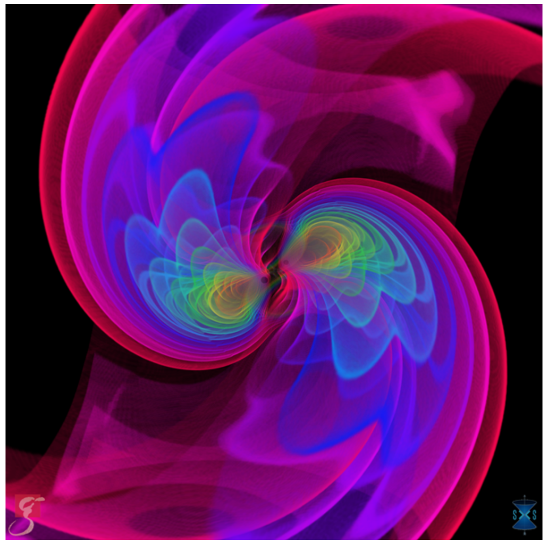
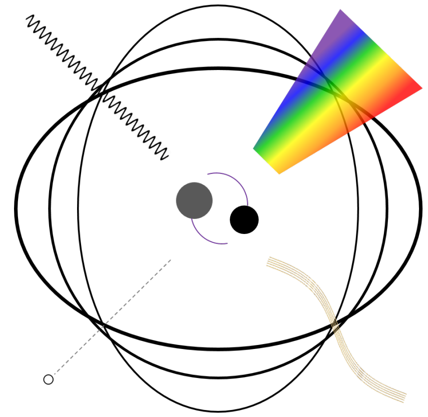
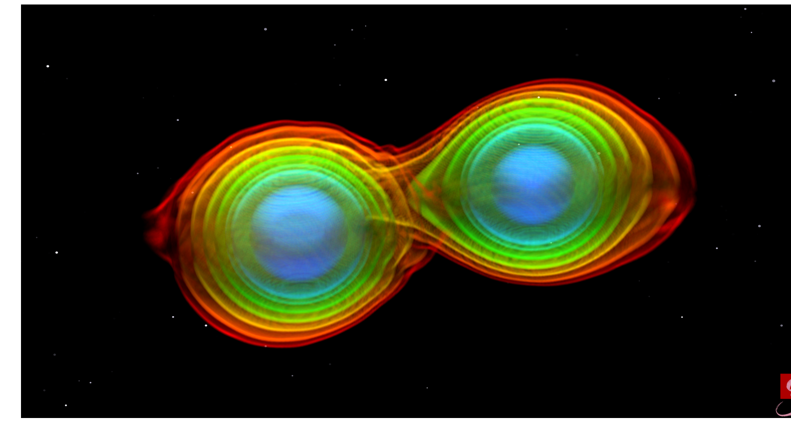
   

The next theoretical challenges in gravitational-wave observations

Alessandra Buonanno

Max Planck Institute for Gravitational Physics

(Albert Einstein Institute)

Department of Physics, University of Maryland

"Sackler Conference 2018: Gravitational Wave Astrophysics", Harvard University **May 7, 2018**

Outline

- The science from GW experiments stems on our ability to make precise theoretical predictions of gravitational waveforms. Success of analytical/ numerical-relativity interface program.

- For upcoming runs, do we need more accurate or complete waveform models to interpret observations & extract information? Requirements depend on goals.

- Science: observing & inferring information of NSBHs, intermediate mass BBHs; discriminating among binary formation scenarios; probing GR, EOS of NS, and cosmology:

  - higher harmonics (i.e., beyond quadrupolar radiation)
  - gravitational self-force formalism (for small-(or large) mass ratio binaries)
  - eccentricity
  - deviations from GR
  - tides

Solving two-body problem in General Relativity (including radiation)

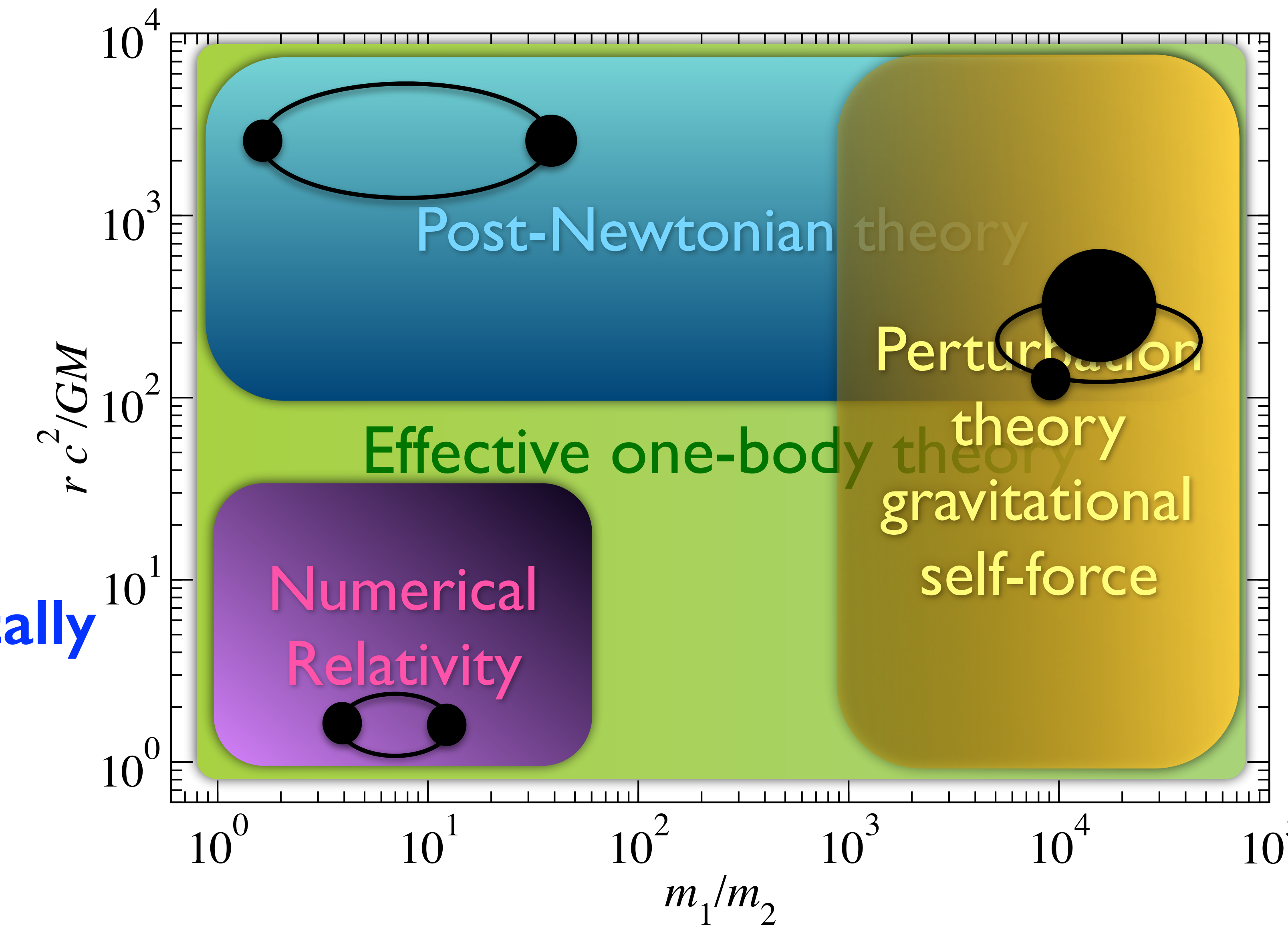
$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \frac{8\pi G}{c^4} T_{\mu\nu}$$

- **GR** is **non-linear theory.**

- Einstein's field equations can be solved:

  - **approximately,** but **analytically** (**fast** way)
  - **exactly,** but **numerically** on supercomputers (**slow** way)

$v^2/c^2 \sim GM/rc^2$



(AB & Sathyaprakash 14)

- **Synergy** between **analytical** and **numerical relativity** is **crucial.**

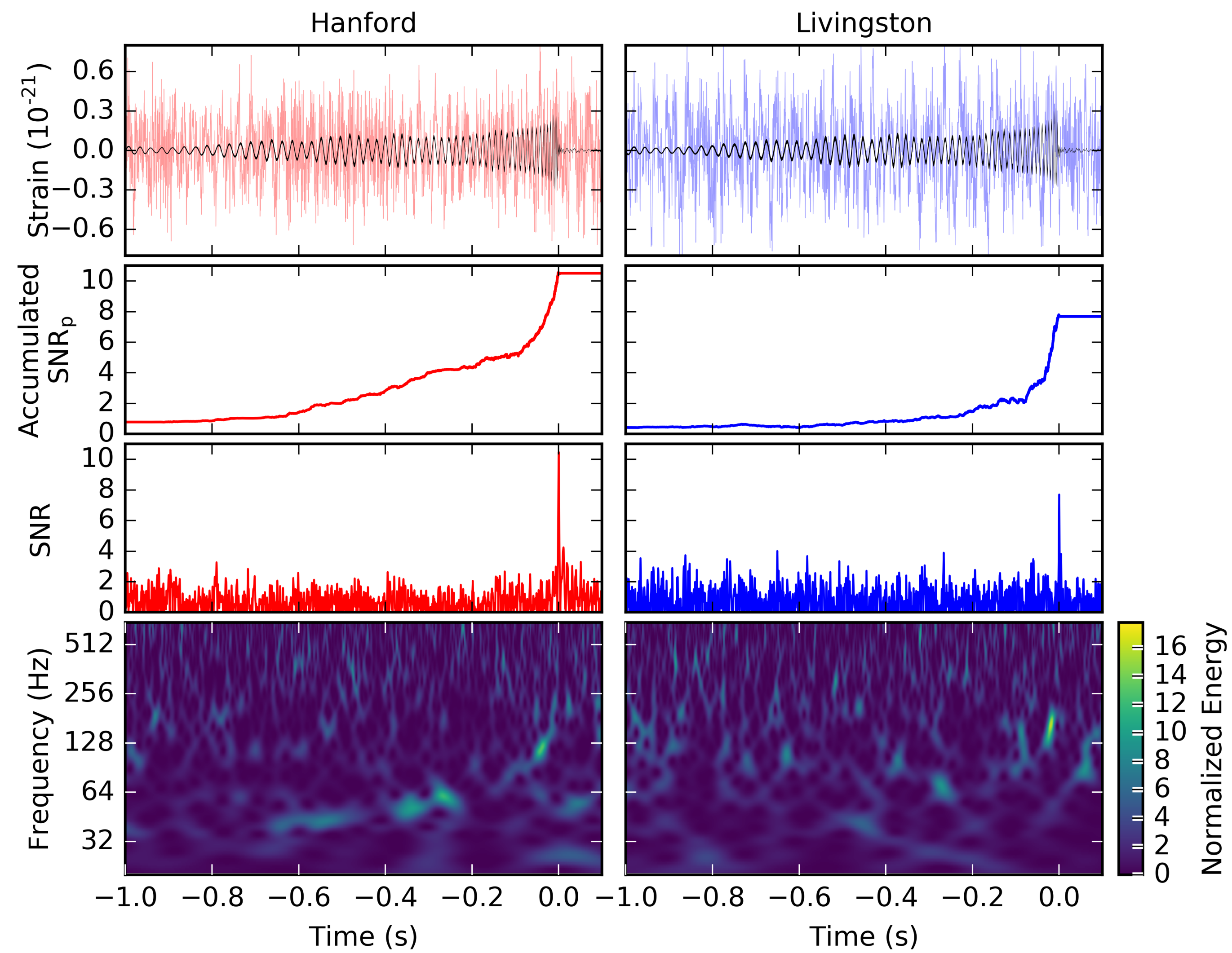
- Physical (EOBNR) and phenomenological (Phenom) **inspiral-merger-ringdown waveforms.**

Solving two-body problem in General Relativity (including radiation)

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \frac{8\pi G}{c^4} T_{\mu\nu}$$

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

- **GW151226**: SNR=13, 55 cycles (from 35 Hz), **1 sec.**



- **GR** is **non-linear theory.**
- Einstein's field equations can be solved:
  - **approximately,** but **analytically** (**fast** way)
  - **exactly**, but **numerically** on supercomputers (**slow** way)
- **Synergy** between **analytical** and **numerical relativity** is **crucial.**
- Physical (EOBNR) and phenomenological (Phenom) **inspiral-merger-ringdown waveforms.**

Solving two-body problem in General Relativity (including radiation)

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \frac{8\pi G}{c^4} T_{\mu\nu}$$

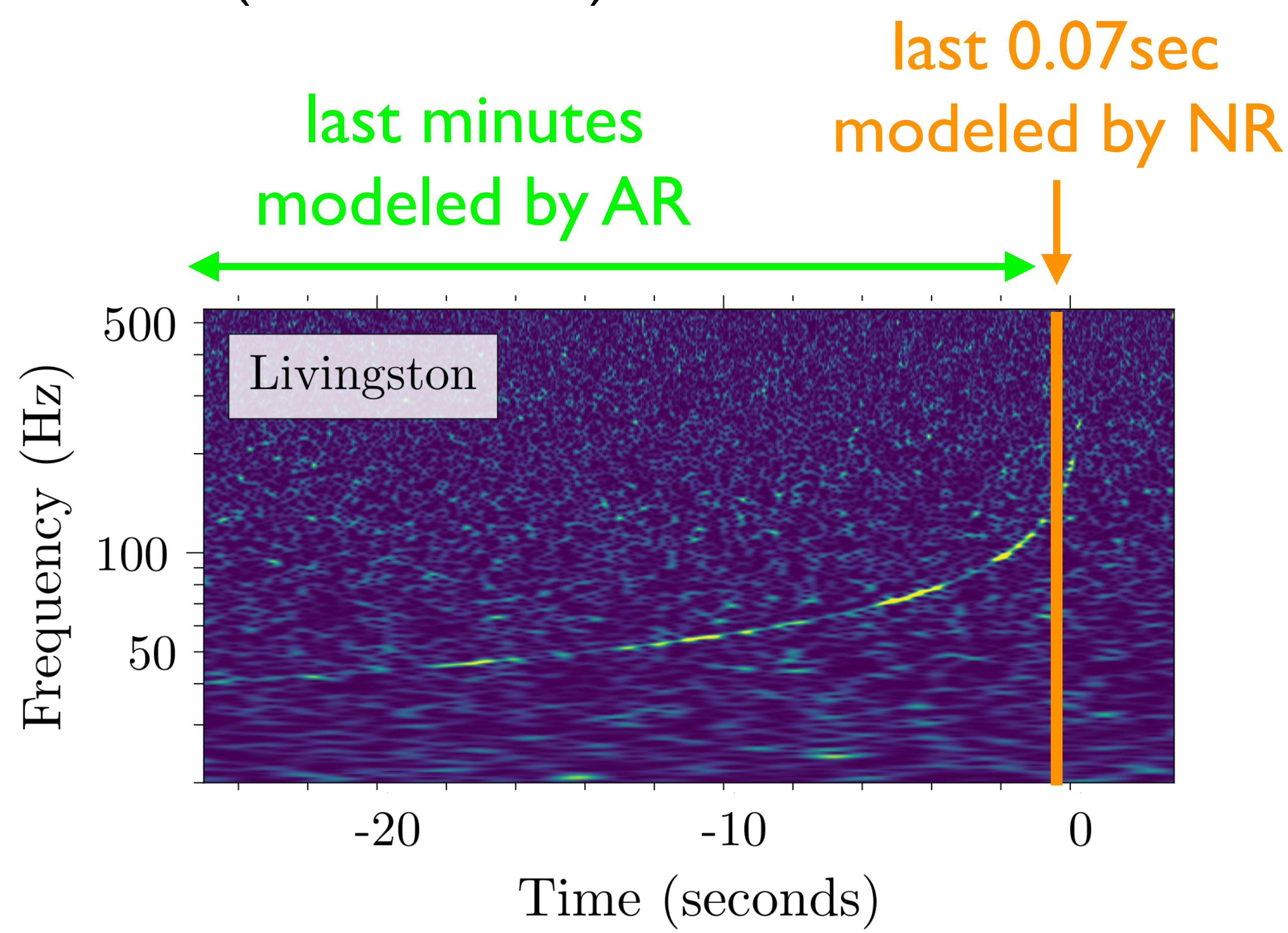
(Abbott et al. PRL 119 (2017) 161101)

- **GW170817**: SNR=32, 3000 cycles (from 30 Hz), one **minute.**

- **GR** is **non-linear theory**.

- Einstein's field equations can be solved:

  - **approximately,** but **analytically** (**fast** way)
  - **exactly**, but **numerically** on supercomputers (**slow** way)

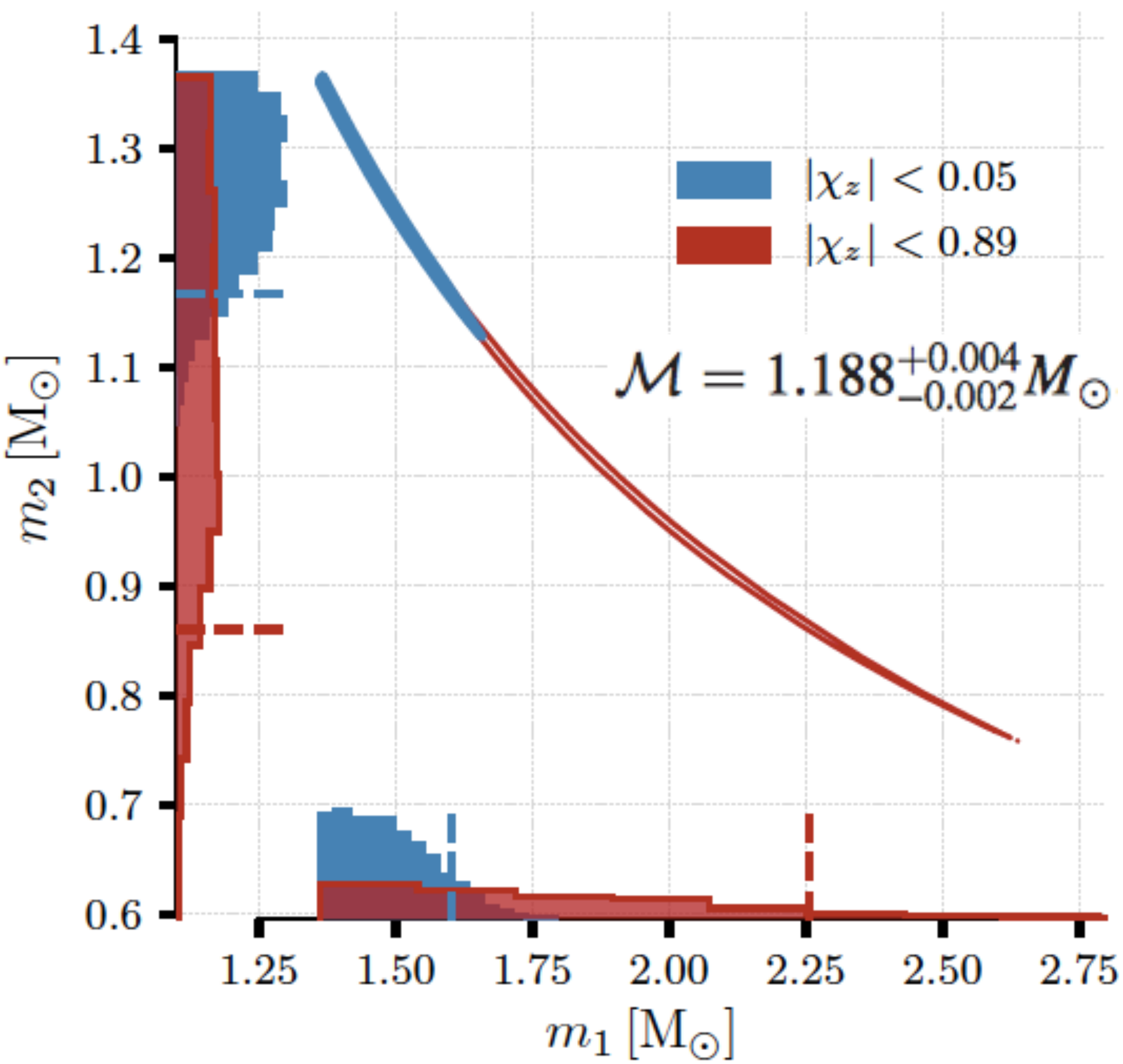


- **Synergy** between **analytical** and **numerical relativity** is **crucial.**

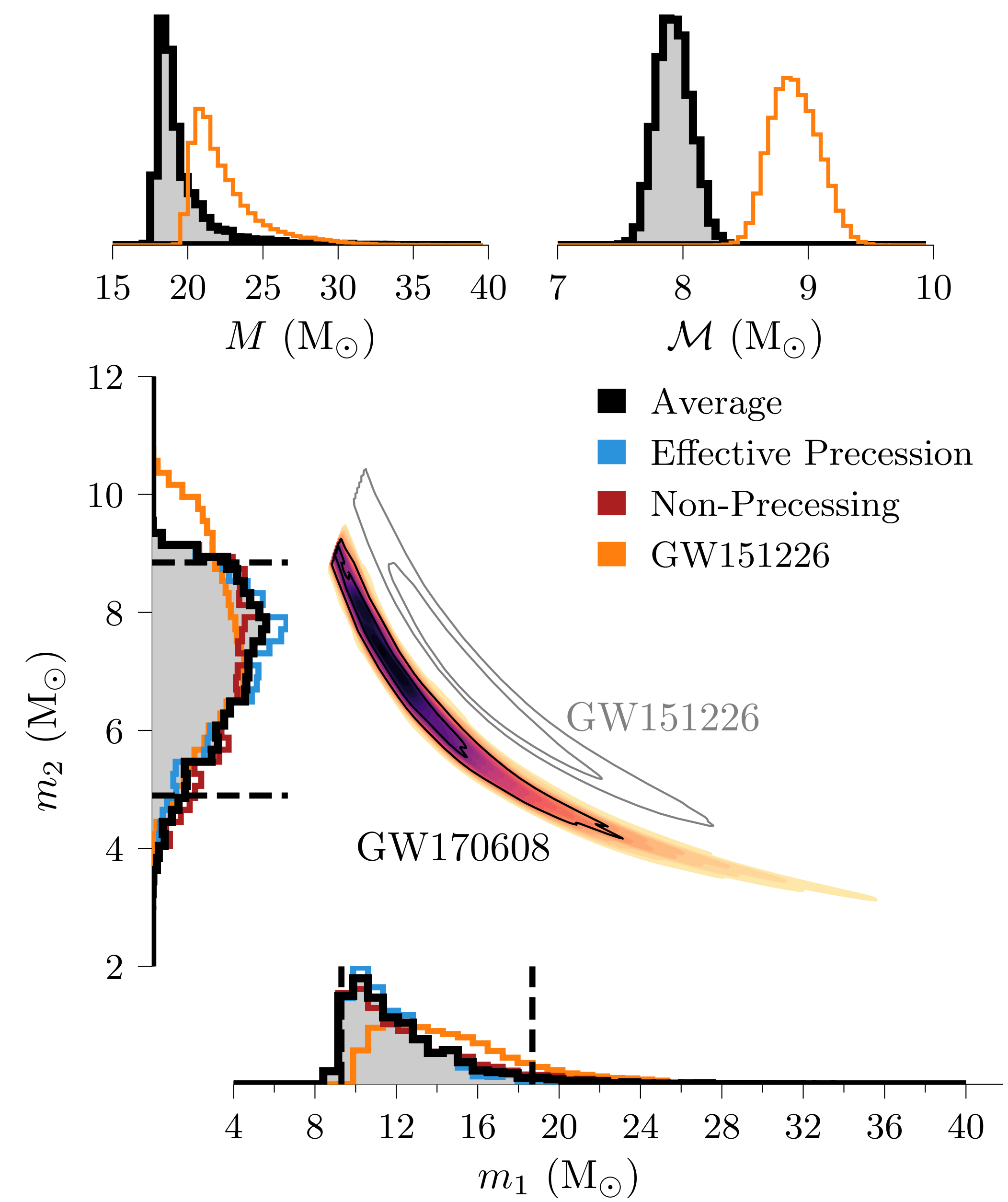
- Physical (EOBNR) and phenomenological (Phenom) **inspiral-merger-ringdown waveforms.**

Unveiling binary black-hole properties: masses

(Abbott et al. PRL 119 (2017) 161101)



(Abbott et al. ApJ 851 (2017) 1, L16)

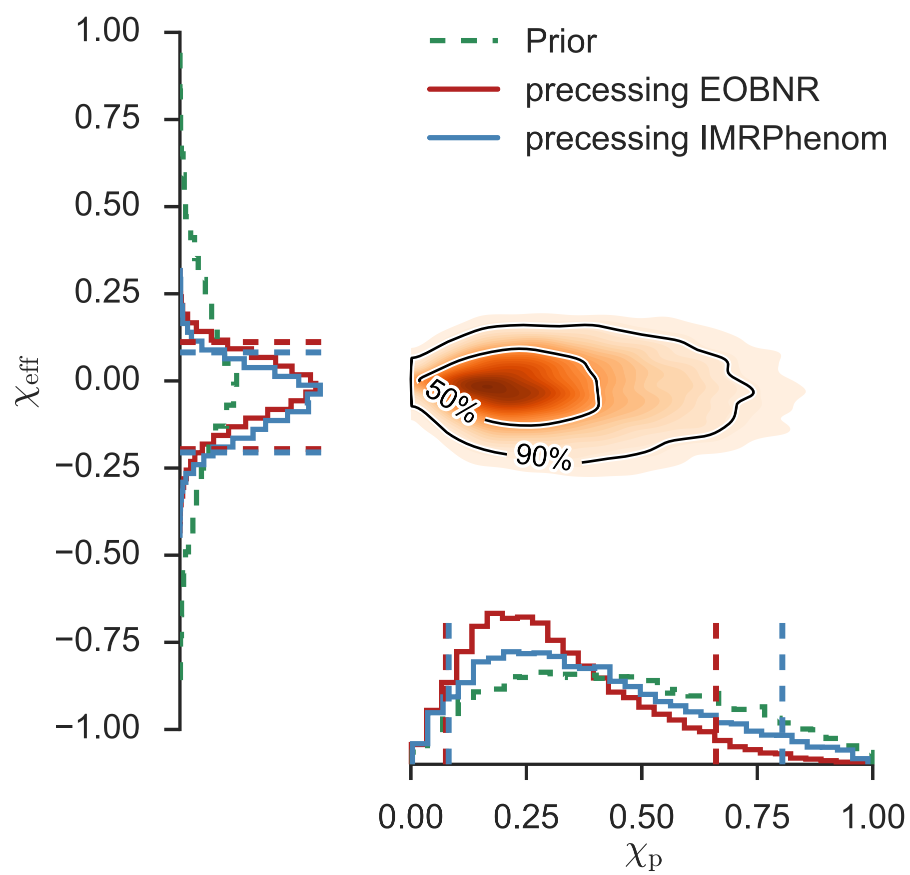


- **Chirp mass** is **best measured**. **Individual masses** can be **better measured** if **merger is observed**, because total mass is measured at merger. **Spin/mass degeneracy,** it can be broken by precession and higher harmonics.

Unveiling binary black-hole properties: spins

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

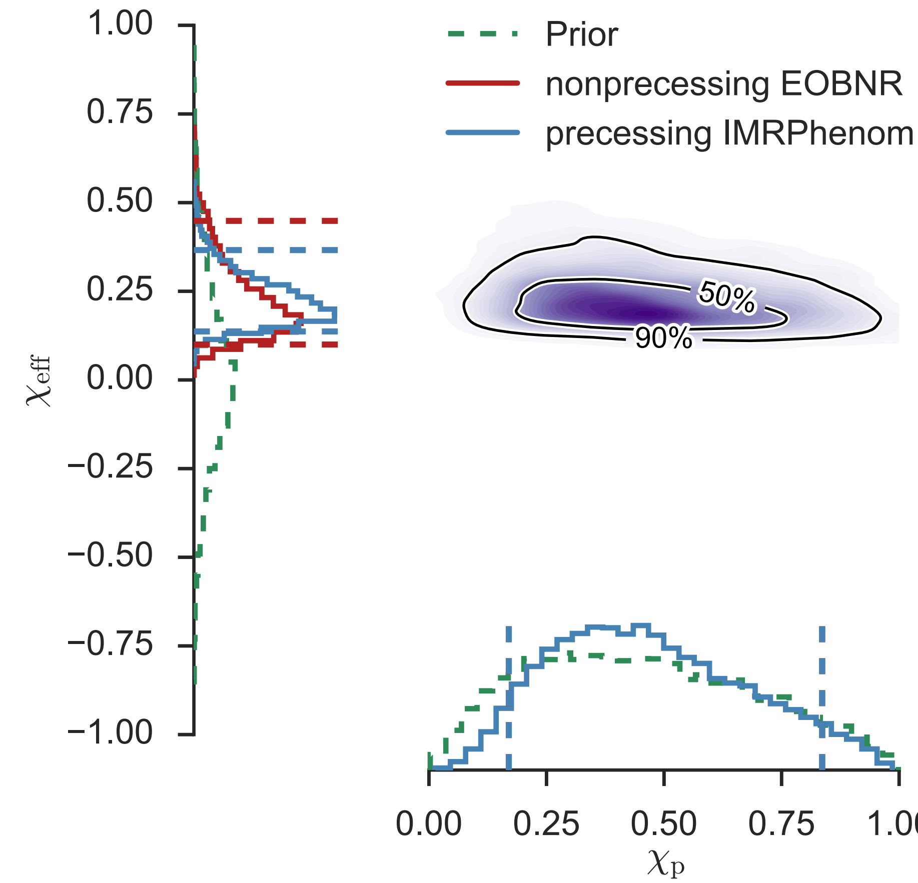
GW150914

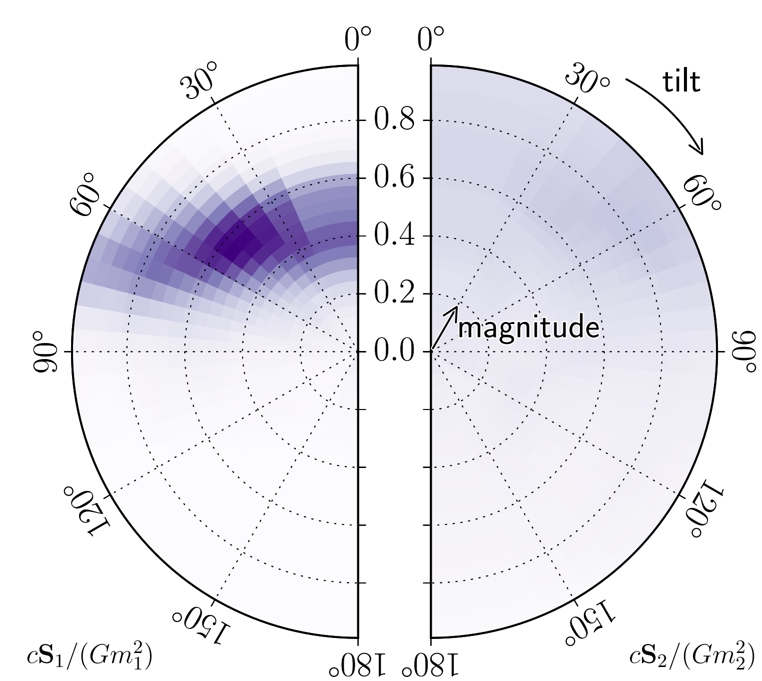


$$\chi_{\rm eff} = \frac{c}{GM}\left(\frac{\boldsymbol{S}_1}{m_1} + \frac{\boldsymbol{S}_2}{m_2}\right)\cdot\frac{\boldsymbol{L}}{|\mathbf{L}|}$$

- **Spins along** orbital **angular momentum** better **measured**.
- **Spins magnitudes < 0.7**.

GW151226



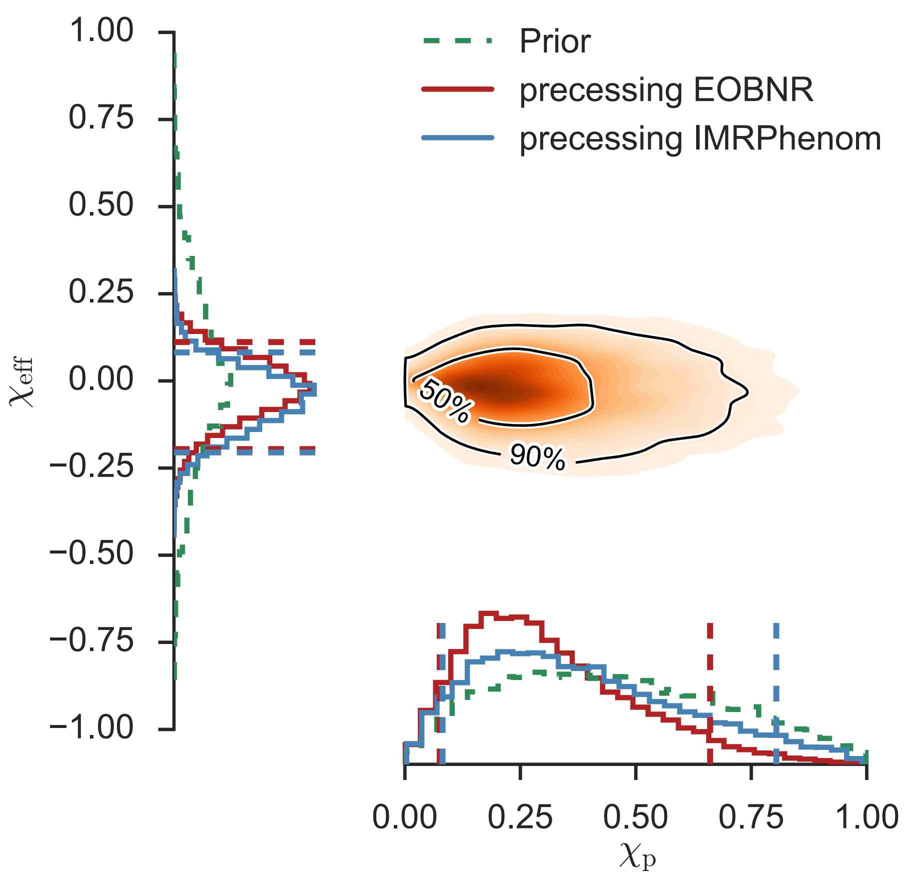


(Abbott et al. PRL 116 (2016) 241103)

Unveiling binary black-hole properties: spins

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

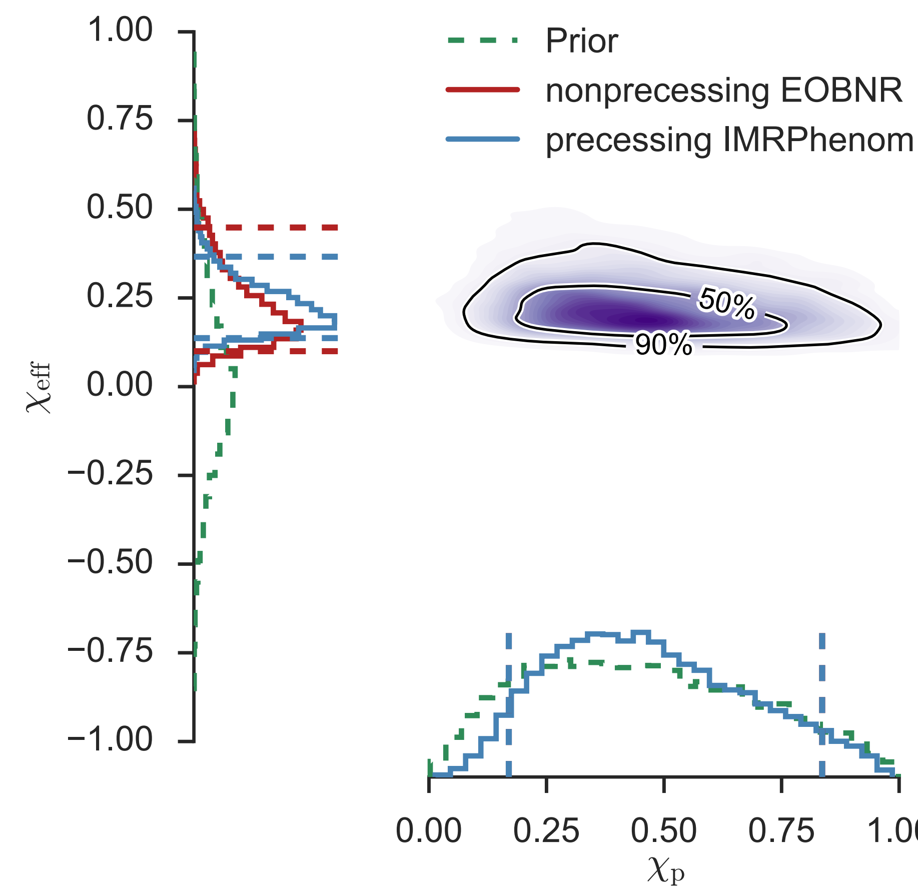
GW150914

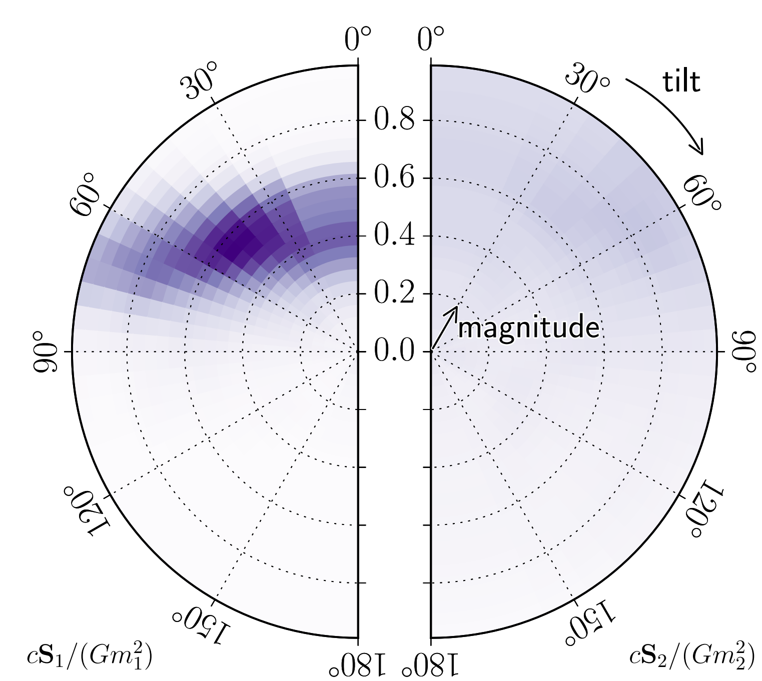


$$\chi_p = \frac{c}{B_1 G m_1^2} \max(B_1 S_{1\perp}, B_2 S_{2\perp})$$

- **Spins along** orbital **angular momentum** better **measured**.
- **Spins magnitudes < 0.7**.
- **No information** about **precession**.

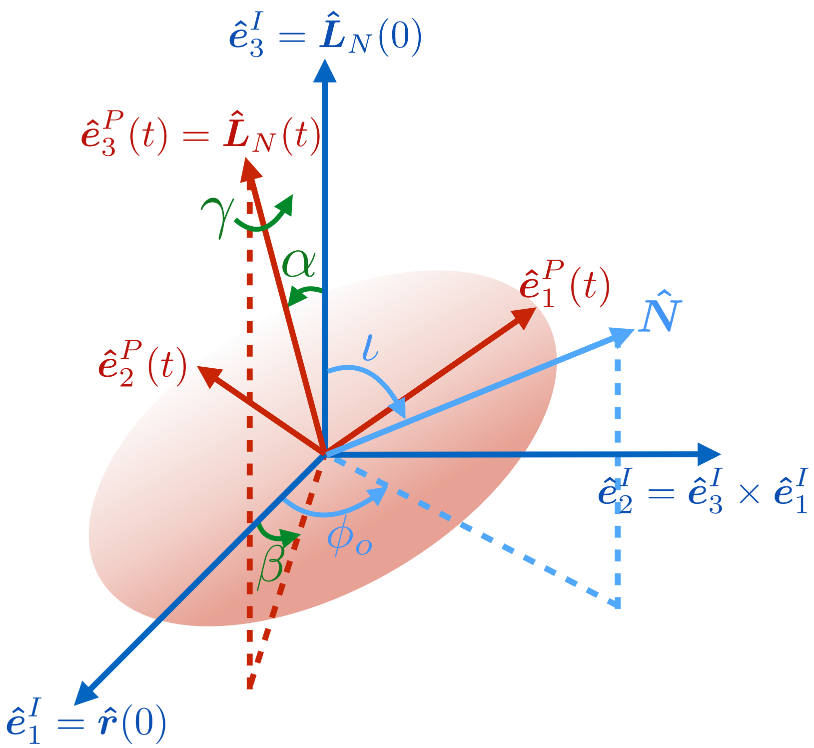
GW151226

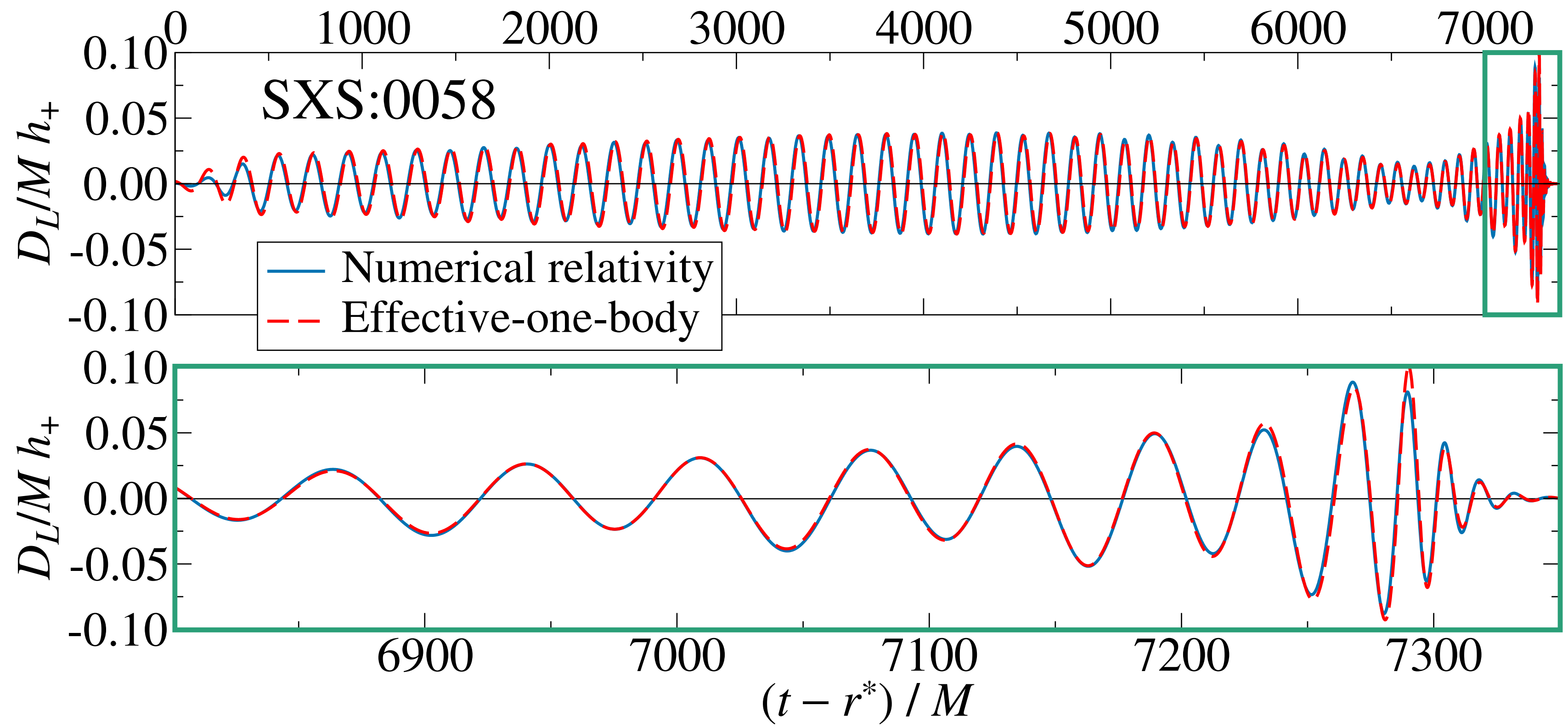




(Abbott et al. PRL 116 (2016) 241103)

Spin precessing waveform models





Precessing (co-rotating) frame

(AB, Chen & Vallisneri 03, Boyle et al. 11, Schmidt et al. 11, O'Shaugheessy et al. 11)

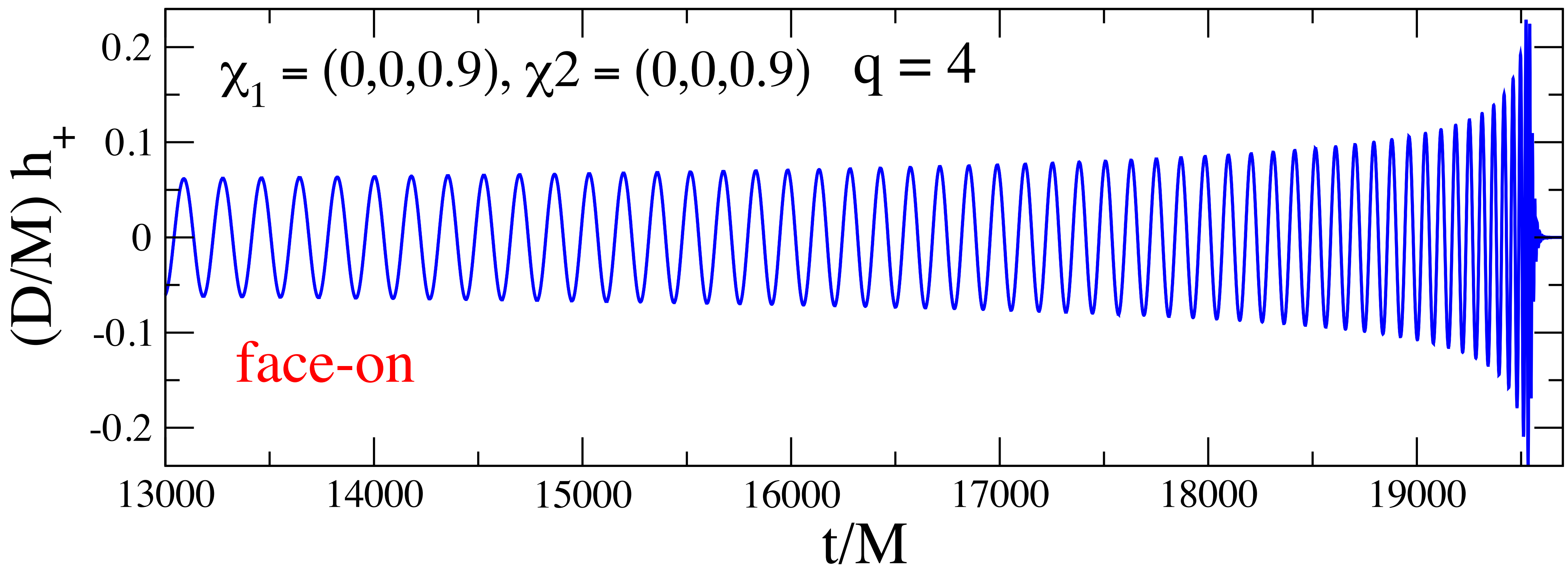
(Pan et al. 14, Babak et al. 16)

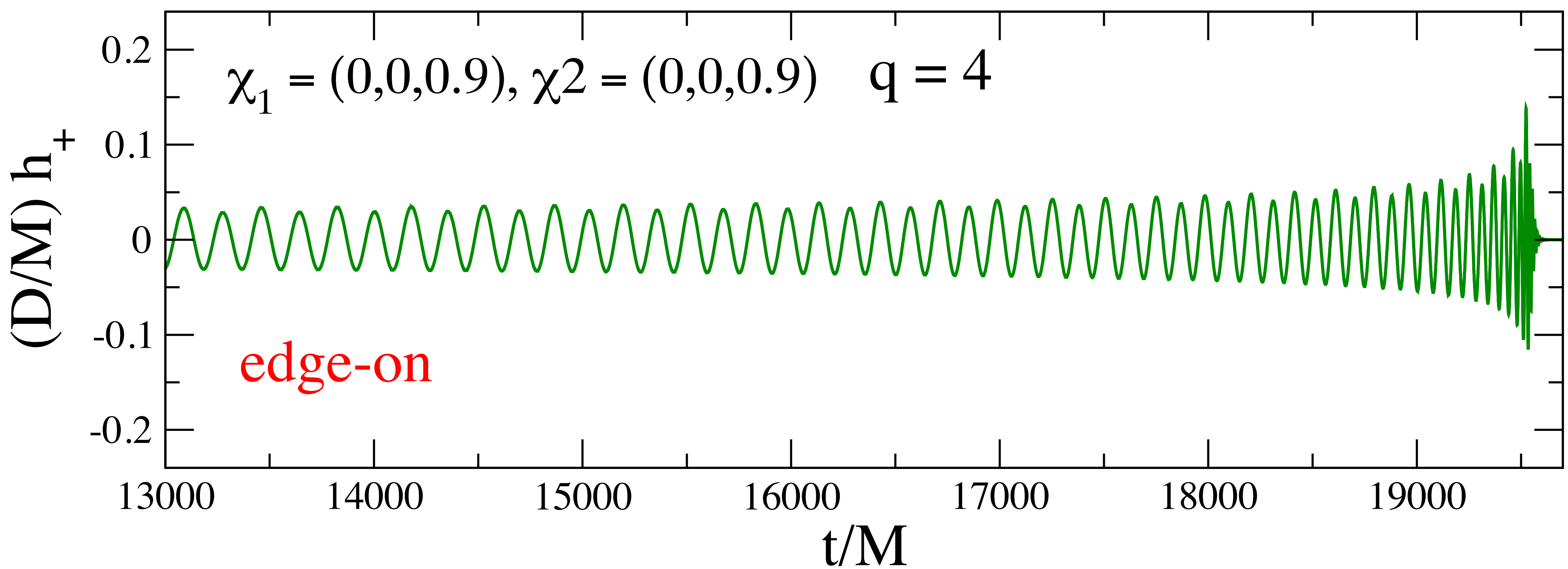
- **Single** effective-**spin precessing** waveform model in **frequency domain** (IMR phenomenological, 13-independent parameters; (2,2) mode). *(Schmidt et al. 12, Hannam et al. 14)*

- **Double-spin precessing** waveform model in **time domain** (EOBNR, 15-independent parameters; (2,2) & (2,1) modes). *(Pan et al. 14, Babak et al. 16)*

Effect of orientation of binary's orbital plane

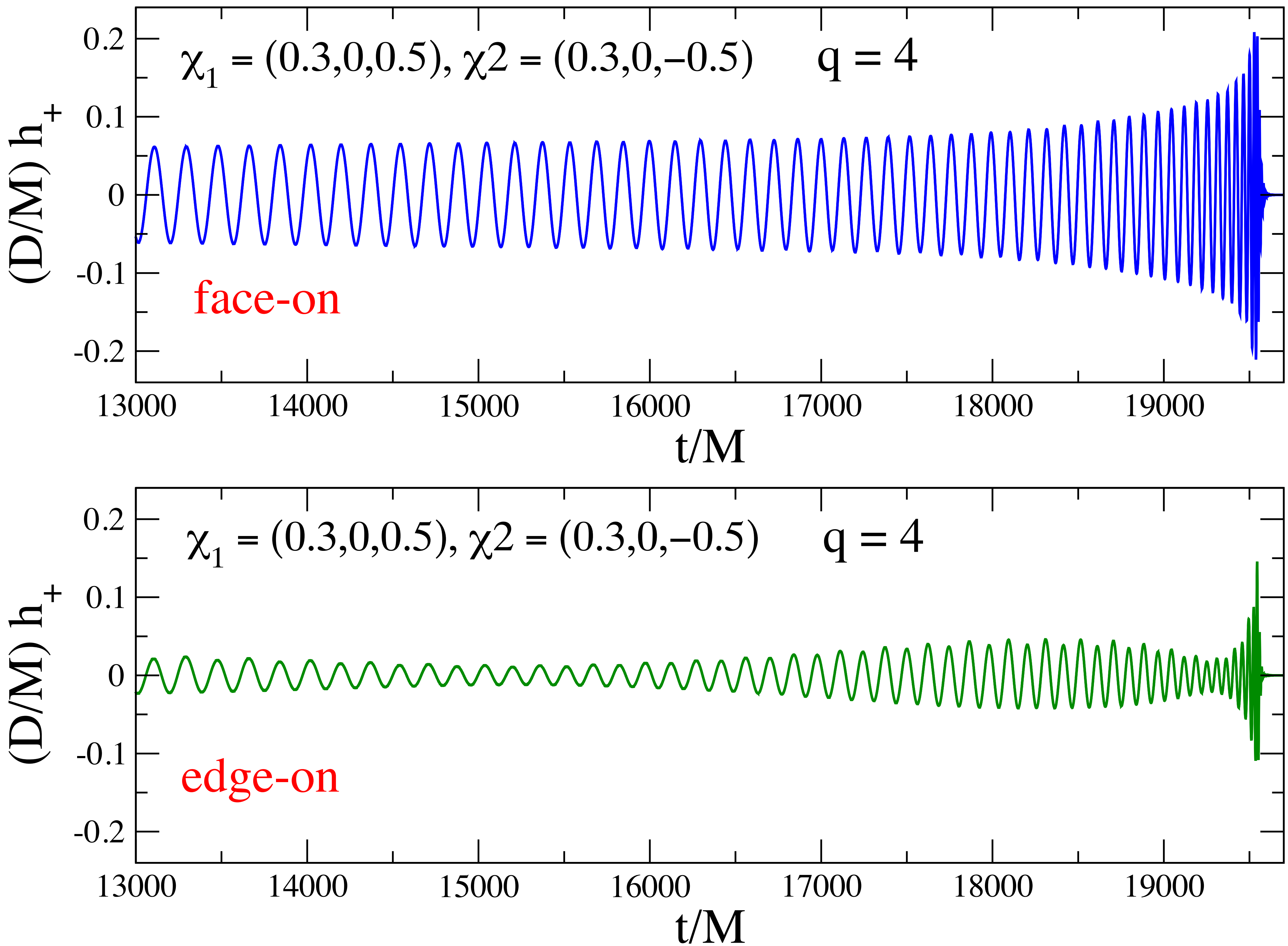
spin nonprecessing binary





Effect of orientation of binary's orbital plane

spin precessing binary

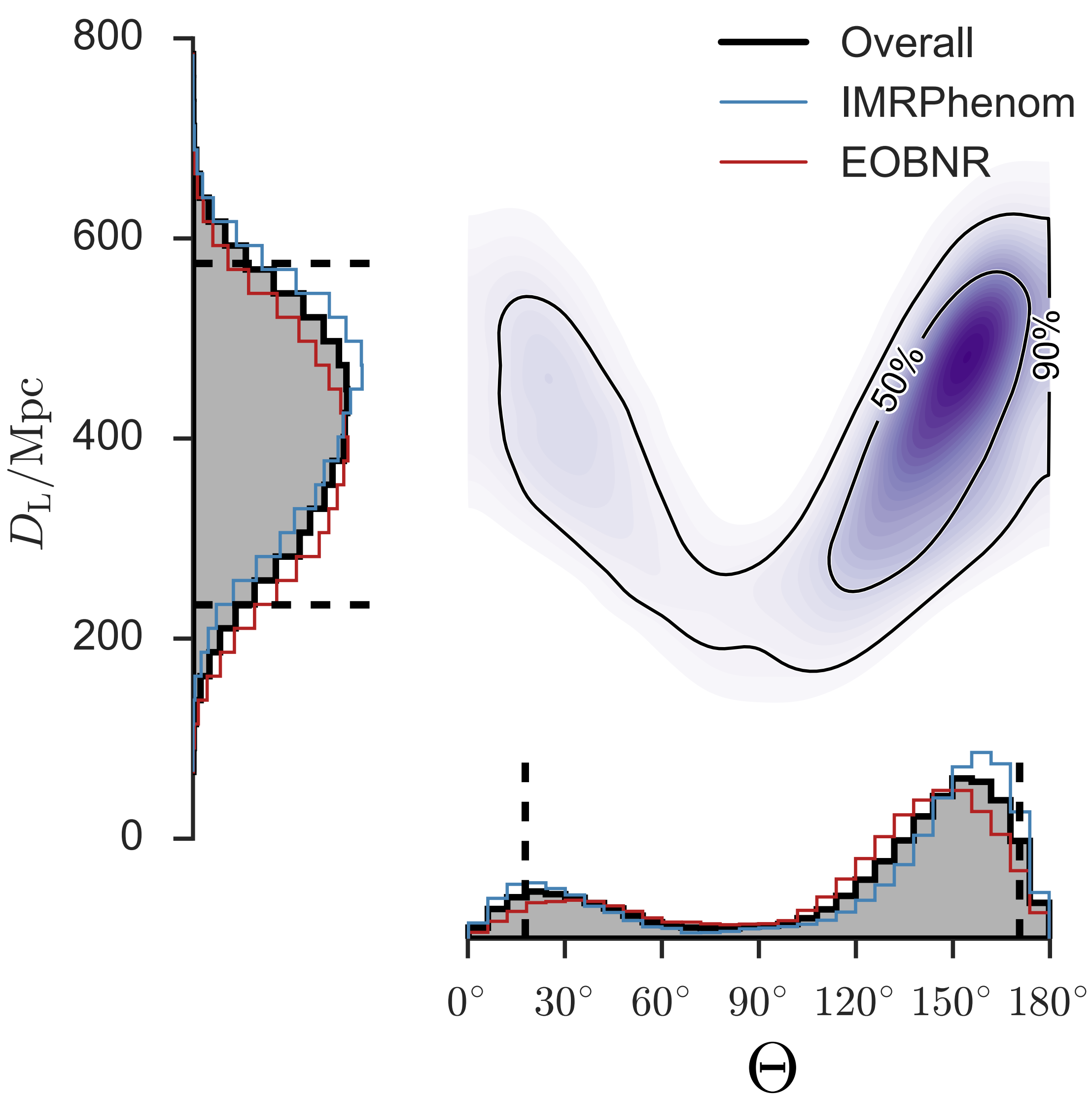


Binaries' distance and inclination angle

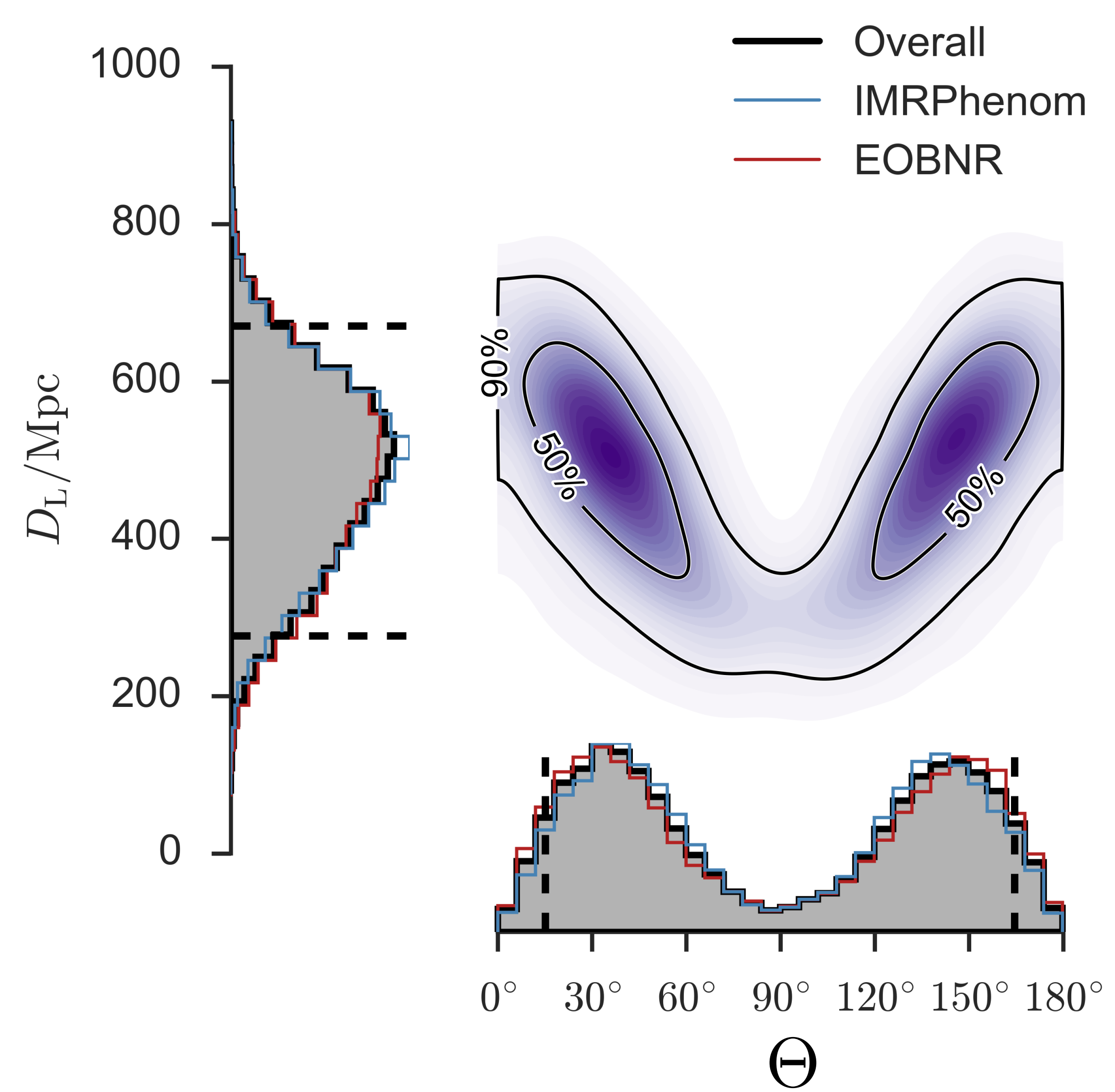
$$h(t) = \frac{2\mathcal{M}}{D}\,\mathcal{A}(\theta,\phi,\psi;\Theta)\,[\mathcal{M}\omega(t)]^{2/3}\,\cos(2\Phi(t)+2\Phi_0-\alpha)$$

- So far, BBHs **observed closer to face-on/face-off: are observations biased?**

GW150914



GW151226

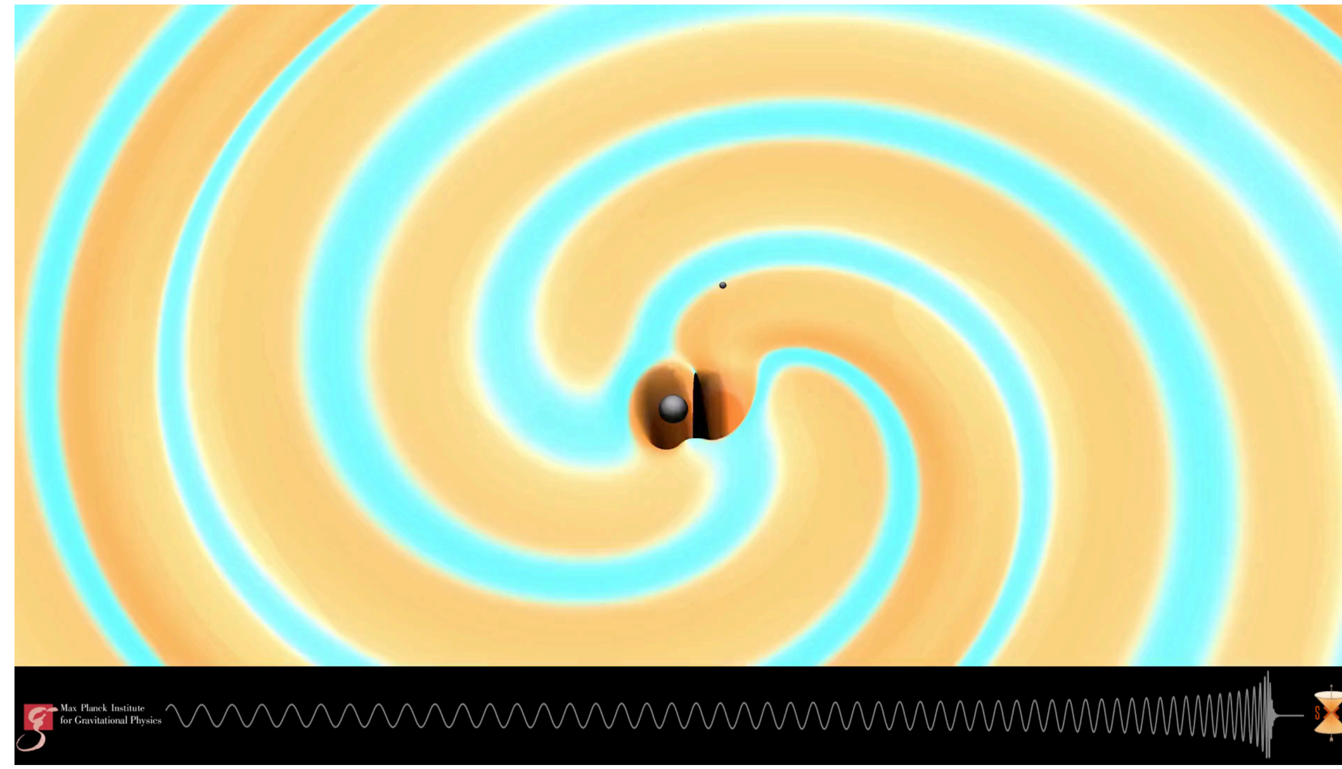


(Abbott et al. PRX 6 (2016) 041015)

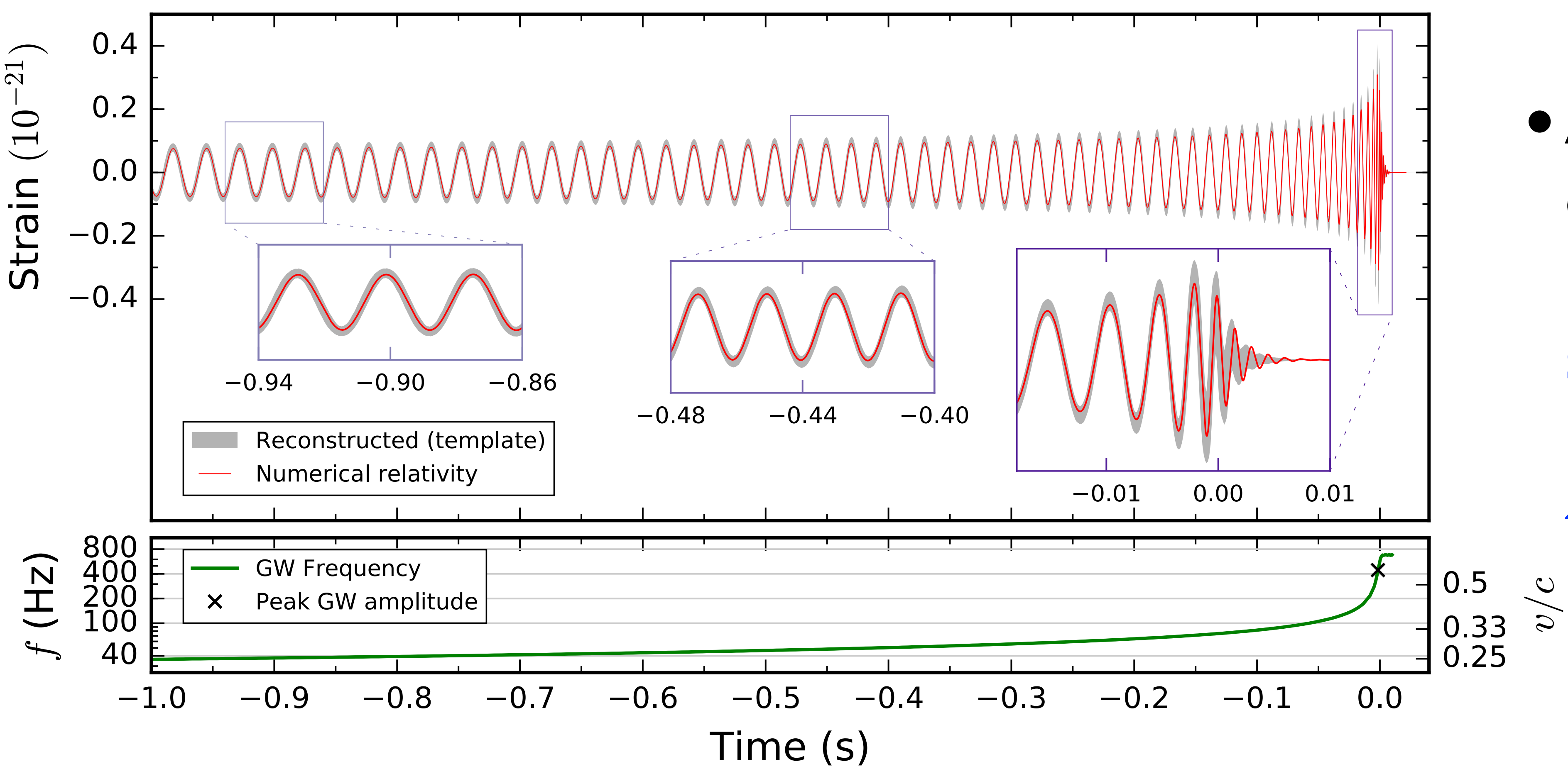
How waveform models compare with NR for BBHs observed?

(visualization credit: Dietrich, Haas @AEI)

(Ossokine, AB & SXS project)



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

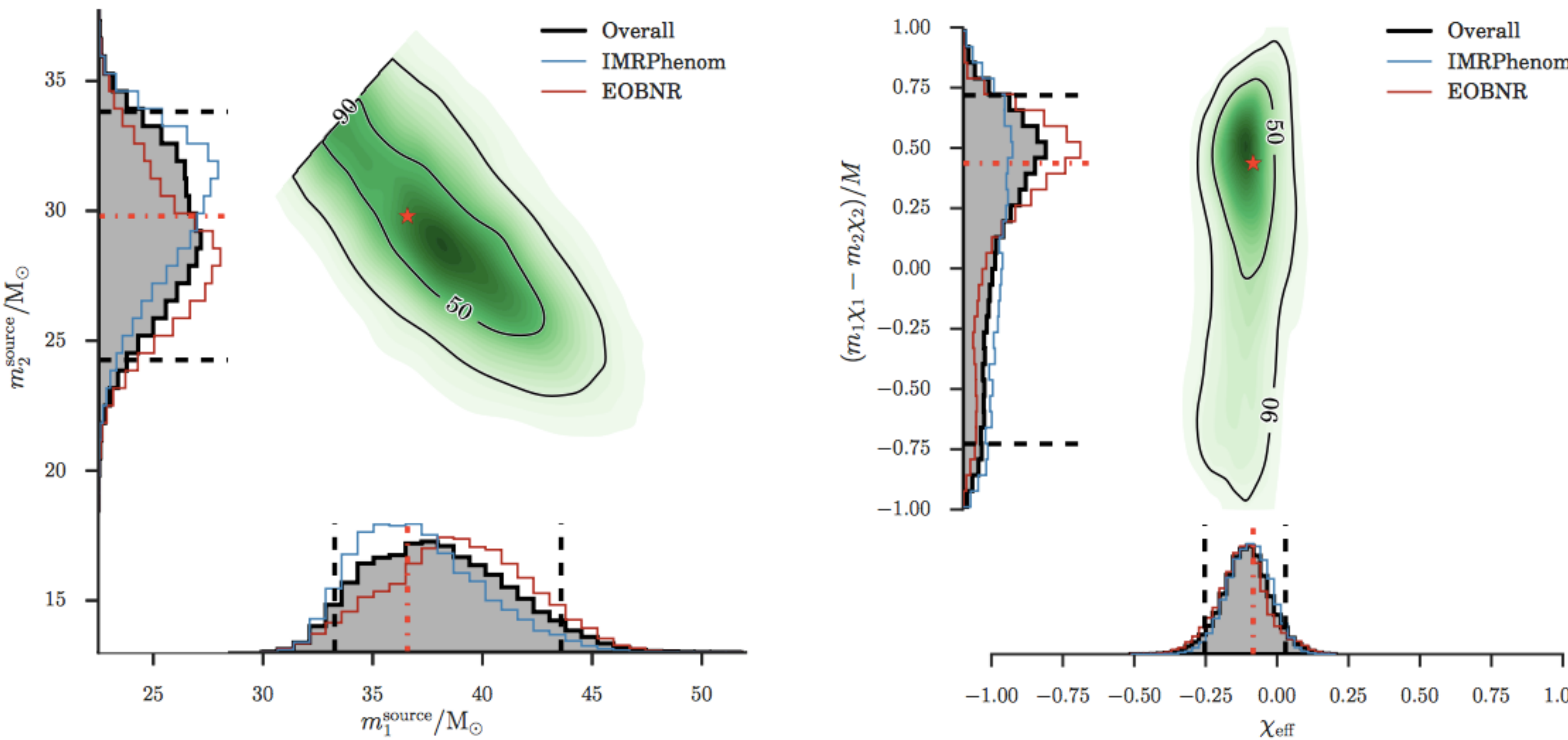


- Around region of original parameter recovery of BBHs, **systematics** due to modeling **are smaller than statistical** errors.

On systematics due to modeling comparing to NR waveform

- **Mock signal** from NR simulation with parameters close to GW150914.

(Abbott et al. CQG 34 (2017) 104002)



- **Overall, no evidence for systematic bias** relative to the statistical error of original parameter recovery of GW150914.

On systematics due to modeling comparing to NR waveform (contd.)

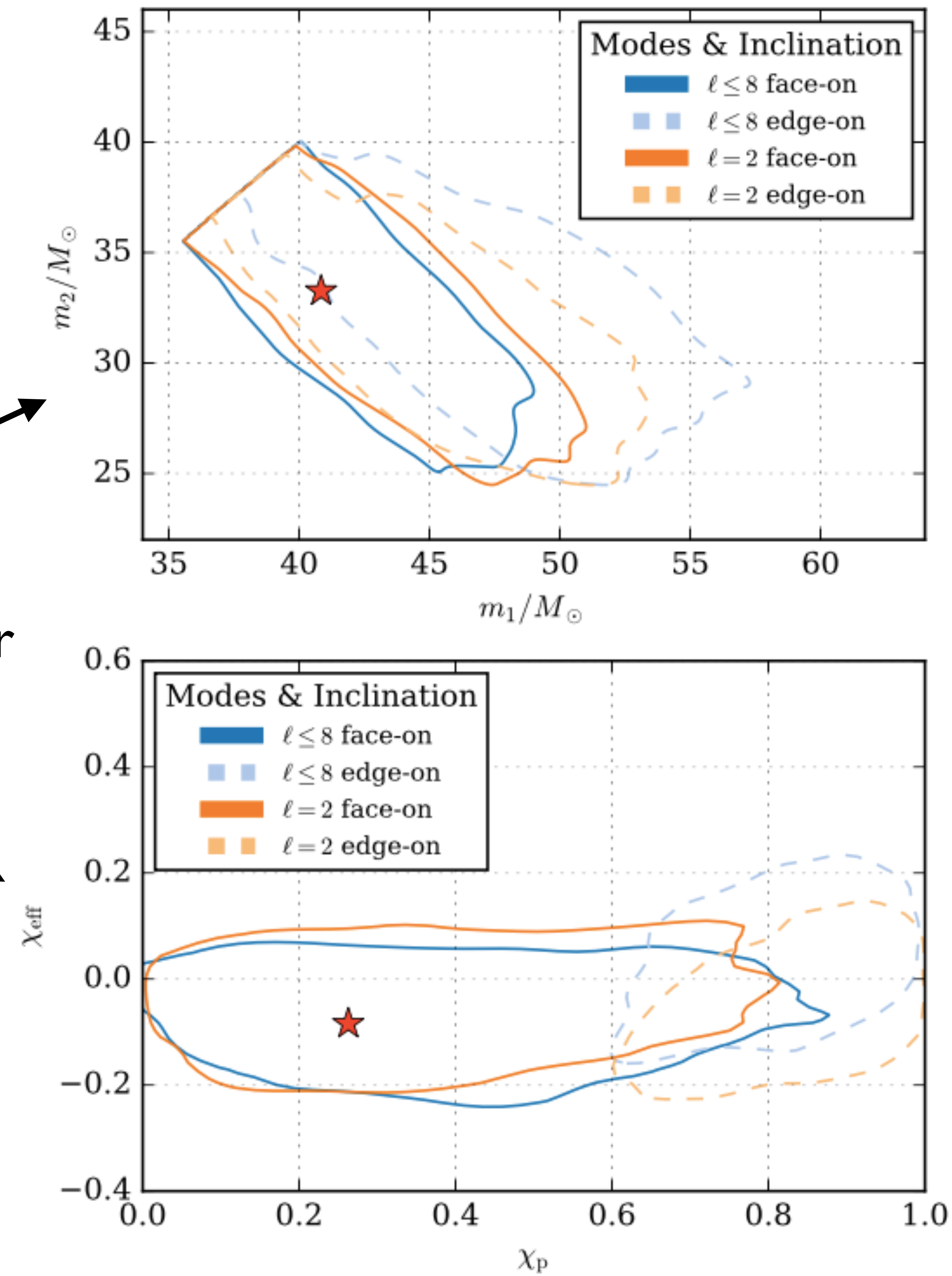
(Abbott et al. CQG 34 (2017) 104002)

- **Parameter biases** are found to occur for some **configurations disfavored by data** of GW150914.

- E.g., biases are present for **binaries inclined edge-on to the detector** over a small range of choices of polarization angles.

(see also Williamson et al. 2017)

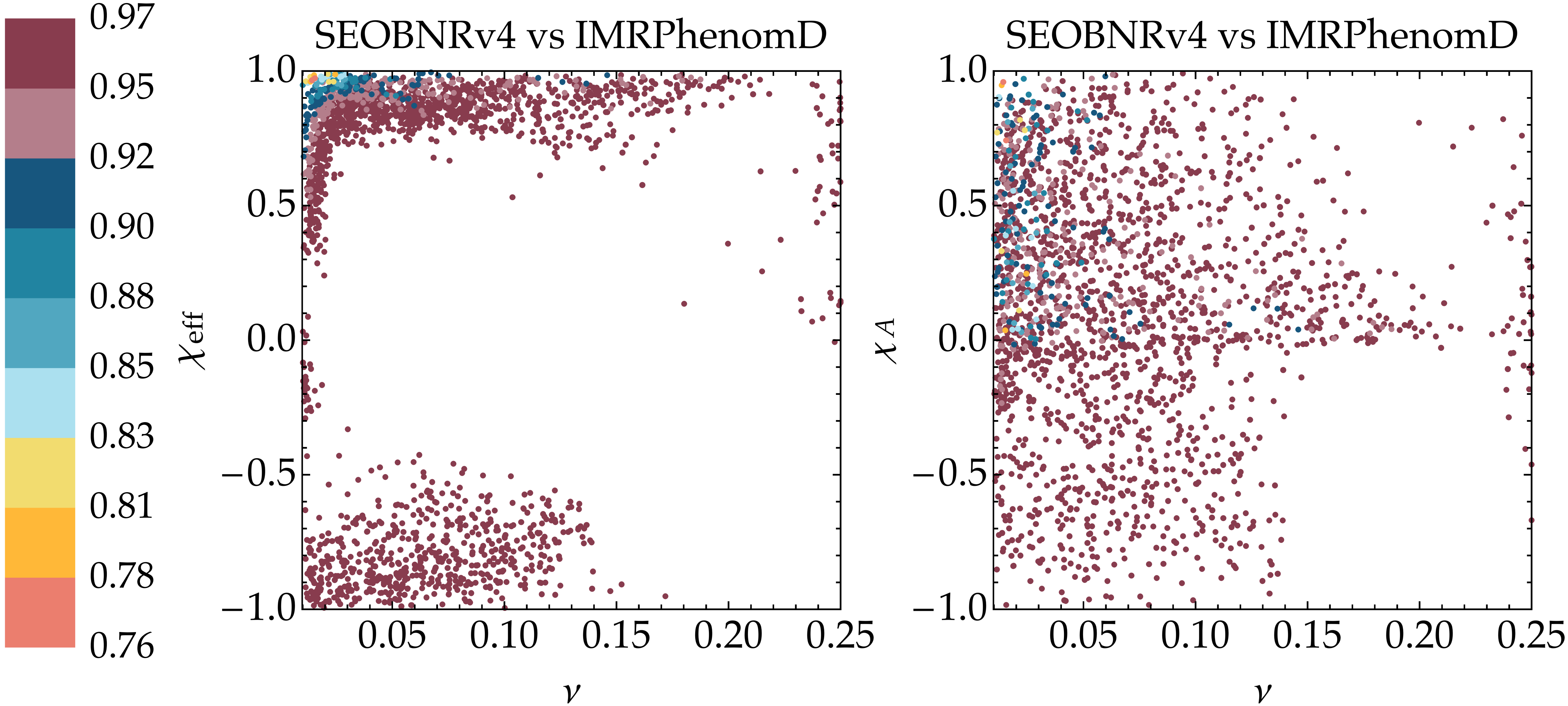
- Biases can be present for **binaries with eccentricity > 0.05**.



Comparing EOBNR & IMRPhenom models: detection

- **Aligned/anti-aligned** waveform models. Only dominant **(2,2) mode**.

Effectualness *(Bohe',…, AB et al. 16)*

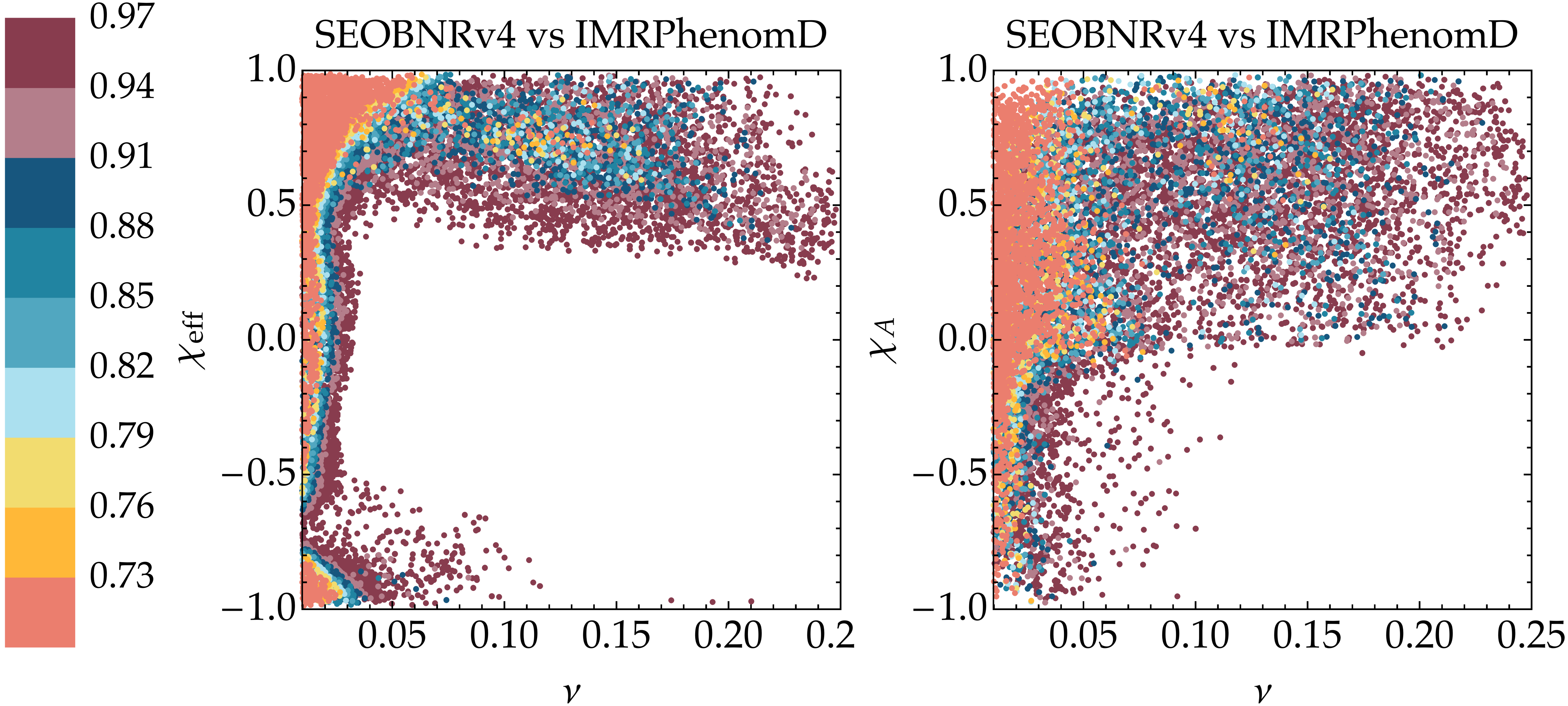


[Note that only 2.1% of 100,000 points have matches < 97%.]

Comparing EOBNR & IMRPhenom models: inferring parameters

- **Aligned/anti-aligned** waveform models. Only dominant **(2,2) mode**.
- Differences for **large mass ratios** (> 4) **and large spins** (> 0.8).

Faithfulness *(Bohe',…, AB et al. 16)*

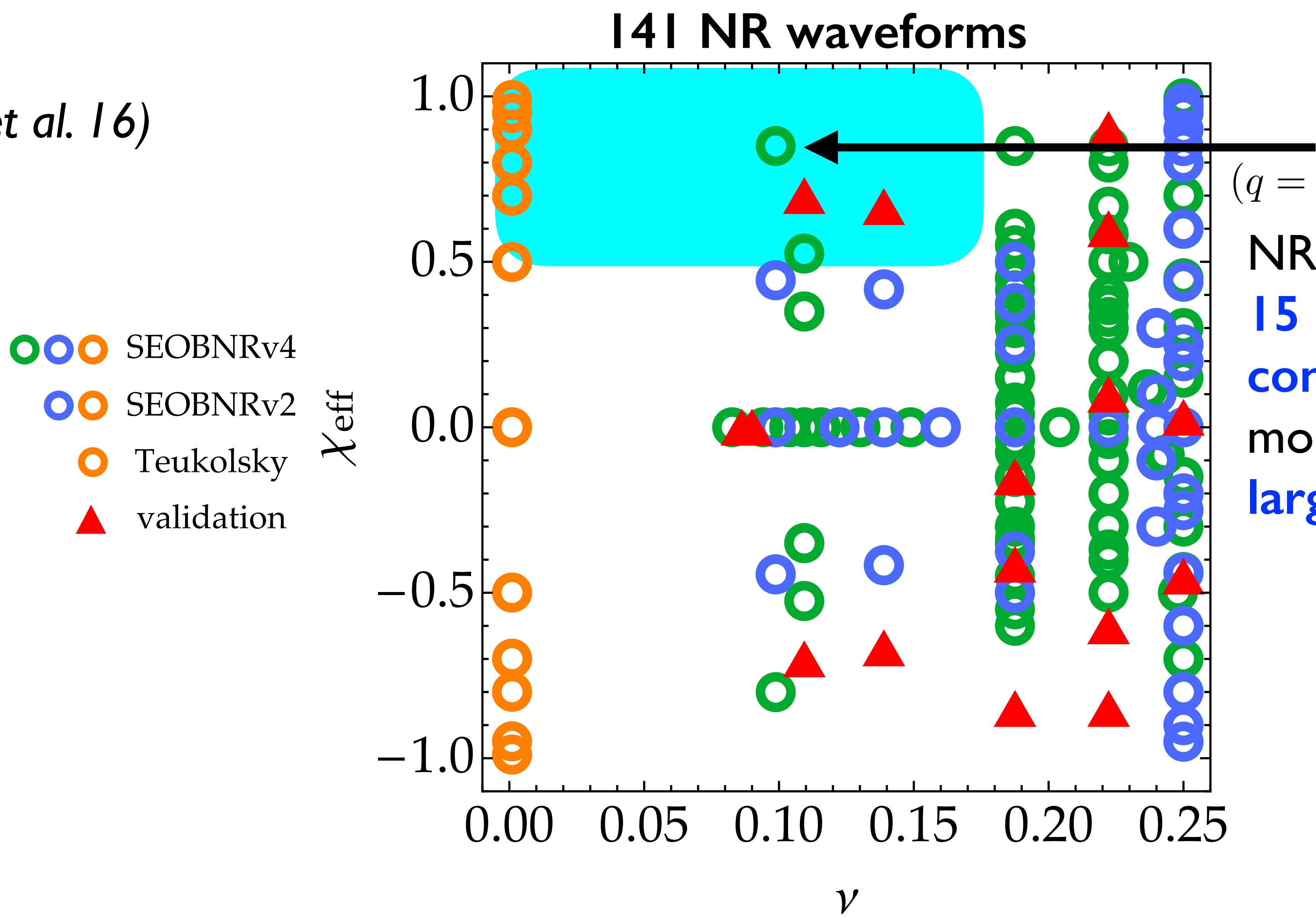


[Note that only 7% of 200,000 points have matches < 97%.]

Extending waveform model in all BBH parameter space

- Difficult to run **NR simulations** for **large mass ratios** (> 4) **and large spins** (> 0.8), with **large number** of GW **cycles** (> 50).

(Bohe',…, AB et al. 16)



NR waveform with only **15 GW cycles, it constrains** EOBNR model only for **masses larger than 150 Msun.**

- For large mass ratios (> 4) combine **PN & GSF** results in **EOB** framework.
  (Damour 09; Barausse et al. 12, Le Tiec et al. 12, Bini et al. 12-16, Antonelli et al. in progress)

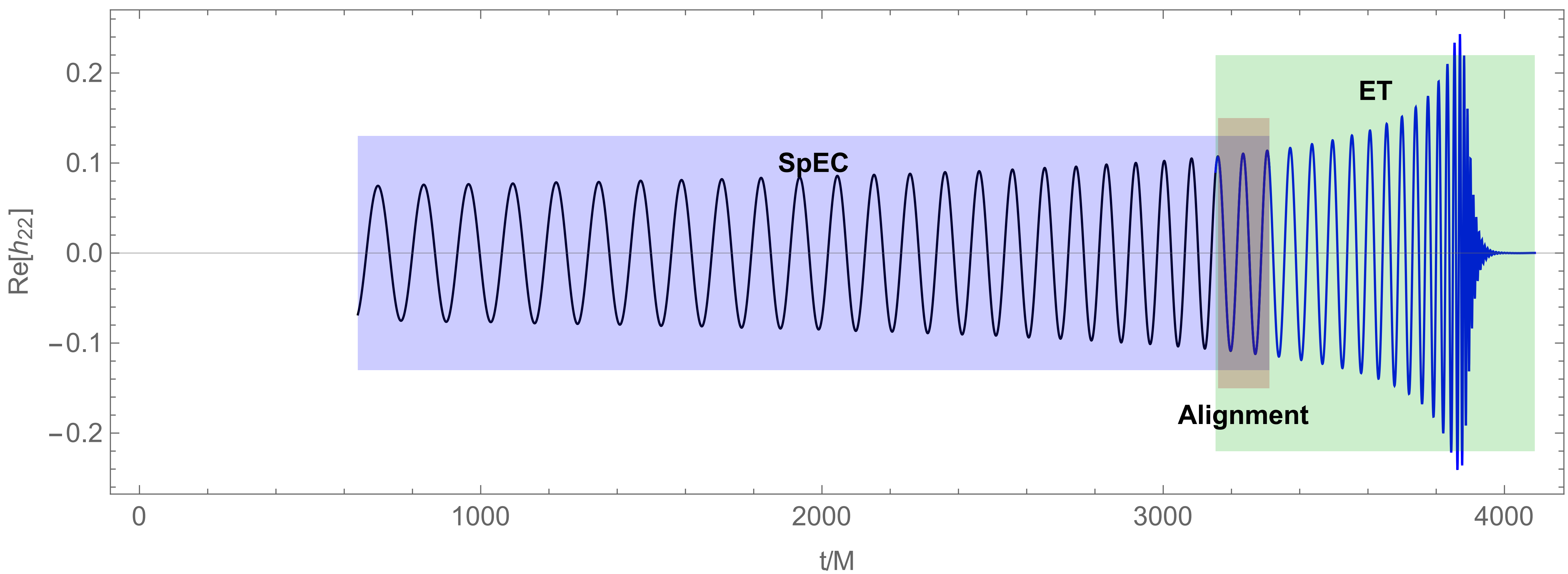
- Inclusion of **GSF** also important for **EMRIs** (LISA) and **IMRIs** (3G detectors).

Solution? Waveforms combining NR codes

- **"Best"** use **of finite-difference** (Einstein Toolkit, ET) & pseudo **spectral** (SpEC) **codes**

(Hinder, Ossokine et al. in prep 18)

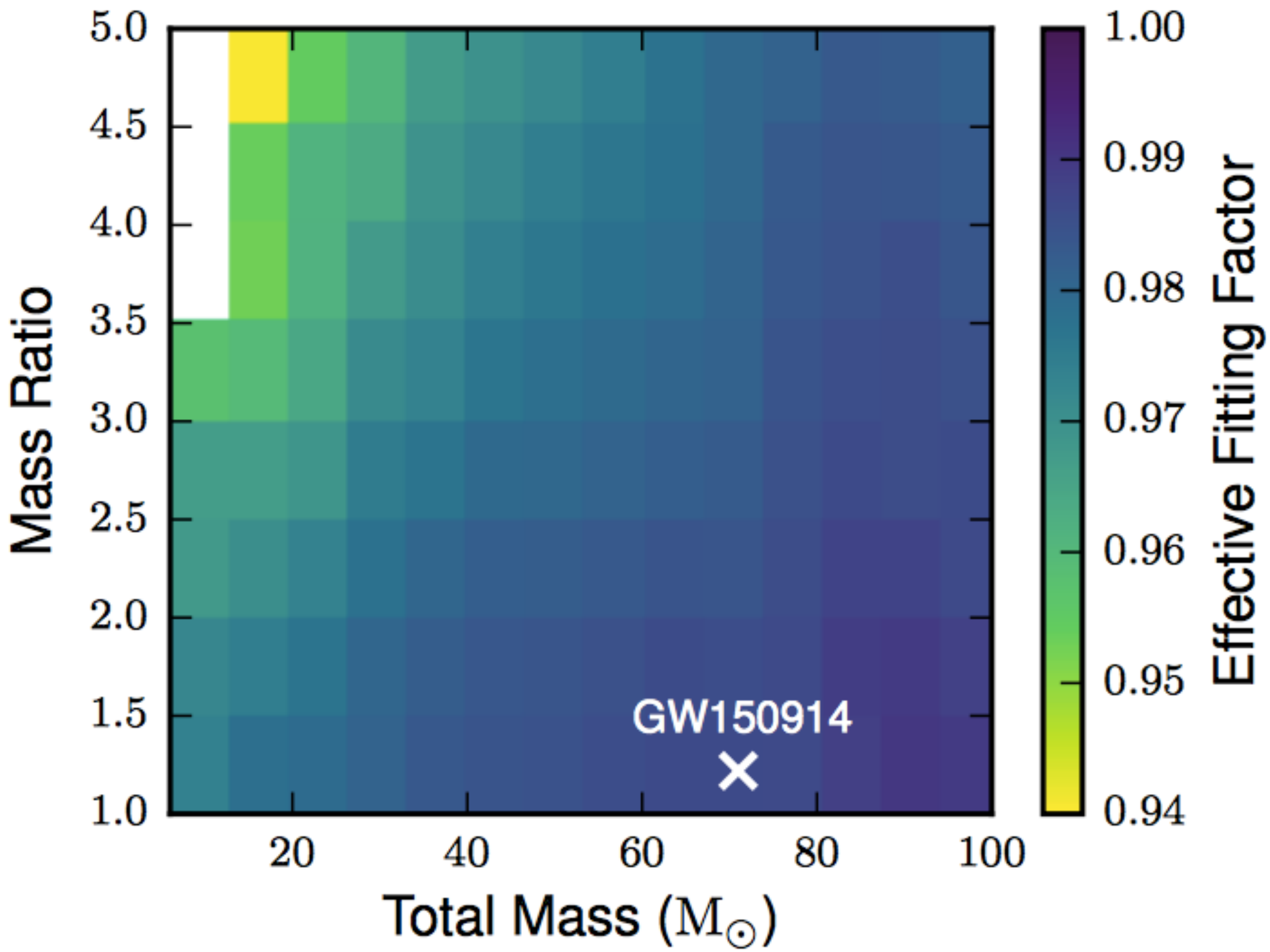
$$q = 4 \quad \chi_1 = 0.9 \quad \chi_2 = 0.9$$



Are we missing GWs from spin precessing BBHs?

- **Modeled searches** in O1 & O2 used **templates** with **aligned/anti-aligned spins.**

(Abbott et al. PRD93 (2016)122003)



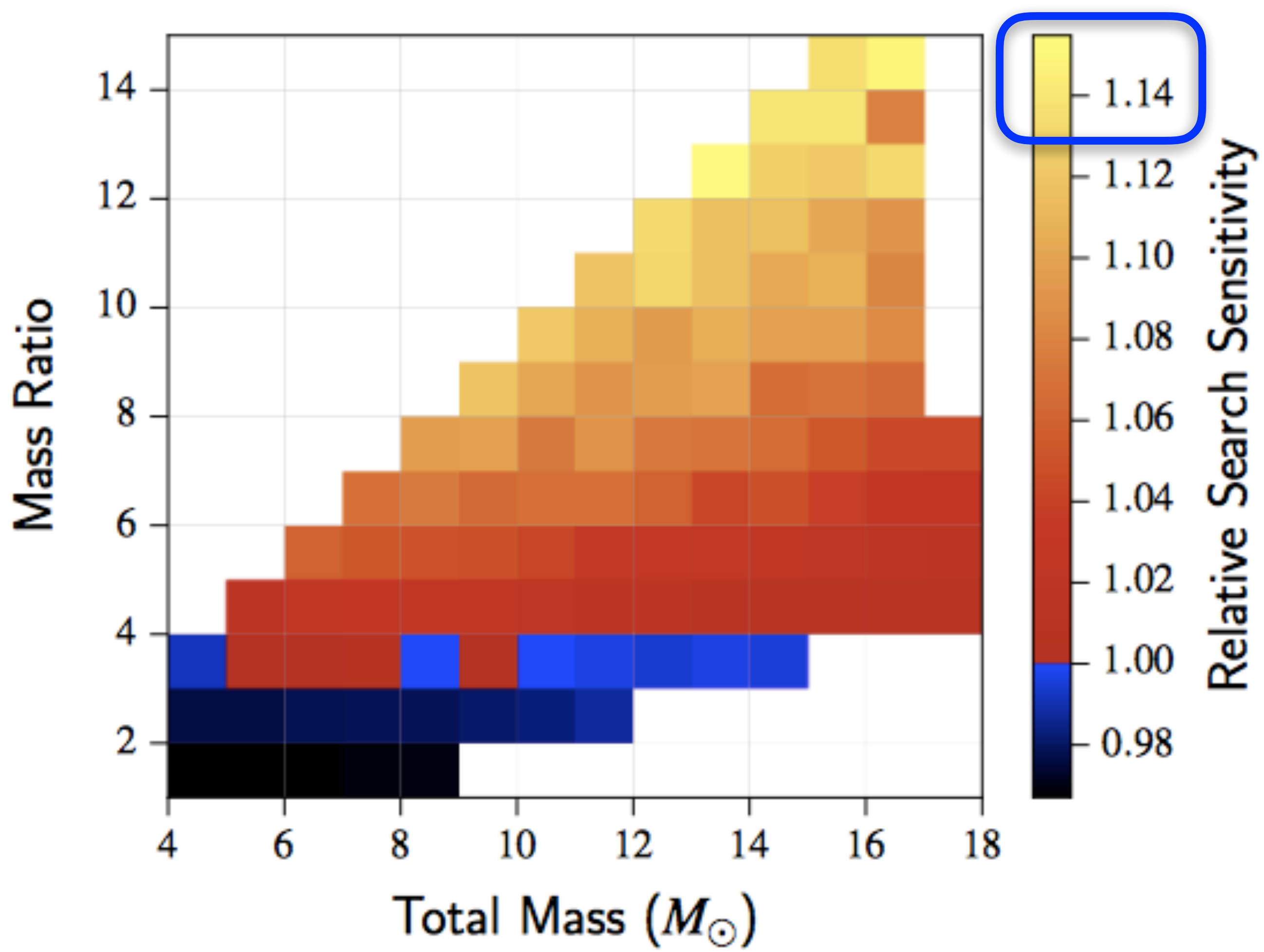
(Apostolatos et al. 1996, AB et al. 03; Harry, Privitera, Bohe' & AB 16)

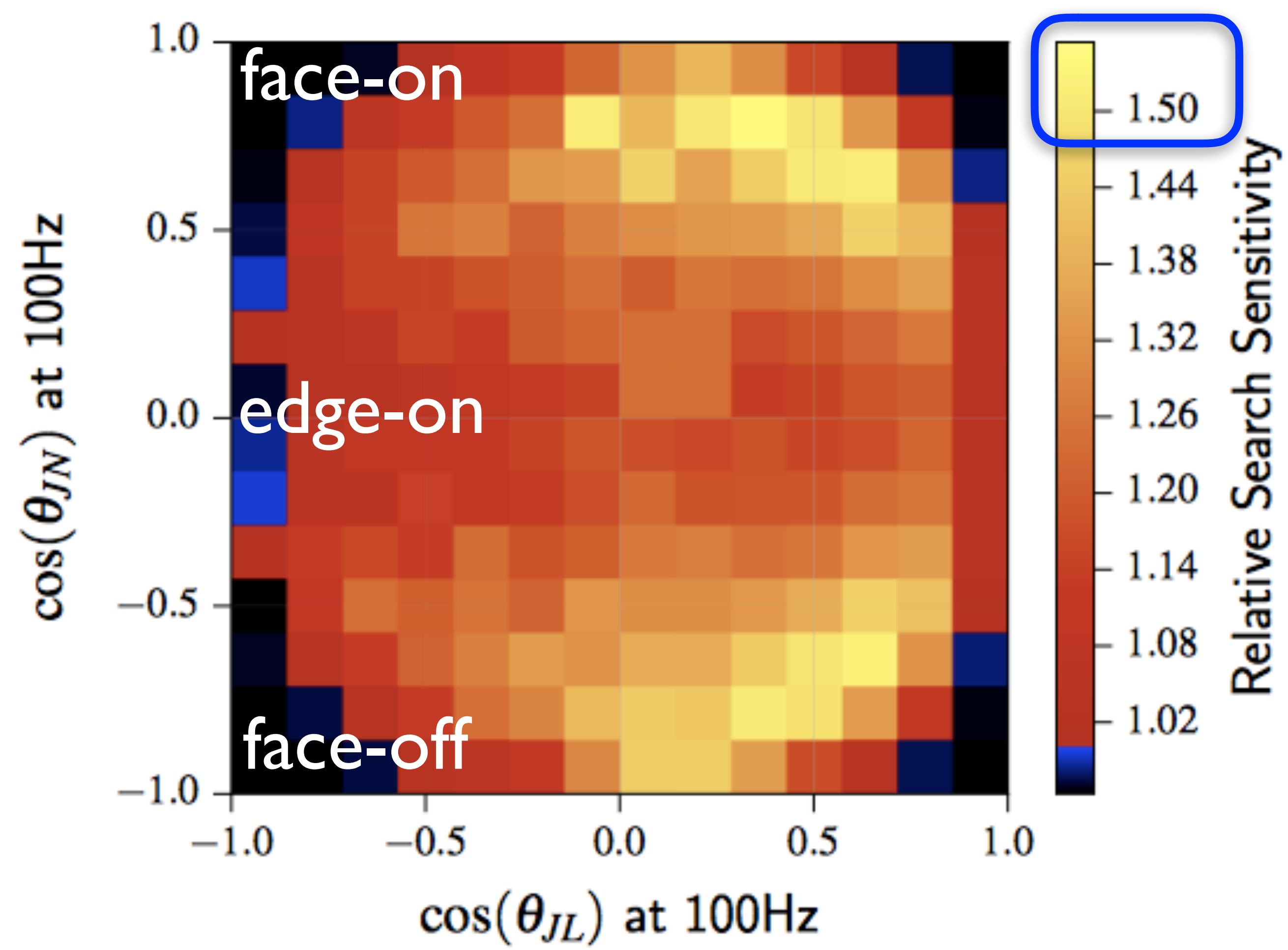
Should we employ spin precessing searches for NSBHs ?

(Harry, Privitera, Bohe' & AB 16)

- **Spin-precessing** template bank **constructed**.
- Factor of about **10 increase** wrt **non-precessing** template **bank**.

NSBH parameter ranges	
m_1	$[3, 15]\ M_\odot$
m_2	$[1, 3]\ M_\odot$
$\lvert\chi_1\rvert$	$[0, 1.0]$
$\lvert\chi_2\rvert$	$[0, 0.05]$





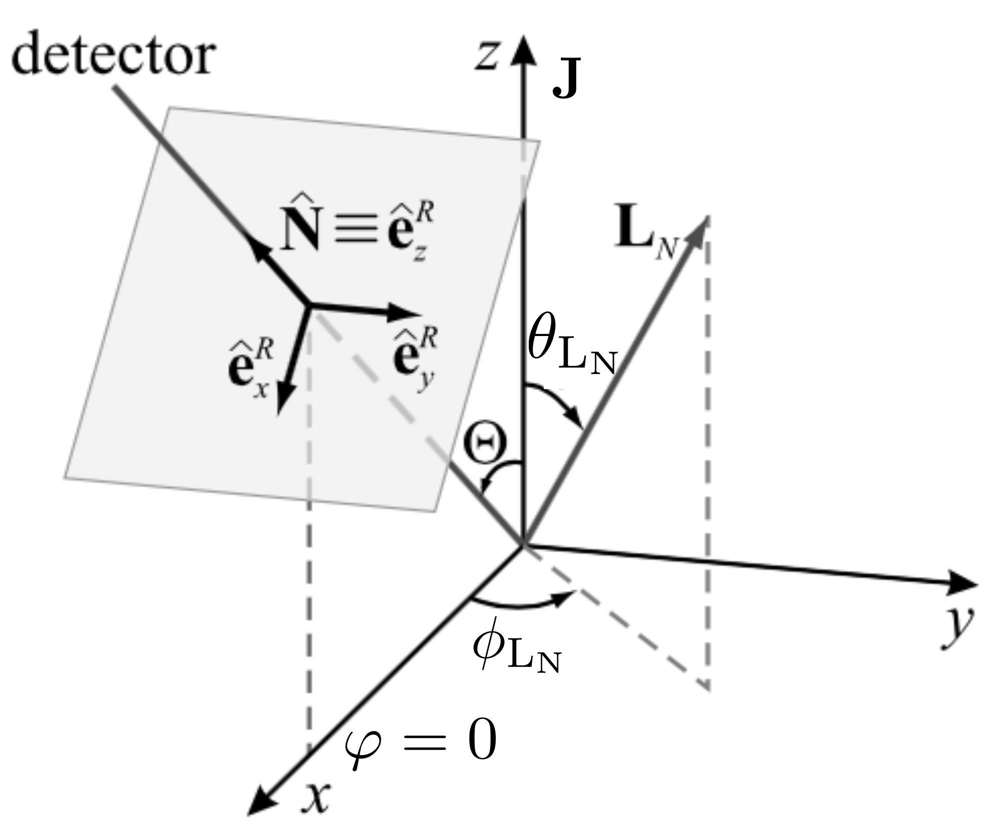
- Mergers with **misaligned spins** provide unique **astrophysical insights** into **formation** scenarios.

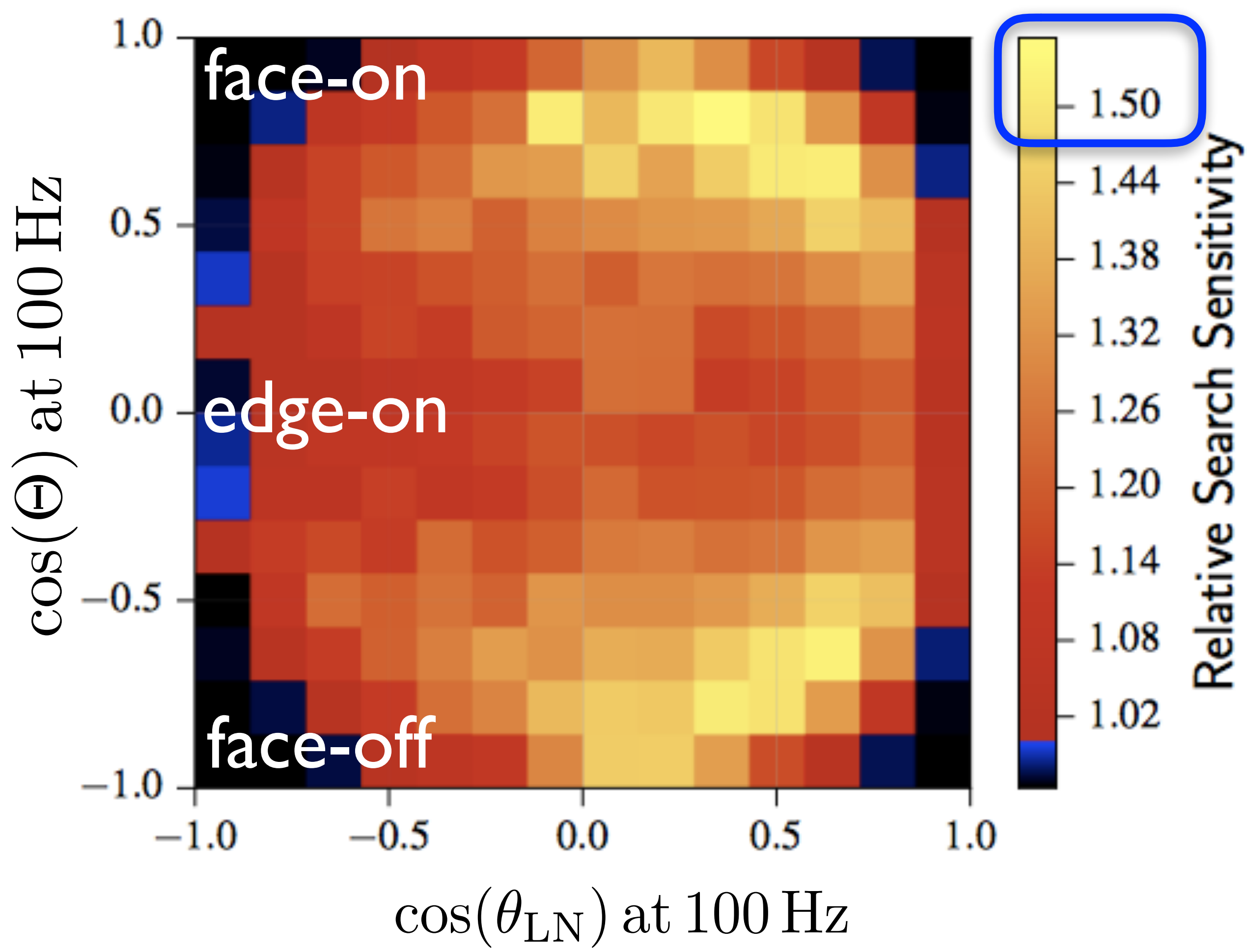
Should we employ spin precessing searches for NSBHs ?

(Harry, Privitera, Bohe' & AB 16)

- **Spin-precessing** template bank **constructed**.
- Factor of about **10 increase** wrt **non-precessing** template **bank**.

NSBH parameter ranges	
m_1	$[3, 15]\ M_\odot$
m_2	$[1, 3]\ M_\odot$
$\lvert\chi_1\rvert$	$[0, 1.0]$
$\lvert\chi_2\rvert$	$[0, 0.05]$



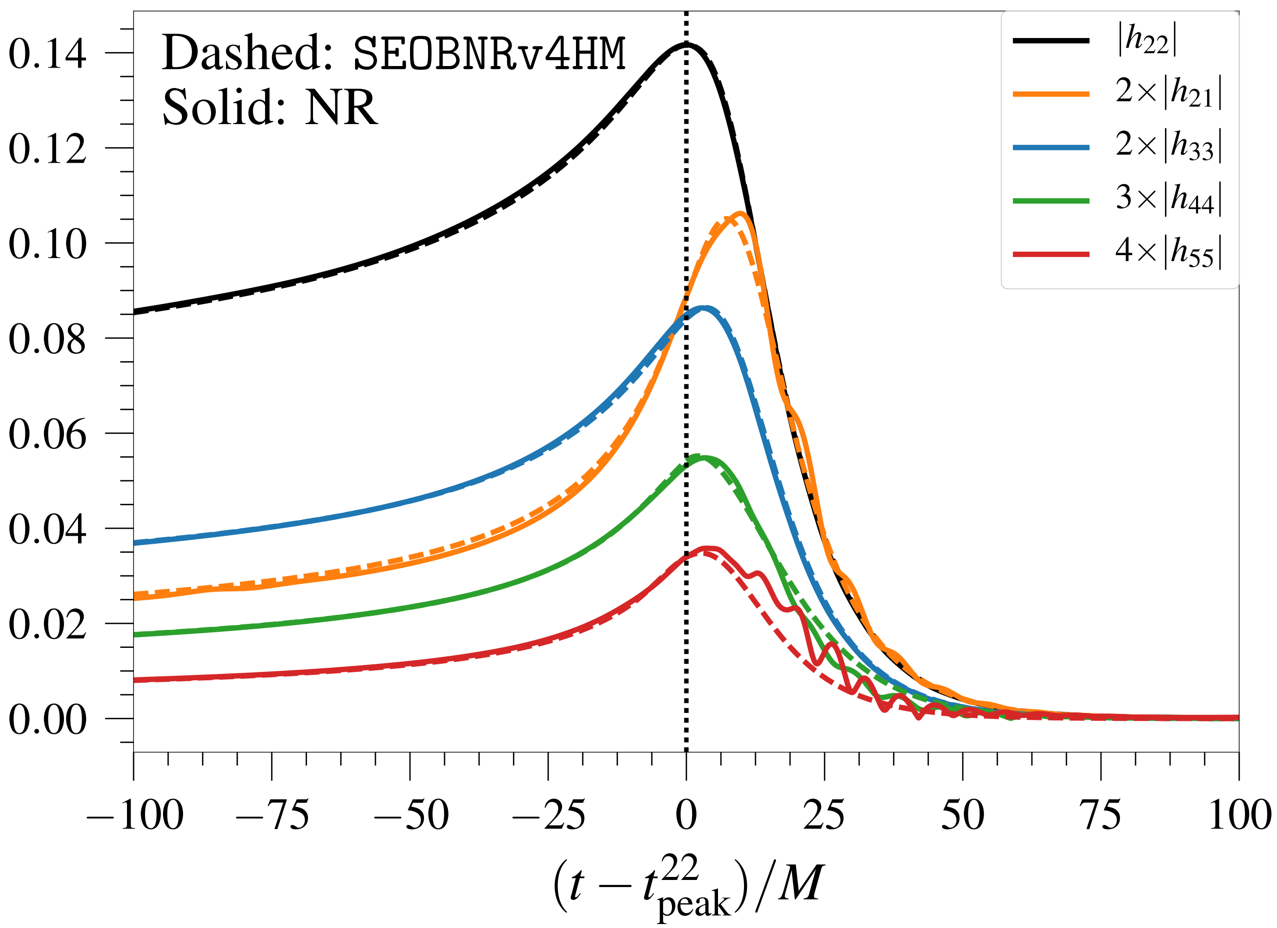


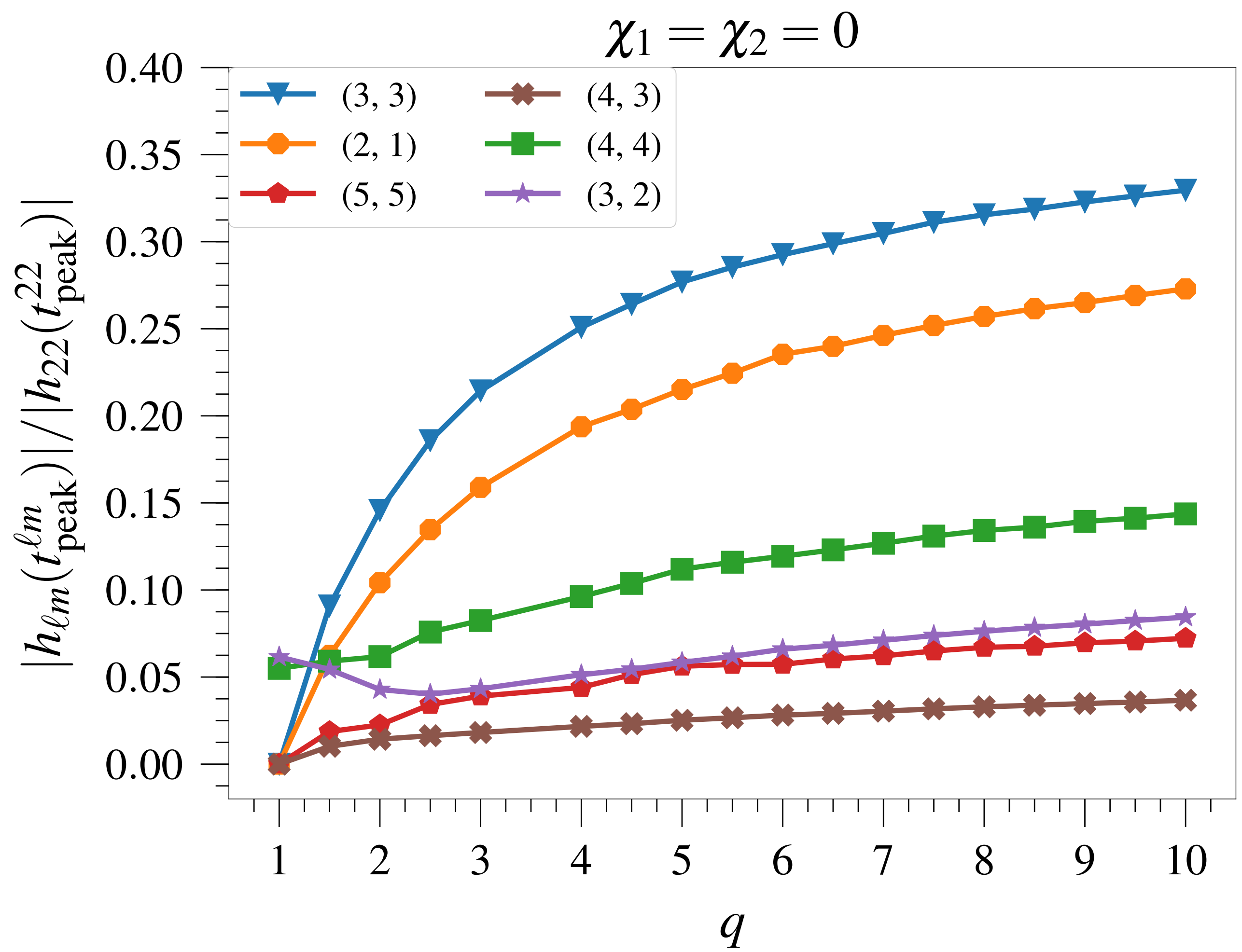
- Mergers with **misaligned spins** provide unique **astrophysical insights** into **formation** scenarios.

Importance of higher harmonics: varying mass ratio

$$h_+(t;\Theta,\varphi) - i\,h_\times(t;\Theta,\varphi) = \sum_{\ell=2}^{\infty}\sum_{m=-\ell}^{\ell} {}_{-2}Y_{\ell m}(\Theta,\varphi)\,h_{\ell m}(t)$$

(Cotesta, AB et al. 18)



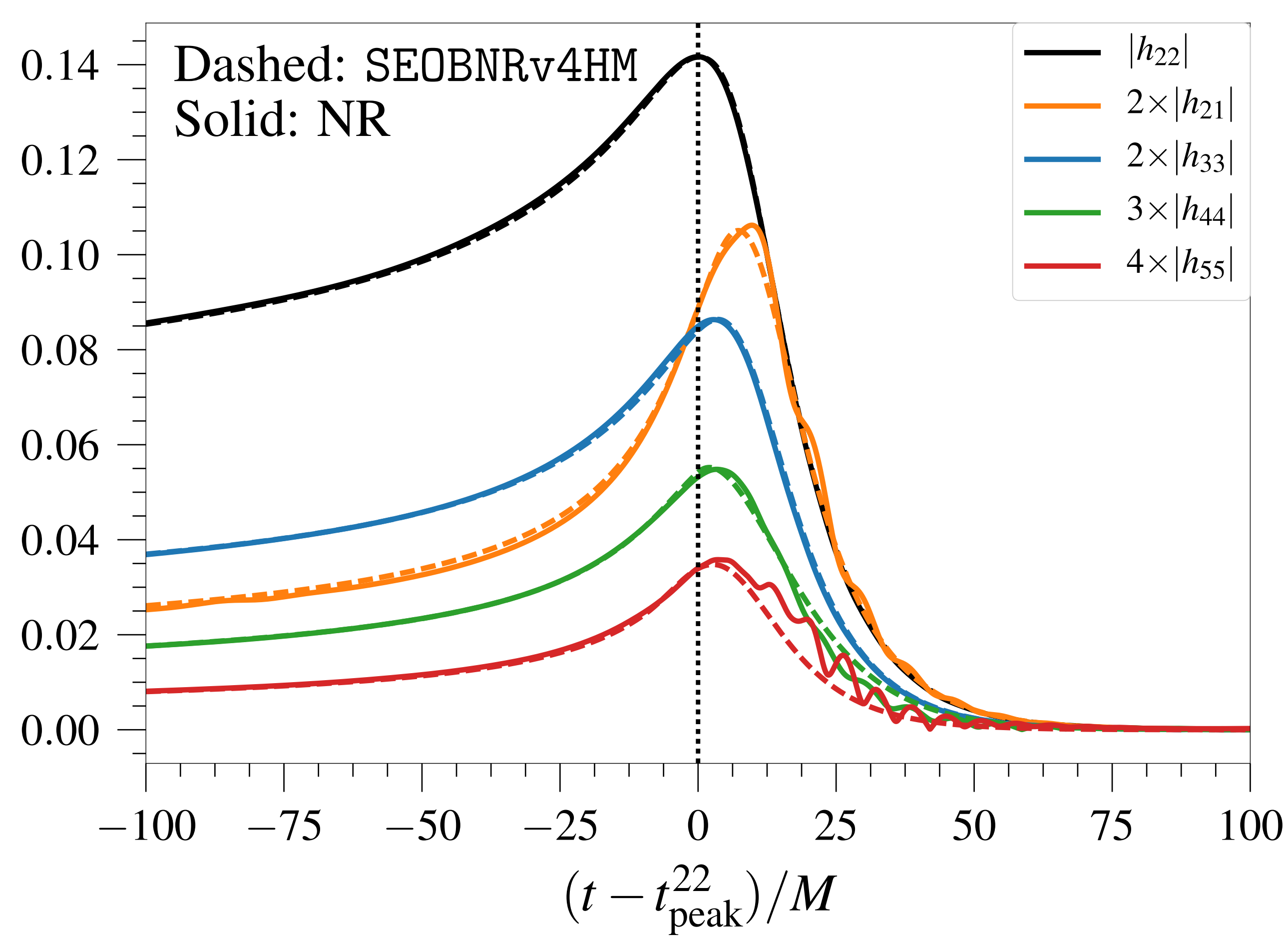


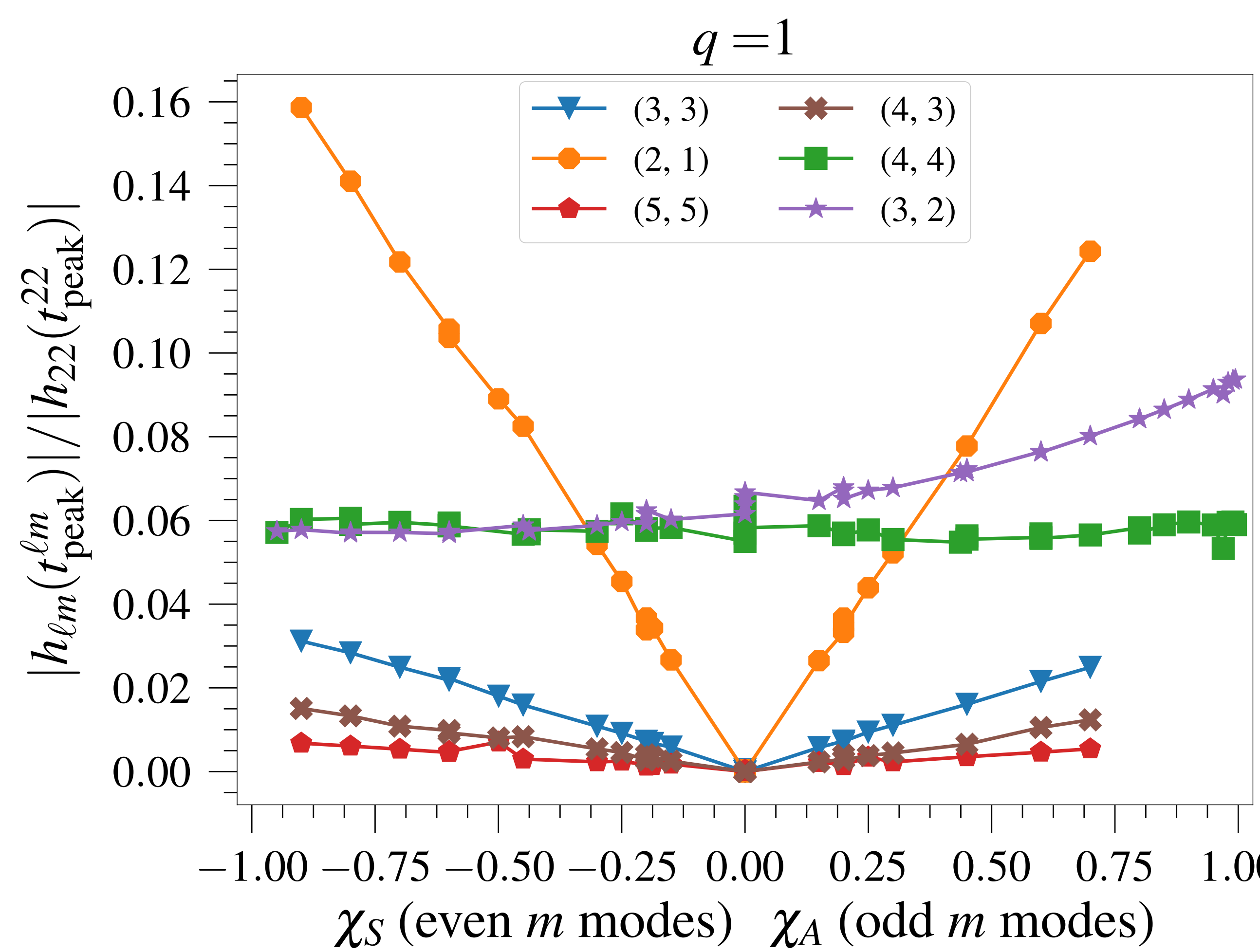
- Merger-ringdown EOBNR model **reproduces time & phase shifts between NR modes' at peak.**

Importance of higher harmonics: varying spins

$$h_+(t;\Theta,\varphi) - i\,h_\times(t;\Theta,\varphi) = \sum_{\ell=2}^{\infty}\sum_{m=-\ell}^{\ell} {}_{-2}Y_{\ell m}(\Theta,\varphi)\,h_{\ell m}(t)$$

(Cotesta, AB et al. 18)





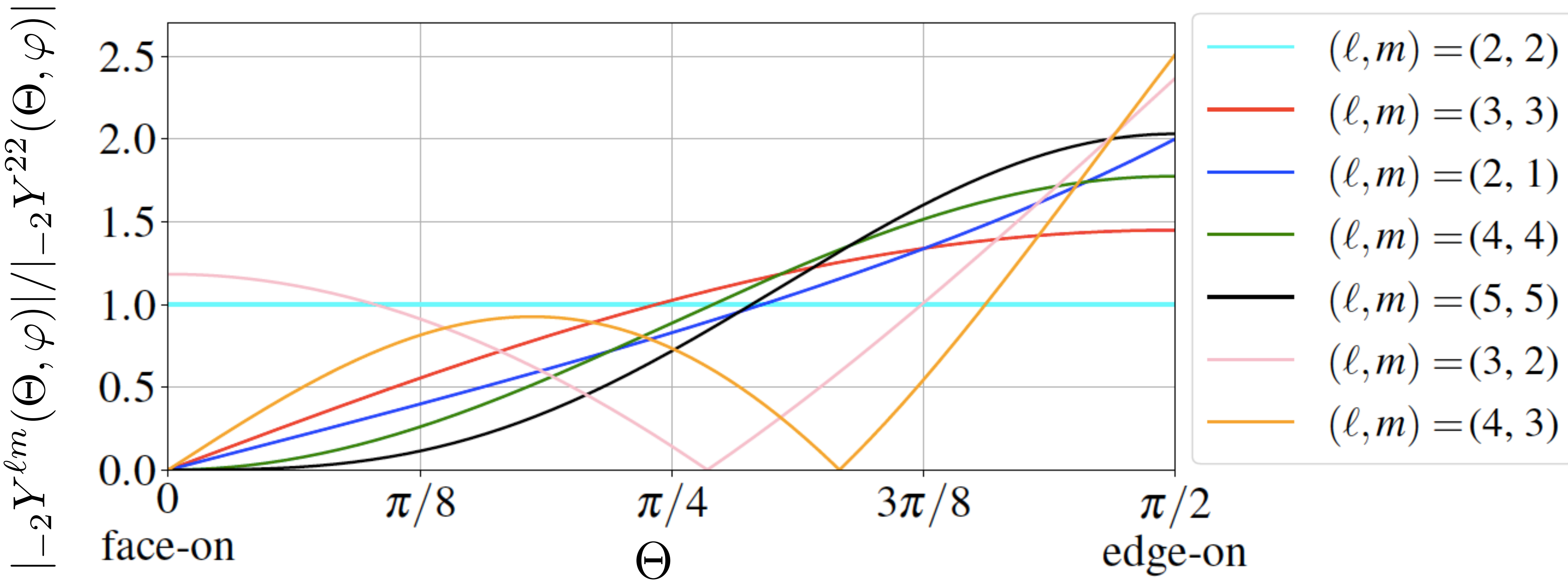
- Merger-ringdown EOBNR model **reproduces time & phase shifts between NR modes' at peak.**

Importance of higher harmonics also depends on geometric factor

$$h_+(t;\Theta,\varphi) - i\,h_\times(t;\Theta,\varphi) = \sum_{\ell=2}^{\infty}\sum_{m=-\ell}^{\ell} {}_{-2}Y_{\ell m}(\Theta,\varphi)\, h_{\ell m}(t)$$

geometric factor is important to determine **strength** of **higher harmonics**

(Cotesta, AB et al. 18)

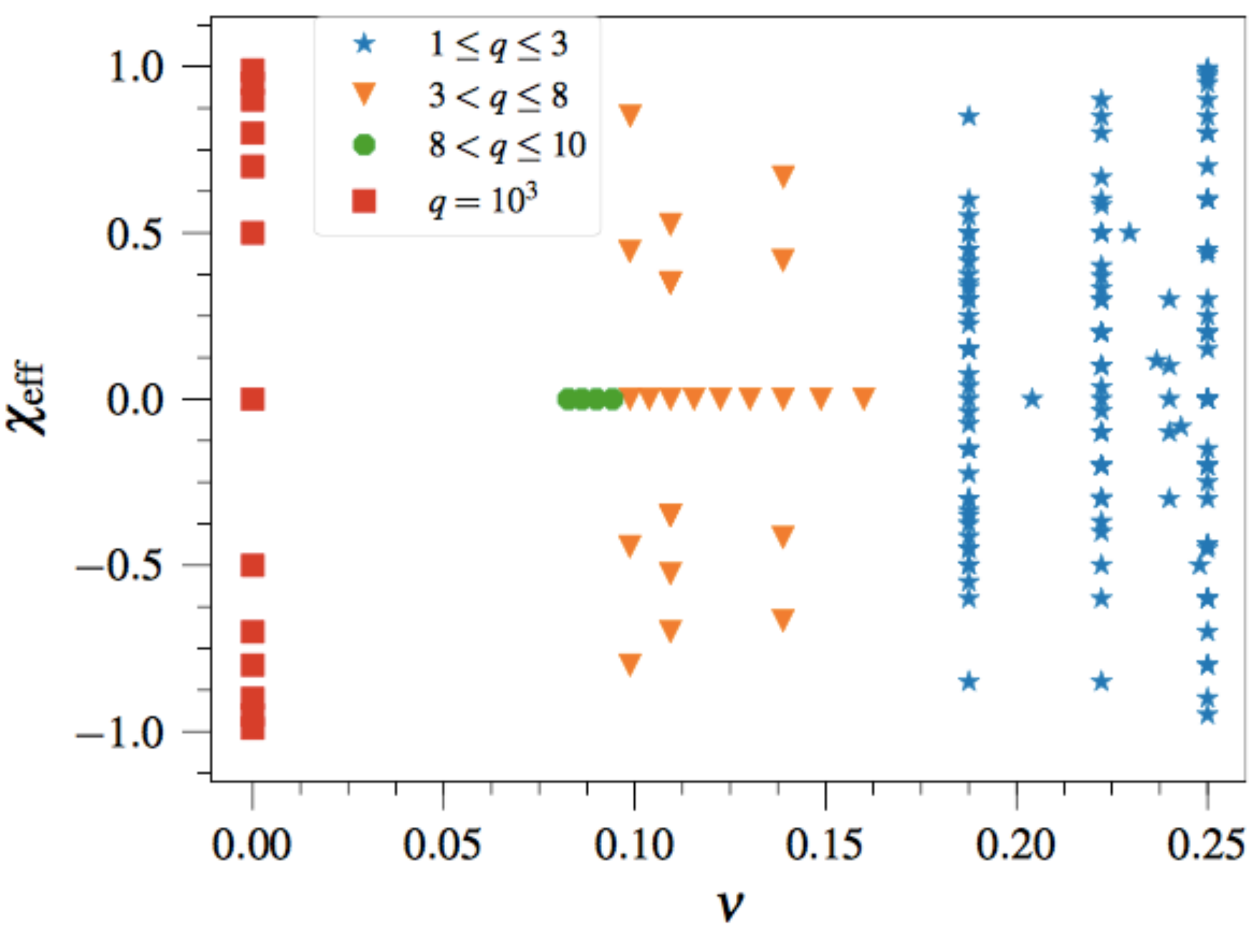


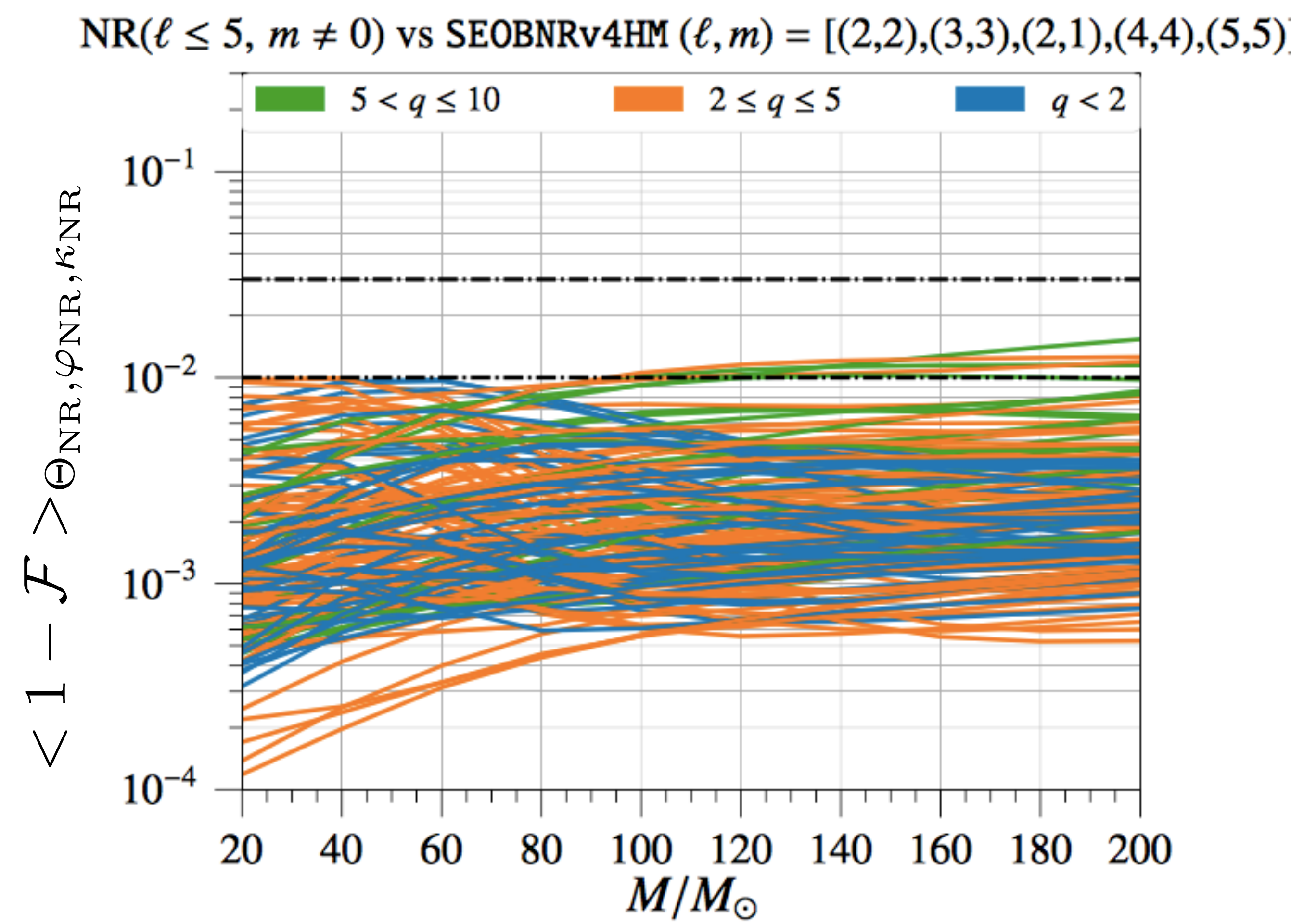
Accuracy of multipolar EOBNR model against NR

- **Non-precessing spin EOBNR** waveform model with **(2,1), (3,3), (4,4) & (5,5) modes.**

(Cotesta, AB et al. 18)

141 NR waveforms



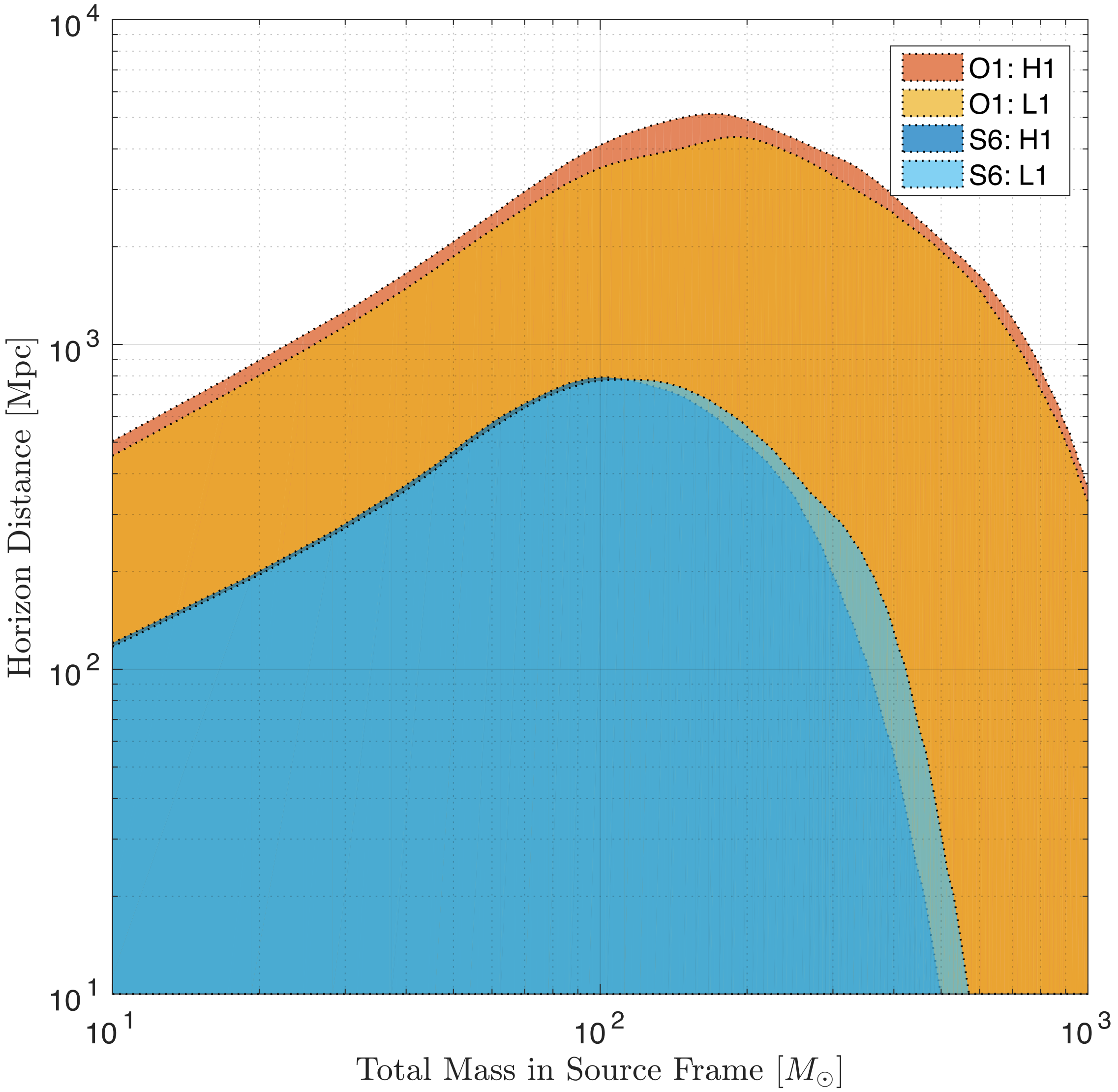


- **Extending analysis** to **other modes requires** producing **accurate NR waveforms** for those modes.

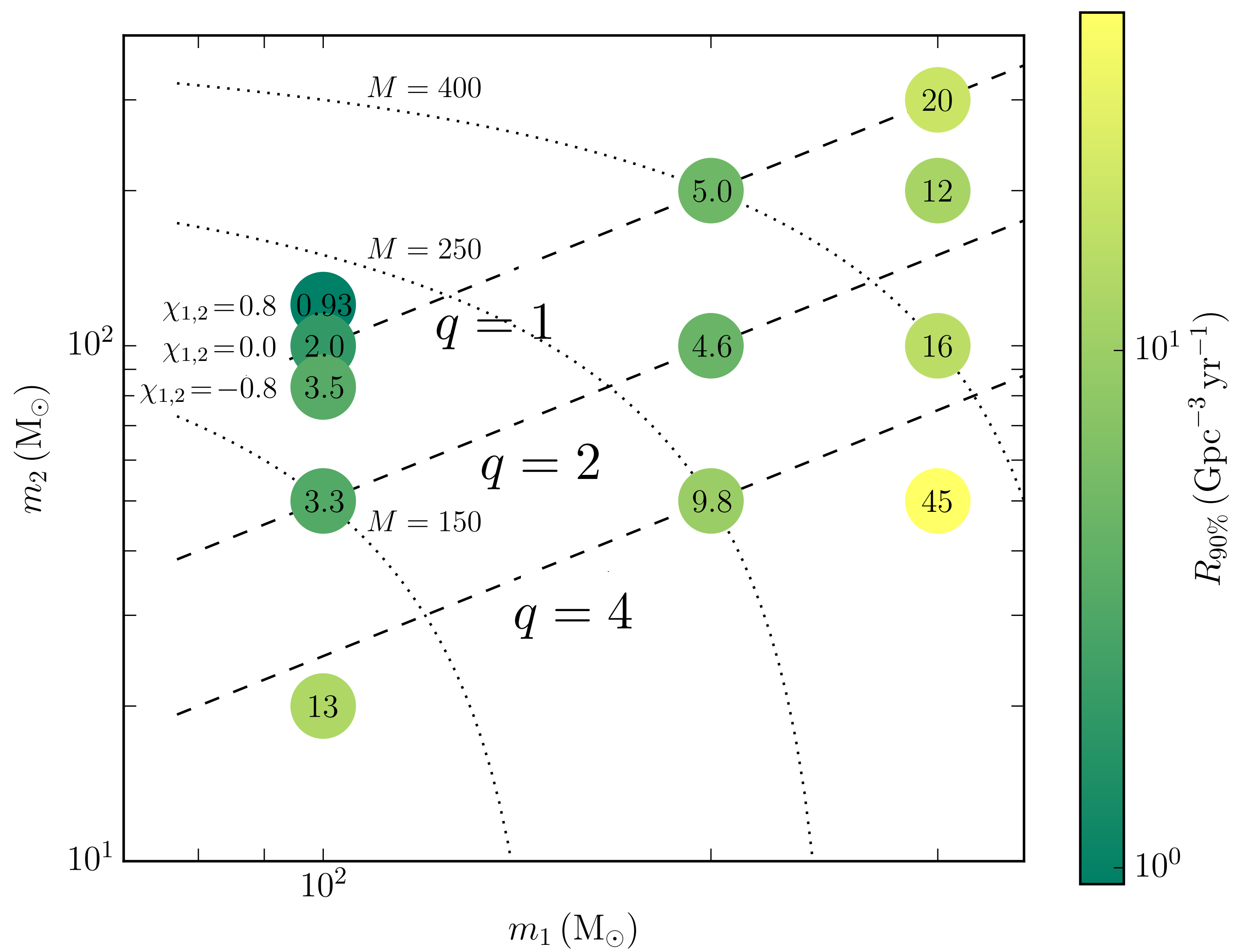
(for modeling see also Mehta et al. 17, London et al. 17; for searches see Capano, …, AB 16, Harry et al. 18)

Intermediate-mass binary black holes (IMBBHs): search in O1

(Abbott et al. PRD96 (2017) 022001)



- **IMBHBs**: M > 100 Msun, 1< q < 10
- Only **dominant (2,2) mode** used.



- **Two searches employed**: matched-filter & minimal-assumption algorithms.
- **BBH** (100 Msun, aligned spins) **rate < 0.93/(Gpc)^3/yr** at 90% confidence.

Relevance of higher harmonics for IMBBHs

- **Non-spinning EOBNR** waveform model with **(2,1), (3,3), (4,4) & (5,5) modes.**

  (Pan, AB et al. 11)

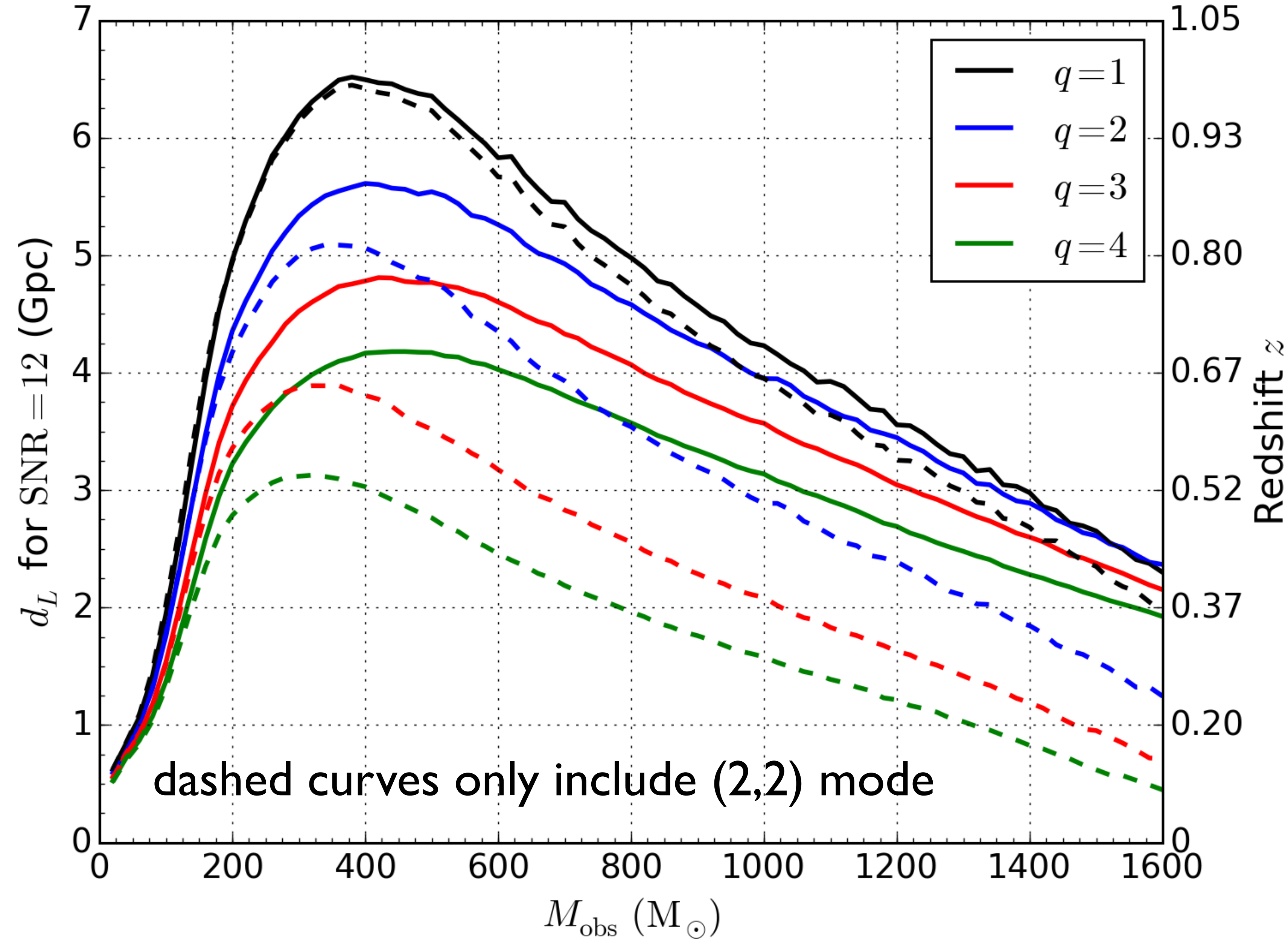
- **Improvements in measurement** of **masses** & **orientation angles** with higher harmonics.

- **Total mass better measured** than chirp mass **for IMBBHs.**

(see also Haster et al. 15)

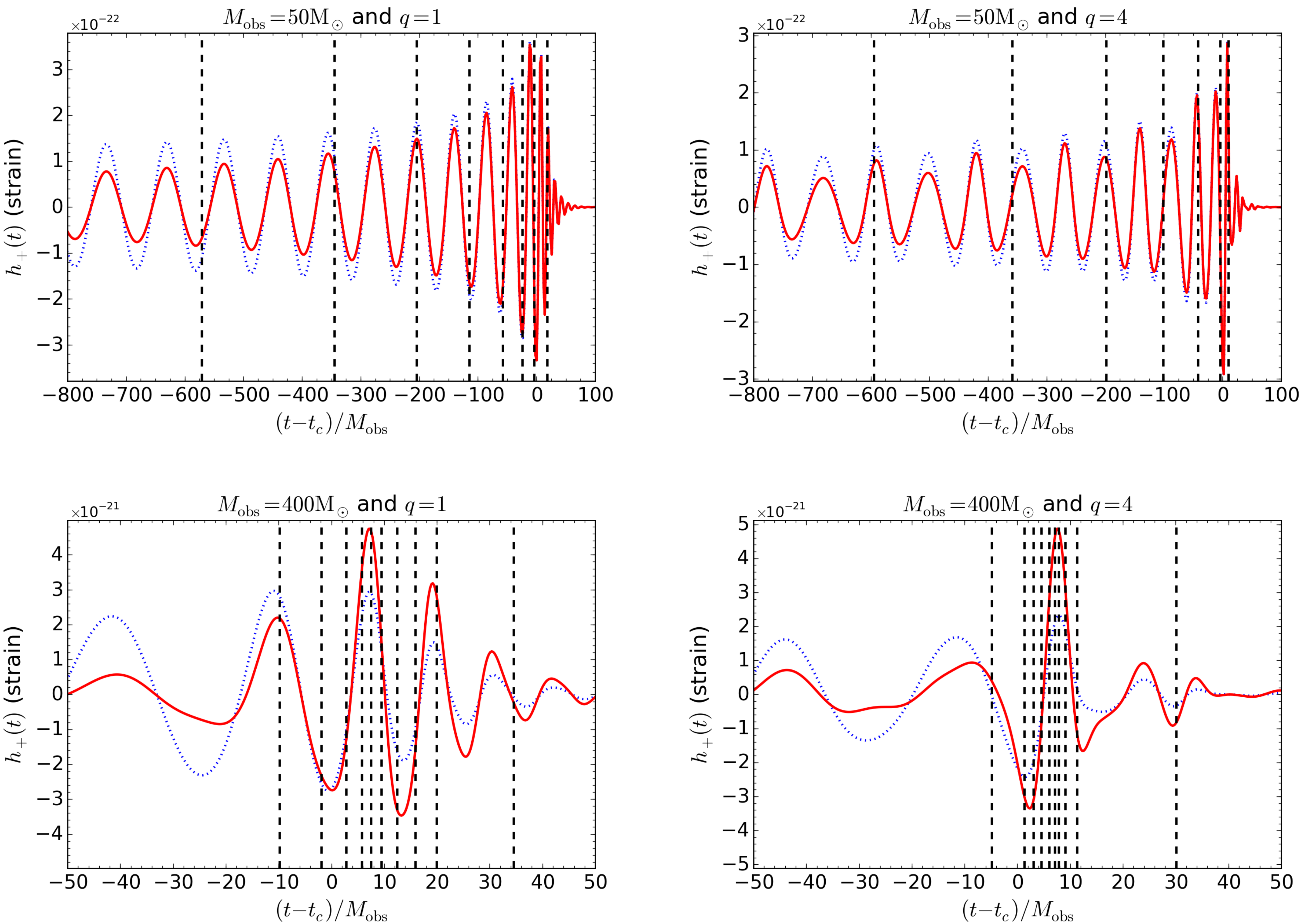
(Graff, AB & Sathyaprakash 15)

distance reach versus observed total mass
(averaged on sky location and polarization)



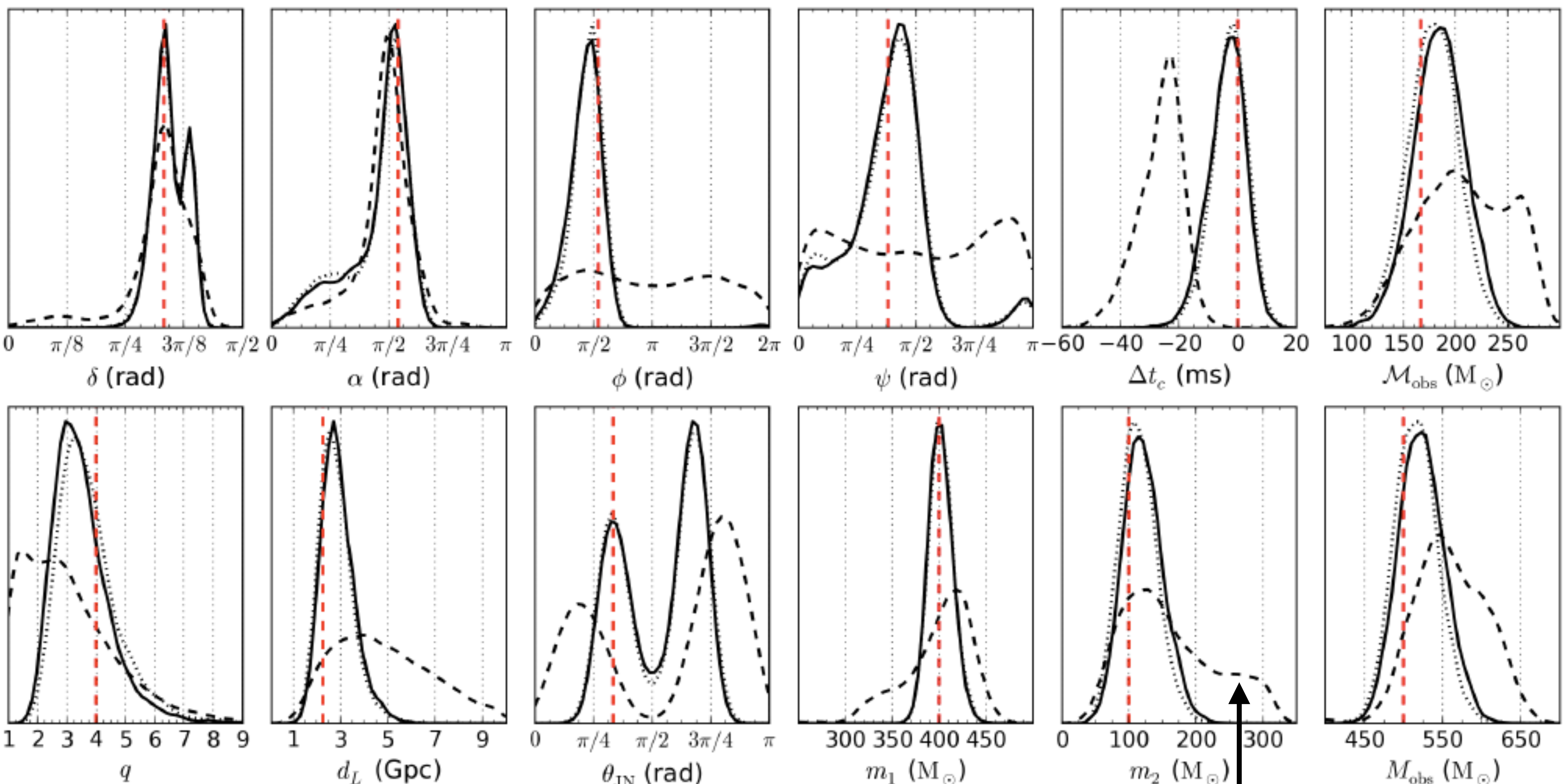
Relevance of higher harmonics for IMBBHs (contd.)

(Graff, AB & Sathyaprakash 14)



Relevance of higher harmonics for IMBBHs (contd.)

(Graff, AB & Sathyaprakash 14)



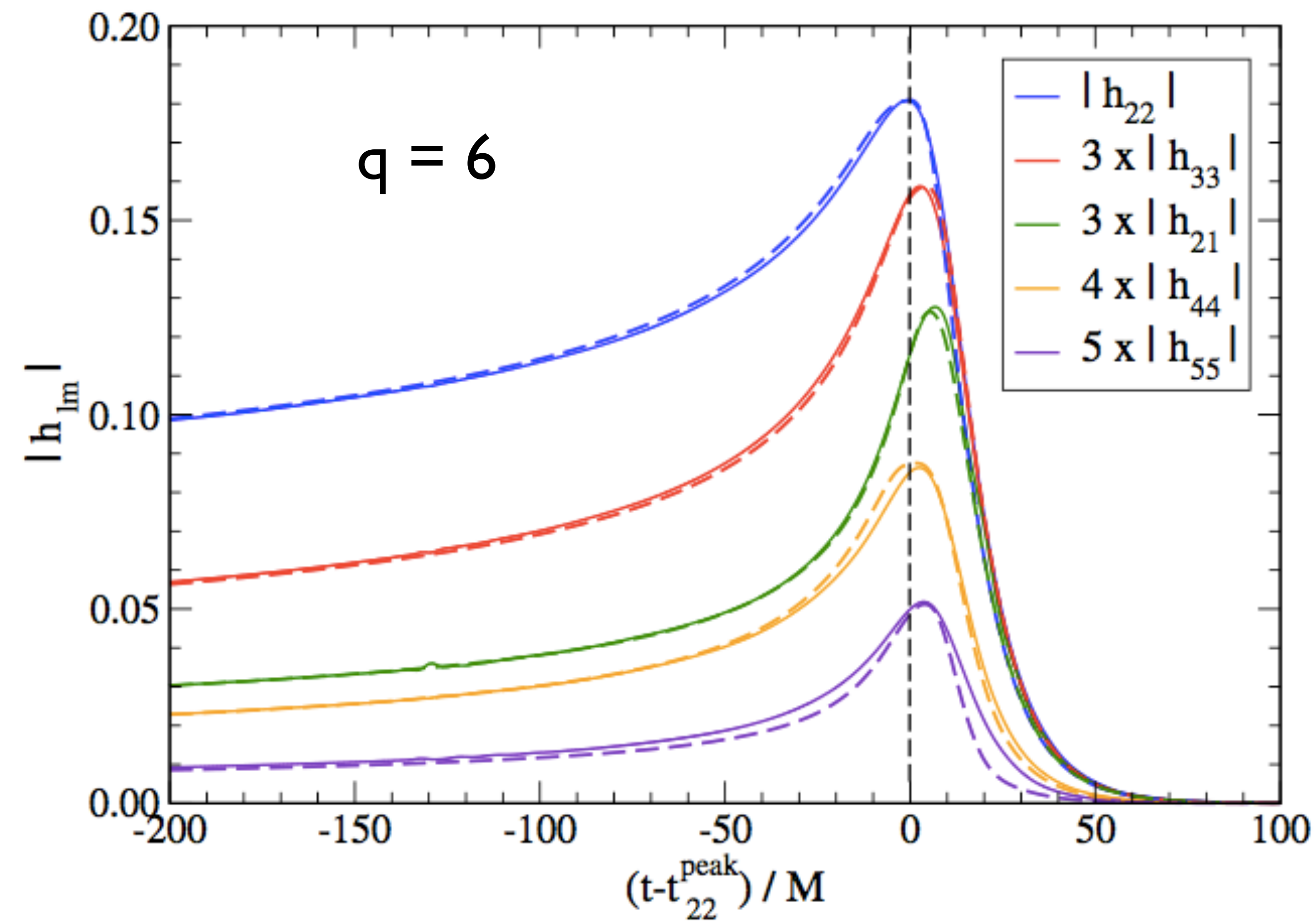
$$\mathrm{SNR} = 12, M_{\mathrm{obs}} = 500 M_{\odot}, q = 4, \theta_{\mathrm{JN}} = \pi/3$$

dashed curves only include (2,2) mode

Unveiling the quasi-normal modes' ringing of BHs

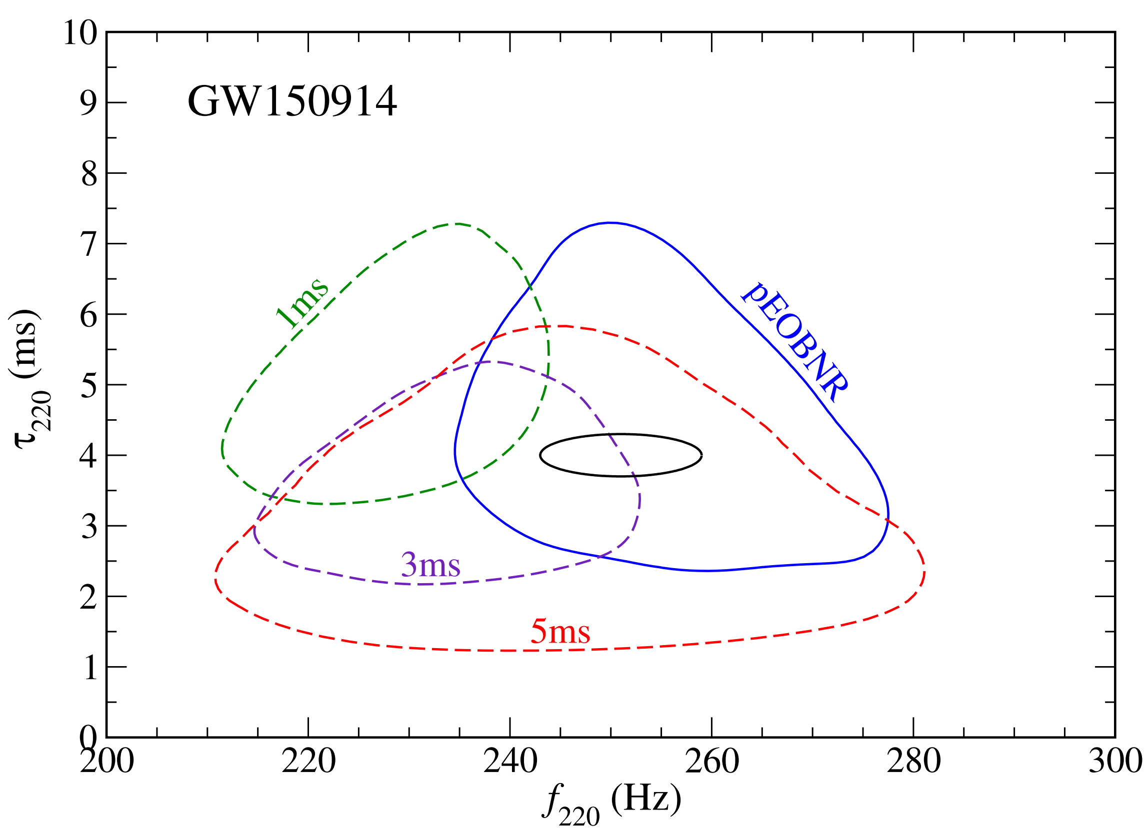
- **BH spectroscopy: unveiling nature of merger's remnant**

  (Dreyer et al. 2004, Berti et al. 2006, Gossan et al. 2012, Meidam et al. 2014, Bhagwat et al. 2017, Yang et al. 2017)



(Brito, AB & Raymond 18)

- We employ **parametrized inspiral-merger-ringdown** waveform model (pEOBNR) that includes modes beyond the dominant (2,2).

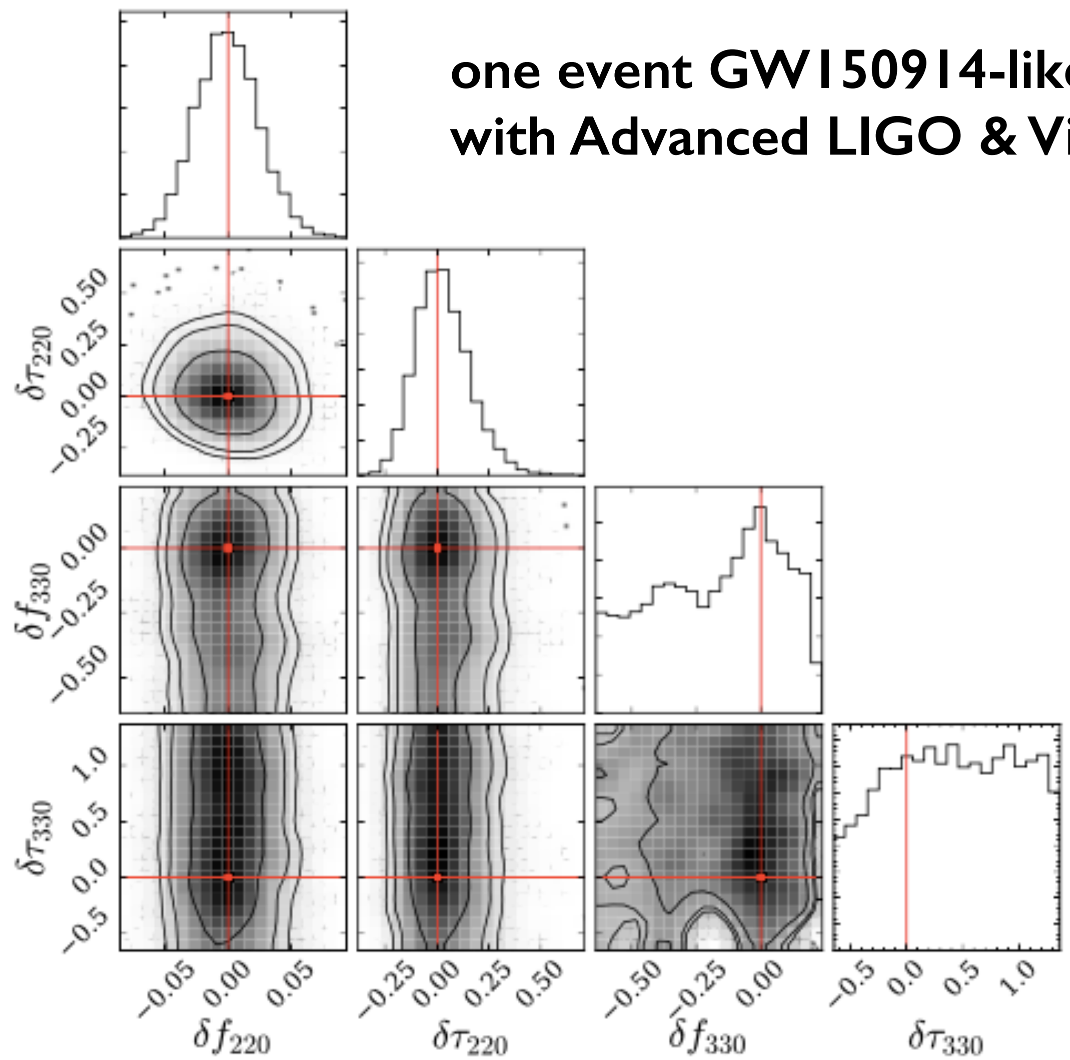


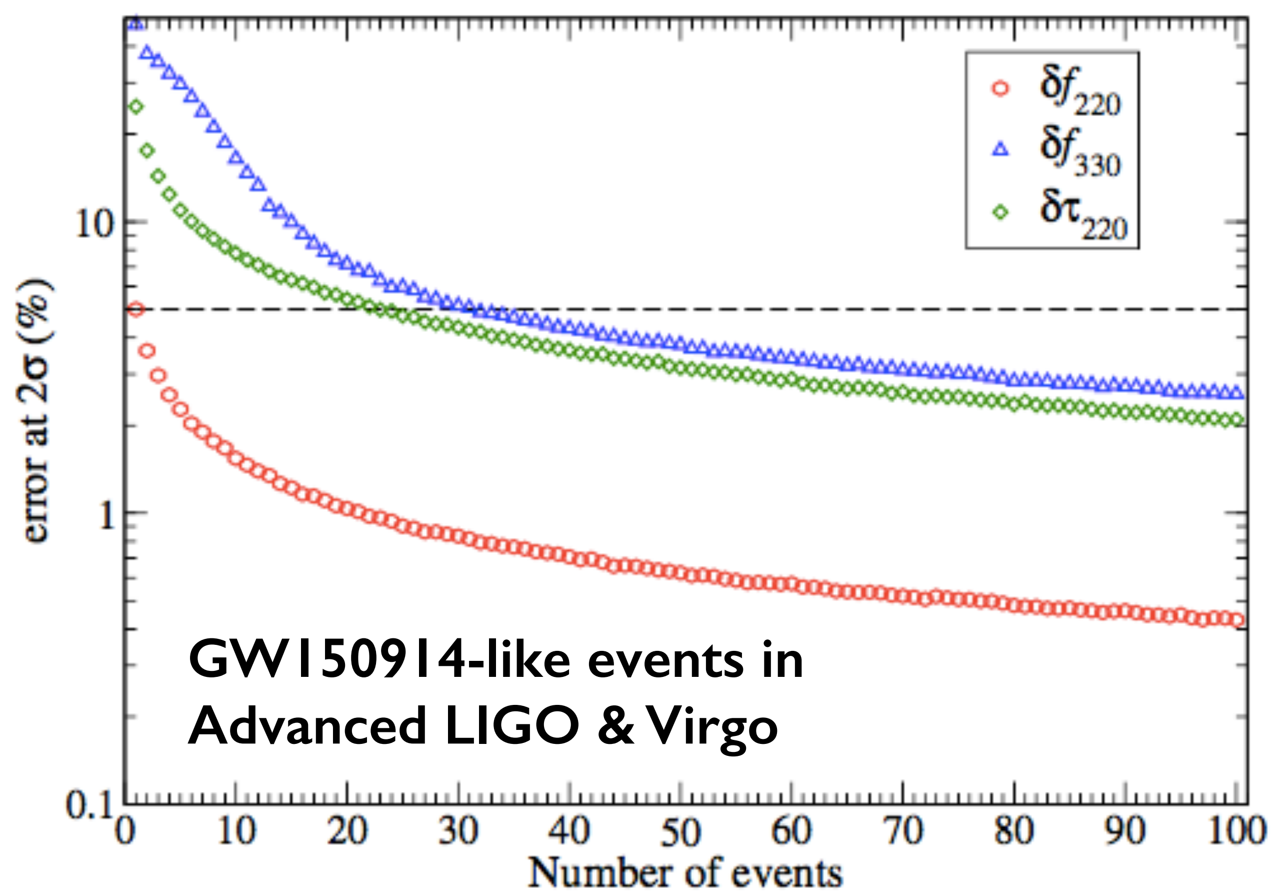
- Using pEOBNR we recover **more stringent bounds** on **frequency** and **decay time** of **GW150914 QNM**, than using damped sinusoid model.

Unveiling the quasi-normal modes' ringing of BHs (contd.)

(Brito, AB & Raymond 18)

- Let us assume we **did not find deviations from GR**.
- We bound **quasi-normal mode frequencies & decay times** by **combining several BH observations.** $\sigma_{lm} = \sigma_{lm}^{\mathrm{GR}}(1+\delta\sigma_{lm})$



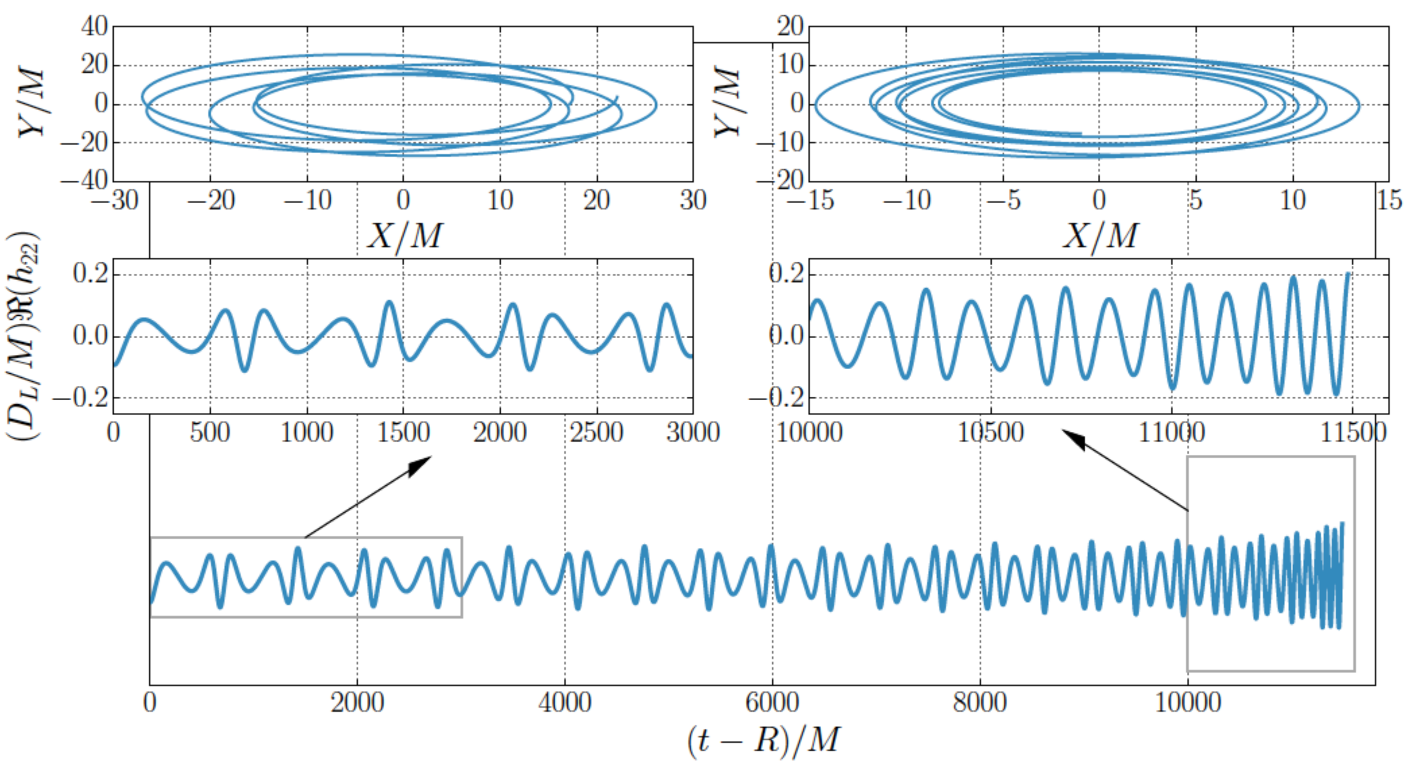


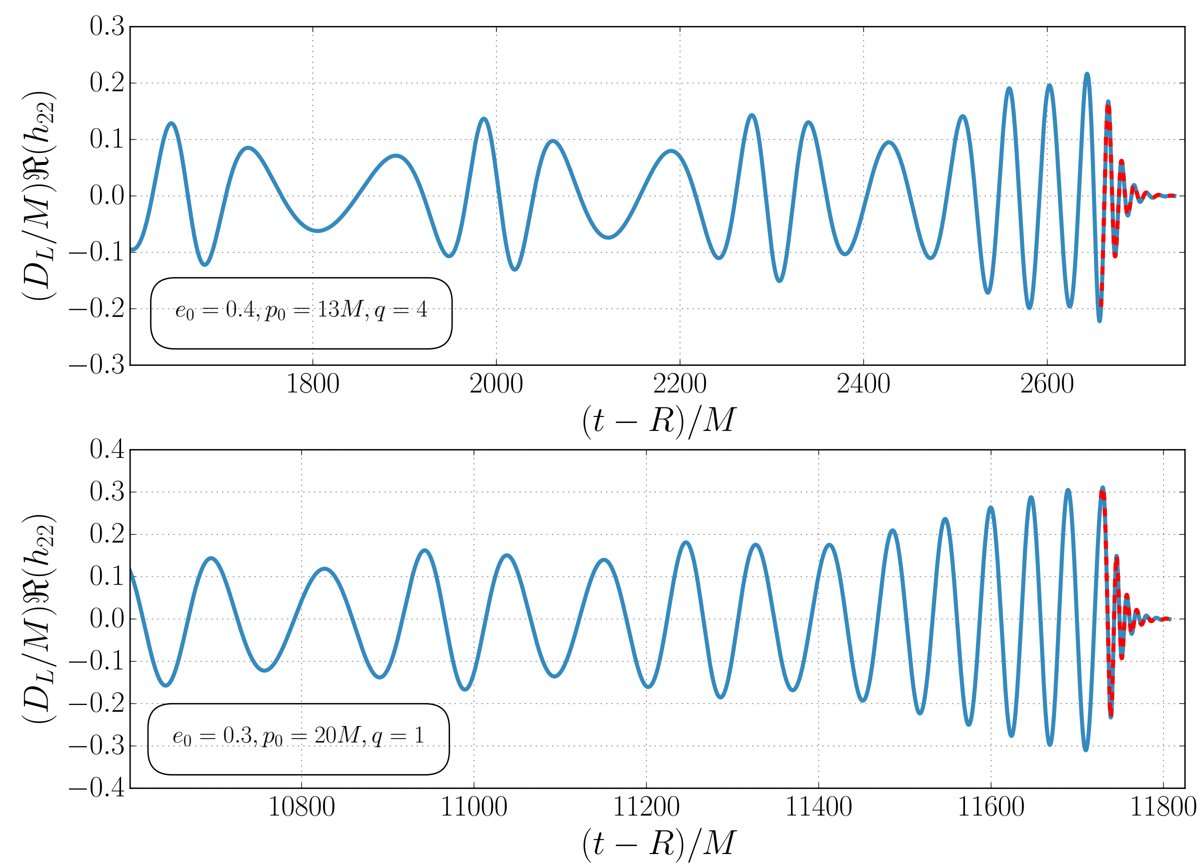
- About **30 GW150914-like events** are needed **to achieve errors of 5%** and **test no-hair conjecture**.

Eccentric waveform models

- **EOB dynamics** & **waveform** extended to ***any* eccentricity value** for **nonspinning binaries.**
- Binary's **degrees of freedom** are divided into a **set of phase variables**, and a **set of quantities that are constant** in the absence of radiation reaction.

(Hinderer & Babak 17)

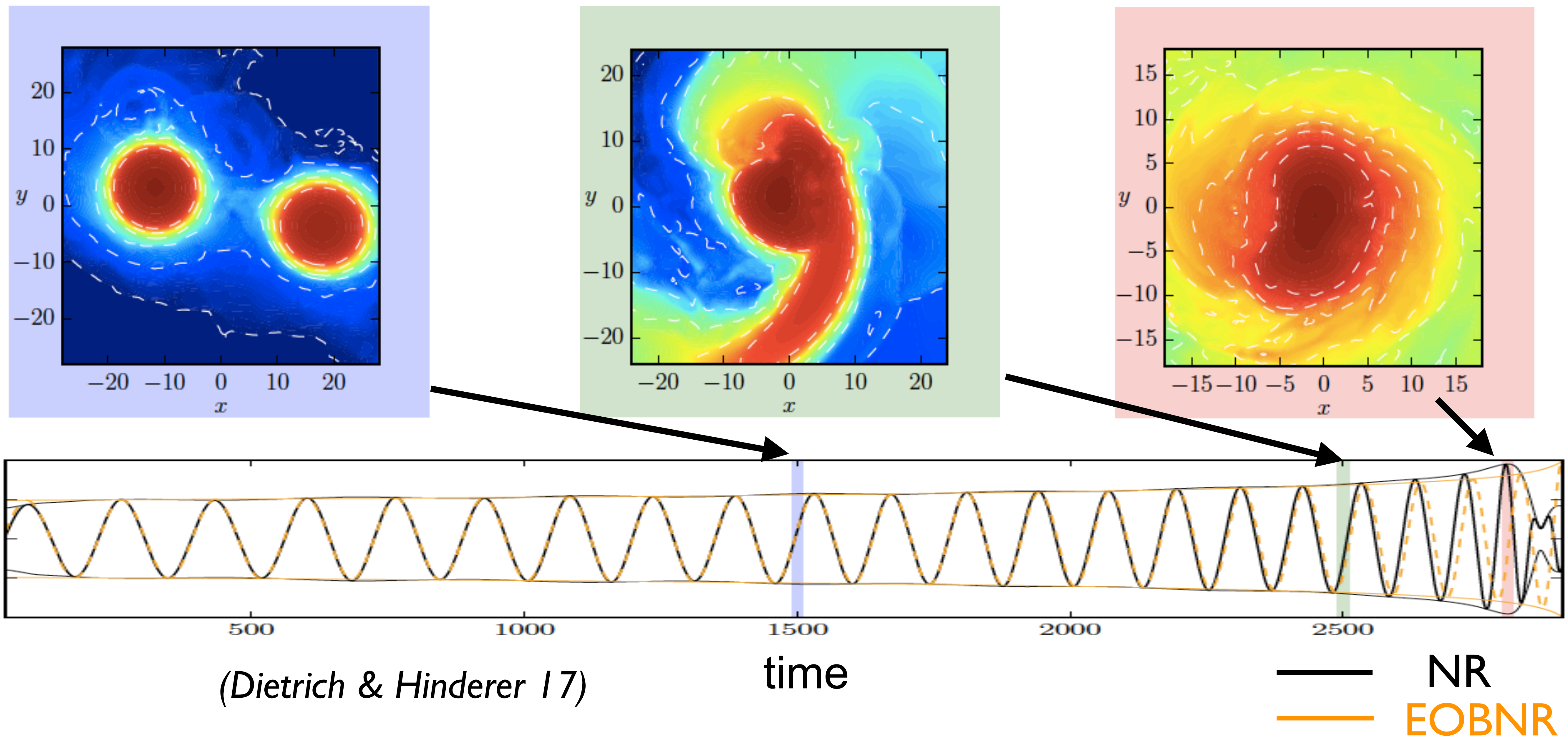




(for eccentricity modeling see also Huerta et al. 14, 16; Hinder et al. 17; Loutrel & Yunes 16, 17)

How waveform models compare with NR for BNS observations?

- We rely on **AR models calibrated to point-mass NR** (i.e., BBHs) for long inspiral, and **can tune** them over **last 15-20 GW cycles** to NR waveforms.

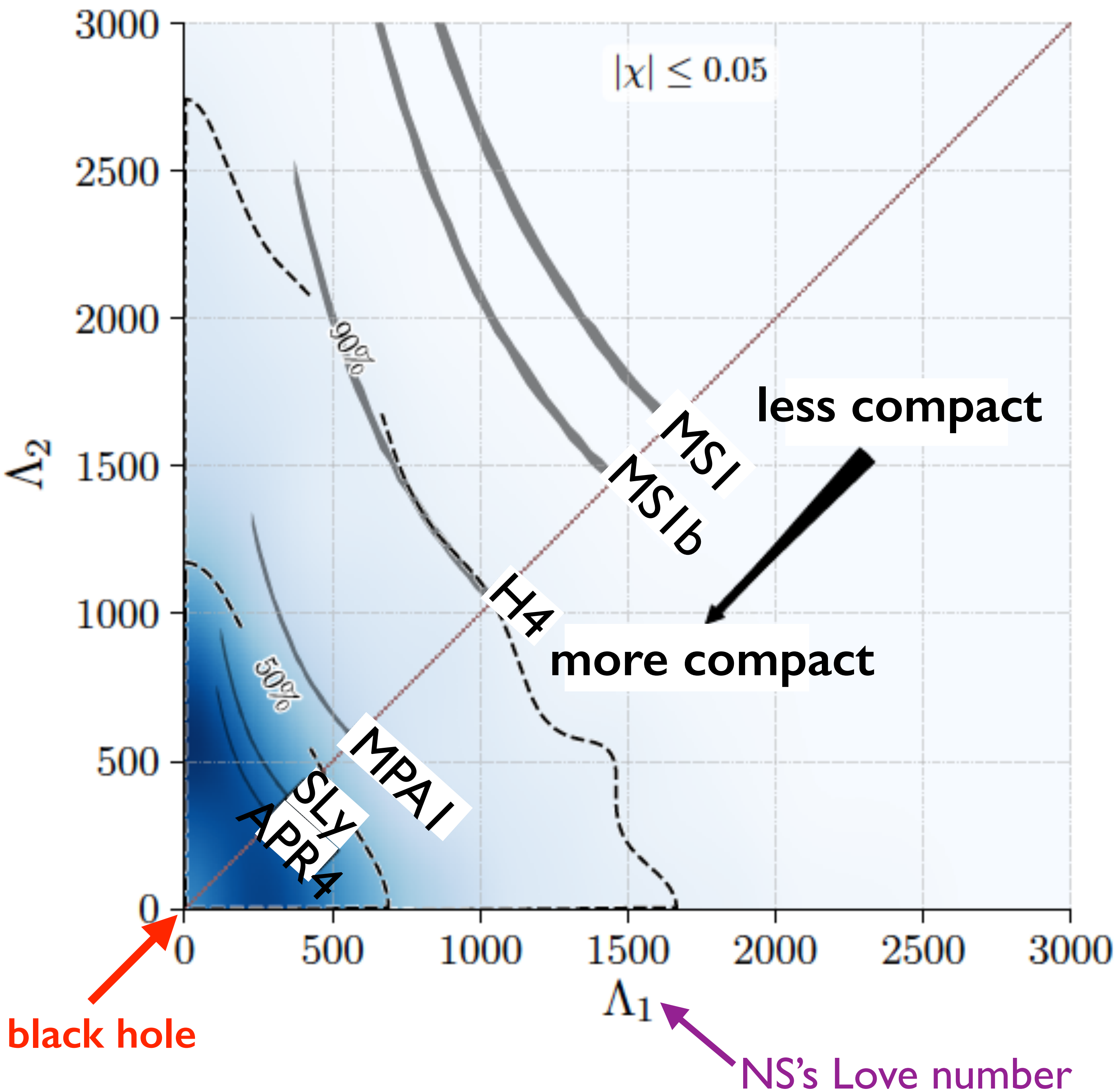


(Dietrich & Hinderer 17)

(Damour 1983, Flanagan & Hinderer 08, Binnington & Poisson 09, Vines et al. 11, Damour & Nagar 09, 12, Bernuzzi et al. 15, Hinderer et al. 16, Steinhoff et al. 16, Dietrich et al. 17, Dietrich et al. 18)

A first glimpse in EOS of neutron stars: GW170817

(Abbott et al. PRL 119 (2017) 161101)



Depends on EOS & compactness

$$\Lambda = \frac{\lambda}{m_{\rm NS}^5} = \frac{2}{3} k_2 \left(\frac{R_{\rm NS} c^2}{G m_{\rm NS}} \right)^5$$

- With **state-of-art waveform models, tides are reduced by ~20%.** LVC analyses are ongoing.

- For NS spins > 0.1-0.15, **spin-quadrupole** affects GW phasing.

  (Harry & Hinderer 17, Dietrich et al. 18)

Including dynamical tidal effects in EOB model

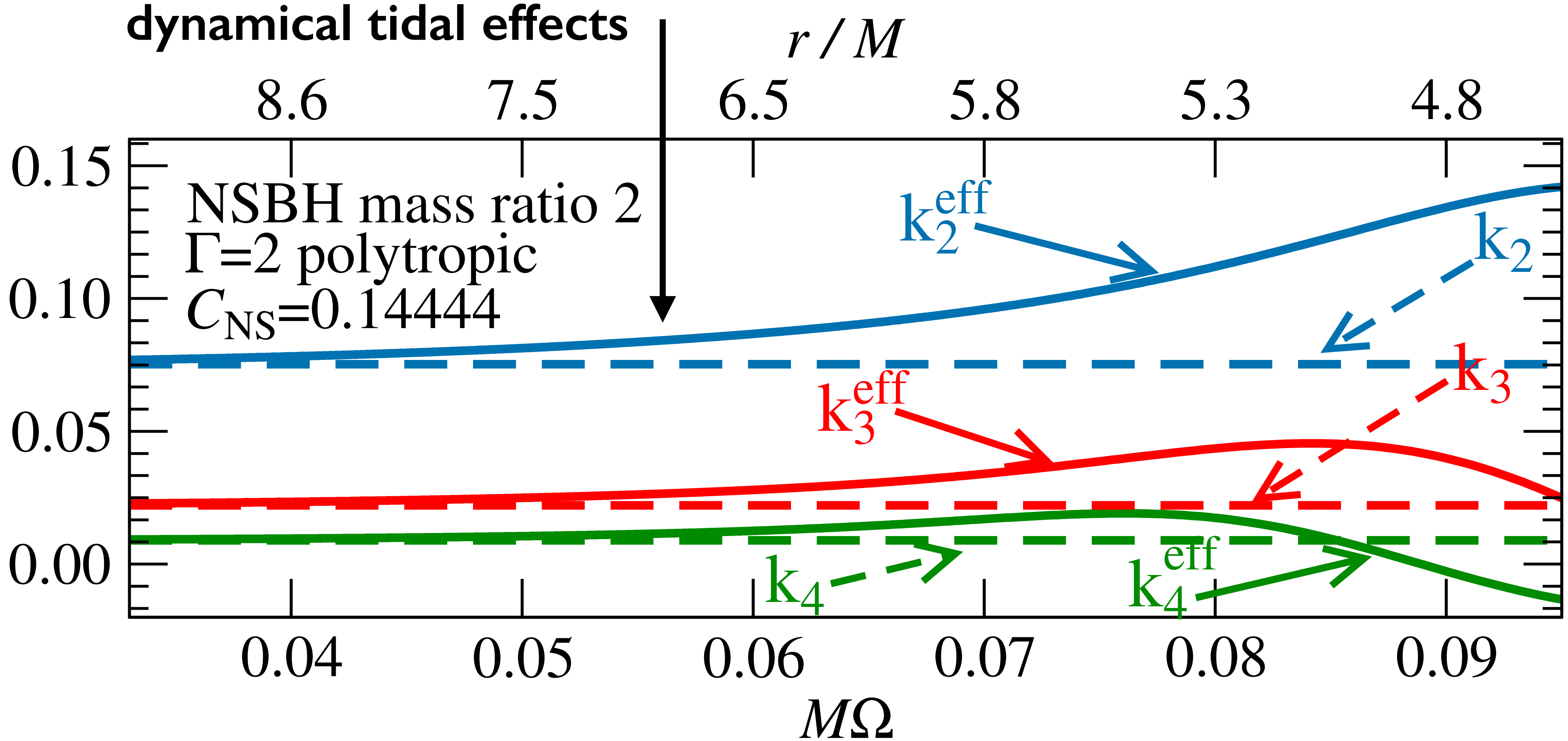
- **Dynamical tides**: NS's f-modes can be excited.
- **Tidal forcing frequency approaches** eigenfrequency of **NS's normal modes of oscillation**, resulting in an enhanced, more complex tidal response.

(Kokkotas et al. 1995, Flanagan et al. 08, Hinderer, … AB et al. 16, Steinhoff, … AB et al. 16)

(Hinderer, …, AB et al. 16)

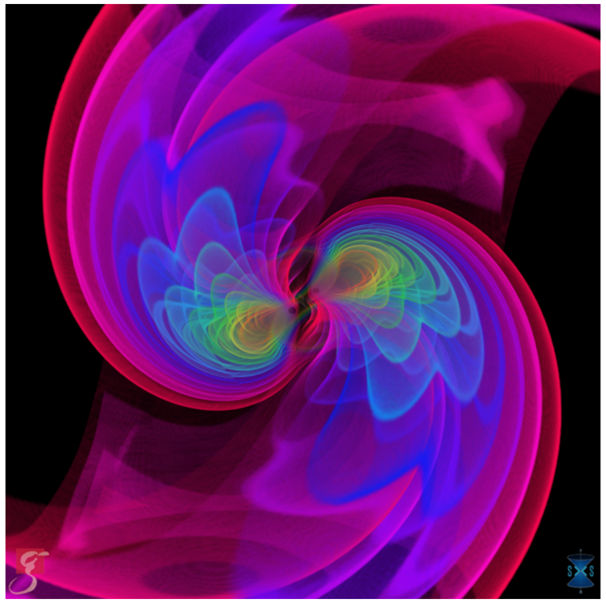
$$k_2 = \frac{3}{2}\frac{\lambda}{R_{\rm NS}^5}$$

NS's effective response to dynamical tidal effects

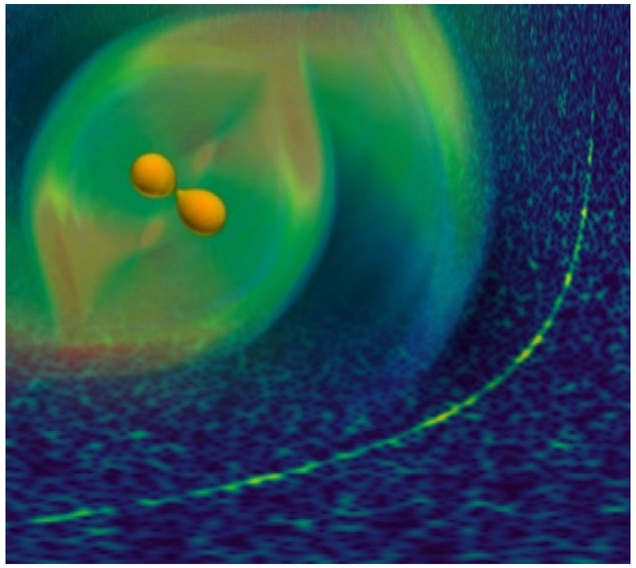


The new era of precision gravitational-wave (astro)physics

- Theoretical groundwork in **analytical and numerical relativity** has allowed us to build **faithful waveform models** to **search** for signals, **infer** astrophysical and cosmological **properties** and **test GR**.



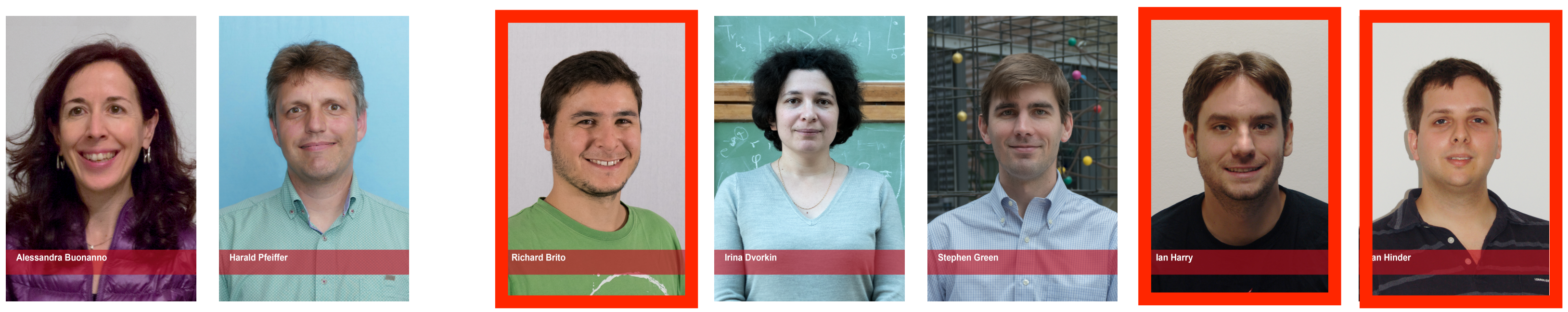
- **To take full advantage of discovery potential** in next years and decades **we need** to continue to make **precise theoretical predictions.**

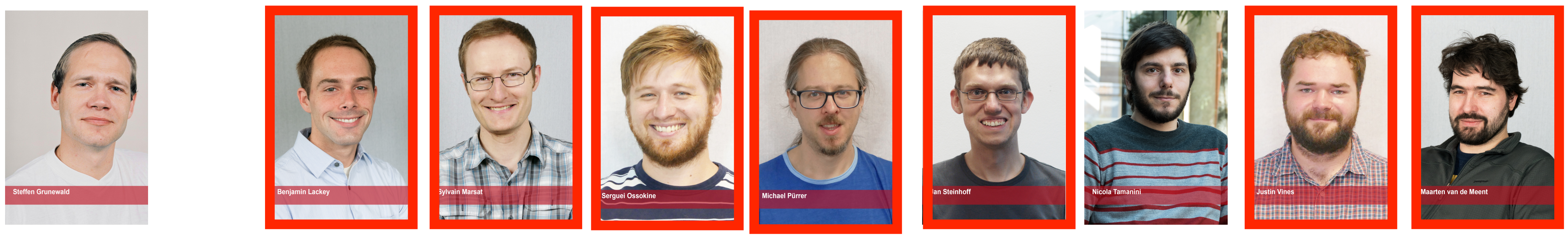


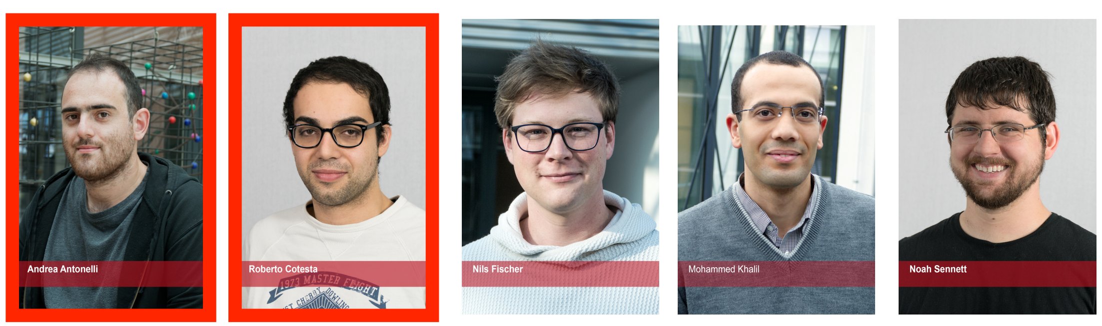
- For next few years, crucial (urgent) to **improve accuracy** of waveform models **for mass ratios > 4 & spins > 0.8,** include **higher harmonics** in spin **precessing waveforms.** This is **important for** inferring **science of BBHs, NSBH & BNS.**

“Astrophysical & Cosmological Relativity” Department

- Current members







- Past members contributed to work presented