Searching for gravitational wave bursts with the new global detector network

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Syracuse University Physics Colloquium
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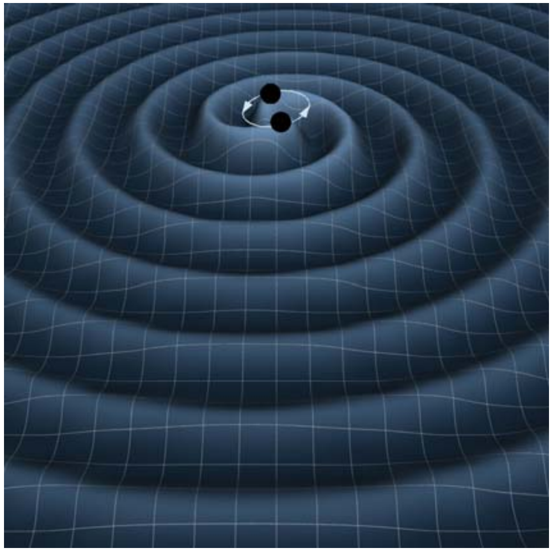
Gravitational Waves

Properties

Sources

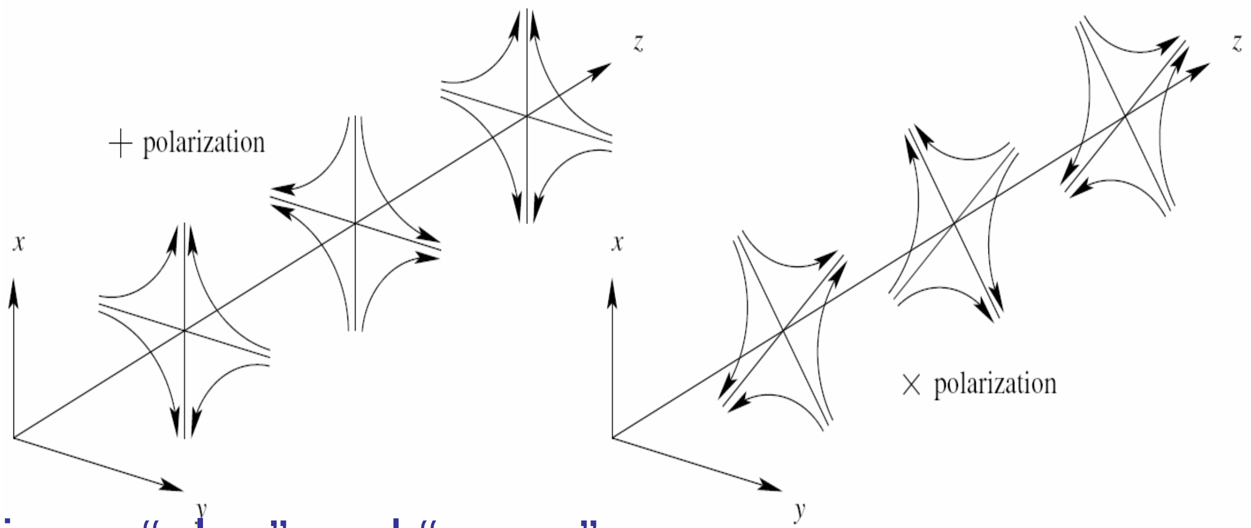
Detectors

Gravitational Waves



- Required by Special Theory of Relativity
  - Produced by the acceleration of matter
  - Travel at the speed of light
- Described by General Theory of Relativity
  - Linear perturbations of space-time
  - Yields wave equation and plane waves
- Produce a differential strain in space h

$$\frac{h}{2} = \frac{\Delta L}{L}$$

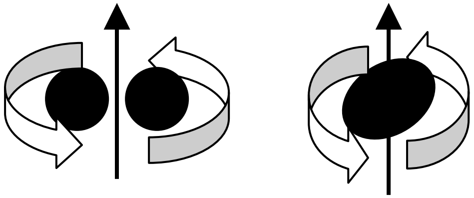


- Have two polarizations, “plus” and “cross”

Setting the scale

- Need qaudrupolar motion of matter since there is only one type of gravitational “charge”

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



- Strongest signals are produced by relativistic motions of massive objects

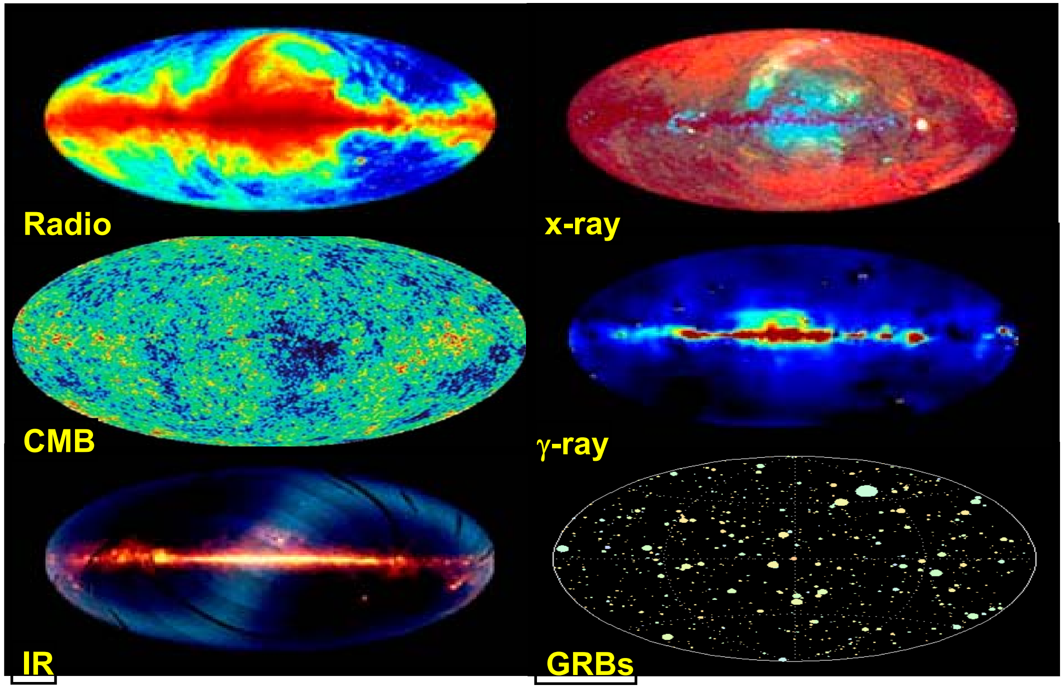
$$h \lesssim \frac{1}{d}\frac{2GM}{c^2} \lesssim 10^{-19}\left(\frac{M}{M_\odot}\right)\left(\frac{d}{\mathrm{Mpc}}\right)^{-1}$$

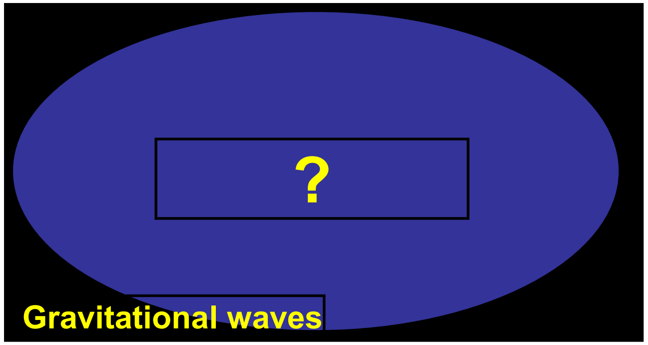
- The effect is extraordinarily small (and these assumptions are very optimistic!)
- Strain amplitude varies inversely with distance
- Highest frequency given by round trip light travel time at a Schwarzschild radius

$$f \lesssim \frac{c^3}{4\pi GM} \sim 16\left(\frac{M}{M_\odot}\right)^{-1} \quad \mathrm{kHz}$$

An astronomical endeavor

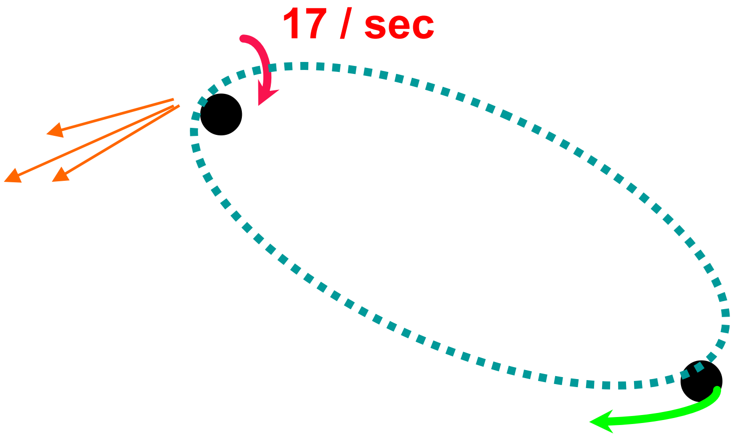
- Gravitational waves interact extremely weakly with matter:
  - They are very difficult to detect
  - We need massive objects moving at relativistic speeds
  - They are not obscured by intervening matter
  - They directly probe regions of strong space-time curvature and nuclear densities that are not currently accessible





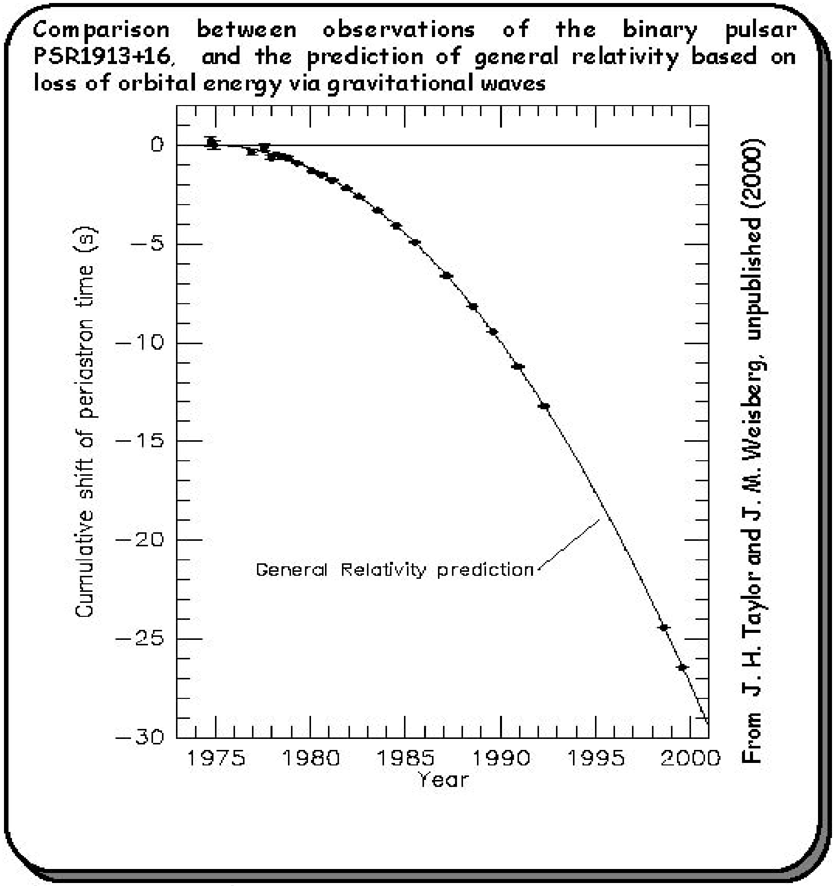
Existing evidence

- There is already good evidence for gravitational waves!
- Observations of the binary pulsar system PSR 1913+16 by Hulse, Taylor, and colleagues show that its orbital decay agrees with the predicted energy loss due to gravitational radiation



Neutron Star Binary System
- **separated by 10^6 miles**
- **$m_1 = 1.4m_\odot$; $m_2 = 1.36m_\odot$; $\varepsilon = 0.617$**

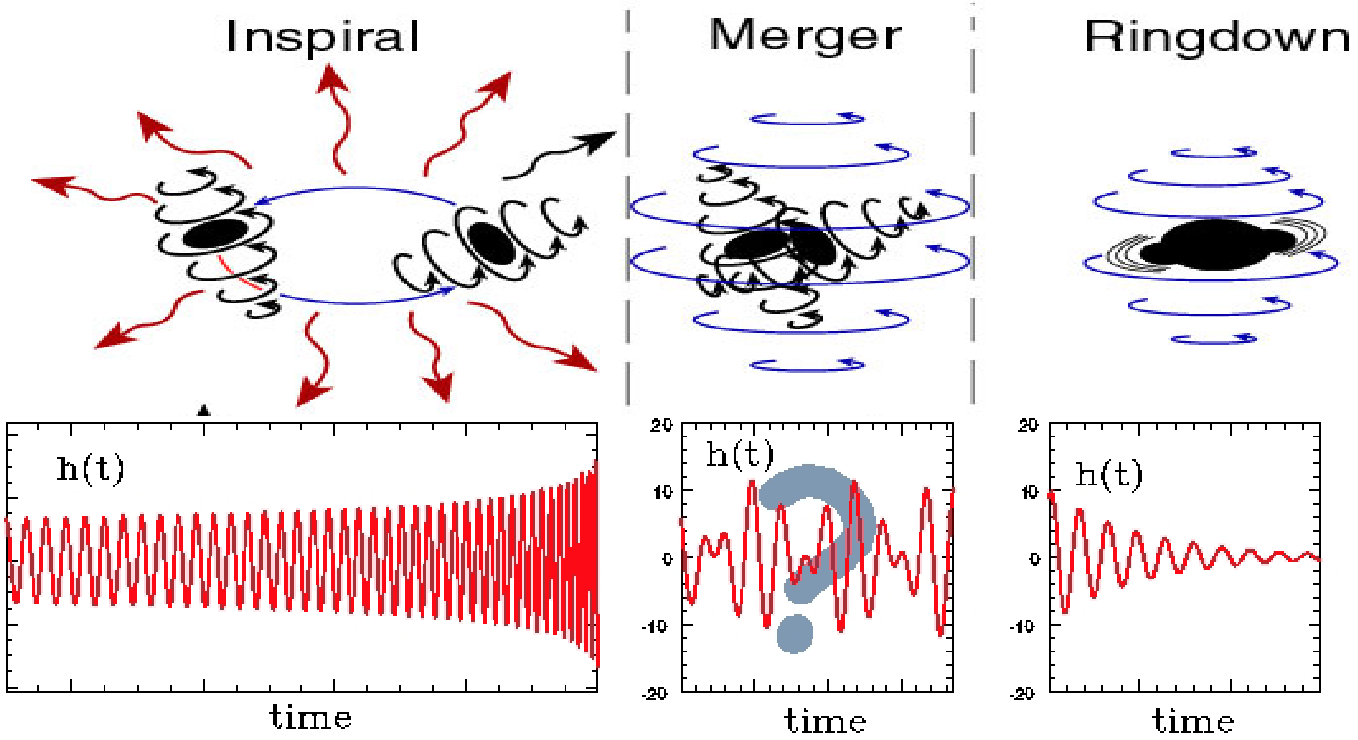
Exact match to general relativity
- **spiral in by 3 mm/orbit**
- **shortening of orbital period**


Comparison between observations of the binary pulsar PSR1913+16, and the prediction of general relativity based on loss of orbital energy via gravitational waves

From J. H. Taylor and J. M. Weisberg, unpublished (2000)

Coalescing Binary compact objects

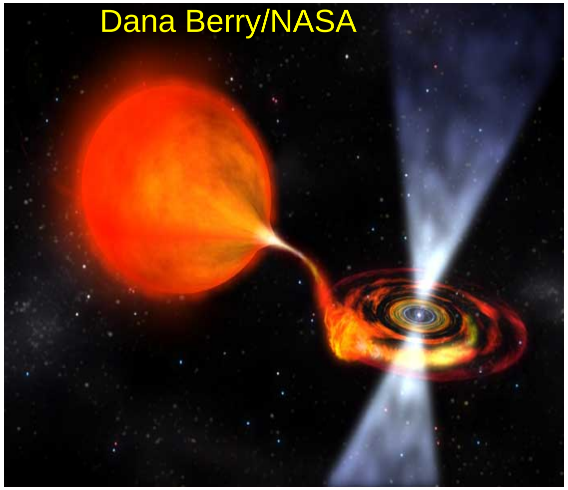
- Eventually the binary pulsar system PSR 1913+16 will merge
- The final inspiral of binary neutron stars and potentially binary black holes is the most likely and most well understood potential source for gravitational-wave detectors



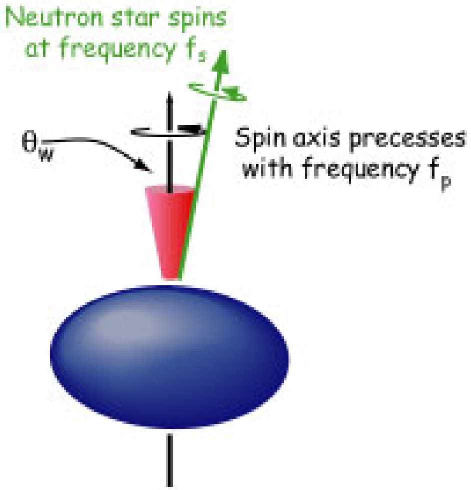
- Matched filter approach is possible since waveform is known

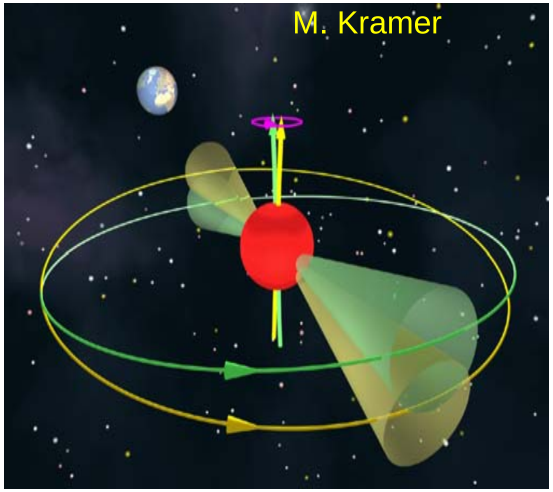
Periodic sources

- Continuous gravitational wave emission is possible from asymmetric spinning objects
  - Isolated neutron stars with mountains or wobbles
  - Accreting neutron stars



Dana Berry/NASA



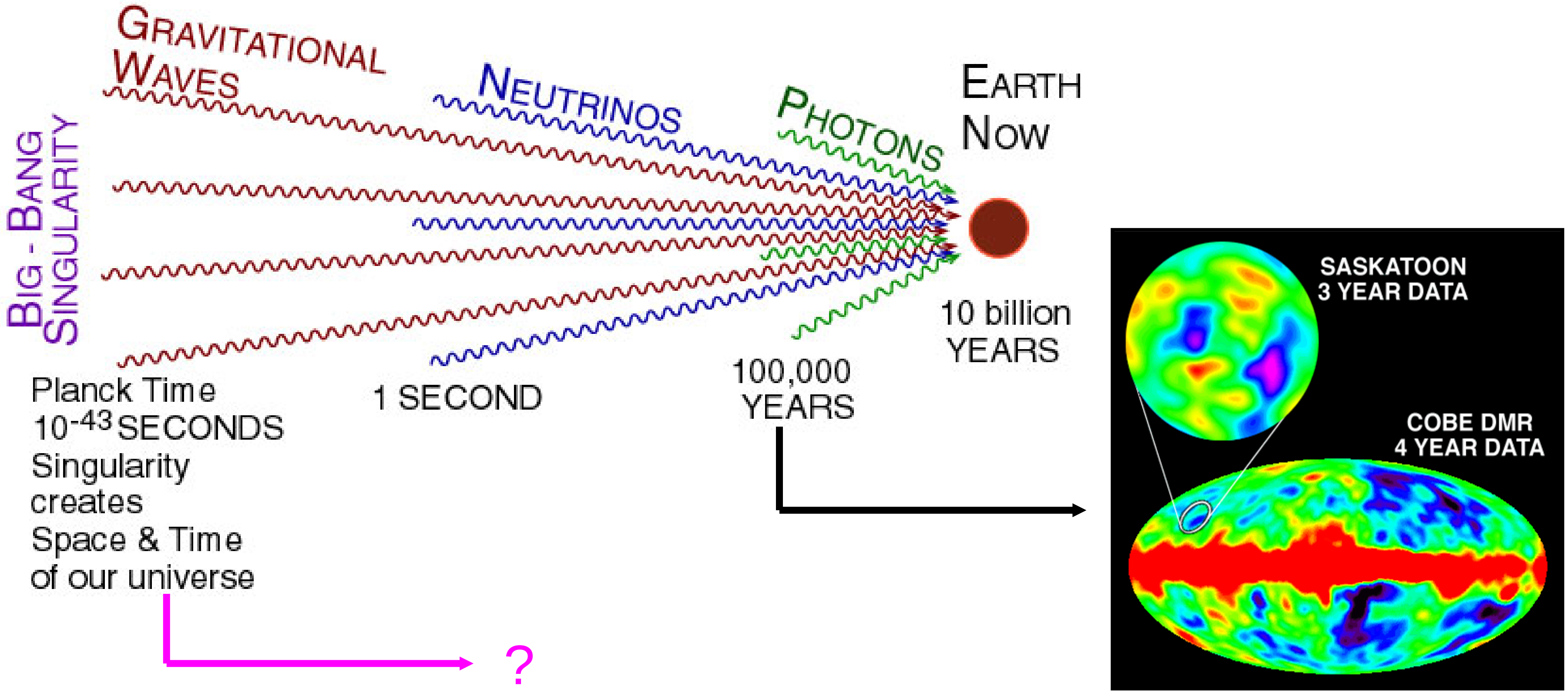


M. Kramer

- Gravitational waves emitted at twice the spin frequency
- Signal is always on and can be integrated over time to increase sensitivity and reject instrument lines
- Can place limits on ellipticity and spin down for known pulsars

Stochastic sources

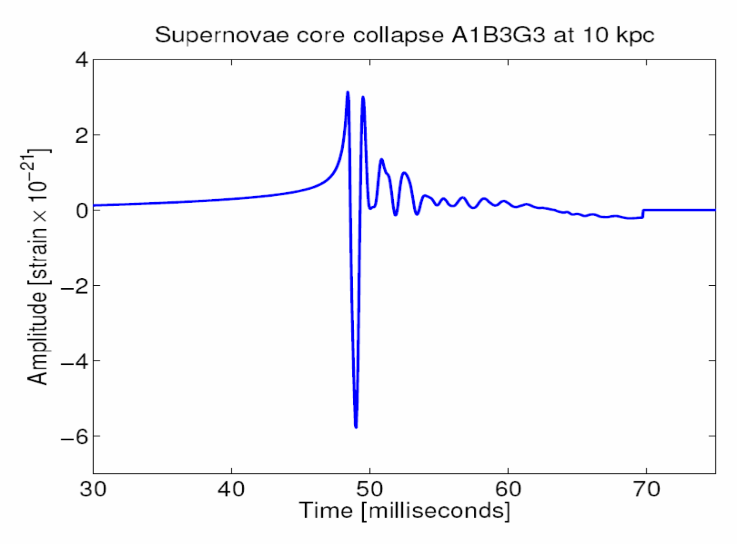
- Random gravitational wave background due to either
  - Relic gravitational waves from the early universe
  - Ensemble of many unresolved sources

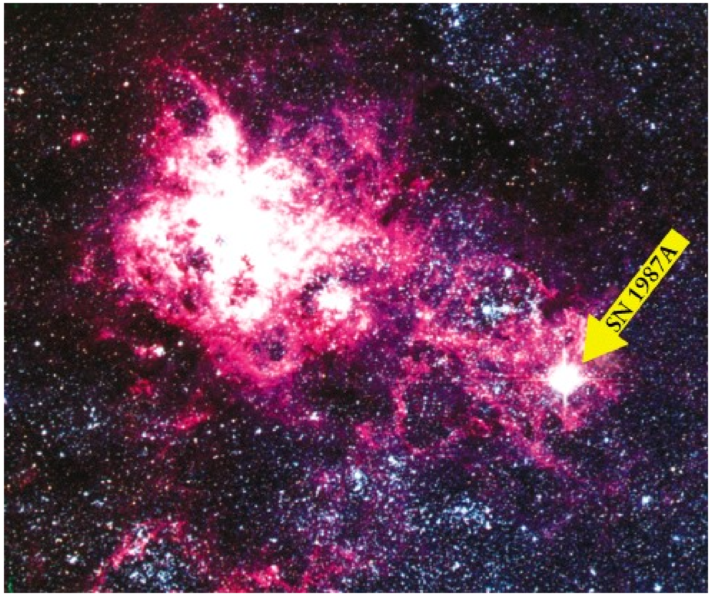


- Search for coherent background in multiple detectors

Burst sources

- Short duration bursts of unknown waveform
  - Asymmetric core collapse supernovae
  - Merger phase of binary coalescence
  - Neutron star instabilities
  - Gravitational waves associated with gamma ray bursts
  - Unexpected sources!





- Search for coincident signals in multiple detectors

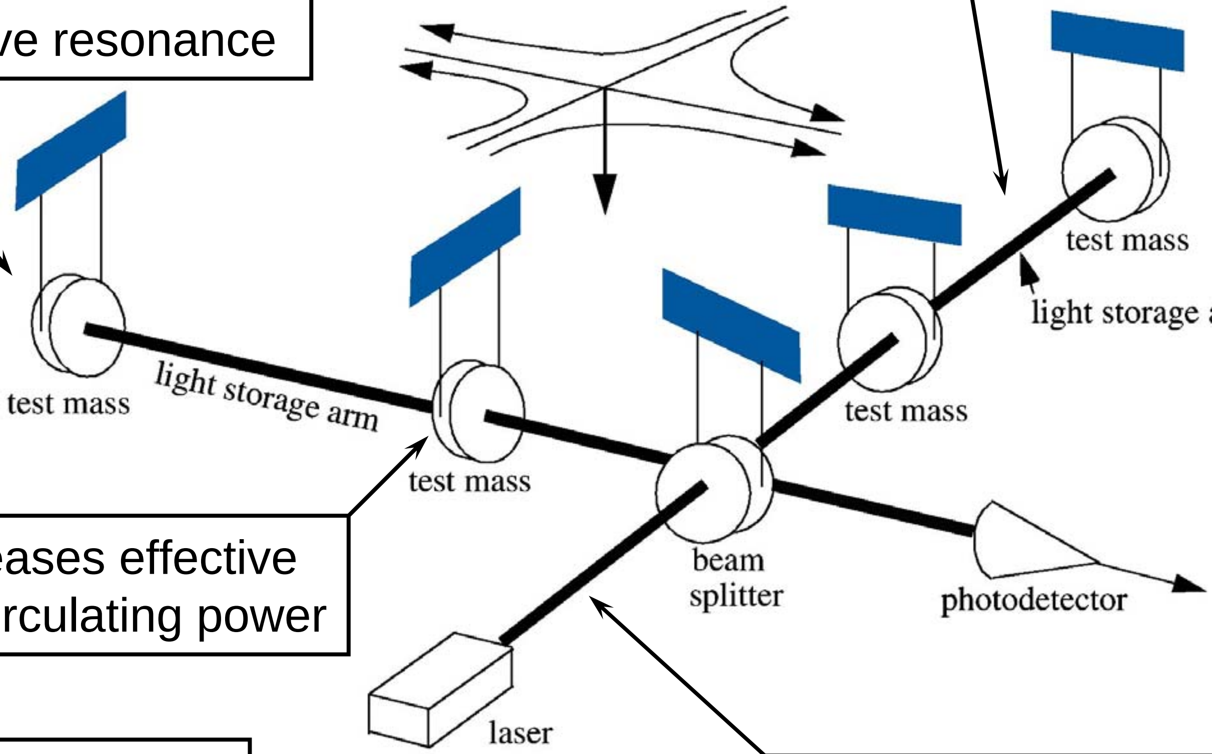
Interferometric detectors

In vacuum to avoid light scattering and accoustic noise

Signal proportional to arm length
L~4km, h~10^{-21}, ΔL~10^{-18} m

Mirrors on pendula behave like free masses above resonance

$$h = \Delta L / L$$



Cavity arms increases effective arm length and circulating power

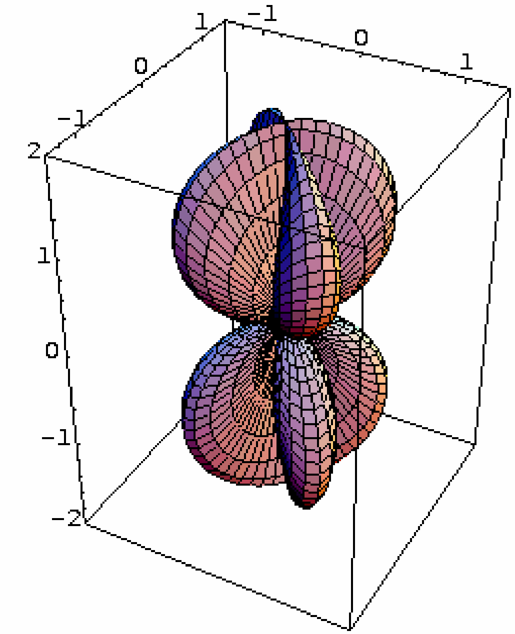
Seismically isolated from ground motion

Recycling mirror increases circulating power (not shown)

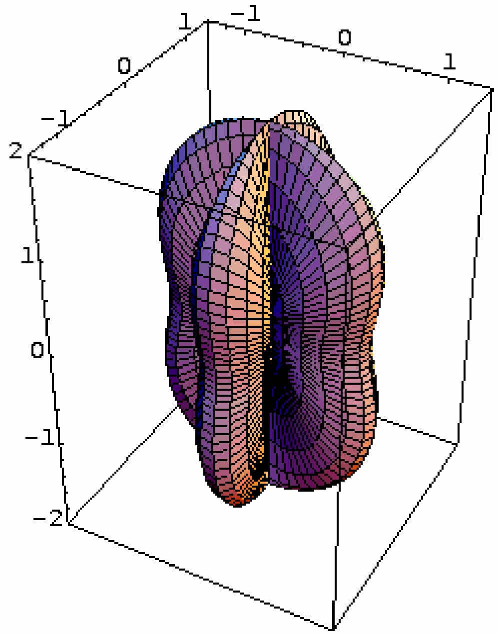
Interferometer antenna pattern

- Directional sensitivity depends on polarization of waves

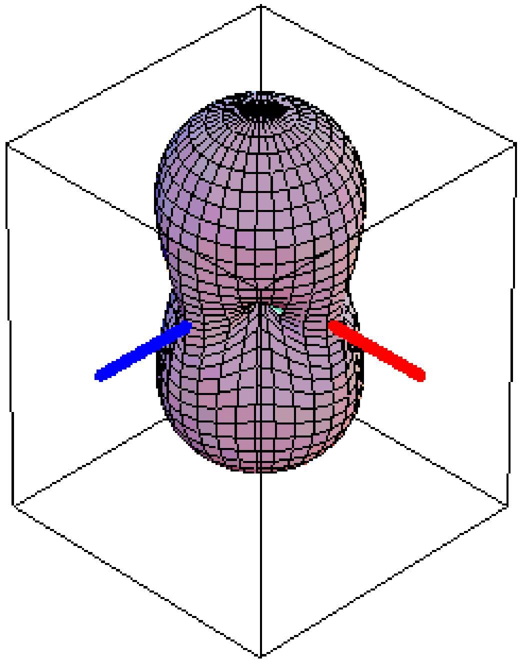
"×" polarization



"+" polarization



RMS sensitivity



- Interferometers have a broad antenna pattern
  - Cannot locate direction of the source with a single detector
  - Can scan large portions of the sky simultaneously

LIGO

Overview

Sensitivities

Status

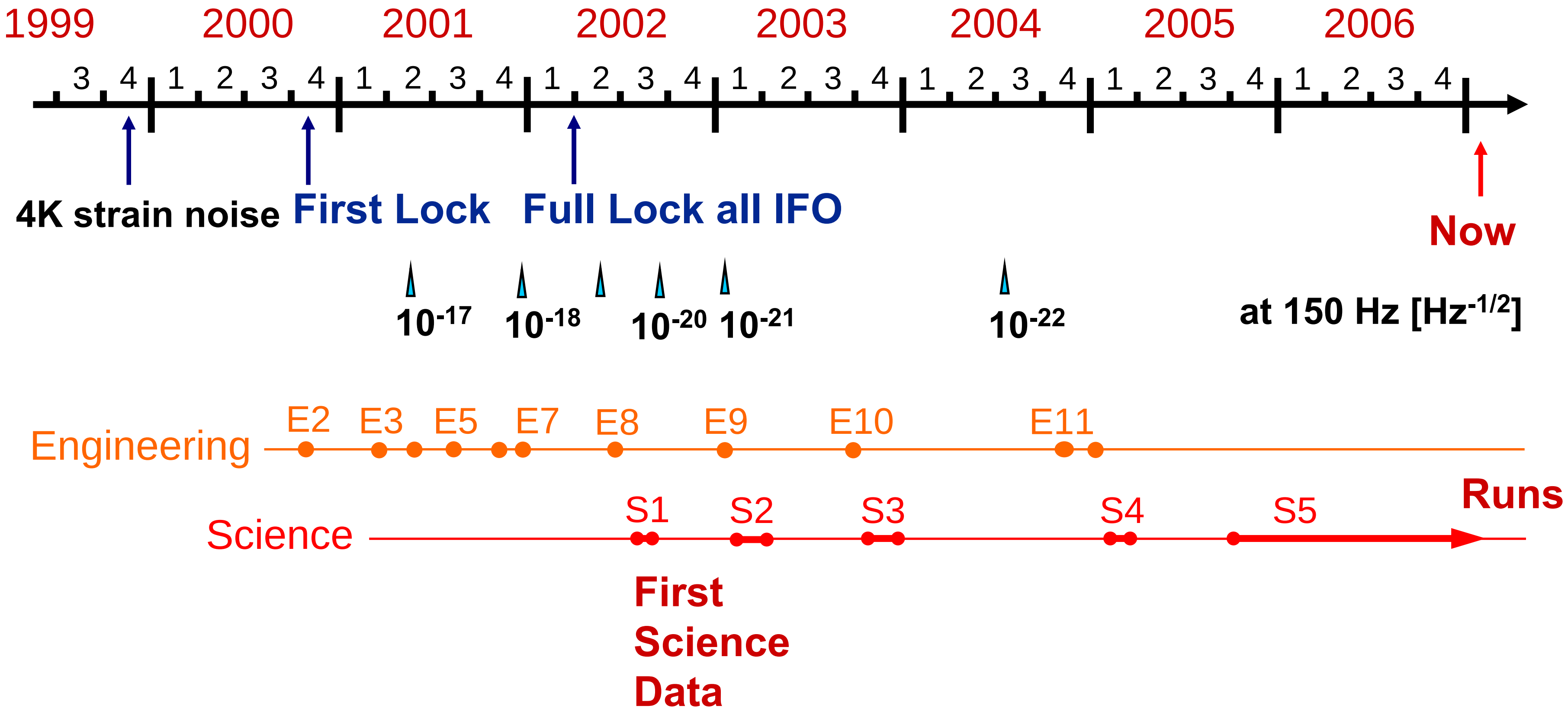
Results

LIGO

- Laser Interferometer Gravitational Wave Observatory (LIGO)
- LIGO consists of three detectors at two observatories in the US:
- Hanford, Washington (LHO)
  - Two aligned detectors: a 2 km detector and a 4 km detector
- Livingston, Louisiana (LLO)
  - One 4 km detector roughly aligned with Hanford detectors
- 10 millisecond speed of light travel time

LIGO Time line

- Starting in August of 2002, LIGO initiated periods of science runs separated by periods of commissioning work.



4K strain noise **First Lock** **Full Lock all IFO**

Now

10^{-17} **10^{-18}** **10^{-20}** **10^{-21}** **10^{-22}** **at 150 Hz [$\mathrm{Hz}^{-1/2}$]**

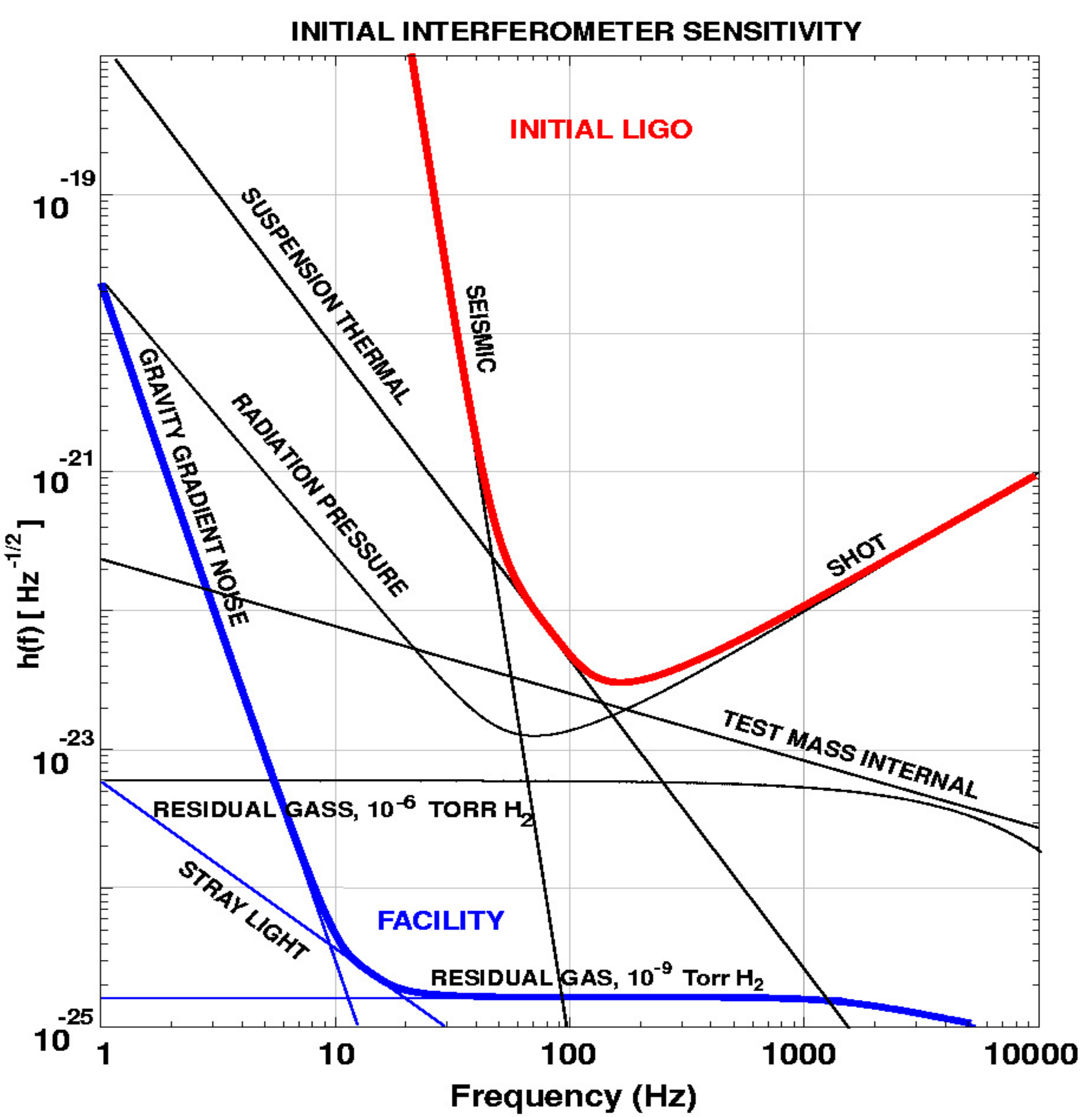
Engineering E2 E3 E5 E7 E8 E9 E10 E11

Science S1 S2 S3 S4 S5

Runs

First Science Data

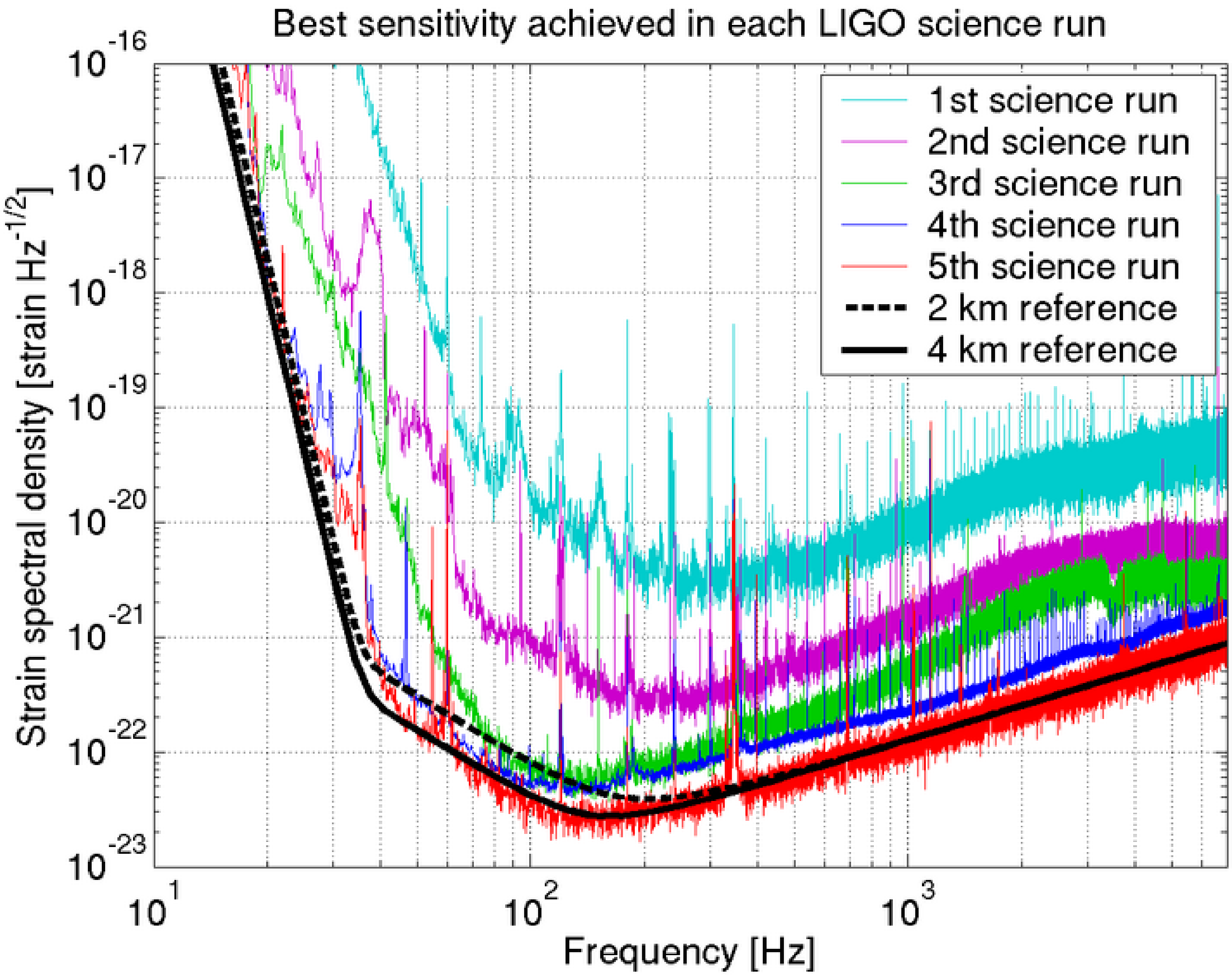
Initial LIGO Sensitivity Goal



Dominant noise sources:

- Seismic noise at low frequencies
- Thermal fluctuations at intermediate frequencies
- Photon shot noise at high frequencies

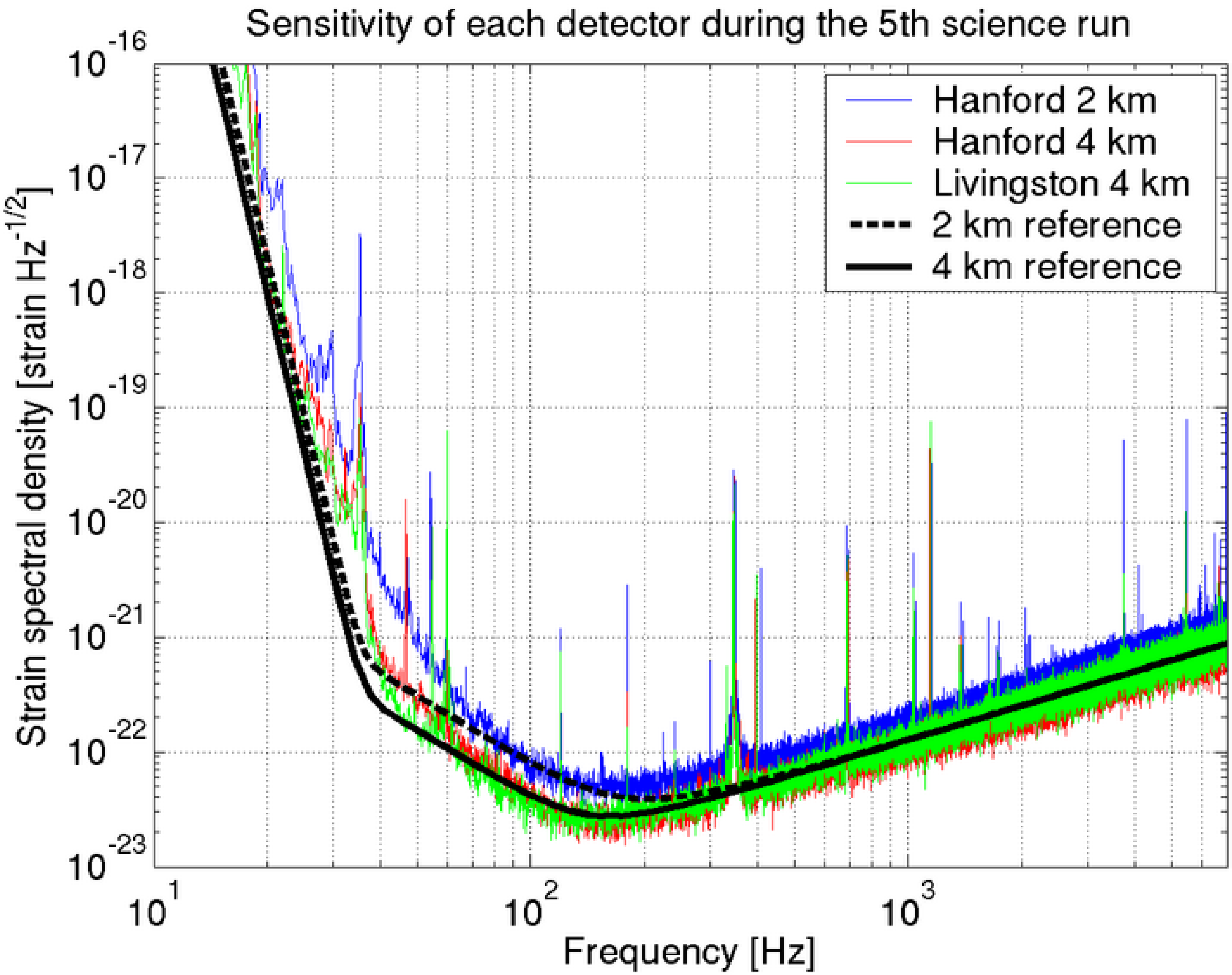
Science run sensitivities



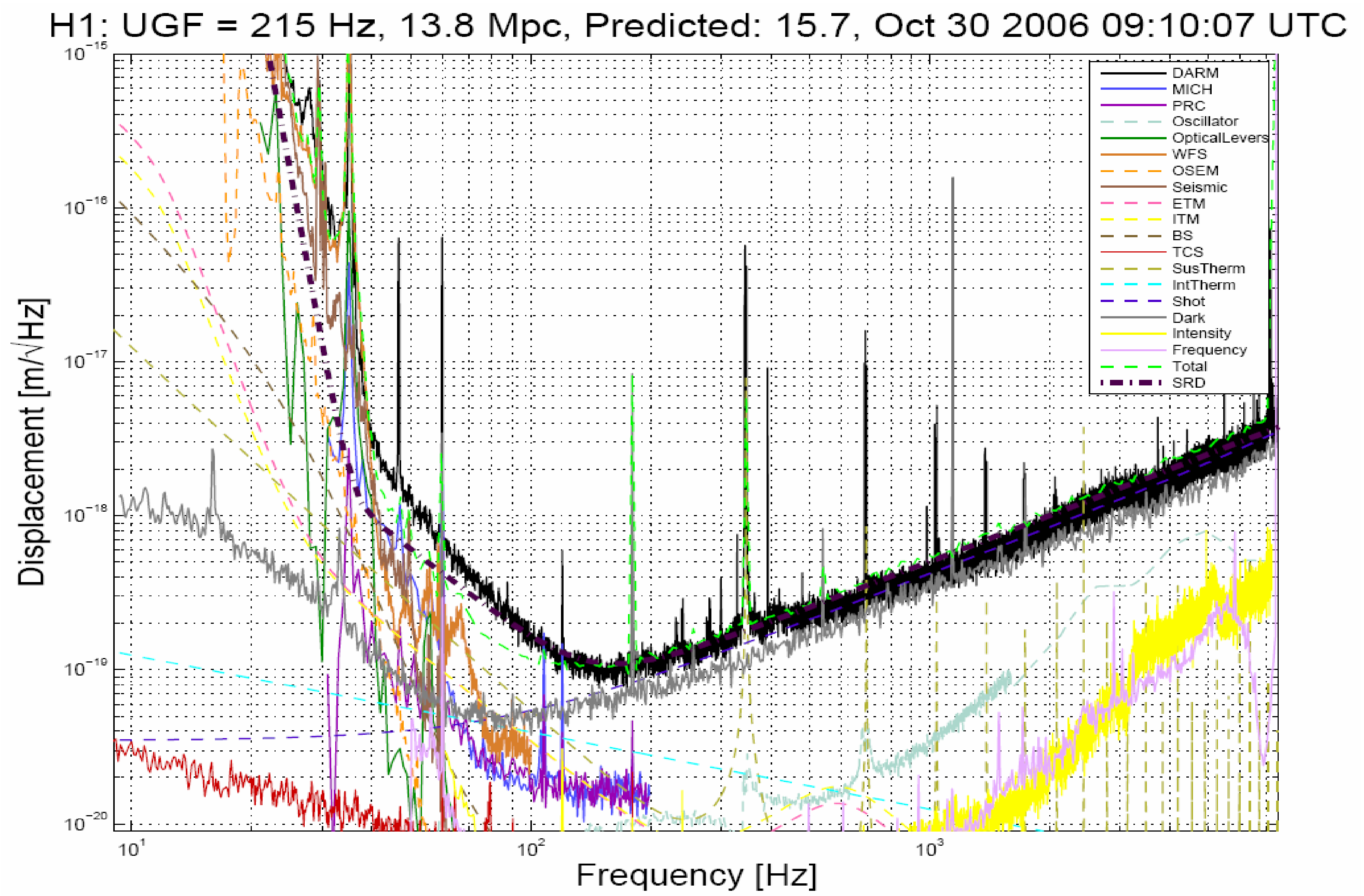
5th Science run

- In the fall of 2006, LIGO reached its initial design sensitivity of 10^{-21} RMS strain in a 100 Hz band
- Science Run 5 (S5) commenced in November 2006
- The goal is to accumulate one year of coincident science mode data at or above design sensitivity.
- S5 is expected to last between 1.5 and 2 years
- Schedule permits minor interruptions for maintenance and improvements

Sensitivities during 5th science run

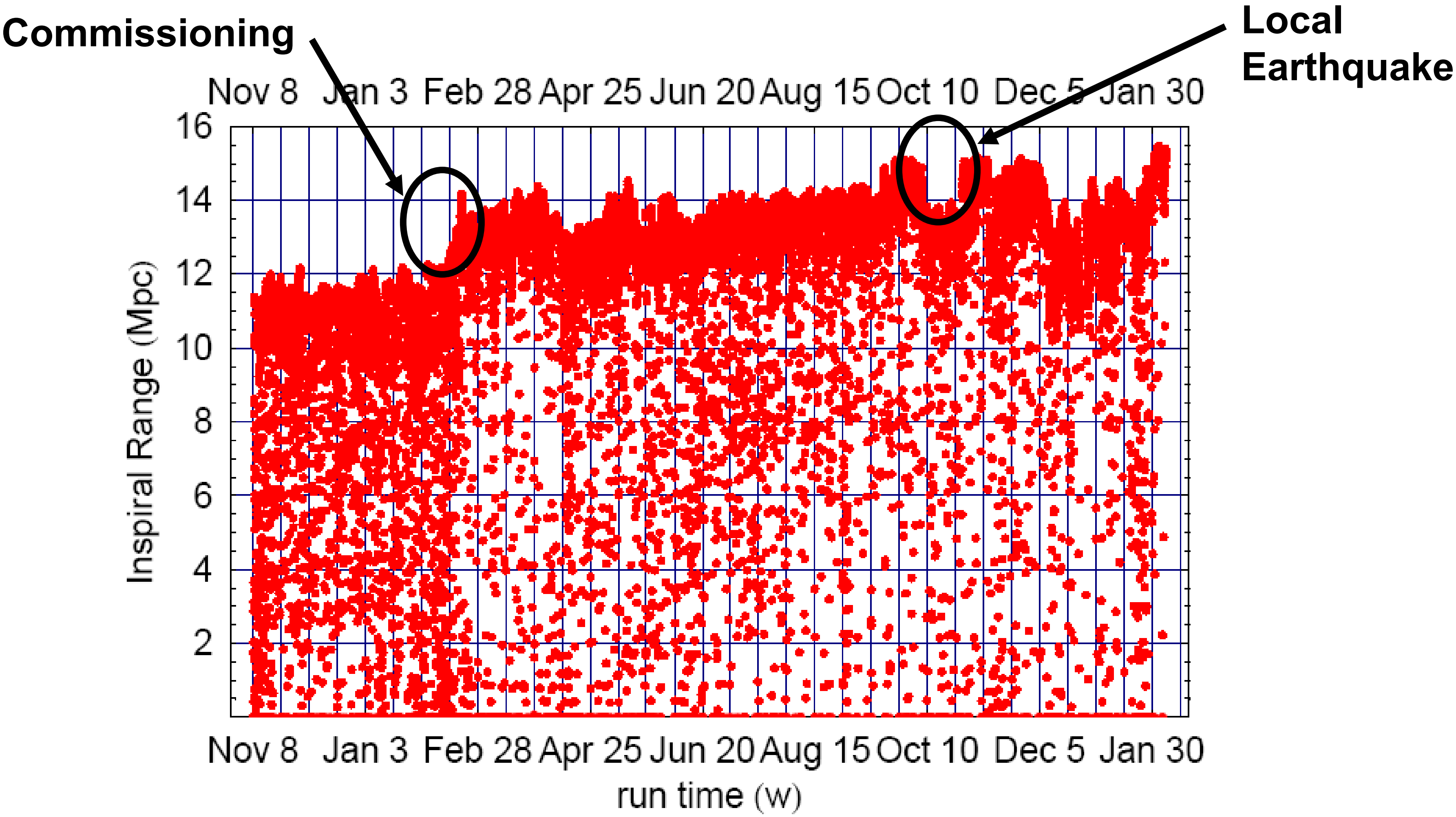


Noise budget



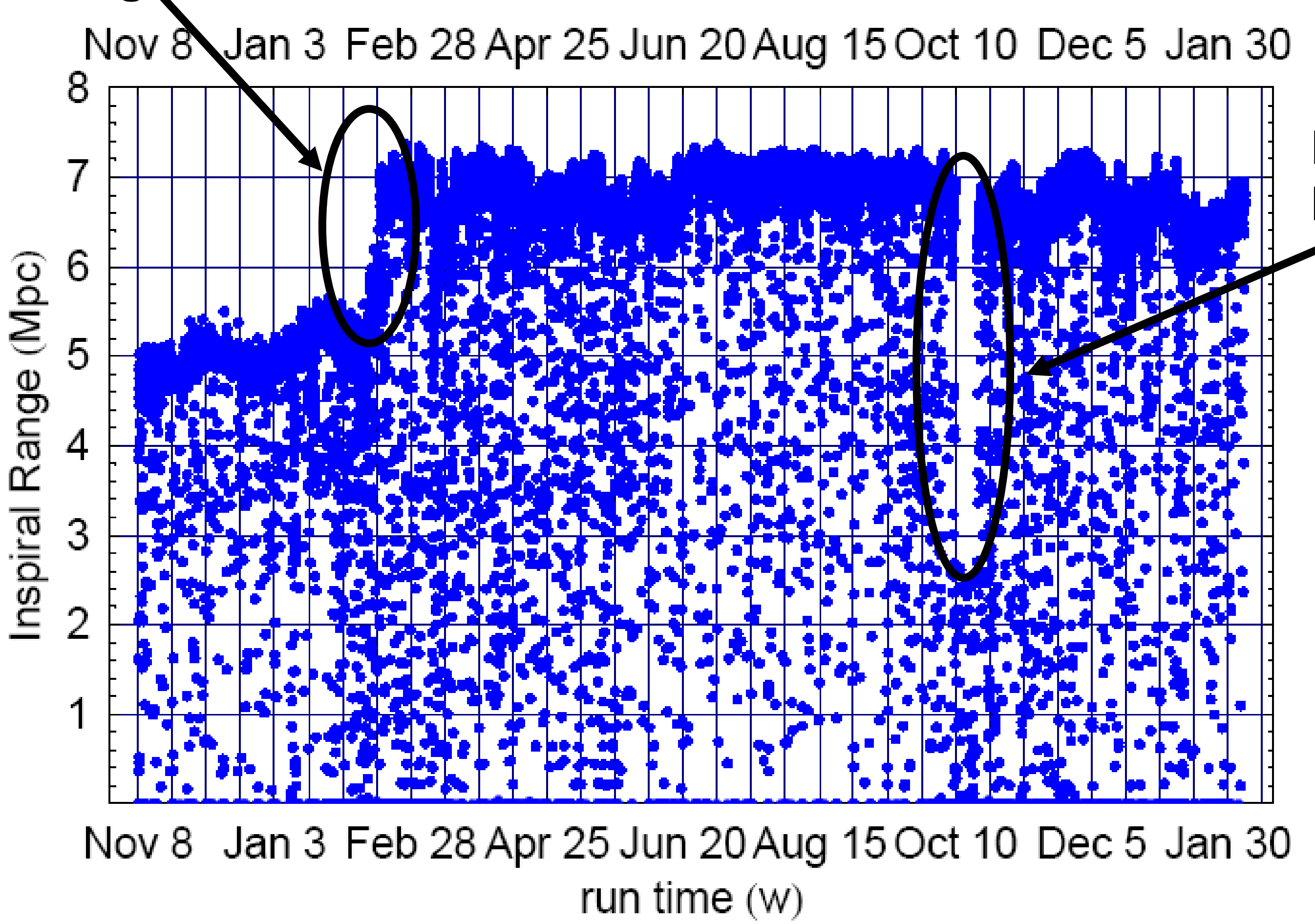
Hanford 4km sensitivity during S5

- Detectable range to randomly oriented 1.4, 1.4 solar mass binary neutron star inspiral at an SNR of 8.



Hanford 2km sensitivity during S5

- Detectable range to randomly oriented 1.4, 1.4 solar mass binary neutron star inspiral at an SNR of 8.

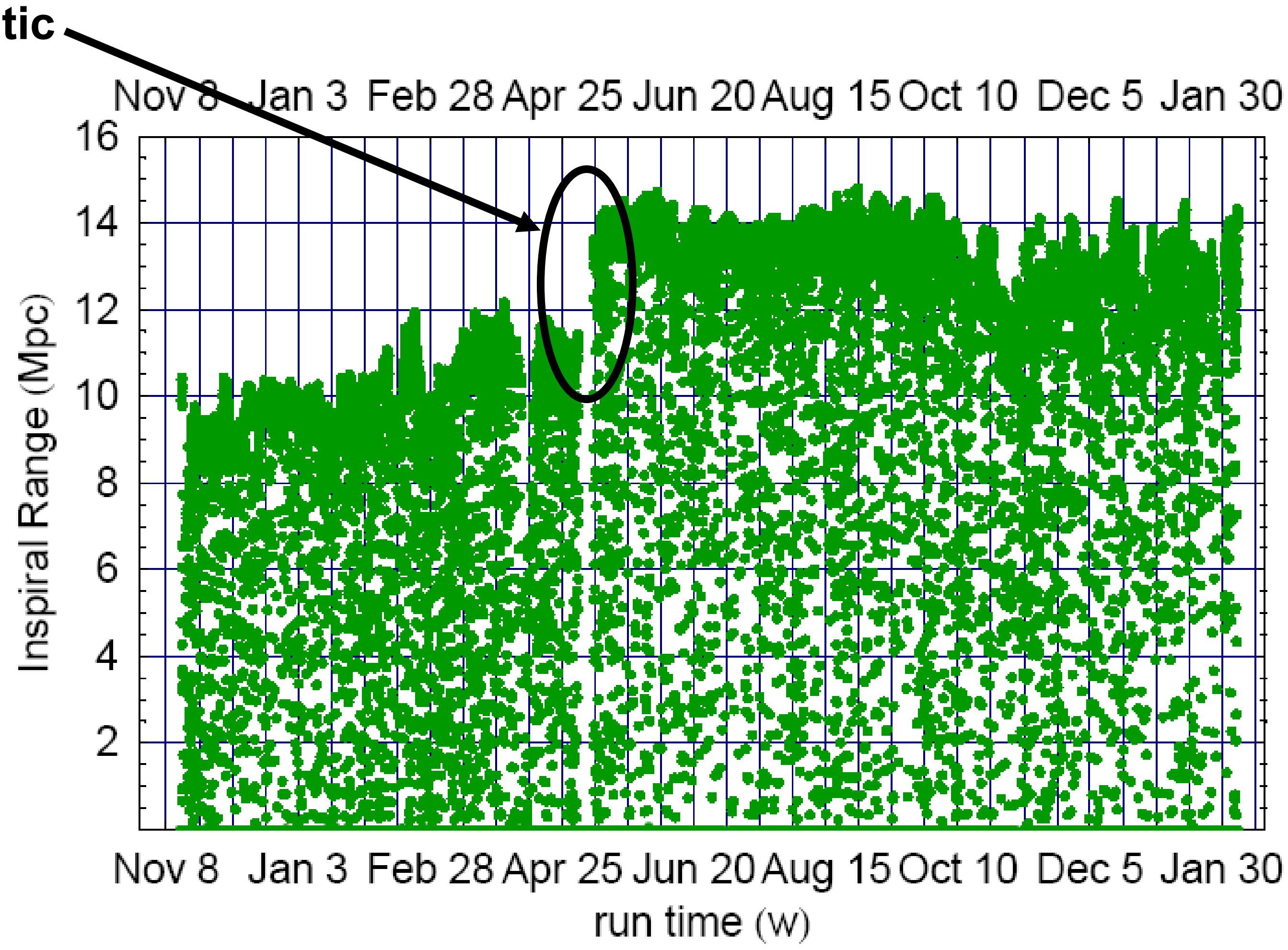


Commissioning

Local Earthquake

Livingston 4km sensitivity during S5

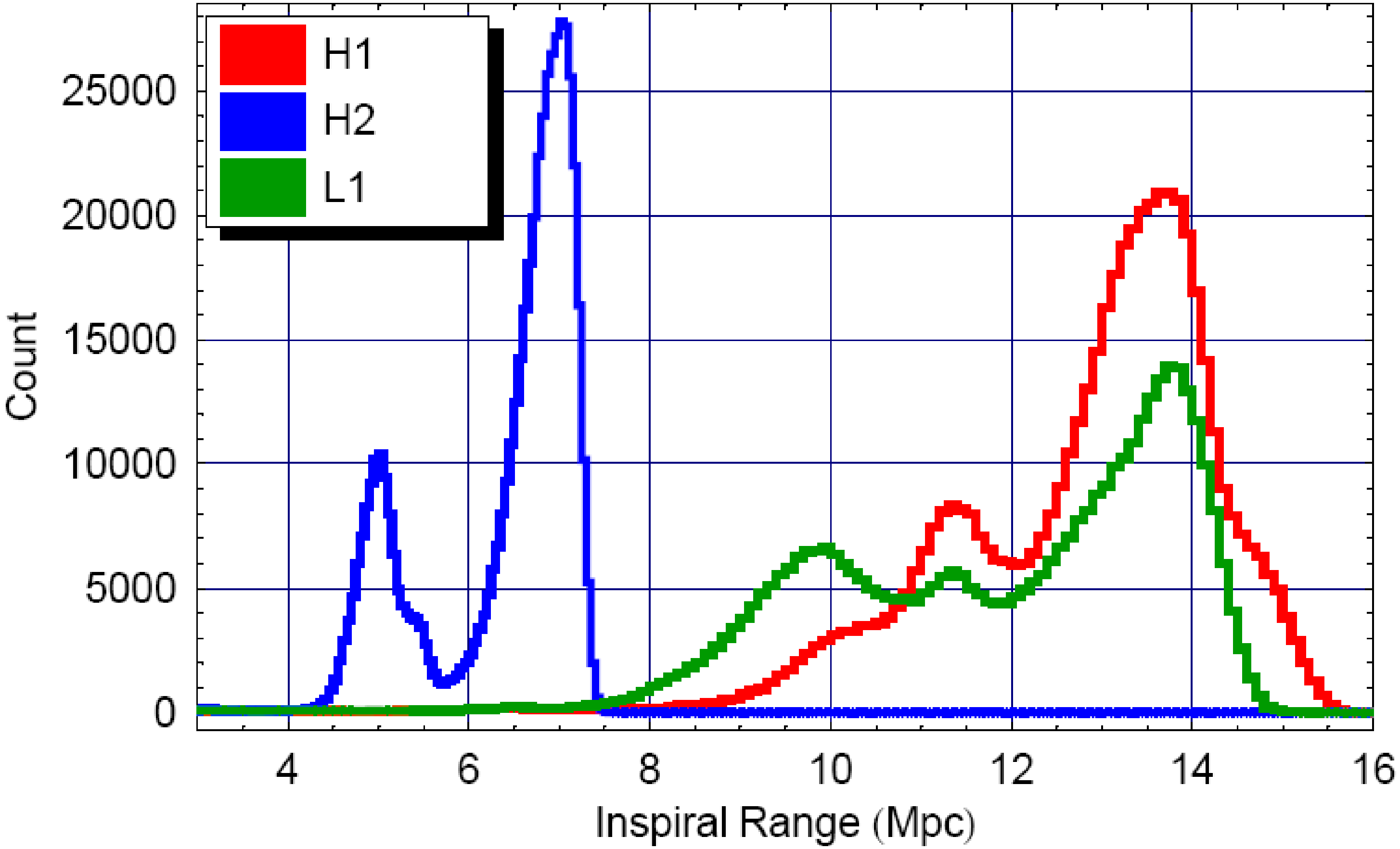
- Detectable range to randomly oriented 1.4, 1.4 solar mass binary neutron star inspiral at an SNR of 8.



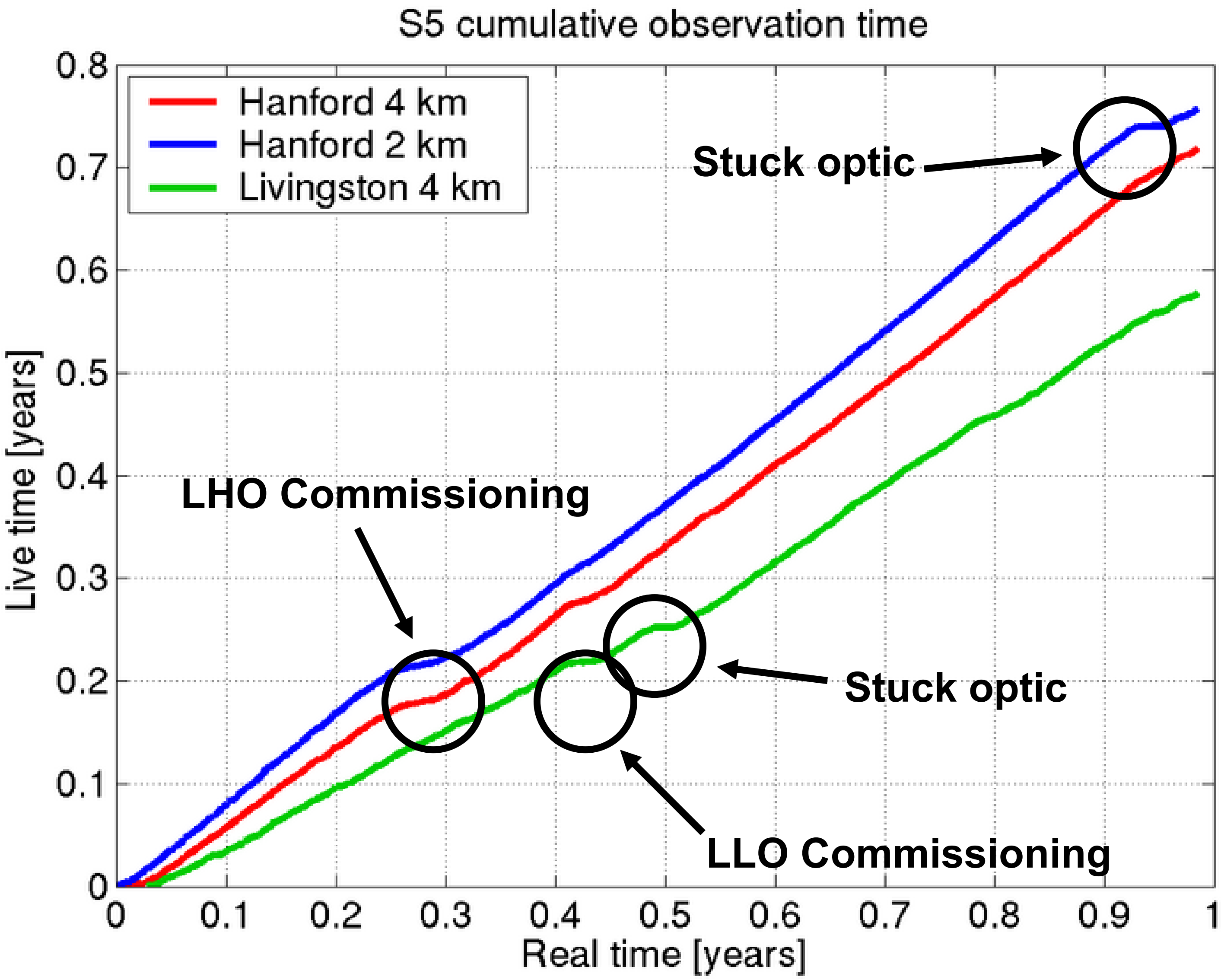
Stuck optic

Histogram of sensitivity during S5

- Detectable range to randomly oriented 1.4, 1.4 solar mass binary neutron star inspiral at an SNR of 8.



S5 detector observation time



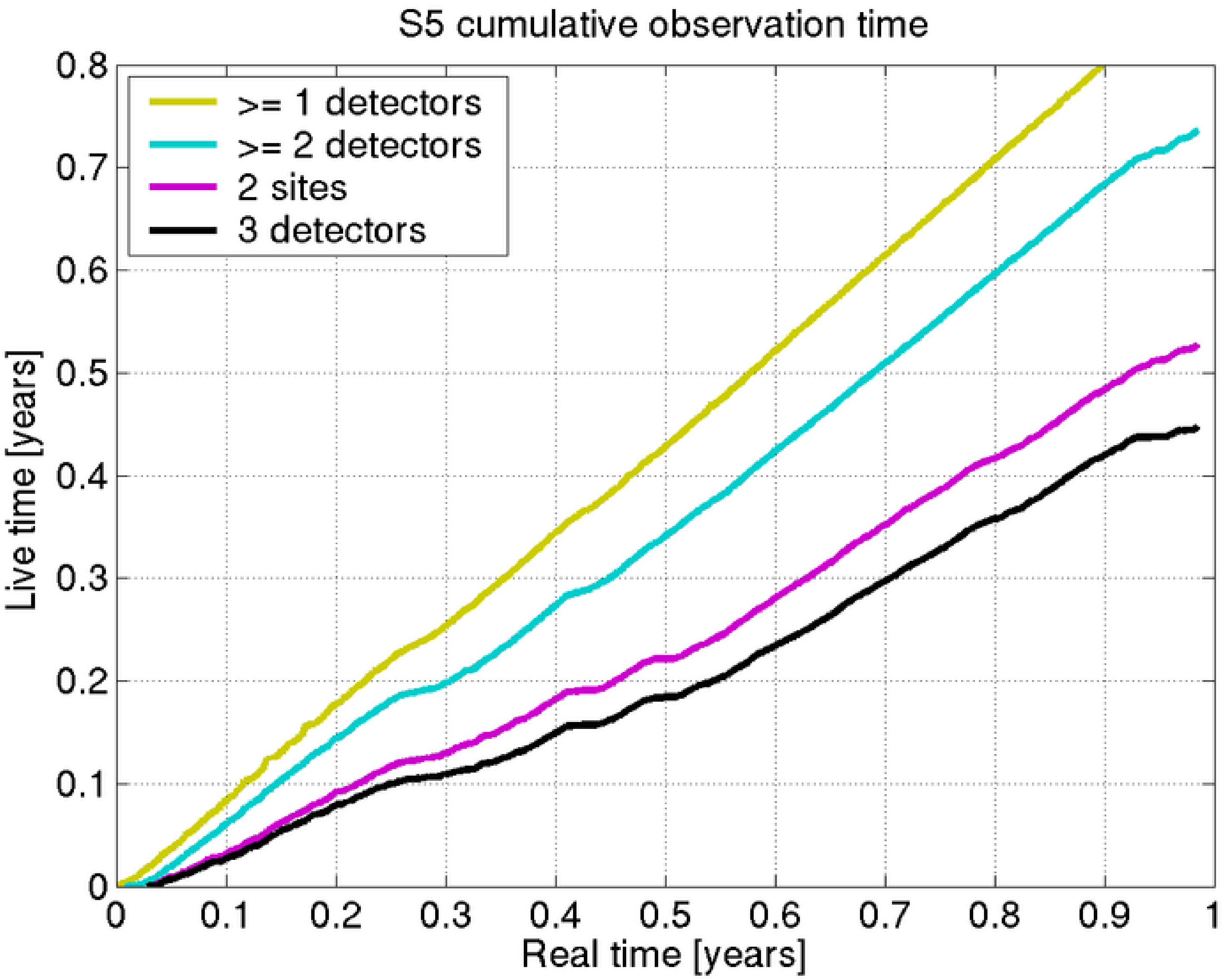
Stuck optic

LHO Commissioning

Stuck optic

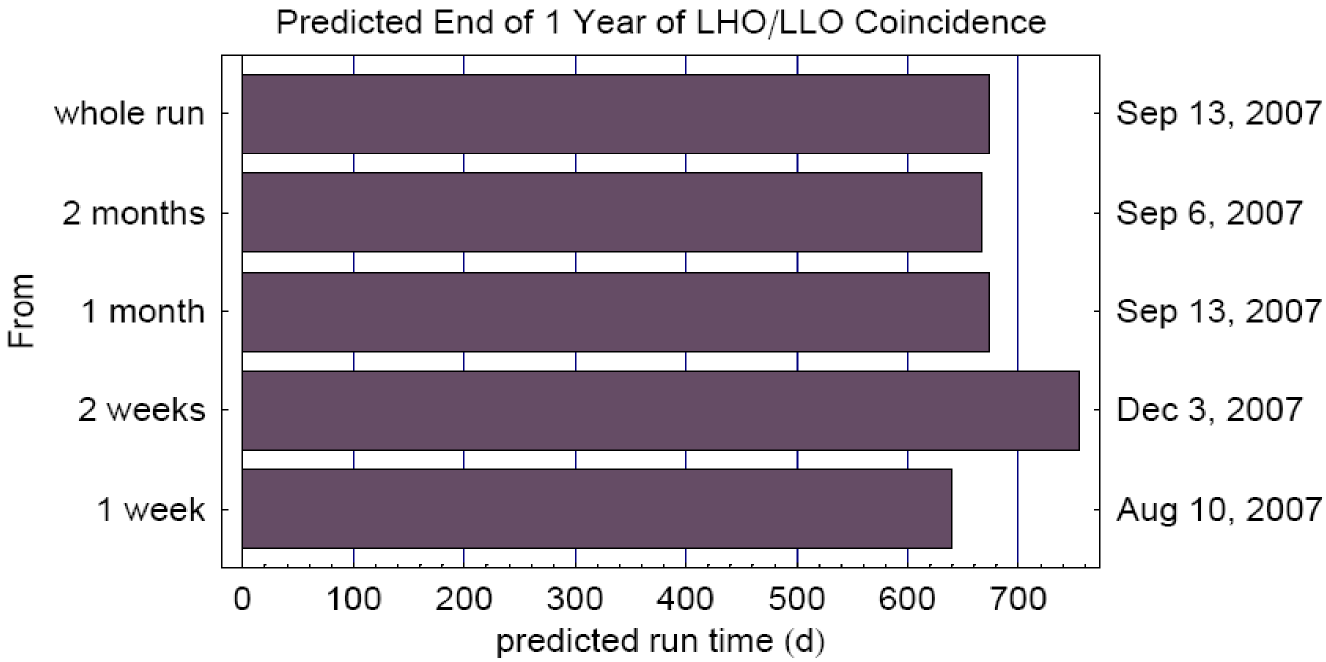
LLO Commissioning

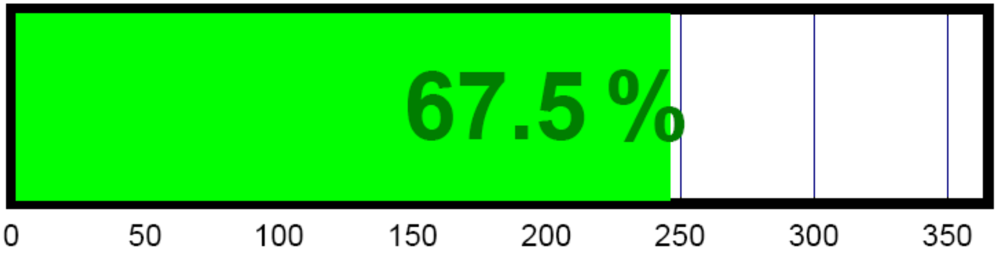
S5 network observation time



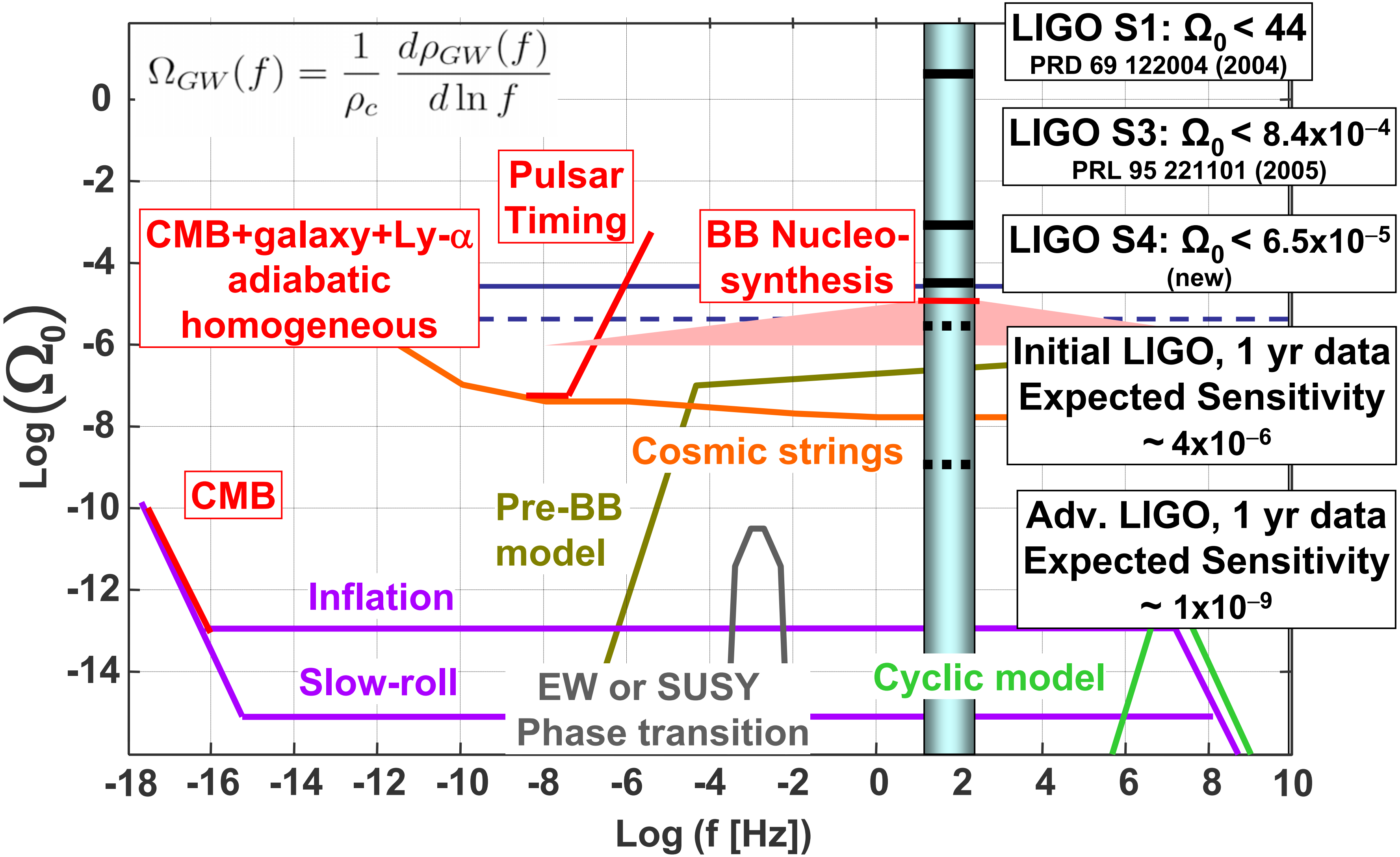
Predicted end of S5

- Extrapolated from two site coincident science mode duty cycle in the last week, 2 weeks, month, 2 months, and the entire run to dat





Sensitivity to stochastic sources



Sensitivity to periodic sources

- Joint 95% upper limits for 97 pulsars using ~10 months of the LIGO S5 run. Results are overlaid on the estimated median sensitivity of this search.

For 32 of the pulsars we give the *expected* sensitivity upper limit (red stars) due to uncertainties in the pulsar parameters .

Pulsar timings provided by the Jodrell Bank pulsar group

Lowest GW strain upper limit:

PSR J1802-2124

(f_{gw} = 158.1 Hz, r = 3.3 kpc)

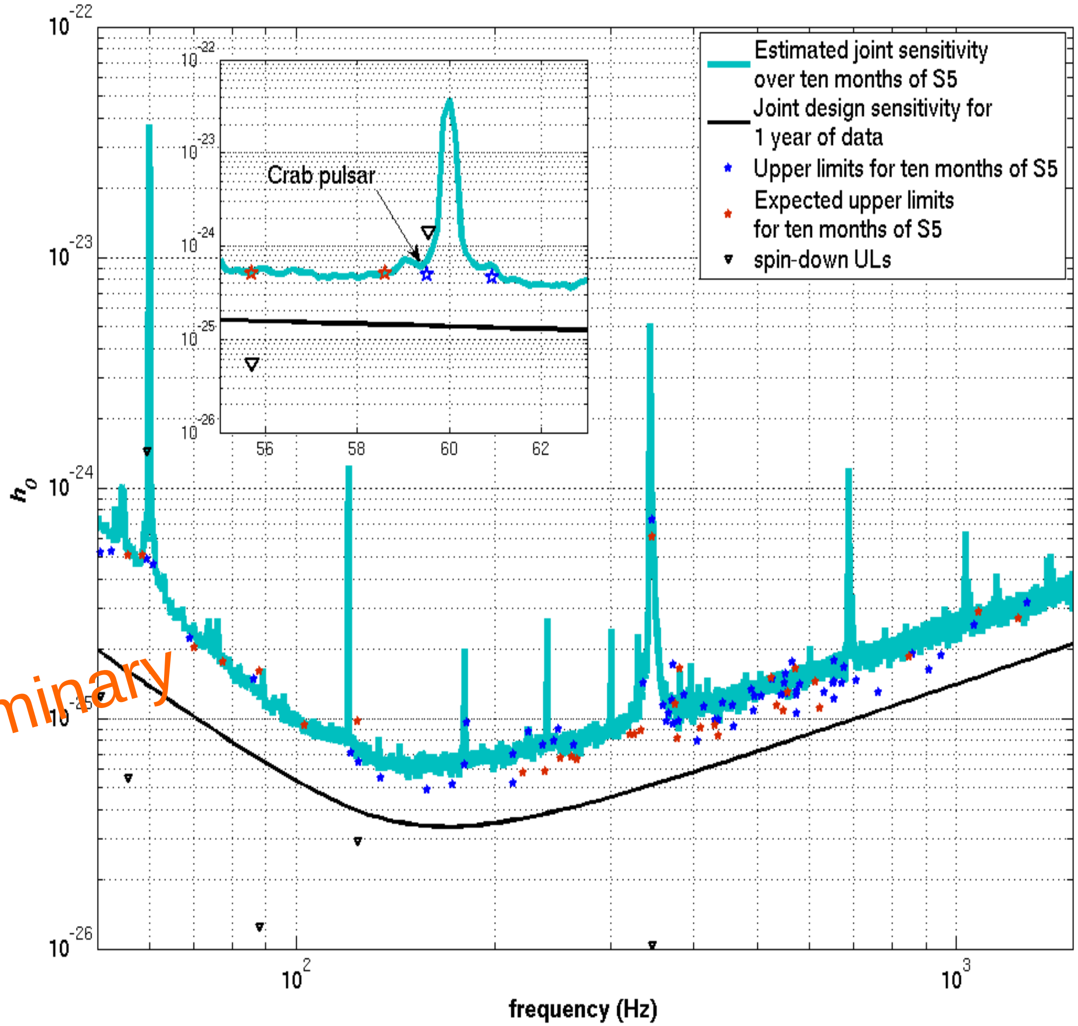
$\mathbf{h_0 < 4.9\times10^{-26}}$

Lowest ellipticity upper limit:

PSR J2124-3358

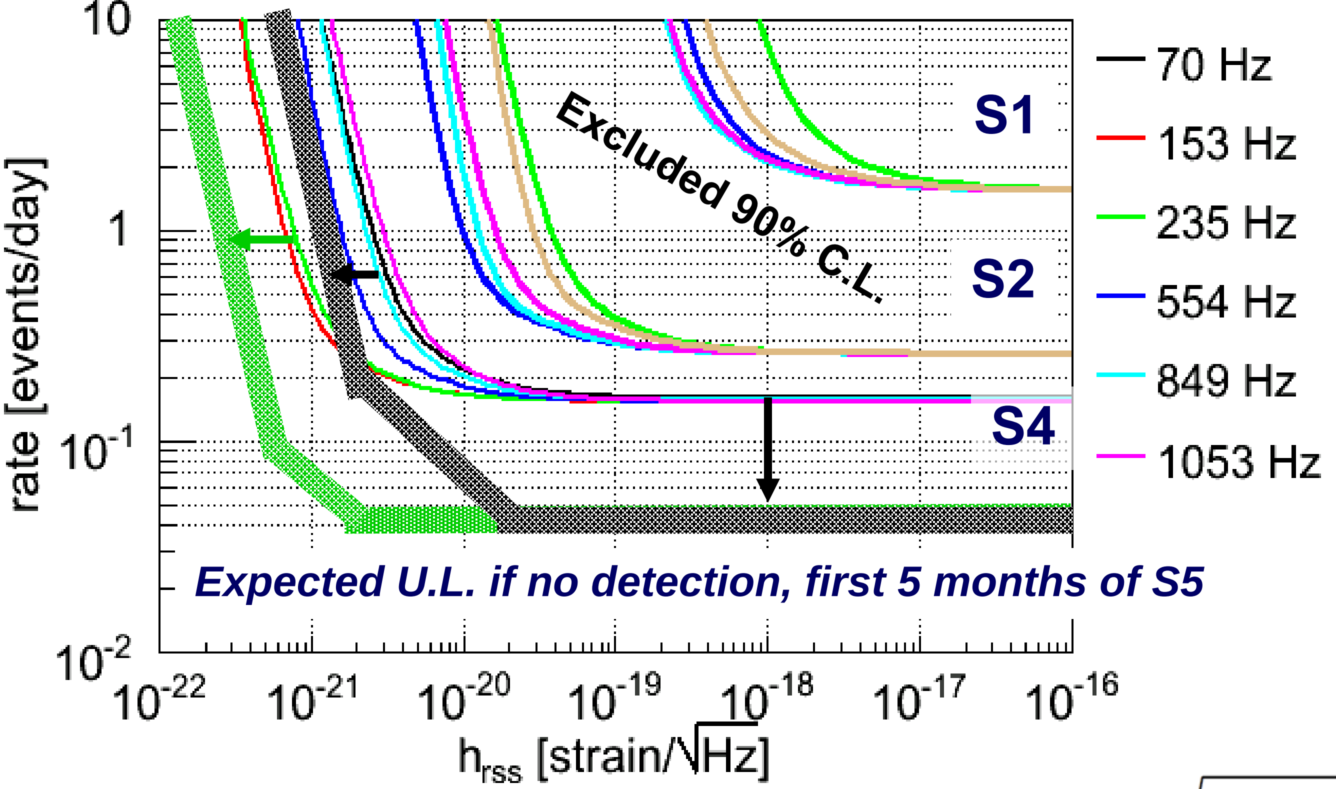
(f_{gw} = 405.6 Hz, r = 0.25 kpc)

$\boldsymbol{\varepsilon < 1.1\times10^{-7}}$



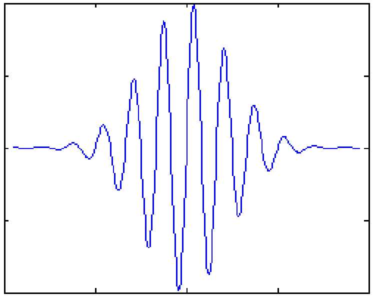
Sensitivity to burst sources

Sine-Gaussian waveforms, Q=8.9



Excluded 90% C.L.

Expected U.L. if no detection, first 5 months of S5



PRELIMINARY

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

We are sensitive to $E_{GW} \sim 0.1\ M_\odot c^2$ at 20Mpc @153Hz

Global Network

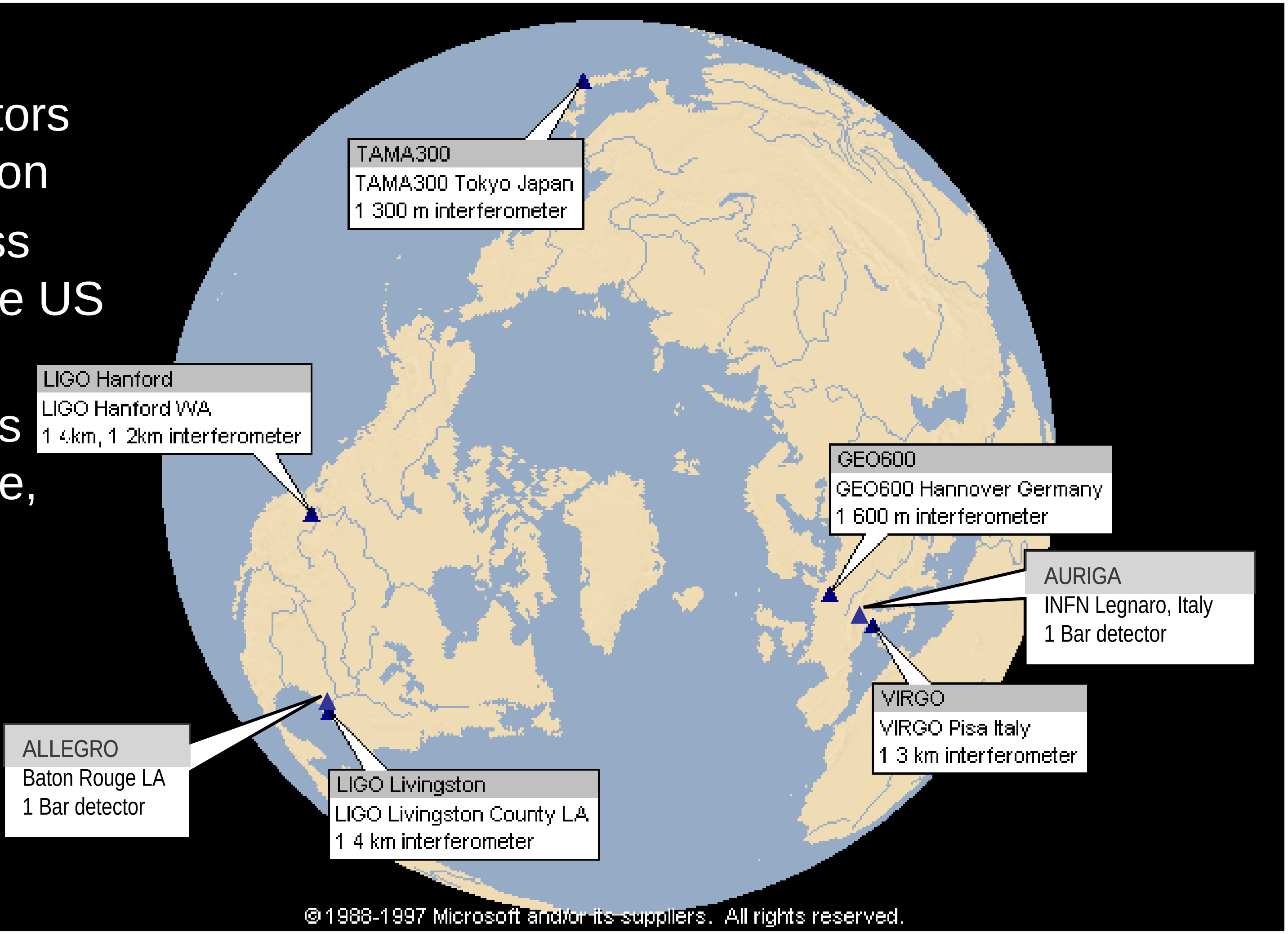
Detectors

Benefits of joint analysis

LIGO/Virgo agreement

The global detector network

- Several detectors now in operation
- Resonant mass detectors in the US and Europe
- Interferometers the US, Europe, and Japan



Benefits of a global network

- Improved sky coverage
    - Less likely that event occurs in null of detector network
- Improved duty cycle
    - More likely that at least one detector observes an event
- Improved search algorithms
    - Three non-aligned detectors permit fully coherent search
- Improved detection confidence
    - Multi-detector coincidence greatly reduces false rate
    - Coherent consistency tests can differentiate between gravitational-wave signals and instrumental glitches

Benefits of a global network

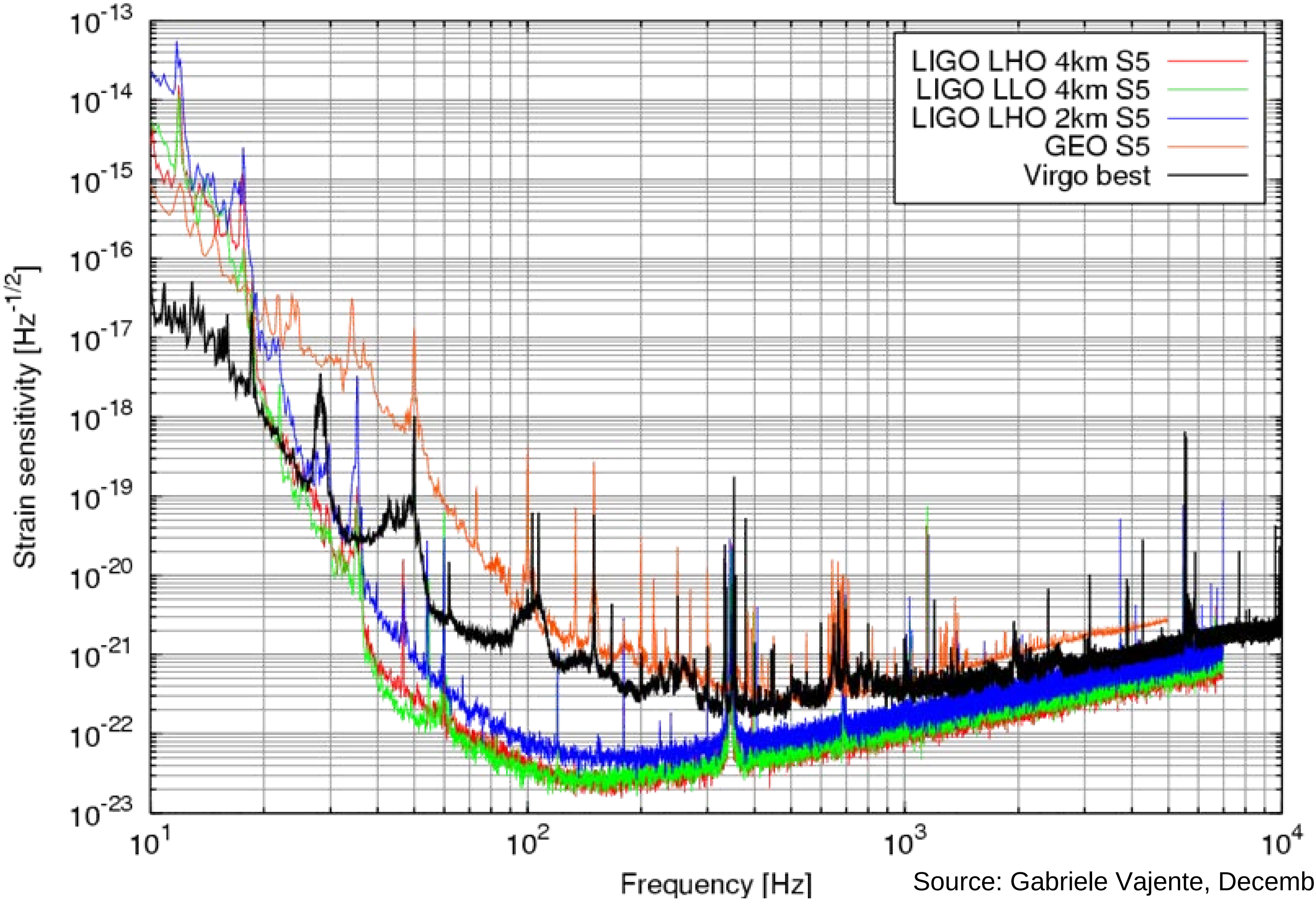
- Improved source reconstruction
  - Inverse problem requires three non-aligned detectors
  - Sky position reconstruction, waveform reconstruction, astrophysical parameter estimation, etc.
  - This is where the science is!
- Shared best practices
  - Learn from each other's approaches

LIGO/Virgo

- The LIGO Scientific Collaboration (LSC) and the Virgo collaboration have entered into an agreement that will lead to future joint analysis of data
- Joint data analysis group meetings are already taking place
- The first joint meeting of the LSC and Virgo will be this March
- The Virgo detector is currently in commissioning and focusing on a high frequency sensitivity comparable to the LIGO detectors
- Joint data analysis will begin when Virgo reaches roughly comparable sensitivity over a scientifically interesting frequency region.

- Joint data analysis exercises with simulated data have already been performed for the inspiral, burst, and stochastic analysis
- A prototype burst analysis of ~48 hours of real data is in progress

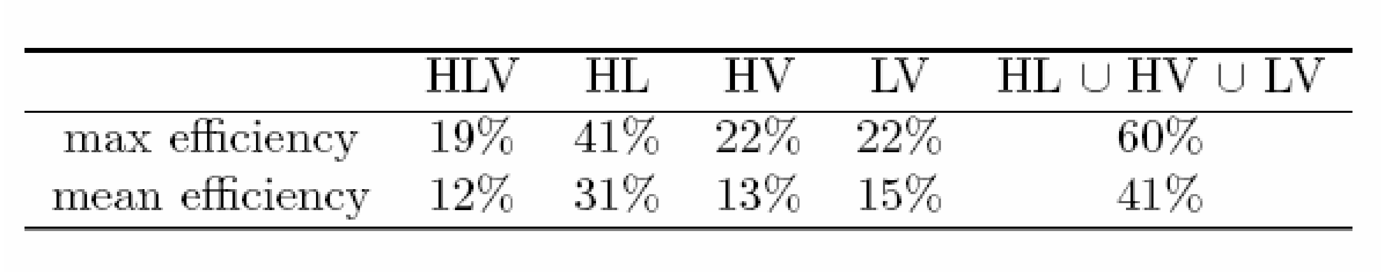
Sensitivity comparison



Source: Gabriele Vajente, December 2006

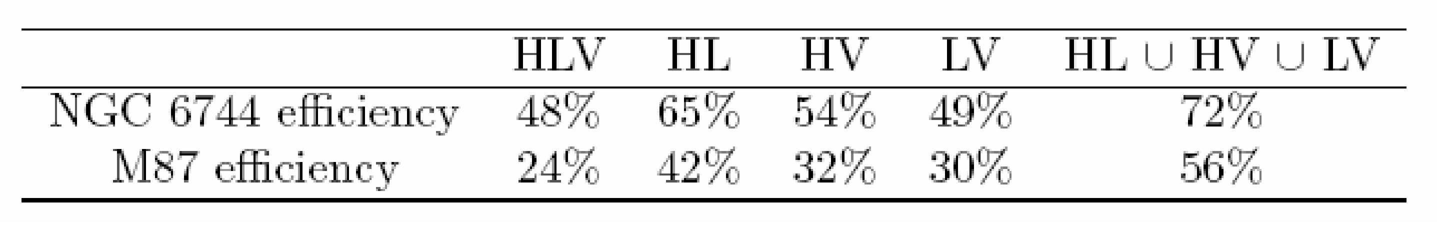
Coincident analysis strategies

- For coincident searches, union of double coincident detector networks provides improved performance
- Burst results for simulated supernovae in the direction of the galactic center at a 1 μHz false rate:



	HLV	HL	HV	LV	HL ∪ HV ∪ LV
max efficiency	19%	41%	22%	22%	60%
mean efficiency	12%	31%	13%	15%	41%

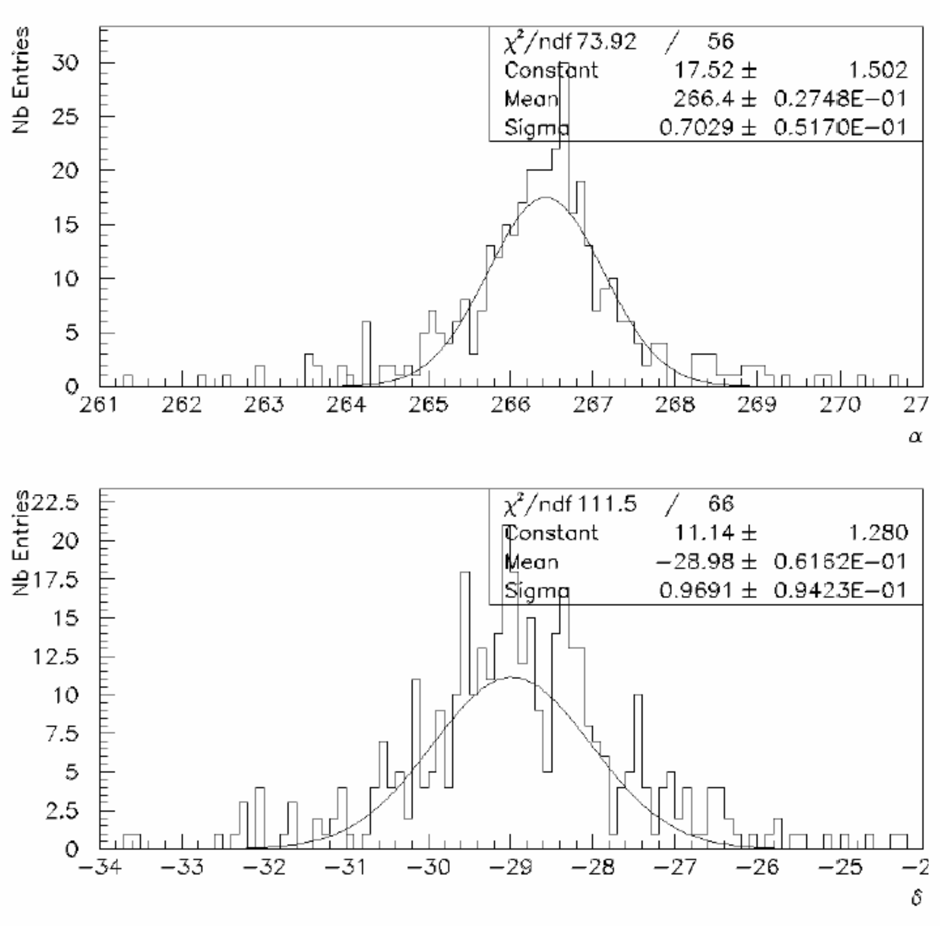
- Inspiral results for simulated signals from M87 and NGC 6744 at an SNR threshold of 6:



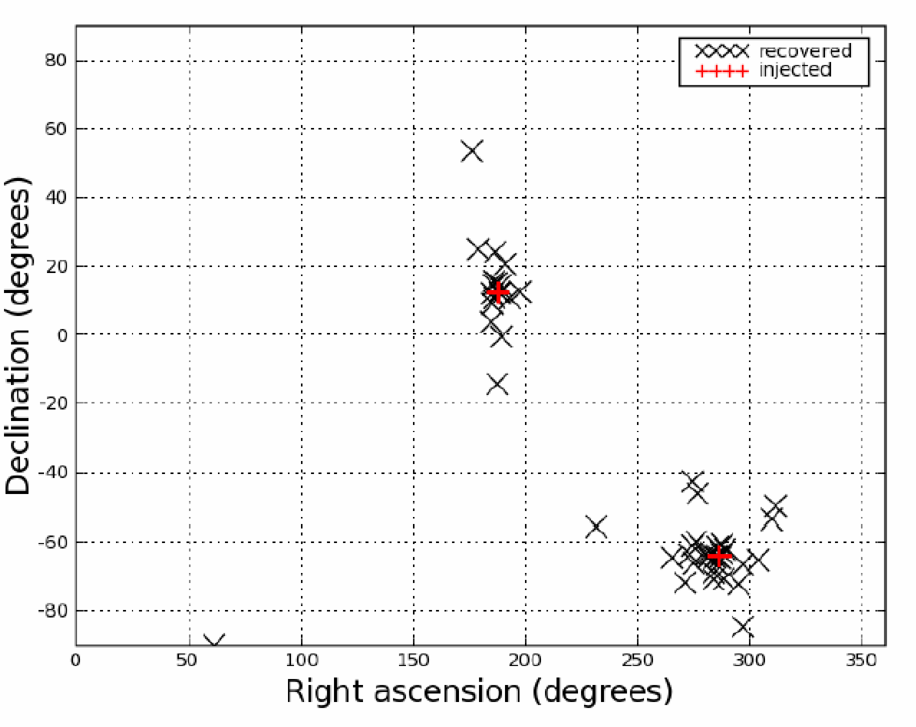
	HLV	HL	HV	LV	HL ∪ HV ∪ LV
NGC 6744 efficiency	48%	65%	54%	49%	72%
M87 efficiency	24%	42%	32%	30%	56%

Timing based recovery of sky position

Recovery of burst sky position



Recovery of inspiral sky position

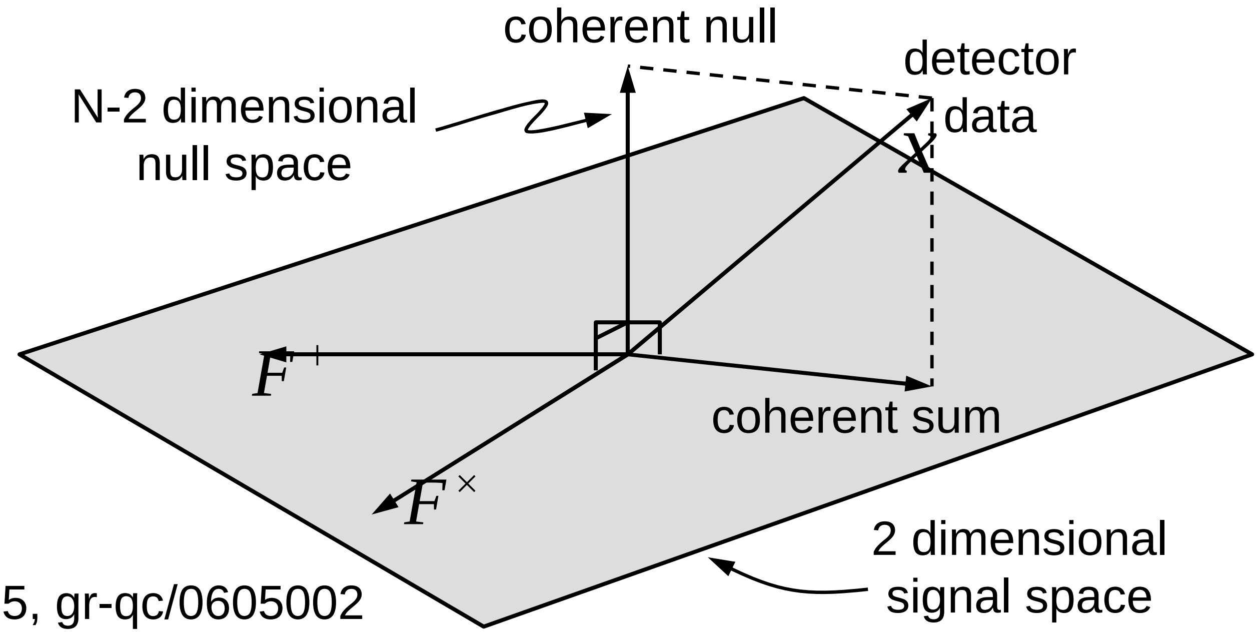


Fully coherent search methods

$$\begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_N \end{bmatrix} = \begin{bmatrix} F_1^{+} & F_1^{\times} \\ F_2^{+} & F_2^{\times} \\ \vdots & \vdots \\ F_N^{+} & F_N^{\times} \end{bmatrix} \begin{bmatrix} h_+ \\ h_\times \end{bmatrix} + \begin{bmatrix} n_1 \\ n_2 \\ \vdots \\ n_N \end{bmatrix}$$

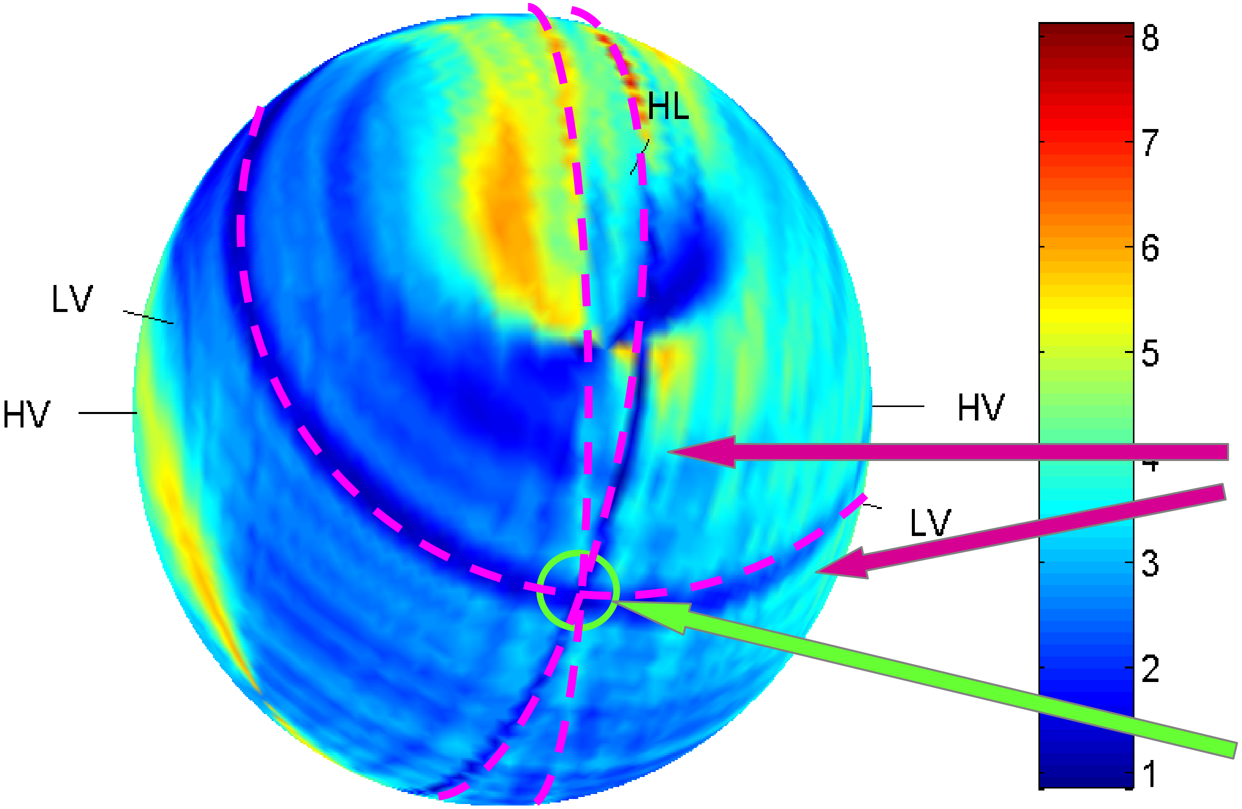
Coherent sum:
Find linear combinations of detector data that maximize signal to noise ratio

Null sum:
Linear combinations of detector data that cancel the signal provide useful consistency tests.



Phys.Rev. D74 (2006) 082005, gr-qc/0605002

Example: Supernova GWB



χ^2 / DOF consistency with a GWB as a function of direction for a simulated supernova (~1 kpc)

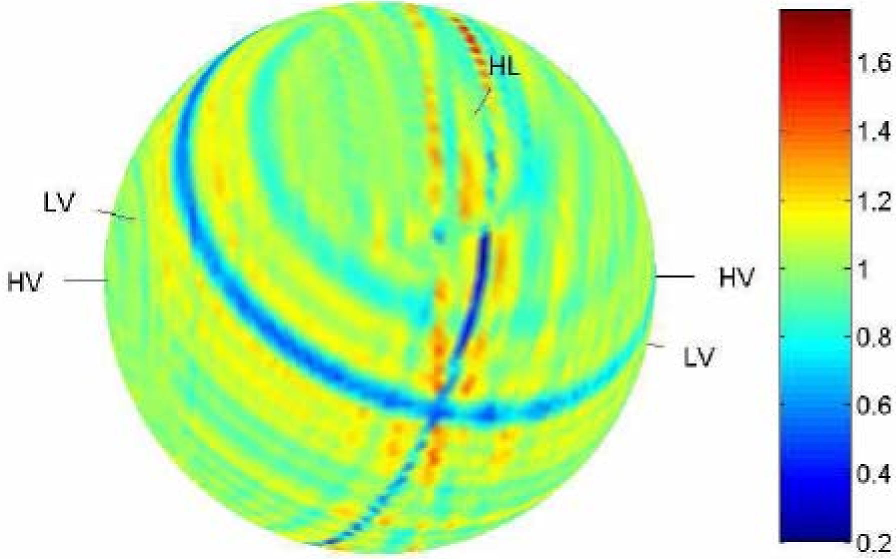
Interference fringes from combining signal in two detectors.

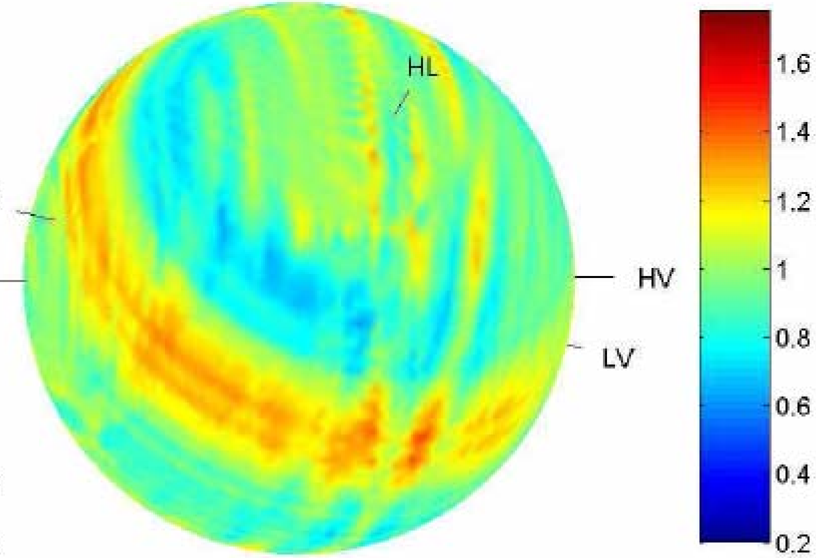
True source location:
– intersection of fringes
– χ^2 / DOF ~ 1

GWB: Dimmelmeier et al. A1B3G3 waveform, Astron. Astrophys. 393 523 (2002) , SNR = 20
Network: H1-L1-Virgo, design sensitivity

Example consistency sky maps

Simulated gravitational-wave burst

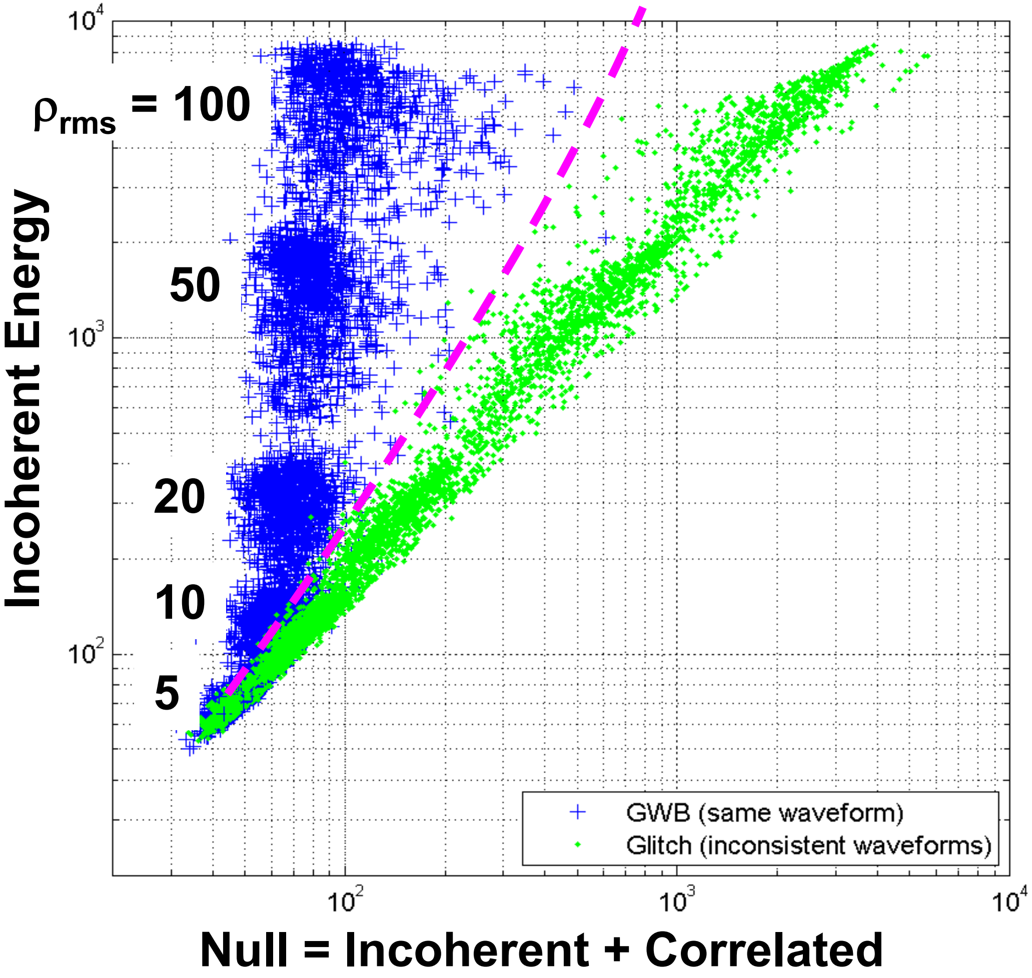




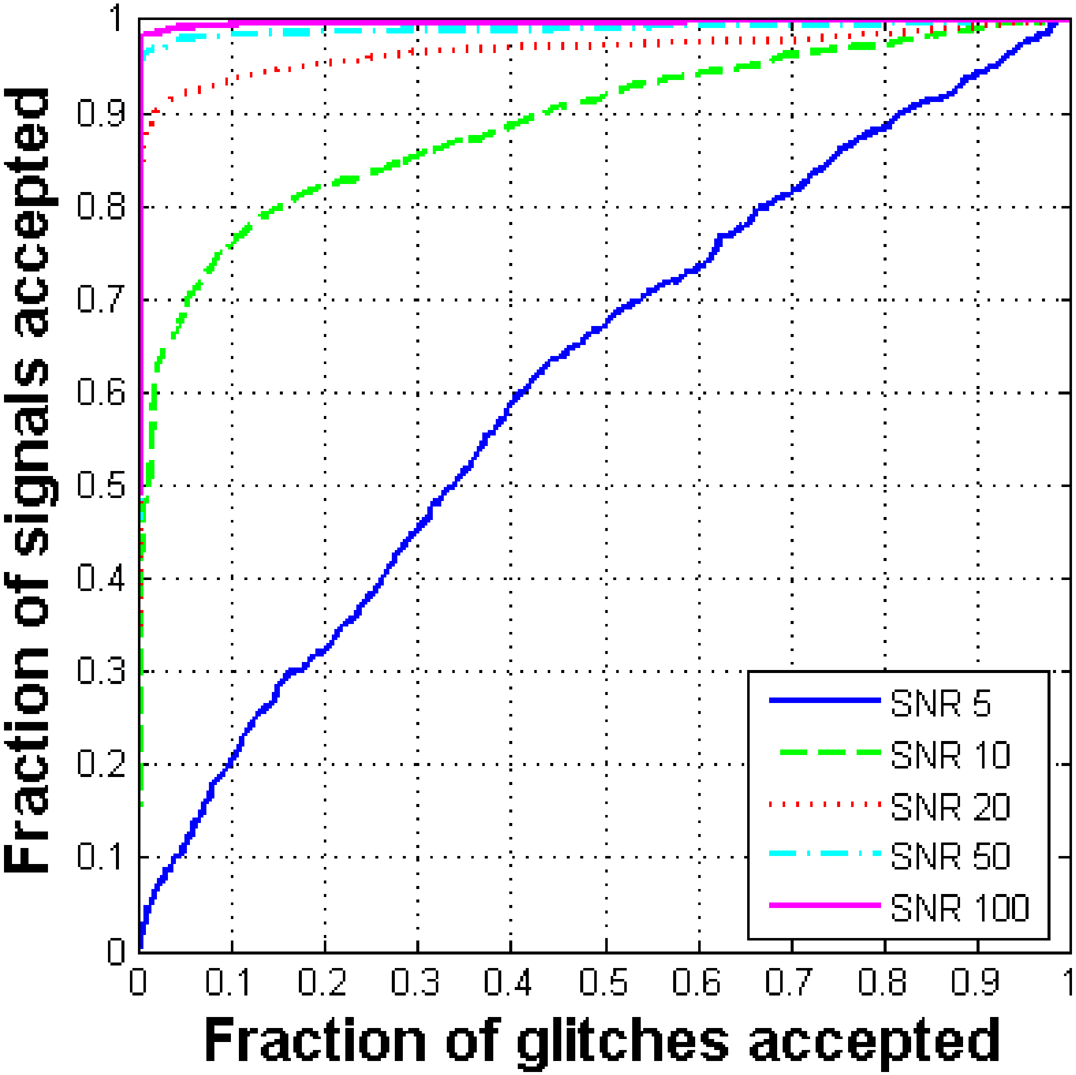
Simulated coincident glitch

Example: 5000 bursts vs. 5000 glitches

- One point from each simulation.
  - sky position giving strongest cancellation
- GWB and glitch populations clearly distinguished for SNR > 10-20.
- Similar to detection threshold in LIGO.



Distinguishing signals from artifacts



Simple example: collocated detectors

- The two LIGO Hanford detectors (H1H2) can be combined to form two new detector data streams

H+ The optimal linear combination that maximizes the signal to noise ratio of potential signals.

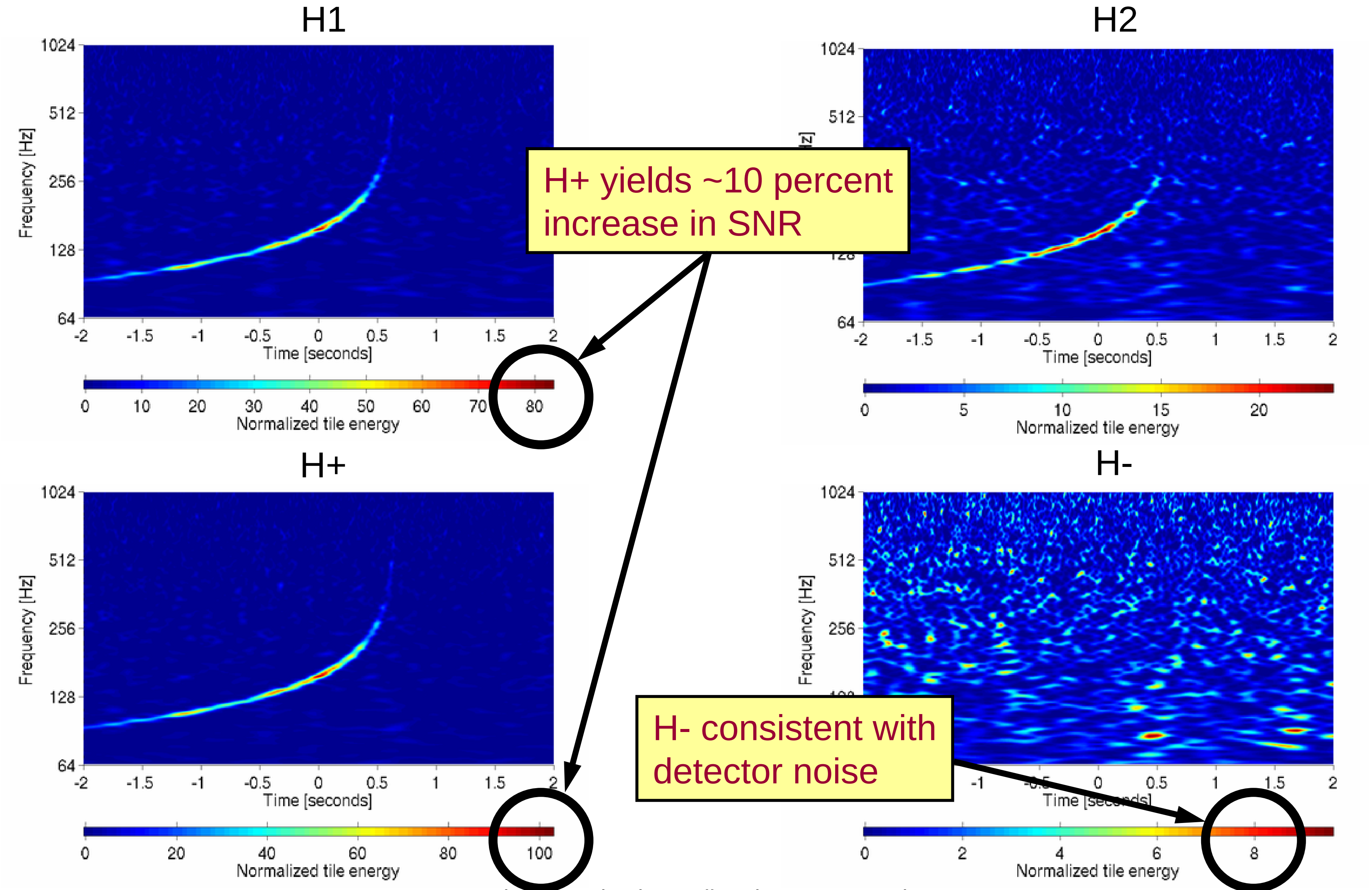
$$H_{+} = \left(\frac{1}{S_1} + \frac{1}{S_2} \right)^{-1} \left(\frac{H_1}{S_1} + \frac{H_2}{S_2} \right)$$

  - Weighting is inversely proportional to detector noise S
  - Resulting SNR is the quadrature sum of SNRs

H- The null stream, which should be consistent with noise in the case of a true gravitational-wave

$$H_{-} = H_1 - H_2$$

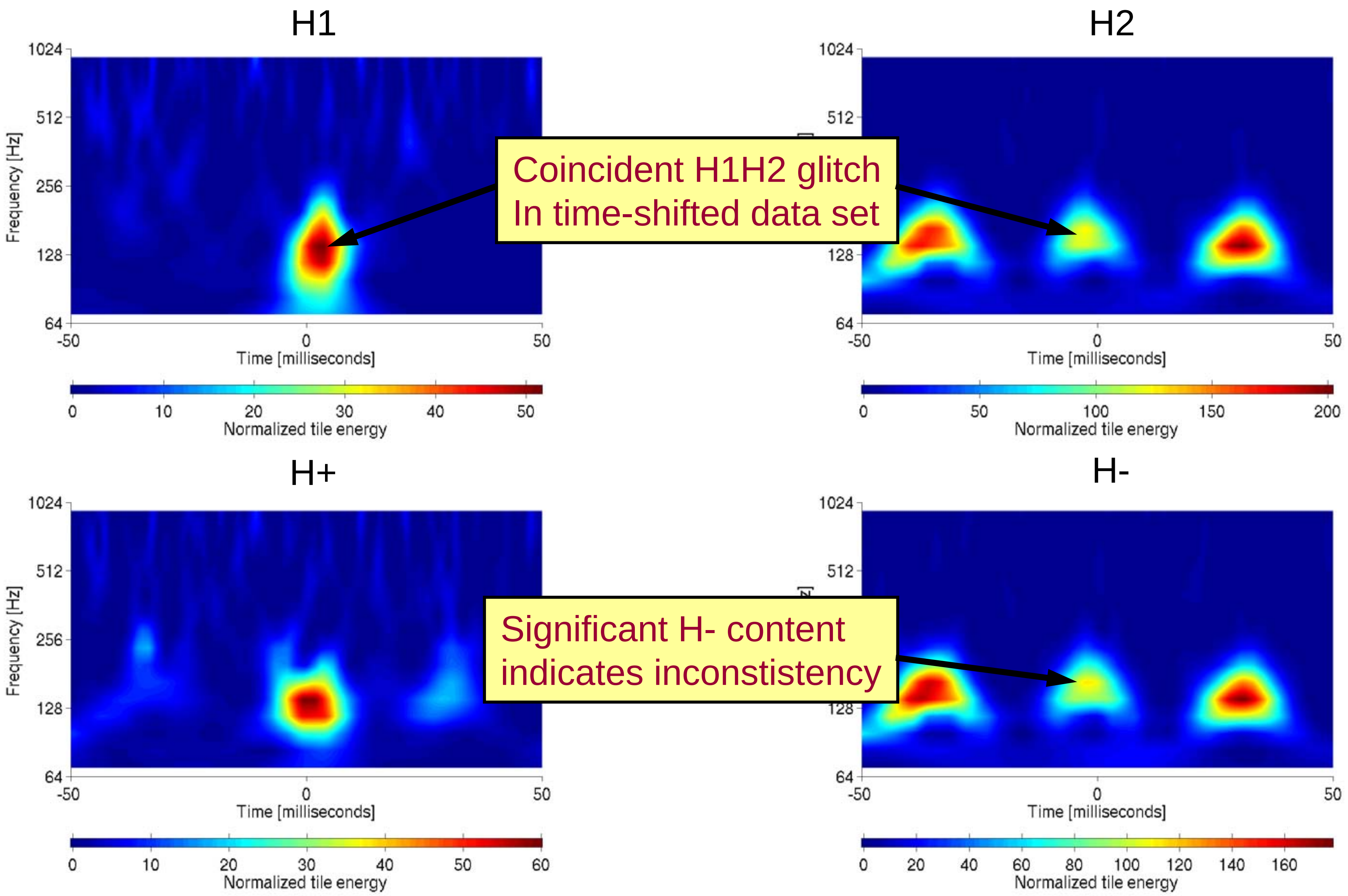
H1H2 example: Inspiral at 5 Mpc



H+ yields ~10 percent increase in SNR

H- consistent with detector noise

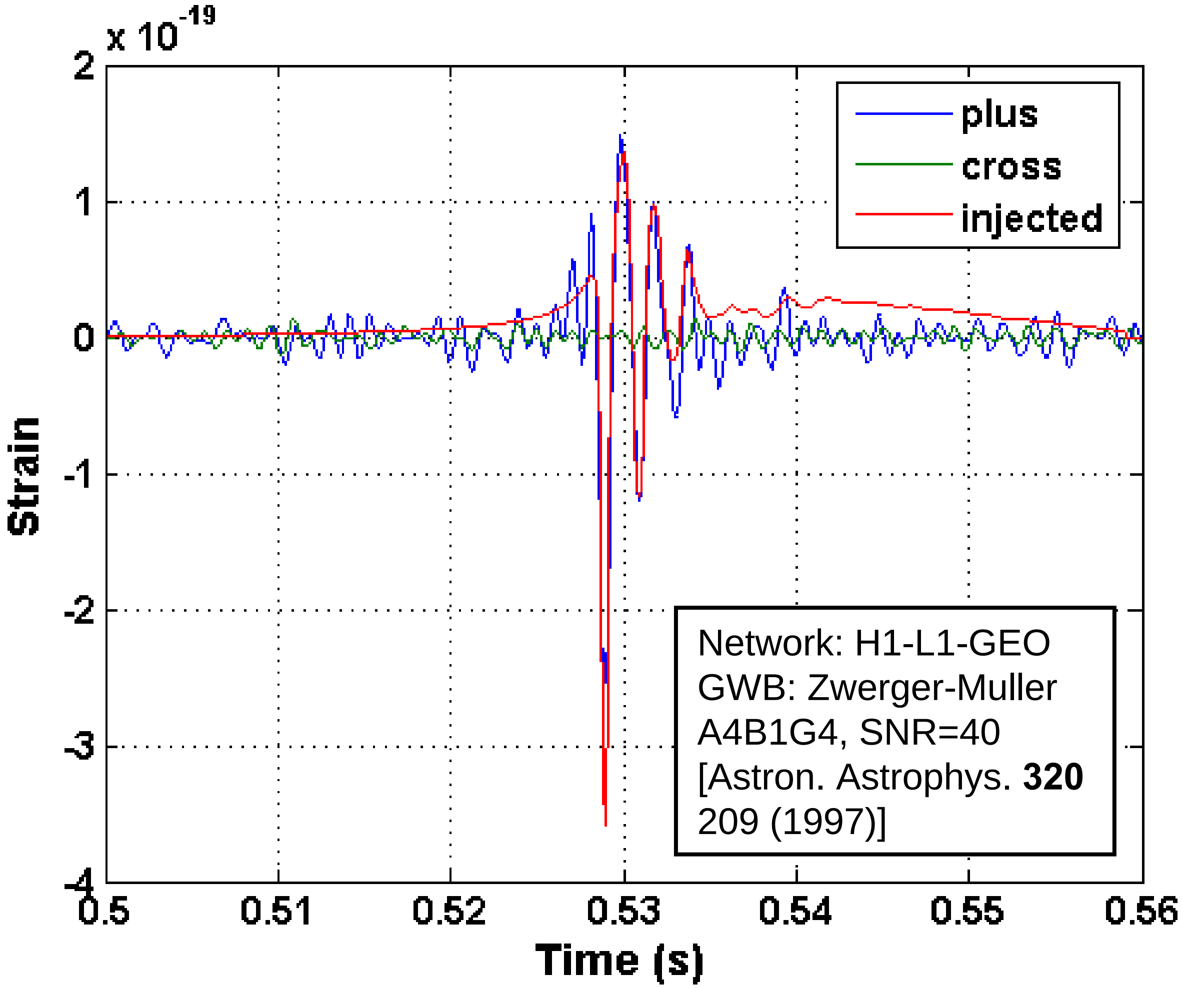
H1H2 example: time shifted glitch



Coincident H1H2 glitch
In time-shifted data set

Significant H- content
indicates inconsistency

Simulated waveform recovery



Network: H1-L1-GEO
GWB: Zwerger-Muller
A4B1G4, SNR=40
[Astron. Astrophys. **320**
209 (1997)]

Recovered signal (blue) is a noisy, band-passed version of injected GWB signal (red)

Injected GWB signal has $h_x = 0$.

Recovered h_x (green) is just noise.

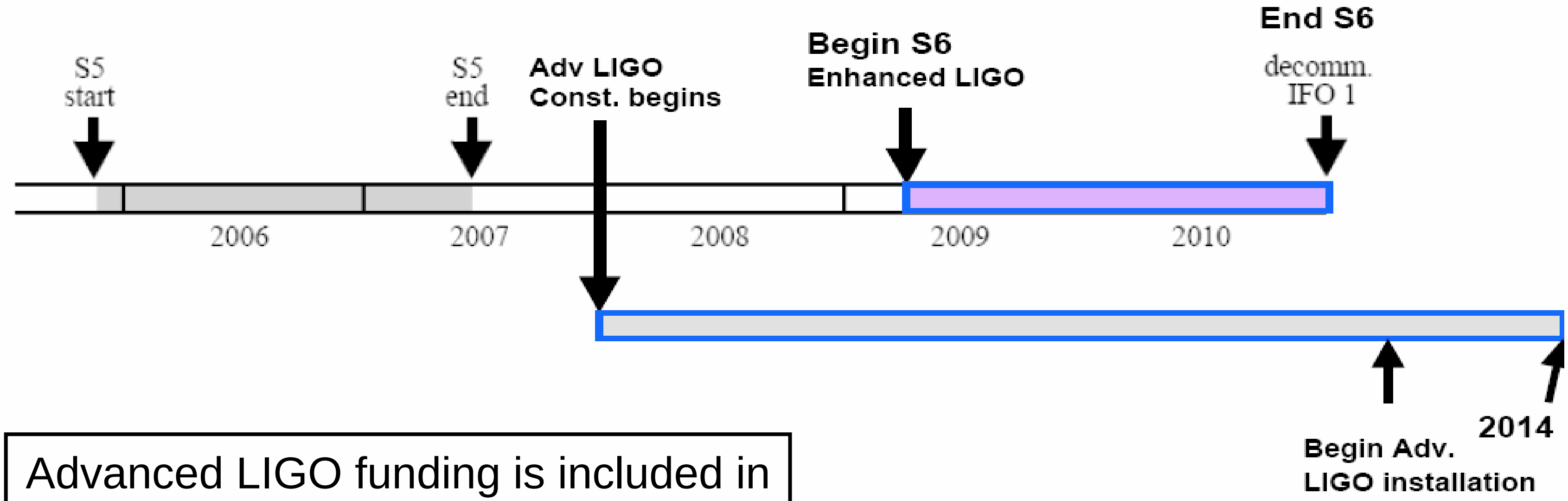
Future

Advanced detectors

Space based detectors

Enhanced and advanced LIGO

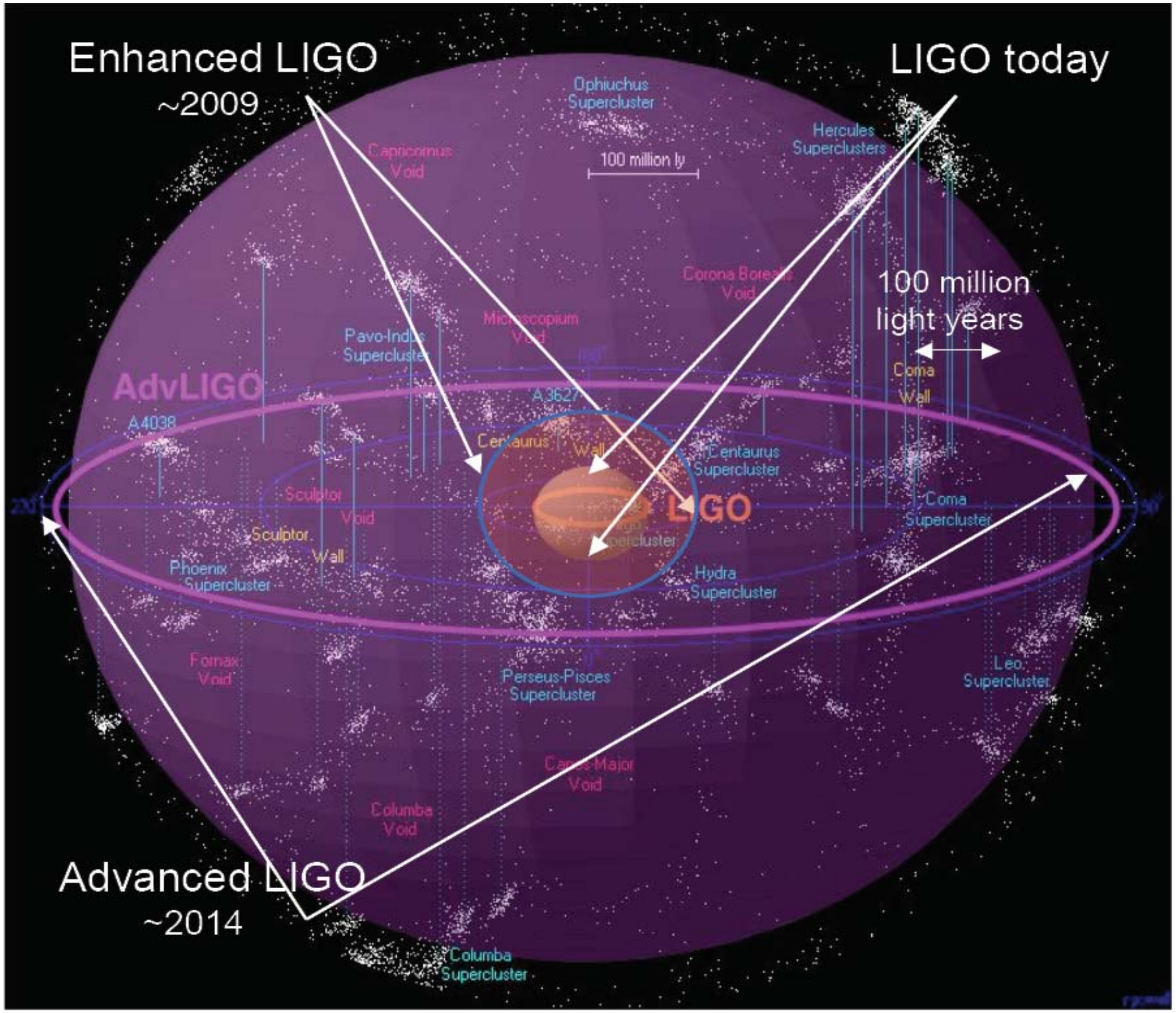
- Planning for both enhanced LIGO and advanced LIGO is already well underway.
- Expect factor of ~2 increase in strain sensitivity and ~8 increase in volume sensitivity for enhanced LIGO
- Expect factor of ~10 increase in strain sensitivity and ~1000 increase in volume sensitivity for advanced LIGO



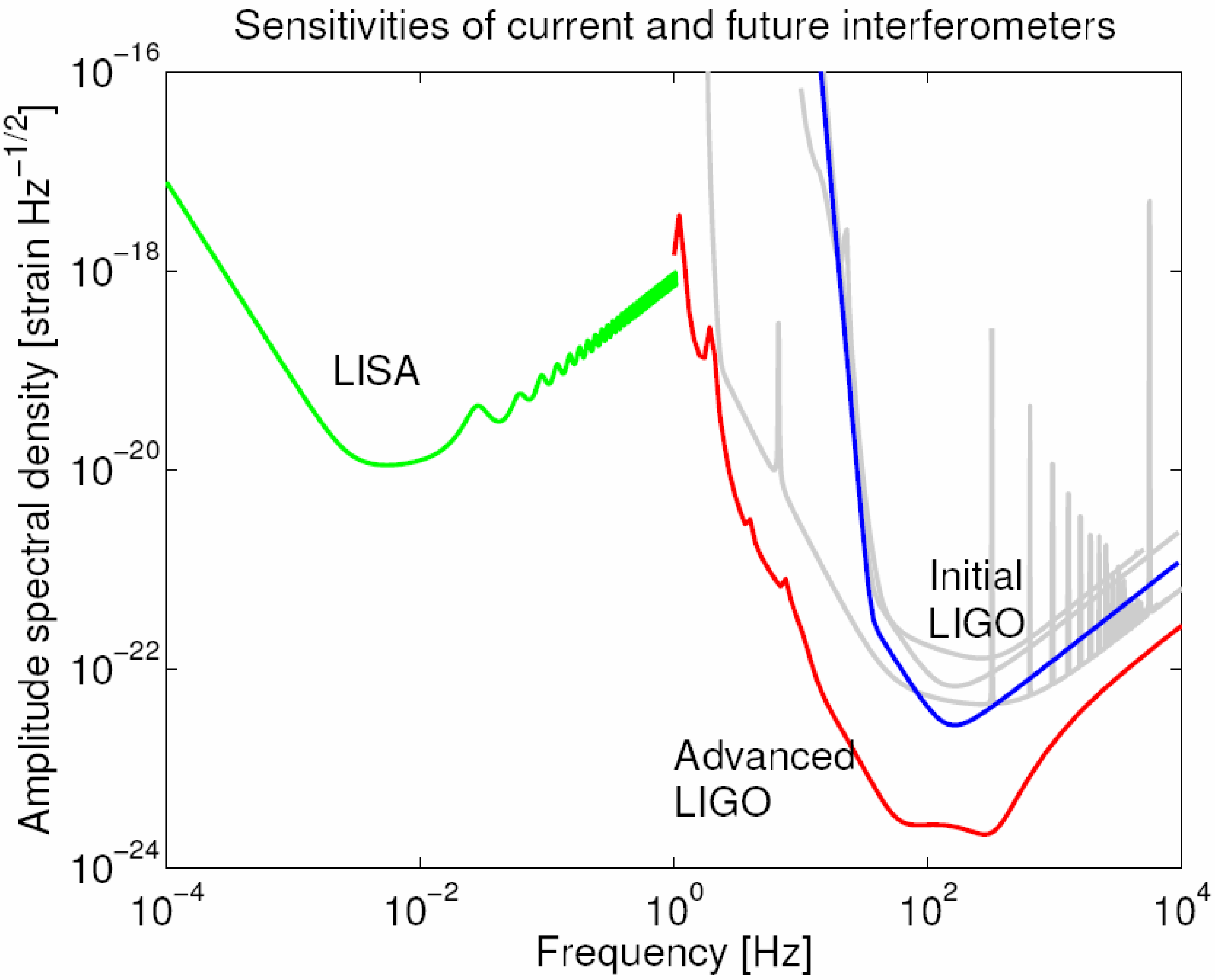
Advanced LIGO funding is included in The president's 2008 budget request!

Enhanced and advanced LIGO

- Predicted detectable range to binary neutral star inspirals.



Future observatories



Future prospects

- Initial LIGO sensitivity:
  - Core collapse supernovae within the Milky Way
  - Binary black hole mergers in the Virgo cluster
  - Interesting chance of detection
  - Perhaps constrain more optimistic population models
- Advanced LIGO sensitivity:
  - Binary black hole mergers at cosmological distances!
  - Absence of a detection is surprising and interesting!
- Coherent network searches will be able to take advantage of a detection to extract astrophysical information and test theory.

> “Last August, the bookmaker Ladbrokes offered the public a chance to bet on science. When the betting opened, Ladbrokes was offering odds of 500/1 that gravitational waves would be detected by LIGO before 2010. When the betting closed a few weeks later the odds had shortened to 2/1.”
>
> — Physics World, January 2005