The Advanced LIGO Detectors in the Era of First Discoveries

Daniel Sigg

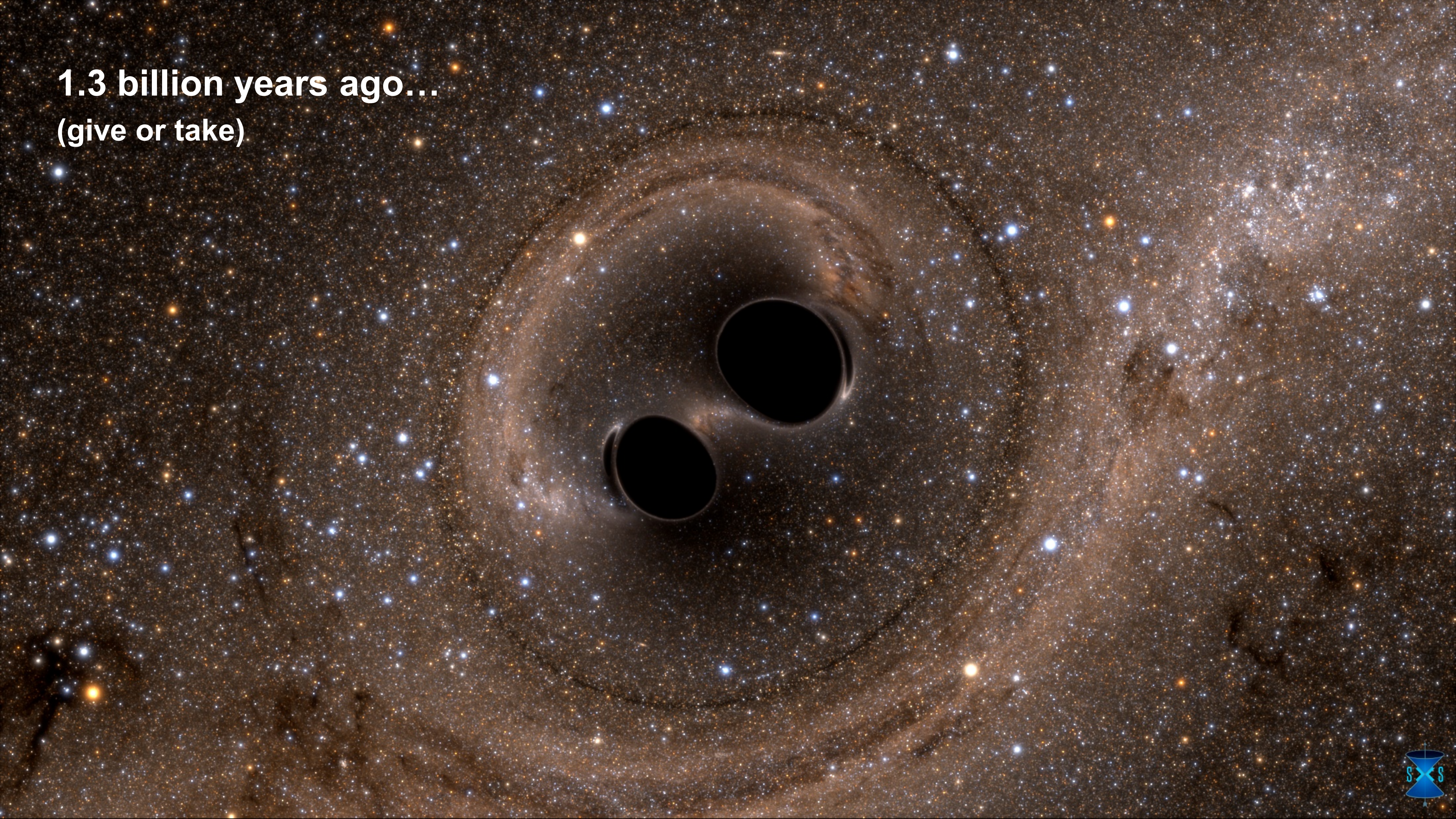
LIGO Hanford Observatory

California Institute of Technology

August 25, 2016

For the LIGO Scientific Collaboration and the Virgo Collaboration

LIGO-G1600772-v1


1.3 billion years ago…
(give or take)

2016: The Centenary of Gravitational Waves

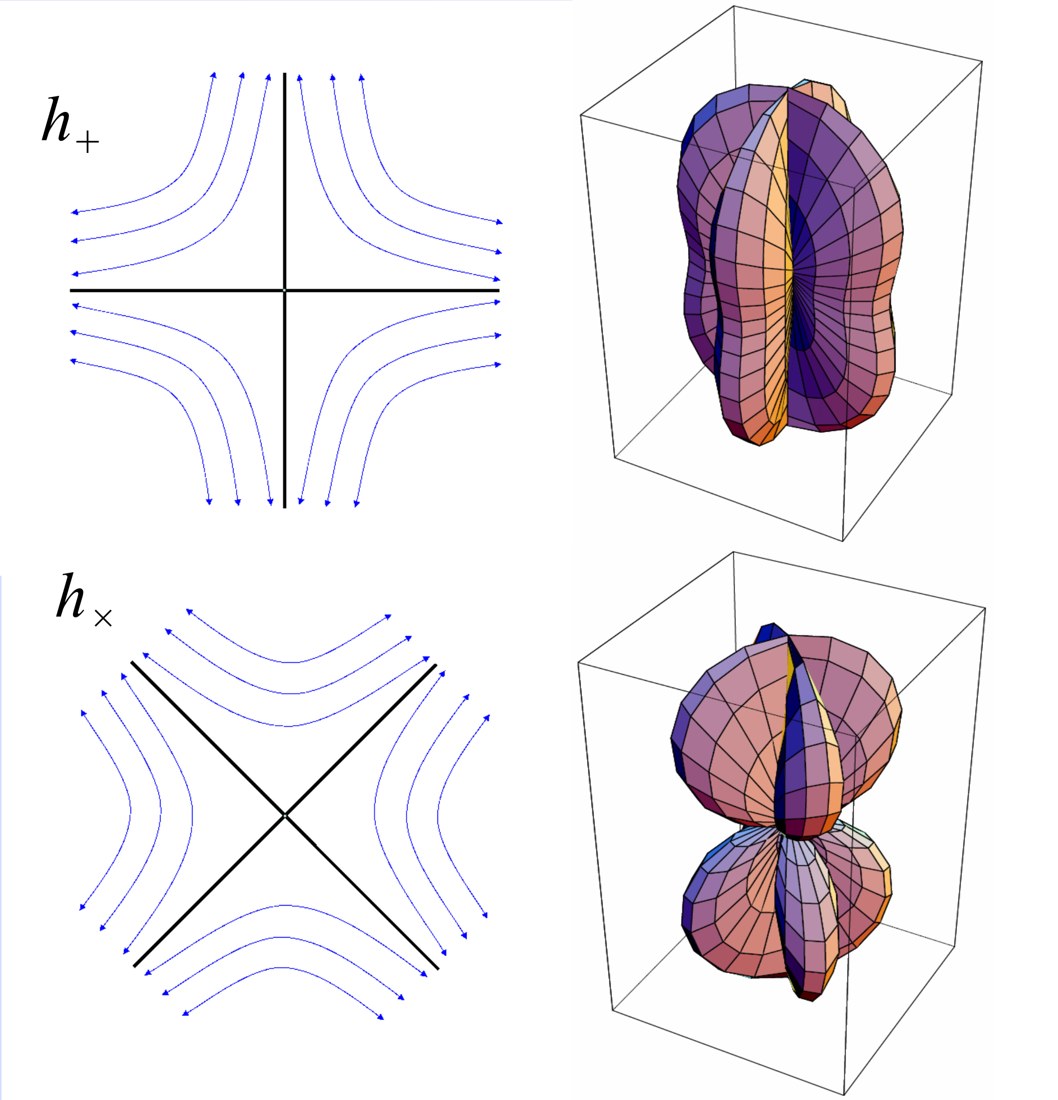
Metric: $ds^2 = g_{\mu\nu} dx^\mu dx^\nu$

Weak field: $g_{\mu\nu} \approx \eta_{\mu\nu} + h_{\mu\nu}$

In vacuum: $h_{\mu\nu} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & h_+ & h_\times & 0 \\ 0 & h_\times & -h_+ & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$

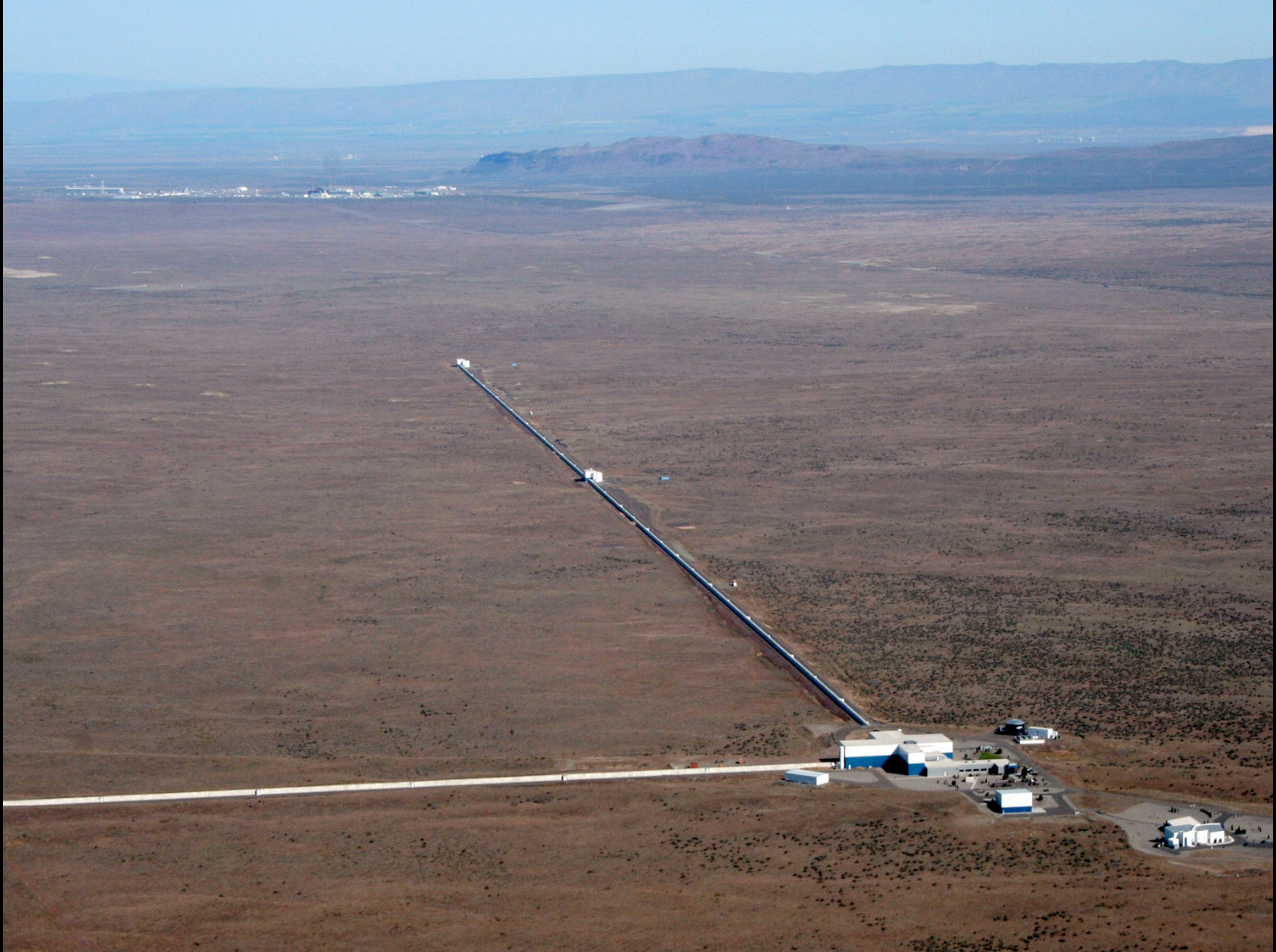
Physically,
h is a strain ~ $\Delta L/L$

Measure with a Michelson interferometer

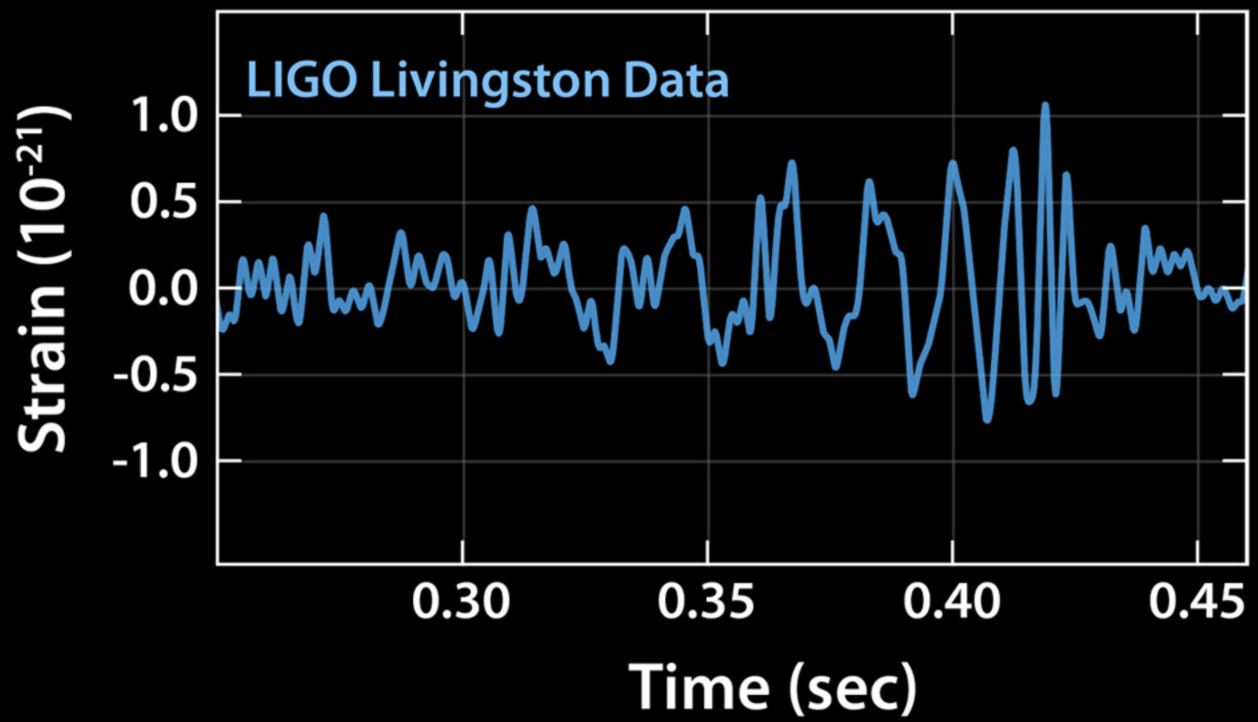


Livingston Observatory

Hanford Observatory

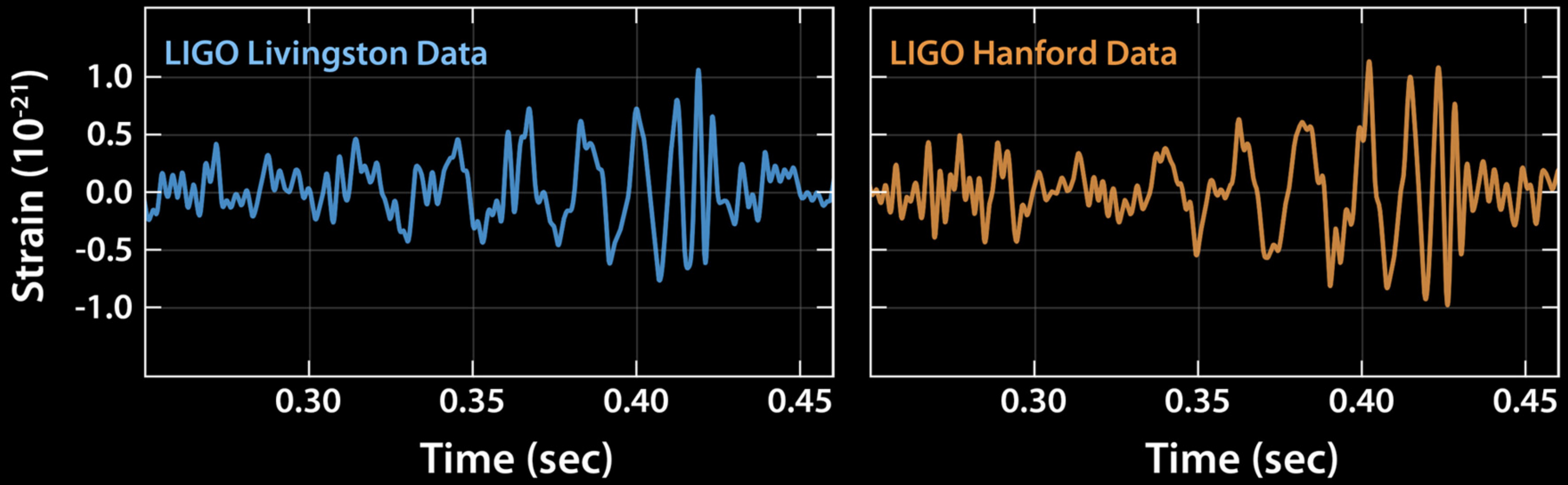


GW150914



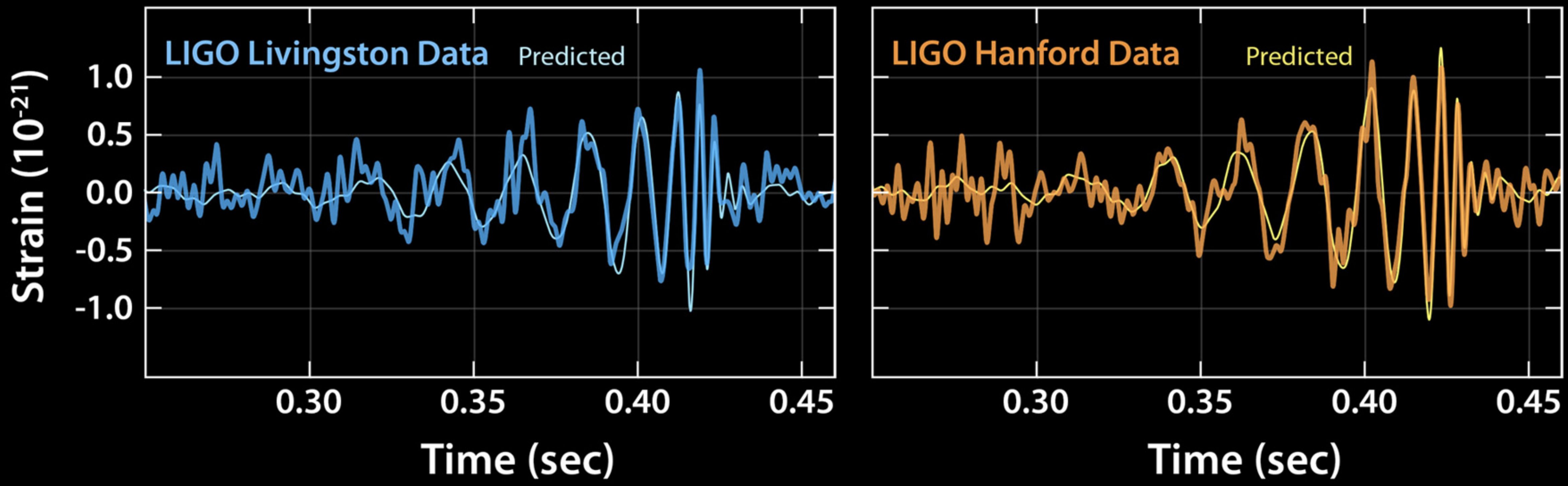
~1/200th proton radius

GW150914

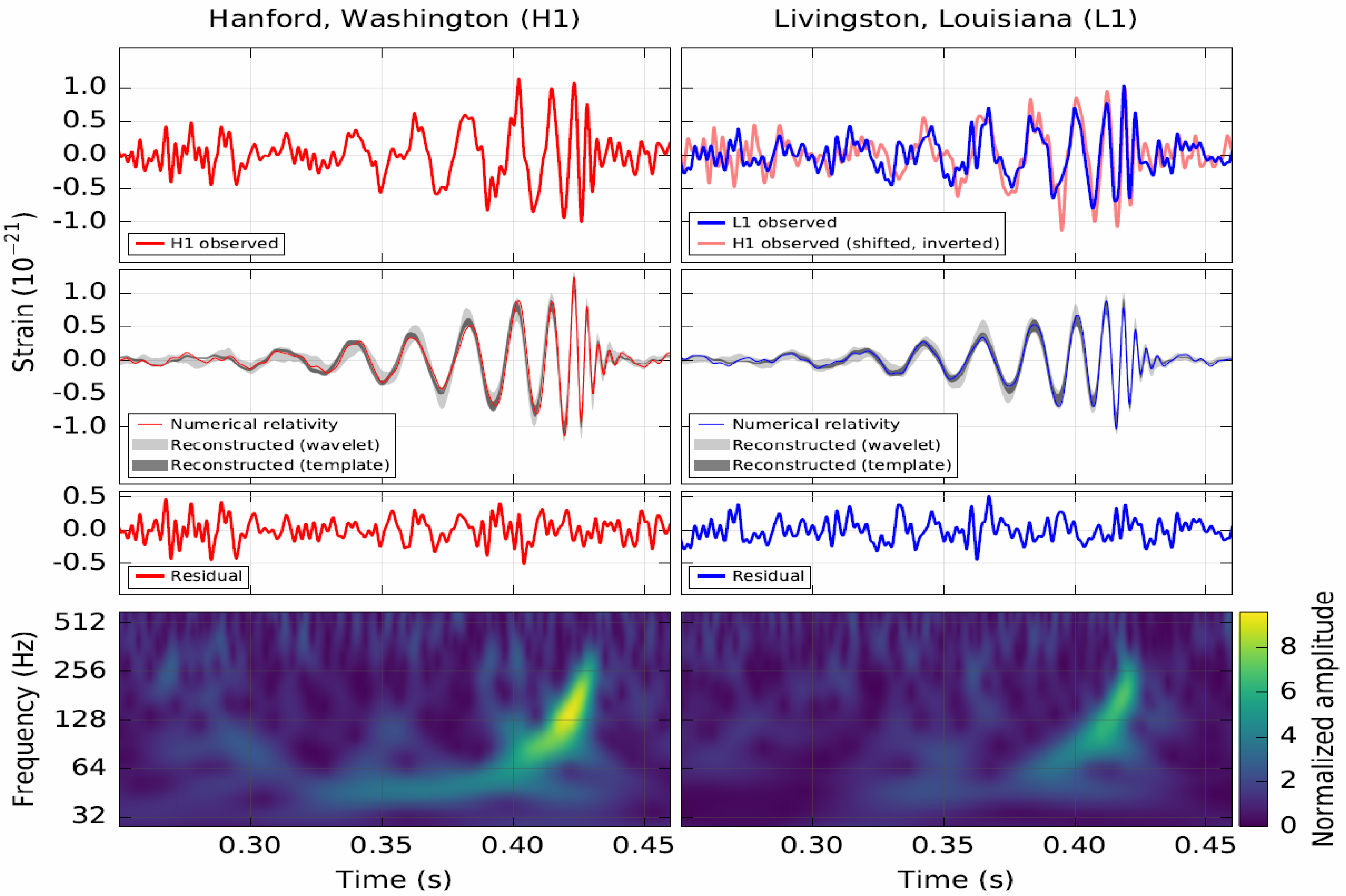


LIGO Livingston Data
LIGO Hanford Data
Strain (10^-21)
1.0
0.5
0.0
-0.5
-1.0
0.30
0.35
0.40
0.45
Time (sec)
0.30
0.35
0.40
0.45
Time (sec)

GW150914

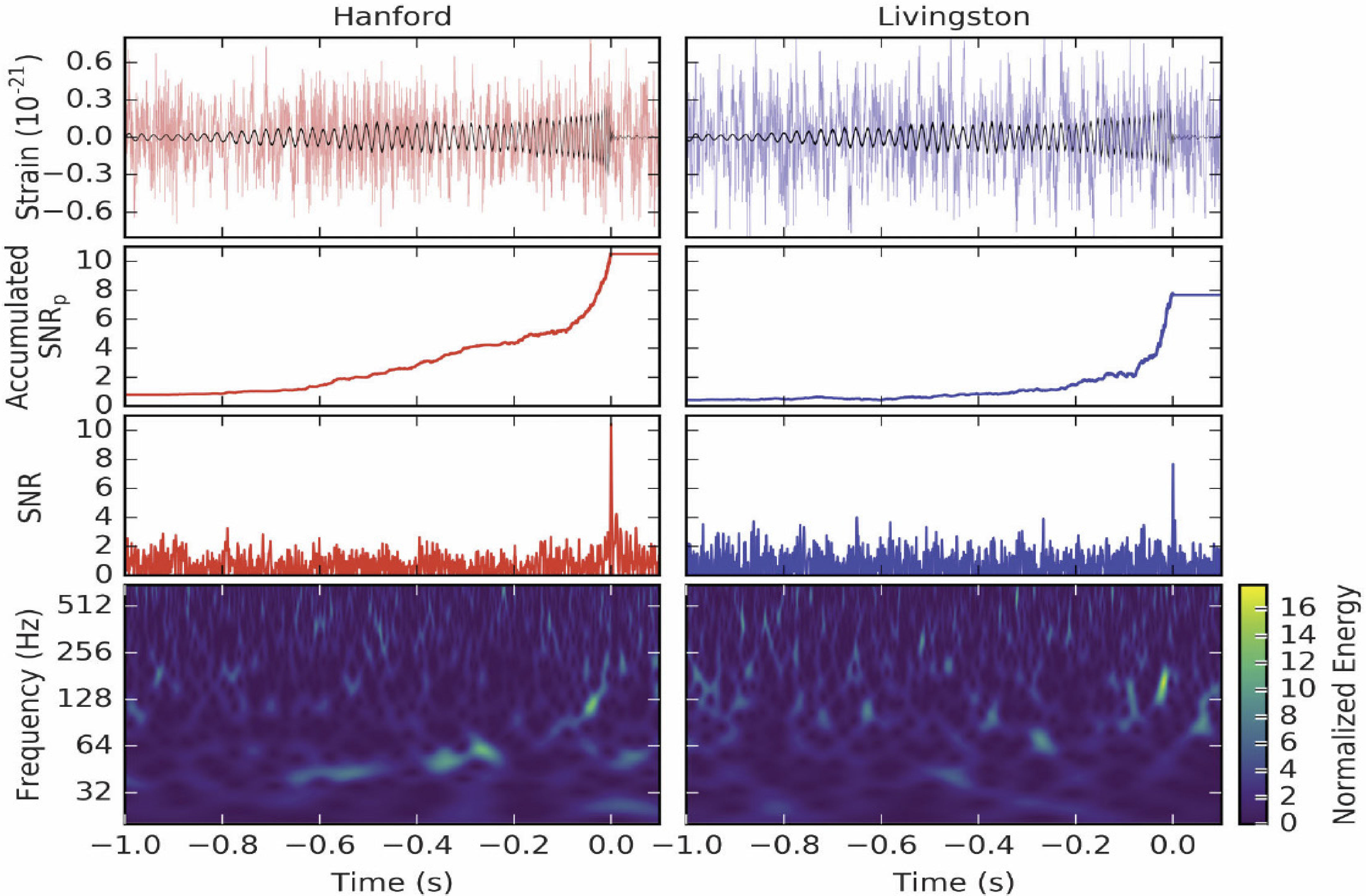

LIGO Livingston Data
Predicted
LIGO Hanford Data
Predicted
Strain (10^{-21})
1.0
0.5
0.0
-0.5
-1.0
0.30
0.35
0.40
0.45
Time (sec)
0.30
0.35
0.40
0.45
Time (sec)

GW150914

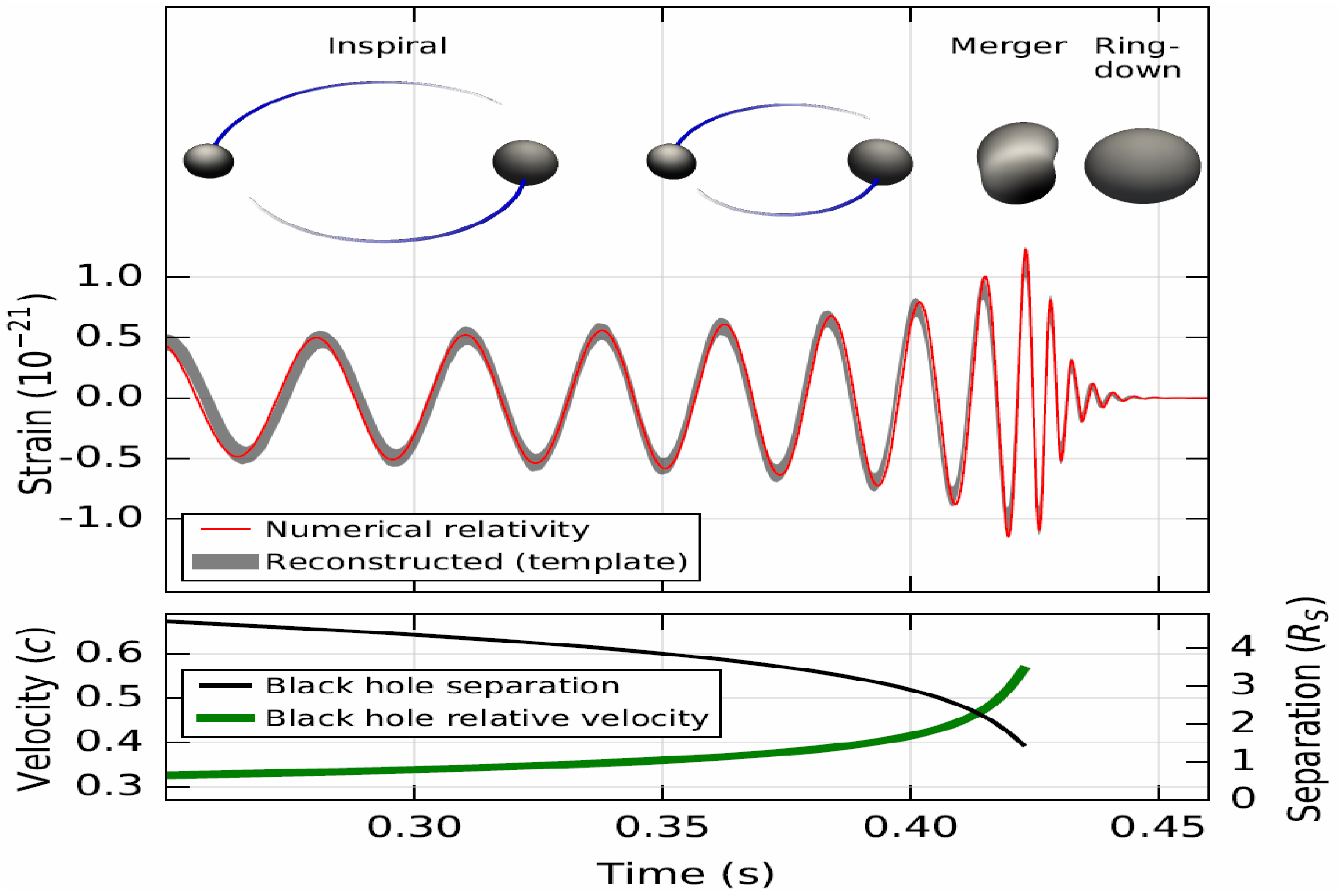


Hanford, Washington (H1)
Livingston, Louisiana (L1)
Strain (10^{-21})
1.0
0.5
0.0
-0.5
-1.0
H1 observed
L1 observed
H1 observed (shifted, inverted)
Numerical relativity
Reconstructed (wavelet)
Reconstructed (template)
Residual
Frequency (Hz)
512
256
128
64
32
0.30
0.35
0.40
0.45
Time (s)
Normalized amplitude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

GW151226

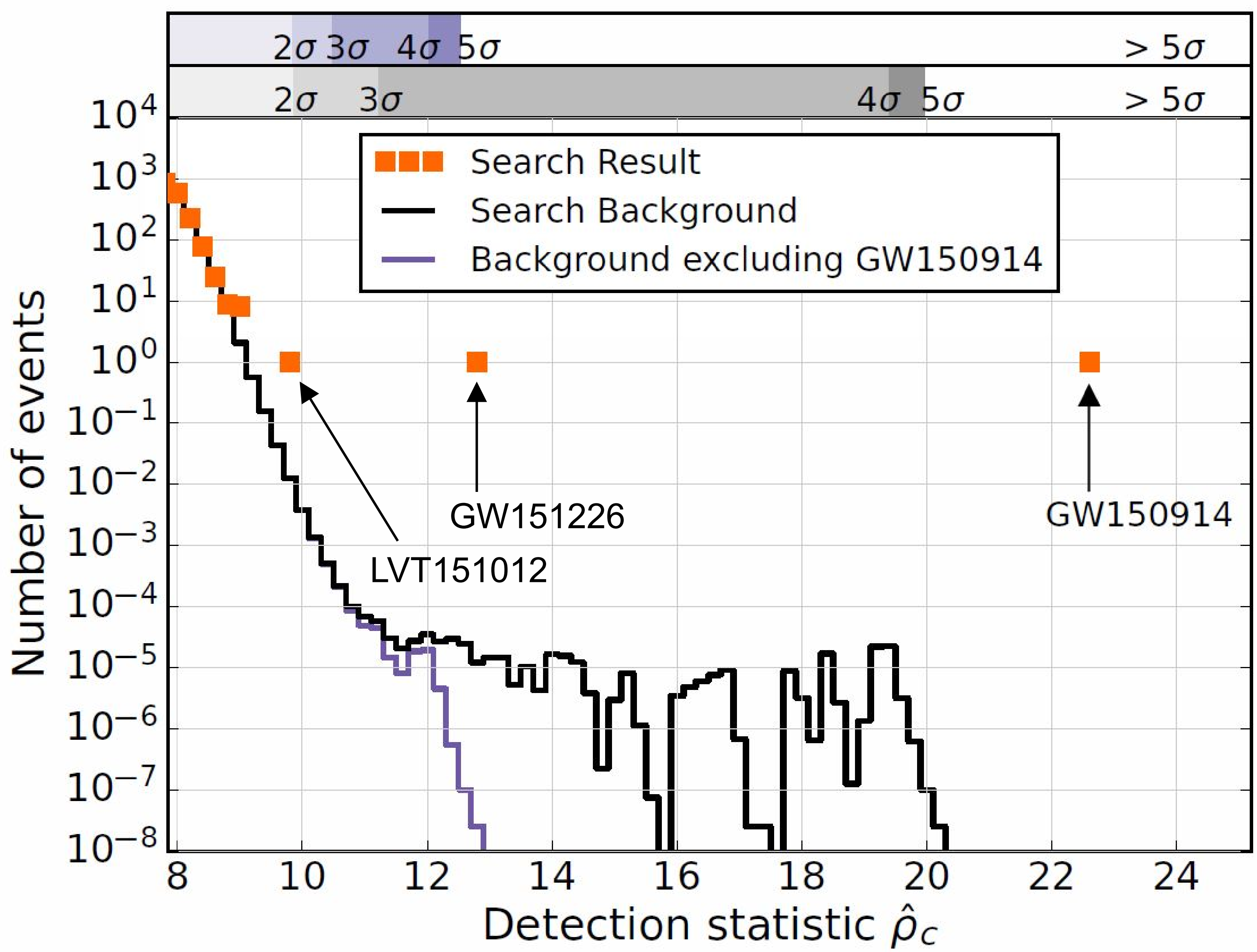


Hanford
Livingston
Strain (10^{-21})
0.6
0.3
0.0
−0.3
−0.6
Accumulated SNR$_p$
10
8
6
4
2
0
SNR
10
8
6
4
2
0
Frequency (Hz)
512
256
128
64
32
−1.0
−0.8
−0.6
−0.4
−0.2
0.0
Time (s)
Time (s)
Normalized Energy
16
14
12
10
8
6
4
2
0



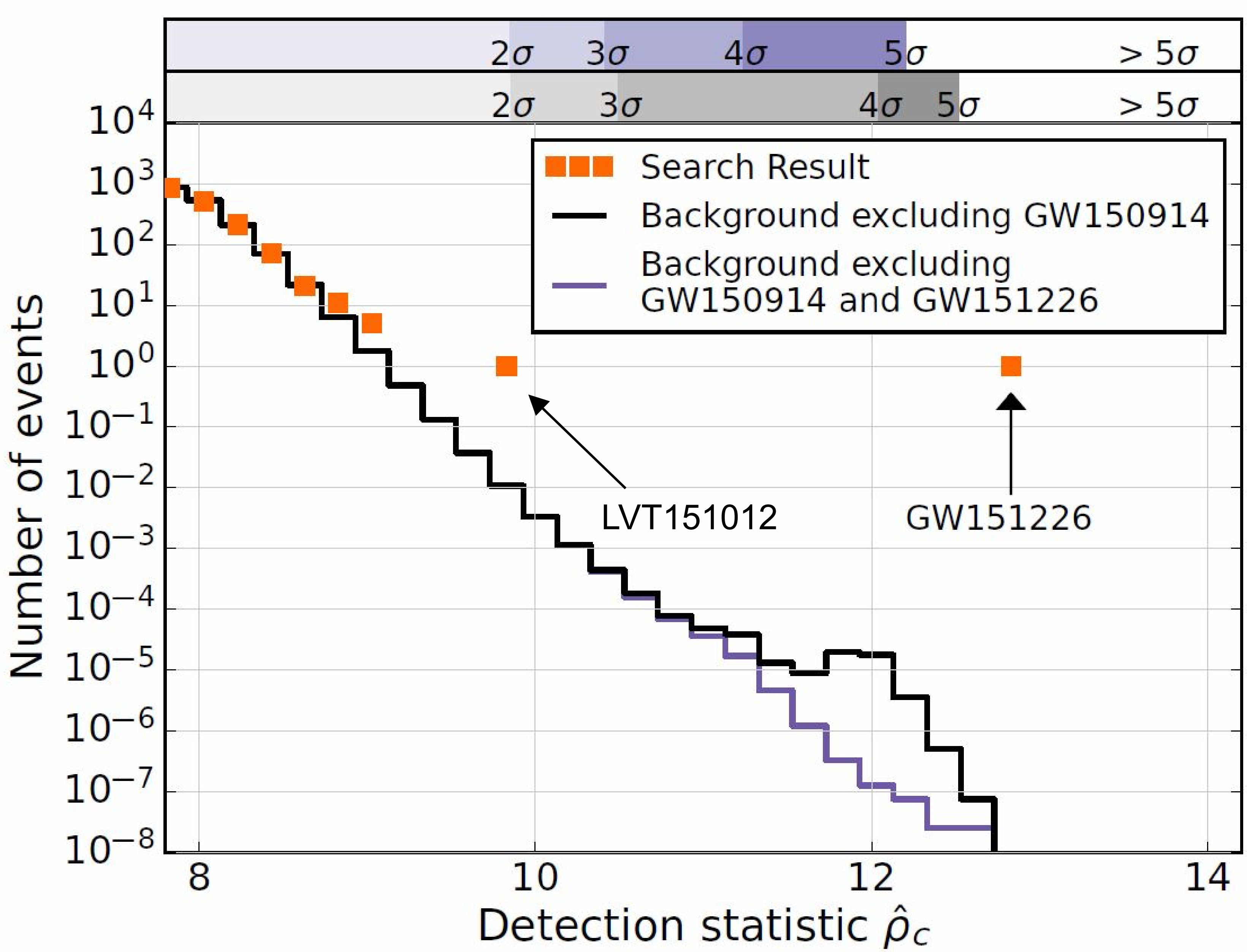
Inspiral
Merger
Ring-down
Strain (10^{-21})
1.0
0.5
0.0
-0.5
-1.0
Numerical relativity
Reconstructed (template)
Velocity (c)
0.6
0.5
0.4
0.3
Black hole separation
Black hole relative velocity
Separation (R_S)
4
3
2
1
0
0.30
0.35
0.40
0.45
Time (s)

GW150914



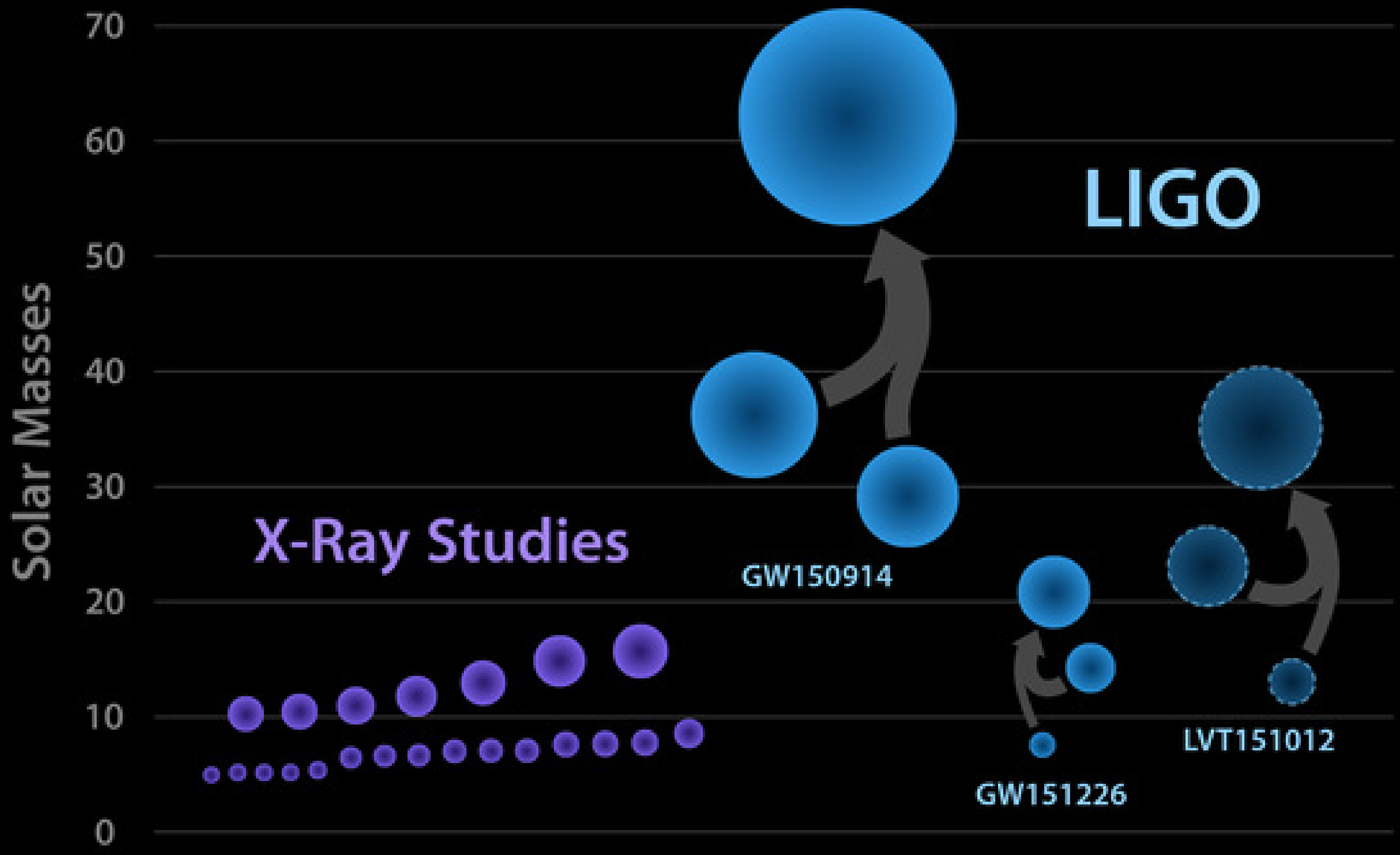
2σ 3σ 4σ 5σ > 5σ
2σ 3σ 4σ 5σ > 5σ
Search Result
Search Background
Background excluding GW150914
Number of events
GW151226
GW150914
LVT151012
Detection statistic ρ̂c

GW151226

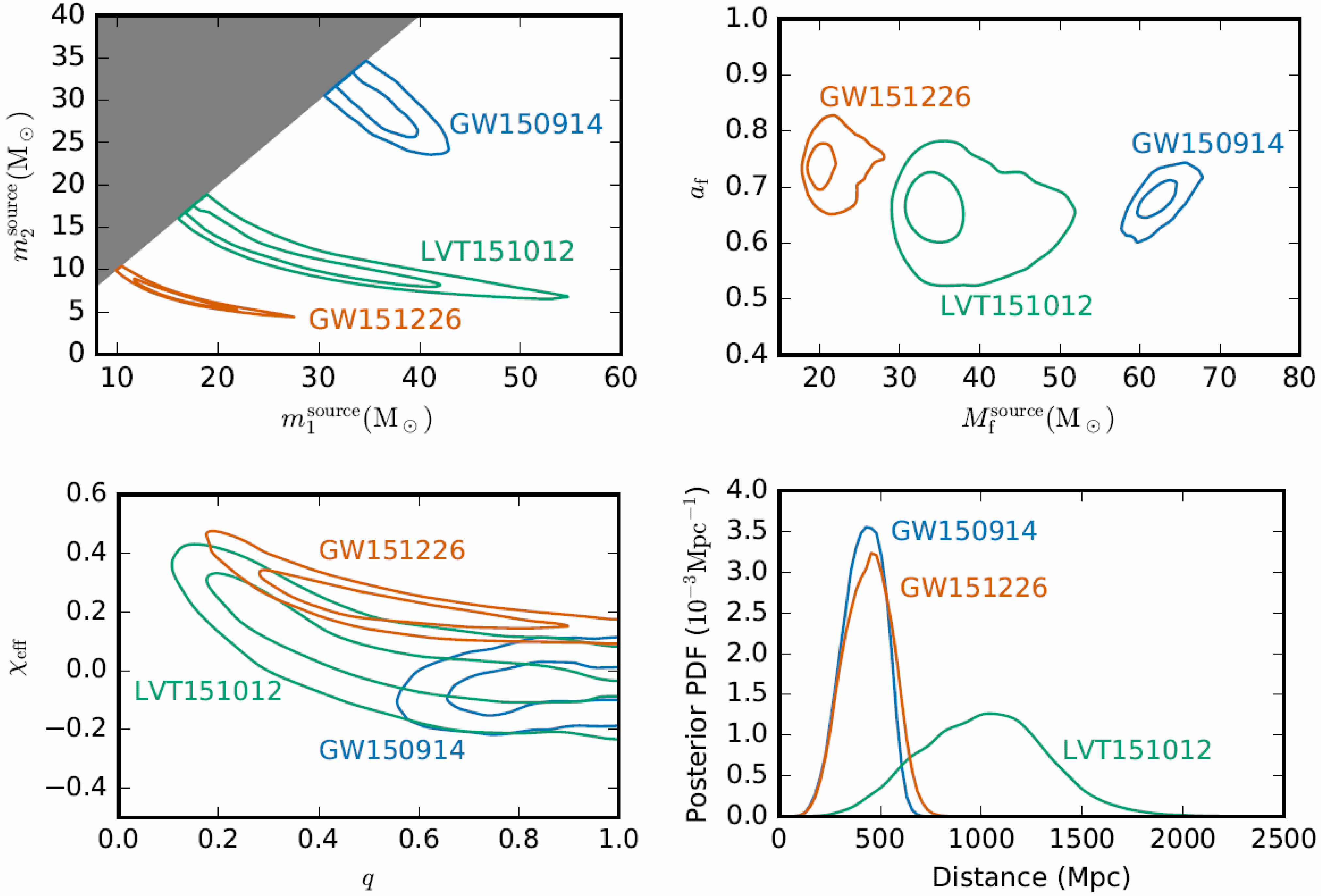


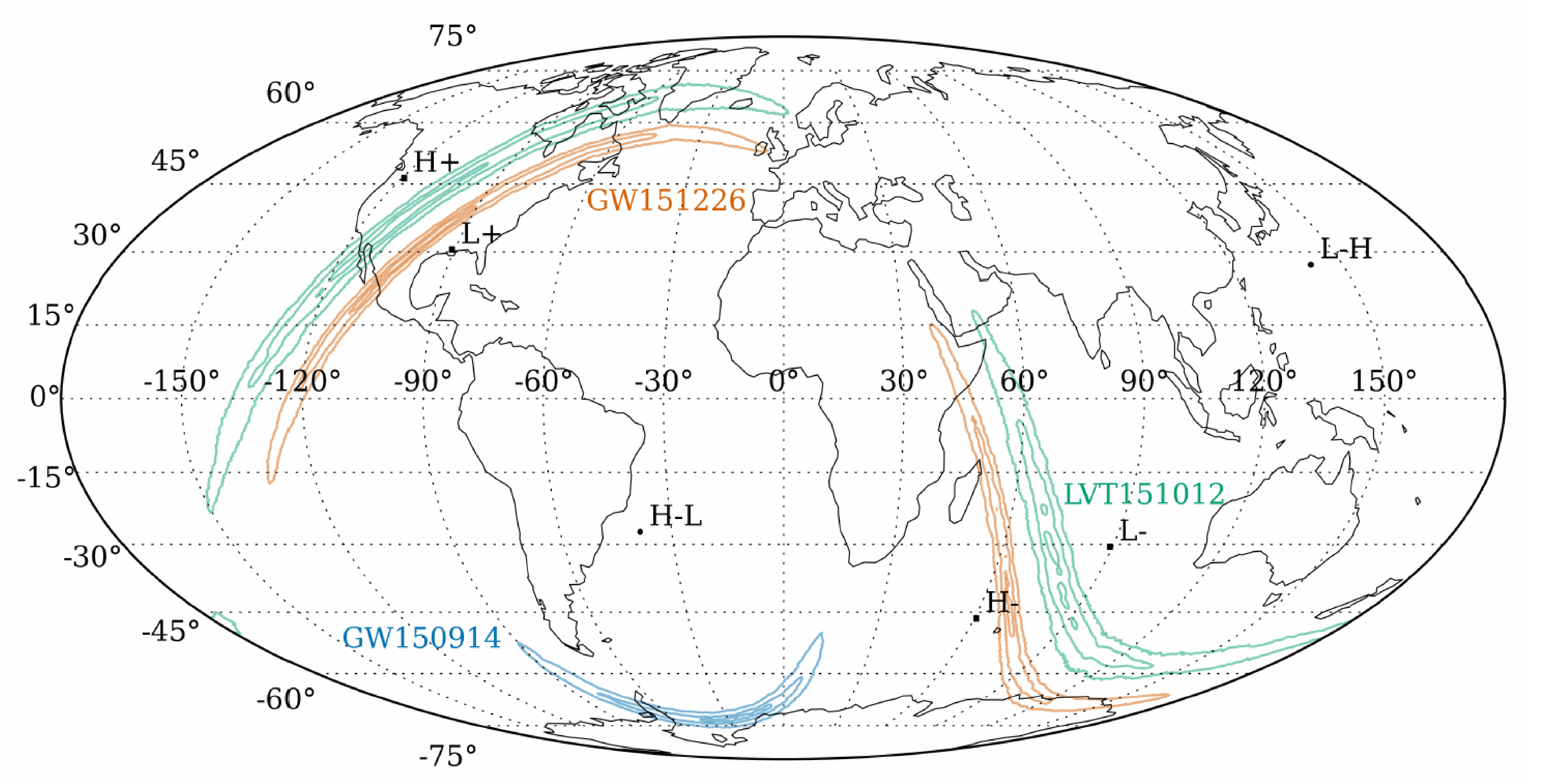
2σ 3σ 4σ 5σ > 5σ
2σ 3σ 4σ 5σ > 5σ
Search Result
Background excluding GW150914
Background excluding GW150914 and GW151226
Number of events
10^4 10^3 10^2 10^1 10^0 10^{-1} 10^{-2} 10^{-3} 10^{-4} 10^{-5} 10^{-6} 10^{-7} 10^{-8}
LVT151012
GW151226
8 10 12 14
Detection statistic $\hat{\rho}_c$

Black Holes of Known Mass



Black Hole Parameters





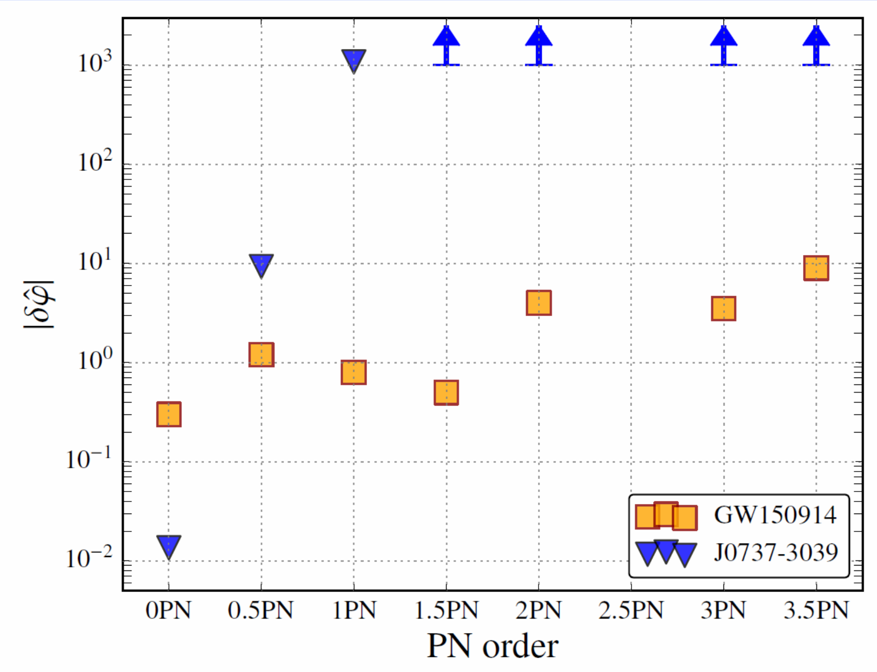
75°
60°
45°
30°
15°
0°
-15°
-30°
-45°
-60°
-75°
-150°
-120°
-90°
-60°
-30°
0°
30°
60°
90°
120°
150°
H+
L+
GW151226
L-H
LVT151012
H-L
L-
H-
GW150914

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	$^{+0.09}_{-0.09}$	

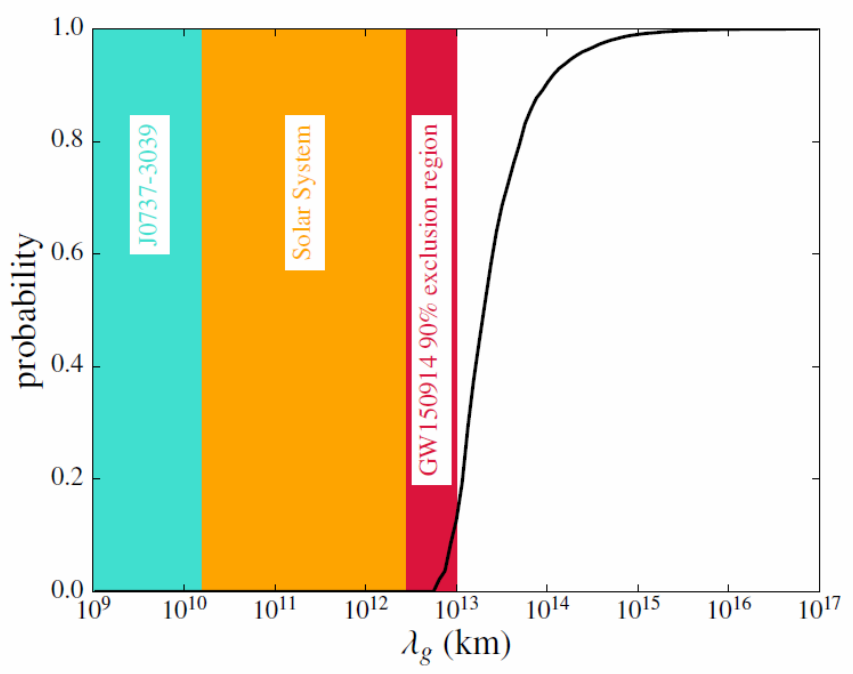
General Relativity Tests

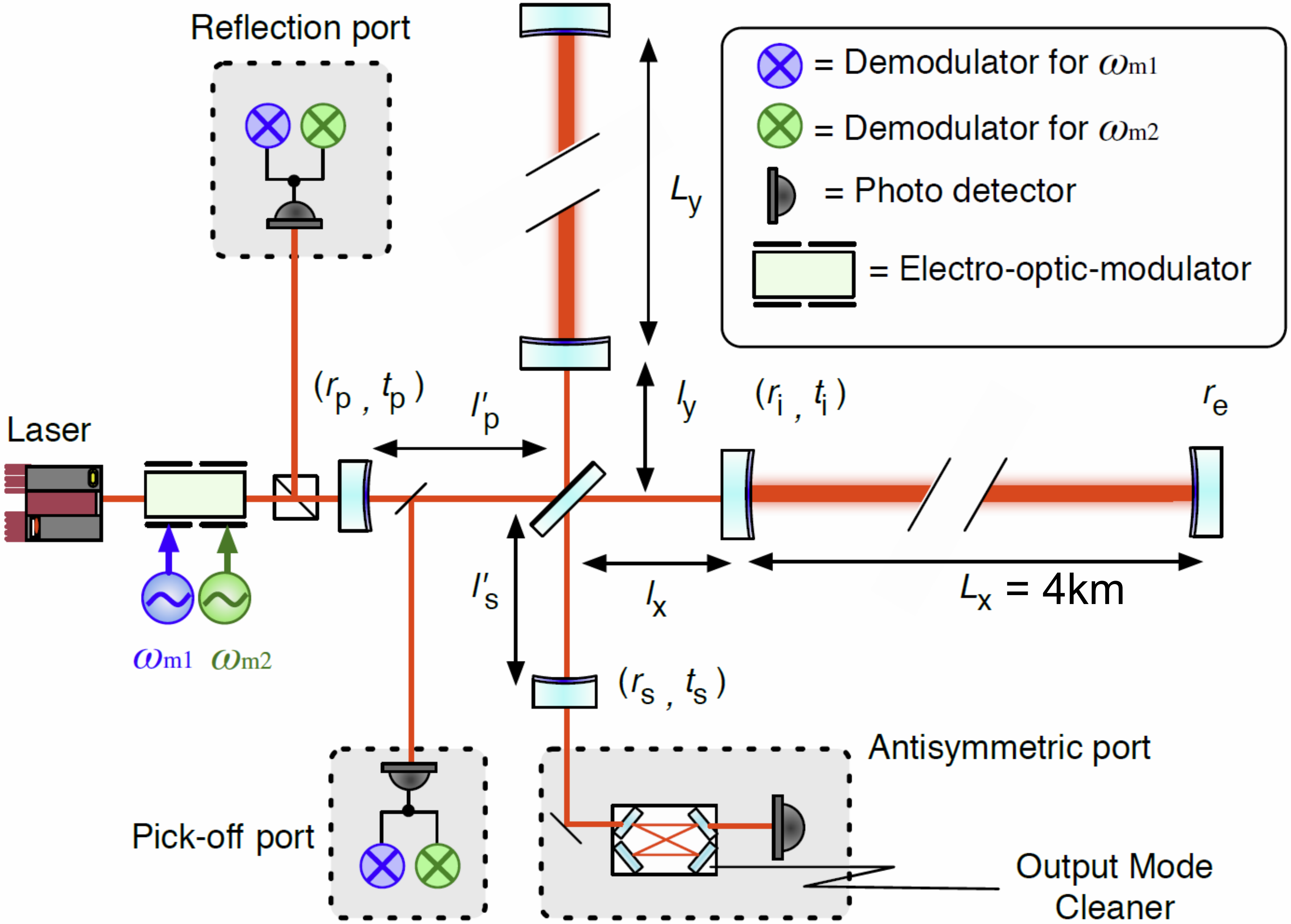
GW150914 is the first observation of a binary black hole merger…
… and thus is the best test of GR in the strong field, nonlinear regime

Post Newtonian Approximation



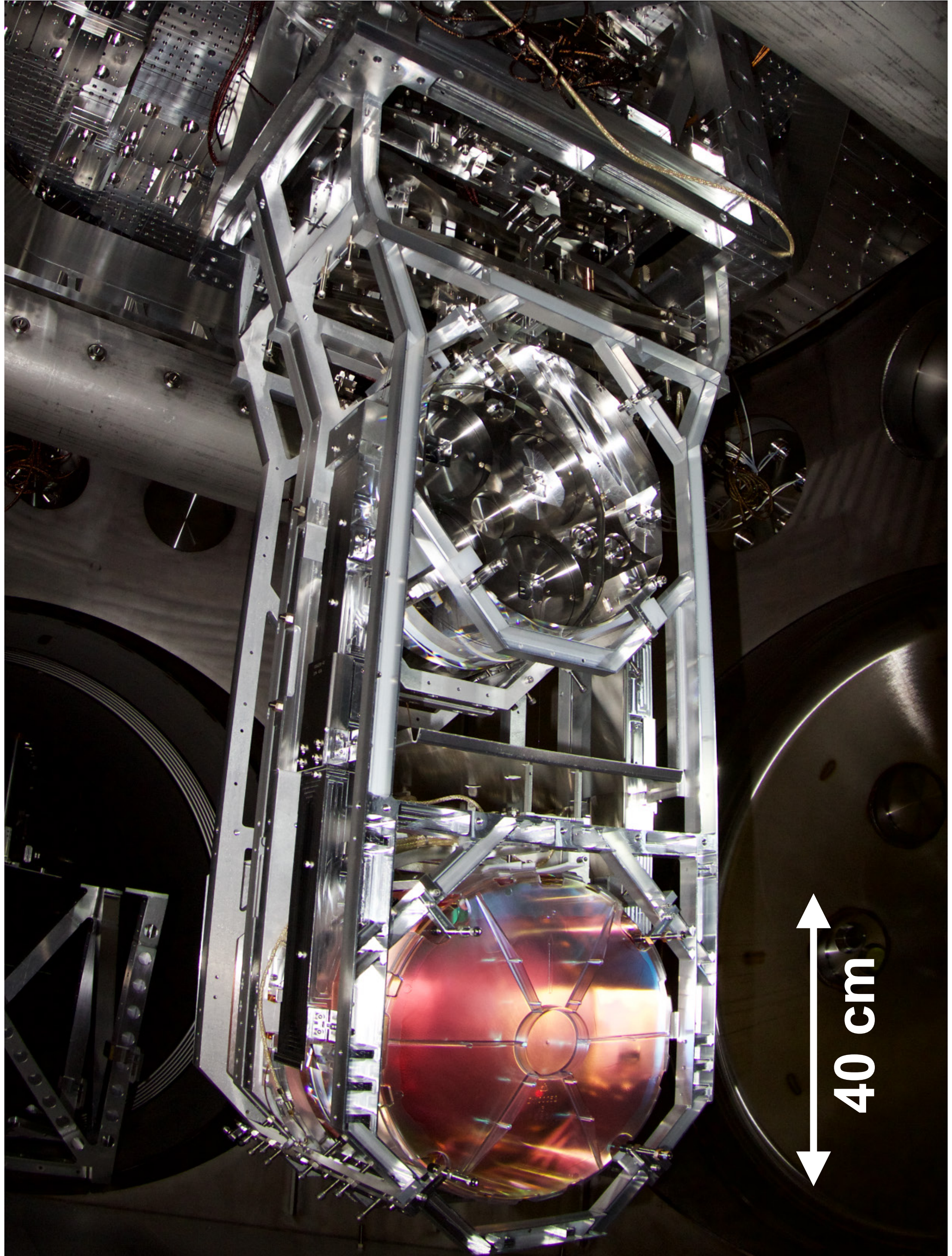
Graviton Compton Wavelength

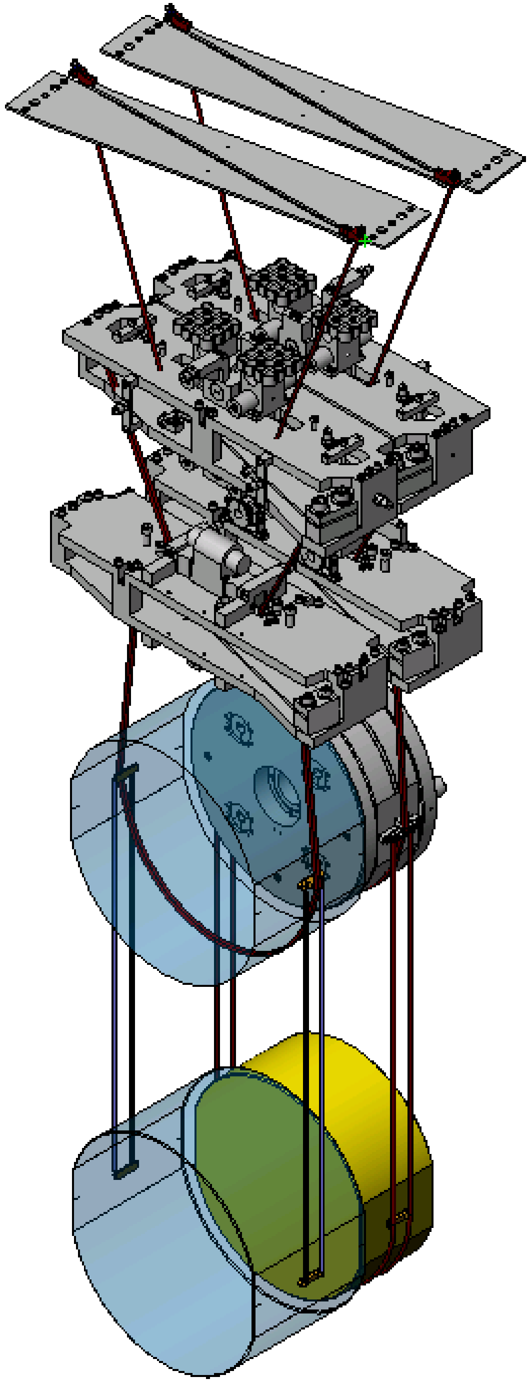




Reflection port
= Demodulator for ω_{m1}
= Demodulator for ω_{m2}
= Photo detector
= Electro-optic-modulator
L_y
(r_p, t_p)
l'_p
l_y
(r_i, t_i)
r_e
Laser
l'_s
l_x
L_x = 4km
ω_{m1} ω_{m2}
(r_s, t_s)
Antisymmetric port
Pick-off port
Output Mode Cleaner

Test Mass Suspension

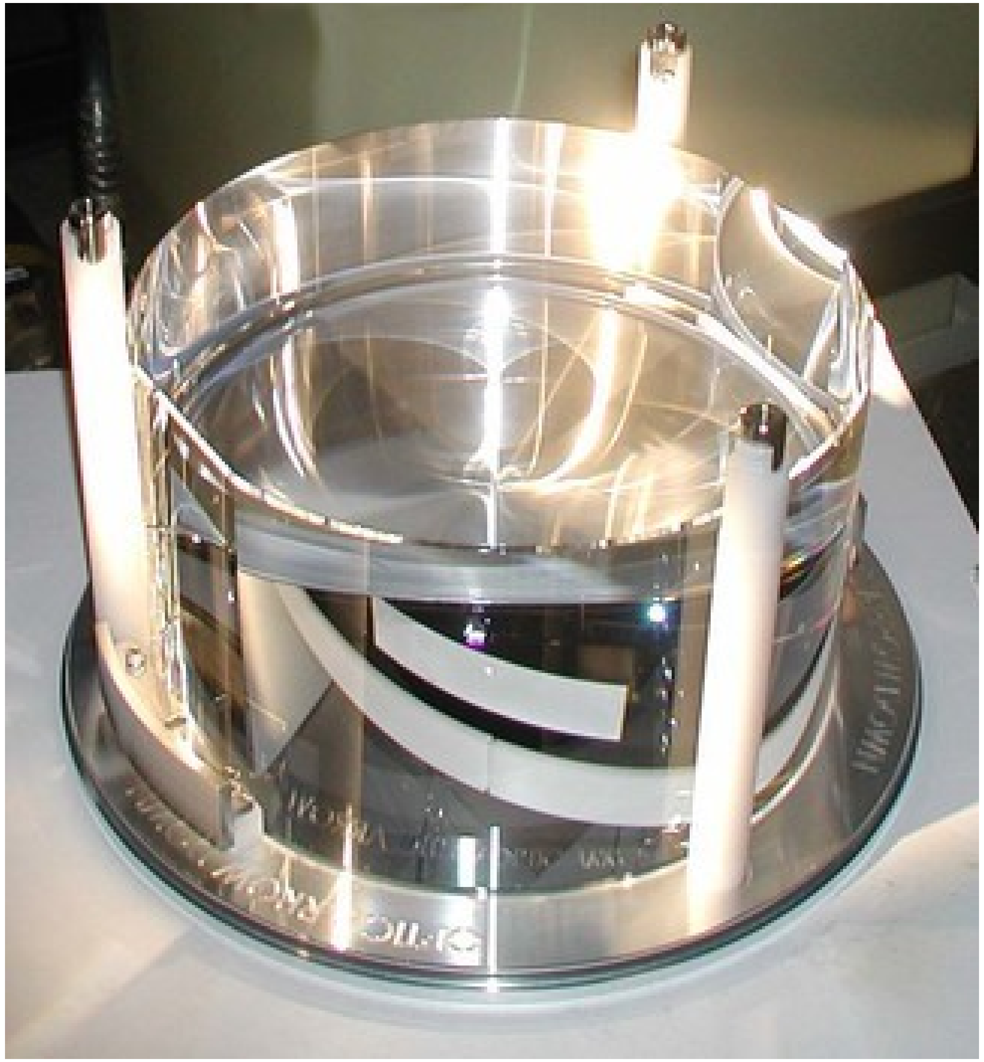




Large Test Mass Optics

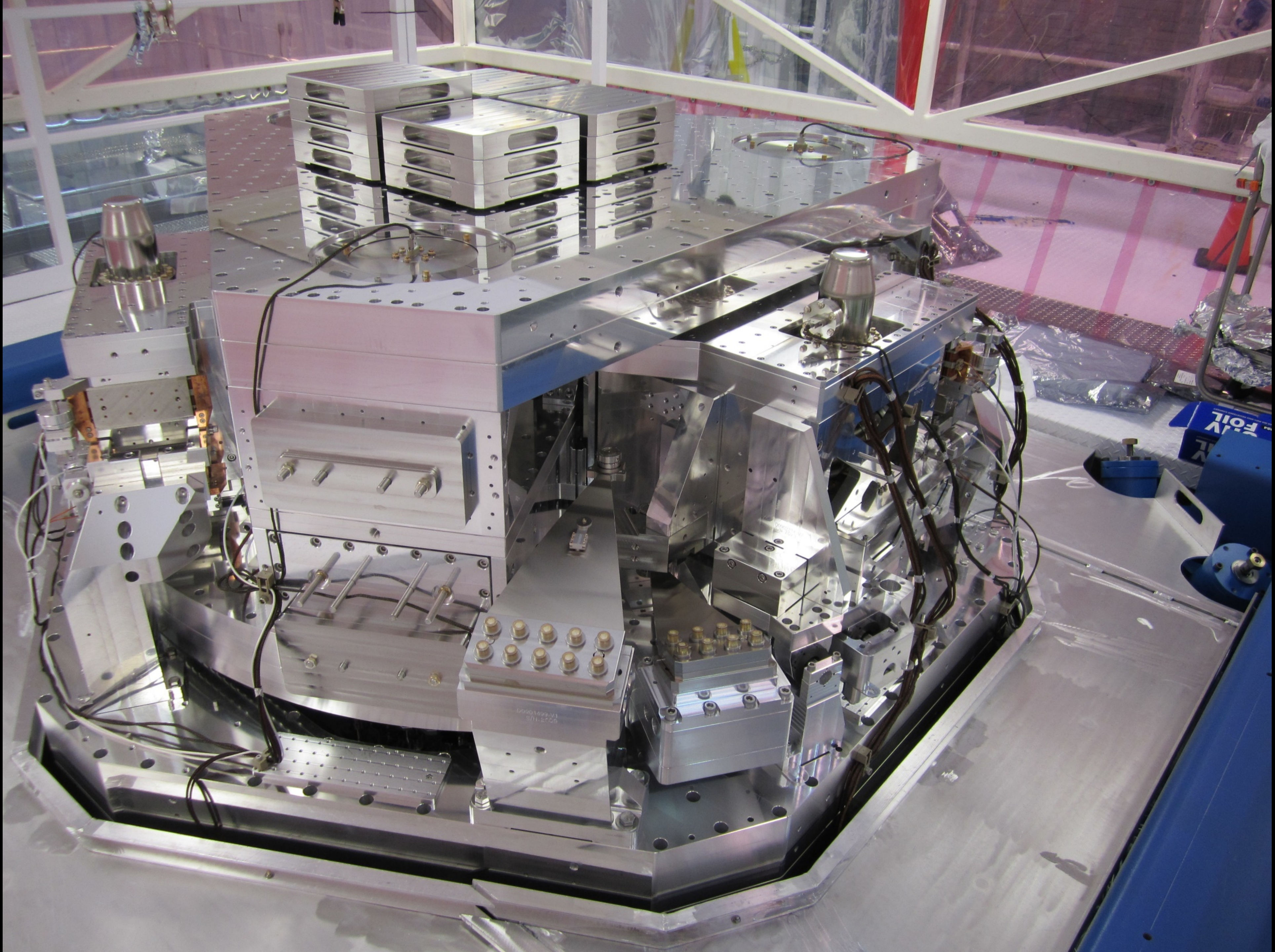
Specifications:

- 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

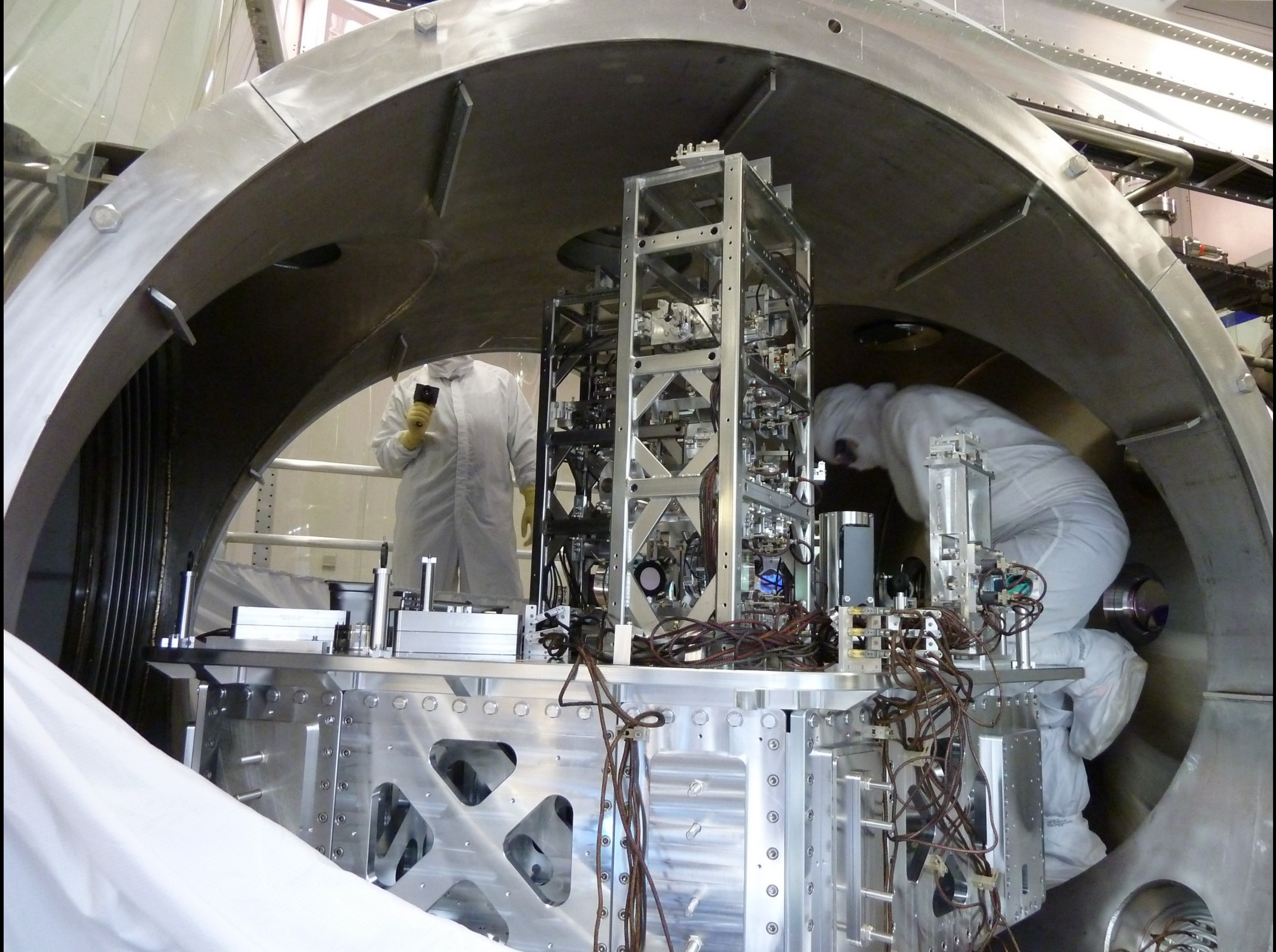


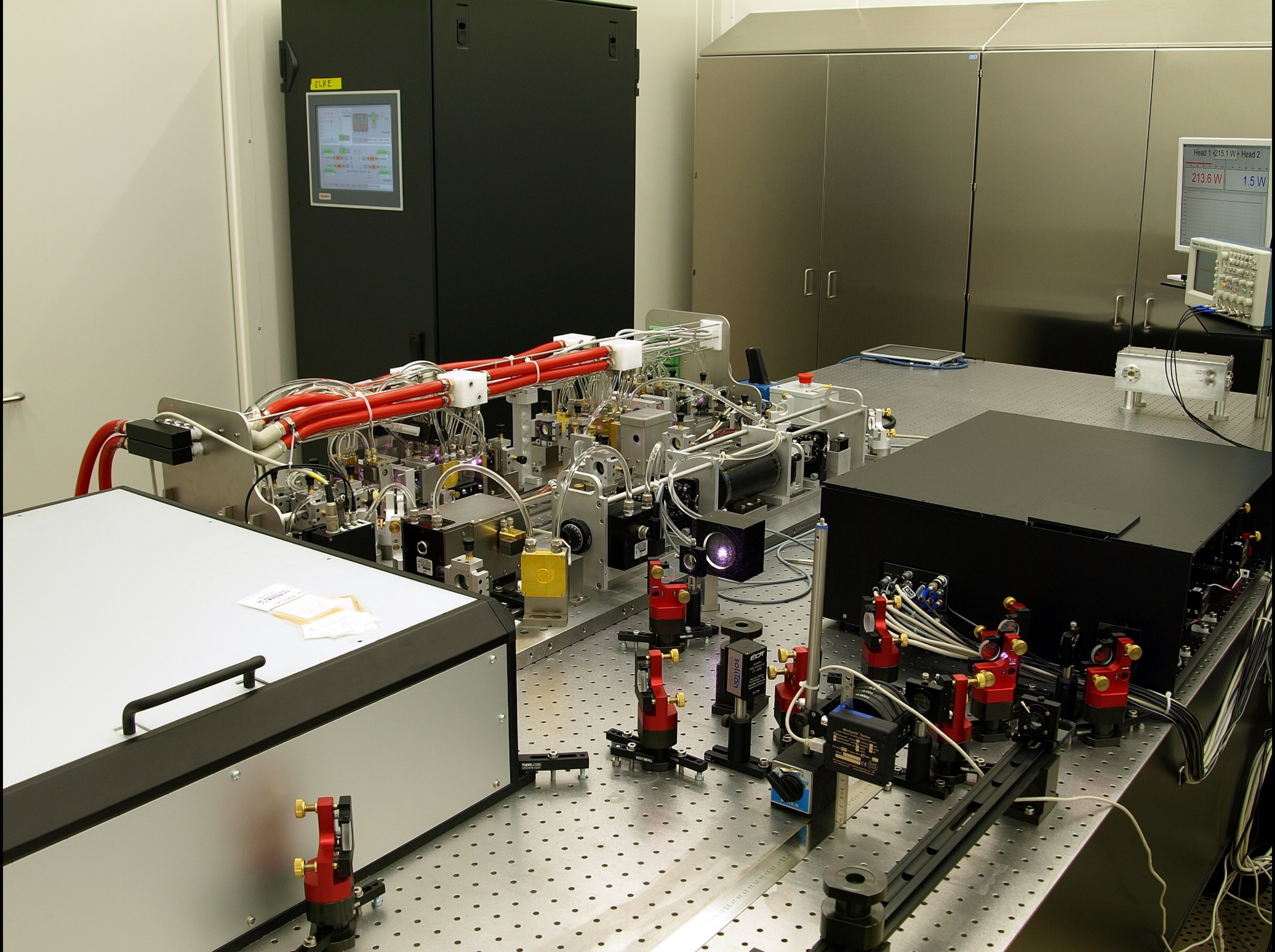
Vacuum System Vertex

Seismic Isolation Platform



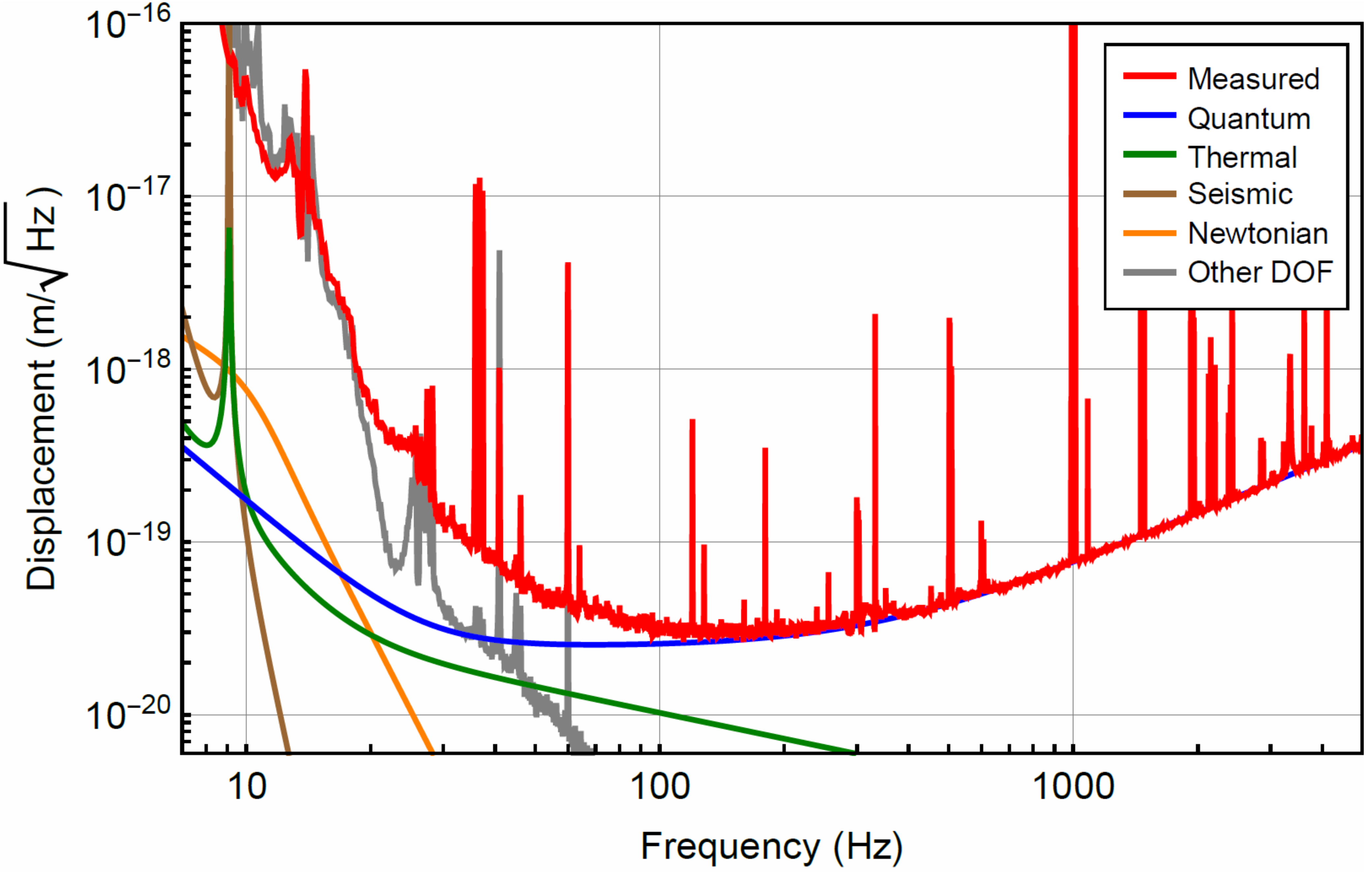
Input Optics Table



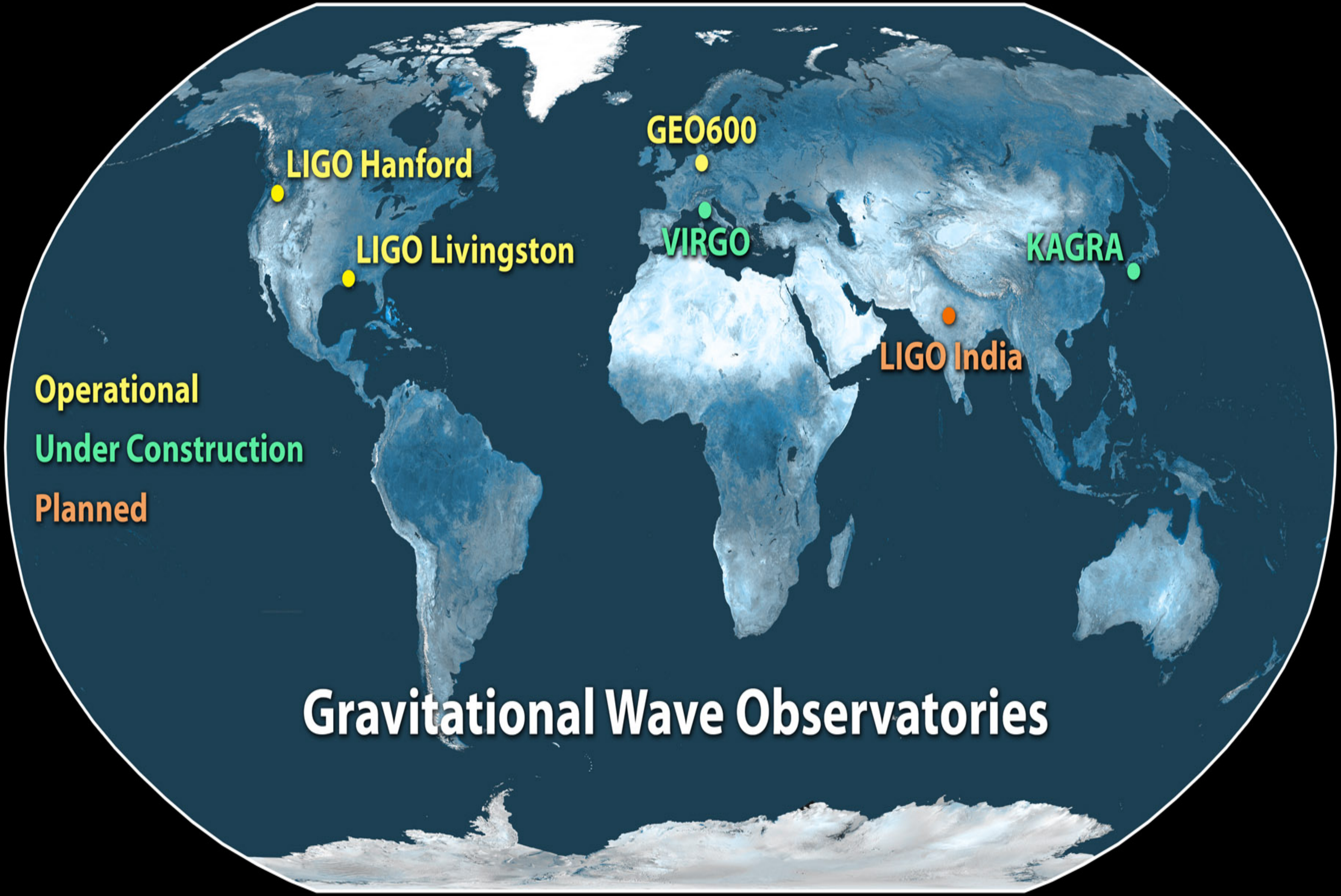


200W Pre-Stabilized Laser


Control Room
DELL



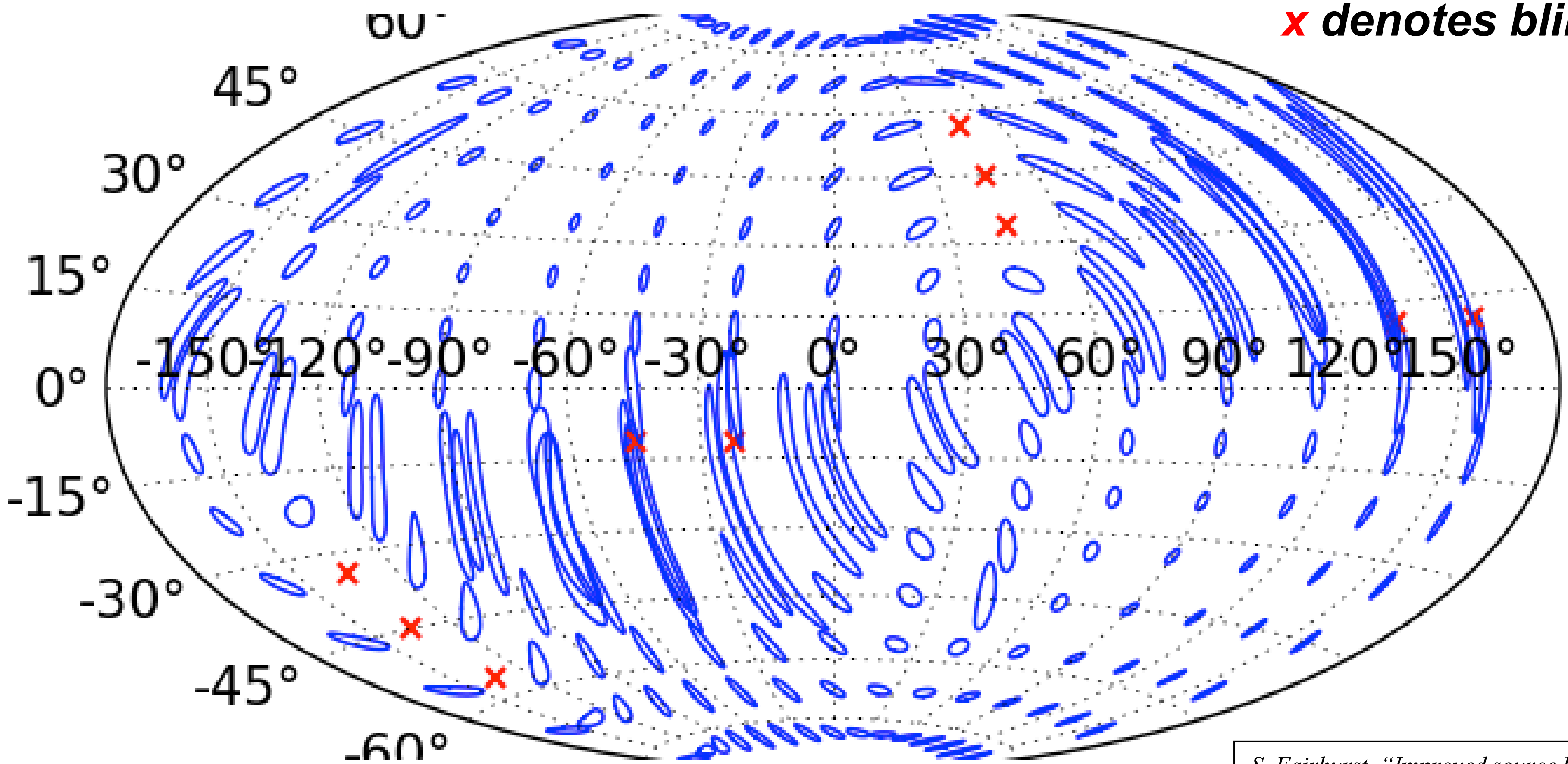
Measured
Quantum
Thermal
Seismic
Newtonian
Other DOF
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
Displacement (m/$\sqrt{\text{Hz}}$)
10
100
1000
Frequency (Hz)


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

Binary Neutron Star Merger Localization: Hanford-Livingston-Virgo

3 site network

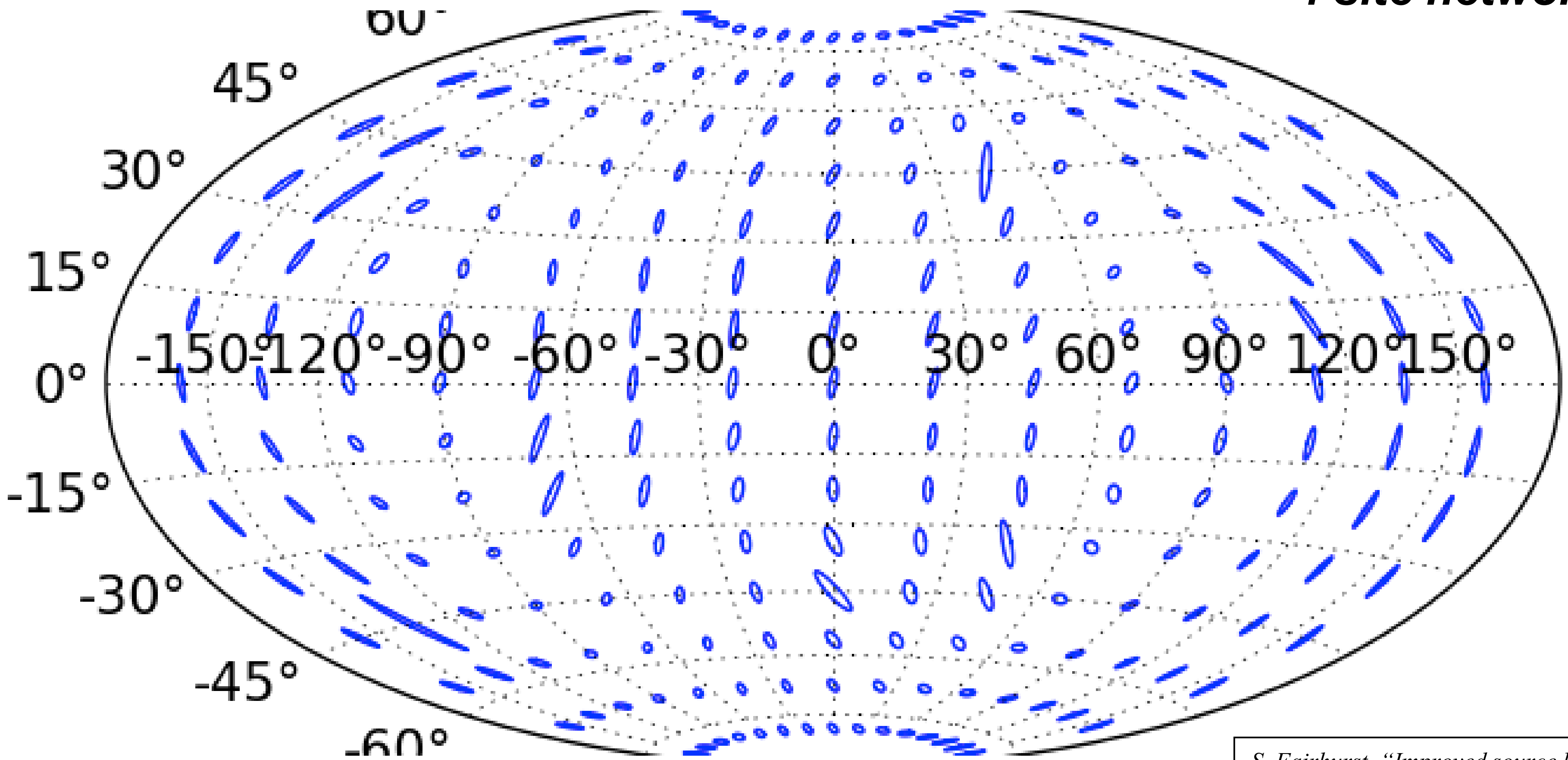
x denotes blind spots



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

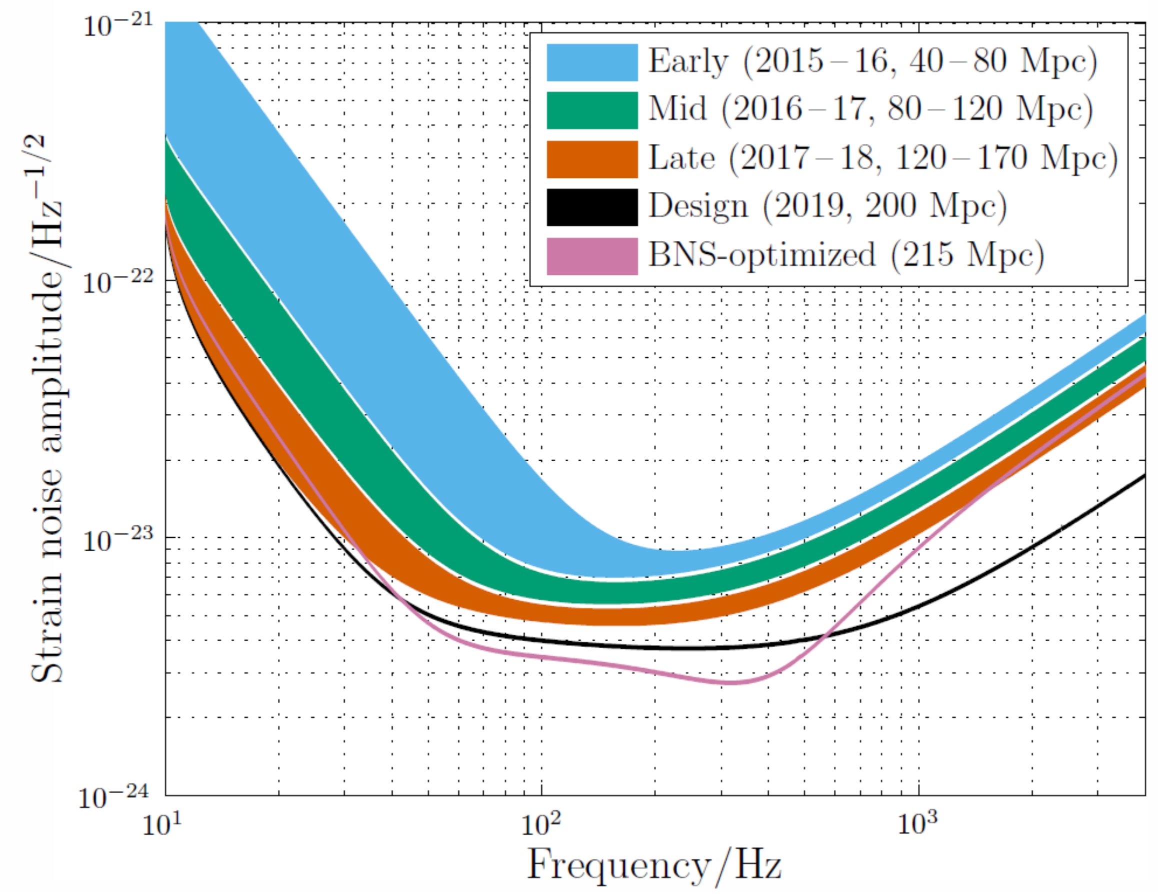
Binary Neutron Star Merger Localization: Hanford-Livingston-Virgo-India

4 site network

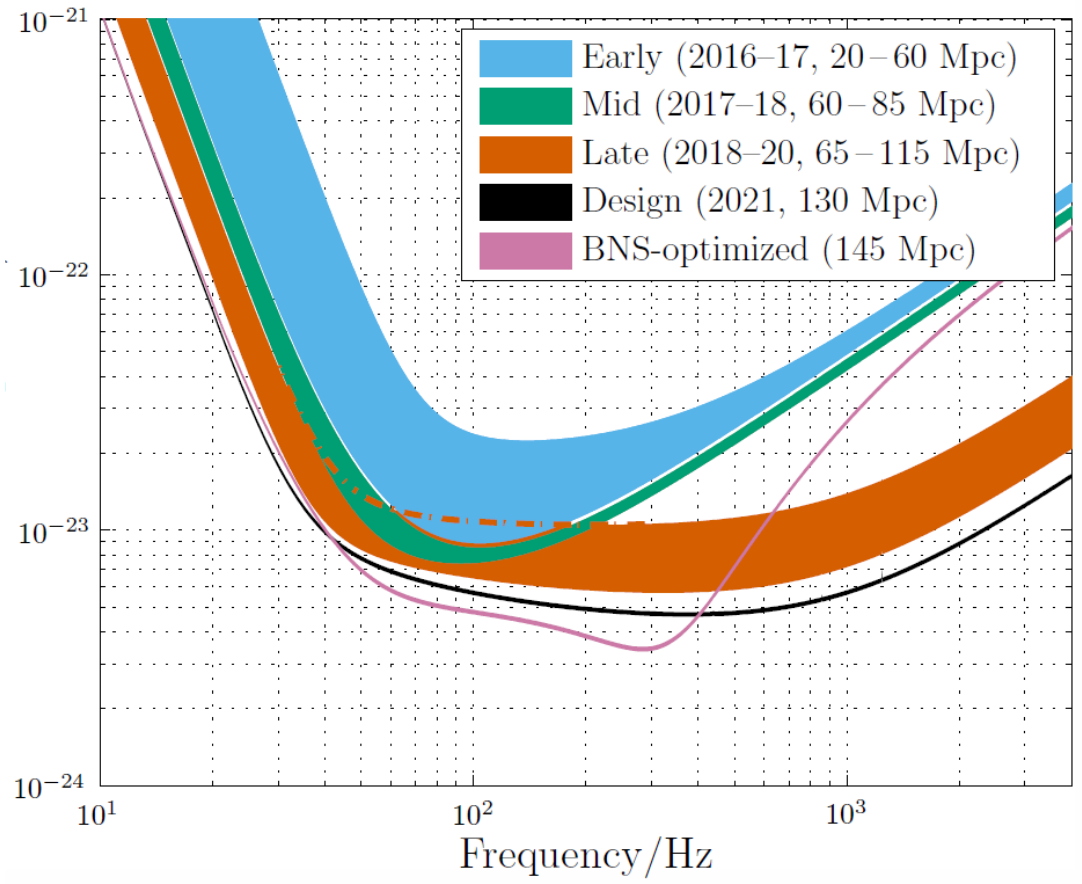


S. Fairhurst, "Improved source localization with LIGO India", [J. Phys.: Conf. Ser. ***484*** *012007]*

Preparation for Second Observation Run



Advanced LIGO

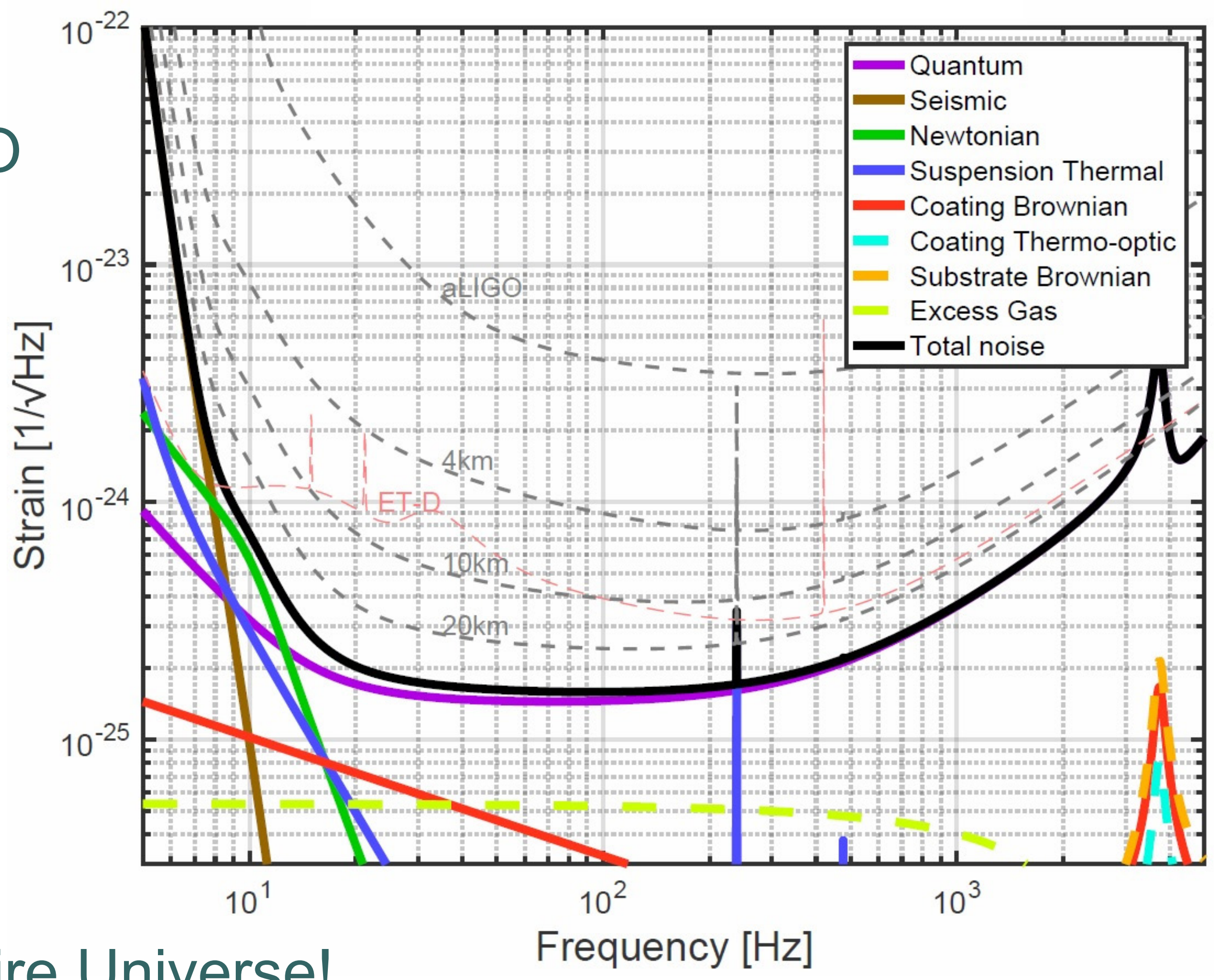


Advanced VIRGO

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!

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

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

- ***Two merging binary black hole systems have 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:

ligo.caltech.edu

LIGO
LASER INTERFEROMETER GRAVITATIONAL-WAVE OBSERVATORY

www.ligo.org

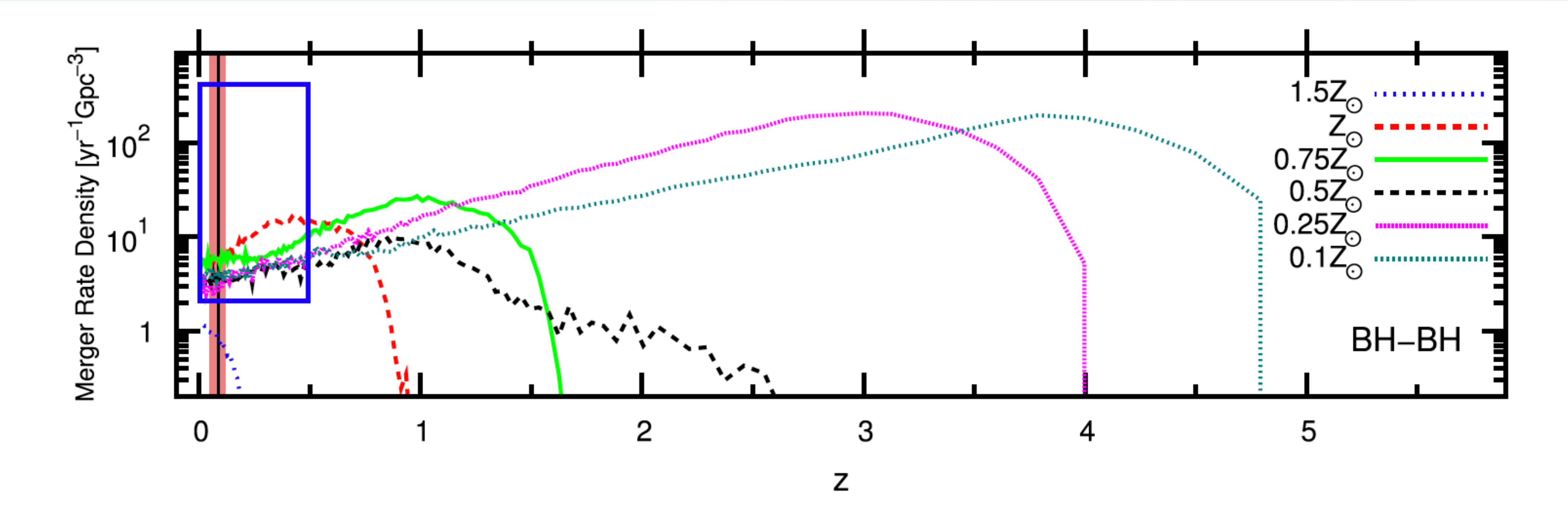
LIGO VIRGO

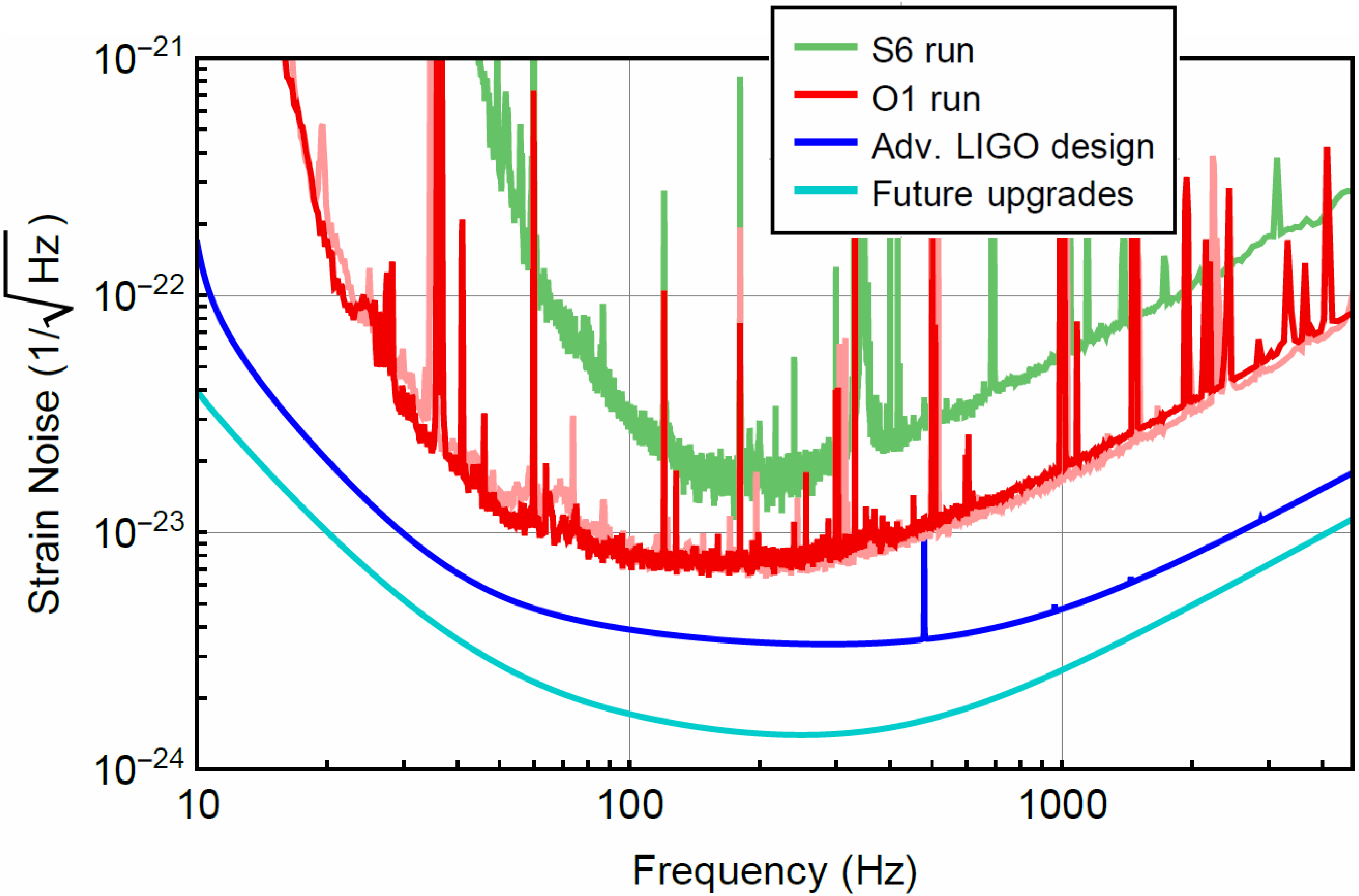
Support: National Science Foundation

NSF

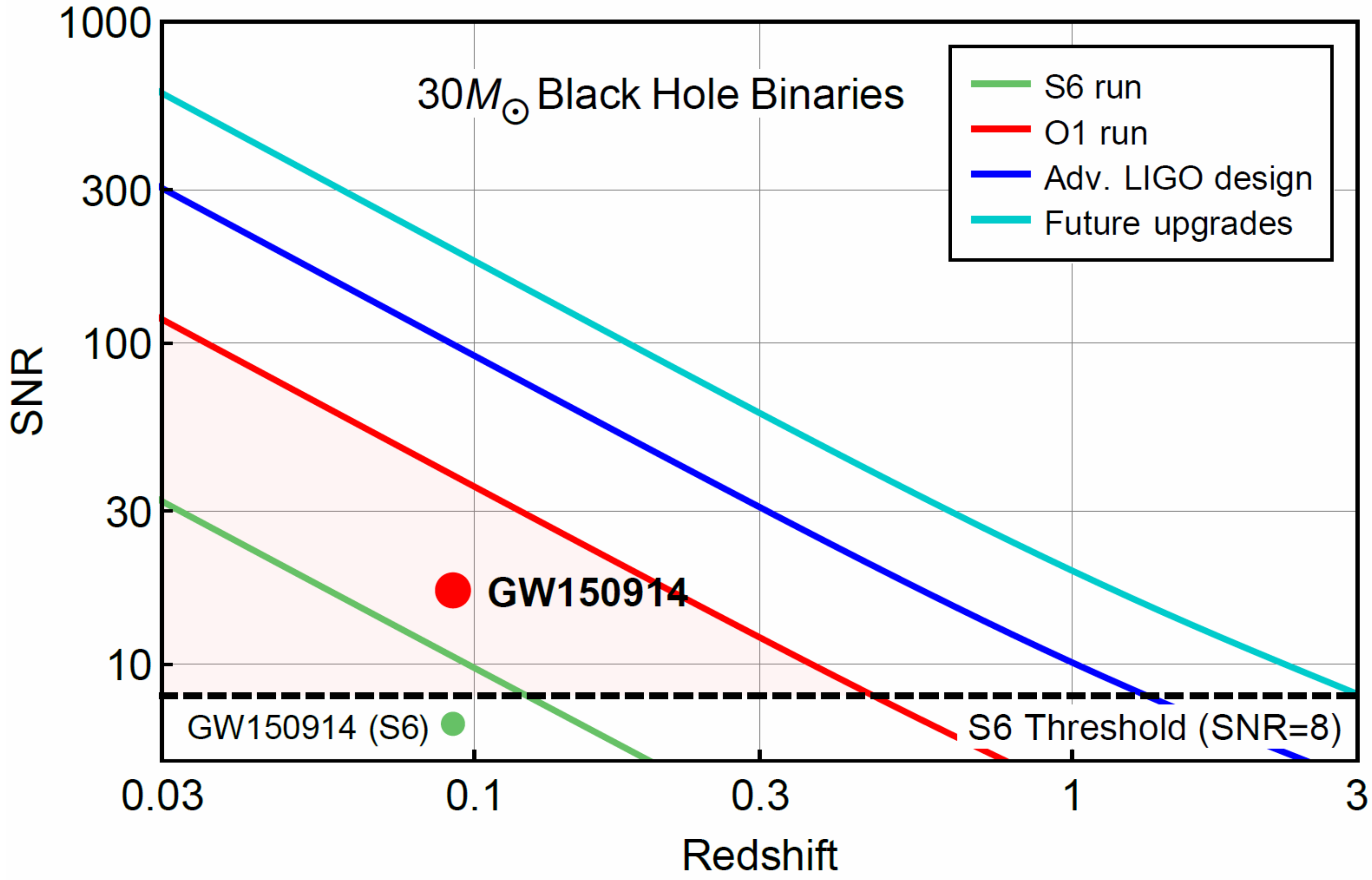
Astrophysical Implications

- Merger rate of stellar mass BBHs implied by the detection: 9–240/Gpc^3 yr
- Most robust evidence for existence of ‘heavy’ stellar mass black holes: > 20 $M_\odot$
- Most likely formed in a low-metallicity environment: <½ $Z_\odot$ and possibly even <¼ $Z_\odot$
- BBH formation in dense clusters is consistent with GW150914:
  - Clusters have typical metallicities less than $Z_\odot$ to form ‘heavy’ stellar mass BHs
  - Most mergers occur outside the clusters following dynamical BBH ejection



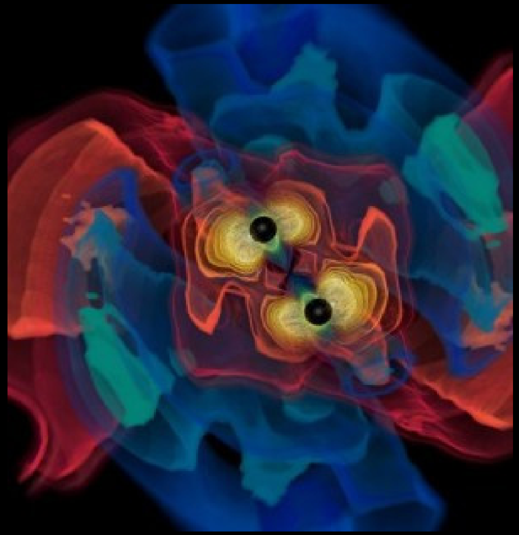


S6 run
O1 run
Adv. LIGO design
Future upgrades
Strain Noise (1/√Hz)
10−21
10−22
10−23
10−24
10
100
1000
Frequency (Hz)



1000
300
100
30
10
SNR
0.03
0.1
0.3
1
3
Redshift
$30M_\odot$ Black Hole Binaries
S6 run
O1 run
Adv. LIGO design
Future upgrades
GW150914
GW150914 (S6)
S6 Threshold (SNR=8)

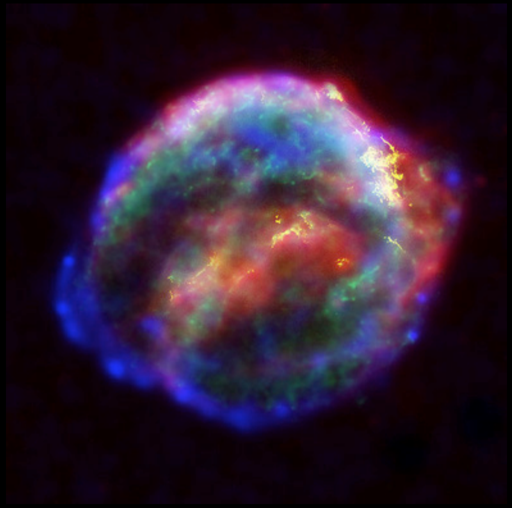
Astrophysical Targets for Ground-based Detectors



Credit: AEI, CCT, LSU

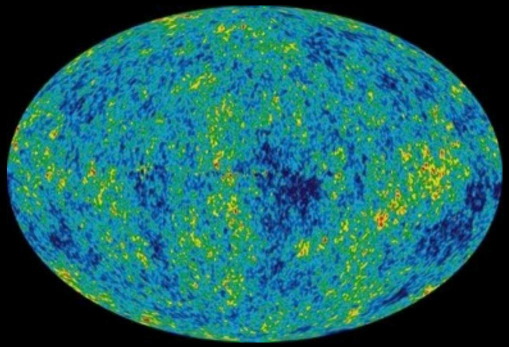
Coalescing Binary Systems

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



'Bursts'

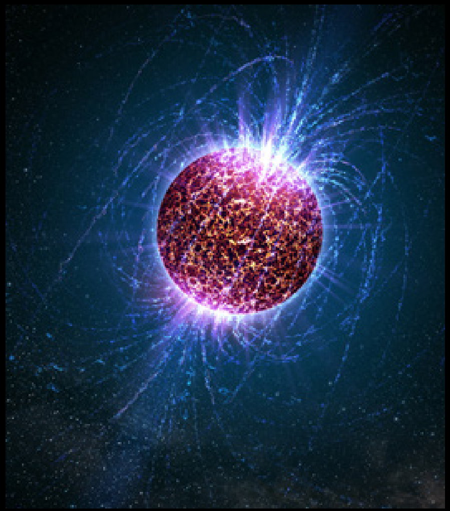
- *Unmodeled*
- *galactic asymmetric core collapse supernovae*
- *cosmic strings*
- ***???***



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'*

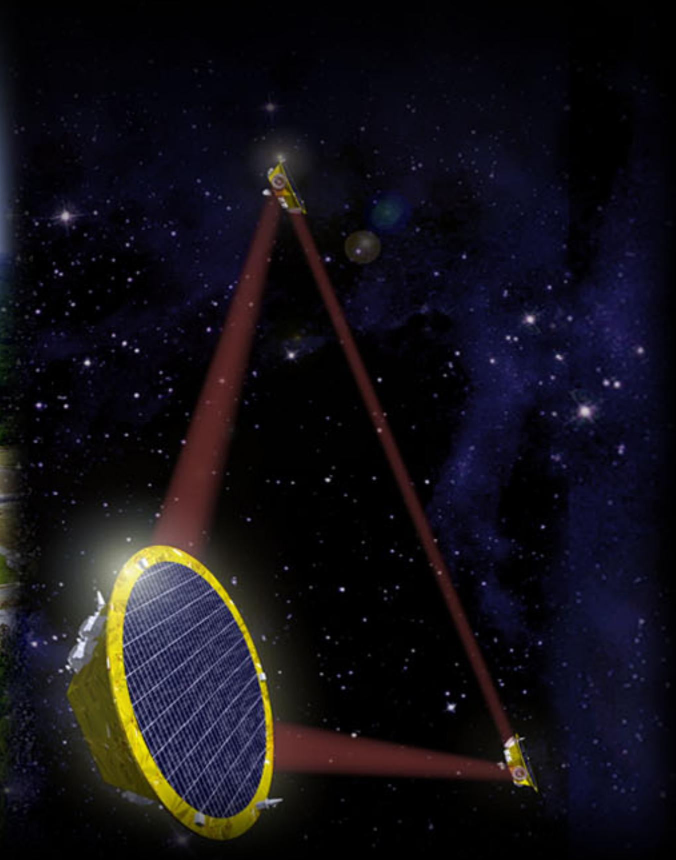
Gravitational Wave Periods

Milliseconds

Gravitational Wave Periods

Milliseconds

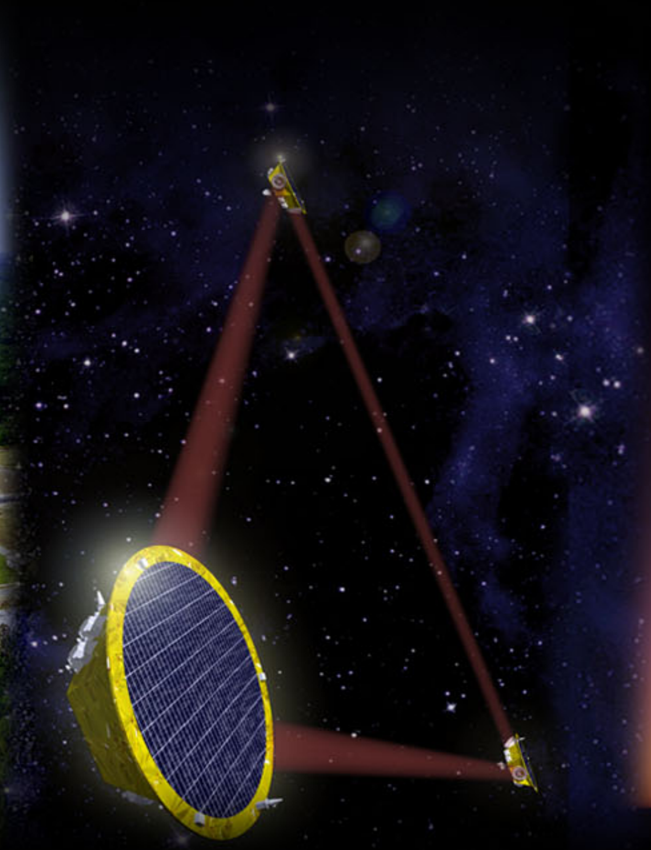
Minutes
to Hours



Gravitational Wave Periods

Milliseconds

Minutes to Hours

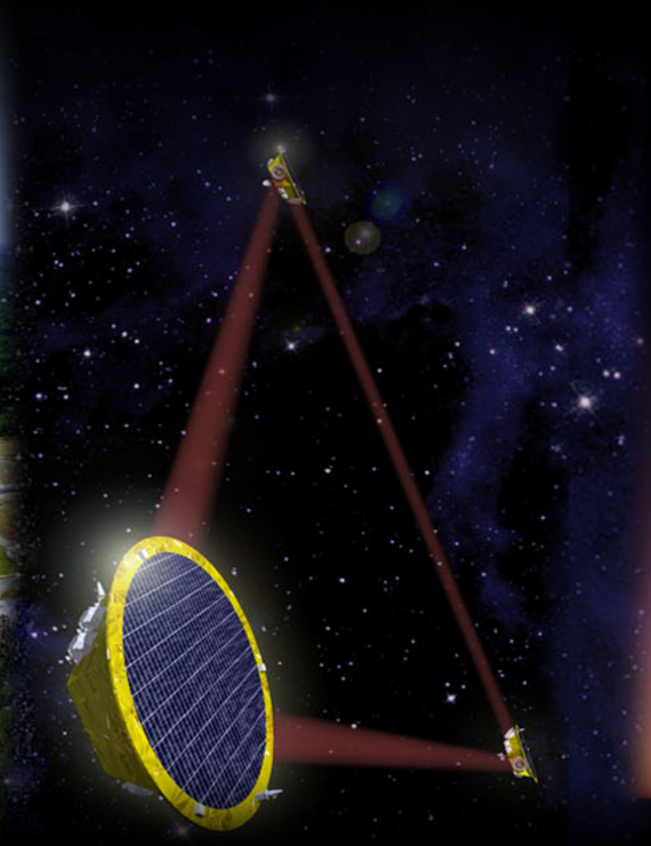


Years to Decades

Gravitational Wave Periods

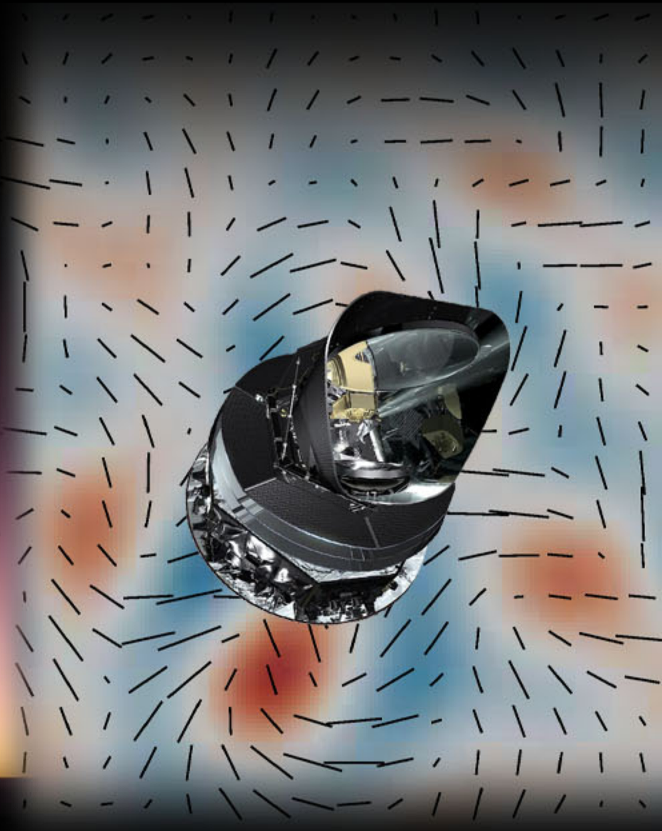
Milliseconds

Minutes to Hours



Years to Decades

Billions of Years



The Gravitational-wave Spectrum