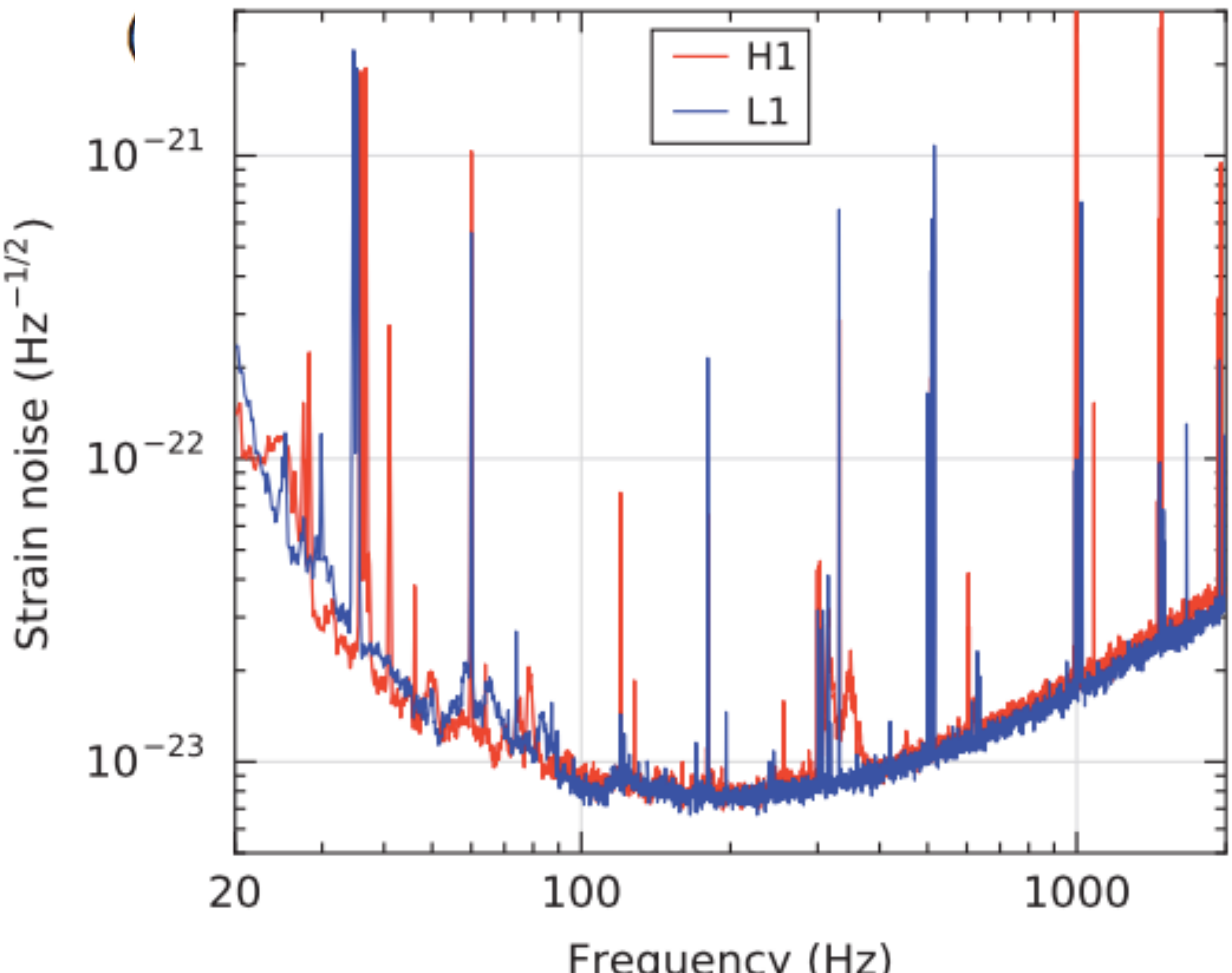
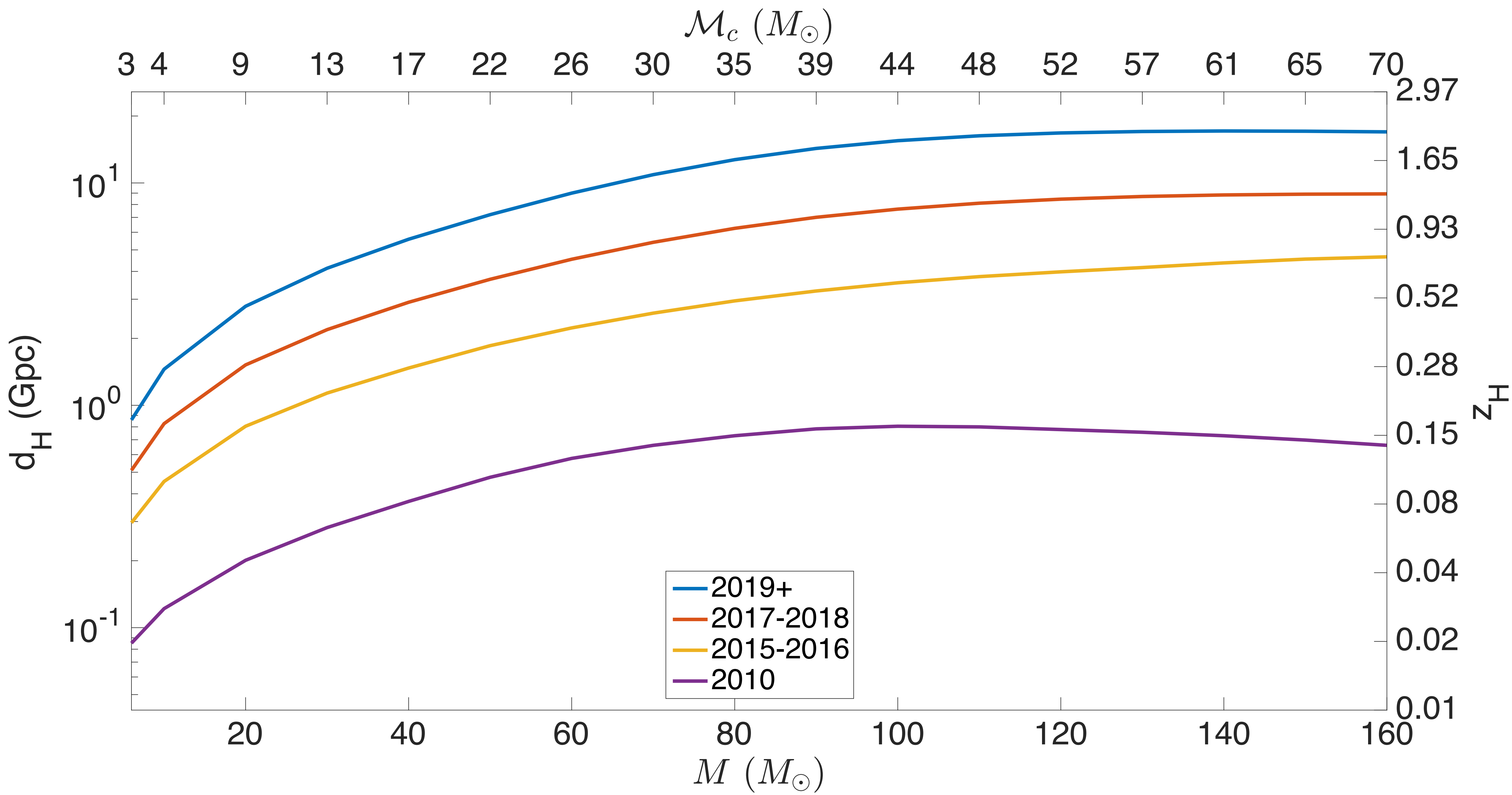
Advanced LIGO noise spectral density

(Abbott et al. PRL 116 (2016) 061102)



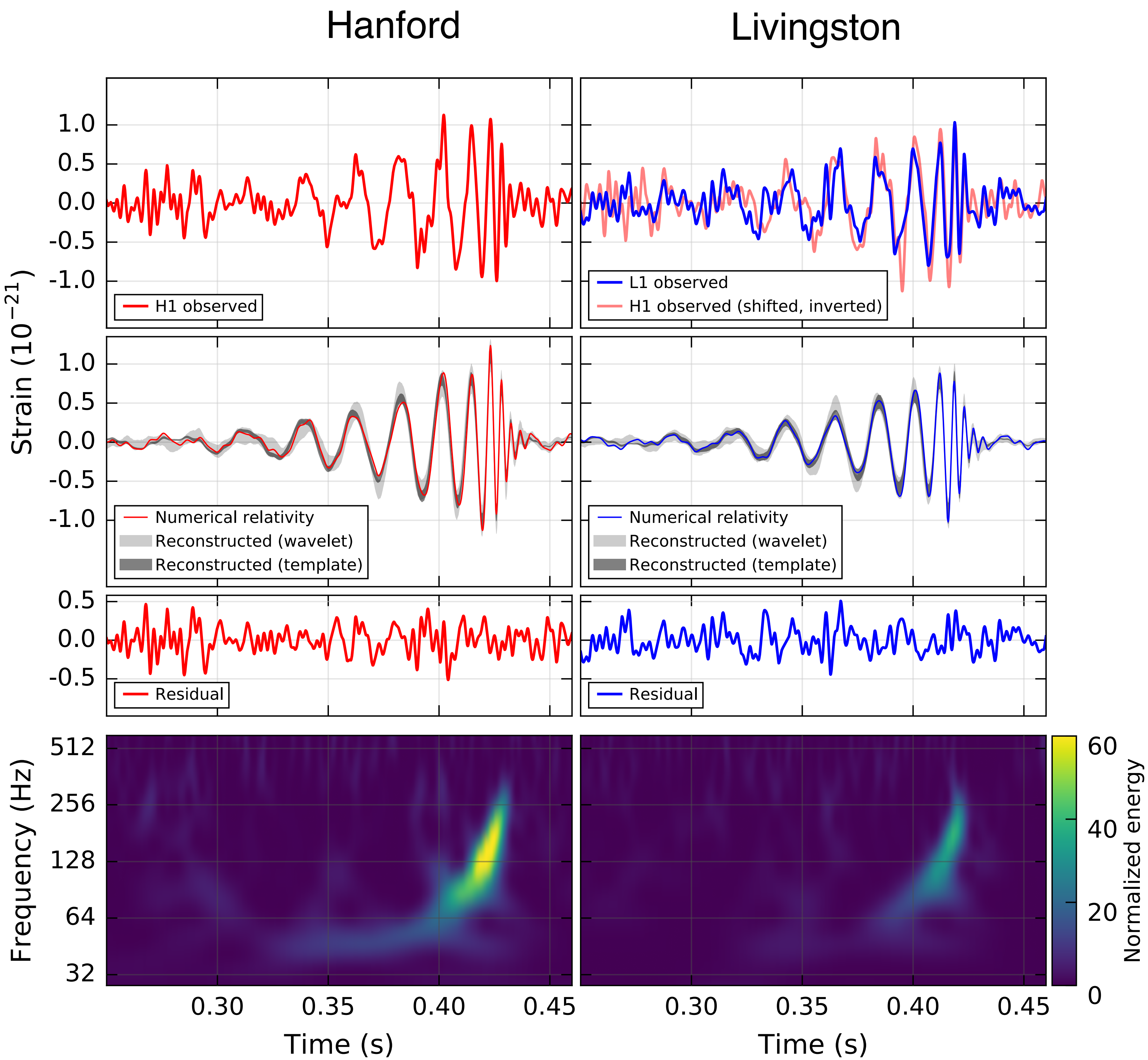
Horizon distance

(Abbott et al. ApJ 818 (2016) no.2, L22)



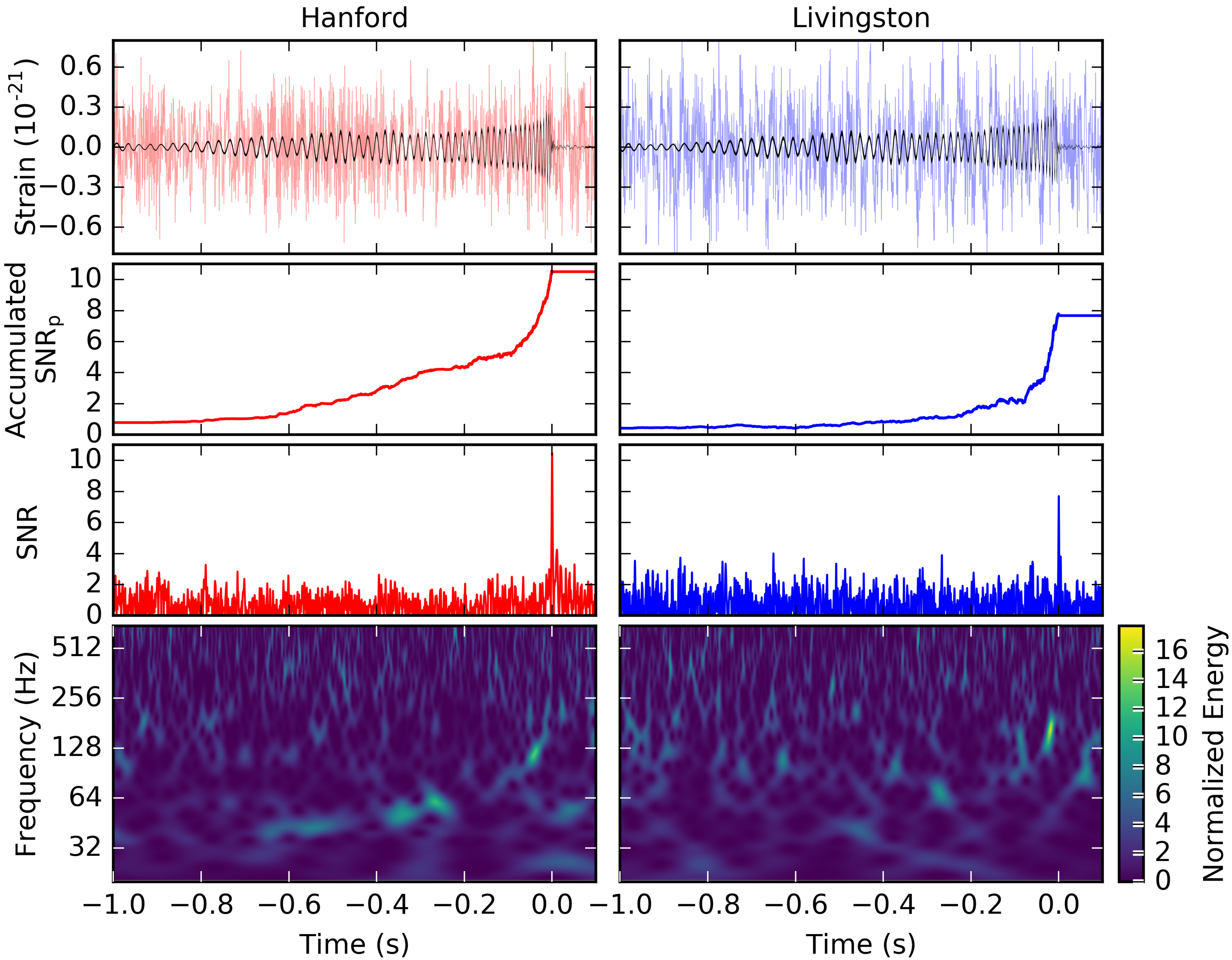
LIGO detections during O1: GW150914

(Abbott et al. PRL 116 (2016) 061102)

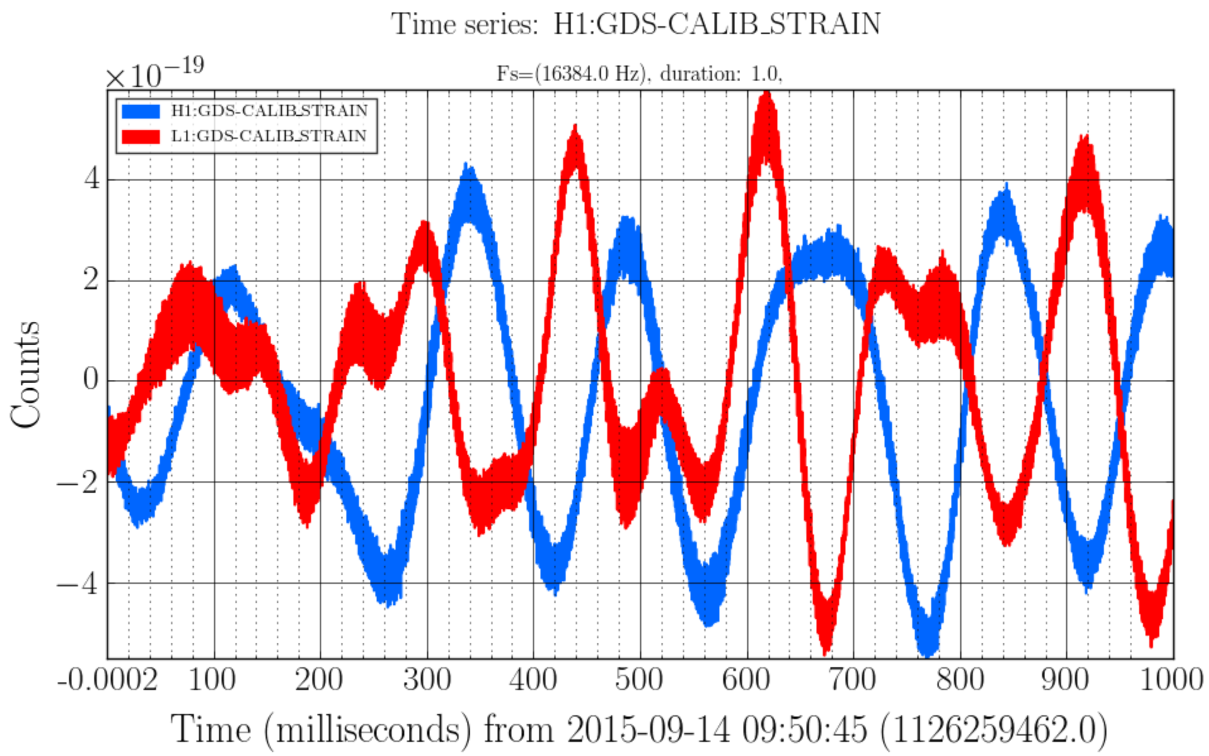


LIGO detections during O1: GW151226

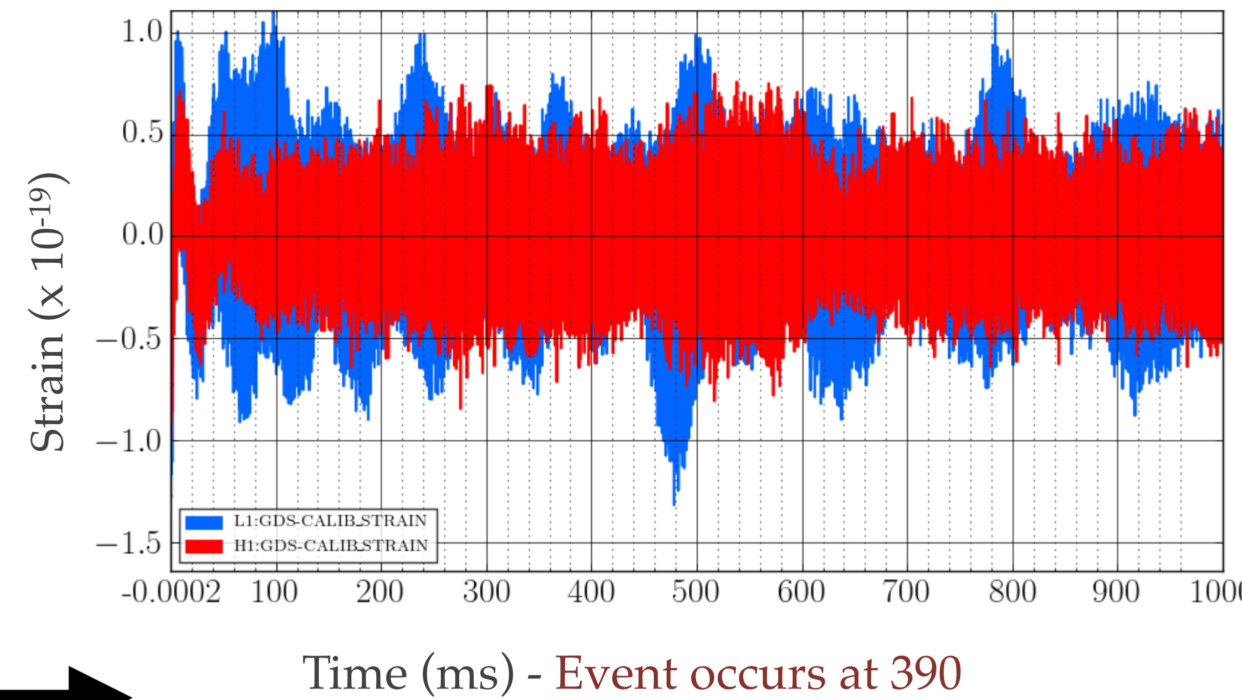
(Abbott et al. PRL 116 (2016) 241103)



What was originally observed?

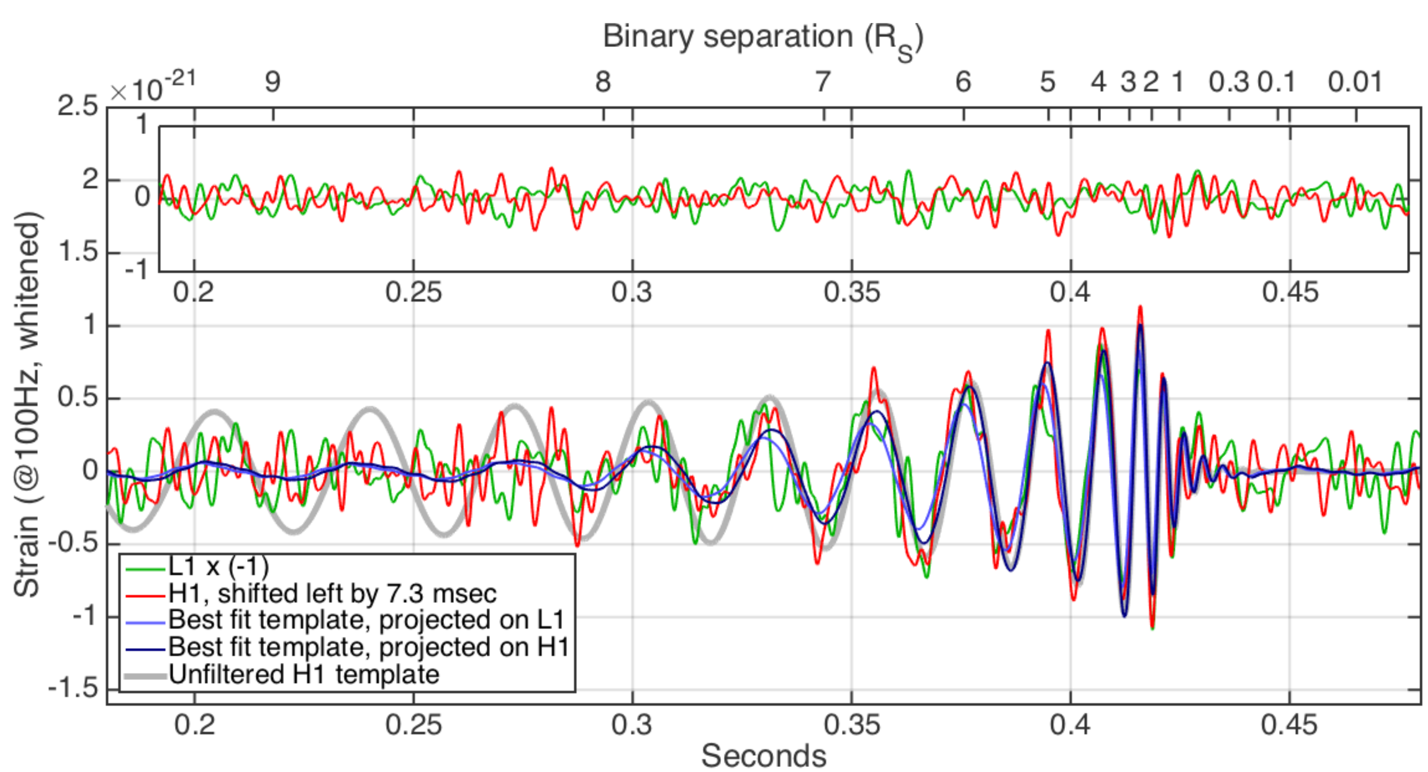


(Harry & LIGO Scientific Collaboration)



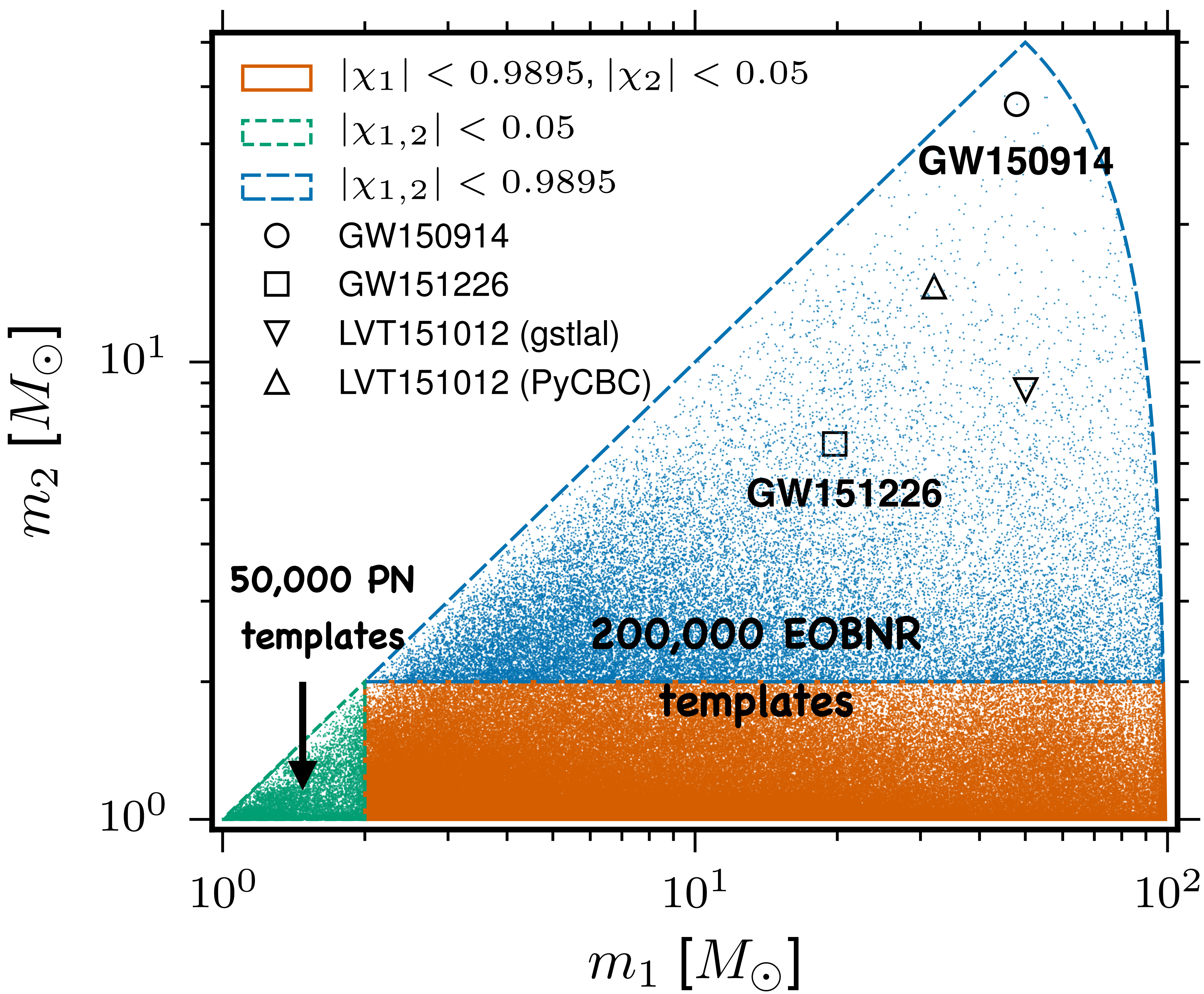
highpass filter

lowpass filter & whitened



The template bank ("uberbank") for O1

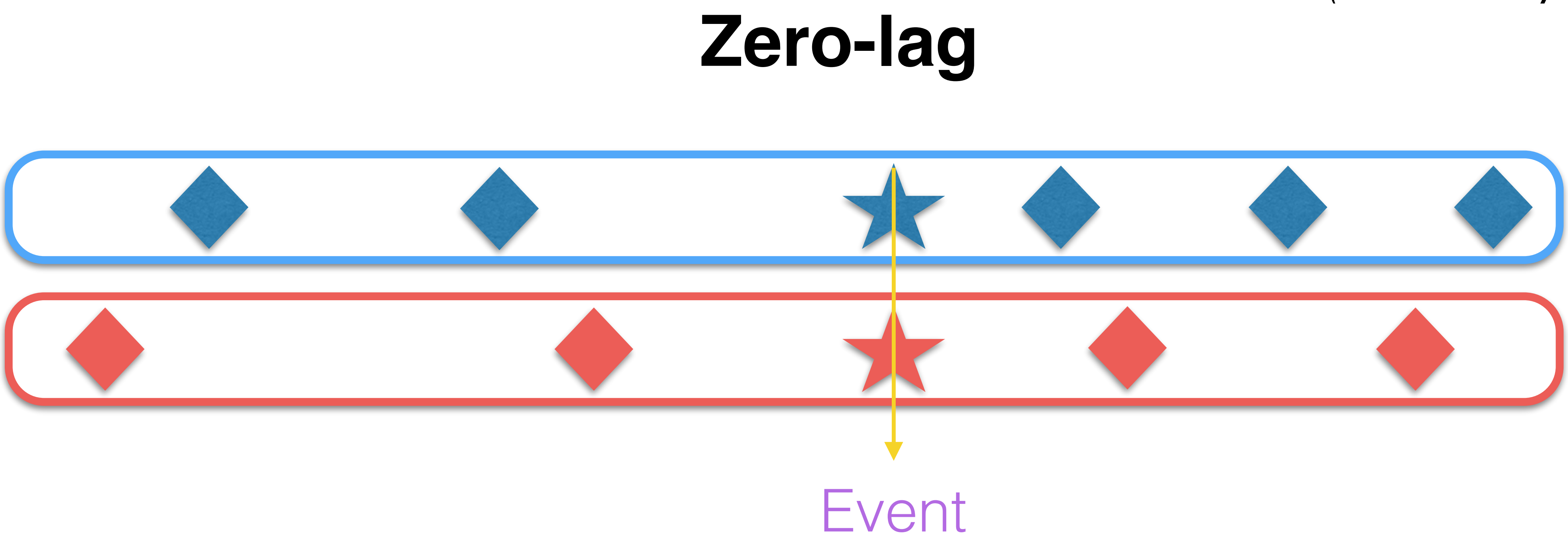
(Abbott et al. arXiv:1606.04856)



Assessing confidence in LIGO detection

Could the **signal** be **due** to **noise fluctuations**?

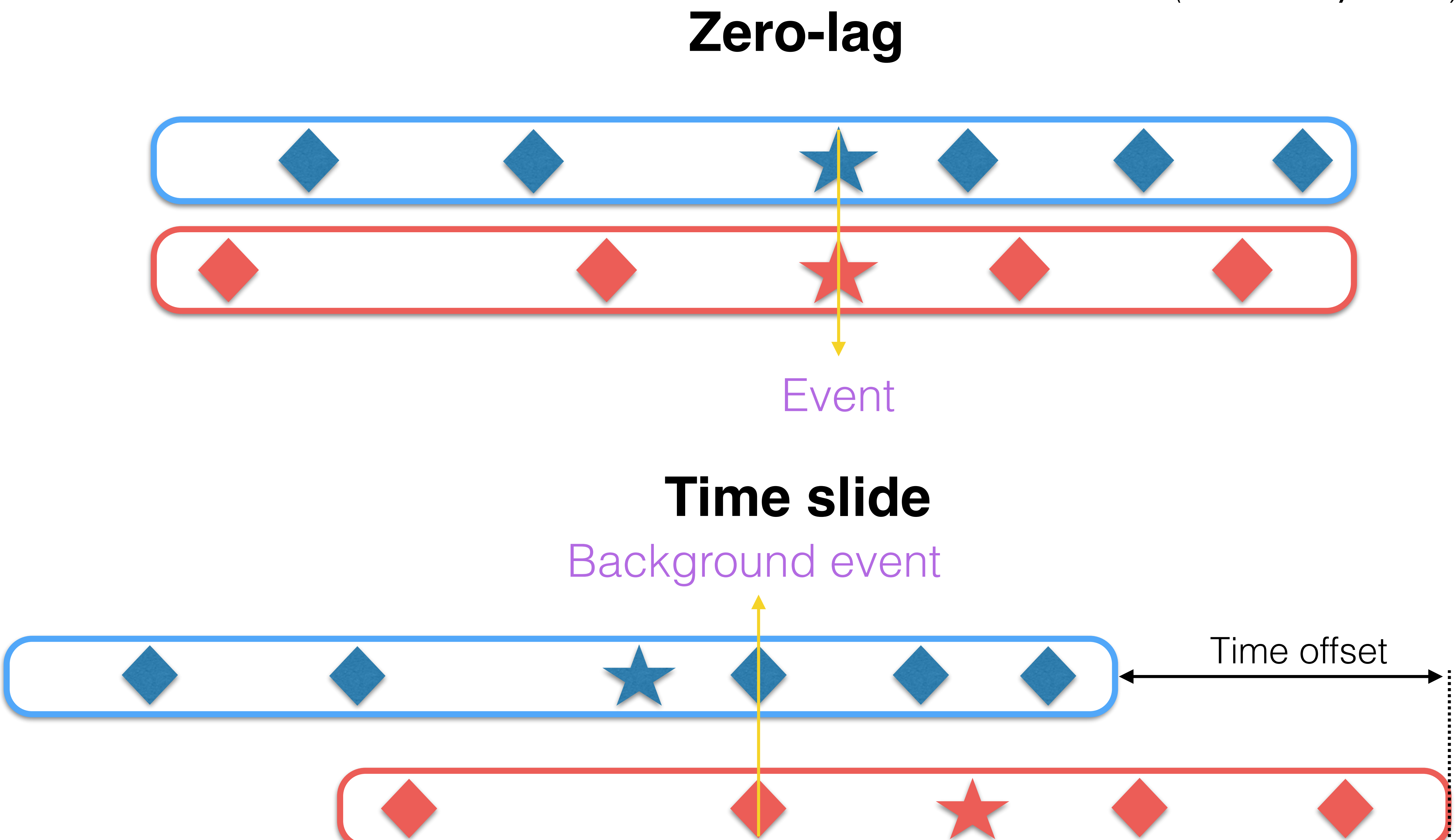
(animation by Nuttall)



Assessing confidence in LIGO detection

Building larger background by time-shifting the data

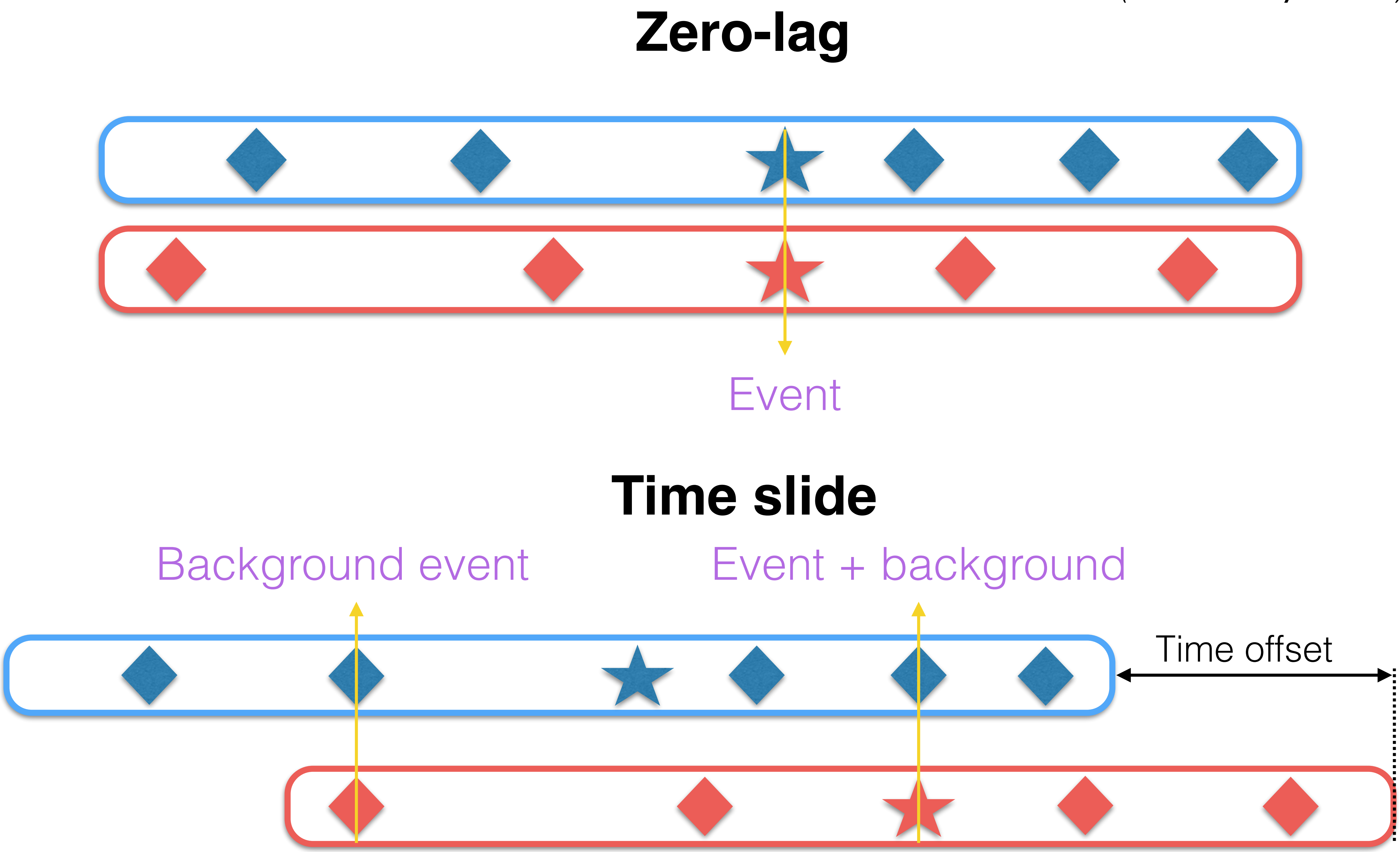
(animation by Nuttall)



Assessing confidence in LIGO detection

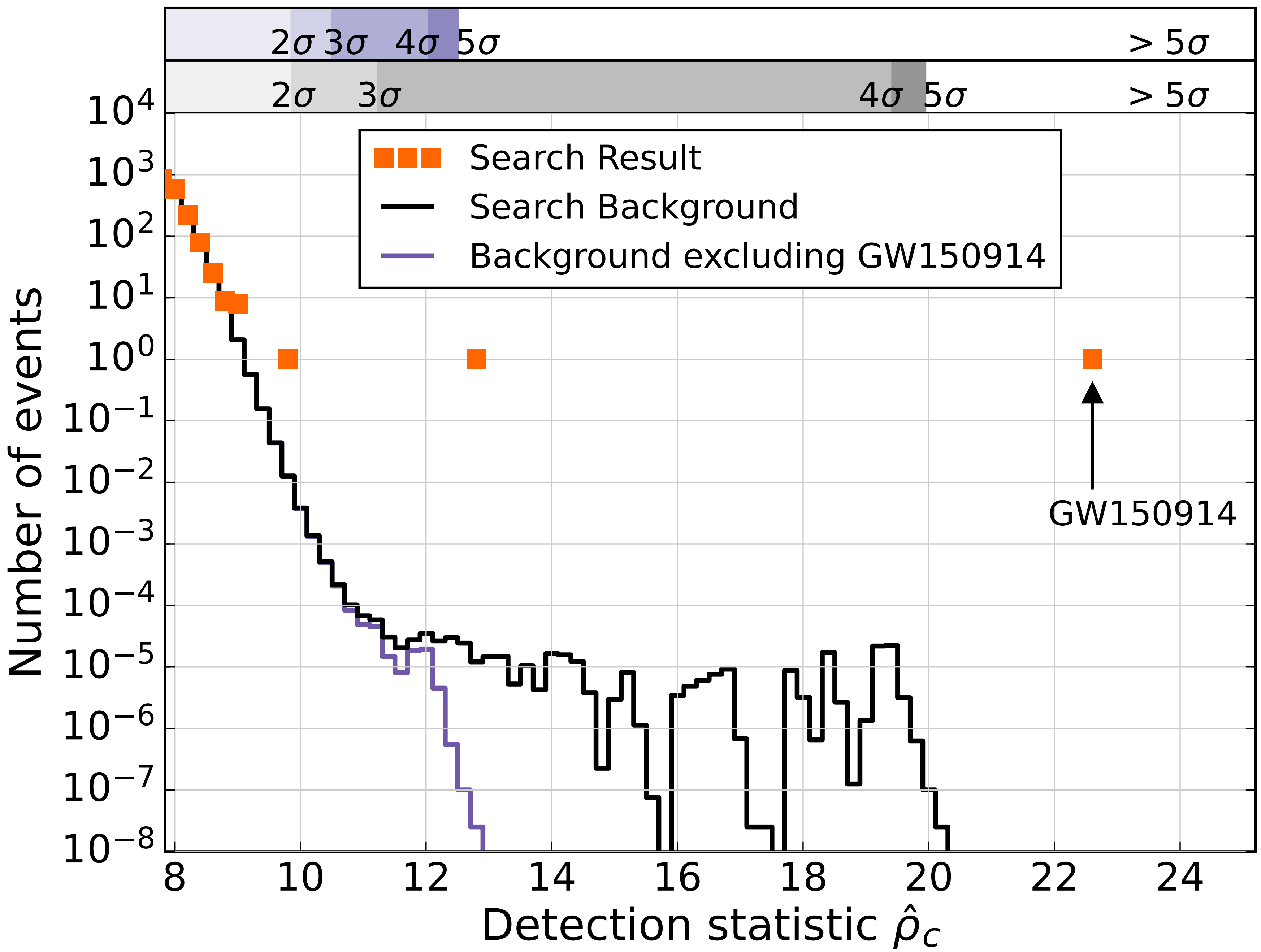
Building larger background by time-shifting the data

(animation by Nuttall)



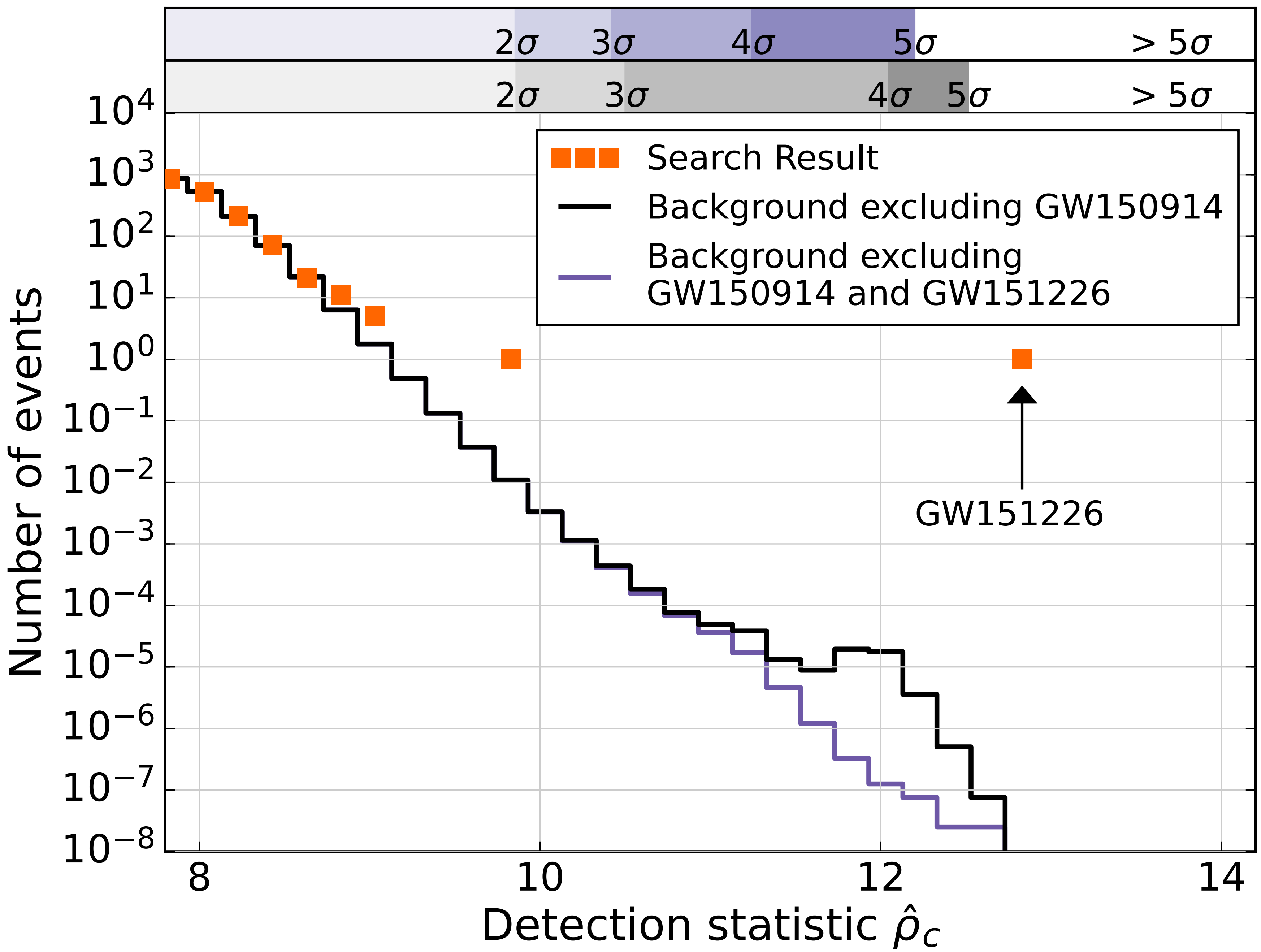
Detection confidence with modeled search in O1

(Abbott et al. arXiv:1606.04856)



Detection confidence with modeled search in O1

(Abbott et al. arXiv:1606.04856)

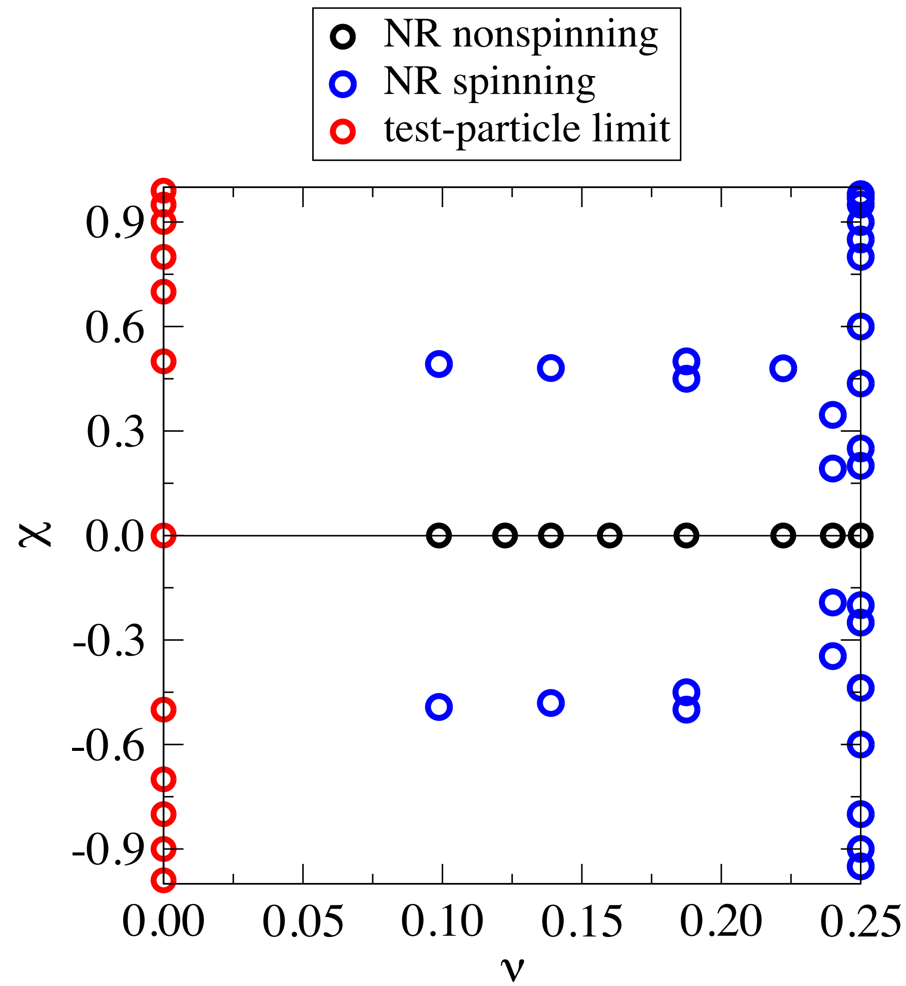


EOBNR waveforms used in LIGO O1

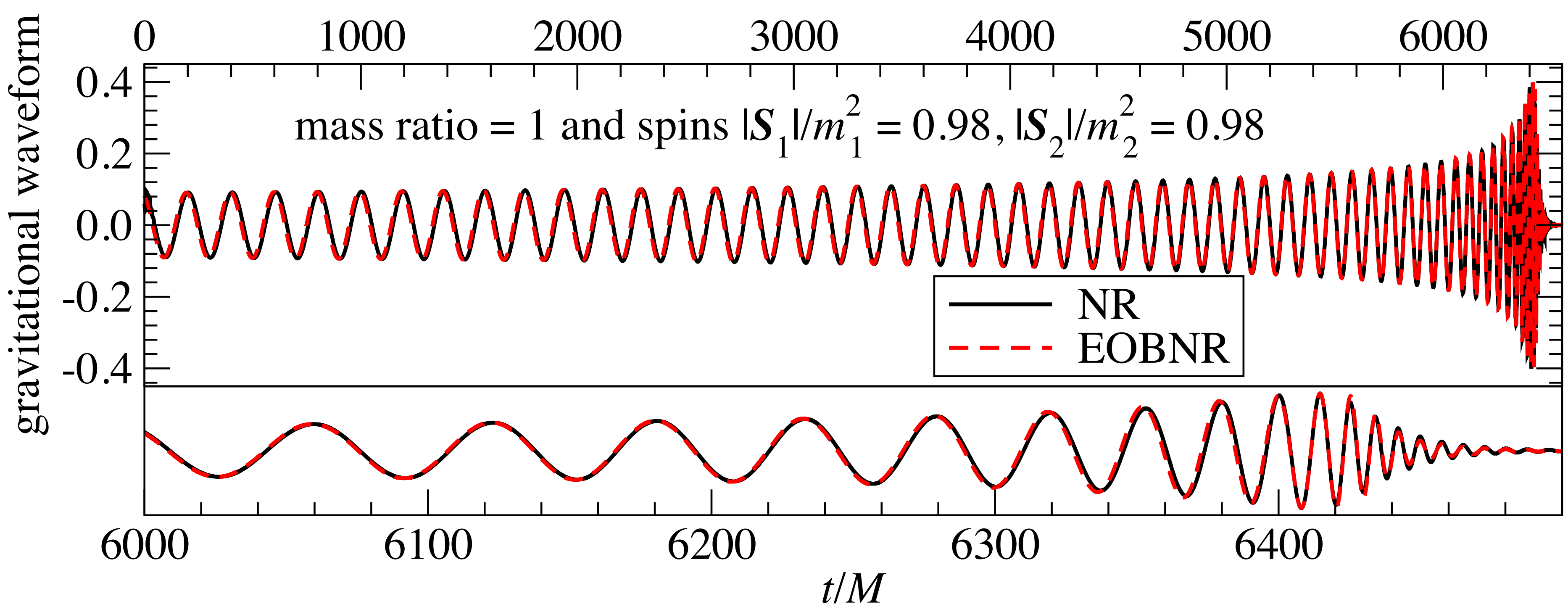
- EOB waveforms with **nonprecessing spins** calibrated to NR waveforms

  (Taracchini, AB, Pan, Hinderer & SXS 14)

  (Barausse & AB 10, 11, Barausse et al. 09, Damour & Nagar 09, Pan et al. 08, Damour et al. 08)



38 SXS simulations



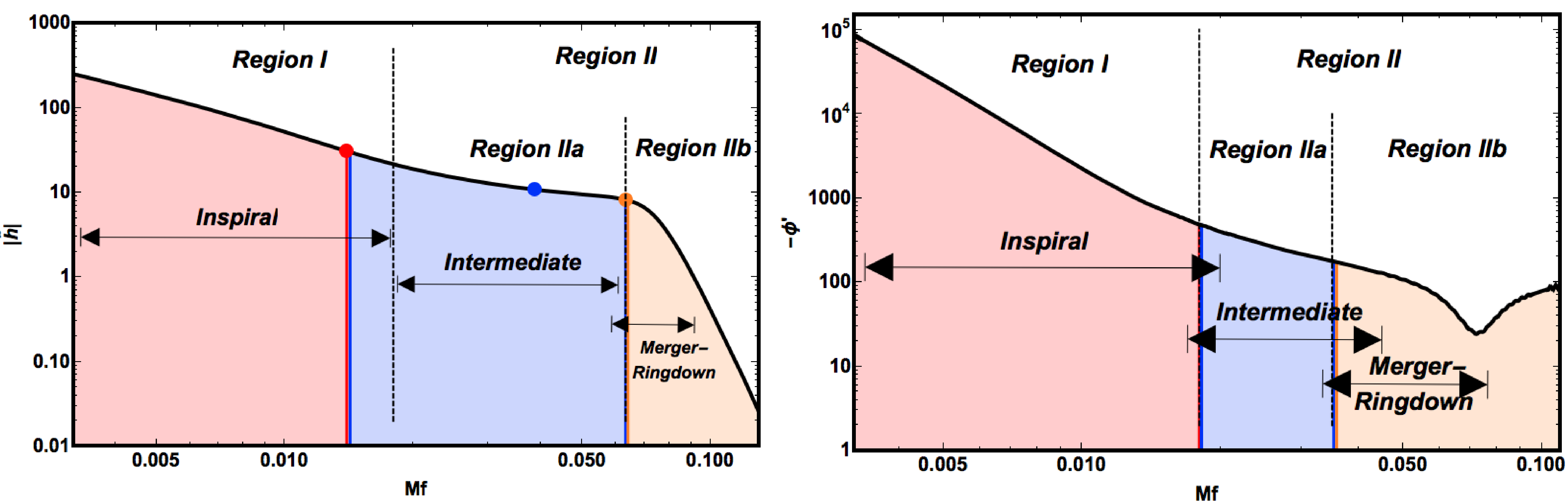
(Taracchini et al. 14)

IMR phenomenological waveforms used in LIGO O1

- First works in mid-late 2000 (Ajith et al. 07, Pan et al. 07, Ajith et al 11, Santamaria et al. 10)

- **Fast, frequency-domain** waveform model hybridizing and fitting EOB & NR (Khan et al. 15; Husa et al. 15)

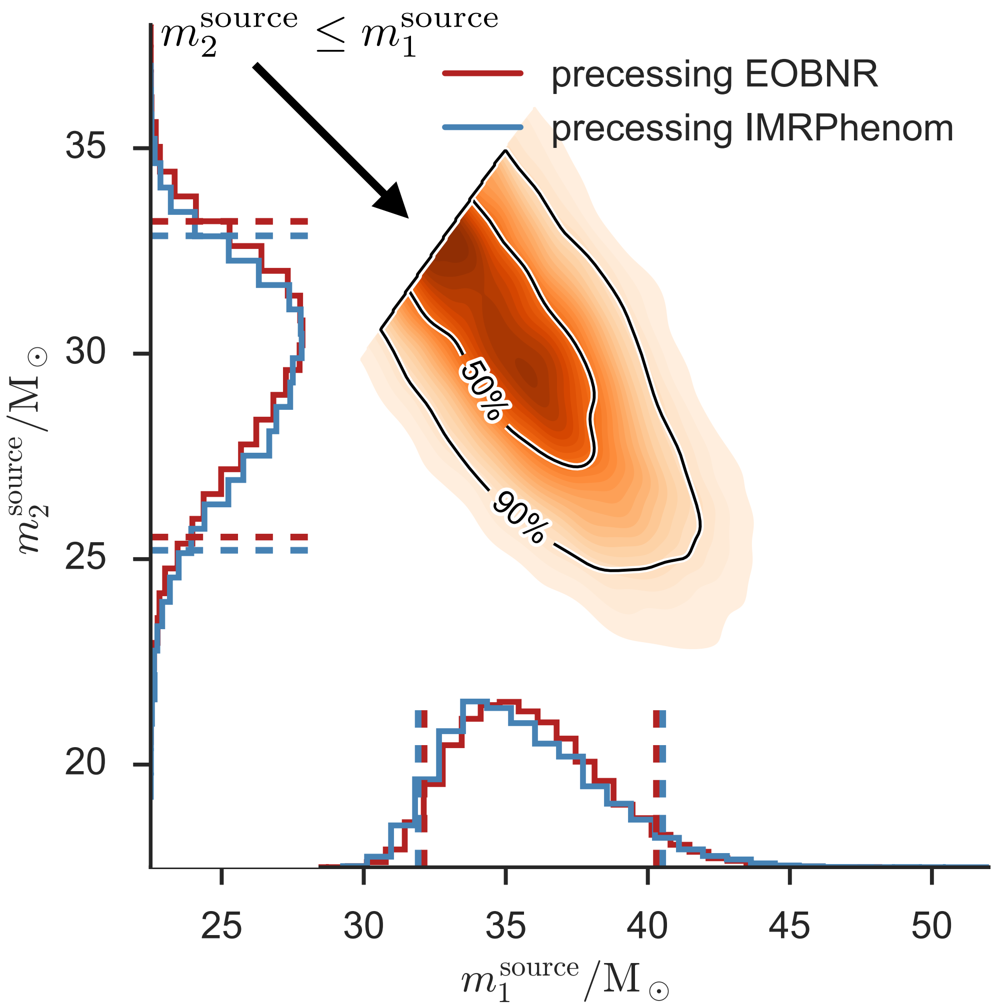
$$\tilde{h}(f;\lambda_i) = \mathcal{A}(f;\lambda_i)\, e^{i\phi(f;\lambda_i)}$$



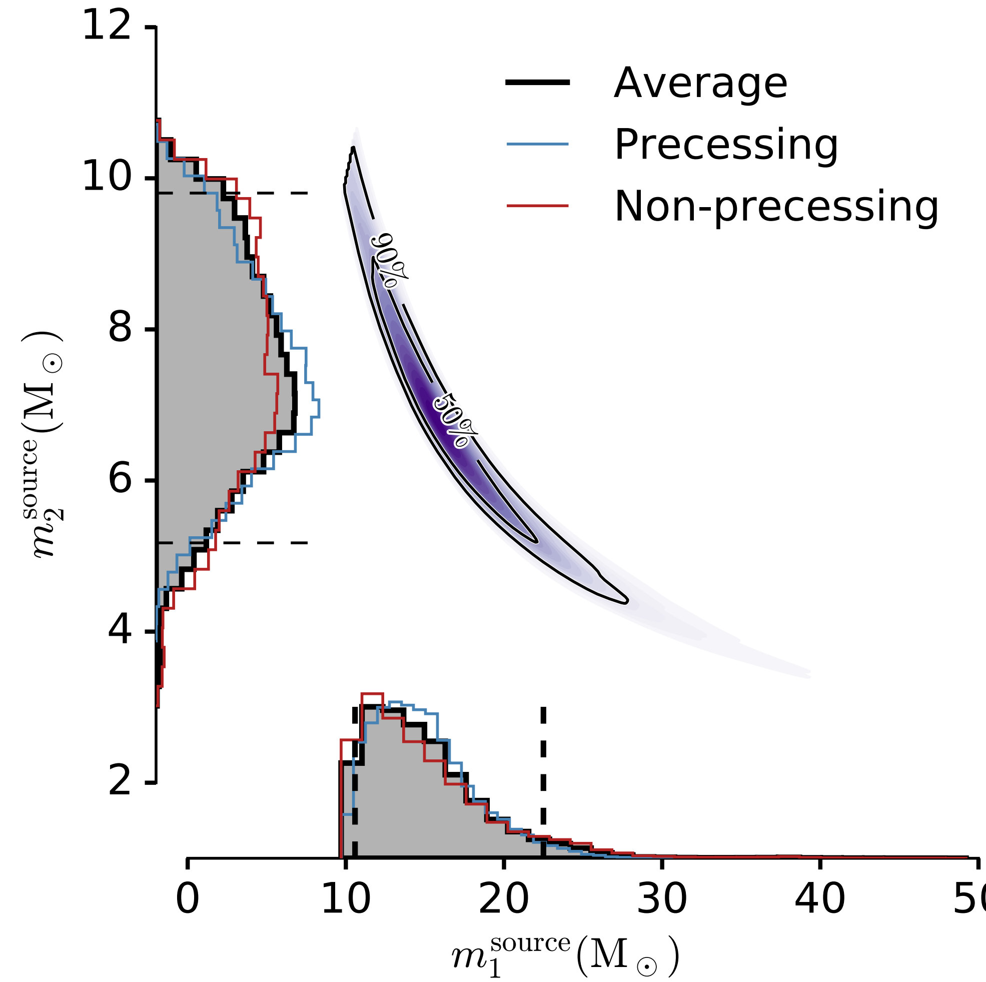
Unveiling binary black holes properties: masses

(Abbott et al. PRX 6 (2016) 041014)

GW150914



GW151226



(Abbott et al. PRL 116 (2016) 241103)

- We **measure best** the **"chirp" mass** $\mathcal{M} = M\,\nu^{3/5}$
- **GW150914**: merger in band, total mass well measured, good measurement of individual masses.
- **GW151226**: merger outside band, individual masses measured less precisely.

Effect of total mass on the waveform

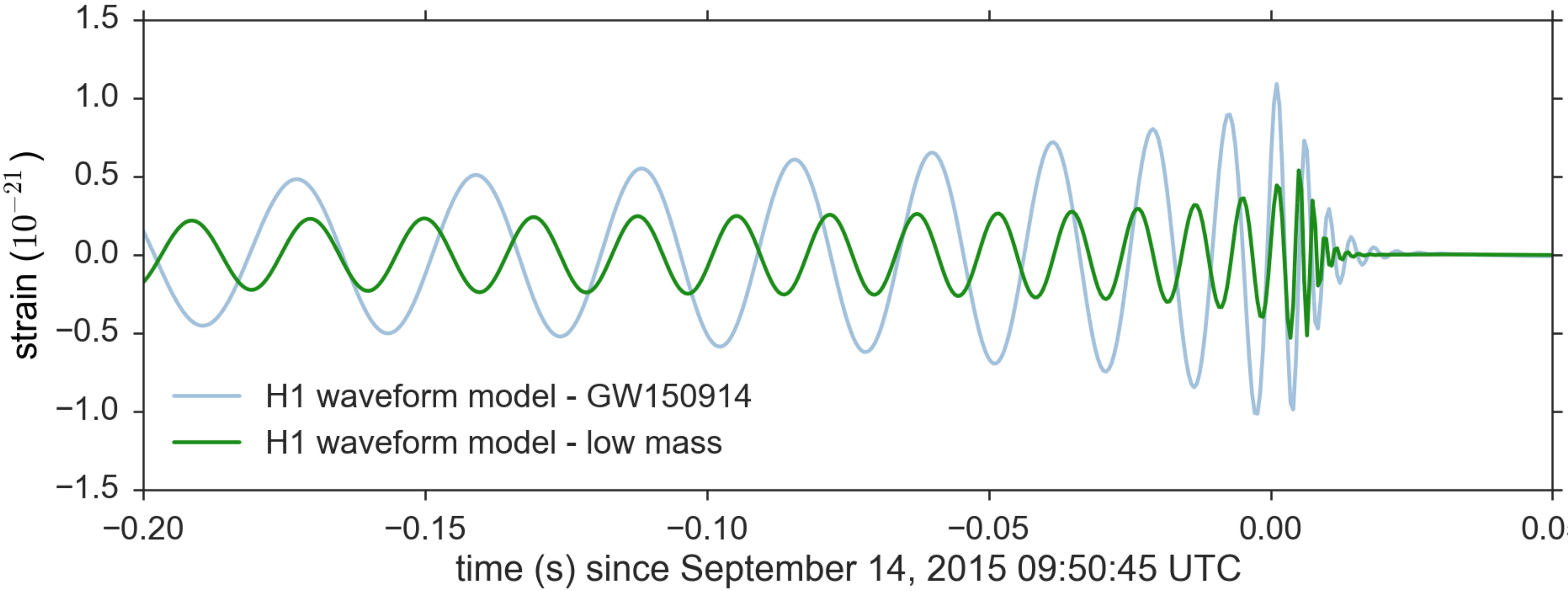
$$\mathcal{M} = 30.4 M_\odot \qquad q = 1.24$$

$$\downarrow$$

$$\mathcal{M} = 15.2 M_\odot \qquad q = 1.24$$

$$\mathcal{M} = M\,\nu^{3/5}$$

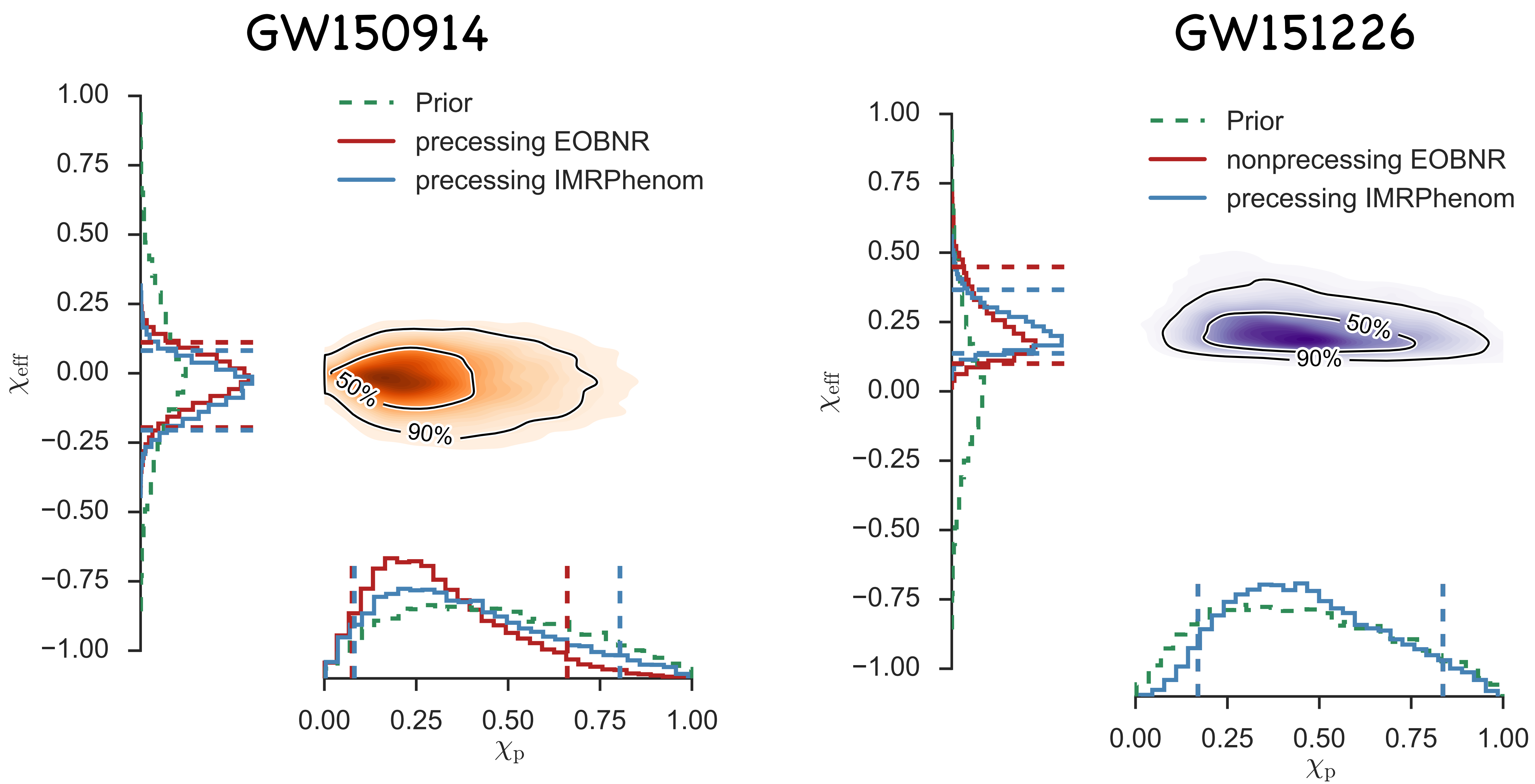
$$\nu = \frac{q}{(1+q)^2}$$



(credit by Raymond)

Unveiling binary black-holes properties: spins

(Abbott et al. PRX 6 (2016) 041014)



(Abbott et al. PRL 116 (2016) 241103)

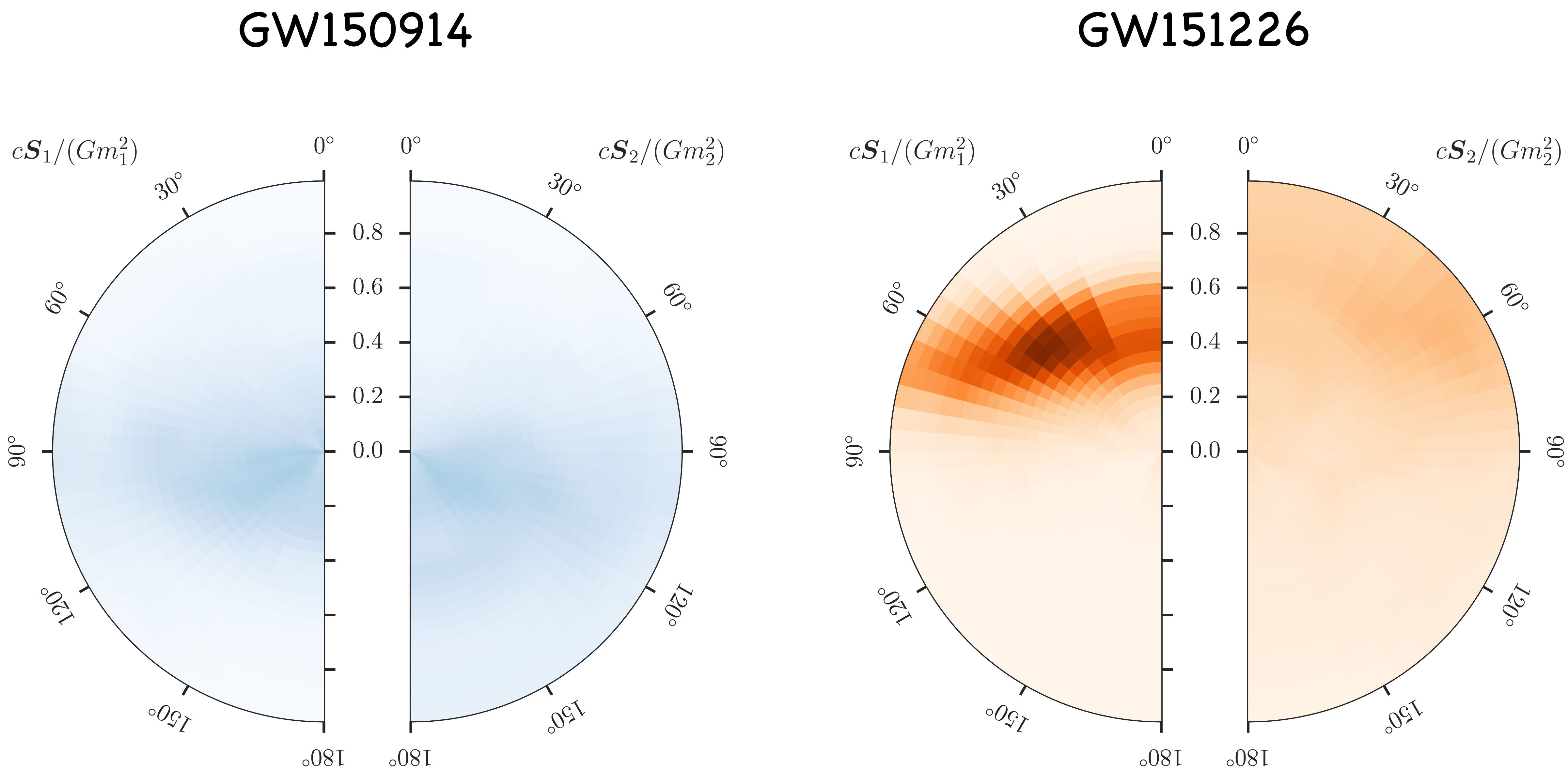
- BHs' **spins not maximal**, and for GW151226 **one BH's spin larger than 0.2** at 99% confidence.

$$\chi_{\rm eff} = \left(\frac{\mathbf{S}_1}{m_1} + \frac{\mathbf{S}_2}{m_2}\right) \cdot \left(\frac{\hat{\mathbf{L}}}{M}\right)$$

- **Spin of primary BH < 0.7. No information** about **precession**.

Unveiling binary black-holes properties: spins

(Abbott et al. arXiv:1606.01210)

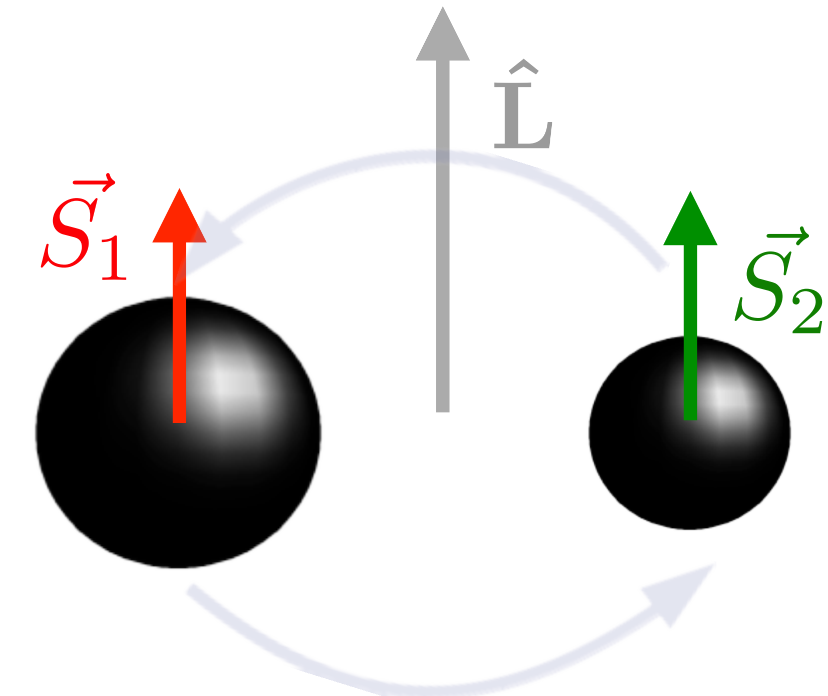


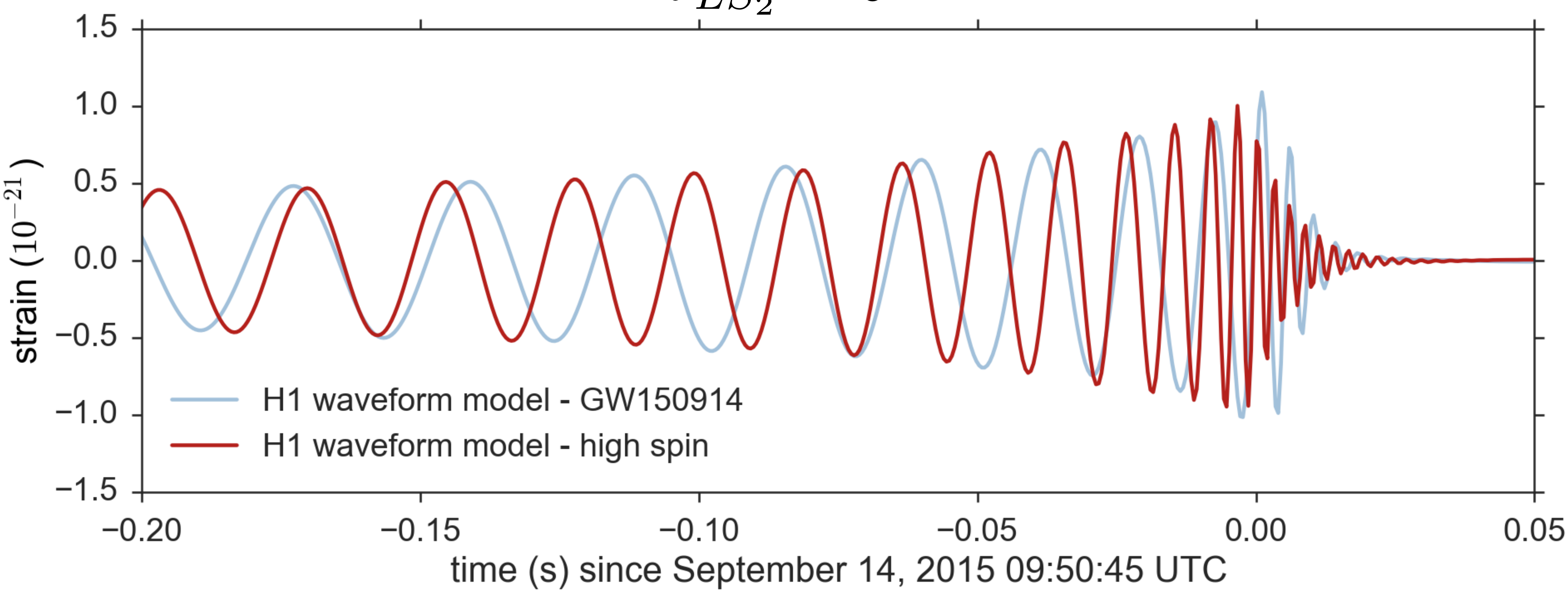
- Bins are constructed linearly in spin magnitude & cosine of tilt angles

$$\cos\theta_{LS_i} = \hat{\mathbf{S}}_i \cdot \hat{\mathbf{L}}$$

Effect of aligned spins on the waveform

$\mathcal{M} = 30.4 M_\odot$	$\mathcal{M} = 30.4 M_\odot$
$q = 1.24$	$q = 1.24$
$\chi_1 = 0.81$	$\chi_1 = 0.99$
$\chi_2 = 0.54$	$\chi_2 = 0.99$
$\theta_{LS_1} = 116^\circ$	$\theta_{LS_1} = 0^\circ$
$\theta_{LS_2} = 15^\circ$	$\theta_{LS_2} = 0^\circ$

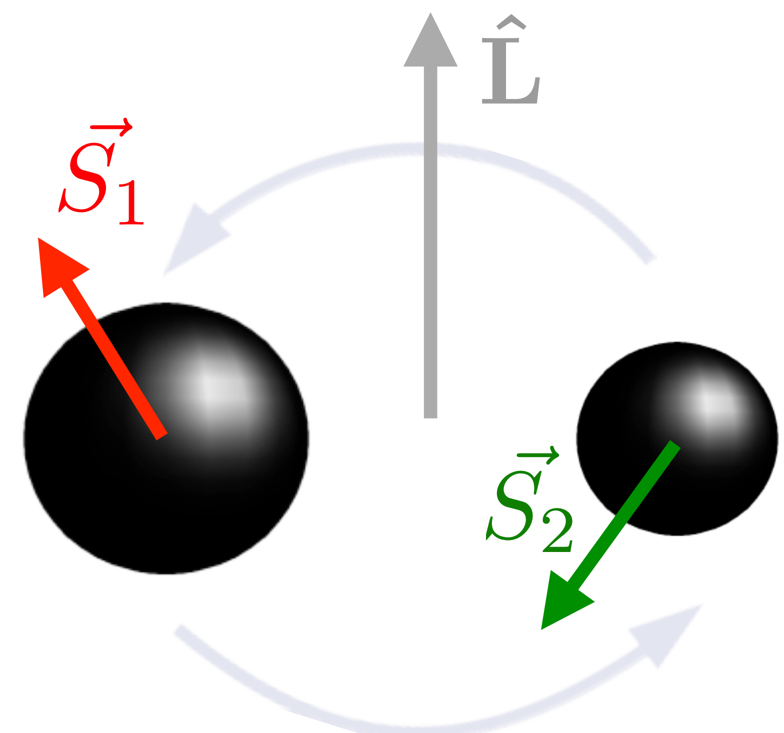


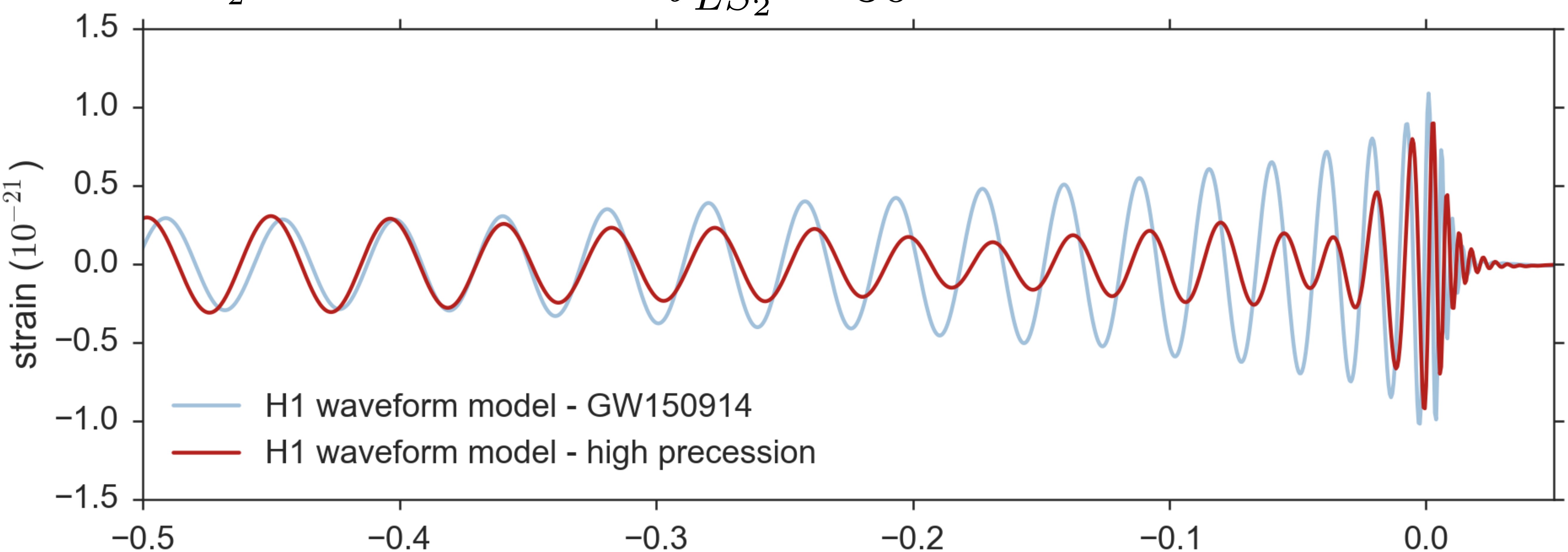


(credit by Raymond)

Effect of precessing spins/mass ratio on the waveform

$\mathcal{M} = 30.4 M_\odot$	$\mathcal{M} = 30.4 M_\odot$
$q = 1.24$	$q = 4$
$\chi_1 = 0.81$	$\chi_1 = 0.99$
$\chi_2 = 0.54$	$\chi_2 = 0.99$
$\theta_{LS_1} = 116^\circ$	$\theta_{LS_1} = 45^\circ$
$\theta_{LS_2} = 15^\circ$	$\theta_{LS_2} = 30^\circ$

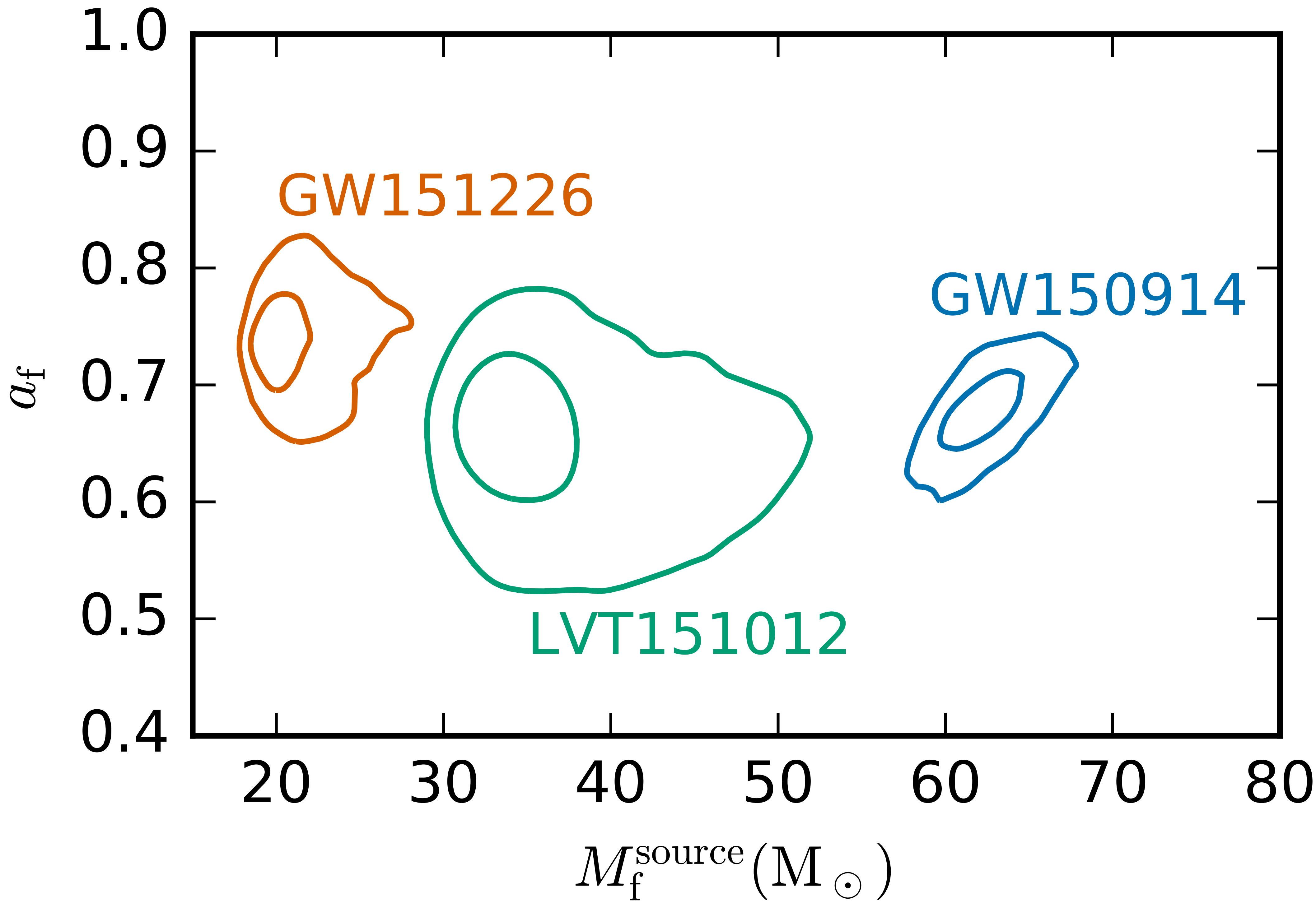




(credit by Raymond)

Properties of final black hole formed after merger

(Abbott et al. arXiv:1606.04856)

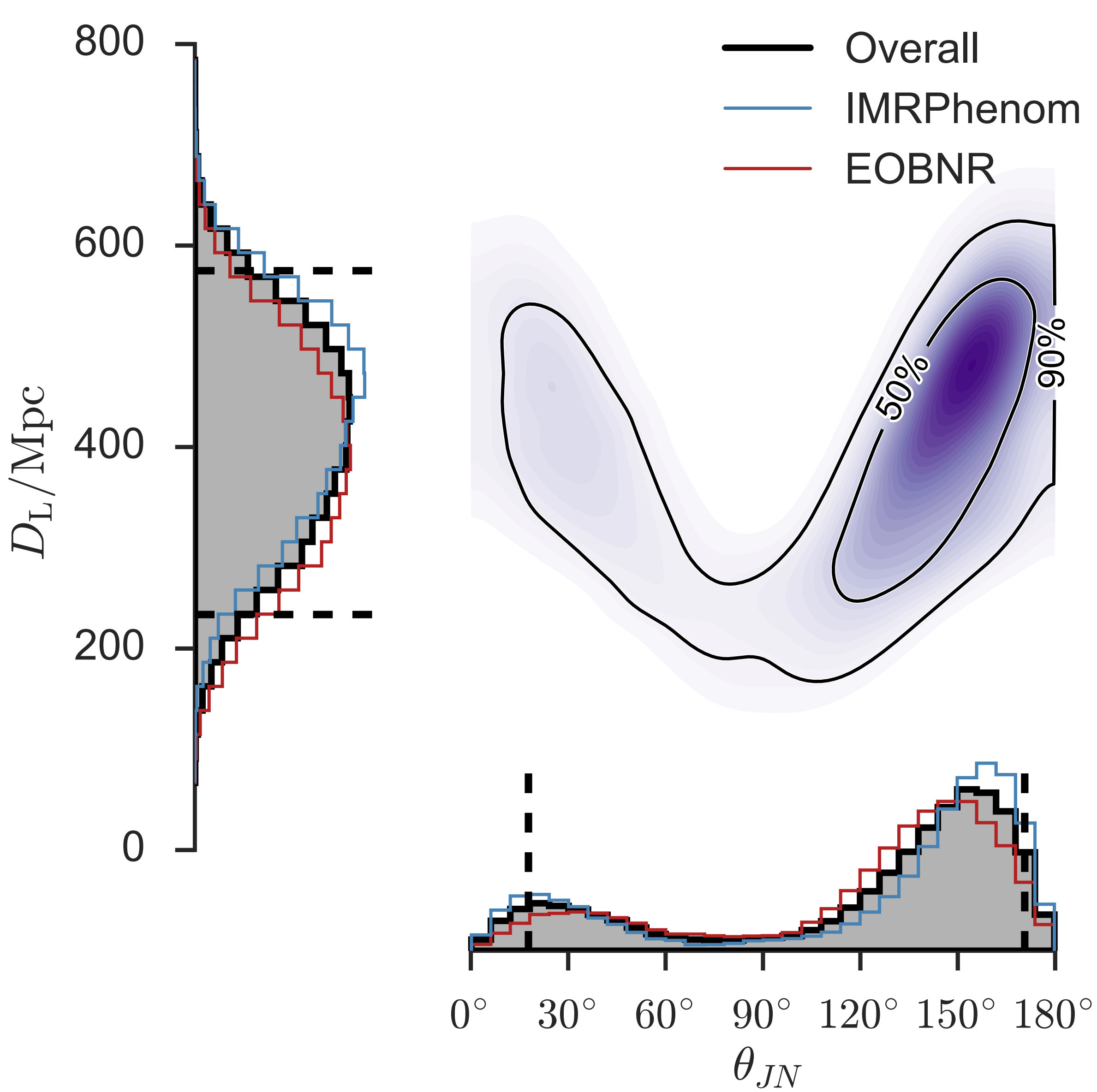


(Abbott et al. arXiv:1606.01210)

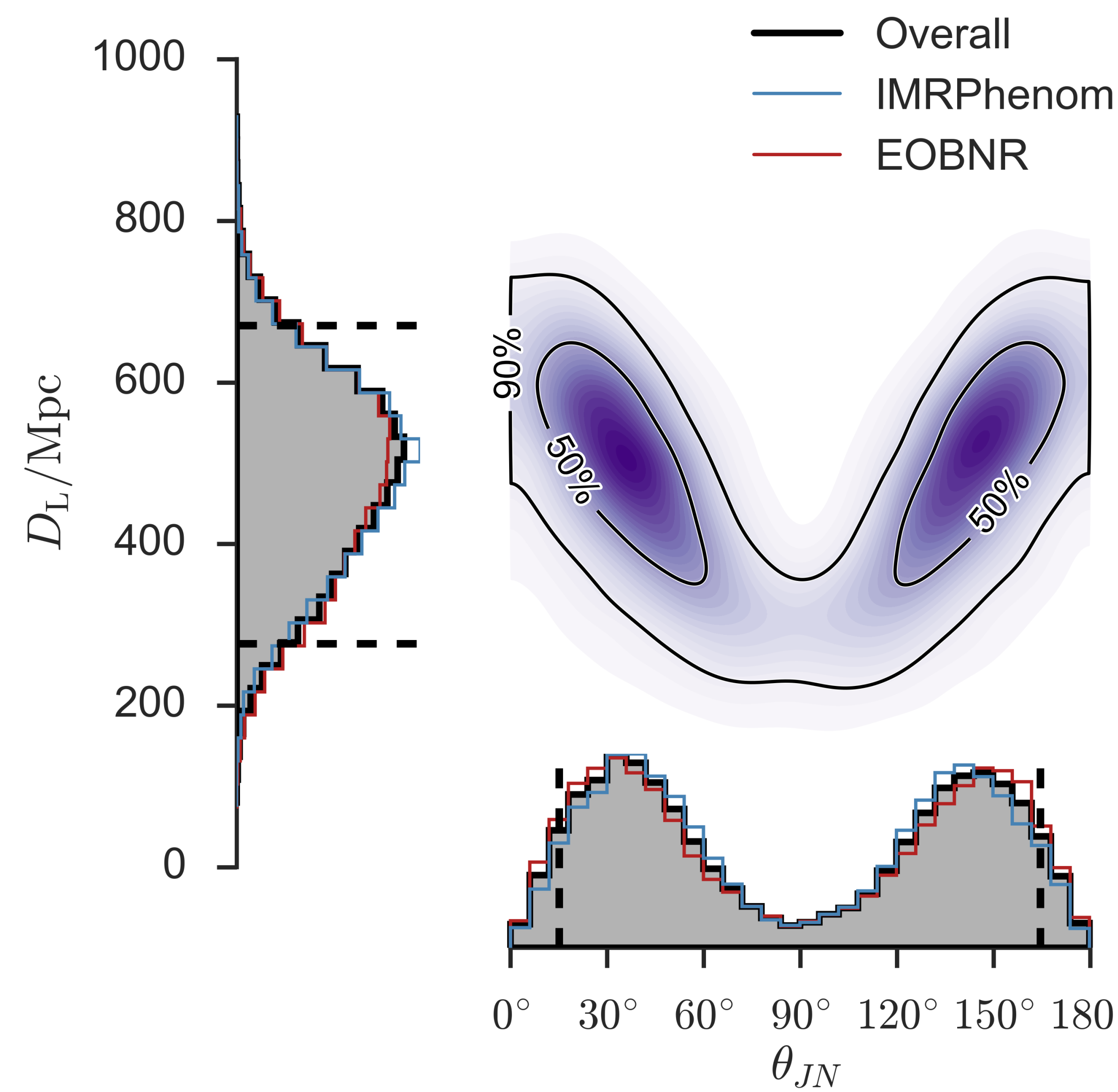
Binaries' distance and orbital-plane inclination with respect to line of sight

(Abbott et al. arXiv:1606.04856)

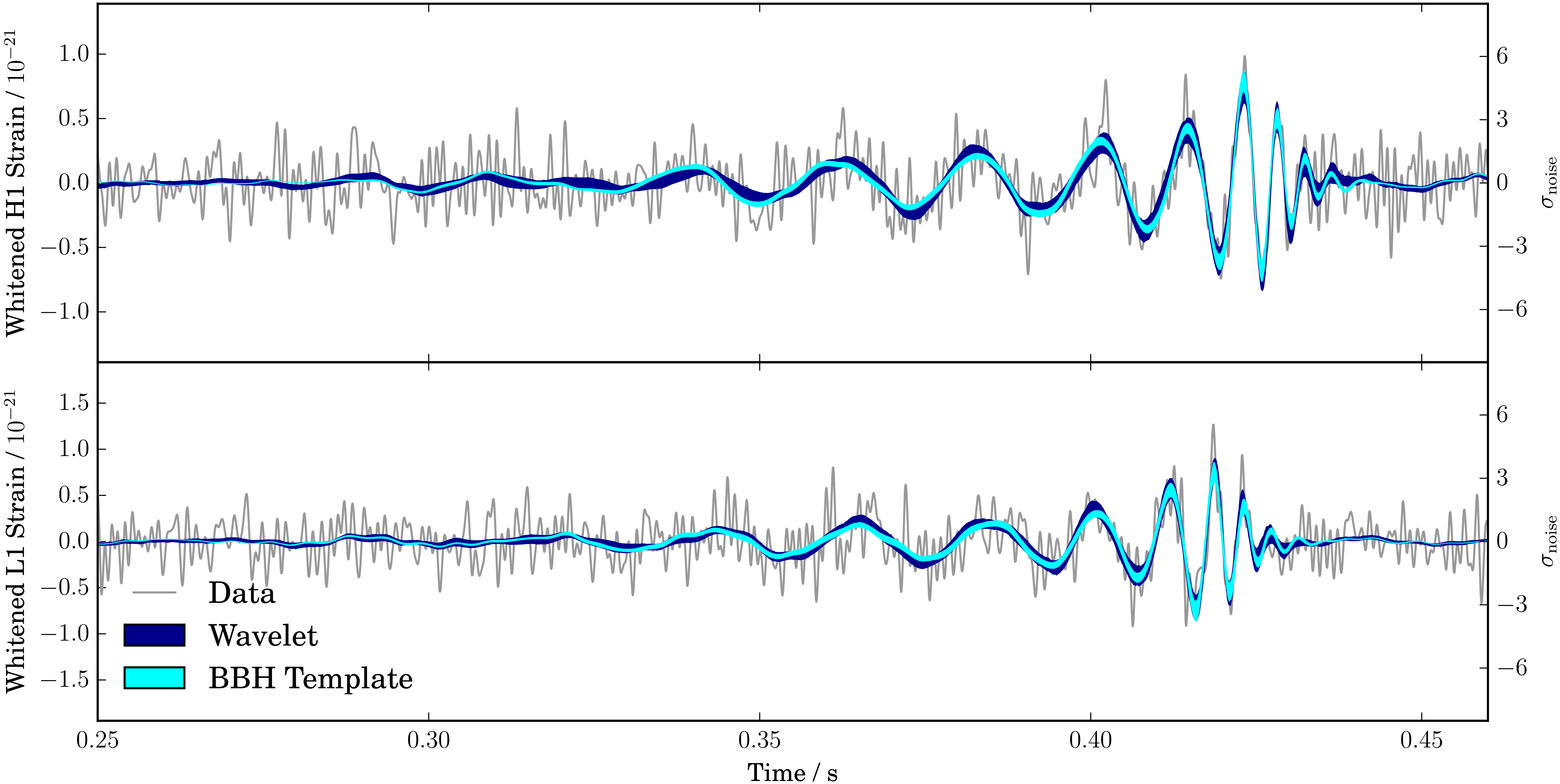
GW150914



GW151226

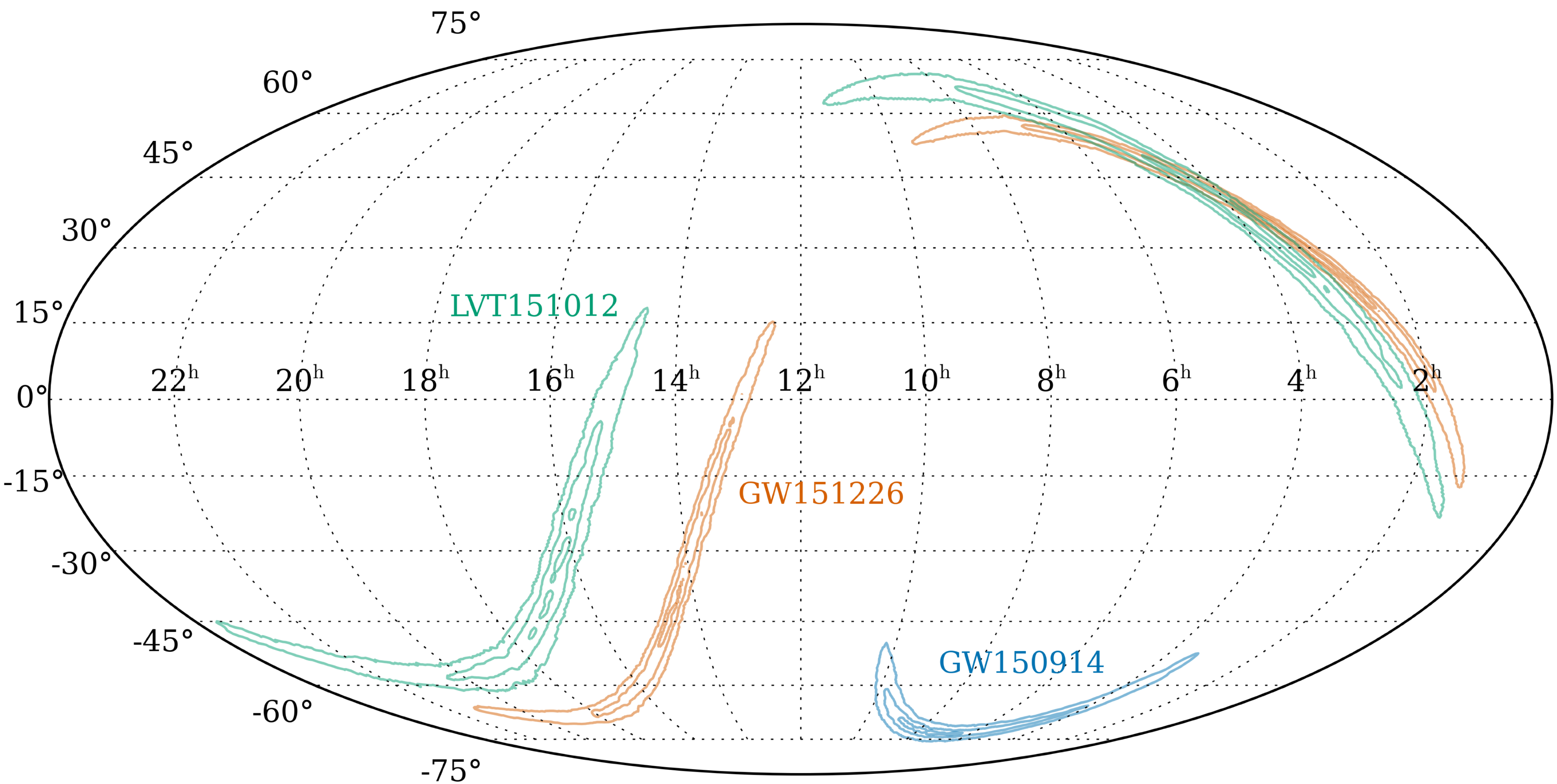


Time-domain data and reconstructed waveforms

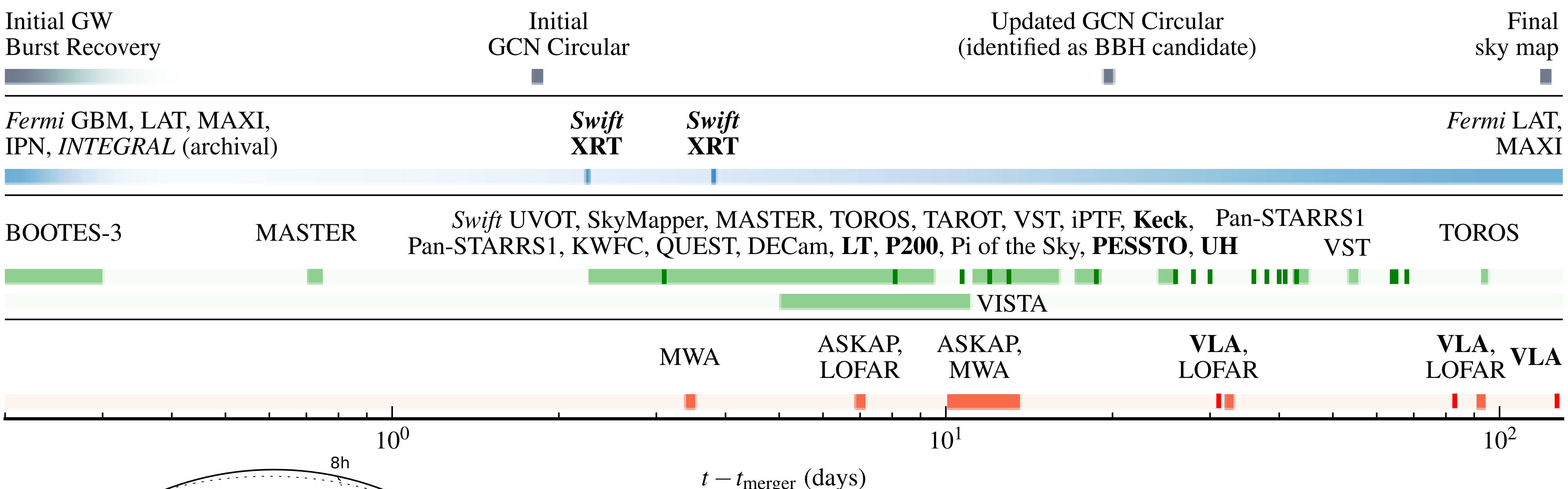


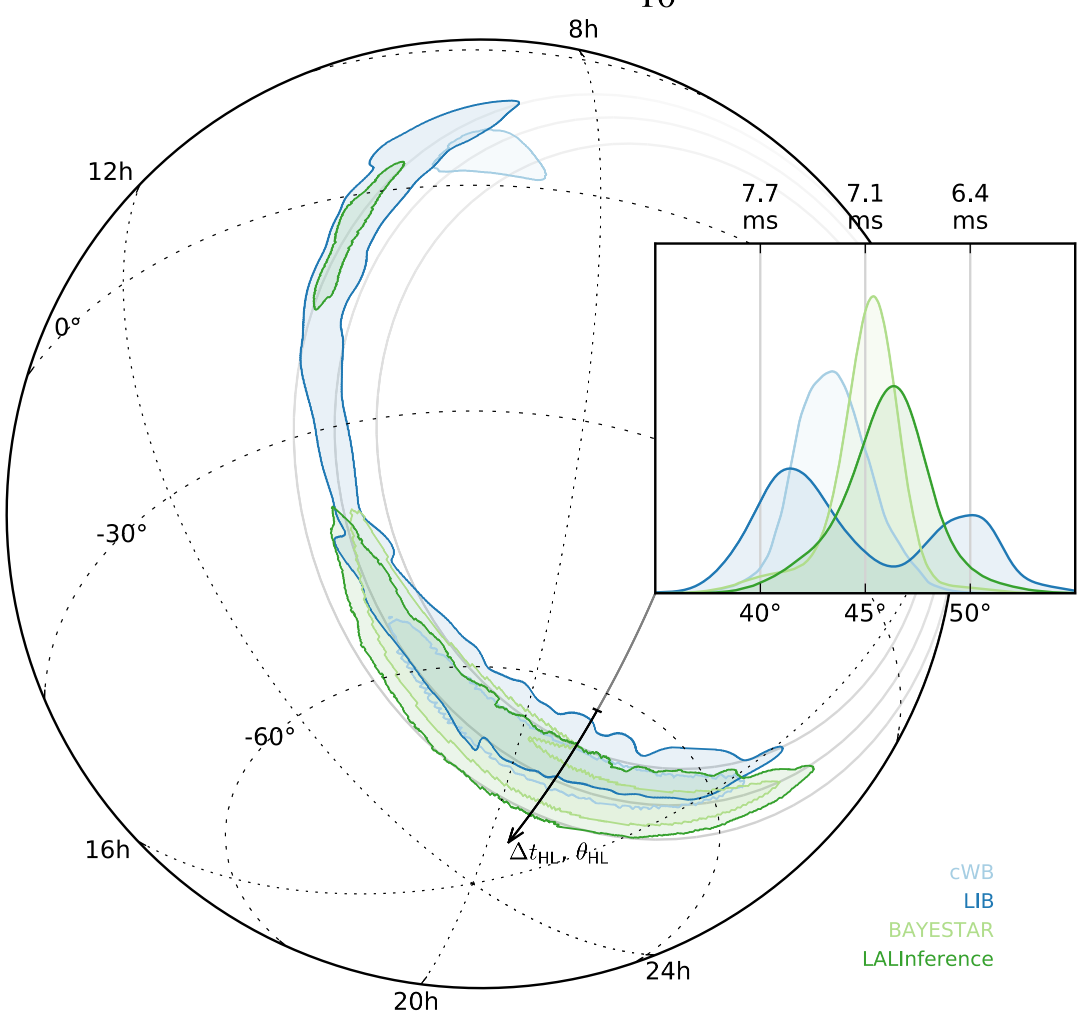
Sky map for all LIGO O1 events

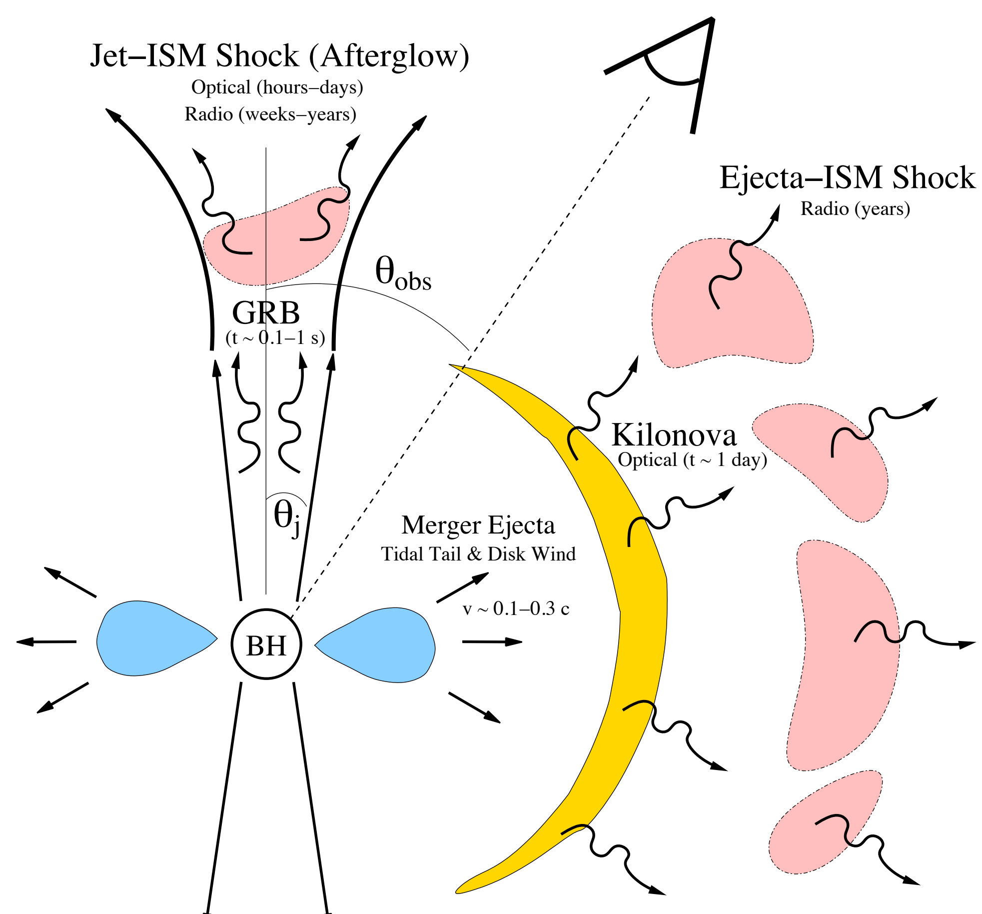
(Abbott et al. arXiv:1606.04856)



First campaign for electromagnetic counterparts







(Berger & Metzger 11)

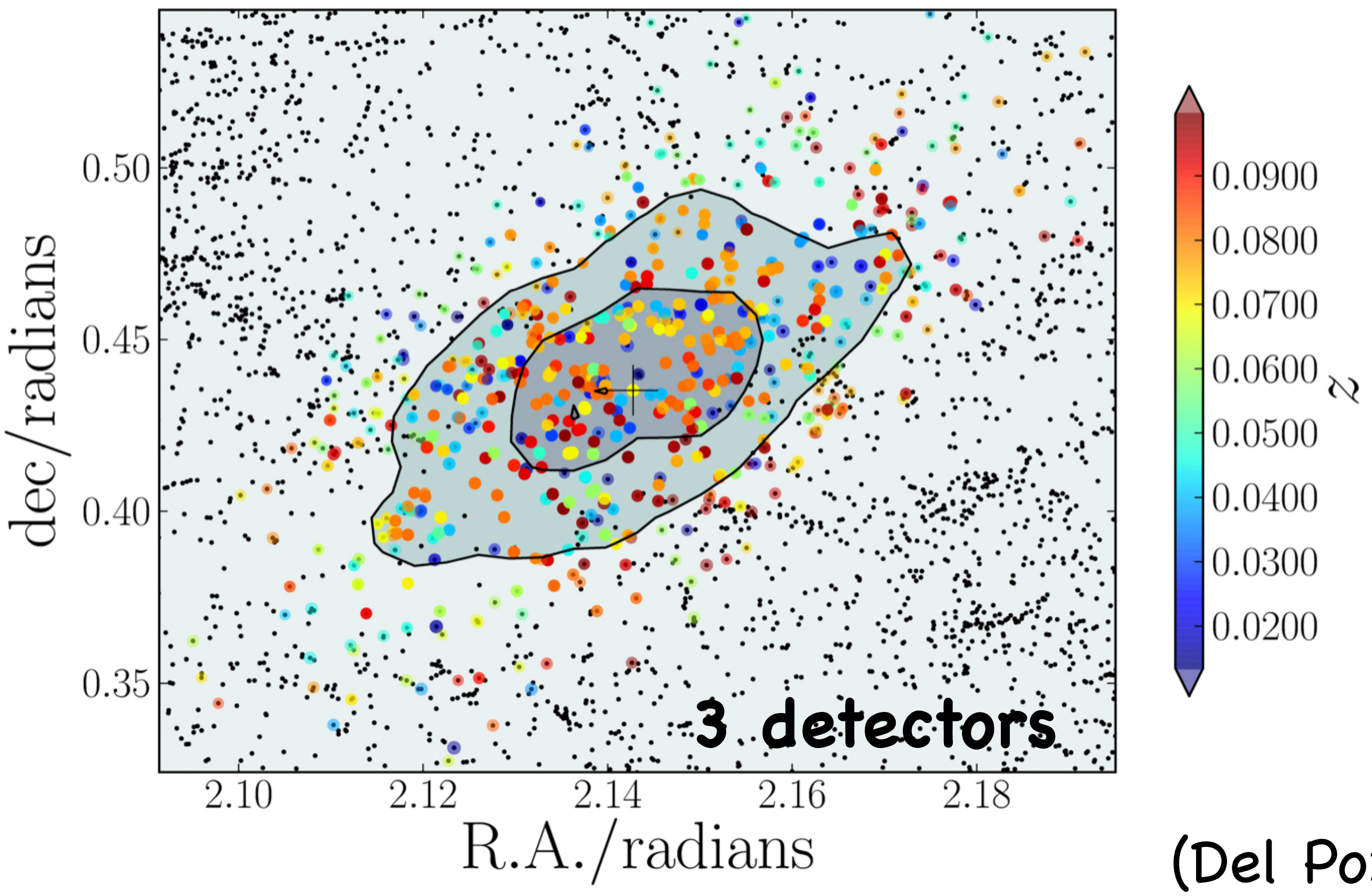
(Abbott et al. APJ L13 (2016) 826)

Inference of cosmological parameters in future LIGO searches

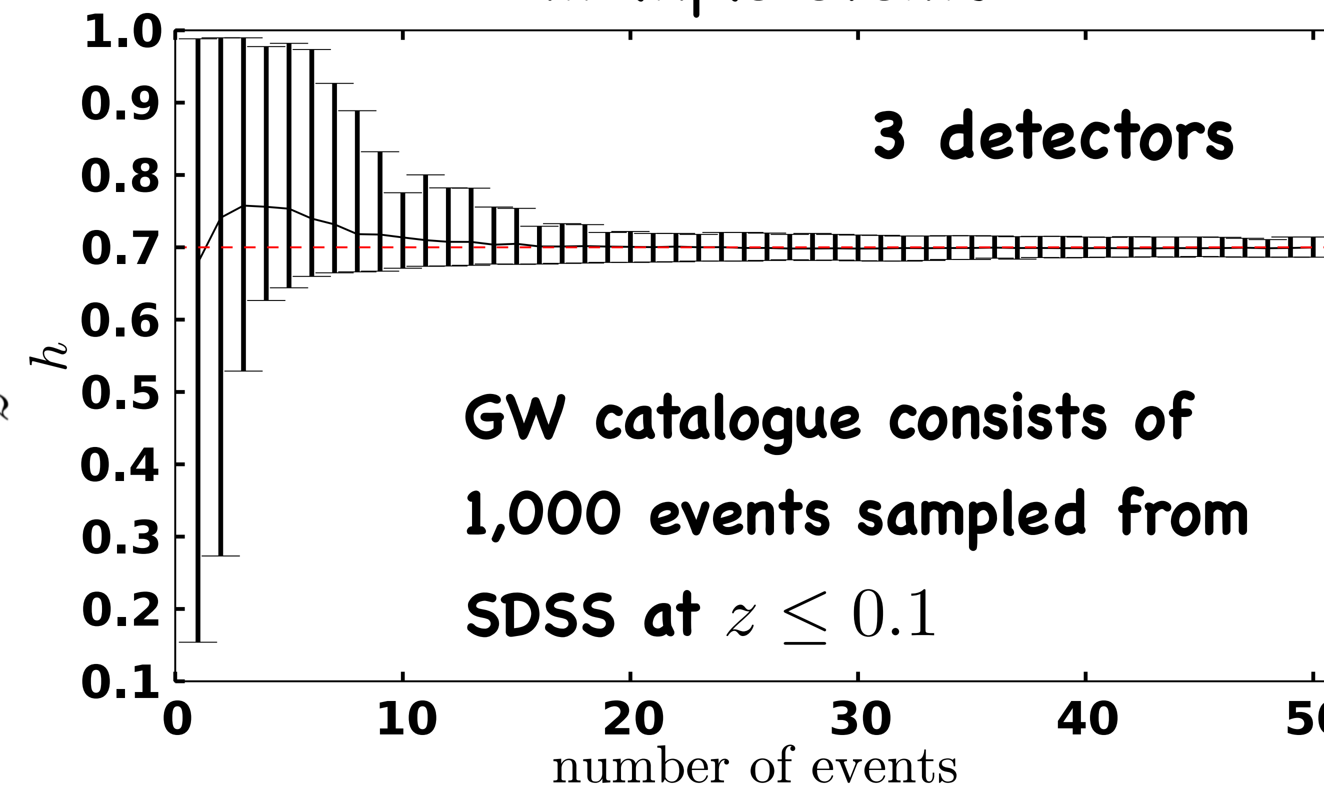
- **Wide-field galaxy surveys** can provide (**sky positions** and) **redshifts**

(Schutz 1986)

single GW event



multiple events

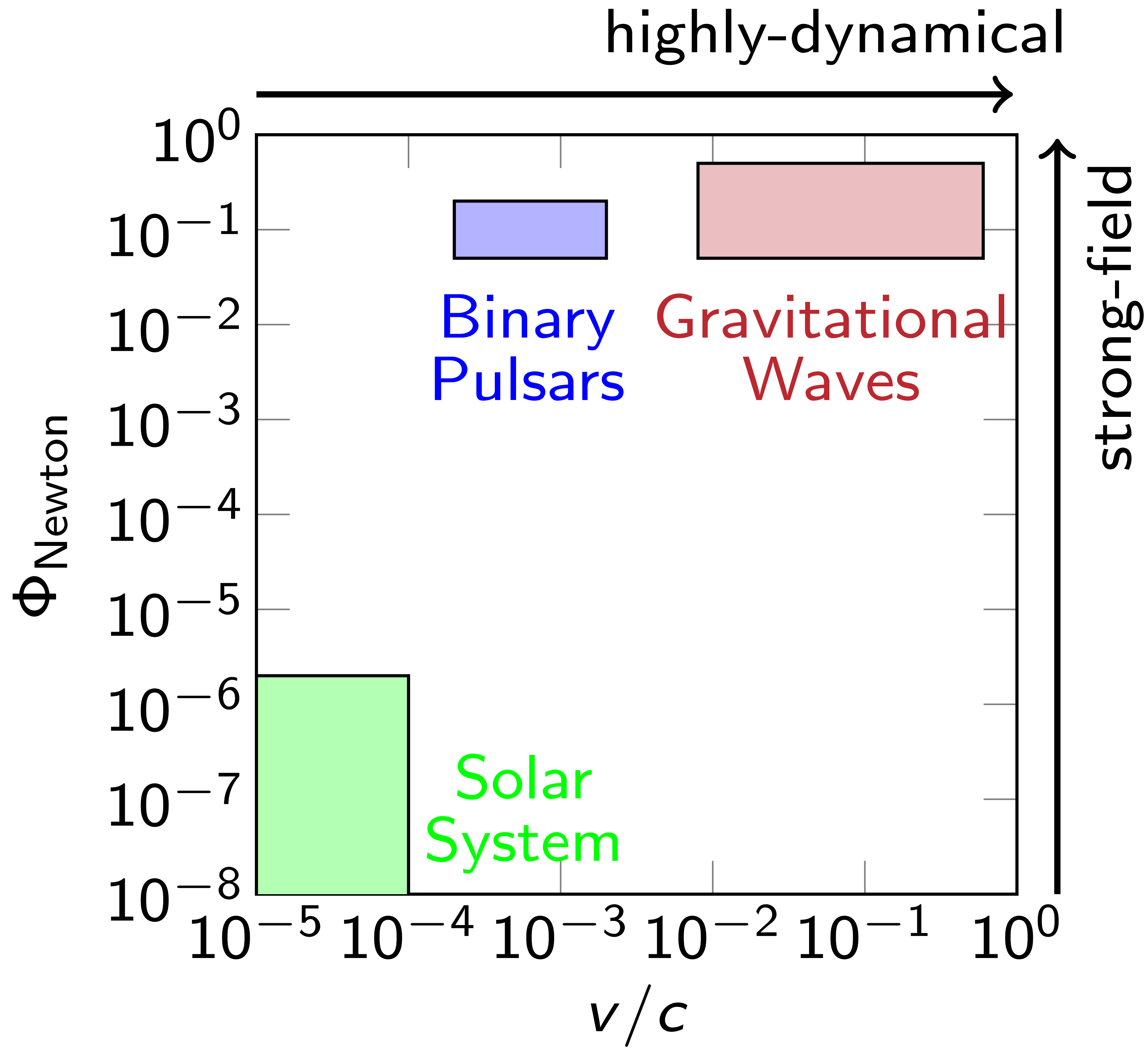


(Del Pozzo 12)

- Measurement of **Hubble constant** H_0 with accuracy of **5%** at 95% confidence **after 40-50 GW observations with 3 detectors.**

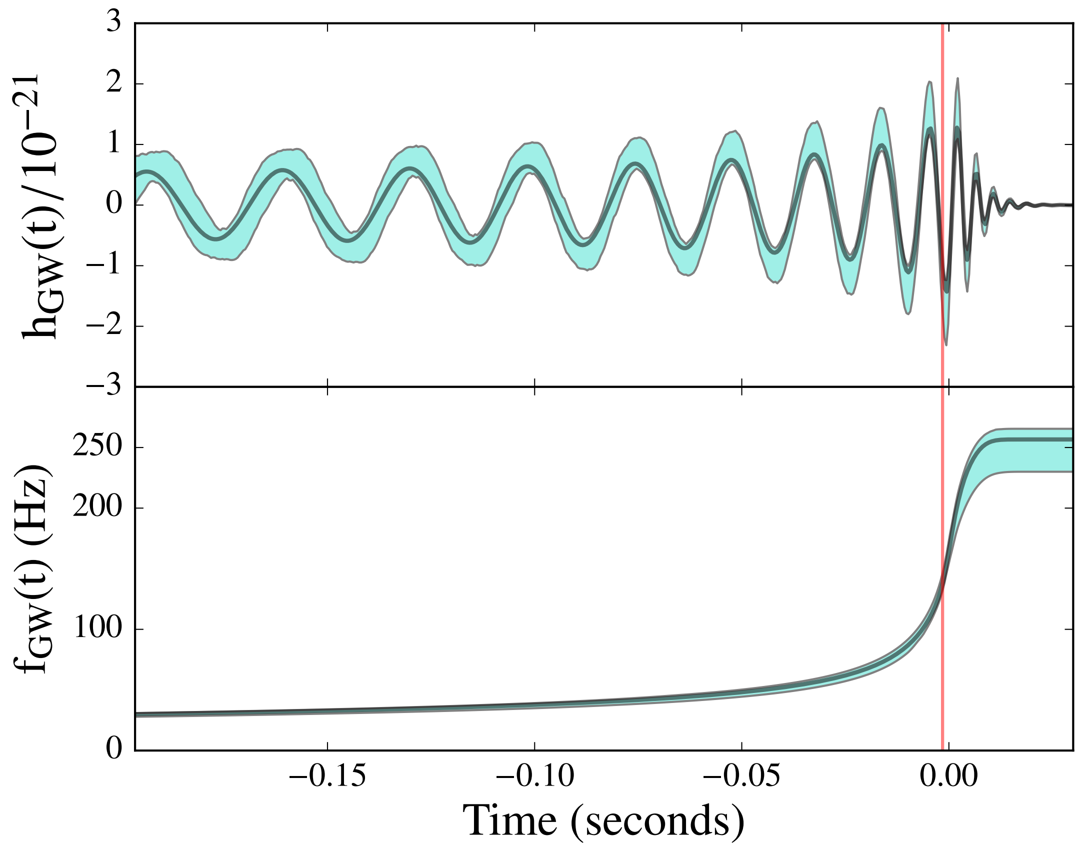
Tests of GR with LIGO's sources

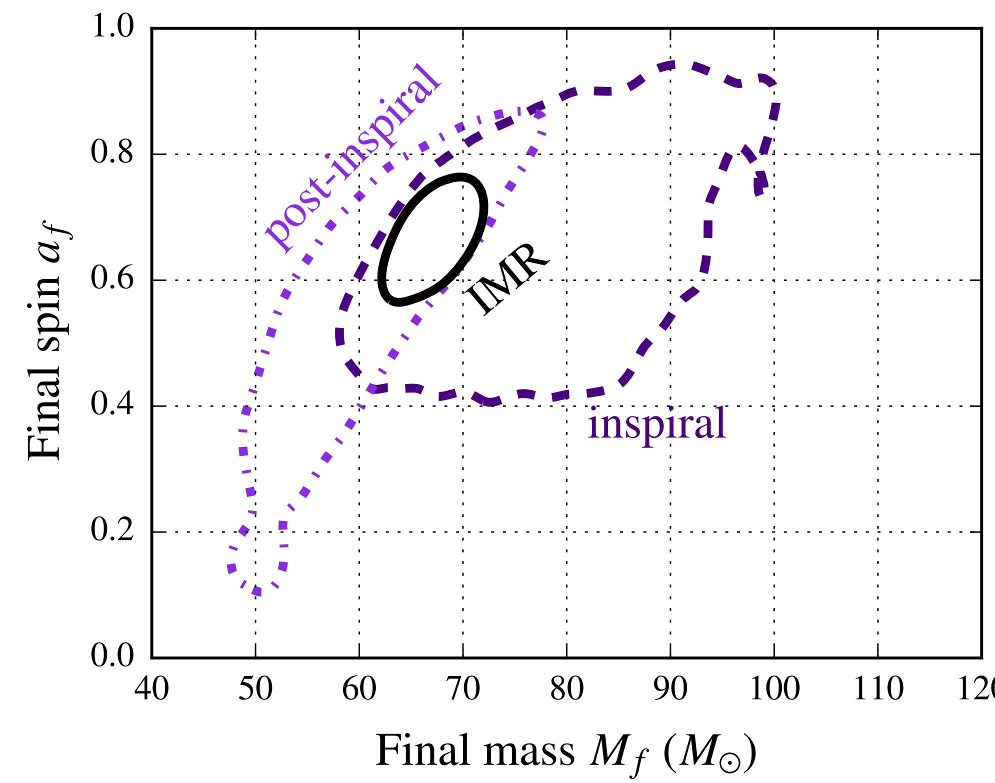
- Given **current tight constraints** on GR (e.g., Solar system, binary pulsars), can **any GR deviation be observed with LIGO**?



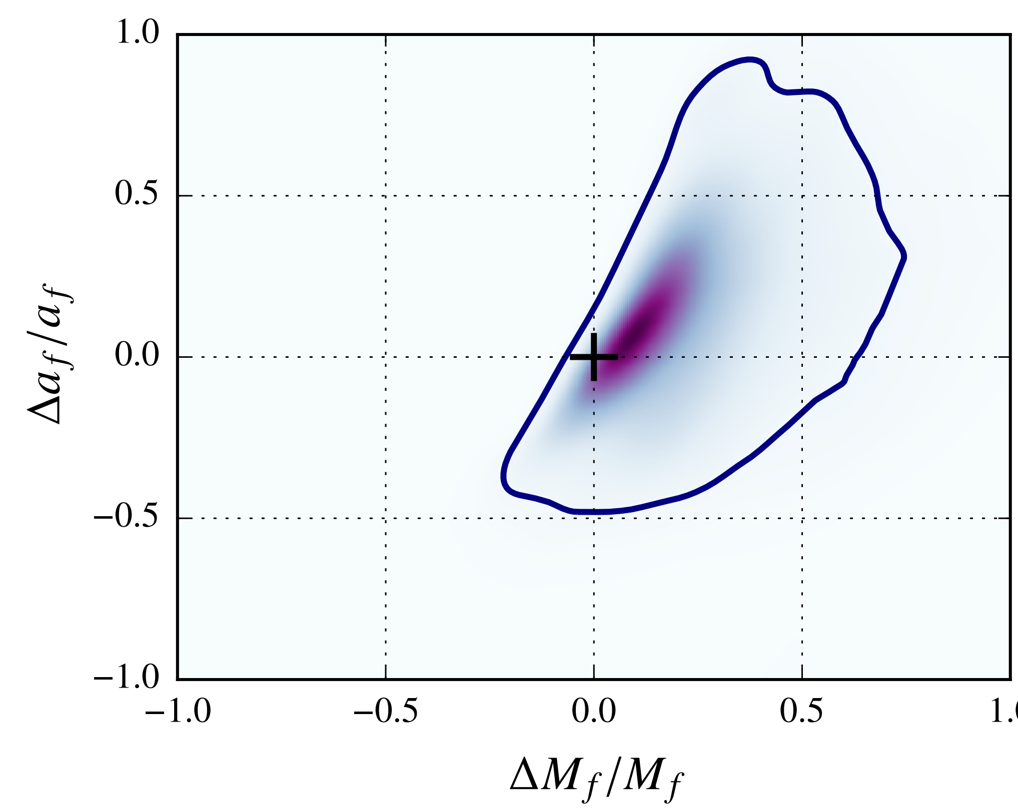
(credit: Sennett)

Inspiral-merger-ringdown consistency test





- Does **GW150914 deviate** from binary **black-hole predictions** in GR?
- We **compare final mass and spin** estimates **from inspiral and post-inspiral**.
- **No** evidence of **discrepancy from GR**.



(Abbott et al. PRL 116 (2016) 221101)

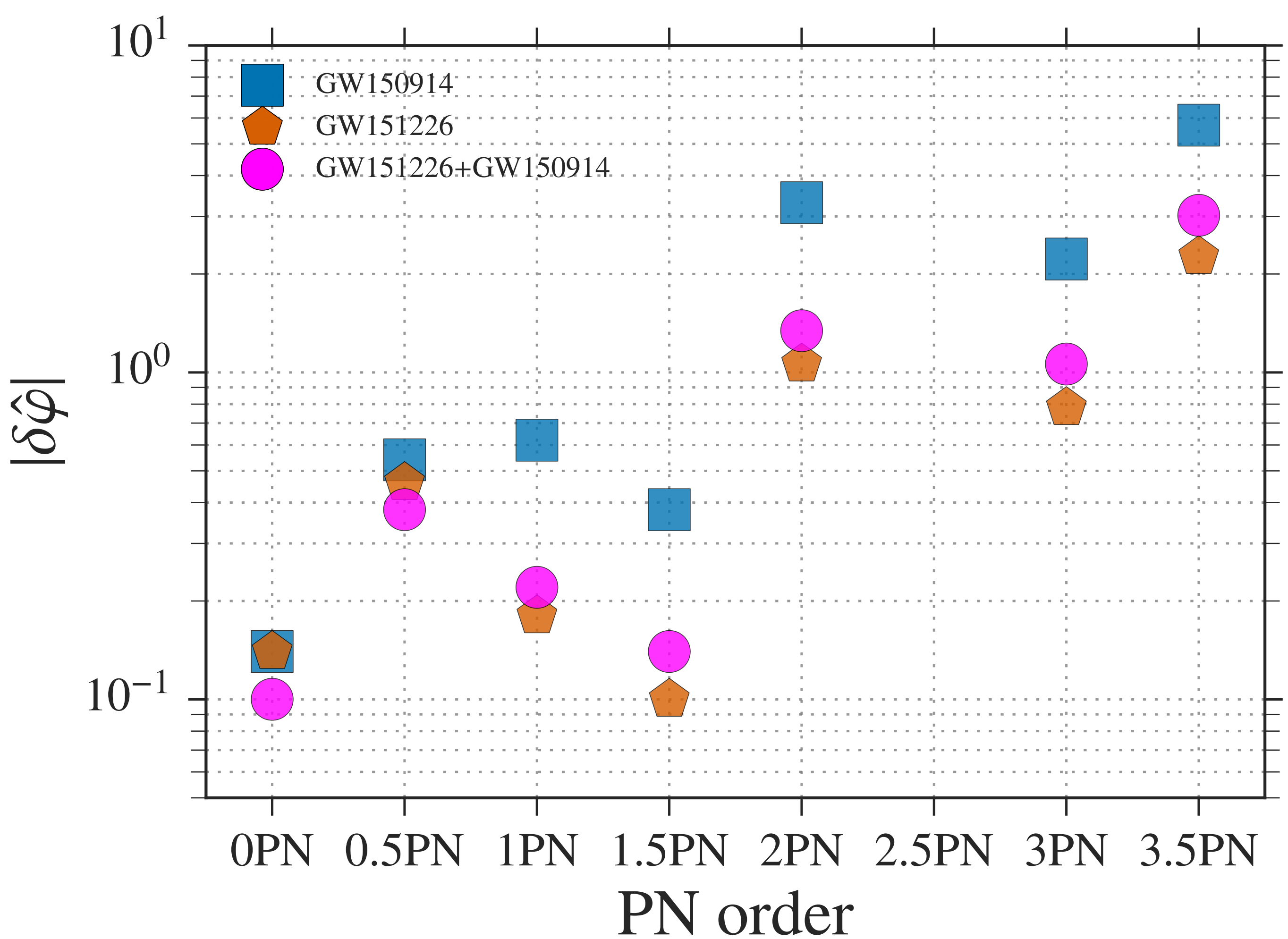
Tests of GR with LIGO's BHs: inspiral

- GW150914/GW122615's **rapidly varying orbital periods** allow us to **bound higher-order PN coefficients** in gravitational phase.

$$\tilde{h}(f) = \mathcal{A}(f)e^{i\varphi(f)}$$

$$\varphi(f) = \varphi_{\rm ref} + 2\pi f t_{\rm ref} + \varphi_{\rm Newt}(Mf)^{-5/3} + \varphi_{\rm 0.5PN}(Mf)^{-4/3} + \varphi_{\rm 1PN}(Mf)^{-1} + \varphi_{\rm 1.5PN}(Mf)^{-2/3} + \cdots$$

(Abbott et al. arXiv:1606.04856)



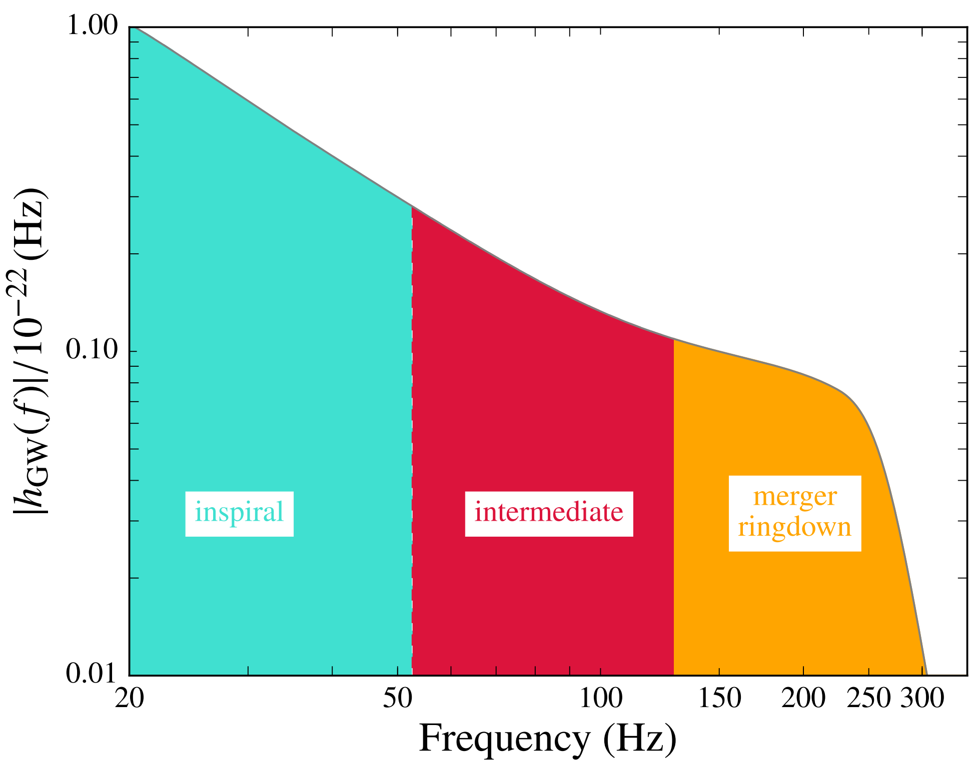
(Arun et al. 06 , Mishra et al. 10, Yunes & Pretorius 09, Li et al. 12)

- **PN parameters** describe: **tails** of radiation due to backscattering, **spin-orbit** and **spin-spin** couplings.

- First **GR test** in the genuinely dynamical, **strong-field regime.**

Tests of GR with LIGO's BHs: late-inspiral—merger-RD

(Abbott et al. arXiv:1602.03841)



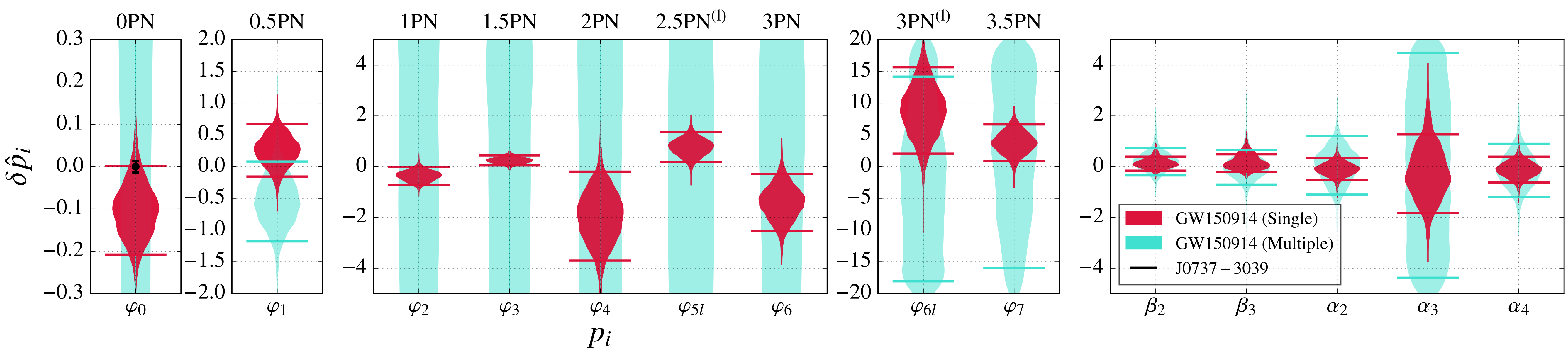
(Yunes & Pretorius 09, Li et al. 12)

$$
\begin{aligned}
\varphi(f) = &\varphi_{\rm ref} + 2\pi f t_{\rm ref} + \varphi_{\rm Newt}(Mf)^{-5/3} \\
&+ \varphi_{\rm 0.5PN}(Mf)^{-4/3} + \varphi_{\rm 1PN}(Mf)^{-1} \\
&+ \varphi_{\rm 1.5PN}(Mf)^{-2/3} + \cdots + \beta_2 \log(Mf) \\
&+ \cdots + \alpha_4 \tan^{-1}(aMf + b)
\end{aligned}
$$

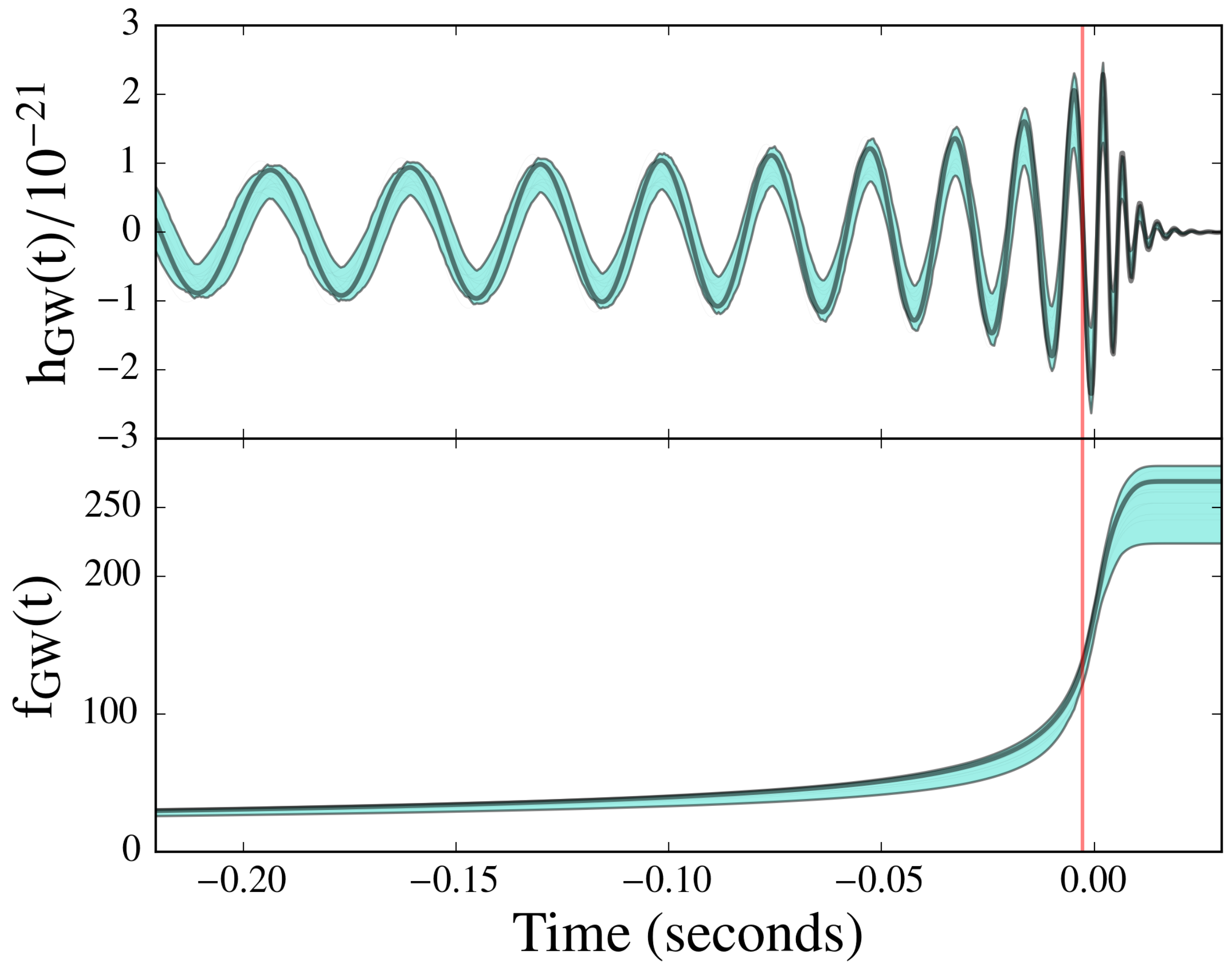
(Khan et al. 16)

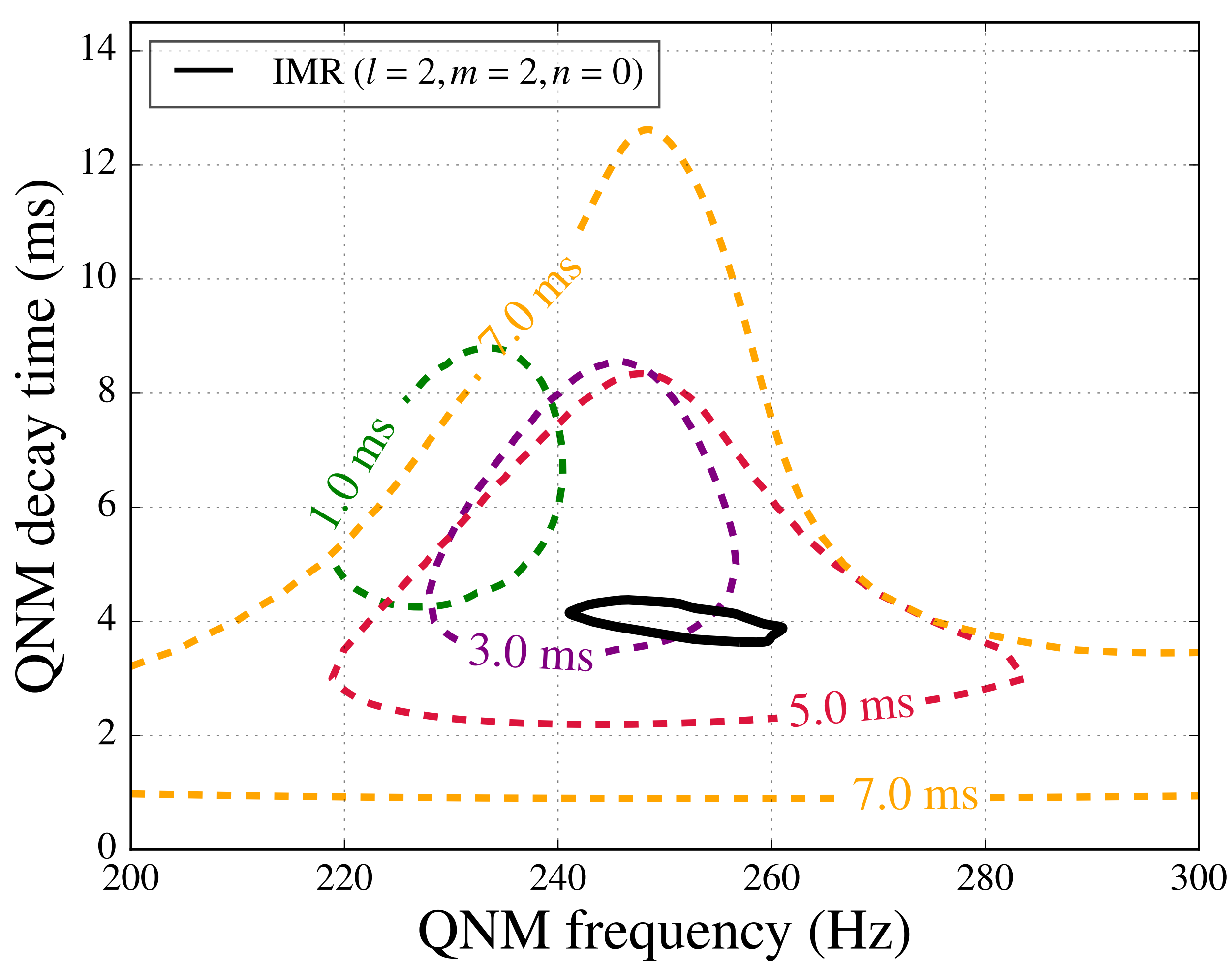
- Merger-ringdown **phenomenological parameters** (β_i and α_i) not yet **expressed in terms** of relevant **parameters in GR and modified theories of GR.**

low frequency → **high frequency**



Could we prove that GW150914's remnant is a BH?





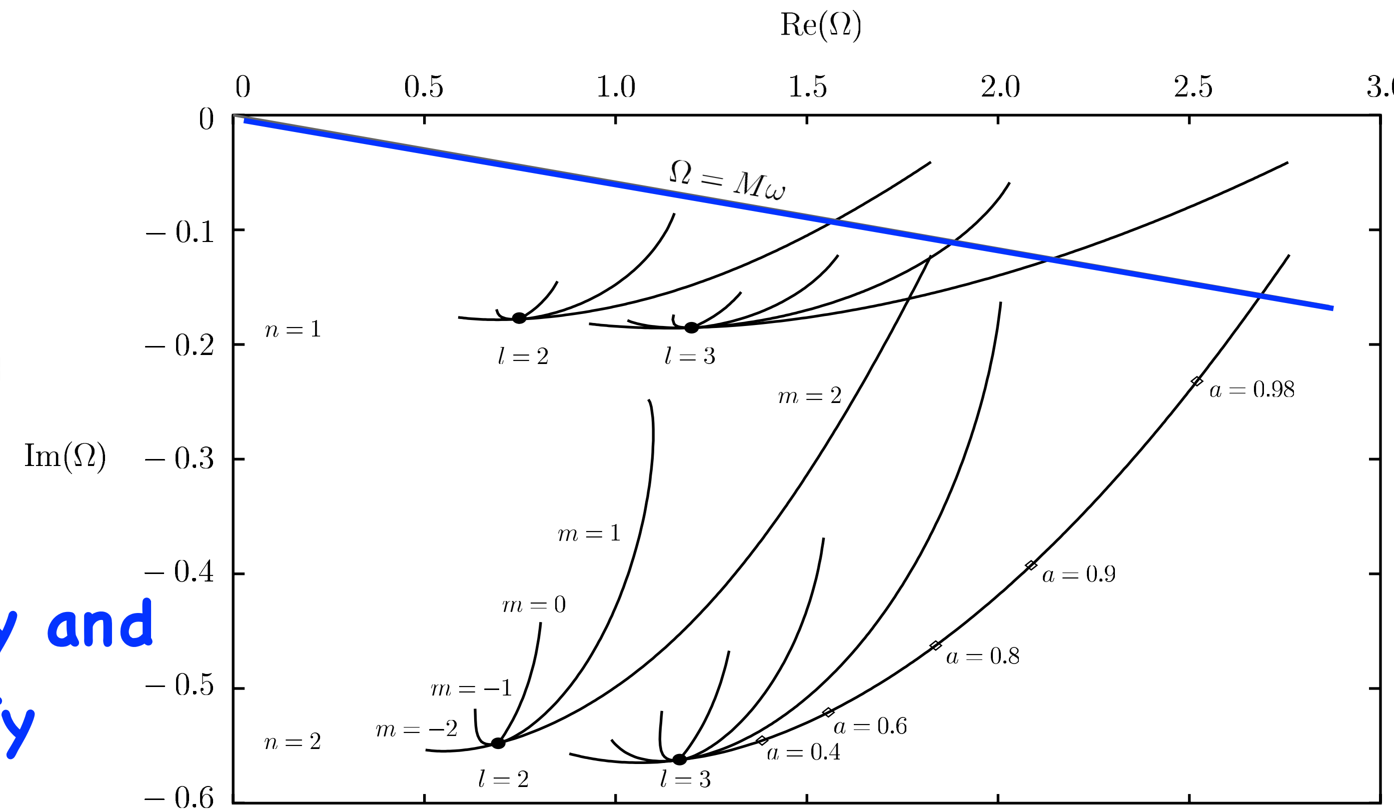
(Abbott et al. PRL 116 (2016) 221101)

- We measured frequency & decay time of **damped sinusoid** in the data after GW150914's peak.

- **Multiple QNMs** need to be measured to extract mass and spin of remnant, test **no-hair theorem** and **second-law black-hole mechanics** (Israel 69, Carter 71; Hawking 71, Bardeen 73).

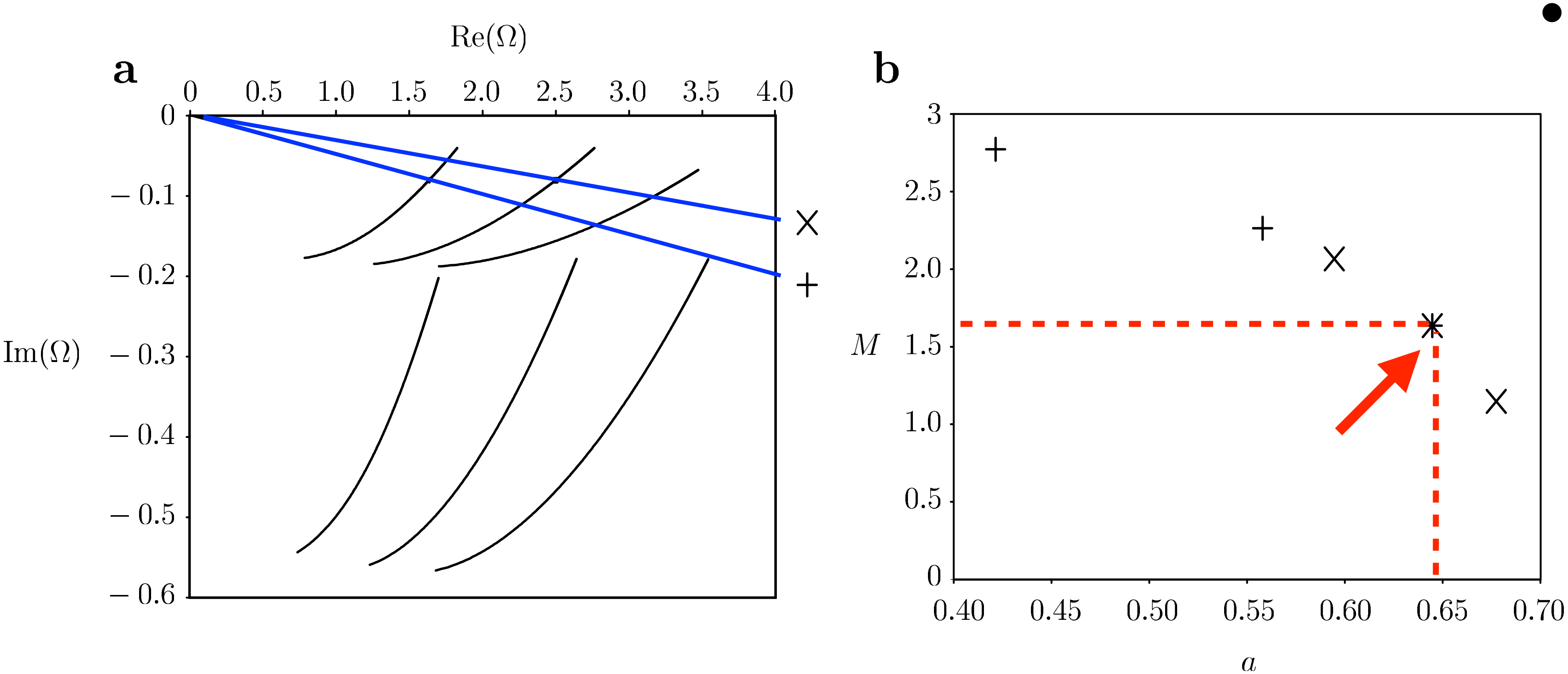
Measuring BH's mass and spin from multiple QNMs

$$\Omega_{n\ell m} = {\color{red} M\omega_{n\ell m}}$$
$$= \left(2\pi F_{n\ell m} + \frac{i}{T_{n\ell m}}\right)$$



(Dreyer et al. 03)

- By knowing only **one frequency and decay time,** we **cannot identify** final BH's mass and spin.



- To **measure multiple modes,** one needs either **high SNR** of O(50-100) **or "stack" many events.**

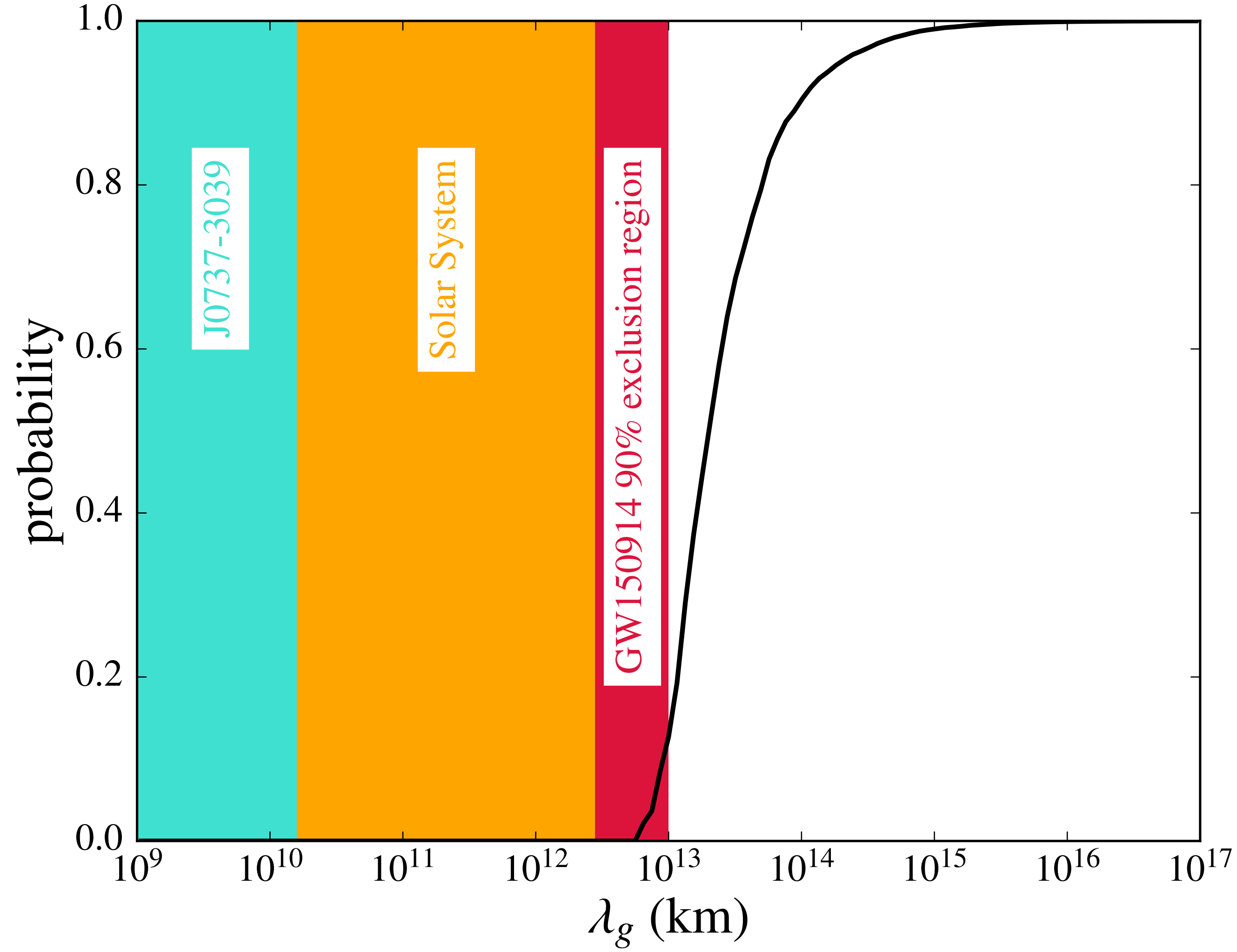
Bounding the graviton Compton wavelength (mass)

- Phenomenological approach: **modified dispersion relation**, thus GWs travel at speed different from speed of light. (Will 94)

$$E^2 = p^2c^2 + m_g^2 c^4 \qquad \lambda_g = \frac{h}{m_g c}$$

- **Lower** frequencies **propagate slower than higher** frequencies.

(Abbott et al. arXiv:1602.03841)

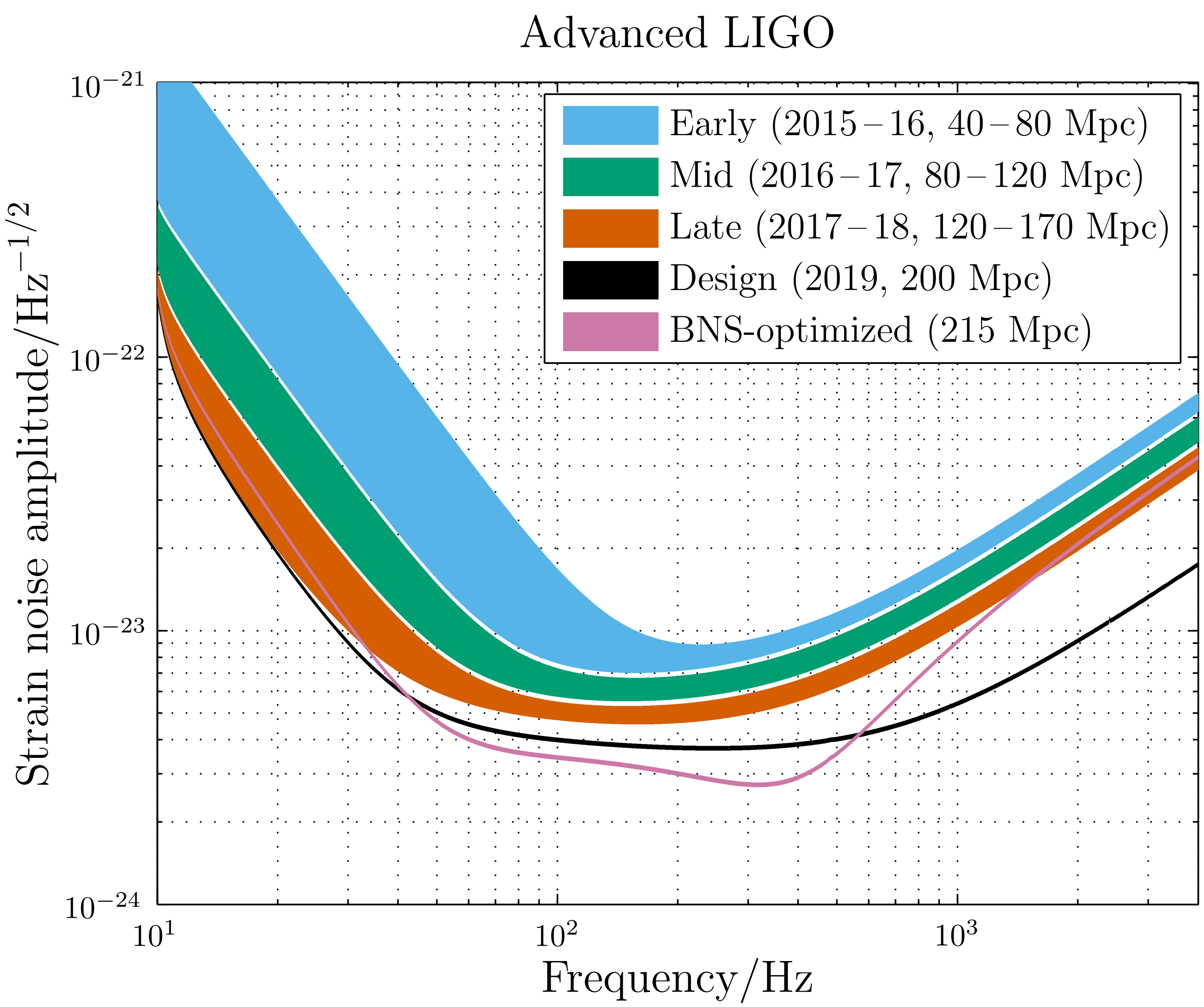


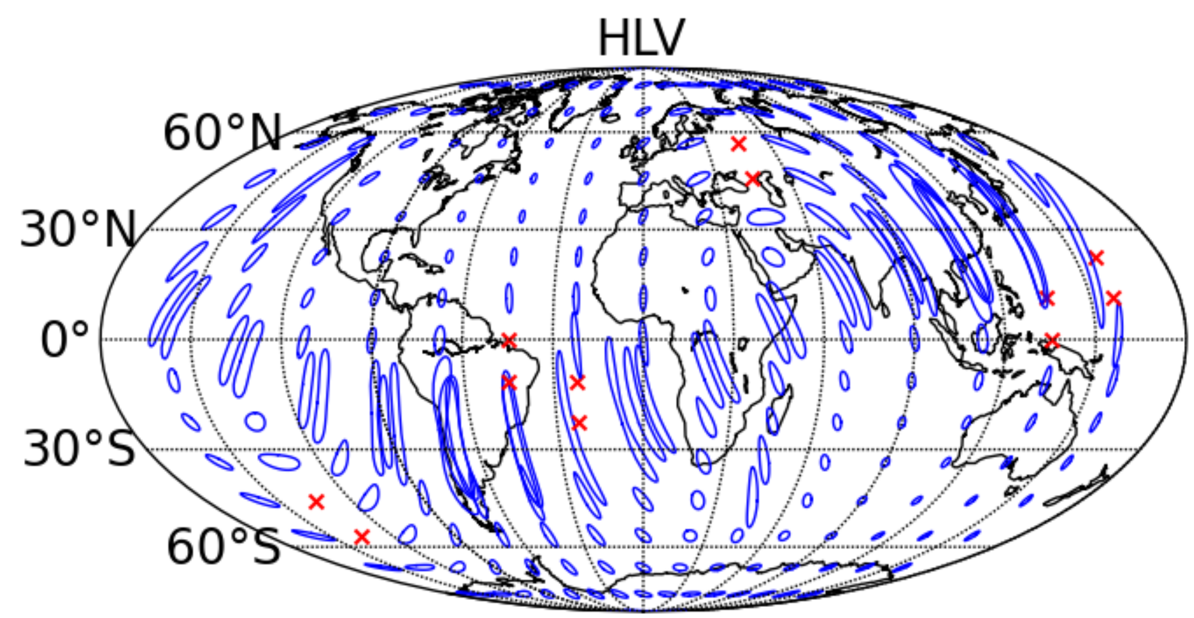
$$\frac{v_g^2}{c^2} = 1 - \frac{h^2c^2}{\lambda_g^2 E^2} \longrightarrow \varphi_{\rm MG} = -\frac{\pi D c}{\lambda_g^2(1+z) f} \qquad m_g \leq 1.2 \times 10^{-22} \mathrm{eV/c^2}$$

(see Yunes et al 16. for constraints on other dispersion relations, super- and sub-luminal GW propagation, Lorentz violation)

Advanced detectors' roadmap and sky localization

(Aasi et al. arXiv:1304.0670)





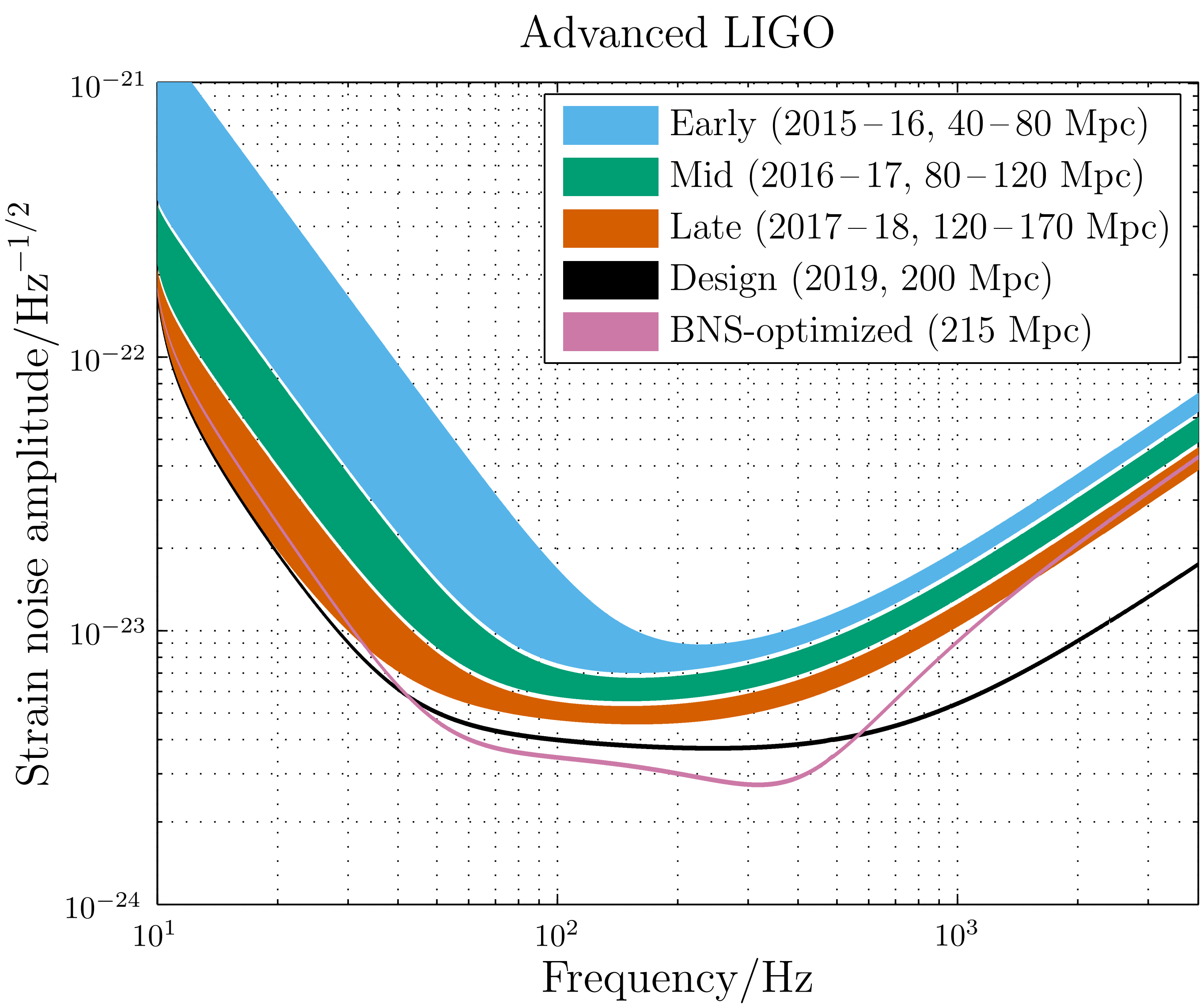
- Few **tens or hundred** square degrees

Detection rates @ **design sensitivity**:

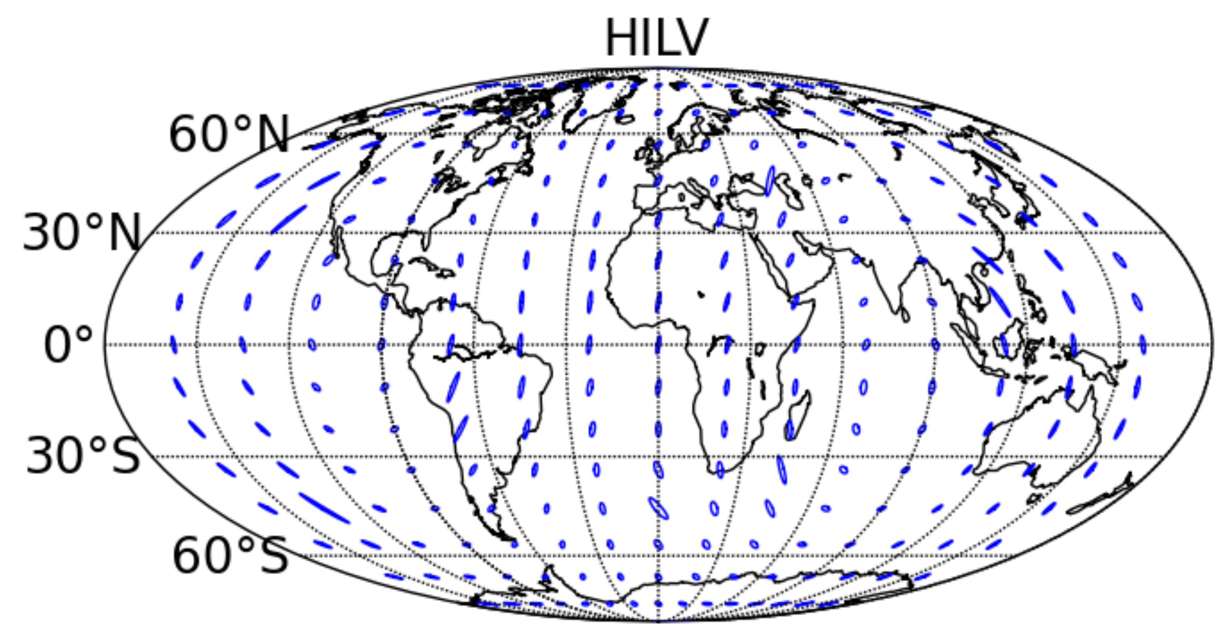
- **Binary neutron stars: 0.2 - 200 per year**
- **Binary black holes: tens to hundreds per year!**

Advanced detectors' roadmap and sky localization

(Aasi et al. arXiv:1304.0670)



with LIGO-India



- **Few** square degrees!

Detection rates @ **design sensitivity**:

- **Binary neutron stars: 0.2 - 200 per year**
- **Binary black holes: tens to hundreds per year!**