Gravitational Wave Detectors

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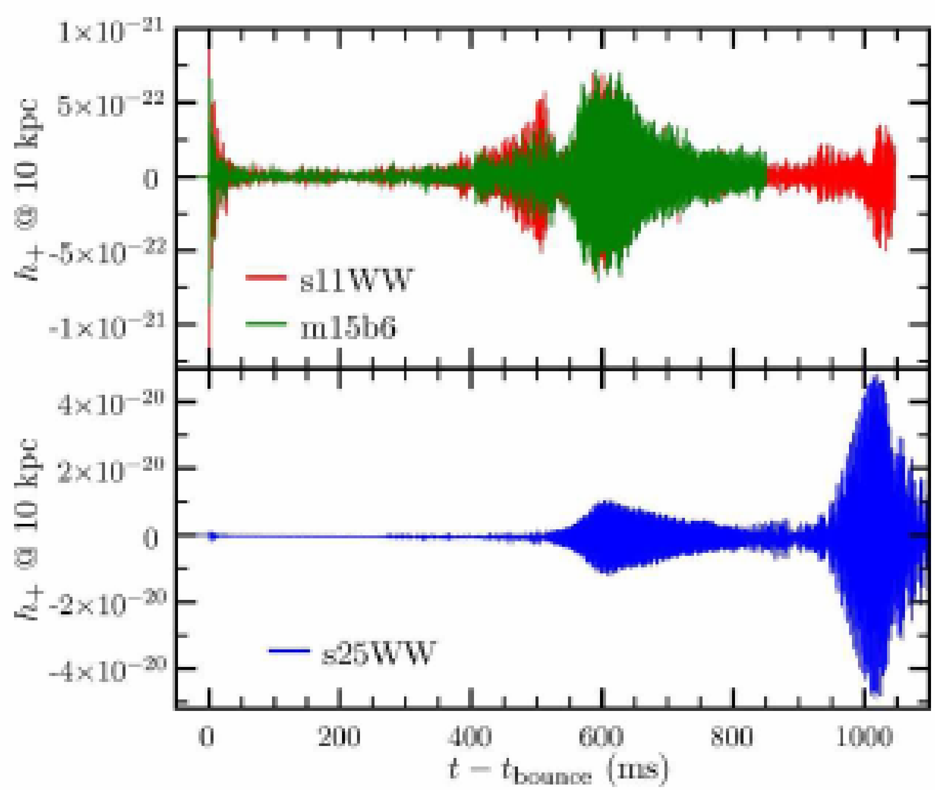
MIT
Twenty Years After SN1987A
Waikoloa, Hawaii
February 25, 2007

Observing the Universe



Ott, Burrows, Lessart, Livne, 2006

licholas Suntzeff, this conference

J. Van der Velde, this conference

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

Outline

- Gravitational waves
- Gravitational wave detectors
- Searches for gravitational waves
- Network of gravitational wave detectors
- Advanced detectors
- Conclusions

The theory of gravitational radiation

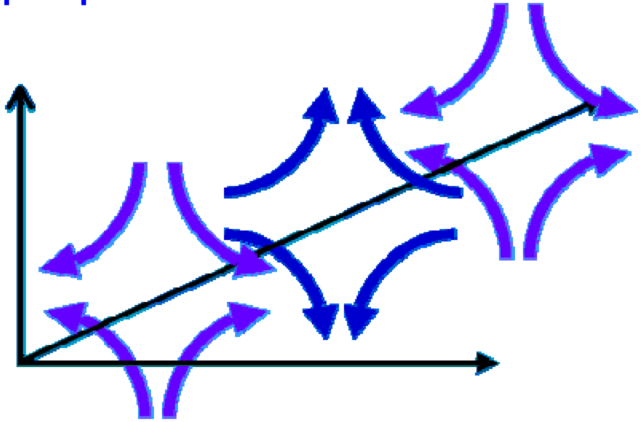
- Einstein's general relativity

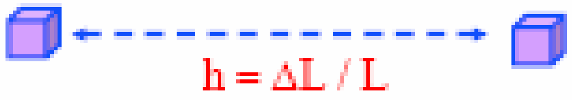
$$G_{\mu\nu} = 8\pi T_{\mu\nu}$$

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

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

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





$h = \Delta L / L$

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:
  - » $h \sim (c/r)\ Q''\ 1/\boxed{(c^5/G)}$ ← '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:

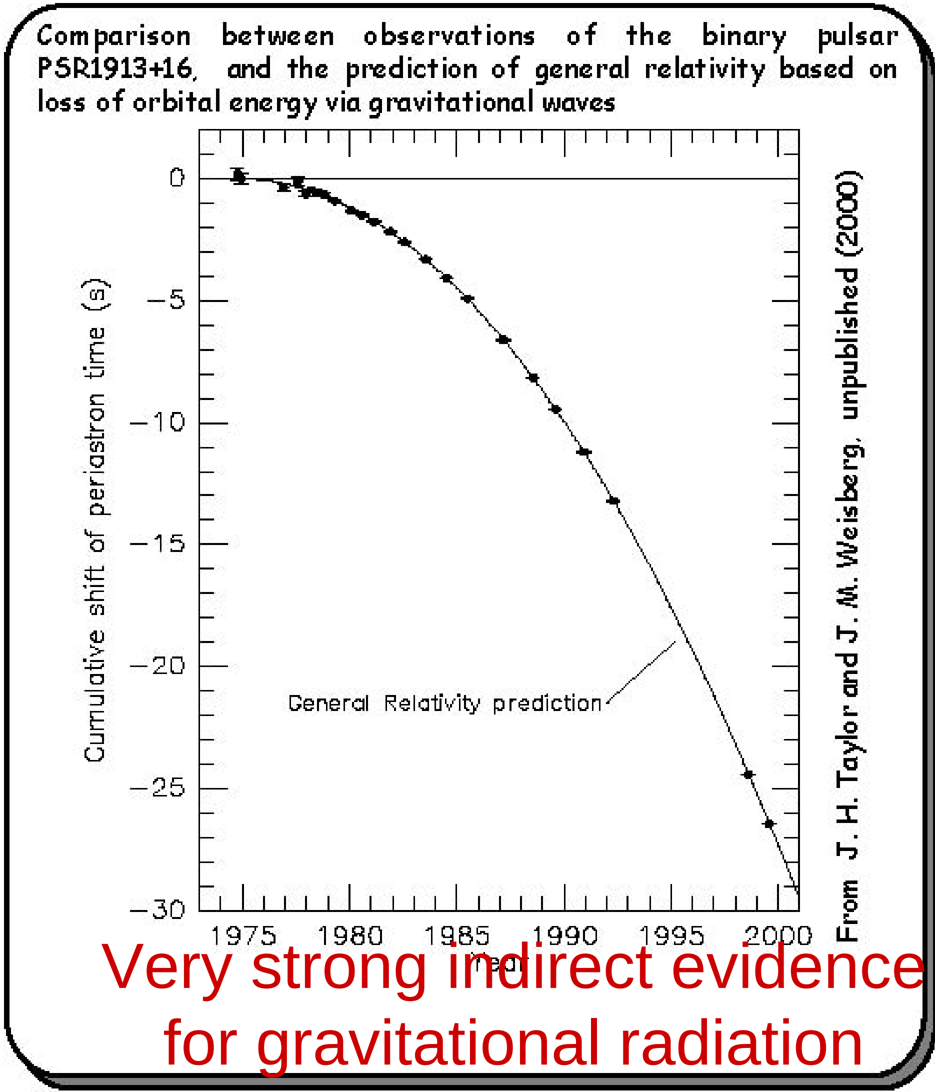
$|h| = 32\pi^2 G/c^4\ f^2 M r^2/R$ ...plug in some numbers...

$M = 1.4\ M_{o\ ,}\ f \sim 400\mathrm{Hz},\ r = 20\mathrm{km},$

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

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!**



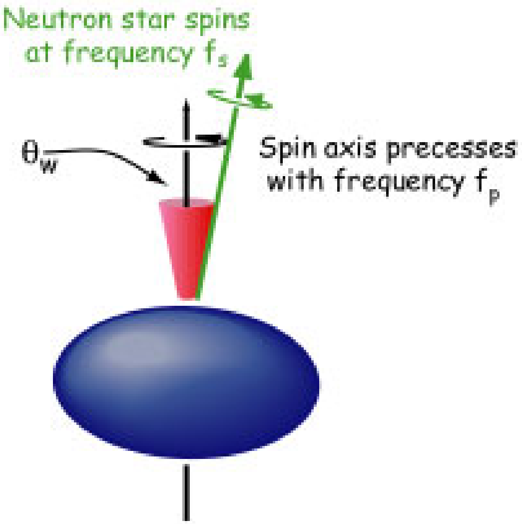
Comparison between observations of the binary pulsar PSR1913+16, and the prediction of general relativity based on loss of orbital energy via gravitational waves

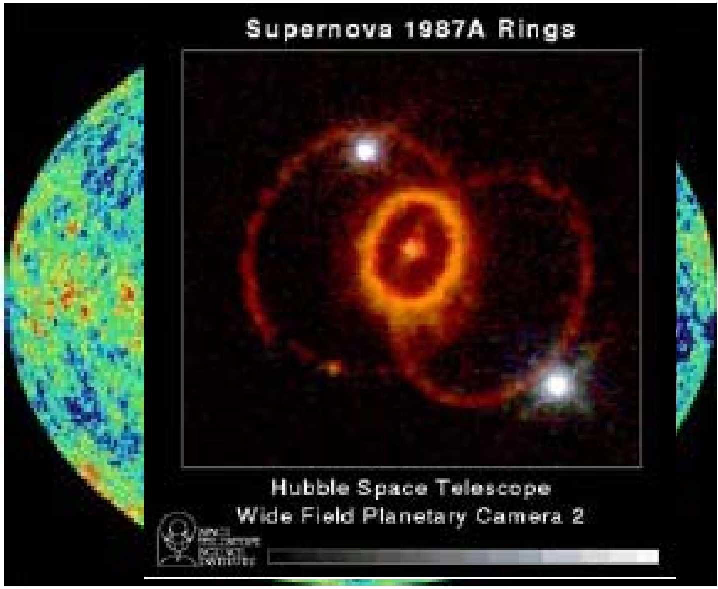
From J. H. Taylor and J. M. Weisberg, unpublished (2000)

Very strong indirect evidence for gravitational radiation

Sources of Gravitational Radiation

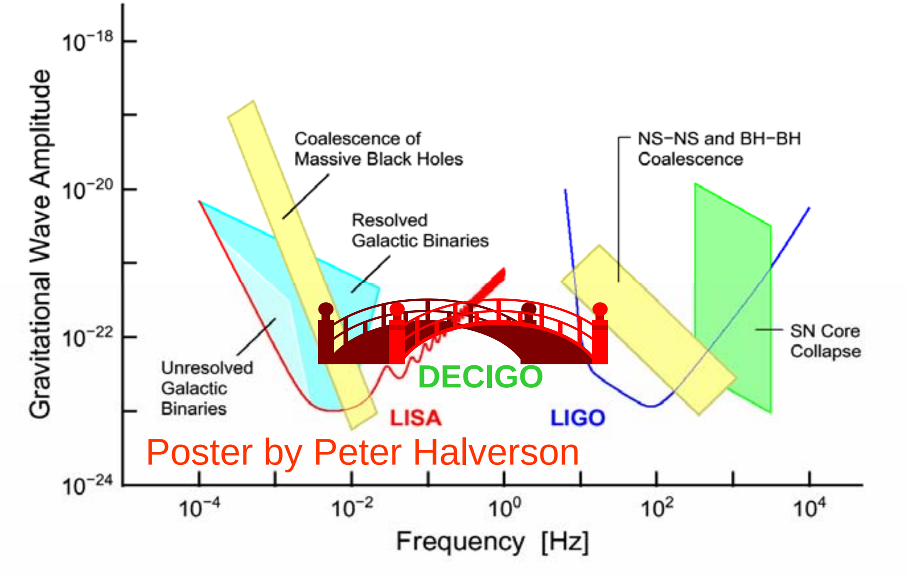
- “Inspiral” of a compact binary system
  - Two neutron stars, two black holes, or one of each
- Burst sources
  - » Short duration transients, inherently powerful, accompanying cosmic catastrophes
  - » Merging of two compact objects, strong gravity limi poor knowledge of the waveforms
  - » Ringing oscillations of newly formed black holes
  - » Supernovae explosions
- Continuous waves
  - » LMXB’s, known and unknown pulsars in our galaxy
- Stochastic background
  - » Random type of radiation described by its spectrum
  - » Big bang, other early universe processes
  - » Many weak unresolved sources emitting gravitational waves independently
- The unexpected!



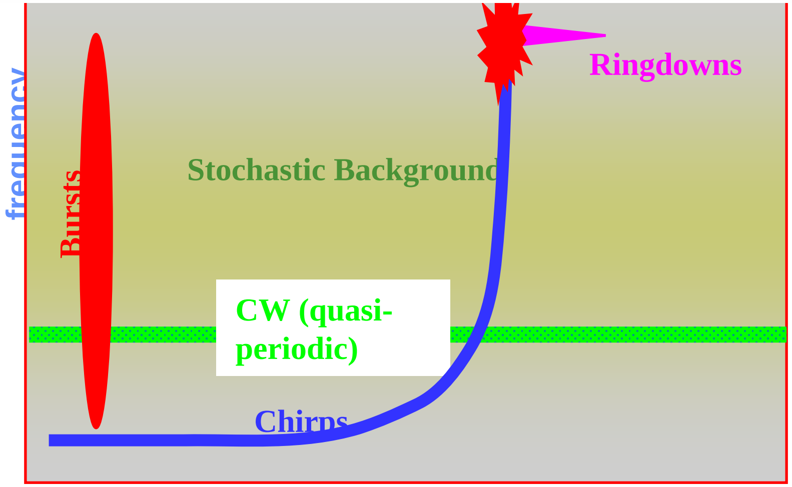


The gravitational wave endeavor

- 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

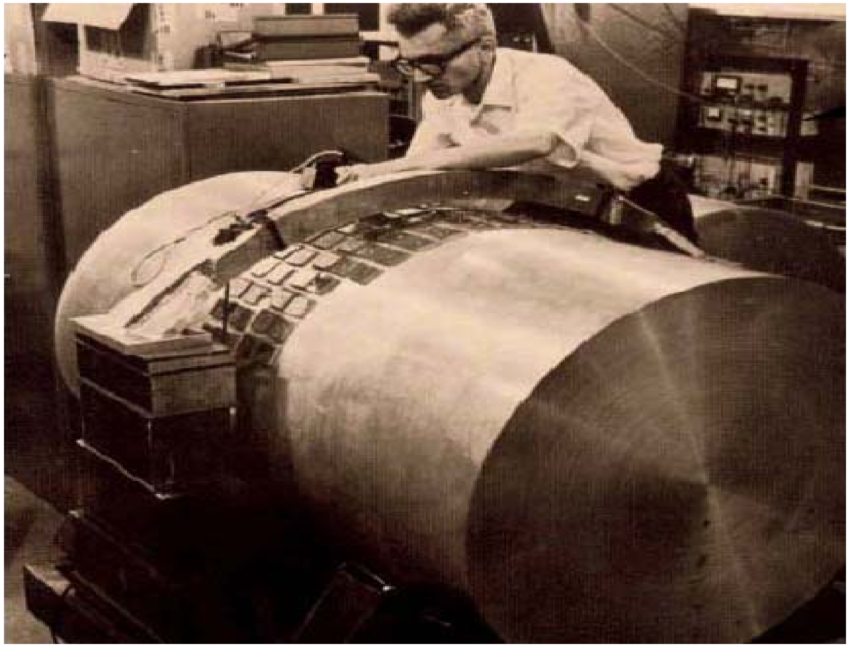


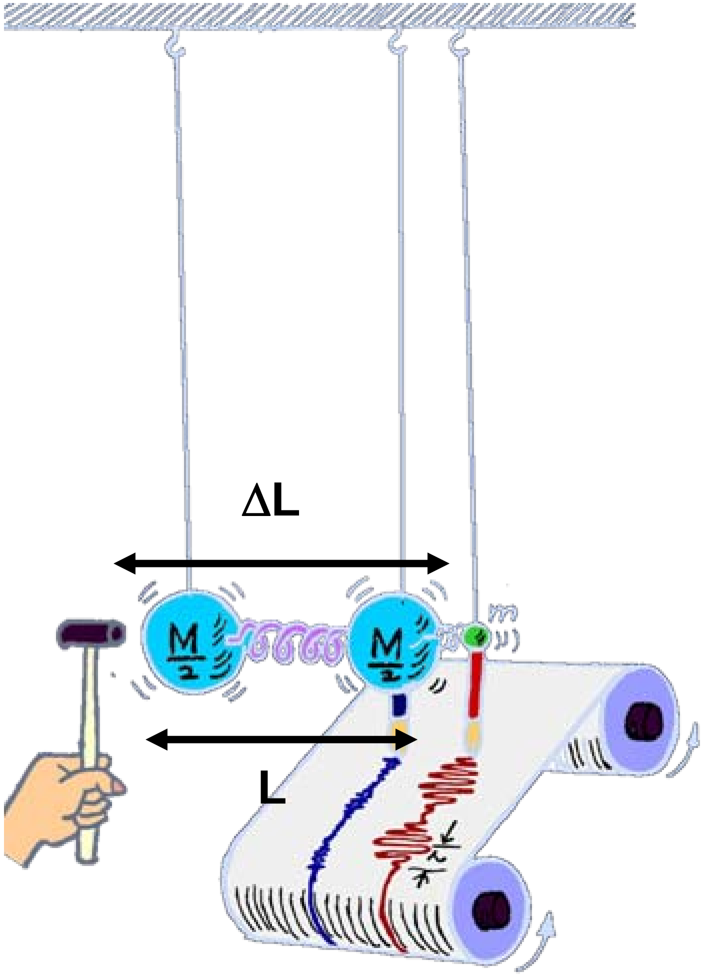
Poster by Peter Halverson



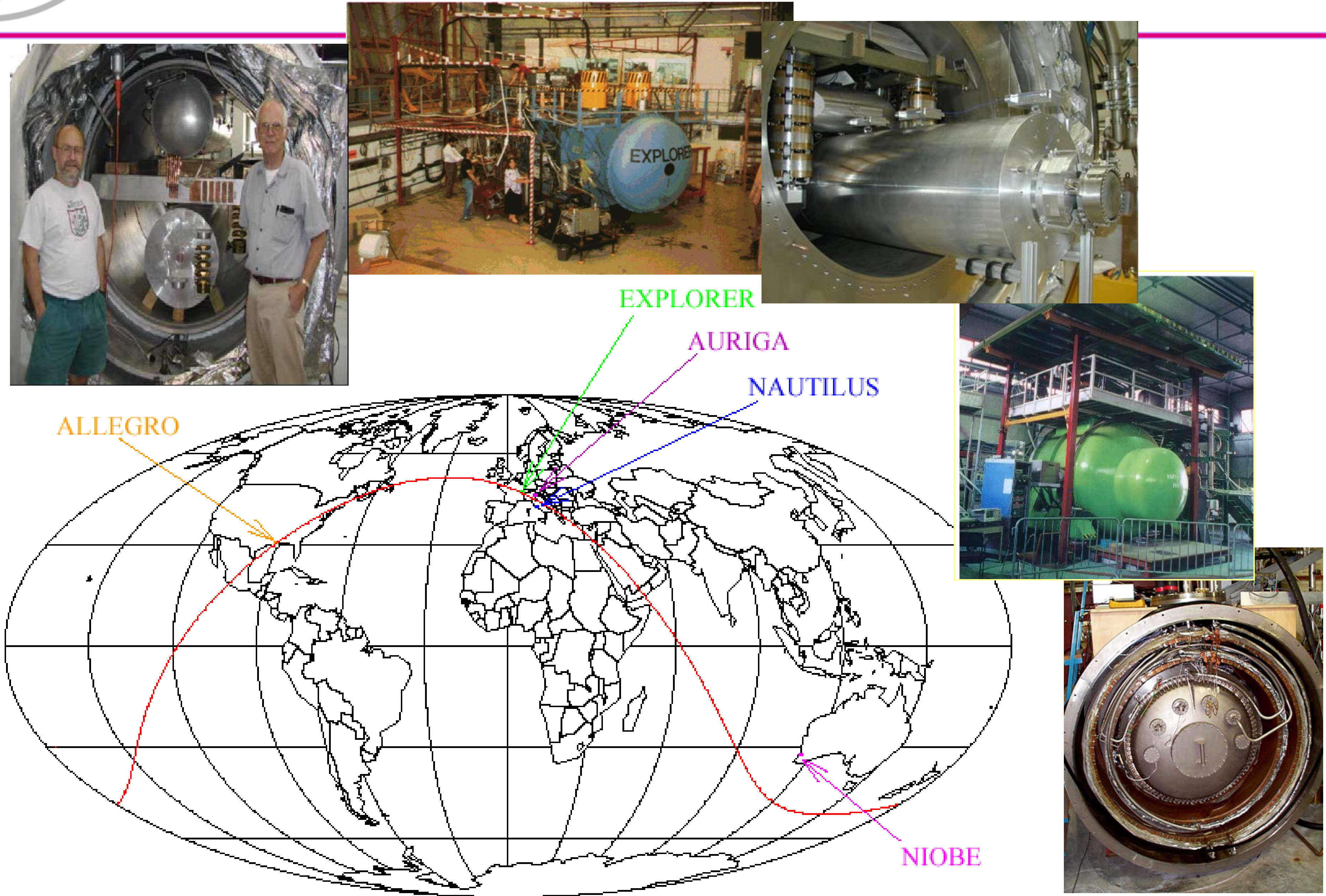
Turning strain *h* into a measurement

- Resonant mass detector:
  - » Translate induced excitations to electrical signal by a motion or strain transducer which is then amplified
- J. Weber's aluminum bars



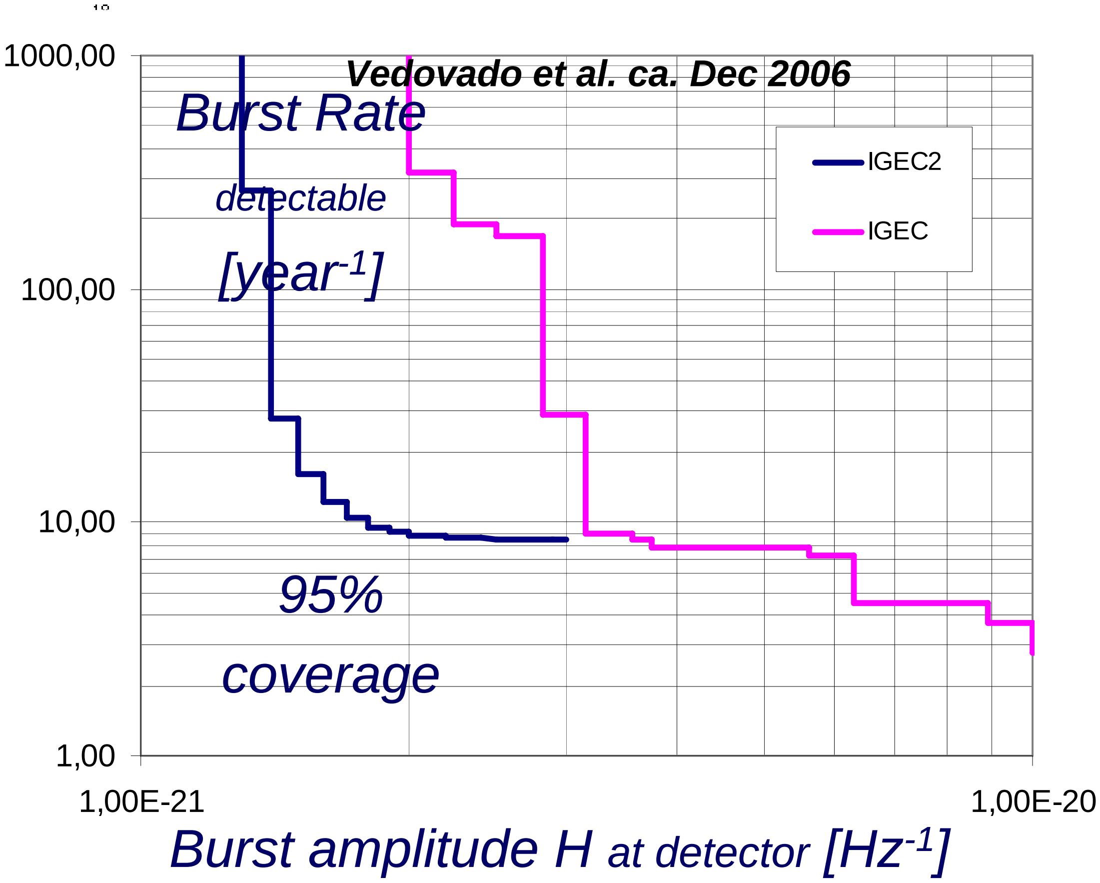


Bar Detector Network



Measurements with the bar detectors

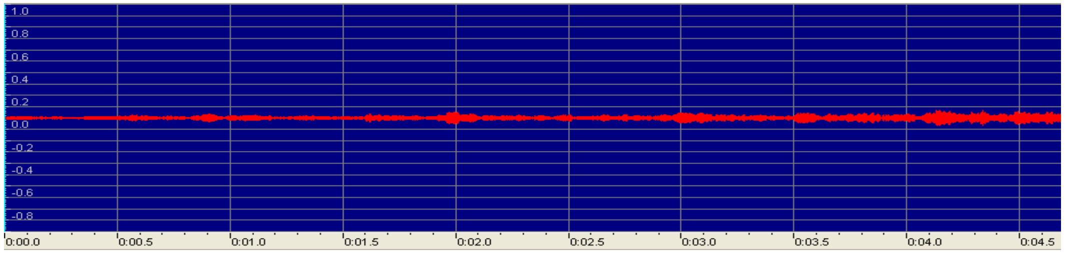
- It’s a hard measurement!
- Narrow band detectors (few tens of Hz) around the bars’ resonant frequency (~900Hz)
- Most suited for broad-band transient signals
- Operated as a network of detectors, “IGEC”, in 1997-2000 and are resuming network analysis in 2005 as “IGEC2”
- Very high duty cycle and very low false alarm network



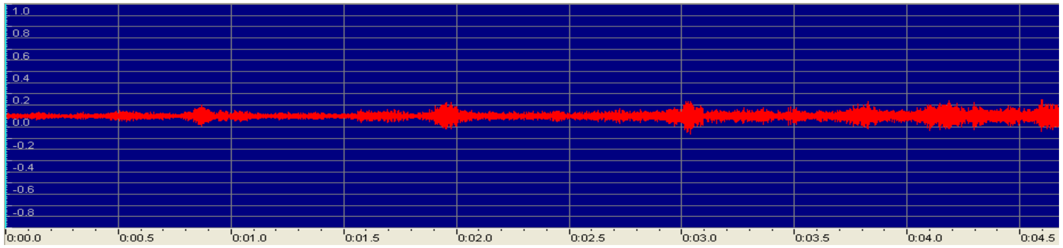
No candidate event was found

What can bandwidth do for you?

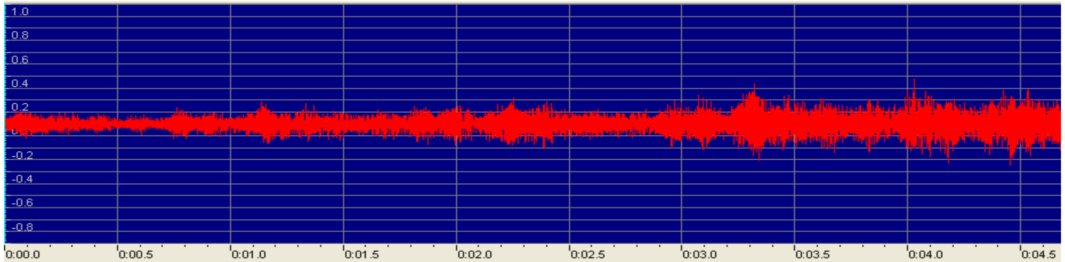
- An evening visit to the Boston Symphony equipped with an 800-1100Hz ear:



- Same visit but with an improved ear, sensitive to 600-1200Hz:



- And another one, but now sensitive in 100-8000Hz:

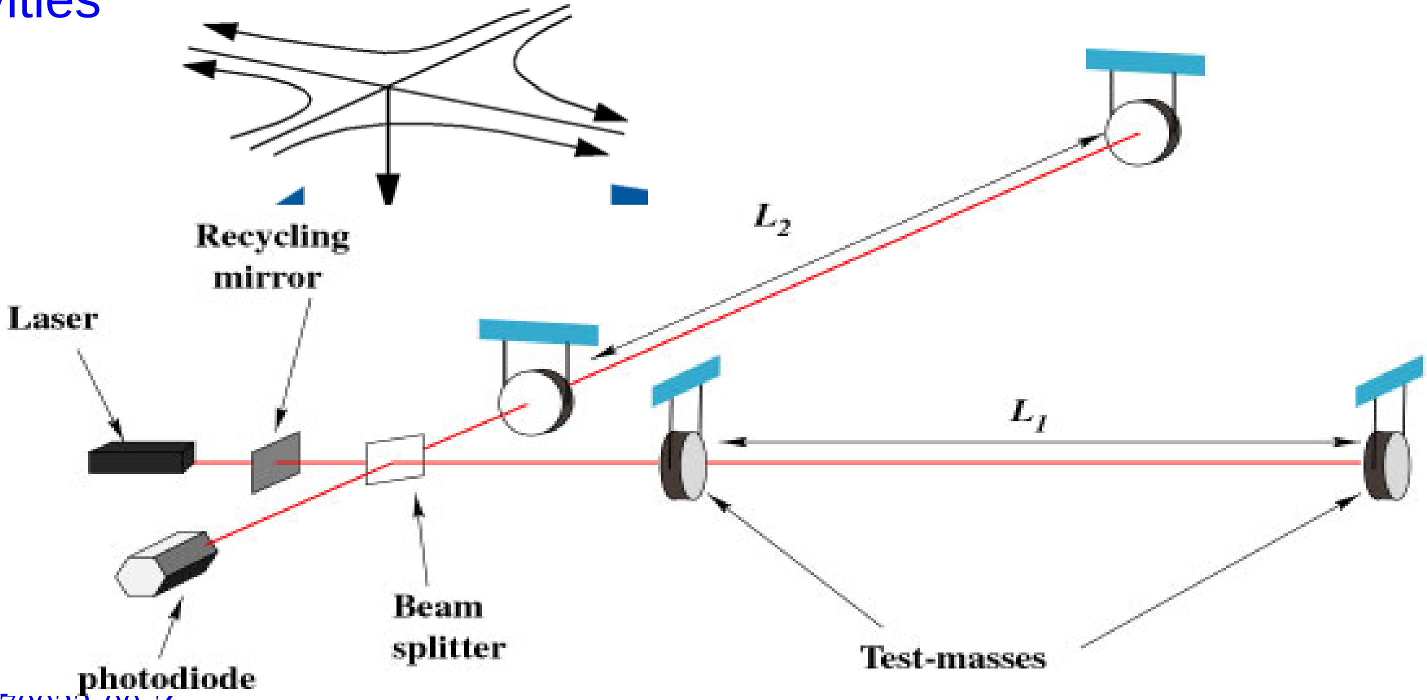


- These could be nature's waveforms and sounds! how can we capture its full glory?

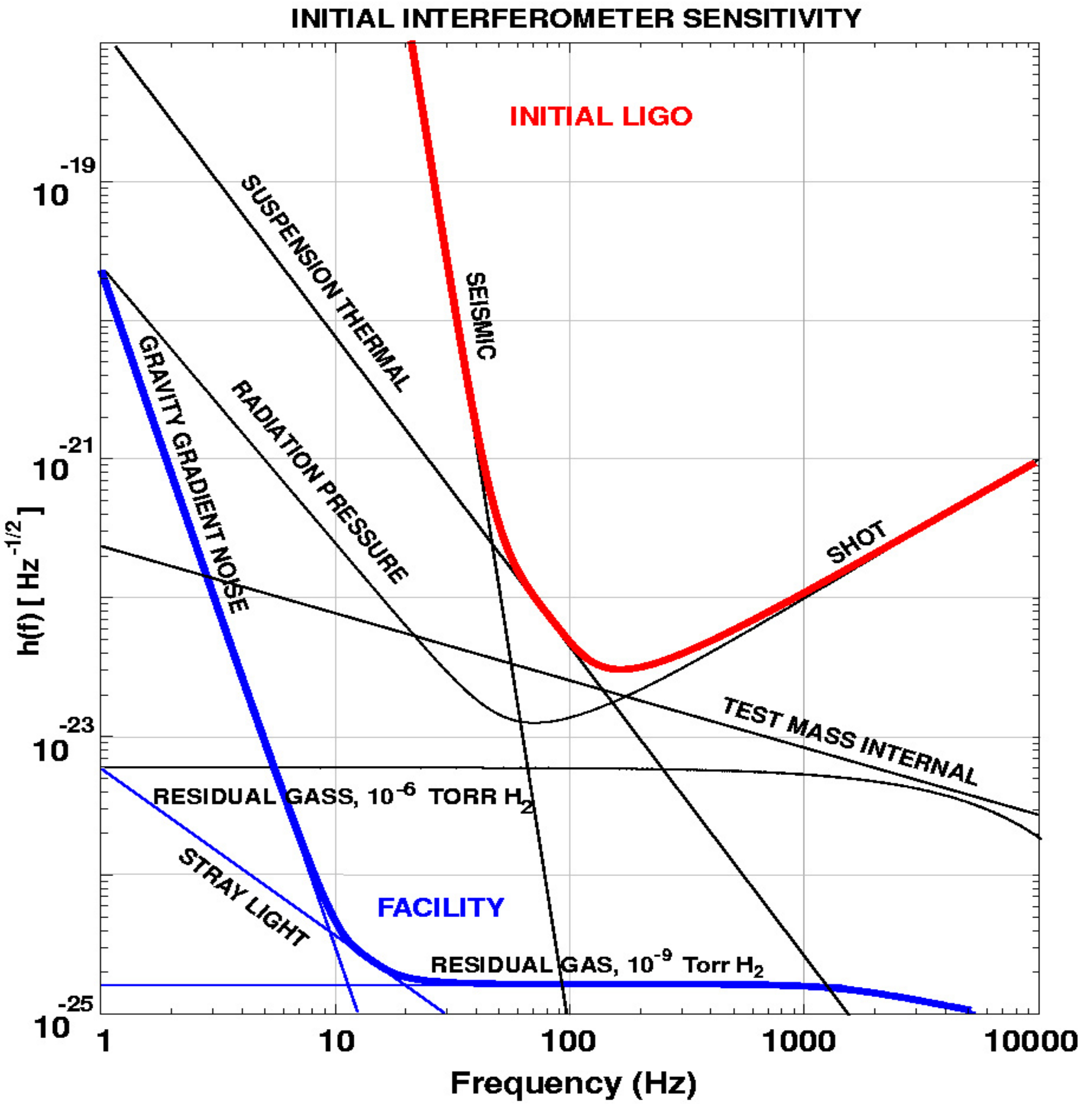
Interferometer Concept

- 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* ~ 4 km and for a hypothetical wave of *h* ~ 10^{-21}

  $\Delta L \sim 10^{-18}$ m !
- Power-recycled Michelson interferometer with Fabry-Perot arm cavities

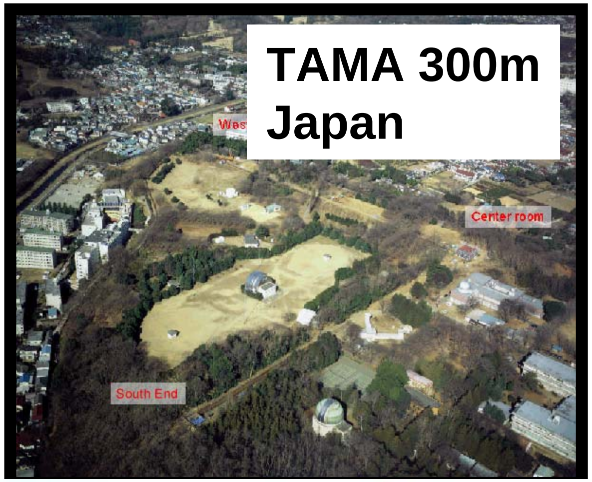


Ground interferometers' noise budget



- Best strain sensitivity ~3x10^{-23} 1/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

Interferometric Detectors


TAMA 300m
Japan


VIRGO 3km
Italy


LIGO Louisiana 4km
USA

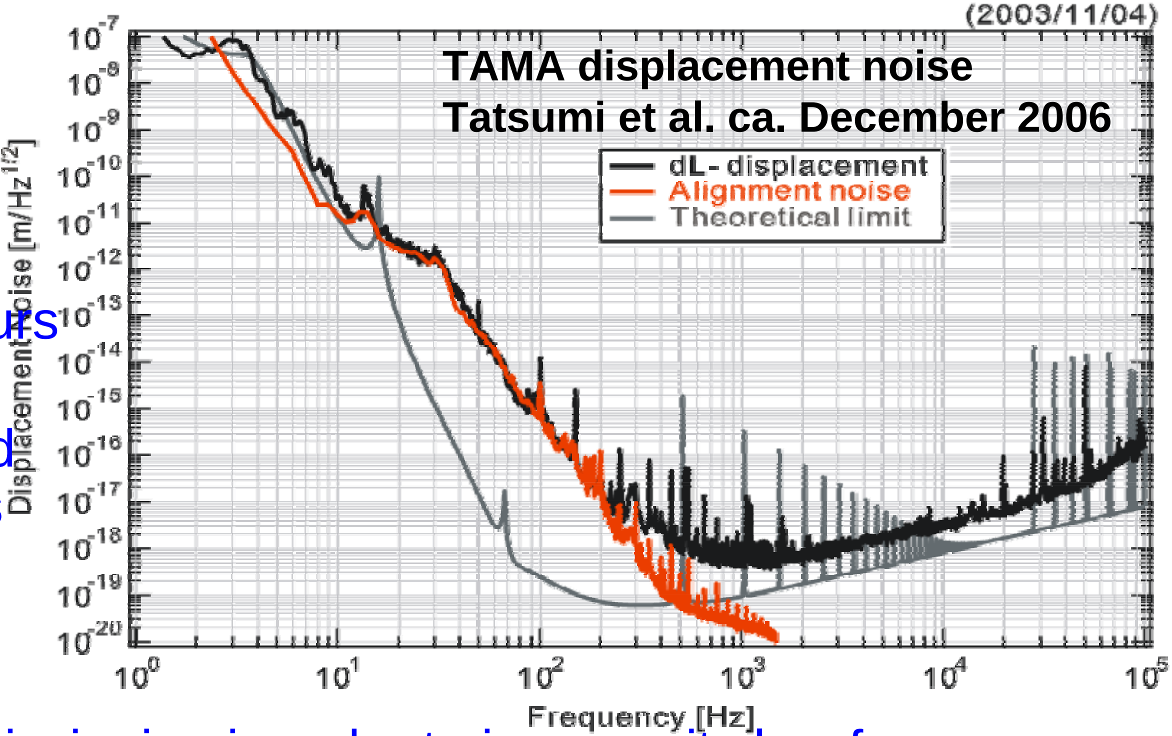

CLIO 100m
Japan


GEO 600m
Germany


LIGO Washington 2km& 4km
USA

TAMA and CLIO

- TAMA: first interferometric detector to come online in 1999
- By 2004, nine data taking periods collected ~3000 hours of data
- Several searches performed for transient and continuous sources and upper limit placed



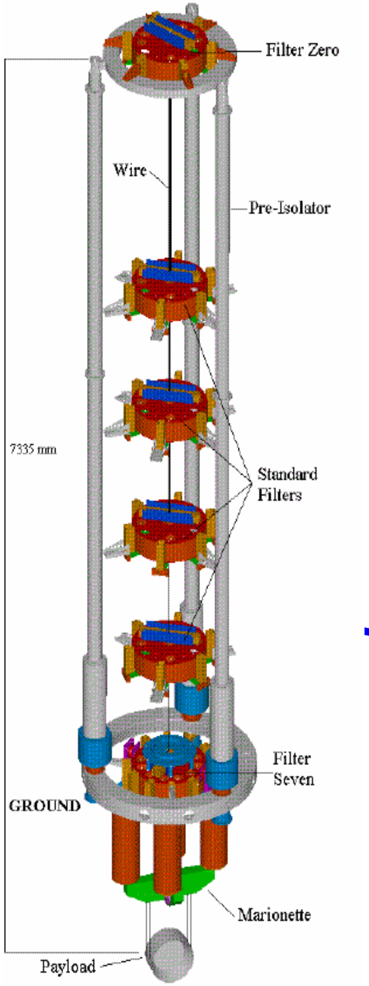
TAMA displacement noise
Tatsumi et al. ca. December 2006

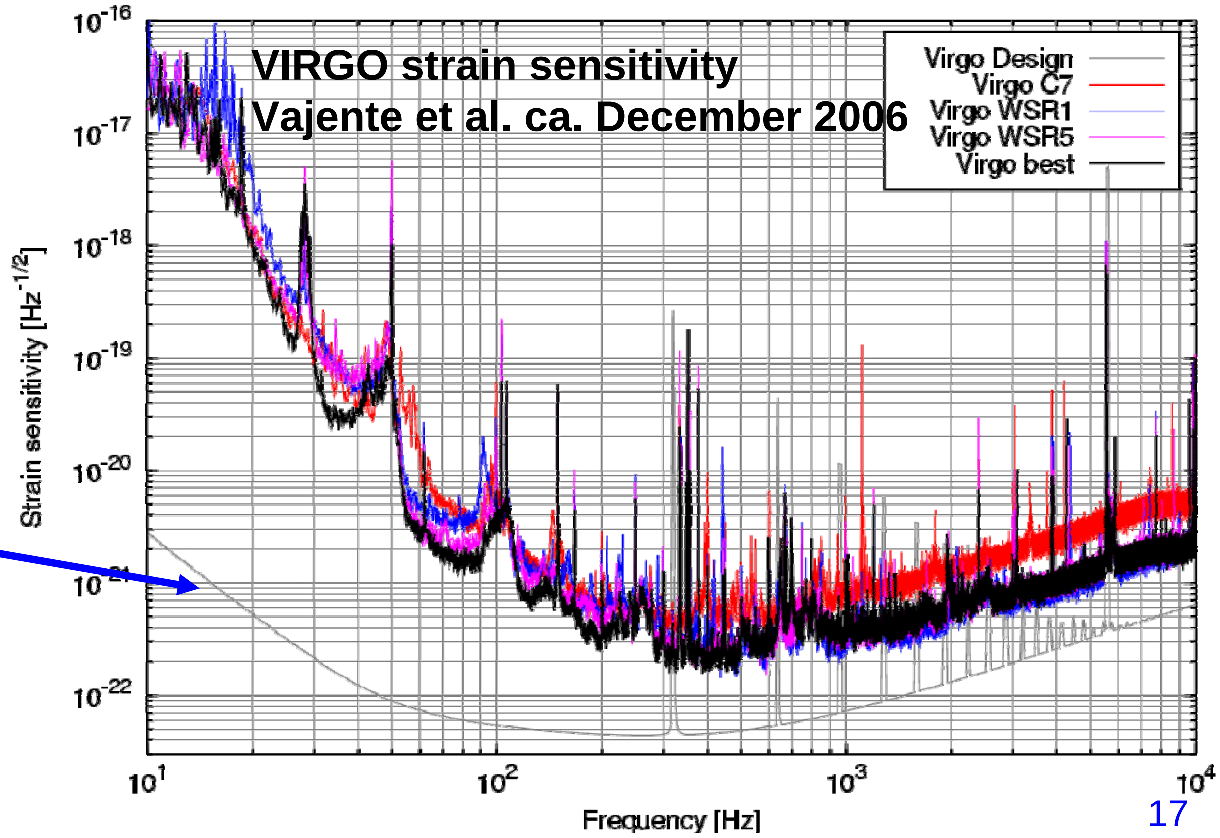
- Currently undergoing commissioning in order to improve its low frequency noise
- CLIO: first cryogenic interferometer test drive in February 2006
- Noise hunting continues
- R&D facilities for next generation large cryogenic detector at Kamioka mine

Poster by Shinji MIyoki

VIRGO

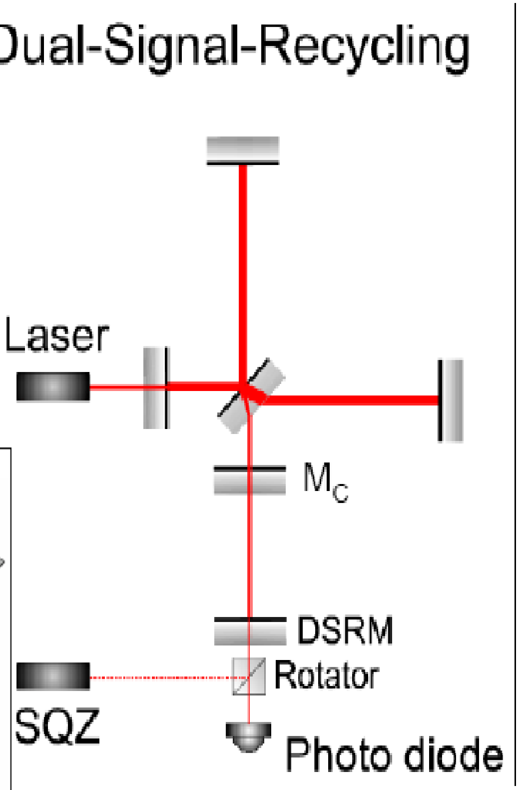
- A French-Italian collaboration that built a 3km interferometer in Cascina, Italy
- Commissioning is in the final stages and short data-taking started in Sep 2006
- Instrument features ‘super attenuators’ able to filter seismic noise above ~10Hz

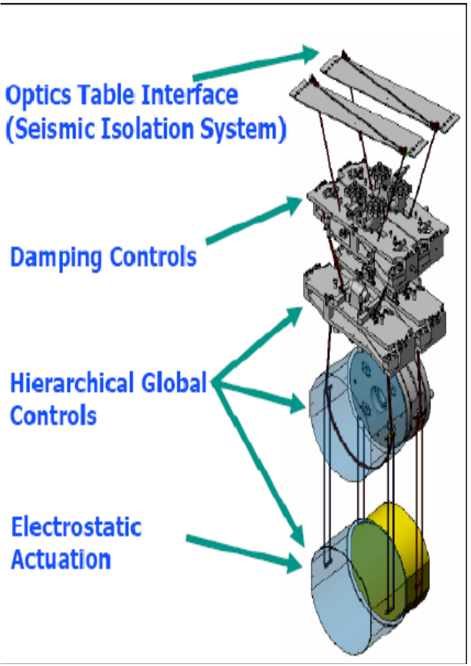



VIRGO strain sensitivity
Vajente et al. ca. December 2006

GEO

- German-UK collaboration built and operates a 600m interferometer in Hannover, Germany.
- Part of the LIGO Scientific Collaboration’s (LSC) instruments
- Developed and implemented advanced technology: signal recycling, monolithic suspensions
- Participated in the LSC science runs so far, currently undergoing commissioning interleaved with data taking

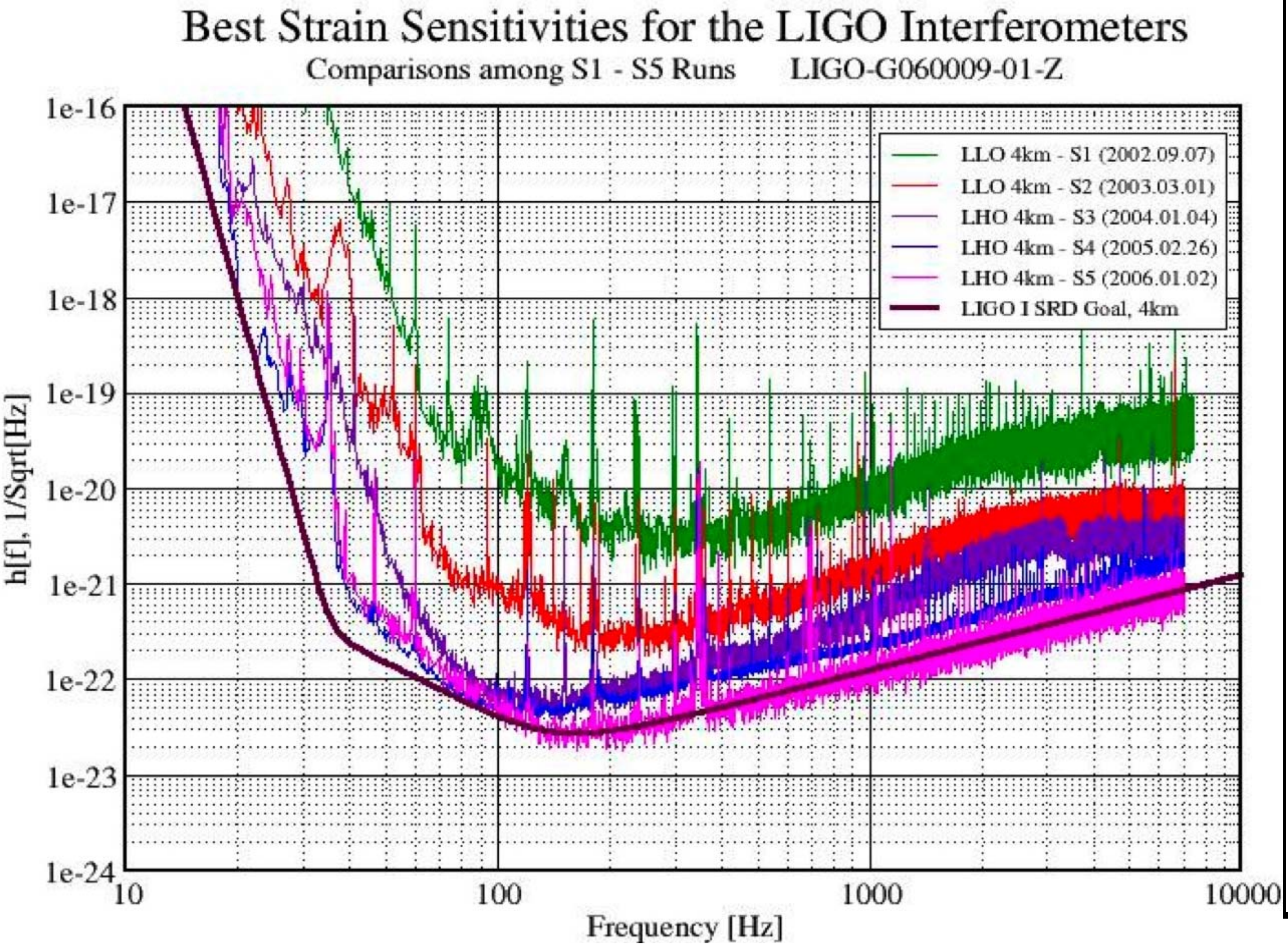




LIGO

- 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

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'

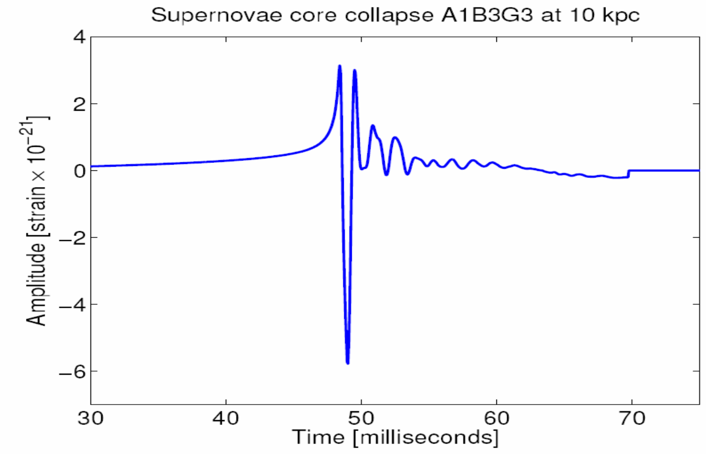
LSC Observational results

- Searches for all-sky and targeted gravitational wave transients
- Searches for coalescing compact binaries with modeled waveforms (inspirals)
- Searches for continuous waves from known pulsars and all-sky search for unknown spinning neutron stars
- Searches for a stochastic background of gravitational waves of cosmological or astrophysical origin

- No discoveries reported
- Analysis of the first two science runs (S1/S2) complete and results published or in press
- Most of S3/S4 analysis are complete and paper publications in preparation
- S5 analyses are ongoing

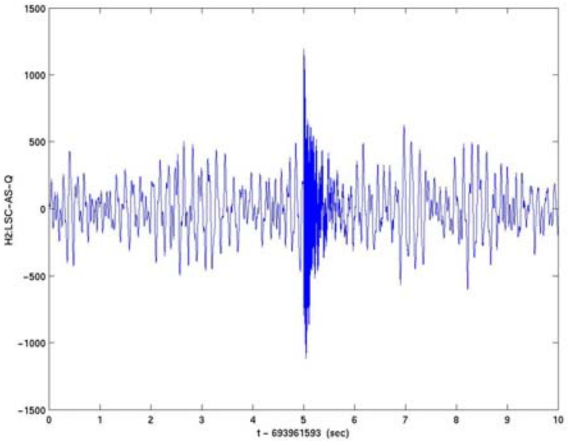
Search for Bursts

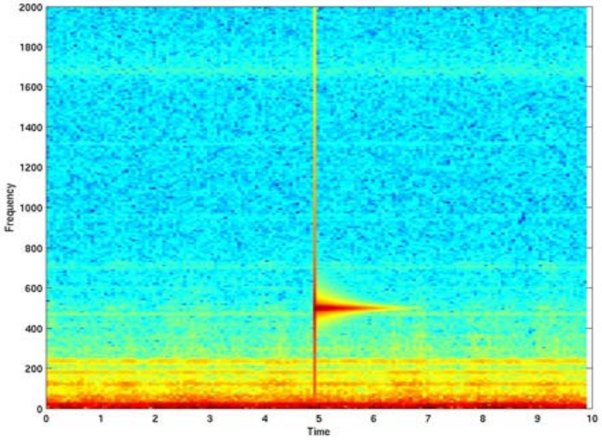
- Sources emitting short transients of gravitational radiation
  - » Supernovae core-collapse
  - » Binary black holes mergers
  - » Black hole normal modes
  - » Neutron star instabilities
  - » Cosmic string cusps and kinks
  - » The unexpected!

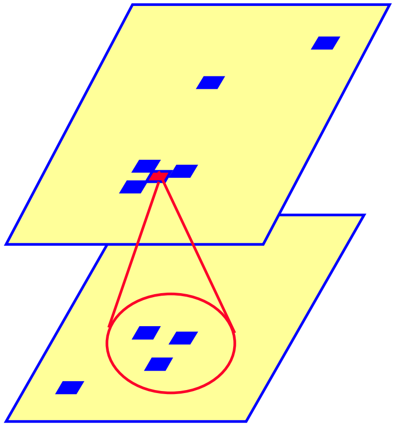


- What we know about them …
  - » Catastrophic astrophysical events observed in the particle and/or electromagnetic sector will plausibly be accompanied by short signals in the gravitational wave sector ➡ *plausible suspects*
  - » Exact waveforms are not or poorly modeled
  - » Durations from few millisecond 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

Burst search: a time-frequency method



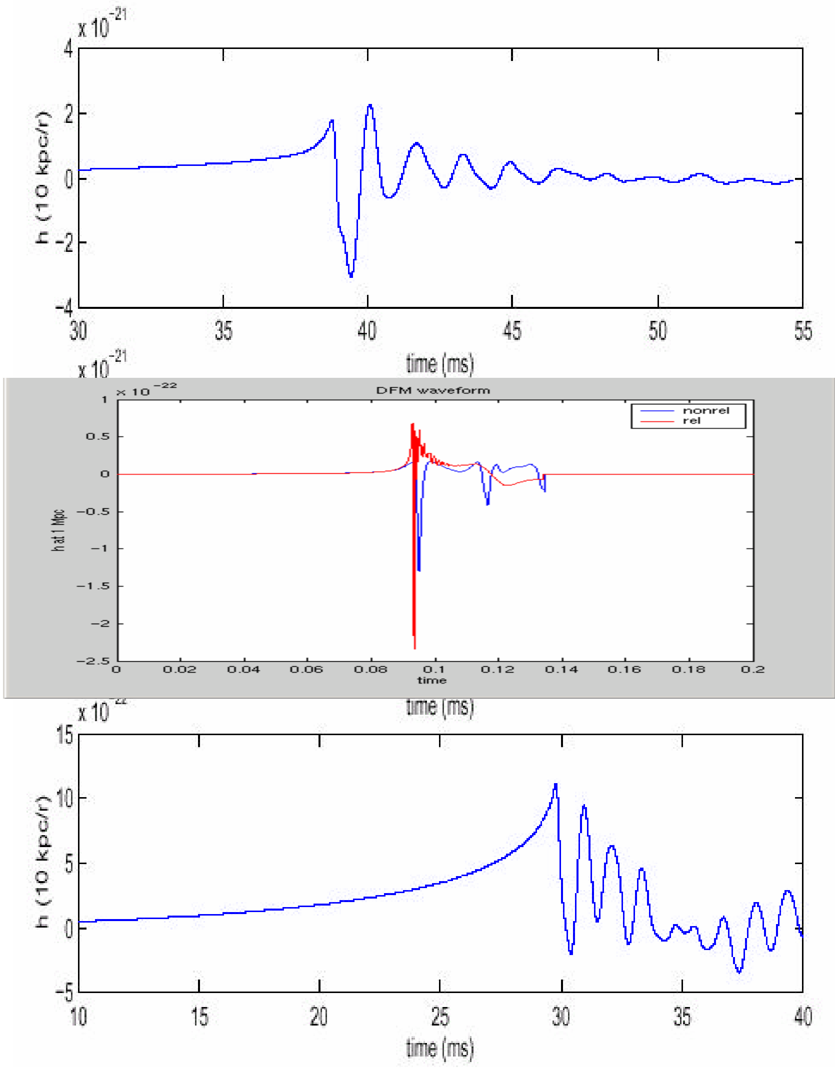




- Compute time-frequency decomposition in a Fourier or wavelet basis
- Threshold on power in a pixel; search for clusters of pixels
- basic assumption: multi-interferometer response consistent with a plane wave-front incident on network of detectors:
  - use temporal coincidence of the 3 interferometer's '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

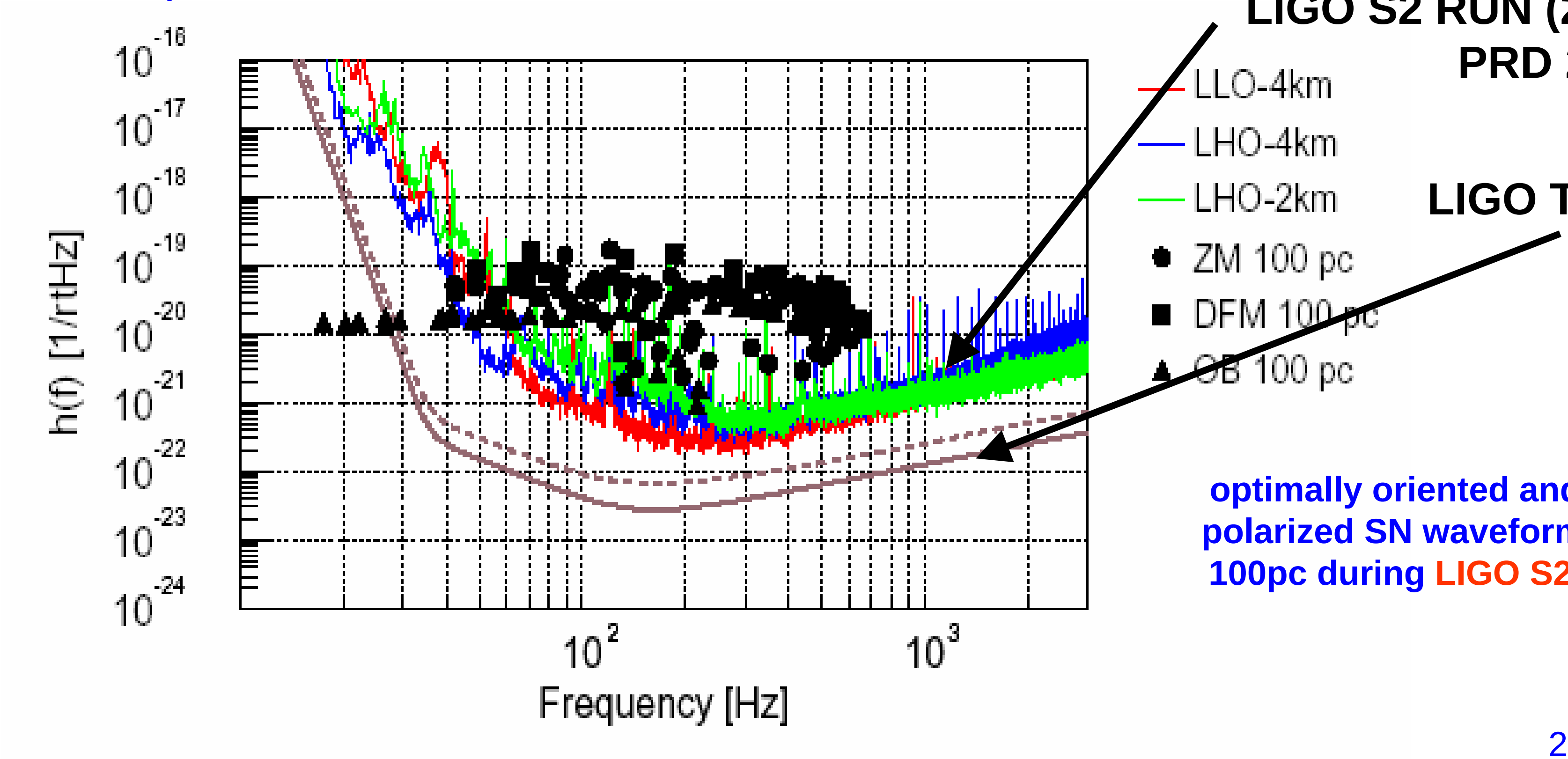
Astrophysical waveforms

- 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



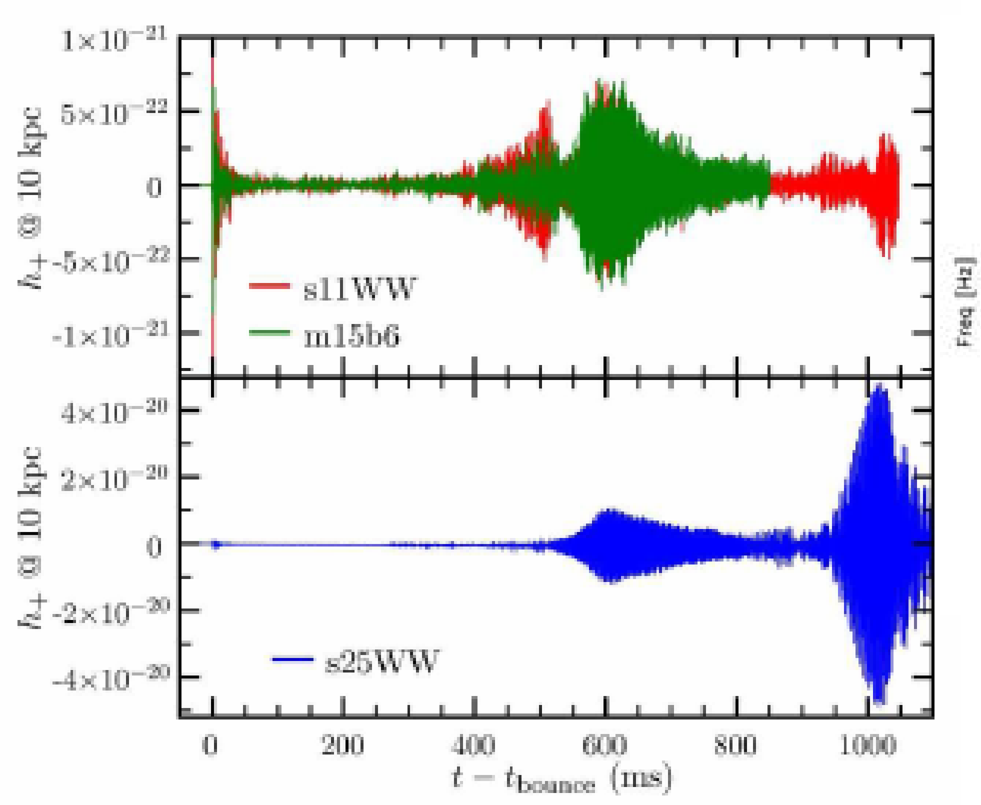
LIGO S2 RUN (2003)
PRD 2005

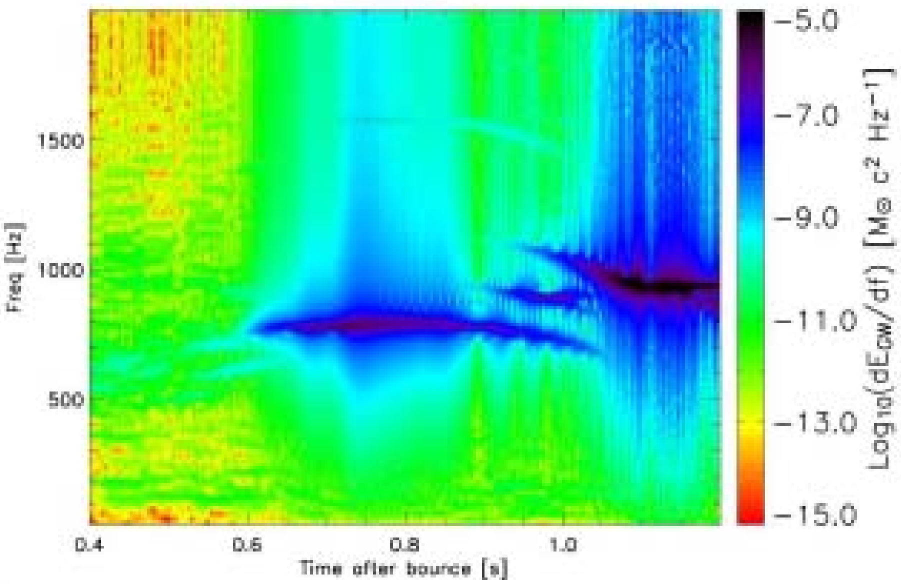
LIGO TODAY

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

Mass equivalence: order of magnitude analysis

- Instantaneous energy flux:

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

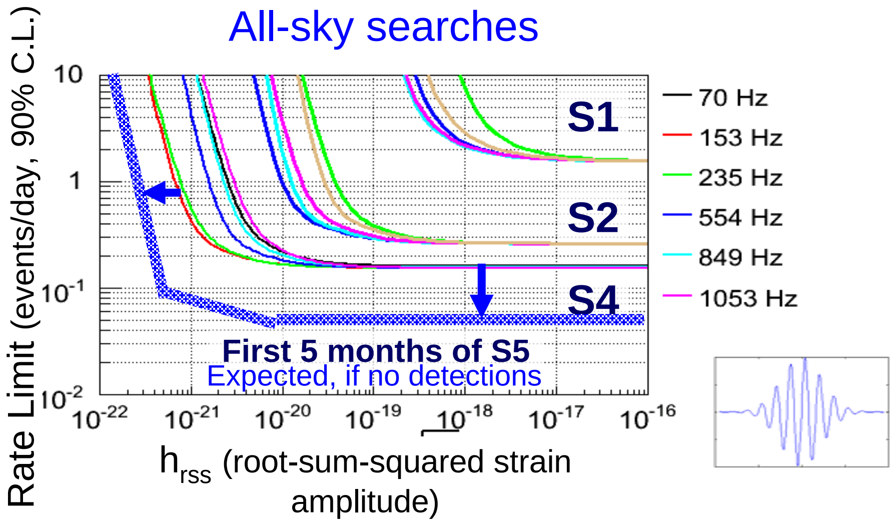
- integrate over signal duration and over a sphere at radius r assuming a sine-gaussian signal of frequency f_0 and quality factor Q:

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

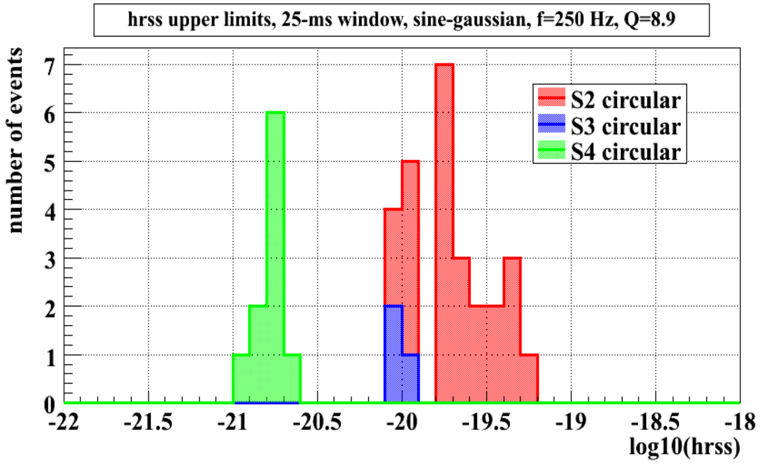
- Assume for a sine-Gaussian-like signal, 153 Hz, Q=8.9, h_{rss} at 50% efficiency is 6.5 x 10^{-22} $Hz^{-1/2}$
  - » 2 x 10^{-8} $M_\odot$ emitted at 10 kpc
  - » 0.05 $M_\odot$ emitted at Virgo Cluster

Results from burst searches (preliminary)

- Complementary detection algorithms tuned for 64–1600 Hz, duration << 1 sec
- Data quality cuts and vetoes help reduce rate of false alarms from artifacts
- Search done blind; “box opened” at end
- No GW event candidates found in S1/2/3/4. S5 search is in progress
- Sensitivity of search evaluated for simulated signals with ad-hoc waveforms
- Corresponding energy emission sensitivity $E_{GW} \sim 10^{-1}\ M_{sun}c^2$ at 20 Mpc (153 Hz case)



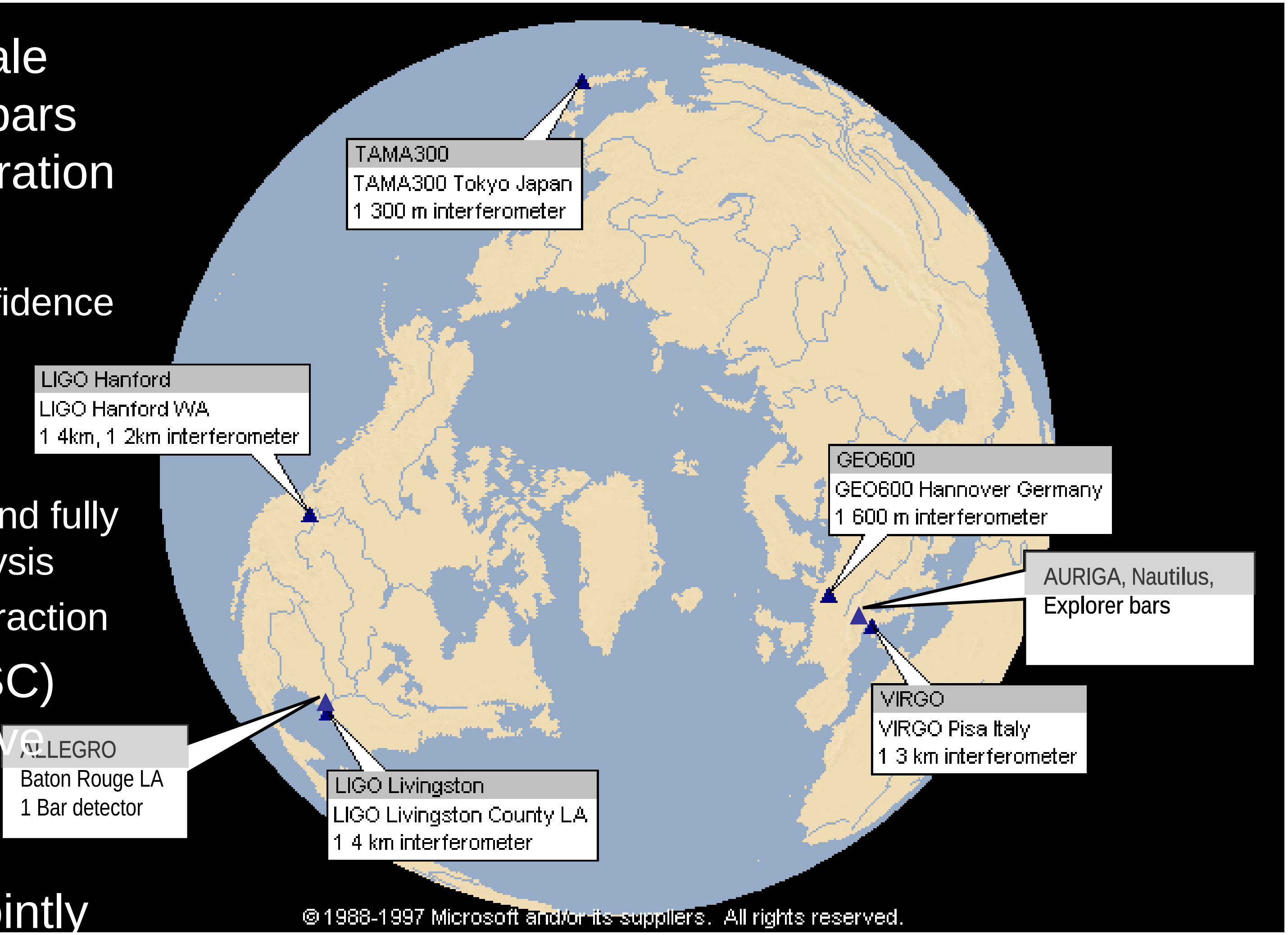
- Search LIGO data surrounding GRB trigger using cross-correlation method
- No GW signal found associated with 39 GRB GRB in S2, S3, S4 runs and limits on GW signal amplitude were set
- 53 GRB triggers for the first five months of LIGO S5 run
- Typical S5 sensitivity at 250 Hz: E_{GW} ~ 0.3 Msun at 20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



The path to gravitational wave astronomy

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



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Detections ⟶ astrophysics

- The inverse problem:

$$\underbrace{s_i(t)}_{\text{Detector output}} = \underbrace{n_i(t)}_{\text{noise}} + \underbrace{F_{+,i}}_{\text{Antenna factor}} \underbrace{h_+(t-d_i)}_{\text{Our goal}} + \underbrace{F_{\times,i}}_{\text{Antenna factor}} \underbrace{h_\times(t-d_i)}_{\text{Our goal}}$$

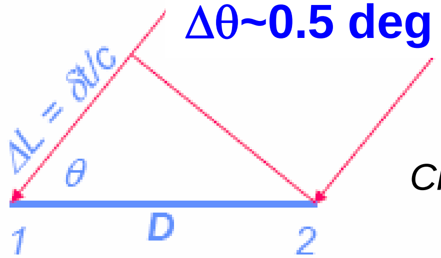
- At least three detector sites are needed in order to extract source waveform information
- Fully coherent analyses: a powerful tool for burst searches
  - » Maximum likelihood (“null stream”)
  - » Regularized likelihoods
  - » Improved consistency tests
  - » Maximum entropy
- Recovery of the waveform is essential for the study of the astrophysics of the sources

Source localization

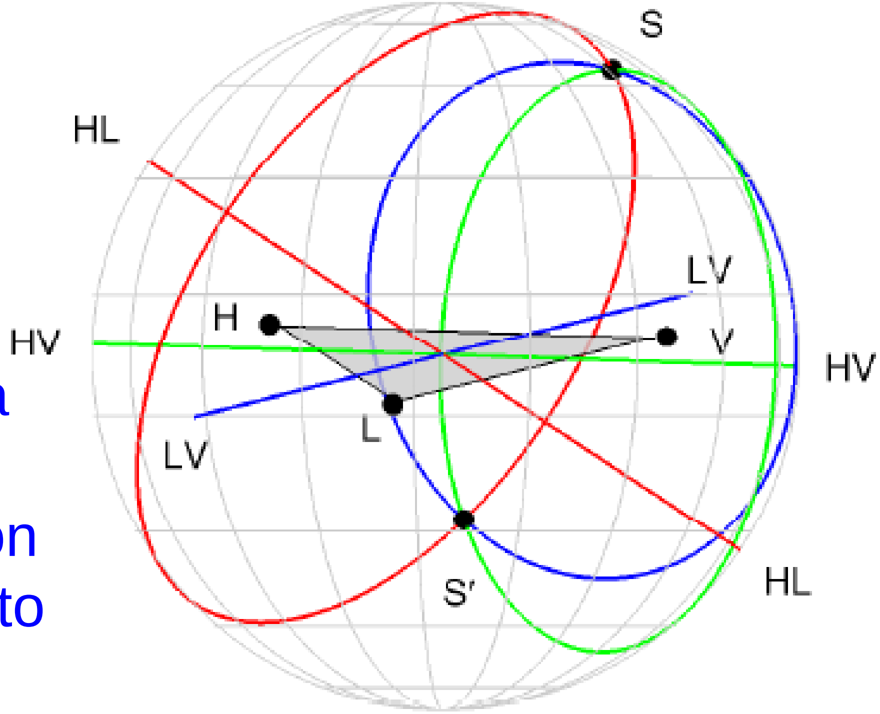
- Geometry of the network:
  - Time delays between any two detectors define a ring on the sky
  - For a 3-detector network these ring intersect in two locations
  - Degeneracy can be resolved by examining amplitudes
- Automatic in fully coherent analyses: the sky position that minimizes χ^2
- Fully coherent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

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

$\Delta\theta$~0.5 deg



Chatterji et al, PRD 2006



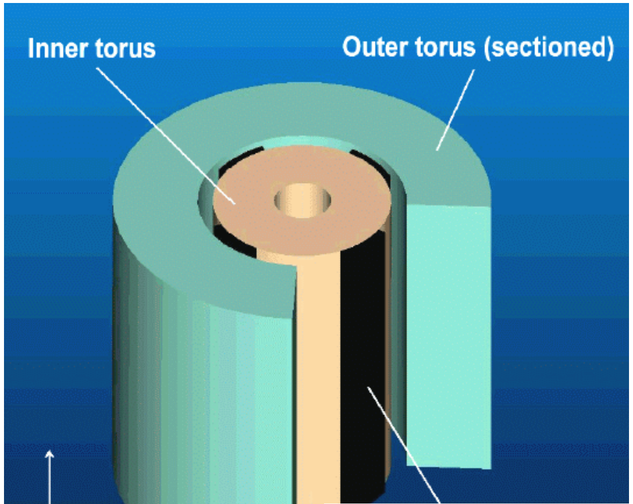
Present ⟶ advanced detectors

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

Resonant mass detectors

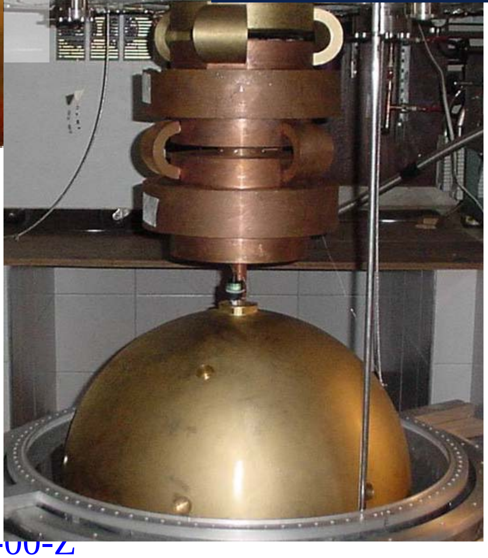
MiniGRAIL
(Leiden-Rome)

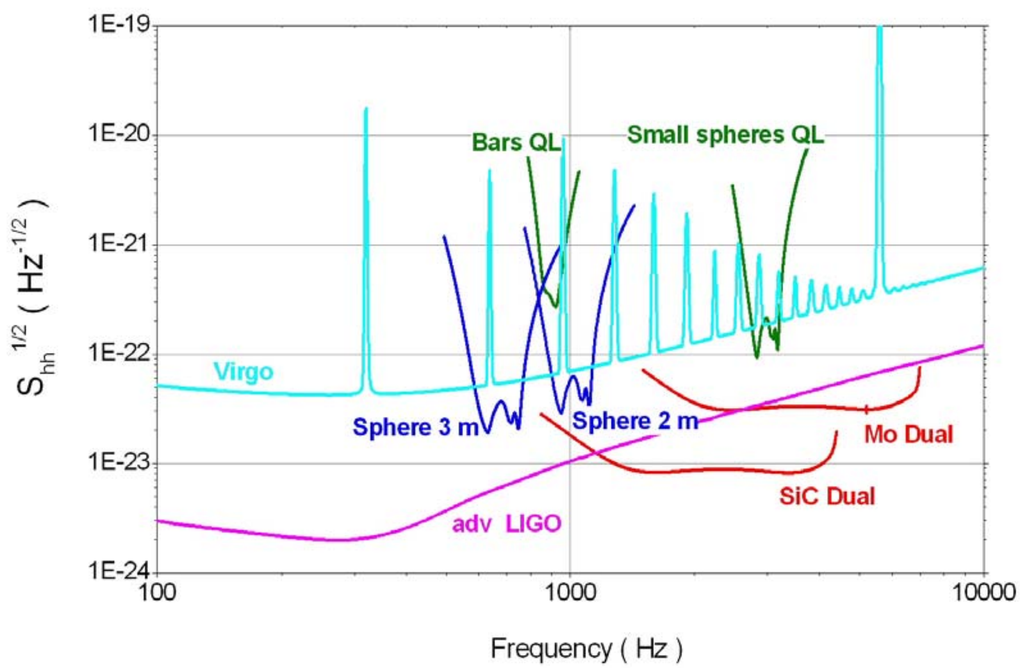


DUAL (Padova): two nested mechanical resonators whose relative vibrations is measured by non-resonant readout

2008-2012 prospective

Schenberg
(Brasil)





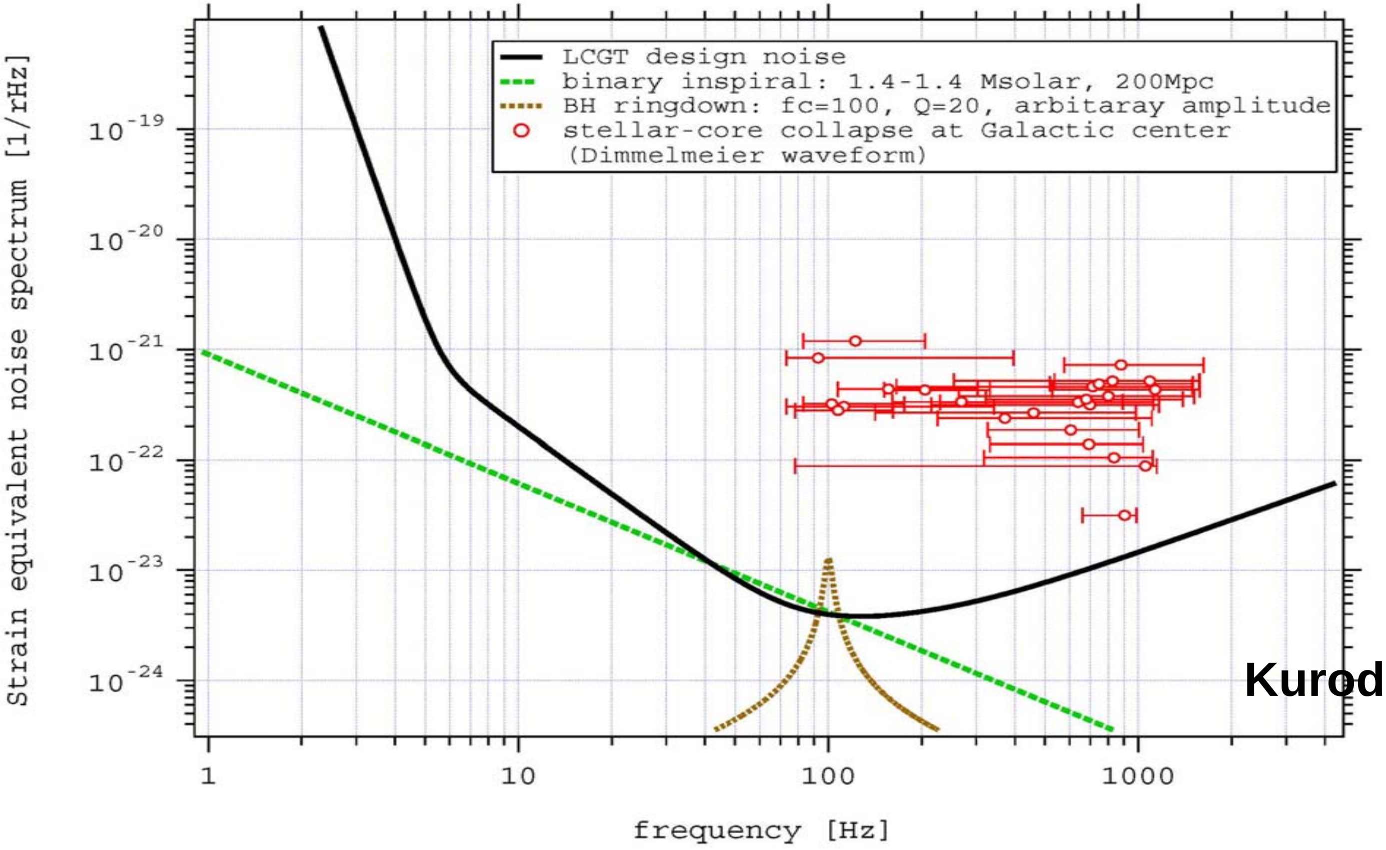
Australian International Gravitational Observatory (AIGO)

- High optical power laser research facility
- Plans for a 5km interferometer
- May be realized with community support in the next 8 years

Blair et al. 2006

Large-scale Cryogenic Gravitational-wave Telescope (LCGT)

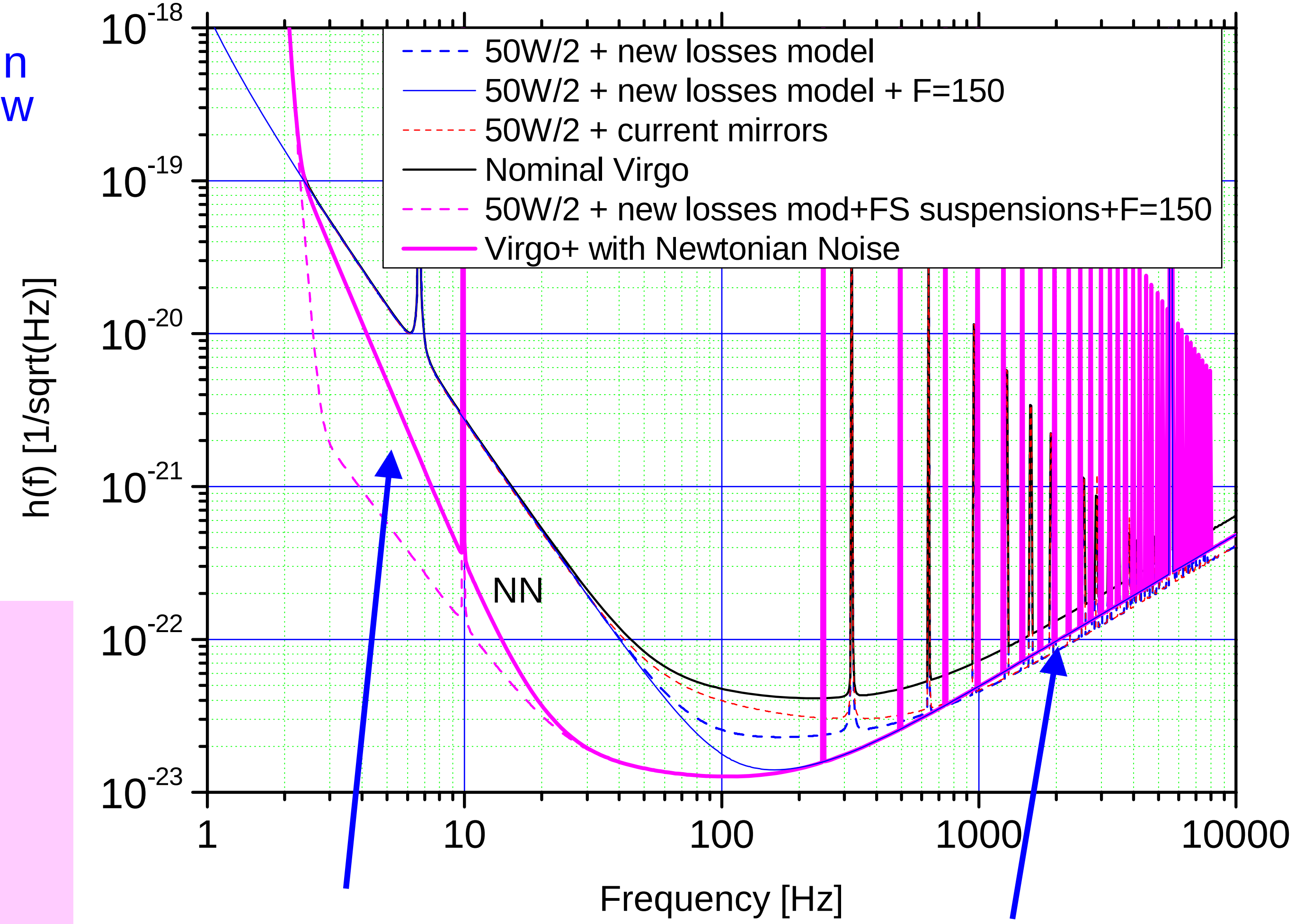
- Located at Kamioka underground site
- 3km long arms
- 150W laser
- Low seismic noise
- Features cryogenic (20K) sapphire mirrors for low thermal noise



Kuroda et al. 2006

VIRGO+

- Modest updates within the 2008-2009 window



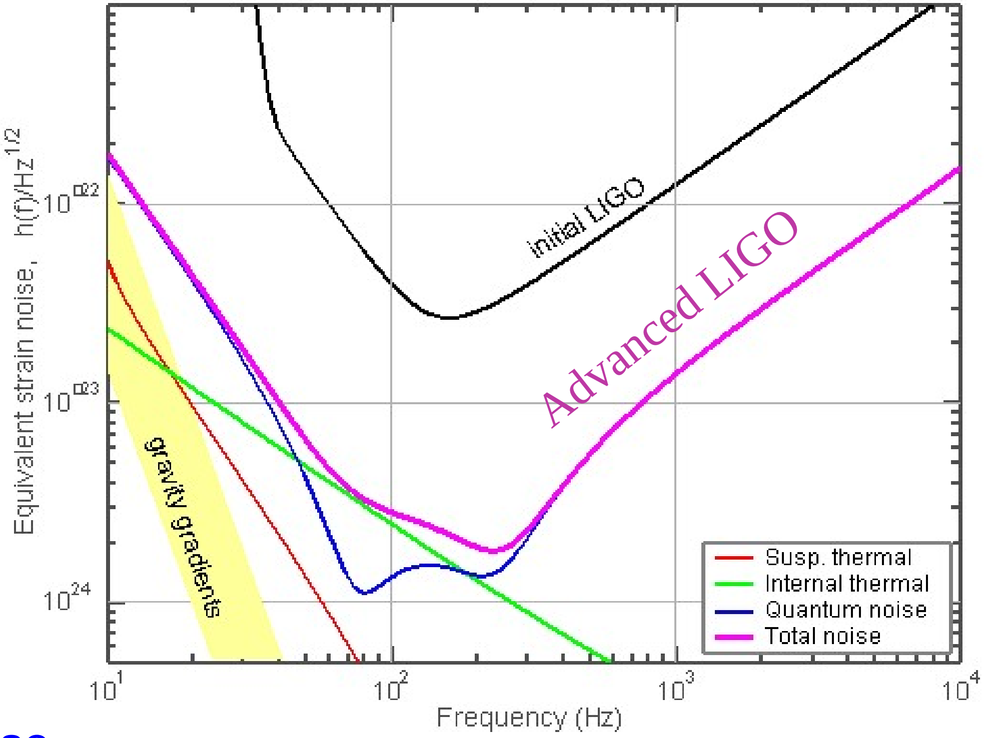
- 50 W laser, F=150 cavities
- Low loss suprasil end mirrors
- Monolitic suspensions

Thermal noise decreased

Shot noise decreased

Advanced LIGO

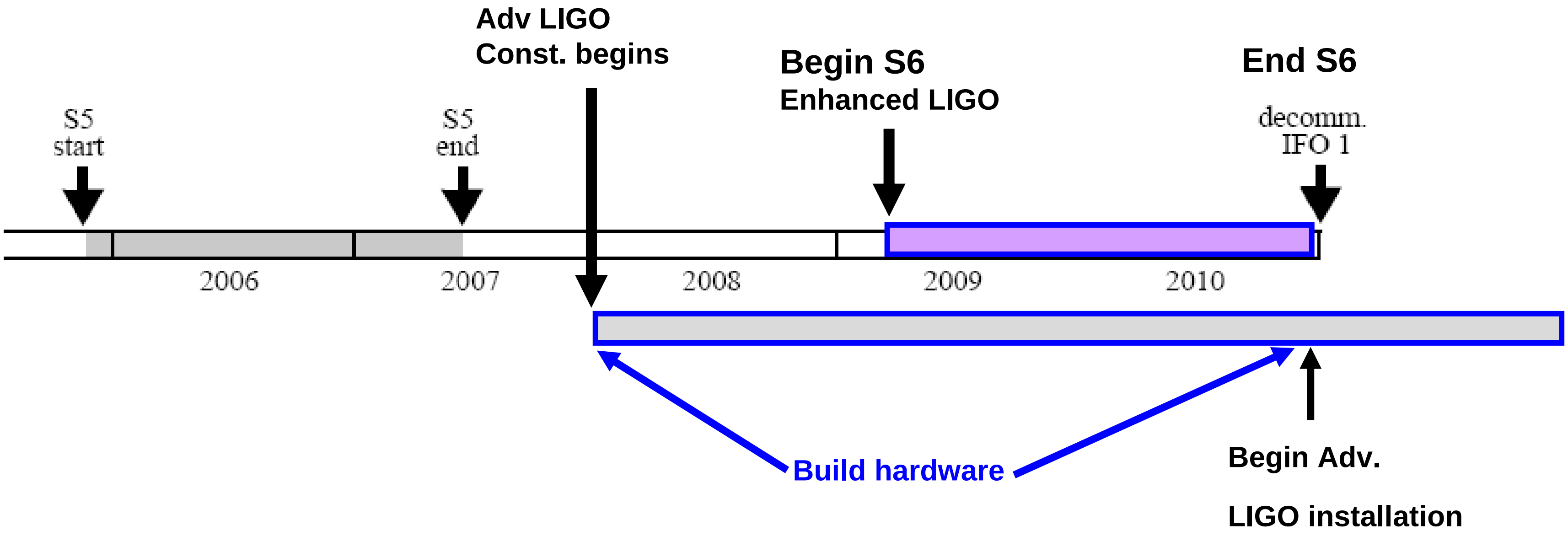
- Factor 10 better amplitude sensitivity
  - » (Reach)^3 = rate
- Factor 4 lower frequency bound
- Infrastructure of initial LIGO but replace many detector components with new designs



- 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.

LIGO → eLIGO → AdvLIGO

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



Adv LIGO
Const. begins

Begin S6
Enhanced LIGO

End S6

Build hardware

Begin Adv.

LIGO installation

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
- Stay tuned! (we’ll surely stay tuned to you!)

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