BINARY BLACK HOLE MERGERS IN THE FIRST ADVANCED LIGO OBSERVING RUN

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Cardiff University

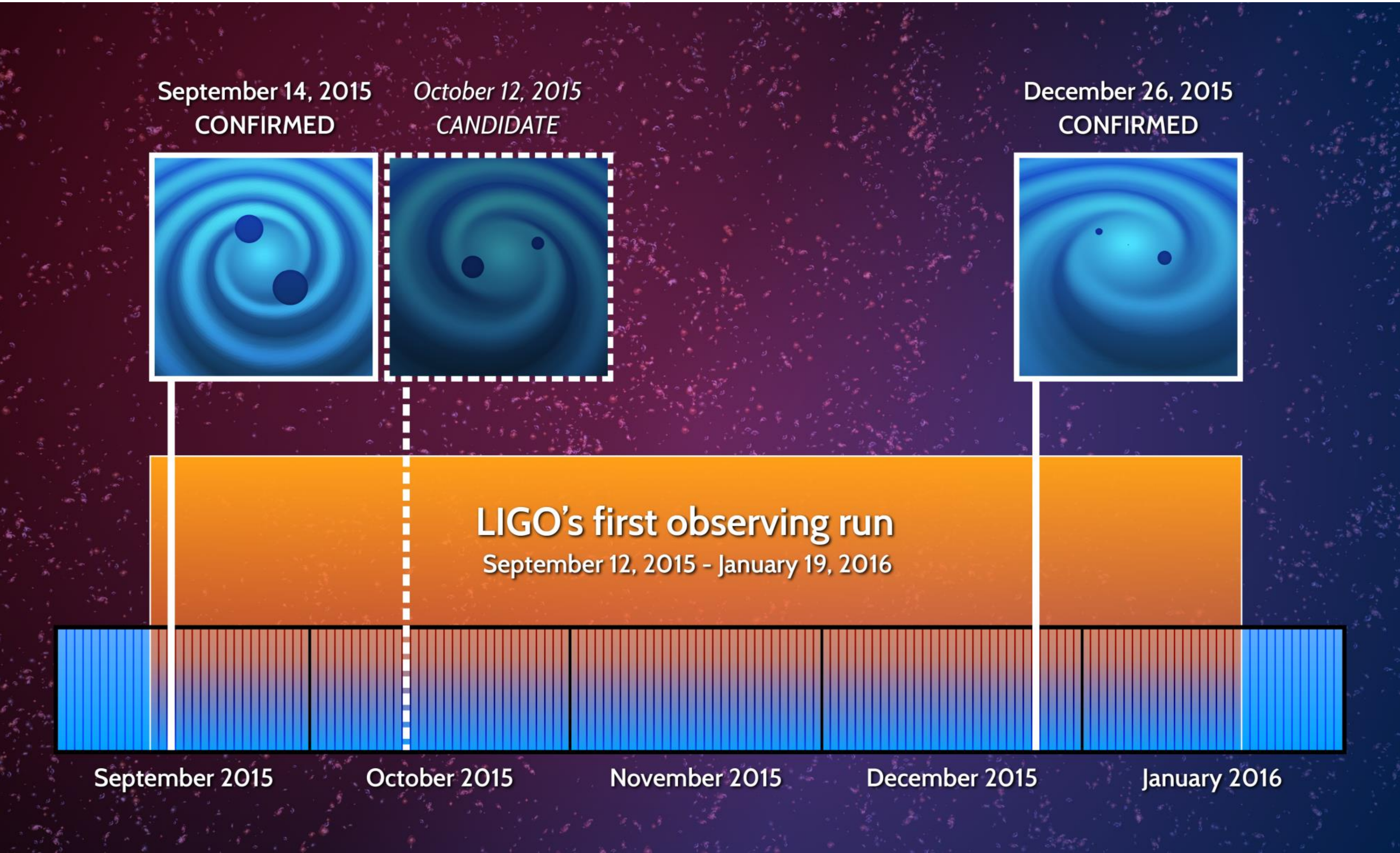
for the LIGO Scientific and Virgo Collaborations

References

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

GW150914: PRL 116, 061102 (2016)

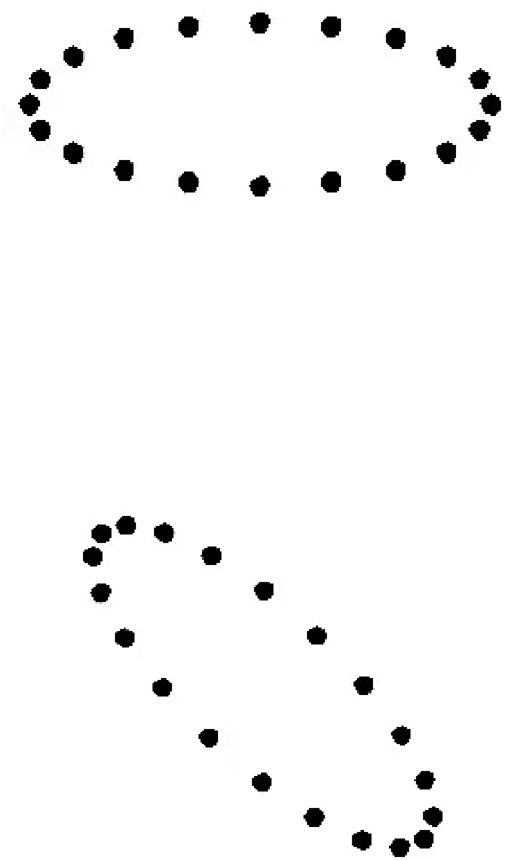
GW151226: PRL 116, 241103 (2016)



September 14, 2015
CONFIRMED
October 12, 2015
CANDIDATE
December 26, 2015
CONFIRMED
LIGO's first observing run
September 12, 2015 - January 19, 2016
September 2015
October 2015
November 2015
December 2015
January 2016

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, $h = \frac{\delta L}{L}$



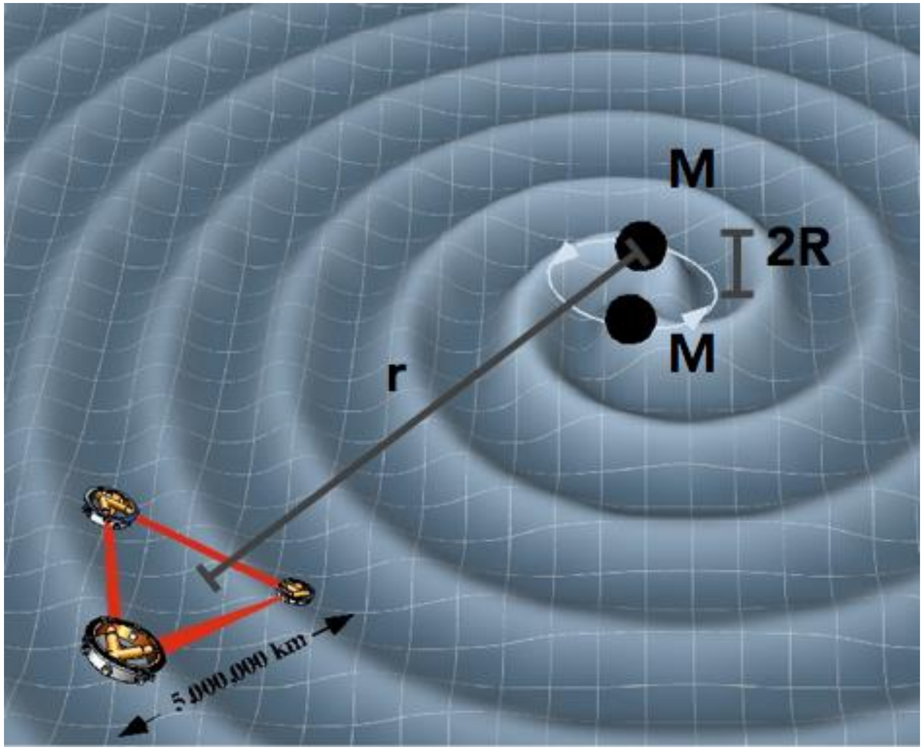
Generating gravitational waves

- Time varying mass quadrupole generates gravitational waves

- Binary system is ideal

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

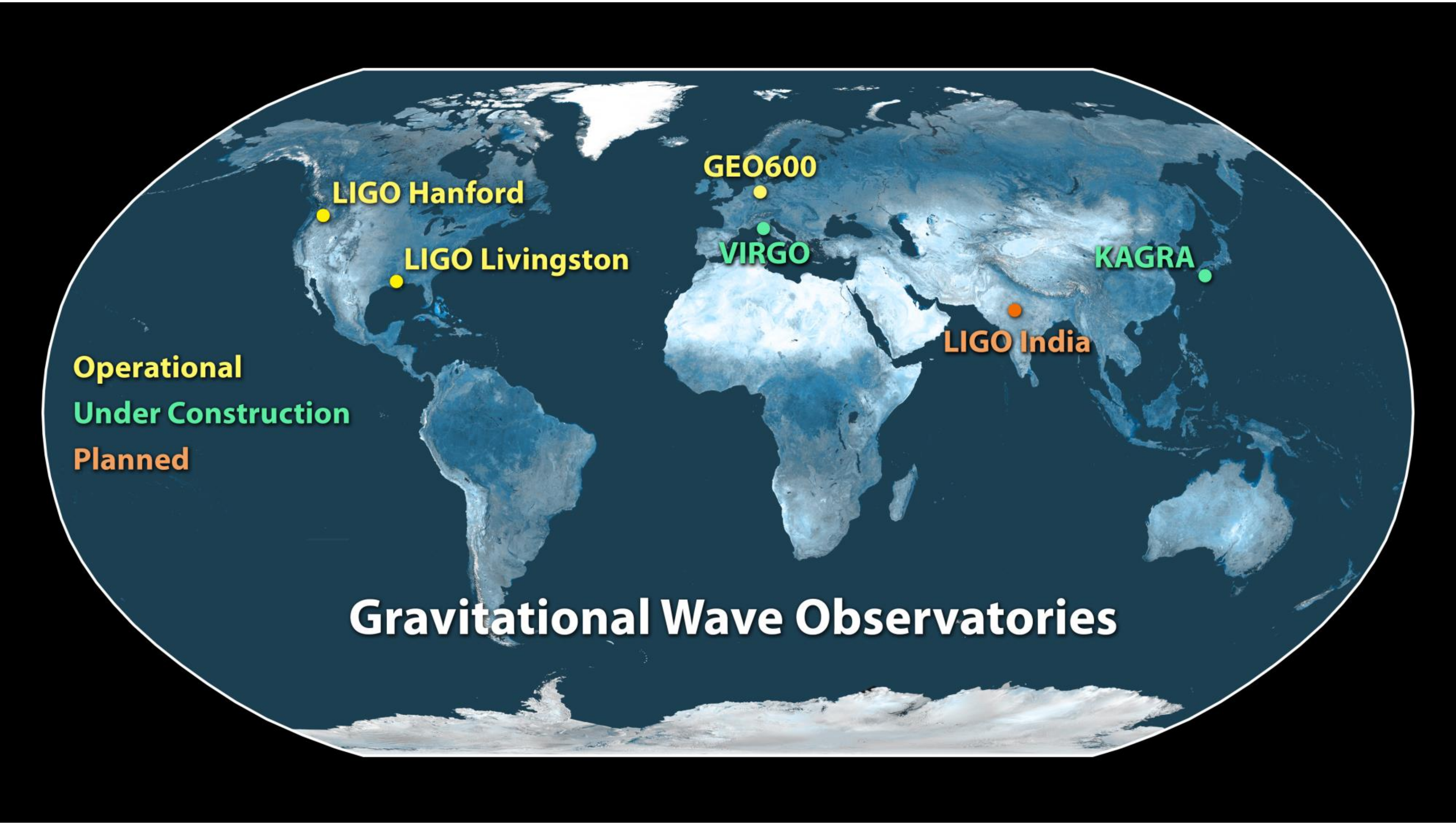
$$P \sim \frac{GM^2 v^6}{c^5 R^2}$$



For a black hole:

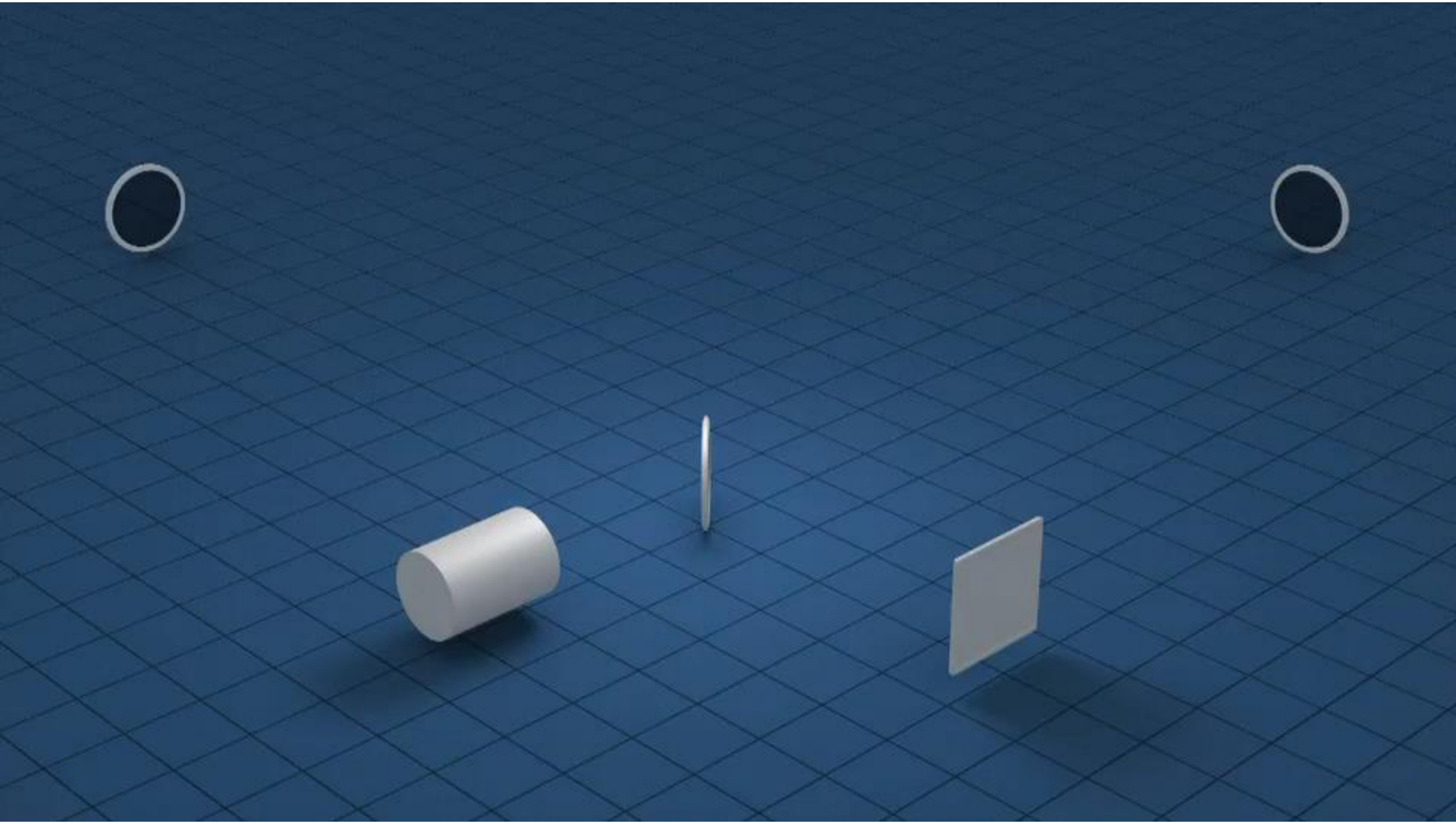
$$R_{\mathrm{Sch}} = \frac{2GM}{c^2}$$

A global network



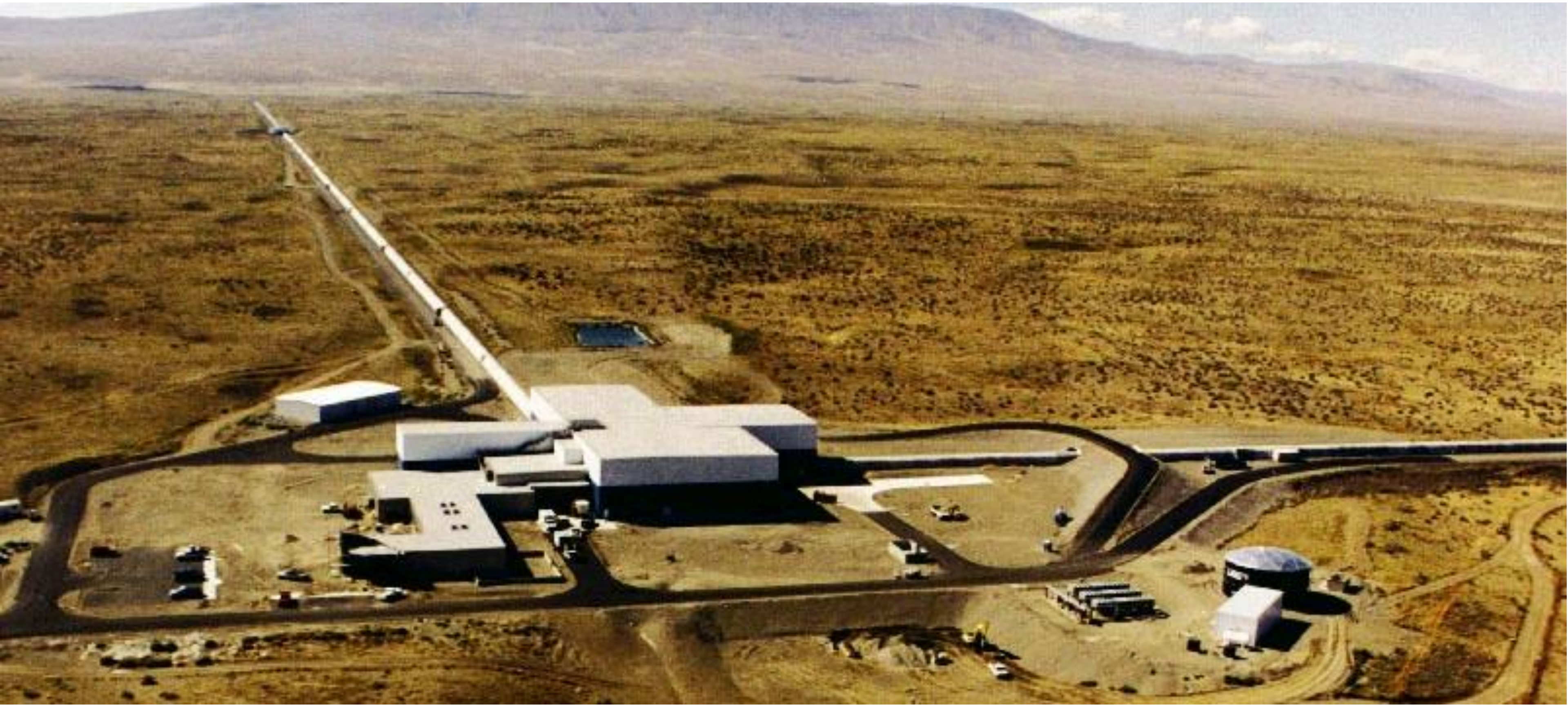
LIGO Livingston Observatory


LIGO Hanford Observatory
LIGO Hanford
LIGO Livingston



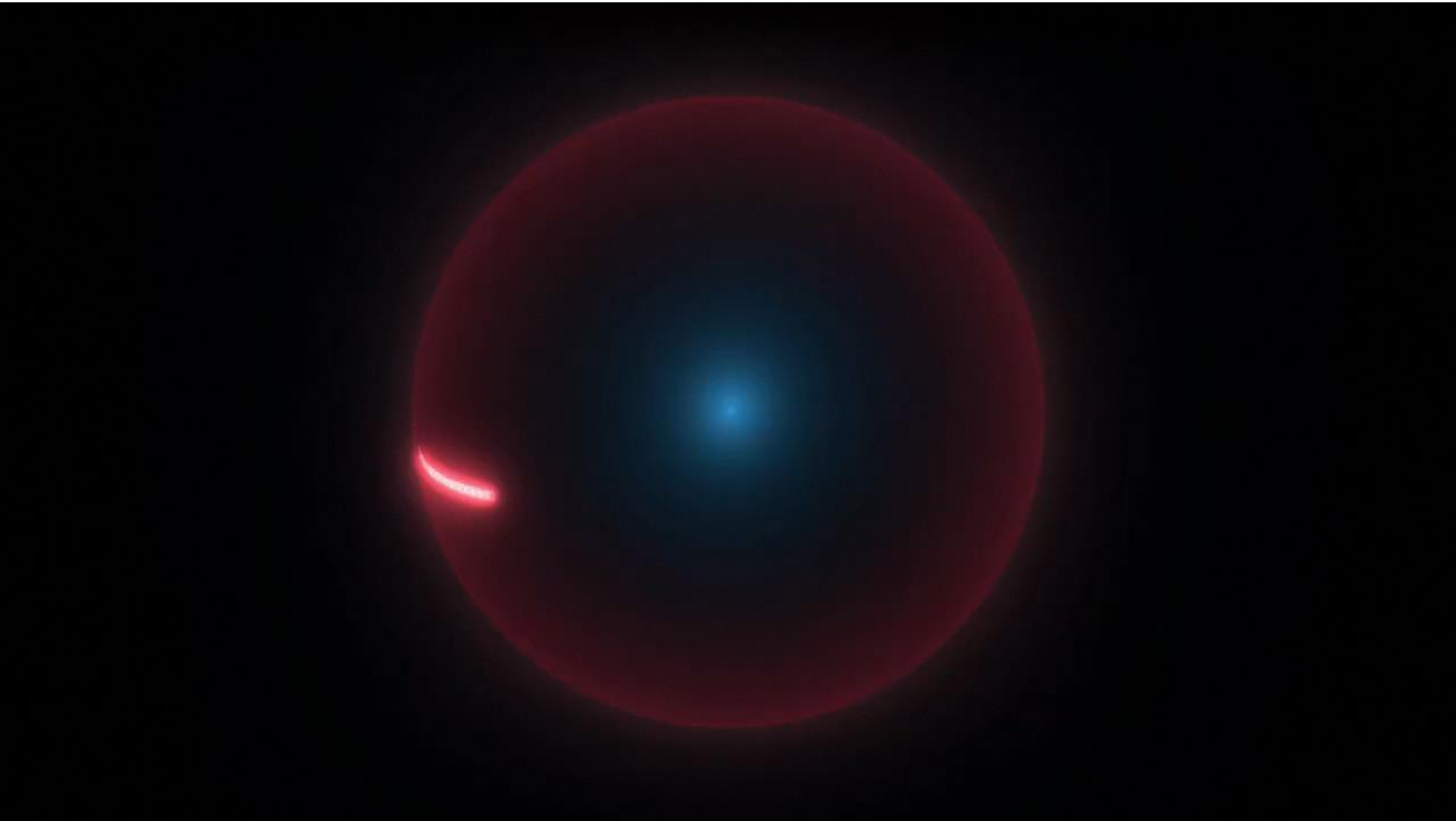
LIGO The Scale of the Challenge

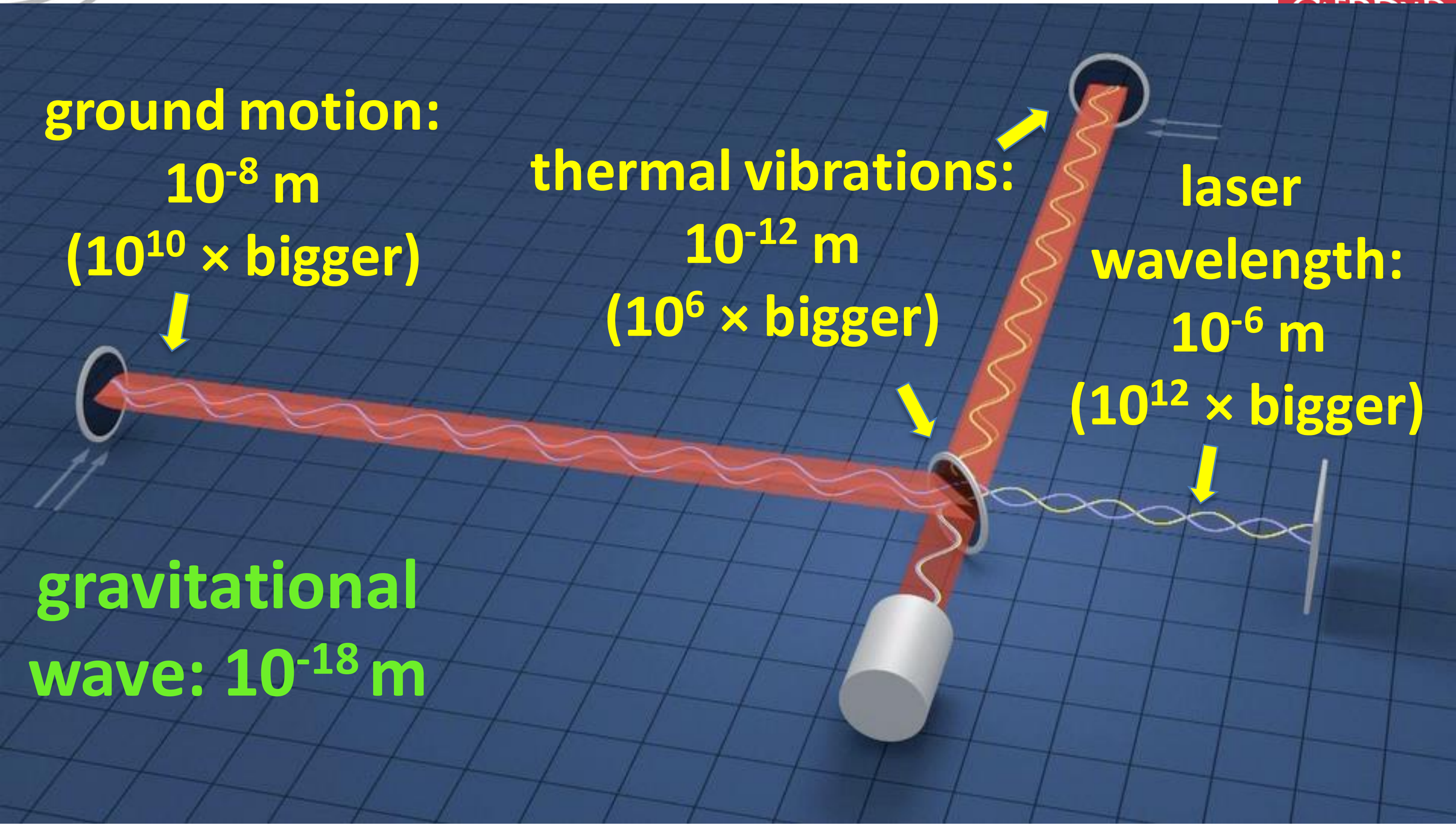
CARDIFF UNIVERSITY PRIFYSGOL CAERDYDD

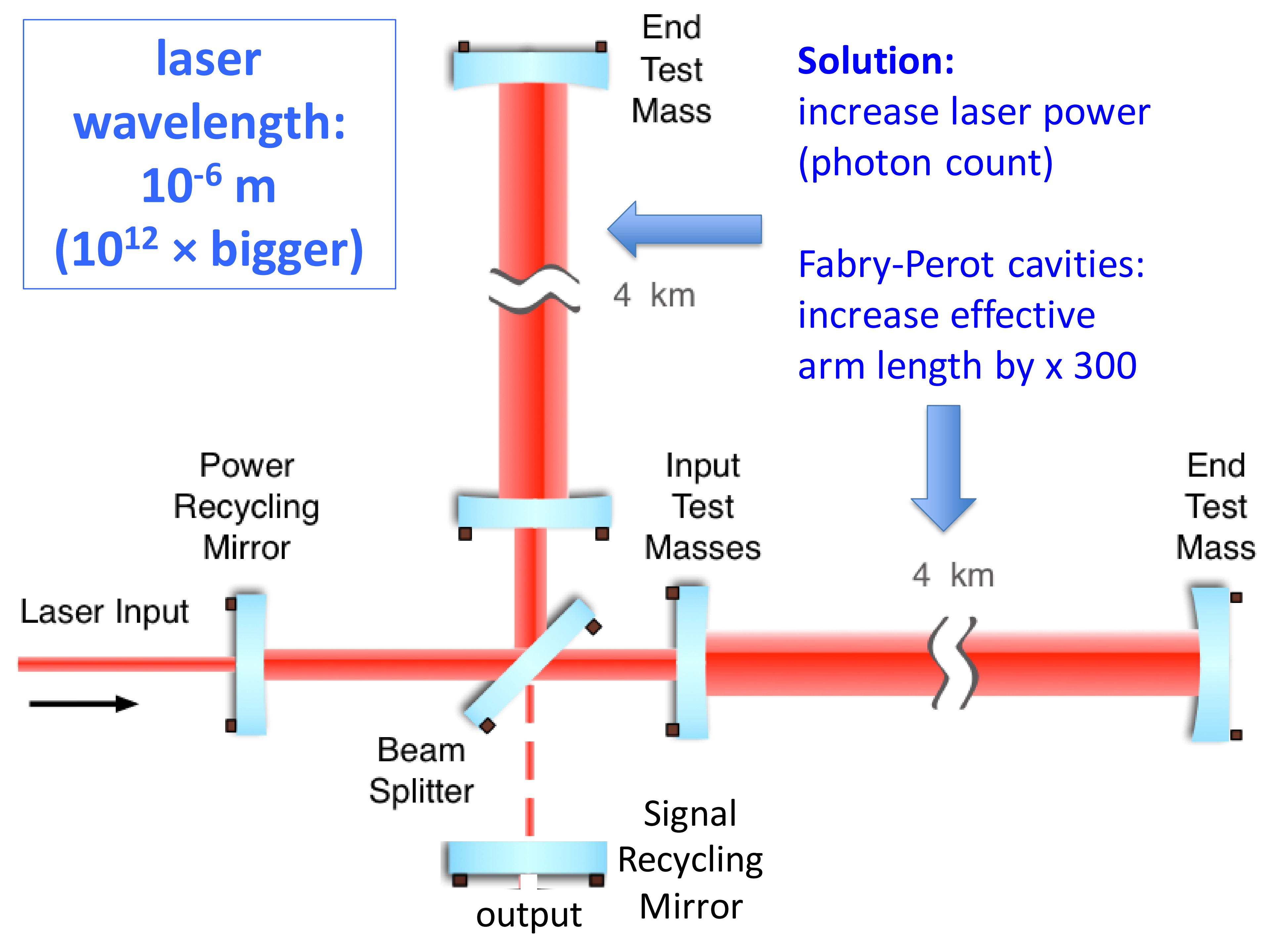


10^{-22} change in length of a LIGO arm: 10^{-18} m

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

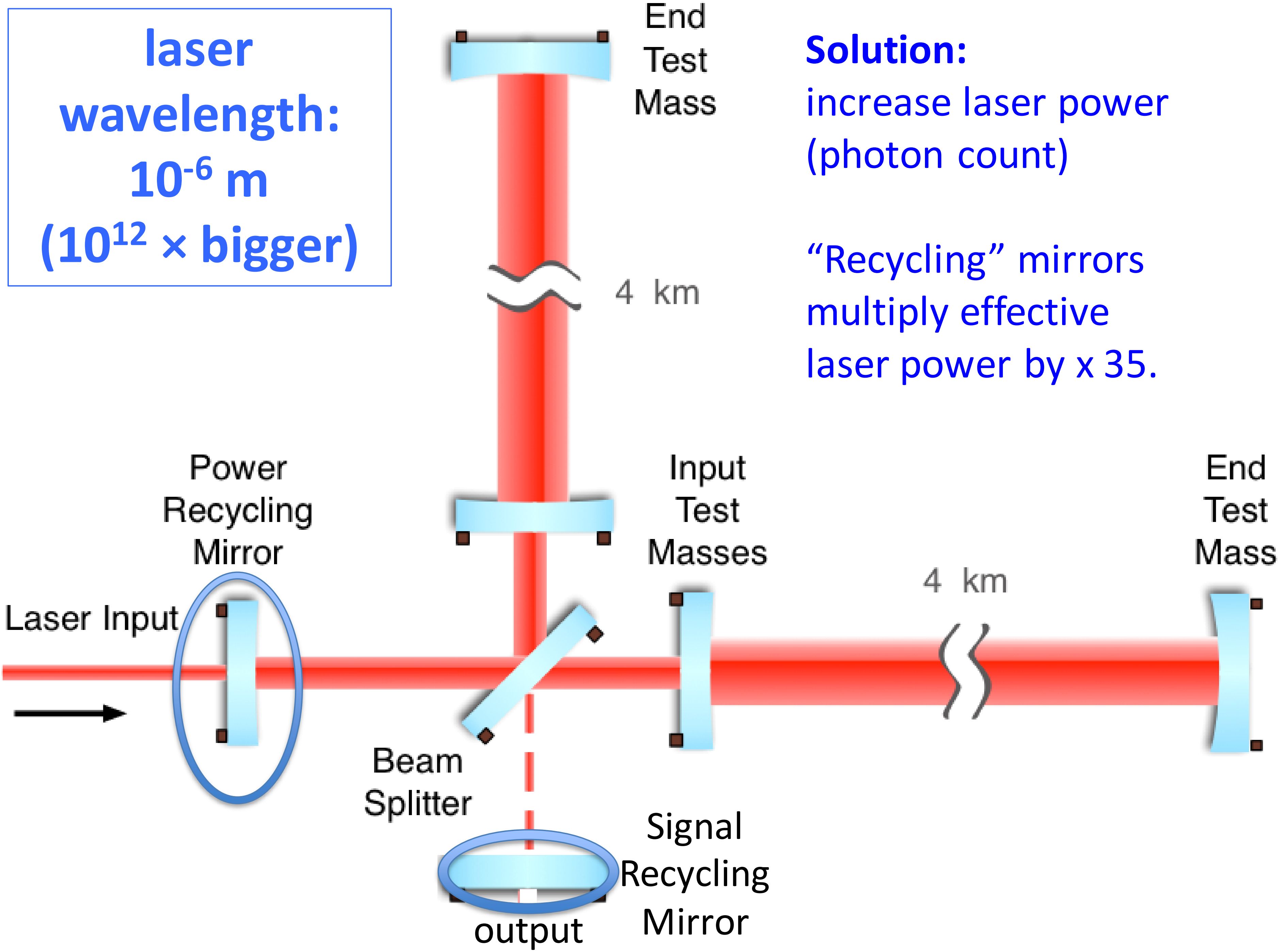


laser wavelength: 10^{-6} m (10^{12} × bigger)
End Test Mass
Solution:
increase laser power (photon count)
4 km
Fabry-Perot cavities: increase effective arm length by x 300
Power Recycling Mirror
Input Test Masses
End Test Mass
4 km
Laser Input
Beam Splitter
Signal Recycling Mirror
output

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

Solution:
increase laser power (photon count)

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



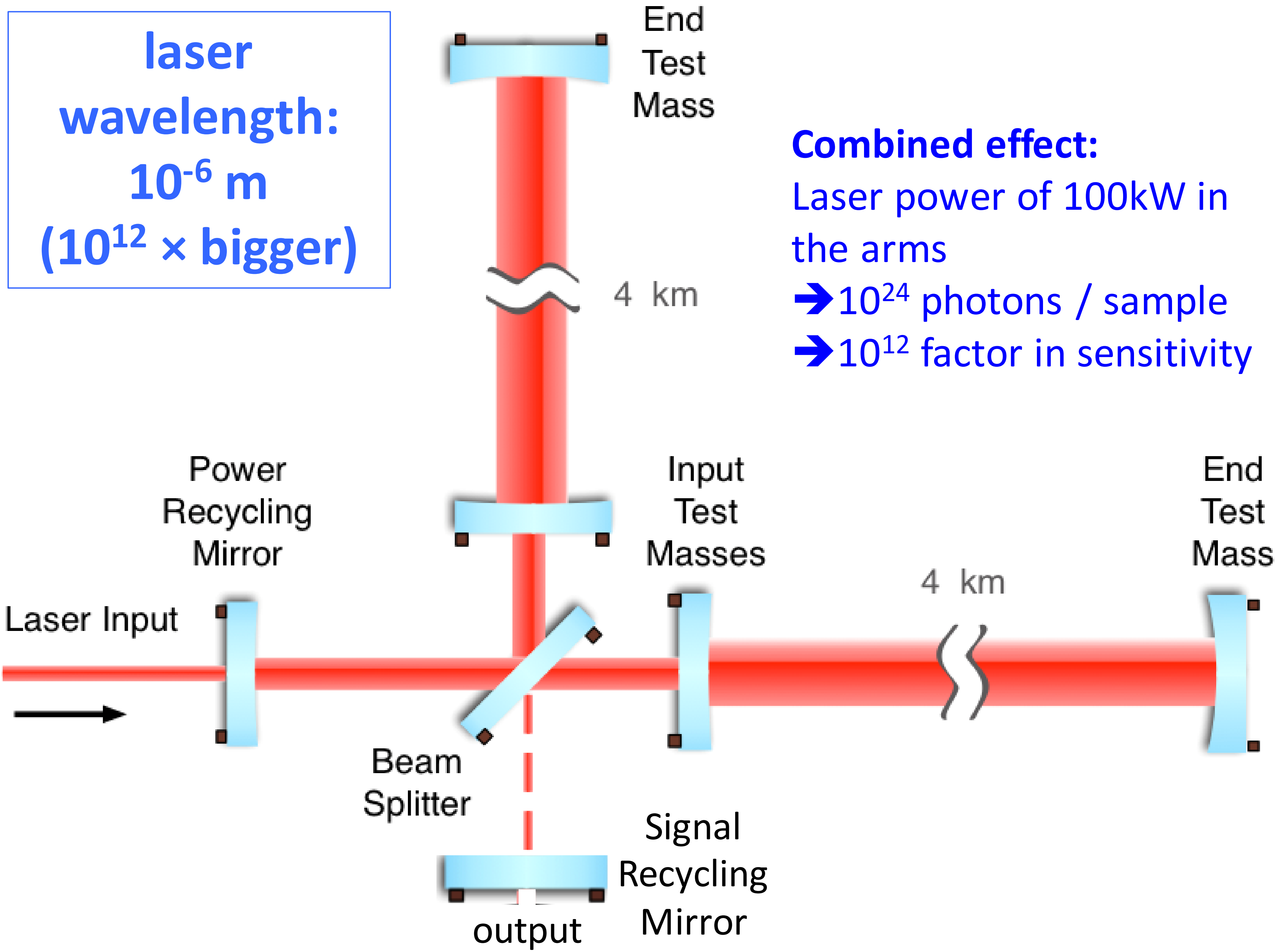
laser wavelength: 10^{-6} m (10^{12} × bigger)

Combined effect:

Laser power of 100kW in the arms

➔ 10^{24} photons / sample

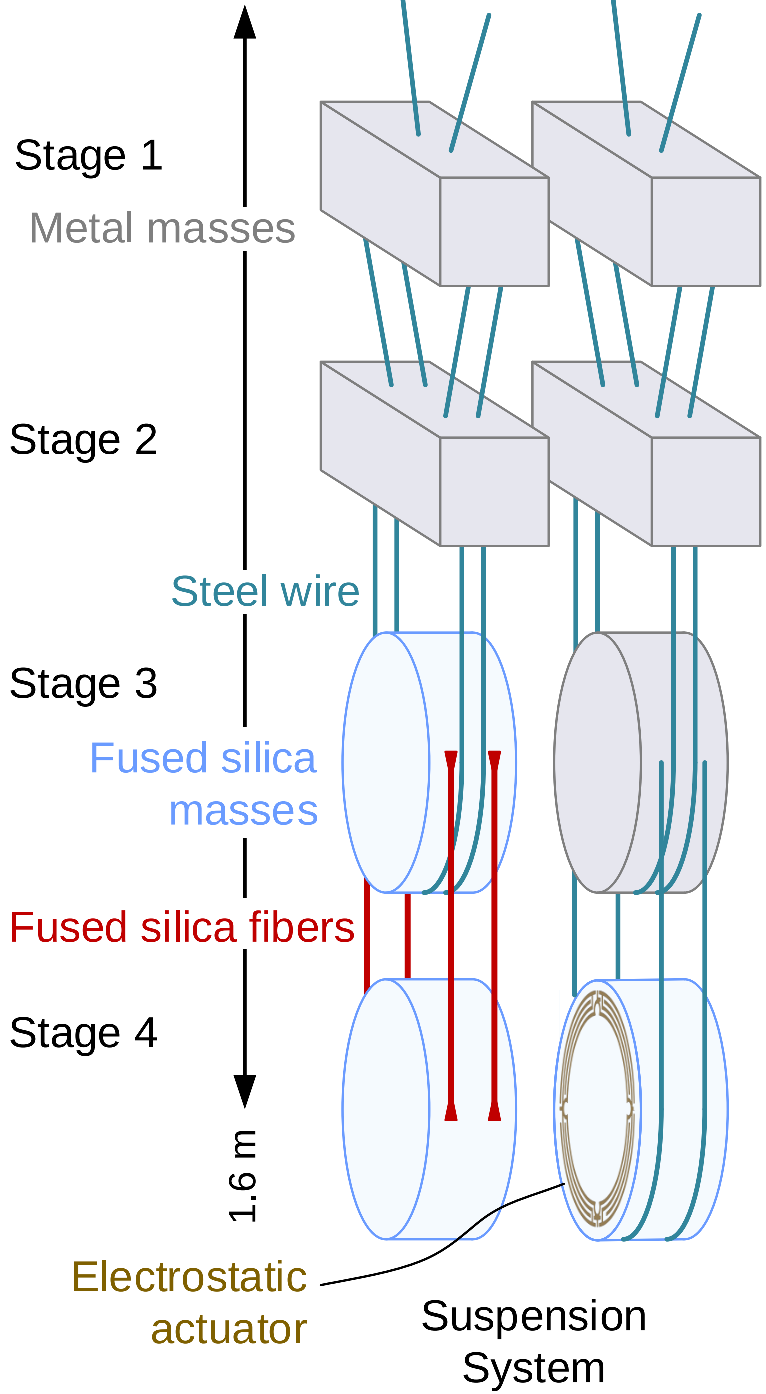
➔ 10^{12} factor in sensitivity

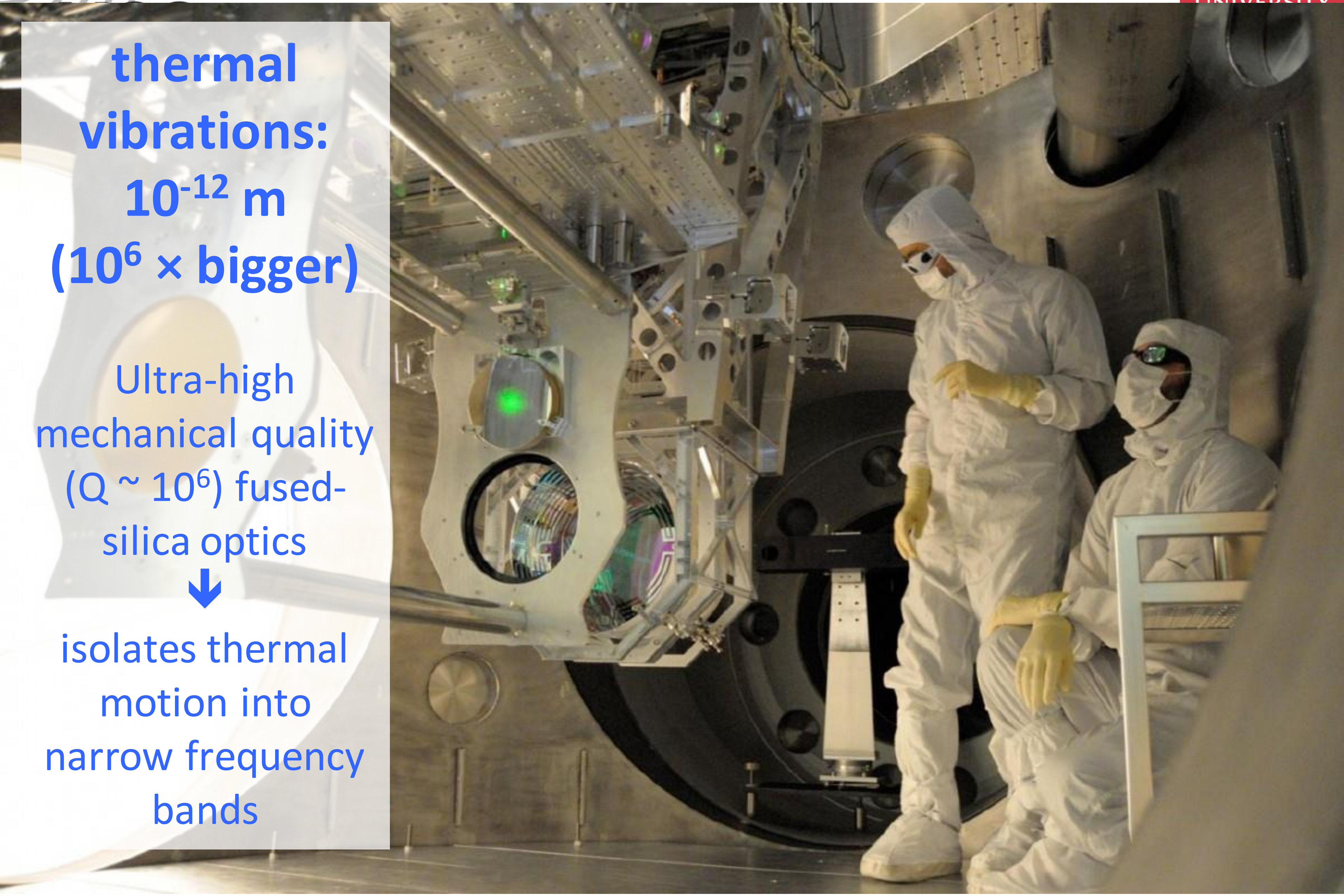


LIGO

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

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





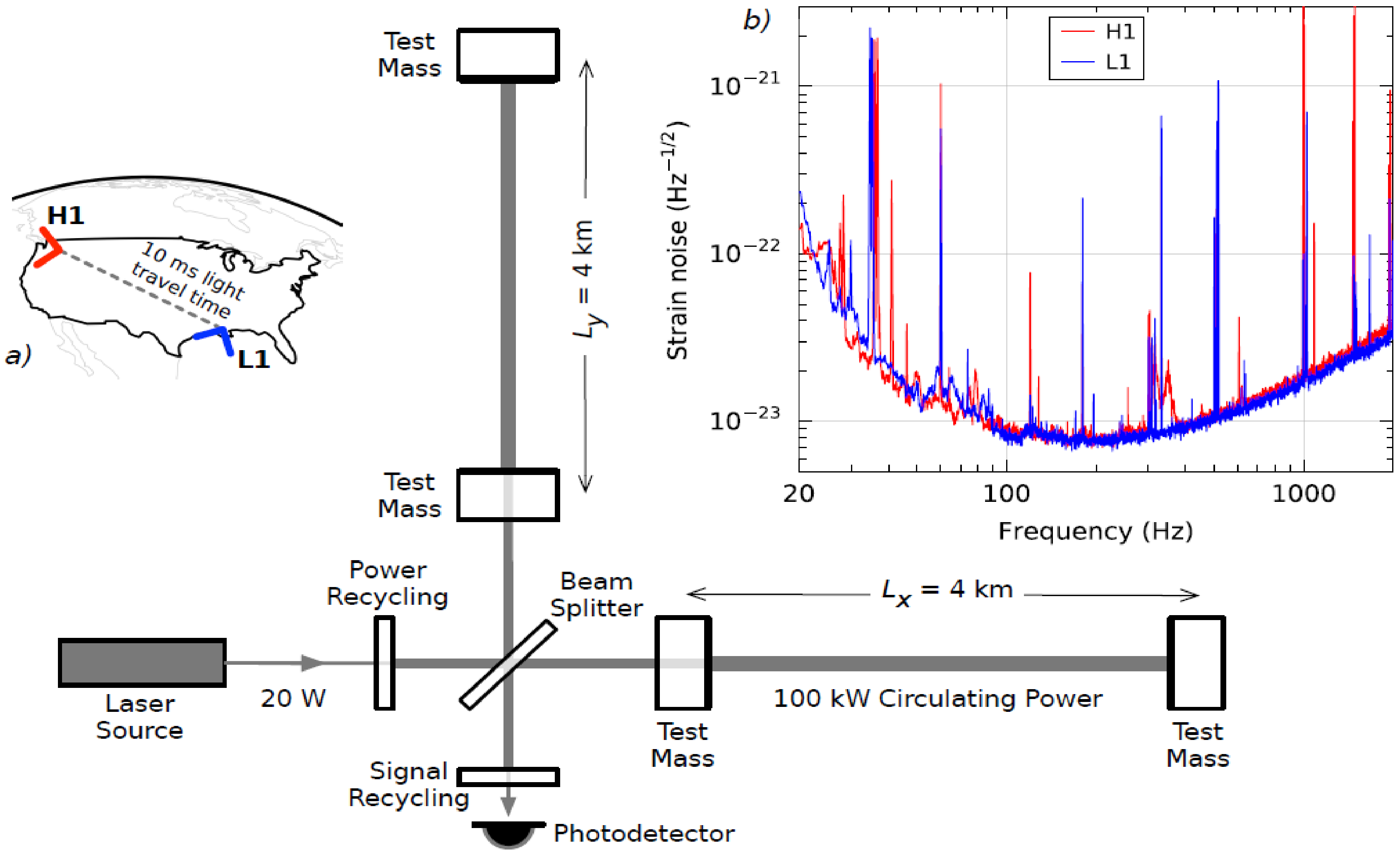
thermal vibrations: 10^{-12} m (10^6 × bigger)

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

↓

isolates thermal motion into narrow frequency bands

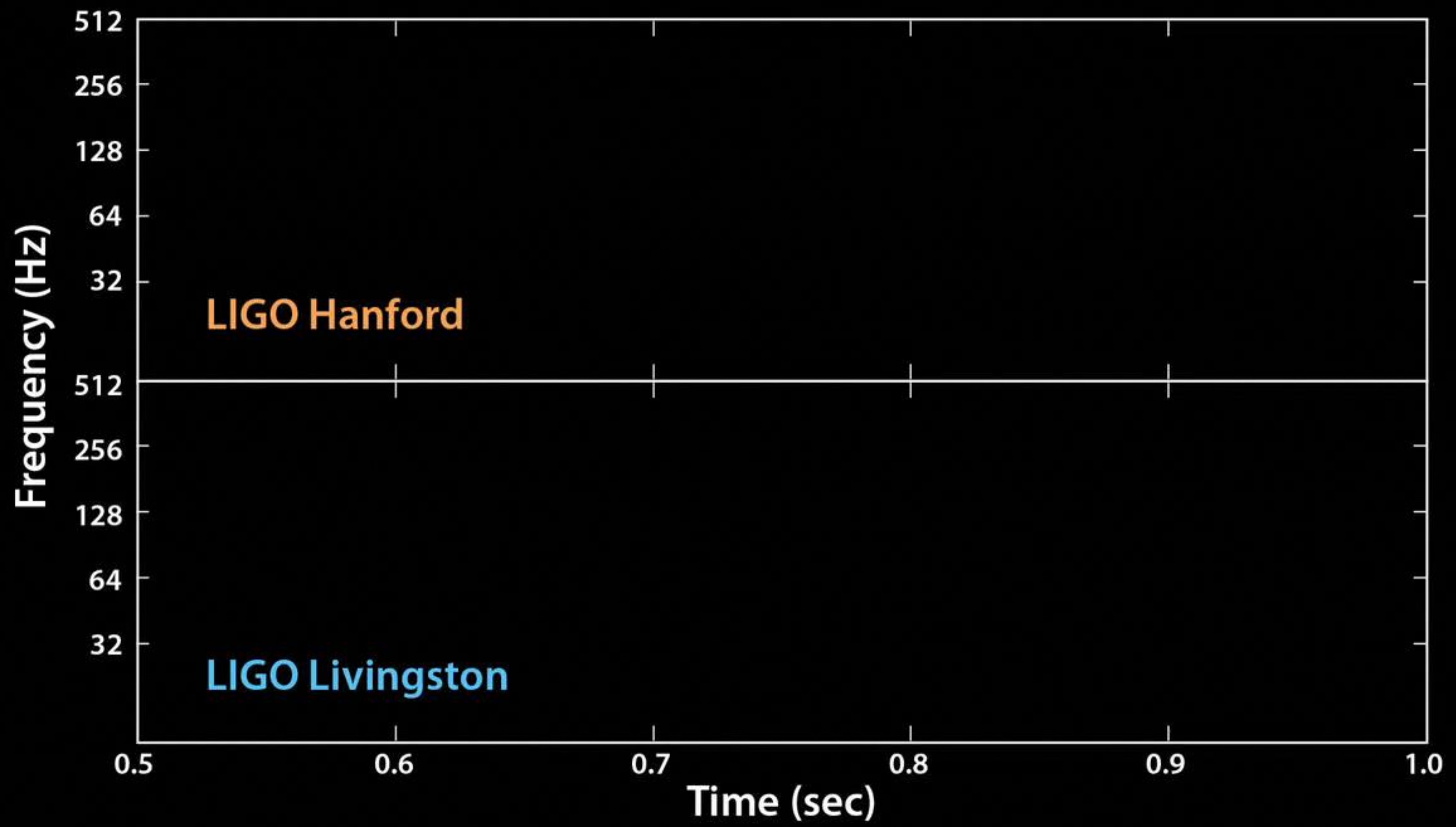
O1 Data Taking



GW150914

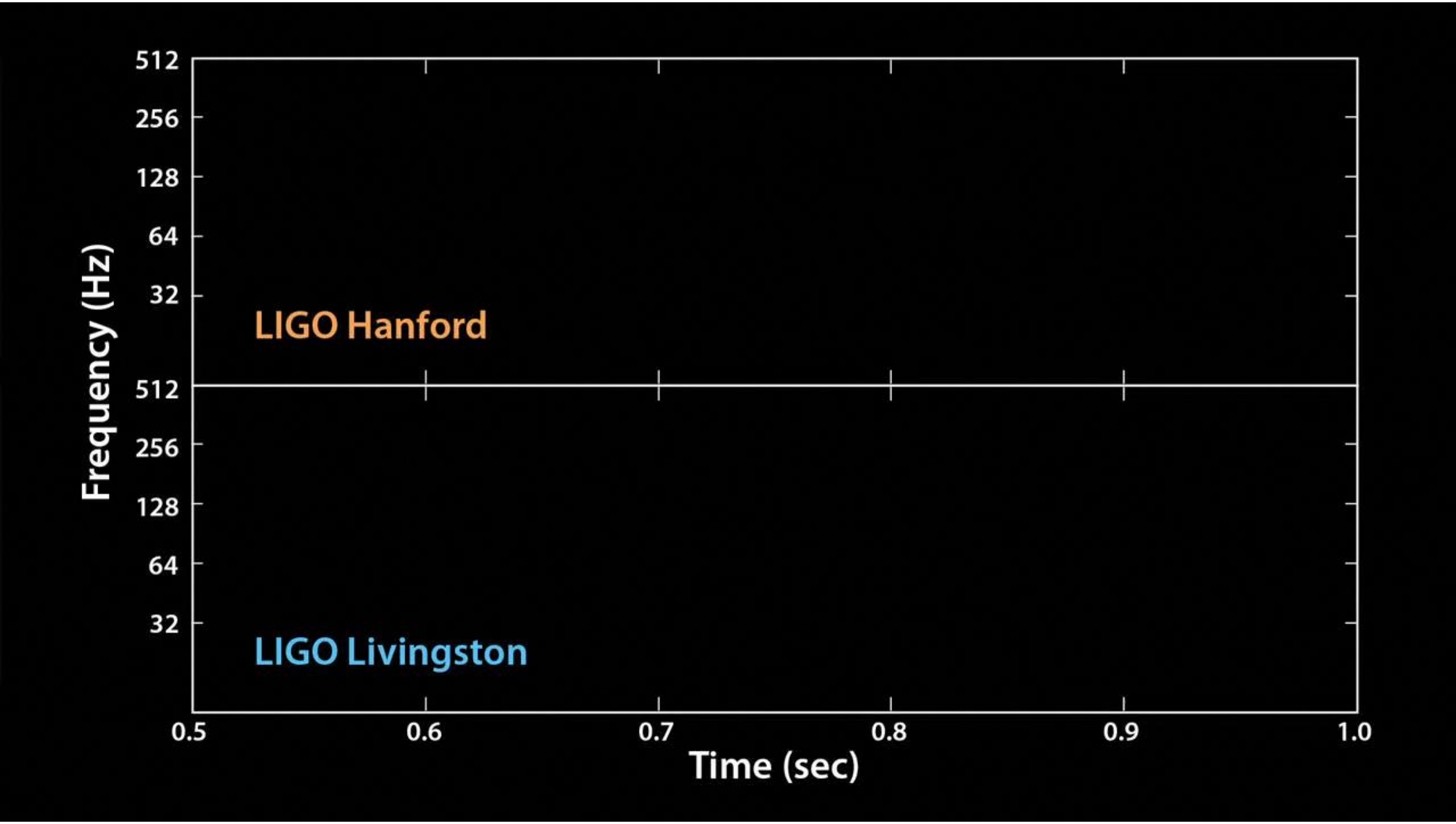
- In September 2015, we were in the final stages of preparation for first Advanced LIGO data run (O1).
- The very last step is a short “Engineering Run,” during which on Sept 14 our online monitor recorded GW150914.
- We identified the signal within 3 minutes
- We responded by starting the data run officially, keeping all settings fixed and ran for 16 live days coincidence time (long enough to assess background levels, etc)
- First GW announcement reported on that data.
- O1 data taking continued until 12 Jan 2016

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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128
64
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LIGO Livingston
Frequency (Hz)
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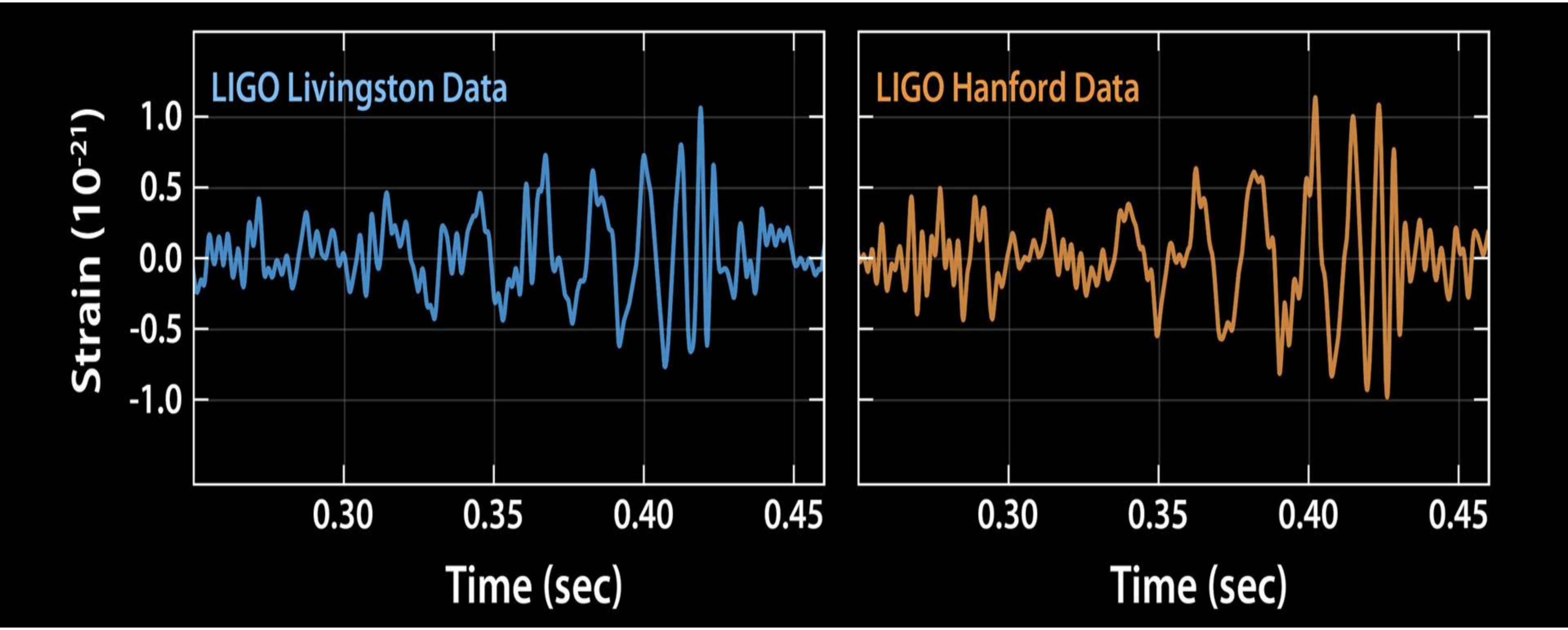
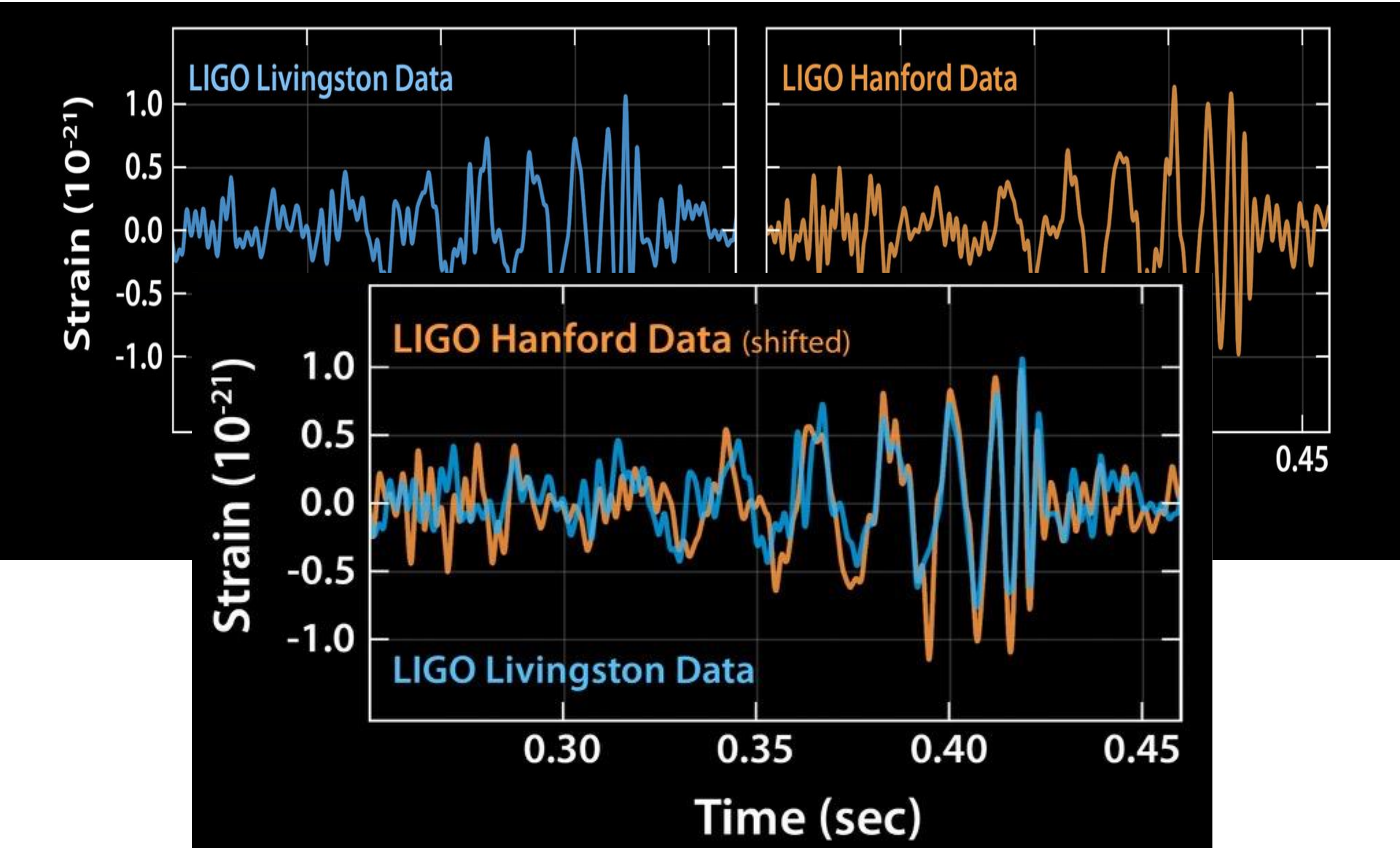
0.6
0.7
0.8
0.9
1.0
Time (sec)

GW 150914

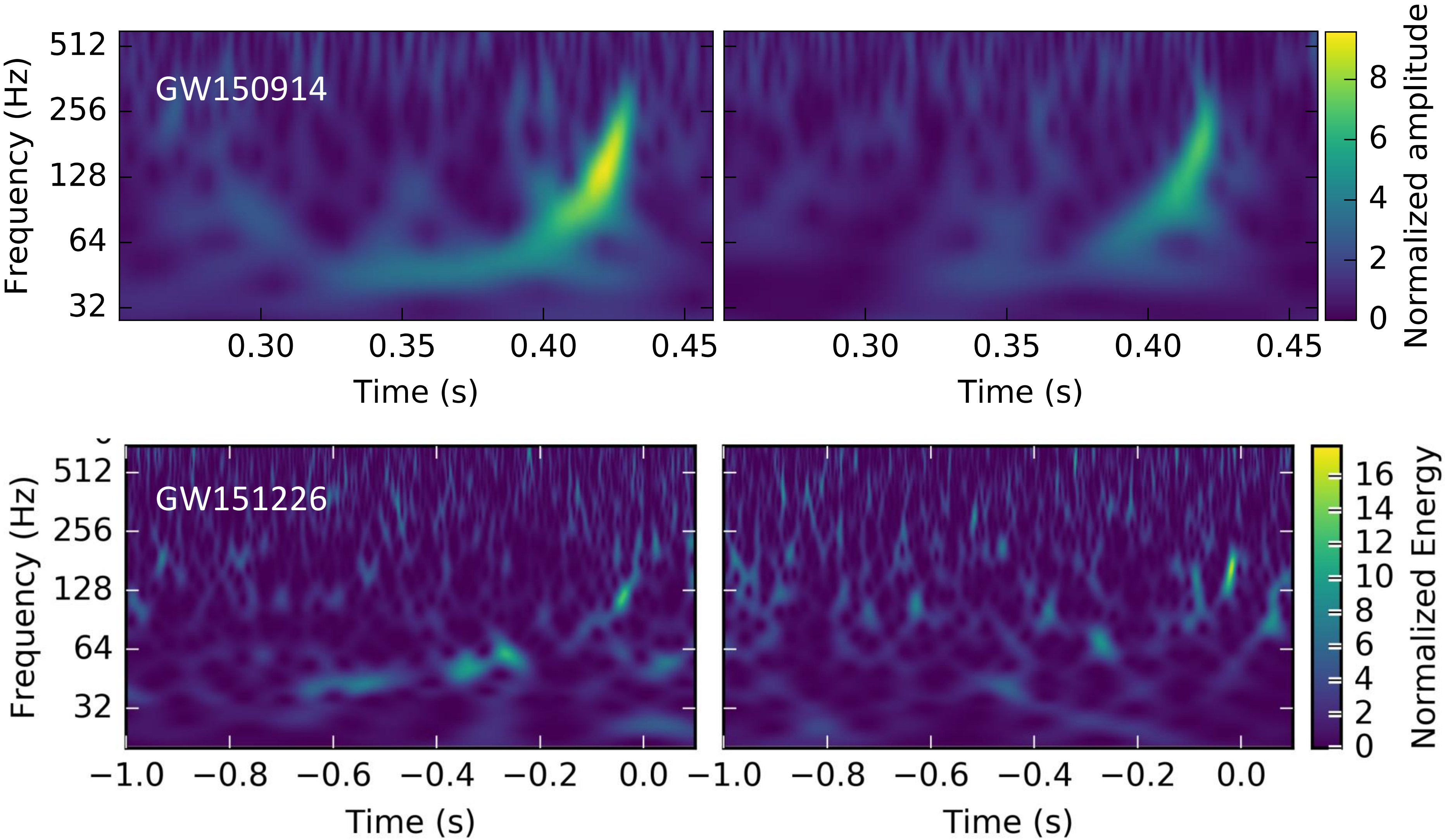


LIGO Livingston Data
LIGO Hanford Data
Strain (10^{-21})
1.0
0.5
0.0
-0.5
-1.0
0.30
0.35
0.40
0.45
Time (sec)
Time (sec)

GW 150914

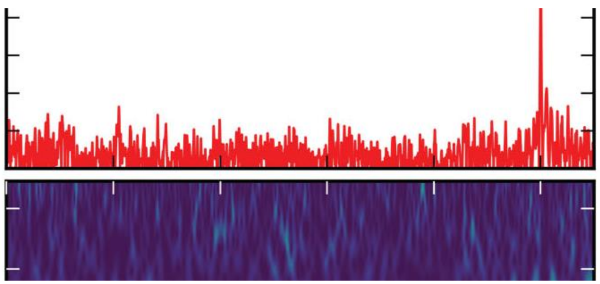

LIGO Livingston Data
LIGO Hanford Data
Strain (10⁻²¹)
1.0
0.5
0.0
-0.5
-1.0
0.45
LIGO Hanford Data (shifted)
Strain (10⁻²¹)
1.0
0.5
0.0
-0.5
-1.0
LIGO Livingston Data
0.30
0.35
0.40
0.45
Time (sec)

Identifying the signals



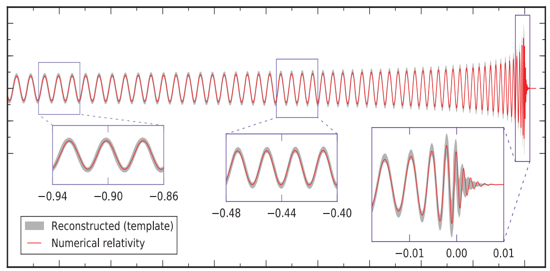
Matched filtering

Data



X

Waveform



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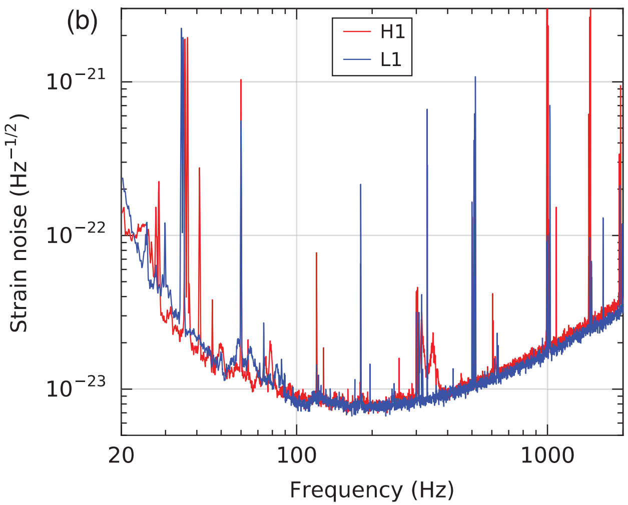
Sensitivity



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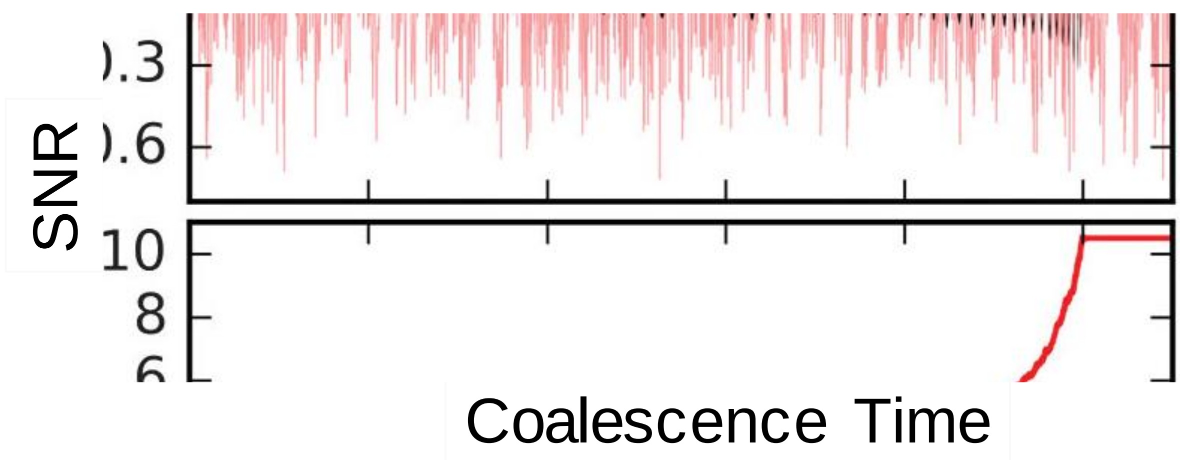
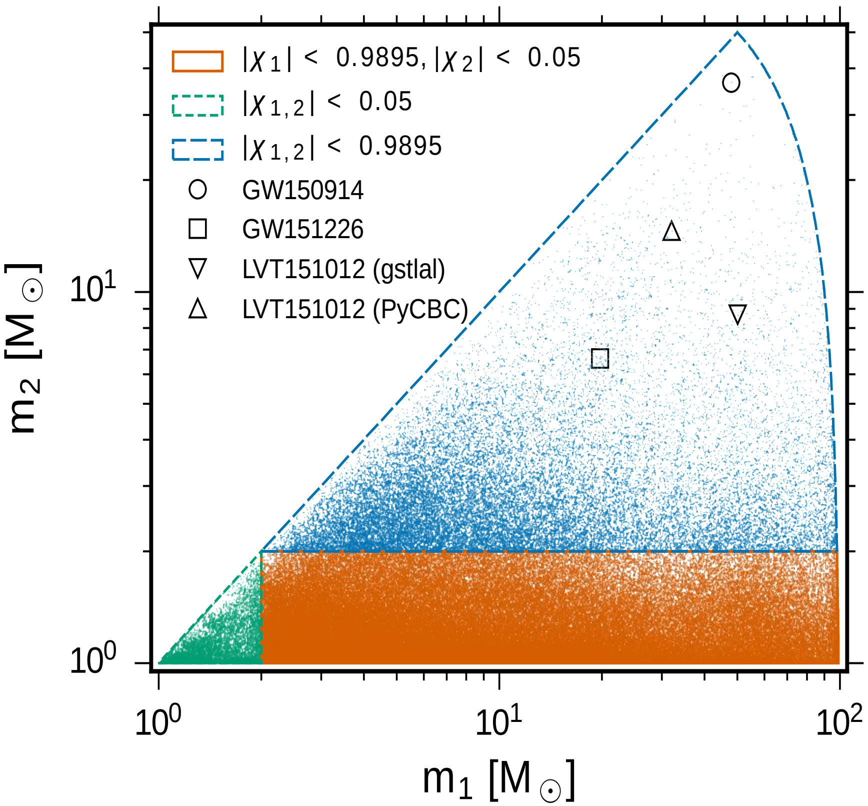
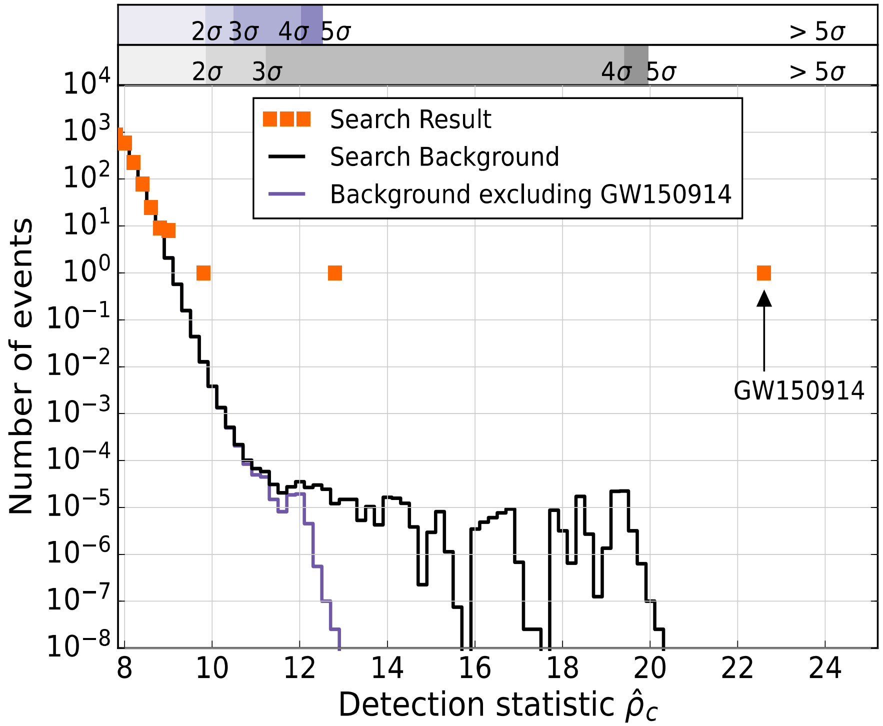


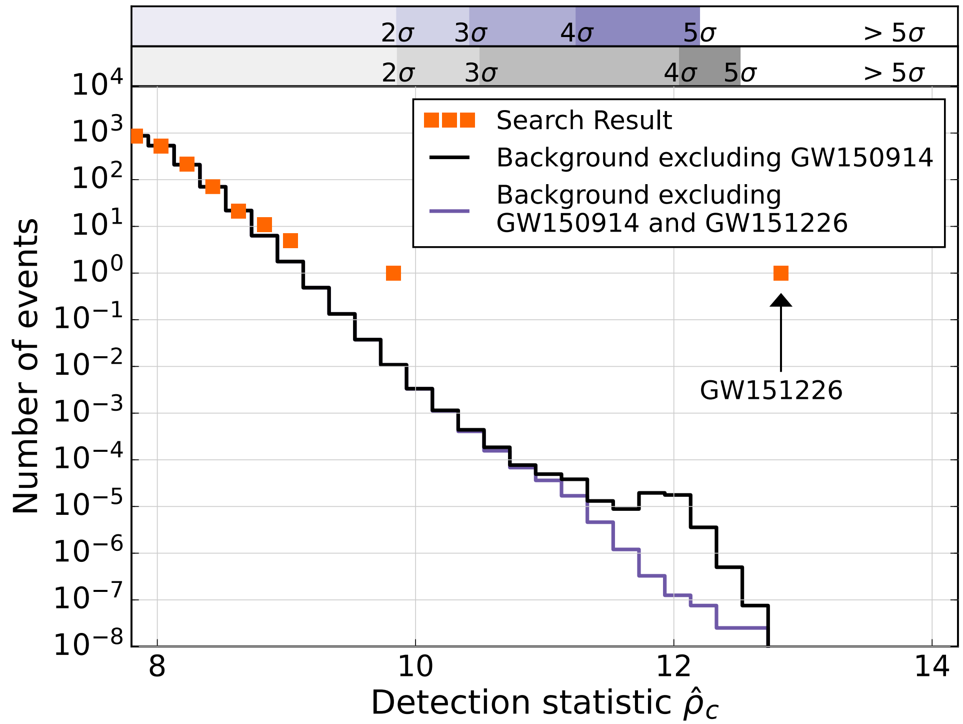
Binary Merger Search

- Use known waveforms to search for binary signals.
- Calculate Signal to Noise Ratio (SNR), $\rho(t)$, identify maxima, and reweight by a χ^2 consistency measure.
- Require coincidence between detectors within 15 msec.
- Detection statistic: quadrature sum of the signal to noise in each detector.
- Background: Time shift by multiples of 0.1 seconds and repeat search.

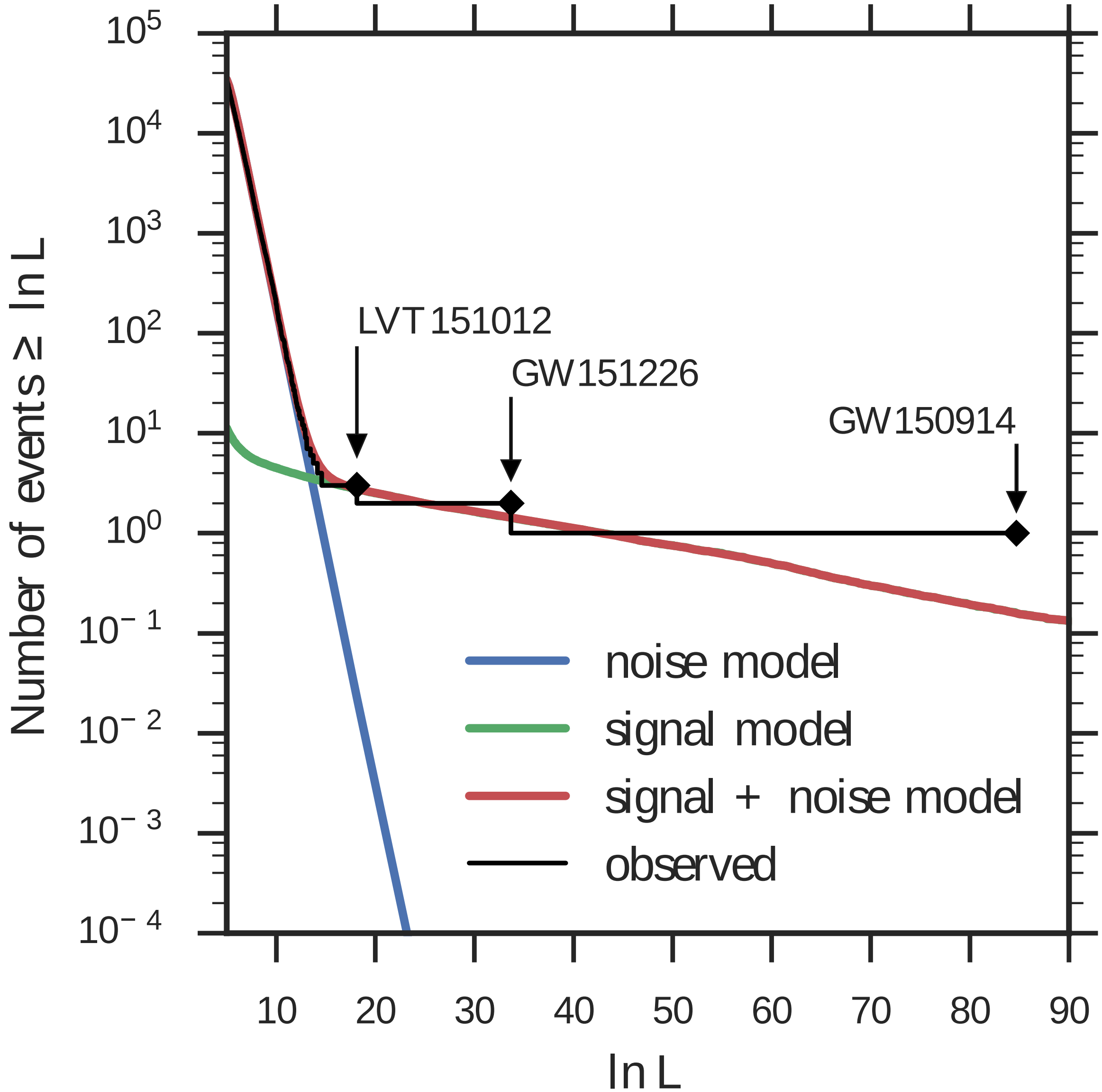


Statistical Significance





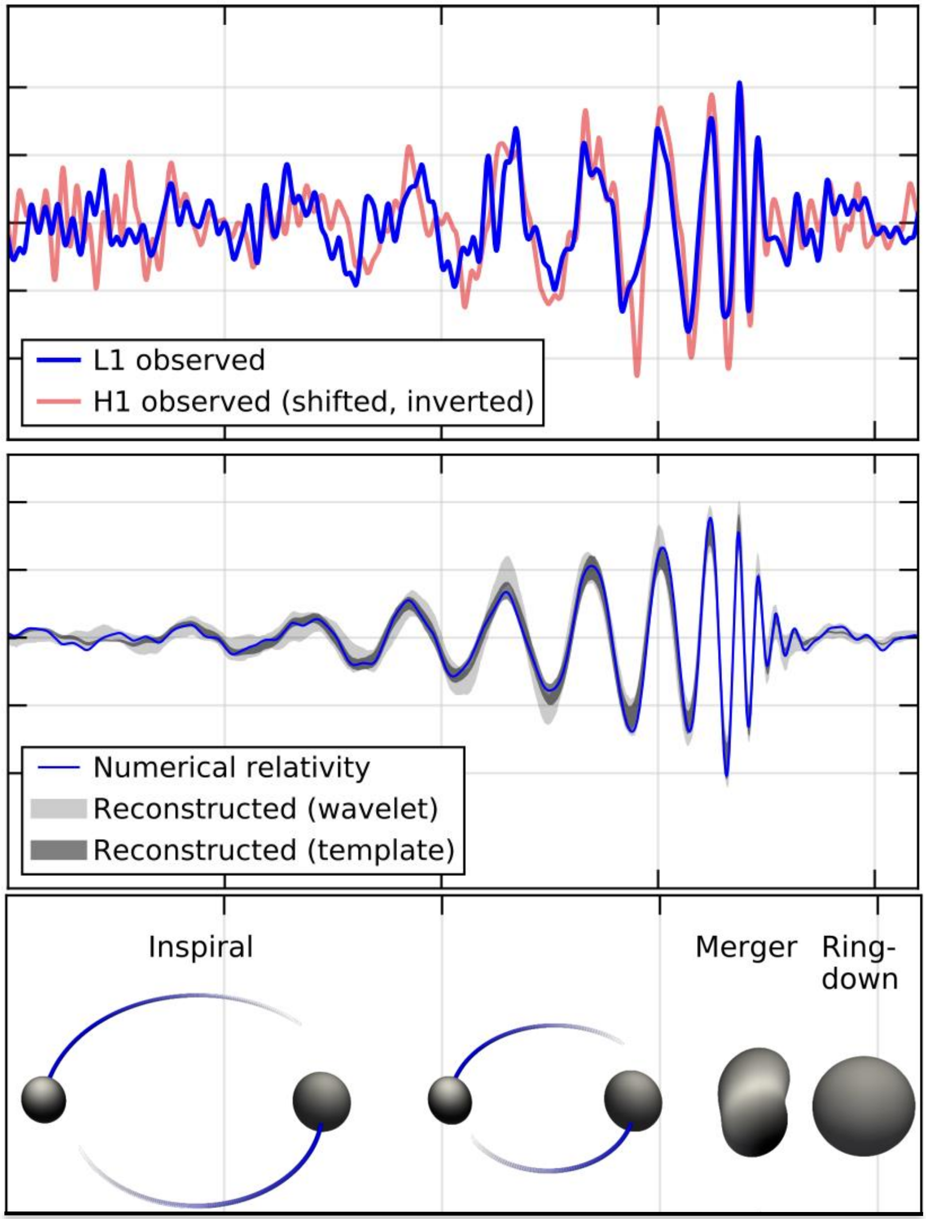
Statistical Significance



GW150914: A black hole binary

- Orbits decay due to emission of gravitational waves

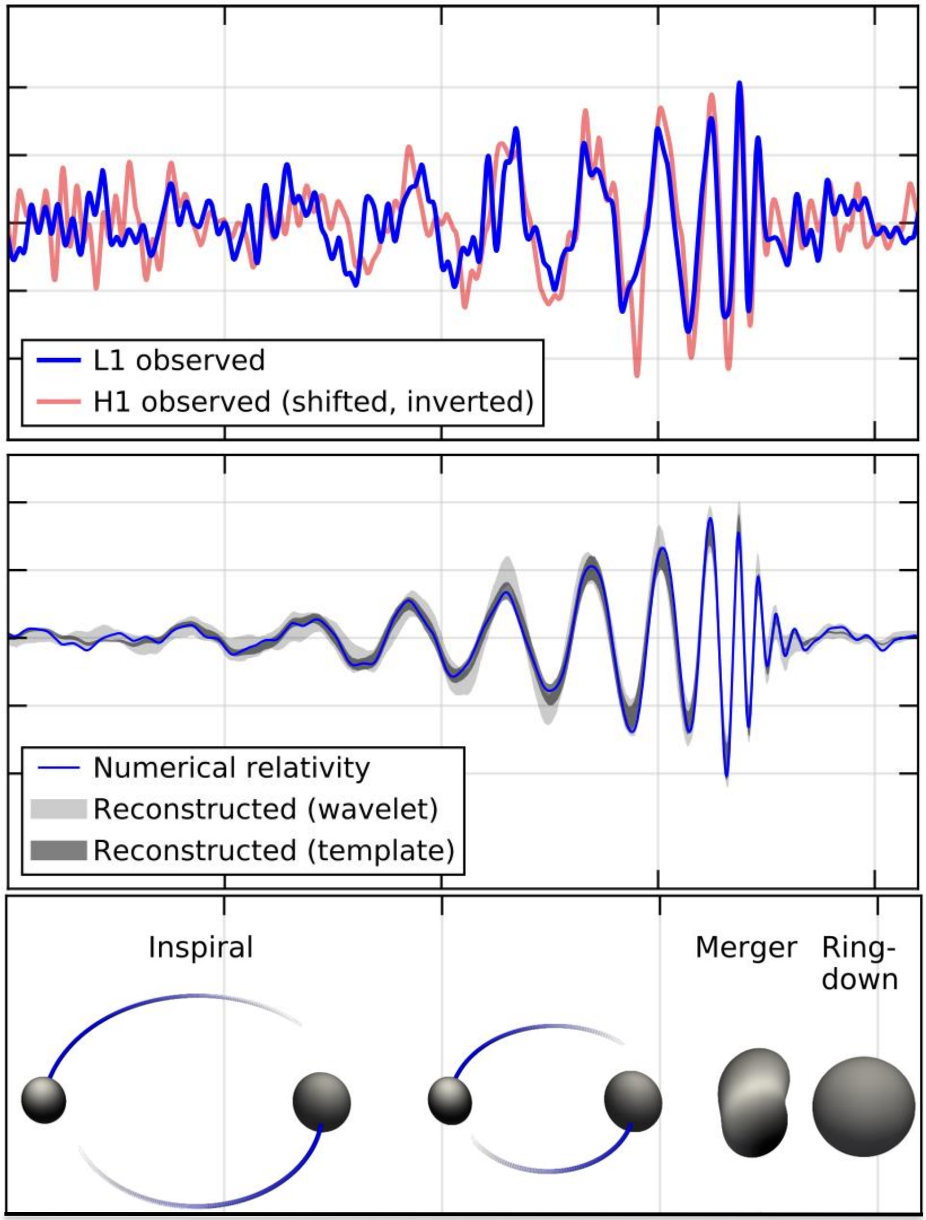
- **Leading order** determined by "chirp mass"

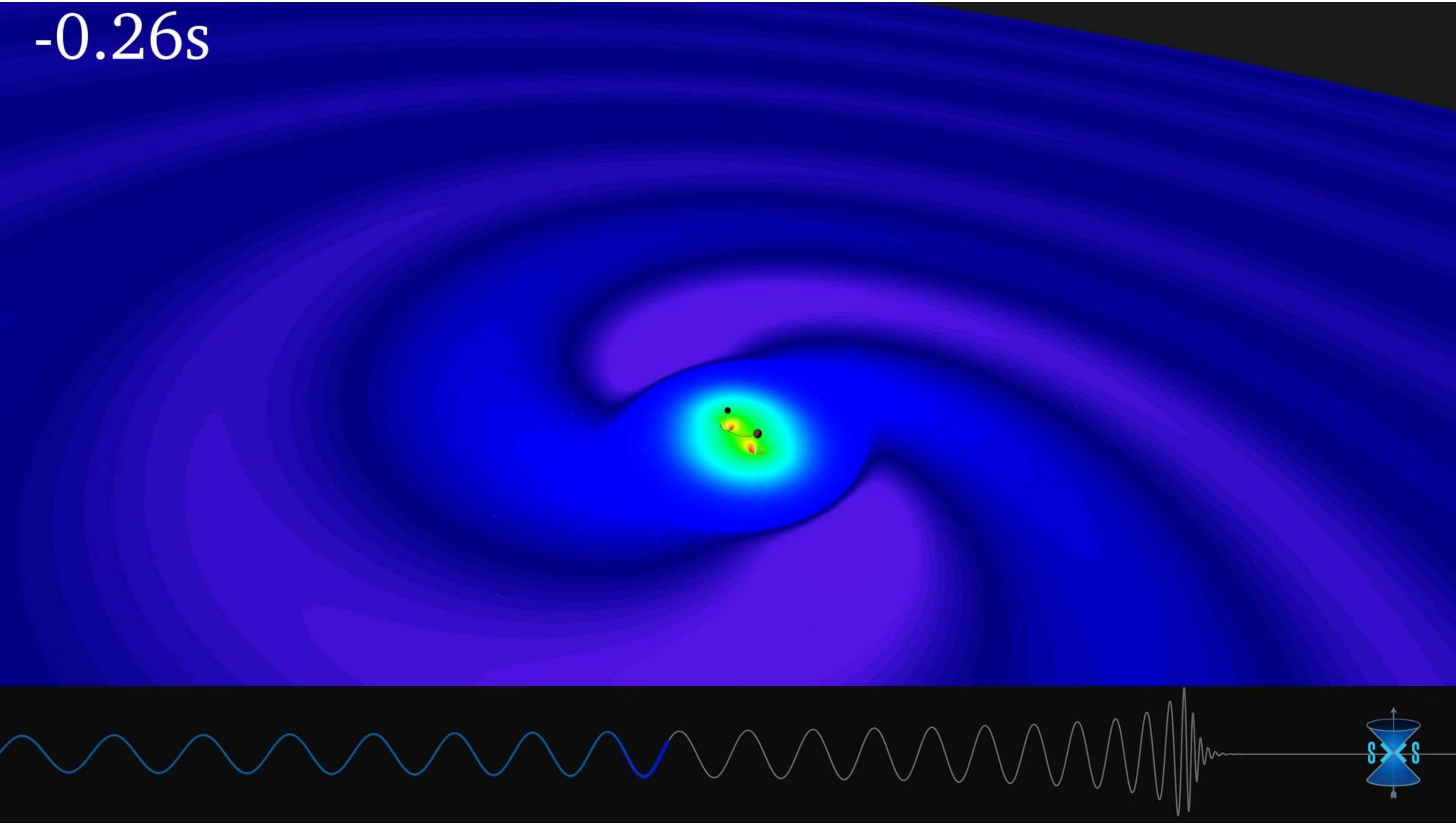


$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{M^{1/5}} \simeq \frac{c^3}{G}\left[\frac{5}{96}\pi^{-8/3} f^{-11/3} \dot{f}\right]^{3/5}$$

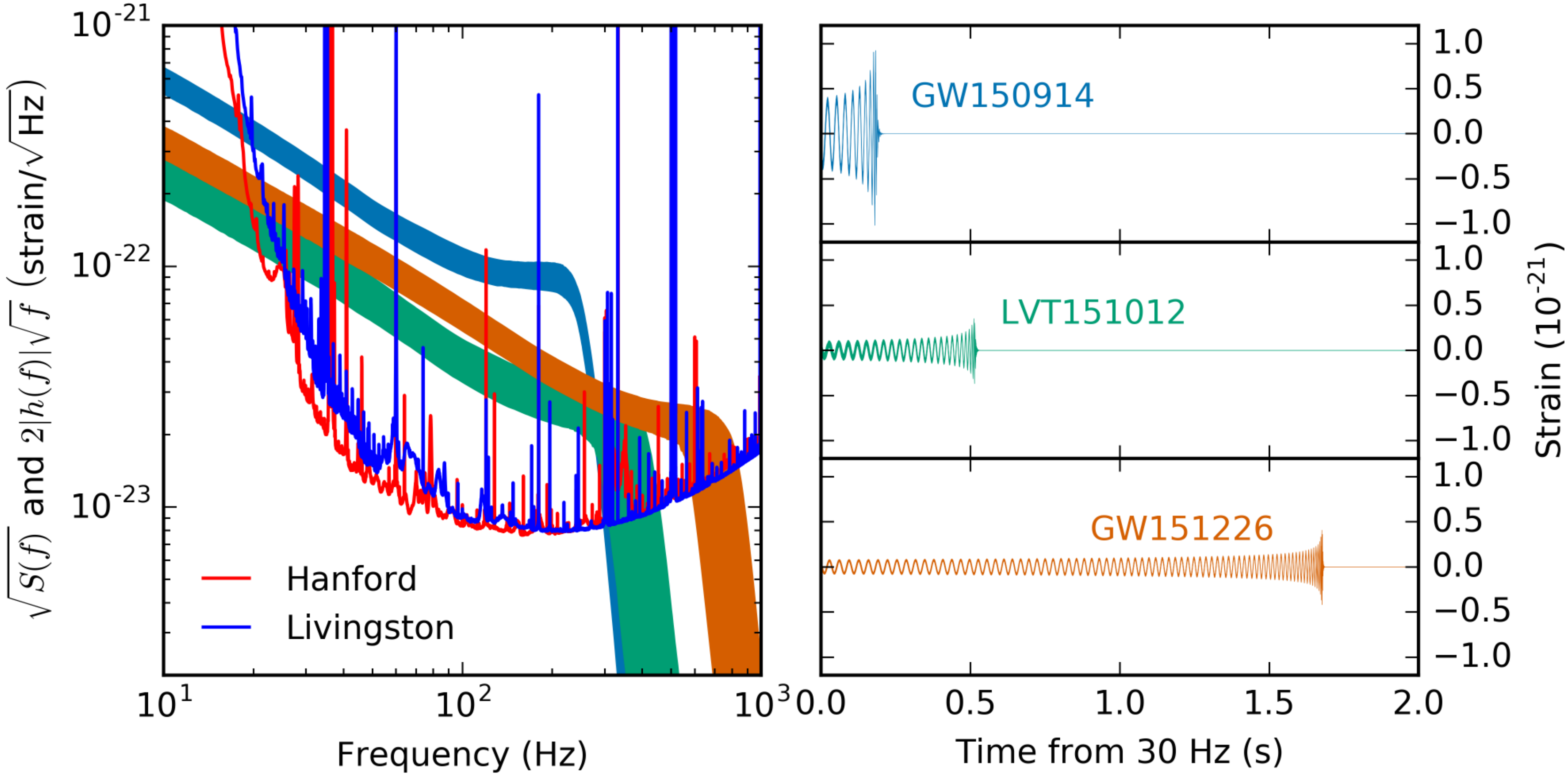
GW150914: A black hole binary

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

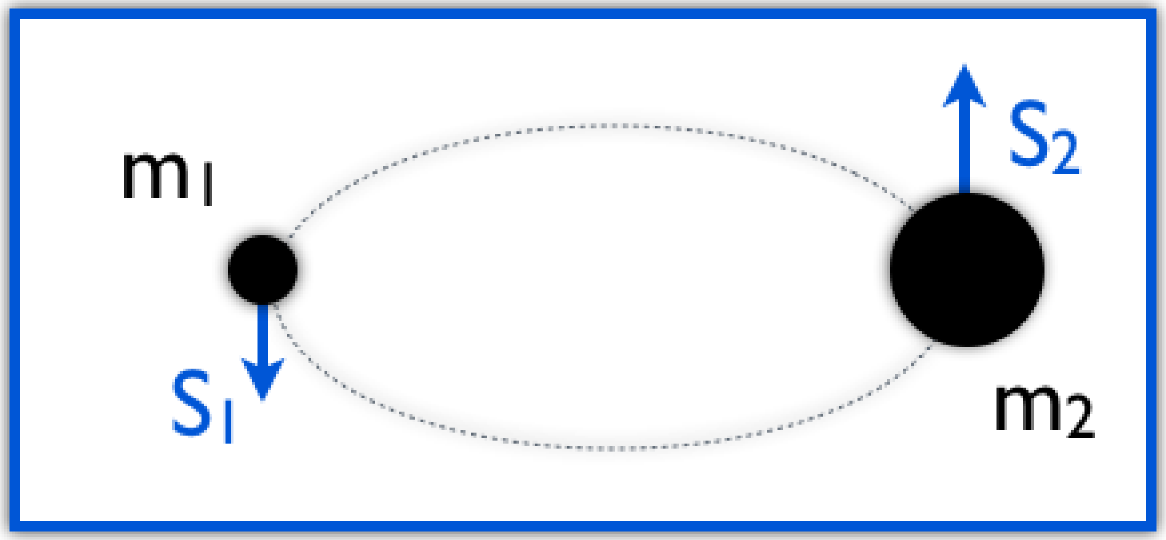



-0.26s

Observed Signals



Measuring masses and spins

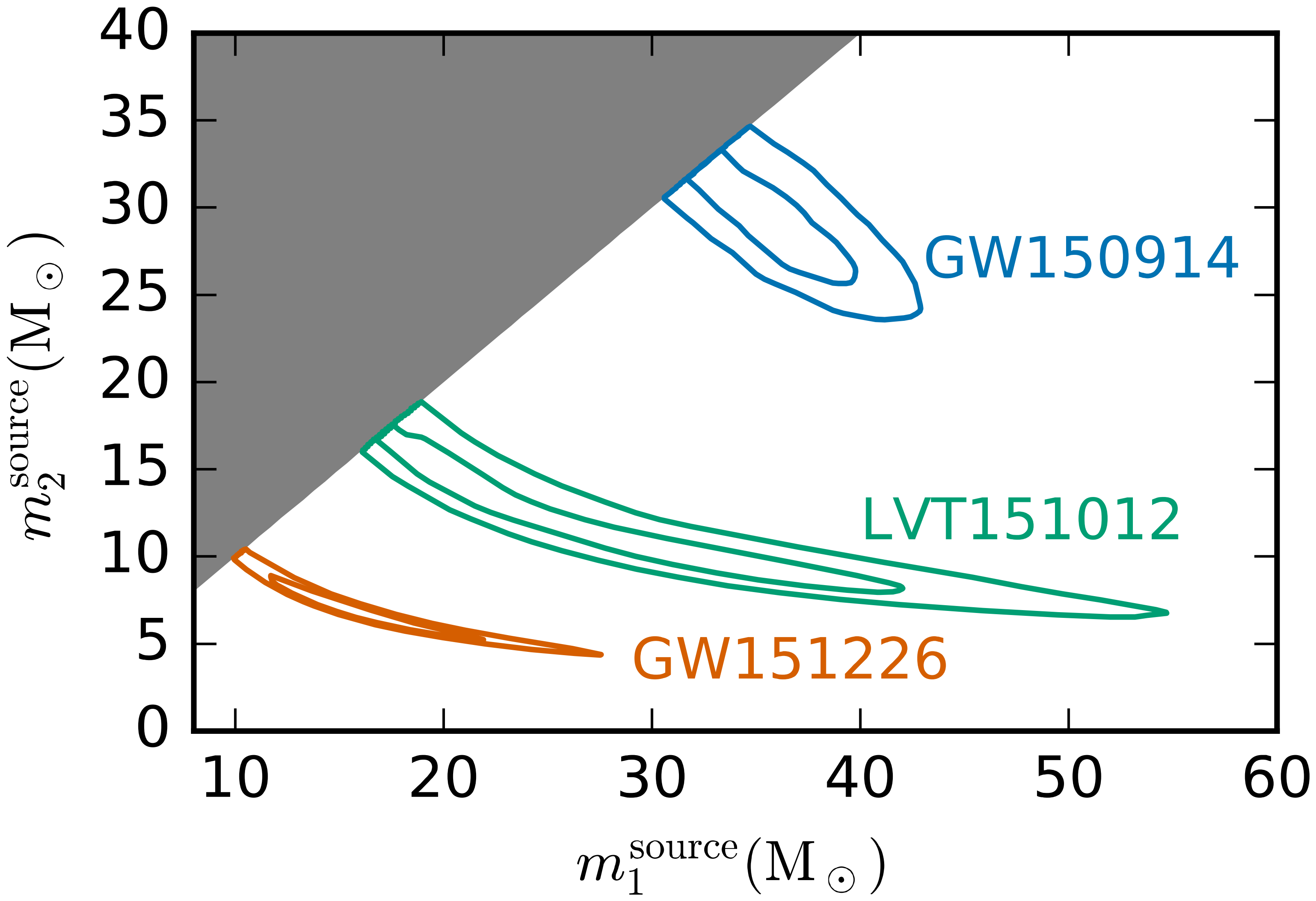


- Chirp mass
  - Leading order inspiral rate
- Mass ratio and spins
  - Change in amplitude / frequency evolution
  - "effective" spin has the dominant effect
- Misaligned spins lead to orbital precession

Cosmological effects

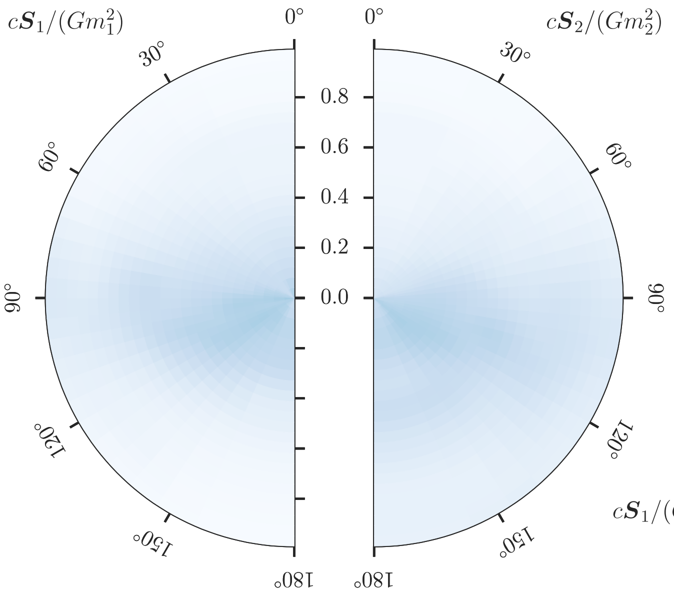
- Binary merger signal has a characteristic shape
  - Scales with the mass, M, of the system
- Redshift reduces observed frequencies
  - Indistinguishable from change in mass
    => measure M (1 +z)
- Amplitude scales
  - inversely with the co-moving distance, D_C
  - with the total mass, M
- Directly measure:
  - luminosity distance, $D_L = D_C (1 + z)$
  - Redshifted mass, M (1 + z)

Masses



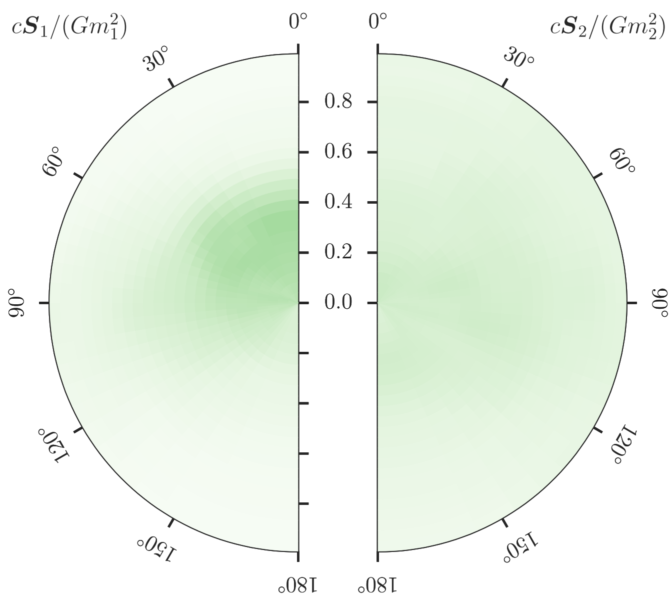
40
35
30
25
20
15
10
5
0
10
20
30
40
50
60
$m_2^{\mathrm{source}}(\mathrm{M}_\odot)$
$m_1^{\mathrm{source}}(\mathrm{M}_\odot)$
GW150914
LVT151012
GW151226

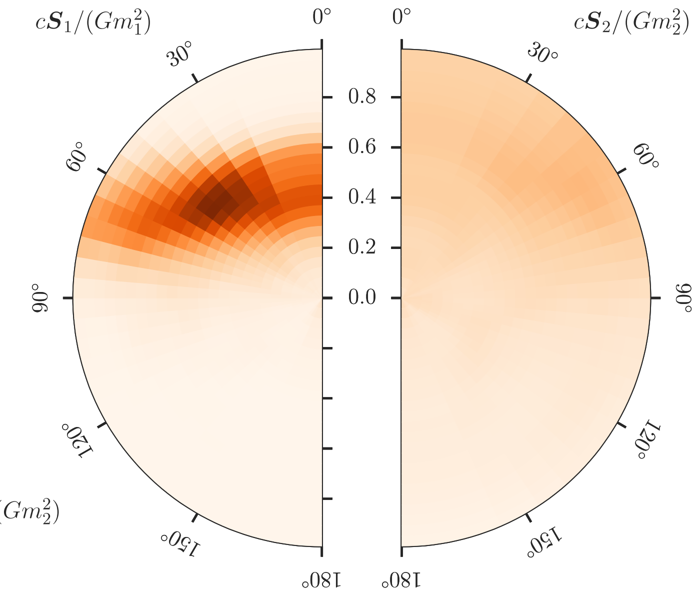
Spins



GW150914

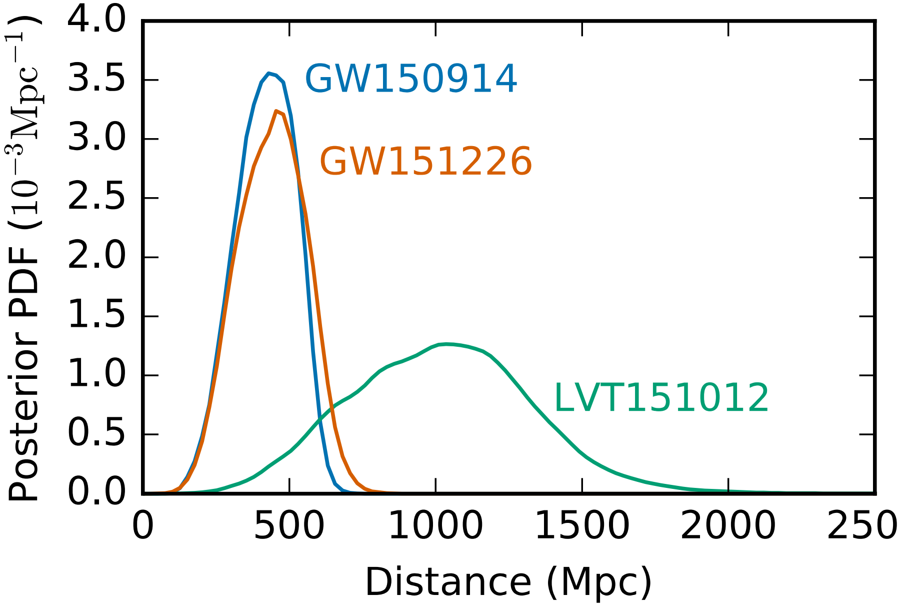
LVT151012

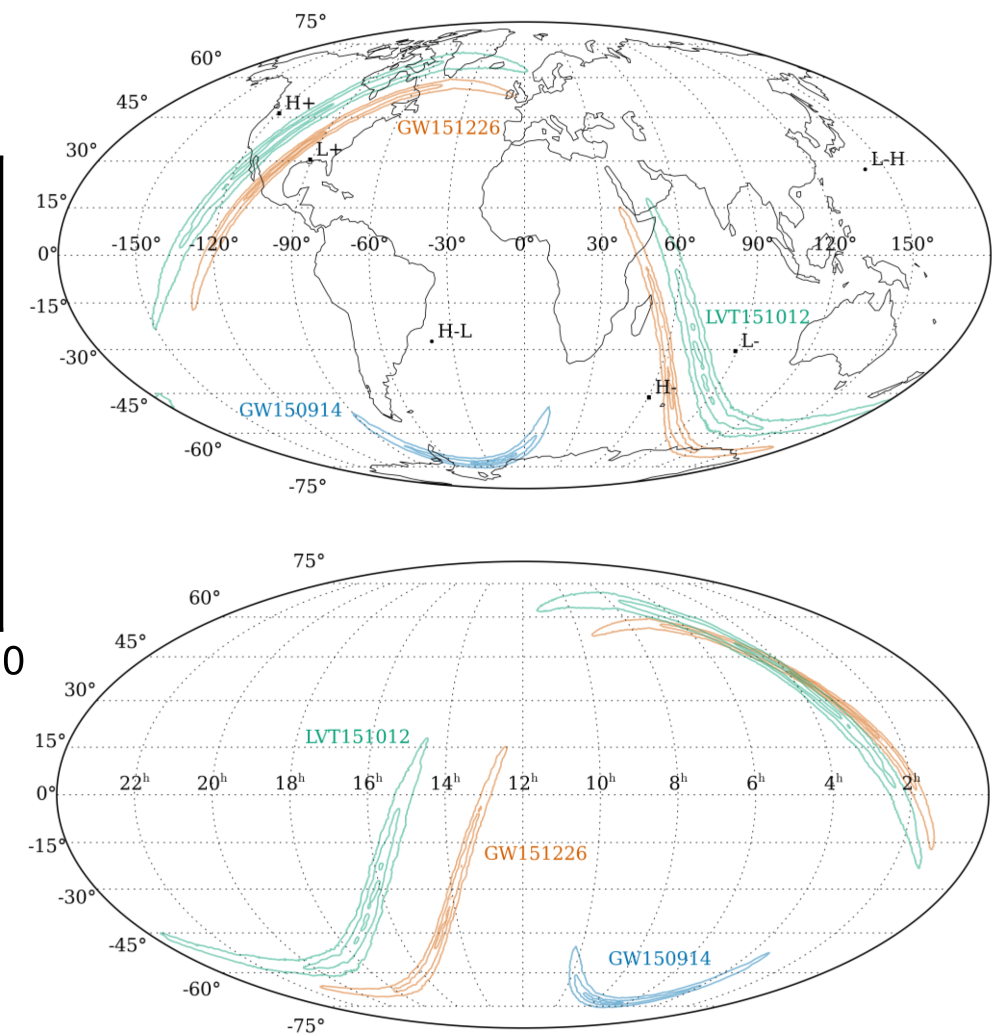




GW151226

Distance and sky position





LIGO

Final mass and spin

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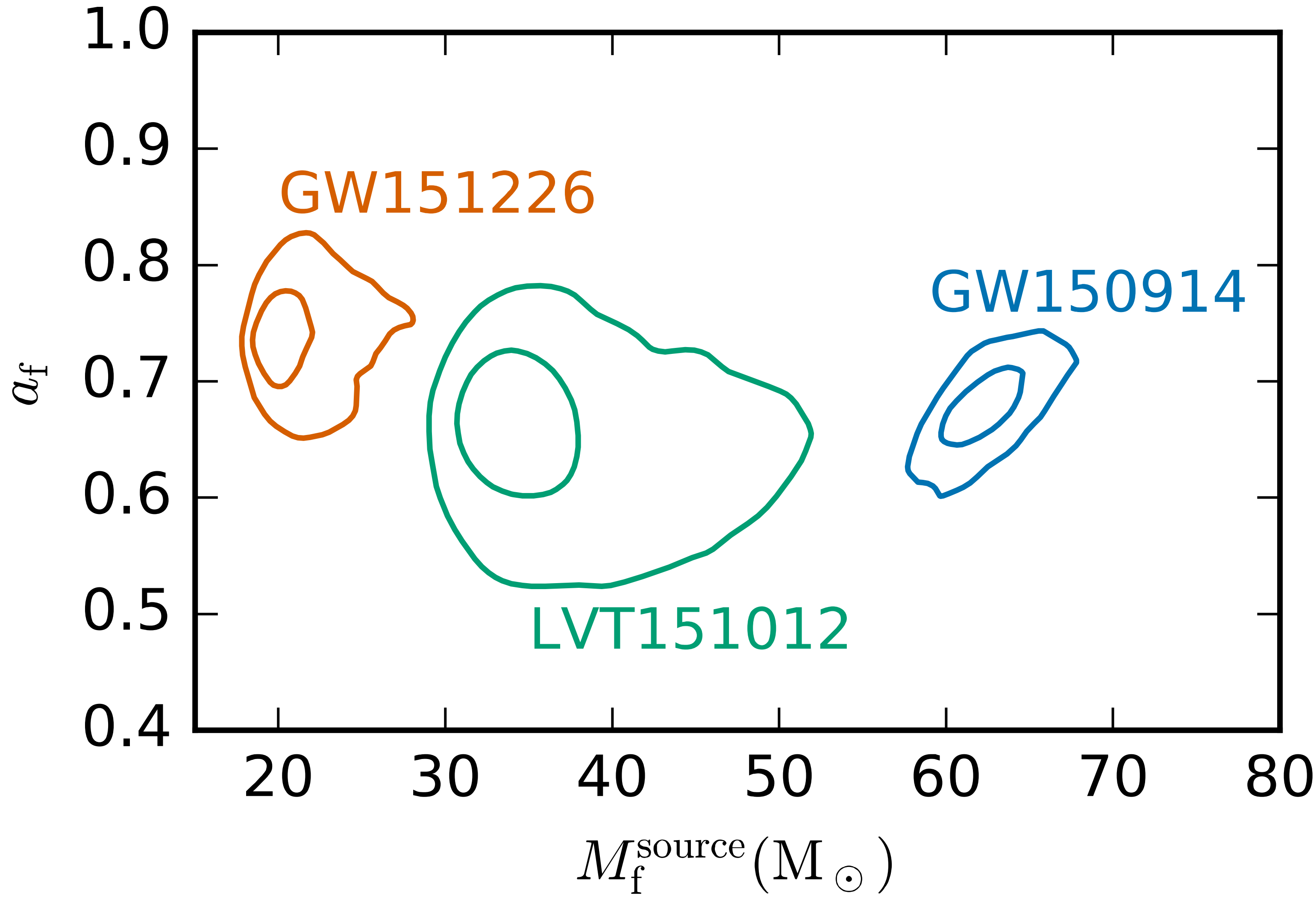

Event summary

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}	$0.68^{+0.05}_{-0.06}$	$0.74^{+0.06}_{-0.06}$	$0.66^{+0.09}_{-0.10}$
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

Event summary

Event	GW150914	GW151226	LVT151012
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p-value	7.5×10^{-8}	7.5×10^{-8}	0.045
Significance	$> 5.3\sigma$	$> 5.3\sigma$	1.7σ
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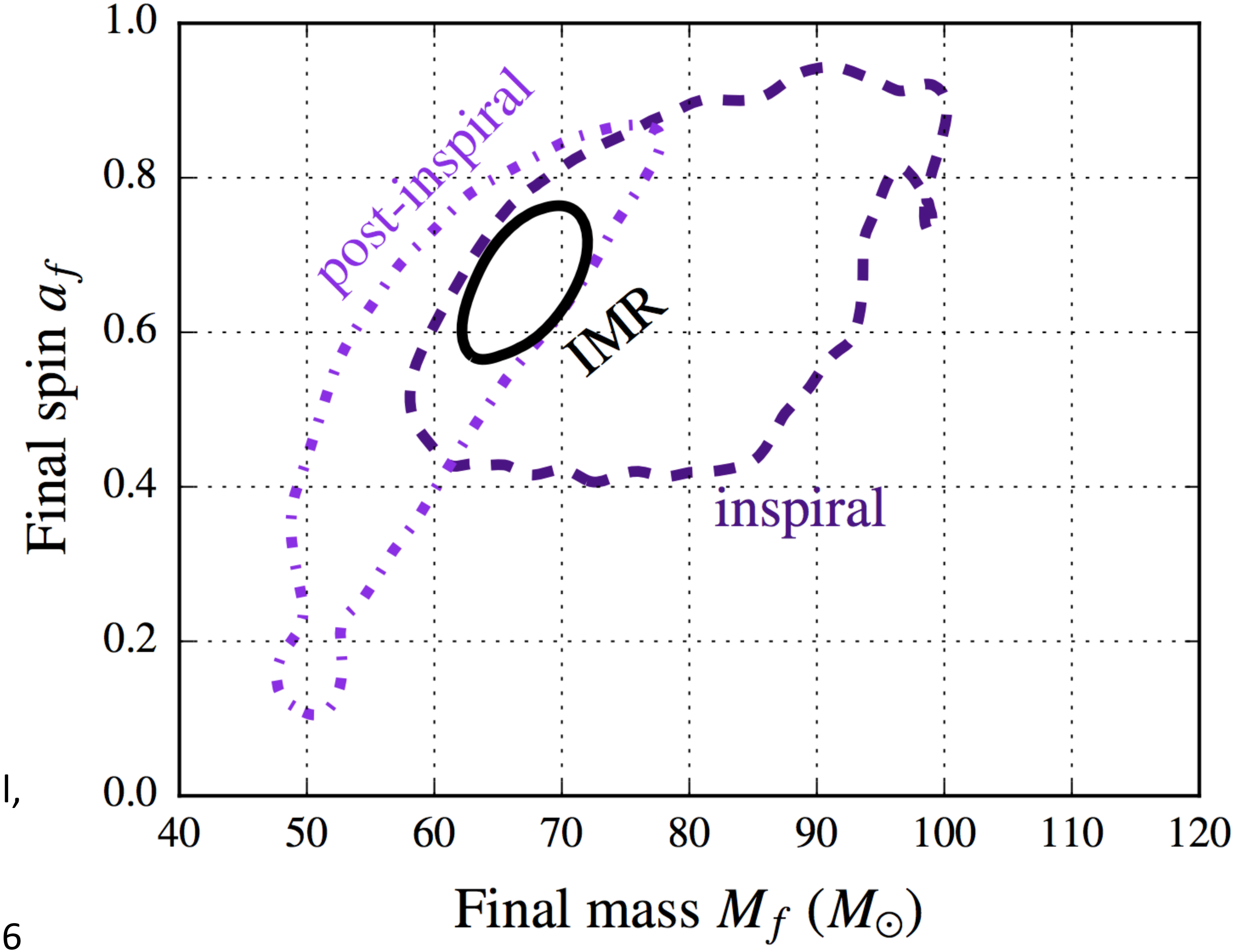
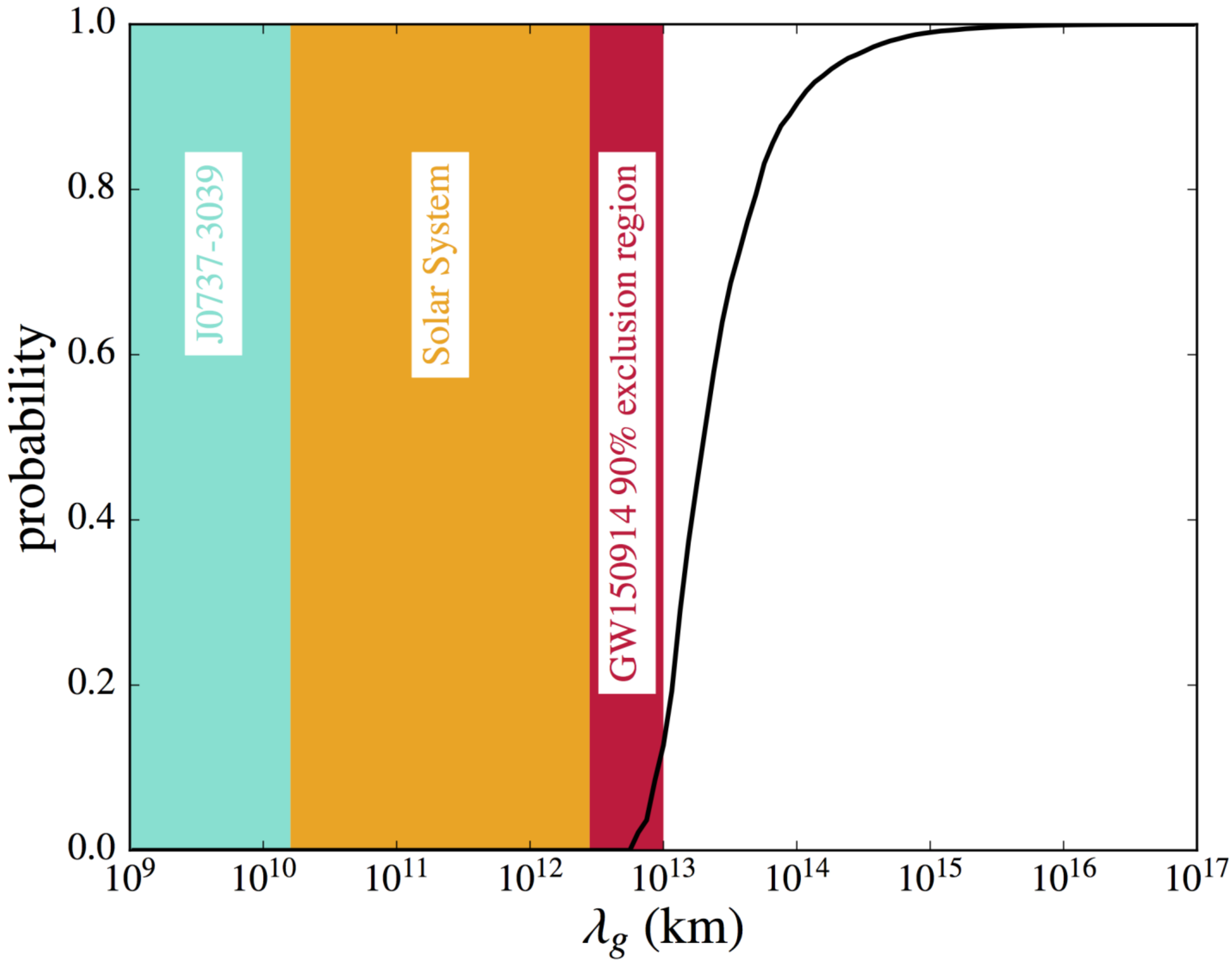
Final mass $M_f^{\mathrm{source}}/\mathrm{M}_\odot$	$62.3^{+3.7}_{-3.1}$	$20.8^{+6.1}_{-1.7}$	35^{+14}_{-4}
Final spin a_f	$0.68^{+0.05}$ [illegible]	$0.74^{+0.06}$ [illegible]	$0.66^{+0.09}$ [illegible]
Radiated energy $E_{\mathrm{rad}}/(\mathrm{M}_\odot c^2)$	$3.0^{+0.5}_{-0.4}$	$1.0^{+0.1}_{-0.2}$	$1.5^{+0.3}_{-0.4}$
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_L/Mpc	420 [illegible] $_{-180}$	440 [illegible] $_{-190}$	1000 [illegible] $_{-500}$
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

Consistency with GR



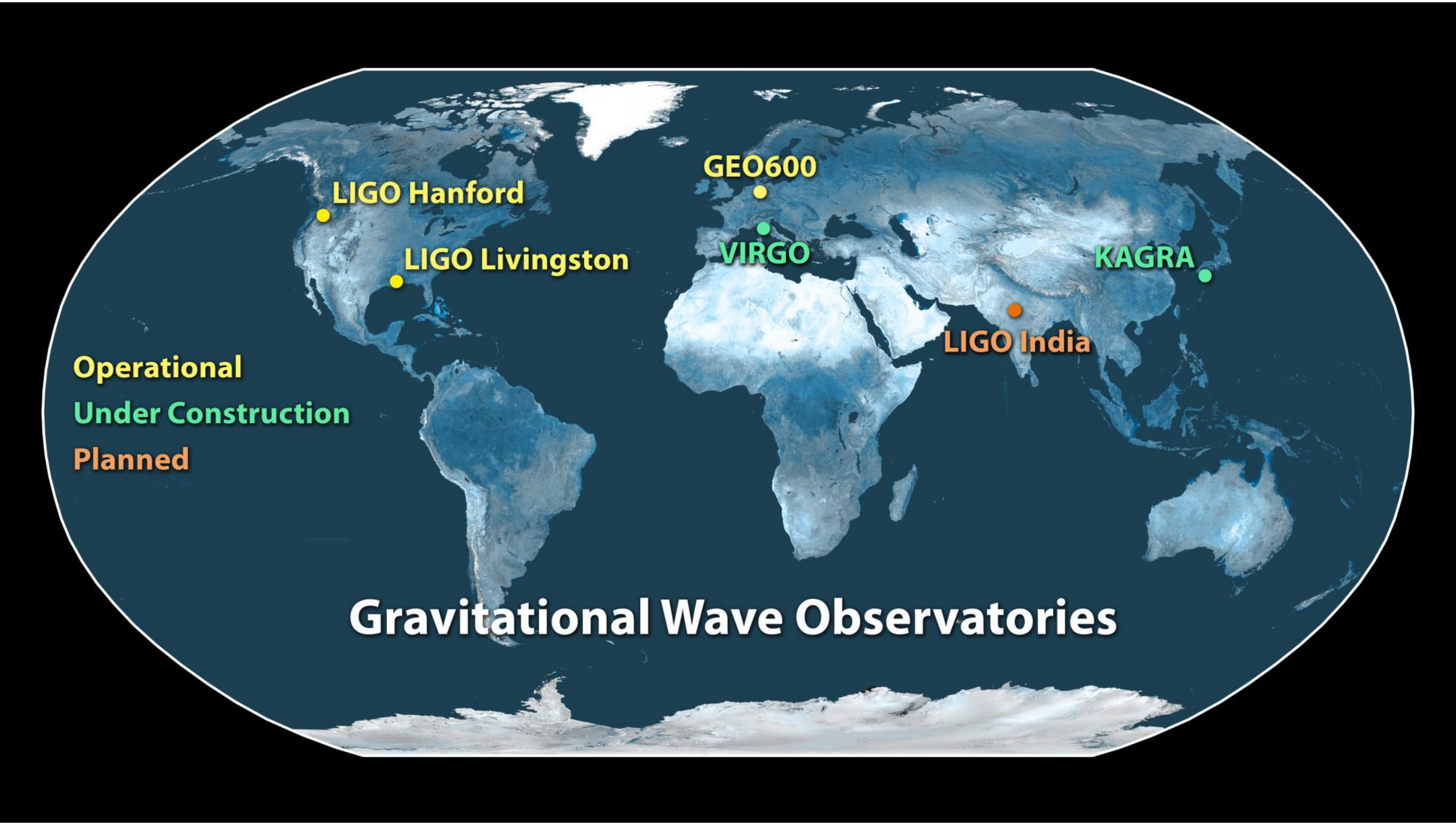
From Abbott et al, "Tests of general relativity with GW150914", 2016

Consistency with GR

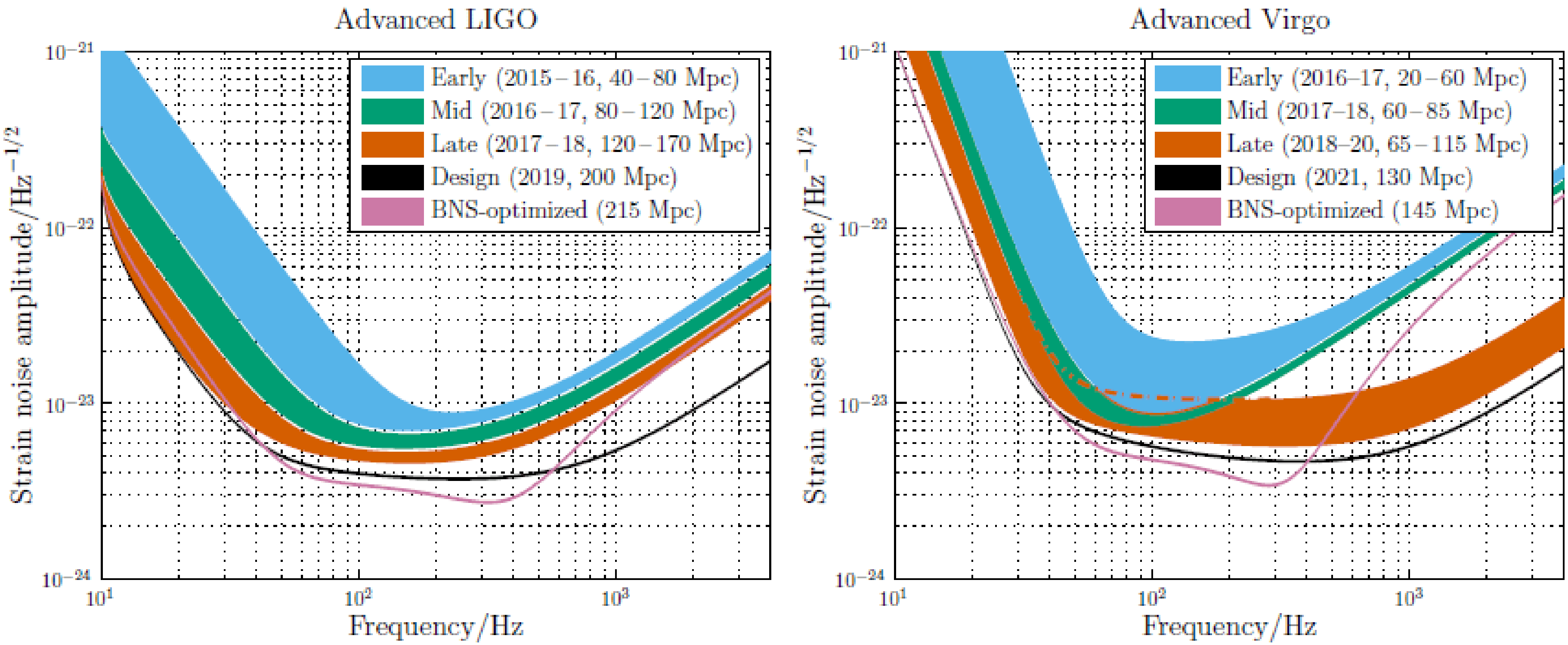


From Abbott et al, "Tests of general relativity with GW150914", 2016

Future Observing

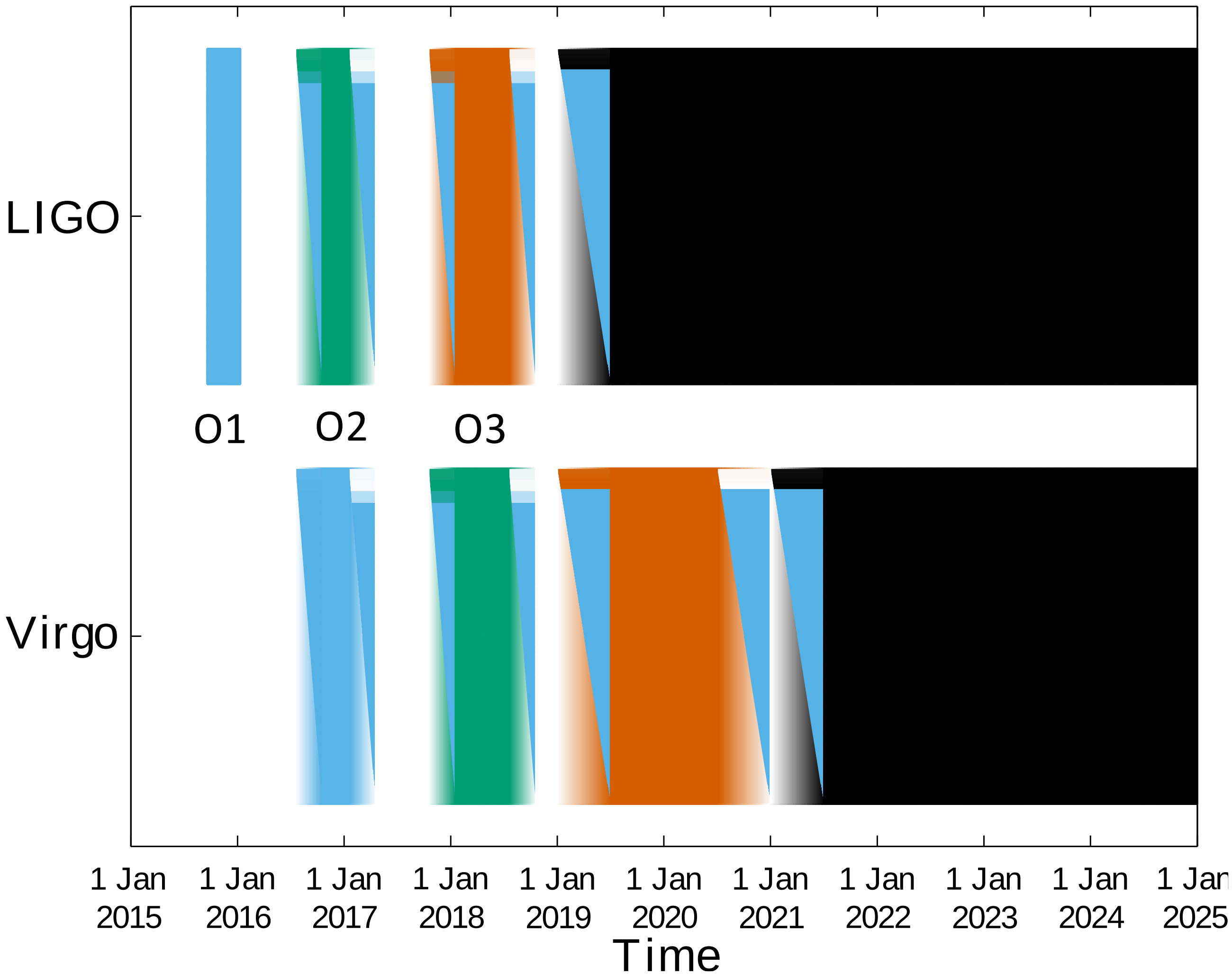


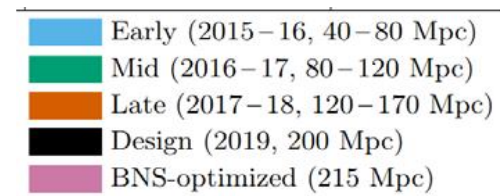
Planned LIGO-Virgo Observing



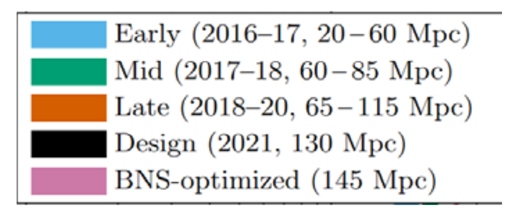
[Living Rev. Relativity 19 (2016), 1]

Planned LIGO-Virgo Observing





orientation-averaged distance for BNS detection with SNR = 8



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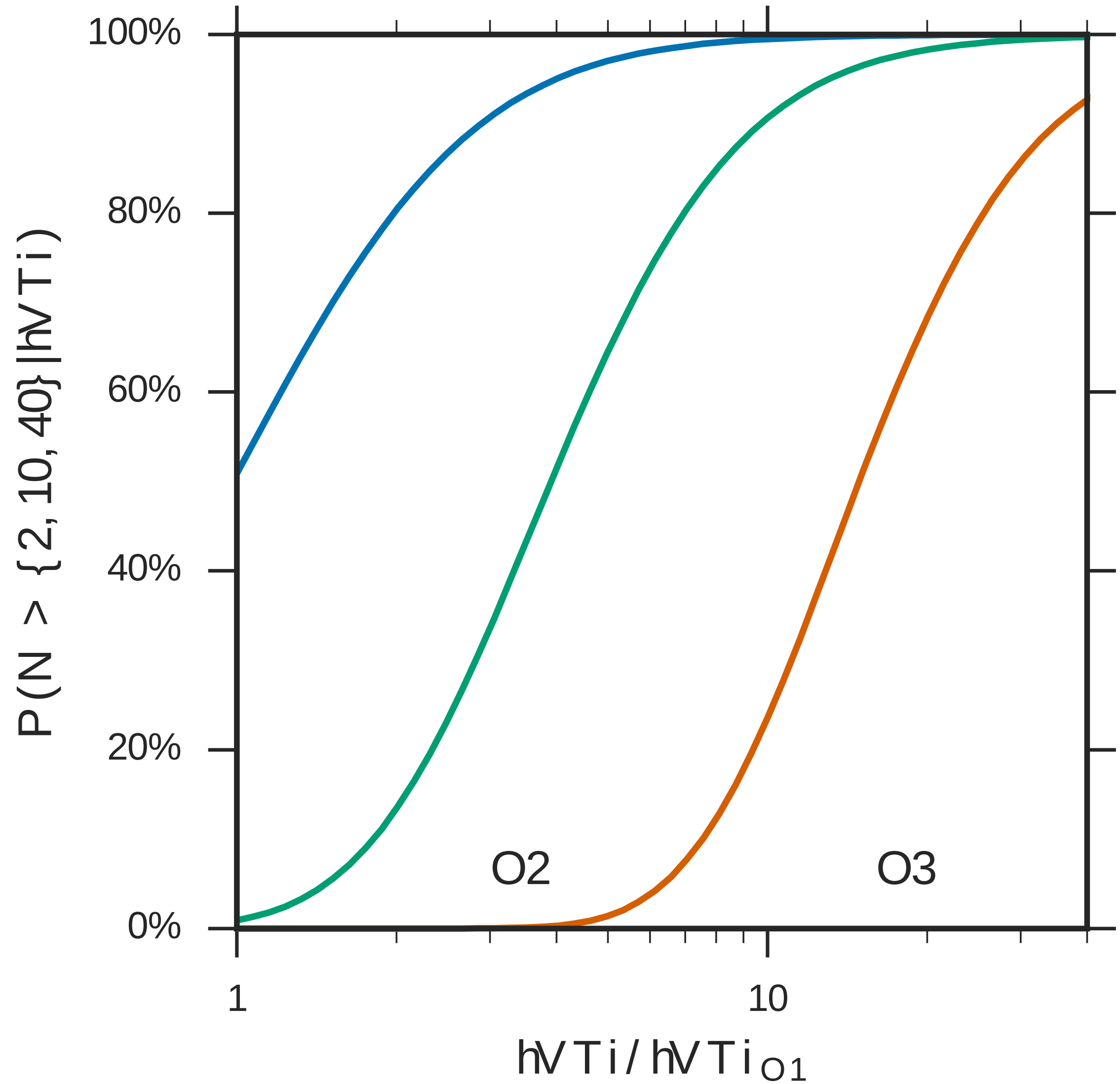
Expectations for future runs

Probability of observing

- N > 2 (blue)
- N > 10 (green)
- N > 40 (red)

highly significant events, as a function of surveyed time-volume.



Summary

- GW150914 and GW151226 are the *first direct detections* of GWs and the *first observations of binary black hole mergers*.
- GW150914 contains the *most massive known stellar-mass black holes*.
- GW150914 and GW151226 provide the opportunity *test General Relativity* in the large velocity, highly nonlinear regime.
- LIGO resumed the search for gravitational waves on November 30, 2016.
- We expect to observe many more binary black hole mergers in the coming years, as well as binaries containing neutron stars.
- Continue to look for electromagnetic counterparts to gravitational wave signals.

Stellar mass black holes