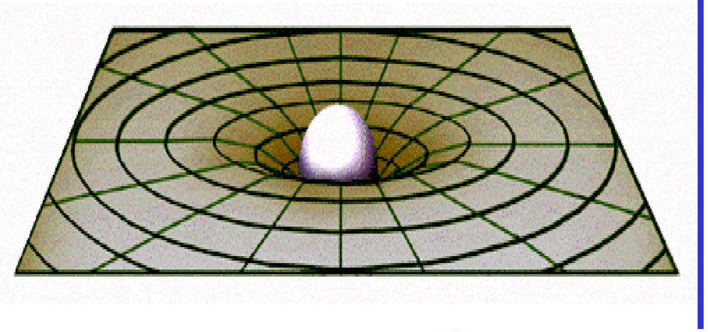
Overview of LIGO

23rd Texas Symposium on Relativistic Astrophysics
December 11, 2006

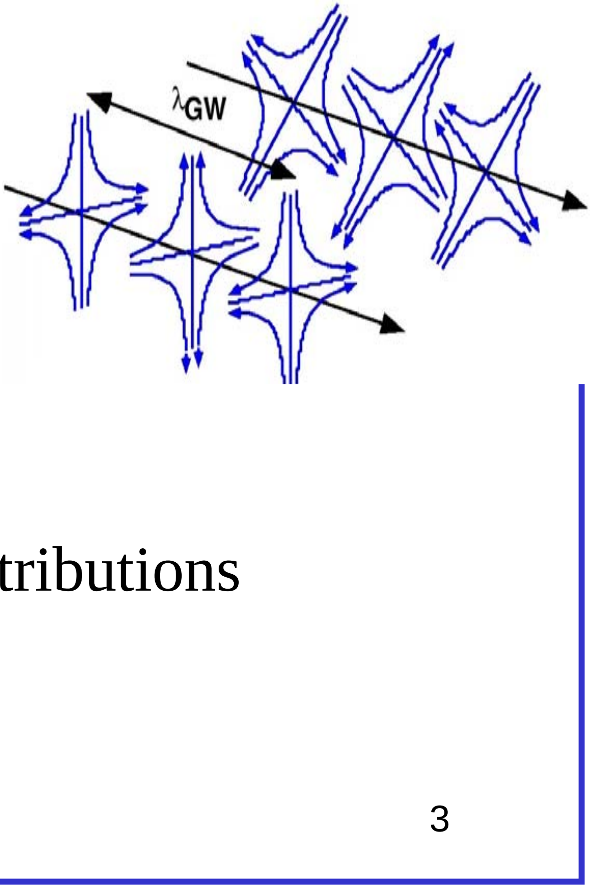
Jay Marx
(on behalf of the
LIGO Scientific Collaboration)

- Introduction
  - Gravitational waves and their characteristics
  - Astrophysical sources of detectable gravitational waves
- LIGO
  - How LIGO works
  - The experimental challenges and limitations
- The current status of LIGO
  - The current science run
  - LIGO’s future evolution
- Some LIGO astrophysics results
- The world-wide network of ground-based detectors for gravitational waves

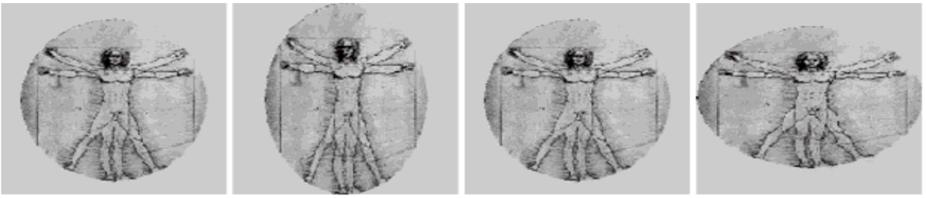
Gravitational waves



- Ripples of space-time curvature that propagate at the speed of light



- Transverse, quadrupole waves with 2 polarizations that stretch and squeeze space transverse to direction of propagation



- Emitted by accelerating aspherical mass distributions
- Matter is transparent to gravitational waves
- Wavelength ~ source size →

Strength of GWs: *e.g. Neutron Star Binary* in the Virgo cluster

- Gravitational wave amplitude (strain)

$$h_{\mu\nu} = \frac{2G}{c^4 r}\ddot{I}_{\mu\nu} \Rightarrow h \approx \frac{4\pi^2 \bigcirc\!\!\!\!\!G\, MR^2 f_{orb}^2}{\bigcirc\!\!\!\!\!c^4 r}$$

I = quadrupole mass distribution of source

- For a binary neutron star

~1.4 M_o pair in Virgo cluster

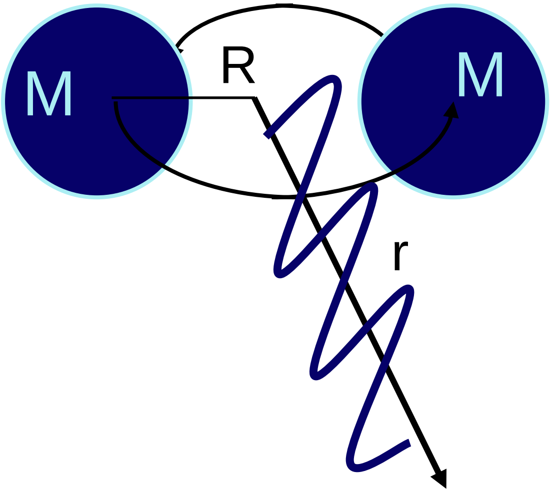
$M \approx 10^{30}$ kg

$R \approx 20$ km

$f \approx 400$ Hz

$r \approx 10^{23}$ m

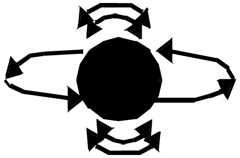
⇨ $\boxed{h \sim 10^{-21}}$



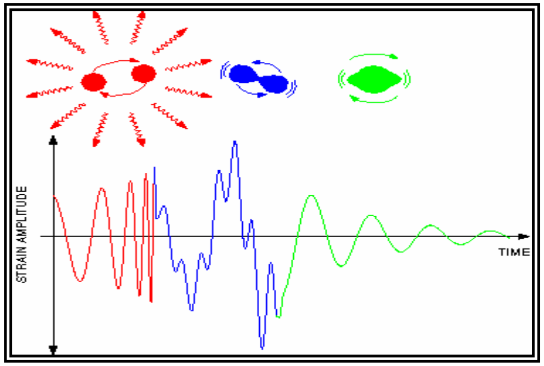
Astrophysical sources of GWs sought by LIGO

- Periodic sources

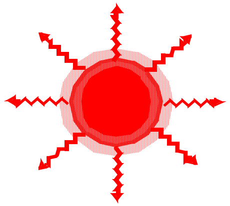
  Binary Pulsars, Spinning neutron stars, Low mass X-ray binaries



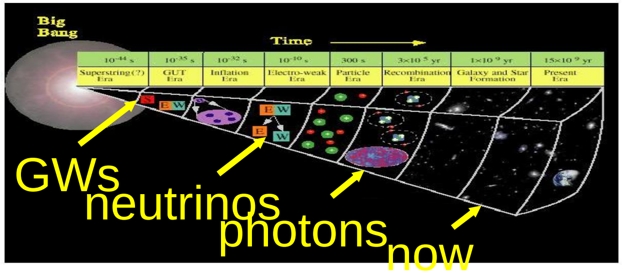
- Coalescing compact binaries
  - Classes of objects: NS-NS, NS-BH, BH-BH
  - Physics regimes: Inspiral, merger, ringdown
  - Numerical relativity will be essential to interpret GW waveforms



- Burst events
  - e.g. Supernovae with asymmetric collapse



- Stochastic background
  - Primordial Big Bang (t = 10^{-22} sec)
  - Continuum of sources
- The Unexpected



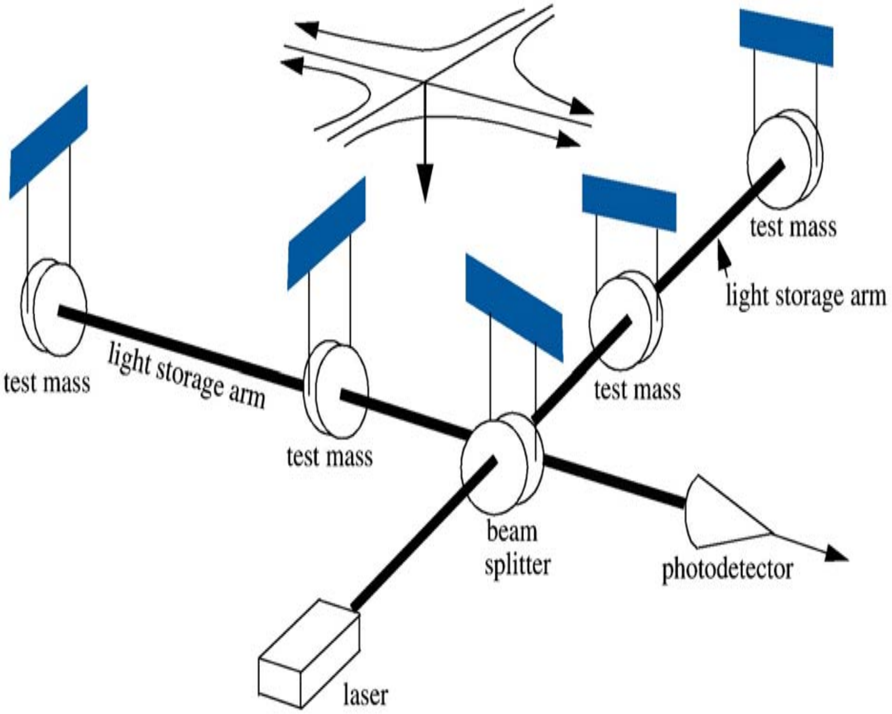
Detecting GWs with Precision Interferometry

- Suspended test masses act as “freely-falling” objects tied to their space-time coordinates

- A passing gravitational wave alternately stretches (compresses) space-time and thus the arms.

- Interferometery is used to determine relative distance between test masses (mirrors) in L-shaped arms

- Due to interference, a differential stretch/compress gives a time varying signal at the photo-detector



Experimental challenges and limitations

$$h = \Delta L / L$$

For $h \sim 10^{-21}$ and L ~ 4 km

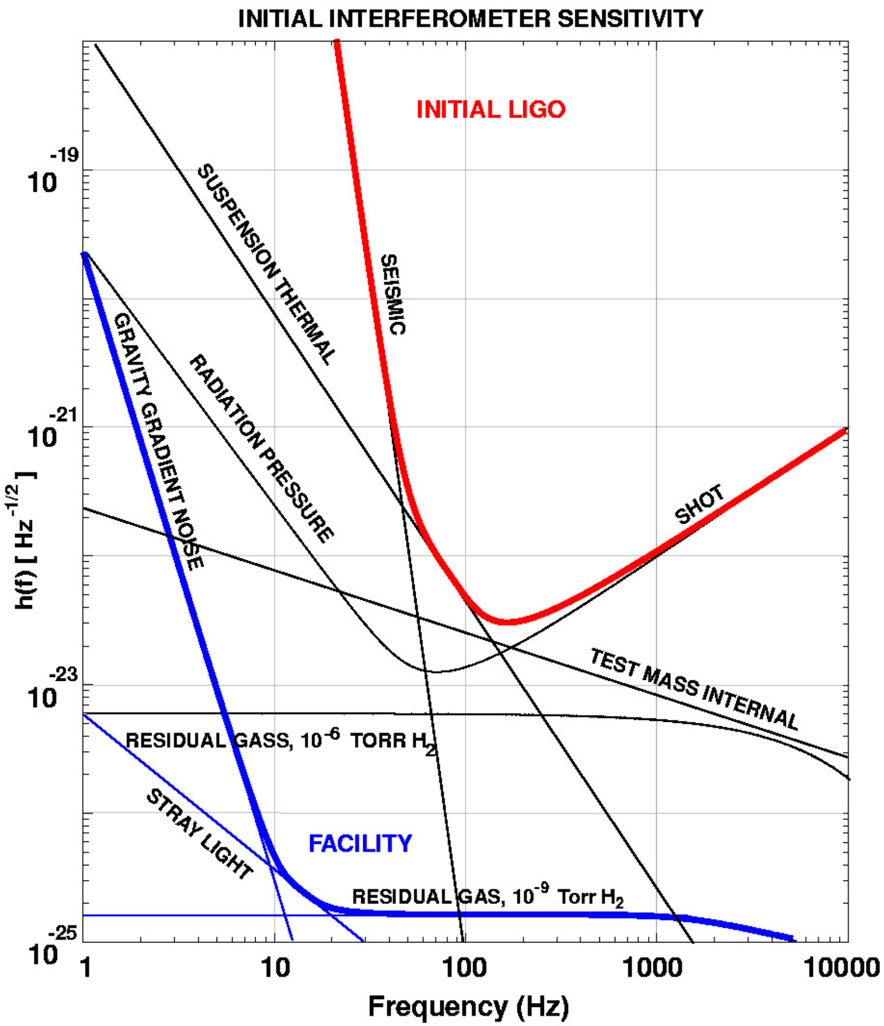
$\Delta L \sim 10^{-18}$ m

Challenge--to measure relative distance of test masses in interferometers arms to ~ 10^{-18} m --1/1000 the size of a proton!

What makes it hard?

- –Gravitational wave amplitude is very small
- –External forces also push the mirrors around
- –Laser light has fluctuations in its phase and amplitude

Major noise sources for LIGO

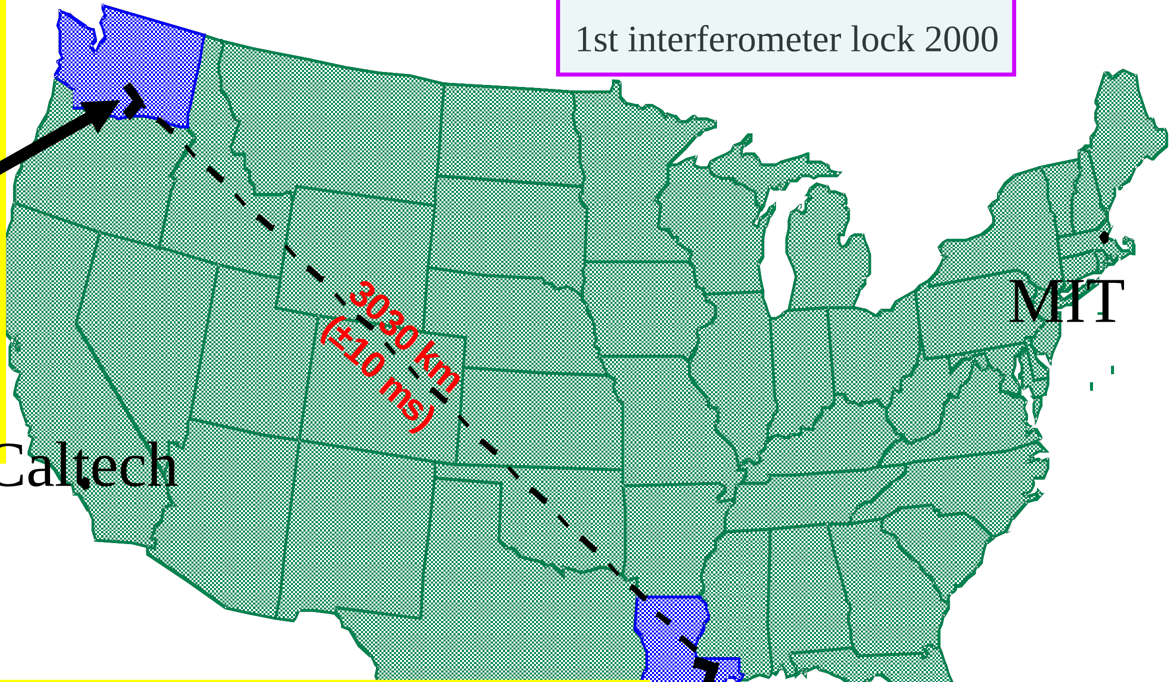


- Displacement Noise
  - Seismic motion (limit at low frequencies)
    - Ground motion from natural and anthropogenic sources
  - Thermal Noise (limit at mid-frequencies)
    - vibrations due to finite temperature
  - Radiation Pressure
- Sensing Noise (limit at high frequency)
  - Photon Shot Noise
    - quantum fluctuations in the number of photons detected
- Facilities limits
  - Residual Gas (scattering)
- Inherent limit on ground
  - Gravity gradient noise

LIGO Laser Interferometer Gravitational-wave Observatory

Ground breaking 1995

1st interferometer lock 2000

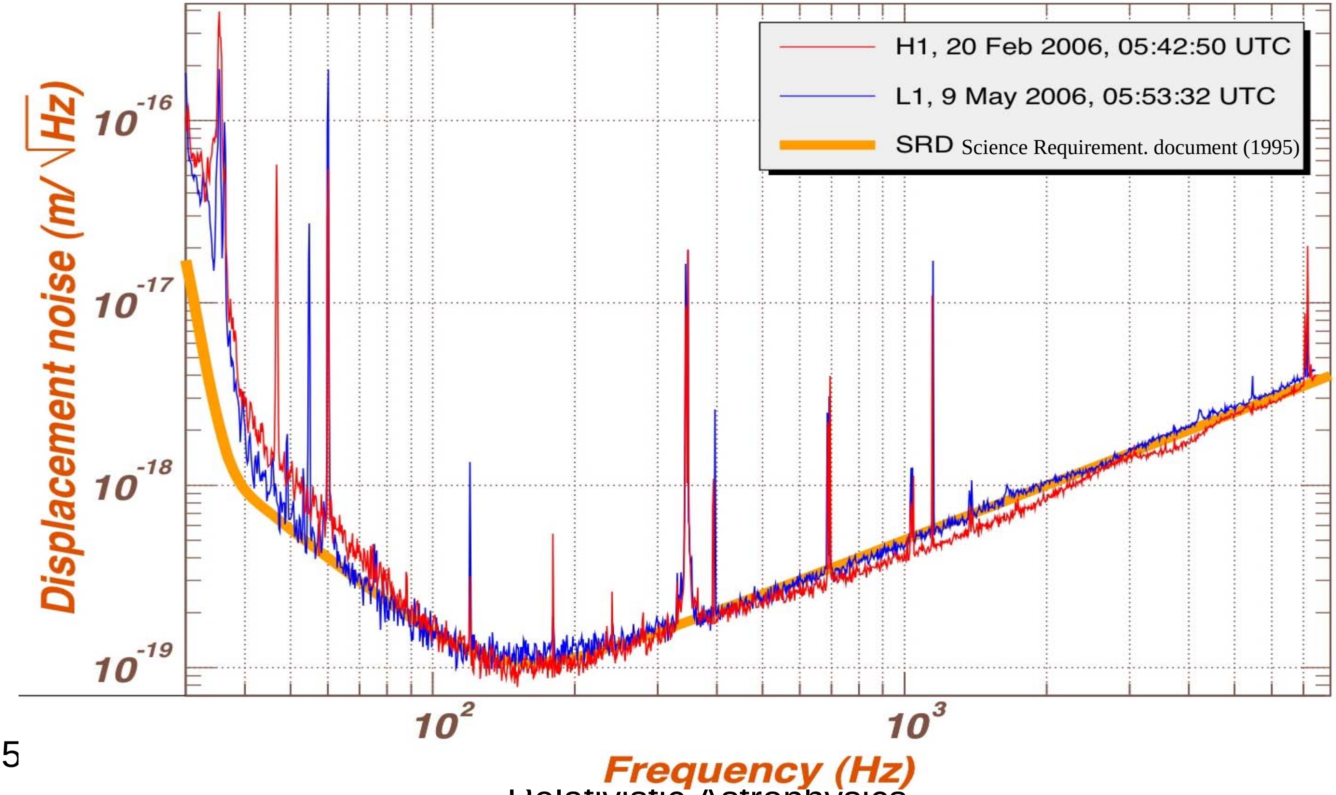


- **Managed and operated by Caltech & MIT with funding from NSF**
- **LIGO Scientific collaboration- 45 institutions, world-wide**

Some LIGO hardware

Meeting the experimental challenge

- After 5 years of intense effort to reduce noise by ~ 3 orders of magnitude, the design sensitivity predicted in the 1995 LIGO Science Requirements Document was reached in 2005--a great achievement



The current search for gravitational waves

- A science run (S5) at design sensitivity began in November 2005 and is ongoing;
  - Will end summer 2007
  - With 1 year live-time of 2-site coincident data

- Searching for signals in audio band (~50 Hz to few kHz)

- Run is going extremely well
  - Range at beginning of run---(for 1.4 M_o neutron star pairs; S/N=8)
    - for 4 km IFOs-- over 10 Mpc
    - for 2 km IFO--- over 5 Mpc
  - Range is now 40% greater than beginning of run

Range figure of merit since beginning of S5
--*1.4 M_O NS-NS inspiral range* (*S/N=8*)--

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

Next step-Enhancements to initial LIGO

- After current run, make modest changes to LIGO to enhance range by ~2
    - To both 4 km interferometers, not the 2 km
    - Reduce noise at readout and increase laser power by ~3
- Increase number of sources in range by factor ~8
- Goal- next science run with enhanced range in 2009

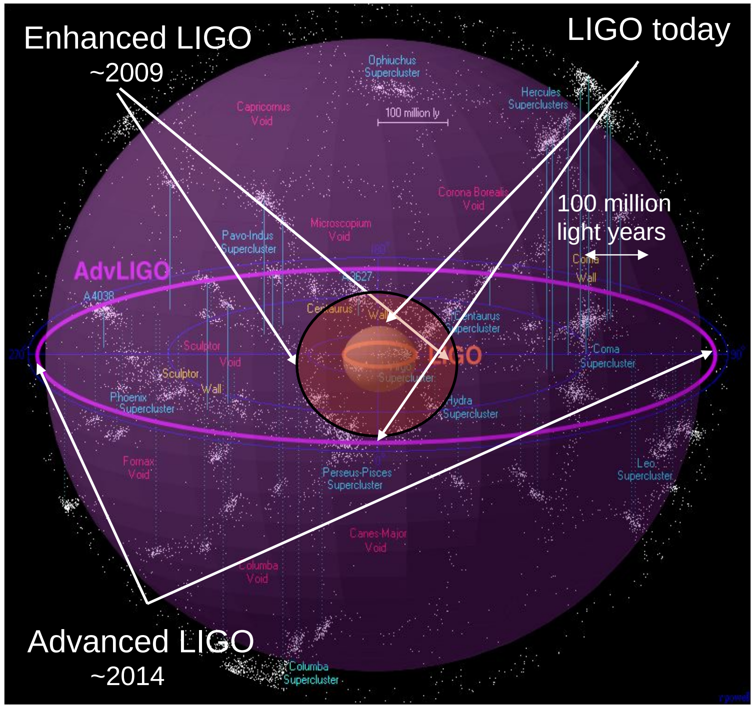
Advanced LIGO-

the next big step towards GW astrophysics

- Major project to improve the sensitivity and range of LIGO by a factor of 10
  - 20x higher power laser, improved seismic suspension and isolation, signal recycling, improved readout (like enhancements), larger mirrors (to handle increased thermal load), etc.
- Increase the number of sources in range by ~1000
  - Expect signals at few/day to few/week rate
- Go beyond discovery of GW; do astrophysics with GWs
- Advanced LIGO to start construction in 2008; completion ~2013-2014
  - Cost- US ~$200M and significant hardware contributions from the UK and Germany

The scientific evolution of LIGO

- 1st full science run of LIGO at design sensitivity in progress
  - Began November 2005; ~60% complete
  - Hundreds of galaxies now in range for 1.4 M_o NS-NS binaries
- Enhancement program
  - In 2009 ~8 times more galaxies in range
- Advanced LIGO
  - Construction start expected in FY08
  - 1000 times more galaxies in range
  - Expect ~1 signal/day- 1/week in ~2014
  - Will usher in era of gravitational wave Astrophysics
  - Numerical relativity will provide the templates for interpreting signals

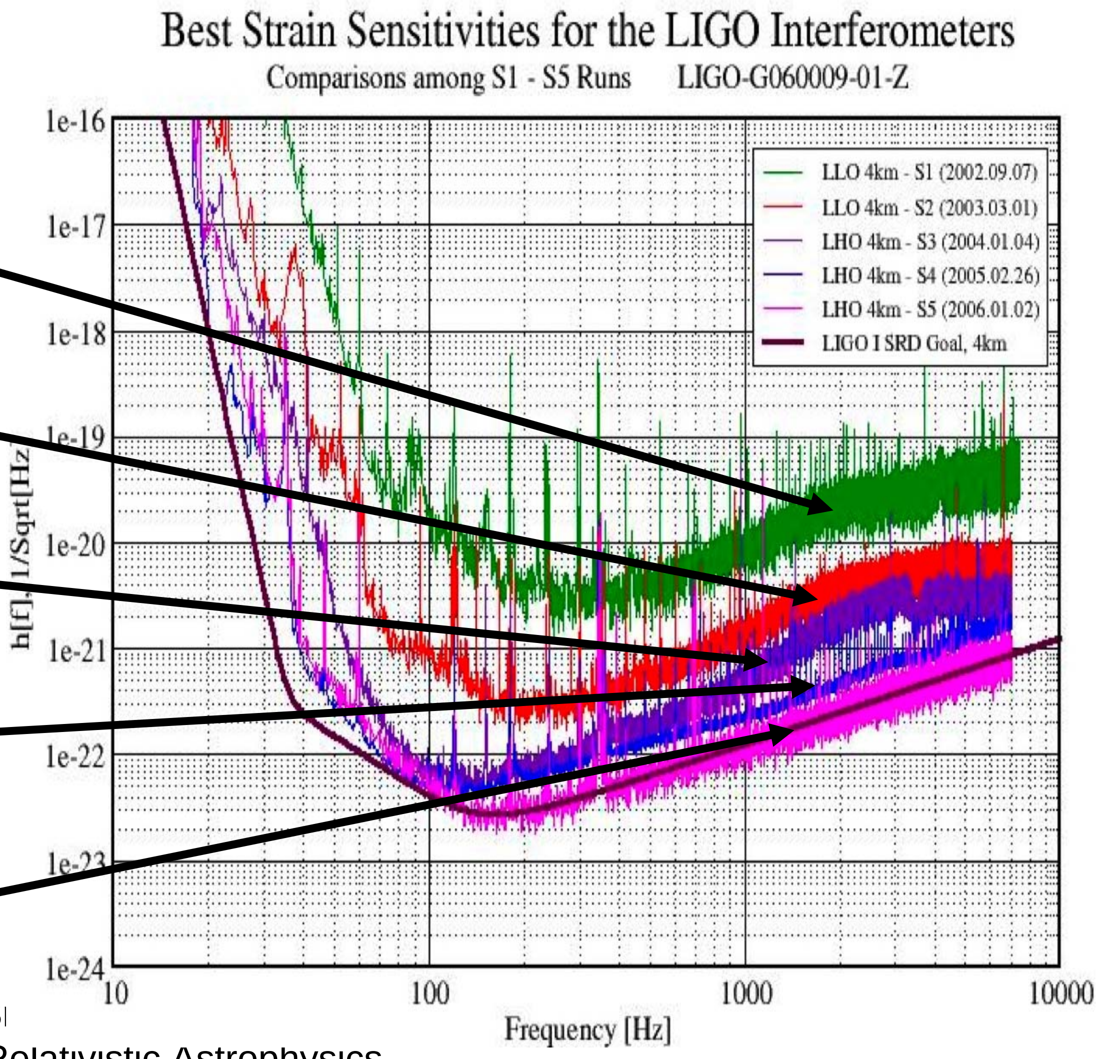


Science runs of LIGO and some astrophysics results

--no discovery to report--

Science runs and sensitivity

Run	# days
S1 Sept ‘02	17
S2 Feb 02-Apr 03	59
S3 Nov 03-Jan 04	70
S4 Feb- March 05	30
S5 Nov 05------	ongoing

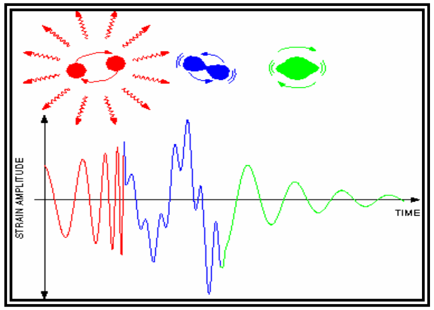


Data analysis

Data analysis by the LIGO Scientific Collaboration (LSC) is organized into four types of analysis:

1. Binary coalescences with modeled waveforms (“inspirals”);
2. Transients sources with unmodeled waveforms (“bursts “)
3. Continuous wave sources (“GW pulsars”)
4. Stochastic gravitational wave background (cosmological & astrophysical foregrounds)

Searches for coalescing compact binaries- S3 & S4



- Use modeled waveforms to filter data
- Sensitive to binaries with masses:

  $0.35\ M_{sun} < m_1, m_2 < 1\ M_{sun}$

  $1\ M_{sun} < m_1, m_2 < 3\ M_{sun}$

  $3\ M_{sun} < m_1, m_2 < 80\ M_{sun}$
- No plausible detections
- Sensitivity:
  - S3: 0.09 yr of data;

    ~3 Milky Way equivalent galaxies for 1.4 – 1.4 M_{sun} (NS-NS)
  - S4: 0.05 yr of data;

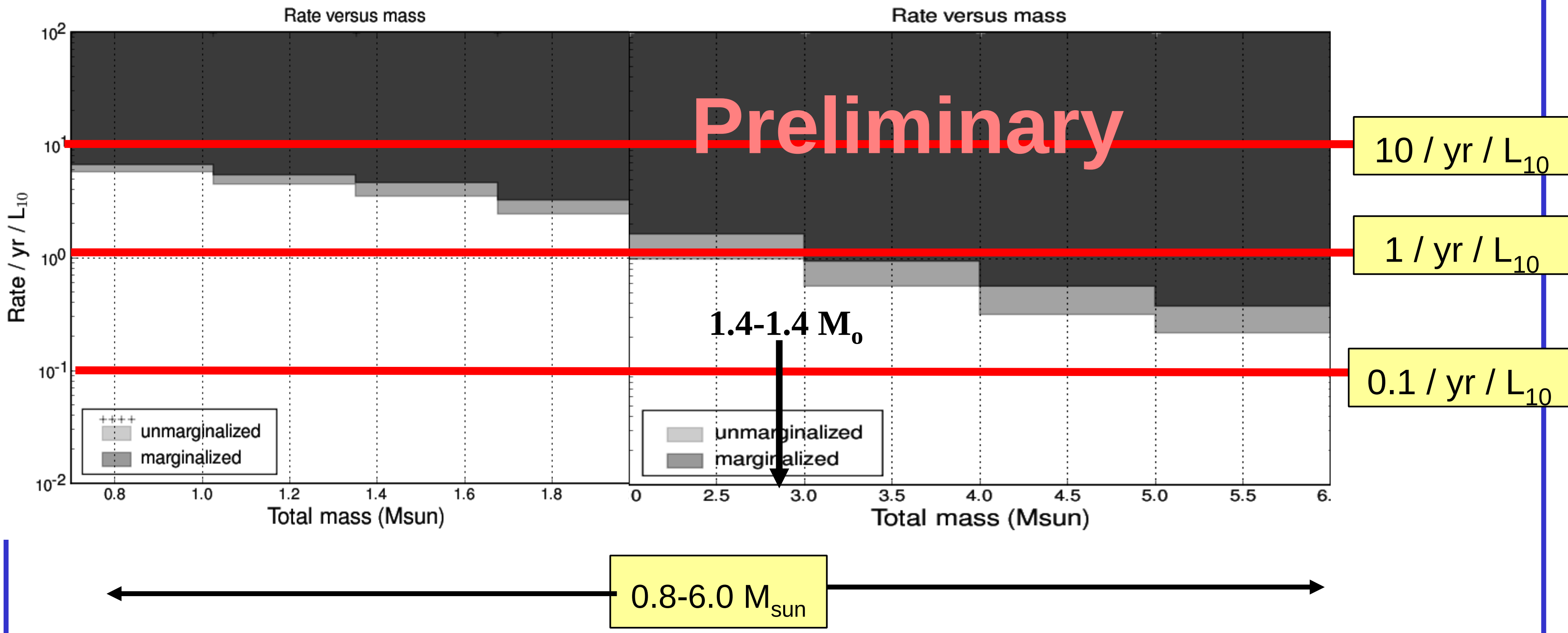
    ~24 Milky Way equivalent galaxies for 1.4 – 1.4 M_{sun} (NS-NS)

    ~150 Milky Way equivalent galaxies for 5.0 – 5.0 M_{sun} (BH-BH)

S4 upper limits-compact binary coalescence

- Rate/year/L_{10} vs. binary total mass

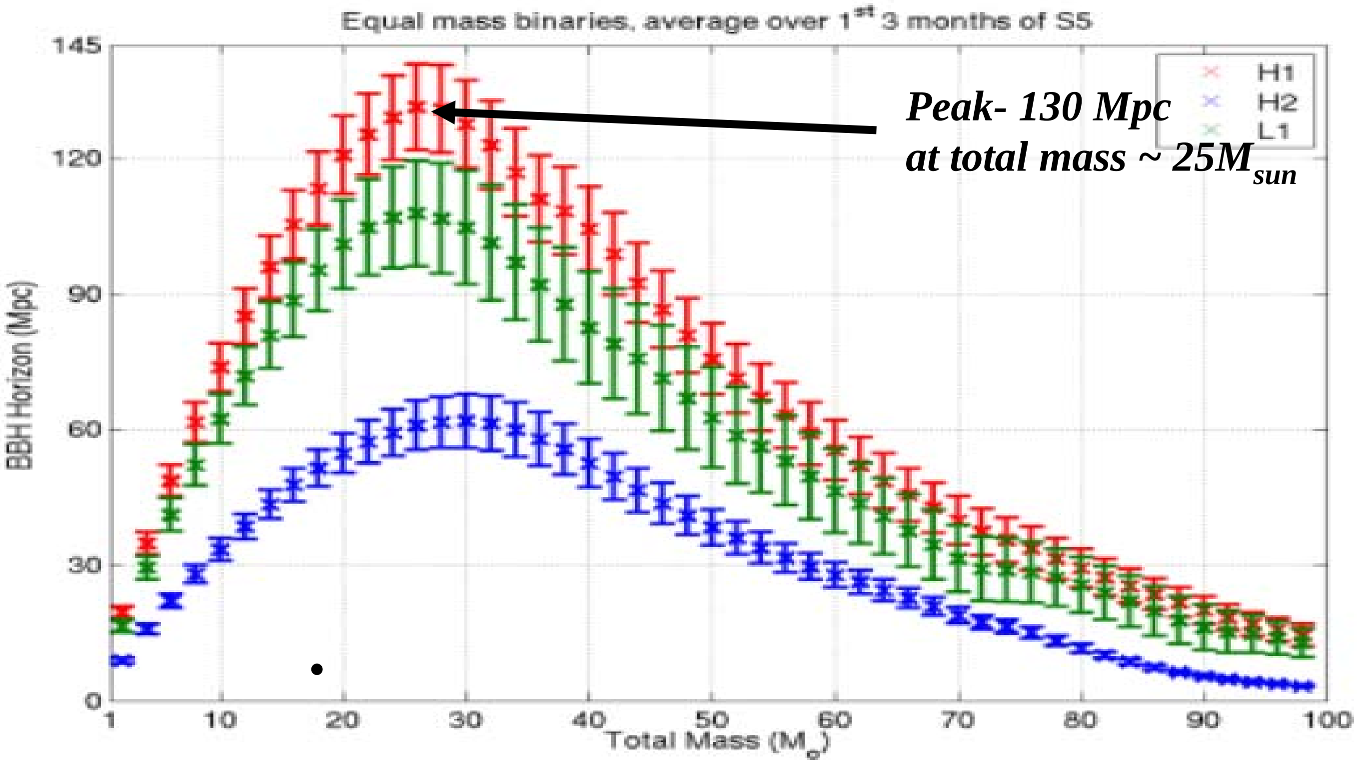
  $L_{10} = 10^{10}\ L_{sun,B}$ (1 Milky Way = 1.7 L_{10})
- Dark region excluded at 90% confidence.



S5 search for compact binary signals

- 3 months of data analyzed- no signals seen
- For 1.4-1.4 M_o binaries, ~ 200 MWEGs in range
- For 5-5 M_o binaries, ~ 1000 MWEGs in range
- Plot- Inspiral horizon for equal mass binaries vs. total mass

(horizon=range at peak of antenna pattern; ~2.3 x antenna pattern average)



Peak- 130 Mpc
at total mass ~ 25M_{sun}

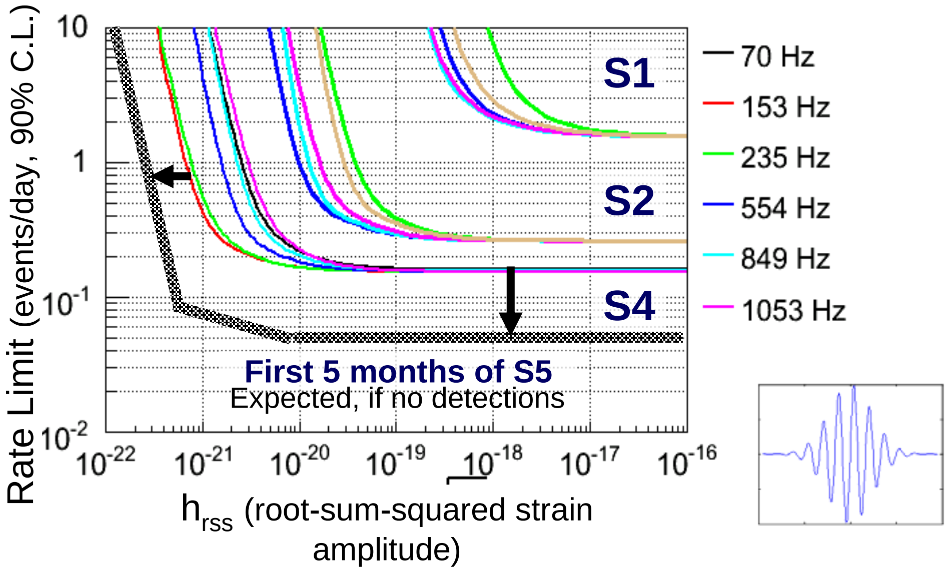
Untriggered GW burst search

- Look for short, unmodeled GW signals in LIGO’s frequency band
  - –From stellar core collapse, compact binary merger, etc. — or unexpected source
- Look for excess signal power and/or cross-correlation among data streams from different detectors

- No GW bursts detected in S1/S2/S3/S4; preliminary results from 1st 5 months of S5

Limit on GRB rate vs. GW signal strength sensitivty

- Detection algorithms tuned for 64–1600 Hz, duration << 1 sec
- Veto thresholds pre-established before looking at data
- Corresponding energy emission sensitivity **$E_{GW} \sim 10^{-1} M_{sun}$ at 20 Mpc** (153 Hz case)



preliminary

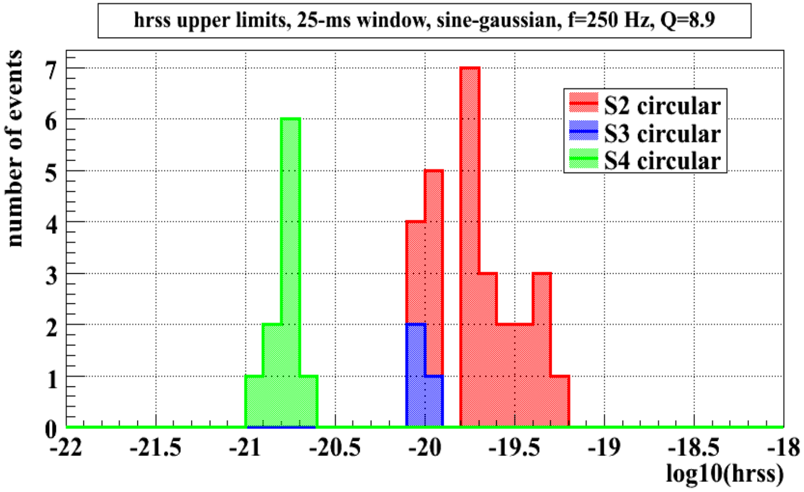
Triggered Searches for GW Bursts

Soft Gamma Repeater 1806-20

- galactic neutron star (10-15 kpc) with intense magnetic field (~1015 G)
- source of record gamma-ray flare on December 27, 2004
- quasi-periodic oscillations found in RHESSI and RXTE x-ray data
- search LIGO data for GW signal associated with quasi-periodic oscillations-- no GW signal found
- sensitivity: E_{GW} ~ 10–7 to 10–8 Msun for the 92.5 Hz QPO
- this is the same order of magnitude as the EM energy emitted in the flare

Gamma-Ray Bursts

- search LIGO data surrounding GRB trigger using cross-correlation method
- no GW signal found associated with 39 GRBs in S2, S3, S4 runs
- set limits on GW signal amplitude
- 53 GRB triggers for the first five months of LIGO S5 run
- typical S5 sensitivity at 250 Hz: **E_{GW} ~ 0.3 M_{sun}** at 20 Mpc



Search for known pulsars- preliminary

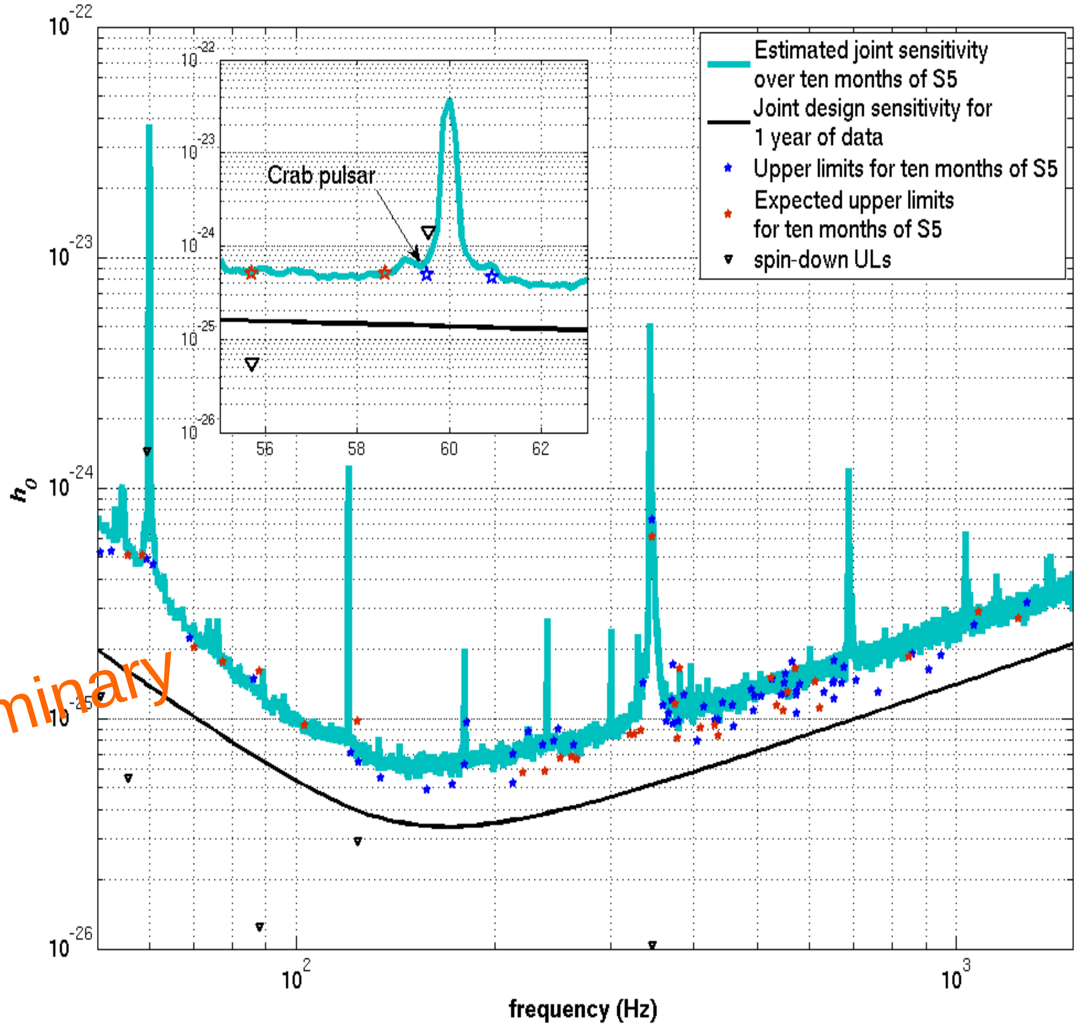
- Joint 95% upper limits for 97 pulsars using ~10 months of the LIGO S5 run. Results are overlaid on the estimated median sensitivity of this search.

For 32 of the pulsars we give the *expected* sensitivity upper limit (red stars) due to uncertainties in the pulsar parameters .

Pulsar timings provided by the Jodrell Bank pulsar group

Lowest GW strain upper limit:
PSR J1802-2124
(f_{gw} = 158.1 Hz, r = 3.3 kpc)
$h_0 < 4.9\times10^{-26}$

Lowest ellipticity upper limit:
PSR J2124-3358
(f_{gw} = 405.6 Hz, r = 0.25 kpc)
$\varepsilon < 1.1\times10^{-7}$



LIGO **limits** on isotropic stochastic GW signal

- Cross-correlate signals between 2 interferometers

$H_0 = 72$ km/s/Mpc

- LIGO S1: $\Omega_{GW} < 44$

  PRD 69 122004 (2004)

- LIGO S3: $\Omega_{GW} < 8.4\times10^{-4}$

  PRL 95 221101 (2005)

- LIGO S4: $\Omega_{GW} < 6.5\times10^{-5}$ (new upper limit; accepted for publication in ApJ)
  - Bandwidth: 51-150 Hz;

- Initial LIGO, 1 yr data

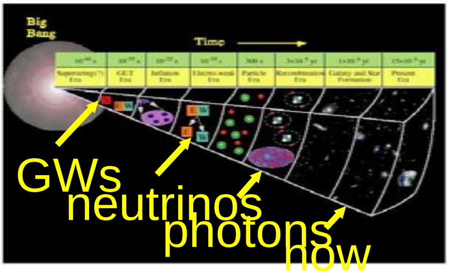
  Expected sensitivity ~ 4×10^{-6}

  upper limit from Big Bang nucleosynthesis 10^{-5}; interesting scientific territory

- Advanced LIGO, 1 yr data

  Expected Sensitivity ~1×10^{-9}

Cosmic strings (?) ~10^{-8}
Inflation prediction ~10^{-14}



See LIGO posters at this meeting:

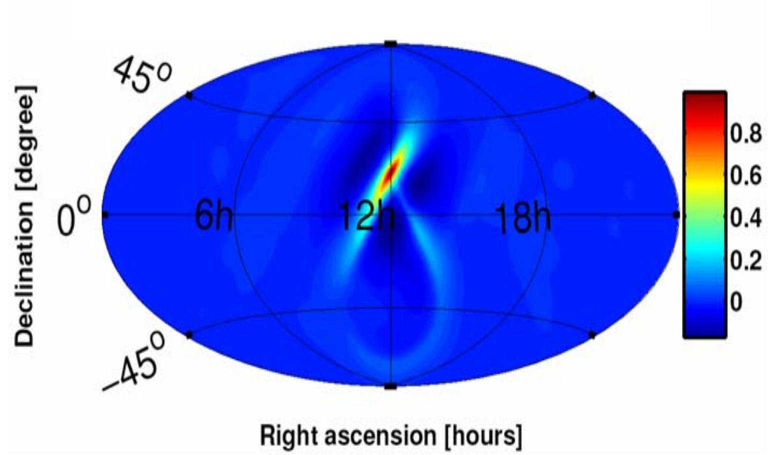
"Searching for Stochastic GW Background with LIGO"-- Vuk Mandic
"Upper Limits of a Stochastic Background of Gravitational Waves"--Stefan Ballmer

Upper limit map of a stochastic GW background

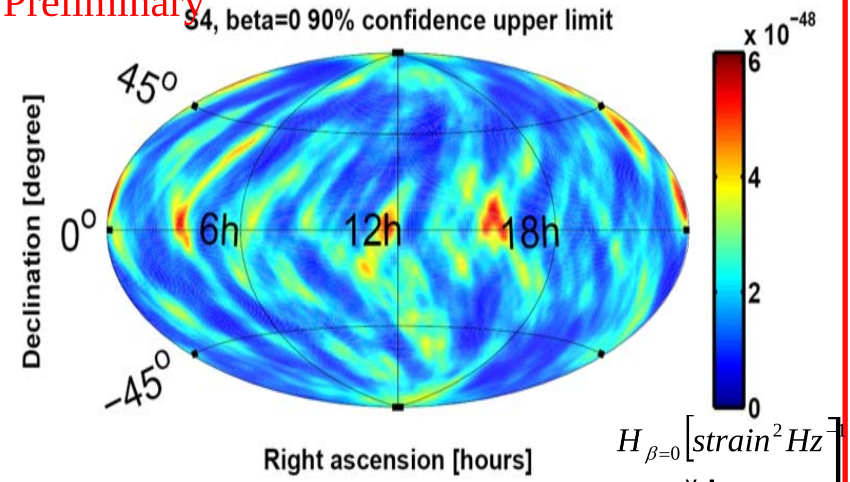
- S4 data- 16 days of 2 site coincidence data
- Get positional information from sidereal modulation in antenna pattern and time shift between signals at 2 separated sites
- **No signal was seen**.
- Upper limits on broadband radiation source strain power originating from any direction.

(0.85-6.1 x 10^{-48} (Hz^{-1}) for min-max on sky map; flat source power spectrum)

Point Spread Function (calculated)



Preliminary



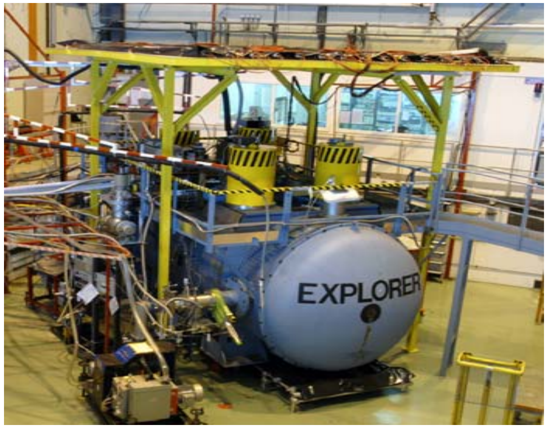
$H_{\beta=0}\left[strain^2 Hz^{-1}\right]$

The international scene

Ground-based GW detectors

Cryogenic Resonant detectors-
sensitivity ~ $h_{rms} \sim 10^{-19}$; excellent duty cycle

Explorer (at CERN)
Univ. of ROME ROG group

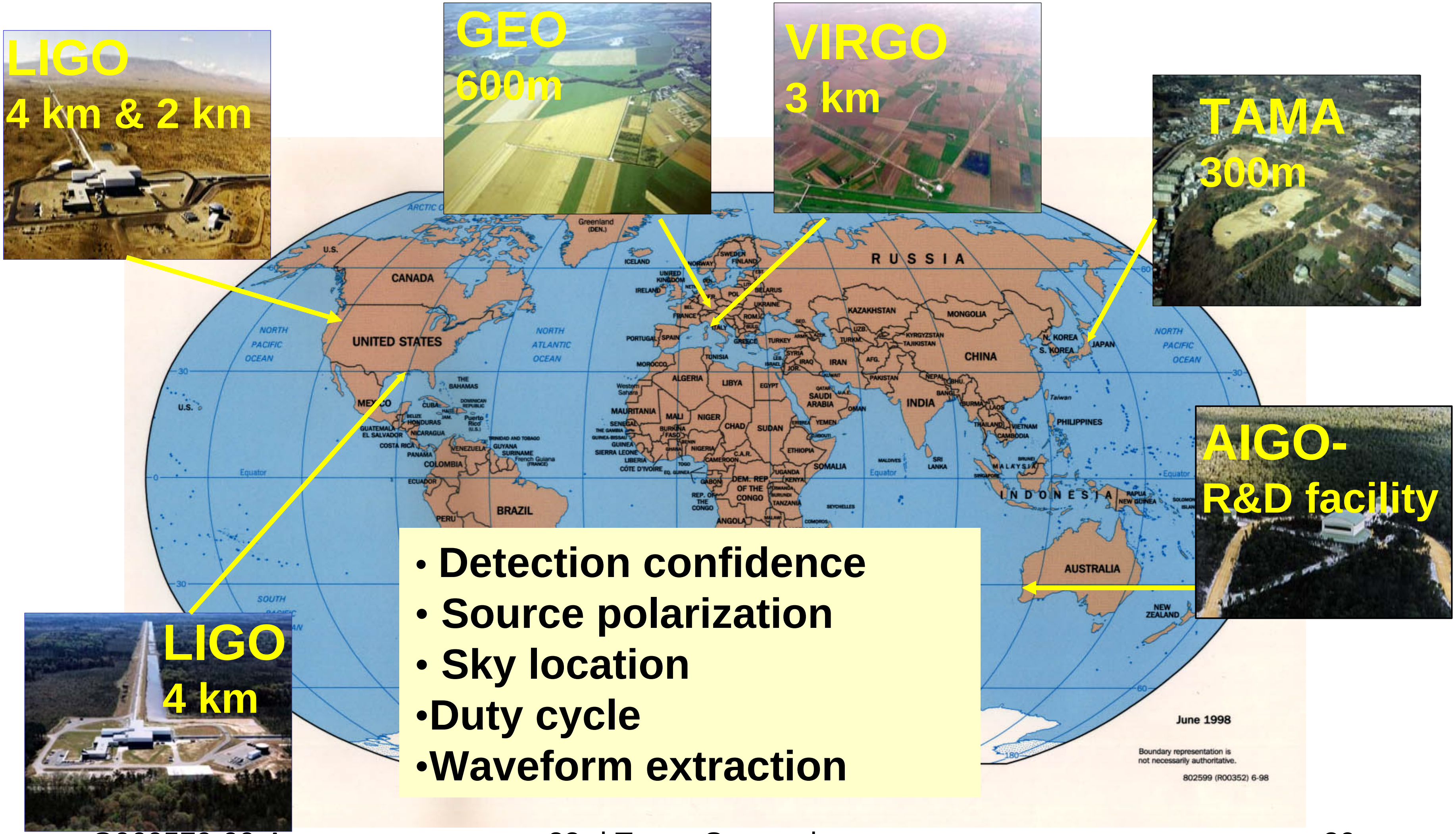


Nautilus (at Frascati)
Univ. of ROME ROG group

AURIGA LNL, Padova

ALLEGRO, LSU

Global network of interferometers



- Detection confidence
- Source polarization
- Sky location
- Duty cycle
- Waveform extraction

Status of the global network

- GEO and LIGO carry out all observing and data analysis as one team, the LIGO Scientific Collaboration (LSC).
- LSC and Virgo have almost concluded negotiations on joint operations and data analysis.
  - This collaboration will be open to other interferometers at the appropriate sensitivity levels.
- LIGO carries out joint searches with the network of resonant detectors.

The future for ground based GW interferometers

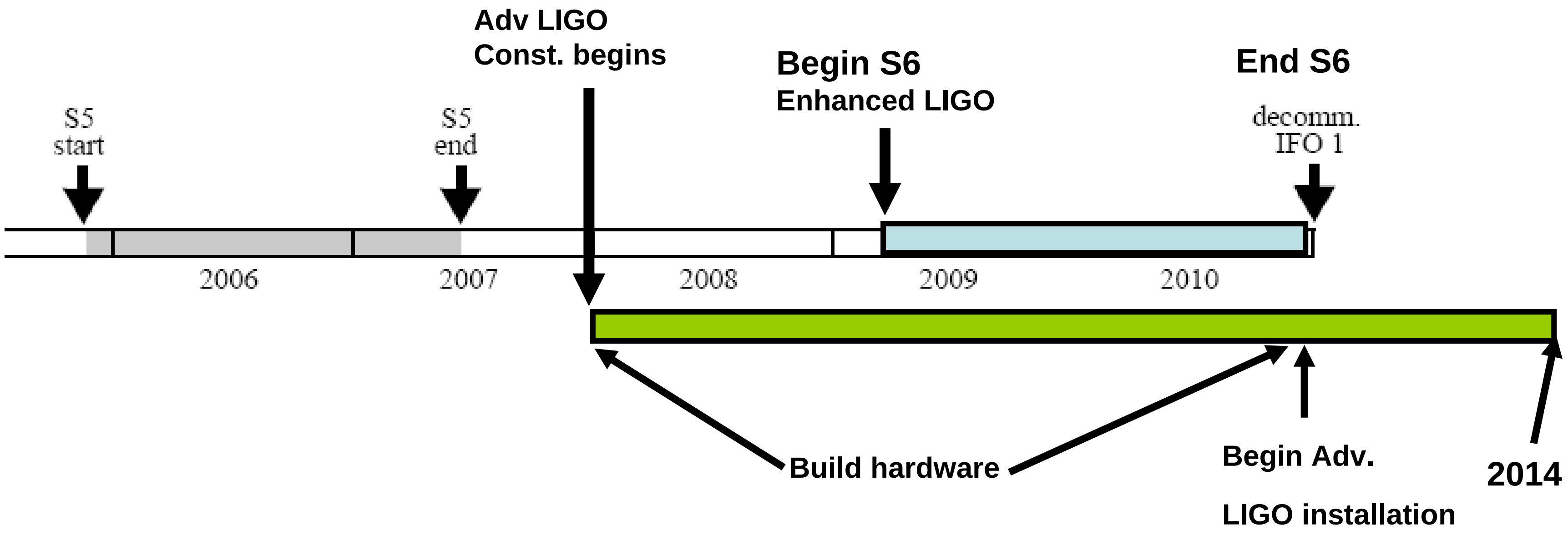
- Advanced LIGO will be operating in ~2014
- Advanced Virgo will be built on the same time scale as Advanced LIGO, and will achieve comparable sensitivity.
- GEO HF will improve the sensitivity beyond GEO600, mainly at high frequencies
- The Japanese GW community is proposing LCGT, a 3 km cryogenic interferometer in the Kamioka mine.
- The Australian GW community is working towards AIGO, a 5 km interferometer at the Gingin site near Perth
- Ongoing technology development towards the third generation-- even better sensitivity and lower frequency

Summary

- LIGO is operating in a science mode at design sensitivity
  - 1st long science run is ~60% complete
  - No detection yet
- Sensitivity/range will be increased by ~ 2 in 2009 and another factor of 10 in ~2014 with Advanced LIGO
  - Expect to be doing GW astrophysics with Advanced LIGO
- LIGO data analysis is producing some interesting upper limits
- Efforts towards an international network of ground-based GW detectors are gaining momentum

Backup slides

Simplified timeline for LIGO



Adv LIGO
Const. begins

Begin S6
Enhanced LIGO

End S6

Build hardware

Begin Adv.

LIGO installation

2014

First stochastic measurement correlating resonant bar with interferometer

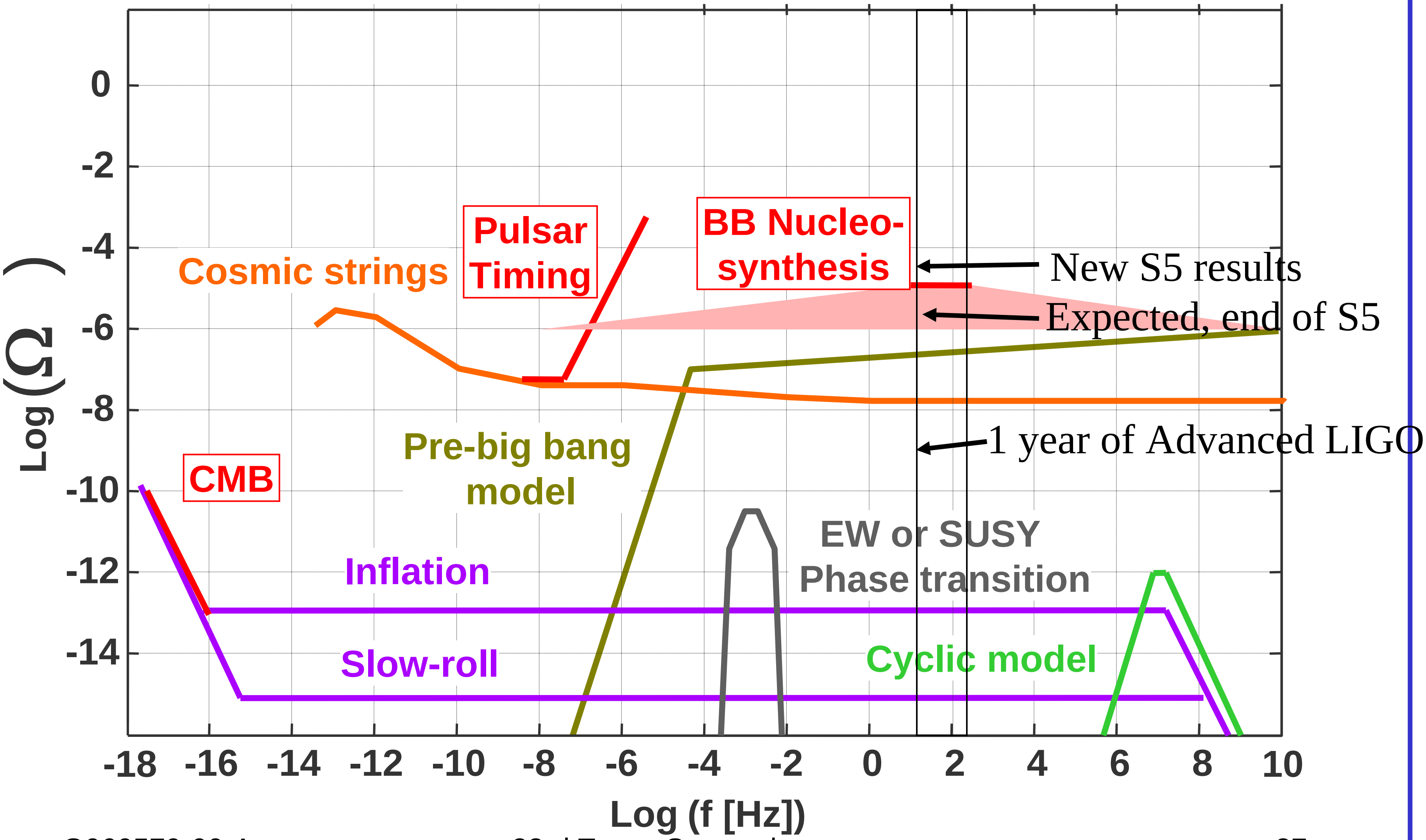
- Correlate LIGO with ALLEGRO resonant bar
  - located within ~40 km or each other so delay time vs. point on sky not an issue
- Probes higher frequency band than IFO-IFO correlations:

  ~850Hz – 950Hz
- Preliminary upper limit results from S4; ~370 hrs of data:

  $\sqrt{S_{gw}}(915\text{Hz}) < 1.5 \times 10^{-23}\ \text{Hz}^{-1/2}$

  i.e., $\Omega_{gw}(915\text{Hz}) < 1.02$ $[h^2_{100}\ \Omega_{gw}(915\text{Hz}) < 0.53]$,
  - 100× improvement over EXPLORER-NAUTILUS limit from the Rome group)

Stochastic sources including Big Bang -- Predictions --



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

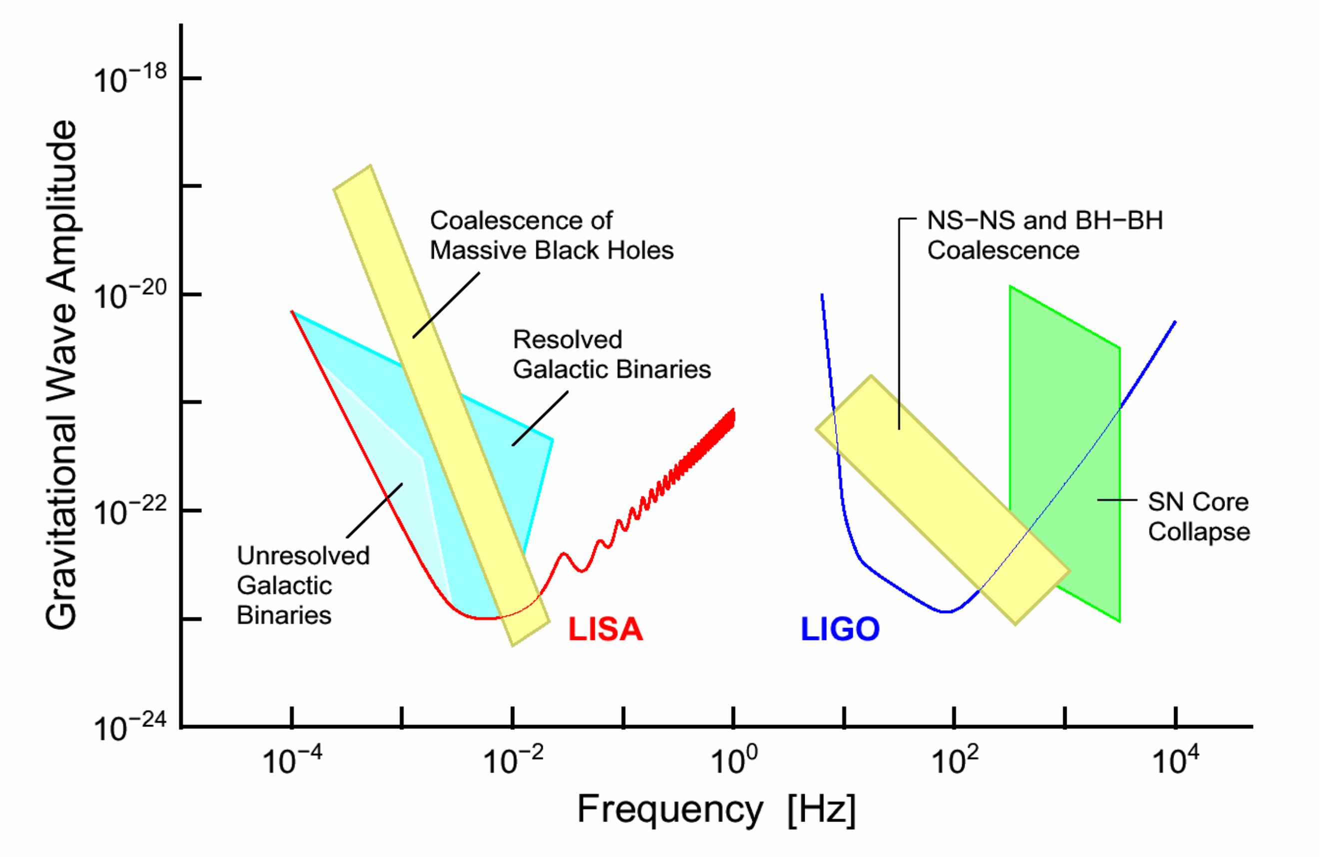
- Very different information, mostly mutually exclusive

How do we avoid fooling ourselves?

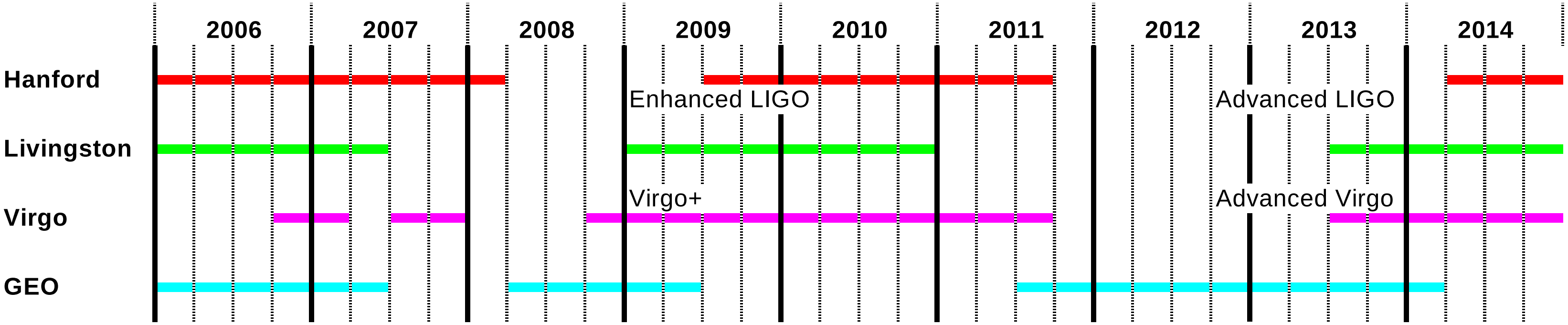
Seeing a false signal or missing a real one

- At least 2 independent signals--e.g. coincidence between interferometers at 2 sites for inspiral and burst searches, external trigger for GRB or nearby supernova.
- Constraints- Pulsar ephemeris, ~ inspiral waveform, time difference between sites.
- Environmental monitor as vetos-
  - Seismic/wind-- seismometers, accelerometers, wind-monitors
  - Sonic/accoustic- microphones
  - Magnetic fields- magnetometers
  - Line voltage fluctuations-- volt meters
- Hardware injections of pseudo signals (actually move mirrors with actuators)
- Software signal injections

LIGO


Gravitational Wave Amplitude
10^{-18}
10^{-20}
10^{-22}
10^{-24}
Coalescence of Massive Black Holes
Resolved Galactic Binaries
Unresolved Galactic Binaries
LISA
NS−NS and BH−BH Coalescence
SN Core Collapse
LIGO
10^{-4}
10^{-2}
10^{0}
10^{2}
10^{4}
Frequency [Hz]

Illustrative Scenario for Run Coordination



- One scenario to illustrate—others are possible
- Hope to involve future Japanese (LCGT) and Australian (AIGO) facilities as well