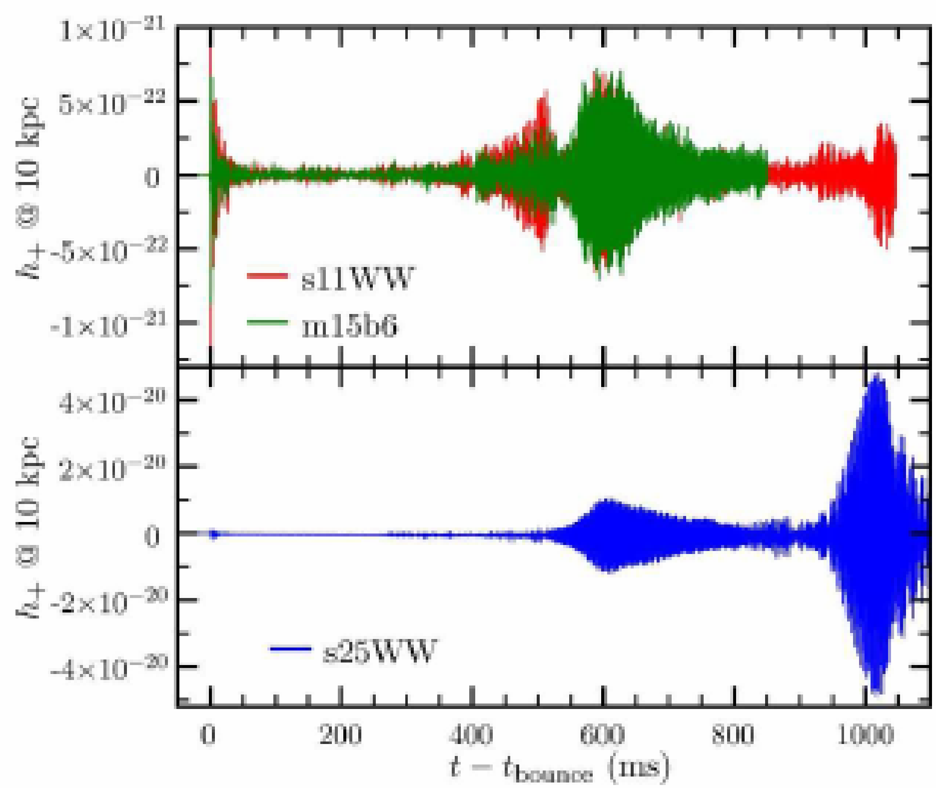
Listening the Bursting Universe with Gravitational Waves

Erik Katsavounidis
MIT
May 31, 2007
Universita' di Roma – Tor Vergata

Observing the Universe



Ott, Burrows, Lessart, Livne, 2006

Iicholas Suntzeff, this conference

J. Van der Velde, this conference

- Electromagnetic waves
- Particles: neutrinos, cosmic rays
- Gravitational waves

Outline

- Gravitational waves: concepts and sources
- Gravitational wave detectors
- Searches for gravitational waves bursts
- Network of gravitational wave detectors
- Advanced detectors
- Conclusions

The theory of gravitational radiation

- Einstein's general relativity

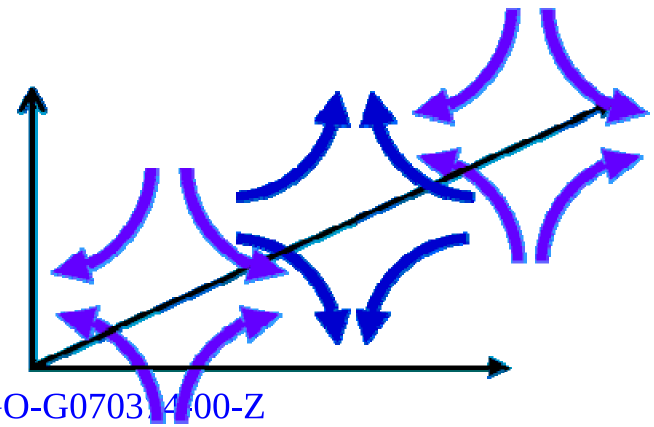
$$G_{\mu\nu} = 8\pi T_{\mu\nu}$$

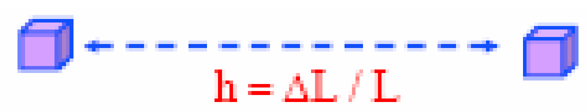
- Gravity is not a force, but curvature of space-time
- When matter moves or changes its configuration, a wave of space-time curvature arise

  $g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$

$$\left(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right) h = 0$$

- Waves propagate at the speed of light
- They distort space itself: stretching one direction and squeezing the perpendicular in the first half period and vice versa in the second half
- They have two polarizations, the "plus" and "cross"





Generating Gravitational Waves

- Existence of gravity waves only of formal interest if there were no ways to generate them!
- Changing quadrupole moment of mass ($Q \sim Mx^2$)
- Estimate strain at distance r away:
  - » $h \sim (c/r)\, Q'' \, 1/(c^5/G)$ ← 'standard' power, 10^{52} J/s
  - » laboratory-generated gravitational radiation, e.g., a rotating dumbbell (1ton, 2m, 1kHz): power radiated ~ 10^{-16} J/sec or h at $r \sim \lambda$ of 10^{-38} !!
  - » Only real hope for studying gravity waves is to look to processes of astrophysical and cosmological magnitude
- Astrophysical dumbbells=binary stars, expected strain:

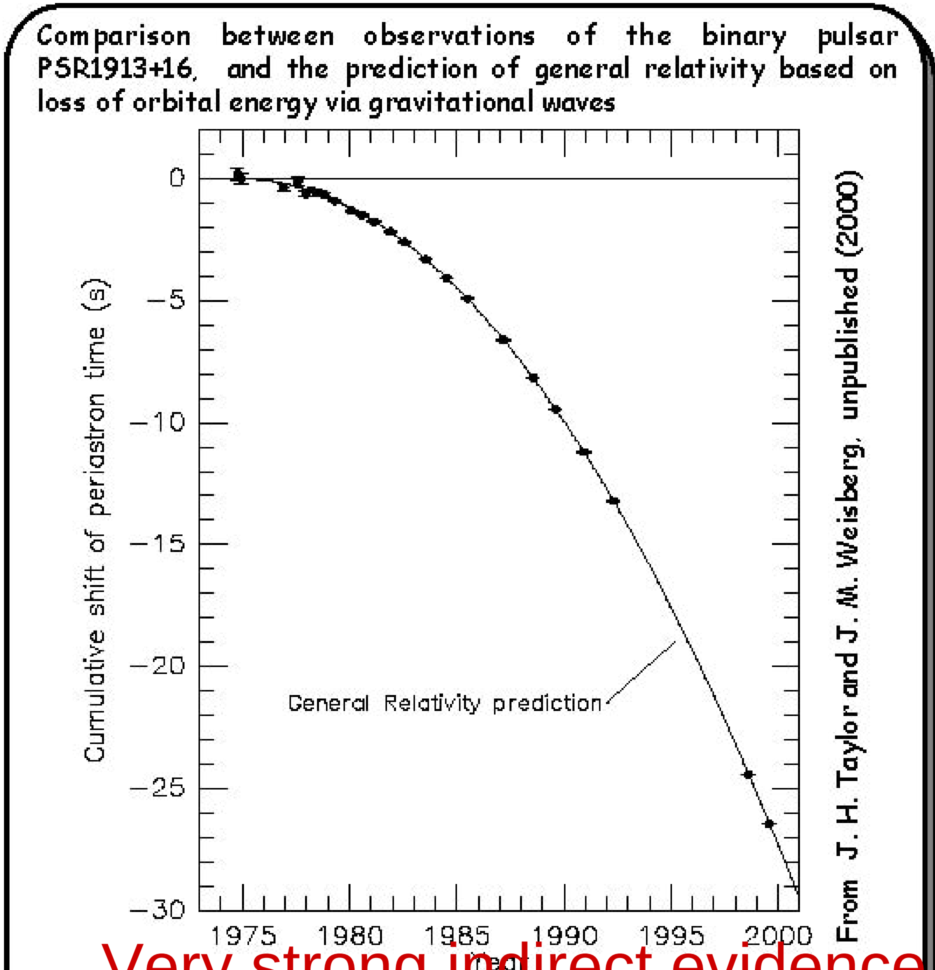
$|h| = 32\pi^2 G/c^4 \, f^2 M r^2 / R$ ...plug in some numbers...

$M = 1.4\, M_o$, $f \sim 400$Hz, $r = 20$km,

$R \sim 15$Mpc => $h \sim 10^{-21}$ ($\delta L/L$)

The Evidence for Gravitational Waves

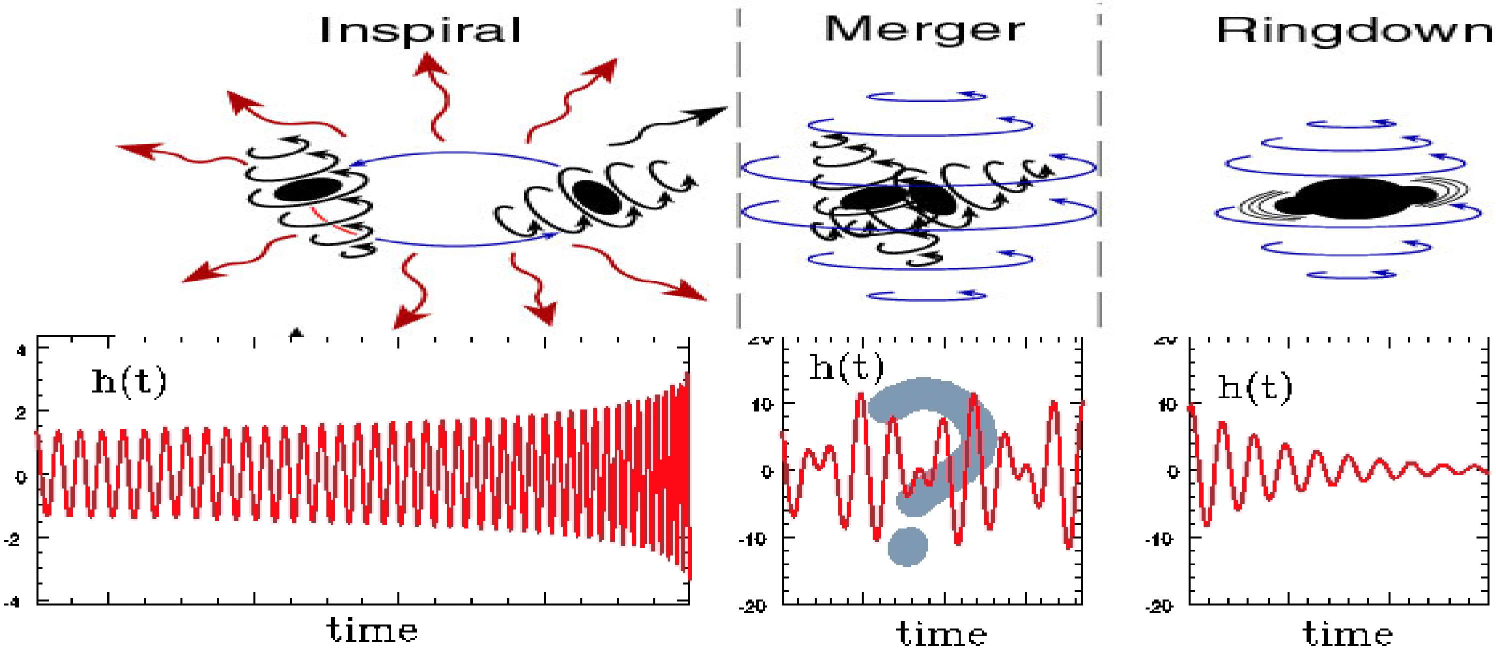
- **Radio pulsar B1913+16, discovered in 1974 by Hulse and Taylor as part of a binary system**
- **Long-term radio observations have yielded neutron star masses and orbital parameters**
- **System shows very gradual orbital decay just as general relativity predicts!**



Very strong indirect evidence for gravitational radiation

Gravitational wave sources: 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

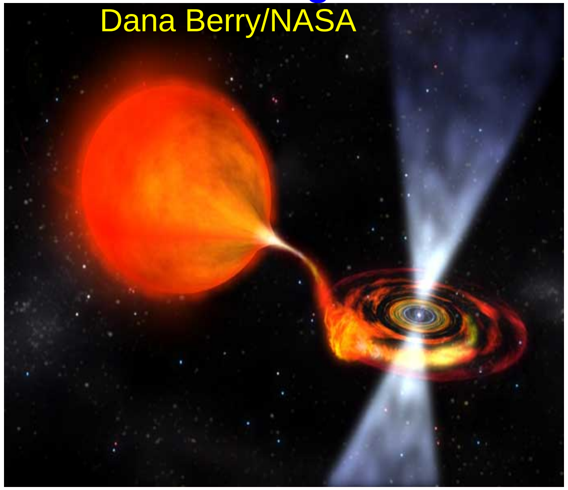


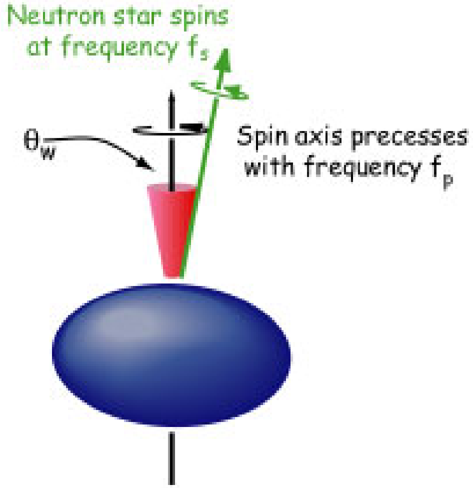
Kip Thorne

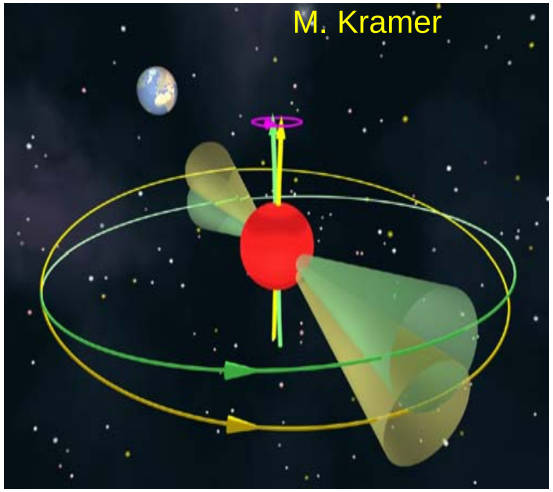
- Matched filter approach is possible since waveform is known

Gravitational wave sources: periodic

- Nearly monochromatic continuous gravitational wave emission is possible from asymmetric spinning objects
  - » Isolated neutron stars with mountains or wobbles
  - » Accreting neutron stars



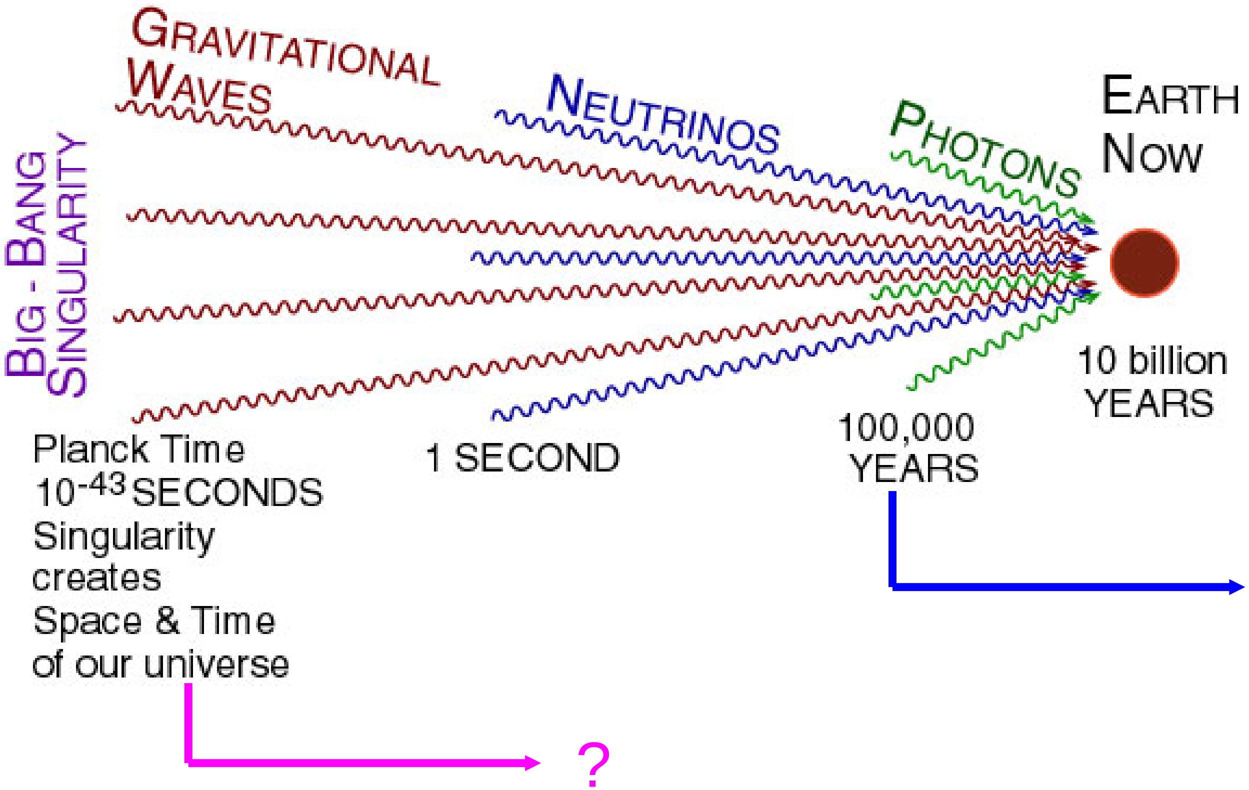


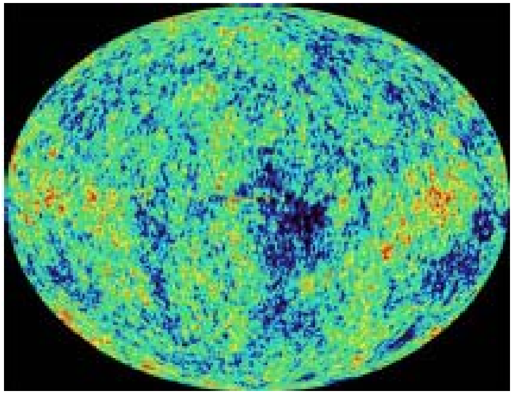


- Gravitational waves emitted at twice the spin frequency
- Signal is always on and can be integrated over time to increase sensitivity and reject instrument lines
- Can place limits on ellipticity and spin down for known pulsars

Gravitational wave sources: stochastic

- Random type of radiation (described by its spectrum) due to either
  - » Big bang, other early universe processes
  - » Many weak unresolved sources emitting gravitational waves independently

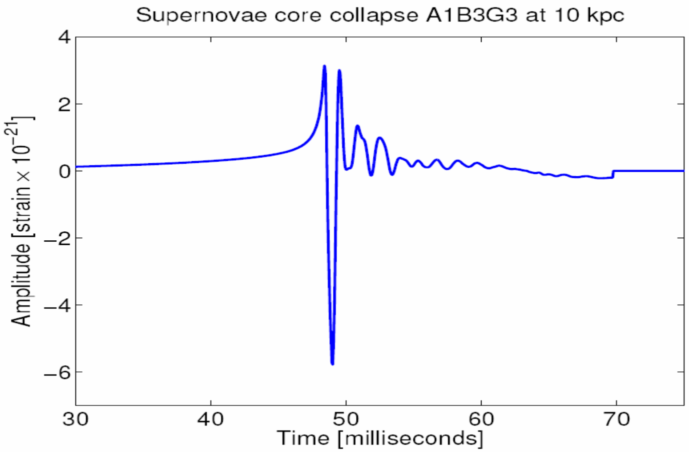




- Search for coherent background in multiple detectors

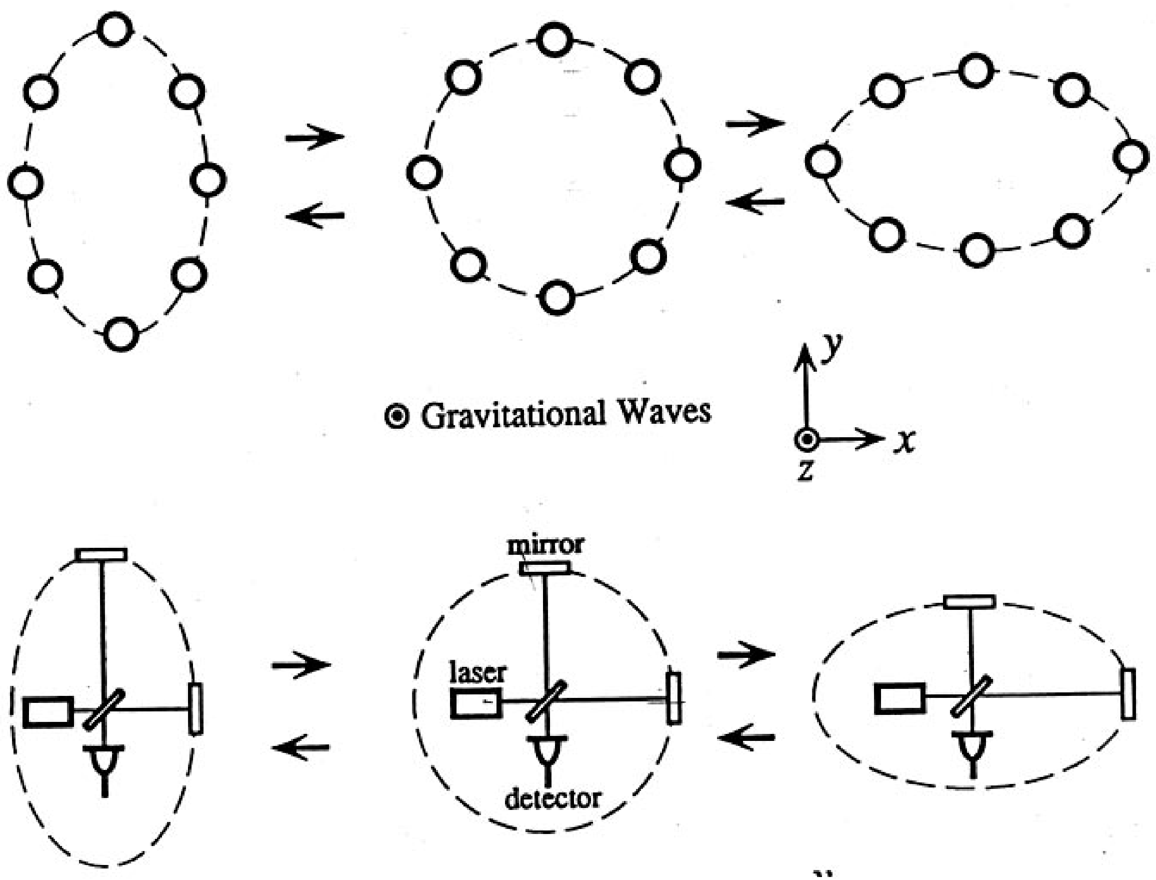
Gravitational wave sources: bursts

- Sources emitting short transients of gravitational radiation
  - » Supernovae core-collapse
  - » Merger phase of binary compact objects
  - » Black hole normal modes
  - » Neutron star instabilities
  - » Cosmic string cusps and kinks
  - » The unexpected!



- What we know about them …
  - » Catastrophic astrophysical events observed in the particle and/or electromagnetic sector will plausibly be accompanied by short signals in the gravitational wave sector ➡ *plausible suspects*
  - » Exact waveforms are not or poorly modeled
  - » Durations from few millisecond to x100 millisecond durations with enough power in the instruments sensitive band (100-few KHz)
  - » Searches tailored to the *plausible suspects* ➡ "triggered searches"
  - » …or aimed to the all-sky, all-times blind search for the unknown using minimal assumption on the source and waveform morphology ➡ "untriggered" searches
- Multi-detector analyses are of paramount importance

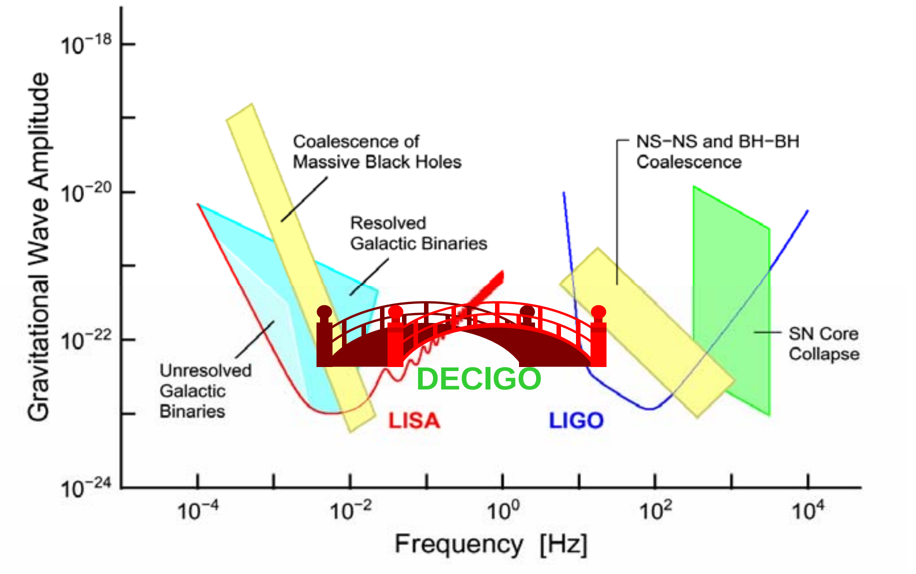
LIGO Direct detection of gravitational waves

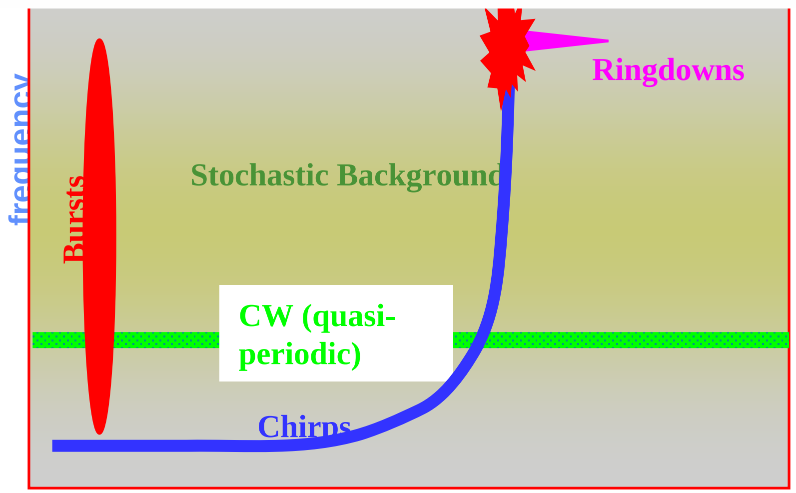


The game really begins when h ~10^{-21} ($\delta L/L$)

The gravitational wave endeavor

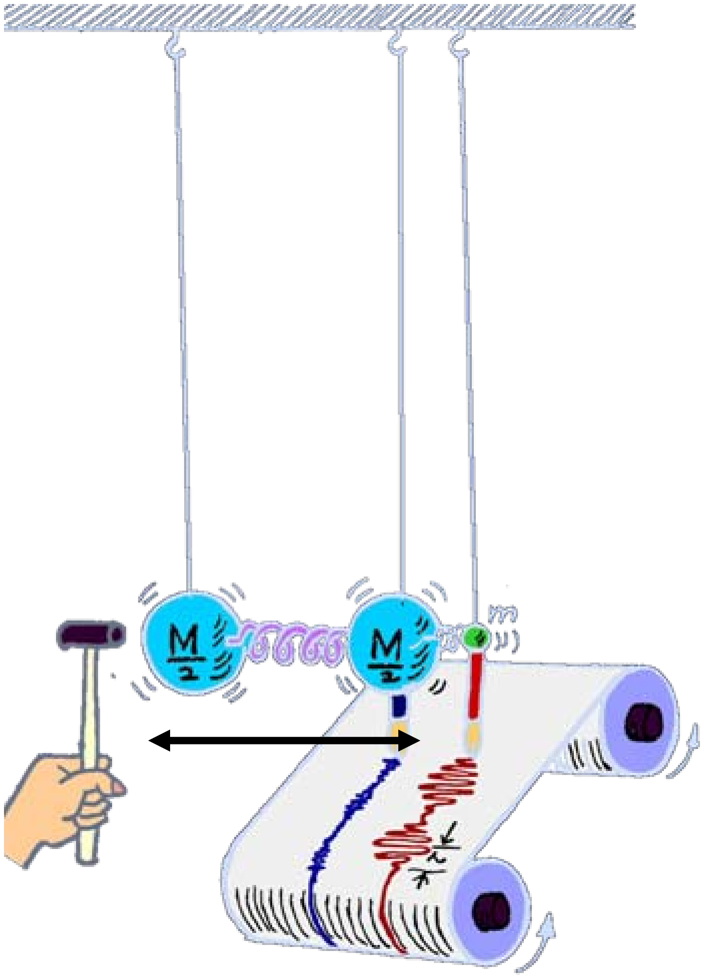
- Need very massive objects
- Moving at relativistic velocities
- Terrestrial sources are not detectable
- Extremely weak amplitude
- Very difficult to detect
- Not obscured by intervening matter
- Probe regions currently inaccessible by electromagnetic radiation





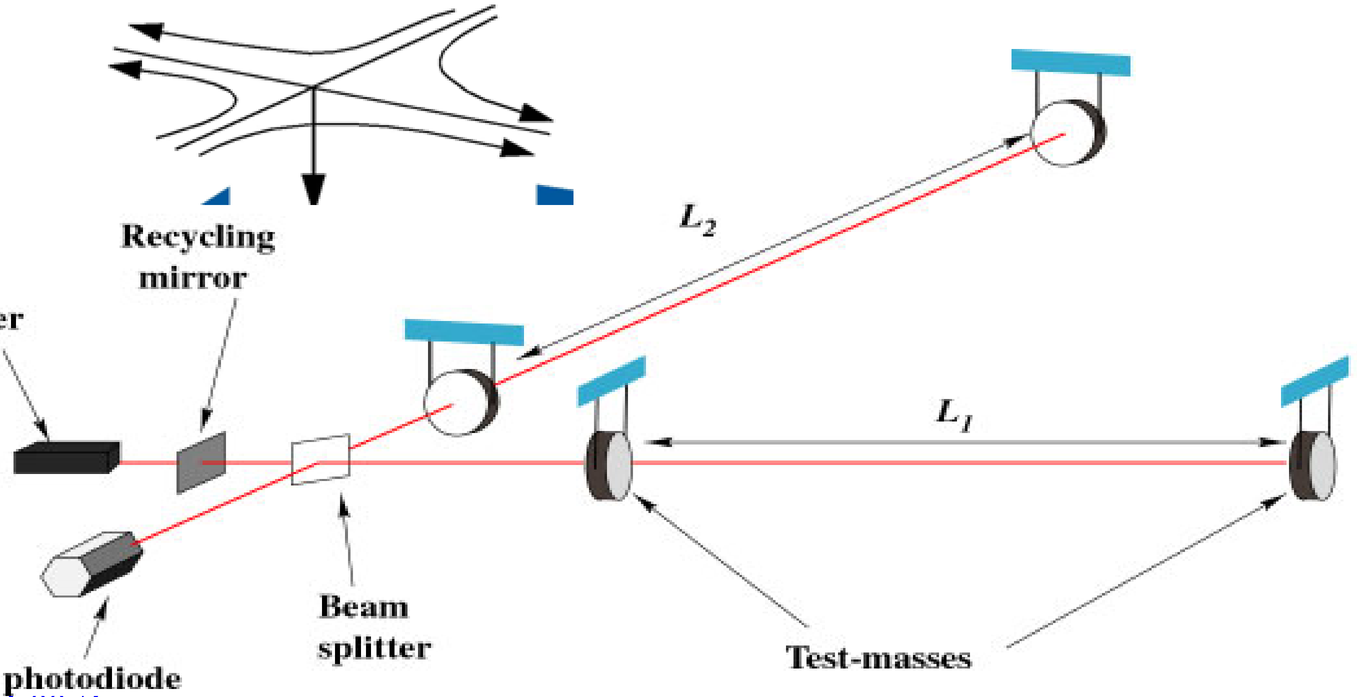
Turning strain *h* into a measurement

- Resonant mass detector:
  - » Translate induced excitations to electrical signal by a motion or strain transducer which is then amplified
- Aluminum bars



Interferometer Concept

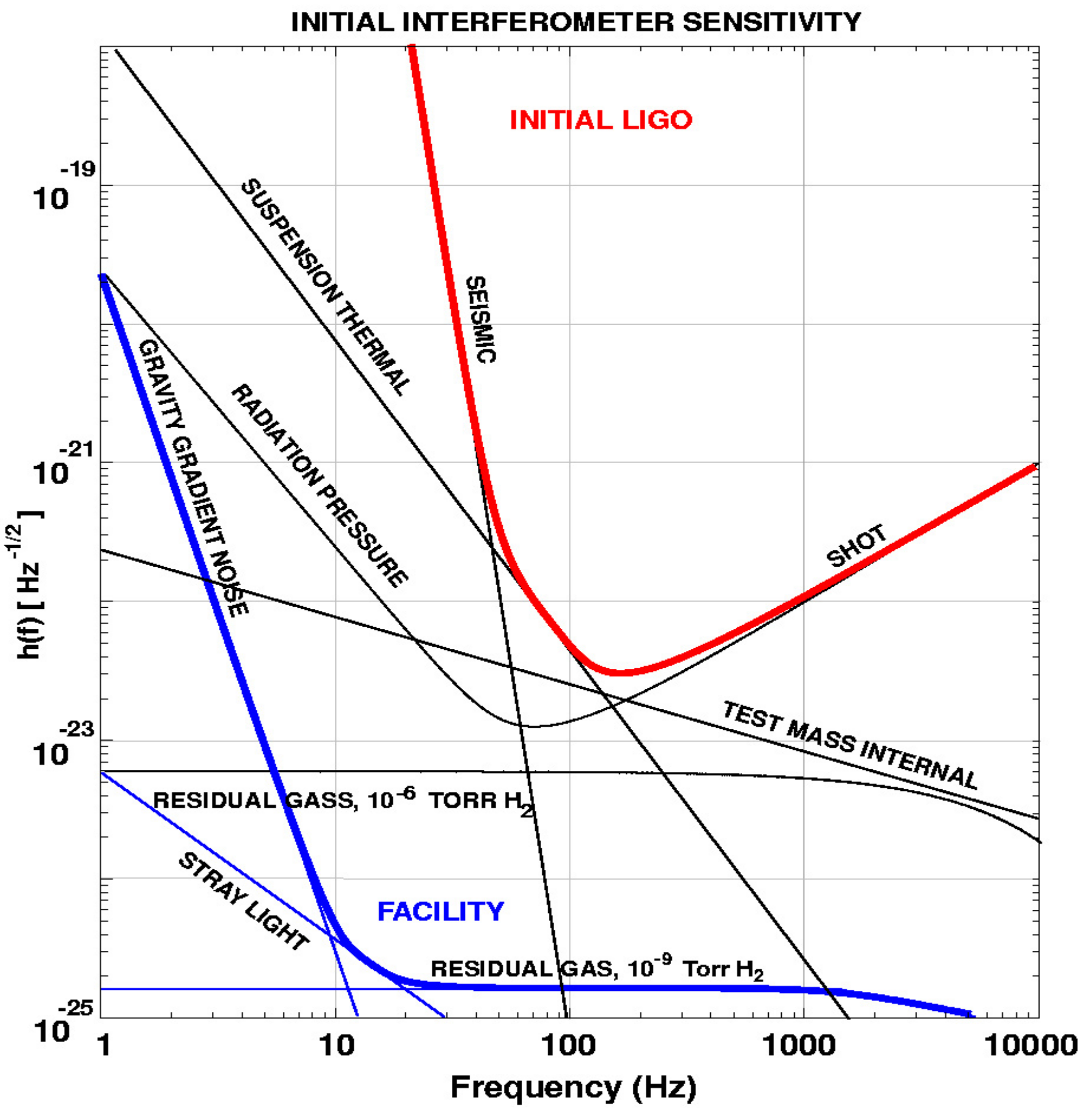
- Orthogonal arm lengths change in different ways as they interact with a gravitational wave
- Use Laser to measure relative lengths $\Delta L/L$ by observing the changes in interference pattern at the anti-symmetric port, for example, for $L \sim 4$ km and for a hypothetical wave of $h \sim 10^{-21}$, $\Delta L \sim 10^{-18}$ m !
- Power-recycled Michelson interferometer with Fabry-Perot arm cavities



LIGO

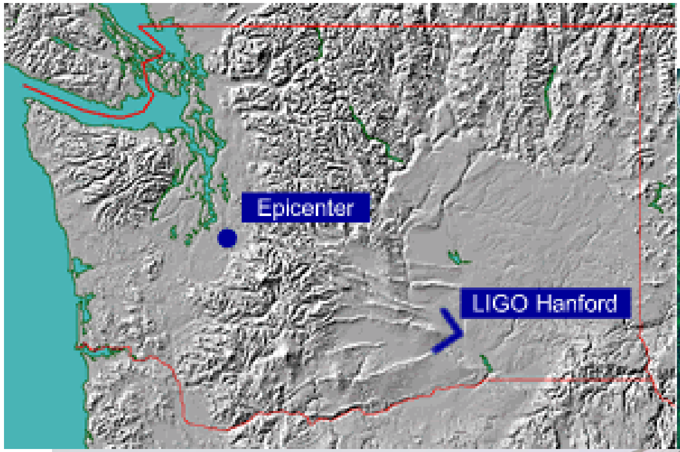
- Laser Interferometer Gravitational-wave Observatory
- Hanford, Washington: 2 km and 4 km detectors
- Livingston, Louisiana: 4 km detector
- 10 ms light travel time
- Managed and operated by Caltech and MIT with NSF funding
- LIGO Scientific Collaboration – 500+ researchers from 45 institutions worldwide in order to run and analyze the data from the LIGO and GEO instruments

Ground interferometers' noise budget



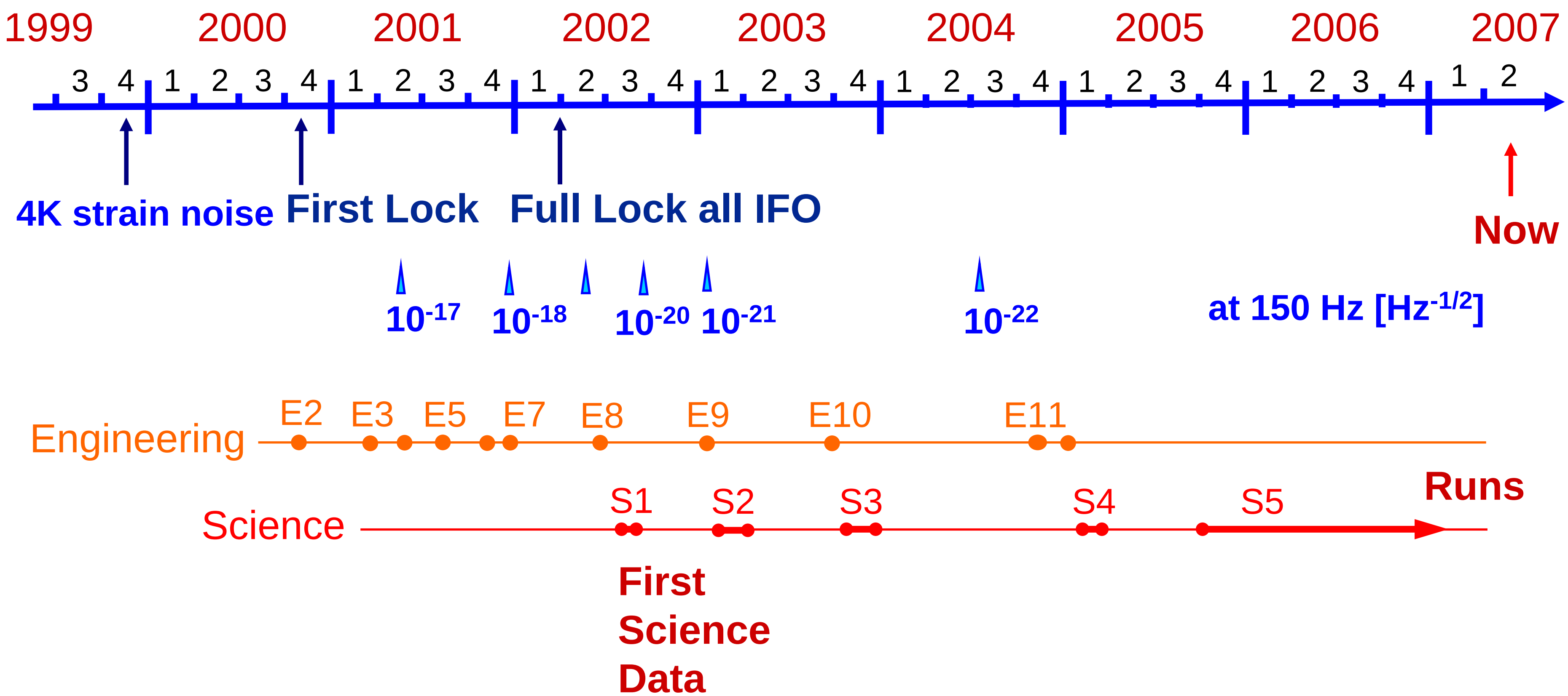
- Best strain sensitivity ~3×10^{-23} $1/\mathrm{Hz}^{1/2}$ at 200 Hz
- Displacement Noise
  - » Seismic motion
  - » Thermal Noise
  - » Radiation Pressure
- Sensing Noise
  - » Photon Shot Noise
  - » Residual Gas
- Facilities limits much lower
- Several ground interferometers are currently operating at or near design sensitivity

The road to design sensitivity…

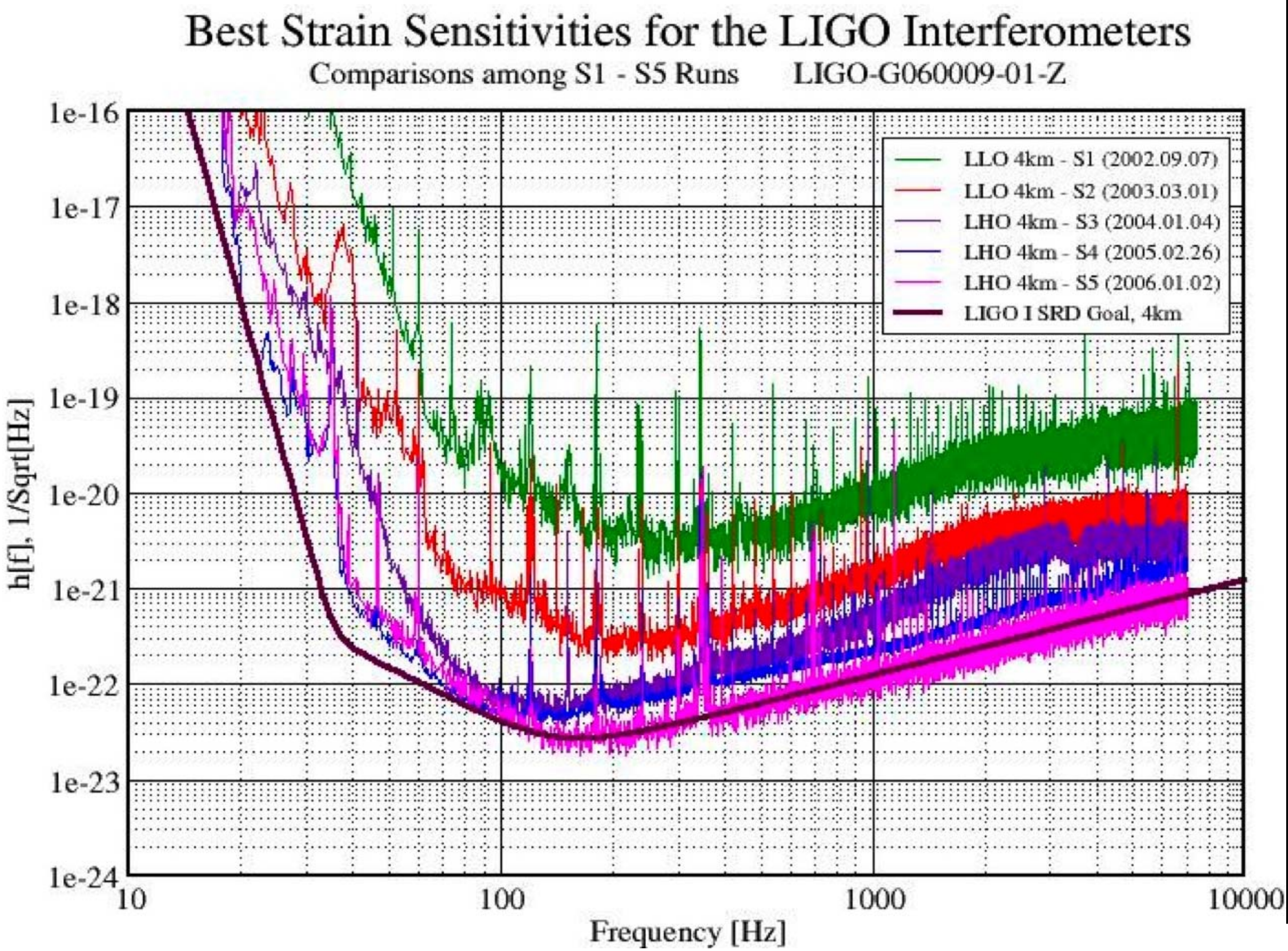


LIGO time line

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

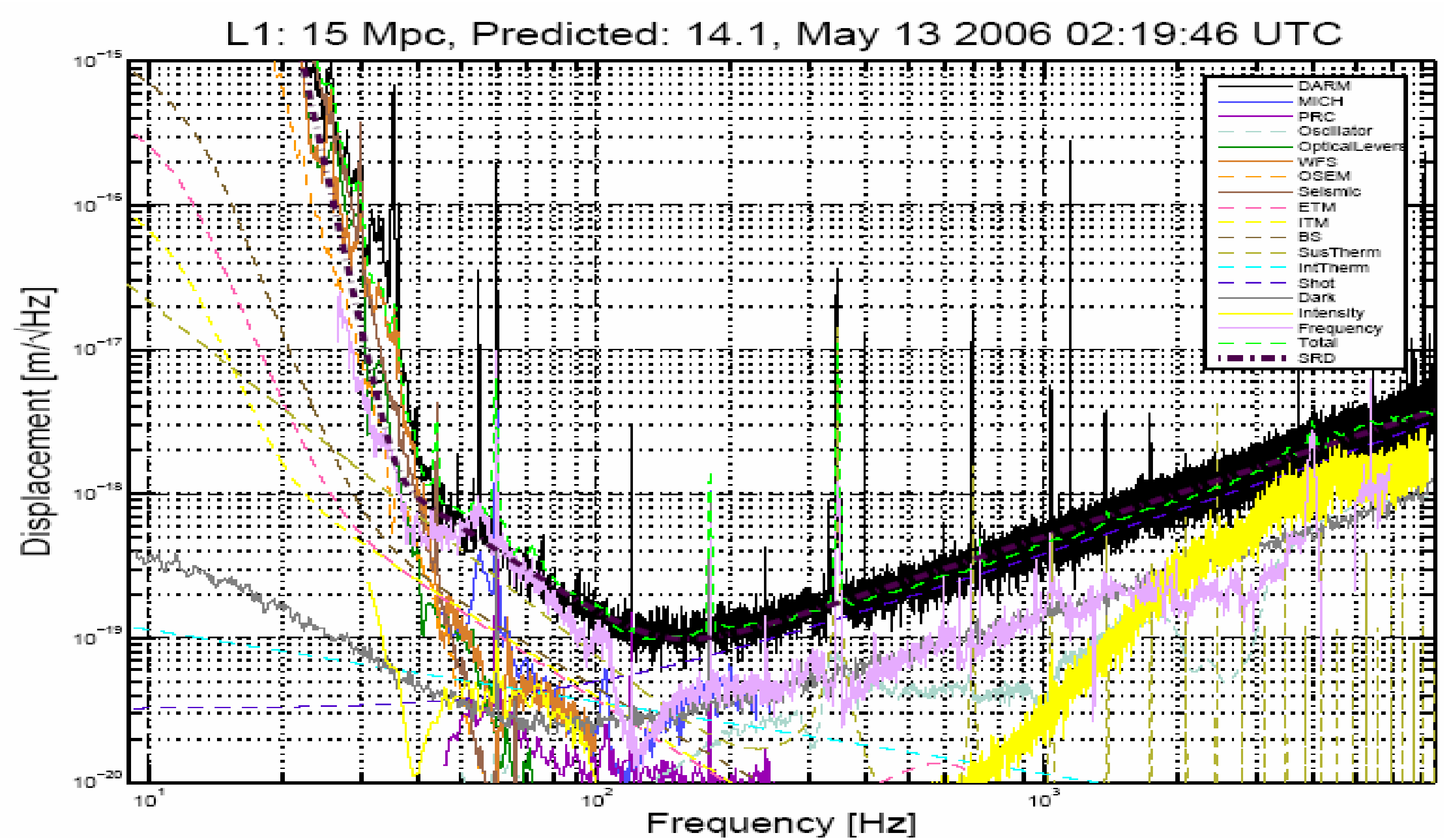


LIGO science runs and sensitivities



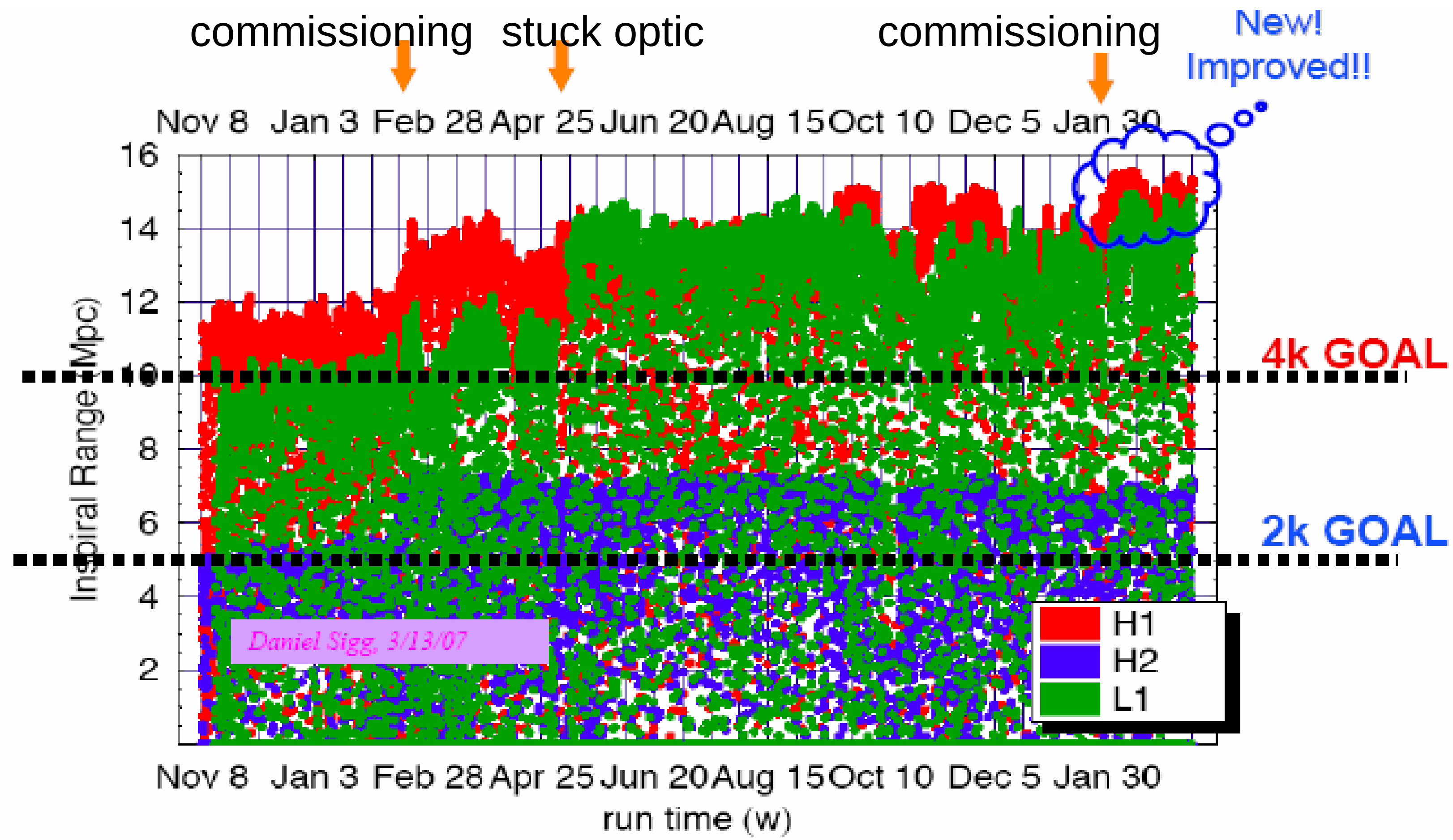
- **S1: 23 Aug – 9 Sep '02**
- **S2: 14 Feb – 14 Apr '03**
- **S3: 31 Oct '03 – 9 Jan '04**
- **S4: 22 Feb – 23 Mar '05**
- **S5: 4 Nov '05 – in proress**
- **Goal is to *"collect at least a year's data of coincident operation at the science goal sensitivity"***
- **Expect S5 to end in Fall 2007**
- **S5 is not completely 'hands-off'**

Noise anatomy



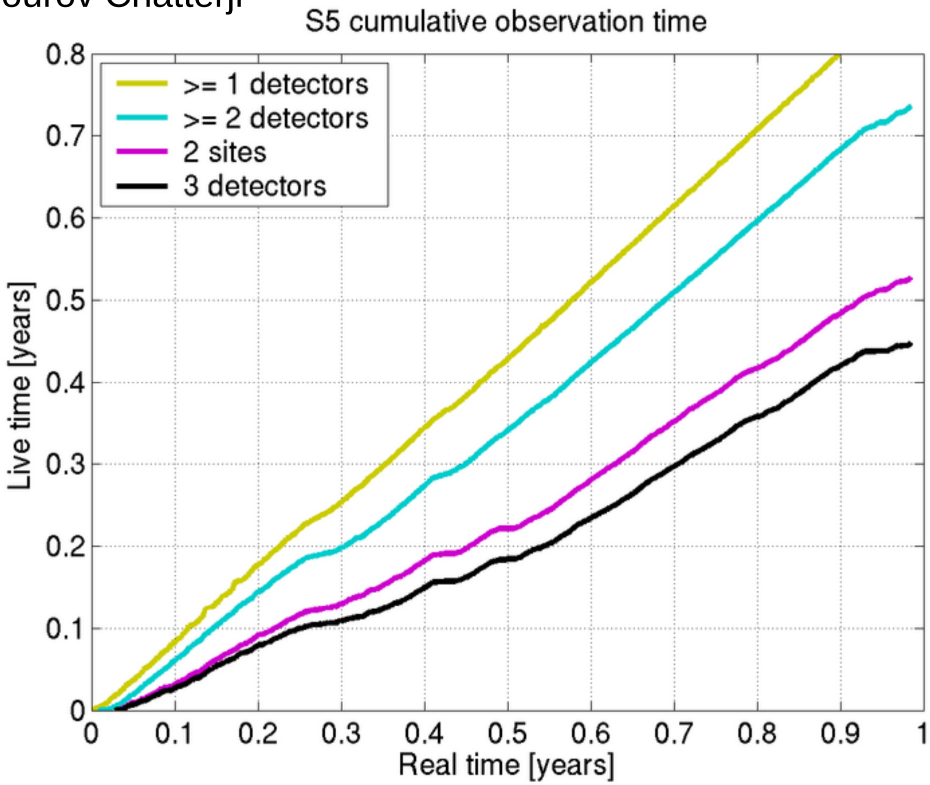
Performance of the detectors

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

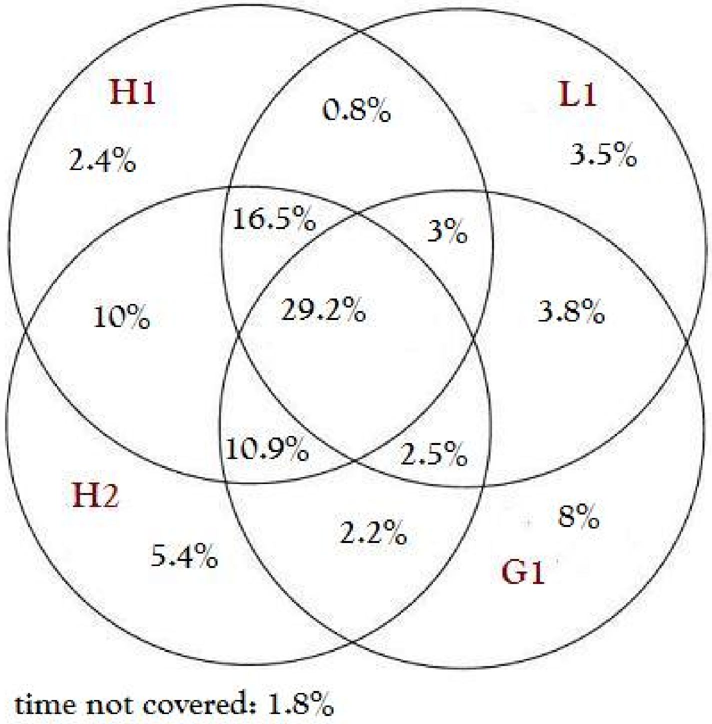


S5 network observation time

Shourov Chatterji

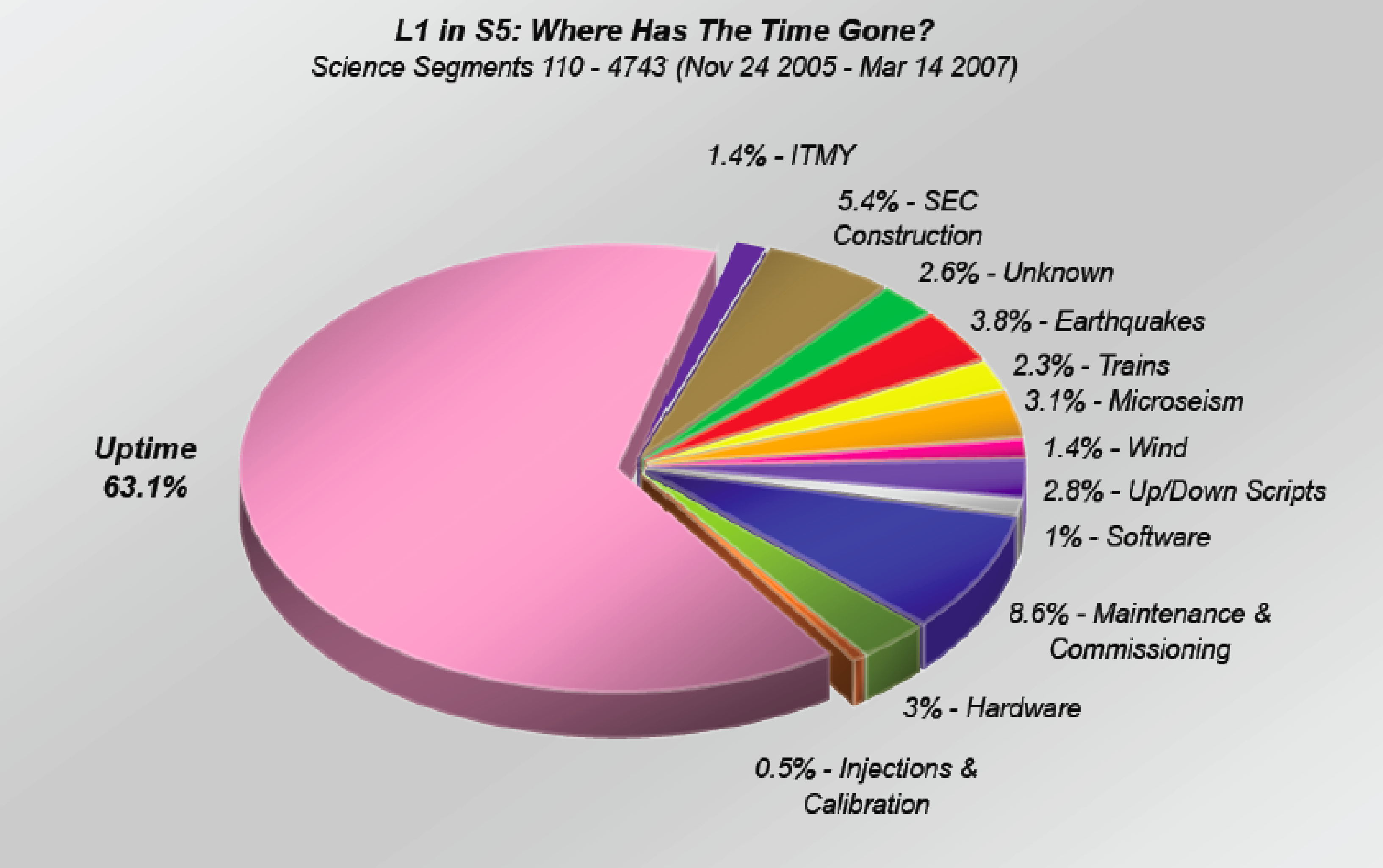


Olga Petrova



Expected end of S5: ~September 2007

Breakdown of livetime loss

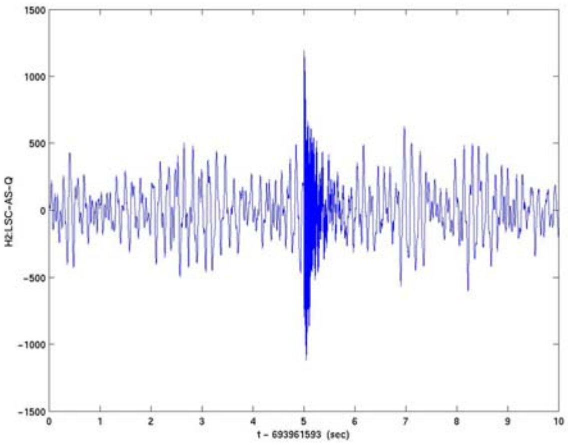


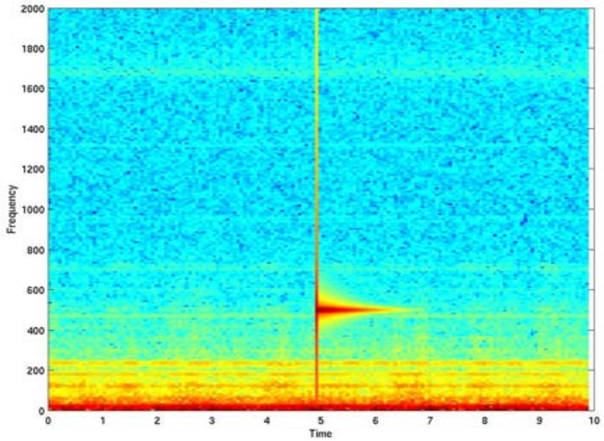
Searching for gravitational wave bursts

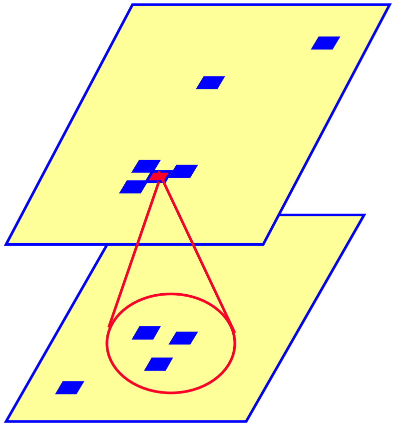
Searching for gravitational wave bursts with LIGO

- Four all-sky, all-times, searches using data from S1-S2-S3-S4 completed and published
  - Hierarchical approach: incoherent combination of statistically significant excesses in the three LIGO detectors, with coherent follow-up
  - No detections made, upper limits on the flux of gravitational wave bursts at the instruments and interpretations in terms of rate vs strength made
- GRB-triggered searches in S2-S3-S4
- Currently in progress: analysis of S5 data
  - Fully-coherent network methods
  - Any two or more instruments coincidence livetime
  - First look at 54 live-days in triple coincidence from Nov 17, 2005 to April 3, 2006 part of the S5 run using the S1-S2-S3-S4 methodology

Burst search: a time-frequency method



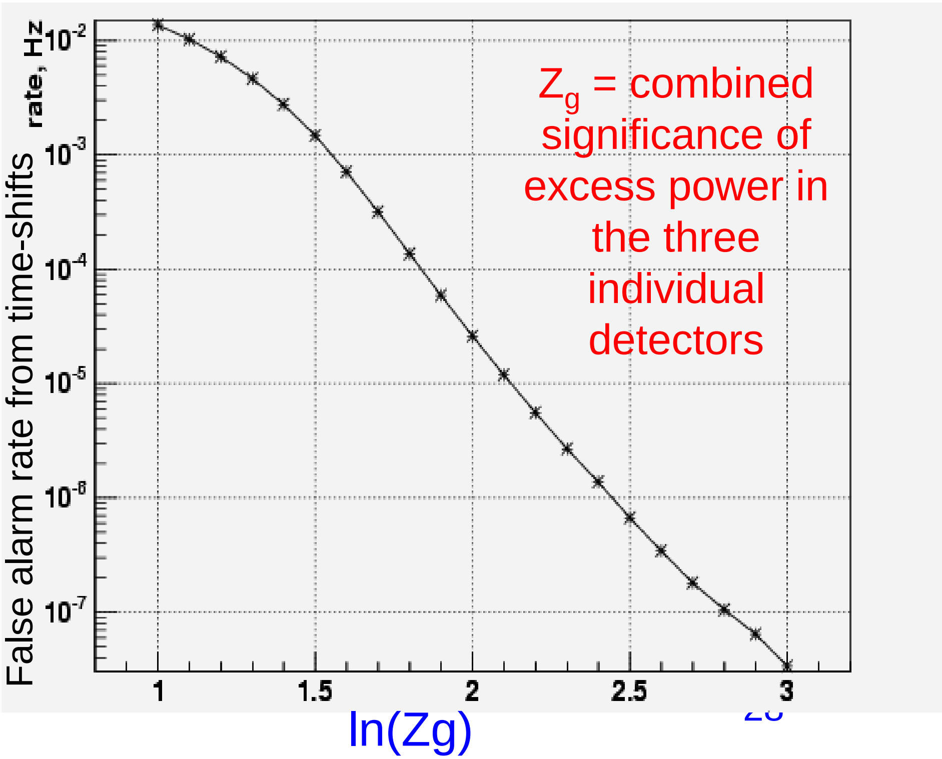




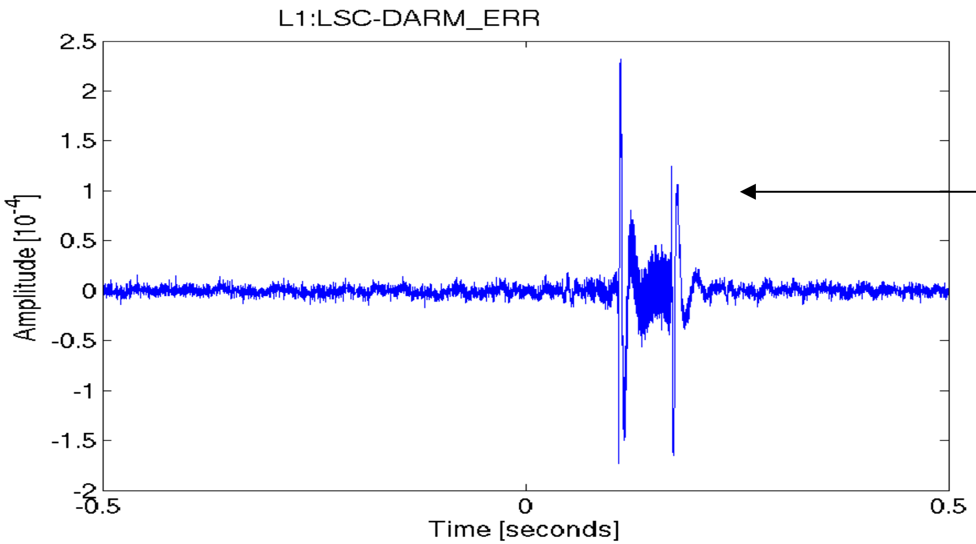
- Compute time-frequency decomposition in a Fourier or wavelet basis
- Threshold on power in a pixel; search for clusters of pixels
- Basic assumption: multi-interferometer response consistent with a plane wave-front incident on network of detectors:
  - » use temporal coincidence of the 3 interferometer's 'loudest pixels'
  - » correlate frequency features of candidates (time-frequency domain analysis)
  - » check consistency of the signal amplitude
  - » test the list of coincident event candidates for waveform consistency (correlation) between signals from three LIGO interferometers.
- End result of analysis pipeline: number of triple coincidence events

Tuning and selection strategy

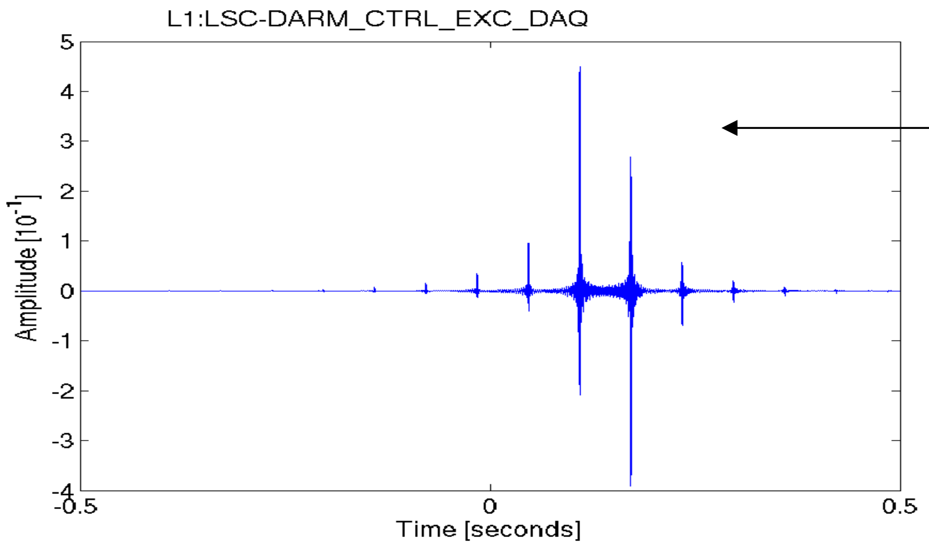
- Analyses are “blind”
  - » Time-shifted data (100 times, about 13.5 years of equivalent triple coincidence running) and software signal injections are used for deciding on all analysis cuts
- Thorough data quality and vetoes study
  - » Tuning based on single-instrument triggers or time-shifted coincidence data
- Select tiles in the 60-1600Hz
- Threhold on their significance
- Apply data quality and vetoes
- Apply waveform-consistency cuts



Role of data quality and vetoes:
An example of calibration malfunction



Gravity wave channel

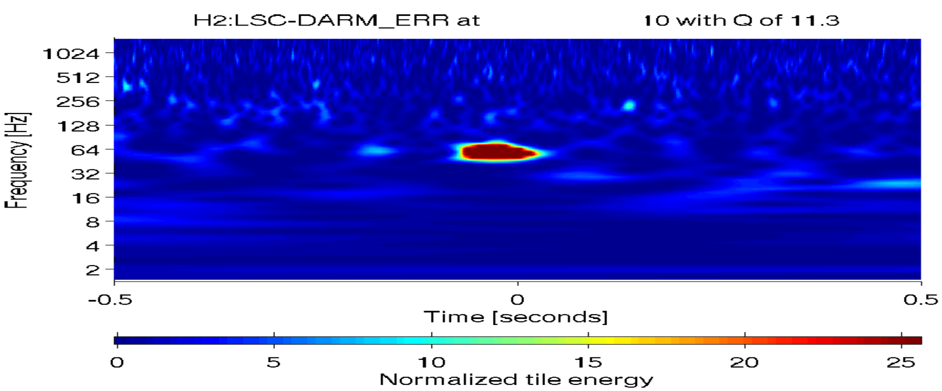


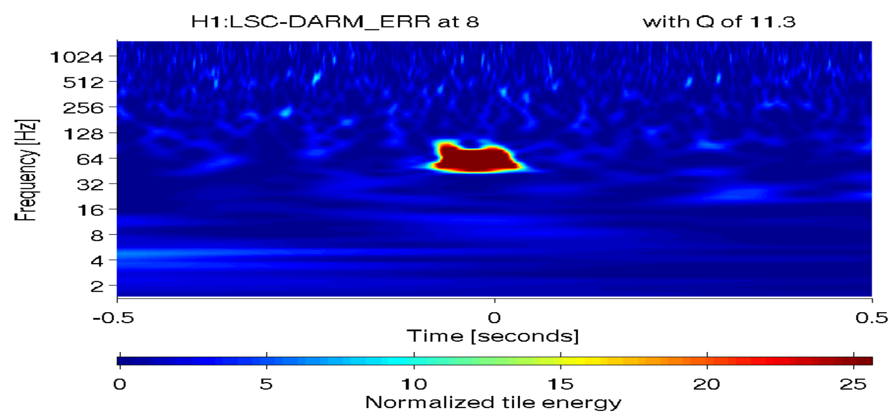
Channel which contains injected calibration line

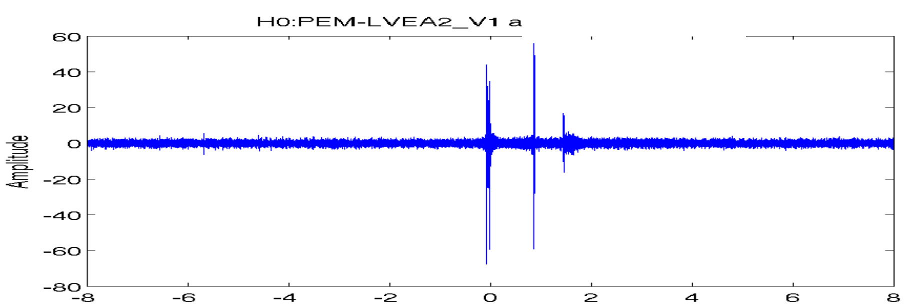
Category 1 Data quality flag
Dead-Time ~ 0.02 %

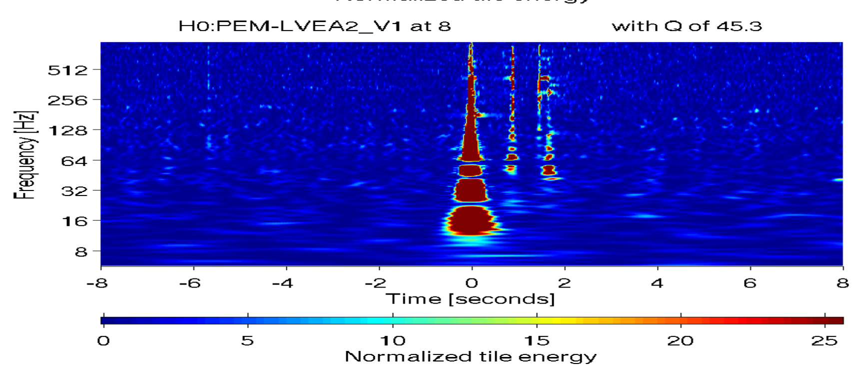
Power line, magnetic glitches

- Coincidence analysis and event classification has provided evidence of events resulting from extreme power line glitches reflected all across the H1-H2 instruments



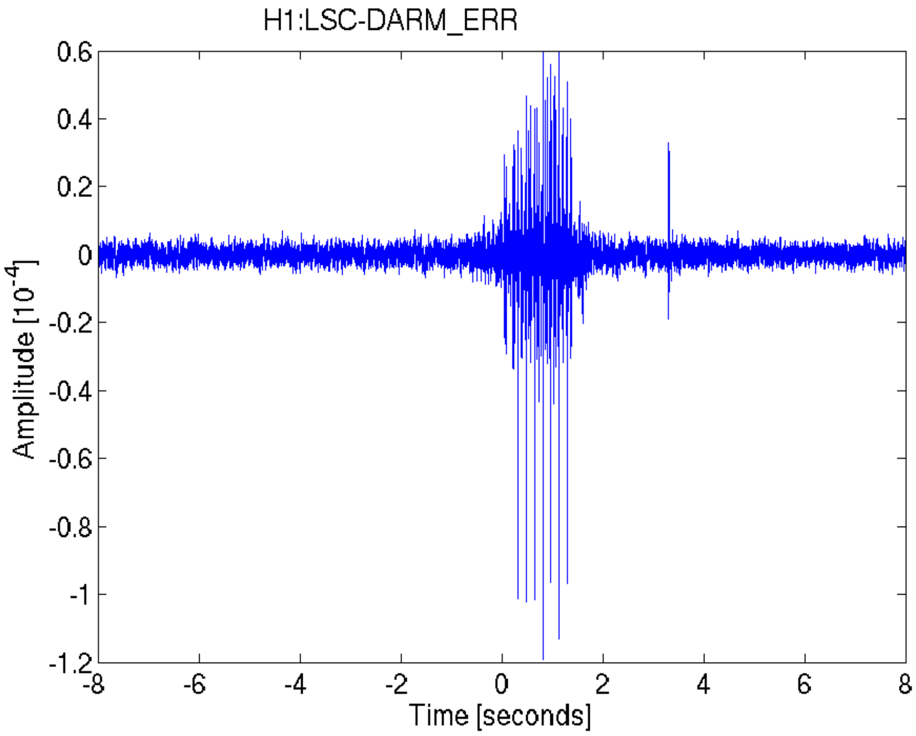




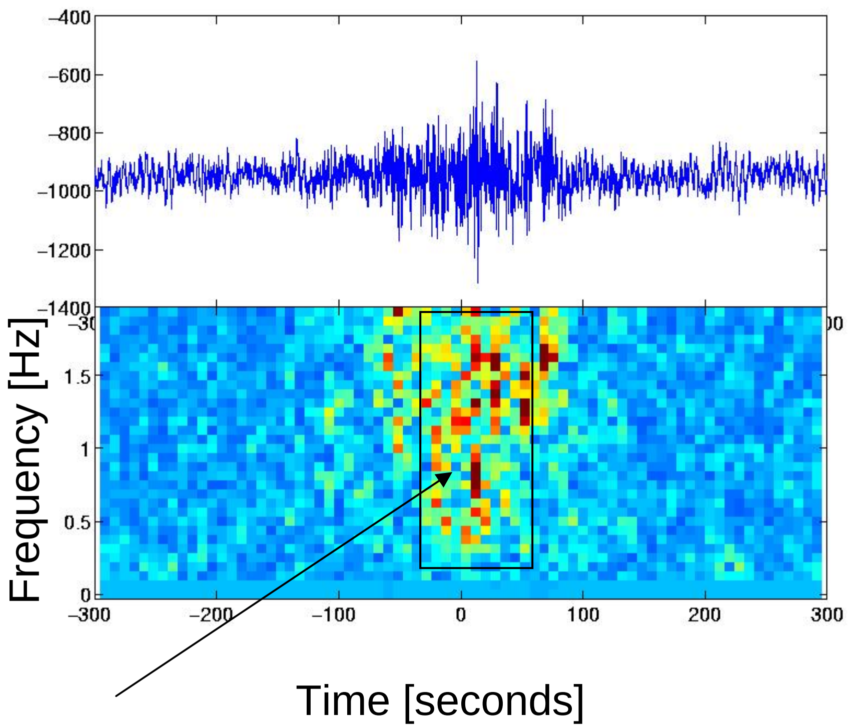


Example: Seismic Noise

- Transient seismic noise < 10Hz getting up-converted into LIGO band



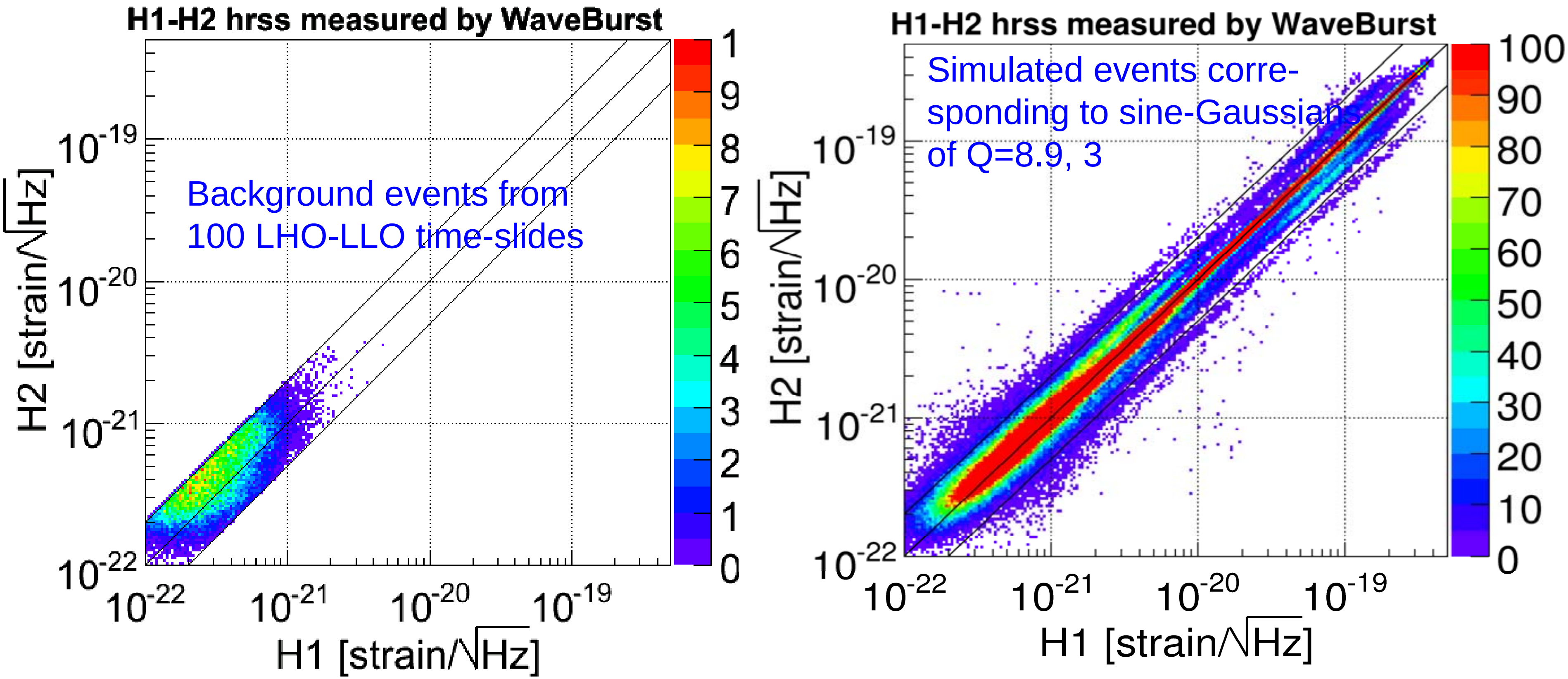
Hanford Y-end seismometer



Category-3 Data quality flag
Dead-Time ~ 0.6 %

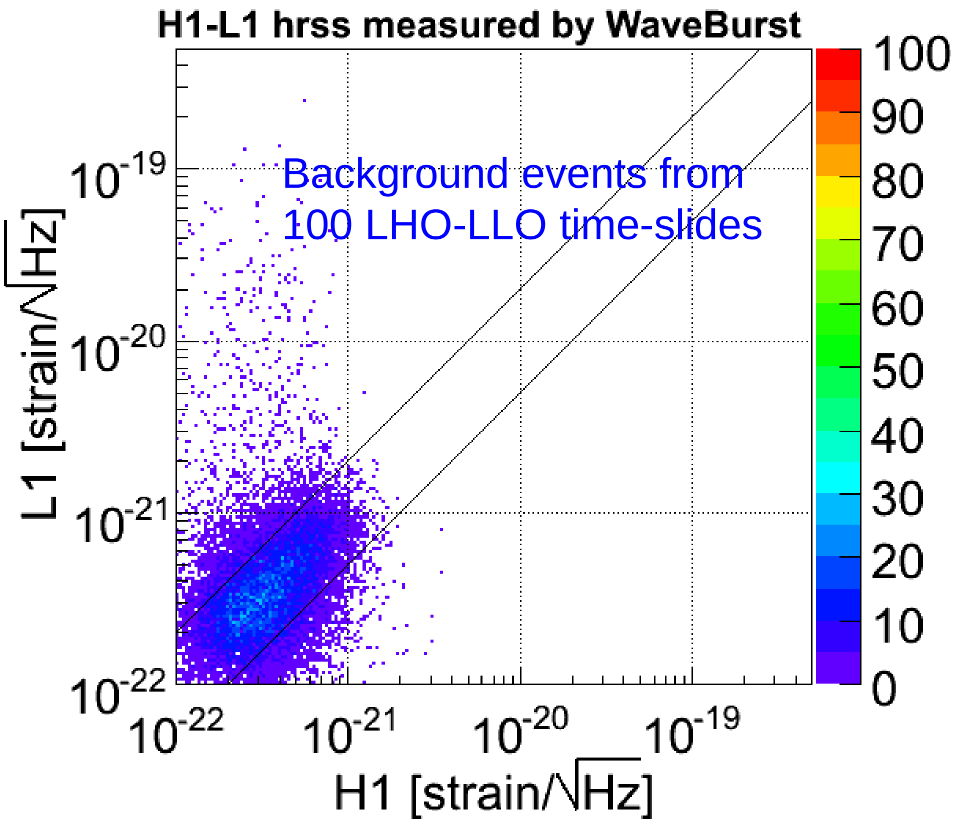
Excess Seismic noise

H1-H2 Consistency Checks

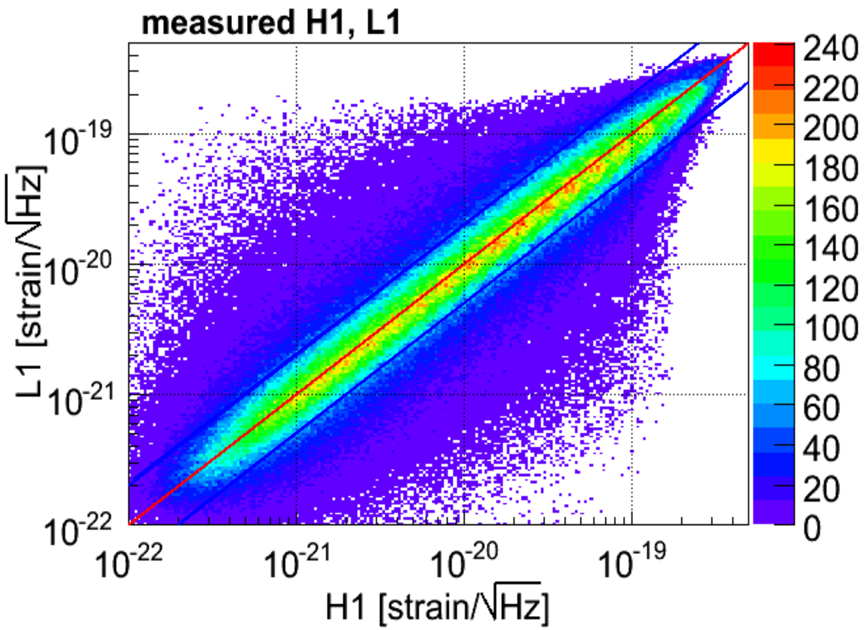


- Require:
  - » Estimated amplitudes must agree within a factor of two
  - » Signals must be positively correlated

L1-H1 Cut



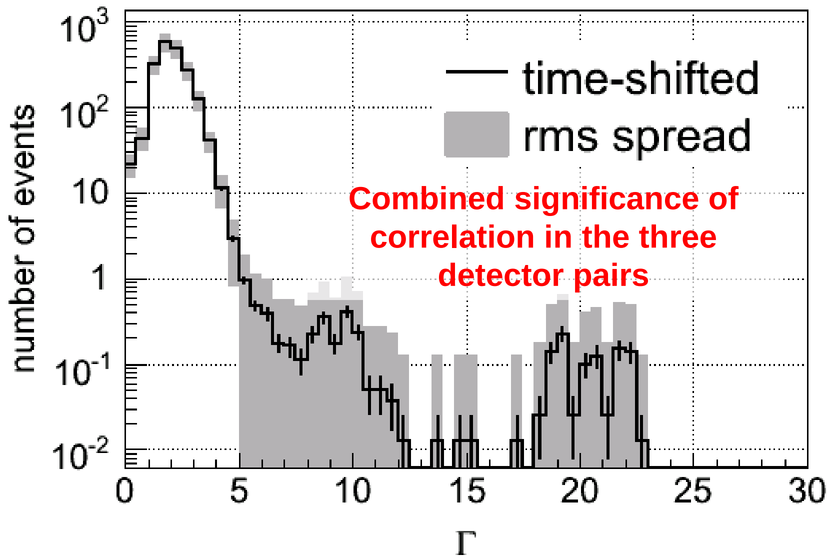
Simulated events corre-
sponding to sine-Gaussians
of Q=8.9, 3

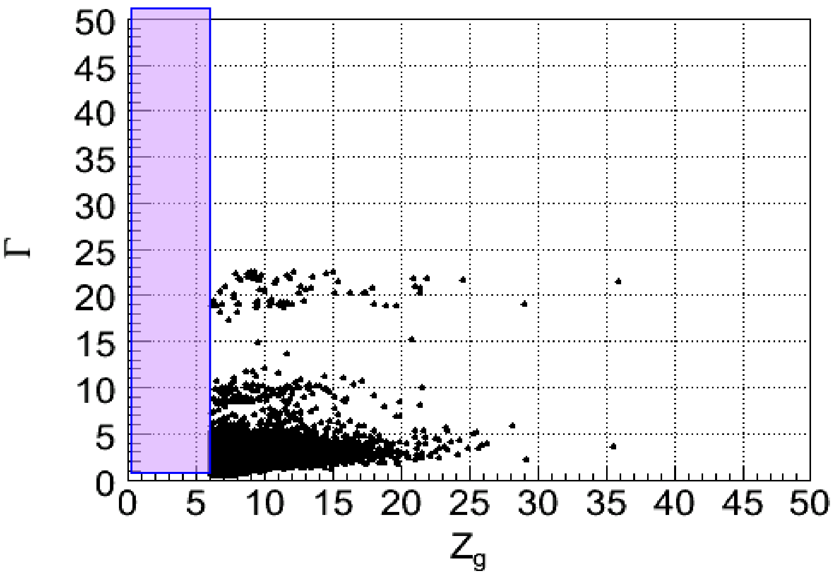


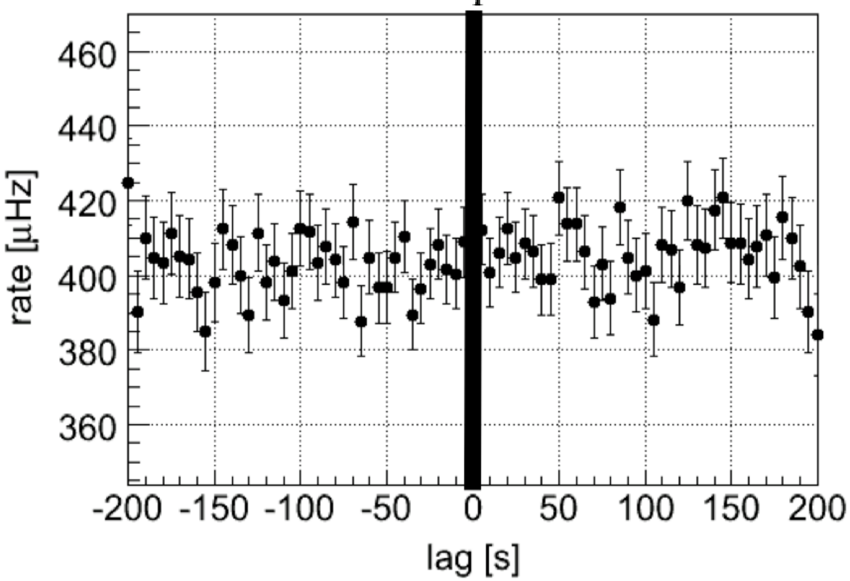
- Require:
  - » H1-L1 cross-correlation coefficient be >3 (less than 0.1% probability to get the measured linear cross-correlation from uncorrelated noise at L1 and H1)

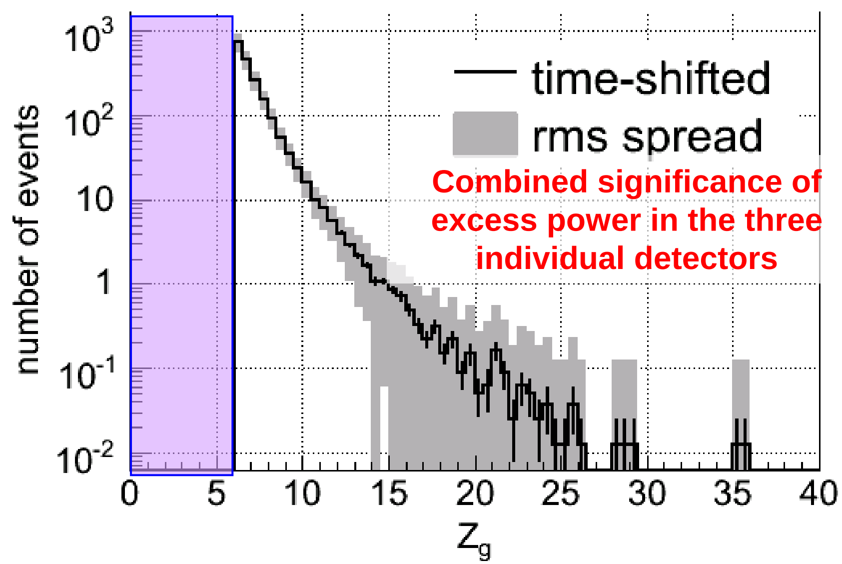
LIGO

Background events before any cuts

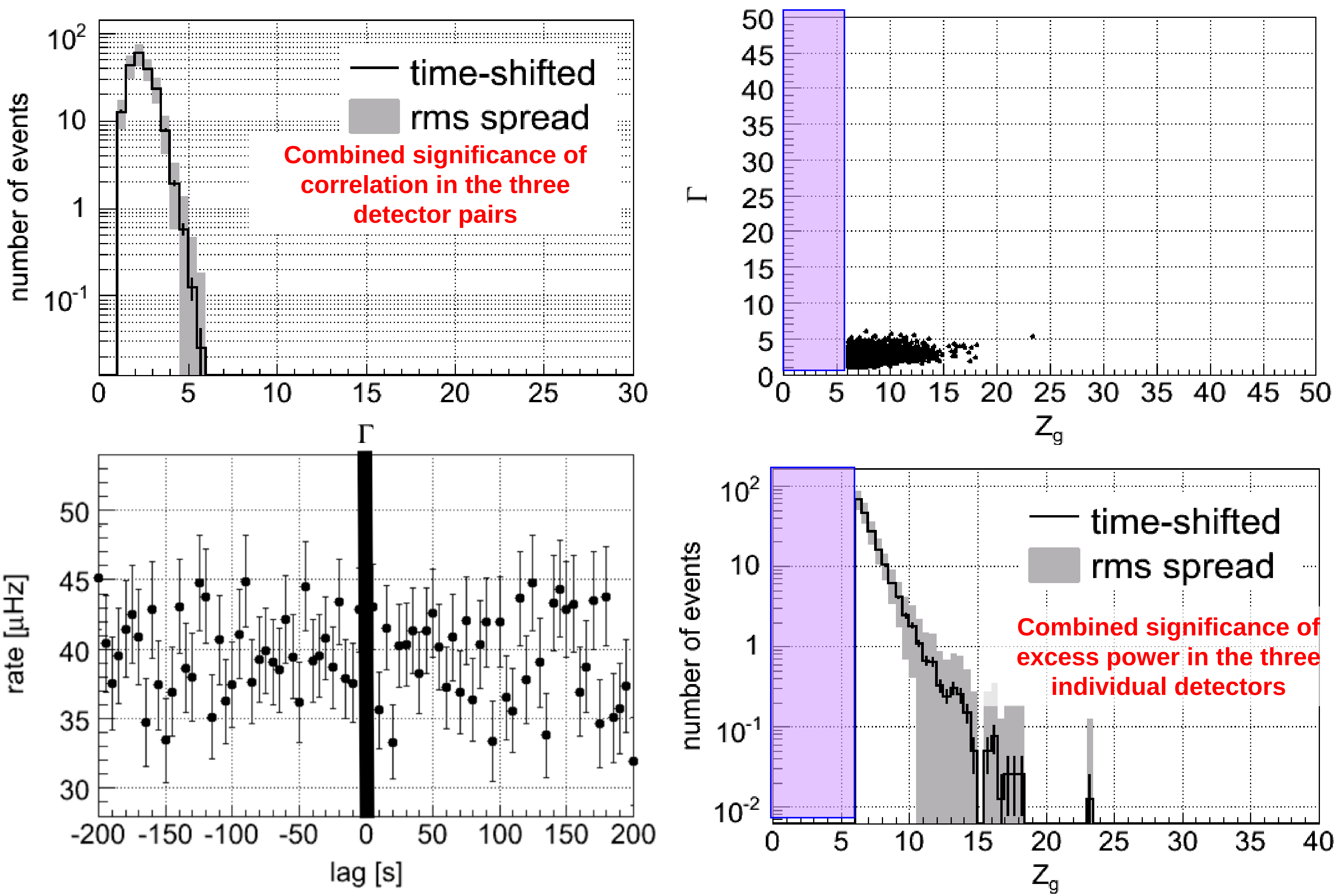




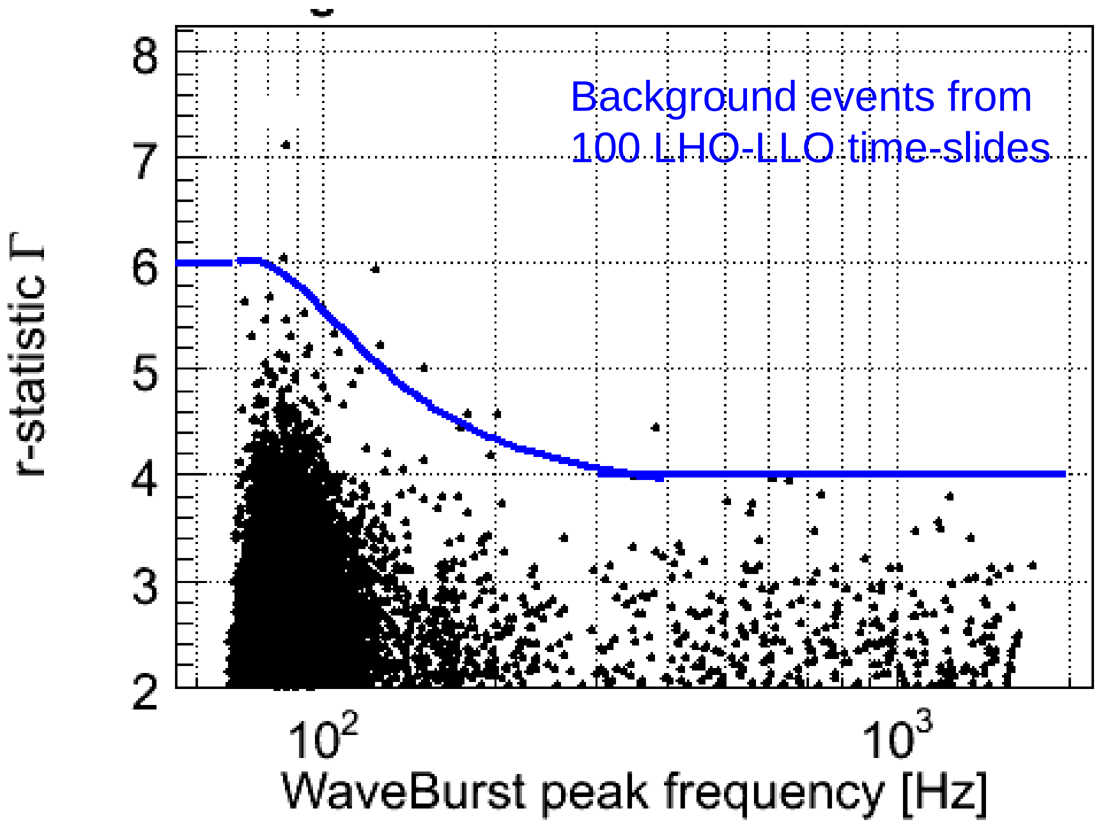




Background events after data quality and analysis cuts



LIGO Frequency Dependent Threshold



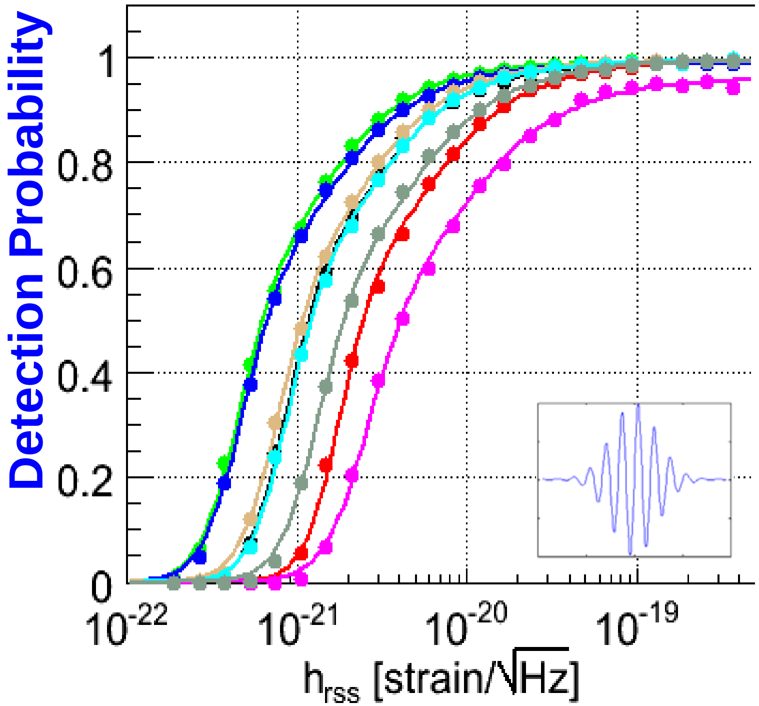
Empirically chosen, frequency-dependent threshold on Γ

~1/(f-64Hz) in 100-300Hz,
4 at high frequency,
6 at low frequency

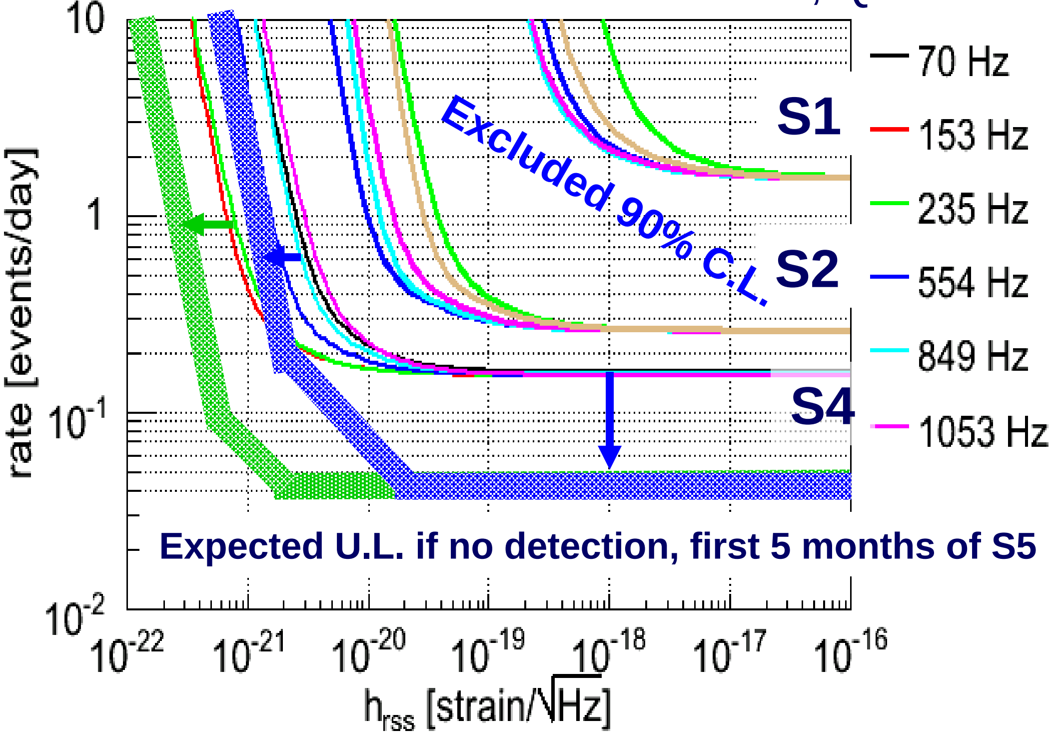
Target rate of accidentals:
<< 1 per analysis period
Expect 0.06 in early S5,
0.4/year

100 LHO-LLO time-slides, equivalent to 13.5 years of triple coincidence data

Preliminary detection efficiency and upper limit reach for initial part of S5



Sine-Gaussian waveforms, Q=8.9



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

PRELIMINARY

Mass equivalence: order of magnitude analysis

- Instantaneous energy flux:

$$\frac{\mathrm{d}^2 E_{\mathrm{GW}}}{\mathrm{d}A\,\mathrm{d}t} = \frac{1}{16\pi}\frac{c^3}{G}\left\langle (\dot{h}_+)^2 + (\dot{h}_\times)^2 \right\rangle$$

- Integrate over signal duration and over a sphere at radius r assuming a sine-gaussian signal of frequency f_0 and quality factor Q:

$$E_{\mathrm{GW}} = \frac{r^2 c^3}{4G}(2\pi f_0)^2 h_{\mathrm{rss}}^2$$

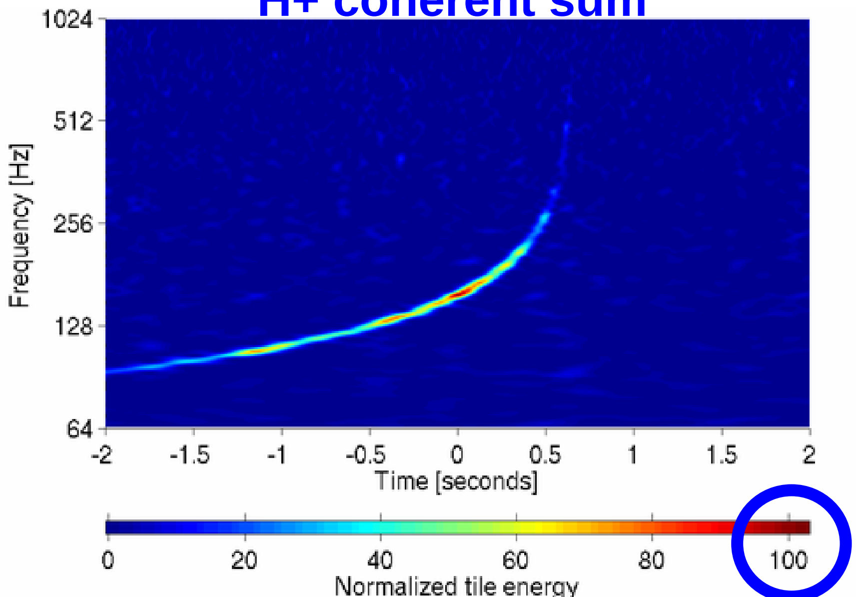
- Assume for a sine-Gaussian-like signal, 153 Hz, Q=8.9, h_{rss} at 50% efficiency is 6.5 x 10^{-22} $\mathrm{Hz}^{-1/2}$
  - » 2 x 10^{-8} $M_\odot$ emitted at 10 kpc
  - » 0.05 $M_\odot$ emitted at Virgo Cluster

Toward coherent searches: the "Q" pipeline search

- Multi-resolution time-frequency search for GW bursts
- Looks for statistically-significant excess signal energy
- Takes advantage of co-located Hanford detectors (H1, H2)
  - » Power-weighted "coherent sum" (H+) maximizes signal from GW bursts
  - » Differential "null stream" (H-) should be consistent with detector noise
- Search for Livingston (L1) events coincident with H+ events

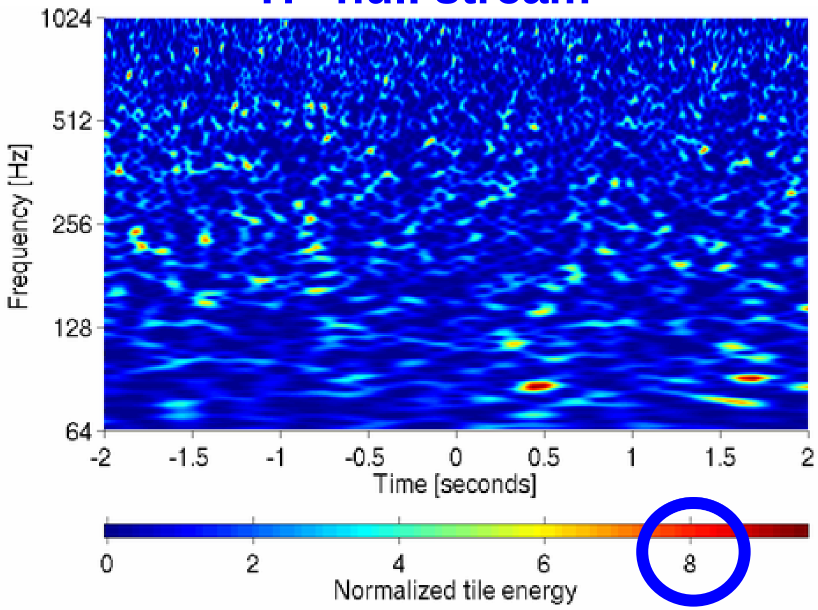
Simulated 1.4/1.4 $M_\odot$ inspiral injected at 5Mpc

H+ coherent sum



~10% increase in SNR

H– null stream

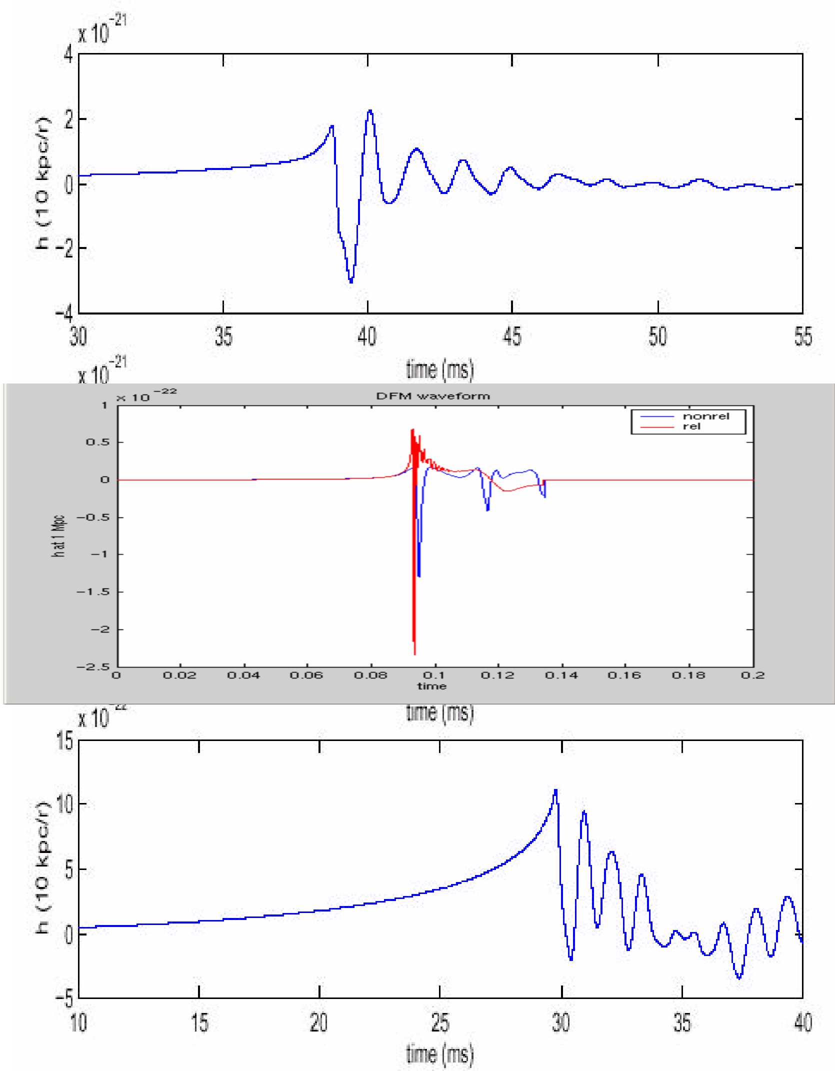


consistent with noise

Shourov Chatterji

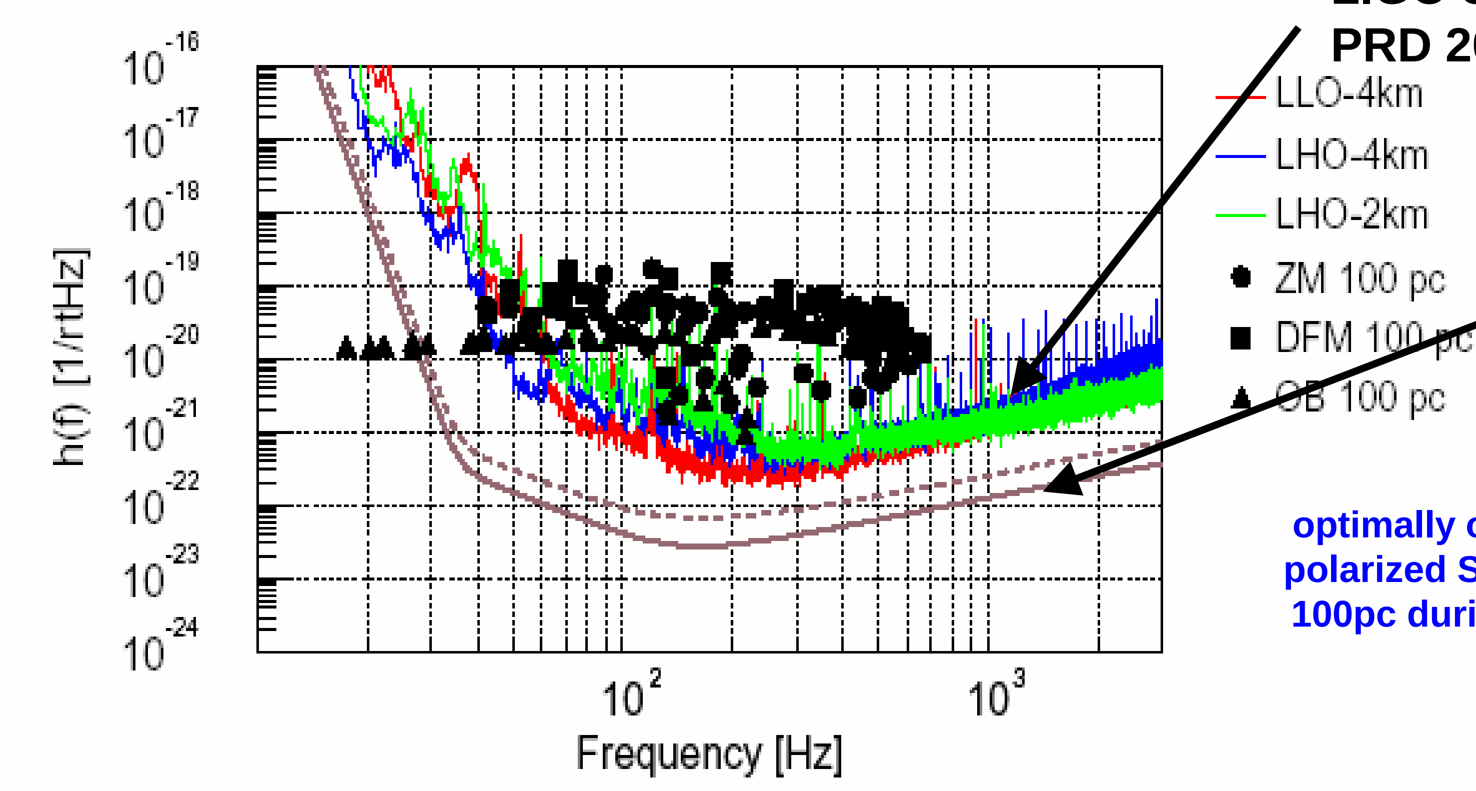
Astrophysical waveforms

- Zwerger-Müller (Astron. Astroph. 1997)
  - » 2D hydrodynamical model enforcing axisymmetry of the rotating star
  - » Waveforms sample initial angular momentum, rotational energy and adiabatic index
- Dimmelmeier, Font and Müller (Ap J Lett 2001)
  - » relativistic effects included
- Ott, Burrows, Livne, Walder, (Ap J 2004)
  - » Updated progenitor models and nuclear EoS



Astrophysical waveforms and LIGO

- Widely varying signal morphologies and relevant strengths
- Lasting from fraction of a 1ms to 10-100 ms
- Not all of them have enough power in instruments' sensitive band
- They are distance calibrated



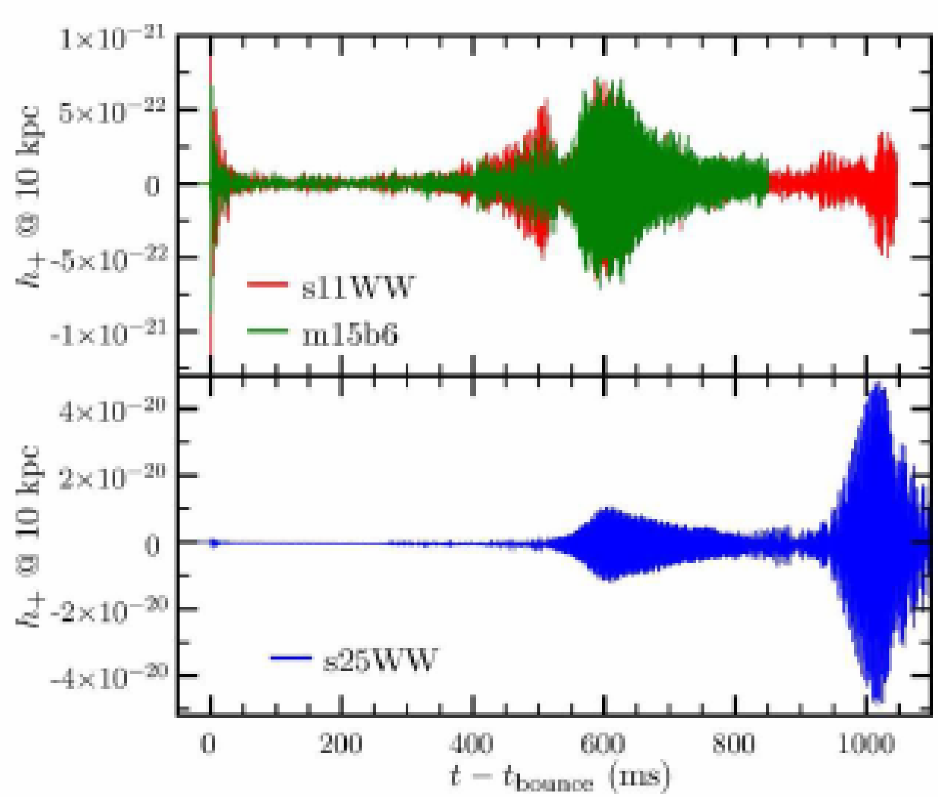
LIGO S2 RUN (2003)
PRD 2005

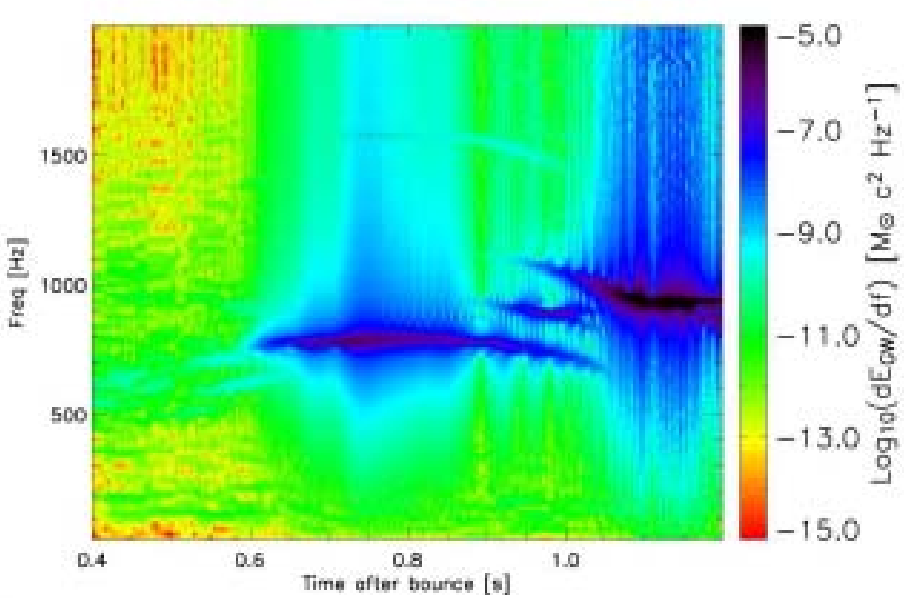
LIGO TODAY

optimally oriented and polarized SN waveforms at 100pc during LIGO S2 run

…and a new mechanism!

- Burrows, Livne, Dessart, Ott, Murphy (ApJ 2006) and Ott, Burrows, Dessart, Livne (PRL 2006)
  - » Axisymmetric simulations with non-rotating progenitor
  - » In-falling material eventually drives oscillations of the core
  - » Hundreds of ms after the bounce and lasting several hundred ms

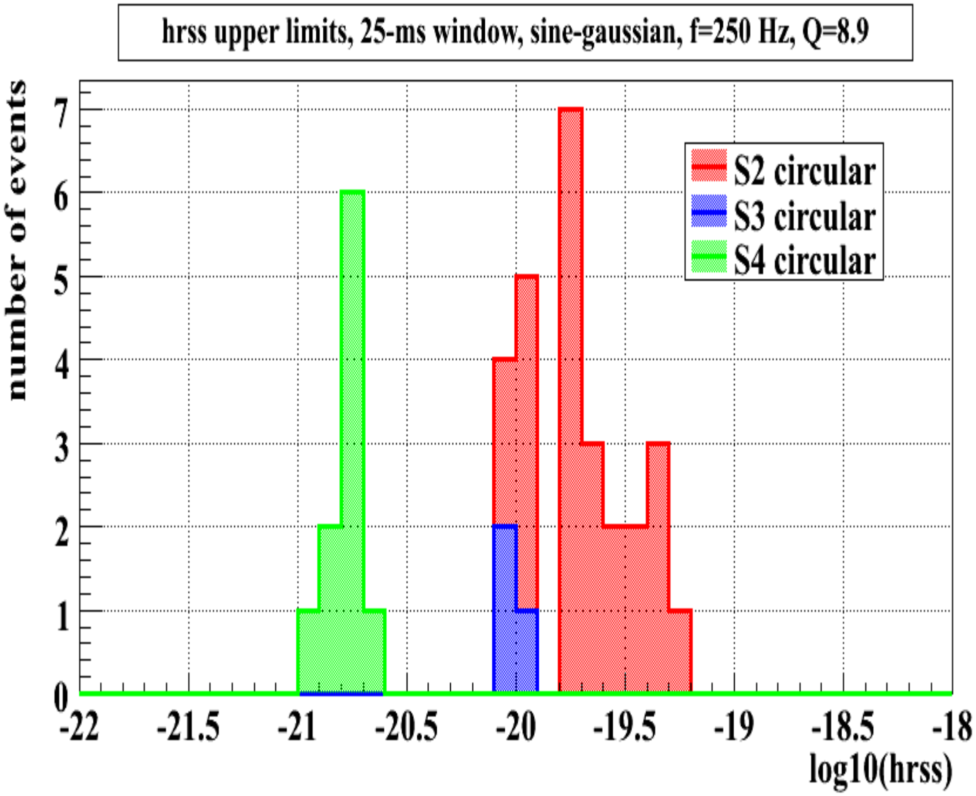




Ott, Burrows, Lessart, Livne, PRL 2006

Searching for bursts associated with GRBs

- Search LIGO data surrounding GRB trigger using cross-correlation method
- No GW signal found associated with 39 GRB GRB in S2, S3, S4 runs and limits on GW signal amplitude were set
- 53 GRB triggers for the first five months of LIGO S5 run
- Typical S5 sensitivity at 250 Hz: E_{GW} ~ 0.3 Msun at 20 Mpc
- Also, searched for GW emission associated with the Soft Gamma Repeater 1806-20 – no signal found

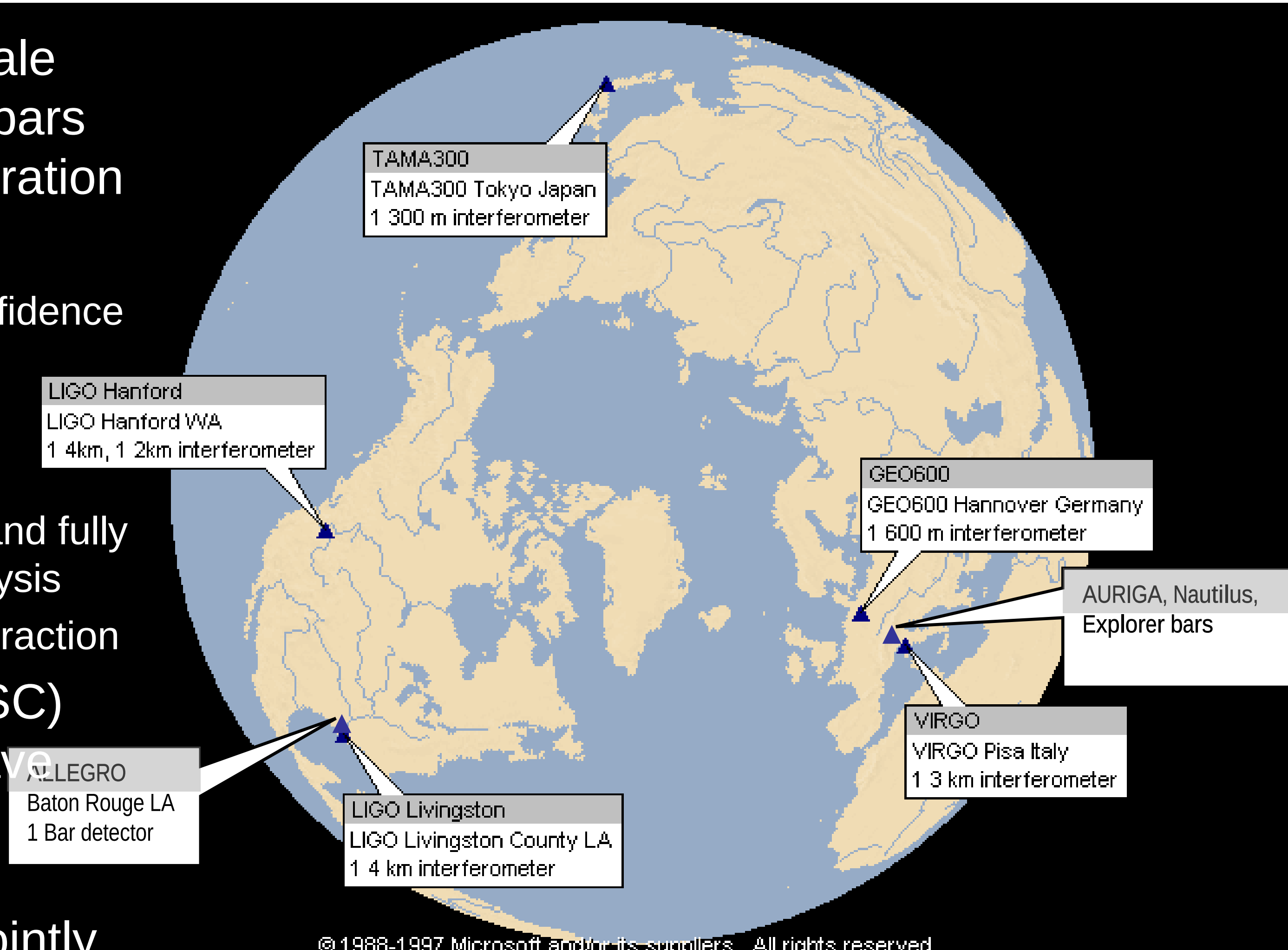


The path to gravitational wave astronomy

"Are we there yet?" cartoon from http://media.bestprices.com/

LIGO Individual detectors ⟶ global network

- Several km-scale detectors and bars are now in operation
- Network gives:
  - » Detection confidence
  - » Sky coverage
  - » Duty cycle
  - » Direction by triangulation and fully coherent analysis
  - » Waveform extraction
- LIGO-GEO (LSC) and VIRGO have completed negotiations to analyze data jointly



Detections $\longrightarrow$ astrophysics

- The inverse problem:

$$s_i(t) = n_i(t) + F_{+,i}\, h_+(t-d_i) + F_{\times,i}\, h_\times(t-d_i)$$

Detector output — noise — Antenna factor — Our goal — Antenna factor — Our goal

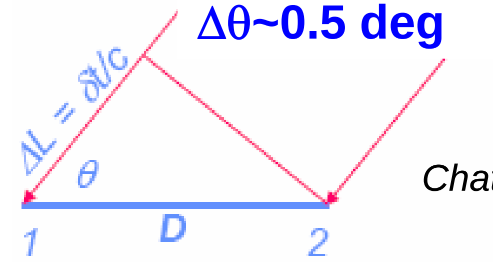
- At least three detector sites are needed in order to extract source waveform information
- Fully coherent analyses
  - » Maximum likelihood ("null stream")
  - » Regularized likelihoods
  - » Improved consistency tests
  - » Maximum entropy
- Recovery of the waveform is essential for the study of the astrophysics of the sources:
  - » Equation of state polytropic index, differential rotation, rotational kinetic energy

Source localization

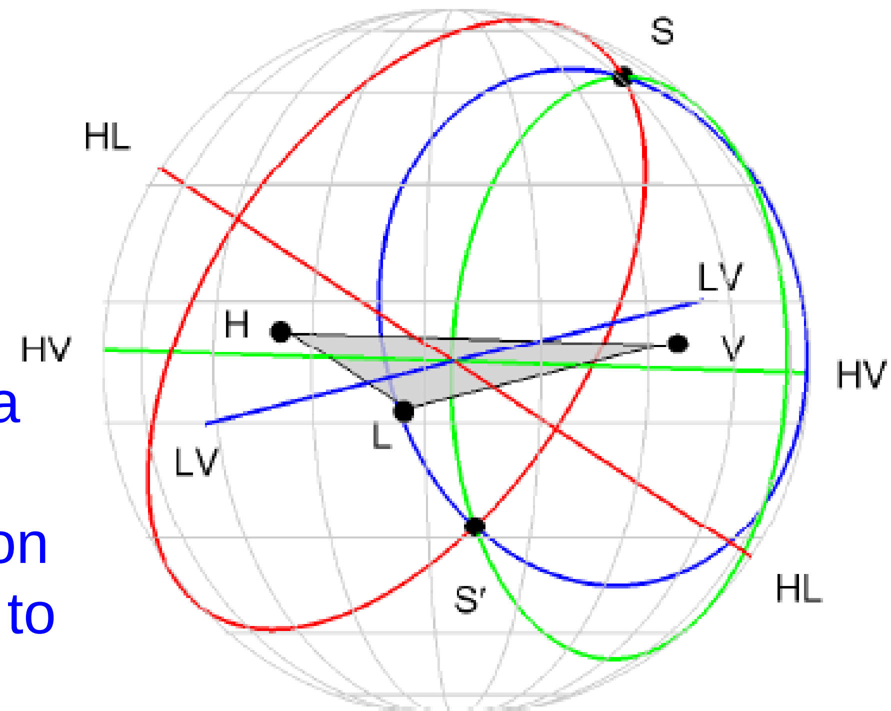
- Geometry of the network:
  - » Time delays between any two detectors define a ring on the sky
  - » For a 3-detector network these ring intersect in two locations
  - » Degeneracy can be resolved by examining amplitudes
- Automatic in fully coherent analyses: the sky position that minimizes χ^2
- Fully coherent and incoherent data analysis techniques for detection, glitch rejection, waveform extraction and source location being applied to the LIGO-GEO-VIRGO data

$\cos\theta = c\Delta t/D$

$\Delta\theta \sim 0.5$ deg



Chatterji et al, PRD 2006



LIGO

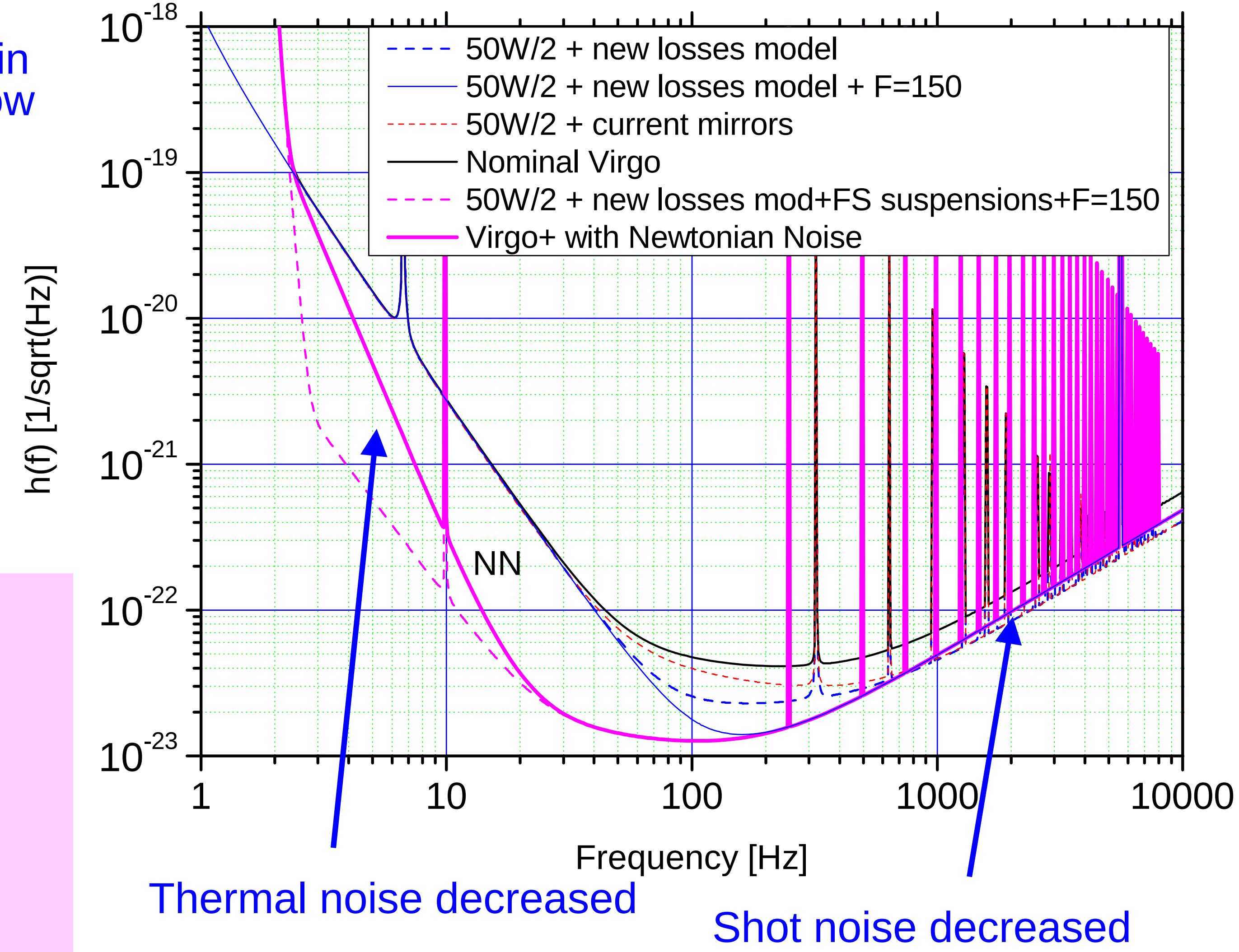
Present ⟶ advanced detectors

Challenges for advanced detectors

- Extending bandwidth of resonant mass detectors
- Reducing noise to the level of interferometers
- Seismic isolation
- Thermal noise suppression
- High power lasers
- Thermal lensing effects in optical components
- Mirror coatings

VIRGO+

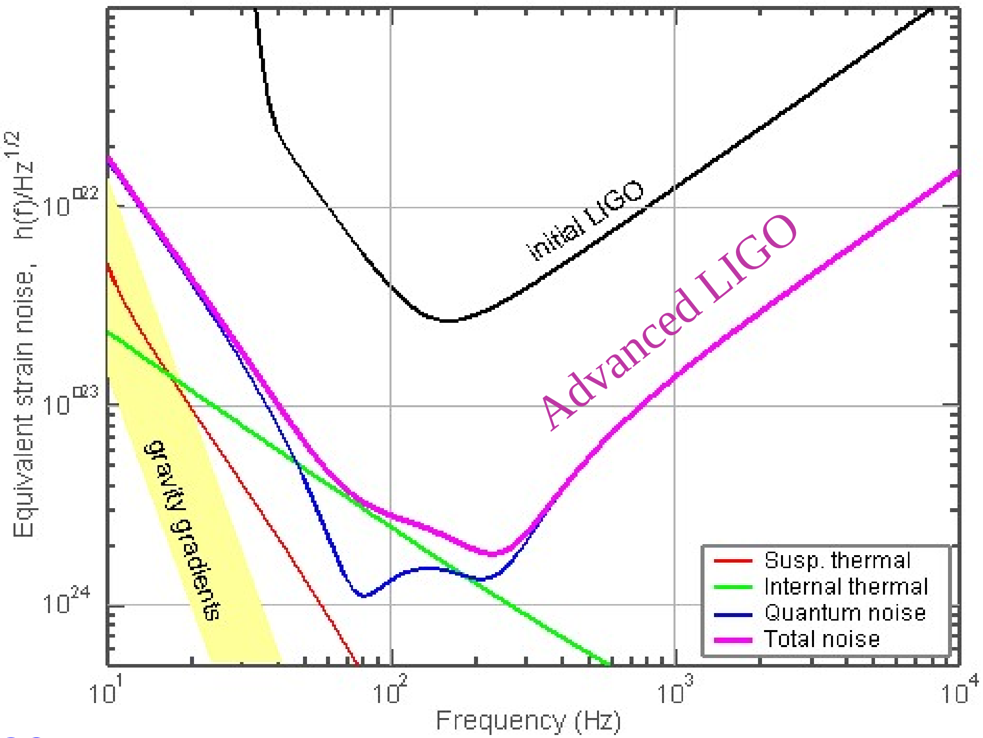
- Modest updates within the 2008-2009 window



- 50 W laser, F=150 cavities
- Low loss suprasil end mirrors
- Monolitic suspensions

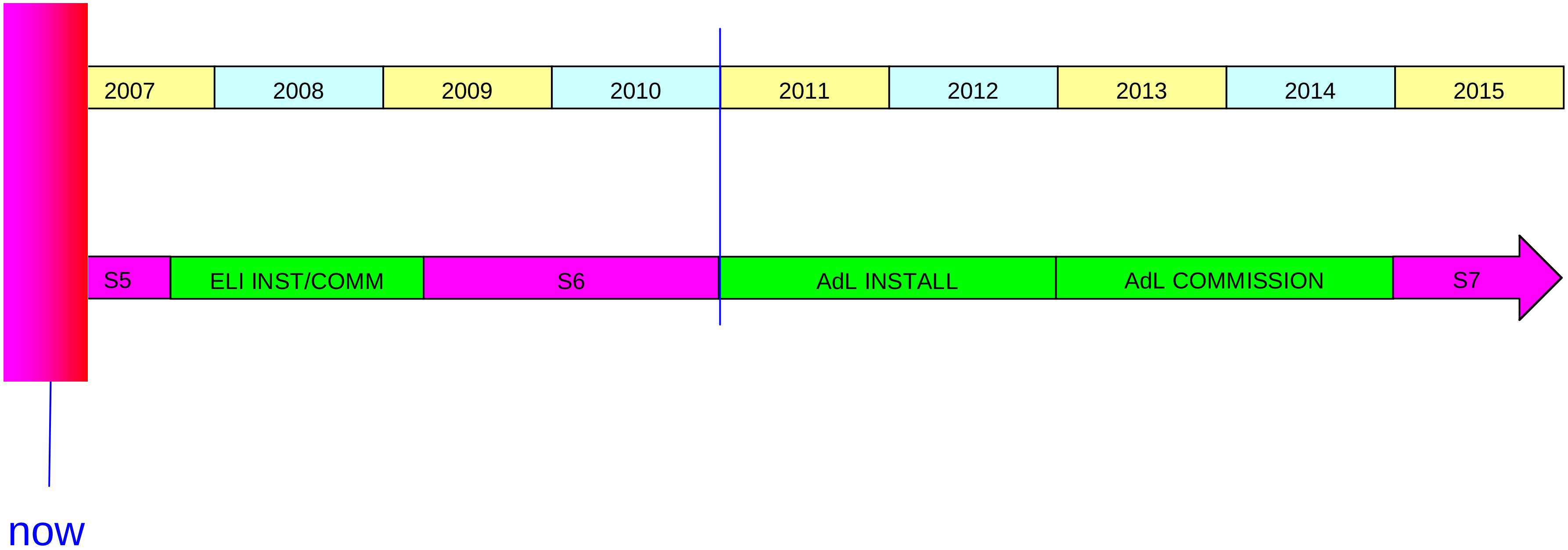
Advanced LIGO

- Factor 10 better amplitude sensitivity
  - » (Reach)^3 = rate
- Factor 4 lower frequency bound
- Infrastructure of initial LIGO but replace many detector components with new designs



- Increase laser power in arms.
- Better seismic isolation.
  - » Quadruple pendula for each mass
- Larger mirrors to suppress thermal noise.
- Silica wires to suppress suspension thermal noise.
- “New” noise source due to increased laser power: radiation pressure noise.
- Signal recycling mirror: Allows tuning sensitivity for a particular frequency range.

Timeline of advanced instruments



- AdvLIGO was approved by the US-NSB in 2004.
- It is in the President’s budget for start in 2008!

Conclusions

- A global network of gravitational wave detectors is recording data at an unprecedented sensitivity ever and we are working together to get the most out of data
- New upper limits are being set for the major sources of gravitational wave sources: binary inspirals, periodic sources, burst sources and stochastic background.
- Getting ready to transition from upper limits to first detections and source astrophysics
- Next generation detectors and upgrades of existing ones that will bring guaranteed sources are planned or getting underway