Gravitational Wave Astronomy I

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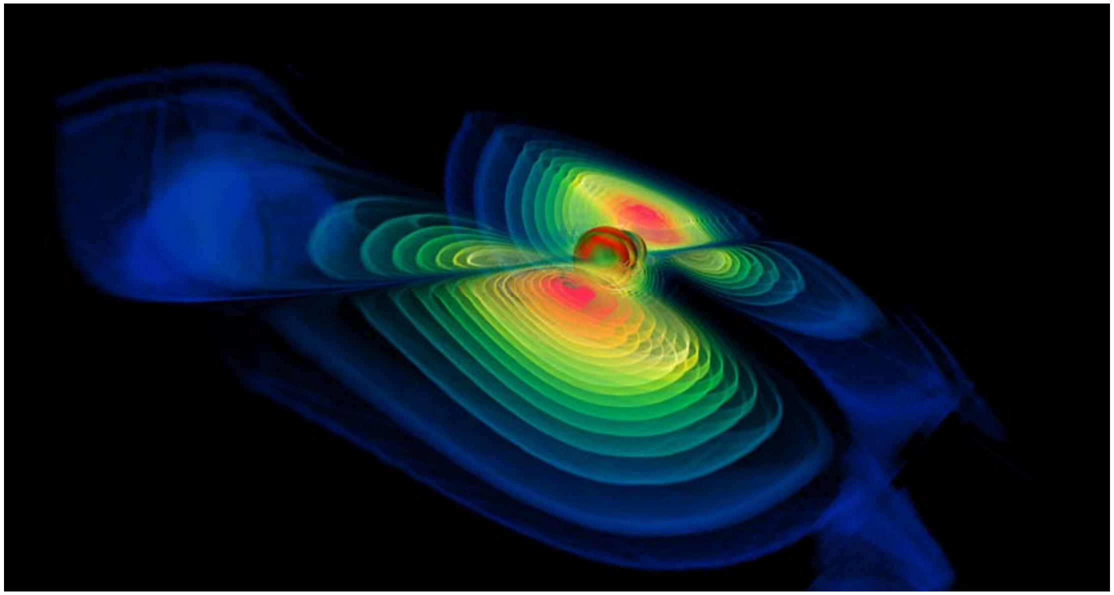
on behalf of the
LIGO Scientific Collaboration
http://www.ligo.org

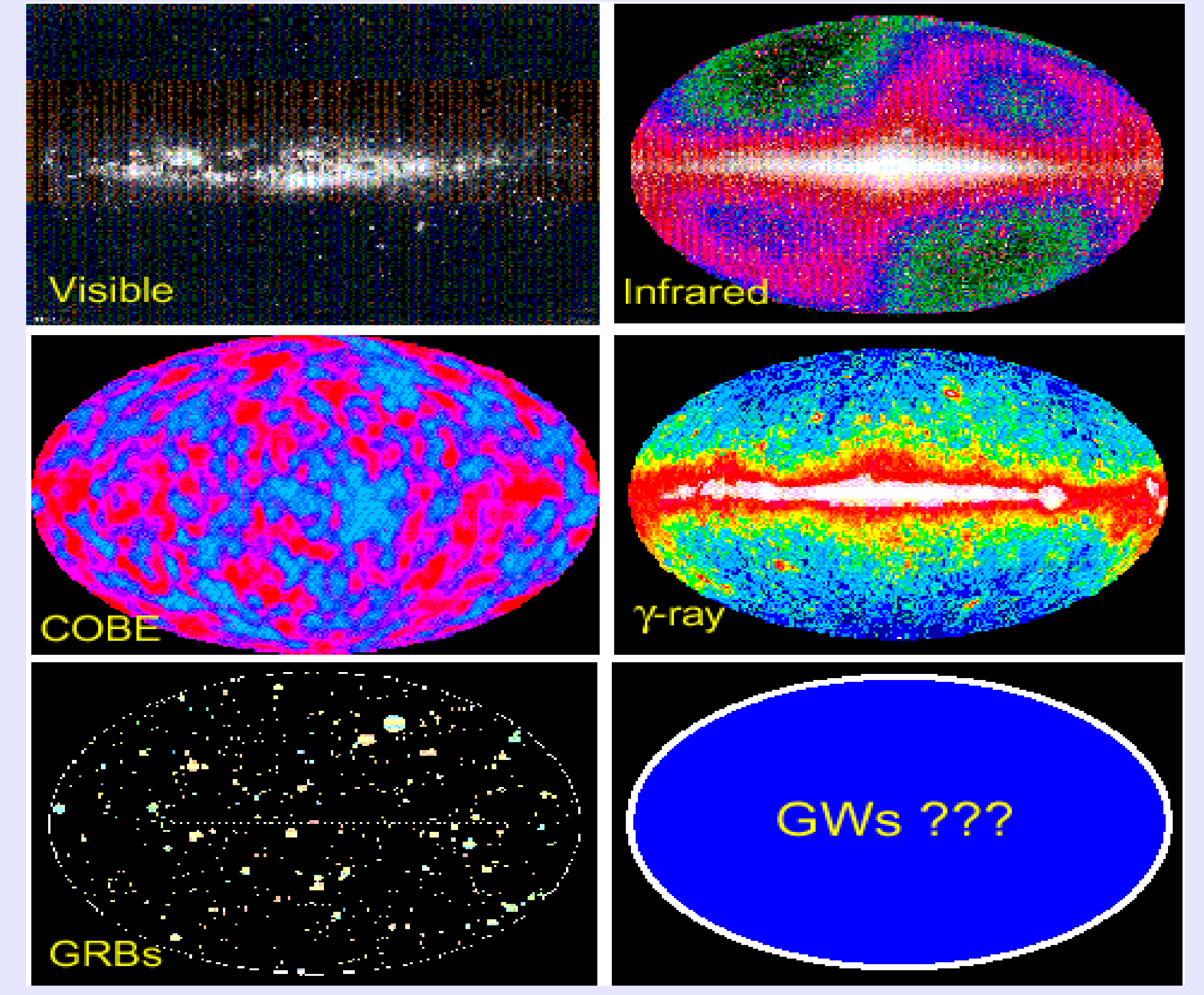


Credit: Werner Benger/ZIB/AEI/CCT-LSU

CERN
Oct 16-18, 2006

LIGO-G060513-00-Z

New windows



Challenges for a young field

- First direct detection of gravitational waves
  - » Detection possible with existing detectors
  - » Probable with upgrades to existing facilities, and/or near-future new ones
- Transition to a field of observational astronomy
  - » EM emission – incoherent superposition of many emitters
  - » Gravitational wave (GW) emission – coherently produced by bulk motions of matter
  - » Matter is largely transparent to gravitational waves
    - Makes them hard to detect
    - Makes them a good probe of previously undetectable phenomena, e.g. dynamics of supernovae, black hole and neutron star mergers
  - » Gravitational wave detectors are naturally all-sky devices; “pointing” can be done later in software

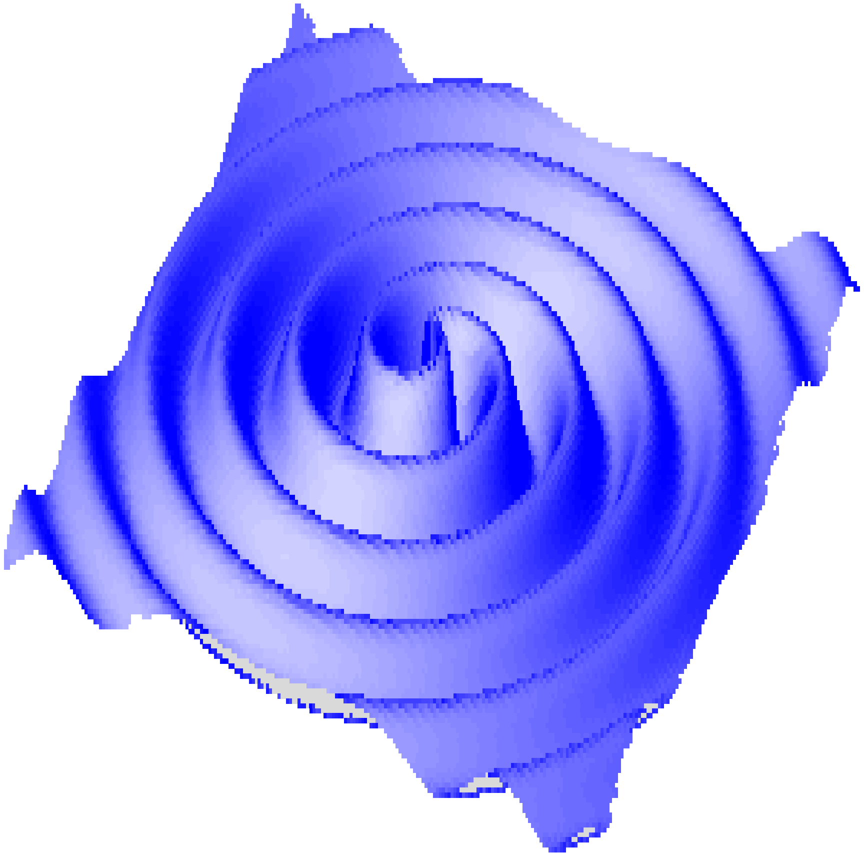
Overview

- Day 1 : Introduction. Sources. Detectors.
  - » An introduction to gravitational wave astronomy
  - » What are gravitational waves
  - » Sources
  - » Brief survey of detectors: bars, ground-based interferometers (each with one or two highlights), LISA
- Day 2 : Ground-based interferometry
  - » Interferometric detectors
    - – LIGO, GEO, Virgo
  - » Some topics in commissioning: the path to design sensitivity
  - » Science mode running with LIGO, GEO and TAMA
- Day 3 : Data analysis. Future detectors.
  - » Search methods
  - » Analyses from science runs for inspiral, burst, stochastic and continuous wave sources
  - » Advanced LIGO

Gravitational waves

- GWs are "ripples in spacetime": rapidly moving masses generate fluctuations in spacetime curvature:
  - » They are expected to propagate at the speed of light
  - » They stretch and squeeze space

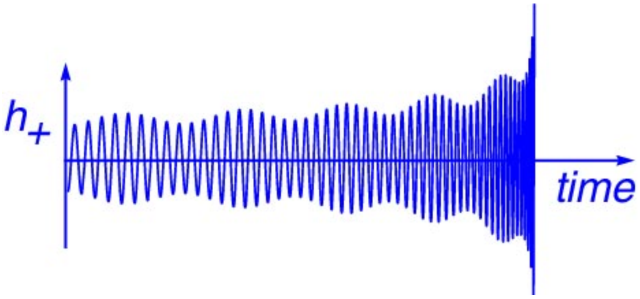
$$g_{\mu\nu} = \eta_{\mu\nu} + \boxed{h_{\mu\nu}}$$

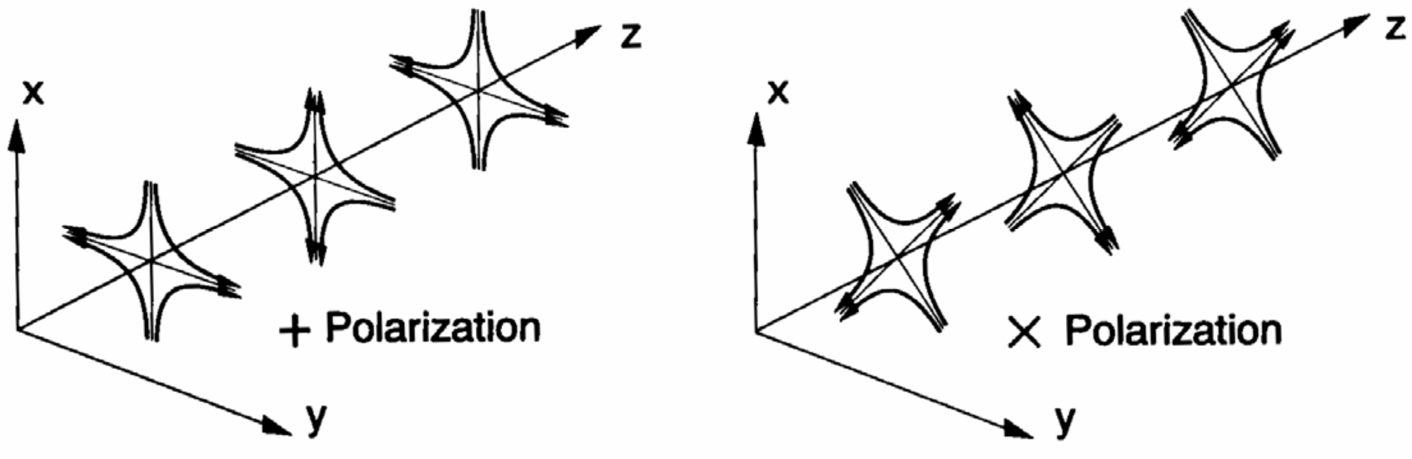


LIGO-G060513-00-Z

The two polarizations: the gravitational waveforms

- The fields are described by **2** independent polarizations: $h_+(t)$ and $h_x(t)$
- The waveforms carry detailed information about astrophysical sources
- With gravitational wave detectors one observes (a combination of) $h_+(t)$ and $h_x(t)$)





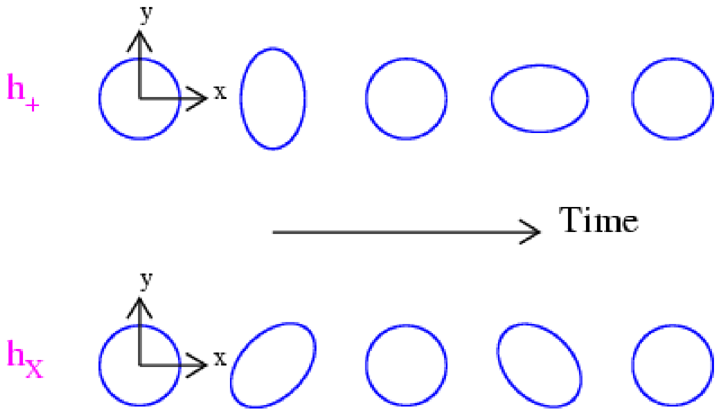
What is the observable effect?

Example:

Ring of test masses

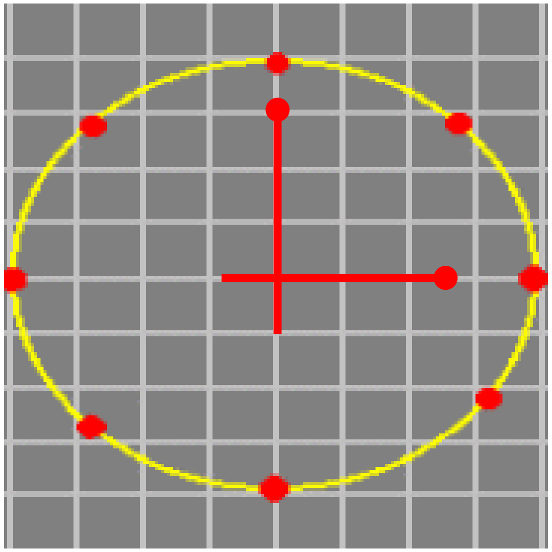
responding to wave

propagating along z



Amplitude parameterized by (tiny) dimensionless strain h:

$$h(t) = \frac{\delta L(t)}{L}$$



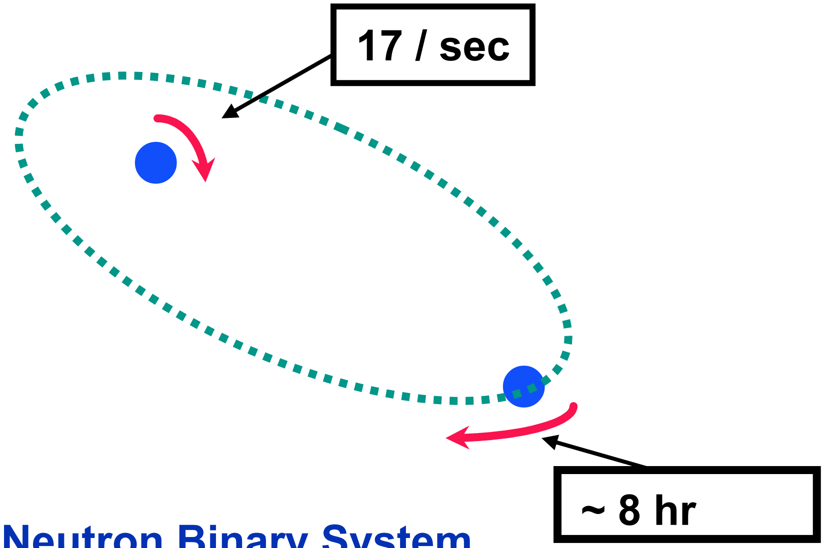
Why look for gravitational radiation?

- "Because it's there!"
  - George Mallory upon being asked, "why climb Everest?"
- 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 / stellar envelopes
  - Detectable sources some of the most interesting, least understood in the Universe
  - **Opens up entirely new non-electromagnetic spectrum.**
  - **May find something unexpected**

Orbital decay : strong indirect evidence

Neutron Binary System – Hulse & Taylor

PSR 1913 + 16 -- Timing of pulsars



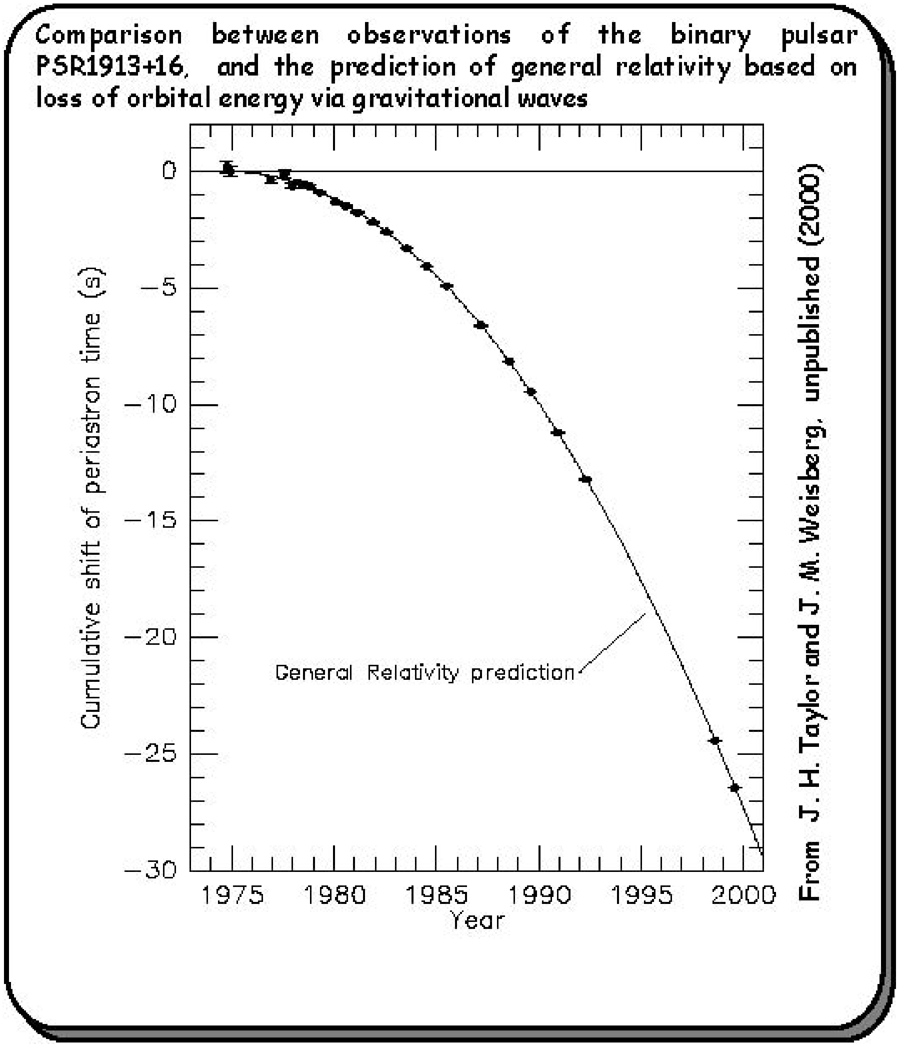
Neutron Binary System

- **separated by ~2×10^6 km**
- **$m_1 = 1.44 m_\odot$; $m_2 = 1.39 m_\odot$; $\varepsilon = 0.617$**

Prediction from general relativity

- **spiral in by 3 mm/orbit**
- **rate of change orbital period**

Emission of gravitational waves



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)

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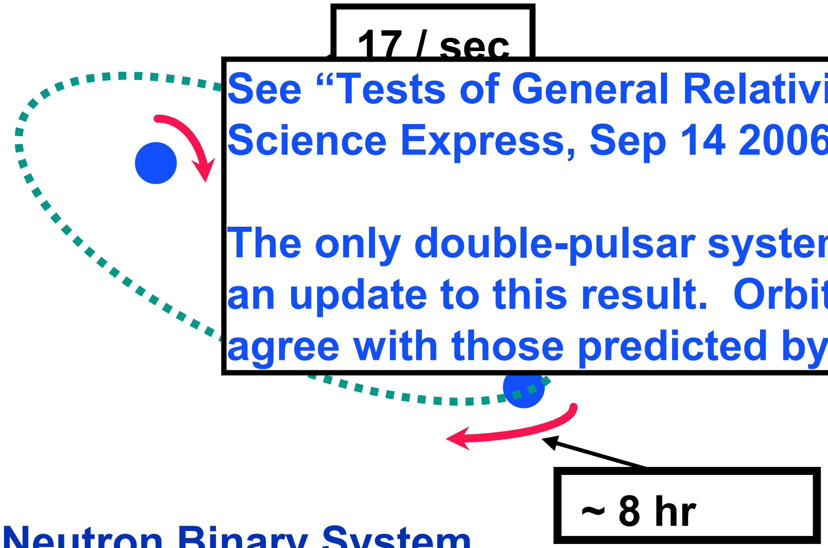

See "Tests of General Relativity from Timing the Double Pulsar" Science Express, Sep 14 2006

The only double-pulsar system know, PSR J0737-3039A/B provides an update to this result. Orbital parameters of the double-pulsar system agree with those predicted by GR to 0.05%

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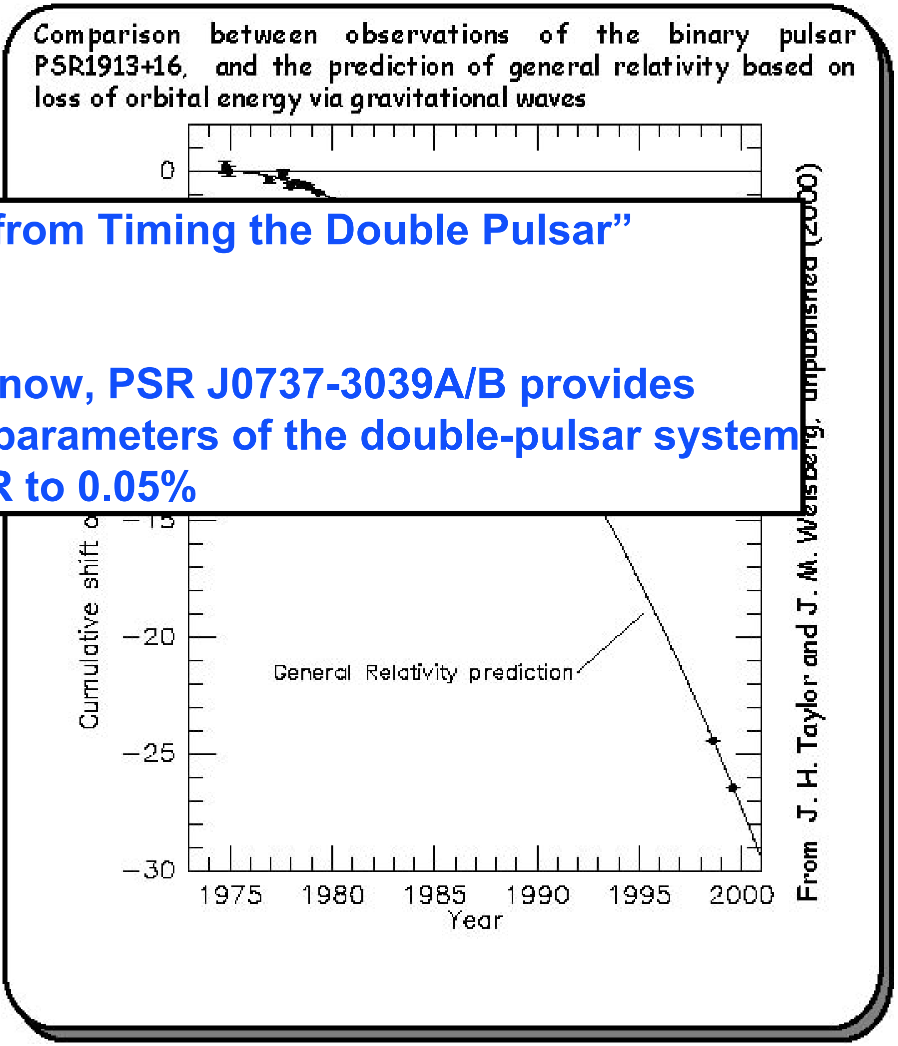


Comparison between observations of the binary pulsar PSR1913+16, and the prediction of general relativity based on loss of orbital energy via gravitational waves

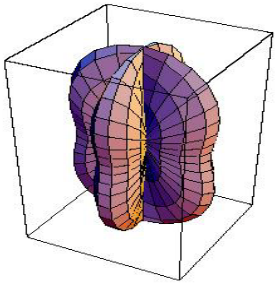
Aside: some terminology

Beam patterns

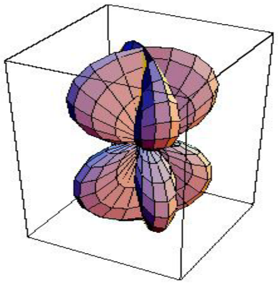
$$\frac{\delta L(t)}{L} = h(t) = F^{+}h_{+}(t) + F^{\times}h_{\times}(t)$$

- F^{+}, F^{x} : [-1, 1]
- F = F(t; α, δ)

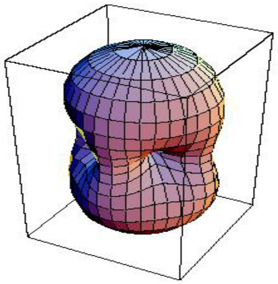
LIGO example:



F^{+}

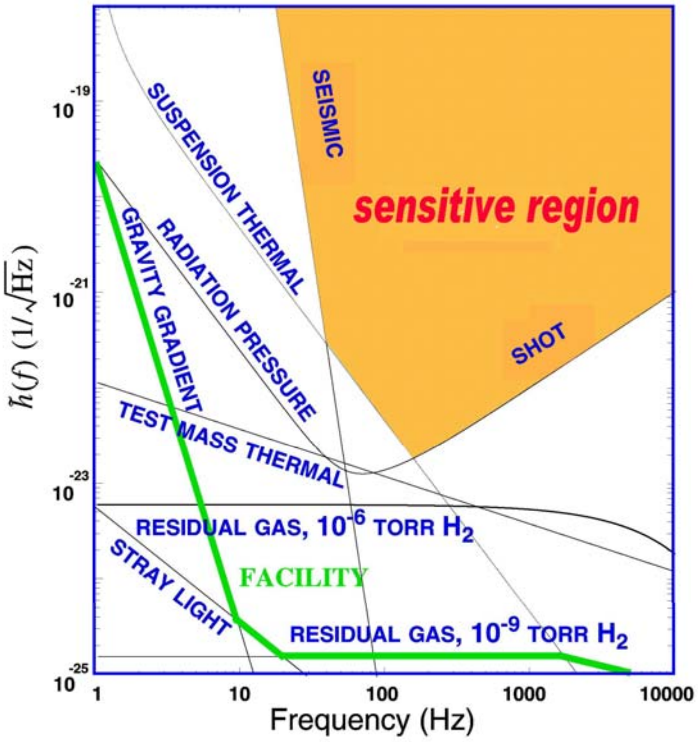


F^{x}



average

Strain noise curves



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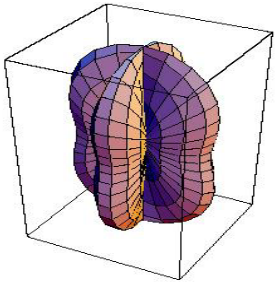
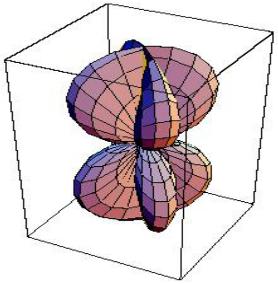
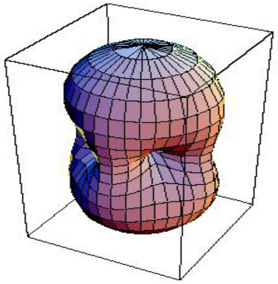


F^{+}



F^{x}



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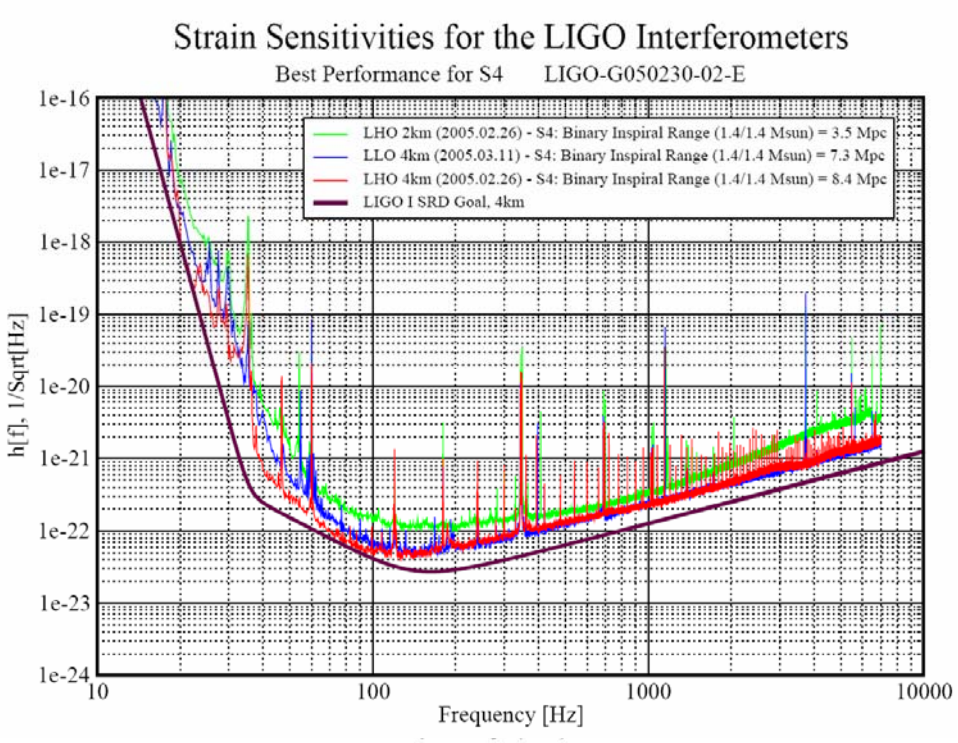
Strain noise curves



Sources

- Very high (10^4Hz ≤ f ≤ 10^5Hz) gravitational waves
  - Few sources expected, but, for example: neutron star oscillations
  - Ground-based interferometers sensitive not only in low-f (near-DC) audio band, but again in higher bands (e.g. LIGO ~37kHz, ~74kHz)

Ground-based detectors

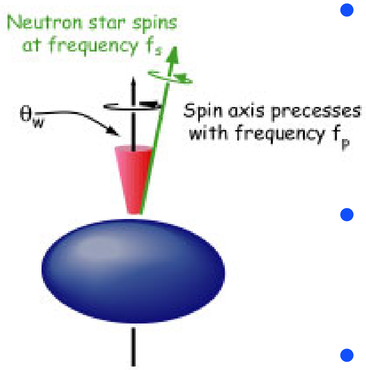
- High (1Hz ≤ f ≤ 10^4Hz) gravitational waves (audio band)
  - Continuous waves: spinning compact objects
  - Binary neutron star and black hole coalescences
  - Burst events
  - Stochastic backgrounds

Space-based detectors

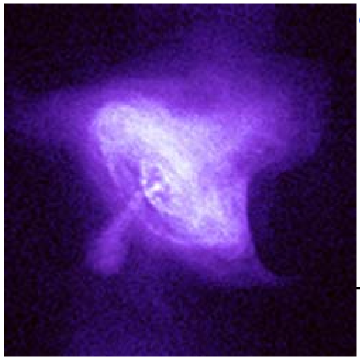
- Low (10^{-5}Hz ≤ f ≤ 1Hz) gravitational waves
  - Continuous waves: binary compact objects
  - Binary-black hole coalescences
  - Stochastic backgrounds
- Very low (10^{-9}Hz ≤ f ≤ 10^{-7}Hz) gravitational waves
  - Stochastic sources: pulsar timing yields best observational limit on stochastic background
- Ultra low (10^{-18}Hz ≤ f ≤ 10^{-13}Hz) gravitational waves
  - Stochastic sources: polarization of CMB yields limit

Continuous Waves

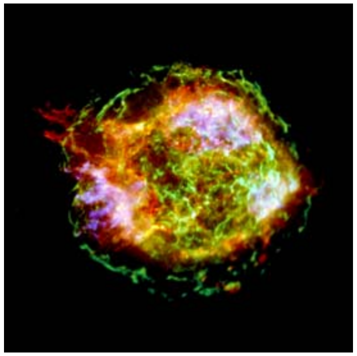
Audio sources I



- Waves from a single compact object such as a neutron or strange star (with a mountain, or precession, or with dynamic modes) in our galaxy
- Results in nearly-sinusoidal continuous gravitational waves
- Signal is doppler modulated by relative motion of star and detector, and amplitude modulated by beam pattern of detectors
- Known radio pulsars, either isolated or in binary systems
- Known x-ray neutron stars, or x-ray pulsars, LMXBs
- Unknown neutron stars – all sky, blind searches



Crab nebula
Credit: NASZ/HST/ Chandra

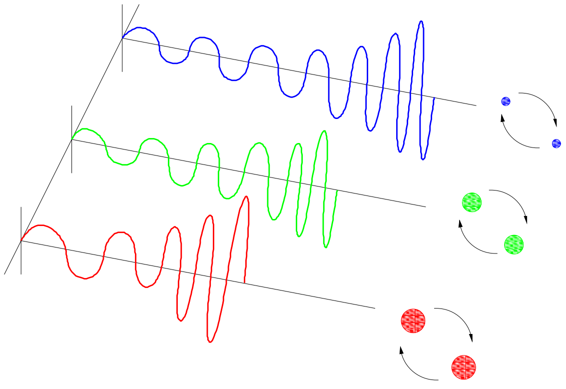


Supernova remnant Cas A
Credit: NASA/CXC/ GSFC/U. Hwang et al.

Inspiral and merger of Black Holes and Neutron Stars

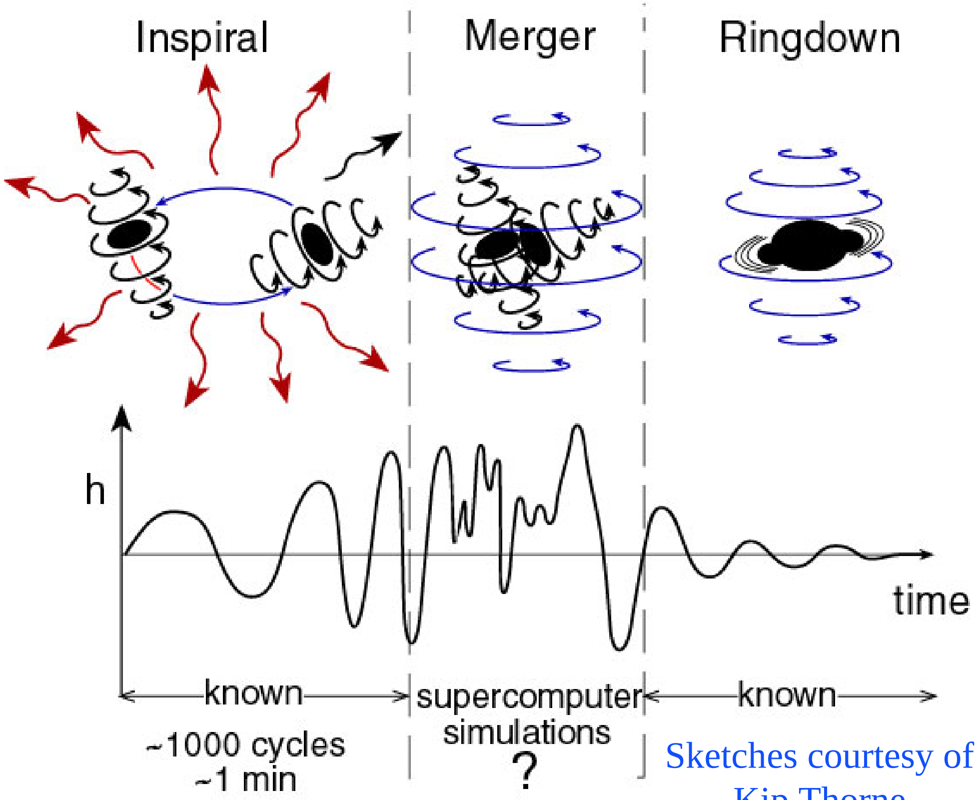
Audio sources II

NS-NS waveforms are well described
BH-BH need better waveforms



NS-NS
(no noise)

BH-BH
(no noise)



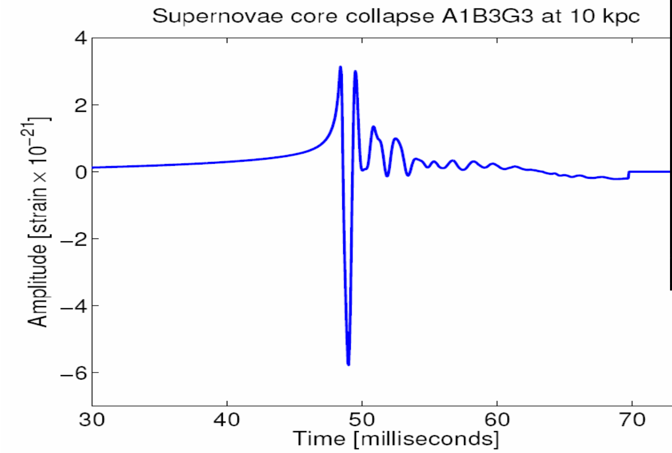
Sketches courtesy of Kip Thorne

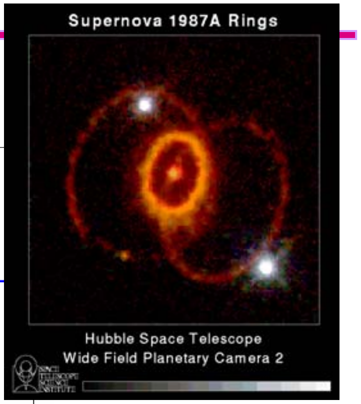
Significant theoretical advances in simulation of BHBH mergers, see:
Pretorius, 2005;
Baker et al, 2005;
Campanelli et al, 2005

Bursts sources

Audio sources III

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





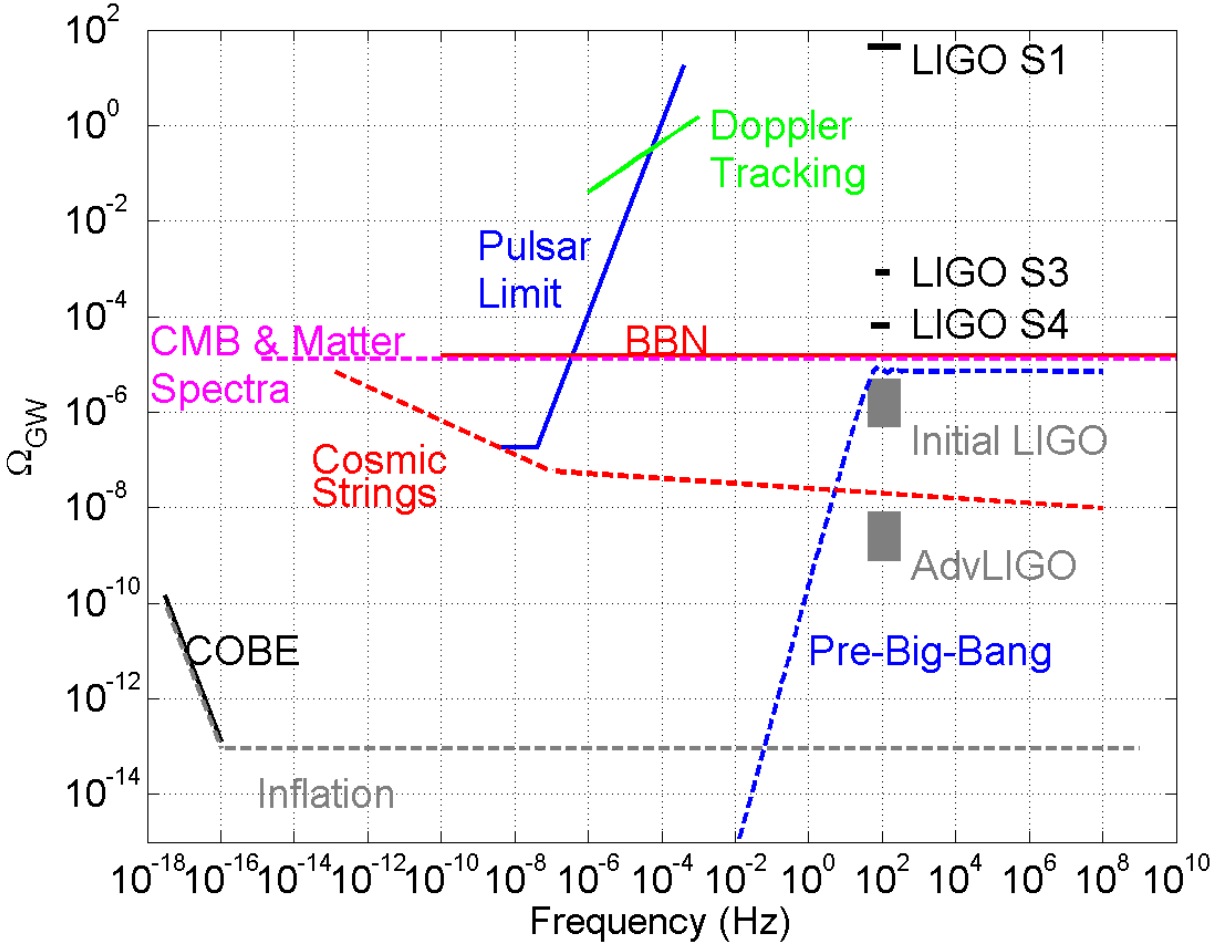
- What we know about them …
  - » Catastrophic astrophysical events observed in the particle and/or electromagnetic sector will plausibly be accompanied by short signals in the gravitational wave sector ➡ *plausible suspects*
  - » Exact waveforms are not or poorly modeled
  - » Durations from few millisecond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

Stochastic sources and limits

Audio sources IV

Characterized by log-frequency spectrum:

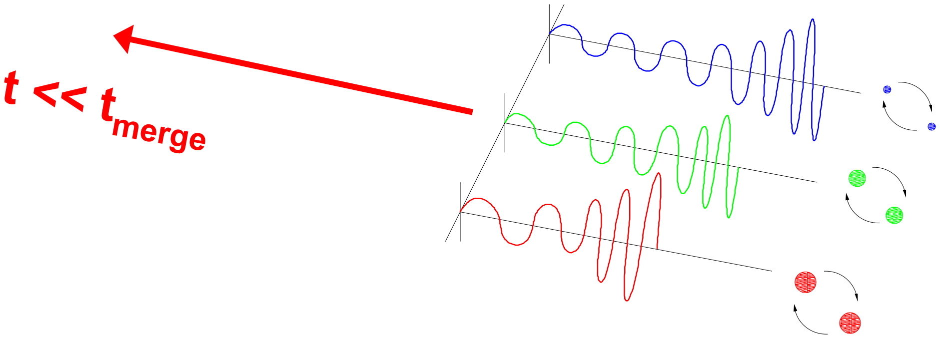
$$\Omega_{GW}(f) = \frac{1}{\rho_c}\,\frac{d\rho_{GW}(f)}{d\ln f}$$

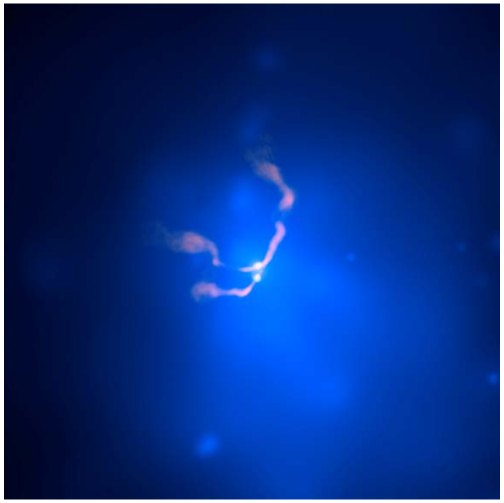


Low frequency sources

low f sources

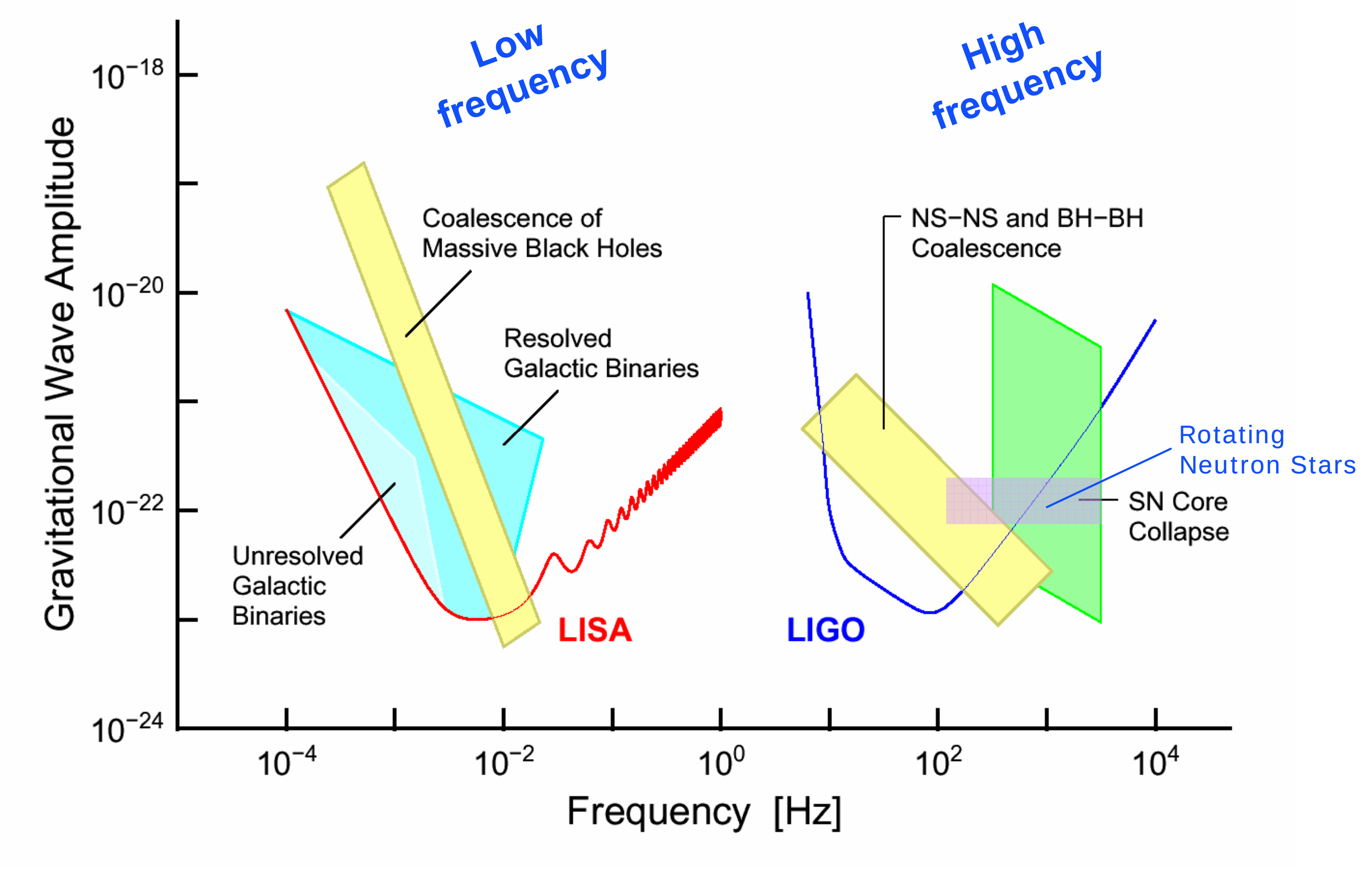
- Low frequency (10^{-5}Hz ≤ f ≤ 1Hz) sources are thought to be guaranteed
- Majority are long-lived
- One year of LISA data contains:
  - » A dozen of known solar mass binaries (verification sources)
  - » ~ 10000 white dwarf binaries (a few with NS companion)
  - » ~ 100 extreme mass-ratio inspirals
  - » ~ 10 massive BH binaries
  - » Some short lived burst events
  - » Stochastic foregrounds and backgrounds





Binary black hole 3C 75
Credit: NASA/CXC/Hudson et al.
NRAO/VLA/NRL

Gravitational wave spectrum



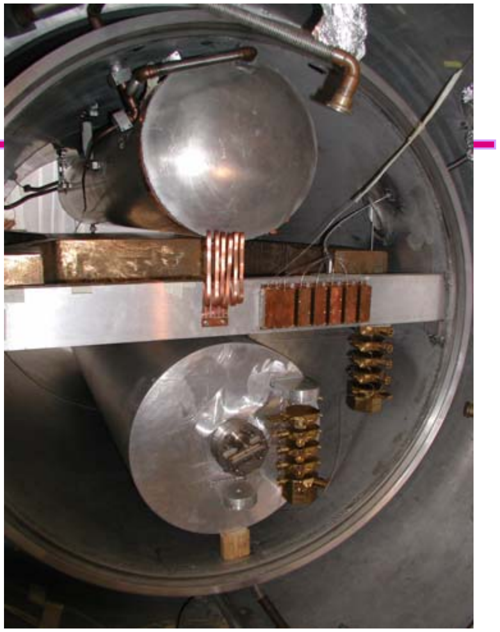
First efforts for direct detection

- Pioneered by Joseph Weber in the early 1960’s
- Room temperature in-vacuum resonant mass detectors
- Piezoelectric strain gauges at center of bar
- Narrow band instruments with sensitivity near 1kHz
- Looked for coincident burst events with detectors in Washington D.C. and Chicago
- Controversy in detection claims that have not be verified in follow up searches

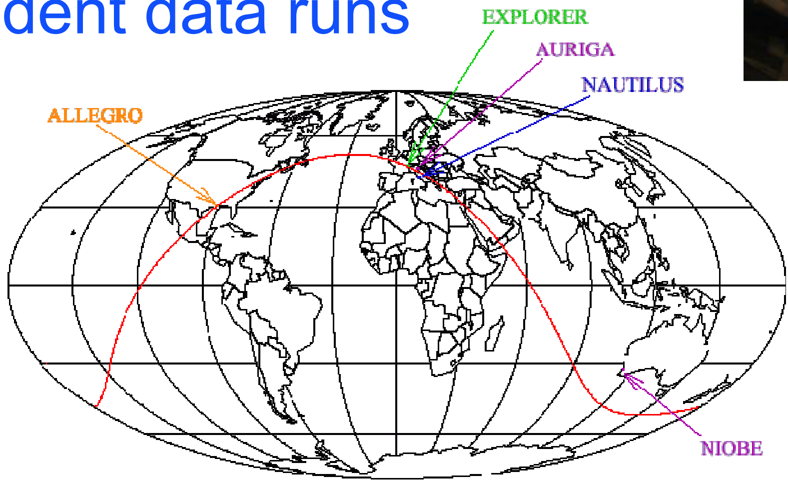

AIP Emilio Segre’ Visual Archives


LIGO Hanford lobby

Resonant mass detectors

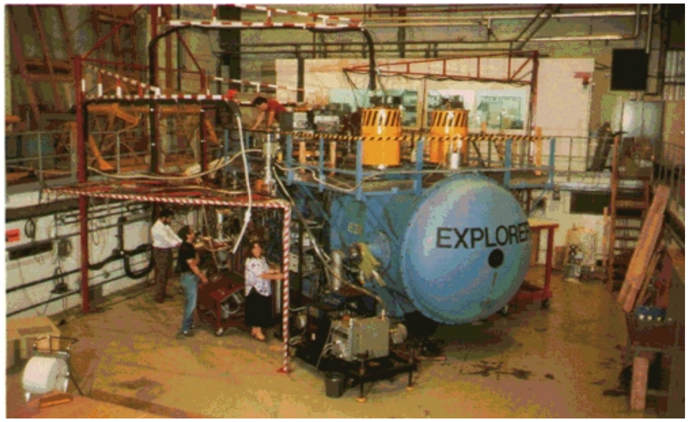


- Cryogenic bars with end transducers
- Use of SQUID low-noise amplifiers
- Vibration isolation
- Since 1997, Nearly-continuous coverage in coincident data runs



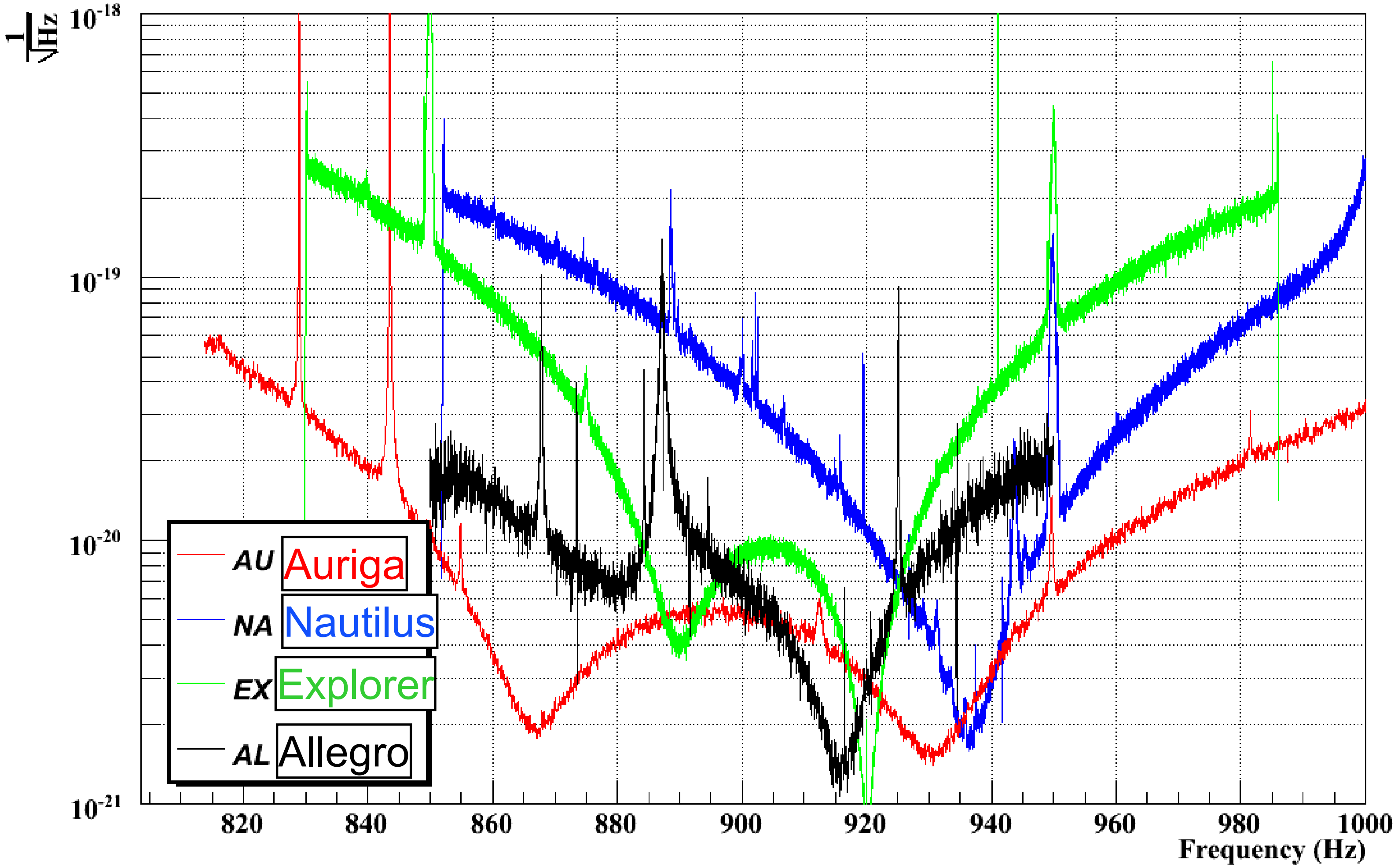
Allegro @LSU

Explorer @CERN

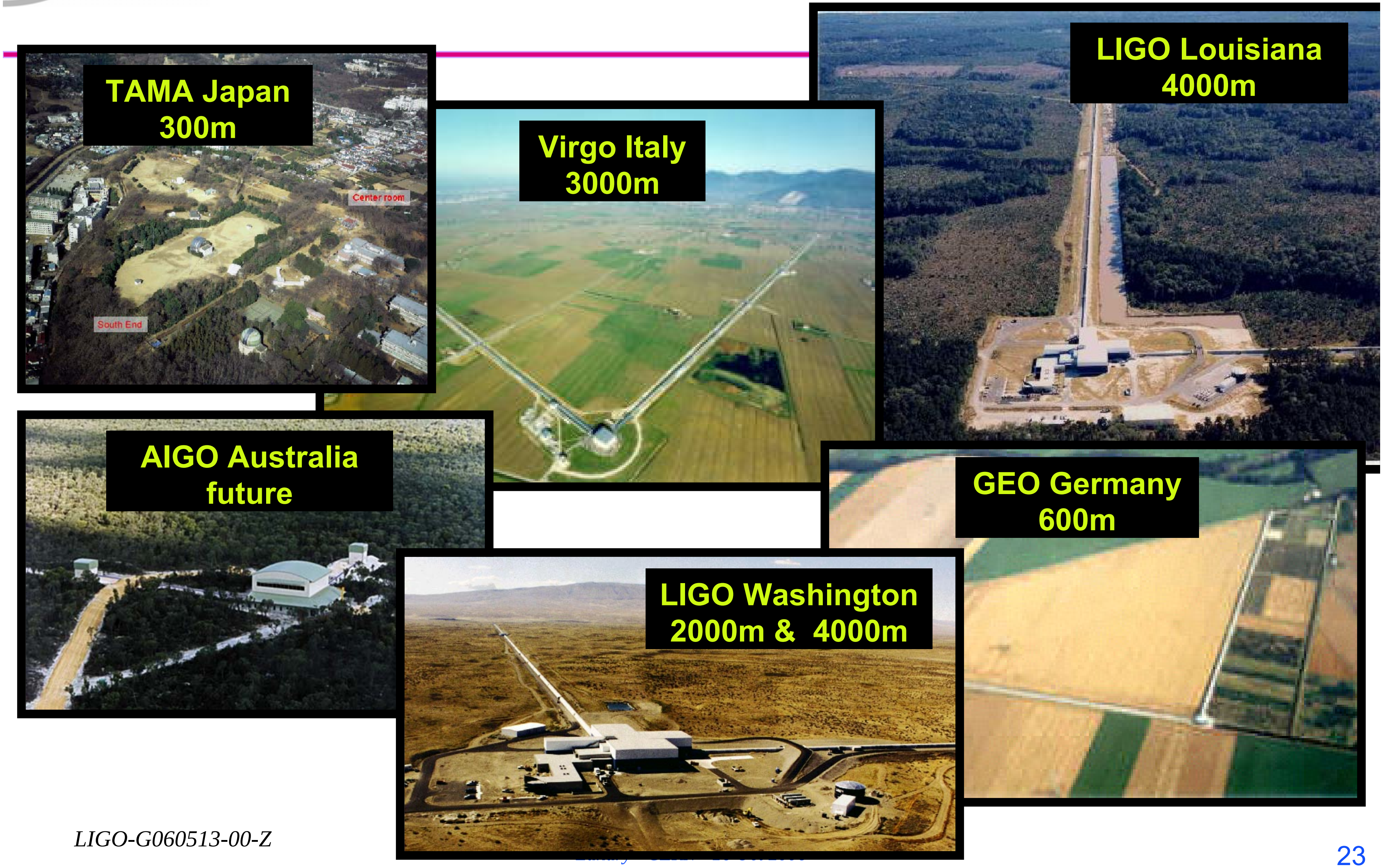


IGEC : International Gravitational Event Collaboration

Strain Noise Amplitude of IGEC2 detectors

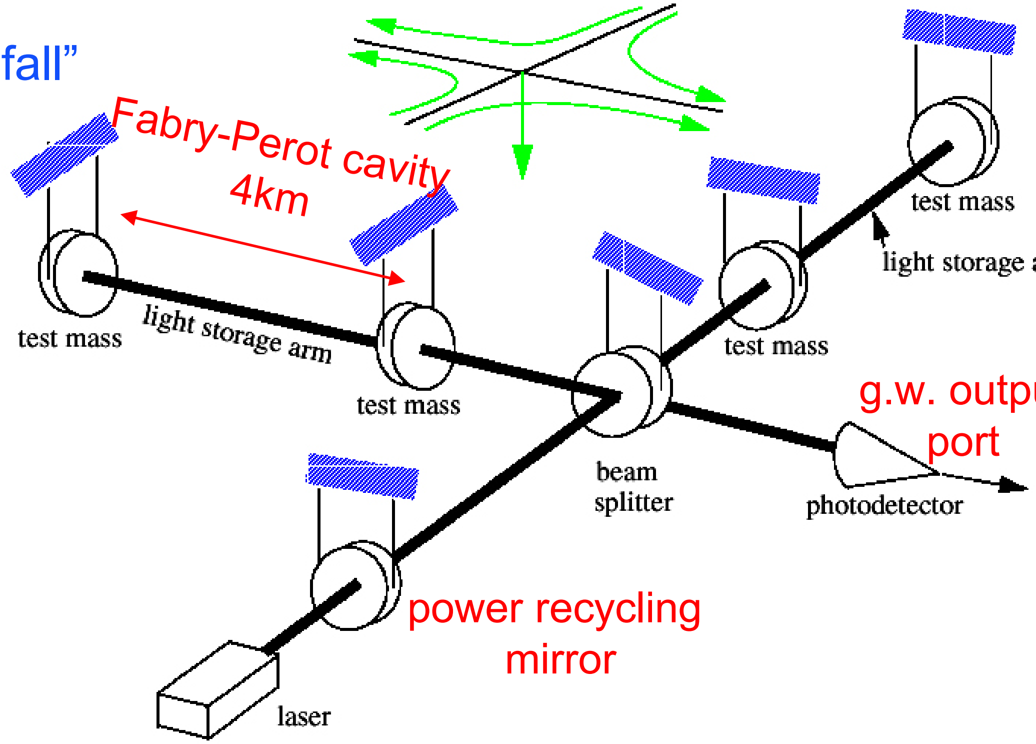


Ground based interferometers



Interferometric gravitational wave detection

- Suspended Interferometers
  - » 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)


Fabry-Perot cavity 4km

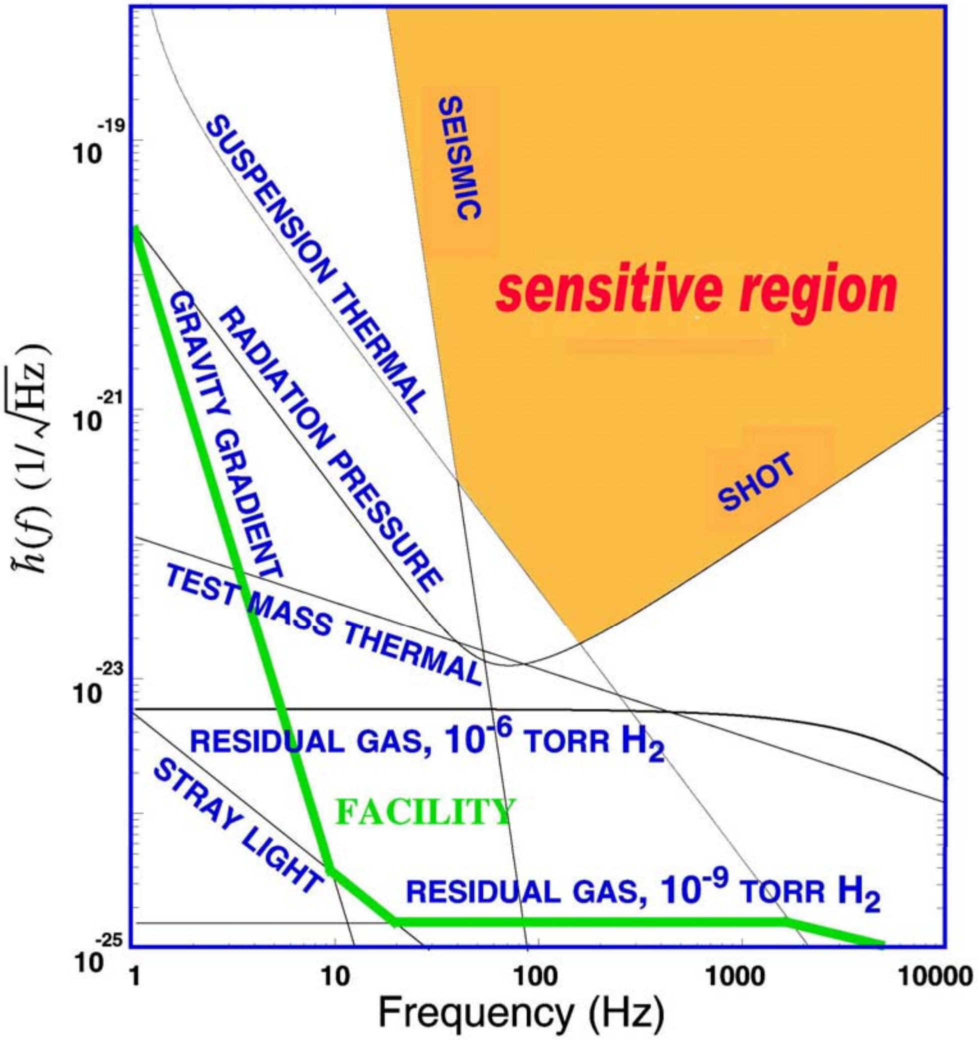
g.w. output port

power recycling mirror

LIGO design length sensitivity: 10^{-18}m

What Limits Sensitivity of 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



Interferometers in Asia, Australia

TAMA 300 (Japan)
(300-m)

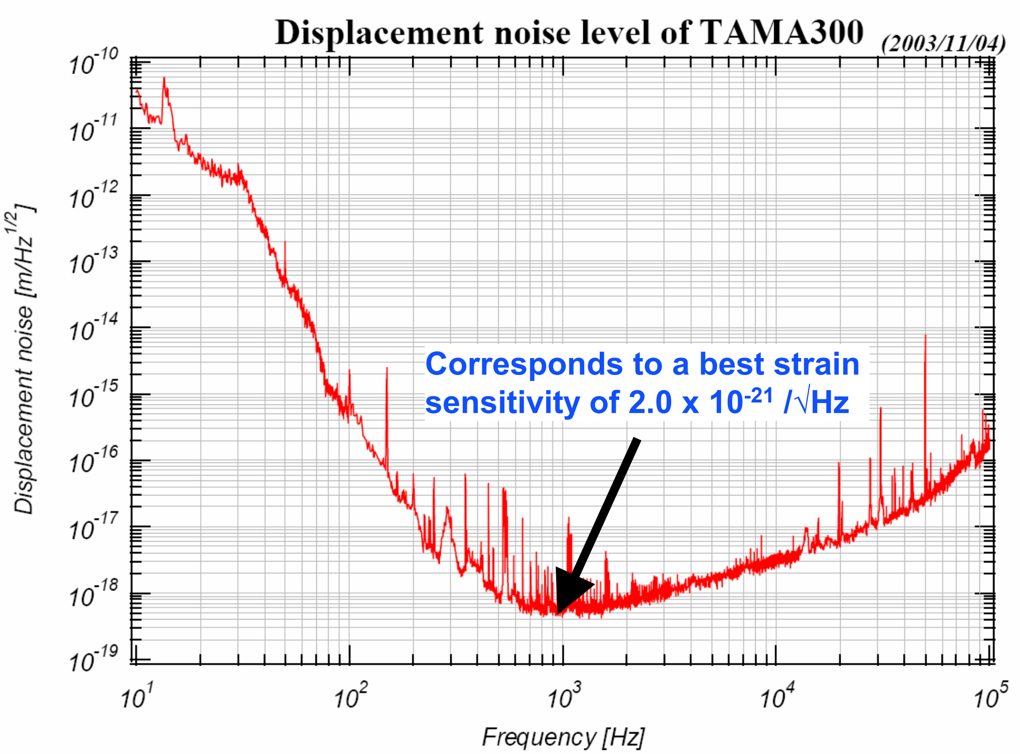
Longest running detector: 9 data runs!

AIGO (Australia)
(80-m, but 3-km site)

Operated by ACIGA; part of LIGO Scientific Collaboration.

Interferometers in Asia, Australia

TAMA 300 (Japan) (300-m)

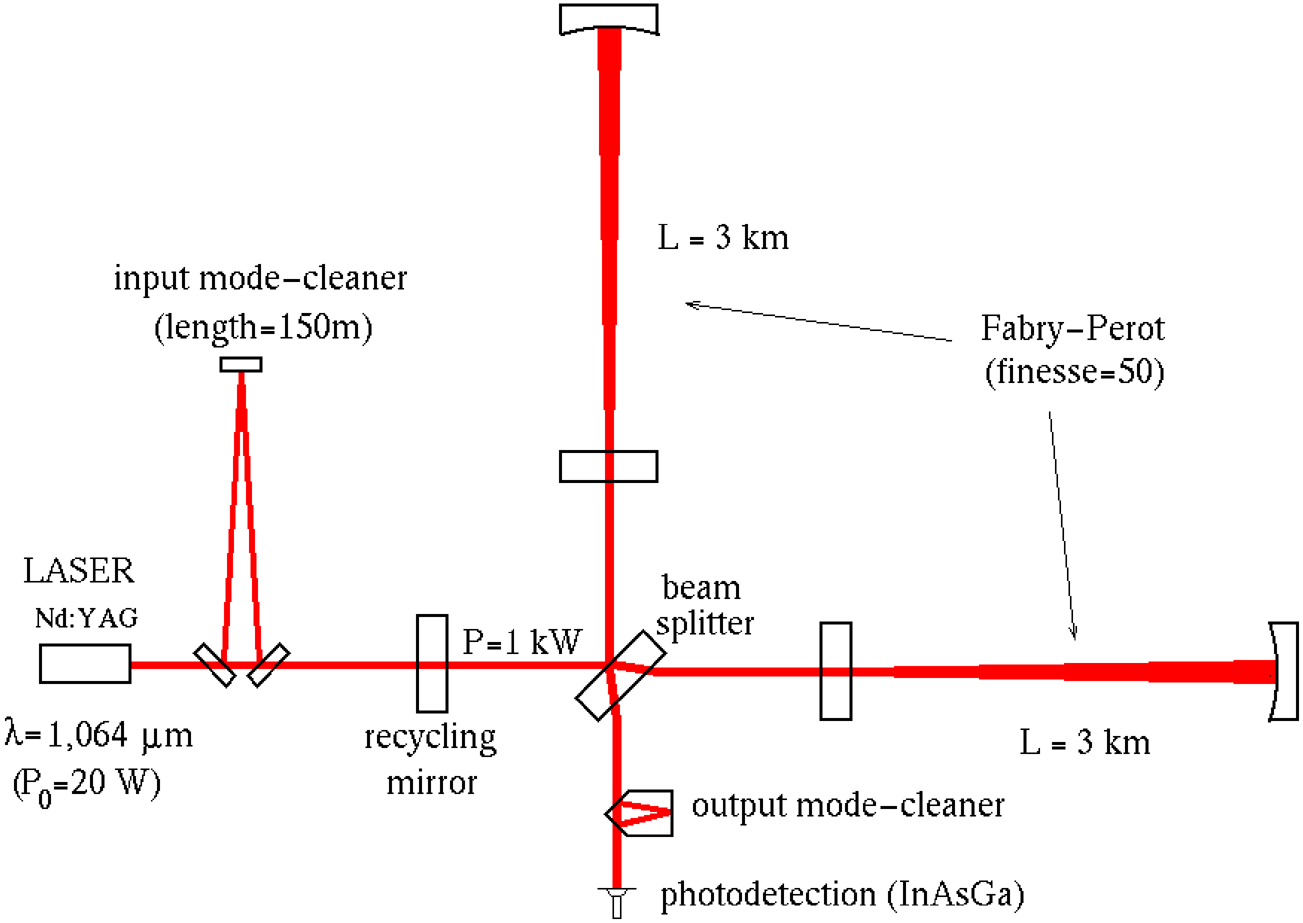

Displacement noise level of TAMA300 *(2003/11/04)*

Corresponds to a best strain sensitivity of 2.0 x 10^{-21} /√Hz

AIGO (Australia) (80-m, but 3-km site)

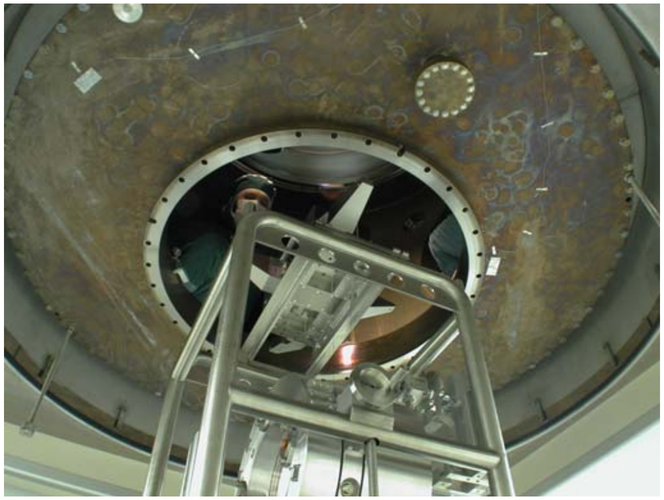
Operated by ACIGA; part of LIGO Scientific Collaboration.

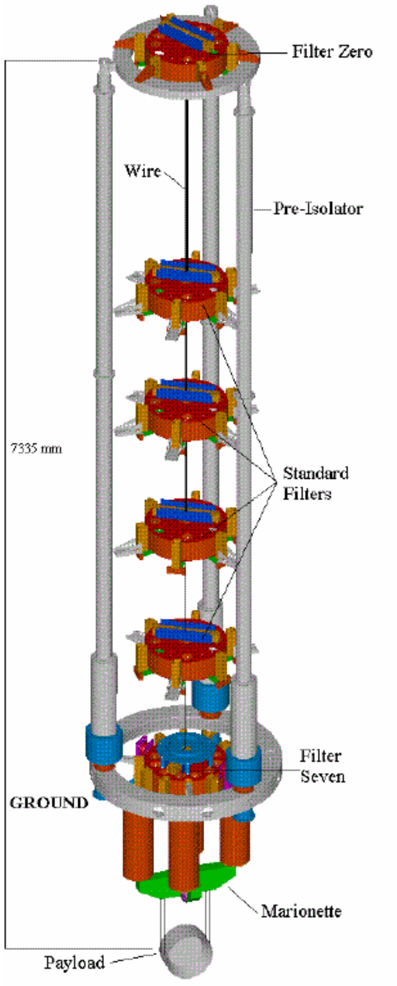
Virgo Optical Configuration

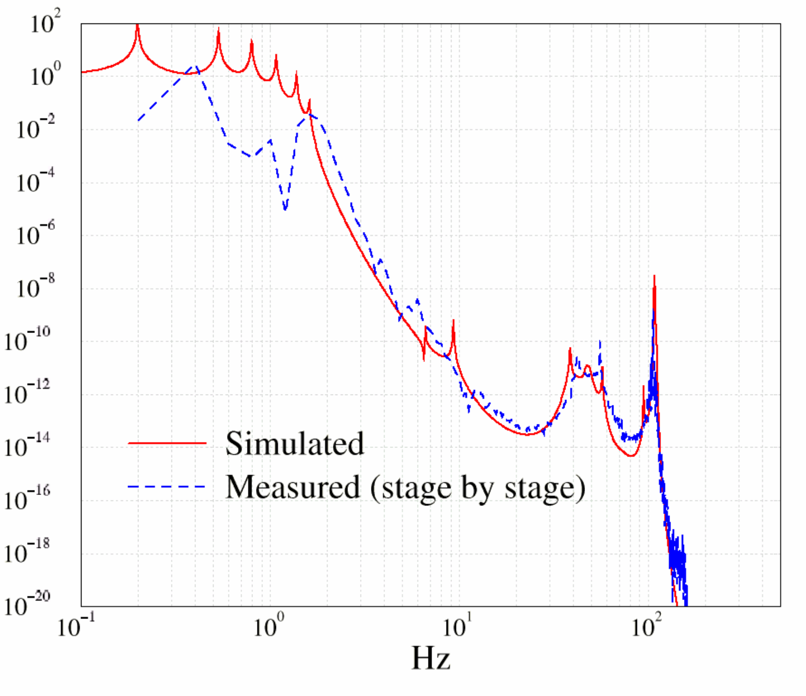


VIRGO Super Attenuator

“Long Suspensions”
- **inverted pendulum**
- **five intermediate filters**

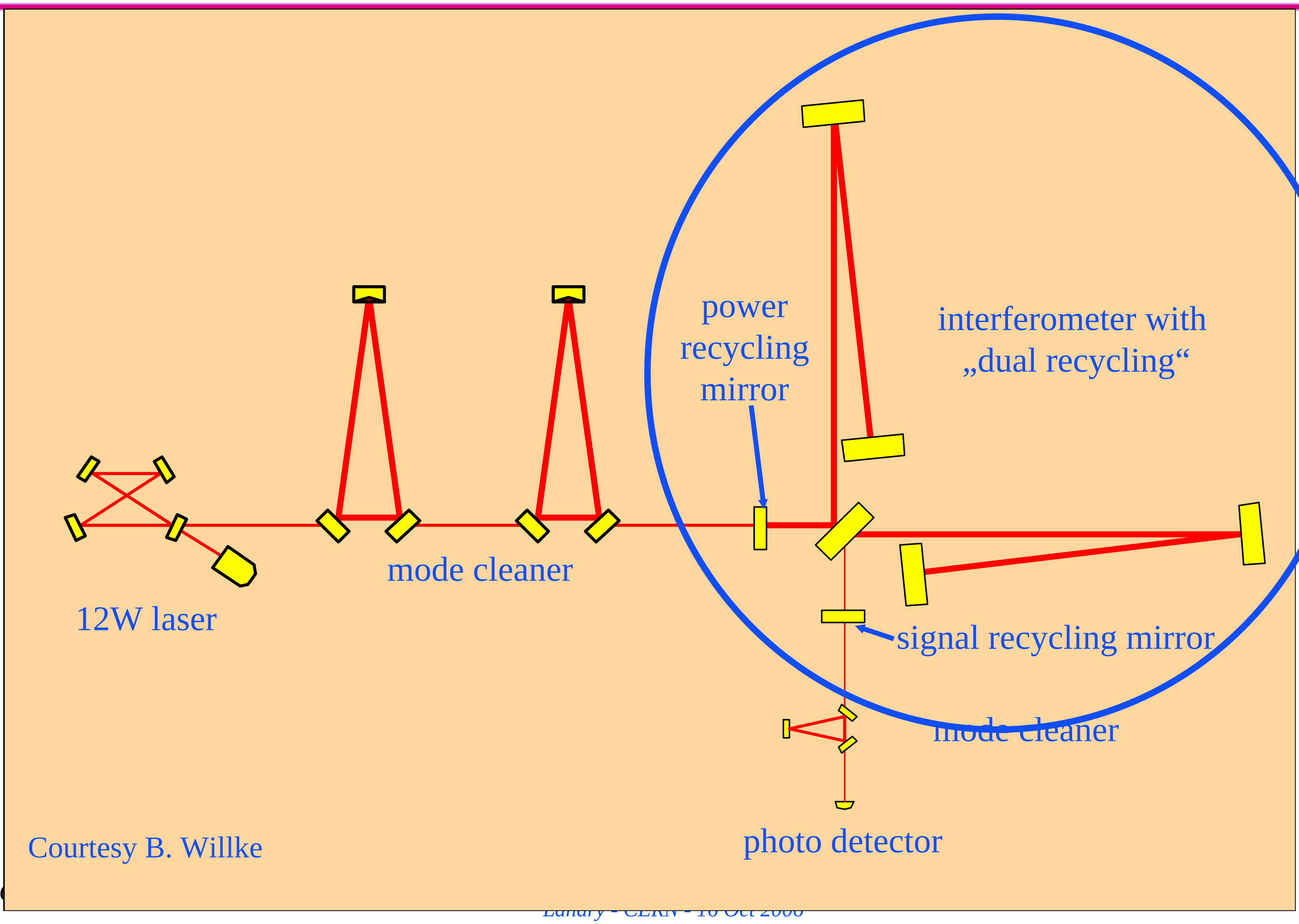






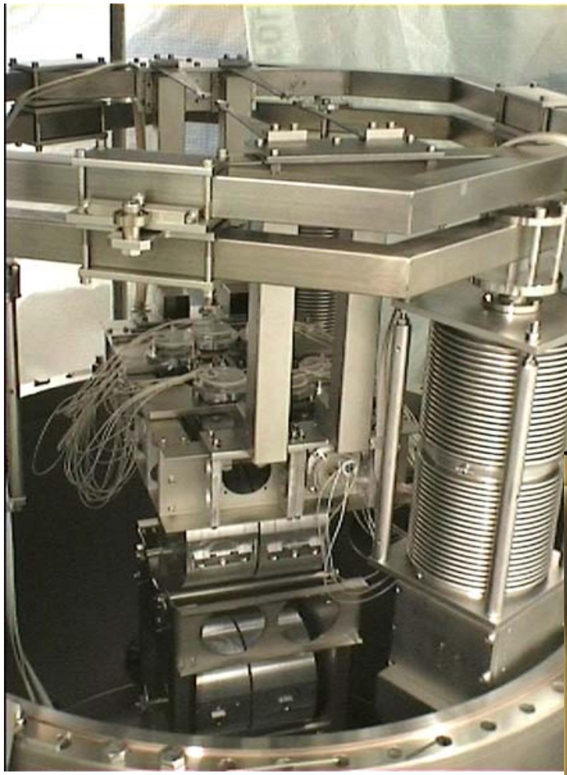
Suspension vertical transfer function measured and simulated (prototype)

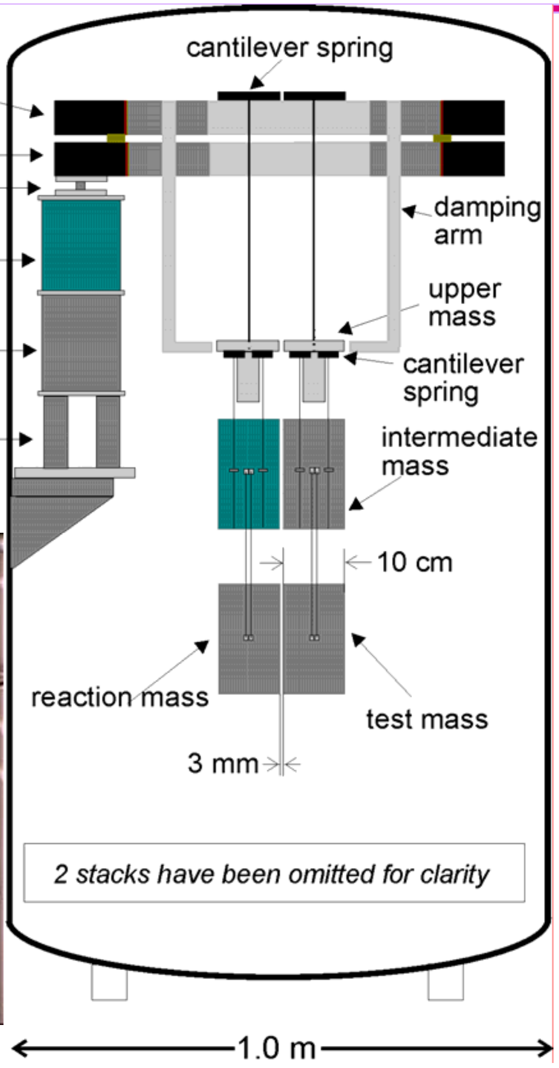
GEO600
Optical Configuration



Courtesy B. Willke

GEO600 Seismic Isolation and Suspension





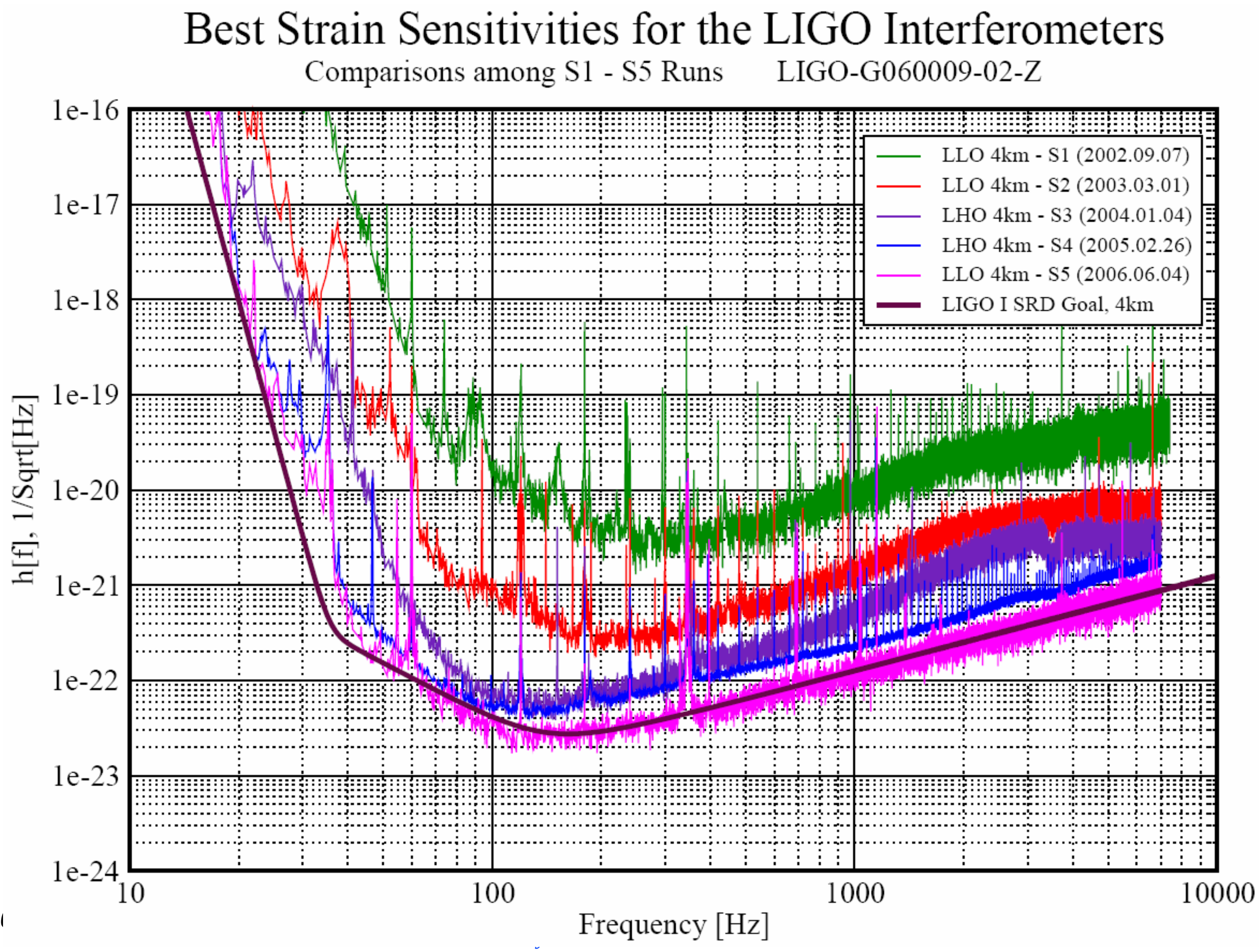
2 stacks have been omitted for clarity

LIGO – Laser Interferometer Gravitational Wave Observatory

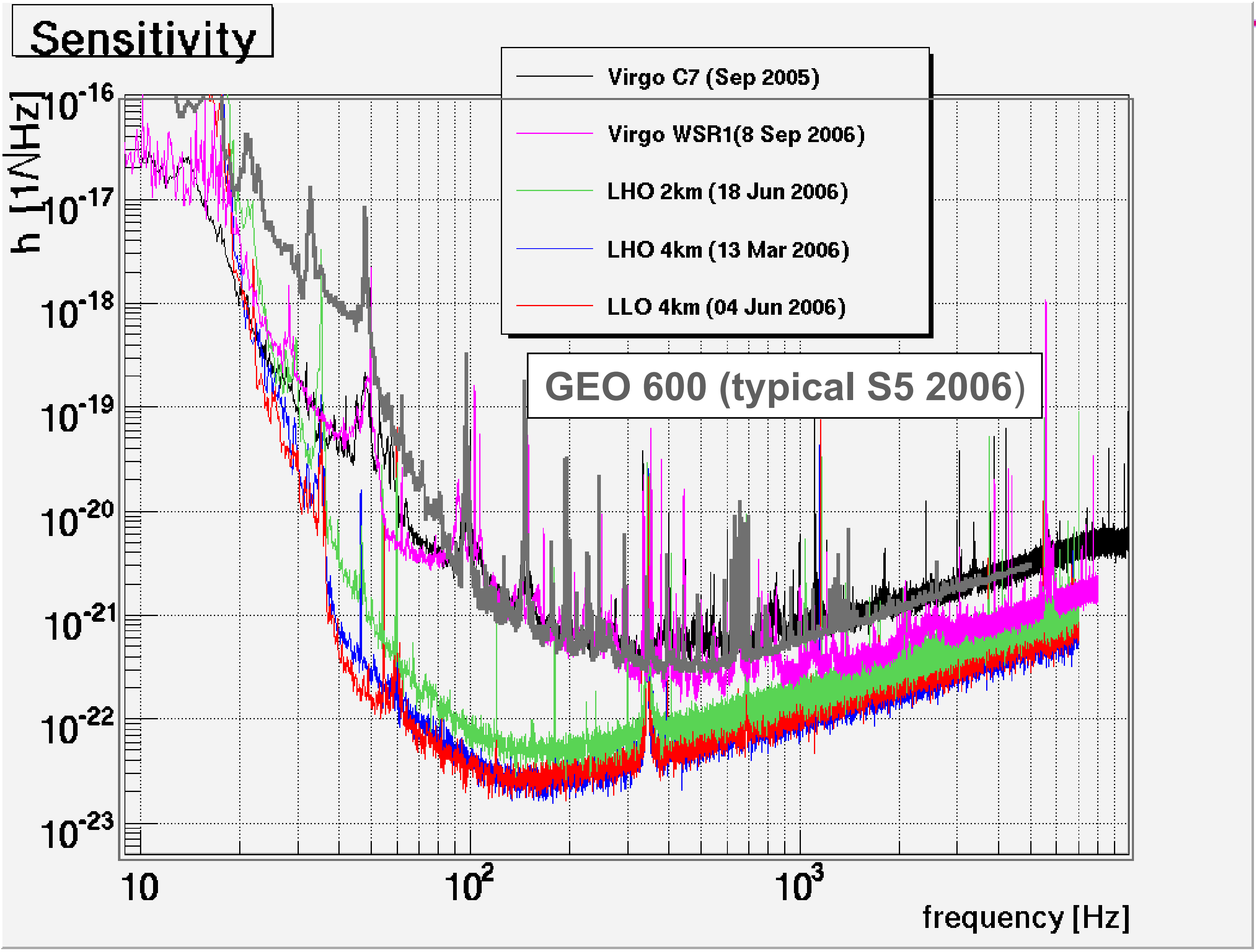
- Three interferometers at two distant sites
- Design philosophy: rely on proven technologies, scale up from prototype by two-orders of magnitude
- Achieved design sensitivity in Nov 05, currently operating with GEO in data-collection “science” mode

http://maps.google.com

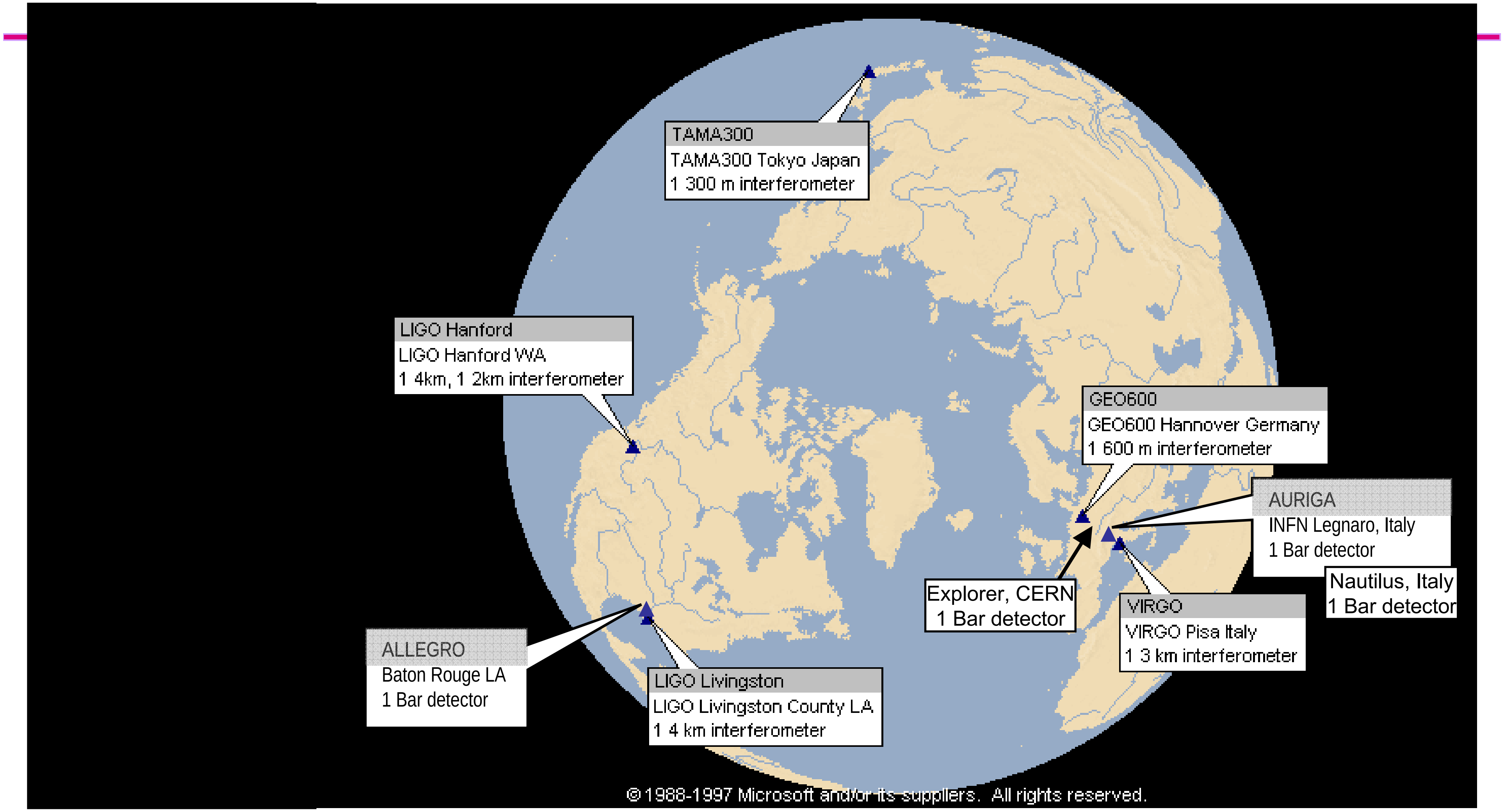
LIGO noise progress



Comparing strain noise



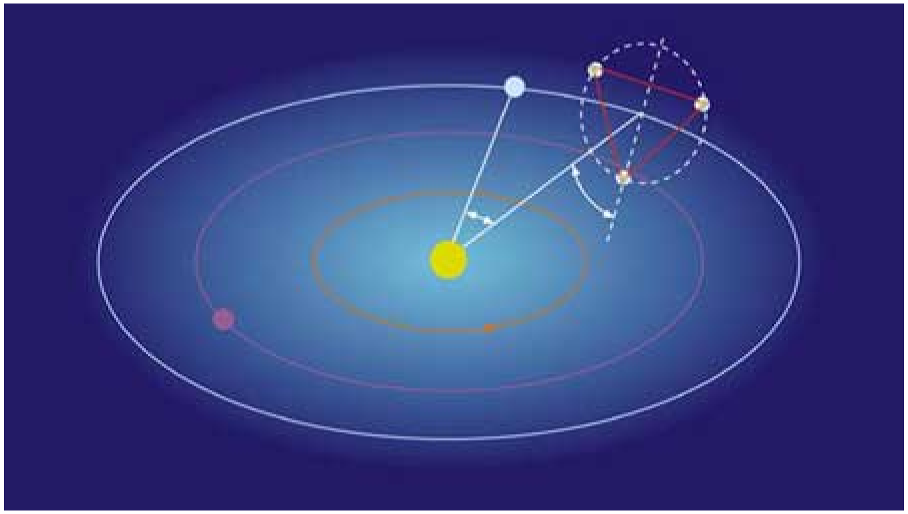
Ground-based instruments

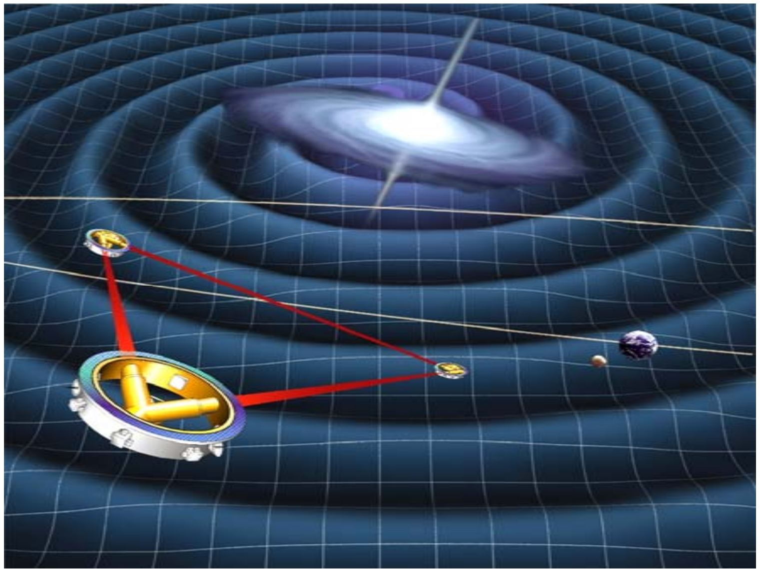


LISA

LISA is a joint ESA/NASA mission with launch date in the time frame 2014/15

- A gravitational wave telescope in the frequency band 10^{-5} - 1 Hz
- All sky monitor
- 3 drag-free satellites separated by 5×10^6 km, and trailing the earth by 20 deg
- Precision 10 pm
- Redundancy if one spacecraft fails
- Beam pattern from roll



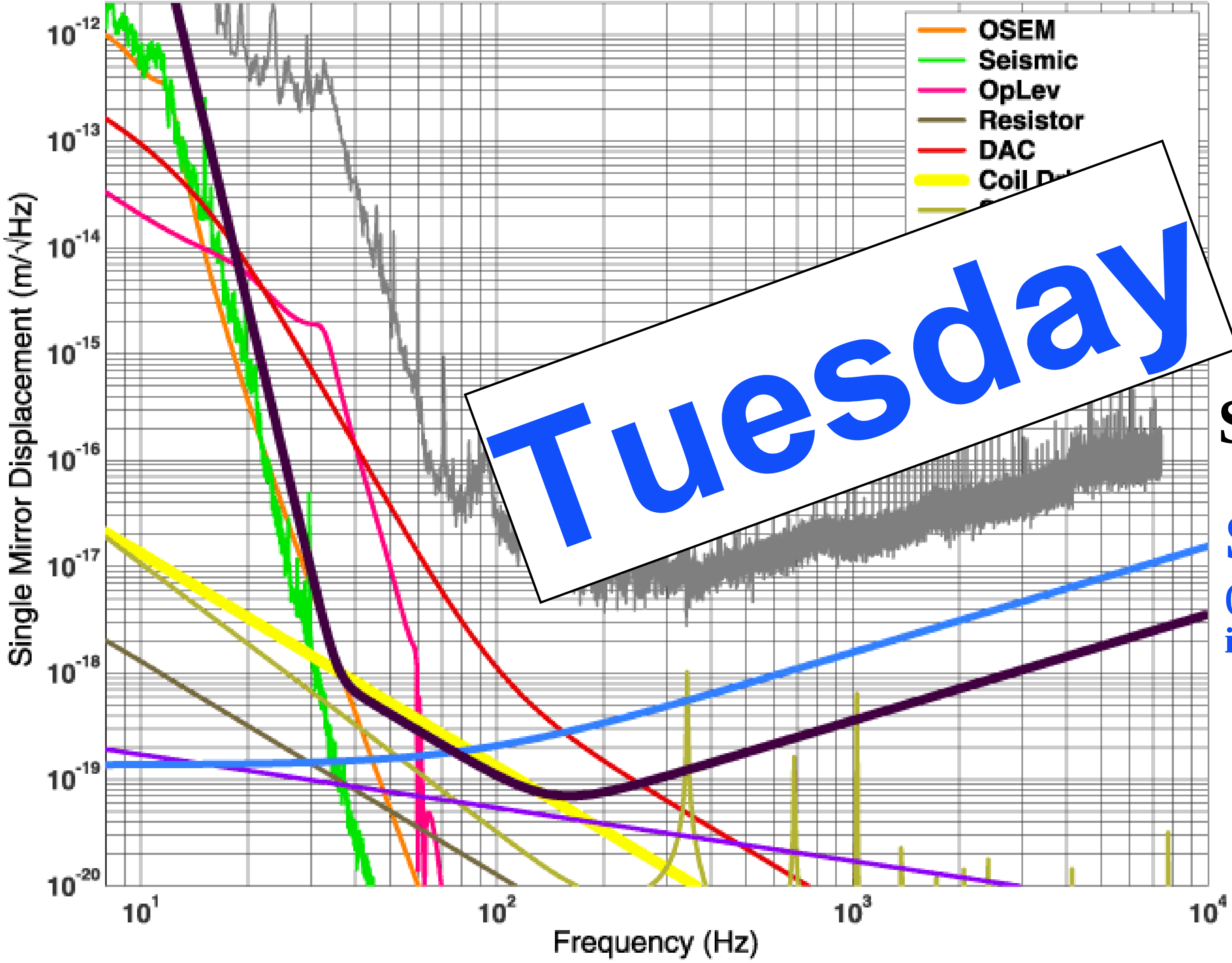


LIGO-G060513-00-Z

Concluding remarks

- Search for direct detection of gravitational waves complicated by tiny signal, $\delta L \sim 10^{-18}$m; space is stiff, and sources are distant
- Requires cooperation in a global network of detectors
- Expect to make first detection within the next decade, possibly with existing detectors
- But for the next two days…

Estimated noise limits for S2 (as planned in October 2002)



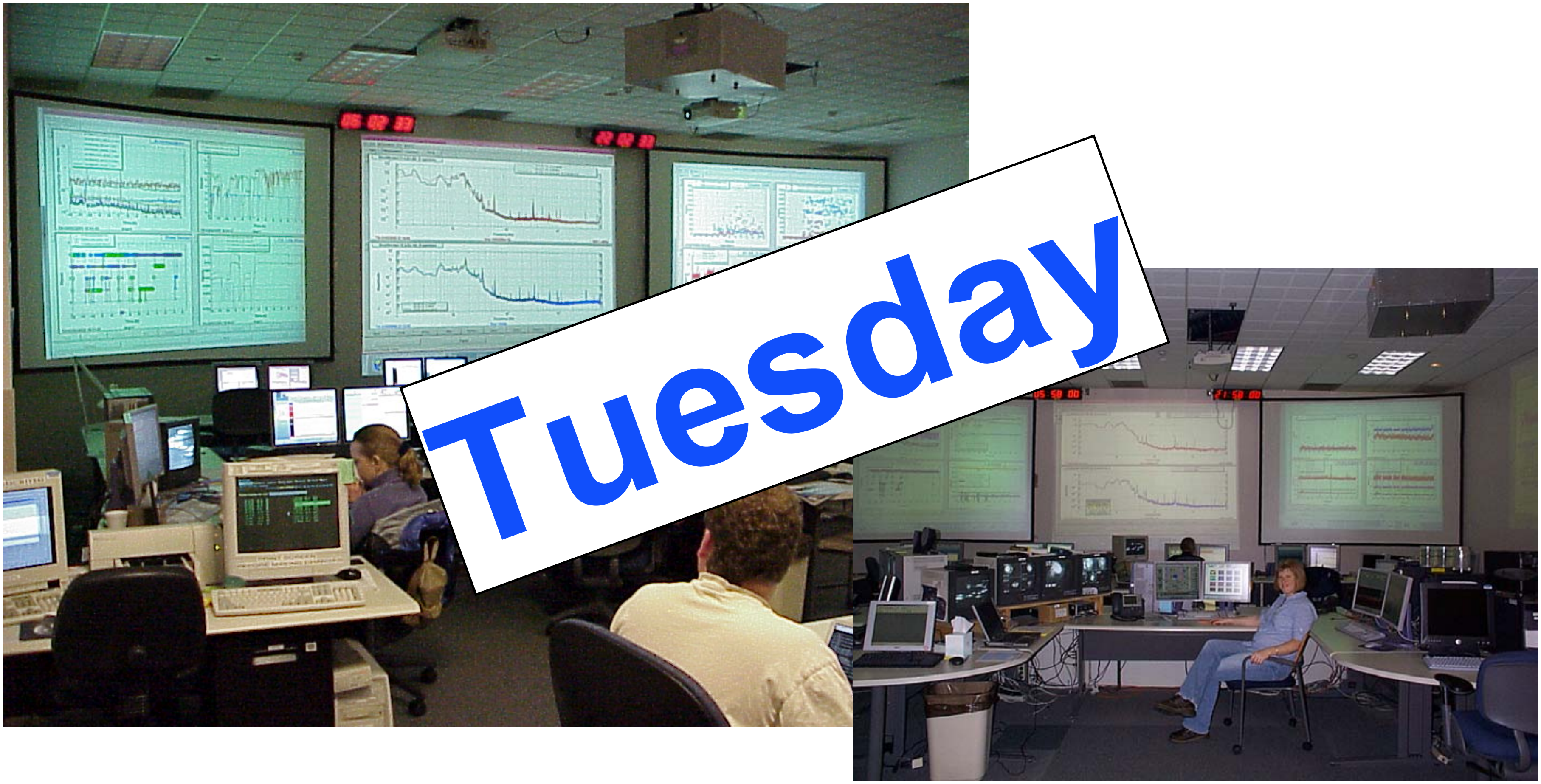
Tuesday

S1

S2

(expected from targeted improvements)

Science runs and analyses



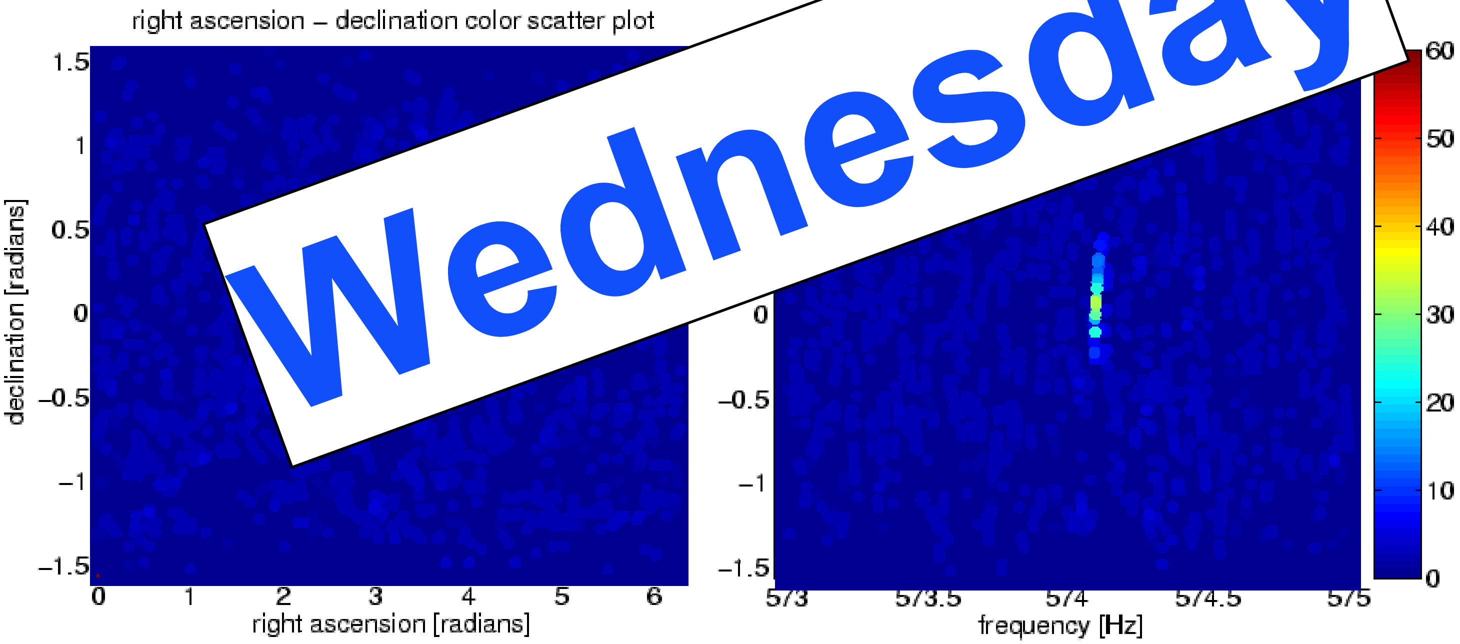
Tuesday

LIGO Hanford control room
31 Mar 2006 – S5

What would a pulsar look like?

- Post-processing step: find points on the sky and in frequency that exceeded threshold in many of the sixty ten-hour segments
- Software-injected fake pulsar signal is recovered l

Wednesday



Simulated (software) pulsar signal in S3 data

Advanced LIGO

Detector Improvements:

New suspensions:

Single → Quadruple pendulum

Lower suspensions thermal
in bandwidth

Wednesday

improved seismic isolation:

Passive → Active

Lowers seismic “wall” to ~10 Hz