Hearing Black Holes Collide with the Laser Interferometer Gravitational-wave Observatory

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California Institute of Technology

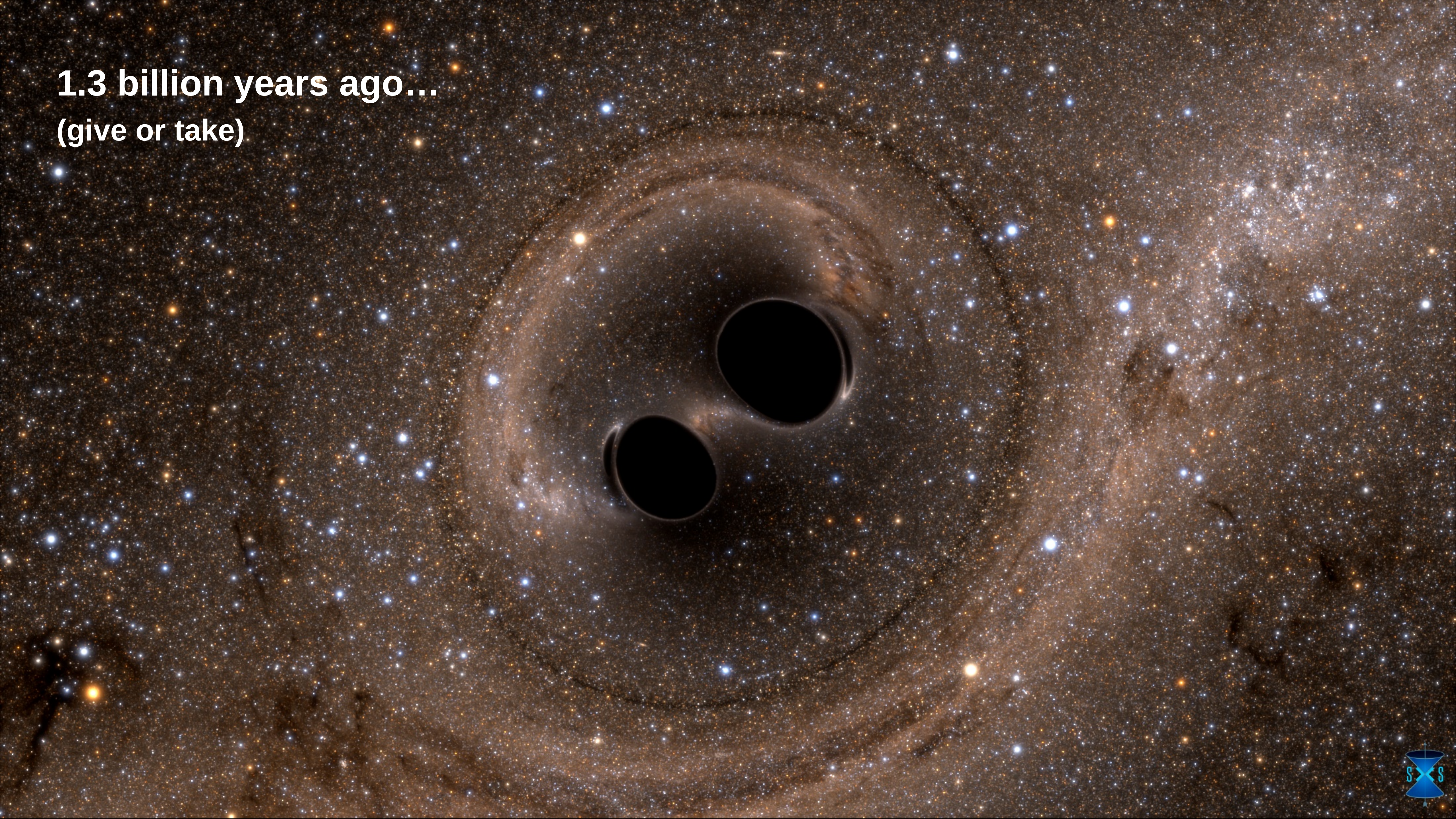
University of Adelaide,
May 15, 2017

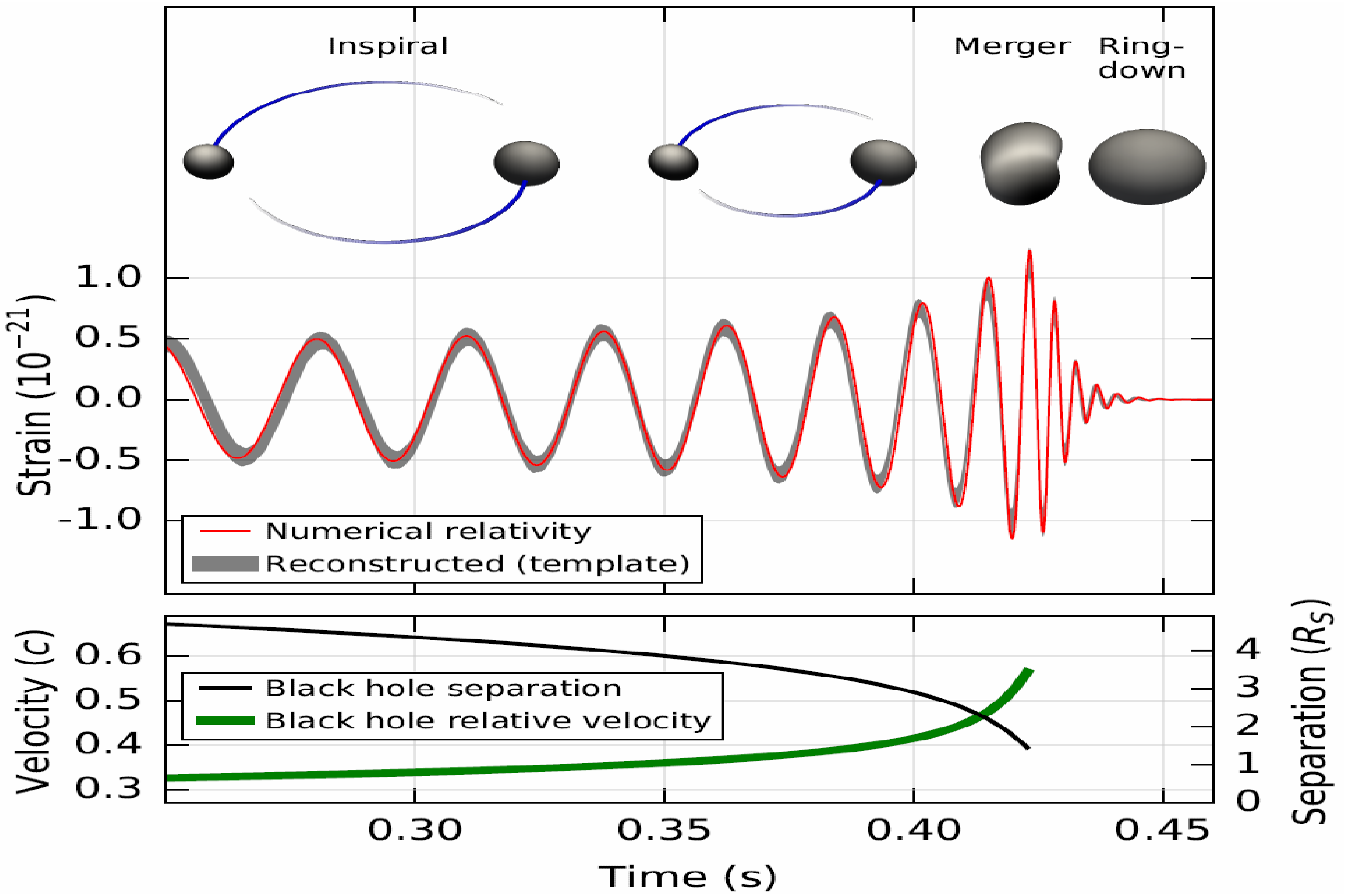
For the LIGO Scientific Collaboration and the Virgo Collaboration

LIGO-G1700572-v1

1.3 billion years ago…

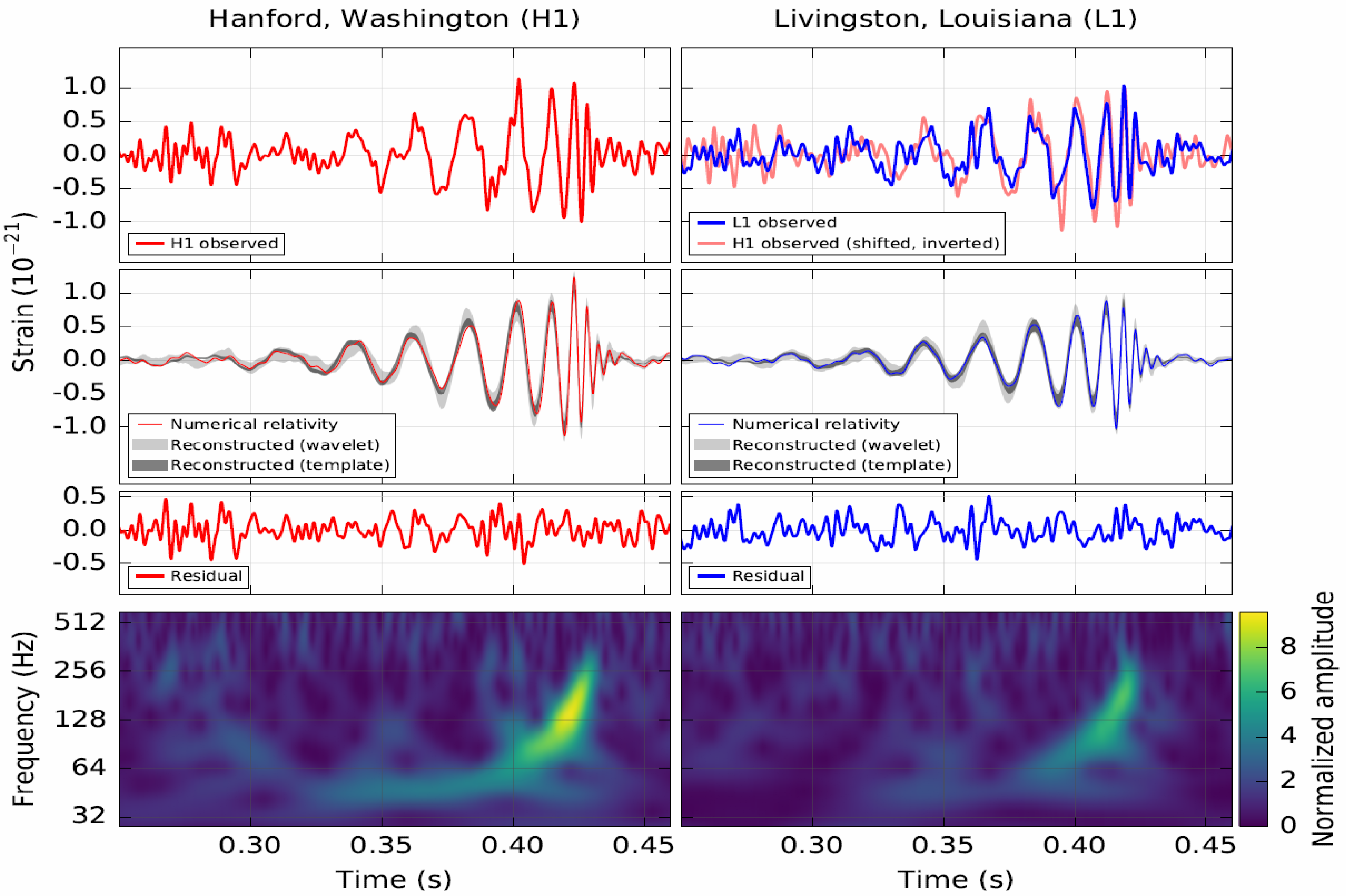
(give or take)





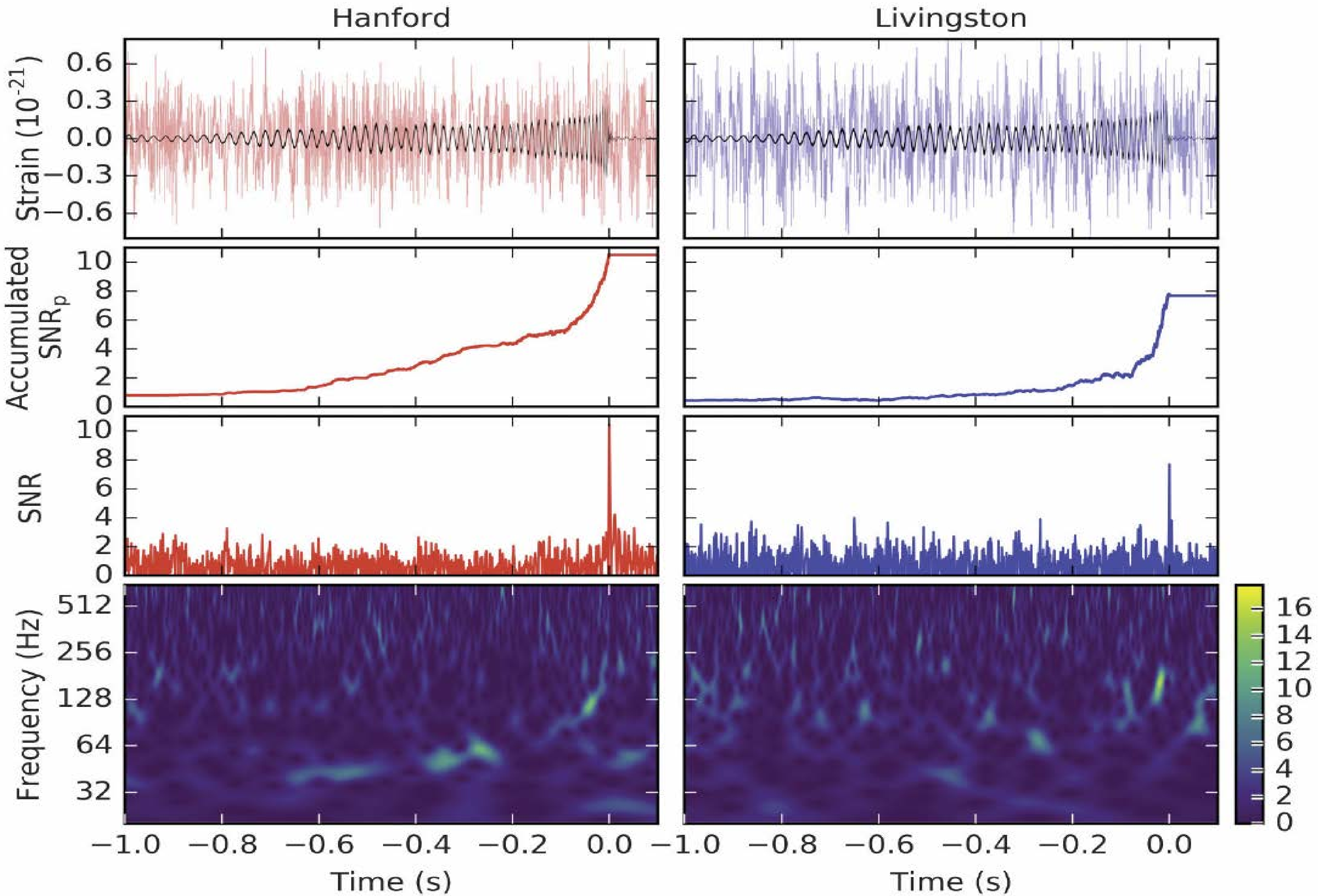
Phys. Rev. Lett. 116, 061102 (2016)

GW150914



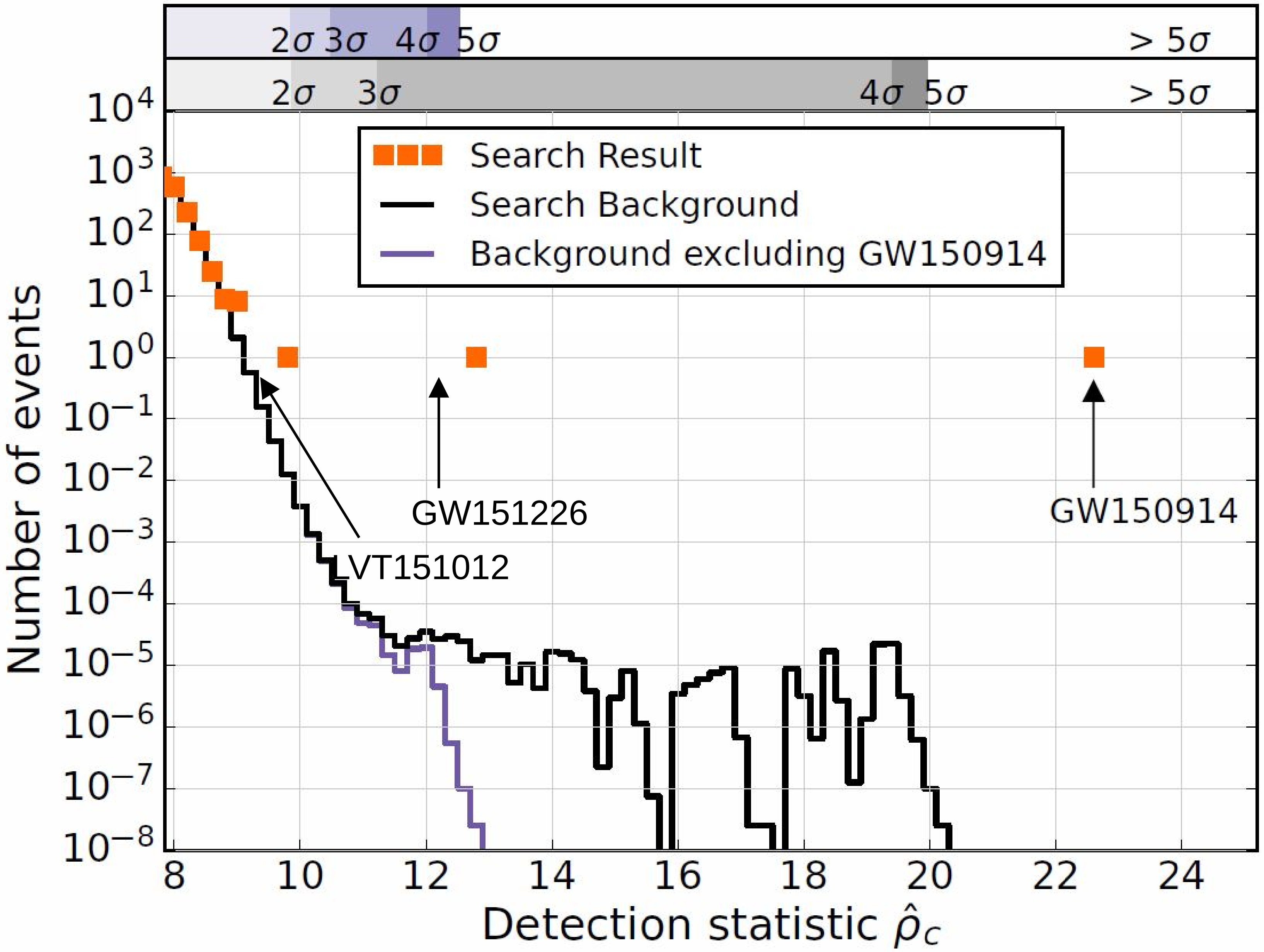
Hanford, Washington (H1)
Livingston, Louisiana (L1)
Strain (10^{-21})
H1 observed
L1 observed
H1 observed (shifted, inverted)
Numerical relativity
Reconstructed (wavelet)
Reconstructed (template)
Residual
Frequency (Hz)
Normalized amplitude
Time (s)

GW151226



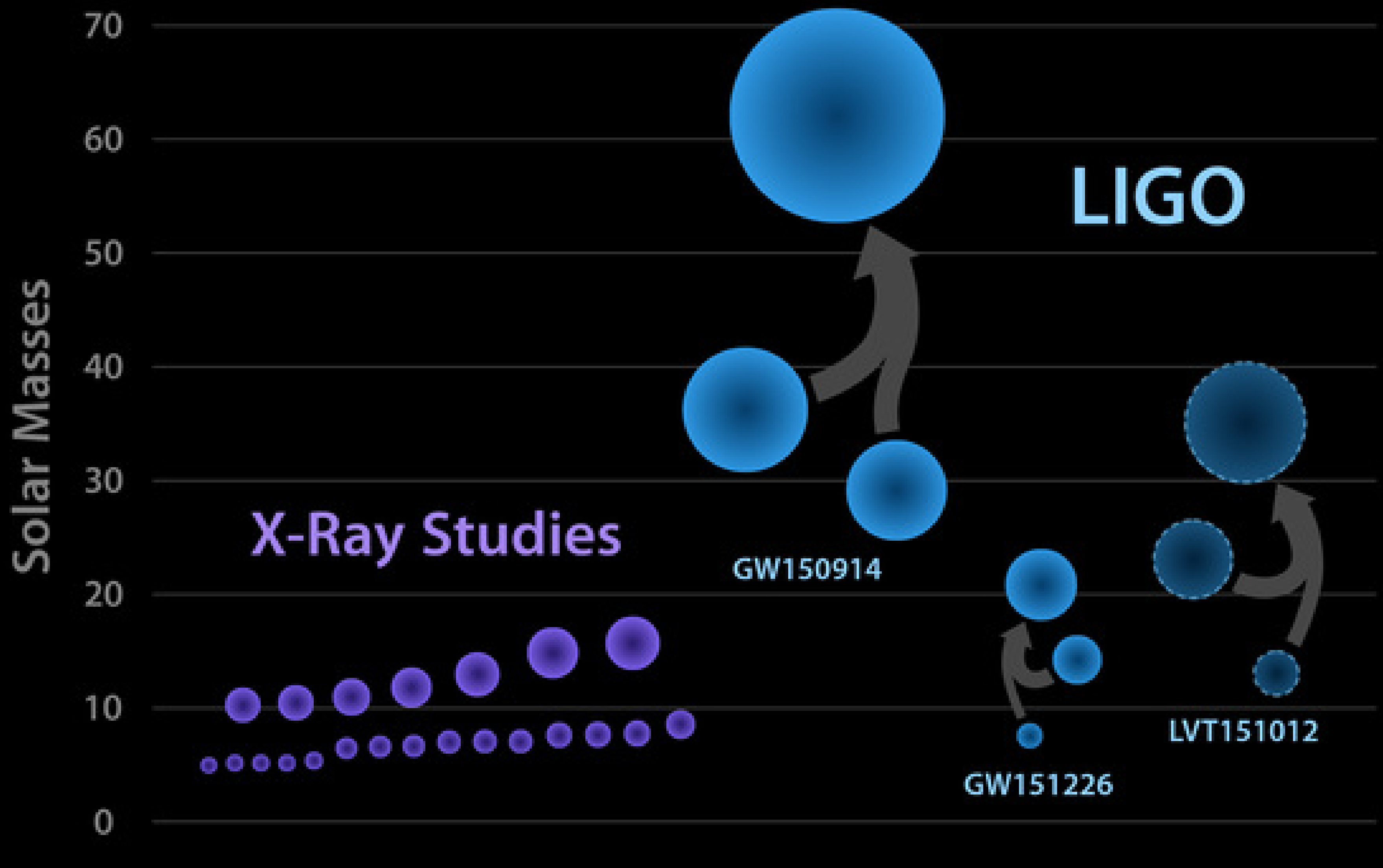
Phys. Rev. Lett. 116, 241103 (2016)

GW150914



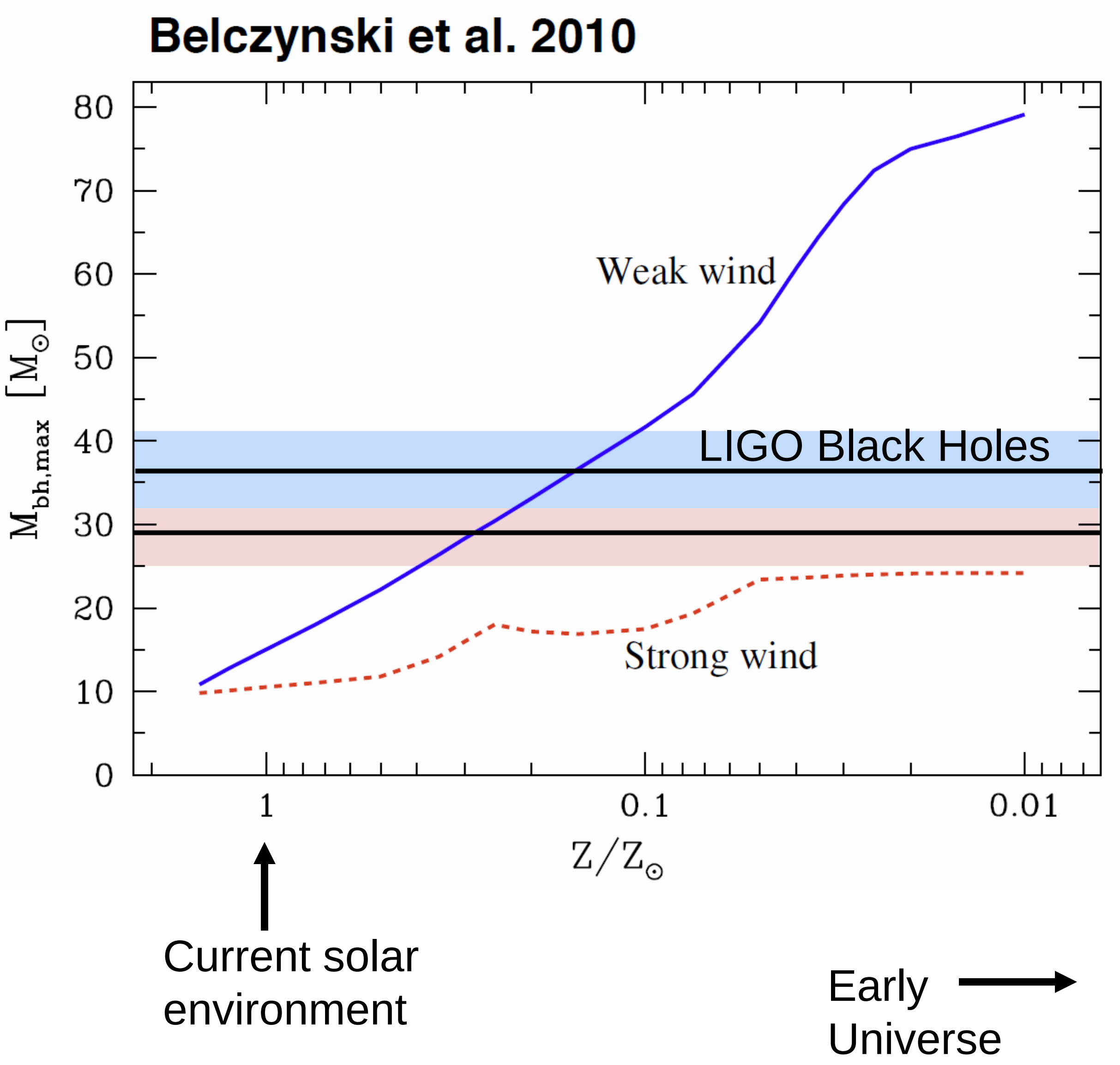
2σ 3σ 4σ 5σ
> 5σ
2σ 3σ
4σ 5σ
> 5σ
Search Result
Search Background
Background excluding GW150914
GW151226
GW150914
LVT151012
Number of events
Detection statistic $\hat{\rho}_c$

Black Holes of Known Mass

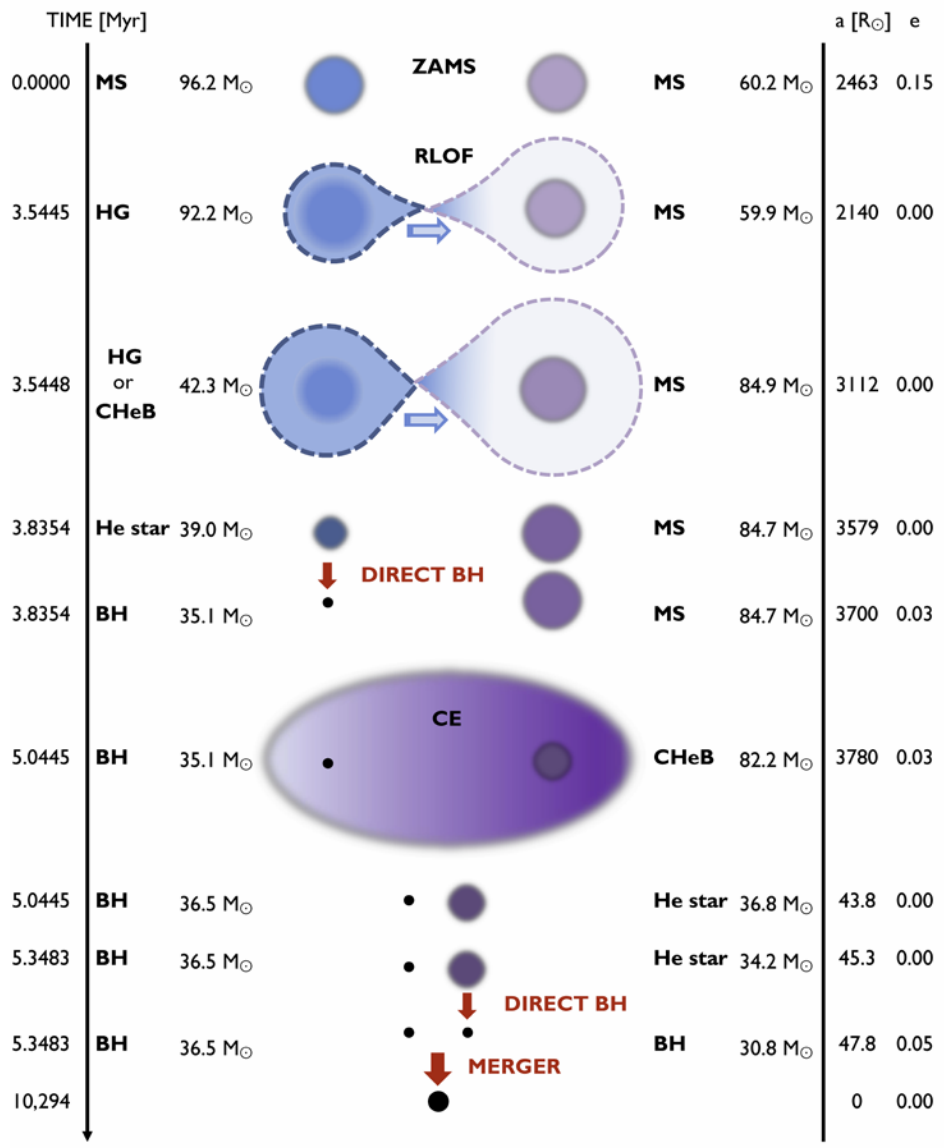


Astrophysical Implications

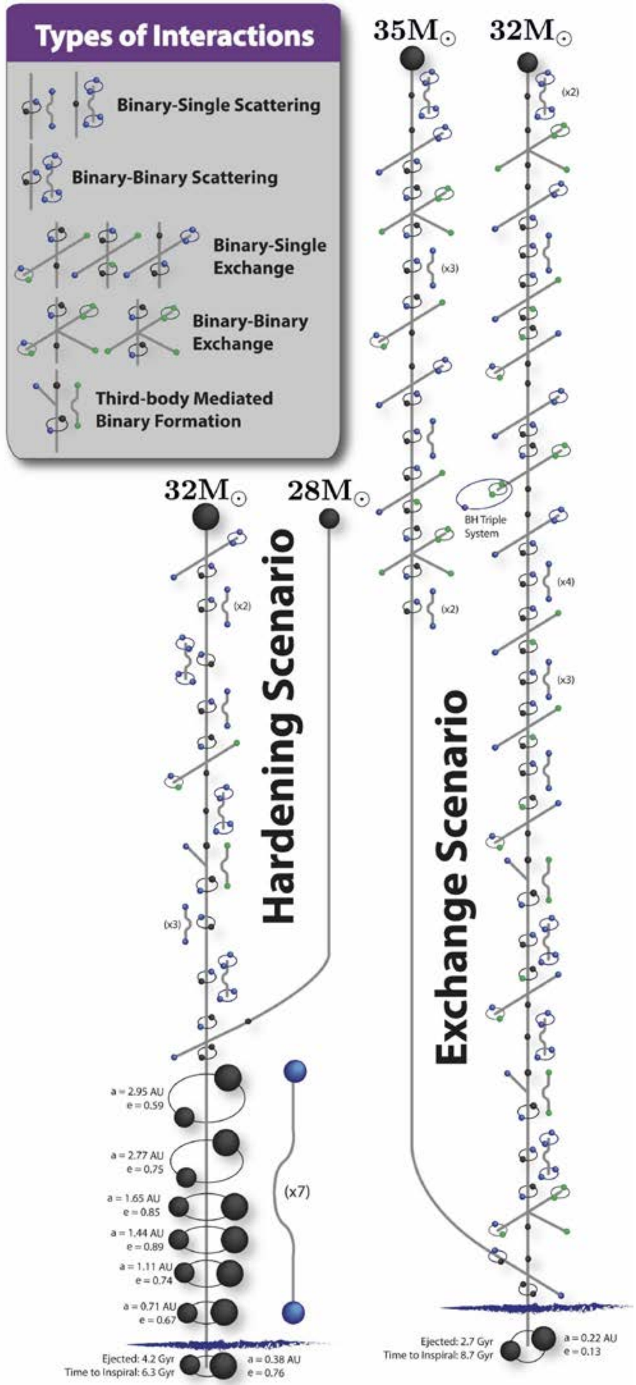
- Early in the Universe monster stars can form out of Hydrogen only
- Stars produce metals (Metal in astronomy is anything heavier than Helium)
- 30 solar mass black holes can not be formed with core collapses in the current solar environment



Binary Black Hole Formation



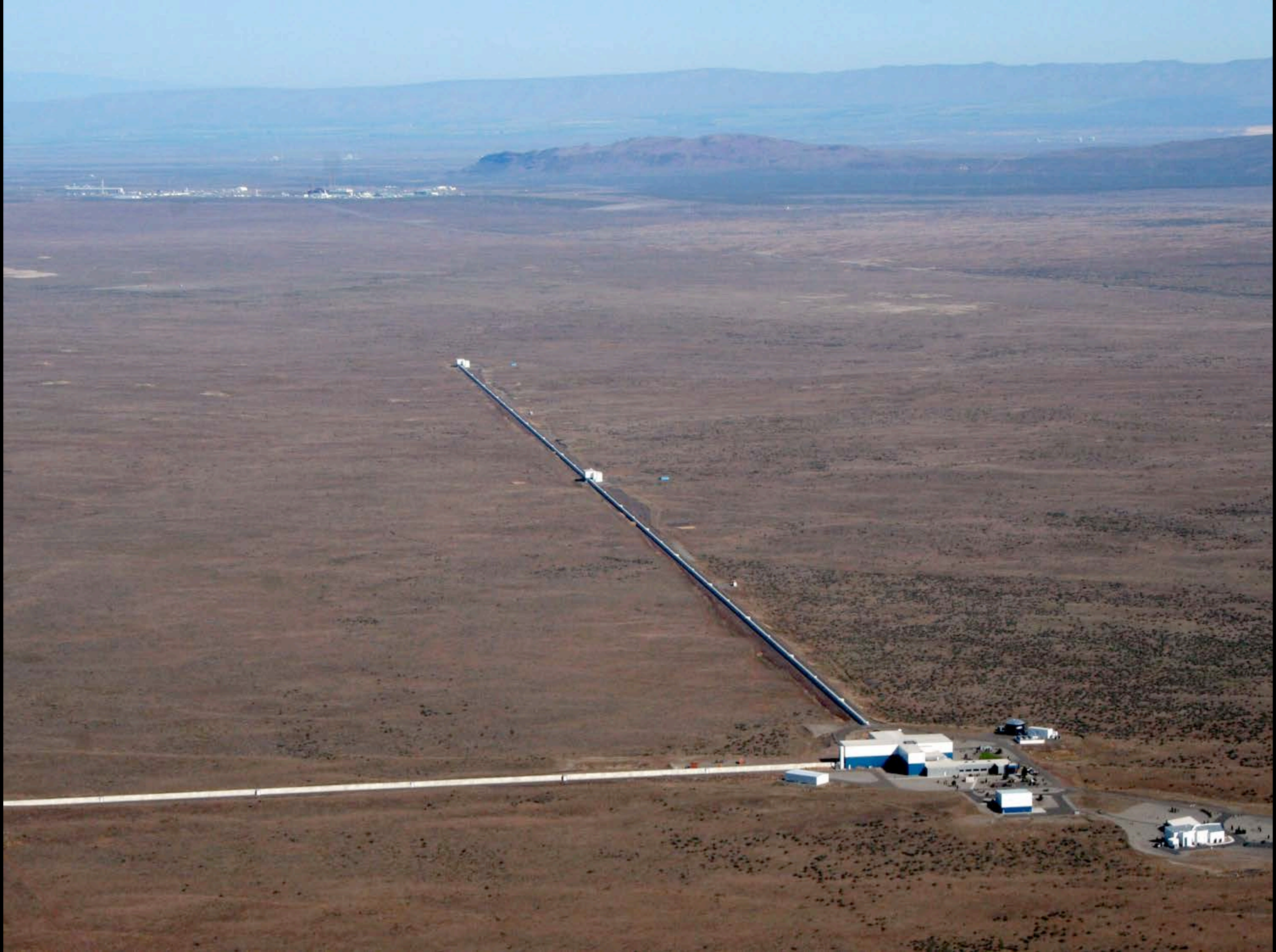
From isolated stars



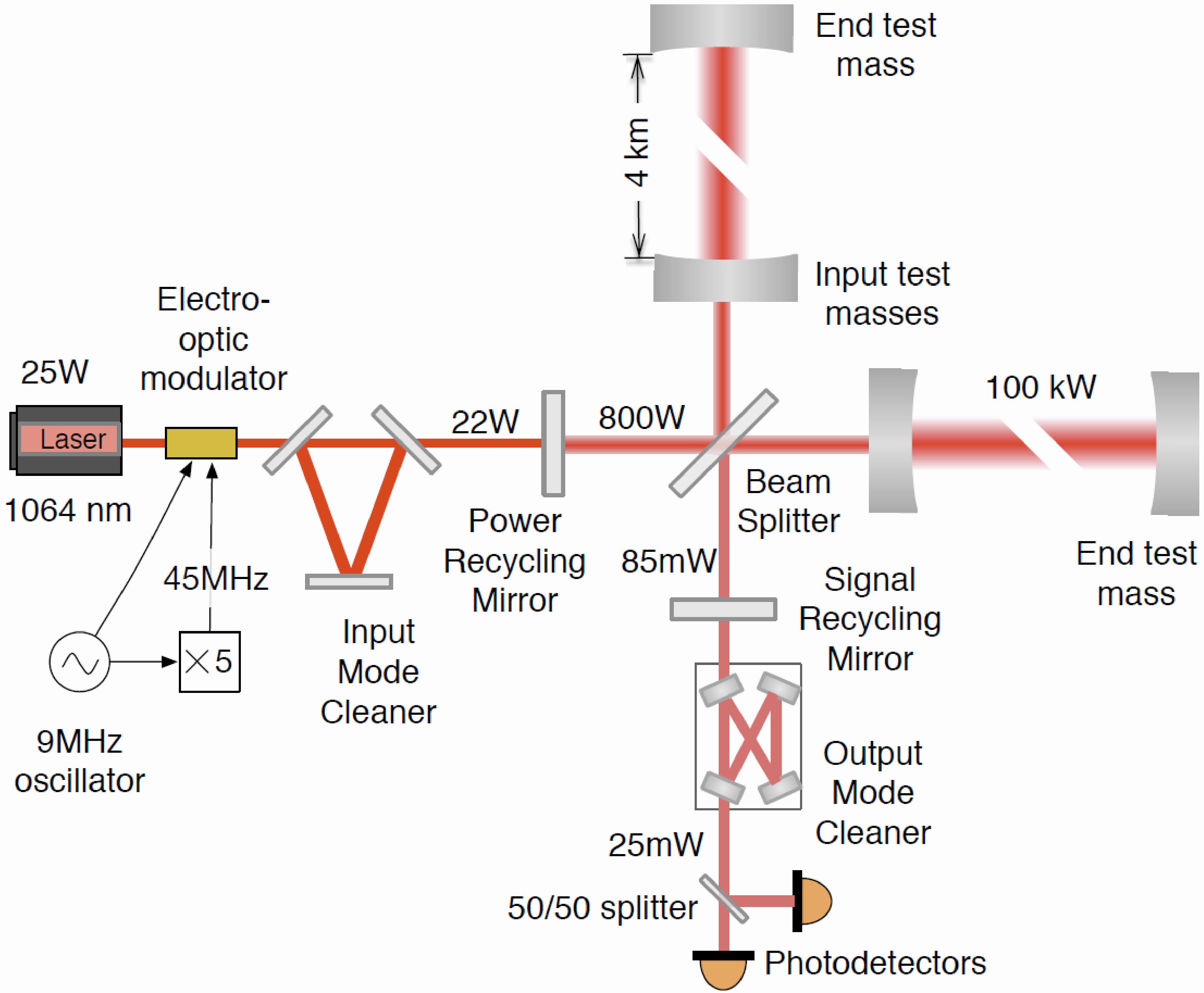
Inside globular clusters

Livingston Observatory

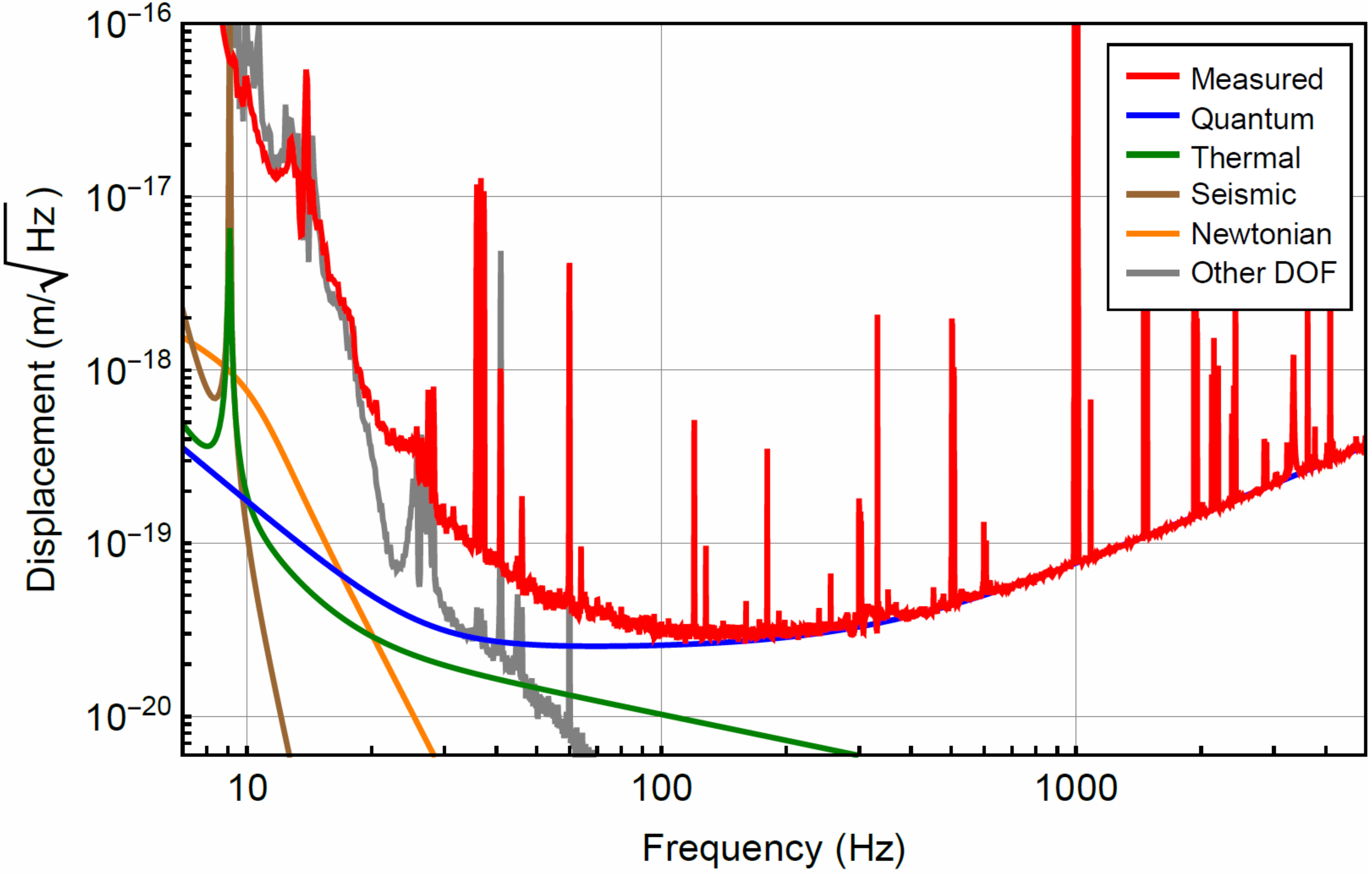
Hanford Observatory



Dual Recycled Michelson Fabry-Perot Arm Cavities



Displacement Sensitivity



Phys. Rev. Lett. 116, 131103 (2016)

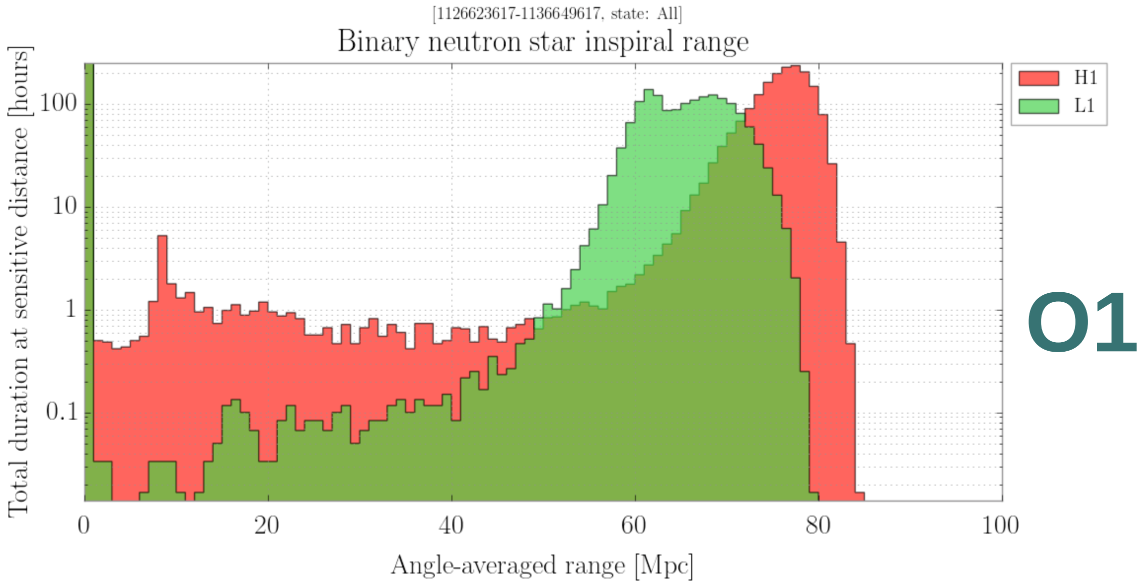
2nd Observation Run

Start:

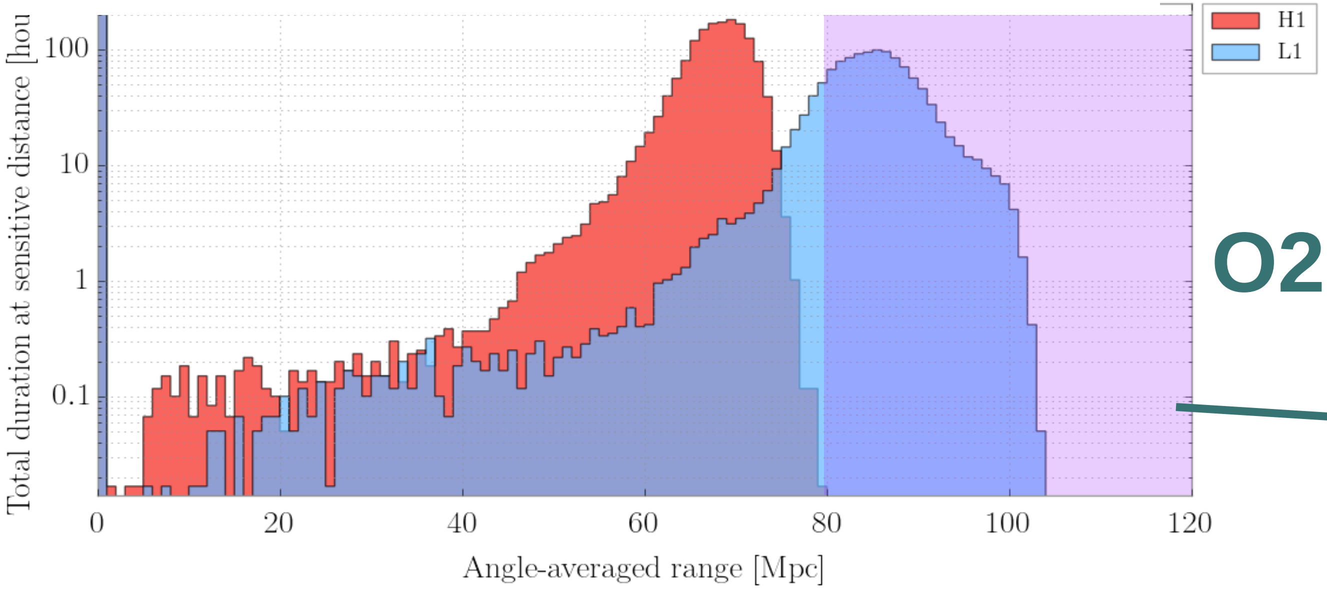
Dec 2016

End:

Aug 2017



O1



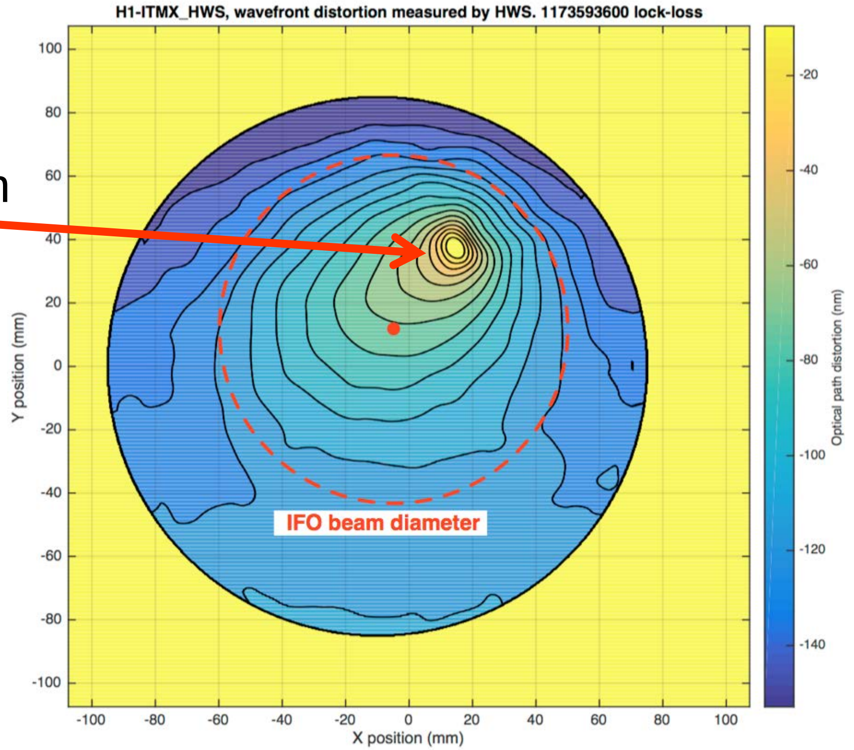
O2

Volume-Time product now about the same for O1 & O2

Goal was 80-120 Mpc

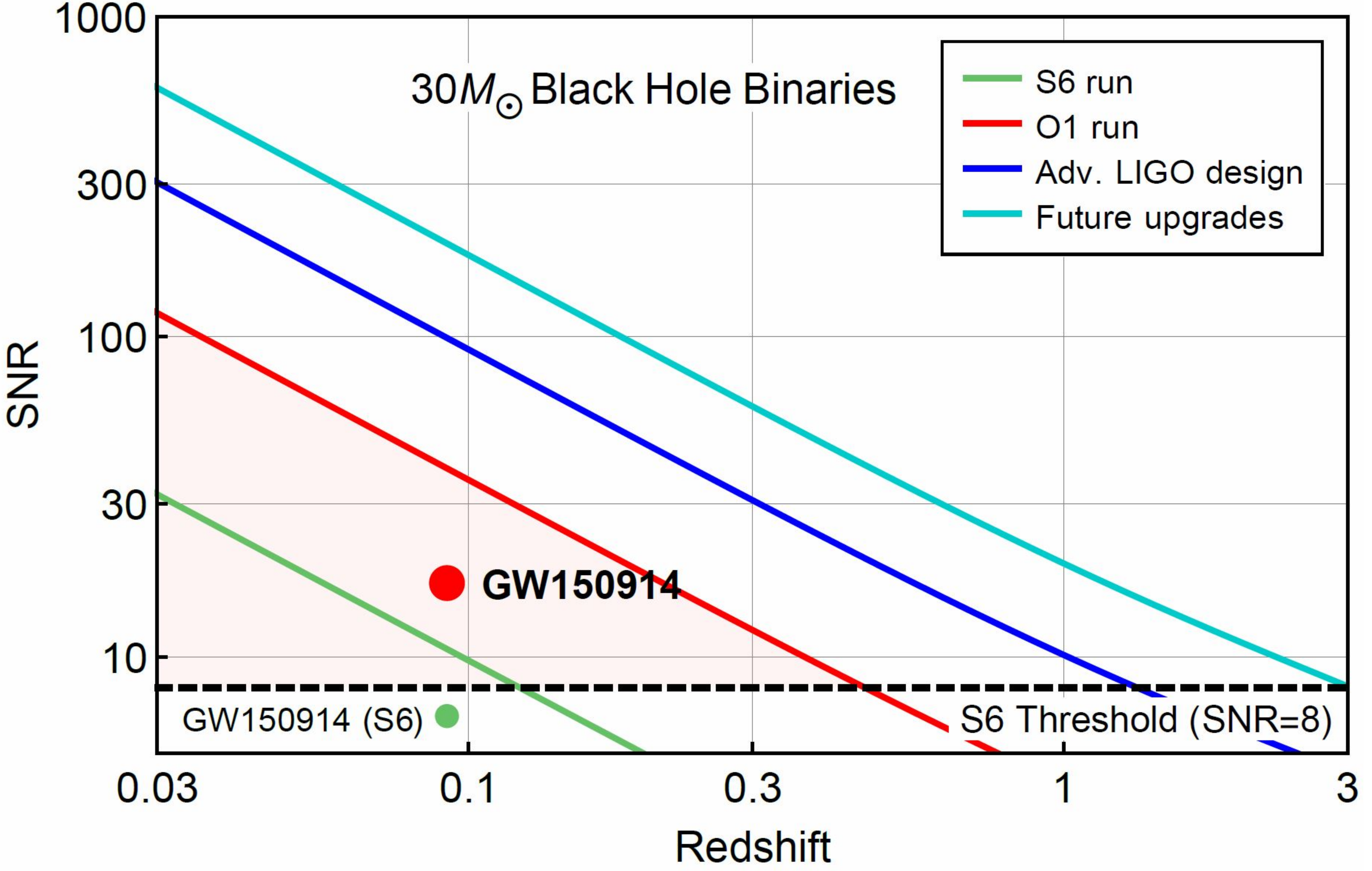
Next Commissioning After the Run

- ❑ **Fix LHO-ITMX Contamination**
  - ➢ Hartmann wavefront sensor
  - ➢ Small point absorber (~10mW)
  - ➢ Resulting phase front distortion is problematic



- ❑ **Squeezed Light injection at LLO**
  - ➢ Target is 3 dB of effective squeezing: equivalent to doubling the laser power
  - ➢ Possibly LHO as well?
- ❑ **Stray Light Control improvements**
- ❑ **70 W amplifier stage at LLO to double the laser power**
  - ➢ LHO: likely to move from the HPO to a 70 W amplifier as well
- ❑ **Replace End Reaction Masses with Annular versions**
  - ➢ Squeezed film damping; possibly electro-static charge
  - ➢ May also replace ETMs at LHO
- ❑ **Monolithic Signal Recycling Mirrors**
- ❑ **Remove several kHz peak in DARM; lower frequency impact?**

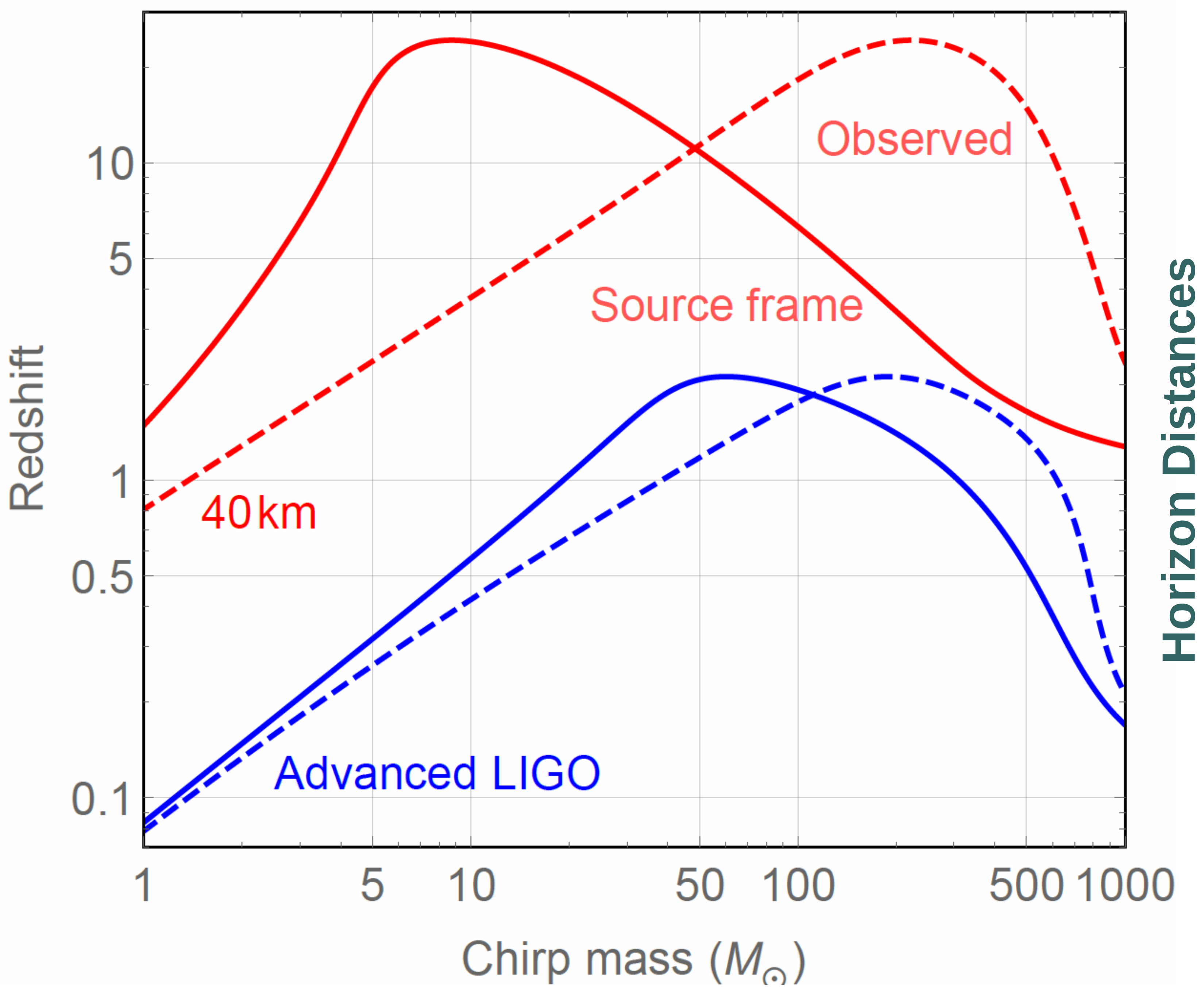
LIGO SNR vs. Horizon



Future Large Facilities

Potential to see all stellar size black hole mergers in the entire Universe!

Learn about Early Star and Structure Formation



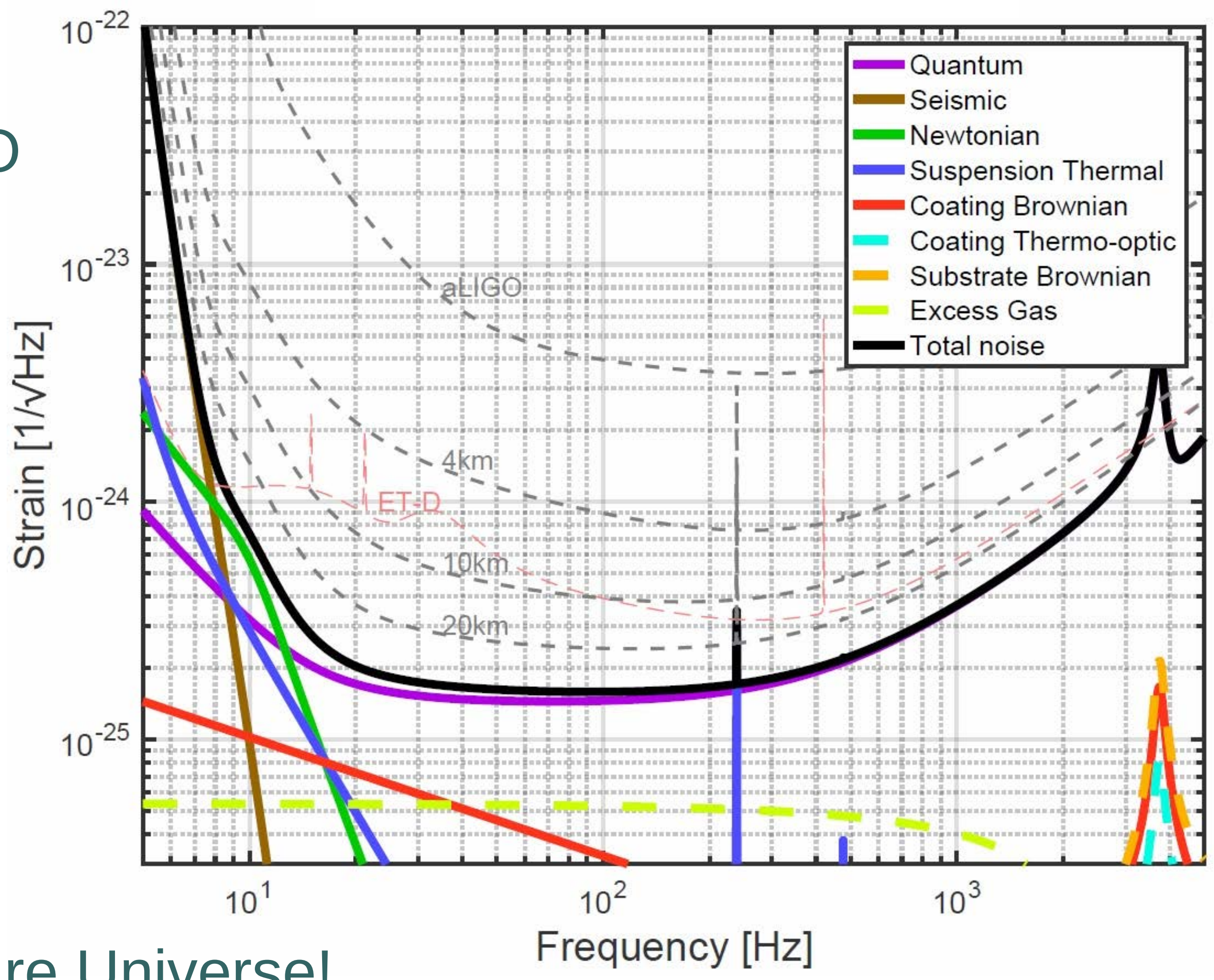
Next Generation Gravitational Wave Detectors

Current Facilities:

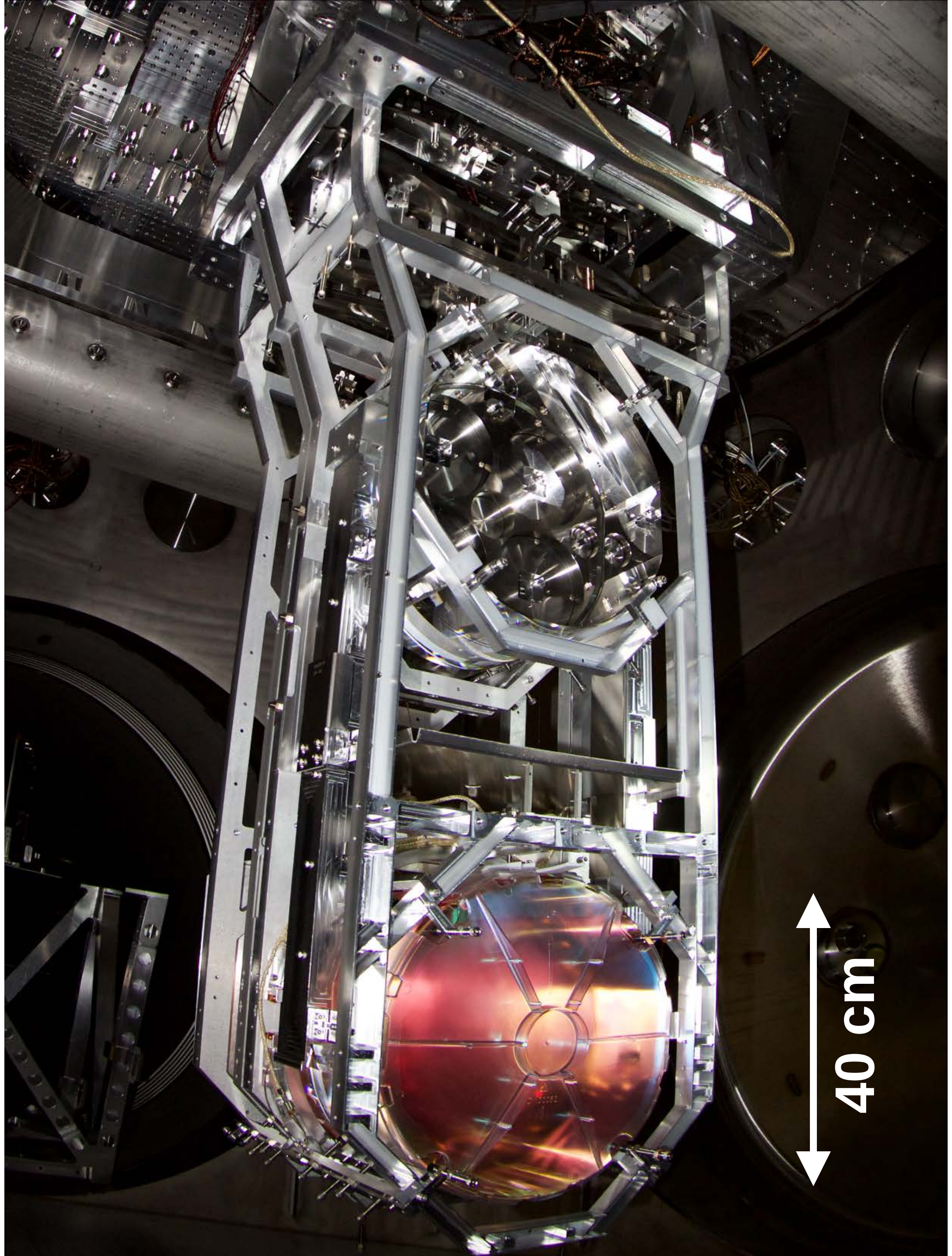
- Until 2020: Advanced LIGO/VIRGO
- Beyond 2020: A+ Upgrade
  Aims at a factor of 2 improvement using squeezed light
- 2030 time frame: Voyager
  Possible cryogenic detector

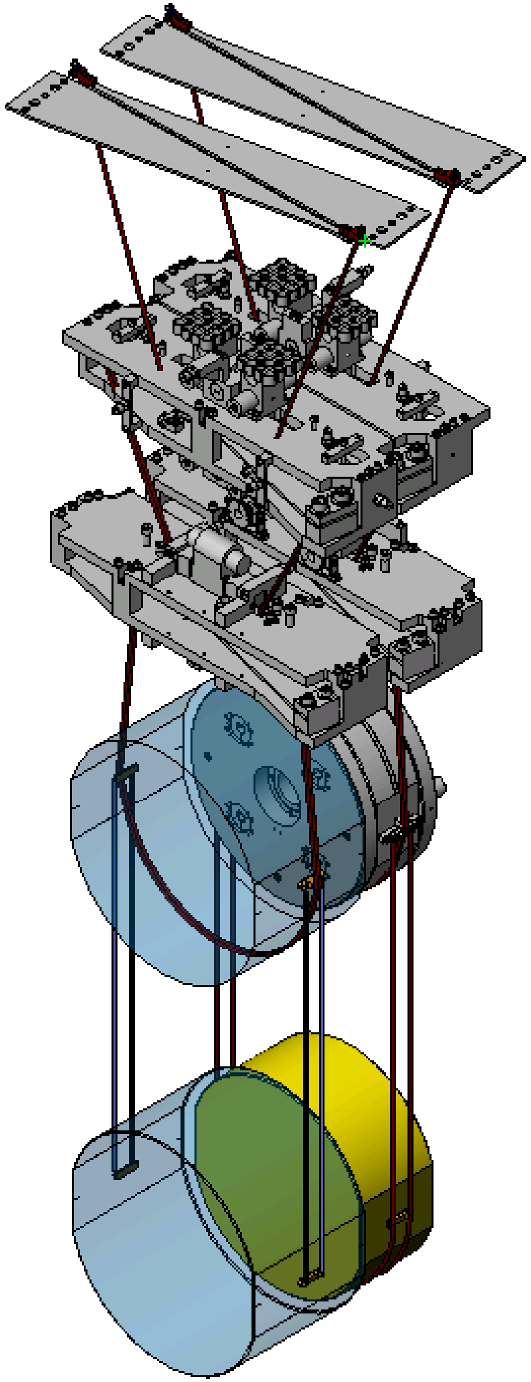
20 Years+: New Facilities Needed

- Einstein Telescope (10 km)
- Cosmic Explorer (40 km)
  Every black hole merger in the entire Universe!



Test Mass Suspension

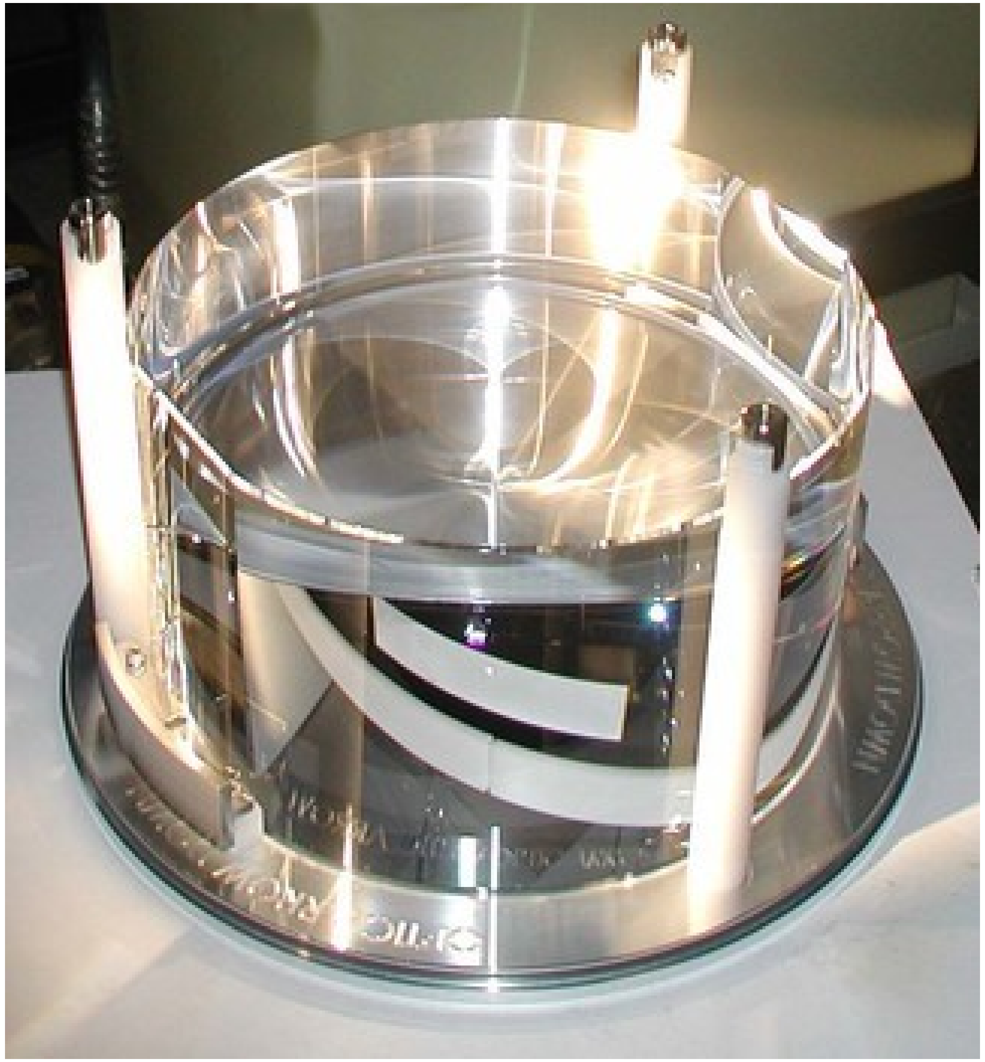




Large Test Mass Optics

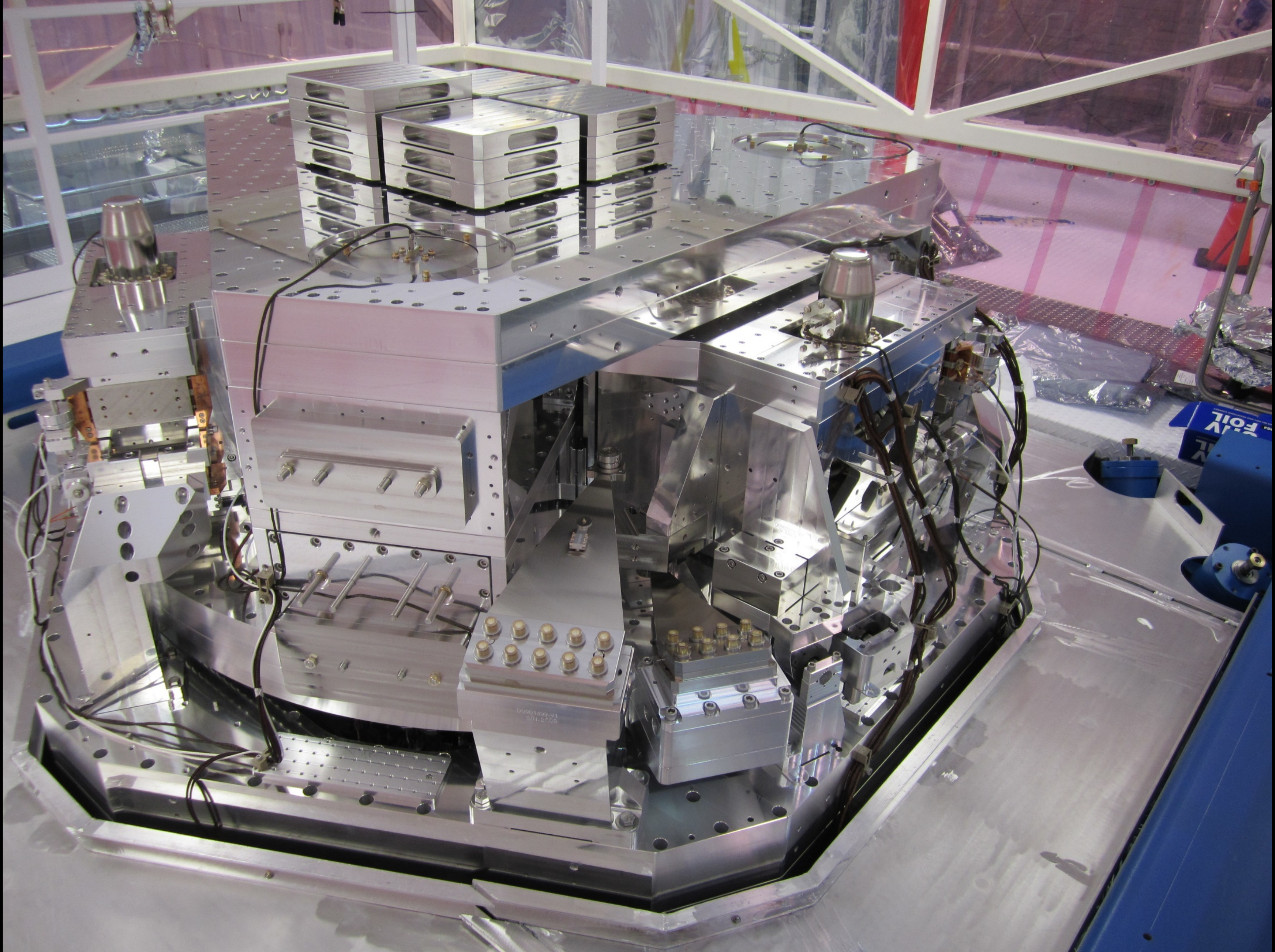
Specifications:

- Diameter: 340 mm
- Thickness: 200 mm
- Mass: 39.6 kg
- ROC: 2250 m / 1940 m
- Figure: <1 nm rms
- Scatter: ~10 ppm
- Surface absorption: ~0.3 ppm
- Bulk absorption: ~0.2 ppm/cm
- HR transmission: ~4 ppm
- AR reflectivity: ~200 ppm

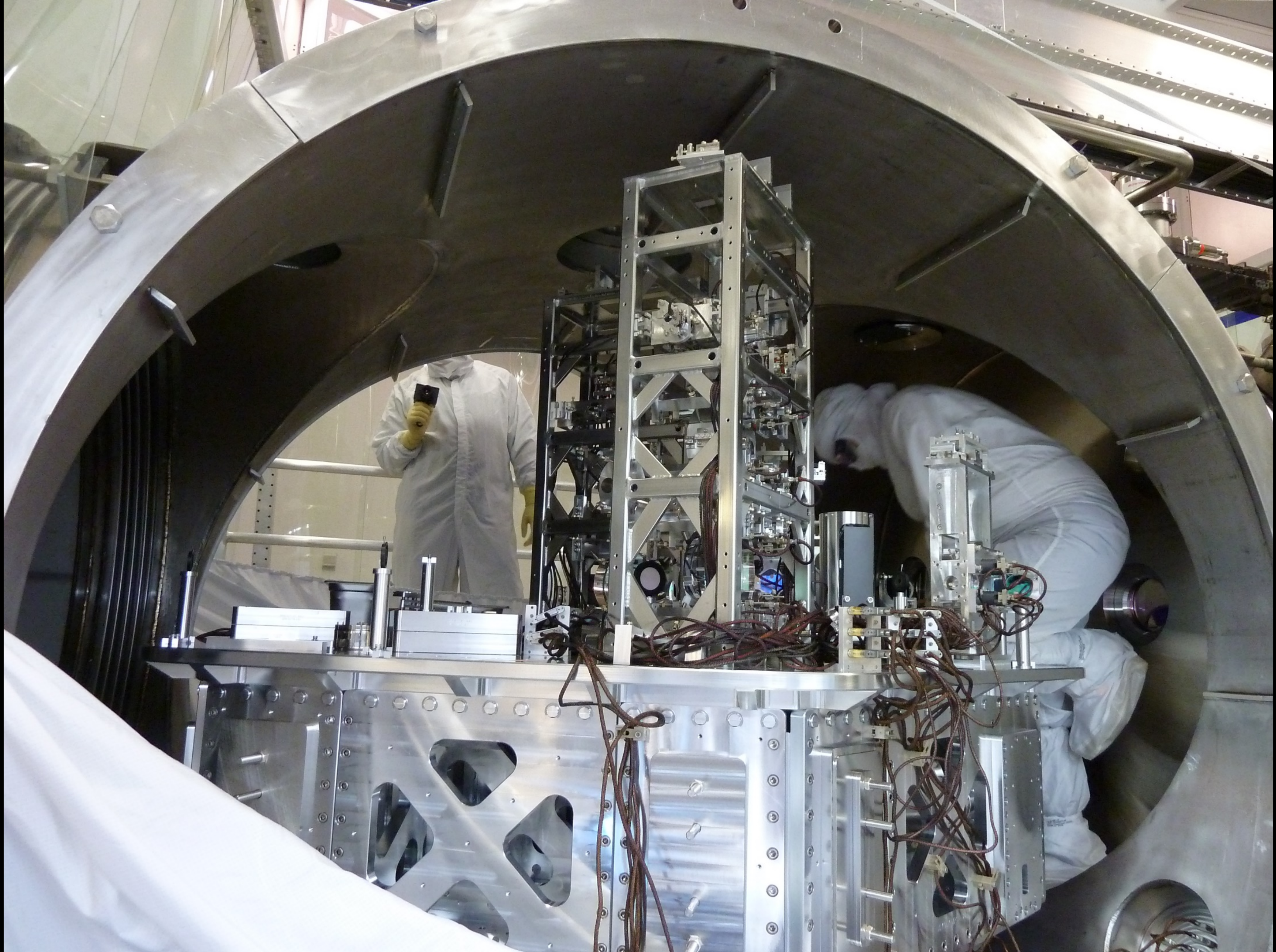


Vacuum System Vertex

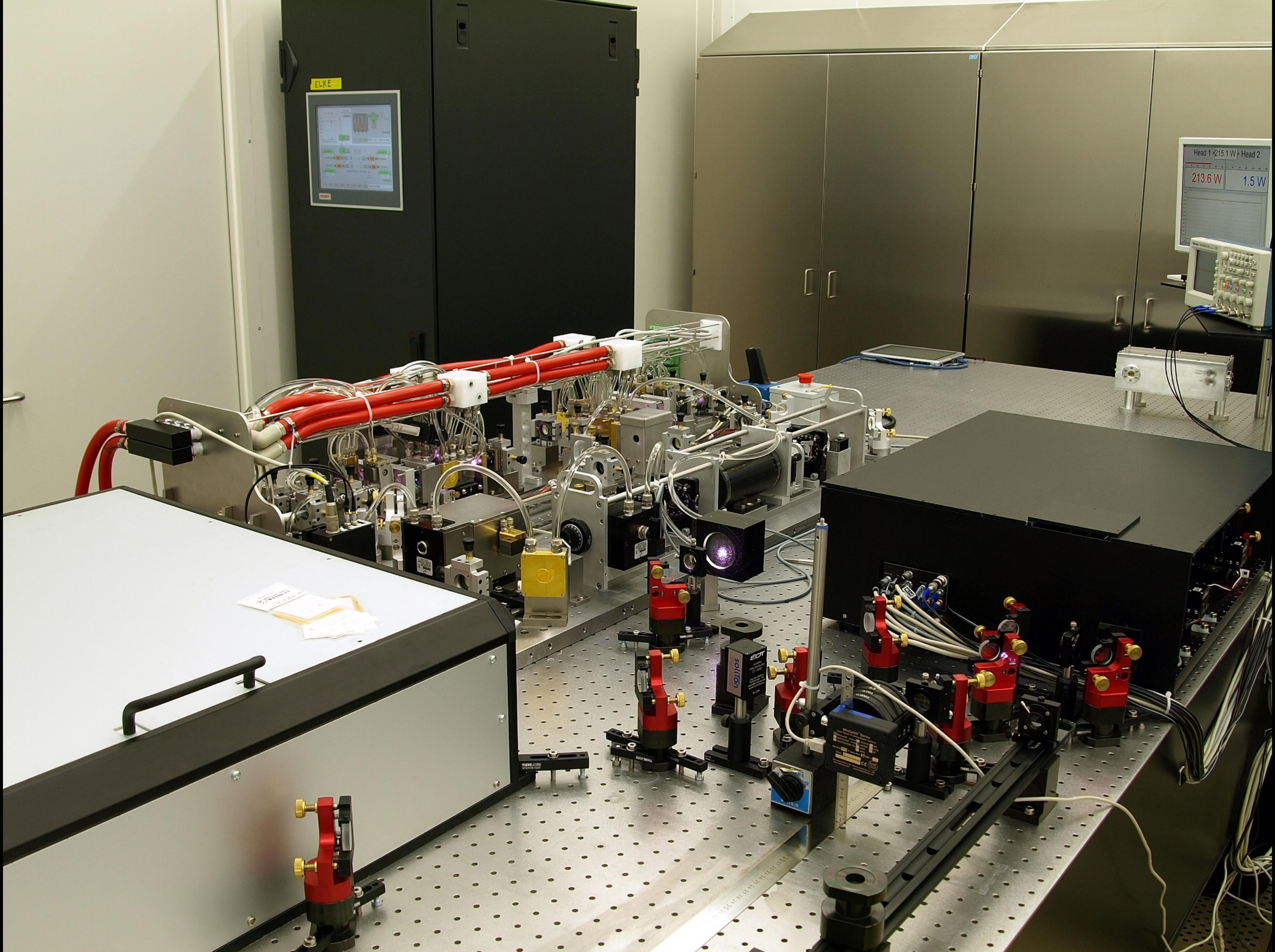
Seismic Isolation Platform



Input Optics Table



200W Pre-Stabilized Laser



Control Room

1970s

Early work on gravitational-wave detection by laser interferometers, including a 1972 MIT study describing a kilometer-scale interferometer and estimates of its noise sources.

1979

The National Science Foundation (NSF) funds a new group at Caltech for laser interferometer research and a prototype interferometer. It funds MIT to complete its prototype and design and lead industry study of technology, costs and sites for a kilometer-scale interferometer.

1983

MIT and Caltech jointly present results of the kilometer-scale interferometer study to NSF. Receive NSF committee endorsement on new large programs in physics.

1984

LIGO founded as a Caltech/MIT project. National Science Board approves LIGO development plan.

1986

Physics Decadal Survey and special NSF Panel on Gravitational Wave Interferometers endorse LIGO.

1990

The National Science Board (NSB) approves LIGO construction proposal, which envisions initial interferometers followed by advanced interferometers.

1992

NSF selects LIGO sites in Hanford, Washington, and Livingston, Louisiana. NSF and Caltech sign LIGO Cooperative Agreement.

1994-95

Site construction begins at Hanford and Livingston locations.

1997

The LIGO Scientific Collaboration (LSC) is established and expands LIGO beyond Caltech and MIT, including the British/German GEO collaboration, which operates the GEO600 interferometer in Hannover, Germany.

2002

First coincident operation of initial LIGO interferometers with GEO600 interferometer.

2004

NSB approves Advanced LIGO.

2006

Initial LIGO design sensitivity achieved. First gravitational wave search at design sensitivity.

2007

Joint data analysis agreement ratified between LIGO and the Virgo Collaboration, which operates the Virgo interferometer in Cascina, Italy. Joint observations with enhanced initial LIGO interferometer and Virgo.

2008

Start of Advanced LIGO construction.

2010

Initial LIGO operations conclude; Advanced LIGO installation begins.

2011-14

Advanced LIGO installation and testing.

2014

Advanced LIGO installation complete.

2014-15

Advanced LIGO sensitivity surpasses initial LIGO.

9/2015

During an engineering test a few days before the first official search begins, Advanced LIGO detects strong gravitational waves from collision of two black holes.

Image credit: Werner Benger/ Max Planck Institute for Gravitational Physics

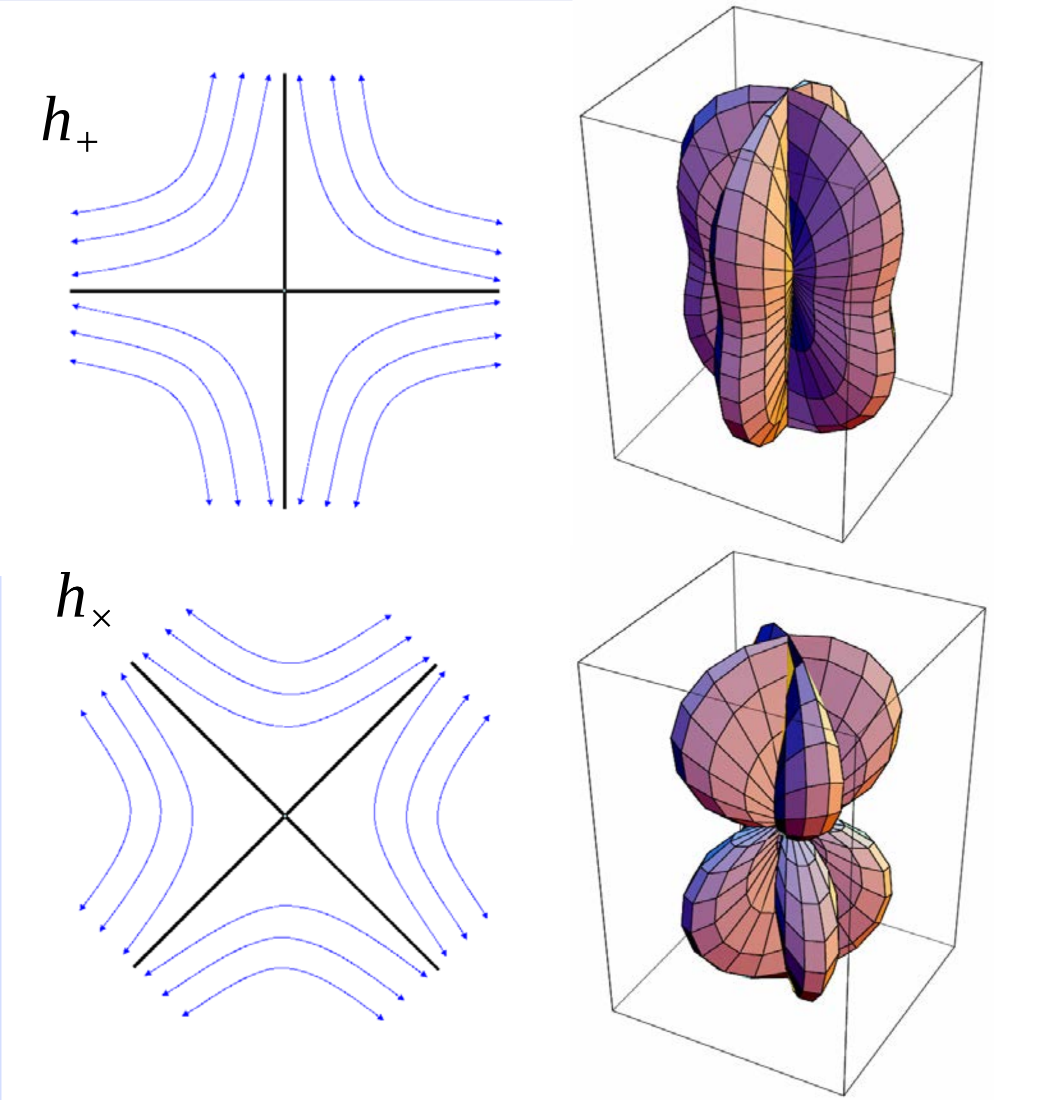
2016: The Centenary of Gravitational Waves

Physically,
h is a strain ~ $\Delta L/L$
LIGO measures: h ~ 10^{-21}

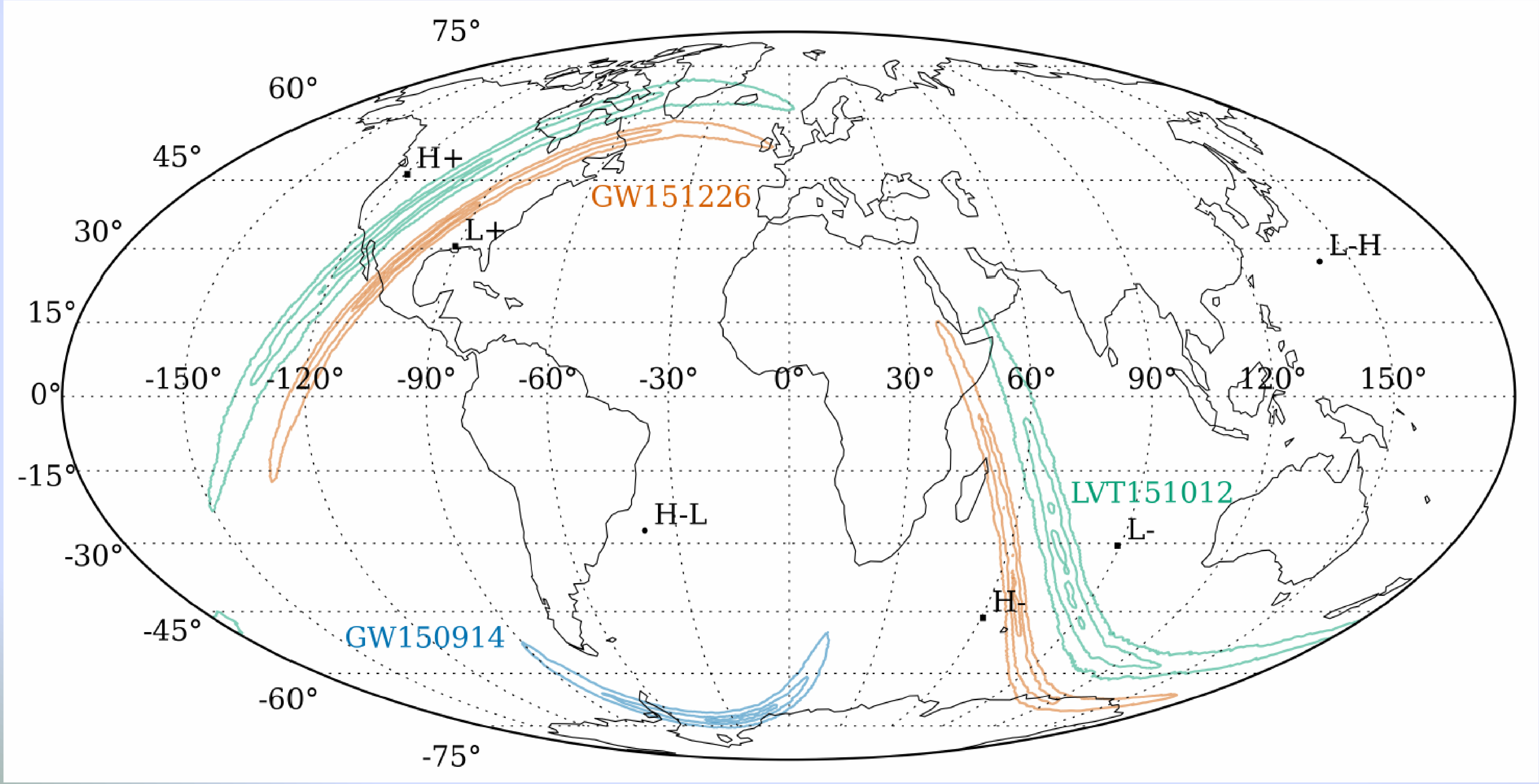
For Example:
L = 4 km → 4 x 10^{-18} m
(Proton radius ~ 1 fm)

L = 4.4 ly (Alpha Centauri)
→ ~40 μm (human hair)

Measure with a Michelson interferometer



Parameter	GW150914		GW151226		LVT151012		Unit
	Value	90% Error	Value	90% Error	Value	90% Error	
Signal-to-Noise Ratio (SNR)	23.7		13.0		9.7		
Primary black hole mass	36	$^{+5}_{-4}$	14.2	$^{+8.3}_{-3.7}$	23	$^{+18}_{-6}$	$M_\odot$
Secondary black hole mass	29	$^{+4}_{-4}$	7.5	$^{+2.3}_{-2.3}$	13	$^{+4}_{-5}$	$M_\odot$
Final black hole mass	62	$^{+4}_{-4}$	20.8	$^{+6.1}_{-1.7}$	35	$^{+14}_{-4}$	$M_\odot$
Total radiated energy	3.0	$^{+0.5}_{-0.5}$	1.0	$^{+0.1}_{-0.2}$	1.5	$^{+0.3}_{-0.4}$	$M_\odot$
Final black hole spin	0.67	$^{+0.05}_{-0.07}$	0.74	$^{+0.06}_{-0.06}$	0.66	$^{+0.09}_{-0.10}$	
Luminosity distance	410	$^{+160}_{-180}$	440	$^{+180}_{-190}$	1000	$^{+500}_{-500}$	Mpc
Source redshift z	0.09	$^{+0.03}_{-0.04}$	0.09	$^{+0.03}_{-0.04}$	0.20	$^{+0.09}_{-0.09}$	

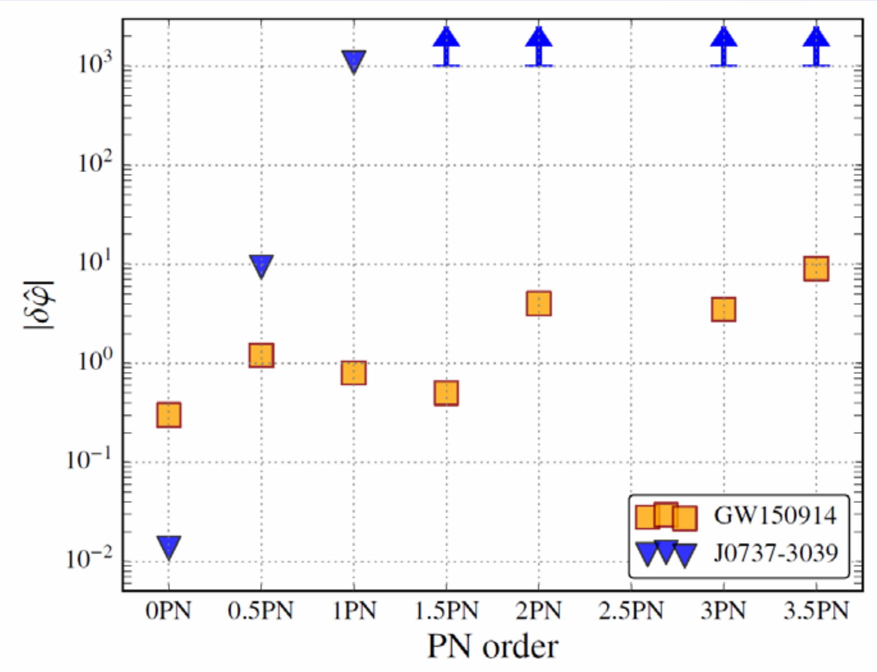


75°
60°
45°
30°
15°
0°
-15°
-30°
-45°
-60°
-75°
-150°
-120°
-90°
-60°
-30°
0°
30°
60°
90°
120°
150°
H+
L+
GW151226
L-H
H-L
L-
H-
LVT151012
GW150914

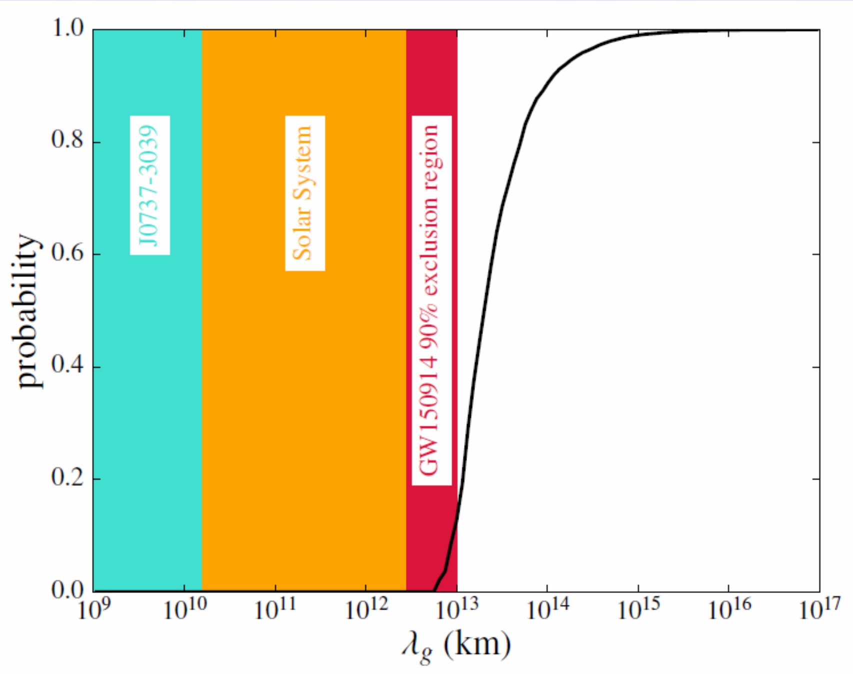
General Relativity Tests

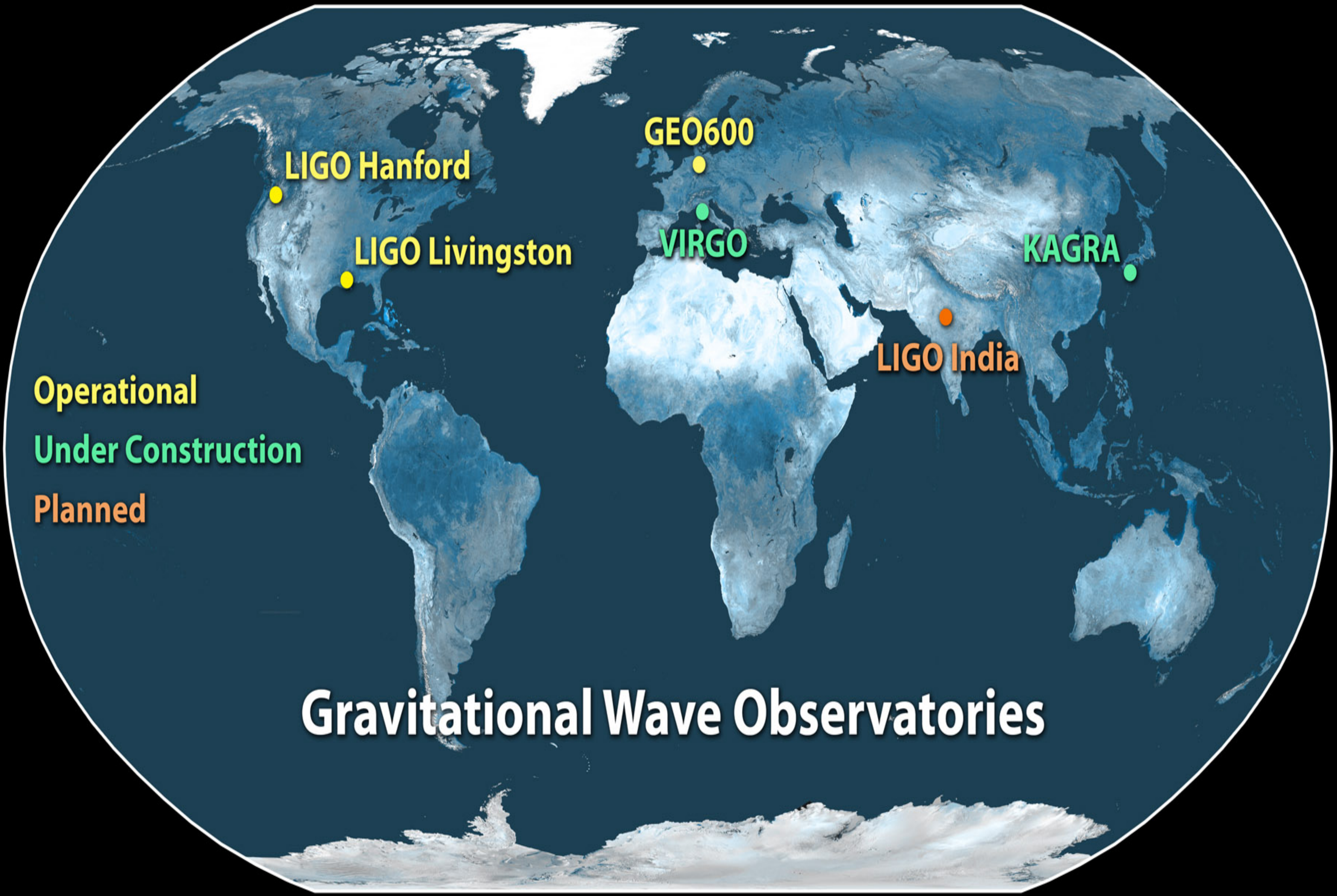
GW150914 is the first observation of a binary black hole merger…
… and thus is the best test of GR in the strong field, nonlinear regime

Post Newtonian Approximation



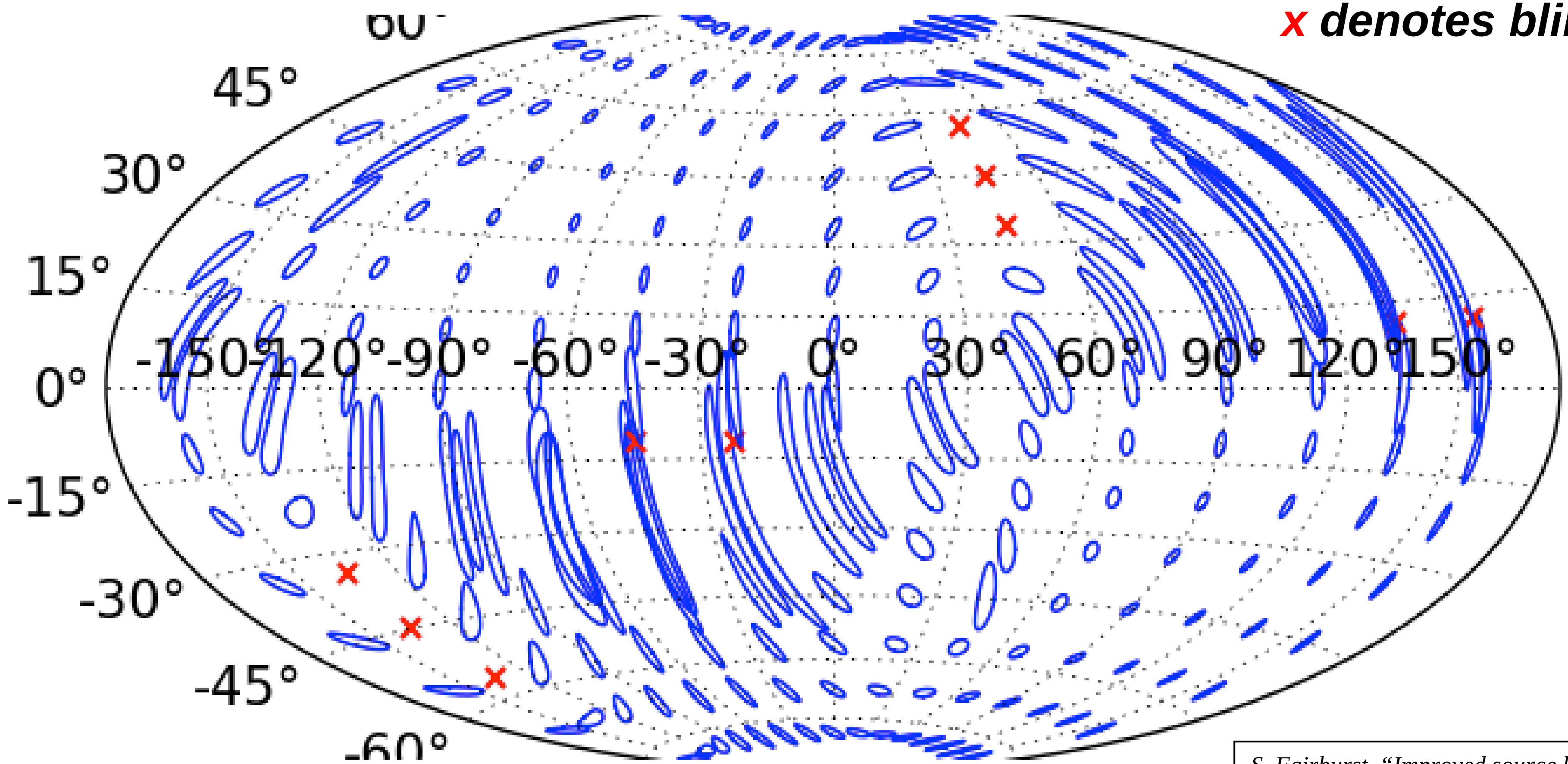
Graviton Mass / Compton Wavelength




LIGO Hanford
LIGO Livingston
GEO600
VIRGO
KAGRA
LIGO India
Operational
Under Construction
Planned
Gravitational Wave Observatories

Binary Neutron Star Merger Localization: Hanford-Livingston-Virgo

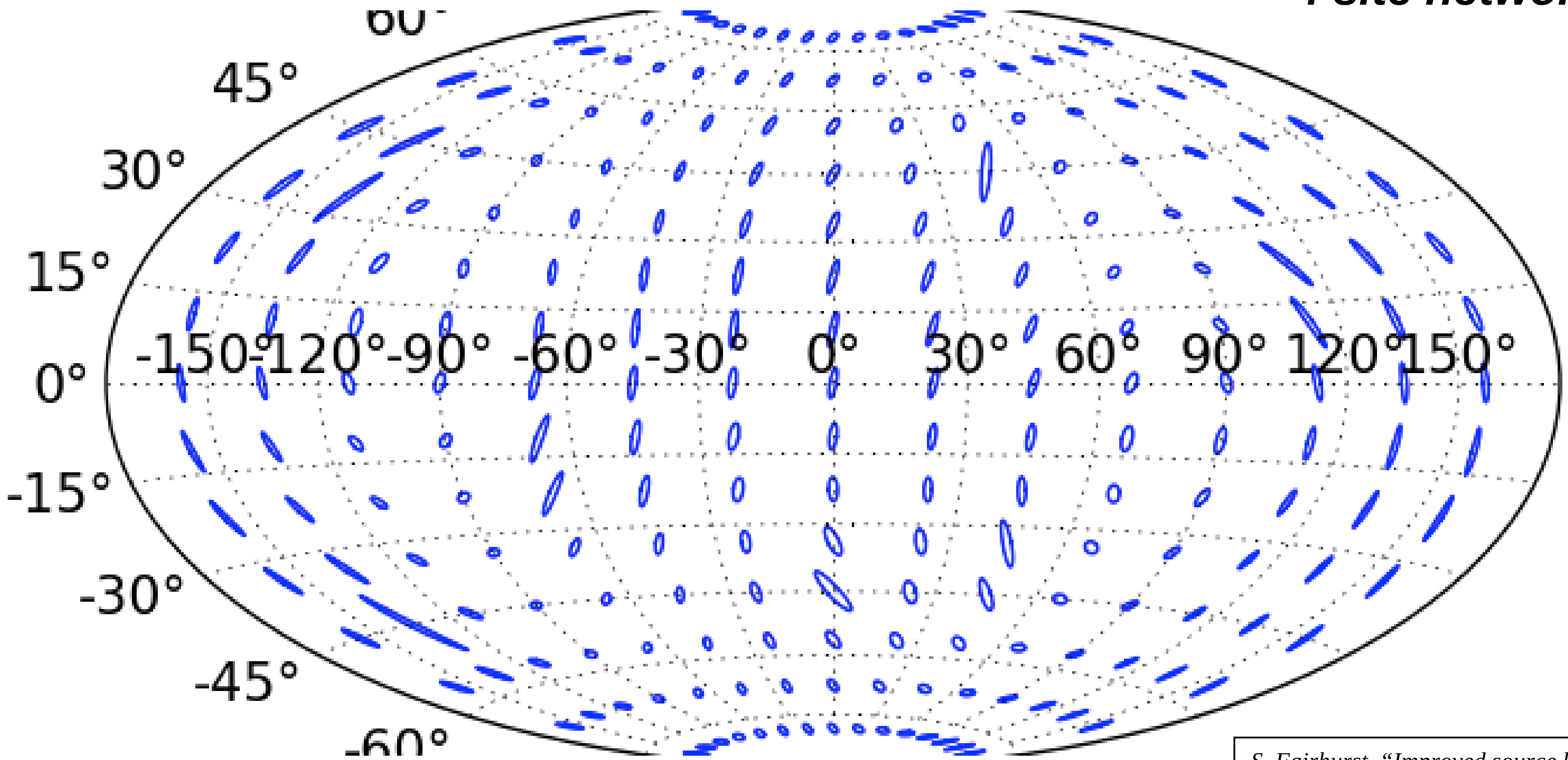
3 site network
x denotes blind spots



*S. Fairhurst, "Improved source localization with LIGO India", [J. Phys.: Conf. Ser. **484** 012007]*

Binary Neutron Star Merger Localization: Hanford-Livingston-Virgo-India

4 site network



S. Fairhurst, "Improved source localization with LIGO India", J. Phys.: Conf. Ser. ***484*** *012007*

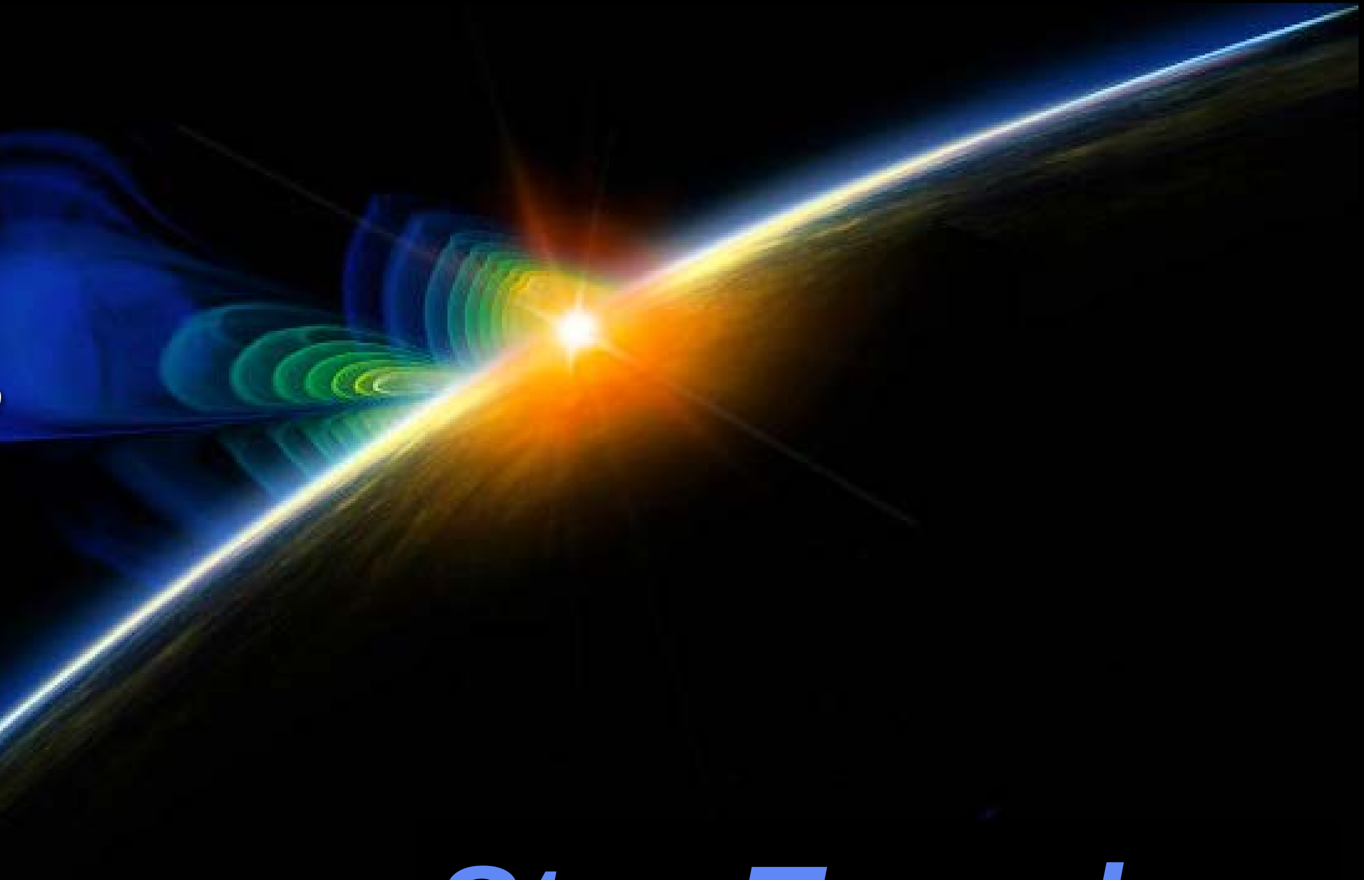
Advanced LIGO and the Dawn of Gravitational-waves Physics and Astronomy

- ***LIGO has made the first measurement of gravitational wave amplitude and phase***

- ***A merging binary black hole system has been observed for the first time***

- ***LIGO has resumed the search for gravitational waves until the Fall of 2017; Virgo will join in***

- ***The next few years will be very interesting ones for the field of gravitational-wave science!***



Stay Tuned…

Thanks to:

ligo.caltech.edu

LIGO
LASER INTERFEROMETER GRAVITATIONAL-WAVE OBSERVATORY

www.ligo.org

Support: National Science Foundation