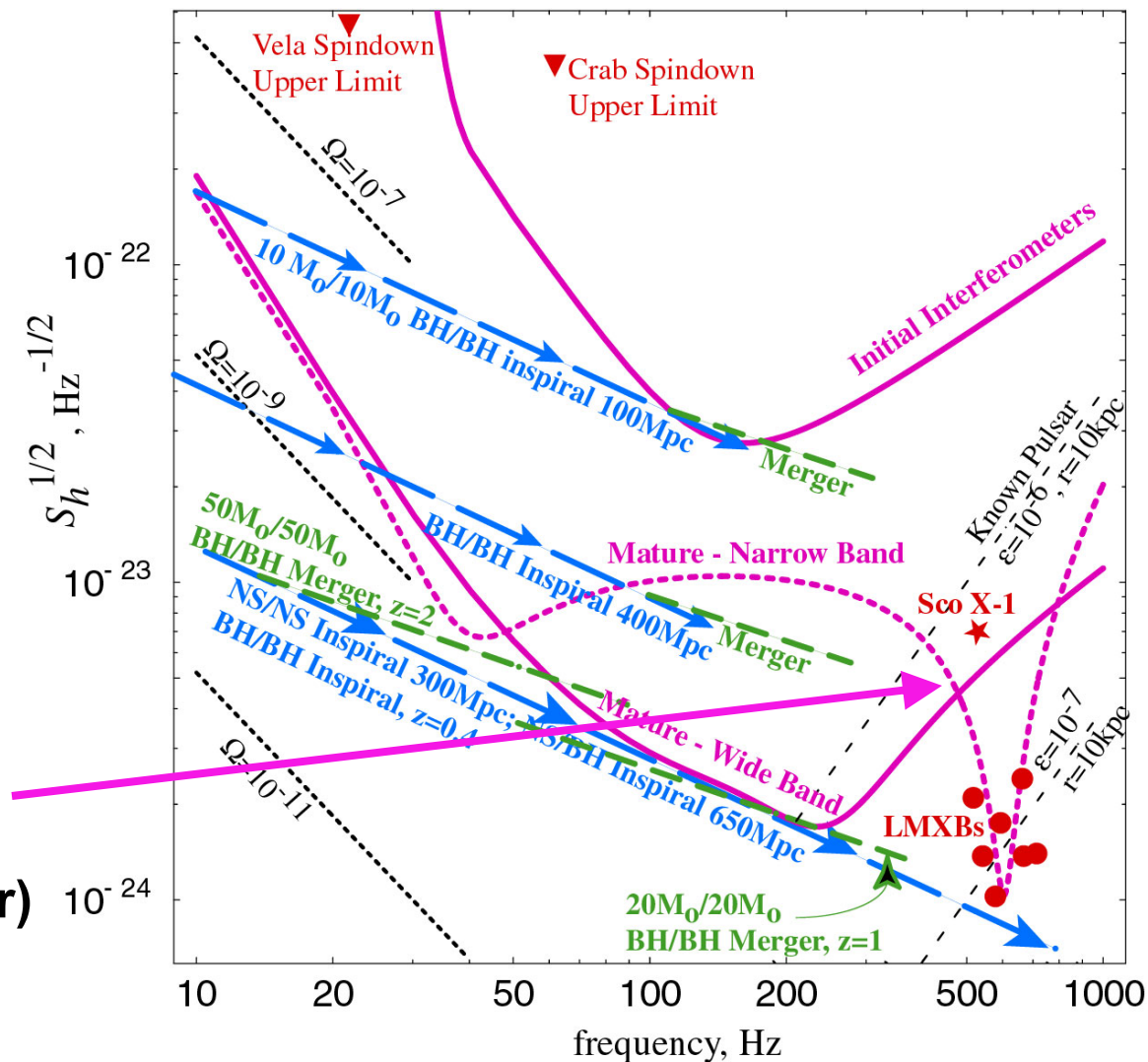


# Advanced LIGO

Sampling of source strengths vis a vis Initial LIGO and Advanced LIGO

Lower  $h_{\text{rms}}$  and wider bandwidth both important

“Signal recycling” offers potential for tuning shape of noise curve to improve sensitivity in target band (e.g., known pulsar cluster)



# Advanced LIGO

Increased laser power:

**10 W → 180 W**

Improved shot noise (high freq)

Higher-Q test mass:

**Fused silica with better optical coatings**

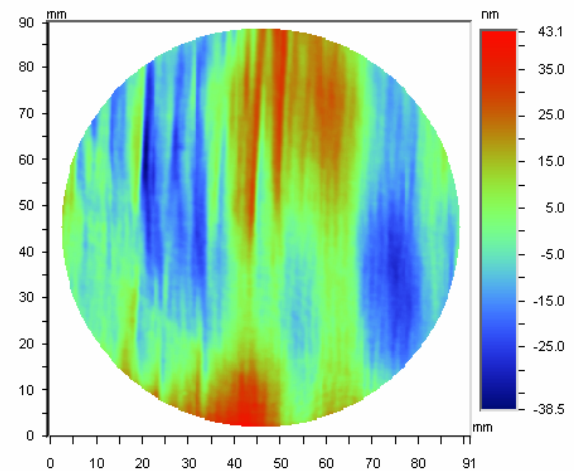
Lower internal thermal noise in bandwidth

Increased test mass:

**10 kg → 40 kg**

Compensates increased radiation pressure noise

## Sapphire Optics



Date: 10/25/2001  
Time: 13:59:18  
Wavelength: 1.064 um  
Pupil: 100.0 %  
PV: 81.6271 nm  
RMS: 13.2016 nm

X Center: 172.00  
Y Center: 145.00  
Radius: 163.00 pix  
Terms: None  
Filters: None  
Masks:

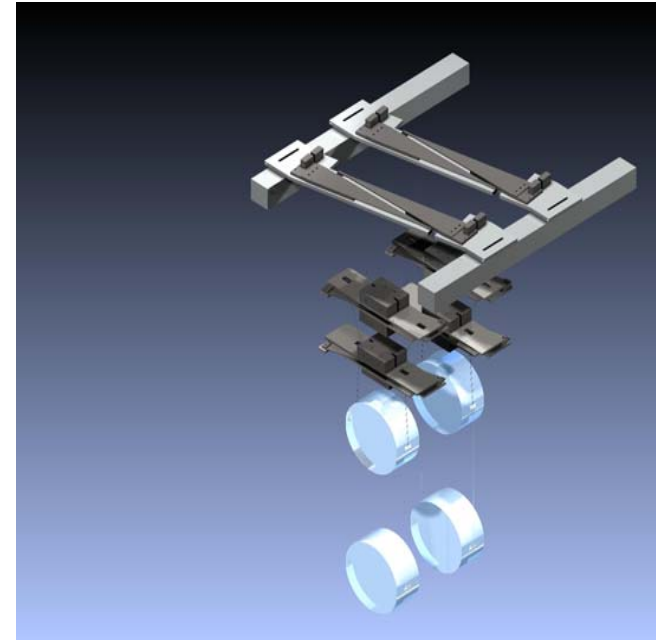
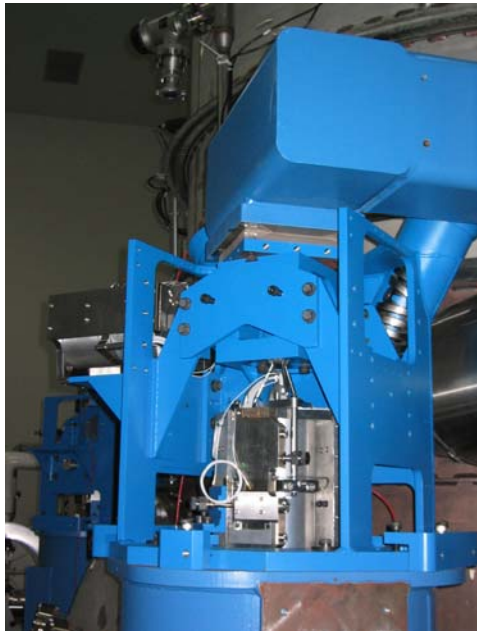
# Advanced LIGO

## Detector Improvements:

### New suspensions:

**Single → Quadruple pendulum**

**Lower suspensions thermal noise  
in bandwidth**



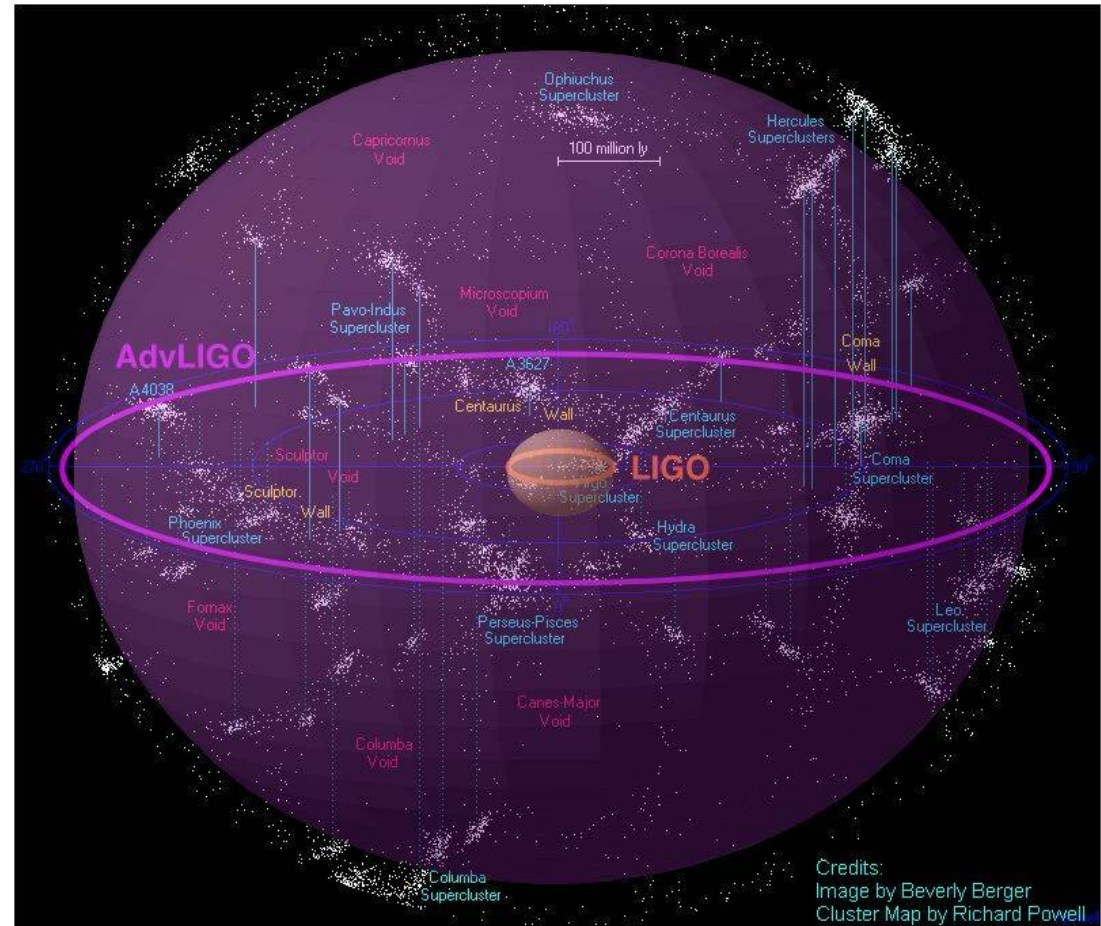
### Improved seismic isolation:

**Passive → Active**

**Lowers seismic “wall” to ~10 Hz**

# Advanced LIGO

**Neutron Star Binaries:**  
Horizon > 300 Mpc  
Most likely rate ~ 40/year !



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

# Conclusions

## Two-year data run recently completed

- Hope for discovery as we keep “opening boxes”
- Limits on radiation now constraining astrophysical processes

## Our Plan:

- Upgrade to “enhanced LIGO”
- Keep 2-km interferometer running in “AstroWatch” (supernova watch)  
→ Many thanks to Philip Roberts of Andrews for hands-on help!
- Take another ~1.5 years of data with ~2 times improvement  
(~8 times event rate!)  
→ Discovery is quite serious prospect
- Upgrade to Advanced LIGO  
→ Routine GW detection within 10 years

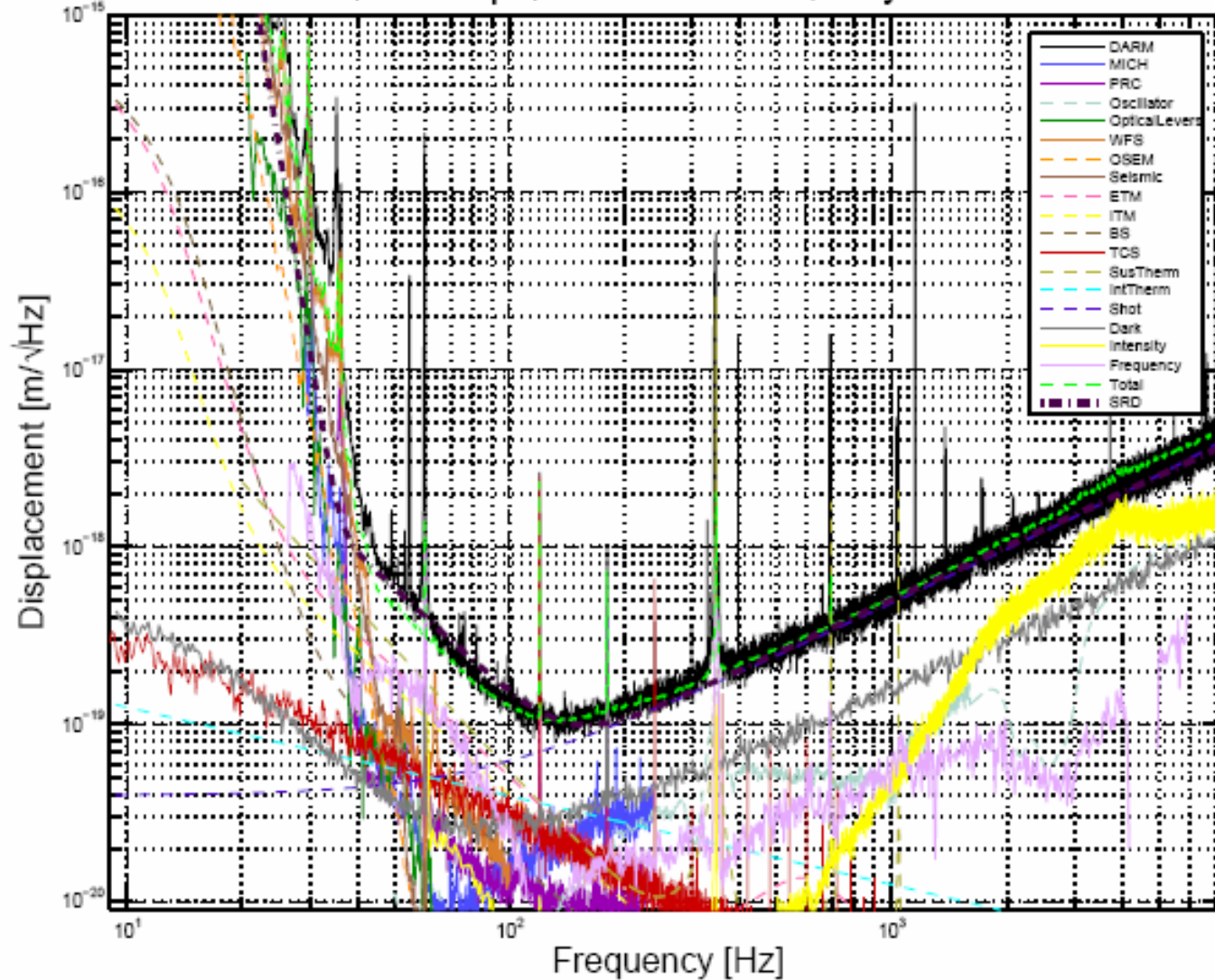


**THE END**



# Livingston noise budget

L1: UGF = 155 Hz, 14.5 Mpc, Predicted: 15.6, May 17 2007 05:27:40 UTC





# “Locking” the Inteferometer

Sensing gravitational waves requires sustained resonance in the Fabry-Perot arms and in the recycling cavity

- Need to maintain half-integer # of laser wavelengths between mirrors
- Feedback control servo uses error signals from imposed RF sidebands
- Four primary coupled degrees of freedom to control
- Highly non-linear system with 5-6 orders of magnitude in light intensity

Also need to control mirror rotation (“pitch” & “yaw”)

- Ten more DOF’s (but less coupled)

And need to stabilize laser (intensity & frequency), keep the beam pointed, damp out seismic noise, correct for tides, etc.,...

## Compact Binary Inspirals: Match filtering

- **Known waveform:**  $\Rightarrow$  use match filtering technique

$$z(t) = 4 \int_0^{\infty} \frac{\tilde{s}(f) \tilde{h}^*(f)}{S_n(f)} e^{2\pi i f t} df$$

Diagram illustrating the match filtering technique. The equation shows the matched filter output  $z(t)$  as a function of time  $t$ . The integrand consists of the Fourier transform of the data  $\tilde{s}(f)$  (labeled "Data"), the complex conjugate of the Fourier transform of the template  $\tilde{h}^*(f)$  (labeled "Template"), and the inverse of the noise power spectral density  $S_n(f)$  (labeled "Noise power spectral density").

- Calculated templates for inspiral phase (“chirp”)

Waveform parameters:

distance, orientation, position,

$\mathbf{m}_1, \mathbf{m}_2, t_0, \phi$  (+ spin, ending cycles ...)

- **Different template families used for different searches**

Example: S3-S4 searches

- **Binary Neutron Stars:** “physical templates” (2<sup>nd</sup> order restricted post-Newtonian, stationary-phase approximations)
- **Binary Black Holes:** “phenomenological templates” (BCV)

