Modeling gravitational waves from compact-object binaries

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[https://dcc.ligo.org/G1602133]

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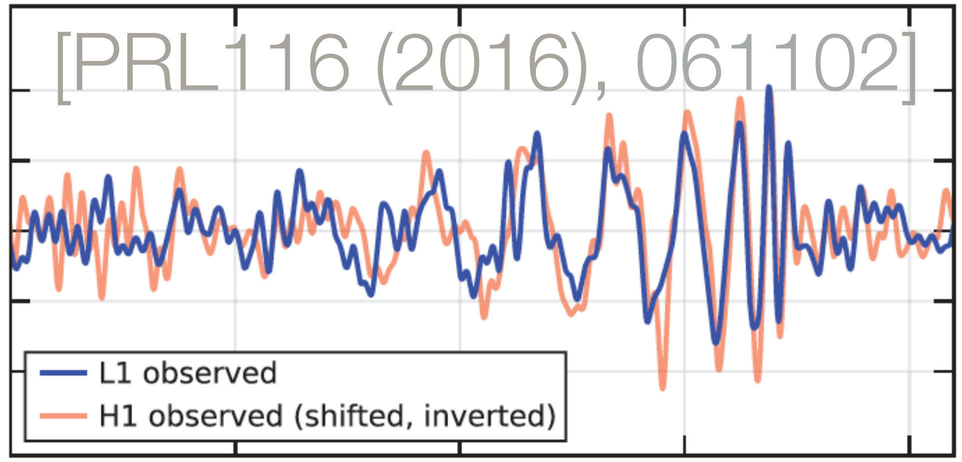
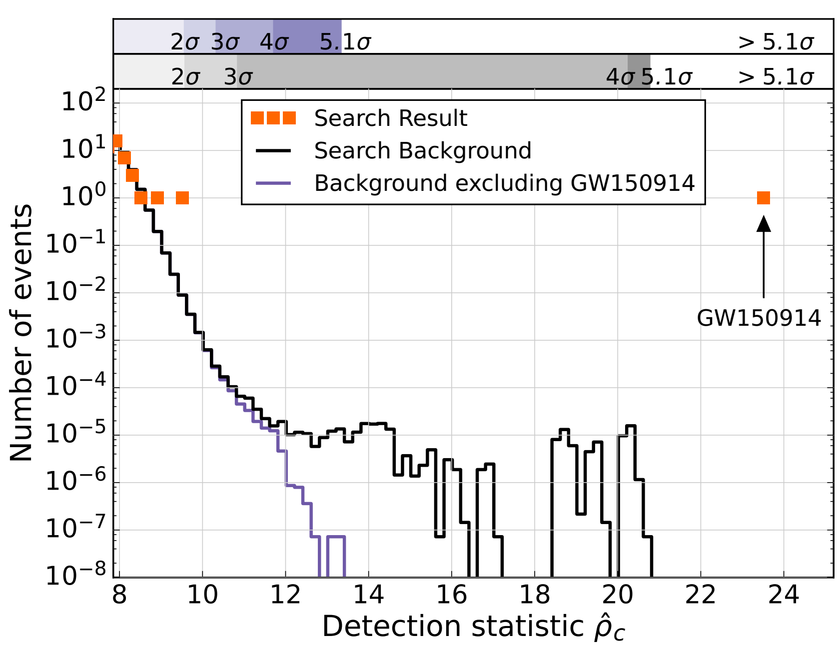
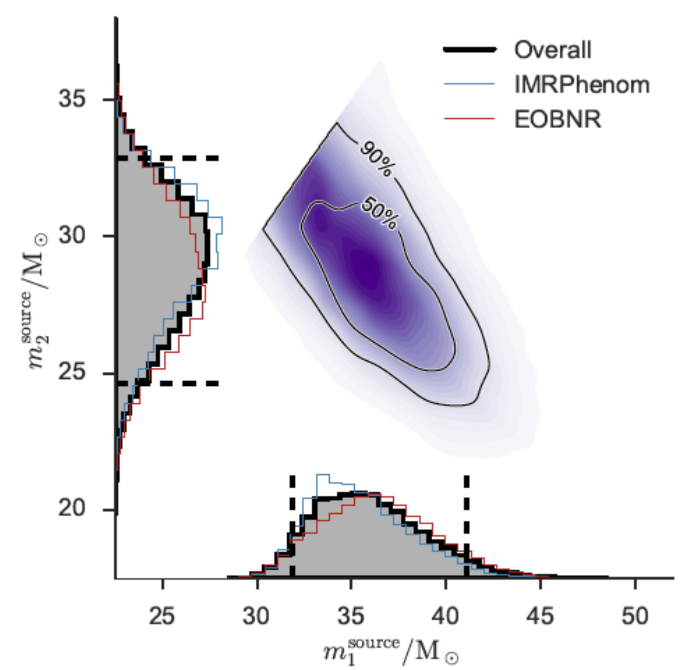
Introduction

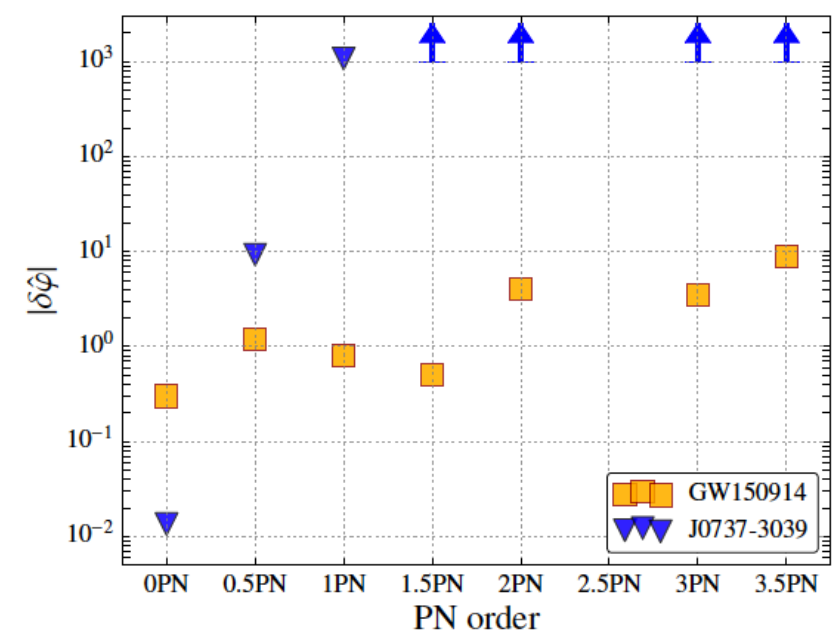
Role of numerical/analytical relativity in GW150914



- **Synergy of numerical relativity and analytical relativity = waveform models** crucial for
  1. establishing 5-sigma **significance** of detection [LVC1602.03839]
  2. measuring **properties of the source** [LVC1602.03840, LVC1606.01210, LVC1606.01262]
  3. performing **tests of general relativity** (GR) [PRL116 (2016) 221101]



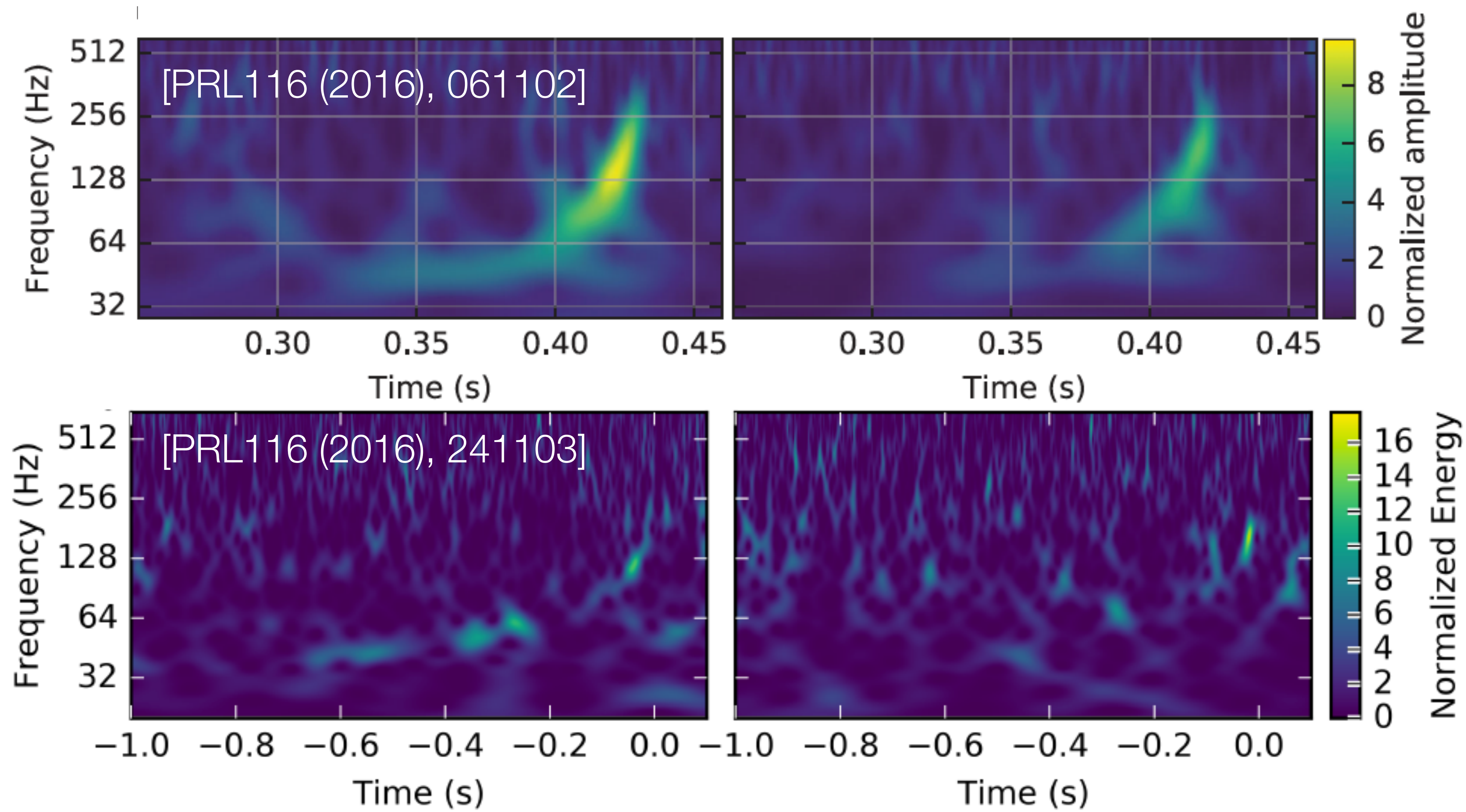




Role of numerical/analytical relativity in GW151226

GW150914

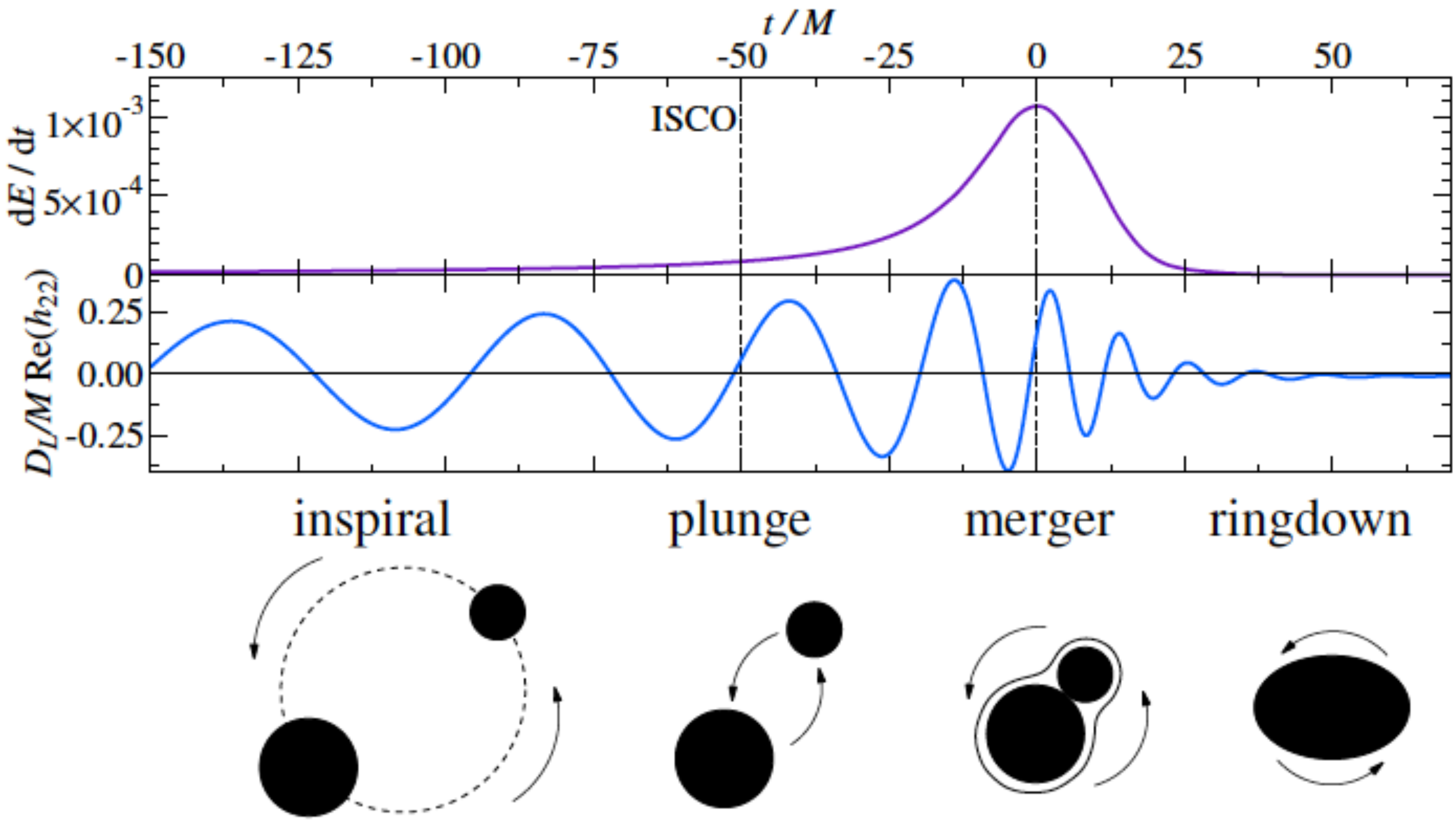
GW151226



- **Template-based** online pipeline was needed to observe it
- NR+AR waveforms as important for significance, parameter estimation, and tests of GR

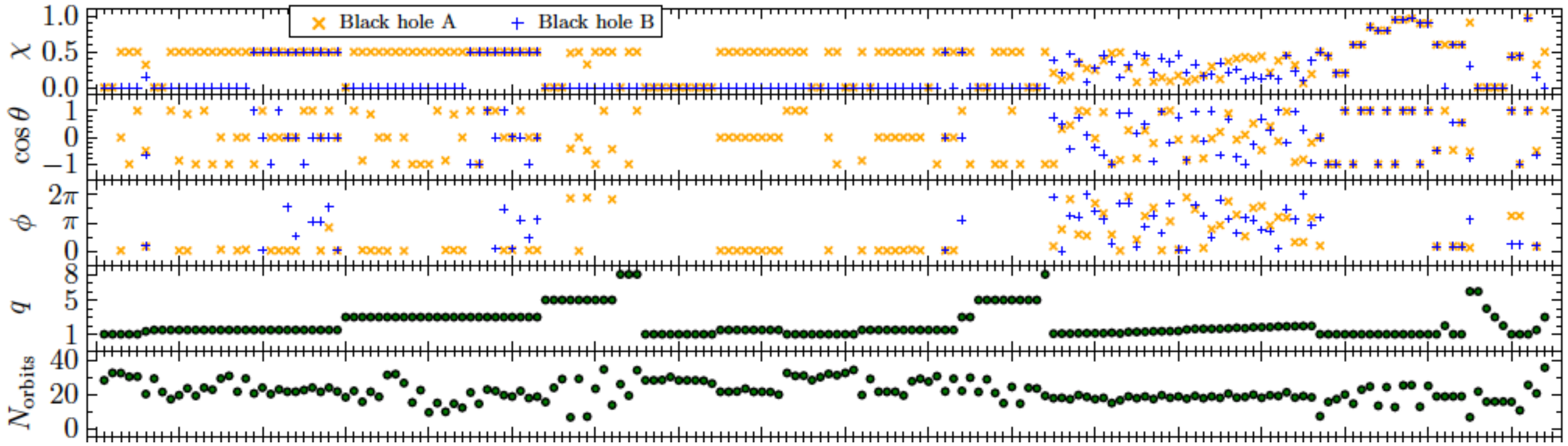
Quasicircular binary black holes: numerical relativity

BBH coalescence as predicted by GR

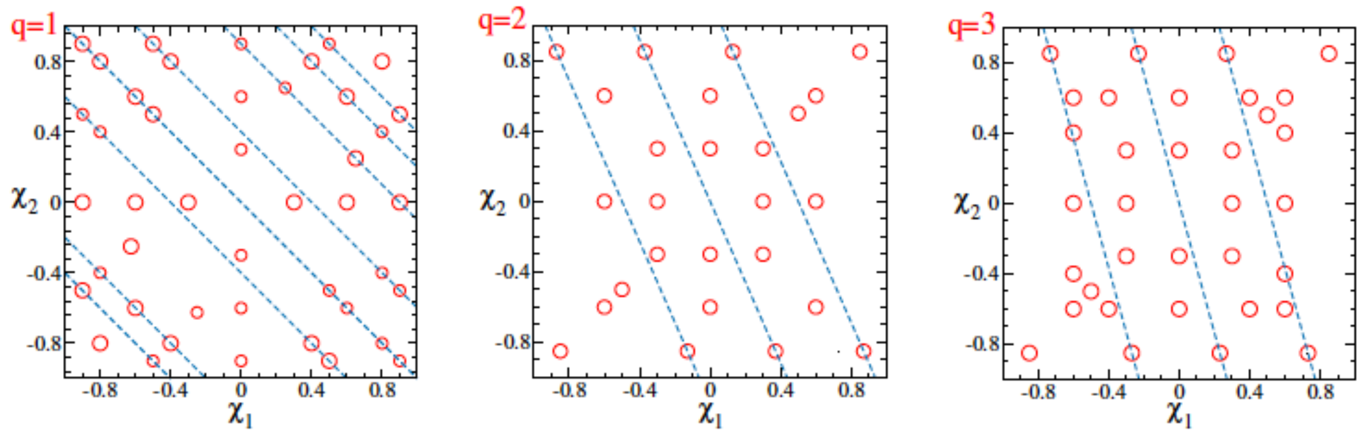


Intrinsic parameters: BH masses and BH spin vectors

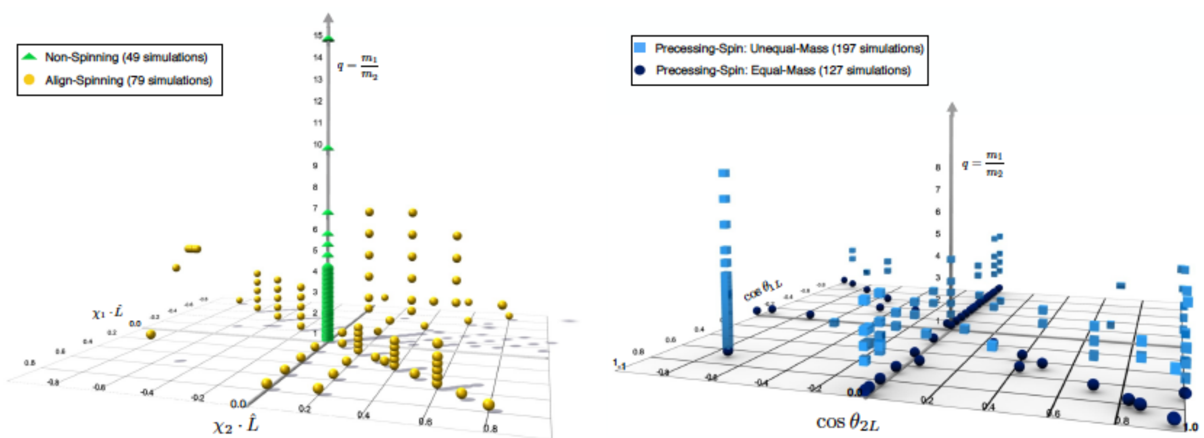
Numerical relativity catalogs of BBHs



[Mroue+13]



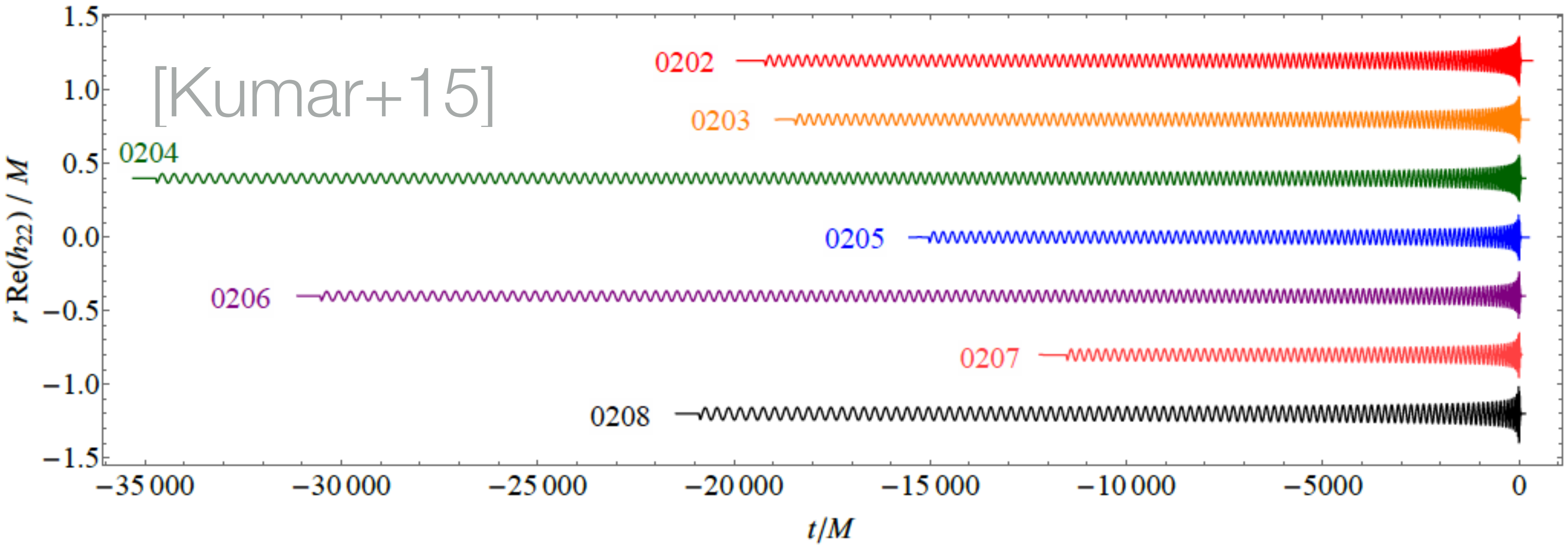
[Chu+15]



[Jani+16]

… and many more NR waveforms [SXS, GATech, RIT, Cardiff-UIB, Cactus]
(also generated for followup of LVC observations)

Challenging configurations



q	$\vec{\chi}_1$
7	(0, 0, 0.6)
7	(0, 0, 0.4)
7	(0, 0, 0.4)
7	(0, 0, −0.4)
7	(0, 0, −0.4)
7	(0, 0, −0.6)
5	(0, 0, −0.9)

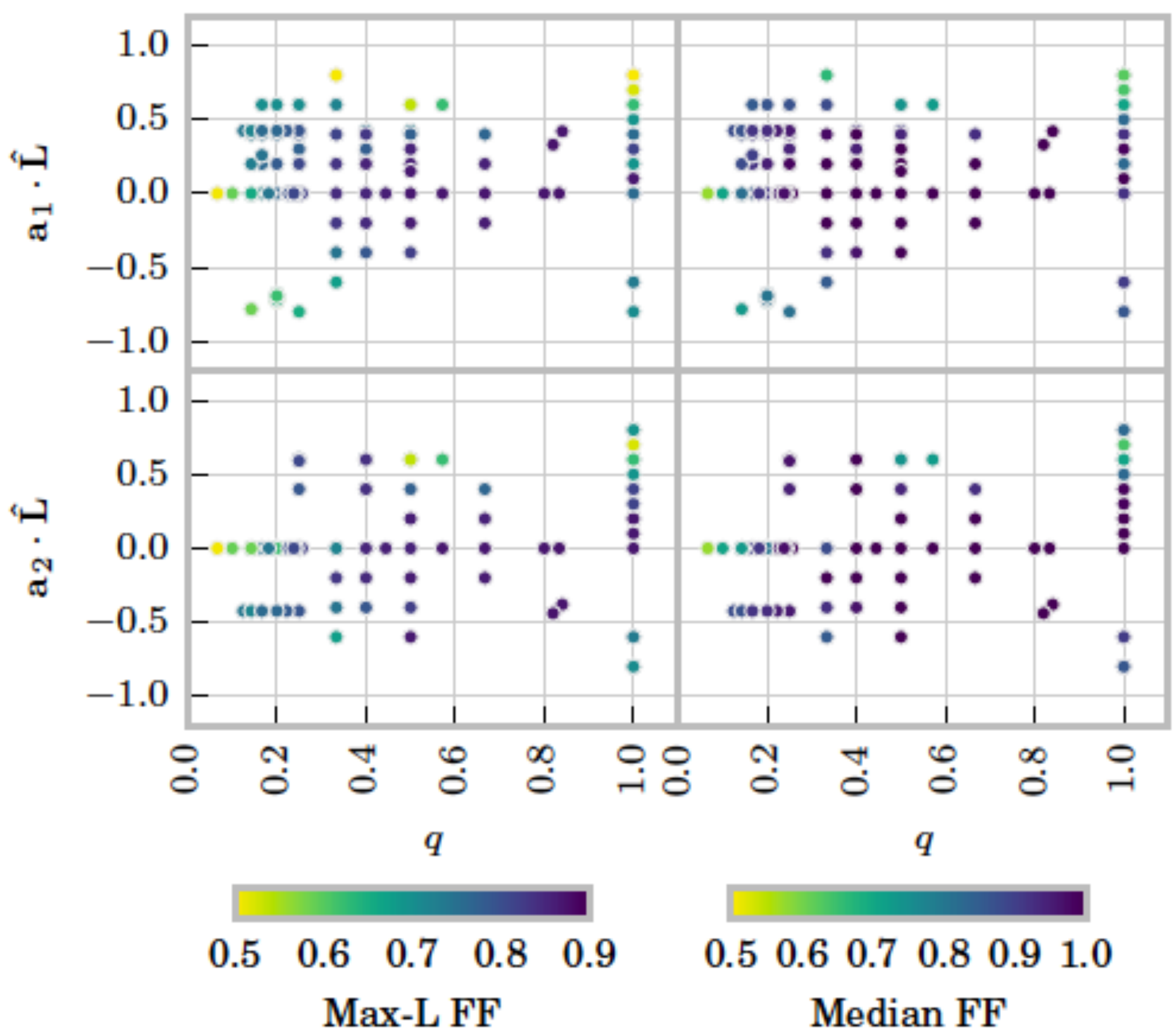
- **Longterm** BBH simulations at mass ratio 7 [Szilagyi+14, Kumar+15]
- **Almost extremal** BBH simulations: equal-mass, aligned-spins 0.99, 0.994 [Scheel+14]
- New initial data for challenging configurations [Ossokine+15]

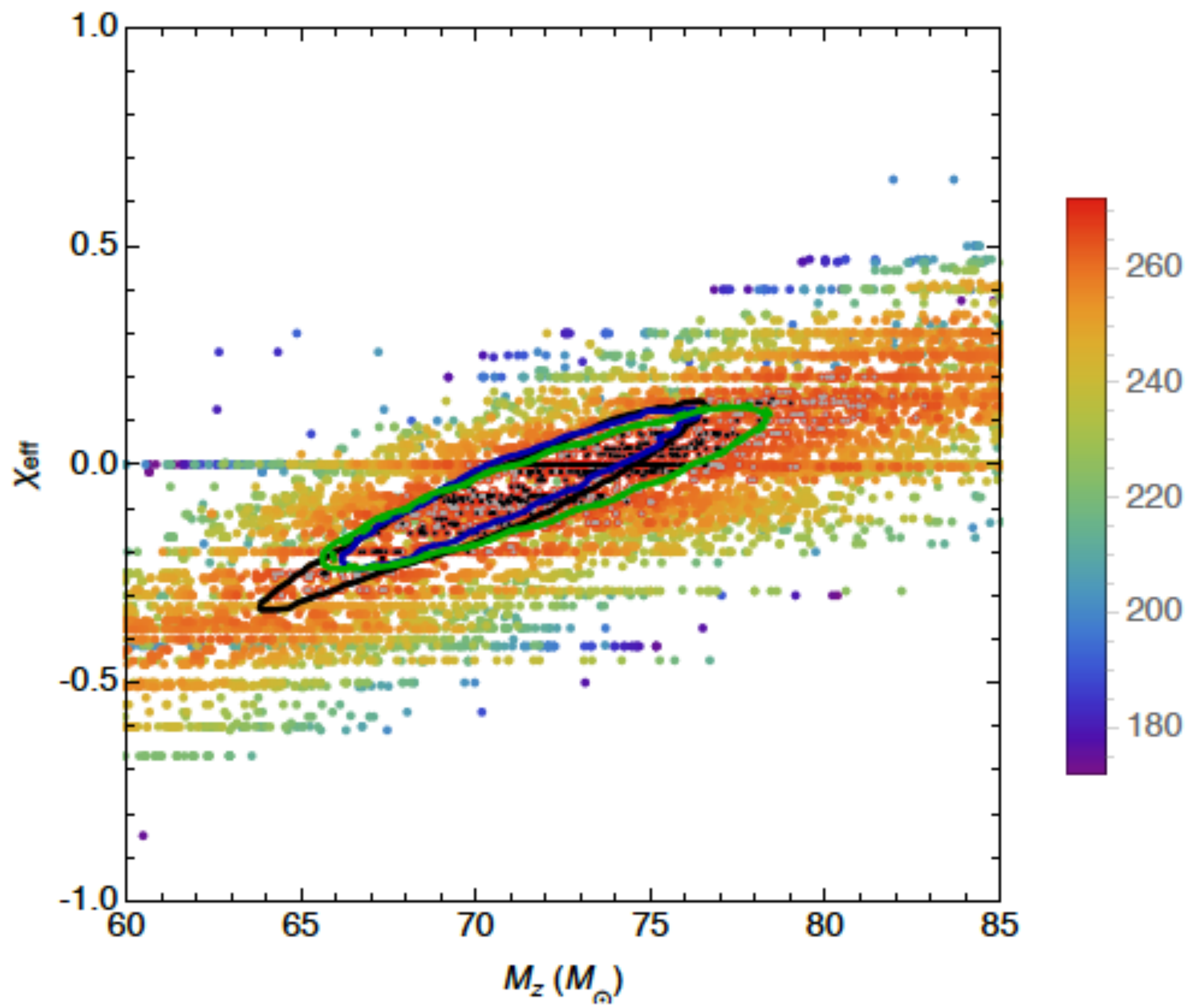
q	χ_1	χ_2	D_0/M
1	(0, 0, 0.9999)	(0, 0, 0.9999)	14.17
3	(0, 0.49, -0.755)	(0, 0, 0)	15.48
10	(0.815, -0.203, 0.525)	(-0.087, 0.619, 0.647)	15.09
50	(-0.045, 0.646, -0.695)	(0, 0, 0)	16

Direct use of numerical relativity waveforms

- **Direct comparison of NR catalogs to observations**

$$\ln \mathcal{L}(\lambda;\theta) = -\frac{1}{2}\sum_k \langle h_k(\lambda,\theta) - d_k | h_k(\lambda,\theta) - d_k\rangle_k - \langle d_k|d_k\rangle_k$$



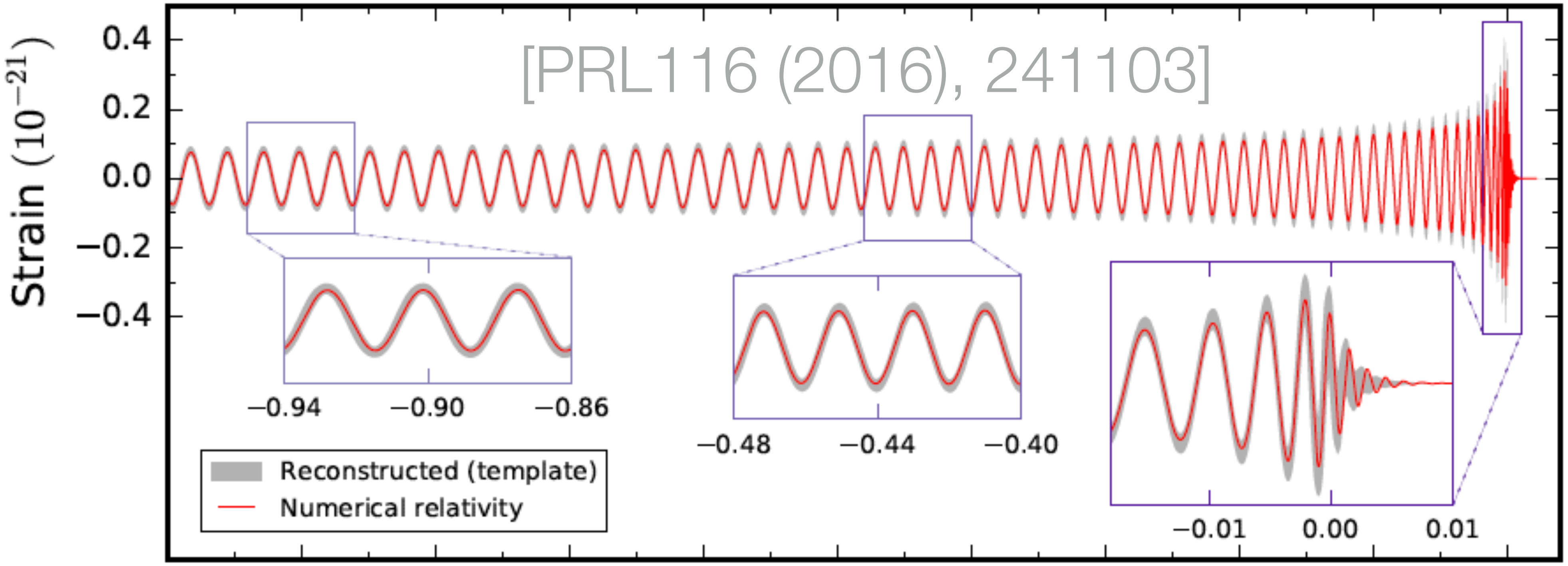


[LVC1602.03843]

[LVC1606.01262]

Direct use of numerical relativity waveforms

- **NR followup to observations** [Lovelace+16]



- **Surrogate waveform models** [Blackman+15,(in prep)]
  1. restricted parameter space (high mass, q<=2, spins<=0.8, one spin aligned)
  2. many NR simulations to construct basis
  3. **interpolation** across NR runs
  4. they do not extrapolate to low mass: need models or long NR

Quasicircular binary black holes: models

How good is a model?

$$\langle h_{\rm NR}, h_{\rm model}\rangle = 4\,{\rm Re}\int_{f_{\rm low}}^{f_{\rm high}} \frac{\tilde{h}_{\rm NR}(f)\tilde{h}^*_{\rm model}(f)}{S_n(f)}df$$

$$\mathcal{O}(h_{\rm NR}, h_{\rm model}) = \frac{\langle h_{\rm NR}, h_{\rm model}\rangle}{\sqrt{\langle h_{\rm NR}, h_{\rm NR}\rangle\langle h_{\rm model}, h_{\rm model}\rangle}}$$

- **Template banks** accept 97% overlaps ~ 10% loss in event rate
- **Parameter estimation**: (sufficient) accuracy requirement [Lindblom+08]

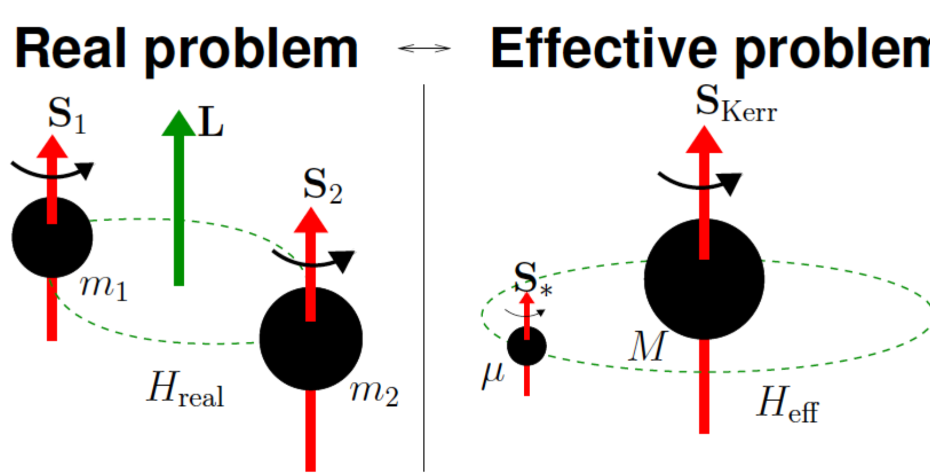
$$\mathcal{O}(h_{\rm NR}, h_{\rm model}) > 1 - \frac{1}{2\,{\rm SNR}^2}$$

Effective-one-body models of nonprecessing BBHs

- Nonspinning case: particle in deformation of Schwarzschild [Buonanno & Damour99]. Spinning case: **spinning particle in deformation of Kerr** [Barausse & Buonanno10,11;Nagar+14]

- Inspiral waveforms/radiation reaction from **resummation post-Newtonian formulas** [Damour+07,09; Pan+11;Nagar+16]

- Ringdown from **superposition of quasinormal modes** of remnant BH



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

$$H_{\rm eff} = \mu c^2\sqrt{A(R)\left[1+\frac{\mathbf{P}^2}{\mu^2c^2}+\frac{1}{\mu^2c^2}\left(\frac{A(R)}{D(R)}-1\right)\left(\frac{\mathbf{R}\cdot\mathbf{P}}{R}\right)^2\right]}$$

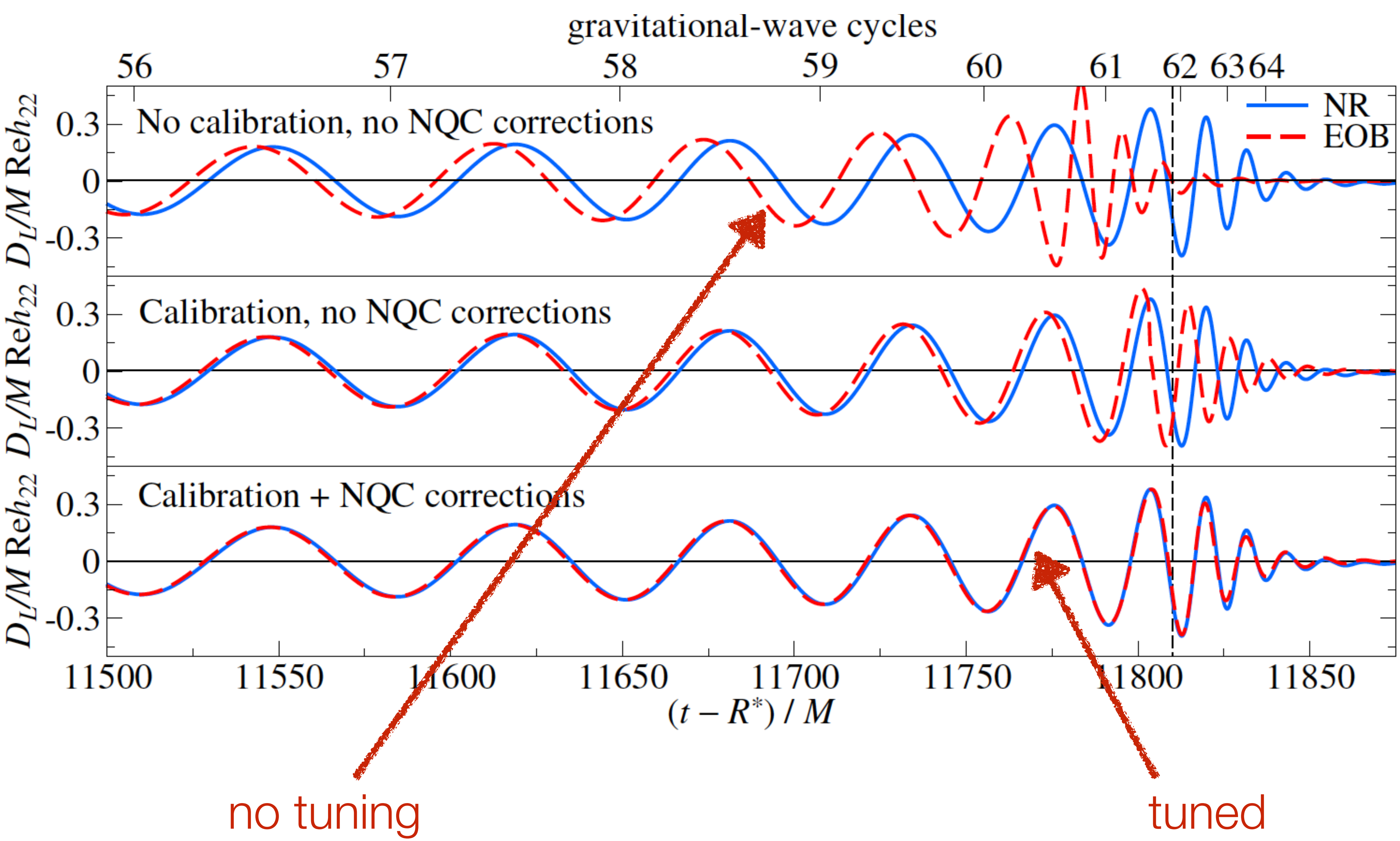
$$A = \overbrace{1-2u}^{\rm Schwarzschild} + 2\nu u^3 + \left(\frac{94}{3}-\frac{42}{32}\pi^2\right)\nu u^4 + a_5 u^5 + \cdots \quad (u = GM/Rc^2)$$

$$\nu = \frac{m_1 m_2}{(m_1+m_2)^2}$$

example of tuning parameter

Effective-one-body models of nonprecessing BBHs

- Tuning to numerical-relativity simulations

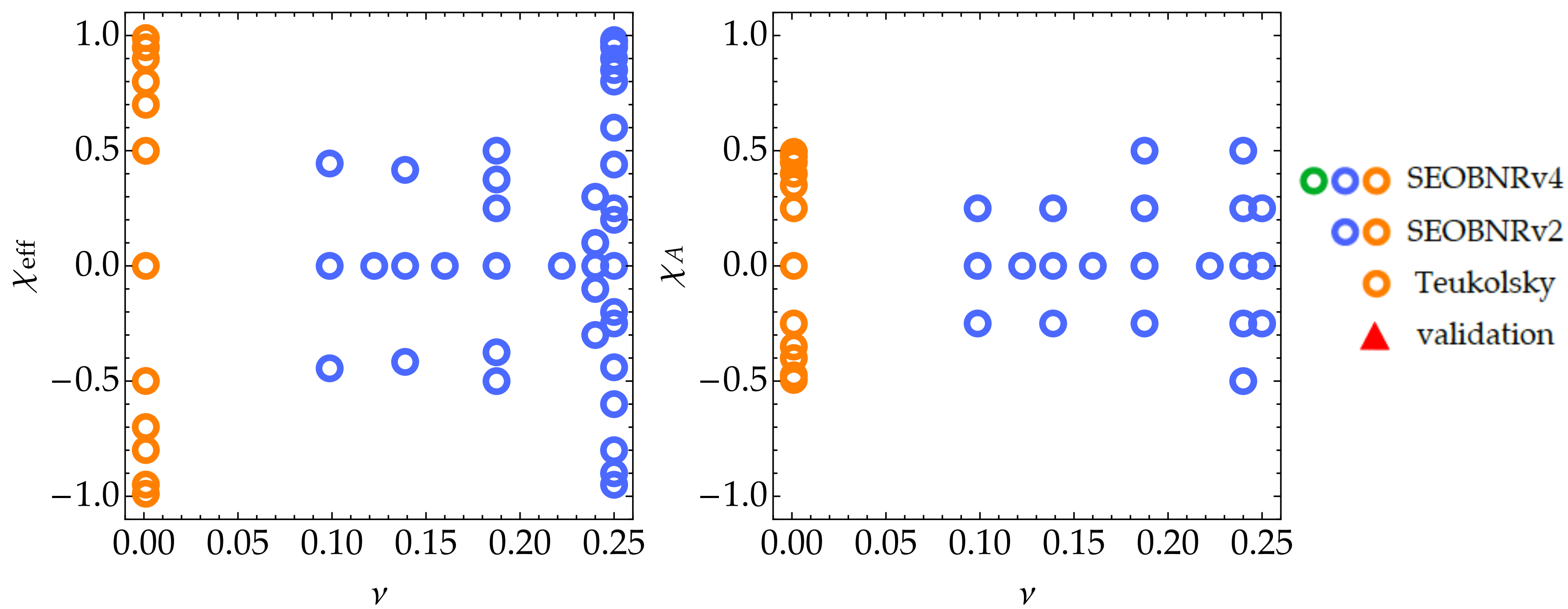


Effective-one-body model of nonprecessing BBHs for O1

$$\nu = \frac{m_1 m_2}{(m_1+m_2)^2}$$

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

$$\chi_{\rm A} = \left(\frac{\boldsymbol{S}_1}{m_1^2} + \frac{\boldsymbol{S}_2}{m_2^2}\right)\cdot \hat{\boldsymbol{L}}$$



- **SEOBNRv2** calibrated to better than 99% overlap with NR for design aLIGO [AT+14]

- Used in its **reduced-order-model** version [Pürrer14,15] in O1 for filtering and parameter estimation

- Similar set of calibration waveforms used in IHES models [Nagar +15,16]

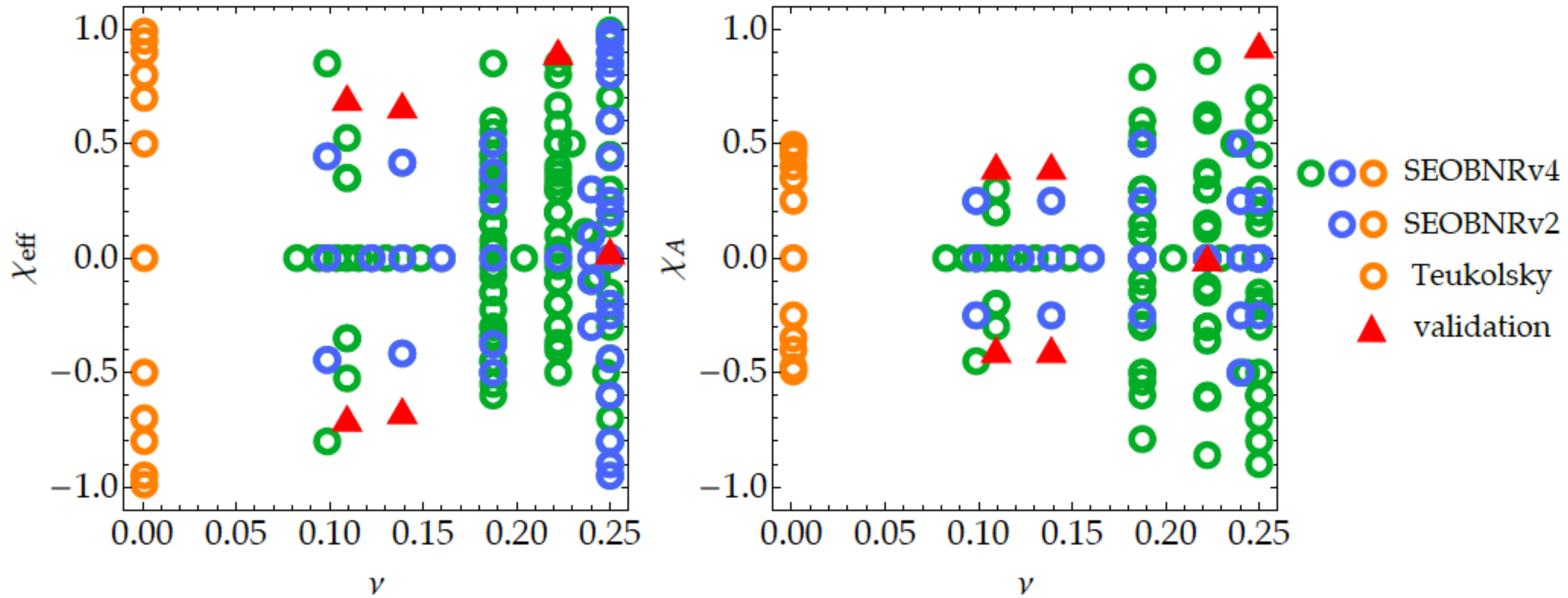
Effective-one-body model of nonprecessing BBHs for O2

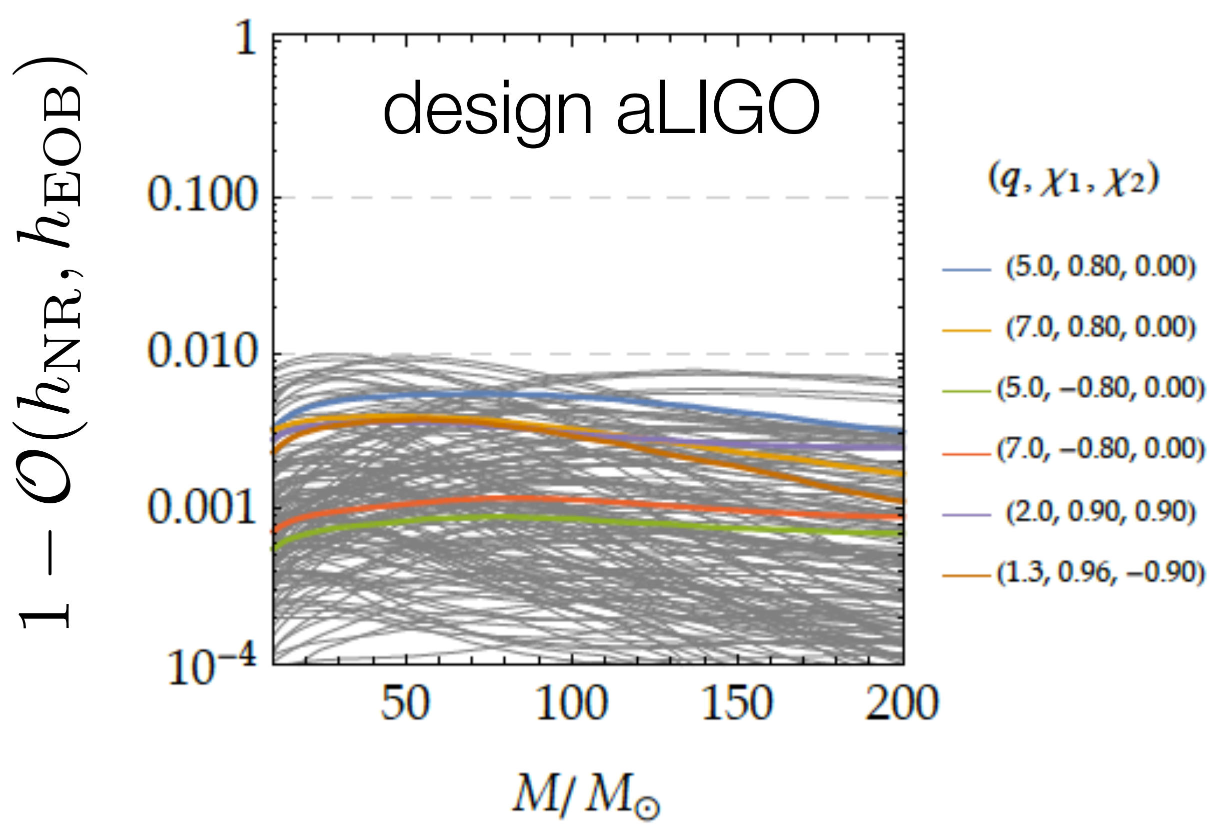
- **SEOBNRv4** [Bohe,Shao,AT+(in prep)]

$$\nu = \frac{m_1 m_2}{(m_1+m_2)^2}$$

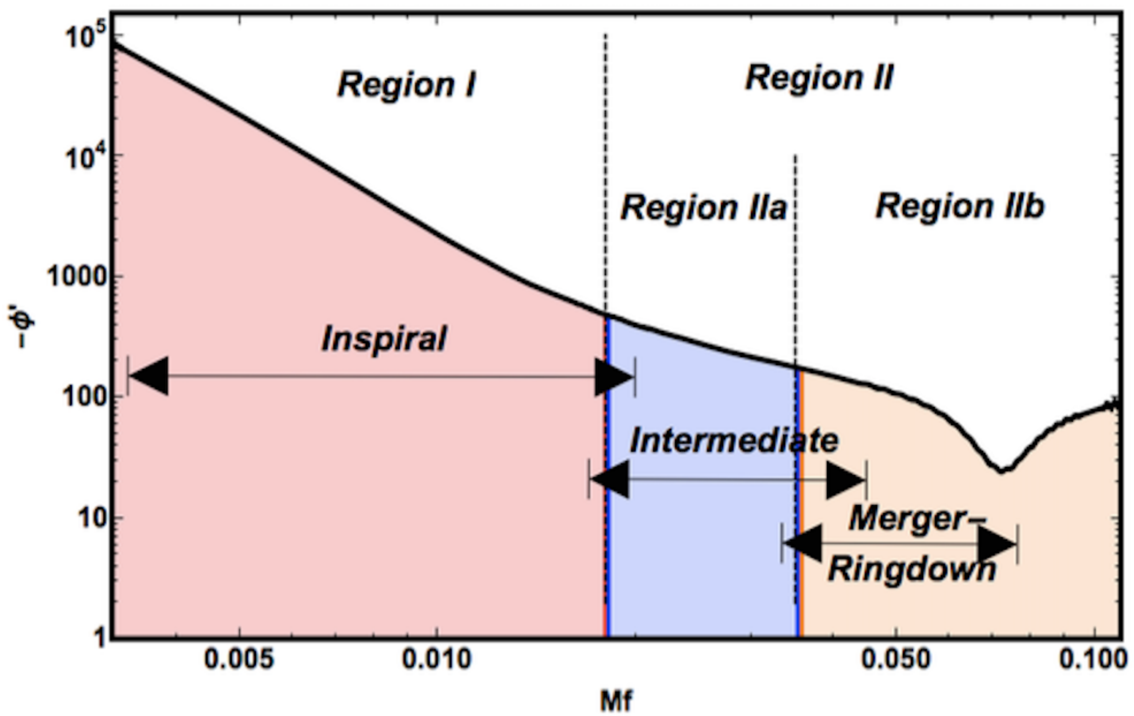
$$\chi_{\rm eff} = \left(\frac{\boldsymbol{S}_1}{m_1} + \frac{\boldsymbol{S}_2}{m_2}\right)\cdot \hat{\boldsymbol{L}}$$

$$\chi_{\rm A} = \left(\frac{\boldsymbol{S}_1}{m_1^2} + \frac{\boldsymbol{S}_2}{m_2^2}\right)\cdot \hat{\boldsymbol{L}}$$





Phenomenological model of nonprecessing BBHs

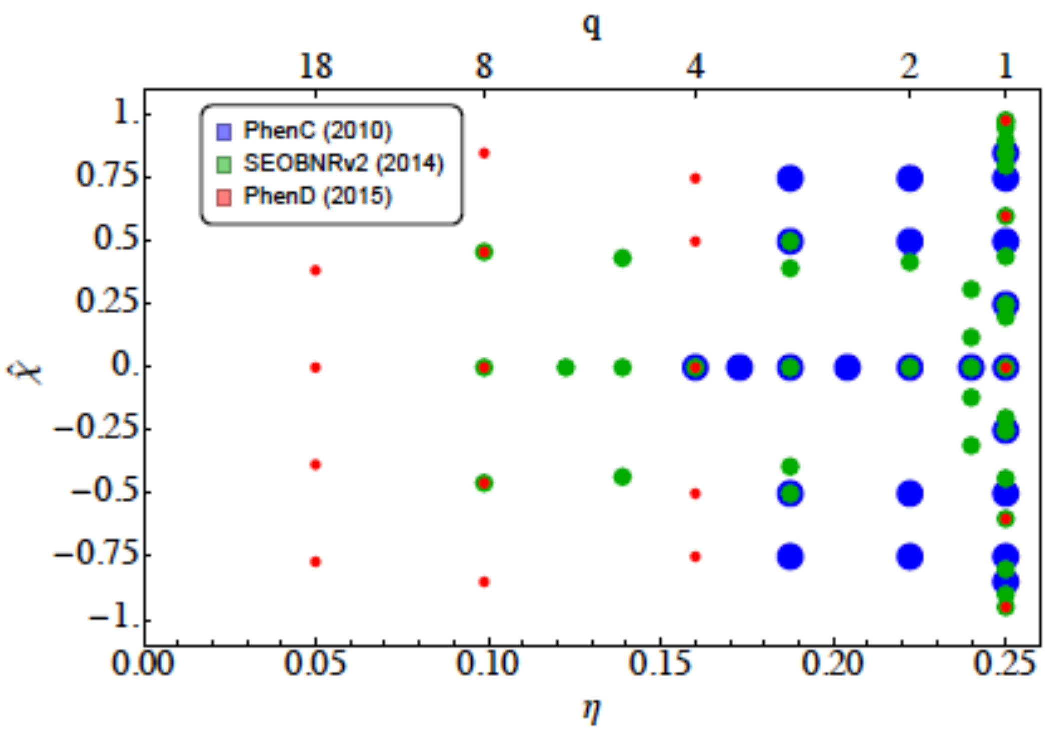


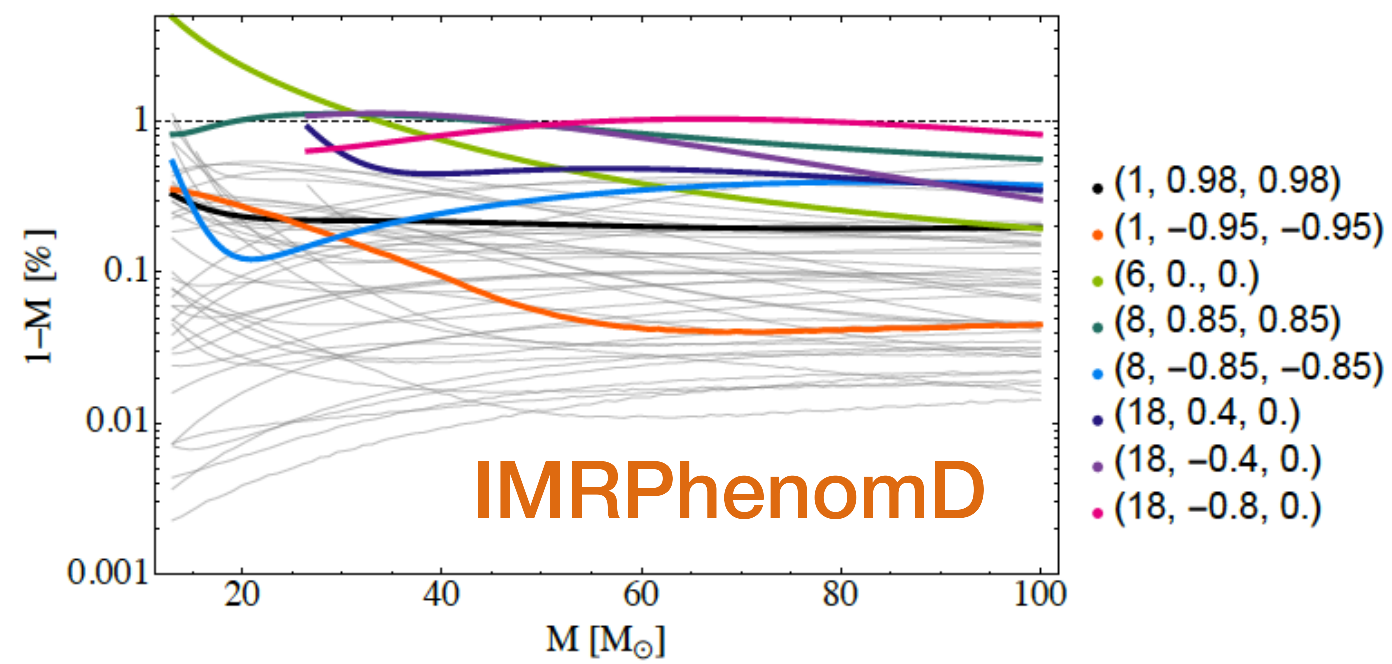
$$\phi_{\rm Ins} = \phi_{\rm TF2}(Mf;\Xi) + \frac{1}{\eta}\left(\sigma_0 + \sigma_1 f + \frac{3}{4}\sigma_2 f^{4/3} + \frac{3}{5}\sigma_3 f^{5/3} + \frac{1}{2}\sigma_4 f^2\right)$$

$$\phi_{\rm Int} = \frac{1}{\eta}\left(\beta_0 + \beta_1 f + \beta_2 \,{\rm Log}(f) - \frac{\beta_3}{3} f^{-3}\right)$$

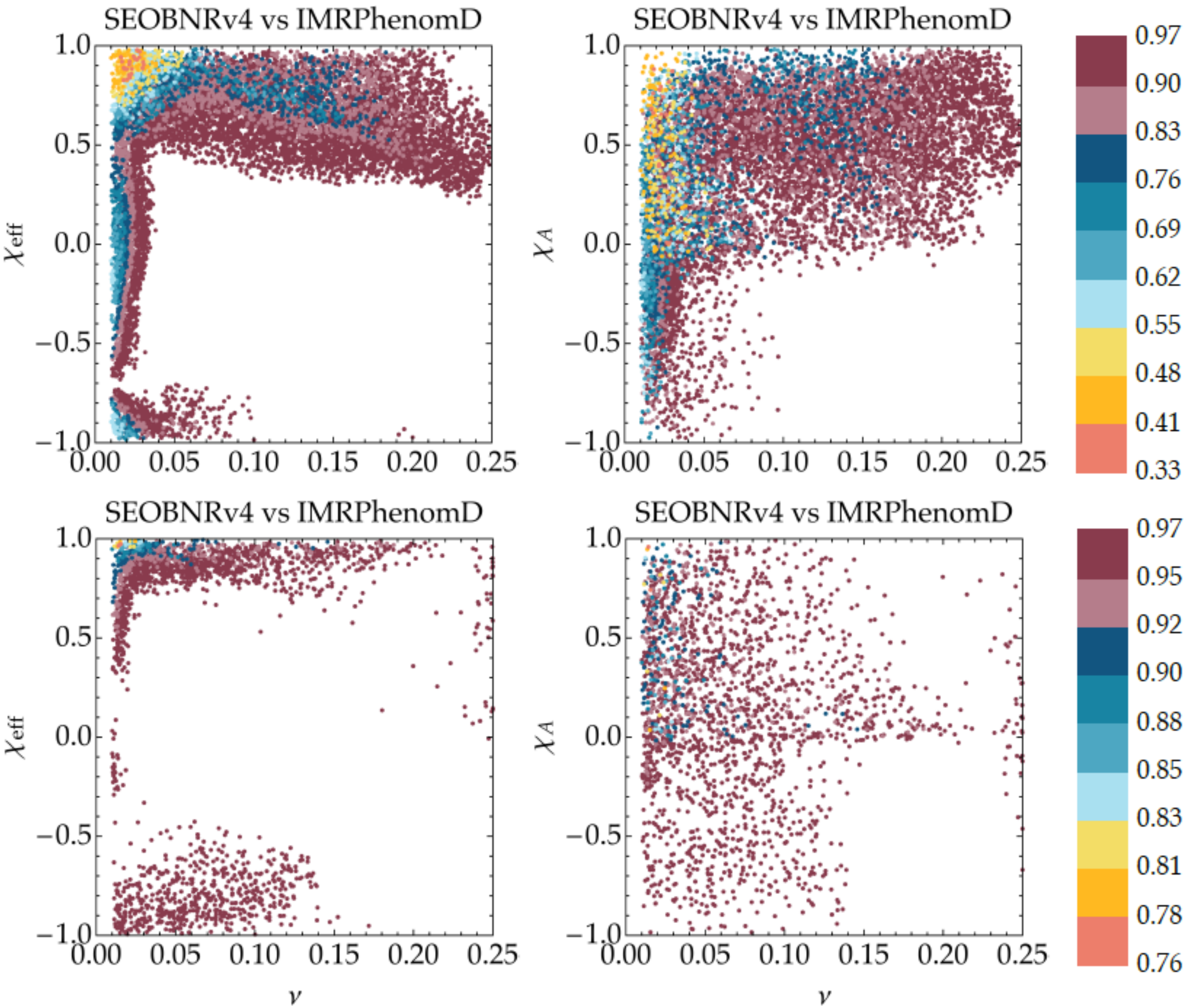
$$\phi_{\rm MR} = \frac{1}{\eta}\left\{\alpha_0 + \alpha_1 f - \alpha_2 f^{-1} + \frac{4}{3}\alpha_3 f^{3/4} + \alpha_4 \tan^{-1}\left(\frac{f - \alpha_5 f_{\rm RD}}{f_{\rm damp}}\right)\right\} .$$

- Fit to **hybrids** of uncalibrated EOB and NR [Husa+15, Khan+15]





Comparing nonprecessing BBH models



$$\mathcal{O}(h_1, h_2)$$

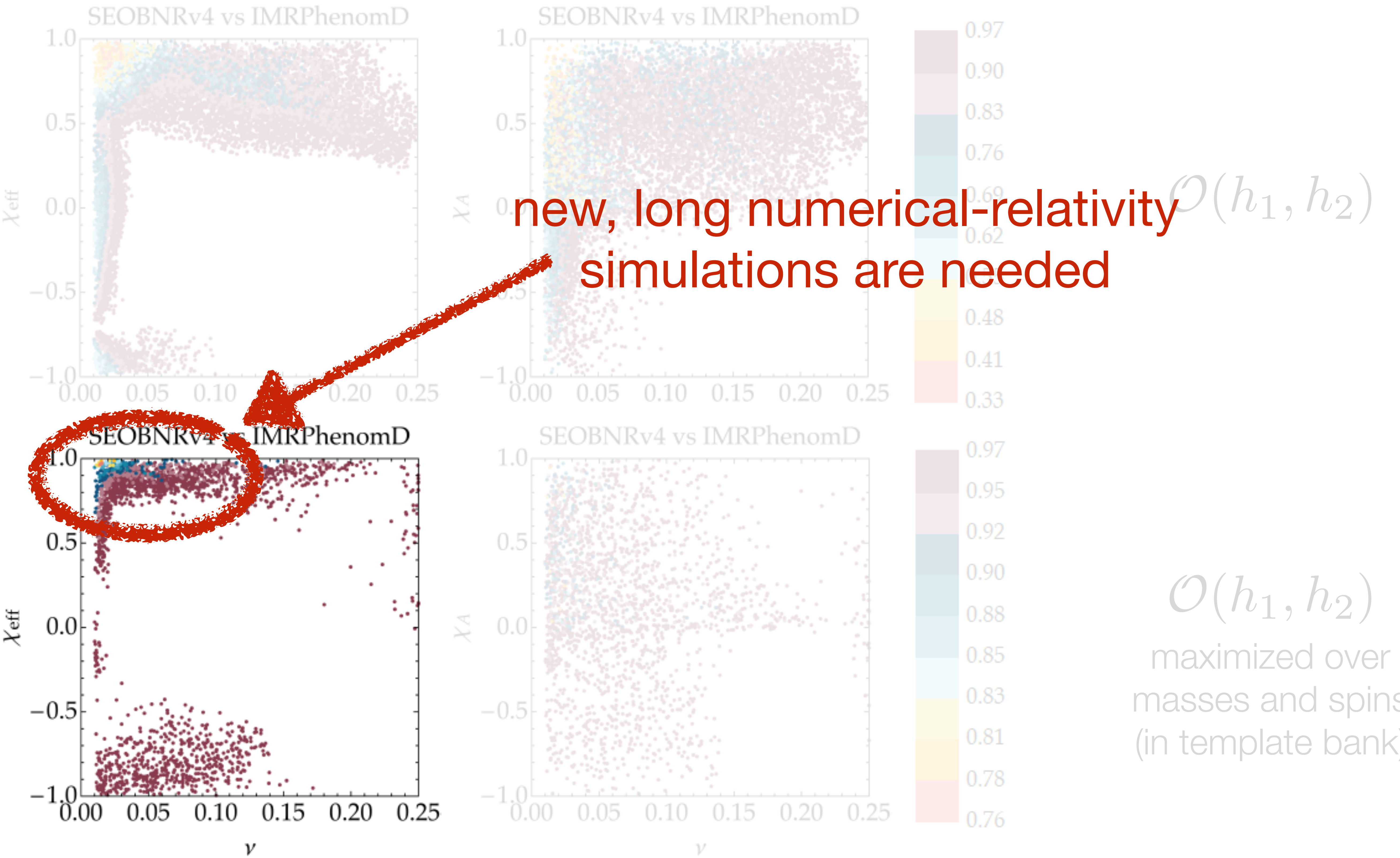
$$\mathcal{O}(h_1, h_2)$$

maximized over masses and spins (in template bank)

[Bohe,Shao,AT+(in prep)]

(O1 aLIGO)

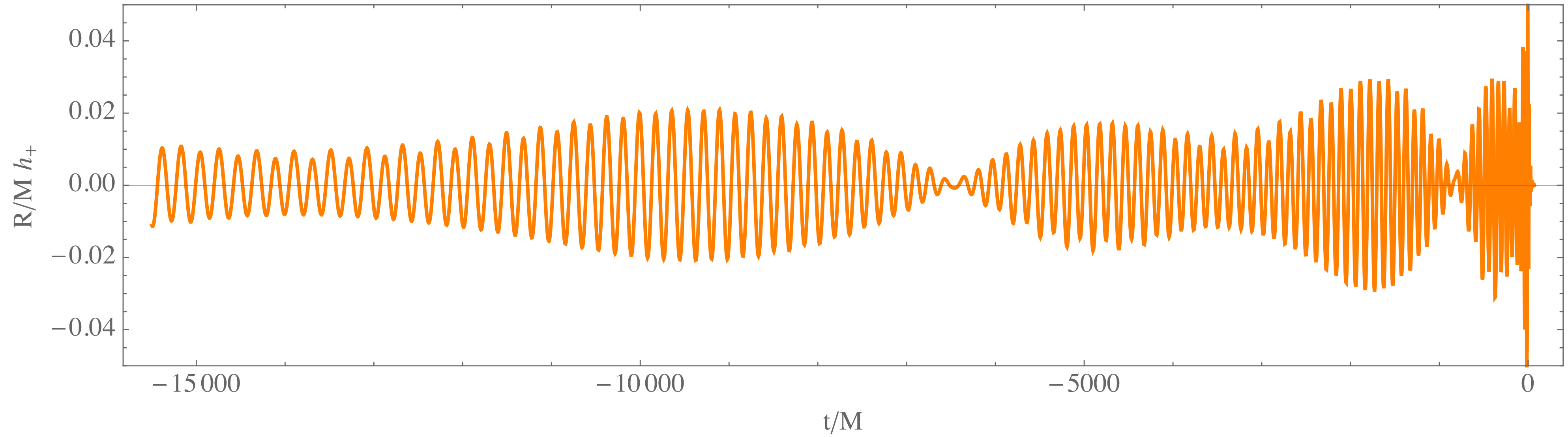
Comparing nonprecessing BBH models



[Bohe,Shao,AT+(in prep)]

(O1 aLIGO)

Precessing BBH models

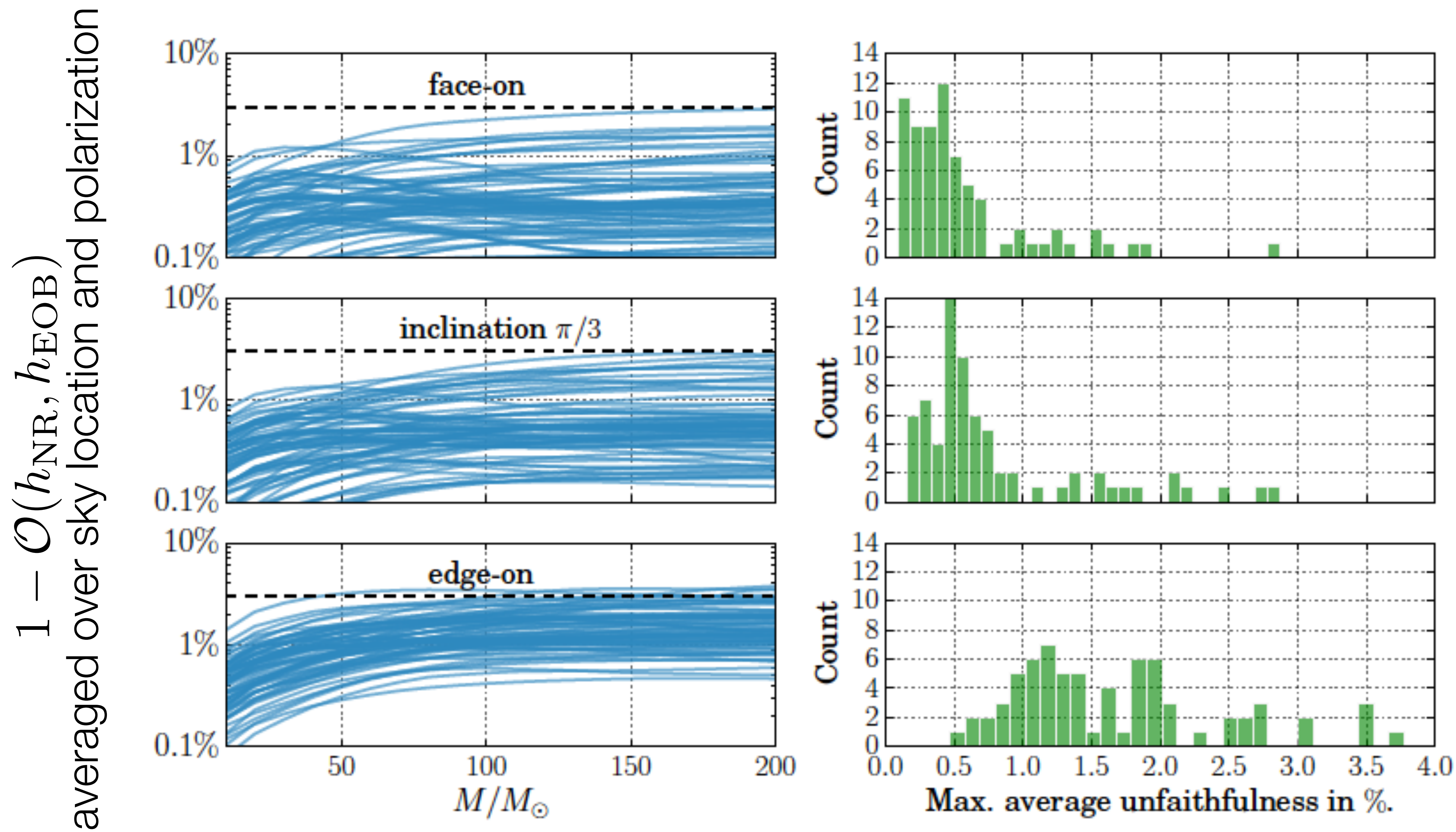


- When BH spins are not parallel to angular momentum of the binary, the **orbital plane precesses**

- **Precessing frame** [Buonanno+03, Schmidt+11, O'Shaughnessy+11, Boyle+11]
  1. In precessing frame, use **calibrated nonprecessing model**
  2. Inertial-frame modes from **rotation of precessing-frame modes according to motion of orbital angular momentum**

- Both effective-one-body [Pan+13, Babak, AT, Buonanno16] and phenomenological [Hannam+13] models available

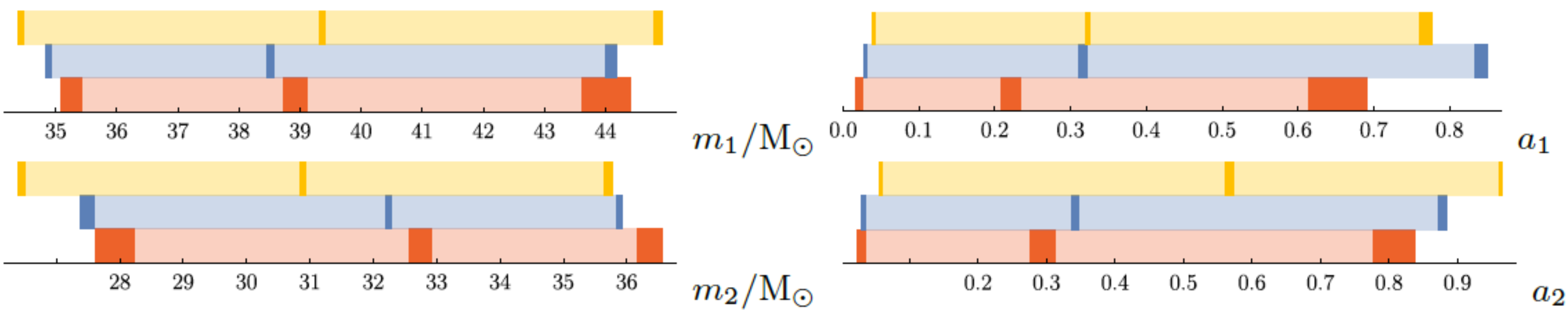
Effective-one-body model for precessing BBHs



[Babak, AT, Buonanno16]

Different models vs GW150914

- **Nonprecessing EOBNR**, **precessing EOBNR**, and **precessing Phenom** measure consistent parameters for GW150914
  1. SNR
  2. comparable mass
  3. face off/on
  4. short signal



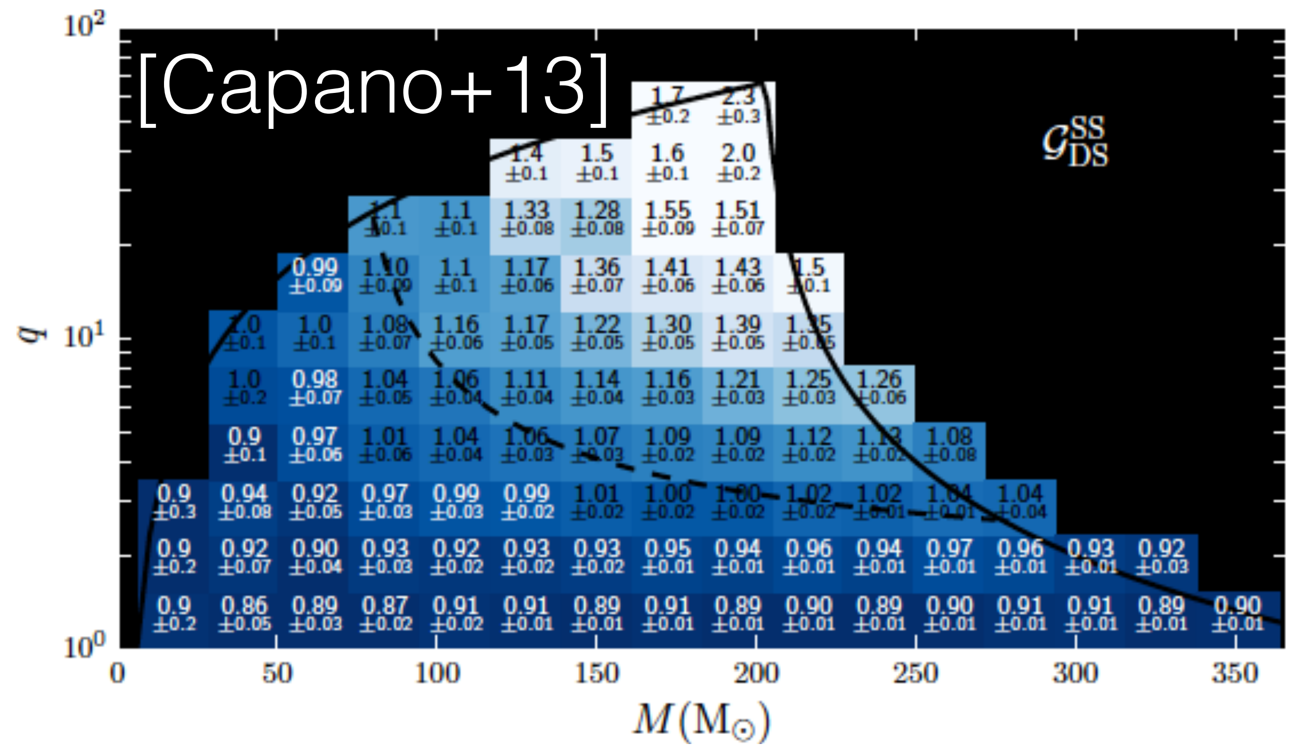
[LVC1606.01262]

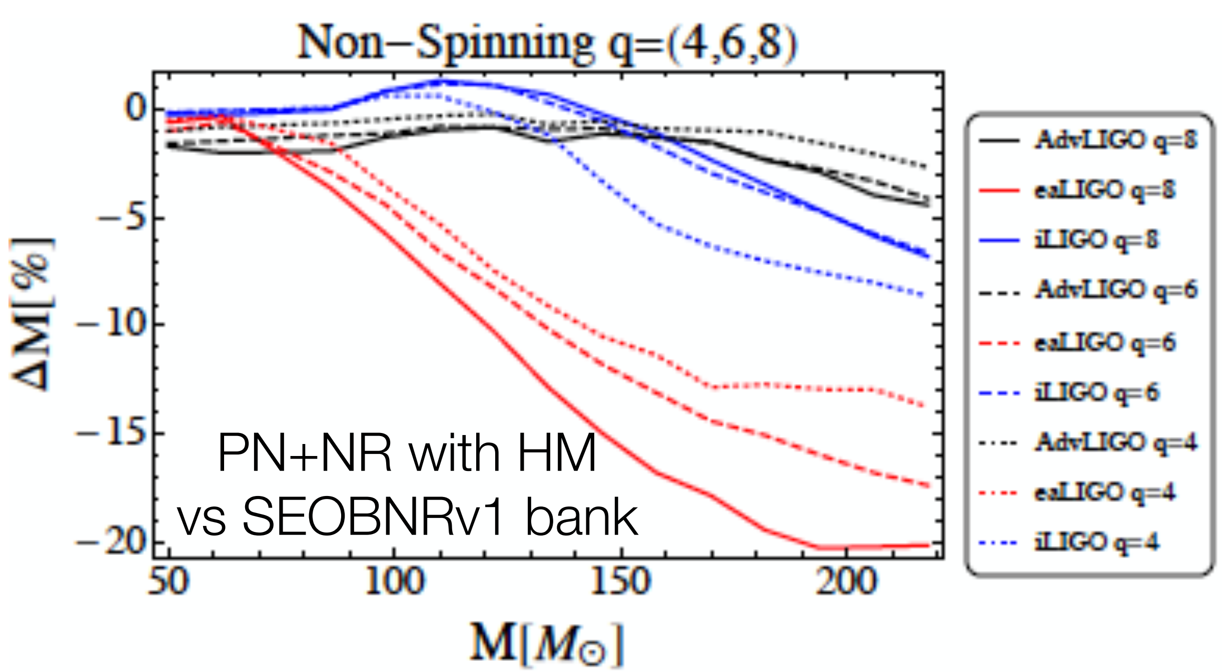
Quasicircular binary black holes: open problems

Open problems for quasicircular BBH models

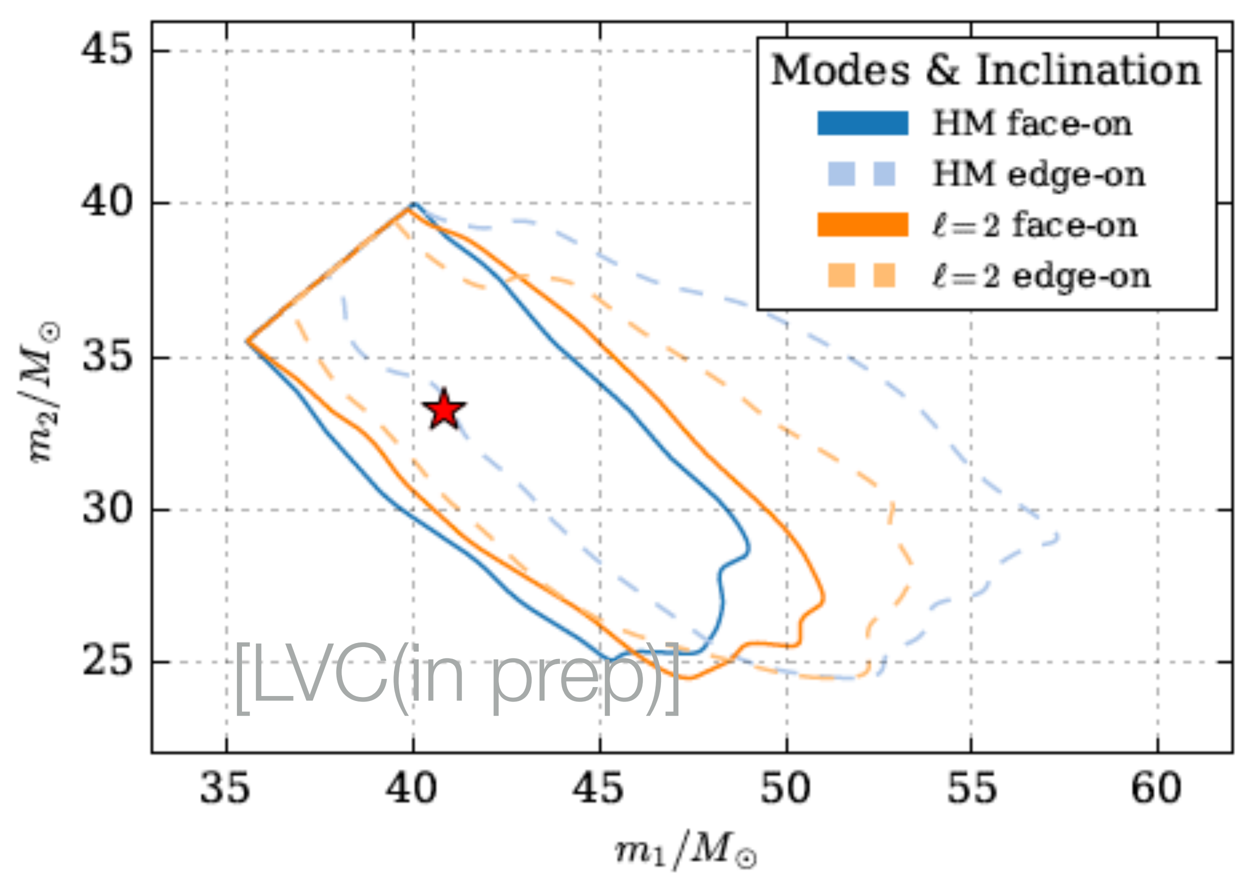
- **Problem of extrapolation** outside calibration domains, i.e., high mass ratios, spins

- **IMR higher-order modes** for spinning binaries are not available



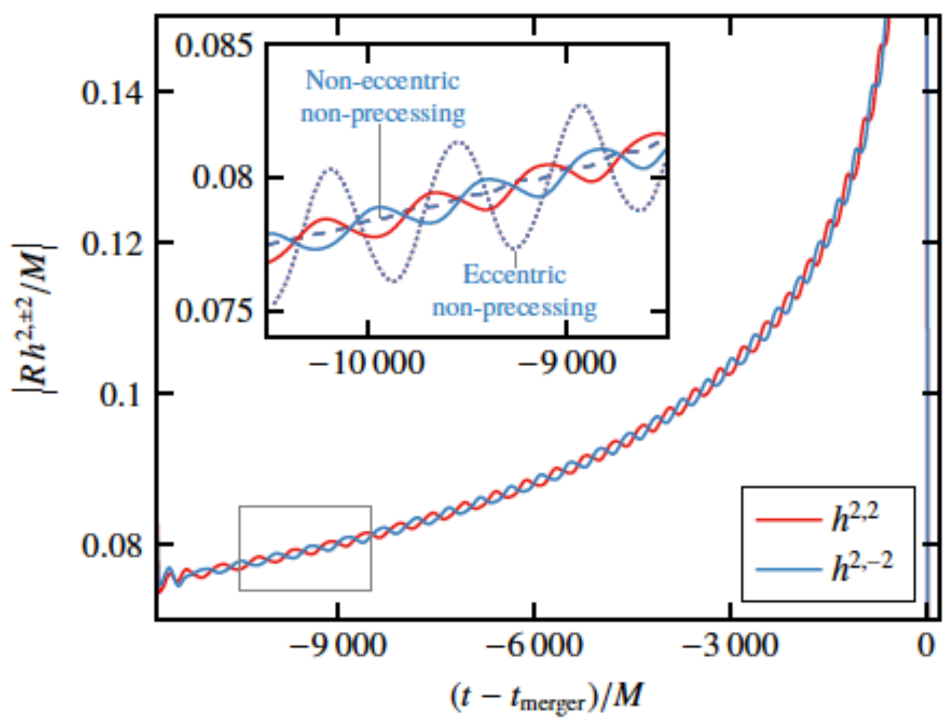


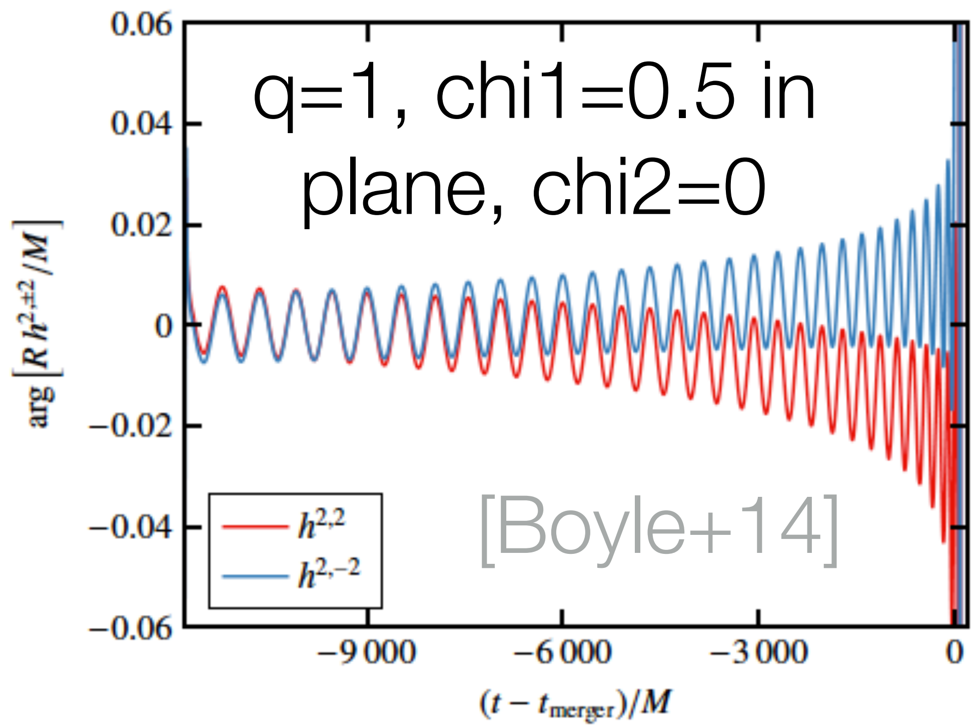
[Calderon-Bustillo+15]



Open problems for quasicircular BBH models

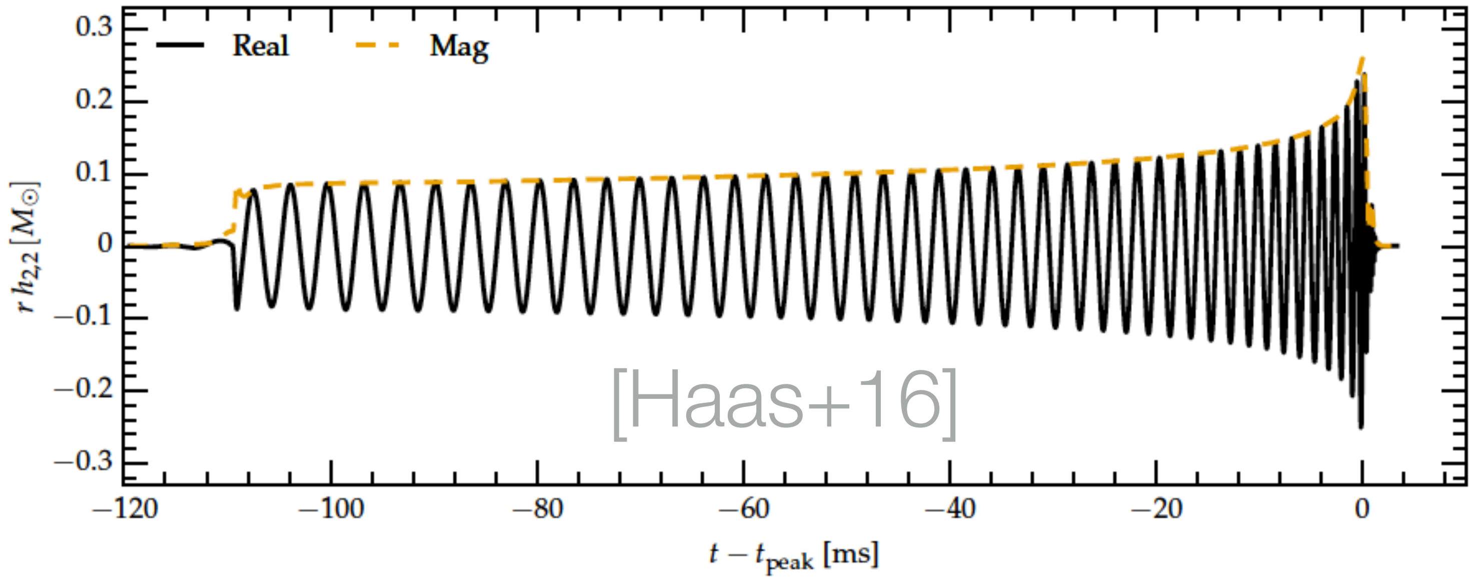
- **Precessional effects** not fully modeled
  1. mode asymmetry in coprecessing frame [O'Shaughnessy+13, Pekowsky+14, Boyle+14]
  2. radiation axis keeps precessing during ringdown [O'Shaughnessy+13]
  3. no calibration to precessing NR

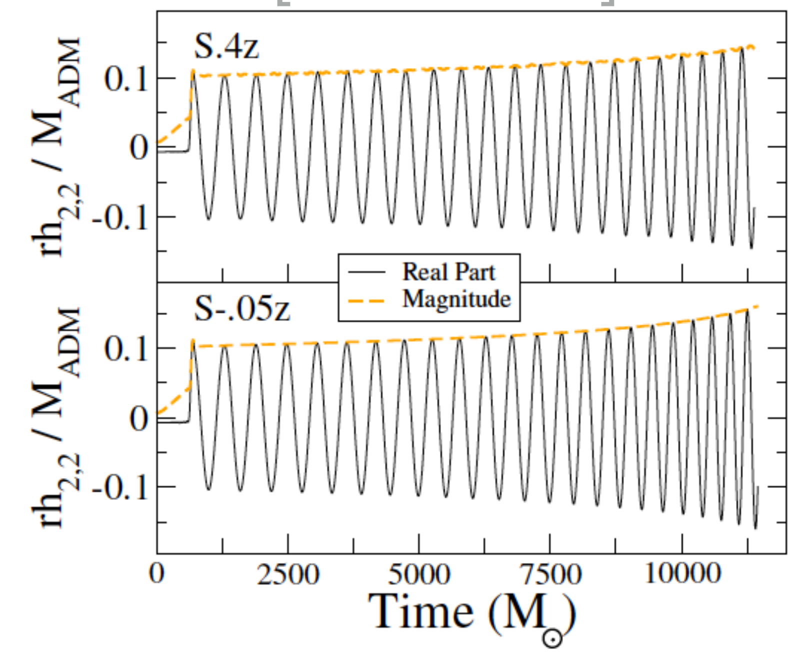




Binary neutron stars

BNS in numerical relativity



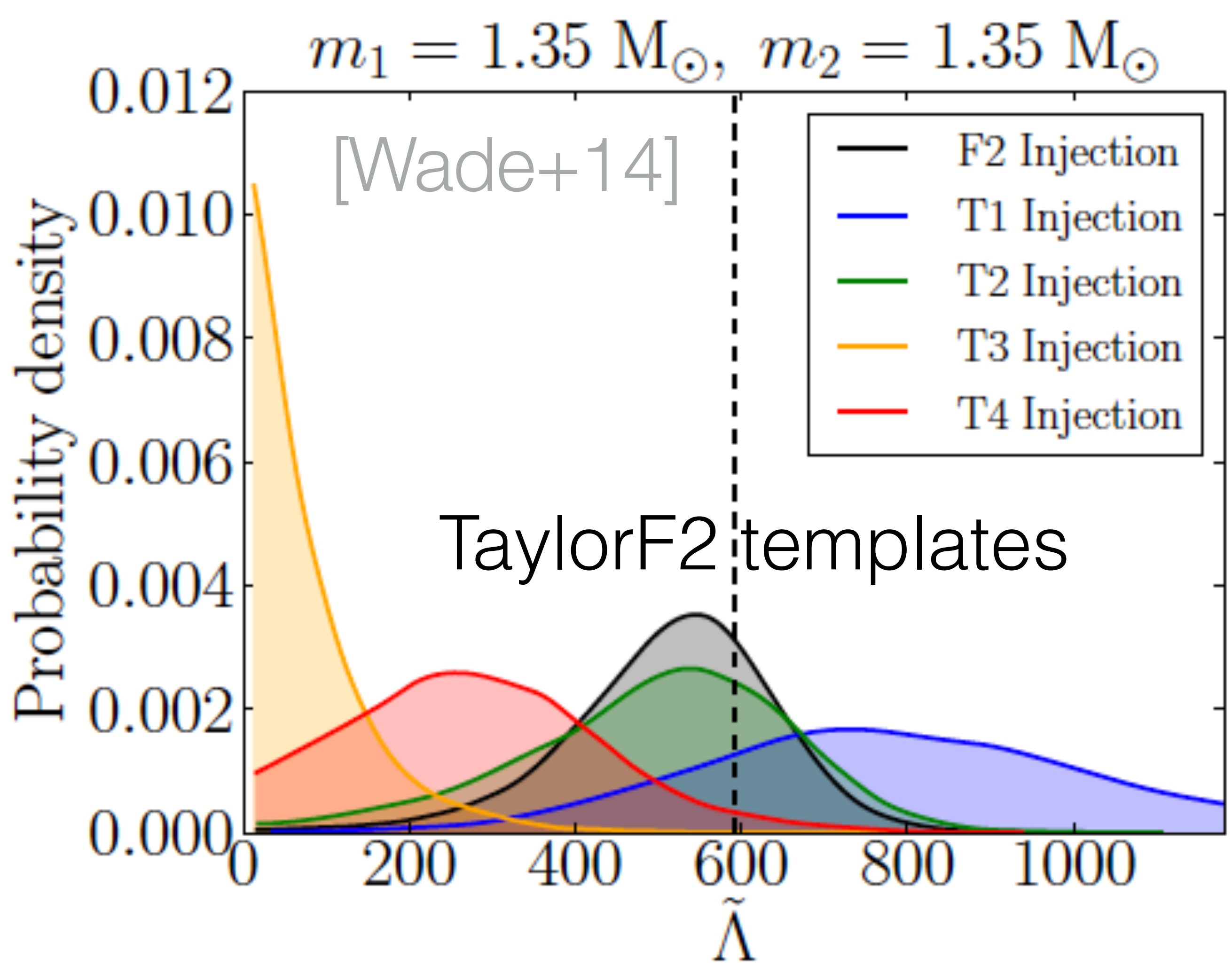


- **Longer simulations** with polytropic EOS: SACRA longterm simulations [Hotokezaka+15], 22 orbits in SpEC [Haas+16]

- Evolutions with **spin precession** [Tacik+15, Dietrich+15], **unequal mass** [Lehner+15, Dietrich+16], **more physics** (neutrino cooling, nuclear EOS, magnetic fields) [Foucart+15, Palenzuela+15, Endrizzi+16]

- New schemes that allow **smaller errors** [Bernuzzi+16]

Why modeling BNS waveforms is important

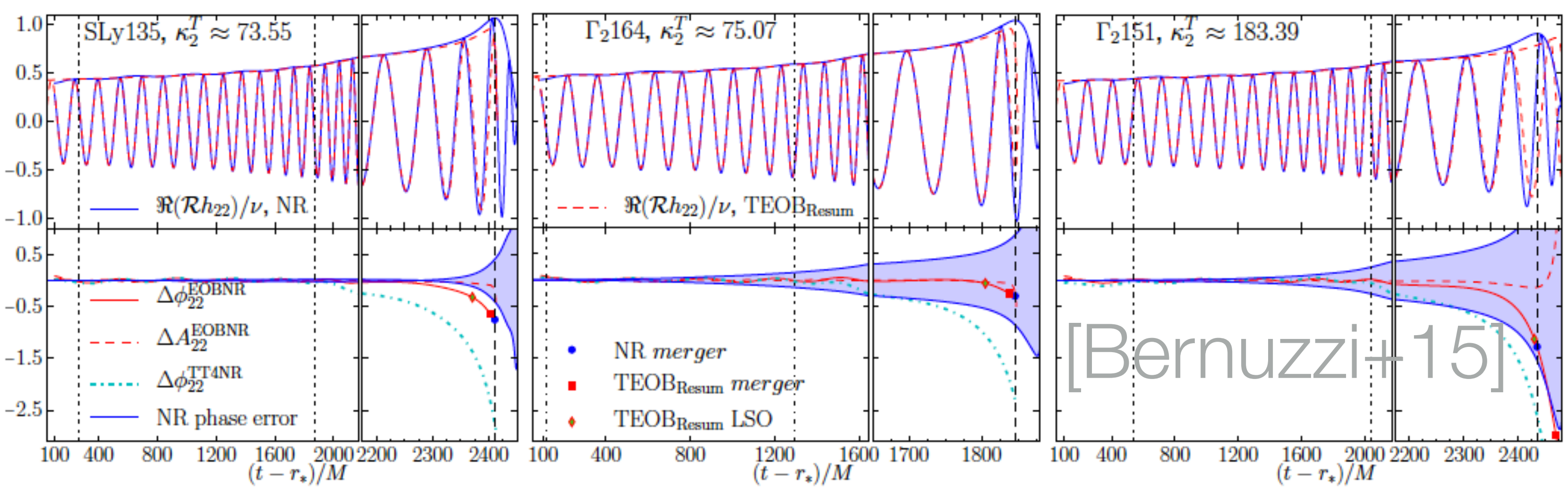


$$\tilde{\Lambda} = \frac{8}{13}\left[\left(1+7\eta-31\eta^2\right)\left(\Lambda_1+\Lambda_2\right)+\sqrt{1-4\eta}\left(1+9\eta-11\eta^2\right)\left(\Lambda_1-\Lambda_2\right)\right]$$

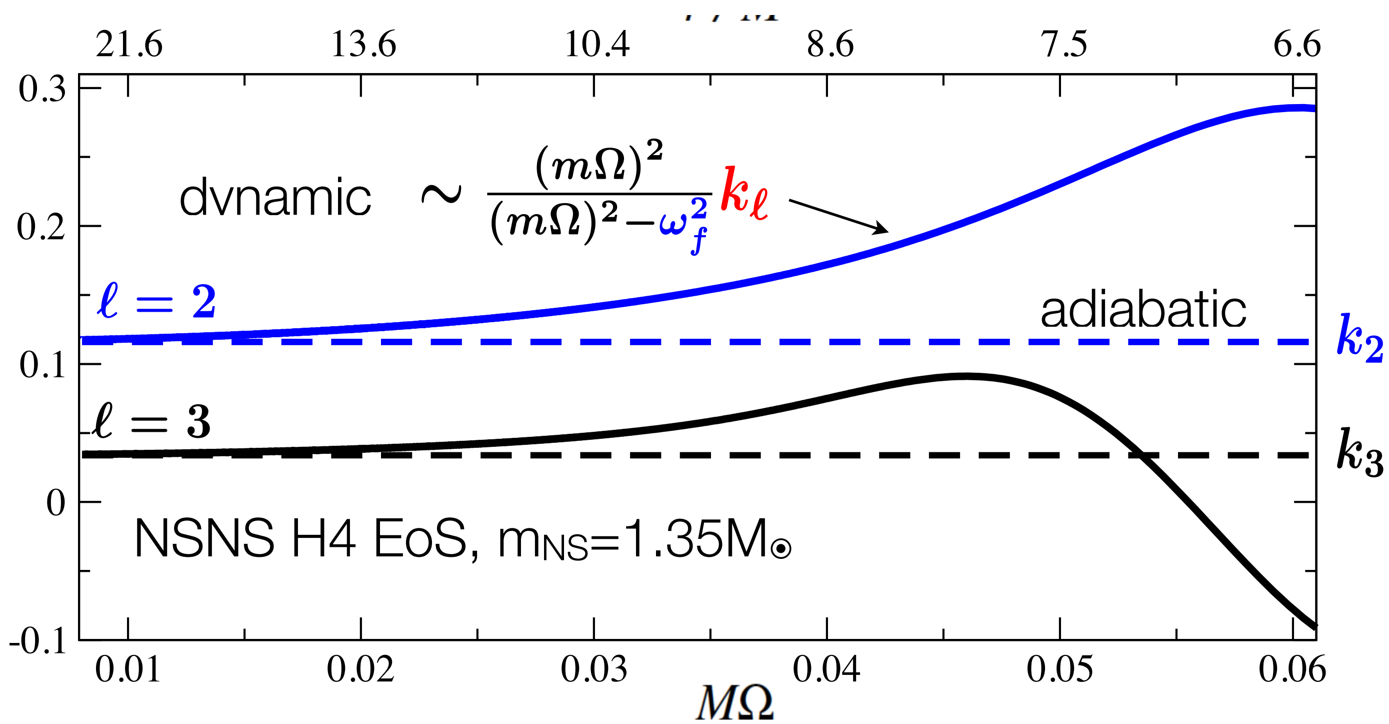
- Templates that are good for detecting BNSs can create **large biases** in measurement of tidal parameters [Yagi+14, Favata+14, Wade+14, Hotokezaka+16]

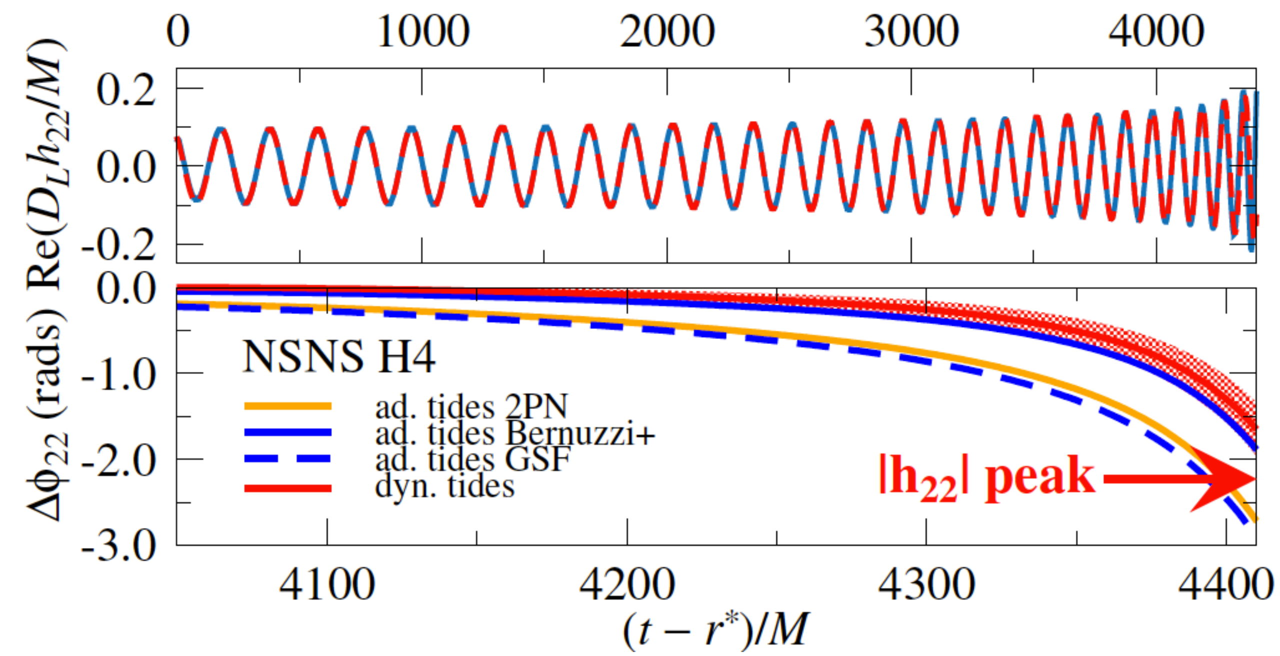
Models of inspiraling BNSs

- Splicing long NR BBH with PN tidal effects [Barkett+15]
- Augment EOB potentials by tidal effects: (i) **gravitational self-force** [Bernuzzi+15], (ii) **dynamic tides** [Hinderer+16]



[Bernuzzi+15]

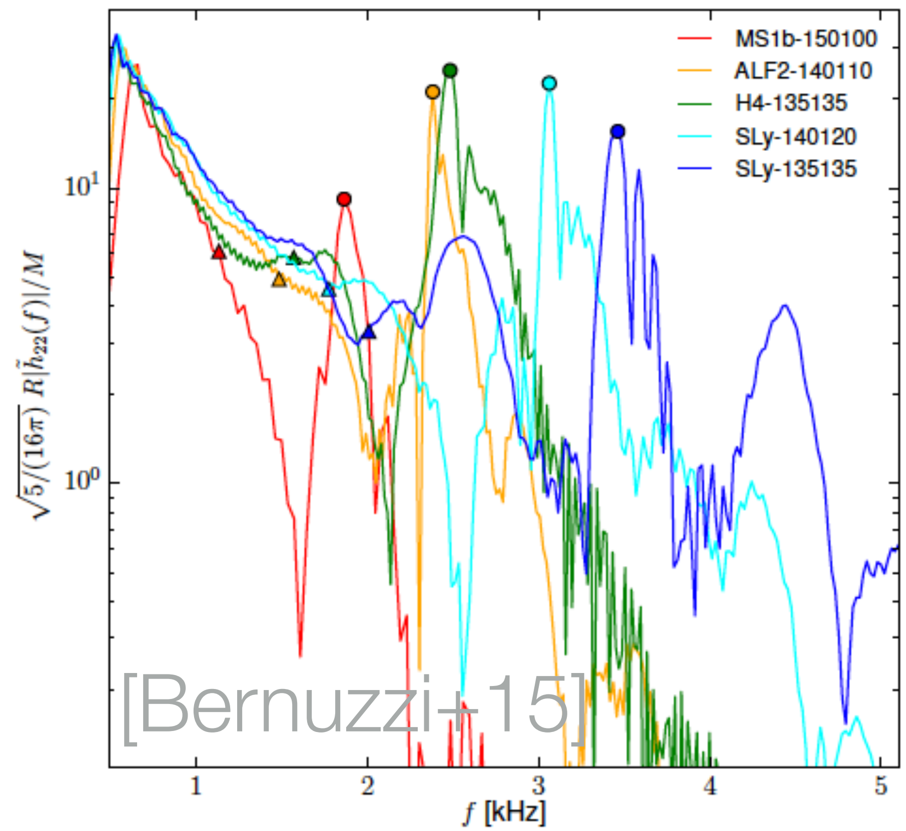


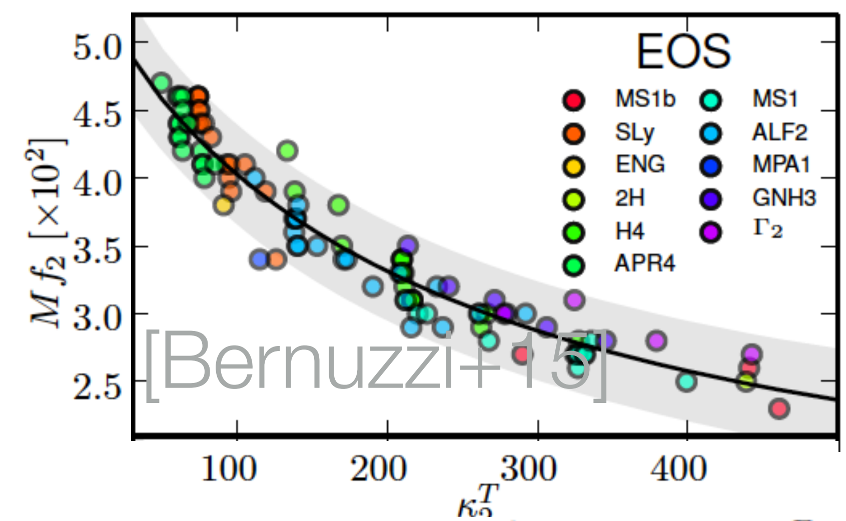


[Hinderer+16]

Models of the post-merger signal

- If M<2.9MSun, hypermassive NS forms after BNS merger
- **Peak frequencies** correlate with radius at fiducial mass, compactness, etc., in an EOS-independent way [Bauswein+12, Hotokezaka+13,Takami+14,Bernuzzi+14]



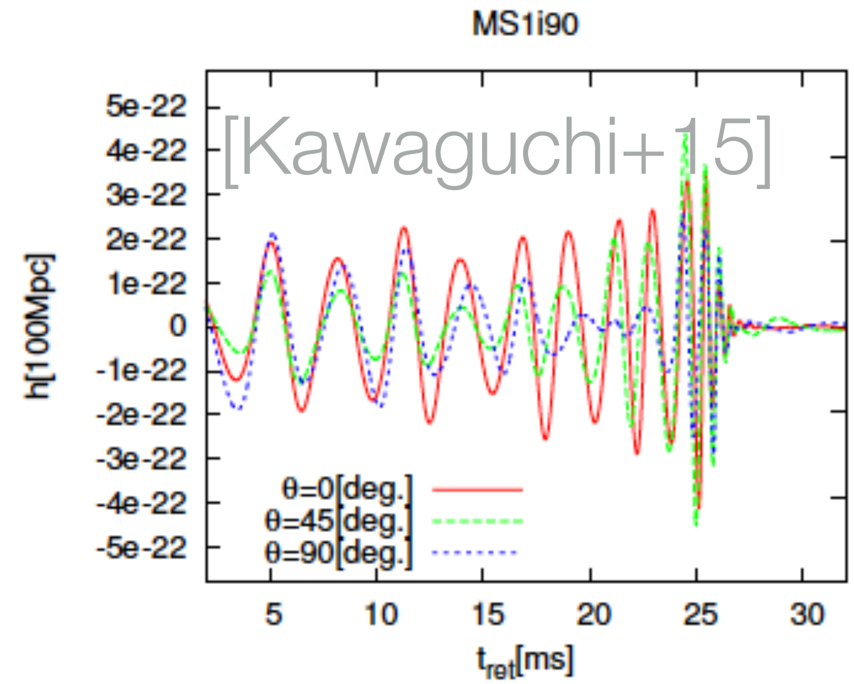


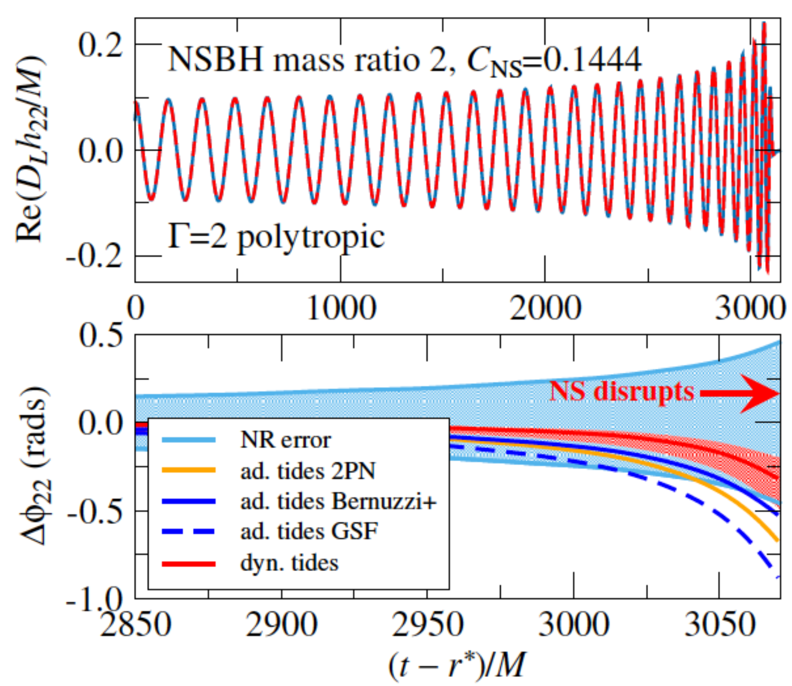
$$\kappa_2^T = 2\left(\frac{q^4}{(1+q)^5}\frac{k_2^A}{C_A^5} + \frac{q}{(1+q)^5}\frac{k_2^B}{C_B^5}\right)$$

Neutron-star / black-hole binaries

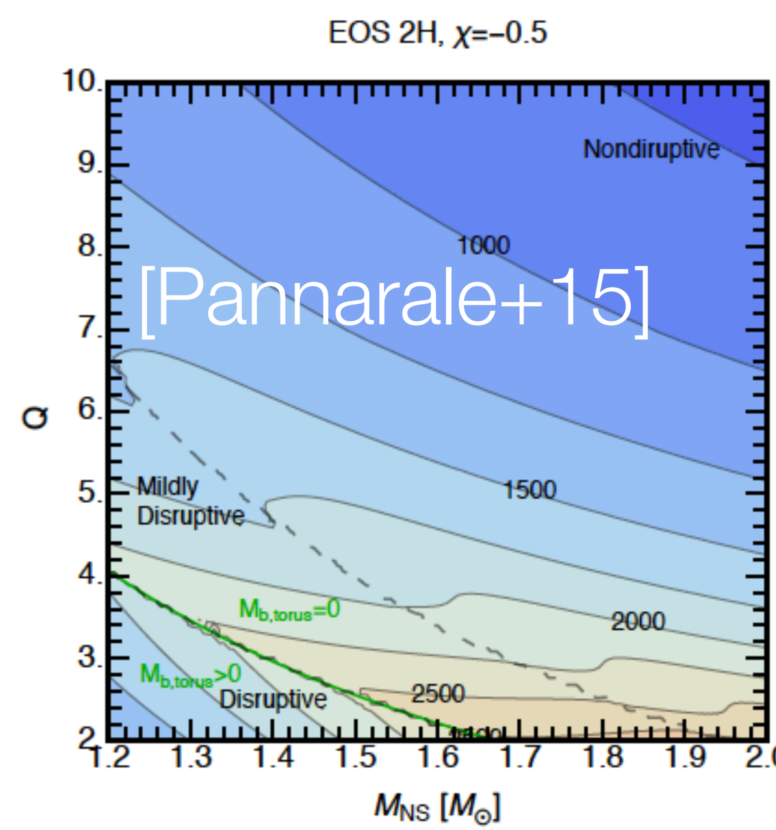
Neutron star / black hole binaries

- **Long NSBHs**: small errors [Foucart+15], with precession [Kawaguchi+15]
- Model for **disruption frequency** and freq-domain amplitude model [Pannarale+15]
- EOB model with dynamical tides [Hinderer+16]





[Hinderer+16]



Conclusions

Conclusions

- **Binary black holes**
  1. many new NR runs (calibration, surrogates, direct use)
  2. challenging configurations becoming feasible
  3. models include info from NR catalogs
  4. towards complete IMR models with eccentricity

- **Binary neutron stars & neutron-star / black-hole binaries**
  1. longterm accurate NR runs
  2. inclusion of tidal effects in accurate point-mass models
  3. universality relations for postmerger
  4. models of disruption frequency

- **Numerical + analytical relativity crucial for best characterization of future GW observations**

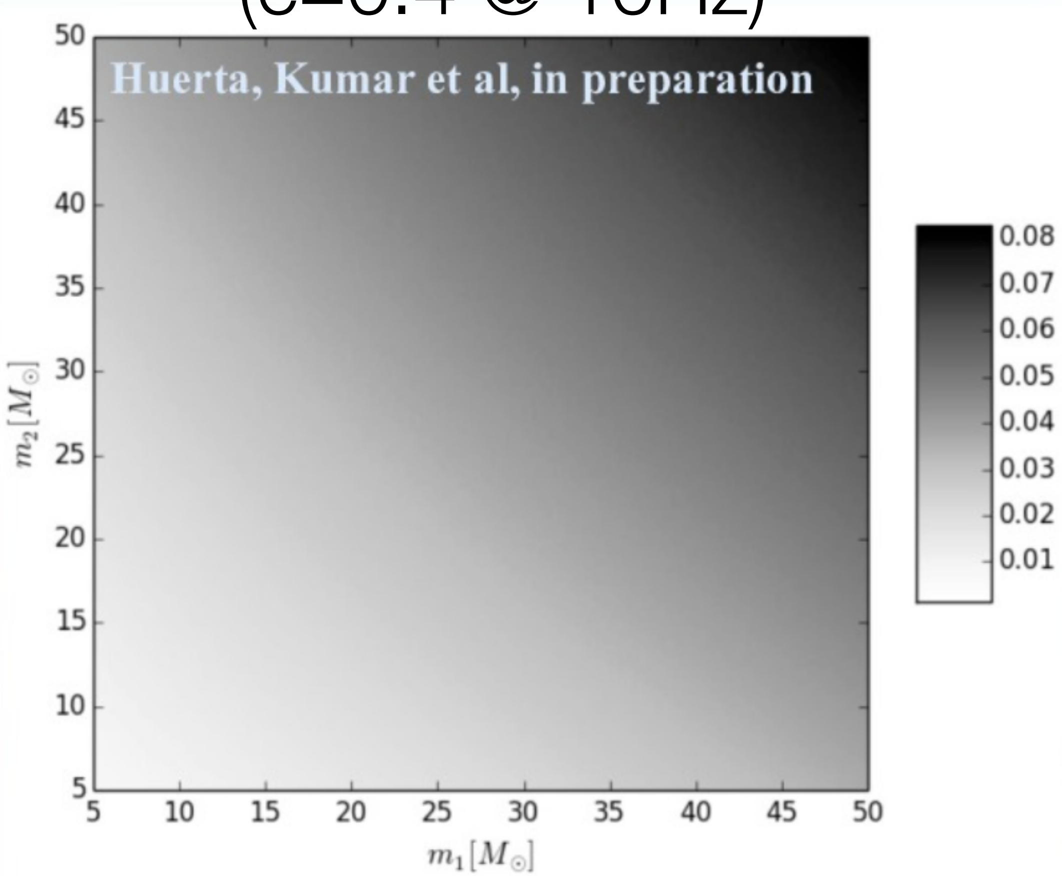
Additional slides

Eccentric binaries

Eccentric binaries

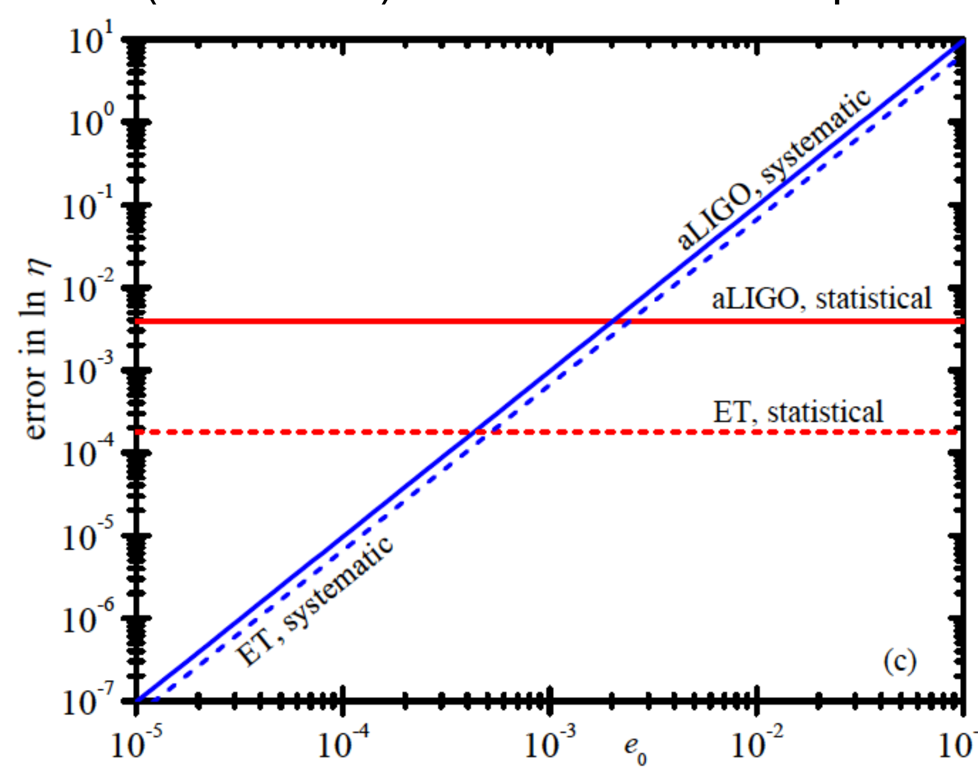
- **Dynamical formation** scenarios instead of field binary evolution
- Searches for BNS using quasicircular templates ok for e<=0.02 (M=2.6Msun) [Huerta+13]
- Small residual eccentricity can **bias** parameter estimation [Favata14]

residual eccentricity @ ISCO (e=0.4 @ 10Hz)



[Huerta+16]

(1.4+1.4) Msun @ 100Mpc



[Favata14]

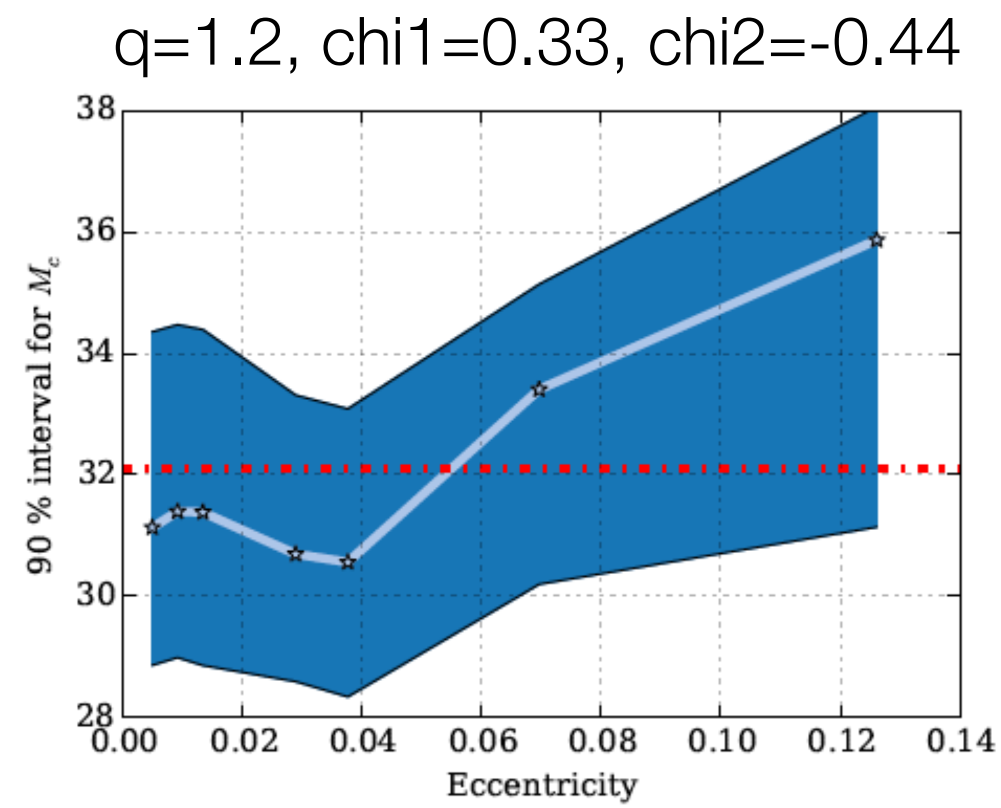
Eccentric binaries

- Frequency/time-domain **PN inspiral** waveforms [Arun+09, Yunes+09, Huerta+14, Tanay+16]. Small-ecc corrections up to 3PN [Moore,Favata+16]

- **IMR** waveforms based on **geodesic** motion in Kerr [East+13]

- **IMR** waveforms based on **PN inspiral + self force + NR-informed ringdown** [Huerta+16]

- Ongoing work on eccentric IMR waveforms based on EOB/Phenom



[LVC(in prep)]