GRAVITATIONAL WAVES:
A NEW WINDOW ON THE UNIVERSE

Stephen Fairhurst

for the LIGO Scientific and
Virgo Collaborations

References

Phys. Rev. X **6**, 041015 (2016)

GW150914: PRL 116, 061102 (2016)

GW151226: PRL 116, 241103 (2016)

GW170104: PRL 118, 221101 (2017)

Manhattan Mini Storage.com
212-storage
Scientists found gravitational waves in outer space.
If only it were that easy to find a walk-in closet in NYC.
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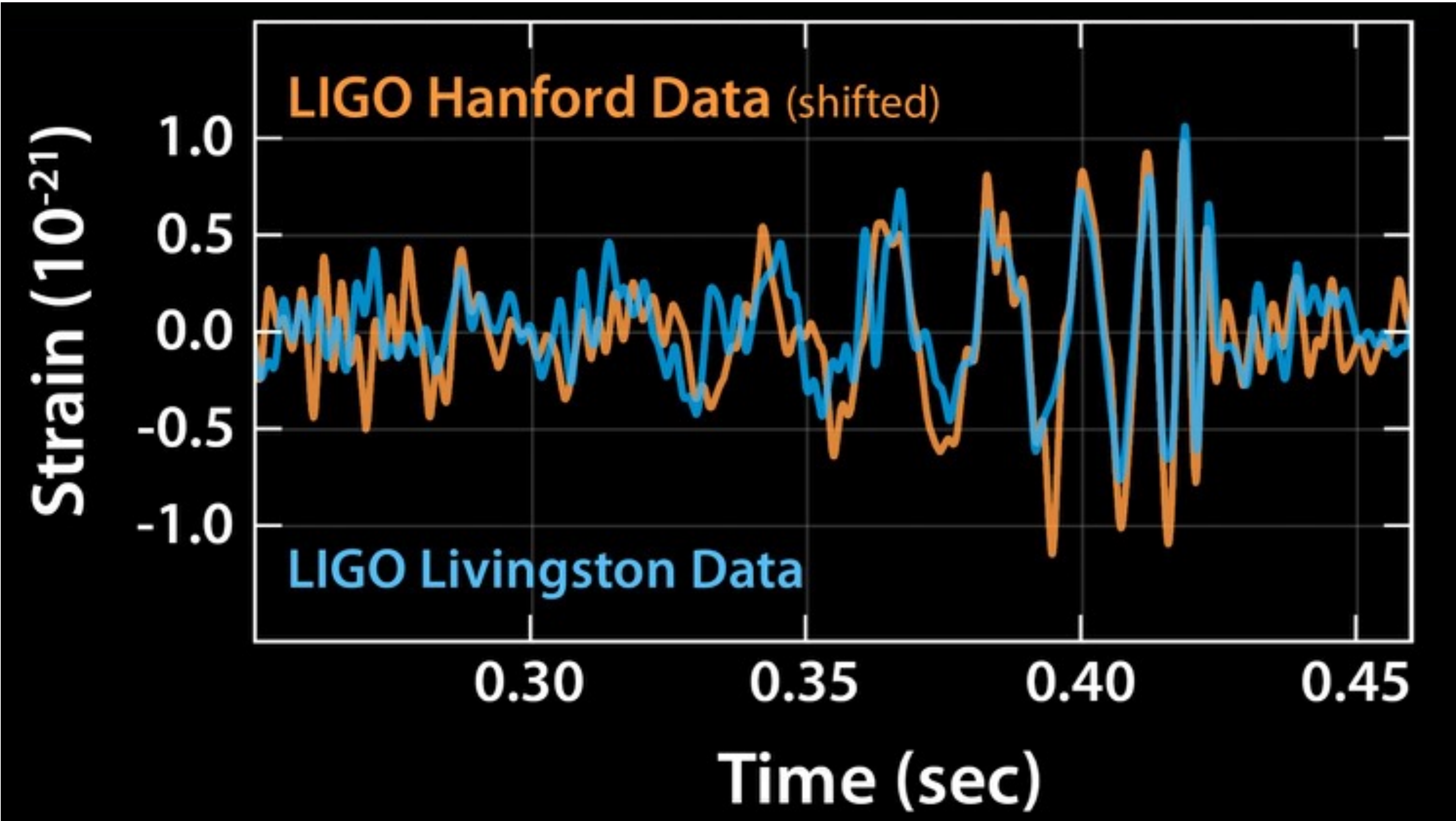
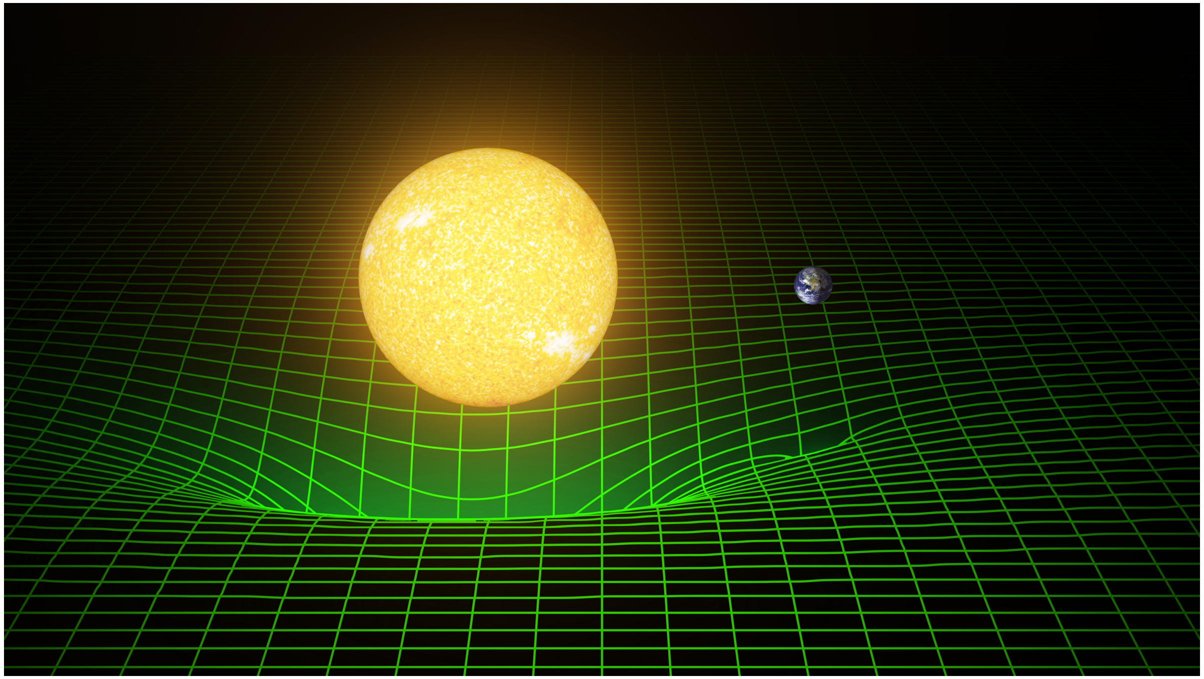

LIGO Hanford Data (shifted)
LIGO Livingston Data
Strain (10^-21)
1.0
0.5
0.0
-0.5
-1.0
0.30
0.35
0.40
0.45
Time (sec)

General Relativity

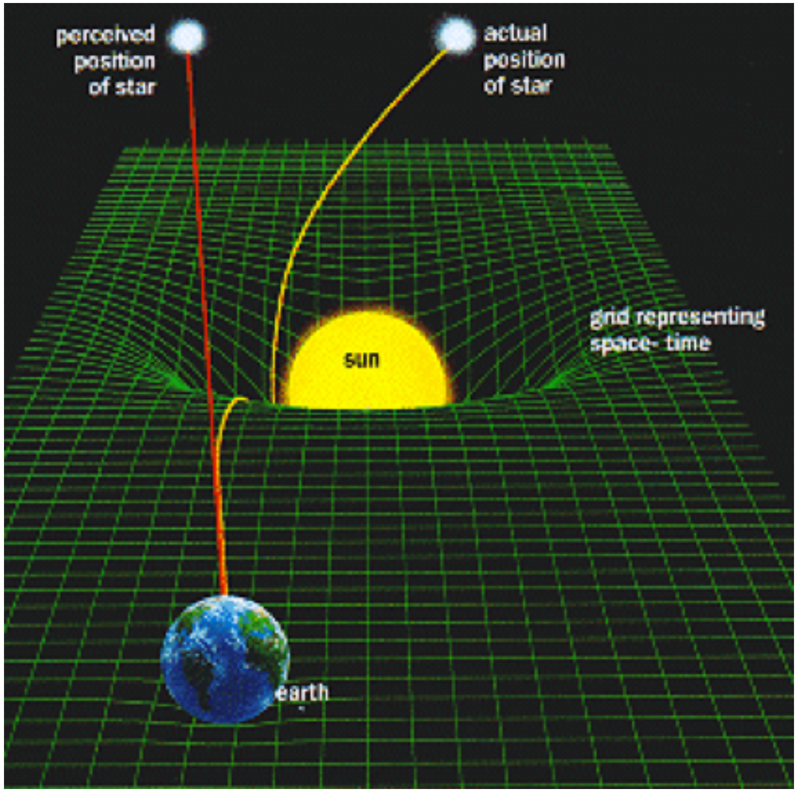
$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} = 8\pi G T_{\mu\nu}$$

Matter tells space how to curve.
Space tells matter how to move.
- John Wheeler



General Relativity

$$\frac{D^2 X^\mu}{dt^2} = R^\mu{}_{\nu\rho\sigma} T^\nu T^\rho X^\sigma$$



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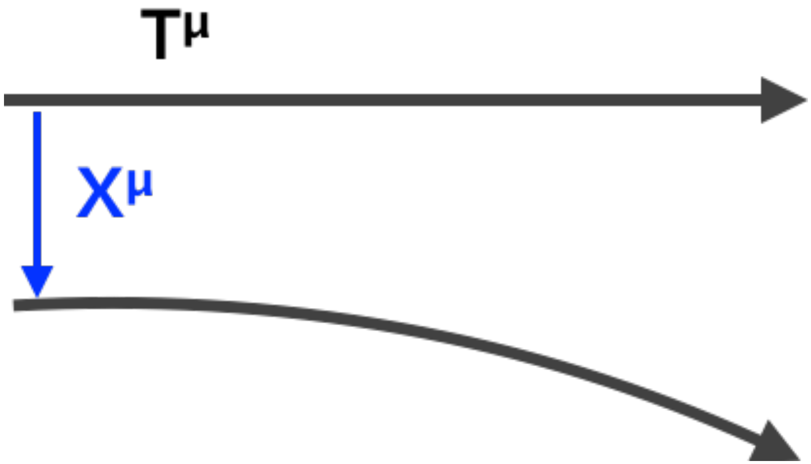
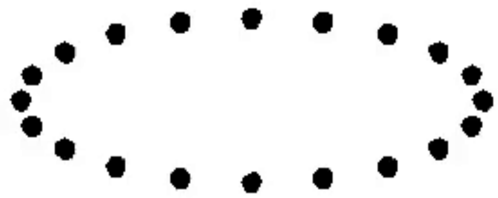
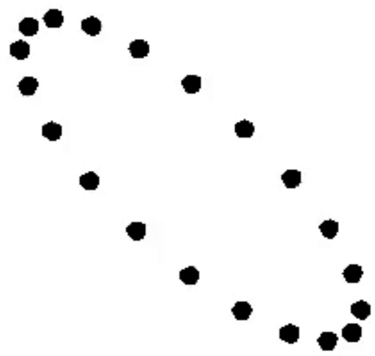


Linearized gravity

- Flat, empty space is a solution to general relativity.
- Leading order correction, $h_{\mu\nu}$, satisfies wave equation
- These waves create a tidal distortion in space-time, $h = \frac{\delta L}{L}$





LIGO

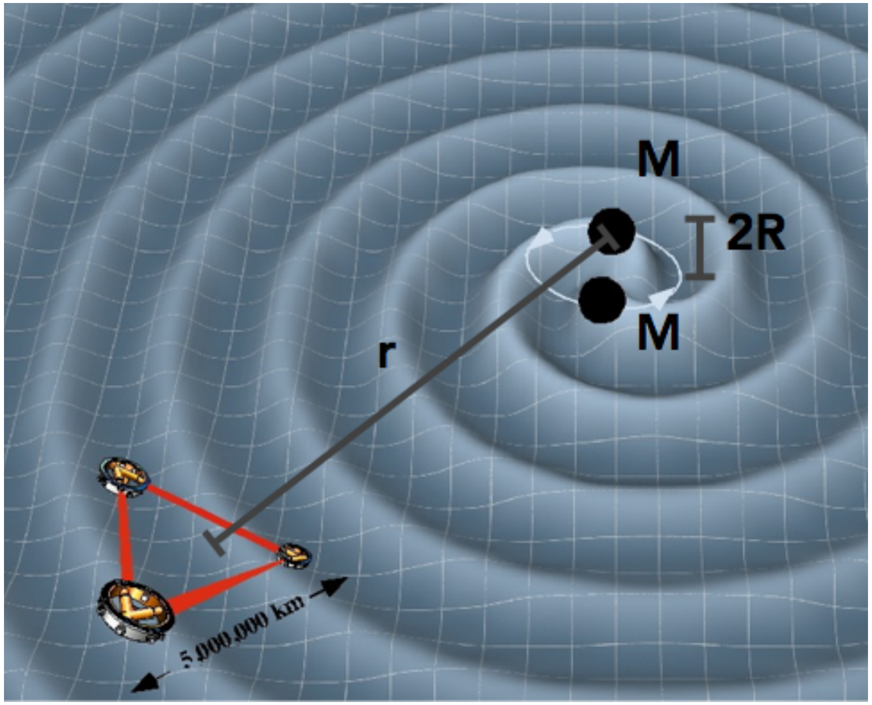
Generating gravitational waves

- Time varying mass quadrupole generates gravitational waves

- Binary system is ideal

$$h \sim \left(\frac{GM}{c^2 R}\right)\left(\frac{GM}{c^2 r}\right)$$

$$P \sim \frac{GM^2 v^6}{c^5 R^2}$$



Generating gravitational waves

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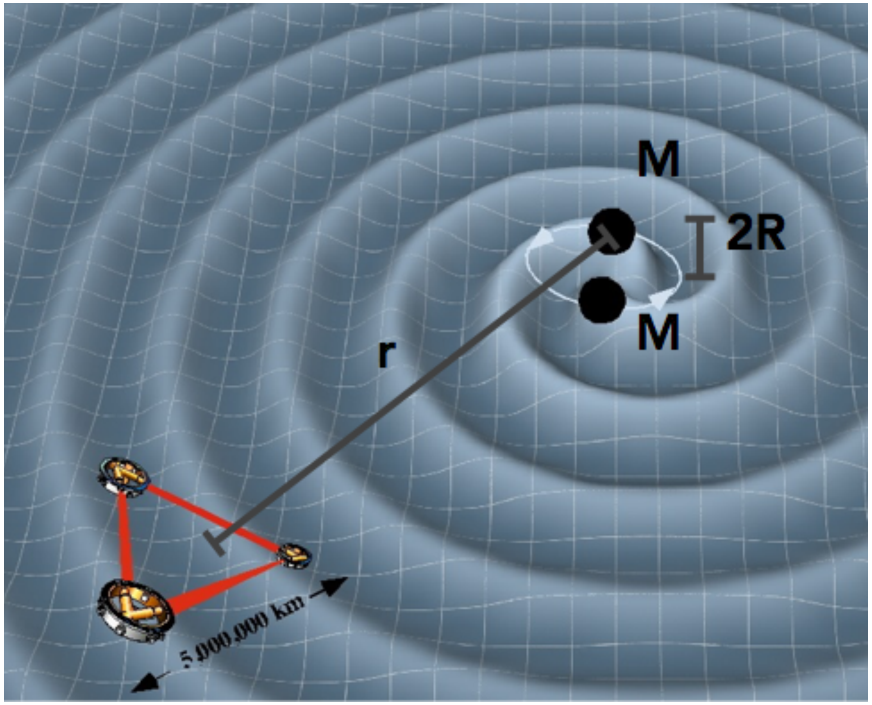
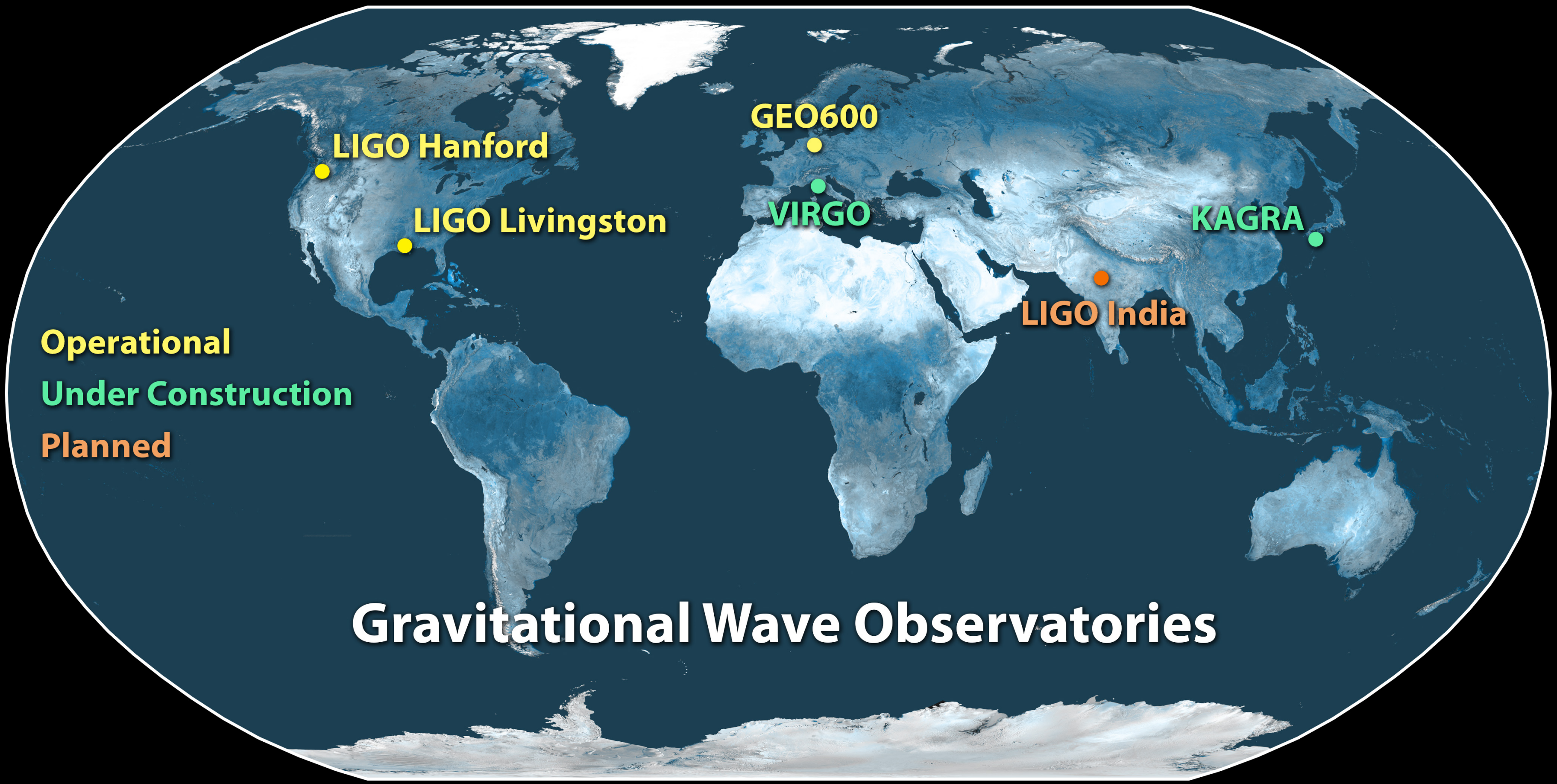


For a black hole:

$$R_{\mathrm{Sch}} = \frac{2GM}{c^2}$$

A global network



LIGO

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LIGO Hanford Observatory
LIGO Hanford
LIGO Livingston

LIGO

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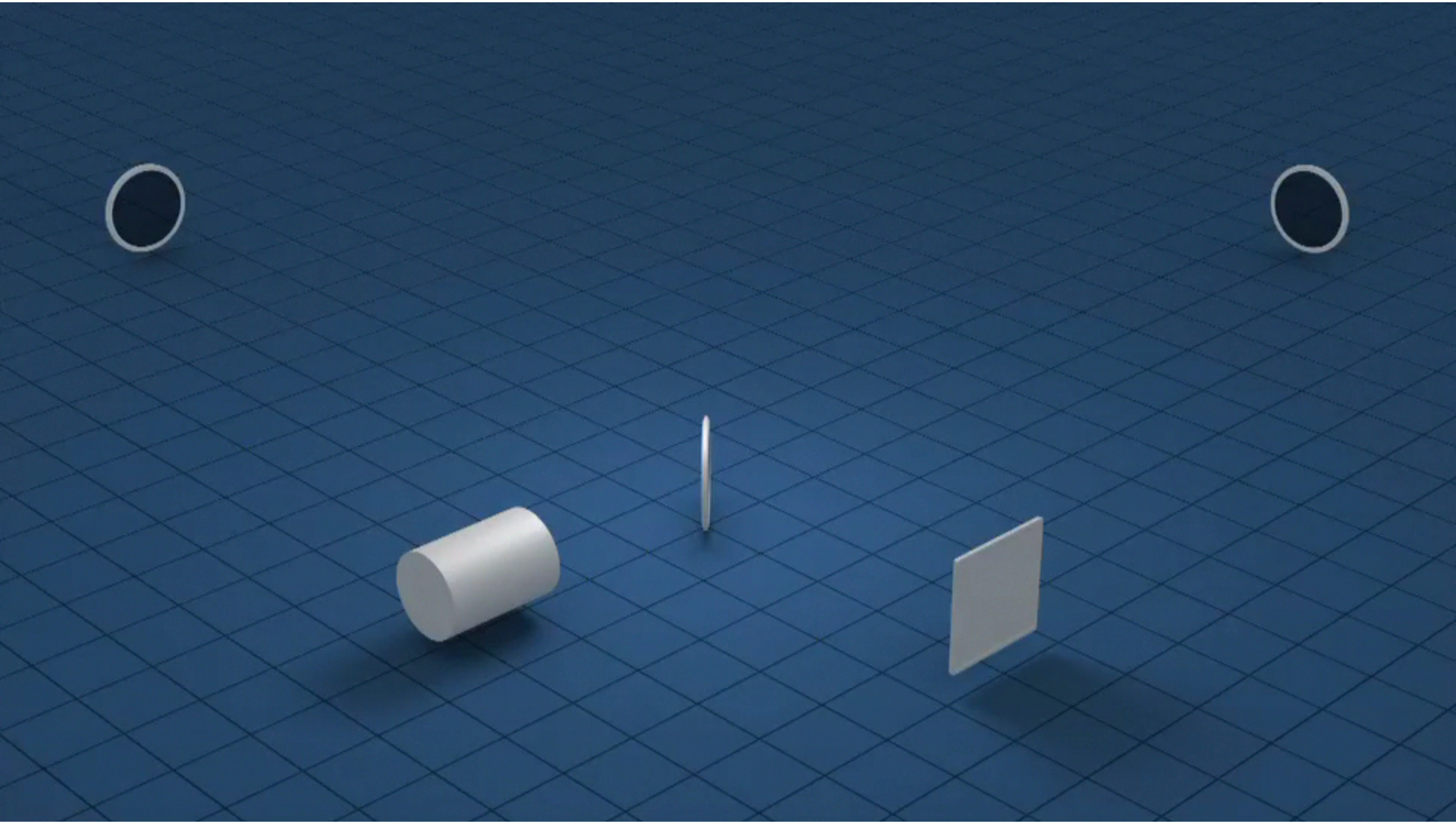

LIGO The Scale of the Challenge

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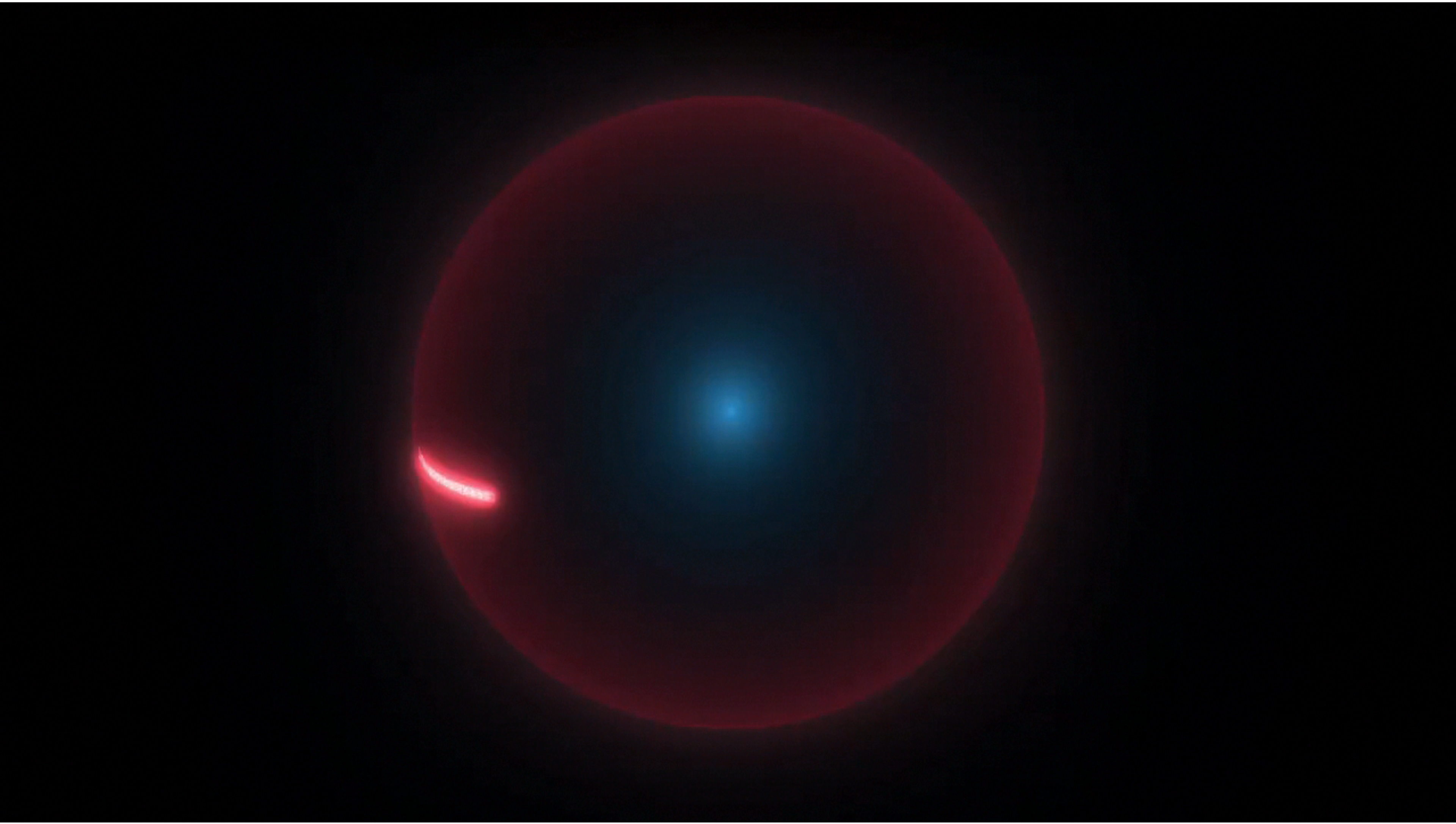
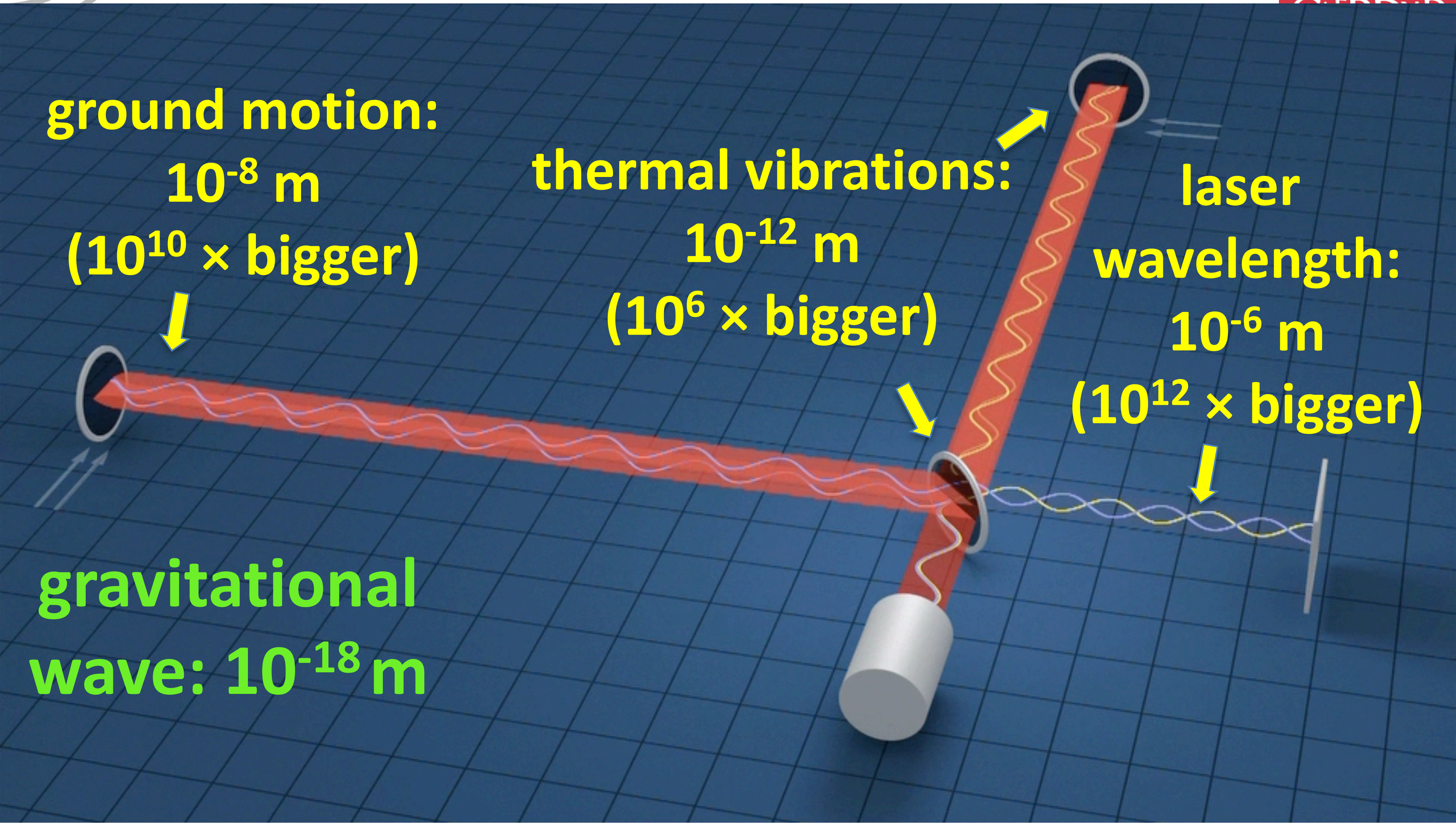
10^{-22} change in length of a LIGO arm: 10^{-18} m

LIGO The Scale of the Challenge

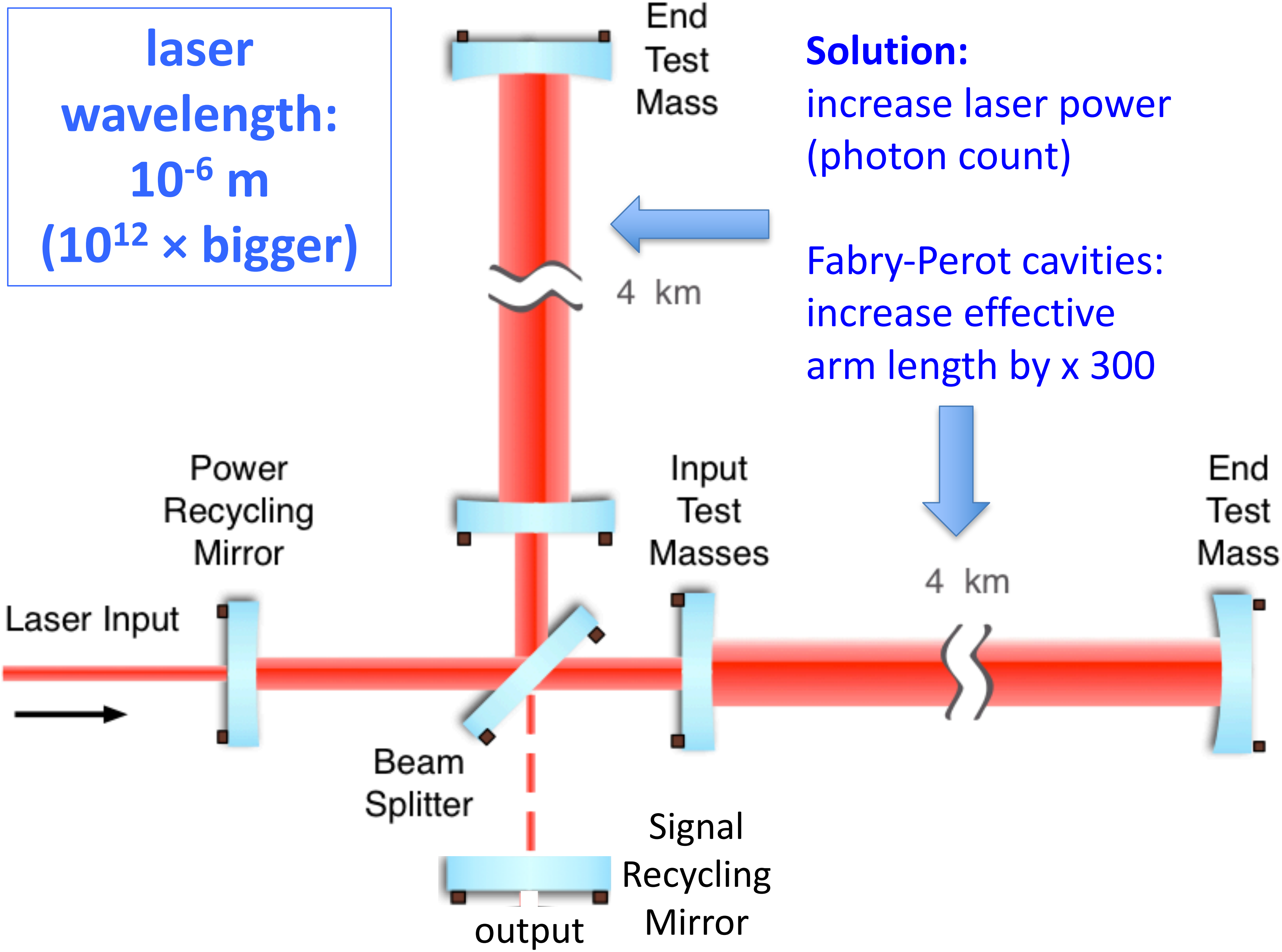



ground motion:
10^{-8} m
(10^{10} × bigger)
thermal vibrations:
10^{-12} m
(10^{6} × bigger)
laser
wavelength:
10^{-6} m
(10^{12} × bigger)
gravitational
wave: 10^{-18} m

laser wavelength: 10^{-6} m (10^{12} × bigger)

Solution:
increase laser power (photon count)

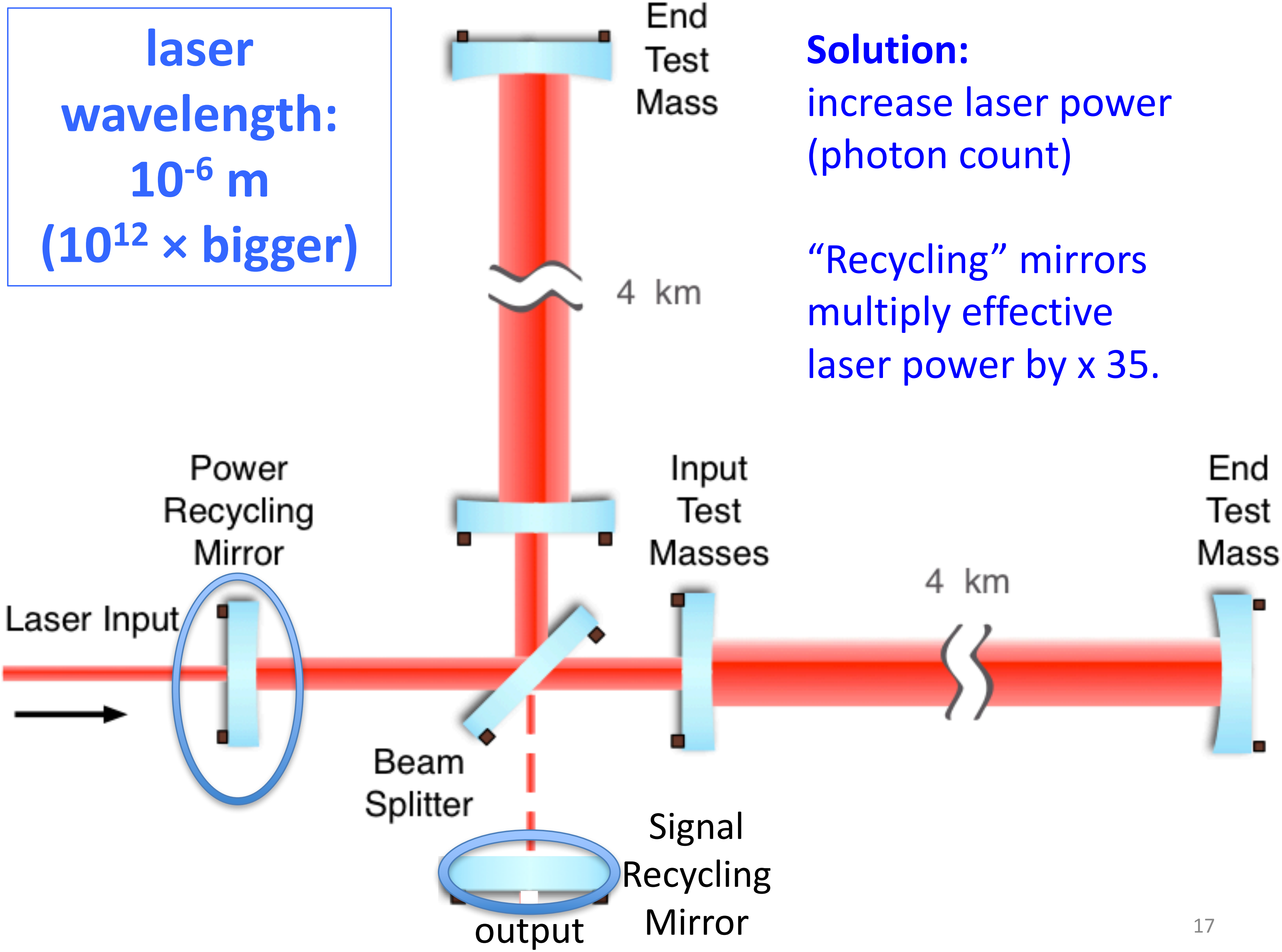
Fabry-Perot cavities: increase effective arm length by x 300



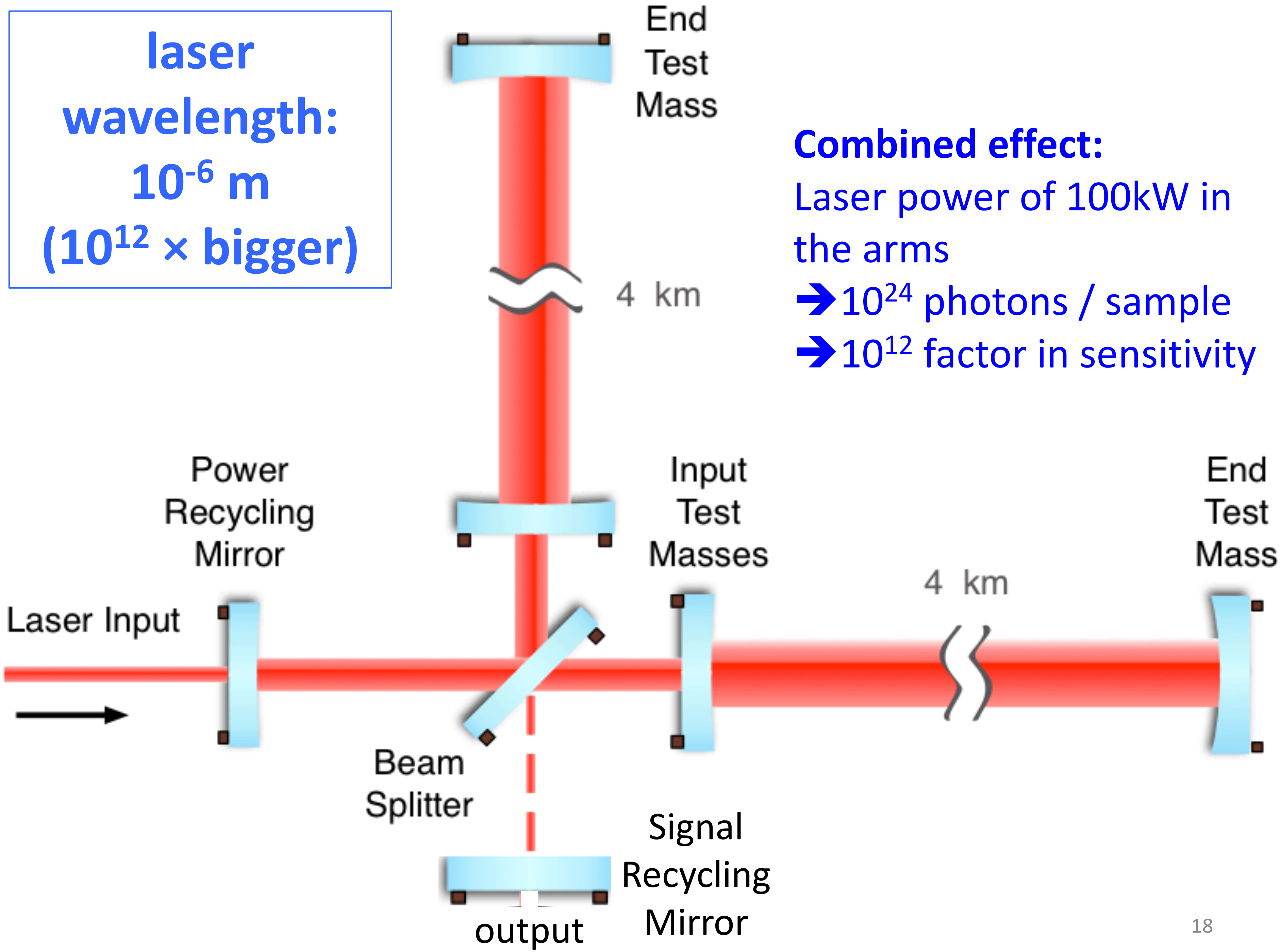
laser wavelength: 10^{-6} m ($10^{12} \times$ bigger)

Solution:
increase laser power (photon count)

"Recycling" mirrors multiply effective laser power by x 35.



laser wavelength: 10^{-6} m (10^{12} × bigger)



Combined effect:

Laser power of 100kW in the arms

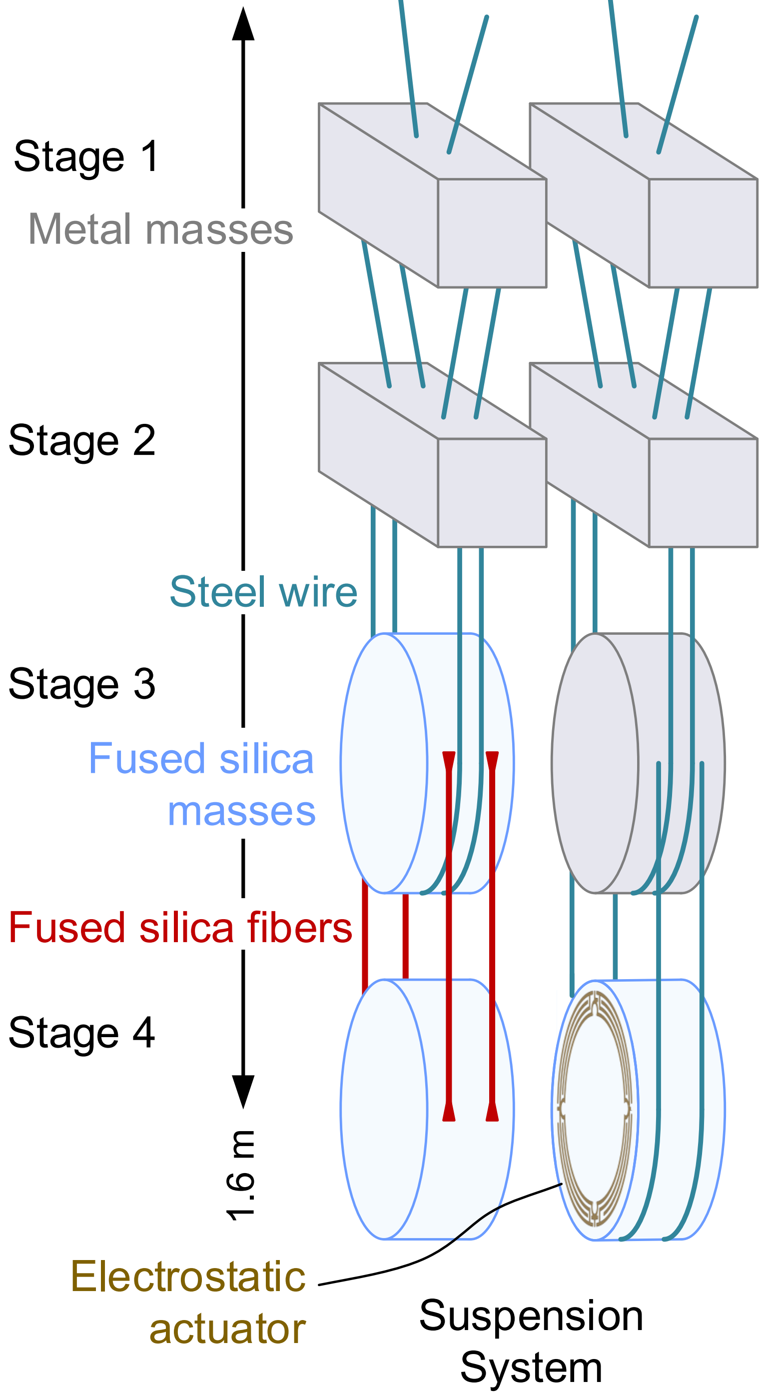
→ 10^{24} photons / sample

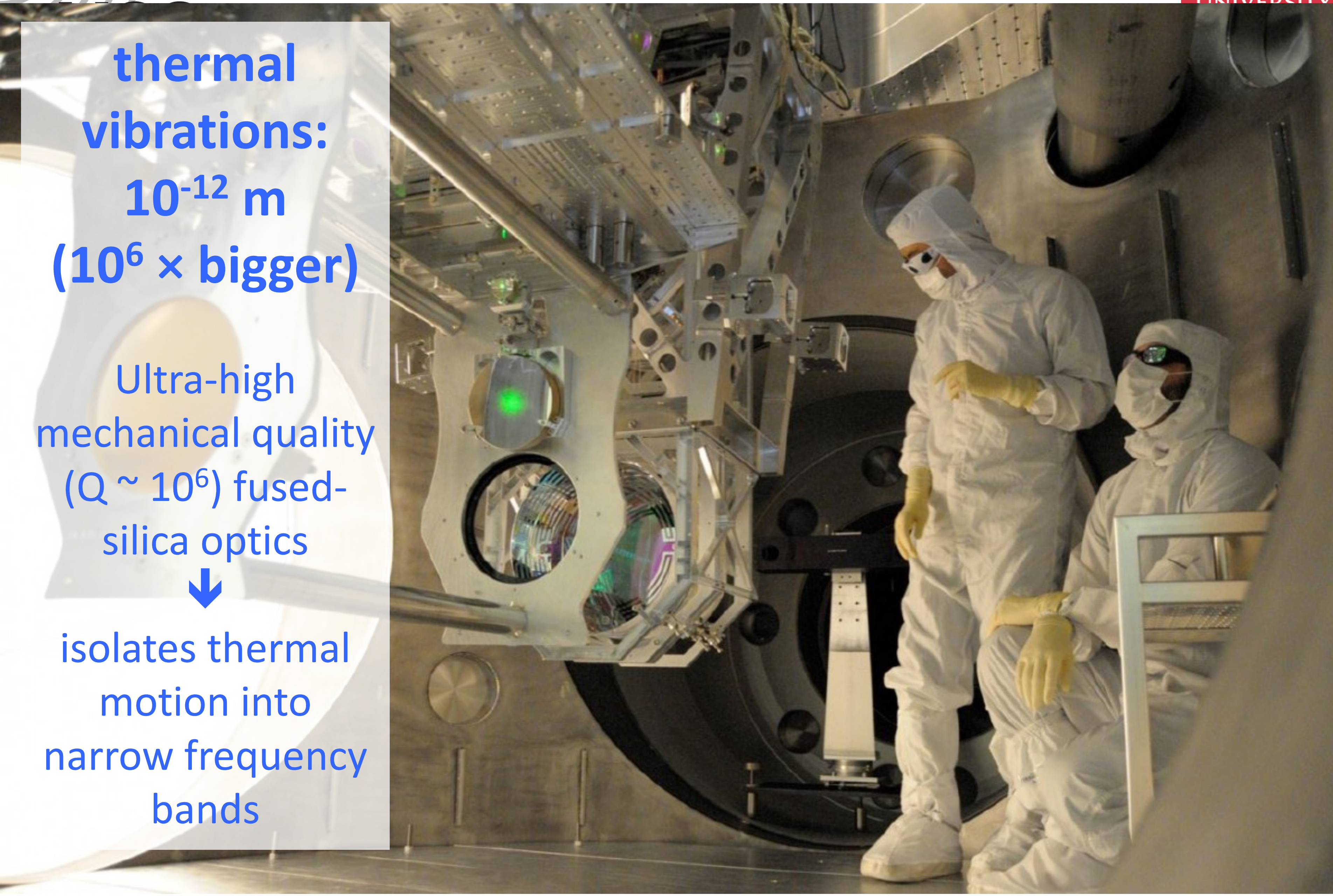
→ 10^{12} factor in sensitivity

LIGO

ground motion:
10^{-8} m
(10^{10} × bigger)

Quadruple pendulum suspension system: **10^7**
+
Active seismic isolation: **10^3**





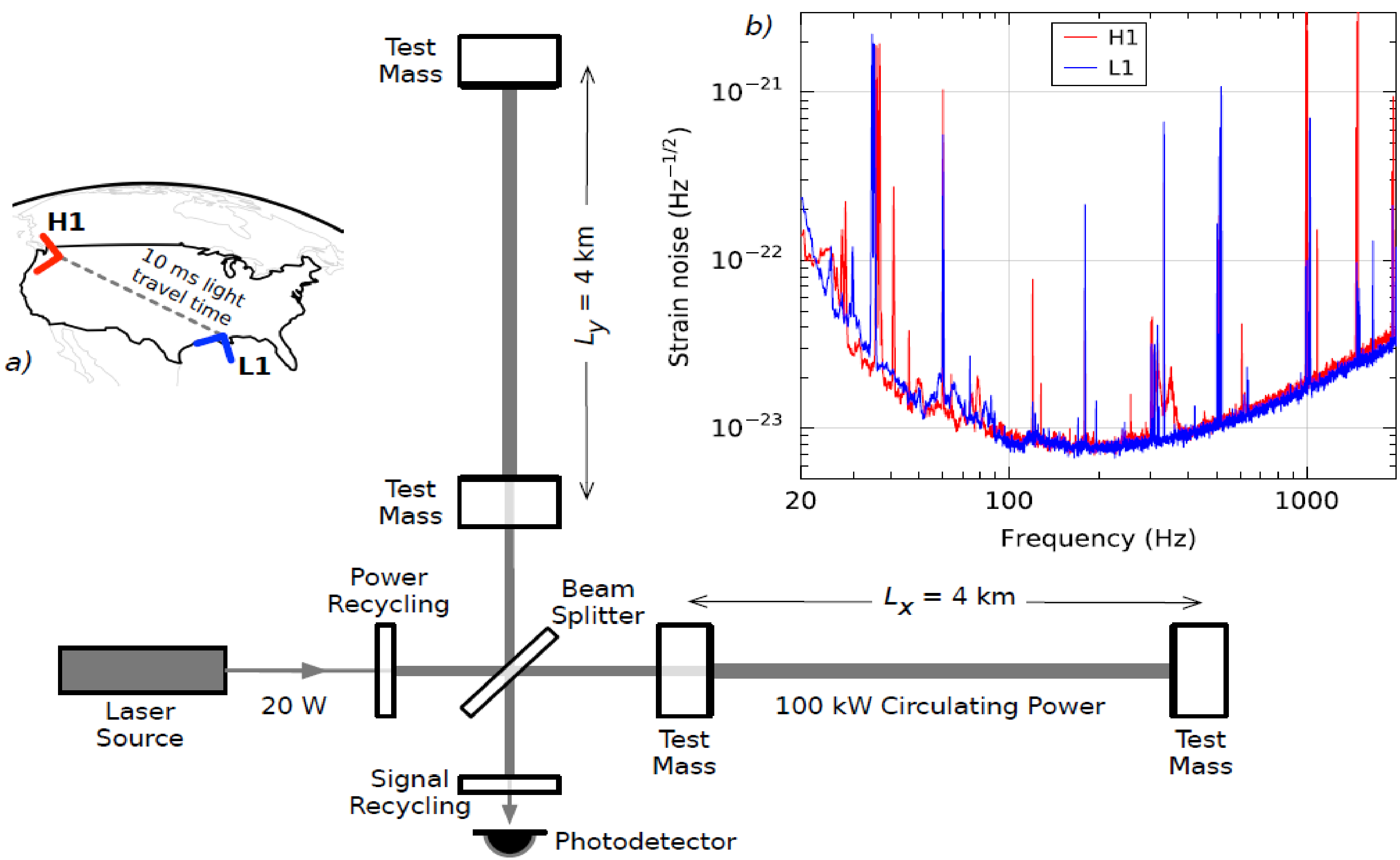
thermal vibrations: 10^{-12} m (10^{6} × bigger)

Ultra-high mechanical quality ($Q \sim 10^{6}$) fused-silica optics

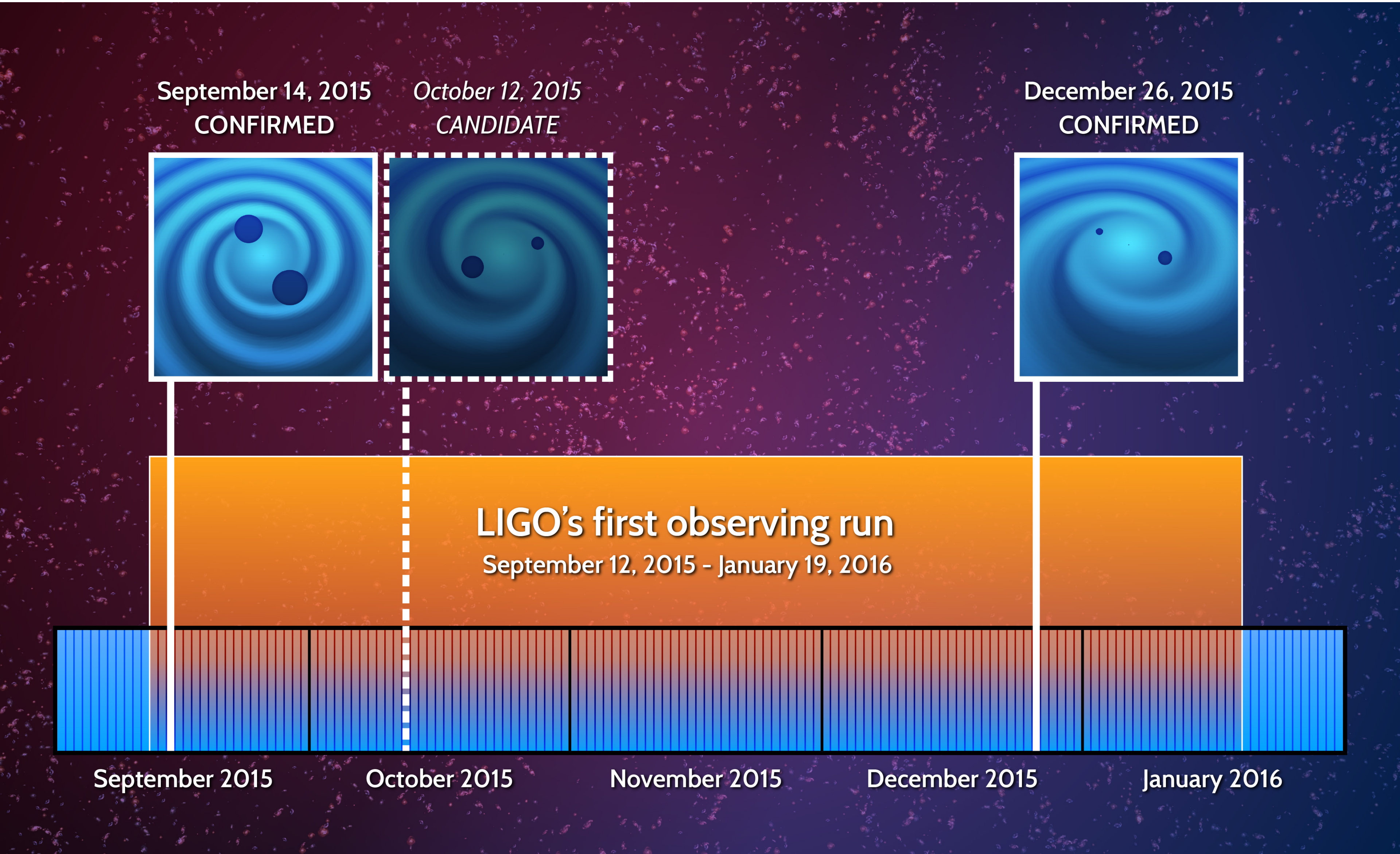
↓

isolates thermal motion into narrow frequency bands

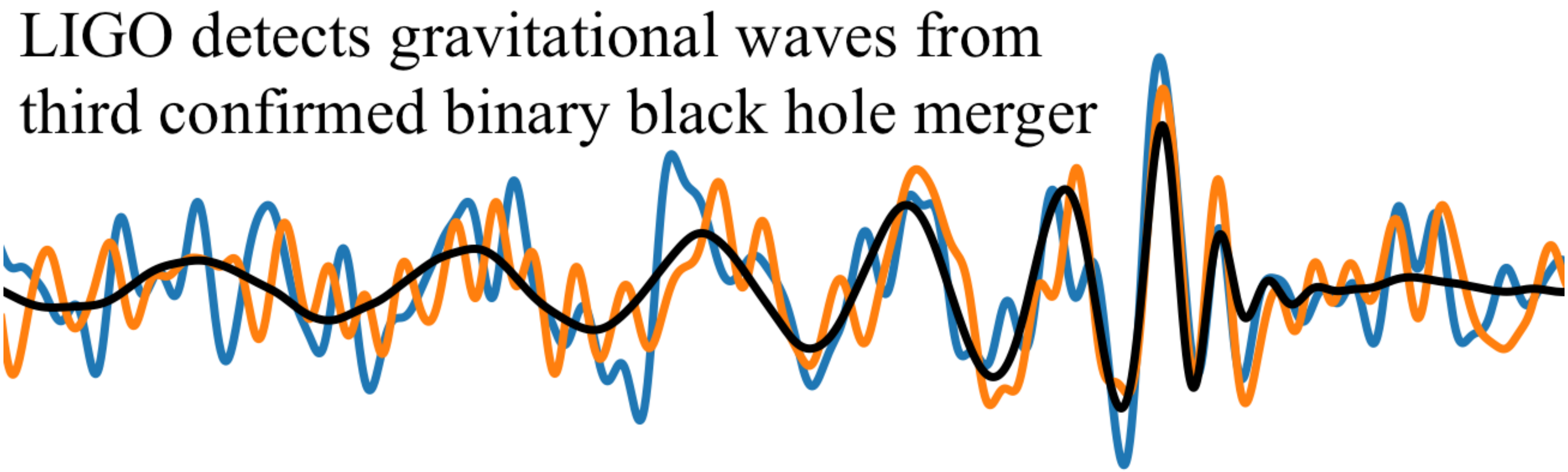
First Observing Run



First Observing Run



Second Observing Run



- Second run began on 30 November, 2016
- Another binary black hole merger GW170104 was detected on January 4, 2017

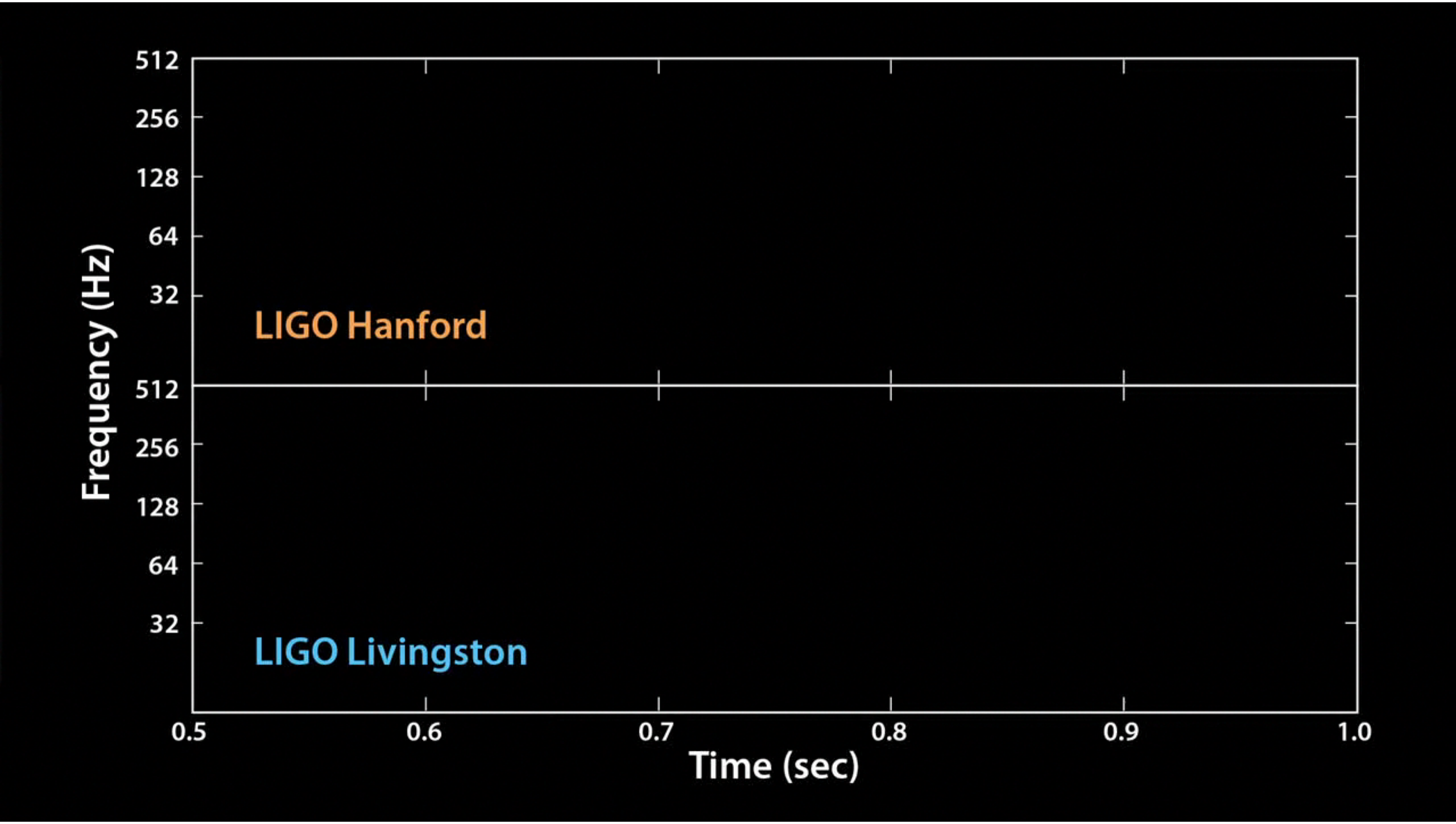
Second Observing Run

- Virgo joined the run on 1st August 2017
- Run ended on 25 August 2017

A VERY EXCITING LIGO-VIRGO OBSERVING RUN IS DRAWING TO A CLOSE AUGUST 25

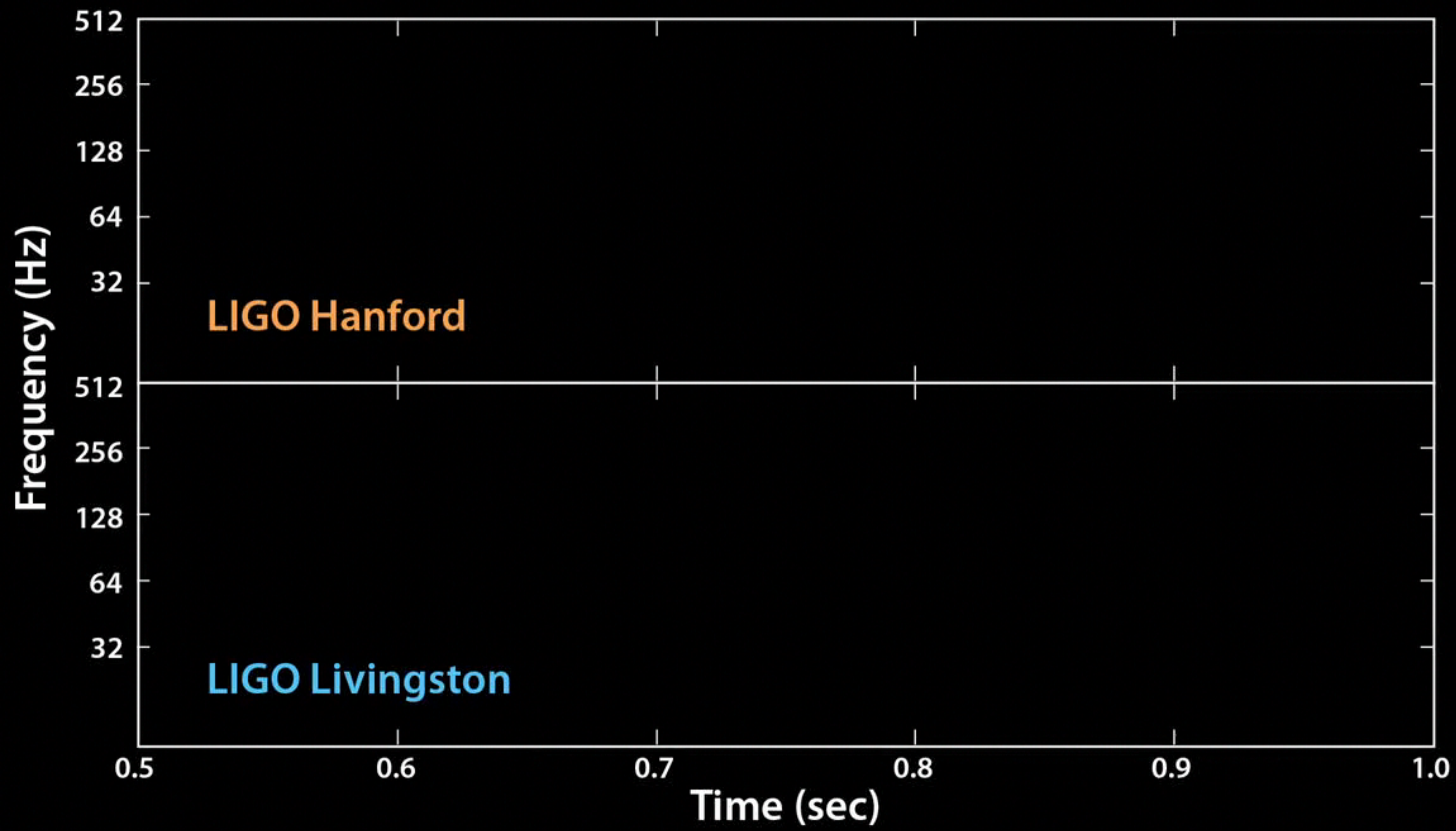
25 August 2017 -- The Virgo and LIGO Scientific Collaborations have been observing since November 30, 2016 in the second Advanced Detector Observing Run 'O2' , searching for gravitational-wave signals, first with the two LIGO detectors, then with both LIGO and Virgo instruments operating together since August 1, 2017. Some promising gravitational-wave candidates have been identified in data from both LIGO and Virgo during our preliminary analysis, and we have shared what we currently know with astronomical observing partners. We are working hard to assure that the candidates are valid gravitational-wave events, and it will require time to establish the level of confidence needed to bring any results to the scientific community and the greater public. We will let you know as soon we have information ready to share.

GW150914



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)

GW150914



512
256
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Frequency (Hz)
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0.7
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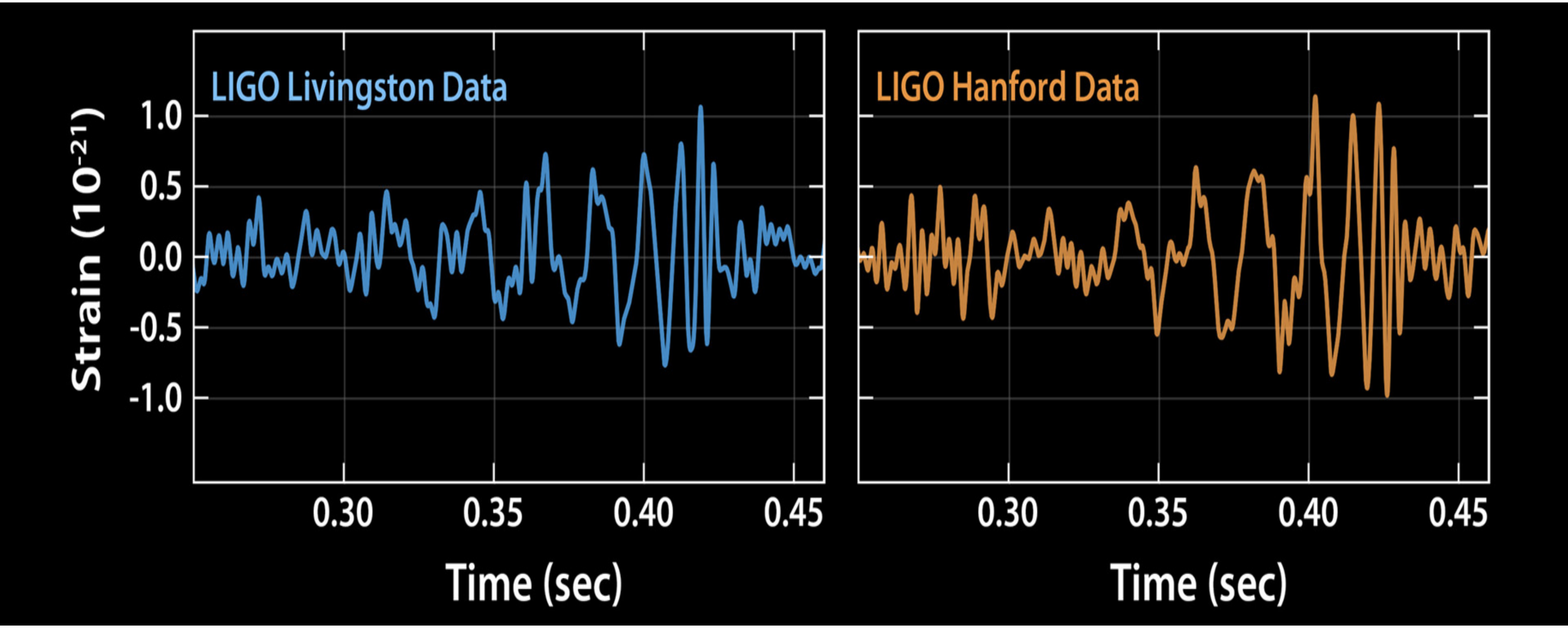
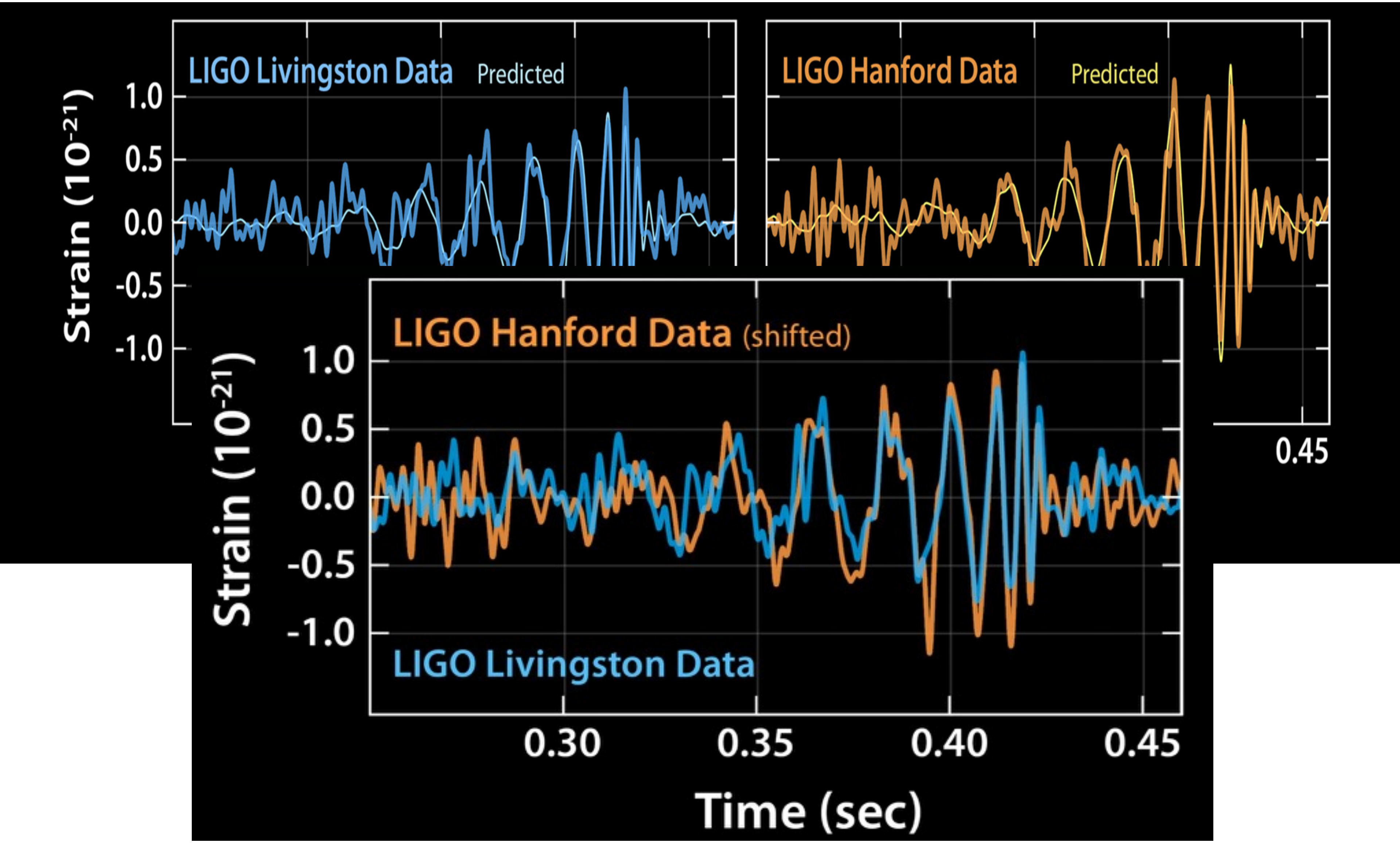
Time (sec)

GW 150914



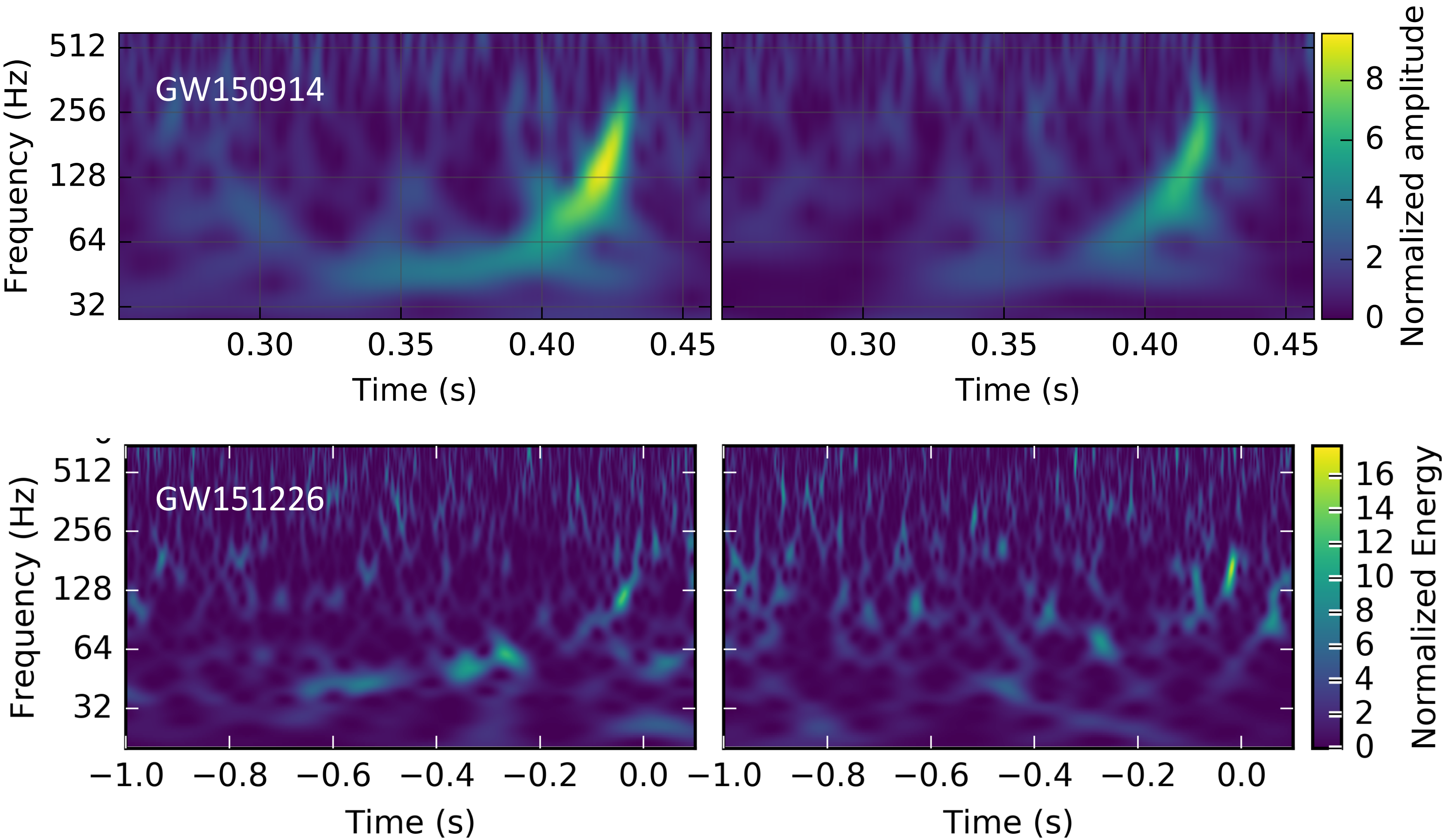
LIGO Livingston Data
LIGO Hanford Data
Strain (10⁻²¹)
1.0
0.5
0.0
-0.5
-1.0
0.30
0.35
0.40
0.45
Time (sec)
Time (sec)

GW 150914



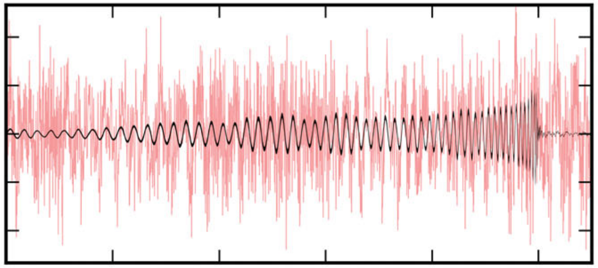
LIGO Livingston Data
Predicted
LIGO Hanford Data
Predicted
Strain (10^-21)
1.0
0.5
0.0
-0.5
-1.0
0.45
LIGO Hanford Data (shifted)
LIGO Livingston Data
0.30
0.35
0.40
0.45
Time (sec)

Identifying the signals



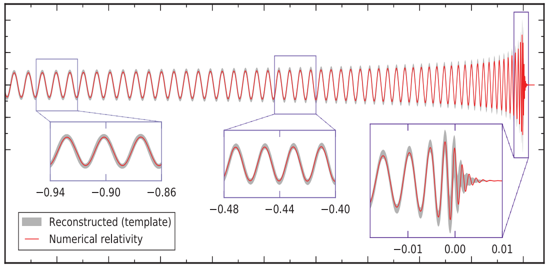
Matched filtering

Data



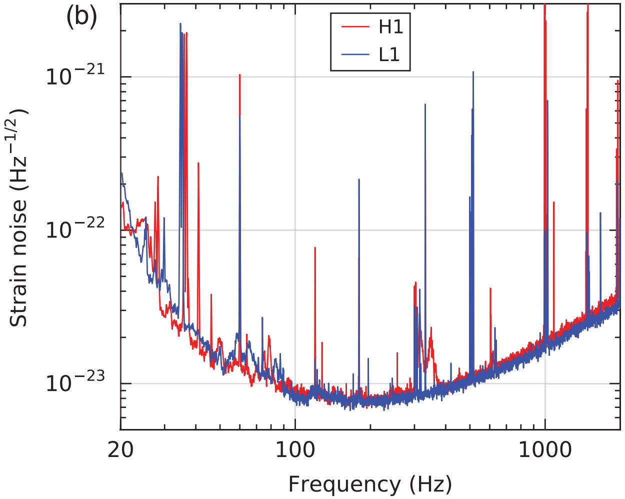
X

Waveform



/

Sensitivity



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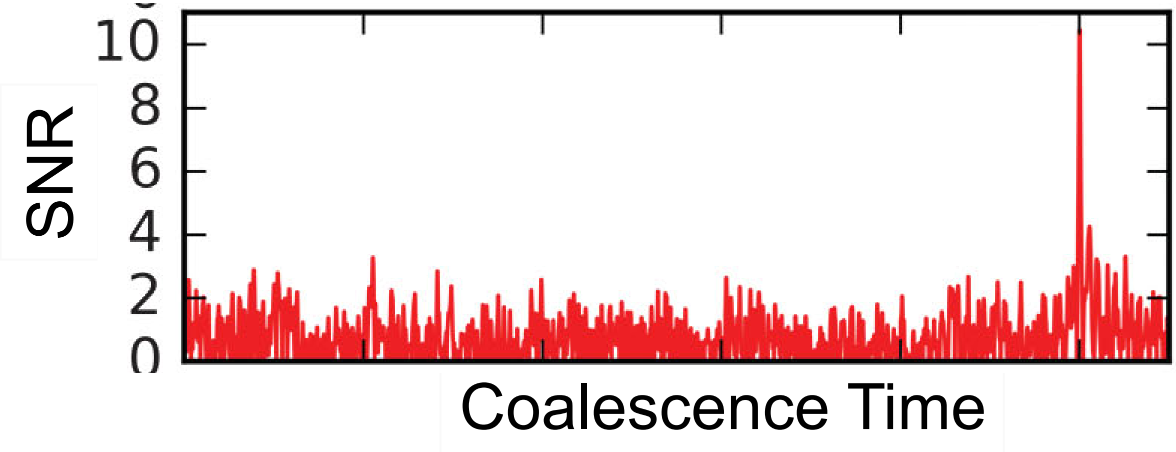
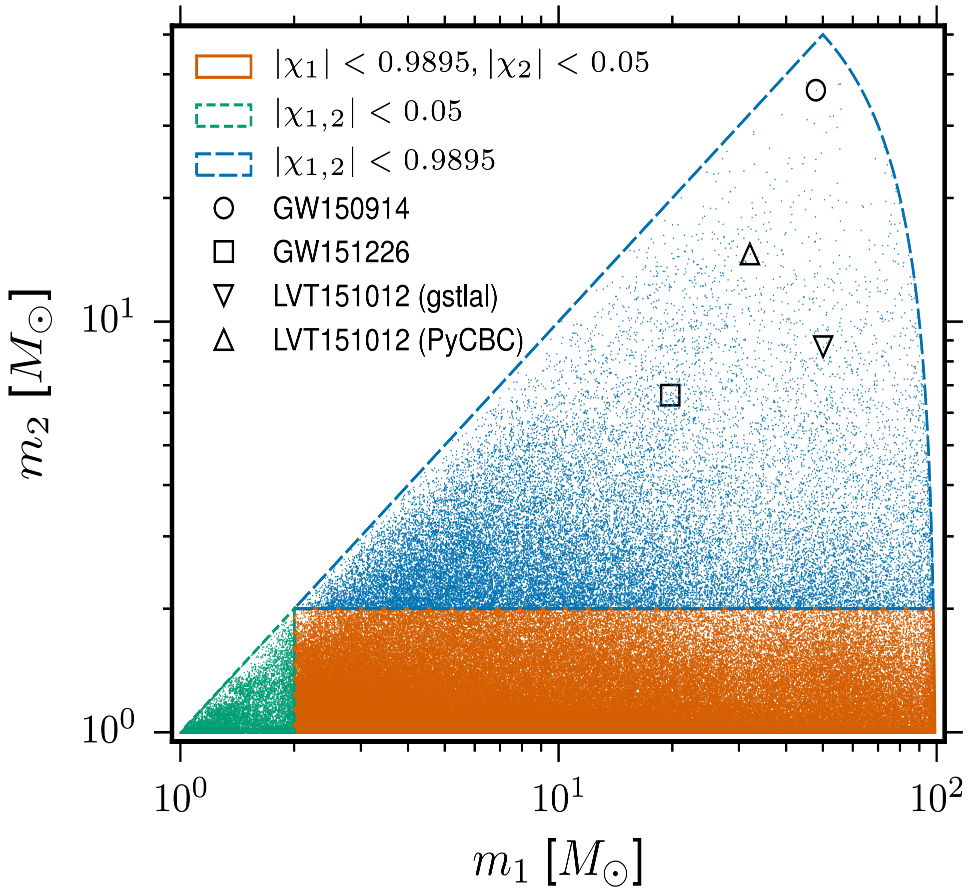
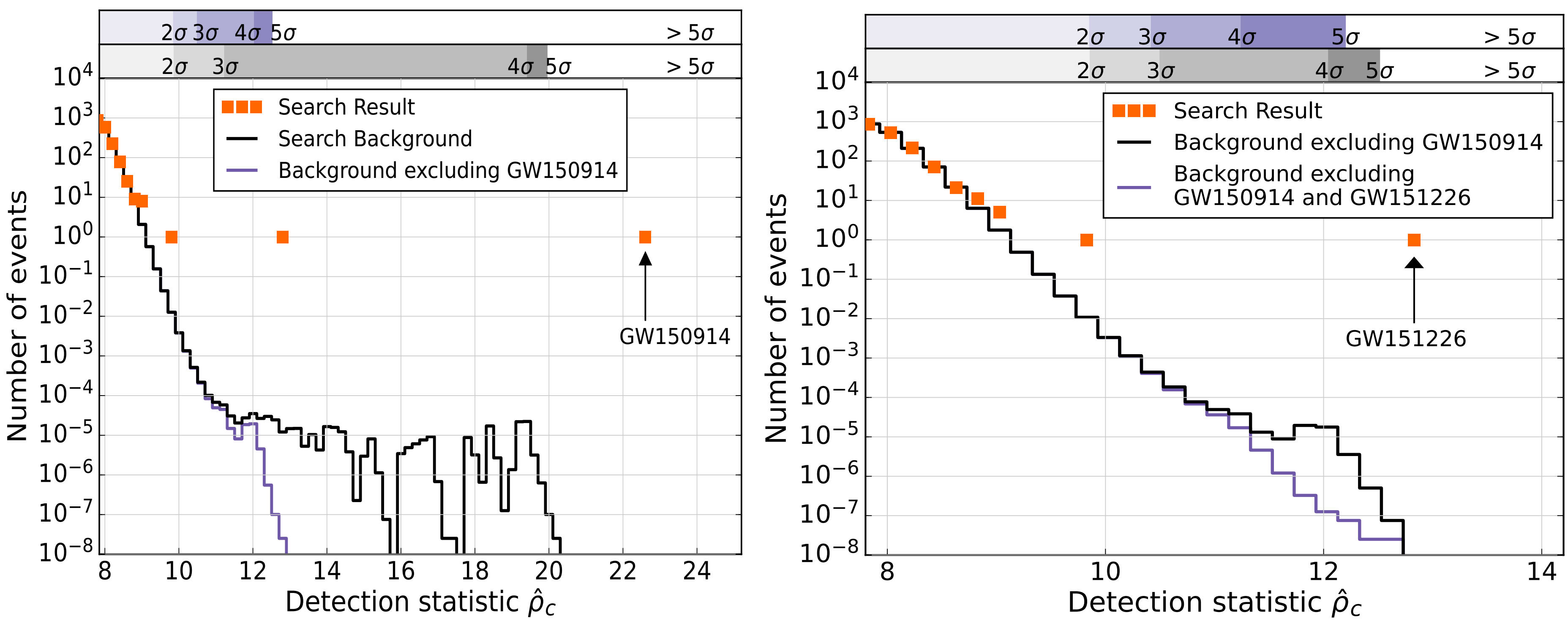


Binary Merger Search

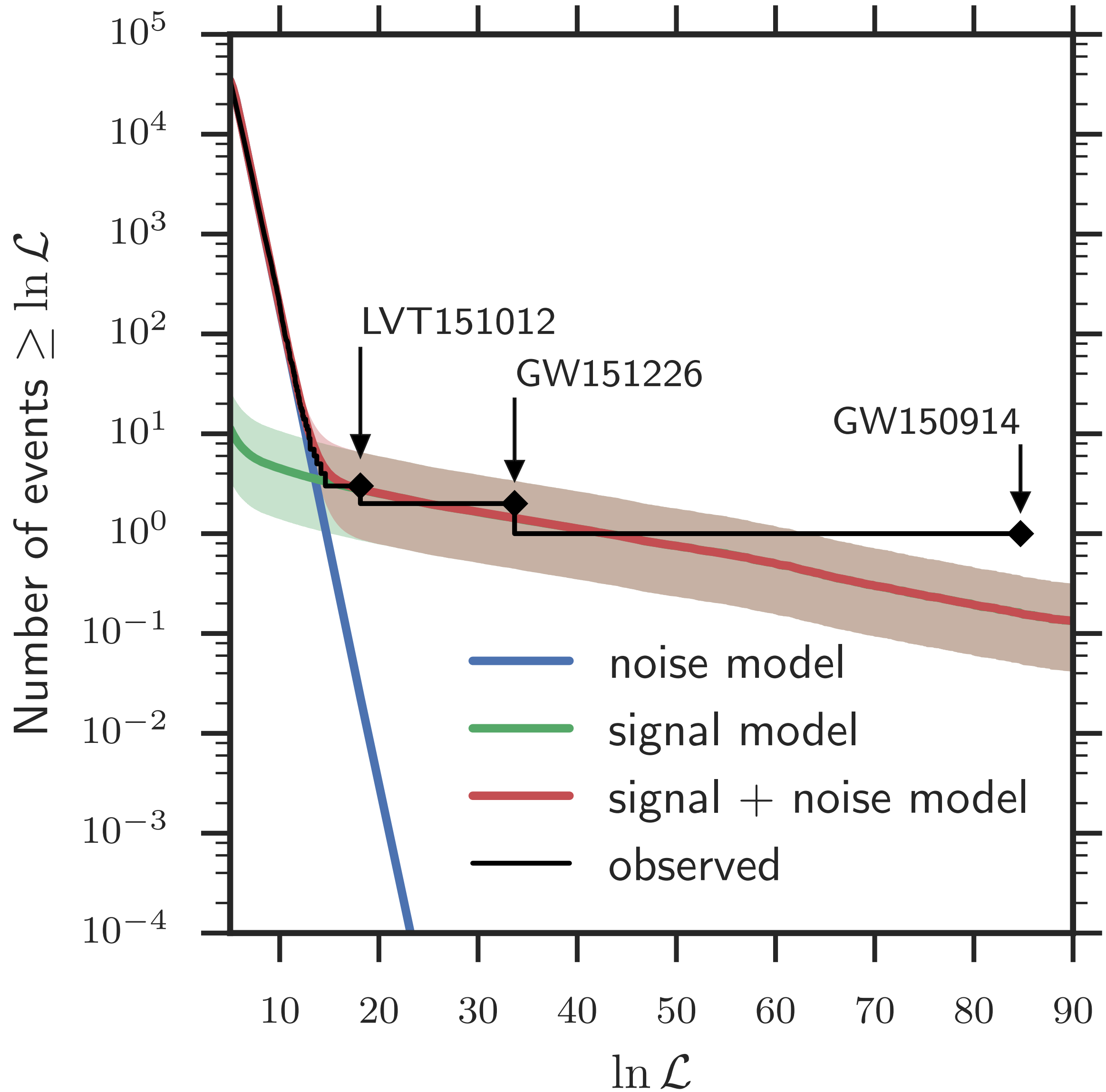
- Use known waveforms to search for binary signals.
- Calculate Signal to Noise Ratio (SNR), and signal significance in each detector.
- Require time coincidence between detectors.
- Background: Time shift by multiples of 0.1 seconds and repeat search.



Statistical Significance



Statistical Significance

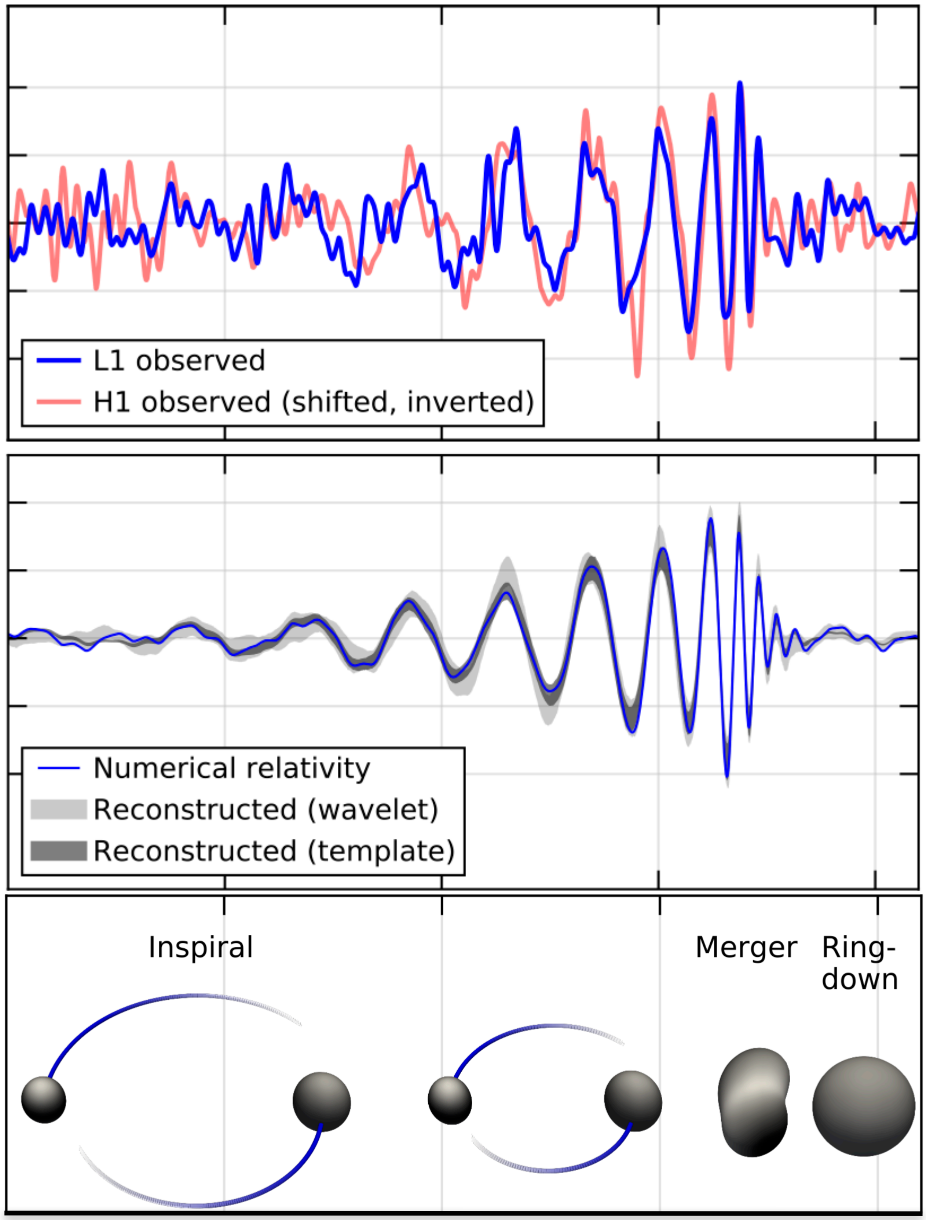


LIGO

A black hole binary

- Orbits decay due to emission of gravitational waves

- **Leading order** determined by "chirp mass"

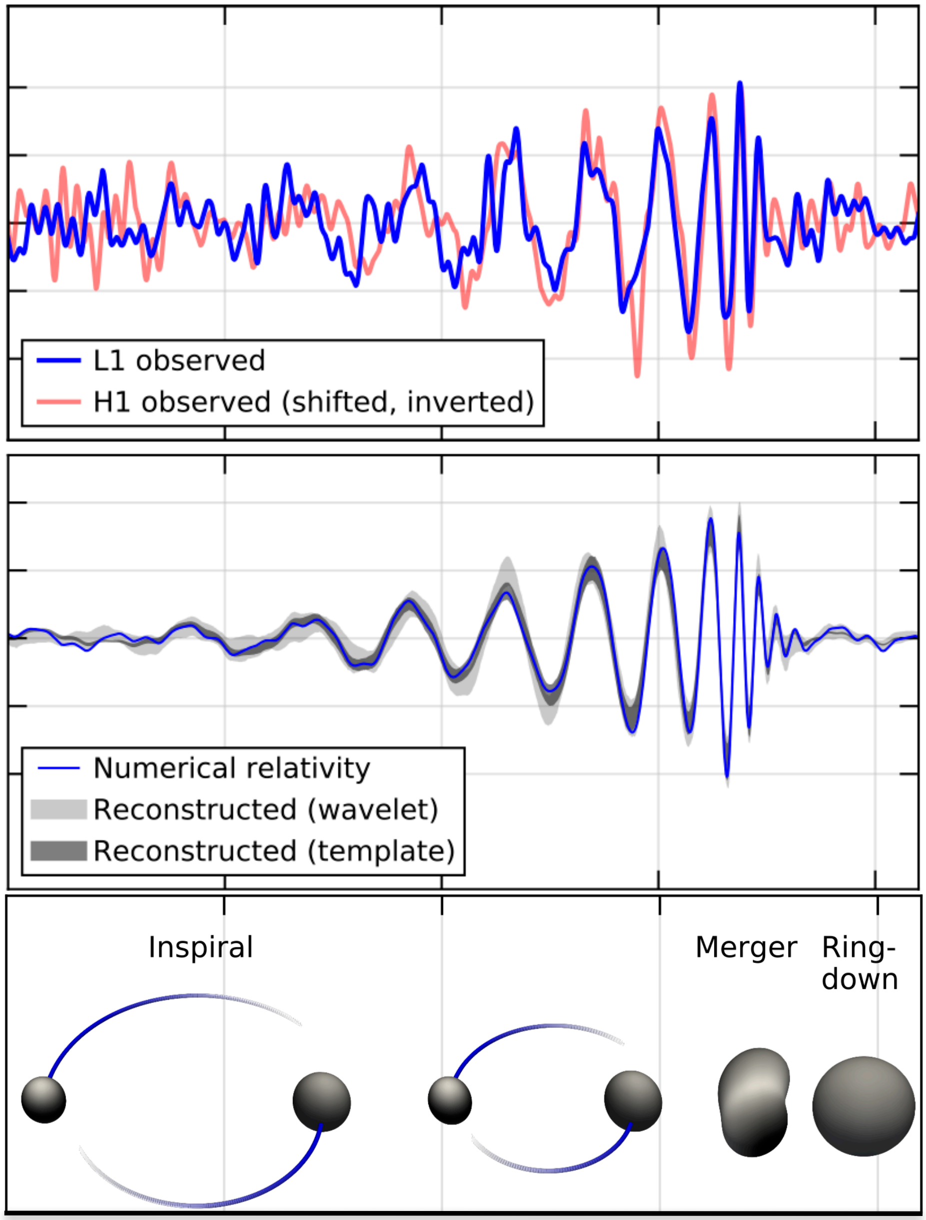


$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{M^{1/5}} \simeq \frac{c^3}{G}\left[\frac{5}{96}\pi^{-8/3} f^{-11/3} \dot{f}\right]^{3/5}$$

LIGO

A black hole binary

- Binary is at least sixty times as massive as the sun.
- Bodies are in orbit until centres are separated by a few hundred km.



LIGO

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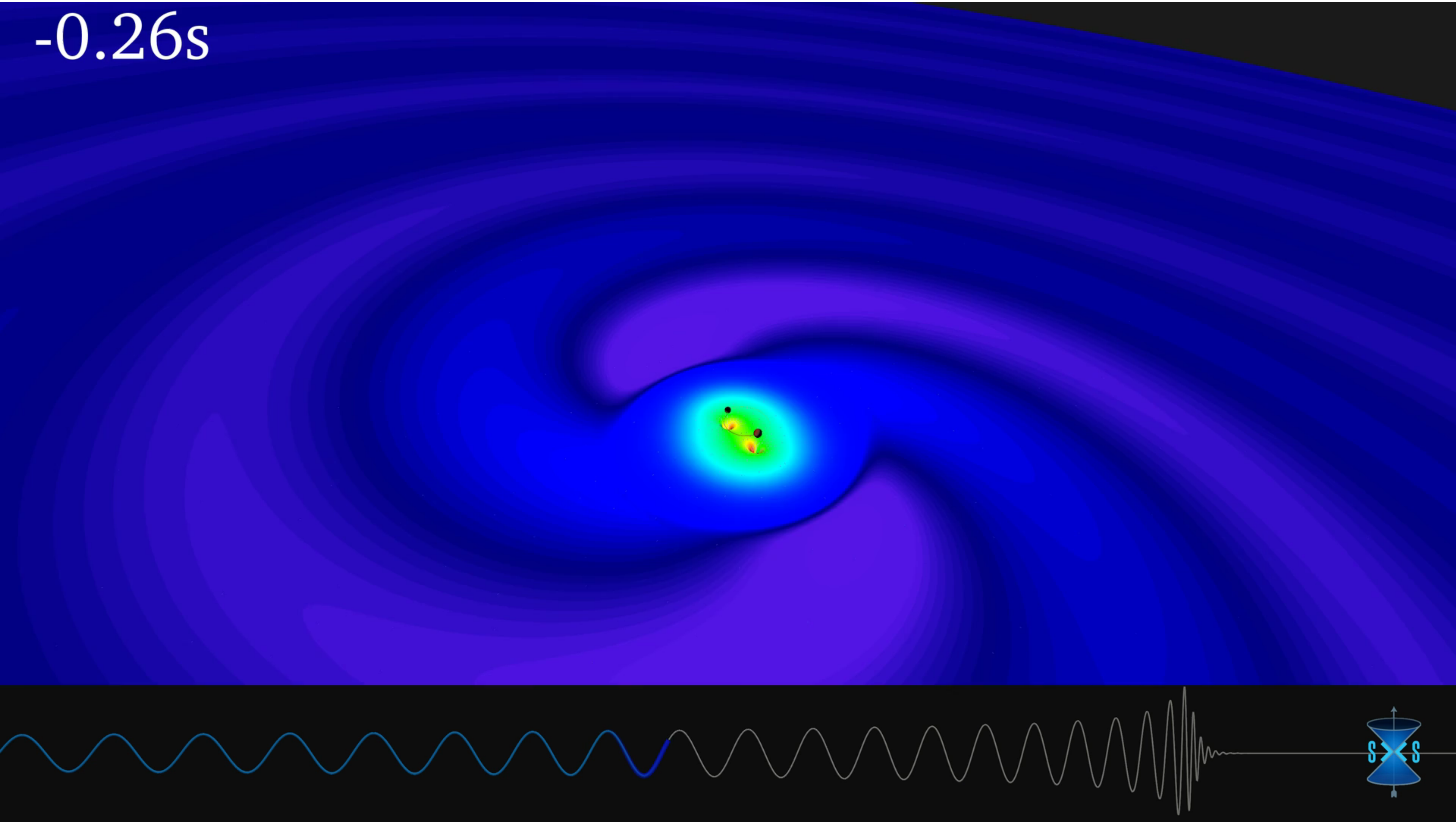
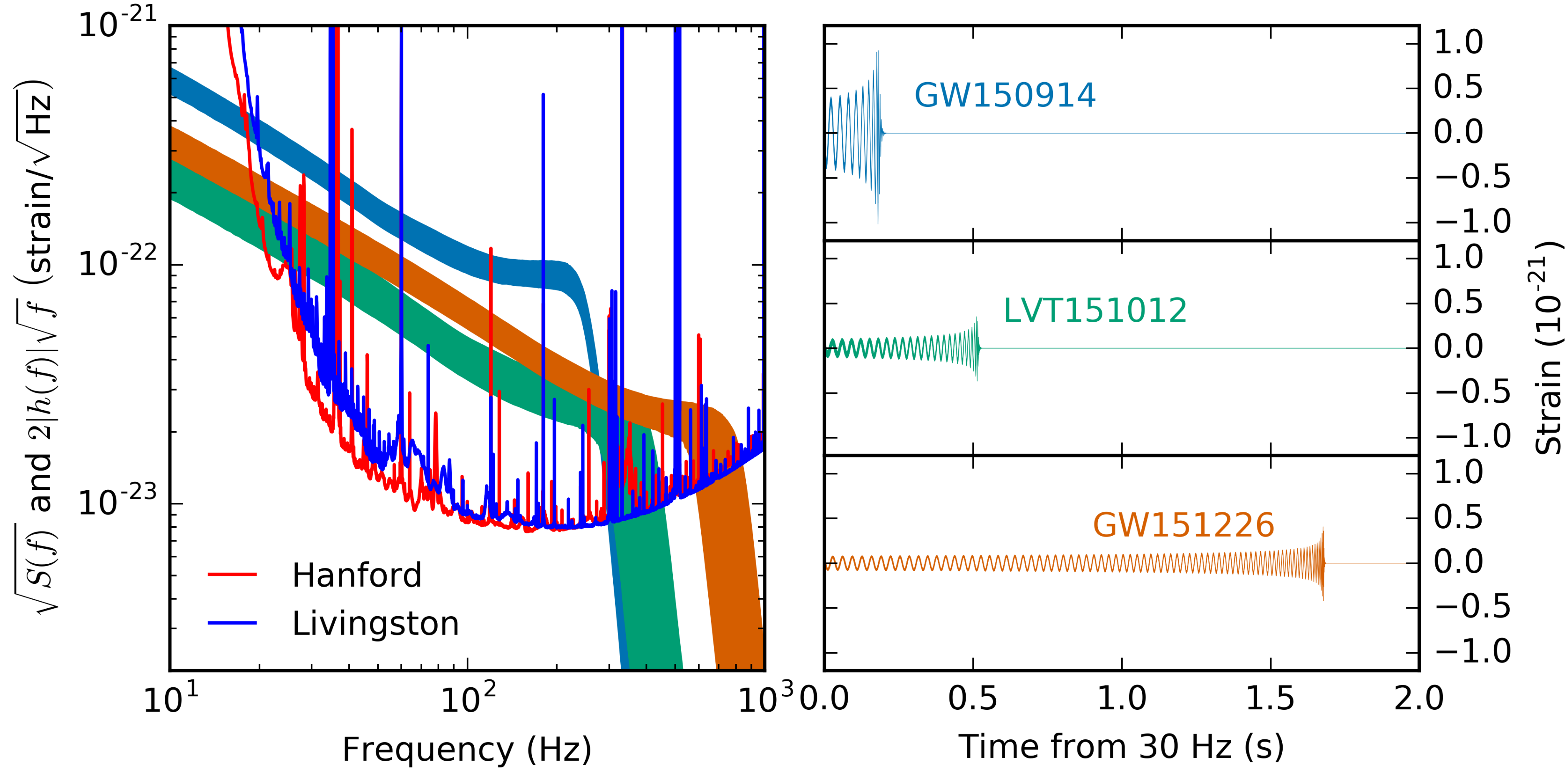
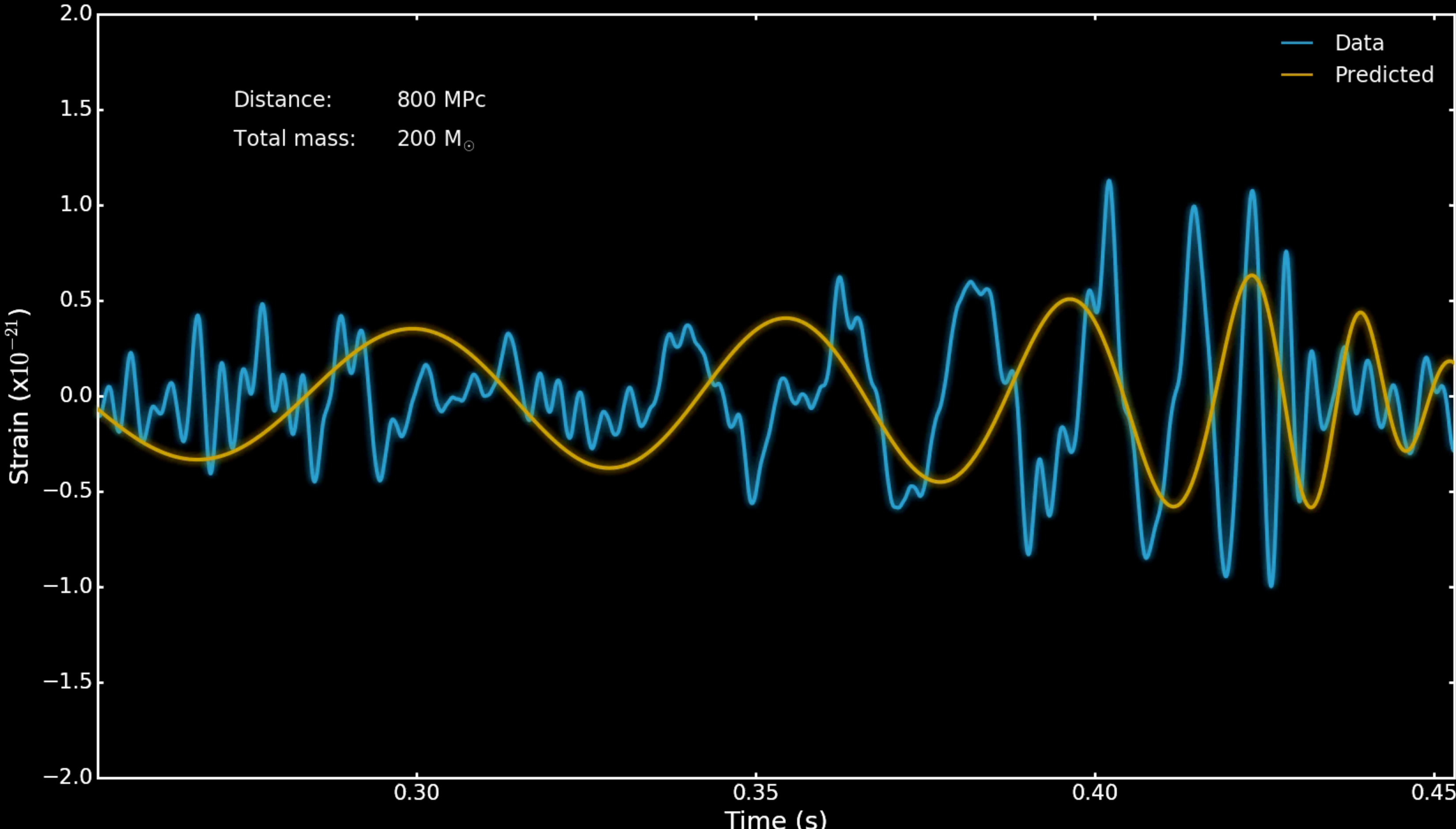


Observed Signals

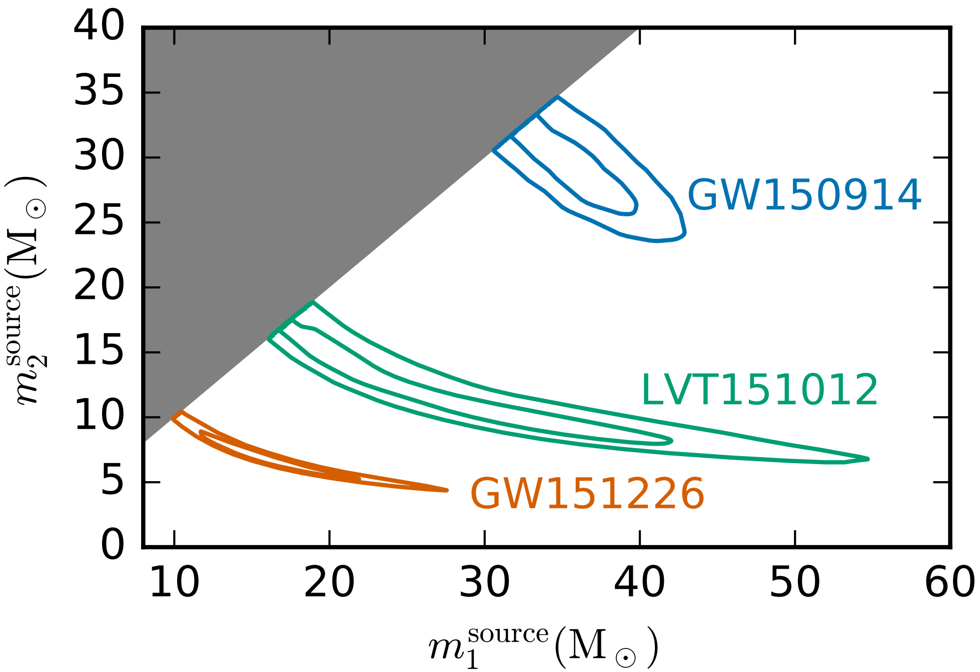


Parameter fitting

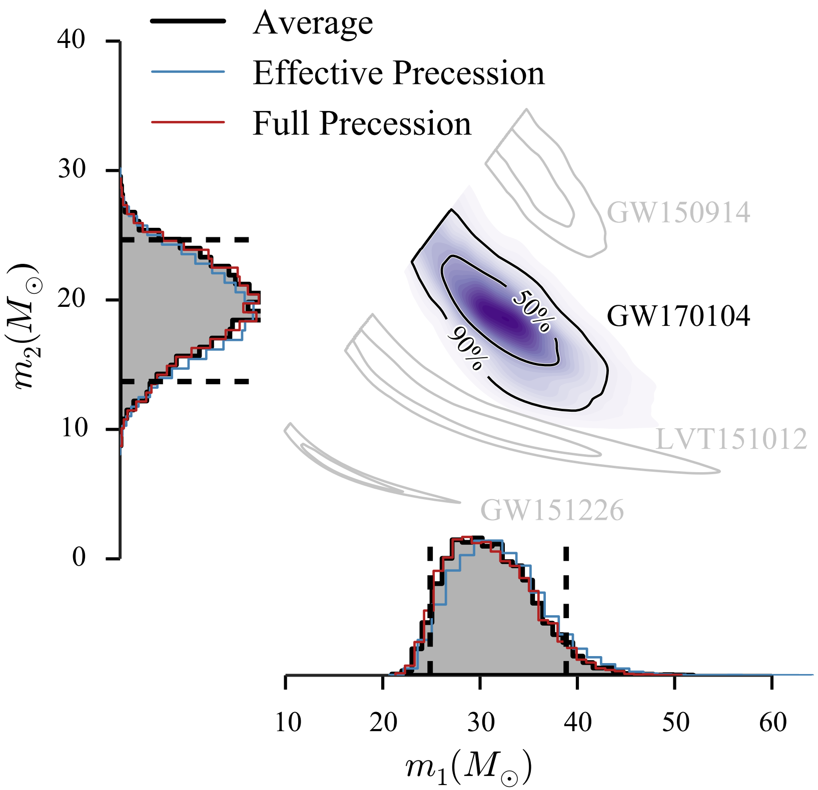


Data & Best-fit Waveform: LIGO Open Science Center (losc.ligo.org); Prediction & Animation: C.North/M.Hannam (Cardiff University)

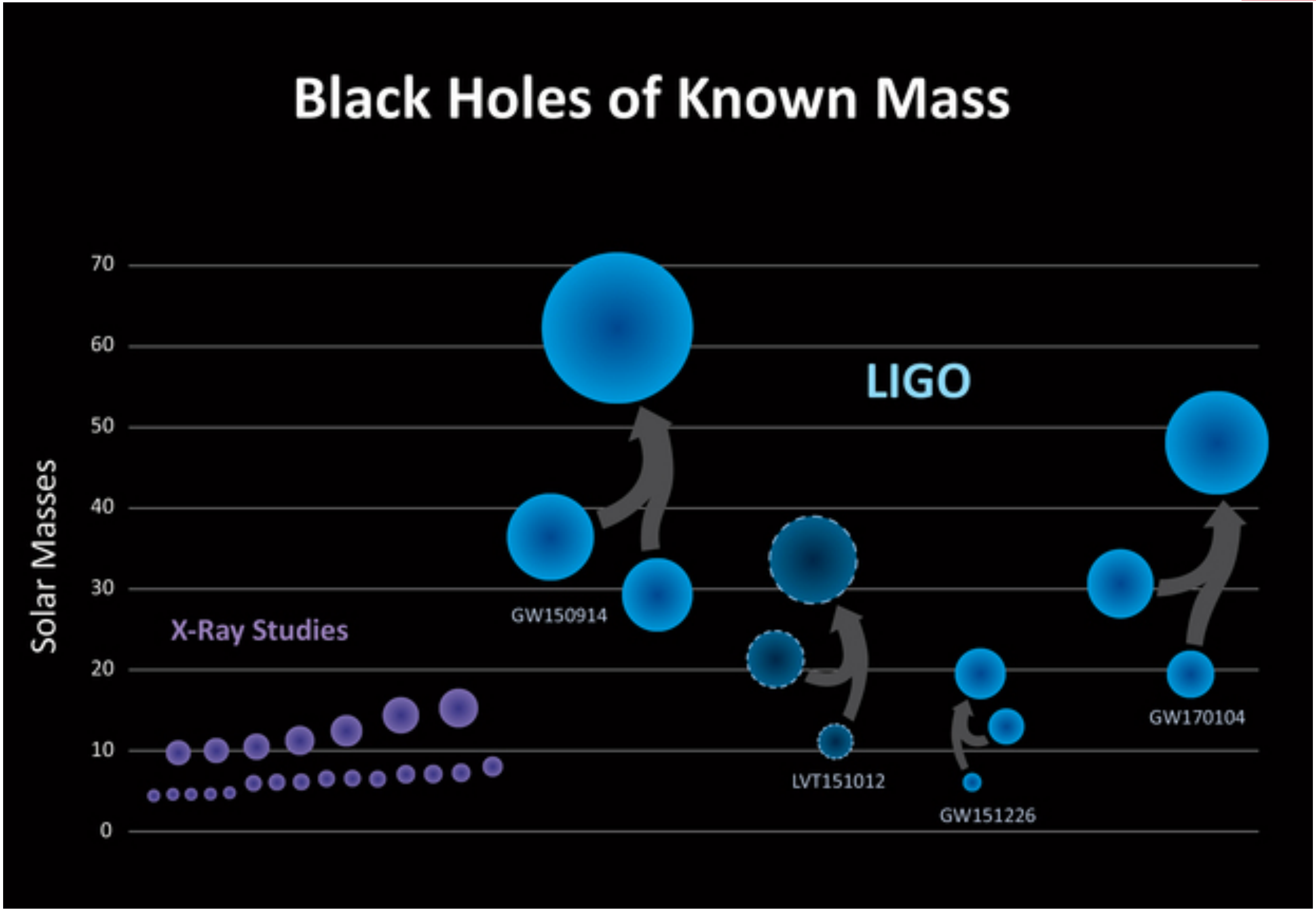
Masses



GW150914
LVT151012
GW151226
$m_1^{\mathrm{source}}(\mathrm{M}_\odot)$
$m_2^{\mathrm{source}}(\mathrm{M}_\odot)$

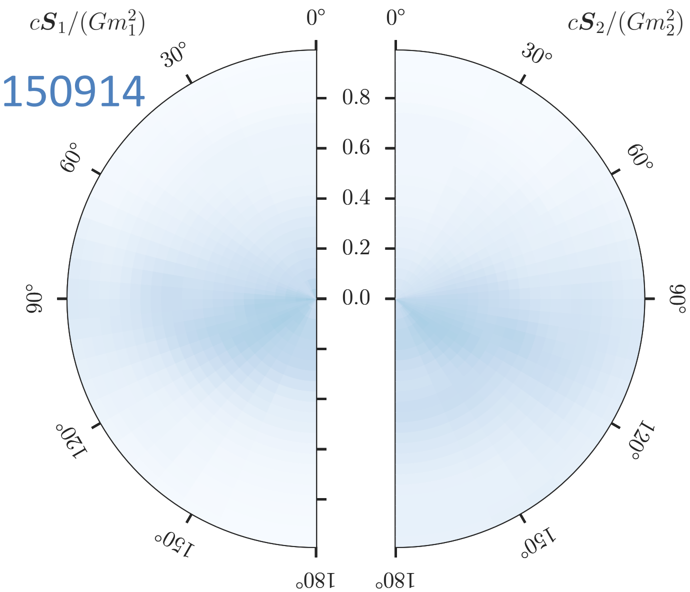


Average
Effective Precession
Full Precession
GW150914
GW170104
50%
90%
LVT151012
GW151226
$m_1(M_\odot)$
$m_2(M_\odot)$

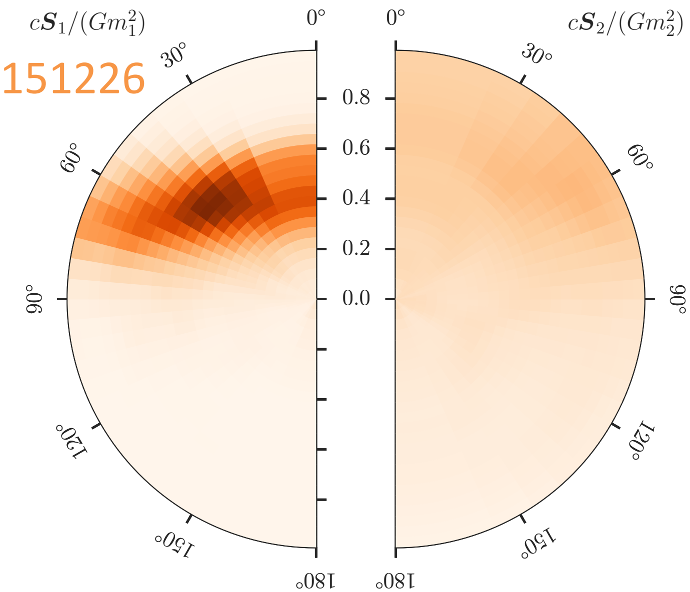

Black Holes of Known Mass
Solar Masses
70
60
50
40
30
20
10
0
LIGO
X-Ray Studies
GW150914
LVT151012
GW151226
GW170104

Spins

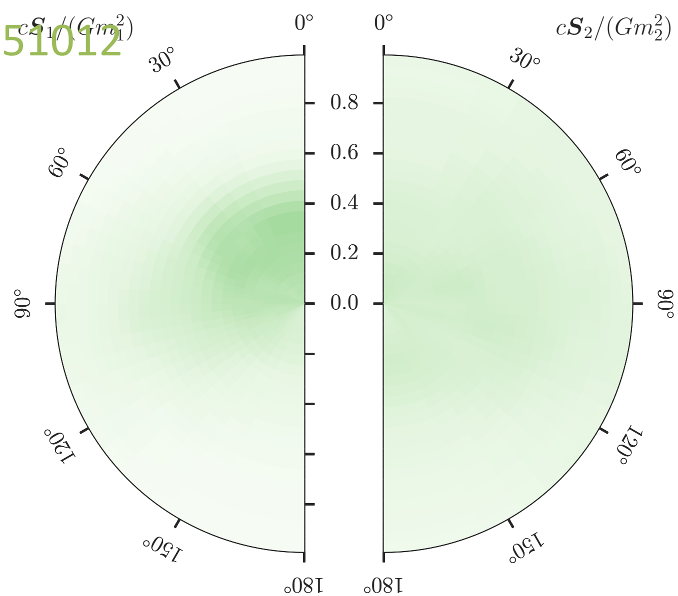
GW150914



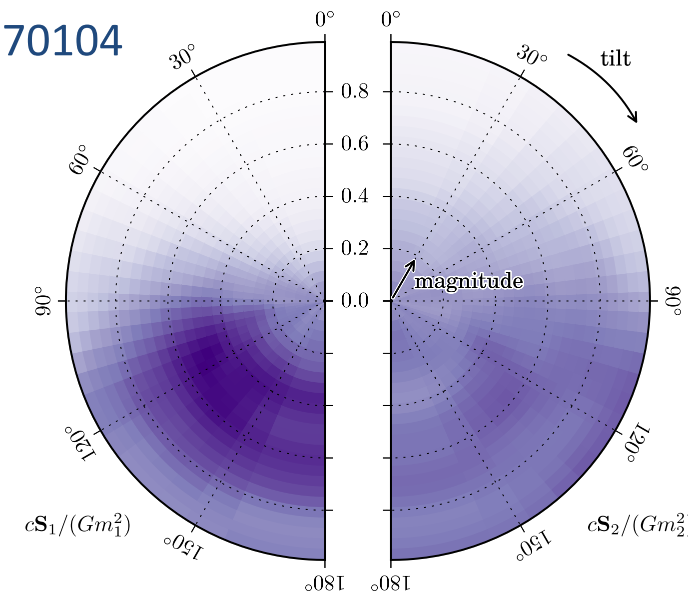
GW151226



LVT151012



GW170104



LIGO

Spins

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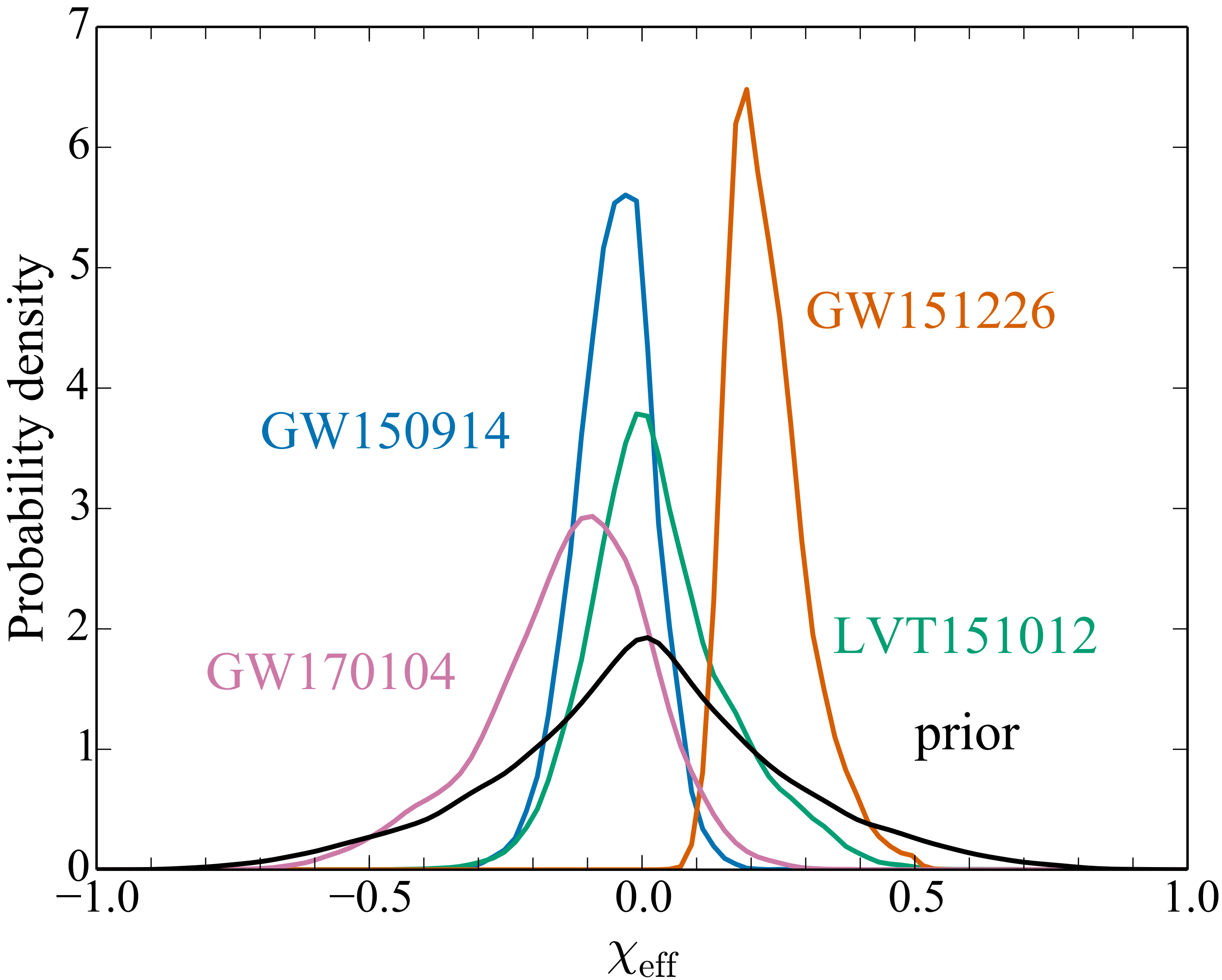
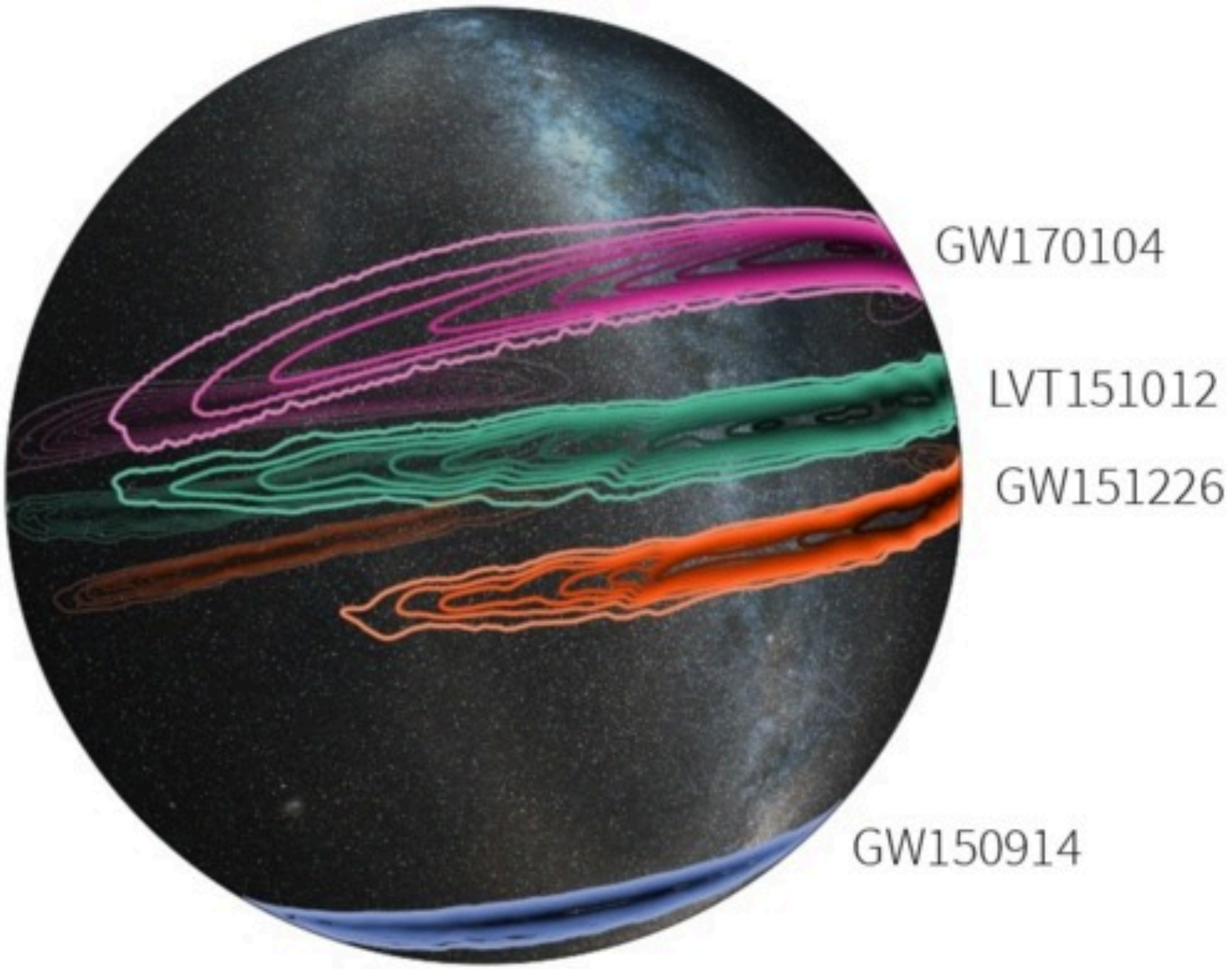
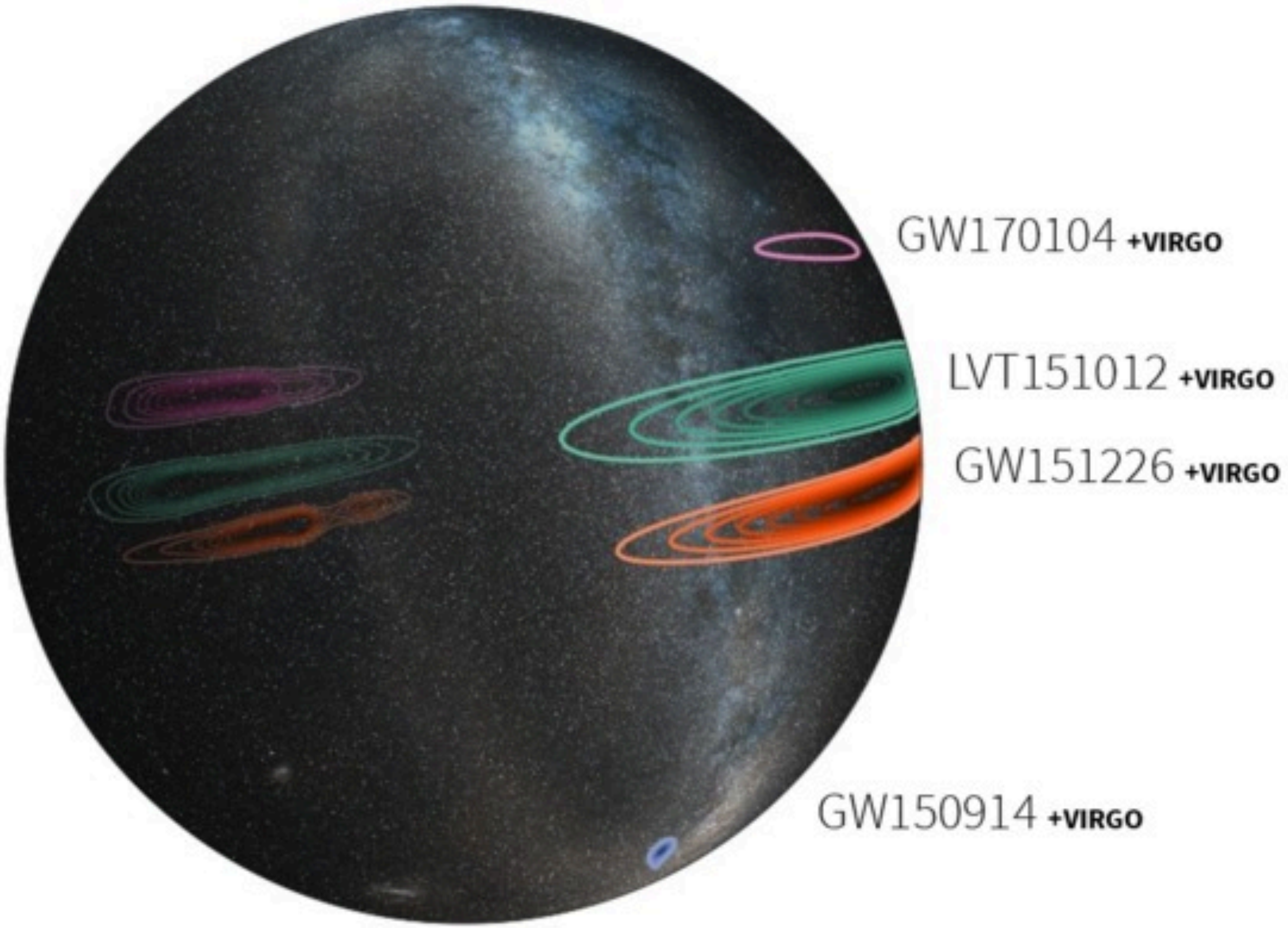


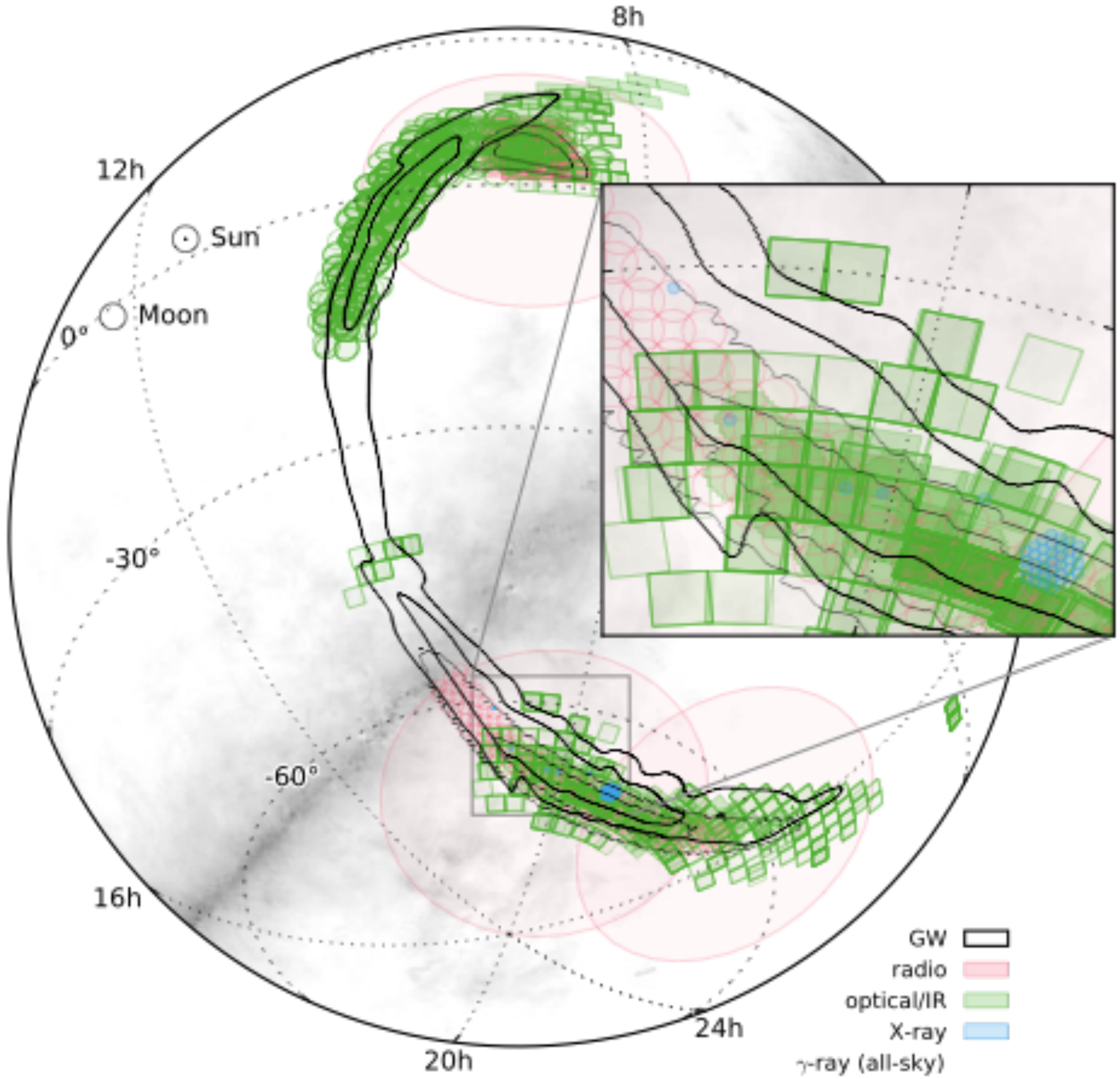
Sky localization



Sky localization – if Virgo was observing



Telescope Observations



Event summary

Event	GW150914	GW151226	LVT151012
Signal-to-noise ratio ρ	23.7	13.0	9.7
False alarm rate FAR/yr^{-1}	$< 6.0 \times 10^{-7}$	$< 6.0 \times 10^{-7}$	0.37
p-value	7.5×10^{-8}	7.5×10^{-8}	0.045
Significance	$> 5.3\sigma$	$> 5.3\sigma$	1.7σ
Primary mass $m_1^{\mathrm{source}}/\mathrm{M}_\odot$	$36.2^{+5.2}_{-3.8}$	$14.2^{+8.3}_{-3.7}$	23^{+18}_{-6}
Secondary mass $m_2^{\mathrm{source}}/\mathrm{M}_\odot$	$29.1^{+3.7}_{-4.4}$	$7.5^{+2.3}_{-2.3}$	13^{+4}_{-5}
Chirp mass $\mathcal{M}^{\mathrm{source}}/\mathrm{M}_\odot$	$28.1^{+1.8}_{-1.5}$	$8.9^{+0.3}_{-0.3}$	$15.1^{+1.4}_{-1.1}$
Total mass $M^{\mathrm{source}}/\mathrm{M}_\odot$	$65.3^{+4.1}_{-3.4}$	$21.8^{+5.9}_{-1.7}$	37^{+13}_{-4}
Effective inspiral spin χ_{eff}	$-0.06^{+0.14}_{-0.14}$	$0.21^{+0.20}_{-0.10}$	$0.0^{+0.3}_{-0.2}$
Final mass $M_{\mathrm{f}}^{\mathrm{source}}/\mathrm{M}_\odot$	$62.3^{+3.7}_{-3.1}$	$20.8^{+6.1}_{-1.7}$	35^{+14}_{-4}
Final spin a_{f}	$0.68^{+0.05}_{-0.06}$	$0.74^{+0.06}_{-0.06}$	$0.66^{+0.09}_{-0.10}$
Radiated energy $E_{\mathrm{rad}}/(\mathrm{M}_\odot c^2)$	$3.0^{+0.5}_{-0.4}$	$1.0^{+0.1}_{-0.2}$	$1.5^{+0.3}_{-0.4}$
Peak luminosity $\ell_{\mathrm{peak}}/(\mathrm{erg\,s}^{-1})$	$3.6^{+0.5}_{-0.4} \times 10^{56}$	$3.3^{+0.8}_{-1.6} \times 10^{56}$	$3.1^{+0.8}_{-1.8} \times 10^{56}$
Luminosity distance $D_{\mathrm{L}}/\mathrm{Mpc}$	420^{+150}_{-180}	440^{+180}_{-190}	1000^{+500}_{-500}
Source redshift z	$0.09^{+0.03}_{-0.04}$	$0.09^{+0.03}_{-0.04}$	$0.20^{+0.09}_{-0.09}$
Sky localization $\Delta\Omega/\mathrm{deg}^2$	230	850	1600

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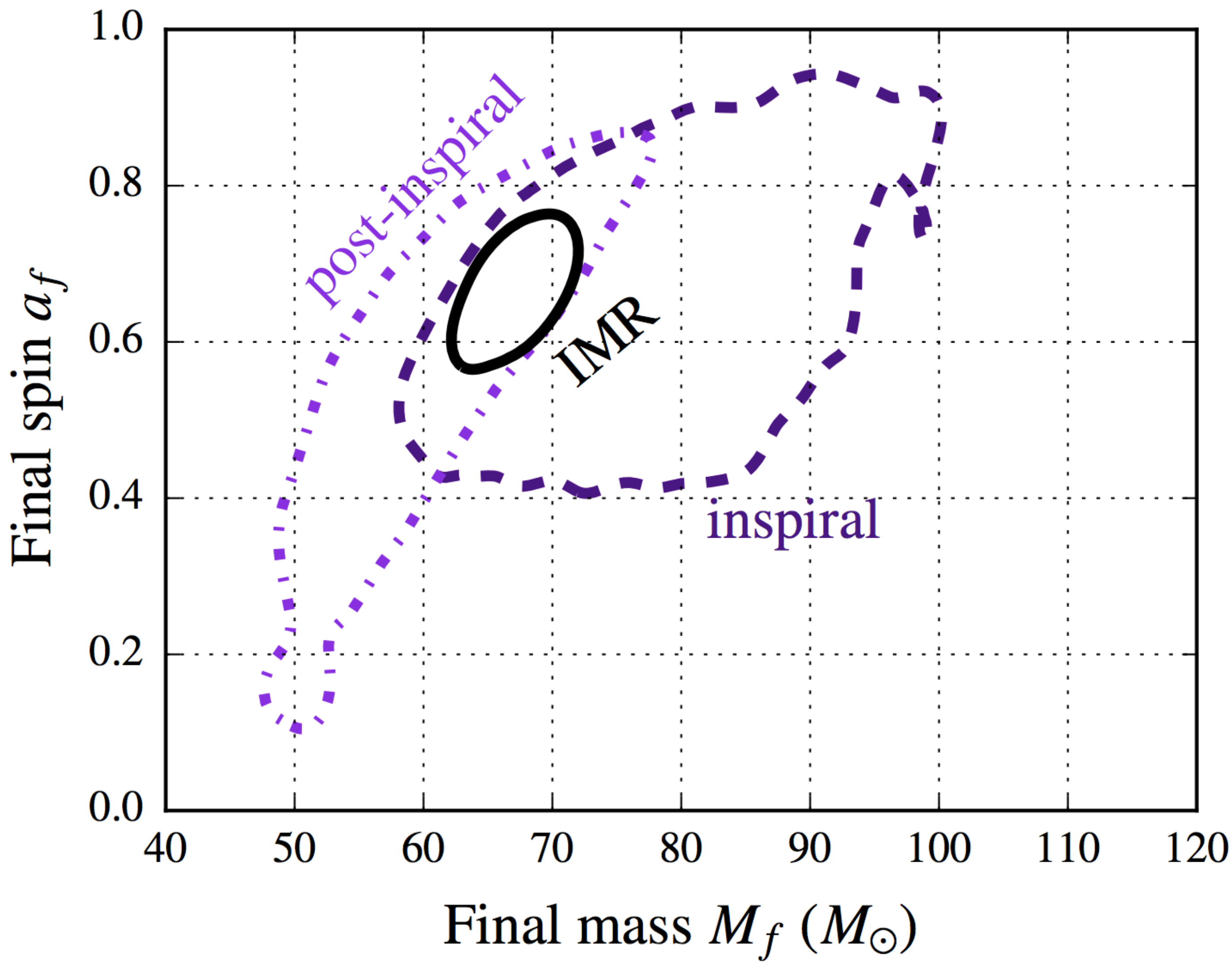
Event summary

Event	GW150914	GW151226	LVT151012
Signal-to-noise ratio ρ	23.7	13.0	9.7
False alarm rate FAR/yr^{-1}	$< 6.0 \times 10^{-7}$	$< 6.0 \times 10^{-7}$	0.37
p-value	7.5×10^{-8}	7.5×10^{-8}	0.045
Significance	$> 5.3\sigma$	$> 5.3\sigma$	1.7σ
Primary mass $m_1^{\mathrm{source}}/\mathrm{M}_\odot$	$36.2^{+5.2}_{-3.8}$	$14.2^{+8.3}_{-3.7}$	23^{+18}_{-6}
Secondary mass $m_2^{\mathrm{source}}/\mathrm{M}_\odot$	$29.1^{+3.7}_{-4.4}$	$7.5^{+2.3}_{-2.3}$	13^{+4}_{-5}
Chirp mass $\mathcal{M}^{\mathrm{source}}/\mathrm{M}_\odot$	$28.1^{+1.8}_{-1.5}$	$8.9^{+0.3}_{-0.3}$	$15.1^{+1.4}_{-1.1}$
Total mass $M^{\mathrm{source}}/\mathrm{M}_\odot$	$65.3^{+4.1}_{-3.4}$	$21.8^{+5.9}_{-1.7}$	37^{+13}_{-4}
Effective inspiral spin χ_{eff}	$-0.06^{+0.14}_{-0.14}$	$0.21^{+0.20}_{-0.10}$	$0.0^{+0.3}_{-0.2}$
Final mass $M_{\mathrm{f}}^{\mathrm{source}}/\mathrm{M}_\odot$	$62.3^{+3.7}_{-3.1}$	$20.8^{+6.1}_{-1.7}$	35^{+14}_{-4}
Final spin a_{f}	$0.68^{+0.05}$ [illegible]	$0.74^{+0.06}$ [illegible]	$0.66^{+0.09}$ [illegible]
Radiated energy $E_{\mathrm{rad}}/(\mathrm{M}_\odot c^2)$	$3.0^{+0.5}_{-0.4}$	$1.0^{+0.1}_{-0.2}$	$1.5^{+0.3}_{-0.4}$
Peak luminosity $\ell_{\mathrm{peak}}/(\mathrm{erg\,s^{-1}})$	$3.6^{+0.5}_{-0.4} \times 10^{56}$	$3.3^{+0.8}_{-1.6} \times 10^{56}$	$3.1^{+0.8}_{-1.8} \times 10^{56}$
Luminosity distance $D_{\mathrm{L}}/\mathrm{Mpc}$	420_{-180} [illegible]	440_{-190} [illegible]	1000_{-500} [illegible]
Source redshift z	$0.09^{+0.03}_{-0.04}$	$0.09^{+0.03}_{-0.04}$	$0.20^{+0.09}_{-0.09}$
Sky localization $\Delta\Omega/\mathrm{deg}^2$	230	850	1600

Consistency with General Relativity



From Abbott et al, "Tests of general relativity with GW150914", 2016

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Consistency with General Relativity

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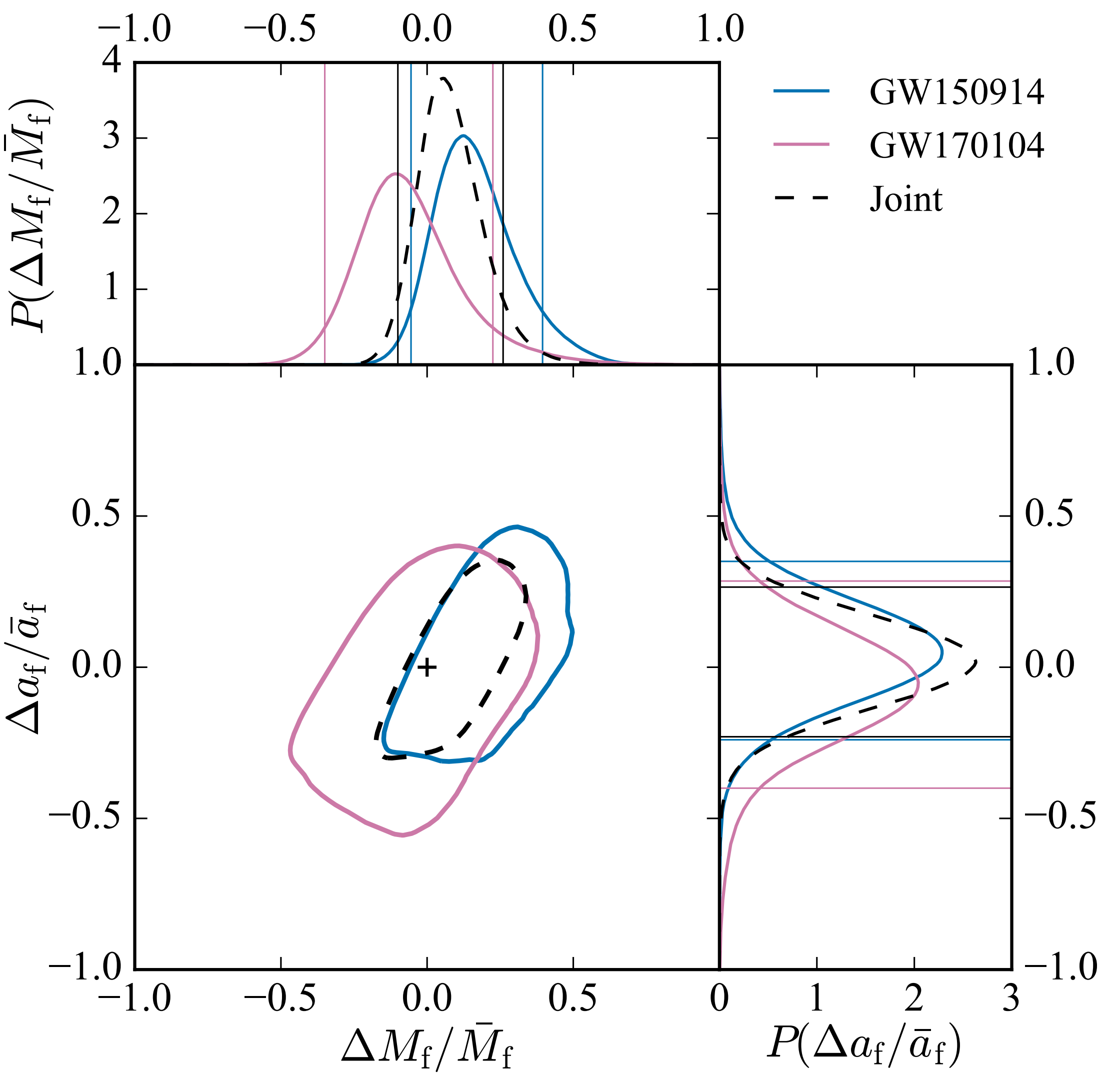
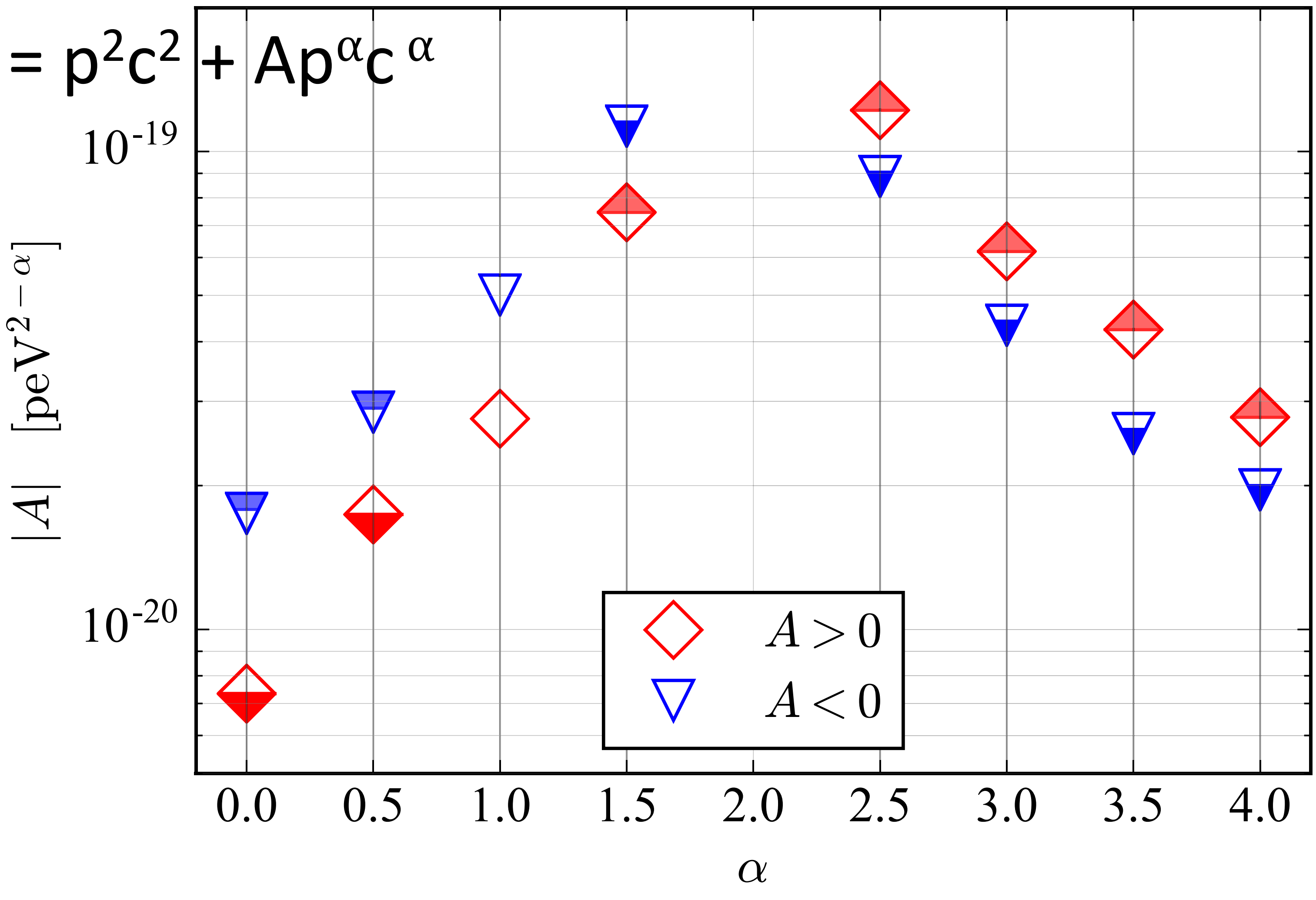
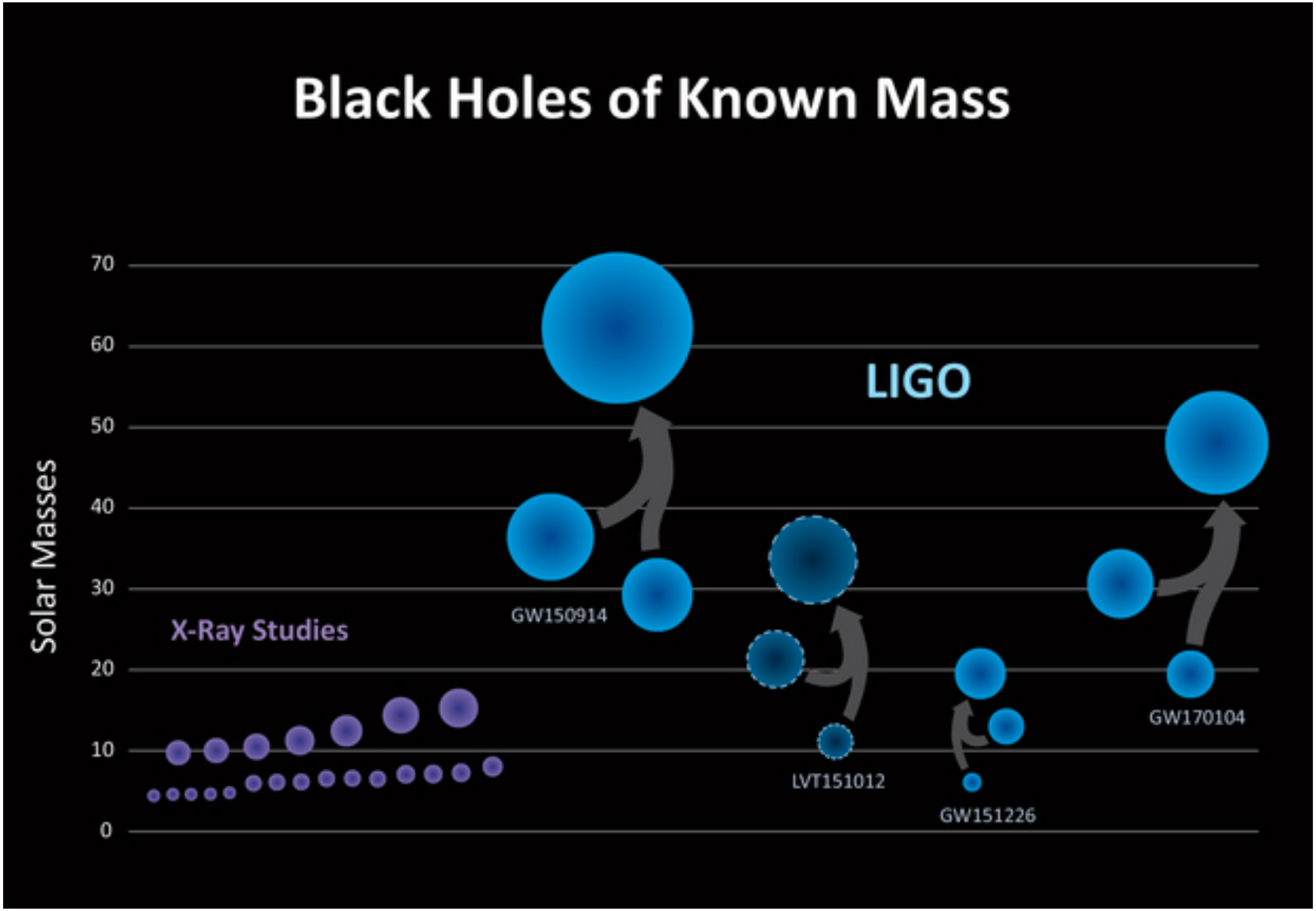


Constraints on dispersion of gravitational waves

$E^2 = p^2c^2 + Ap^{\alpha}c^{\alpha}$



Summary



Black Holes of Known Mass
Solar Masses
70
60
50
40
30
20
10
0
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X-Ray Studies
GW150914
LVT151012
GW151226
GW170104