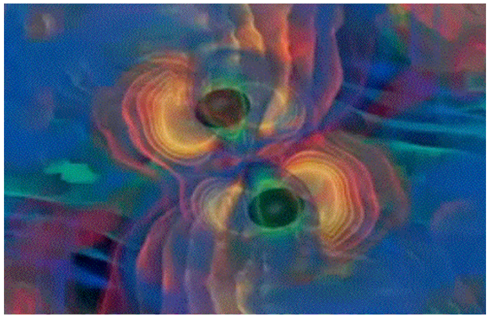


Gravitational Waves: a new window to the Universe

Gabriela González

Physics and Astronomy, Louisiana State University

LIGO Scientific Collaboration

VII Mexican School on Gravitation and Mathematical Physics

Playa del Carmen, Mexico

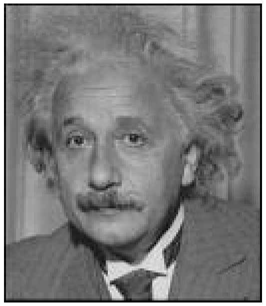
November 27-28, 2006

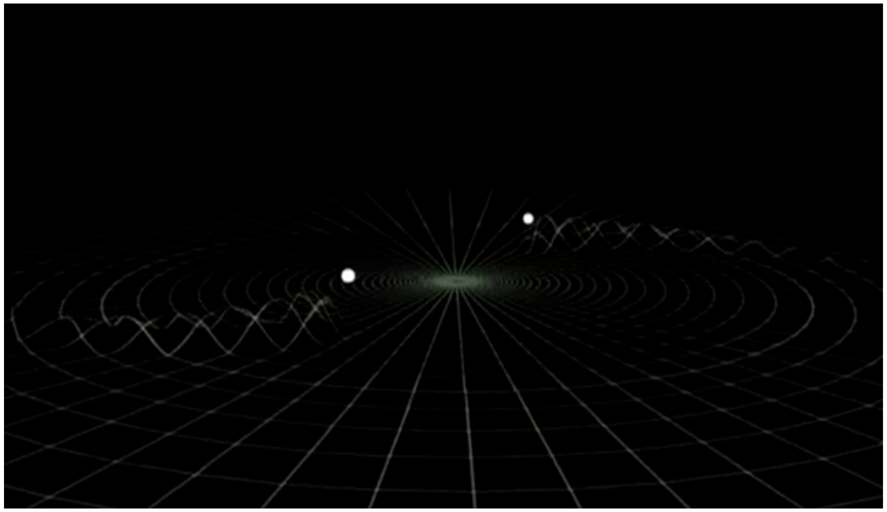
Outline

- Today: **Gravitational wave detectors**
  - Gravitational waves: the basics
  - Bars, ground and space interferometers
  - LIGO detectors:
    - Present sensitivity
    - Plans for the future
- Tomorrow: **LIGO data analysis**
  - LIGO science runs
  - Completed results from data analysis:
    - Continuous waves
    - Bursts
    - Stochastic background
    - Binary systems
  - Prospects for the future

Einstein's gravitation

When masses move, they wrinkle the space time fabric, making other masses move…

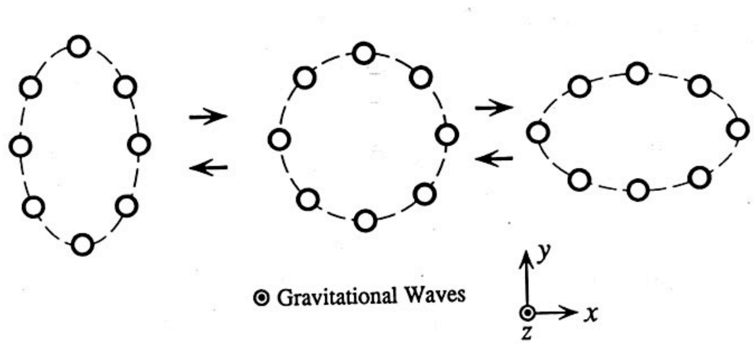




Einstein's messengers,
National Science Foundation video

The theory predicts gravitational waves traveling away from moving masses.

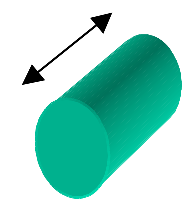
Gravitational waves



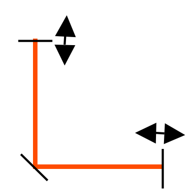
Gravitational waves are quadrupolar distortions of distances between freely falling masses. They are produced by time-varying mass quadrupoles.

Amplitude of GWs produced by binary neutron star systems in the Virgo cluster have $h=\Delta L/L \sim 10^{-21}$ and frequencies sweeping up to ~1400 Hz.

Resonant systems can measure elastic response to distance distortion: resonant bar detectors.



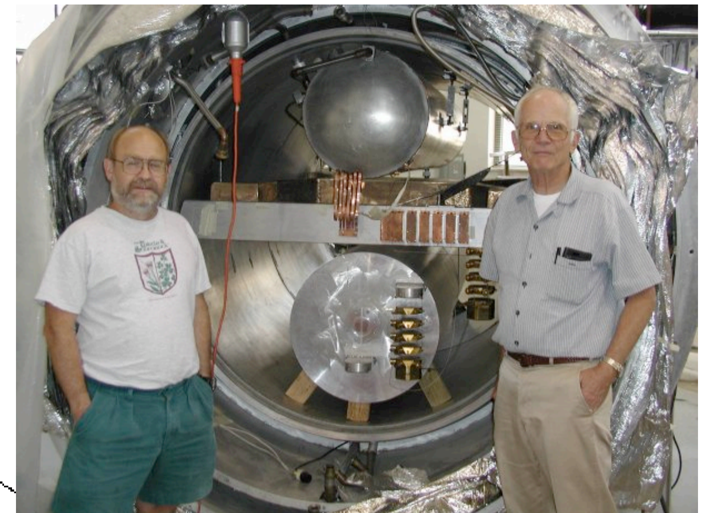
Michelson-type interferometers can detect distance changes in orthogonal directions.



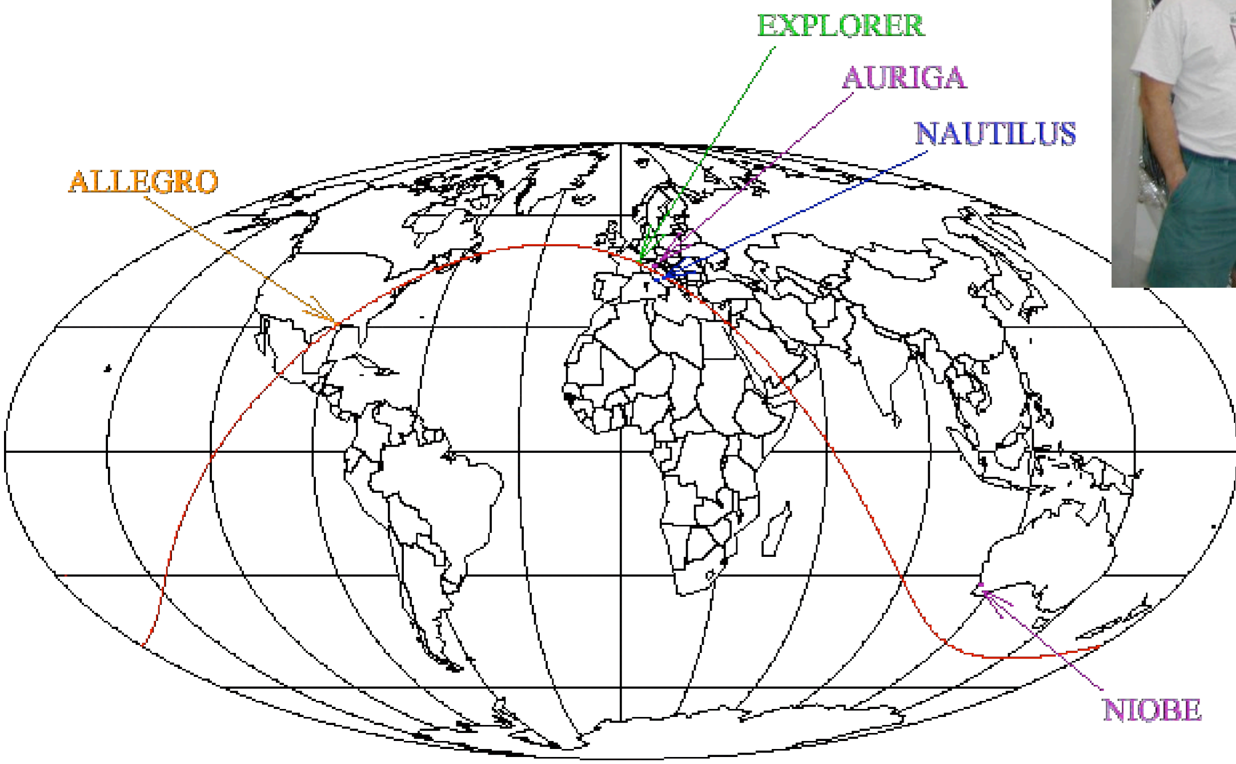
In both cases, what's measured is $\Delta L = hL$

Bar detectors

Warren Johnson, Bill Hamilton (LSU)



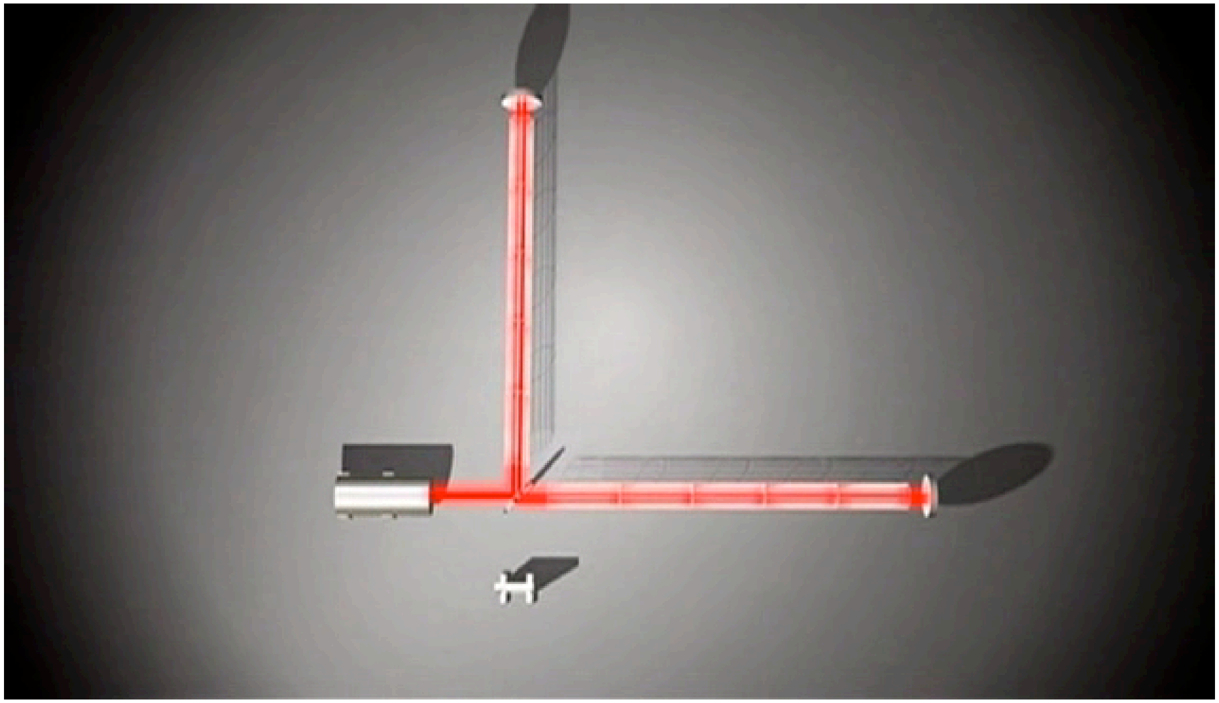
Bar detectors in the world:
International Gravitational-wave Event Collaboration



Joseph Weber (Maryland)

Present sensitivities are $h \sim 10^{-20}$ @ f~1kHz

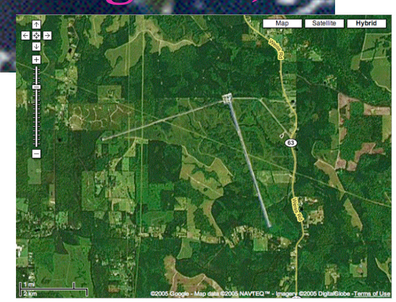
Interferometers



Einstein's messengers,
National Science Foundation video

The LIGO project

$h = \Delta L / L \sim 10^{-21}$ and $L = 4k \Rightarrow \Delta L = hL \sim 10^{-18}$ m !



Hundreds of people working on the experiment and looking at the data: LIGO Scientific Collaboration

LIGO detector in Louisiana

sciencebulletins.amnh.org

We can presently measure $\Delta x \sim 10^{-19}$ m at $f \sim 100$ Hz !!

Ground interferometric gravitational waves detectors

GEO600 (British-German)
Hannover, Germany

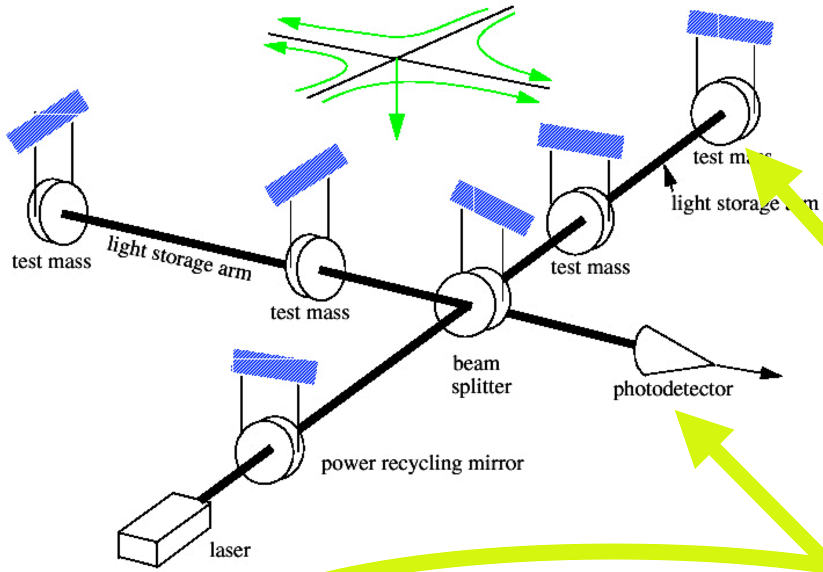
LIGO (USA)
Hanford, WA and Livingston, LA

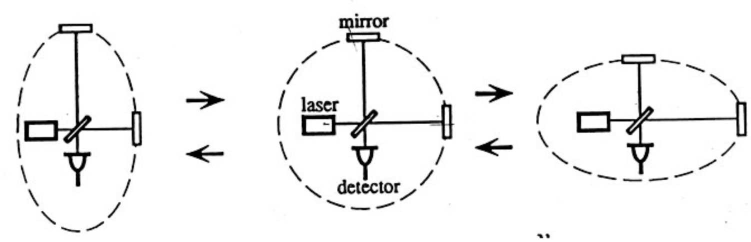
TAMA (Japan)
Mitaka

AIGO (Australia),

VIRGO (French-Italian)
Cascina, Italy

GW LIGO detectors: interferometers



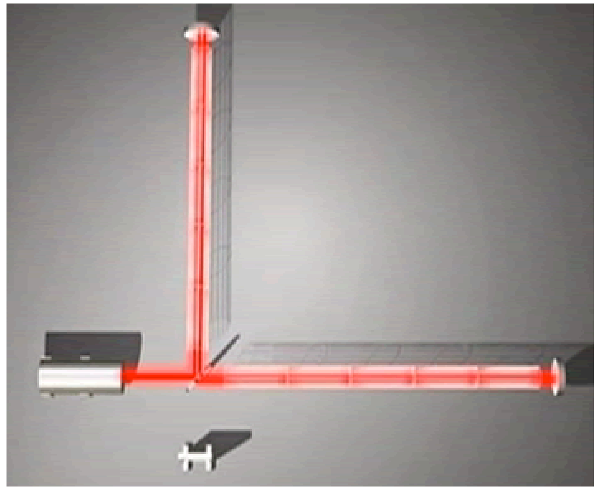


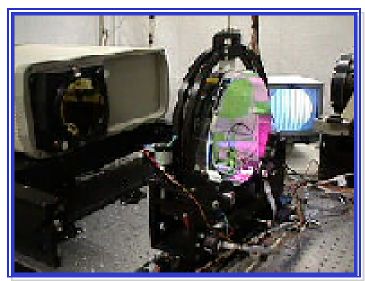
suspended test masses
("freely falling objects")

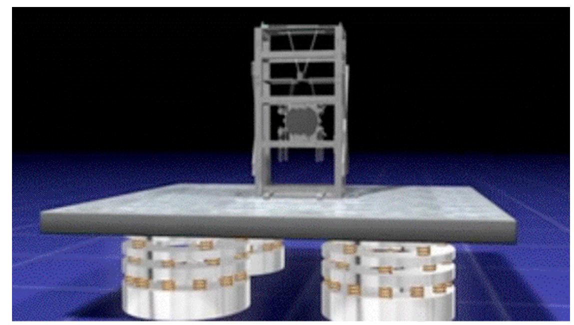
dark port
(RF heterodyne modulation)

Three LIGO detectors: 4km long in Livingston, La (L1); 4km and 2km long in Hanford, WA (H1, H2).

GW Detection: a difficult and fun experiment

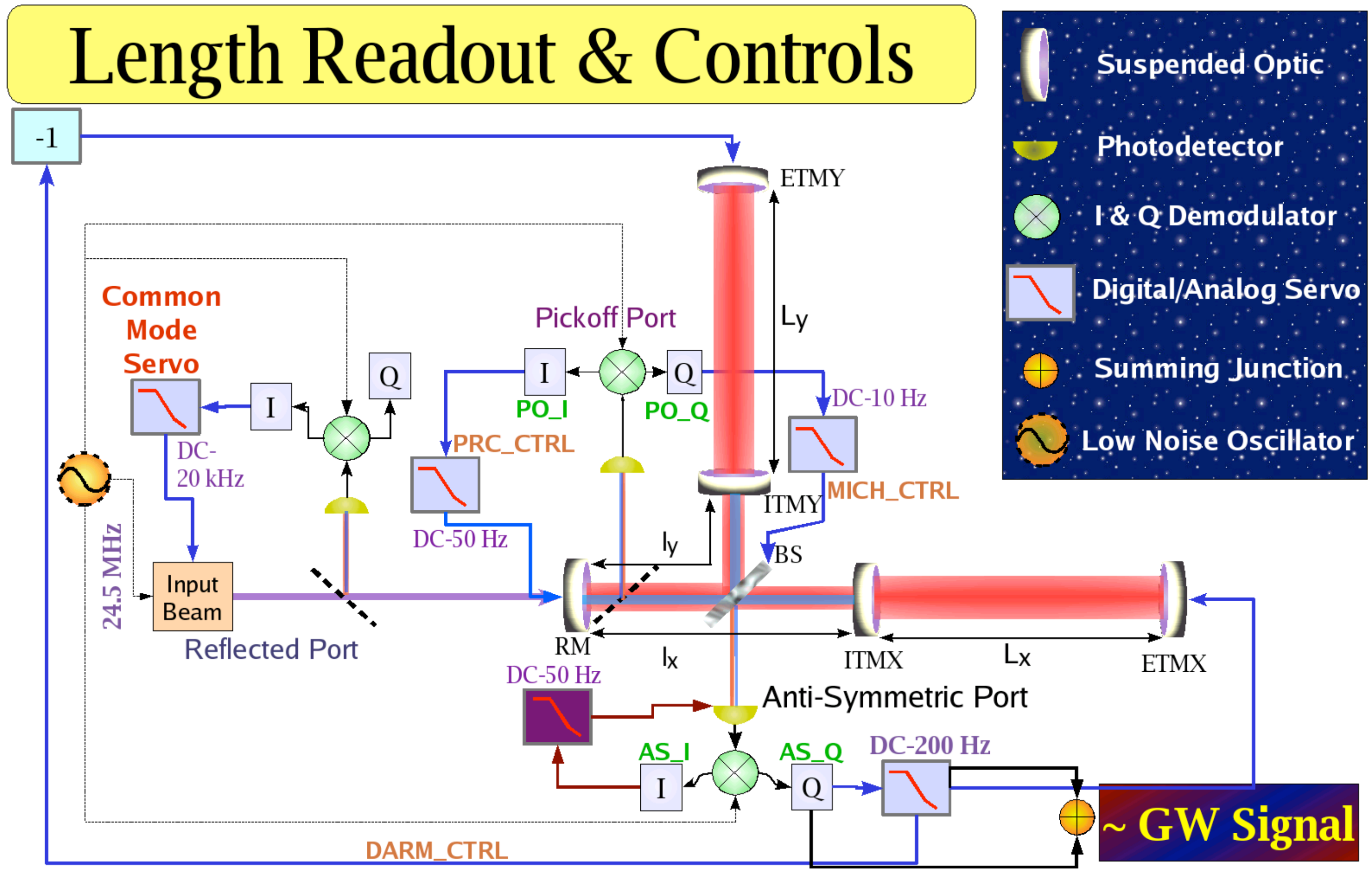




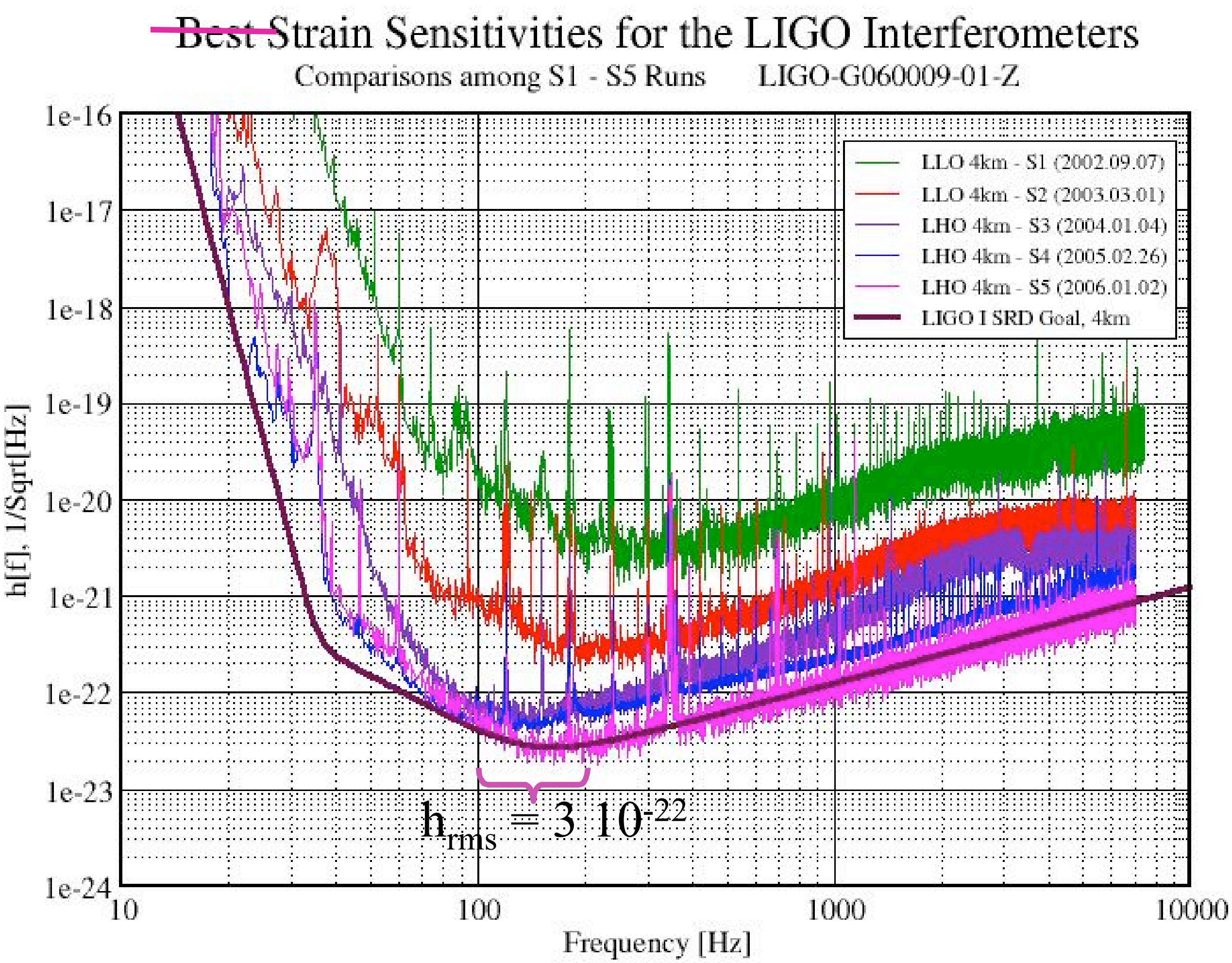


Length Sensing and Control: practice

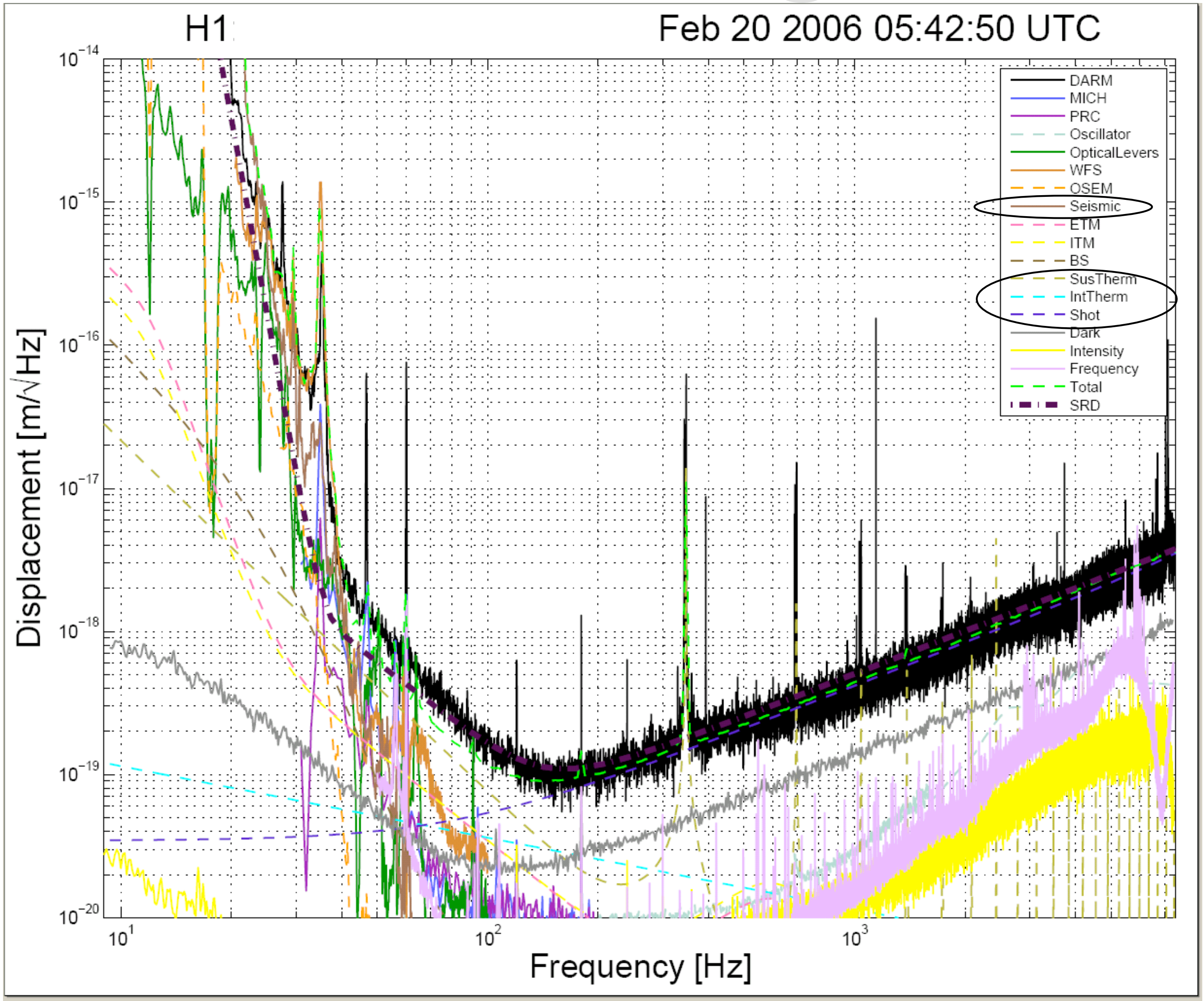
4 loops:
- DARM
- CARM/CM
- MICH
- PRC



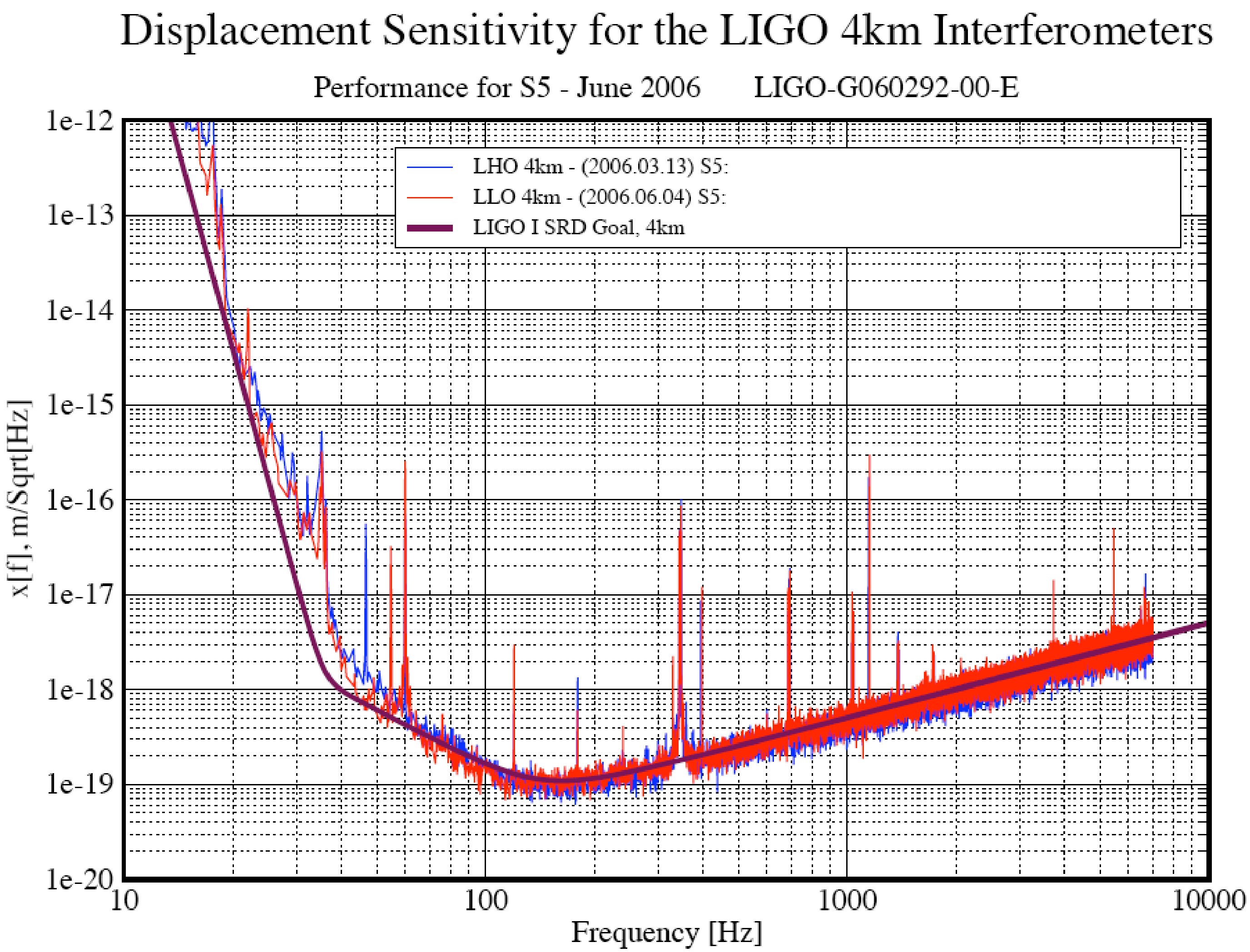
LIGO: Steady progress



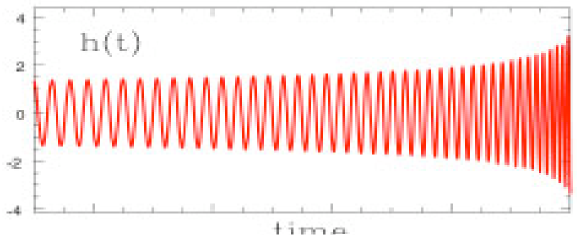
“Noise Budget”

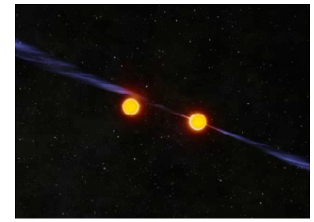


Current sensitivity

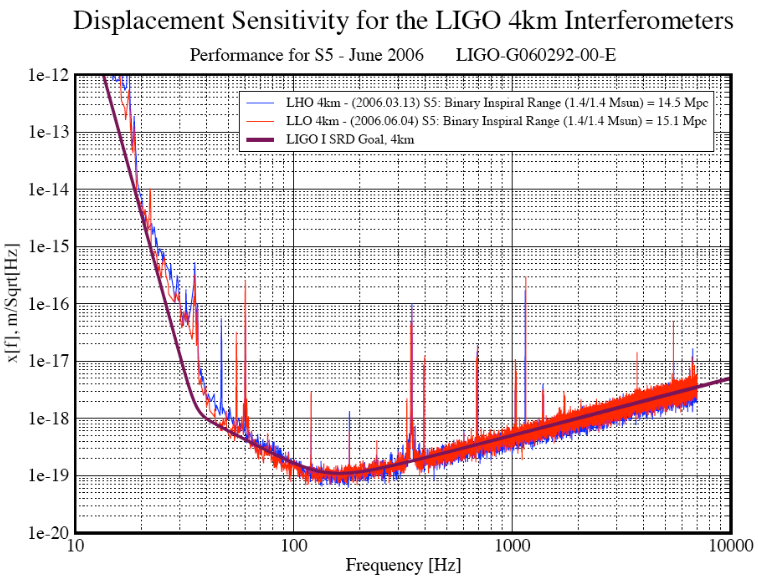


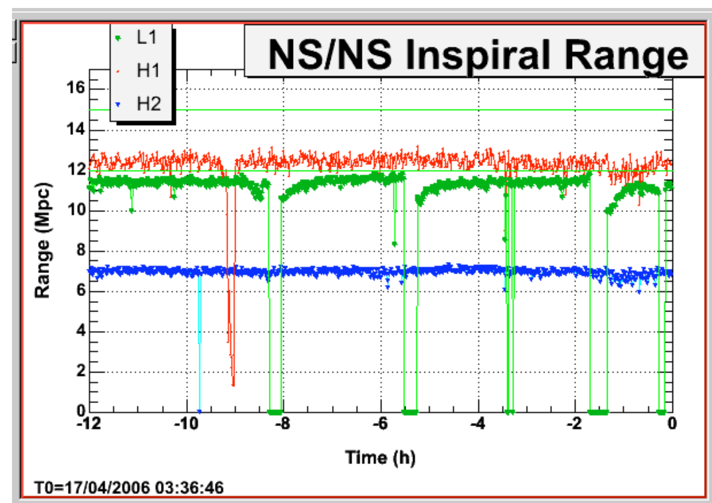
Binary systems: a measure of performance





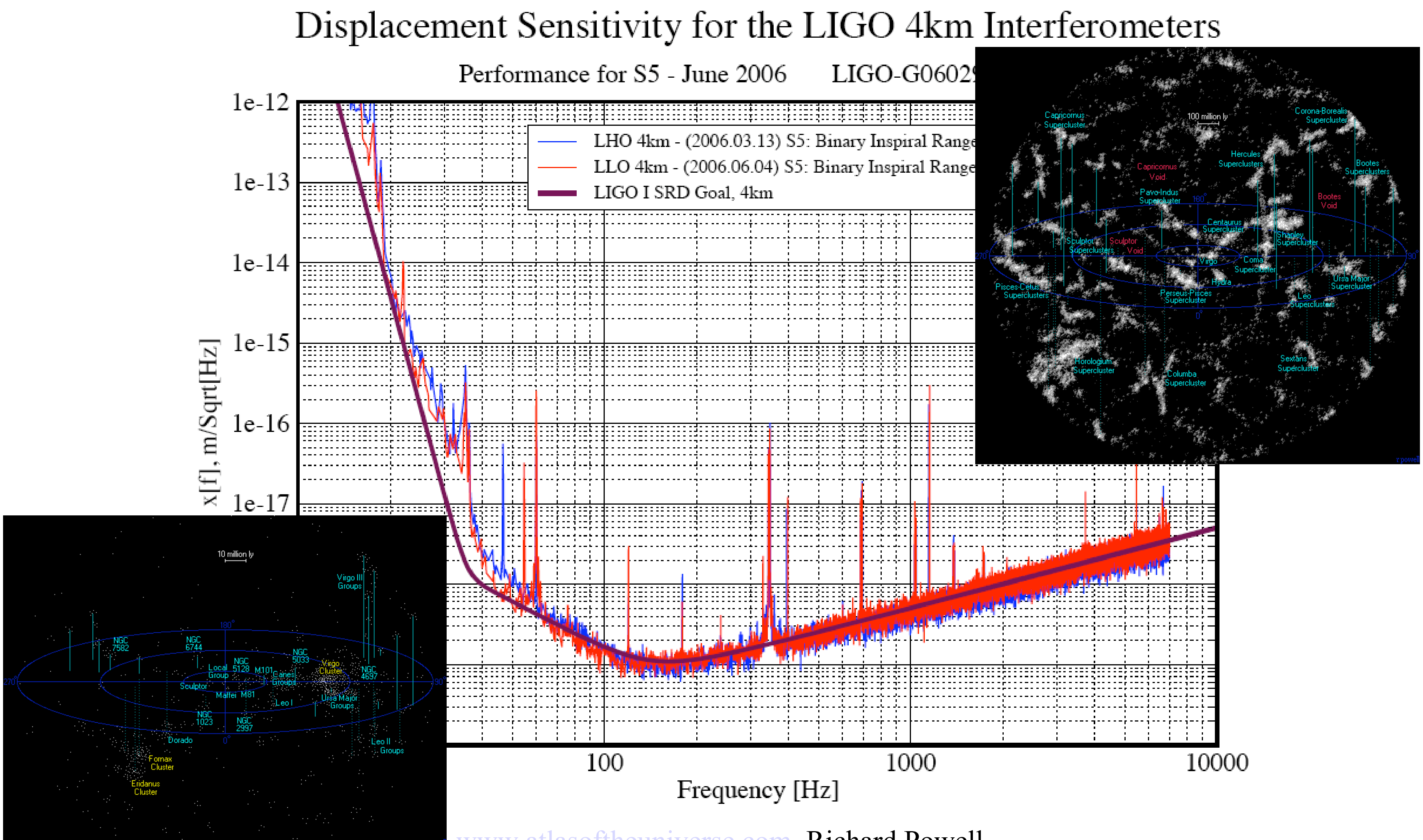
Can translate strain amplitude into (effective) distance





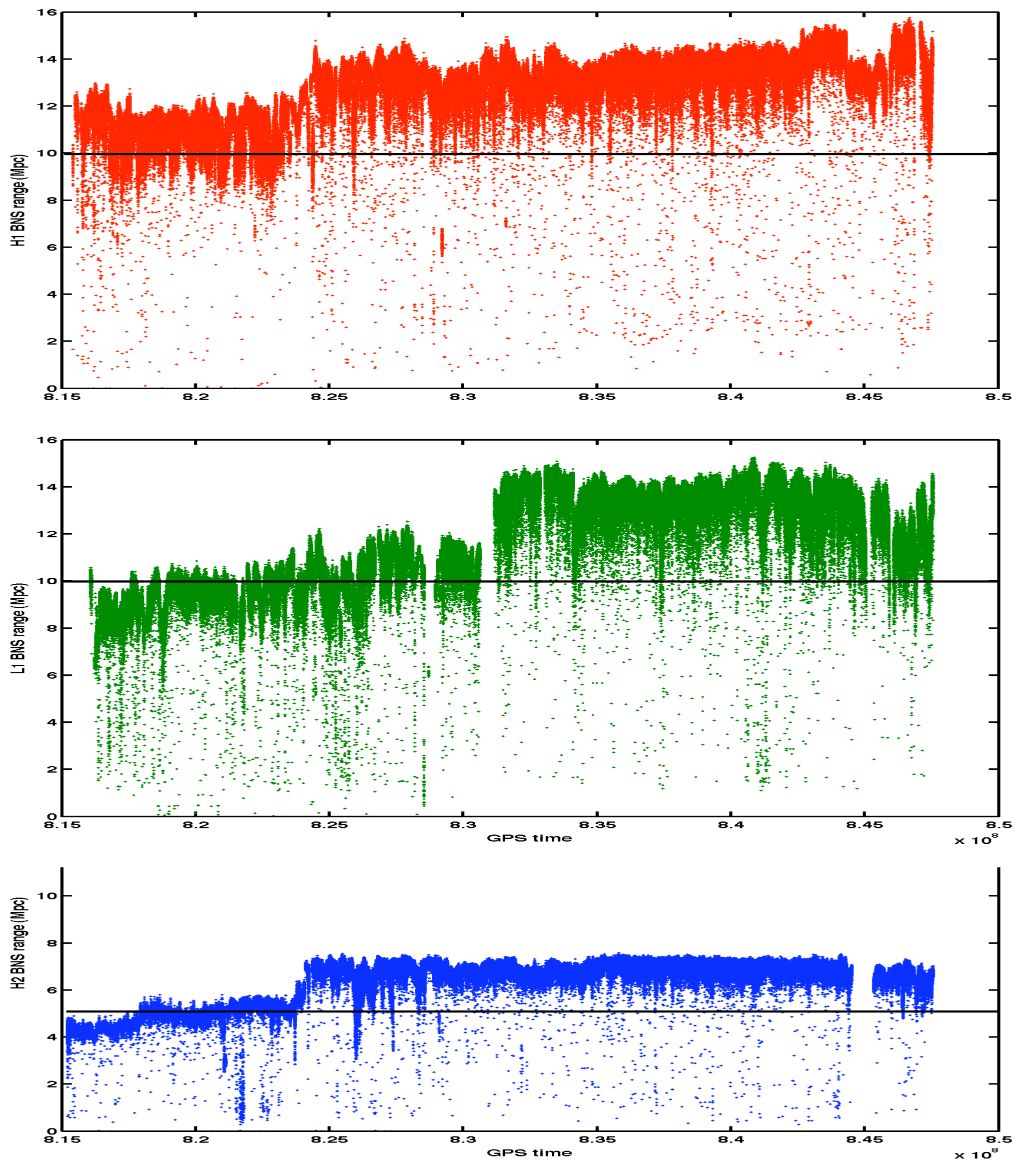
If system is optimally located and oriented, we can see even further: we are surveying <u>hundreds of galaxies</u>!

Current sensitivity



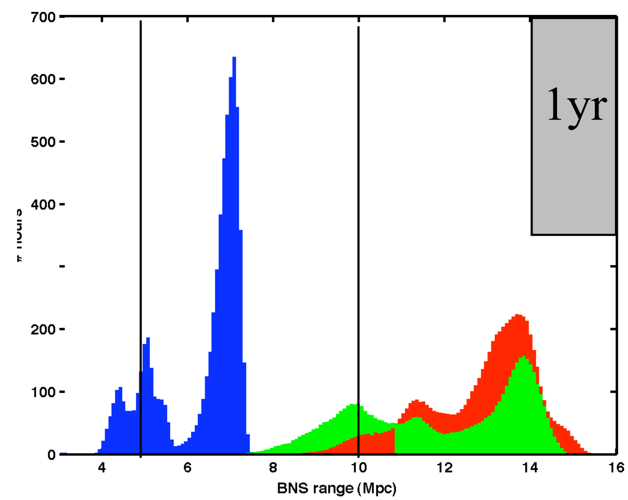
www.atlasoftheuniverse.com, Richard Powell

S5 performance: Nov 4 ‘05 - Nov 14 ‘06



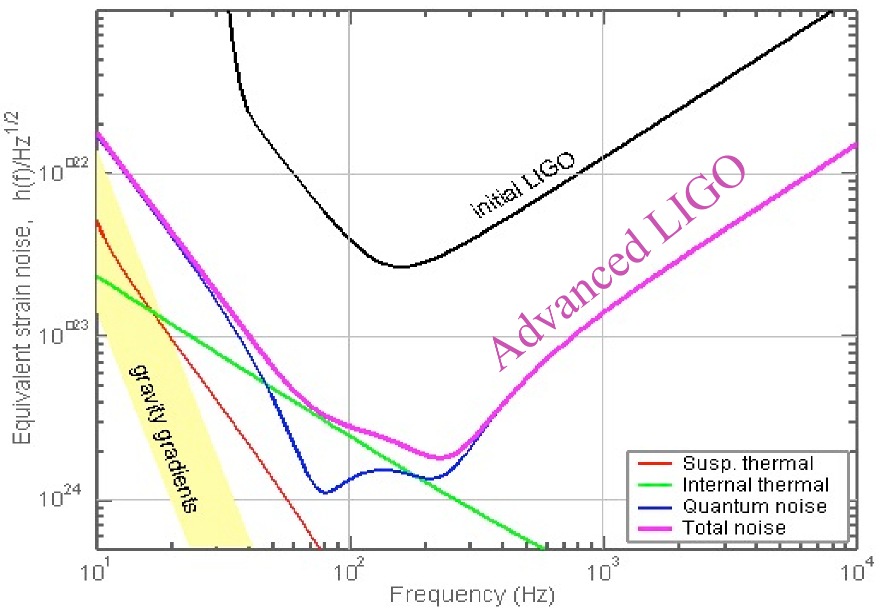
In “science mode”:

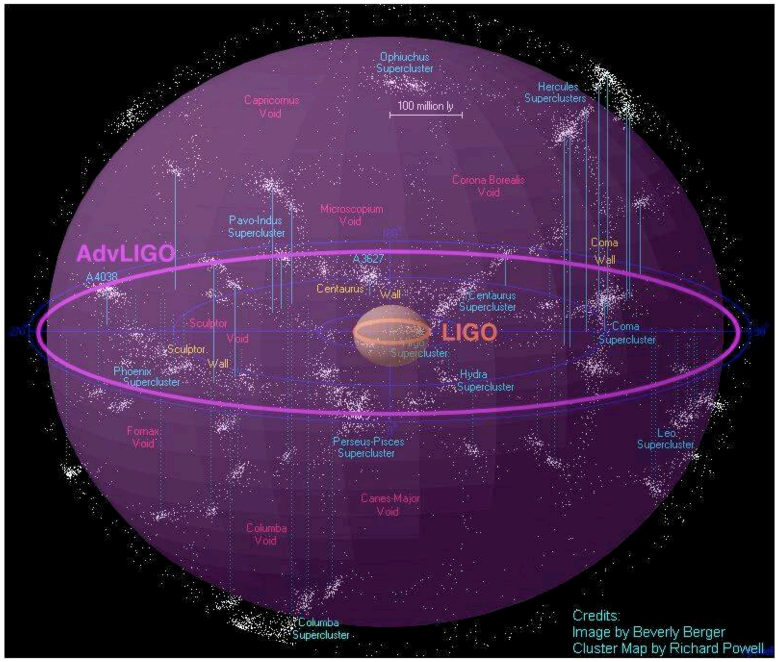
H1: 268 days
L1: 215 days
H2: 283 days
H1/L1: 176 days



LIGO detectors: future

- **Neutron Star Binaries:**
  Initial LIGO: ~10-20 Mpc →
  Advanced LIGO: ~200-350 Mpc
  Most likely rate: 1 every 2 days !
- **Black hole Binaries:**
  Up to 30 M_o, at ~ 100 Mpc
  → up to 50 M_o, in most of the observable Universe!



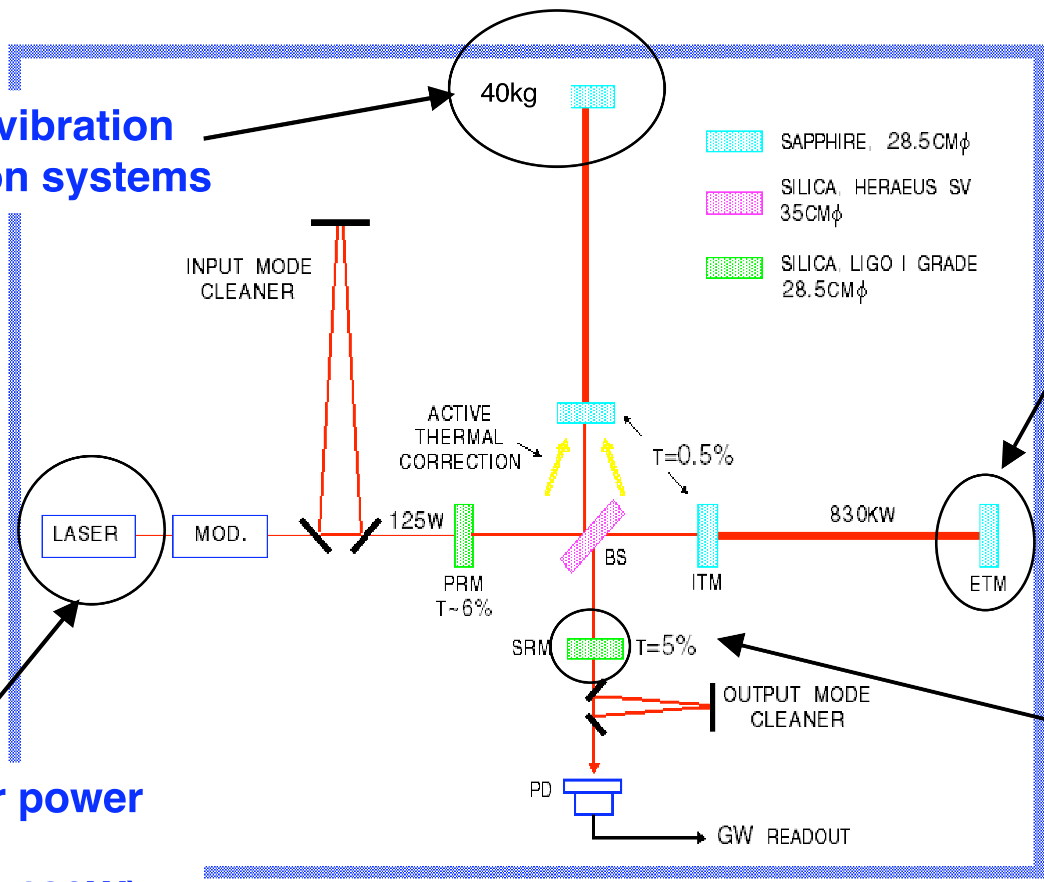


x10 better amplitude sensitivity
⇒ x1000 rate=(reach)^3
⇒ 1 year of Initial LIGO
< 1 day of Advanced LIGO !

Planned NSF Funding in FY'08 budget (being decided right now!).

Design Features of Advanced LIGO

Active vibration isolation systems

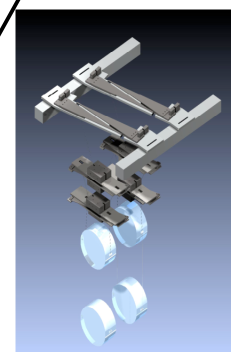


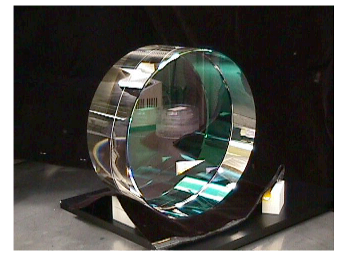
Higher power laser (10W→180W)

Quadruple pendulum

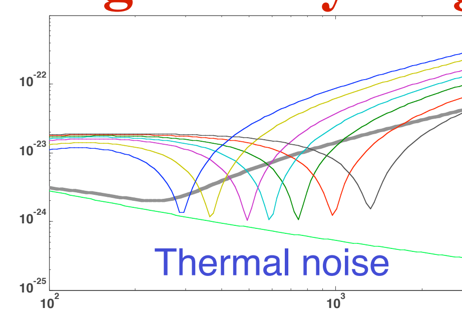
Fused silica optics (40 kg)

Silica suspension fibers





Signal recycling



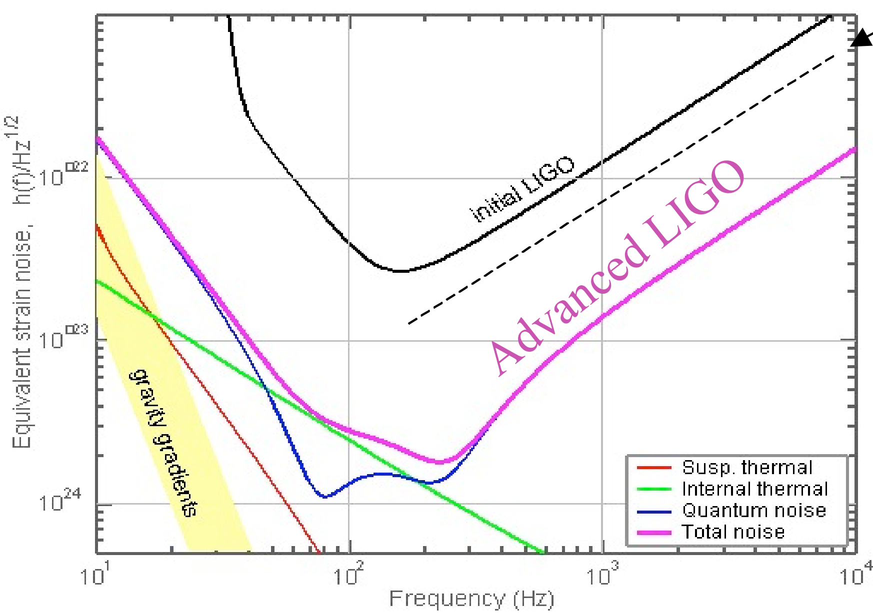
High Frequency narrow-banding

The Next 5-6 Years

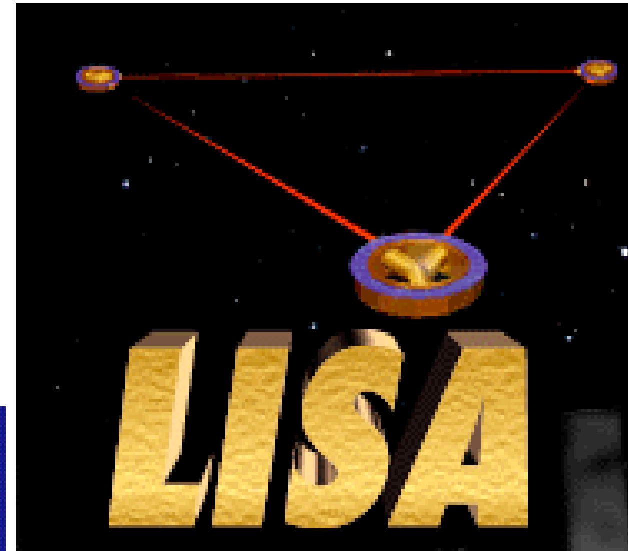
4Q '05 | 4Q '06 | 4Q '07 | 4Q '08 | 4Q '09 | 4Q '10

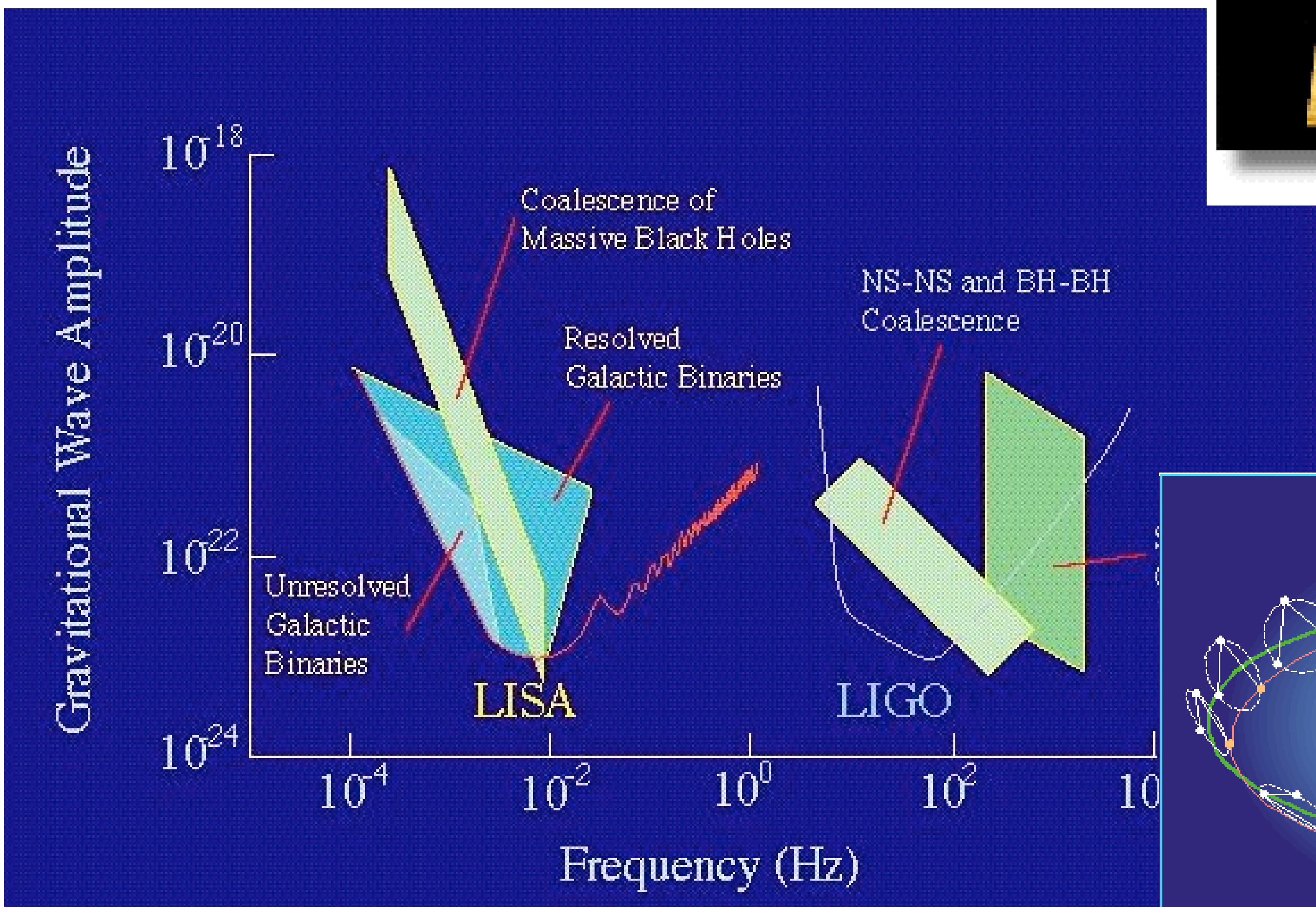
S5 | ***~2 years*** | **S6?** | ***Decomm IFO1***

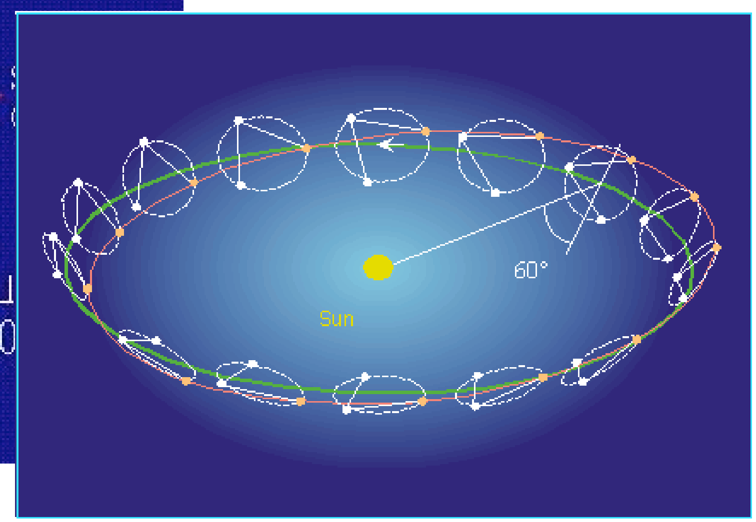
today



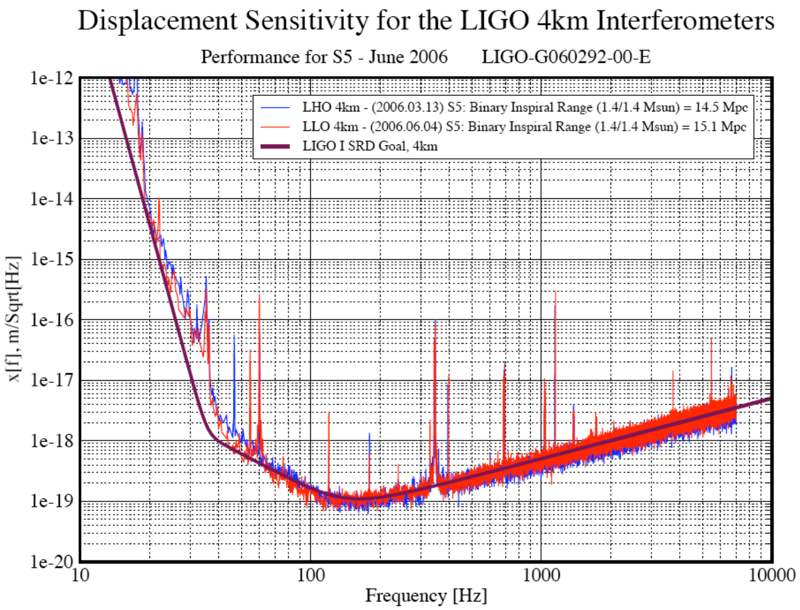
Space interferometer: LISA





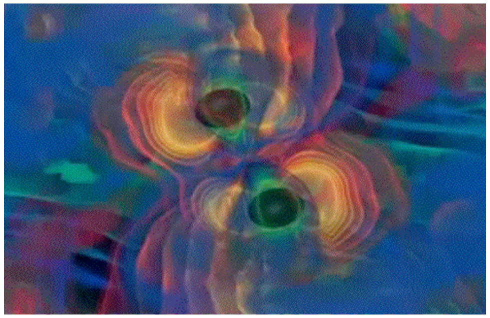


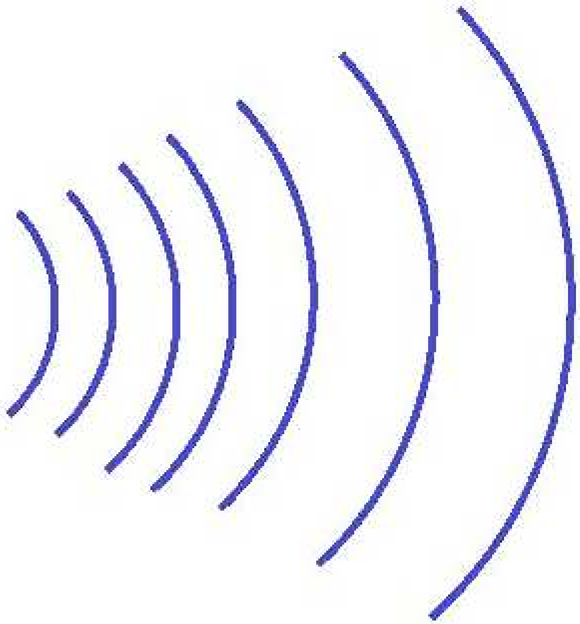
These are exciting times!



- We are taking data at unprecedented sensitivity, and we are searching for gravitational waves.
- We are getting ready for Advanced LIGO.

- We are preparing ourselves for a direct observation of gravitational waves:
  not if, but when!
- LIGO detectors and their siblings will open a new window to the Universe: what's out there?





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    - Stochastic background
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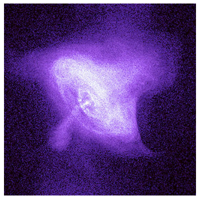
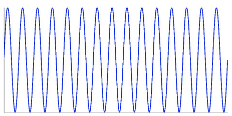
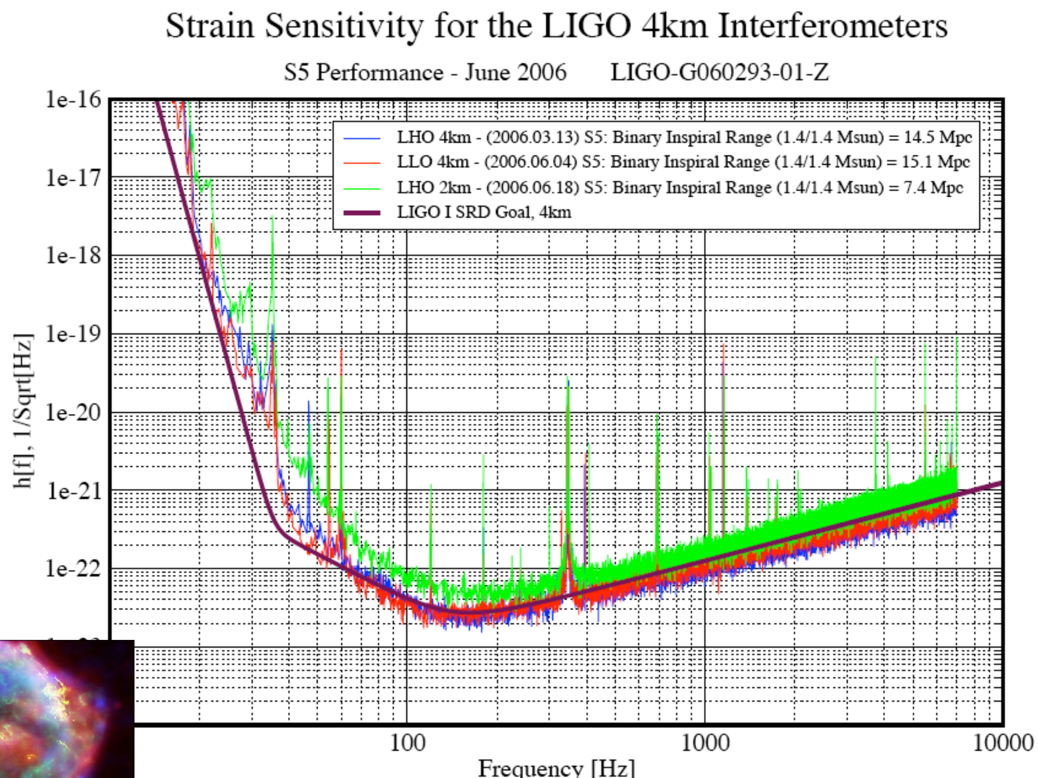
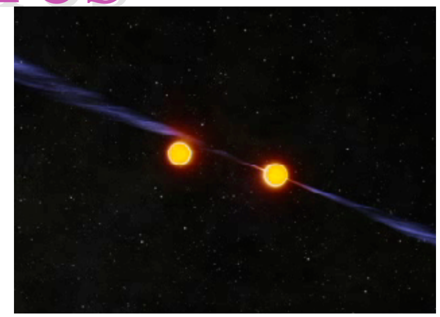
Look for different signatures



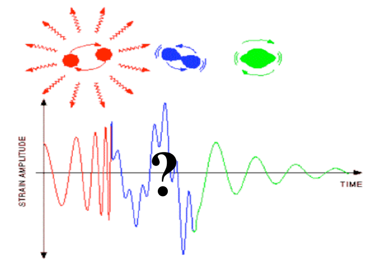
Crab pulsar (NASA, Chandra Observatory)

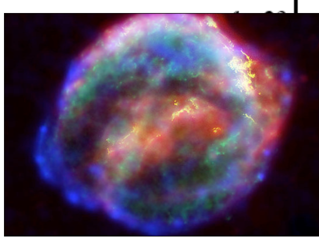




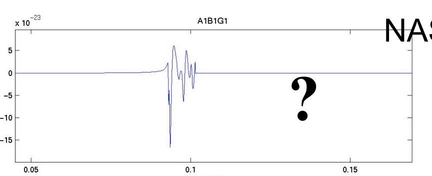


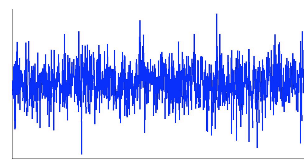
John Rowe, CSIRO

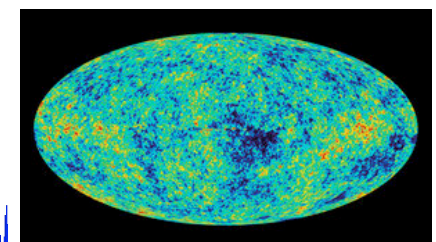




NASA, HEASARC

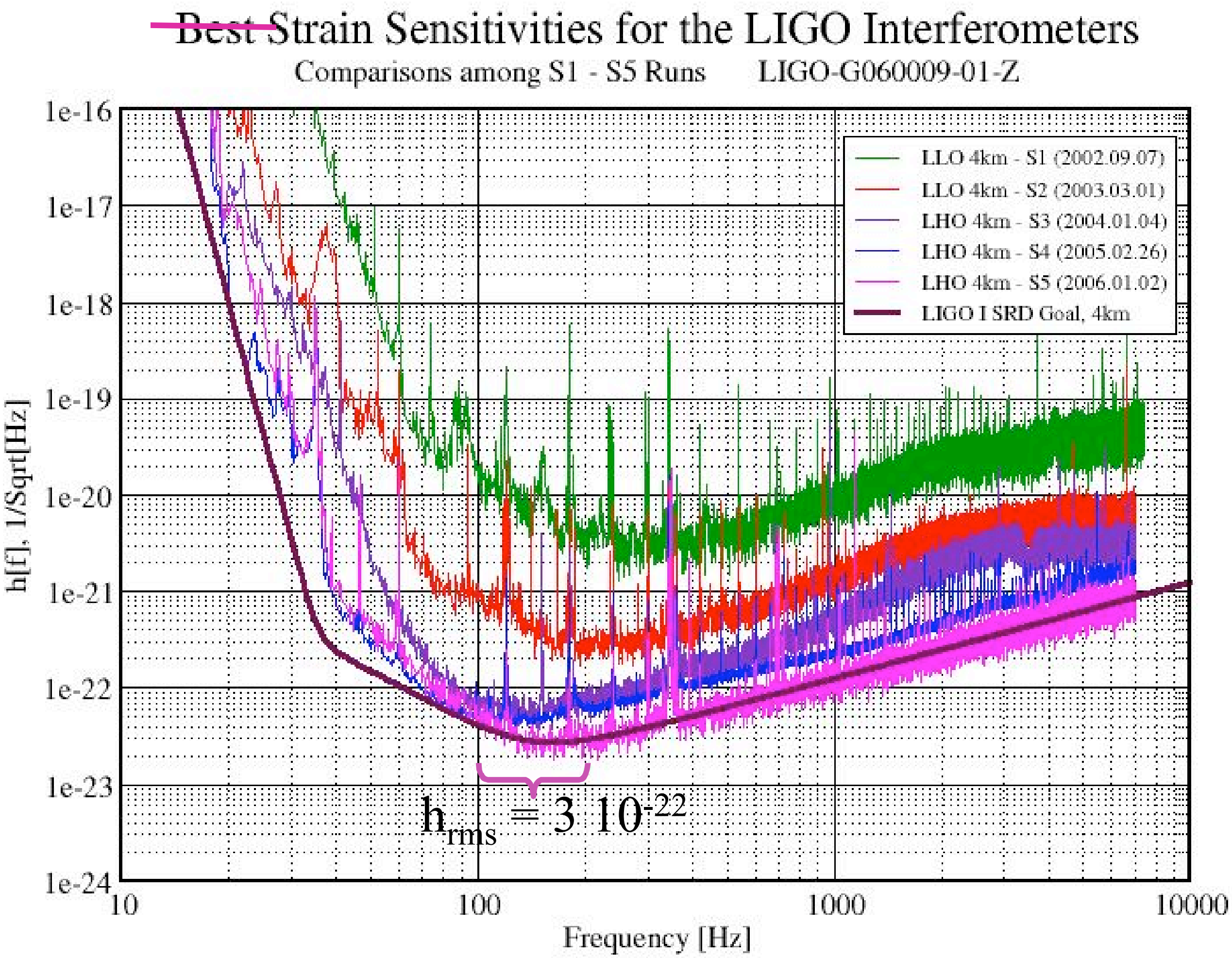




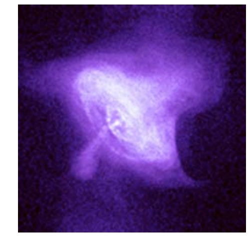


NASA, WMAP

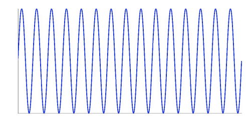
LIGO: Steady progress



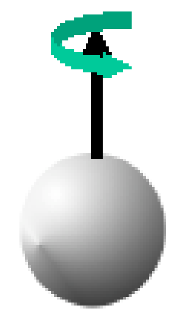
Gravitational wave searches: pulsars



Crab pulsar
(Chandra Telescope)



- Rotating stars produce GWs if they have asymmetries or if they wobble.
- Observed spindown can be used to set strong indirect upper limits on GWs.
- There are many known pulsars (rotating stars!) that produce GWs in the LIGO frequency band (40 Hz-2 kHz).
  - Targeted searches for 73 known (radio and x-ray) systems in S5: isolated pulsars, binary systems, pulsars in globular clusters…
- There are likely to be many non-pulsar rotating stars producing GWs.
  - All-sky, unbiased searches; wide-area searches.
- GWs (or lack thereof) can be used to measure (or set up upper limits on) the ellipticities of the stars.
- Search for a sine wave, modulated by Earth's motion, and possibly spinning down: easy, but computationally expensive!

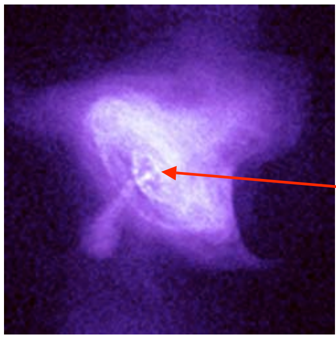


Gravitational wave searches: pulsars

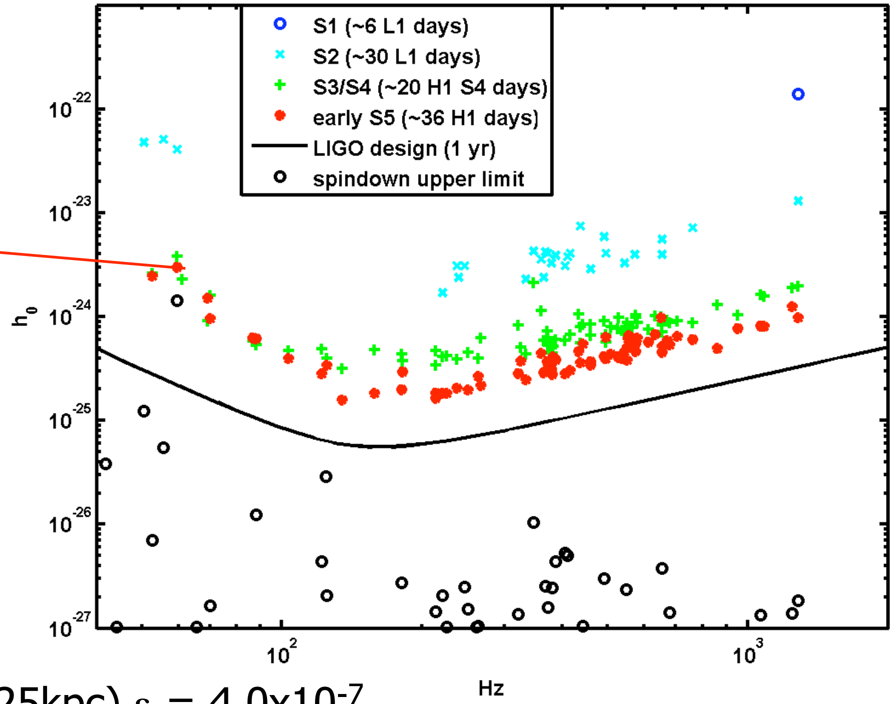
B. Abbott et al. (LIGO Scientific Collaboration):

- S1: Setting upper limits on the strength of periodic gravitational waves from PSR J1939 2134 using the first science data from the GEO 600 and LIGO detectors, Physical Review D 69, 082004, (2004)
- S2: Limits on gravitational wave emission from selected pulsars using LIGO data (LSC+M. Kramer and A. G. Lyne), Phys. Rev. Lett. 94, 181103 (2005)
- S2: First all-sky upper limits from LIGO on the strength of periodic gravitational waves using the Hough transform, Phys. Rev. D 72, 102004 (2005)
- S3, S4: completed with Einstein@home
- S5: in progress

Crab pulsar



Upper limits on GWs from targeted pulsars:



Best limit on ellipticity:

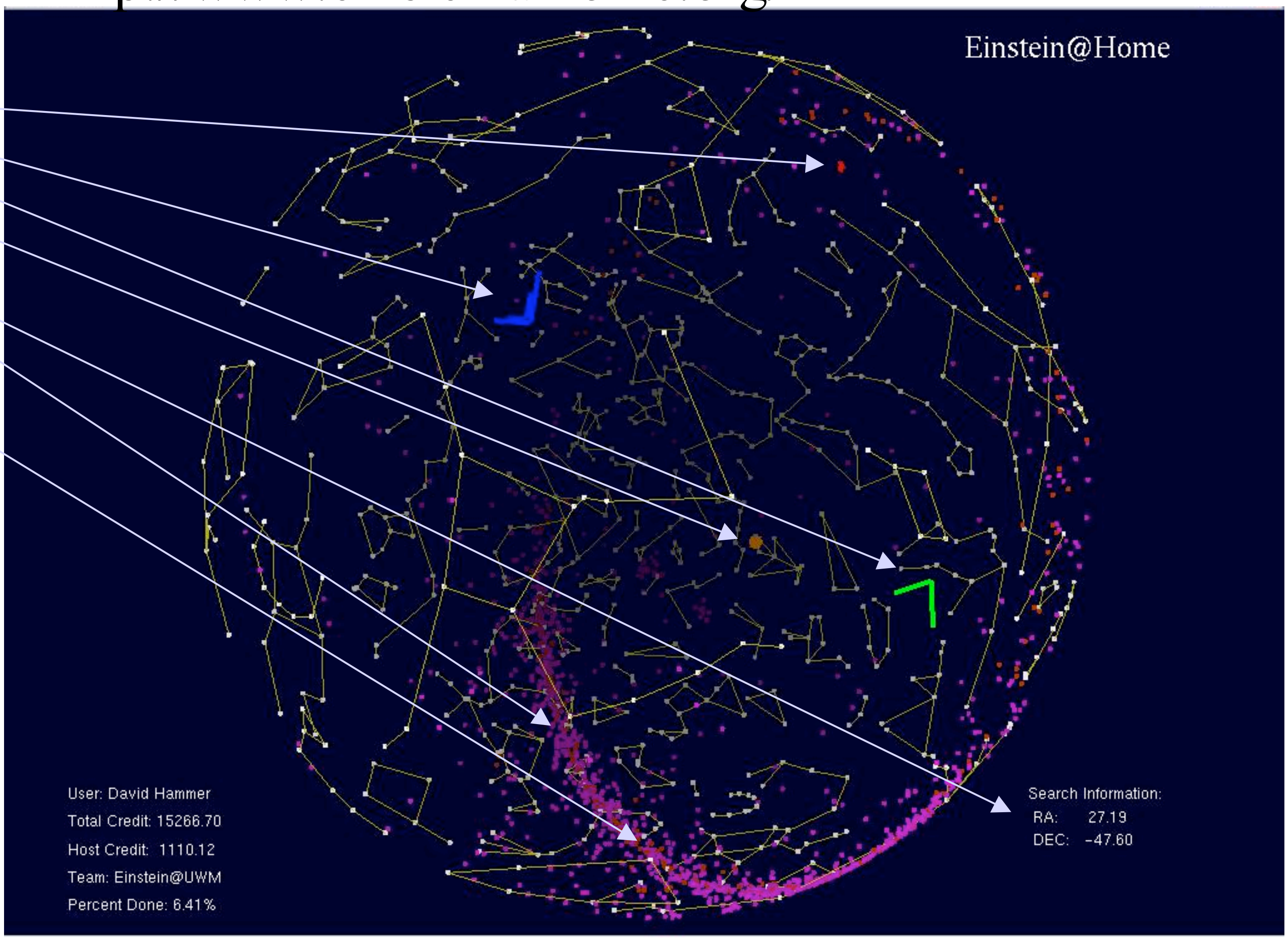
PSR J2124-3358 (f_{gw} = 405.6Hz, r = 0.25kpc) $\varepsilon = 4.0\times10^{-7}$

EINSTEIN@HOME

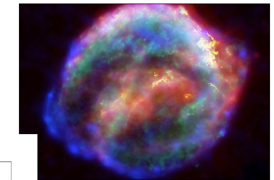
Catch a Wave From Space

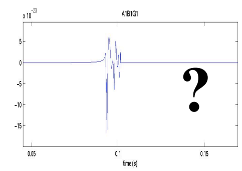
http://www.einsteinathome.org/

- GEO-600 Hannover
- LIGO Hanford
- LIGO Livingston
- Current search point
- Current search coordinates
- Known pulsars
- Known supernovae remnants

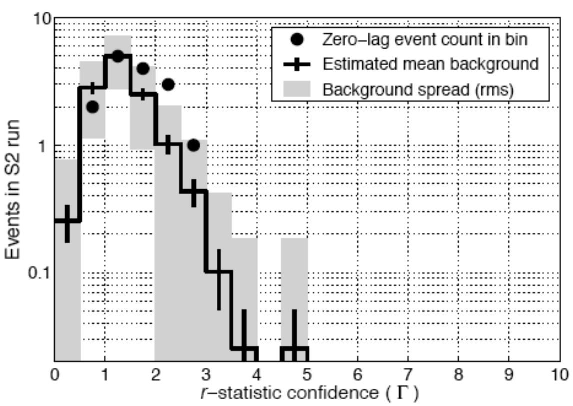


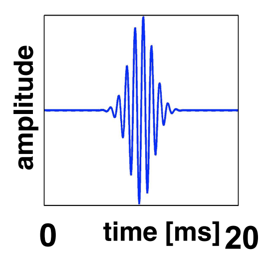
LIGO searches: "burst" sources (untriggered)



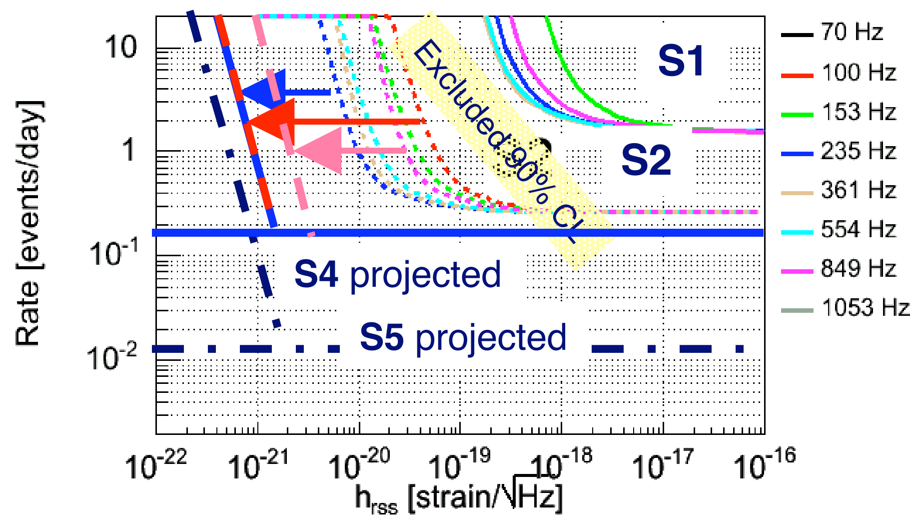


- **Search for <u>triple coincident</u> triggers with a wavelet algorithm**
- **Measure waveform consistency**
- **Set a threshold for detection for <u>low false alarm probability</u>**
- **Compare with efficiency for detecting simple waveforms**



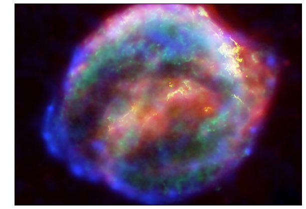


PRD 72 (2005) 042002

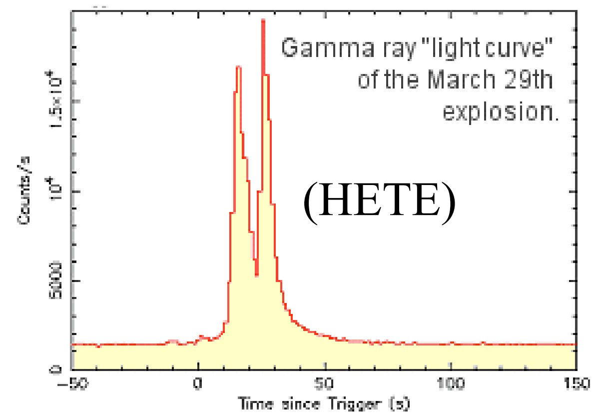


- S1: First upper limits from LIGO on gravitational wave bursts, Phys. Rev. D 69, 102001 (2004)
- S2: Upper Limits on Gravitational Wave Bursts in LIGO's Second Science Run, Phys. Rev. D 72, 062001 (2005)
- S2: Upper Limits from the LIGO and TAMA Detectors on the Rate of Gravitational-Wave Bursts, Phys. Rev. D 72, 122004 (2005)
- S3: Search for gravitational wave bursts in LIGO's third science run, Class. Quant. Grav. 23, S29-S39 (2006)
- S4: results completed, paper in progress
- S5 analysis in progress

LIGO searches: burst sources (triggered)



Follow up GRB triggers looking at cross-correlation from data in at least two detectors. For a set of GRBs, search for cumulative effect with statistical tests.



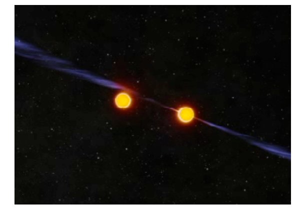
- HETE GRB030329 : during S2, search resulted in no detection (**PRD** 72, 042002, 2005)

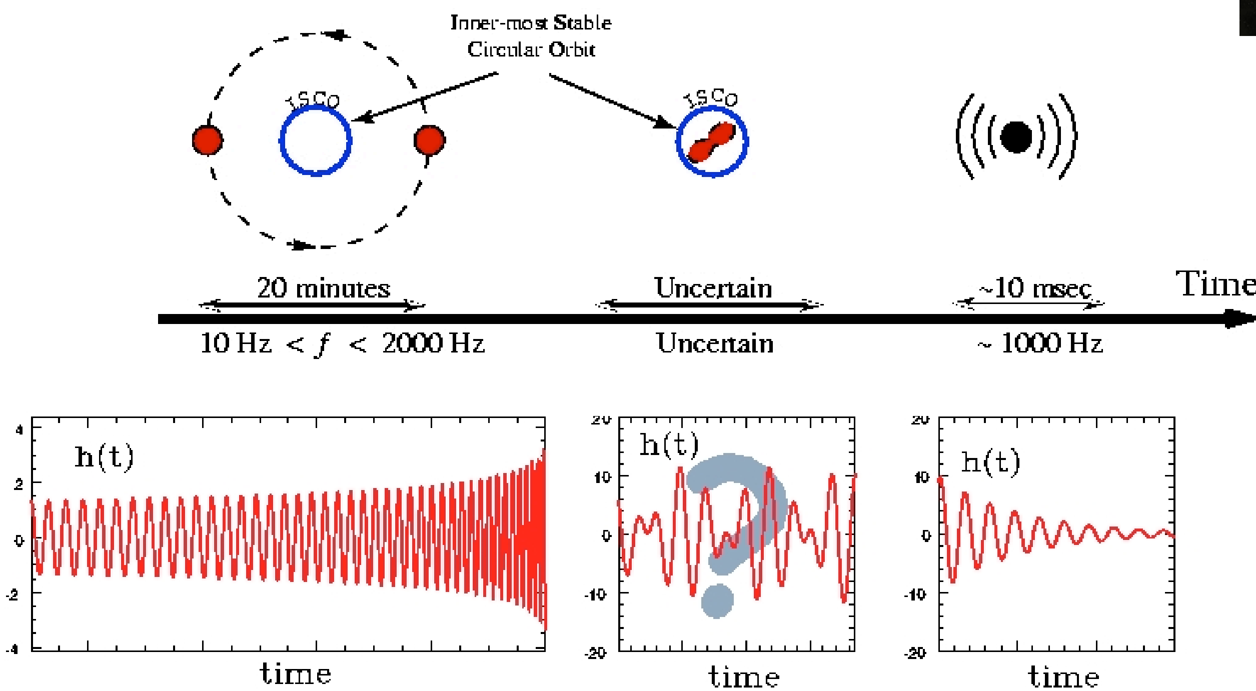
- SWIFT, IPN, HETE-2, Konus-Wind: 39 triggers during S2/S3/S4: no loud event from any GRB, or from the set.
- S5 run: ~75 GRBs (mostly SWIFT) in 5 months.

- Massive flare from SGR 1806: analysis completed, paper in progress.
- In the future: follow up short GRBs with a search for inspiral waveforms

Coalescing Binaries

LIGO is sensitive to gravitational waves from neutron star and black hole binaries





Inspiral

Merger

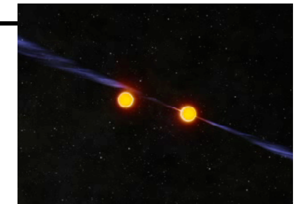
Ringdown

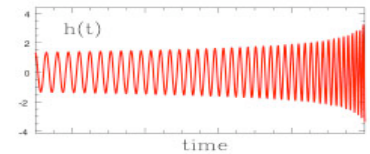
S1 BNS search

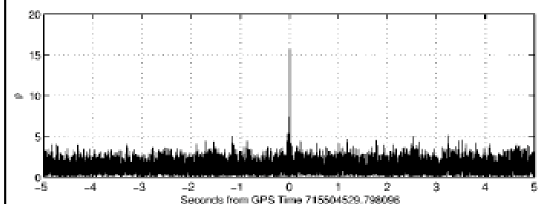
Analysis of LIGO data for gravitational waves from binary neutron stars,
The LIGO Scientific Collaboration, Phys. Rev. D 69, 122001 (2004)

Use triggers from H 4km and L 4km interferometers:

- *T = 295.3 hours analyzed (~12 days)*
- *Max SNR observed:* ***15.9****(!)* in L1 only
- There were no event candidates in the double or triple coincidence (with SNR>8); there were ~1,000 triggers in L1 with SNR>8; expected: SNR 16, 1/1e42yrs; SNR 8, 1/2.5 yr :(

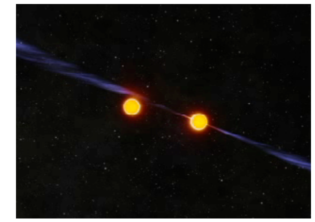




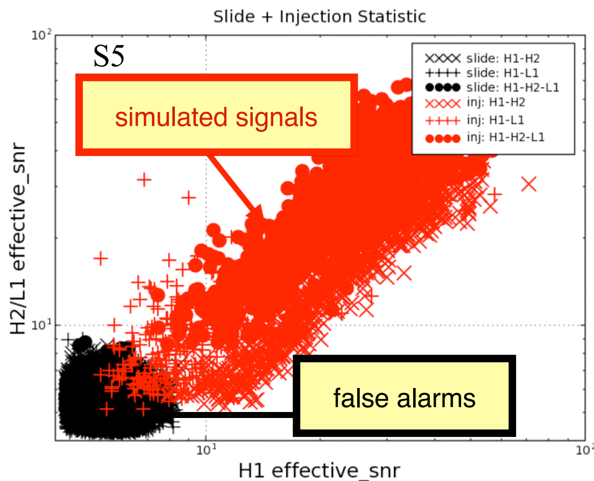


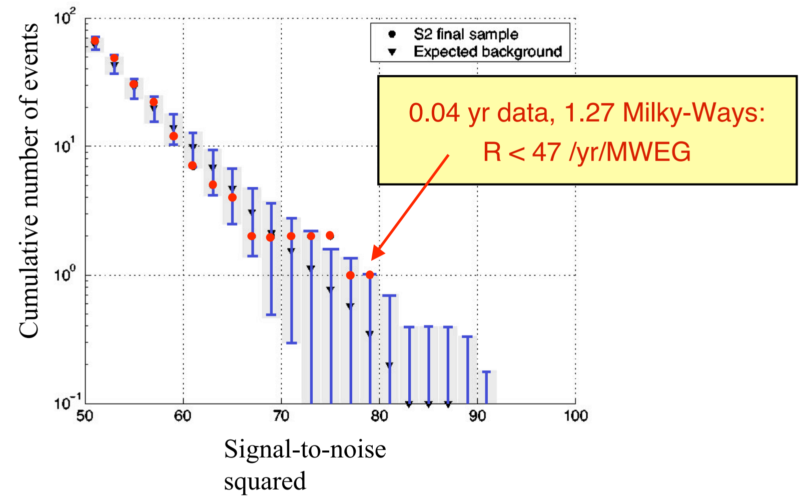
Search for binary systems

- Use two or more detectors: search for double or triple *coincident* “triggers”
- Can infer masses and “effective” distance.
- Estimate false alarm probability of resulting candidates: detection?
- Compare with expected efficiency of detection and surveyed galaxies: upper limit



John Rowe, CSIRO



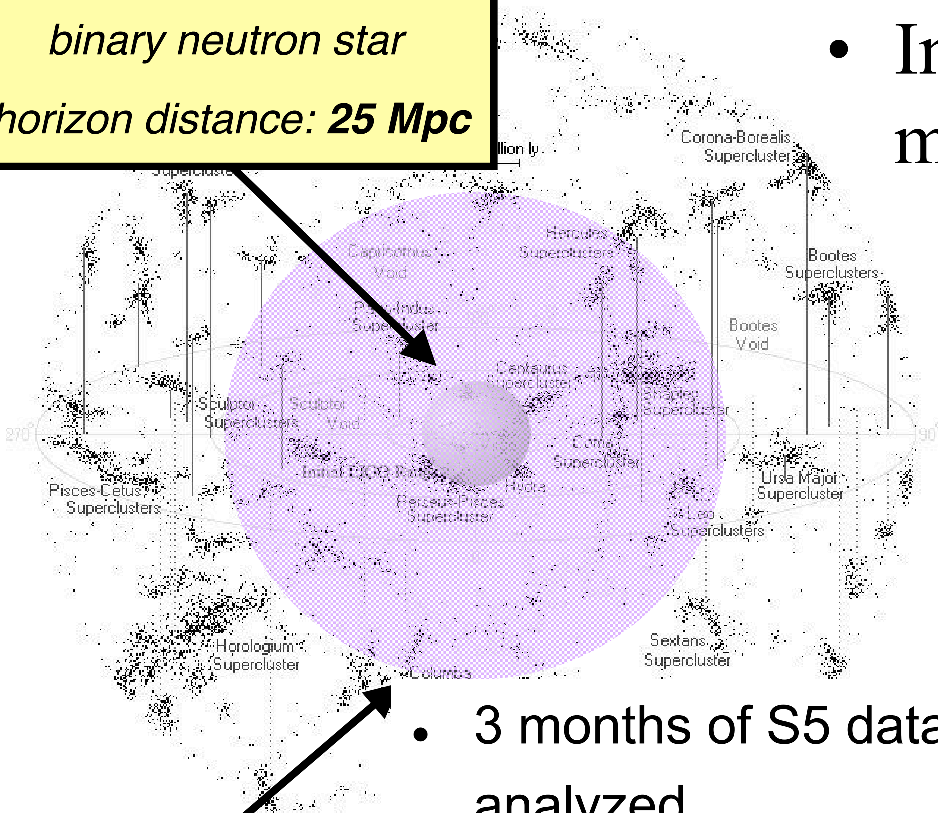


B. Abbott et al. (LIGO Scientific Collaboration):

- S1: Analysis of LIGO data for gravitational waves from binary neutron stars, Phys. Rev. D 69, 122001 (2004)
- S2: Search for gravitational waves from primordial black hole binary coalescences in the galactic halo, Phys. Rev. D 72, 082002 (2005)
- S2: Search for gravitational waves from galactic and extra-galactic binary neutron stars, Phys. Rev. D 72, 082001 (2005)
- S2: Search for gravitational waves from binary black hole inspirals in LIGO data, Phys. Rev. D 73, 062001 (2006)
- S2: Joint Search for Gravitational Waves from Inspiralling Neutron Star Binaries in LIGO and TAMA300 data (LIGO, TAMA collaborations), PRD, in press
- S3, S4: finished searched for BNS, BBH, PBBH: no detection; paper in progress
- S5: analysis in progress

Searches for coalescing compact binary signals in S5

*binary neutron star horizon distance: **25 Mpc***

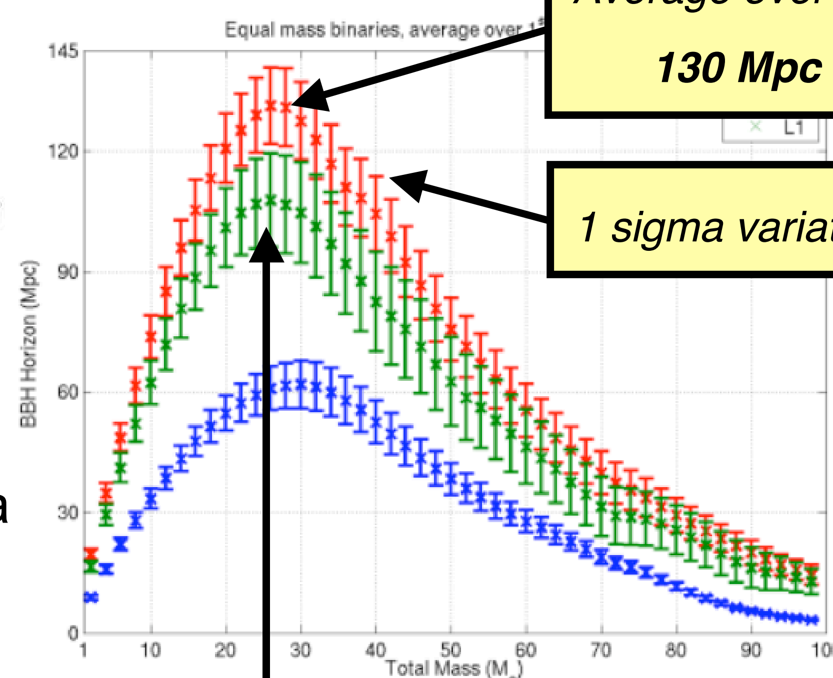


- Inspiral Horizon distance vs mass

Average over run

130 Mpc

1 sigma variation

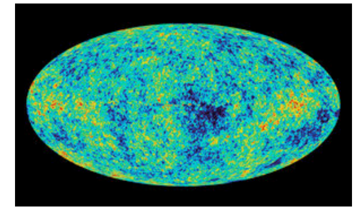


Peak at total mass ~ $25M_{sun}$

- 3 months of S5 data analyzed
- 1 calendar yr in progress

binary black hole horizon distance

Gravitational Wave sources: Stochastic Background



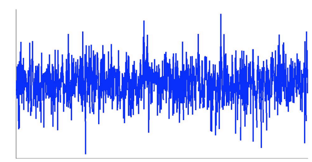
NASA, WMAP

- A primordial GW stochastic background is a prediction from most cosmological theories.
- Given an energy density spectrum $\Omega_{gw}(f)$, there is a strain power spectrum:

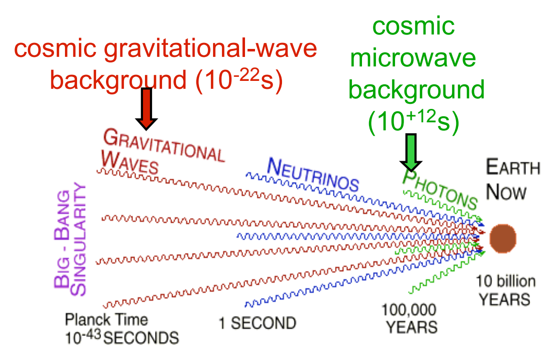
$$\Omega_{GW}(f) = \frac{1}{\rho_c} \frac{d\rho_{GW}(f)}{d\ln f}$$

$$S_{\rm gw}(f) = \frac{3H_0^2}{10\pi^2} f^{-3} \Omega_{\rm gw}(f)$$

$$h(f) = S_{\rm gw}^{1/2}(f) = 5.6\times10^{-22}\, h_{100} \sqrt{\Omega_0} \left(\frac{100\mathrm{Hz}}{f}\right)^{3/2} \mathrm{Hz}^{1/2}$$



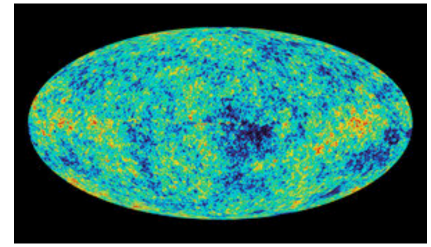
- The signal can be searched from cross-correlations in different pairs of detectors: L1-H1, H1-H2, L1-ALLEGRO… the farther the detectors, the lower the frequencies that can be searched.



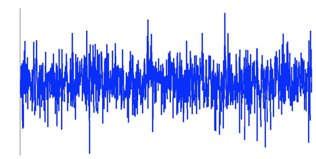
Stochastic Background

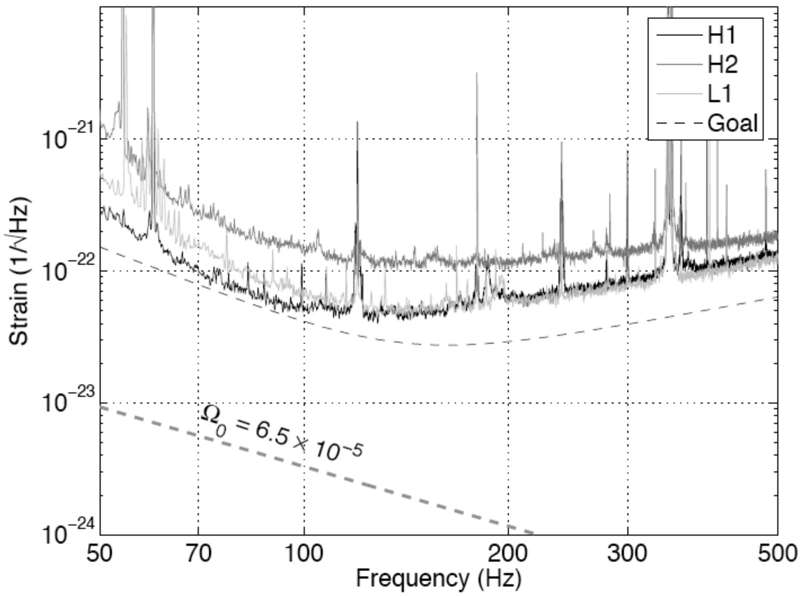
B. Abbott et al. (LIGO Scientific Collaboration):

- S1: Analysis of first LIGO science data for stochastic gravitational waves, Phys. Rev. D 69, 122004 (2004)
- S3: Upper Limits on a Stochastic Background of Gravitational Waves, Phys. Rev. Lett. 95, 221101 (2005)
- S4: Searching for a Stochastic Background of Gravitational Waves with, astro-ph/0608606

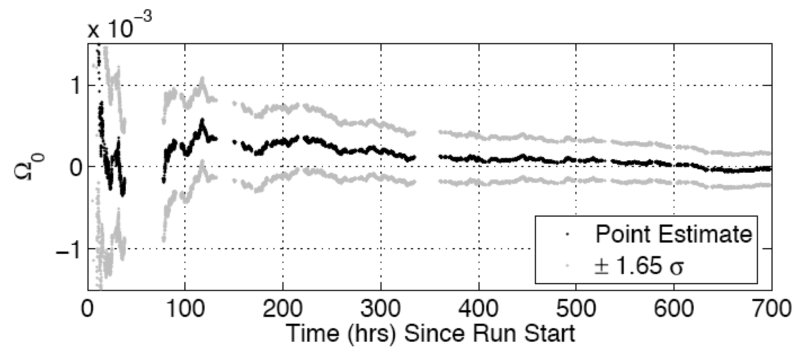


NASA, WMAP



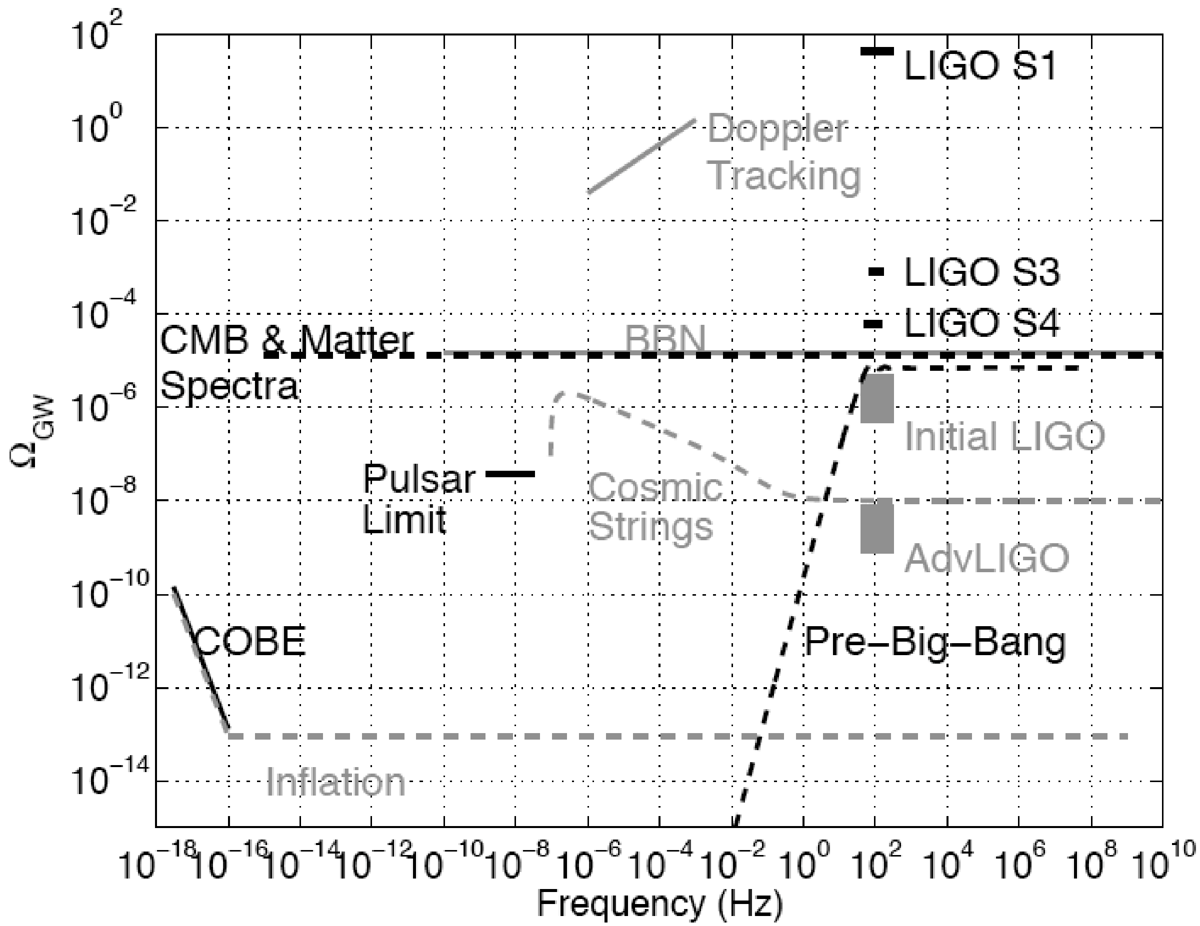


S4



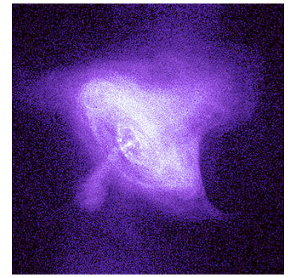
- S4 H1-L1 and H2-L1 Bayesian 90% UL: _$_{90\%}$ = **6.5 _ 10^{-5}** (51-150 Hz)
- Also:
  - Search for frequency dependent Ω(f)
  - directional ("radiometer") search (Ballmer, gr-qc/0510096)

Stochastic Background: the landscape

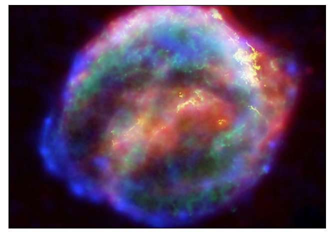


When will we see something?

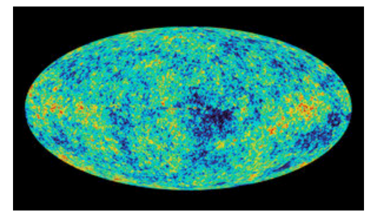
Predictions are difficult… many unknowns!



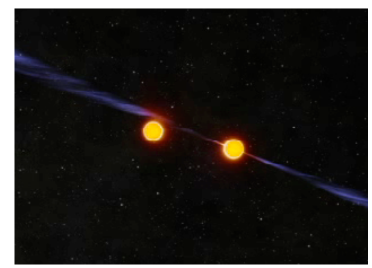
- Rotating stars: how lumpy are they?



- Supernovae, gamma ray bursts:
  how strong are the waves
  (and what do they look like)?

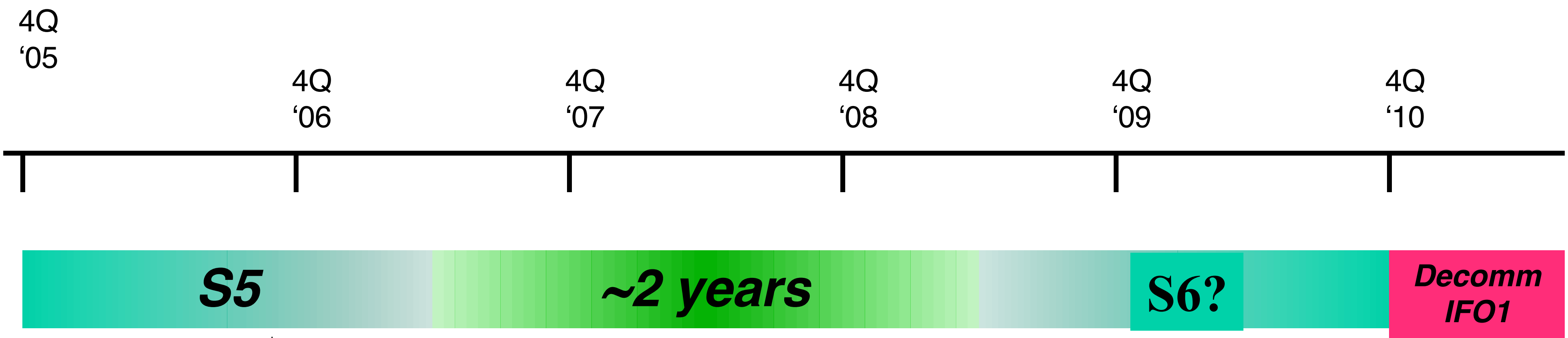


- Cosmological background:
  how did the Universe evolve?



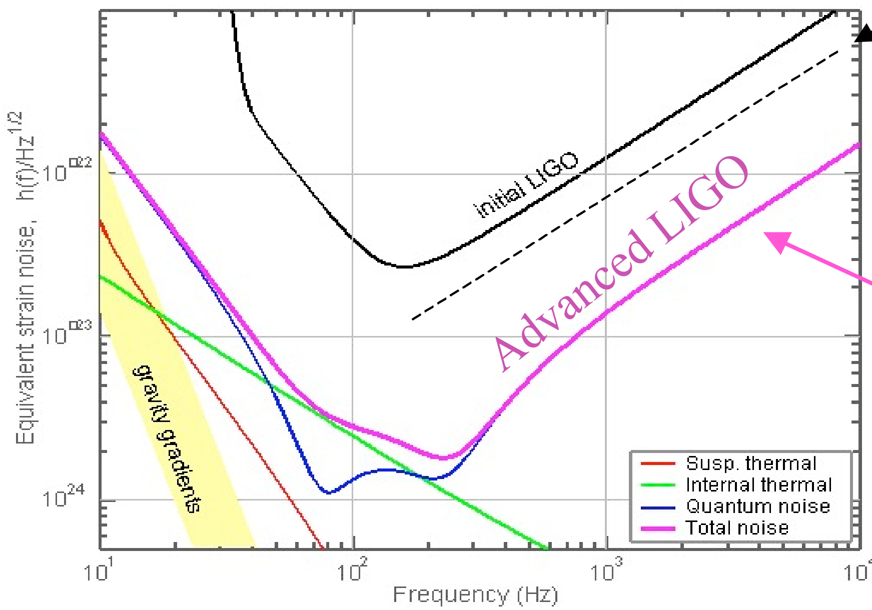
- Binary black holes: how many are there?
  What masses do they have?
- Binary neutron stars: from observed systems
  in our galaxy, predictions are up to 1/3yrs,
  but most likely one per 30 years,
  at LIGO's present sensitivity. For advanced LIGO, it's 1/2 days!
- From rate of short GRBs, much more optimistic
  predictions for BNS and BBH rates? ⇣ Ready to be tested with S5!

Present, future



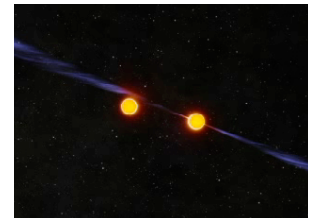
today

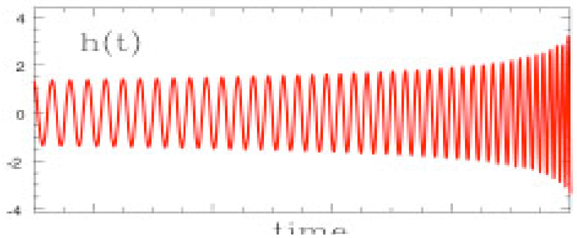
BNS: 1/30 yr
BBH: ??



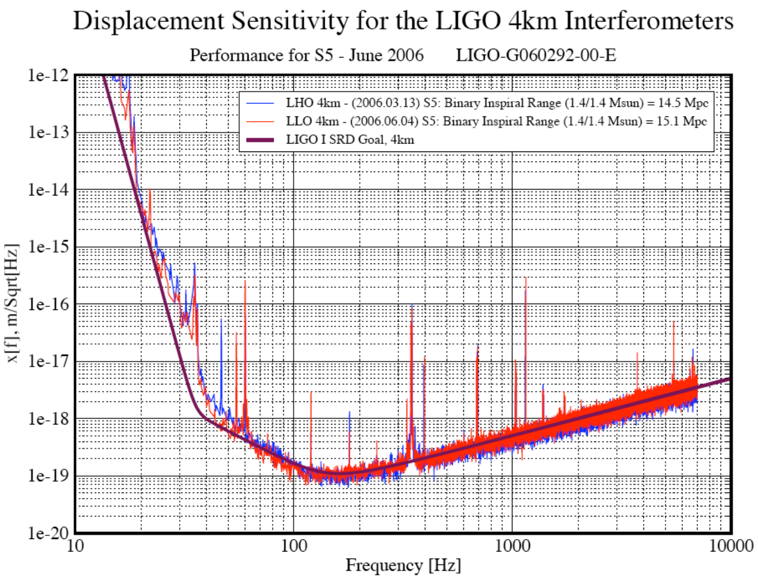
BNS: 1/2days
BBH: we'll measure it!

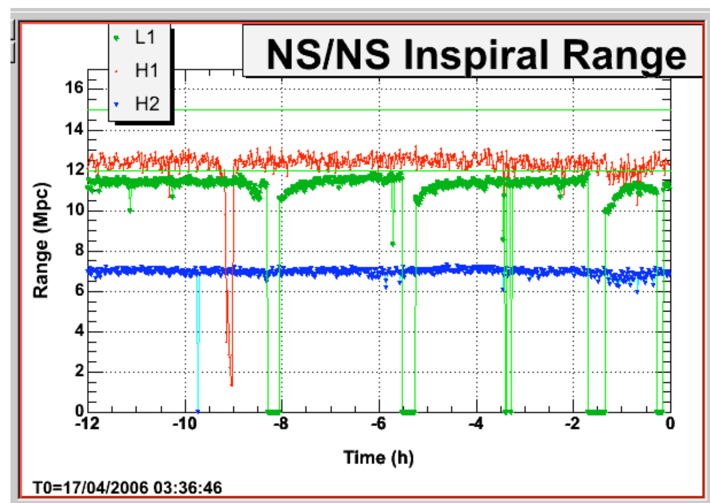
Binary systems: a measure of performance





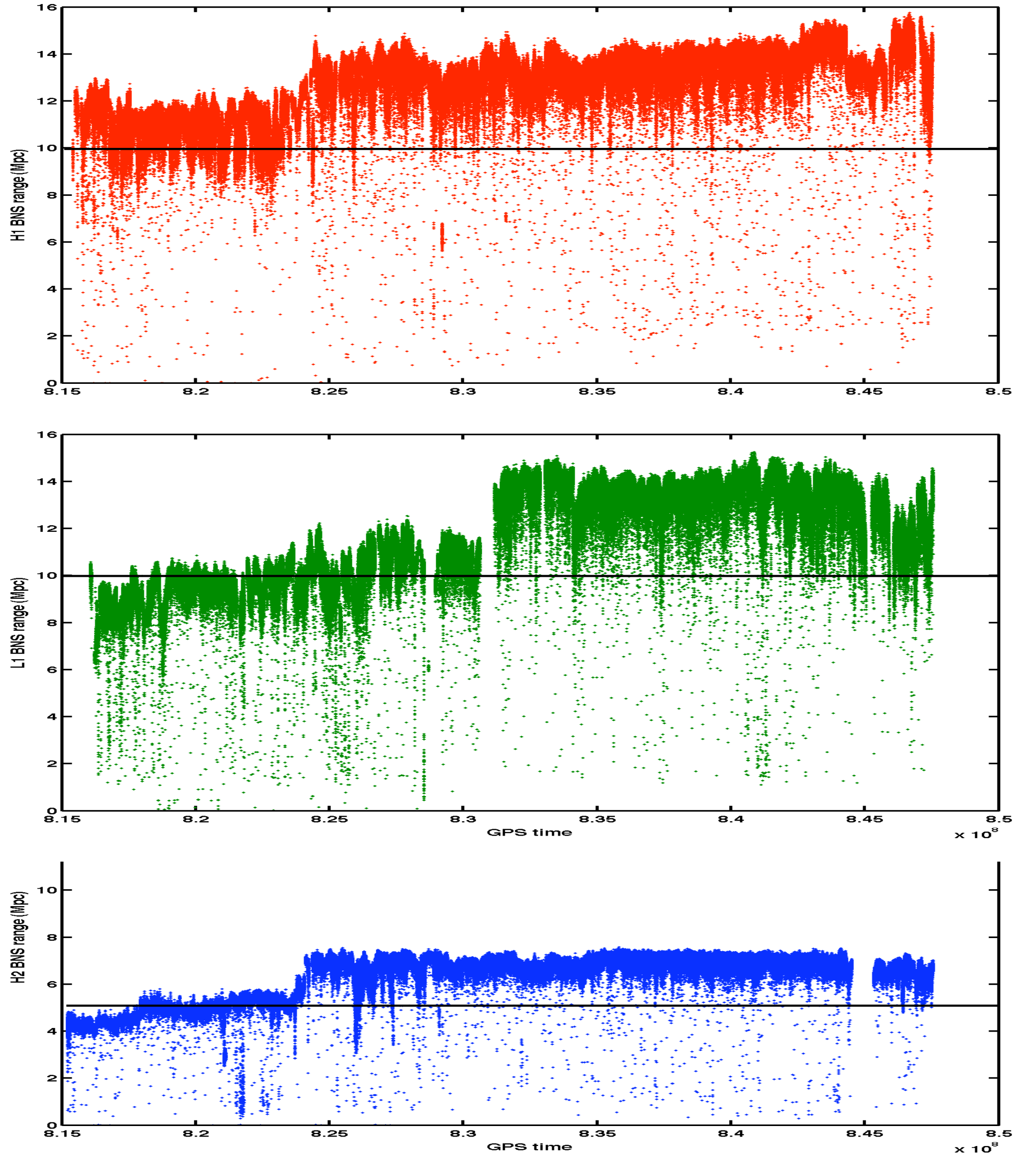
Can translate strain amplitude into (effective) distance





If system is optimally located and oriented, we can see even further: we are surveying <u>hundreds of galaxies</u>!

S5 performance: Nov 4 ‘05 - Nov 14 ‘06



In “science mode”:

H1: 268 days
L1: 215 days
H2: 283 days
H1/L1: 176 days