Towards gravitational wave astronomy

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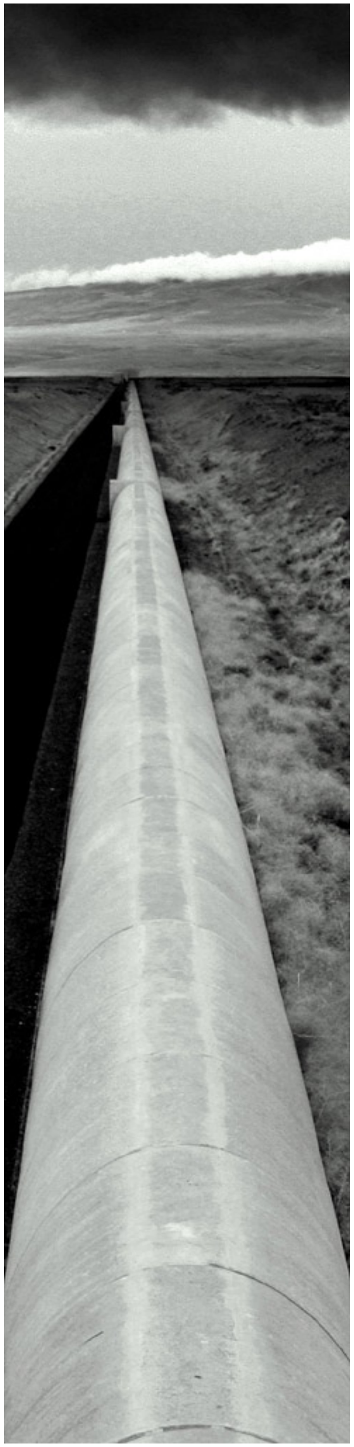
on behalf of the LIGO Scientific Collaboration
http://www.ligo.org

TRIUMF
Nov 22, 2007
Vancouver, Canada

LIGO-G070631-00-Z



LIGO Scientific Collaboration

- Australian Consortium for Interferometric Gravitational Astronom
- The Univ. of Adelaide
- Andrews University
- The Australian National Univ.
- The University of Birmingham
- California Inst. of Technology
- Cardiff University
- Carleton College
- Charles Sturt Univ.
- Columbia University
- Embry Riddle Aeronautical Univ.
- Eötvös Loránd University
- University of Florida
- German/British Collaboration for the Detection of Gravitational Waves
- University of Glasgow
- Goddard Space Flight Center
- Leibniz Universität Hannover
- Hobart & William Smith Colleges
- Inst. of Applied Physics of the Russian Academy of Sciences
- Polish Academy of Sciences
- India Inter-University Centre for Astronomy and Astrophysics
- Louisiana State University
- Louisiana Tech University
- Loyola University New Orleans
- University of Maryland
- Max Planck Institute for Gravit

- University of Michigan
- University of Minnesota
- The University of Mississippi
- Massachusetts Inst. of Technology
- Monash University
- Montana State University
- Moscow State University
- National Astronomical Observatory of Japan
- Northwestern University
- University of Oregon
- Pennsylvania State University
- Rochester Inst. of Technology
- Rutherford Appleton Lab
- University of Rochester
- San Jose State University
- Univ. of Sannio at Benevento, and Univ. of Salerno
- University of Sheffield
- University of Southampton
- Southeastern Louisiana Univ.
- Southern Univ. and A&M College
- Stanford University
- University of Strathclyde
- Syracuse University
- Univ. of Texas at Austin
- Univ. of Texas at Brownsville
- Trinity University
- Universitat de les Illes Balears
- Univ. of Massachusetts Amherst
- University of Western Australia
- Univ. of Wisconsin-Milwaukee
- Washington State University
- University of Washingto

LIGO-centric milestones since last TRIUMF talk (Feb 05)

- All 3 interferometers reached design sensitivity
  - » Operation at high laser power
  - » Many improvements in performance and robustness
- 28 observational papers published or submitted
- Completed fourth (S4) and fifth (S5) science runs (fifth science run: 1 year of triple-coincidence data)
- Short-term (~2yr timescale) improvements "Enhanced LIGO" enhancements underway
- Longer-term upgrade Advanced LIGO included in FY2008 Congressional budget, awaits conclusion
- Collaboration started with VIRGO

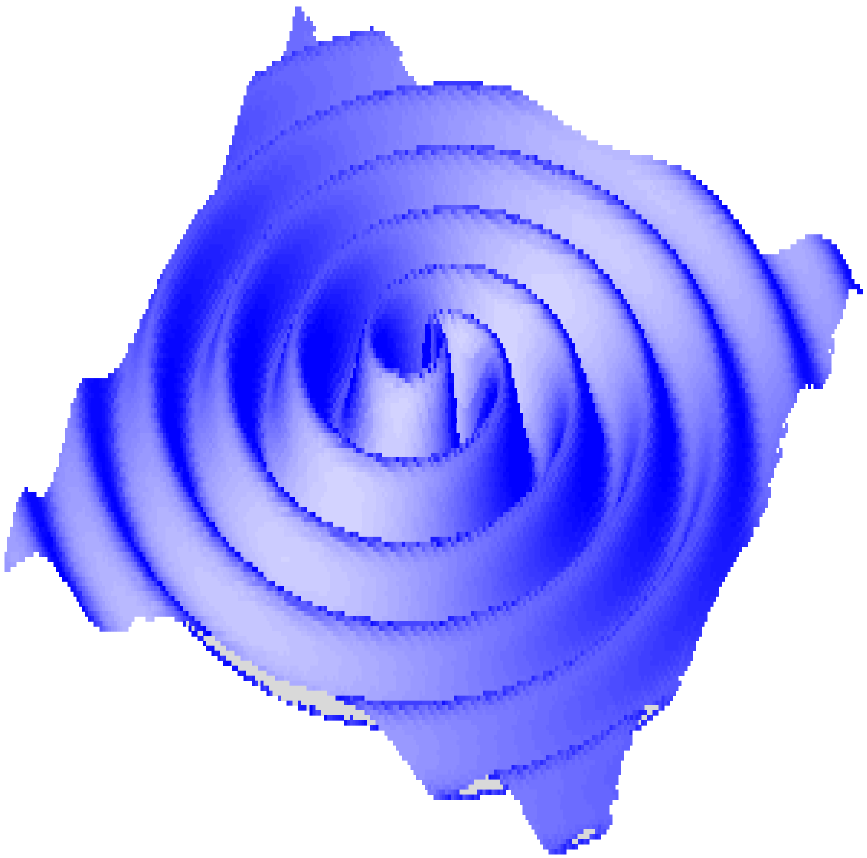
What we'll go through

- Gravitational waves
- Initial LIGO
  - » Preliminary astrophysical results from the fifth science run (one final one from S4)
- Enhanced LIGO
- Advanced LIGO
- LISA

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

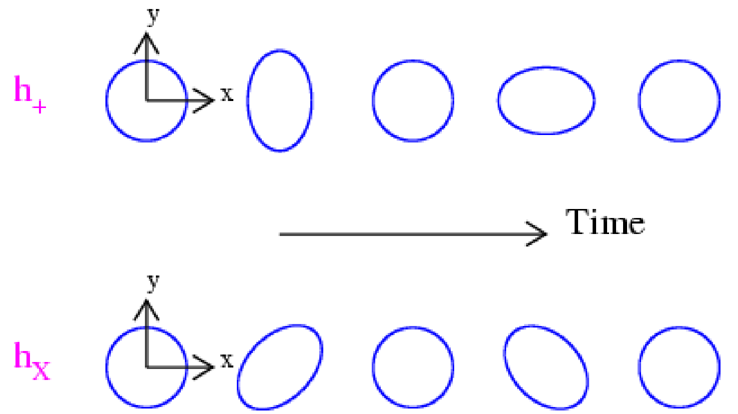
$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

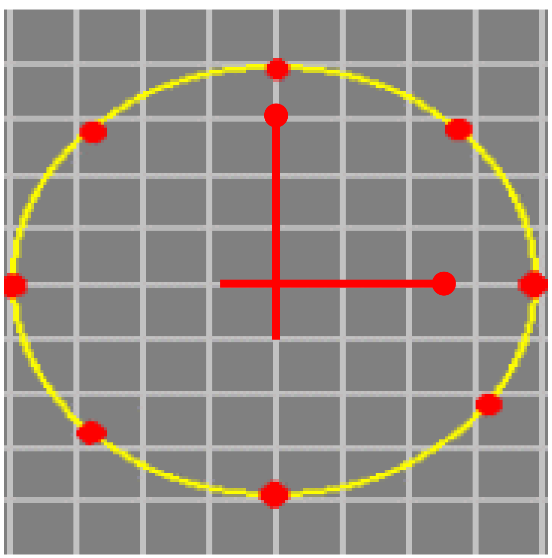


What is the observable effect?

Example:

Ring of test masses responding to wave propagating along z

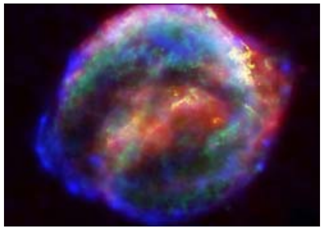
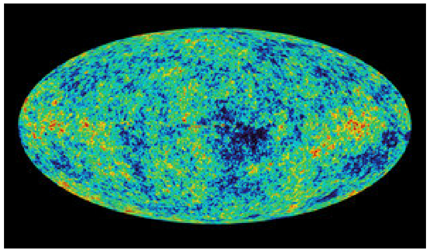
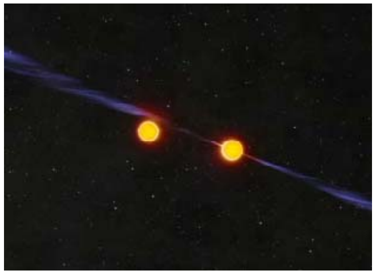
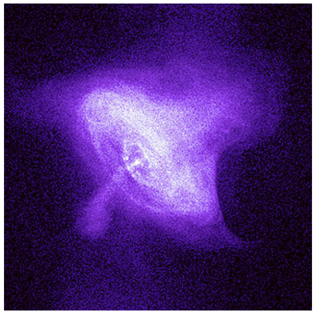




Amplitude parameterized by (tiny) dimensionless strain h:

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

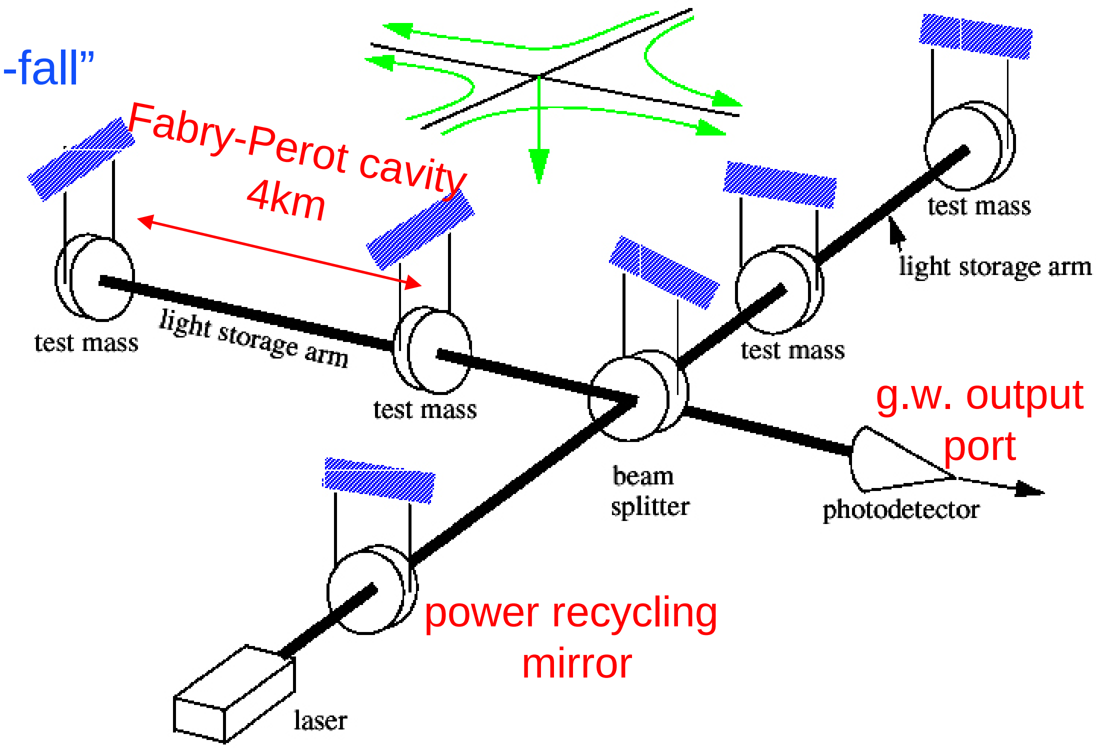
Signal duration and template

	Short duration	Long duration
template-less methods		
matched filter		

Credit: NASA/CXC/ASU/J. Hester et al.

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)



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

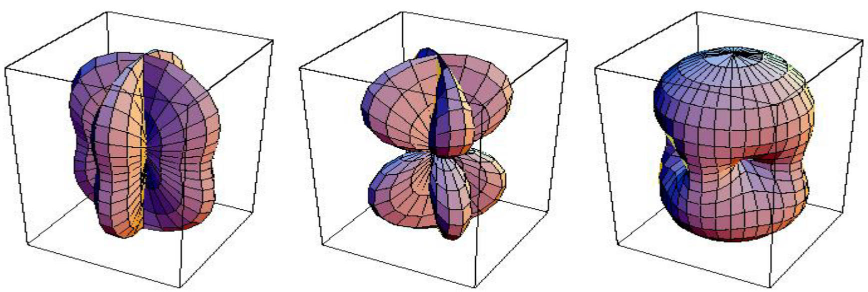
Aside: some terminology

Beam patterns

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

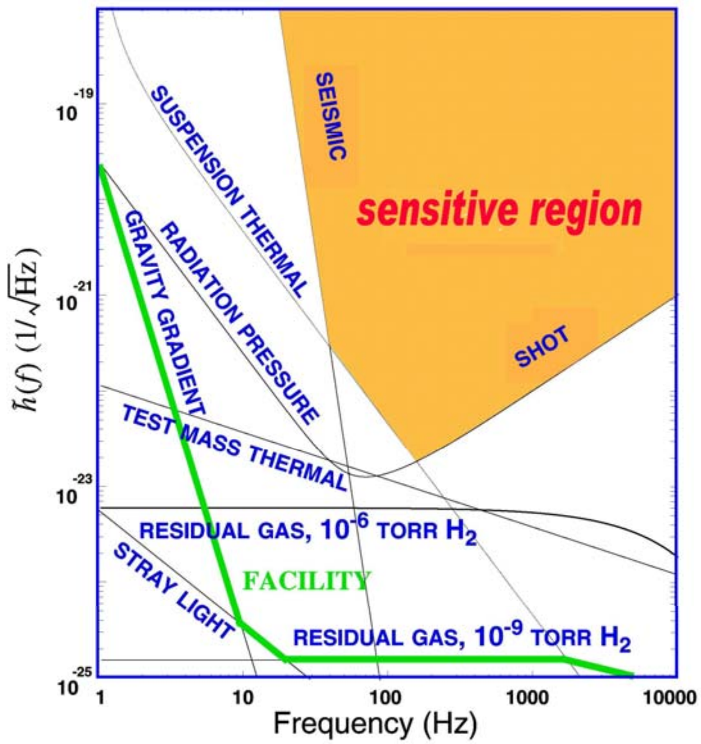
- F^{+}, F^{x} : [-1, 1]
- F = F(t; α, δ)

LIGO example:



F^{+} F^{x} average

Strain noise curves



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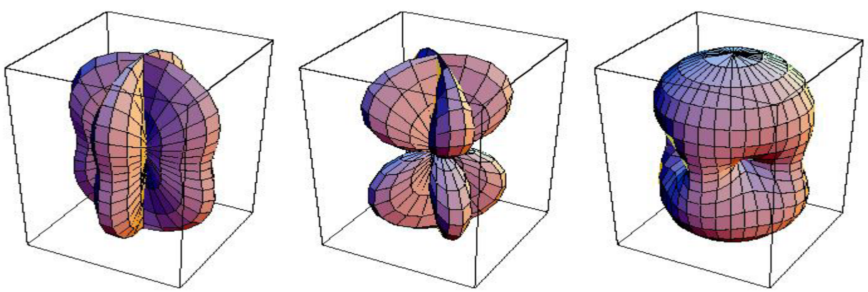
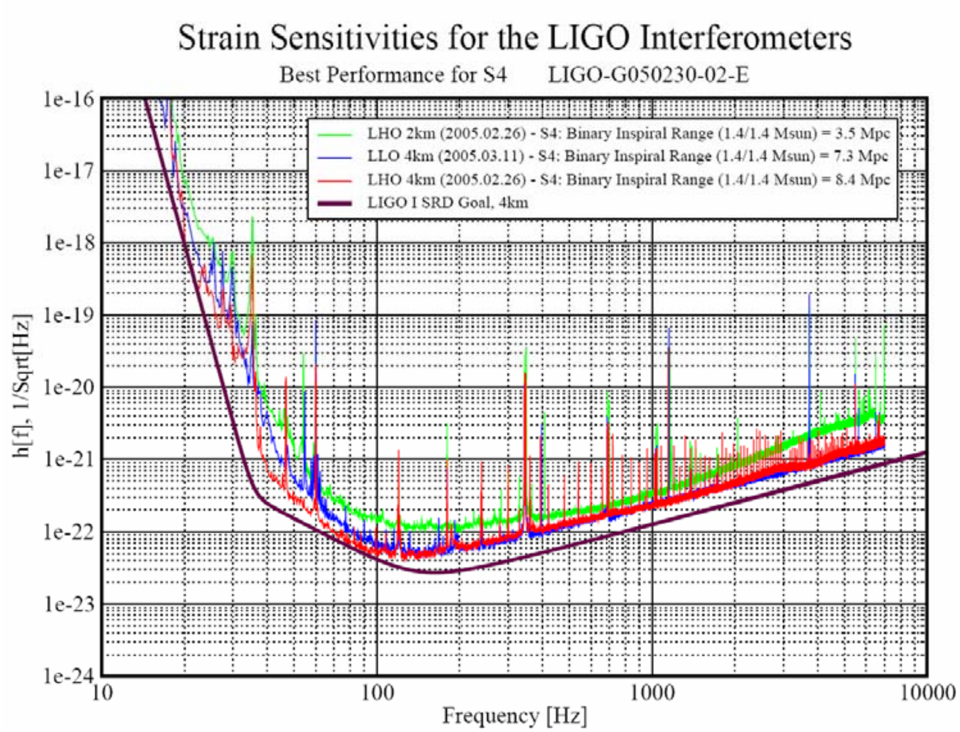
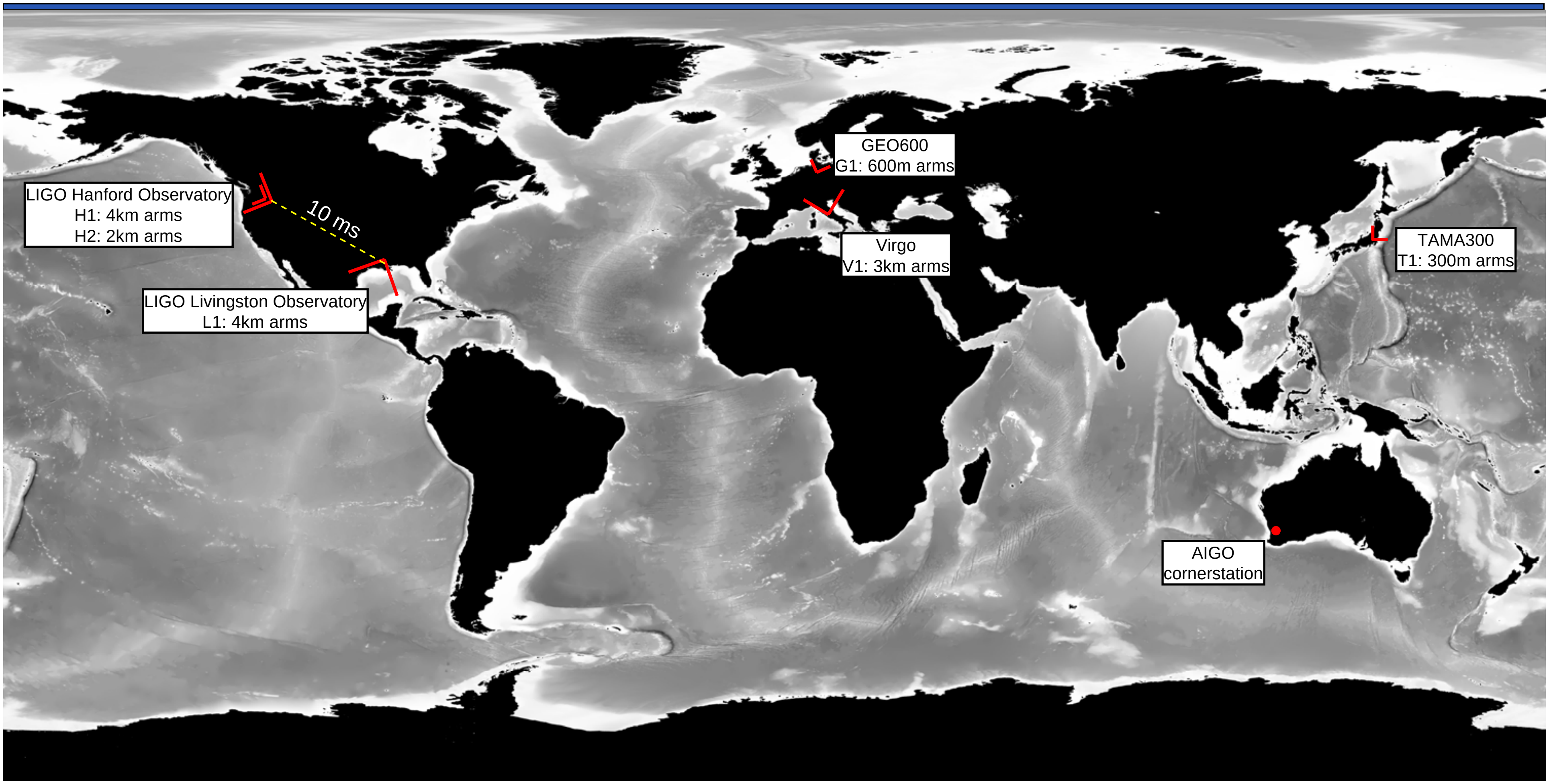


F+ Fx average

Strain noise curves

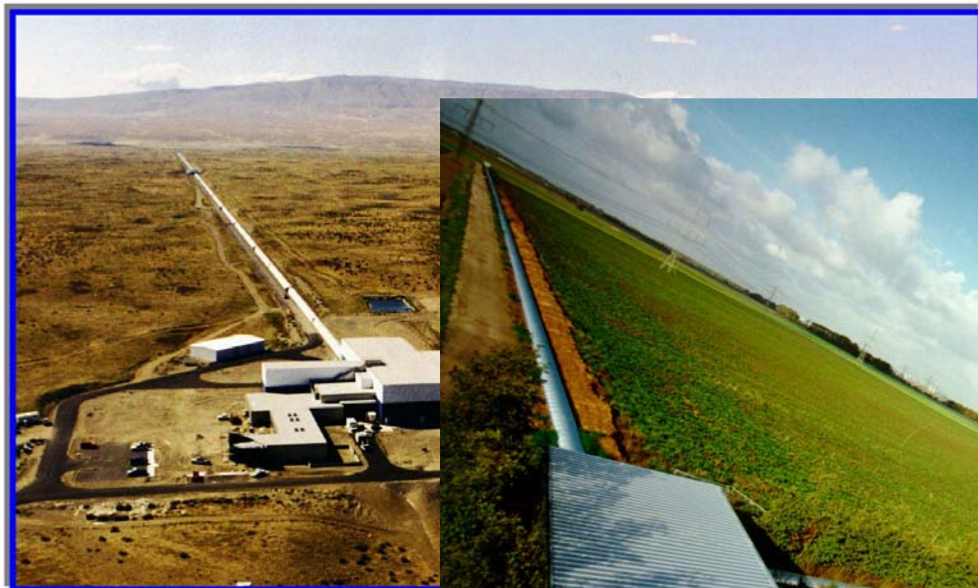


Interferometer network



Credit: NASA's Earth Observatory

LSC Sites

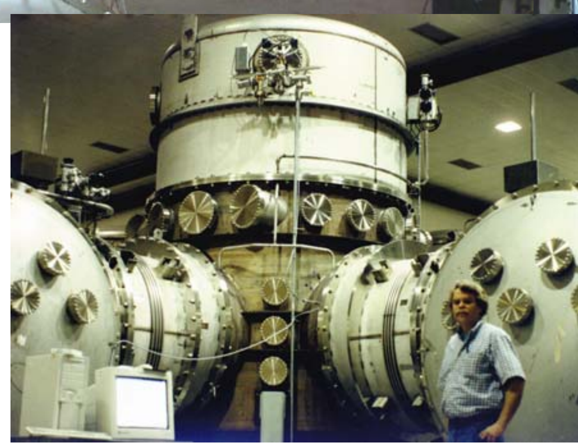


LIGO Hanford Obs

GEO600

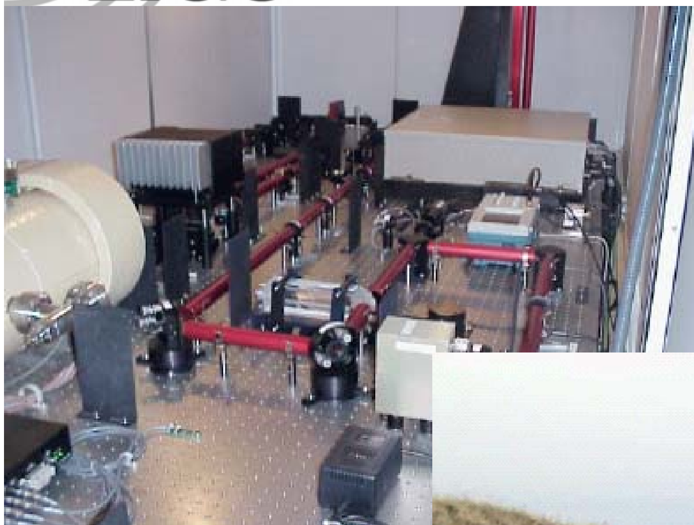
Observatory

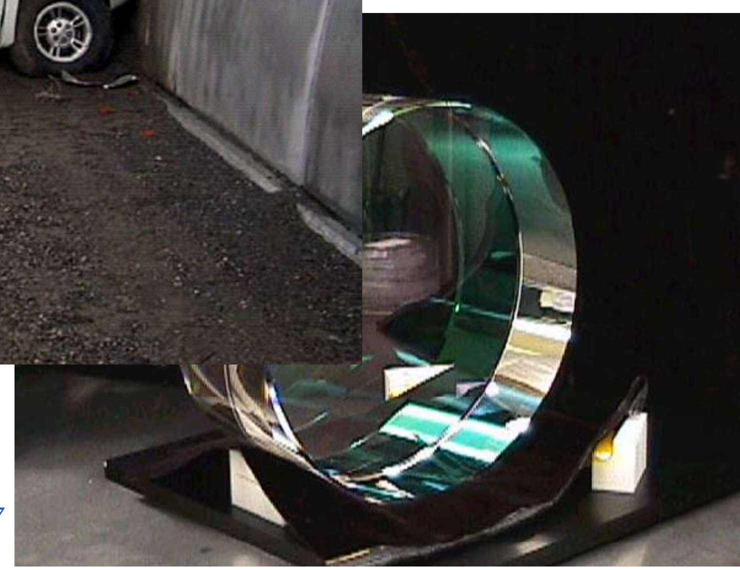
LIGO Hanford cornerstation



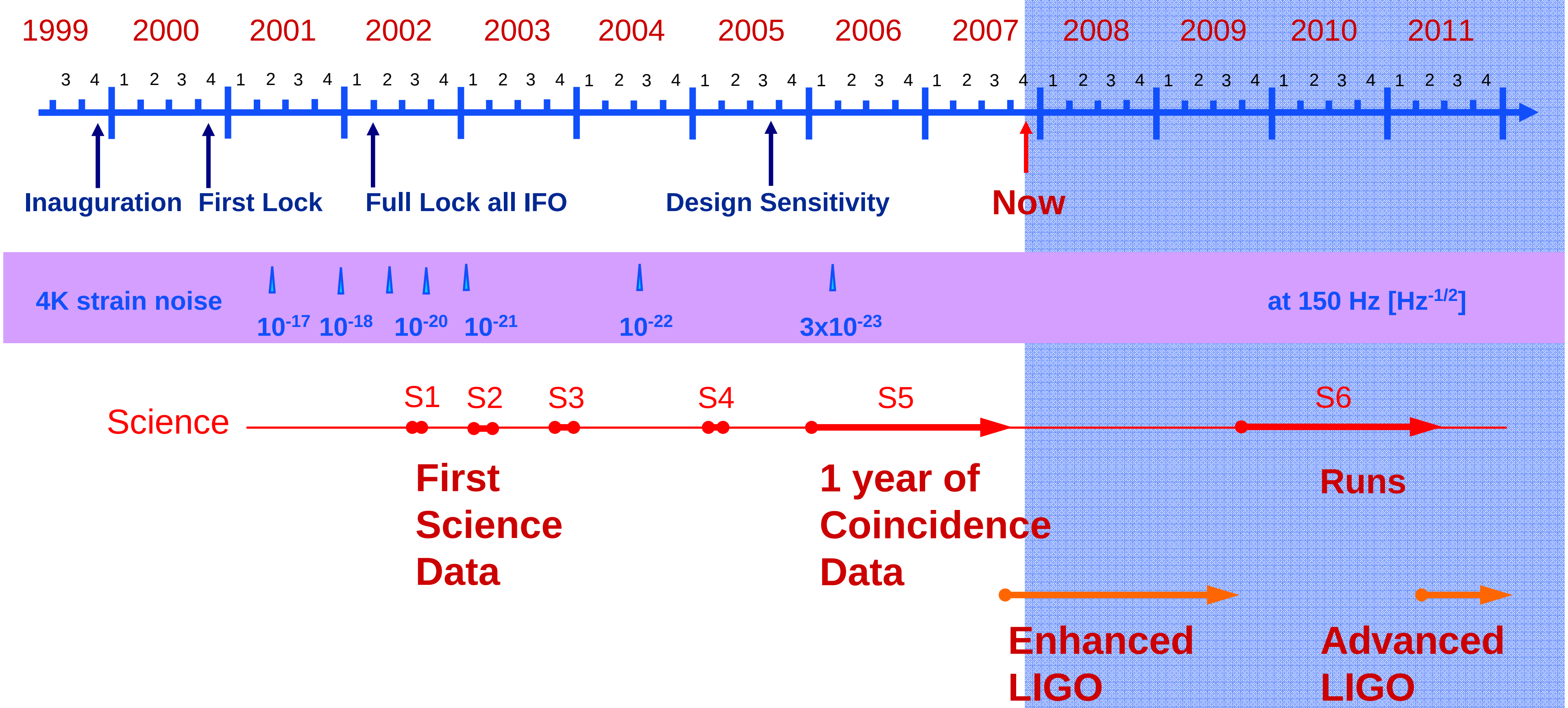
John Worden at the 4k beam splitter. John's talk today: *The LIGO vacuum systems*, 3:30pm, auditorium

Installations

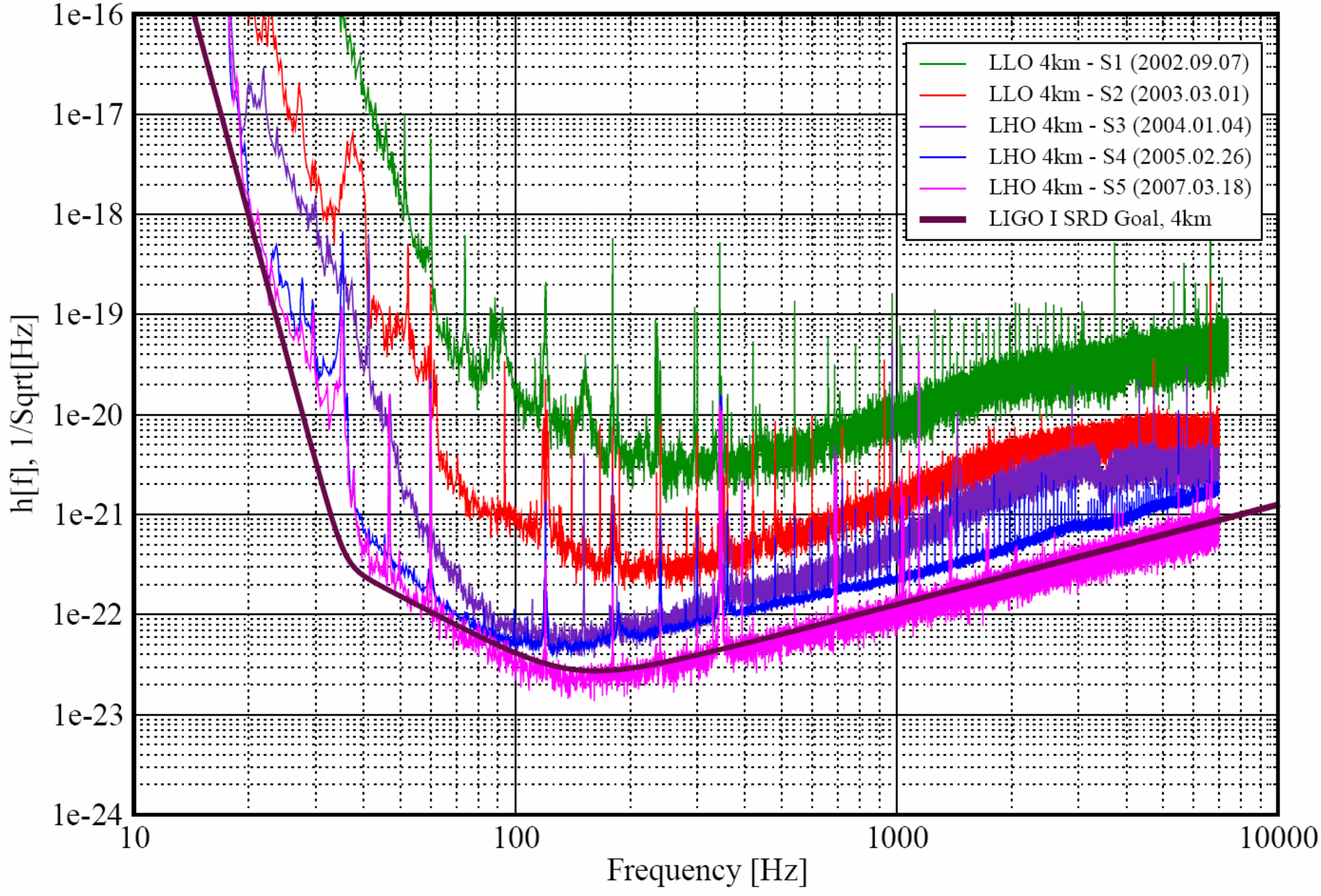




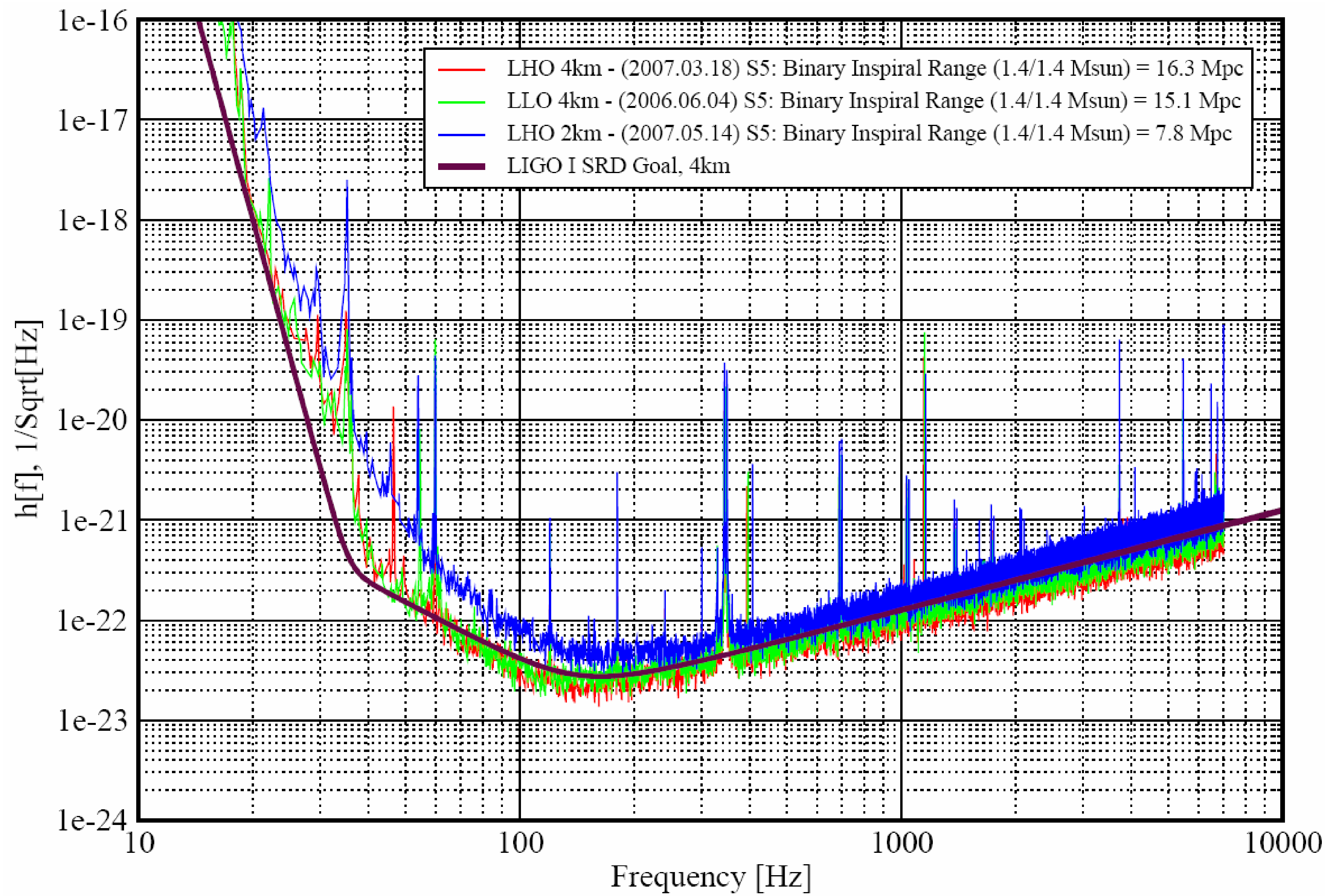
Time Line


1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011
Inauguration
First Lock
Full Lock all IFO
Design Sensitivity
Now
4K strain noise
10^{-17} 10^{-18} 10^{-20} 10^{-21} 10^{-22} $3x10^{-23}$
at 150 Hz [$Hz^{-1/2}$]
Science
S1 S2 S3 S4 S5 S6
First Science Data
1 year of Coincidence Data
Runs
Enhanced LIGO
Advanced LIGO

Progress in sensitivity

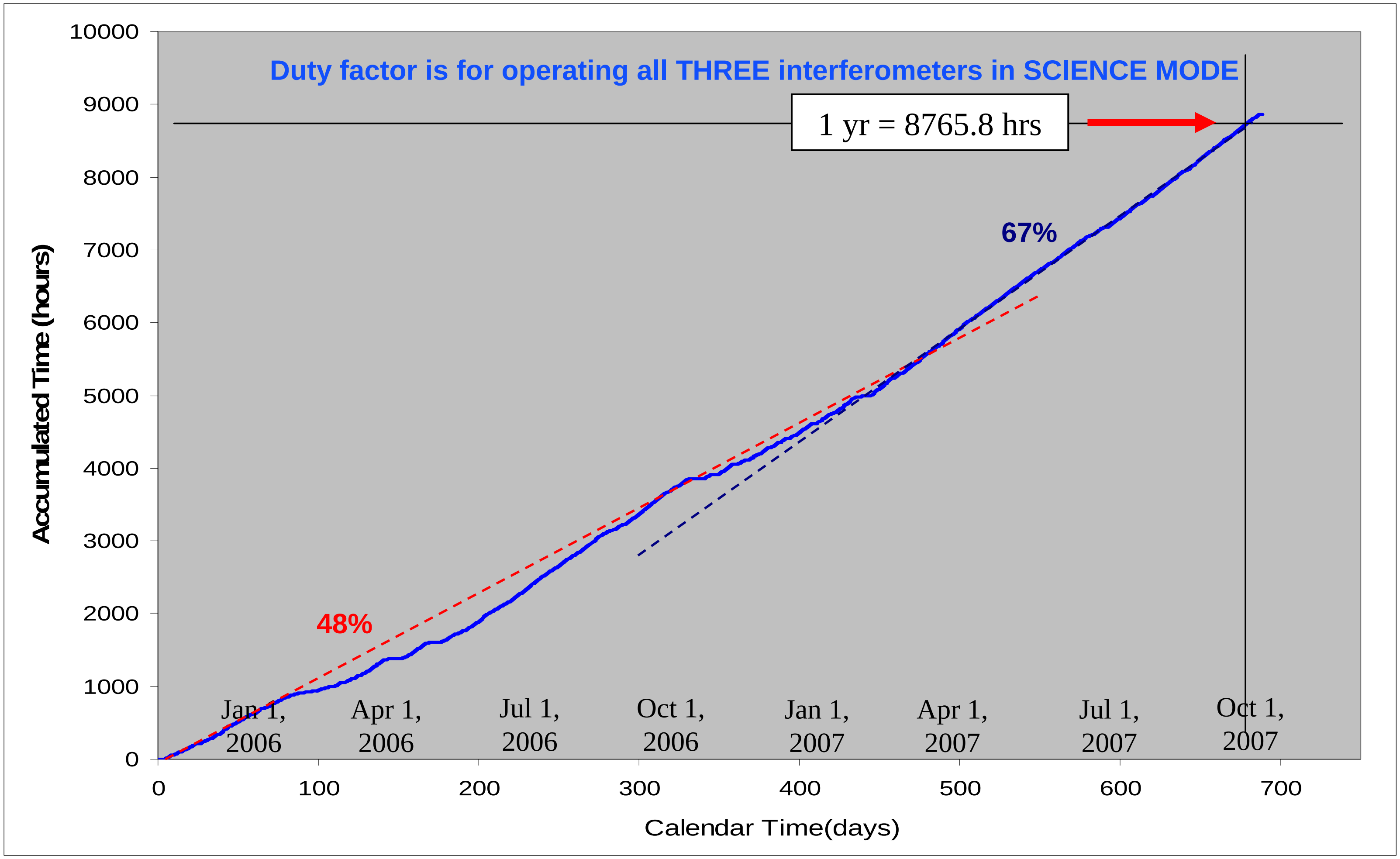


S5 noise

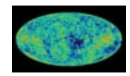
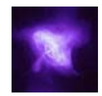
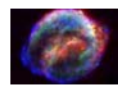


LHO 4km - (2007.03.18) S5: Binary Inspiral Range (1.4/1.4 Msun) = 16.3 Mpc
LLO 4km - (2006.06.04) S5: Binary Inspiral Range (1.4/1.4 Msun) = 15.1 Mpc
LHO 2km - (2007.05.14) S5: Binary Inspiral Range (1.4/1.4 Msun) = 7.8 Mpc
LIGO I SRD Goal, 4km
h[f], 1/Sqrt[Hz]
1e-16
1e-17
1e-18
1e-19
1e-20
1e-21
1e-22
1e-23
1e-24
10
100
1000
10000
Frequency [Hz]

Accumulated triple-coincidence vs. the calendar

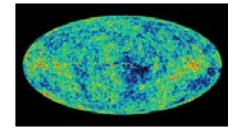


Recent search results

- No gravitational waves detected
- Example result from each search group
  - » Final S4 result in search for stochastic source 
  - » Preliminary S5 results
    - – Upper limits from spinning neutron stars 
    - – Targeted search on GRB 070201
      - • Search for compact binaries 
      - • Search for burst sources 

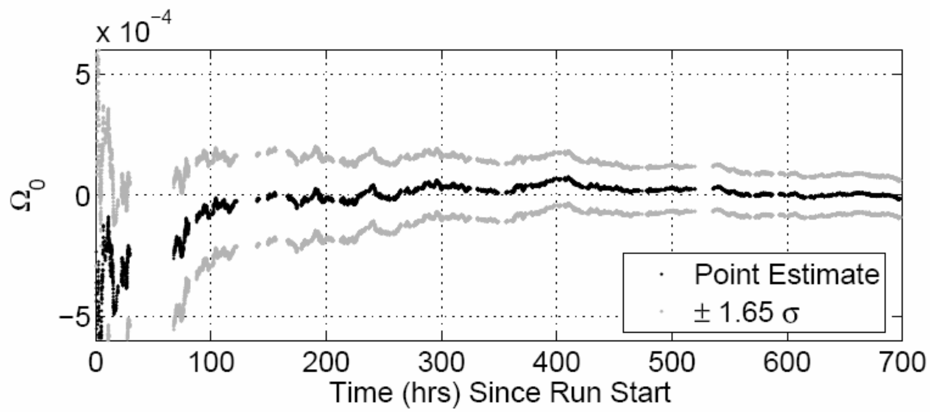
Targeted.

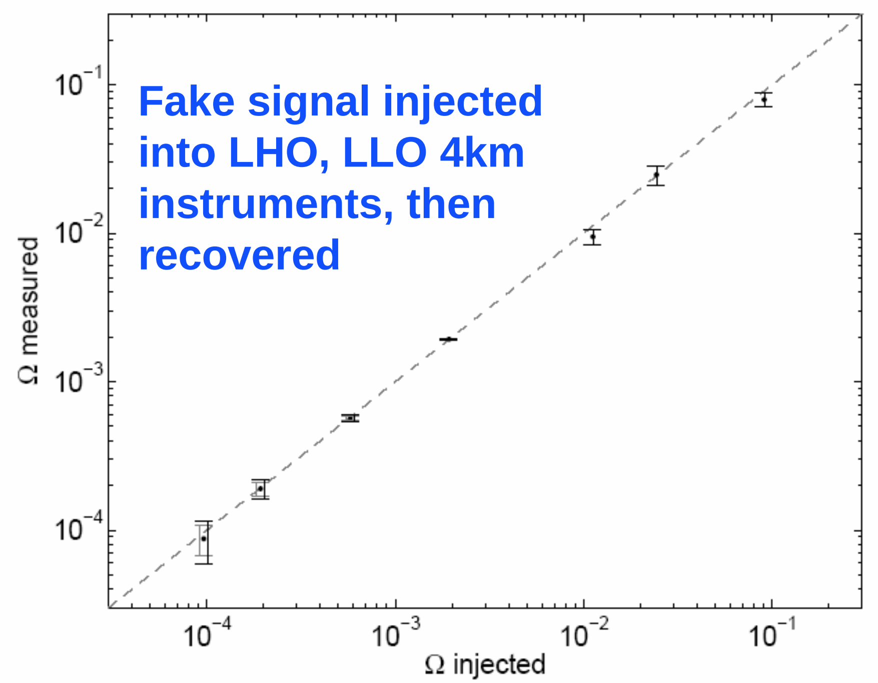
- Many other LSC searches underway, and with more S5 data



Analysis I: stochastic background

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



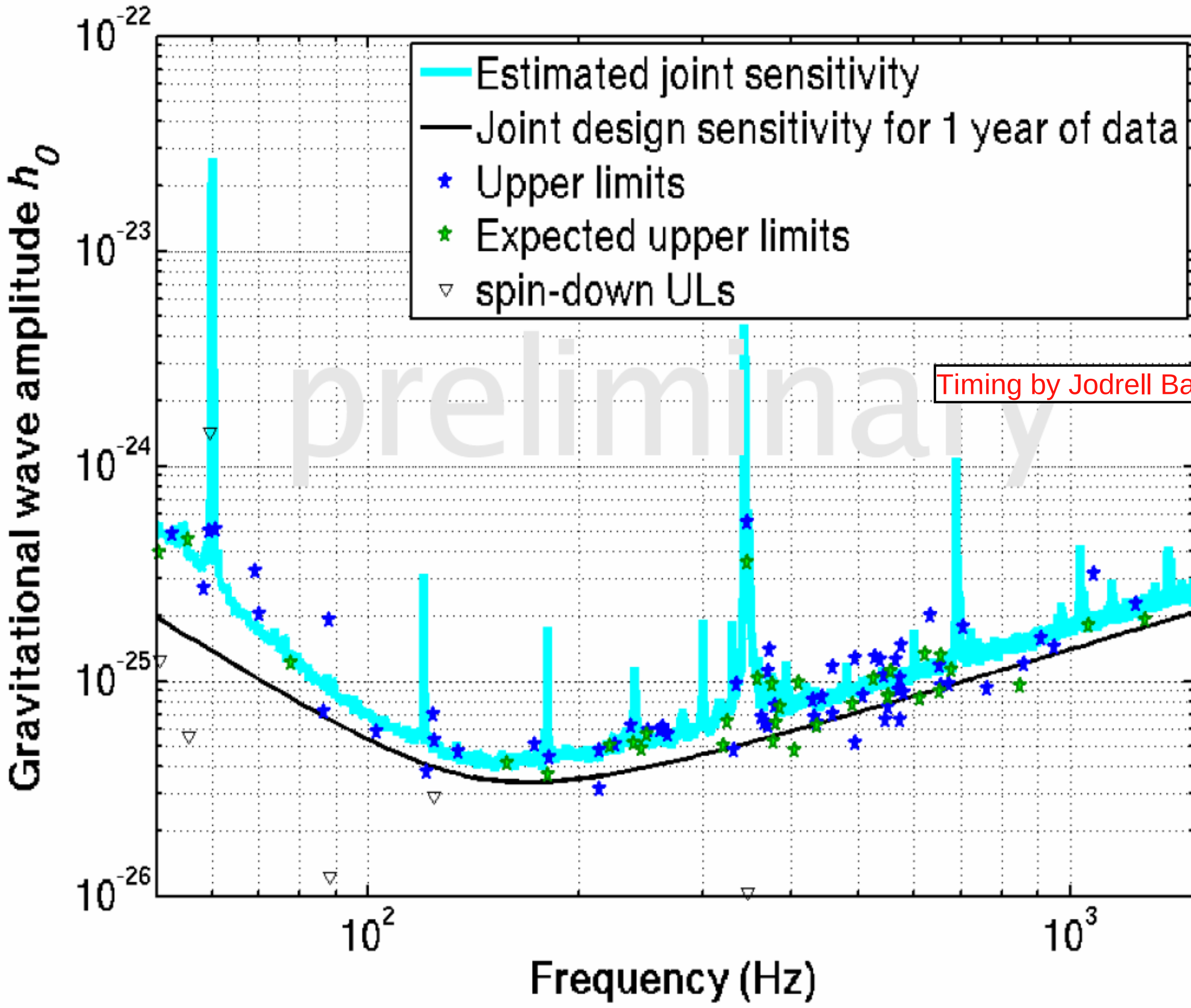


S4 result
Ap. J., 659 (2007) 082003
(astro-ph/0608606):

$$\Omega_{GW} < 6.5\times10^{-5}$$

Bayesian 90% U.L.

Analysis II: known pulsars



Short duration GRBs

Oct. 6, 2005

Fox, et al., Nature 437, 845 (2005)

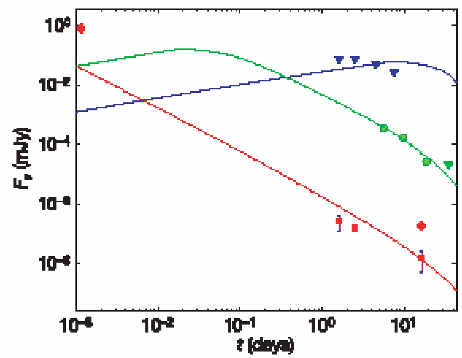


Figure 3 | **Observations of the GRB 050709 afterglow and illustrative models.** The X-ray (red), optical (green) and radio (blue) data taken from

Gehrels, et al., Nature 437, 851 (2005)

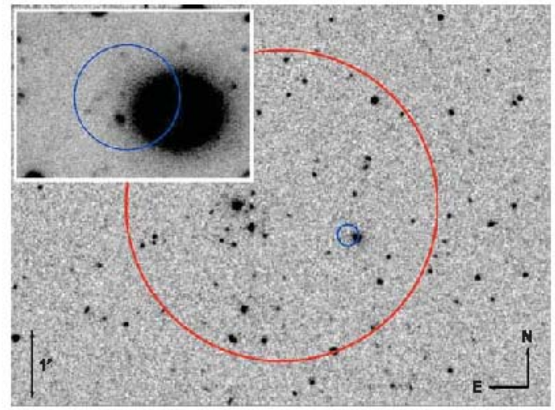
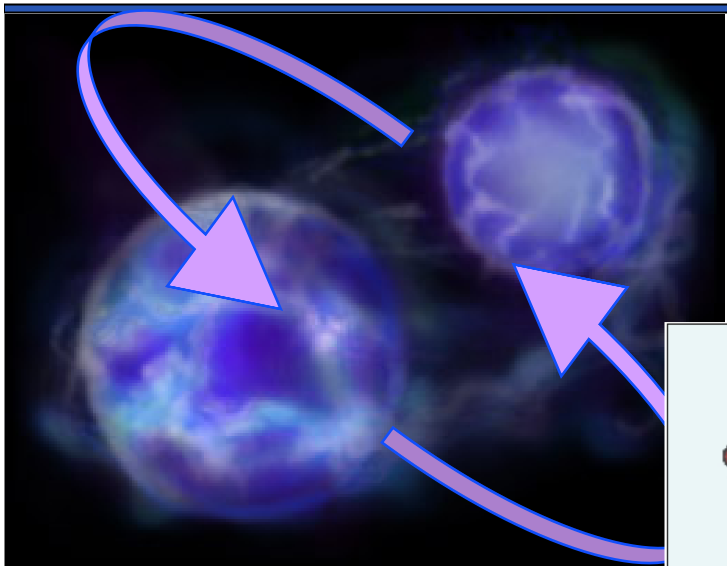


Figure 1 | **Optical images of the region of GRB 050509B showing the association with a large elliptical galaxy.** The Digitized Sky Survey image.

"There may be more than one origin of short GRBs, but this particular short event has a high probability of being unrelated to star formation and of being caused by a binary merger."

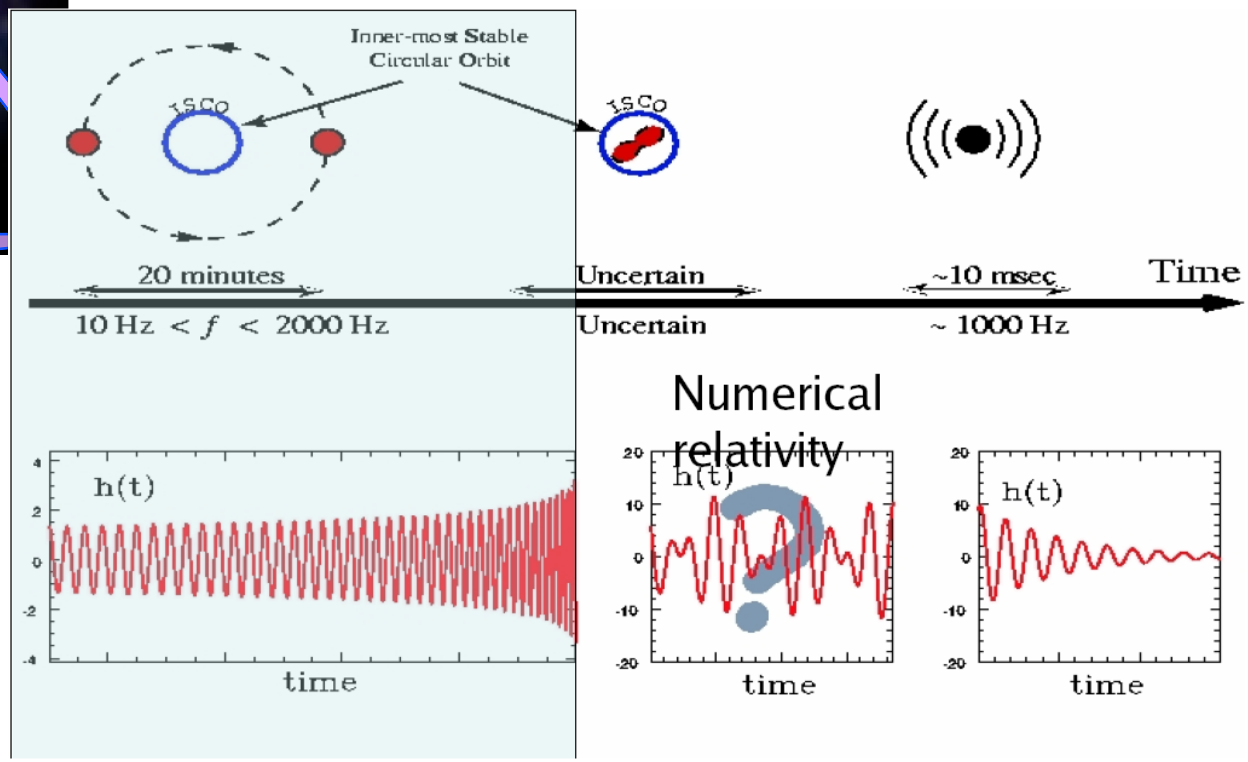
"In all respects, the emerging picture of SHB properties is consistent with an origin in the coalescence events of neutron star–neutron star or neutron star–black hole binary systems."

Analysis III : compact binary inspirals
Analysis IV: bursts



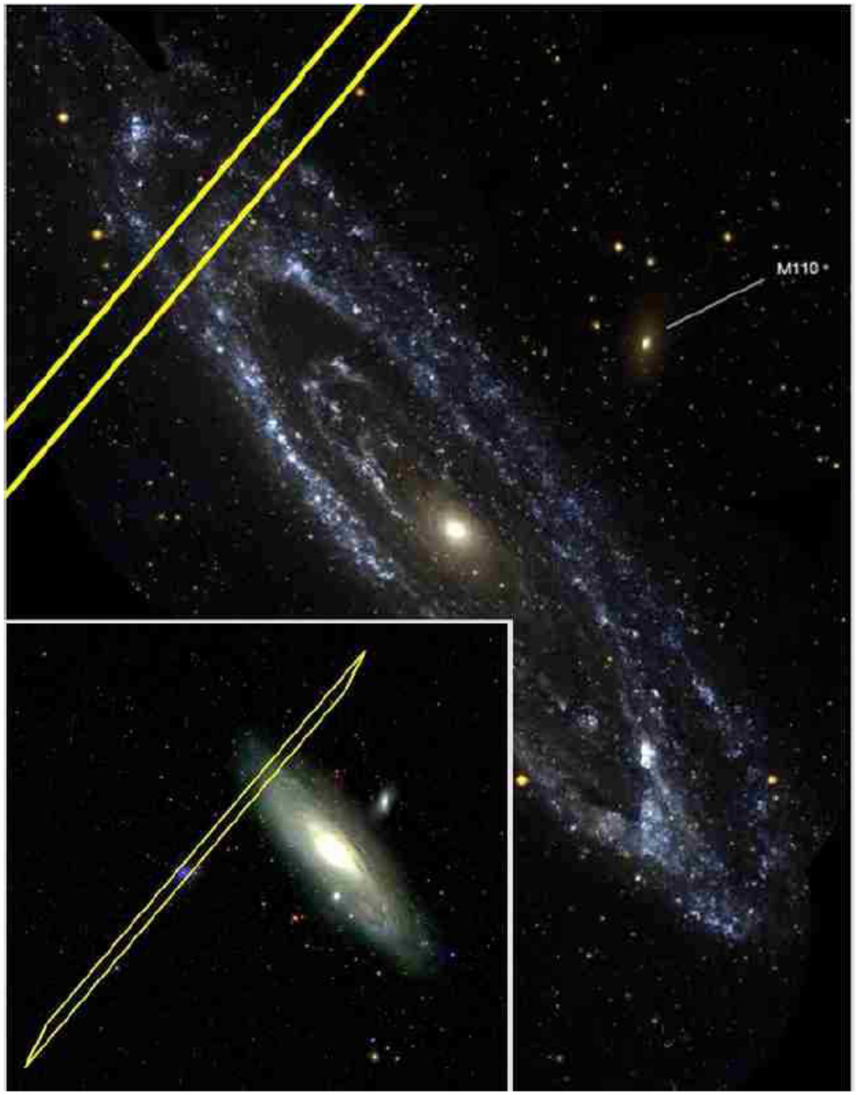
Credit: Jillian Bornak

Binary neutron stars, or a neutron star/black hole binary sytem, may inspiral and merge and be both chirp and burst waveform sources of gravitational waves



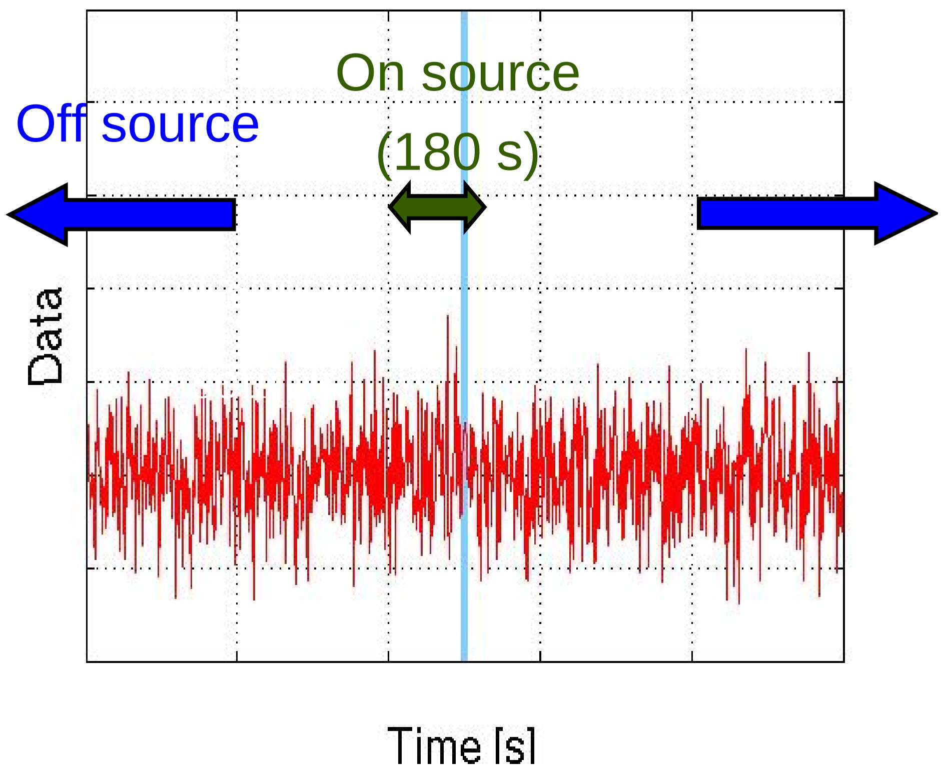
GRB 070201

- Feb 1, 2007: short hard γ burst
- Observed by five spacecraft
- Location consistent with M31spiral arms (0.77 Mpc)
- At the time of the event, both Hanford instruments were recording data (H1, H2), while others were not (L1, V1, G1)
- Short GRB: could be inspiral of compact binary system, or perhaps soft gamma repeater (SGR: ~15% of short GRBs thought to be SGRs)



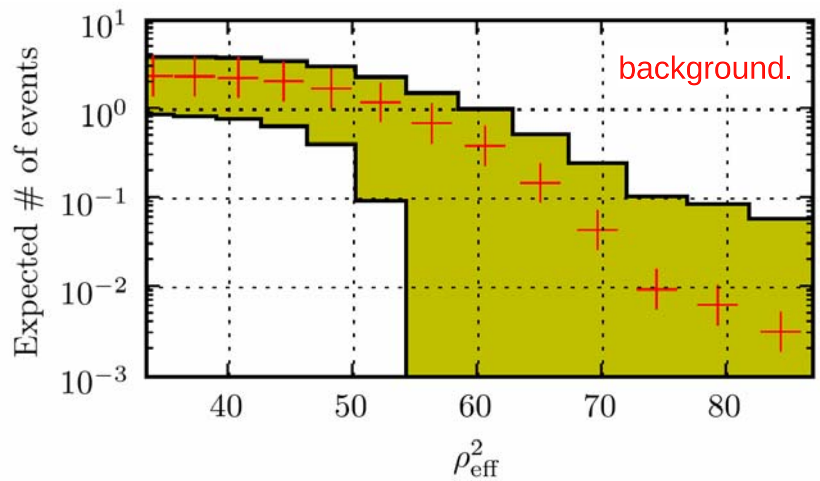
Inspiral and burst analyses

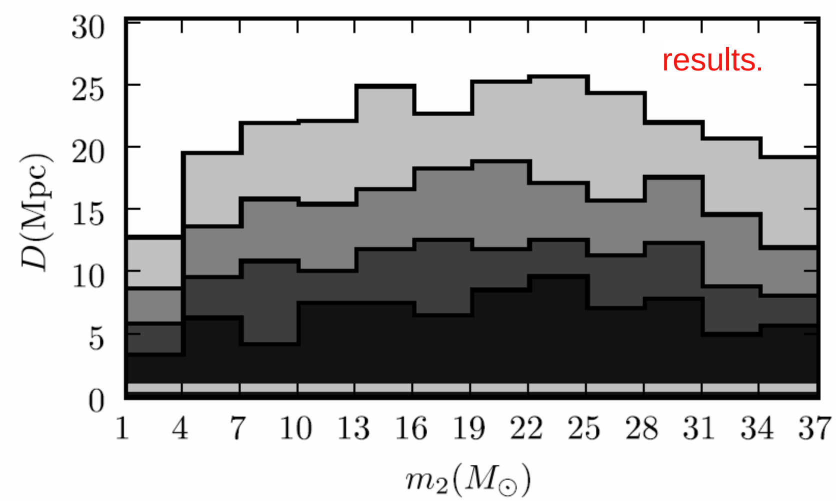
- On source data: 180s around GRB
- Off source, for background est.
  - inspiral: -14h, +8h
  - burst: -1.5h, +1.5h
- Some (.9%) off source data excluded, based on data quality cuts obtained from playground studies (e.g. excess seismic noise, digital overflows, hardware injections of fake signals)
- Assume gravitational waves travel at the speed of light



Inspiral search - GRB 070201

- Matched template analysis, $1M_{\odot} < m_1 < 3M_{\odot}$, $1M_{\odot} < m_2 < 40M_{\odot}$
- H1 ~ 7200 templates, H2 ~ 5400 templates, obtain filter SNR
- Require consistent timing and mass parameters between H1, H2
- Additional signal-based tests : χ^2, and r^2 veto
- SNR and χ^2 combined into effective SNR ρ_{eff}
- No gravitational wave candidates found
- Compact binary in M31 excluded at 99% confidence

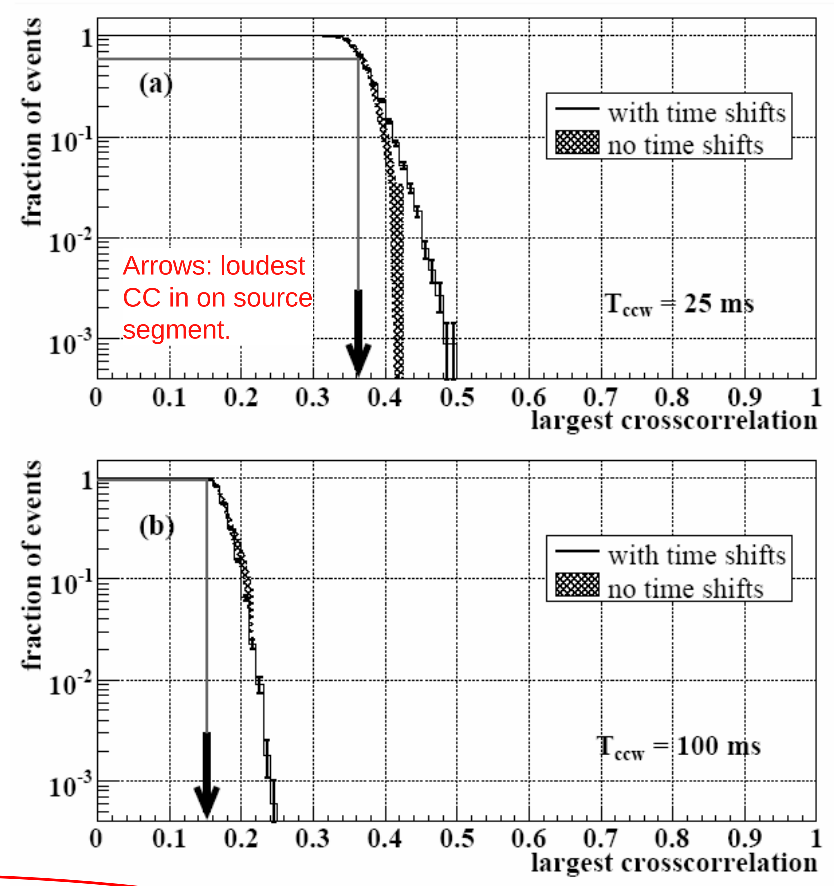




Triggered burst search

$$cc = \frac{\sum_{i=1}^{n}[s_1(i)-\mu_1][s_2(i)-\mu_2]}{\sqrt{\sum_{j=1}^{n}[s_1(j)-\mu_1]^2}\sqrt{\sum_{k=1}^{n}[s_2(k)-\mu_2]^2}}$$

- Burst waveform not well modelled
- Cross-correlate (CC) detector data streams, both on and off source
- Use two windows, 25ms and 100ms
- No candidates found
- GRB emitted < $4.4\times10^{-4}\ M_{\odot}c^2$ in GW in <100ms, if source in M31, isotropic, and peaked at ~150Hz



Results of binary inspiral and burst searches, "Implications for the origin of GRB 070201 from LIGO", submitted last week to arXiv:0711.1163v1

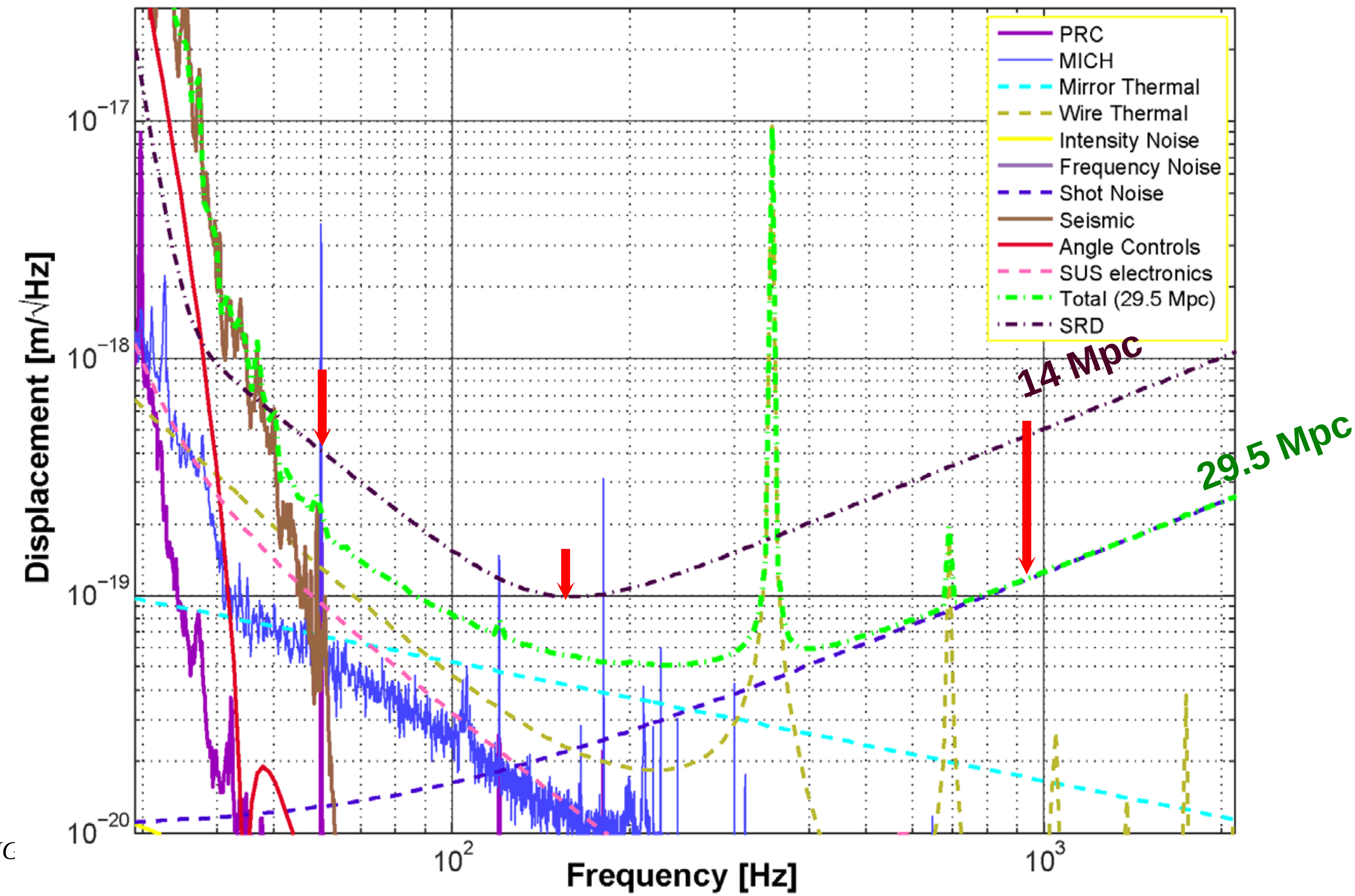
Enhanced LIGO

- Factor of ~2 improvement in strain sensitivity of the two 4km instruments (nearly order-of-magnitude improvement in rate)
- All upgrades make use of Advanced LIGO technology: retire risk
- Vacuum broken at Livingston; follow suit at Hanford next week

Enhanced LIGO

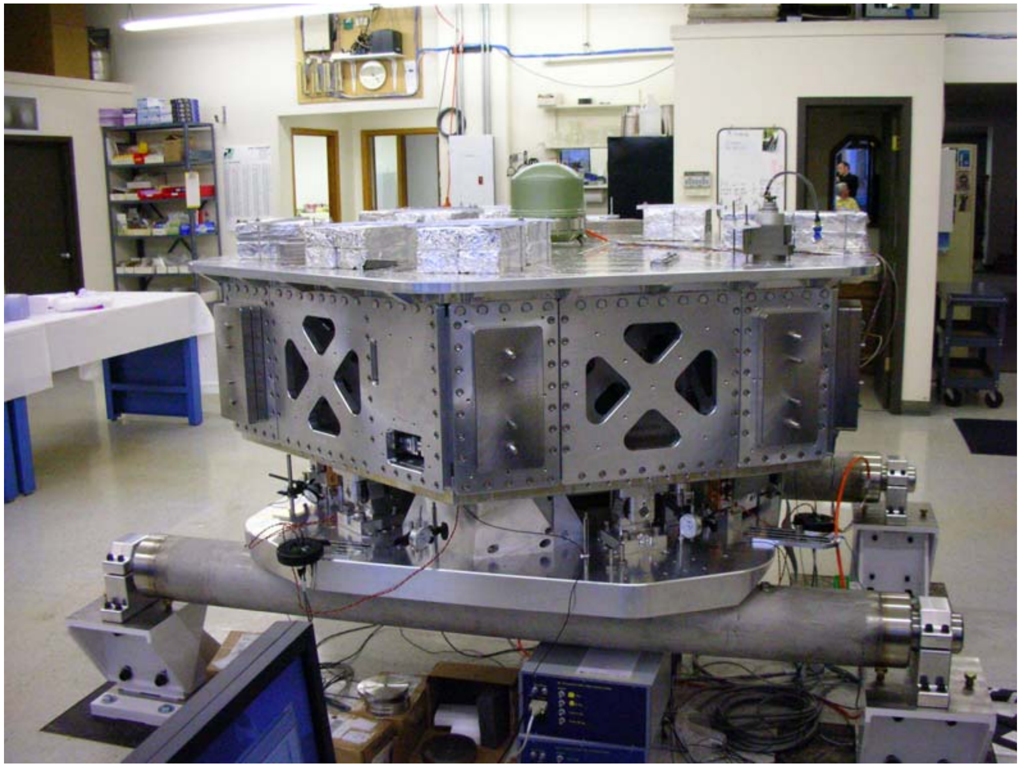
- 35 W Laser
  - » 3.5x increase in power
  - » The “front-end” of the AdL laser
  - » Supplied by LZH/AEI as part of Adv. LIGO
- High Power Input Optics
  - » AdL electroptic Modulators (UF)
  - » AdL Faraday Isolators (UF & IAP, Russia)
- AS detection in vacuum
  - » AdL active seismic system in HAM6
  - » Output mode cleaner
  - » In-vacuum AdL photodetectors
- DC Readout of GW Strain
  - » AdL readout scheme (DC instead of RF)
  - » AdL Output Mode Cleaner cavity
- Thermal Compensation
  - » Upgraded power & beam shaping

Noise and the enhanced detector



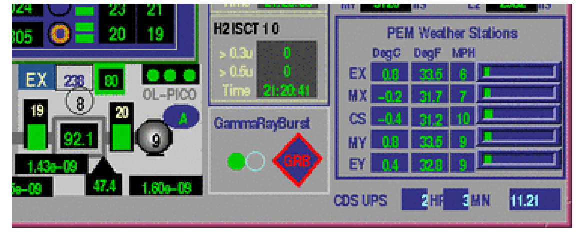
Active seismic isolation

- Two active seismic isolation systems on outputs of 4km interferometers (L1, H1)
- Six onboard GS-13 seismometers and six position sensors measure velocity and position
- Feedback to six coil actuators



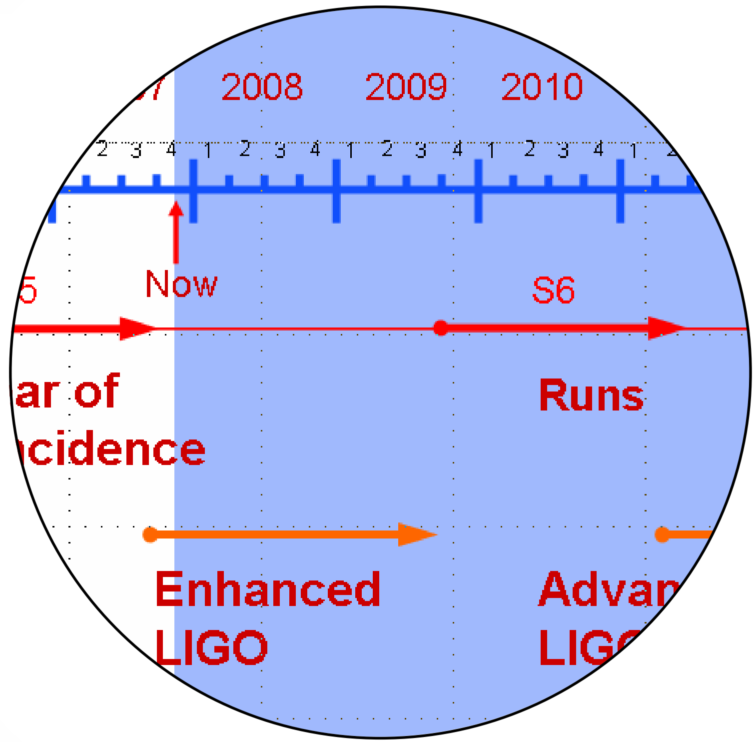
Testing at HPD, Boulder, last week.

Astrowatch



- Galactic supernova rate ~ 1/50 years
- GRBs routinely observed by IPN et al.
- Resonant mass detectors off during SN1987A
- LIGO and Virgo down for enhancements in 2008 : potential to miss interesting triggers
- Astrowatch! H2-G1 coincidence, manned by graduate students

Recall timeline:

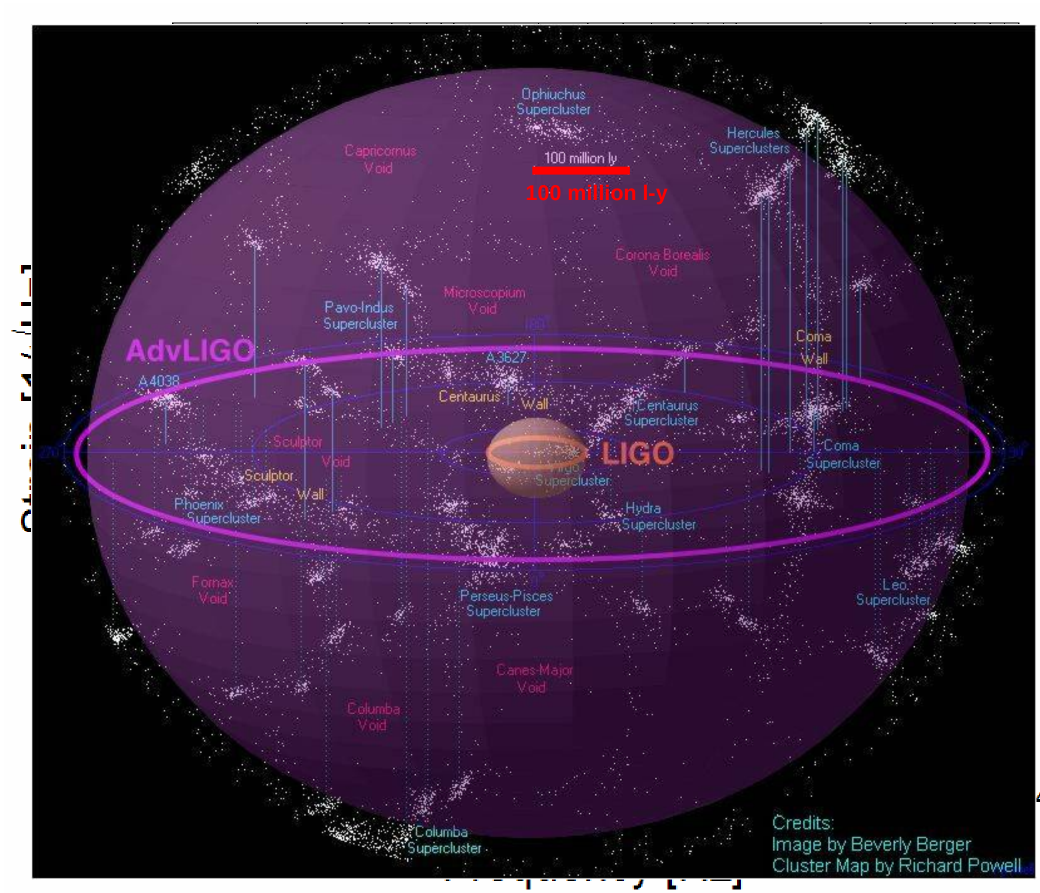


LHO 2km

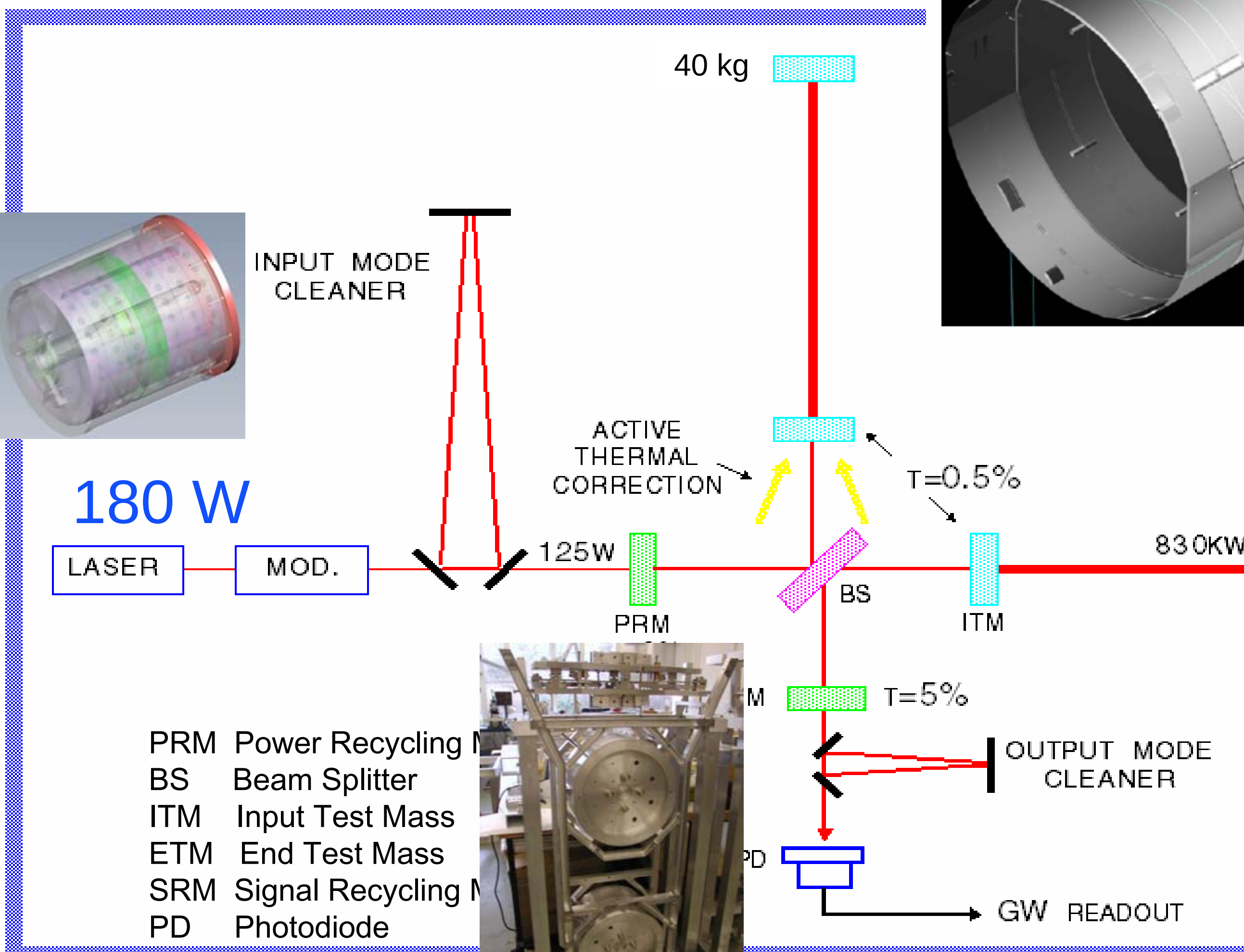
GEO600

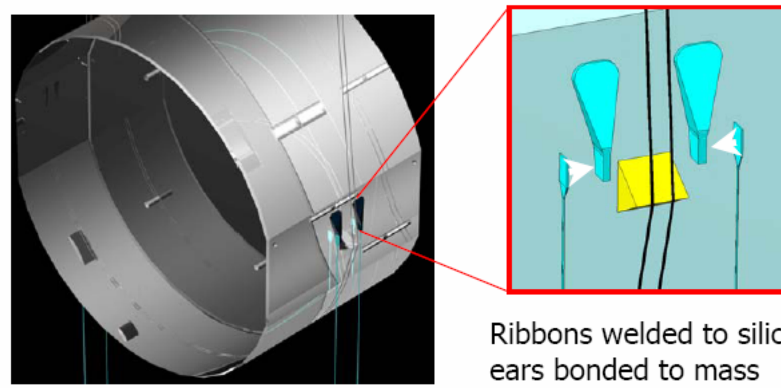
LIGO: The Next Generation

- LIGO is currently detection rate-limited at 0.01 events per year for NS/NS inspirals
- Advanced LIGO will increase sensitivity (hence rate) over initial LIGO
  - » range *r* ~ *1/h*
  - » Event rate ~ r^3
- Most probable NS/NS event rate in Advanced LIGO is 40/yr
- Anticipate funding to start in early 2008, construction to begin in 2011



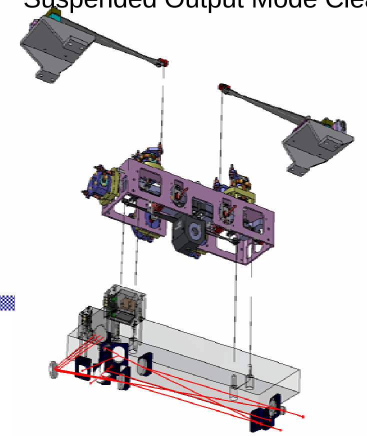
Advanced LIGO





Ribbons welded to silica ears bonded to mass

Suspended Output Mode Cleaner



Status of Advanced LIGO

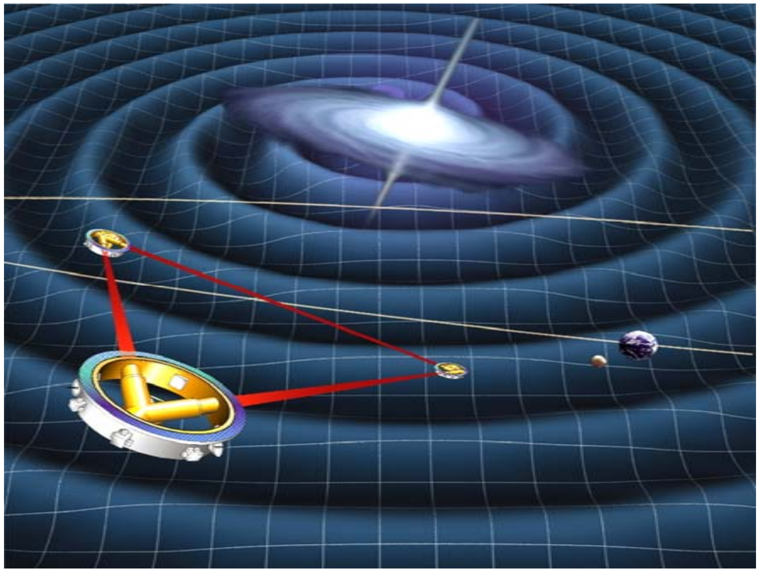
- Baseline Review in June 2006, plus follow-on reviews in June 2007 and November 2008…project ready

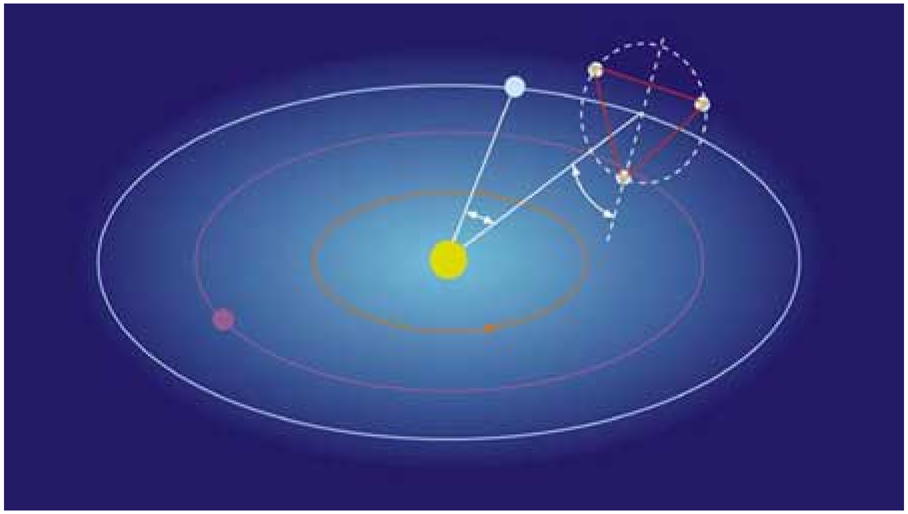
- Construction start awaits the conclusion of the budget process for FY08 in Washington….
  - » If funding starts as expected …
    - – Breach vacuum in 2010 (termination of the S6 eLIGO observational run)
    - – Start commissioning 1st interferometer for Advanced LIGO in 2013

LISA

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

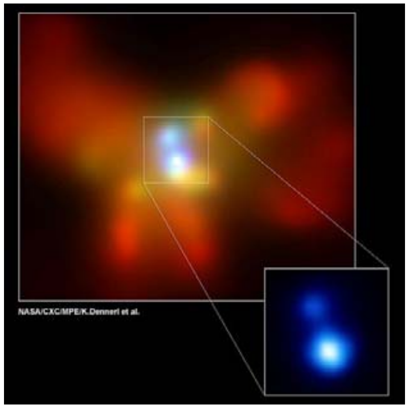
- » A gravitational wave telescope in the frequency band 10^{-5} - 1 Hz
- » All sky monitor
- » 3 drag-free satellites separated by 5×10^{6} km, and trailing the earth by 20 deg
- » Precision 10 pm
- » Redundancy if one spacecraft fails
- » Beam pattern from roll



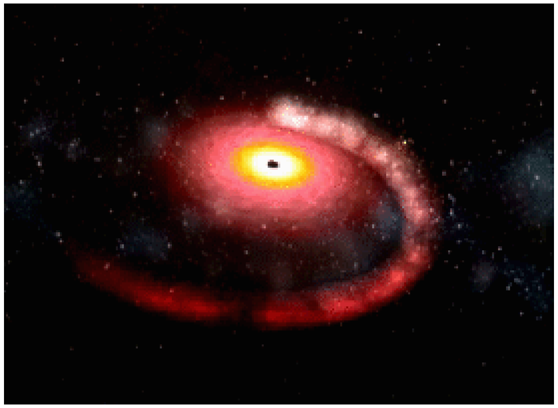


LISA sources

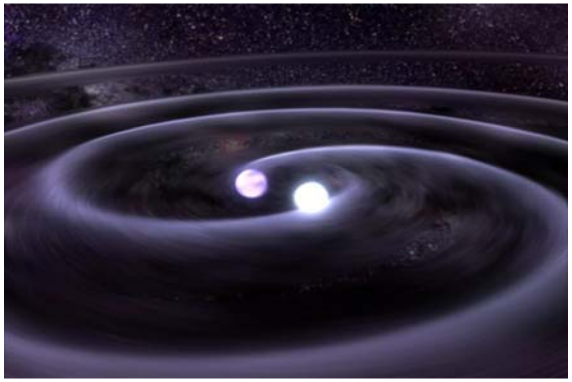
1. **Super-massive Black Hole mergers**



Chandra: NGC6240



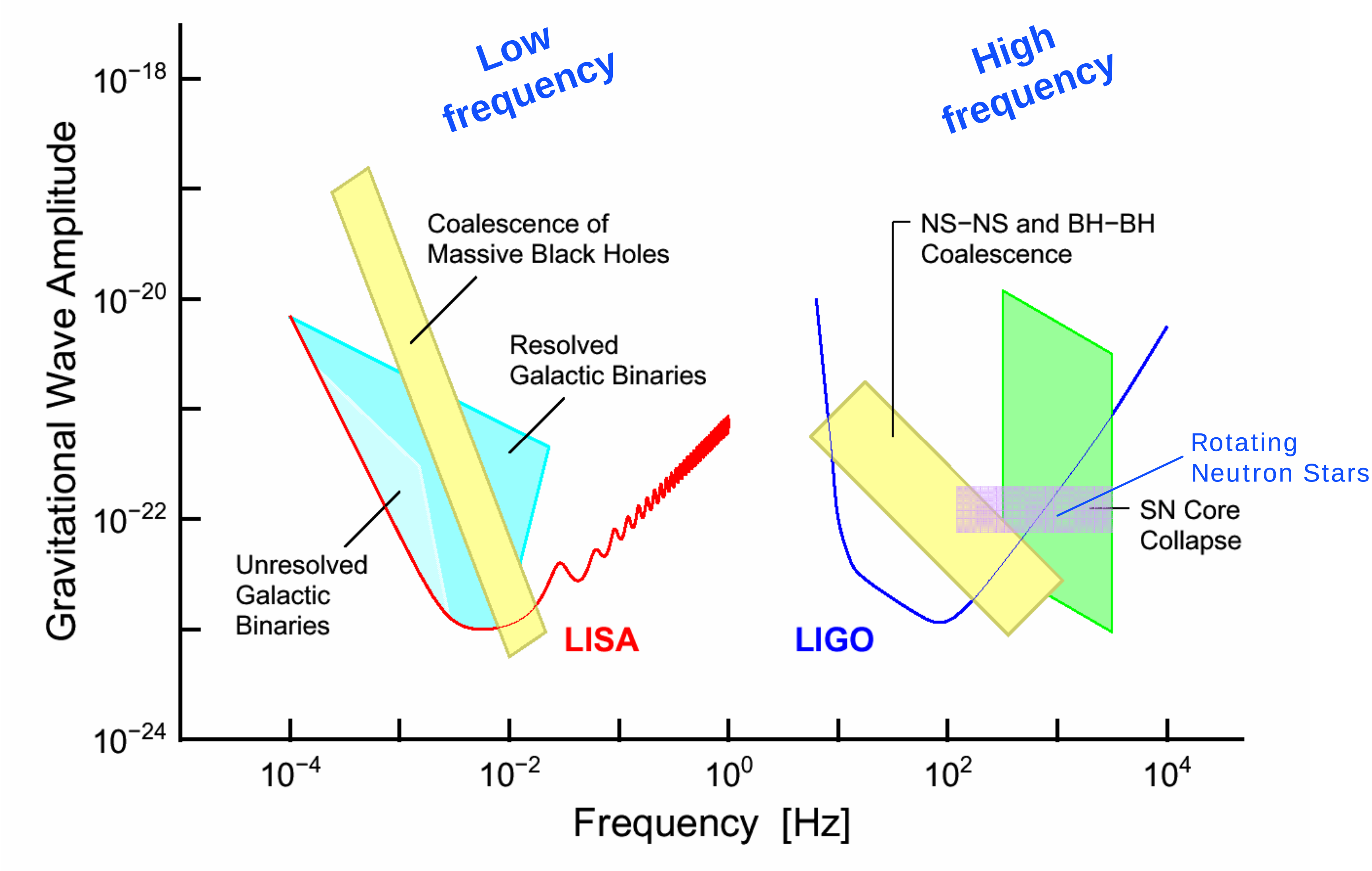
2. **Extreme mass ratio Inpirals (EMRIs)**



3. **Galactic Binaries**

Credit: Tod Strohmayer (GSFC)

Gravitational wave spectrum



BEPAC

Beyond Einstein Program Assessment Committee (BEPAC) was asked by NASA and DOE to:
Assess the five proposed Beyond Einstein missions and recommend which of these five should be developed and launched first, using a funding wedge that is expected to begin in FY2009.

"LISA is an extraordinarily original and technically bold mission concept. LISA will open up an entirely new way of observing the universe, with immense potential to enlarge our understanding of physics and astronomy in unforeseen ways. LISA, in the committee's view, should be the flagship mission of a long-term program addressing Beyond Einstein goals."

"On purely scientific grounds LISA is the (Beyond Einstein) mission that is most promising and least scientifically risky. Even with pessimistic assumptions about event rates, it should provide unambiguous and clean tests of the theory of general relativity in the strong field dynamical regime and be able to make detailed maps of space time near black holes. Thus, the committee gave LISA its highest scientific ranking."

Summary

- Initial LIGO
  - » All interferometers at design sensitivity
  - » S5 run, one year of triple-coincidence, complete and under analysis
  - » Preliminary null results astrophysically interesting
- Enhanced LIGO
  - » Short-term gain of X2 in sensitivity, plus, retire Advanced LIGO risk
  - » While commissioning: Astrowatch with LHO 2km and GEO600
- Experiments in the coming decade will transition field to observational astronomy
  - » Advanced LIGO
  - » LISA

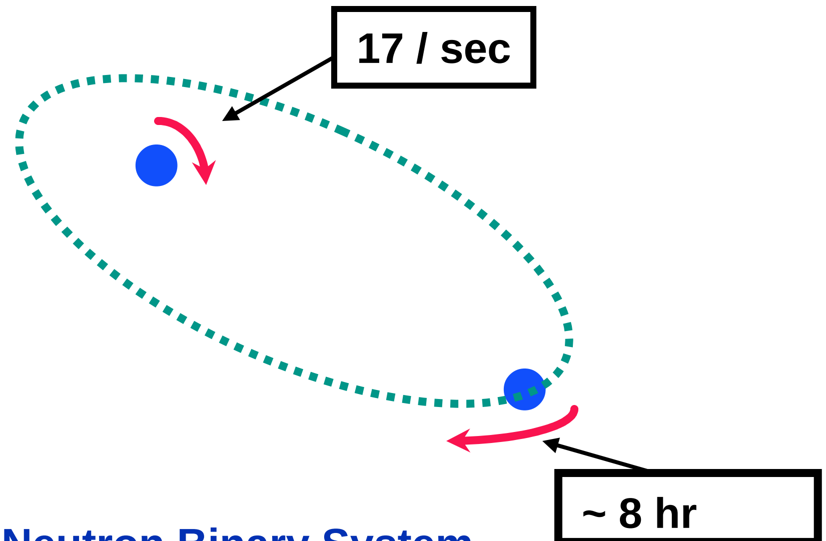
We should be detecting gravitational waves regularly within the next 10 years!

Background material

Orbital decay : strong indirect evidence

Neutron Binary System – Hulse & Taylor

PSR 1913 + 16 -- Timing of pulsars



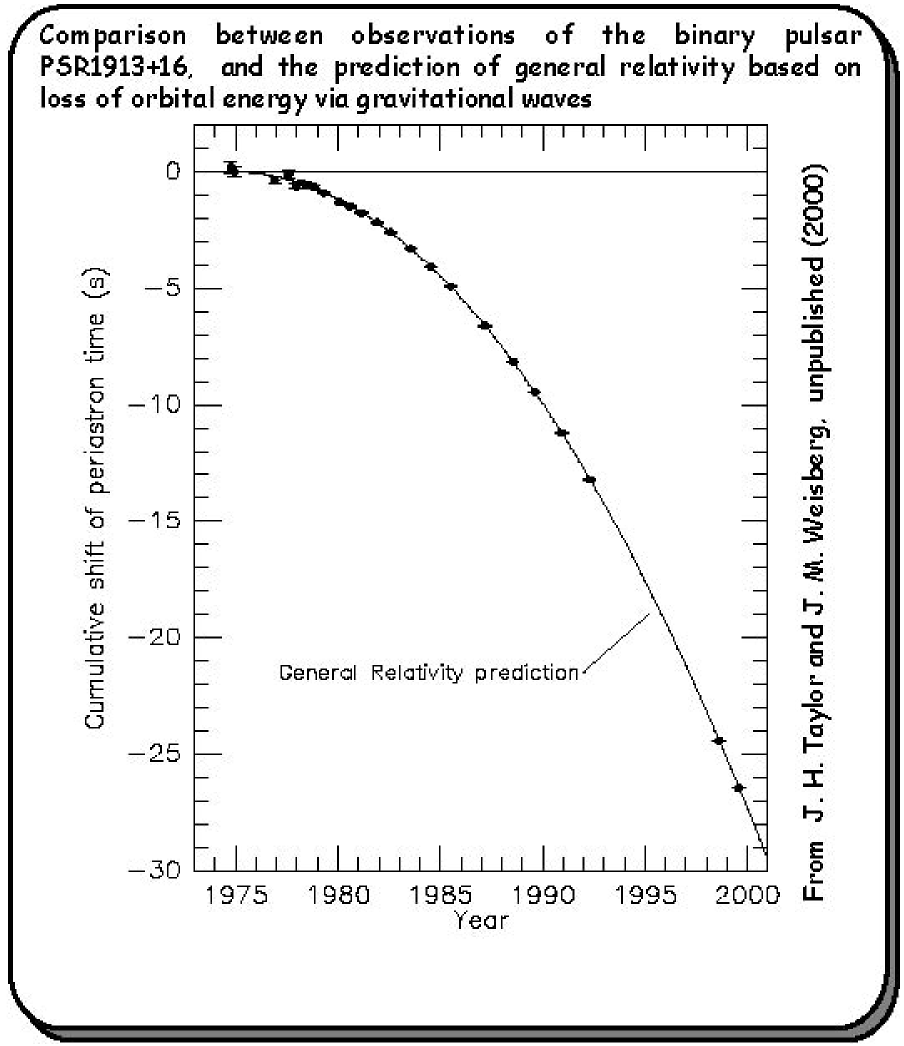
Neutron Binary System

- **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



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strong indirect evidence

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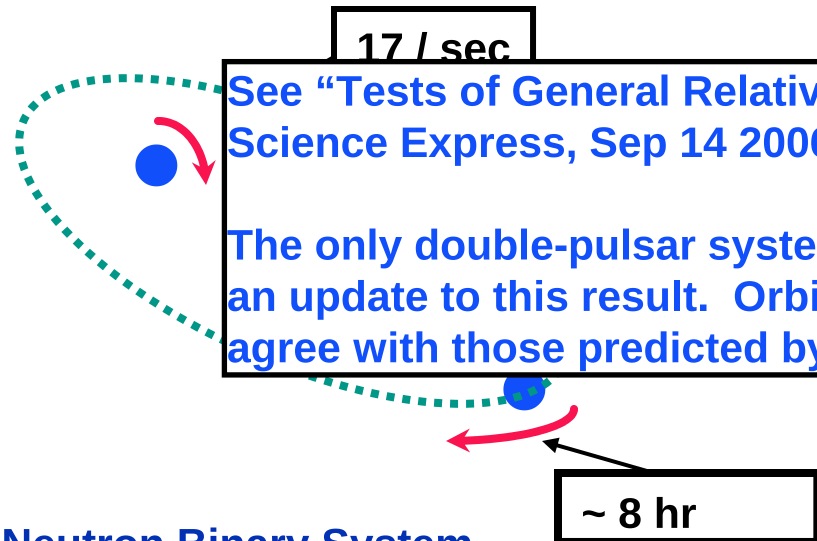

See "Tests of General Relativity from Timing the Double Pulsar"
Science Express, Sep 14 2006

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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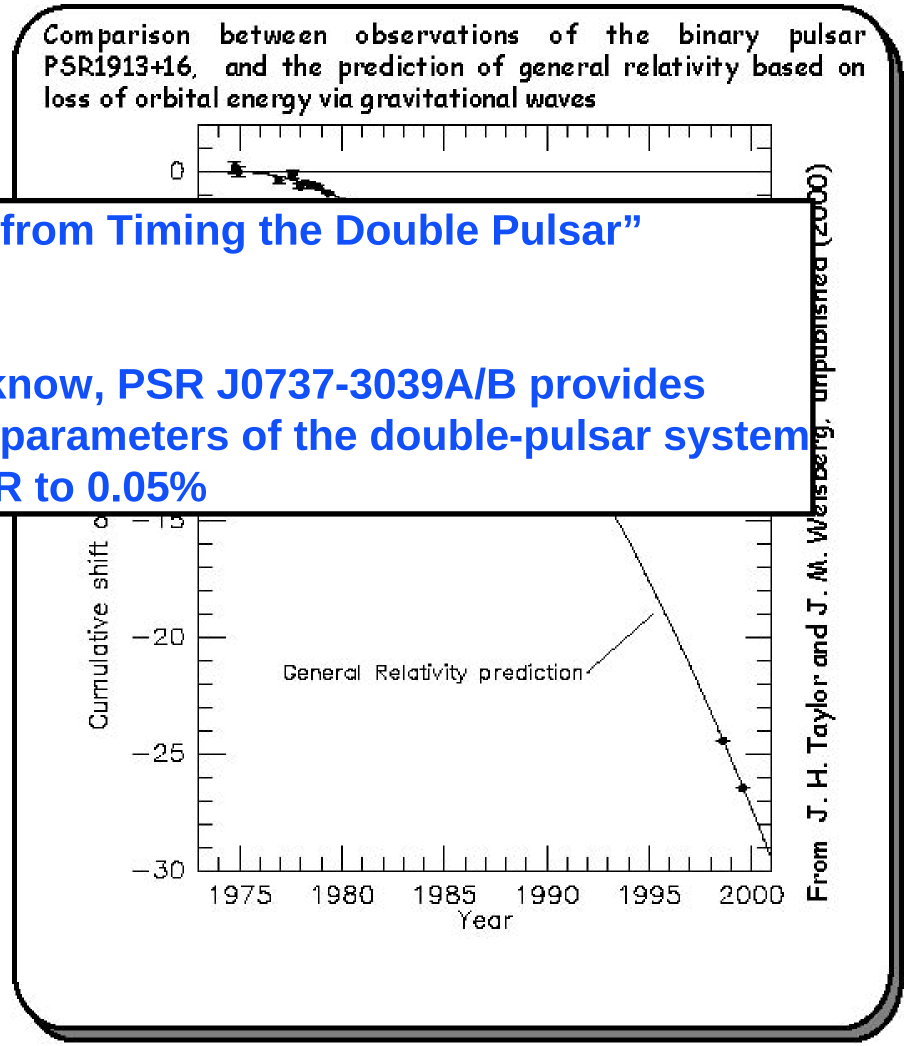
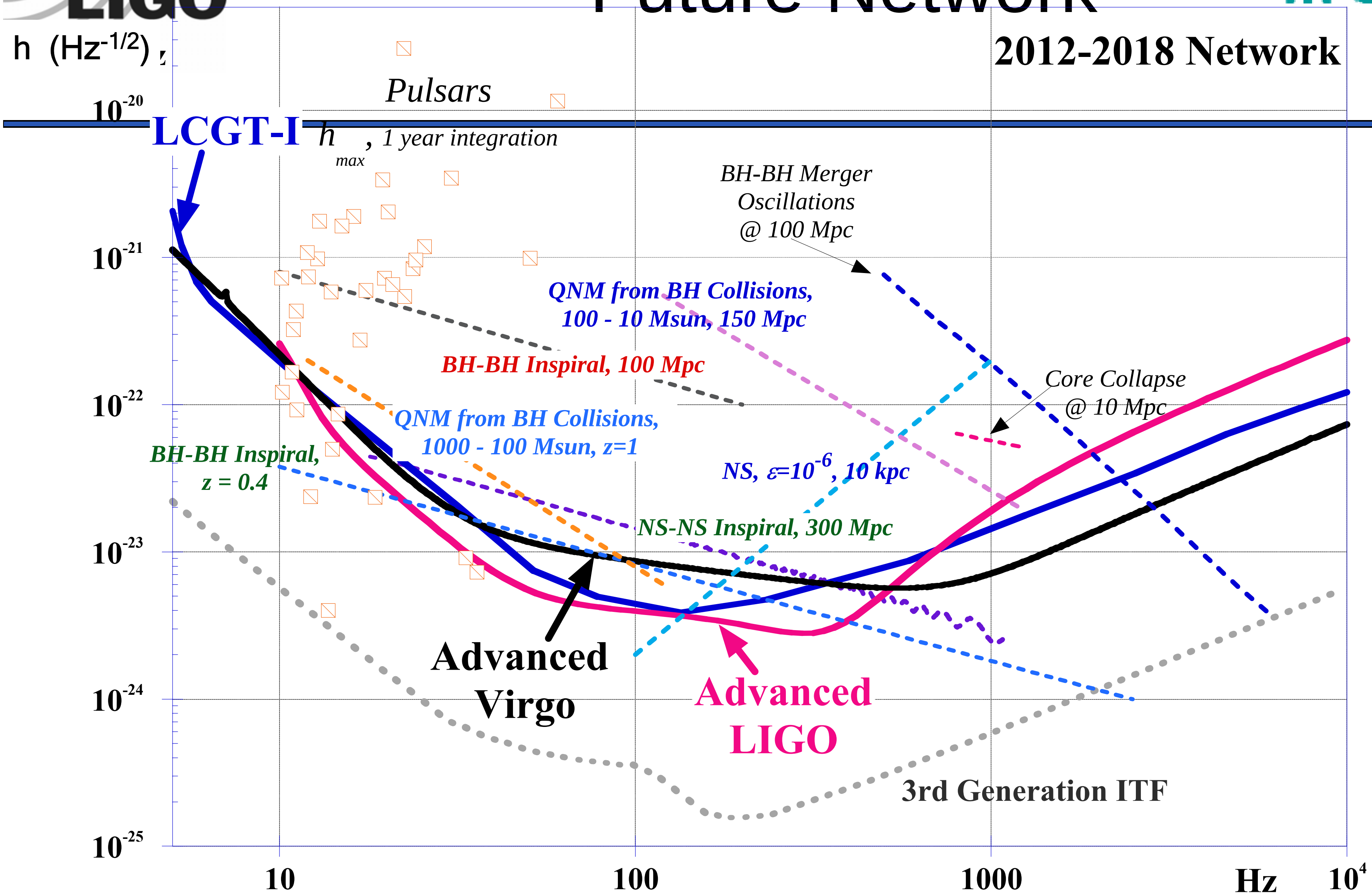


Future Network



P. Rapagnani
Elba, 2006

Advanced LIGO

- MREFC project for $209M ...
  - » Second generation of detectors in LIGO
  - » Factor ~10X in amplitude sensitivity (over S5 Initial LIGO)
  - » Factor ~4X lower frequency 'wall'
- Mostly quantum limited at highest power & midrange frequencies
  - » Recombined Fabry-Perot Michelson
  - » ~20X higher input power
  - » Signal recycling → tunable
- For lower power & lowest frequencies, limited by gravitational gradient,
  thermal noise limits
  - » 40 kg fused silica masses
  - » Fused silica suspension
  - » Aggressive seismic isolation