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



Daniel Sigg

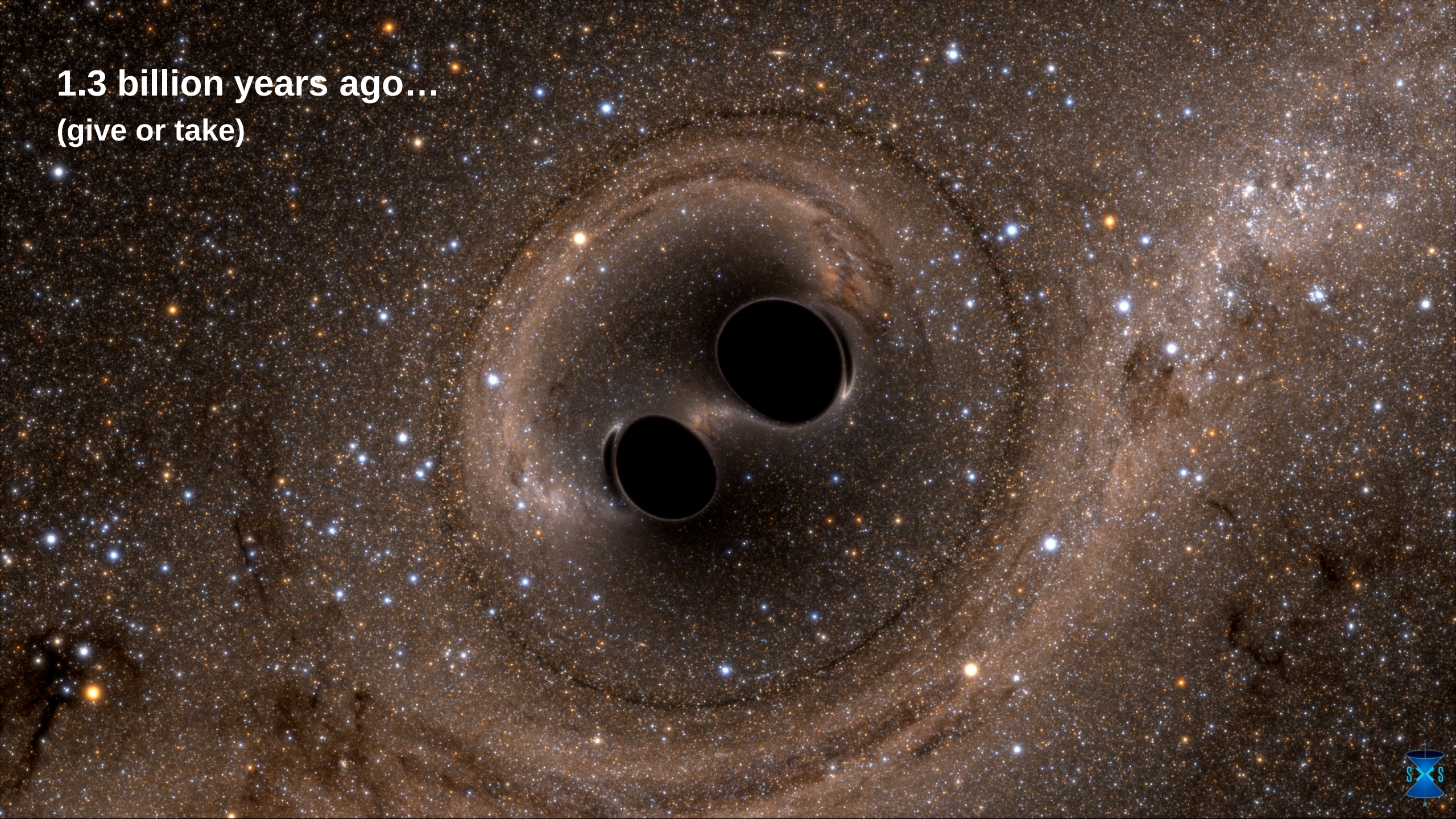
LIGO Hanford Observatory

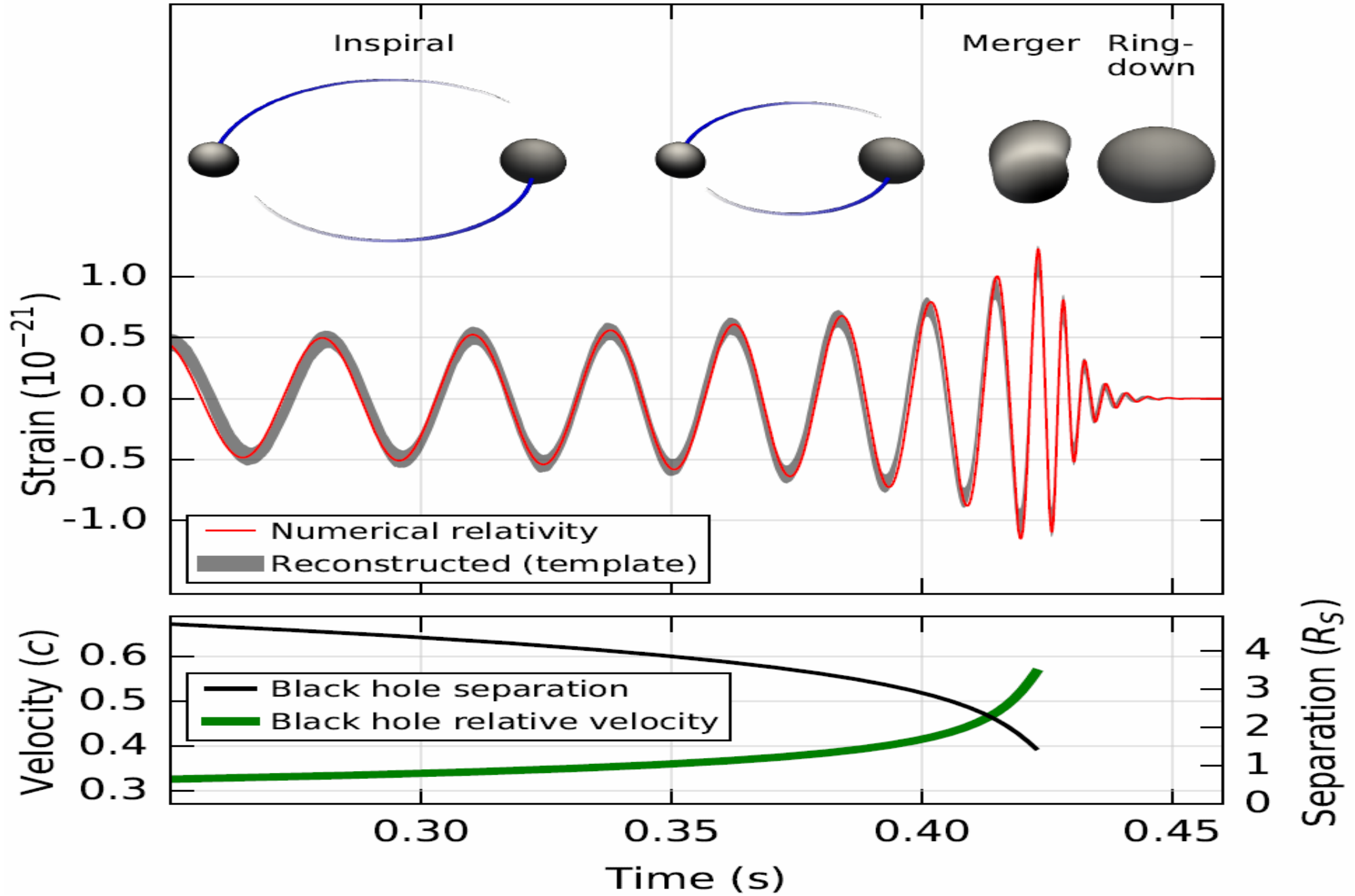
California Institute of Technology

November 26, 2016

For the LIGO Scientific Collaboration and the Virgo Collaboration

LIGO-G1601750-v1


1.3 billion years ago…
(give or take)



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

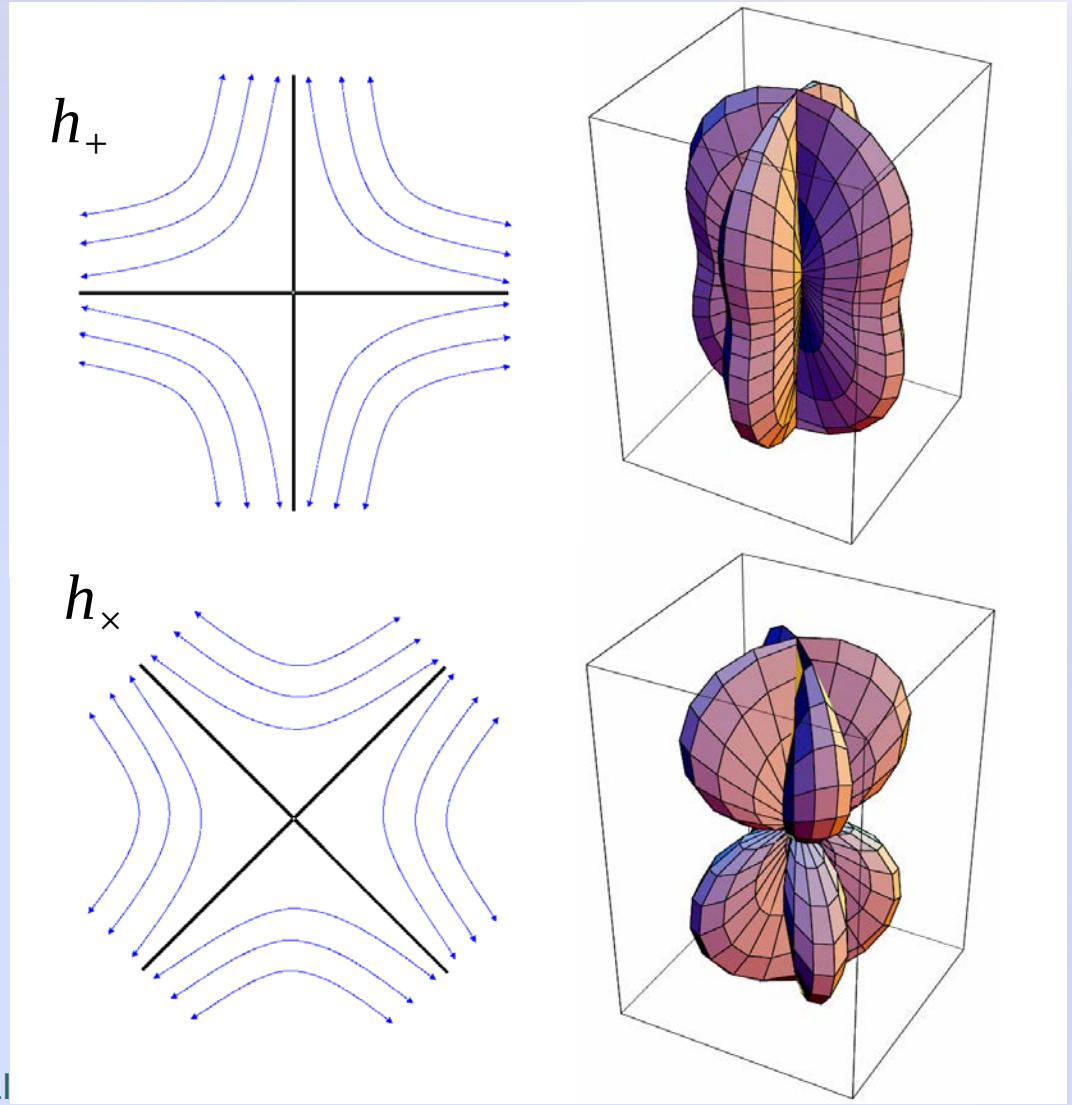
2016: The Centenary of Gravitational Waves

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)

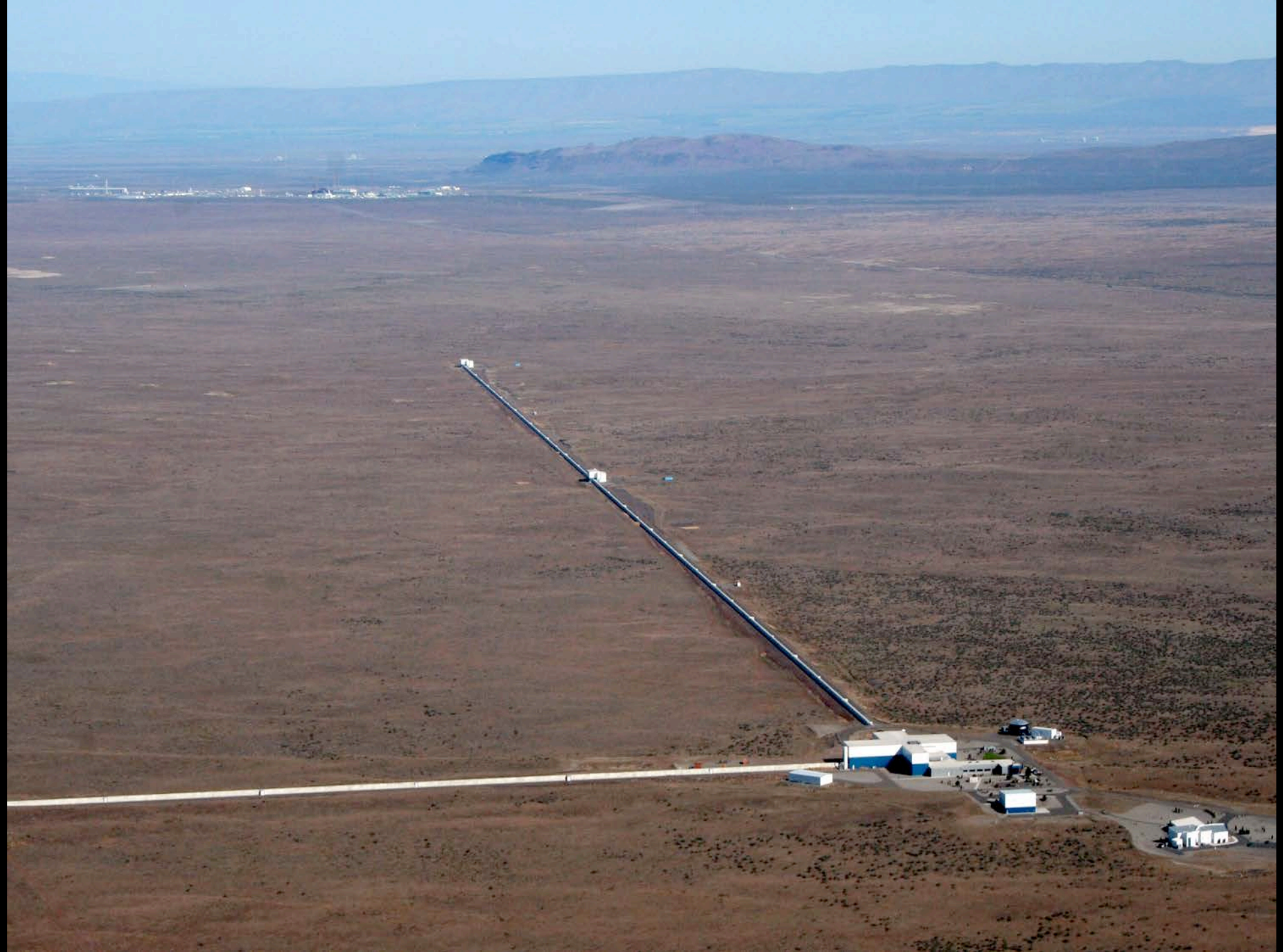
Measure with a Michelson interferometer



Livingston Observatory



Hanford Observatory



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

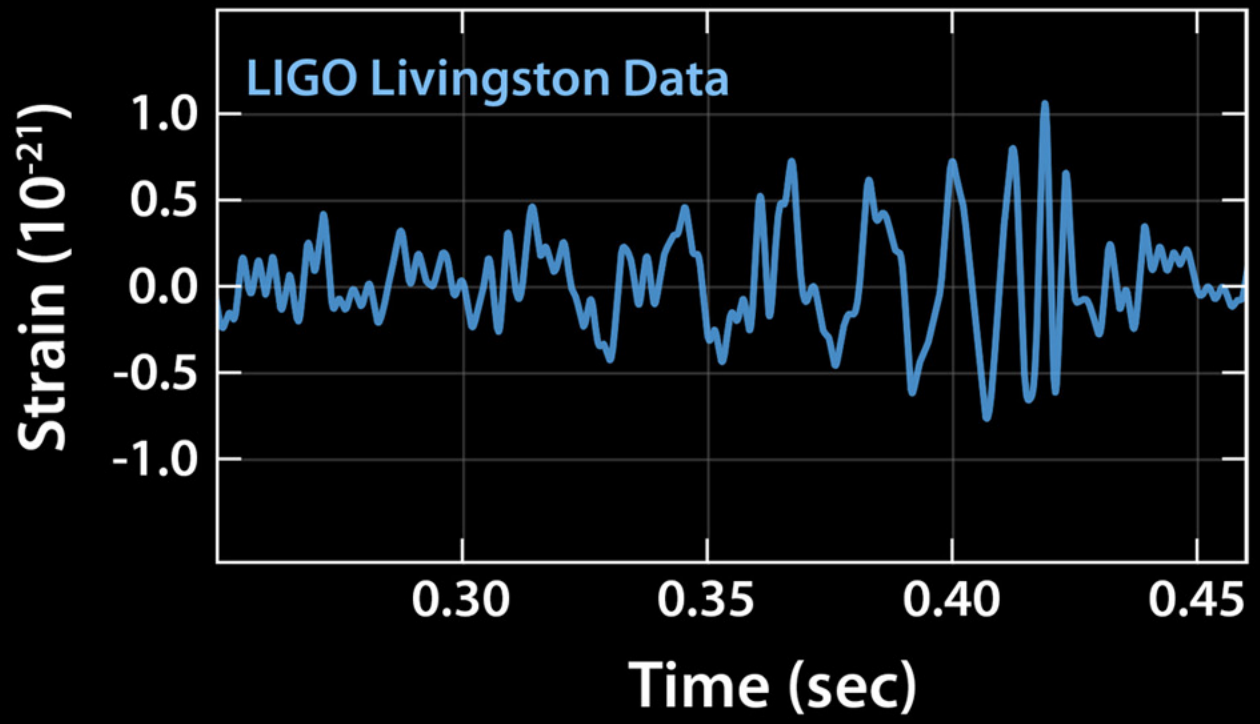
Advanced LIGO sensitivity surpasses initial LIGO.

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.

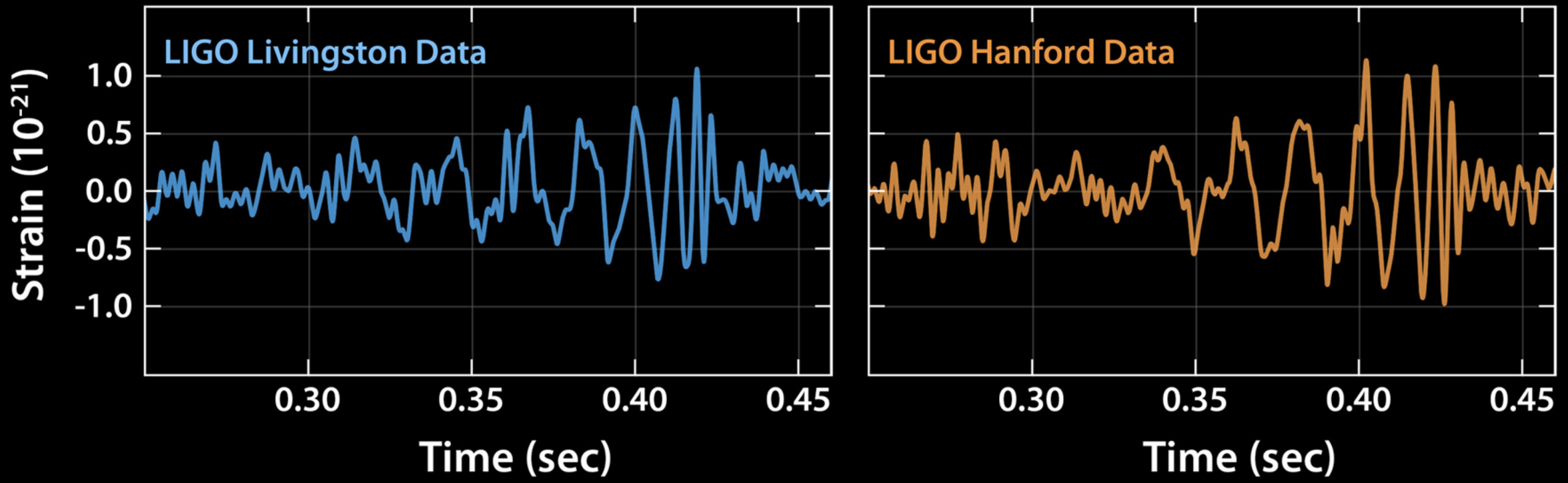
Image credit: Werner Benger/ Max Planck Institute for Gravitational Physics

GW150914

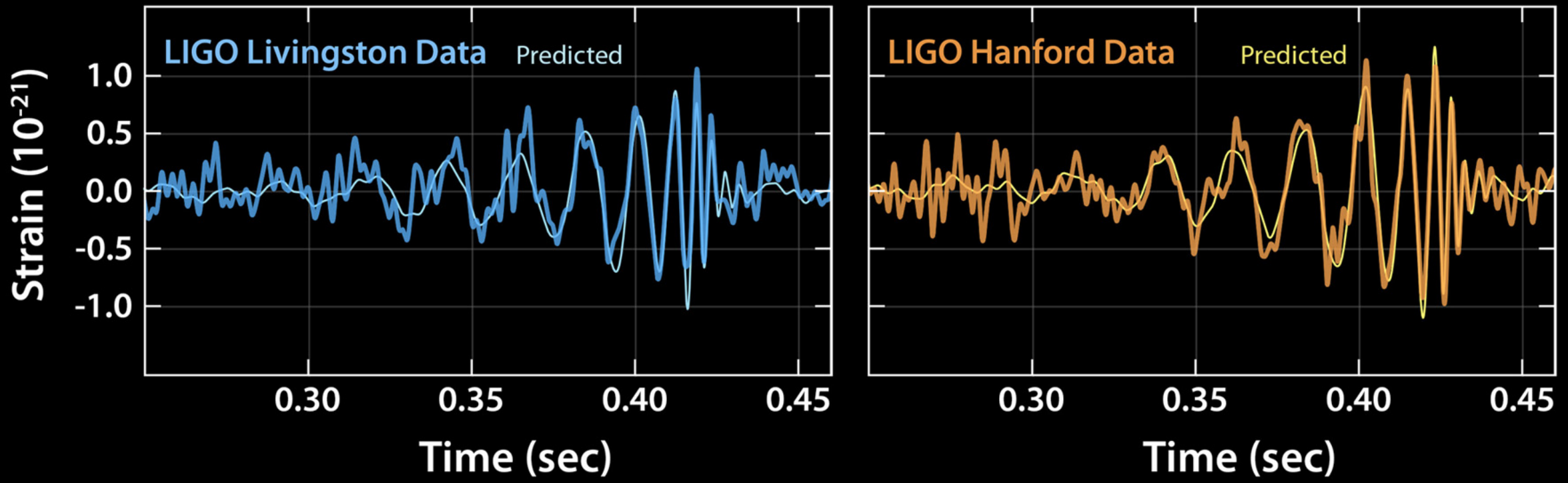


~1/200th proton radius

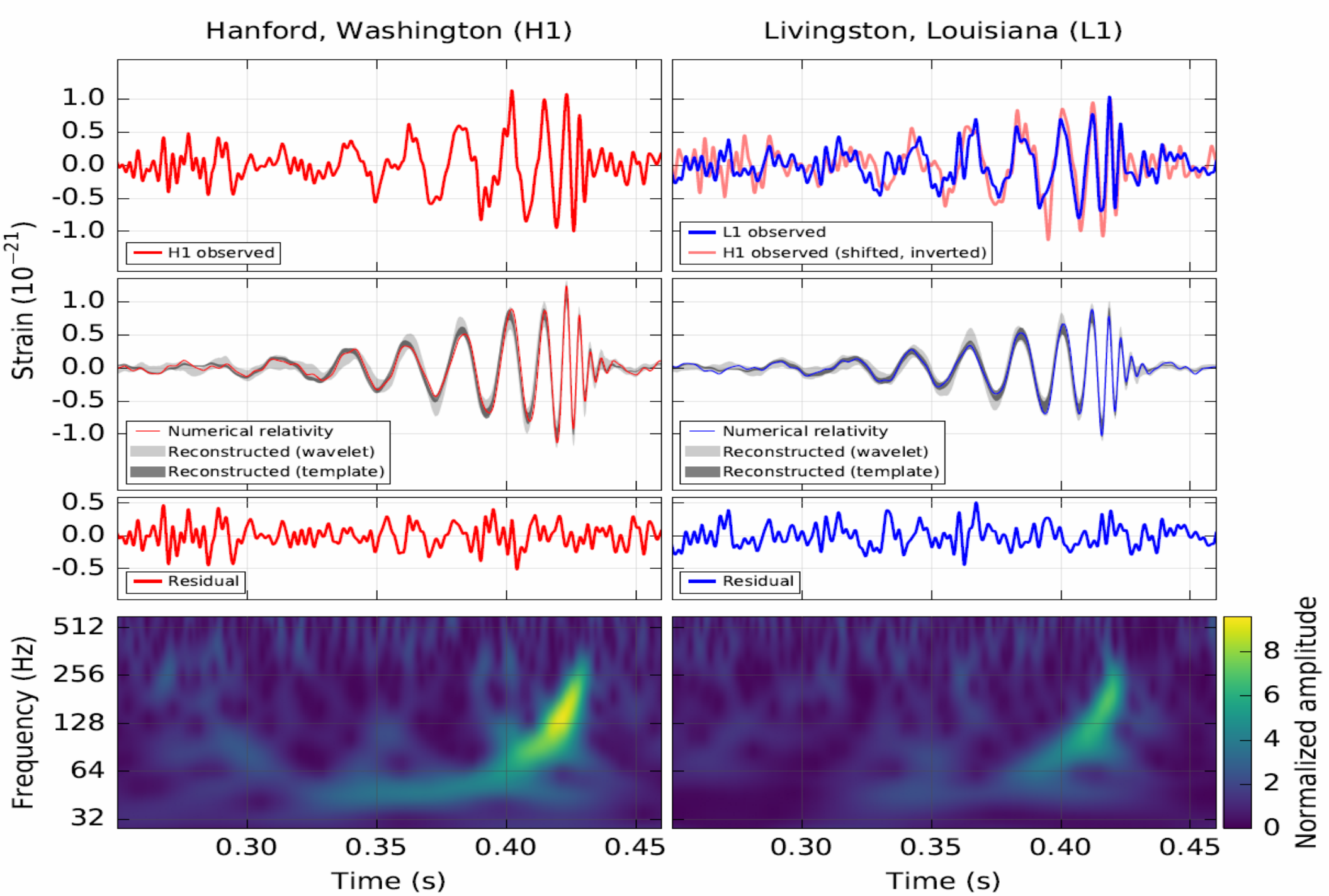
GW150914


LIGO Livingston Data
LIGO Hanford Data
Strain (10-21)
1.0
0.5
0.0
-0.5
-1.0
0.30
0.35
0.40
0.45
Time (sec)
0.30
0.35
0.40
0.45
Time (sec)

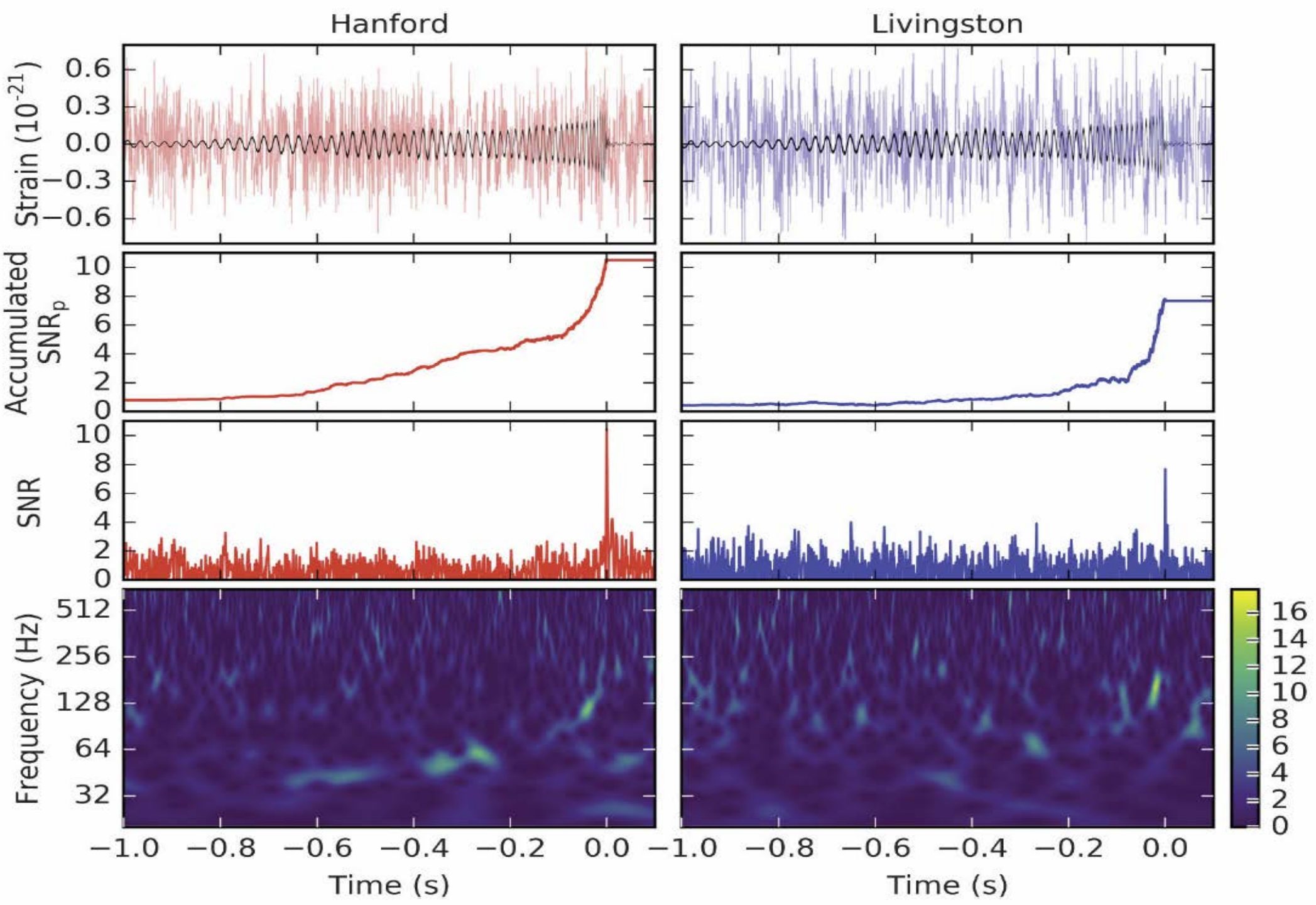
GW150914


LIGO Livingston Data
Predicted
LIGO Hanford Data
Predicted
Strain (10-21)
1.0
0.5
0.0
-0.5
-1.0
0.30
0.35
0.40
0.45
Time (sec)
0.30
0.35
0.40
0.45
Time (sec)

GW150914

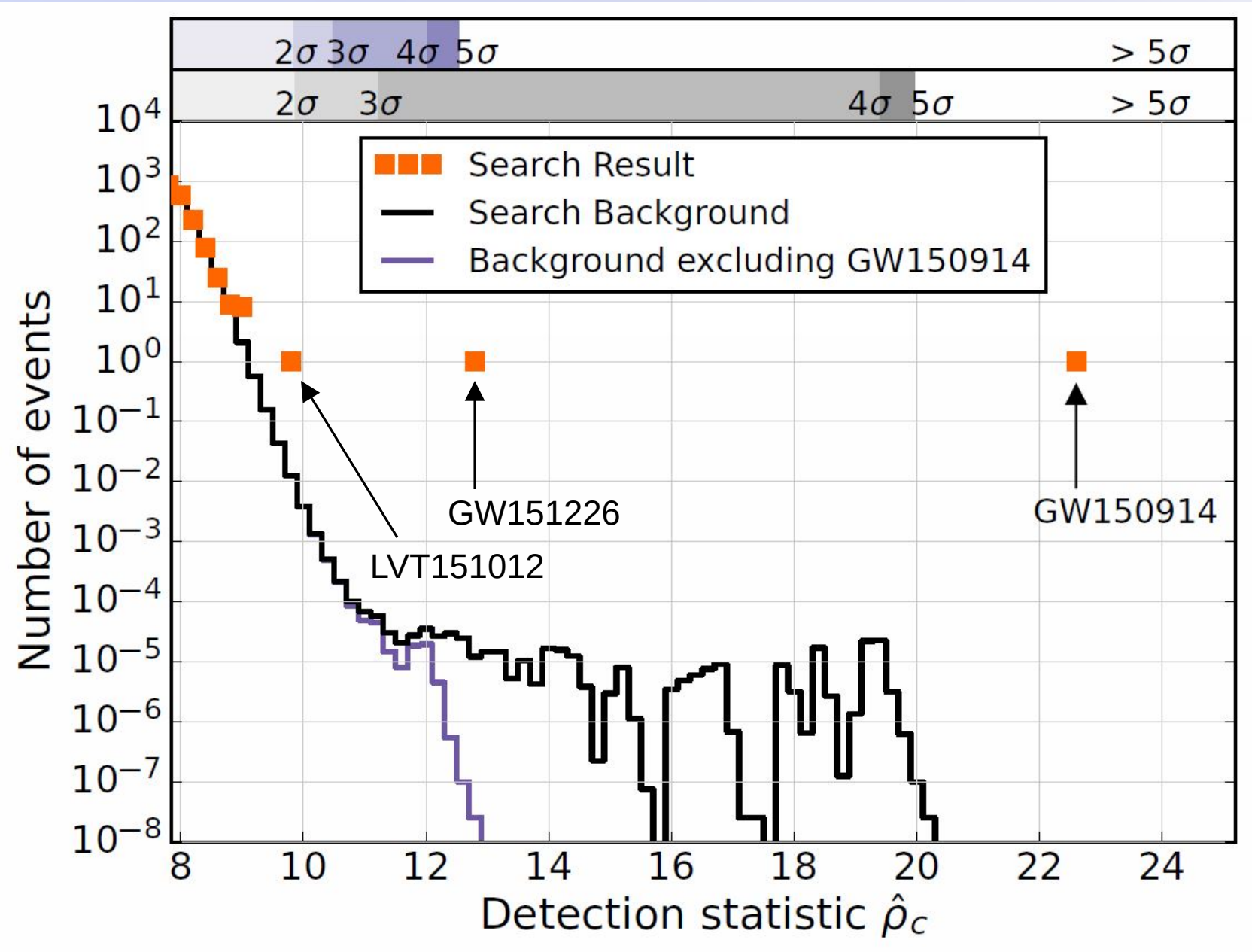

Hanford, Washington (H1)
Livingston, Louisiana (L1)
Strain (10^{-21})
H1 observed
L1 observed
H1 observed (shifted, inverted)
Numerical relativity
Reconstructed (wavelet)
Reconstructed (template)
Residual
Frequency (Hz)
512
256
128
64
32
0.30
0.35
0.40
0.45
Time (s)
Normalized amplitude
0
2
4
6
8

GW151226

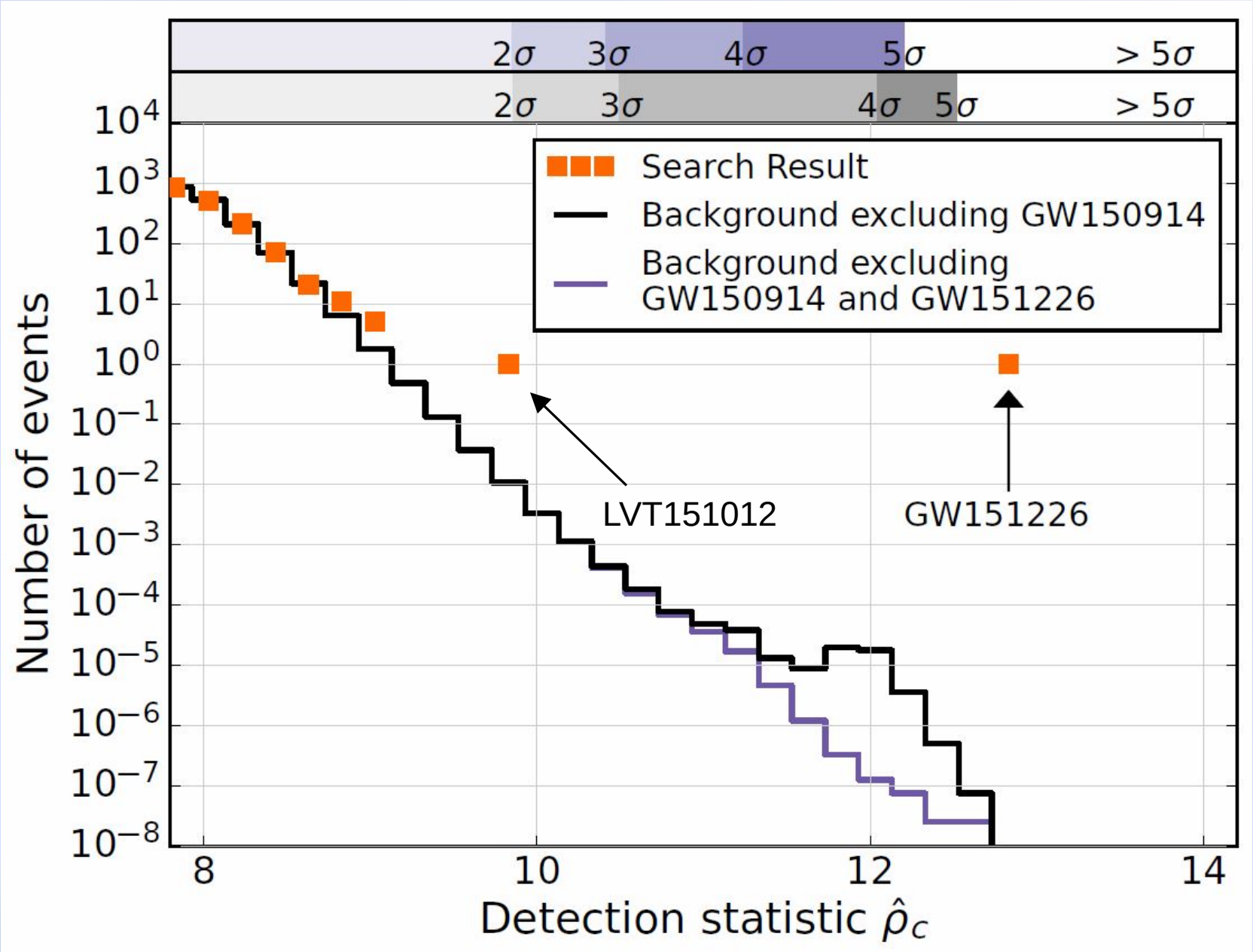


Phys. Rev. Lett. 116, 241103 (2016)

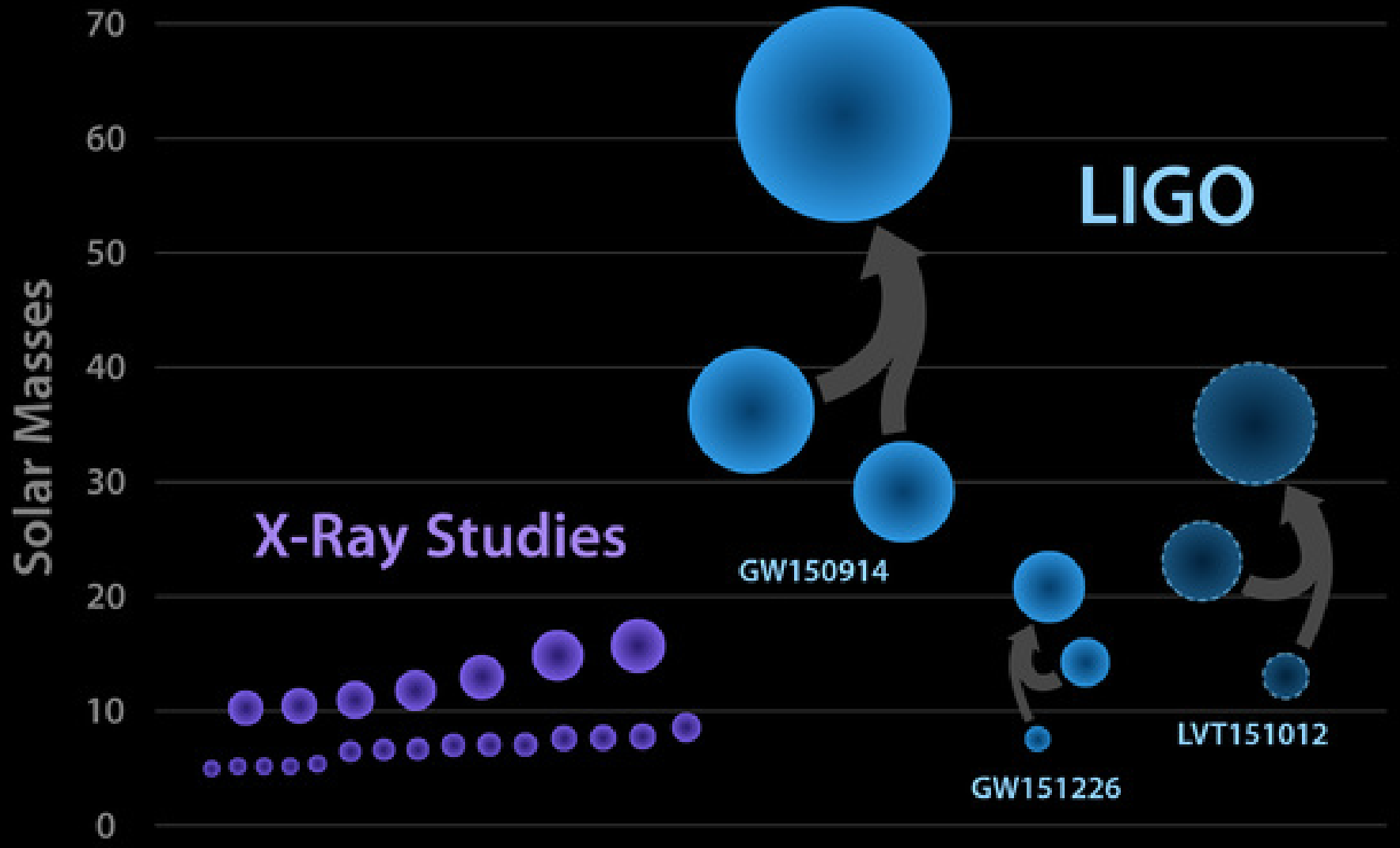
GW150914

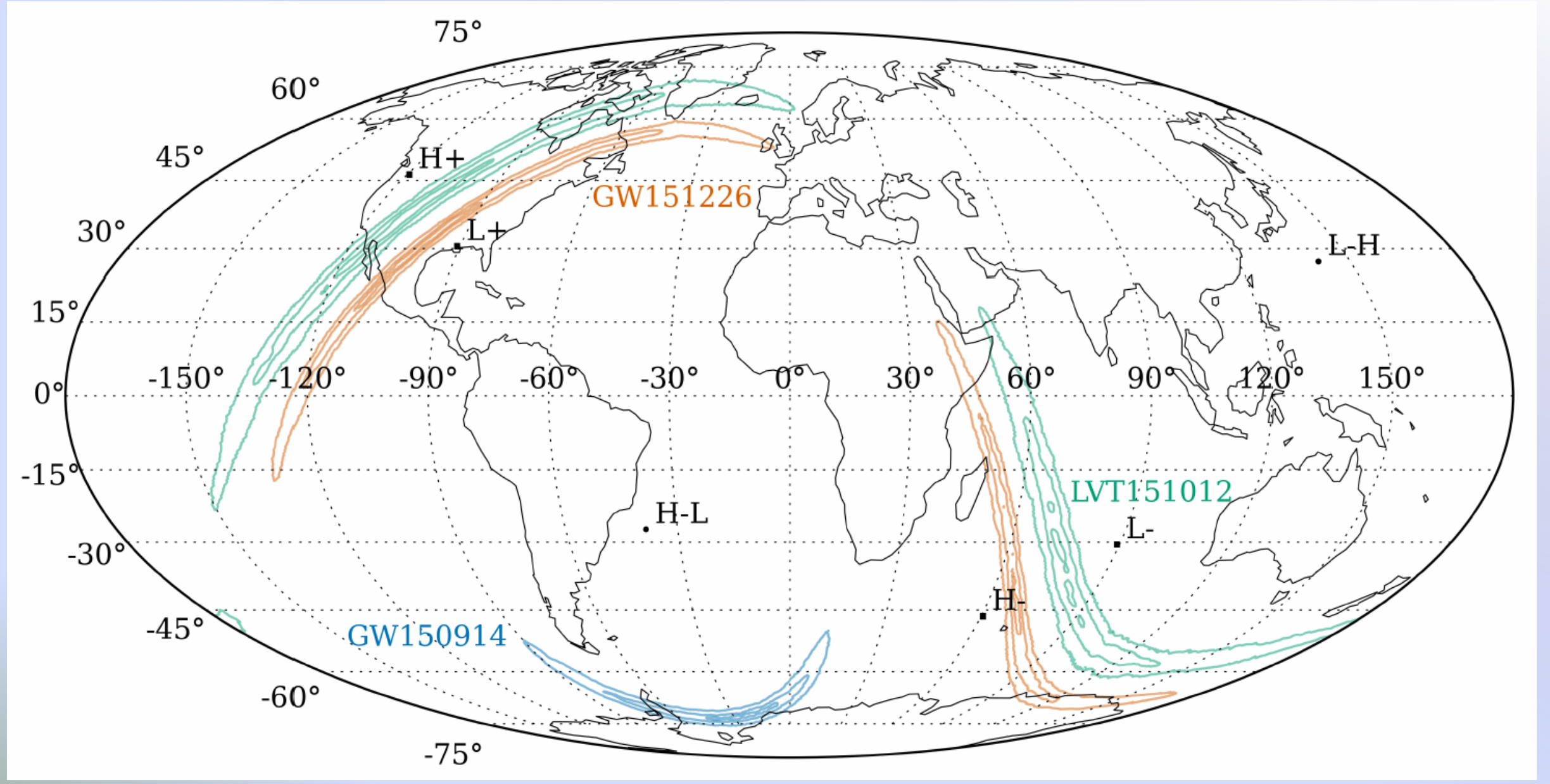

2σ 3σ 4σ 5σ
> 5σ
2σ 3σ
4σ 5σ
> 5σ
Search Result
Search Background
Background excluding GW150914
GW151226
LVT151012
GW150914
Number of events
Detection statistic $\hat{\rho}_c$

GW151226


2σ
3σ
4σ
5σ
> 5σ
2σ
3σ
4σ
5σ
> 5σ
Search Result
Background excluding GW150914
Background excluding GW150914 and GW151226
LVT151012
GW151226
Number of events
Detection statistic $\hat{\rho}_c$
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
8
10
12
14

Black Holes of Known Mass




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

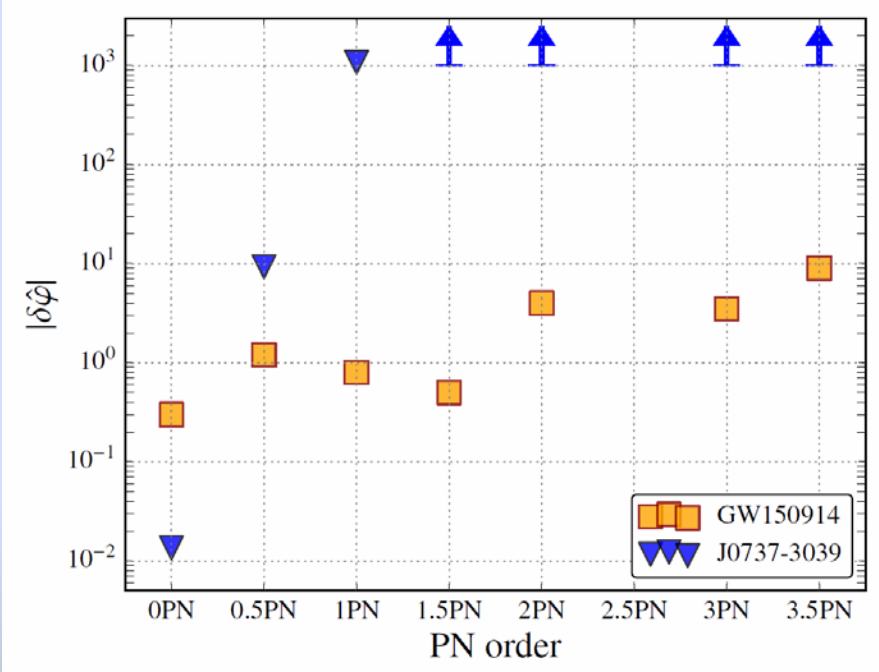
Parameter	GW150914		GW151226		LVT151012		Unit
	Value	90% Error	Value	90% Error	Value	90% Error	
Signal-to-Noise Ratio (SNR)	23.7		13.0		9.7		
Primary black hole mass	36	$^{+5}_{-4}$	14.2	$^{+8.3}_{-3.7}$	23	$^{+18}_{-6}$	$M_\odot$
Secondary black hole mass	29	$^{+4}_{-4}$	7.5	$^{+2.3}_{-2.3}$	13	$^{+4}_{-5}$	$M_\odot$
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	$^{+0.09}_{-0.09}$	

General Relativity Tests

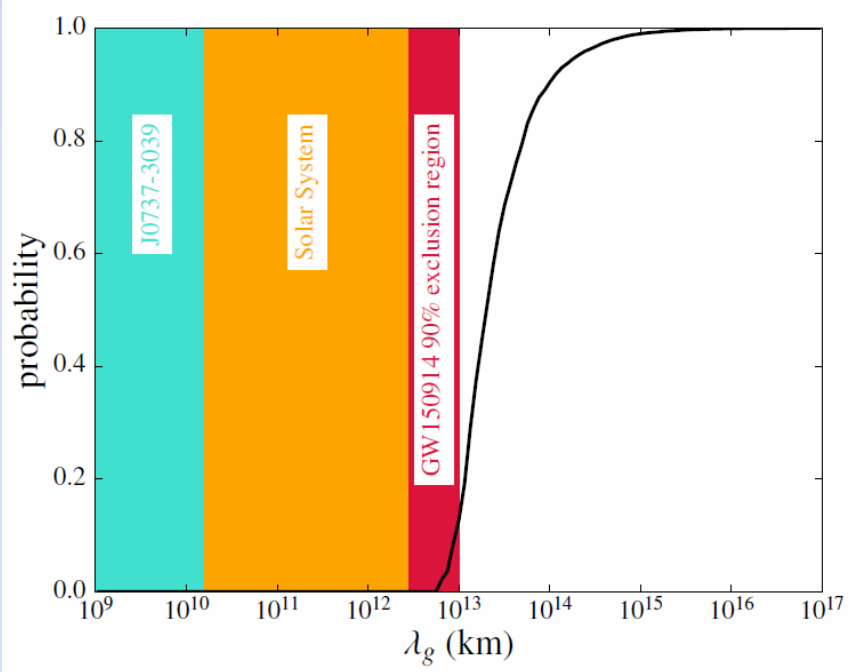
GW150914 is the first observation of a binary black hole merger…

… and thus is the best test of GR in the strong field, nonlinear regime

Post Newtonian Approximation

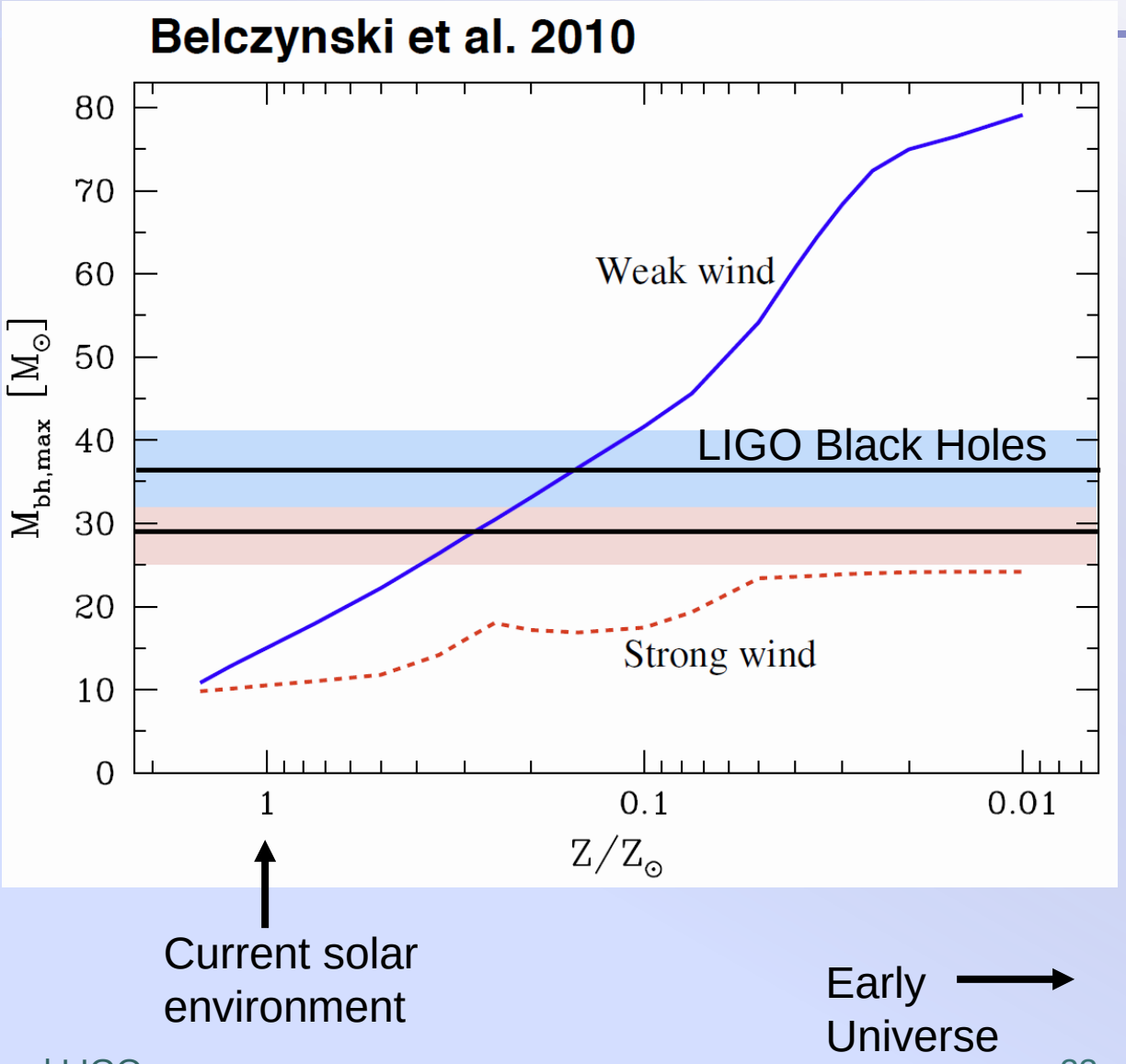


Graviton Mass / Compton Wavelength

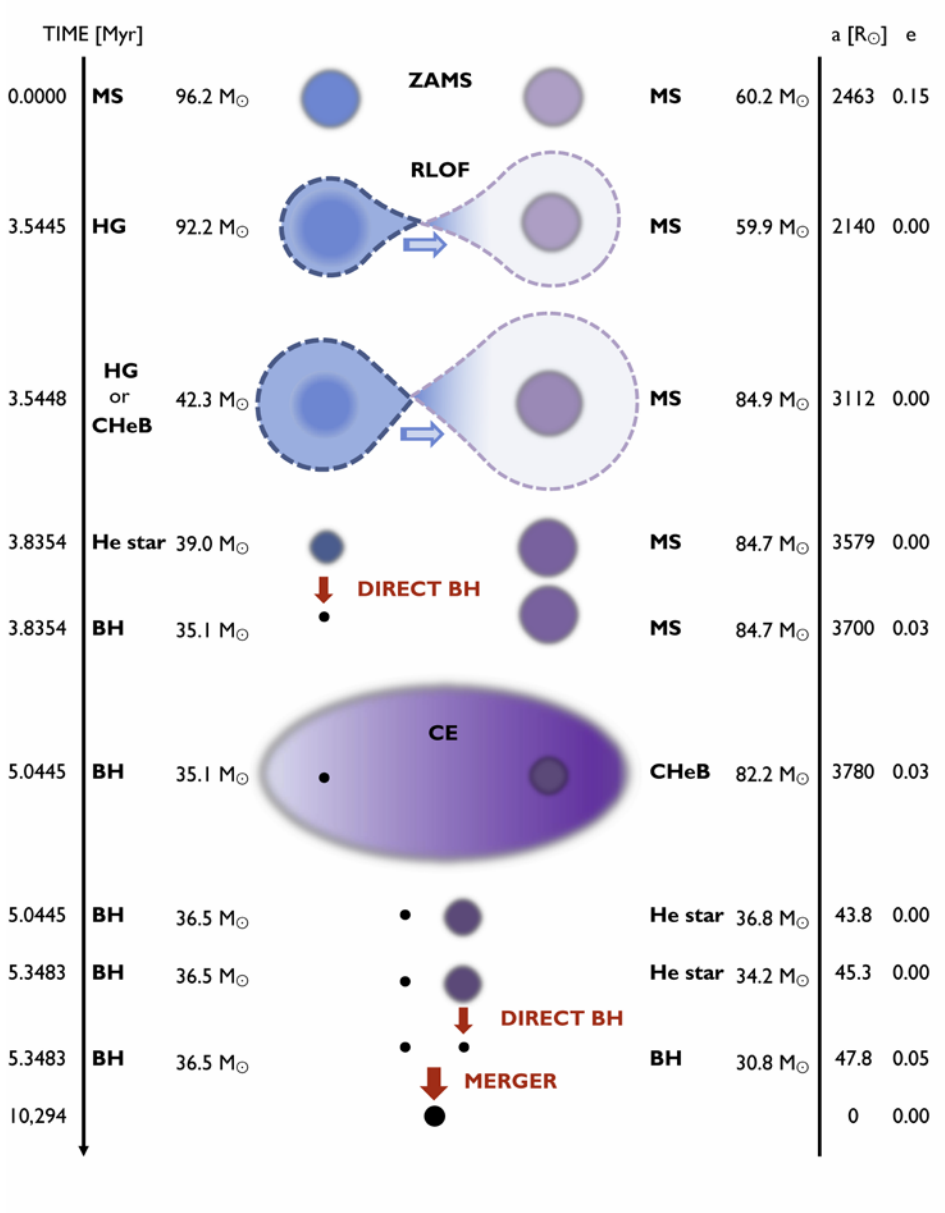


Astrophysical Implications

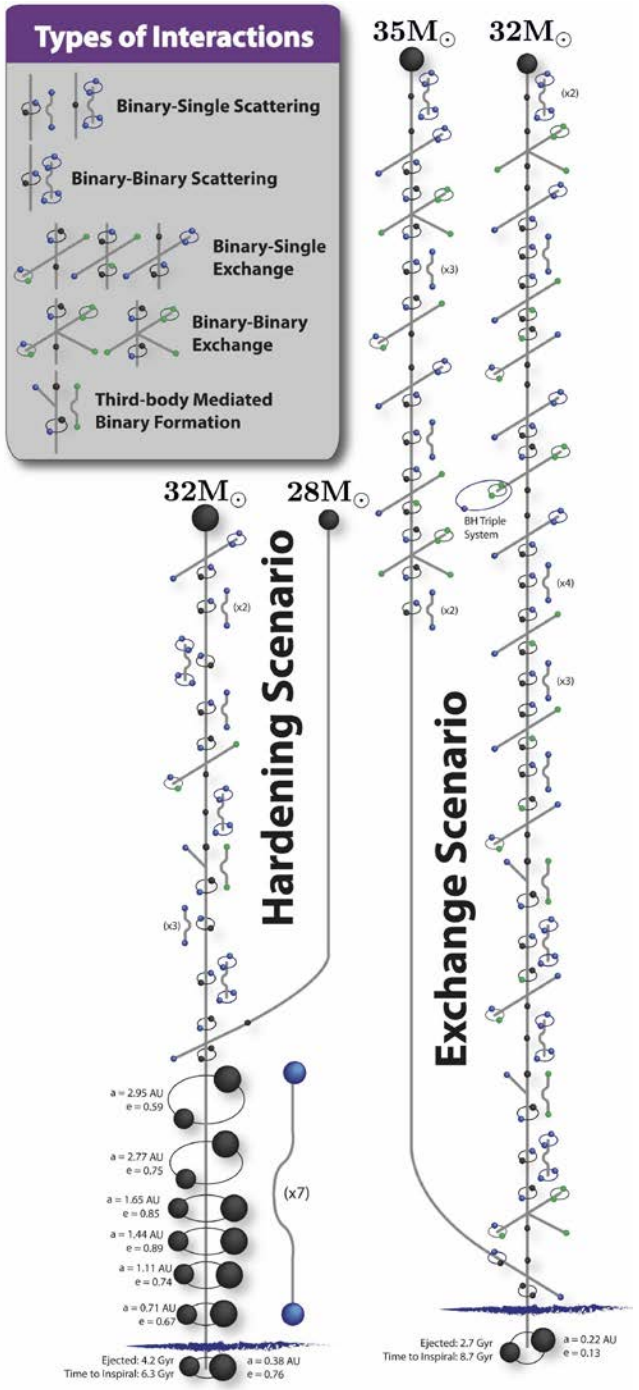
- Early in the Universe monster stars can form out of Hydrogen only
- Stars produce metals (Metal in astronomy is anything heavier than Helium)
- 30 solar mass black holes can not be formed with core collapses in the current solar environment



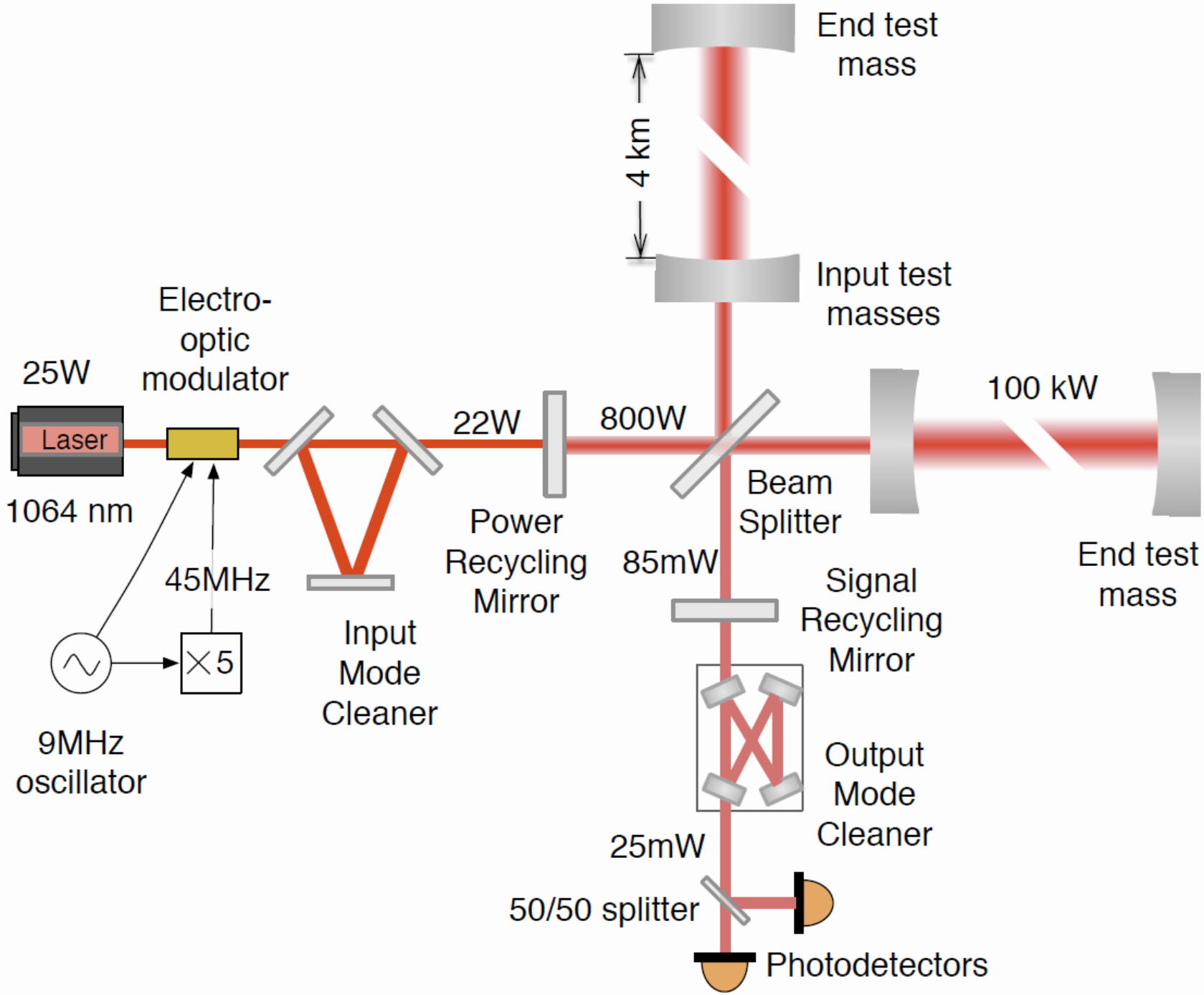
Binary Black Hole Formation



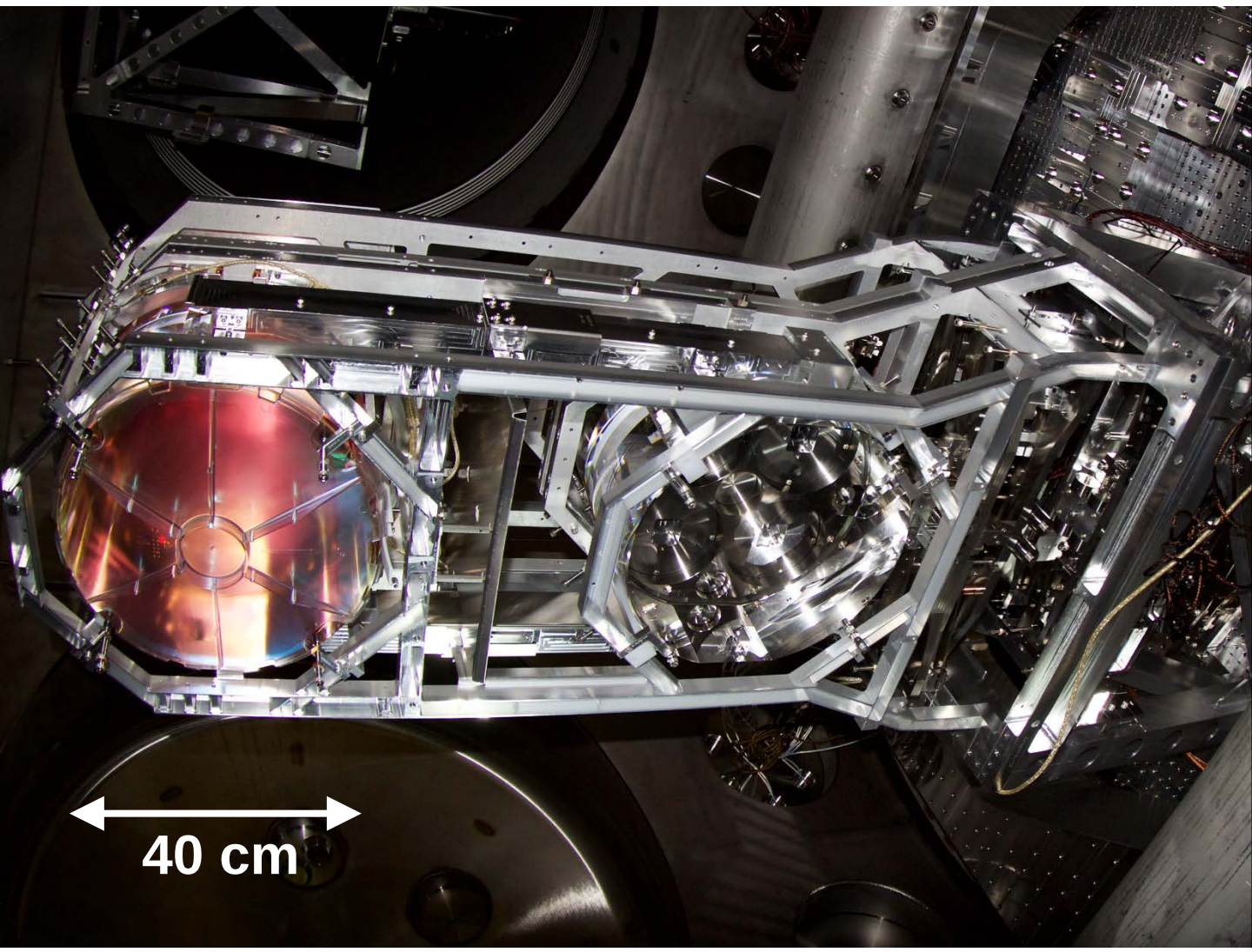
From isolated stars

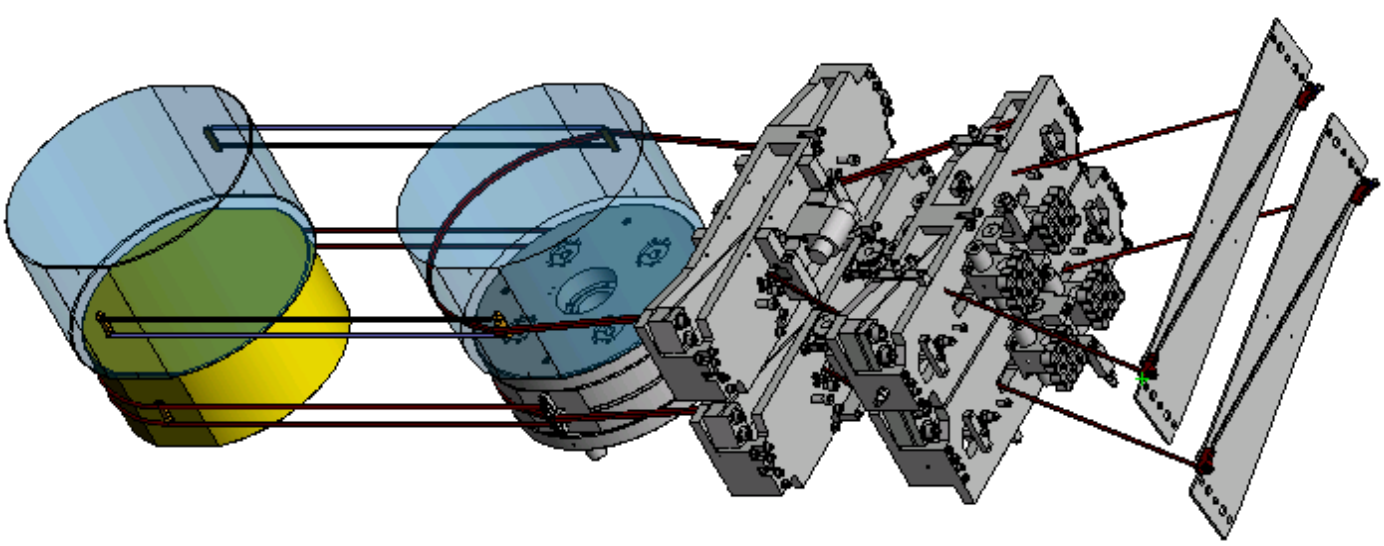


Inside globular clusters


End test mass
4 km
Input test masses
Electro-optic modulator
25W
Laser
1064 nm
22W
800W
100 kW
Beam Splitter
End test mass
Power Recycling Mirror
85mW
Signal Recycling Mirror
45MHz
×5
9MHz oscillator
Input Mode Cleaner
Output Mode Cleaner
25mW
50/50 splitter
Photodetectors

Test Mass Suspension

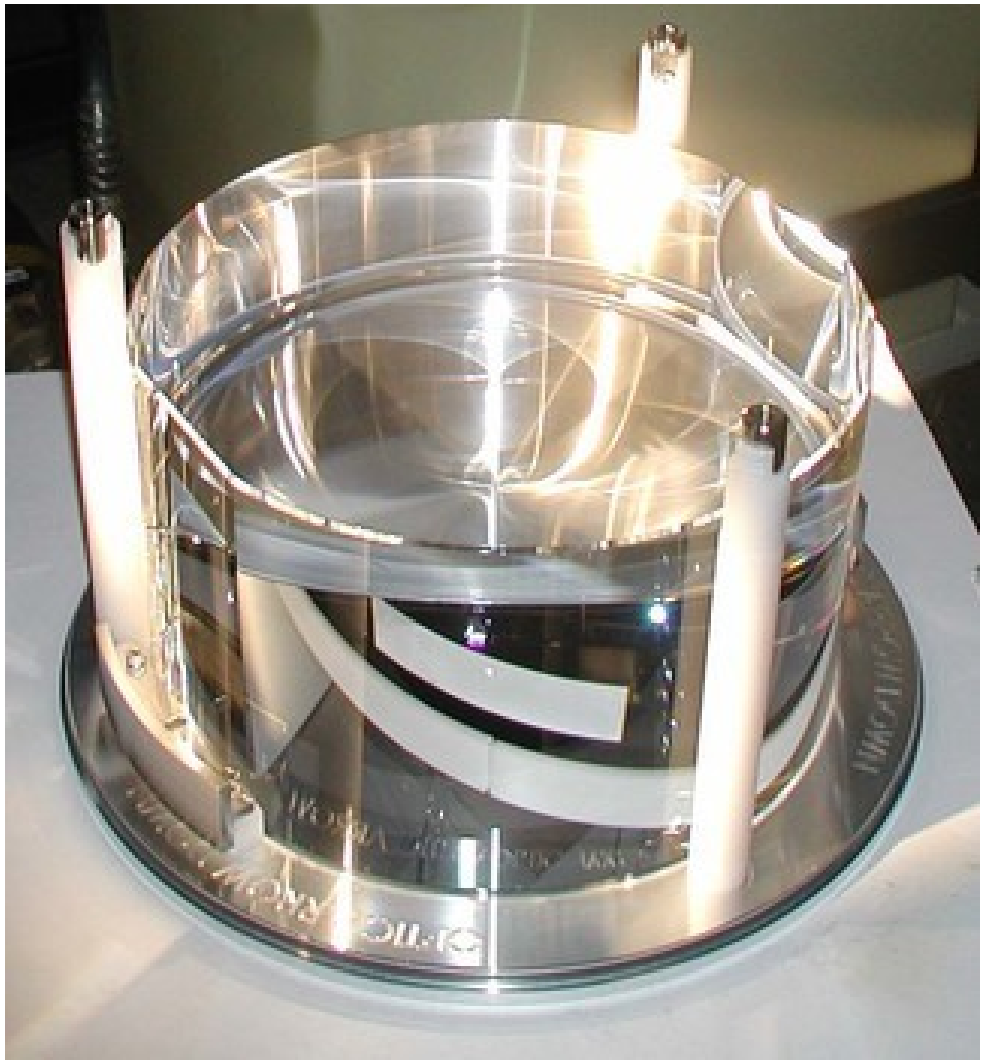




Large Test Mass Optics

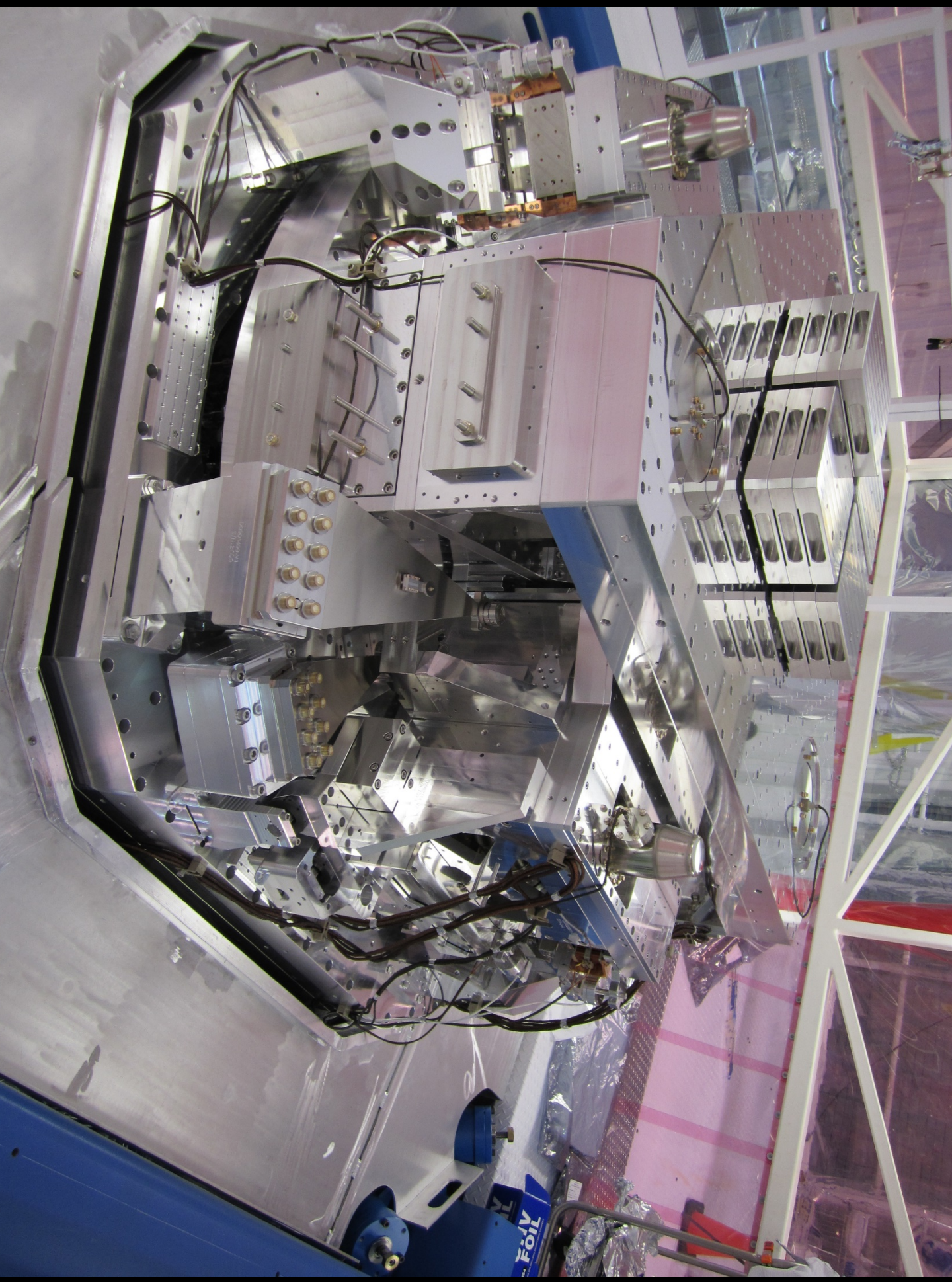
Specifications:

- 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

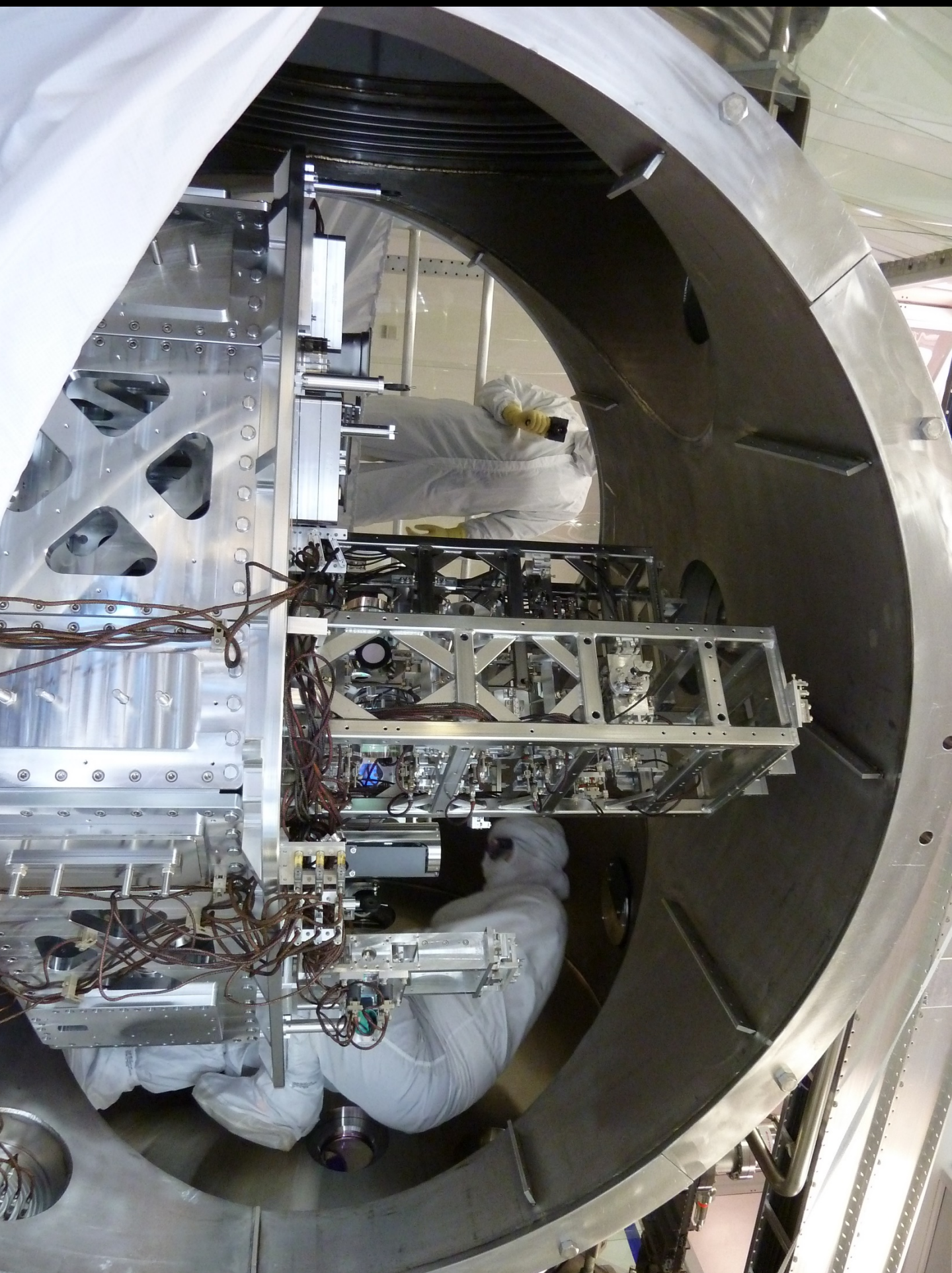


Vacuum System Vertex

Seismic Isolation Platform

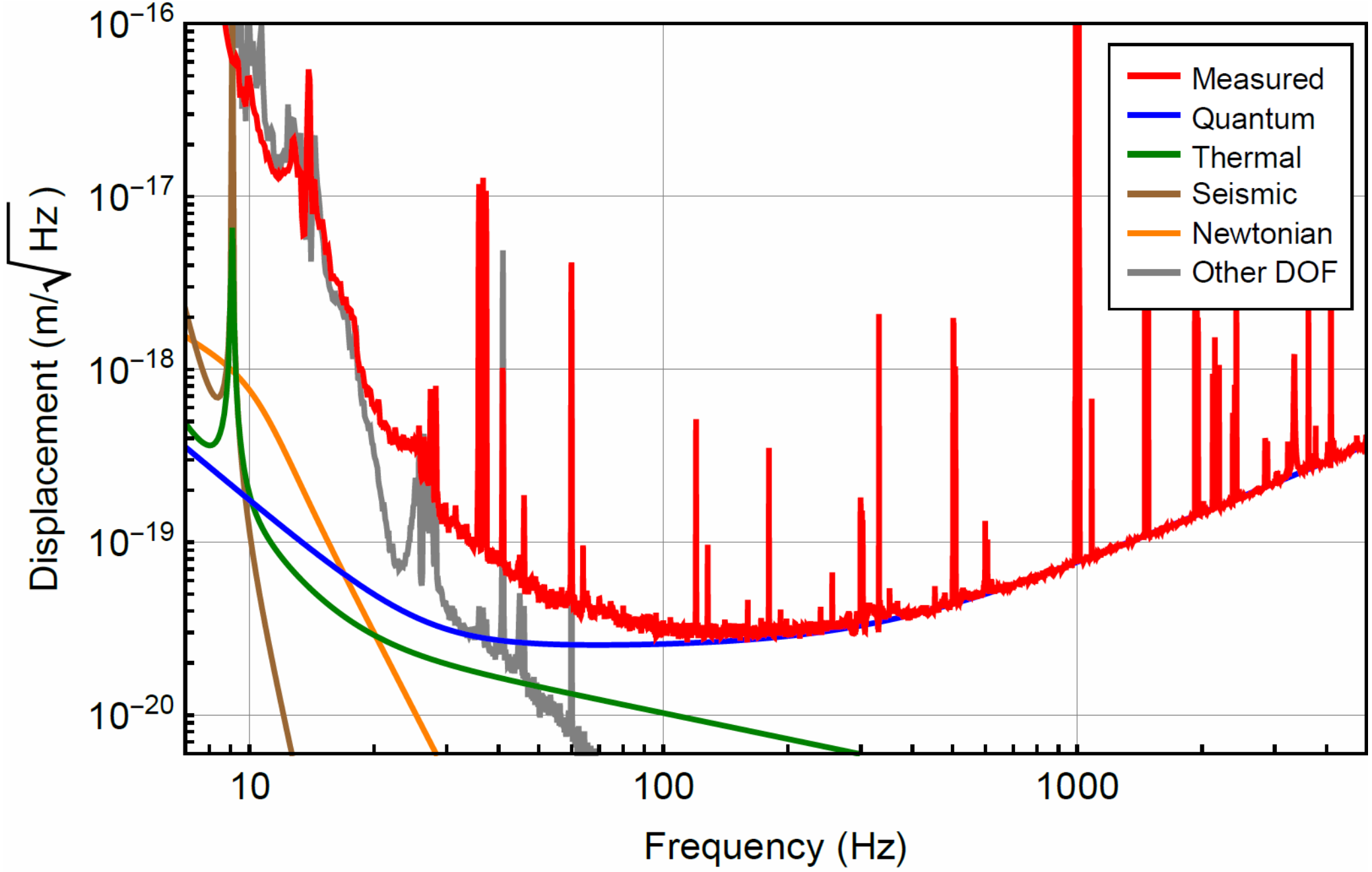


Input Optics Table

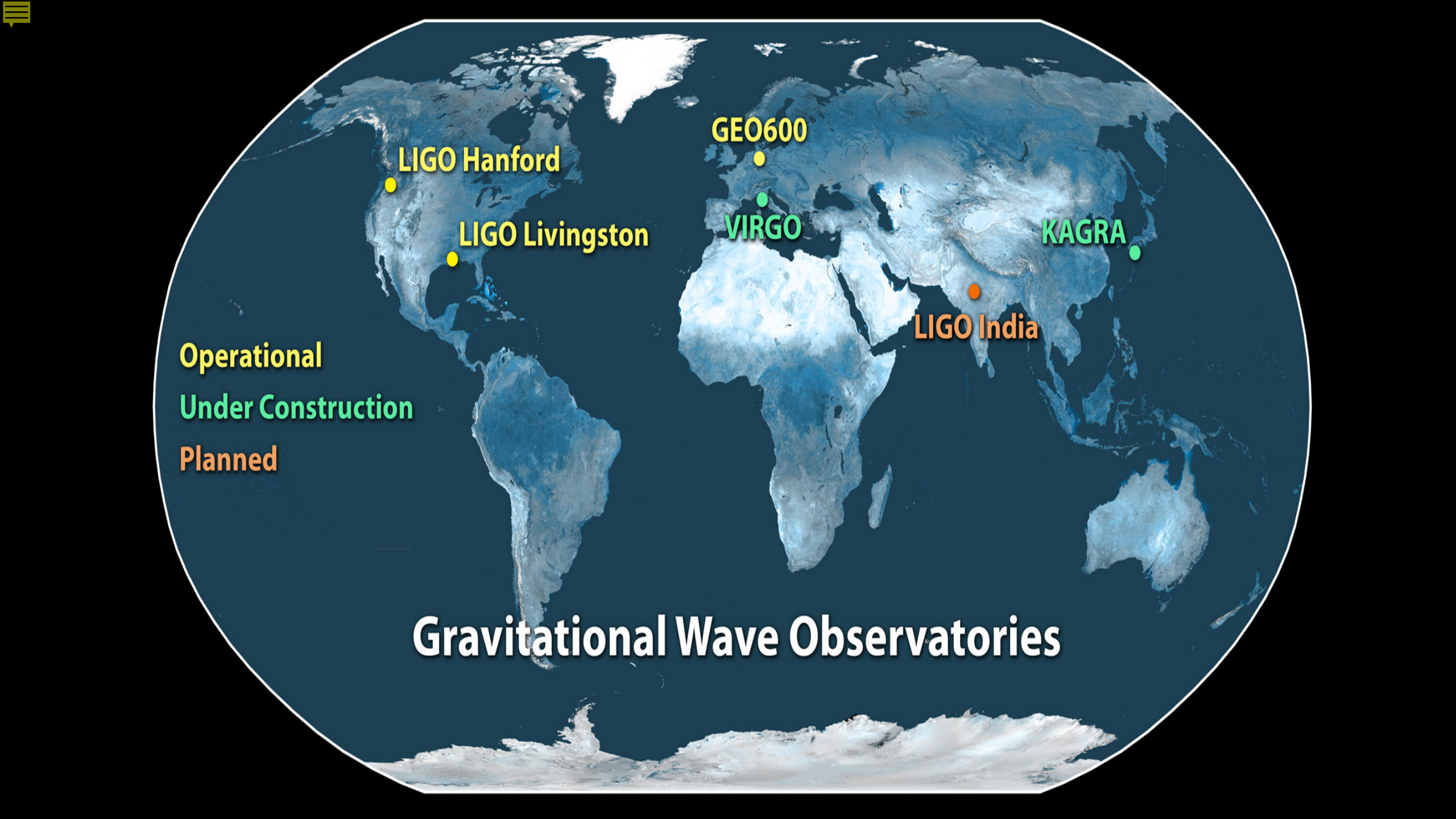


200W Pre-Stabilized Laser


Control Room



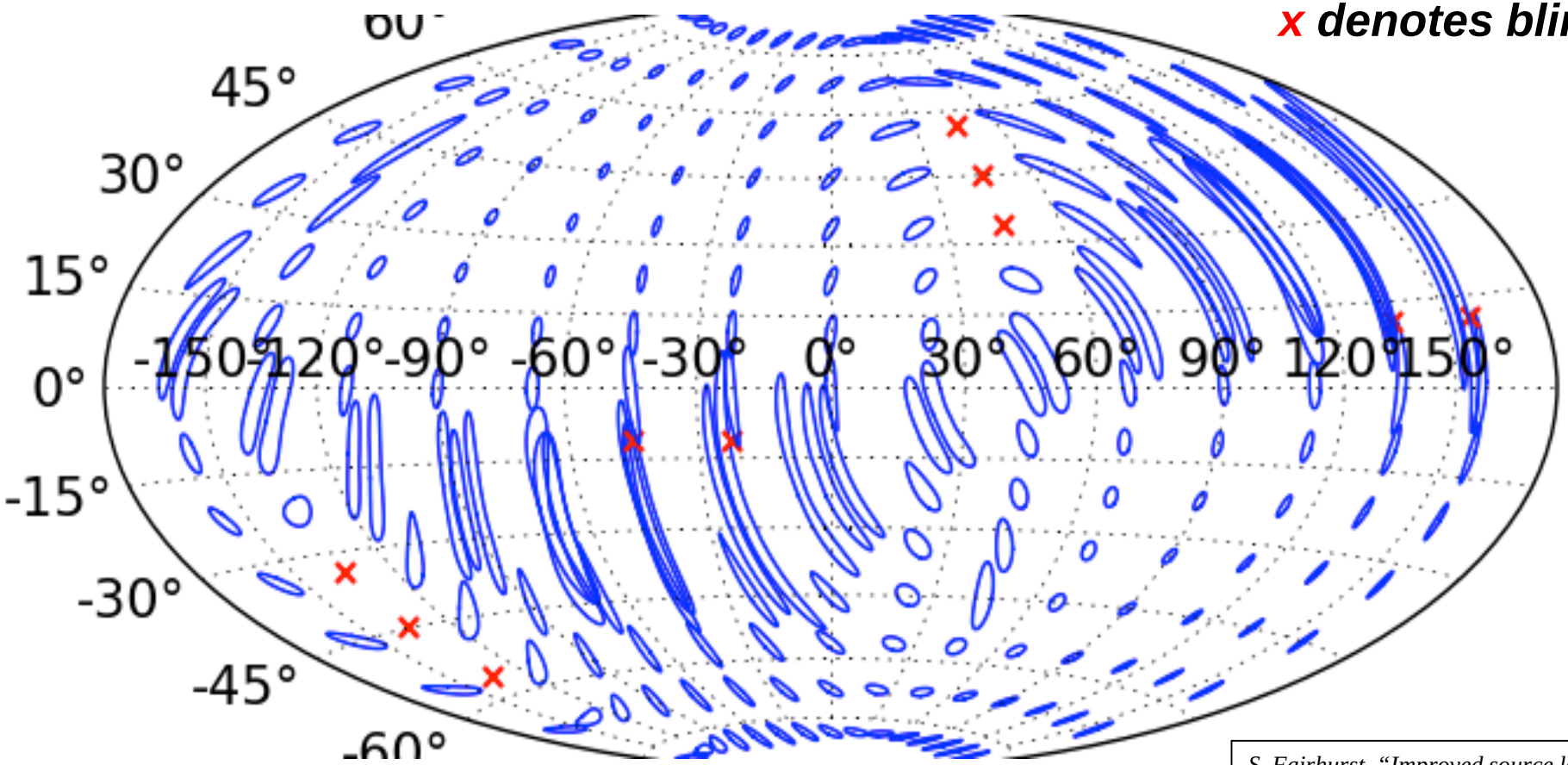
Phys. Rev. Lett. 116, 131103 (2016)


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

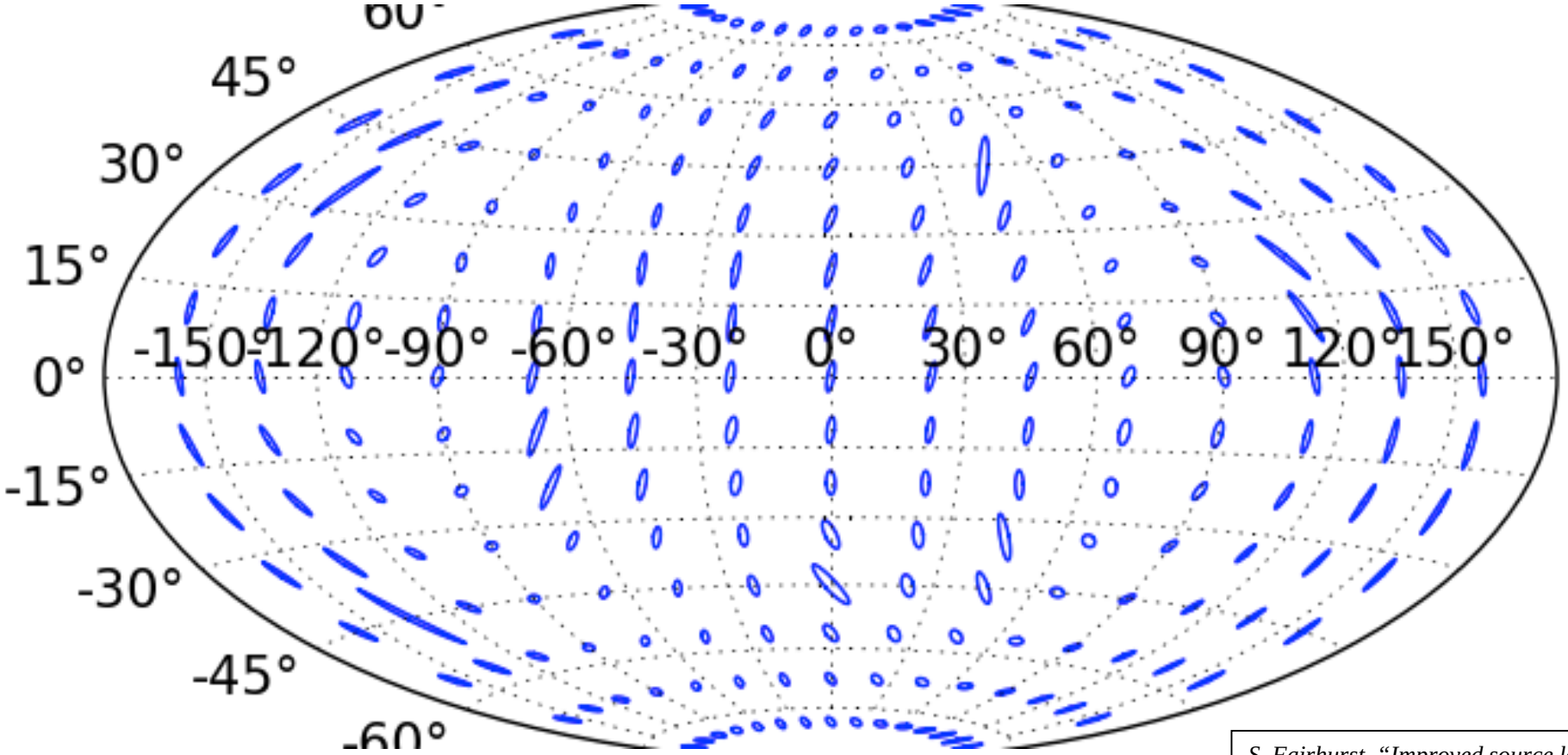
x denotes blind spots



*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*

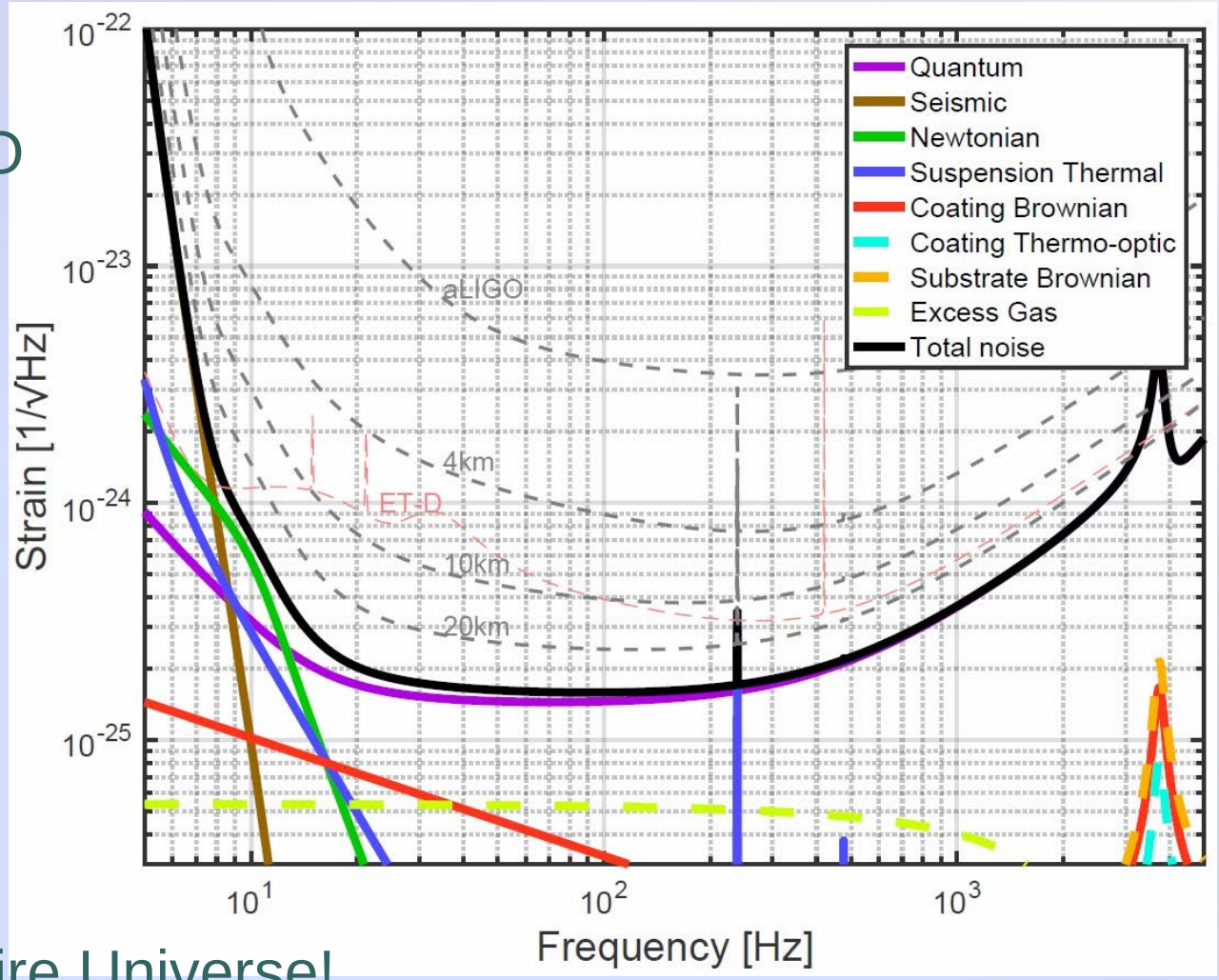
Next Generation Gravitational Wave Detectors

Current Facilities:

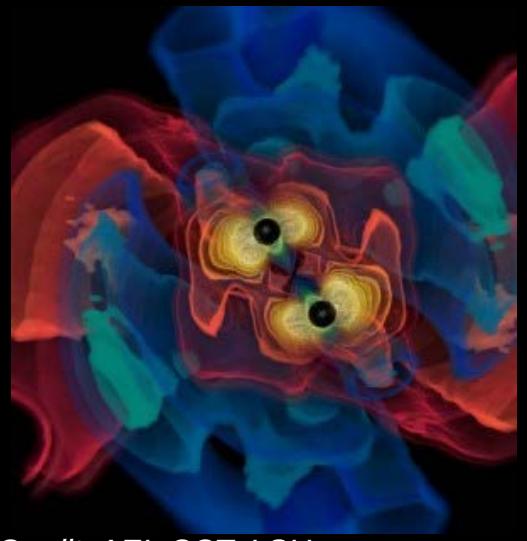
- Until 2020: Advanced LIGO/VIRGO
- Beyond 2020: A+ Upgrade
  Aims at a factor of 2 improvement using squeezed light
- 2030 time frame: Voyager
  Possible cryogenic detector

20 Years+: New Facilities Needed

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



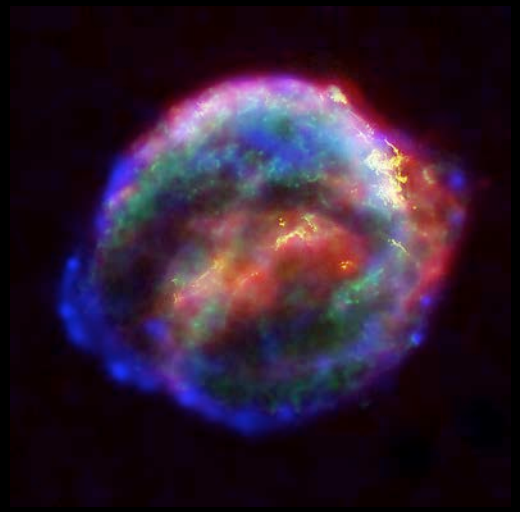
Astrophysical Targets for Ground-based Detectors



Credit: AEI, CCT, LSU

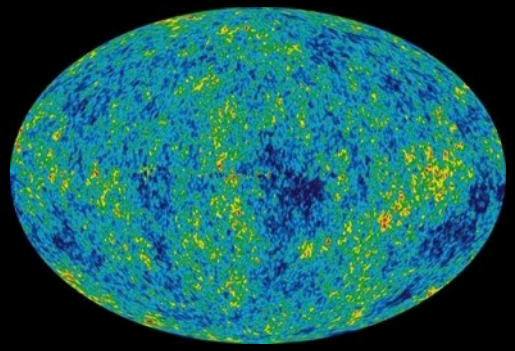
Coalescing Binary Systems

- *Well-modeled*
- *Neutron stars, low mass black holes, and NS/BS systems*



'Bursts'

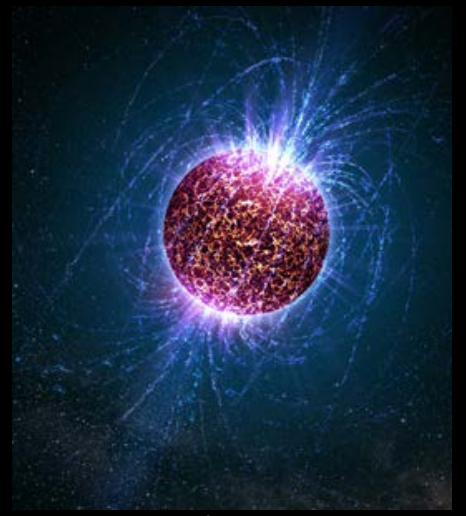
- *Unmodeled*
- *galactic asymmetric core collapse supernovae*
- *cosmic strings*
- ***???***



NASA/WMAP Science Team

Stochastic GWs

- *Noise*
- *Incoherent background from primordial GWs or an ensemble of unphased sources*
- *primordial GWs unlikely to detect, but can bound in the 10-10000 Hz range*



Casey Reed, Penn State

Continuous Sources

- *Essentially Monotone*
- *Spinning neutron stars*
- *probe crustal deformations, equation of state, 'quarki-ness'*

Gravitational Wave Periods

Milliseconds

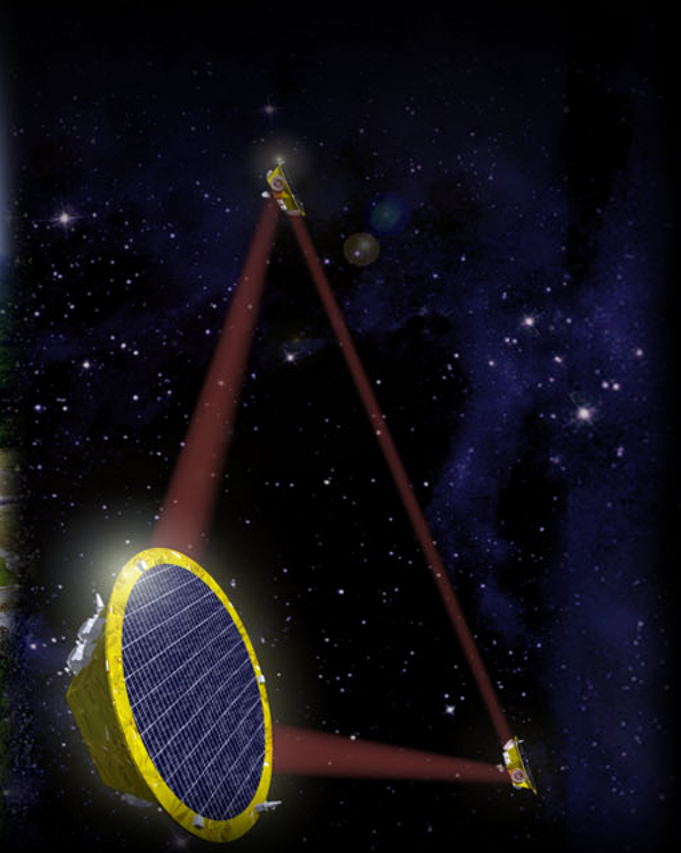


Gravitational Wave Periods

Milliseconds



Minutes
to Hours

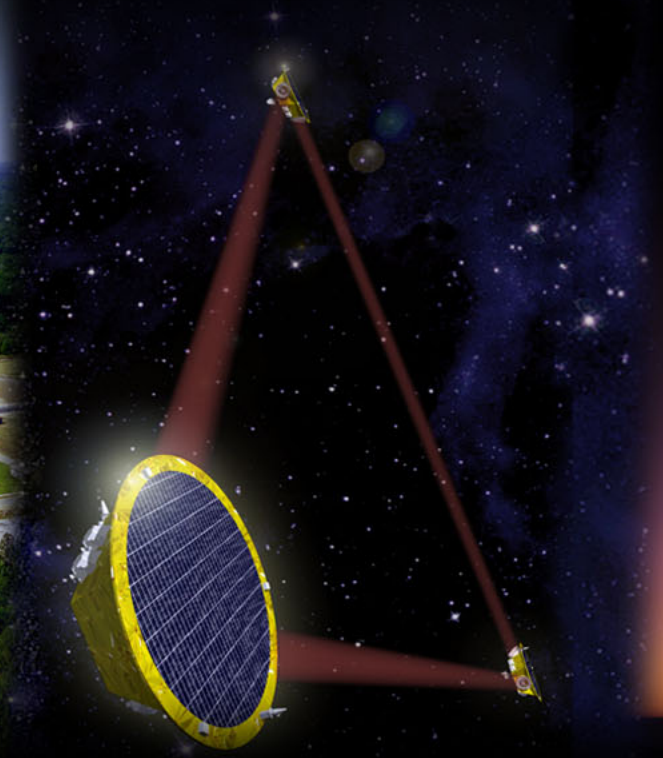


Gravitational Wave Periods

Milliseconds



Minutes
to Hours



Years
to Decades

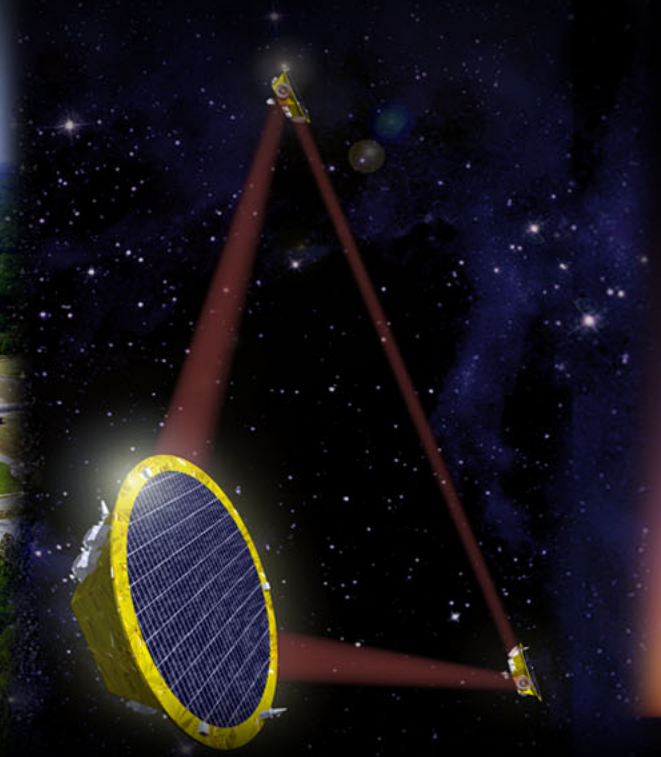


Gravitational Wave Periods

Milliseconds



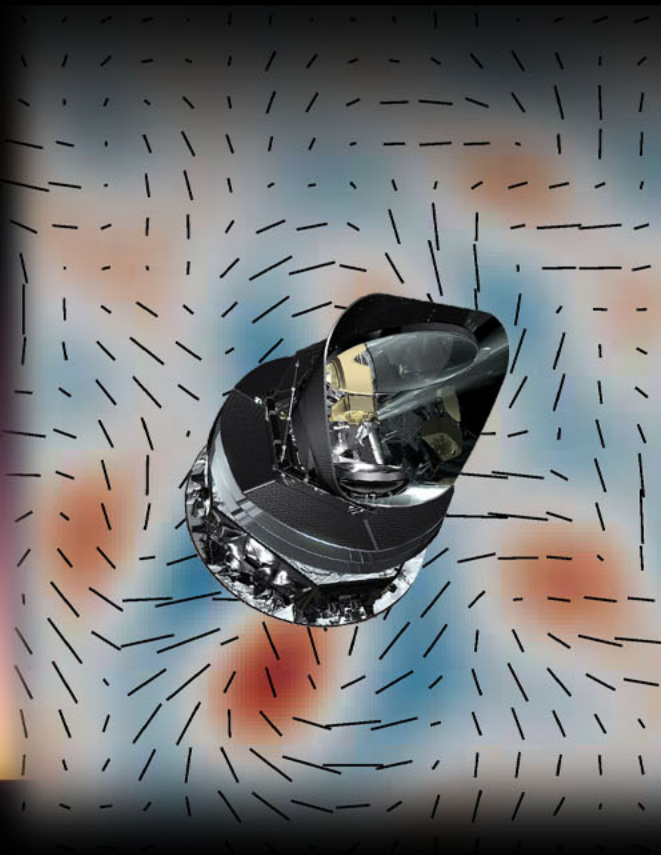
Minutes to Hours



Years to Decades



Billions of Years



The Gravitational-wave Spectrum



Big Bang

Supermassive Black Hole Binary Merger







Compact Binary Inspiral & Merger





Extreme Mass-Ratio Inspirals



Pulsars, Supernovae



The Gravitational Wave Spectrum

Sources

age of the universe

Wave Period

years

hours

seconds

milliseconds

10^{-16} 10^{-14} 10^{-12} 10^{-10} 10^{-8} 10^{-6} 10^{-4} 10^{-2} 1 10^{2}

Wave Frequency

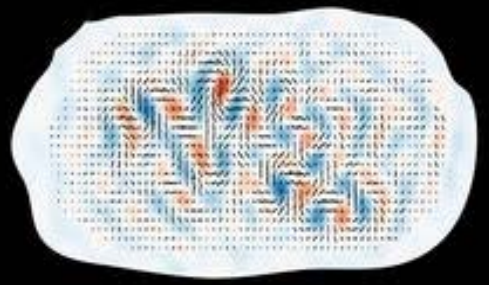
CMB Polarization

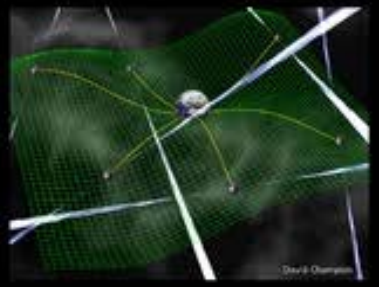
Radio Pulsar Timing Arrays

Space-based interferometers

Terrestrial interferometers

Detectors



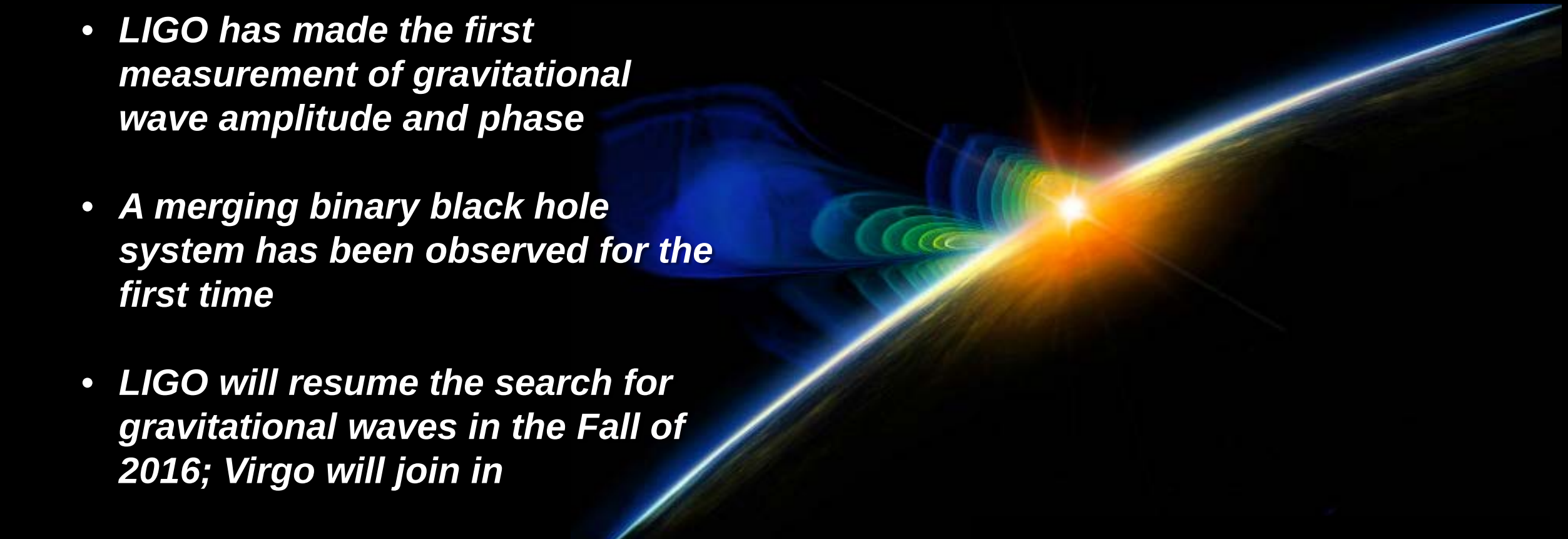






Advanced LIGO and the Dawn of Gravitational-waves Physics and Astronomy

- *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 will resume the search for gravitational waves in the Fall of 2016; Virgo will join in*
- *The next few years will be very interesting ones for the field of gravitational-wave science!*



Stay Tuned…

Thanks to:





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LIGO
LASER INTERFEROMETER GRAVITATIONAL-WAVE OBSERVATORY

www.ligo.org

LIGO VIRGO



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