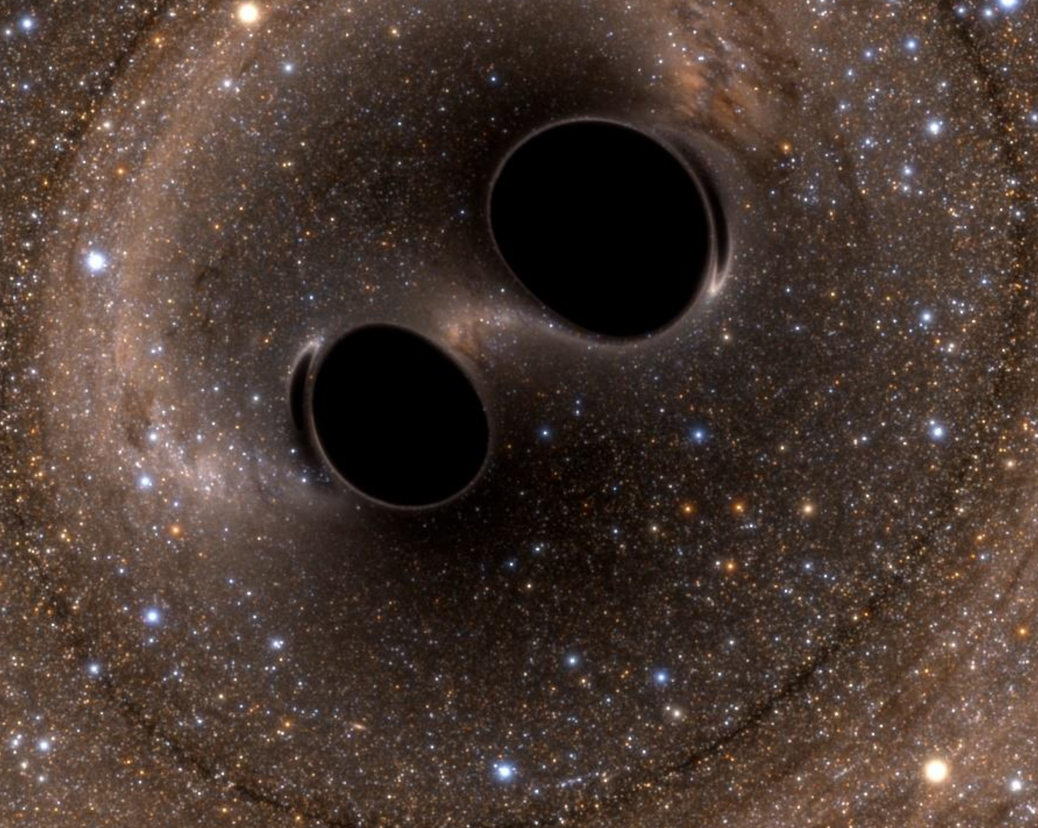
The Search for Gravitational Waves with Advanced LIGO



Daniel Sigg

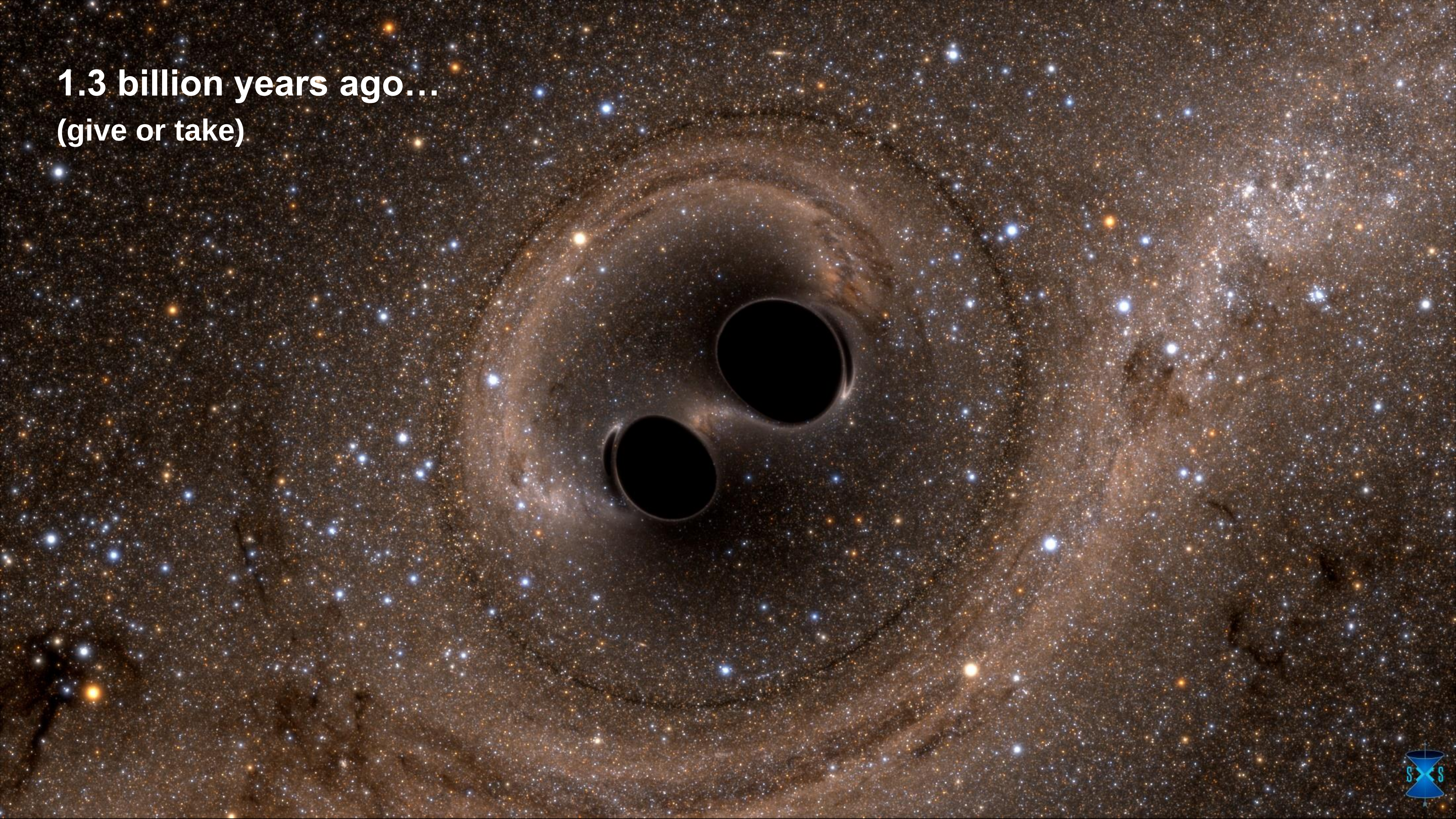
LIGO Hanford Observatory

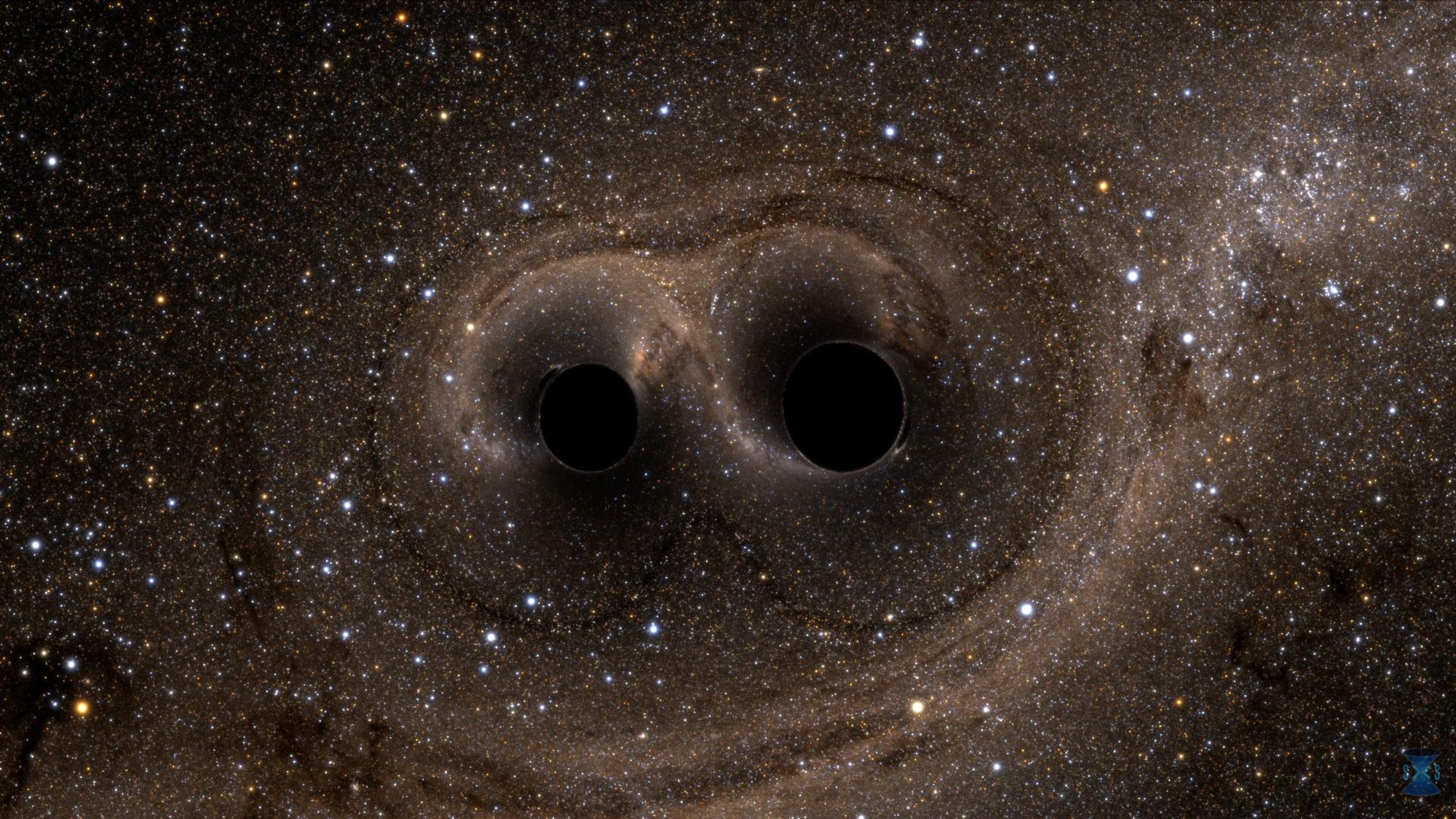
California Institute of Technology

April 6, 2016

For the LIGO Scientific Collaboration and the Virgo Collaboration

LIGO-G1501573-v1


1.3 billion years ago…
(give or take)



2016: The Centenary of Gravitational Waves

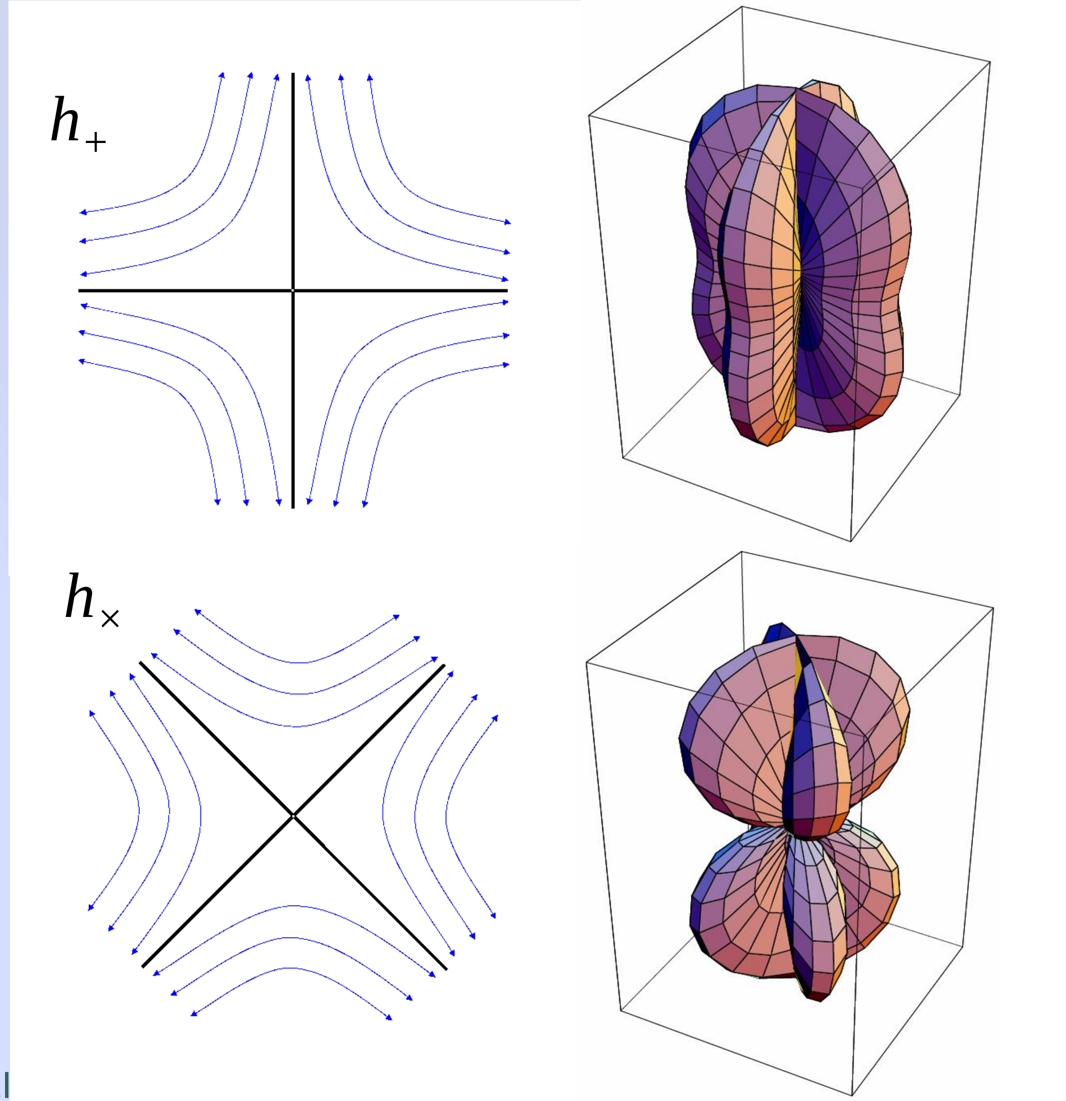
Metric: $ds^2 = g_{\mu\nu} dx^\mu dx^\nu$

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

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

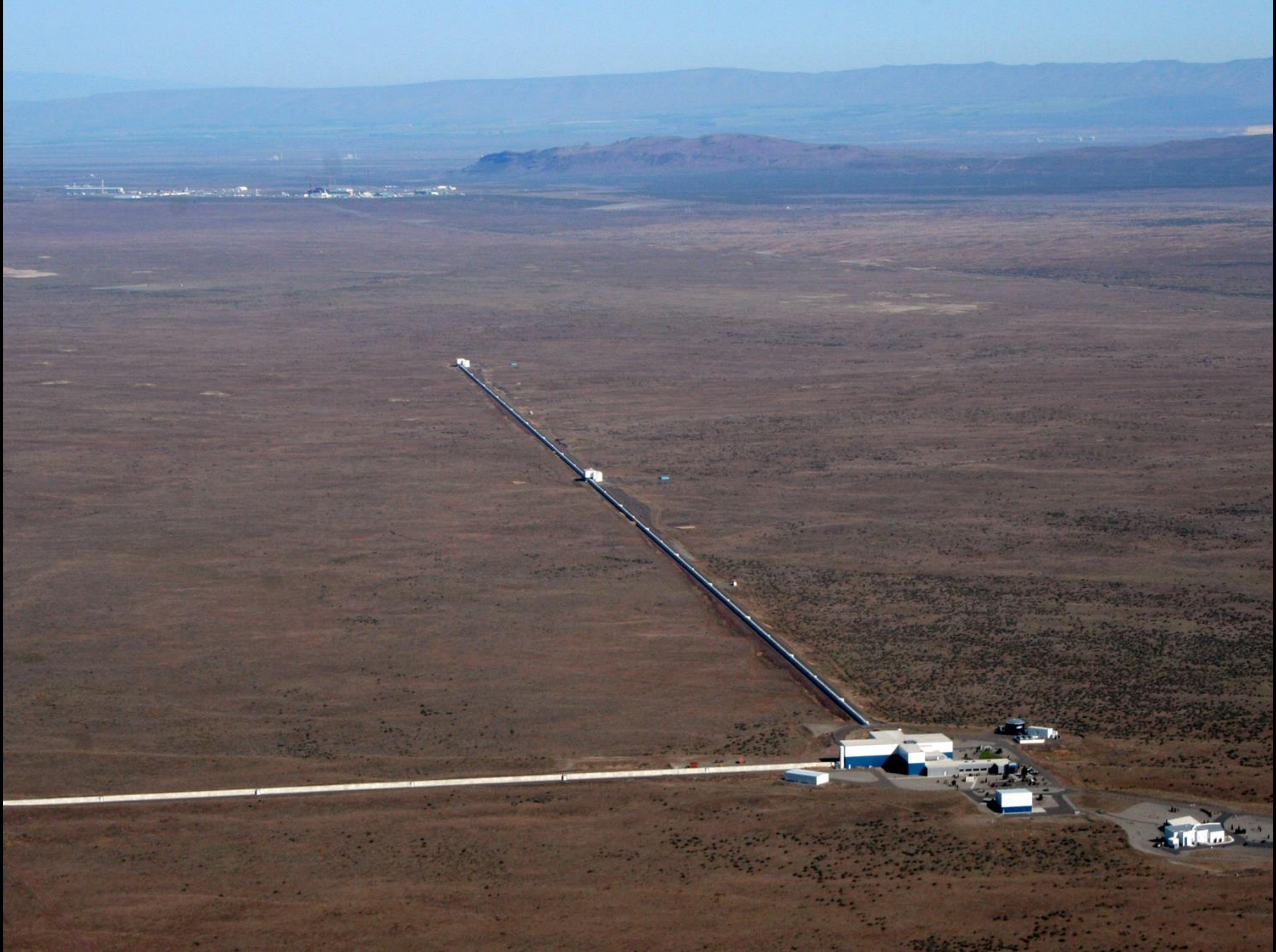
Physically,
h is a strain ~ $\Delta L/L$

Measure with a Michelson interferometer

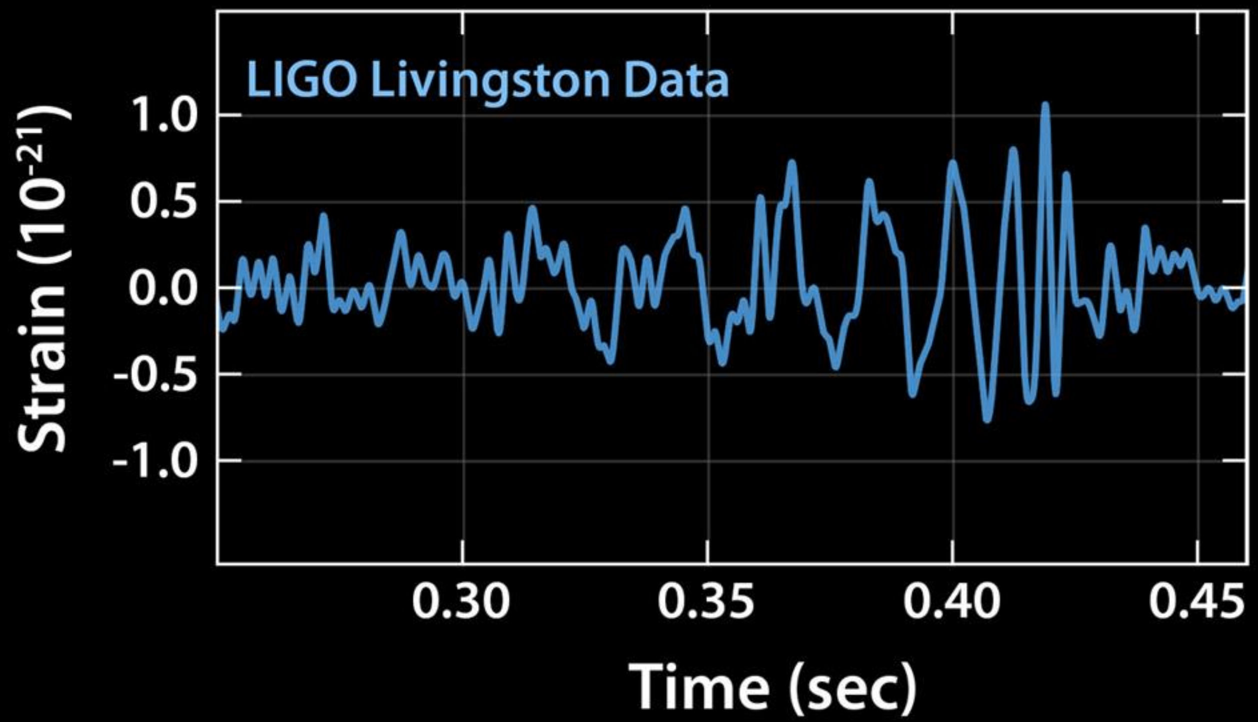


Livingston Observatory

Hanford Observatory

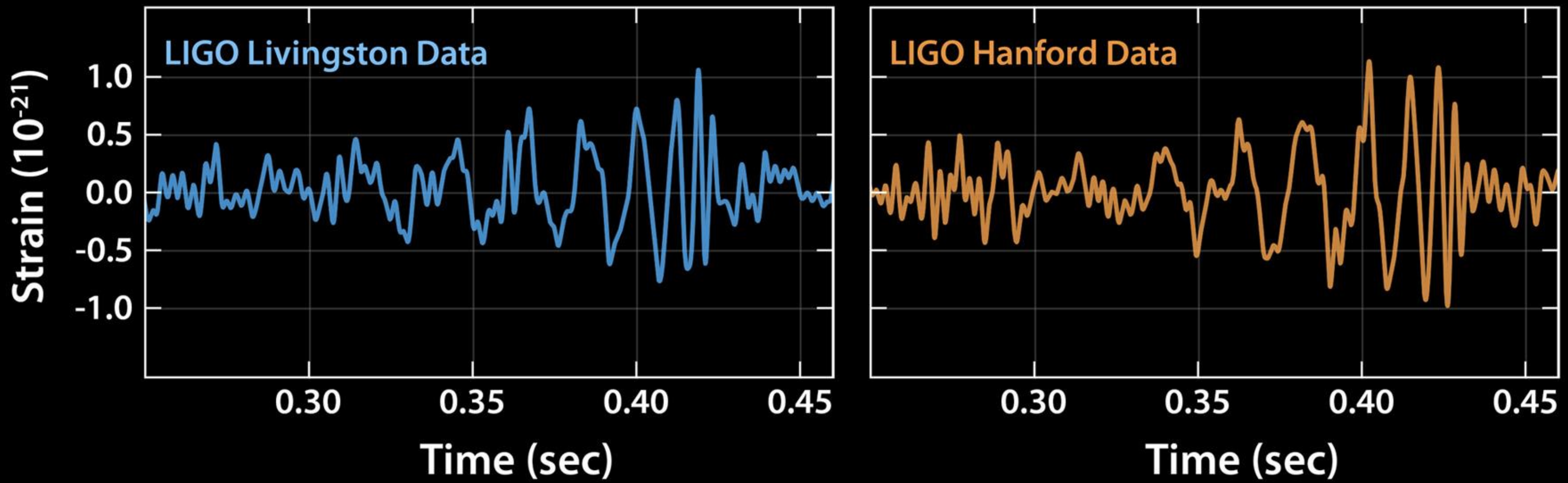


GW150914



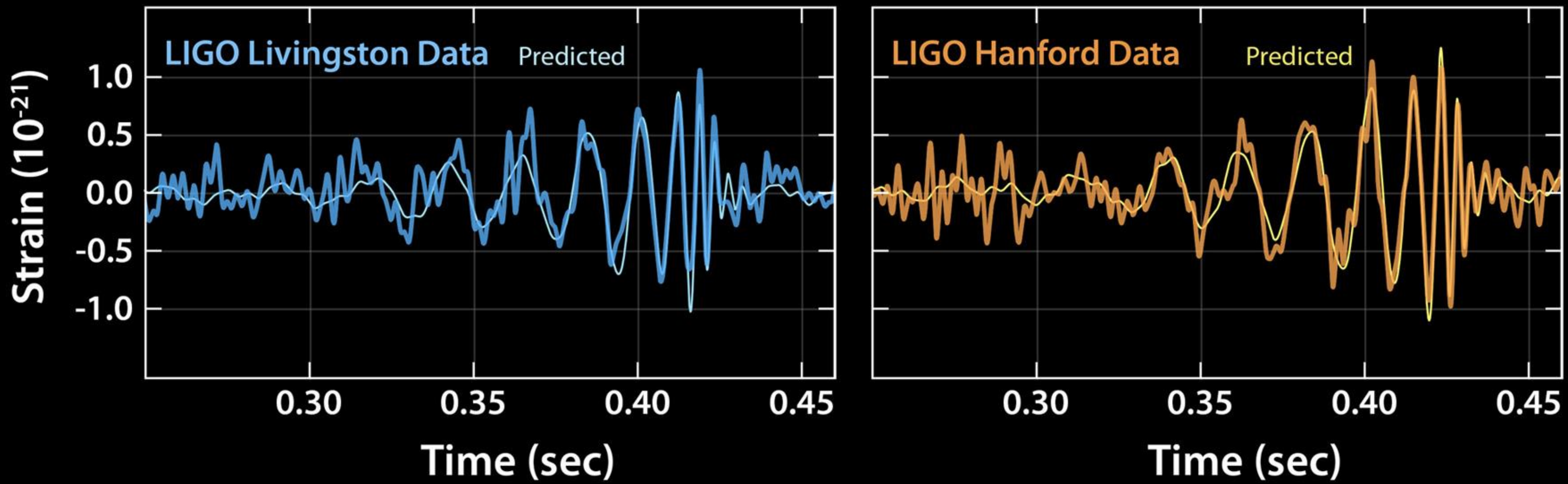
~1/200th proton radius

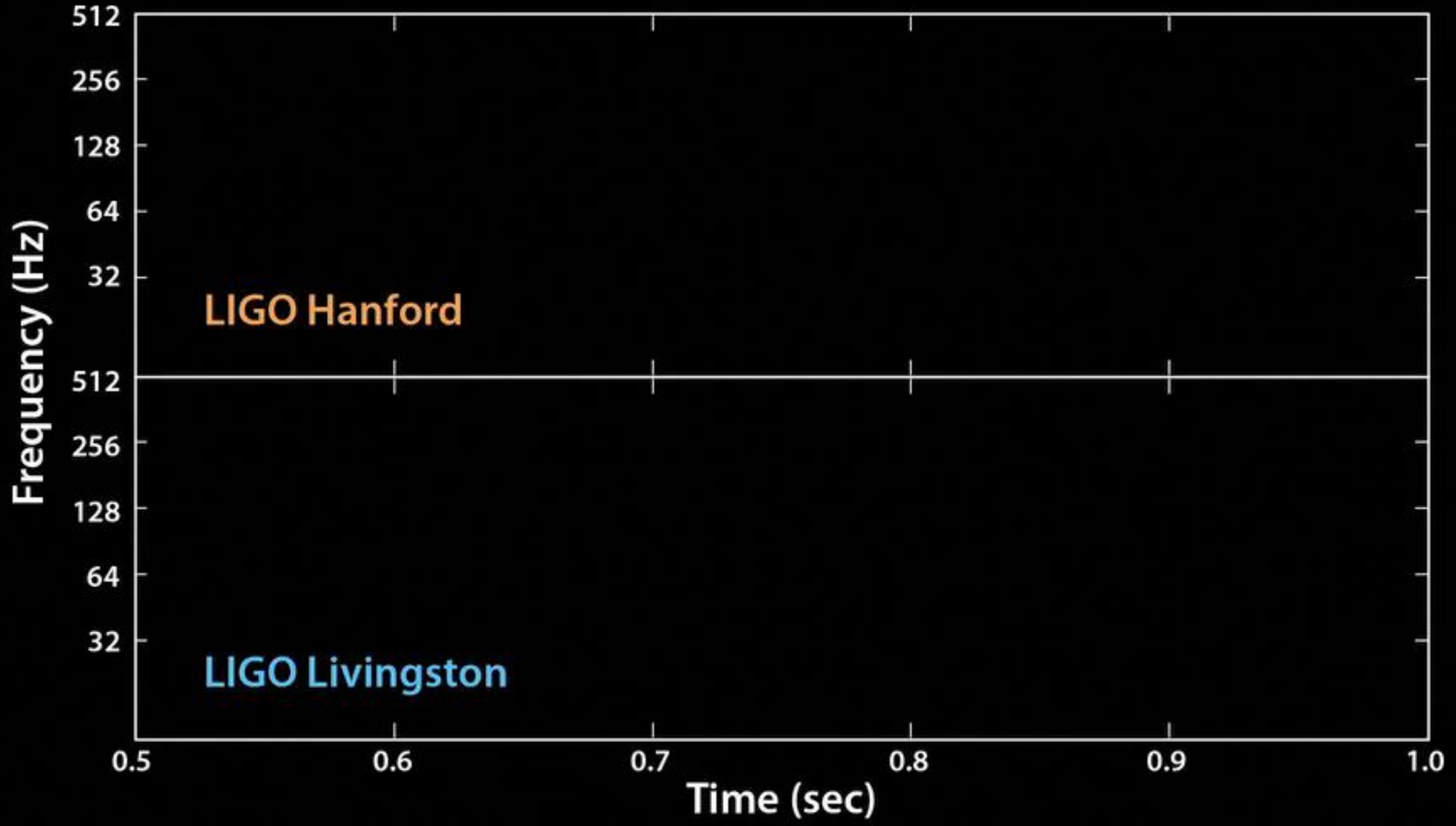
GW150914

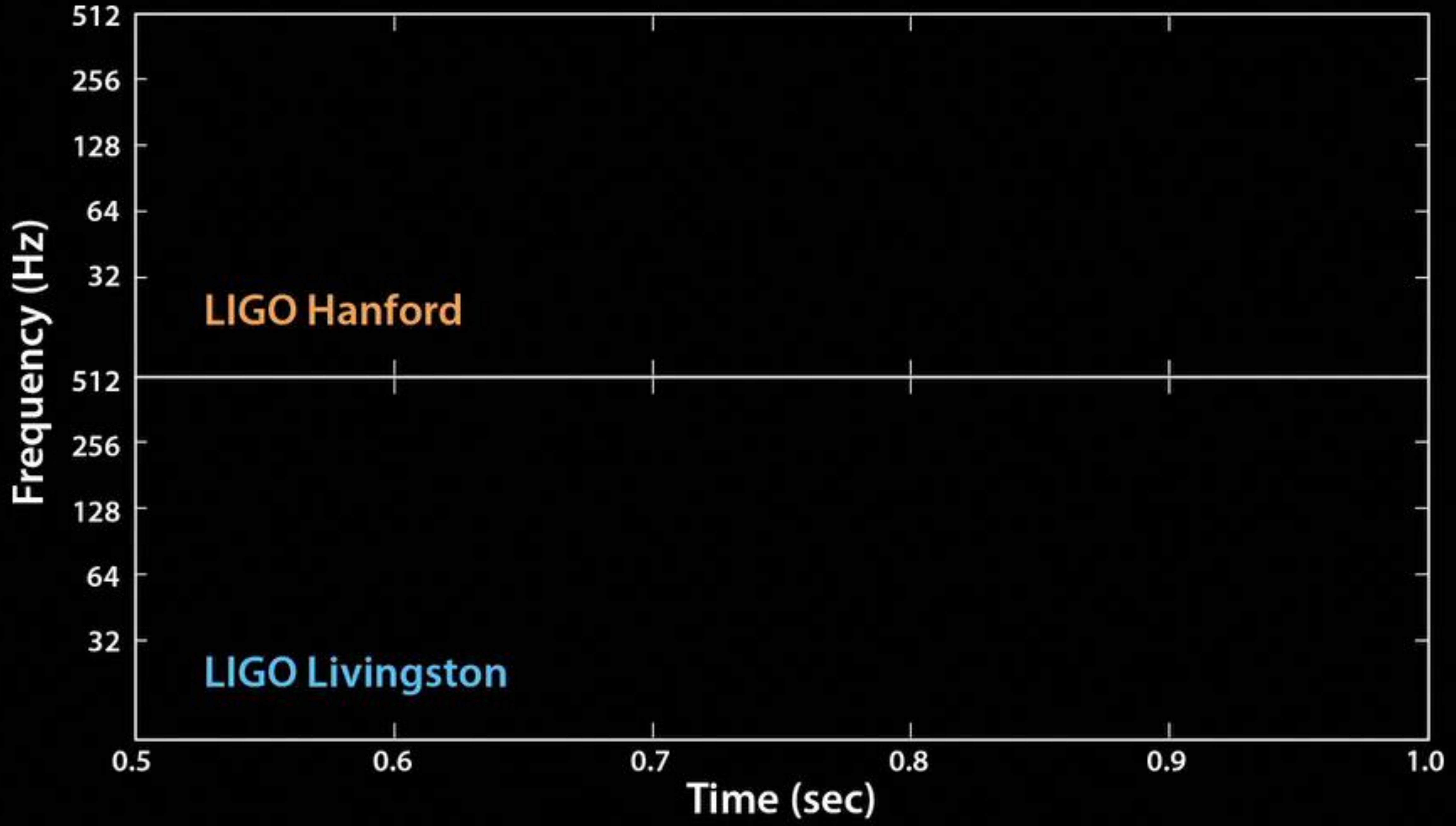


LIGO Livingston Data
LIGO Hanford Data
Strain (10^{-21})
1.0
0.5
0.0
-0.5
-1.0
0.30
0.35
0.40
0.45
Time (sec)
Time (sec)

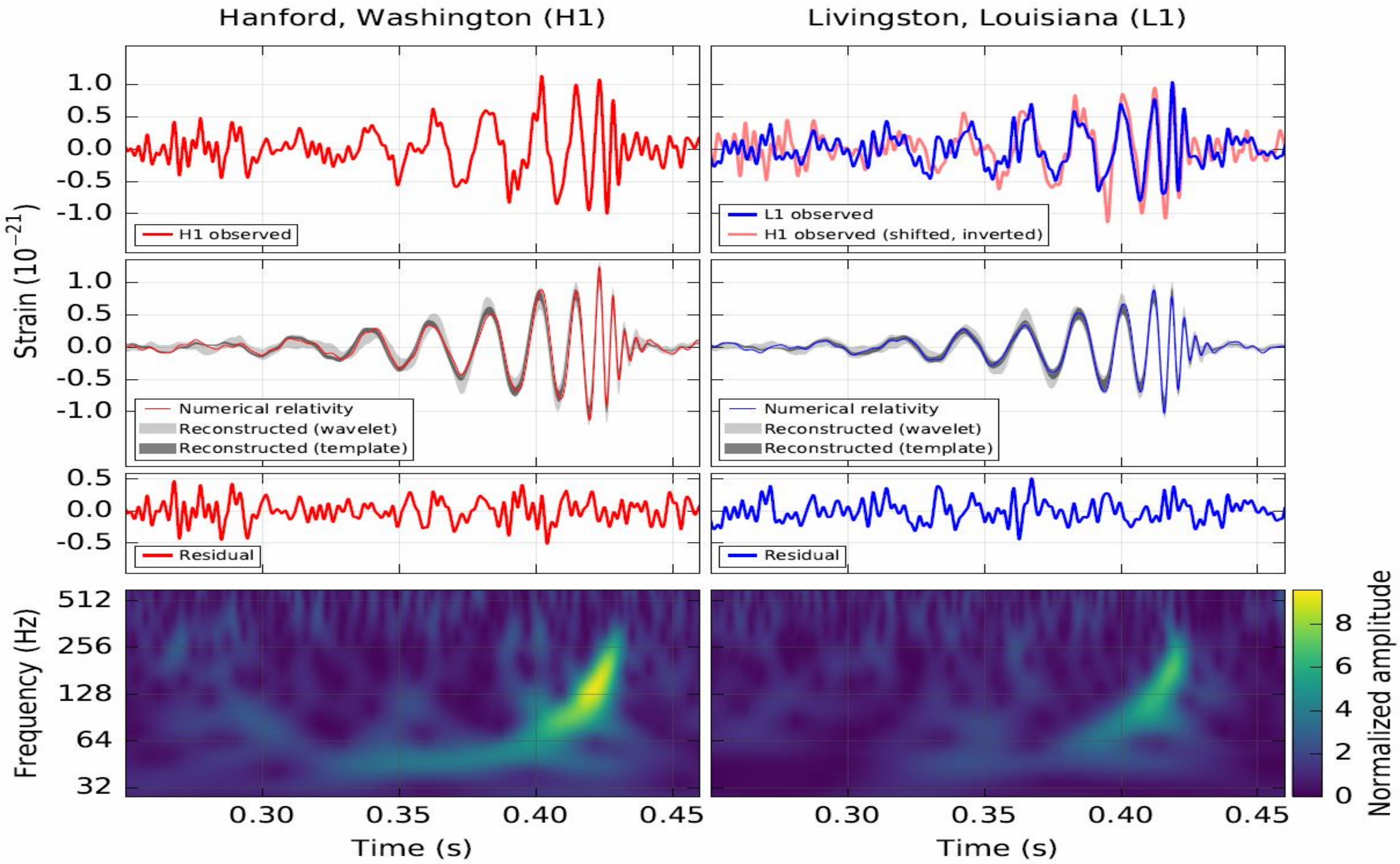
GW150914


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)
Time (sec)

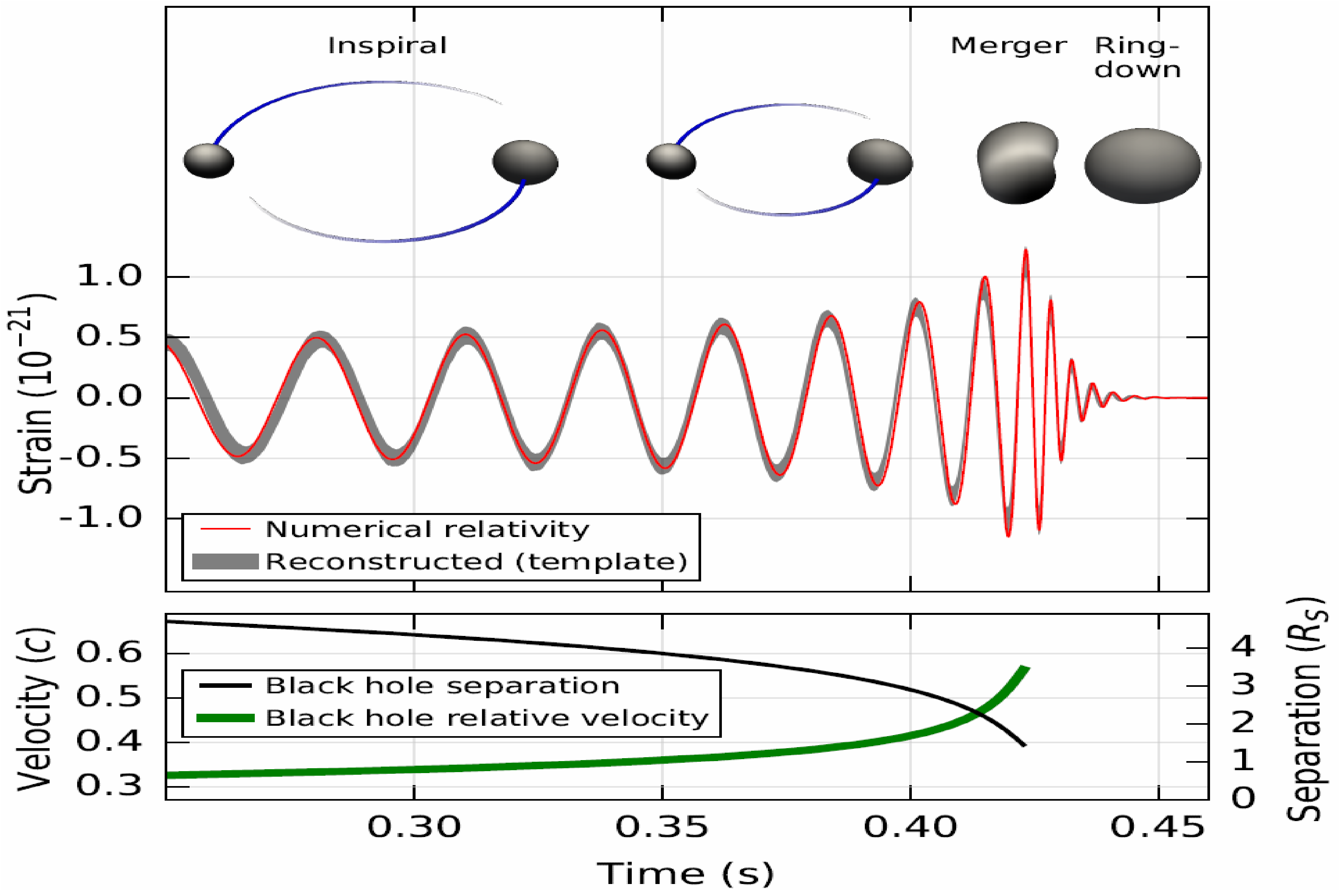

512
256
128
64
32
LIGO Hanford
512
256
128
64
32
LIGO Livingston
Frequency (Hz)
0.5
0.6
0.7
0.8
0.9
1.0
Time (sec)



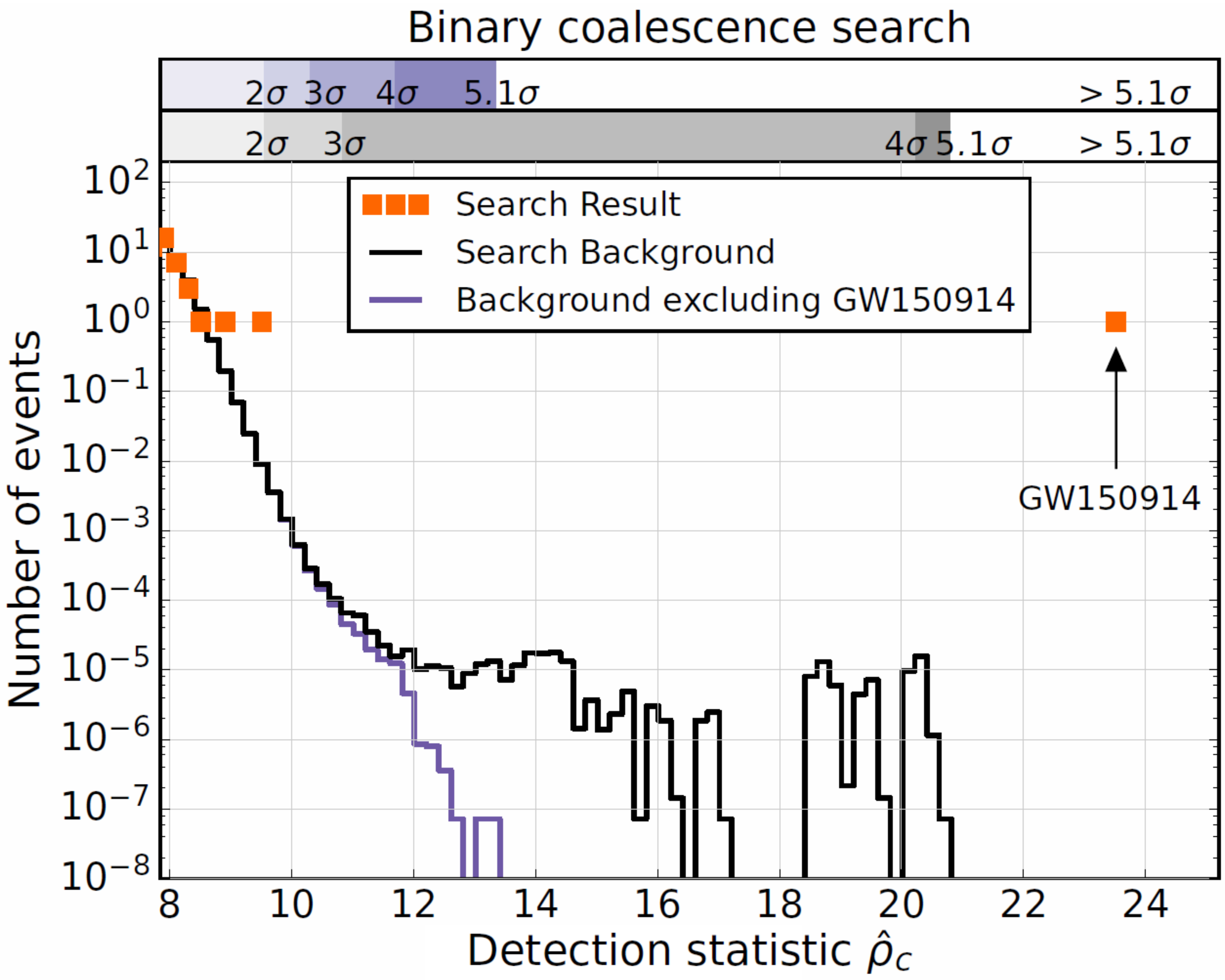
Frequency (Hz)
512
256
128
64
32
LIGO Hanford
512
256
128
64
32
LIGO Livingston
0.5
0.6
0.7
0.8
0.9
1.0
Time (sec)



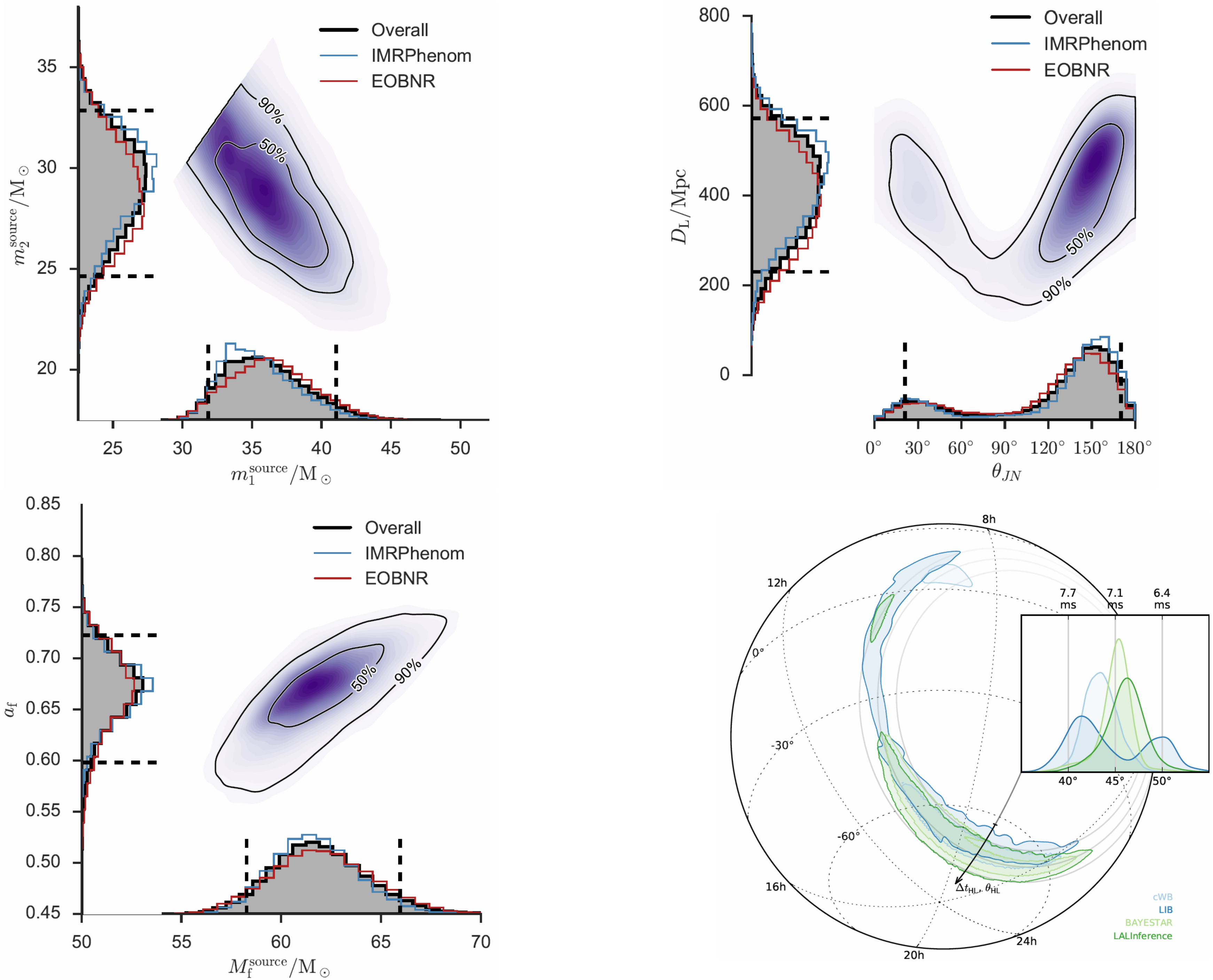
Hanford, Washington (H1)
Livingston, Louisiana (L1)
Strain (10^{-21})
H1 observed
L1 observed
H1 observed (shifted, inverted)
Numerical relativity
Reconstructed (wavelet)
Reconstructed (template)
Residual
Frequency (Hz)
512
256
128
64
32
Time (s)
0.30
0.35
0.40
0.45
Normalized amplitude



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)



Binary coalescence search
2σ 3σ 4σ 5.1σ
> 5.1σ
2σ 3σ
4σ 5.1σ
> 5.1σ
Search Result
Search Background
Background excluding GW150914
GW150914
Number of events
Detection statistic $\hat{\rho}_c$



Overall
IMRPhenom
EOBNR
90%
50%
$m_2^{\mathrm{source}}/\mathrm{M}_\odot$
$m_1^{\mathrm{source}}/\mathrm{M}_\odot$
20
25
30
35
40
45
50
$D_\mathrm{L}/\mathrm{Mpc}$
θ_{JN}
0
200
400
600
800
0° 30° 60° 90° 120° 150° 180°
a_f
$M_\mathrm{f}^{\mathrm{source}}/\mathrm{M}_\odot$
0.45 0.50 0.55 0.60 0.65 0.70 0.75 0.80 0.85
50 55 60 65 70
8h
12h
16h
20h
24h
0°
-30°
-60°
7.7 ms
7.1 ms
6.4 ms
40°
45°
50°
$\Delta t_{\mathrm{HL}}, \theta_{\mathrm{HL}}$
cWB
LIB
BAYESTAR
LALInference

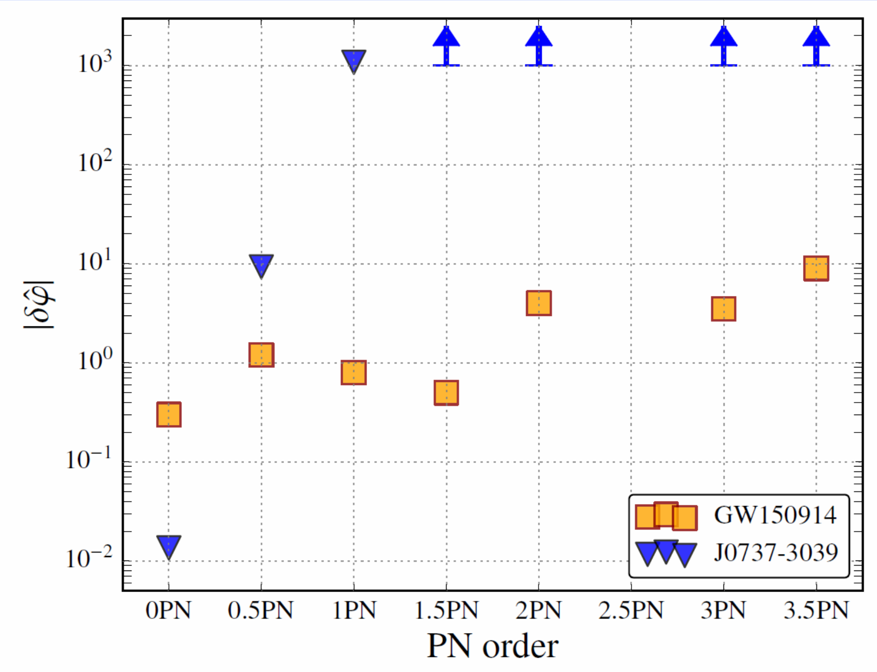
Parameter	Value	90% Error	Unit
Primary black hole mass	36	$^{+5}_{-4}$	$M_\odot$
Secondary black hole mass	29	$^{+4}_{-4}$	$M_\odot$
Final black hole mass	62	$^{+4}_{-4}$	$M_\odot$
Total radiated energy	3.0	$^{+0.5}_{-0.5}$	$M_\odot$
Final black hole spin	0.67	$^{+0.05}_{-0.07}$	
Luminosity distance	410	$^{+160}_{-180}$	Mpc
Source redshift z	0.09	$^{+0.03}_{-0.04}$	

General Relativity Tests

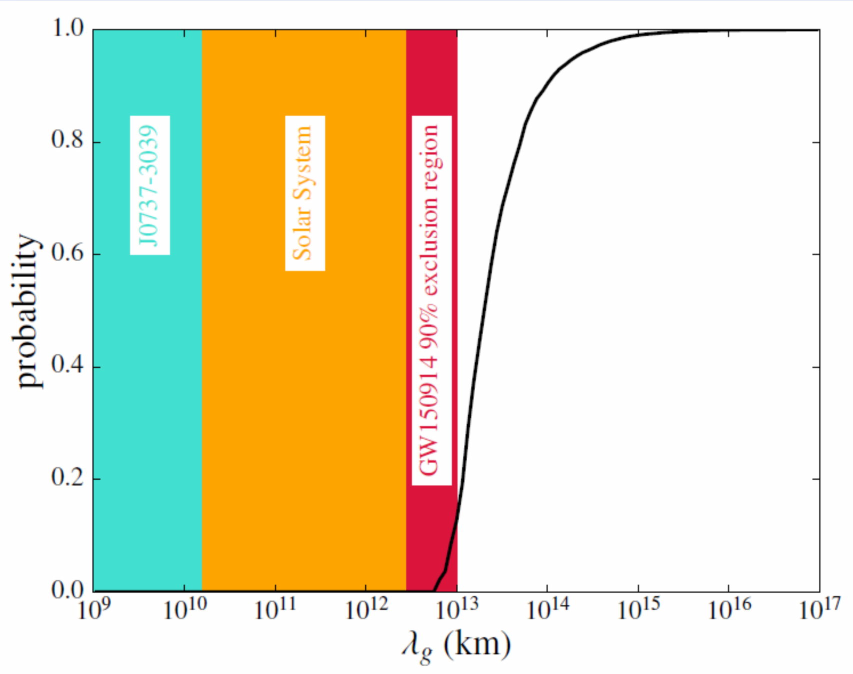
GW150914 is the first observation of a binary black hole merger…

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

Post Newtonian Approximation



Graviton Compton Wavelength



Astrophysical Implications

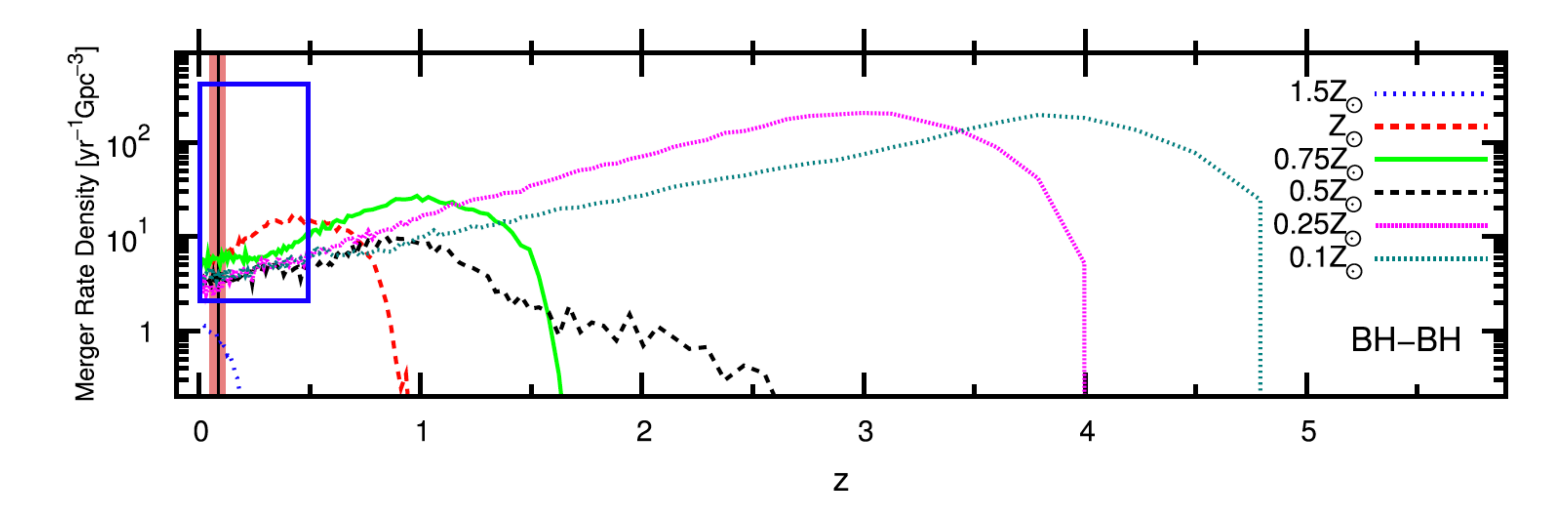
Merger rate of stellar mass BBHs implied by the detection: 2–400/Gpc^3 yr

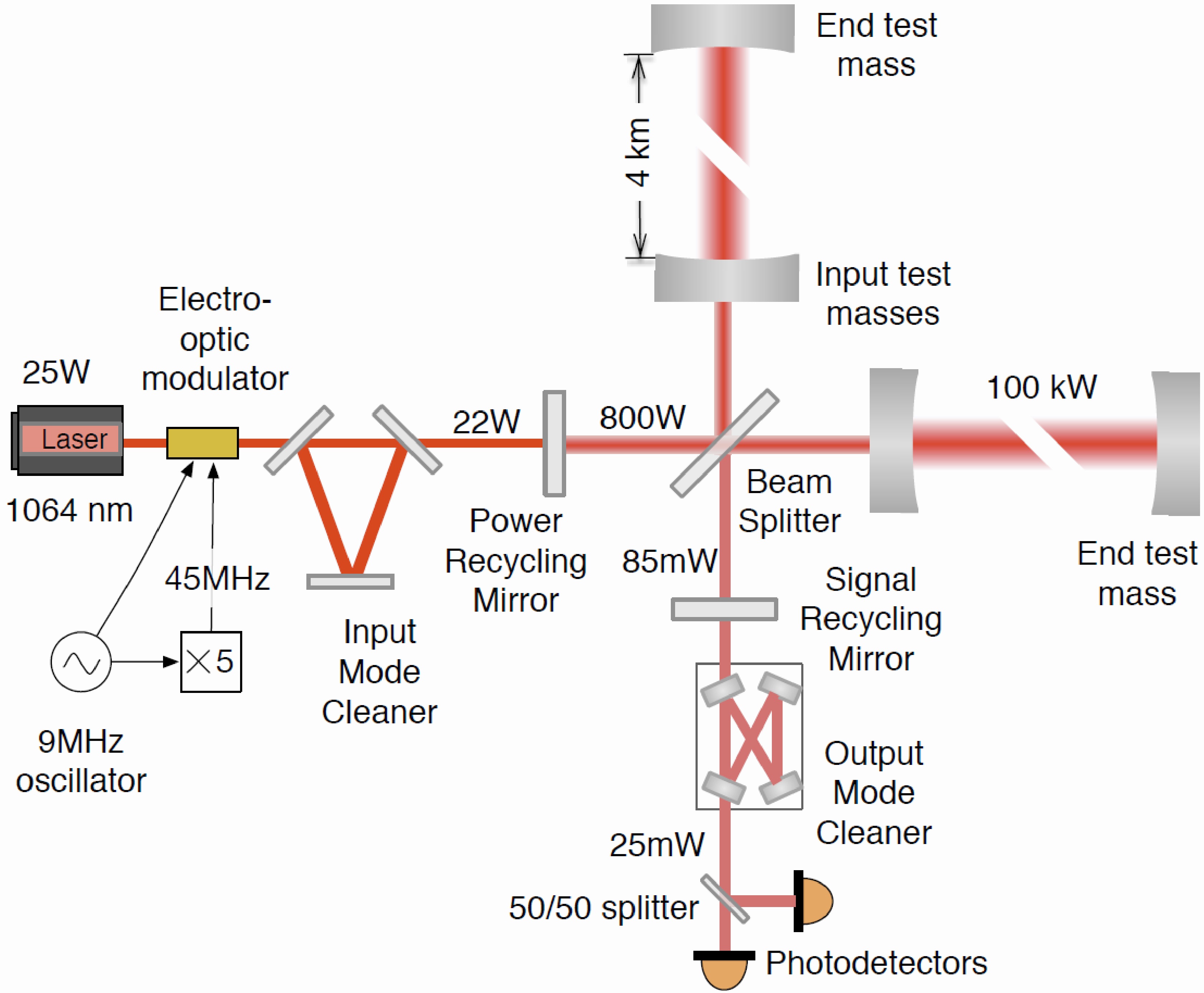
Most robust evidence for existence of 'heavy' stellar mass black holes: > 20 $M_\odot$

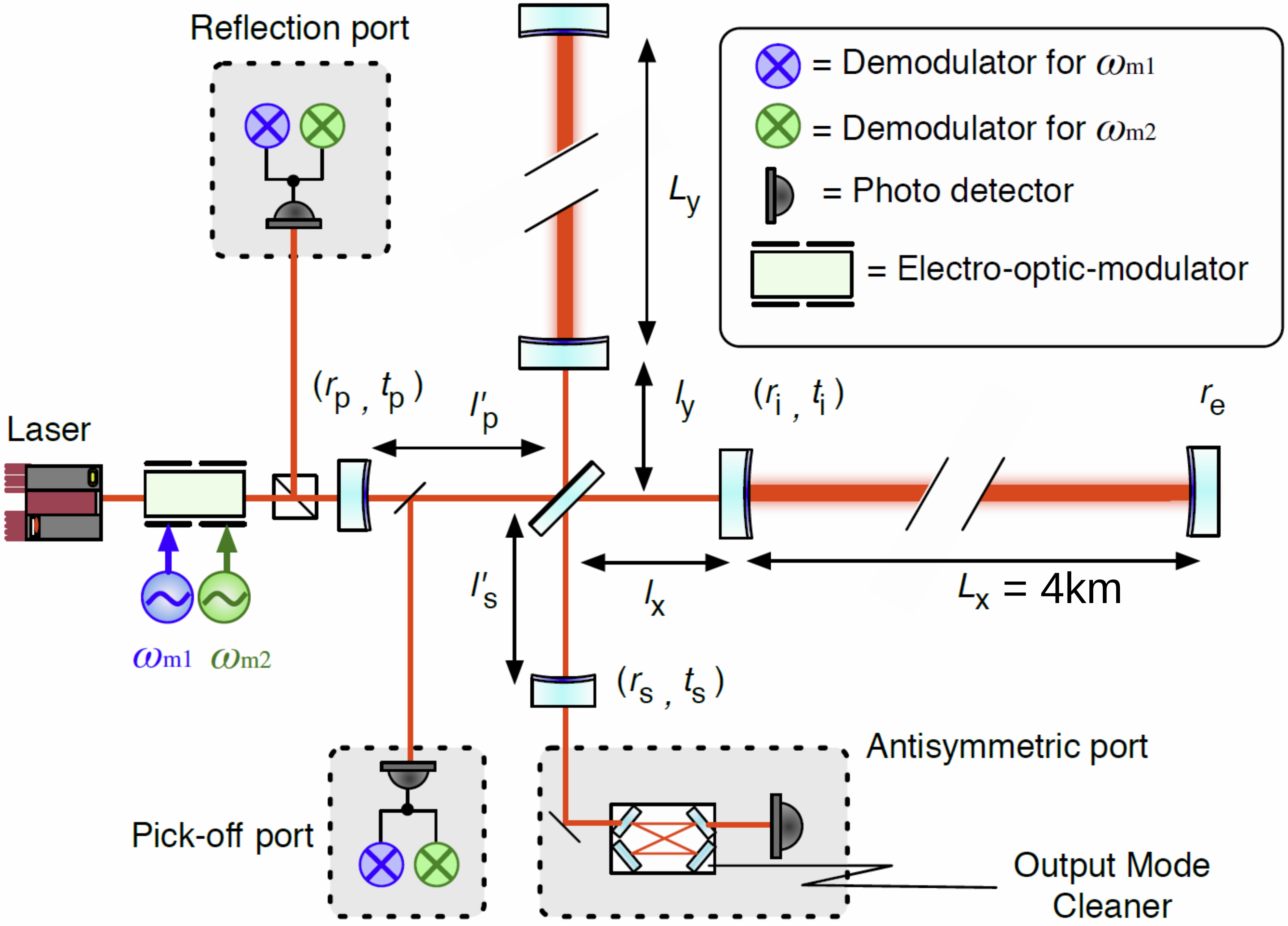
Most likely formed in a low-metallicity environment: <½ $Z_\odot$ and possibly even <¼ $Z_\odot$

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

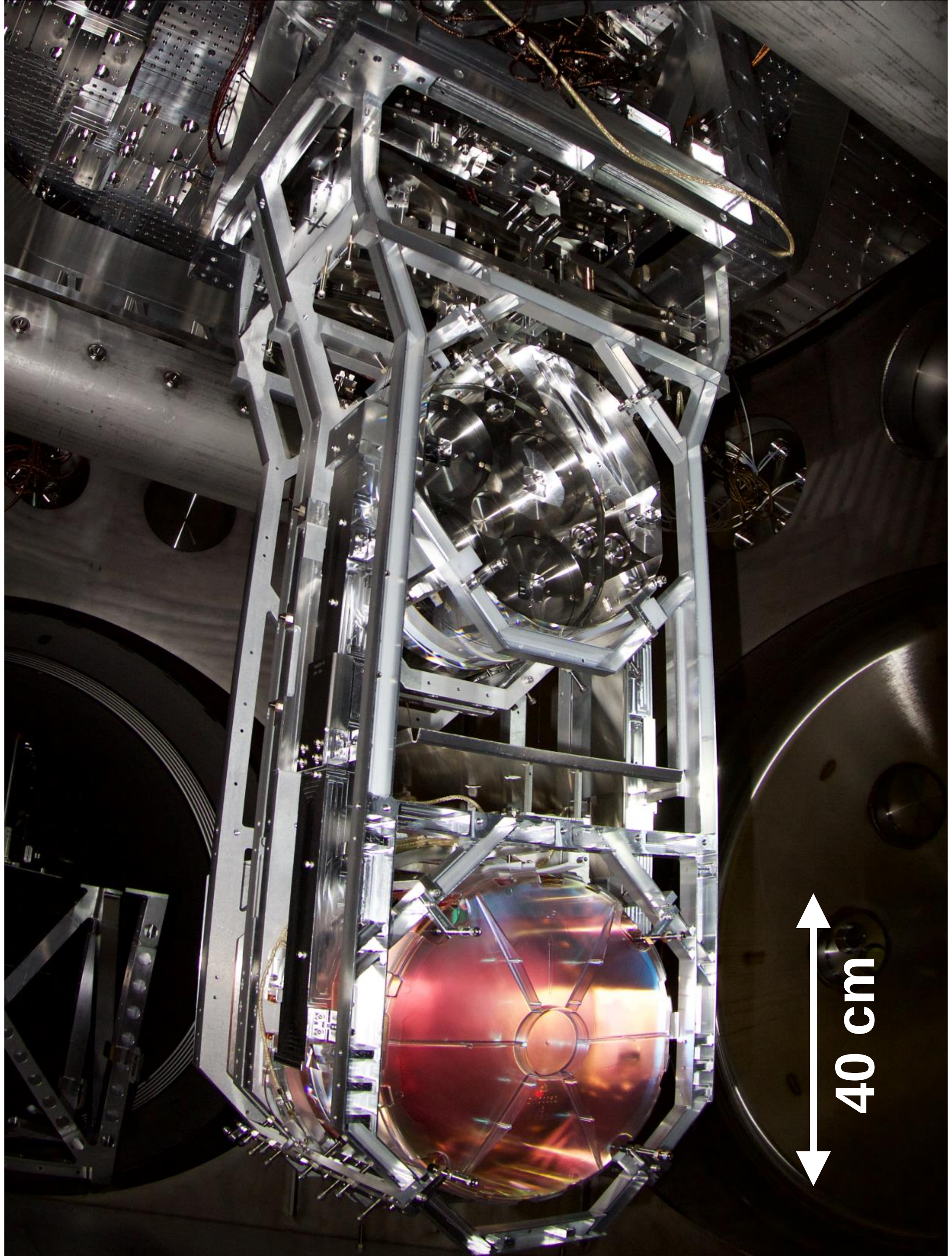


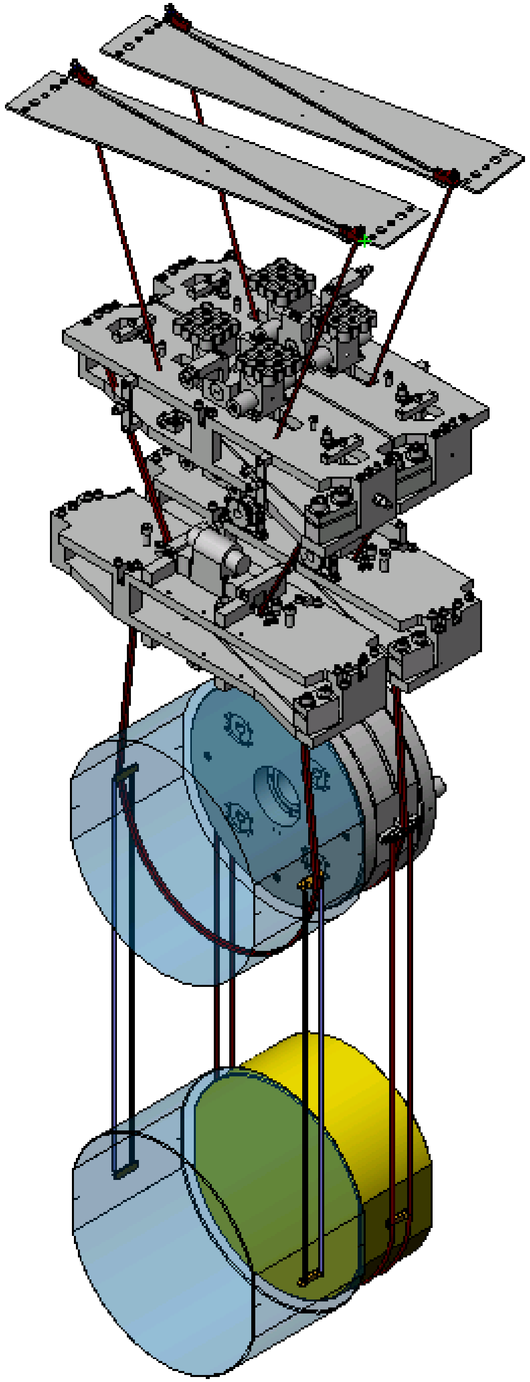

End test mass
4 km
Input test masses
Electro-optic modulator
25W
Laser
1064 nm
22W
800W
100 kW
Beam Splitter
Power Recycling Mirror
85mW
End test mass
45MHz
Signal Recycling Mirror
×5
Input Mode Cleaner
9MHz oscillator
Output Mode Cleaner
25mW
50/50 splitter
Photodetectors



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

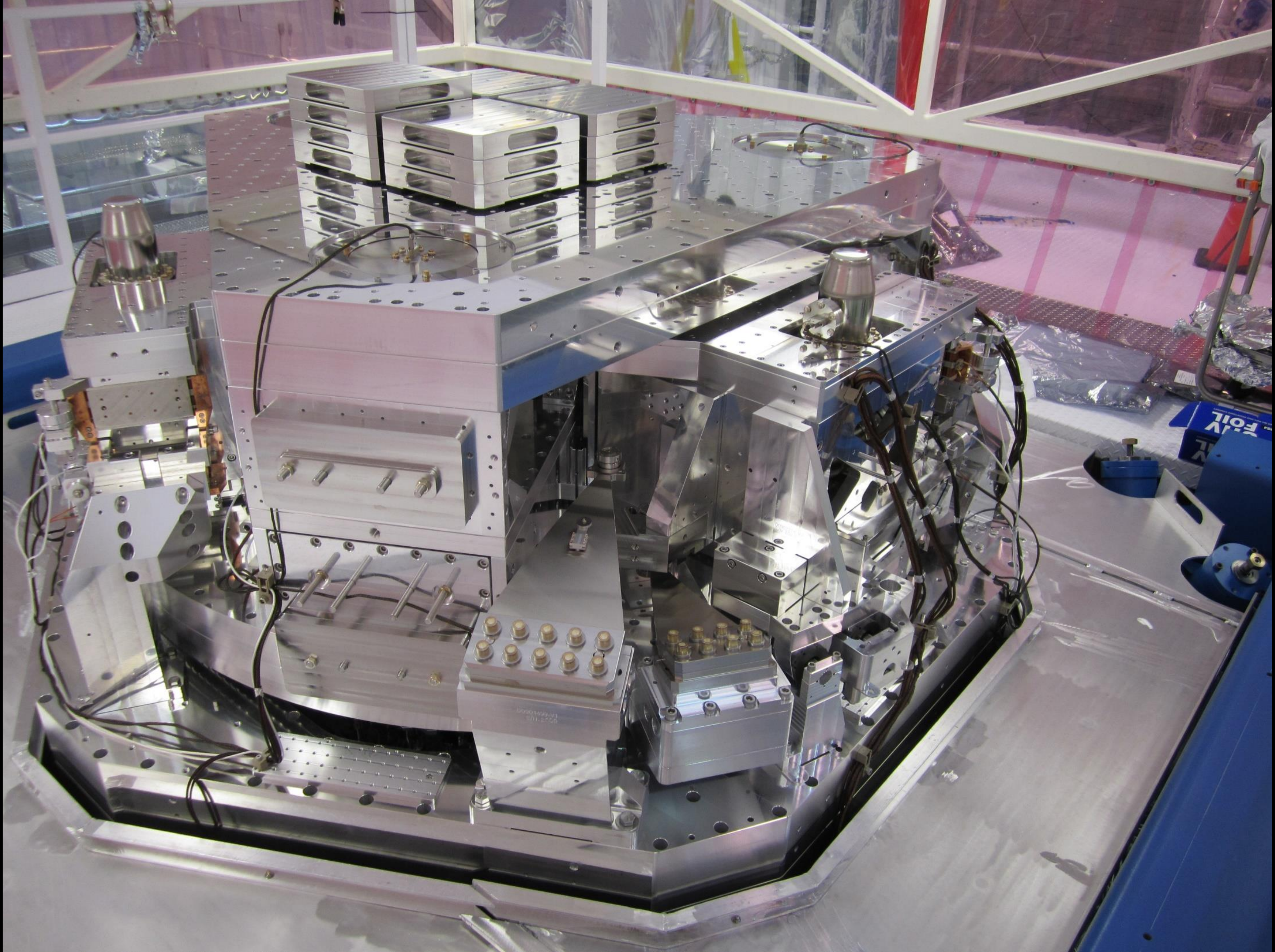
Test Mass Suspension



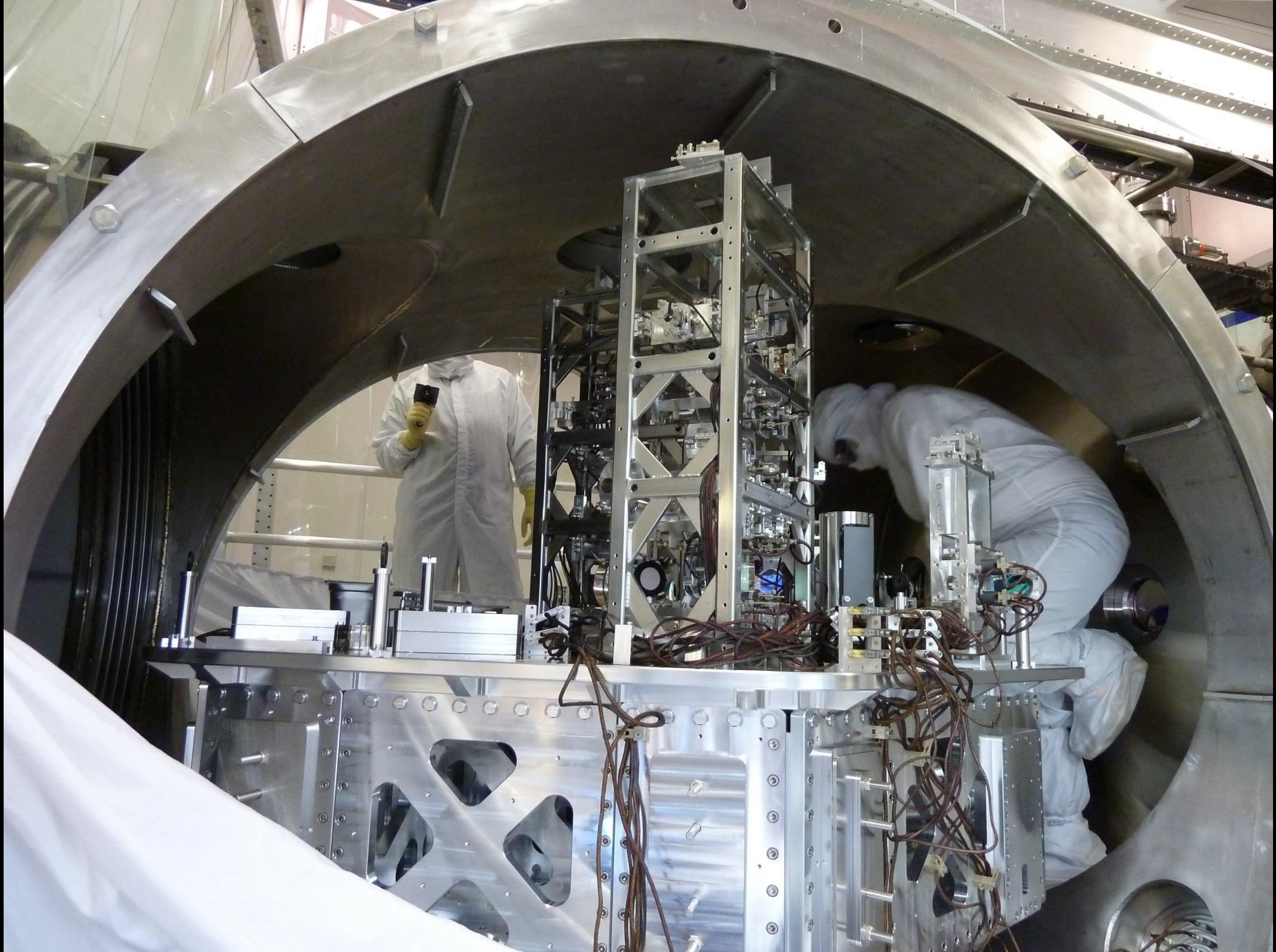


Vacuum System Vertex

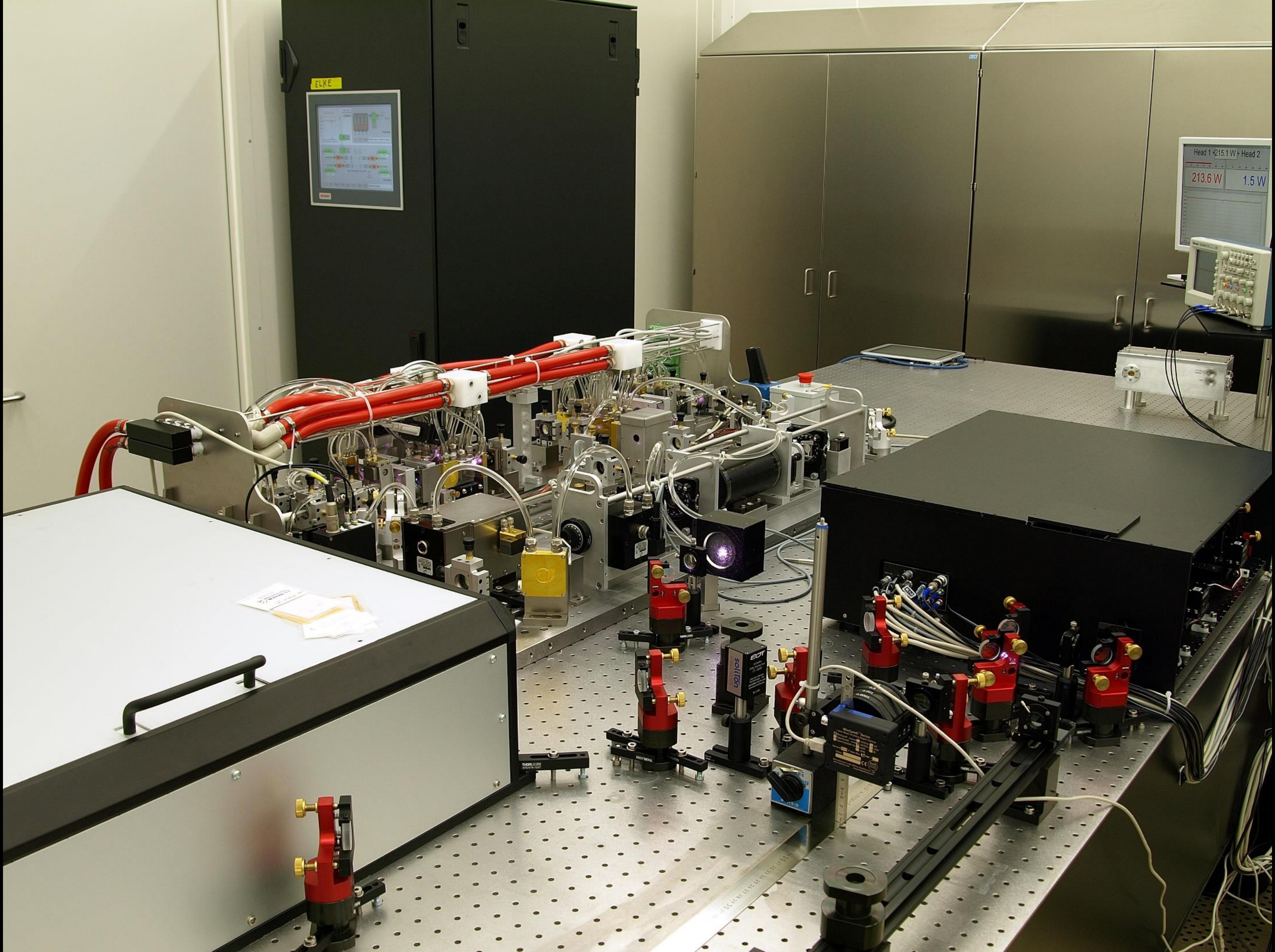
Seismic Isolation Platform



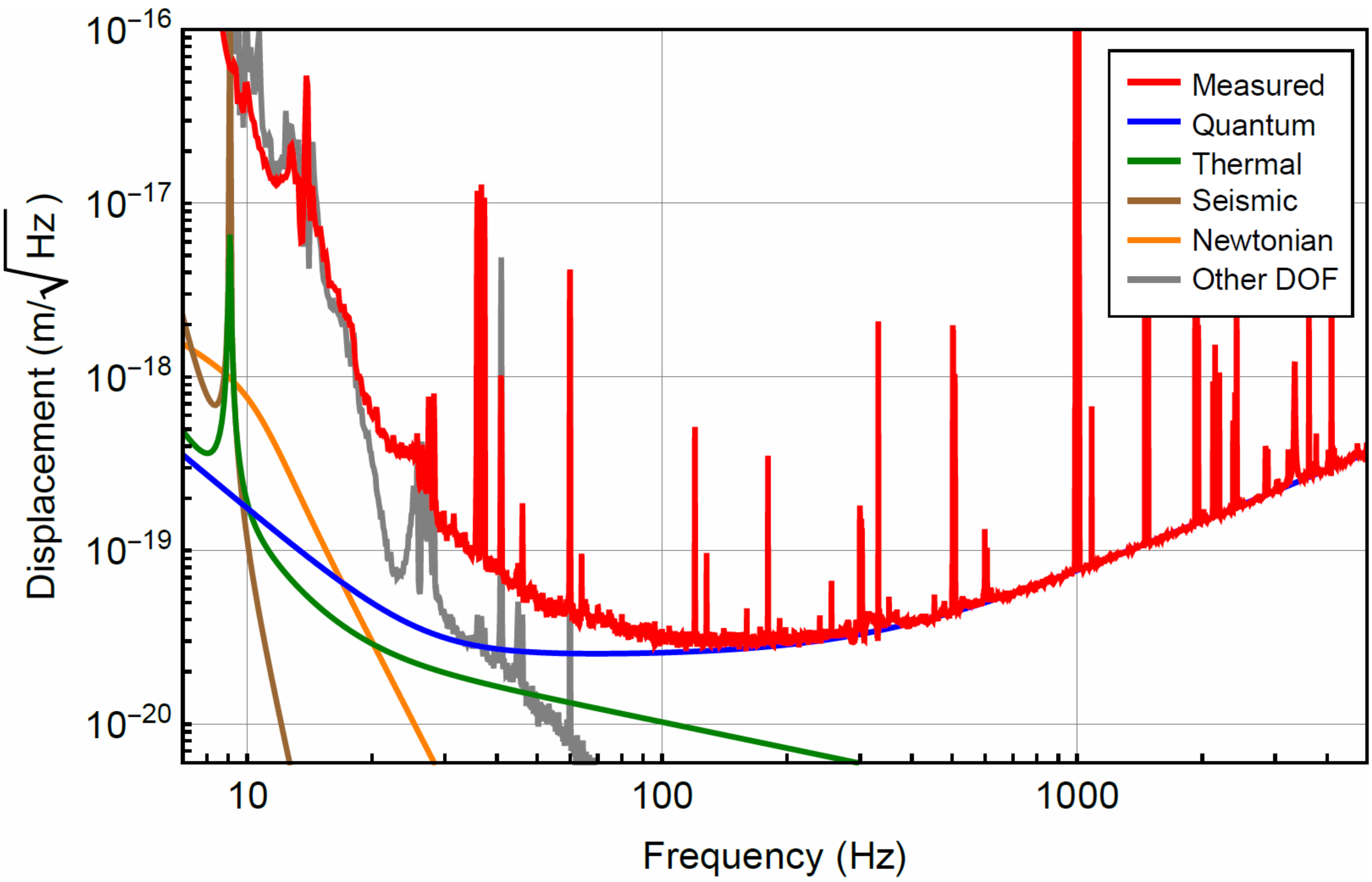
Input Optics Table



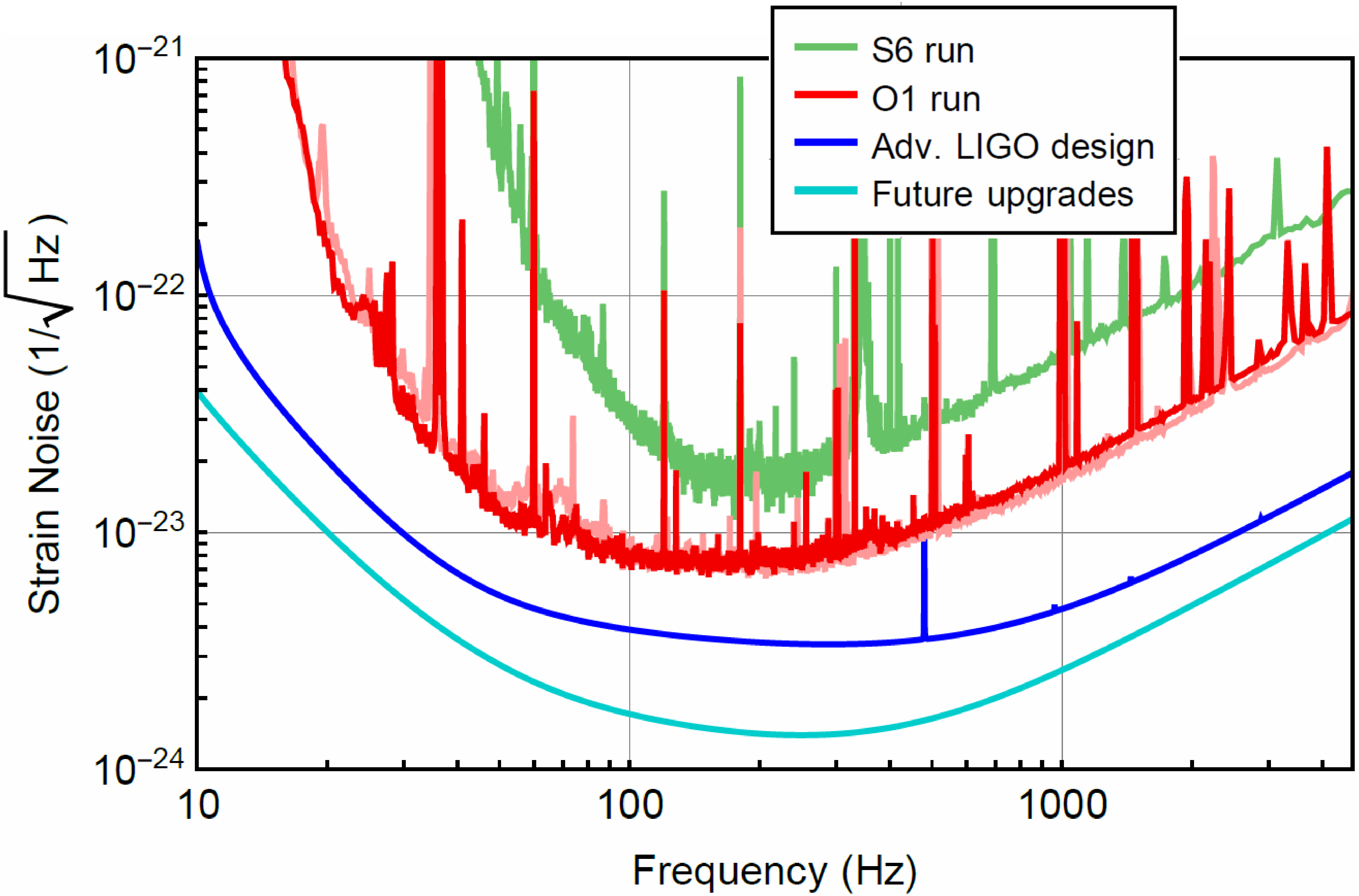
200W Pre-Stabilized Laser



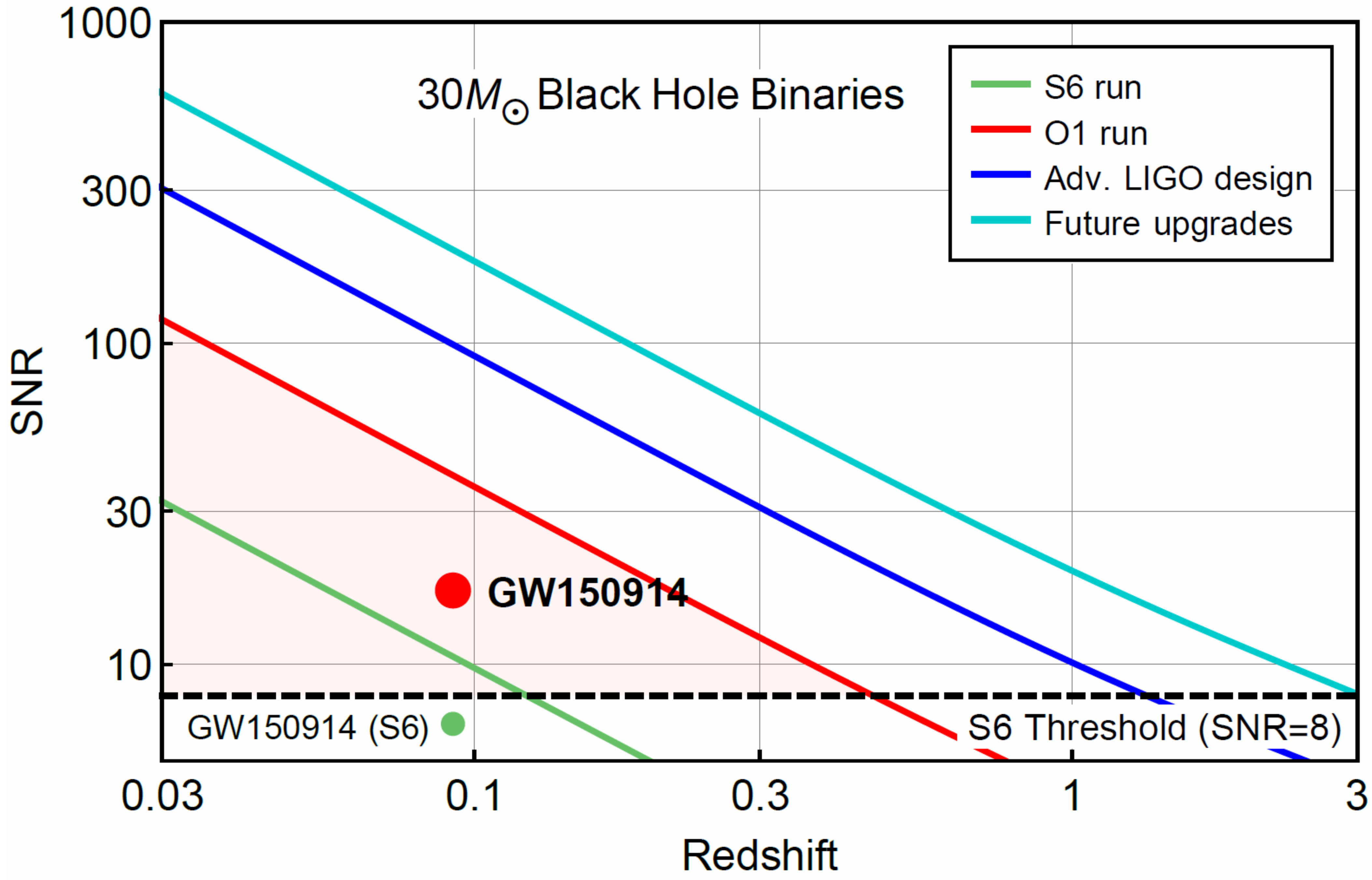
Control Room



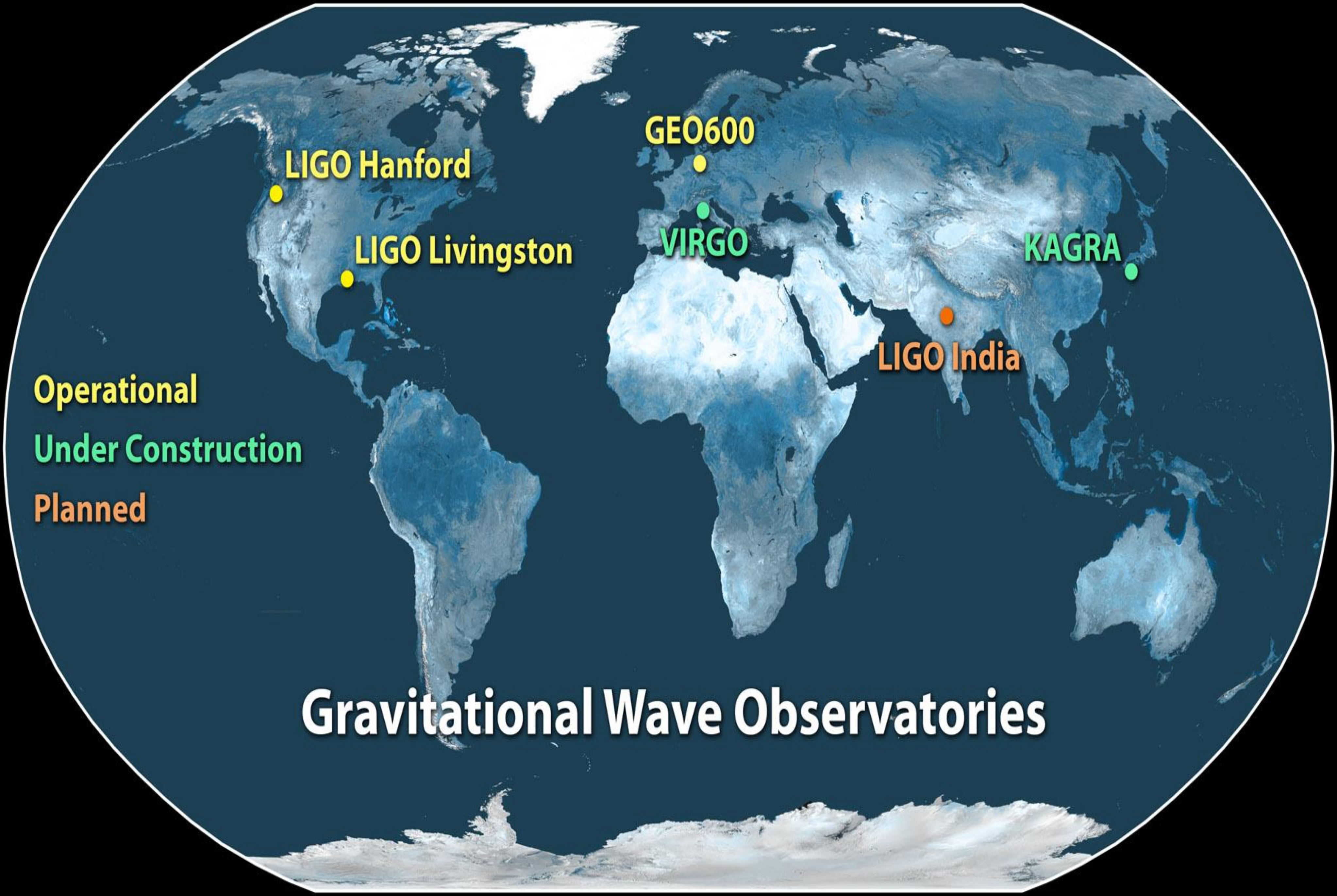
Measured
Quantum
Thermal
Seismic
Newtonian
Other DOF
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
Displacement (m/$\sqrt{\text{Hz}}$)
10
100
1000
Frequency (Hz)



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



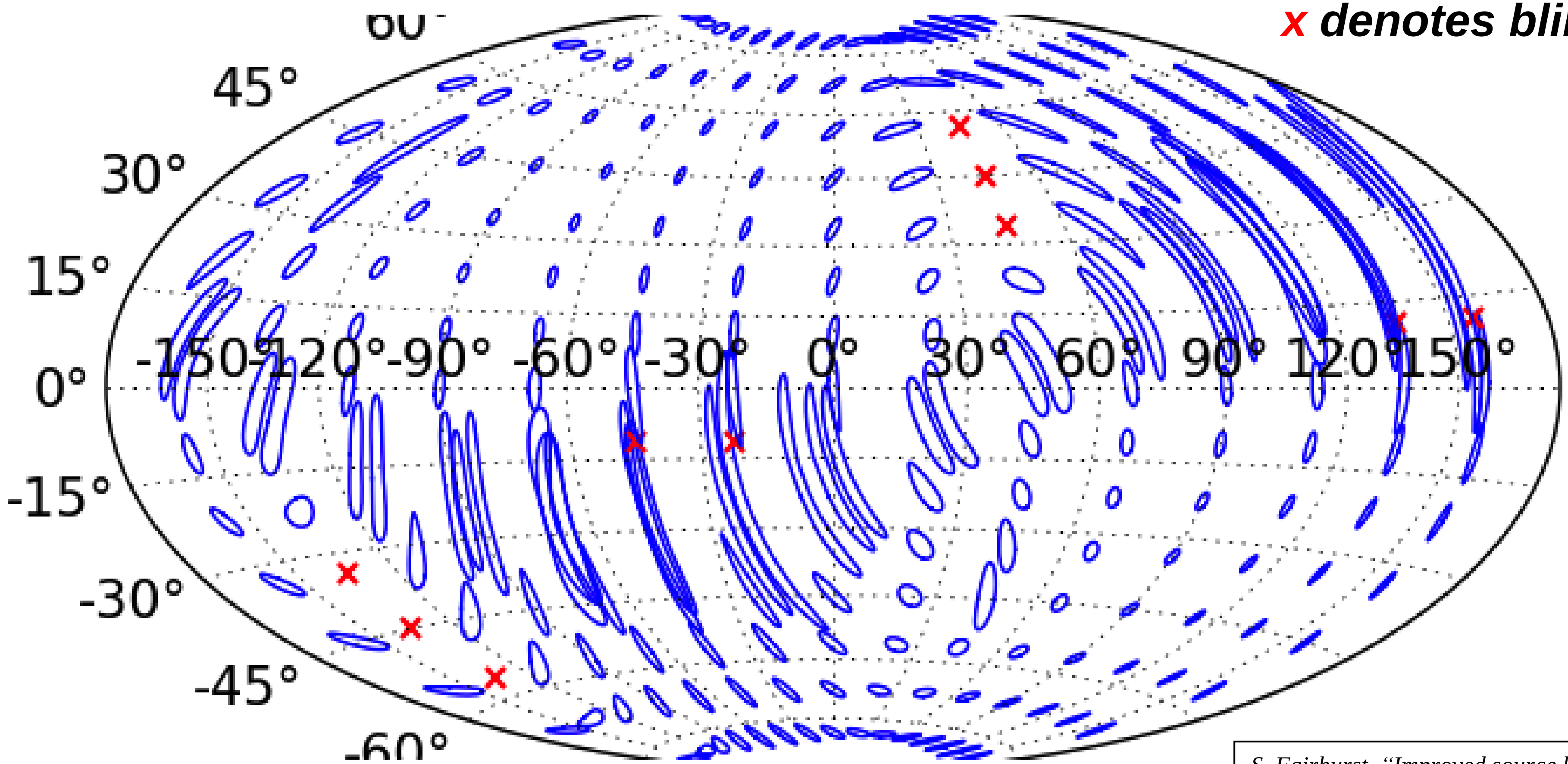
$30M_\odot$ Black Hole Binaries
S6 run
O1 run
Adv. LIGO design
Future upgrades
GW150914
GW150914 (S6)
S6 Threshold (SNR=8)
SNR
1000
300
100
30
10
0.03
0.1
0.3
1
3
Redshift


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

Binary Neutron Star Merger Localization: Hanford-Livingston-Virgo

3 site network

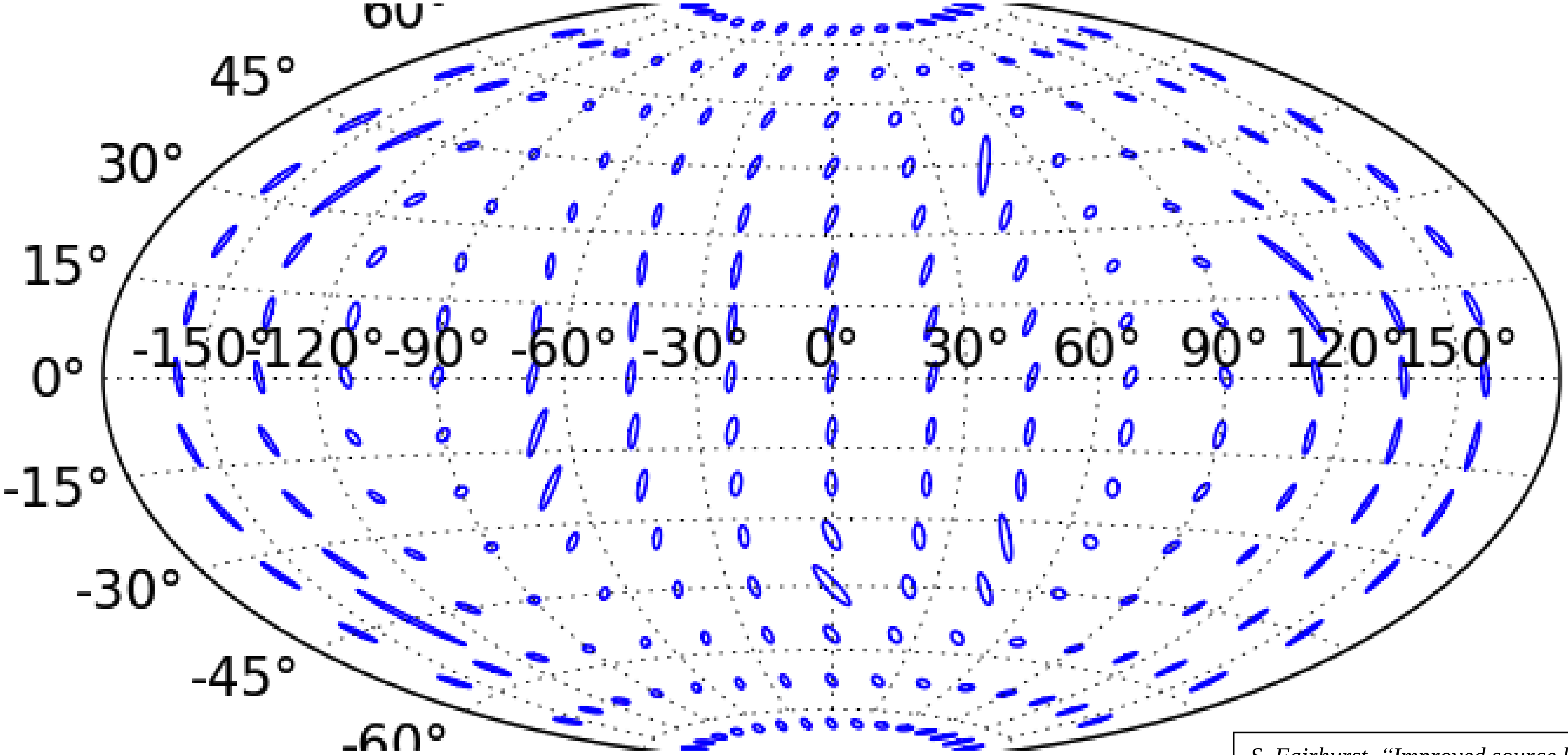
x denotes blind spots



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

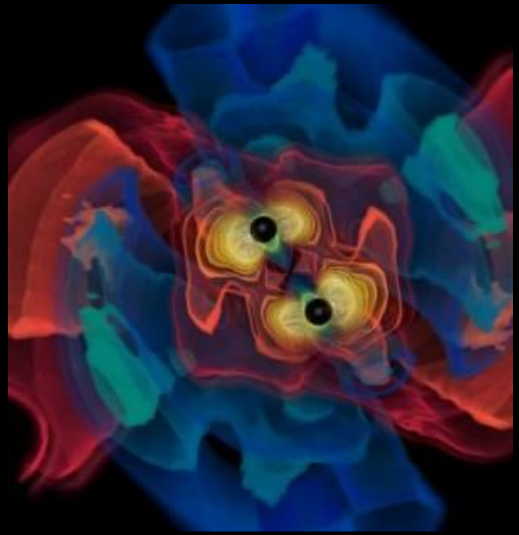
Binary Neutron Star Merger Localization: Hanford-Livingston-Virgo-India

4 site network



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

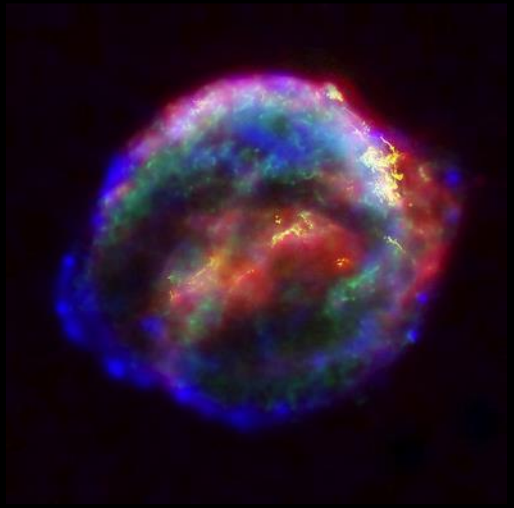
Astrophysical Targets for Ground-based Detectors



Credit: AEI, CCT, LSU

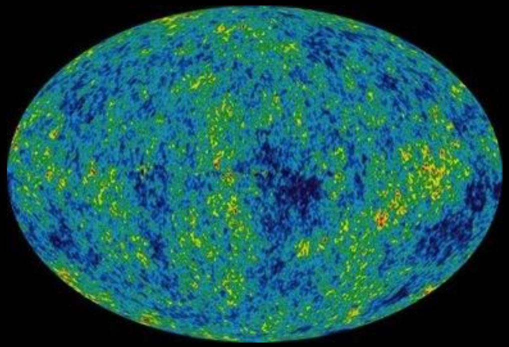
Coalescing Binary Systems

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



'Bursts'

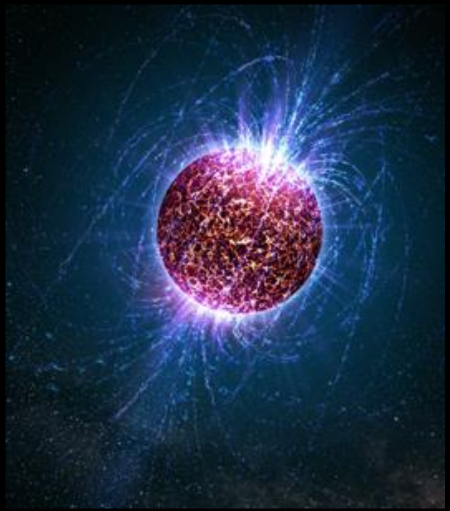
- *Unmodeled*
- *galactic asymmetric core collapse supernovae*
- *cosmic strings*
- ***???***



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'*

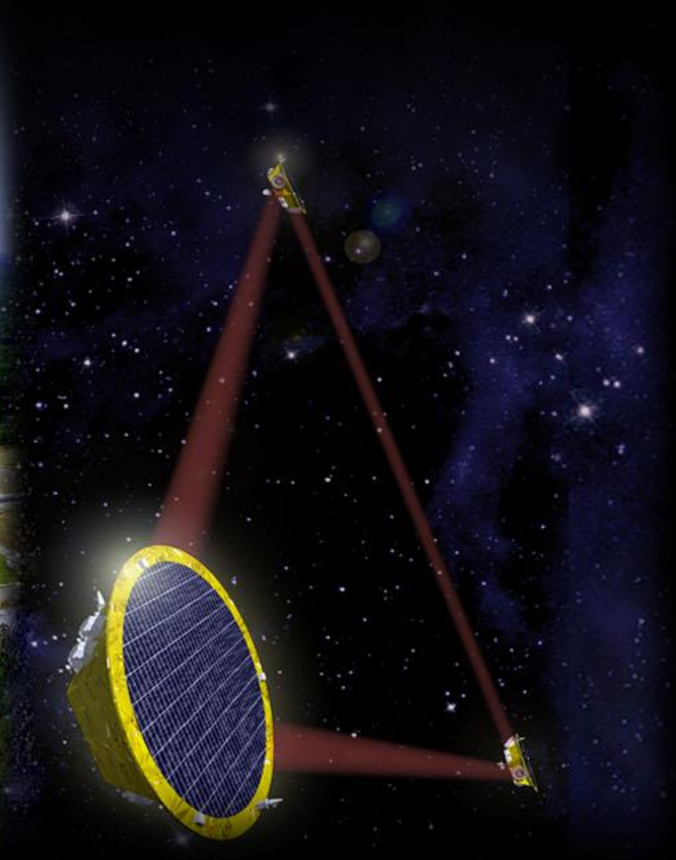
Gravitational Wave Periods

Milliseconds

Gravitational Wave Periods

Milliseconds

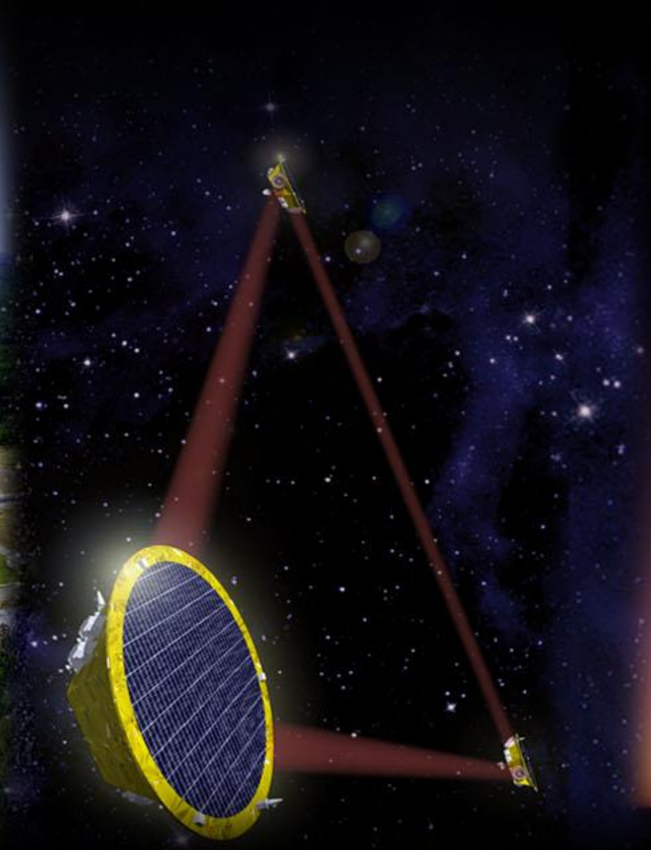
Minutes
to Hours



Gravitational Wave Periods

Milliseconds

Minutes
to Hours

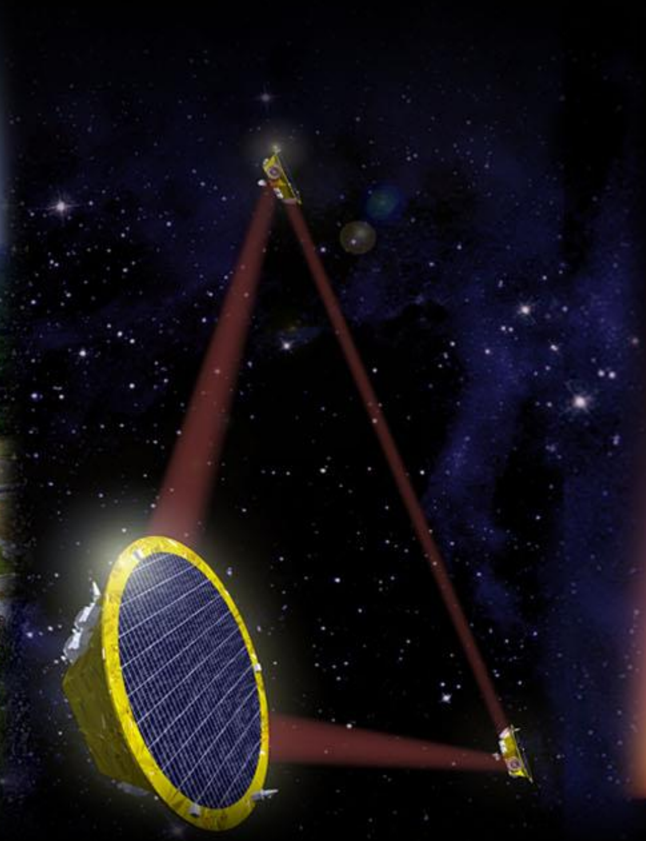


Years
to Decades

Gravitational Wave Periods

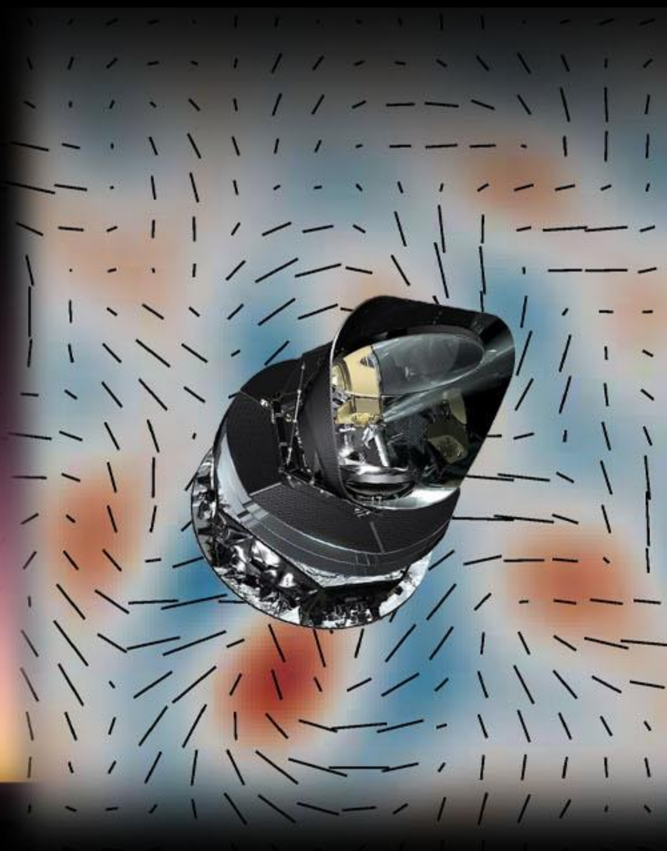
Milliseconds

Minutes
to Hours

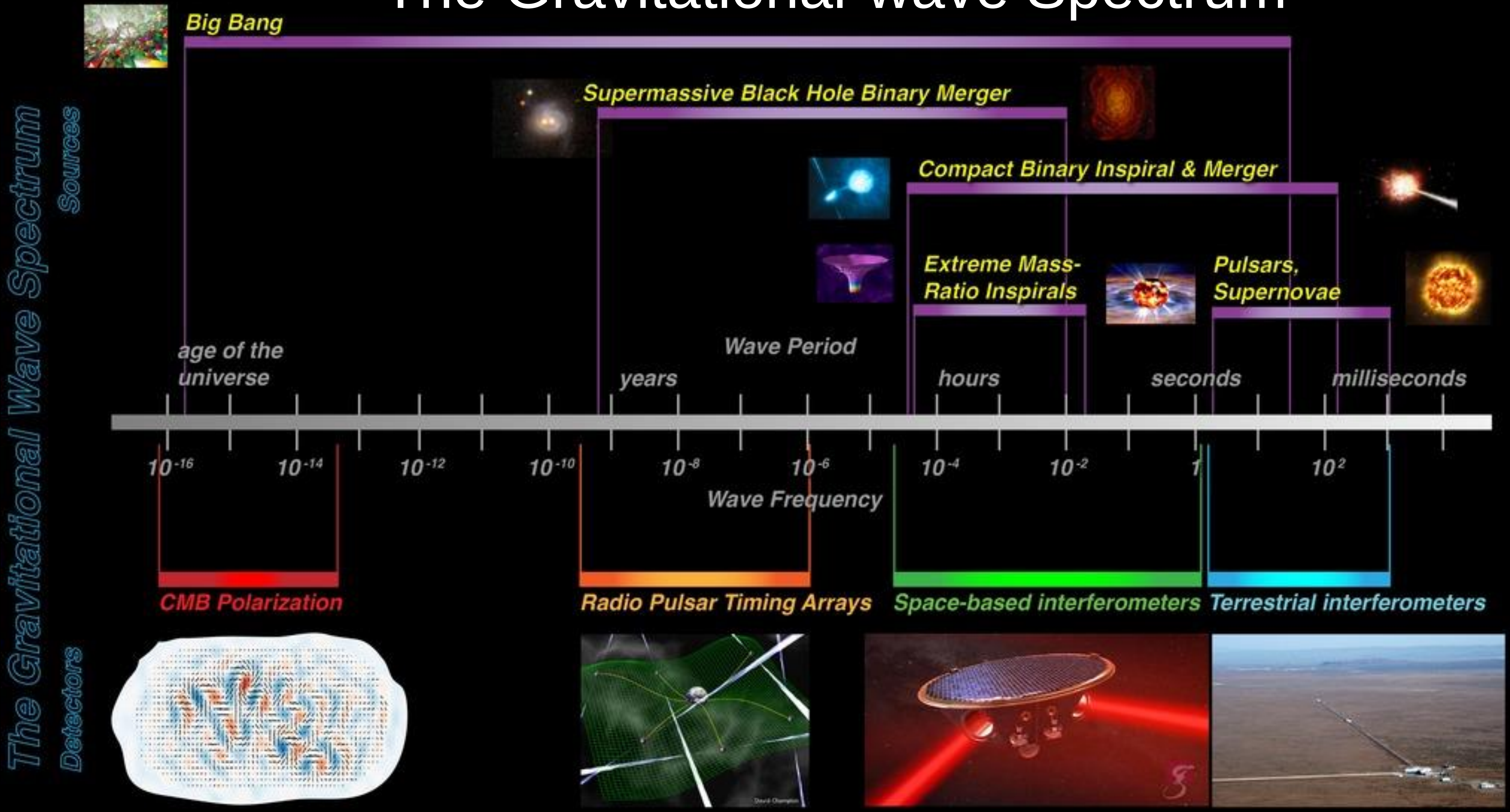


Years
to Decades

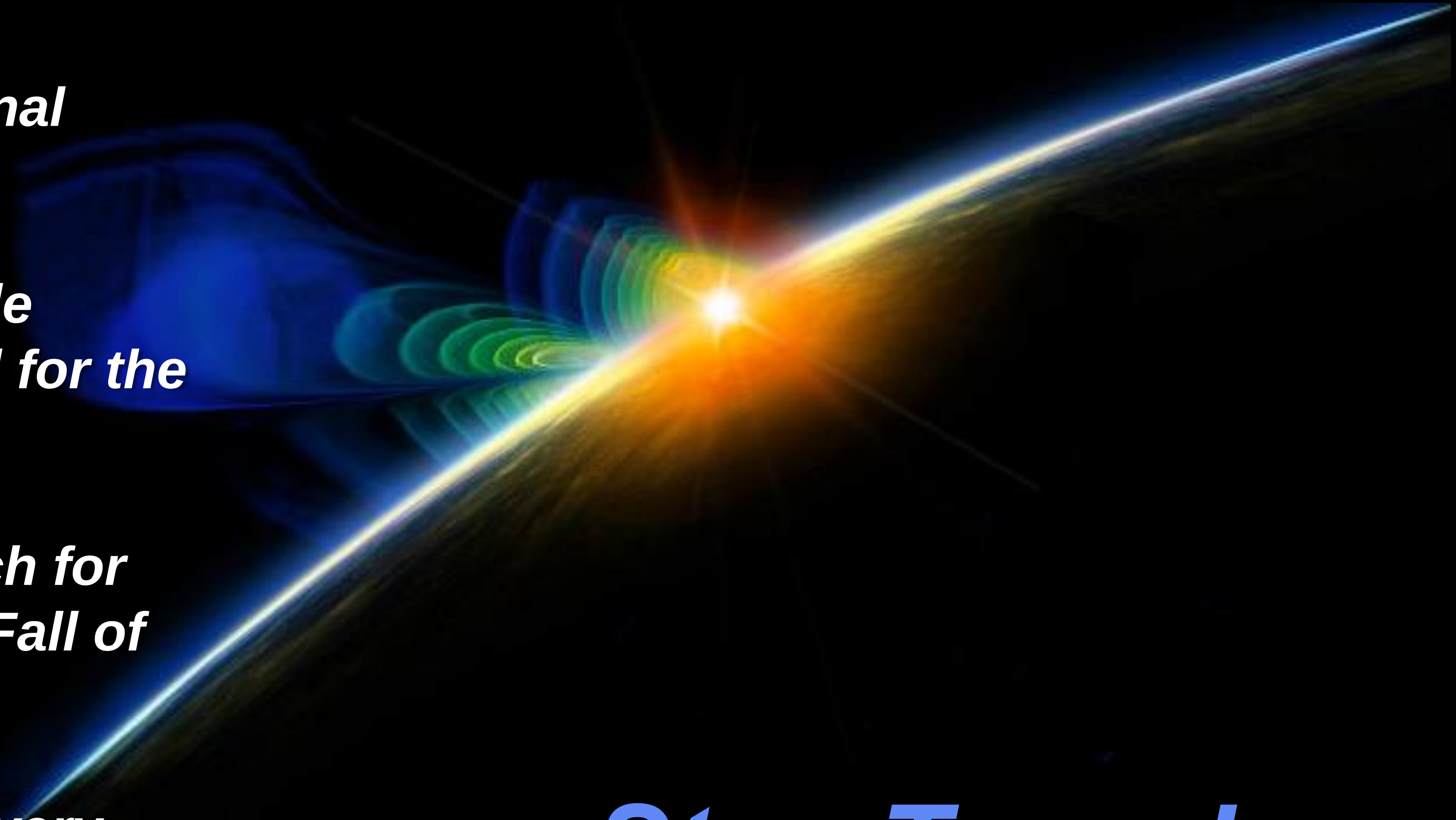
Billions
of Years



The Gravitational-wave Spectrum



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:

ligo.caltech.edu

LIGO
LASER INTERFEROMETER GRAVITATIONAL-WAVE OBSERVATORY

www.ligo.org

Support: National Science Foundation