Searching for Gravitational Waves

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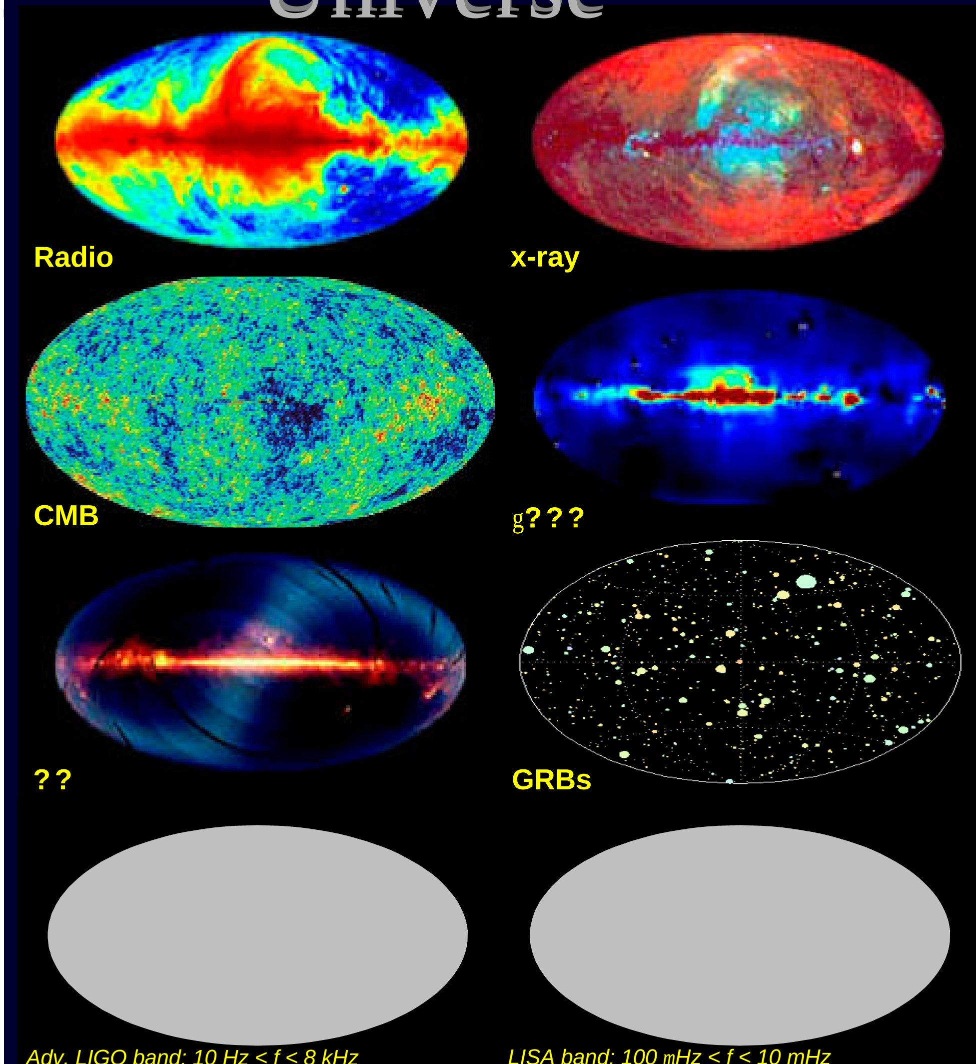
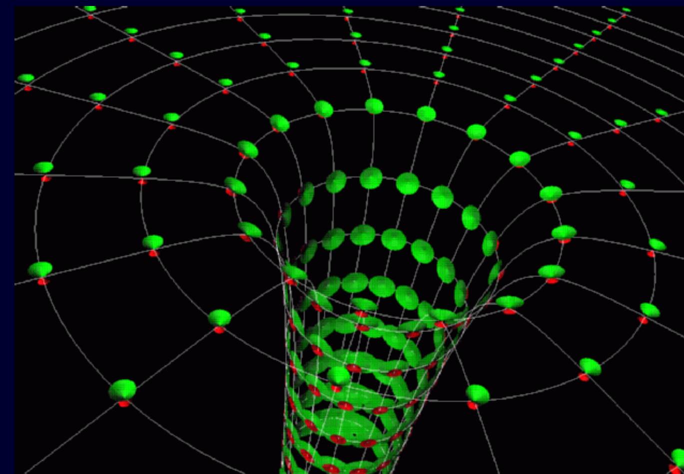
LIGO Scientific Collaboration

The EM Window on the Universe

New Window on Universe





GRAVITATIONAL WAVES WILL GIVE A NEW AND UNIQUE VIEW OF THE DYNAMICS OF THE UNIVERSE.

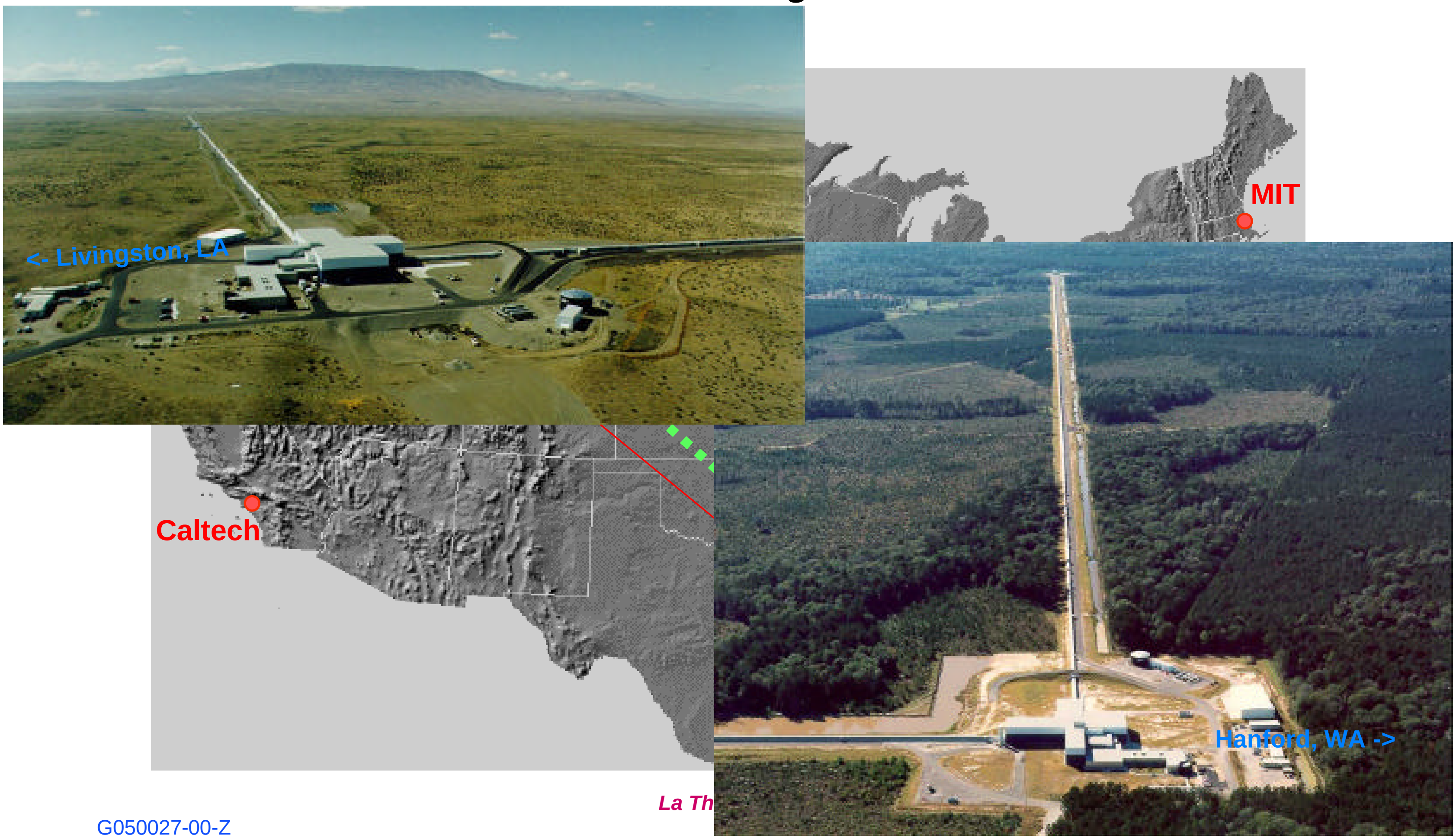
EXPECTED SOURCES:

BLACK HOLES,

SUPERNOVAE, PULSARS AND

The LIGO Observatories

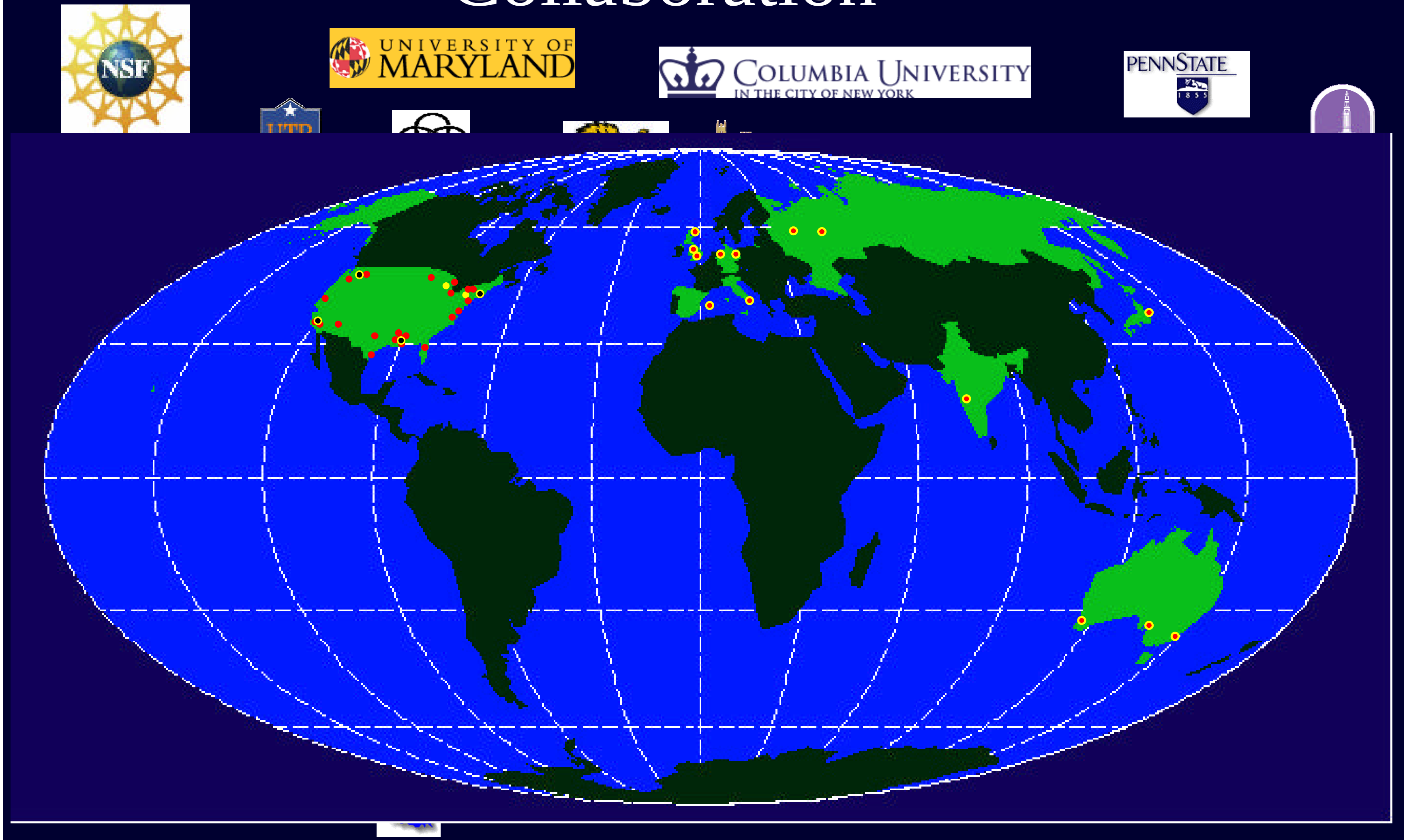
Interferometers are aligned along the great circle connecting the sites



The LIGO Scientific Collaboration

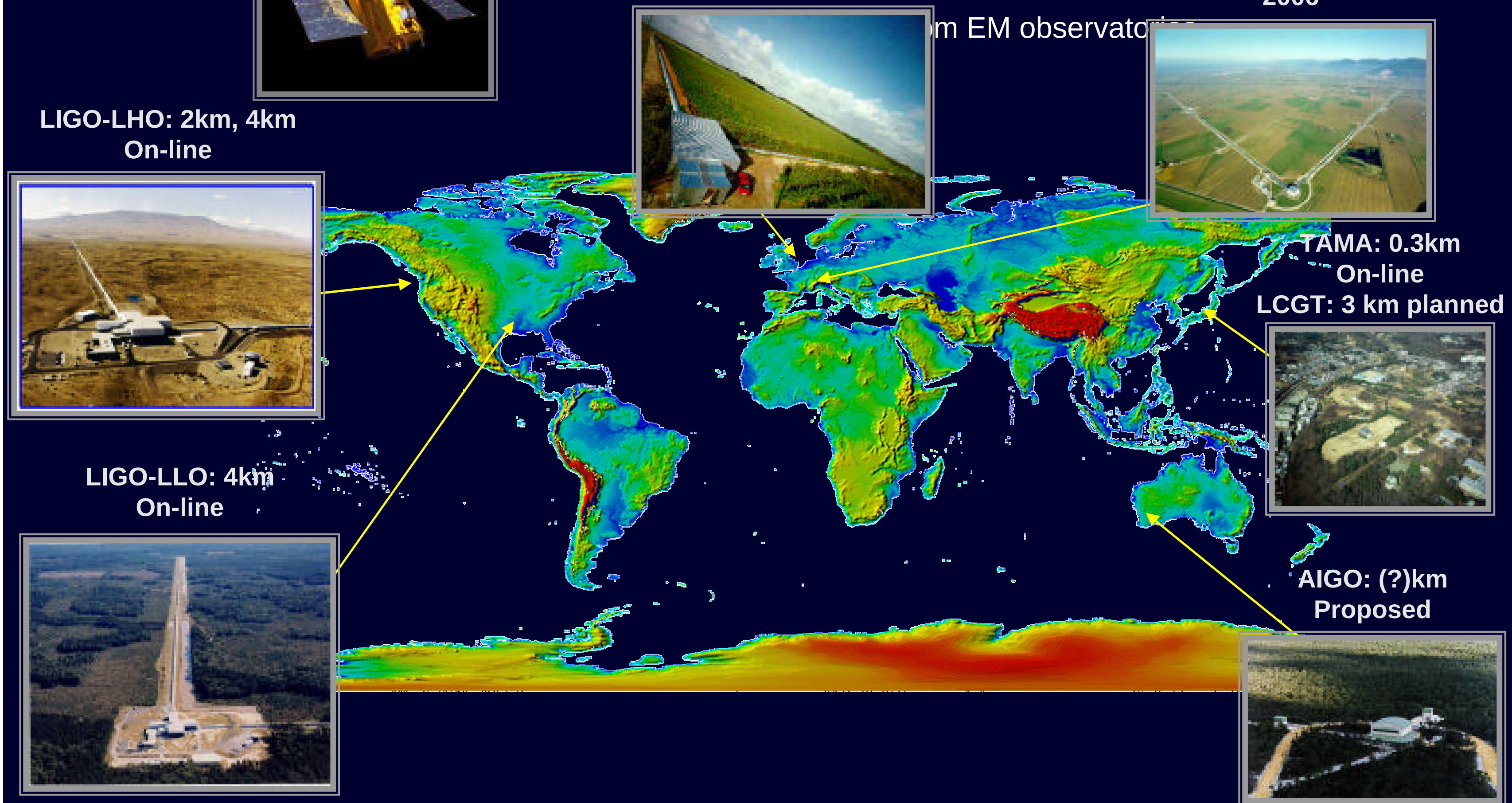
500 scientists at 42 institutions

27 US & 15 international



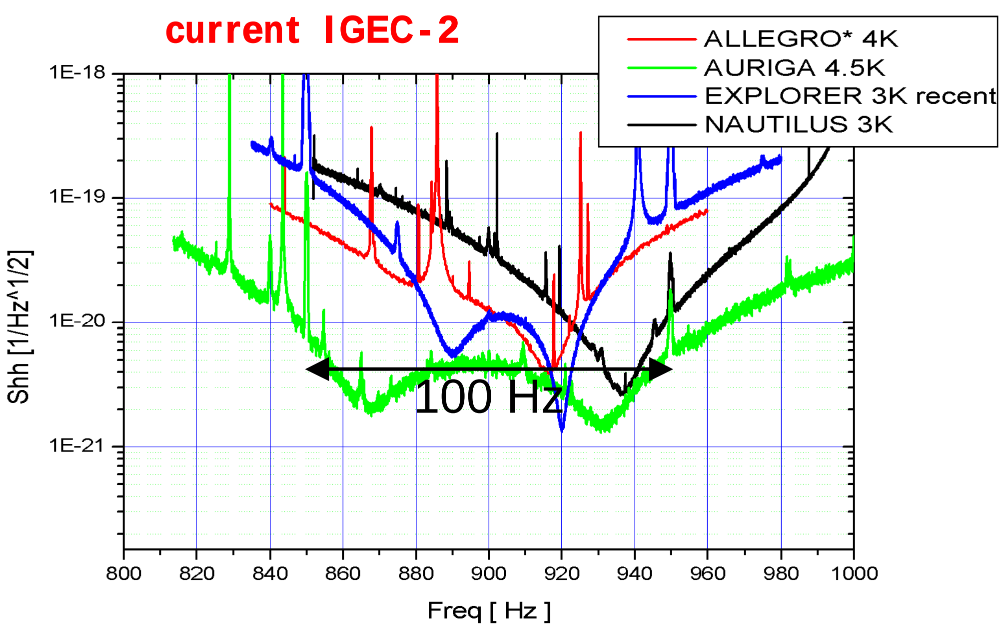
Growing International Network of GW Interferometers

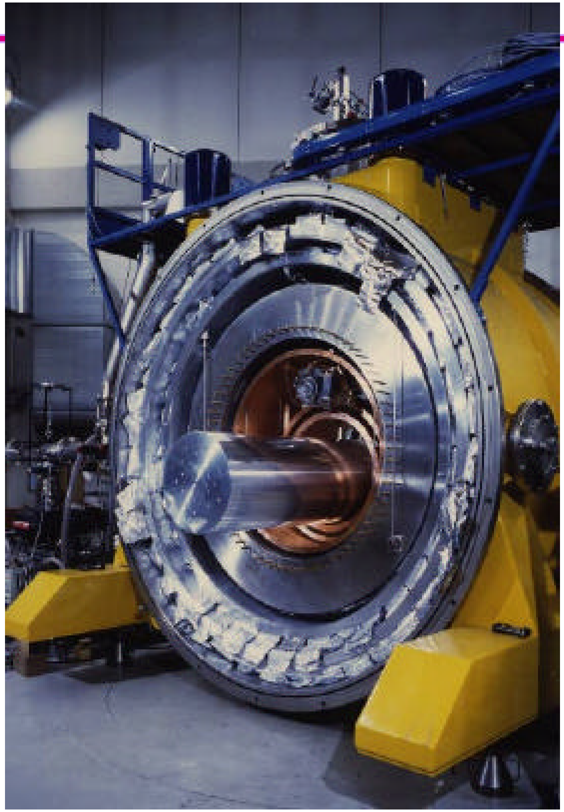
- Enhance detection confidence
- Localize sources
- Decompose the polarization of gravitational waves
- …m EM observato…



Resonant "Bar" Detectors

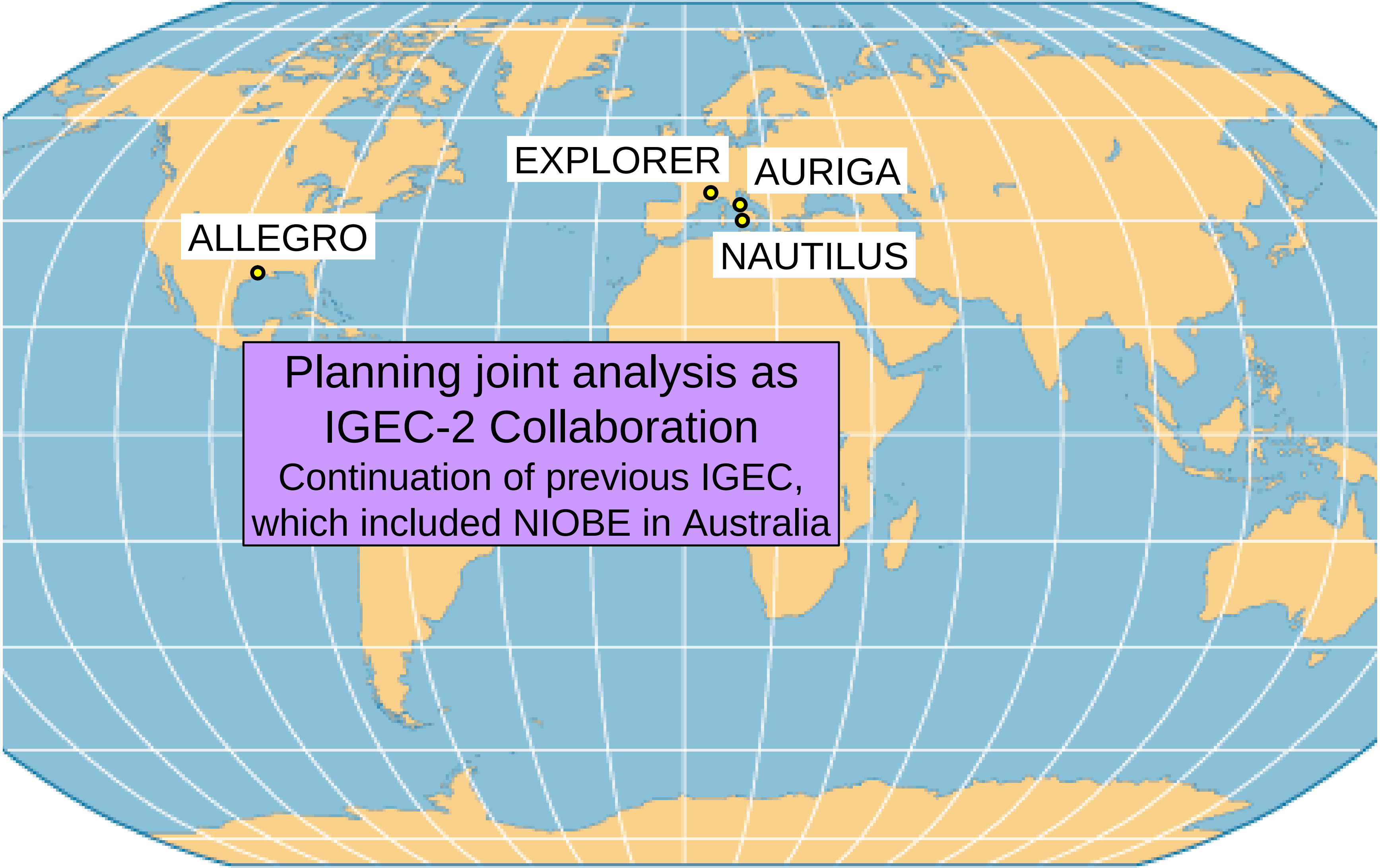
- Aluminum cylinder, suspended in middle
- GW causes it to ring at one or two resonant frequencies near 900 Hz
- Sensitive in fairly narrow band (up to ~100 Hz)





AURIGA detector (open)

Resonant "Bar" Detectors



Planning joint analysis as
IGEC-2 Collaboration
Continuation of previous IGEC,
which included NIOBE in Australia

LIGO is embarking on an important observational campaign

- We have honed our analysis methods on a series of science runs that have produced **12 (10 PRD + 2 PRL)** published results to date
  - Many more publications are in the pipeline
- Scientific output of LIGO is ramping up
- Advanced LIGO start expected for FY2008

OPPORTUNITIES for the Collaboration:

- The current S5 science run will provide at least ***1 year*** of integrated science data at design
- There will be time for one or more additional long observations
- ***Operation in coincidence with other detectors to corroborate detections***
  - Virgo (French-Italian 3km interferometer)
  - GEO600 (UK/German 600m interferometer - part of LSC)
- ***Coordination with g-ray observatories (HETE 2, Swift)***

CHALLENGES for the Collaboration :

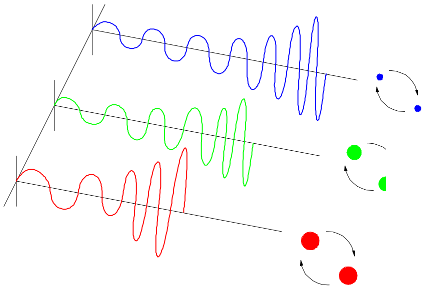
- Maintaining the impetus of a 24x7 campaign of production analysis that will enable timely discovery

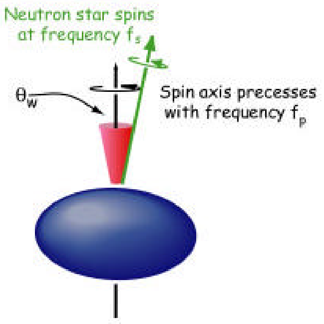
Science Goals

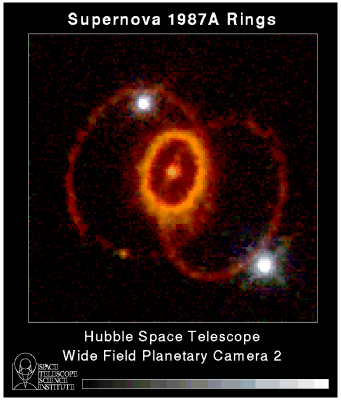
- Direct verification of two of most dramatic predictions of Einstein's general relativity
  - » Existence of gravitational waves
  - » Direct observation of black holes
- Physics
  - » Detailed tests of properties of gravitational waves including speed, polarization, strength, graviton mass, ...
  - » Probe strong field gravity around black holes and in the early universe
  - » Probe the neutron star equation of state
- Astronomy
  - » By performing routine astronomical observations, understand compact binary populations, rates of supernovae explosions, test gamma-ray burst models
- LIGO provides a new window on the Universe

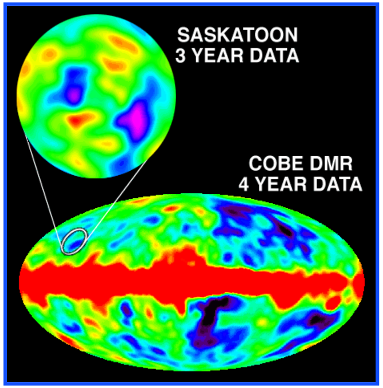
Astrophysical Sources of Gravitational Waves

- Compact binary systems
  - » Black holes and neutron stars
  - » Inspiral and merger
  - » Probe internal structure, populations, and spacetime geometry
- Spinning neutron stars
  - » LMXBs, known & unknown pulsars
  - » Probe internal structure and populations
- Neutron star birth
  - » Tumbling and/or convection
  - » Correlations with EM observations
- Stochastic background
  - » Big bang & other early universe
  - » Background of GW bursts



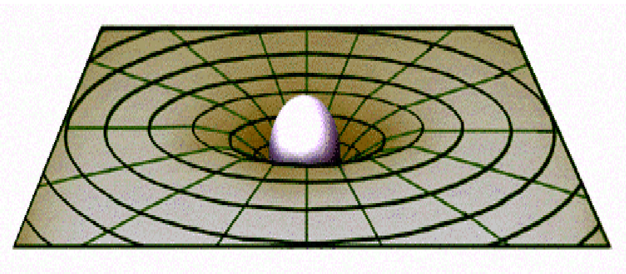






Gravitational waves

- Transverse distortions of the space-time itself ➔ ripples of space-time curvature
- Propagate at the speed of light
- Push on freely floating objects ➔ stretch and squeeze the space transverse to direction of propagation
- Energy and momentum conservation require that the waves are quadrupolar ➔ aspherical mass distribution



$$h = \frac{\Delta L}{L}$$

Astrophysics with GWs vs. E&M

E&M	GW
Accelerating charge	Accelerating aspherical mass
Wavelength small compared to sources ➔ images	Wavelength large compared to sources ➔ no spatial resolution
Absorbed, scattered, dispersed by matter	Very small interaction; matter is transparent
10 MHz and up	10 kHz and down

- Very different information, mostly mutually exclusive
- Difficult to predict GW sources based on EM observations

Strength of GWs: e.g. Neutron Star Binary

- Gravitational wave amplitude (strain)

$$h_{mn} = \frac{2G}{c^4 r}\ddot{I}_{mn} \Rightarrow h \approx \frac{4p^2 GMR^2 f_{orb}^2}{c^4 r}$$

- For a binary neutron star pair

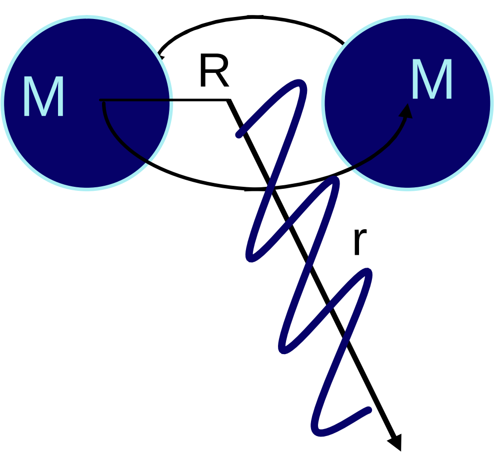
$M \approx 10^{30}$ kg

$R \approx 20$ km

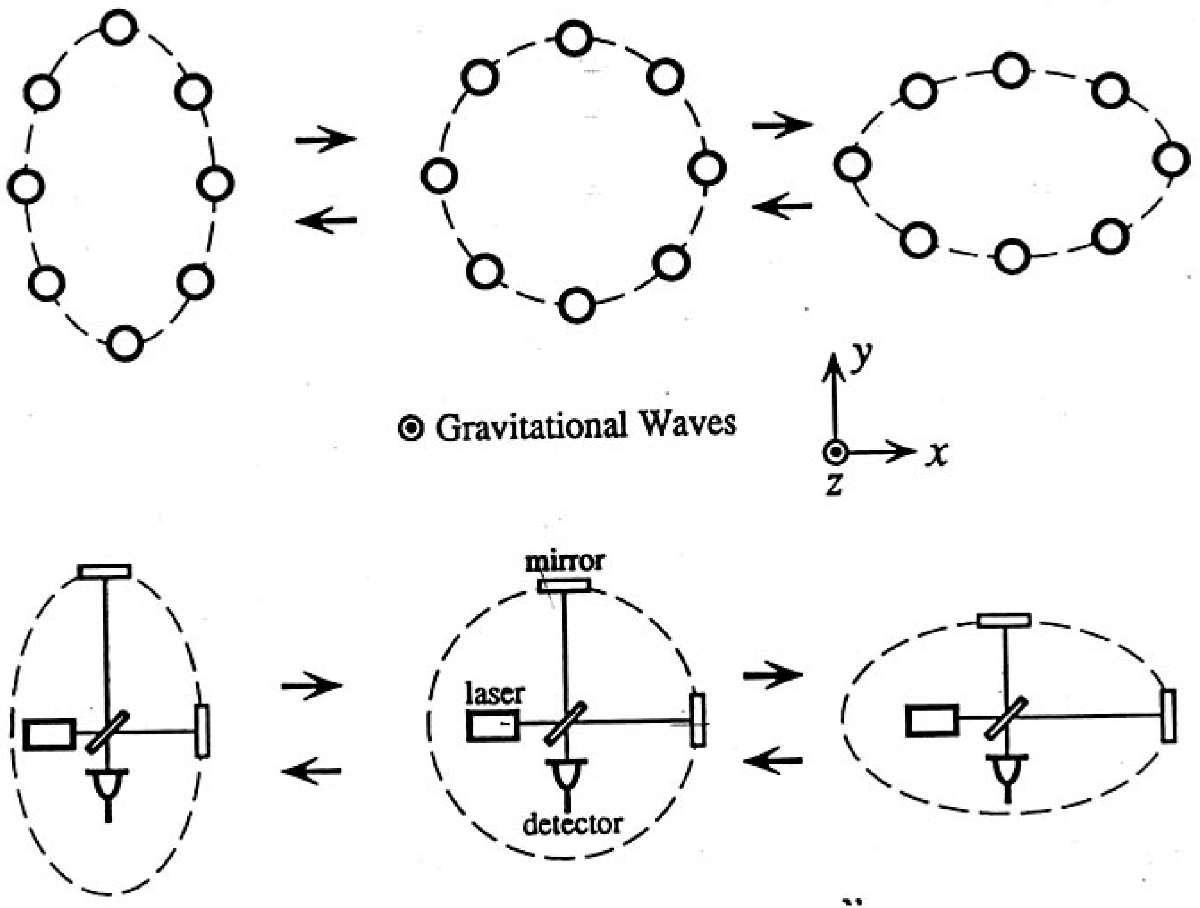
$f \approx 400$ Hz

$r \approx 10^{23}$ m

$\Rightarrow$ $h \sim 10^{-21}$



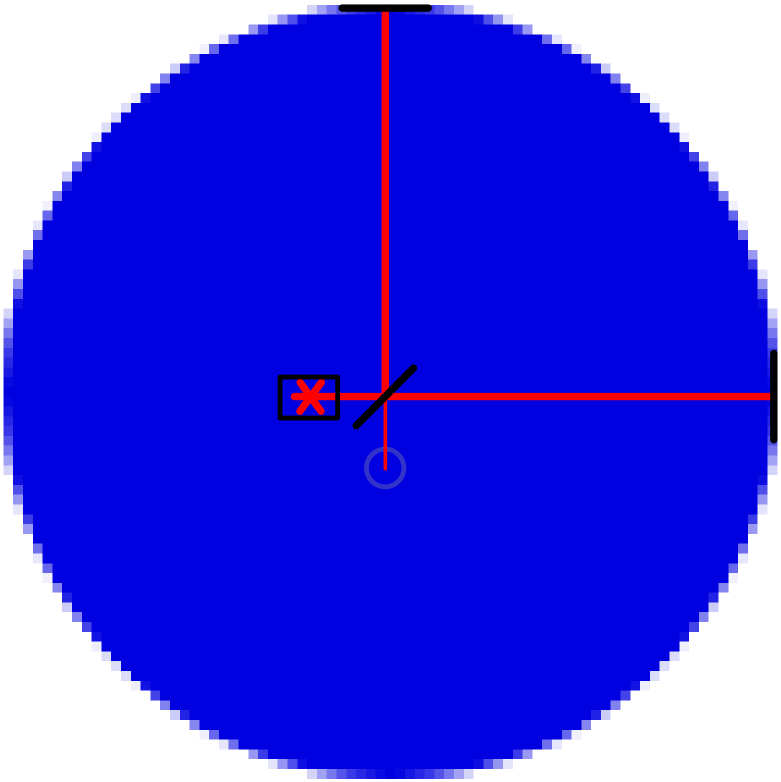
Effect of a GW on matter



Interferometer Response to a GW

- GW causes *differential* changes in arm lengths, sensed interferometrically by photodiode

- Response depends on direction and polarization of incoming wave



Measurement and the real world

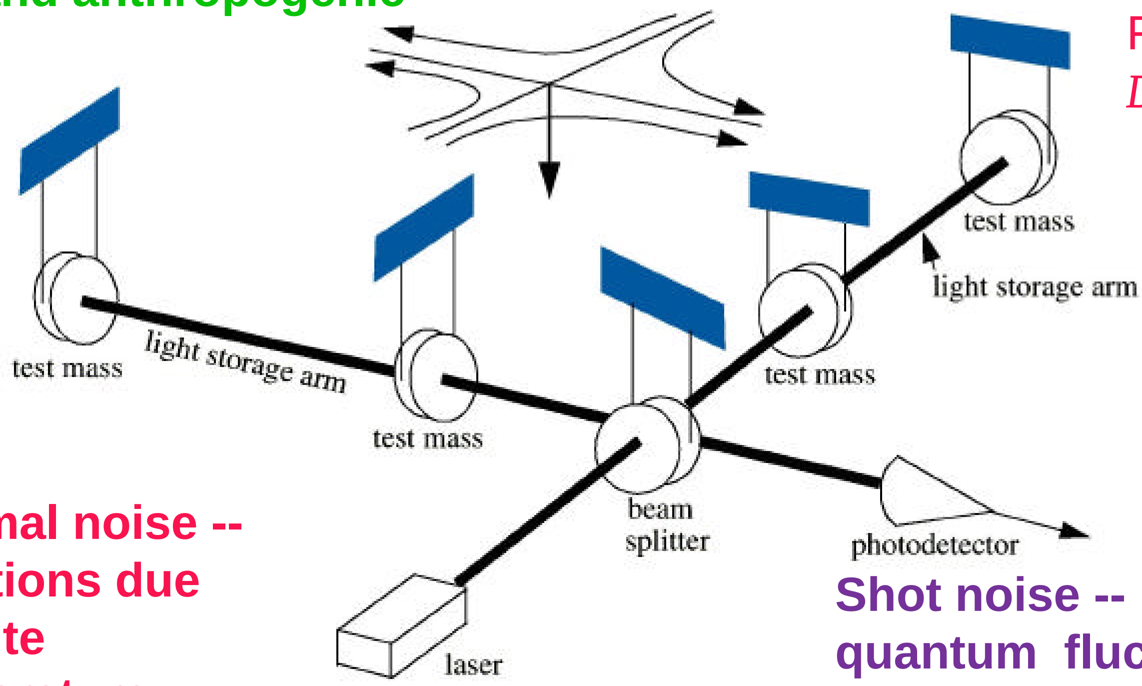
- How to measure the gravitational-wave?
  » Measure the displacements of the mirrors of the interferometer by measuring the phase shifts of the light
- What makes it hard?
  » GW amplitude is small
  » External forces also push the mirrors around
  » Laser light has fluctuations in its phase and amplitude

GW detector at a glance

Seismic motion -- ground motion due to natural and anthropogenic sources

$$h = \Delta L / L$$

$L \sim 4$ km
For $h \sim 10^{-21}$
$DL \sim 10^{-18}$ m

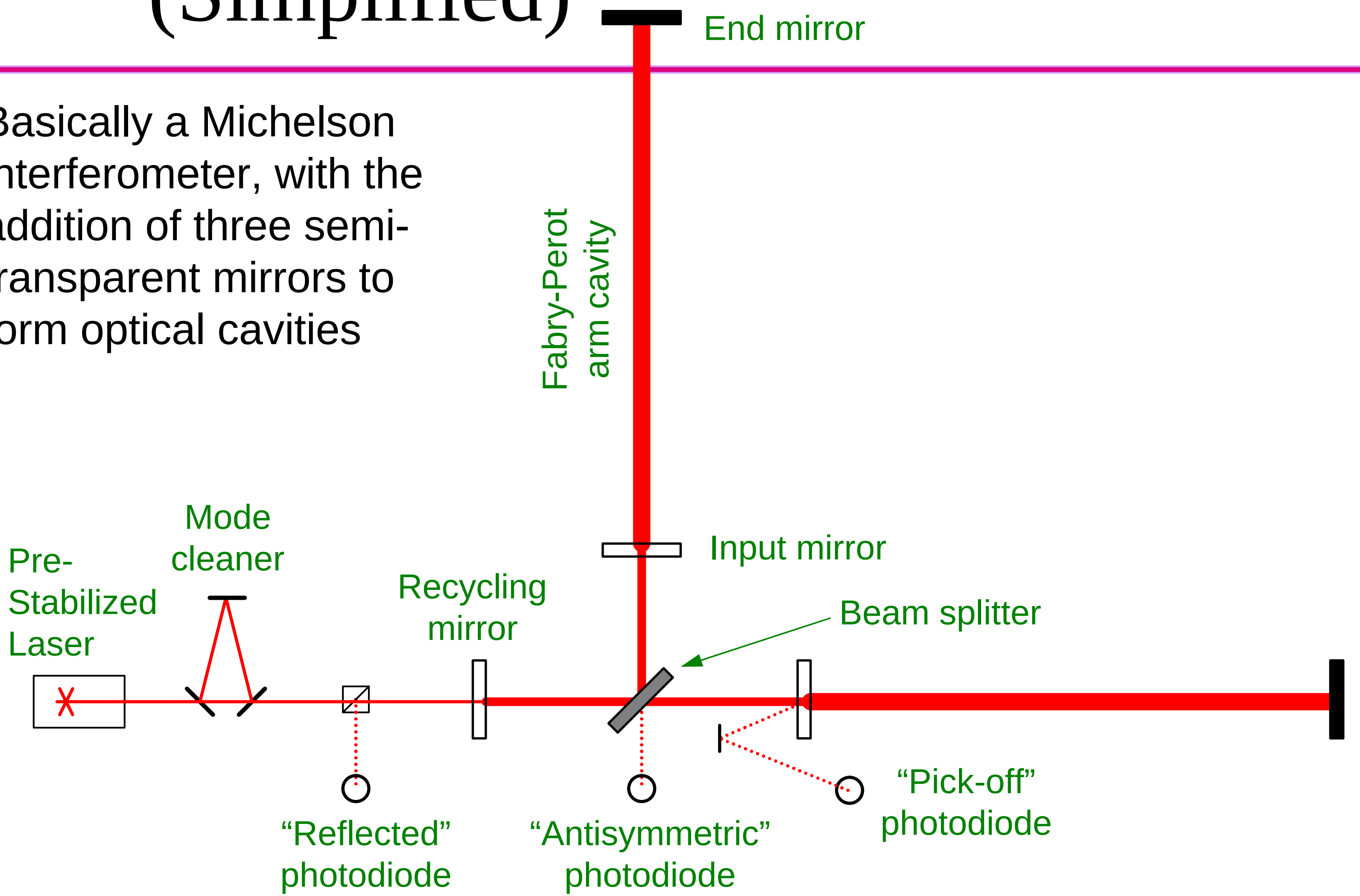


Thermal noise -- vibrations due to finite temperature

Shot noise -- quantum fluctuations in the number of photons detected

LIGO Optical Layout (Simplified)

Basically a Michelson interferometer, with the addition of three semi-transparent mirrors to form optical cavities



La Thuile 2006

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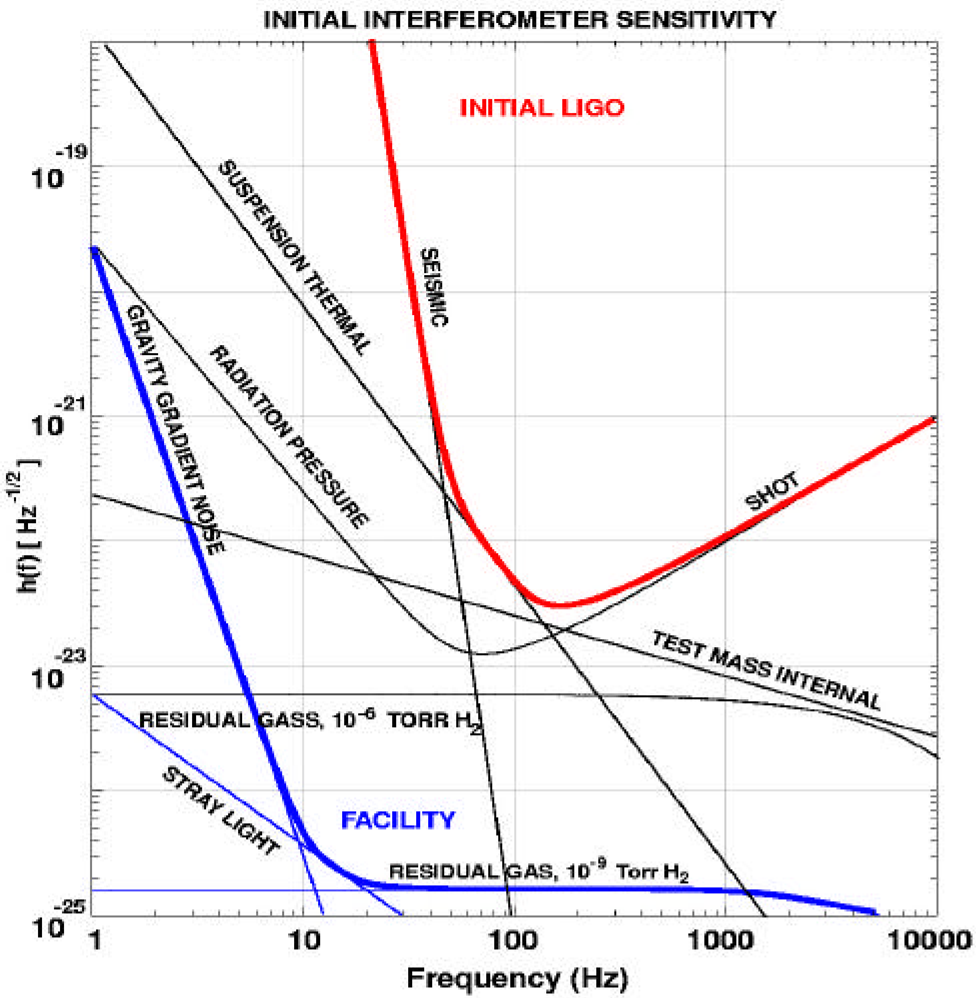
Initial LIGO Sensitivity Goal



Strain sensitivity
< 3×10^{-23} $1/Hz^{1/2}$
at 200 Hz

Have achieved strain RMS of 10^-21 in a 100 Hz bandwidth

Displacement Noise
- Seismic motion
- Thermal Noise
- Radiation Pressure

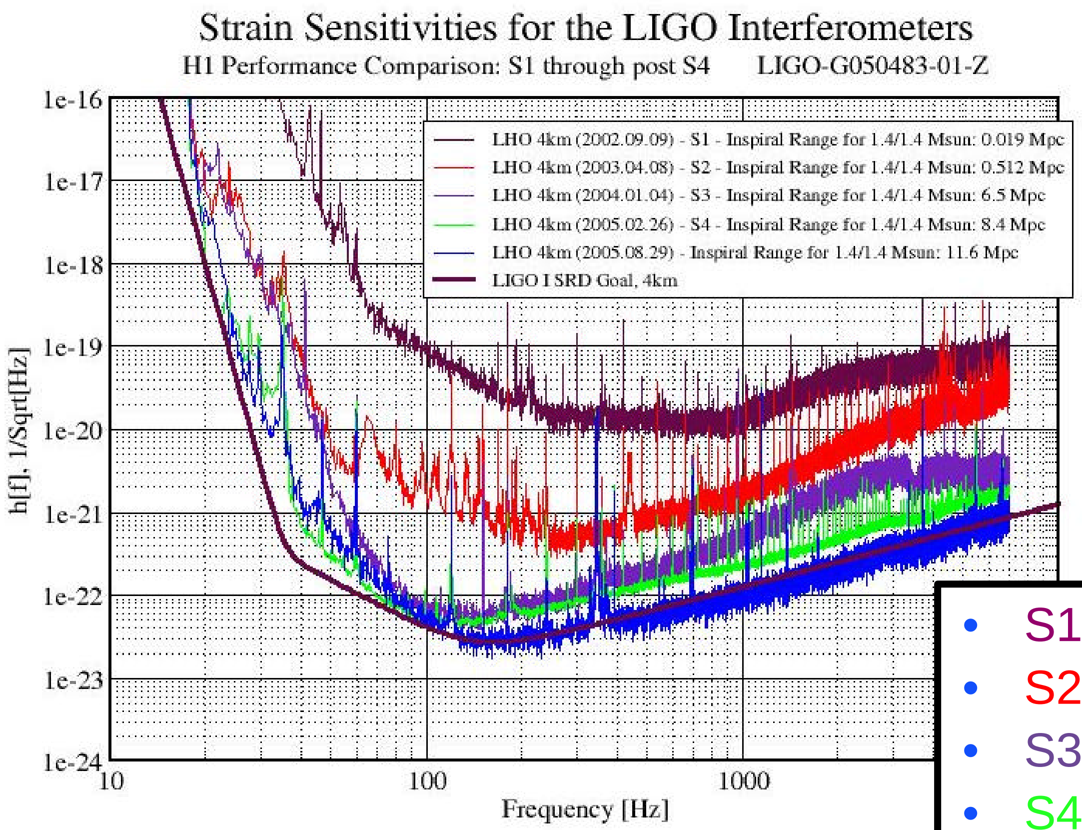
Sensing Noise
- Photon Shot Noise
- Residual Gas

Facilities limits much lower

Reaching LIGO's Science Goals

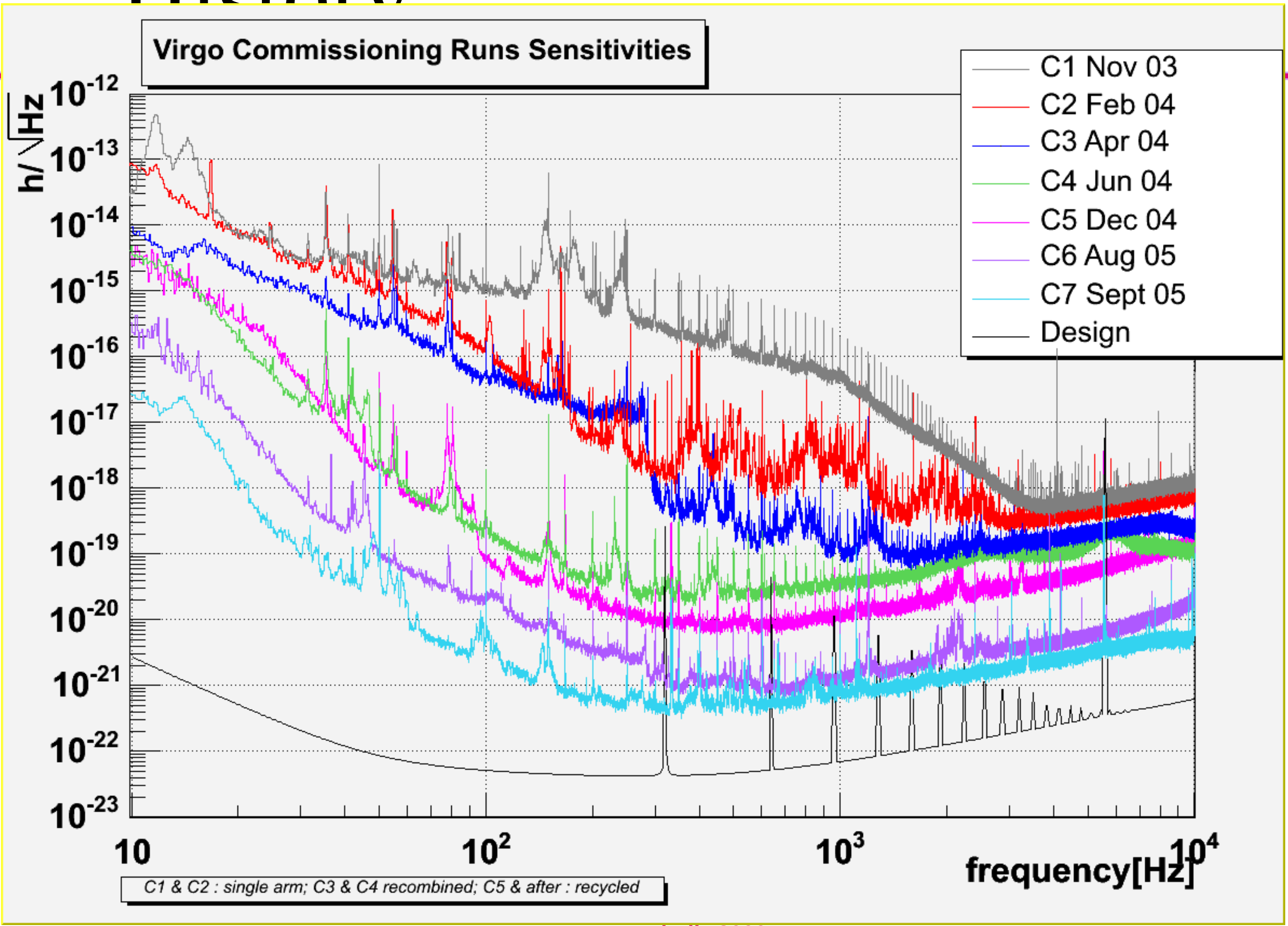
- **Interferometer commissioning**
  - » Intersperse commissioning and data taking consistent with obtaining one year of integrated data at $h = 10^{-21}$ by end of 2006
- **Science runs and astrophysical searches**
  - » Science data collection and intense data mining interleaved with commissioning
    - **S1 Aug 2002 – Sep 2002 duration: 2 weeks**
    - **S2 Feb 2003 – Apr 2003 duration: 8 weeks**
    - **S3 Oct 2003 – Jan 2004 duration: 10 weeks**
    - **S4 Feb 2005 – Mar 2005 duration: 4 weeks**
    - **S5 Nov 2005 – ... duration: 1 yr integrated**
- **Advanced LIGO**

History of science runs



- S1: 23 Aug – 9 Sep ‘02
- S2: 14 Feb – 14 Apr ‘03
- S3: 31 Oct ‘03 – 9 Jan ‘04
- S4: 22 Feb – 23 Mar ‘05
- S5: 4 Nov ‘05 ....

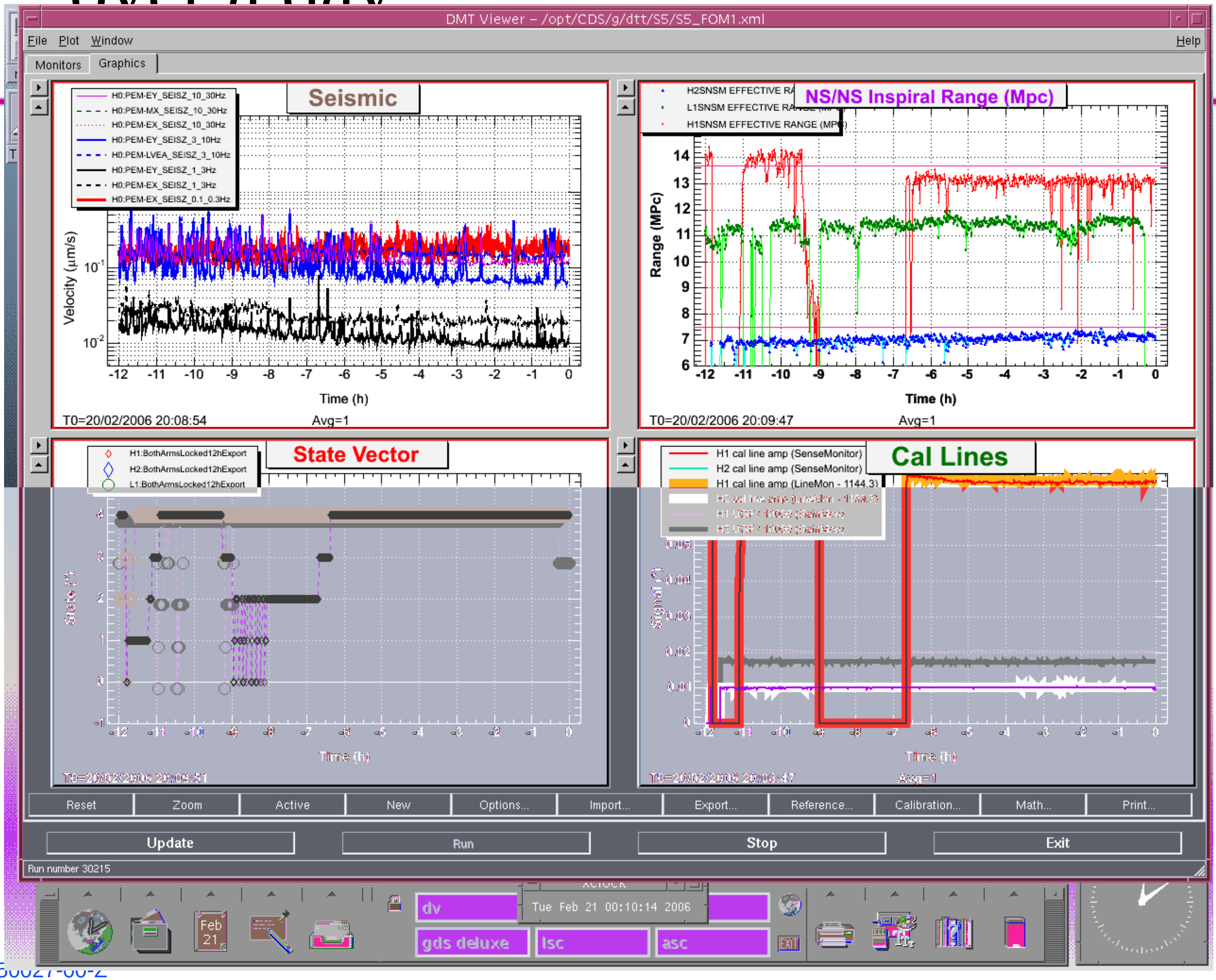
VIRGO Sensitivity History



Science Run 5 (S5) begins

- Schedule
  - » Started in November, 2005
  - » Get 1 year of data at design sensitivity
  - » Small enhancements over next 3 years
- Typical sensitivity (in terms of inspiral distance)
  - » H1 10 to 12 Mpc (33 to 39 million light years)
  - » H2 5 Mpc (16 million light years)
  - » L1 8 to 10 Mpc (26 to 33 million light years)
- Sample duty cycle (Nov. 2005 to Jan. 2006)
  - » 55% (L1), 68% (H1), 83% (H2) individual
  - » 45% triple coincidence

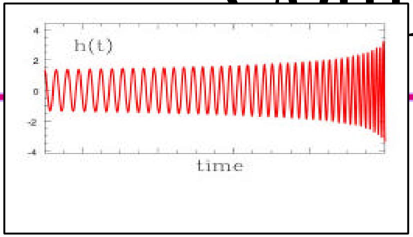
Example of figures of merit over a day

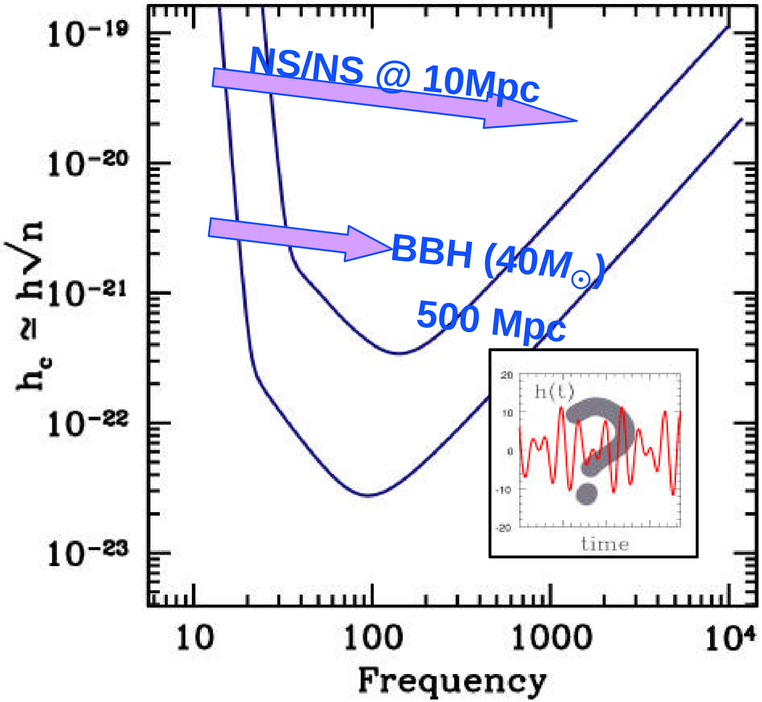


An exciting time in gravitational wave detection

- The initial LIGO detectors have reached their target sensitivity
  - » Incredibly small motion of mirrors → 10^{-19} m (less than 1/1000 the size of a proton)
- LIGO has begun its biggest and most sensitive science data run
- Unprecedented sensitivity - prospects for new science are very promising
  - » On *Science* magazine's list of things to watch out for in 2006
- Growing international collaborative effort (LIGO, GEO, Virgo, TAMA) in the mutual search for events
- Design of an even more sensitive next generation instrument is progressing rapidly

Inspiral and Merger of Compact Binaries

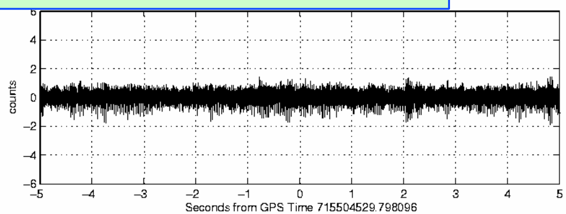




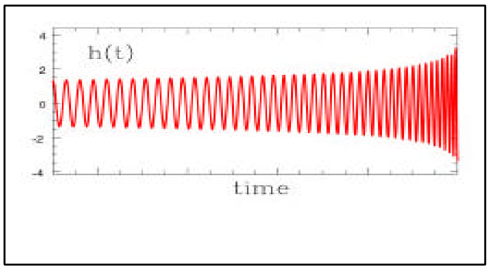
- LIGO is sensitive to:
  - » Gravitational waves from binary systems containing neutron stars & stellar mass black holes
  - » Last several minutes of inspiral driven by GW emission
  - » Clean systems, accurate modeling shows that GW's depend on masses/spins only
- Binary Neutron Star Rates
  - » Theoretical estimates give upper bound of 1/3yr for LIGO S5
- Binary Black Hole Rates
  - » Theoretical estimates give upper bound of 1/yr for LIGO S5

Matched filtering

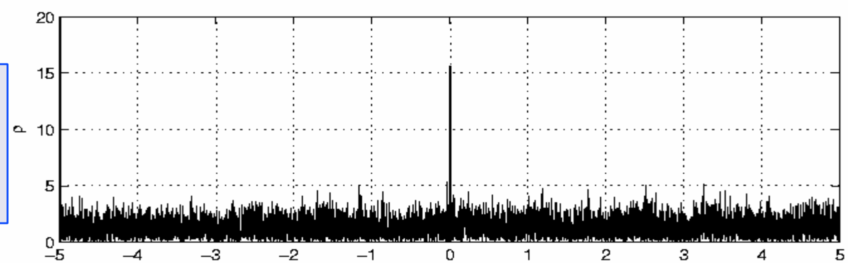
GW Channel
+ simulated inspiral



Filter to suppress high/low freq



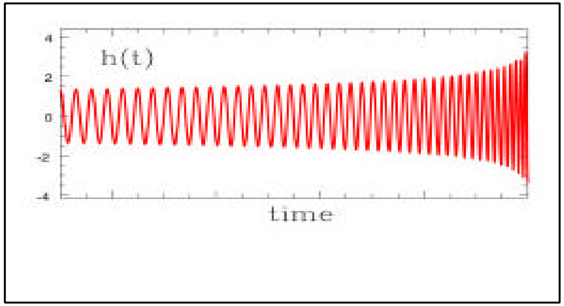
SNR



Coalescence Time

How to detect inspiral waves

- Use template based matched filtering algorithm
- Search for non-spinning binaries
  - » 2.0 post-Newtonian waveforms

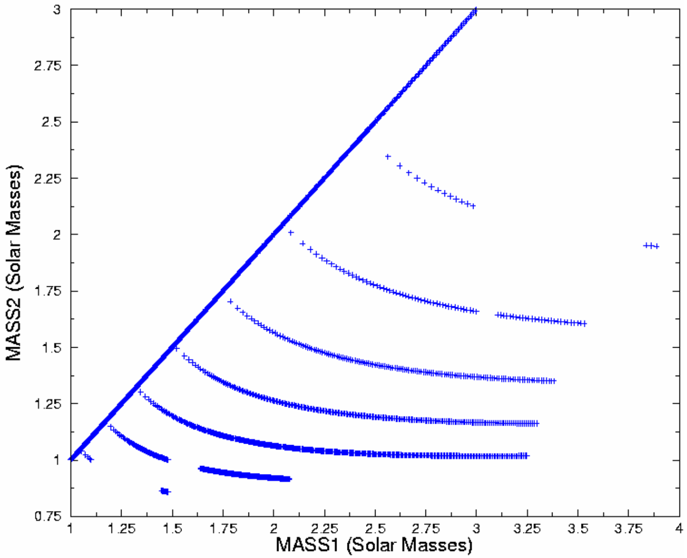


$$s(t) = (1\mathrm{Mpc}/D) \times [\sin(a)\, h^l_s (t-t0) + \cos(a)\, h^l_c (t-t0)]$$

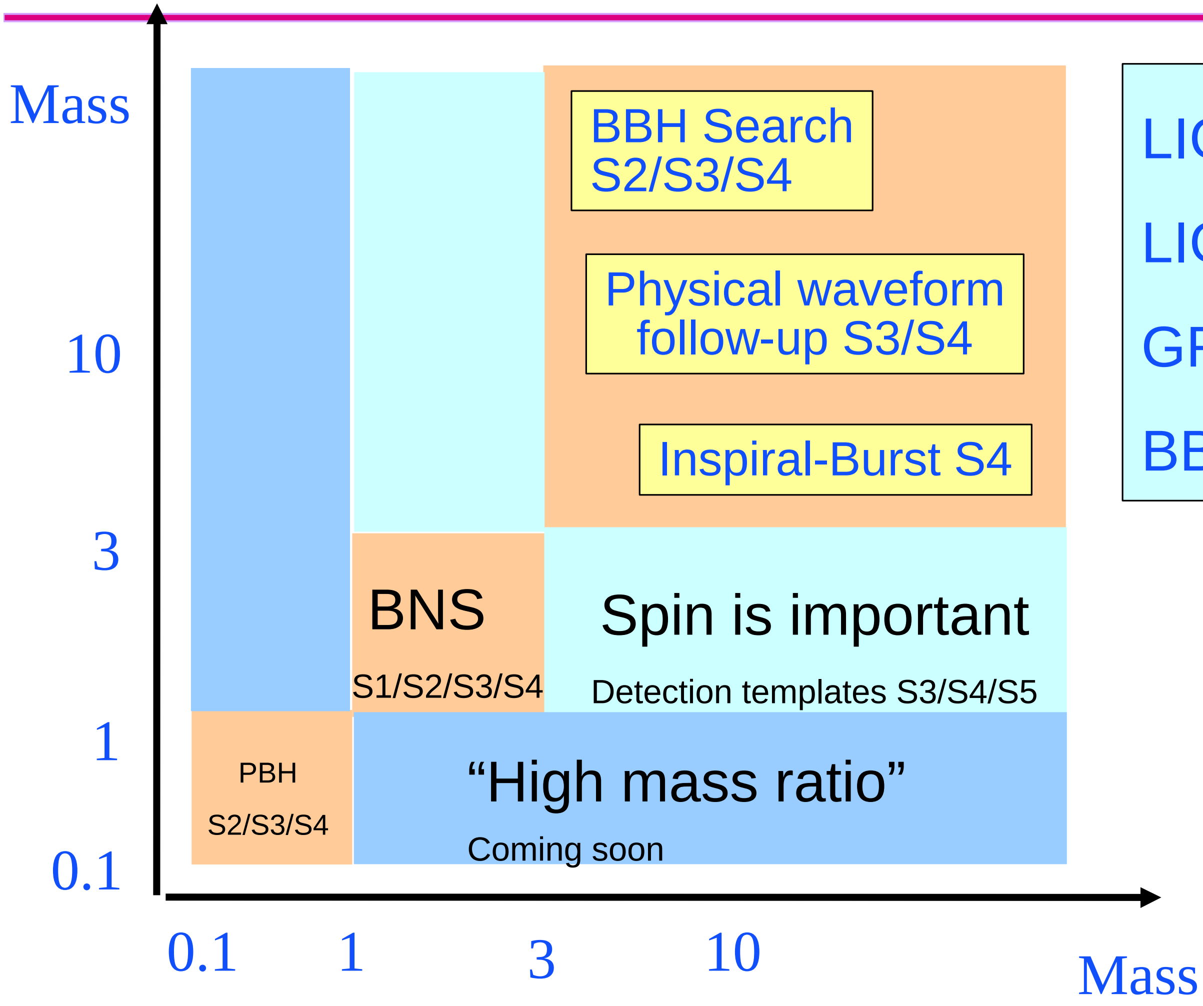
- D: effective distance; a: phase

Discrete set of templates labeled by l=(m1, m2)

- » 1.0 Msun < m1, m2 < 3.0 Msun



Active Inspiral Searches



LIGO-Virgo analysis

LIGO-TAMA analysis

GRB Coincidence

BBH follow up

Binary Neutron Star Inspiral (S2)

- Upper limit on binary neutron star coalescence rate
  - Express the rate as a rate per **Milky-Way Equivalent Galaxies** (MWEG)

$$R_{90\%} = \frac{2.3}{T_{obs} N_G} = \frac{2.3}{355 \text{ hrs } \times 1.14} < 50 \text{ /year/MWEG}$$

Theoretical prediction: R < 2 x 10^{-5} / yr/MWEG

  - Express as the **distance** to which radiation from a 1.4 M_{sun} pair would be detectable with a SNR of 5

$$D = 2 \text{ Mpc} \approx 10^{22} \text{ m}$$

  - Important to look out further, so more galaxies can contribute to population of NS

Phys.Rev. D72 (2005) 082001

New rate predictions from SHBs?

- 4 Short Hard gamma ray Bursts since May 2005
  - » Detected by Swift and HETE-2, with rapid follow-up using Hubble, Chandra, and look-back at BATSE
  - » Find that SHB progenitors are too old (>5 Gyr) to be supernova explosions (cause of long GRBs)
  - » Remaining candidates for progenitors of SHBs: old double neutron star (DNS) or neutron star-black hole (NS-BH) coalescences
  - » Predicted rates for Initial LIGO (S5) could be as high as

$R_{NS\text{-}BH} \sim 30\ yr^{-1}$ $RD_{NS\text{-}NS} \sim 3\ yr^{-1}$

Nakar, Gal-Yam, Fox, astro-ph/0511254

  - » But great uncertainty in rate estimates

Binary Neutron Star Search: LIGO S5 Range

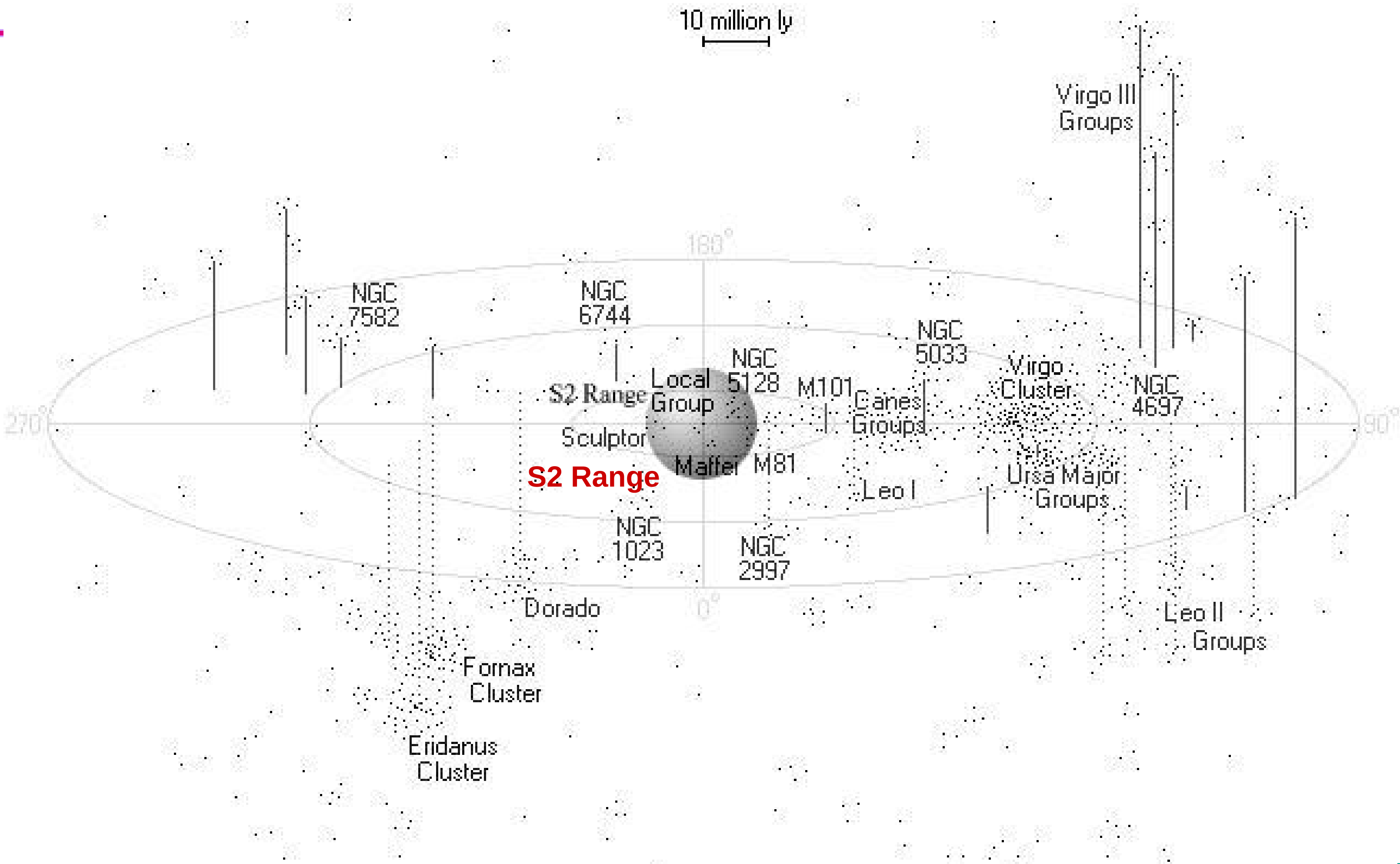


Image: R. Powell

Binary Inspiral Searches: Approximate S5 Ranges

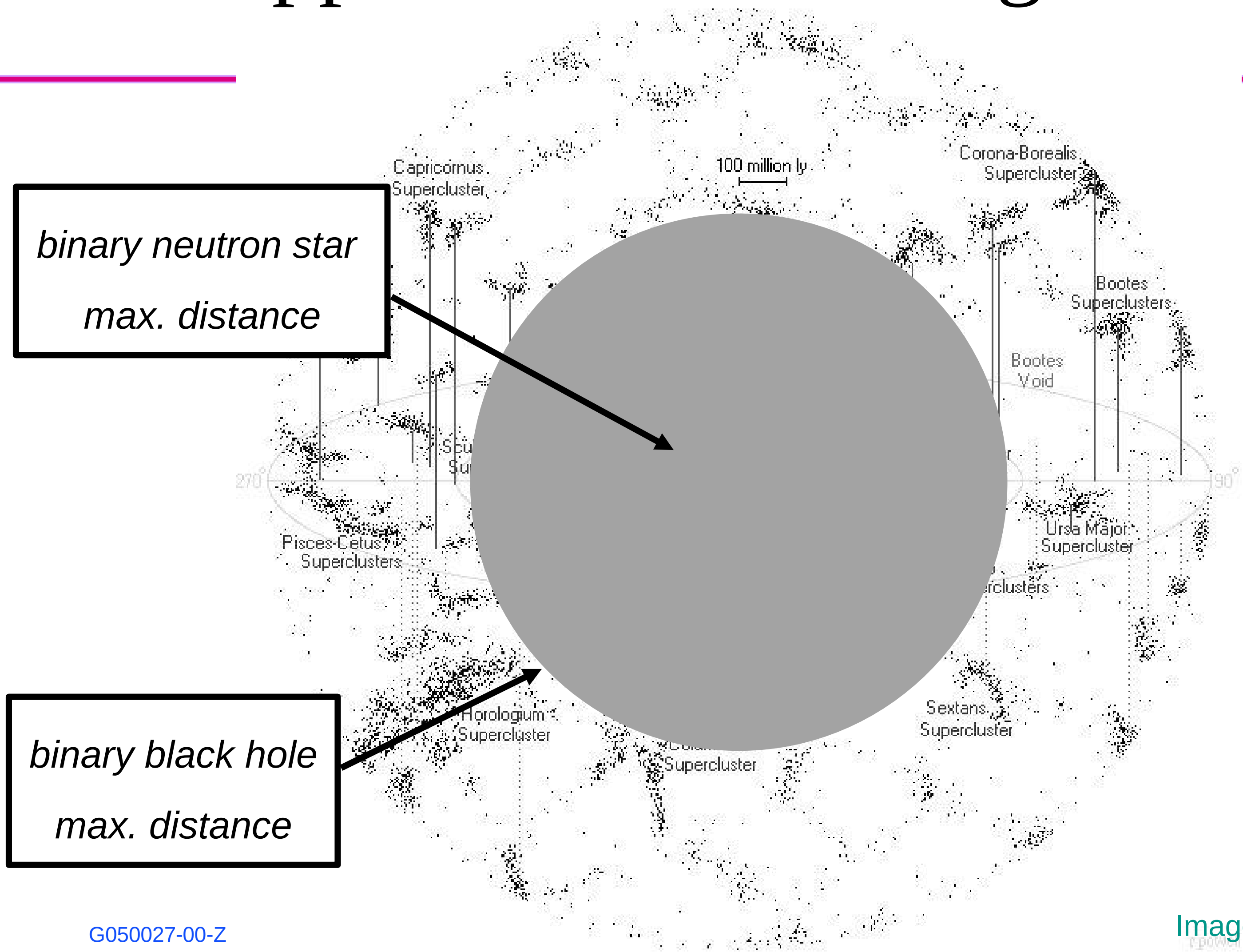
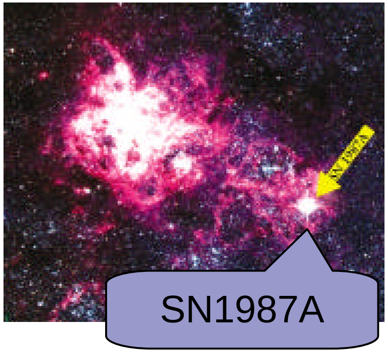


Image: R. Powell

Burst Sources

- General Properties
  - » Duration << observation time
- Promise
  - » Unexpected sources and serendipity
  - » Search techniques must use minimal information
- Examples
  - » Black hole and neutron star merger
  - » Supernovae & gamma-ray bursters
  - » Instabilities in nascent neutron stars
  - » Kinks and cusps on cosmic strings



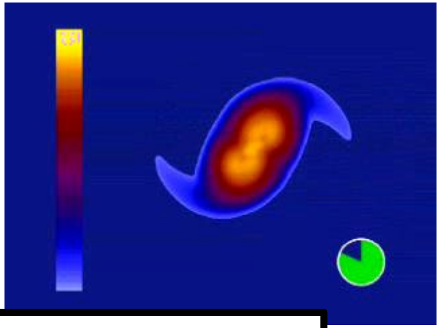


Image: Baumgarte,Shapiro, Shibata

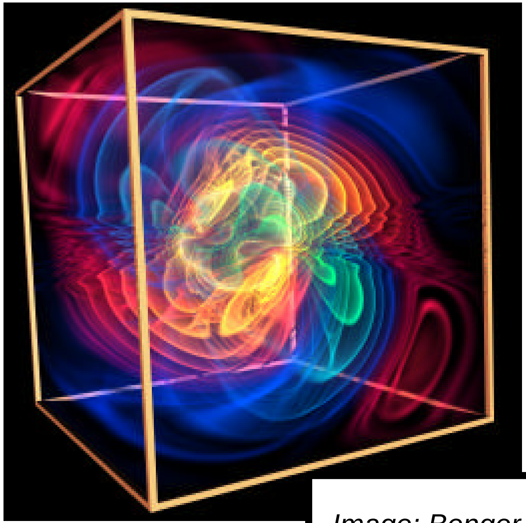


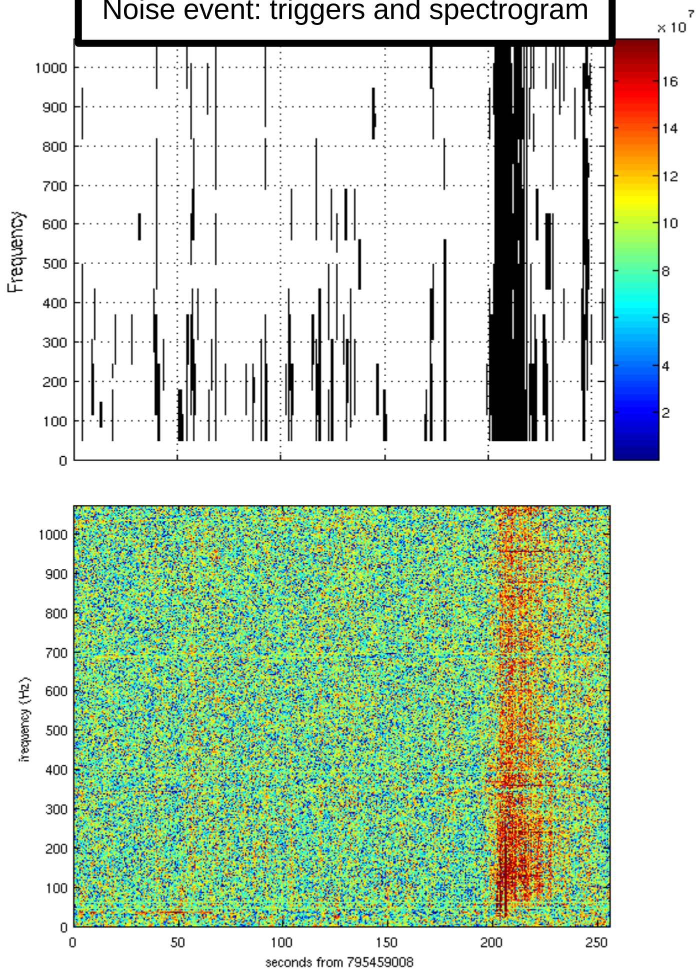
Image: Benger

Burst Group Activities

- Search for bursts of unknown origin/waveform
  - » Generate event triggers for each instrument
  - » Veto triggers due to instrumental artifacts
  - » Determine upper limit on rate as function of strain
  - » Monte Carlo by simulated injections of astrophysical motivated signals and other model burst waveforms
- Ongoing activities
  - » Search for bursts associated with GRB's and other EM triggers
  - » Untriggered searches by broad range of methods (cast wide net)
  - » Inpiral-burst-ringdown coincidence searches
  - » Cosmic string burst search
- Other Activities:
  - » LIGO-TAMA Joint Analysis of S2 Data (complete)
  - » LIGO-VIRGO Working Group

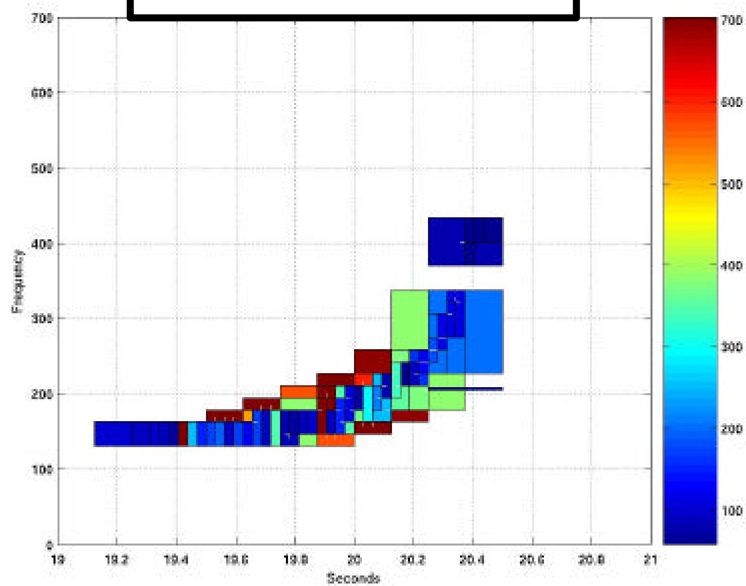
Search Method: Time-frequency decompositions

Noise event: triggers and spectrogram



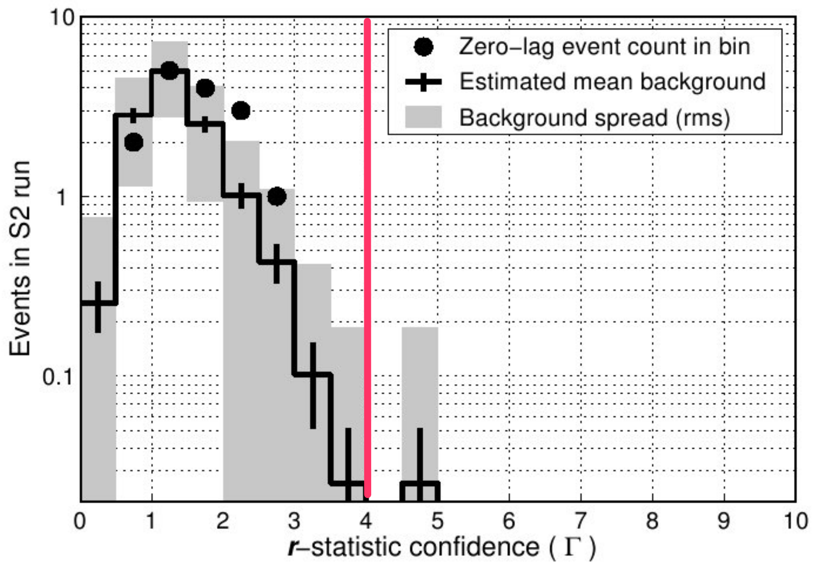
Requires coincidence between at least two interferometers & detailed examination of instrumental & environmental behavior

Simulated injection in hardware



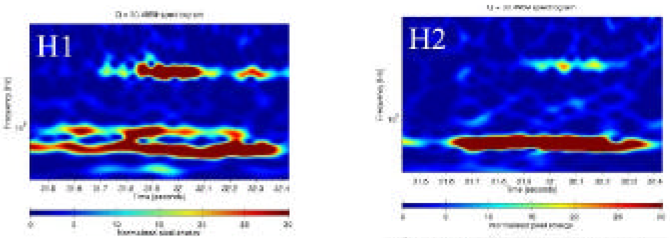
Burst search results

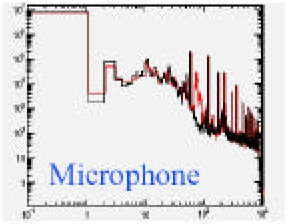
Phys. Rev. D. 72, 062001 (2005)



- Raw results are reported
- Interpreted upper limit on representative waveform families is also report ......

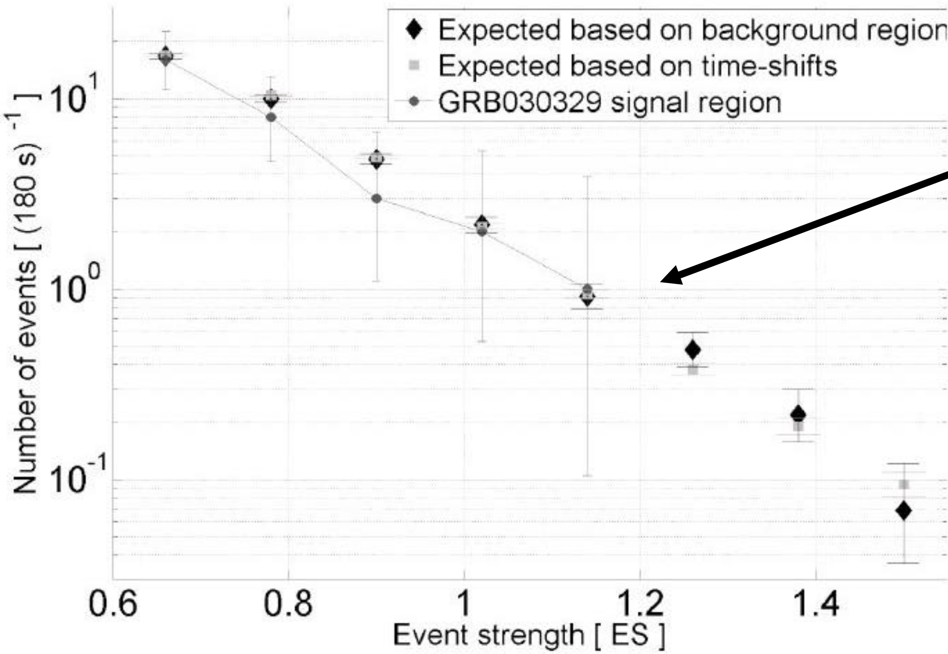
- Burst search triggers
  - » Blind search procedure provide list of coincident triggers
  - » Auxiliary and environmental channels provide important information which can veto a trigger – very important to burst searches.
  - » Example:





Triggered search around GRB030329

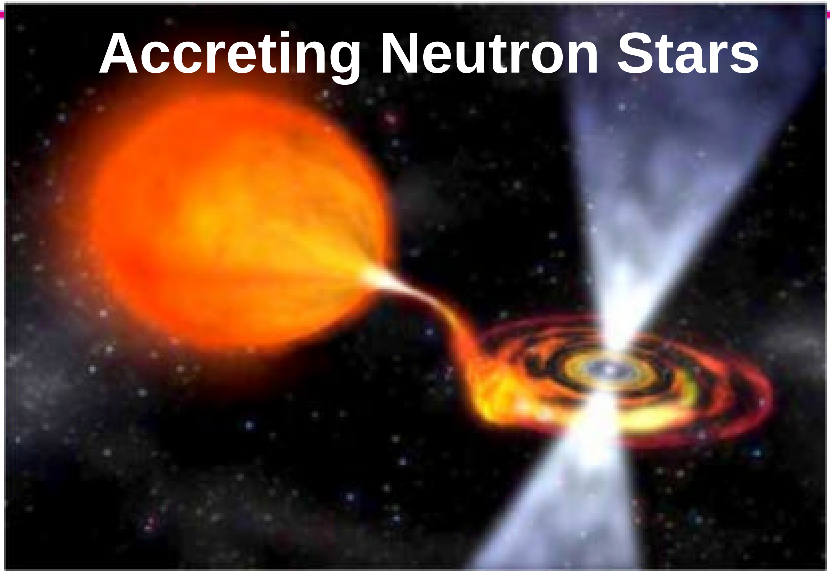
*Physical Review D **72** 042002 (2005)*



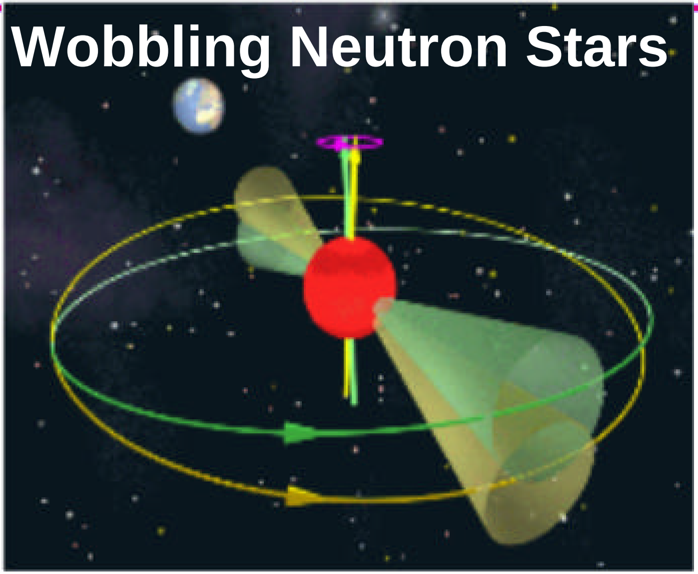
Root sum square sensitivity < 6×10^{-21}

- Cross-correlate data around time of GRB trigger
- Estimate background from off-source times around GRB
- Estimate background from time-slides
- S3/S4 analysis will cover ~20-30 GRB's

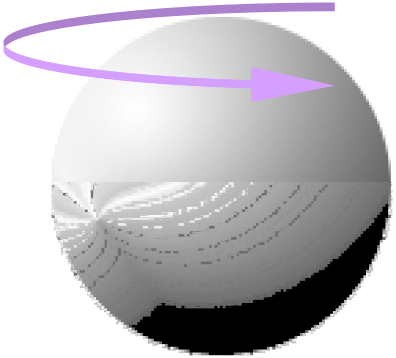
Continuous wave searches: target sources



Credit: Dana Berry/NASA



Credit: M. Kramer



Bumpy Neutron Star

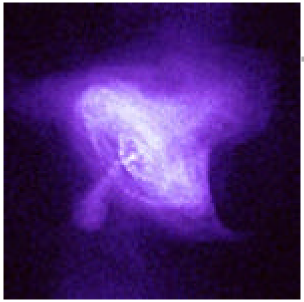
Continuous Wave Group Activities

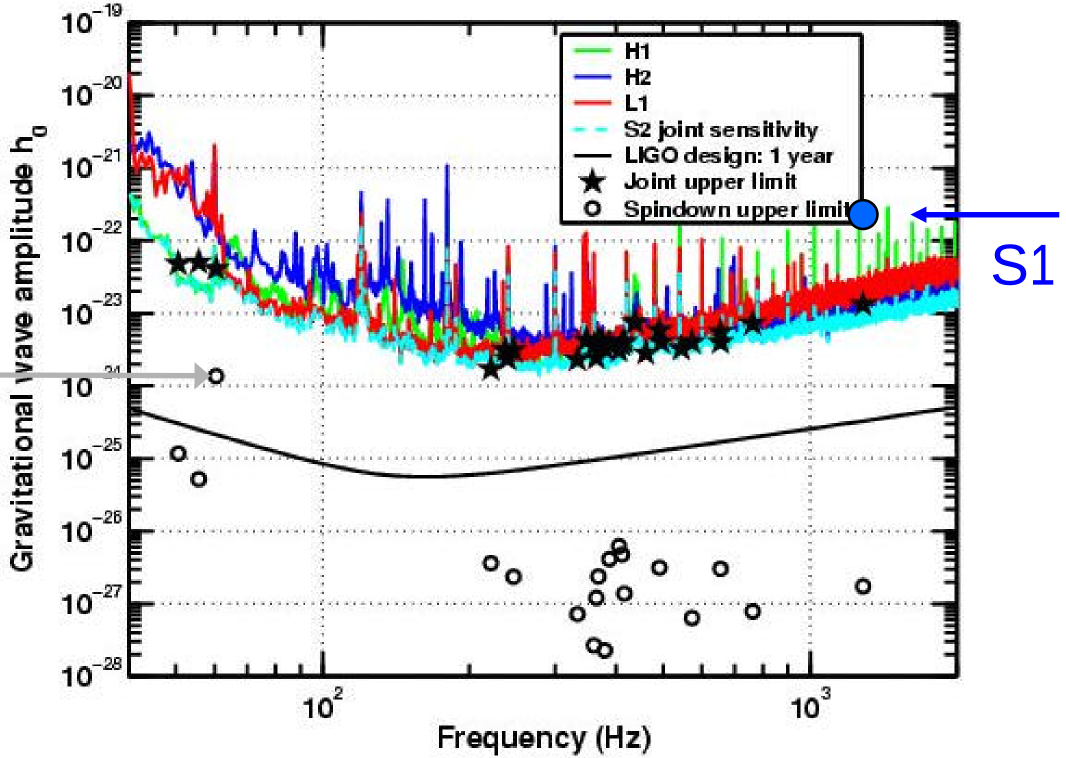
- Known pulsar searches
  - » Catalog of known pulsars
  - » Heterodyne narrow bandwidth folding data
  - » Coherent frequency domain search using Hough transform
- All sky unbiased
  - » Sum short power spectra (no Doppler correction)
- Wide area search
  - » Hierarchical Hough transform code is under development

Summary of pulsar searches

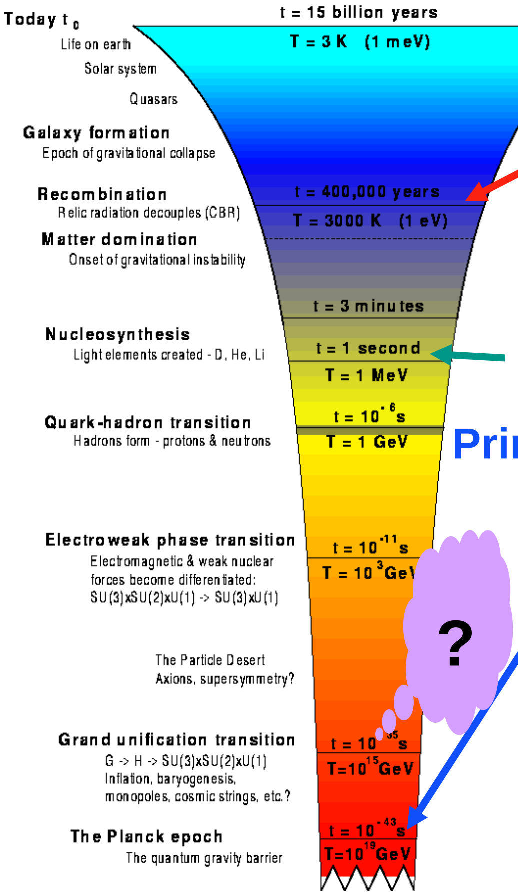
- **S1**→ Setting upper limits on the strength of periodic gravitational waves from PSR J1939 2134 using GEO600 and LIGO data
  - » Phys. Rev. D **69** (2004) 082004
- **S2** → Limits on GW emission from 28 selected pulsars using LIGO data
  - » Phys. Rev. Lett. **94** (2005) 181103

Crab pulsar

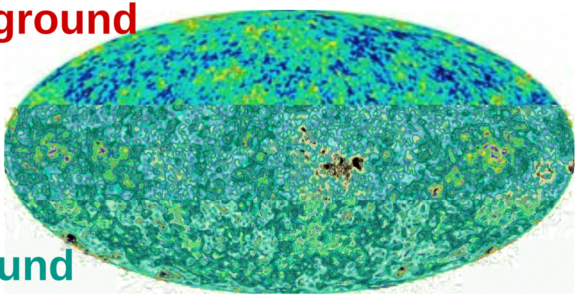




Probing the early Universe

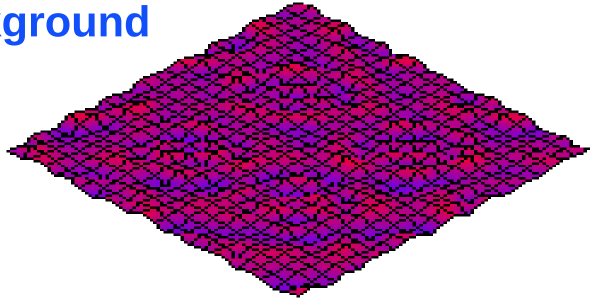


Cosmic Microwave Background



n **Background**

Primordial Gravitational-Wave Background



Stochastic Background of Gravitational Waves

- Given an energy density spectrum $\Omega_{gw}(f)$, there is a GW strain power spectrum

$$\Omega_{GW}(f) = \frac{1}{r_{critical}} \frac{dr_{GW}}{d(\ln f)} \quad \Rightarrow \quad S_{\rm gw}(f) = \frac{3H_0^2}{10\pi^2} f^{-3}\Omega_{\rm gw}(f)$$

- For standard inflation (ρ_c depends on present day Hubble constant)

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

- Search by cross-correlating output of two GW detectors: L1-H1, H1-H2, L1-ALLEGRO
  - » The closer the detectors, the lower the frequencies that can be searched (due to overlap reduction function)

LIGO results for $\Omega_0 h_{100}^2$

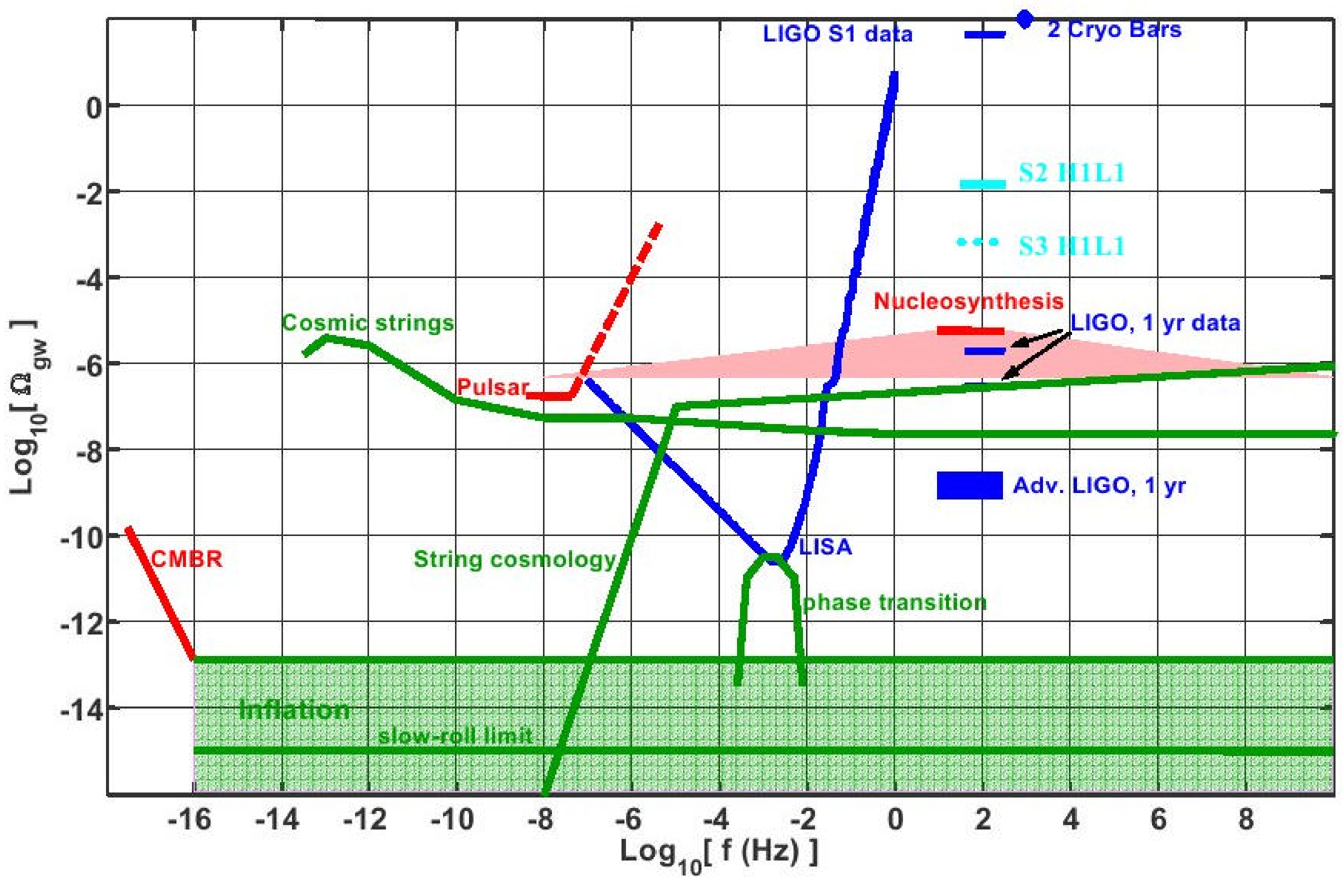
LIGO run	$\Omega_0 h_{100}^2$	Comments	Frequency Range	Observation Time
S1 PRD **69** (2004)	< 23 ⊕ 4.6 (H2-L1)	Cross-correlated instrumental noise found	40 to 314 Hz	64 hours (08/02 – 09/02)
S2	< 0.018 (H1-L1)		50 to 300 H…	…hours …04/03)
S3 PRL **95** (2005)	< …	$\Omega_{gw} = \Omega_a \left(f / 1\ldots \right)^a$ … …otating NS … 2 → pre-BB cosmology	70 to 160 Hz (H1-L1)	200 hrs (H1-L1) (10/03 – 01/04)
S4		Analysis underway		447 hrs (H1-L1) 510 hrs (H1-H2) (02/05 – 03/05)

Initial LIGO (1 yr) $\Omega_0 h_{100}^2 < 2 \times 10^{-6}$

Advanced LIGO (1 yr) $\Omega_0 h_{100}^2 < 7 \times 10^{-10}$

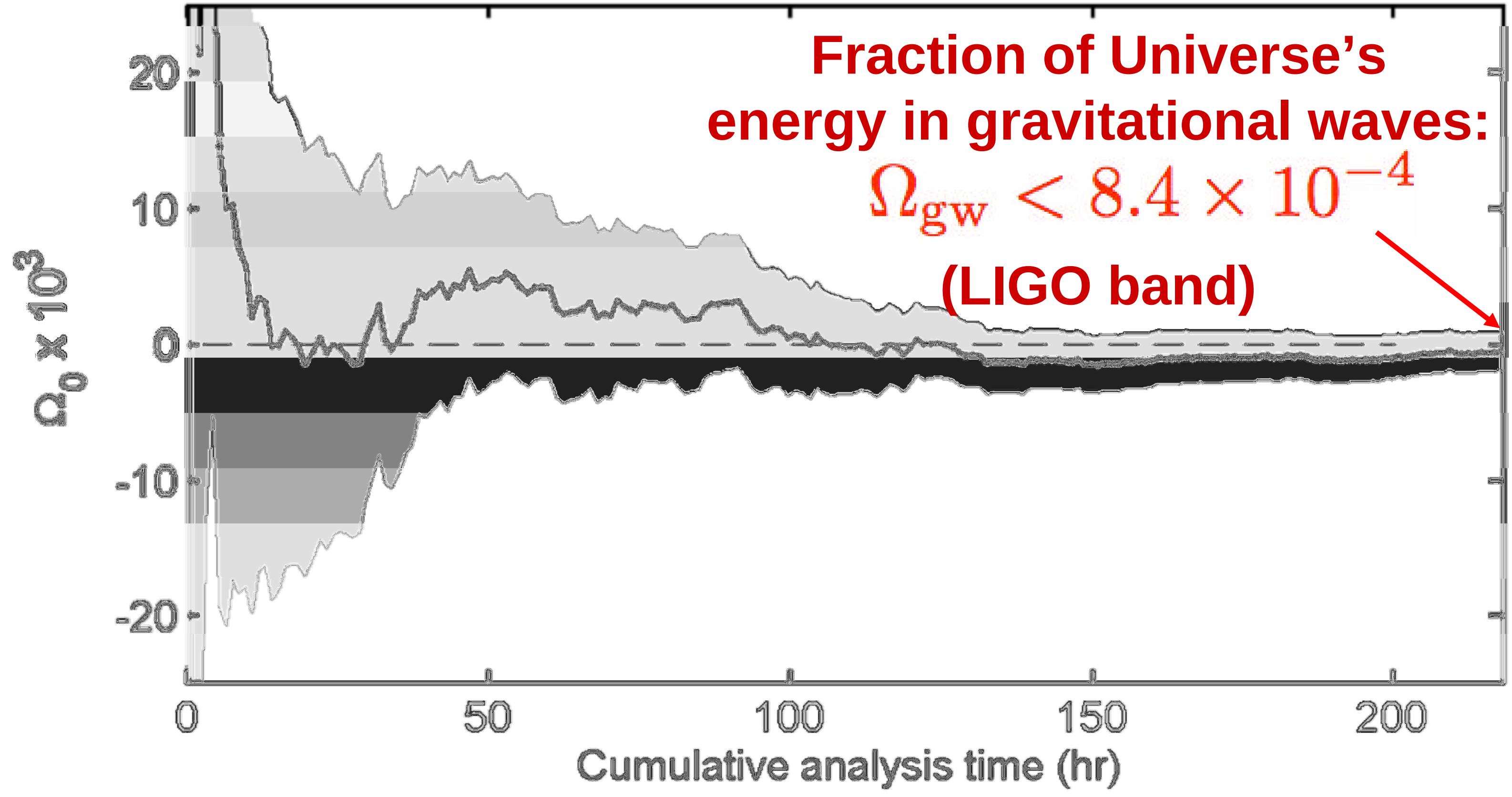
Observational Constraints

•



Stochastic Background Search (S3)

Physical Review Letters, Vol. 95 p. 221101 (2005)

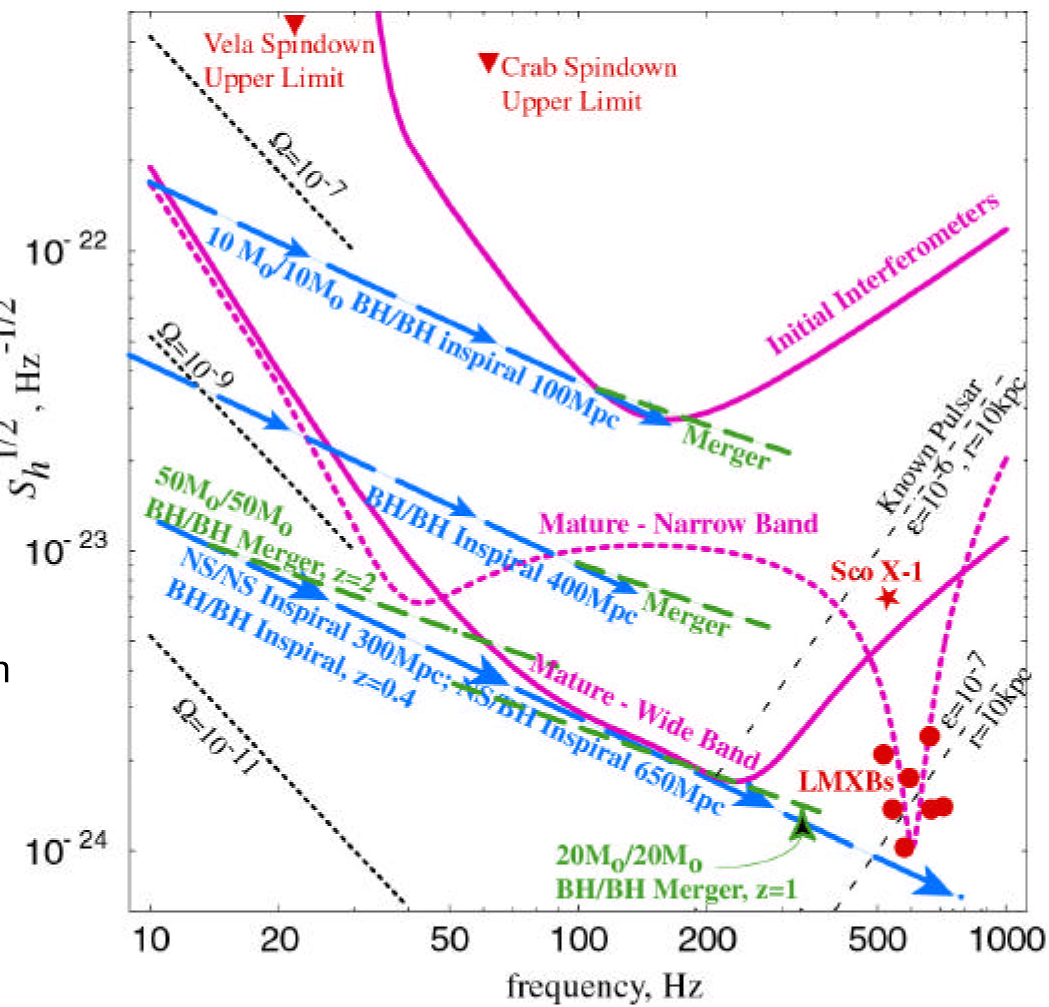


Advanced LIGO Why a better detector? Astrophysics

- Factor 10 better amplitude sensitivity
  - » (Reach)^3 = rate
- Factor 4 lower frequency bound
- Tunable
- Hope for NSF funding in FY08
- Infrastructure of initial LIGO but replace many detector components with new designs
- Expect to be observing 1000x more galaxies by 2013

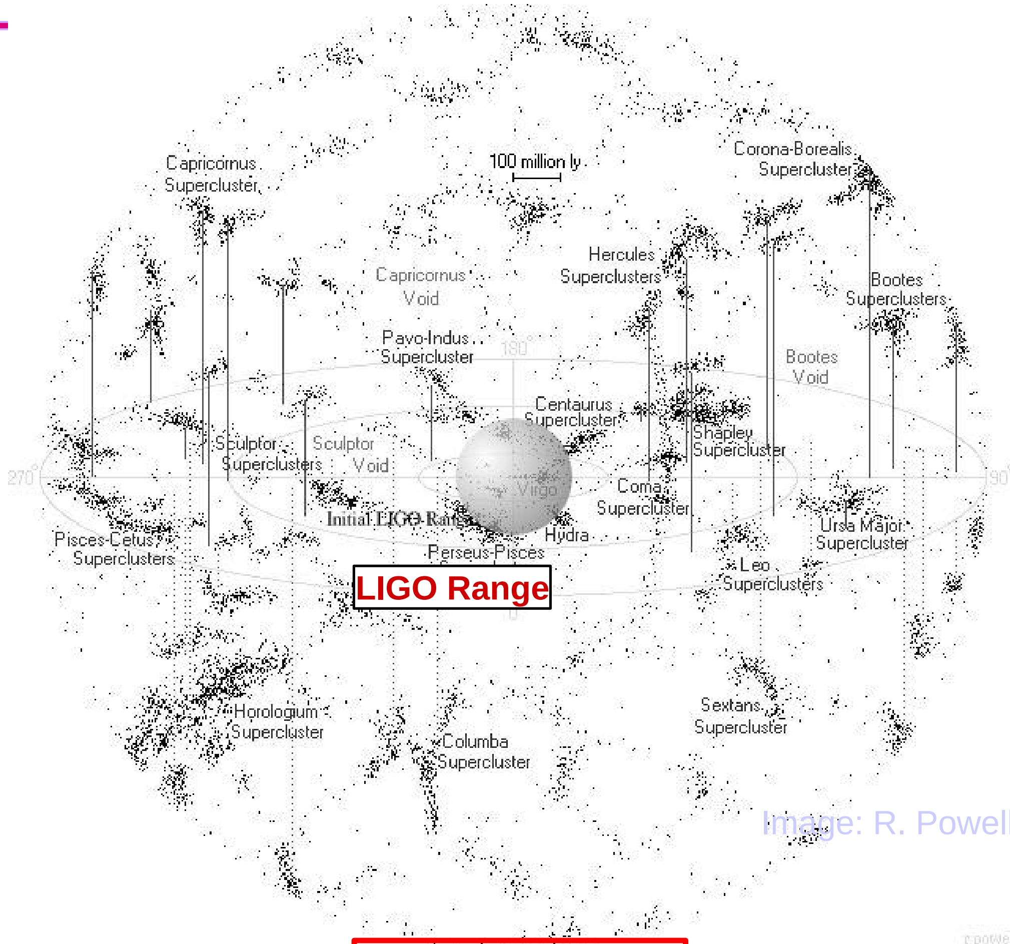
Through these features:

- Fused silica multi-stage suspension
- ~20x higher laser power
- Active seismic isolation
- Signal recycling
- Quantum engineering
  rad'n pressure *vs.* shot noise



Advanced LIGO's reach

- Neutron star binaries
  - Range =350Mpc
  - N ~ 2/(yr) – 3/(day)
- Black hole binaries
  - Range=1.7Gpc
  - N ~ 1/(month) – 1/(hr)
- BH/NS binaries
  - Range=750Mpc
  - N ~ 1/(yr) – 1/(day)

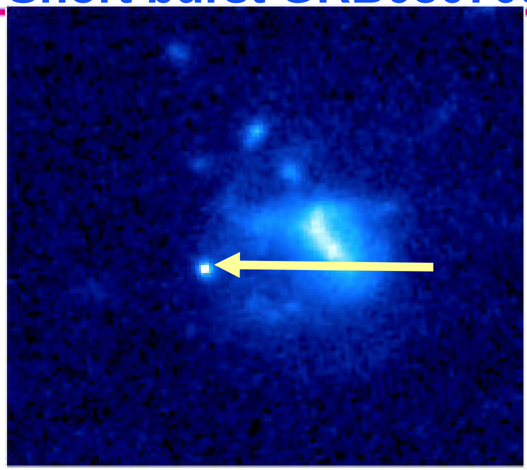


Prospects for Future Large Interferometers

- Advanced LIGO
  - » Order-of-magnitude sensitivity improvement
  - » Received scientific approval from National Science Board
  - » NSF planning to request funding starting in FY 2008
  - » Three advanced detectors observing by 2013 ?
- VIRGO upgrade – Being discussed
- LCGT (Japan)
  - » Two 3-km interferometers in Kamioka mountain
  - » Sensitivity comparable to Advanced LIGO
  - » Hope for funding beginning in FY 2007 ; begin observations in 2011 ?
- AIGO (Australia)
  - » Considering adding 2 km arms to current facility at Gingin
- CEGO (China) ?

Gamma-ray bursts: short and long

Short burst GRB050709



HST Image Credit: Derek Fox

Long burst GRB030329

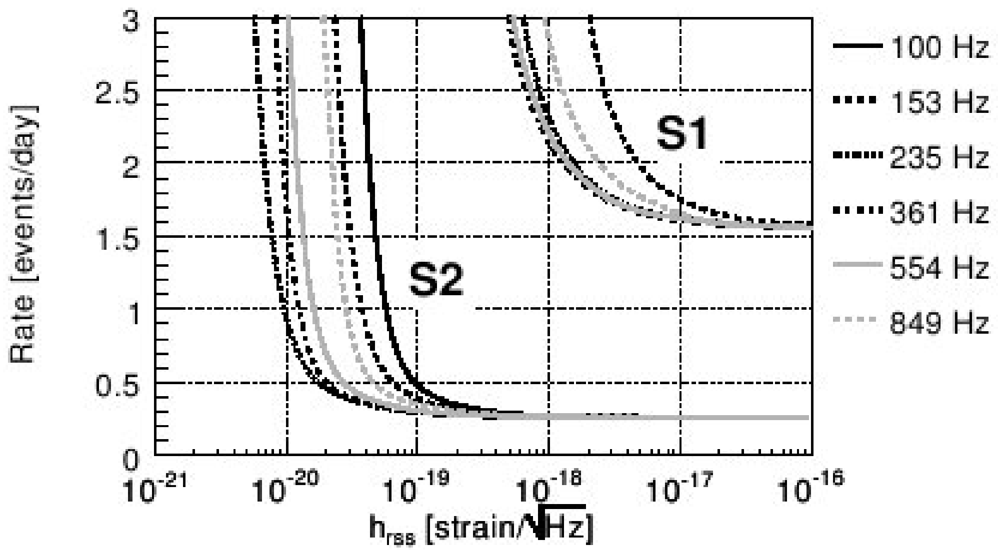
NASA Image

Possible scenario for short GRBs: neutron star/black hole collision

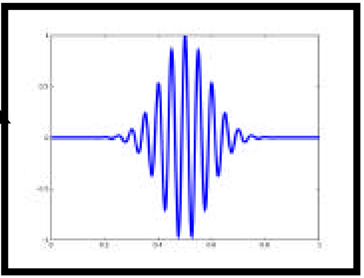
Credit: Dana Berry/NASA

Burst Upper Limit

Sine-Gaussians



Phys. Rev. D. 72, 062001 (2005)



Gaussians