LIGO: Status and Update

XLII Rencontres de Moriond

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(on behalf of the LIGO Scientific Collaboration)

La Thuile, Val d'Aosta, Italy

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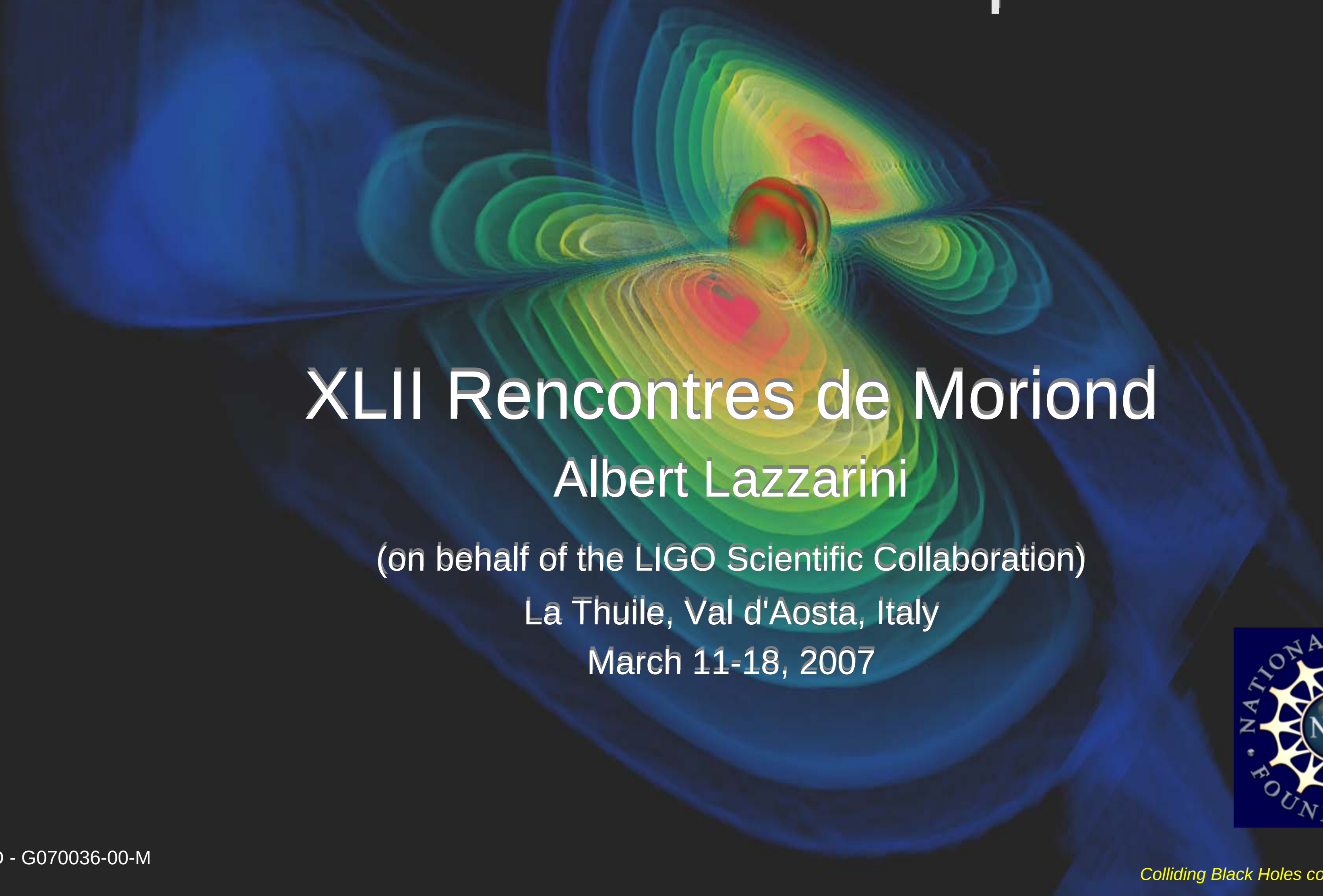


Colliding Black Holes courtesy of NCSA

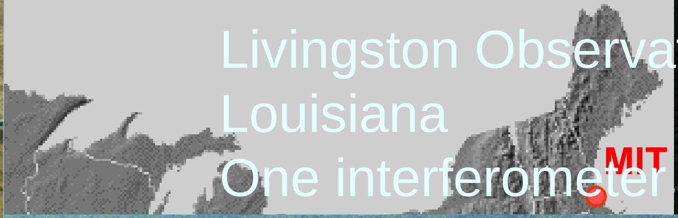
Outline

- Overview of LIGO
- The current status
  - The current science run
  - LIGO’s future evolution
- Astrophysics results
  - Sources
  - Previews of later talks
- Towards a world-wide network of ground-based detectors for gravitational waves

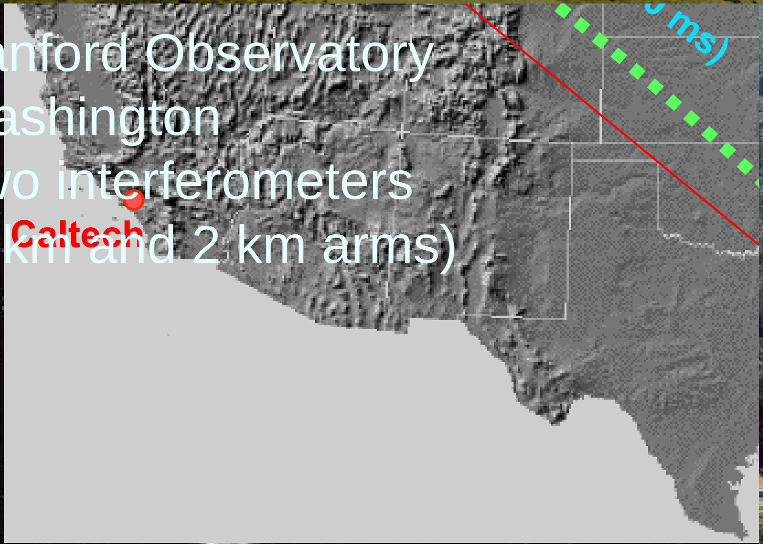
The LIGO Laboratory Sites

…ed along the great circle
…g the sites

…round breaking: 1995
1st interferometer locked: 2000
Design sensitivity run started: 2005



Livingston Observatory
Louisiana
One interferometer (4km)



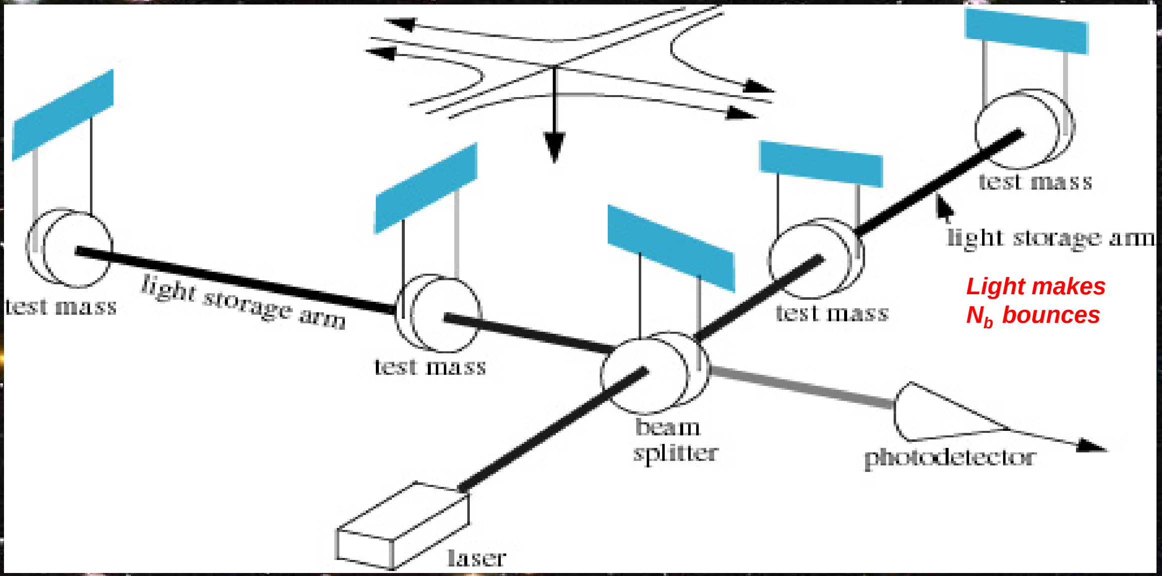
Hanford Observatory
Washington
Two interferometers
(4 km and 2 km arms)

Managed and operated…
funding through a Cooperat…

Scientific Program is coordinated by the LIGO Scientific Collaboration:
45 institutions world-wide, ~500 members

LSC

QuickTime™ and a Animation decompressor are needed to see this picture.



Detector concept

- The concept is to compare the time it takes light to travel in two orthogonal directions transverse to the gravitational waves.
- The gravitational wave causes the time difference to vary by stretching one arm and compressing the other.
- The interference pattern is measured (or the fringe is split) to one part in 10^{10}, in order to obtain the required sensitivity.

$h = \Delta L/L \Rightarrow \Delta\phi/2\pi = 2 N_b hL/\lambda$

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

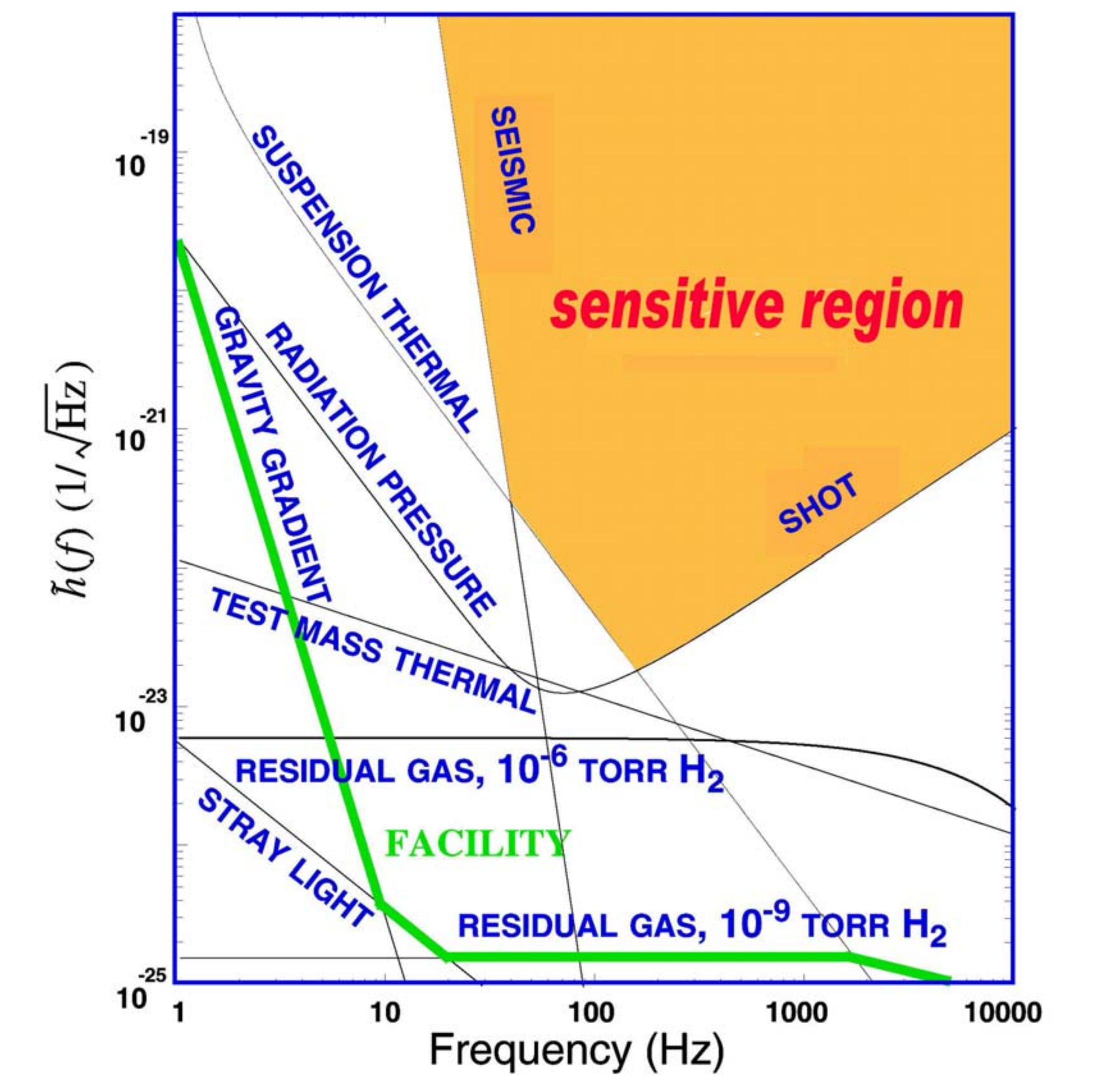
Challenge: to measure relative distance between test masses in interferometers arms to ~ 10^{-18} m -- 1/1000 the size of a proton!

LIGO First Generation Detector
Limiting noise floor

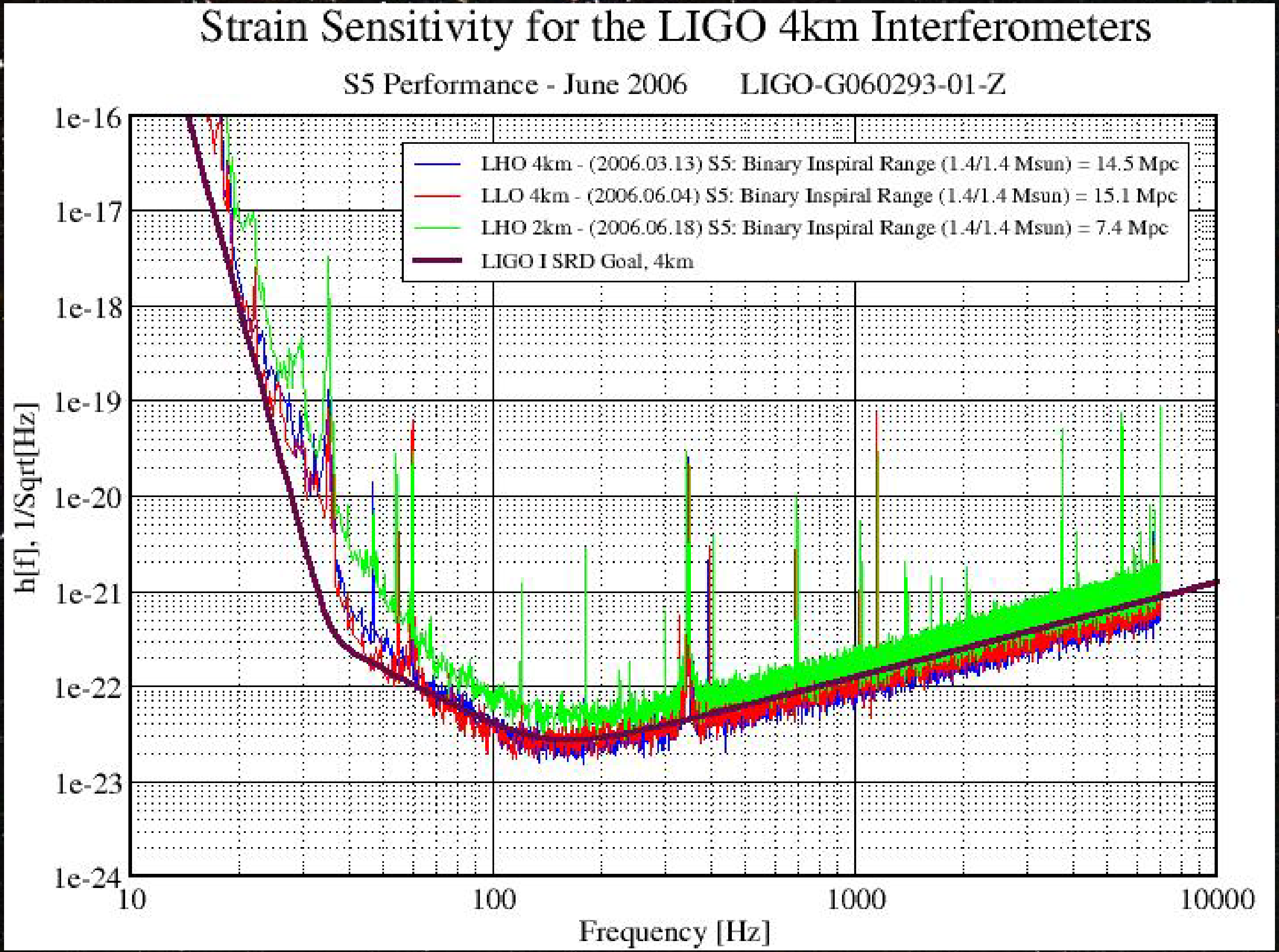
- **Interferometer sensitivity is limited by three fundamental noise sources**
  - <u>seismic noise</u> at the lowest frequencies
  - <u>thermal noise</u> (Brownian motion of mirror materials, suspensions) at intermediate frequencies
  - <u>shot noise</u> at high frequencies

- **Many other noise sources lie beneath and must be controlled as the instrument is improved**

- **Facilities limits support future improvements in detector technology**



2005: Reached SRD (1995) sensitivity requirement
--A major achievement--



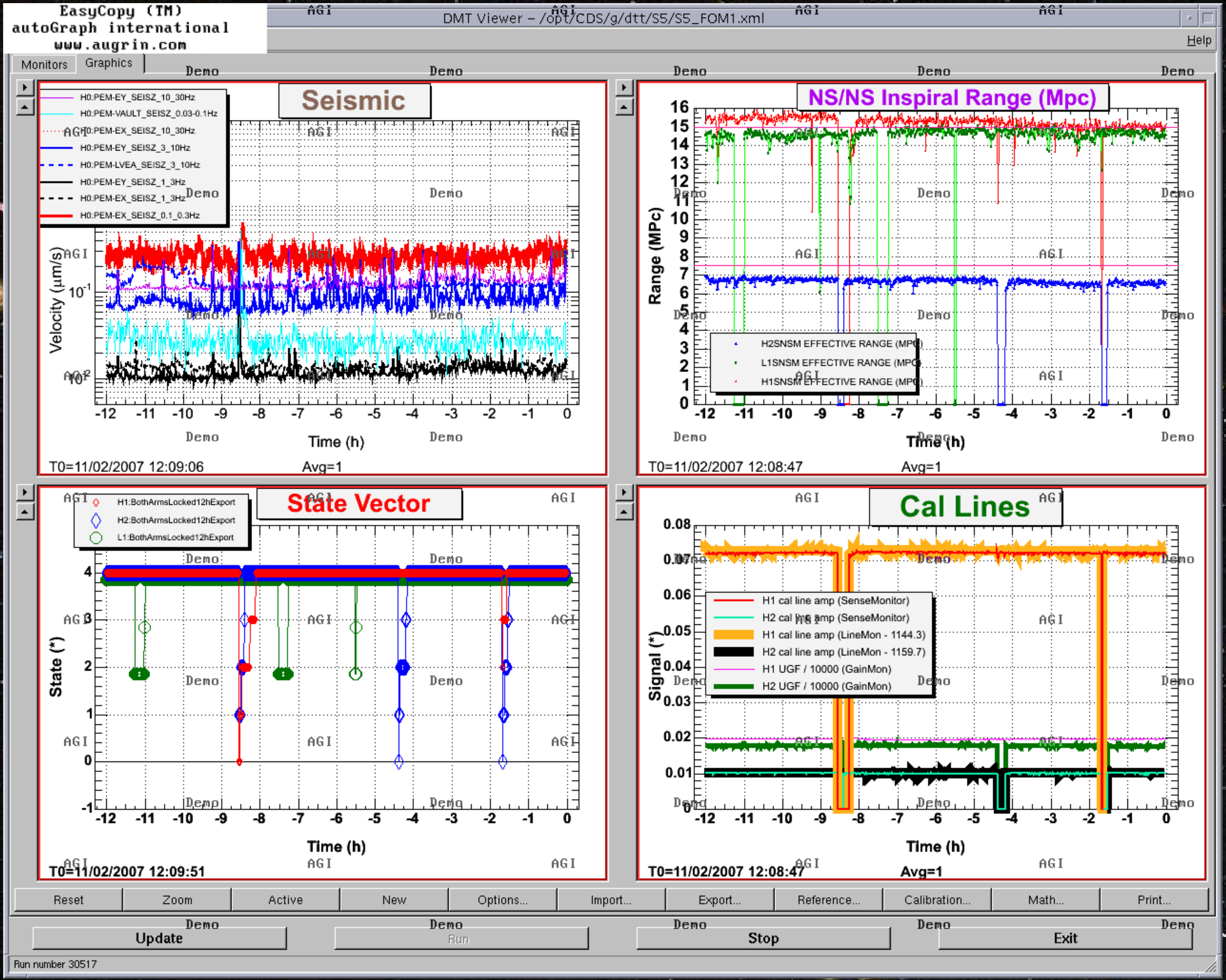
The current search for gravitational waves

- Science Run 5 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
  - Figure of merit: range at beginning of run for 1.4 M_o neutron star pairs
      - Sky and orientation averaged,
      - S/N≡8
    - for 4 km IFOs: > 10 Mpc
    - for 2 km IFO: > 5 Mpc
  - Range is now ~50% greater than beginning of run …

Recent Control Room Graphics



Range -- Trend over entire run S5

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

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TIFF (LZW) decompressor
are needed to see this picture.

Progress of S5
Nov 2005 through Feb 2007

□□□□□□□□□

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TIFF (LZW) decompressor
are needed to see this picture.

Cumulative Up-time

QuickTime™ and a
TIFF (LZW) decompressor
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Projected End of S5

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are needed to see this picture.

1 Year Coincident Observation

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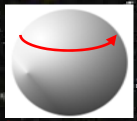
TIFF (LZW) decompressor
are needed to see this picture.

Sources & organization of LIGO searches by the LIGO Scientific Collaboration - *later talks*

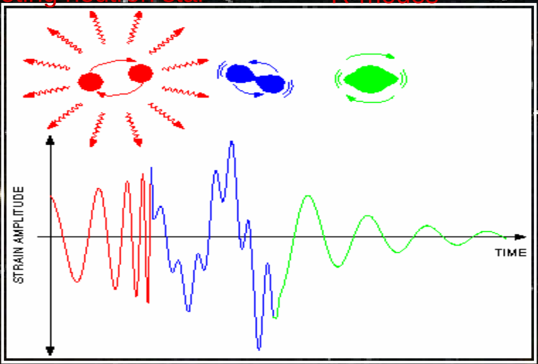

"Mountain" on neutron star


Wobbling neutron star

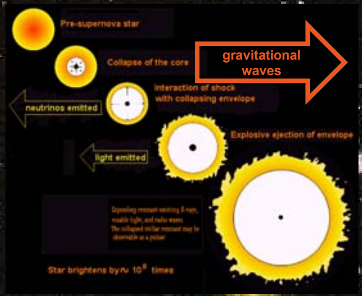

Accreting neutron star


R-modes

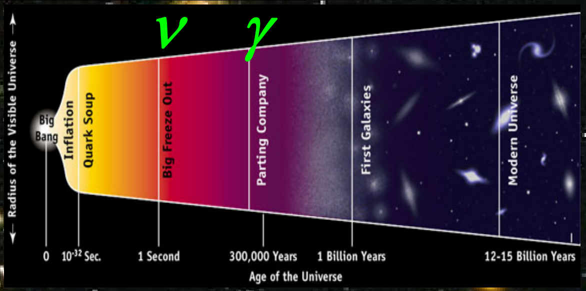
- Periodic sources
  - Binary Pulsars, Spinning neutron stars, Low mass X-ray binaries



- 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 !*

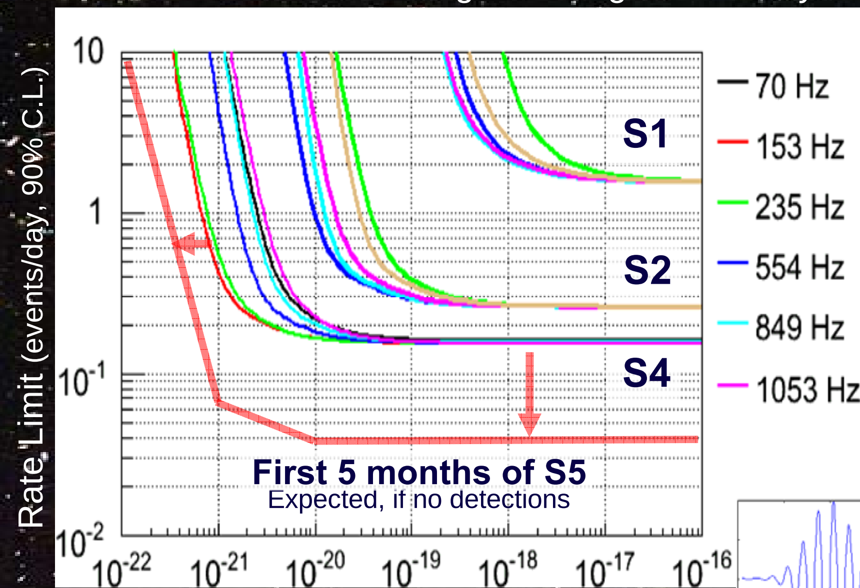
Status of GW Burst Searches

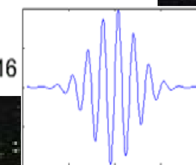
see: Talk by K. Thorne at this conference

UNTRIGGERED

- All-sky search for short, unmodeled signals
- Possible sources: Supernova, compact mergers, the unknown
- Tuned for 64–1600 Hz, duration «1 sec
- No GW bursts signals seen in S1/S2/S3/S4
- Preliminary limit from first 5 months of S5
- Corresponding energy emission sensitivity **E_{GW} ~ 0.1 $M_\odot$ at 20 Mpc** (153 Hz case)

Limit on rate vs. GW signal strength sensitivity





h_{rss} (root-sum-squared strain amplitude)

GRBs

- Search GW data at times of GRB triggers from Swift, HETE-2, etc.
- Target search to sky position when known
- Place limits on GW emission from individual GRBs and from population
- No GW signals found associated with 39 GRBs in S2, S3, S4 runs
- ~10 GRB triggers per month during S5

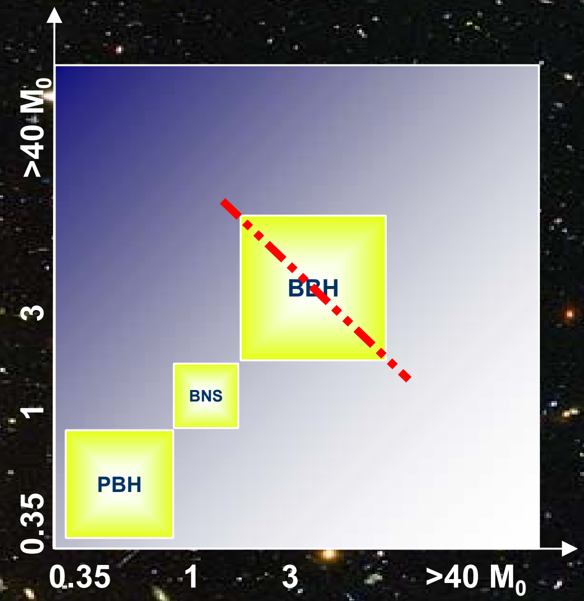
SGR 1806-20

- Record γ-ray flare on December 27, 2004
- Quasi-periodic oscillations (QPO) in x-ray data from RHESSE and RXTE
- Search for quasi-periodic GW signal
- No GW signal found
- Sensitivity for 92.5Hz QPO
- **E_{GW} ~ 10^{-7} to 10^{-8} $M_\odot$ at 5-10 kpc** (same magnitude as EM energy in flare)

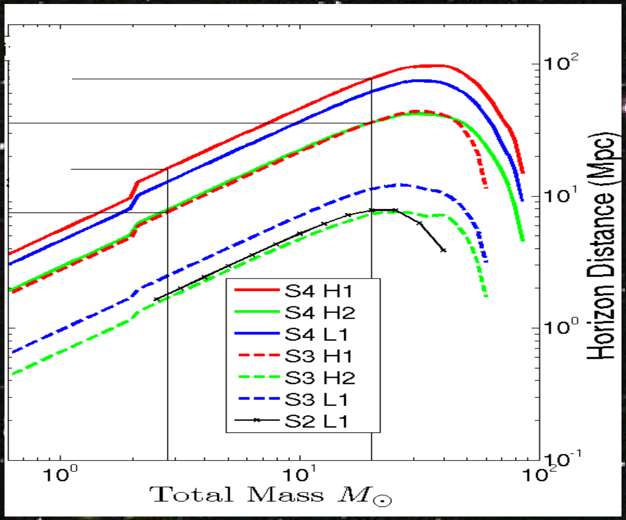
Status of Compact Binary Coalescence Searches

see: Talk by T. Cokalaer at this conference

- Searches with the S3 and S4 science runs
  - ~1300 hours of coincident data
  - Various compact binaries systems:
    - Primordial black holes (M_0<1)
    - Binary neutron stars (1 < M_0<3)
    - Binary black holes (M_0 >3)



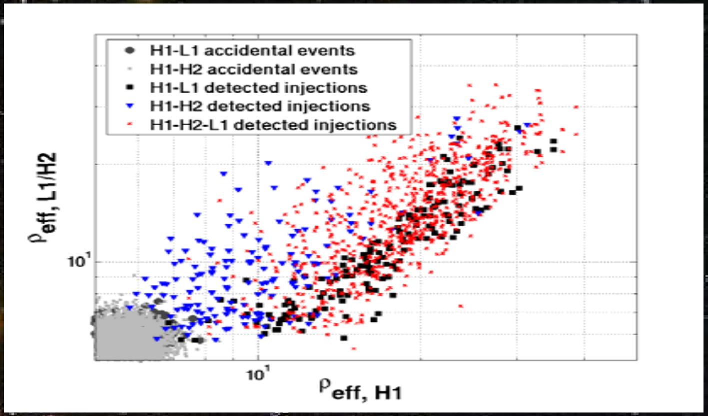
- Horizon distance as far as tens of Mpc

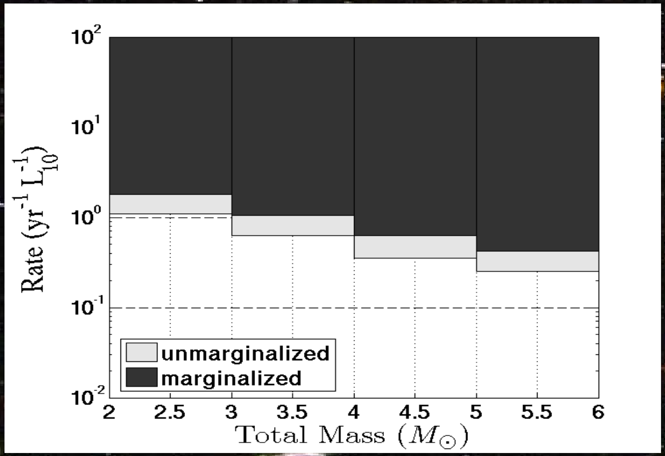


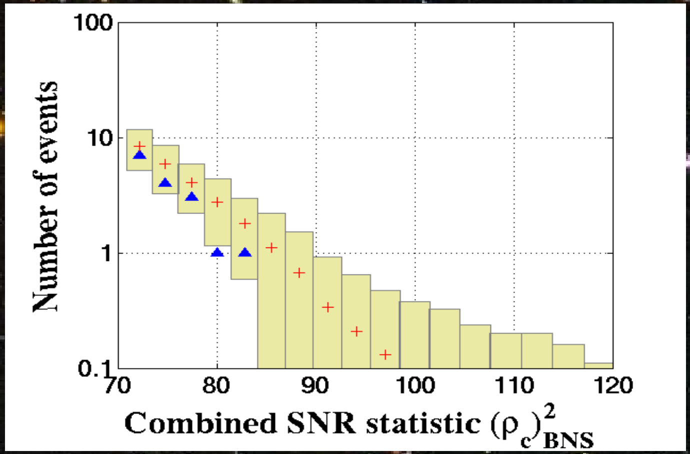
Status of Compact Binary Coalescence Searches (cont.)

see: Talk by T. Cokalaer at this conference

- Investigations …
  - At what SNR can we detect a signal. How well?
  - Differences between the different searches
  - Zero time-lag and background (false alarm) events
  - Final S4 upper limit results



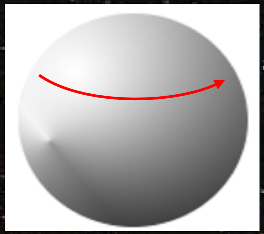




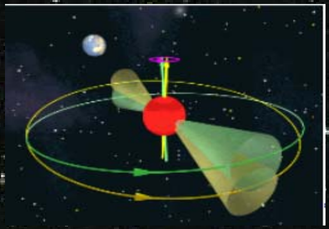
Status of pulsar GW searches

see: Talk by M. Pitkin at this conference

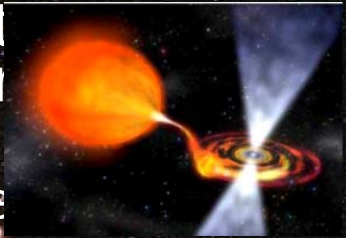
- Rapidly spinning neutron stars provide a potential source of continuous gravitational waves
- To emit gravitational waves they must have some degree of non-axisymmetry
  - Triaxial deformation due to elastic stresses or magnetic fields
  - Free precession about axis
  - Fluid modes e.g. r-modes
- Size of distortions can reveal information about the neutron star equation of state



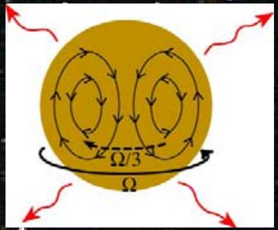
“Mountain” on neutron star



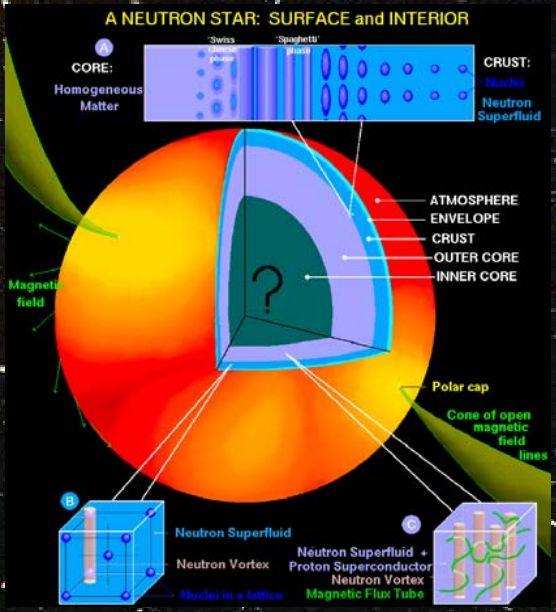
Wobbling neutron star



Accreting neutron star



R-modes



www.astroscu.unam.mx/neutrones/NS-Picture/NStar/NStar_IS.gif

Status of pulsar GW searches (cont.)

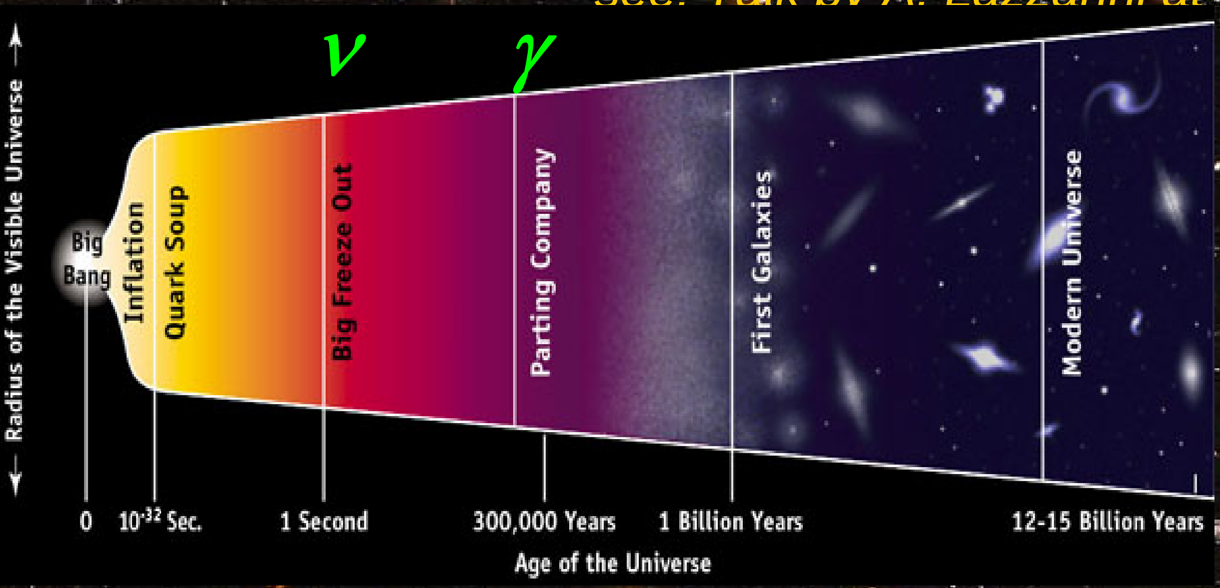
see: Talk by M. Pitkin at this conference

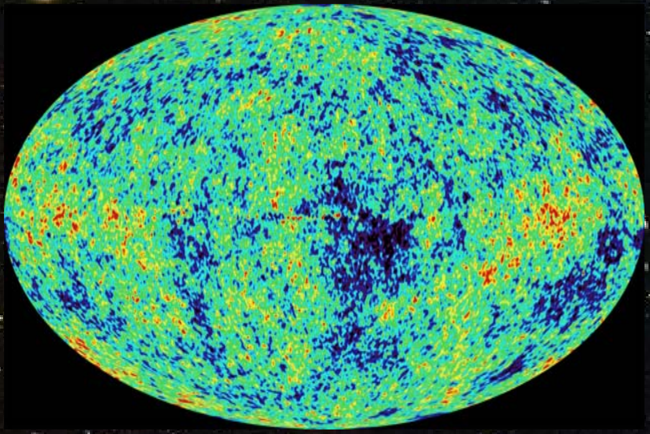
- Targeted search for 97 known pulsars (S5 run)
  - Lowest h_0 upper limit: PSR J1623-2631 (ν_{gw} = 180.6 Hz, r = 3.8 kpc) $h_0 < 4.8\times10^{-26}$
  - Lowest ellipticity upper limit: PSR J2124-3358 (ν_{gw} = 405.6Hz, r = 0.25 kpc) $\varepsilon < 1.1\times10^{-7}$
  - Crab pulsar: *observational GW emission upper limit is smaller than the spin-down derived limit*

- Blind all-sky, broadband search -- Hough transform
  - No unexplained candidates
  - Lowest h_0 upper limit:
    $h_0 < 4.3\times10^{-24}$ *(140.25-140.50 Hz)*

Gravitational waves from a stochastic background

see: Talk by A. Lazzarini at this conference





Analog from cosmic microwave background -- WMAP 2003

GWs can probe the very early universe

- Detect by cross-correlating interferometer outputs in pairs:
  - Hanford - Livingston, Hanford - Hanford

- Good sensitivity requires:
  - ●$_{GW}$ ≥ *2D* (detector baseline)
  - *f ≤ 40 Hz* for LIGO pair over 3000 km baseline

- Initial LIGO limiting sensitivity (1 year search): $\Phi_{GW} < 10^{-6}$

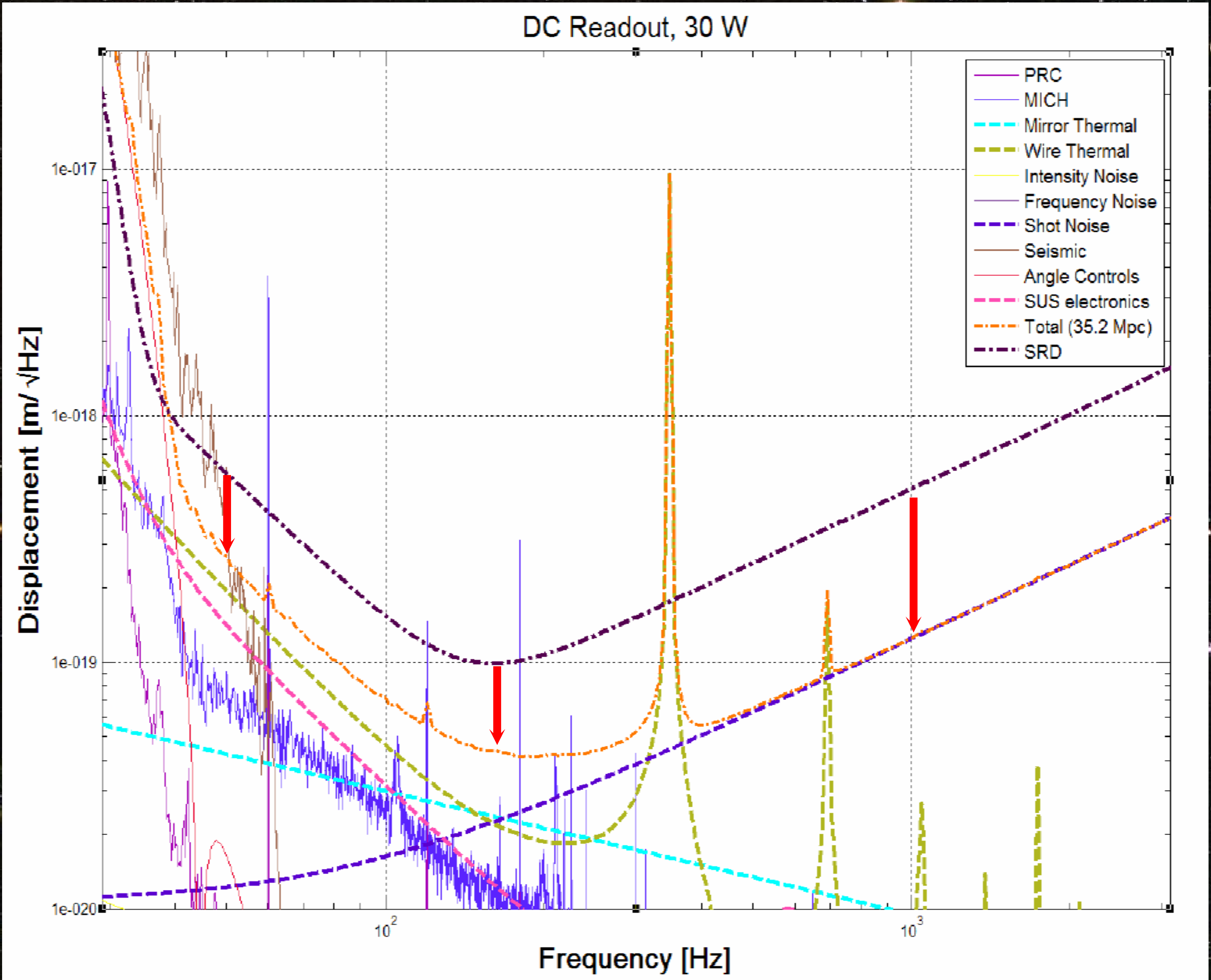
$$\int_0^\infty d\ln f\, \Omega_{gw}(f) = \frac{\rho_{gw}}{\rho_{critical}}$$

The integral of [1/f•Ω_{GW}(f)] over all frequencies corresponds to the fractional energy density in gravitational waves in the Universe

Stochastic signals

see: Talk by A. Lazzarini at this conference

- Stochastic backgrounds can arise either from
  - Cosmological processes, such as inflation, phase transitions, or cosmic strings, or from
  - Astrophysical processes, as the superposition of many signals from the other signal classes already described earlier in talk.
    - e.g., GW spectrum due to cosmological BH ring downs (Regimbau & Fotopoulos
- Characterize the strength by
  - $\Omega_{GW}(f)$, defined as the fraction of cosmic closure density in the background, in a logarithmic frequency interval near frequency f.

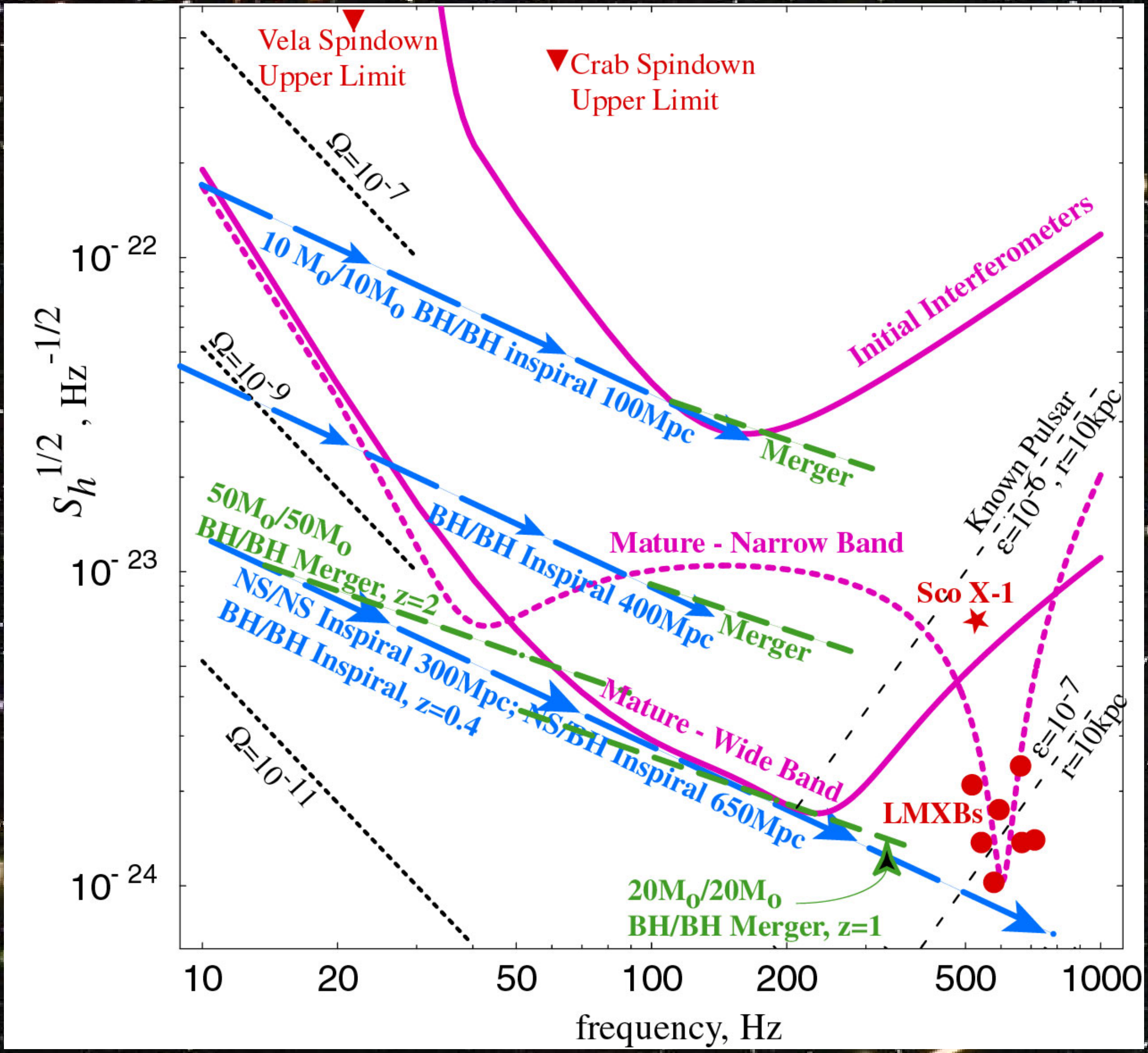


DC Readout, 30 W
PRC
MICH
Mirror Thermal
Wire Thermal
Intensity Noise
Frequency Noise
Shot Noise
Seismic
Angle Controls
SUS electronics
Total (35.2 Mpc)
SRD
1e-017
1e-018
1e-019
1e-020
Displacement [m/ √Hz]
10^2
10^3
Frequency [Hz]

The scientific vision for LIGO

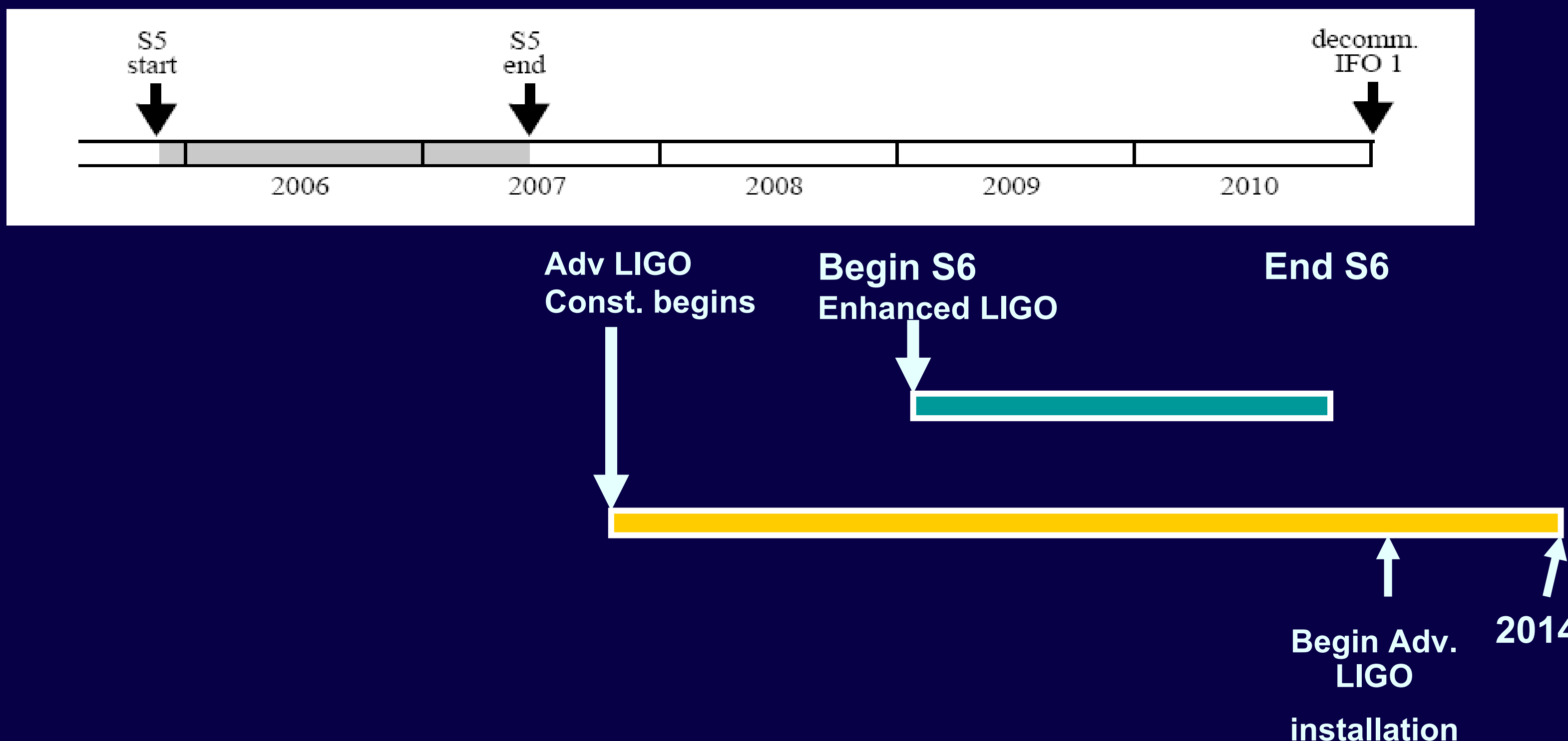
- 1st full science run of LIGO at design sensitivity in progress
  - Began November 2005; >70% complete
  - Hundreds of galaxies now in range
  - Discovery possible but not probable during coming year
- Enhancement program
  - In 2009 ~8X more galaxies in range; discovery probability proportionately increased
- Advanced LIGO project (~$200M)
  - Construction start expected in FY08
  - 1000X more galaxies in range
  - Expect ~1 signal/day- 1/week in ~2014
  - Will usher in era of gravitational wave astrophysics

Initial and Advanced LIGO



Advanced LIGO Construction

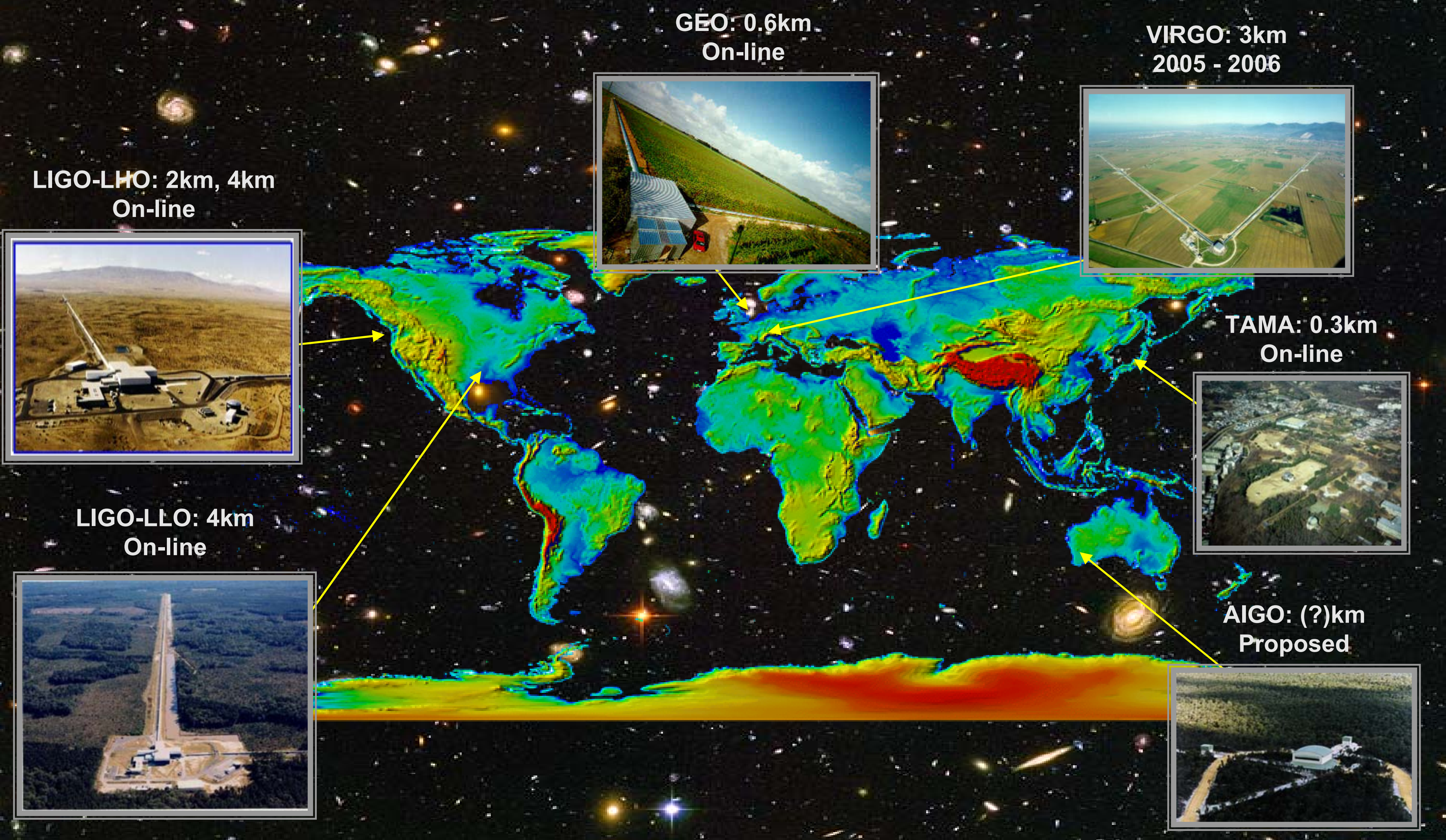
Simplified timeline for LIGO



Growing International Network of GW Interferometers

Operated as a phased array:

- Enhance detection confidence
- Localize sources
- Decompose the polarization of gravitational waves



Status of the global network

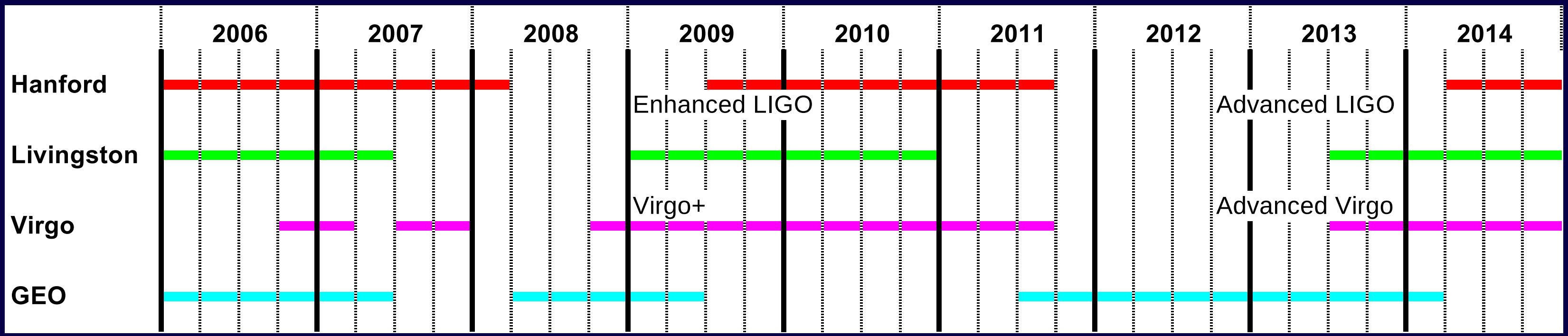
- GEO and LIGO carry out all observing and data analysis as one team, the LIGO Scientific Collaboration (LSC).

- LSC and Virgo have concluded negotiations on joint operations and data analysis.
  - *More on next slide*

- LIGO carries out joint searches with the network of resonant detectors.

LIGO-Virgo Joint Cooperation on Data Analysis

One scenario to illustrate—others are possible



Summary

- LIGO is operating in a science mode at design sensitivity
  - 1st long science run is ~60% complete
  - No detection yet
  - LIGO data analysis is starting to produce interesting upper limits

- Sensitivity/range *relative to S5 sensitivity* will be
  - increased ~ 2X in 2009 and,
  - a factor 10X in ~2014 with Advanced LIGO
  - Expect to be doing GW astrophysics with Advanced LIGO

- Efforts towards an international network of ground-based GW detectors are gaining momentum