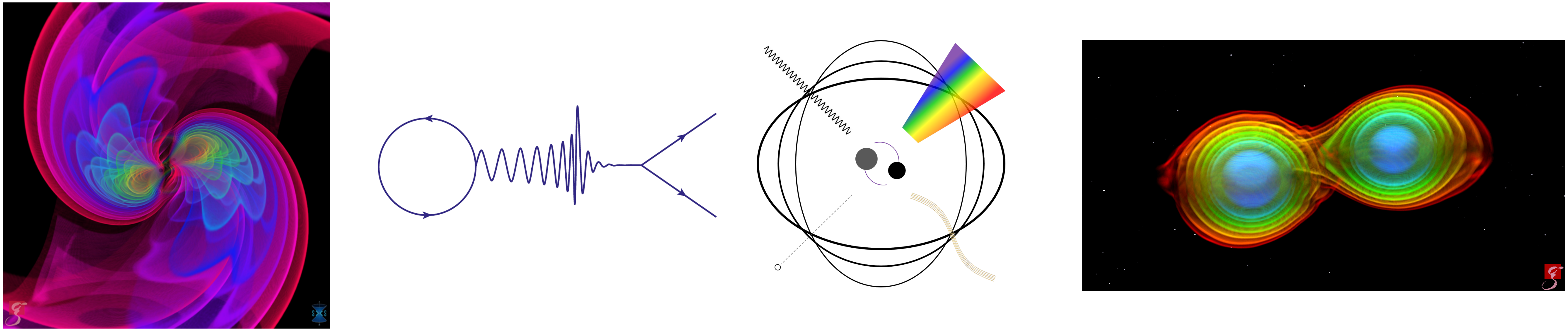

Ever more Physics in Gravitational-Wave Models

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"GW Physics and Astrophysics", KITP, UCSB

July 18, 2019

Outline

- Science from GW experiments stems on our ability to make precise theoretical predictions of gravitational waveforms.

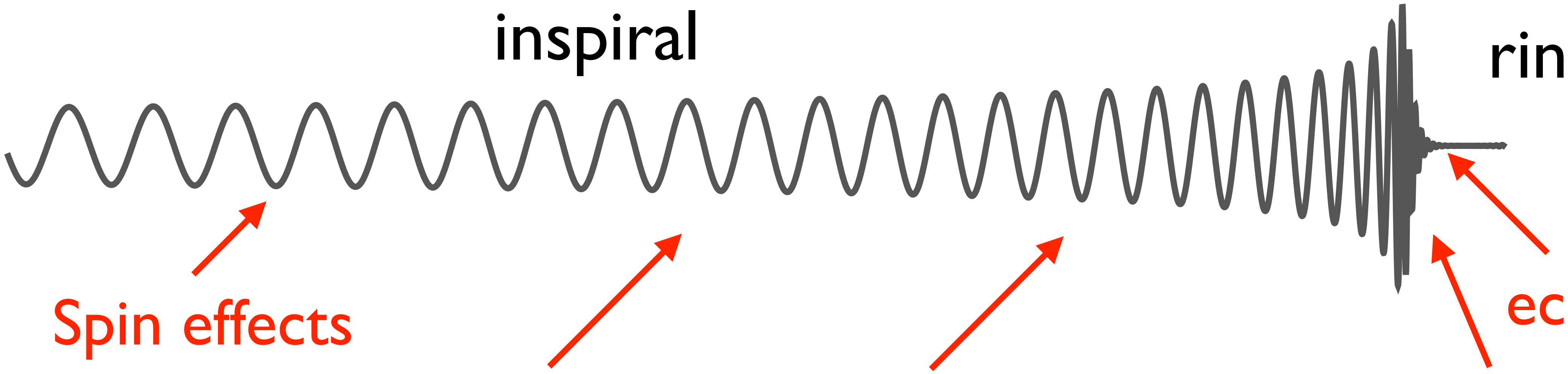
- Are we missing GW signals? Are current inference studies in any way affected by modeling error?

- Discovery potential in next years, ability to infer more precise cosmological and astrophysical information, and carry out more stringent tests of GR require more accurate waveforms and with more physics.

- What are the highest priorities, and what are the challenges in waveform modeling.

Waveforms encode plethora of physical effects

- Binary black hole



merger

inspiral

ringdown

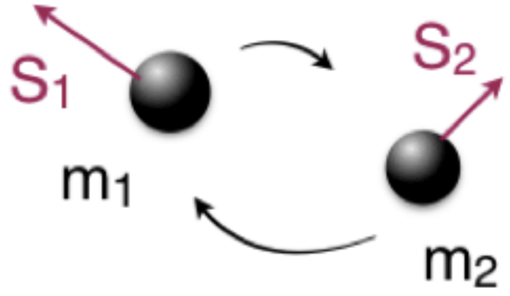
Spin effects

tail effects

BH absorption

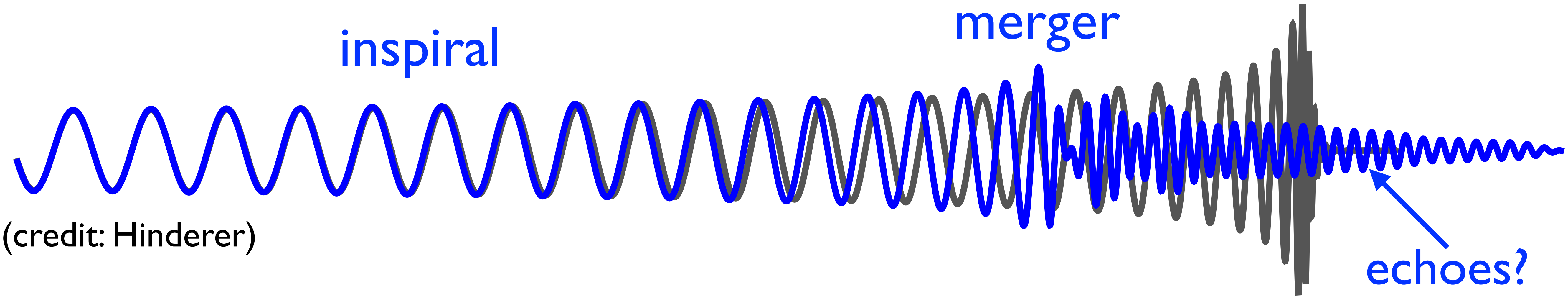
echoes?

quasi-normal modes



(credit: Hinderer)

- **Compact-object binary** with **matter** or in **modified theory** to GR?



inspiral

merger

echoes?

(credit: Hinderer)

Solving two-body problem in General Relativity

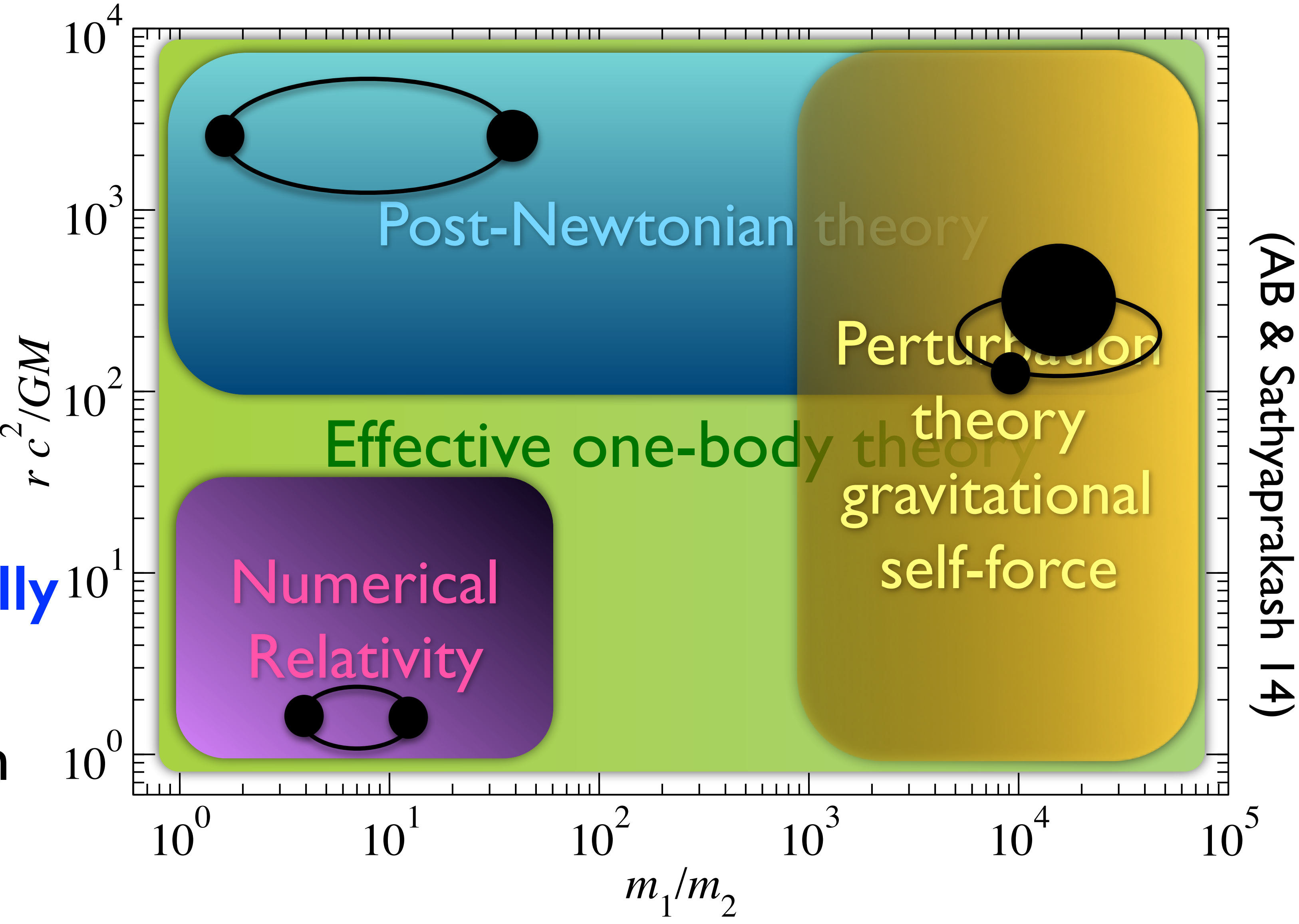
$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \frac{8\pi G}{c^4} T_{\mu\nu}$$

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

- Einstein's field equations can be solved:

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

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



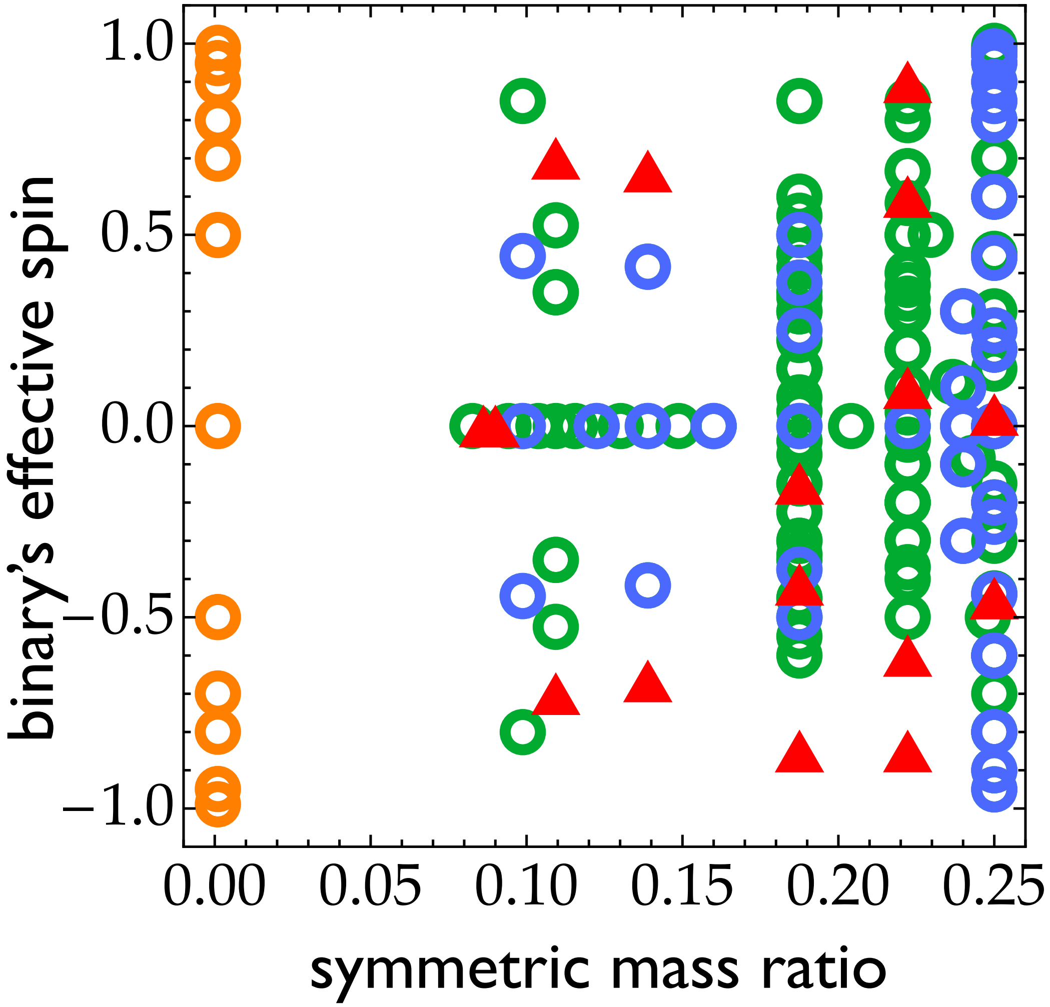
(AB & Sathyaprakash 14)

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

Waveforms for BBH combining analytical & numerical relativity

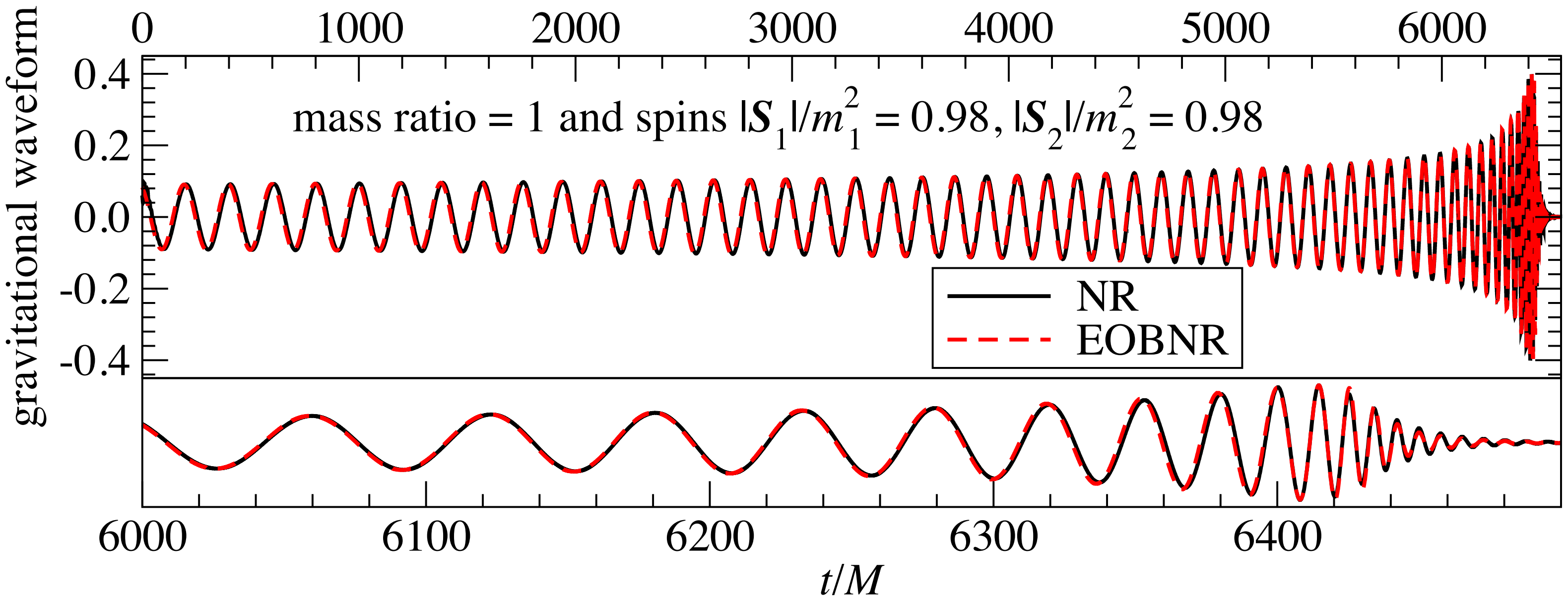
- **Effective-one-body** (EOB) theory & NR (EOBNR)

141 SXS simulations



(Bohe', Shao, Taracchini, AB & SXS 16)

(Taracchini, AB, Pan, Hinderer & SXS 14, Pürrer 15)



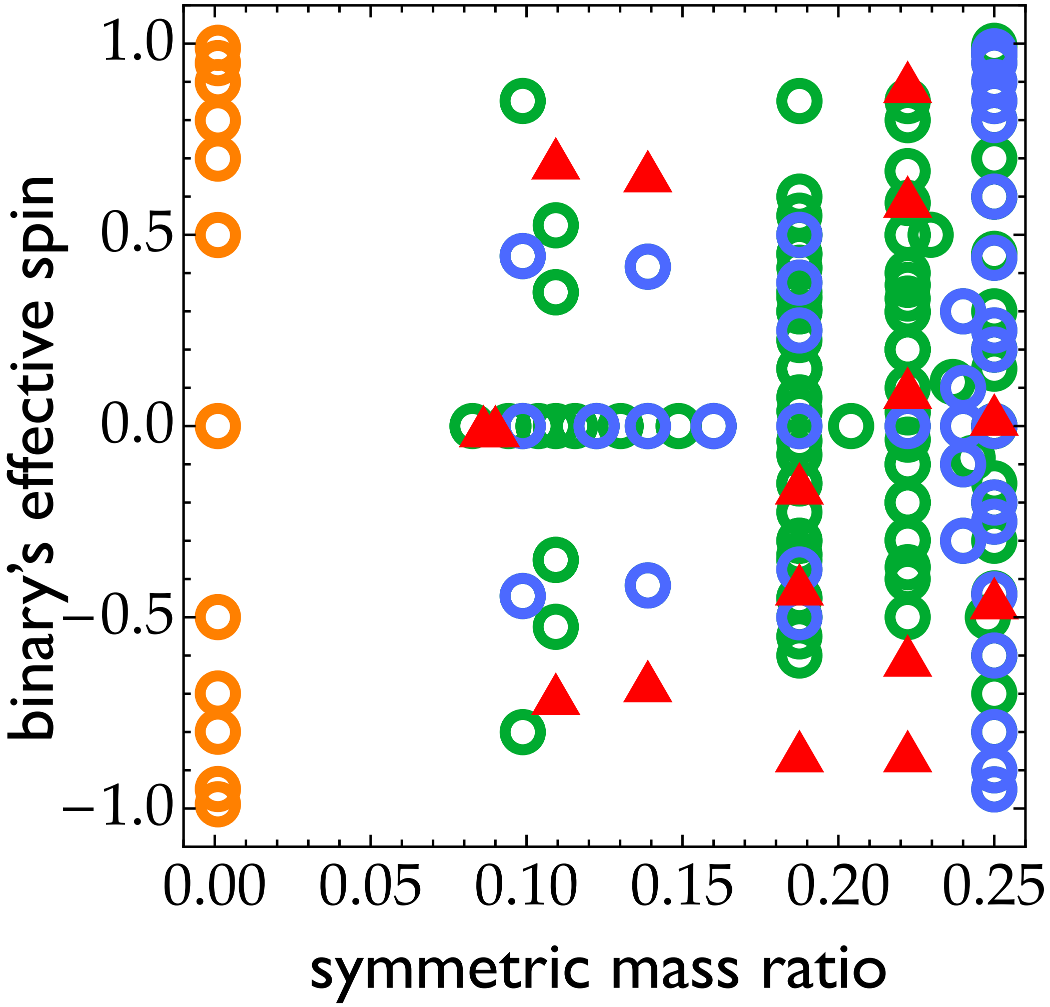
- **Inspiral-merger-ringdown phenomenological** waveforms fitting EOB & NR (IMRPhenom) *(Khan et al. 16, Hannam et al. 16)*

(If PN were used instead, accuracy will degrade, because of "gap" between PN and NR)

Waveforms for BBH combining analytical & numerical relativity

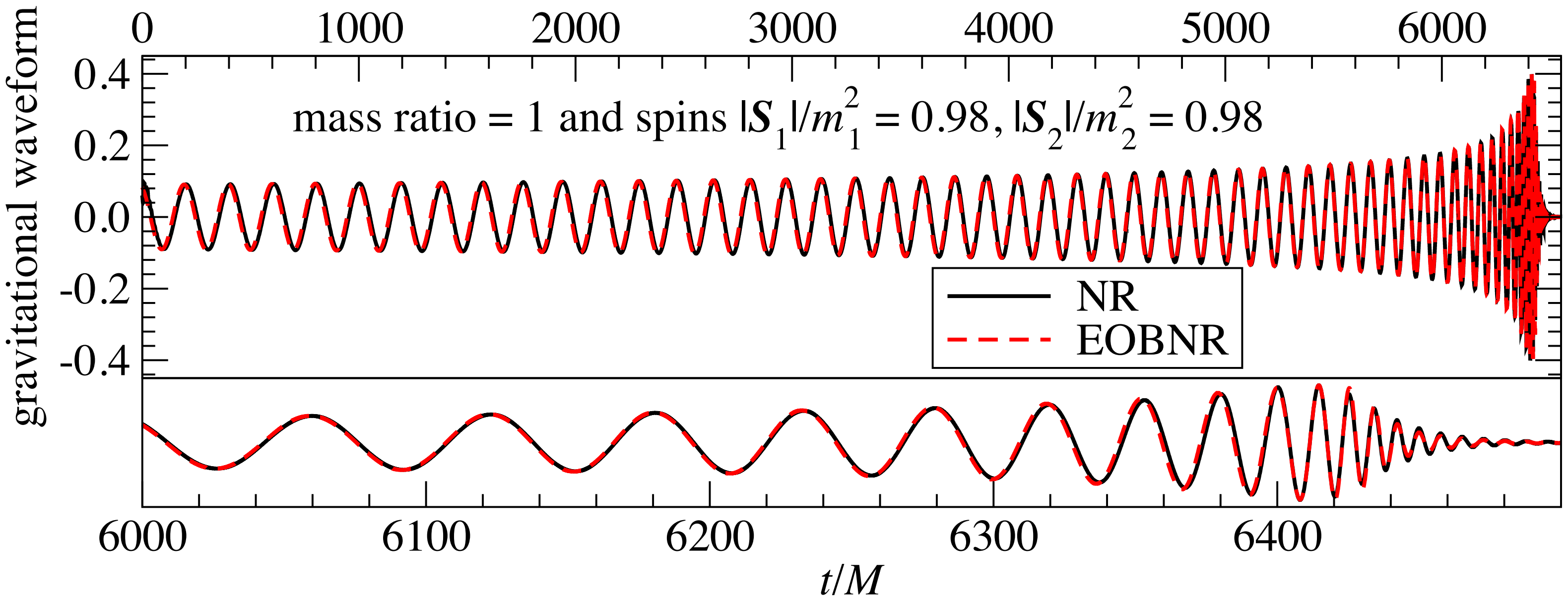
- **Effective-one-body** (EOB) theory & NR (EOBNR)

141 SXS simulations



(Bohe', Shao, Taracchini, AB & SXS 16)

(Taracchini, AB, Pan, Hinderer & SXS 14, Pürrer 15)

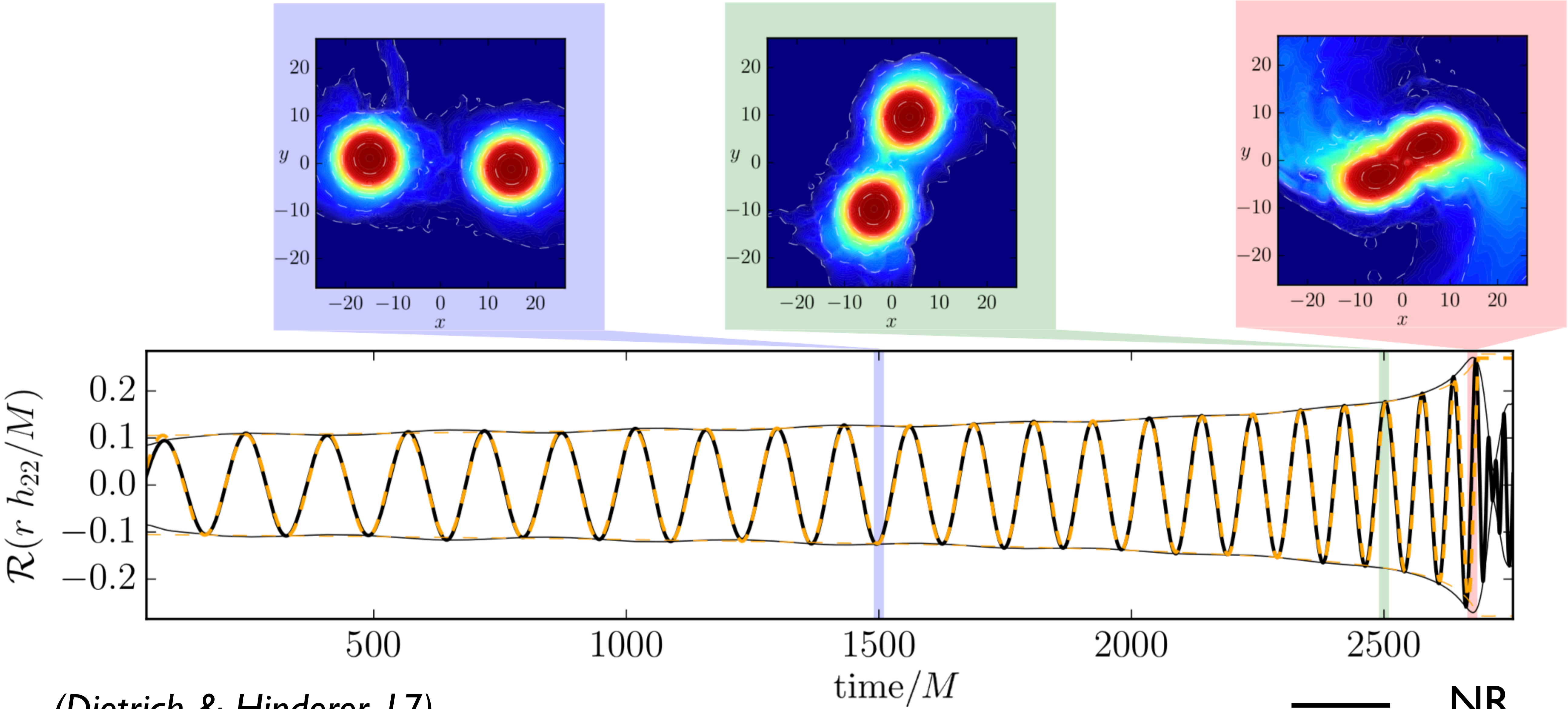


- **NR surrogate models** built **directly** interpolating **NR simulations,** which are **"selected" in parameter space** using analytical waveform models.

(Blackman et al. 17, Varma et al. 18, 19)

Waveforms for BNS combining analytical & numerical relativity

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



(Dietrich & Hinderer 17)

(Damour 1983, Flanagan & Hinderer 08, Binnington & Poisson 09, Vines et al. 11, Damour & Nagar 09, 12, Bernuzzi et al. 15, Hinderer, …AB … et al. 16, Steinhoff, … AB … et al. 16, Dietrich et al. 17-19, Nagar et al. 18)

Gravitational waveforms built from conservative & dissipative dynamics

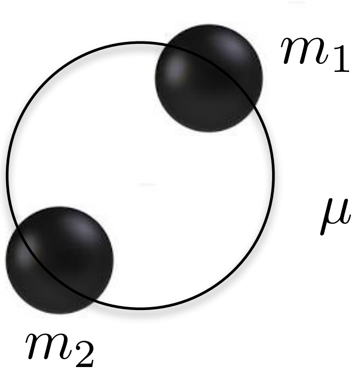
---

- GW from time-dependent **quadrupole moment**: $h_{ij} \sim \frac{G}{c^4} \frac{\ddot{Q}_{ij}}{D}$

$$h = \nu \left(\frac{GM}{c^2 D} \right) \frac{v^2}{c^2} \cos 2\Phi$$

$$\frac{v}{c} = \left(\frac{GM\omega}{c^3} \right)^{1/3}$$

$$\nu = \mu / M$$



$$\mu = m_1 m_2 / M$$

- Center-of-mass energy: $E(\omega)$

$$E(v) = -\frac{\mu}{2} v^2 + \cdots$$

- GW luminosity: $\mathcal{L}_{\mathrm{GW}}(\omega) \equiv F(\omega)$

$$F(v) = \frac{32}{5} \nu^2 \frac{c^5}{G} \left(\frac{v}{c} \right)^{10} + \cdots$$

- Balance equation: $\frac{dE(\omega)}{dt} = -F(\omega) \quad \longrightarrow \quad \dot{\omega}(t) = -\frac{F(\omega)}{dE(\omega)/d\omega}$

- Gravitational-wave **phase**: $\Phi_{\mathrm{GW}}(t) = 2\Phi(t) = \frac{1}{\pi} \int^t \omega(t') dt'$

PN templates for compact-object binary inspirals

0PN

$$\varphi(f) = \varphi_{\rm ref} + 2\pi f t_{\rm ref} + \frac{3}{128\nu} v^{-5} \{1$$

dipole radiation

-1PN

1PN

graviton with non zero mass

$$- \frac{5\,\hat{\alpha}^2}{336\omega_{\rm BD}} v^{-2} - \frac{128}{3} \frac{\pi^2 D M \nu}{\lambda_g^2 (1+z)} v^2$$

1PN

1.5PN

spin-orbit

$$+ \left(\frac{3715}{756} + \frac{55}{9}\nu \right) v^2 - 16\pi v^3 + 4\beta v^3$$

2PN

spin-spin

$$+ \left(\frac{15293365}{508032} + \frac{27145}{504}\nu + \frac{3085}{72}\nu^2 \right) v^4 - 10\sigma v^4$$

5PN

$$\ldots - \frac{39}{2} \tilde{\Lambda}^{\rm t} v^{10} + \ldots \}$$

tidal

$$\tilde{\Lambda}^{\rm t} = f(m_1, m_2, \Lambda^{\rm t}_1, \Lambda^{\rm t}_2)$$

for NSBH: $\tilde{\Lambda}^t \sim \frac{1}{q^4} \Lambda^t_{\rm NS} \quad q \gg 1$

Depends on EOS & compactness

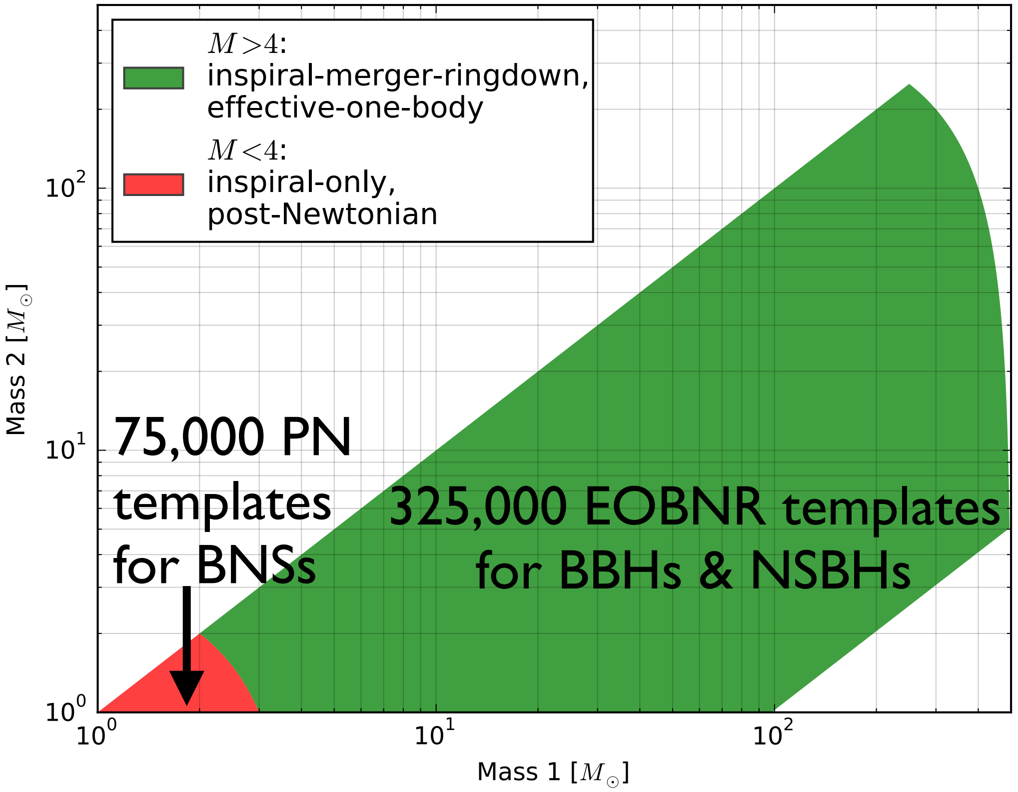
it can be large

$$\Lambda^{\rm t} = \frac{2}{3} \kappa_2 \left(\frac{R_{\rm NS}}{m_{\rm NS}} \right)^5$$

Template bank for modeled search & possible systematics

- **Matched filtering** employed

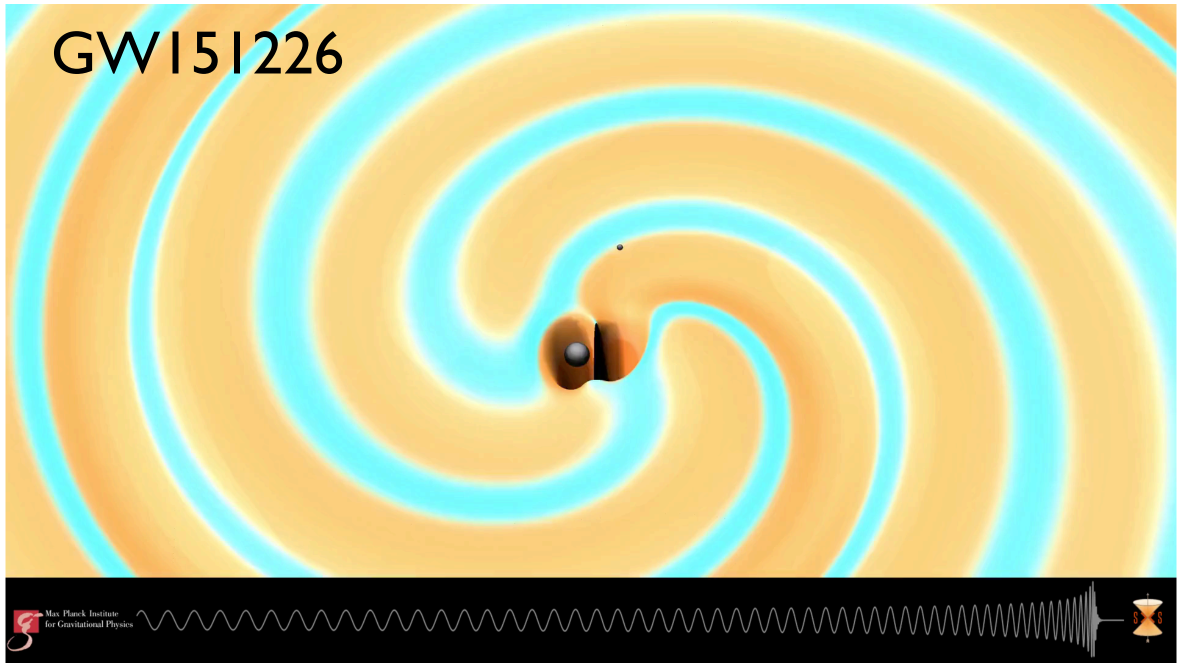
(Dal Canton & Harry 17)



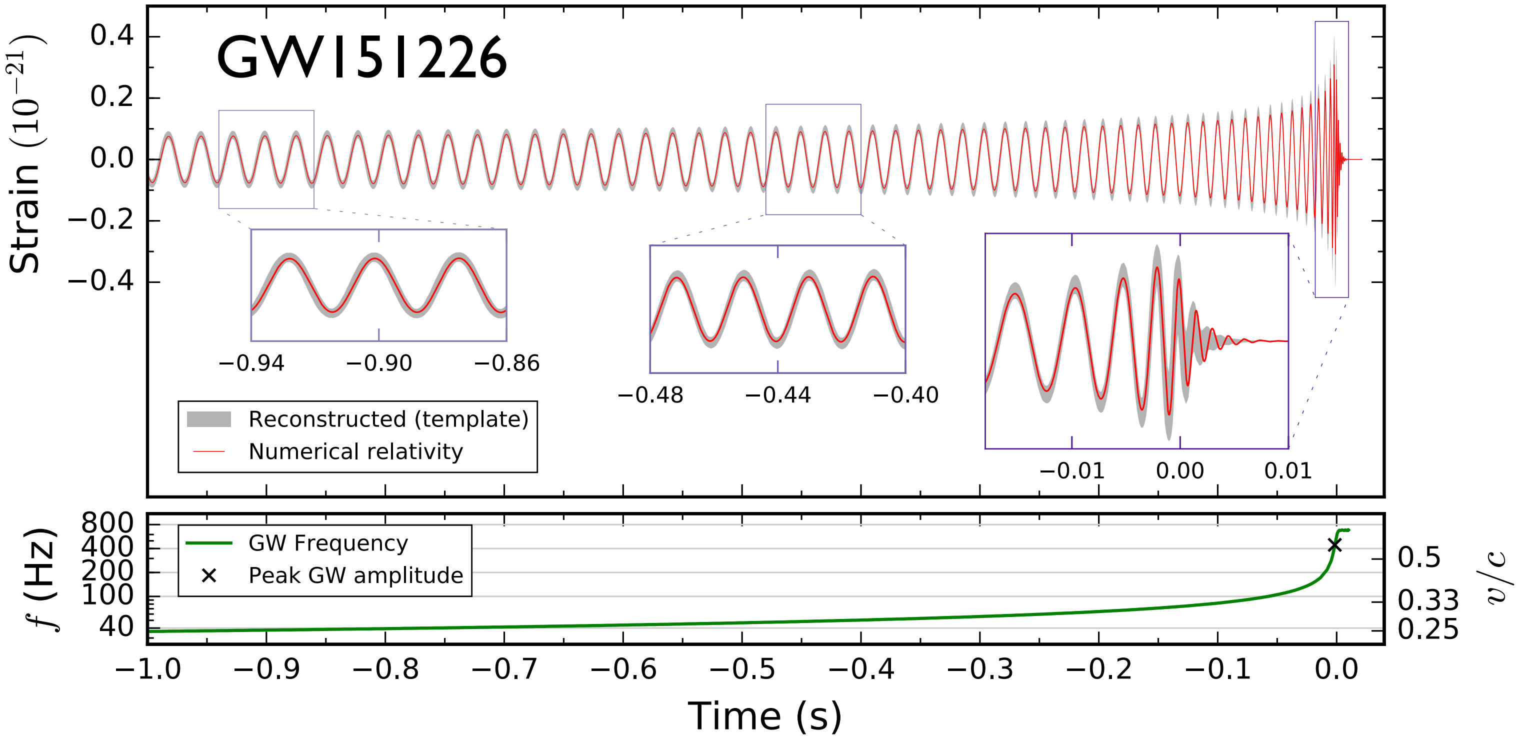
75,000 PN templates for BNSs

325,000 EOBNR templates for BBHs & NSBHs

(visualization credit: Dietrich, Haas @AEI)
(Ossokine, AB & SXS project)



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

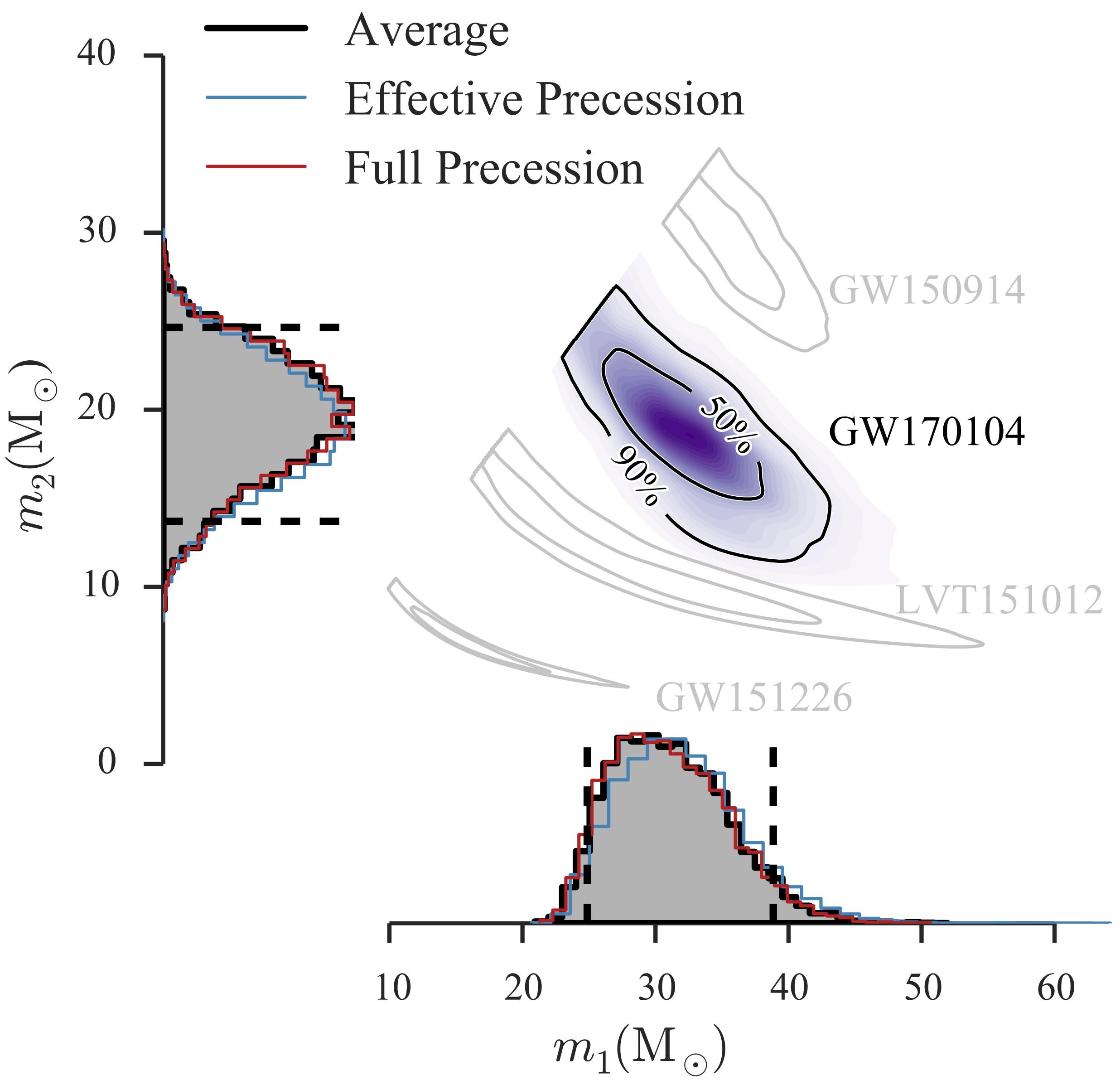


- **Systematics** due to modeling **are smaller than statistical** errors for GW events observed in **O1 & O2 runs**.

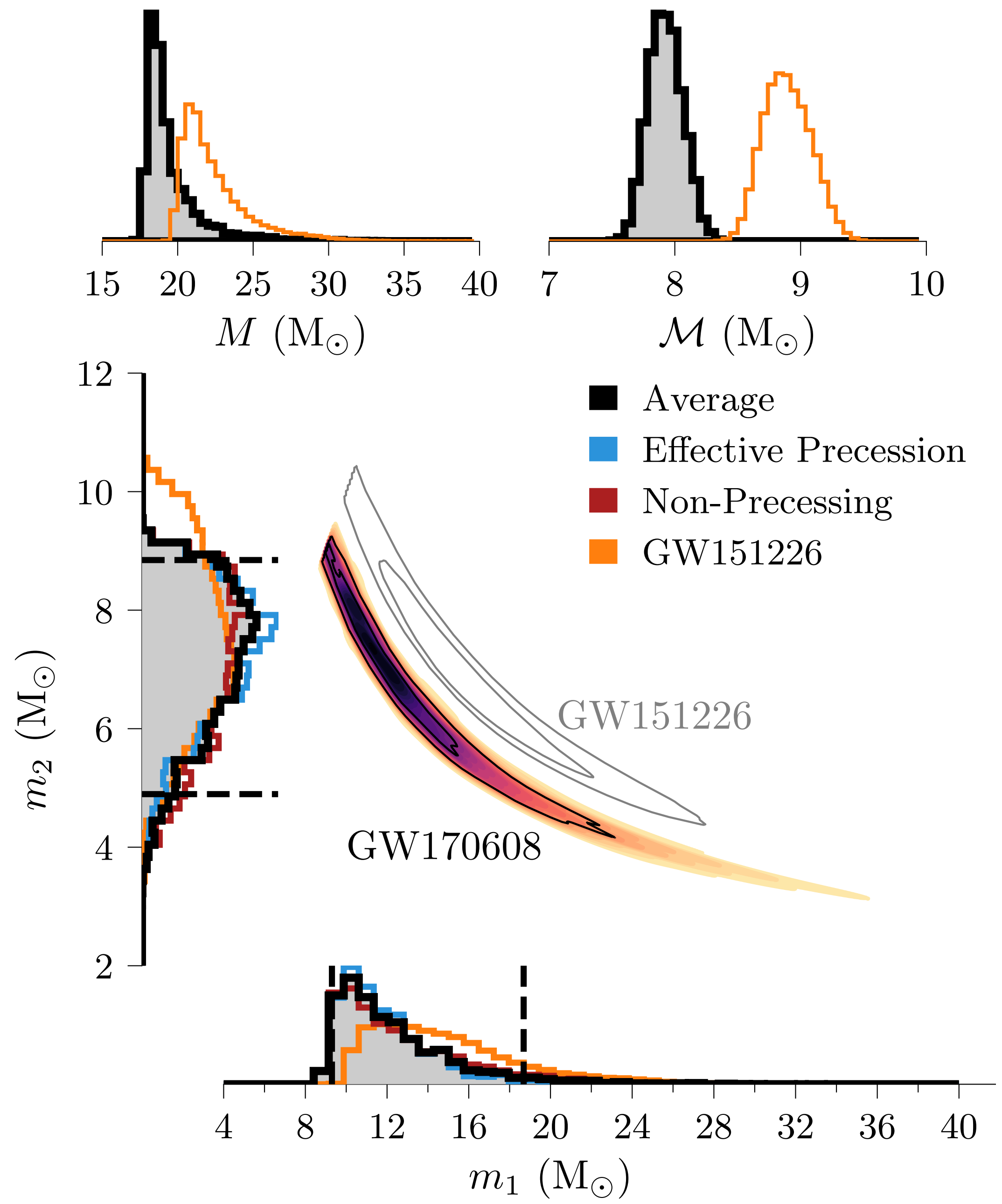
(Abbott et al. CQG 34 (2017) 104002)

Unveiling binary black-hole properties: masses

(Abbott et al. PRL 118 (2017) 221101)



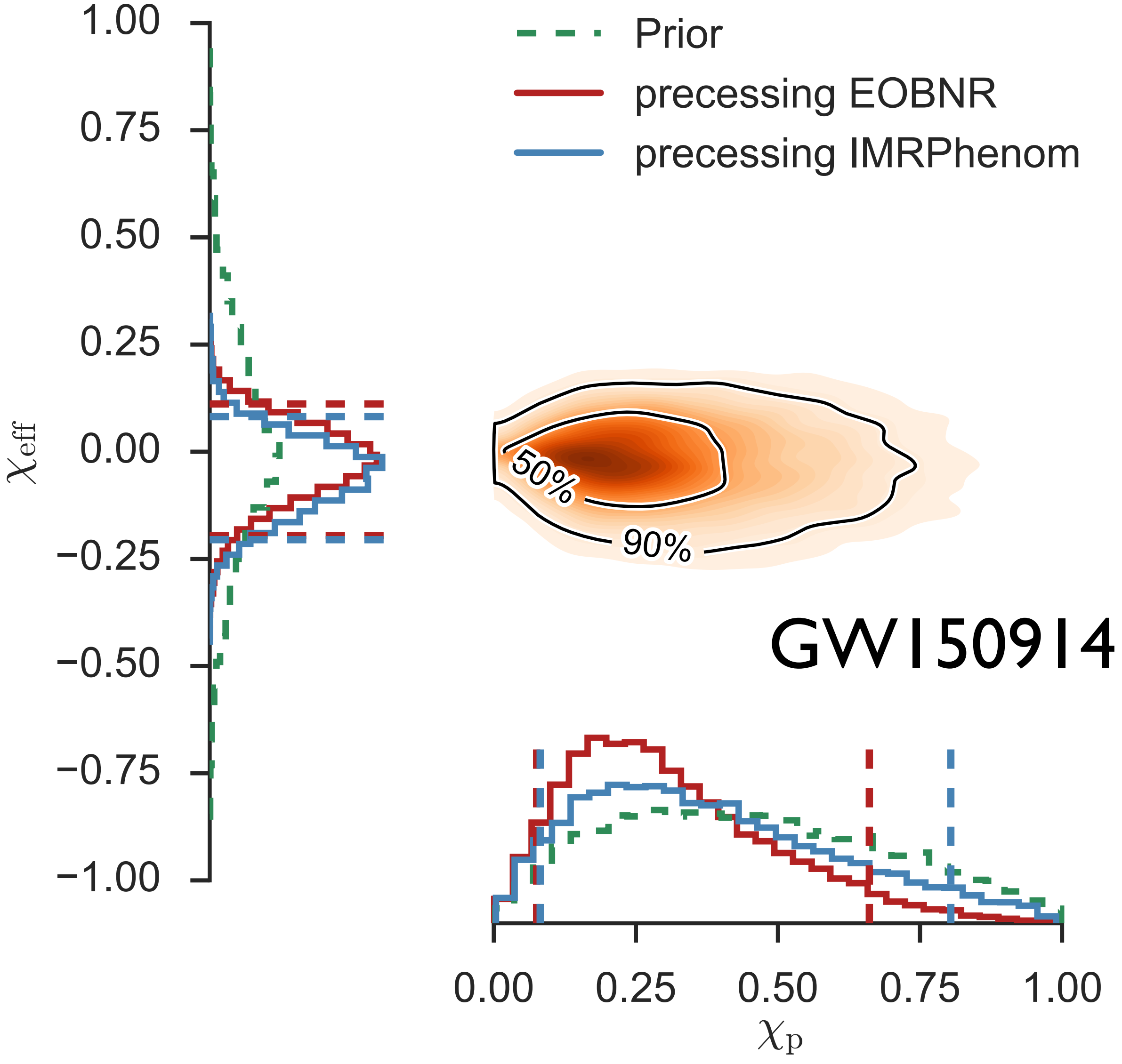
(Abbott et al. ApJ 851 (2017) L35)



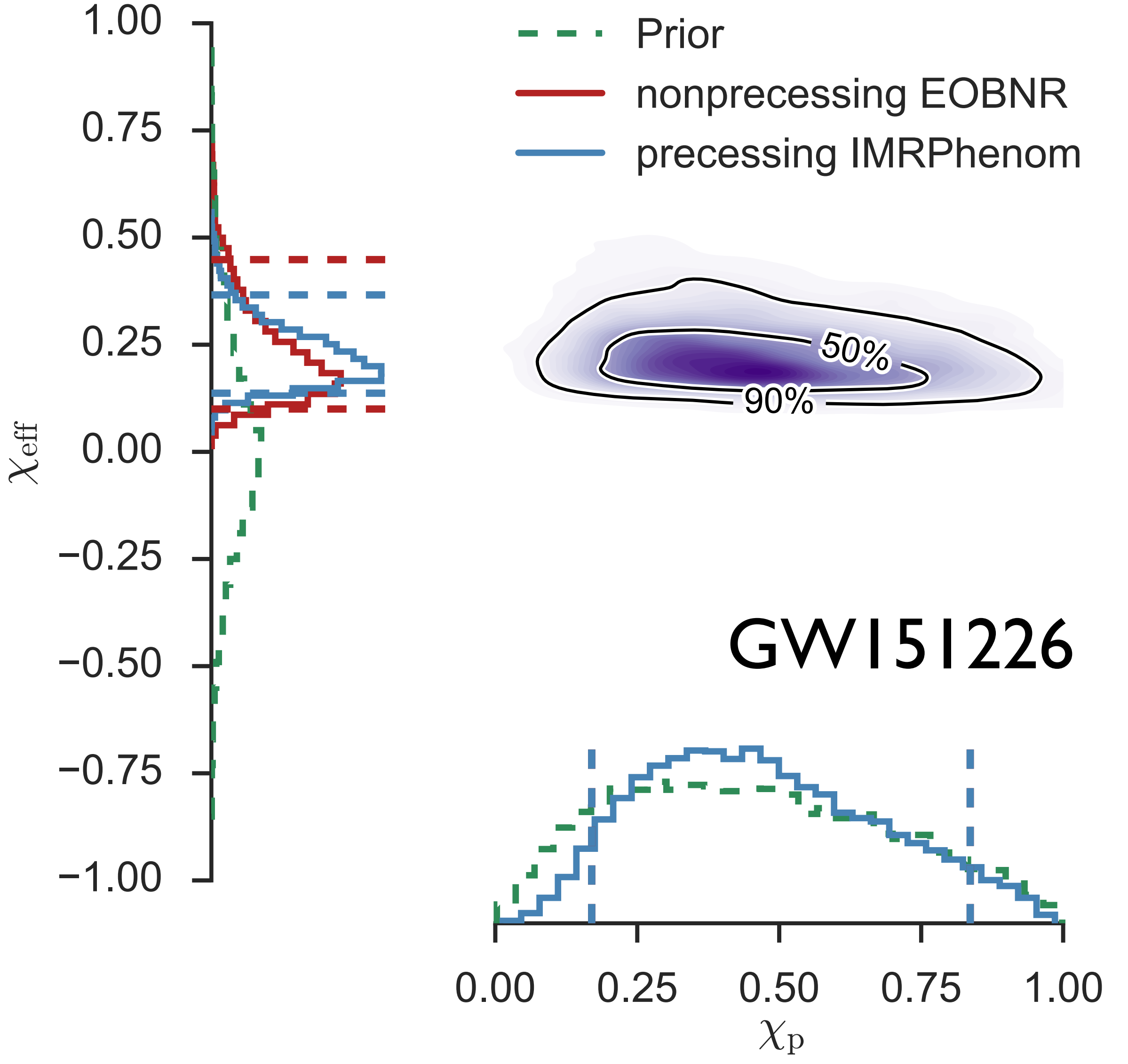
- **Current measurements of masses dominated by statistical error.**

Unveiling binary black-hole properties: spins

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



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

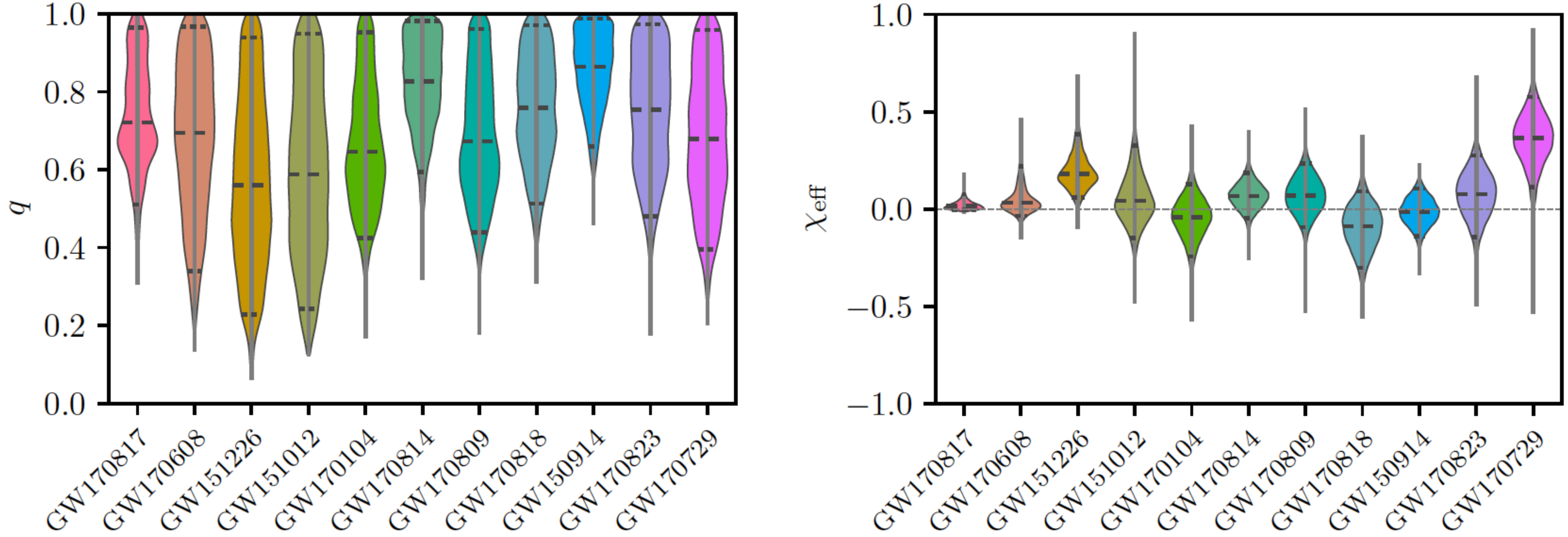


- **Current measurements of masses dominated by statistical error.**

(measurements @ 25Hz)

Unveiling binary black-hole properties: results GWTC-1

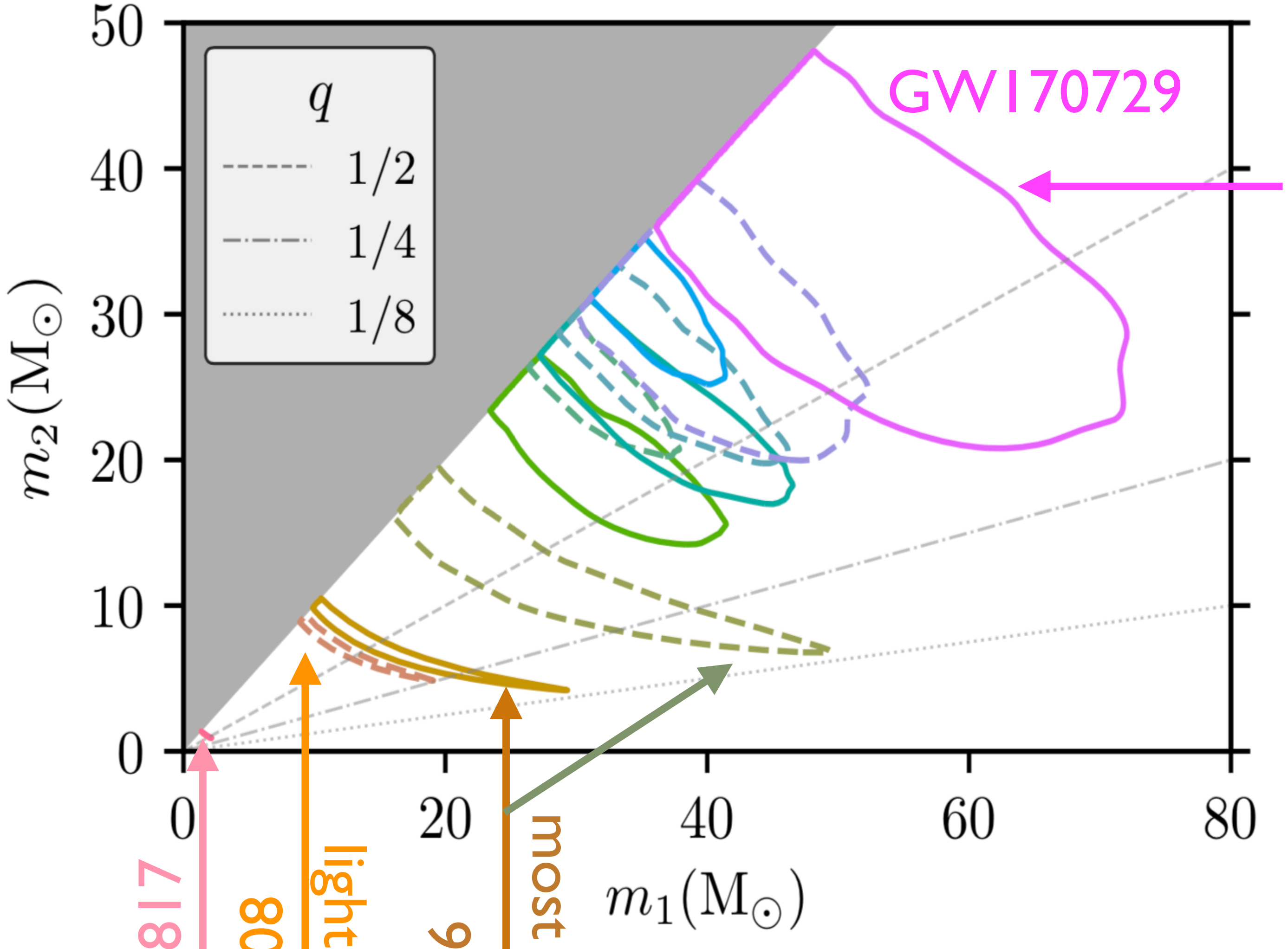
(Abbott et al. arXiv:1811.12907)



- Current **measurements** of masses and spins for GWTC-1 **dominated by statistical instead of modeling** error.
- **Inferences** are obtained combining the **effective (IMRPhenom)** and **full (SEOBNR) spin-precessing** waveform models.

Unveiling binary properties of GWTC-1: masses

(Abbott et al. arXiv:1811.12907)



GW170729

heaviest & most distant BBH

GW170817

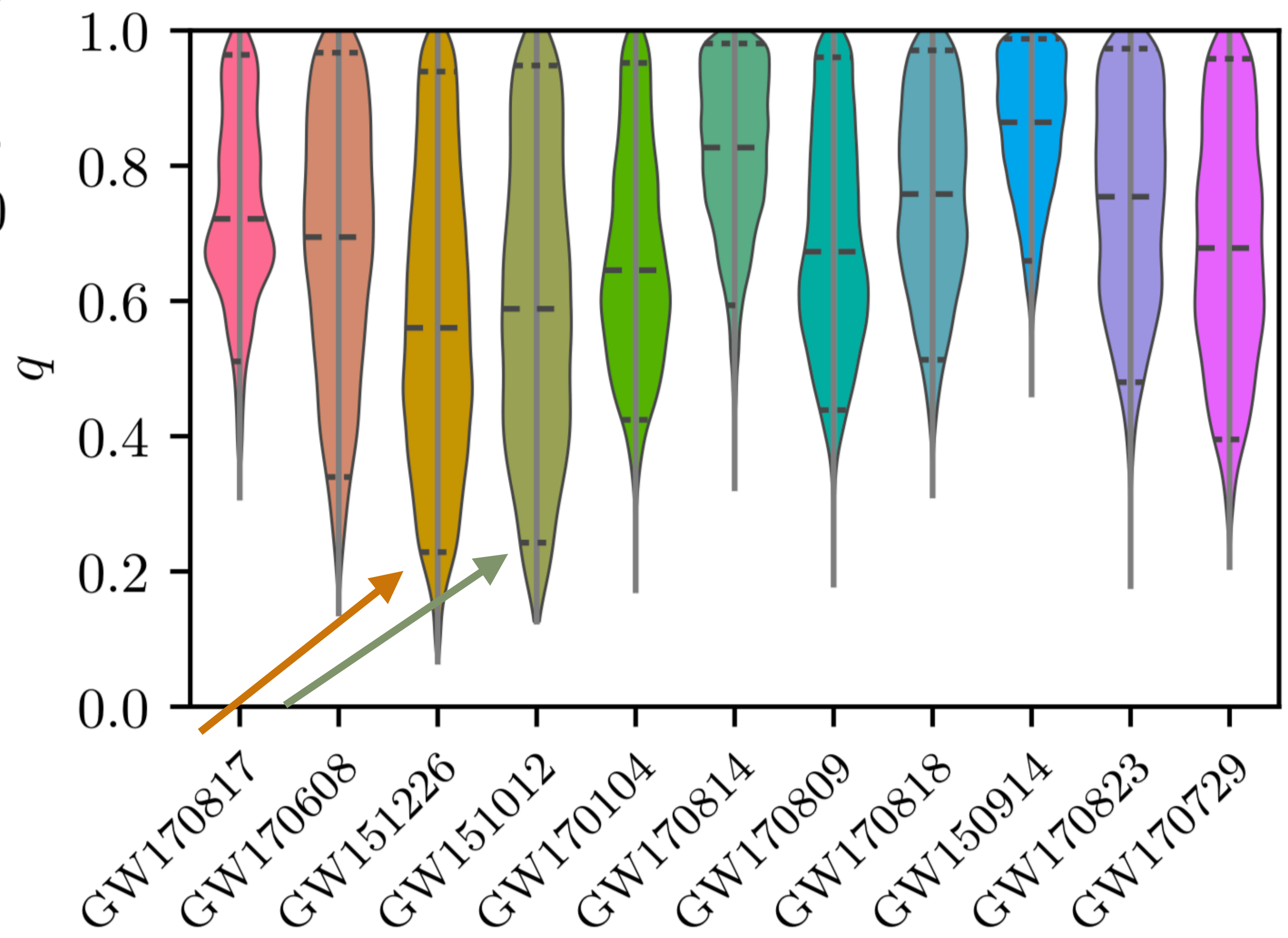
GW170608

lightest & closest

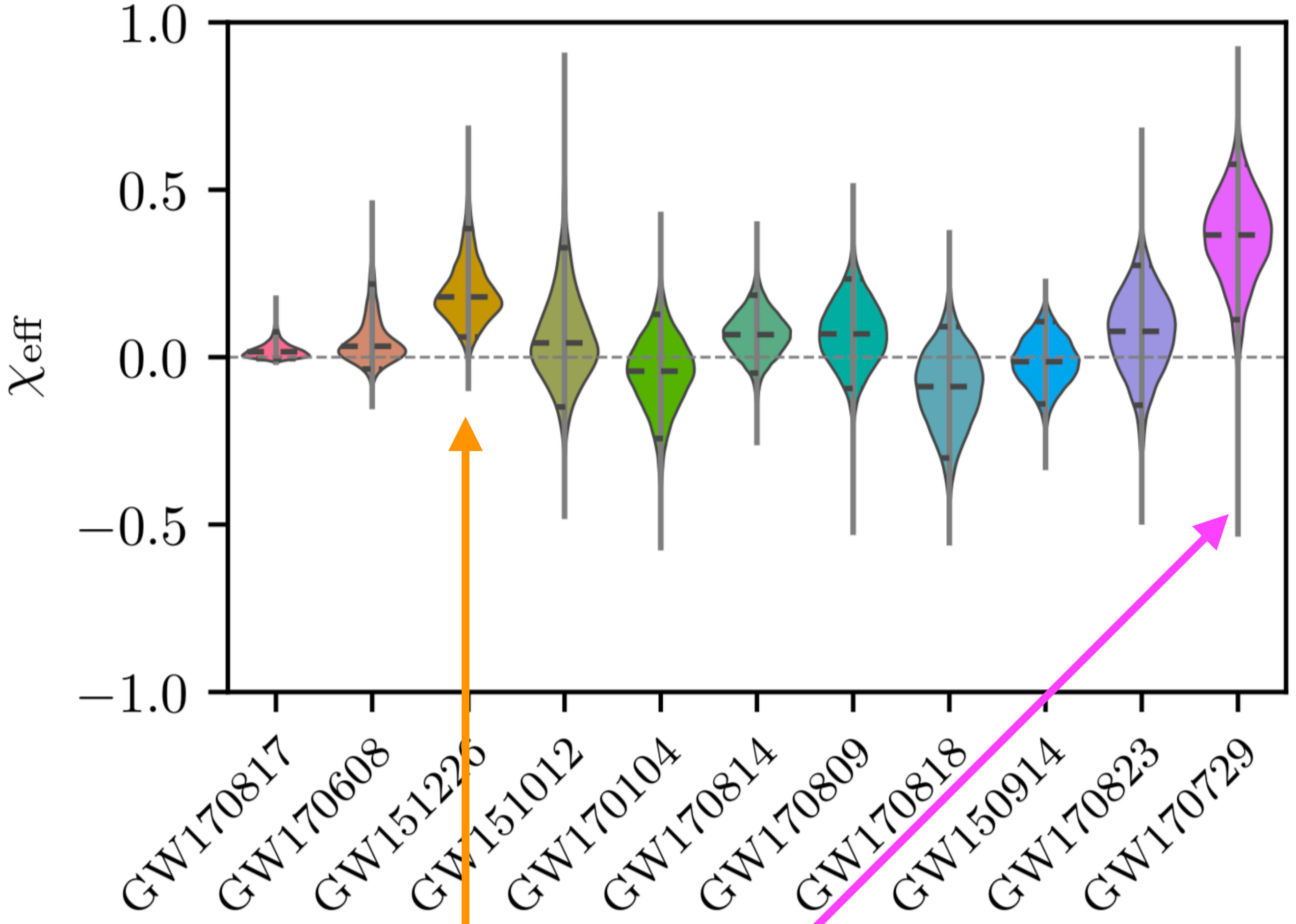
GW151226

most asymmetric

longest GWs
from BBHs



Unveiling binary properties of GWTC-1: spins



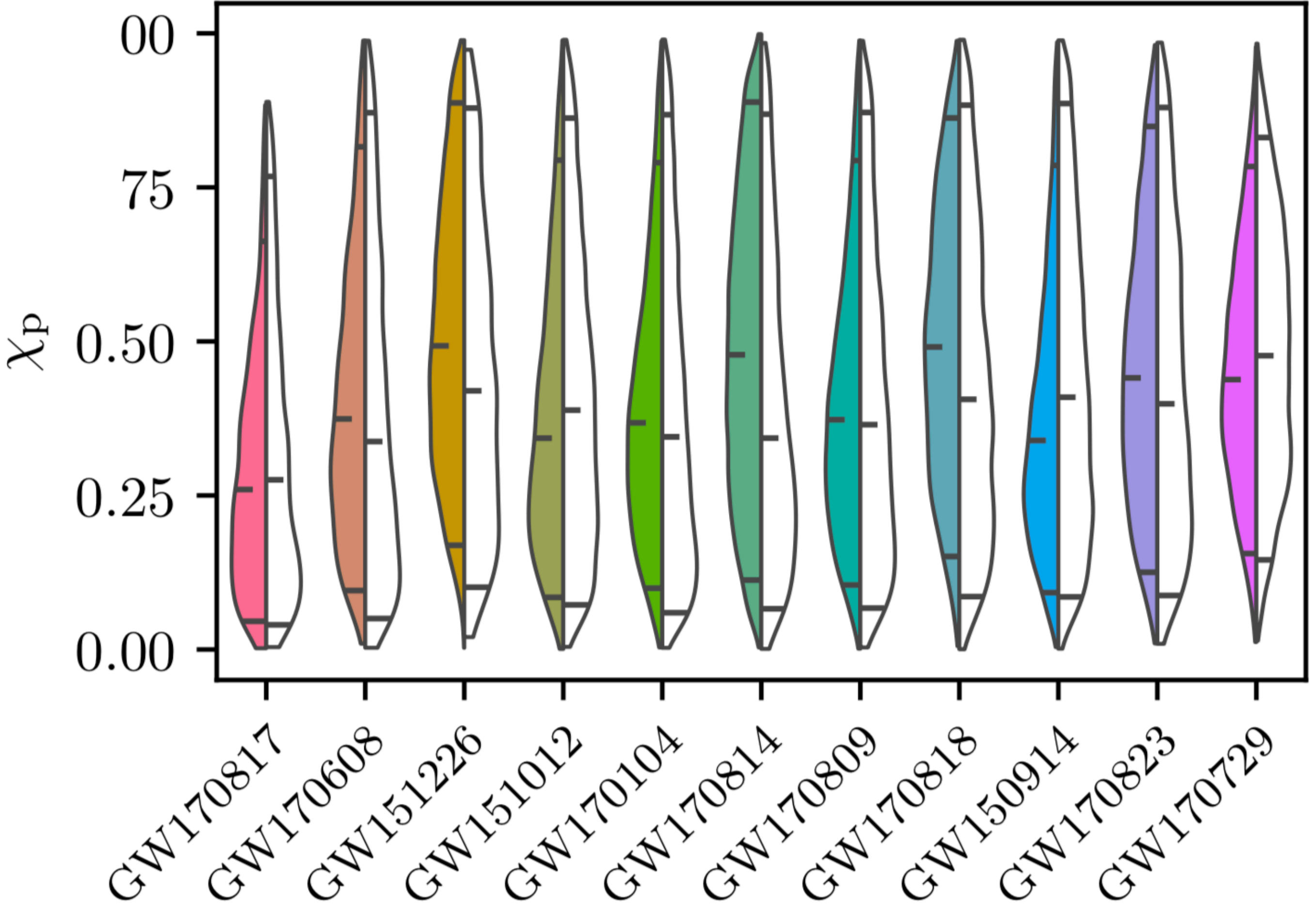
(Abbott et al. arXiv:1811.12907)

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

measures spins perpendicular to orbital plane

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

measures spins on the orbital plane



BH’s spin larger than 0.2 at 99% confidence.

$\chi_{\rm eff} = 0$ excluded at 90%

Robust conclusions:

- **Moderate spins**, say < 0.6.
- **No evidence** for **spin-precession**.

Perturbative deviations from GR: null test

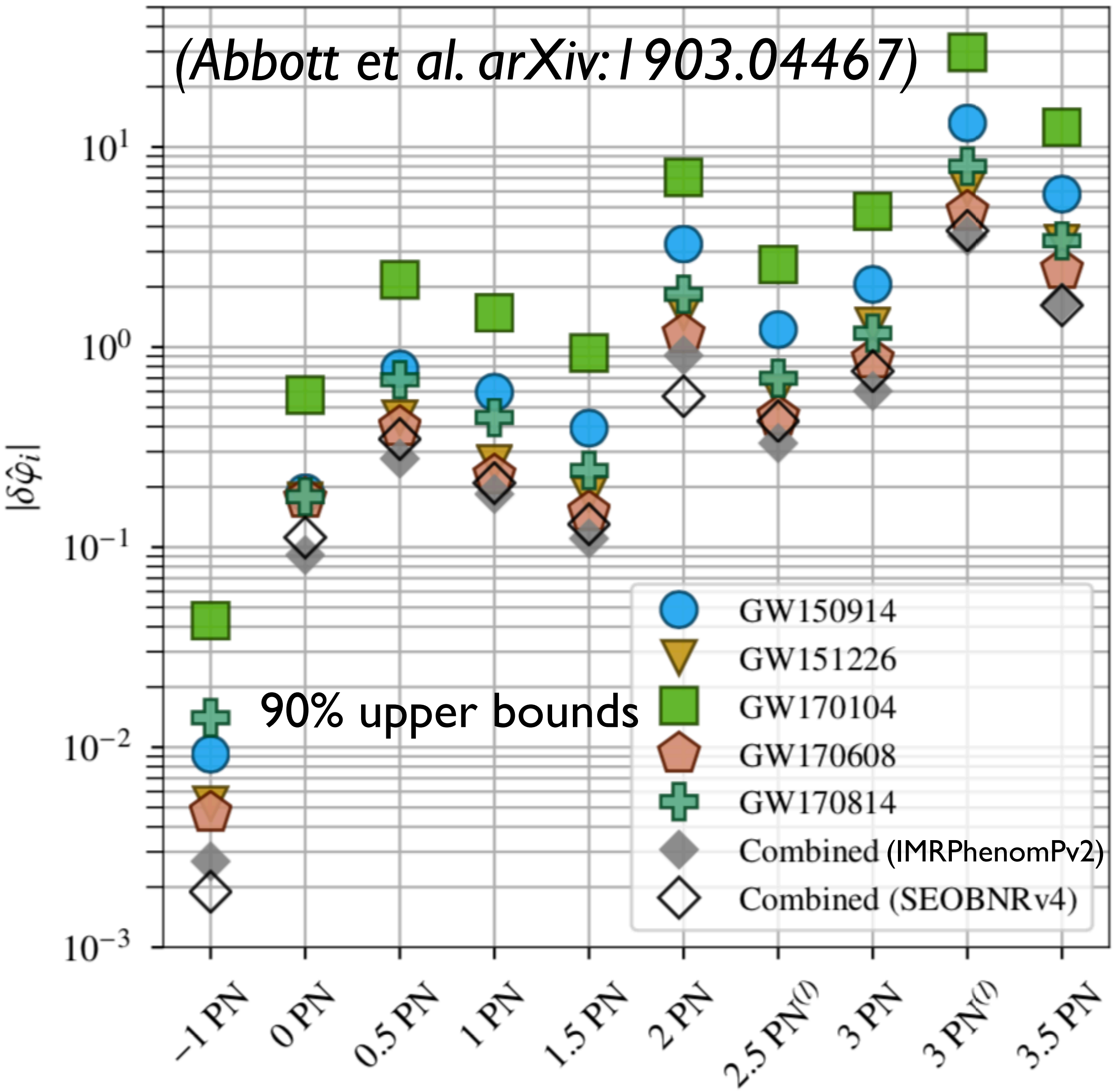
- **Rapidly varying orbital period** of observed GW events allows us to **bound PN coefficients** in gravitational phase.

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

$$v = (\pi M f)^{1/3}$$

$$\varphi(f) = \varphi_{\rm ref} + 2\pi f t_{\rm ref} + v^{-5}\left[\sum_{n=-2}^{7} \varphi_n^{(\rm GR)}(1+\delta\hat{\varphi}_n)v^n + \sum_{n=5}^{6} \varphi_{n\,\ell}^{(\rm GR)}(1+\delta\hat{\varphi}_{n\,\ell})v^n \log v\right]$$

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


(Abbott et al. arXiv:1903.04467)

90% upper bounds

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

- **PN parameters** take **different values** in **modified theories** to GR.

Bounding PN parameters: binary neutron star

- **Constraint** on time-varying **dipole moment**

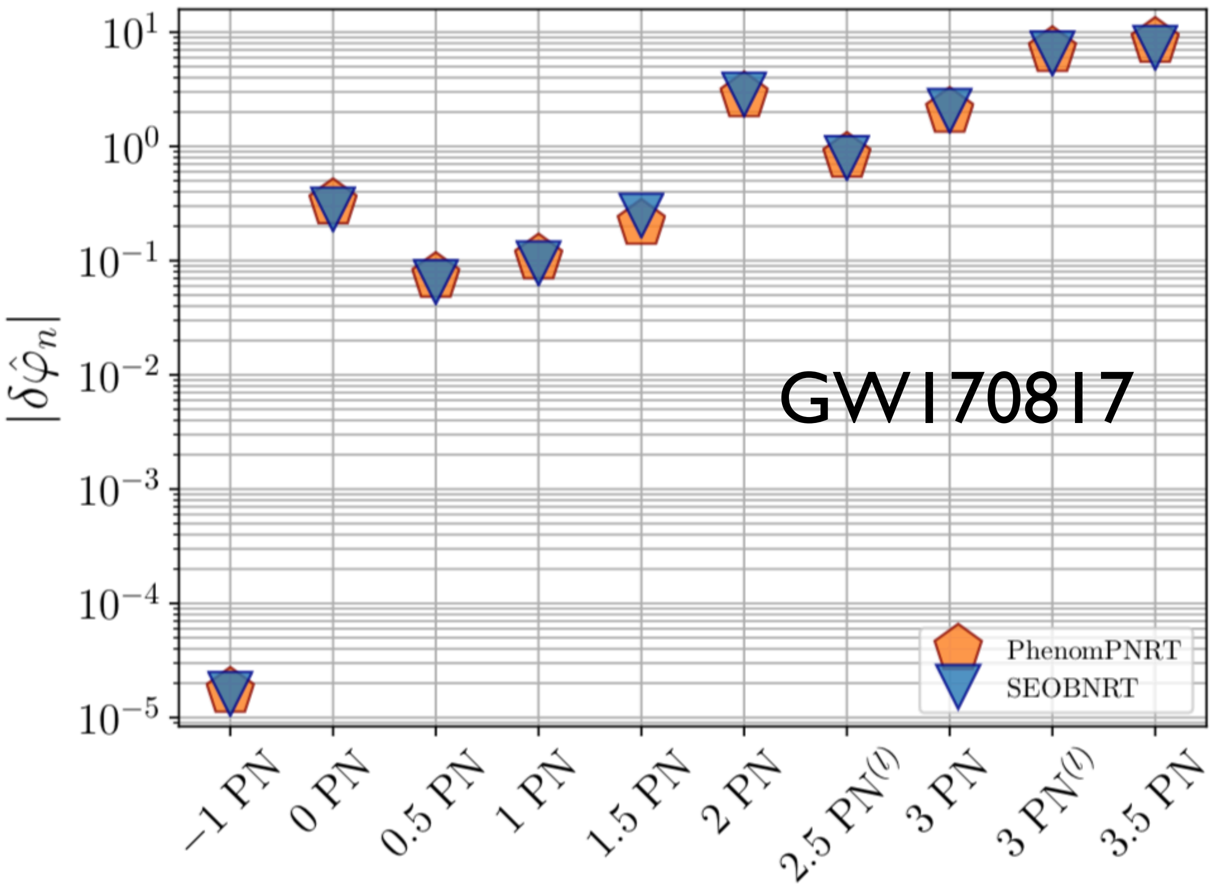
$$\mathcal{F}_{\rm GW} = \mathcal{F}_{\rm GR}\left(1 + B/v^2\right)$$

$$\delta\hat{\varphi}_{-2} = -4B/7 \qquad B \leq 1.2\times10^{-5}$$

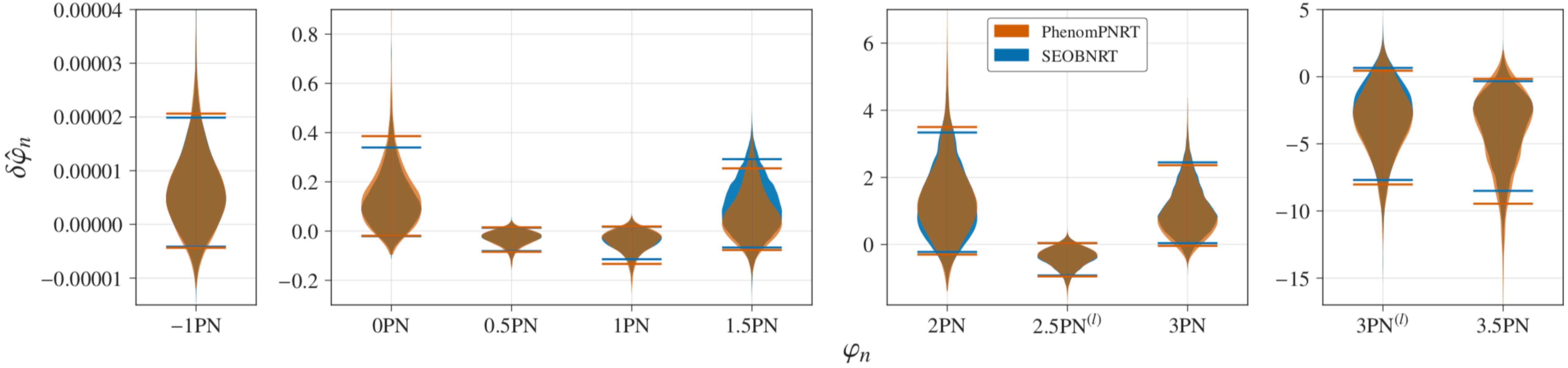
- Constraint from **binary pulsars**

$$|B| \leq 6\times10^{-8}$$

(Abbott et al. arXiv:1811.00364)



low frequency → 1 GW BNS → high frequency

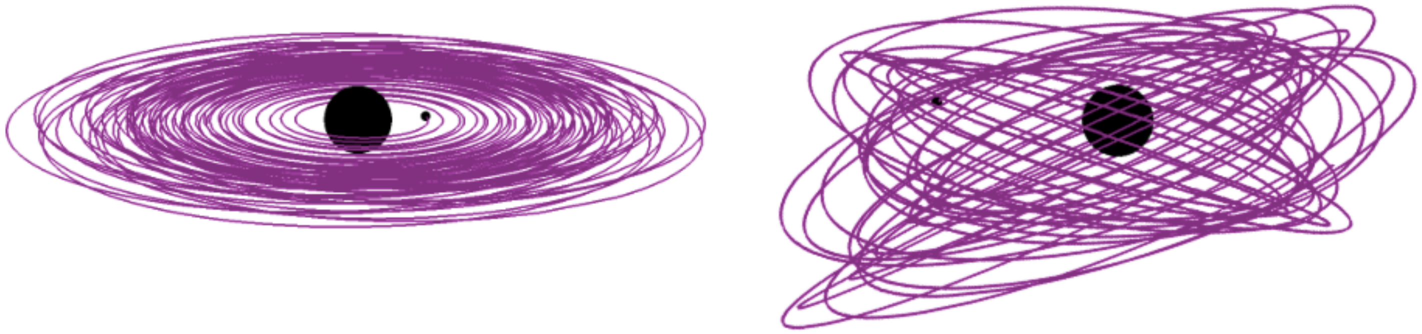


Inferring best science by including more physical effects

- How to **discriminate** among binary's **formation scenarios**, and **probe astrophysical environment**? ***Eccentricity*** and **spin-precession can disclose this information.**

- **Eccentric** compact-object **binary:**

NR simulation

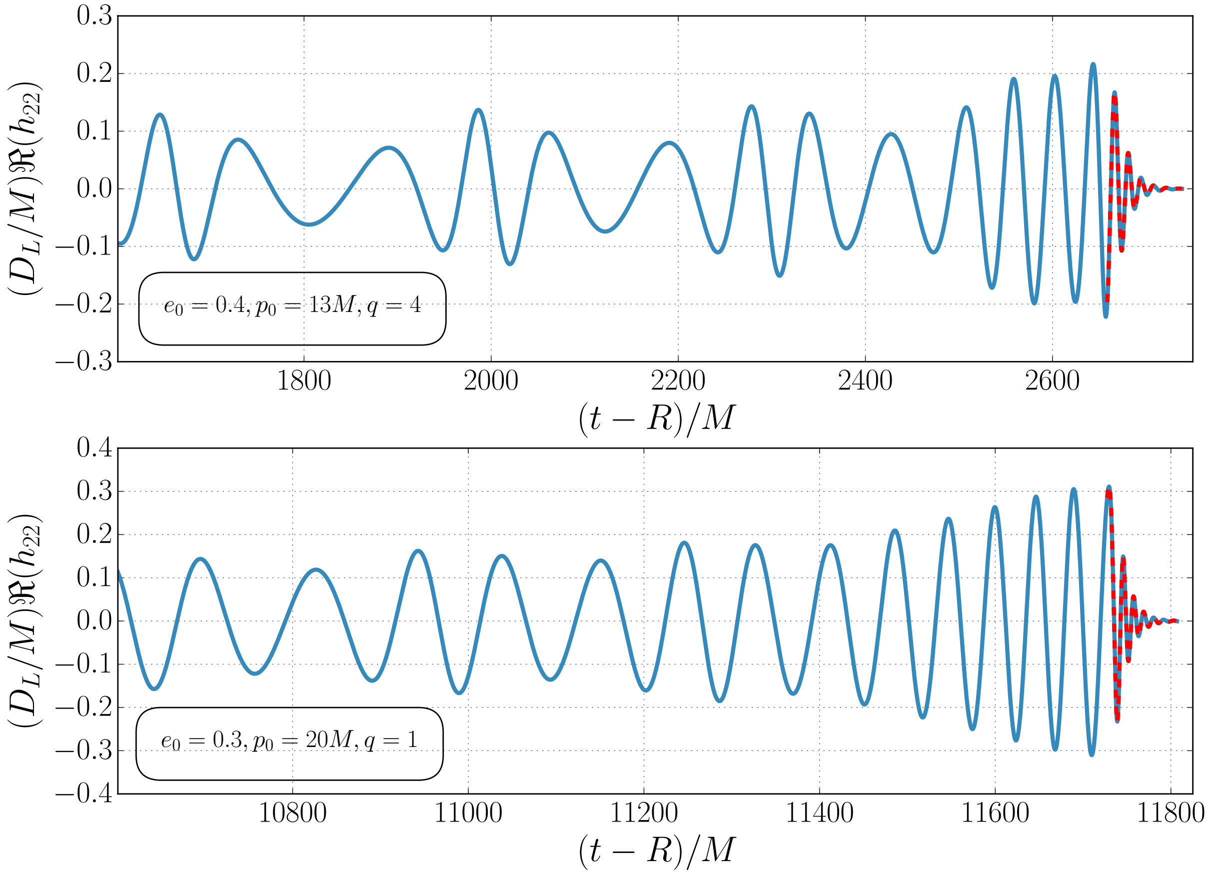


mass ratio = 7

(Lewis et al. 16)

(extensive PN work; East et al. 13, Huerta et al. 14, 16, 18, Hinder et al. 17, Loutrel & Yunes 16, 17, Huerta et al. 19, Ireland et al. 19, Moore & Yunes 19)

EOB waveform model



(Hinderer & Babak 17)

- **Current eccentric** waveform models **do not cover main physical effects** (e.g., spins and harmonics) **and all stages** of coalescence.

Waveforms for eBBHs combining analytical & numerical relativity

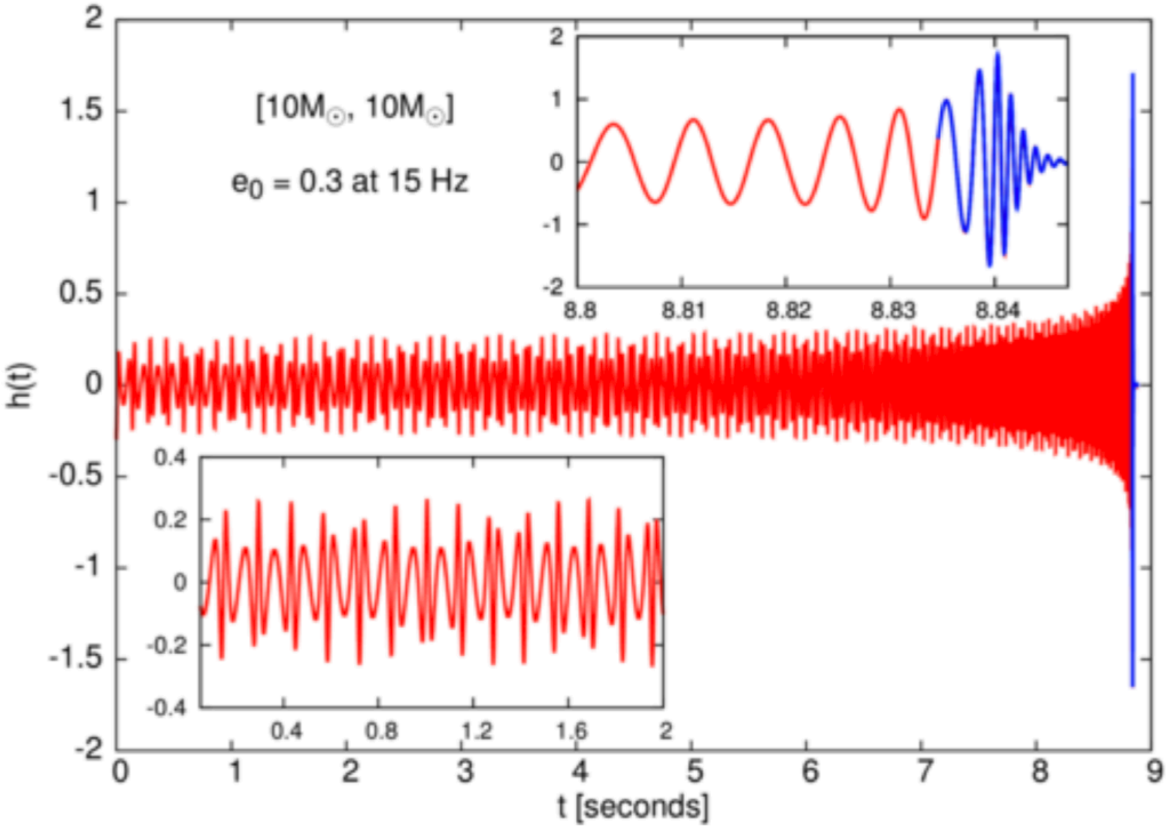
---

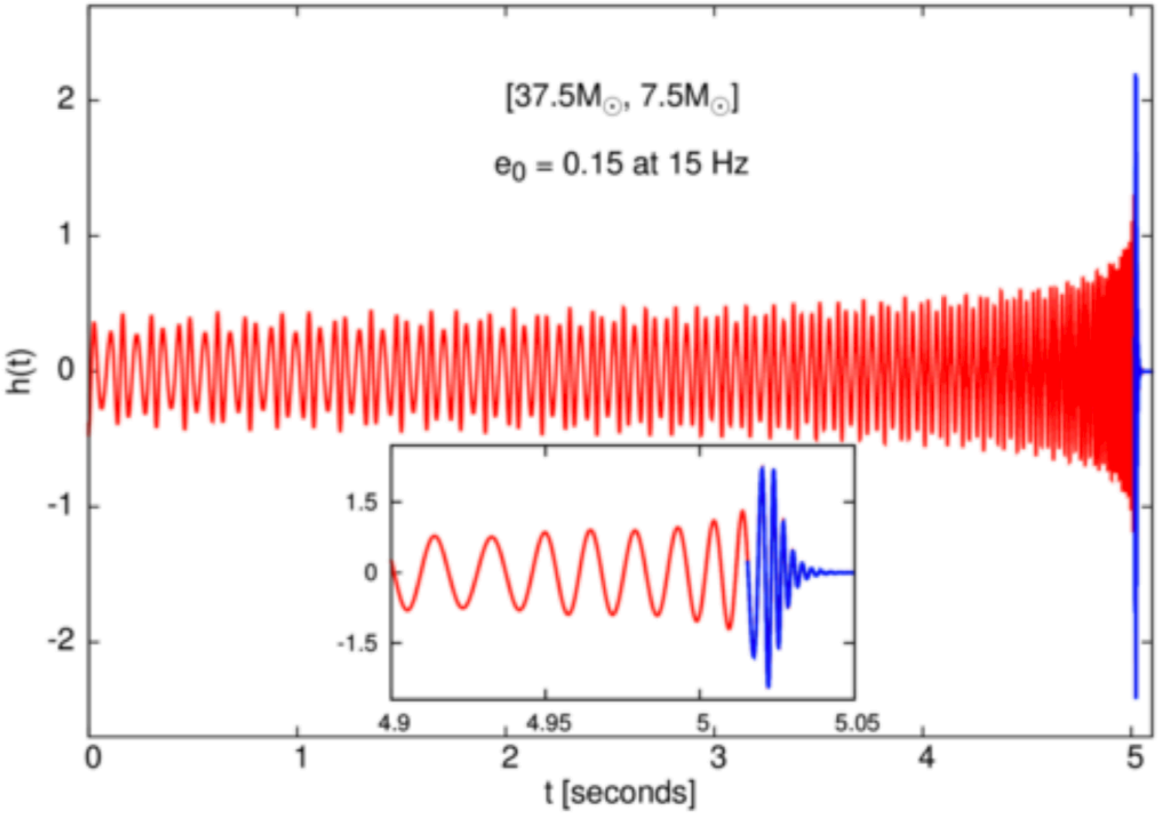
(Huerta et al. 16, see also Hinder et al. 17)

- For **mild eccentricity, plunge-merger signal** almost **identical** to **quasi-circular** orbit one.

- Combine **inspiral** dynamics **with eccentricity** (PN, EOB, etc.) **with plunge-merger-ringdown non-eccentric** waveform ("IRS" model tuned to NR and EOBNR).

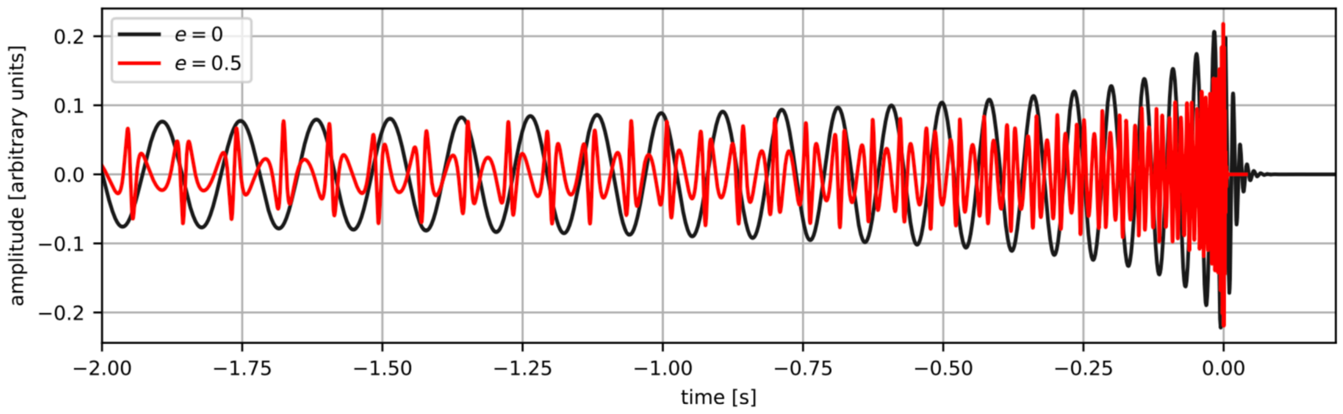
- **Non-spinning** eccentric model.



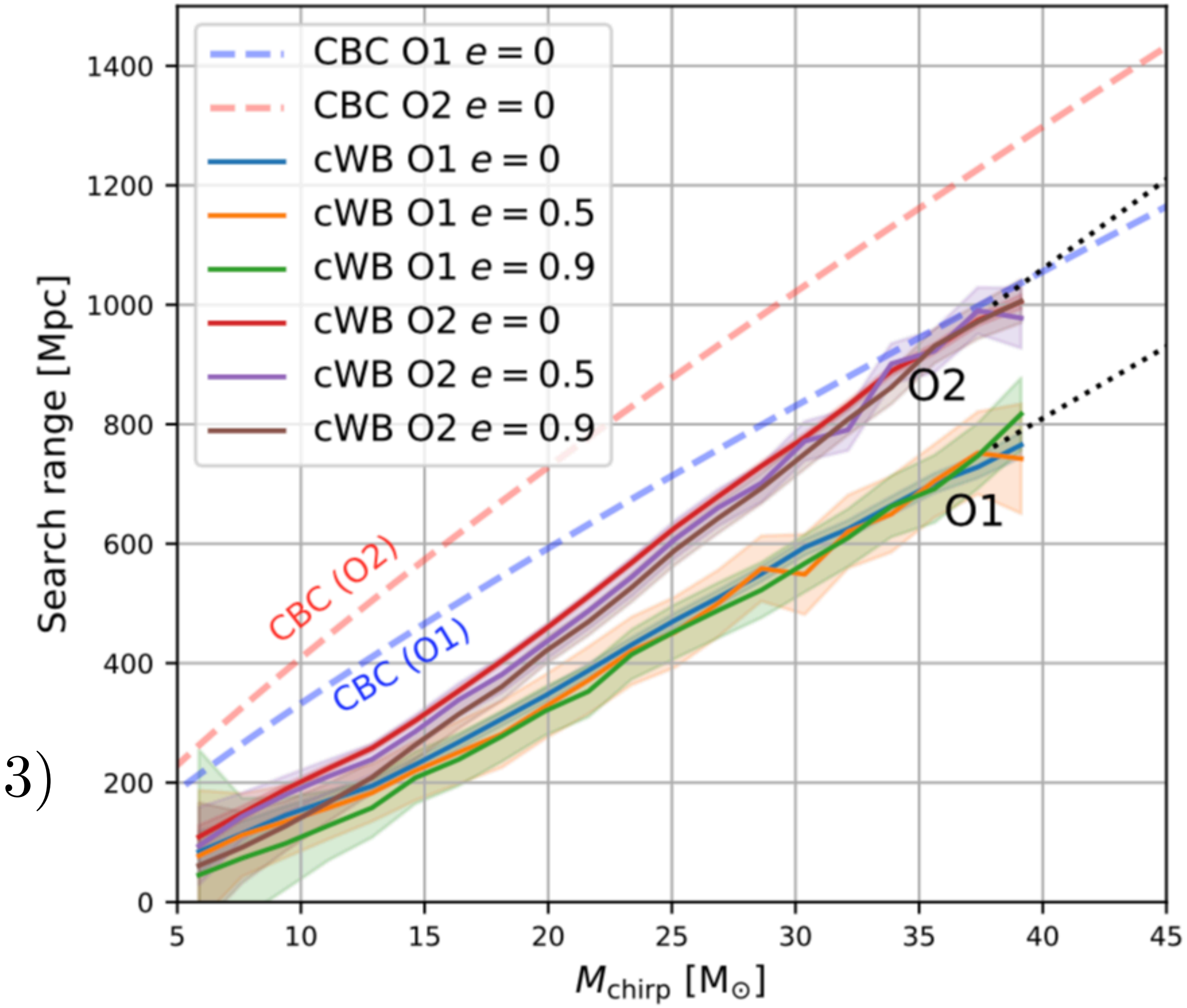


Search of eccentric BBHs in O1 & O2

(Abbott et al. arXiv:1907.09384)



- **Minimal assumption search** (coherent Wave Burst). Sensitivity **independent** on eccentricity.
- **No detection**. Upper limit on rates of eccentric BBHs.



- BHs assumed to have **zero spin**.

  (East et al. 13)
- BBH **population**:

$$m_1, m_2 \in (5M_\odot, 50M_\odot)$$

$$P(m_1) \propto m_1^{-\beta} \quad \text{uniform in } m_2$$

$$VT(\beta) \sim (10^{-1}, 10^{-1.5}, 10^{-2})\mathrm{Gpc}^3\mathrm{yr} \text{ for } \beta = (1,2,3)$$

- **Upper limit** at 90%:

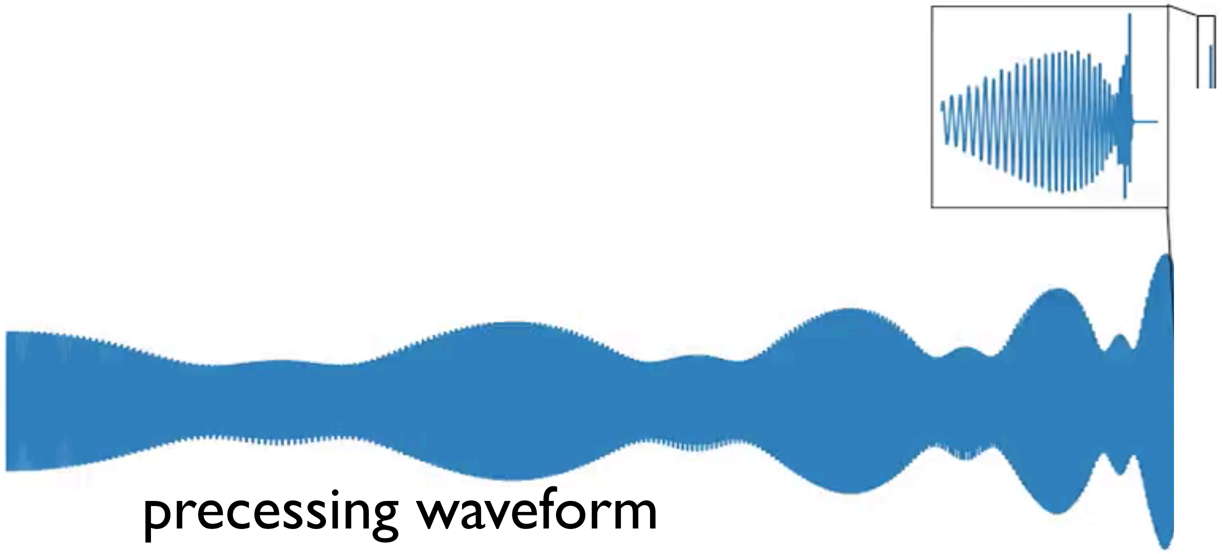
$$(30, 90, 300)\mathrm{Gpc}^{-3}\mathrm{yr}^{-1} \text{ for } \beta = (1,2,3)$$

Characteristics of spin-precessing dynamics and waveform

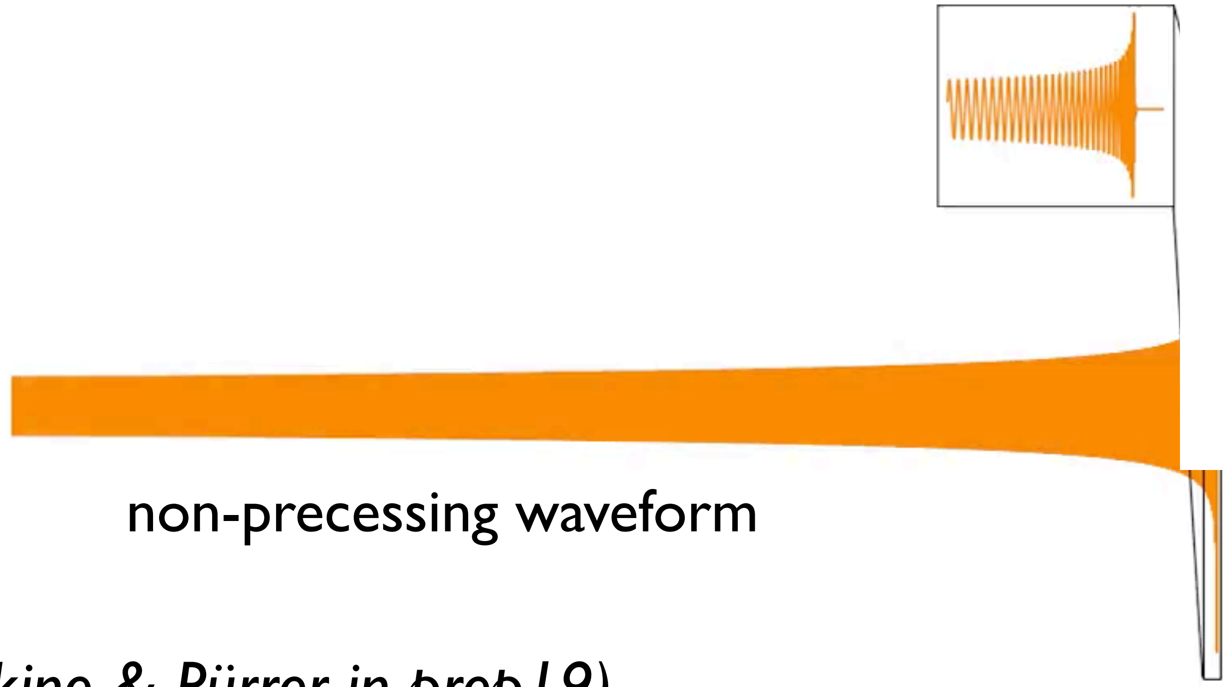
(credit: *Ossokine*)

total mass = **29 Msun**
mass ratio = **5**

574 GW cycles, from 10 Hz
5 precessional cycles
40 sec duration

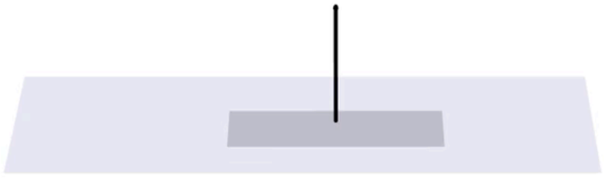


precessing waveform



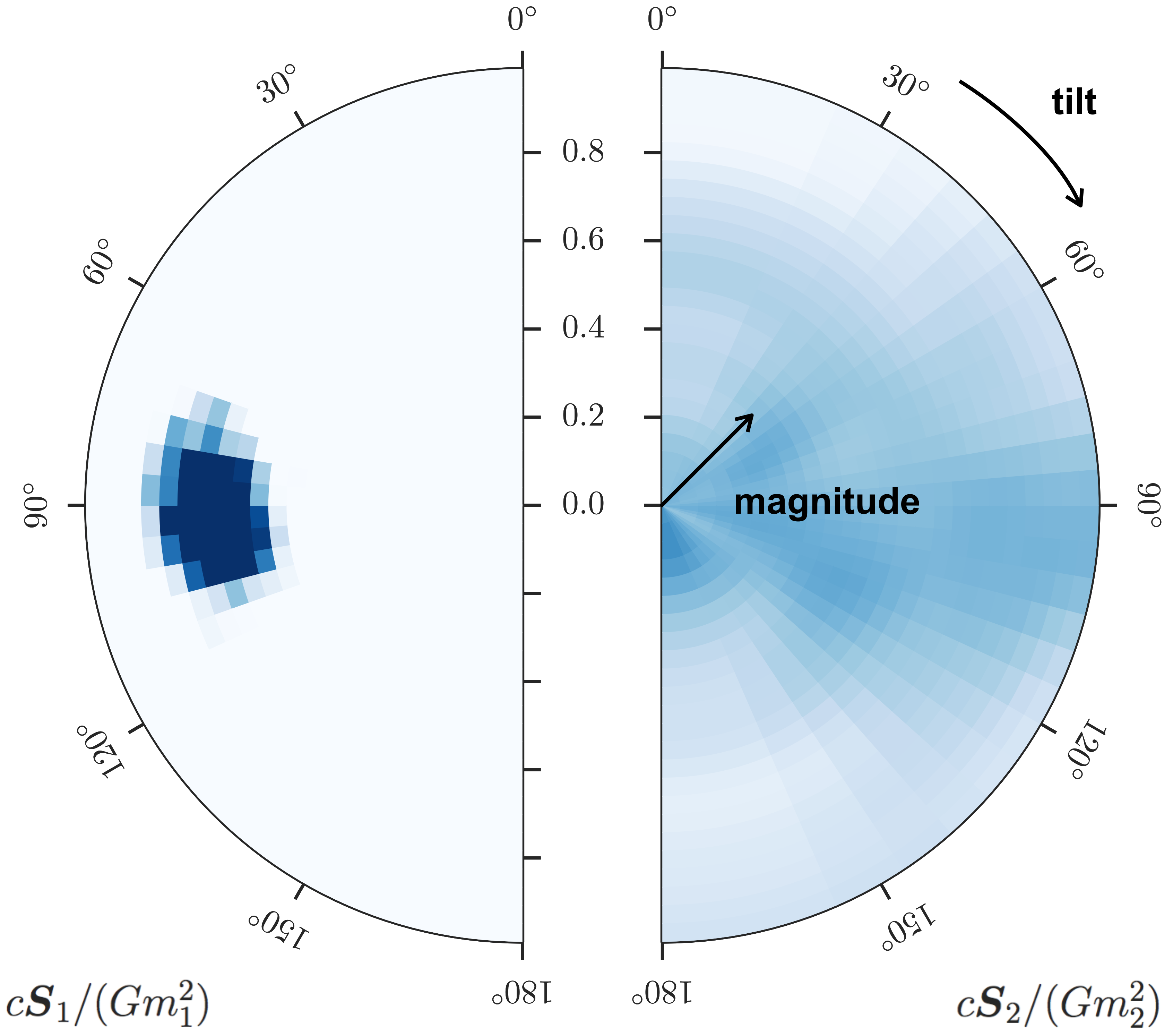
non-precessing waveform

(Ossokine & Pürrer in prep19)



binary orbital plane

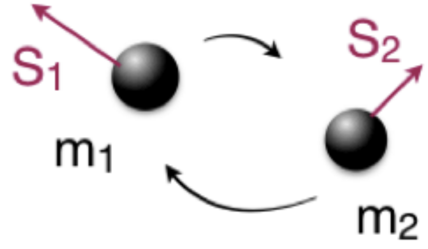
Measuring spin-precession from collision of BHs



SNR ~ 25
aLIGO/Virgo

(credit: *Pürrer*)

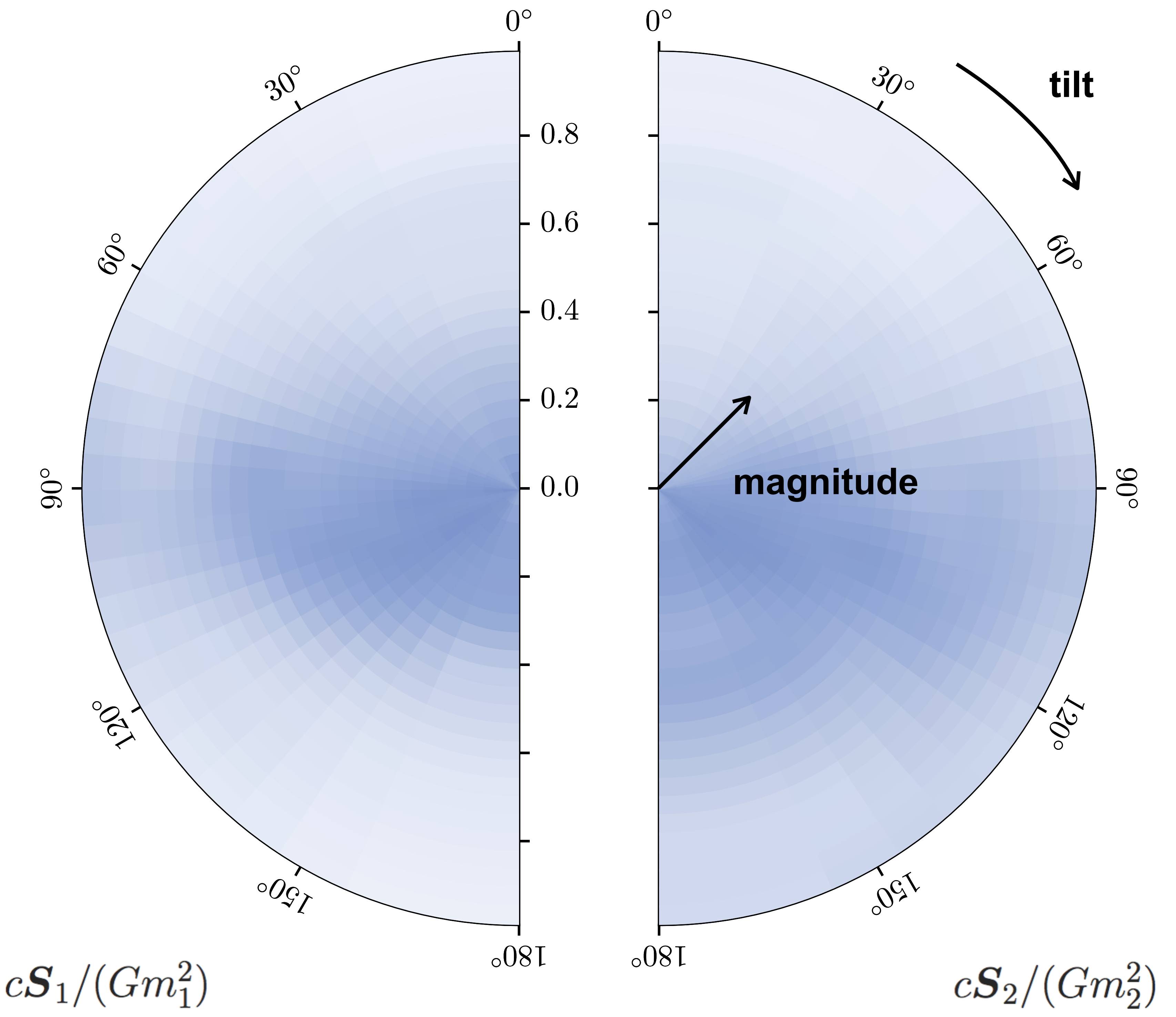
(Ossokine & Pürrer in prep19)



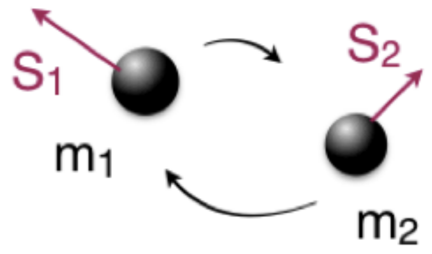
(credit: Hinderer)

Measuring spin-precession with GW150914

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

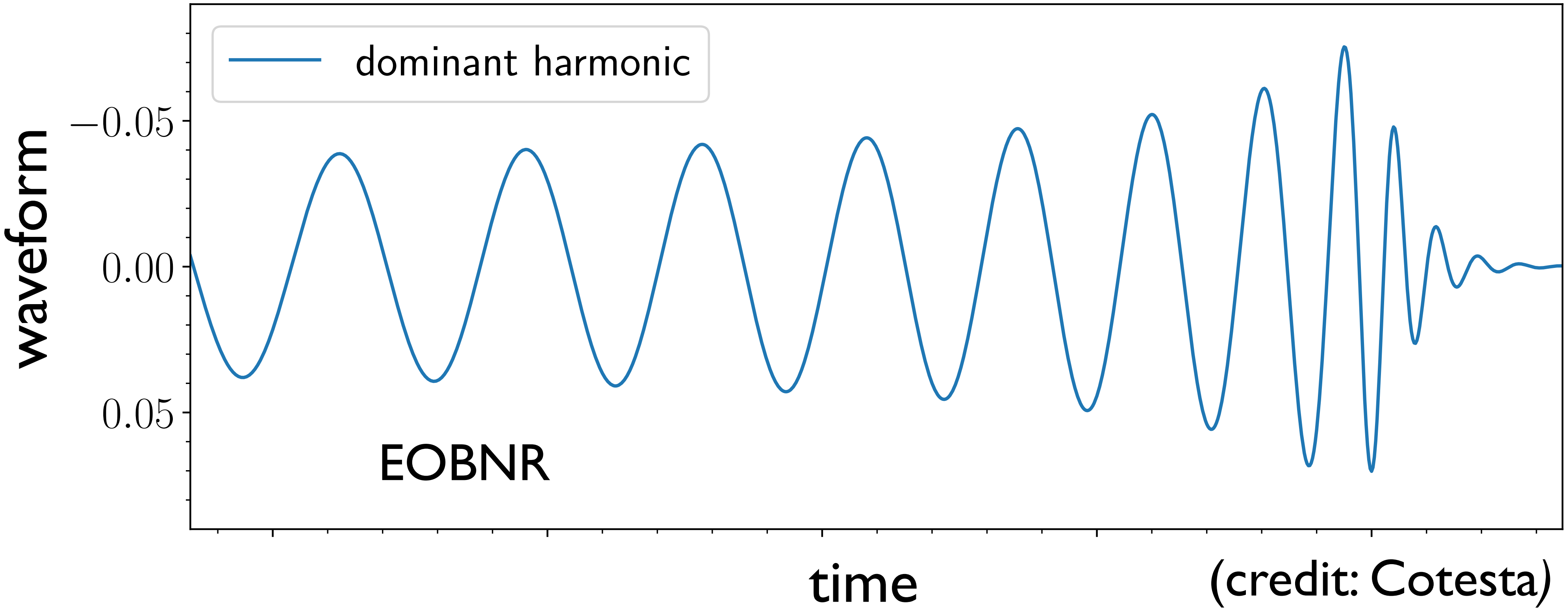


(credit: *Pürrer/LIGO/Virgo*)

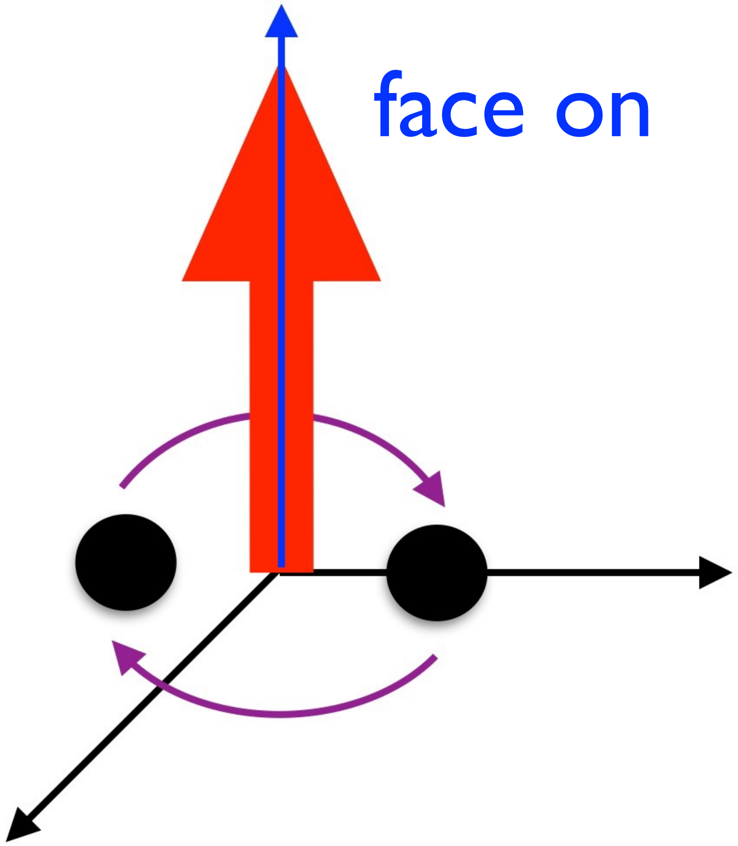


(credit: Hinderer)

Enriching the GW symphony by tuning higher harmonics



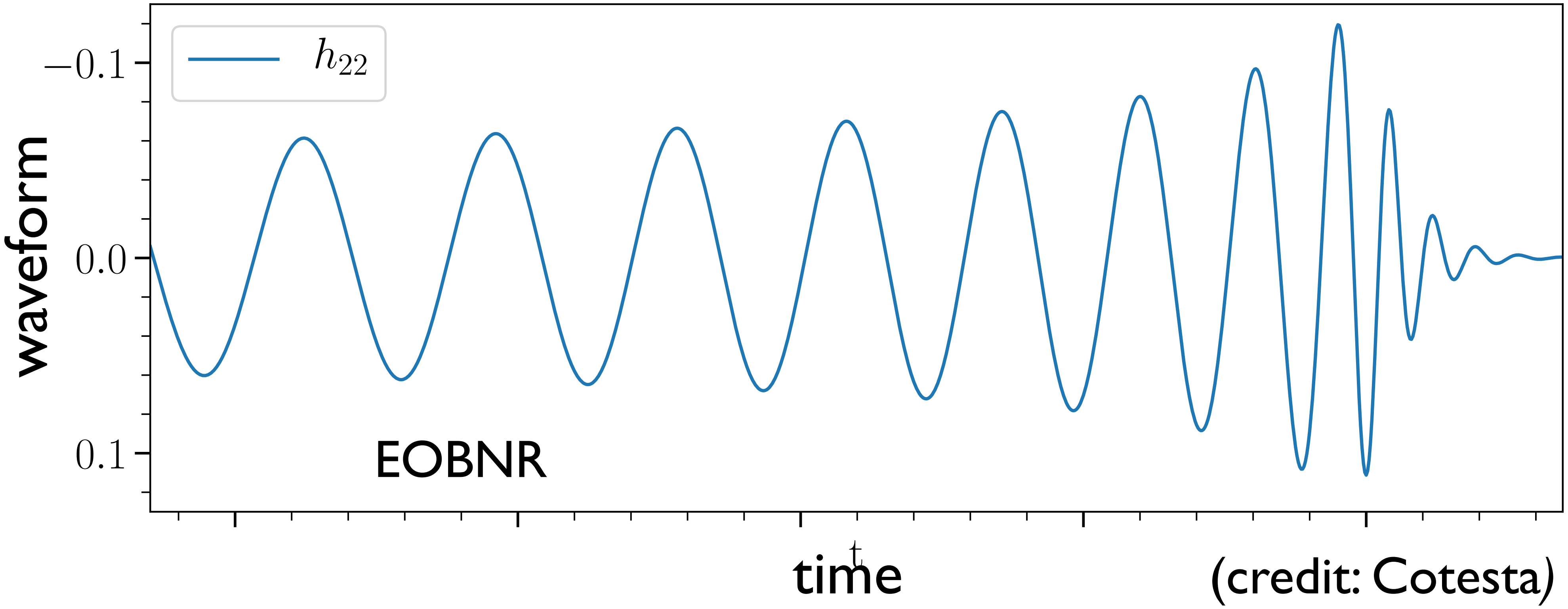
(credit: Cotesta)



- So far, LIGO/Virgo **observed** GW **events mostly face-on/face-off.**
- **Face-on/face-off orientation** suppress **higher harmonics.**

Enriching the GW symphony by tuning higher harmonics (contd.)

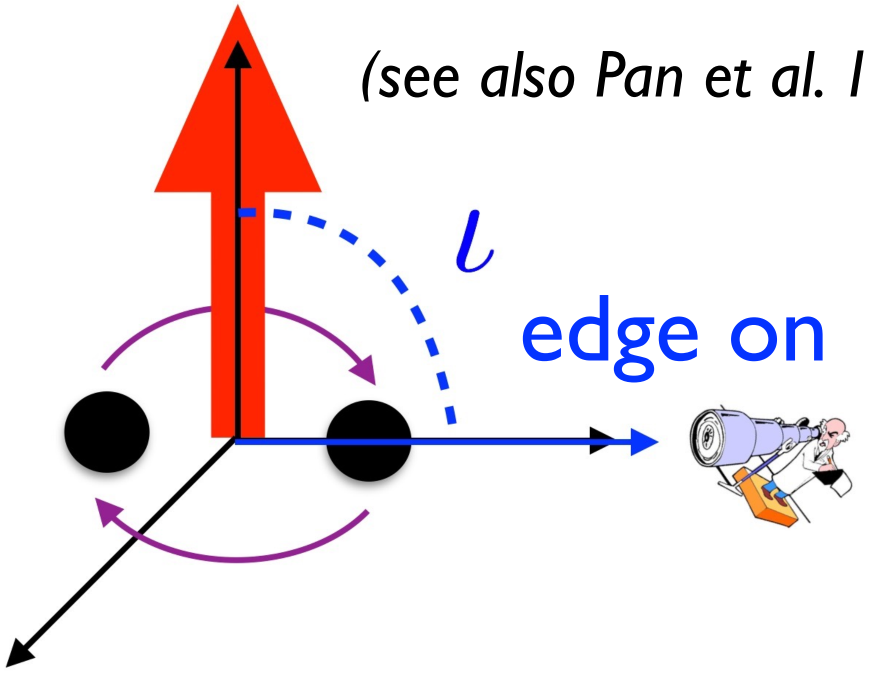
fundamental harmonic



(credit: Cotesta)

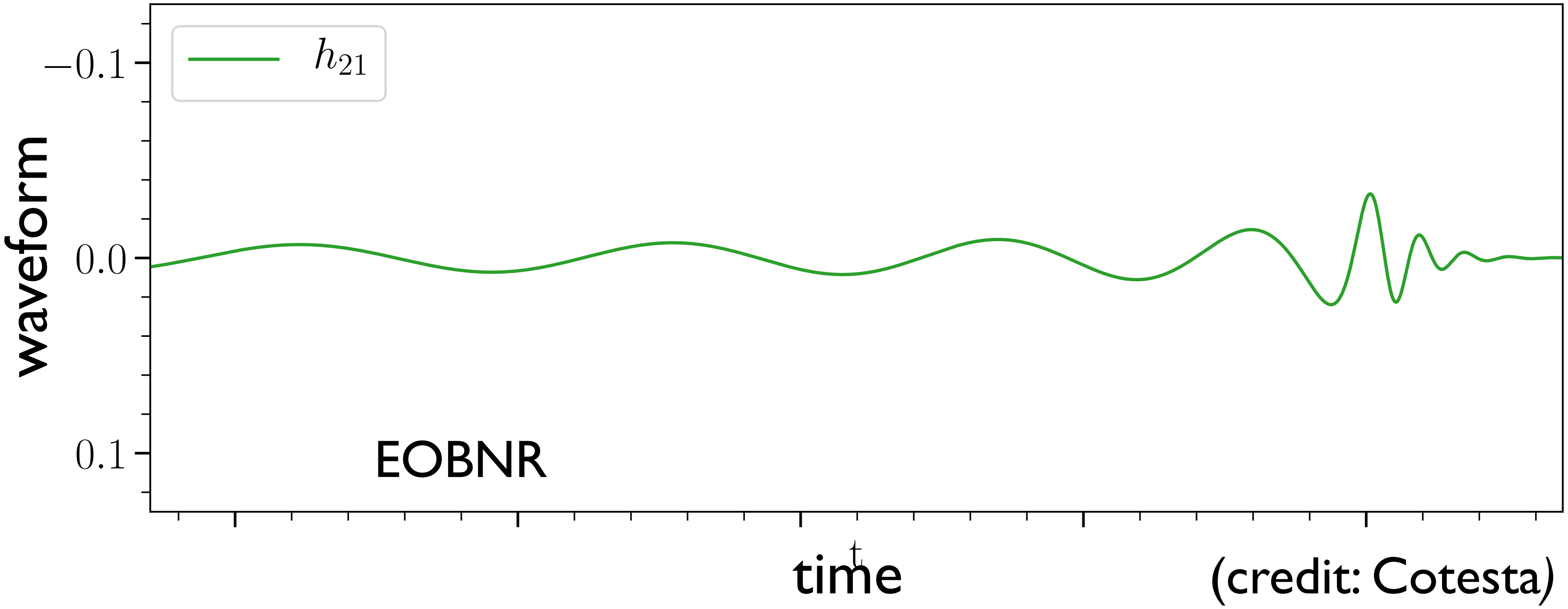
(Cotesta, AB, Bohe, Taracchini, Hinder, Ossokine 18)

(see also Pan et al. 11, London et al. 17, Mehta et al. 17)



Enriching the GW symphony by tuning higher harmonics (contd.)

first harmonic



(credit: Cotesta)

(Cotesta, AB, Bohe, Taracchini, Hinder, Ossokine 18)

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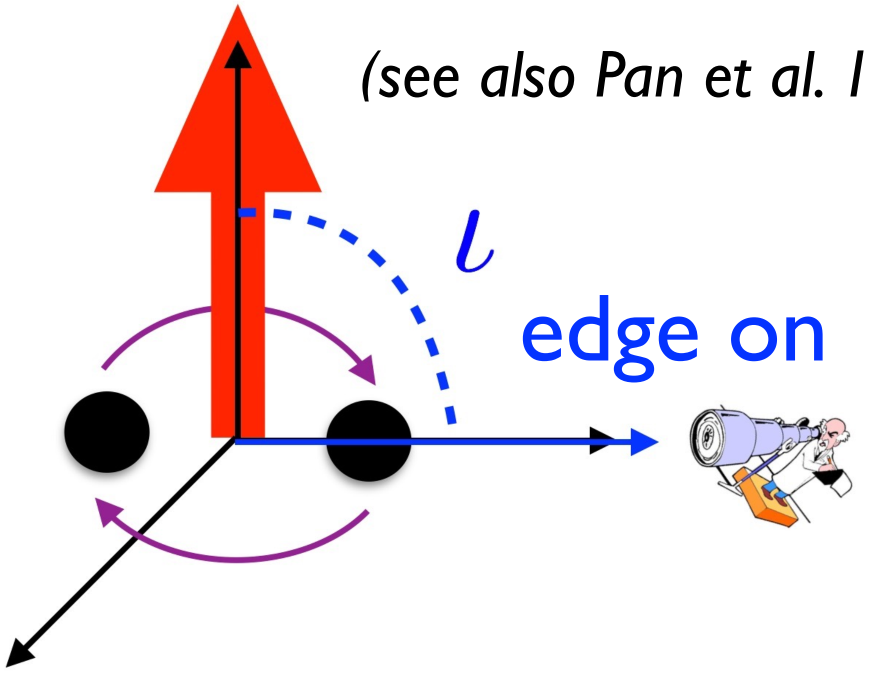
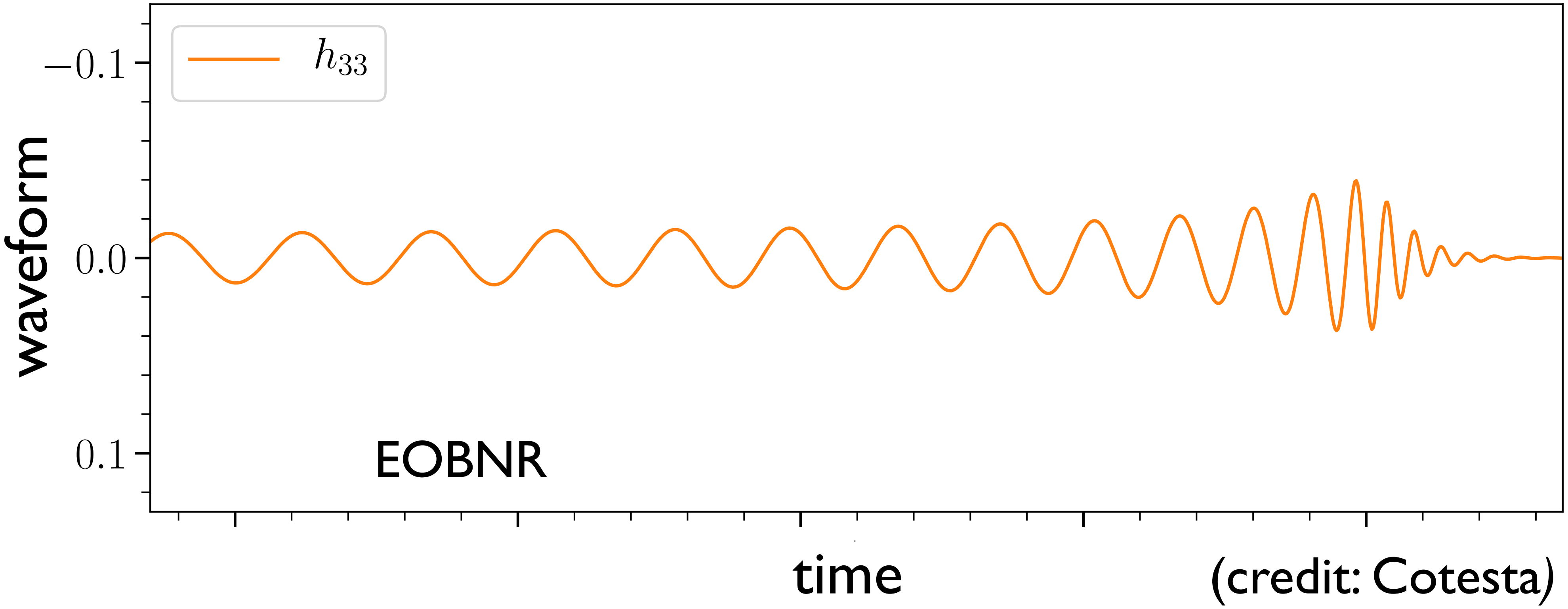


Enriching the GW symphony by tuning higher harmonics (contd.)

third harmonic



(credit: Cotesta)

(Cotesta, AB, Bohe, Taracchini, Hinder, Ossokine 18)

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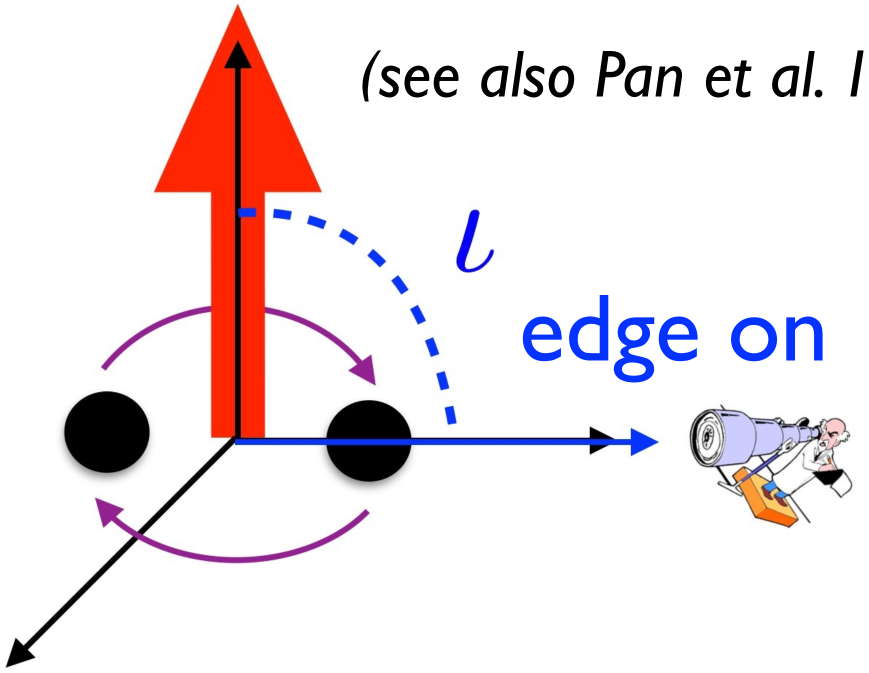
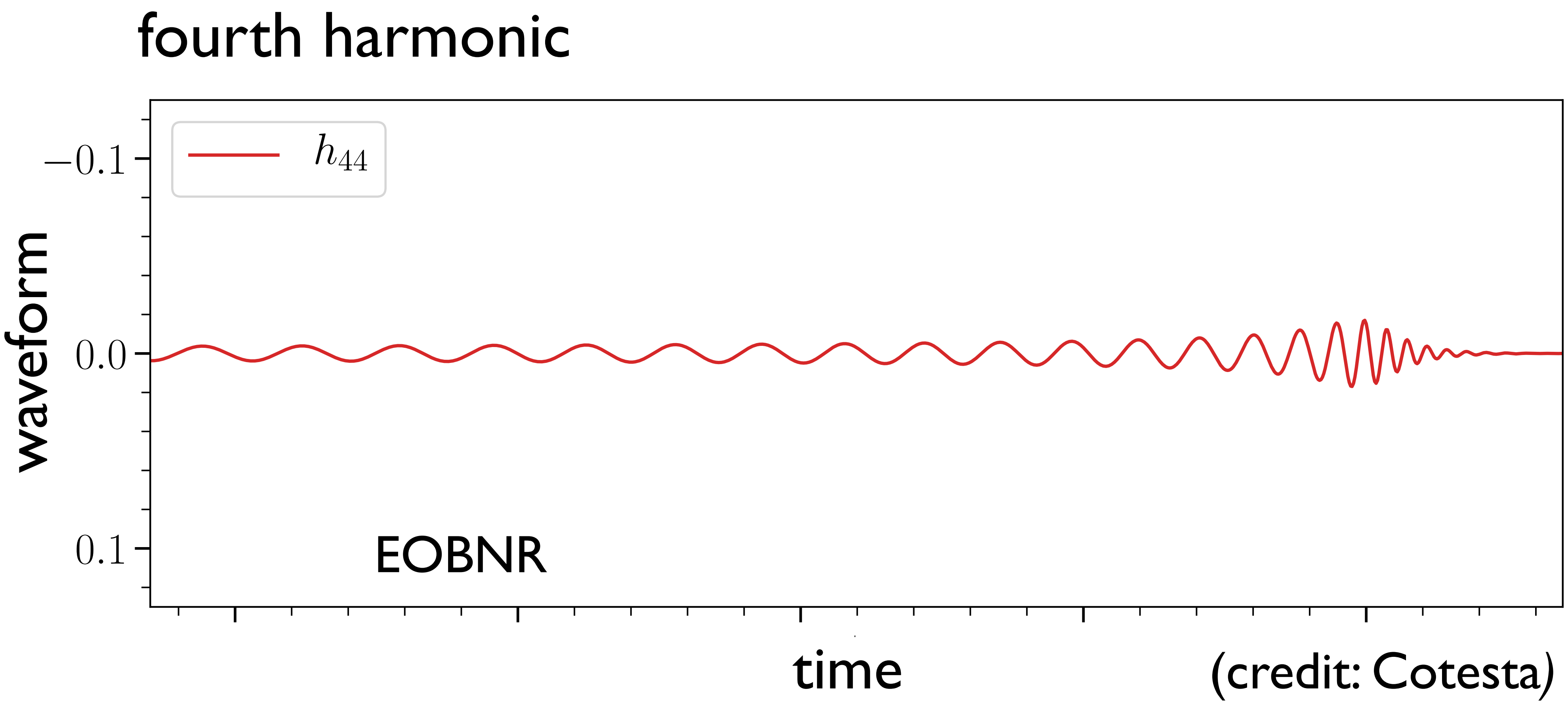


Enriching the GW symphony by tuning higher harmonics (contd.)



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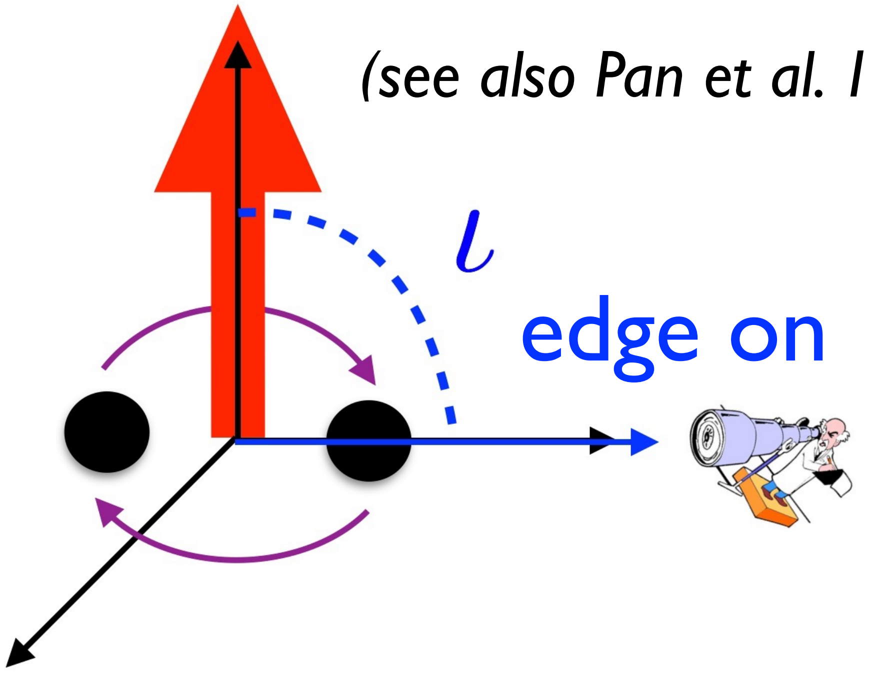
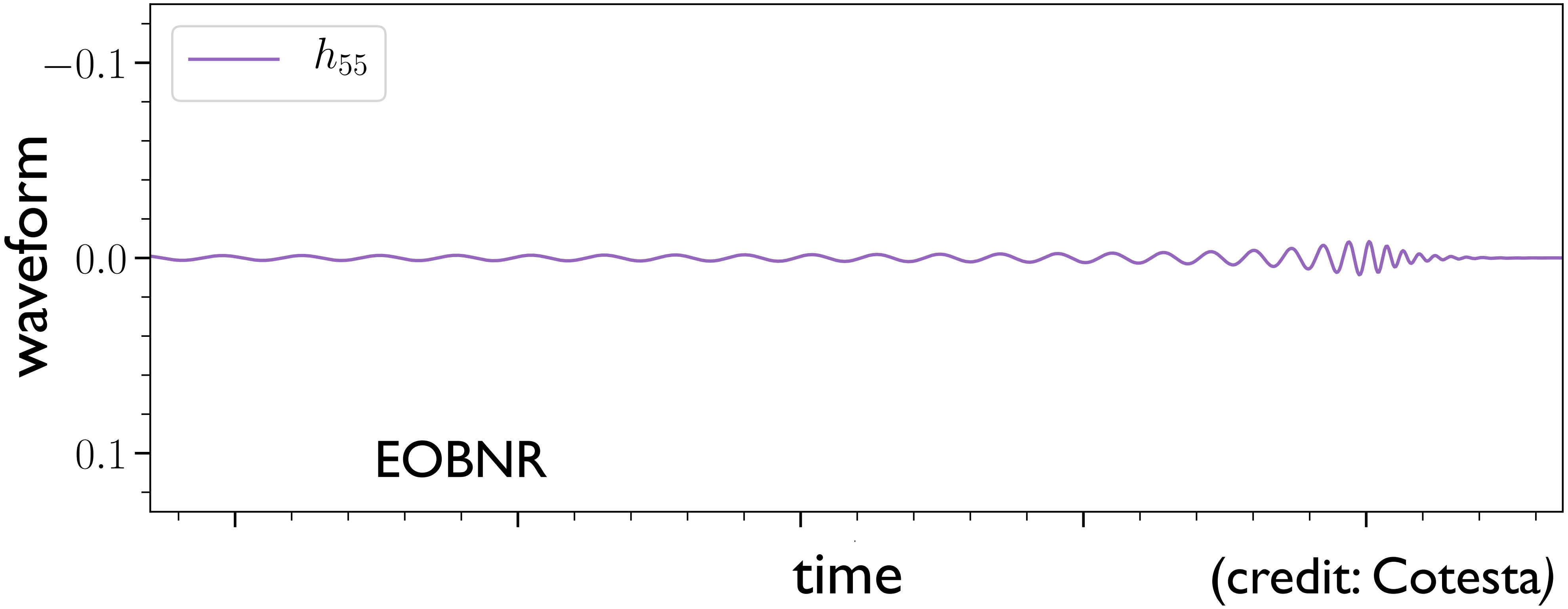


Enriching the GW symphony by tuning higher harmonics (contd.)

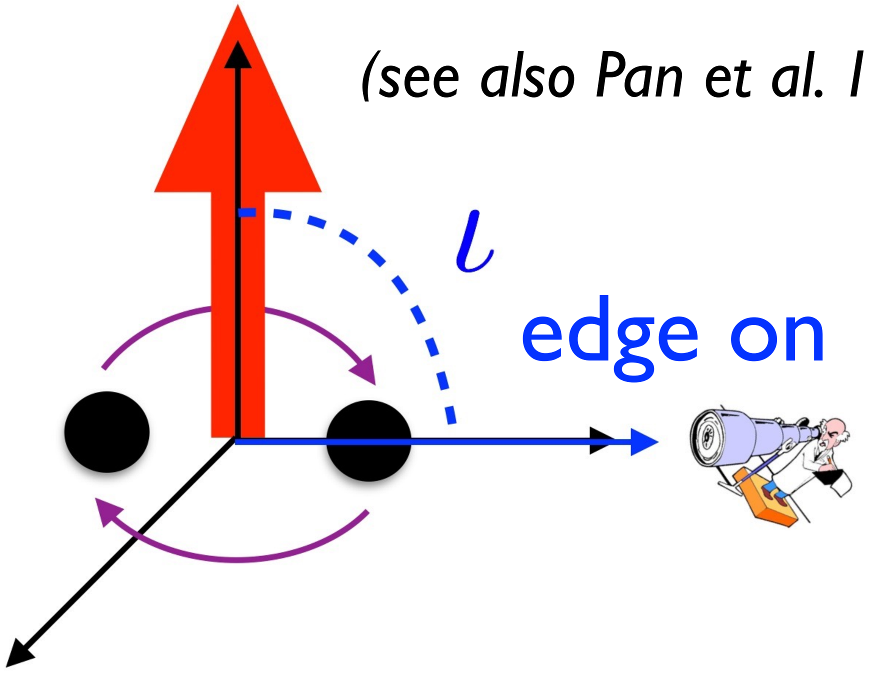
fifth harmonic



(credit: Cotesta)

(Cotesta, AB, Bohe, Taracchini, Hinder, Ossokine 18)

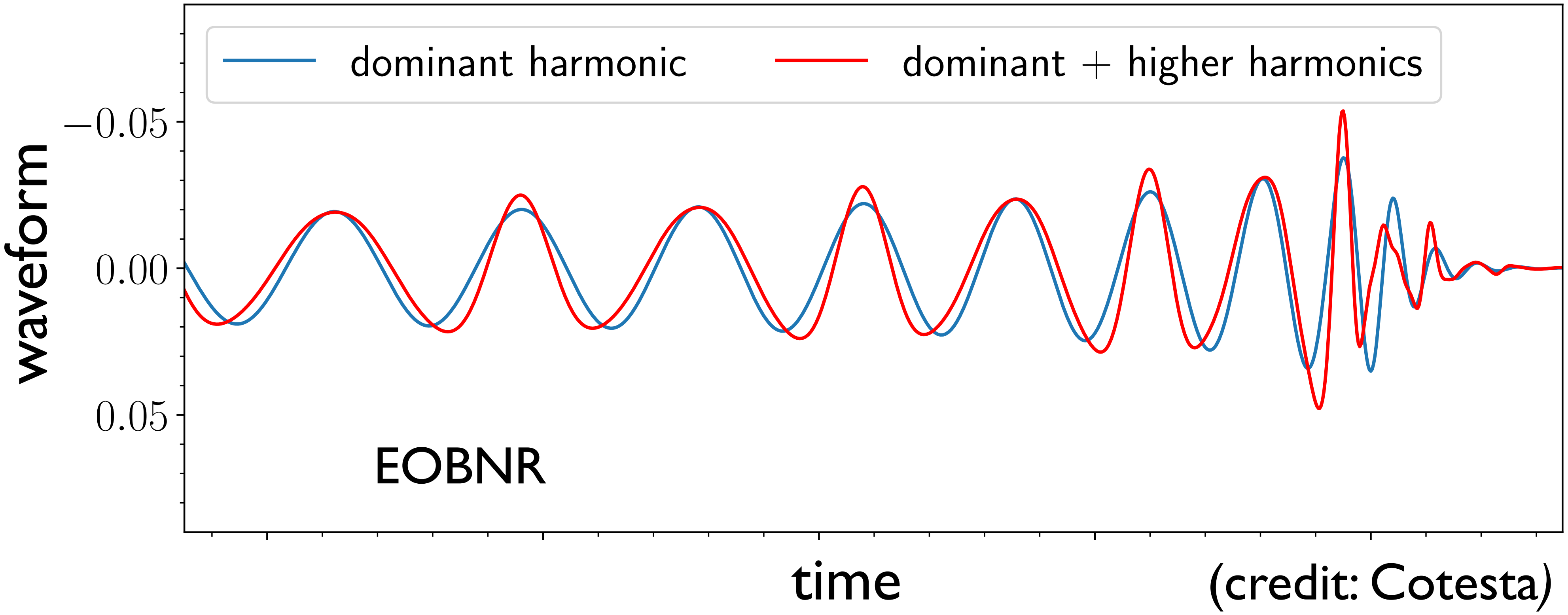
(see also Pan et al. 11, London et al. 17, Mehta et al. 17)



ι

edge on

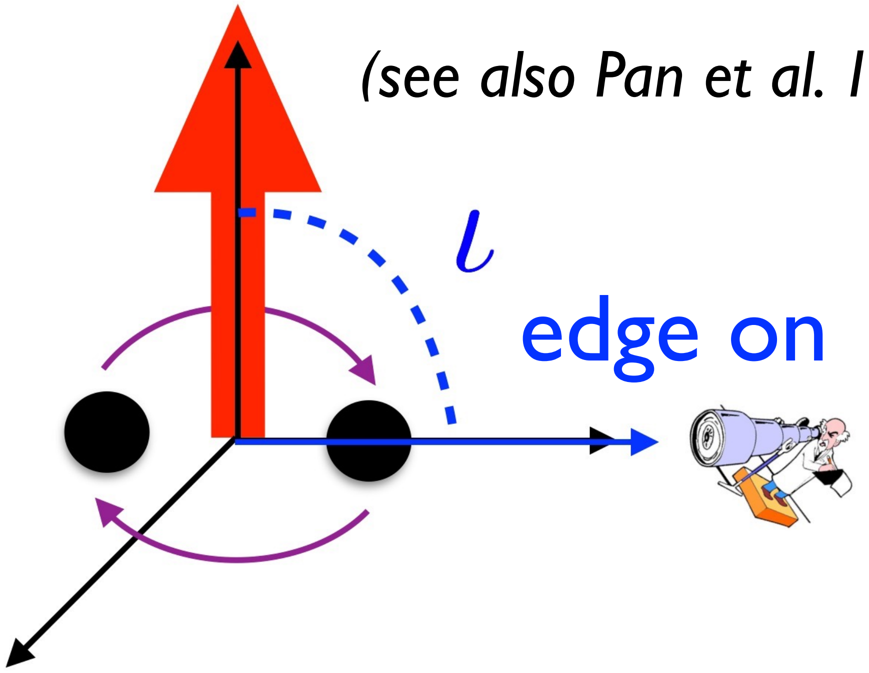
Enriching the GW symphony by tuning higher harmonics (contd.)


adding all five harmonics

(credit: Cotesta)

(Cotesta, AB, Bohe, Taracchini, Hinder, Ossokine 18)

(see also Pan et al. 11, London et al. 17, Mehta et al. 17)



- We could **detect more rare** GW events.
- We could **infer source's properties more accurately**.
- We could **perform more stringent tests** of GR (e.g., BH spectroscopy)

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)

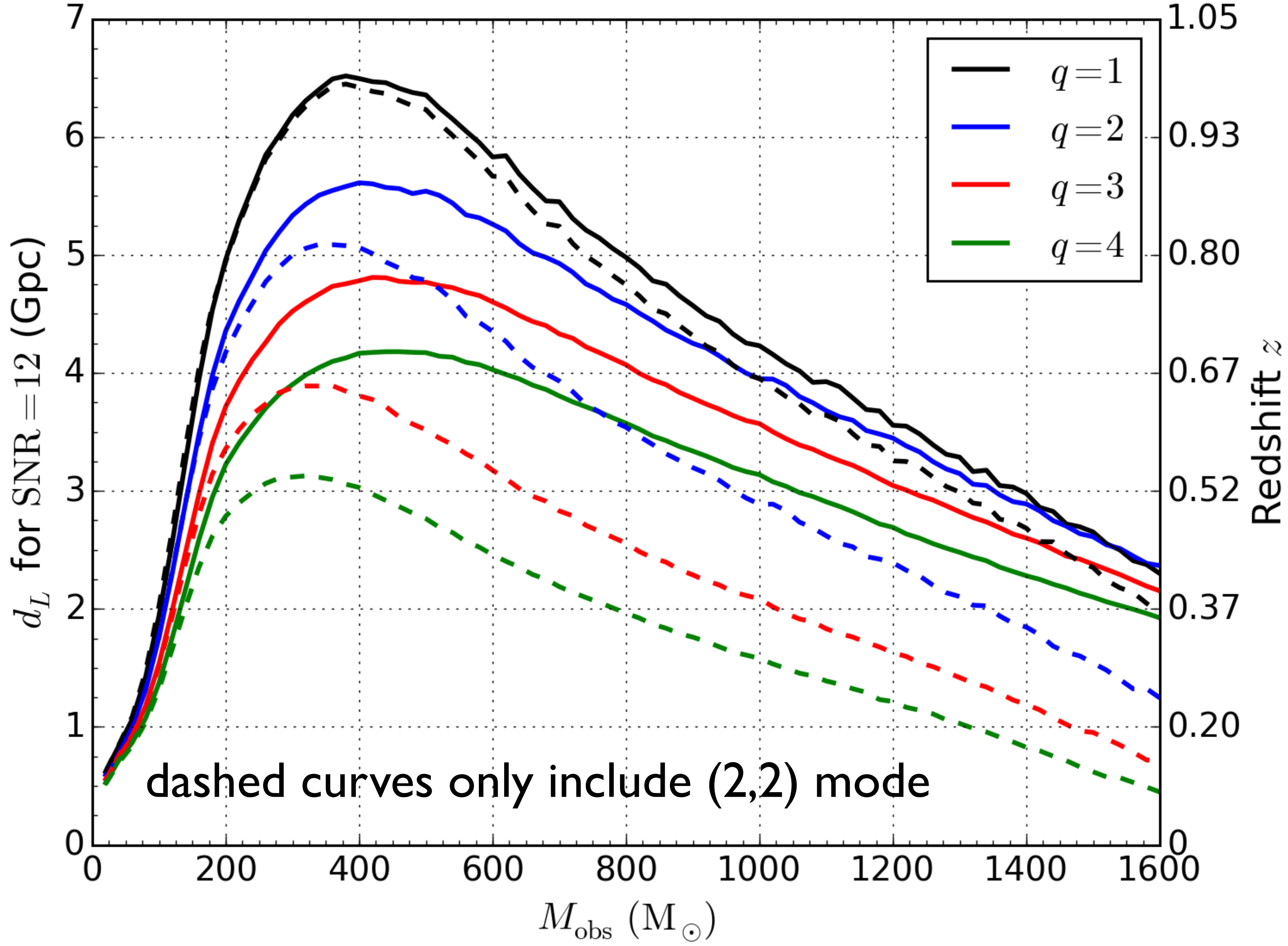
- **Improvements in measurement** of **masses** & **orientation angles** with higher harmonics.

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

(see also Haster et al. 15)

(Graff, AB & Sathyaprakash 15)

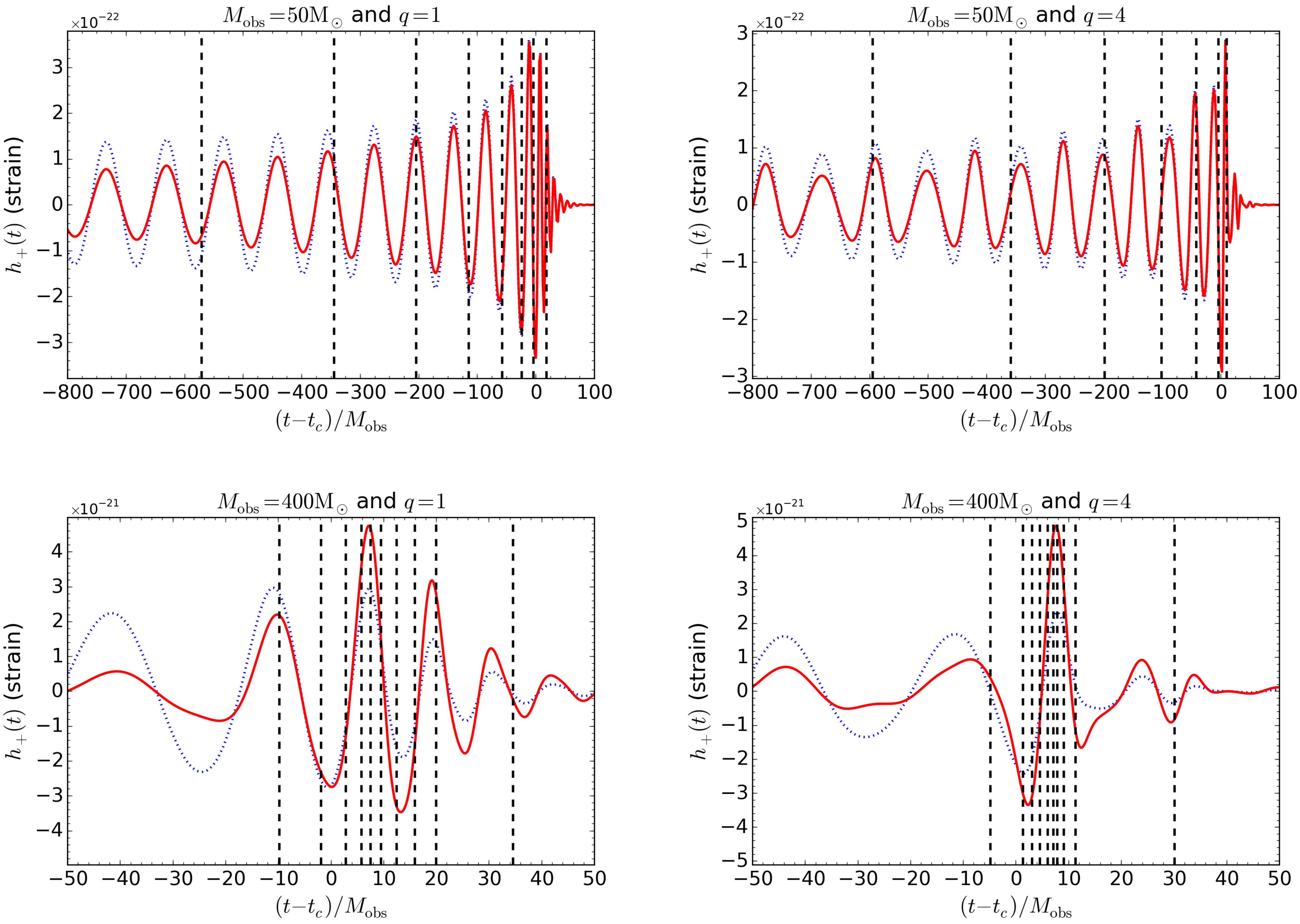
distance reach versus observed total mass
(averaged on sky location and polarization)



dashed curves only include (2,2) mode

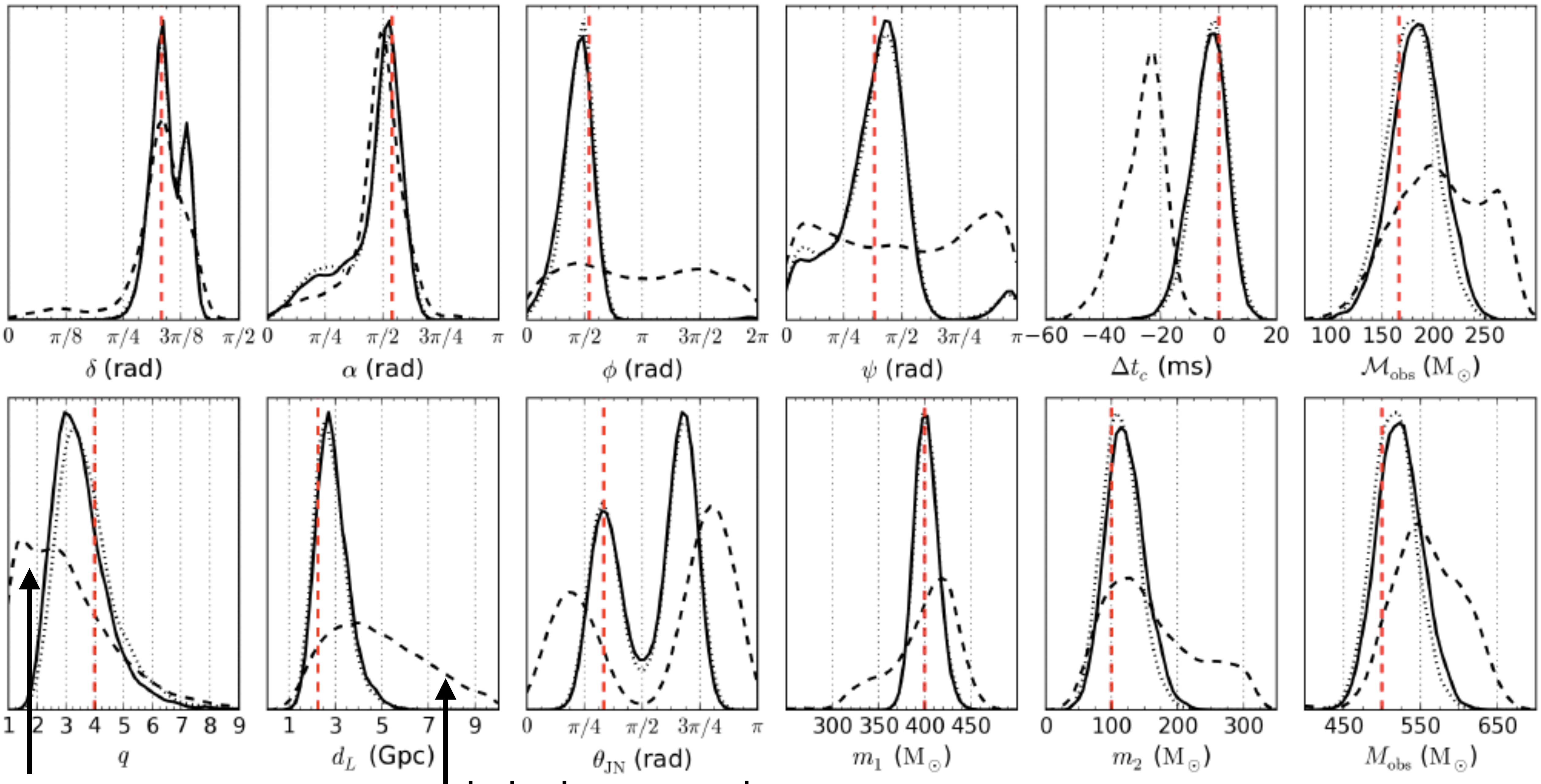
Relevance of higher harmonics for IMBBHs (contd.)

(Graff, AB & Sathyaprakash 14)



Relevance of higher harmonics for IMBBHs (contd.)

(Graff, AB & Sathyaprakash 14)



dashed curves only include (2,2) mode

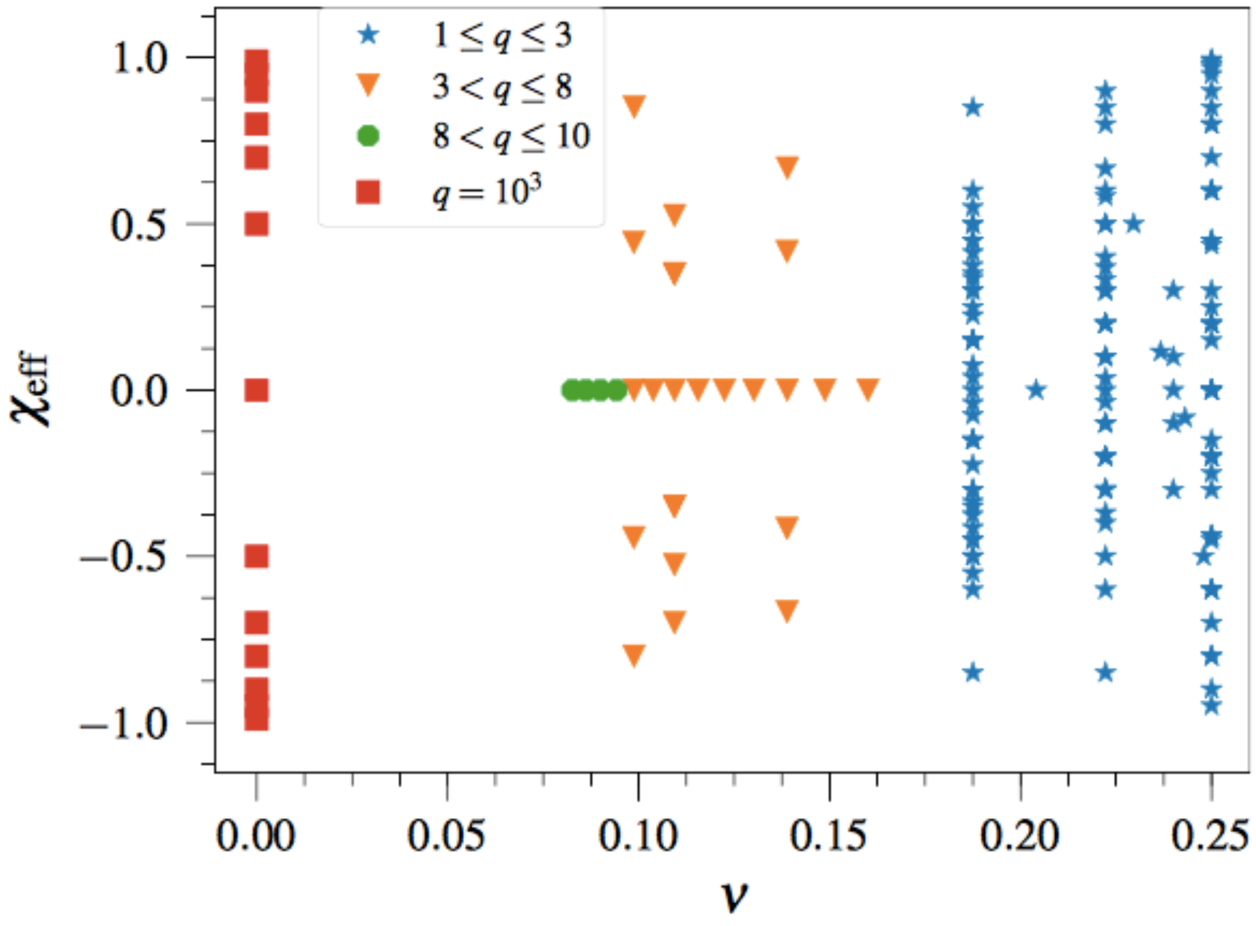
$$\mathrm{SNR} = 12, M_{\mathrm{obs}} = 500 M_{\odot}, q = 4, \theta_{\mathrm{JN}} = \pi/3$$

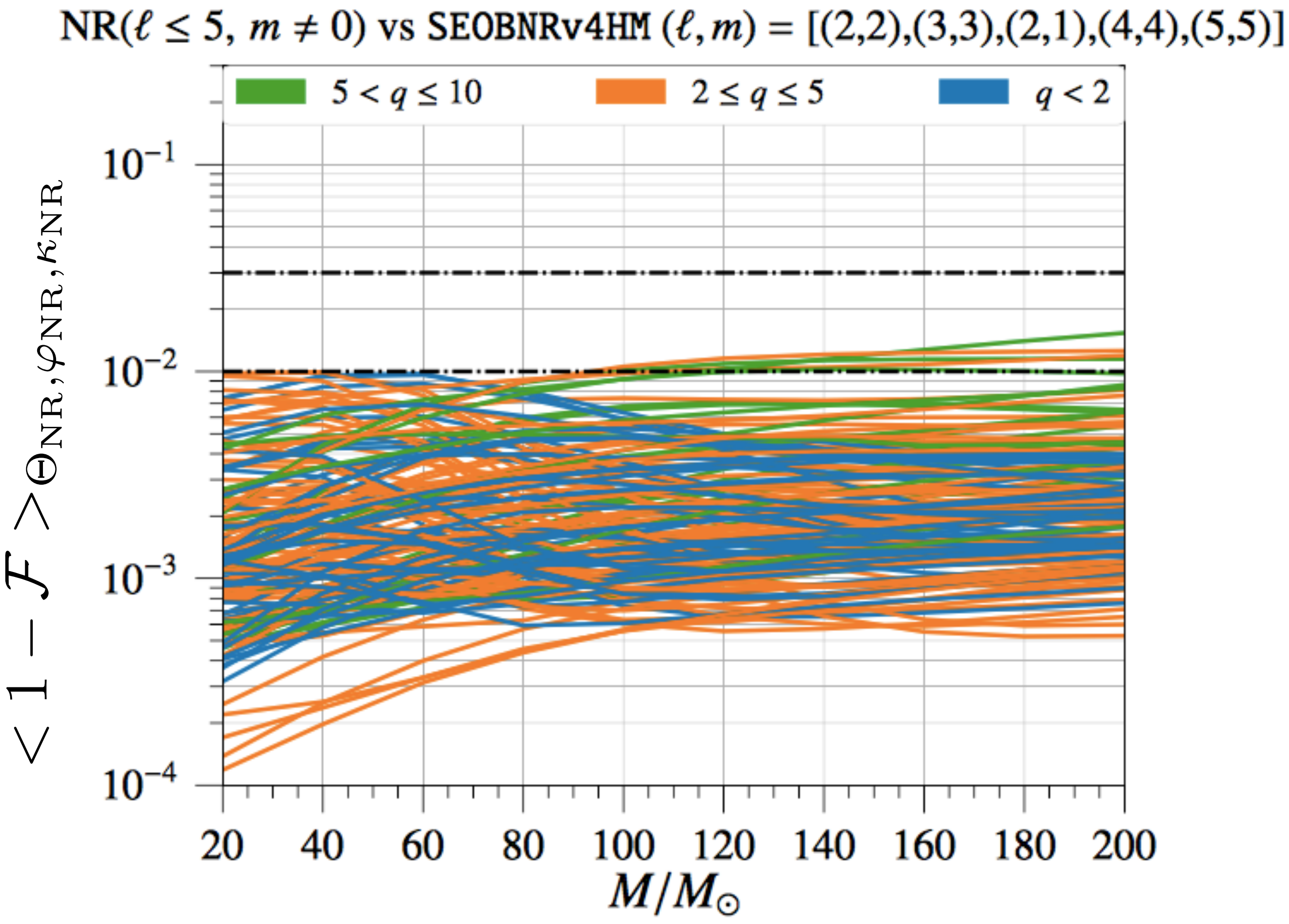
Accuracy of multipolar SEOBNR model against NR

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

(Cotesta, AB et al. 18)

141 NR waveforms





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

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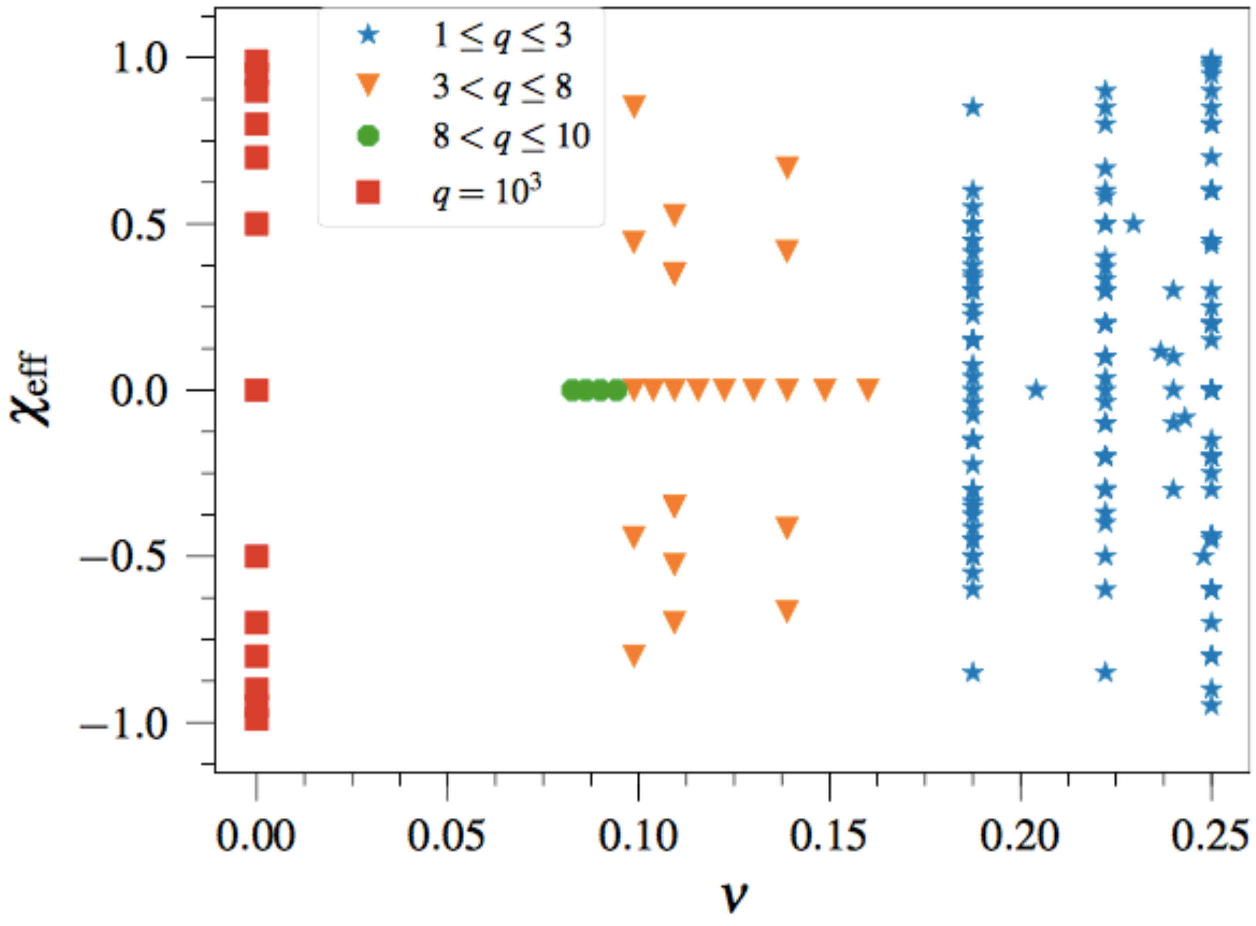
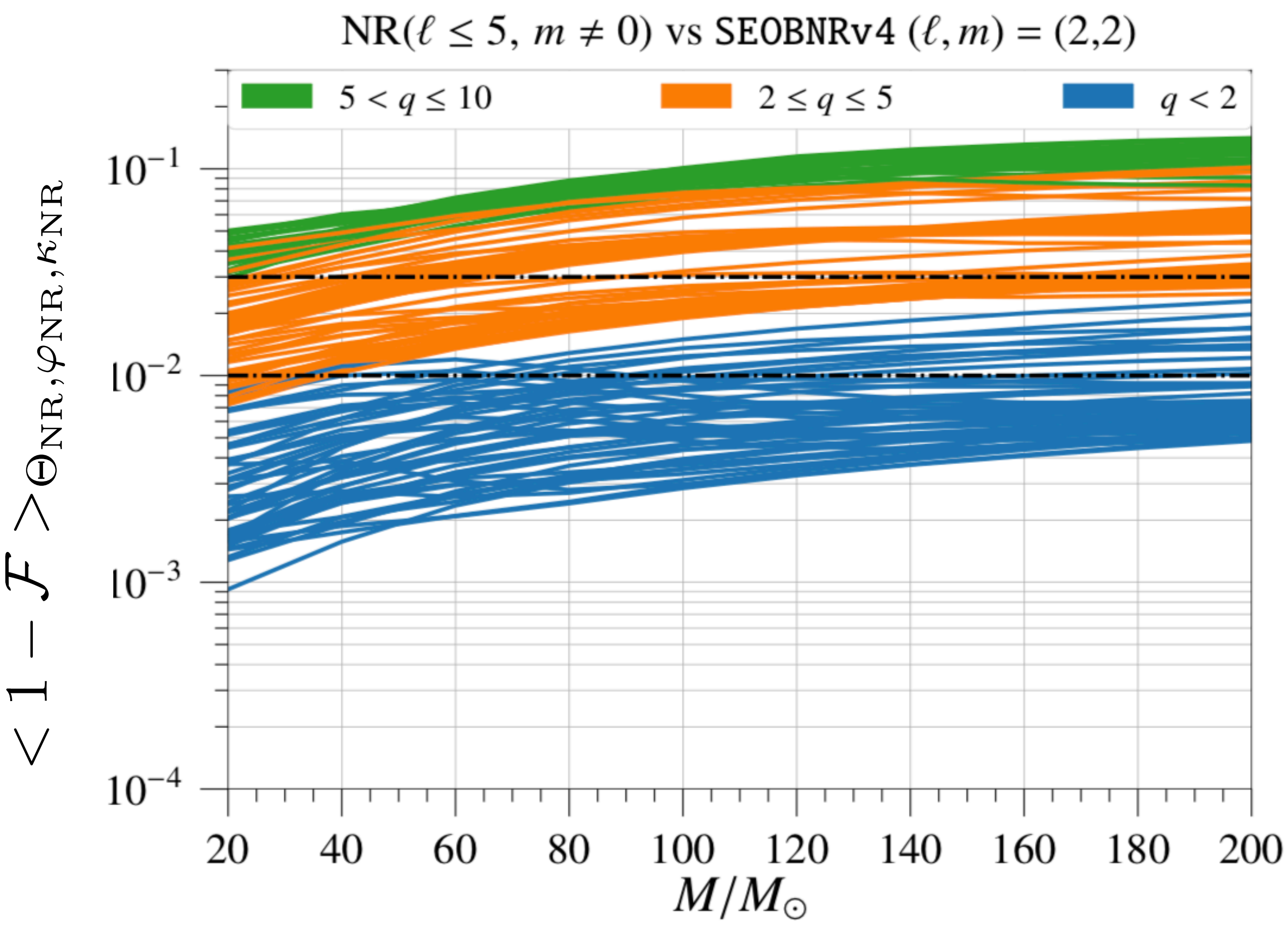
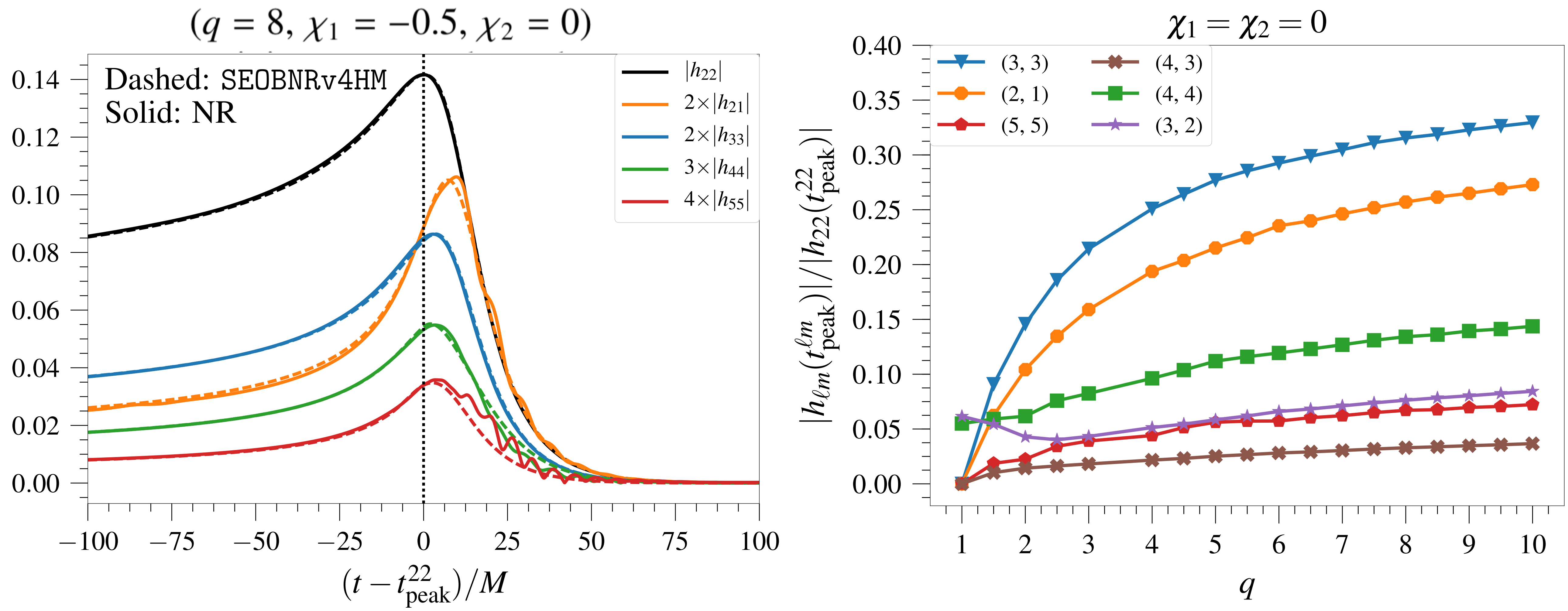




(for modeling see also Mehta et al. 17, London et al. 17; for searches see Capano, …, AB 16, Harry et al. 18)

Importance of higher harmonics: varying mass ratio

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



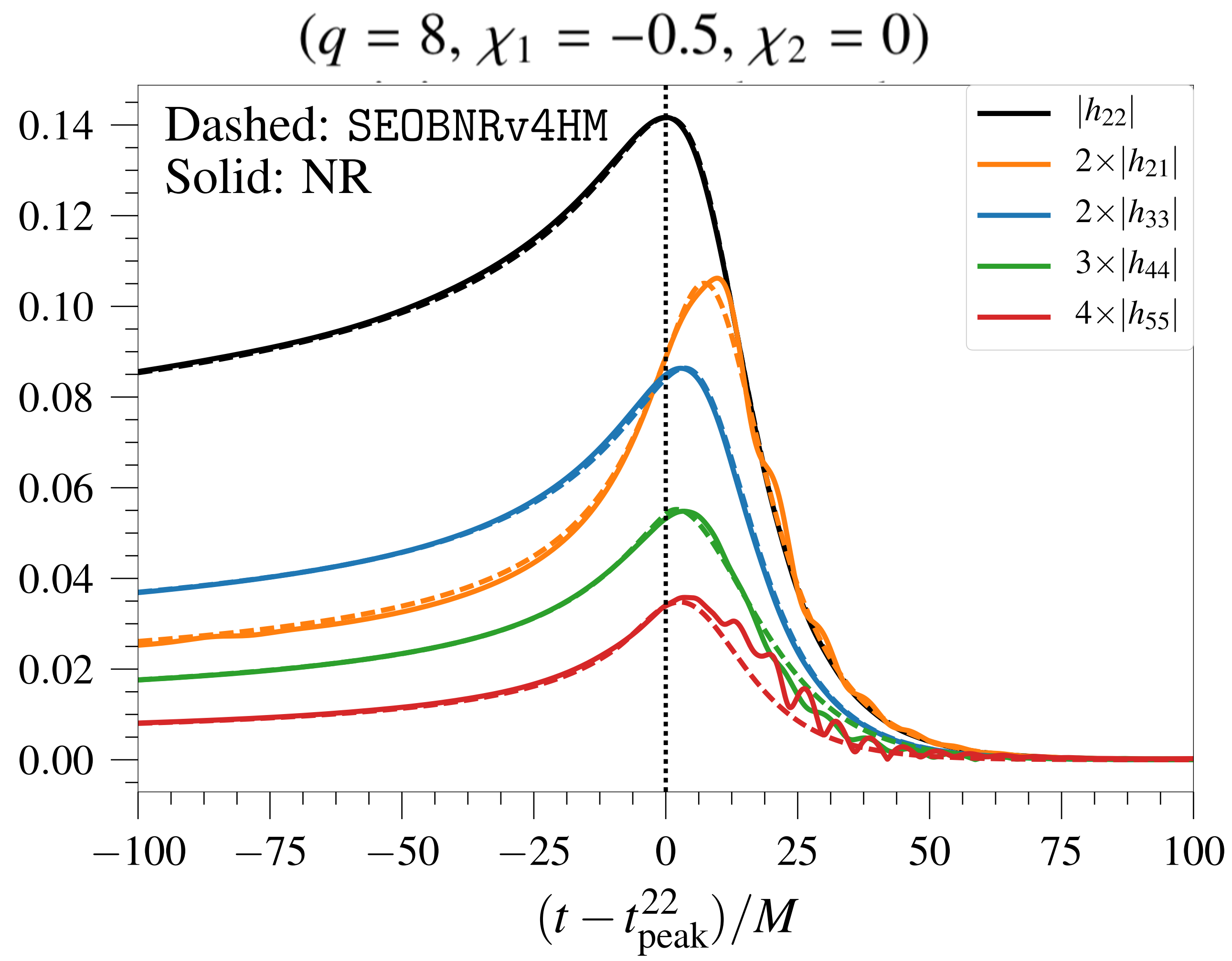
(Cotesta, AB et al. 18)

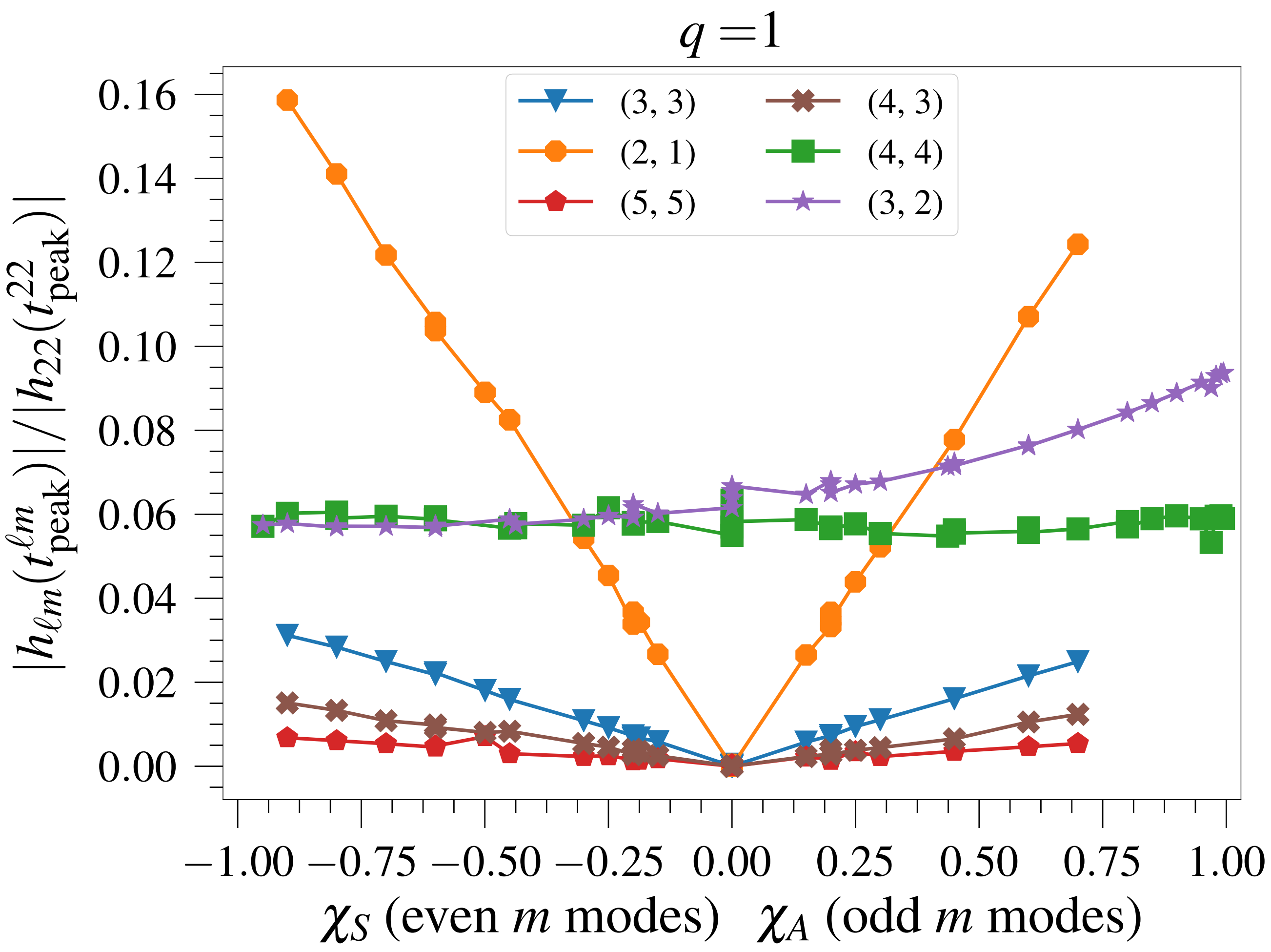
- Merger-ringdown EOBNR model **reproduces time & phase shifts between NR modes' at peak**, which is important for BH spectroscopy.

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)


$(q = 8, \chi_1 = -0.5, \chi_2 = 0)$


$q = 1$

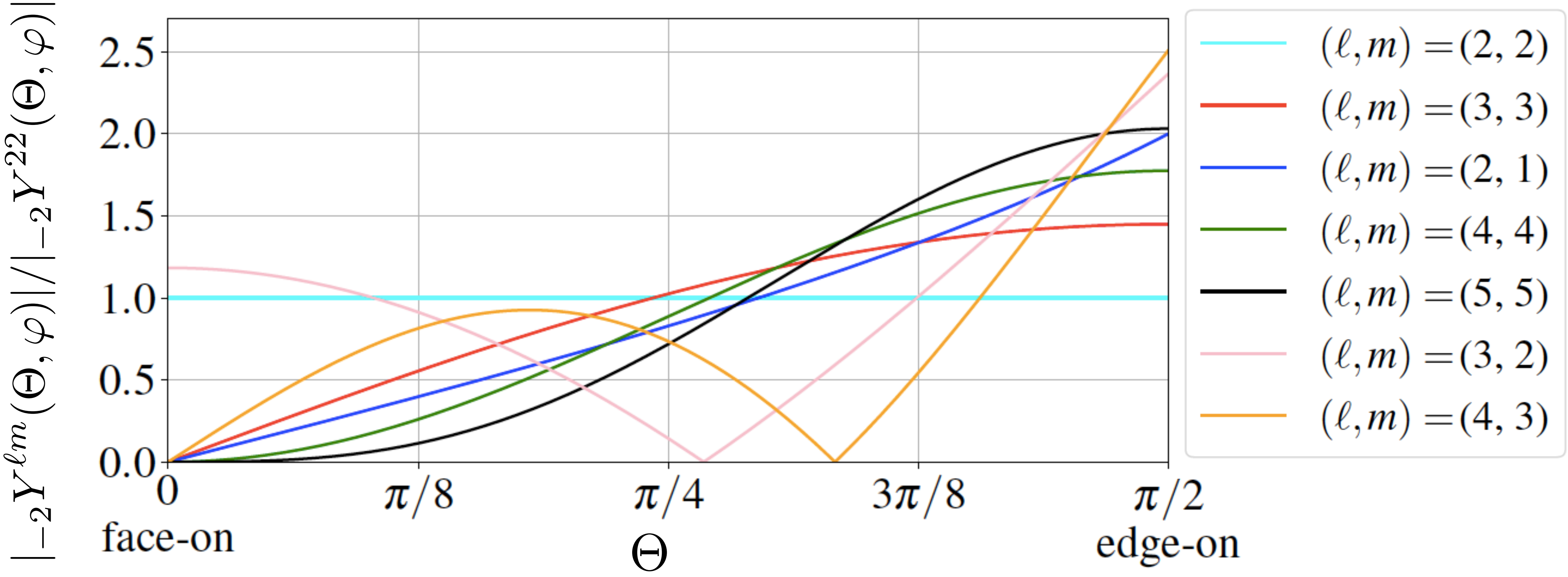
- Merger-ringdown EOBNR model **reproduces time & phase shifts between NR modes' at peak**, which is important for BH spectroscopy.

Importance of higher harmonics also depends on geometric factor

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

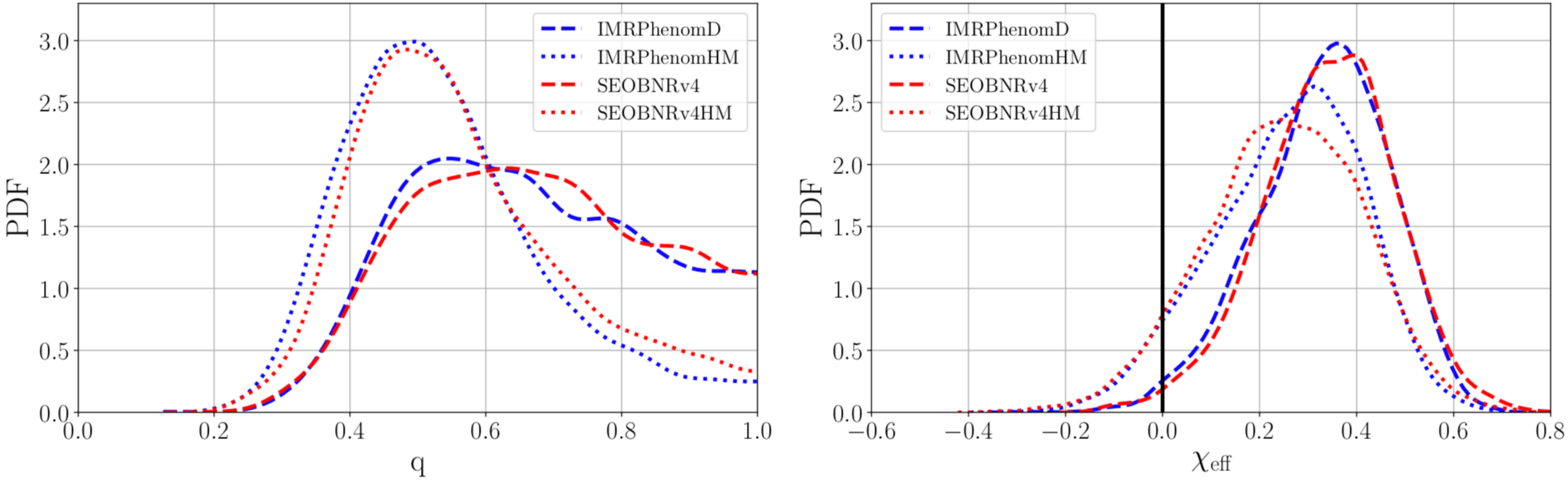
↑ **geometric factor** is important to determine **strength** of **higher harmonics**

(Cotesta, AB et al. 18)



Inference of GW170729 with higher-mode waveform models

(Chatziioannou , … AB …, 19)



- **Improved estimate** for mass ratio of **(0.3 − 0.8)** at 90%. Measurement **excludes equal masses** at 90%.

Accuracy of multipolar precessing SEOBNR model against NR

- **SEOBNRv4PHM**: **new** spin-precessing waveform model

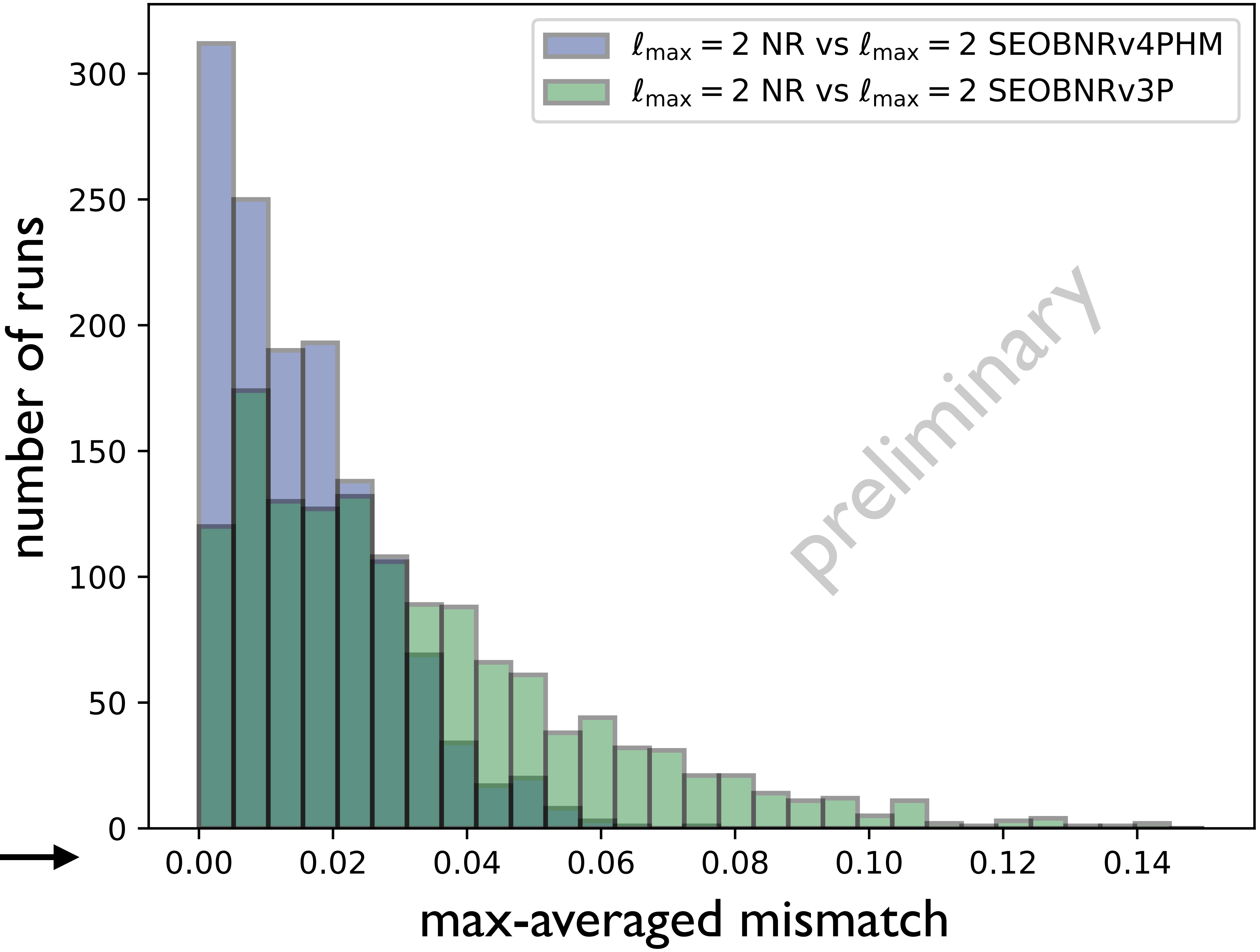
- **SEOBNRv3P**: **old** spin-precessing waveform model, **without HMs, used in O1 & O2.**

(Pan, AB et al. 13, Babak, … AB 17)

- Mismatch against **public SXS** NR catalog **(1344)** plus **non-public SXS** NR waveforms **(141)**.

(Boyle et al. 19)

(Ossokine, Marsat, AB & Cotesta in prep 19)



binary's inclination: $\iota = \pi/3$

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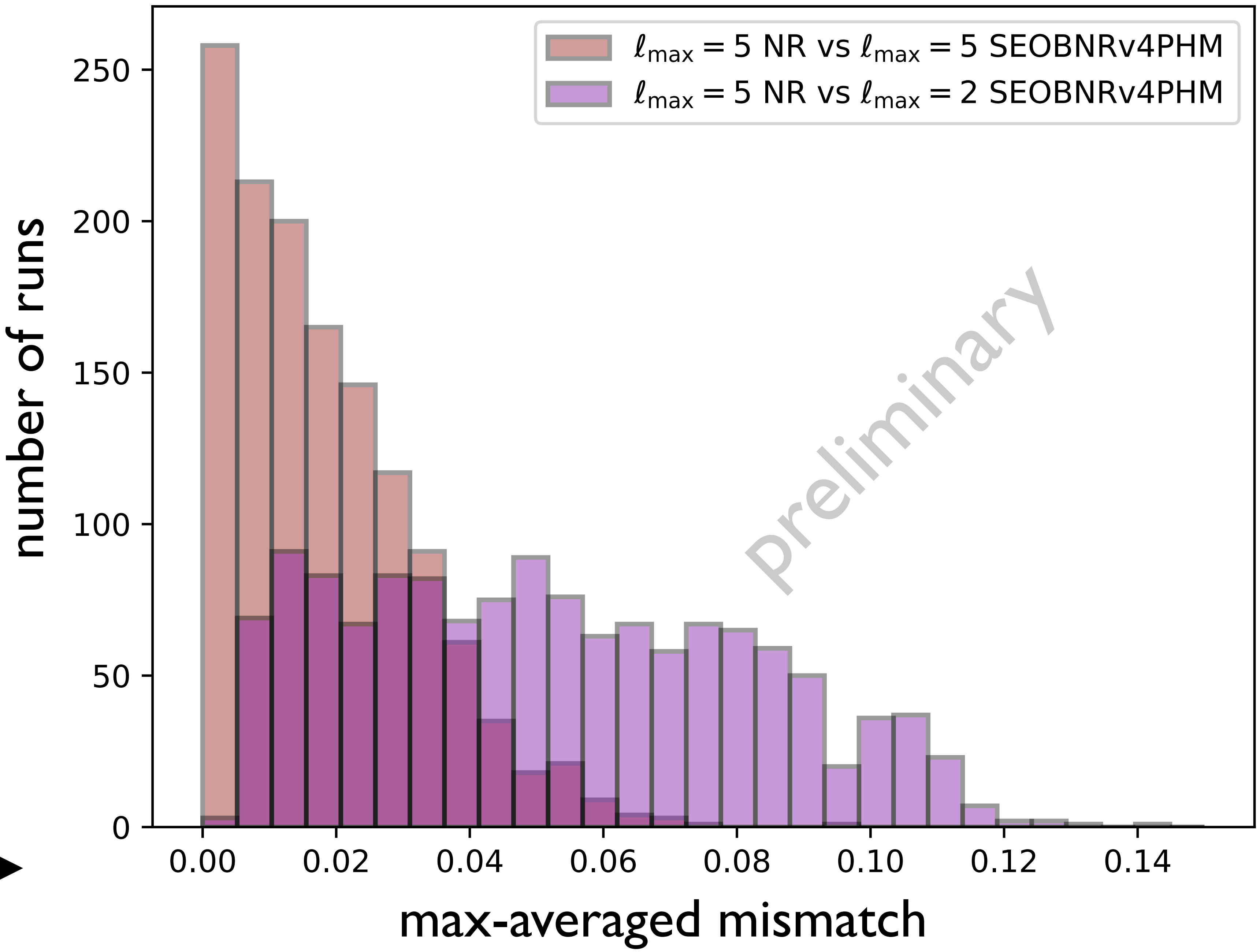
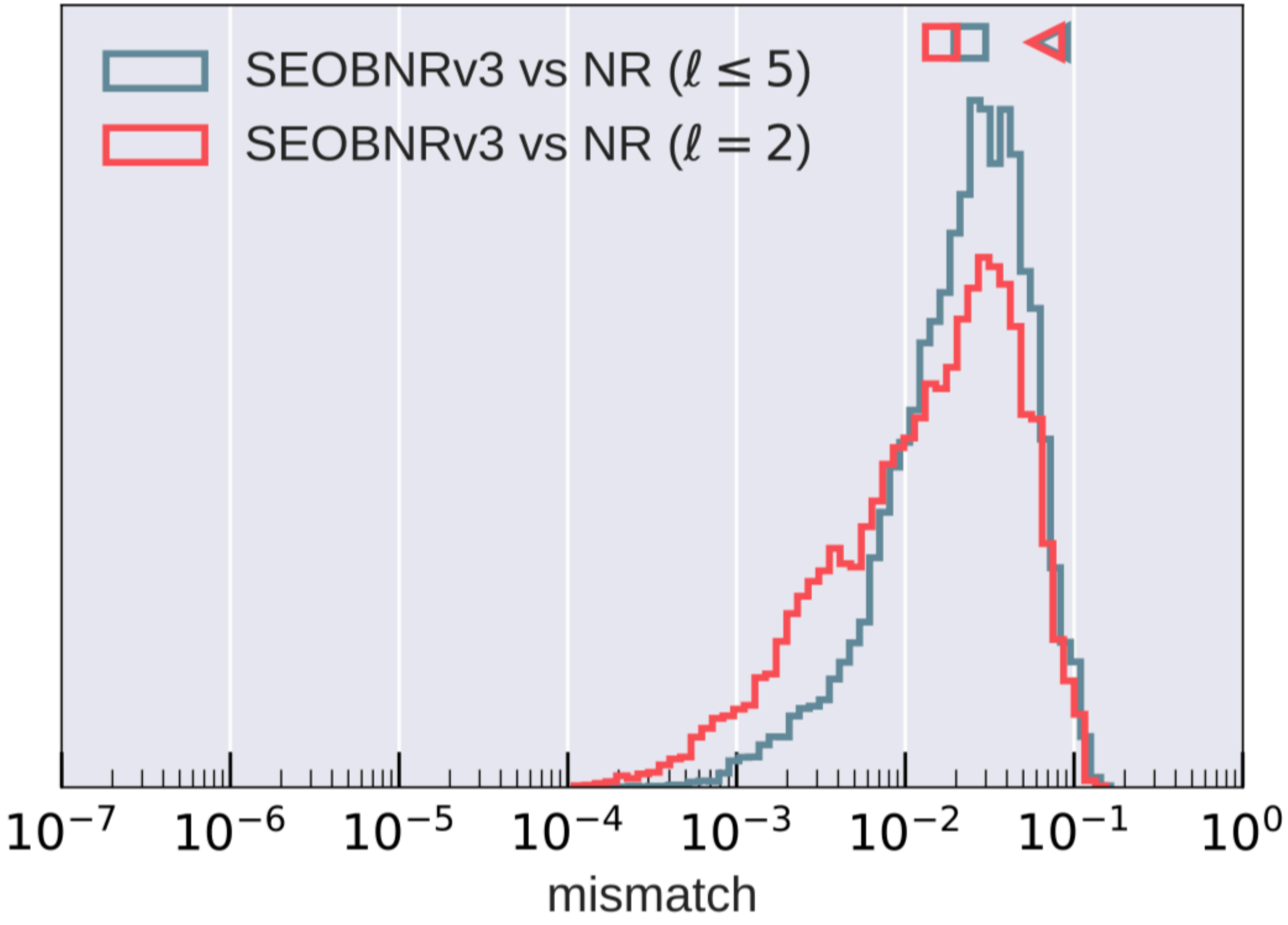


binary's inclination: $\iota = \pi/3$

Accuracy of multipolar precessing (old) SEOBNR model

(Varma et al.19)



- **Surrogate NR model** for mass ratio **< 4** and spins **< 0.8**, and about **20 orbits**.

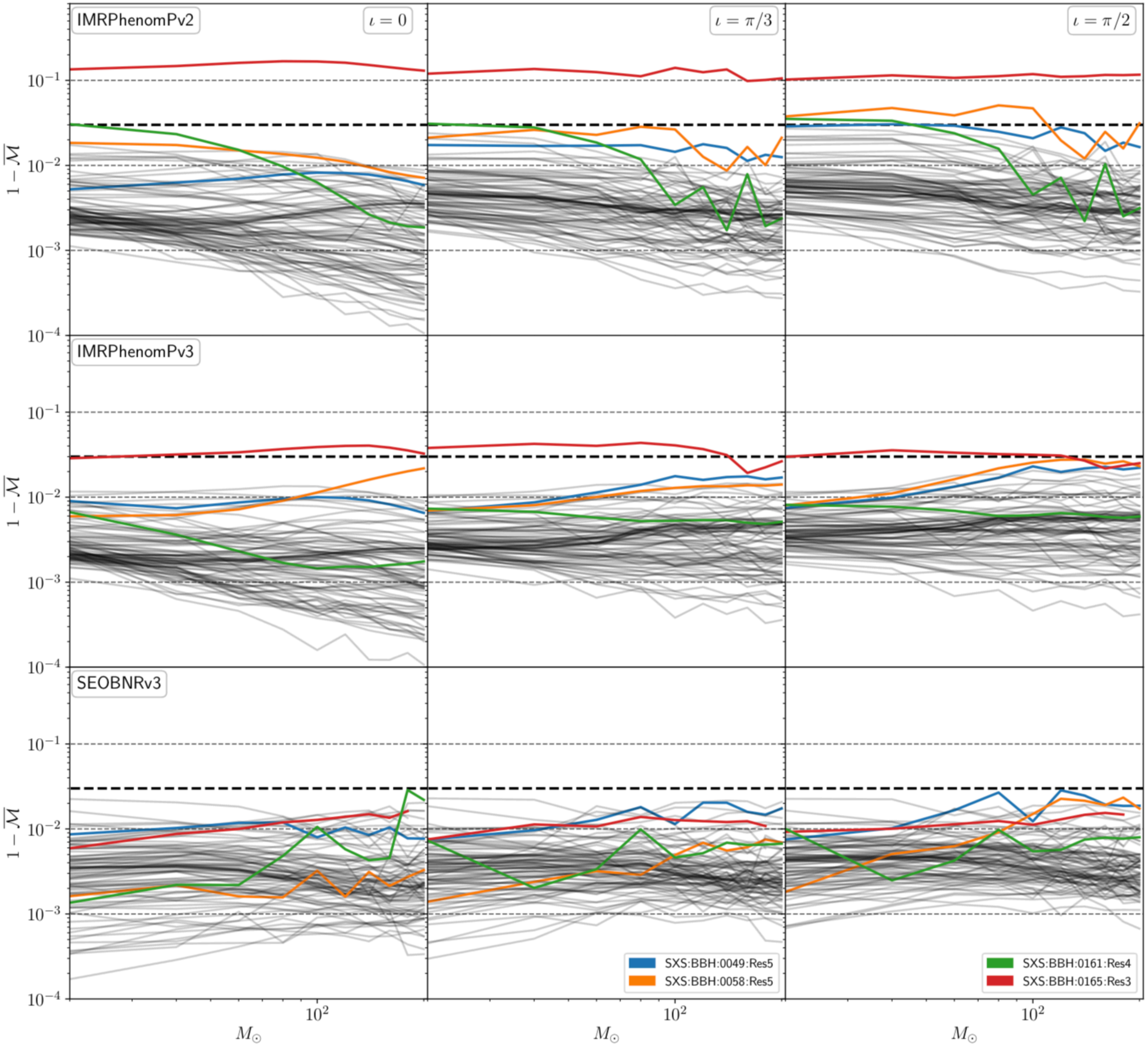
- **Surrogate NR models** accurate and efficient, but limited in binary's parameter space and length. *(Blackman et al. 17, Varma et al. 18, 19)*

Comparing (precessing) SEOBNR & IMRPhenom models

(Khan et al. 18)

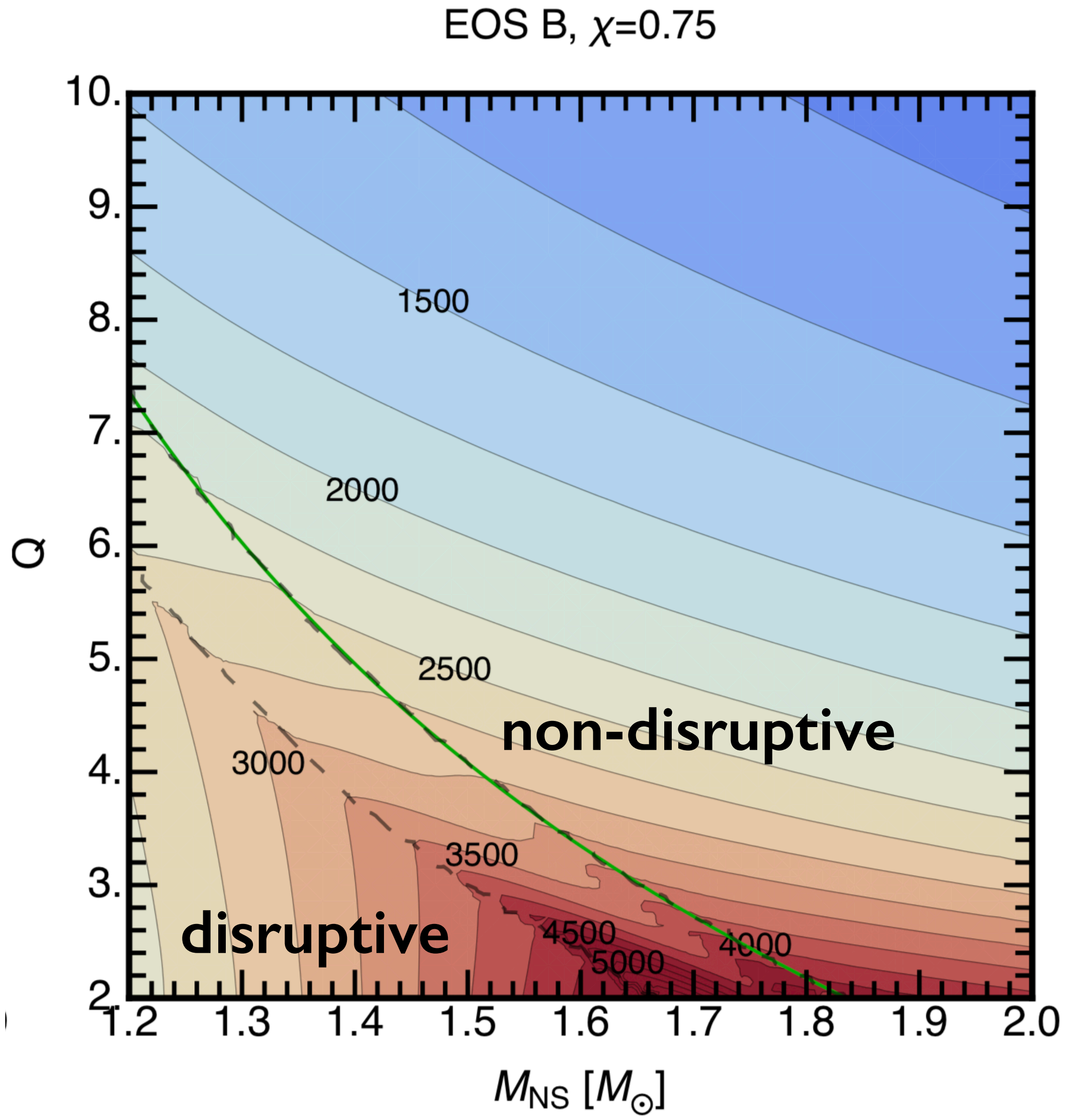
- IMRPhenomPv3: **two independent spins** in precessing dynamics.

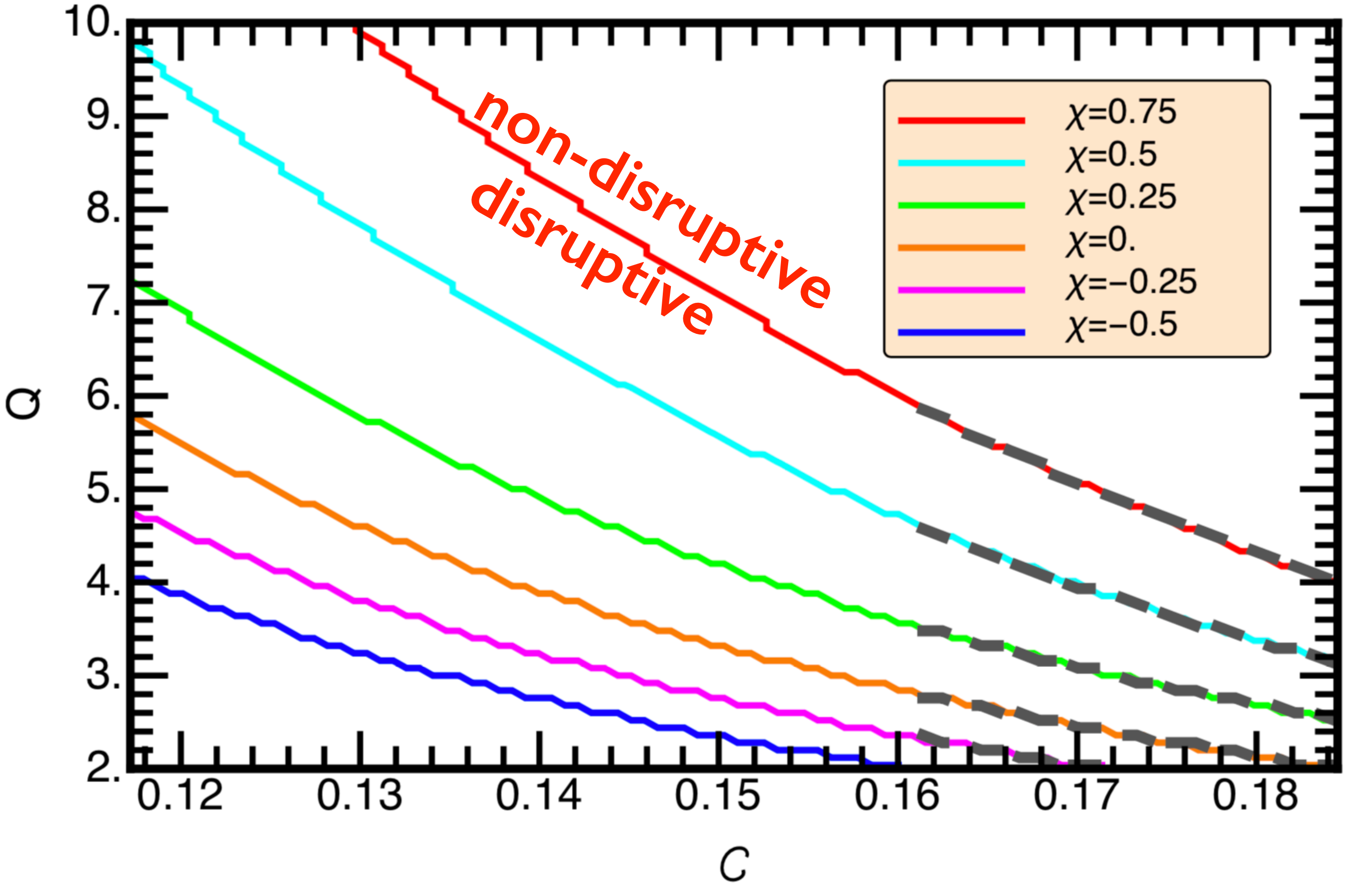
- Mismatch against ~ **90 SXS** NR waveforms.



Waveforms for NSBH combining analytical & numerical relativity

- Synergy between **analytical** and **numerical work** is **crucial.**
- **Current** waveform **models for NSBHs** are **not sufficiently accurate** to extract tidal effects *(Lackey et al. 14, Pannarale et al. 16, Pürrer et al. 17, Chakravarti et al. 17)*





(Pannarale et al. 16)

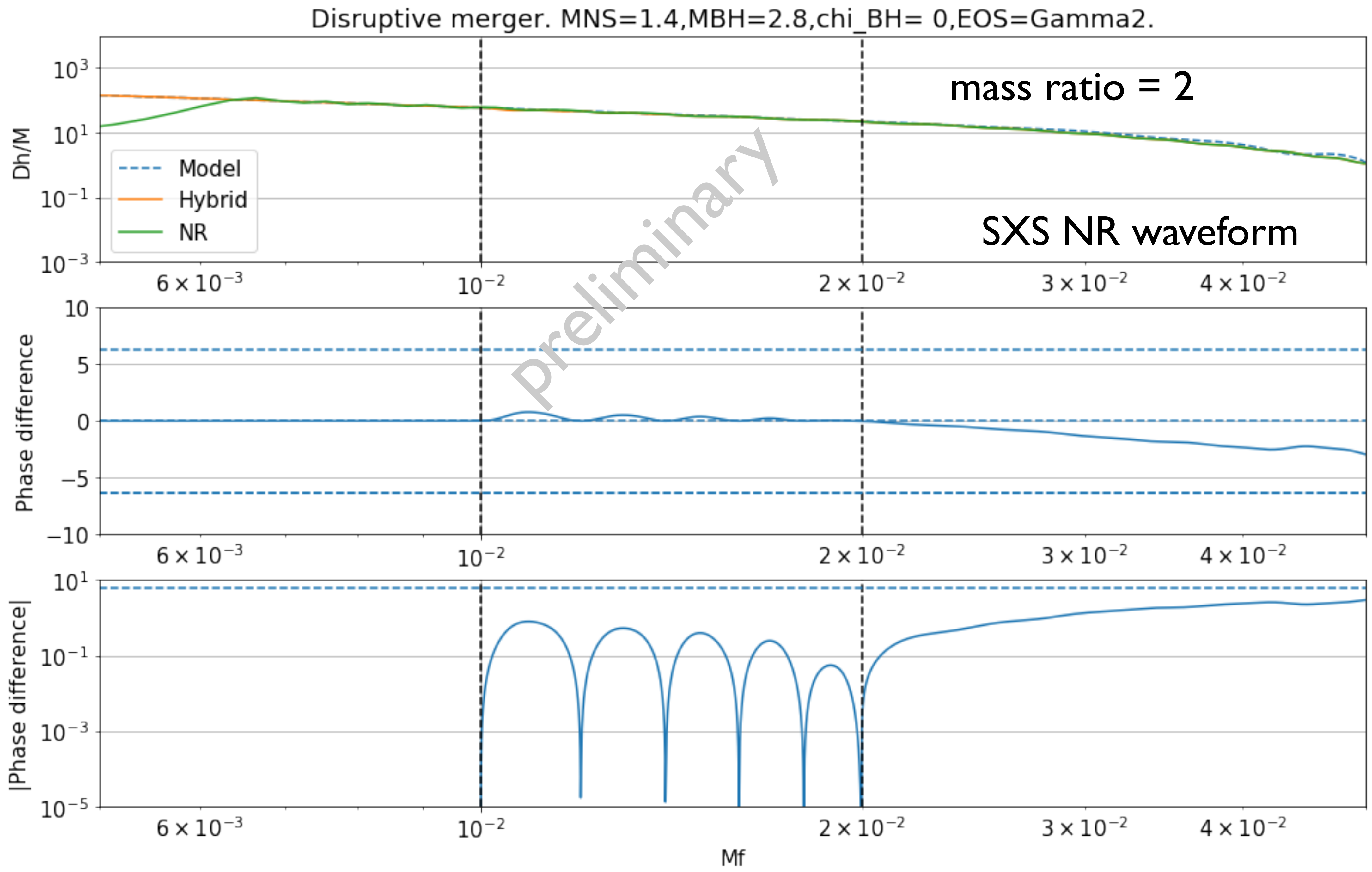
NSBH is disrupted whenever $Q < Q_D(\mathcal{C}, \chi)$

Waveform model for NSBH: disruptive case

$$\tilde{h}(f) = \mathcal{A}(f)e^{i\varphi(f)} \qquad \mathcal{A}(f) = \mathcal{A}_{\mathrm{SEOBNRT}}(f)w^{-}_{f_0,\sigma} + \mathcal{A}_{\mathrm{RD}}w^{+}_{f_0,\sigma} \qquad w^{\pm}_{f_0,\sigma} = \frac{1}{2}\left[1 \pm \tanh\left(\frac{4(f-f_0)}{\sigma}\right)\right]$$

with **tidal effects**

(Matas, AB, Dietrich, Hinderer & Pürrer in prep 19)

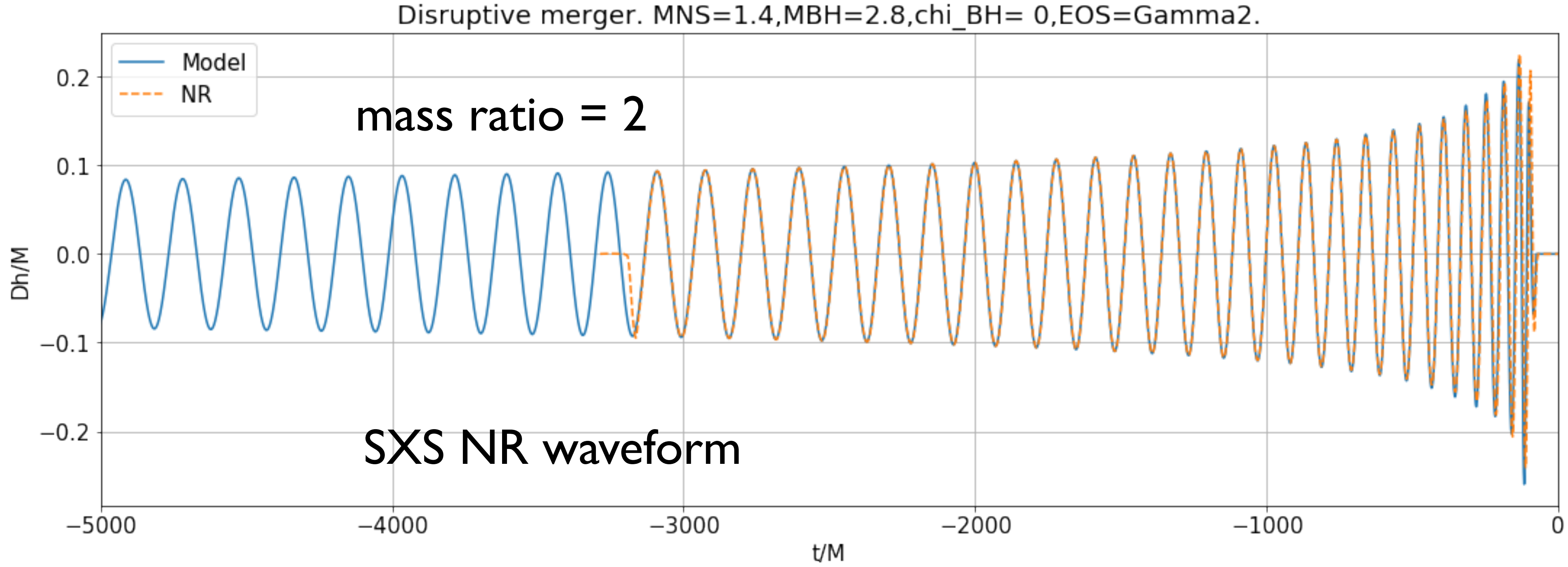


mass ratio = 2

SXS NR waveform

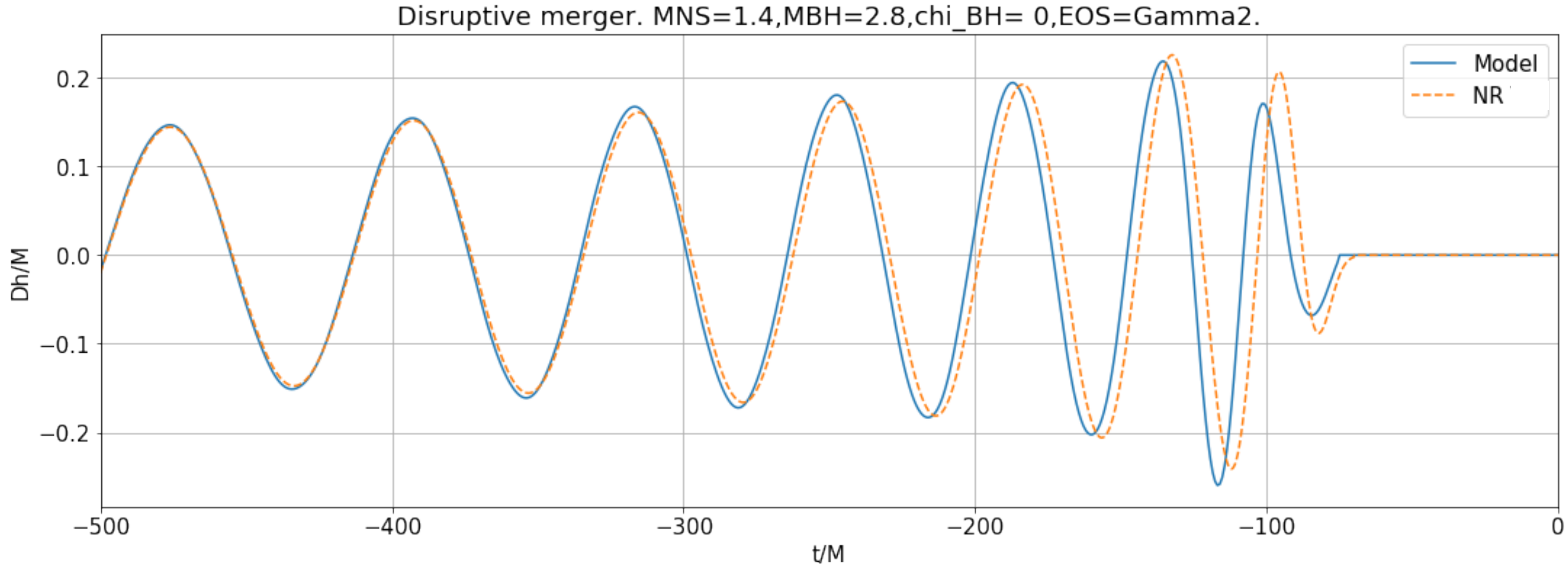
Waveforms for NSBH: disruptive case (contd.)

(Matas, AB, Dietrich, Hinderer & Pürrer in prep 19)



mass ratio = 2

SXS NR waveform



Waveforms for NSBH: non-disruptive case

$$\tilde{h}(f) = \mathcal{A}(f)\, e^{i\varphi(f)} \qquad \mathcal{A}(f) = \mathcal{A}_{\rm SEOBNRT}(f)\, w^{-}_{f_0,\sigma} + \mathcal{A}_{\rm RD}\, w^{+}_{f_0,\sigma} \qquad w^{\pm}_{f_0,\sigma} = \frac{1}{2}\left[1 \pm \tanh\left(\frac{4(f-f_0)}{\sigma}\right)\right]$$

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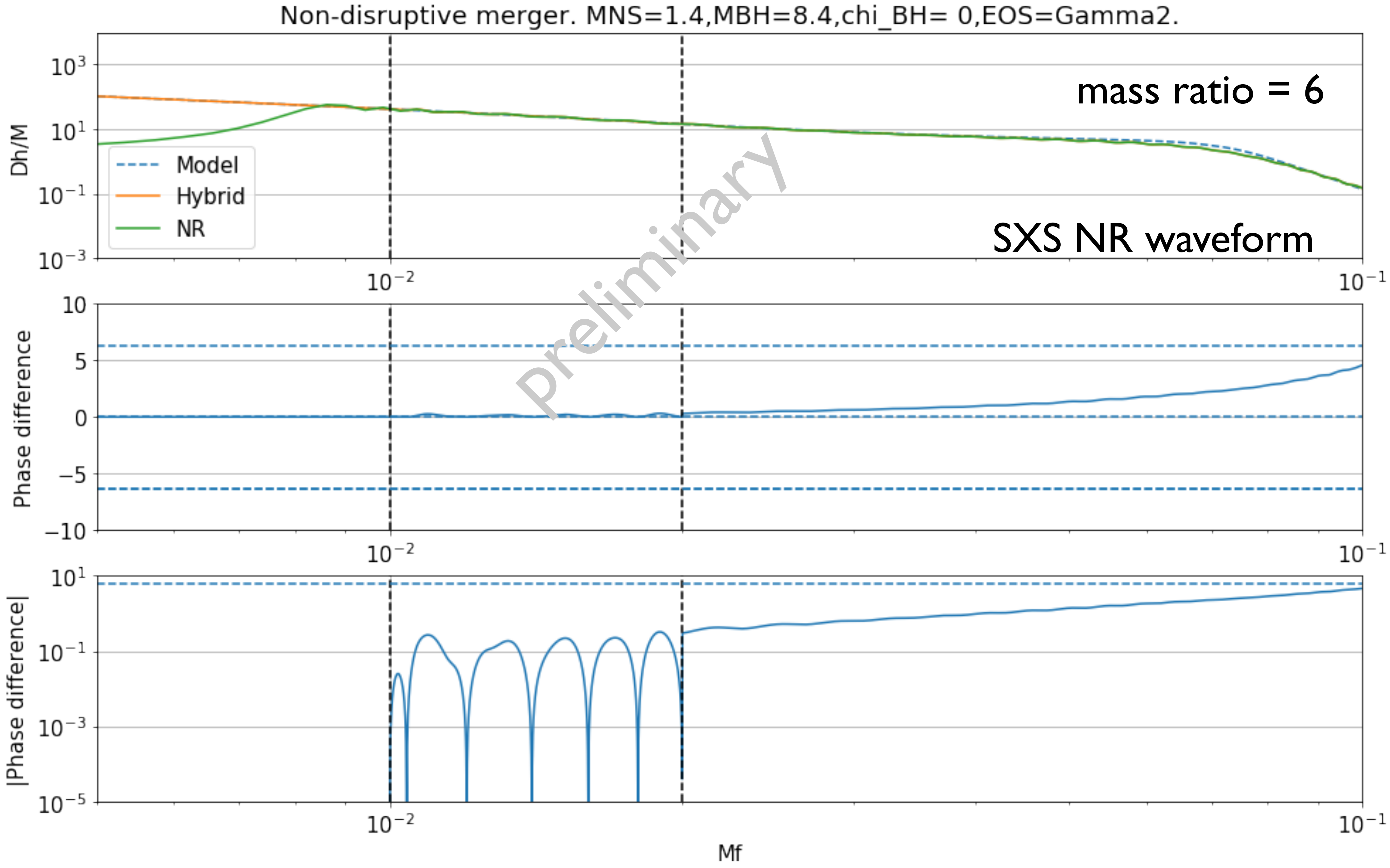
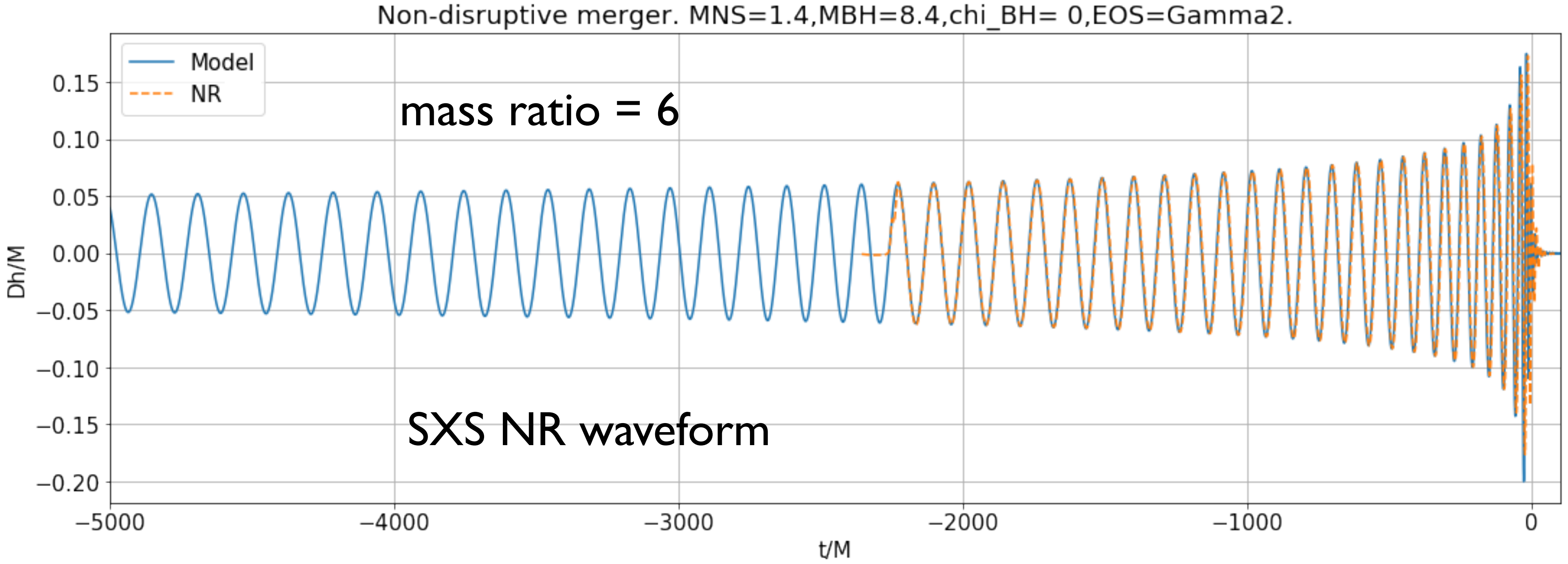


mass ratio = 6

SXS NR waveform

Waveforms for NSBH: non-disruptive case (contd.)

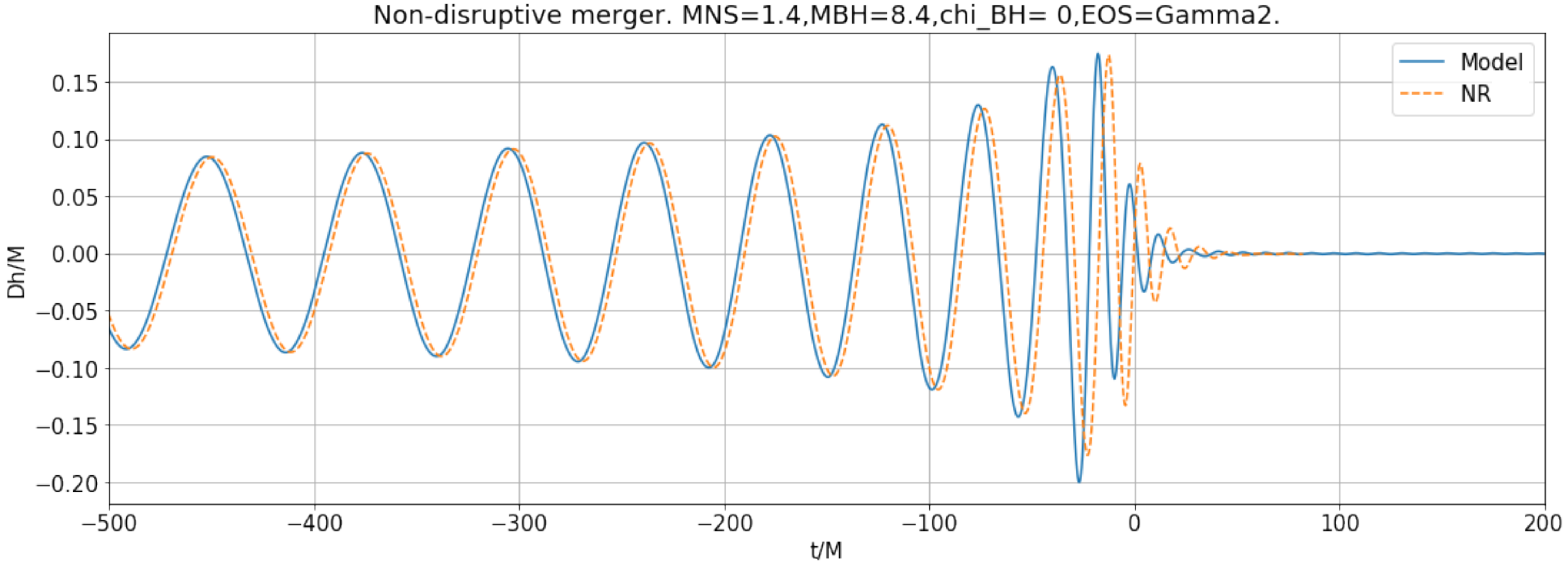
(Matas, AB, Dietrich, Hinderer & Pürrer in prep 19)



Non-disruptive merger. MNS=1.4,MBH=8.4,chi_BH= 0,EOS=Gamma2.

mass ratio = 6

SXS NR waveform

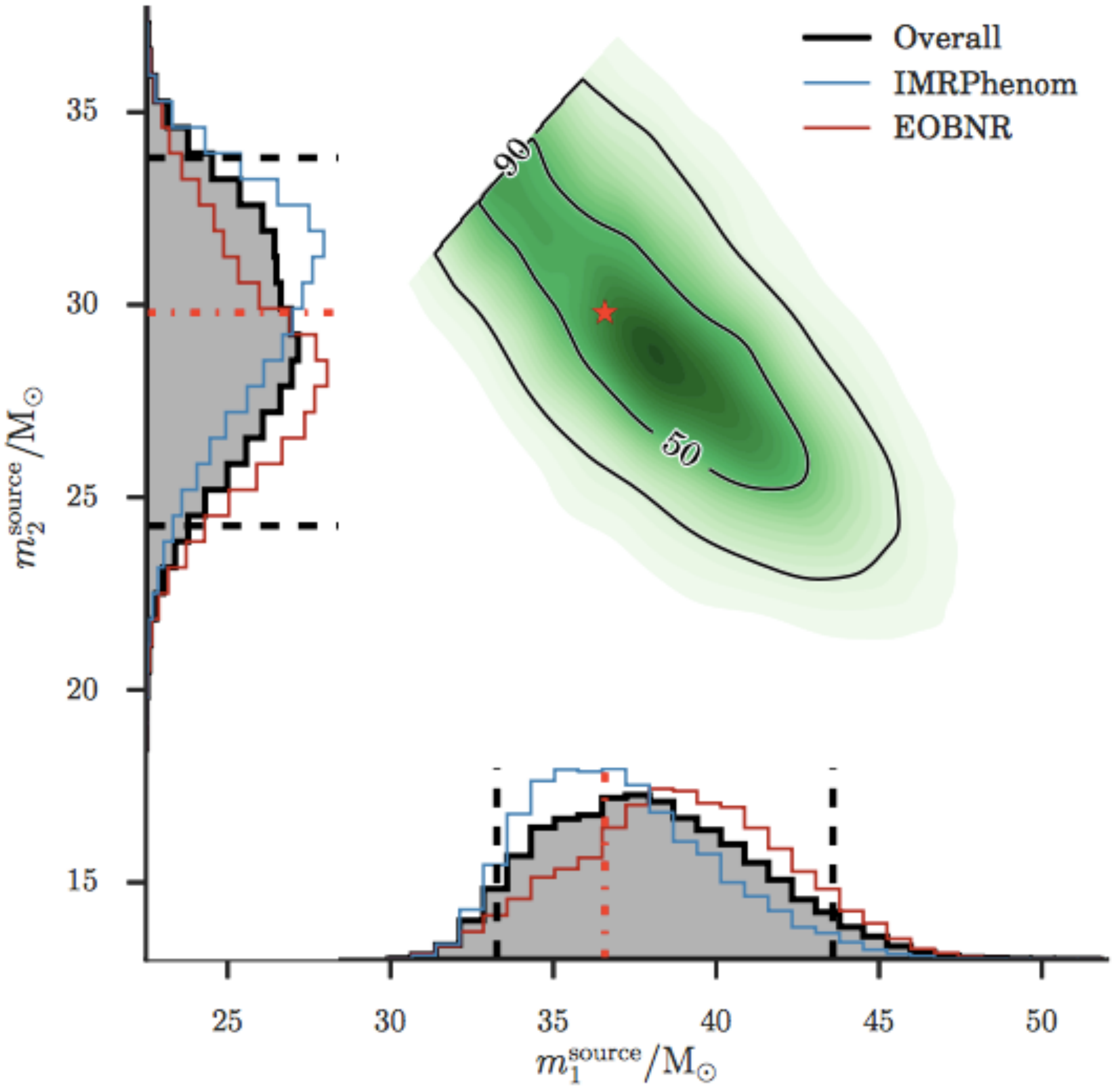


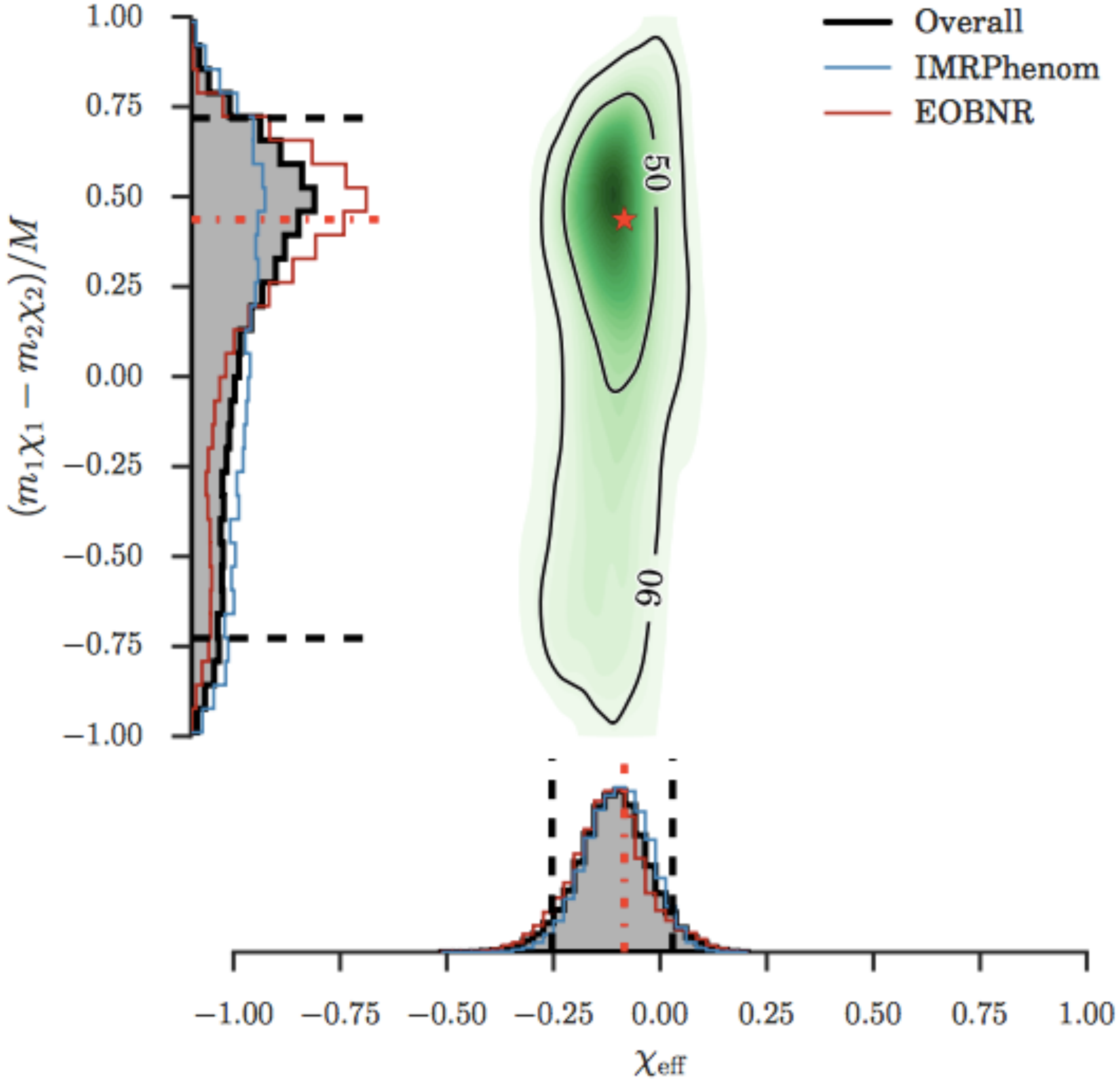
Non-disruptive merger. MNS=1.4,MBH=8.4,chi_BH= 0,EOS=Gamma2.

Systematics of waveform models used in O1 & O2

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

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



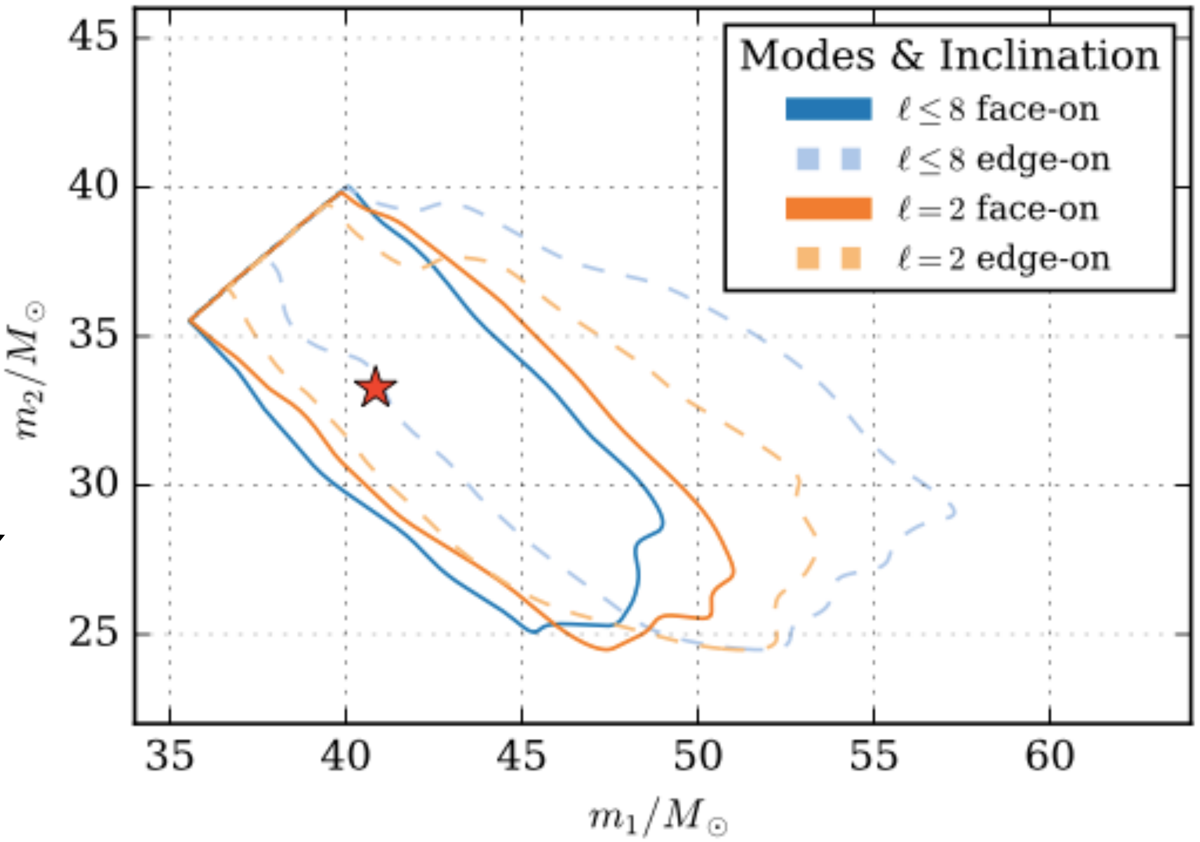


- **Overall, no evidence for systematic bias** relative to the statistical error of original parameter recovery of GW150914.

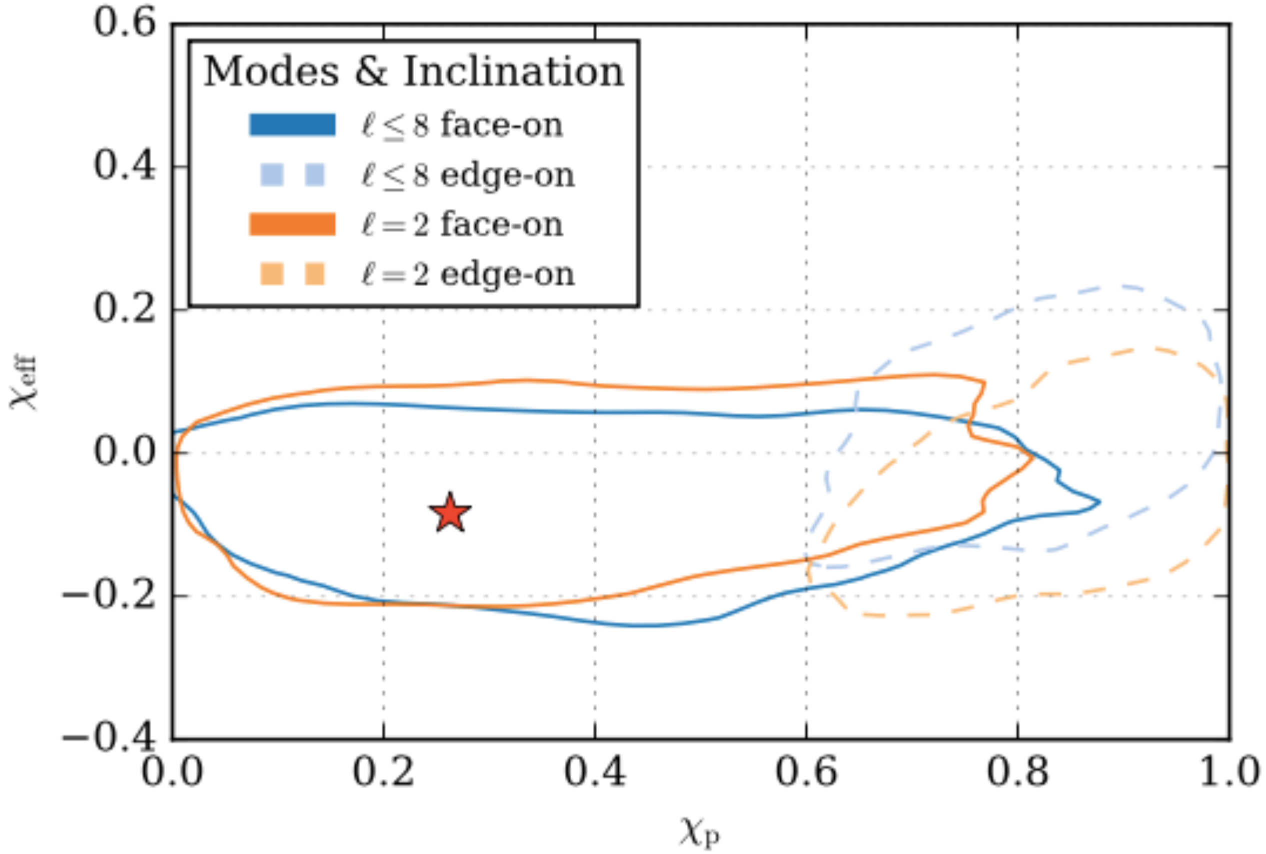
Systematics of waveform models used in O1 & O2 (contd.)

(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)

(see also Kumar et al. 18 using NR surrogate models)

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

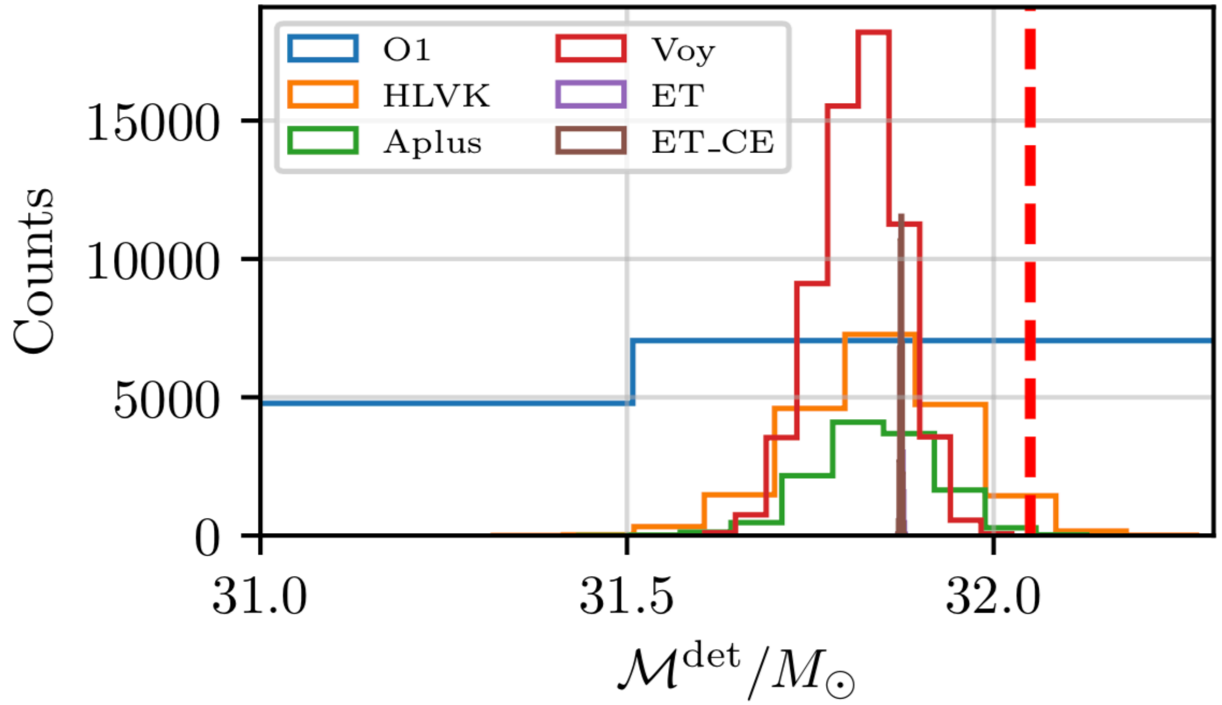
Systematics due to modeling for GW150914-like event

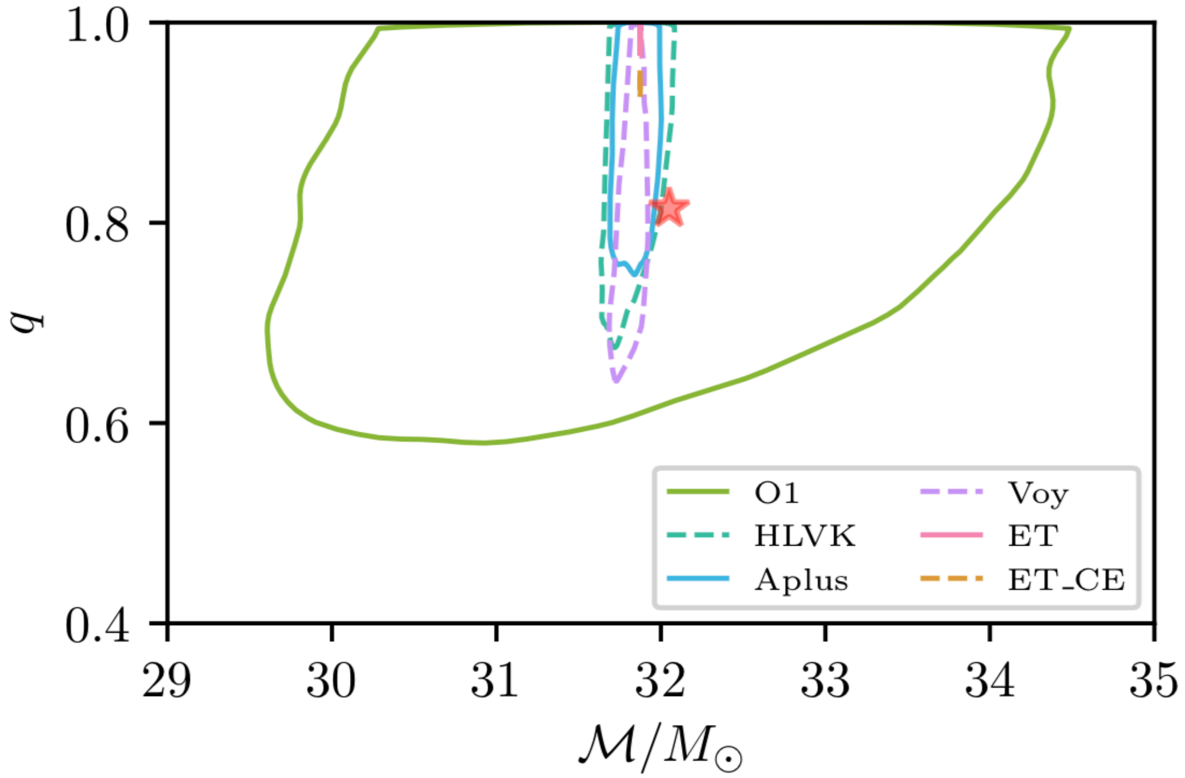
- Synthetic GW signal of a **binary black hole** at **400 Mpc** is **injected** in Gaussian noise with **aLIGO design-sensitivity** noise-spectral density **(SNR ~ 70)**.

- **Inference** with **one** of currently used waveform models (IMRPhenom).

(Pürrer & Haster in prep 19)

- **GW150914-like NR signal** is injected





Systematics due to modeling for GW150914-like event (contd.)

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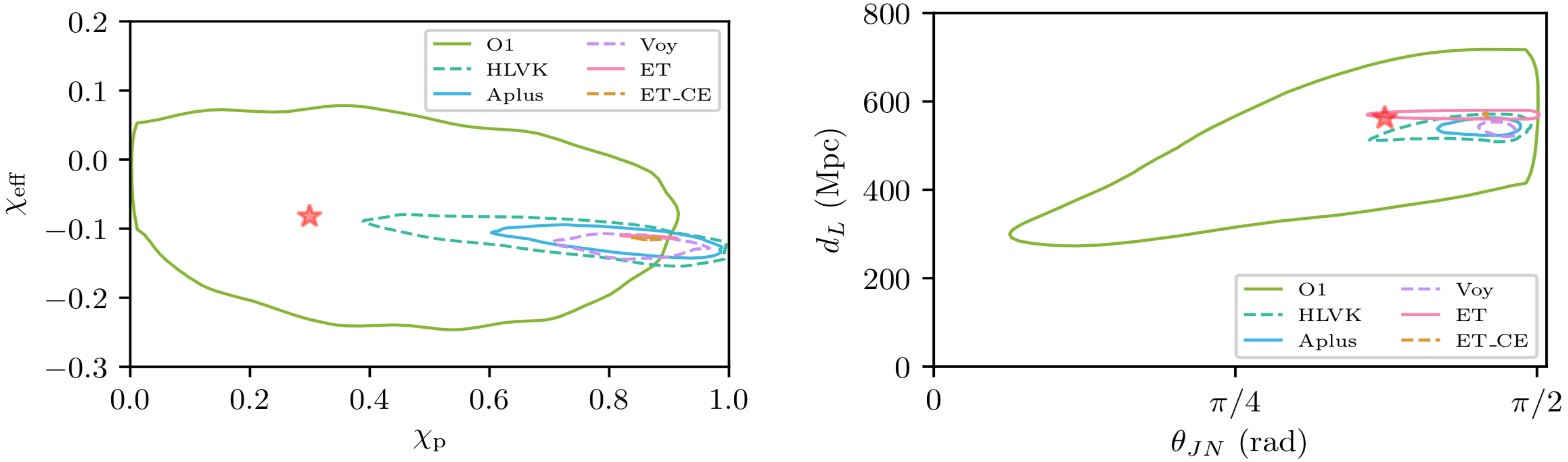


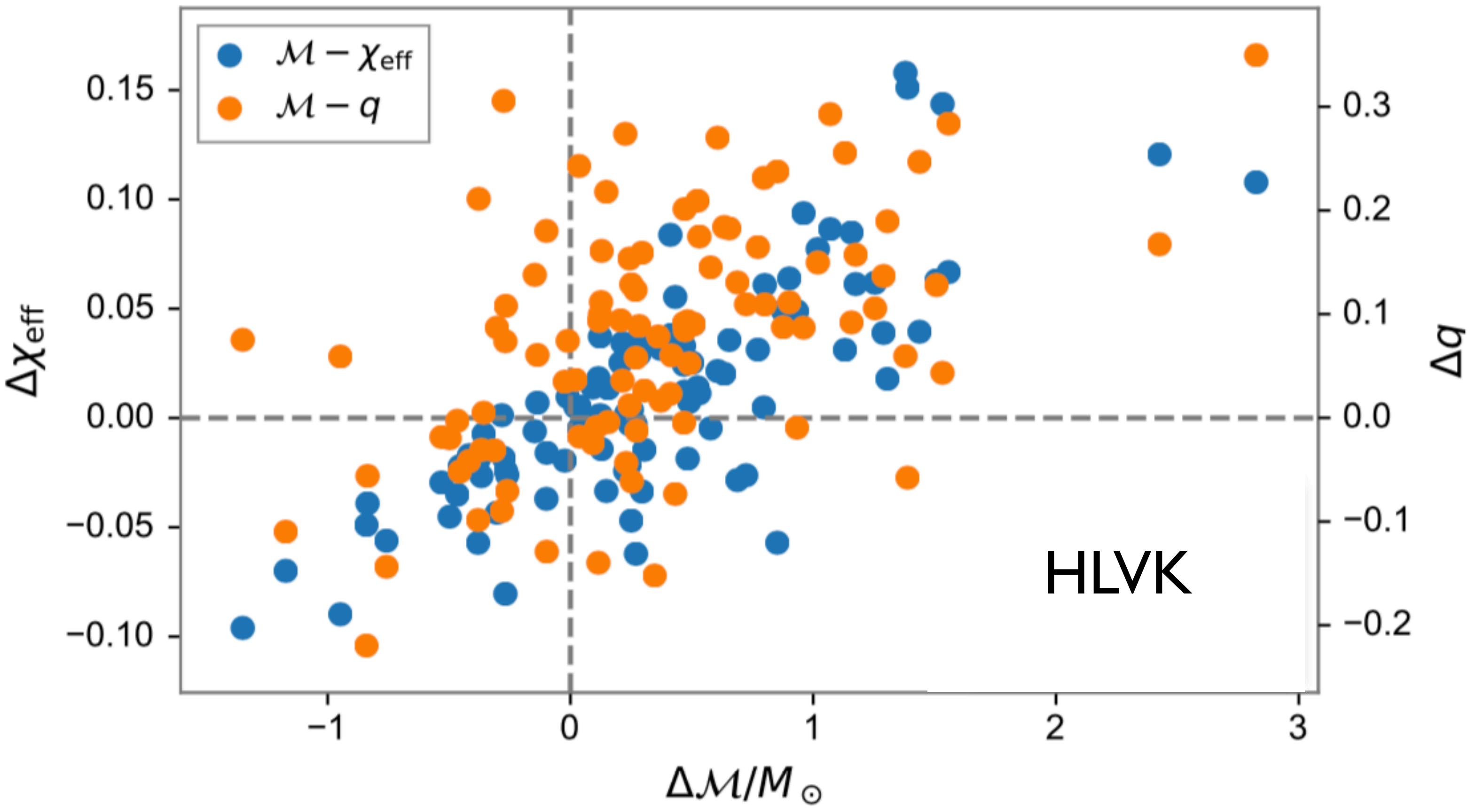
Systematics due to modeling using population

- **Inference** with **one** of currently used waveform models (IMRPhenom).

(Pürrer & Haster in prep 19)

- **Population of 100 precessing NR signals** is injected

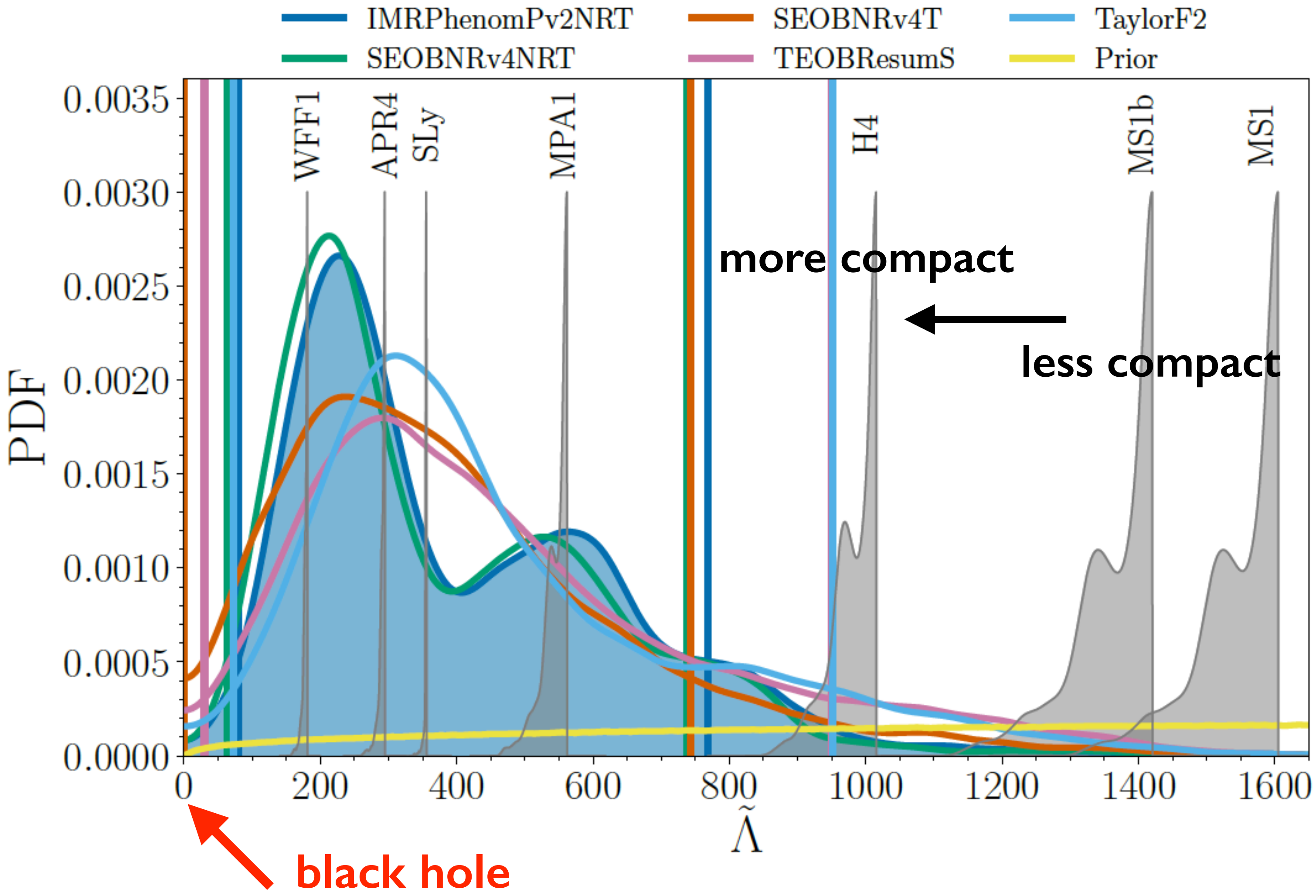
mass ratio = 1-2
spins < 0.8



Constraining NS equation of state with GW170817

(Abbott et al. arXiv:1811.12907)

$$|\chi| \leq 0.05$$



more compact

less compact

black hole

Depends on EOS & compactness

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

- **Effective tidal deformability** enters **GW phase at 5PN order:**

$$\tilde{\Lambda} = \frac{16}{13}\frac{(m_1+12m_2)m_1^4\Lambda_1 + (m_2+12m_1)m_2^4\Lambda_2}{(m_1+m_2)^5}$$

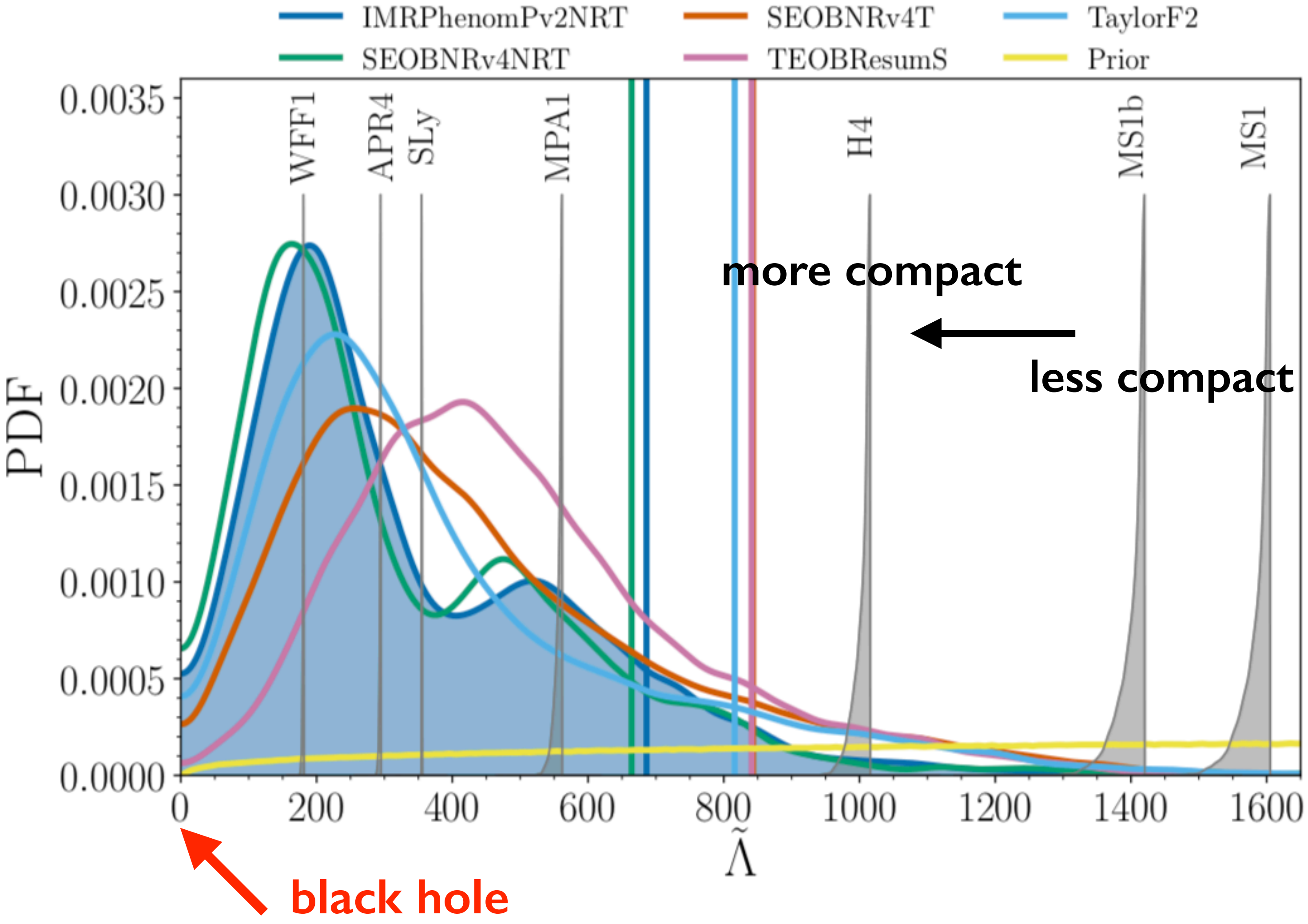
$$\tilde{\Lambda} : 330^{+438}_{-251}$$ @ 90% CL

- Current **measurements** of tidal effects **dominated by statistical** error, but **inference** with **PN inspiral-only** waveform somewhat **stands out.**

Constraining NS equation of state with GW170817

(Abbott et al. arXiv:1811.12907)

$$|\chi| \leq 0.89$$



more compact

less compact

black hole

Depends on EOS & compactness

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

- **Effective tidal deformability** enters **GW phase at 5PN order:**

$$\tilde{\Lambda} = \frac{16}{13} \frac{(m_1 + 12 m_2) m_1^4 \Lambda_1 + (m_2 + 12 m_1) m_2^4 \Lambda_2}{(m_1 + m_2)^5}$$

$\tilde{\Lambda} : 330^{+438}_{-251}$ @ 90% CL

- Current **measurements** of tidal effects **dominated by statistical** error, but **inference** with **PN inspiral-only** waveform somewhat **stands out**.

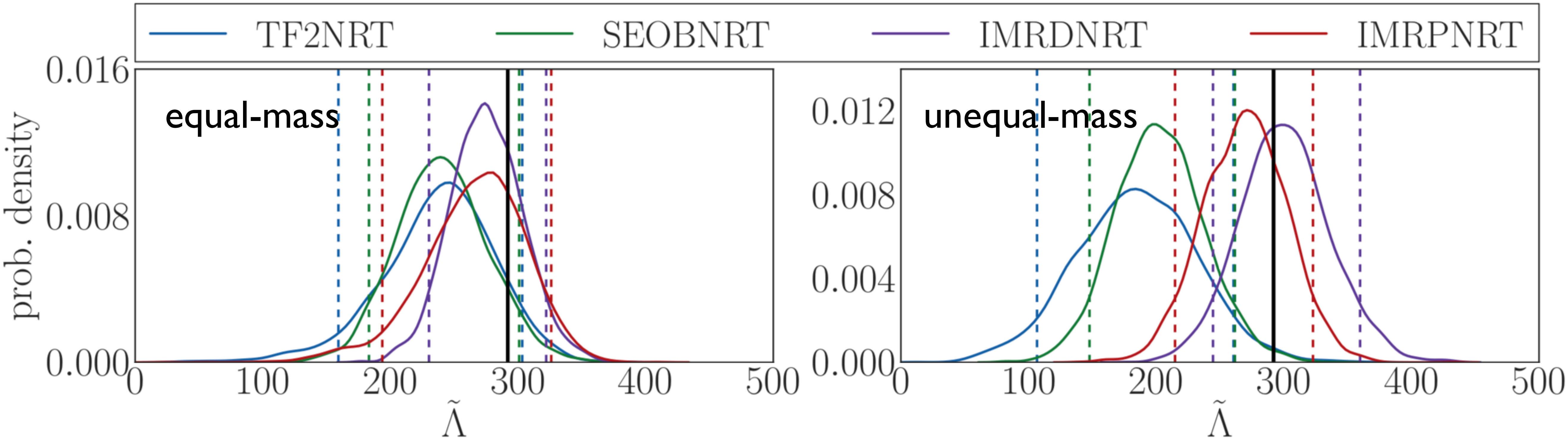
Systematics due to modeling for GW170817-like event

- Synthetic GW signal of a **binary neutron star** at **50 Mpc** is **injected** in Gaussian noise with **aLIGO design-sensitivity** noise-spectral density **(SNR ~ 87)**.

- **Inference** with waveform models that have **same matter effects**, but **baseline point-mass model** is **different**.

(Samajdar & Dietrich 18)

- **IMRPNRT** is injected

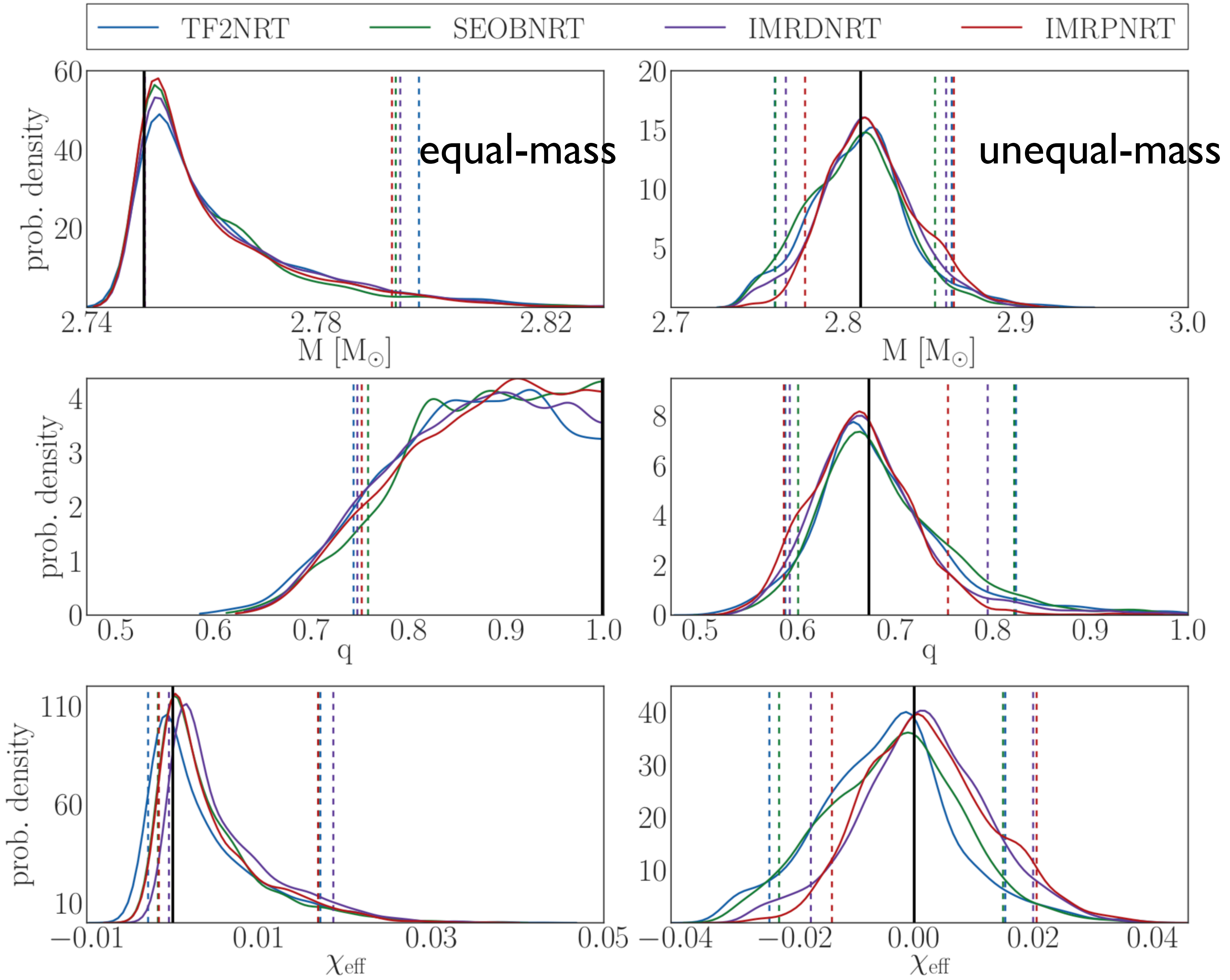


mass ratio = 1.5

Systematics due to modeling for GW170817-like event (contd.)

(Samajdar & Dietrich 18)

- **IMRPNRT** is injected



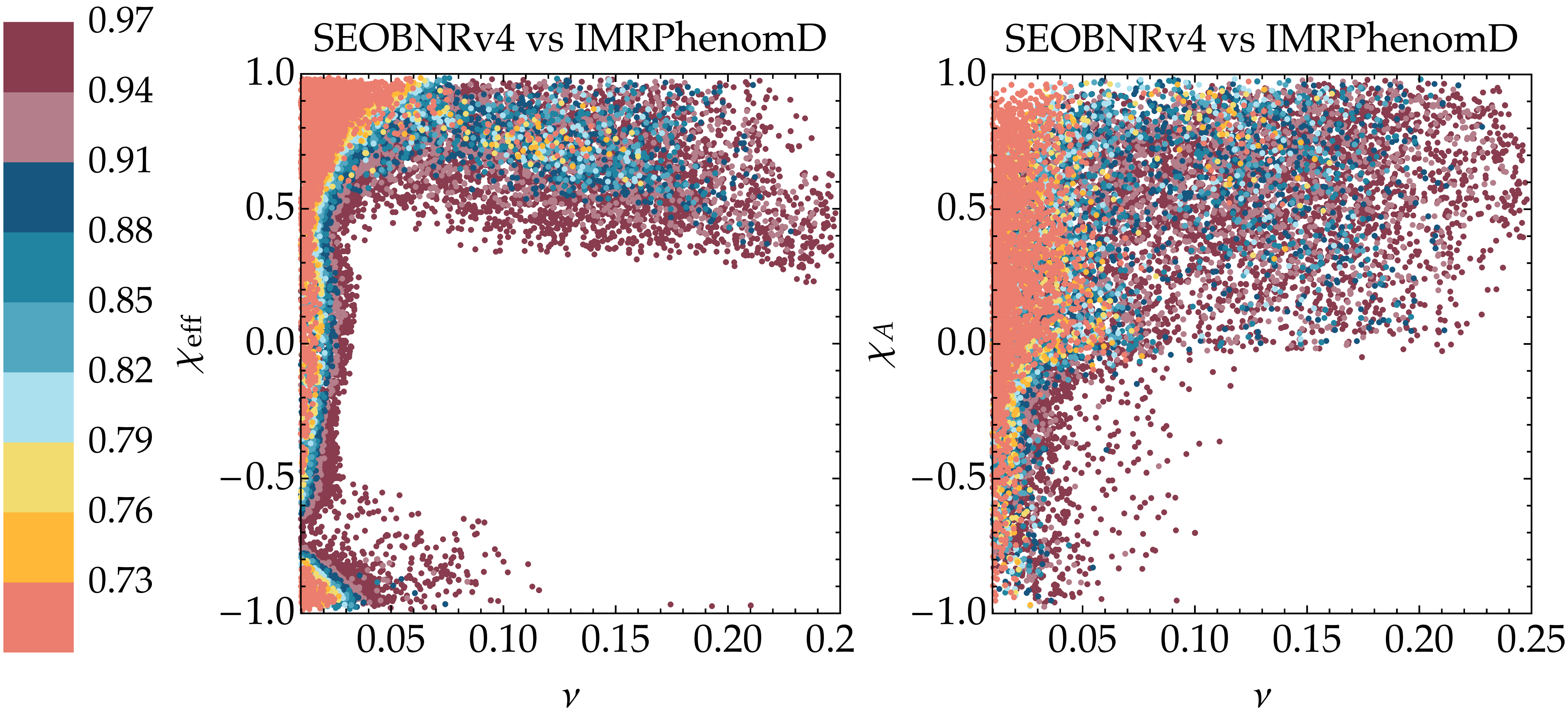
- For highly spinning BNS, **spin-related EOS effects** must be included to avoid biases.

(Harry & Hinderer 18)

Comparing (non-precessing) EOBNR & IMRPhenom models: inference

- **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)*

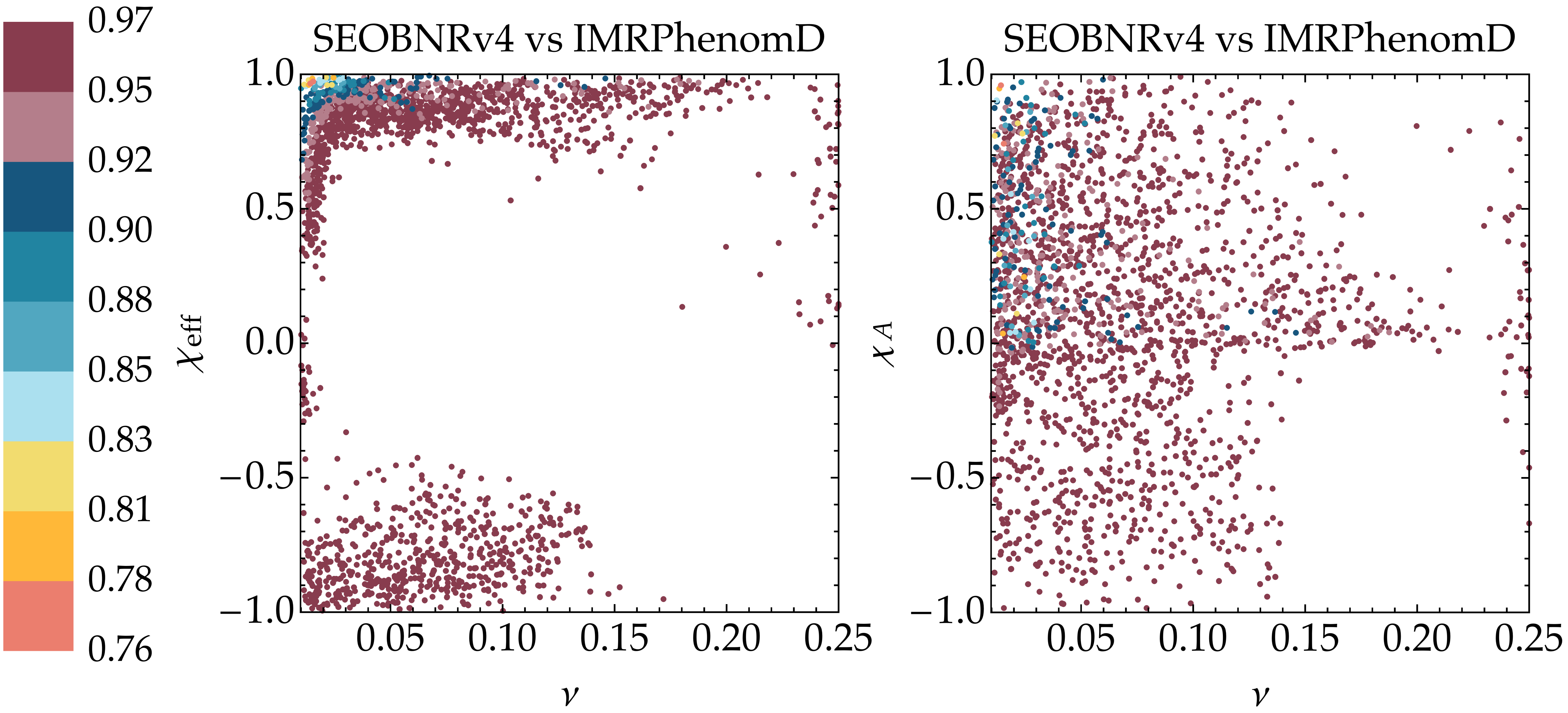


[Note that only 7% of 200,000 points have matches < 97%.]

Comparing (non-precessing) EOBNR & IMRPhenom models: detection

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

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



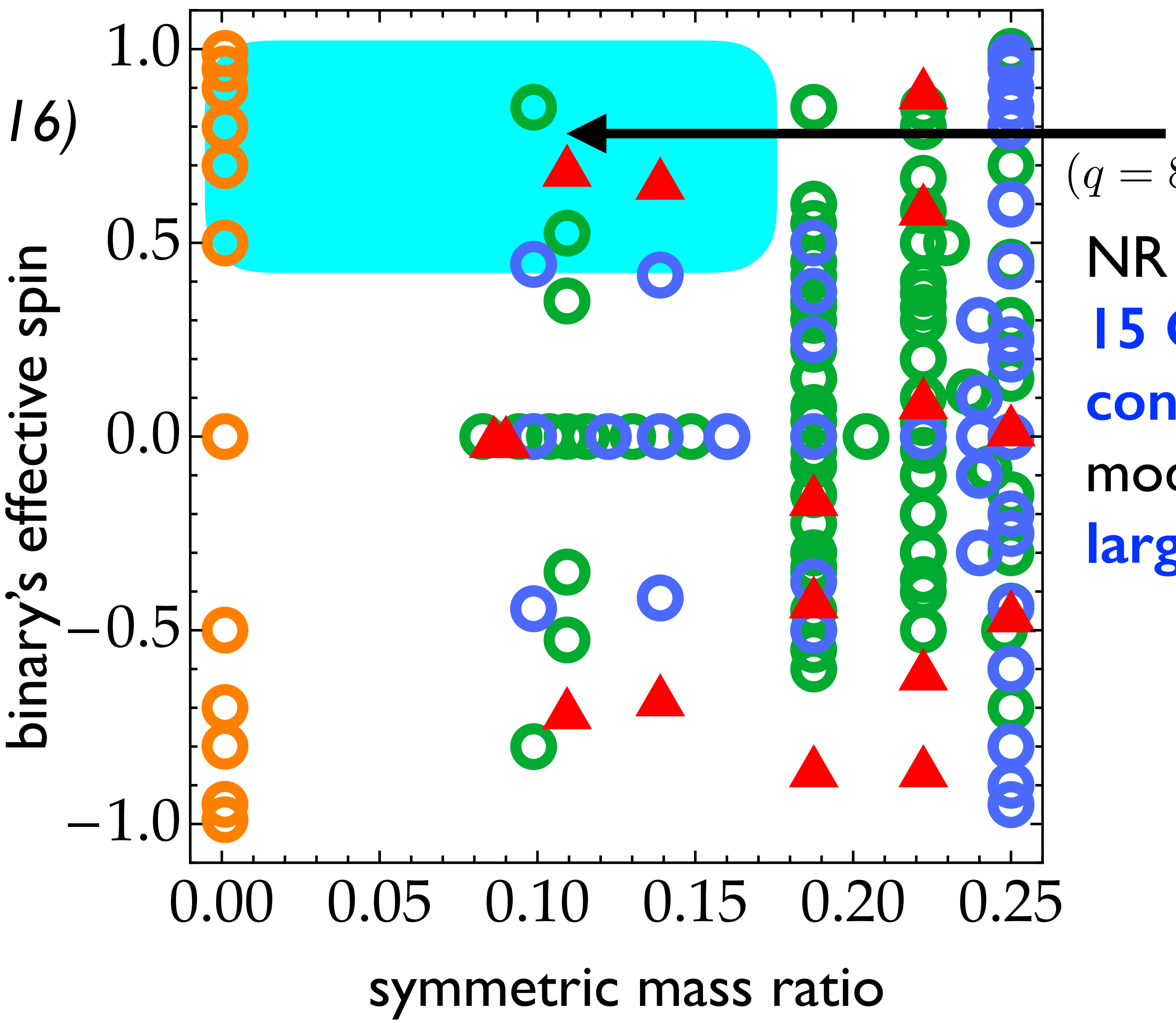
[Note that only 2.1% of 100,000 points have matches < 97%.]

Extending waveform model in all parameter space: systematics

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

141 NR waveforms

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



$(q = 8, \chi_1 = 0.85, \chi_2 = 0.85)$

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

- **Synergistic** use of **NR** codes.

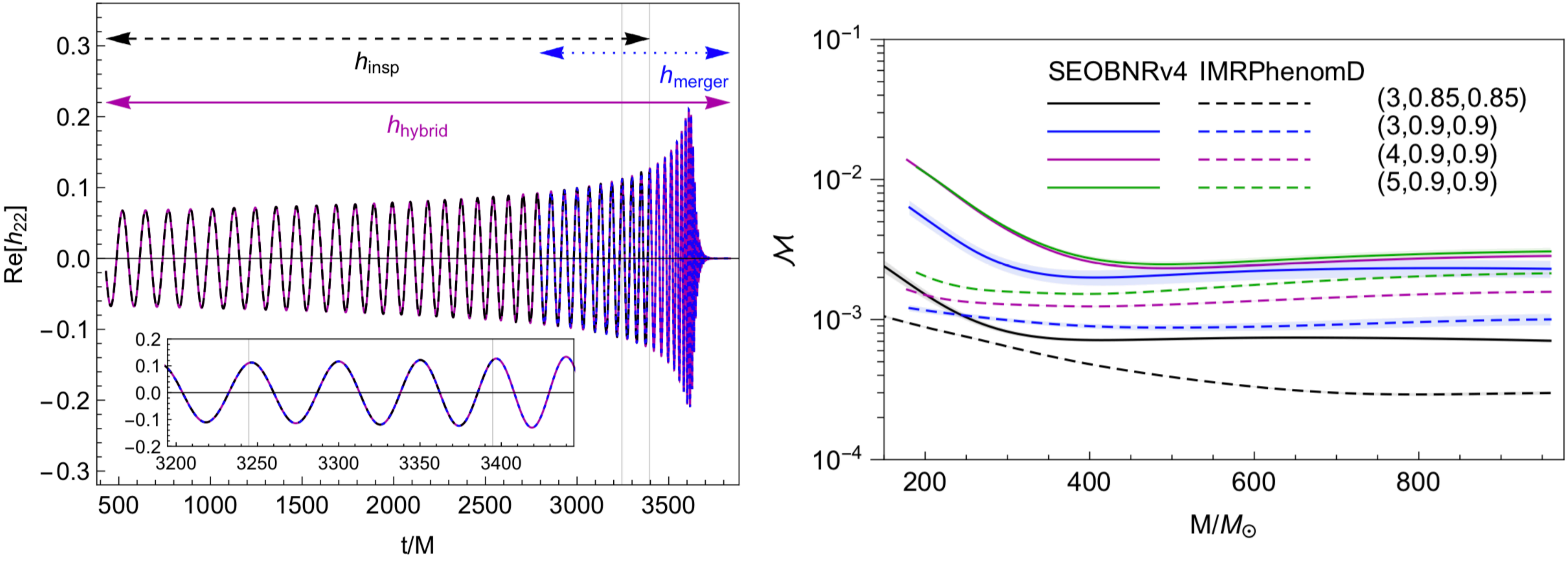
(Hinder, Ossokine, Pfeiffer, AB 18)

- **Surrogate NR models** accurate and efficient, but limited in binary's parameter space and length (unless hybridized with analytical models).

(Blackman et al. 17, Varma et al. 18, 19)

“Temporary” solution? Waveforms combining NR codes

- **Synergistic** use **of finite-difference** (Einstein Toolkit, ET) & pseudo **spectral** (SpEC) **NR codes.**

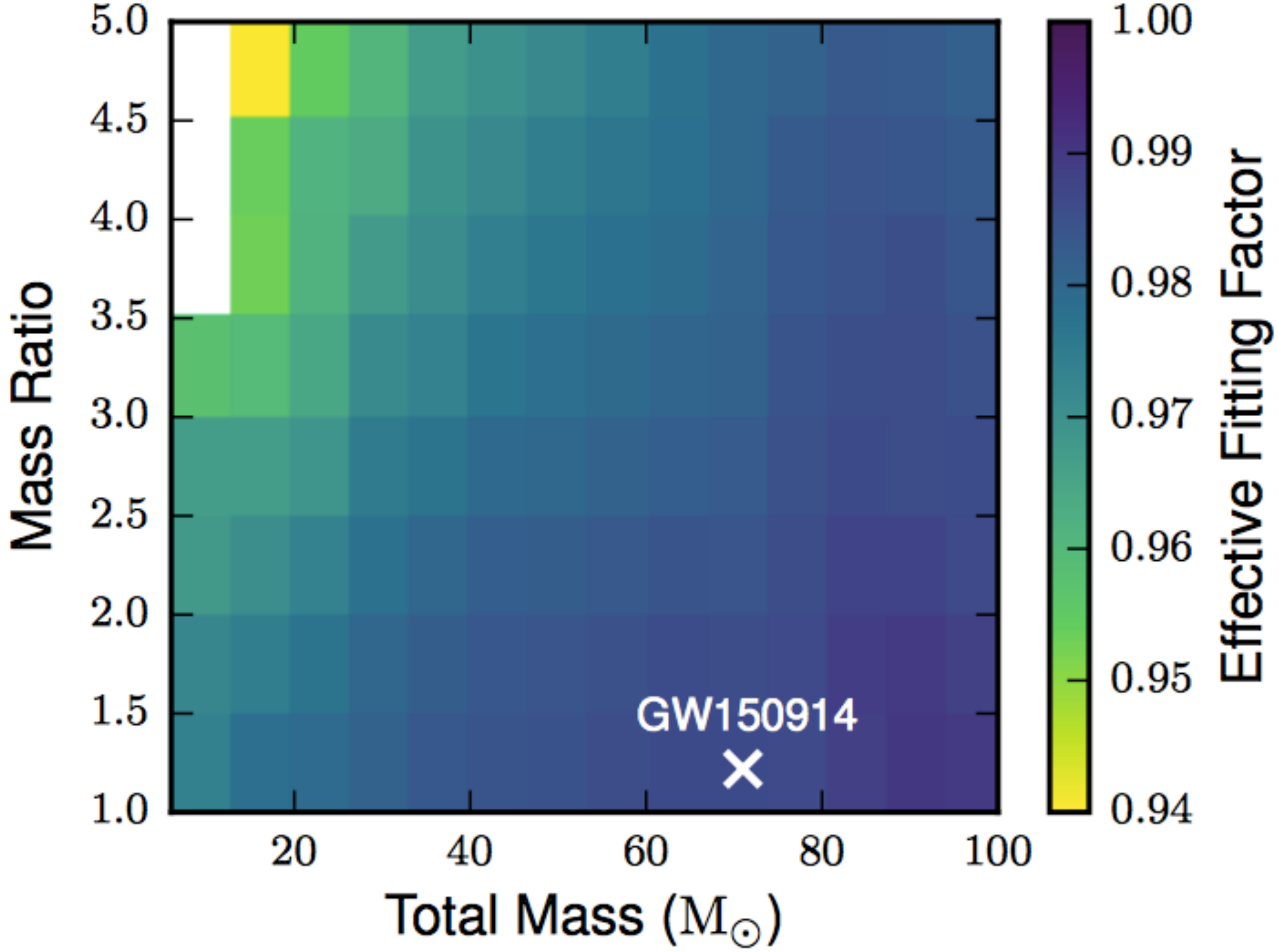


(Hinder, Ossokine, Pfeiffer & AB 18)

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)

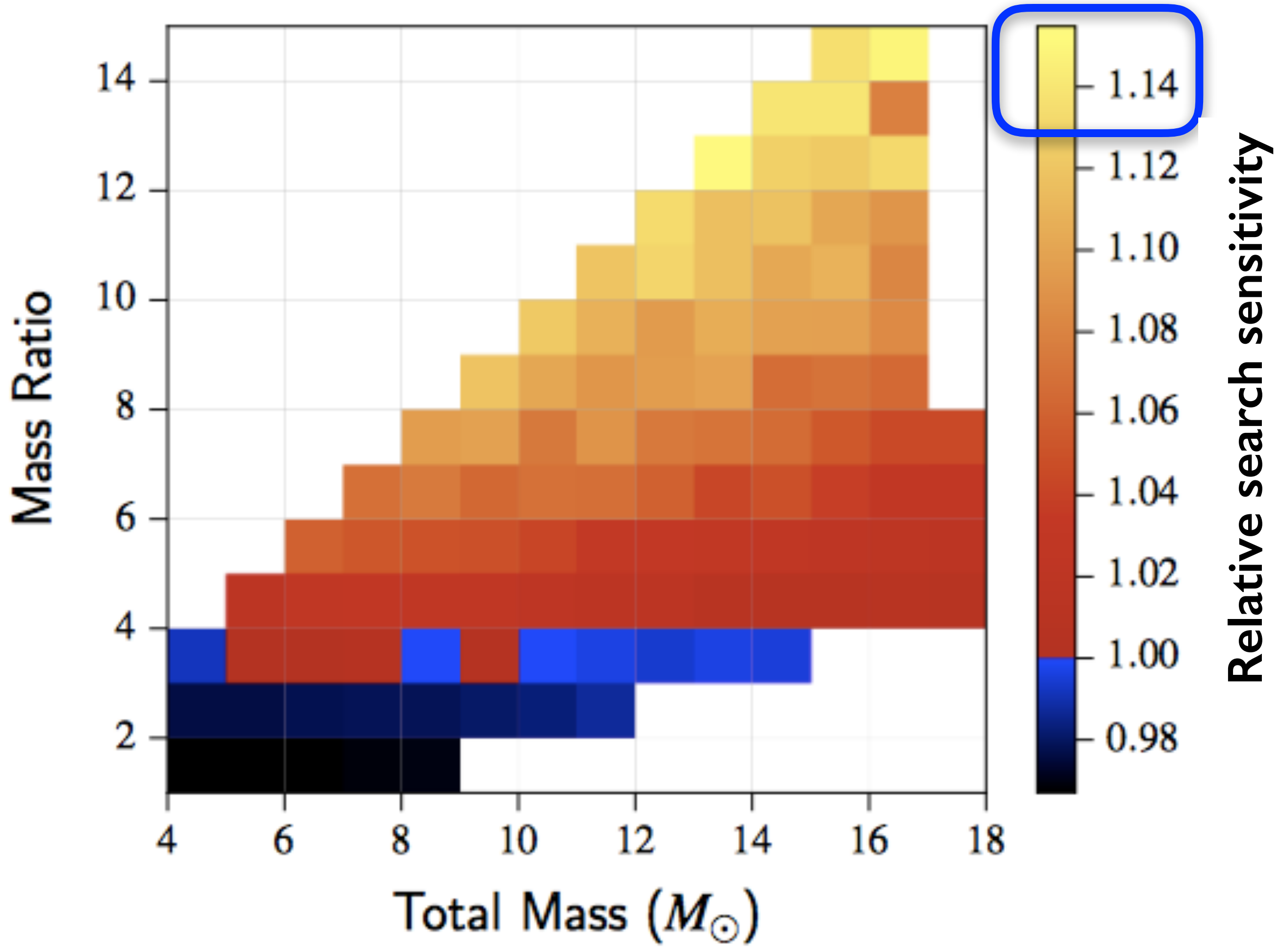
Should we employ spin precessing searches for NSBHs ?

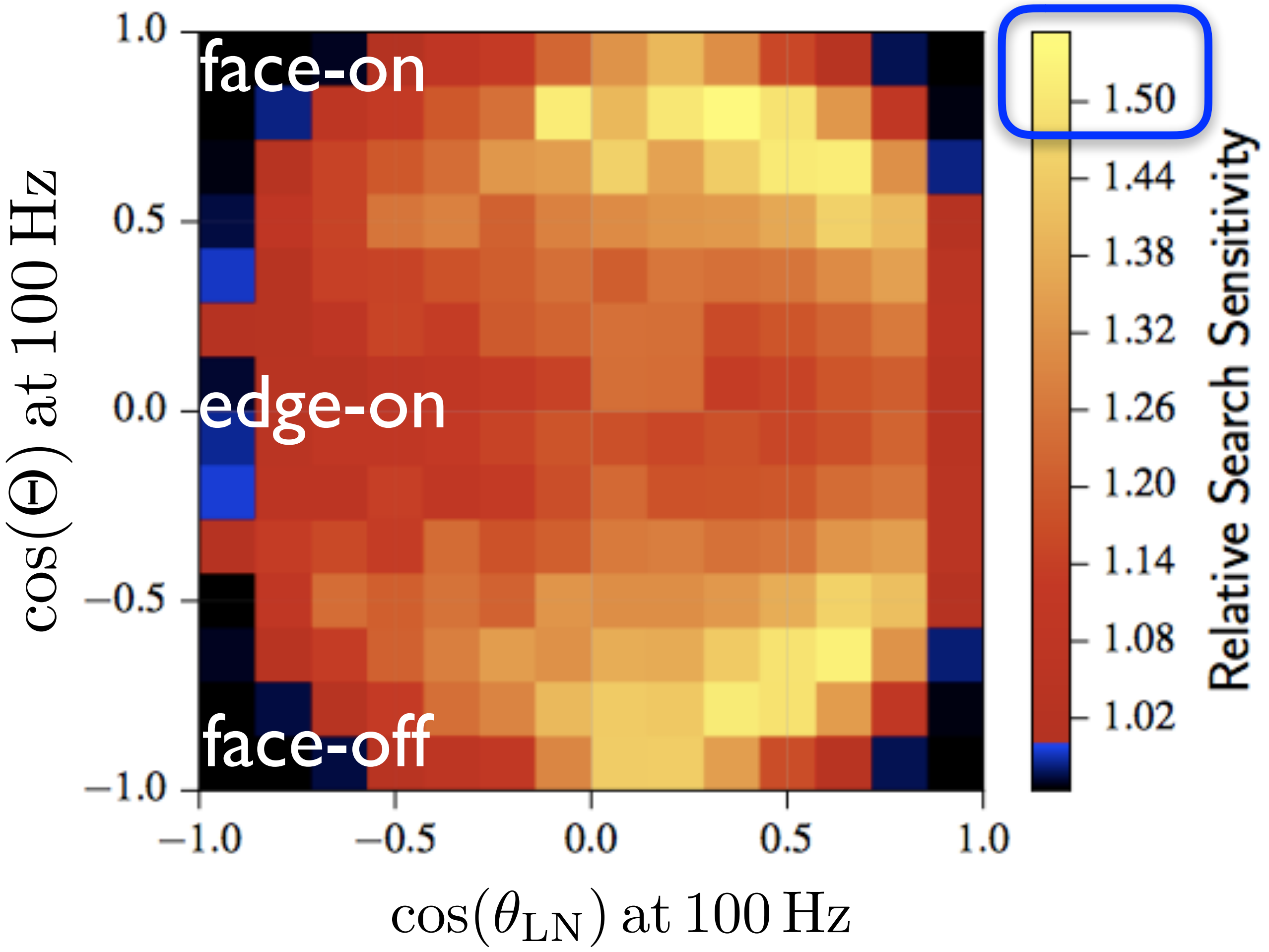
(Harry, Privitera, Bohe' & AB 16)

- **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	$[1, 3]\ M_\odot$
$\|\chi_1\|$	$[0, 1.0]$
$\|\chi_2\|$	$[0, 0.05]$





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

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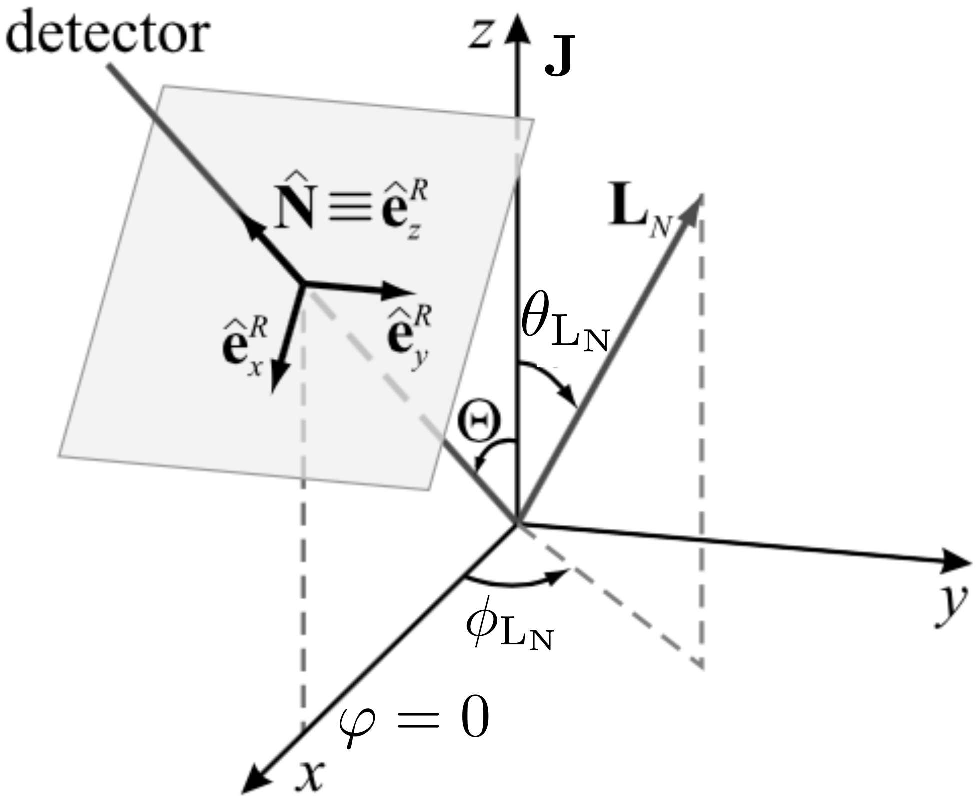

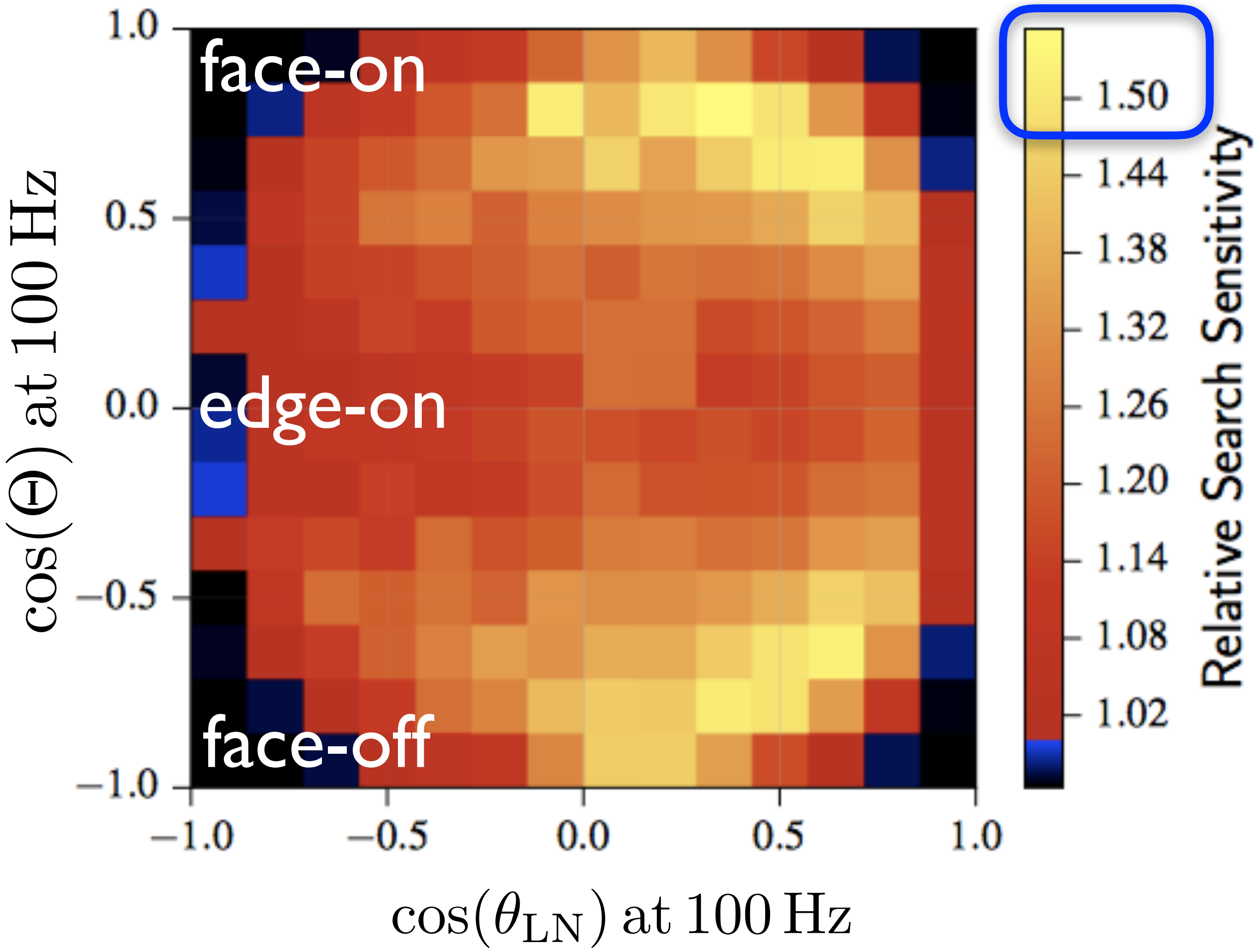

- Mergers with **misaligned spins** provide unique **astrophysical insights** into **formation** scenarios.

Toward the era of precision gravitational-wave astrophysics

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

- We have **not missed "loud" events**. For **sub-threshold events**, it might be **critical** to use waveforms models with **more physics**.

- So far, **inference from GW** observations is **dominated by statistical** instead of modeling **error**.

- **Highest priorities:**
  - **NSBH** modeling
  - inclusion of **eccentricity** and **spins** in **IMR waveforms**
  - NR simulations with **large mass ratios** (> 4) **and large spins** (> 0.8), with **larger number** of GW **cycles** (> 50)

- More **extensive** studies to **assess *real* biases** of waveform models are needed, comparing models **among themselves** and **against NR**.