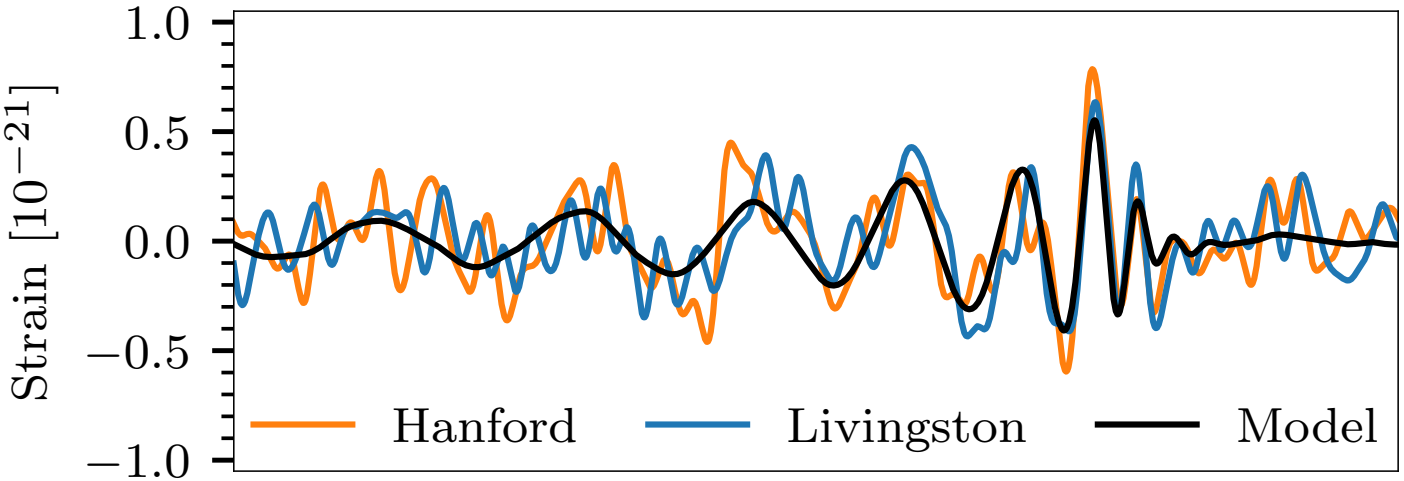
Update on LIGO



Aaron Zimmerman (on behalf of the LSC)
Canadian Institute for Theoretical Astrophysics

Capra 20
June 19, 2017

LIGO Scientific Collaboration

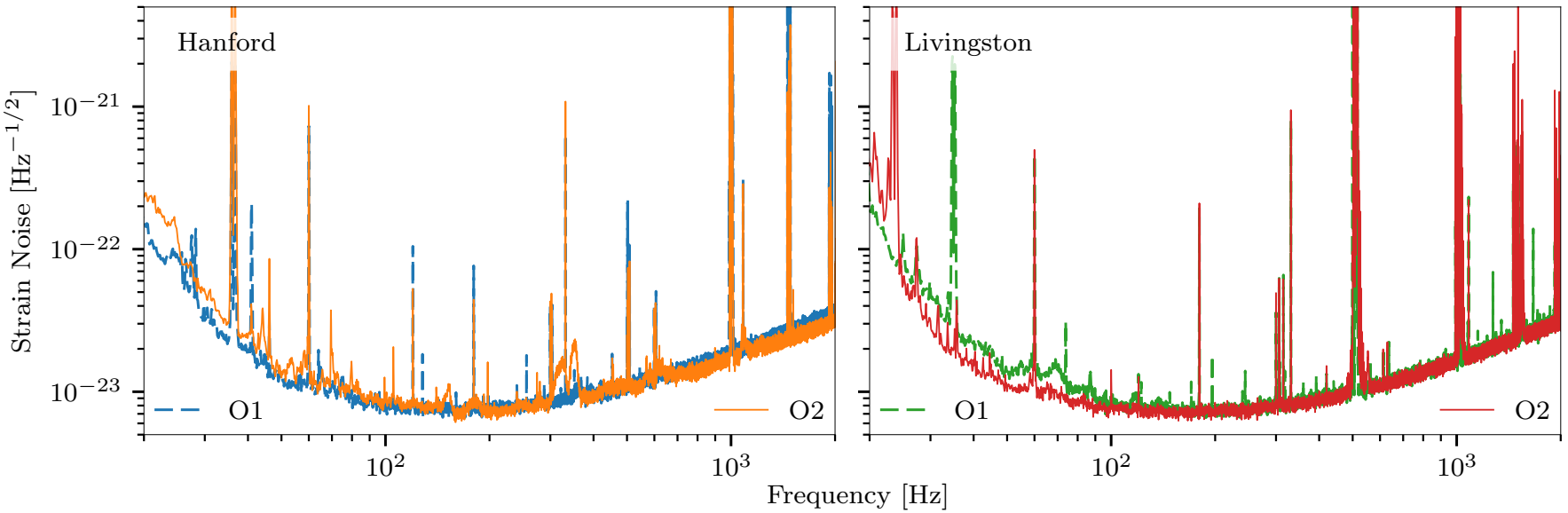
Advanced LIGO

Livingston, LA

Hanford, WA

Photos courtesy LSC

O2 so far



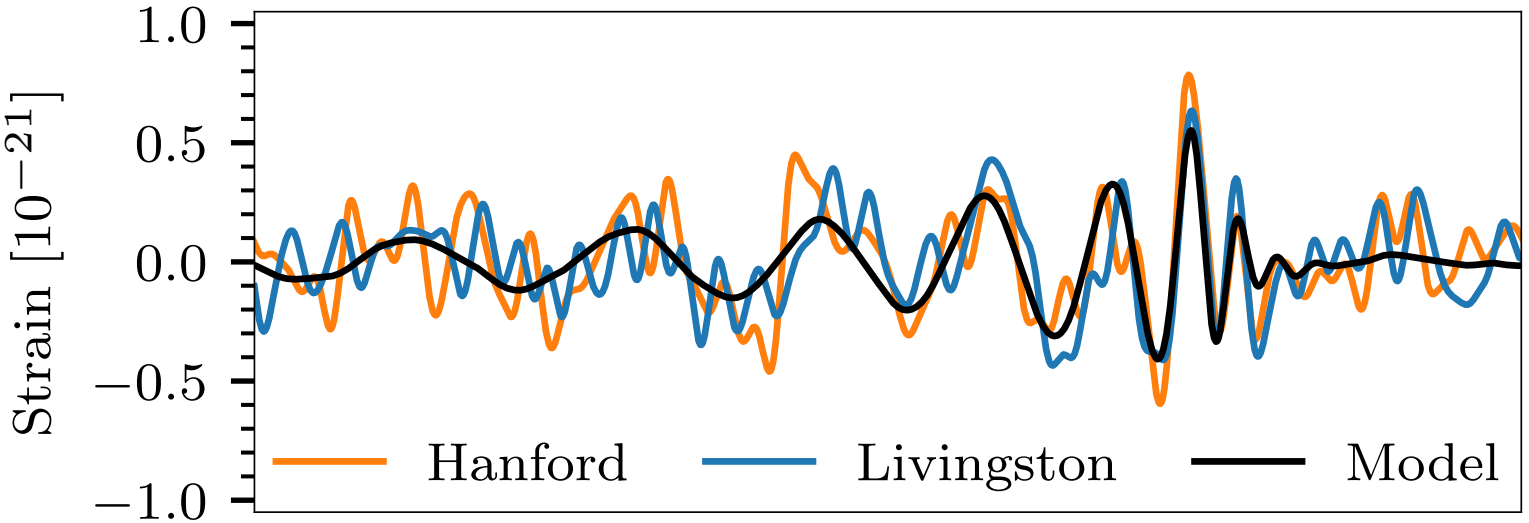
- O1 9/12/15 - 01/19/16: 2.9 detections
- O2 started 11/30/16, ongoing
- First results published June 1: GW170104, a 50 solar-mass BBH

LVC, PRL 118 (2017)

Part 1

GW170104: THE NEW KID ON THE BLOCK

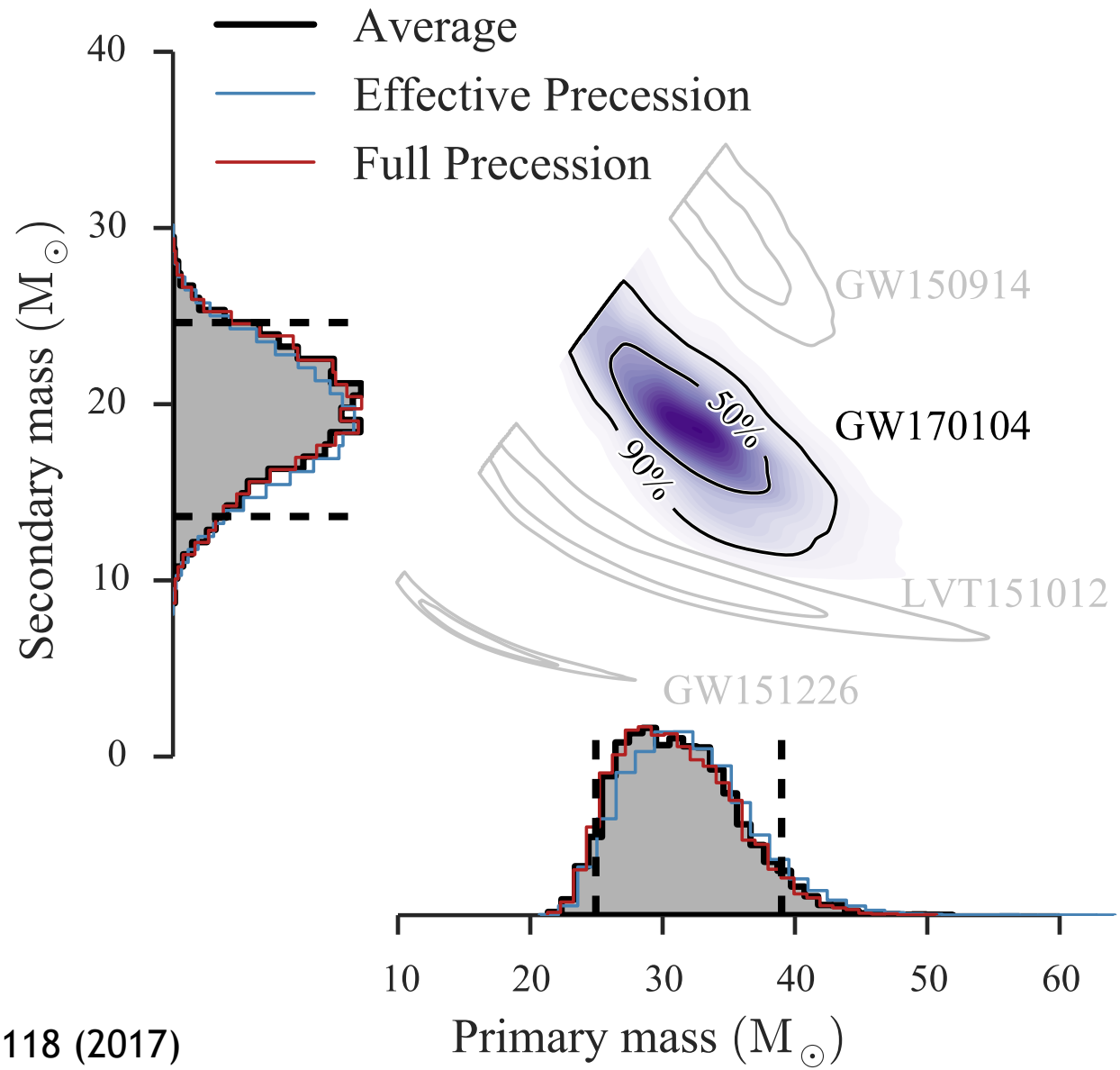
GW170104 at a glance



Primary black hole mass m_1	$31.2^{+8.4}_{-6.0}\,M_\odot$
Secondary black hole mass m_2	$19.4^{+5.3}_{-5.9}\,M_\odot$
Total mass M	$50.7^{+5.9}_{-5.0}\,M_\odot$
Final black hole mass M_f	$48.7^{+5.7}_{-4.6}\,M_\odot$
Luminosity distance D_L	880^{+450}_{-390} Mpc
Source redshift z	$0.18^{+0.08}_{-0.07}$

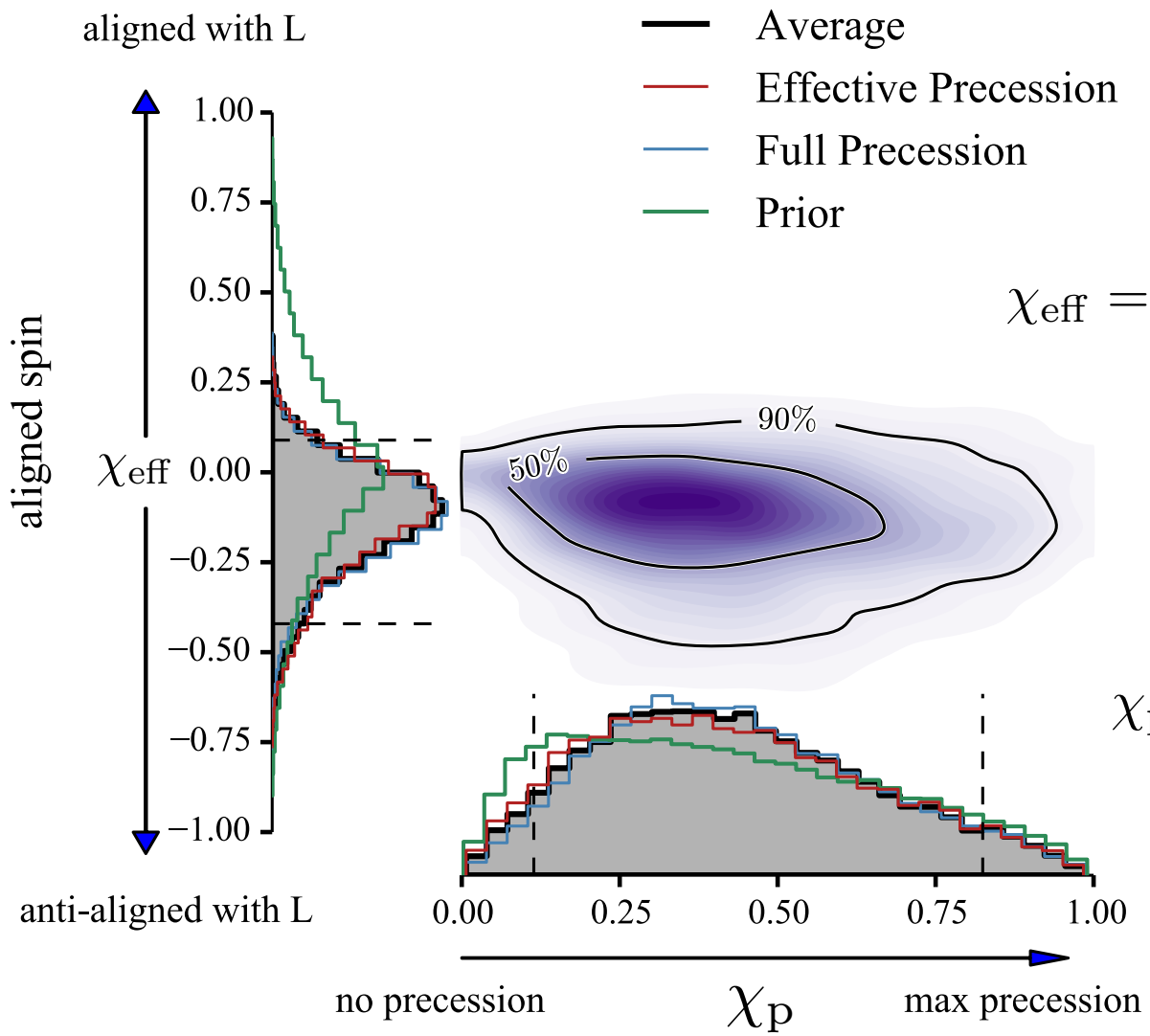
LVC, PRL 118 (2017)

Masses



LVC, PRL 118 (2017)

Spins



$$\chi_{\rm eff} = \frac{m_1 a_{1,\parallel} + m_2 a_{2,\parallel}}{m_1 + m_2}$$

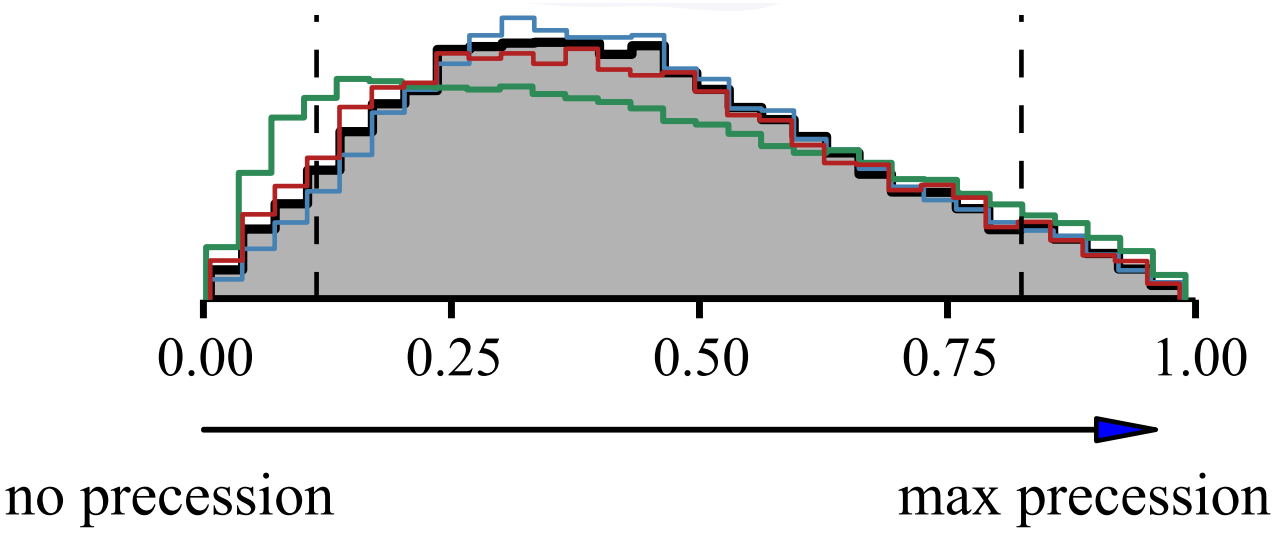
$$\vec{a}_i = \vec{S}_i / m_i^2$$

$$\chi_{\rm p} \sim (a_{1,\perp}, a_{2,\perp})$$

LVC, PRL 118 (2017)

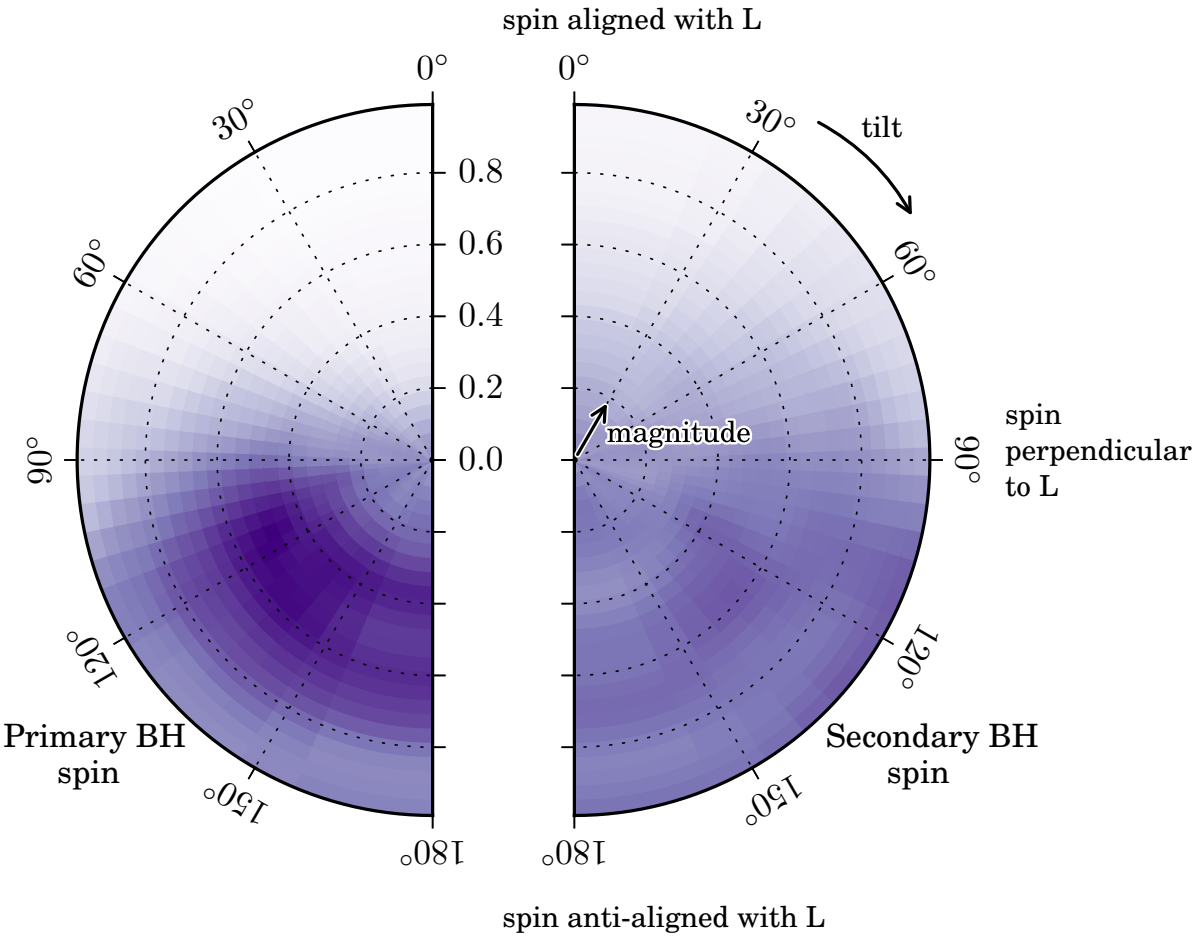
Precession?

- Precession parameter not much different than prior
- Little can be said about precession



LVC, PRL 118 (2017)

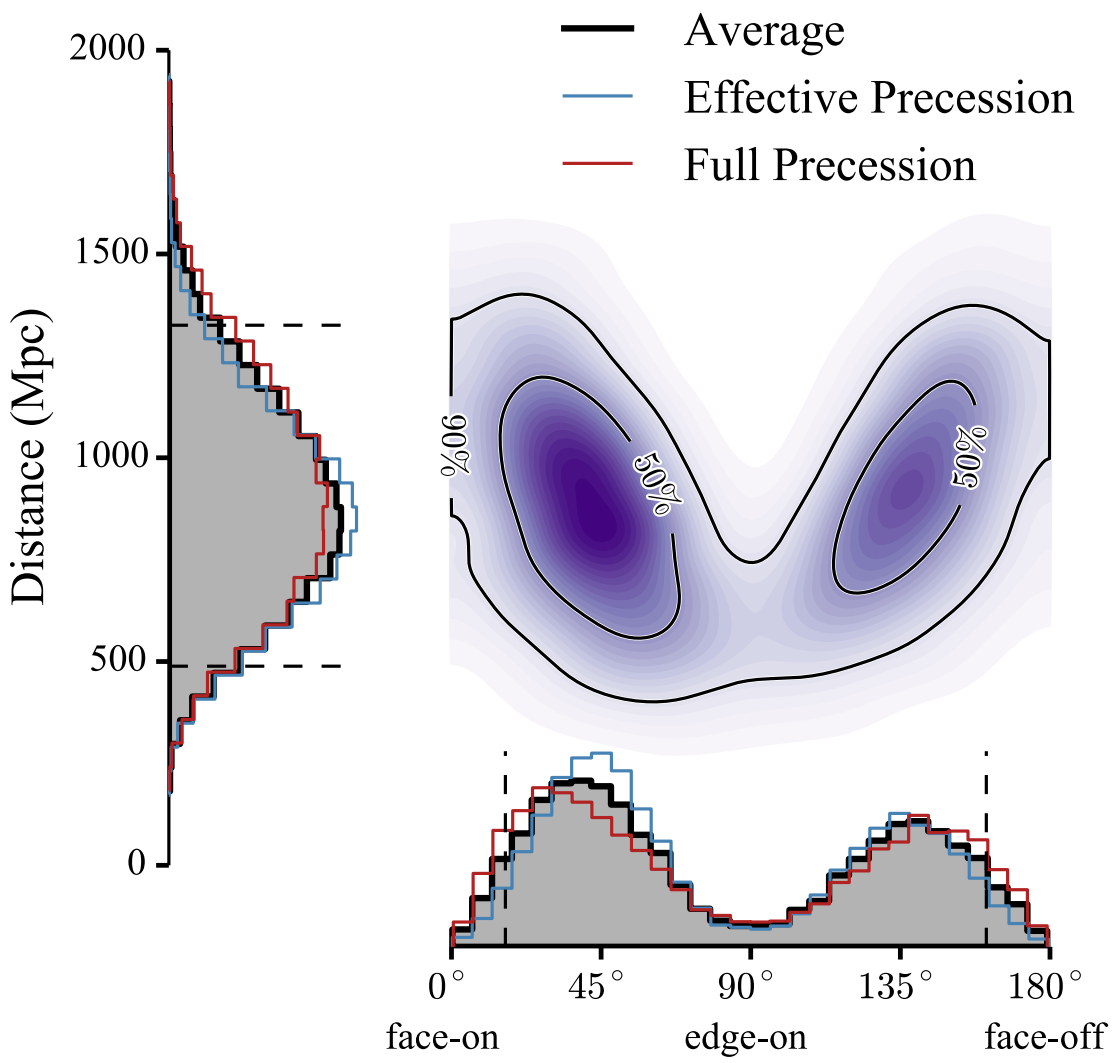
Spins



- Prob($m_1 a_{1,\parallel} + m_2 a_{2,\parallel} > 0$) < 0.18

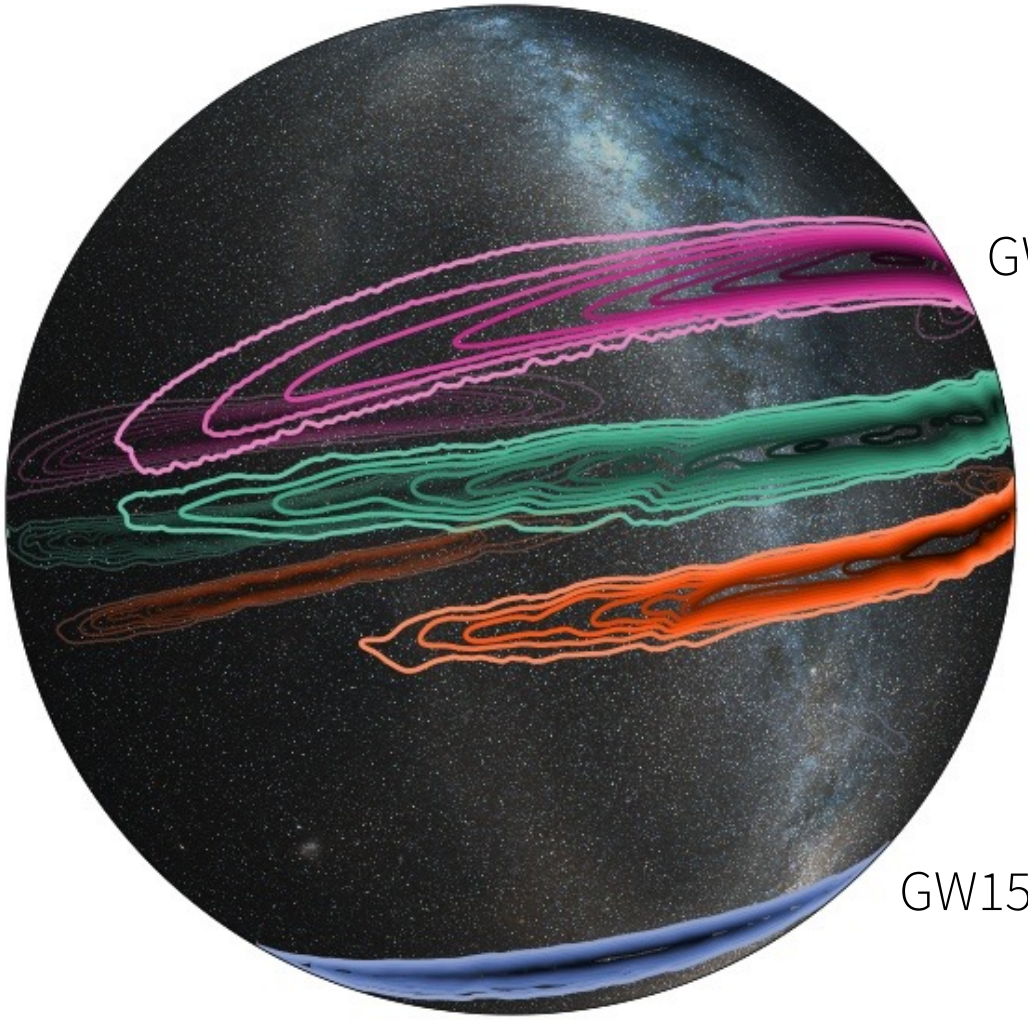
LVC, PRL 118 (2017)

Where?



LVC, PRL 118 (2017)

Where?

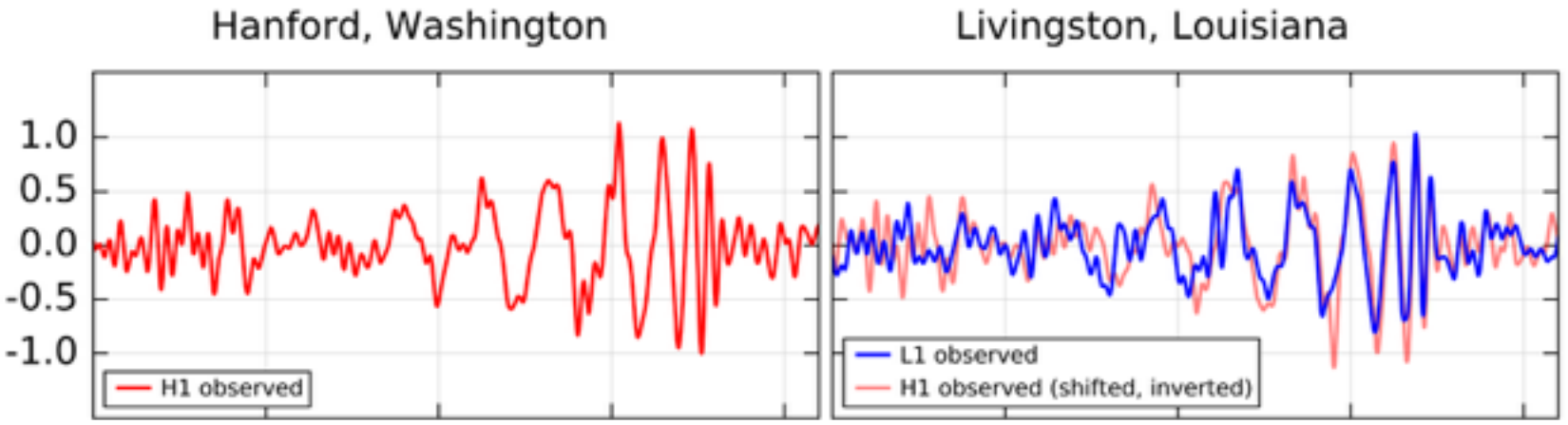


LSC/Leo Singer (Milky Way image: Axel Mellinger)

Part 2

BINARY BLACK HOLES TO DATE

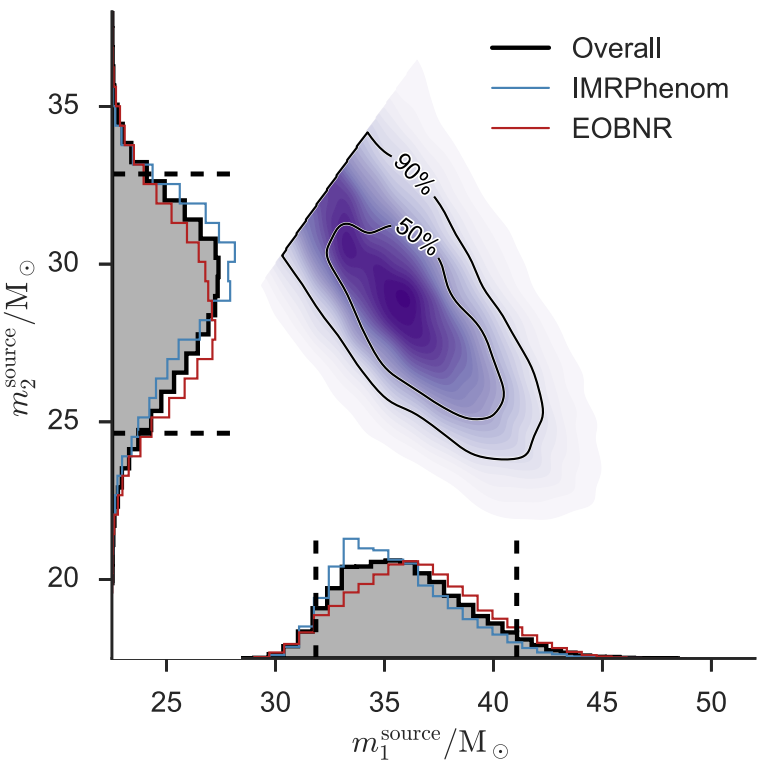
First detection: GW150914

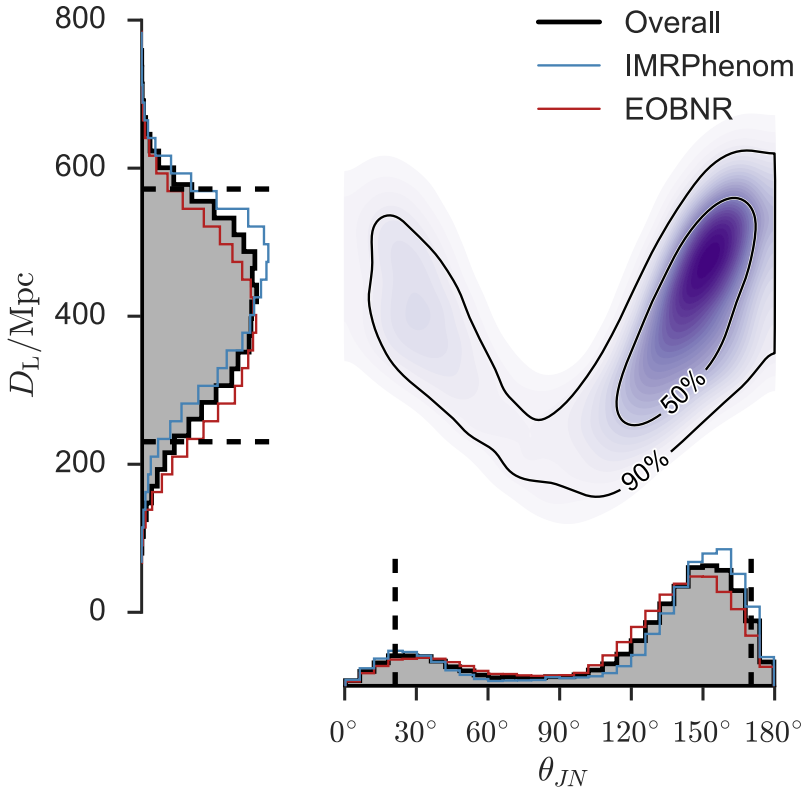


- GW150914: the merger of two BHs
- Masses $m_1 = 36^{+5}_{-4} M_\odot \quad m_2 = 29^{+4}_{-4} M_\odot$
- Final black hole $M_f = 62^{+4}_{-4} M_\odot \quad \chi_f = 0.67^{+0.05}_{-0.07}$
- Luminosity distance $D_L = 410^{+160}_{-180} \mathrm{Mpc}$

LVC arXiv:1602.03837

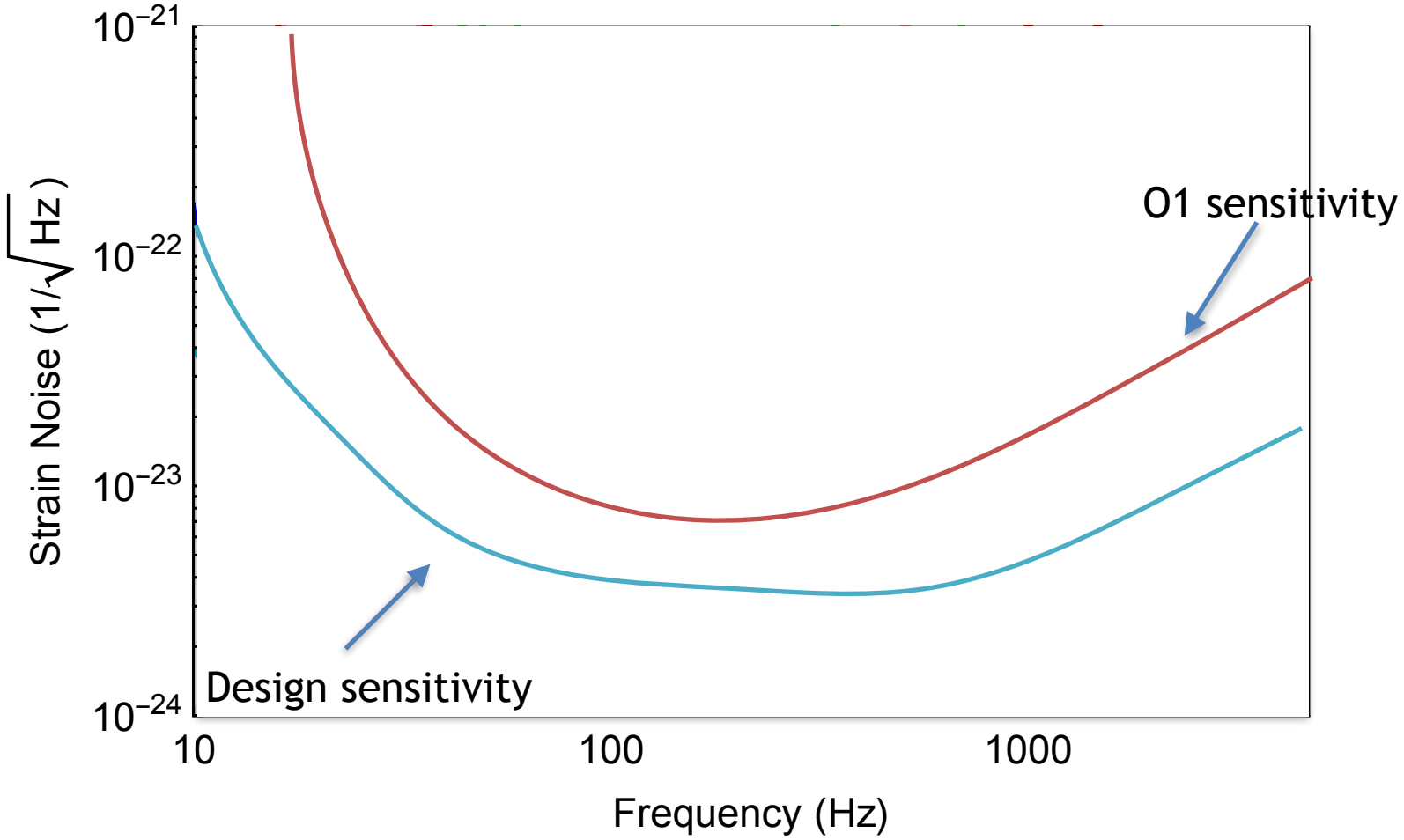
First detection: Massive binary



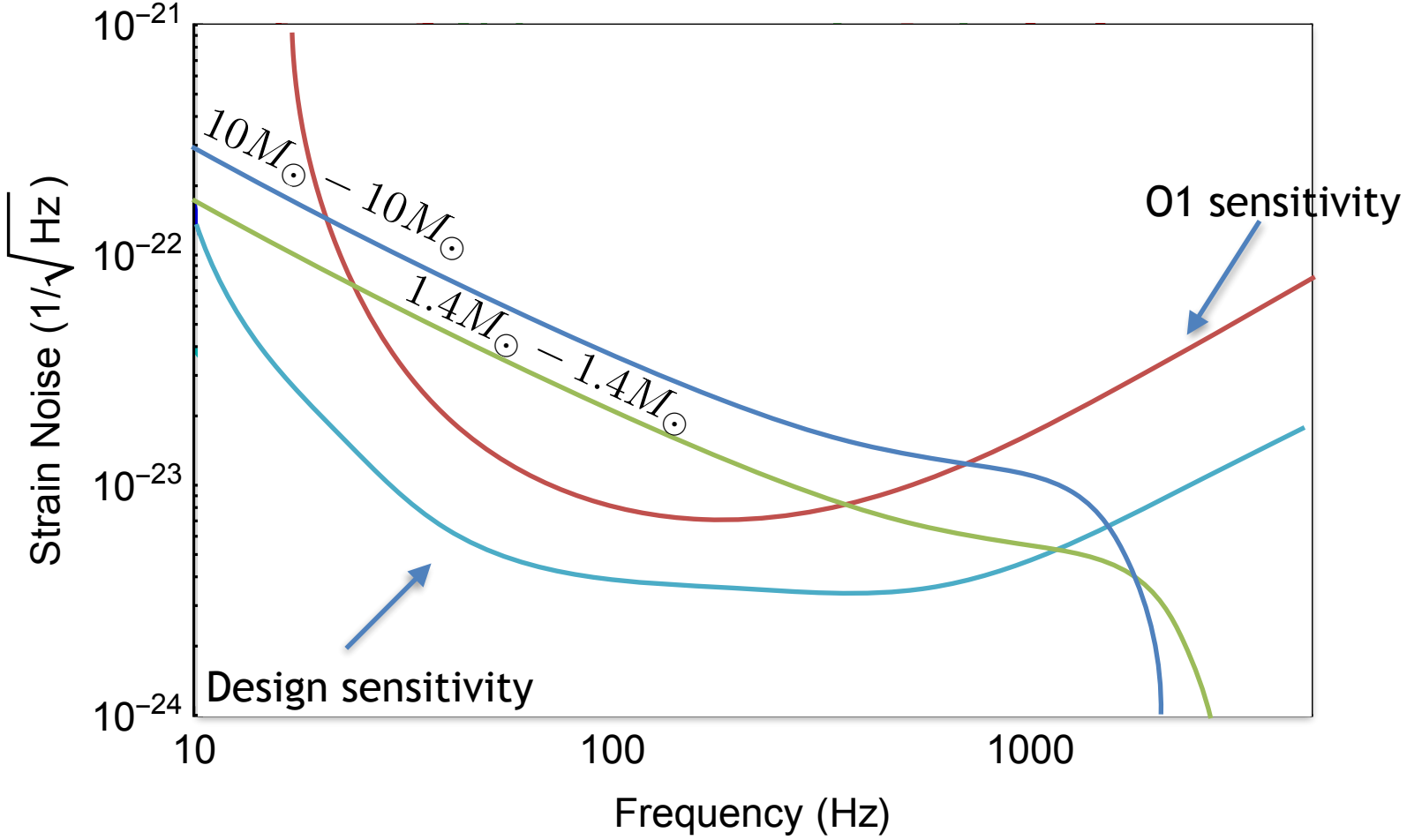


LVC,arXiv:1602.03840

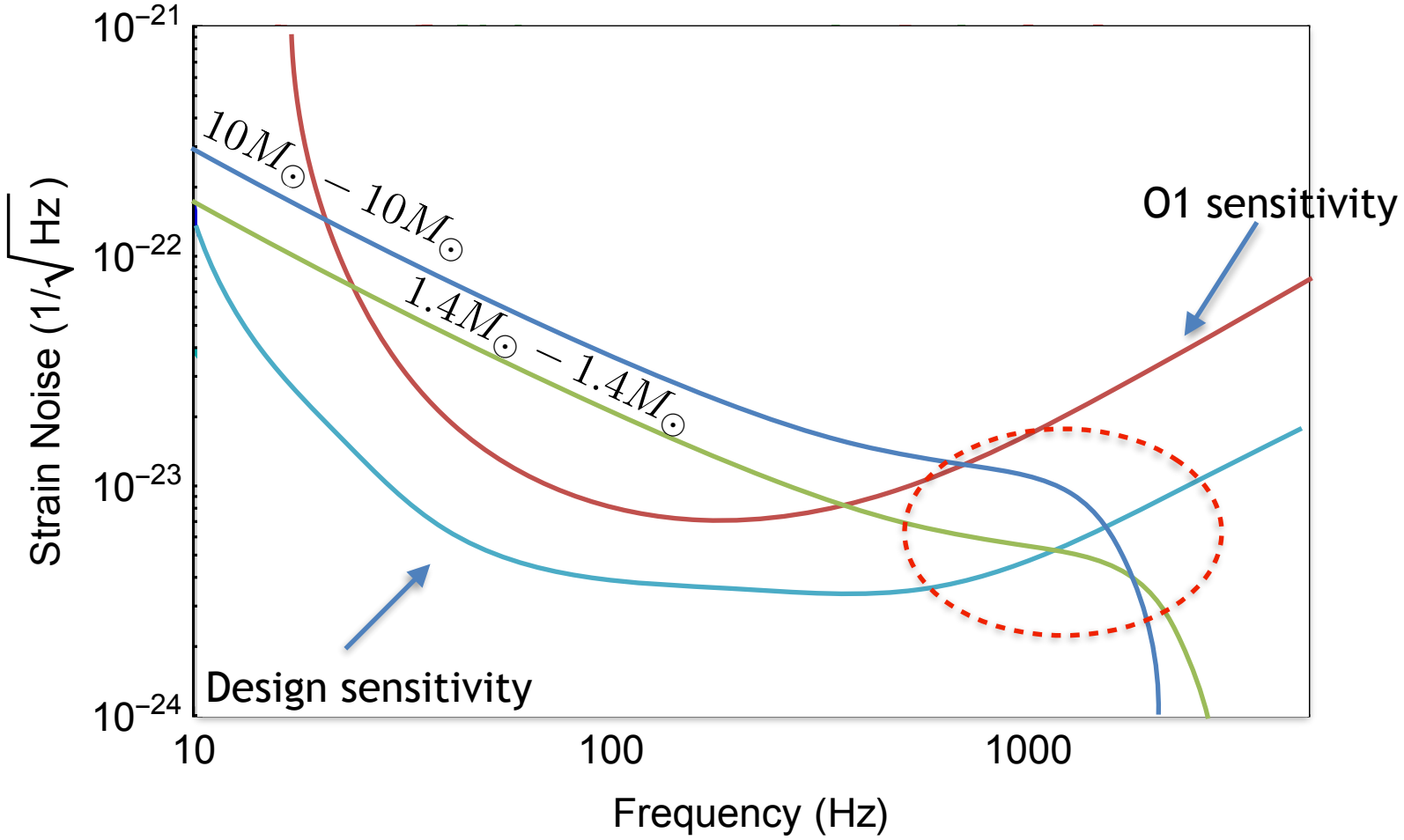
First detection: Massive binary



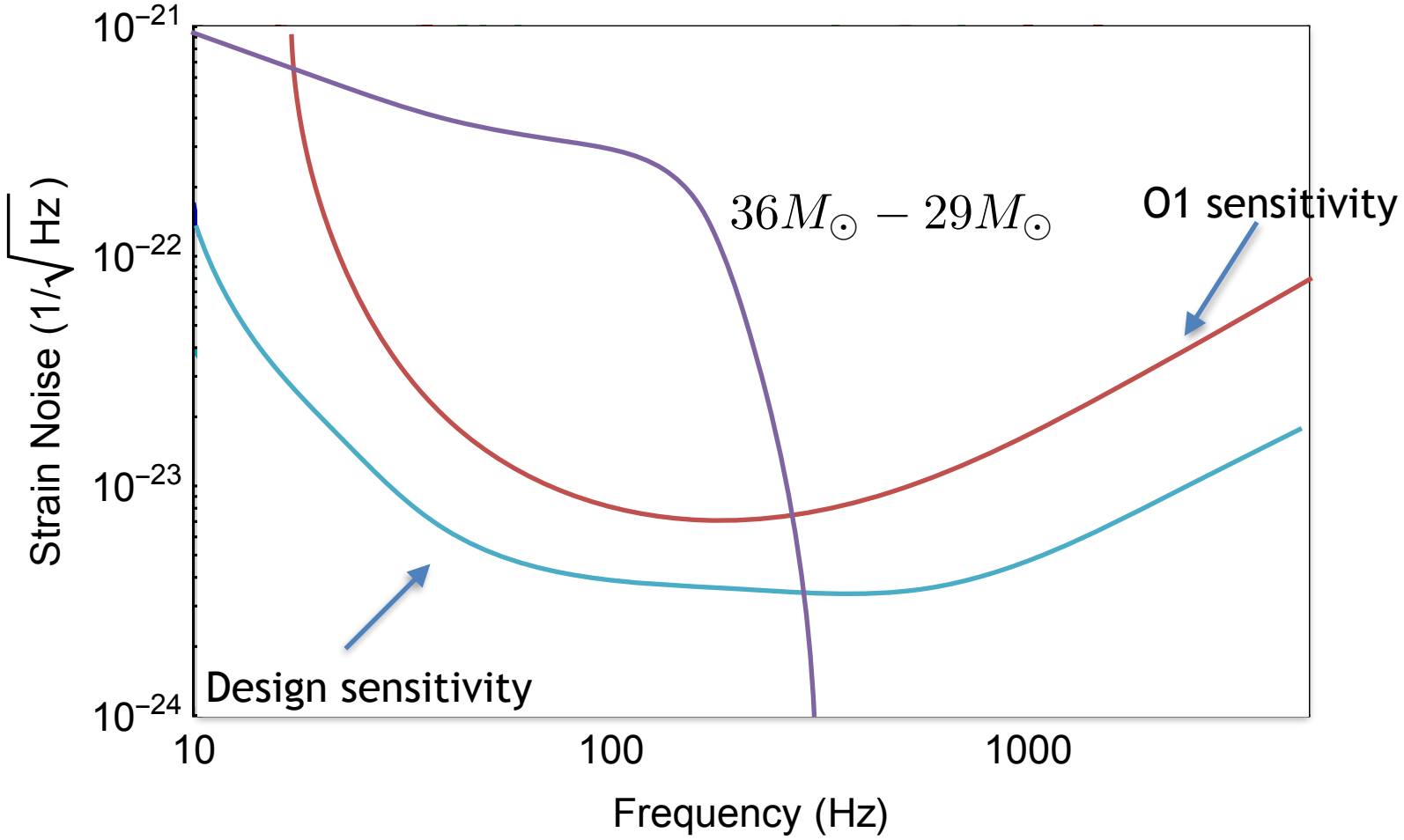
First detection: Massive binary



First detection: Massive binary

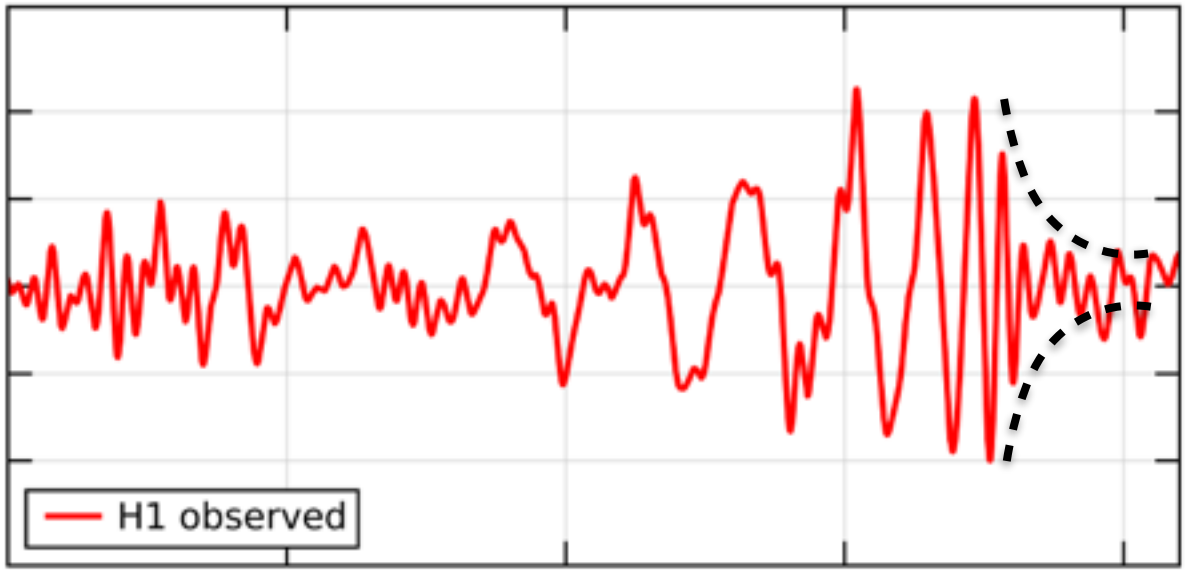


First detection: Massive binary



First detection: A BH ringdown

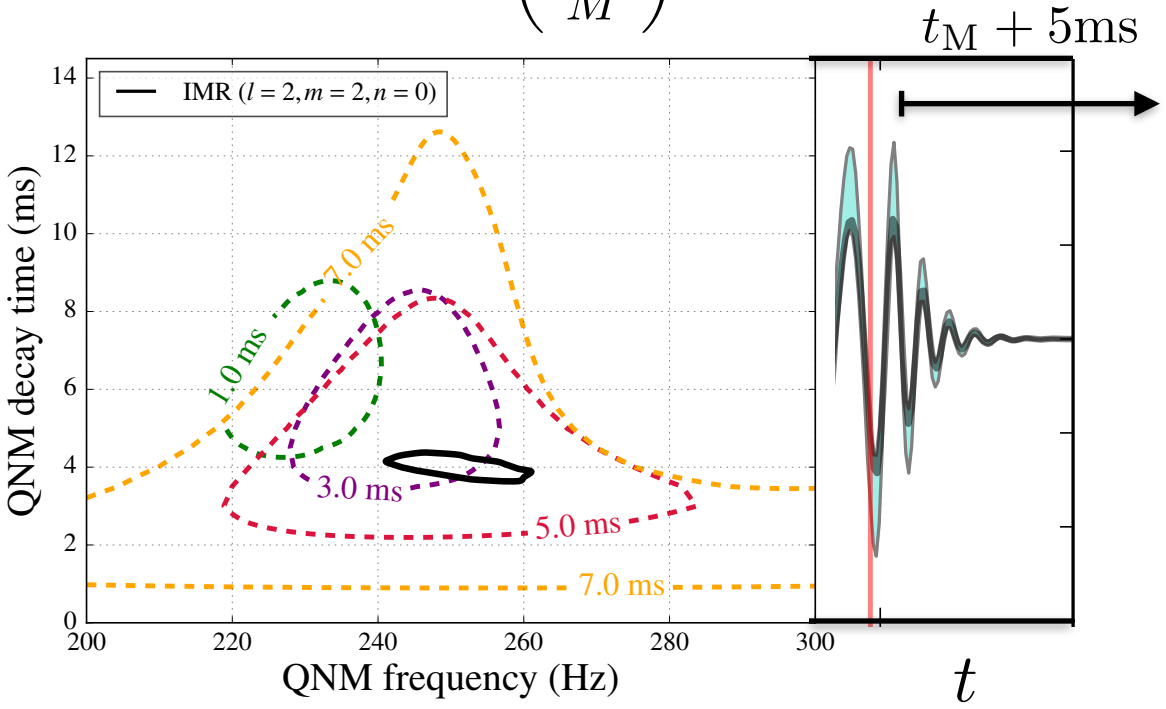
- Most exciting thing about the first detection (to me): observation of ringdown



LVC arXiv:1602.03837

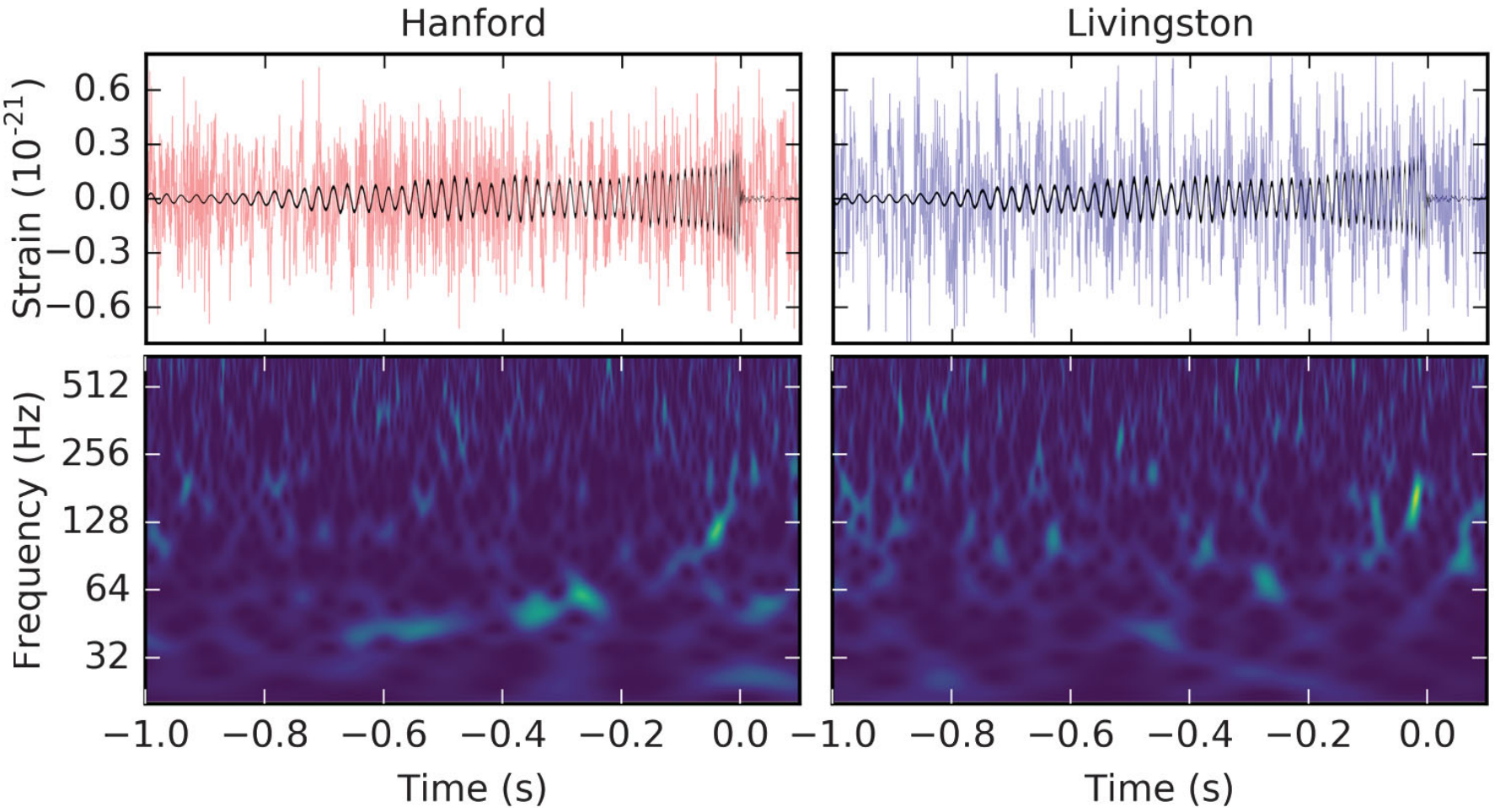
The ringdown of GW150914

- First detection of a BH ringdown
- Freq and decay of lowest overtone for $\ell = 2,\ m = 2$
- Consistent with GR $f \propto 30 \left(\frac{M_\odot}{M}\right) \mathrm{kHz}$



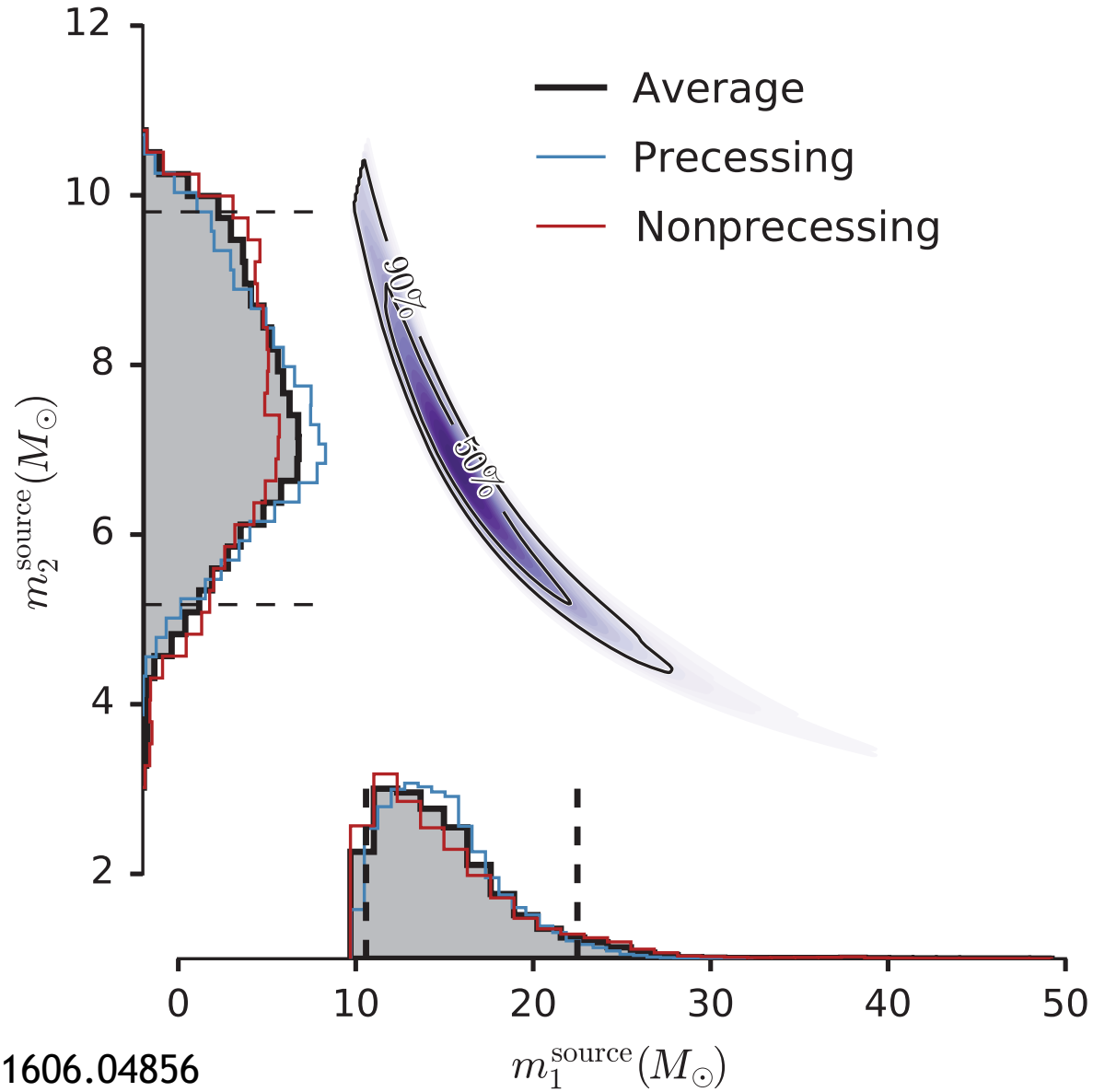
LSC, arXiv:1602.03841

“Boxing Day” GW151226



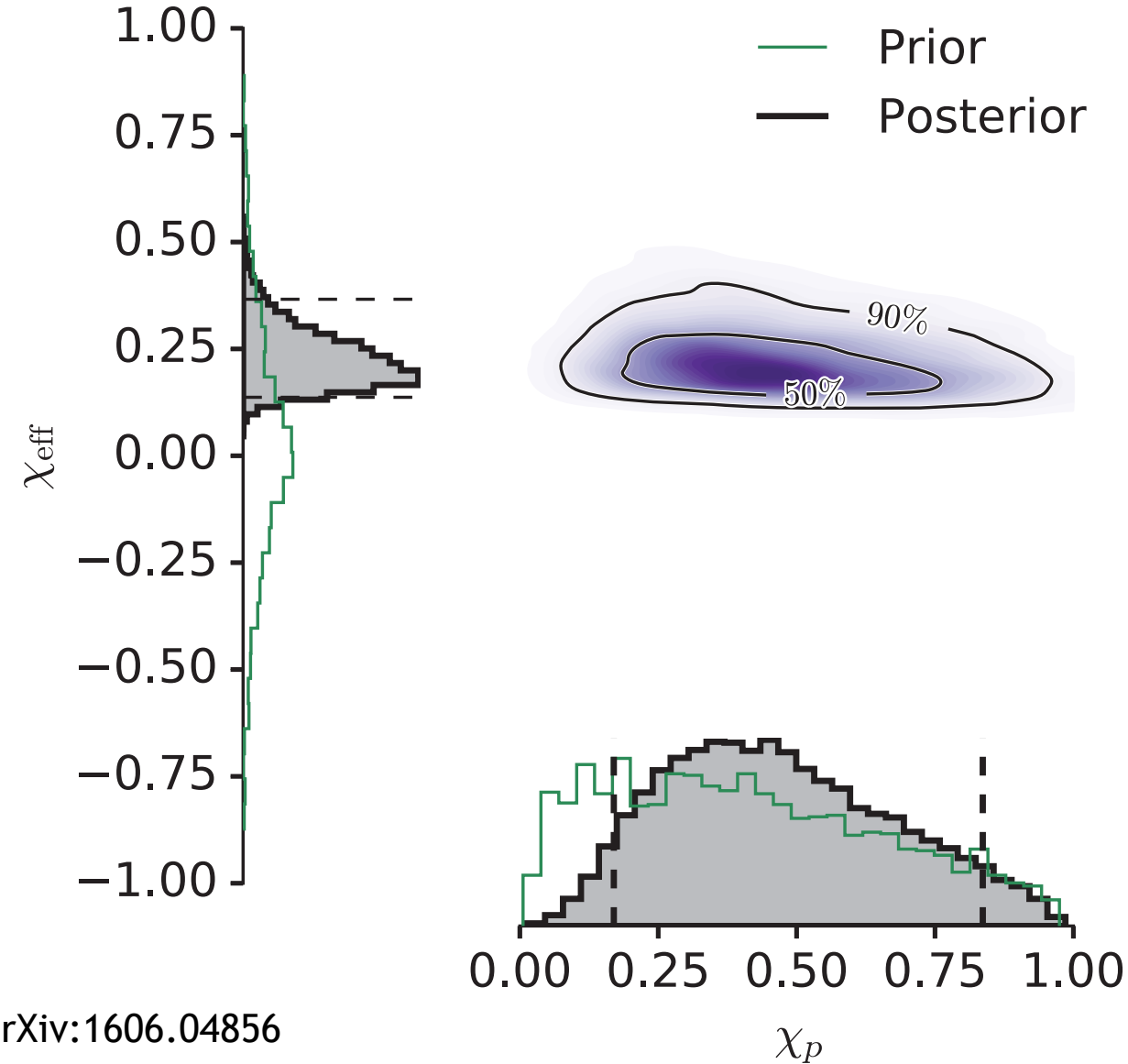
LVC, arXiv:1606.04856

Lowest mass BBH



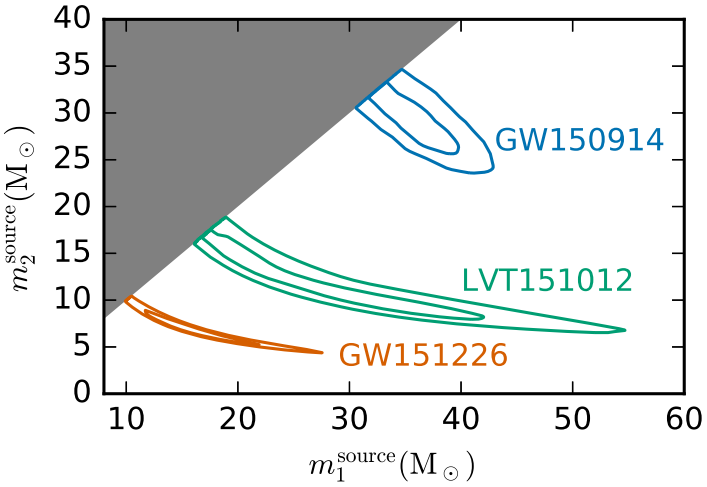
LVC, arXiv:1606.04856

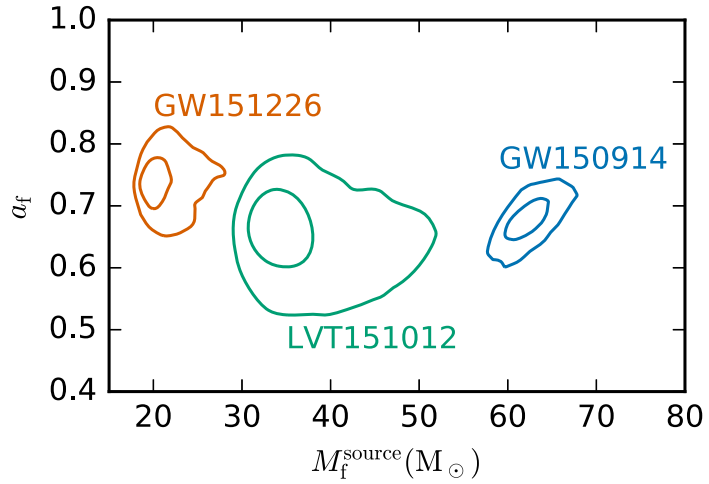
Spin and Boxing Day

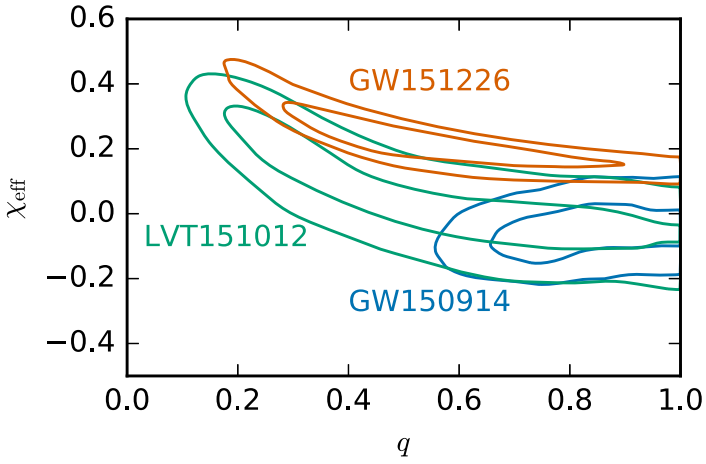


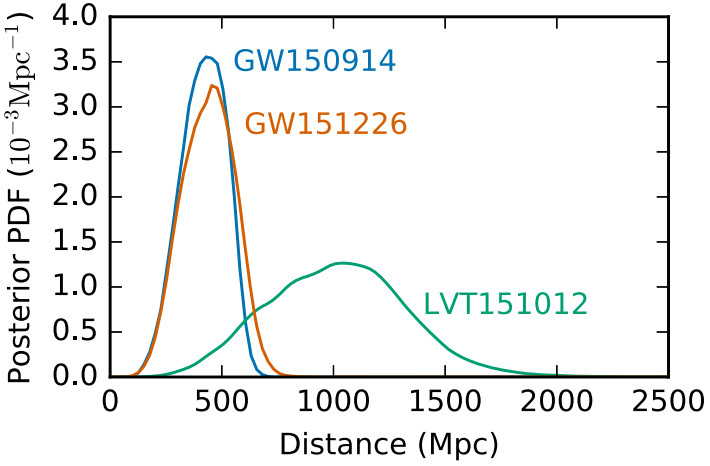
LVC, arXiv:1606.04856

Binary black holes in O1



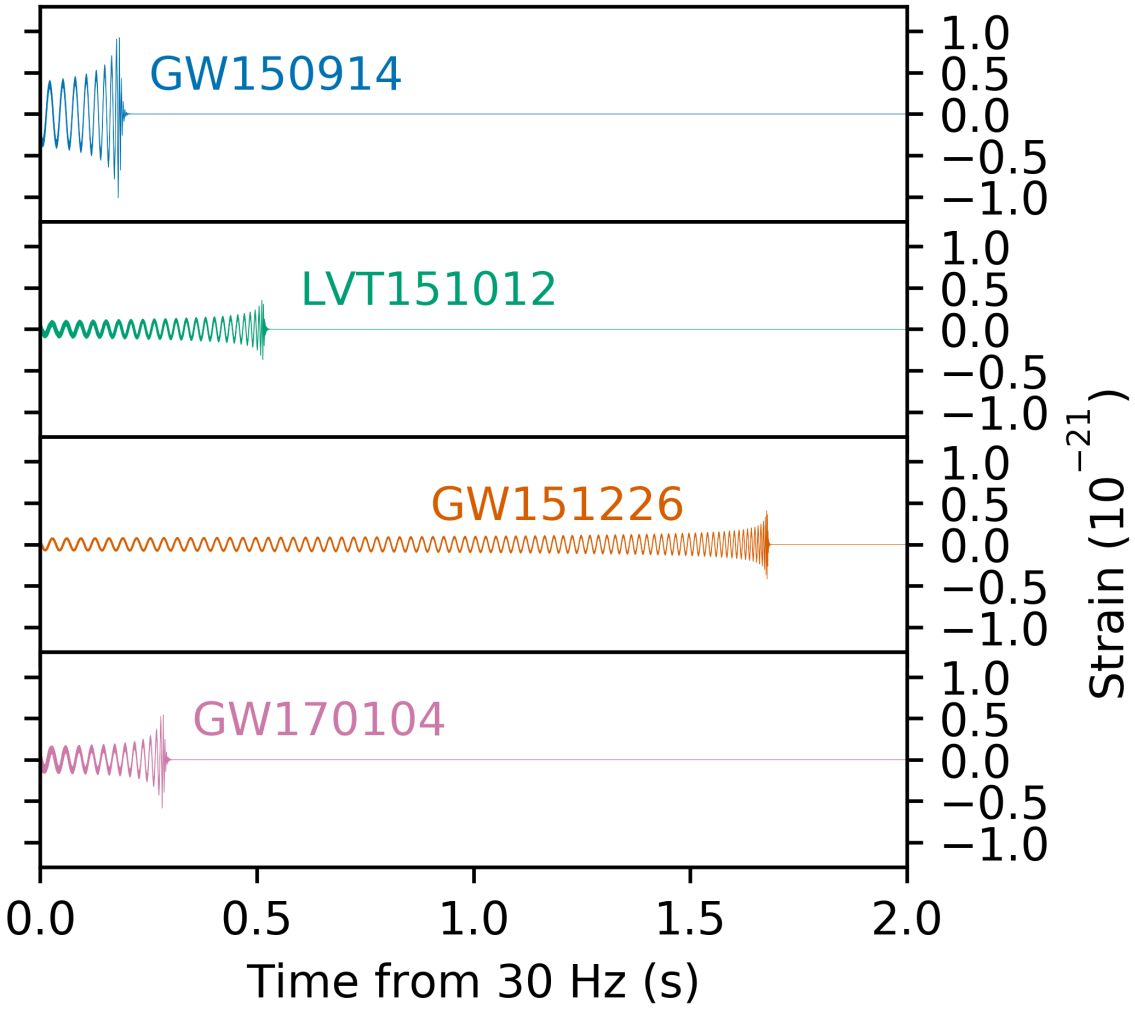






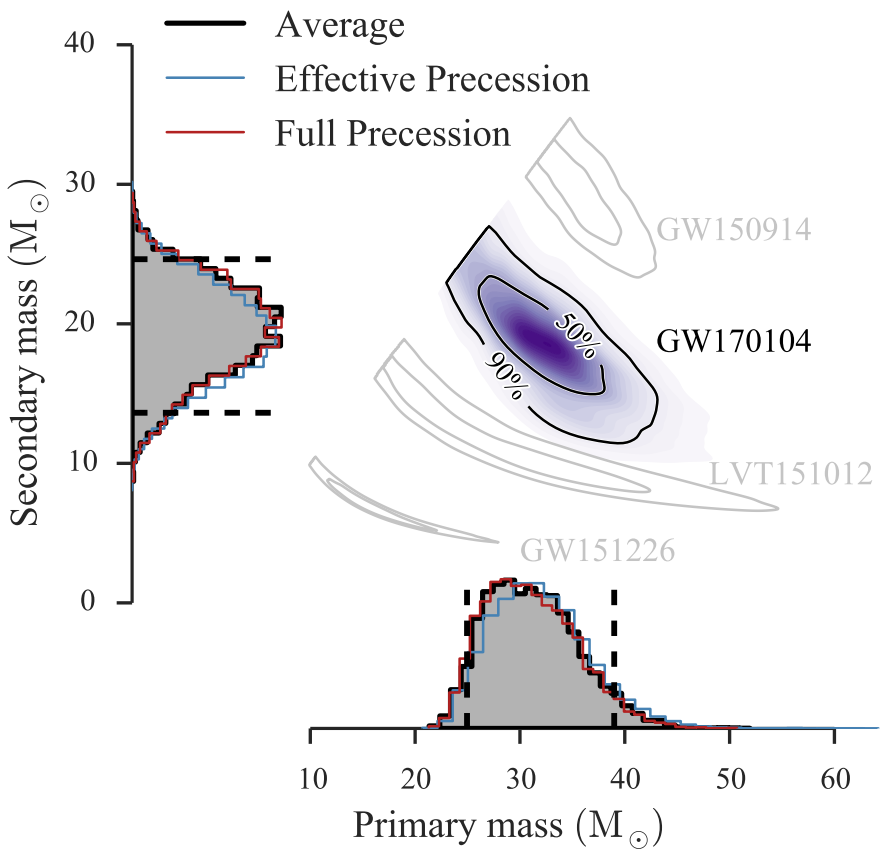
LVC, arXiv:1606.04856

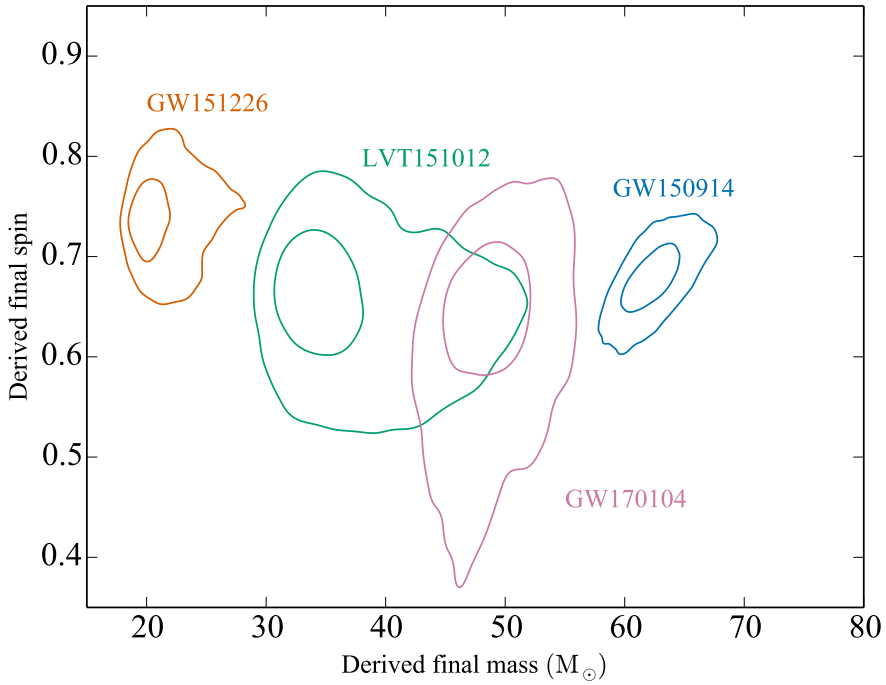
The signals so far



Credit: LSC

Binary black holes so far

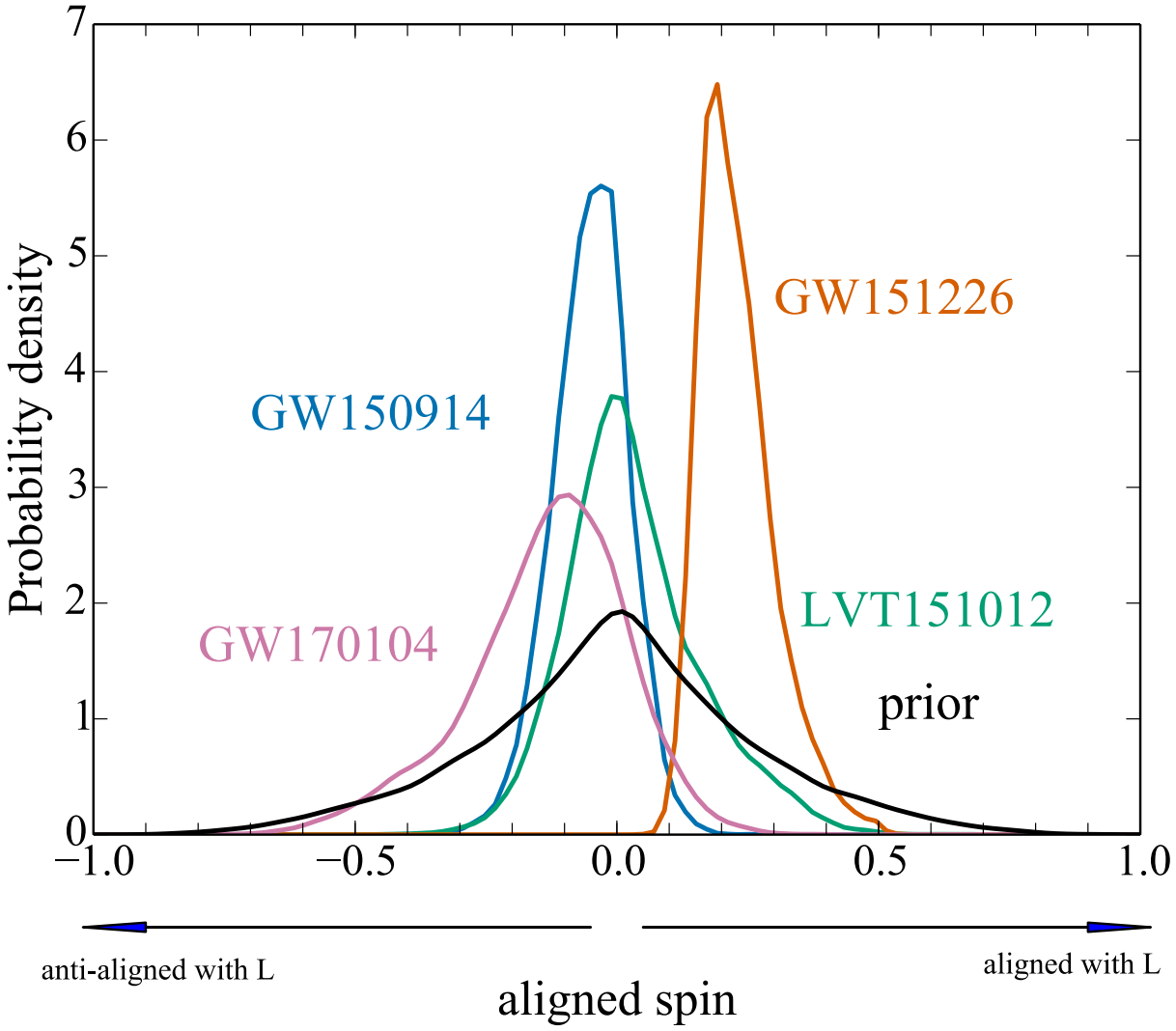




LVC, PRL 118 (2017)

LSC/

Binary black holes so far



LVC, PRL 118 (2017)

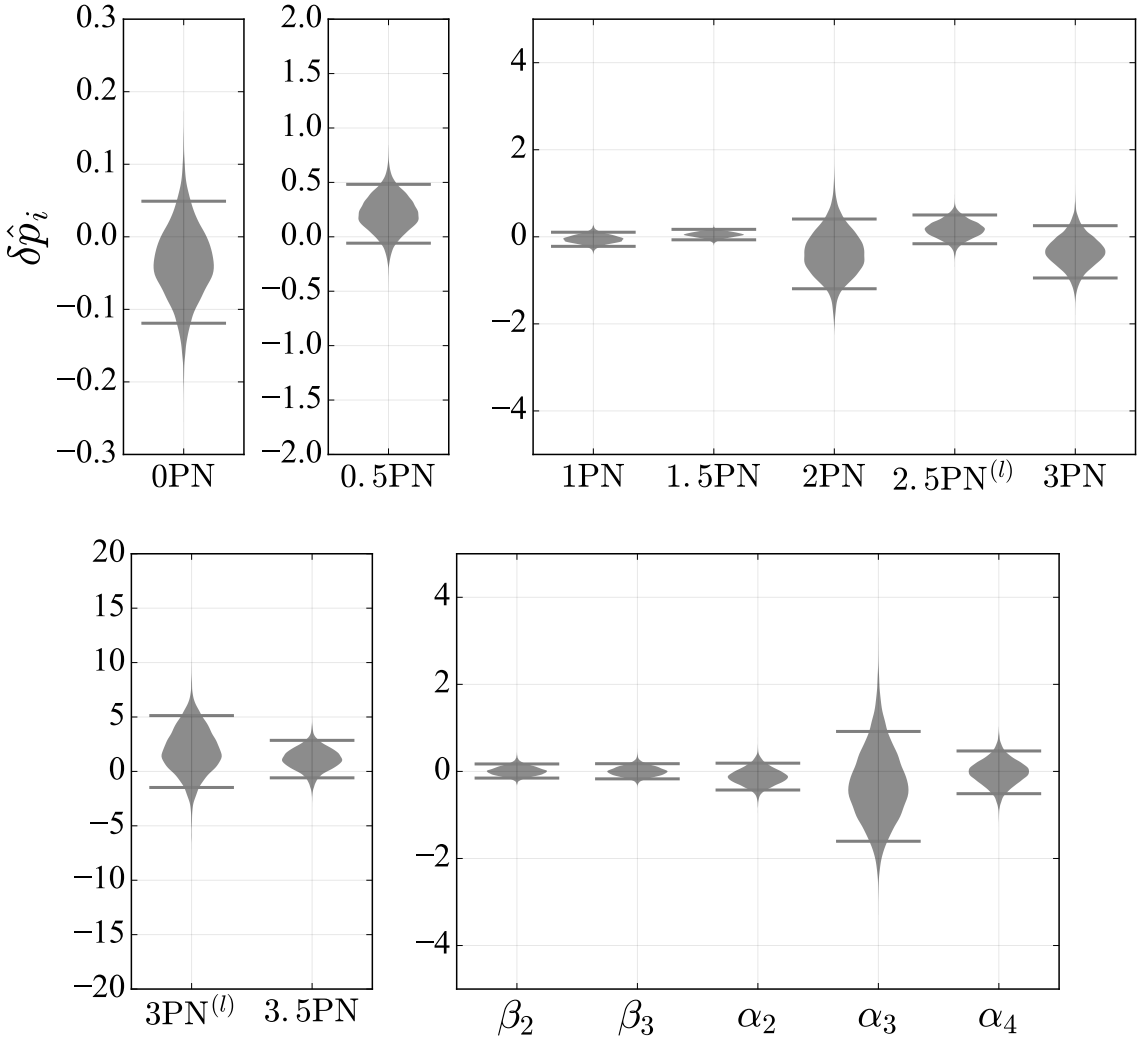
Part 3

TESTS OF GR AND ASTRO IMPLICATIONS

Parameterized tests of GR

$$\Psi = \sum p_i f^i$$

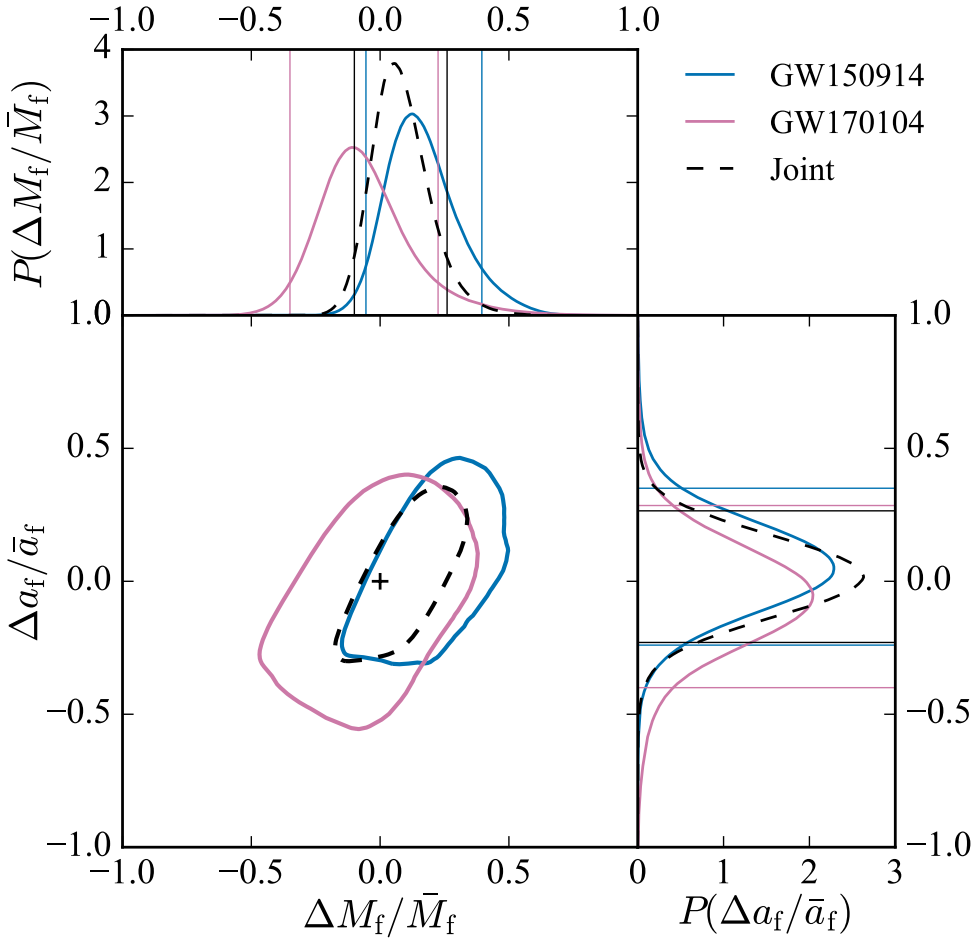
$$p_i \to p_i(1 + \delta\hat{p}_i)$$



LVC, PRL 118 (2017)

IMR consistency test

- Null test of GR
- Split waveform at remnant ISCO freq
- Infer final mass and spin from I and MR separately
- Only possible when SNR in MR large



LVC, PRL 118 (2017)

Lorentz invariance test: back of the envelope

- New test for LIGO: modified dispersion of GWs

$$E^2 = p^2c^2 + Ap^\alpha c^\alpha \qquad \Rightarrow \qquad \delta v_g = (\alpha - 1)AE^{\alpha-2}/2$$

- A has units of energy to some power
- Natural energy scale:

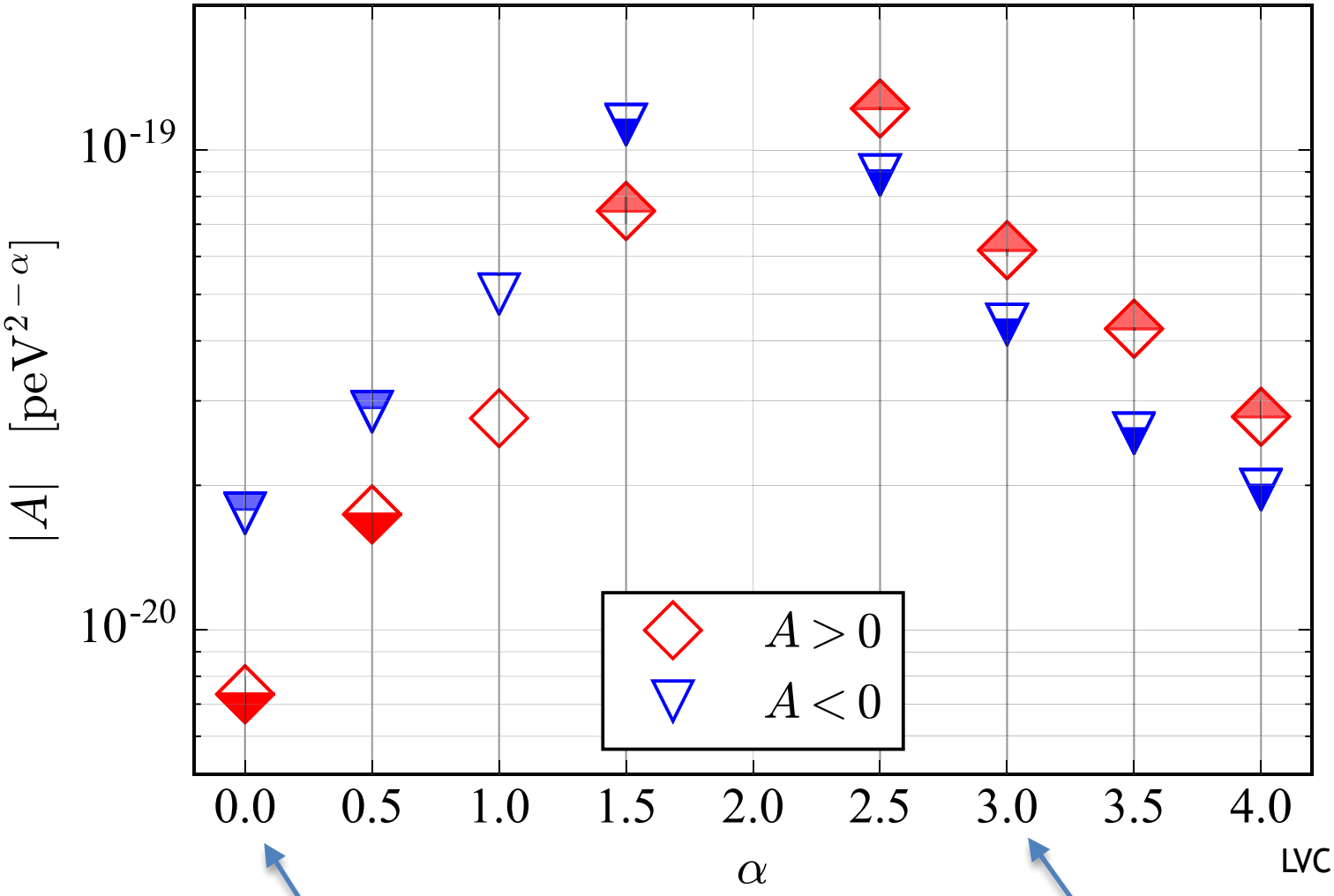
$$h_{\rm P} f \sim h_{\rm P} 250{\rm Hz} \sim 1{\rm peV}$$

- Dispersion modifies phase as

$$\delta\Psi \sim \delta v_g \frac{D}{\lambda_{\rm GW}}$$

- For 800 Mpc and 250Hz, $\delta v_g \sim 5 \times 10^{-20}$

Lorentz invariance test

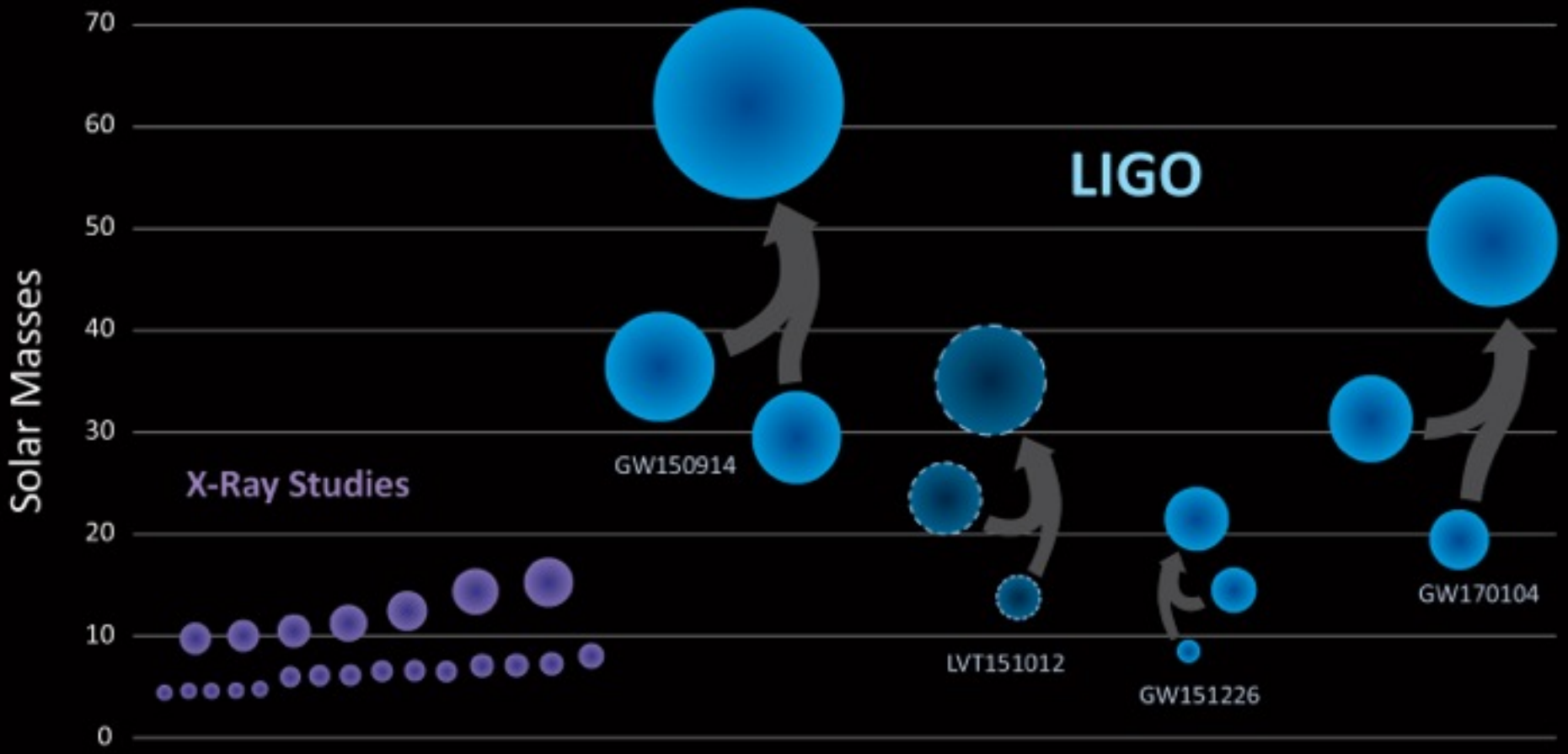


LVC, PRL 118 (2017)

Massive graviton

doubly special relativity

Black Holes of Known Mass



LSC/Sonoma State University/Aurore Simonnet

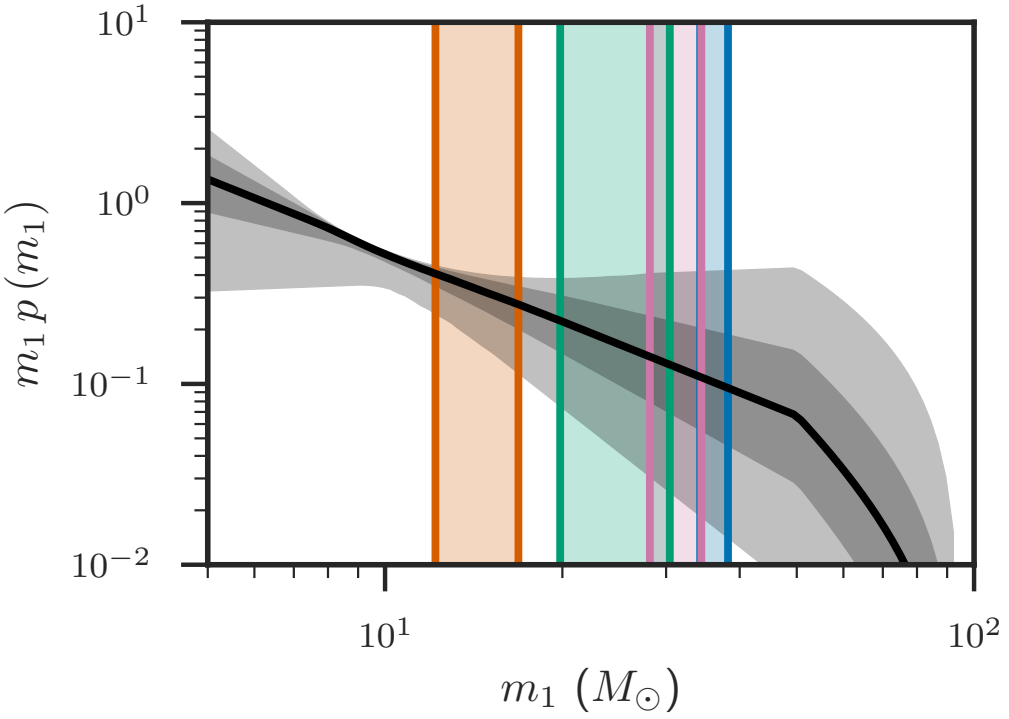
BBH Rates

- Rates based on 62.5 days coincident running (O1 + 11 days in O2)
- ~3.9 BBH detections
- 12-213 $Gpc^{-3}\,yr^{-1}$ (90% CL)

$$R_{\log\,\mathrm{mass}} = 32^{+33}_{-20}\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$$

$$R_{\mathrm{power\,law}} = 103^{+110}_{-63}\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$$

Power law index 2.35

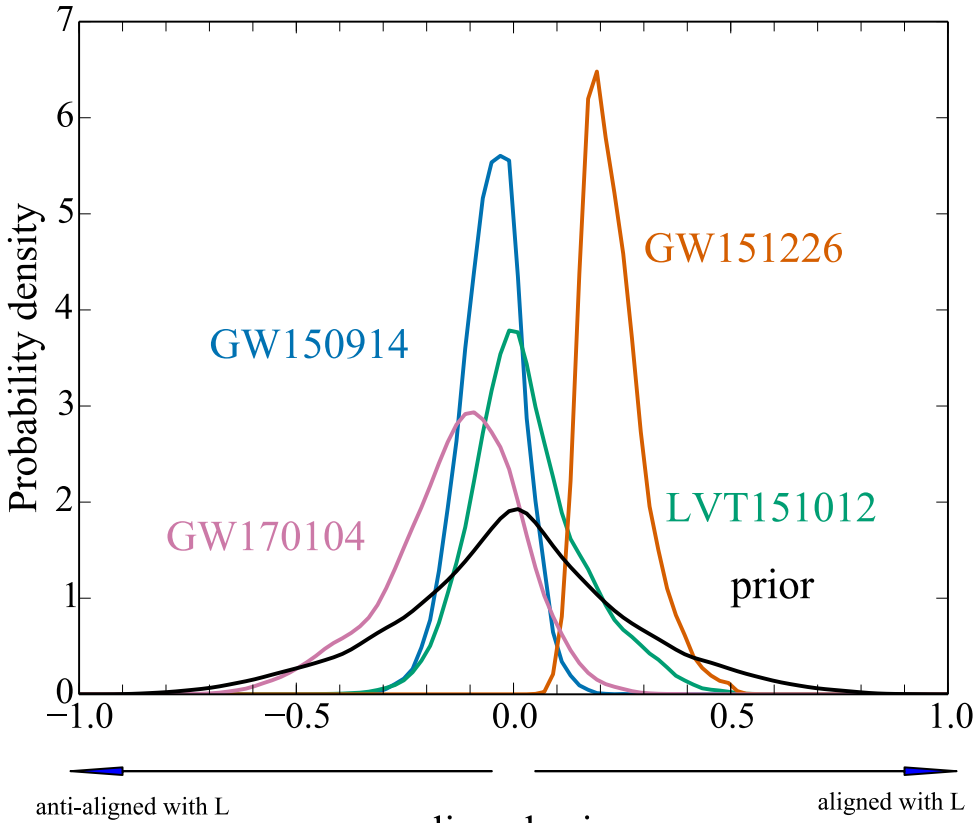


Inferred (modeled) mass distribution

LVC, PRL 118 (2017)

Formation channels

- Spin orientation a discriminator between binary evolution and dynamical formation



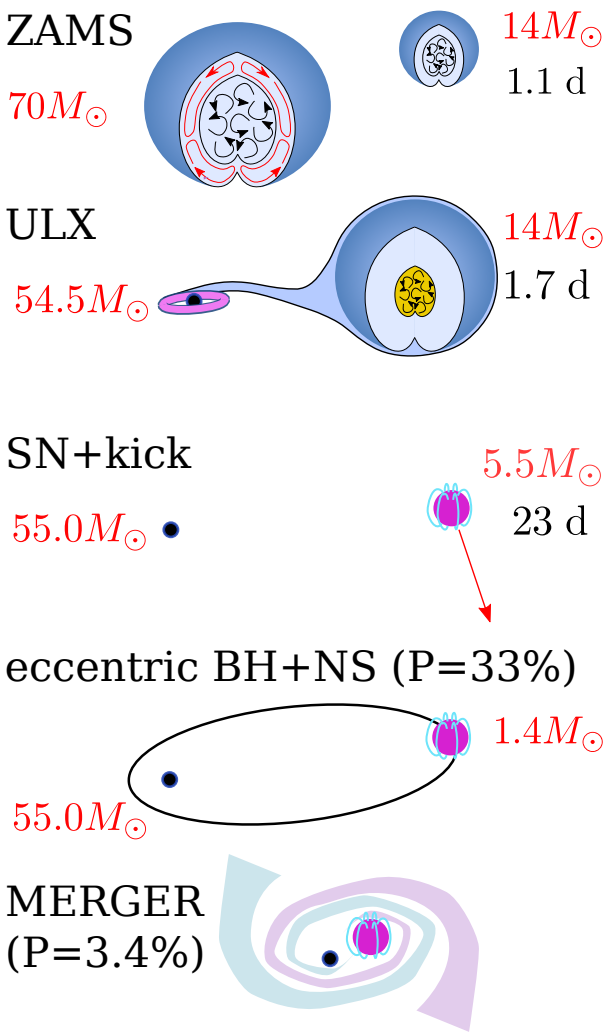
LVC, PRL 118 (2017)

Part 4

OUTLOOK

Role for high mass ratio systems

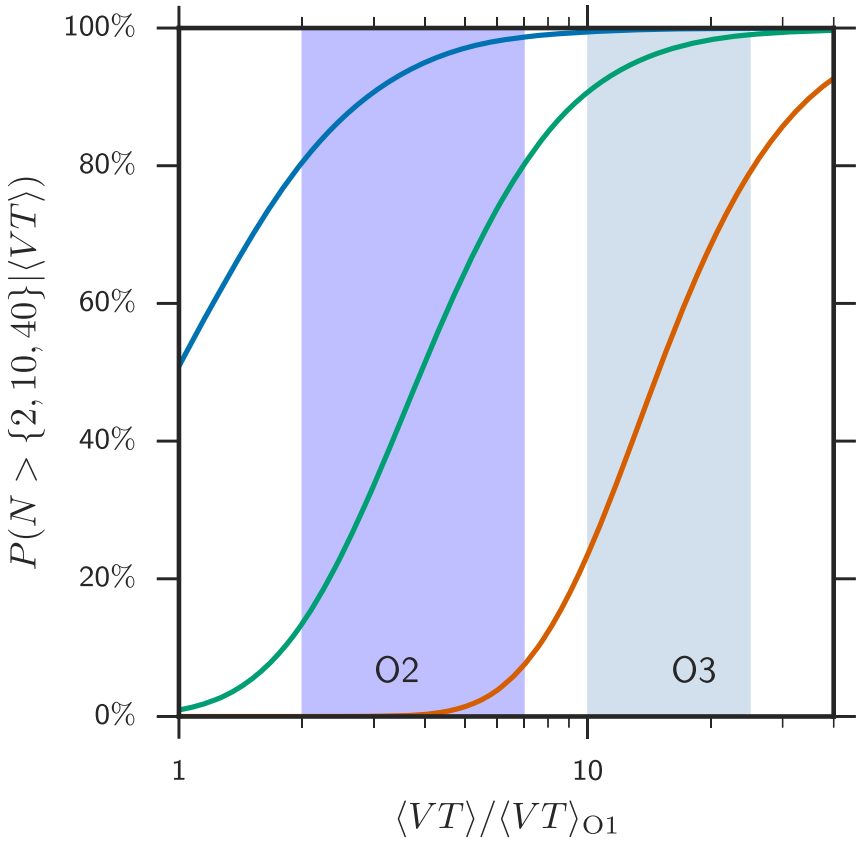
- O2 is ongoing
- IMBH search: masses to $10^5\,M_\odot$ but q$\geq$0.1
- Below 100 $M_\odot$ mass ratios ~ 0.01
- But modeling is poor above q ~ 1/8
- BHNS may have low q (Marchant et al. 2017)



Marchant et al. arXiv:1705.04734

What's up next?

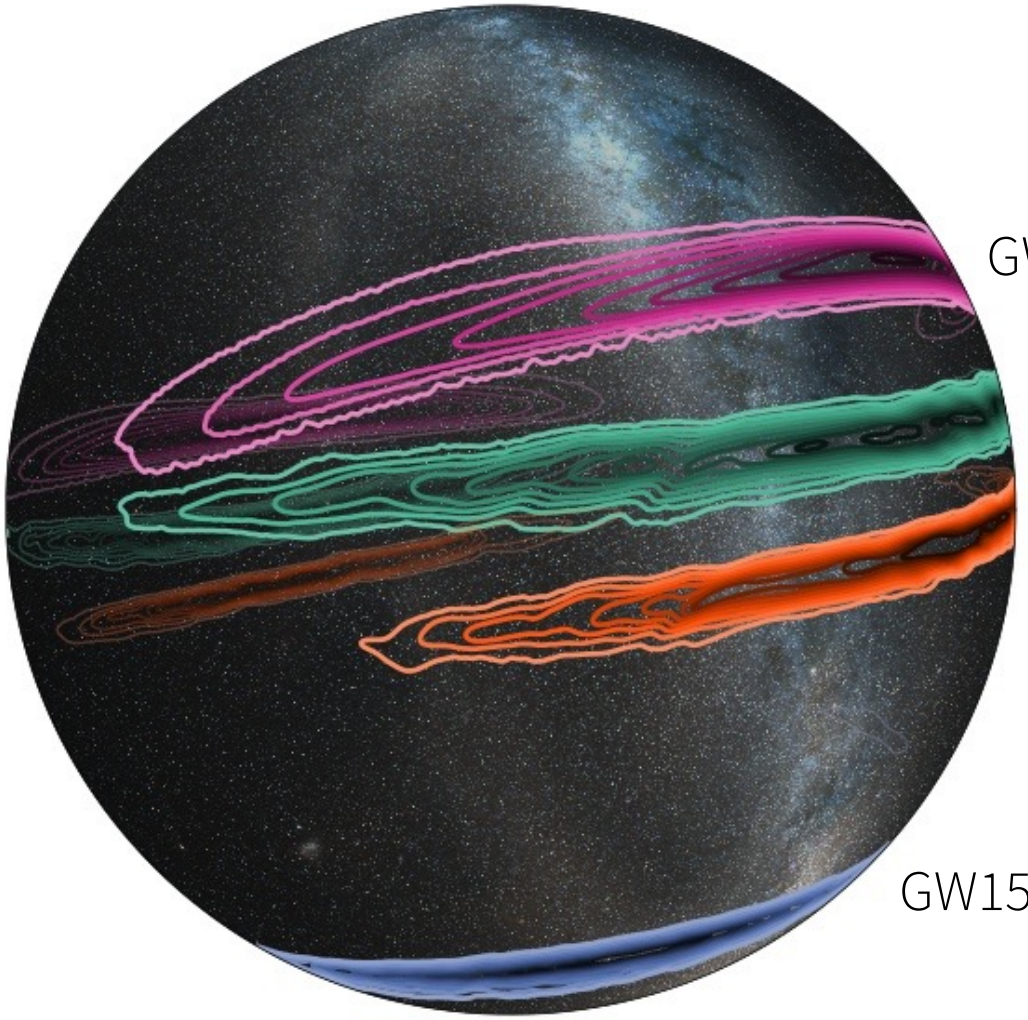
- O2 is ongoing
- Ahead: Virgo, O3, …
- Binary neutron stars:
  $R \lesssim 12,000\,\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$
- Binary black holes: Lives of massive binaries
- Precision tests of GR



LVC, arXiv:1607.07456

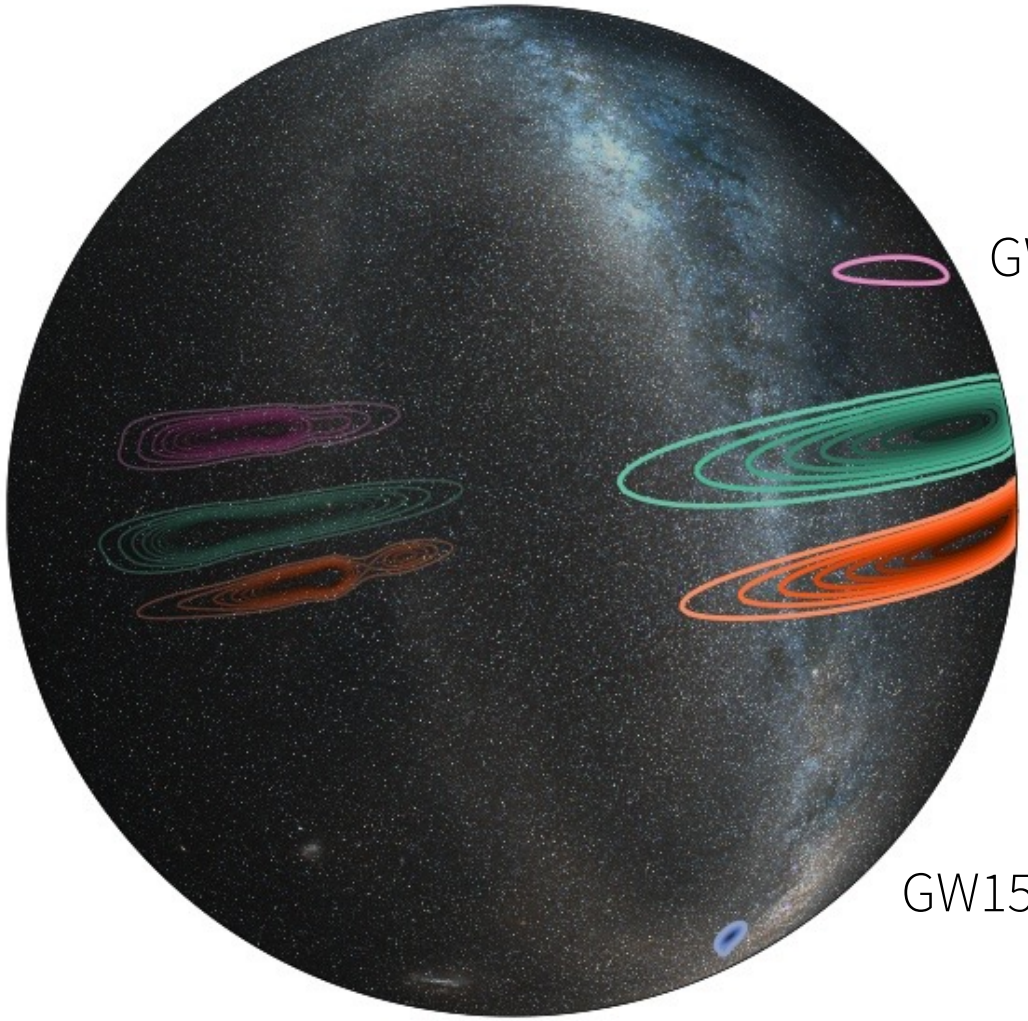
LVC, arXiv:1606.04856

Virgo arriving soon!



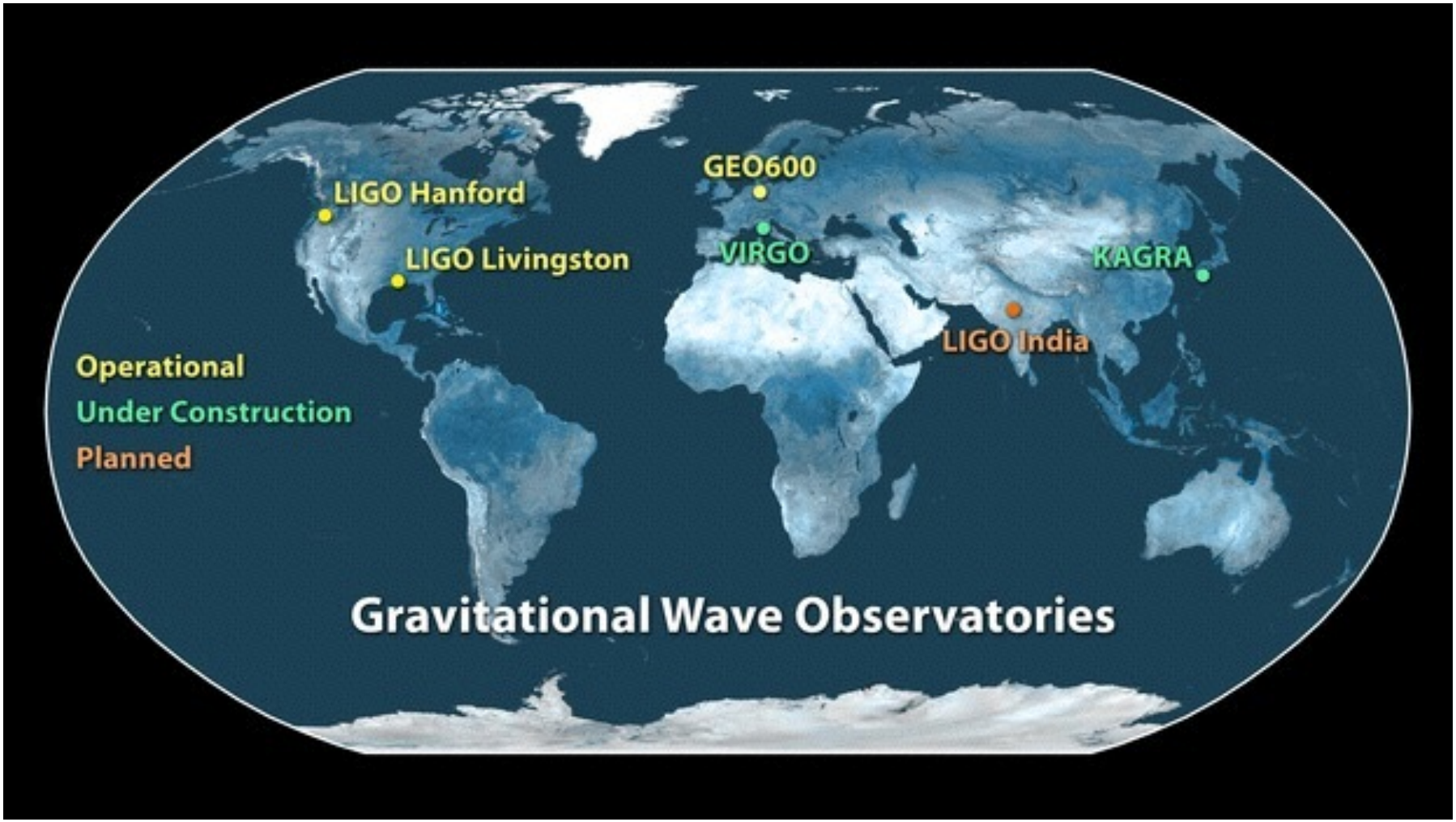
LSC/Leo Singer (Milky Way image: Axel Mellinger)

Virgo arriving soon!



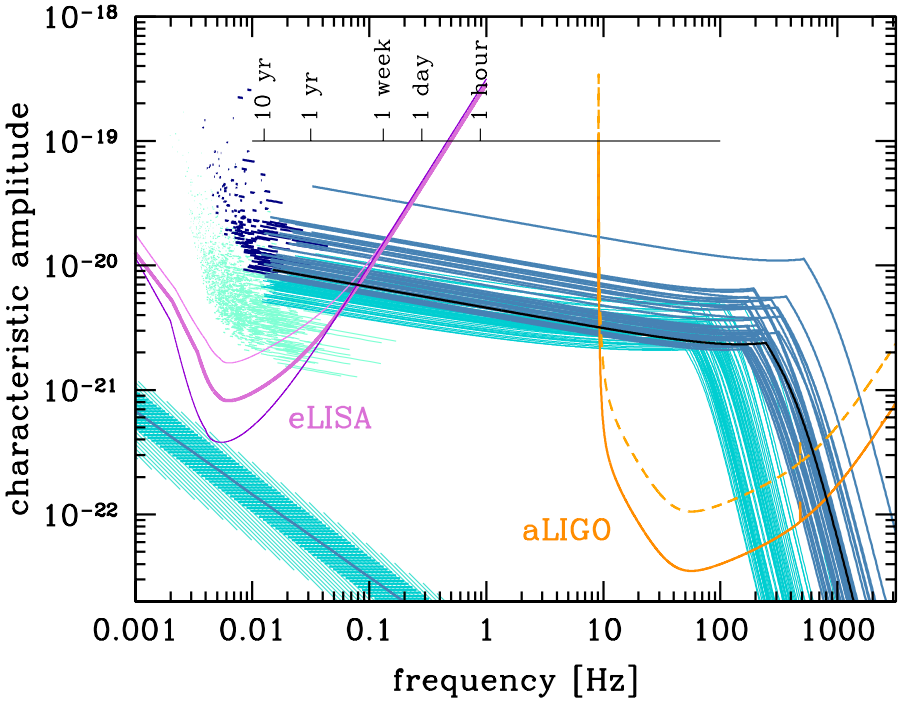
LSC/Leo Singer (Milky Way image: Axel Mellinger)

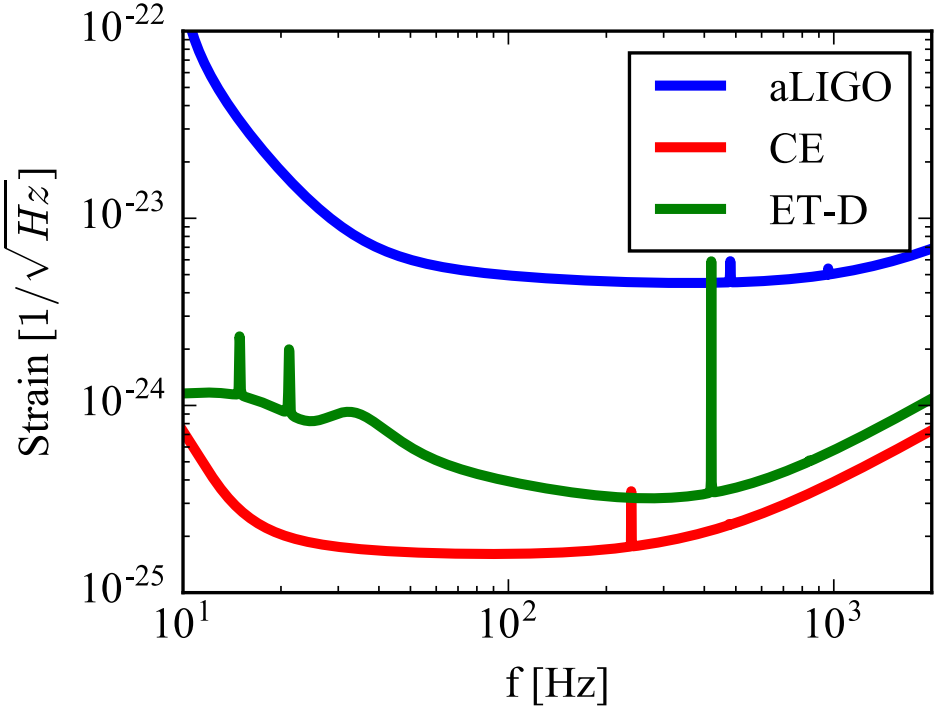
Detector network



Credit: LSC

The future beyond aLIGO

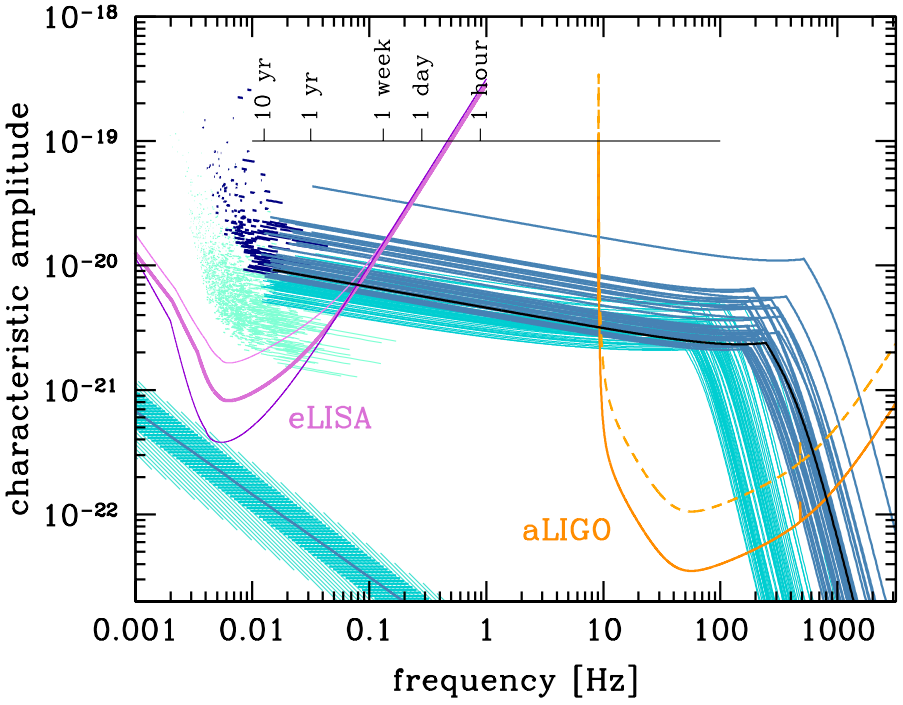


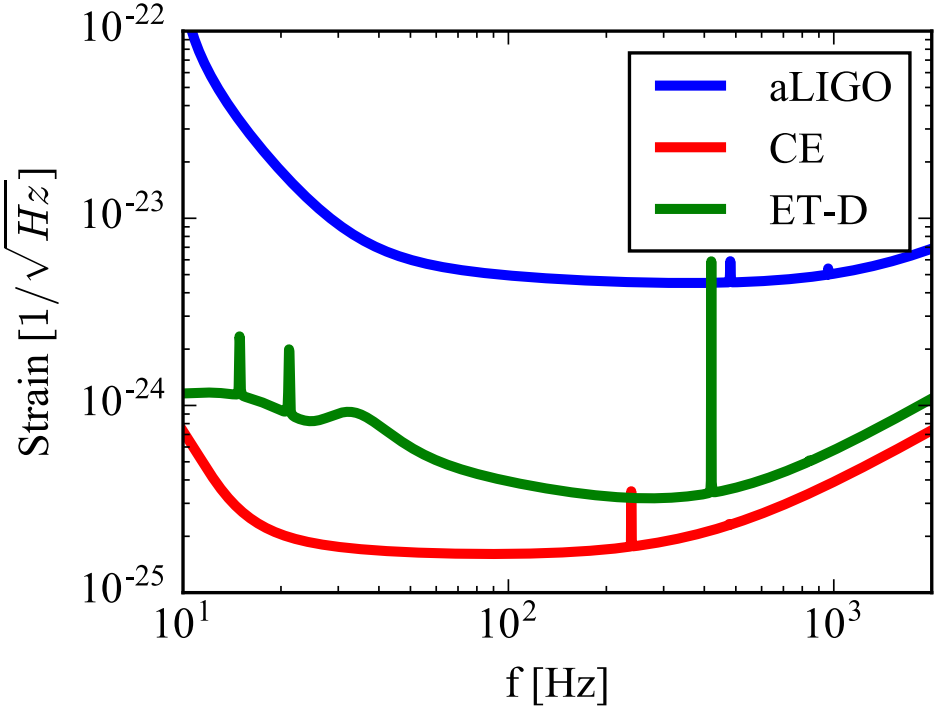


arXiv:1602.0695

arXiv:1610.06917

The future beyond aLIGO





What's next?

arXiv:1602.0695

arXiv:1610.06917