Searching for gravitational waves with LIGO

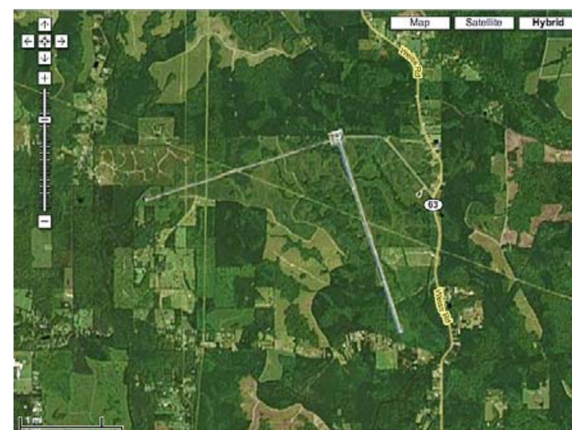
Gabriela González

Louisiana State University

On behalf of the LIGO Scientific Collaboration

APS meeting, April 14 2006

maps.google.com



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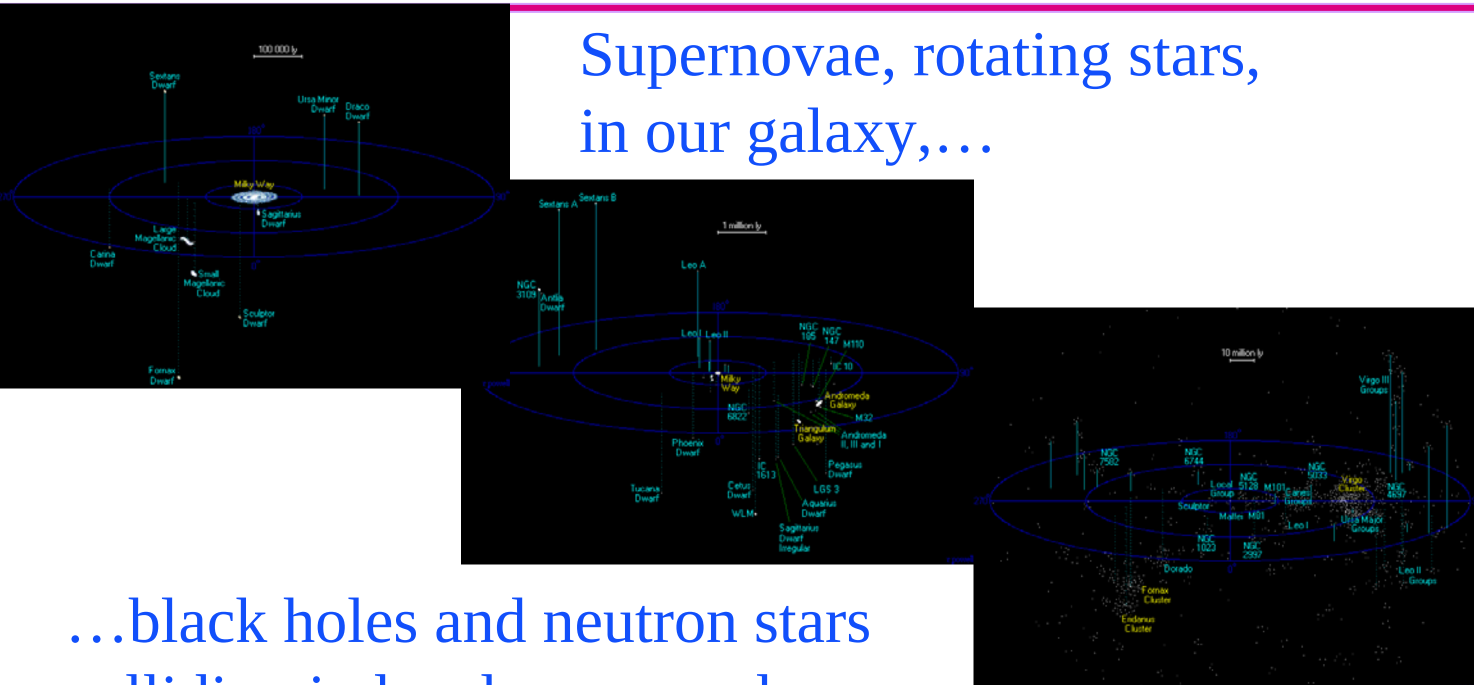
What are we searching for?

Supernovae, rotating stars,
in our galaxy,…



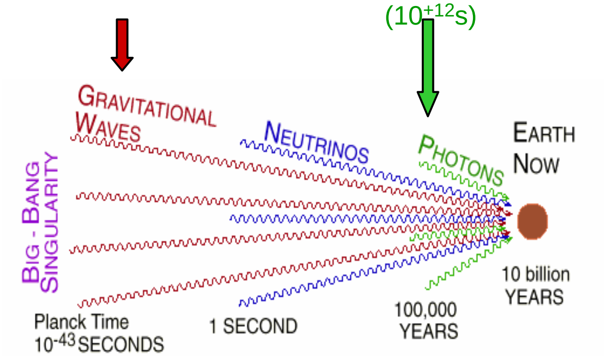
An Atlas of the Universe, Richard Powell

…black holes and neutron stars colliding in local group and VIRGO cluster,…

… and signals from the past, from beginning of the universe

cosmic gravitational-wave background (10^{-22}s)

cosmic microwave background (10^{+12}s)



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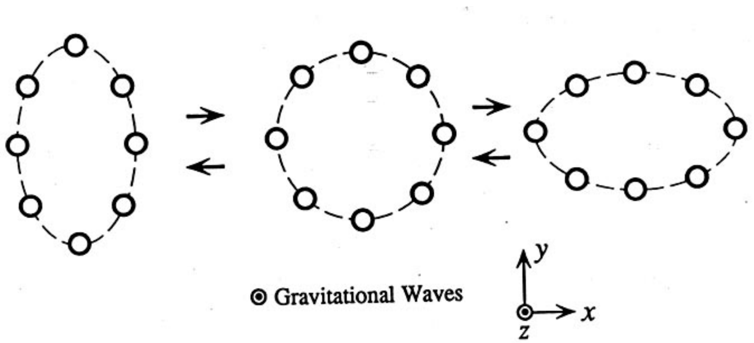
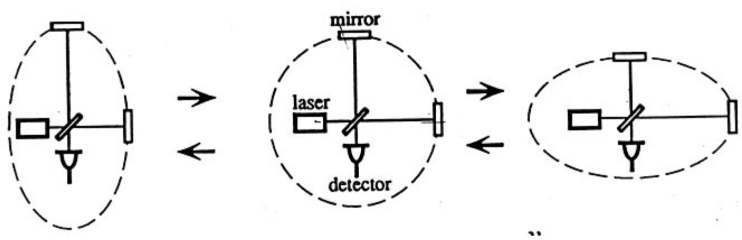
Gravitational waves



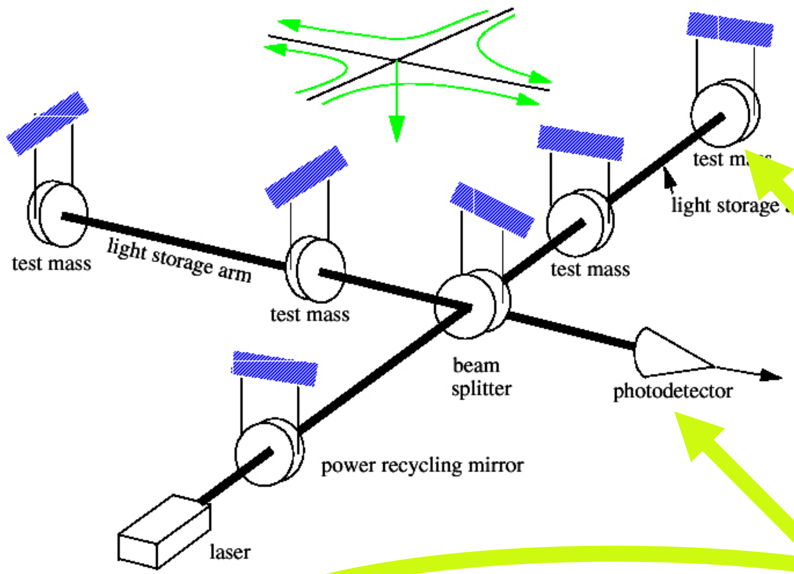
Gravitational waves are quadrupolar distortions of distances between freely falling masses: "ripples in space-time"

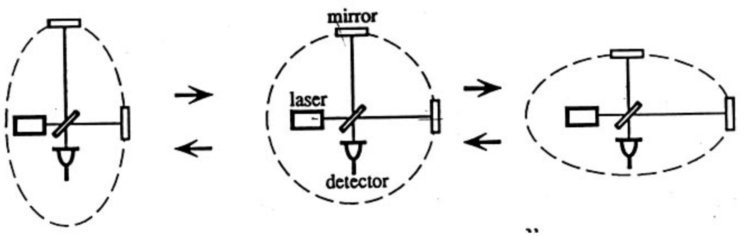
Michelson-type interferometers can detect space-time distortions, measured in "strain" h=ΔL/L.



Amplitude of GWs produced by binary neutron star systems in the Virgo cluster have $h=\Delta L/L \sim 10^{-21}$

GW LIGO detectors: interferometers





$h = \Delta L / L \sim 10^{-21}$ and

$L = 4\text{km} \Rightarrow \Delta L = hL \sim 10^{-18}$ m !

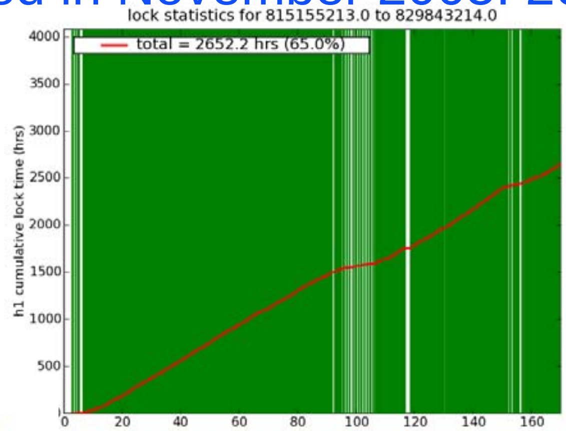
suspended test masses
(“freely falling objects”)

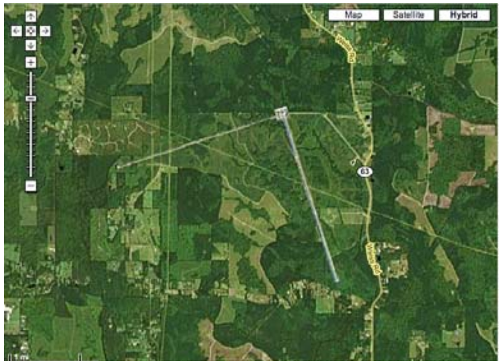
dark port
(RF heterodyne modulation)

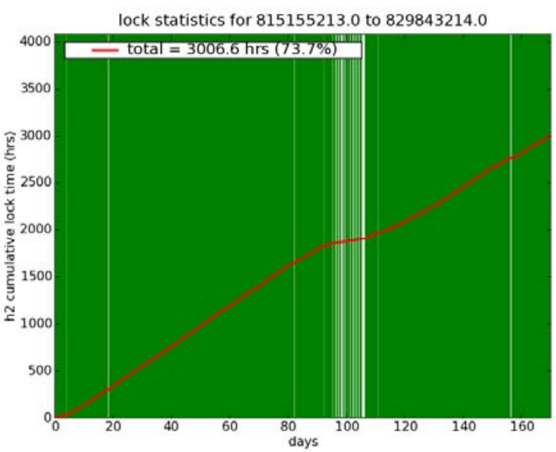
Three LIGO detectors: 4km long in Livingston, La (L1); 4km and 2km long in Hanford, WA (H1, H2).

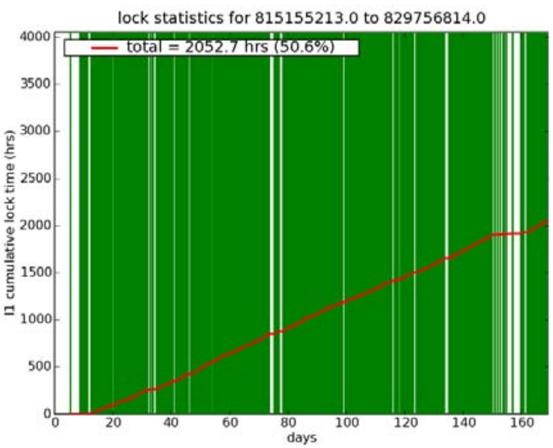
Search for gravitational waves: in progress!

Science run “S5” started in November 2005: 2000+ hours of data collected!



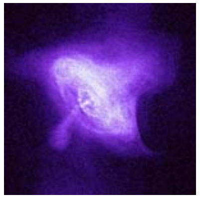




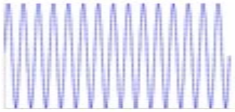


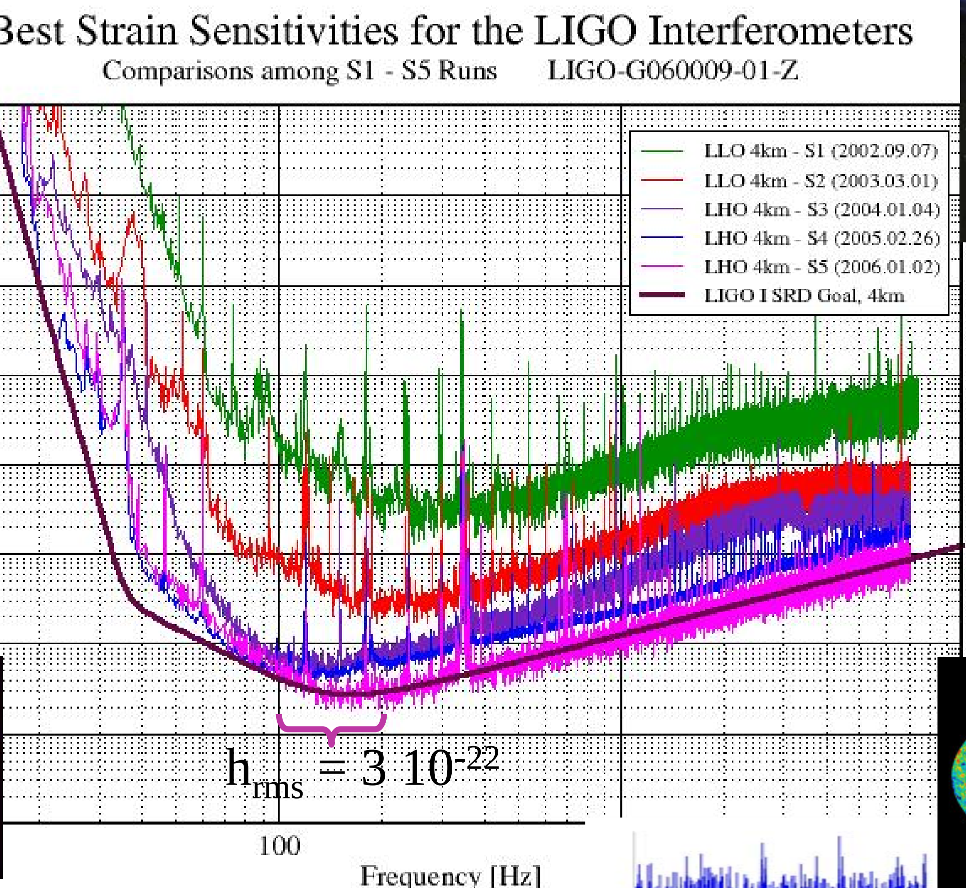
Previous science runs: S1 (Aug-Sep‘02); S2 (Feb-Apr‘03); S3 (Oct‘03- Jan’04); S4 (Feb-Mar ‘05).

Look for different signatures

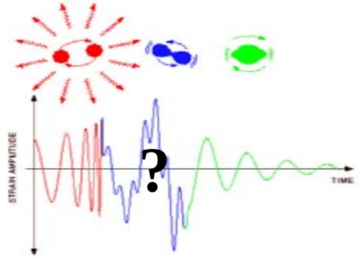


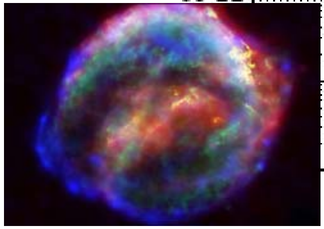
Crab pulsar (NASA, Chandra Observatory)



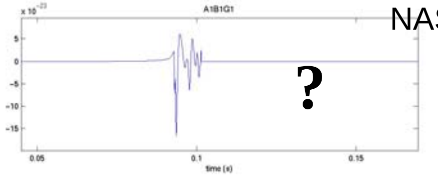


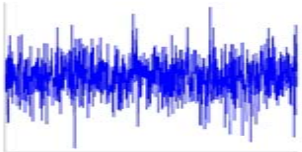
John Rowe, CSIRO

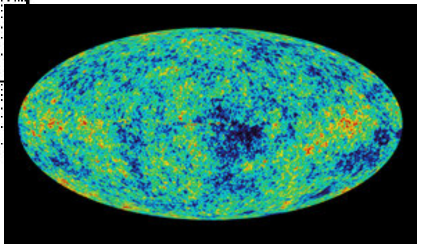




NASA, HEASARC



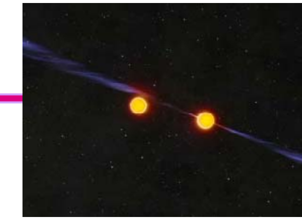




NASA, WMAP

Latest news and details in session W11, 10:45am today!

Search for binary systems



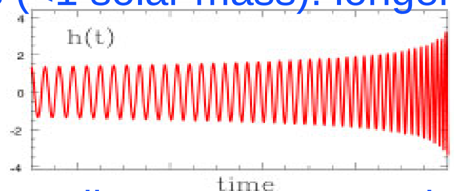
Use calculated templates for inspiral phase (“chirp”) with optimal filtering.

Search for systems with different masses:

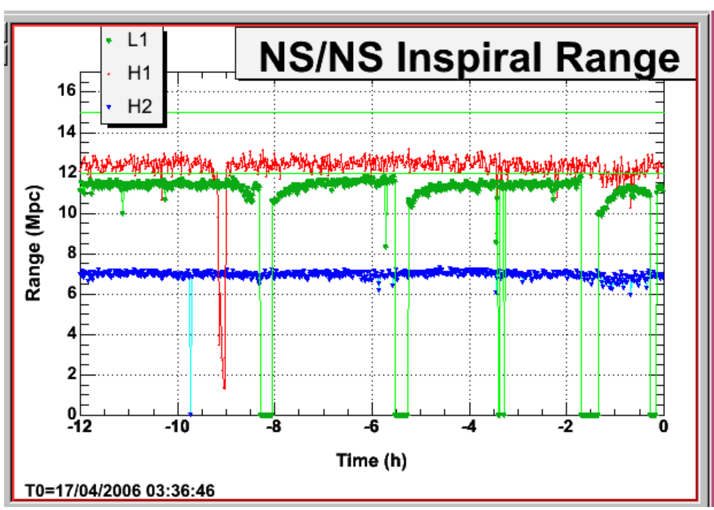
» Binary neutron stars (~1-3 solar masses): ~15 sec templates, 1400 Hz end freq

» Binary black holes (< ~30 solar masses): shorter templates, lower end freq

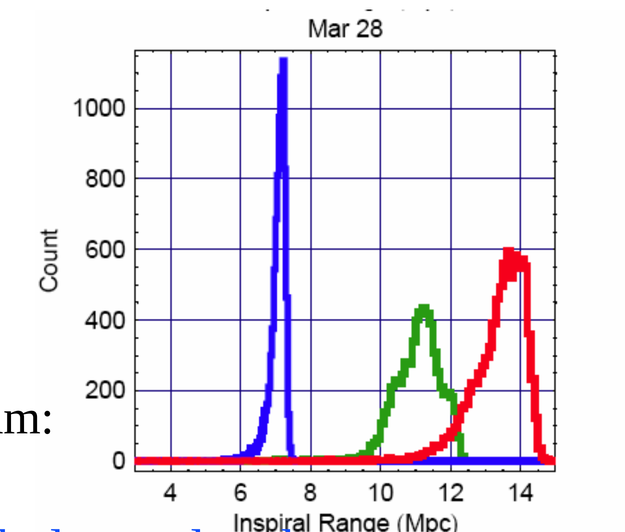
» Primordial black holes (<1 solar mass): longer templates, higher end freq



We can translate the “noise” into distances surveyed.
We monitor this in the control room for binary neutron stars:

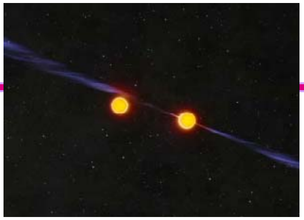


A week’s histogram:



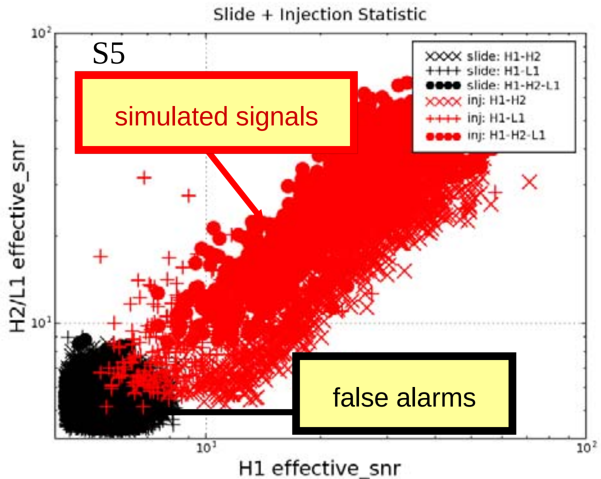
If system is optimally located and oriented, we can see even further: we are surveying hundreds of galaxies!

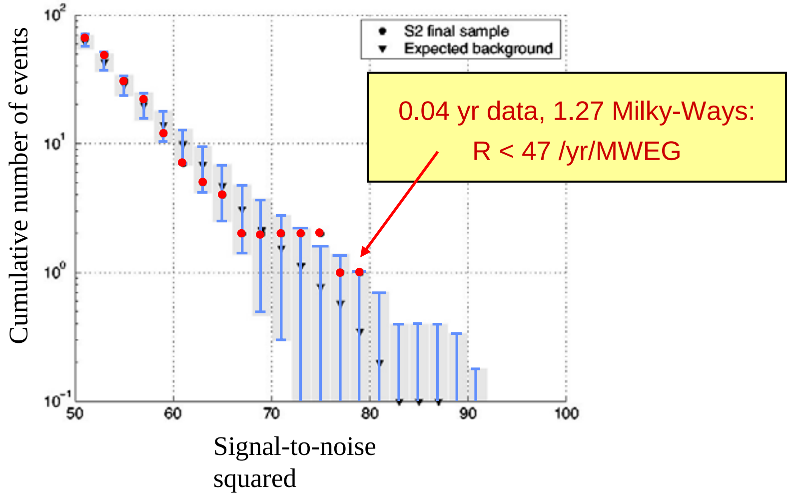
Search for binary systems



John Rowe, CSIRO

- 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



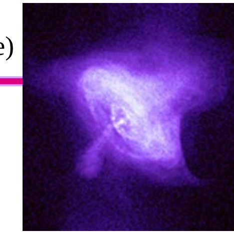


B. Abbott et al. (LIGO Scientific Collaboration):

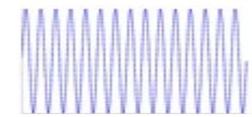
- S1: Analysis of LIGO data for gravitational waves from binary neutron stars, Phys. Rev. D 69, 122001 (2004)
- S2: Search for gravitational waves from primordial black hole binary coalescences in the galactic halo, Phys. Rev. D 72, 082002 (2005)
- S2: Search for gravitational waves from galactic and 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: finished searched for BNS, BBH, PBBH: no detection
- S4, S5: searches in progress (see D. Brown’s talk on BNS in Session W11 later today, T. Cokelaer’s poster on BBH) .

Gravitational wave searches: pulsars

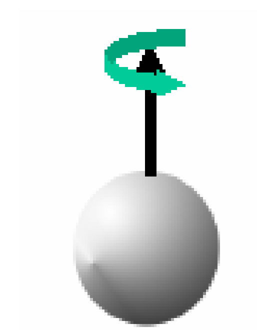
Crab pulsar
(Chandra Telescope)



- 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!



See latest news in Session W11 later today
(G. Mendell, V. Dergachev, K. Kawabe)

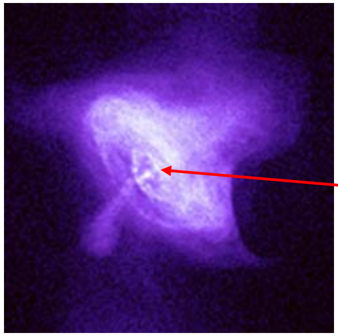
Gravitational wave searches: pulsars

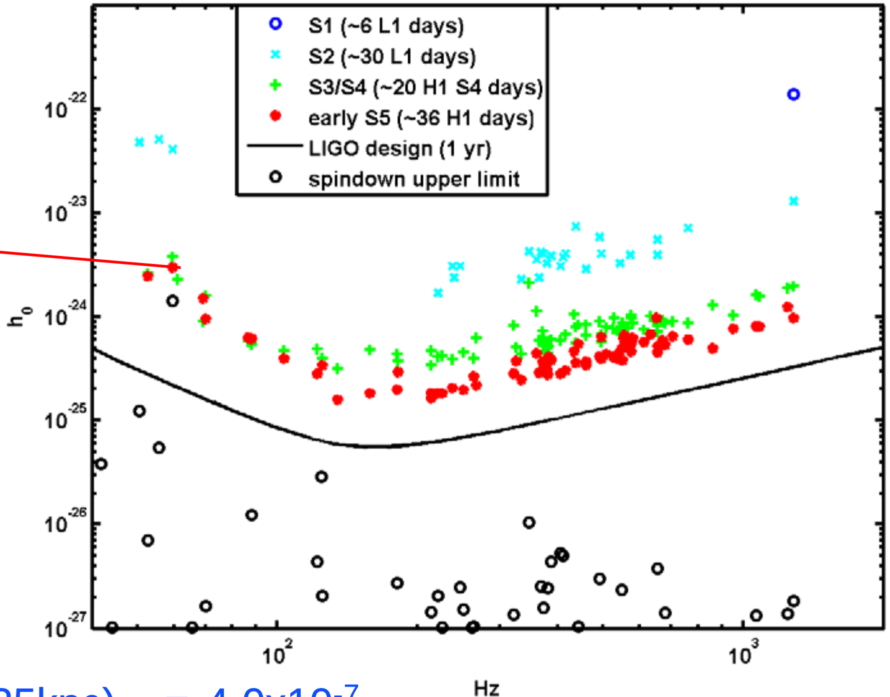
B. Abbott et al. (LIGO Scientific Collaboration):

- 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: in progress with Einstein@home
- S5: in progress, see latest news in session W11

Upper limits on GWs from targeted pulsars:

Crab pulsar





Best limit on ellipticity:

PSR J2124-3358 (f_{gw} = 405.6Hz, r = 0.25kpc) $\varepsilon = 4.0 \times 10^{-7}$

LIGO

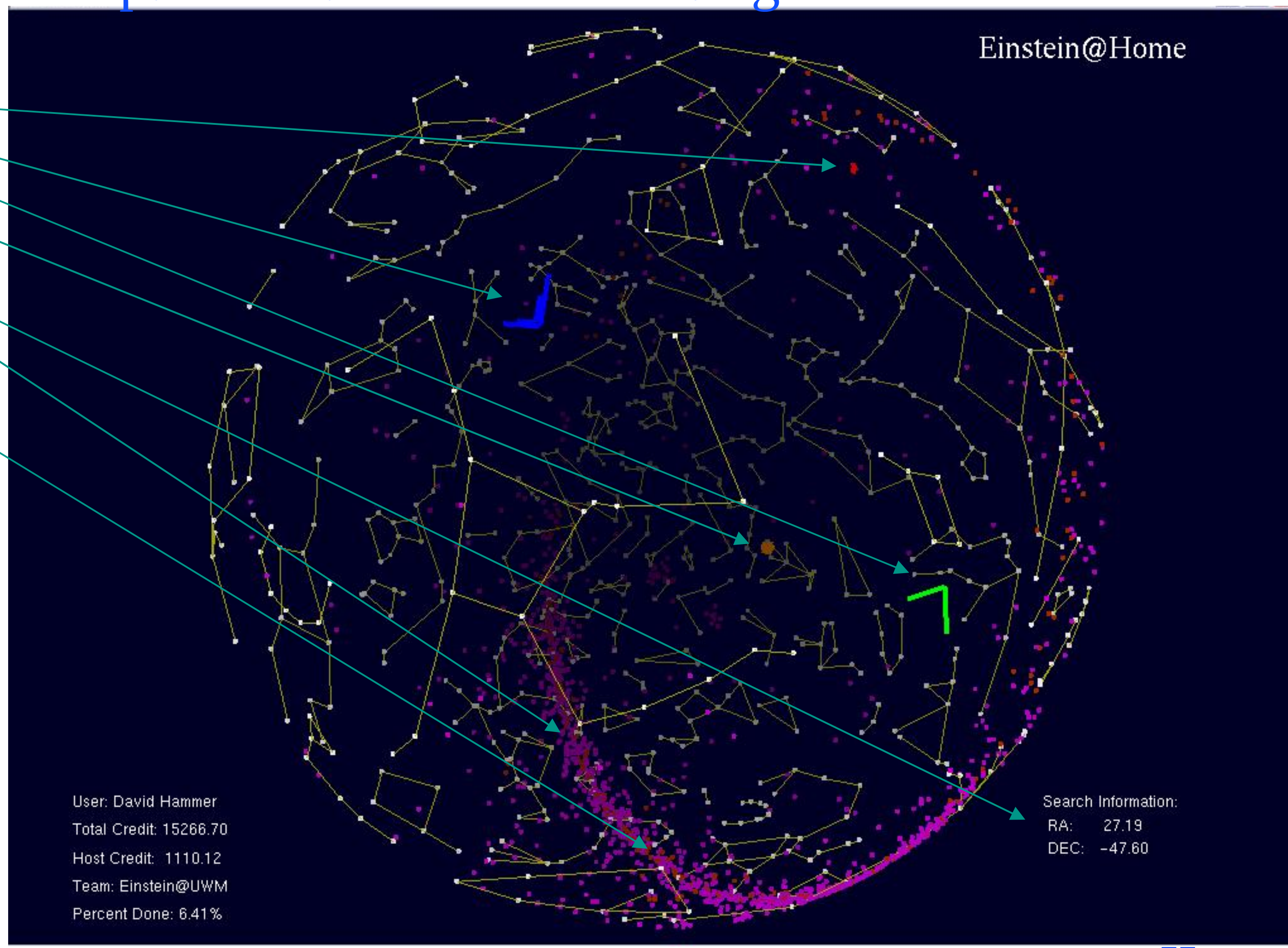
EINSTEIN@HOME

Catch a Wave From Space

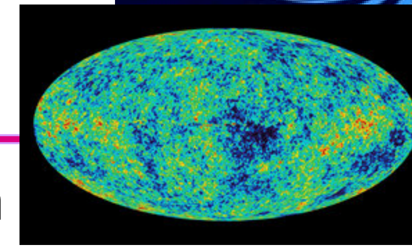
LSC

http://www.einsteinathome.org/

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

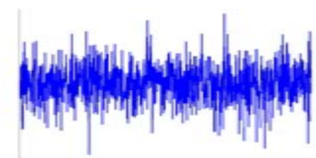


Gravitational Wave sources: Stochastic Background



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:



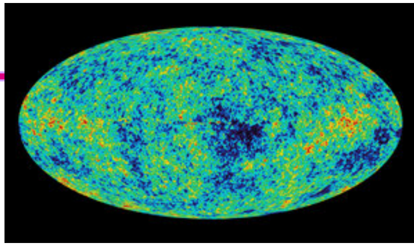
$$\Omega_{GW}(f) = \frac{1}{\rho_c}\frac{d\rho_{GW}(f)}{d\ln f}$$

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

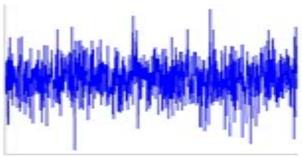
$$h(f) = S_{\rm gw}^{1/2}(f) = 5.6\times 10^{-22}\, h_{100}\sqrt{\Omega_0}\left(\frac{100{\rm Hz}}{f}\right)^{3/2} {\rm Hz}^{1/2}$$

- 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.

LIGO search for a Stochastic Background

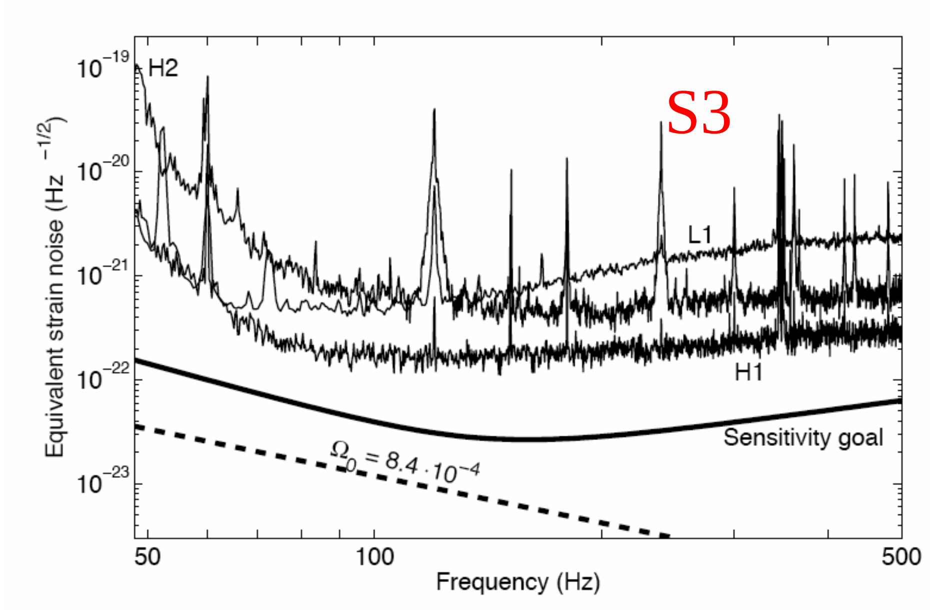


NASA, WMAP



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

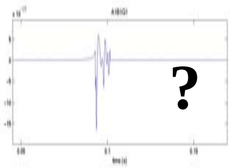
- S1: Analysis of first LIGO science data for stochastic gravitational waves, Phys. Rev. D 69, 122004 (2004)
- S3: Upper Limits on a Stochastic Background of Gravitational Waves, Phys. Rev. Lett. 95, 221101 (2005)



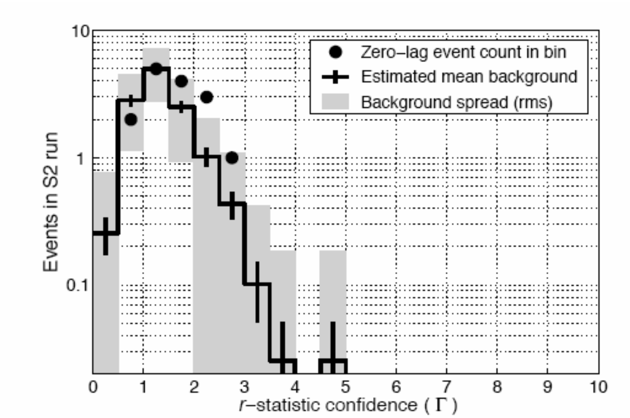
- S4 H1-L1 and H2-L1 Bayesian 90% UL: $\mathbf{\Omega_{90\%} = 6.5 \times 10^{-5}}$ (51-150 Hz)
- Also:
  - » Search for frequency dependent $\Omega(f)$
  - » directional ("radiometer") search (Ballmer, gr-qc/0510096)

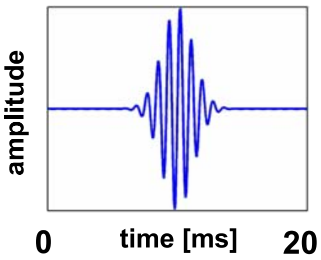
LIGO searches: “burst” sources (untriggered)

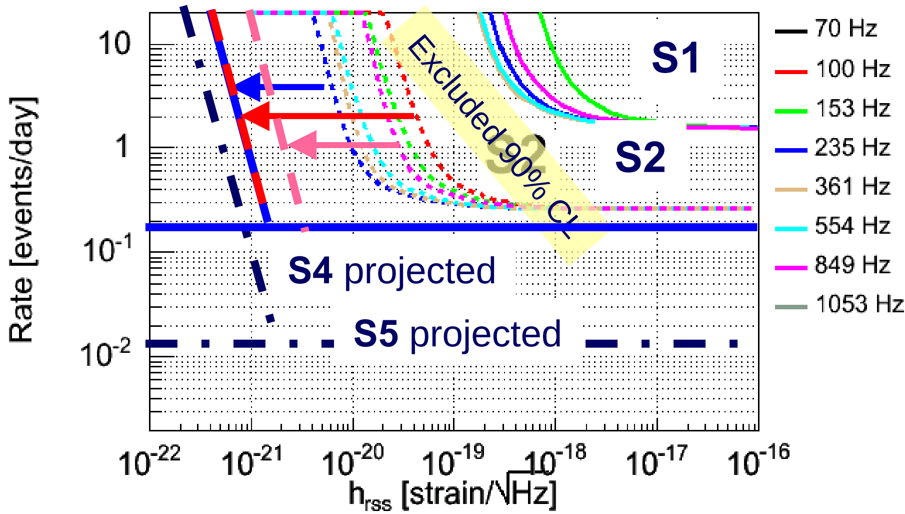
- Search for triple coincident triggers with a wavelet algorithm
- Measure confidence with waveform consistency
- Set a threshold for detection for low false alarm probability
- Compare with efficiency for detecting simple waveforms



PRD 72 (2005) 042002





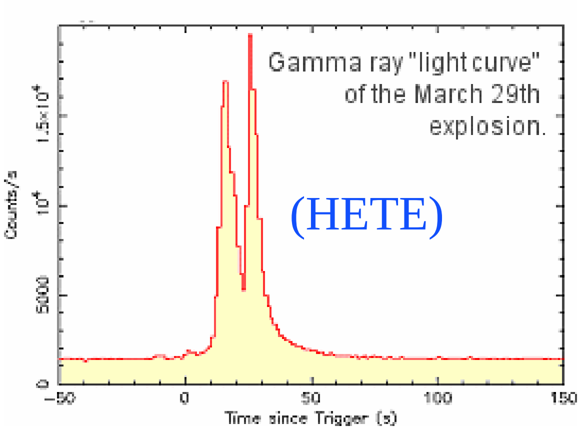


- S1: First upper limits from LIGO on gravitational wave bursts, Phys. Rev. D 69, 102001 (2004)
- S2: Upper Limits on Gravitational Wave Bursts in LIGO's Second Science Run, Phys. Rev. D 72, 062001 (2005)
- S2: Upper Limits from the LIGO and TAMA Detectors on the Rate of Gravitational-Wave Bursts, Phys.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

Latest news later today: P. Shawhan (S4). I. Yakushin (S5), new methods (S. Chatterji)

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.

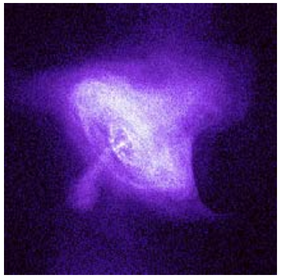


- HETE GRB030329 : during S2, search resulted in no detection (**PRD** 72, 042002, 2005)
- SWIFT, IPN, HETE-2, Konus-Wind: 39 triggers during S2/S3/S4: no loud event from any GRB, or from the set.
- S5 run: 53 GRBs (mostly SWIFT) in 5 months.
- See latest news in I. Leonor’s talk in Session W11.
- Massive flare from SGR 1806: see L. Matone poster.
- In the future: follow up short GRBs with a search for inspiral waveforms (see A. Dietz poster)

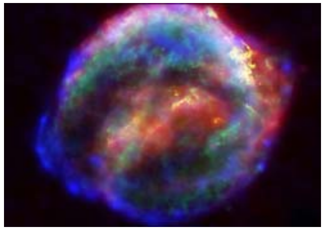
When will we see something?

Predictions are difficult… many unknowns!

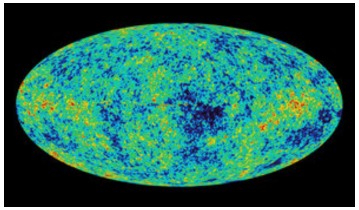
- Rotating stars: how lumpy are they?



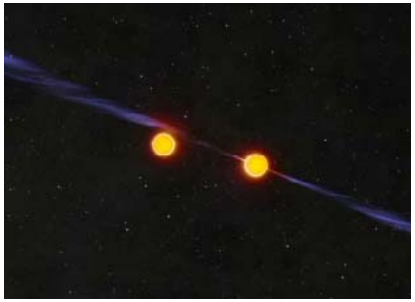
- Supernovae, gamma ray bursts:
  how strong are the waves
  (and what do they look like)?



- Cosmological background:
  how did the Universe evolve?



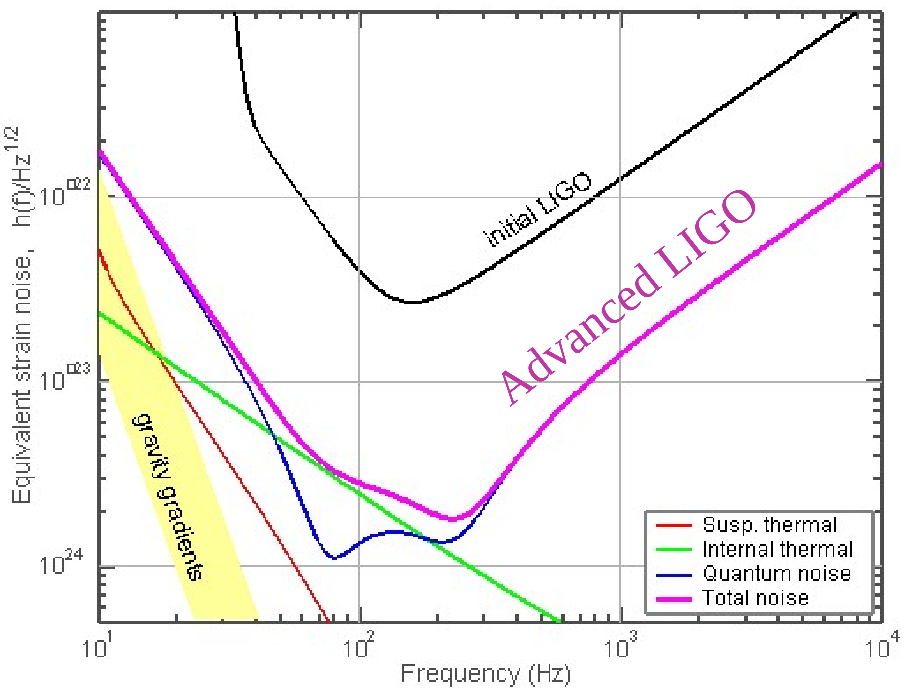
- Binary black holes: how many are there?
  What masses do they have?

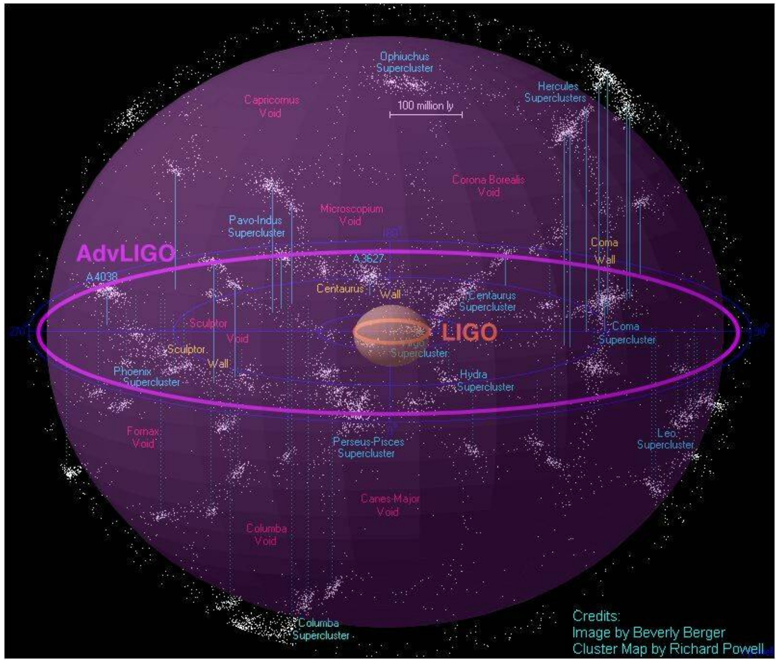


- Binary neutron stars: from observed systems
  in our galaxy, predictions are up to 1/3yrs,
  but most likely one per 30 years,
  at LIGO's present sensitivity
- From rate of short GRBs, much more optimistic
  predictions for BNS and BBH rates? ▪ Ready to be tested with S5!

LIGO detectors: future

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





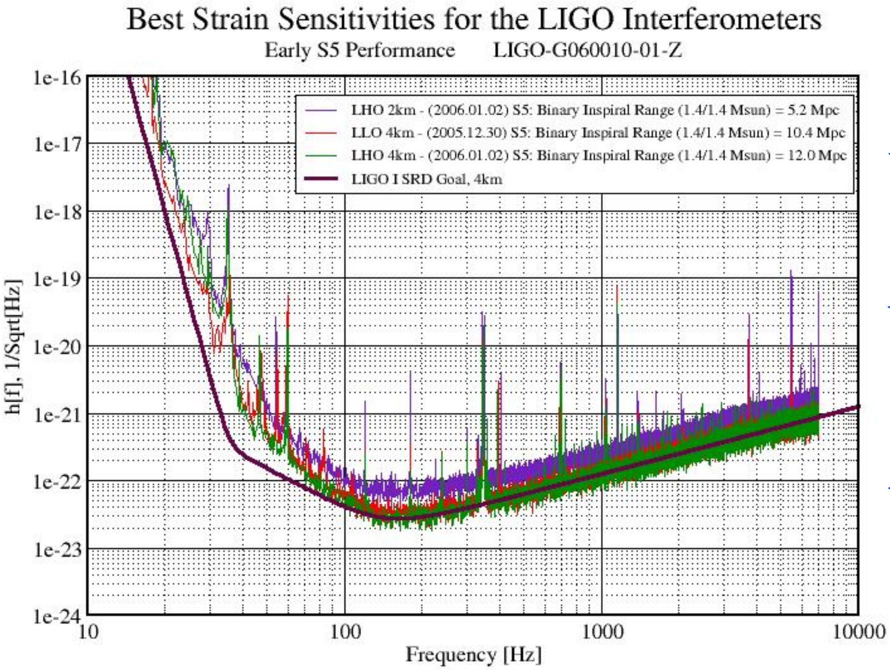
x10 better amplitude sensitivity

⇒ x1000 rate=(reach)^3

⇒ 1 year of Initial LIGO
< 1 day of Advanced LIGO !

Planned NSF Funding
in FY'08 budget.

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?