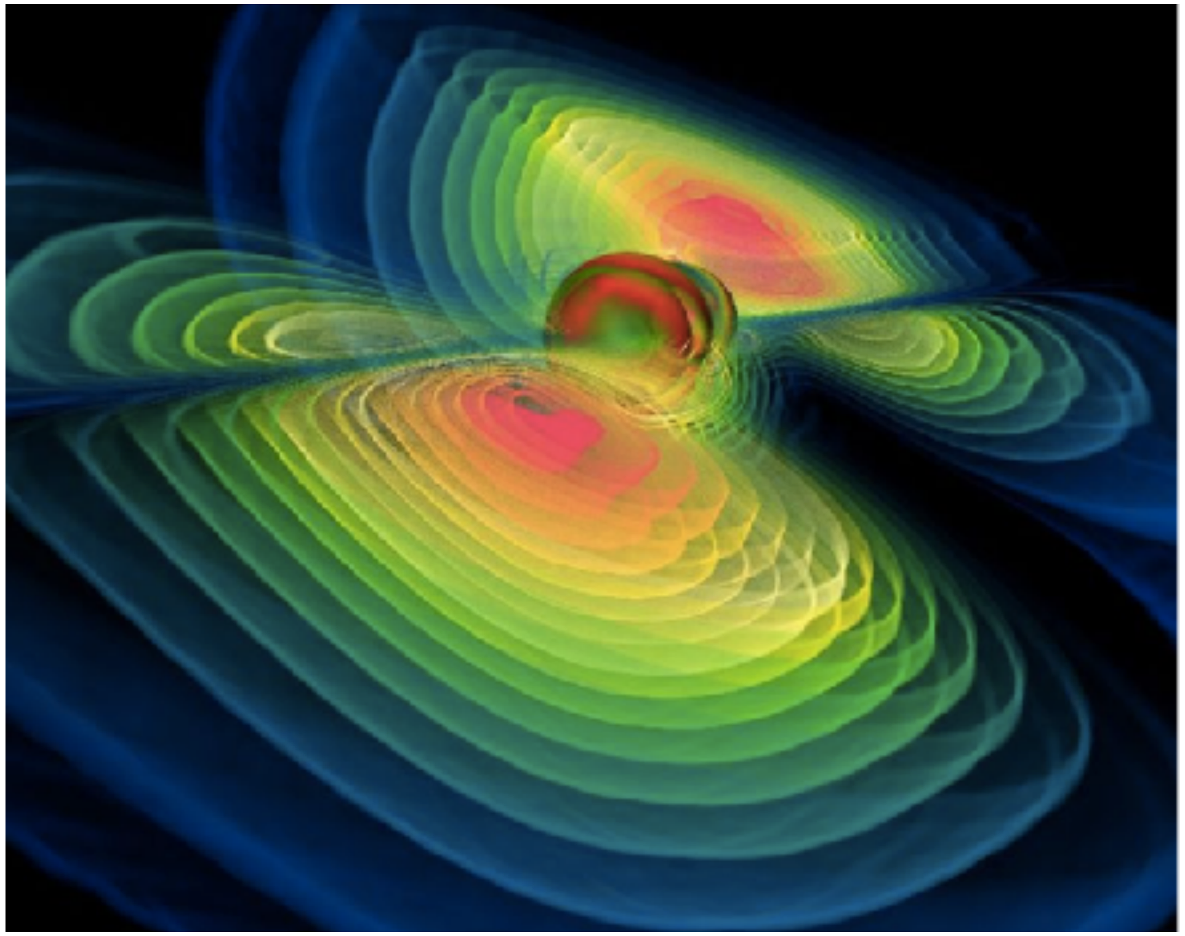
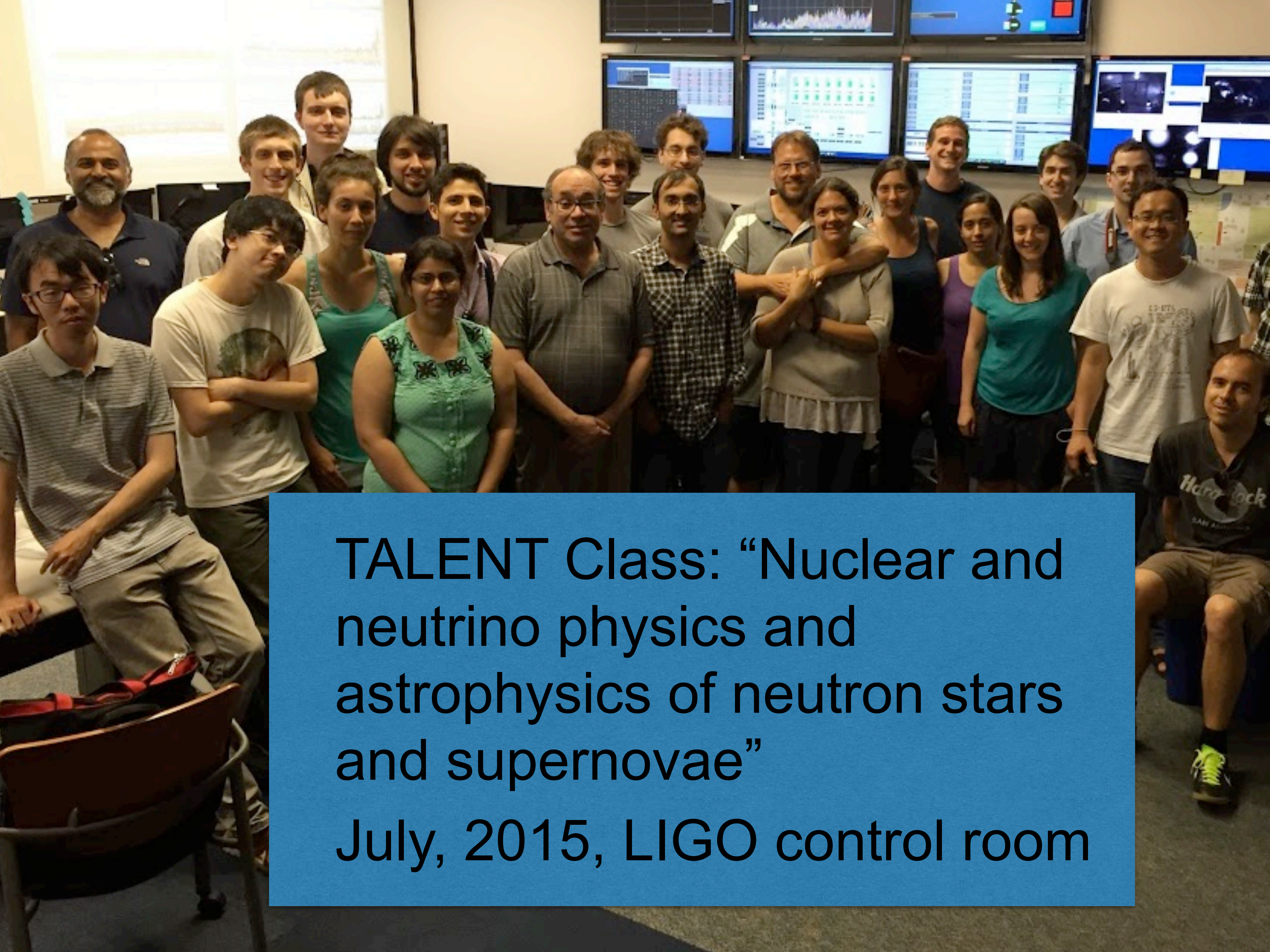
Gravitational Waves



C. J. Horowitz, 2nd Lecture, Indiana University
Joint CNA/JINA-CEE Winter School on Nuclear Astrophysics,
Shanghai, China, Dec. 2016

TALENT Classes

- Training in Advanced Low Energy Nuclear Theory (TALENT) teaches three week advanced classes in nuclear theory / astrophysics in North America and Europe.
- Courses for 2017: (1) “Theory for exploring nuclear structure experiments” at ECT* in Trento, Italy, and (2) “Theory for exploring nuclear reaction experiments” at MSU.
- Check web site http://fribtheoryalliance.org/TALENT/
- Should TALENT be expanded to teach classes in China?

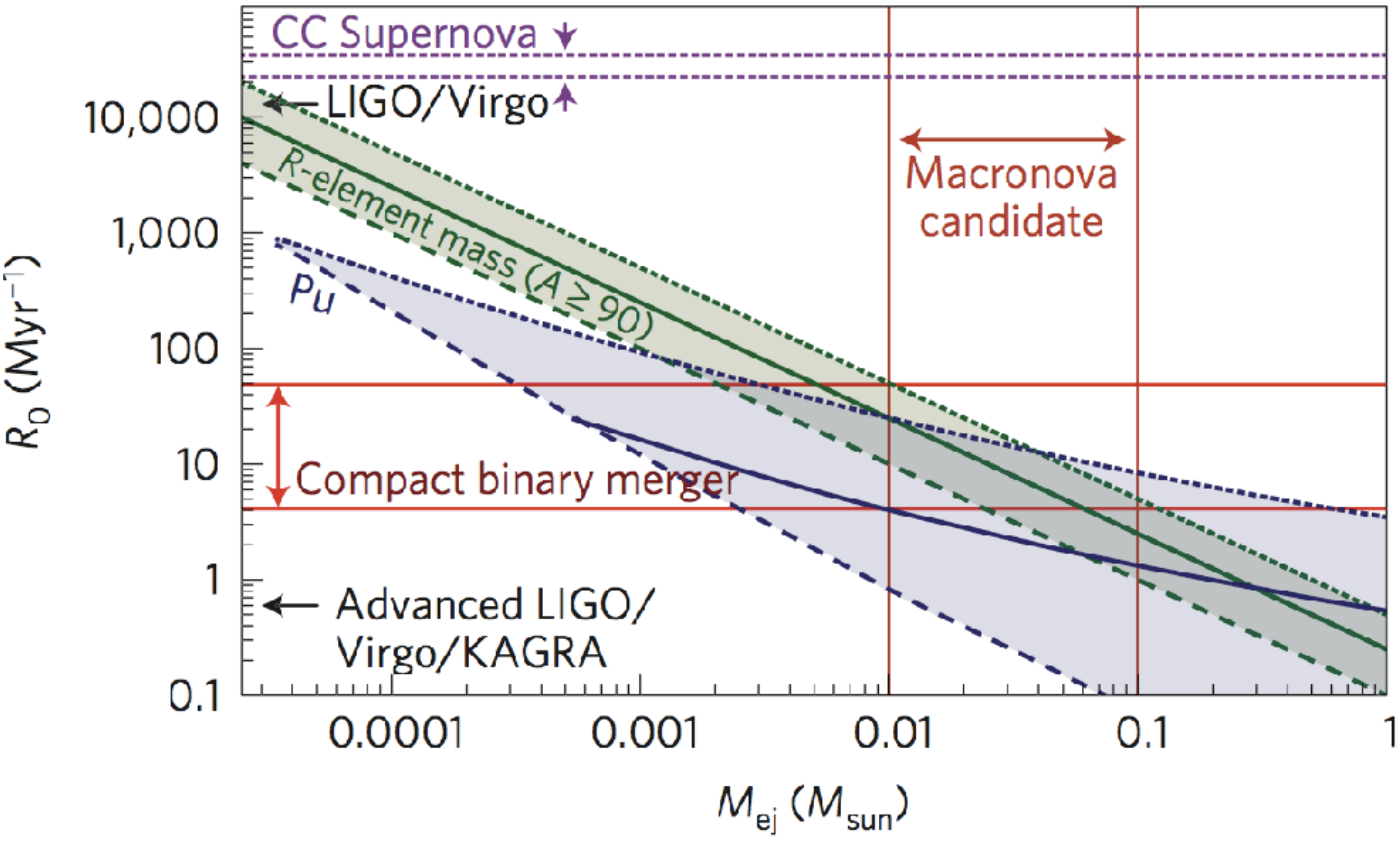


TALENT Class: “Nuclear and neutrino physics and astrophysics of neutron stars and supernovae”

July, 2015, LIGO control room

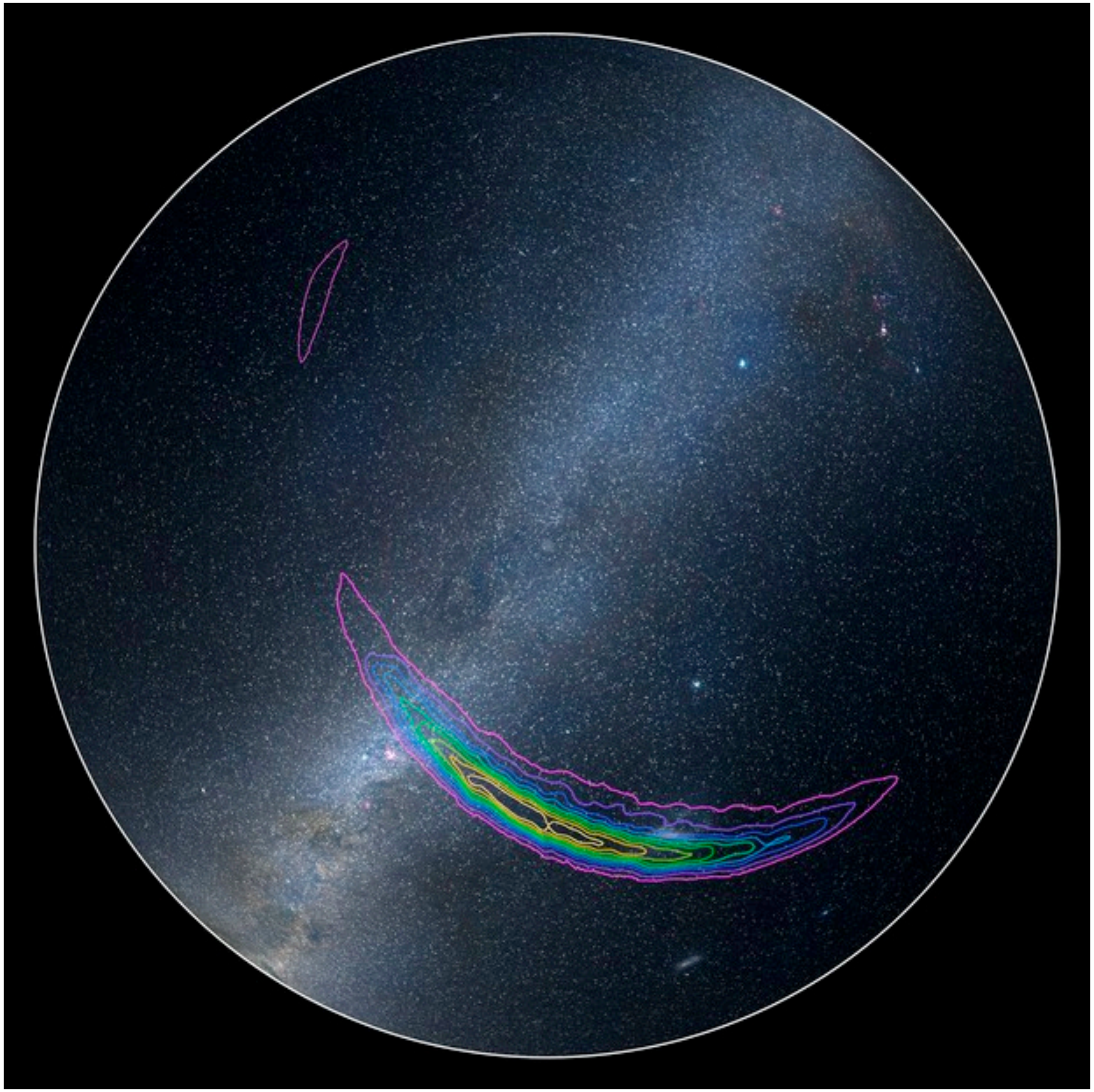
Can NS mergers be the site of the main r-process?

- Abundance of r-process elements: rate of mergers x amount of neutron rich material ejected per merger.
- LIGO is directly measuring merger rate.
- Amount of material ~0.01 M_{sun}. Ejecta components:
  - Tidal tails (increases with NS radius)
  - Collisional ejecta (larger for softer EOS)
  - Evaporation of accretion disk…
- Radioactive decay of newly formed r-process elements may power a “kilonova” (infrared/ visible glow after a NS merger event).

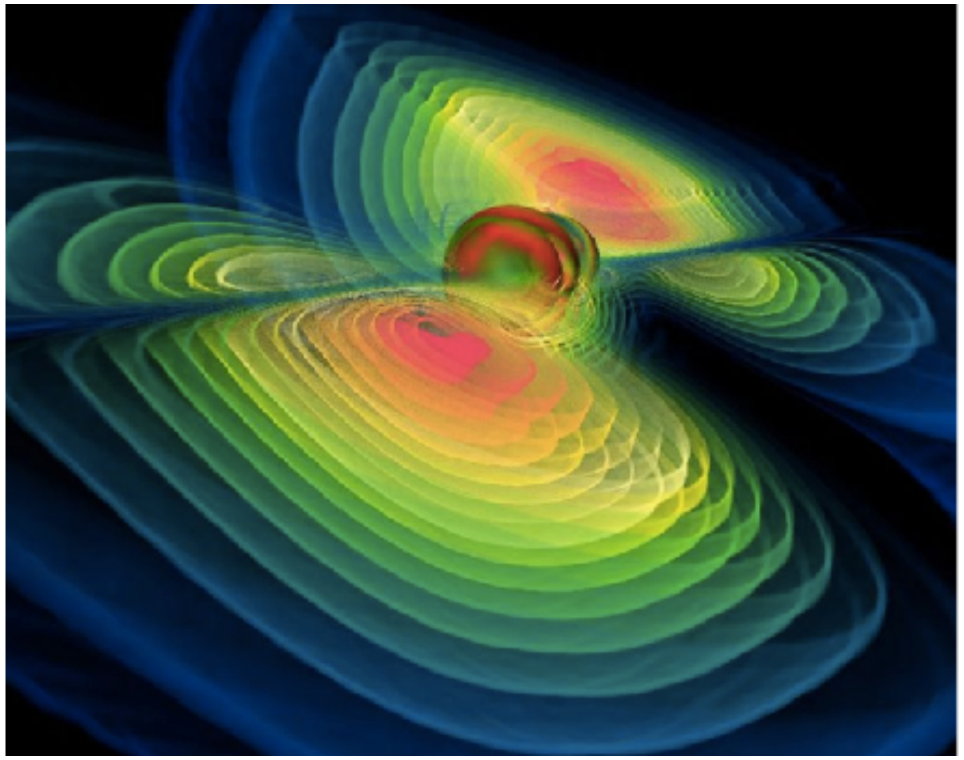

CC Supernova
LIGO/Virgo
R-element mass ($A \geq 90$)
Pu
Macronova candidate
Compact binary merger
Advanced LIGO/Virgo/KAGRA
R_0 (Myr^{-1})
10,000
1,000
100
10
1
0.1
0.0001
0.001
0.01
0.1
1
M_{ej} (M_{sun})

E&M counterpart to GW event

- The race is on to find electromagnetic counterparts to GW events.
- This search may take 5 to 10 years and involve many astronomers and telescopes.
- Problem: sky localization of GW event very poor with only two GW detectors. Very hard to search this huge area for a faint E&M transient.
- Localization much better with additional detectors such as LIGO India.



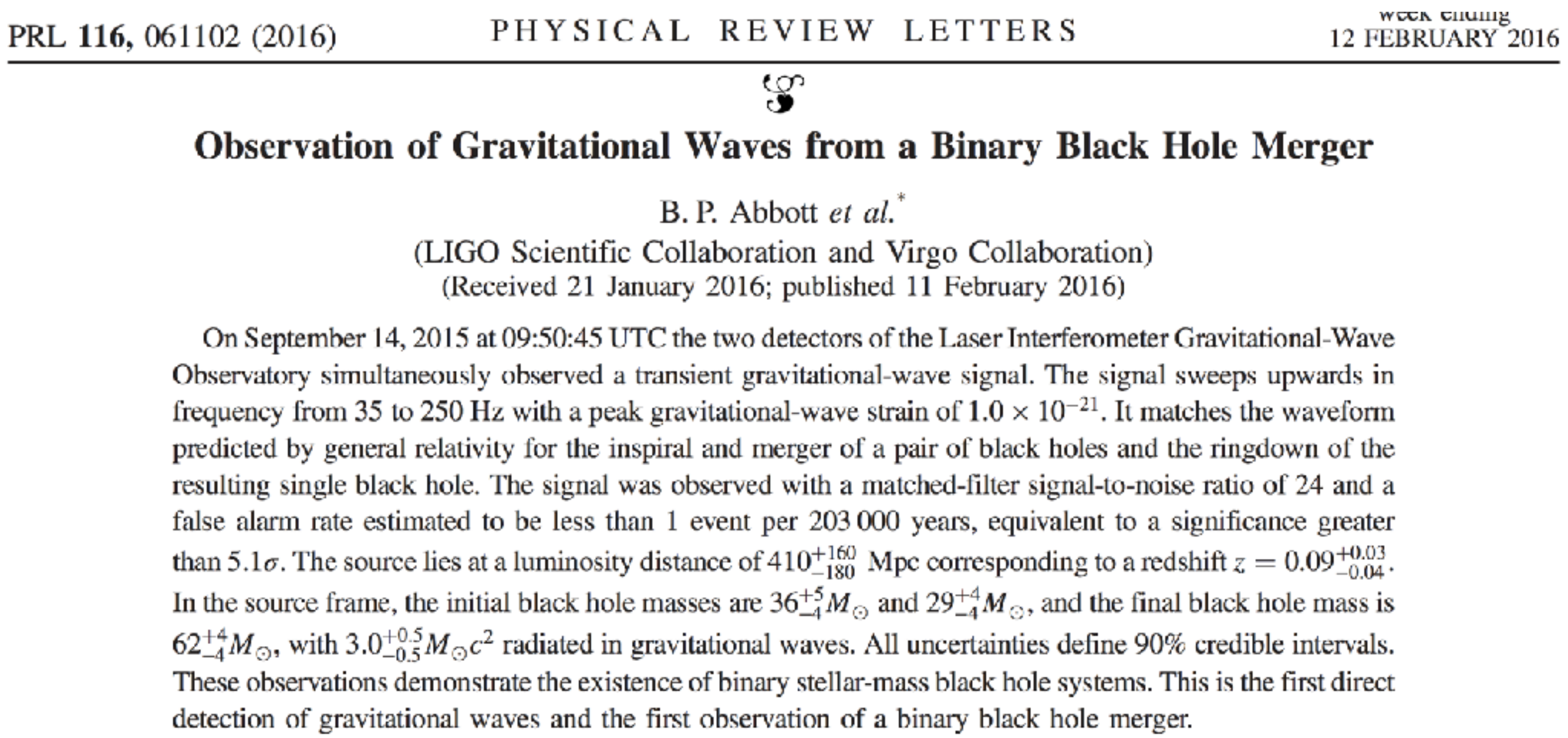
Gravitational Waves



Yesterday, the LIGO Science Collaboration of a thousand people, after two decades of work and a billion dollars, announced the direct observation of gravitational waves.

Introductory movie from New York Times: http://nyti.ms/1o6JL4Q

Charles J. Horowitz, Indiana University, horowit@indiana.edu,
Feb. 12, 2016.



PRL 116, 061102 (2016) PHYSICAL REVIEW LETTERS week ending 12 FEBRUARY 2016

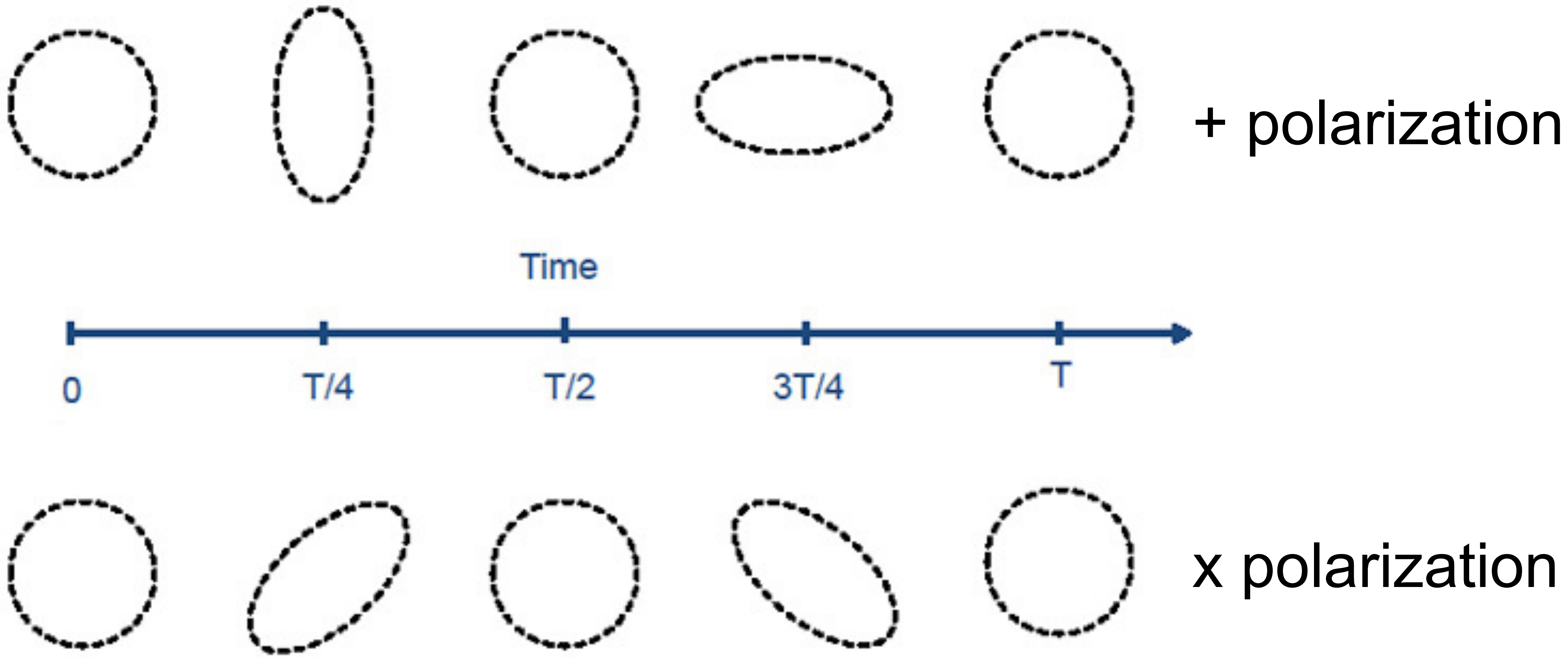
Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.*[*]
(LIGO Scientific Collaboration and Virgo Collaboration)
(Received 21 January 2016; published 11 February 2016)

On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory simultaneously observed a transient gravitational-wave signal. The signal sweeps upwards in frequency from 35 to 250 Hz with a peak gravitational-wave strain of 1.0×10^{-21}. It matches the waveform predicted by general relativity for the inspiral and merger of a pair of black holes and the ringdown of the resulting single black hole. The signal was observed with a matched-filter signal-to-noise ratio of 24 and a false alarm rate estimated to be less than 1 event per 203 000 years, equivalent to a significance greater than 5.1σ. The source lies at a luminosity distance of 410^{+160}_{-180} Mpc corresponding to a redshift $z = 0.09^{+0.03}_{-0.04}$. In the source frame, the initial black hole masses are $36^{+5}_{-4} M_{\odot}$ and $29^{+4}_{-4} M_{\odot}$, and the final black hole mass is $62^{+4}_{-4} M_{\odot}$, with $3.0^{+0.5}_{-0.5} M_{\odot} c^2$ radiated in gravitational waves. All uncertainties define 90% credible intervals. These observations demonstrate the existence of binary stellar-mass black hole systems. This is the first direct detection of gravitational waves and the first observation of a binary black hole merger.

- Describe LIGO detectors,
- Explain numbers in abstract,
- Mention a few implications,
- Discuss what happens next?

+ and x polarizations of GW



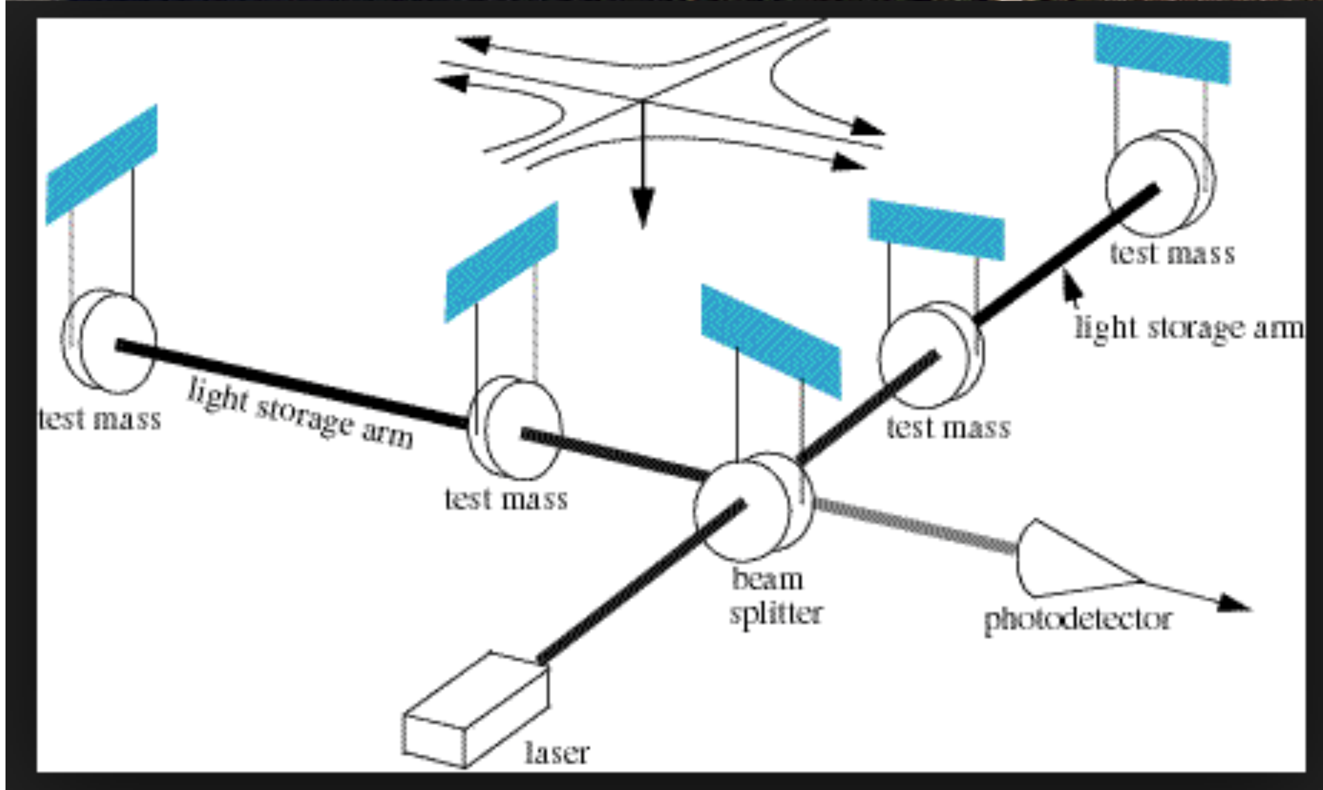
Blayne Heckel.

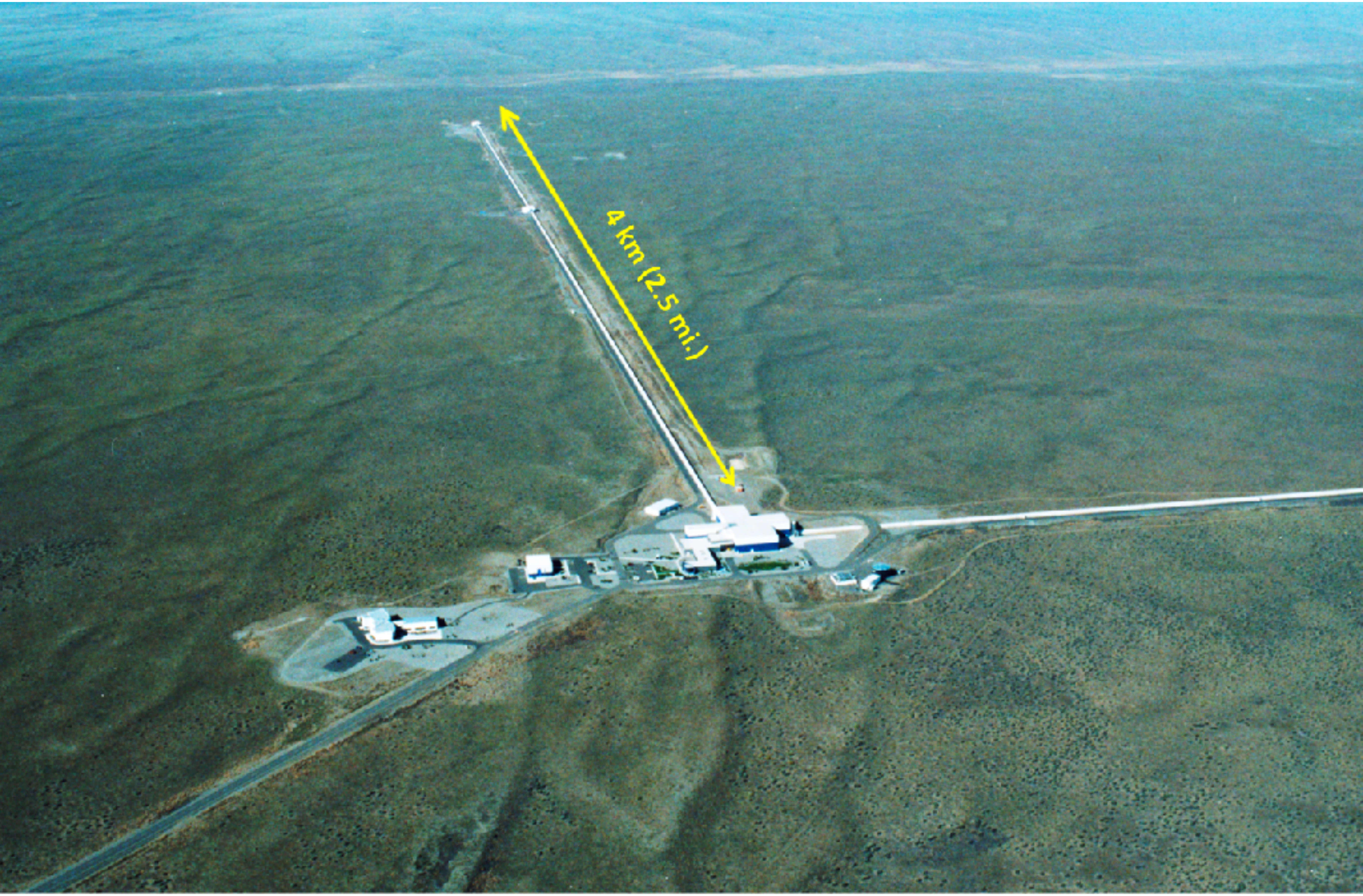
- Passage of GW distorts distances between circle of test bodies.

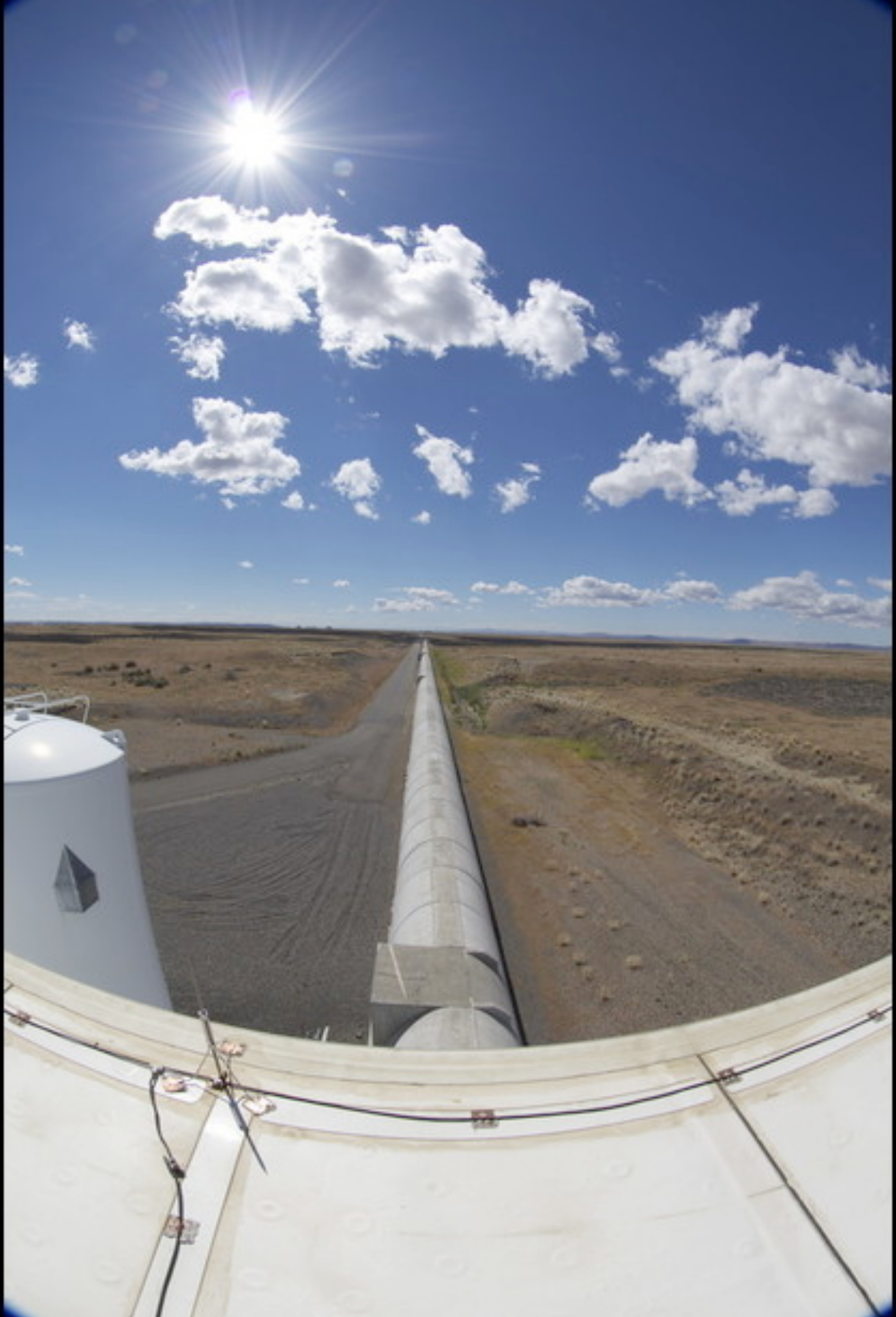
LIGO

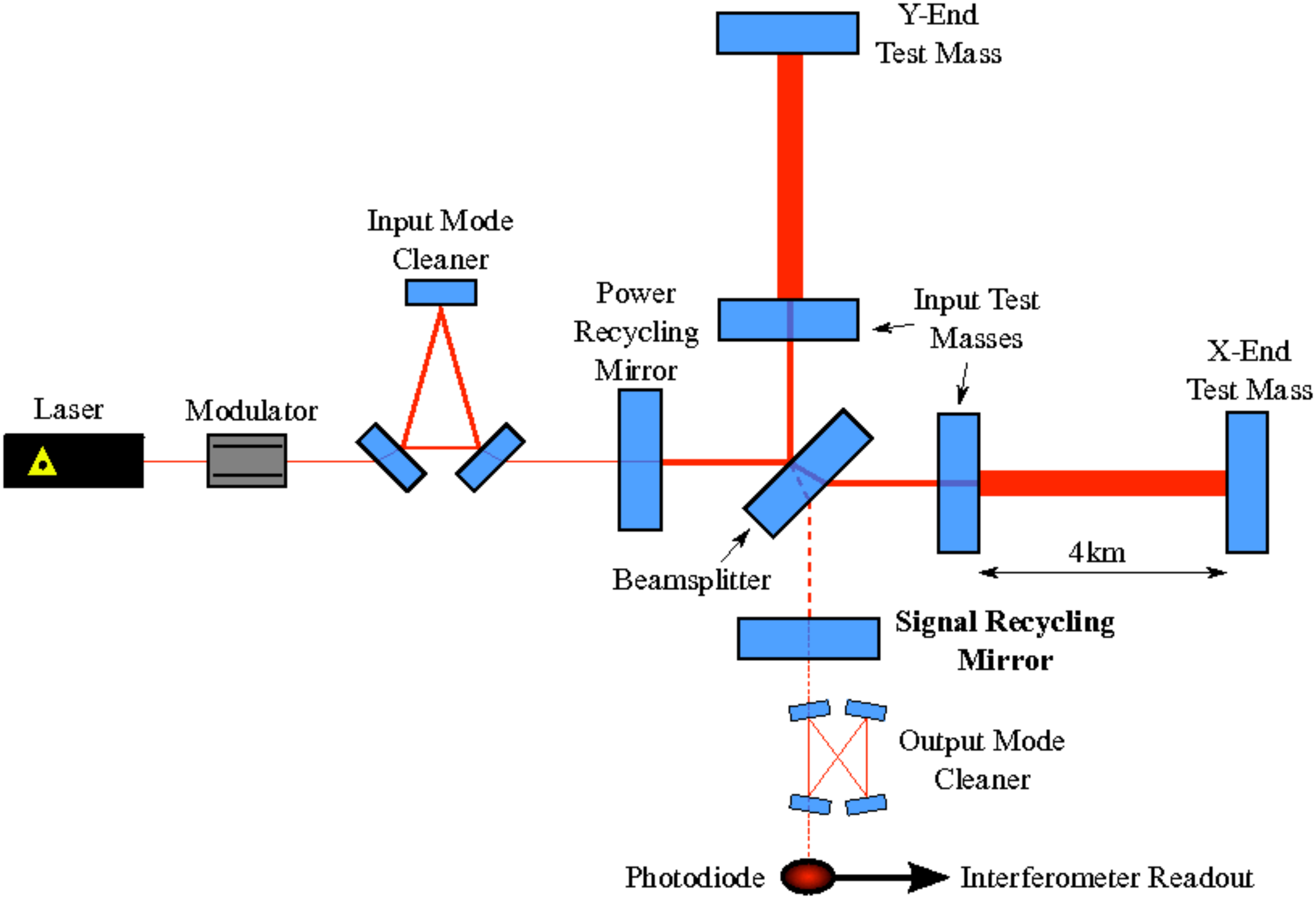
LASER INTERFEROMETER GRAVITATIONAL-WAVE OBSERVATORY

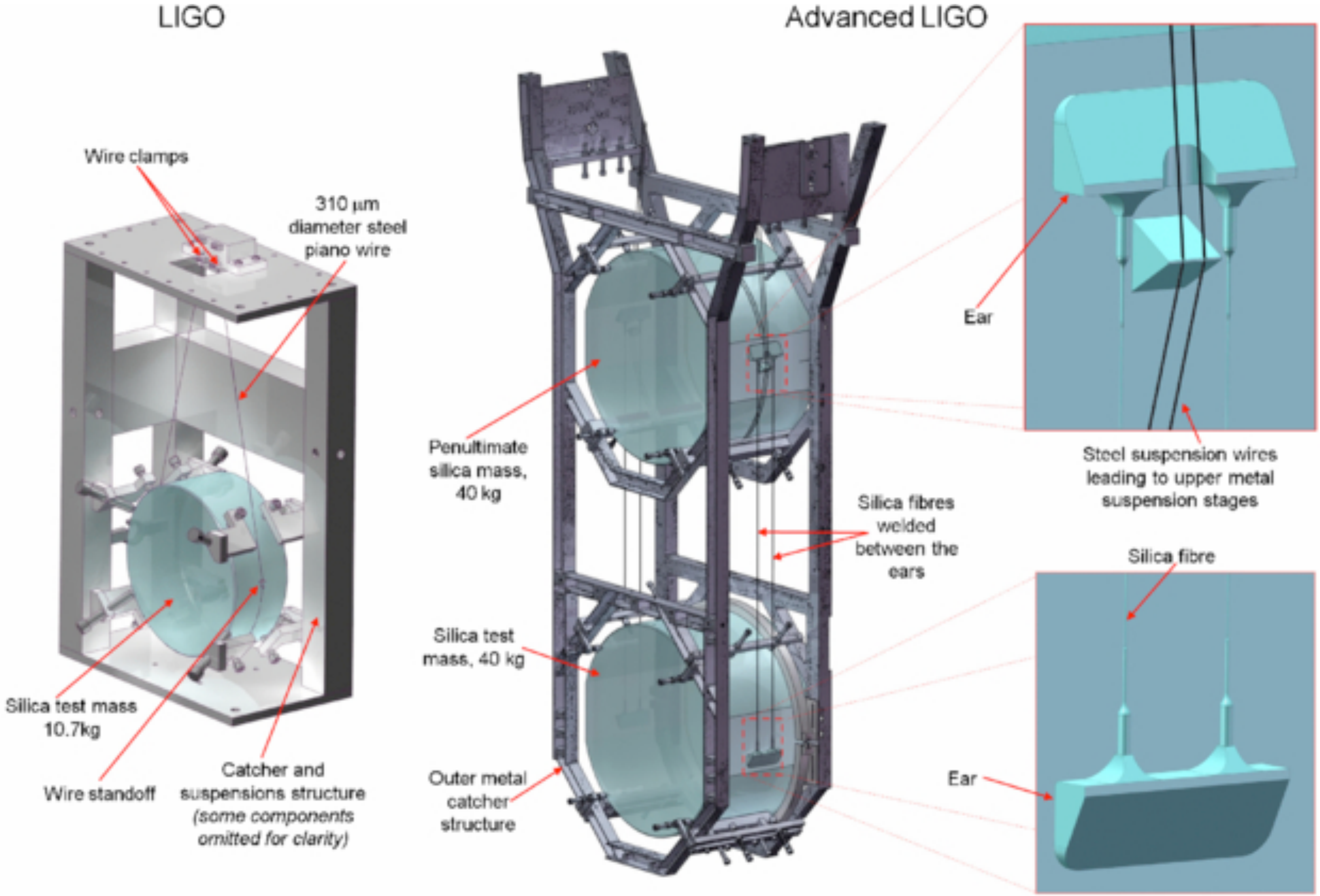
- LIGO consists of two 4km interferometers that have operated for several years at Hanford Washington and Livingston Louisiana.
- Gravitational waves will shrink one 4km arm and stretch the other by of order one part in 10^{21}. That is 1/100 of a fm!
- The small amplitude makes this hundred year quest to observe GW very hard. LIGO has not yet seen a signal.
- LIGO recently upgraded to Advanced LIGO with 10 x sensitivity. First aLIGO science run now!
- Advanced LIGO may make historic observation of GW soon, likely from merger of two neutron stars.




4 km (2.5 mi.)




Y-End
Test Mass
Input Mode
Cleaner
Power
Recycling
Mirror
Input Test
Masses
X-End
Test Mass
Laser
Modulator
Beamsplitter
4km
Signal Recycling
Mirror
Output Mode
Cleaner
Photodiode
Interferometer Readout


LIGO
Advanced LIGO
Wire clamps
310 μm diameter steel piano wire
Silica test mass 10.7kg
Wire standoff
Catcher and suspensions structure *(some components omitted for clarity)*
Penultimate silica mass, 40 kg
Silica test mass, 40 kg
Outer metal catcher structure
Silica fibres welded between the ears
Ear
Steel suspension wires leading to upper metal suspension stages
Silica fibre
Ear

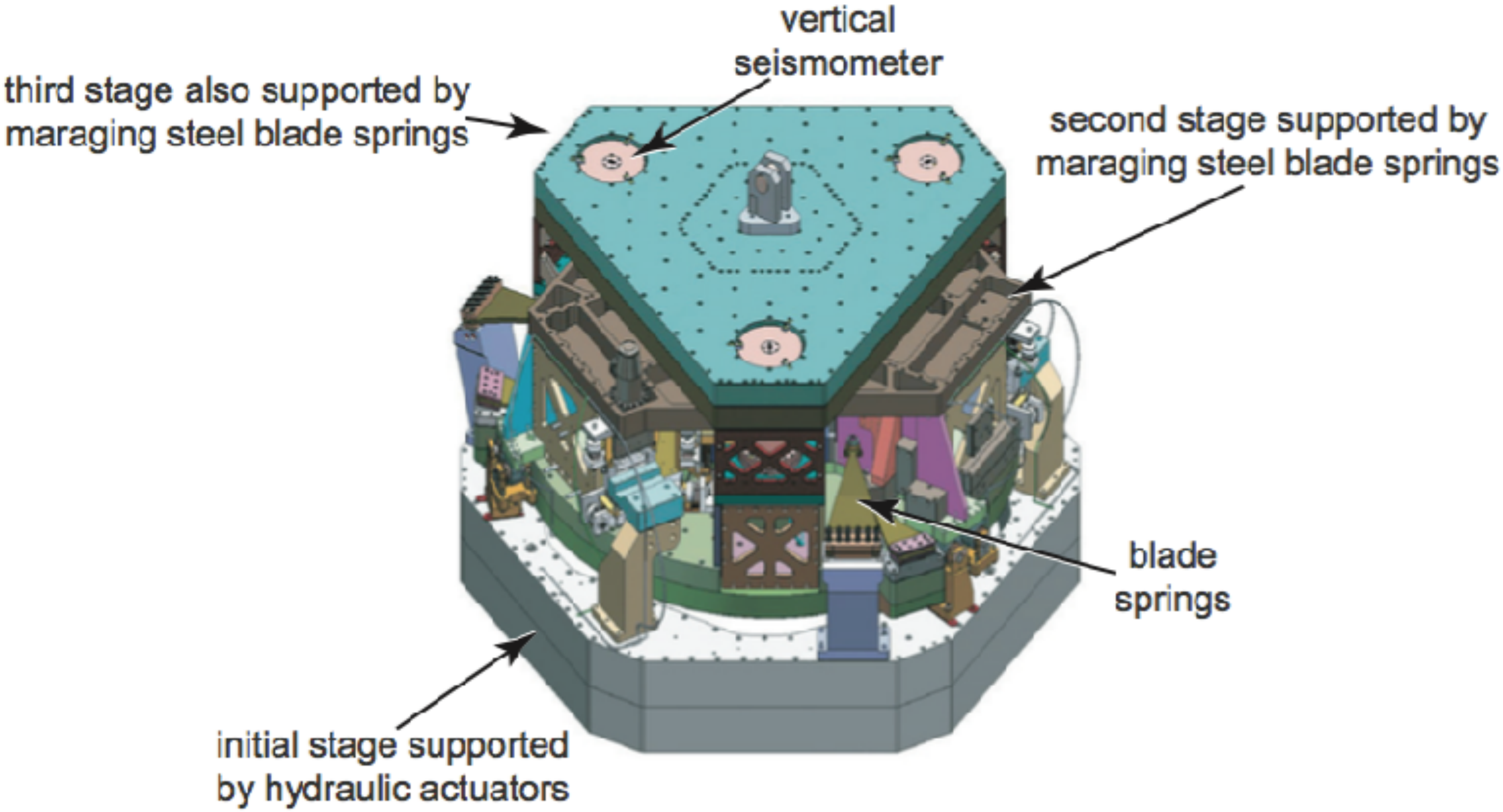
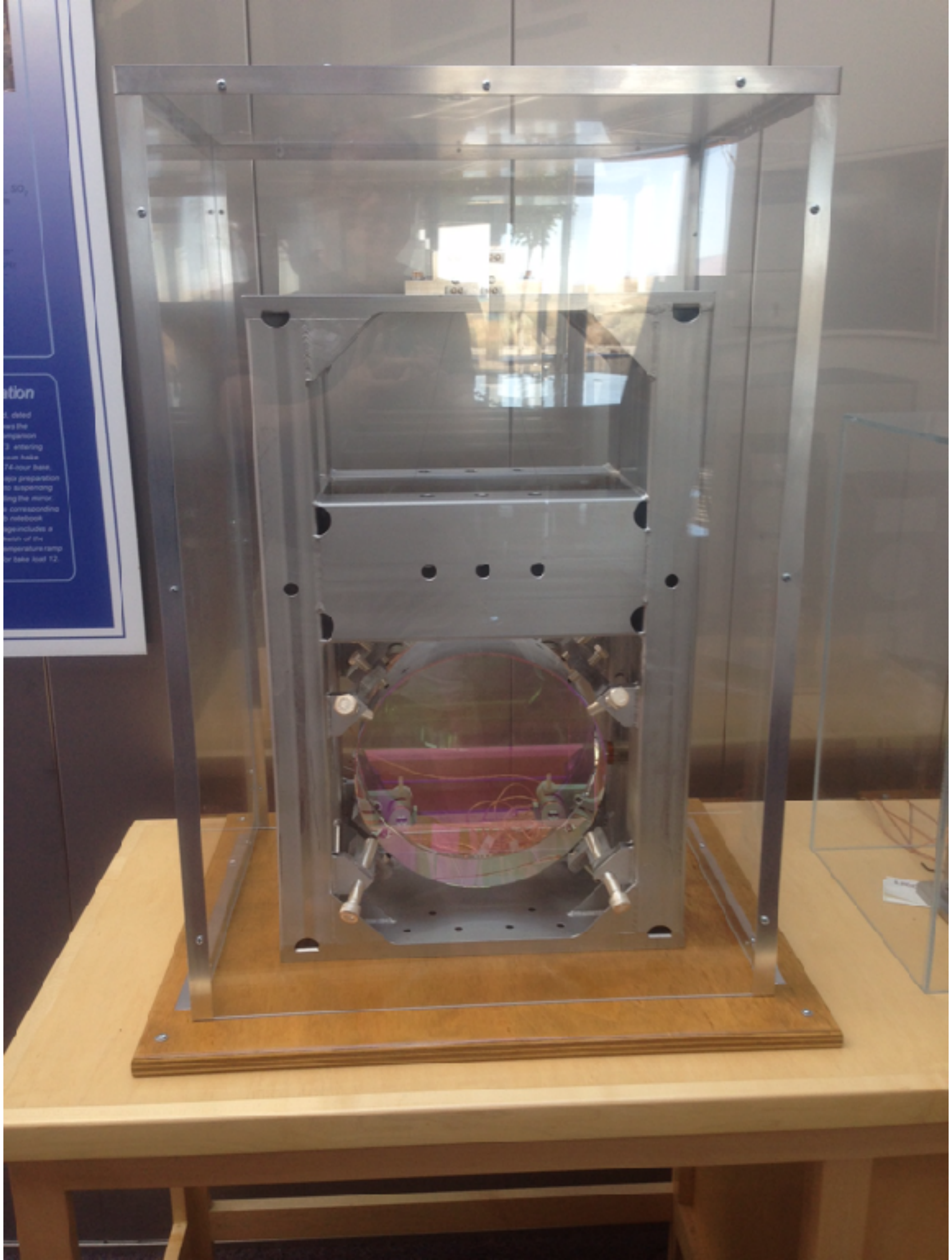
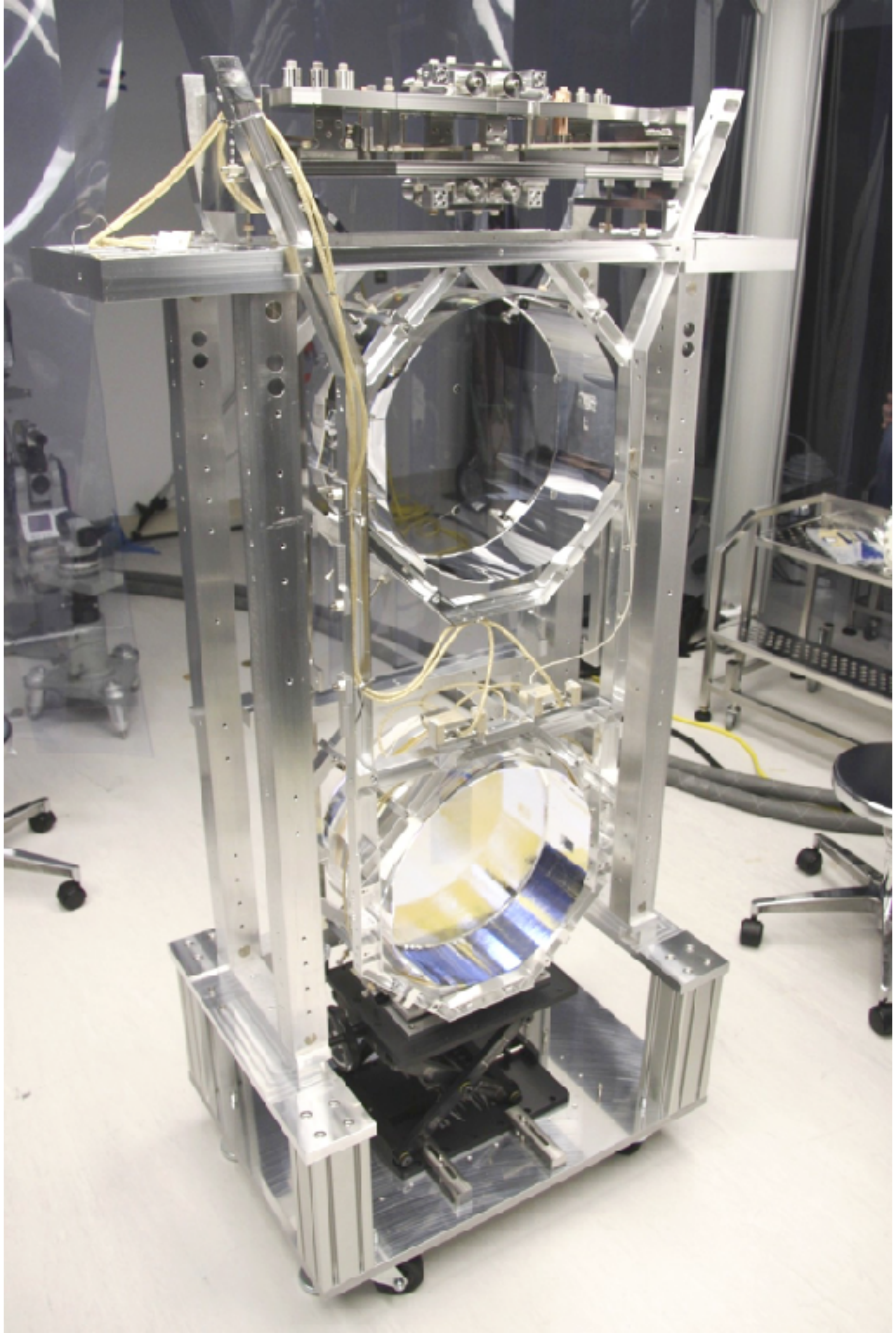
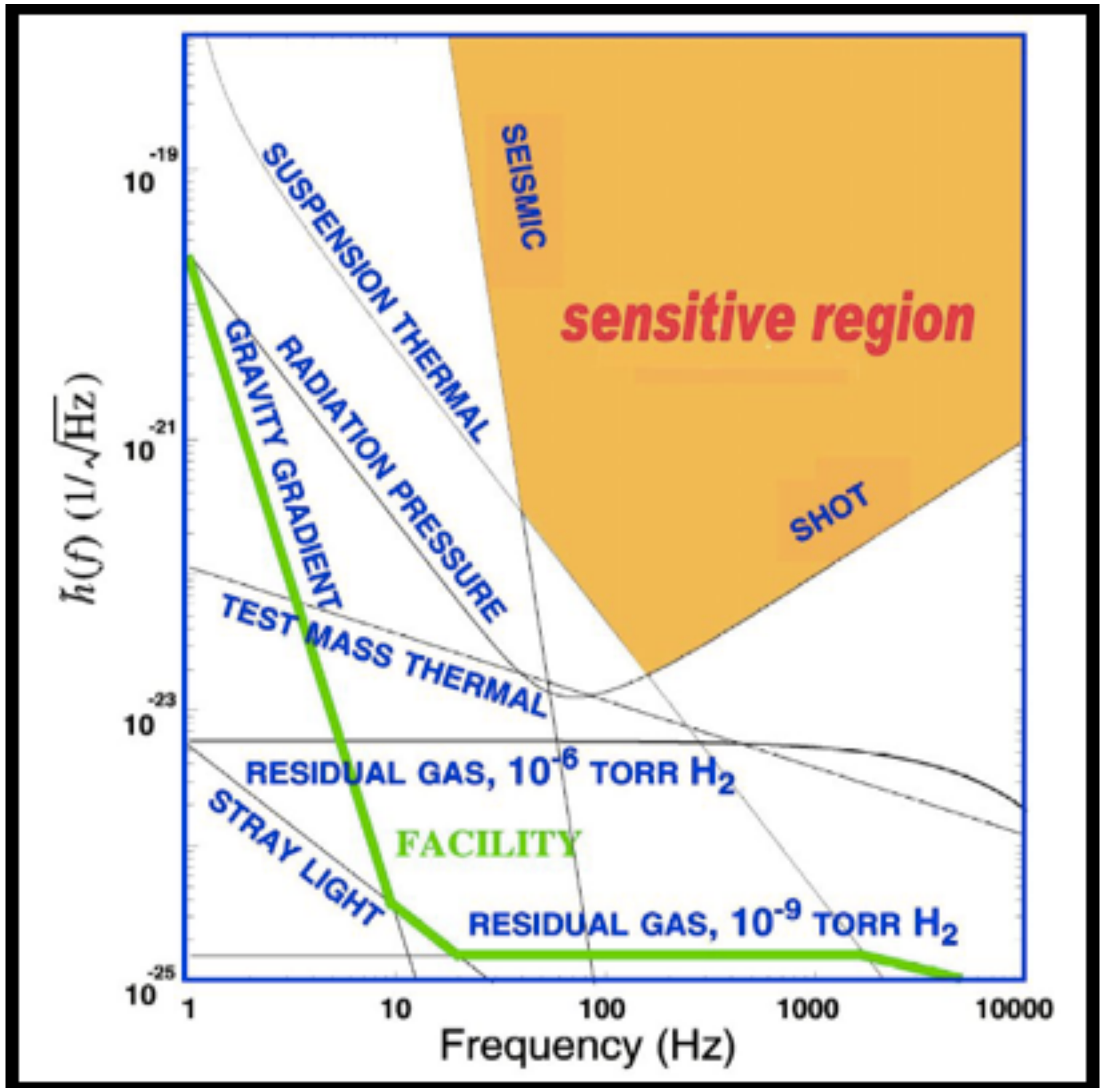


Figure 5: Internal stages of the large chamber seismic isolation system for Advanced LIGO (image is inverted for clarity).





Noise sources



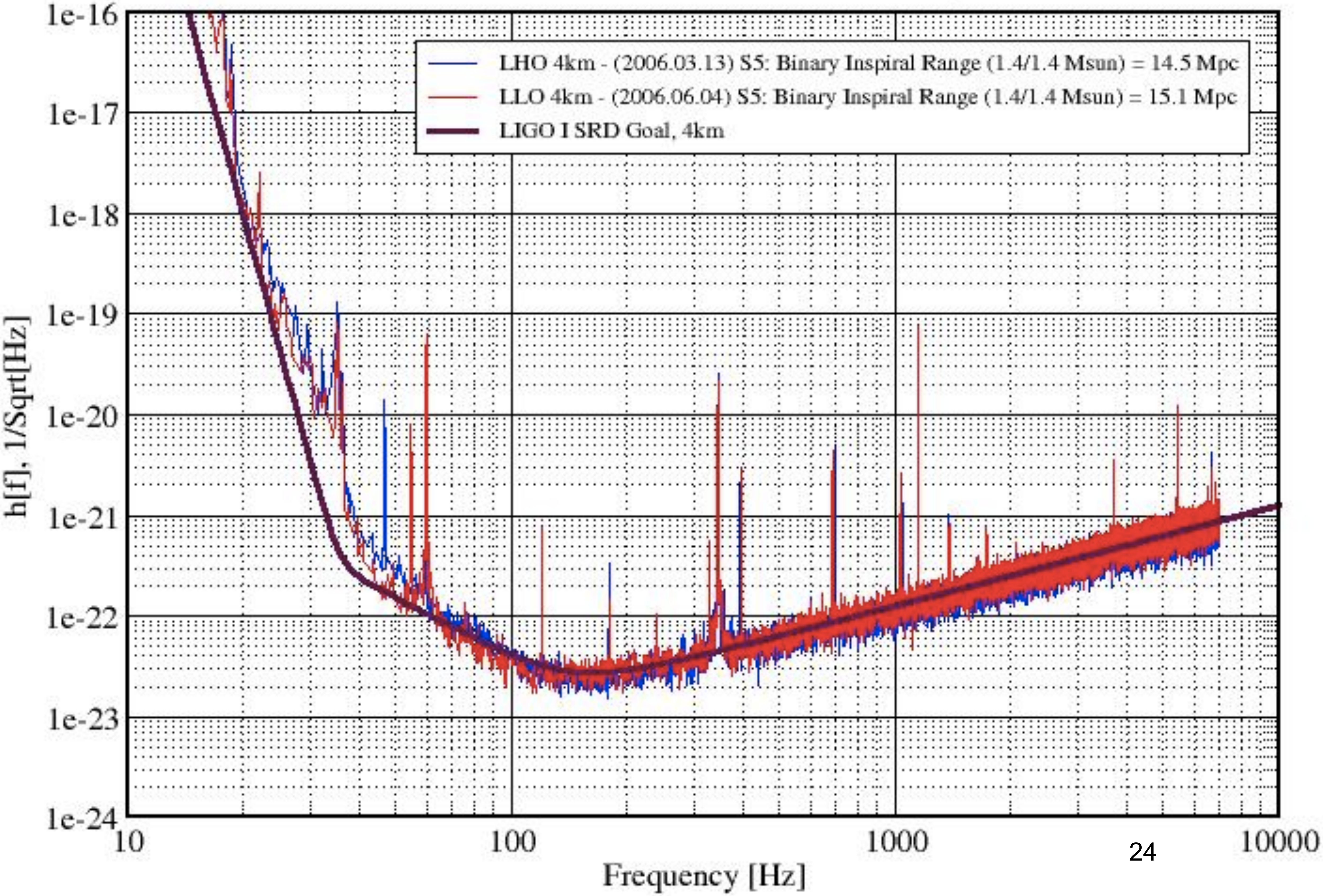
This graph courtesy of LIGO.

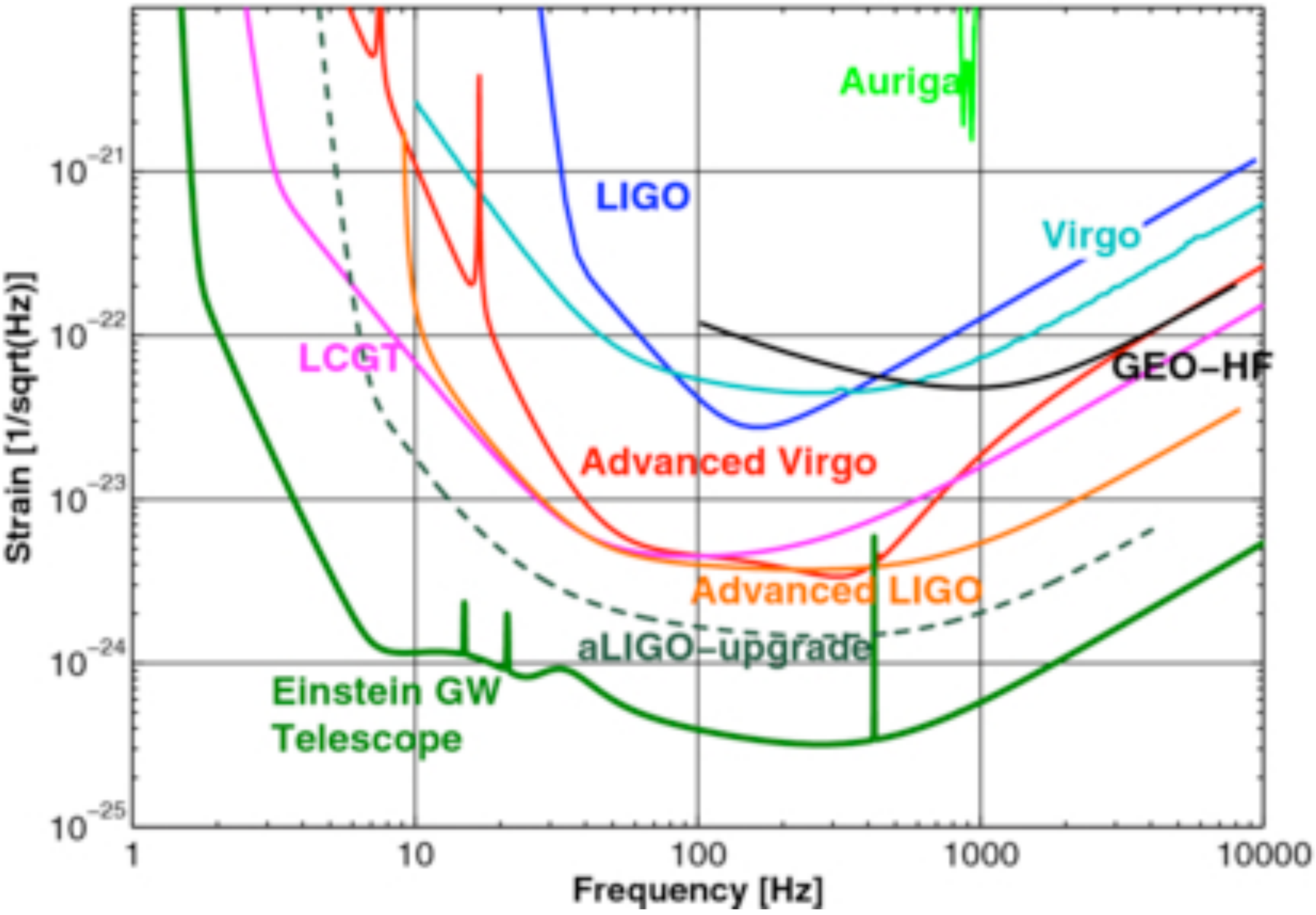
- seismic noise
  - –mechanical vibrations carried through the earth
  - –transmitted into interferometer via infrastructure
  - –caused by plate tectonics, ocean tides, logging, cars, ...
- thermal noise
  - –molecular motion associated with non-zero temperature
  - –most problematic in the suspension system.
- photon shot noise
  - –statistical fluctuations in number of photons measuring mirror position
  - –can be reduced by increasing laser power

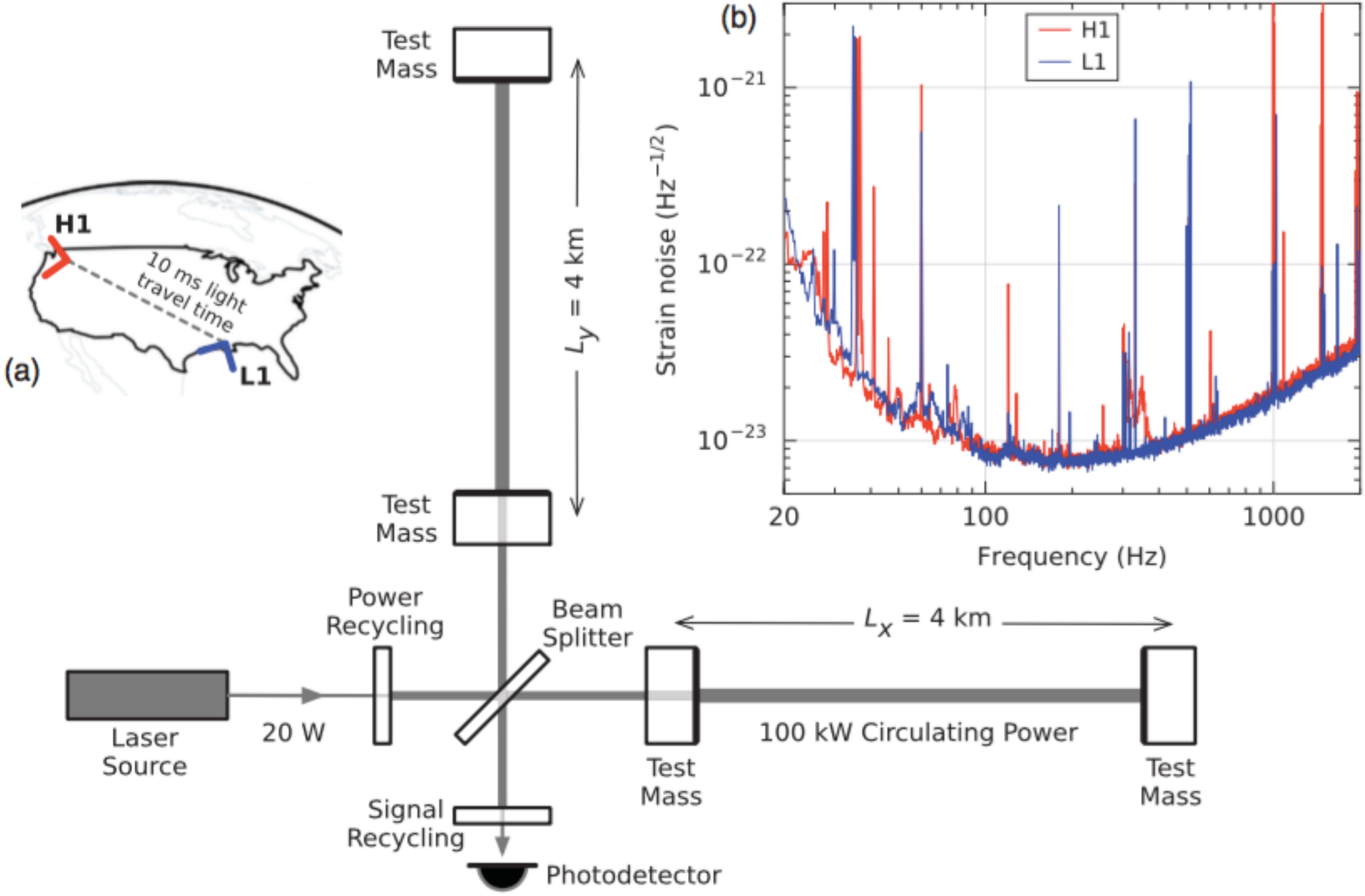
Advanced LIGO: Improve seismic isolation, improve suspensions, and increase laser power. Improves sensitivity by factor of ~10. See merger out to 150 instead of 15 Mpc.

Strain Sensitivity for the LIGO 4km Interferometers

S5 Performance - June 2006 LIGO-G060293-00-Z

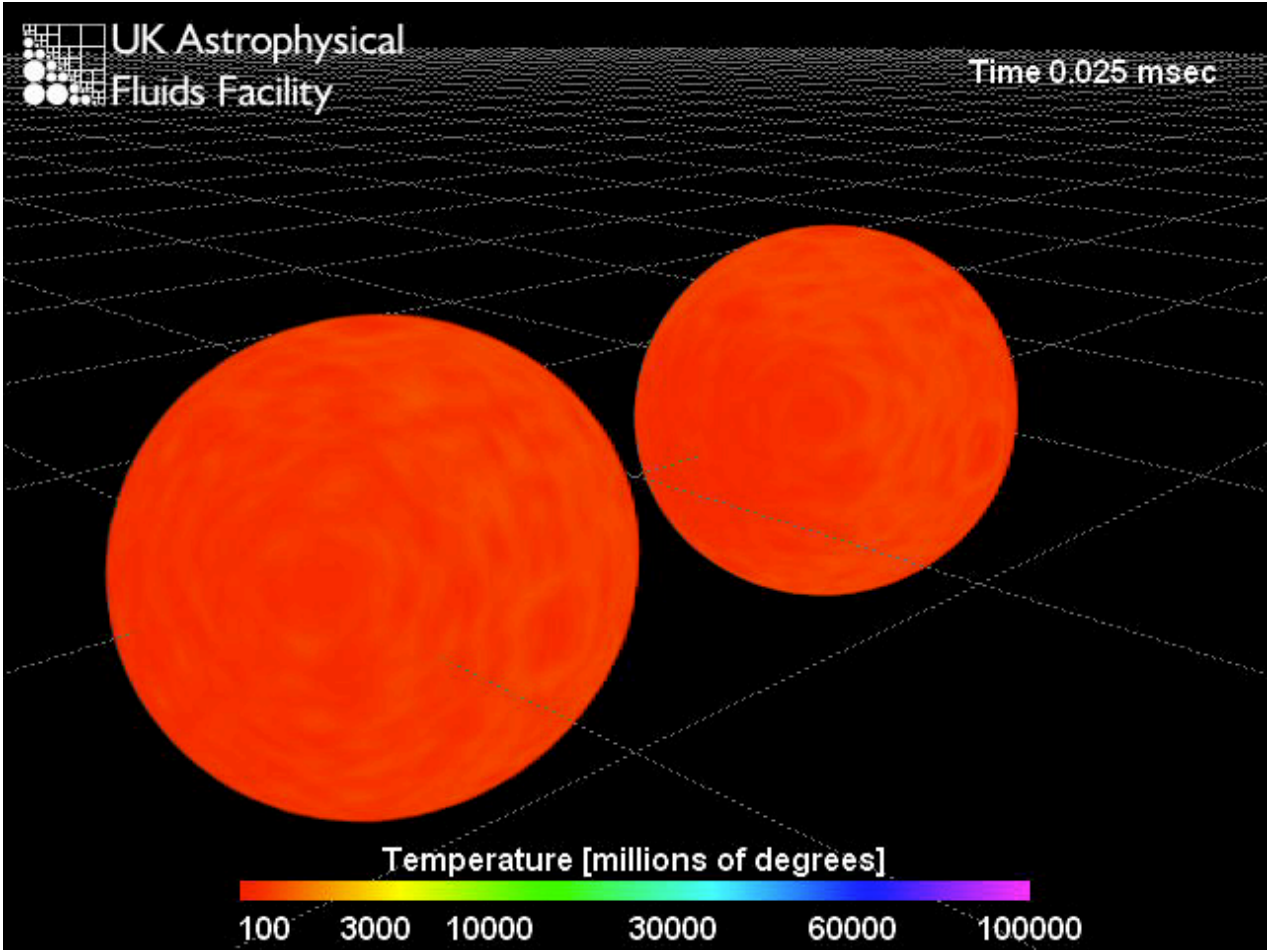



Auriga
LIGO
Virgo
LCGT
GEO−HF
Advanced Virgo
Advanced LIGO
aLIGO−upgrade
Einstein GW
Telescope
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{-25}
Strain [1/sqrt(Hz)]
1
10
100
1000
10000
Frequency [Hz]


(a)
H1
L1
10 ms light travel time
(b)
H1
L1
Strain noise (Hz^−1/2)
10^−21
10^−22
10^−23
20
100
1000
Frequency (Hz)
Test Mass
Test Mass
L_y = 4 km
Power Recycling
Beam Splitter
L_x = 4 km
Laser Source
20 W
Test Mass
100 kW Circulating Power
Test Mass
Signal Recycling
Photodetector

Neutron Star Mergers

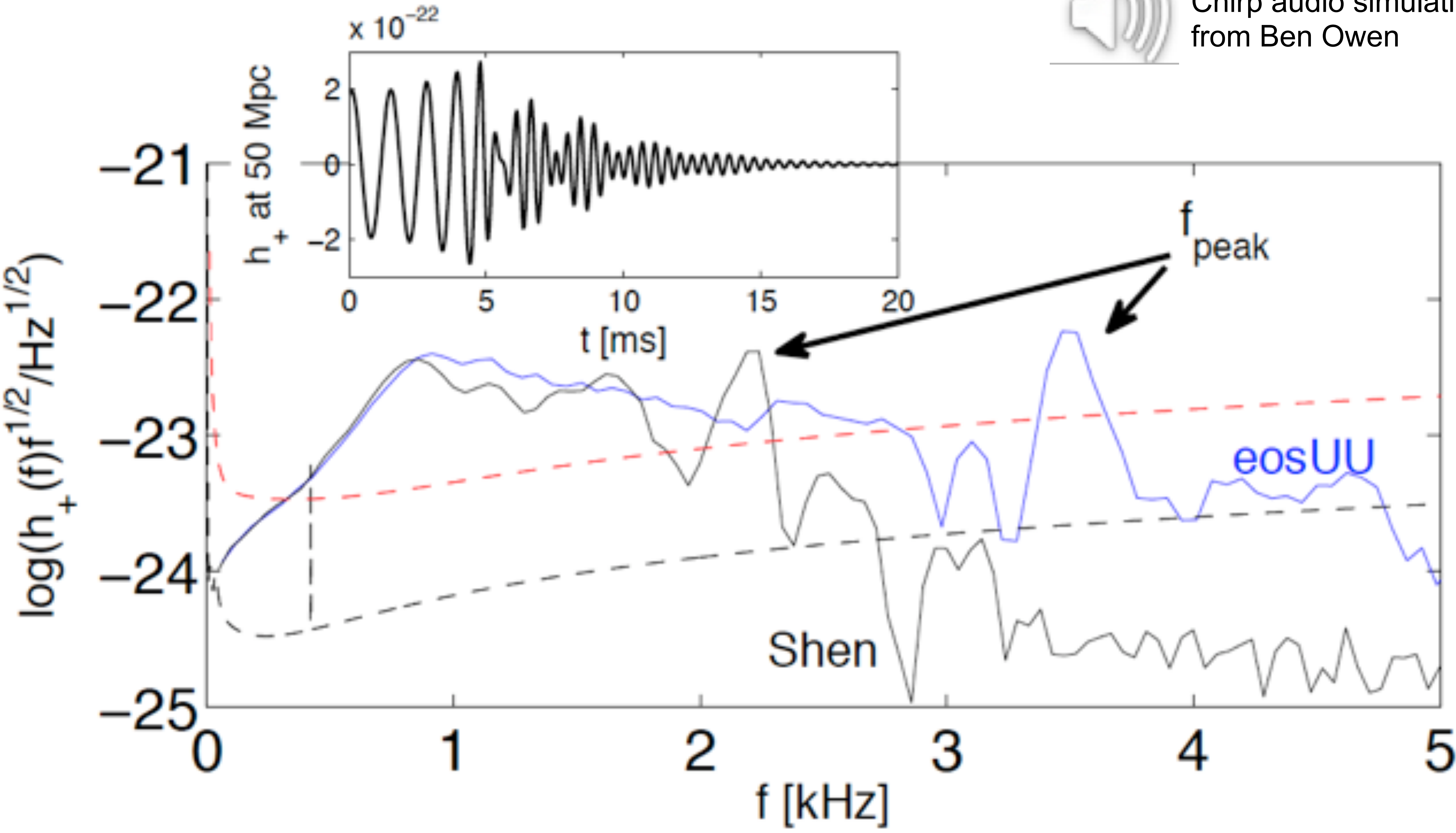
- Consider a binary system of two massive stars. Both stars end their lives as SN and producing two orbiting NS.
- Gravitational radiation slowly shrinks the orbit and the two NS will spiral together.
- Eventually the two NS will merge. Magnetic fields during the merger probably produce jets and a short gamma ray burst.
- Note gamma ray bursts longer than about 2 seconds are the most common and are though to arise from "collapsars". Rapidly rotating very massive stars that collapse to form a black hole and jets.
- NS mergers also produce a strong gravitational wave signal.

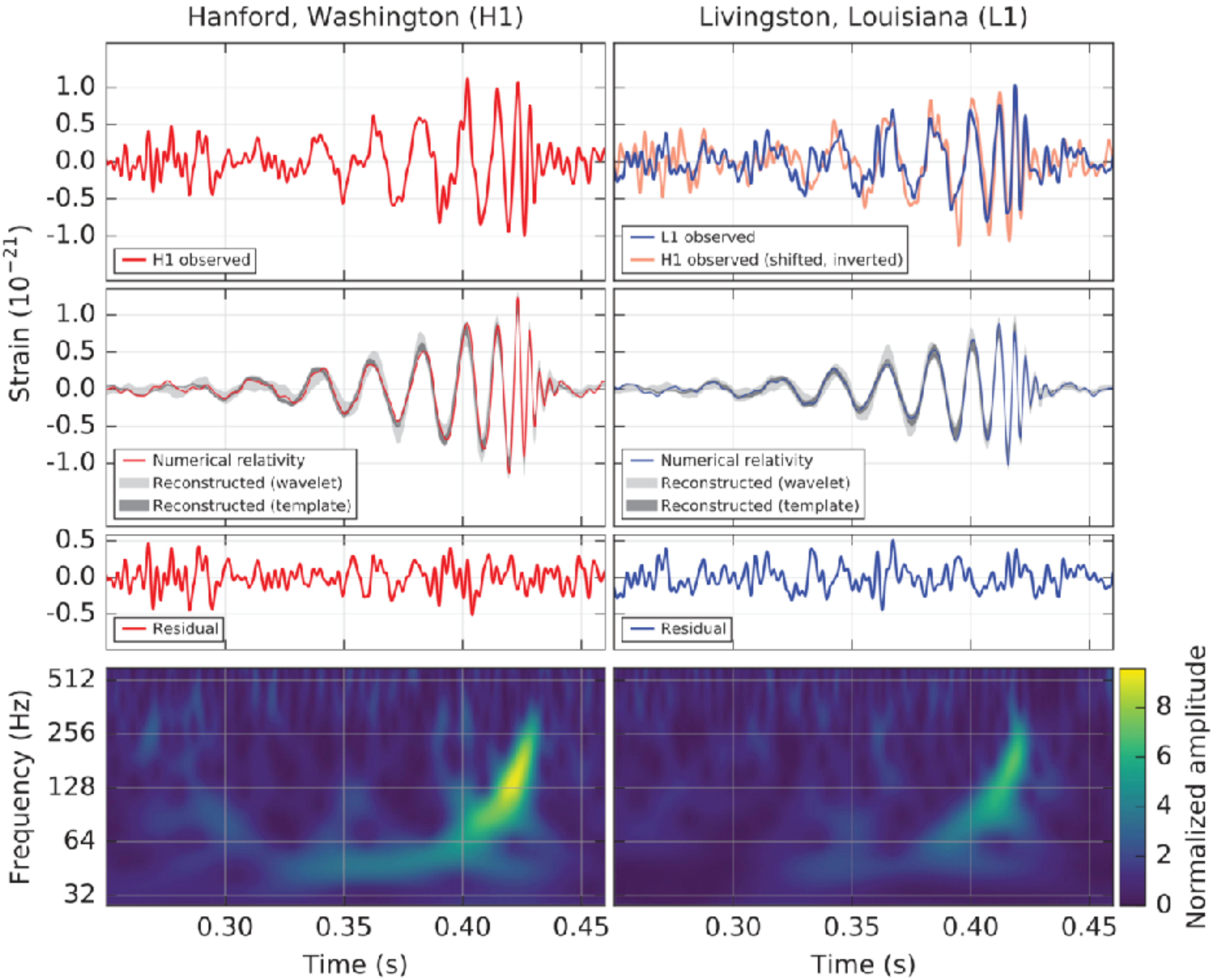


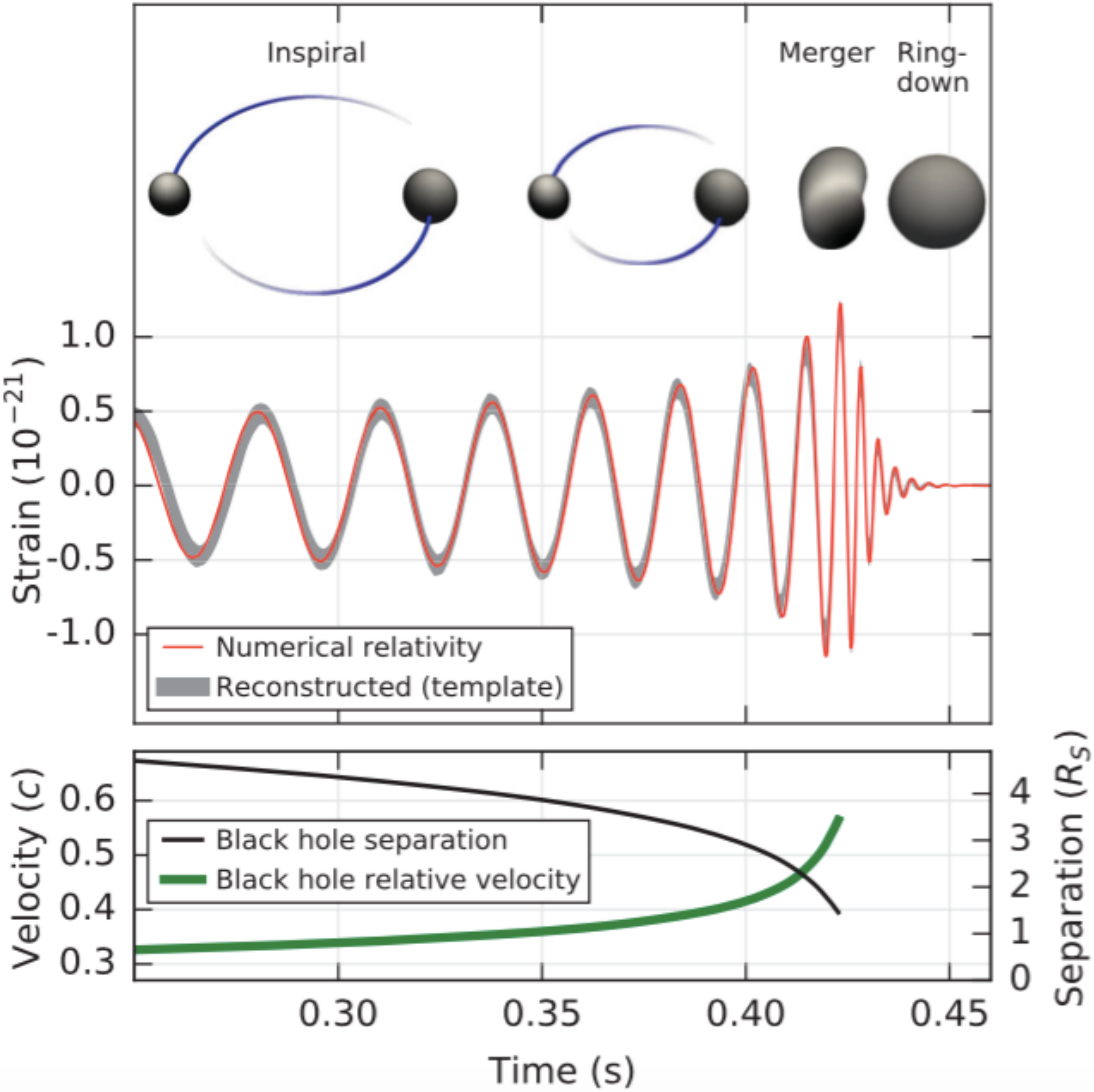
- Simulation by Stephan Rosswog, University of Leicester. Visualisation by Richard West, UKAFF.

Wave form for merging NS

Chirp audio simulation
from Ben Owen




Hanford, Washington (H1)
Livingston, Louisiana (L1)
Strain (10^{-21})
1.0
0.5
0.0
-0.5
-1.0
H1 observed
L1 observed
H1 observed (shifted, inverted)
Numerical relativity
Reconstructed (wavelet)
Reconstructed (template)
Residual
Frequency (Hz)
512
256
128
64
32
Normalized amplitude
0
2
4
6
8
0.30
0.35
0.40
0.45
Time (s)


Inspiral
Merger
Ring-down
Strain (10^{-21})
1.0
0.5
0.0
-0.5
-1.0
Numerical relativity
Reconstructed (template)
Velocity (c)
0.6
0.5
0.4
0.3
Black hole separation
Black hole relative velocity
Separation (R_S)
4
3
2
1
0
0.30
0.35
0.40
0.45
Time (s)

Chirp Mass

- Frequency of orbit depends on mass and radius (Kepler orbit).
- Rate frequency increases because of gravitational radiation (GR) depends on different combination of mass and radius.
- Chirp mass is best measured parameter:

$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}} \qquad \mathcal{M} = \frac{c^3}{G}\left(\frac{5}{96}\pi^{-8/3} f^{-11/3} \dot{f}\right)^{3/5}$$

- Chirp mass too large to be NS merger.

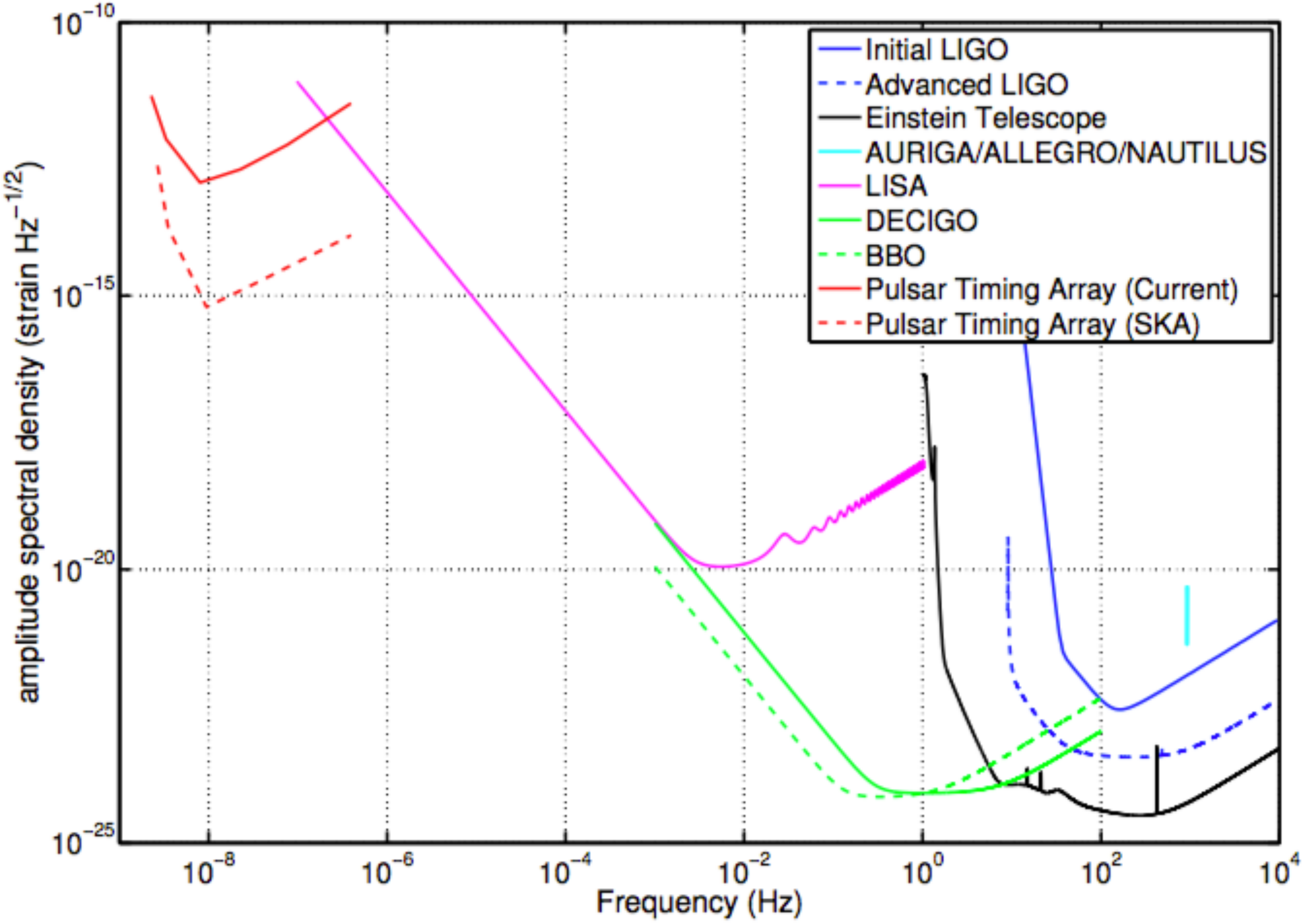


Figure 1: The sensitivity of various gravitational-wave detection techniques across 13 orders of magnitude in frequency. At the low frequency end the sensitivity curves for pulsar timing arrays (based on current observations and future observations with the Square Kilometre Array [108]) are extrapolated from Figure 4 in [325]. In the mid-range LISA, DECIGO and BBO are described in more detail in Section 7, with the DECIGO and BBO sensitivity curves taken from models given in [323]. At the high frequency the sensitivities are represented by three generations of laser interferometers: LIGO, Advanced LIGO and the Einstein Telescope (see Sections 6, 6.3.1 and 6.3.2). Also included is a representative sensitivity for the AURIGA [88], Allegro [226] and Nautilus [239] bar detectors.

Gravitational Wave Astronomy

- Is now real.
- Should have exciting event rate! Factor of ~3 increase in sensitivity, when full aLIGO design sensitivity is reached, implies ~30 times greater event rate than this first run.
- Should see neutron star mergers that probably have E+M counterparts. aVirgo and LIGO India could help locate source on sky, aiding E+M searches.
- Expect surprises!