The search for gravitational waves with LIGO

Romain Gouaty,

Louisiana State University

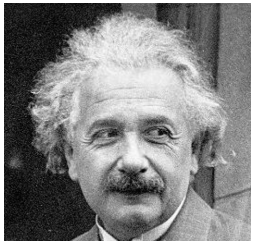
LIGO Scientific Collaboration

2007/10/26 – LAPP Annecy

- *What are gravitational waves ?*
- *The LIGO experiment*
- *Analysis methods and astrophysical observations*
- *Perspectives: a network of advanced detector*

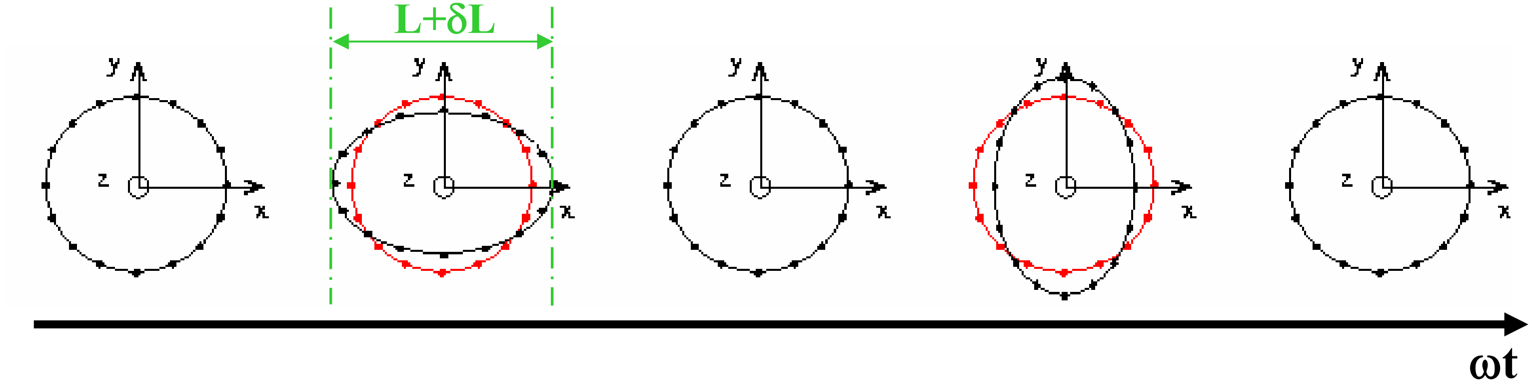
What are gravitational waves ?

Gravitational wave = propagating disturbance of the space-time



- **Predicted by Einstein's General Relativity**
- **Properties:** **- transverse plane waves**
  - travel at the speed of light
  - 2 polarization states
- **Modify distances between free falling masses**

$$\delta L = h \frac{L}{2}$$

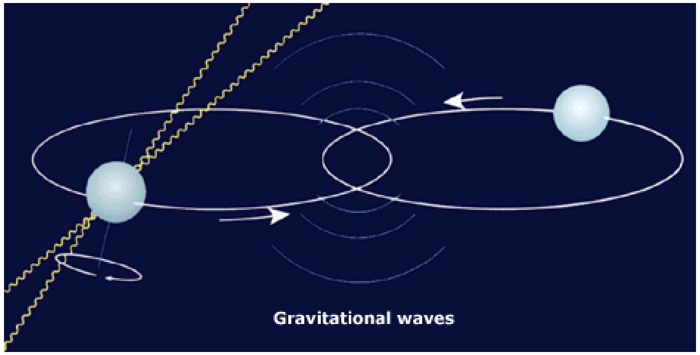


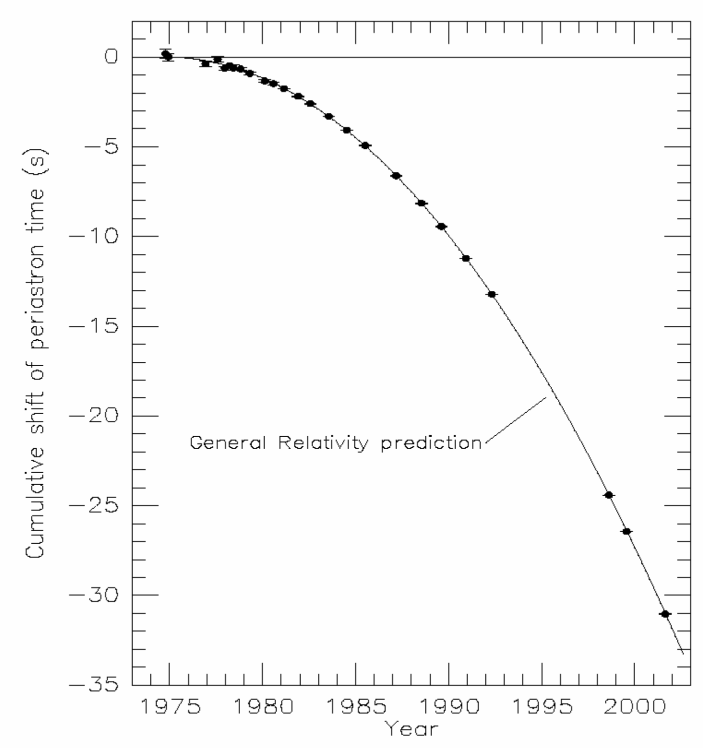
- **Quadrupolar radiation: generated by asymmetric motions of matter**
- **Very weak amplitudes: requires compact, massive, relativistic objects**

Favored astrophysical objects: Neutron Stars, Black Holes, Supernovae, …

An evidence that gravitational waves exist…

- **Binary system 1913+16**: discovered in 1974 by Hulse and Taylor
  - 2 **neutron stars** of 1.4 solar masses
  - one of this star is a **radio pulsar**





⇒ Measurement of the orbital period decrease

In agreement with an energy loss due to gravitational wave radiation

⇒ An indirect evidence for gravitational wave radiation !

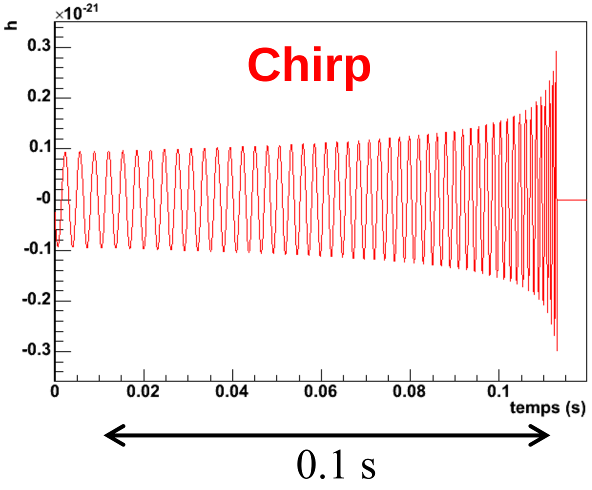
Sources of gravitational waves: Coalescences of compact binaries

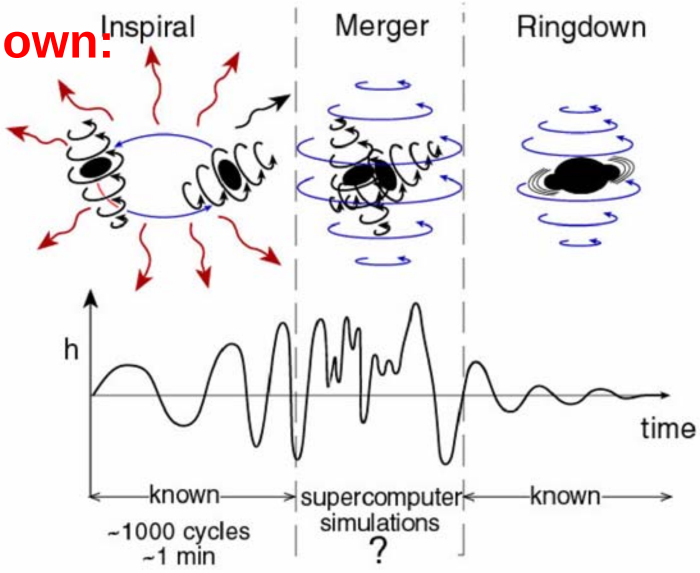
→ **Binary systems of 2 compact objects: Neutron stars, Black holes**

End of the life of the system = coalescence of the 2 stars

→ **During the inspiral phase, the waveform is known:**

(but depends on masses, and spins…)





Starting at low frequency, the signal reaches several hundred Hertz at the end of coalescence ⇒ enters in the band width of detectors such as LIGO/Virgo

Other sources of gravitational waves:

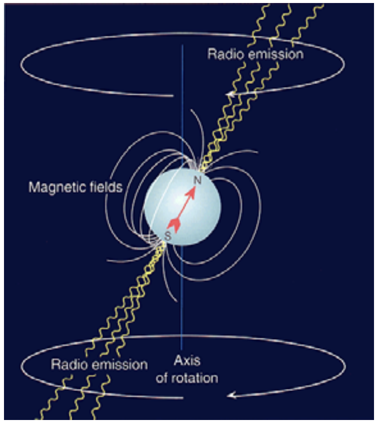
→ **Supernovae (gravitational collapse of massive stars):**

If asymmetrical collapse: produce GW

- Impulsive source: short signal duration (≤ 10 ms)

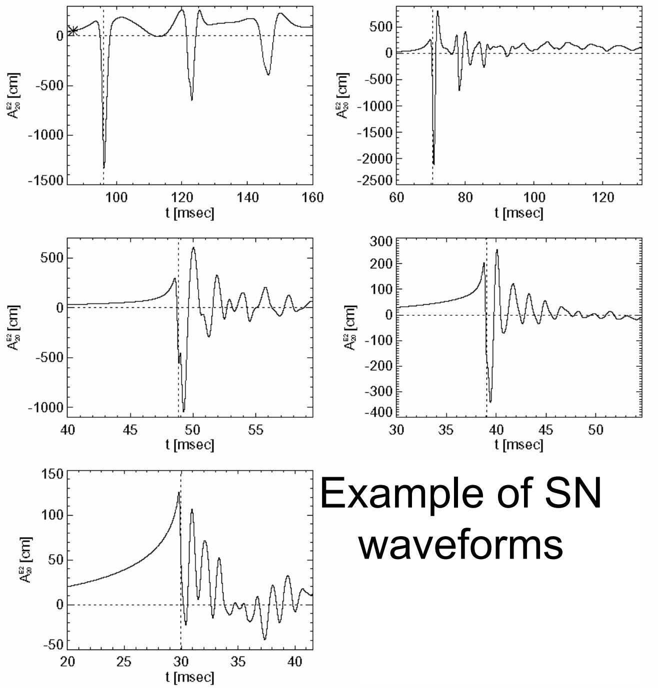
- Waveform and amplitude not very well known

→ **Pulsars (spinning rotating neutron star)**



Low amplitude but periodic source

⇒ Signal can be integrated over long durations



Example of SN waveforms

→ **Stochastic background of gravitational waves** (Big Bang gravitational echo)

Why detecting gravitational waves ?

- **Perform the first direct detection of gravitational waves**

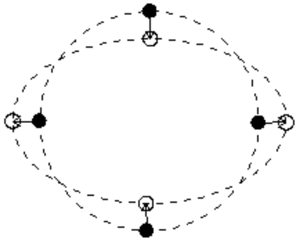
- **Study the gravitational interaction**
  - ➢ Check gravitational wave properties (velocity, polarization)
  - ➢ GW radiated by Black Holes ⇒ test in strong fields the General Relativity

- **A new window to observe the Universe**
  - ➢ Coincidences with other messengers: photons, neutrinos
  - ➢ Observation of regions of the Universe opaque to electromagnetic waves

- *What are gravitational waves ?*
- *The LIGO experiment*
- *Analysis methods and astrophysical observations*
- *Perspectives: a network of advanced detector*

How to detect a gravitational wave ?

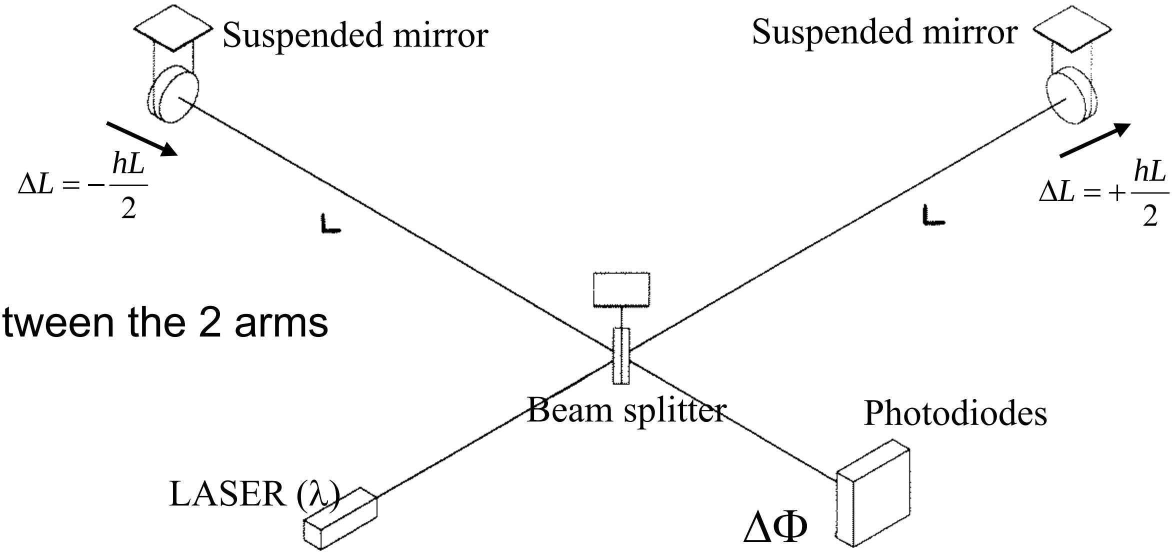
- Variation of the distance between free-falling masses



⇒ **Can be measured with a Michelson interferometer**

- suspended mirrors = free-falling masses
- gravitational wave ⇒ phase difference between the 2 reflected beams

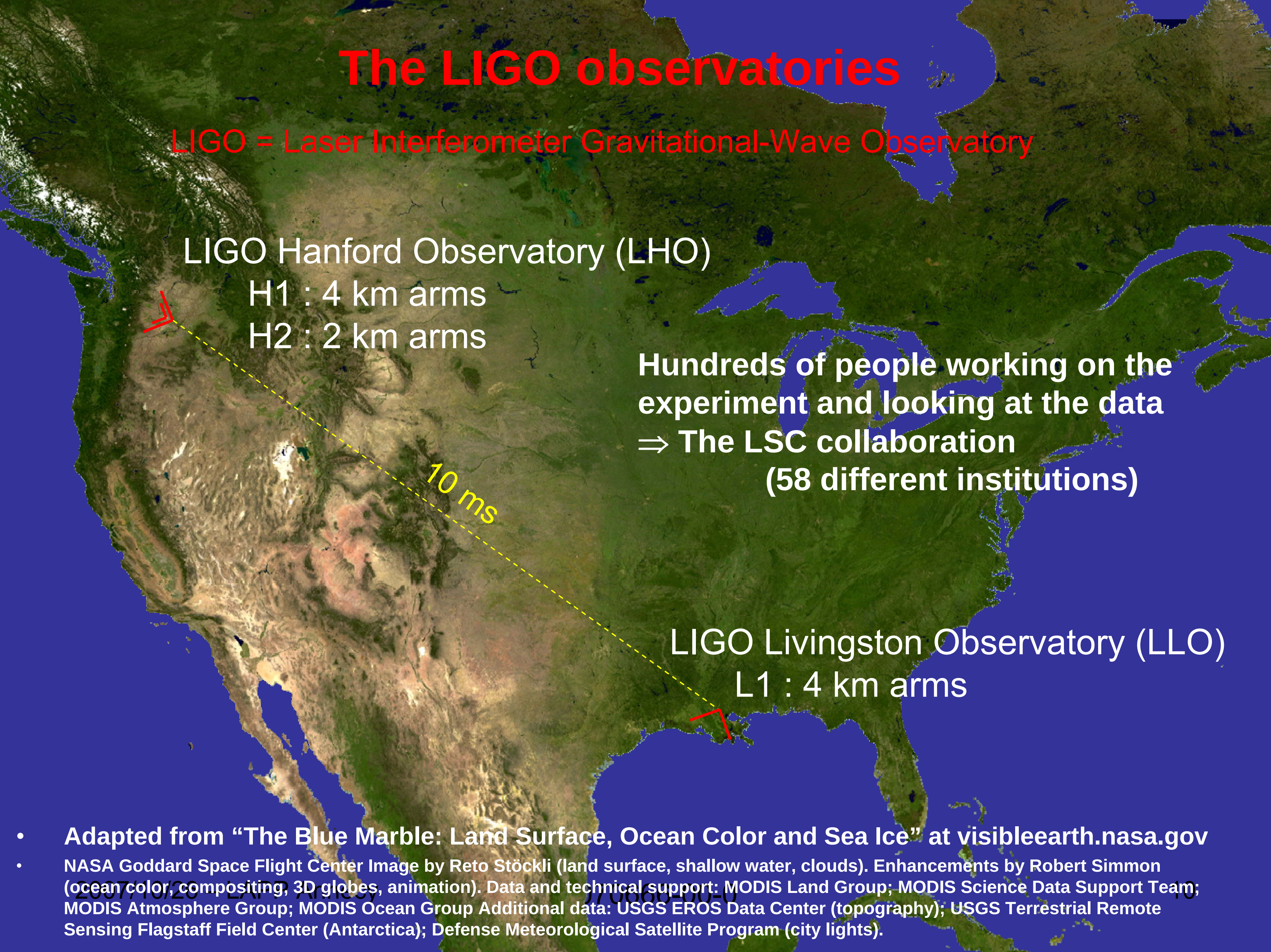
$$\Delta\Phi = \frac{4\pi}{\lambda} hL$$



h = ΔL/L
ΔL = length difference between the 2 arms
L = arm length

The LIGO observatories

LIGO = Laser Interferometer Gravitational-Wave Observatory



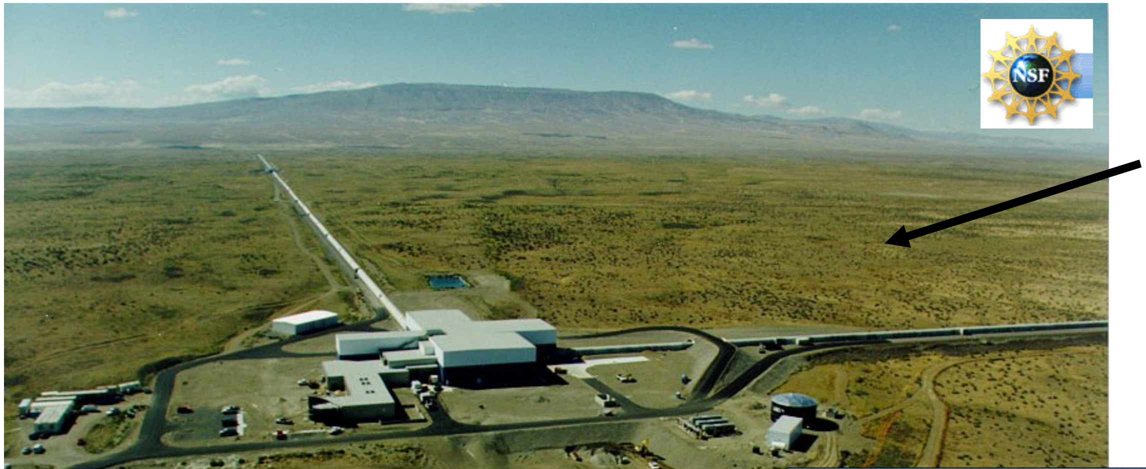
LIGO Hanford Observatory (LHO)
H1 : 4 km arms
H2 : 2 km arms

Hundreds of people working on the experiment and looking at the data
⇒ The LSC collaboration
(58 different institutions)

LIGO Livingston Observatory (LLO)
L1 : 4 km arms

- **Adapted from “The Blue Marble: Land Surface, Ocean Color and Sea Ice” at visibleearth.nasa.gov**
- **NASA Goddard Space Flight Center Image by Reto Stöckli (land surface, shallow water, clouds). Enhancements by Robert Simmon (ocean color, compositing, 3D globes, animation). Data and technical support: MODIS Land Group; MODIS Science Data Support Team; MODIS Atmosphere Group; MODIS Ocean Group Additional data: USGS EROS Data Center (topography); USGS Terrestrial Remote Sensing Flagstaff Field Center (Antarctica); Defense Meteorological Satellite Program (city lights).**

The LIGO observatories



LIGO Hanford:

4km / 2km share the same tubes

LIGO Livingston

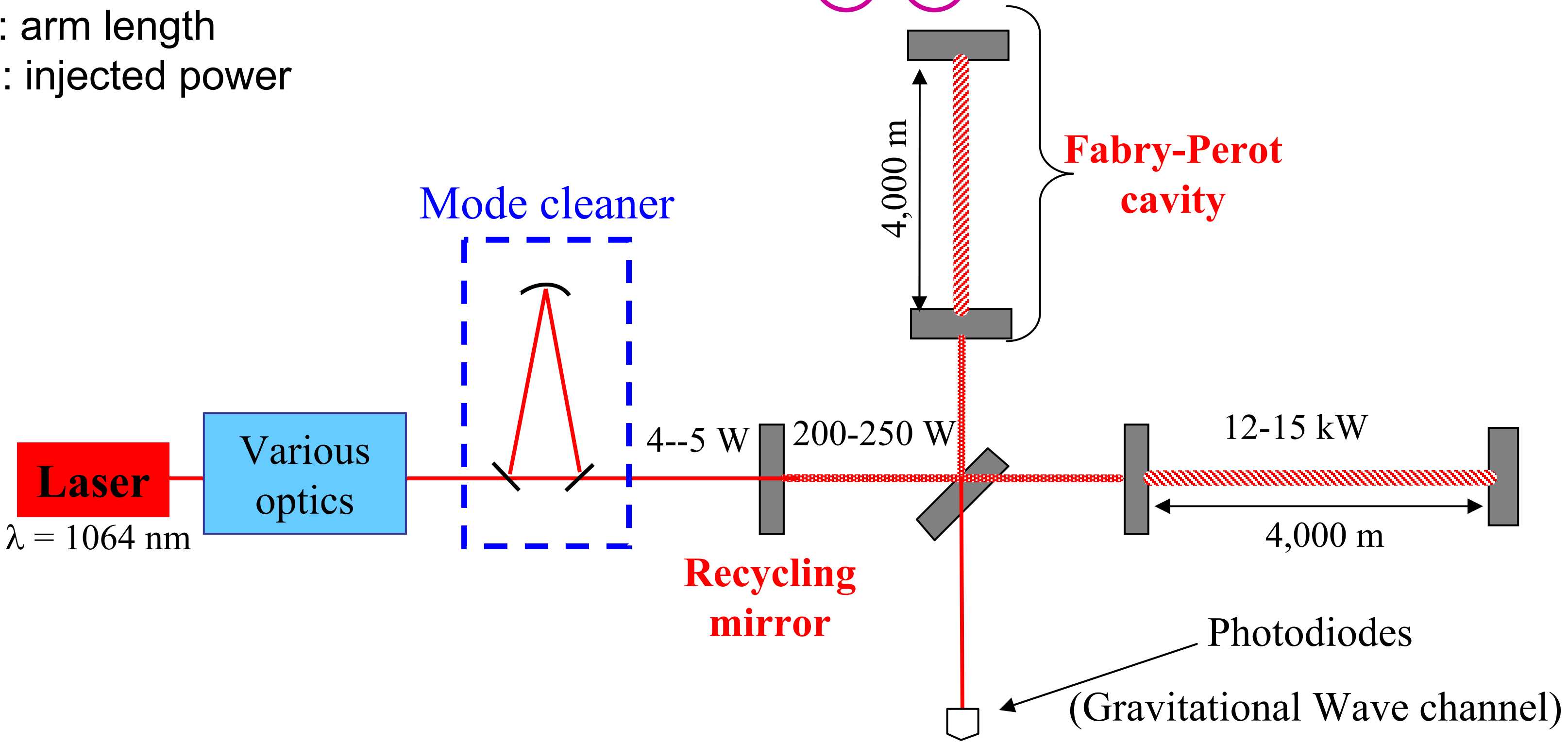
Visitors are welcome !

The LIGO interferometers

Sensitivity of an interferometer limited by shot noise:

Smaller measurable displacement: $\tilde{h} \geq \frac{\lambda}{4\pi}\frac{1}{L}\sqrt{\frac{2\hbar\omega}{P}}$

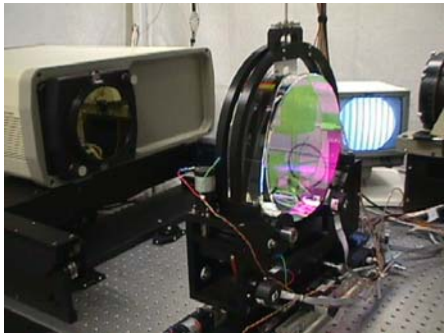
L: arm length
P: injected power



- Fabry-Perot cavity: ~125 round trips ⇒ effective optical path = 500 km
- Recycling cavity: power x 50

Fundamental noises

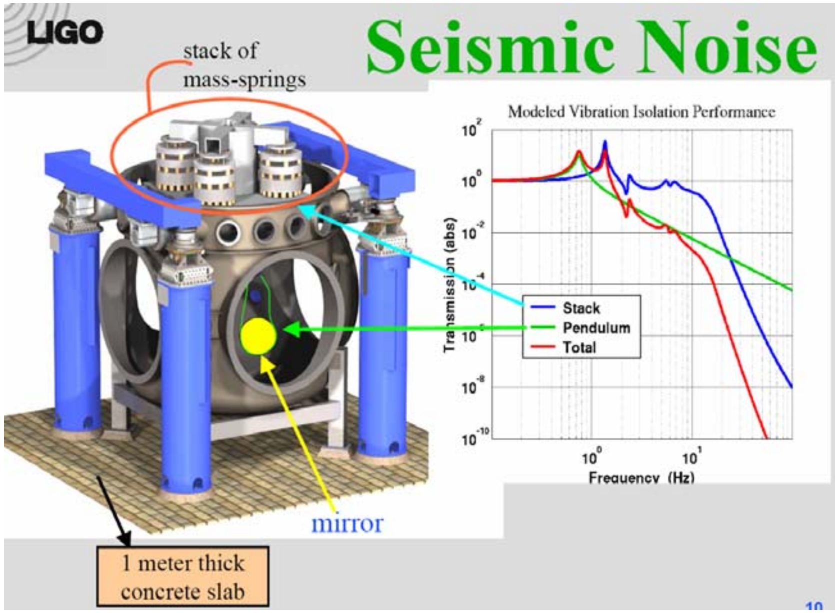
- **Thermal noise:** affecting mirrors and suspensions



- high-purity fused silica
- largest mirrors are 25 cm diameter, 10 cm thick, 10.7 kg
- surfaces polished to ~1 nm rms
- low scattering loss (<50 ppm)

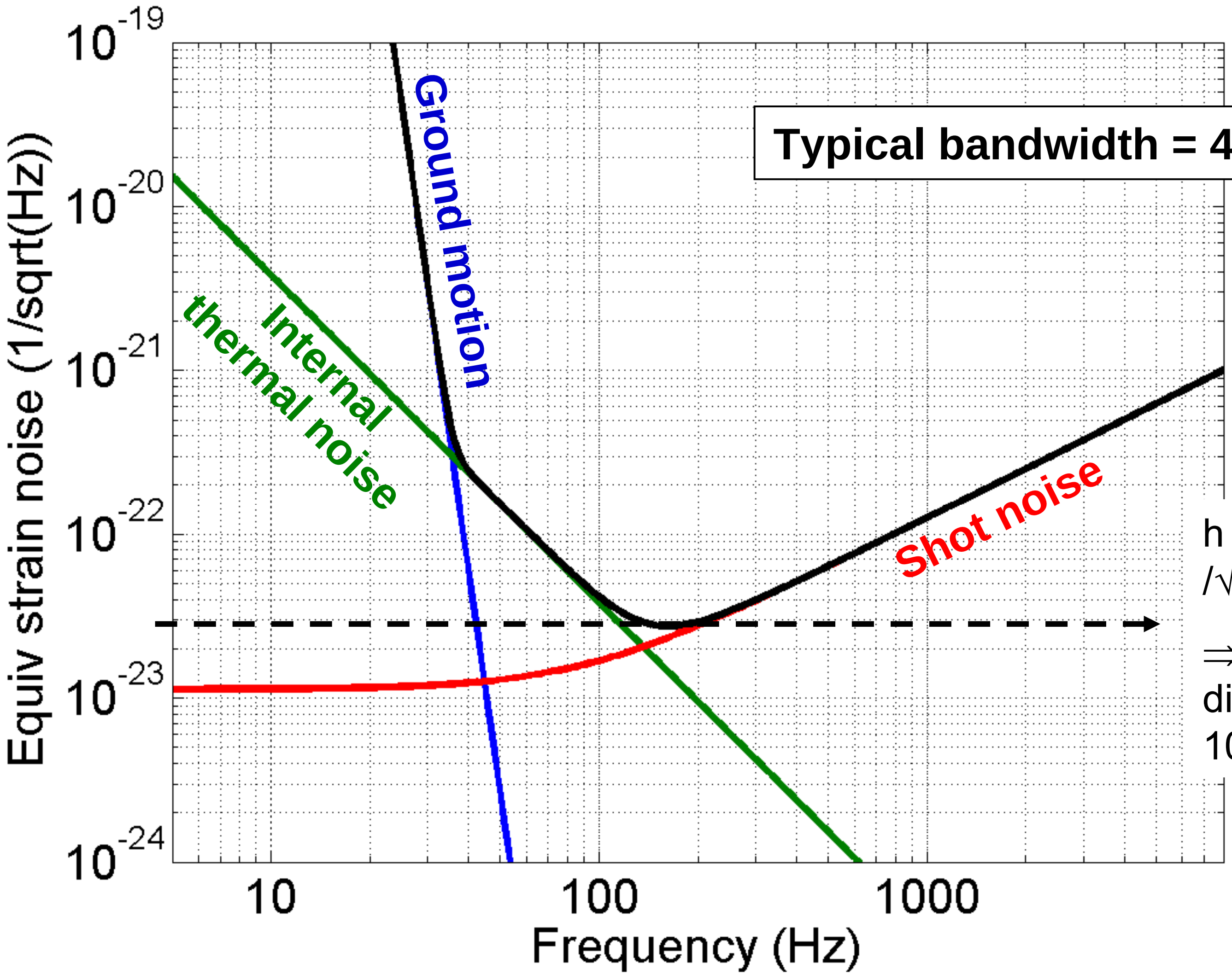
- **Acoustic noise / index fluctuations**

Vacuum equipment



- **Seismic noise**
  - Hydraulic external pre-isolator
  - Stacks
  - Pendulum

Design sensitivity

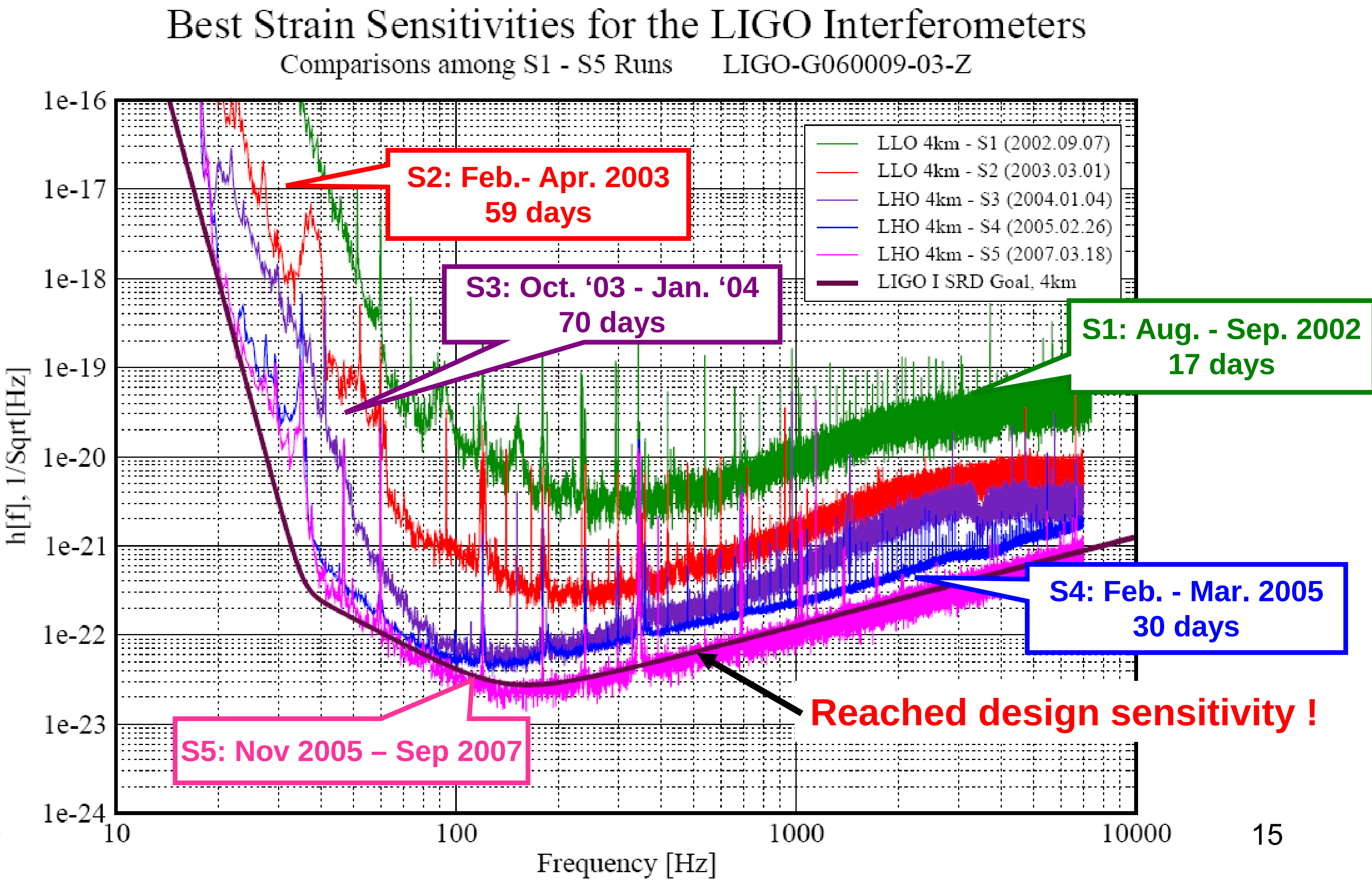


Typical bandwidth = 40-2,000 Hz

h ~ 2 x 10^{-23} /√Hz

⇒ measure displacements of 10^{-19} m

LIGO science runs & sensitivity improvements



S2: Feb.- Apr. 2003
59 days

S3: Oct. '03 - Jan. '04
70 days

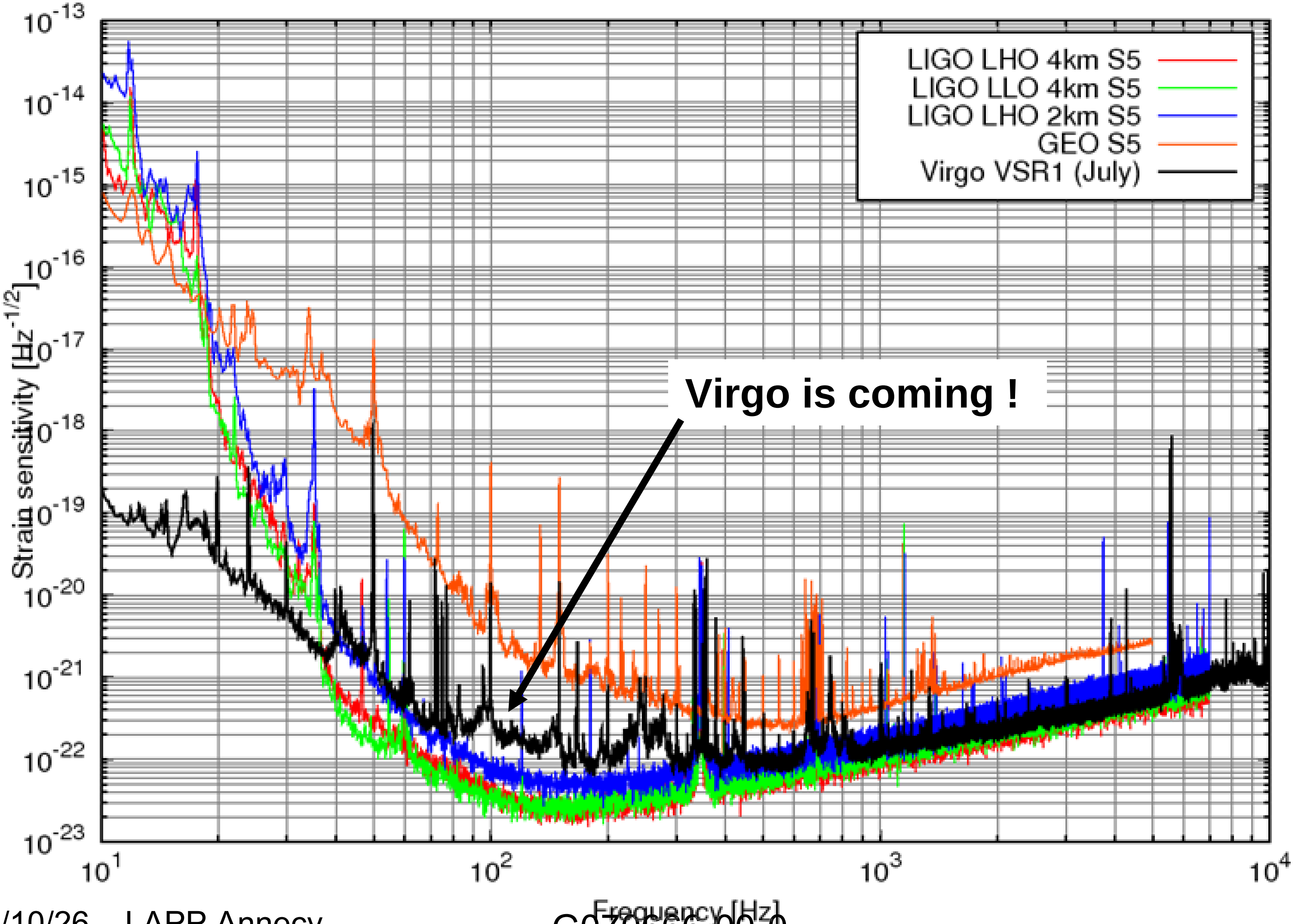
S1: Aug. - Sep. 2002
17 days

S4: Feb. - Mar. 2005
30 days

Reached design sensitivity !

S5: Nov 2005 – Sep 2007

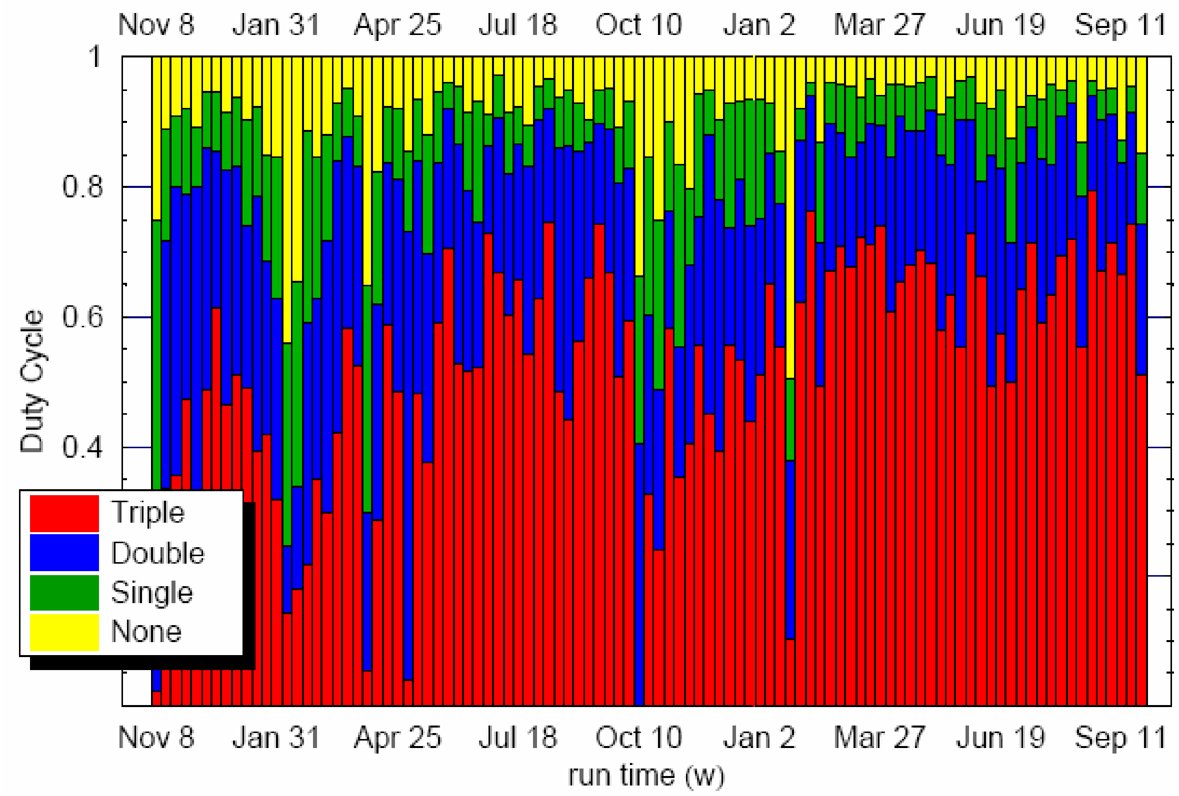
Current sensitivities of the large interferometers



Virgo is coming !

The S5 science run

- Started on Nov 2005 – Ended on Sep 2007
- Completion of one year of triple coincidence data between the 3 LIGO interferometers



S5 duty cycles:

- 52.8 % in triple coincidence
- 57.0 % in H1L1 coincidence
- Total for H1: 77.7 %
- Total for H2: 78.2 %
- Total for L1: 65.7 %

- H1H2L1V1: 11.3 %

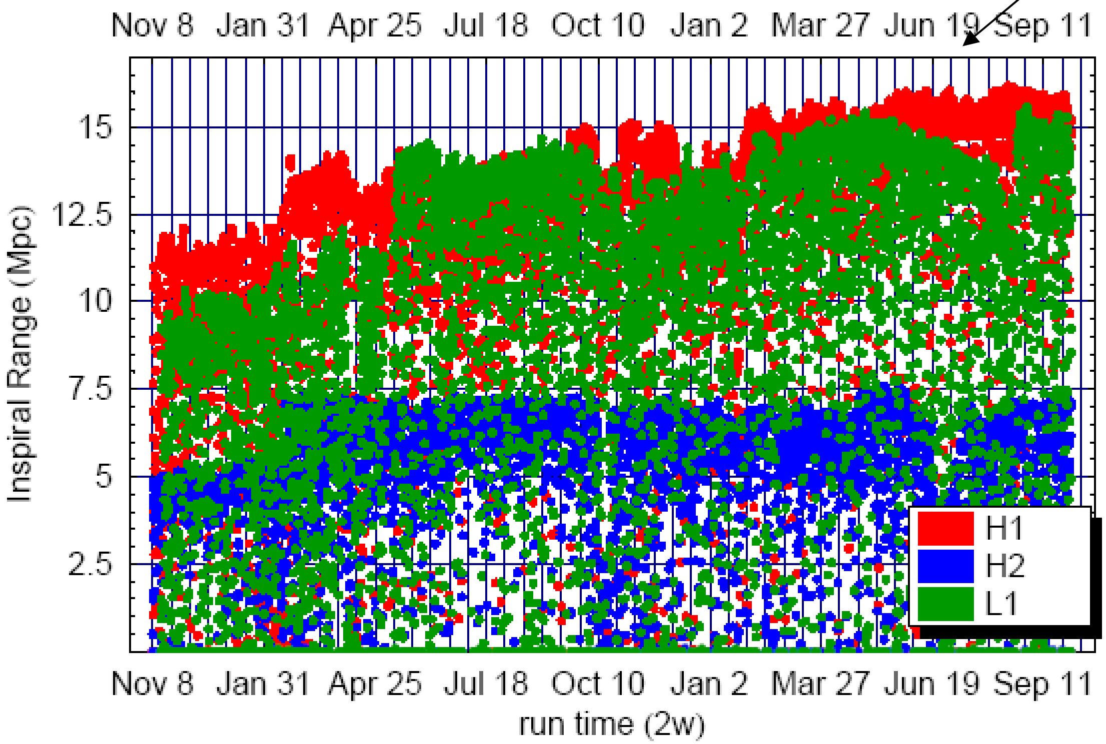
→ **at nominal sensitivity**

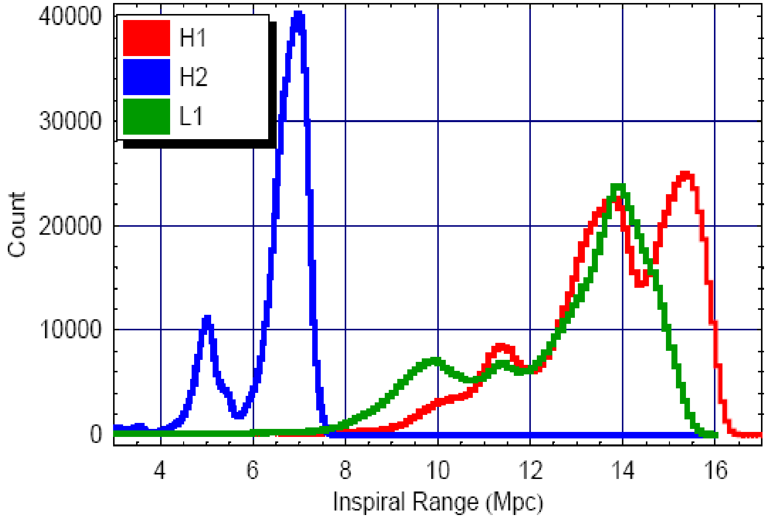
LIGO Range (=averaged horizon) during S5

The sensitivity can be translated into distances surveyed.

Range definition: *distance to which an interferometer can detect an inspiral, averaged over all sky positions and orientations*
(for a 1.4/1.4 solar mass system, with snr = 8)

Affected by microseism, wind, instruments,…

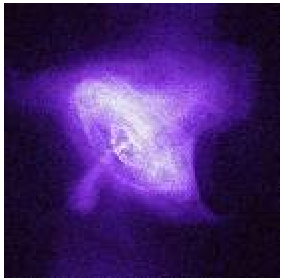
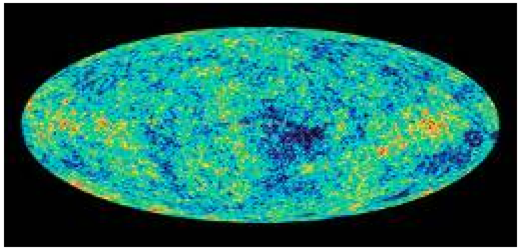
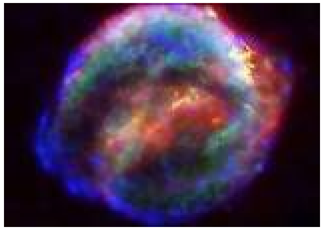




⇒ **H1 reached up to 16 Mpc at the end of the run**

- *What are gravitational waves ?*
- *The LIGO experiment*
- *Analysis methods and astrophysical observations*
- *Perspectives: a network of advanced detector*

Sources and methods

	Long duration	Short duration
Matched filter	 Pulsars	 Compact Binary Inspirals
Template-less methods	 Stochastic Background	 Bursts

Compact Binary Inspirals: Match filtering

- Known waveform: ⇒ use match filtering technique

Data

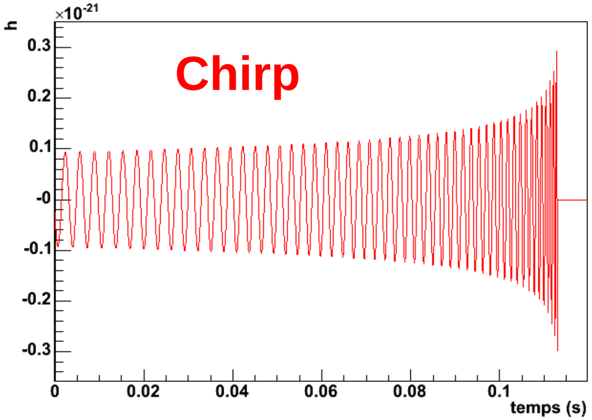
Template

$$z(t) = 4\int_0^\infty \frac{\tilde{s}(f)\ \tilde{h}^*(f)}{S_n(f)}\ e^{2\pi i f t}\ df$$

Noise power spectral density

- Calculated templates for inspiral phase (“chirp”)

Waveform parameters:
distance, orientation, position,
m_1, **m_2**, t_0, ϕ (+ spin, ending cycles …)



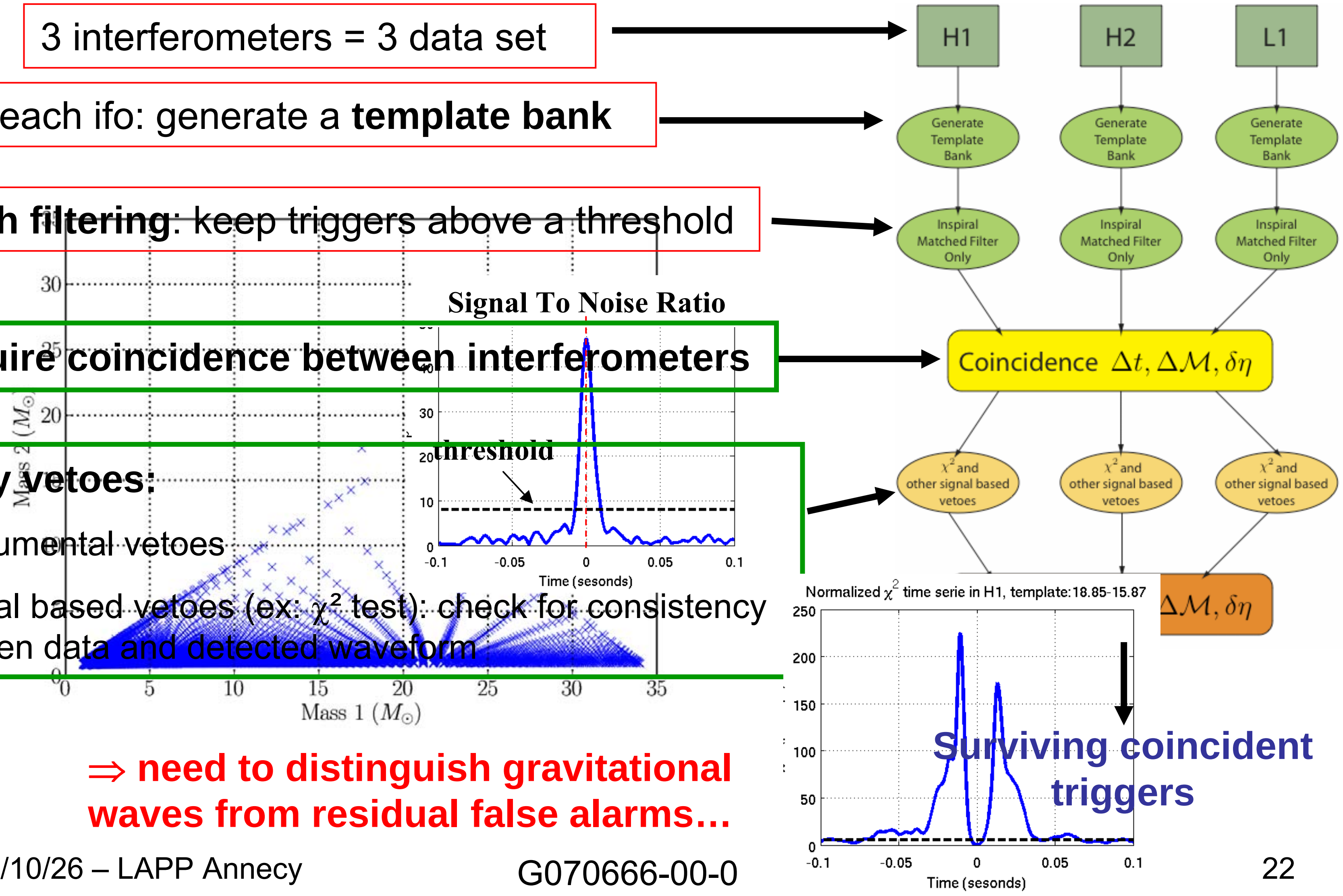
- Different template families used for different searches

Example: S3-S4 searches

\- **Binary Neutron Stars: “physical templates**” (2nd order restricted post-Newtonian, stationary-phase approximations)

\- **Binary Black Holes: “phenomenological templates”** (BCV)

Compact Binary Inspirals: Overview of the search pipeline



3 interferometers = 3 data set

For each ifo: generate a **template bank**

Match filtering: keep triggers above a threshold

Require coincidence between interferometers

Apply vetoes:

- Instrumental vetoes
- Signal based vetoes (ex: χ^2 test): check for consistency between data and detected waveform

Surviving coincident triggers

⇒ need to distinguish gravitational waves from residual false alarms…

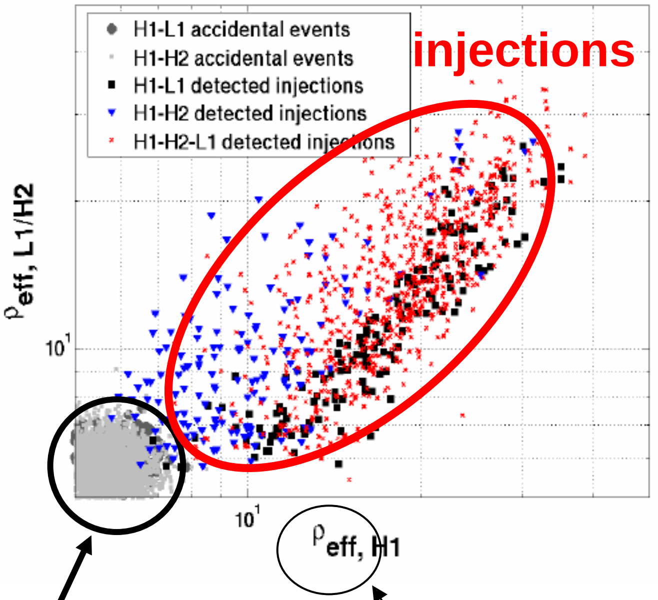
Compact Binary Inspirals:
Identifying a possible gravitational wave (1/2)

- **First step**: estimate the false alarm probability

  ⇒ **compare candidate to expected background**

→ **background estimated by applying time-slides before coincidence**

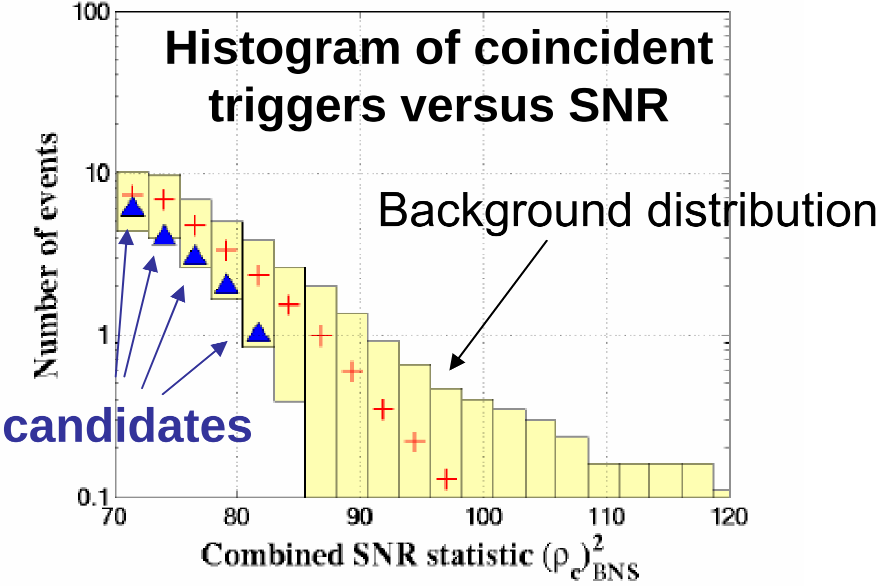
Ex: S4 Binary Neutron Star search [*Preprint arXiv:0704.3368*]



injections

background

Effective signal to noise ratio



Histogram of coincident triggers versus SNR

Background distribution

candidates

If candidates consistent with background ⇒ no detection

Else ?

Compact Binary Inspirals: Identifying a possible gravitational wave (2/2)

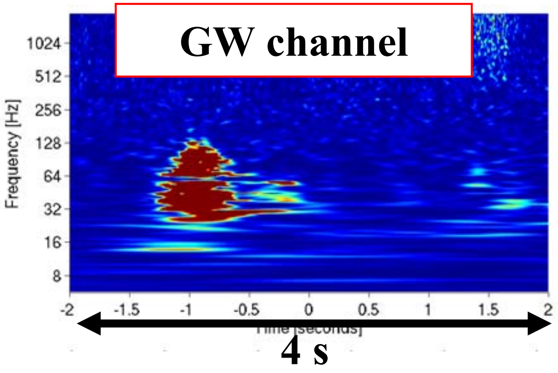
- **Second step**: **Follow up event candidates remaining at end of pipeline**

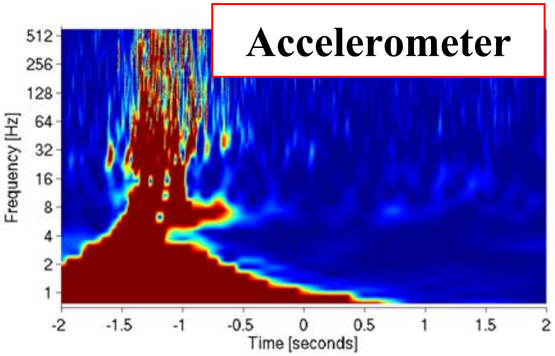
Goal: determine our level of confidence in the detection

→ Each candidate is analyzed through a detection checklist:

- Check for data quality at the time of the detection

- Time - frequency maps of GW channel and auxiliary channels





- Check for detection robustness (ex: robustness versus calibration uncertainties)

- Try to improve parameter estimation (coherent analysis, Markov-Chain Monte Carlo)

- Check for coincidence with independent signals (if available): other gravitational wave detectors, GRB, Supernovae,…

Compact Binary Inspirals: Current results

- **S3/S4 runs:** *[Preprint arXiv:0704.3368]*

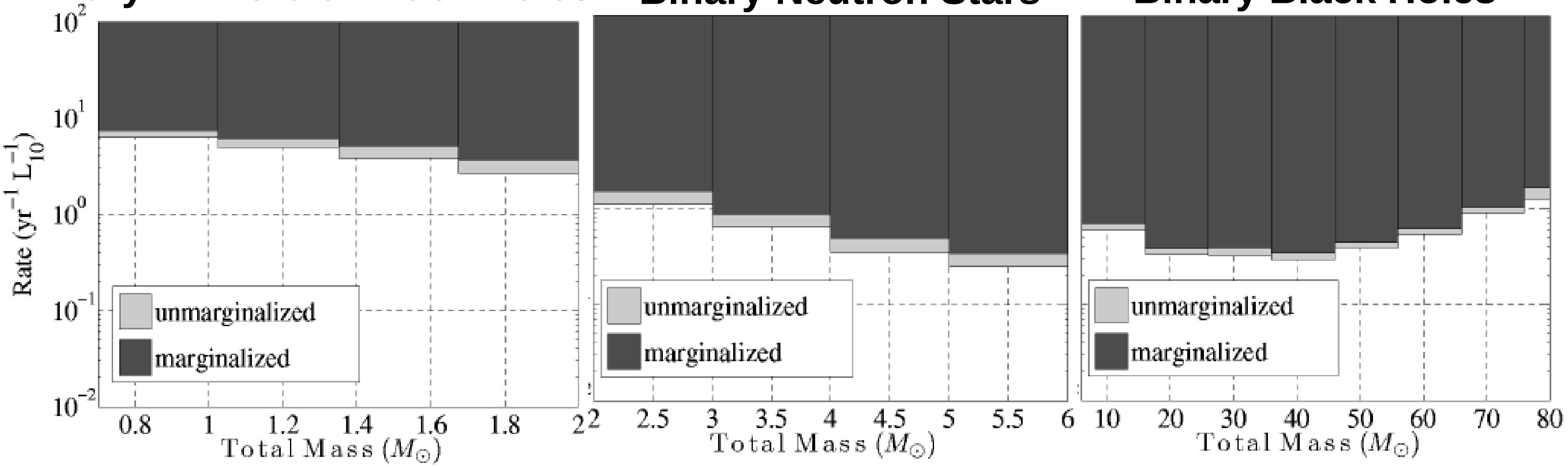
  No GW signals identified

  Binary neutron star signals could be detected out to ~17 Mpc (optimal case)

  Binary black hole signals out to tens of Mpc

  ⇒ Place limits on binary coalescence rate for certain population models

Binary Primordial Black Holes **Binary Neutron Stars** **Binary Black Holes**



- Rate/L$_{10}$ vs. binary total mass

  L$_{10}$ = 10^{10} L$_{\odot,B}$ (1 Milky Way = 1.7 L$_{10}$)
- Dark region excluded at 90% confidence

Compact Binary Inspirals: S5 prospectives

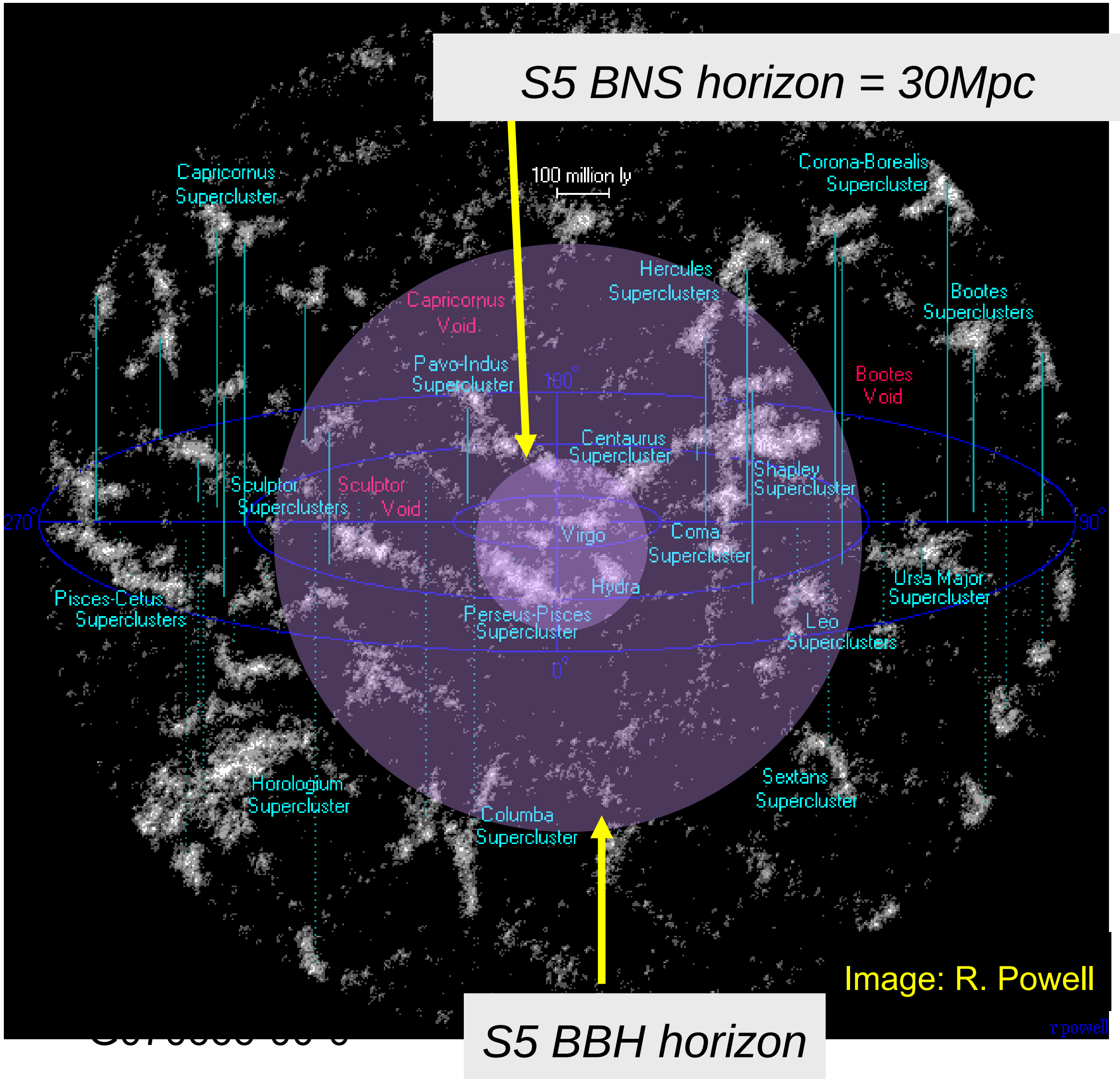
Horizon (optimal) = distance at which an optimally oriented and located binary system can be seen with signal-to-noise ratio $\rho=8$

Expected rate for Binary Neutron Star:

~ 1/100 yrs

$\Rightarrow$ A detection is not granted

Our ability to detect gravitational waves will be tested with **blind injections**



S5 BNS horizon = 30Mpc

S5 BBH horizon

Image: R. Powell

Burst searches

- **Motivations:** minimal assumptions, open to unexpected/unknown waveforms

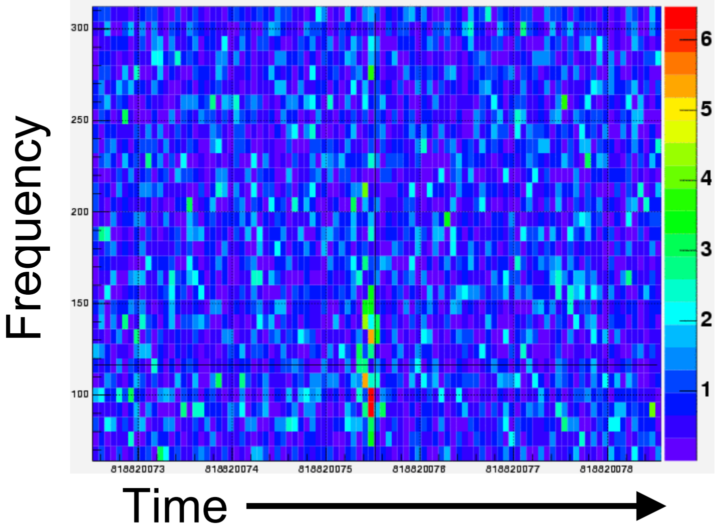
- **Methods:**

- Excess Power:

Decompose data stream into time-frequency pixels

⇒ Look for hot pixels or clusters of pixels

- Calculate cross-correlation between interferometer data streams



- **S4 general all-sky burst search** *[Preprint arXiv:0704.0943]*

Searched 15.53 days of triple-coincidence data (H1+H2+L1) for short (<1 sec) signals with frequency content in range 64-1600 Hz

No event candidates observed

⇒ Upper limit on rate of detectable events

- **S5:** analysis on going …

Periodic signals from Radio/X-ray pulsars (1/2)

- **Targeted searches:**

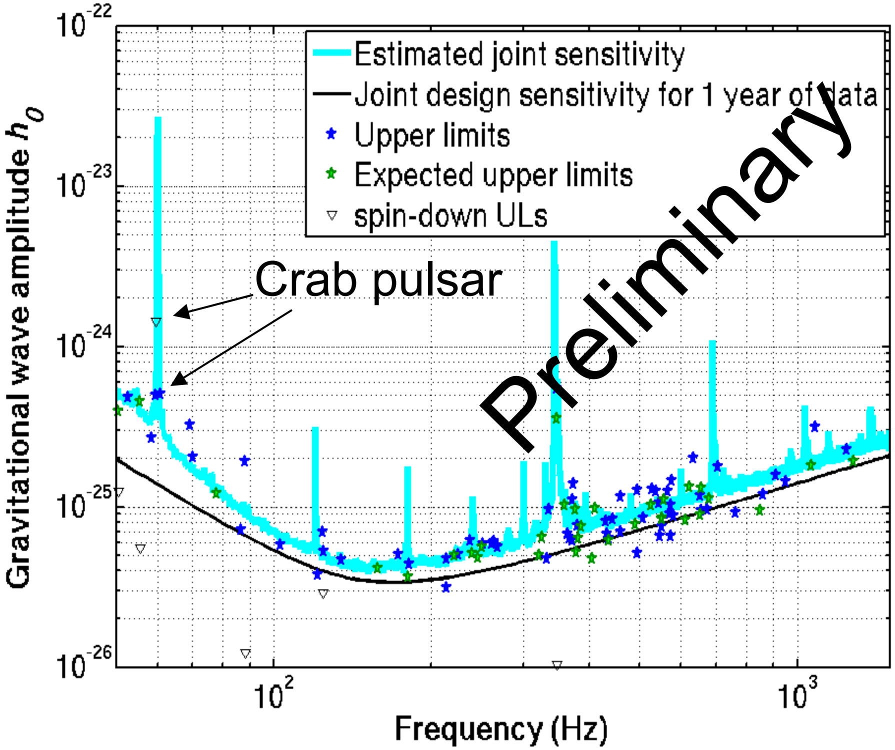
→ for **97 known (radio and x-ray) systems**: isolated pulsars, binary systems, pulsars in globular clusters…

→ place **upper limits** on gravitational wave amplitude and equatorial ellipticities

ε limits as low as ~10^{-7}

Crab pulsar: LIGO limit on GW emission is now **below** upper limit inferred from spindown rate

upper limits from first ~13 months of S5



Periodic signals from Radio/X-ray pulsars (2/2)

- **All-sky, unbiased searches:**

→ Search for a sine wave, modulated by Earth's motion,
and possibly spinning down: easy, but computationally expensive!

http://www.einsteinathome.org/

Einstein@Home

~175,000 users

~75 Tflops on average

- *What are gravitational waves ?*
- *The LIGO experiment*
- *Analysis methods and astrophysical observations*
- *Perspectives: a network of advanced detector*

LSC-Virgo joint data analysis

- **Cooperative agreement for data exchange and joint data analysis for last 5 months of S5**
- **Sharing of data started in May 2007:**

  ⇒ more than 4 months of coincidence between LIGO S5 and Virgo VSR1 runs

- **Benefits of a world wide network:**

  - Reduction of the false alarm rate by coincidence analysis
  - A better coverage of the sky
  - Improve the accuracy on parameter extraction

    ⇒ required for gravitational wave astronomy

  - Can help increasing the duty cycle

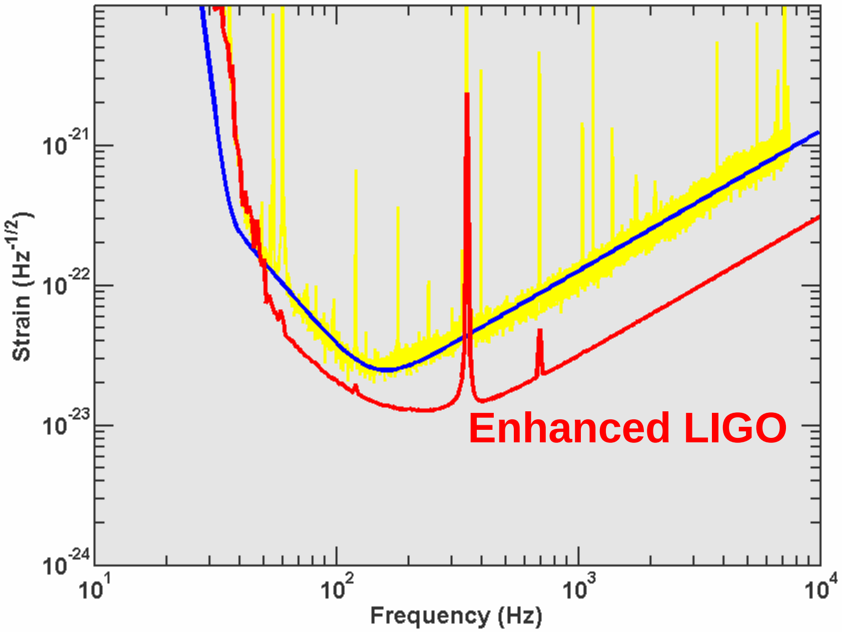
Enhanced LIGO

Starting after S5 (~now): a series of fast upgrades
Goal: **a factor of ~2 sensitivity improvement**

Main upgrades:

- Increase laser power to 35 W
    Requires new thermal compensatio

- DC readout scheme
    Photodetector in vacuum, suspende
    Output mode cleaner

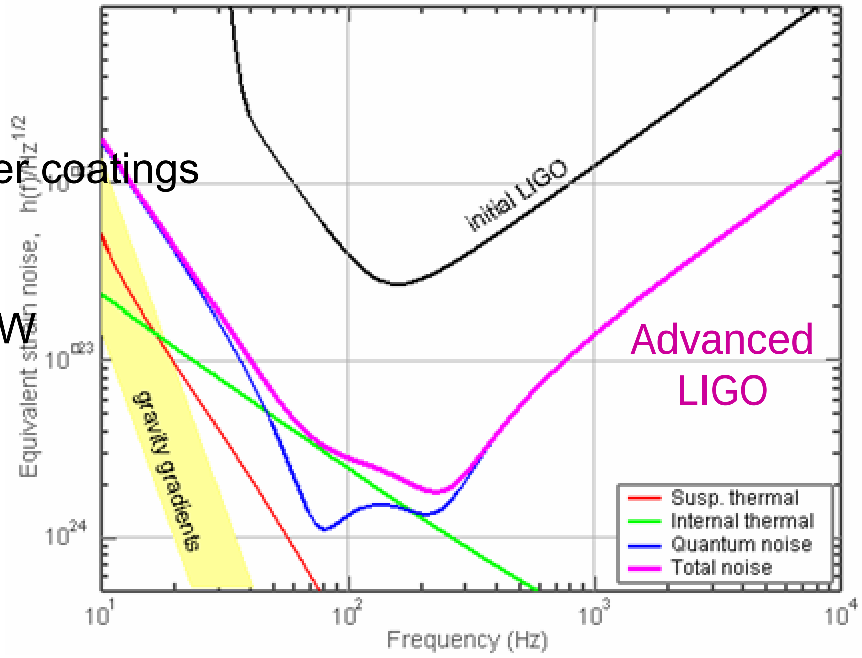


S6 run planned to begin in 2009, duration ~1.5 years
    Virgo improvements and joint running planned on same time scale

Advanced LIGO (1/2)

A series of major improvements after the S6 run (starting ~2010):

- **Seismic noise**
  - Active isolation system
  - Mirrors suspended as fourth stage of quadruple pendulums
- **Thermal noise**
  - Suspension ➔ fused silica fibers
  - Test mass ➔ more massive; better coatings
- **Optical noise**
  - Laser power ➔ increase to ~200 W
  - Optimize interferometer response
  - ➔ signal recycling



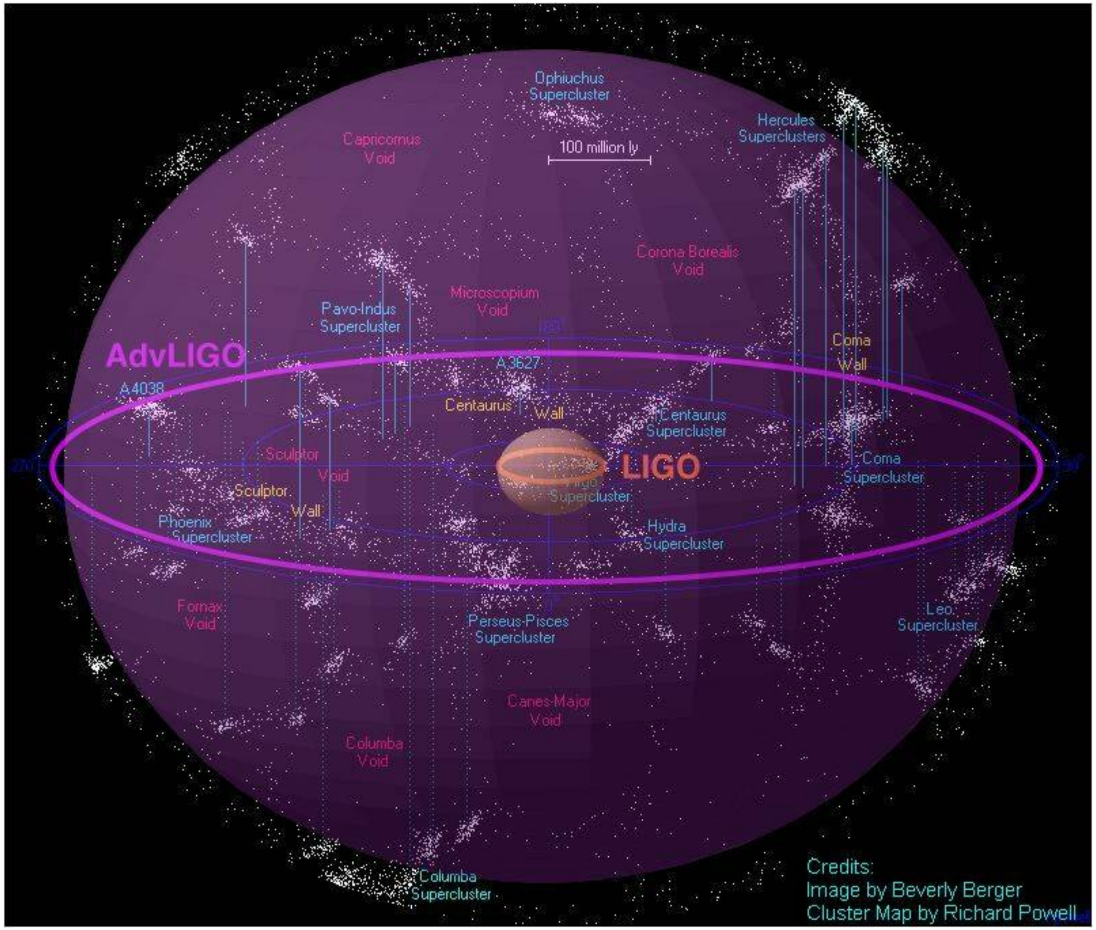
Factor of ~10 better than current LIGO ⇒ factor of ~1000 in volume !

Advanced LIGO (2/2)

Neutron Star Binaries:

Horizon > 300 Mpc

Most likely rate ~ 40/year !



Credits:
Image by Beverly Berger
Cluster Map by Richard Powell

The science from the first 3 hours of Advanced LIGO should be comparable to 1 year of initial LIGO

Summary

- **The LIGO detectors have reached their target sensitivities**
- **A long science run has just been achieved (1 year of data in triple coincidence)**
- **Analysis pipelines have been developed and tested**
- **First upper limits published**
- **A world wide collaboration has started**
- **Advanced detectors should allow us to start real gravitational wave astronomy within 10 years !**

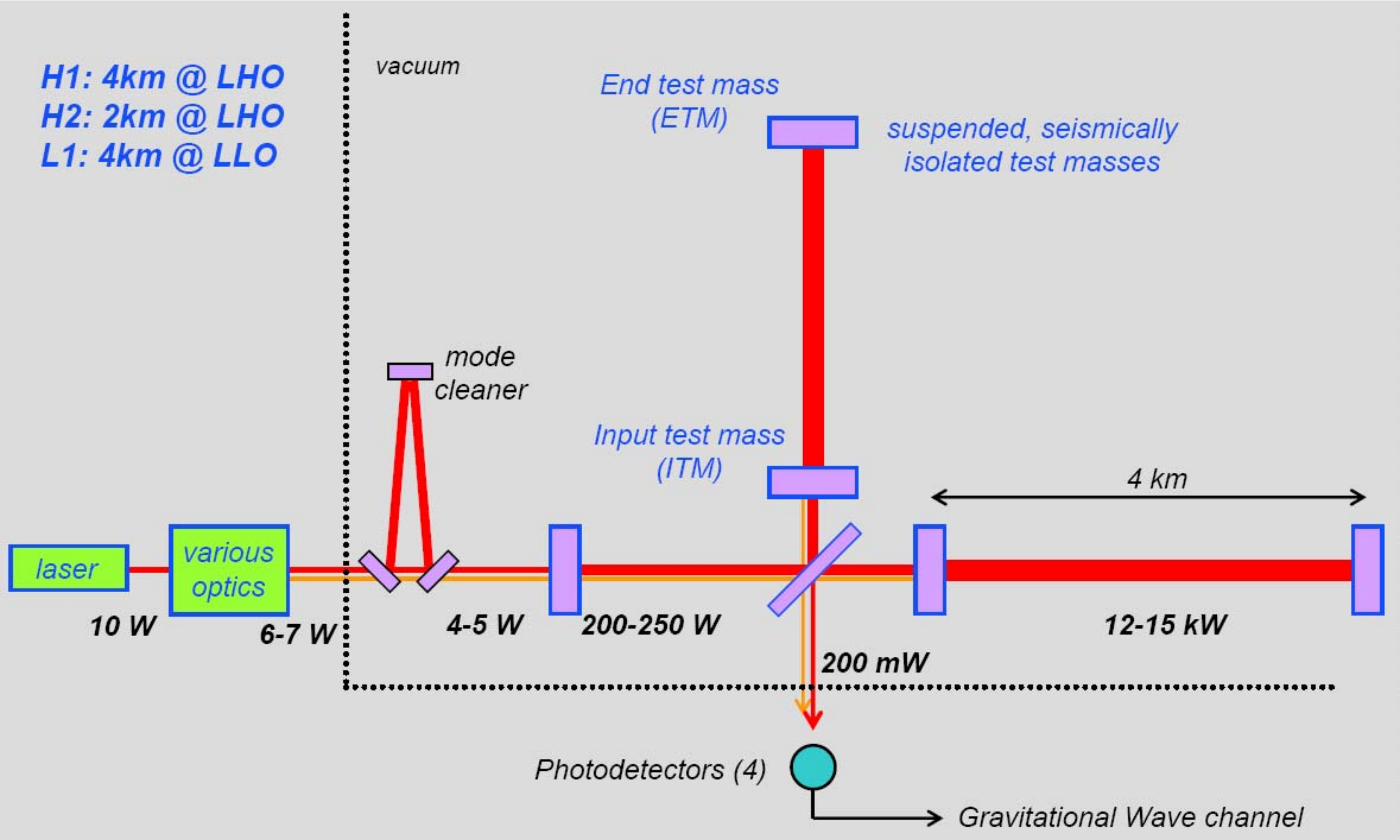
Spares

Australian Consortium
for Interferometric
Gravitational Astronomy
The Univ. of Adelaide
Andrews University
The Australian National Univ.
The University of Birmingham
California Inst. of Technology
Cardiff University
Carleton College
Charles Stuart Univ.
Columbia University
Embry Riddle Aeronautical Univ.
Eötvös Loránd University
University of Florida
German/British Collaboration for
the Detection of Gravitational Wav
University of Glasgow
Goddard Space Flight Center
Leibniz Universität Hannover
Hobart & William Smith Colleges
Inst. of Applied Physics of the Russian
Academy of Sciences
Polish Academy of Sciences
India Inter-University Centre
for Astronomy and Astrophysic
Louisiana State University
Louisiana Tech University
Loyola University New Orleans
University of Maryland
Max Planck Inst. for Gravitati
Physics

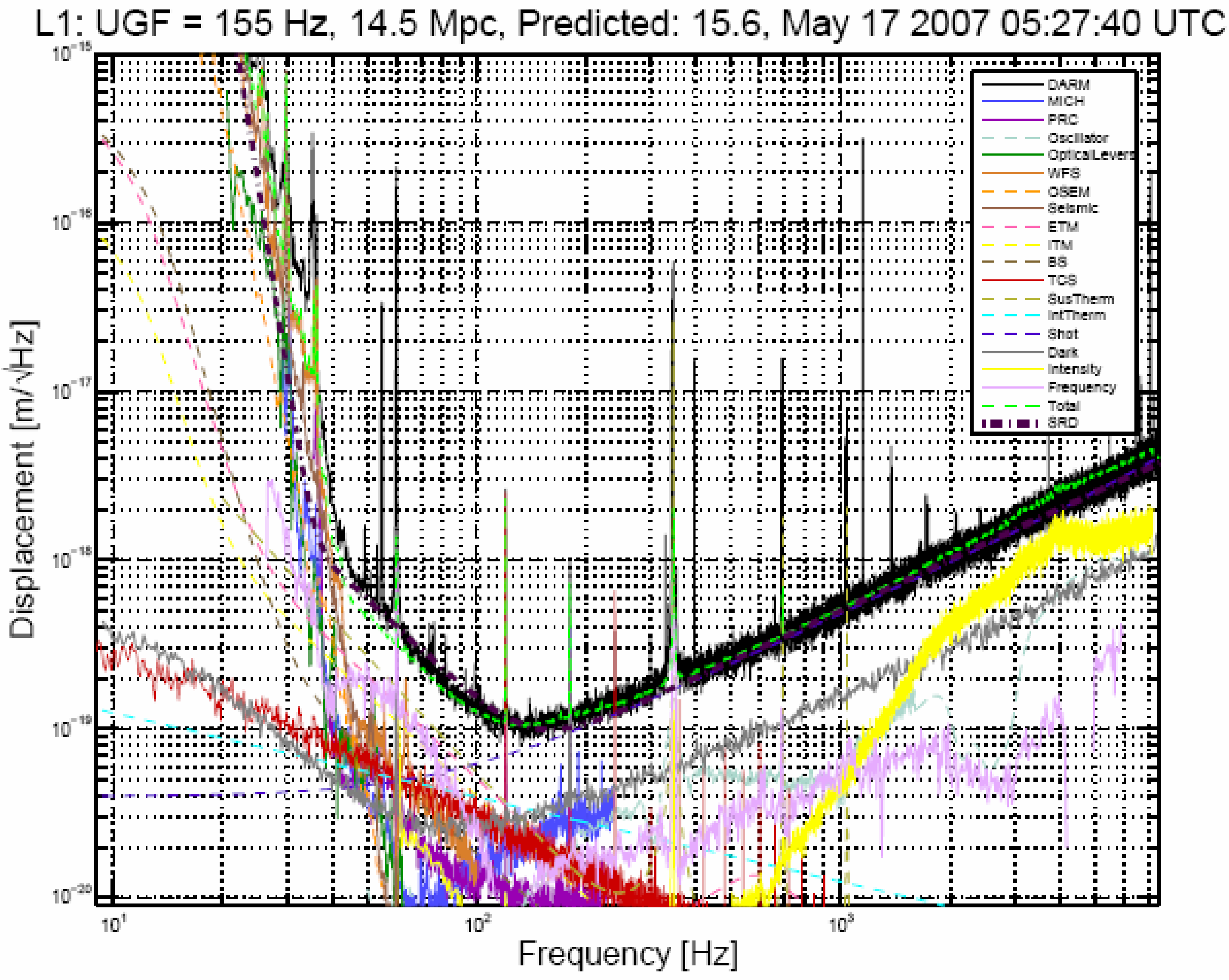
- University of Michigan
- University of Minnesota
- The University of Mississippi
- Massachusetts Inst. of Technology
- Monash University
- Montana State University
- Moscow State University

  National Astronomical
  Observatory of Japan
- Northwestern University
- University of Oregon
- Pennsylvania State University
- Rochester Inst. of Technology
- Rutherford Appleton Lab
- University of Rochester
- San Jose State University
- Univ. of Sannio at Benevento,
  and Univ. of Salerno
- University of Sheffield
- University of Southampton
- Southeastern Louisiana Univ.
- Southern Univ. and A&M College
- Stanford University
- University of Strathclyde
- Syracuse University
- Univ. of Texas at Austin
- Univ. of Texas at Brownsville
- Trinity University
- Universitat de les Illes Balears
- Univ. of Massachusetts Amherst
- University of Western Australia
- Univ. of Wisconsin-Milwaukee
- Washington State University
- University of Washington

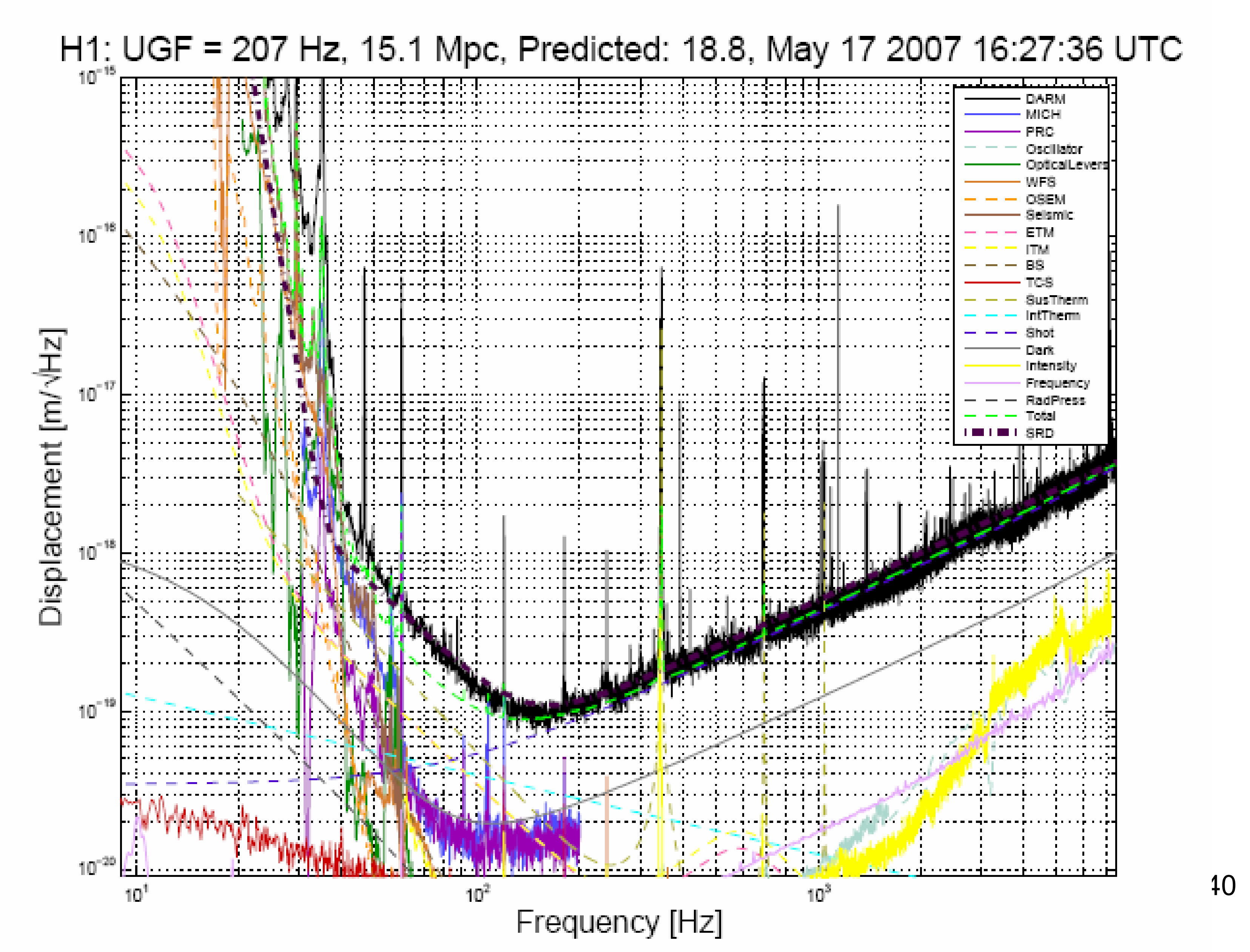
The LIGO interferometers



Livingston noise budget



Hanford (4 km) noise budget



Spin effect

16.8 / 4.4 solar masses

|spin1| = 0.89 / |spin2| = 0.04