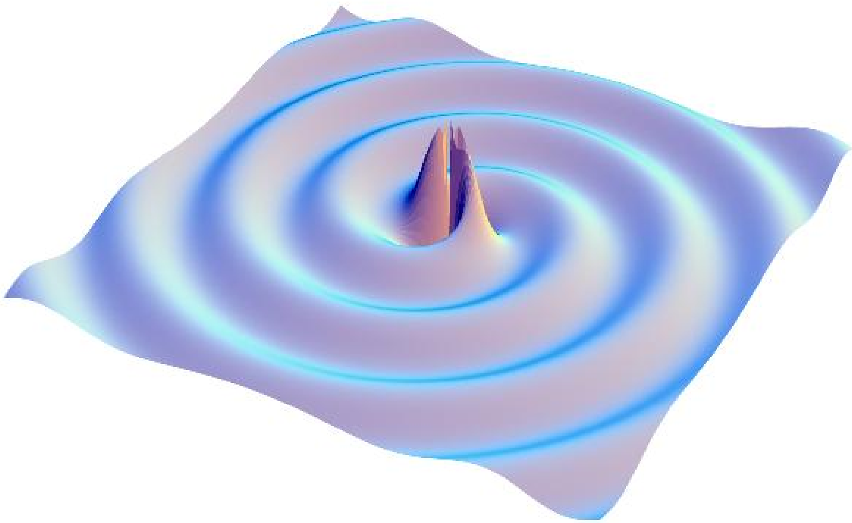
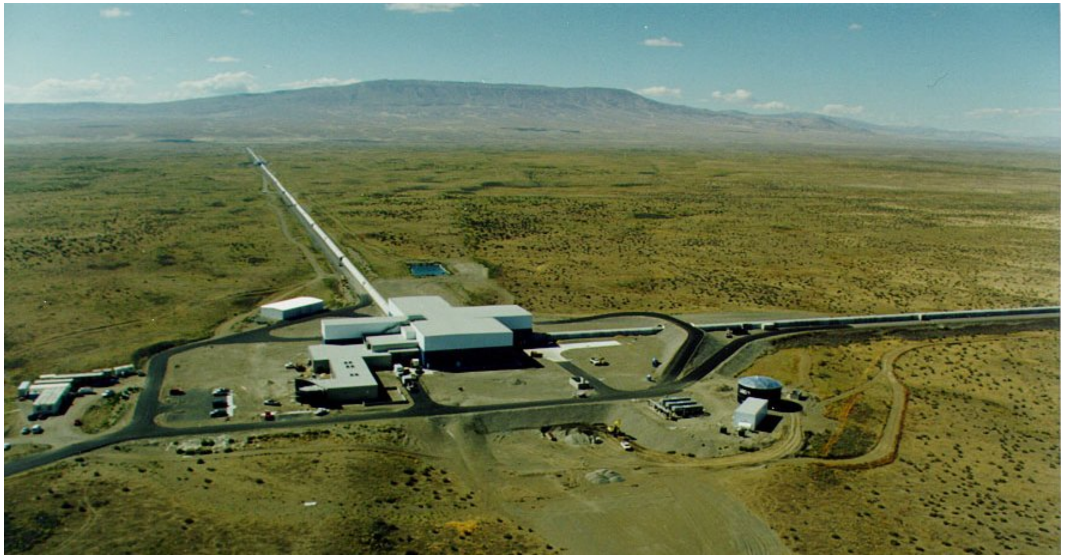
The Hunt for Gravitational Waves
Latest Results from LIGO



Keith Riles
University of Michigan



Physics Colloquium

Oakland University

November 15, 2007

LIGO-G070793

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”

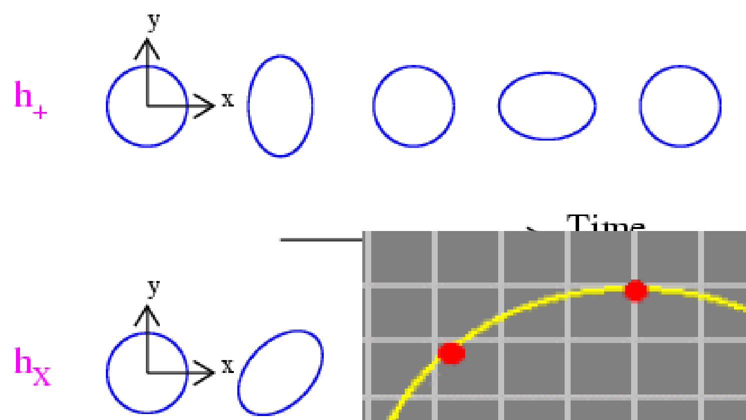
- Perturbation propagation similar to light (obeys same wave equation!)
    - **Propagation speed = c**
    - **Two transverse polarizations - <u>quadrupolar</u>**: + and x

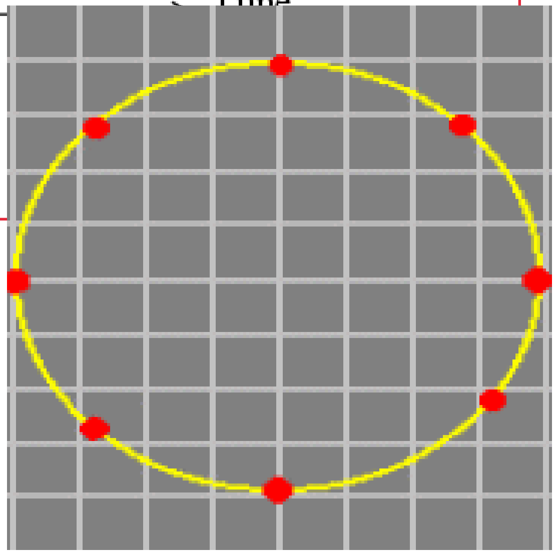
Example:

Ring of test masses

responding to wave

propagating along z





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

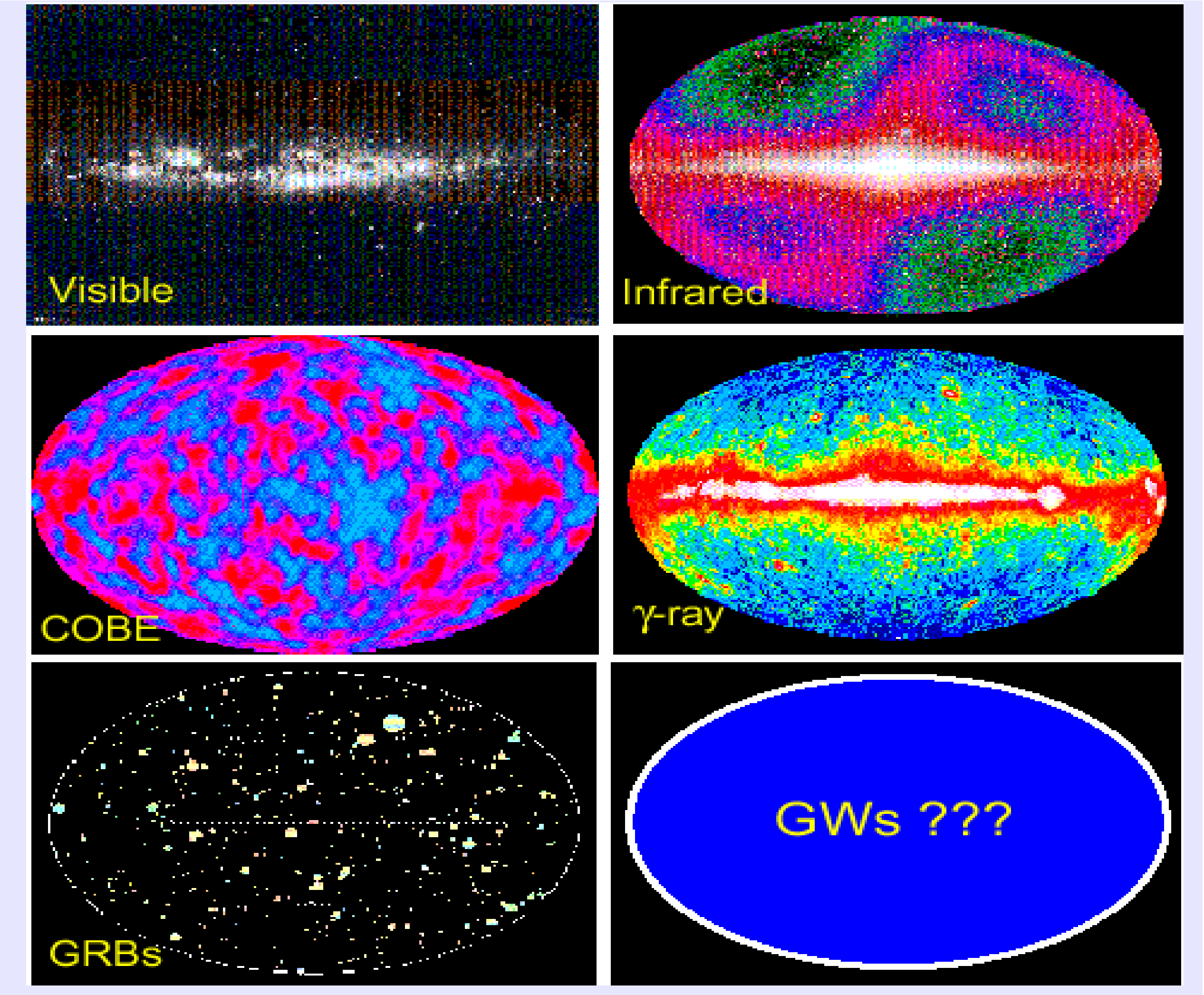
Why look for Gravitational Radiation?

- 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
  - **<u>Opens up entirely new non-electromagnetic spectrum</u>**

What will the sky look like?



Generation of Gravitational Waves

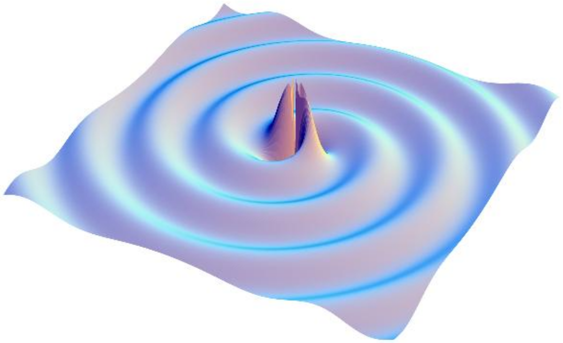
- Radiation generated by quadrupolar mass movements:

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

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

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

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



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?

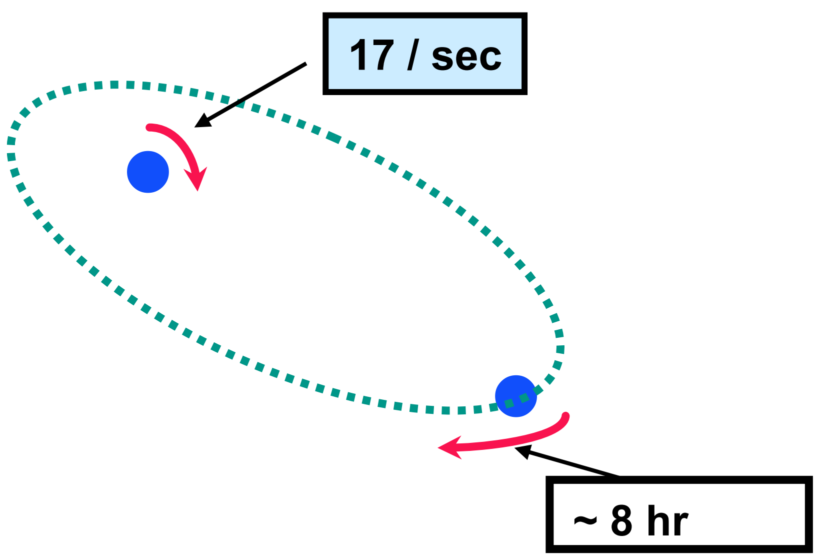
Generation of Gravitational Waves

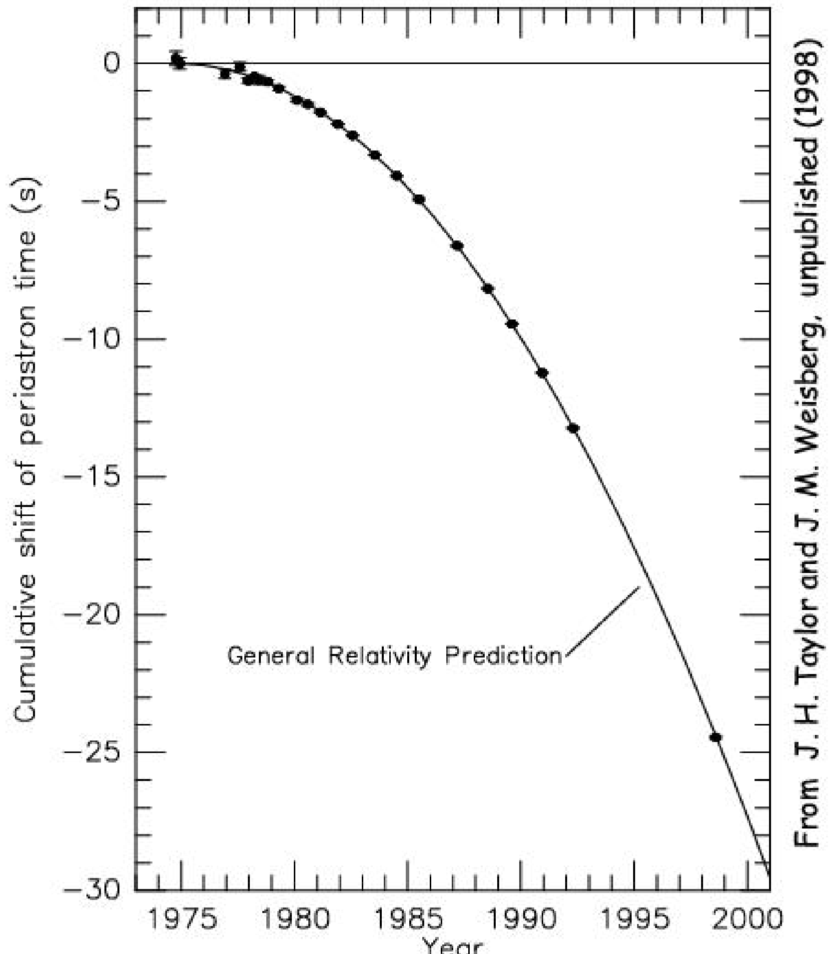
- Strong <u>indirect</u> evidence for GW generation:

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



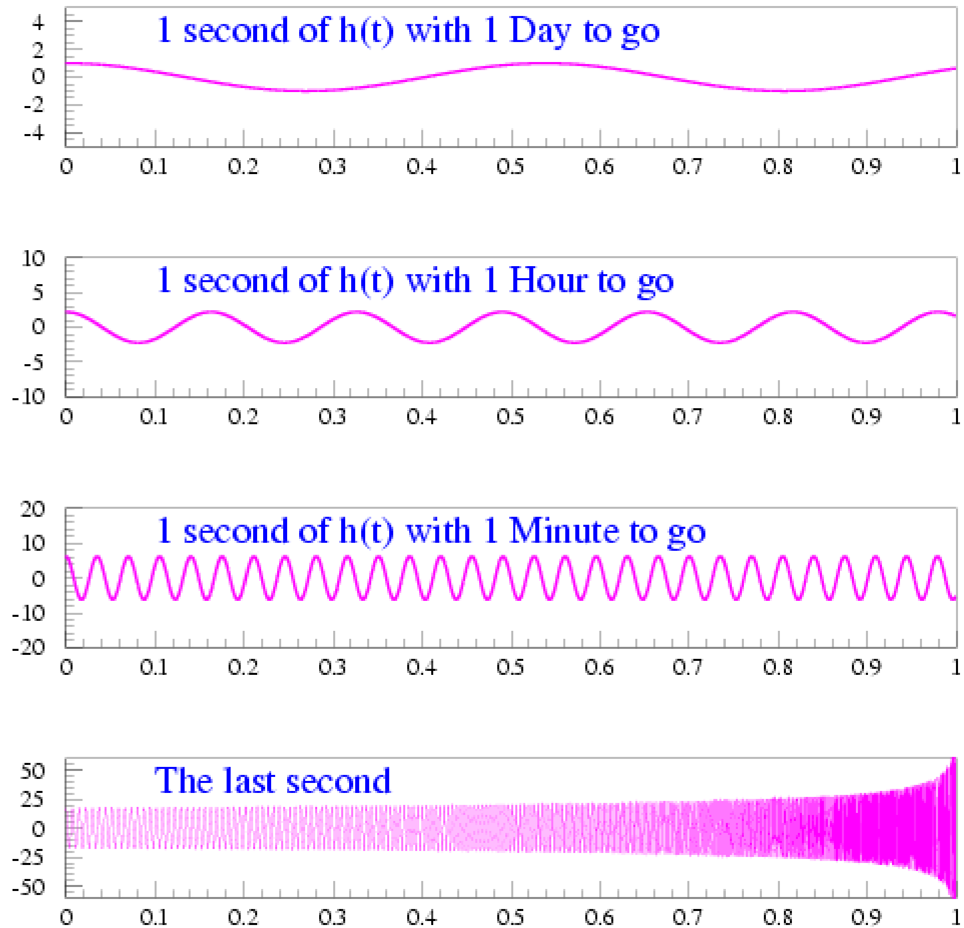


Generation of Gravitational Waves

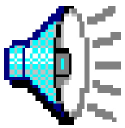
Can we detect this radiation directly?

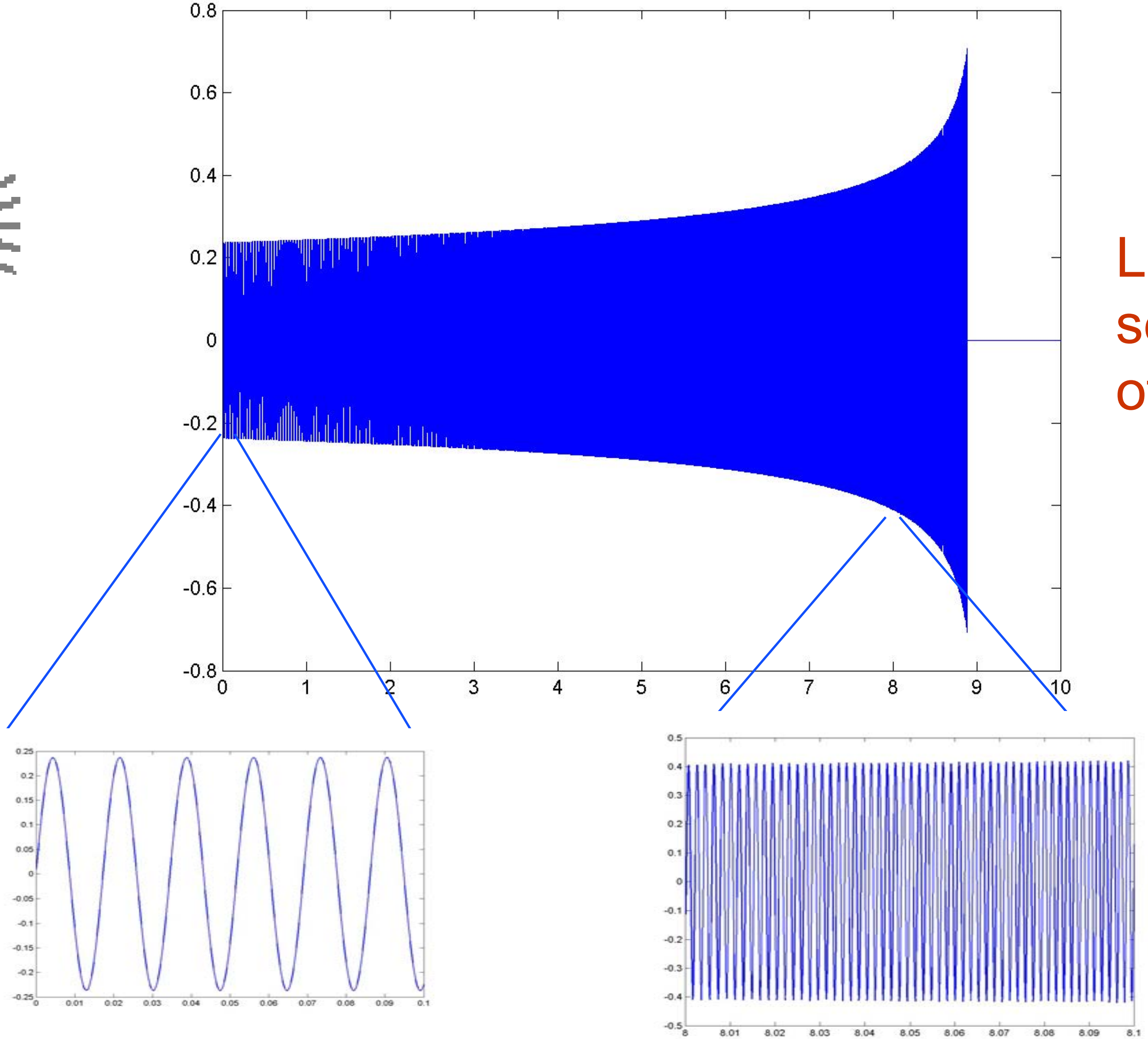
NO - freq too low

Must wait ~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

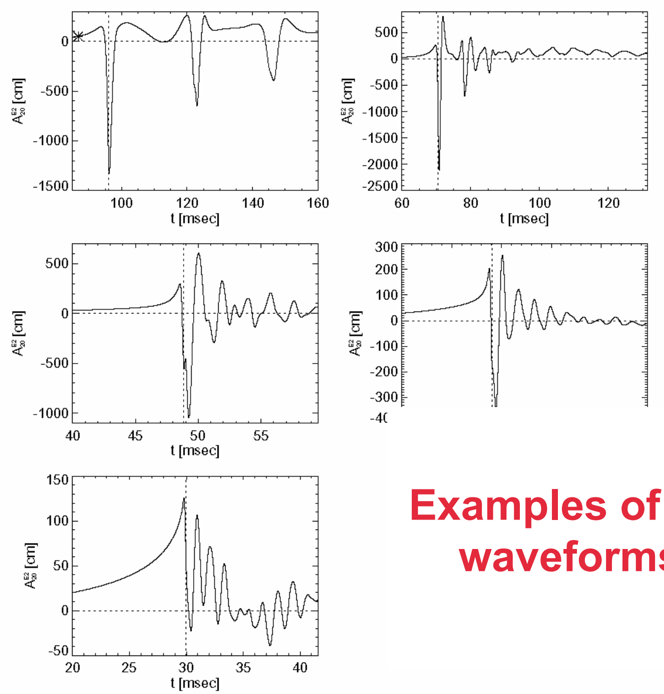
→ Large uncertainties!

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

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

→ Will need Advanced LIGO to <u>ensure</u> detection

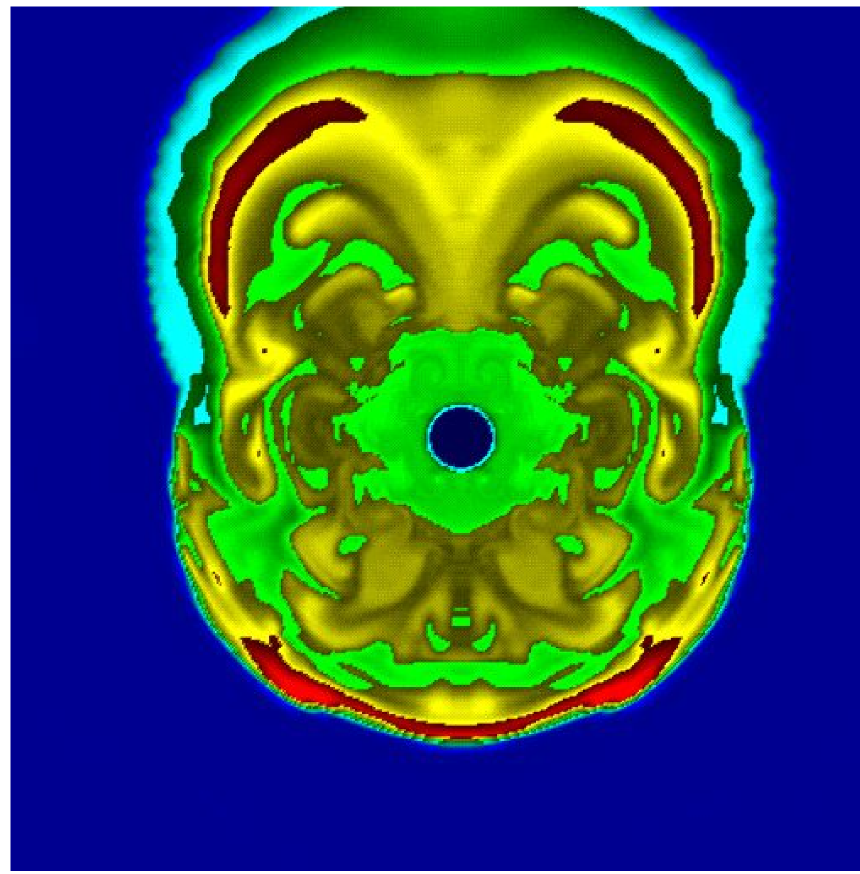
Generation of Gravitational Waves



Examples of SN waveforms

Super-novae

(requires asymmetry in explosions)



Tony Mezzacappa -- Oak Ridge National Laboratory

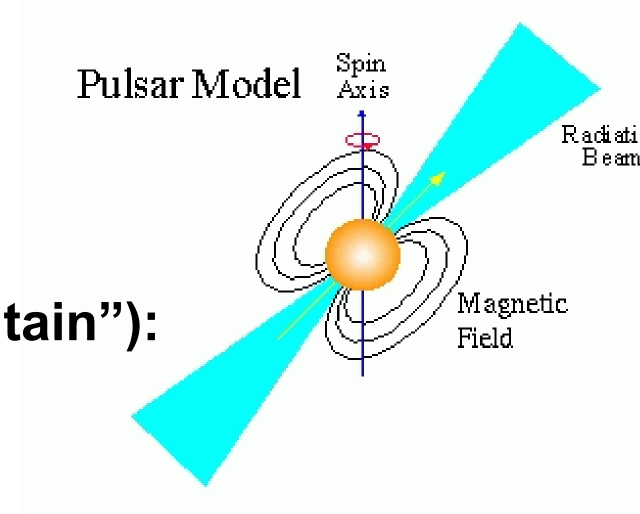
May not know exactly what to look for – must be open-minded with diverse algorithms

Generation of Gravitational Waves

Most promising periodic source: <u>Rotating Neutron Stars</u> (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"):

$$h \;\alpha\; \varepsilon_{equat}$$

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

$$h \;\alpha\; \varepsilon_{pol} \times \Theta_{wobble}$$

(precession due to different L and Ω 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 ε unknown
  - A nearby source could be buried in the data, waiting for just the right algorithm to tease it into view

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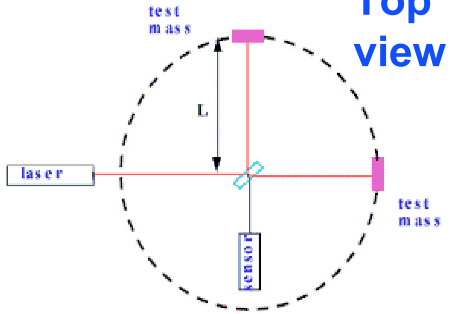
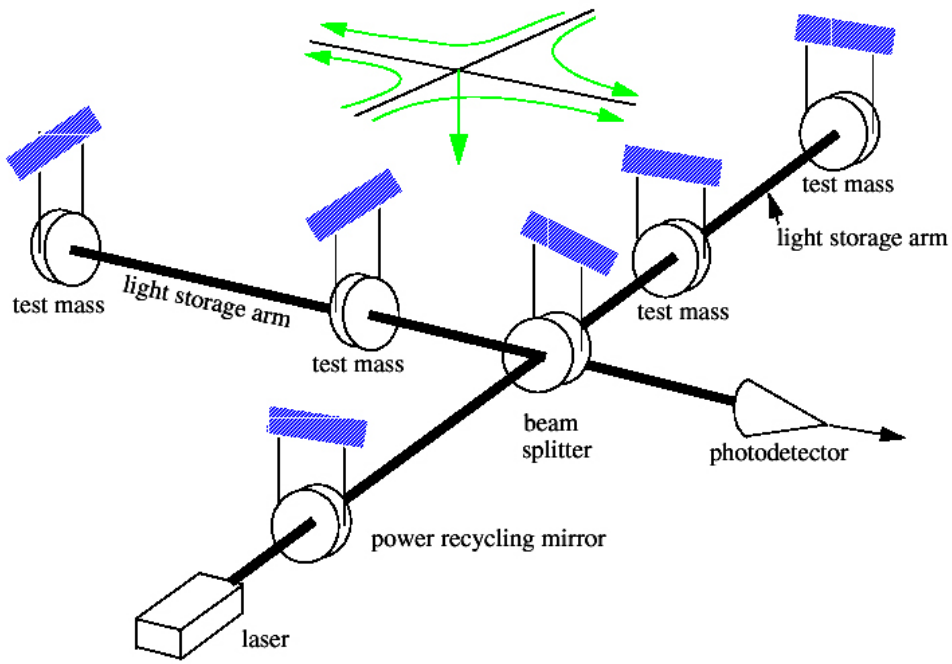
Gravitational Wave Detection

- ❑ 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)

Top view





Gravitational Wave Detection

Major Interferometers world-wide

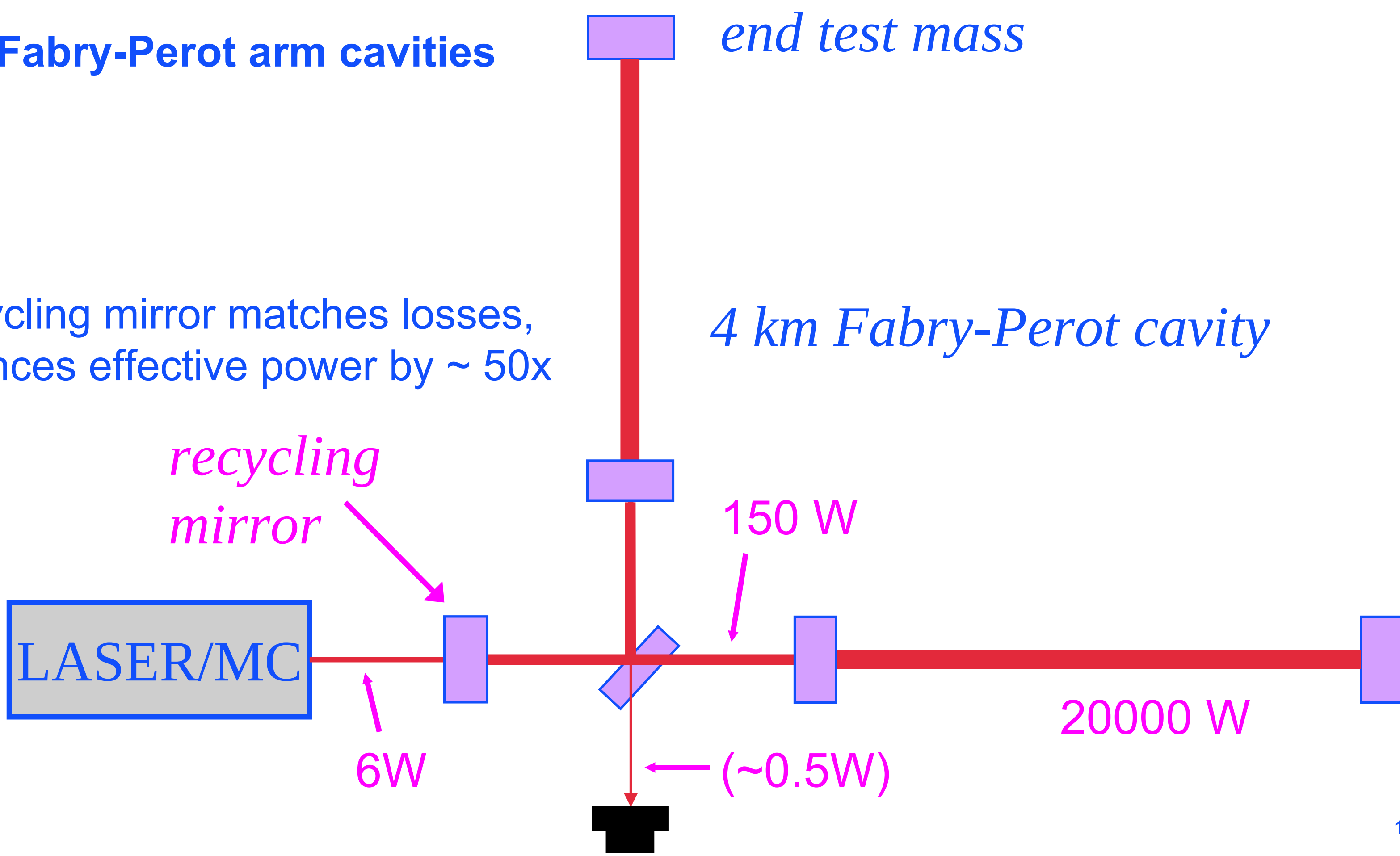
LIGO (NSF-$300M) Livingston, Louisiana & Hanford, Washington	2 x 4000-m 1 x 2000-m	Completed 2-year data run at design sensitivity – “enhancement” begun
VIRGO Near Pisa, Italy	1 x 3000-m	Took ~4 months coincident data with LIGO – approaching design sensitivity
GEO Near Hannover, Germany	1 x 600-m	Resuming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

LIGO Interferometer Optical Scheme

Michelson interferometer

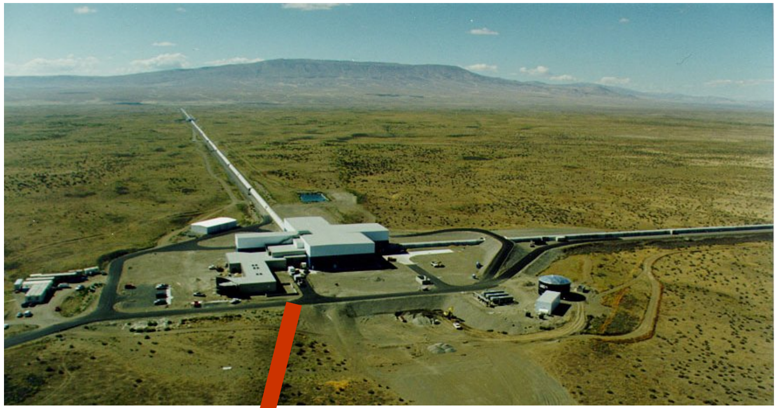
With Fabry-Perot arm cavities

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

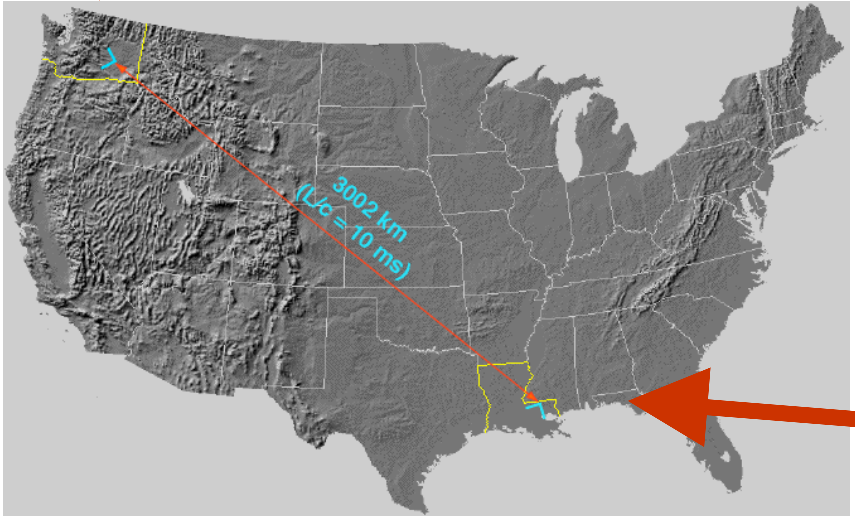


LIGO Observatories

Hanford

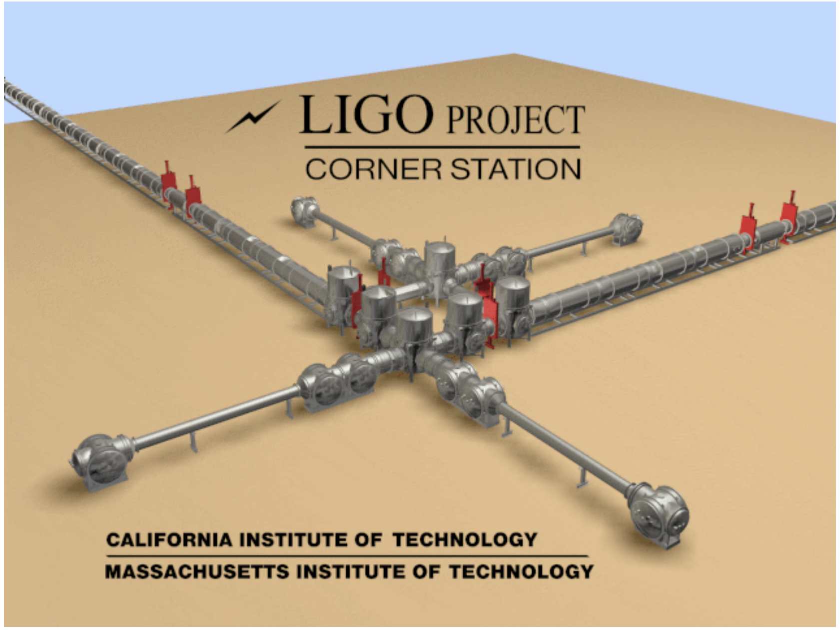


Observation of nearly simultaneous signals 3000 km apart rules out terrestrial artifacts



Livingston

LIGO Detector Facilities



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

Vacuum System

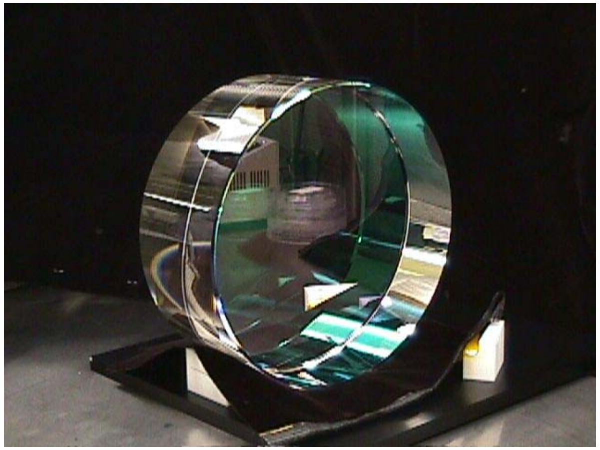
LIGO Detector Facilities

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

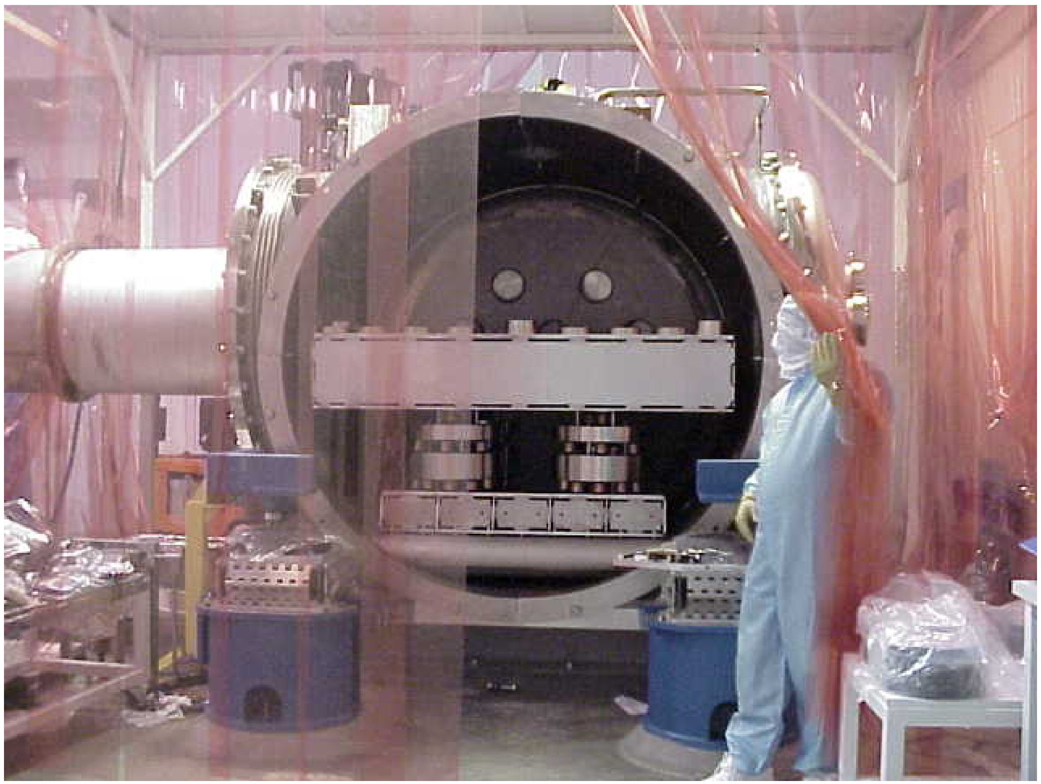
- Fused silica (high-Q, low-absorption, 1 nm surface rms, 25-cm diameter)
- Suspended by single steel wire
- Actuation of alignment / position via magnets & coils

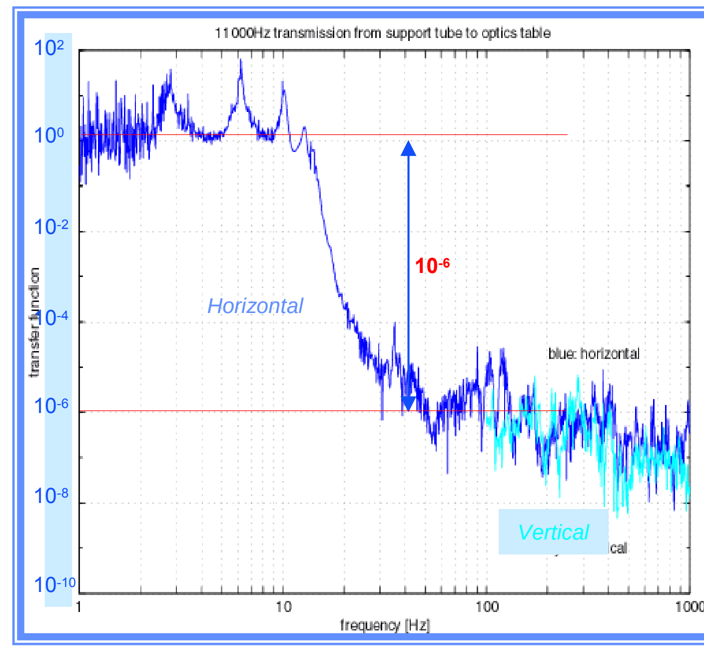


LIGO Detector Facilities

Seismic Isolation

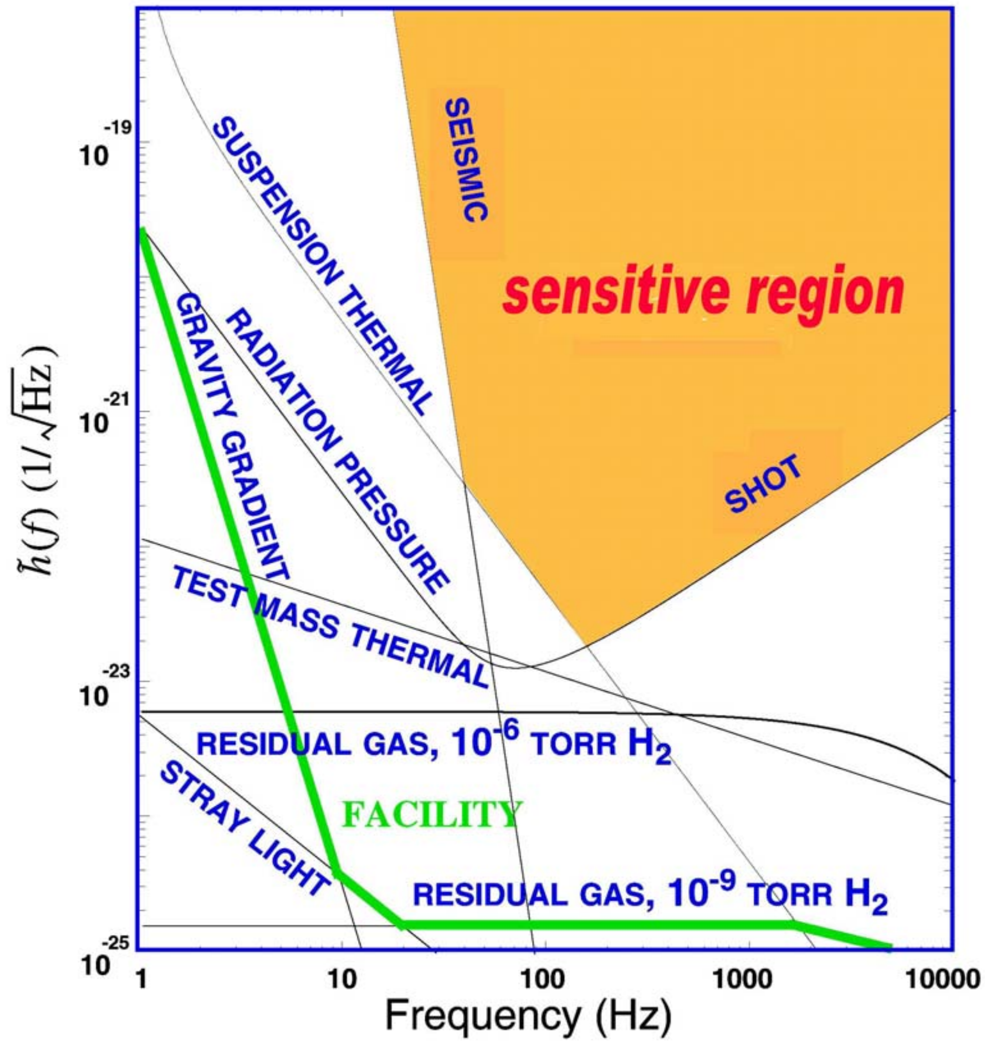
- Multi-stage (mass & springs) optical table support gives 10^6 suppression
- Pendulum suspension gives additional $1 / f^2$ suppression above ~1 Hz





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

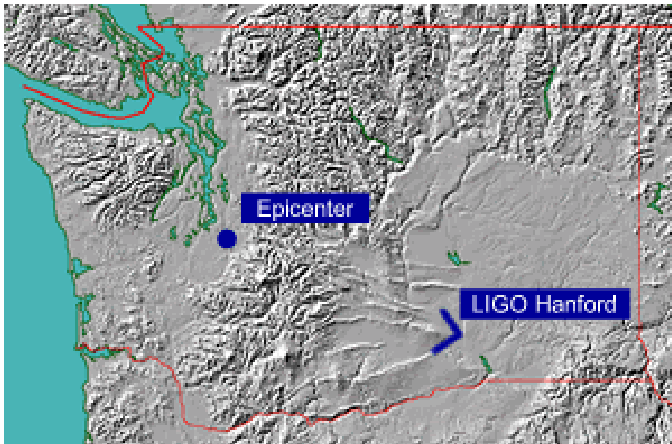


achieved

Best ~~design~~ sensitivity:

~ 3 x 10^{-23} $Hz^{-1/2}$ @ 150 Hz

The road to design sensitivity at Hanford…



Harder road at Livingston…

Livingston Observatory located in pine forest popular with pulp wood cutters

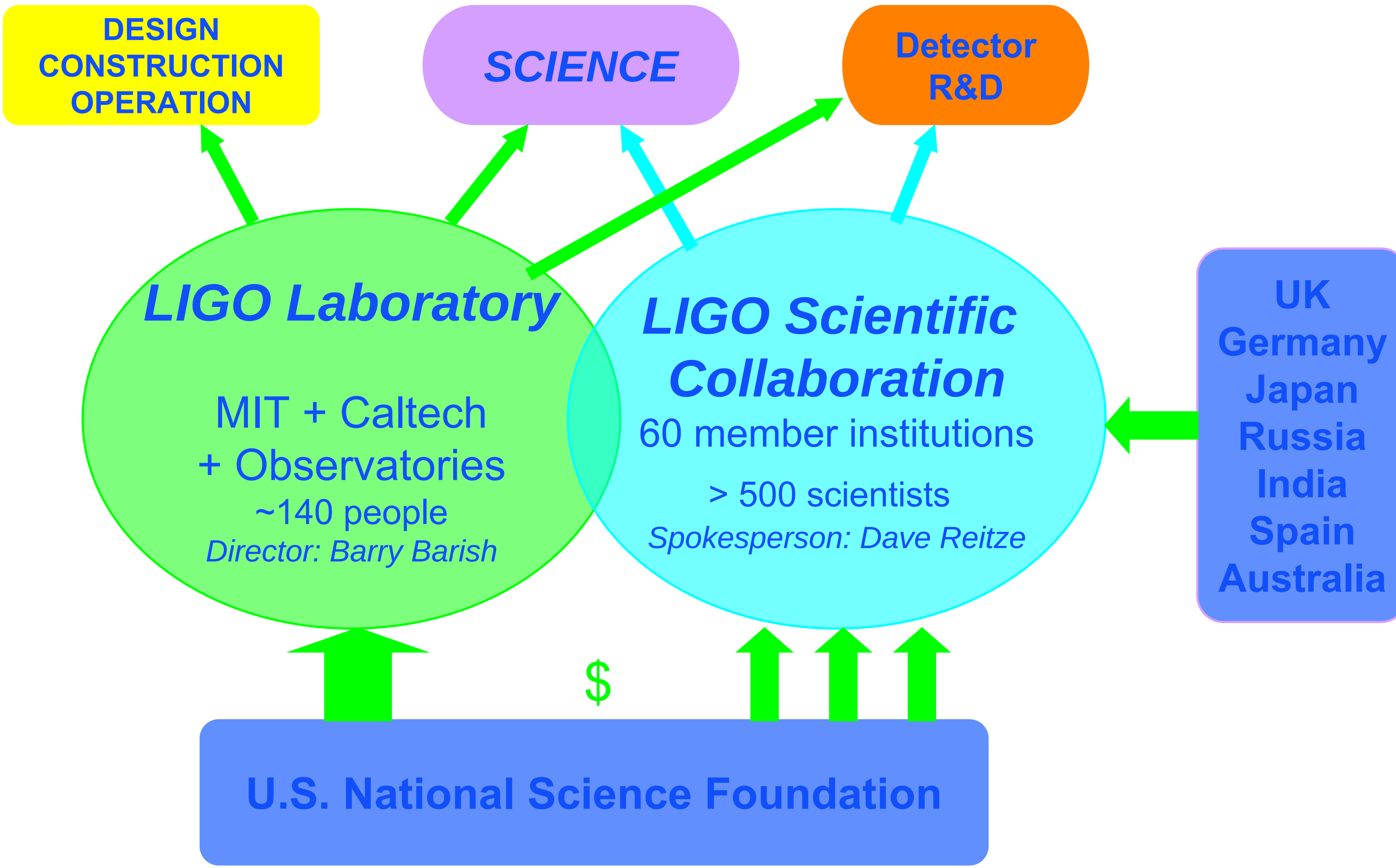
Spiky noise (e.g. falling trees) in 1-3 Hz band creates dynamic range problem for arm cavity control

→ **40% livetime**

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

→ Fixed in 2004

LIGO Organization & Support



LIGO Scientific Collaboration

- Australian Consortium for Interferometric Gravitational Astronom
- The Univ. of Adelaide
- Andrews University
- The Australian National Univ.
- 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 Gravit

- 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 Washingto

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)

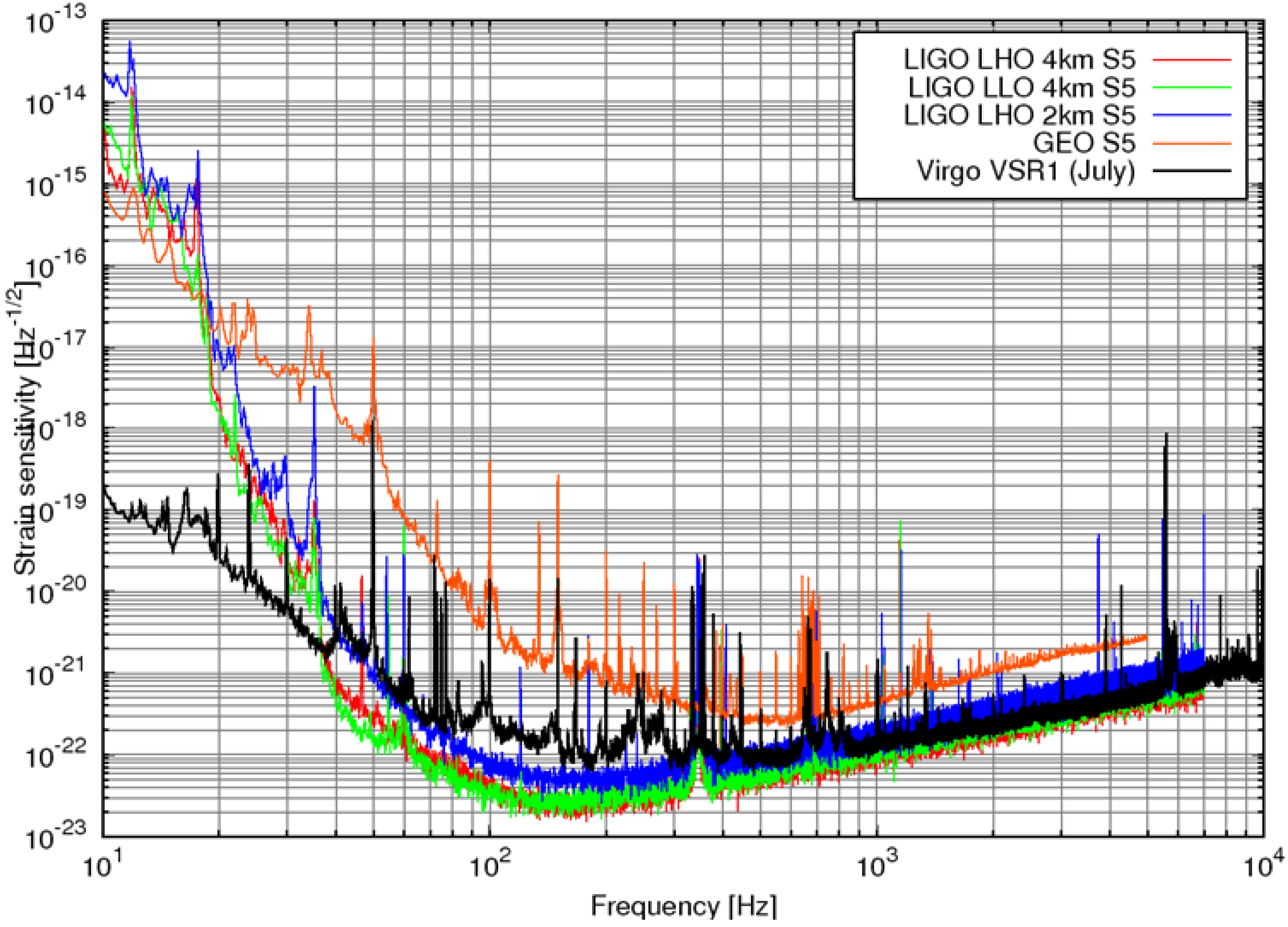
Took data in coincidence for last ~4 months of latest science run

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



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Data Runs

Have carried out a series of Engineering Runs (E1–E12) and <u>Science Runs</u> (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

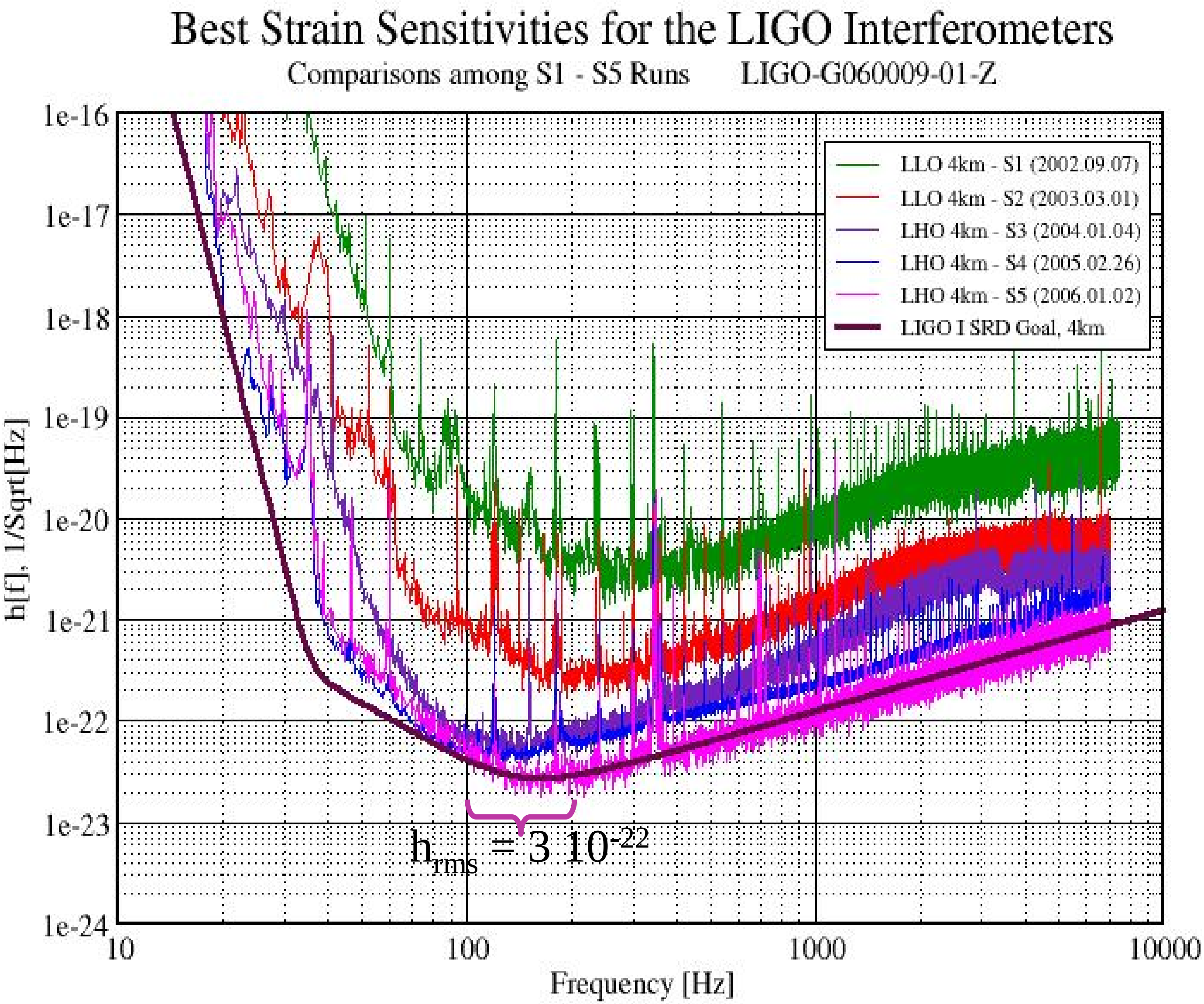
S4 run:

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

S5 run:

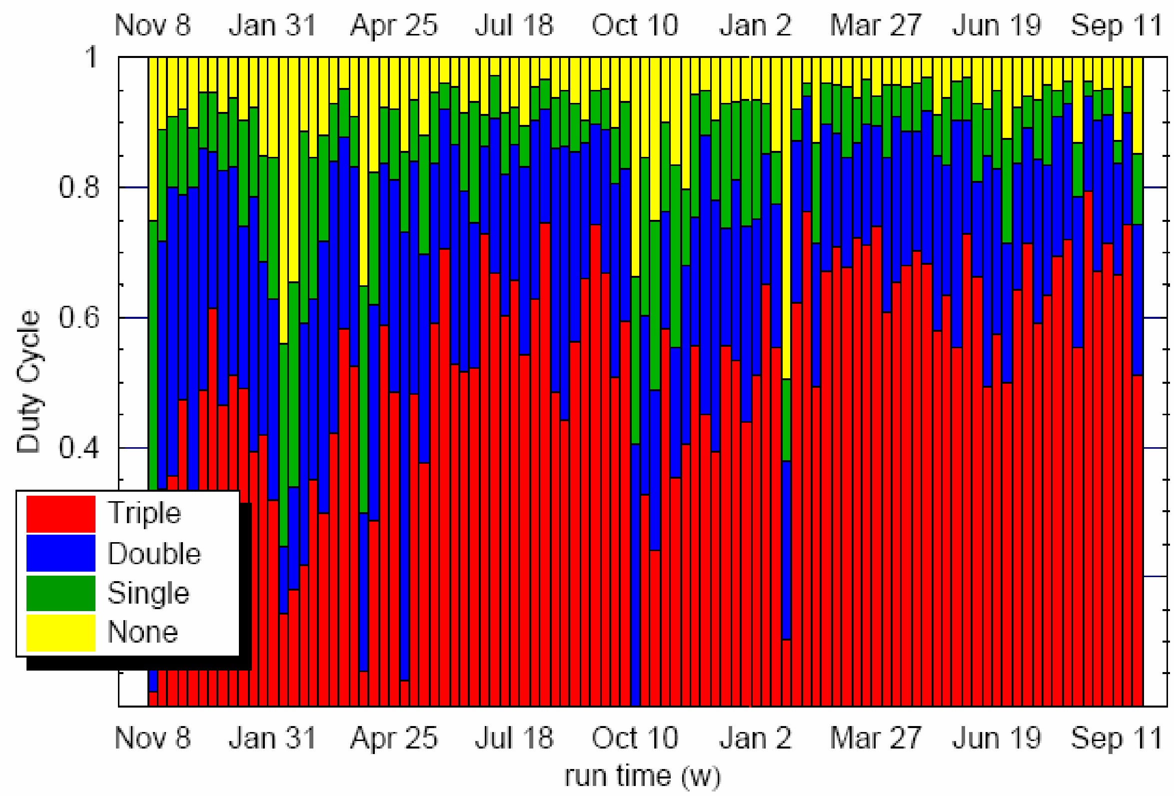
23 months (Nov 2005 – Sept 2007) – Great!

S1 → S5 Sensitivities



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:

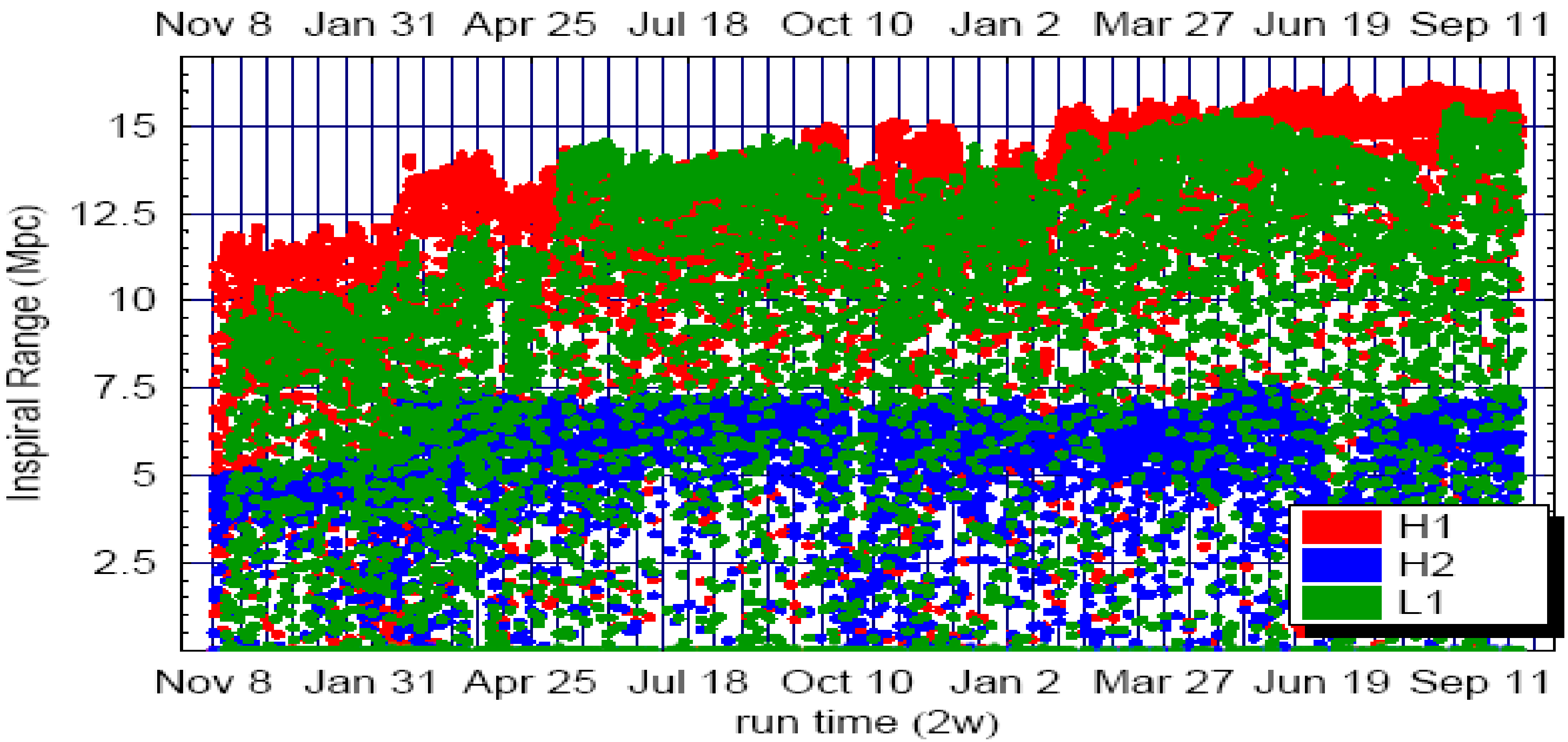
- 52.8 % in triple coincidence
- 57.0 % in H1L1 coincidence
- Total for H1: 77.7 %
- Total for H2: 78.2 %
- Total for L1: 65.7 %

- H1H2L1V1: 11.3 %

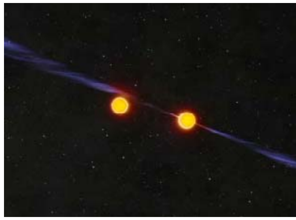
Range (=averaged horizon) during S5

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 snr = 8)



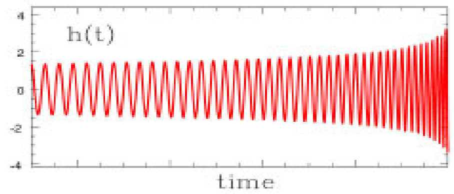
Search for binary systems



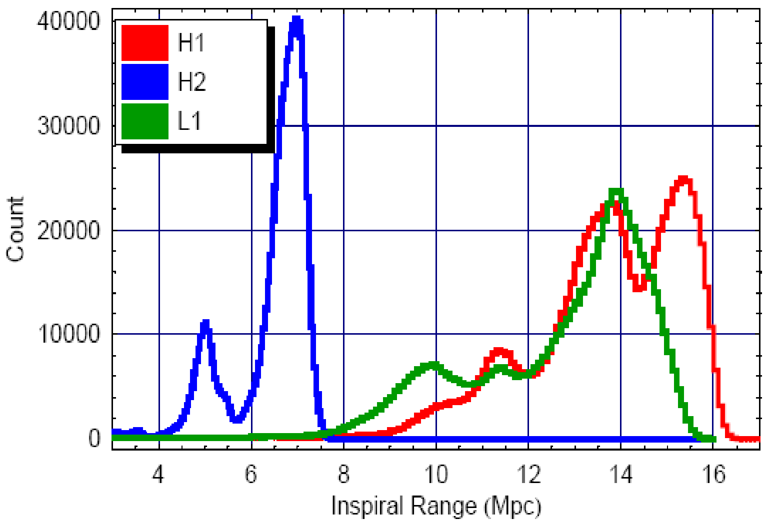
Use calculated templates for inspiral phase ("chirp") with optimal filtering.

Search for systems with different masses:

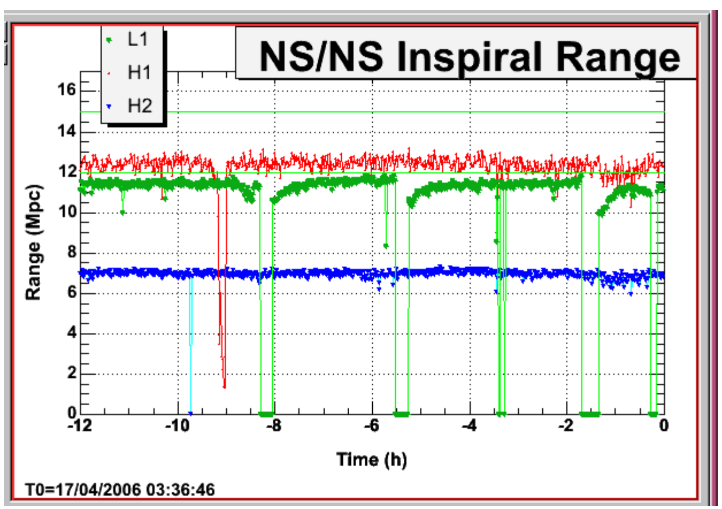
- **Binary neutron stars (~1-3 solar masses): ~15 sec templates, 1400 Hz end freq**
- **Binary black holes (< ~30 solar masses): shorter templates, lower end freq**
- **Primordial black holes (<1 solar mass): longer templates, higher end freq**



S5 range histograms:



"Typical" 12-hour history:



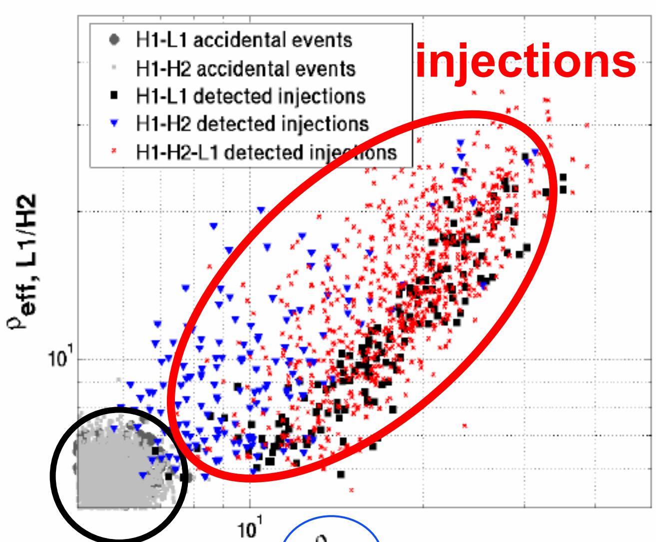
If system is optimally located and oriented, we can see even further: we are surveying <u>hundreds of galaxies</u>!

Estimate the false alarm probability

$\Rightarrow$ **compare candidate to expected background**

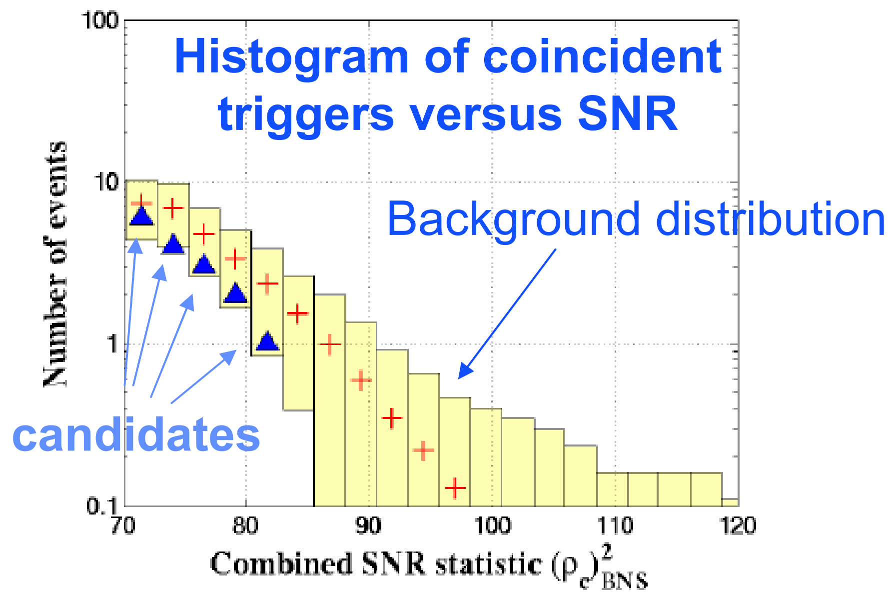
→ **background estimated by applying time-slides before coincidence**

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



background

Effective signal to noise ratio



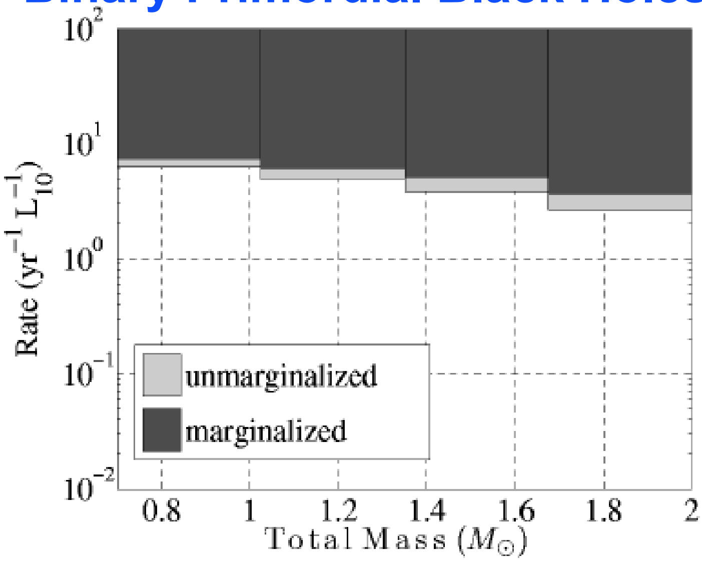
If candidates consistent with background $\Rightarrow$ no detection

Else ?

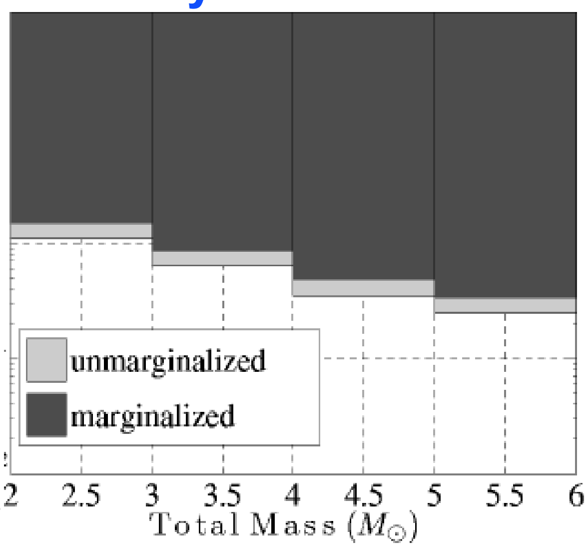
Compact Binary Inspirals

- **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

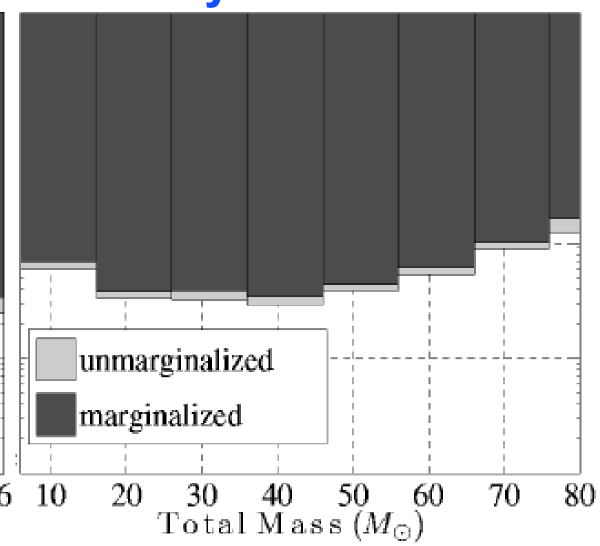
Binary Primordial Black Holes



Binary Neutron Stars



Binary Black Holes



- 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

Compact Binary Inspirals: S5 prospects

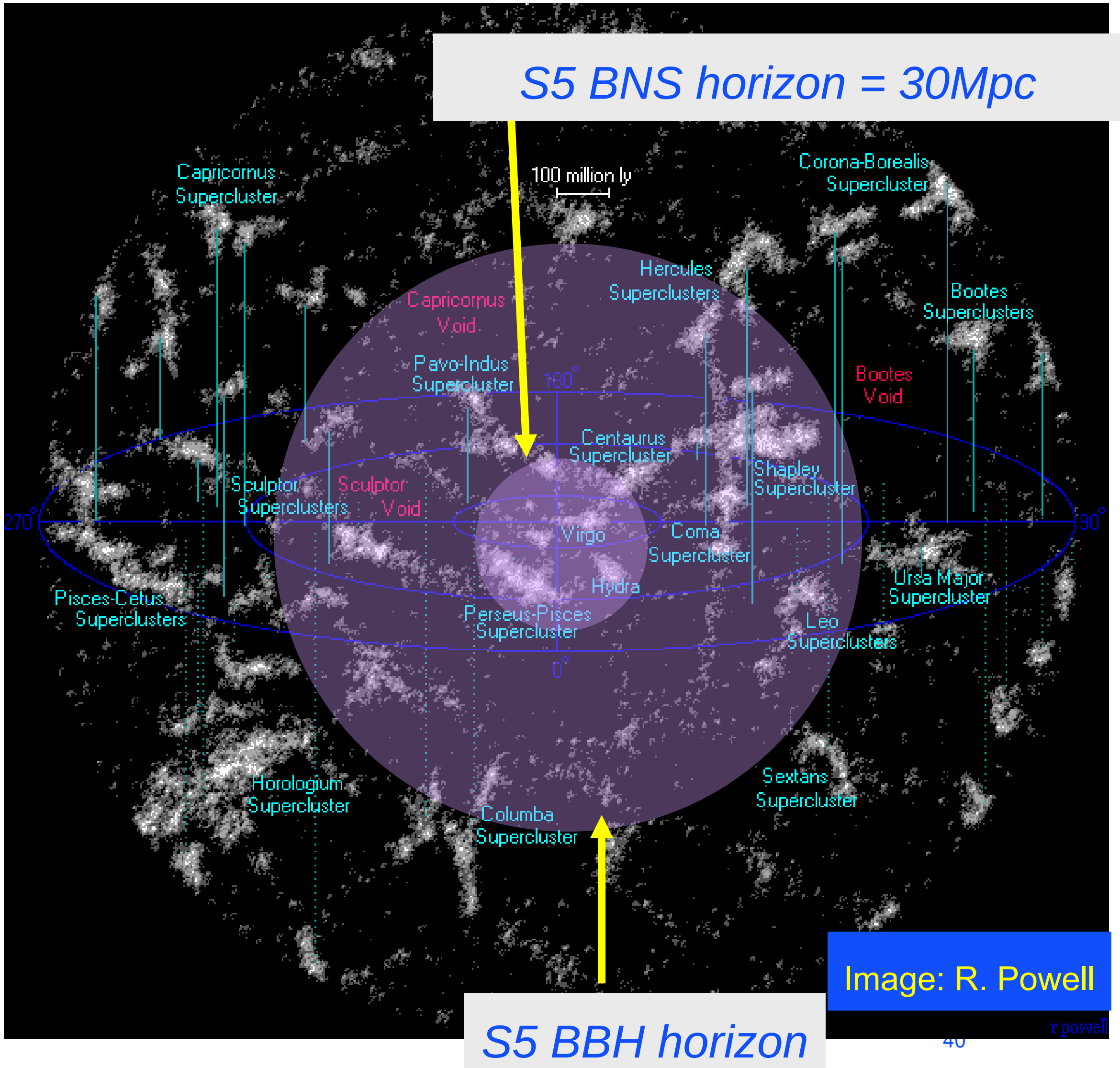
Horizon (optimal) = distance at which an optimally oriented and located binary system can be seen with signal-to-noise ratio $\rho=8$

Expected rate for Binary Neutron Star:

~ 1/100 yrs

⇒ Detection unlikely ☹

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

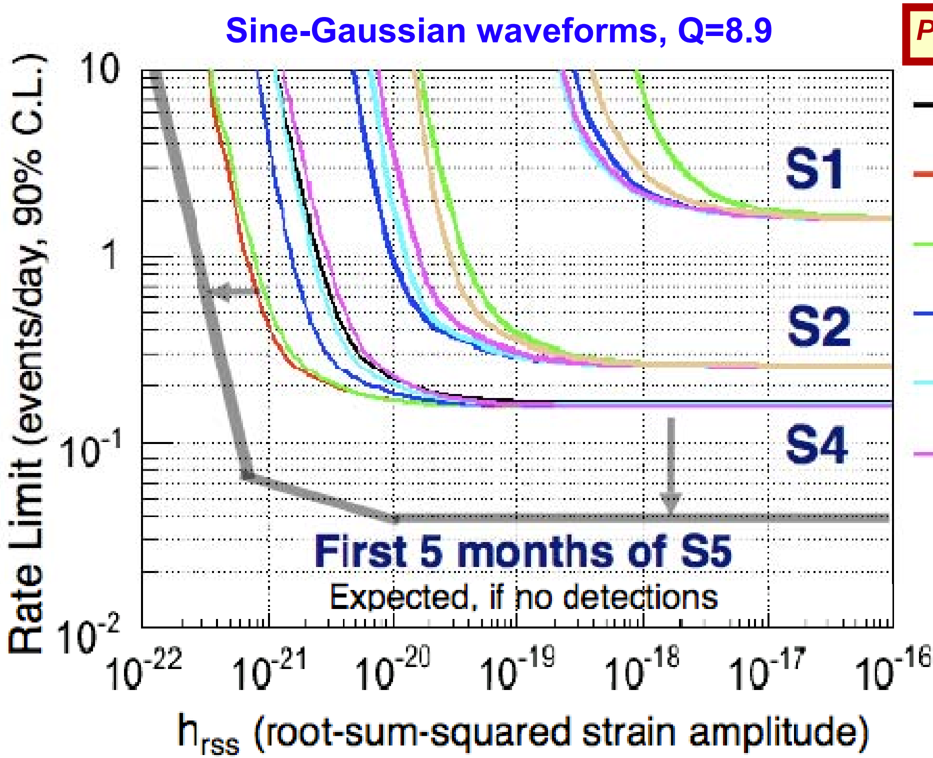


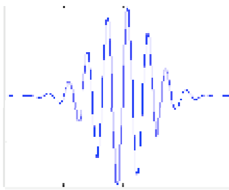
All-Sky Burst Search from S1 to S5

- Tuned for 64–1600 Hz, duration «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)



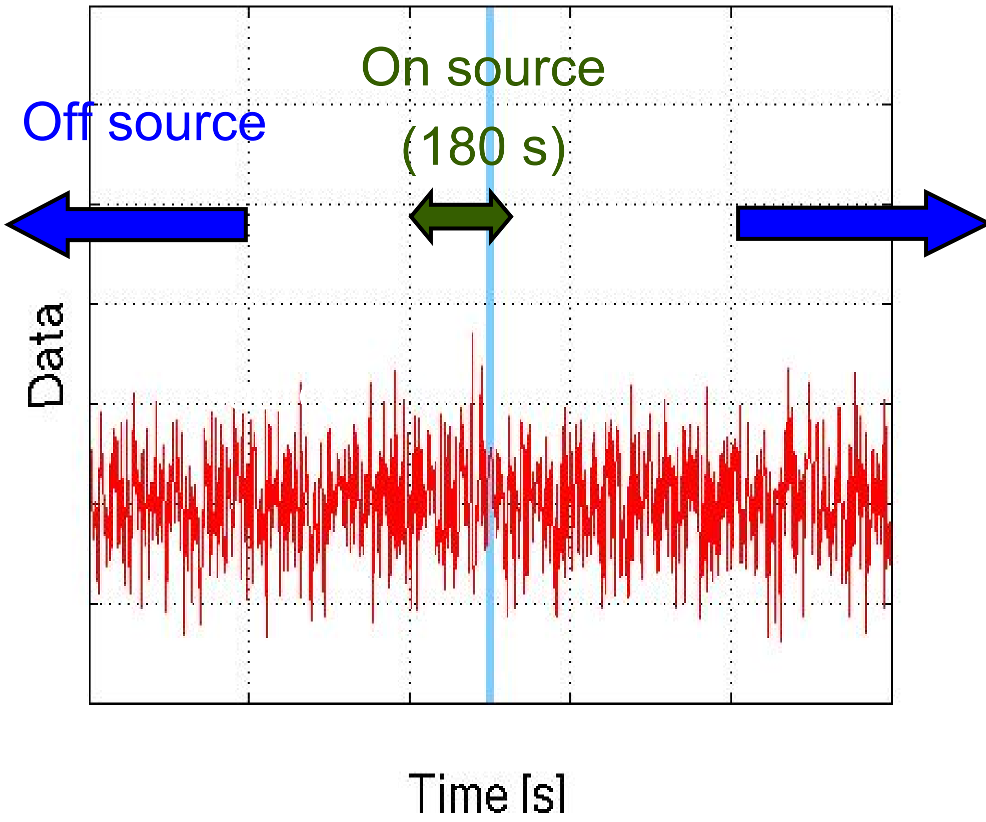


$$h_{\rm rss} \equiv \sqrt{\int \left(|h_+(t)|^2 + |h_\times(t)|^2\right) dt}$$

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

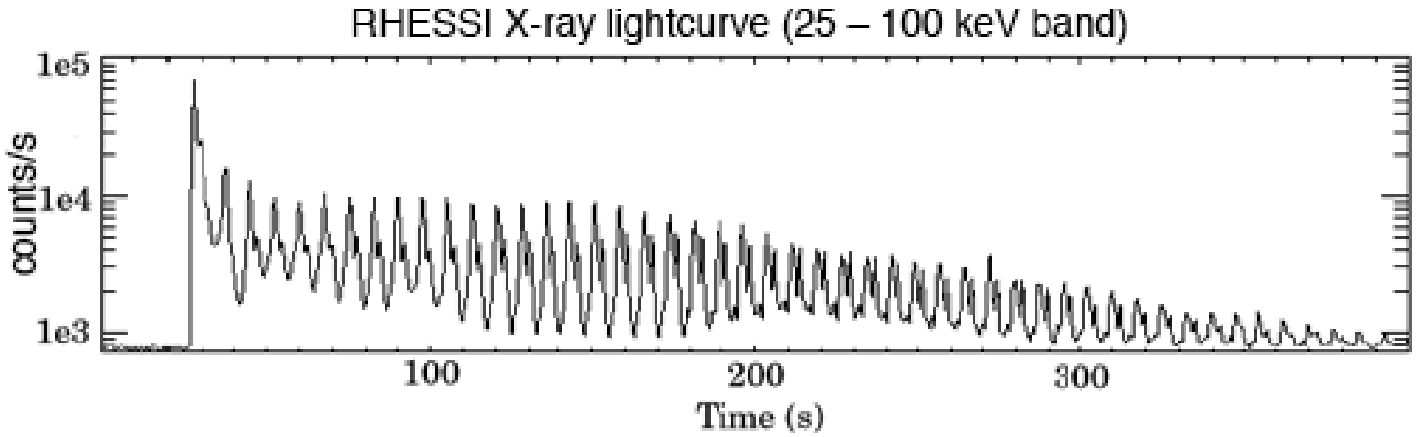
Triggered burst searches

- 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 RHESSE, 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 **$E_{GW} \sim 10^{-7}$ to 10^{-8} M_{SUN} at 5-10 kpc**

(this is comparable to electro-magnetic energy in flare)

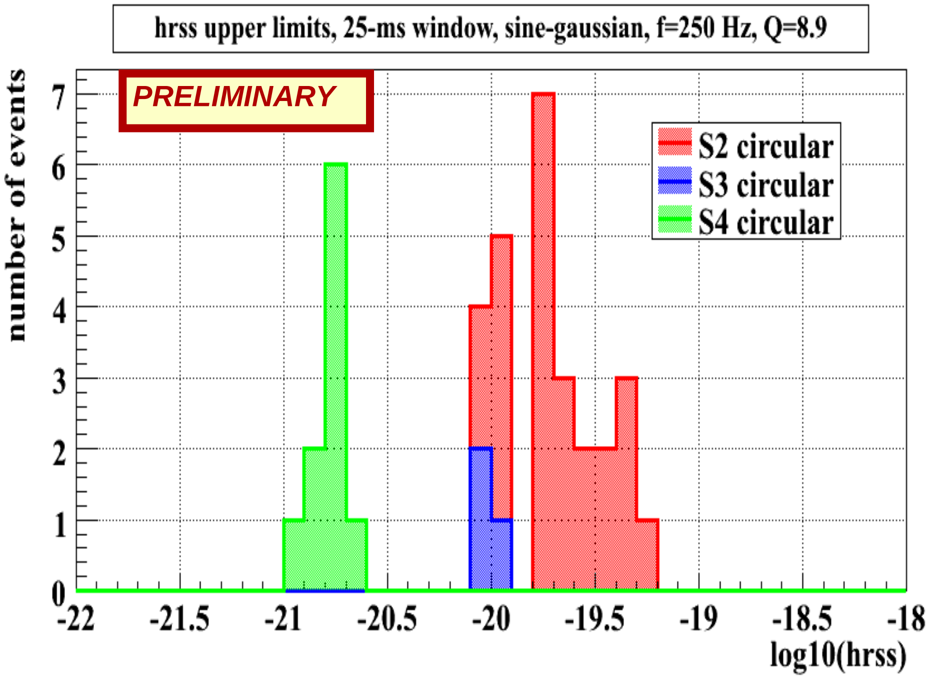
GRB Search Results

- 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: ~1 ms to ~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)

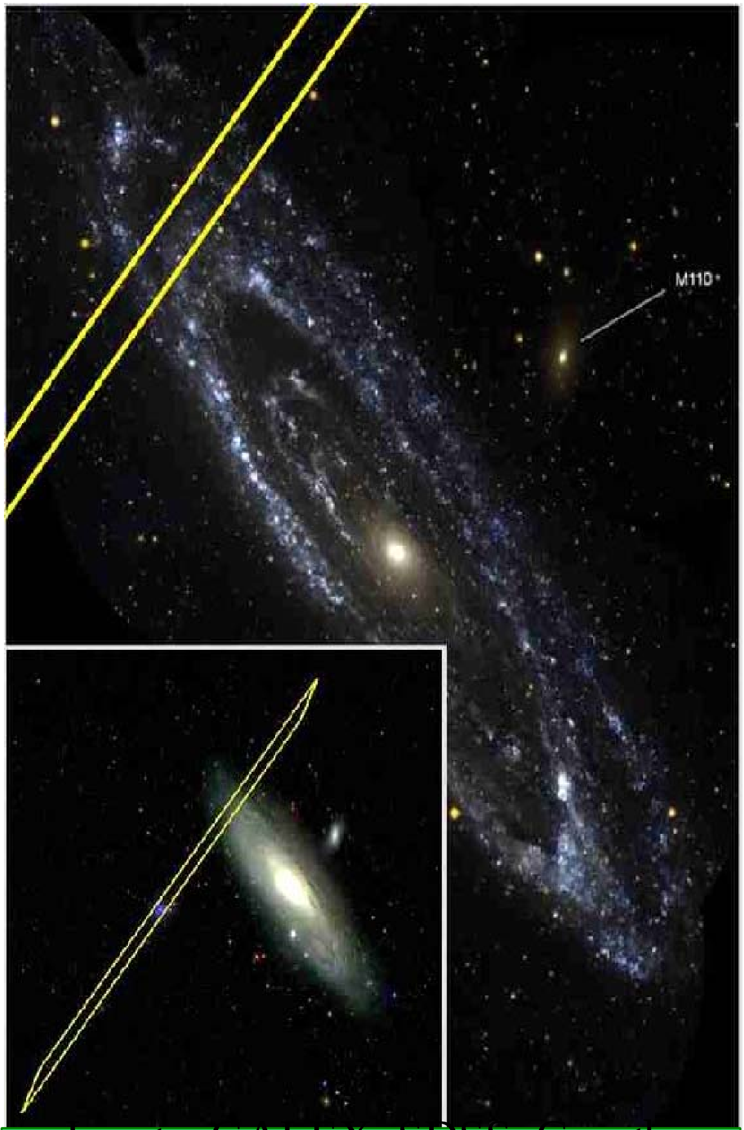
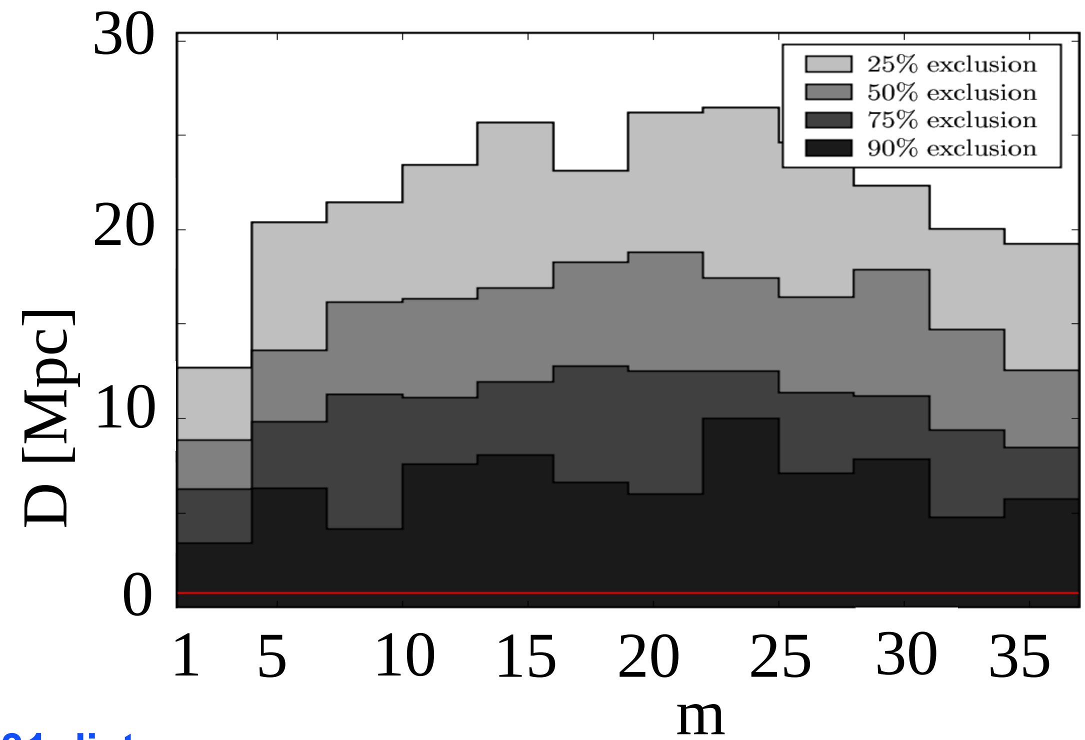


Image: GALEX, SDSS, Google Sky

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

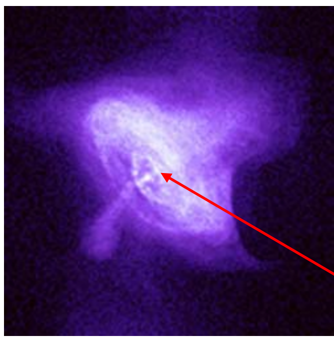


- Burst search:
  - **Cannot exclude a SGR at M31 distance**
  - **Upper limit: 8×10^{50} ergs (4×10^{-4} $M_{\odot}c^2$) (emitted within 100 ms for isotropic emission of energy in GW at M31 distance)**

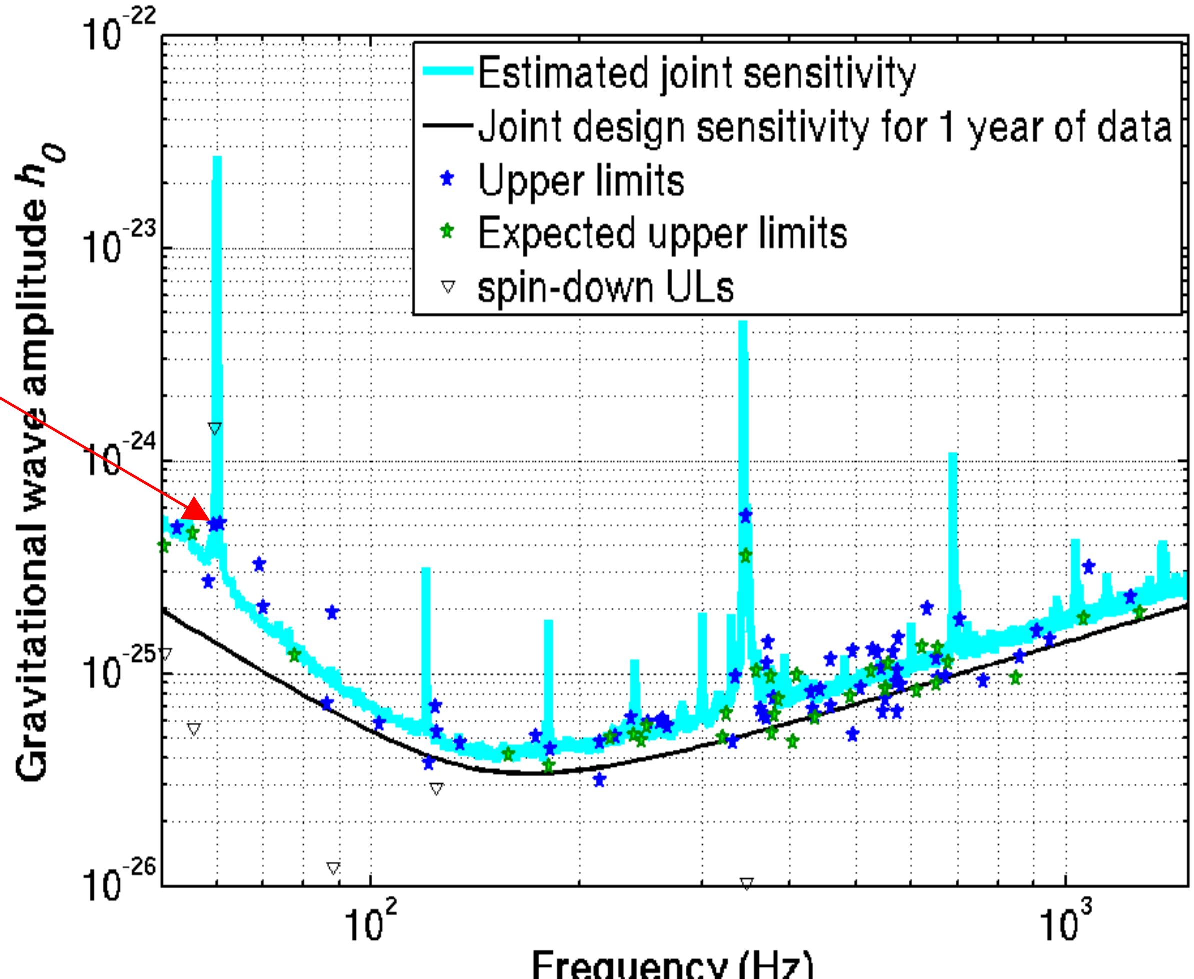
Searches for Pulsars

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

Crab pulsar

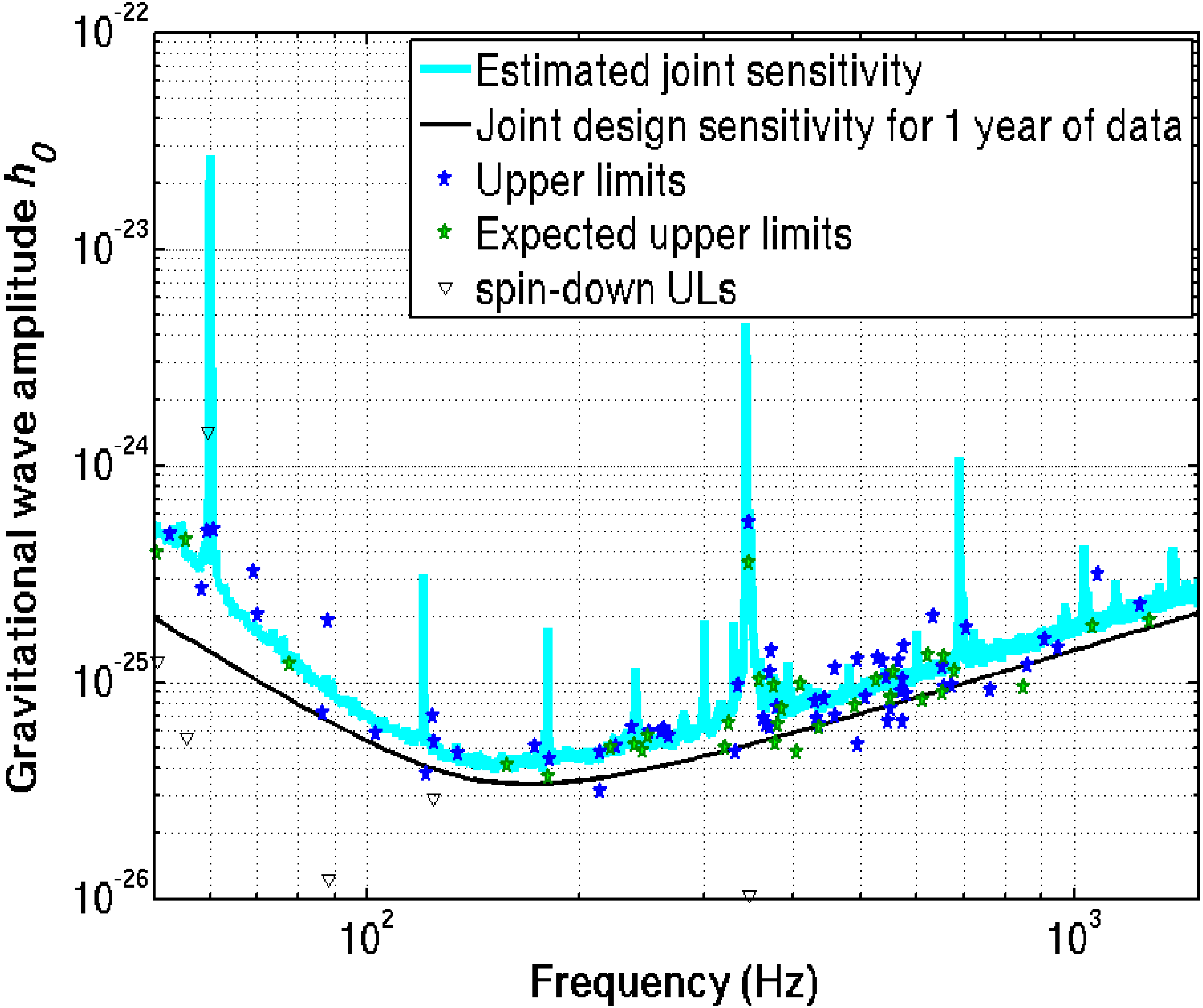


Upper limits on GWs from targeted pulsars:



Will beat spindown limit for Crab from S5 data

Preliminary

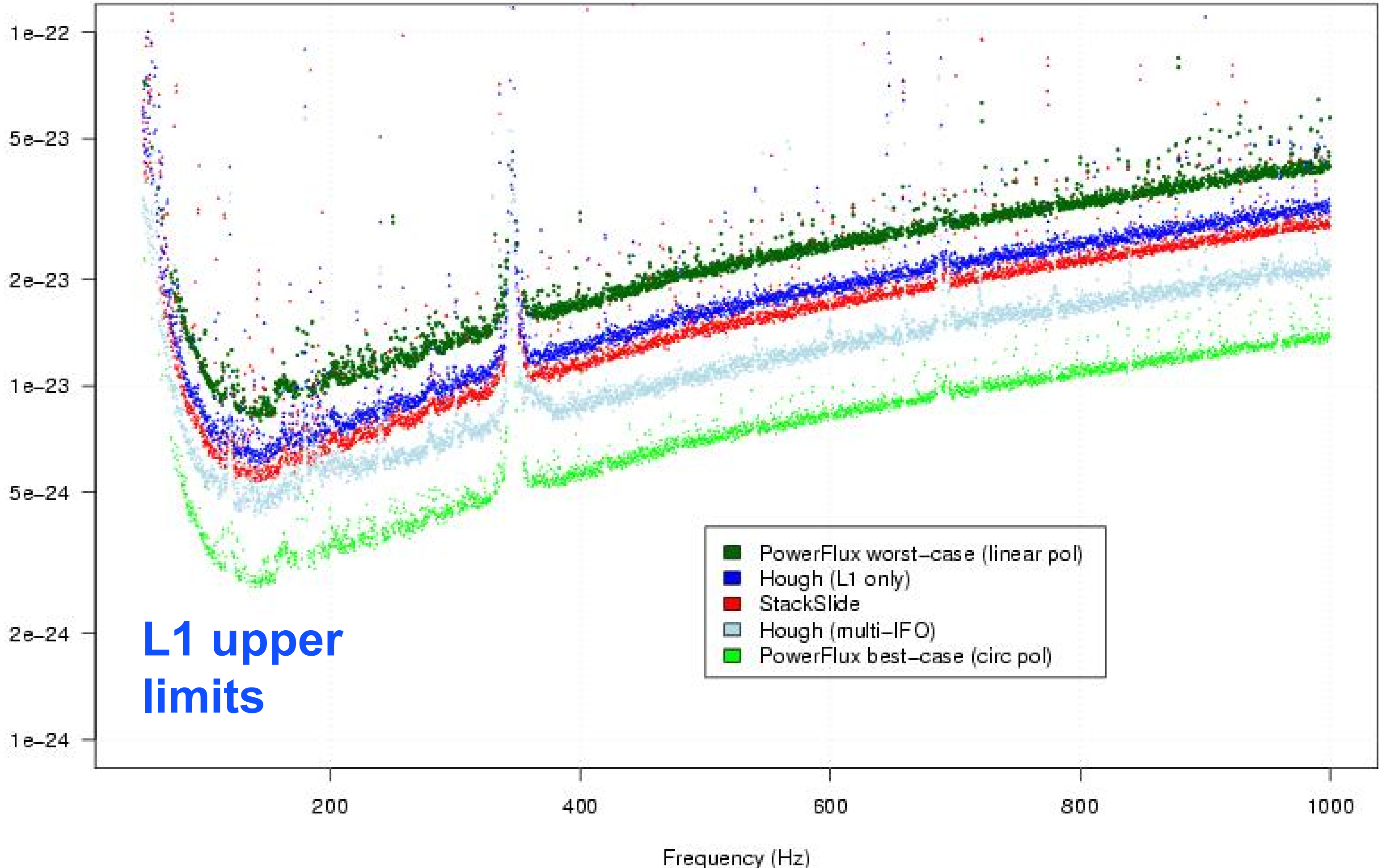


- **Black** curve represents one full year of data for all three interferometers running at design sensitivity
- **Blue** stars represent pulsars for which we are reasonably confident of having phase coherence with the signal model
- **Green** stars represent pulsars for which there is uncertainty about phase coherence

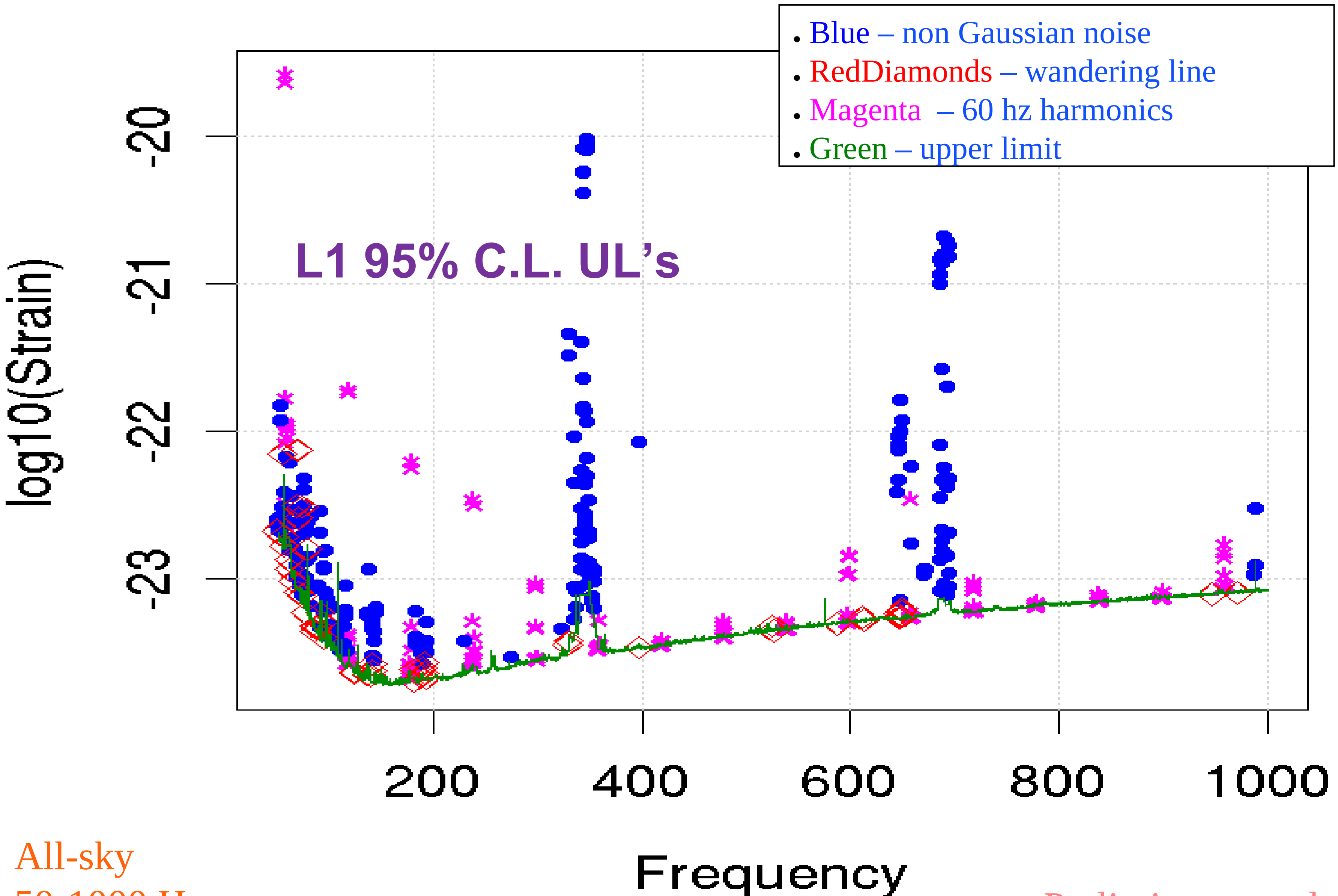
Searches for Pulsars

Broadband, untargeted, all-sky search (S4 data) – arXiv:0708.3818

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



Preliminary S5 results – no spindown



All-sky
50-1000 Hz

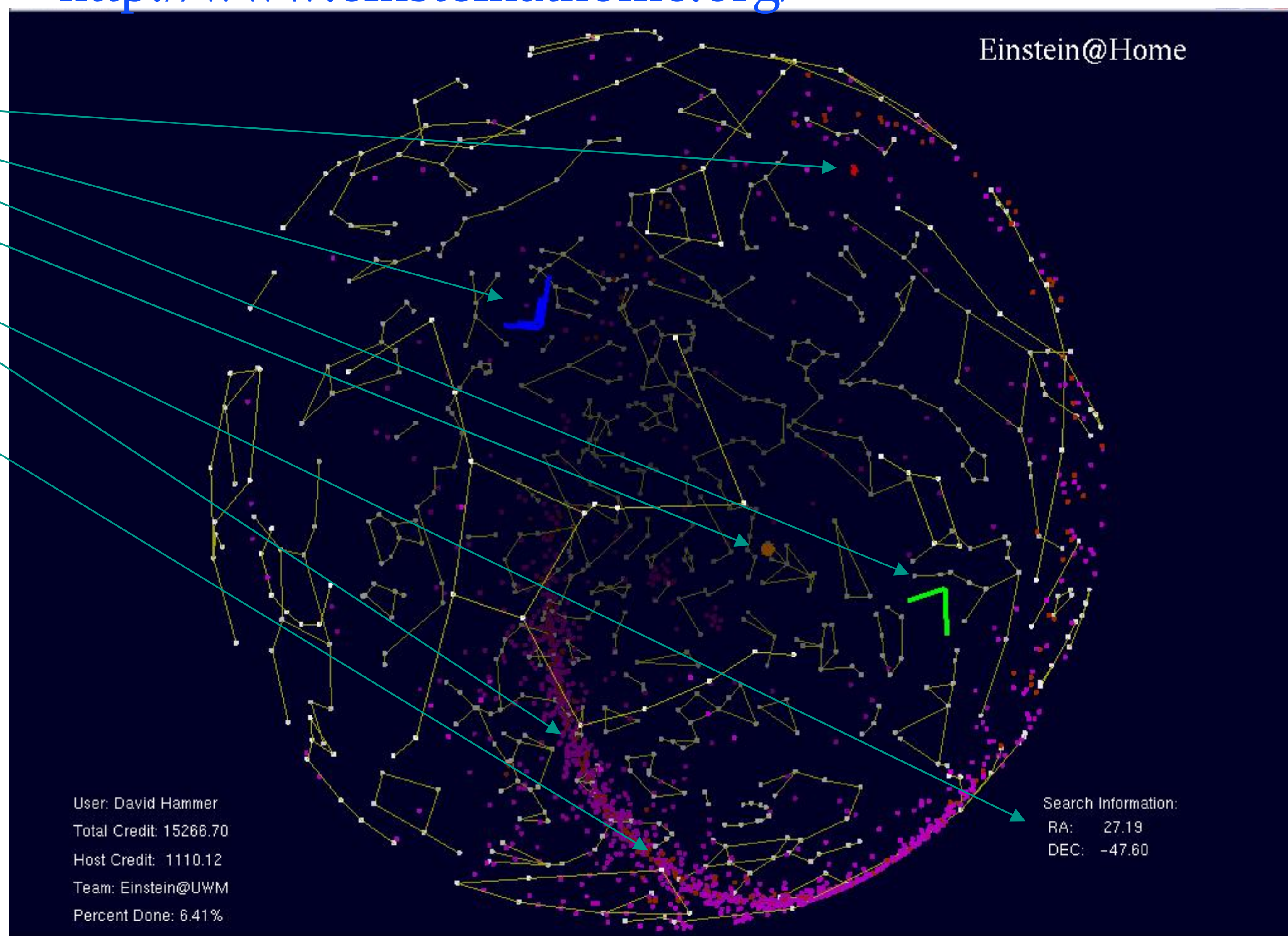
Preliminary results

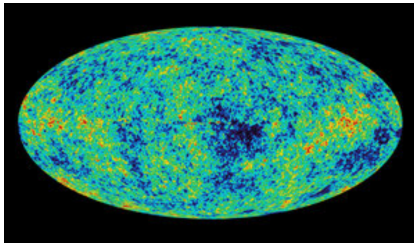
EINSTEIN@HOME

Catch a Wave From Space

http://www.einsteinathome.org/

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



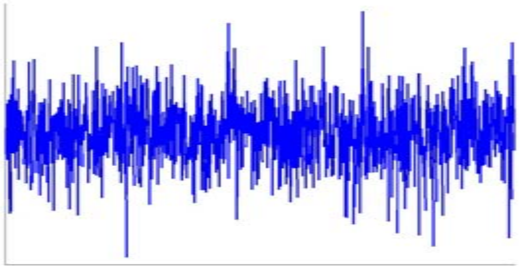


NASA, WMAP

Stochastic Background

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

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

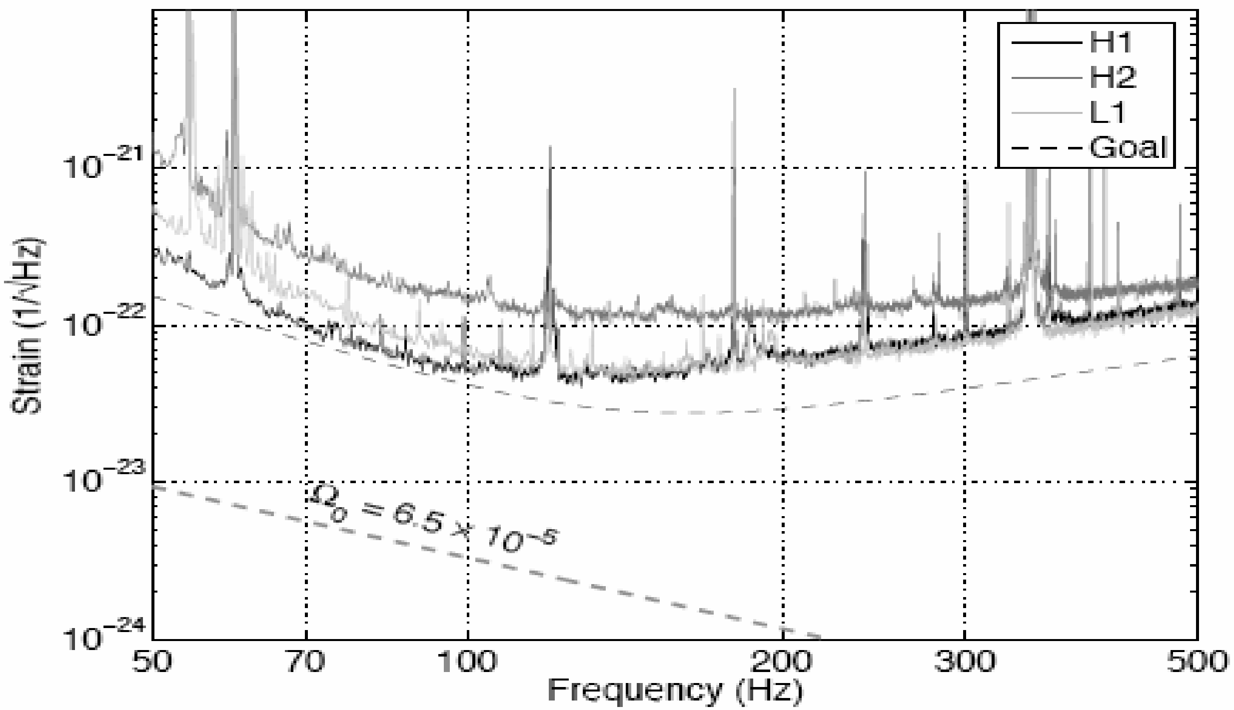


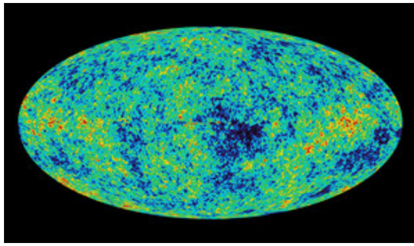
$$S_{\mathrm{gw}}(f) = \frac{3H_0^2}{10\pi^2}\, f^{-3}\,\Omega_{\mathrm{gw}}(f)$$

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

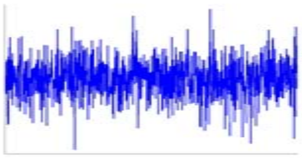
- The signal can be searched from cross-correlations in different pairs of detectors: L1-H1, H1-H2. The farther the detectors, the lower the frequencies that can be searched.

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

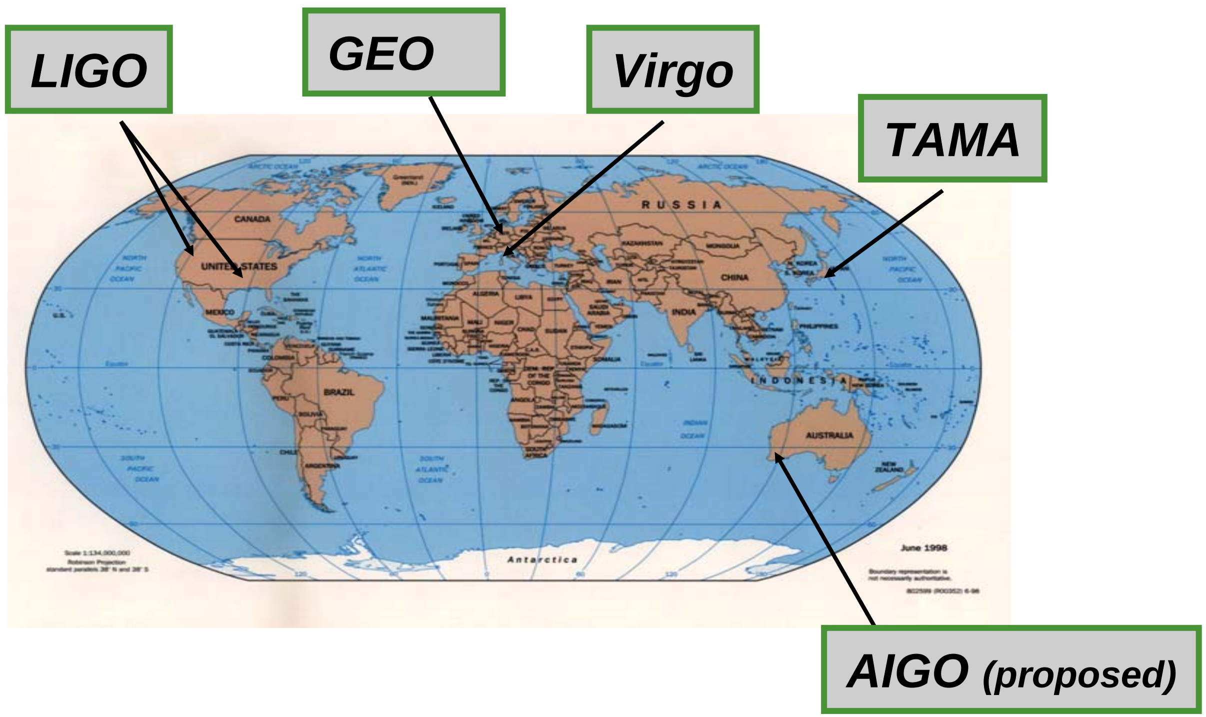
Outline

- 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 <u>Advanced LIGO</u> with another factor of ~10 improved sensitivity.

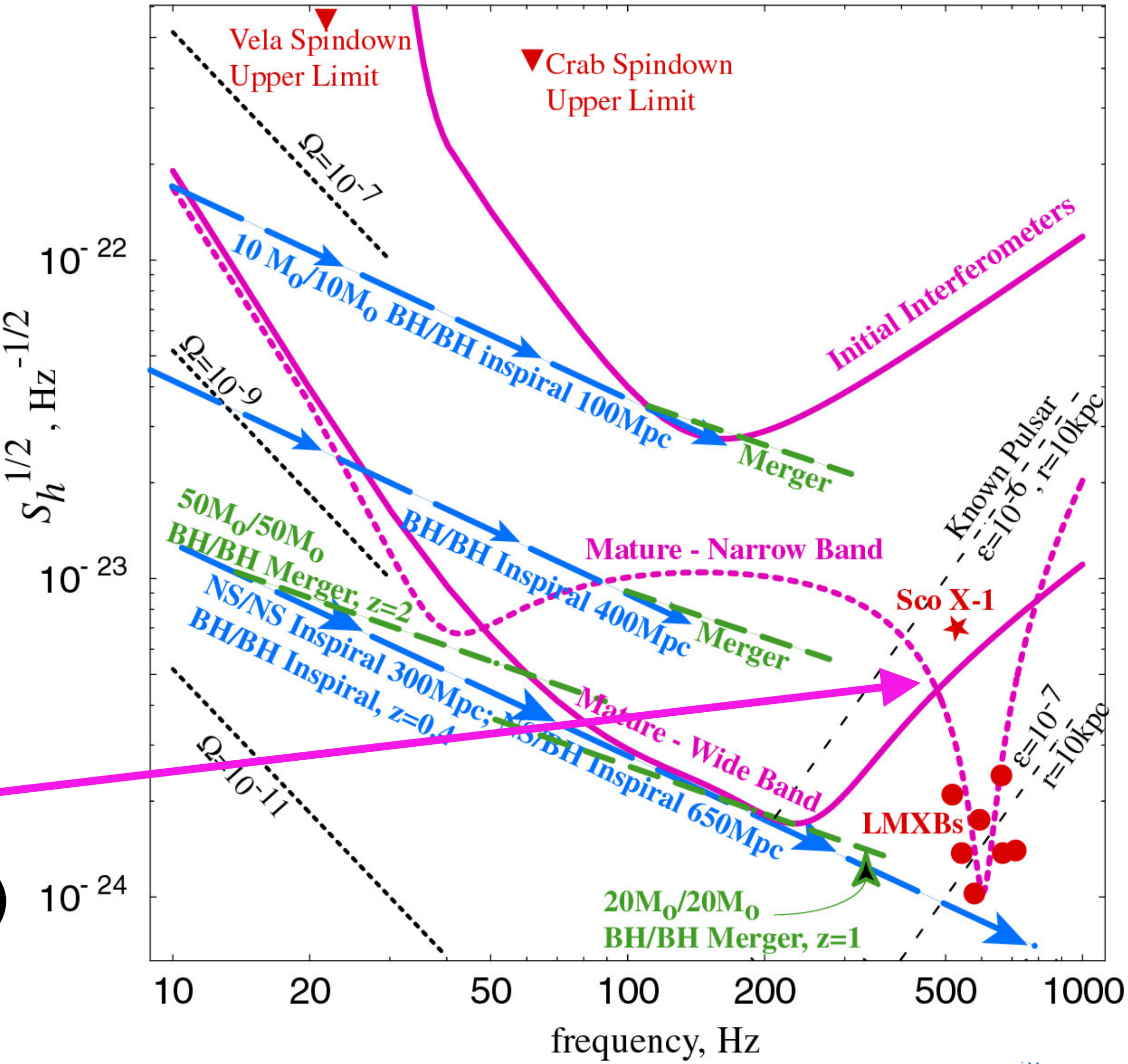
Because LIGO measures GW <u>amplitude</u>, an increase in sensitivity by 10 gives an increase in sampling volume, i.e, rate by ~1000

Advanced LIGO

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

Lower h_{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

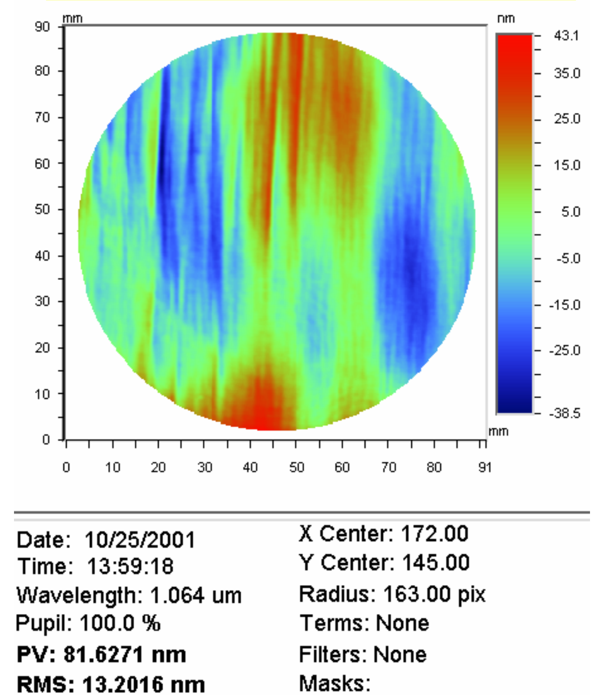
Lower internal thermal noise in bandwidth

Increased test mass:

10 kg → 40 kg

Compensates increased radiation pressure noise

Sapphire Optics



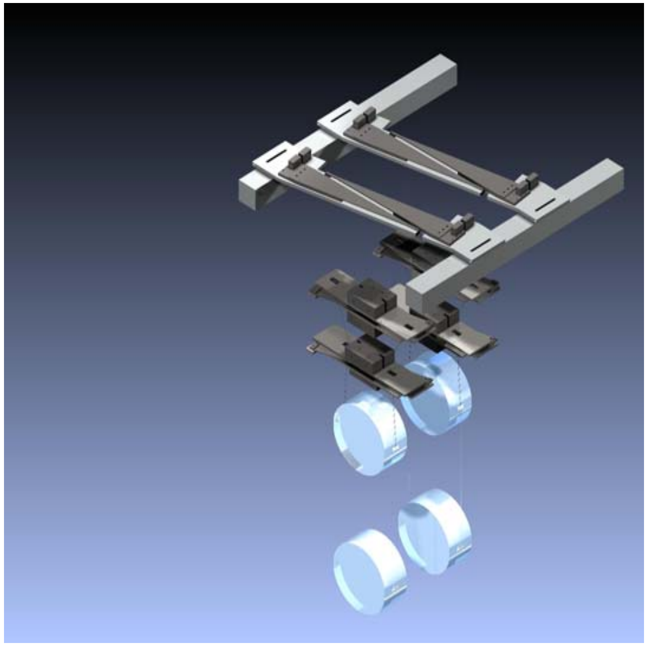
Advanced LIGO

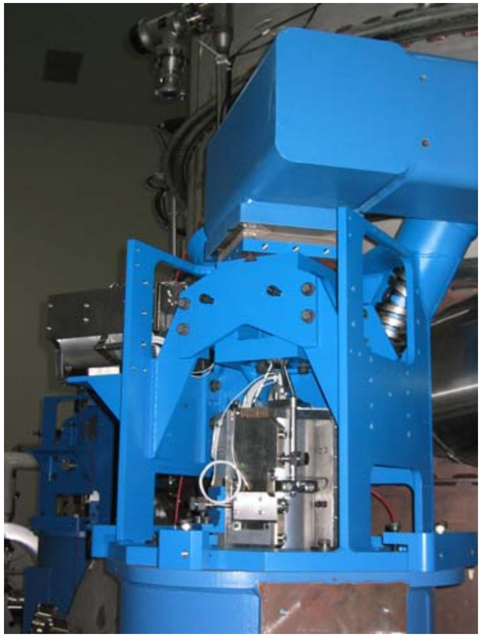
Detector Improvements:

New suspensions:

Single → Quadruple pendulum

Lower suspensions thermal noise in bandwidth





Improved seismic isolation:

Passive → Active

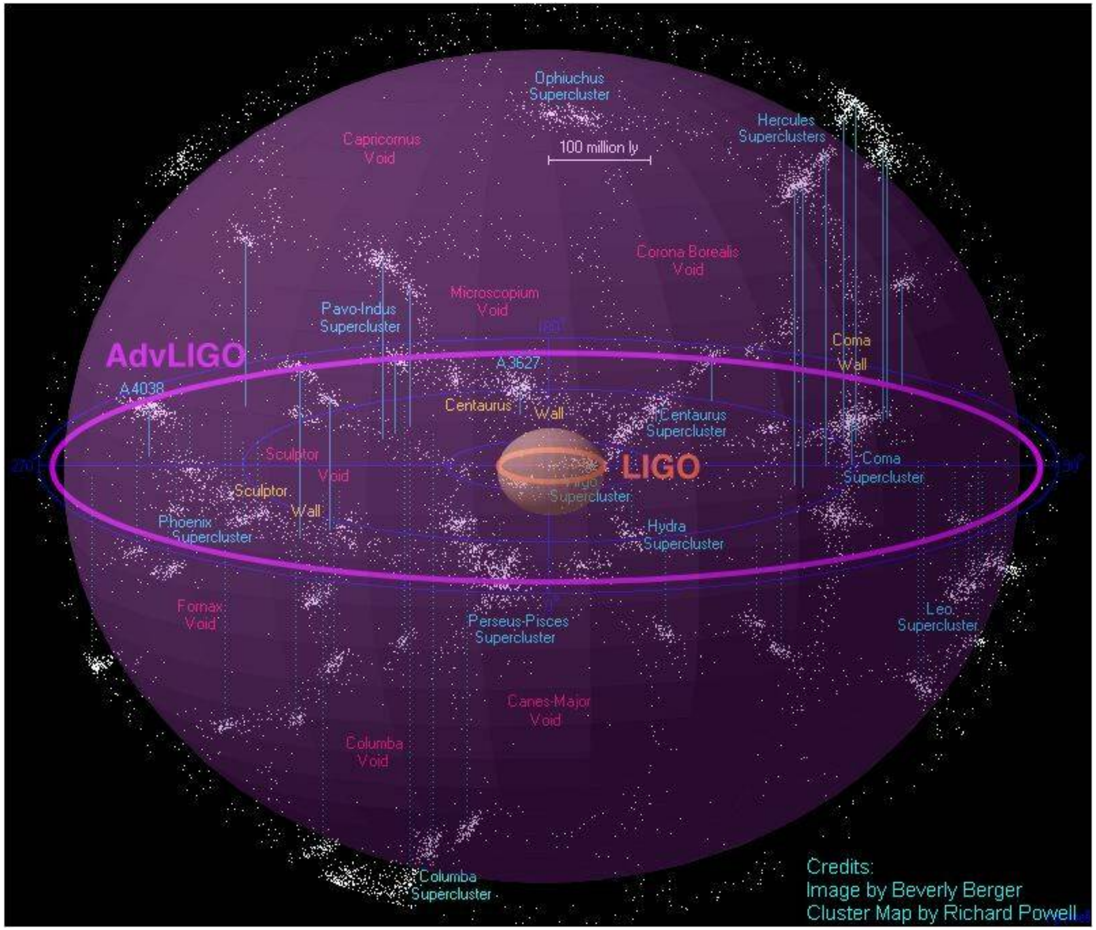
Lowers seismic “wall” to ~10 Hz

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

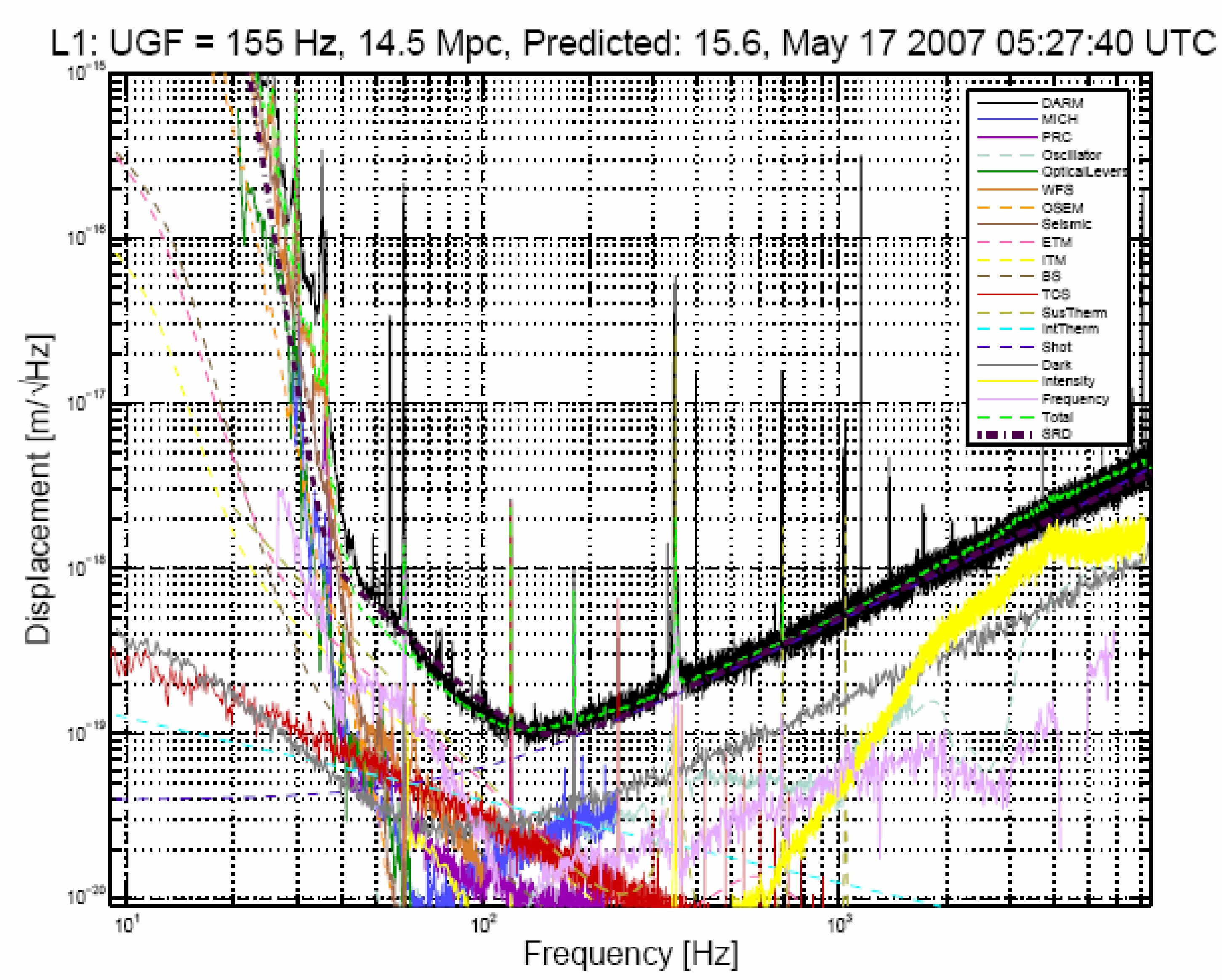
- Hope for discovery as we keep "opening boxes"
- Limits on radiation now constraining astrophysical processes

Our Plan:

- Upgrade to "enhanced LIGO"
- Keep 2-km interferometer running in "AstroWatch" (supernova watch)
- 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



“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: ⇒ use match filtering technique

Data

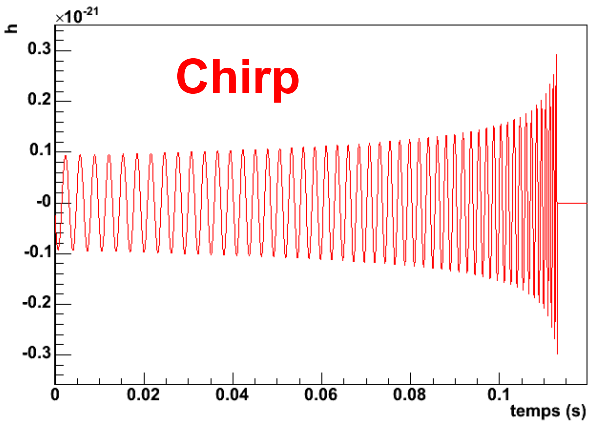
Template

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

Noise power spectral density

- Calculated templates for inspiral phase (“chirp”)

Waveform parameters:
distance, orientation, position,
$\mathbf{m_1}$, $\mathbf{m_2}$, t_0, ϕ (+ spin, ending cycles …)



- Different template families used for different searches

Example: S3-S4 searches

- **Binary Neutron Stars: “physical templates”** (2nd order restricted post-Newtonian, stationary-phase approximations)

- **Binary Black Holes: “phenomenological templates”** (BCV)