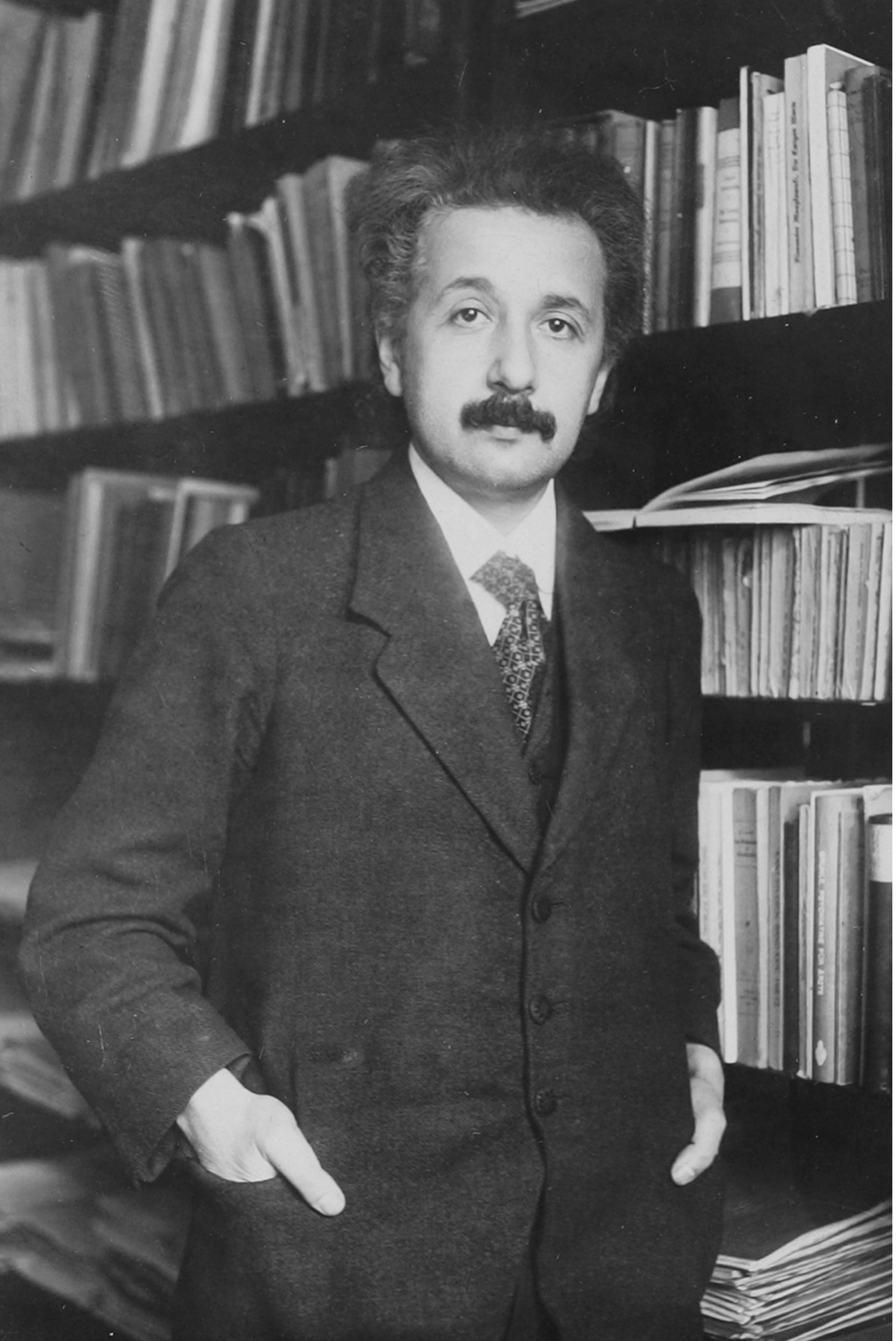

Observation of Gravitational Waves from a Binary Black Hole Merger

Michele Vallisneri

Jet Propulsion Laboratory
California Institute of Technology

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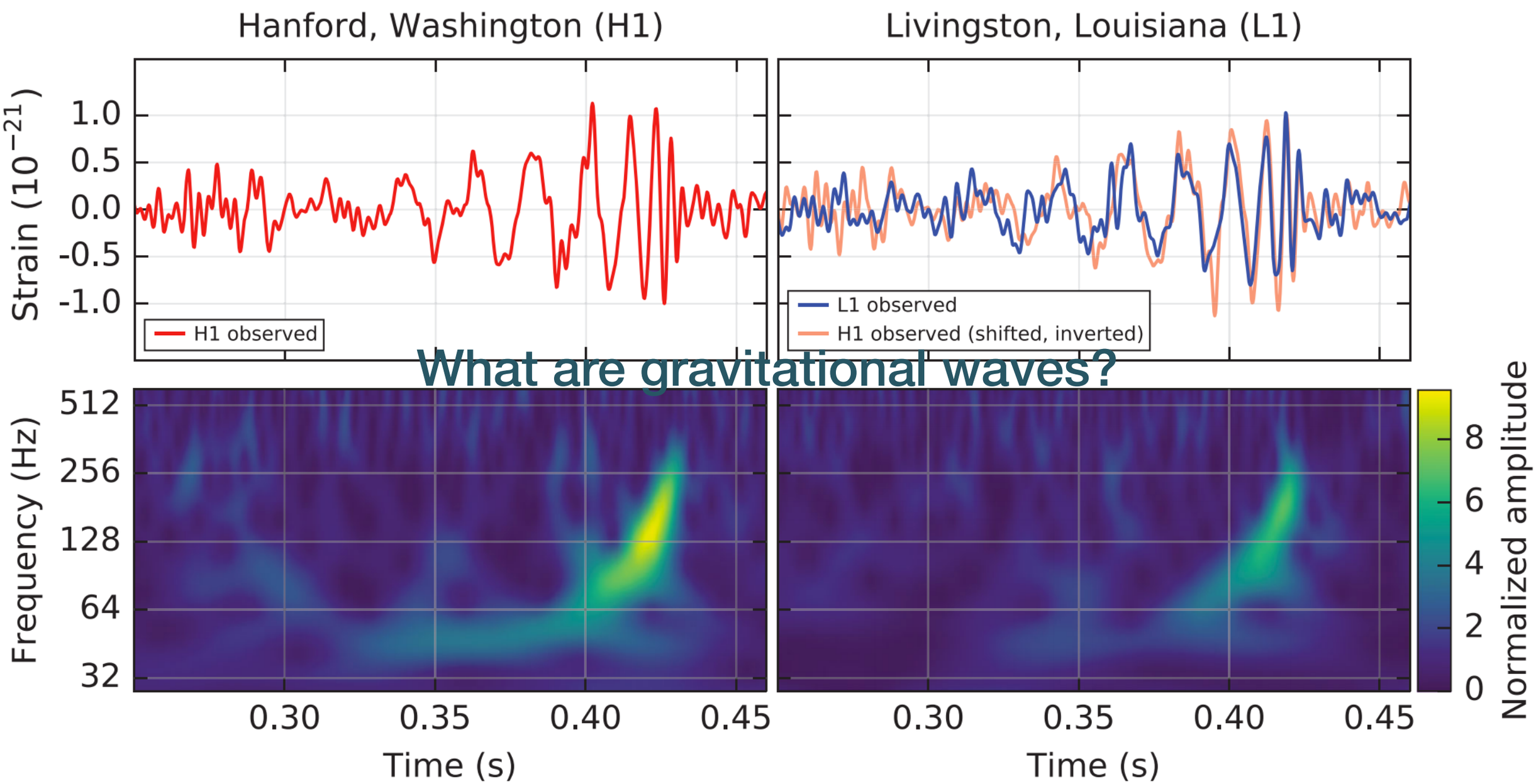
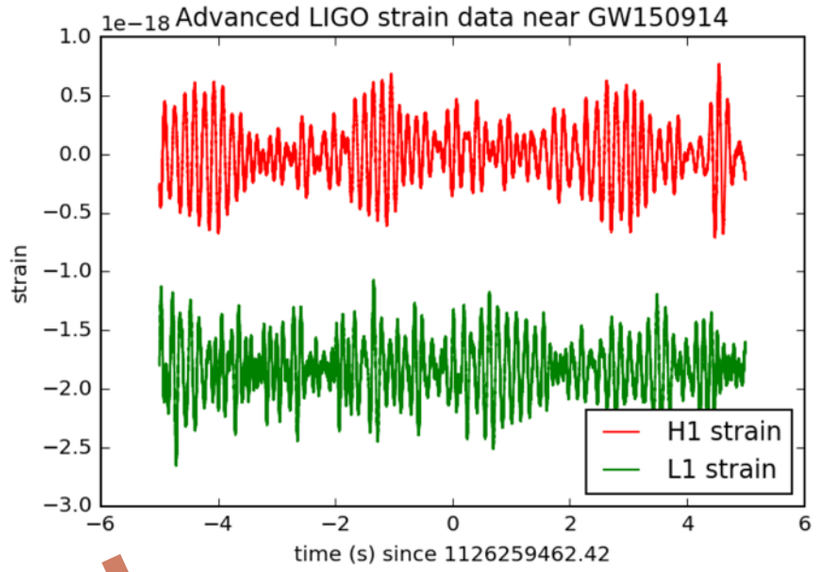
Government sponsorship acknowledged

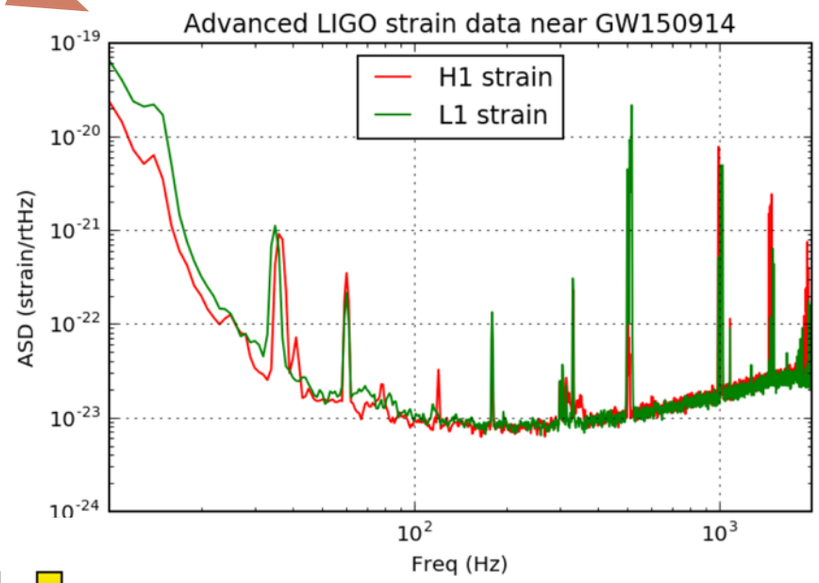


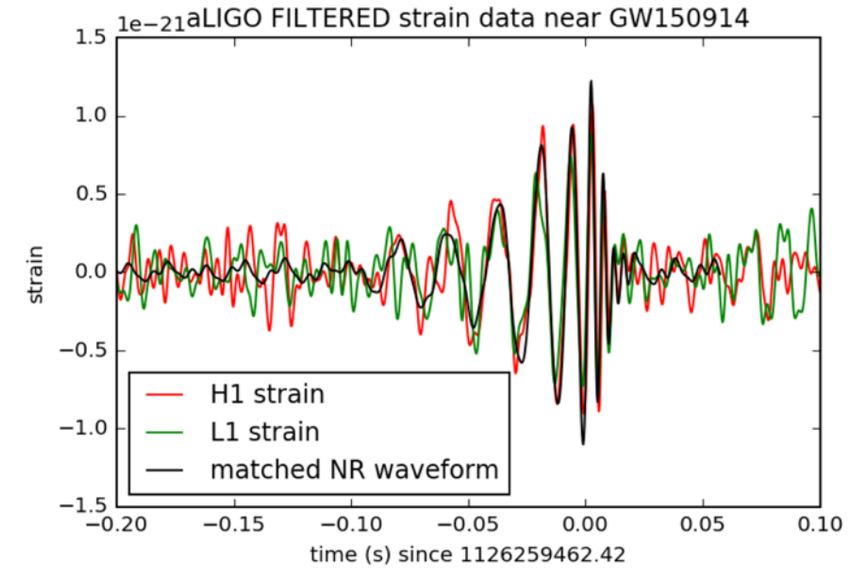
What are gravitational waves?

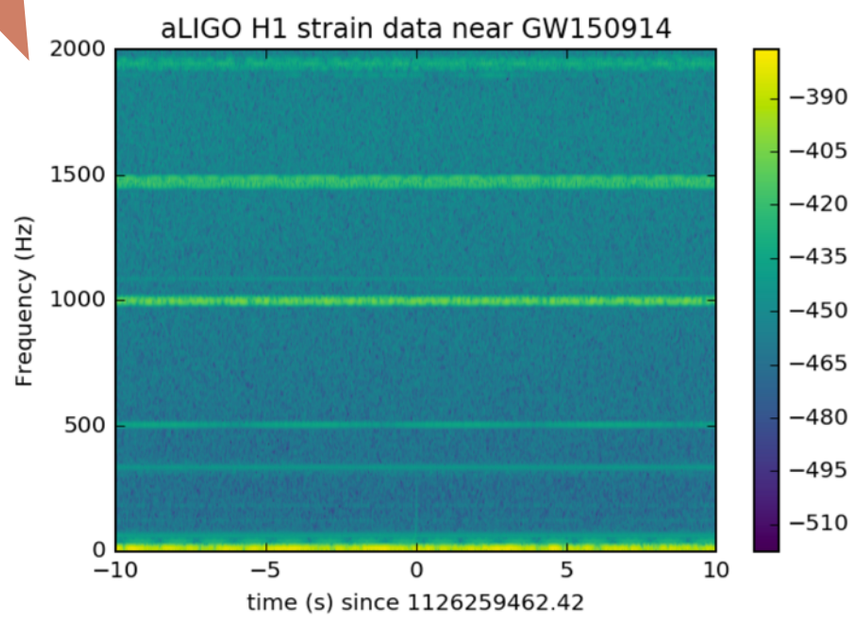
GW150914

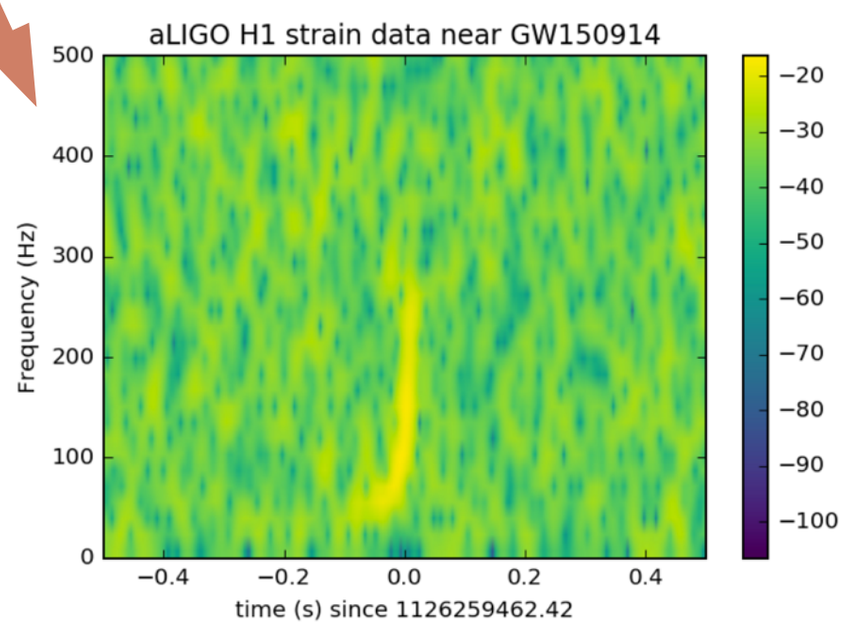
[LVC 2016]





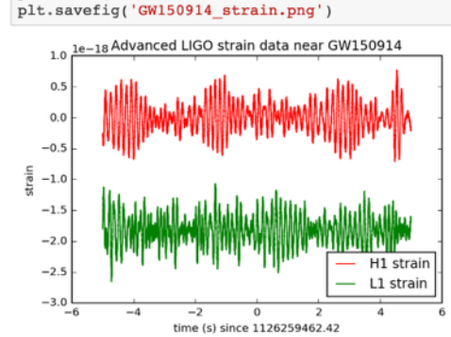






In [6]:
```
# plot +- 5 seconds around the event:
tevent = 1126259462.422          # Mon Sep 14 09:50:45 GMT 2015
deltat = 5.                      # seconds around the event
# index into the strain time series for this time interval:
indxt = np.where((time_H1 >= tevent-deltat) & (time_H1 < tevent+deltat))

plt.figure()
plt.plot(time_H1[indxt]-tevent,strain_H1[indxt],'r',label='H1 strain')
plt.plot(time_L1[indxt]-tevent,strain_L1[indxt],'g',label='L1 strain')
plt.xlabel('time (s) since '+str(tevent))
plt.ylabel('strain')
plt.legend(loc='lower right')
plt.title('Advanced LIGO strain data near GW150914')
plt.savefig('GW150914_strain.png')
```

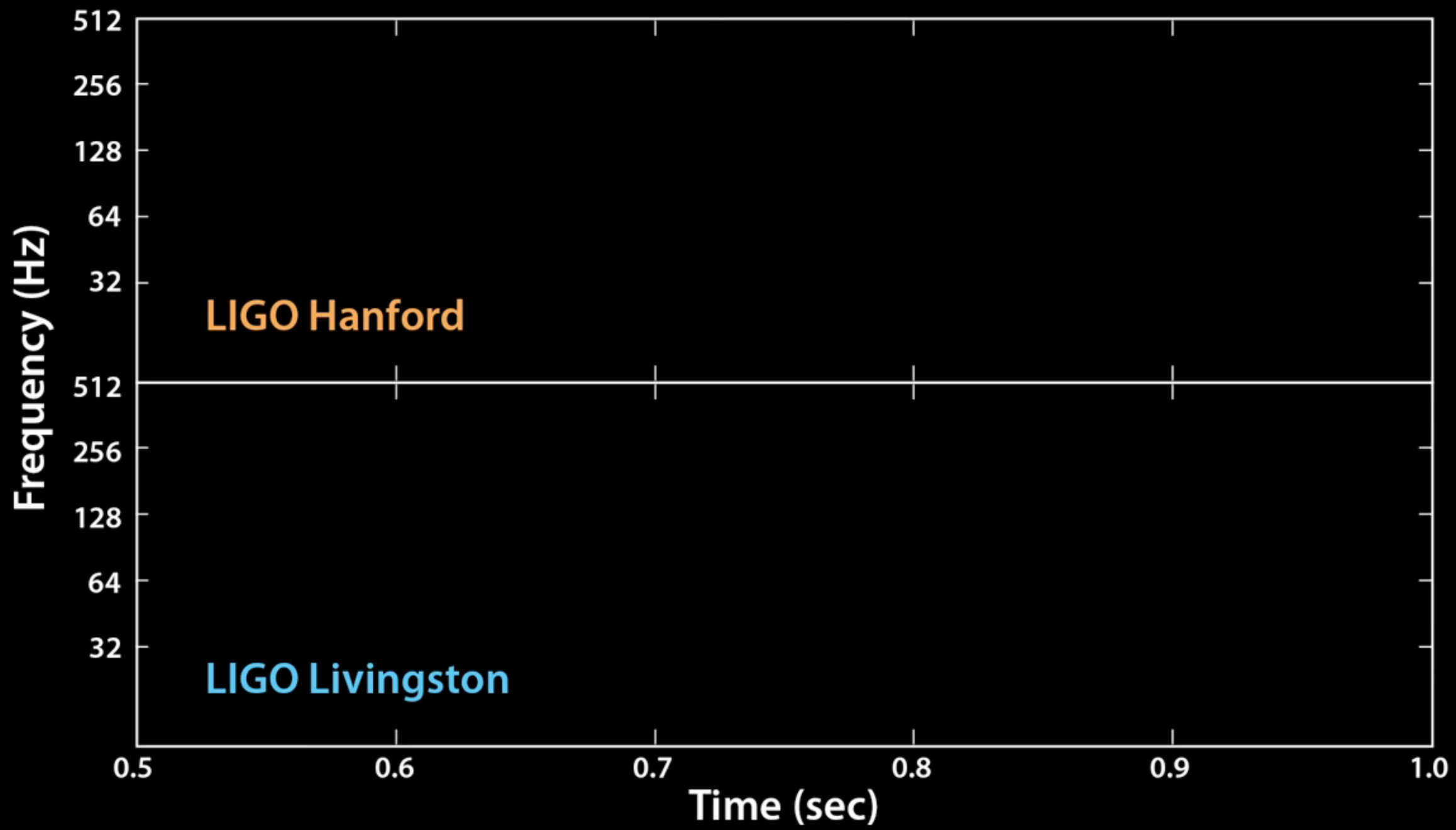


The data are dominated by **low frequency noise**; there is no way to see a signal here, without some signal processing.

There are very low frequency oscillations that are putting the mean of the L1 strain at -2.0e-18 at the time around this event, so it appears offset from the H1 strain. These low frequency oscillations are essentially ignored in LIGO data analysis (see bandpassing, below).

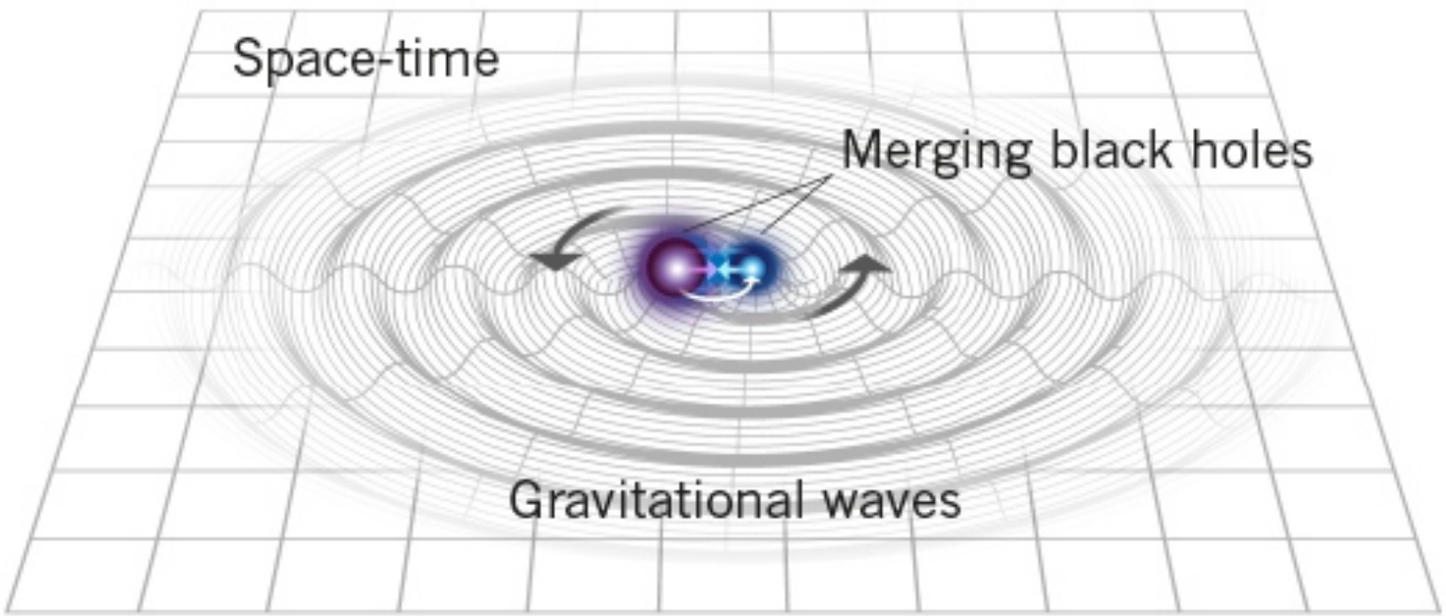
GW150914 data release – losc.ligo.org

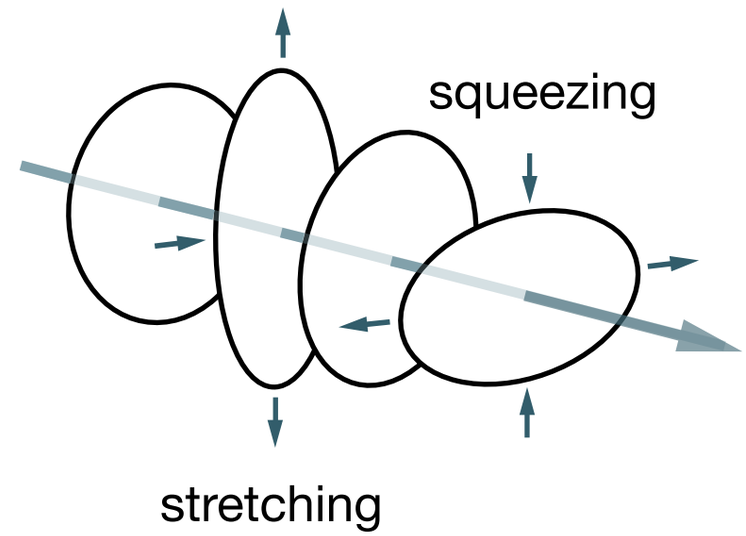
[LVC 2016]



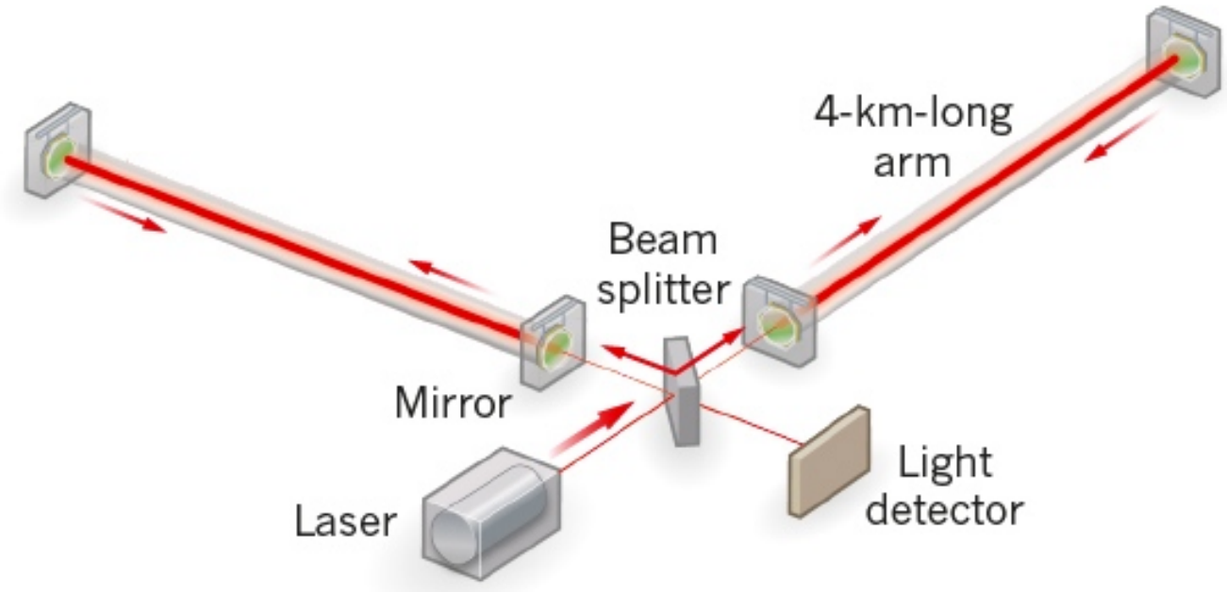
GW150914: GW strain to sound

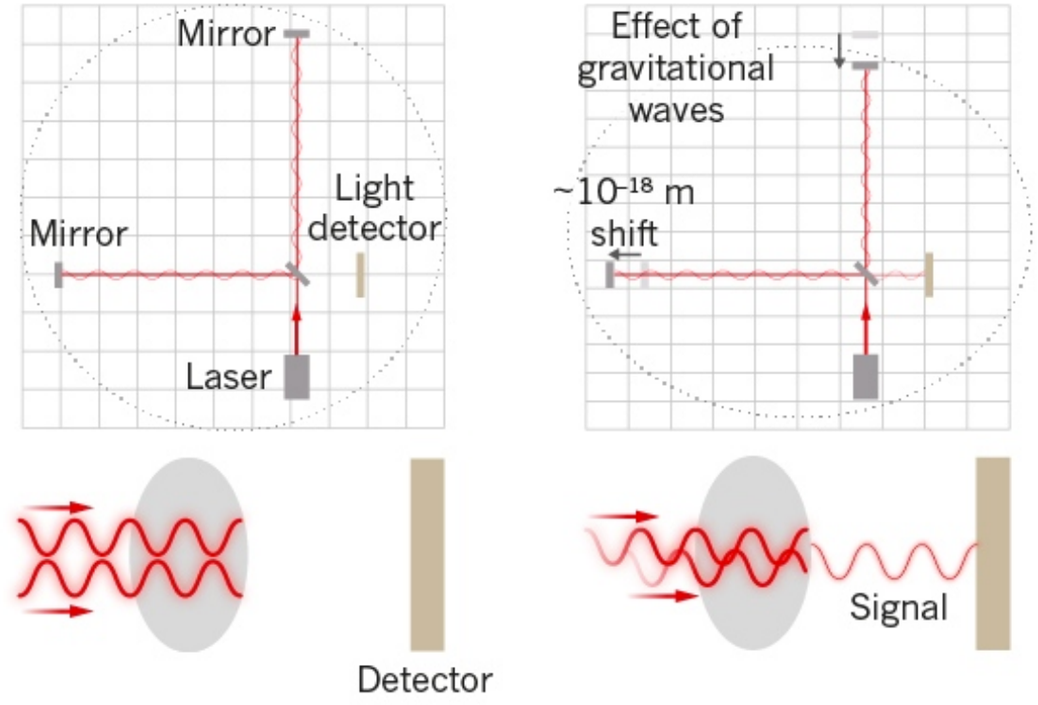
[LVC 2016]





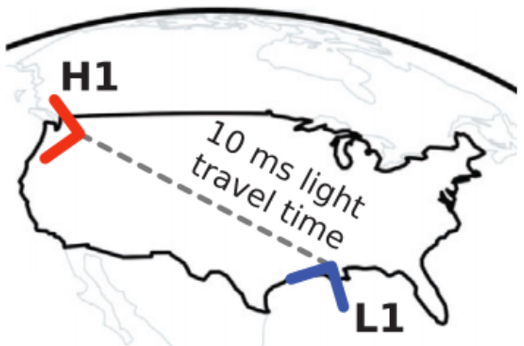
$$\Box \bar{h}^{\alpha\beta} = -16\pi\tau^{\alpha\beta}$$

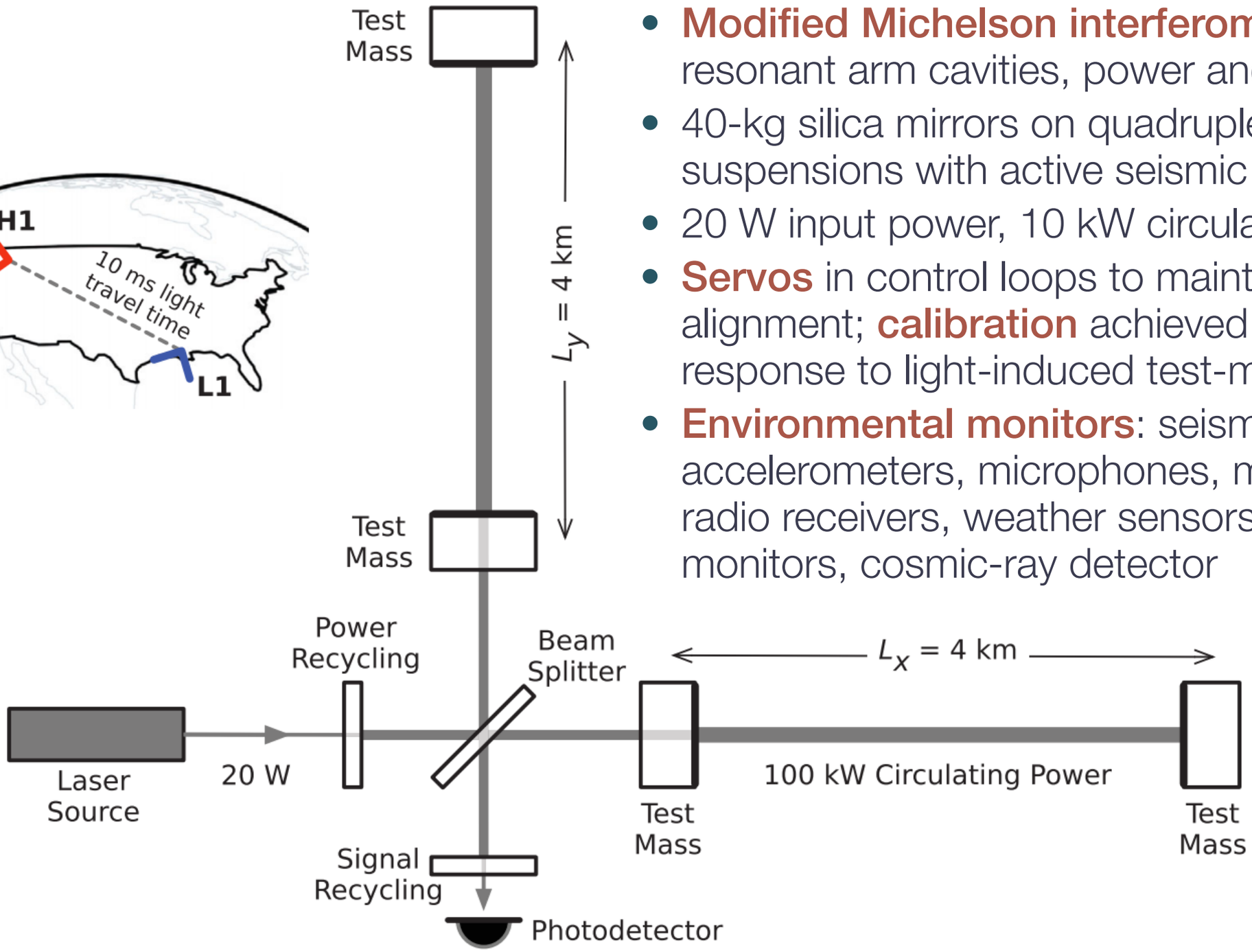




Gravitational waves and their detection

[Nature 2016]

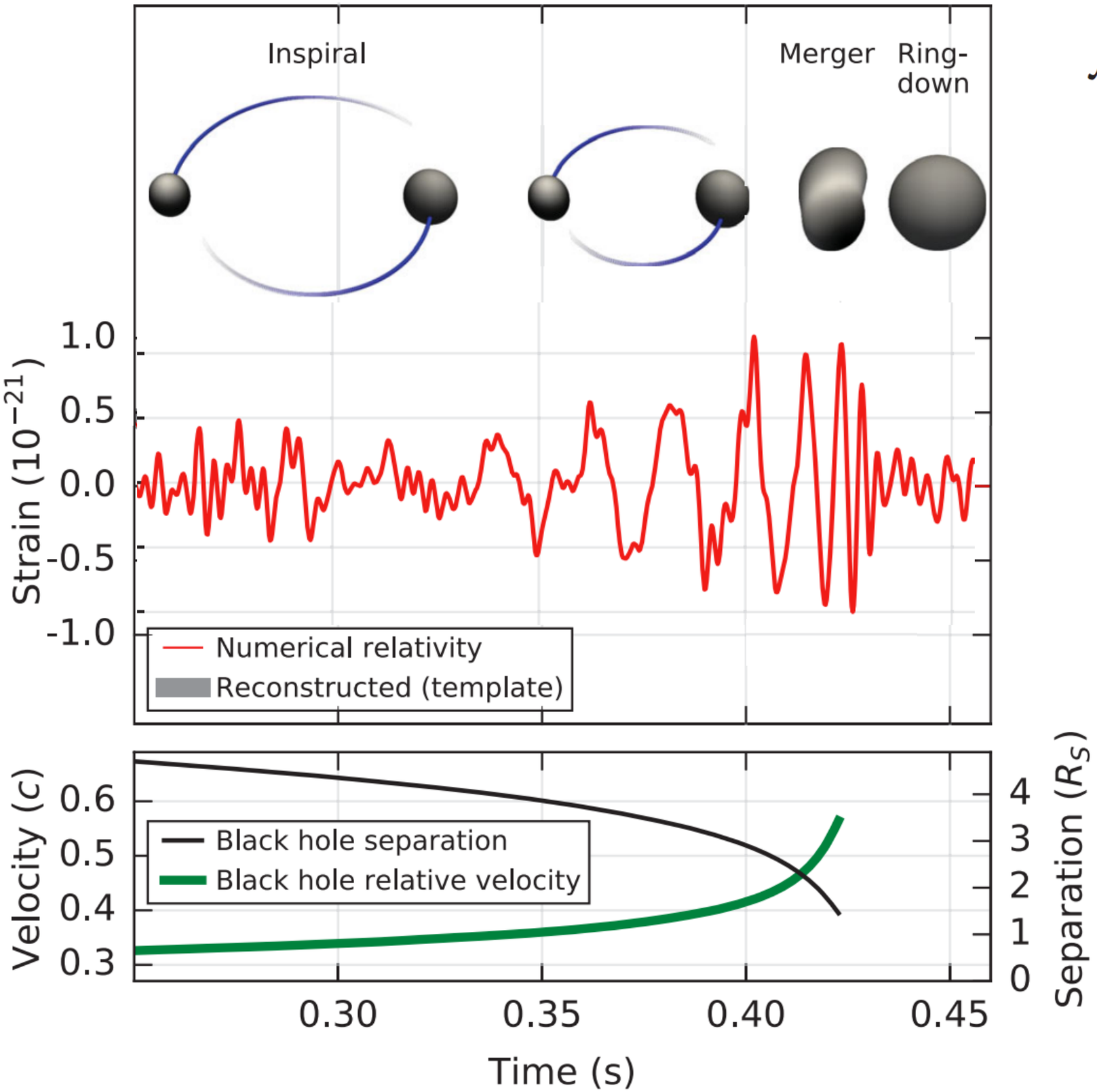




- **Modified Michelson interferometer** with ~300x resonant arm cavities, power and signal recycling
- 40-kg silica mirrors on quadruple-pendulum suspensions with active seismic isolation
- 20 W input power, 10 kW circulating
- **Servos** in control loops to maintain resonance and alignment; **calibration** achieved by measuring response to light-induced test-mass motion
- **Environmental monitors**: seismometers, accelerometers, microphones, magnetometers, radio receivers, weather sensors, ac-power line monitors, cosmic-ray detector

The LIGO observatories

[LVC 2016]

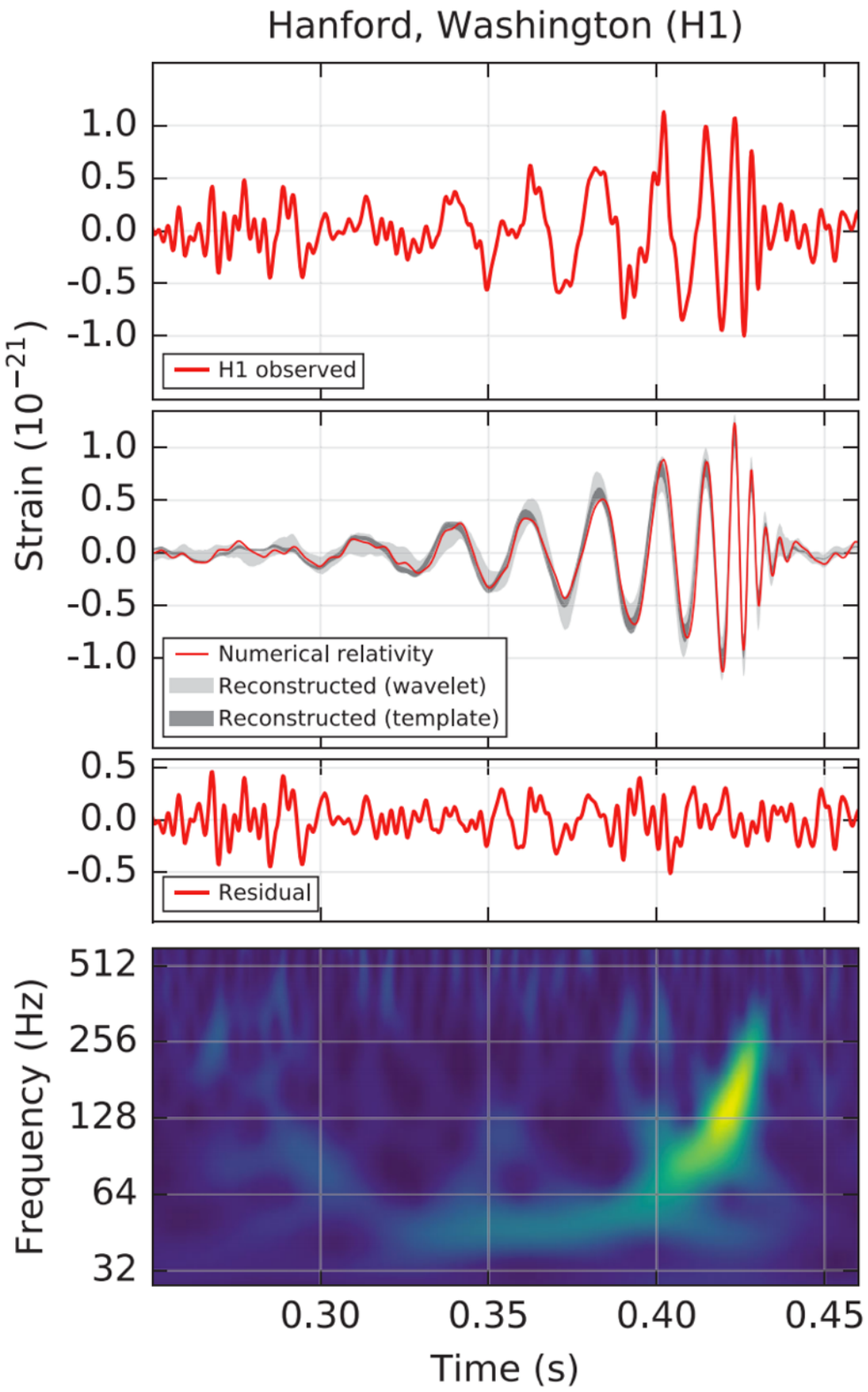


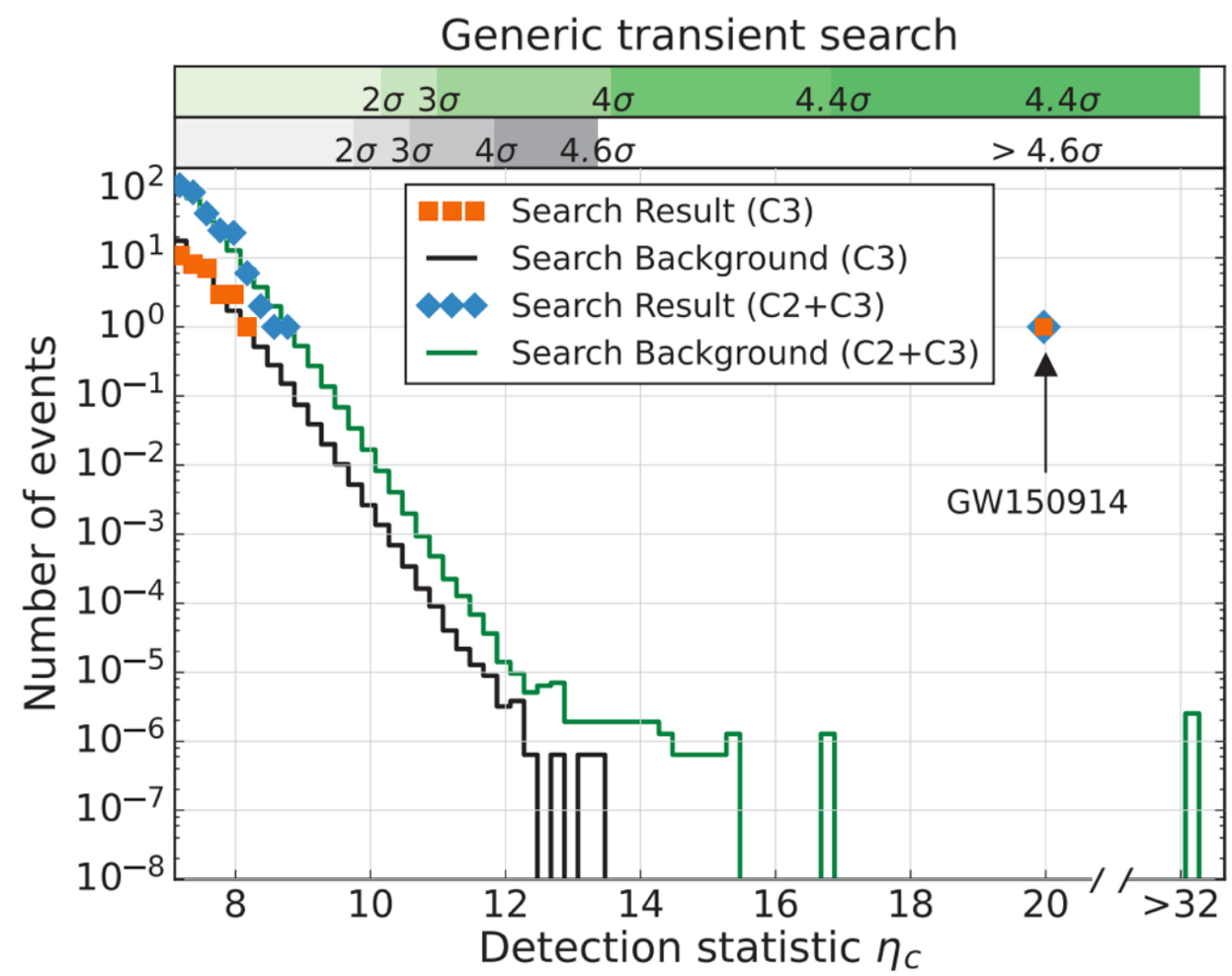
$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$

$$= \frac{c^3}{G}\left[\frac{5}{96}\pi^{-8/3} f^{-11/3}\dot{f}\right]^{3/5}$$

GW150914: inspiral, merger, and ringdown

[LVC 2016]

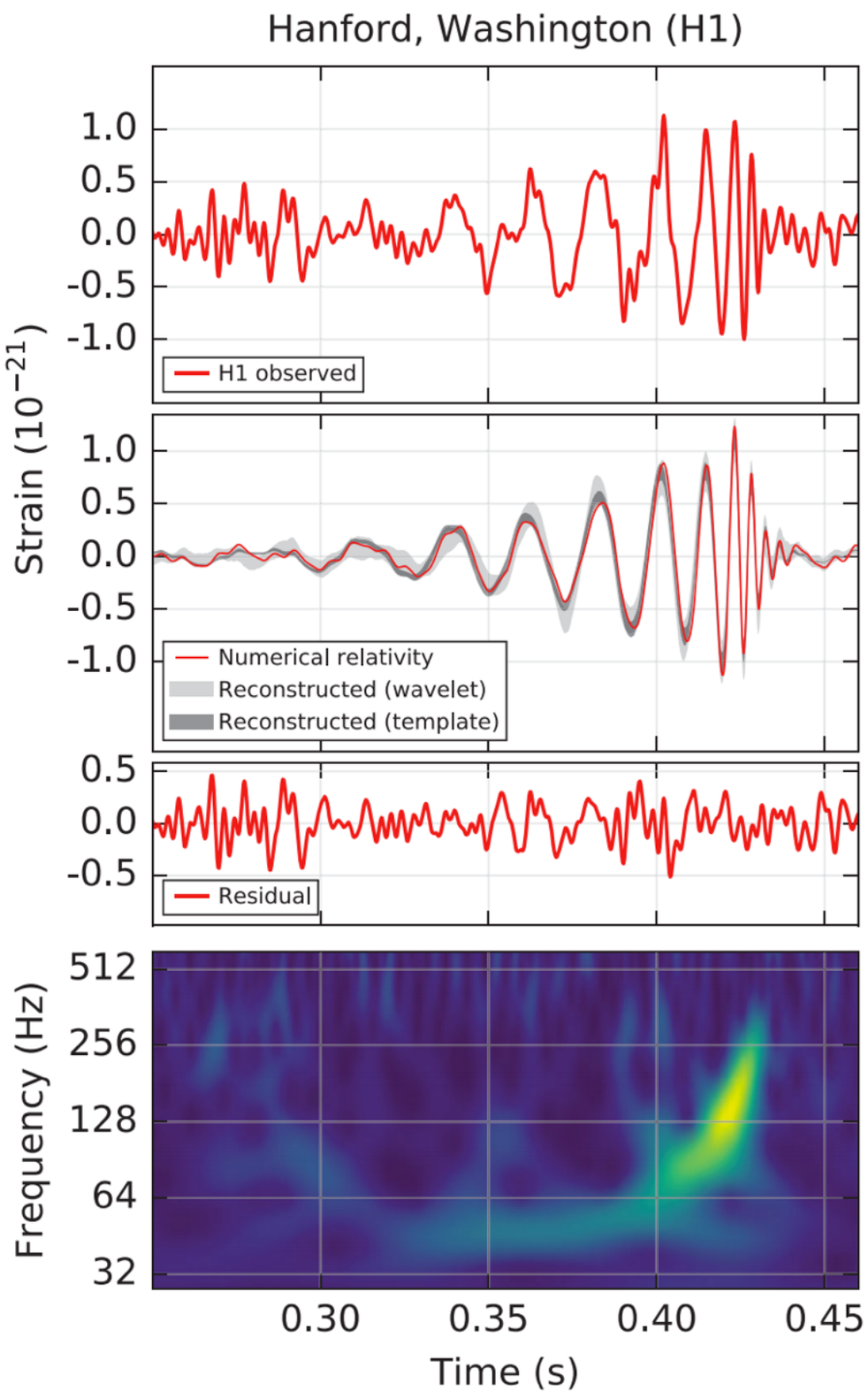


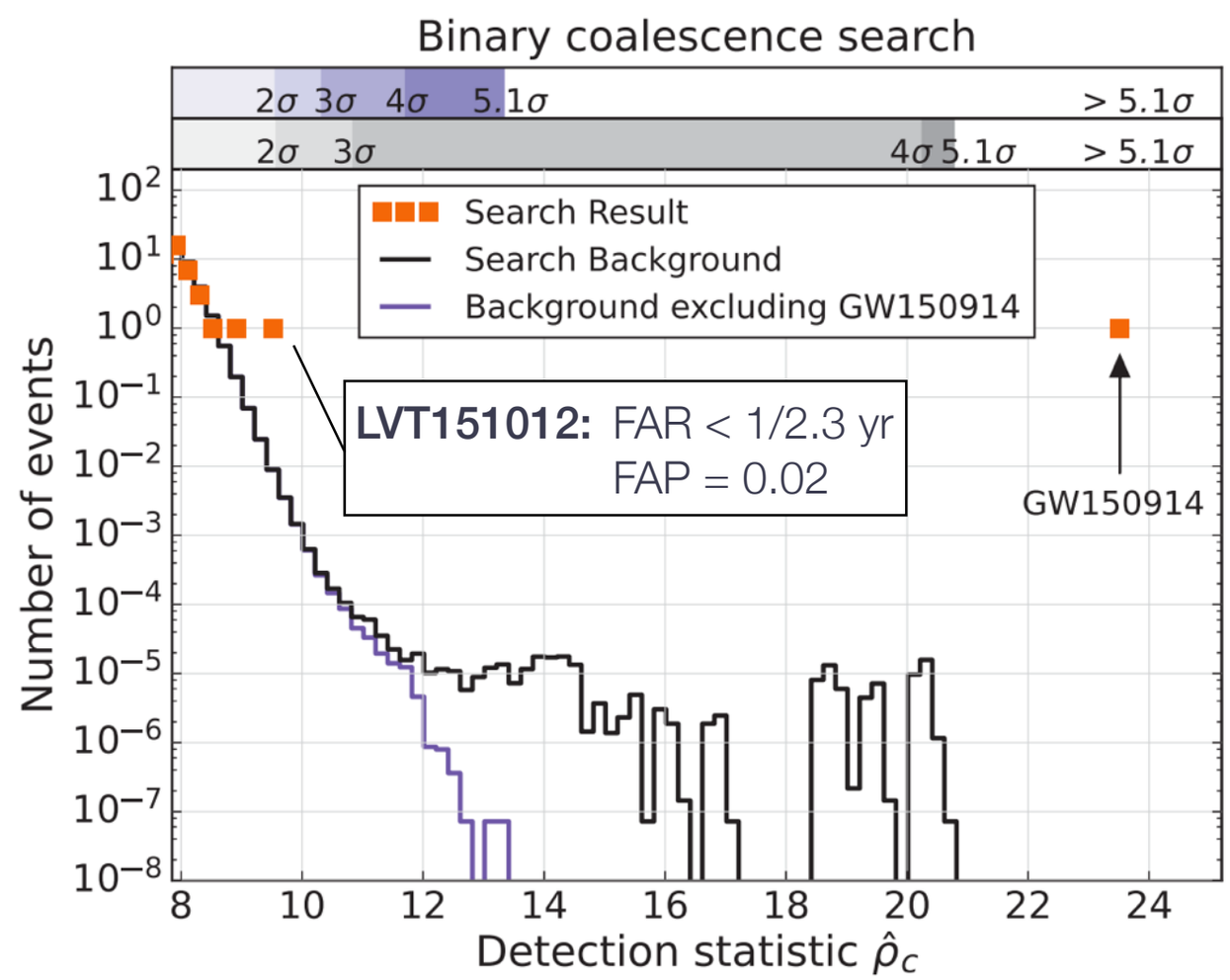


- **C1**: known noise transients; **C3**: chirps; **C2**: everything else
- Measured on 67,400-yr background, false-alarm rate < 1 in 22,500 yr (2×10^{-6} false alarm = 4.6σ)

GW150914: burst search

[LVC 2016]

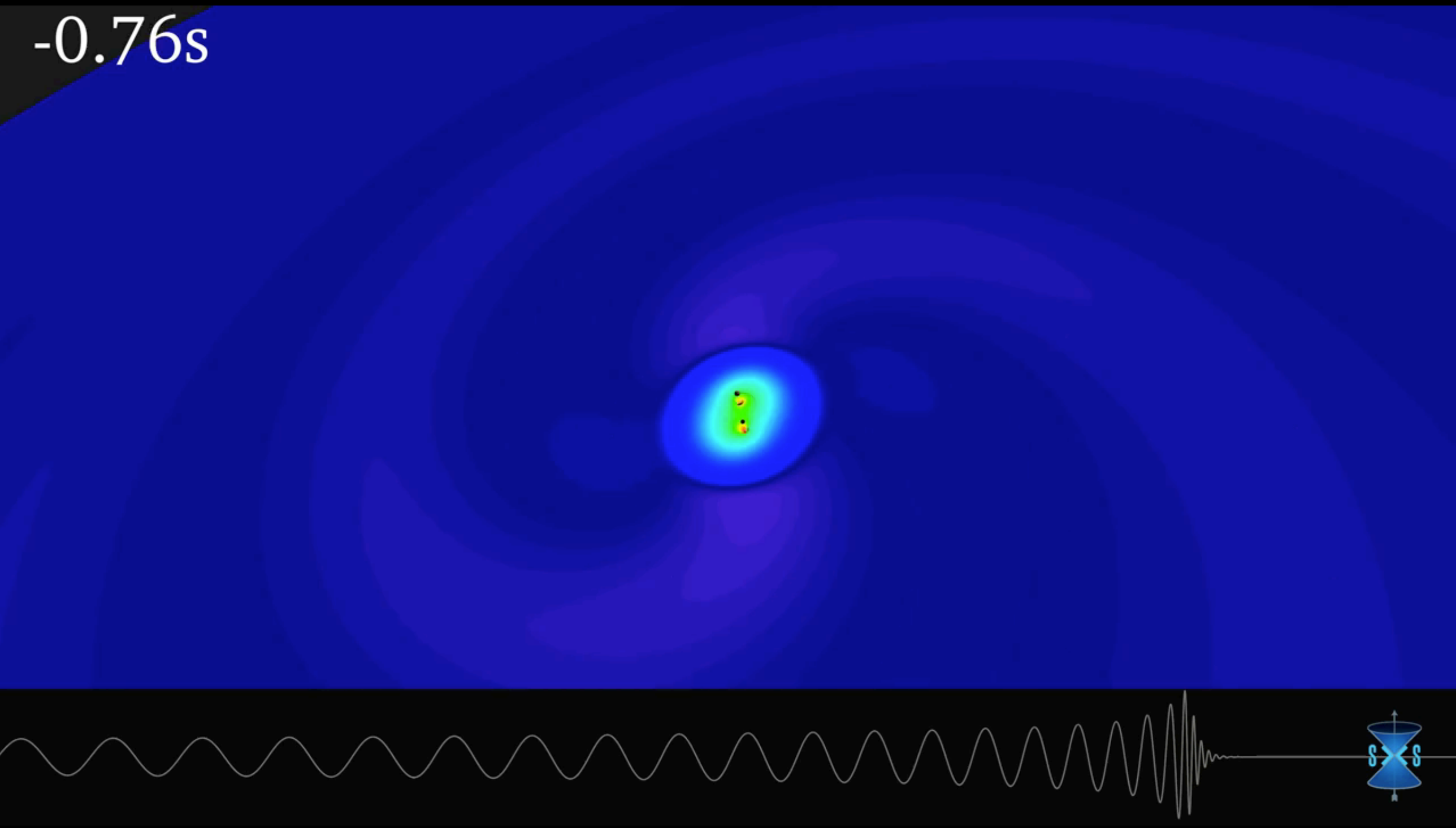




- Binaries with masses 1–99 M⊙, total mass < 100 M⊙, dimensionless spin < 0.99
- 250,000 PN and EOB signal templates. Matched-filter SNR + χ^2 statistic
- Measured on 608,000-yr background, false-alarm rate < 1 in 203,000 yr (2×10^{-7} false alarm = 5.1σ)

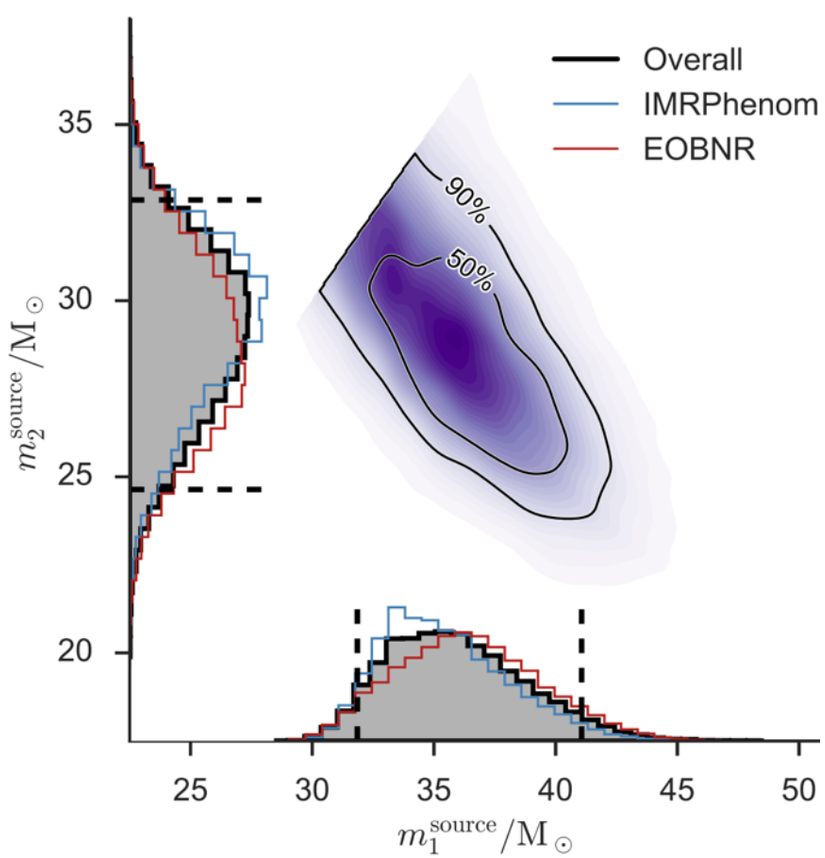
GW150914: matched-filter inspiral search

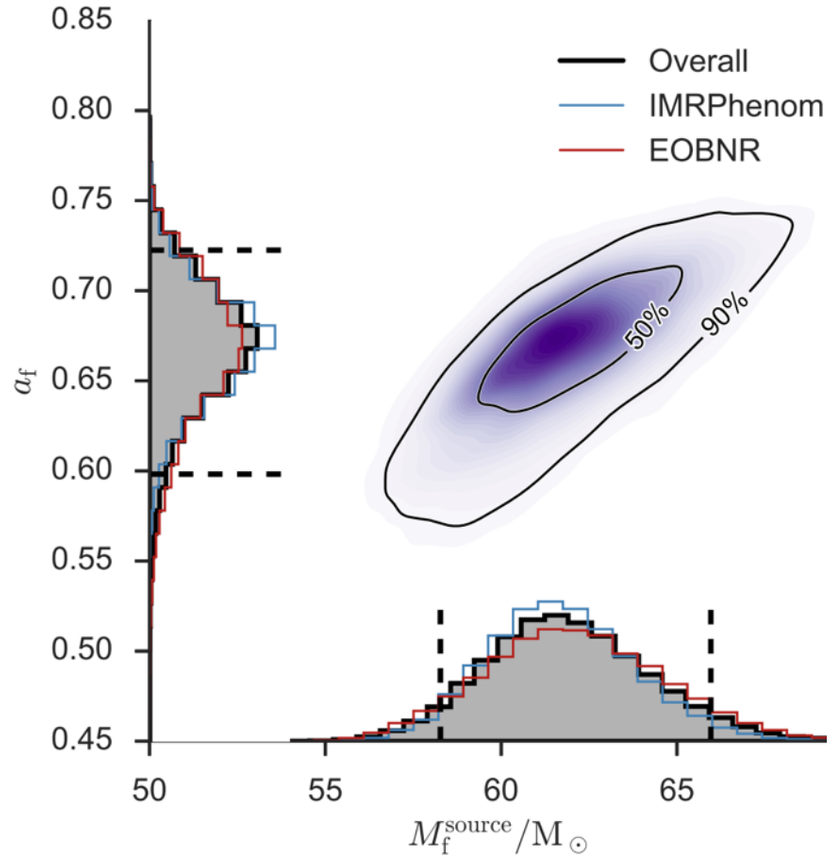
[LVC 2016]

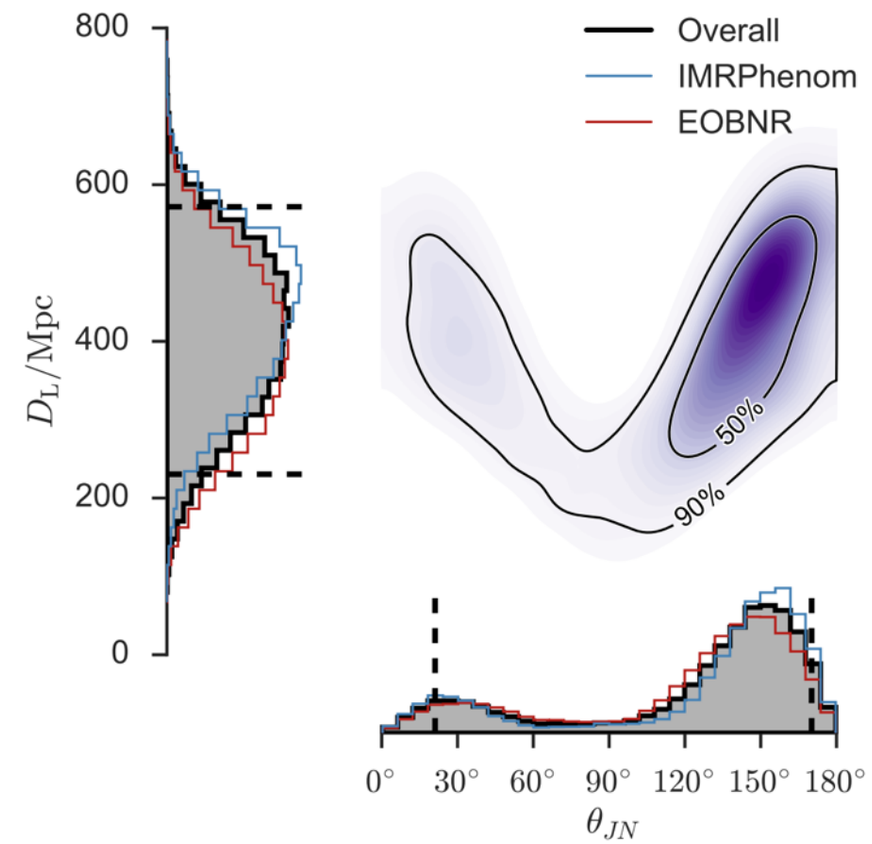


GW150914: numerical relativity simulation

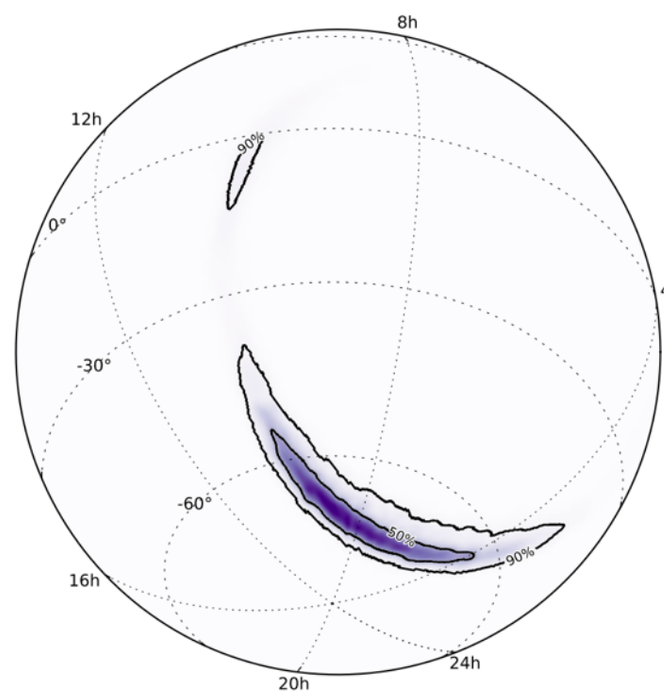
[SXS collaboration 2016]

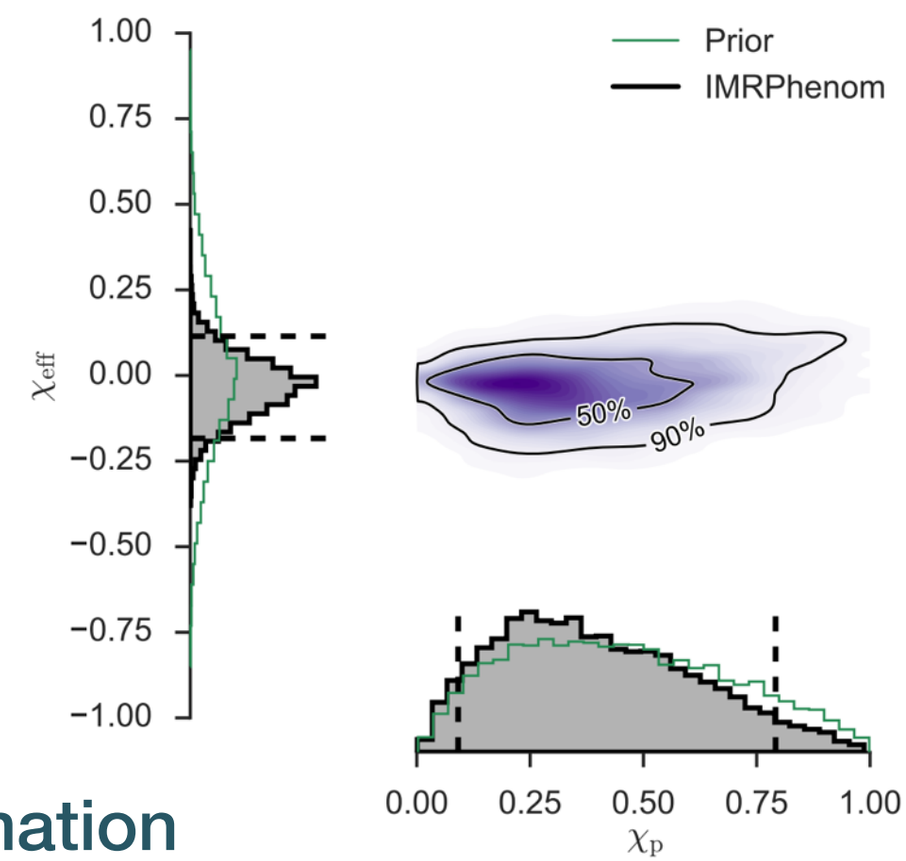






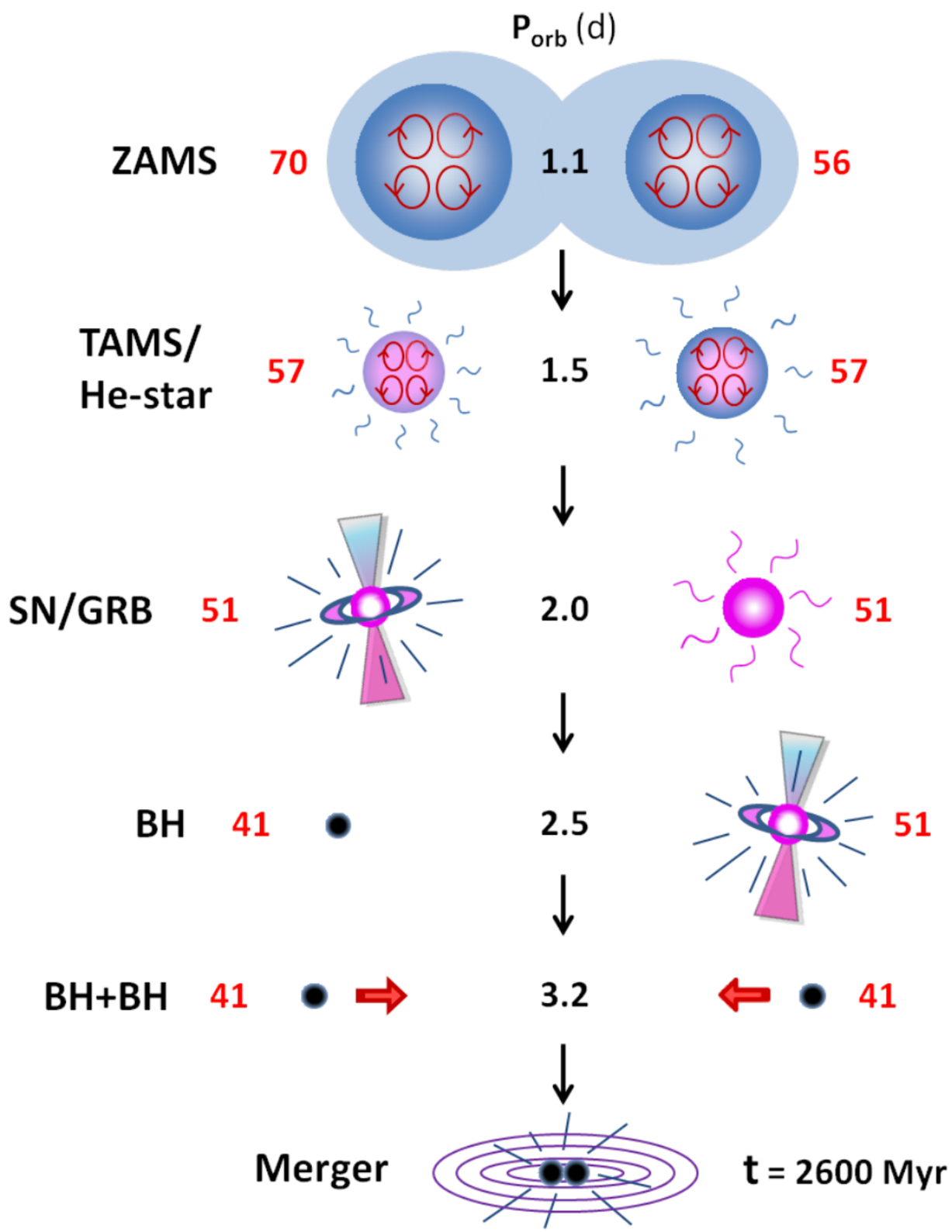
Primary black hole mass	$36^{+5}_{-4} M_\odot$
Secondary black hole mass	$29^{+4}_{-4} M_\odot$
Final black hole mass	$62^{+4}_{-4} M_\odot$
Final black hole spin	$0.67^{+0.05}_{-0.07}$
Luminosity distance	410^{+160}_{-180} Mpc
Source redshift z	$0.09^{+0.03}_{-0.04}$





GW150914: parameter estimation

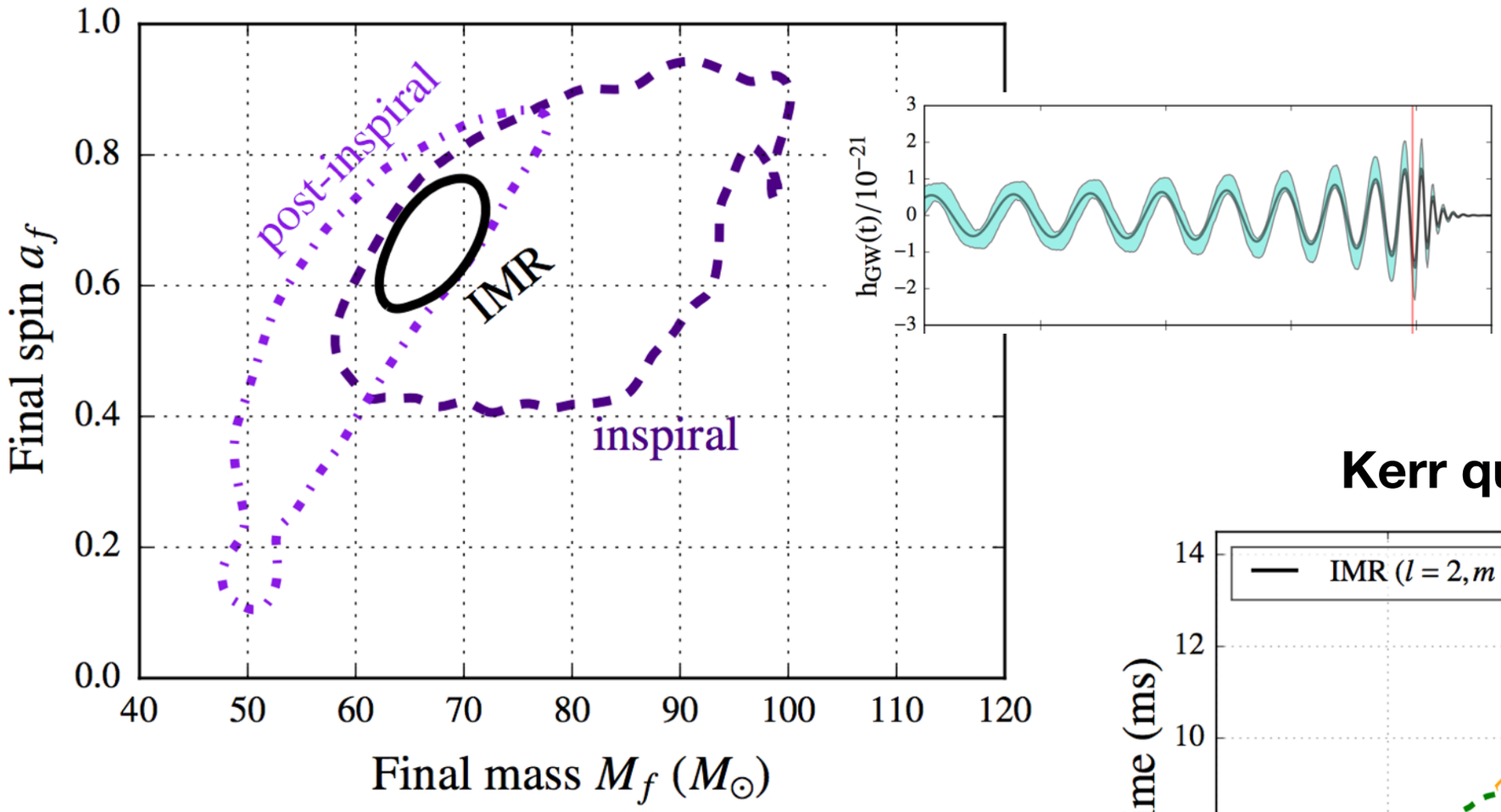
[LVC 2016]



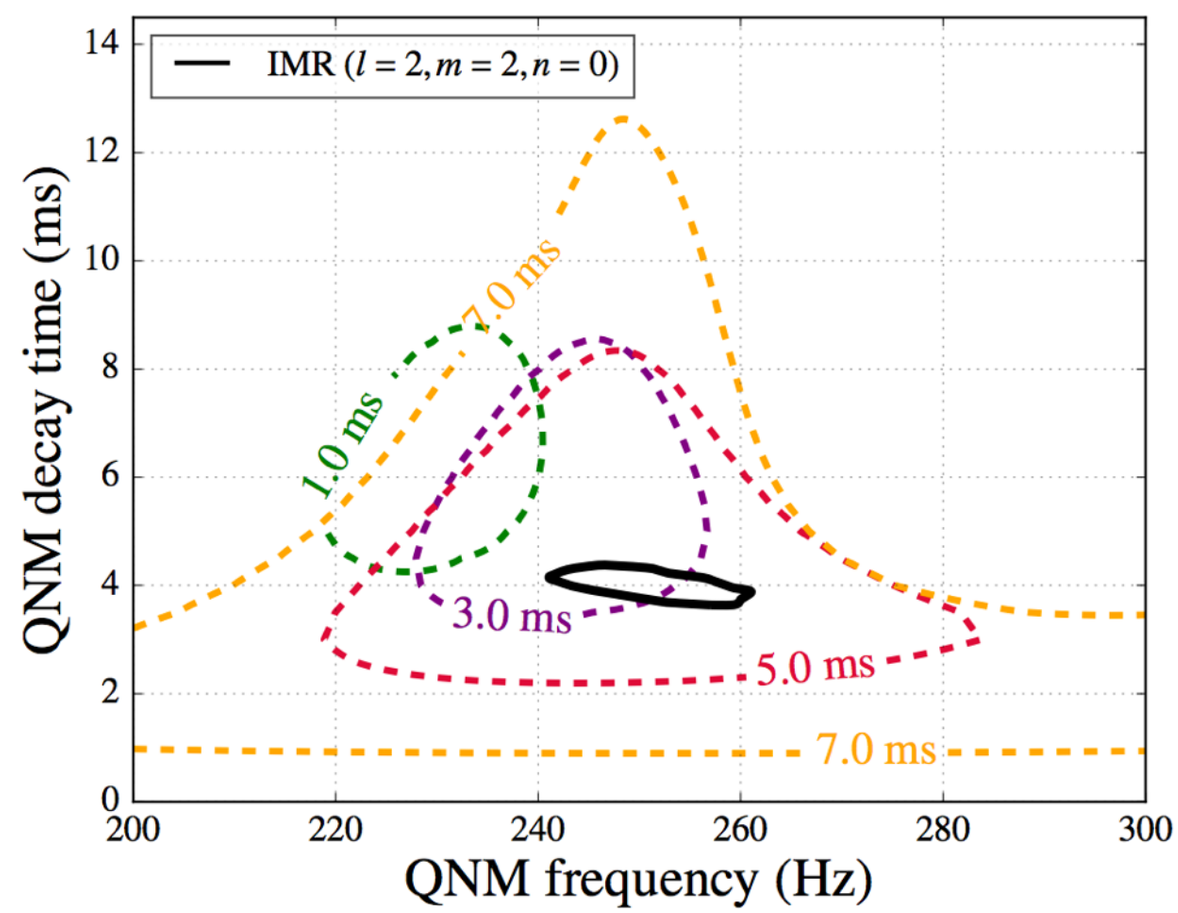
Stellar evolution toward high-mass BBH

[Marchant et al. 2016]

Inspiral vs merger–ringdown consistency



Kerr quasi-normal mode



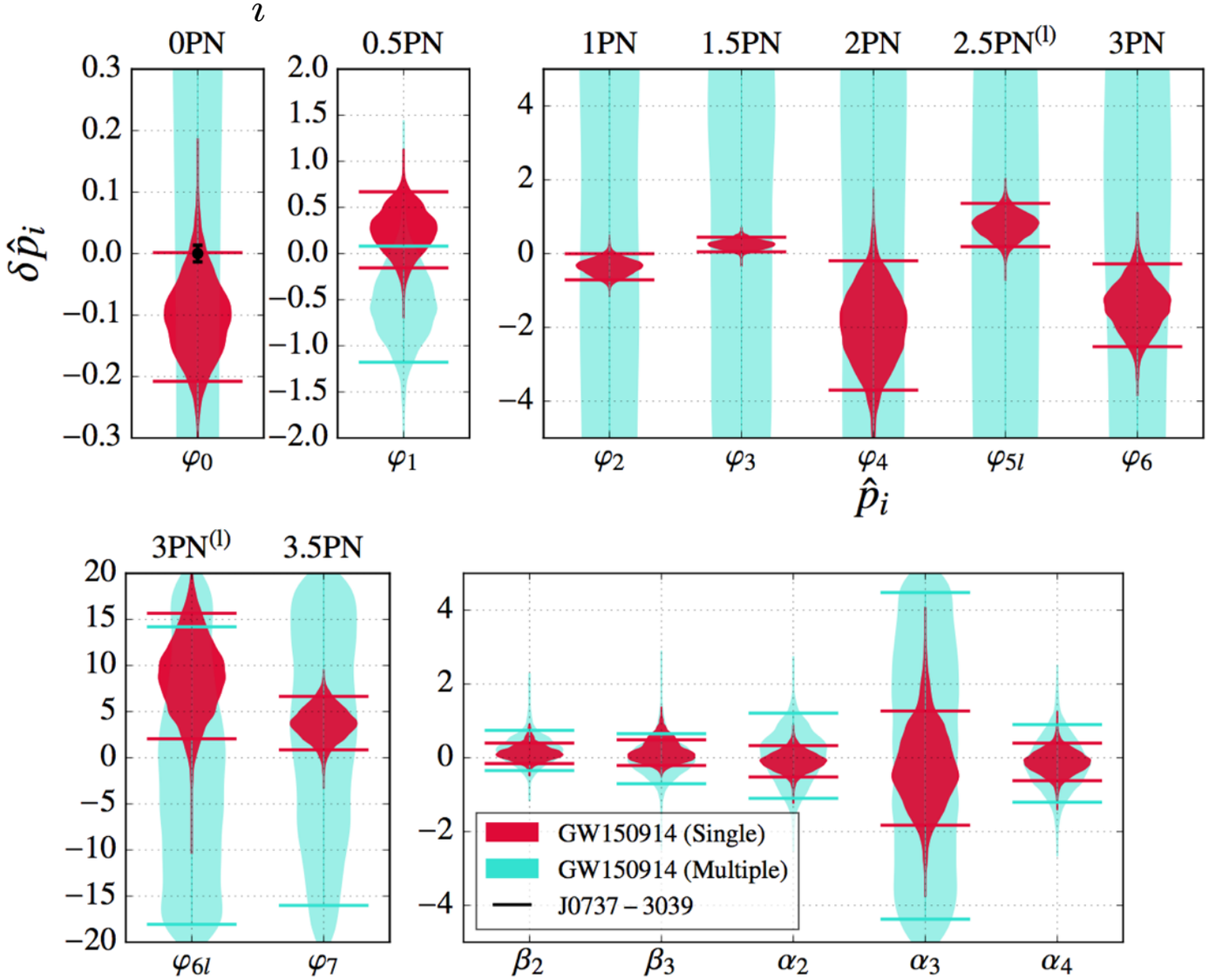
Tests of GR (I)

[LVC 2016]

Parameterized phasing coefficients

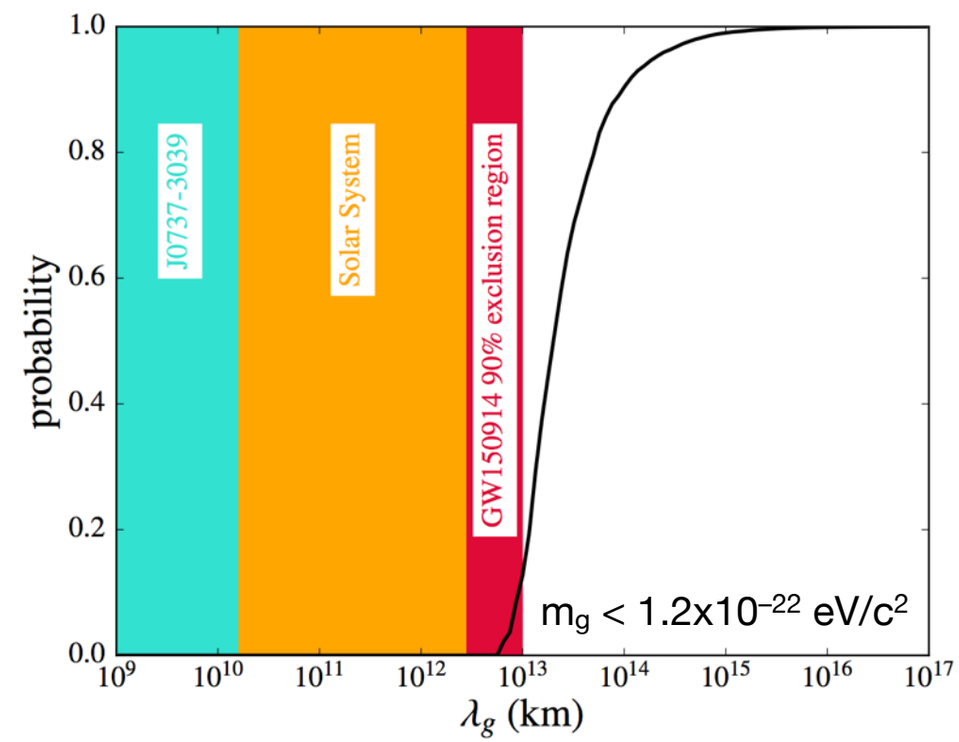
$$h(f) = \frac{1}{D}\frac{\mathcal{A}}{\sqrt{\dot{F}}} f^{2/3} e^{i\Psi(f)}$$

$$\Psi(f) = \sum_i \left[\psi_i + \psi_{il}\log f\right] f^{(i-5)/3} + \Phi^{\mathrm{MR}}[\beta_i, \alpha_i]$$



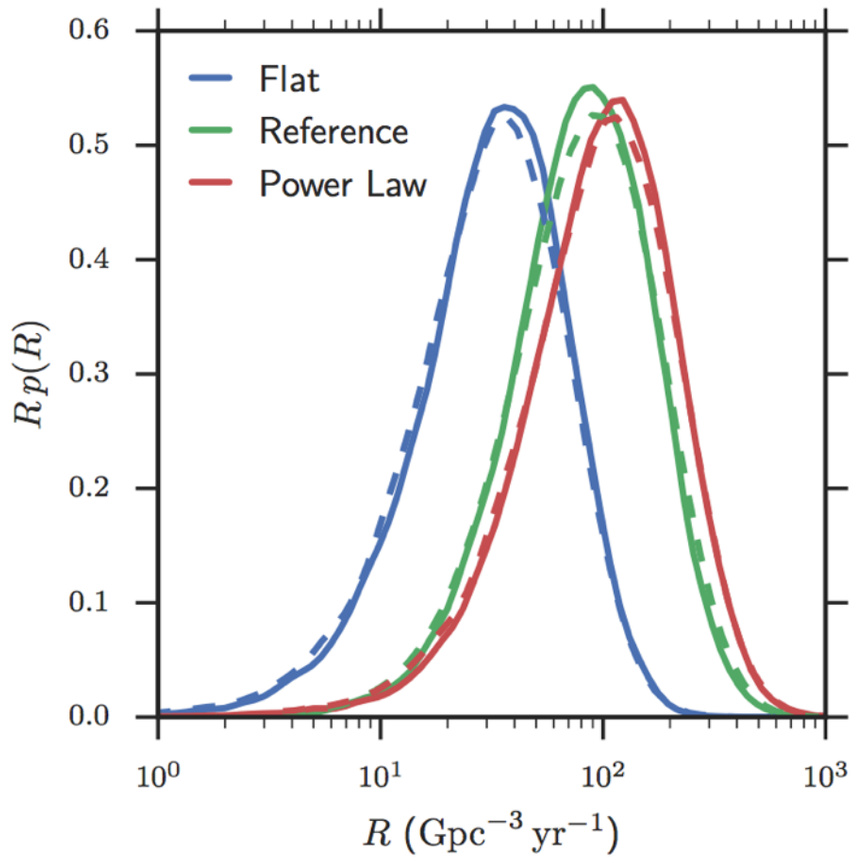
Graviton mass

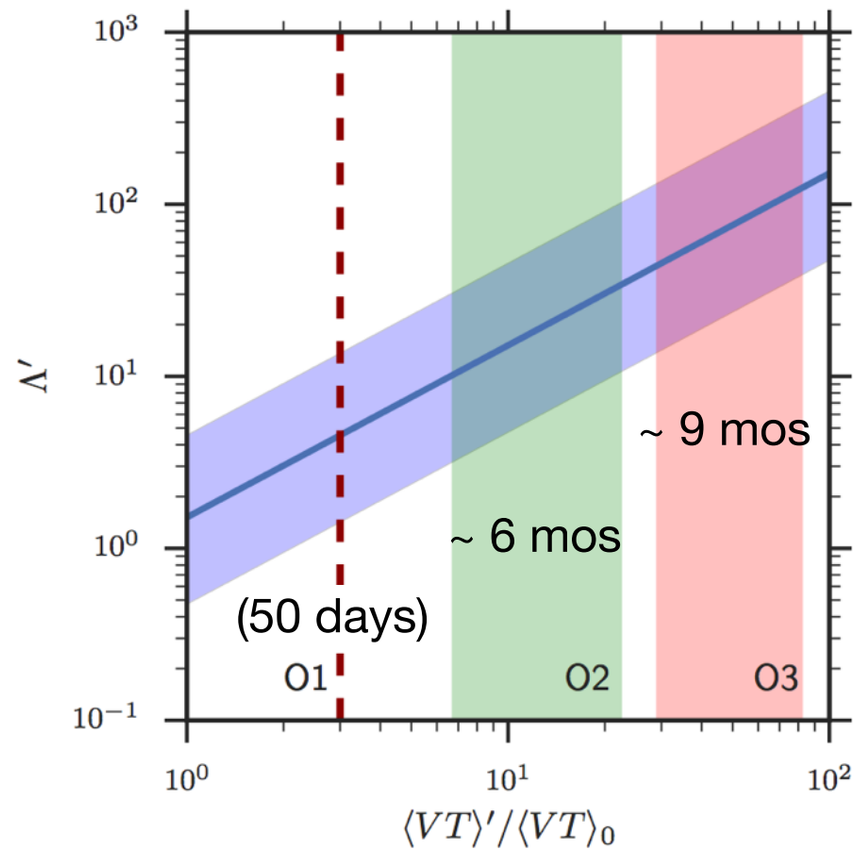
$$\delta\Psi(f) = \frac{\pi D c}{\lambda_g^2 (1+z) f}$$



Tests of GR (II)

[LVC 2016]





Mass Distribution	$R/\left(\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}\right)$		
	pycbc	**gstlal**	Combined
GW150914	16^{+38}_{-13}	17^{+39}_{-14}	17^{+39}_{-13}
LVT151012	61^{+152}_{-53}	62^{+164}_{-55}	62^{+165}_{-54}
Both	82^{+155}_{-61}	84^{+172}_{-64}	83^{+168}_{-63}
	Astrophysical		
Flat	33^{+64}_{-26}	32^{+65}_{-25}	33^{+62}_{-26}
Power Law	102^{+198}_{-79}	99^{+203}_{-79}	100^{+201}_{-79}

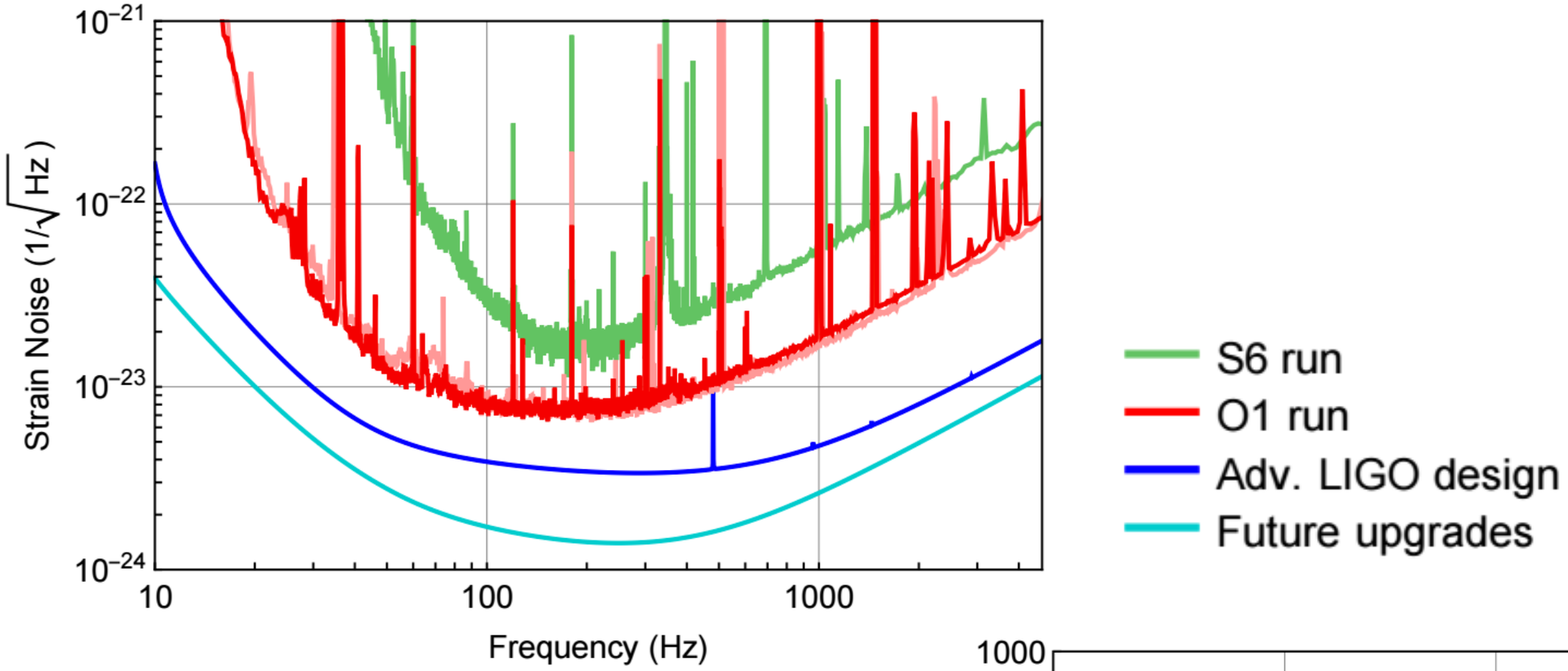
$$\mathcal{L}\left(\{x_j|j=1,\ldots,M\}\,|\Lambda_1,\Lambda_0\right) = \left\{\prod_{j=1}^{M}\left[\Lambda_1 p_1\left(x_j\right)+\Lambda_0 p_0\left(x_j\right)\right]\right\}\exp\left[-\Lambda_1-\Lambda_0\right]$$

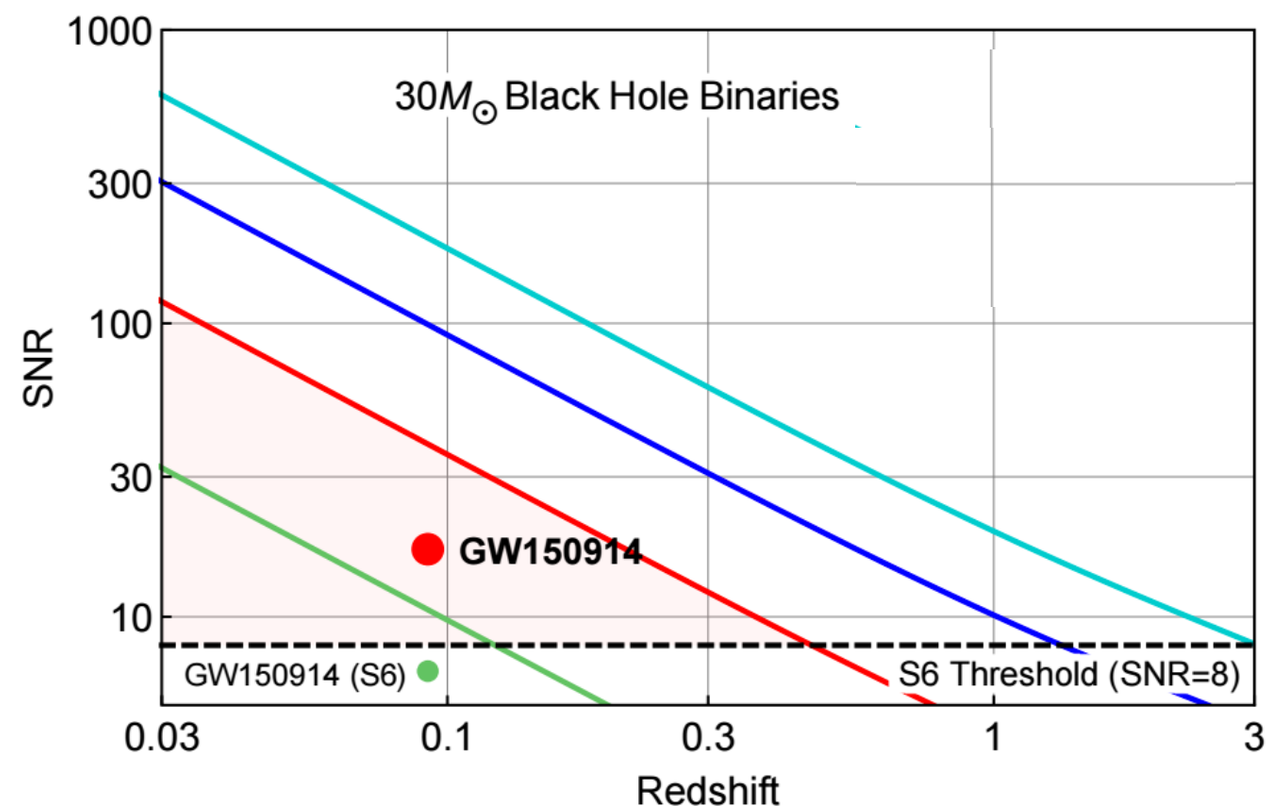
$$R_i = \Lambda_i/\langle VT\rangle$$

$$\langle VT\rangle = T\int \mathrm{d}z\,\mathrm{d}\theta\,\frac{\mathrm{d}V_c}{\mathrm{d}z}\frac{1}{1+z}s_i(\theta)f(z,\theta)$$

Inferred BBH merger rates

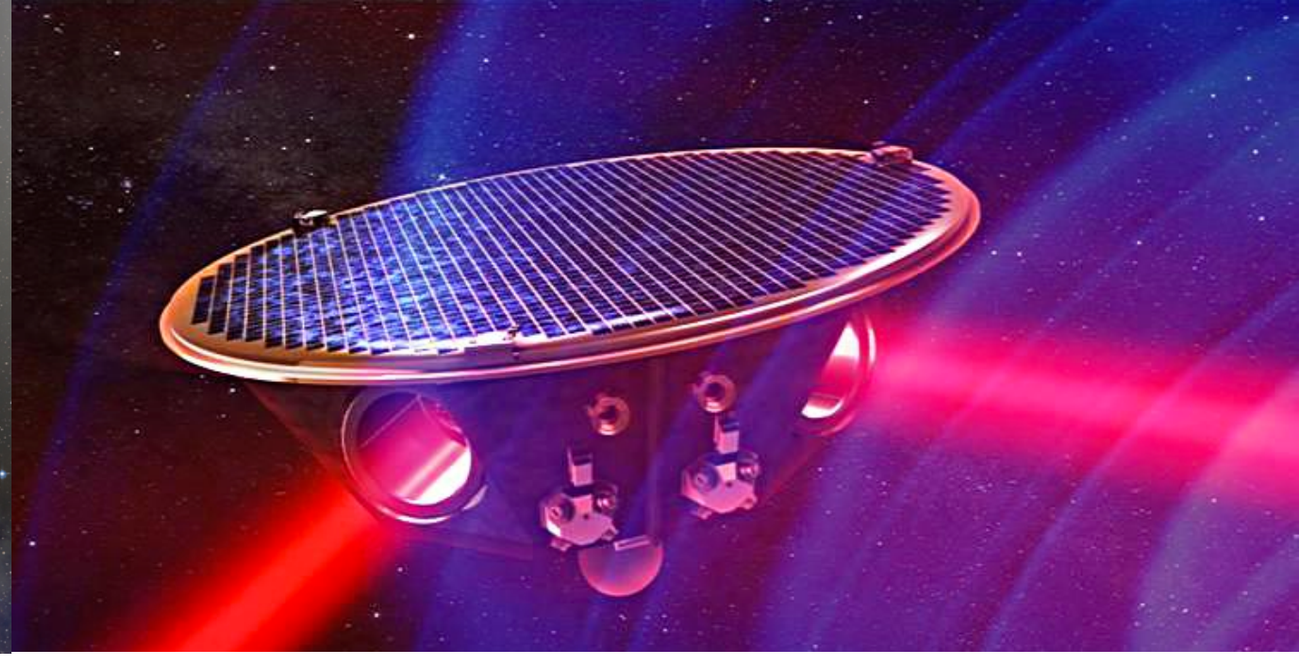
[LVC 2016]



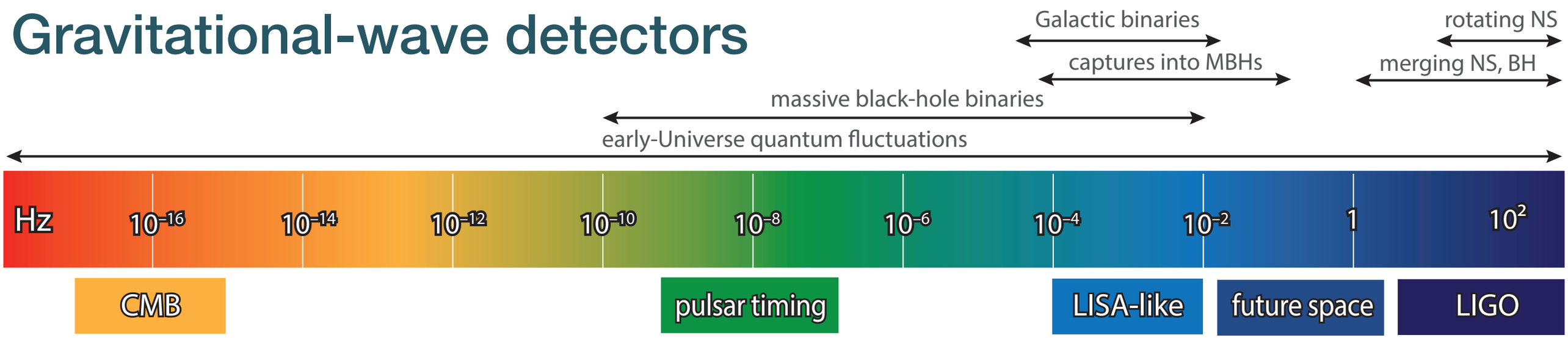


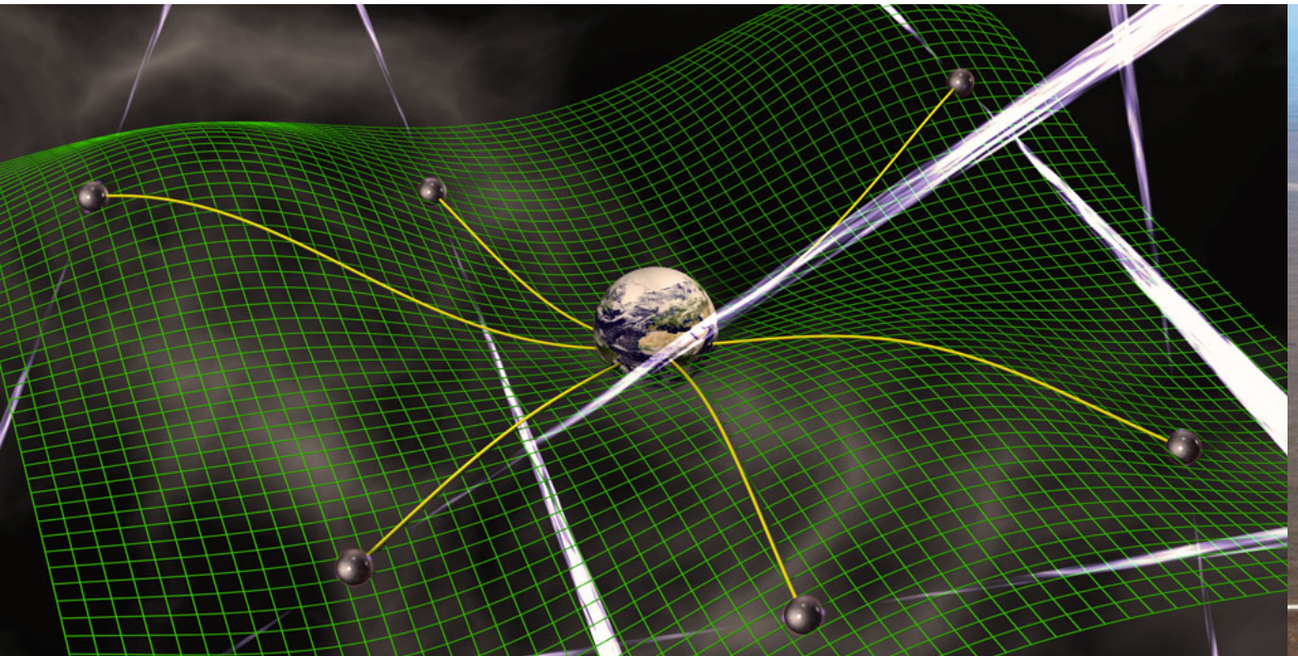
Advanced LIGO sensitivity improvements

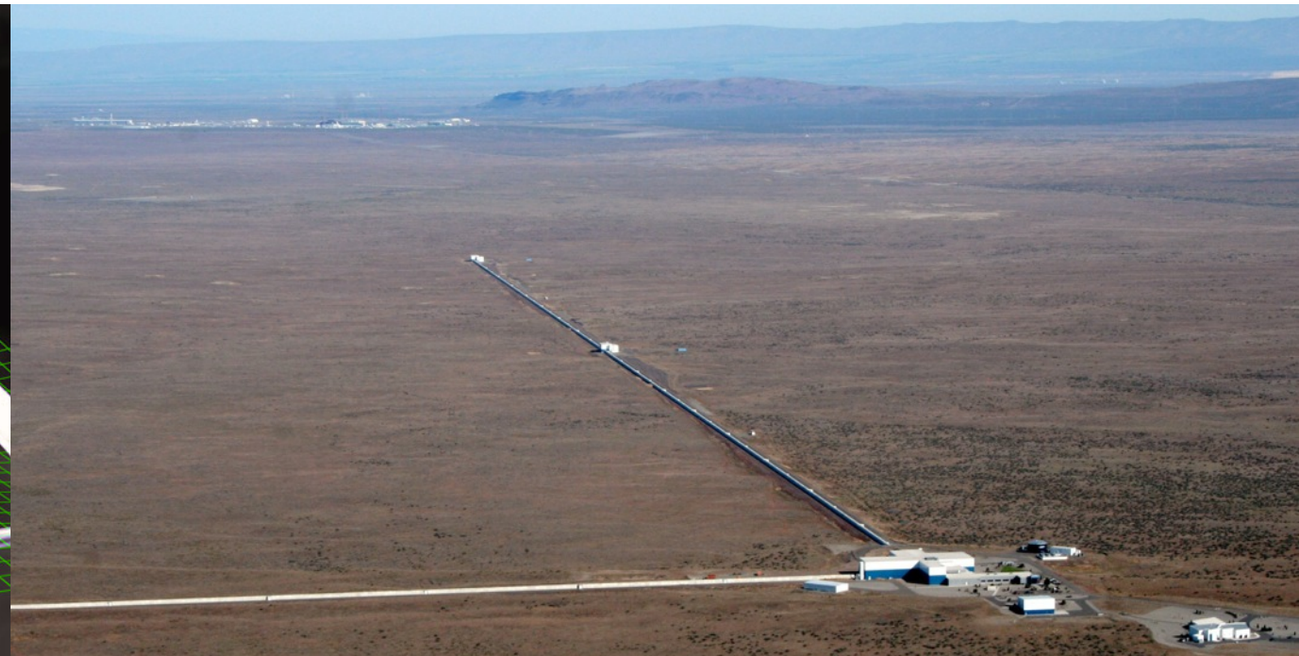
[LVC 2016]

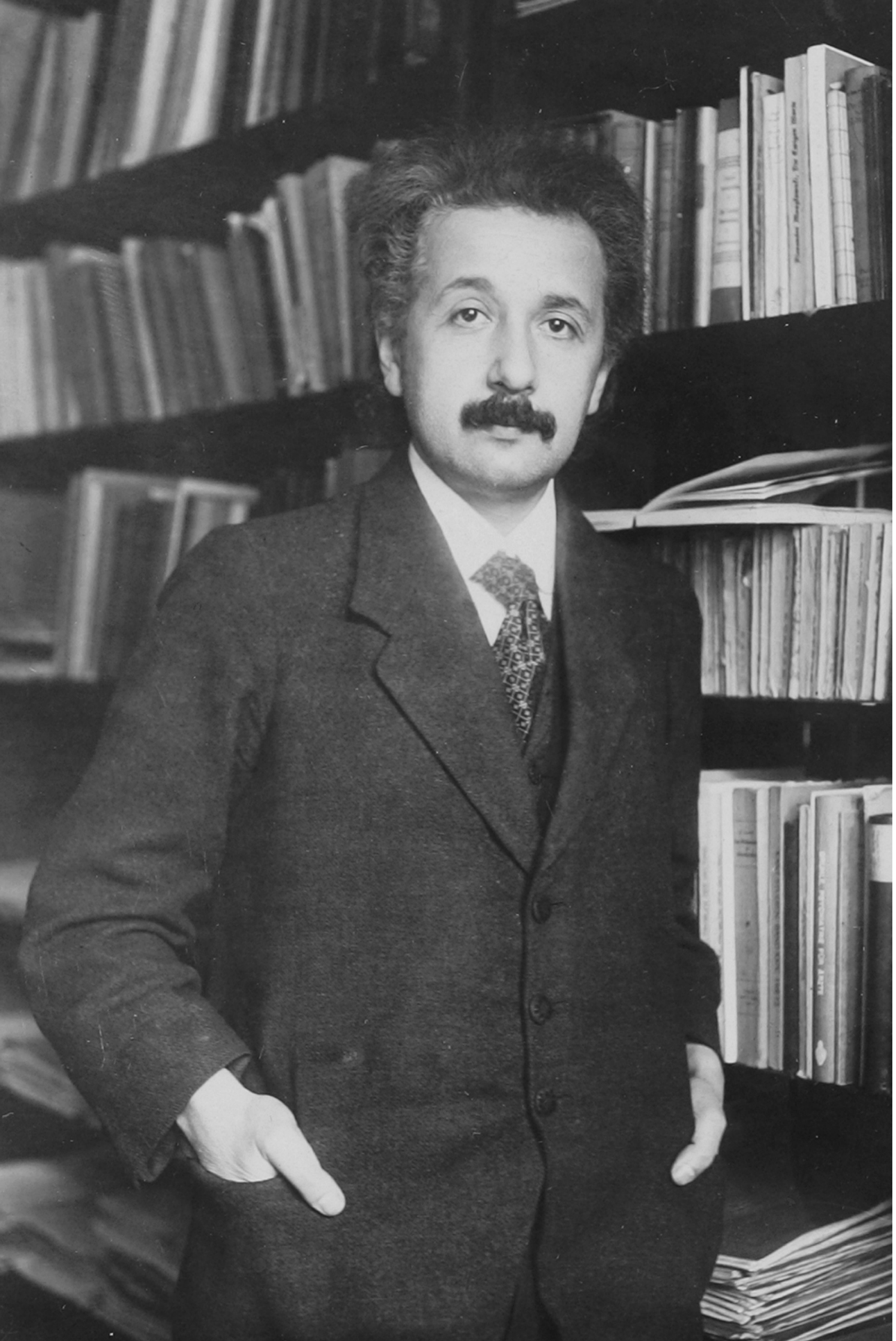


Gravitational-wave detectors









1915: GR
1916: GWs; Schwarzschild metric

1919: Eddington's expedition

1939: gravitational collapse

1957: Chapel Hill conference

1960: Weber bars

1967: "black hole", no-hair theorem

1971: Cygnus X-1
1972: GW interferometer design

1974: PSR B1913+16

1990, 1999: LIGO approved, inaugurated

2002: Sgr A* as black hole
2002–2010: initial LIGO runs

2015: aLIGO; GW150914