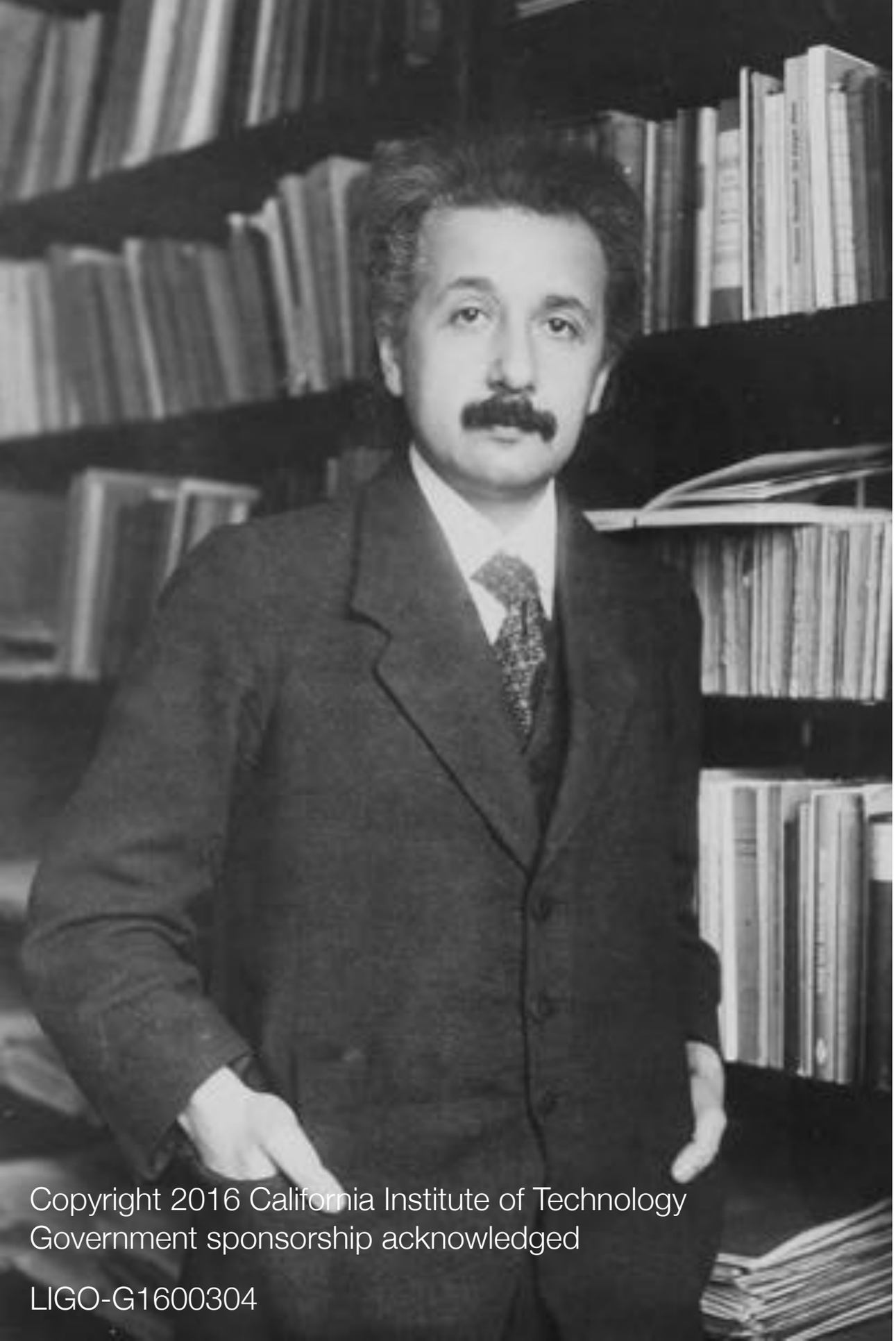


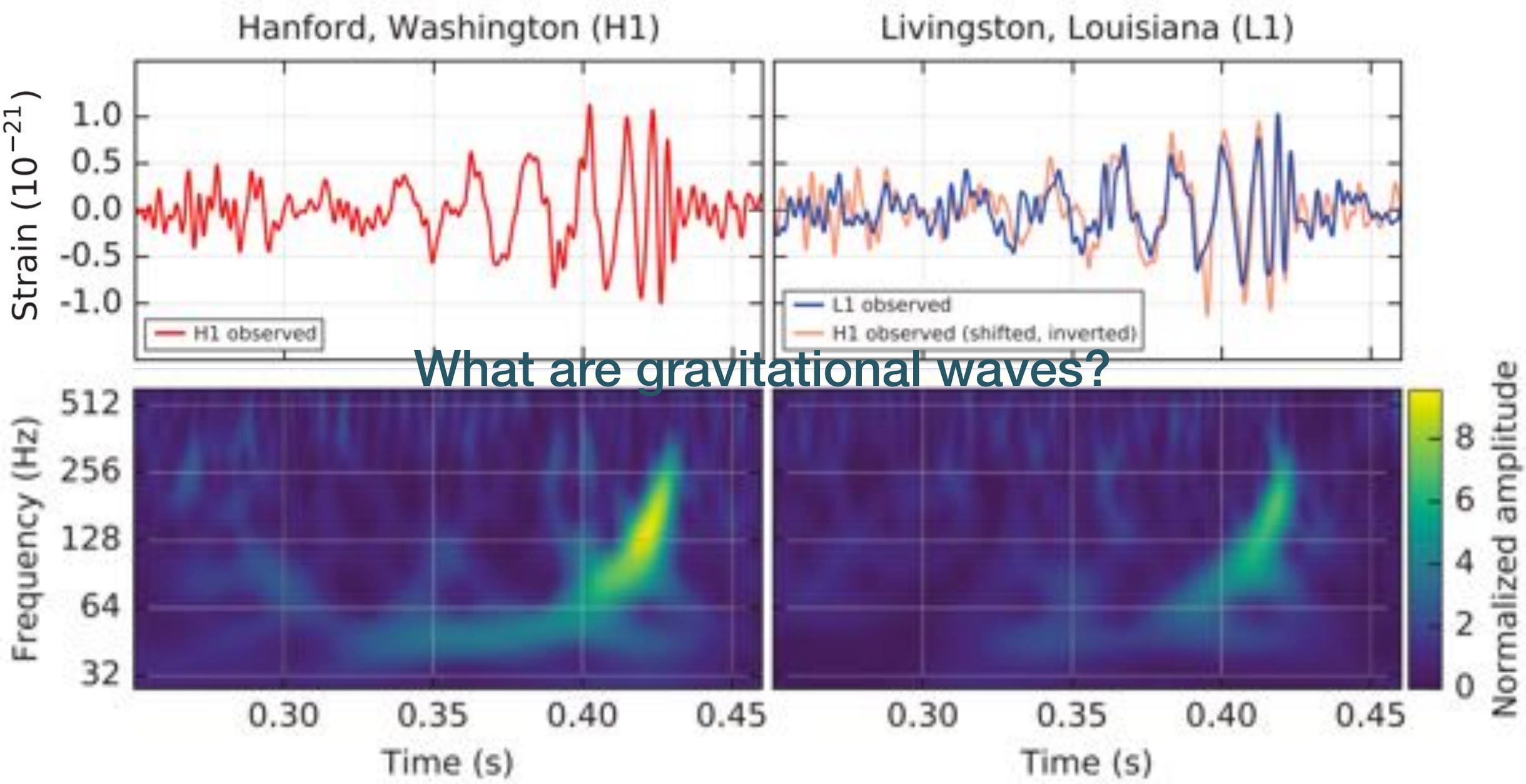
LIGO-G1600304

GW150914: LIGO's First Observation of Gravitational Waves from a Binary Black Hole Merger

Michele Vallisneri
Jet Propulsion Laboratory
California Institute of Technology

for the LIGO scientific collaboration
and the Virgo collaboration

LSC LIGO Scientific Collaboration VIRGO

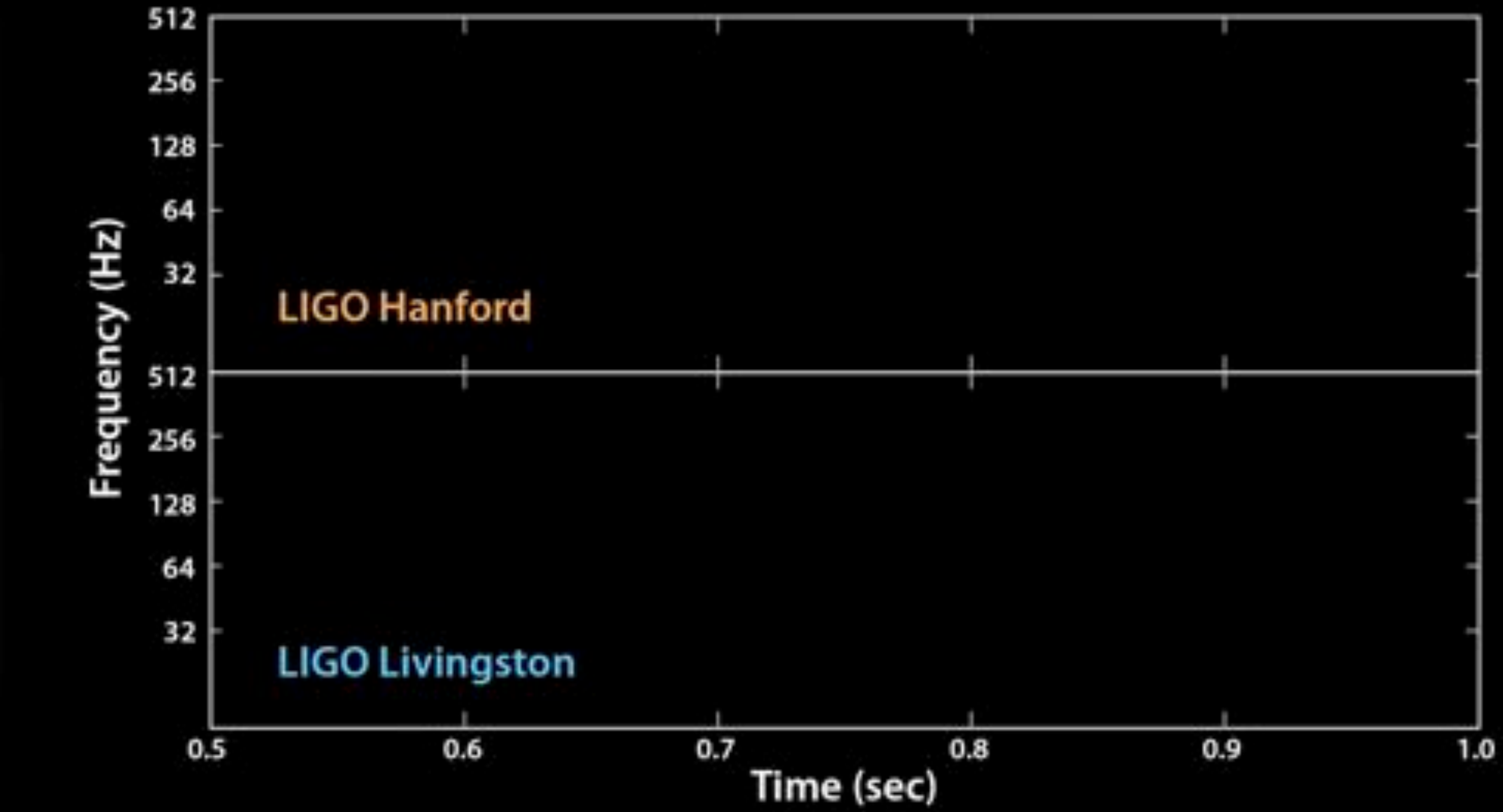


What are gravitational waves?

GW150914: detection and companion papers at papers.ligo.org

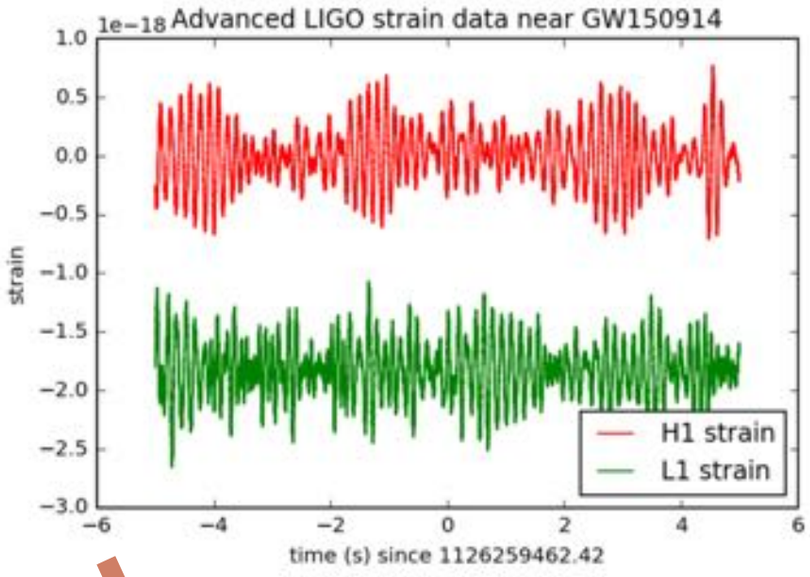
[LVC 2016]

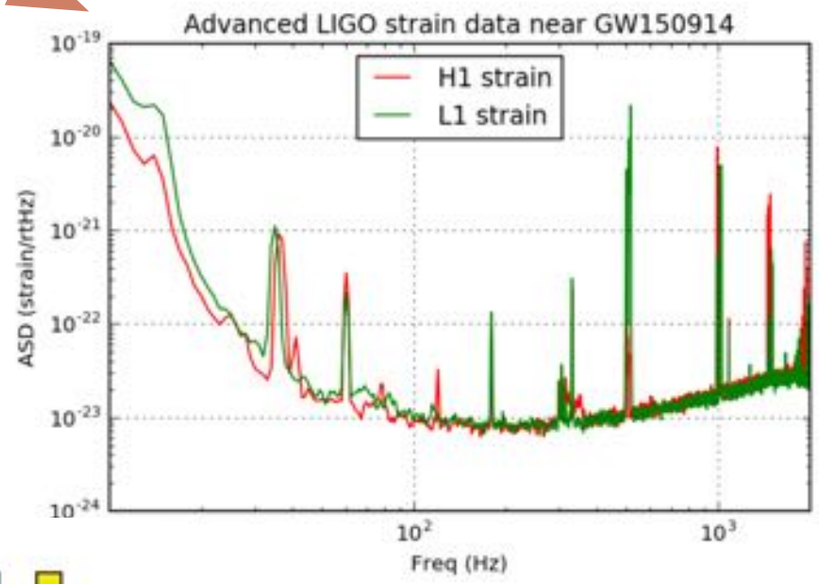
[see this movie at https://youtu.be/QyDcTbR-kEA]

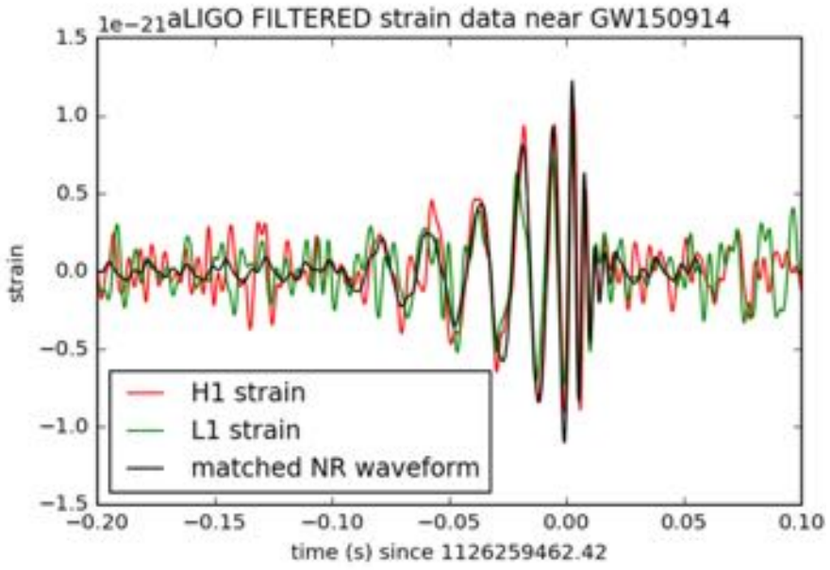


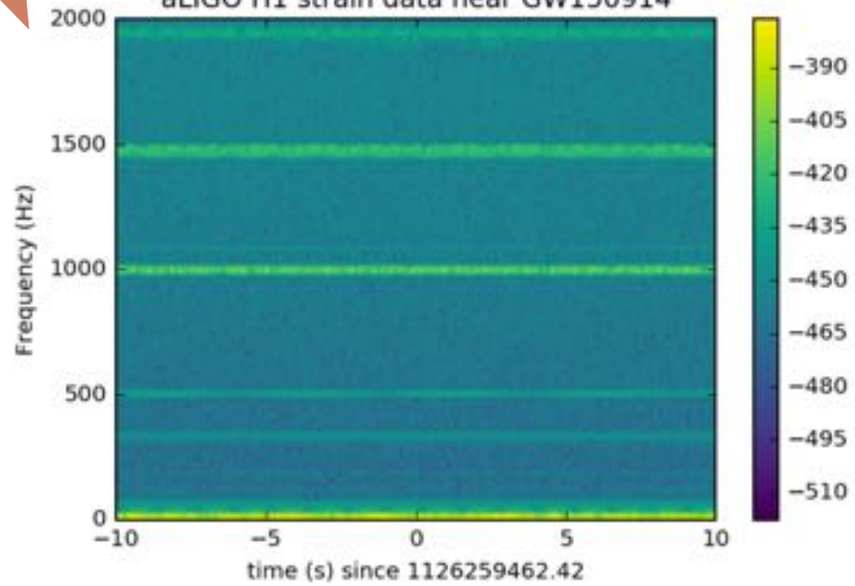
GW150914: GW strain to sound

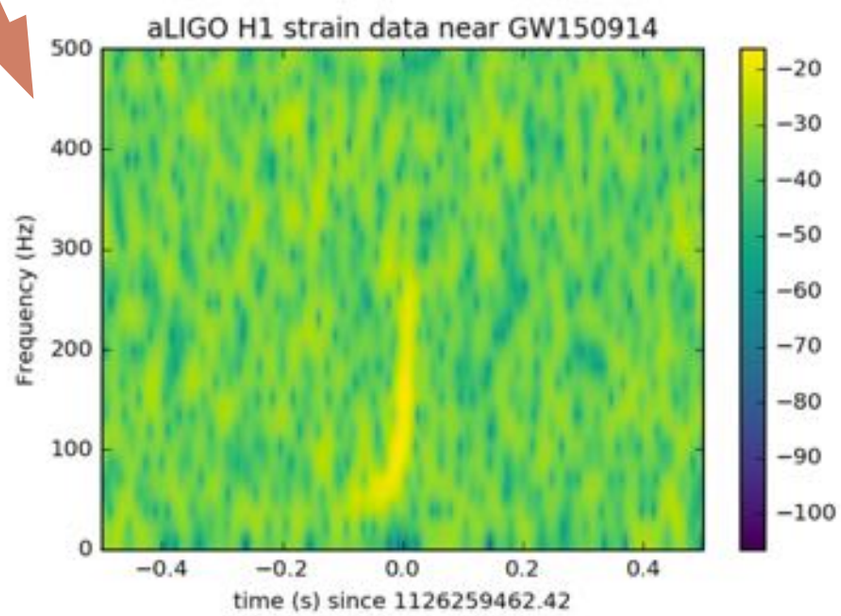
[LVC 2016]





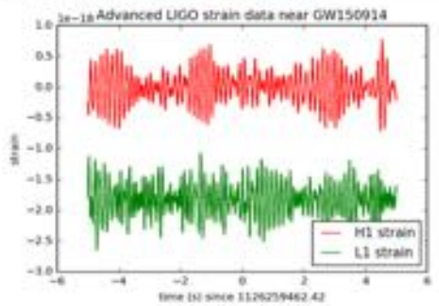






In [6]:
```
# plot +- 5 seconds around the event:
tevent = 1126259462.422           # Mon Sep 14 09:50:45 GMT 2015
deltat = 5.                       # seconds around the event
# index into the strain time series for this time interval:
indxt = np.where((time_H1 >= tevent-deltat) & (time_H1 < tevent+deltat))

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')
```

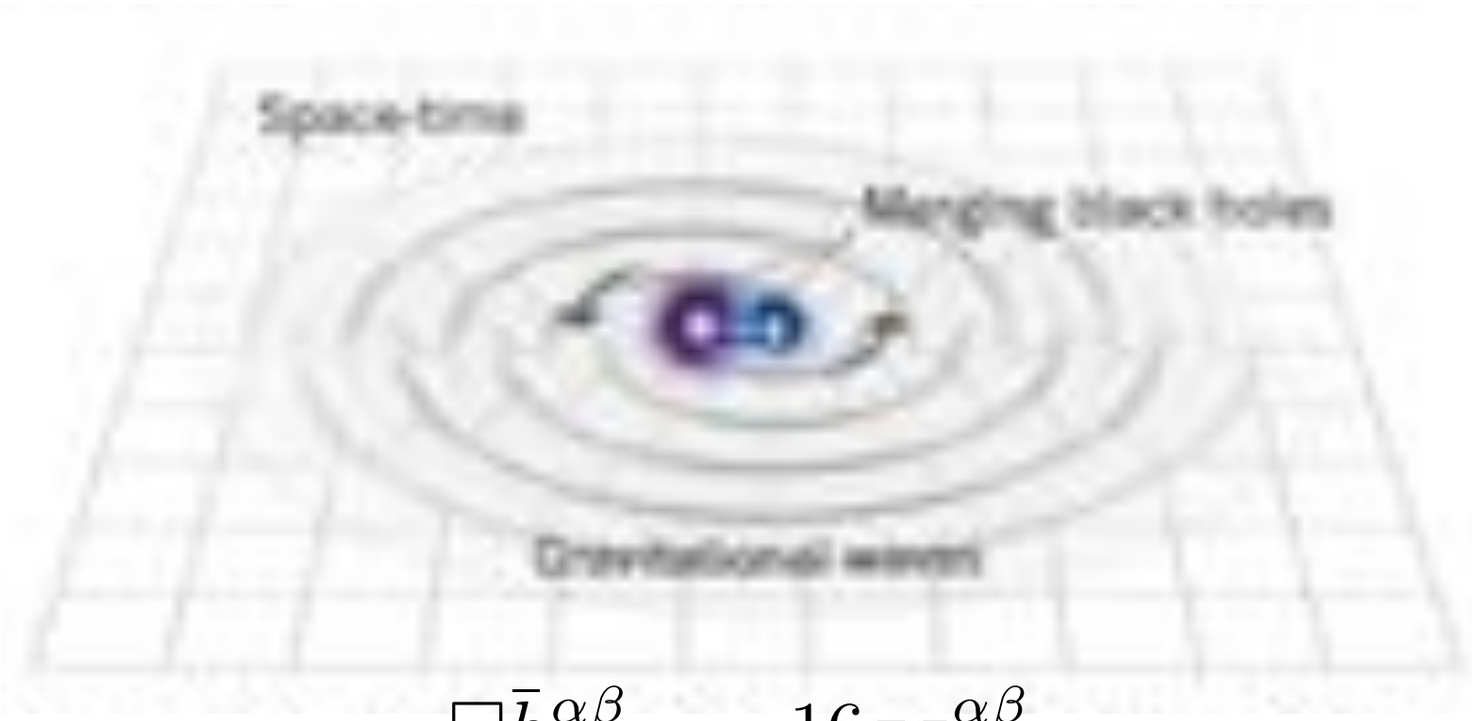


The data are dominated by **low frequency noise**; there is no way to see a signal here, without some signal processing.

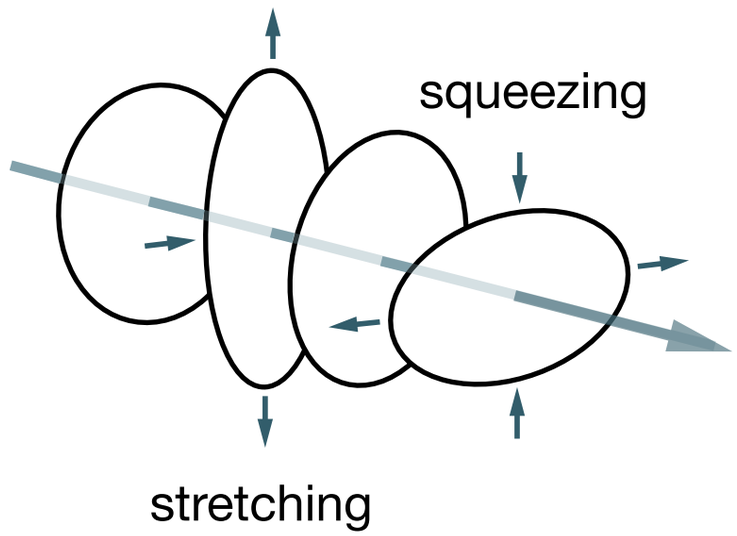
There are very low frequency oscillations that are putting the mean of the L1 strain at -2.0e-18 at the time around this event, so it appears offset from the H1 strain. These low frequency oscillations are essentially ignored in LIGO data analysis (see bandpassing, below).

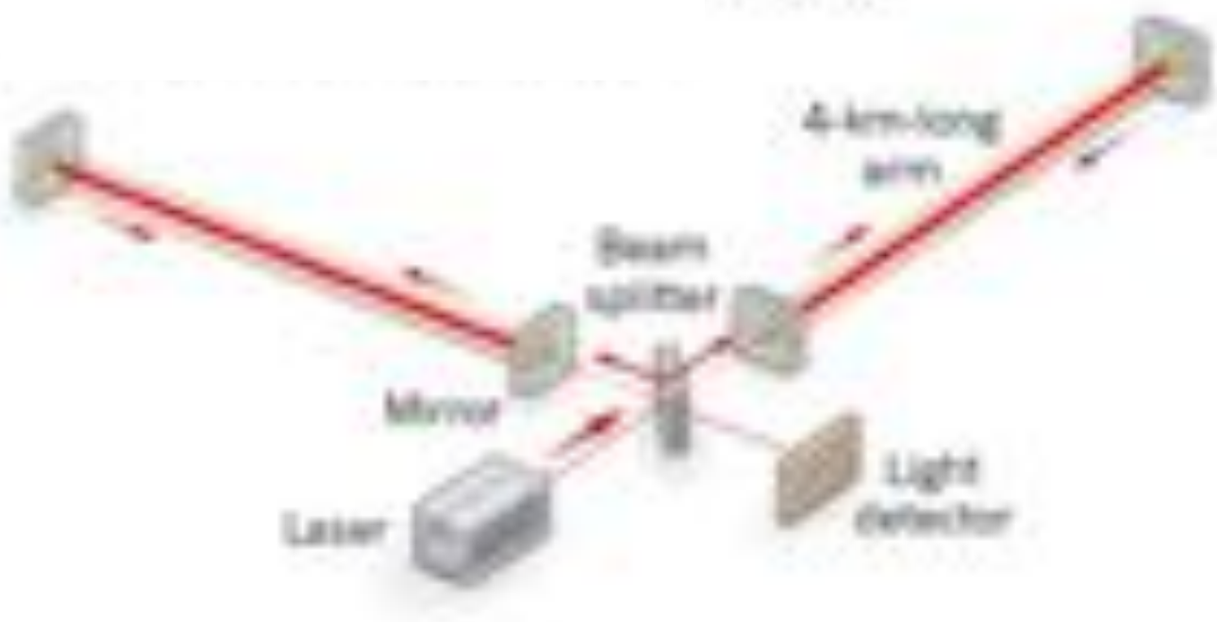
GW150914 data release – losc.ligo.org

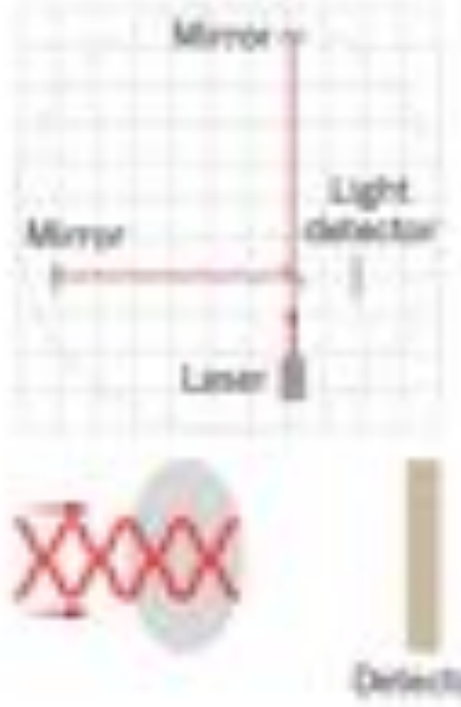
[LVC 2016]

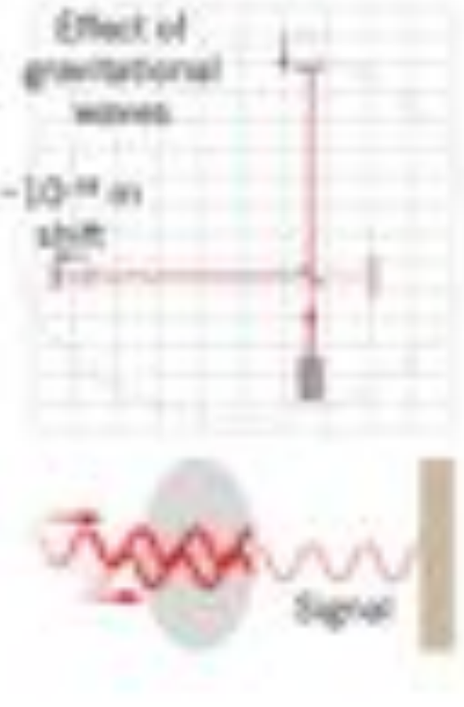


$$\Box \bar{h}^{\alpha\beta} = -16\pi\tau^{\alpha\beta}$$





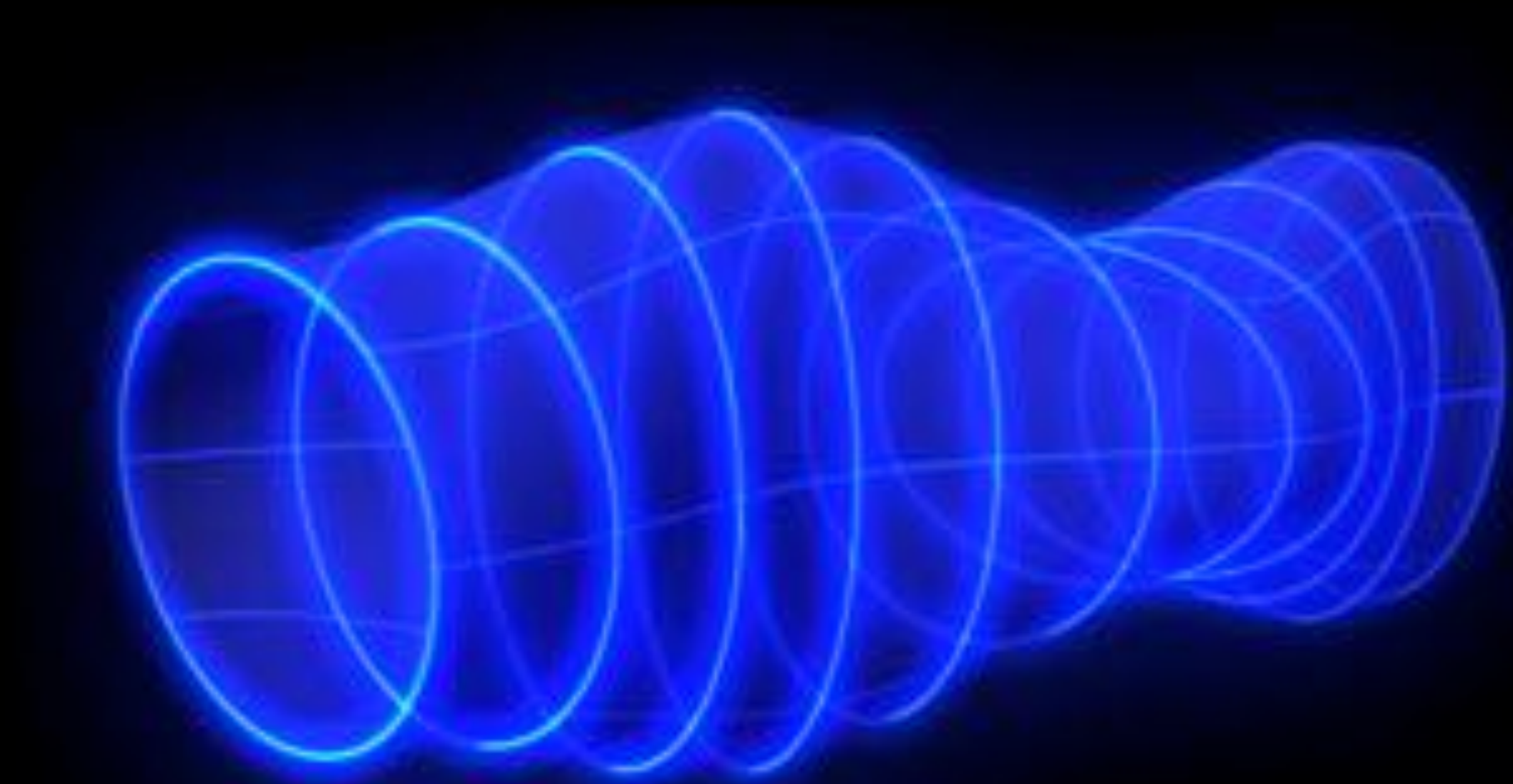




Gravitational waves and their detection

[Nature 2016]

[see this movie at https://youtu.be/R4yfGKM25VQ



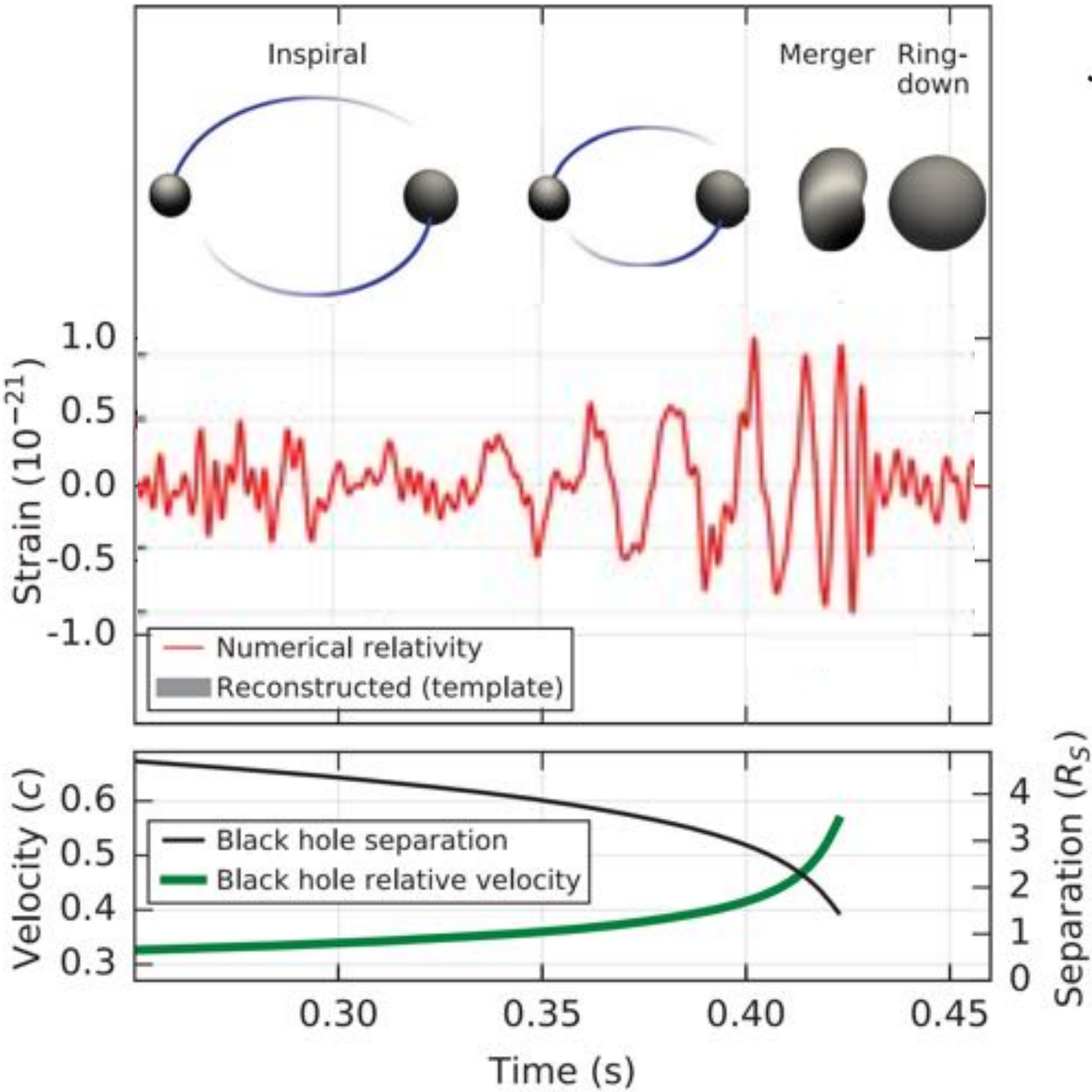
GWs are transverse and traceless tidal fields

[ESA 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]

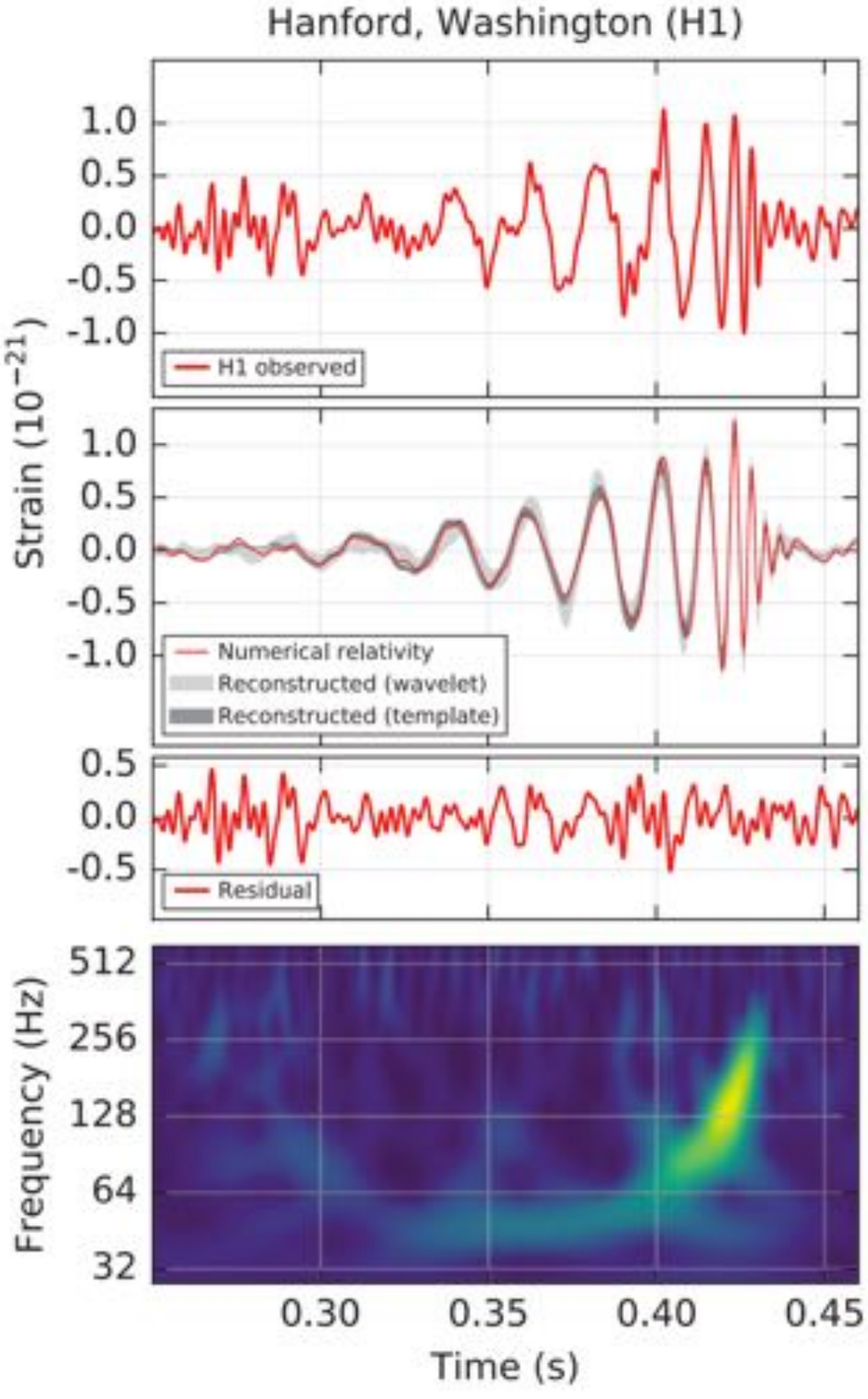


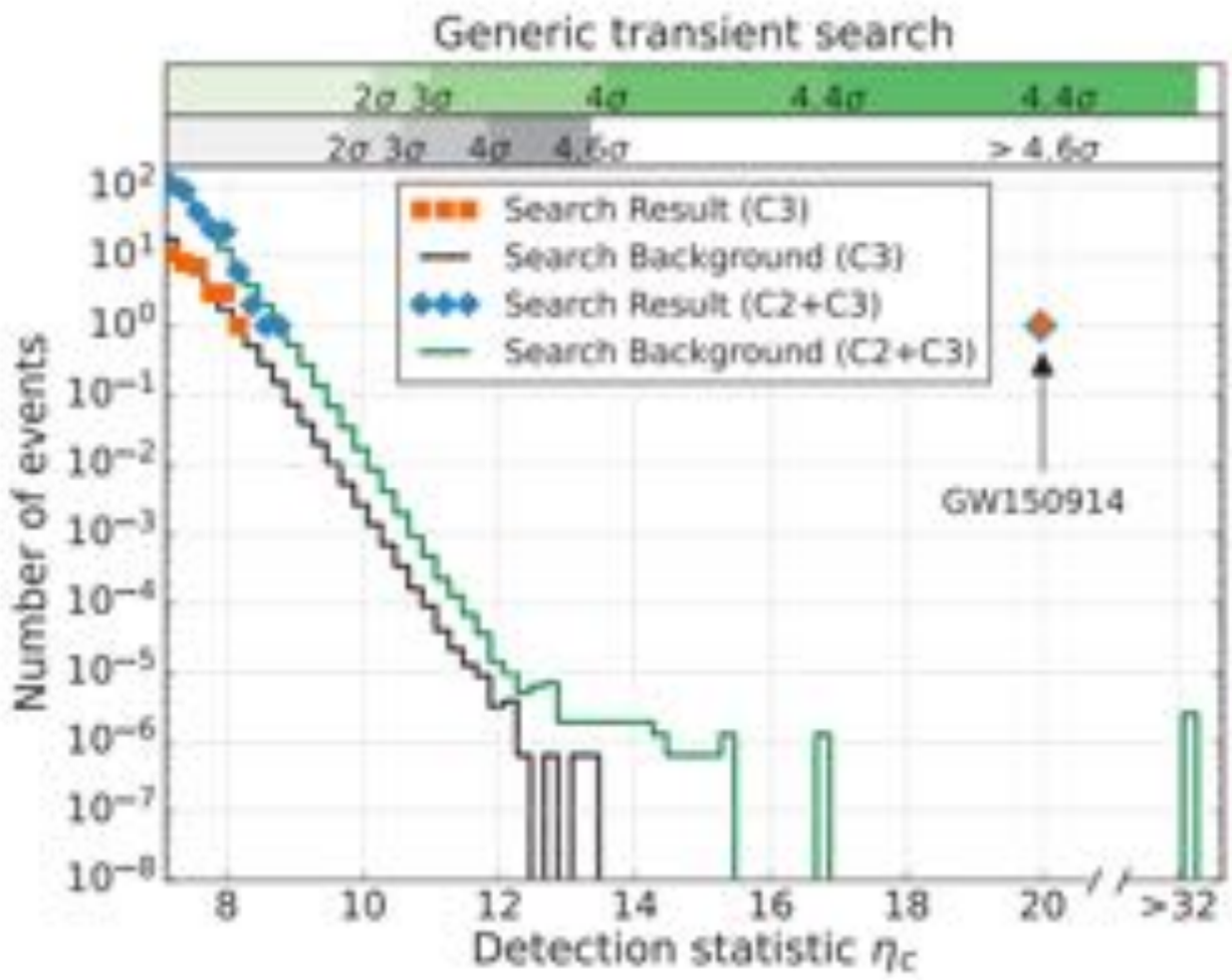
$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$

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

GW150914: inspiral, merger, and ringdown

[LVC 2016]

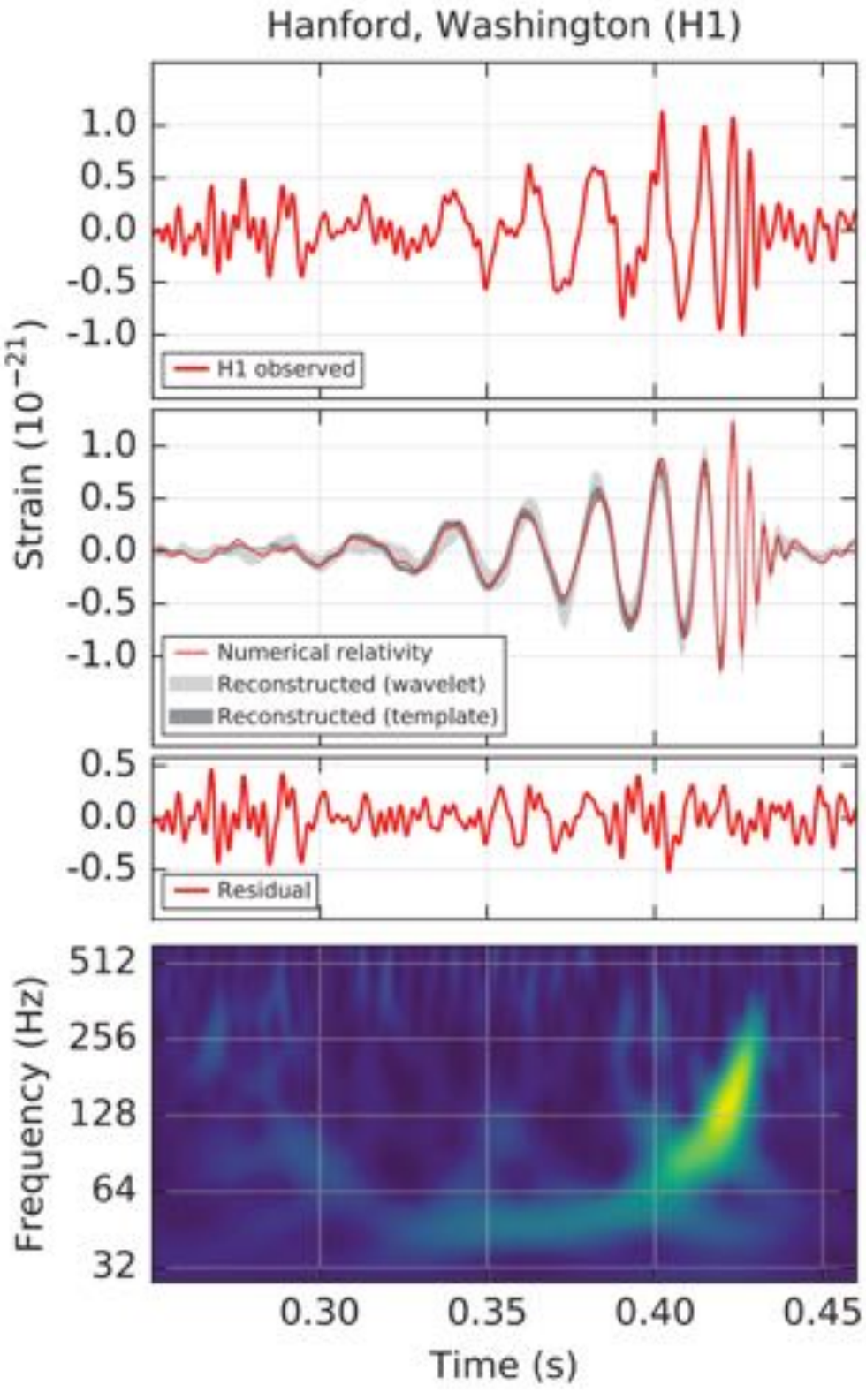


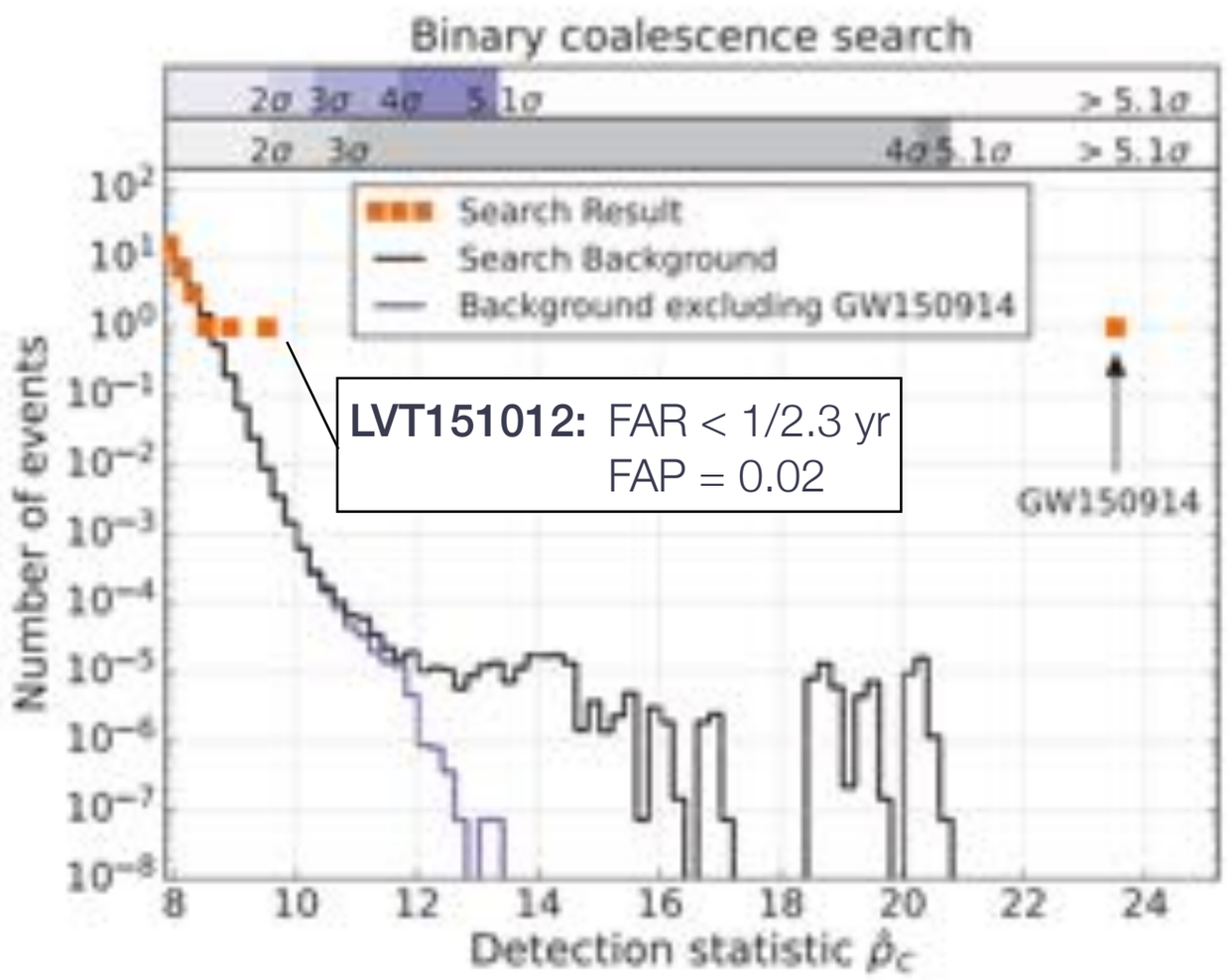


- **C1**: known noise transients; **C3**: chirps; **C2**: everything else
- Measured on 67,400-yr background, false-alarm rate < 1 in 22,500 yr (2×10^{-6} false alarm = 4.6σ)

GW150914: burst search

[LVC 2016]



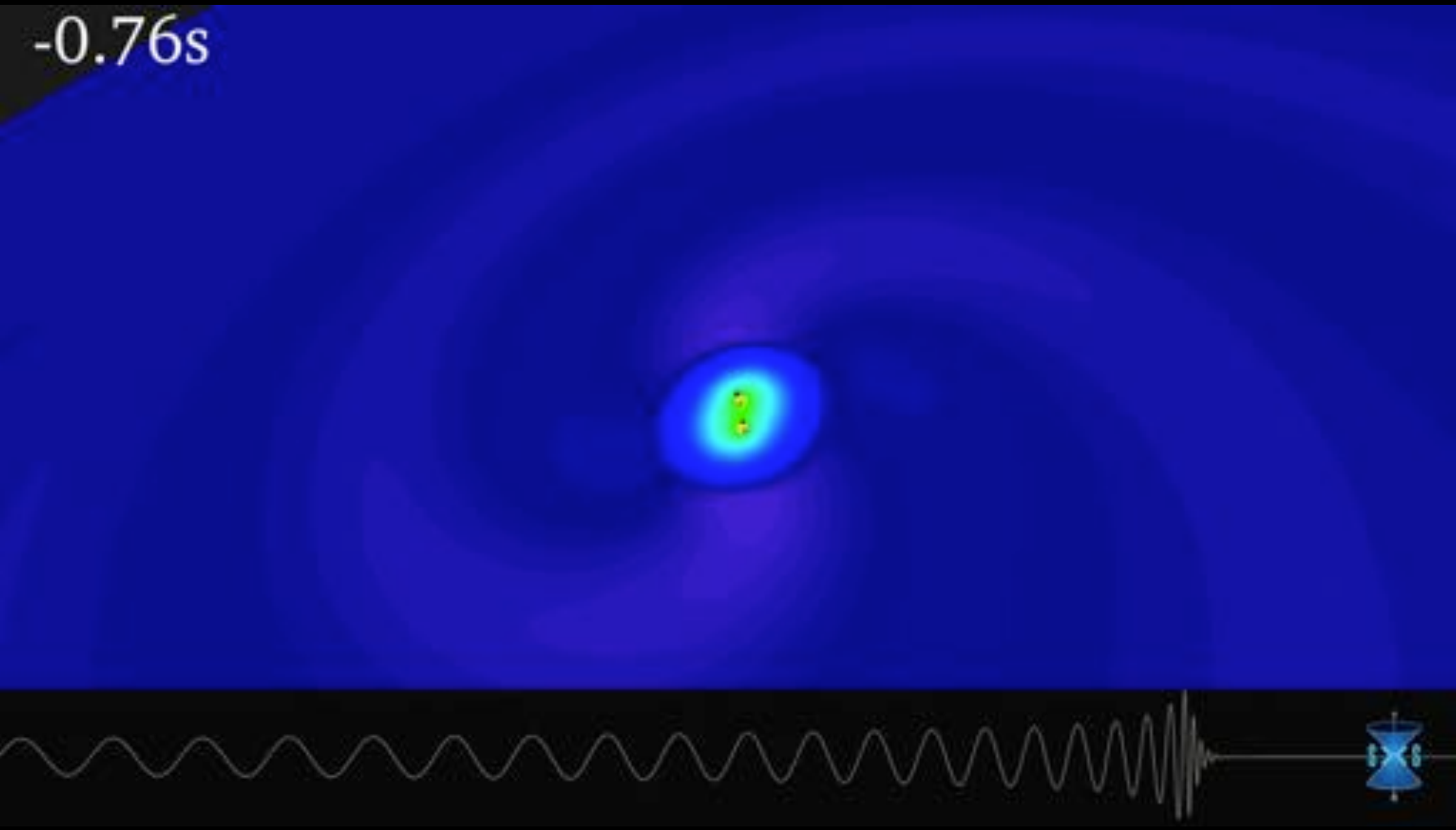


- Binaries with masses 1–99 M⊙, total mass < 100 M⊙, dimensionless spin < 0.99
- 250,000 PN and EOB signal templates. Matched-filter SNR + χ^2 statistic
- Measured on 608,000-yr background, false-alarm rate < 1 in 203,000 yr (2×10^{-7} false alarm = 5.1σ)

GW150914: matched-filter inspiral search

[LVC 2016]

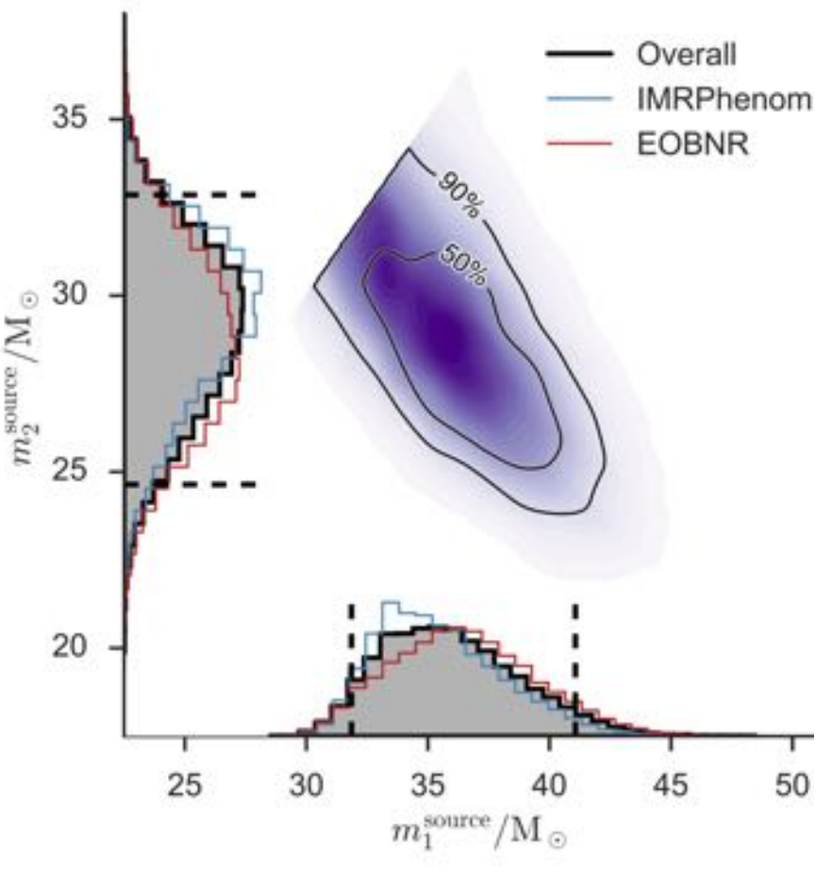
[see this movie at https://youtu.be/1agm33iEAuo]

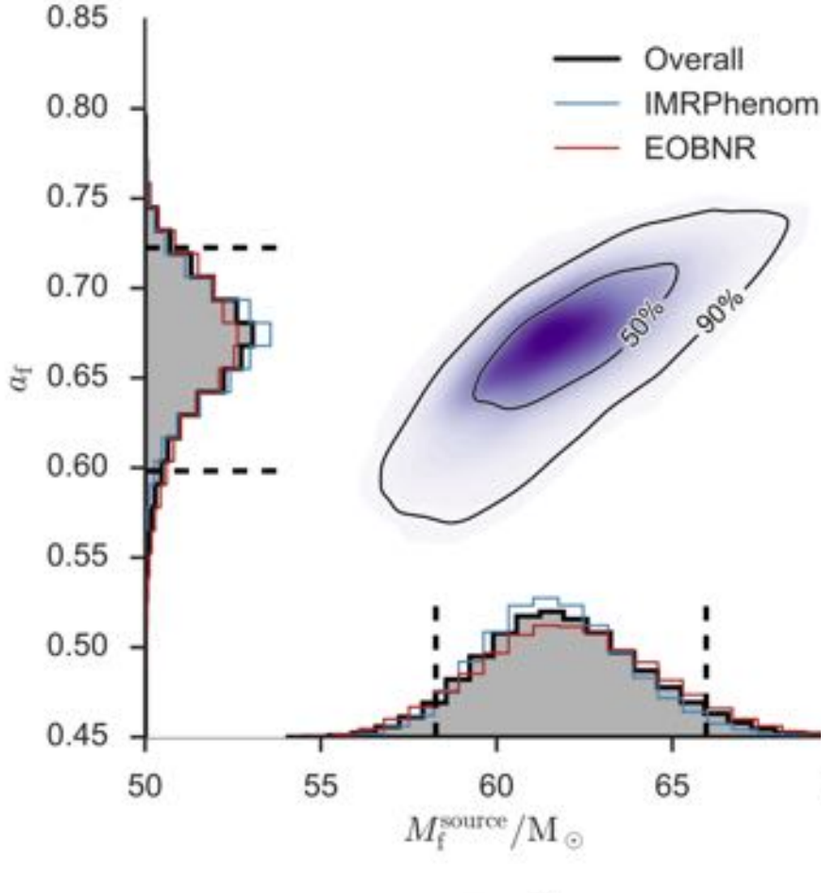


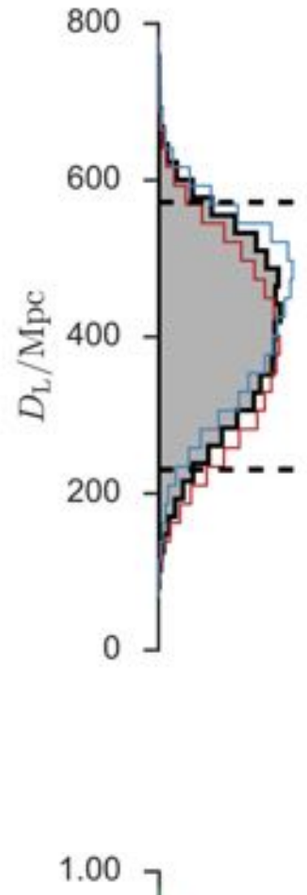
GW150914: numerical relativity simulation

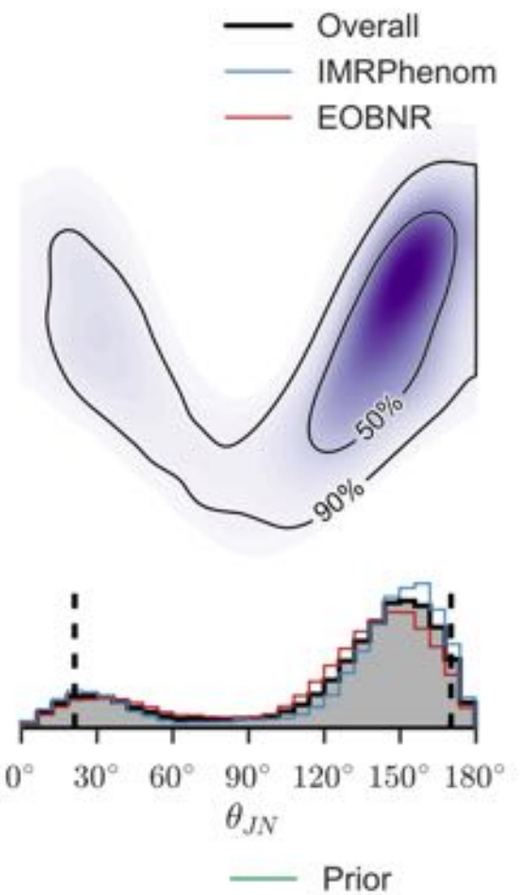
[SXS collaboration 2016]

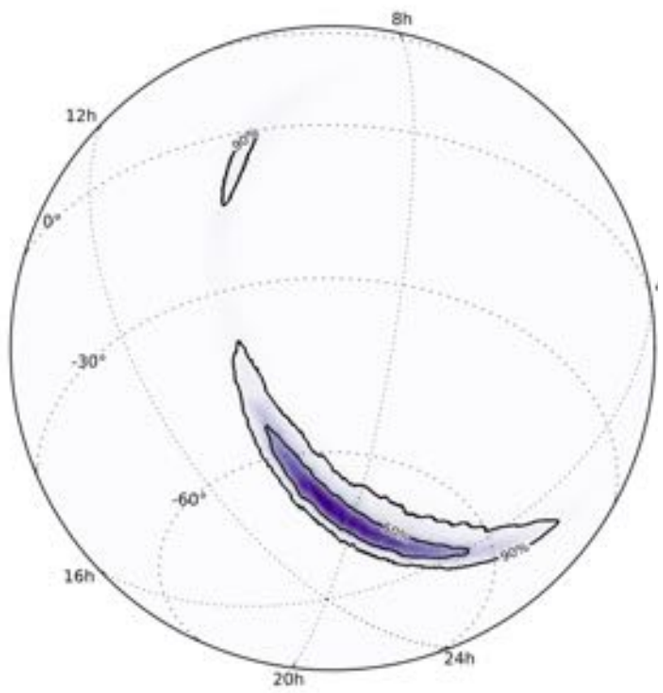
Primary black hole mass	$36^{+5}_{-4} M_\odot$
Secondary black hole mass	$29^{+4}_{-4} M_\odot$
Final black hole mass	$62^{+4}_{-4} M_\odot$
Final black hole spin	$0.67^{+0.05}_{-0.07}$
Luminosity distance	410^{+160}_{-180} Mpc
Source redshift z	$0.09^{+0.03}_{-0.04}$

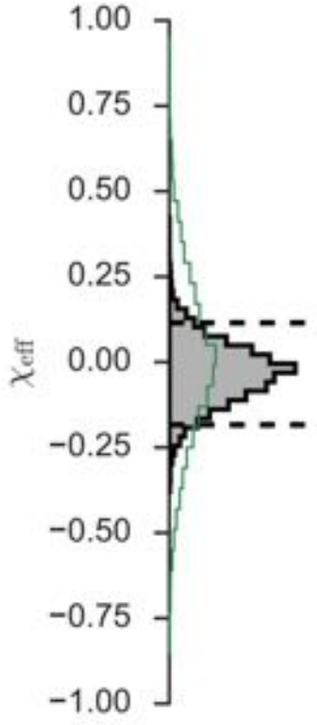


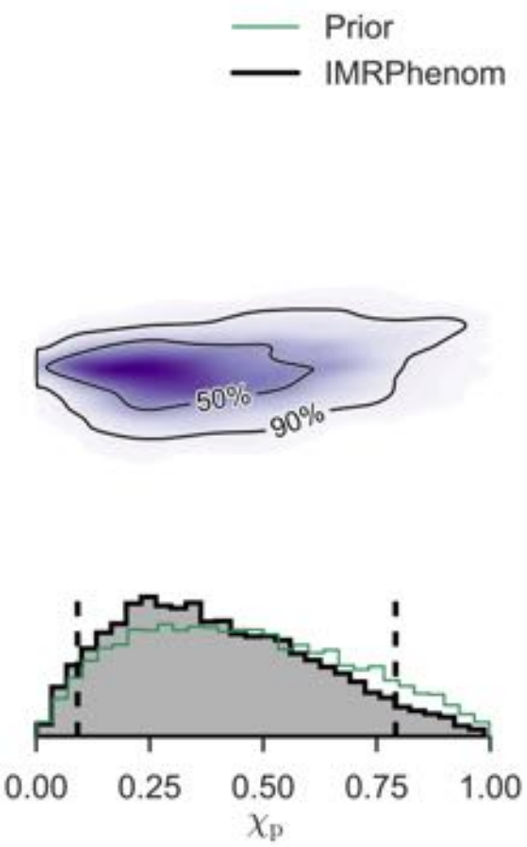






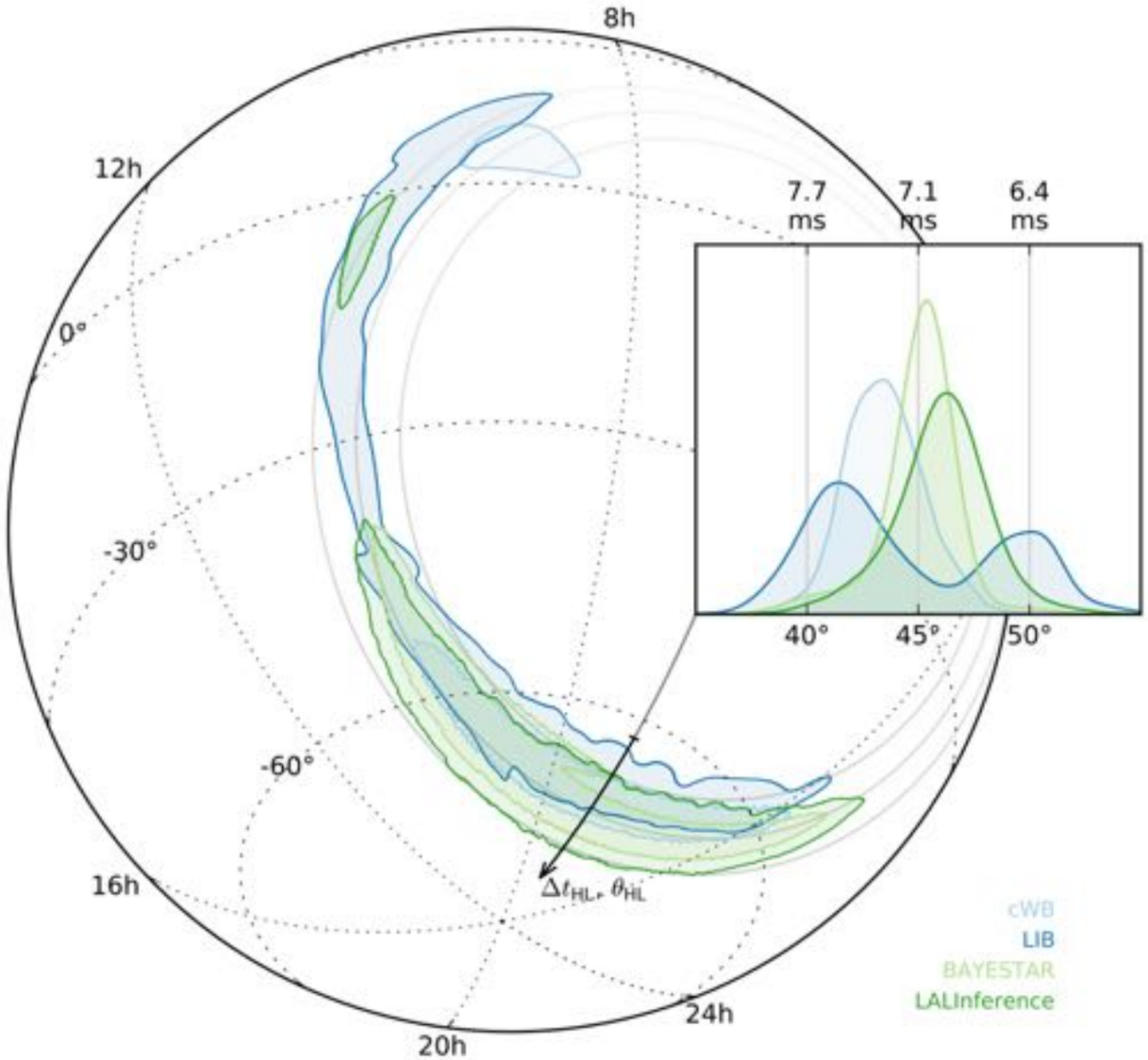


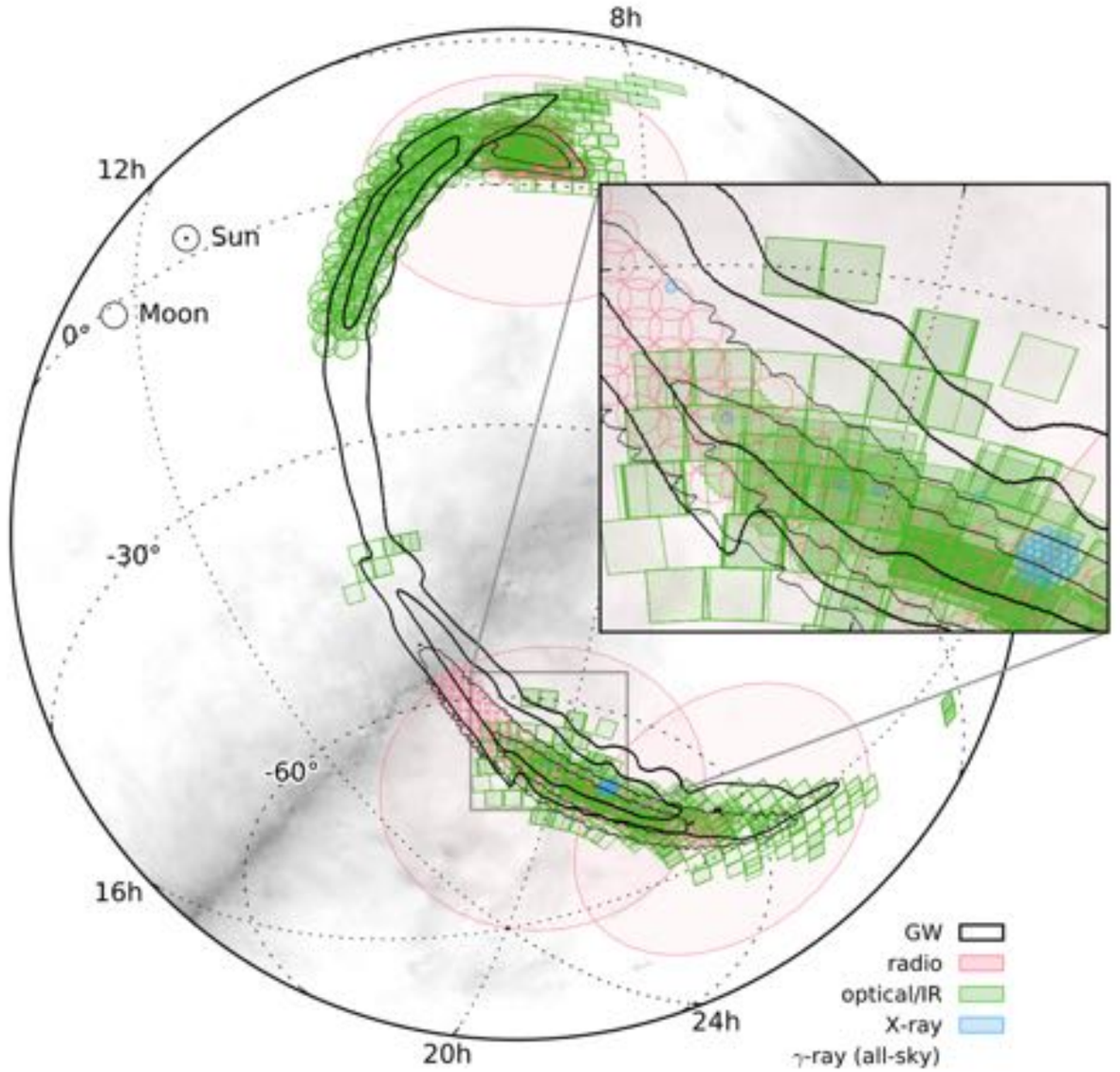




GW150914: parameter estimation

[LVC 2016]





Localization and EM follow up

[LVC 2016]

expected counterparts
for NS–NS or NS–BH binary

prompt:
GRB

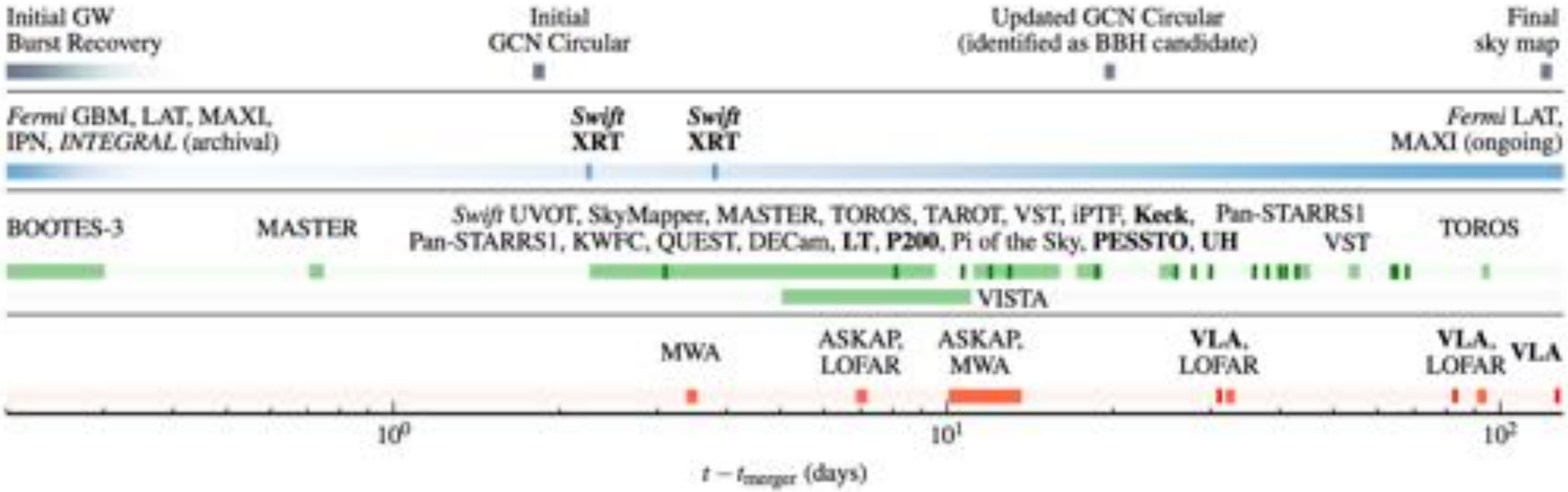
hours to days:
X-ray, **optical**, **radio** **afterglows**

hours to weeks:
optical/IR **kilonova**

months to years:
radio **blast wave**

–seconds to minutes:
radio **burst**

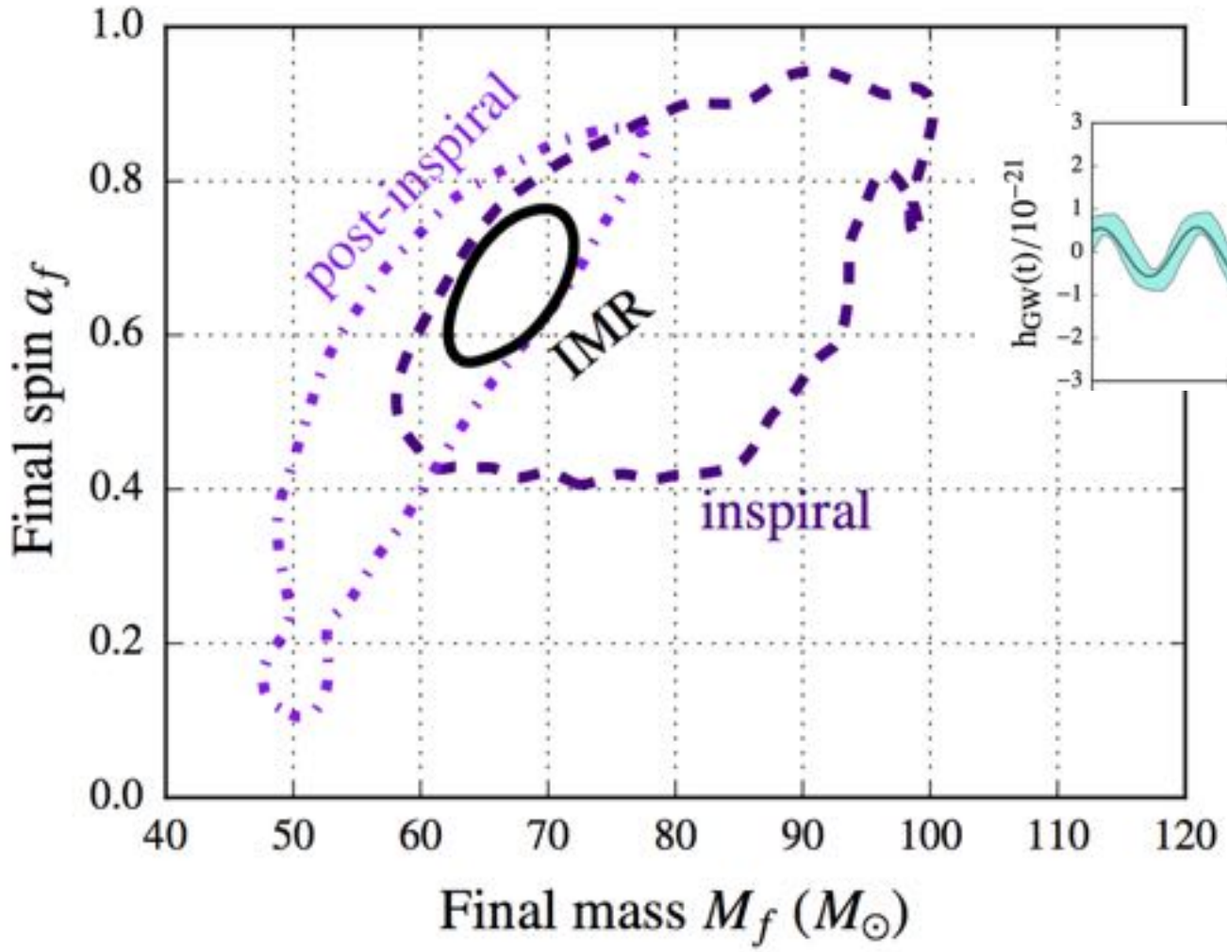
LIGO MOU partners
follow-up campaign

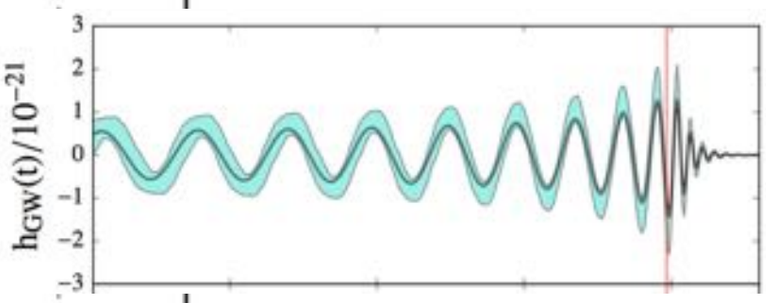


EM follow up

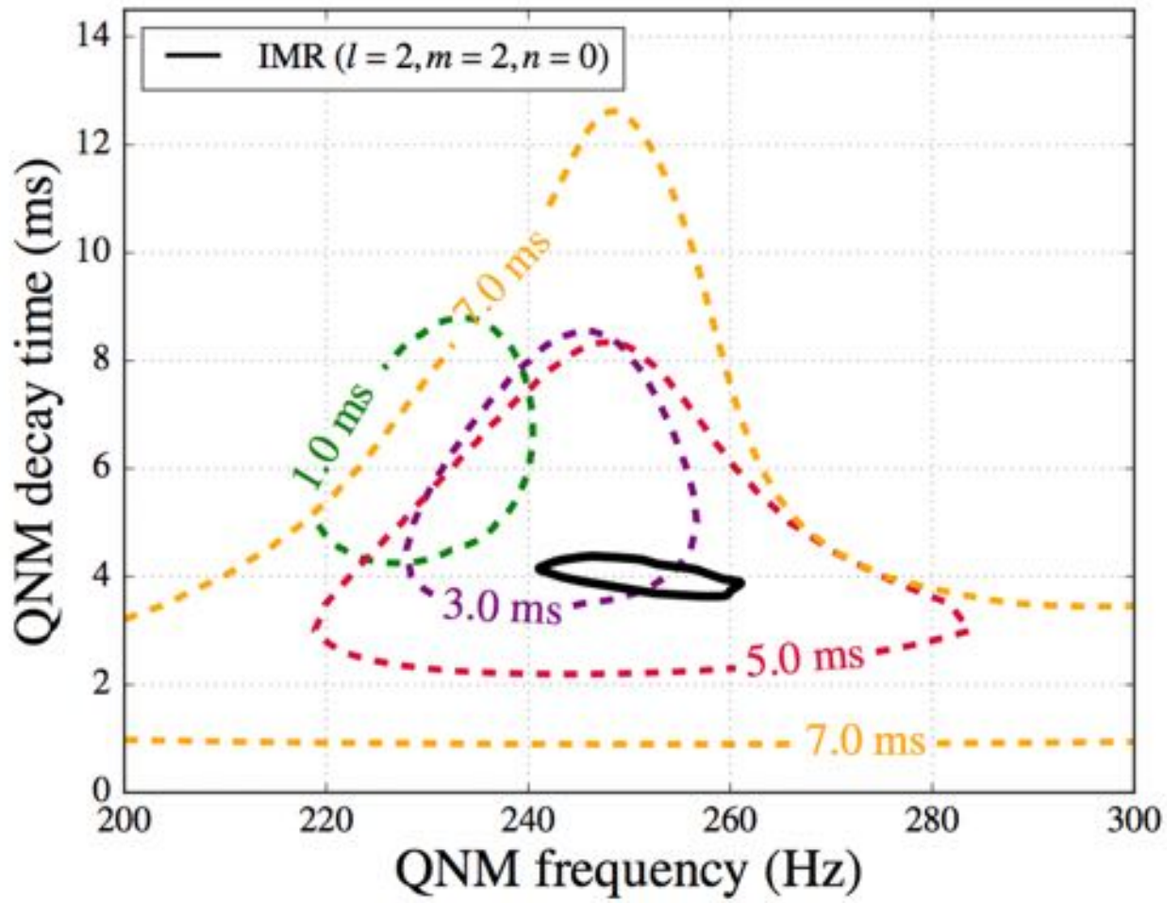
[LVC 2016]

Inspiral vs merger–ringdown consistency





Kerr quasi-normal mode



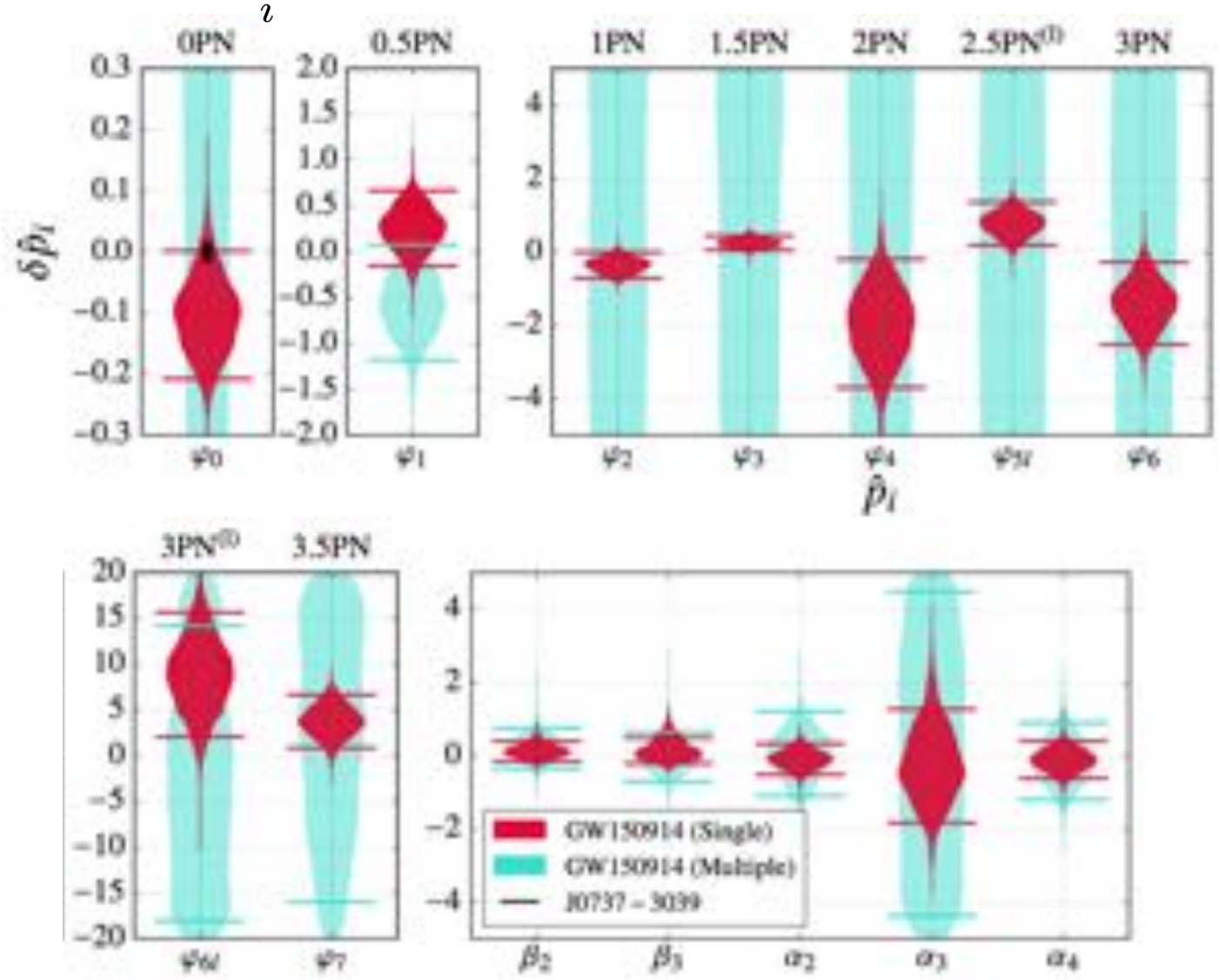
Tests of GR (I)

[LVC 2016]

Parameterized phasing coefficients

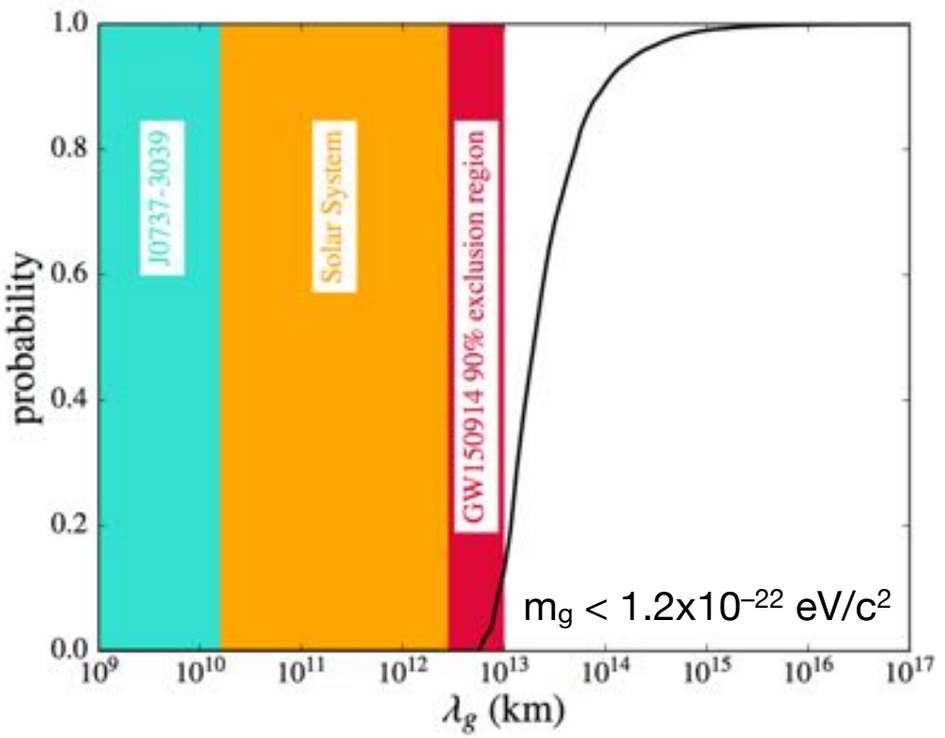
$$h(f) = \frac{1}{D}\frac{\mathcal{A}}{\sqrt{\dot{F}}} f^{2/3} e^{i\Psi(f)}$$

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



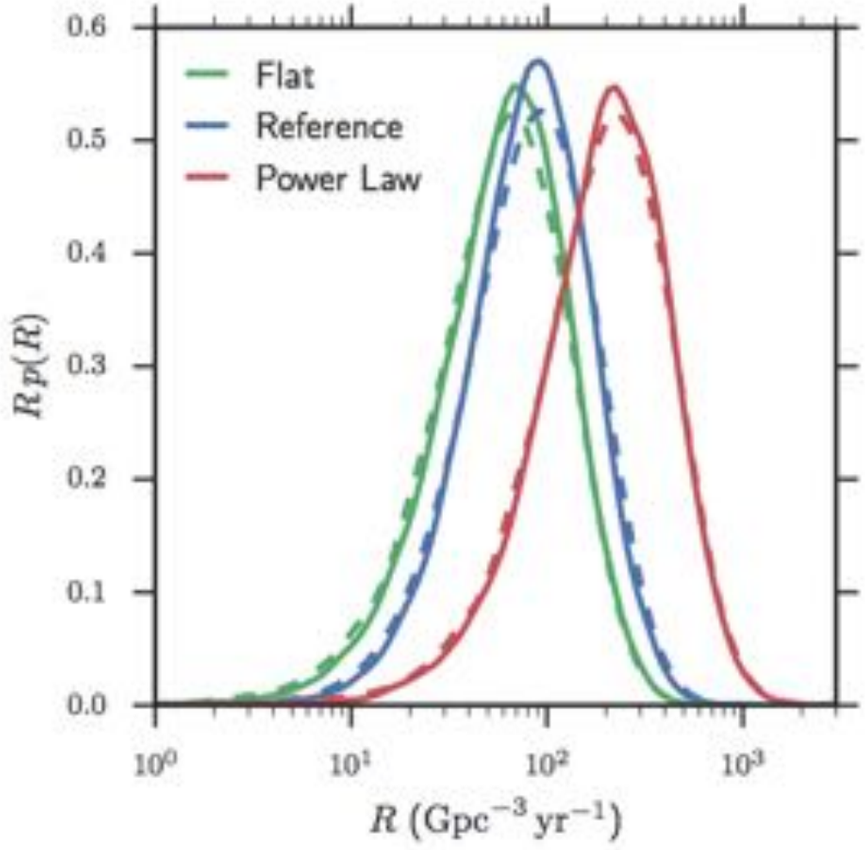
Graviton mass

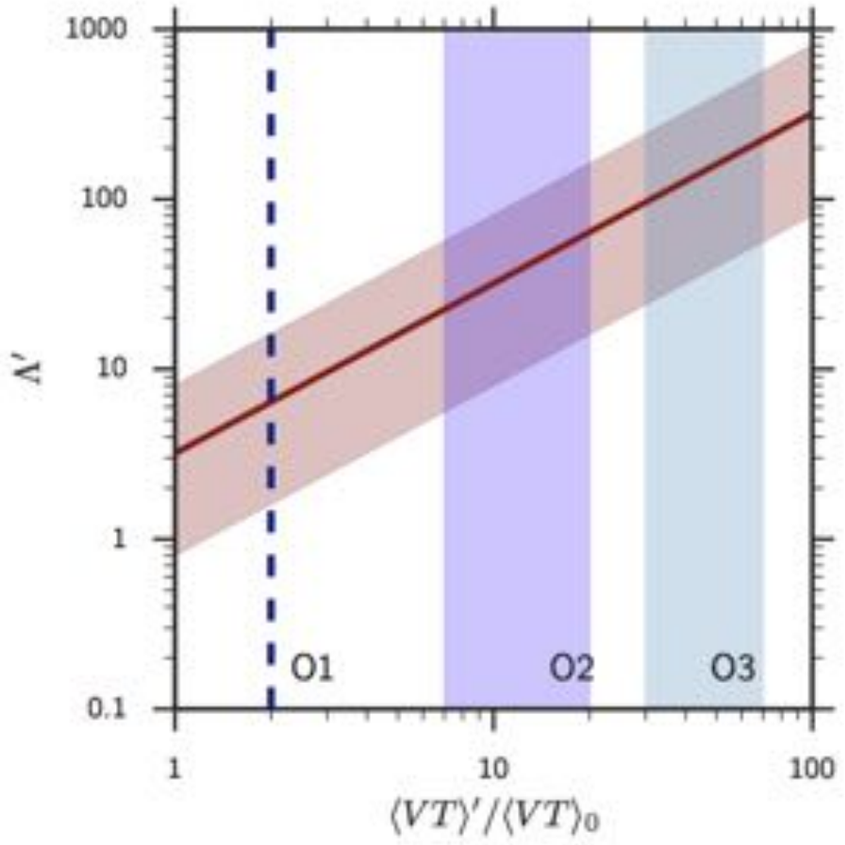
$$\delta\Psi(f) = \frac{\pi D c}{\lambda_g^2 (1+z) f}$$



Tests of GR (II)

[LVC 2016]





Mass Distribution	$R/\left(\mathrm{Gpc^{-3}\,yr^{-1}}\right)$		
	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 in log mass	63^{+121}_{-49}	60^{+122}_{-48}	61^{+124}_{-48}
Power Law (-2.35)	200^{+390}_{-160}	200^{+410}_{-160}	200^{+400}_{-160}

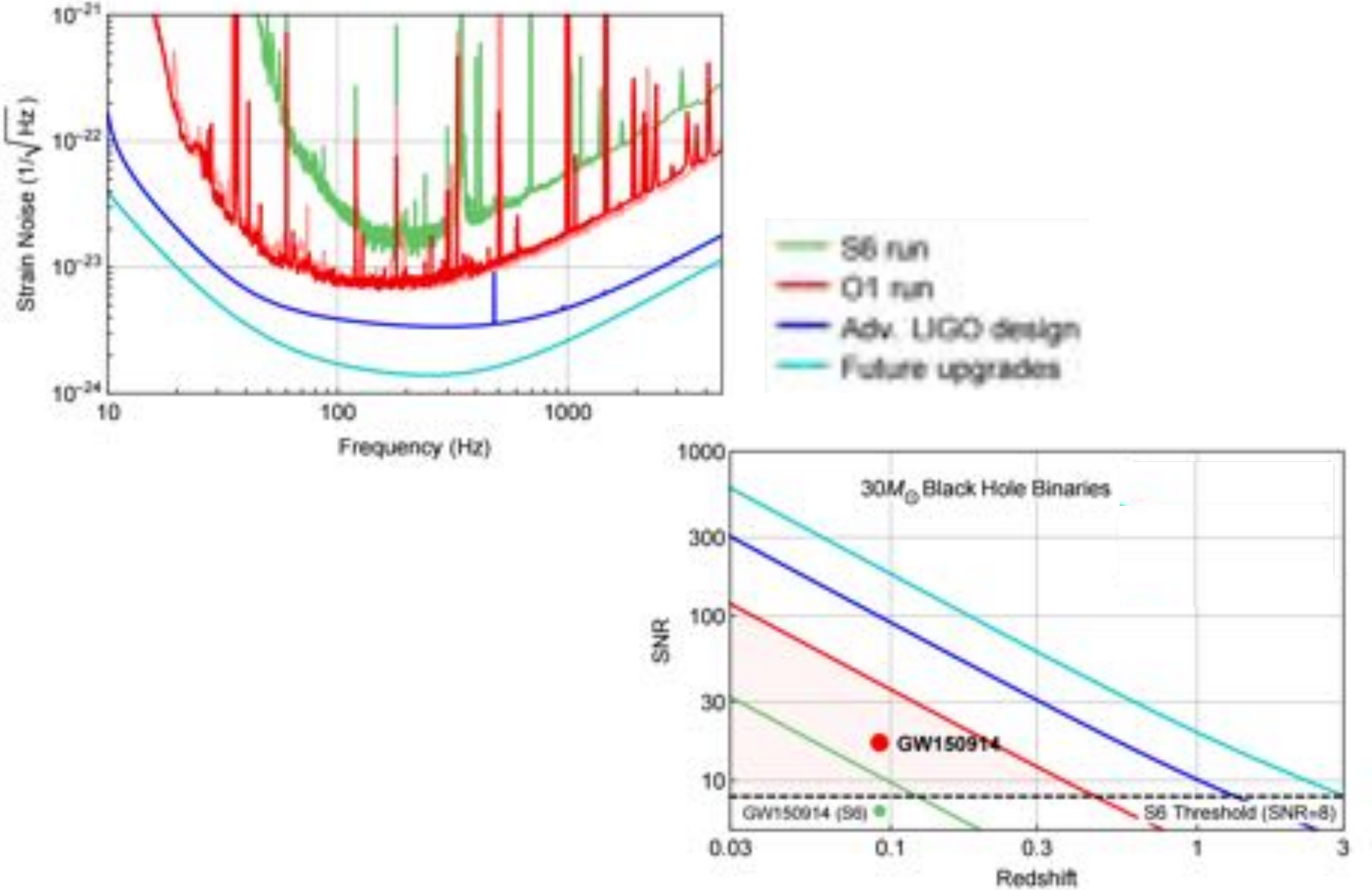
$$\mathcal{L}\left(\{x_j|j=1,\ldots,M\}\,|\Lambda_1,\Lambda_0\right) = \left\{\prod_{j=1}^{M}\left[\Lambda_1 p_1\left(x_j\right)+\Lambda_0 p_0\left(x_j\right)\right]\right\}\exp\left[-\Lambda_1-\Lambda_0\right]$$

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

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

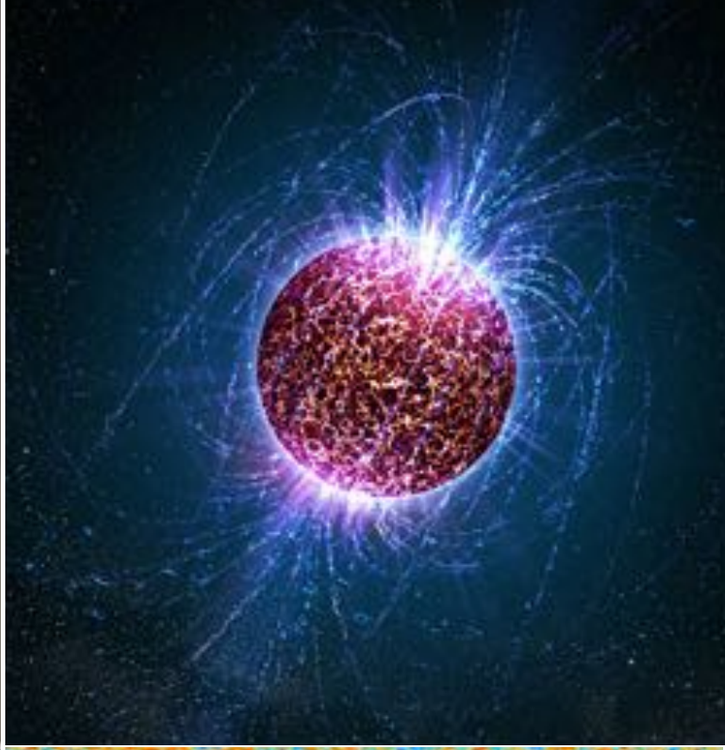
Inferred BBH merger rates

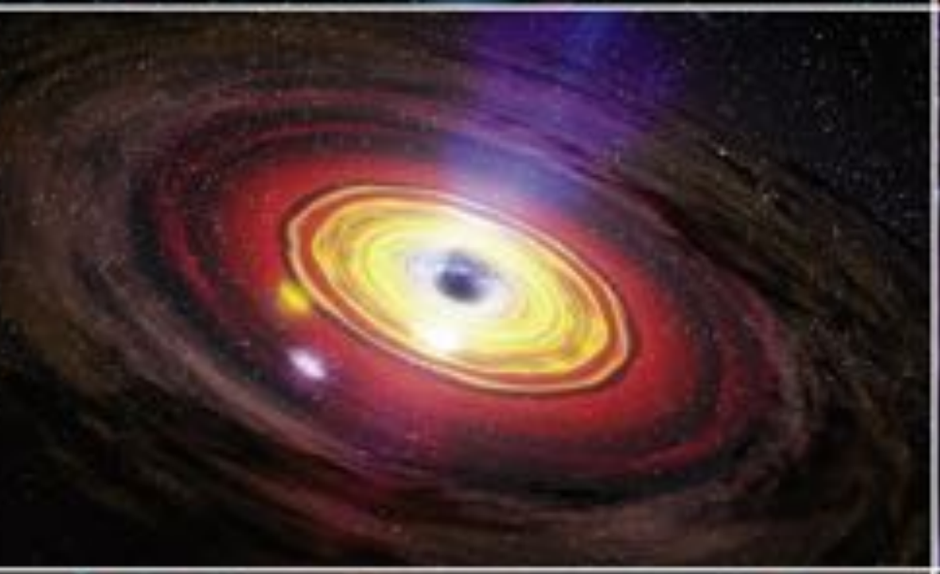
[LVC 2016]

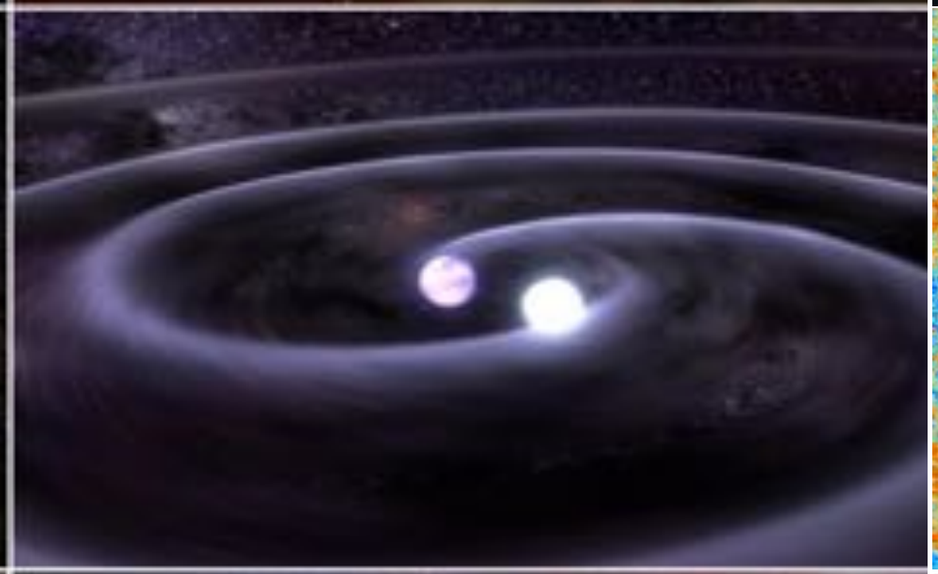


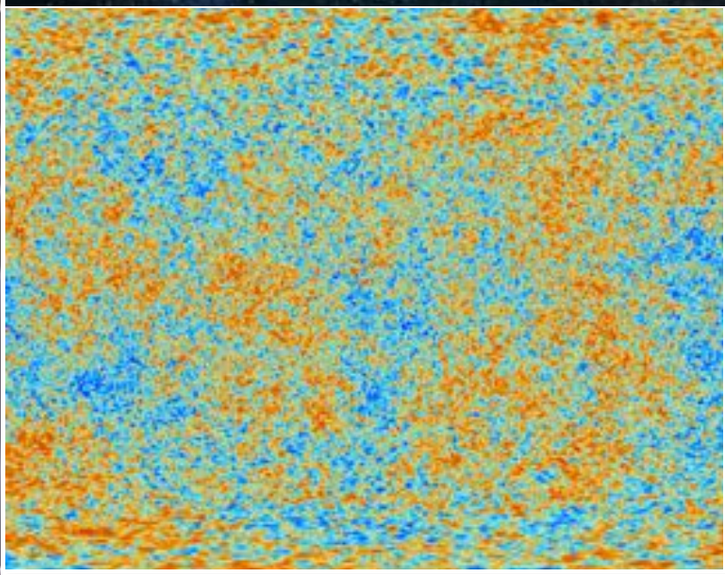
Advanced LIGO sensitivity improvements

[LVC 2016]

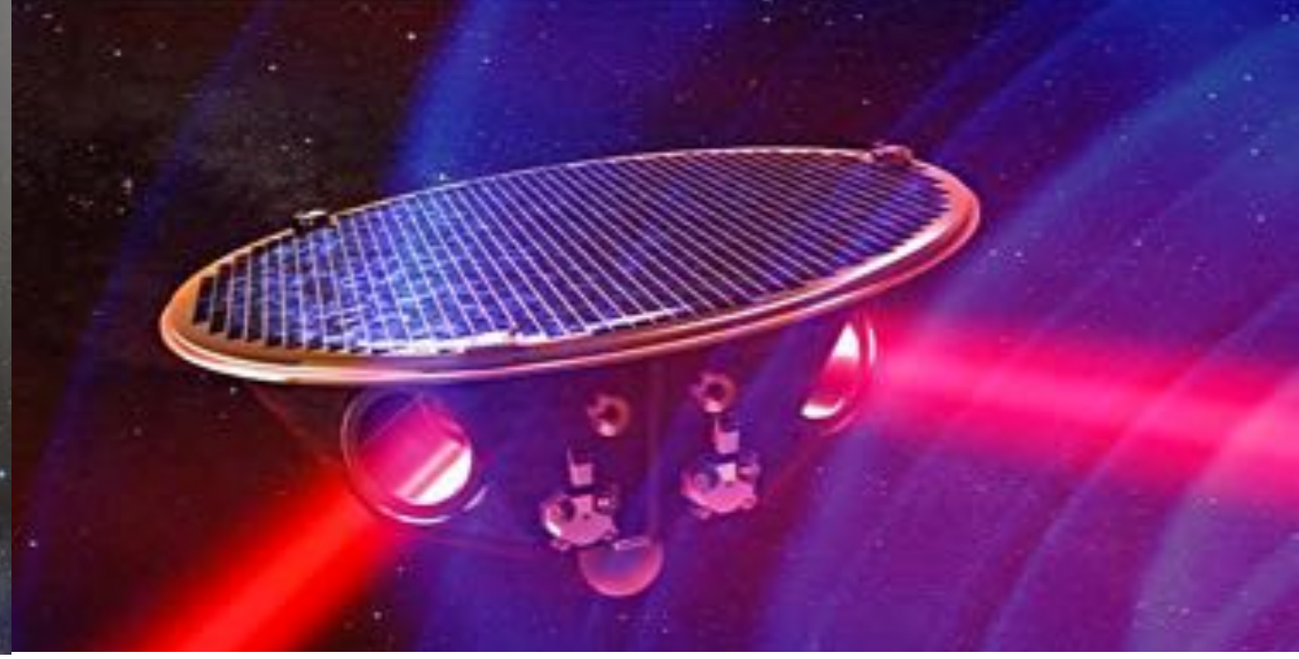




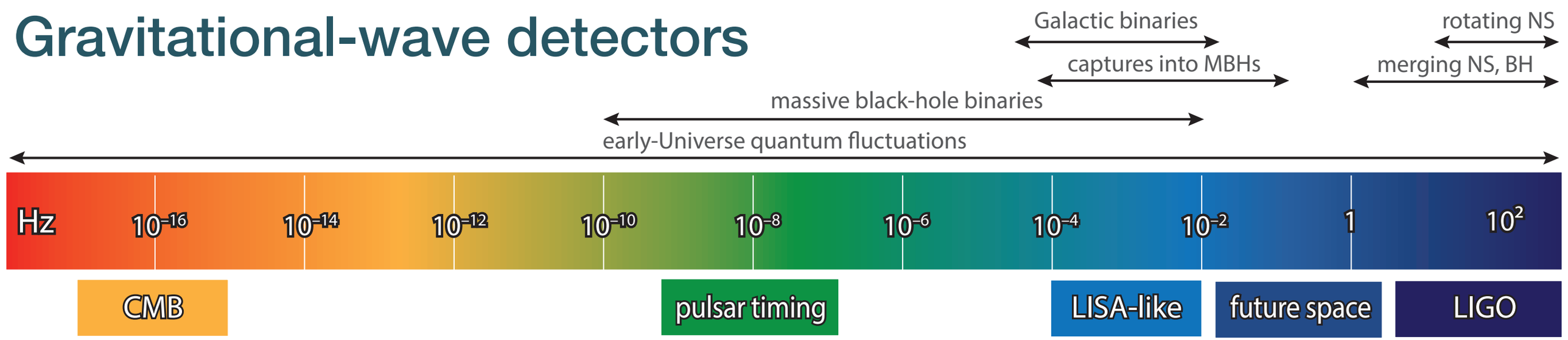


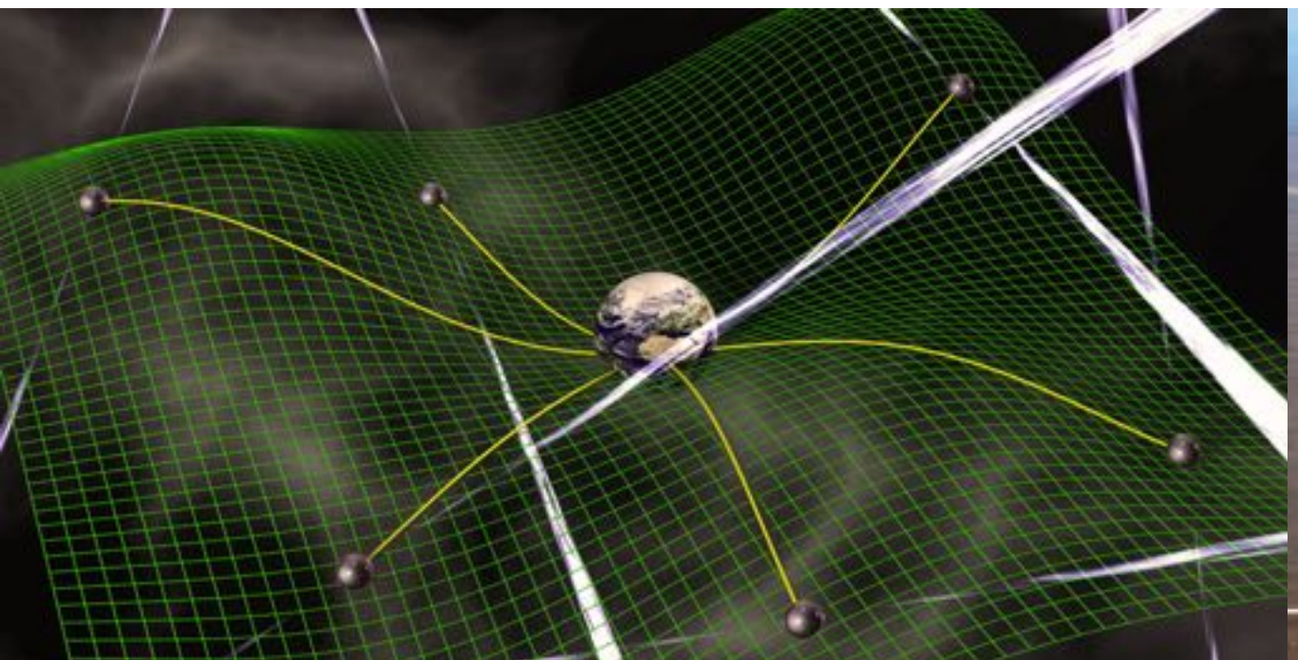


?



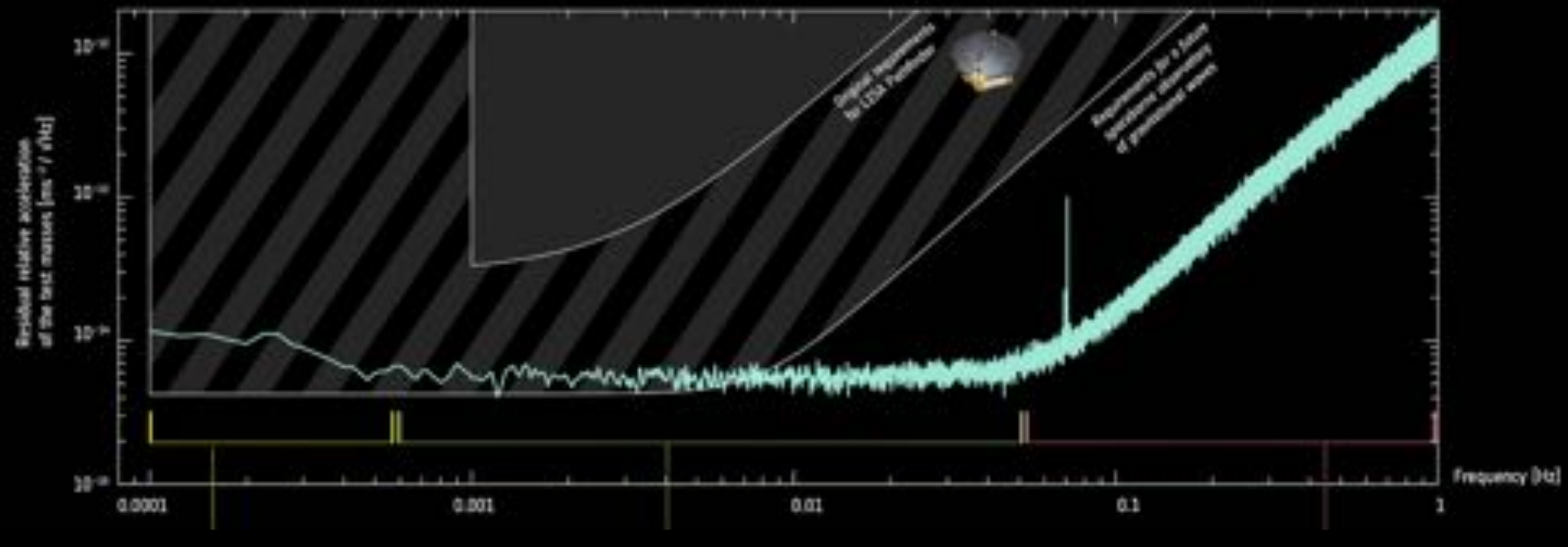
Gravitational-wave detectors

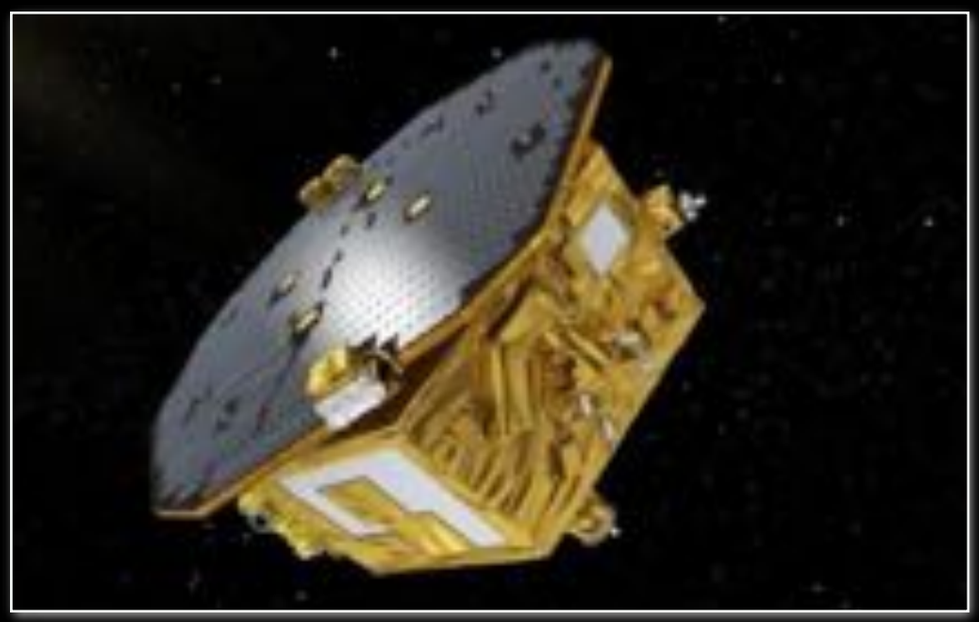


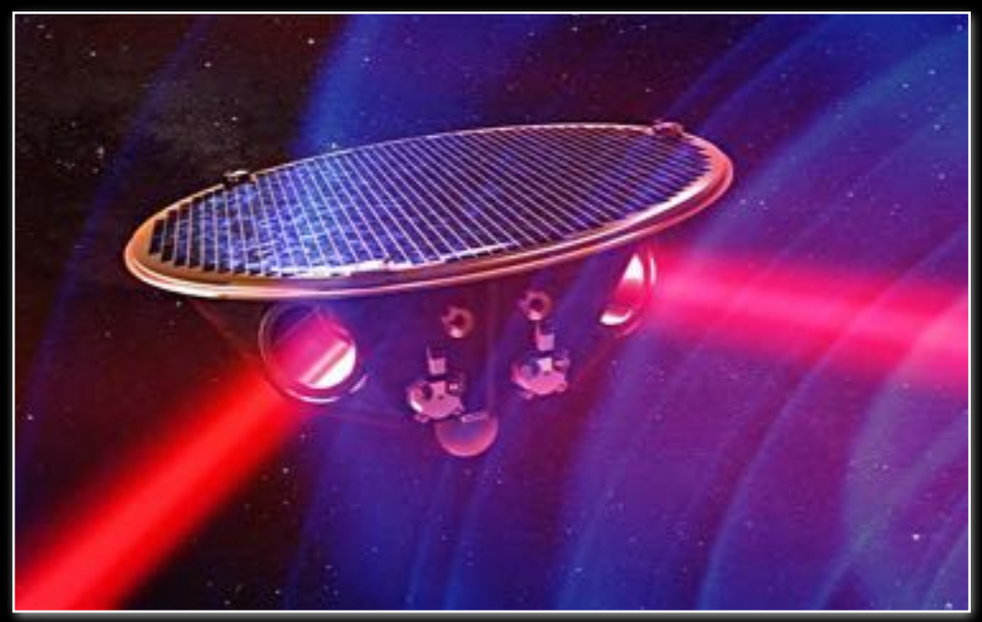


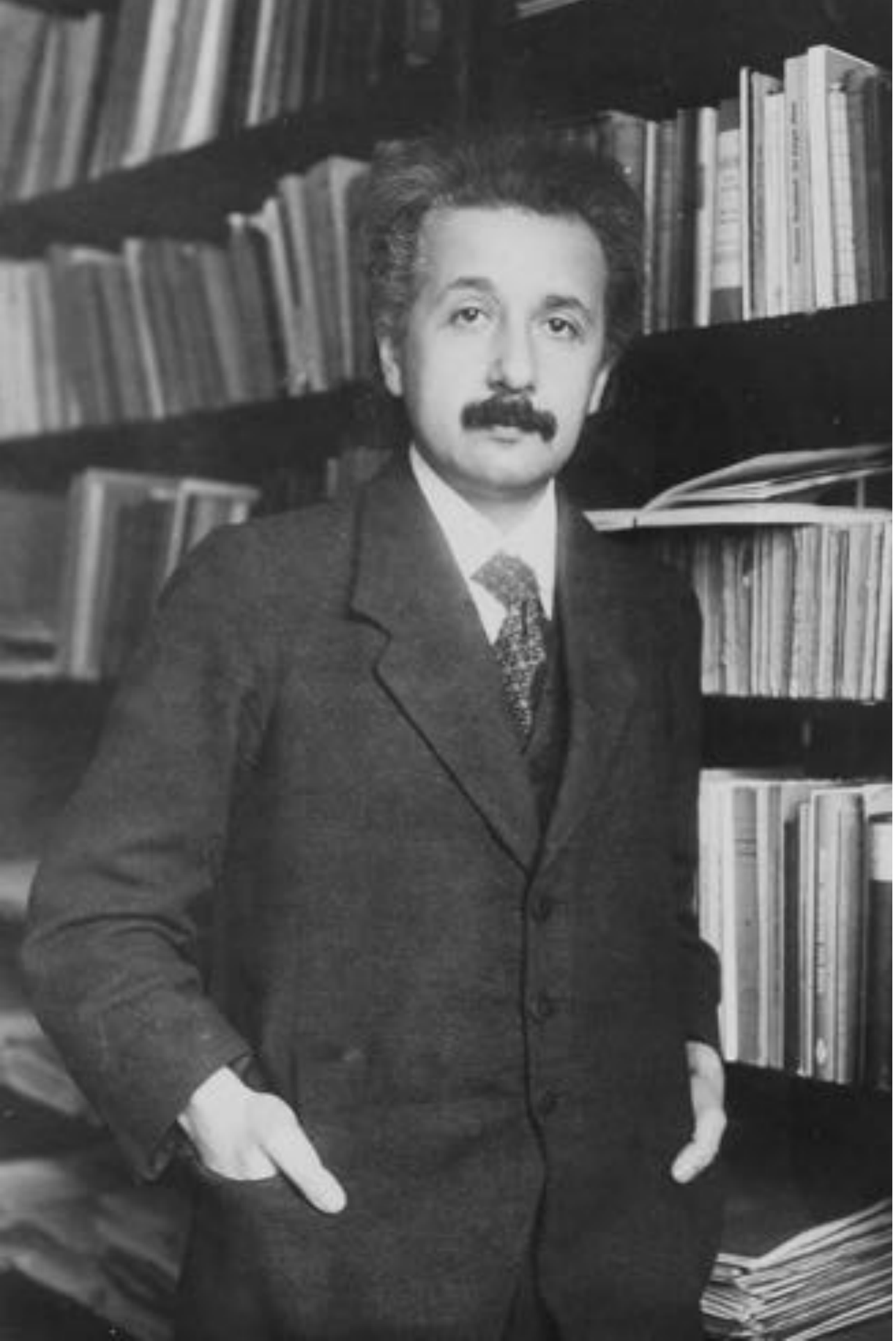
→ LISA PATHFINDER EXCEEDS EXPECTATIONS

esa









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