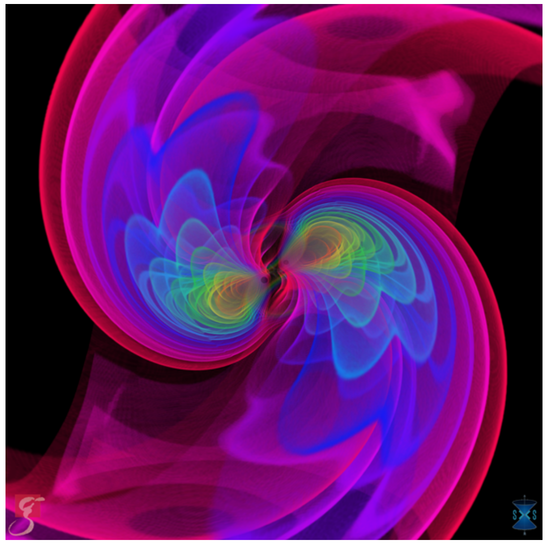
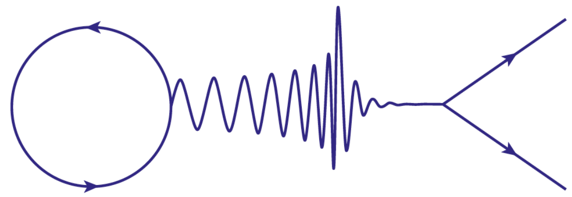
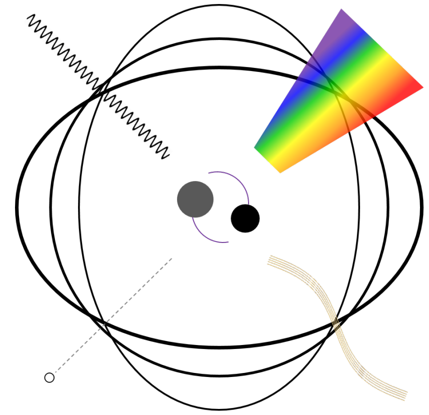
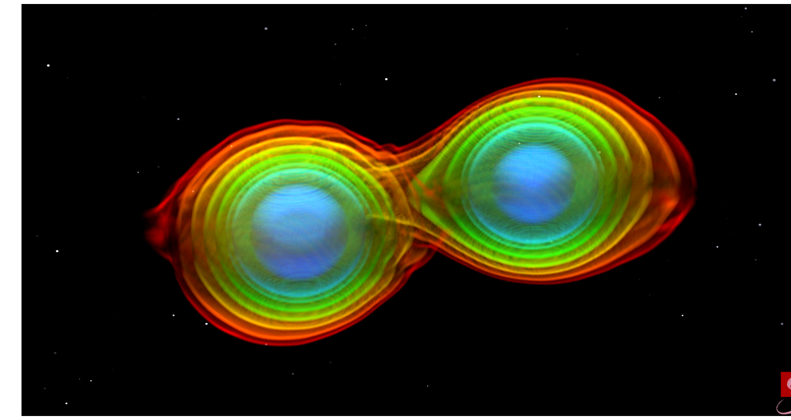








Ever More Physics in Gravitational Waveforms

Alessandra Buonanno

Max Planck Institute for Gravitational Physics

(Albert Einstein Institute)

Department of Physics, University of Maryland

"Black Holes and Neutron Stars with Gravitational Waves", YKIS2019, YITP   Oct 8, 2019

Outline

- Observing gravitational waves and inferring astrophysical/physical information hinge on our ability to make precise predictions of two-body dynamics and gravitational radiation.

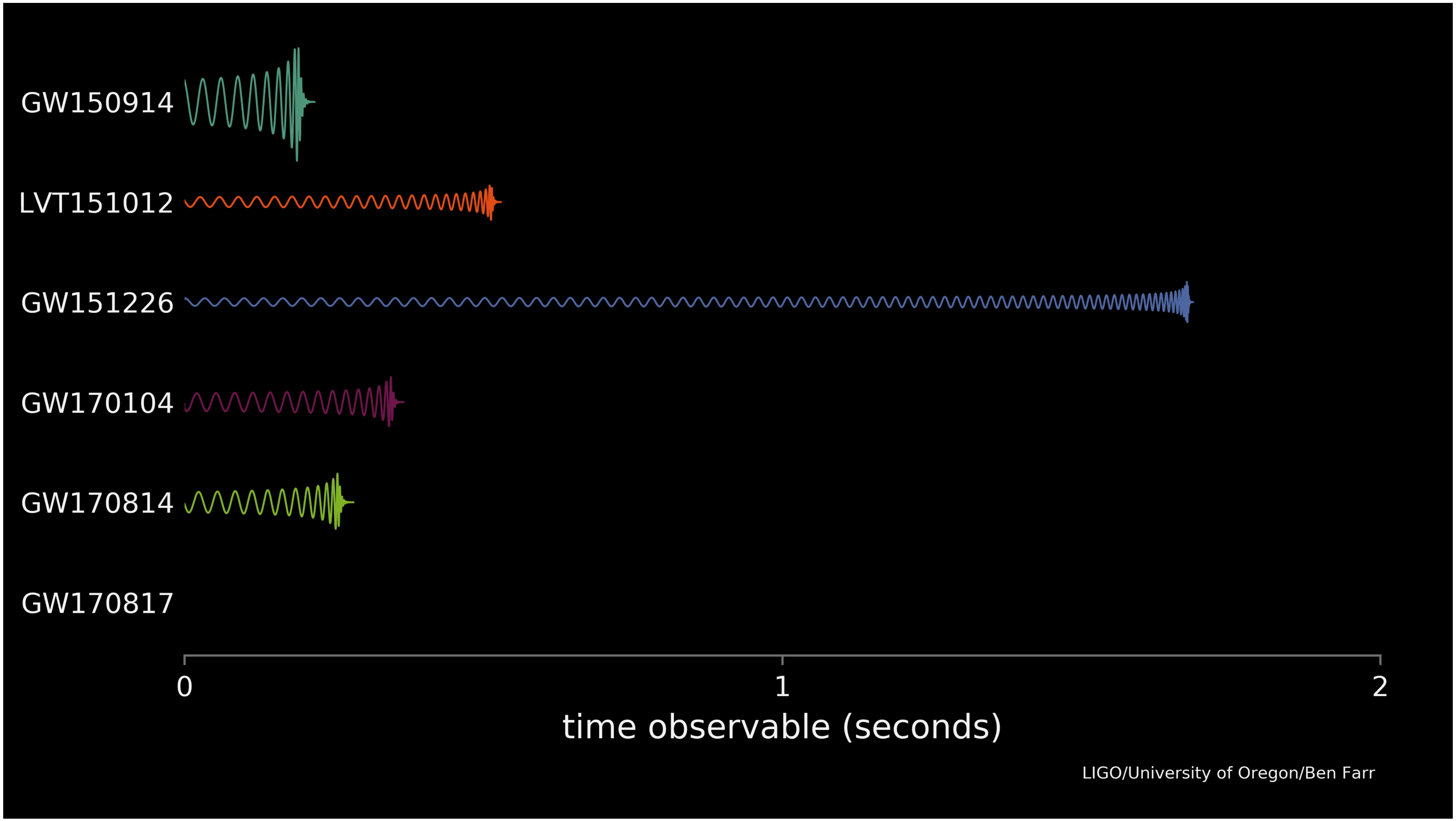
- Are we missing any gravitational-wave signal with LIGO and Virgo detectors? Are current inference studies in any way affected by modeling error?

- Our ability to infer more precise cosmological, fundamental/nuclear physics and astrophysical information, and carry out more stringent tests of GR require more accurate waveforms and with more physics.

- Status of waveform modeling that includes spin-precession, higher modes, matter and eccentricity.

- What are the highest priorities, and what are the challenges in view of more sensitive detectors.

Shape/length of signals detected by LIGO/Virgo in O1 & O2



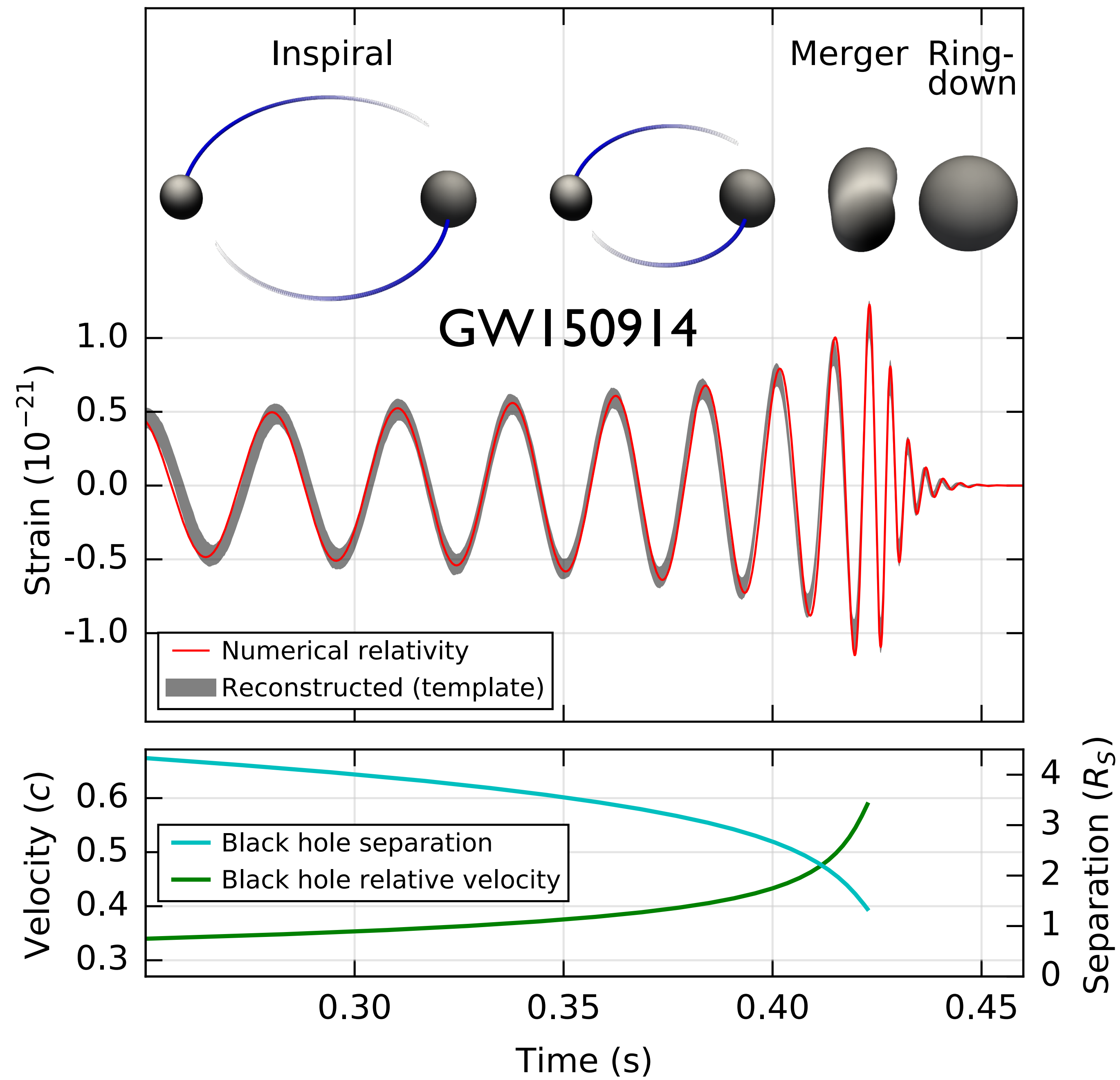
(credit: B. Farr)

- **GW170608 and four GWs** recently announced are **missing from video.**

Characteristics of binary black-hole coalescence

- **Early inspiral:** low velocity & weak gravitational field.
- **Late inspiral/plunge:** high velocity & strong gravitational field.
- **Merger:** nonlinear & non perturbative effects; rapidly varying gravitational field
- **Ringdown:** excitation of quasi-normal modes/spacetime vibrations.

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



Phase/amplitude evolution **encodes unique information** about the source

Black holes of radius of 90 km at separation of 350 km are making 75 orbits per second before merging.

Some outstanding questions in physics and astrophysics

- What are the **properties** of **dynamical spacetime** (gravitational waves)?
- Is **General Relativity still valid** in the highly dynamical, strong-field regime?
- Are **Nature's black holes** the black holes predicted in the **General** theory of **Relativity**?
- How **black holes** and **neutron stars form**, which is their **astrophysical environment**, and how do they **form binaries**?
- How **matter behaves** under **extreme density and pressure**? Can **dark matter** make compact objects?
- What's the **origin** of the **most energetic phenomena** in our Universe?
- Can we discover **new fundamental particles,** and **infer** the **cosmological model of our Universe** through gravitational-wave observations?

Solving two-body problem in General Relativity

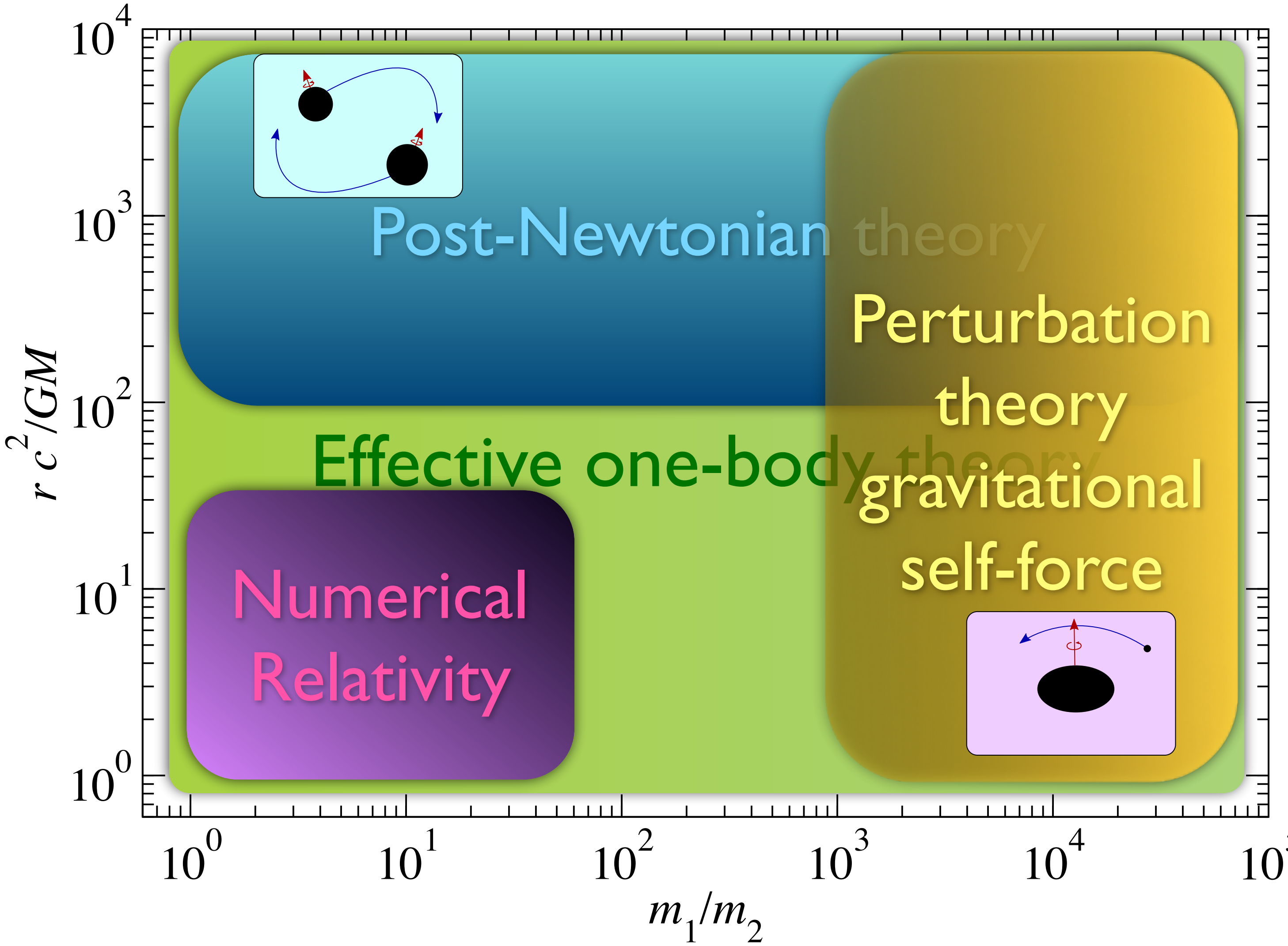
$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \frac{8\pi G}{c^4} T_{\mu\nu}$$

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

- Einstein's field equations can be solved:

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

bound orbits: $v^2/c^2 \sim GM/rc^2$



(AB & Sathyaprakash 14)

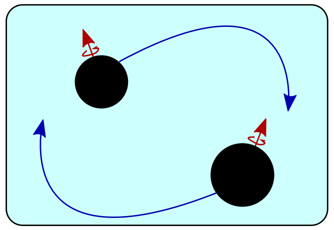
- **Synergy** between **analytical** and **numerical relativity** is **crucial.**

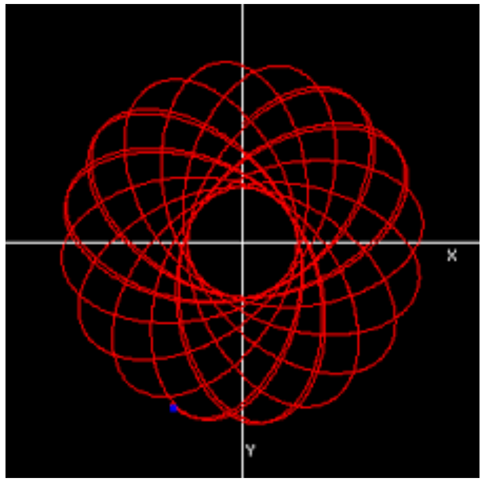
Post-Newtonian approximation

- **First introduced in 1917** *(Droste & Lorentz 1917, … Einstein, Infeld & Hoffmann 1938)*

(Blanchet, Damour, Iyer, Faye, Bernard, Bohe', AB, Marsat; Jaranowski, Schaefer, Steinhoff; Will, Wiseman; Flanagan, Hinderer, Vines; Goldberger, Porto, Rothstein; Kol, Levi, Smolkin; Foffa, Sturani …)

Small parameter is $v/c \ll 1$, $v^2/c^2 \sim GM/rc^2$
large separation and slow motion, natural for **bound orbits**





$$H_{\rm N}(\mathbf{p},\mathbf{r}) = \frac{\mu}{2}\mathbf{p}^2 - \frac{GM\mu}{r}$$

$$H_{\rm 1PN}(\mathbf{p},\mathbf{r}) = \frac{\mu}{8}(3\nu-1)(\mathbf{p}^2)^2 - \frac{\mu}{2}\left[(3+\nu)\mathbf{p}^2 + \nu(\mathbf{n}\cdot\mathbf{p})^2\right]\frac{GM}{r} + \mu\frac{(GM)^2}{2r^2}$$

- Compact object is **point-like body endowed** with time-dependent **multipole moments** (skeletonization).

Small mass-ratio expansion/gravitational self-force formalism

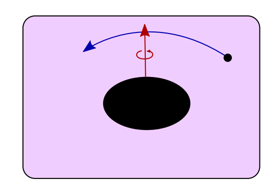
- **First works in 50-70s** *(Regge & Wheeler 56, Zerilli 70, Teukolsky 72)*

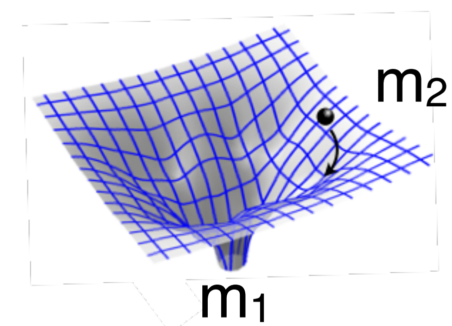
  Small parameter is $m_2/m_1 \ll 1$, $v^2/c^2 \sim GM/rc^2 \sim 1$, $M = m_1 + m_2$

  scattering and bound orbits

  Equation of gravitational perturbations in black-hole spacetime:

$$\frac{\partial^2 \Psi}{\partial t^2} - \frac{\partial^2 \Psi}{\partial r_\star^2} + V_{\ell m} \Psi = S_{\ell m}$$



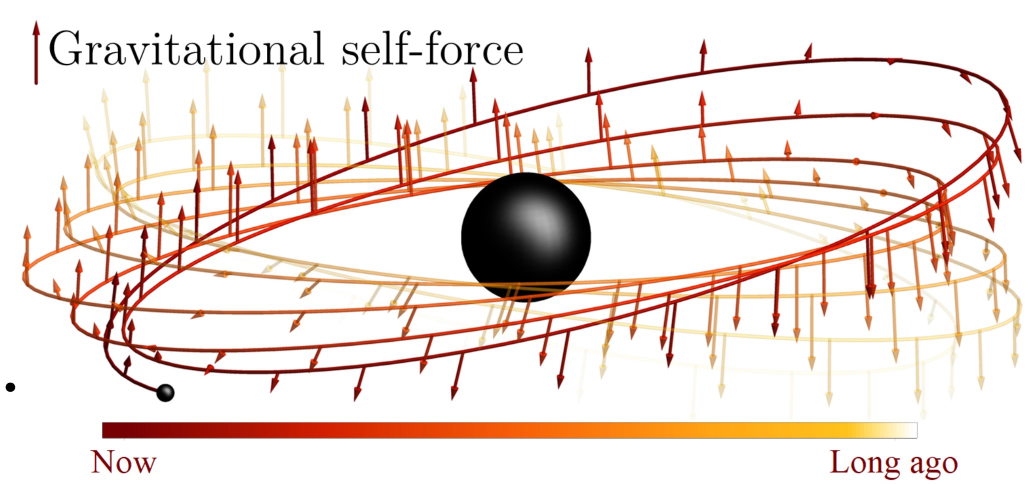


  Computation of Green functions in Schwarzschild/Kerr spacetimes.

  (Fujita, Poisson, Sasaki, Shibata, Khanna, Hughes, Bernuzzi, Harms, Nagar…)

- Accurate modeling of **relativistic dynamics of large mass-ratio** inspirals **requires** to include **back-reaction effects** due to interaction of small object with its own gravitational perturbation field.

(Deitweiler, Whiting, Mino, Poisson, Quinn, Wald, Sasaki, Tanaka, Barack, Ori, Pound, van de Meent, …)

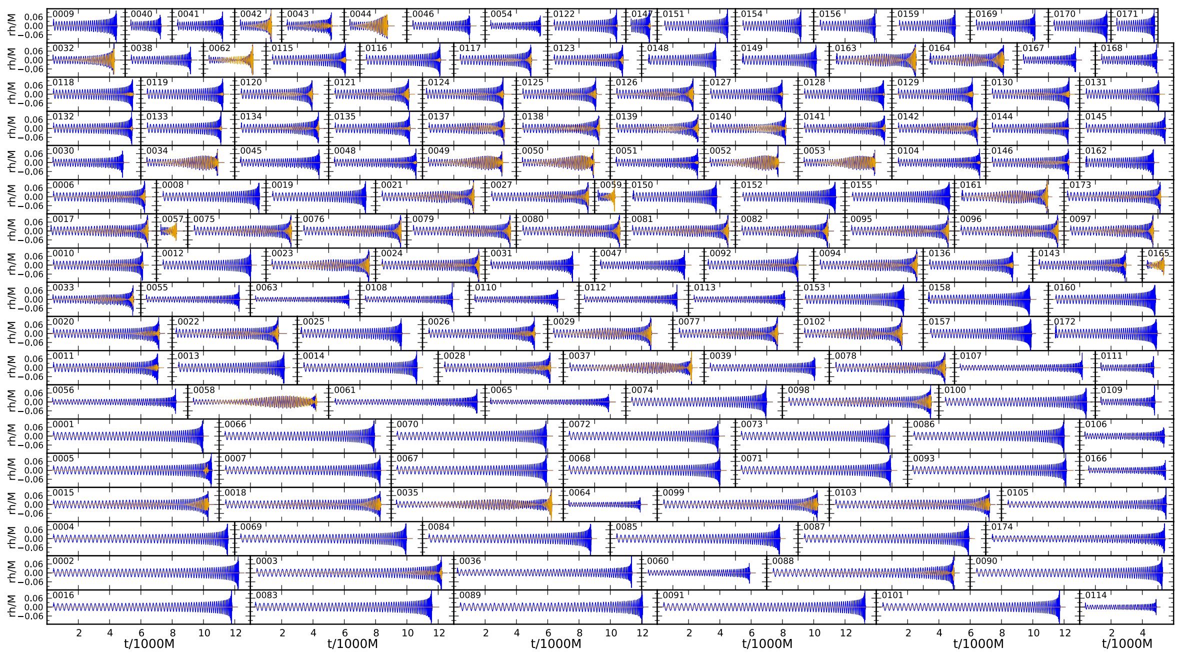


(credit: van de Meent)

Numerical Relativity: catalogues of binary BH waveforms

- **Breakthrough** in 2005 *(Pretorius 05, Campanelli et al. 06, Baker et al. 06)*

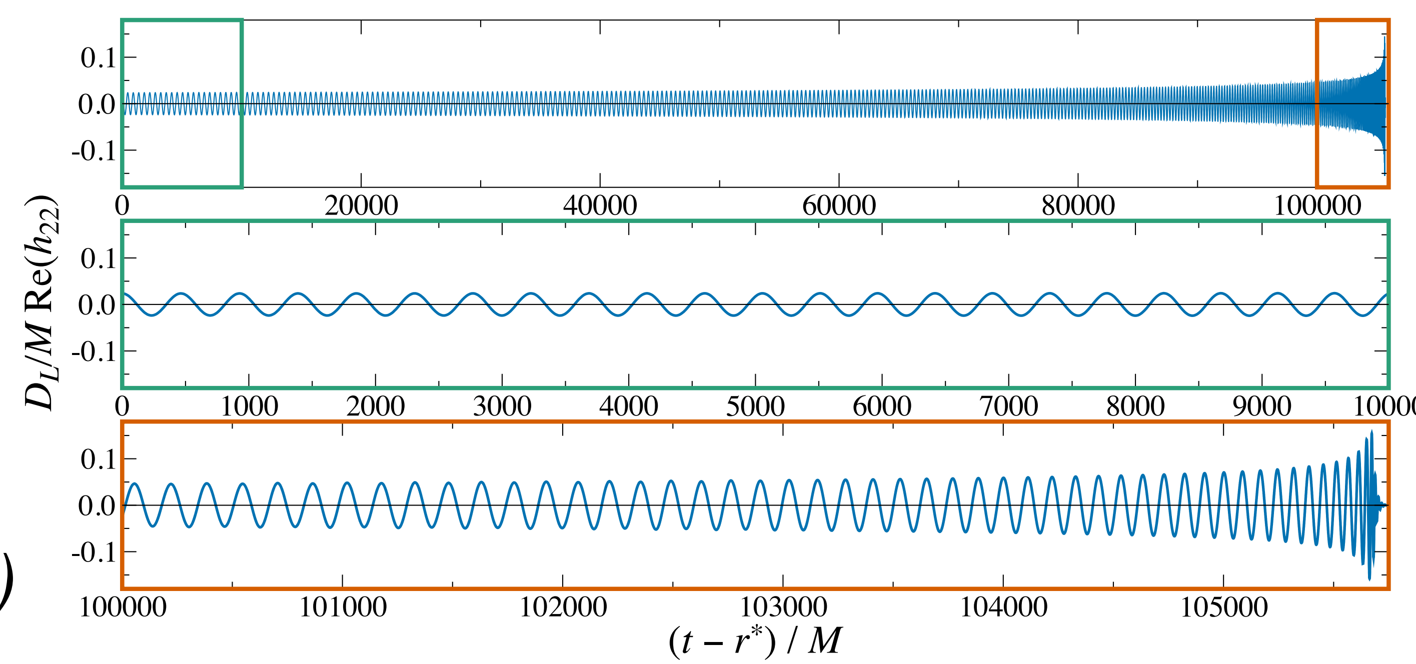
(Kidder, Pfeiffer, Scheel, Lindblom, Szilagyi; Brügmann; Hannam, Husa, Tichy; Laguna, Shoemaker …)



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

- **376 GW cycles**, zero spins & mass-ratio 7 (8 months, few millions CPU-h)

(Szilagyi, Blackman, AB, Taracchini et al. 15)



- **Simulating eXtreme Spacetimes (SXS)** collaboration. *(Mroue et al. 13, Boyle et al. 18)*

- **Other NR catalogues**

(Husa et al. 15, Jani et al. 17, Healy et al. 17, 19)

- **Numerical-Relativity & Analytical-Relativity** collaboration *(Hinder et al. 13)*

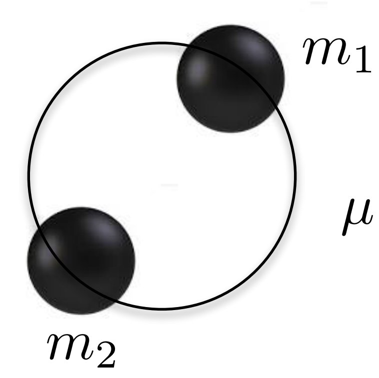
Gravitational waveforms built from conservative & dissipative dynamics

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

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

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

$$\nu = \mu/M$$



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

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

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

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

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

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

PN templates for compact-object binary inspirals

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

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

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

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

0PN

-1PN

dipole radiation

1PN

graviton with non zero mass

1PN

1.5PN

spin-orbit

2PN

spin-spin

5PN

tidal

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

Depends on EOS & compactness

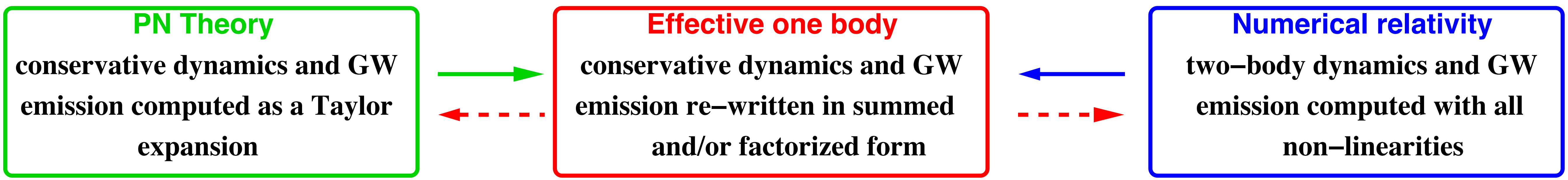
it can be large

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

The effective-one-body (EOB) approach

- **EOB** approach **introduced before NR** breakthrough

(AB, Pan, Taracchini, Barausse, Bohe', Cotesta, Shao, Hinderer, Steinhoff, Vines; Damour, Nagar, Bernuzzi, Bini, Balmelli, Messina; Iyer, Sathyaprakash; Jaranowski, Schäfer)

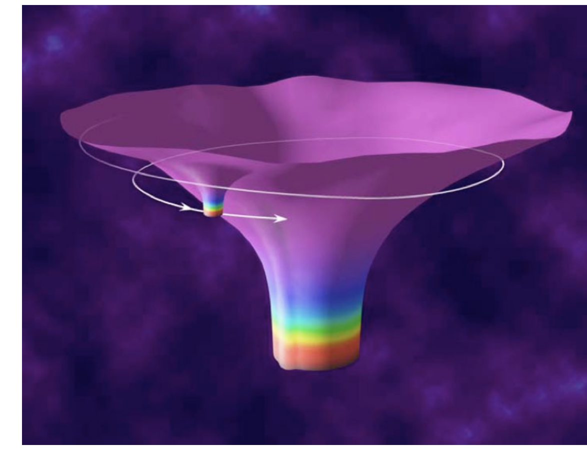


- **EOB** model uses best information available in PN theory, but **resums PN terms** in suitable way to describe accurately dynamics and radiation during inspiral and plunge (going beyond quasi-circular adiabatic motion).

- **EOB** assumes **comparable-mass** description is **smooth deformation of test-particle limit**. It employs non-perturbative ingredients and **models analytically merger-ringdown** signal.

One-body problem: test-particle orbiting non-spinning BH

- **Schwarzschild** metric and **Hamiltonian:**



$$ds^2 = -\left(1 - \frac{2M}{r}\right) dt^2 + \left(1 - \frac{2M}{r}\right)^{-1} dr^2 + r^2 d\Omega^2$$

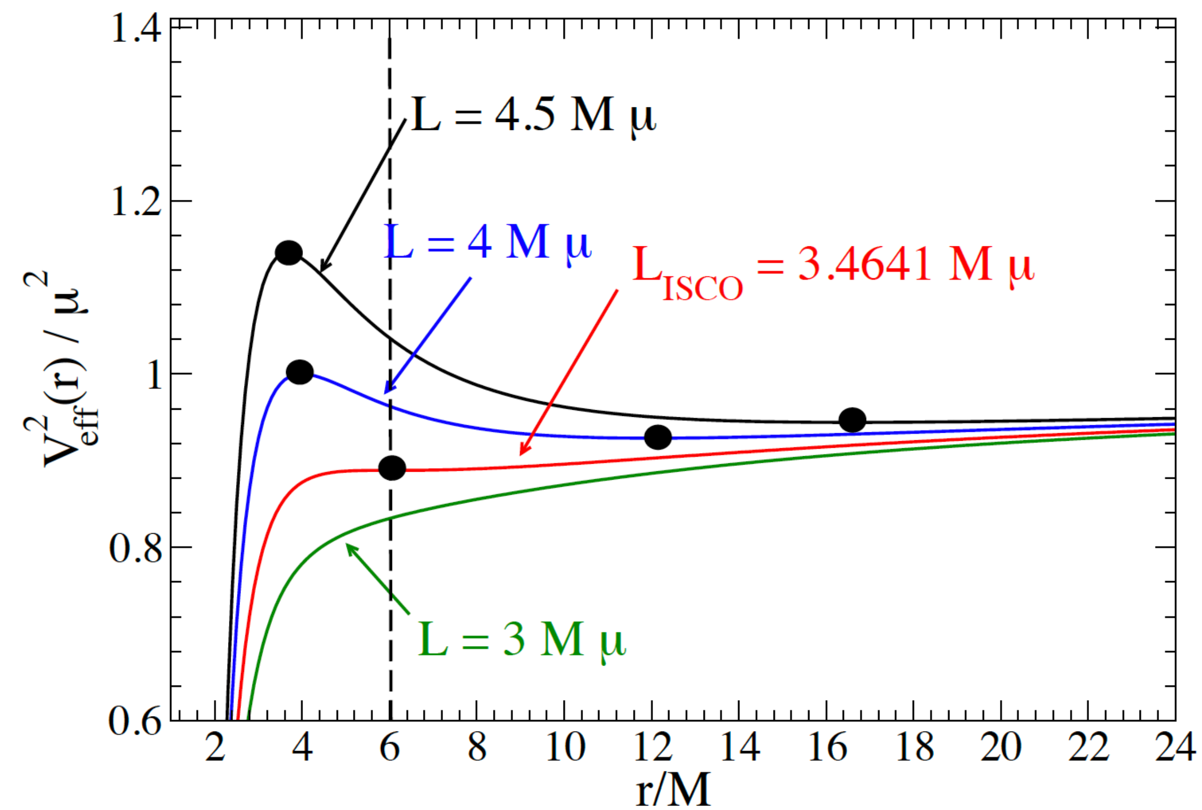
$$H_{\rm Schw}(\mathbf{r}, \mathbf{p}) = \mu \sqrt{\left(1 - \frac{2M}{r}\right) \left[1 + \frac{\mathbf{p}^2}{\mu^2} - \frac{2M}{r} \frac{p_r^2}{\mu^2}\right]}$$

- $H_{\rm Schw}(\mathbf{r}, \mathbf{p})$ describes a **test-particle of mass** μ orbiting a BH **of mass** M

- **Effective** (radial) **potential:**

$$\frac{V_{\rm eff}^2(r)}{\mu^2} = \left(1 - \frac{2M}{r}\right) \left(1 + \frac{L^2}{\mu^2 r^2}\right)$$

- For $L < L_{\rm ISCO}$ **circular orbits no longer exist.**



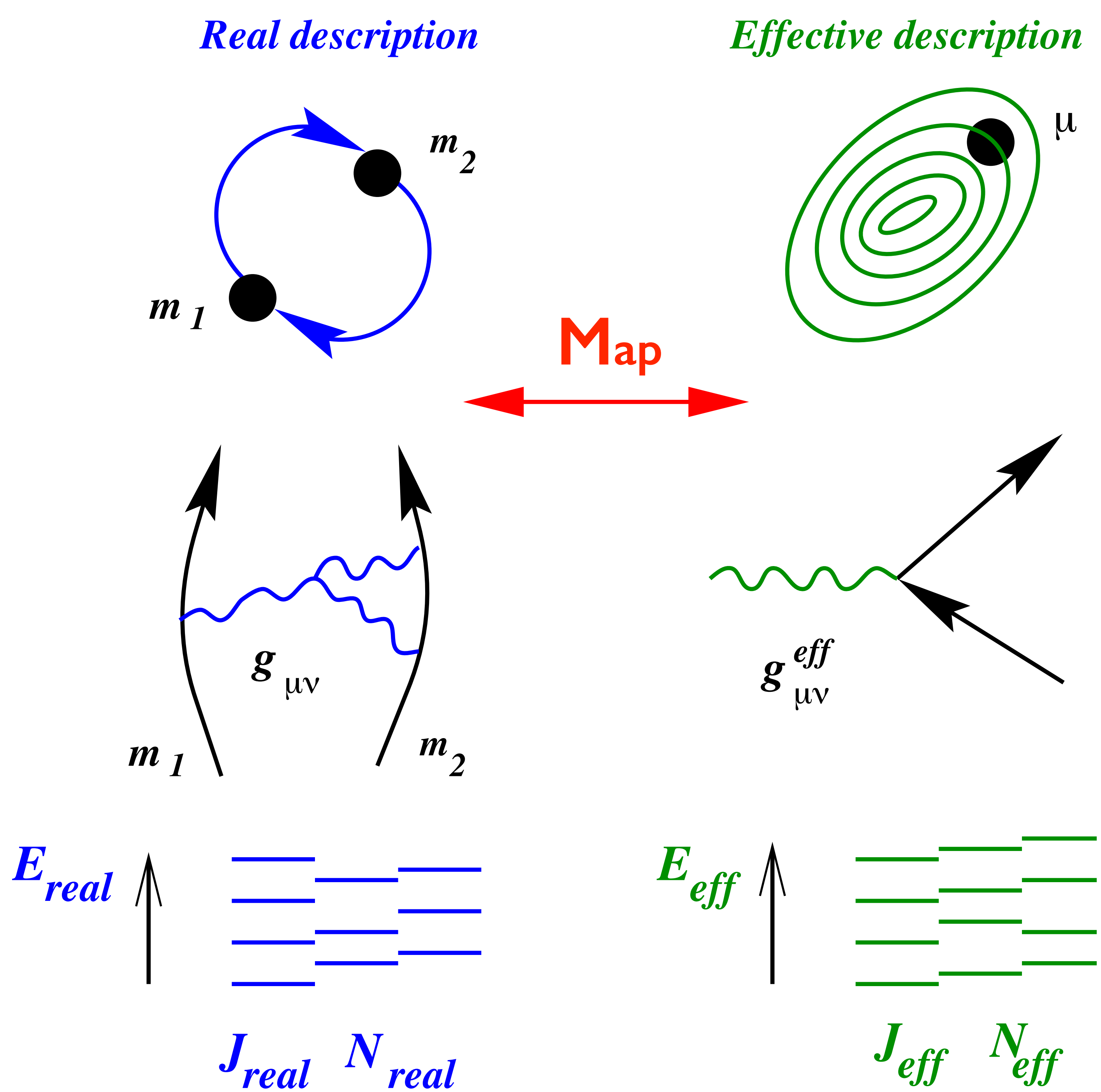
The effective-one-body approach in a nutshell

$$\nu = \frac{\mu}{M} \qquad 0 \leq \nu \leq 1/4$$

$$\mu = \frac{m_1 m_2}{M} \qquad M = m_1 + m_2$$

- **Two-body dynamics is mapped** into dynamics of **one-effective body** moving **in deformed black-hole spacetime**, deformation being the mass ratio.

- Some key **ideas** of EOB model were **inspired by quantum** field **theory** when describing energy of comparable-mass charged bodies.



(AB & Damour 1999)

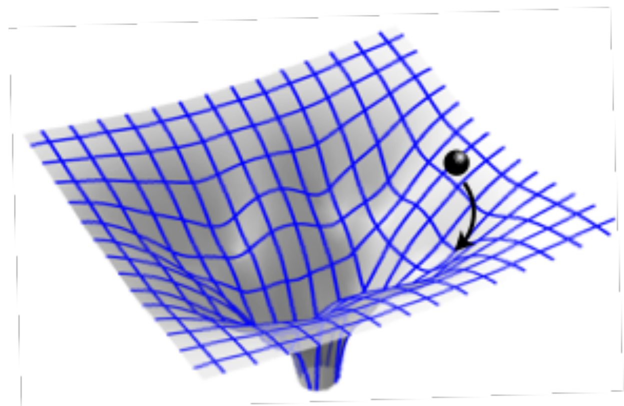
EOB Hamiltonian: resummed conservative dynamics (@2PN)

- Real Hamiltonian → • Effective Hamiltonian

$$H_{\rm real}^{\rm PN} = H_{\rm Newt} + H_{\rm 1PN} + H_{\rm 2PN} + \cdots$$

$$H_{\rm eff}^{\nu} = \mu \sqrt{A_\nu(r)\left[1 + \frac{\mathbf{p}^2}{\mu^2} + \left(\frac{1}{B_\nu(r)} - 1\right)\frac{p_r^2}{\mu^2}\right]}$$

$$ds^2_{\rm eff} = -A_\nu(r)dt^2 + B_\nu(r)dr^2 + r^2 d\Omega^2$$



(credit: Hinderer)

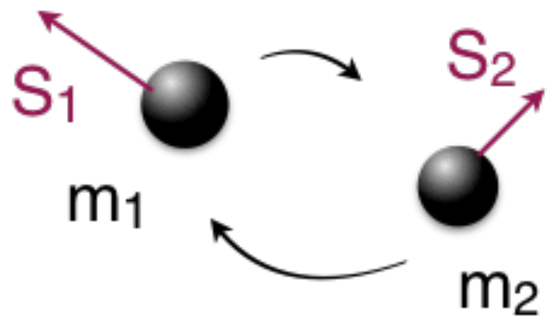
- EOB Hamiltonian: $H_{\rm real}^{\rm EOB} = M\sqrt{1 + 2\nu\left(\frac{H_{\rm eff}{}^{\nu}}{\mu} - 1\right)}$

- Dynamics condensed $A_\nu(r)$ and $B_\nu(r)$

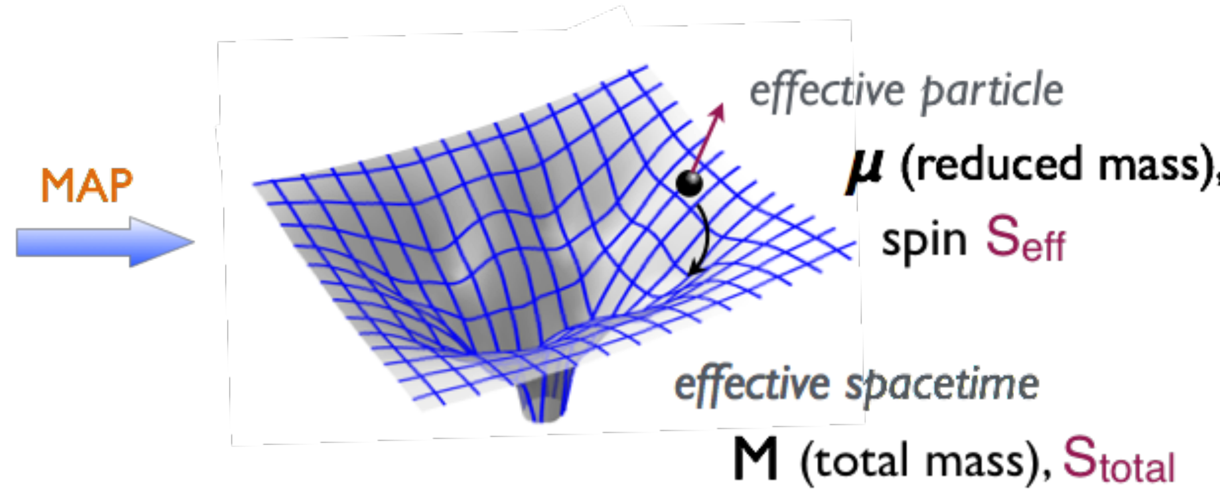
- $A_\nu(r)$, which encodes the energetics of circular orbits, is quite simple:

$$A_\nu(r) = 1 - \frac{2M}{r} + \frac{2M^3\nu}{r^3} + \left(\frac{94}{3} - \frac{41}{32}\pi^2\right)\frac{M^4\nu}{r^4} + \frac{a_5(\nu) + a_5^{\log}(\nu)\log(r)}{r^5} + \frac{a_6(\nu)}{r^6} + \cdots$$

EOB resummed spin dynamics & waveforms



(credit: Hinderer)



$$H_{\rm real}^{\rm EOB} = M\sqrt{1 + 2\nu\left(\frac{H_{\rm eff}{}^{\nu}}{\mu} - 1\right)}$$

- $H_{\rm eff}{}^{\nu}$ with spins, two EOB resummations:

(Barausse, Racine & AB 09; Barausse & AB 10, 11)

(Damour 01, Damour, Jaranowski & Schäfer 08; Damour & Nagar 14)

- EOB equations of motion *(AB et al. 00, 05; Damour et al. 09)*:

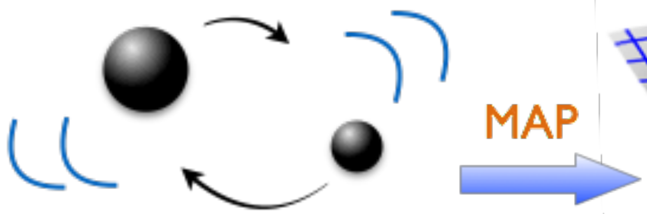
$$\dot{\mathbf{r}} = \frac{\partial H_{\rm real}^{\rm EOB}}{\partial \mathbf{p}} \qquad F \propto \frac{dE}{dt}, \quad \frac{dE}{dt} \propto \sum_{\ell m} |h_{\ell m}|^2$$

$$\dot{\mathbf{p}} = -\frac{\partial H_{\rm real}^{\rm EOB}}{\partial \mathbf{r}} + \mathbf{F} \qquad \dot{\mathbf{S}} = \{\mathbf{S}, H_{\rm real}^{\rm EOB}\}$$

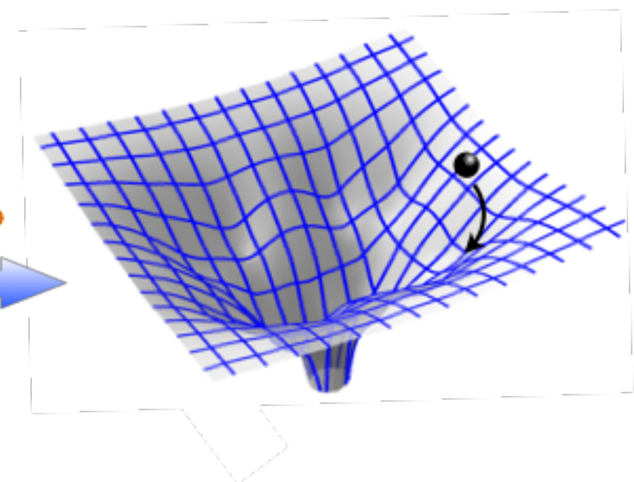
- EOB waveforms *(AB et al. 00; Damour et al. 09; Pan, AB et al. 11)*:

$$h_{\ell m}^{\rm insp-plunge} = h_{\ell m}^{\rm Newt}\, e^{-im\Phi}\, S_{\rm eff}\, T_{\ell m}\, e^{i\delta_{\ell m}}\, (\rho_{\ell m})^{\ell}\, h_{\ell m}^{\rm NQC}$$

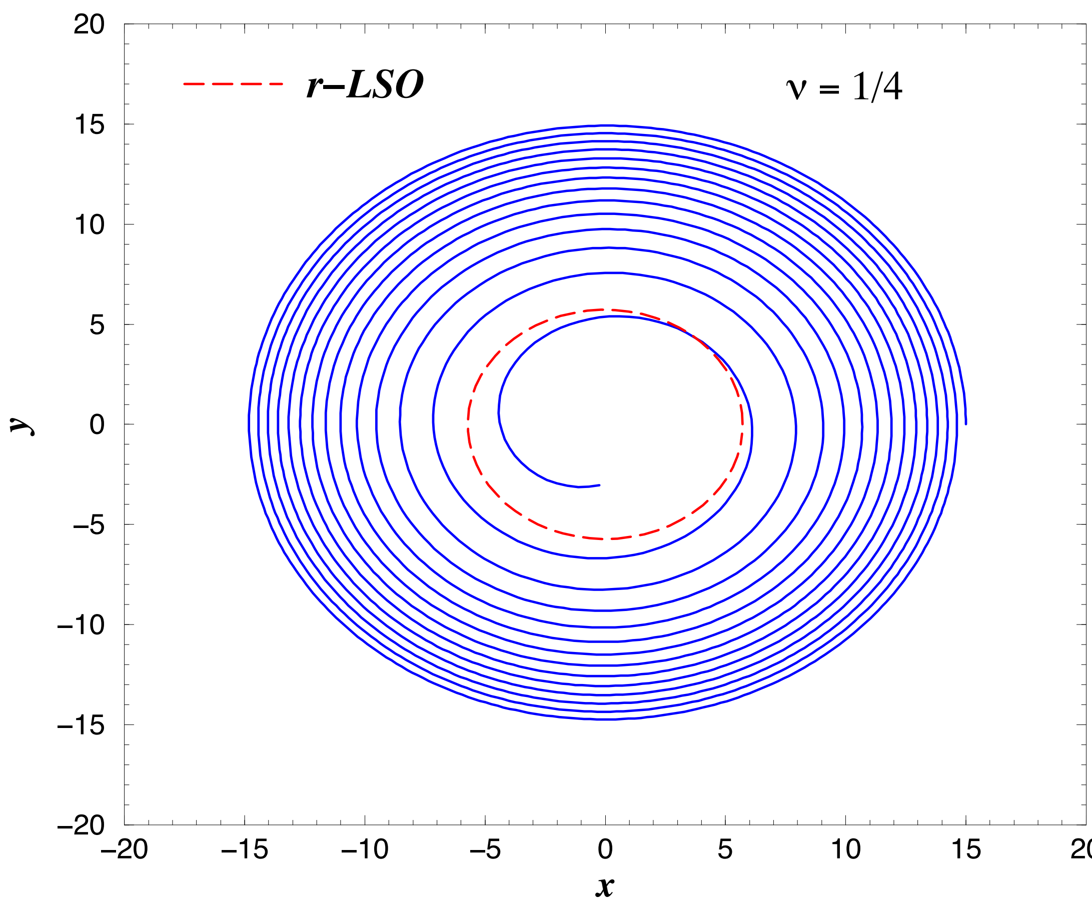
EOB inspiral-merger-ringdown analytic waveform

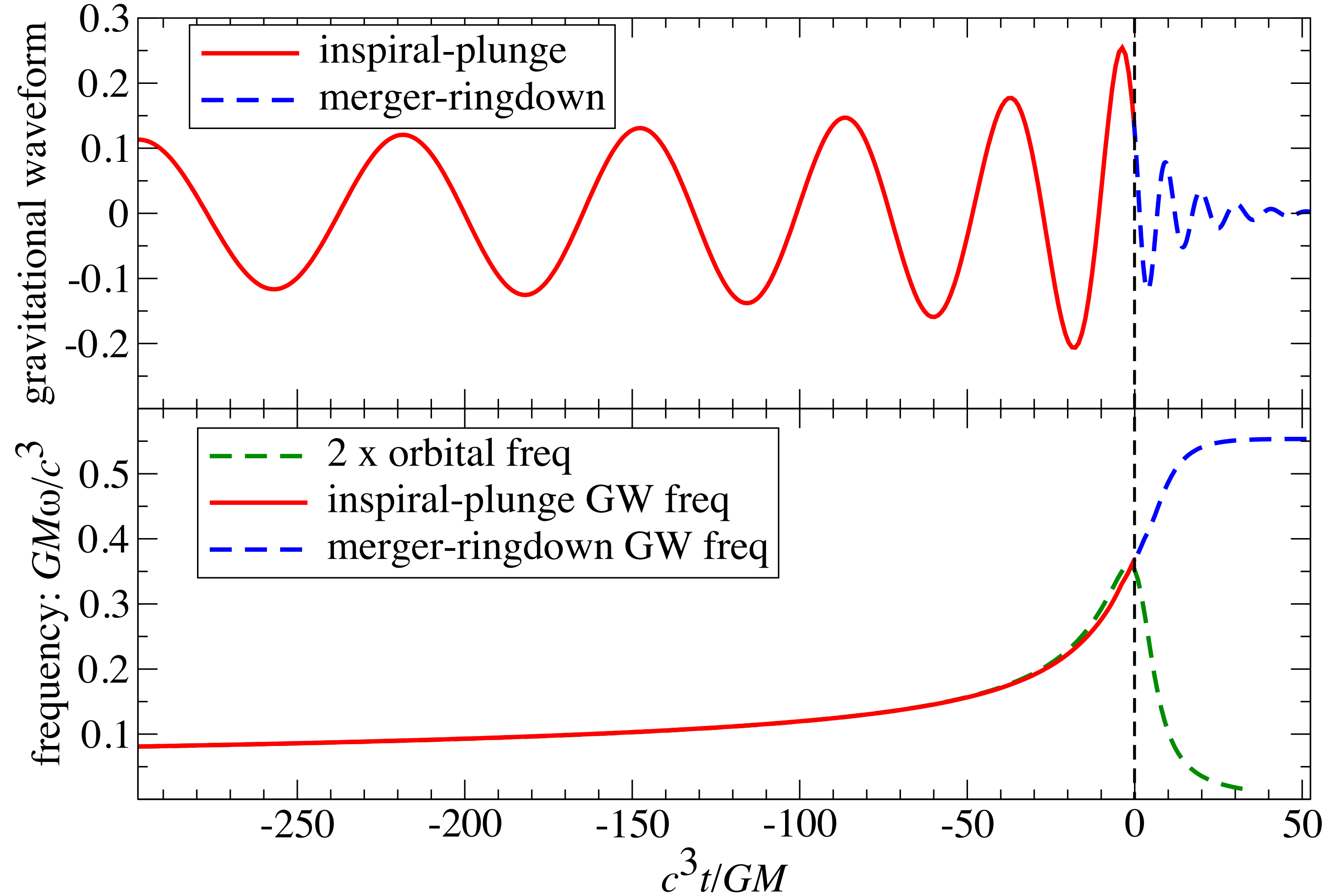


(credit: Hinderer)



$$E^2_{\rm real} = m_1^2 + m_2^2 + 2m_1m_2\left(\frac{E_{\rm eff}}{\mu}\right)$$

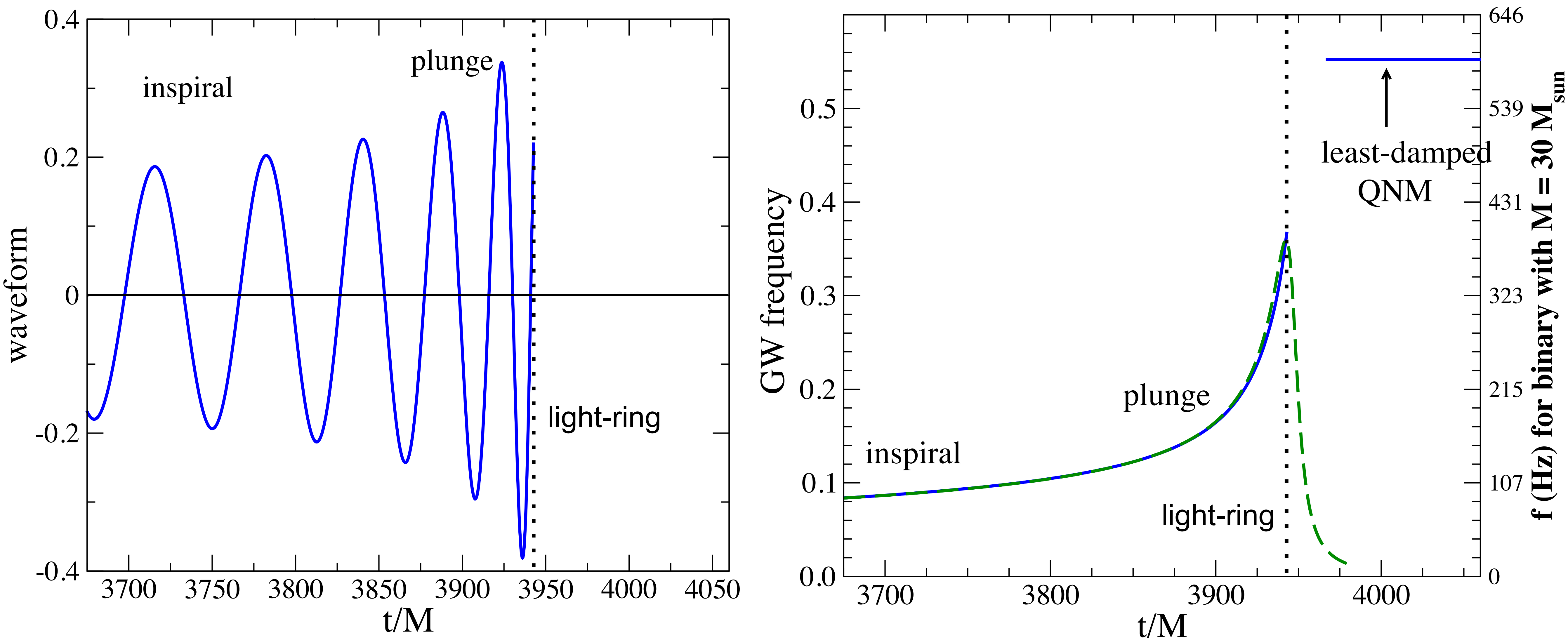




(AB & Damour 00)

EOB inspiral-plunge waveform & frequency

- Evolve **two-body dynamics up to light ring** (or photon orbit) and then …

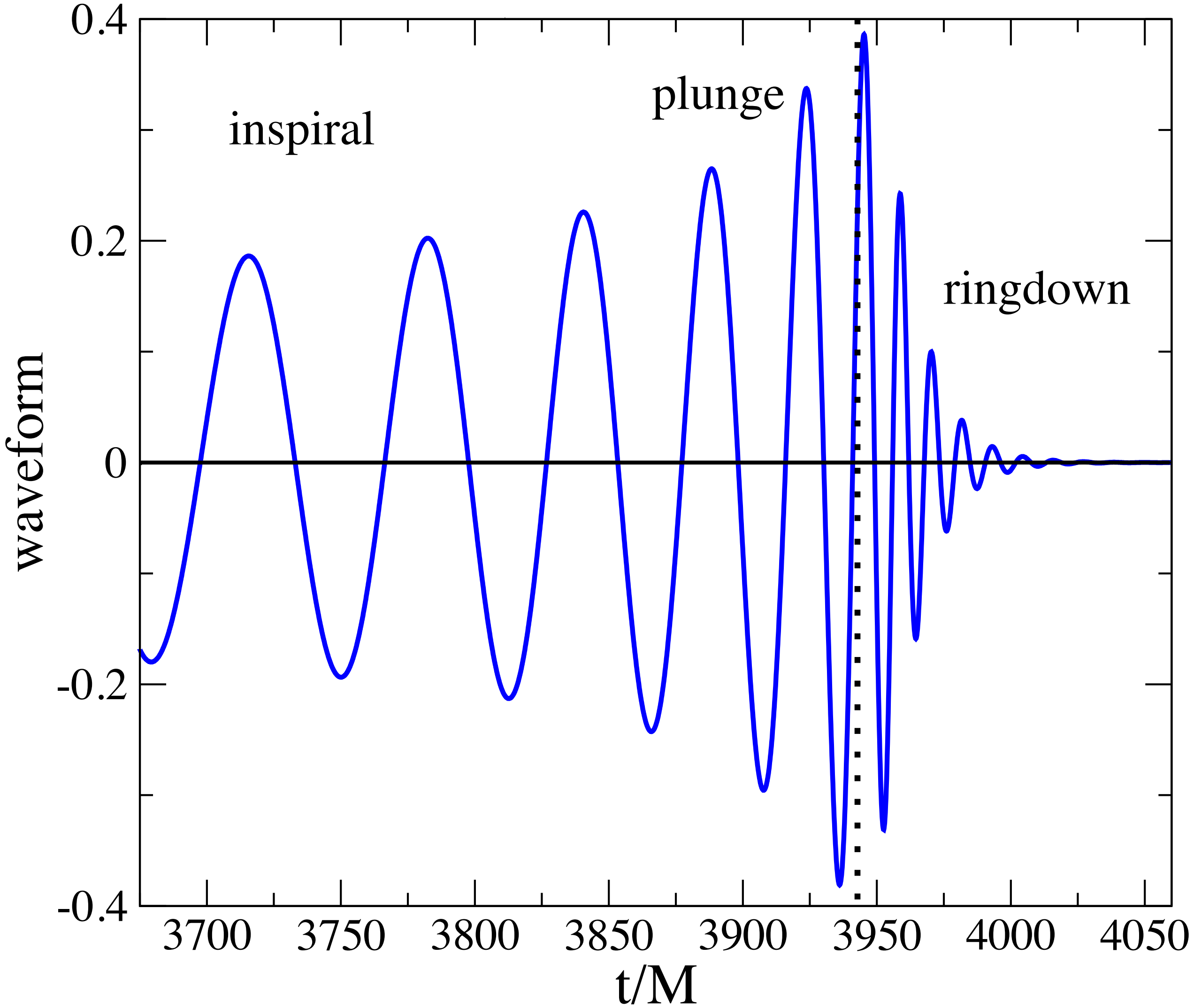


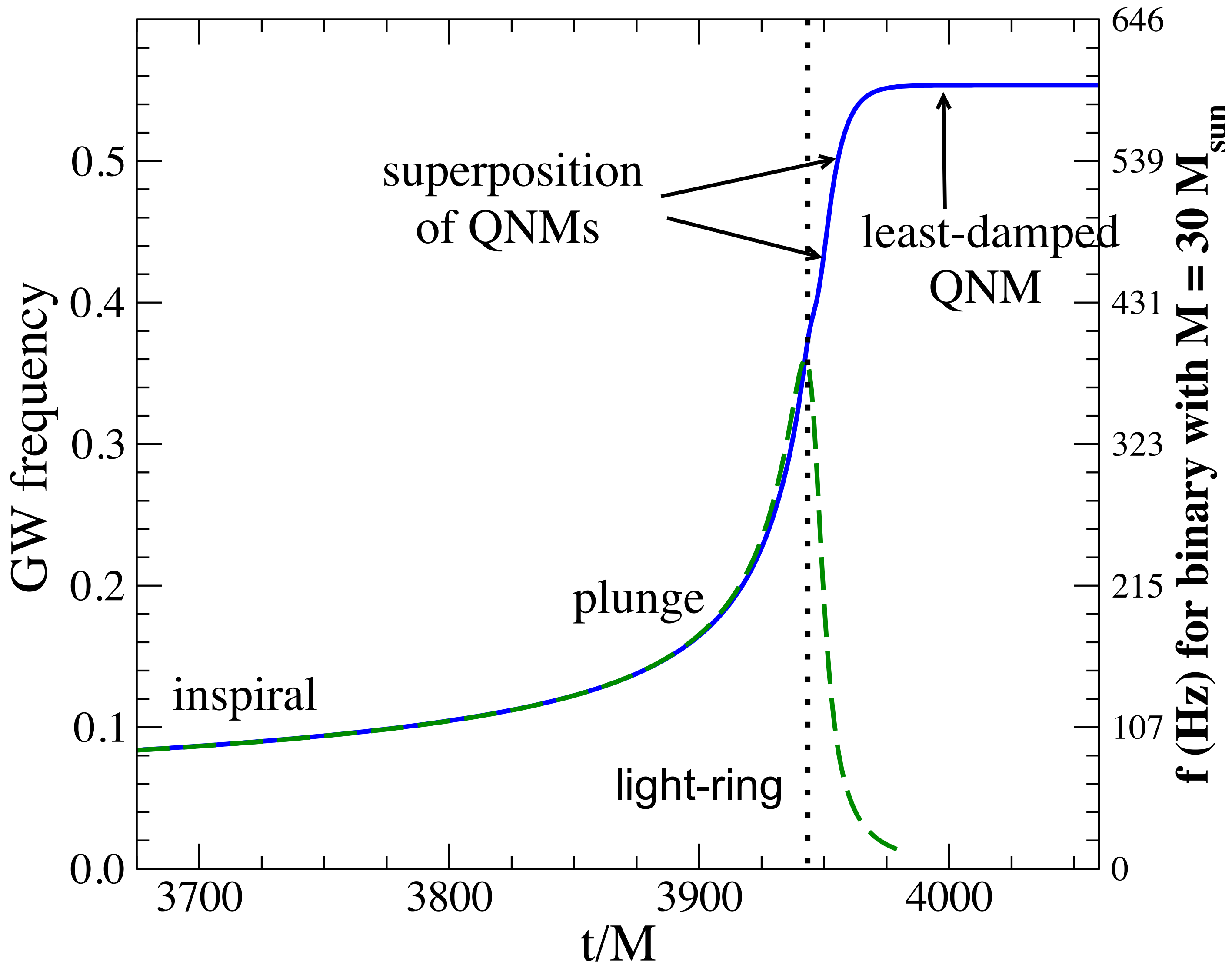
- **Quasi-normal modes** excited at **light-ring crossing**

(Goebel 1972, Davis et al. 1972, Ferrari et al. 1984, Damour et al. 07, Barausse et al. 11, Price et al. 15)

EOB inspiral-merger-ringdown waveform & frequency

… attach **superposition** of **quasi-normal modes** of **remnant** black hole.





- Very **short/simple transition** plunge-merger-ringdown: "easy" to model!

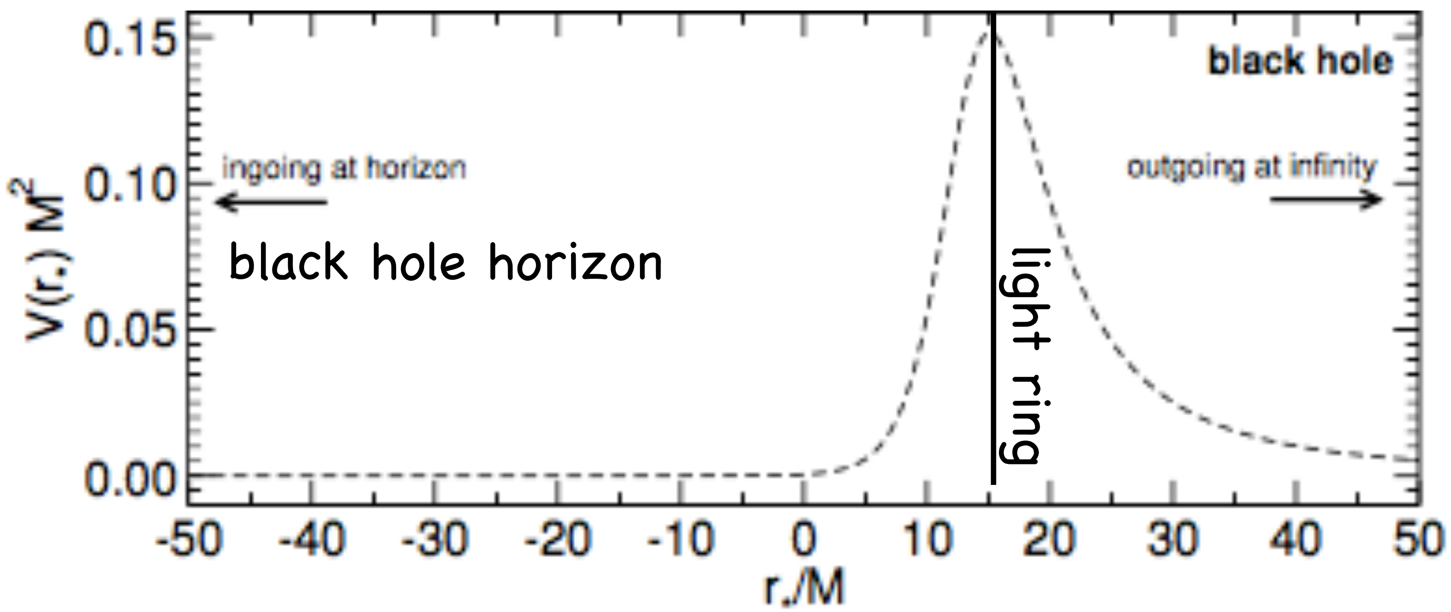
- Energy **quickly released** during merger: 2%-12%M

On the simplicity of merger signal

- Equation of gravitational perturbations
  in black-hole spacetime

(Regge & Wheeler 56, Zerilli 70, Teukolsky 72)

$$\frac{\partial^2 \Psi}{\partial t^2} - \frac{\partial^2 \Psi}{\partial r_\star^2} + V_{\ell m} \Psi = S_{\ell m}$$



- Peak of black-hole potential close to "light ring".

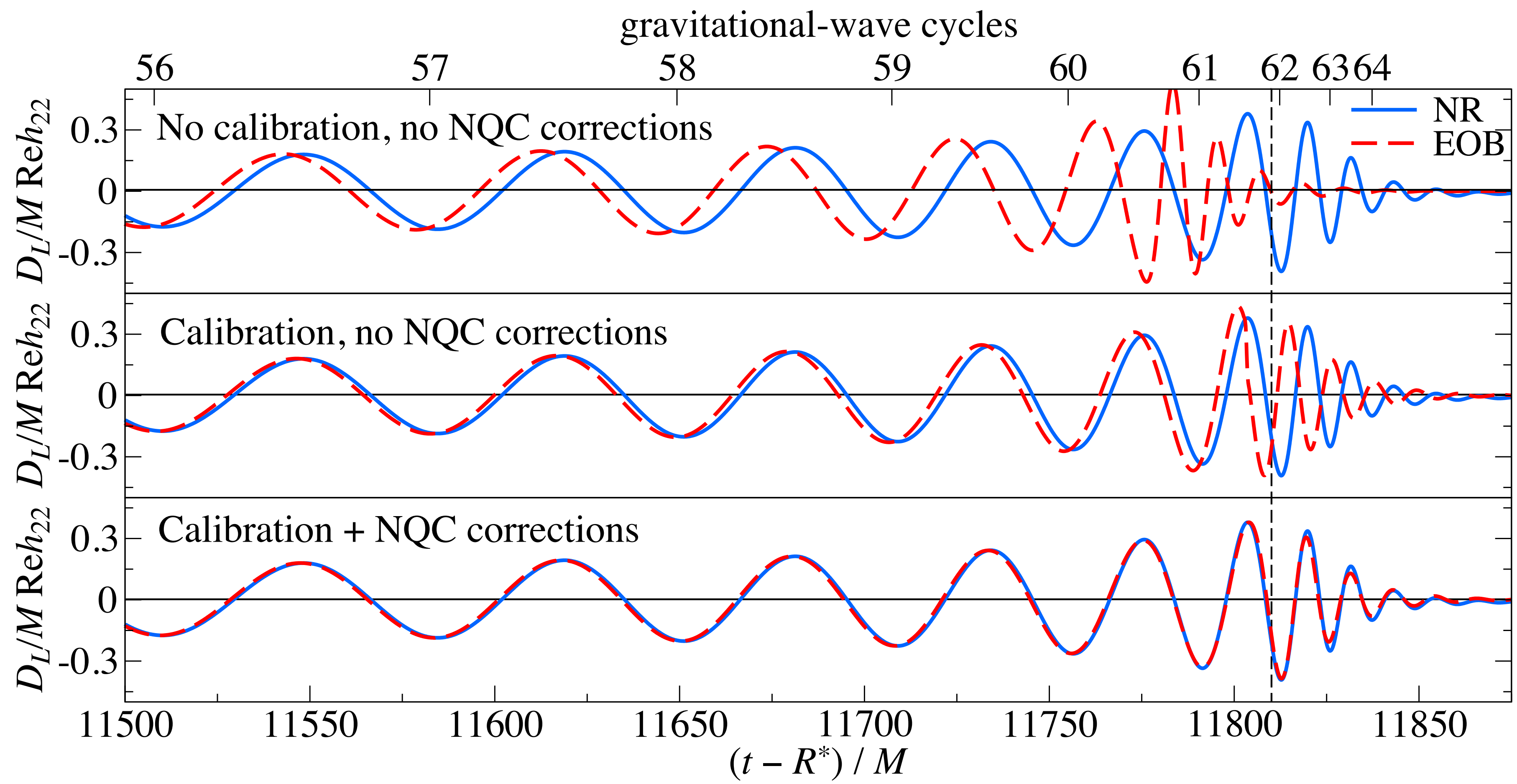
- Once particle is inside potential, direct gravitational radiation from its motion is strongly filtered by potential barrier (high-pass filter).

- Only black-hole spacetime vibrations (quasi-normal modes) leaks out black-hole potential.

(Goebel 1972, Davis et al. 1972, Ferrari & Mashhoon 1984)

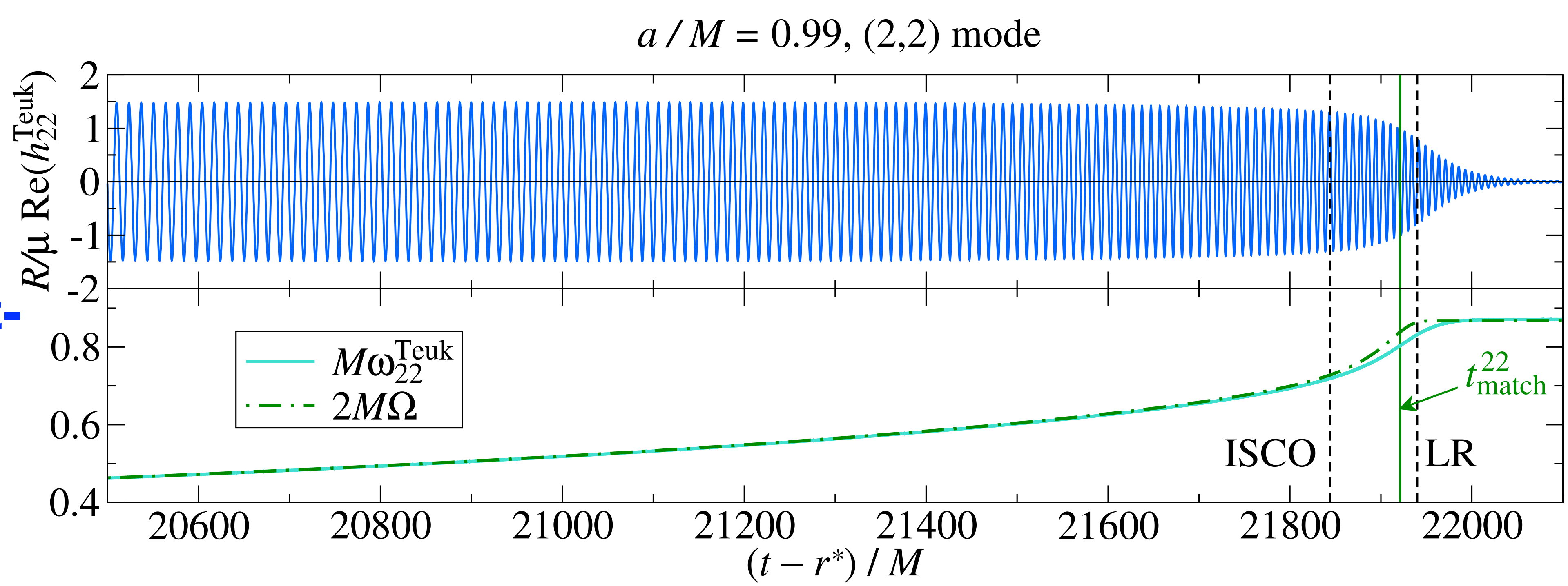
Completing EOB waveforms using NR/perturbation theory information

- We calibrate to inspiral-merger-ringdown **NR** waveforms.



(credit: Taracchini)

- We calibrate to merger-ringdown waveforms in **test-body limit**.

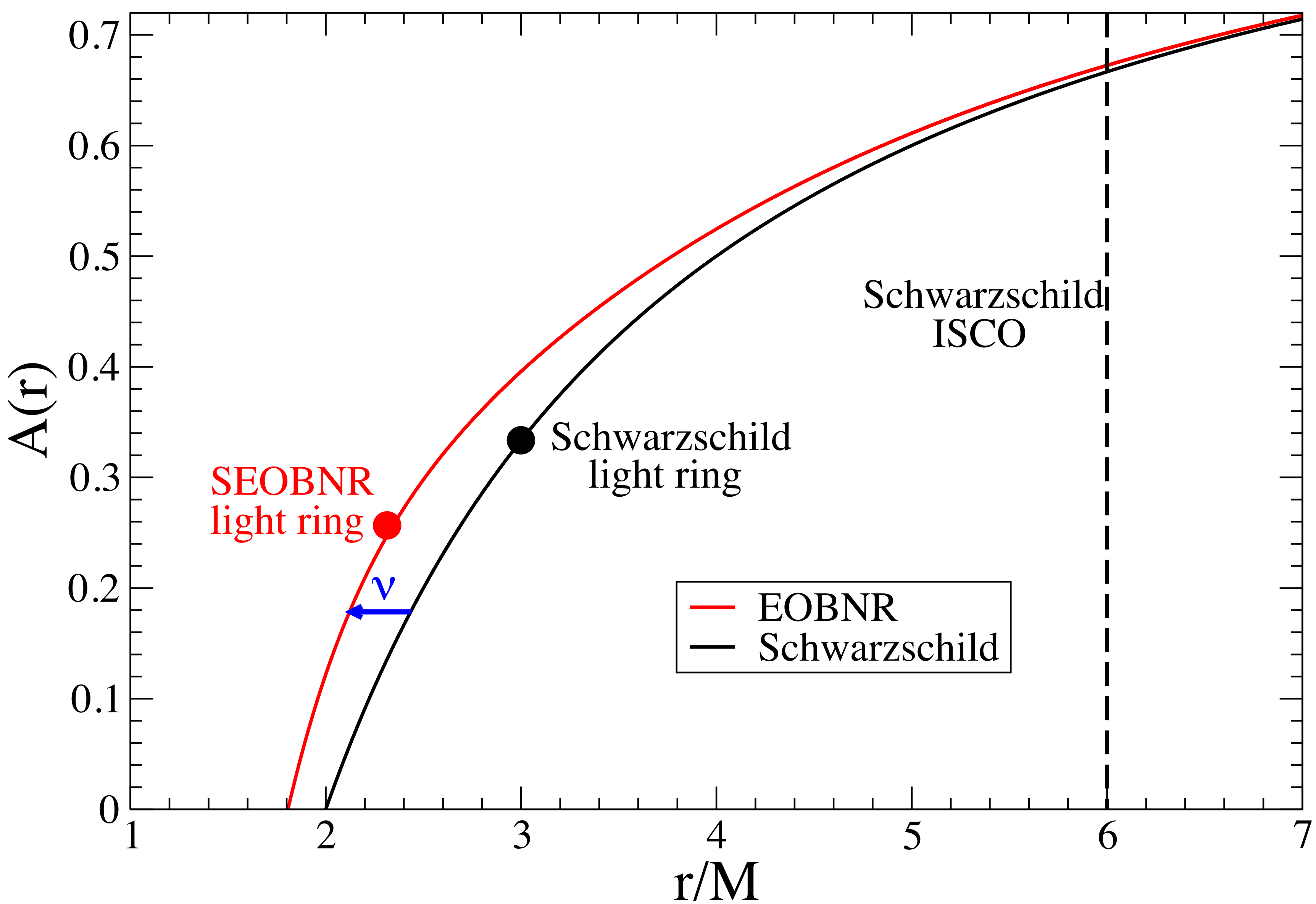


(credit: Taracchini)

Strong-field effects in binary black holes included in EOB

Finite mass-ratio effects make **gravitational** interaction **less attractive**

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

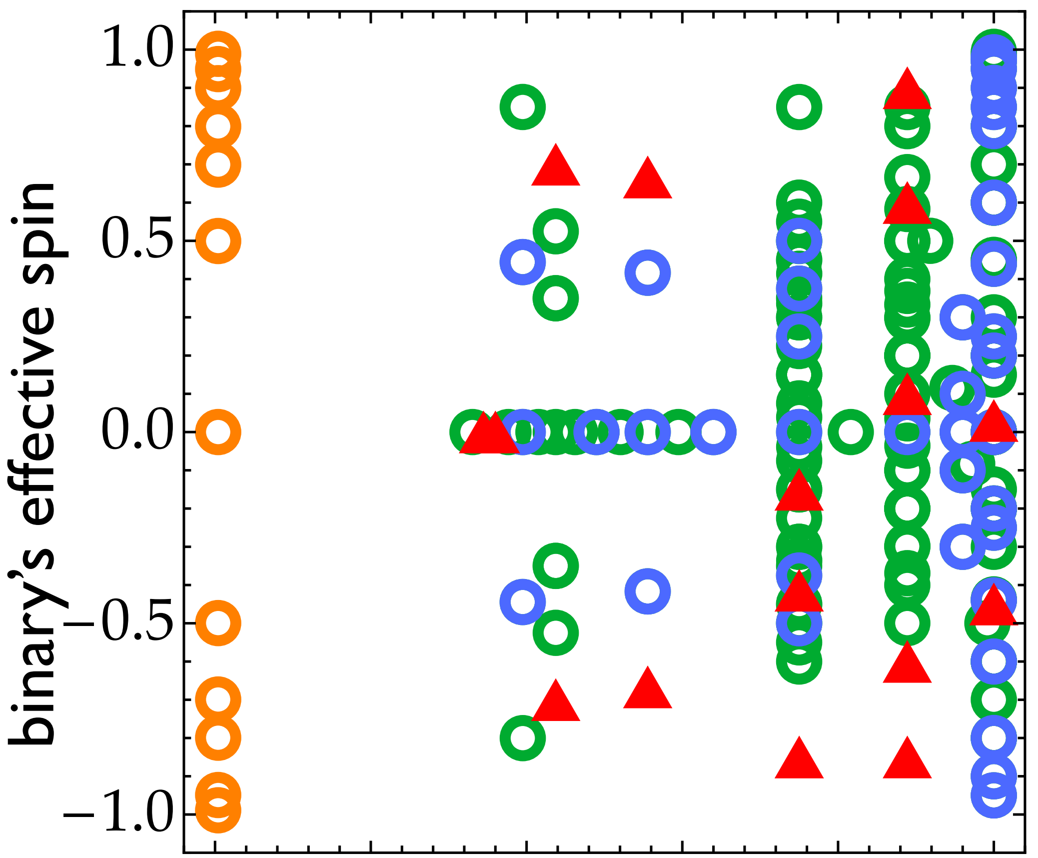


$$A_\nu(r) = 1 - \frac{2M}{r} + \frac{2M^3\nu}{r^3} + \left(\frac{94}{3} - \frac{41}{32}\pi^2\right)\frac{M^4\nu}{r^4} + \frac{a_5(\nu) + a_5^{\log}(\nu)\log(r)}{r^5} + \frac{a_6(\nu)}{r^6} + \cdots$$

Waveforms for BBHs combining analytical & numerical relativity

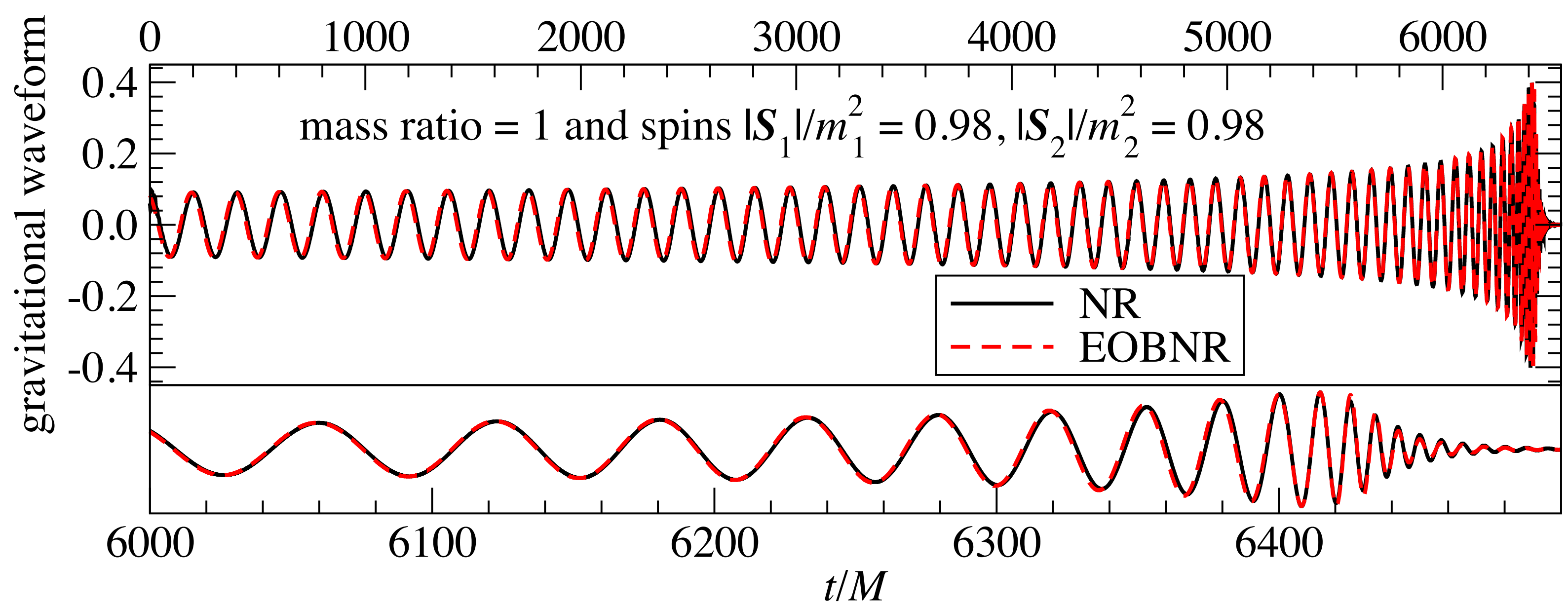
- Effective-one-body (EOB) theory & NR (EOBNR)

141 SXS simulations



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

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



(see also Nagar et al. 18)

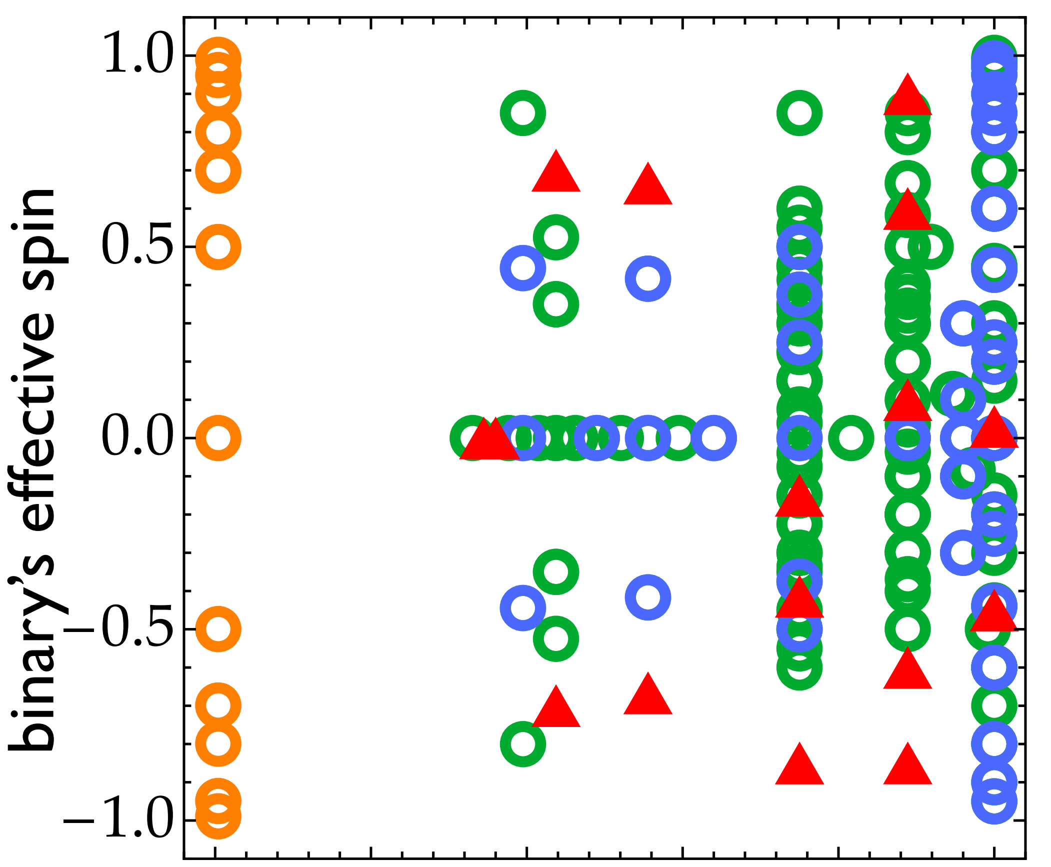
- Inspiral-merger-ringdown phenomenological waveforms fitting EOB & NR (IMRPhenom) *(Khan et al. 16, Hannam et al. 16)*

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

Waveforms for BBHs combining analytical & numerical relativity

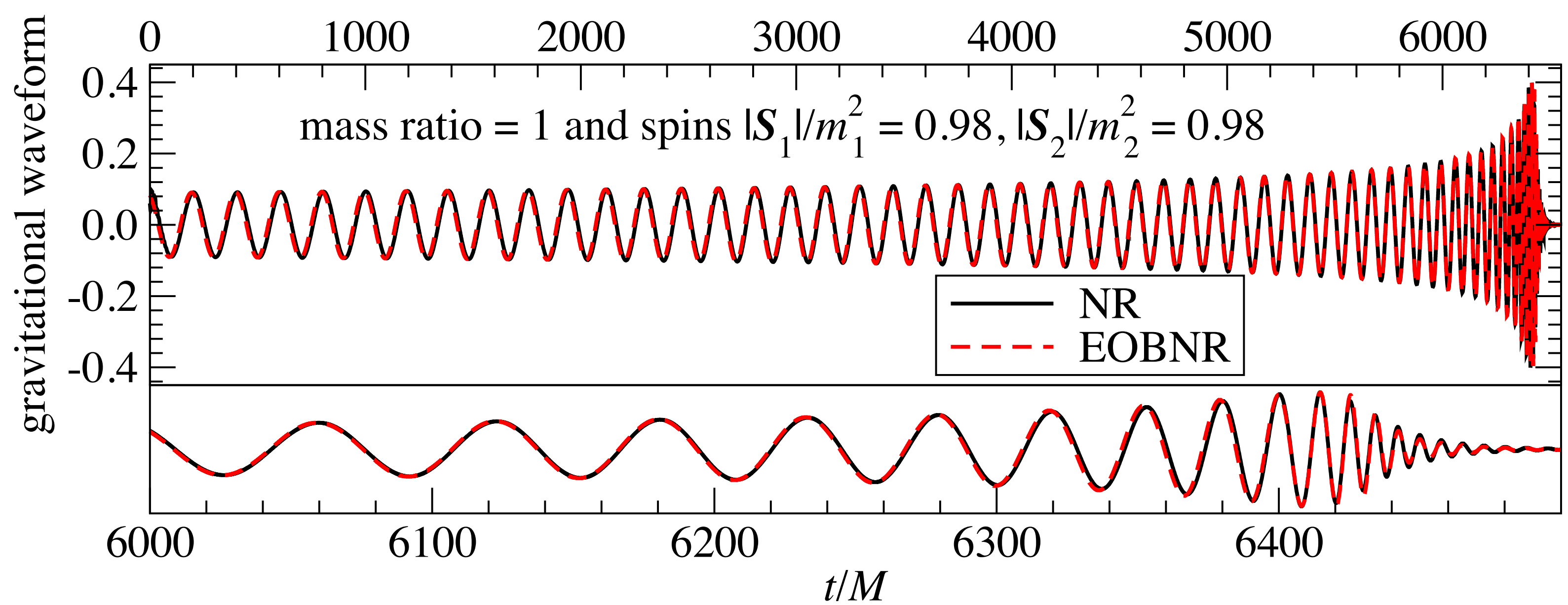
- **Effective-one-body** (EOB) theory & NR (EOBNR)

141 SXS simulations



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

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



(see also Nagar et al. 18)

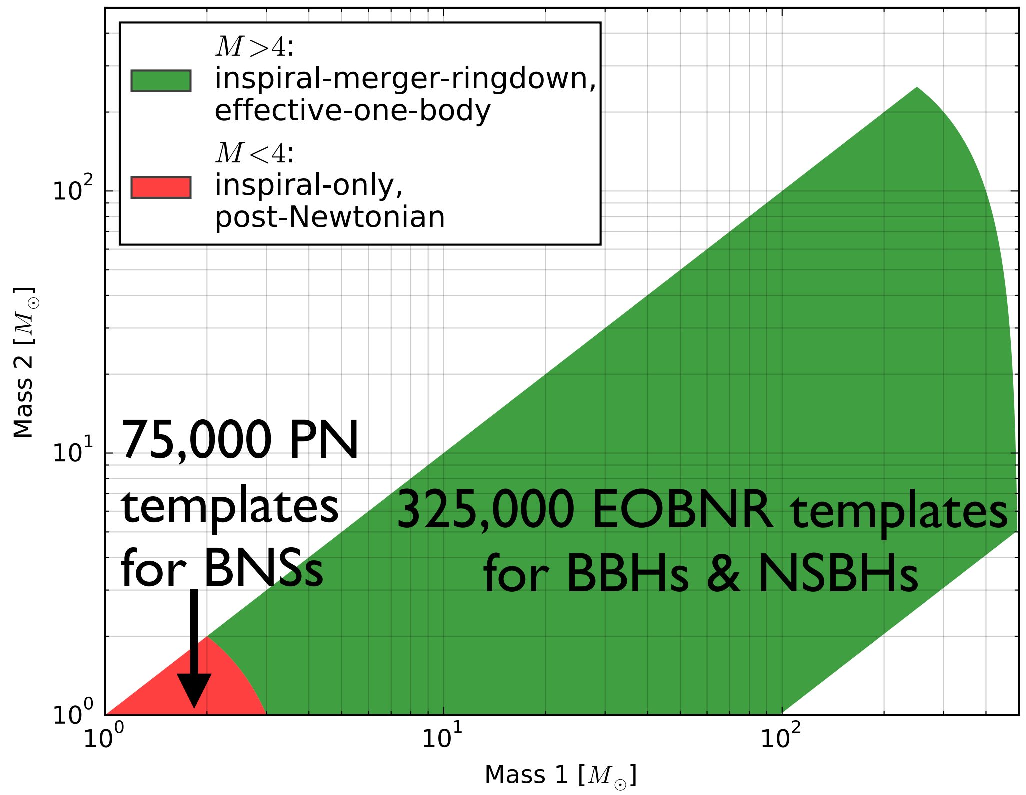
- **NR surrogate models** built **directly** interpolating **NR simulations,** which are **"selected" in parameter space** using analytical waveform models.

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

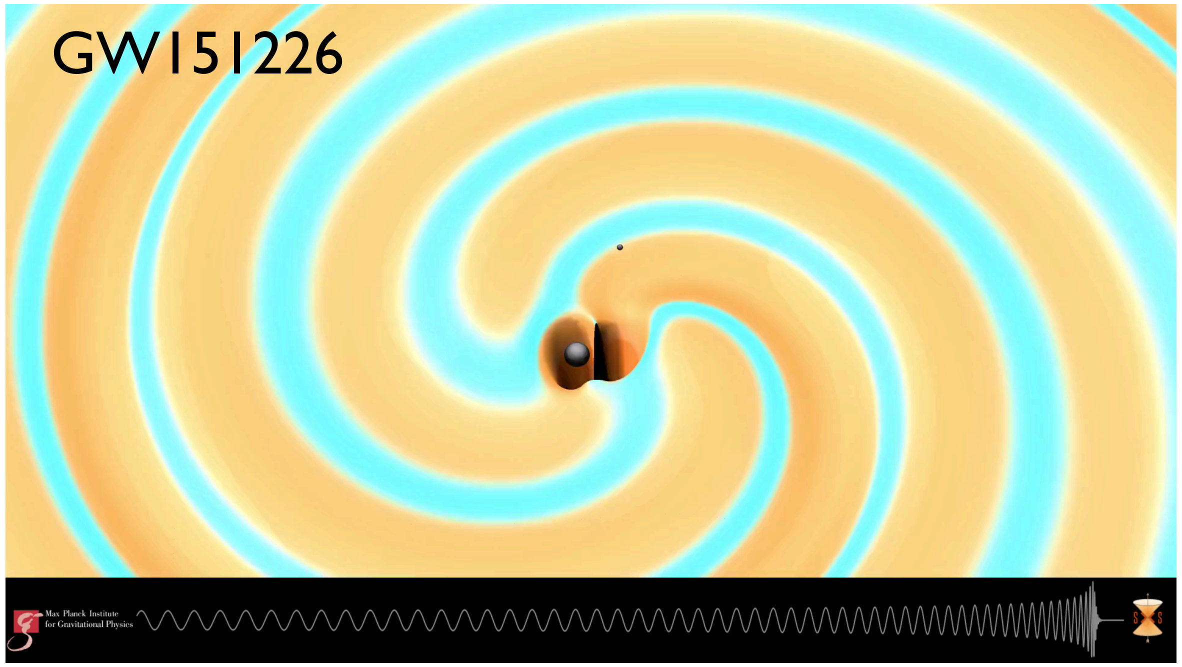
Template bank for modeled search & possible systematics

- **Matched filtering** employed

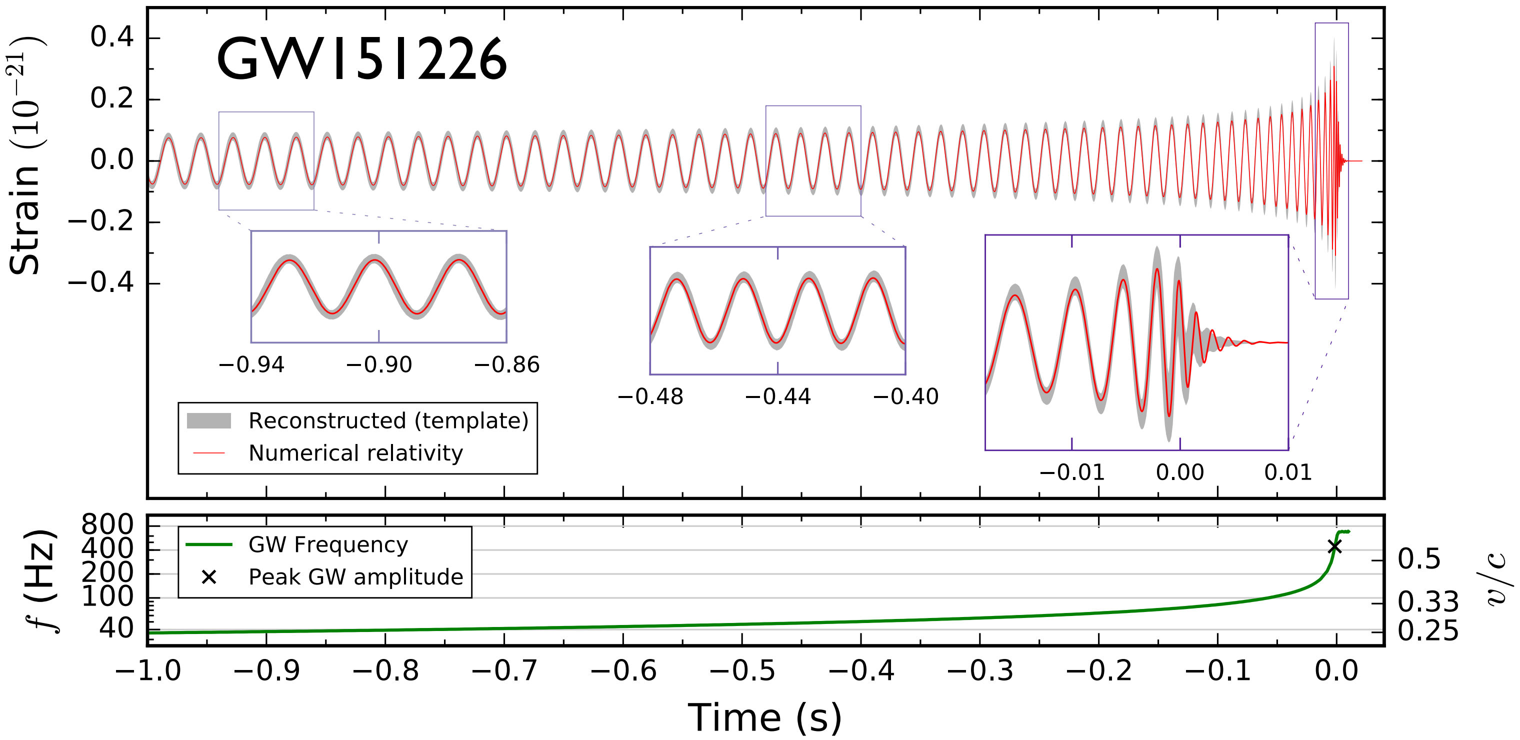
(Dal Canton & Harry 17)



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



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

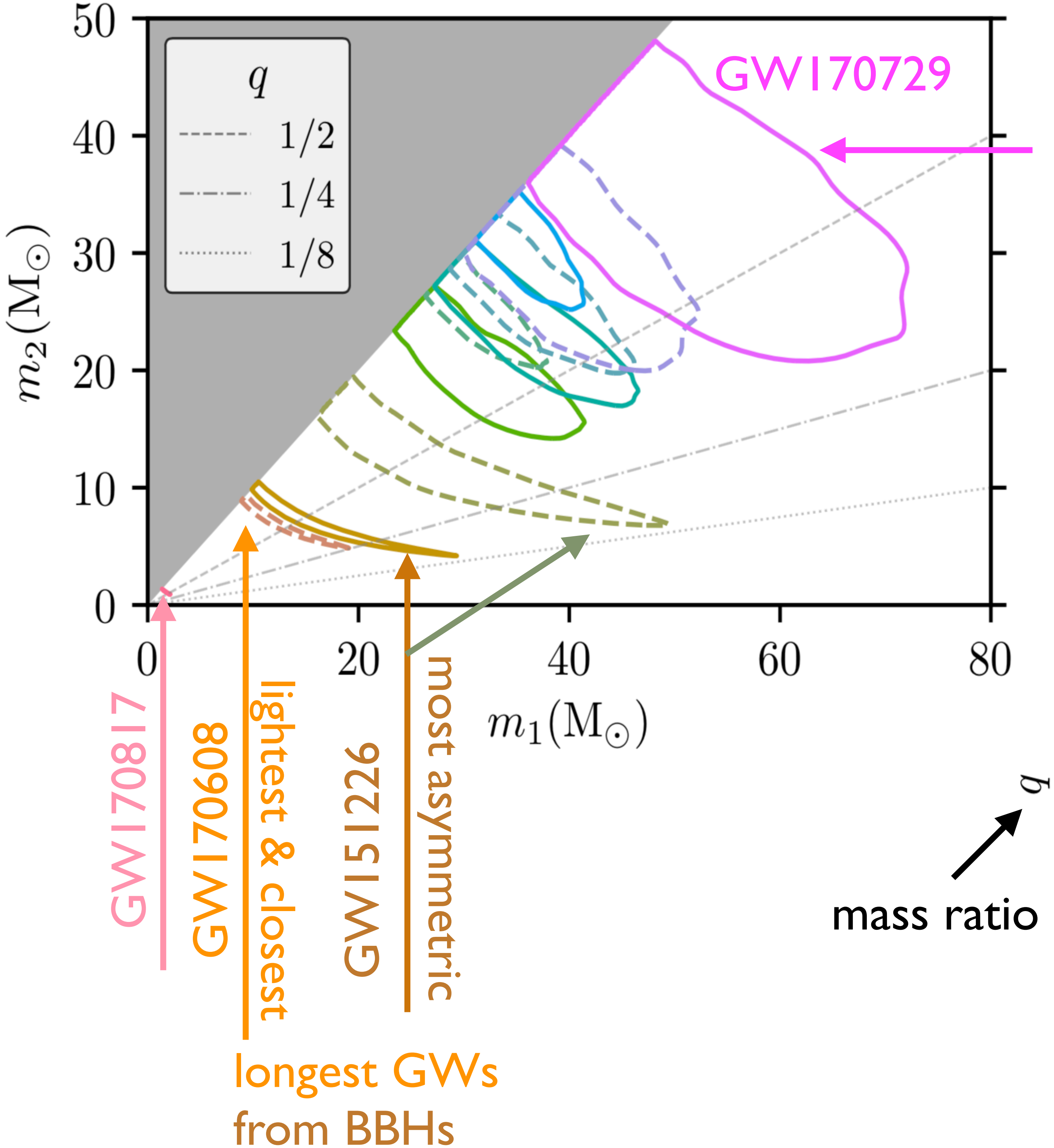


- **Systematics** due to modeling **are smaller than statistical** errors for GW events observed in **O1 & O2 runs**.

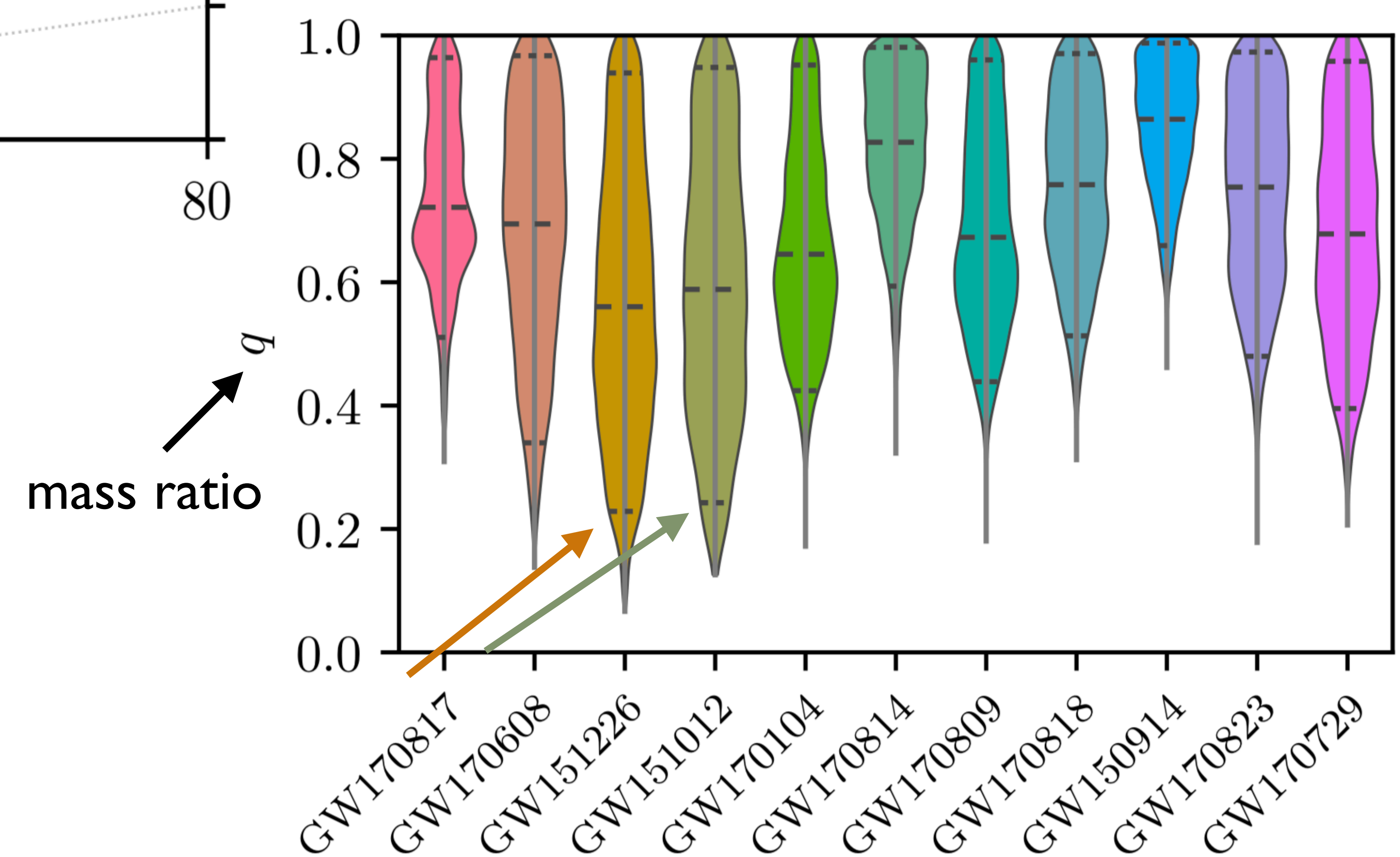
(Abbott et al. CQG 34 (2017) 104002)

Unveiling binary properties of GWTC-1: masses

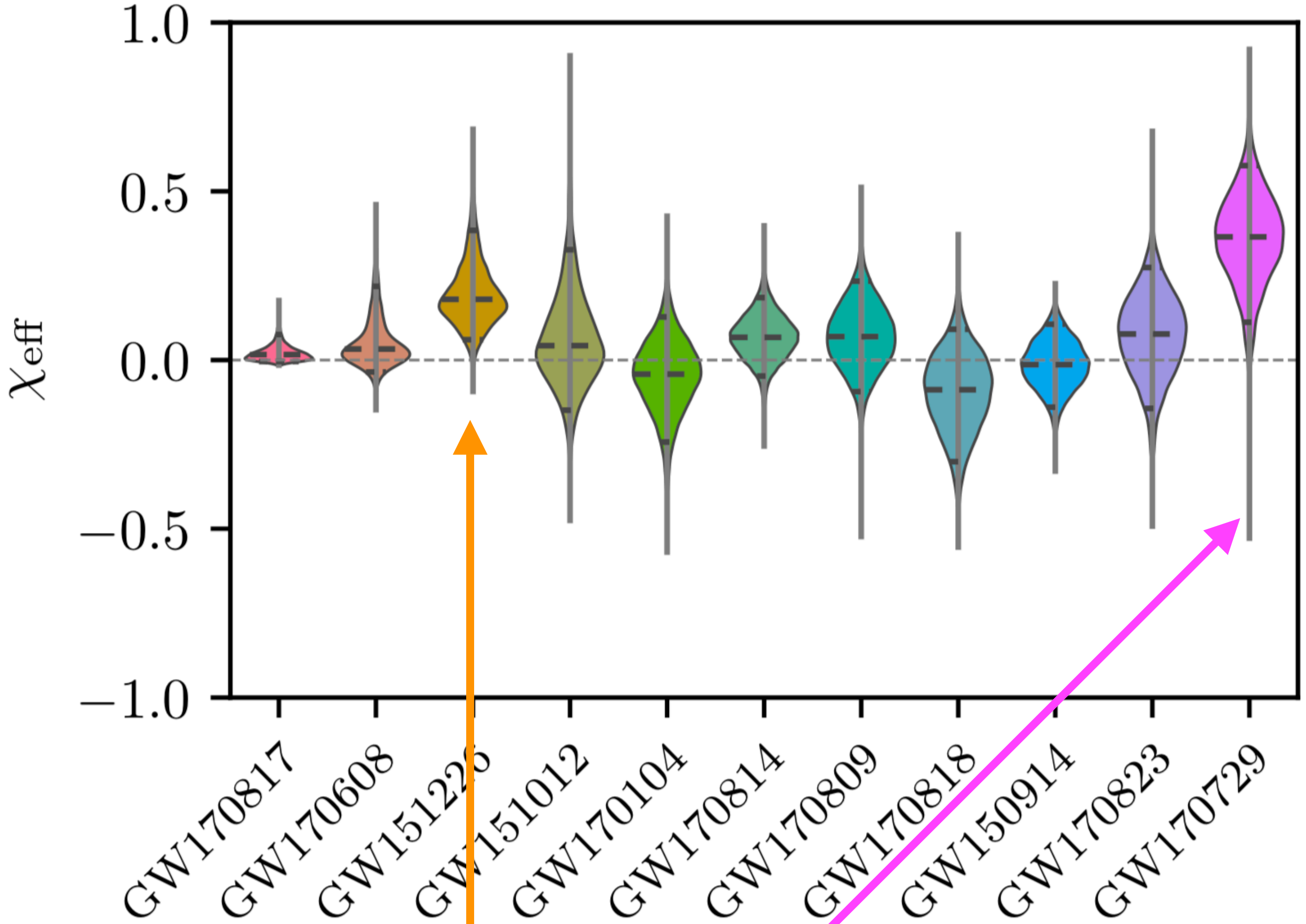
(Abbott et al. PRX 9 (2019) 031040)



(see also Zackay et al. 2019, Venumadhav et al. 2019)



Unveiling binary properties of GWTC-1: spins



(Abbott et al. PRX 9 (2019) 031040)

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

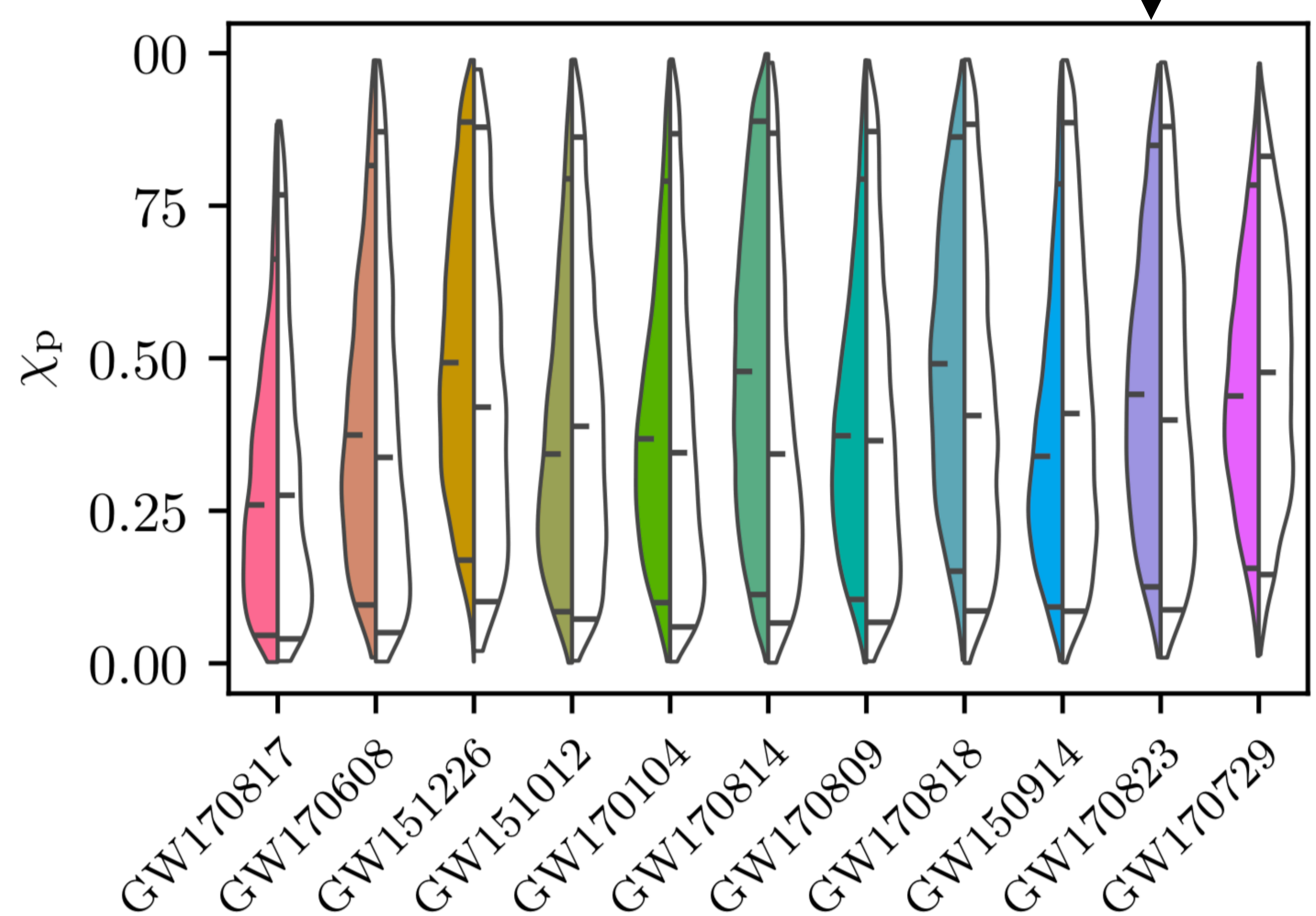
measures spins perpendicular to orbital plane

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

measures spins on the orbital plane

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

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



- **Moderate spins**, say < 0.6.

  (see however Zackay et al. 2019)
- **No evidence** for **spin-precession**.

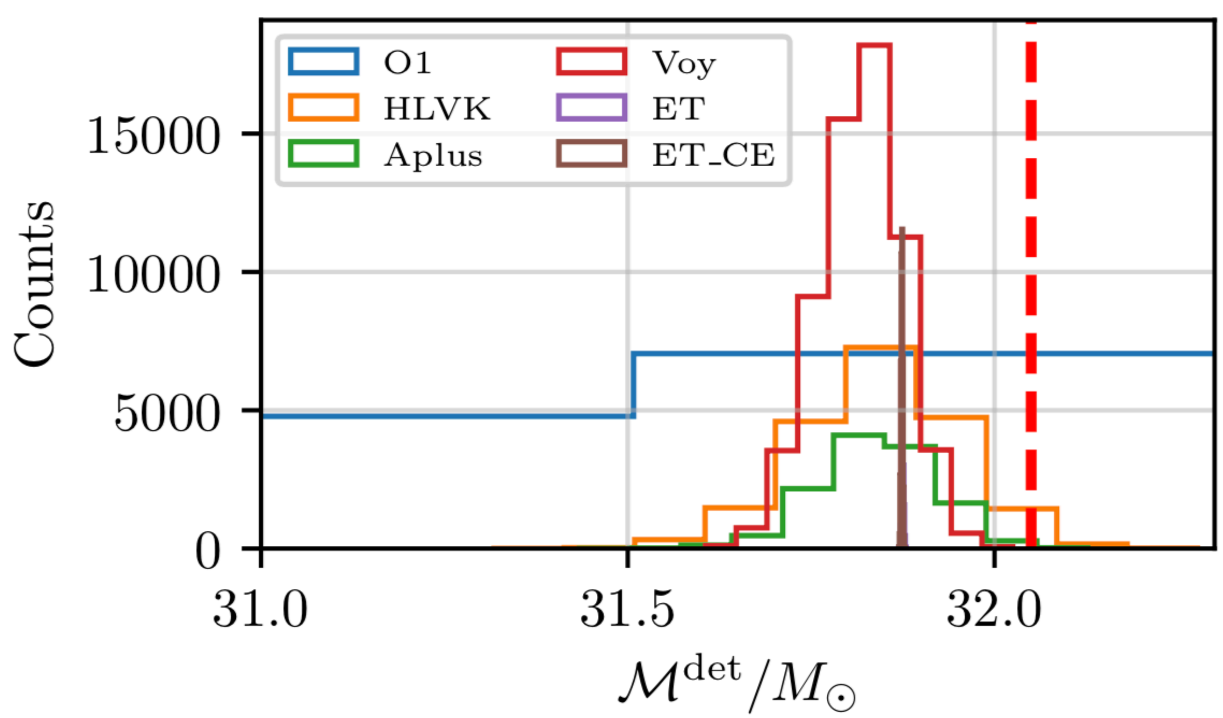
Systematics due to modeling for GW150914-like event

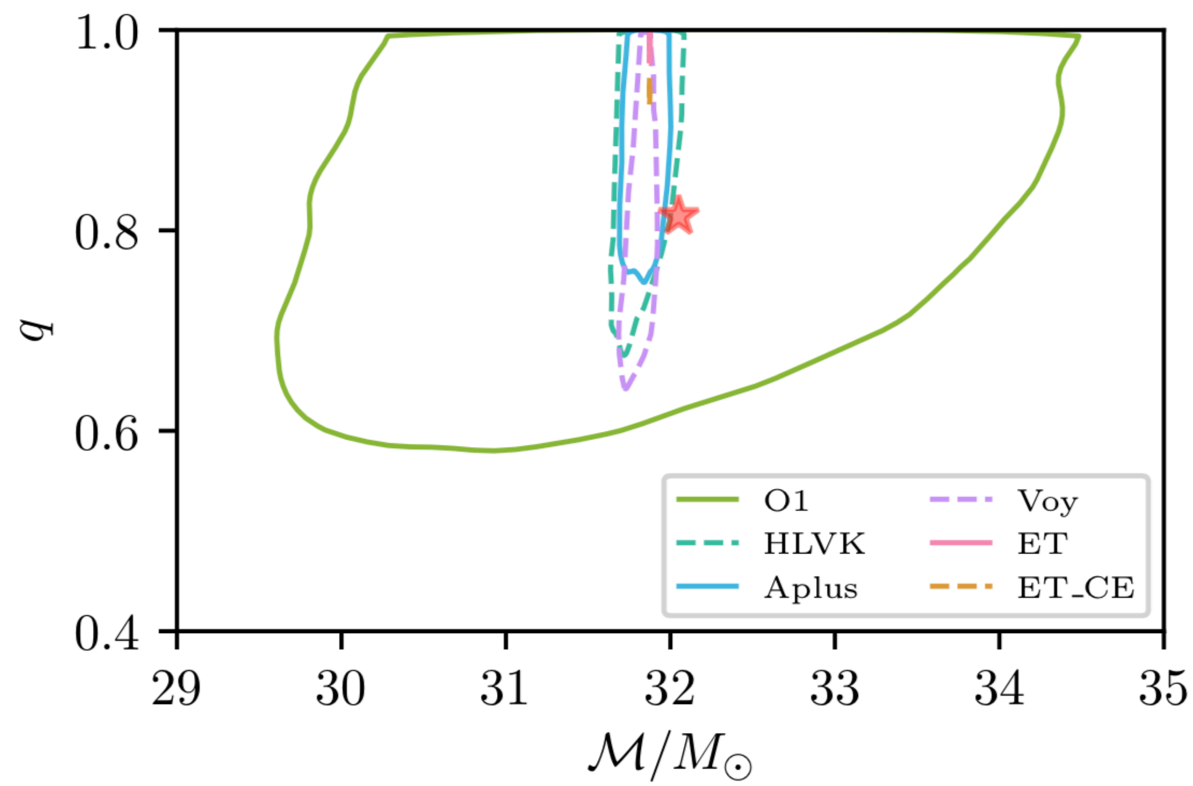
- Synthetic GW signal of a **binary black hole** at **400 Mpc** is **injected** in Gaussian noise with **aLIGO design-sensitivity** noise-spectral density **(SNR ~ 70)**.

- **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.)

- 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)**.

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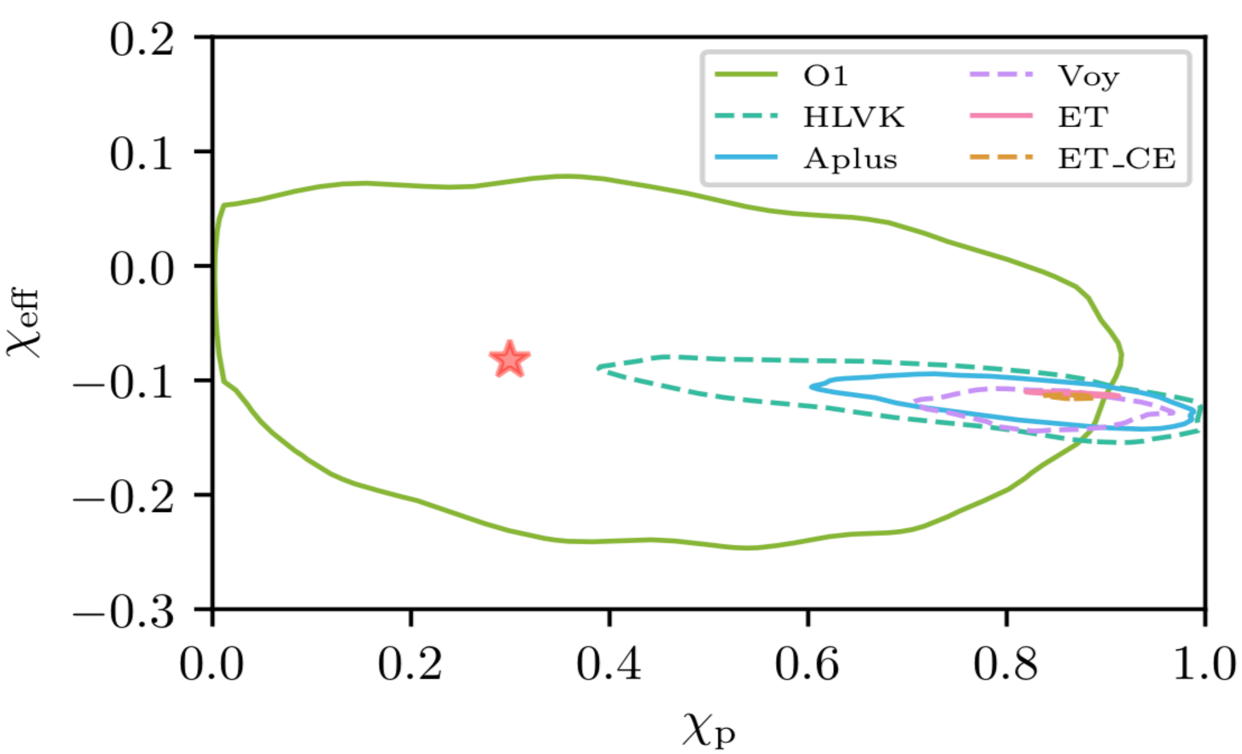
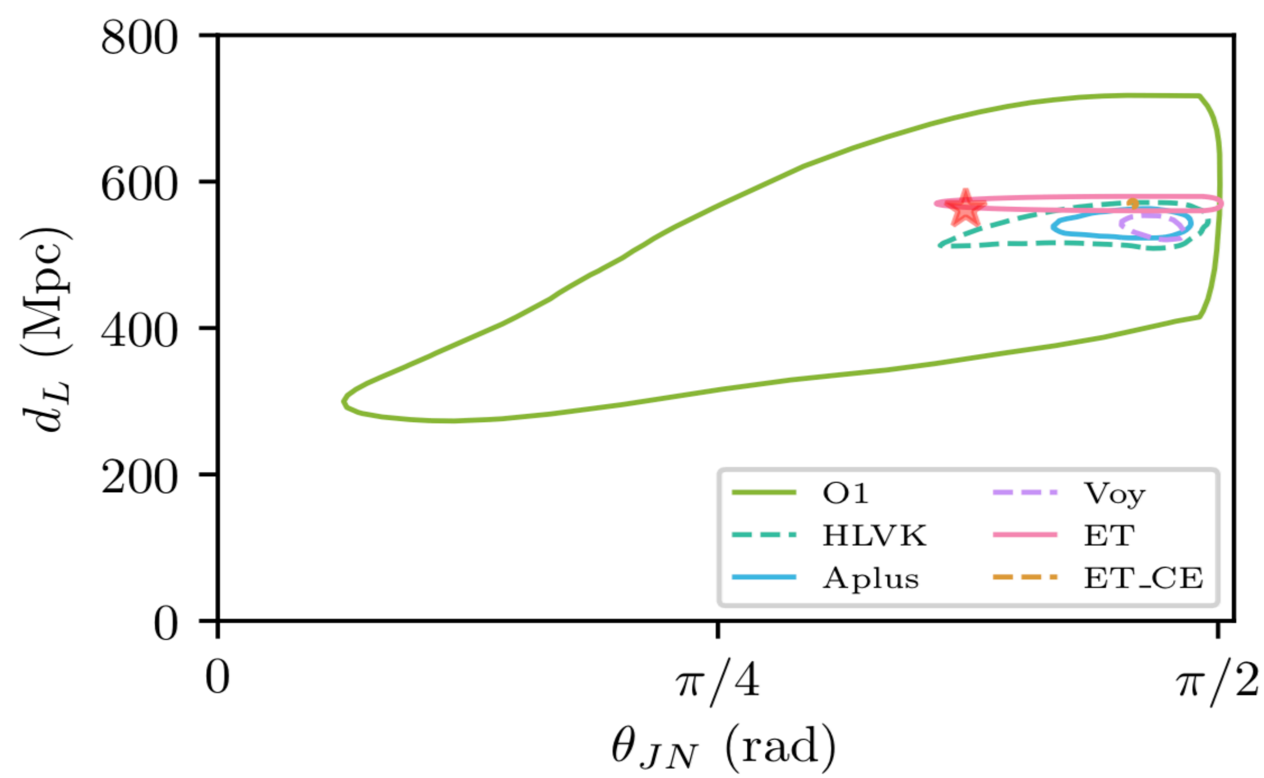




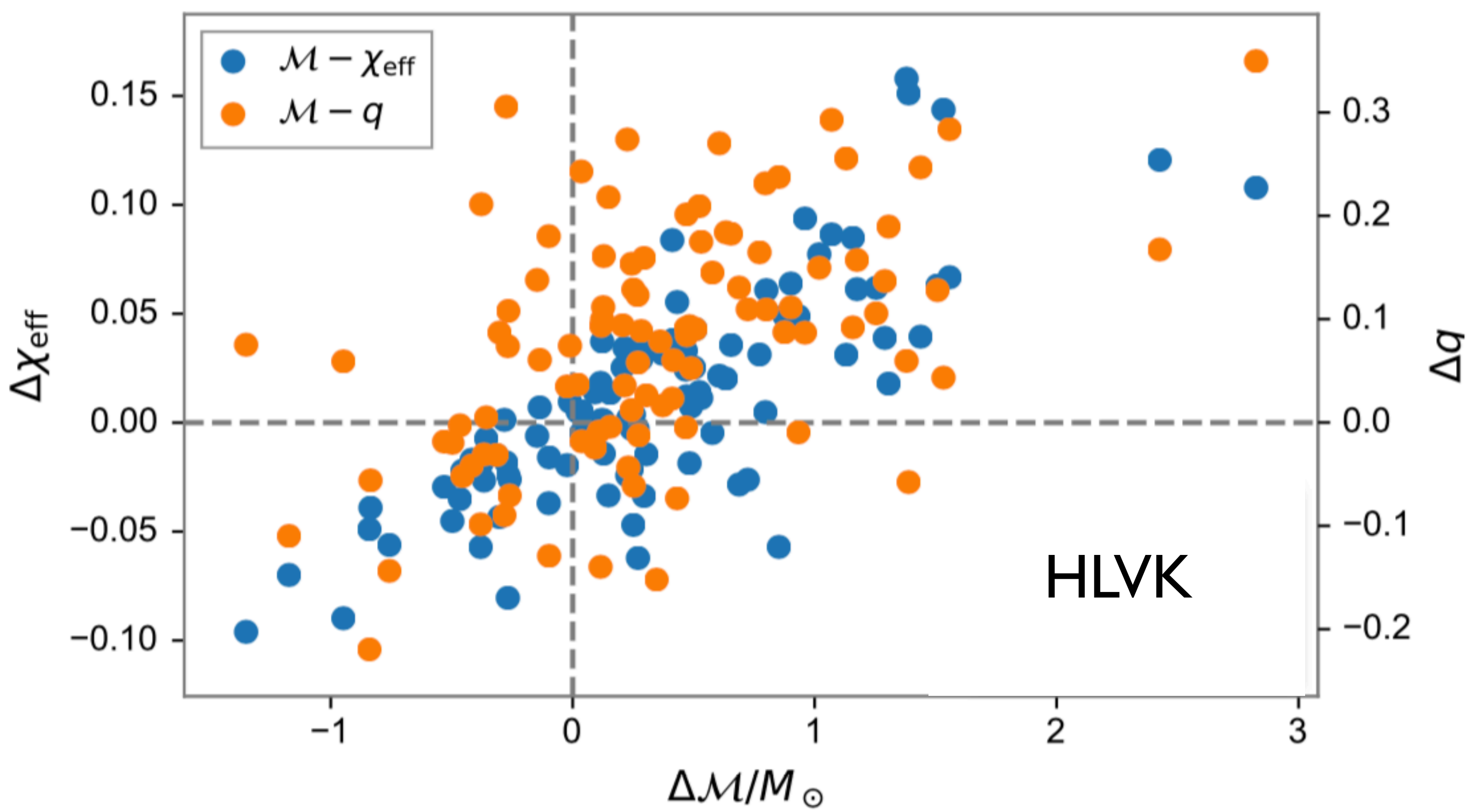
Systematics due to modeling using population

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

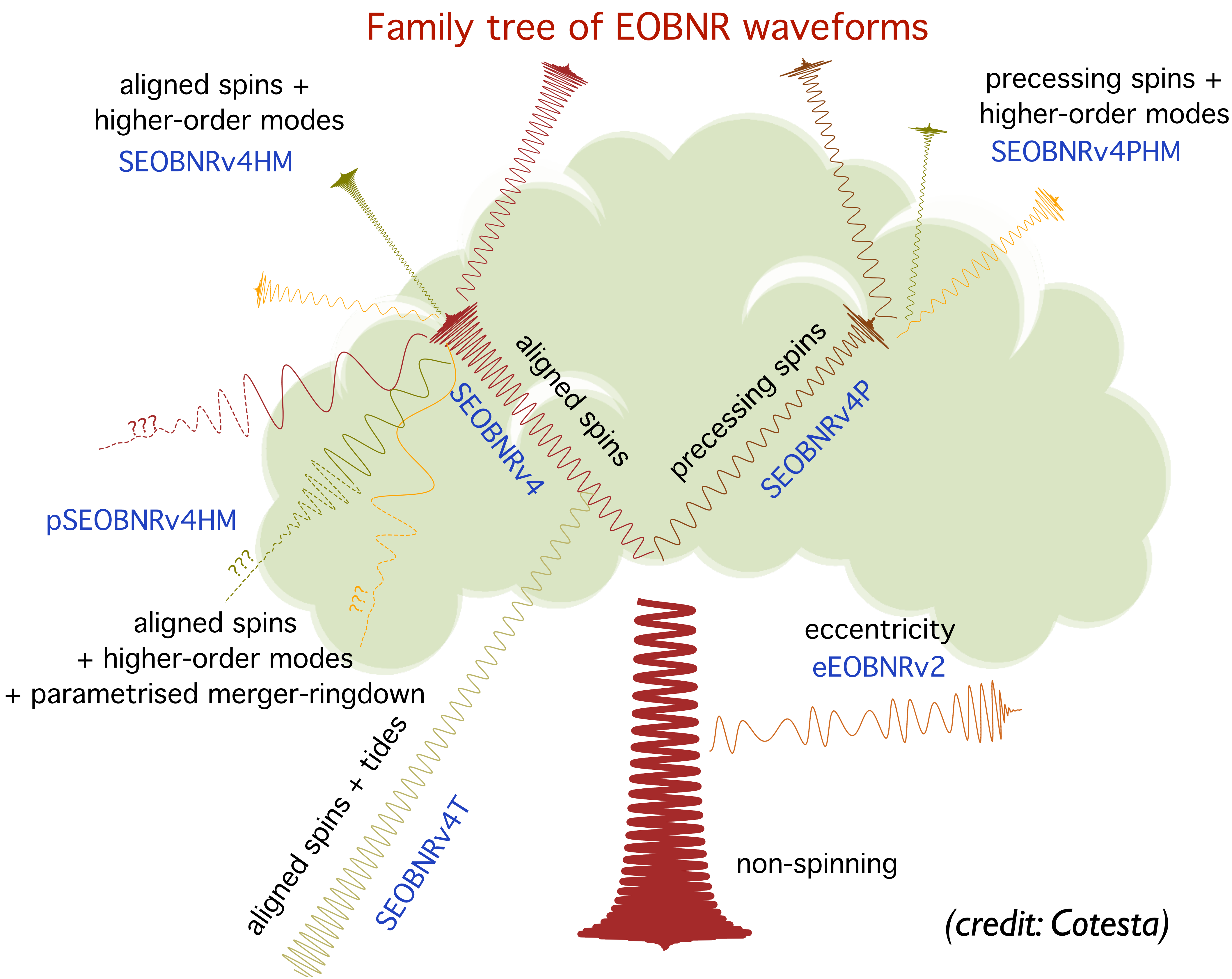
(Pürrer & Haster in prep 19)

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

mass ratio = 1-2
spins < 0.8



Ever more physics in waveform models

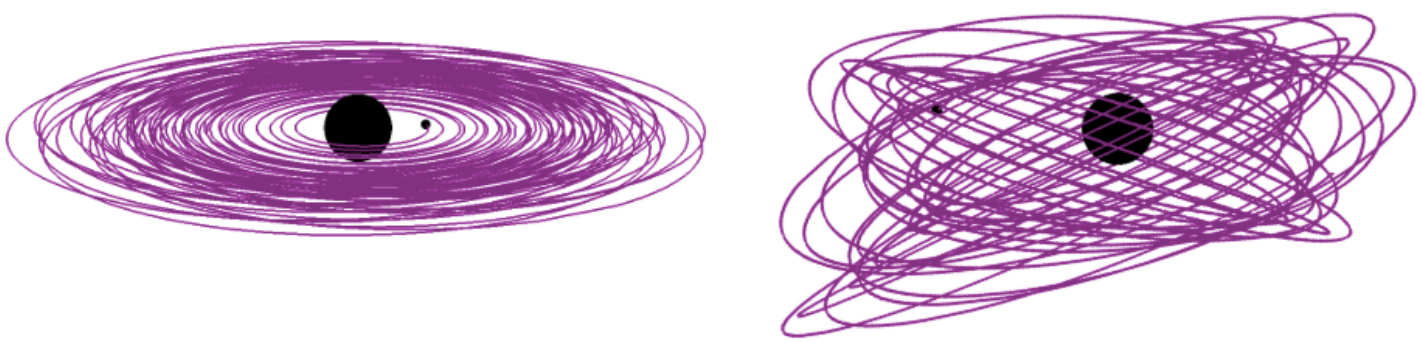


Inferring best science by including more physical effects

- 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

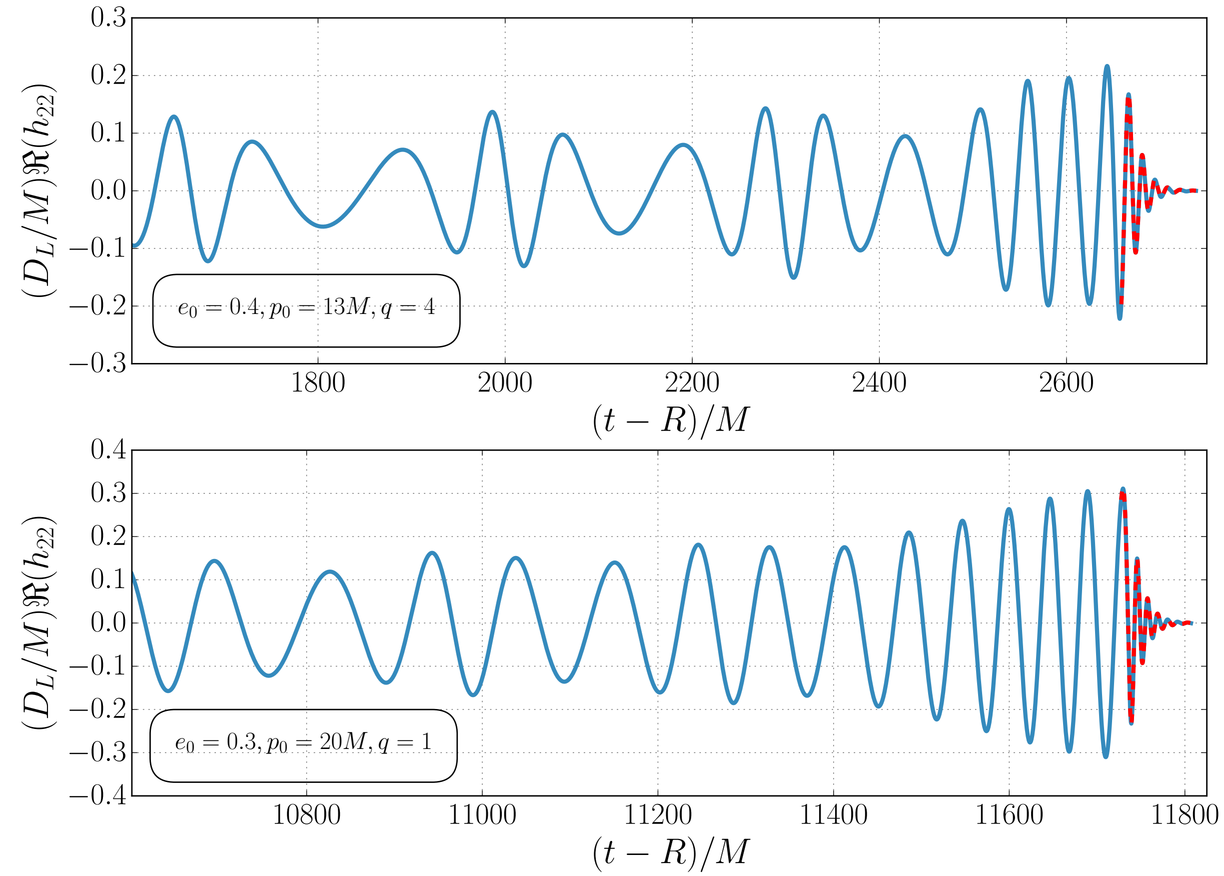


mass ratio = 7

(Lewis et al. 16)

(many PN papers; East et al. 13, Huerta et al. 14, 16, 18, Hinder et al. 17, Cao & Han 17, Loutrel & Yunes 16, 17, Huerta et al. 19, Ireland et al. 19, Moore & Yunes 19)

EOB waveform model



(Hinderer & Babak 17)

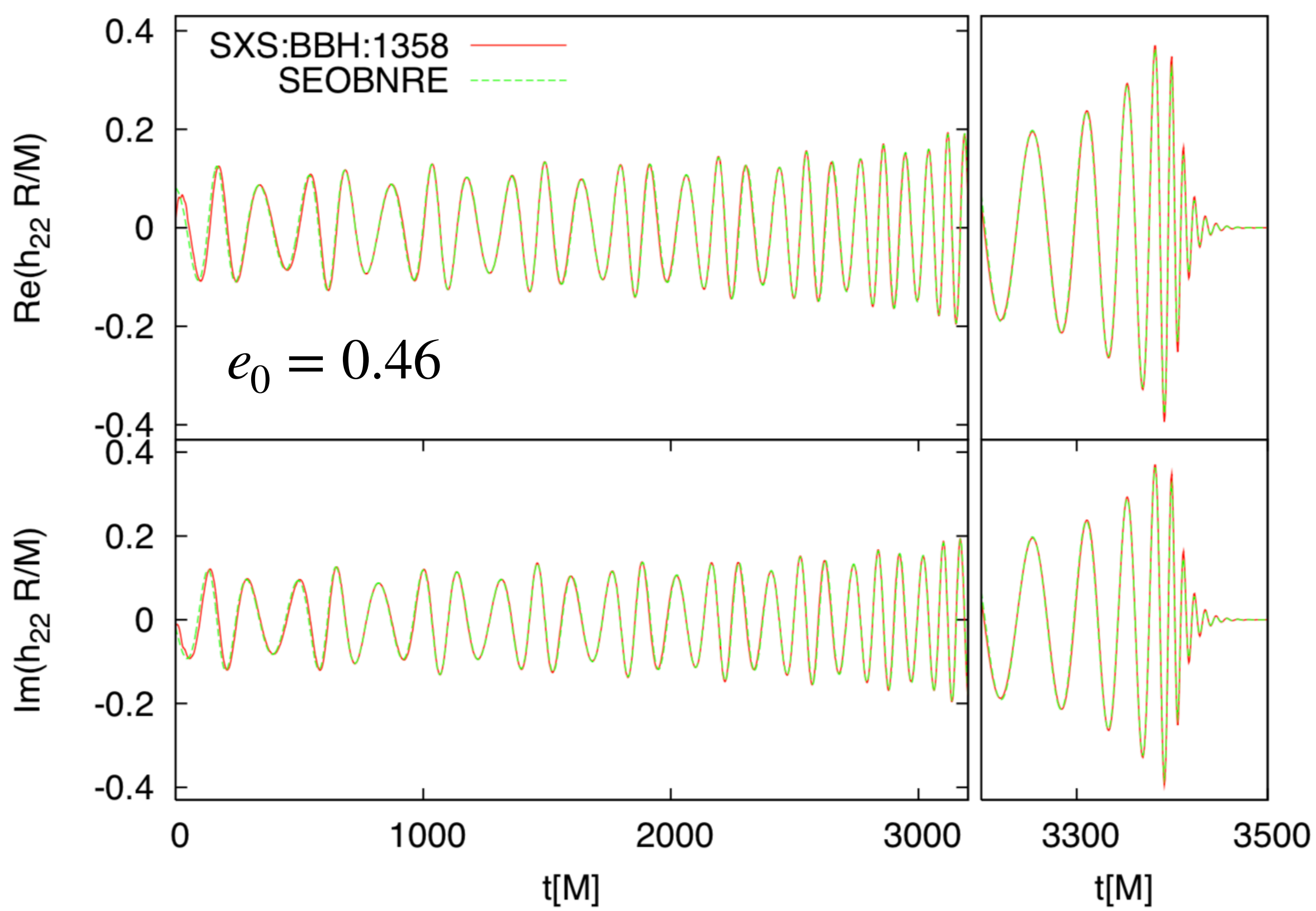
- **Current eccentric** waveform models **do not cover main physical effects** (e.g., spins and harmonics) **and all stages** of coalescence.

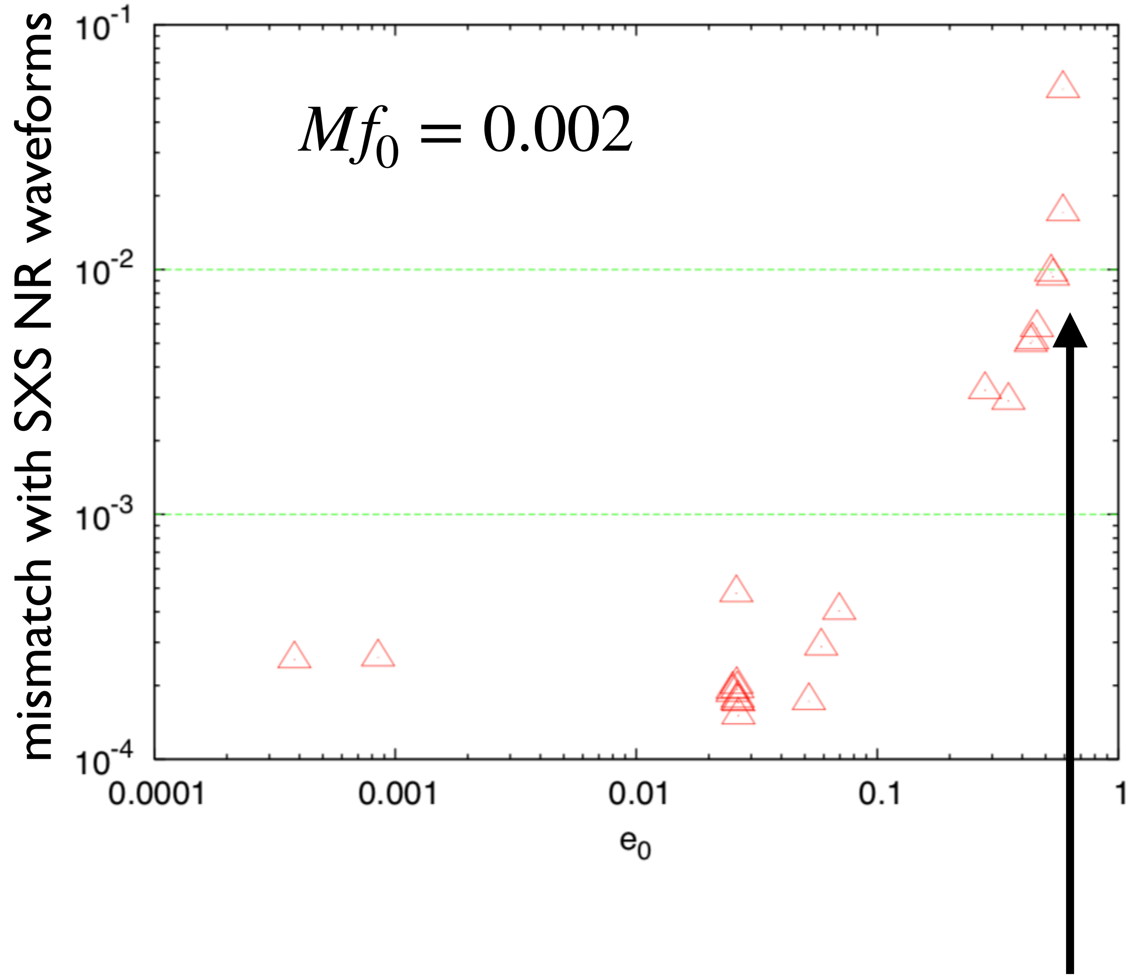
Waveforms for eccentric BBHs using EOB formalism

- **Quasi-circular templates** can be used to match eccentric templates up to $e_0 < 0.1$.
- First **SEOBNR** model with **spins**, up to $+0.6$, and **eccentricity**.

(Cao et al. 17, Liu et al. 19)

SEOBNRE waveform model



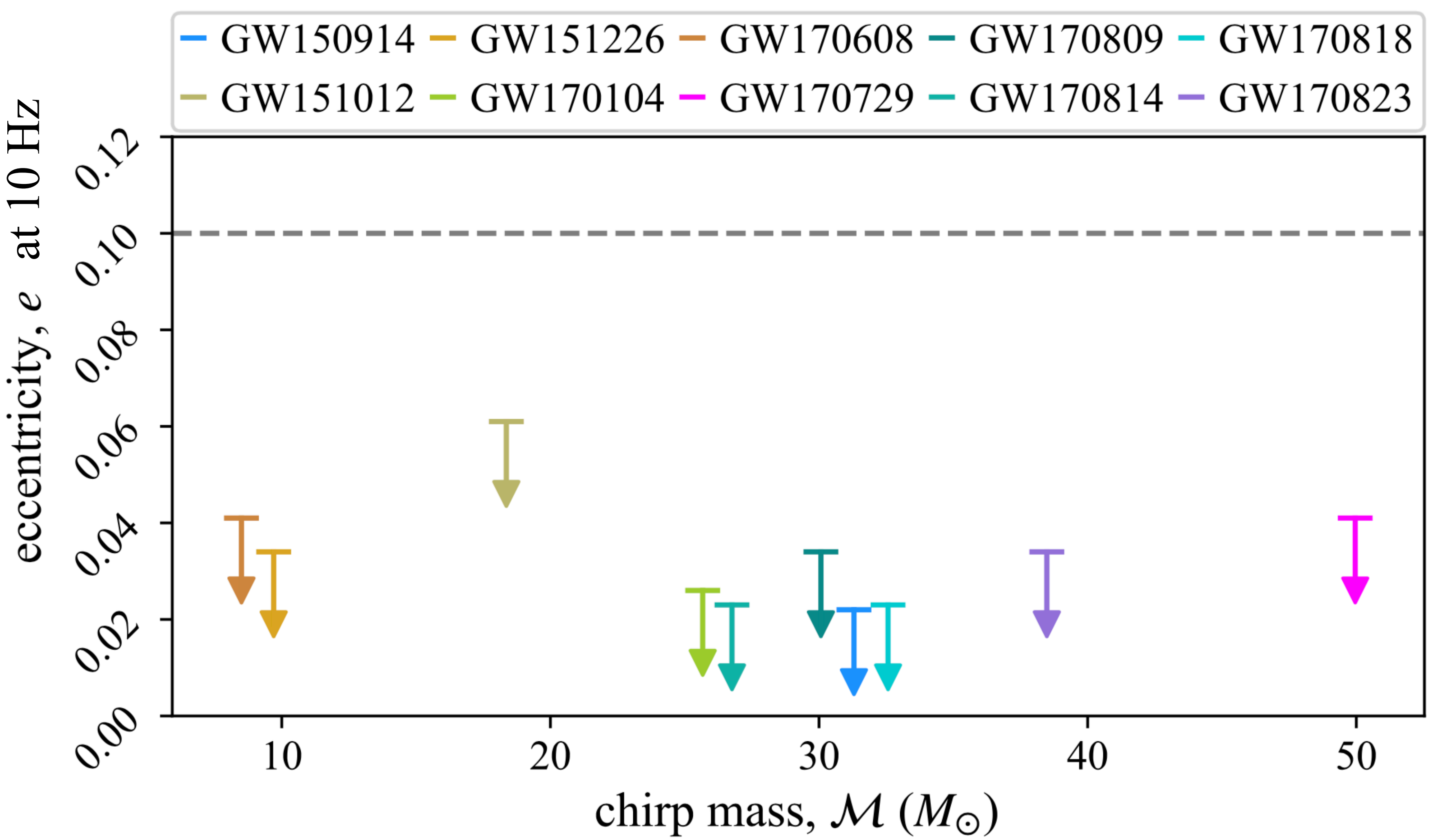


- **Mismatches** smaller than $1\,\%$ up to $e_0 < 0.55$.

SEOBNRE waveforms used to constrain eccentricity of GWTC-1

- **Isolated** binary **evolution** or **dynamical** formation?

(Romera-Shaw, Lasky & Thrane 19)



Event	$e^{90}_{\rm max}$	$\ln \mathcal{B}$
GW150914	0.022	−1.64
GW151012	0.061	−0.96
GW151226	0.034	−1.63
GW170104	0.026	−1.52
GW170608	0.041	−1.47
GW170729	0.041	−0.53
GW170809	0.041	−1.47
GW170814	0.023	−1.48
GW170818	0.023	−1.47
GW170823	0.034	−1.58

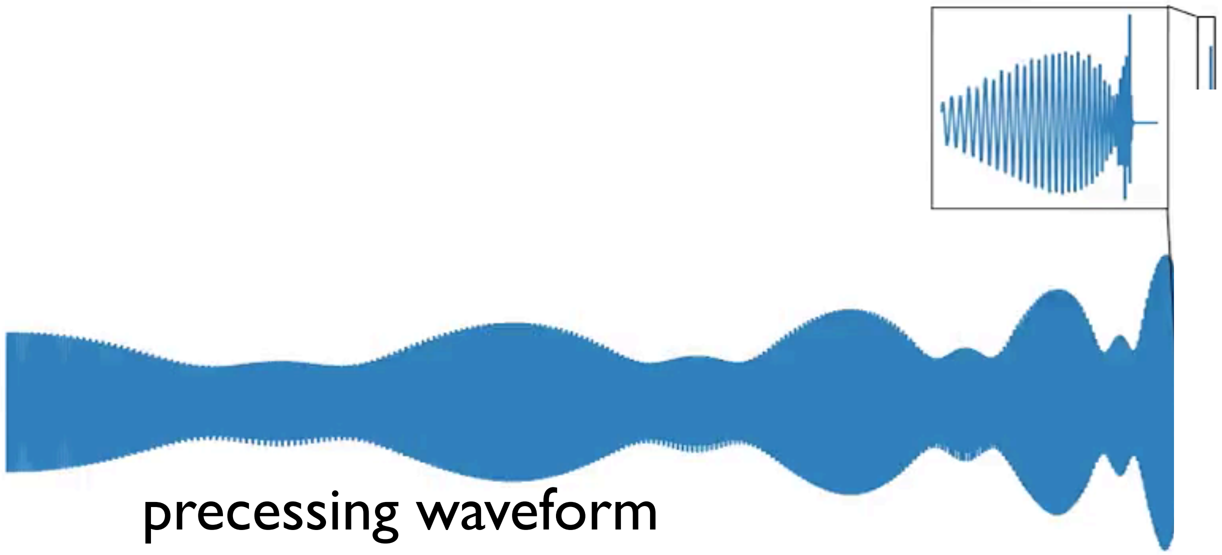
- We should expect to observe $\sim 5\,\%$ of all mergers from **globular clusters** with $e_0 > 0.1$ at 10 Hz. *(Rodriguez et al. 18, Samsing et al. 18)*

Characteristics of spin-precessing dynamics and waveform

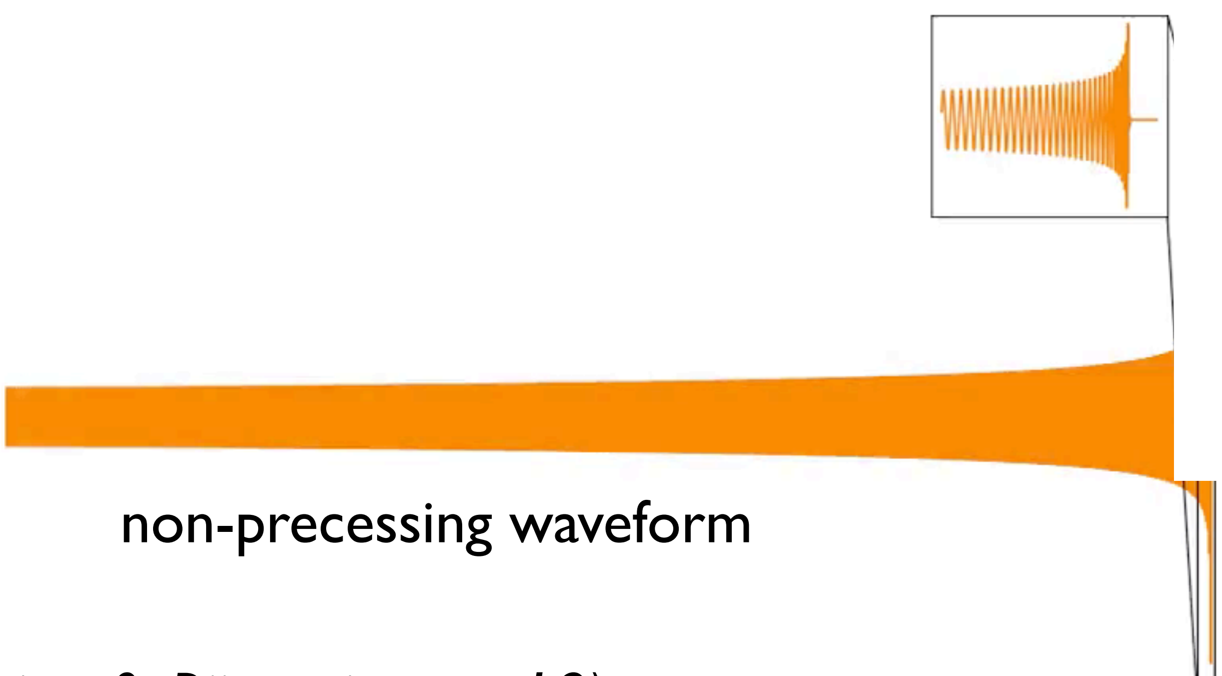
(credit: *Ossokine*)

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

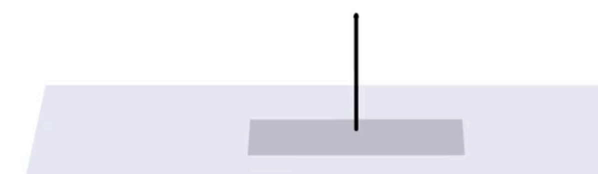
574 GW cycles, from 10 Hz
5 precessional cycles
40 sec duration



precessing waveform



non-precessing waveform

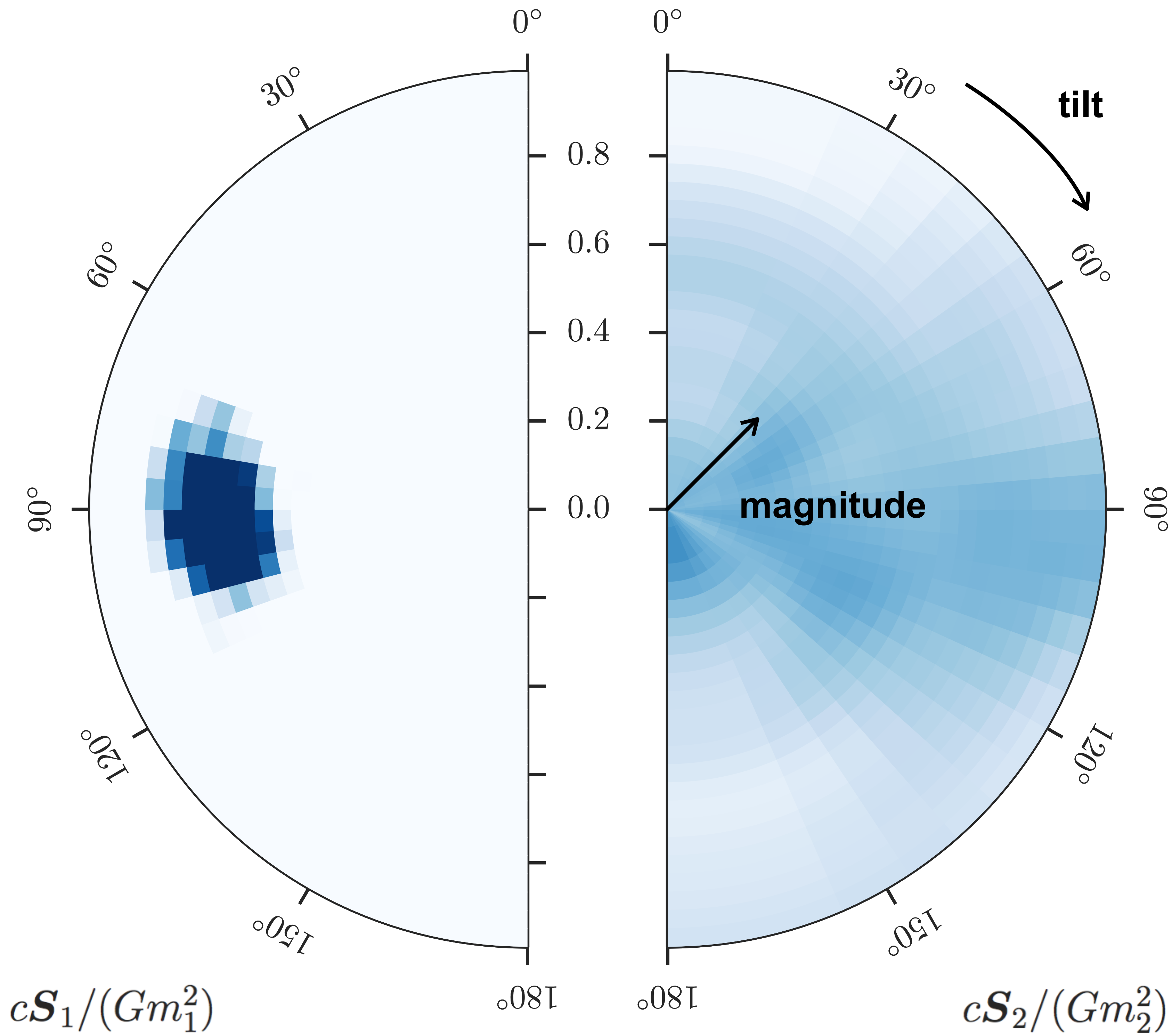


binary orbital plane

(Ossokine & Pürrer in prep19)

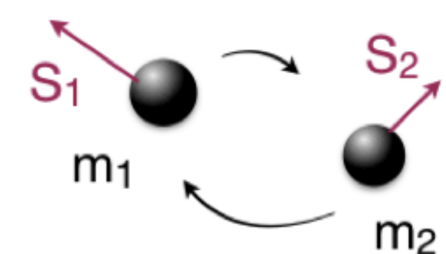
Measuring spin-precession from collision of BHs

SNR ~ 25
aLIGO/Virgo



(credit: *Pürrer*)

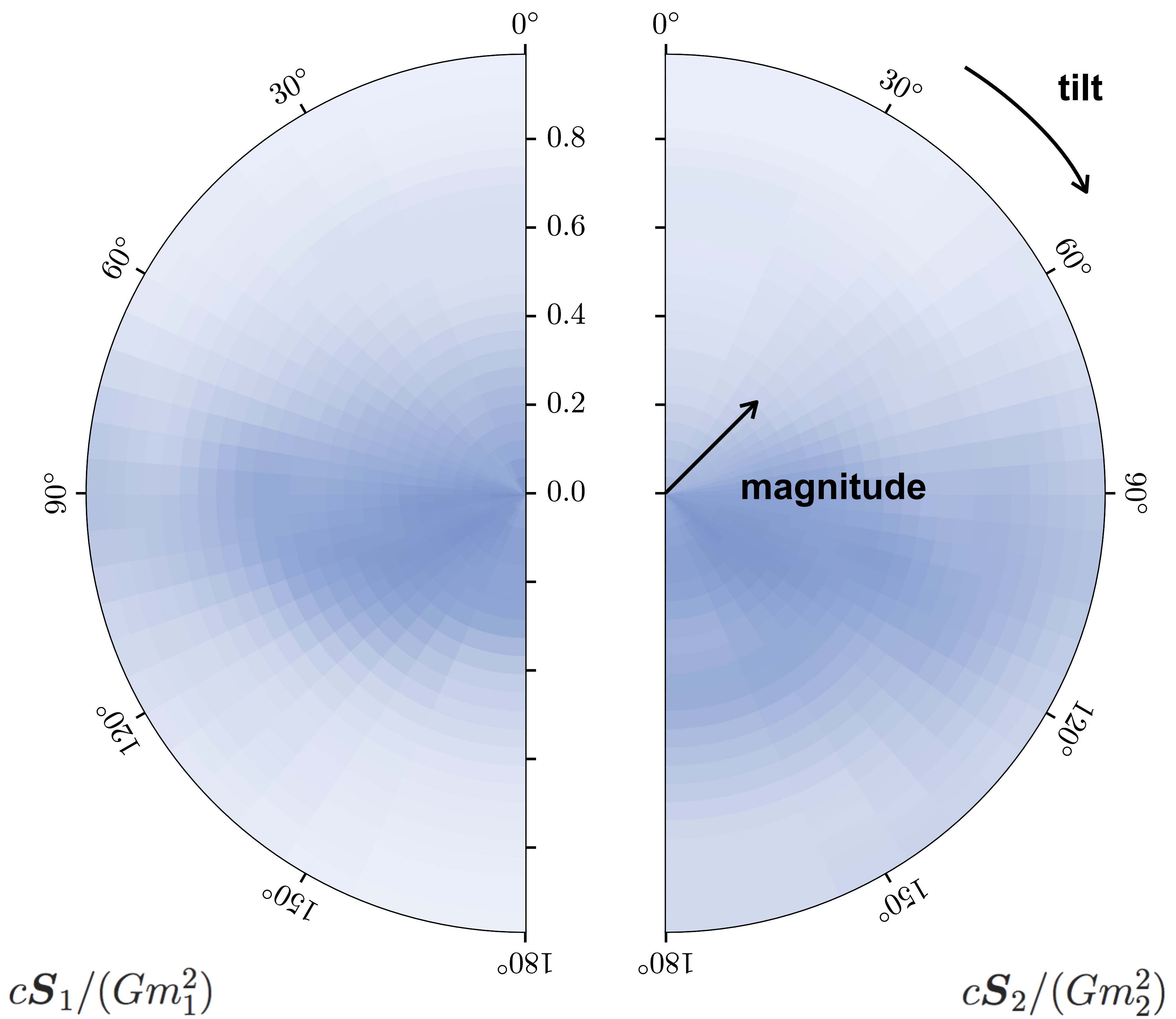
(Ossokine & Pürrer in prep19)



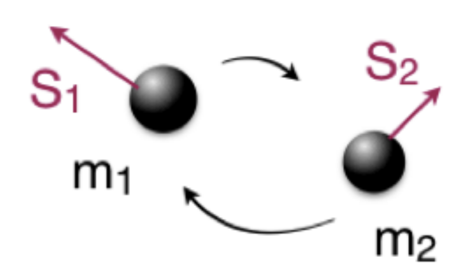
(credit: Hinderer)

Measuring spin-precession with GW150914

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

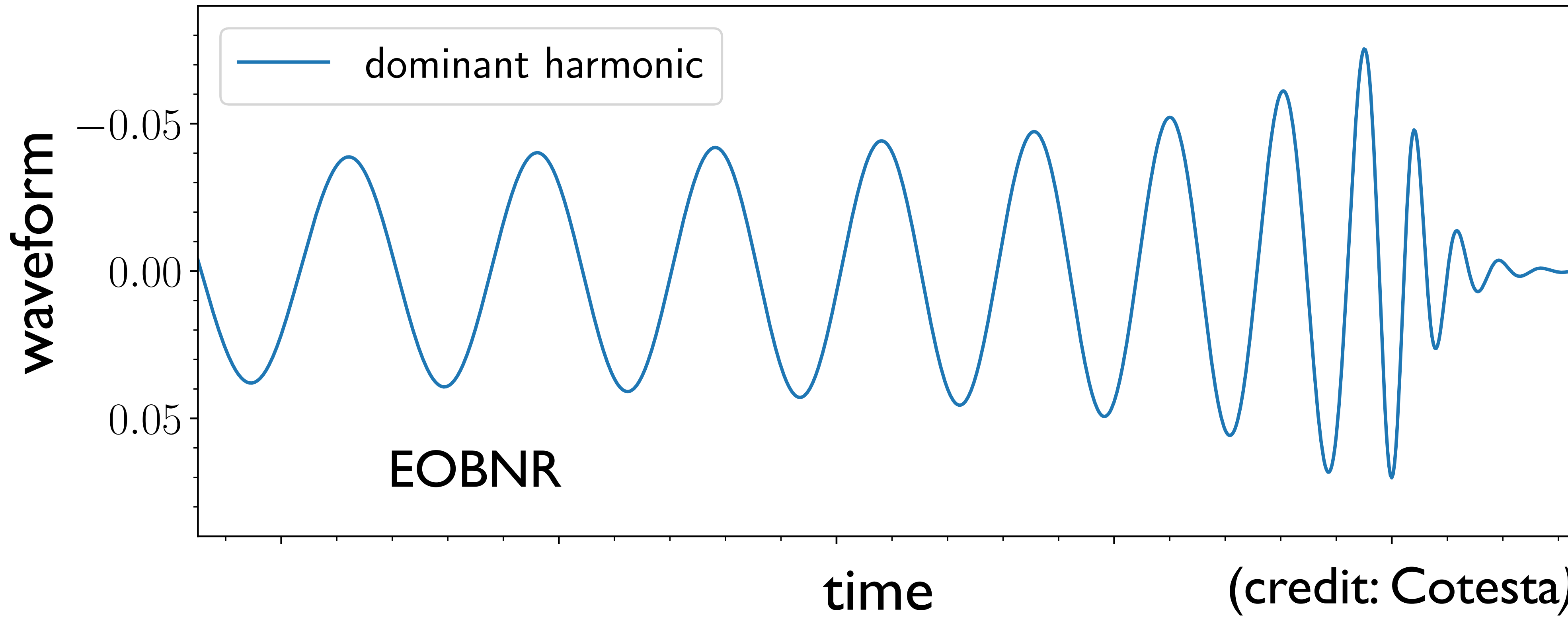


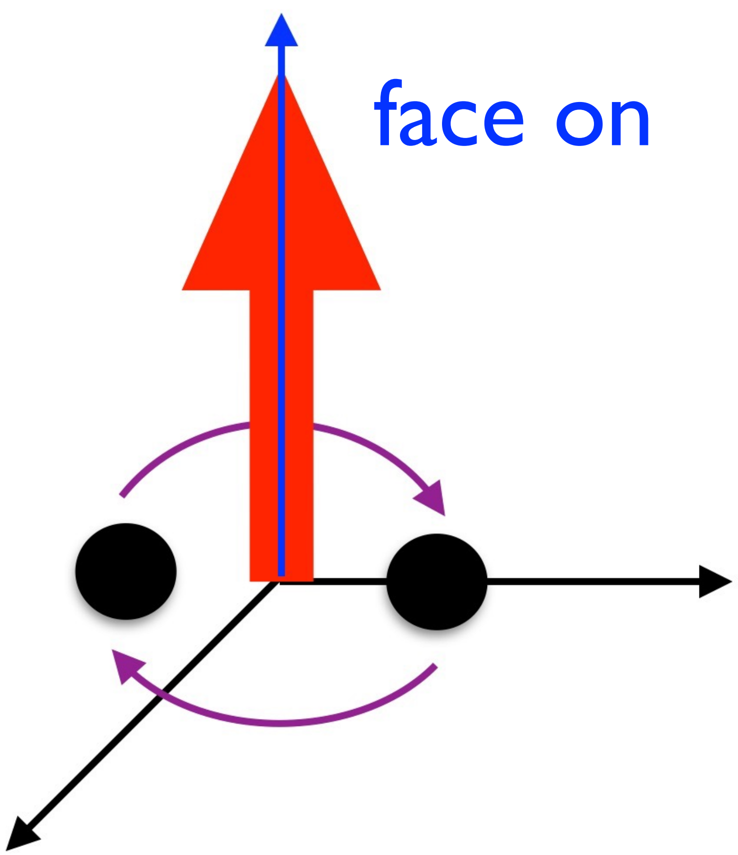
(credit: Pürrer/LIGO/Virgo)



(credit: Hinderer)

Enriching the GW symphony by tuning higher harmonics

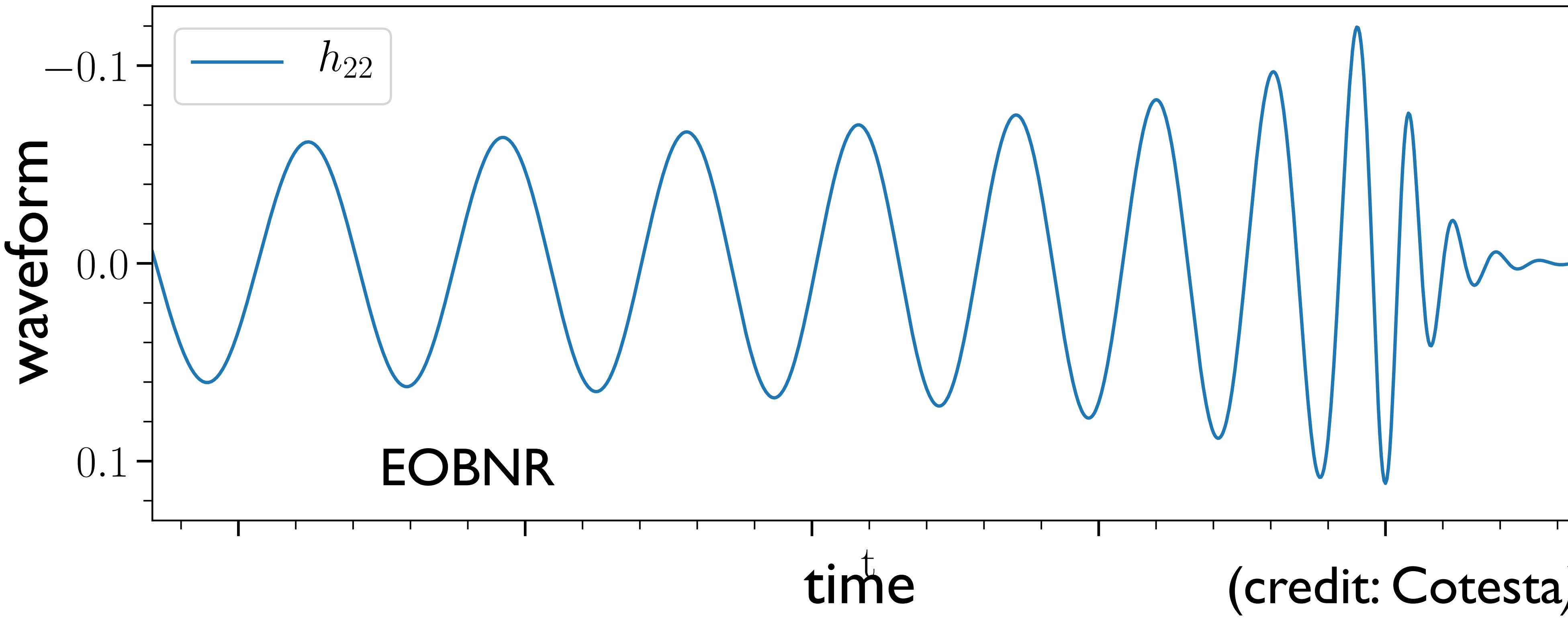




- So far, LIGO/Virgo **observed** GW **events mostly face-on/face-off.**
- **Face-on/face-off orientation** suppress **higher harmonics.**

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

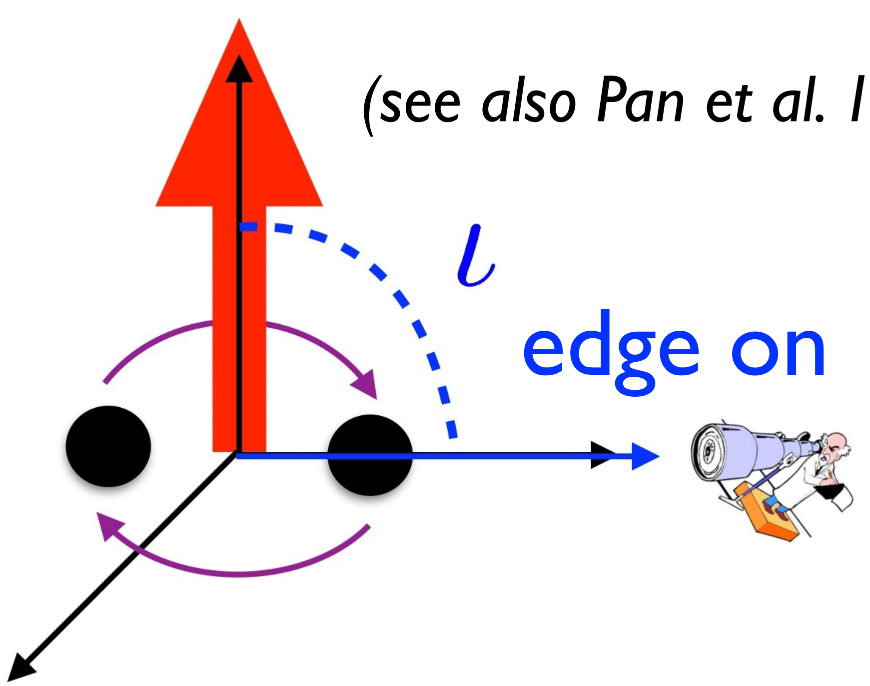
fundamental harmonic



(credit: Cotesta)

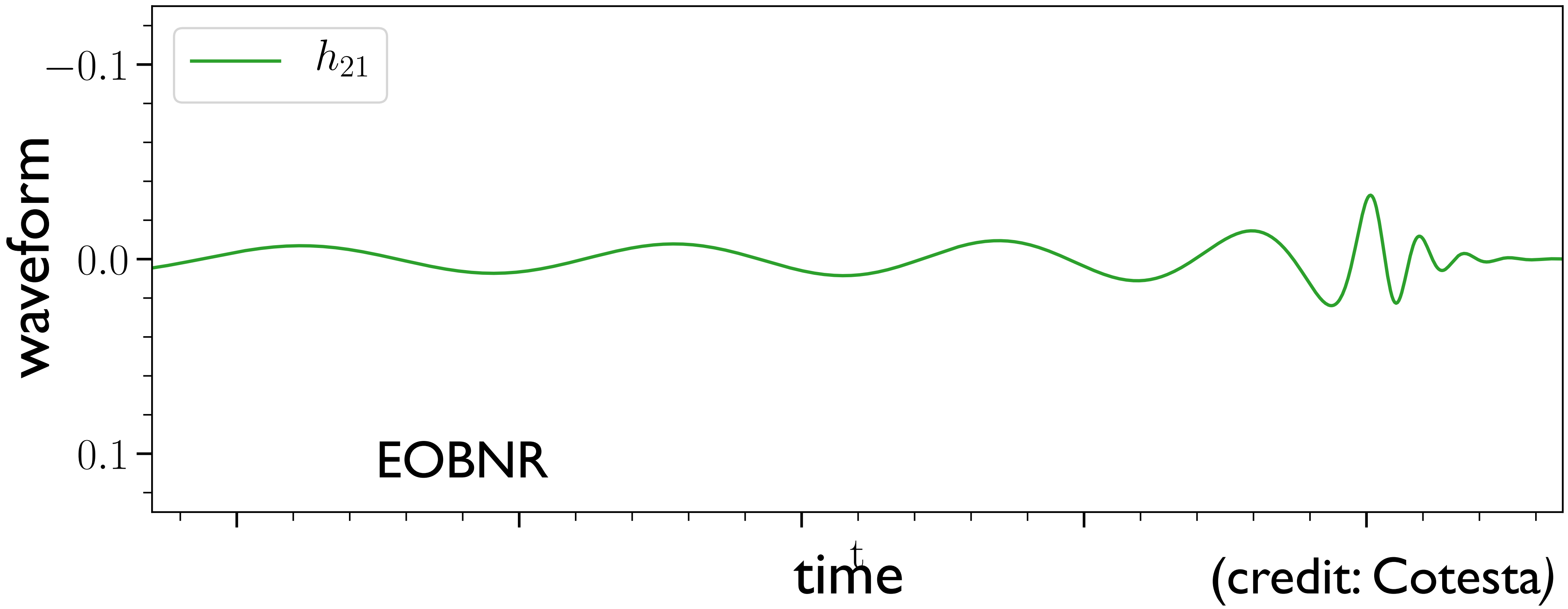
(Cotesta, AB, Bohe, Taracchini, Hinder, Ossokine 18)

(see also Pan et al. 11, London et al. 17, Mehta et al. 17,19, Nagar et al. 19)



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

first harmonic



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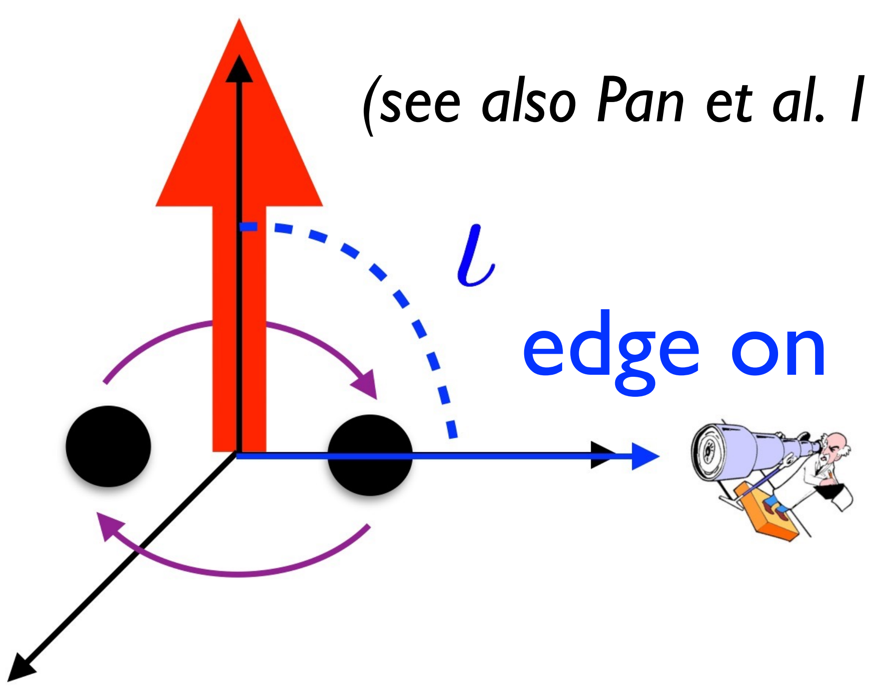
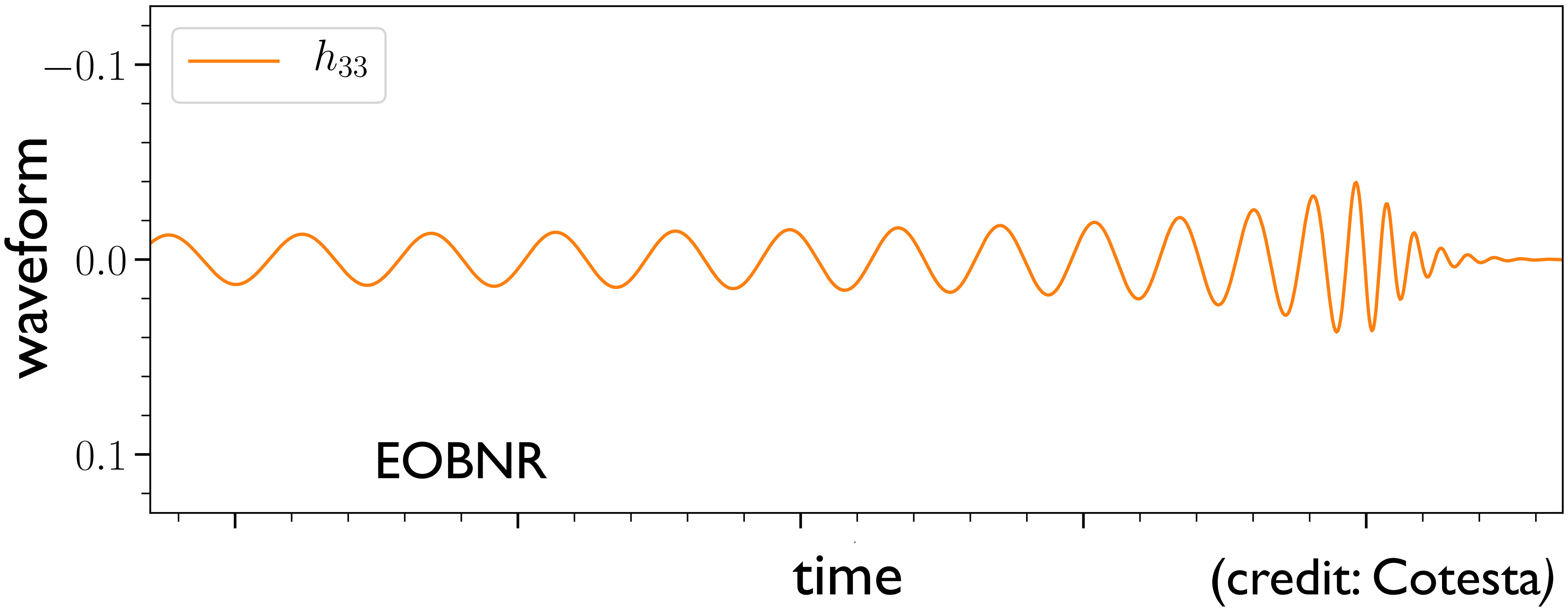


Enriching the GW symphony by tuning higher harmonics (contd.)

third harmonic



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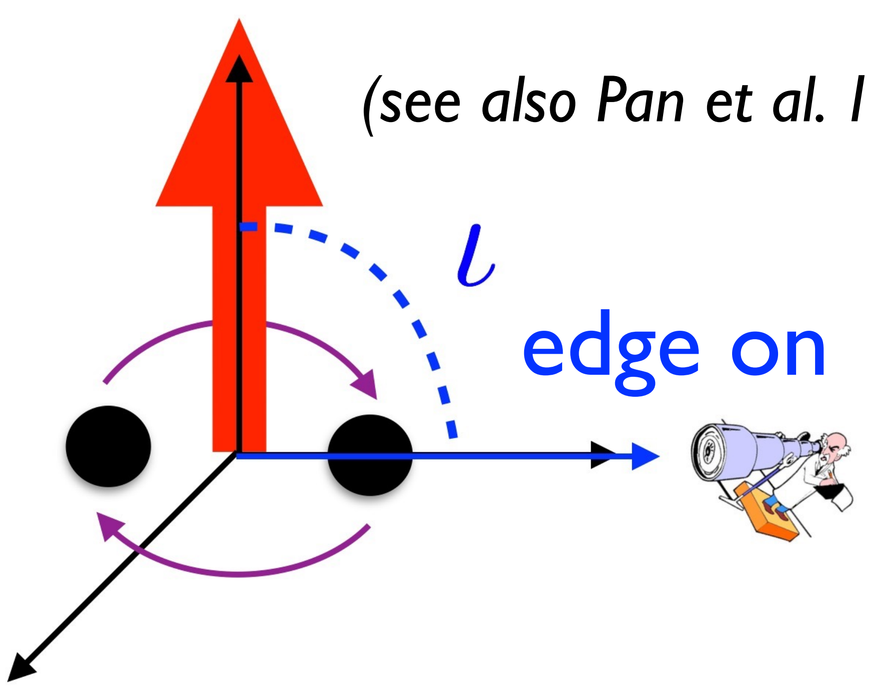
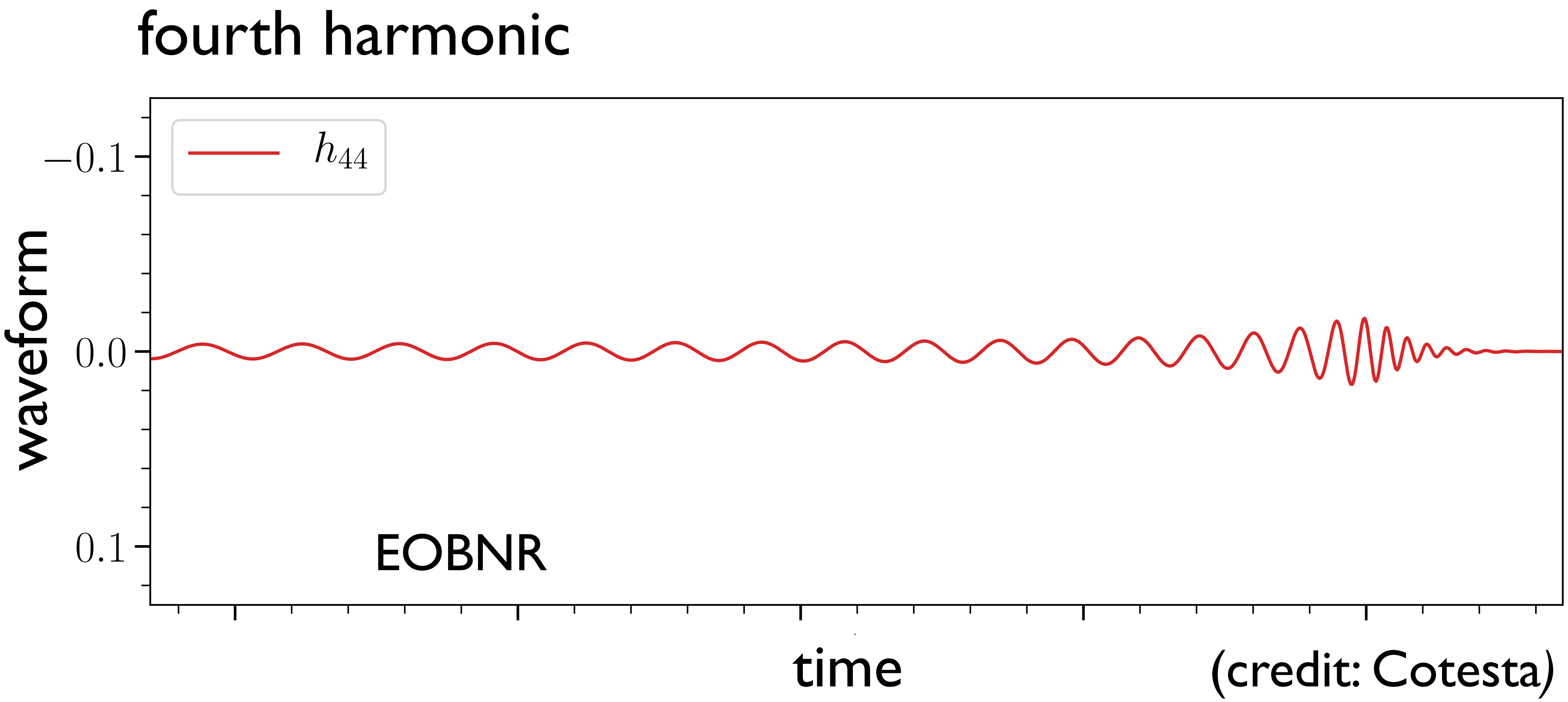


Enriching the GW symphony by tuning higher harmonics (contd.)



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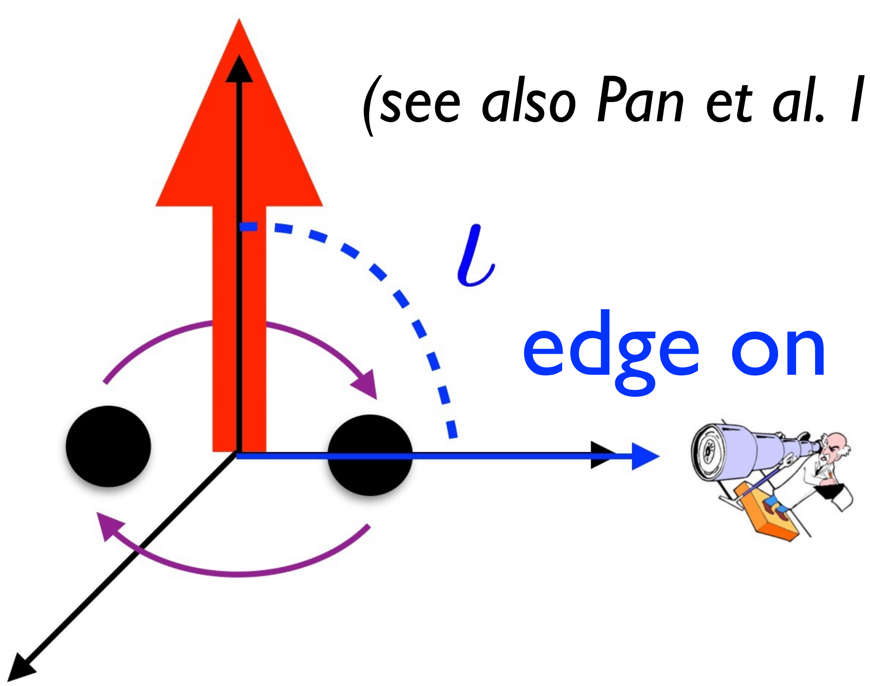
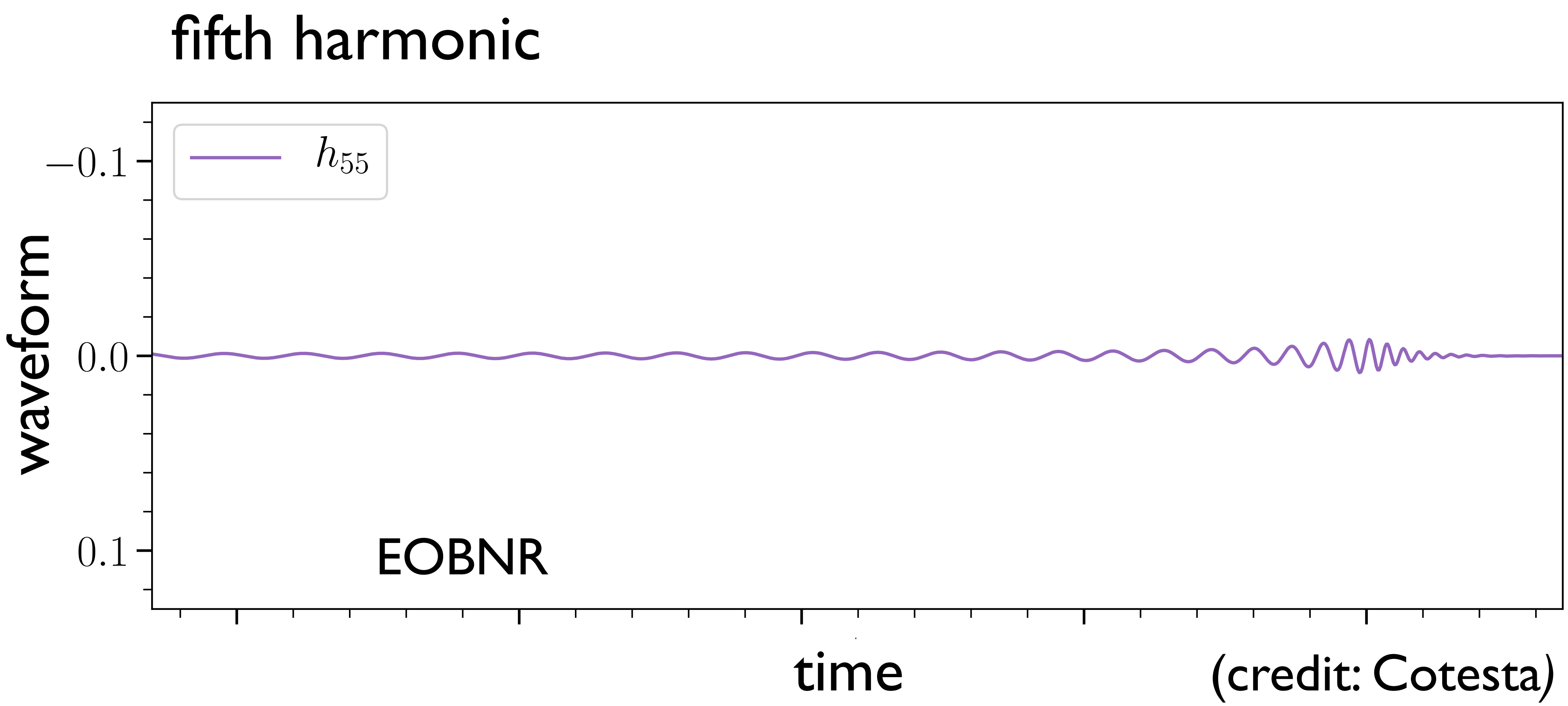


Enriching the GW symphony by tuning higher harmonics (contd.)



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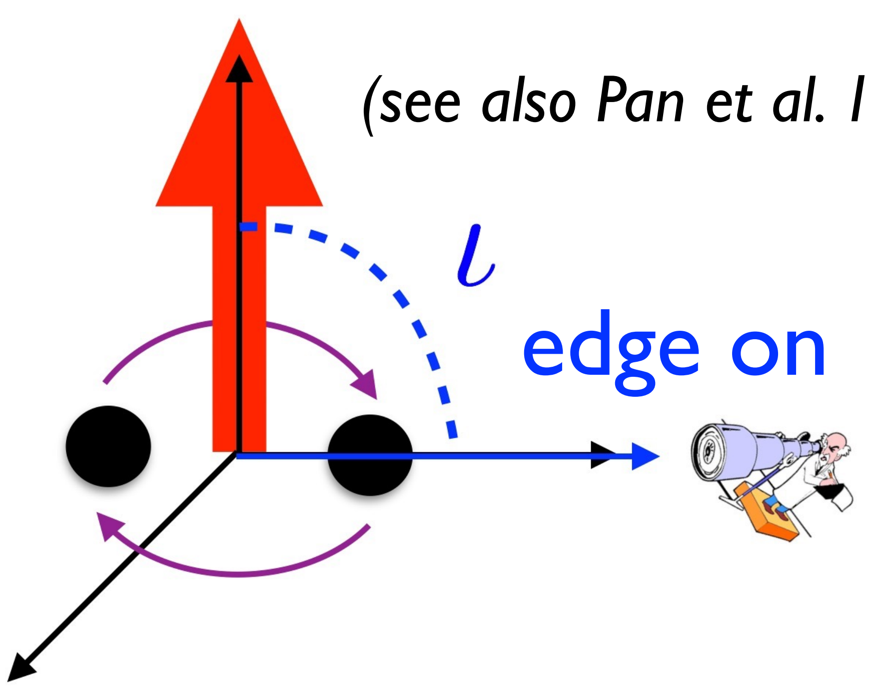
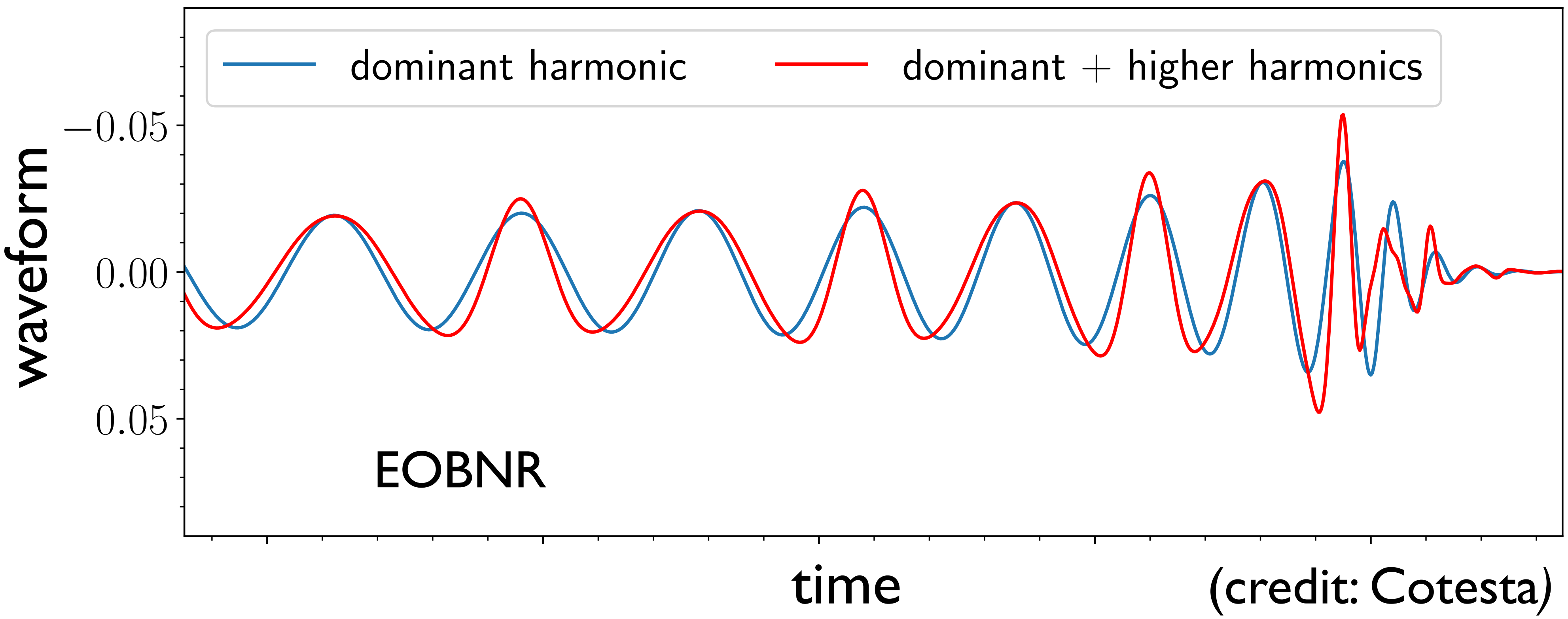


Enriching the GW symphony by tuning higher harmonics (contd.)

adding all five harmonics



(credit: Cotesta)

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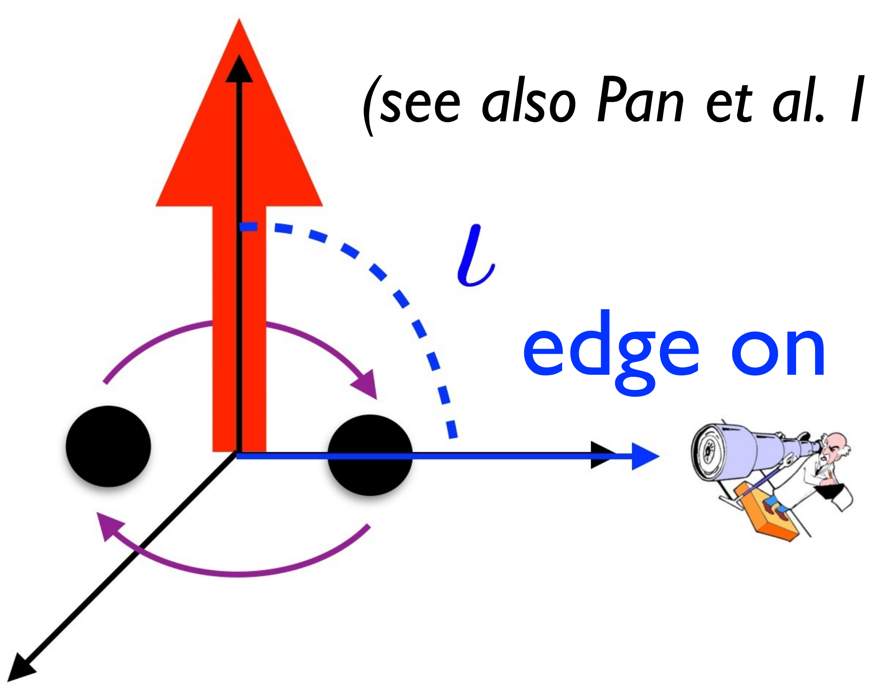
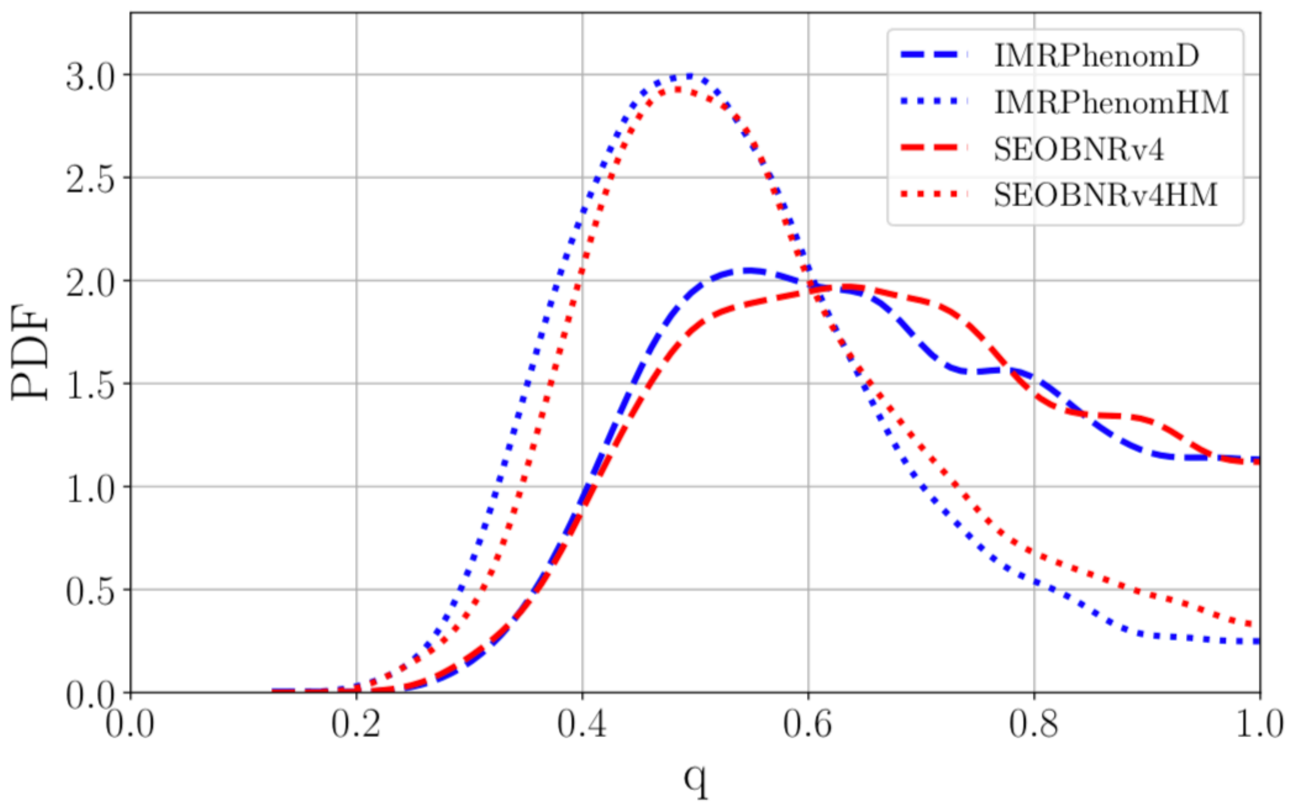
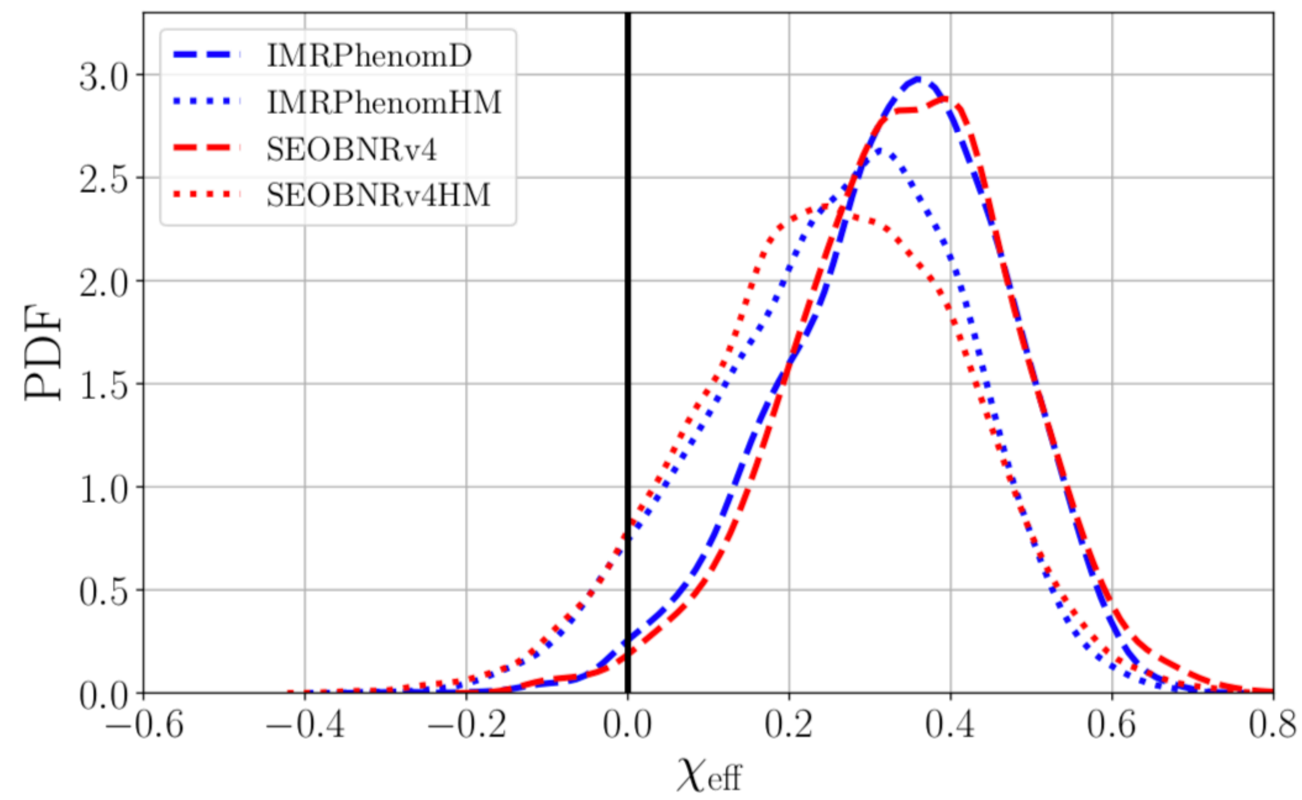


- We can **detect more rare** GW events.
- We can **infer source's properties more accurately**.
- We can **perform more stringent tests** of GR (e.g., BH spectroscopy)

Inference of GW170729 with higher-mode waveform models

(Chatziioannou , … AB …, 19)





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

Accuracy of multipolar precessing SEOBNR model against NR

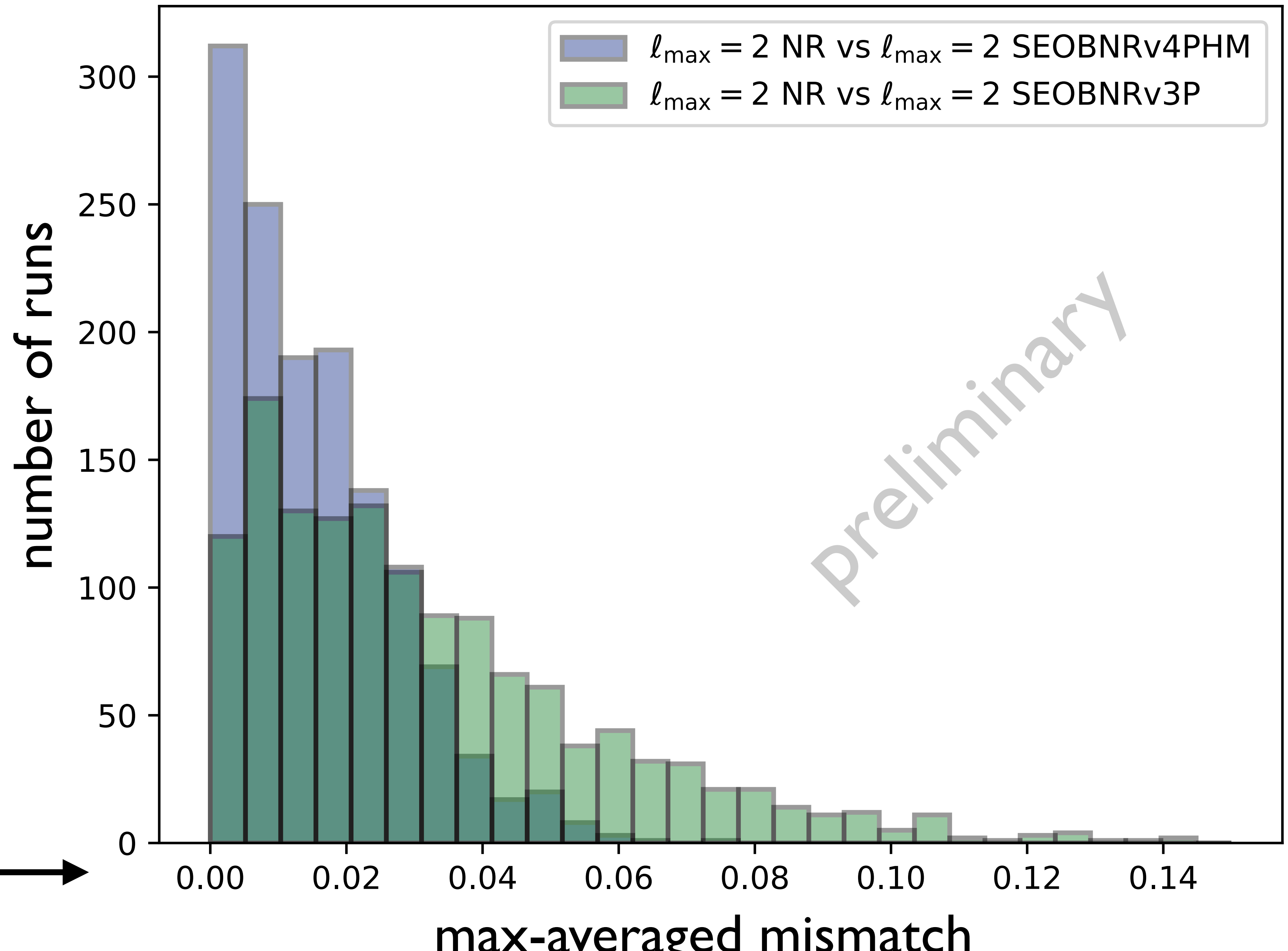
- **SEOBNRv4PHM**: **new** spin-precessing waveform model
- **SEOBNRv3P**: **old** spin-precessing waveform model, **without HMs, used in O1 & O2.**

(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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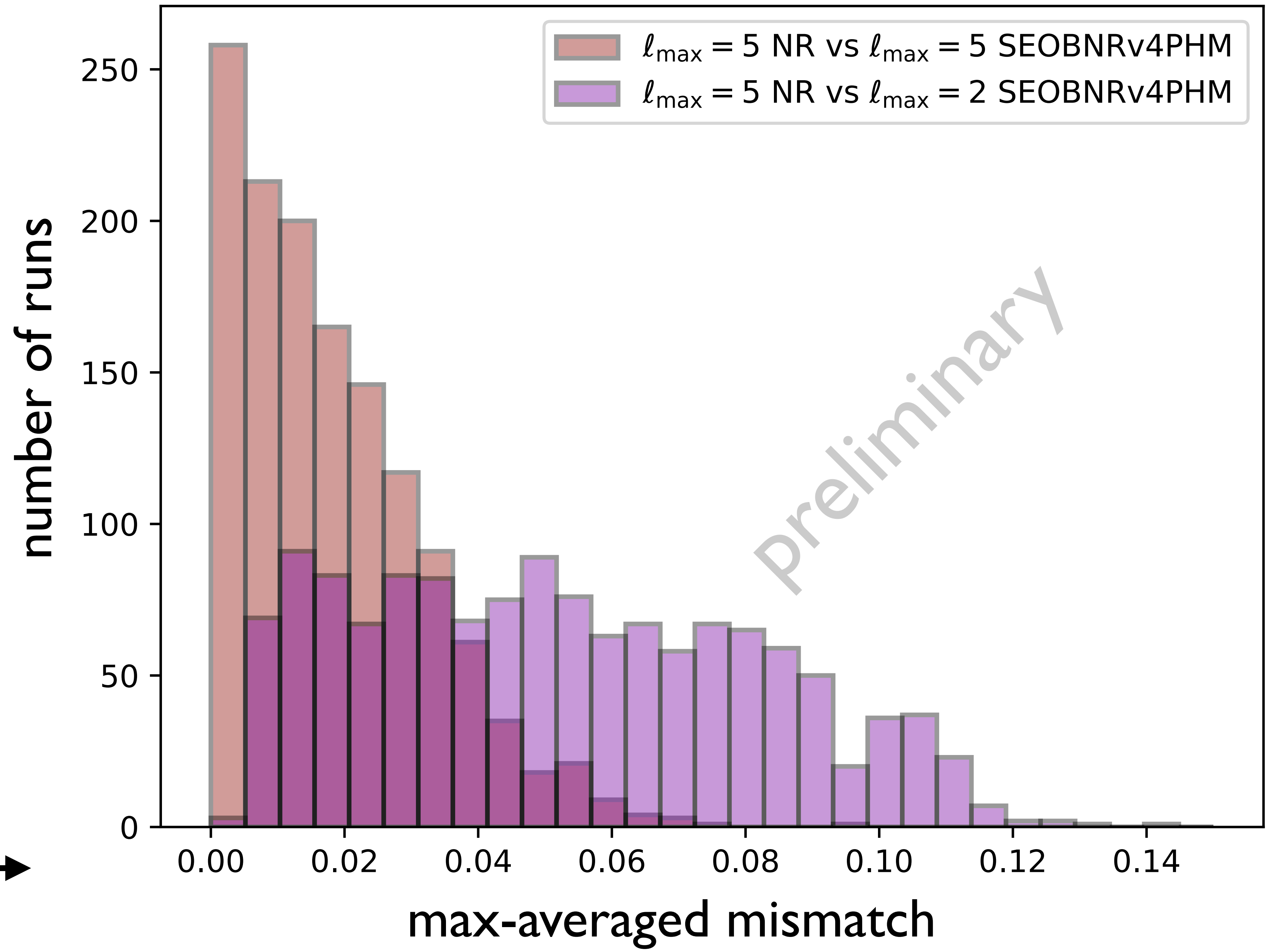
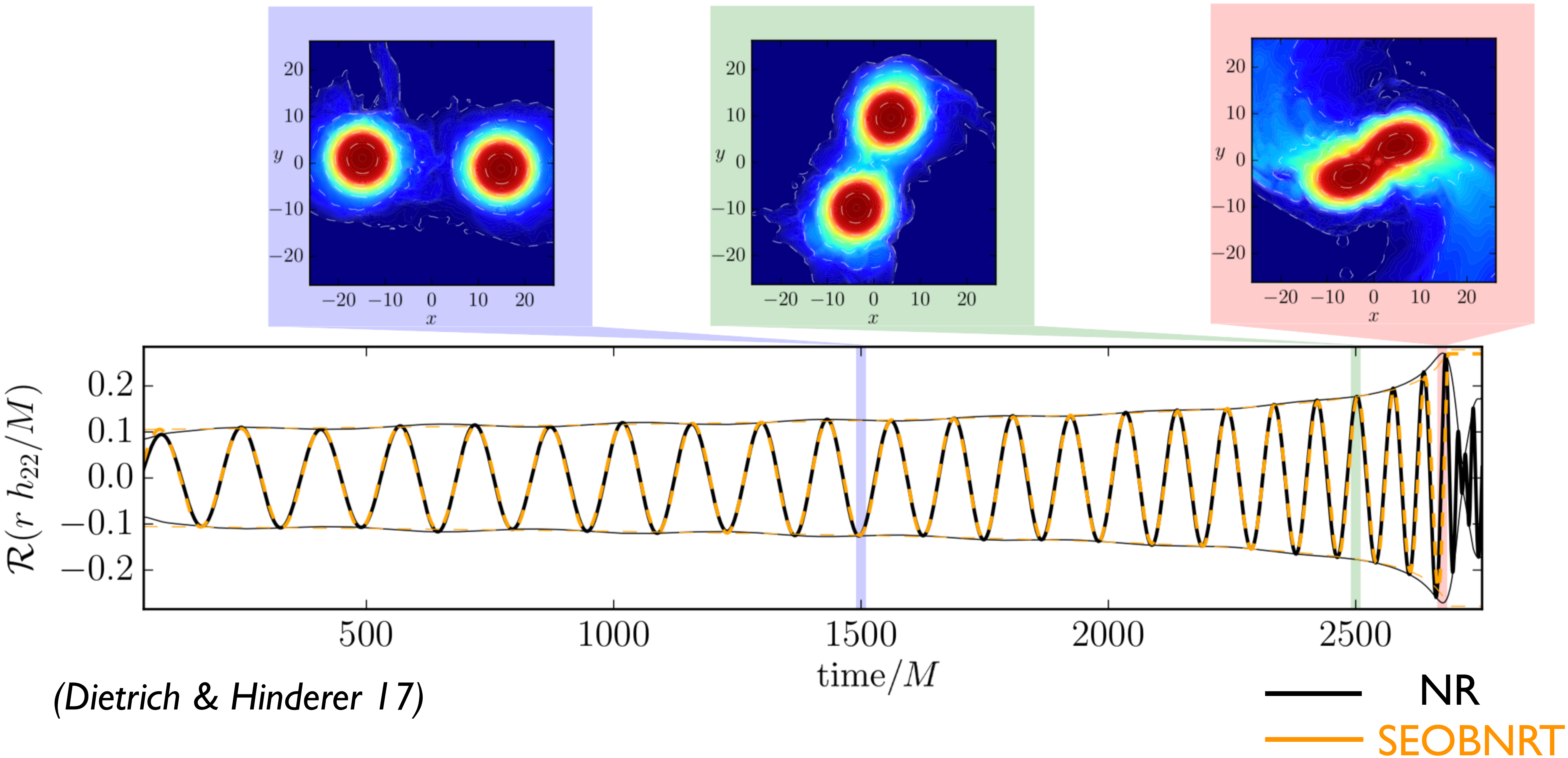


binary's inclination: $\iota = \pi/3$

Waveforms for BNS combining analytical & numerical relativity

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

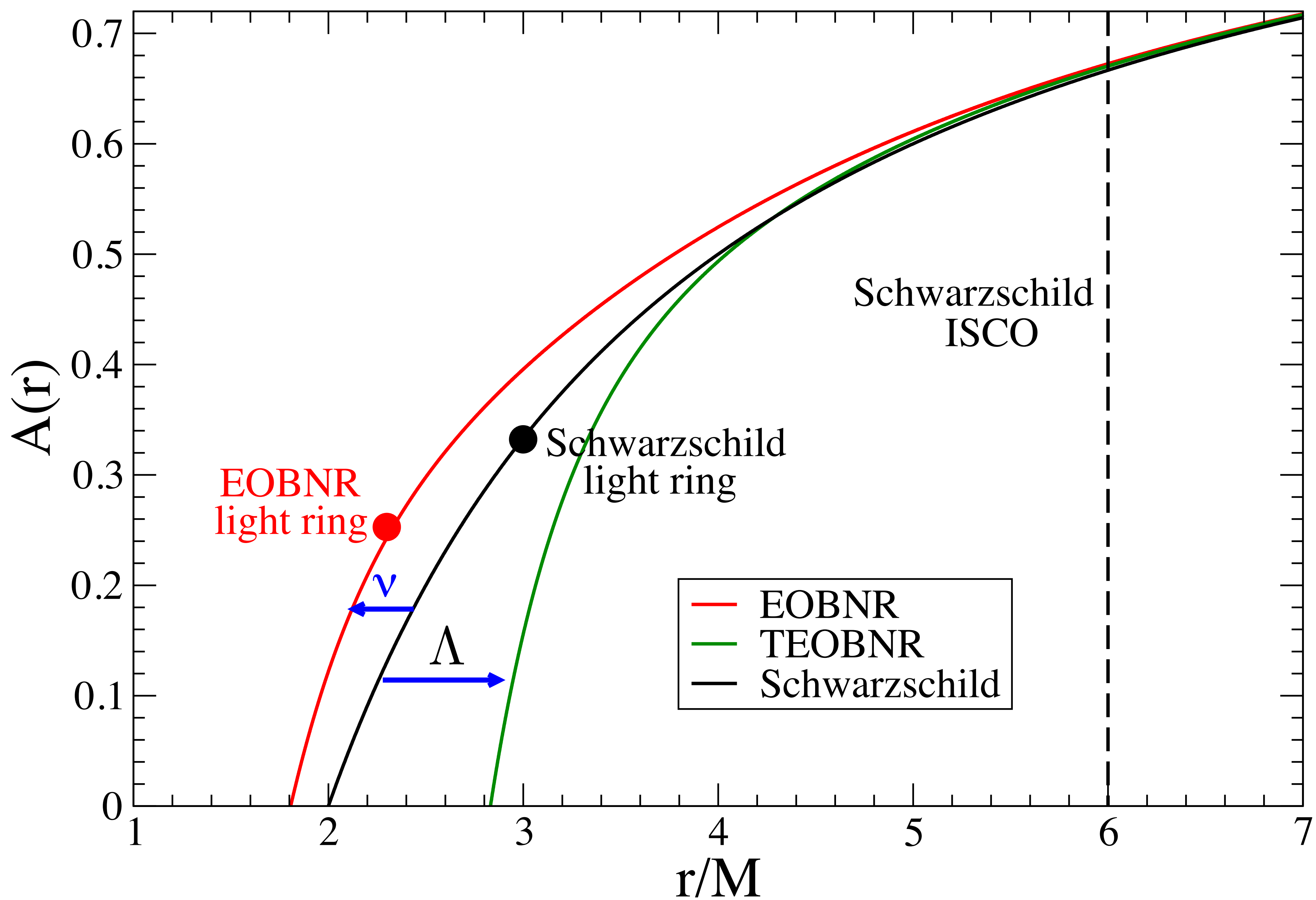


(Dietrich & Hinderer 17)

(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)

Strong-field effects in presence of matter in EOB theory

$$A(r) = A_\nu(r) + A_{\rm tides}(r)$$



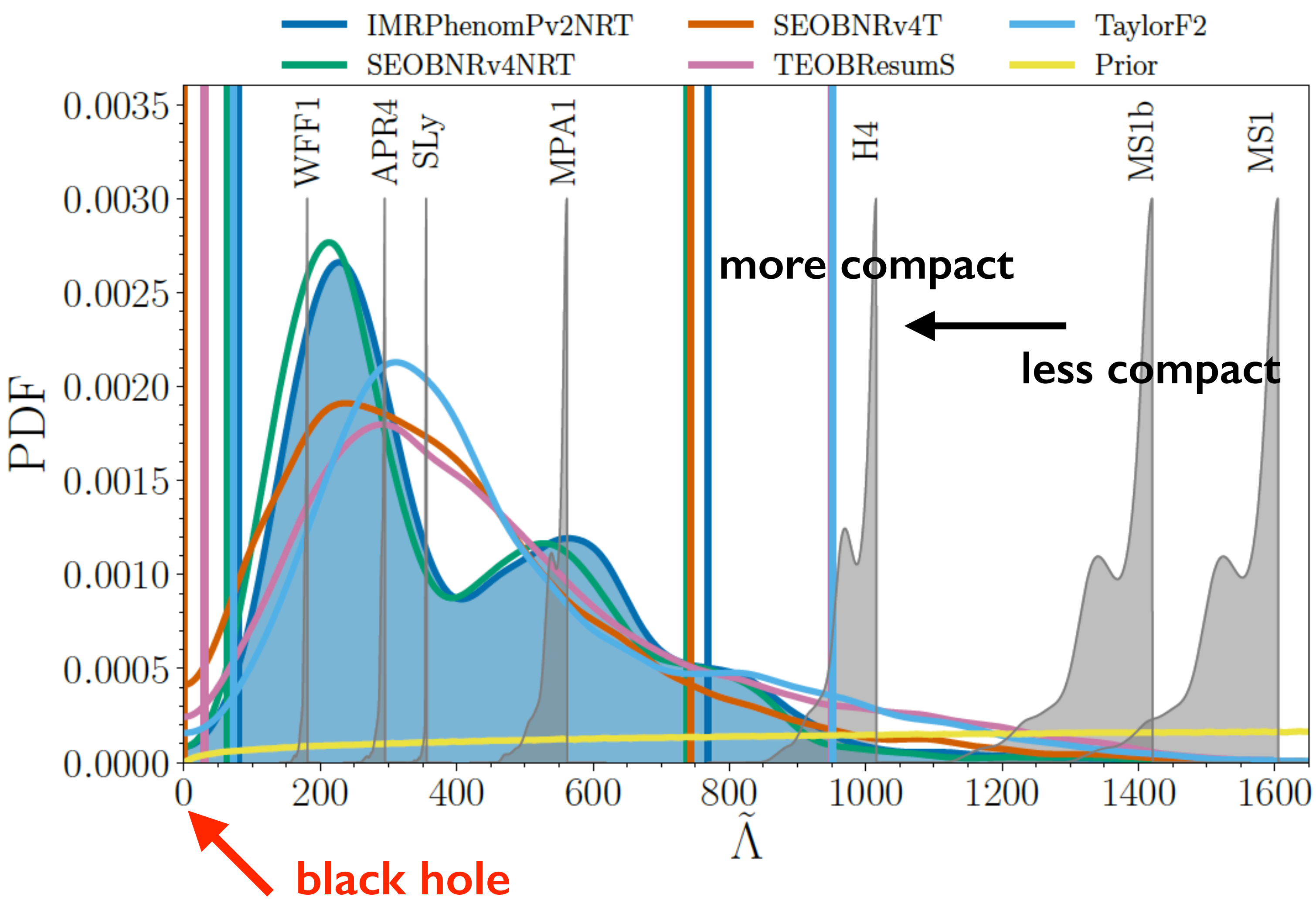
(Hinderer et al. 2016, Steinhoff et al. 2016, see also Bernuzzi et al. 15)

Tides make **gravitational** interaction **more attractive**

Constraining NS equation of state with GW170817

(Abbott et al. PRX 9 (2019) 031040)

$|\chi| \leq 0.05$



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:**

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

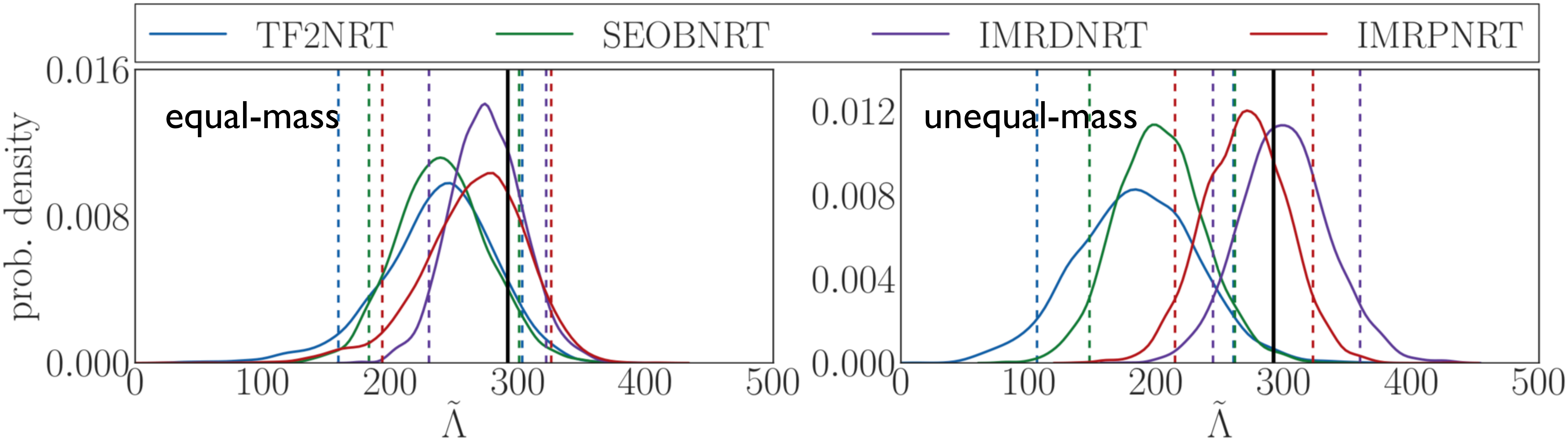
- Current **measurements** of tidal effects **dominated by statistical** error, but **inference** with **PN inspiral-only** waveform somewhat **stands out**.

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

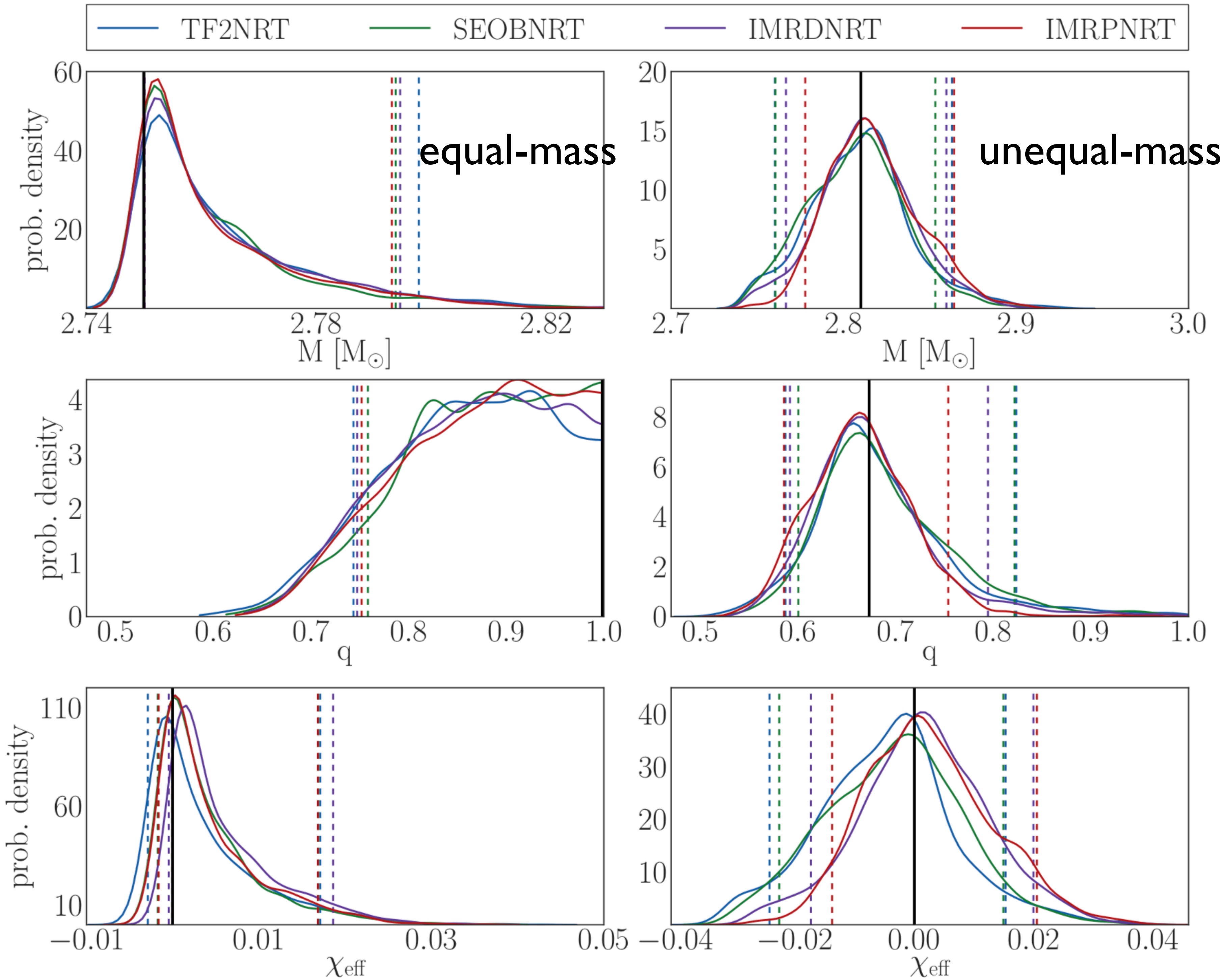


mass ratio = 1.5

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

(Samajdar & Dietrich 18)

- **IMRPNRT** is injected

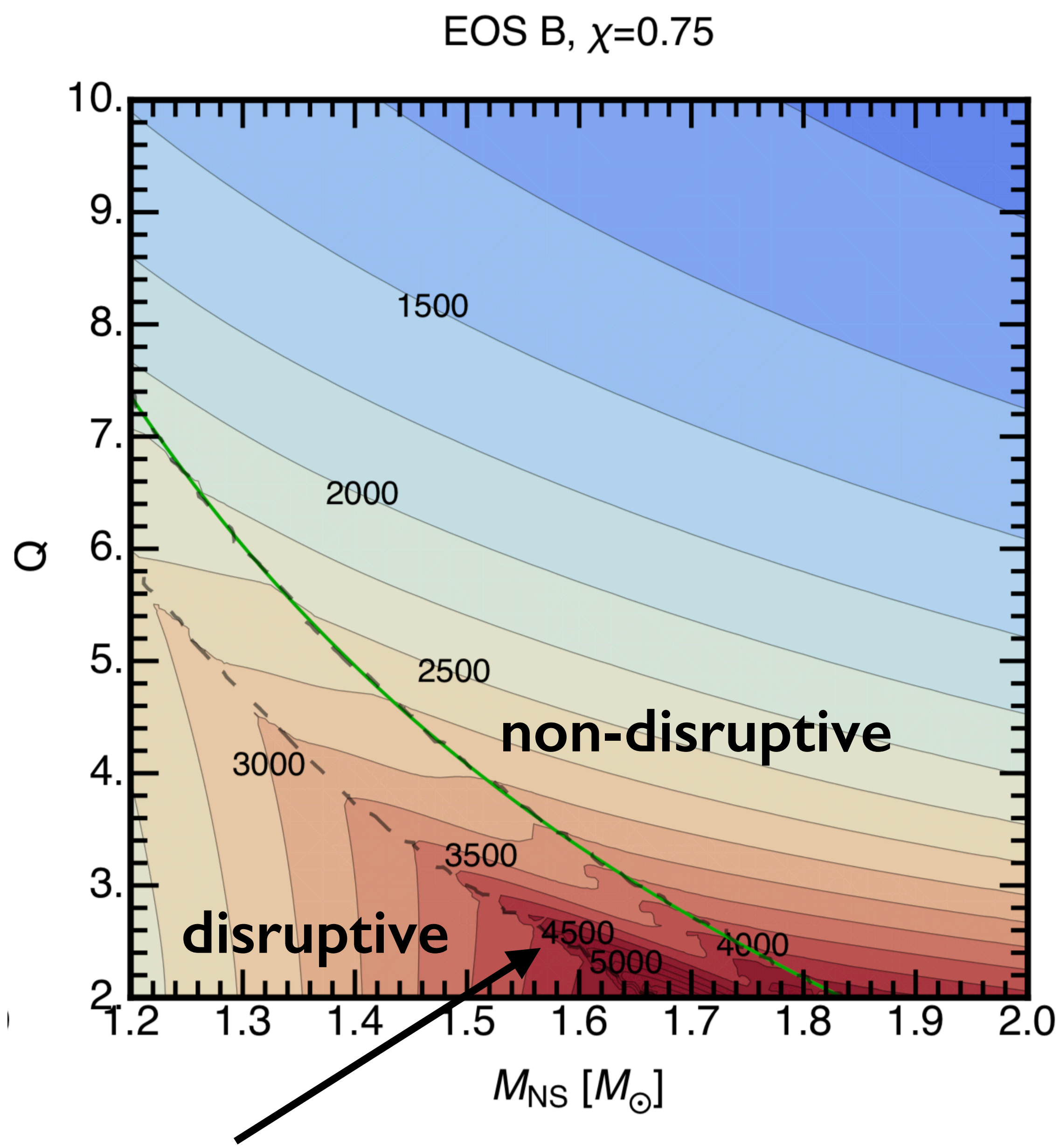


- For highly spinning BNS, **spin-related EOS effects** must be included to avoid biases.

(Harry & Hinderer 18)

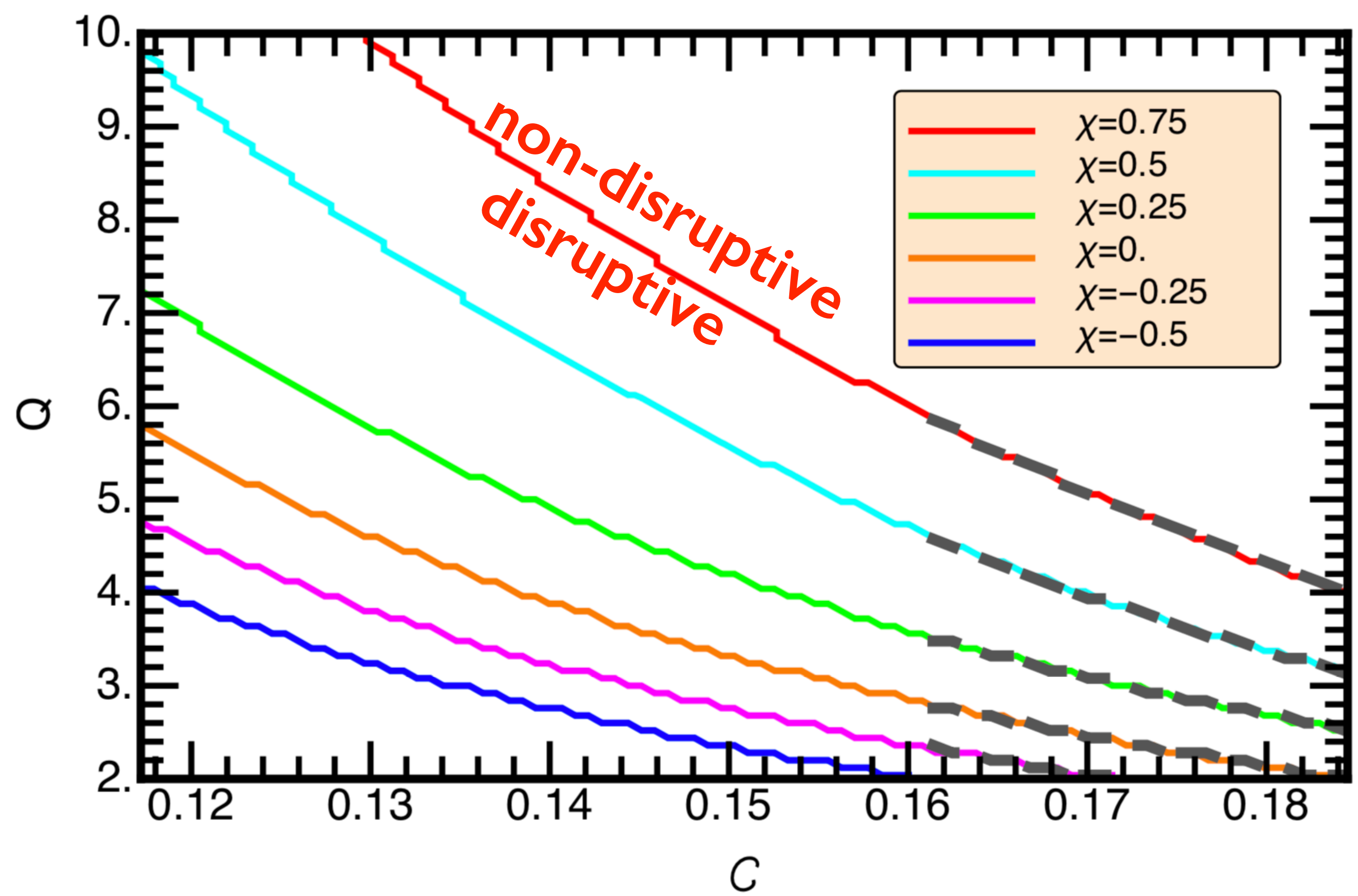
Waveforms for NSBH combining analytical & numerical relativity

- 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)*



$f_{\rm cut}$ $\quad e f_{\rm cut} h(f_{\rm cut}) = f_{\rm max} h(f_{\rm max})$

(Pannarale et al. 16)



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

Waveforms for NSBH: disruptive case (contd.)

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

$$\tilde{h}_{\rm NSBH}(f) = \mathcal{A}_{\rm NSBH}(f) e^{i\varphi_{\rm NSBH}(f)}$$

with **tidal effects** *(Dietrich et al. 17-18)*

$$\mathcal{A}_{\rm NSBH}(f) = w_{\rm D}(f)\, w_{\rm ND}(f)\, \mathcal{A}_{\rm SEOBNRT}(f)$$

- **Disruptive:**

$$w_{\rm D}(f) = w^{-}_{f_D,\sigma_D}(f)$$

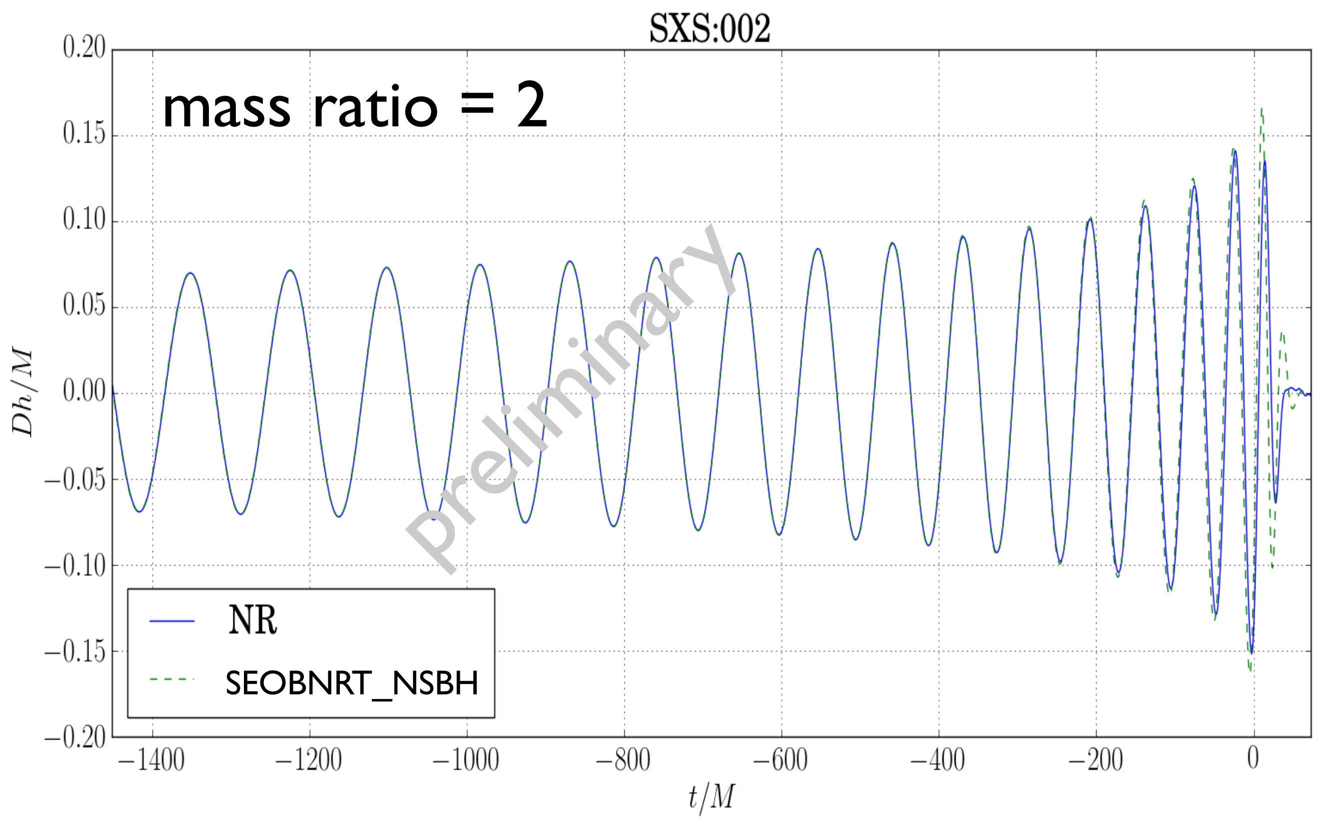
waveform cut off at tidal frequency

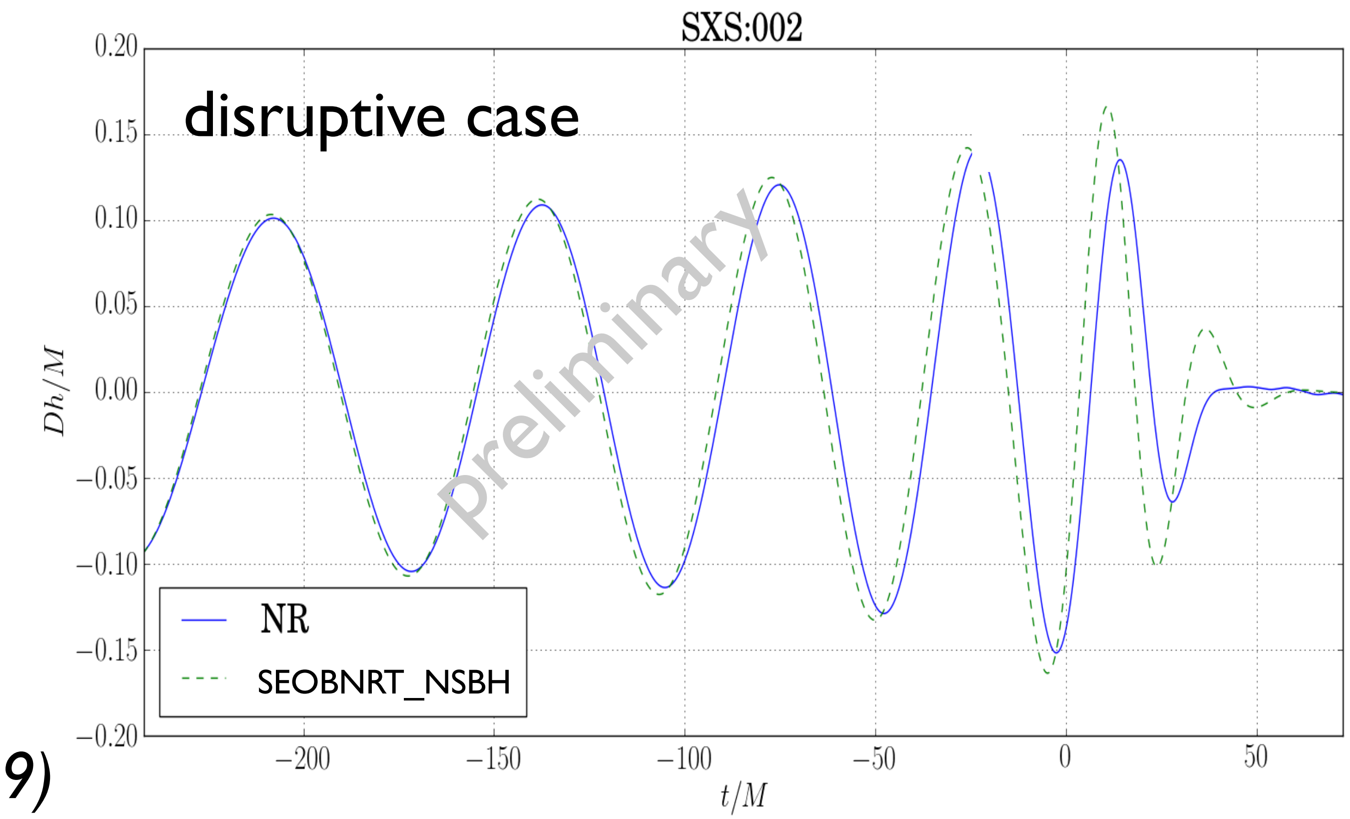
- **Non-disruptive:**

$$w_{\rm ND}(f) = w^{-}_{f_{\rm ND},\sigma_{\rm ND}}(f) + \epsilon\, w^{+}_{f_{\rm ND},\sigma_{\rm ND}}(f)$$

$$w^{\pm}_{f_0,\sigma} = \frac{1}{2}\left[1 \pm \tanh\left(\frac{4(f-f_0)}{\sigma}\right)\right]$$

- **Final mass and spin of NSBHs** *(Zappa et al. 19)*





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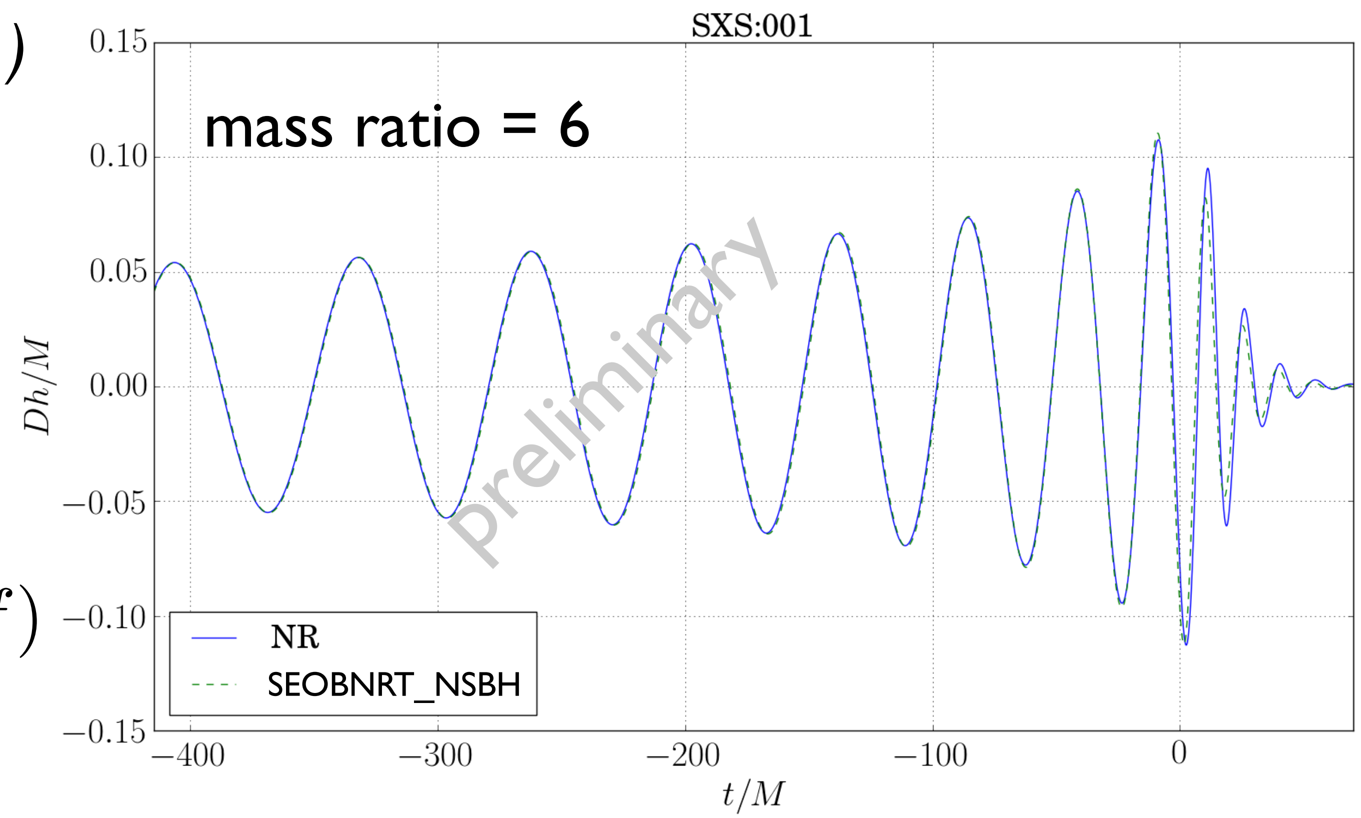

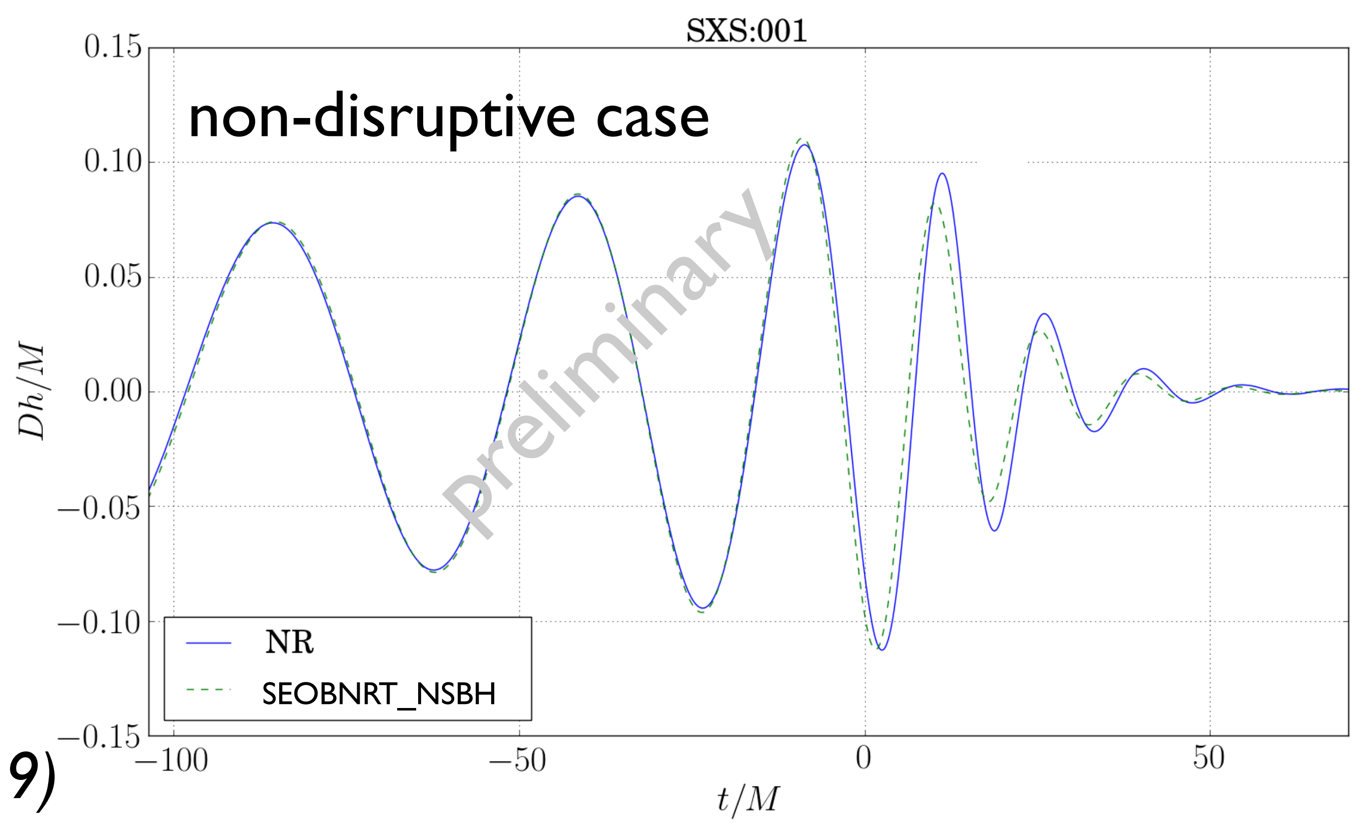

Mismatches of waveform model with NR: no hybridization

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

- **NSBH amplitude model** fitted to **117 spinning NR** waveforms from **Shibata's group** and **5 non-spinning SXS NR** waveforms.

	$M_{\rm NS}$	Q	$\chi_{\rm BH}$	$\Lambda_{\rm NS}$	Mismatch
SXS:001	1.4	6	0	791	4.0×10^{-3}
SXS:003	1.35	3	0	624	9.9×10^{-3}
SXS:002	1.4	2	0	791	4.9×10^{-3}
SXS:006	1.4	1.5	0	791	5.0×10^{-3}
SXS:004	1.4	1	0	791	1.7×10^{-2}

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SXS:004	1.4	1	0	791	7.8 x 10^{-4}

Toward the era of precision gravitational-wave astrophysics

- 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, analytically and numerically
  - inclusion of **eccentricity** and **precessing 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**.