

Modeling binary-black hole signals for gravitational-wave astronomy:

Achievements, systematics and future challenges

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1 - Modeling binary black-hole signals:

- Main modeling frameworks
- Recent developments: orbital eccentricity [Planas+(incl. HE), arXiv:2503.13062 (2025), Gamboa+(incl. HE), PRD 112, 044038 (2025)] and equatorial asymmetries [HE+, arXiv:2506.19911 (2025)]

2 - New results from the O4 observing run:

- GWTC-4.0 [LVK+(incl. HE), arXiv:2508.18082, (2025)]
- Special events: broadening the parameter space, louder signals
- Systematic differences due to waveform models

3 - Expected systematic biases for improved detector sensitivities [Dhani+(incl. HE), PRX 15, 031036 (2025)]

- Biases for LVK-like population
- Biases across parameter space
- Effect on science goals with “golden binaries”

Inferring the source properties from GW observations

We want to infer the source properties of a signal detected on the data

$$d(t) = n(t) + h(t, \lambda)$$

Bayes rule to update **prior probability of parameters** with **likelihood of data being described by the model with those parameters** to obtain **posterior probability of source parameters**

$$p(\lambda | d, h) = \frac{p(d | h(\lambda)) p(\lambda, h)}{p(d, h)}$$

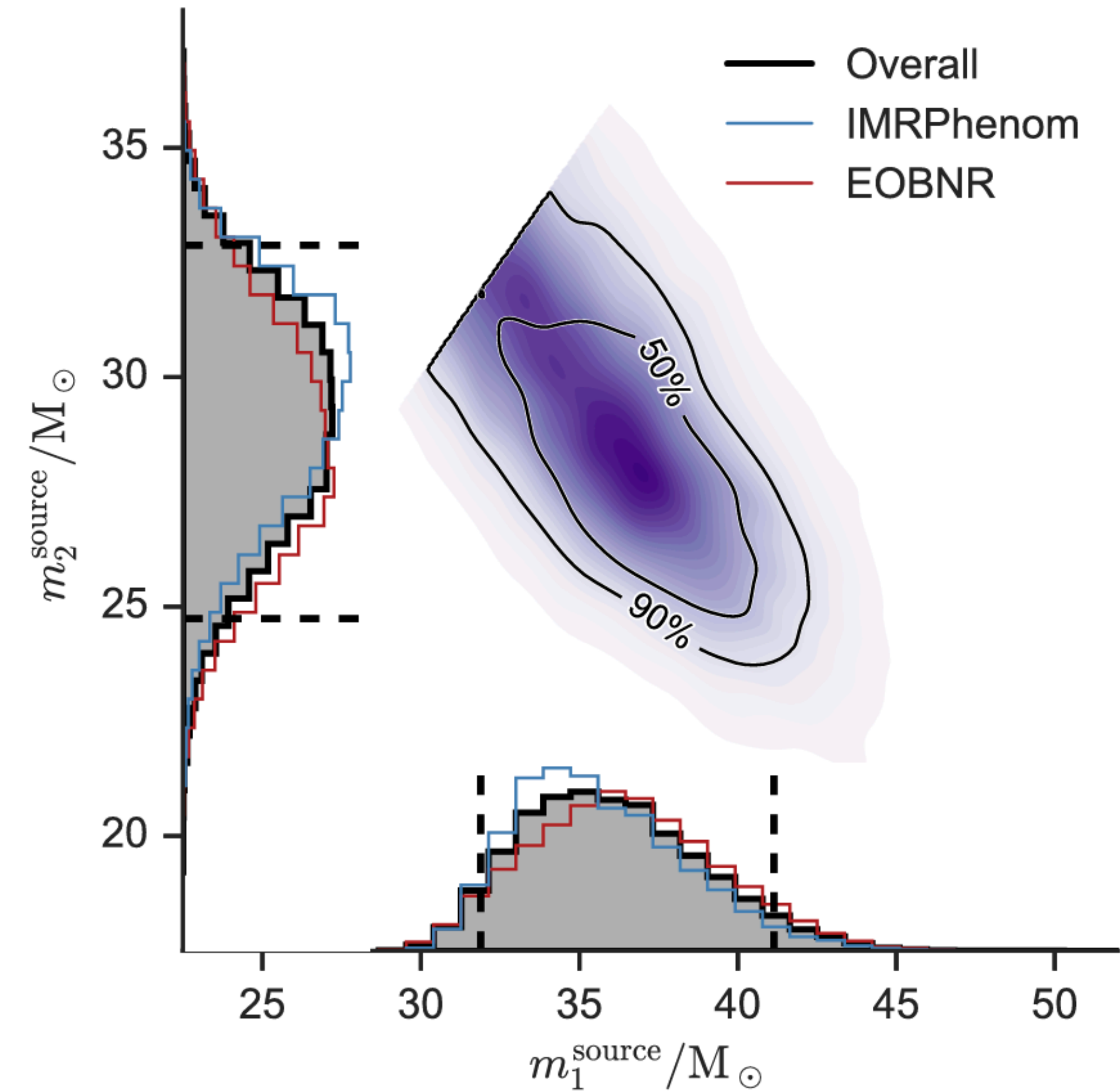
GW likelihood (assuming Gaussian and stationary noise):

$$\ln p(d | h(\lambda)) \propto - (d - h(\lambda) | d - h(\lambda)) \quad (a | b) = 4 \operatorname{Re} \int_0^\infty \frac{\tilde{a}(f) \tilde{b}^*(f)}{S_n(f)} df$$

We rely on the ability to model the signal!

Accurate models: avoid biases on inferred parameters

Efficient models: $10^7 - 10^8$ likelihood evaluations needed with standard stochastic sampling techniques

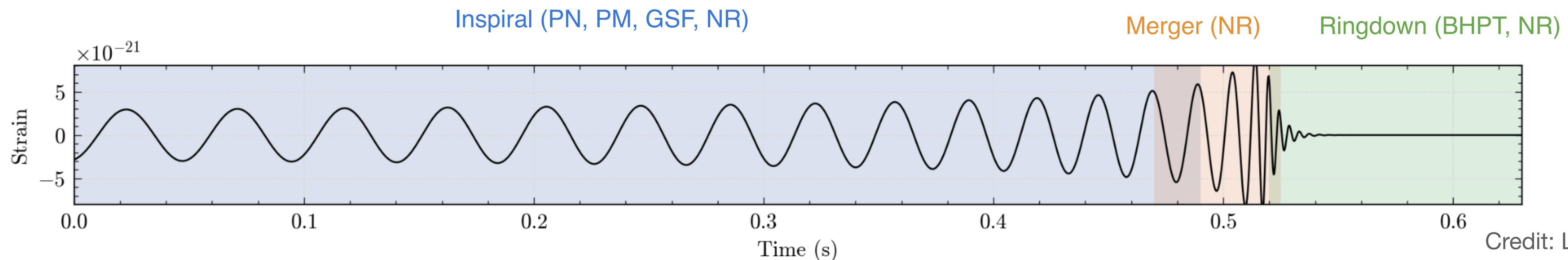
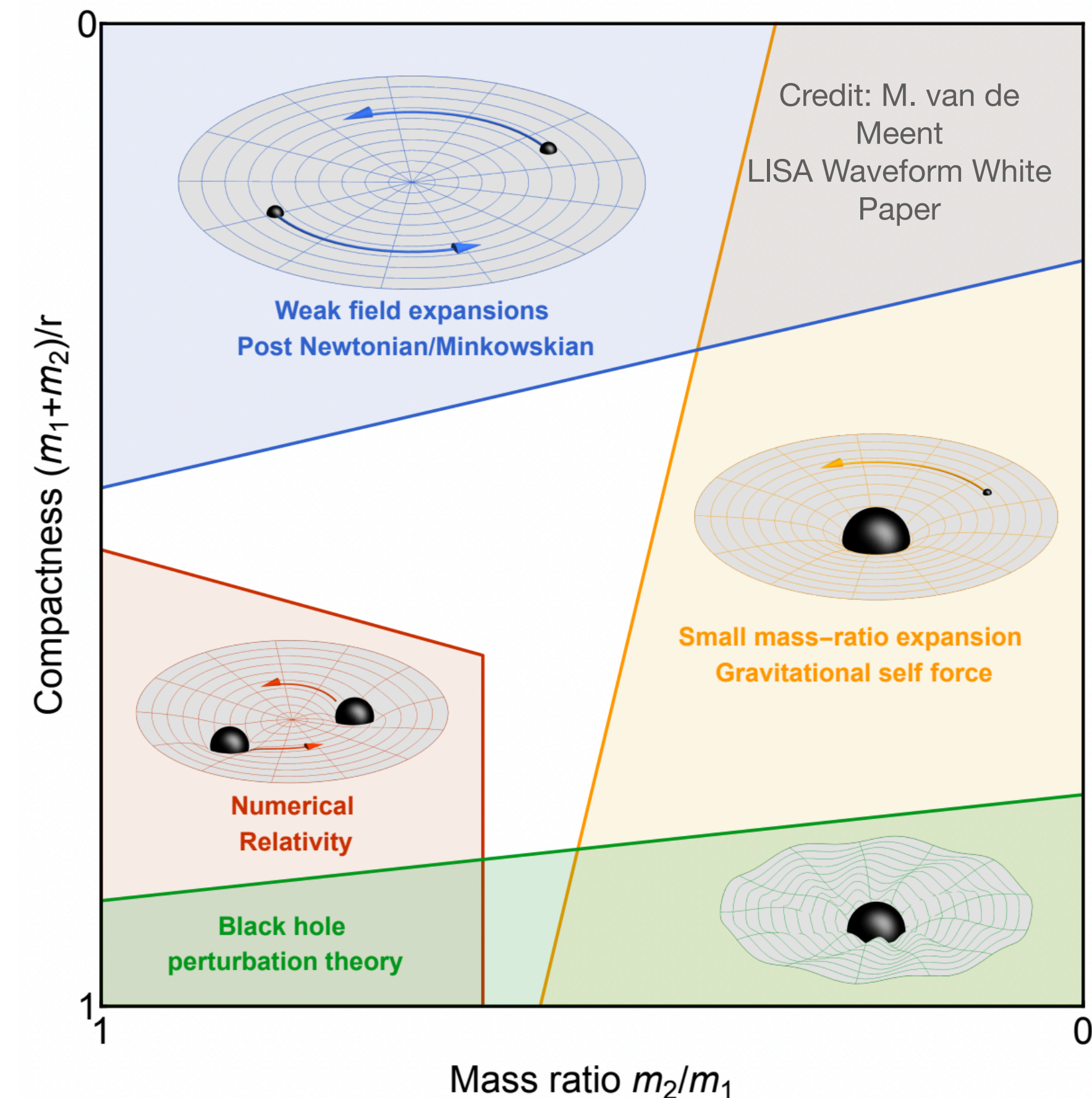


Credit: Abbott+2016

Modeling compact binary coalescences

Theoretical frameworks:

- **Post-Newtonian theory:** valid for slowly moving binaries (expansion in v/c) - can describe inspiral stage.
- **Post-Minkowskian theory:** valid for weakly gravitating sources (expansion in G) - can describe inspiral stage.
- **Gravitational self-force:** valid for high mass-asymmetric systems.
- **Numerical relativity:** numerical evolution of Einstein equations - “exact” solutions, but computationally very expensive - limitations in signal length and parameter space coverage.
- **Black-hole perturbation theory:** can describe ringdown emission of remnant black hole.



Inspiral-merger-ringdown Waveform models

Waveform modeling:

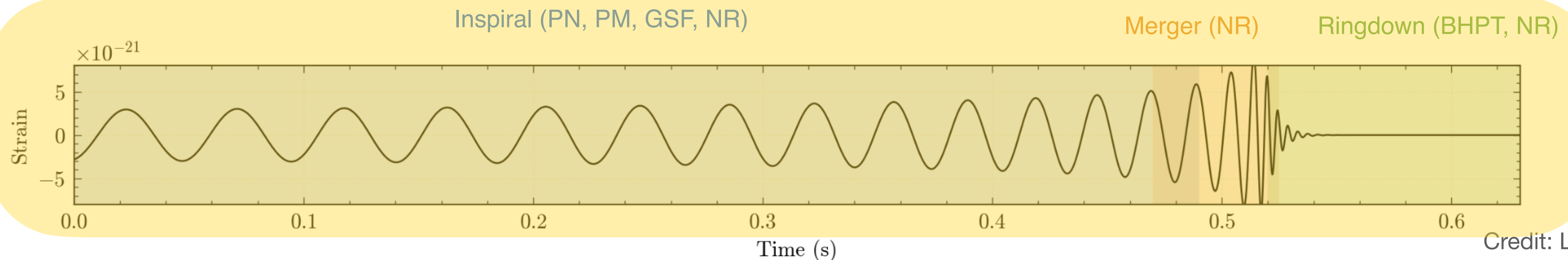
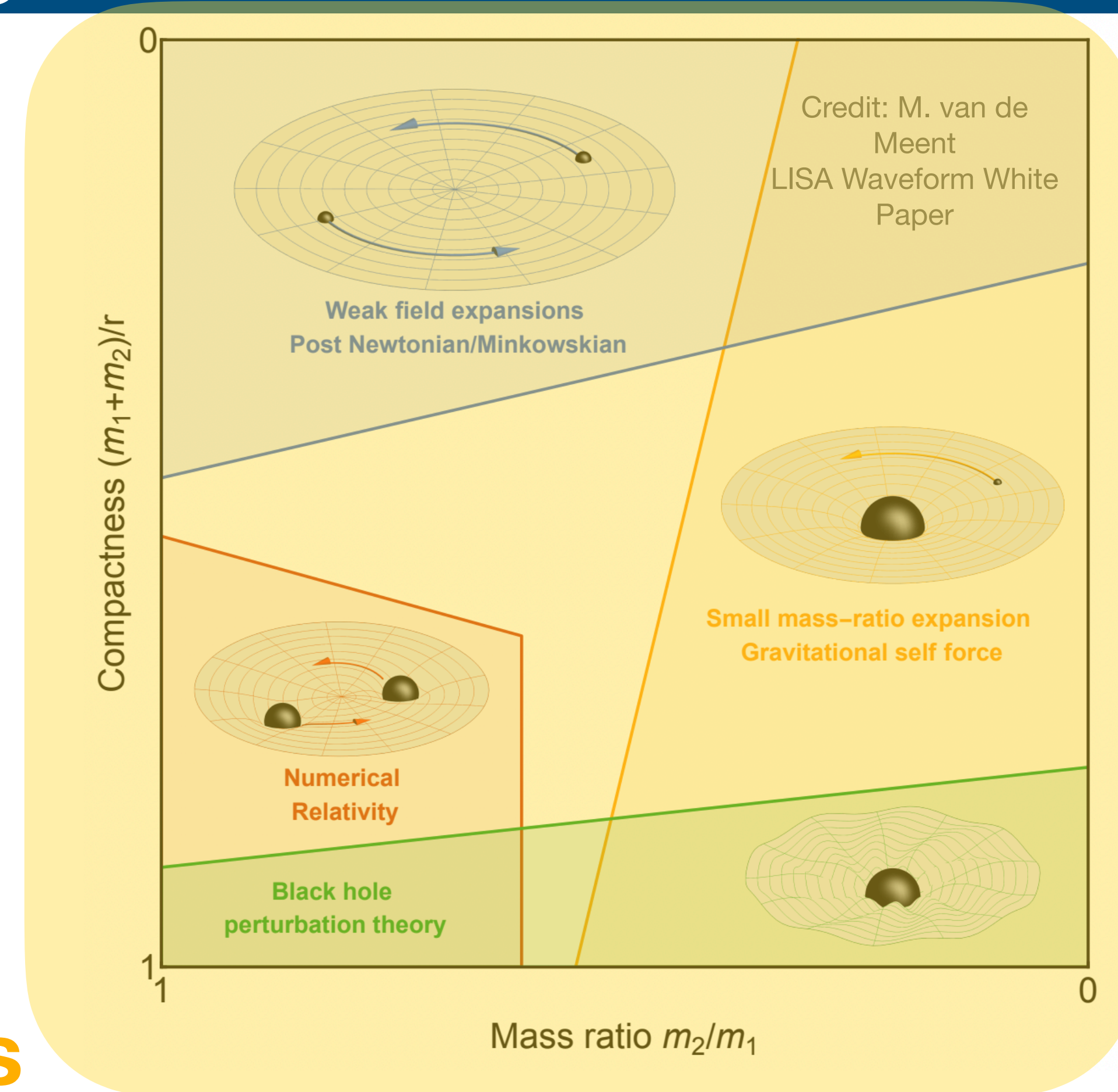
Combine information from numerical and perturbative approaches.

- **Generality:** Aims to cover the full parameter space of signals.
- **Efficiency:** Bayesian parameter source inference require $10^7 - 10^8$ waveform evaluations.
- **Accuracy:** Keep systematic errors below statistical uncertainty.

Main waveform model families: Different trade-offs between efficiency, accuracy and generality

- IMRPhenom (**highly efficient**)
- EOB (SEOBNR, TEOBResum) (**more accurate but more expensive**)
- NRSur (**highly accurate, efficient, but limited in param space and length**)

Waveform models



IMRPhenom: phenomenological modeling

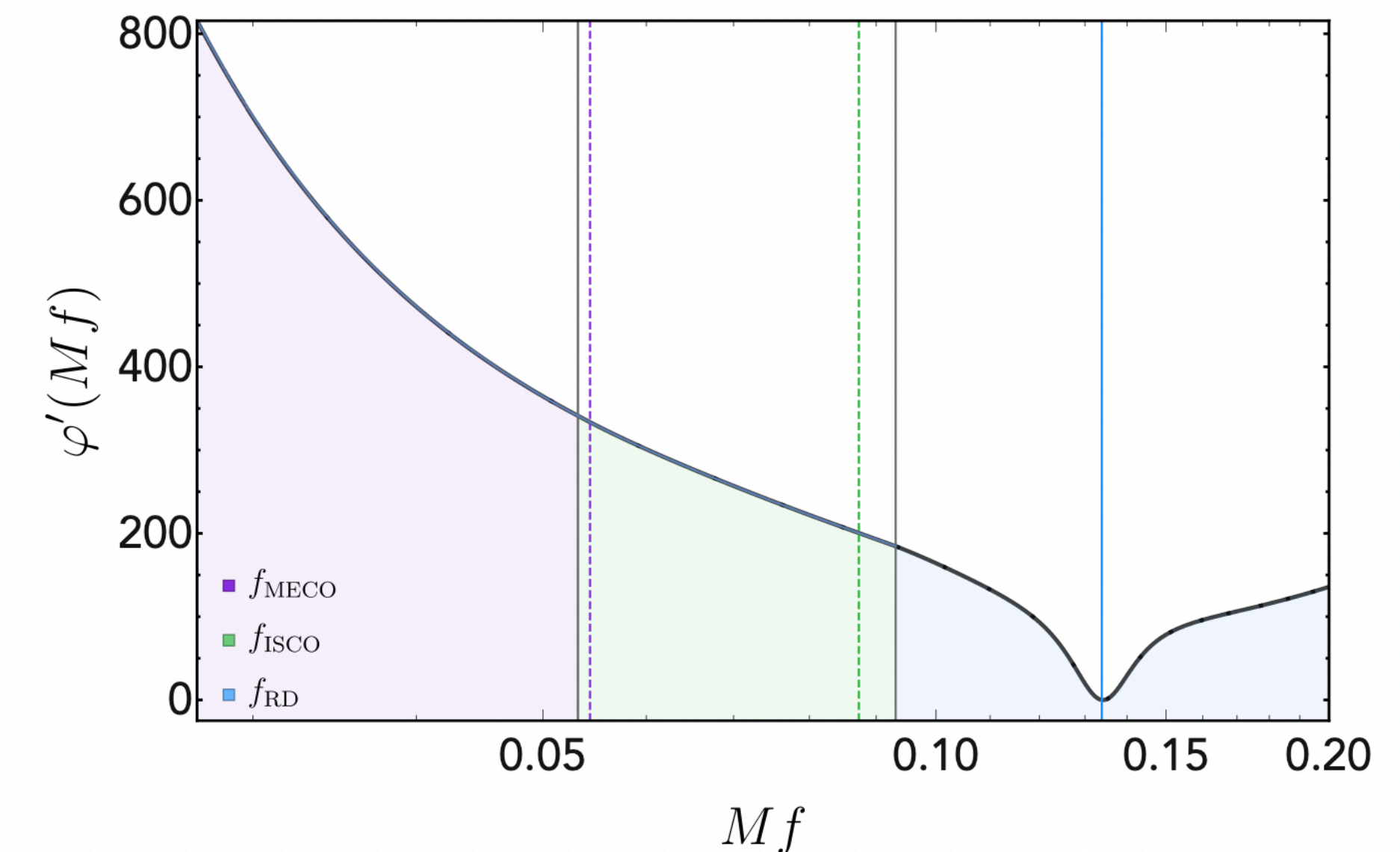
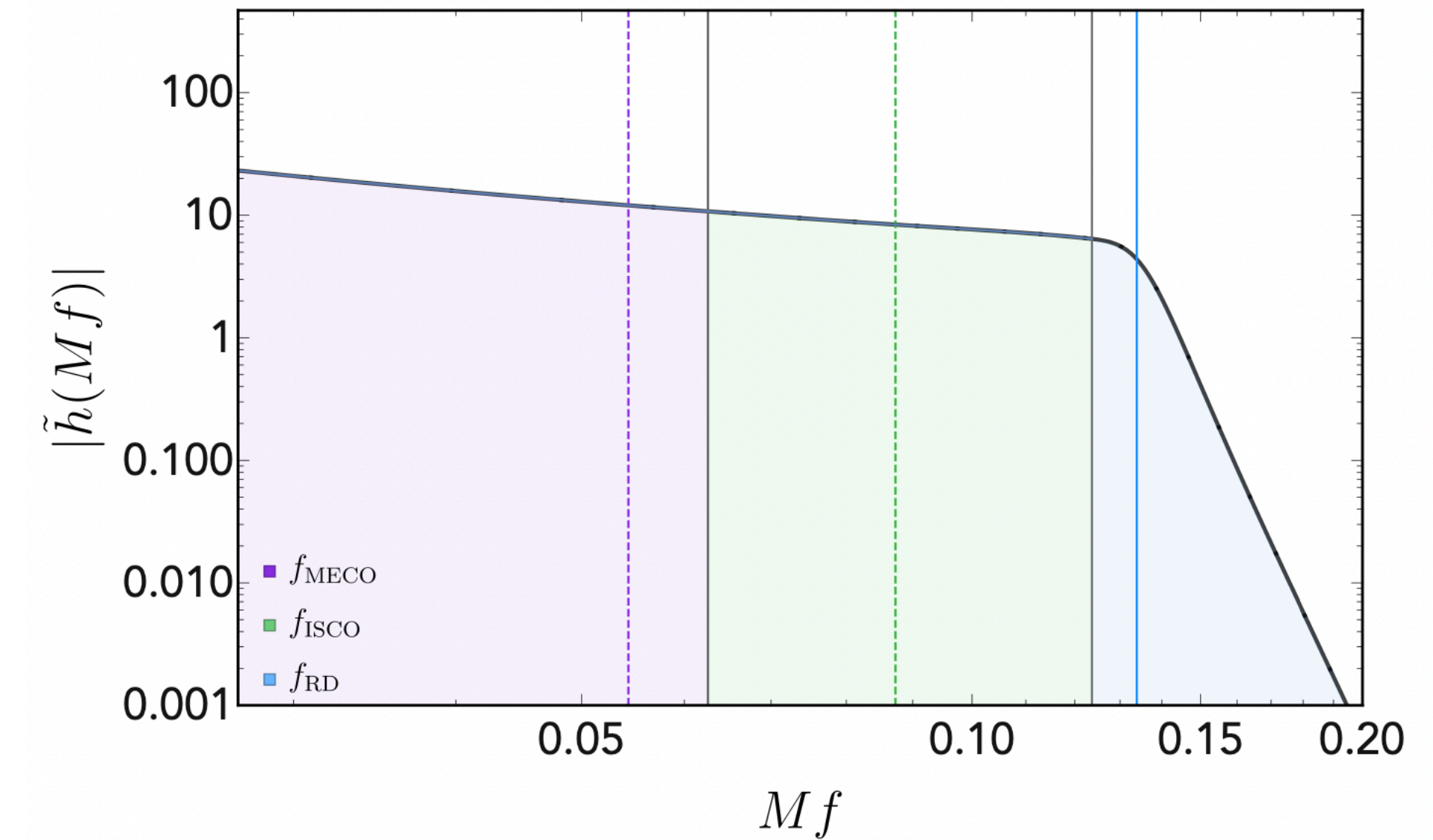
Phenomenological modeling of the **amplitude** and **phase** of the spin-weighted spherical harmonics of the signal. Arun+08, Santamaria+10, Husa+15, Khan+15

$$\tilde{h}_+(f) - i\tilde{h}_\times(f) = e^{i\alpha(f)} \sum_{\ell m} A_{\ell m}(f) e^{im\psi_{\ell m}(f)} {}_{-2}Y_{\ell m}[\beta(f), \gamma(f)]$$

Closed-form piece-wise expressions (in Fourier-domain or time-domain) for **amplitude** and **phase** of each harmonic.

Closed-form or numerical evolution of spin-precession of the orbital plane.

1. **Inspiral** using Post-Newtonian results augmented with calibration to Numerical Relativity and Teukolsky waveforms.
2. **Intermediate** using calibrated phenomenological expressions to describe the late-inspiral and plunge
3. **Merger-ringdown** using calibrated expressions including the decay time and asymptotic ringdown frequencies from perturbation theory.



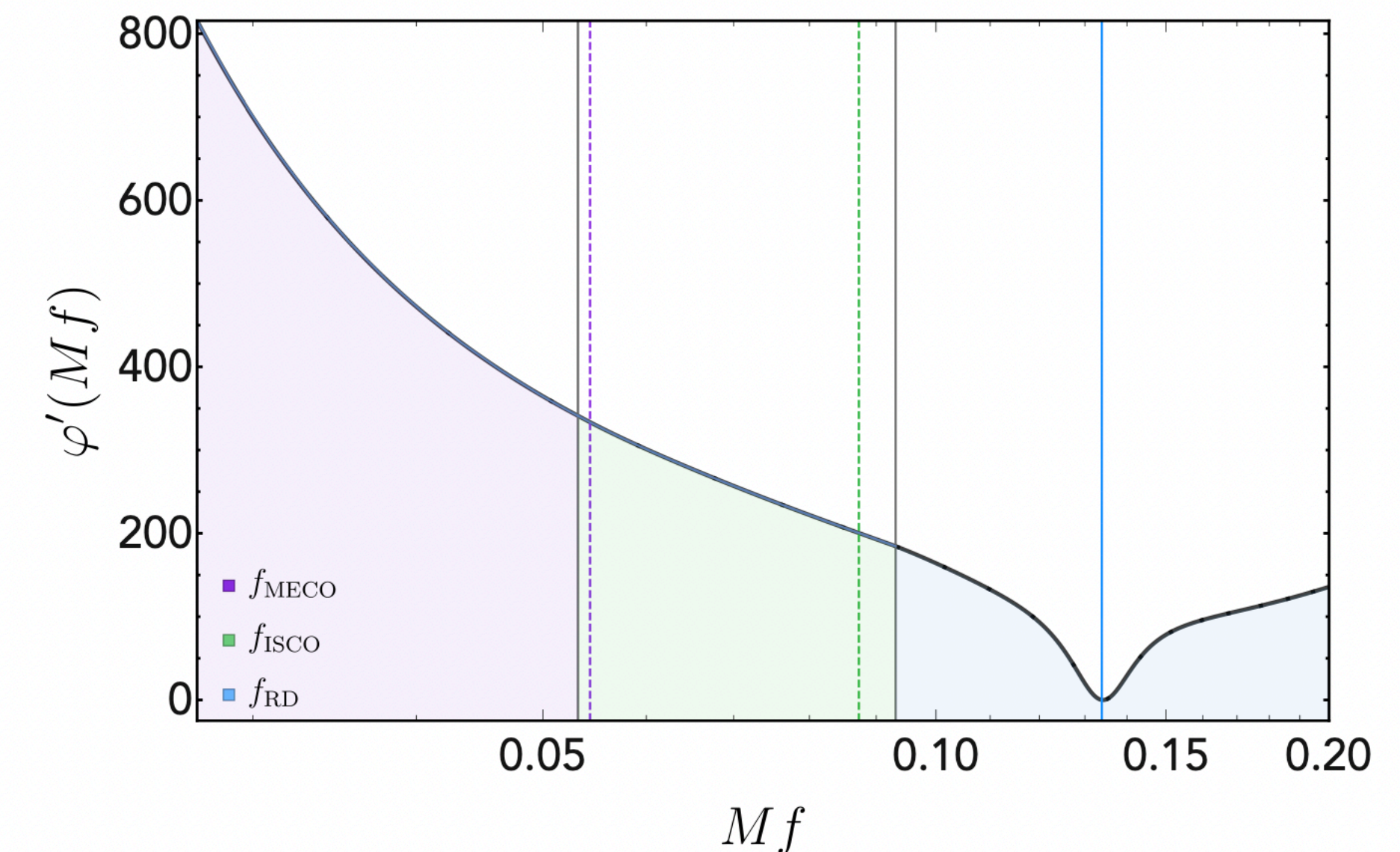
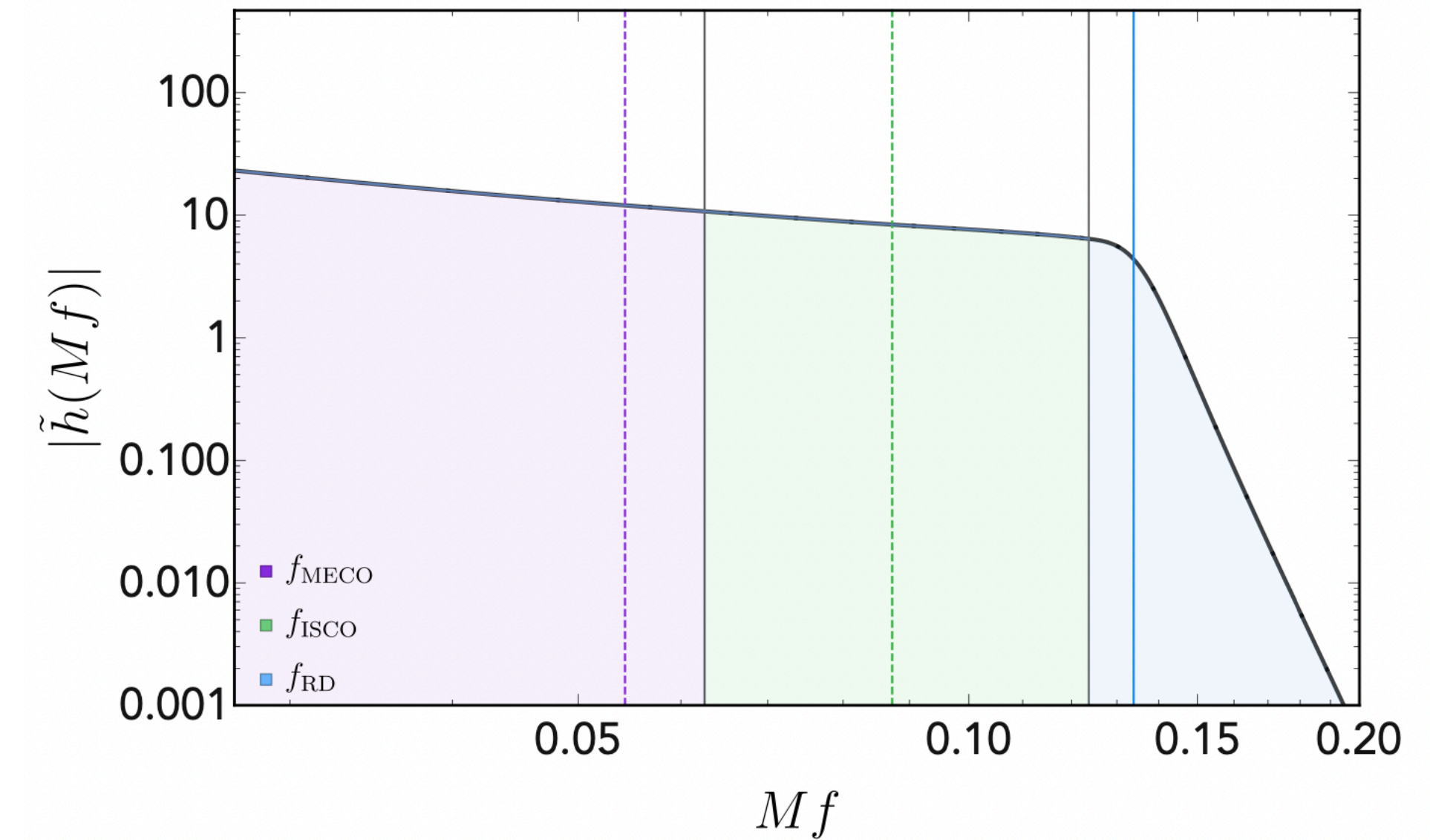
Credit: Pratten+2020

IMRPhenom: phenomenological modeling

Fourier-domain models: highly efficient, direct application in current data-analysis methods, but shortcomings for modeling complex signals (eccentricity, spin-precession)

$$\tilde{h}_+(f) - i\tilde{h}_\times(f) = e^{i\alpha(f)} \sum_{\ell m} A_{\ell m}(f) e^{im\psi_{\ell m}(f)} {}_{-2}Y_{\ell m}[\beta(f), \gamma(f)]$$

- IMRPhenomXPHM [Pratten+(incl. HE), PRD 103, 104056 (2021)]: multipolar spin-precessing model, with closed-form double spin solution for the spin dynamics
- IMRPhenomXPHM-SpinTaylor [Colleoni+, PRD 111, 064025 (2025)]: improved spin-precessing during inspiral using numerical spin evolution
- IMRPhenomXO4a [Thompson+, PRD 109, 063012 (2024)]: Partial calibration to spin-precessing NR simulations, inclusion of dominant equatorial-asymmetry.
- IMRPhenomXPNR [Hamilton+, arXiv:2507.02604 (2025)]: Combination of SpinTaylor and XO4a improvements.



Credit: Pratten+2020

IMRPhenom: phenomenological modeling

Time-domain models: still efficient, more direct connection with system dynamics (improved modeling of spin-precession and eccentricity), higher accuracy than Fourier-domain models.

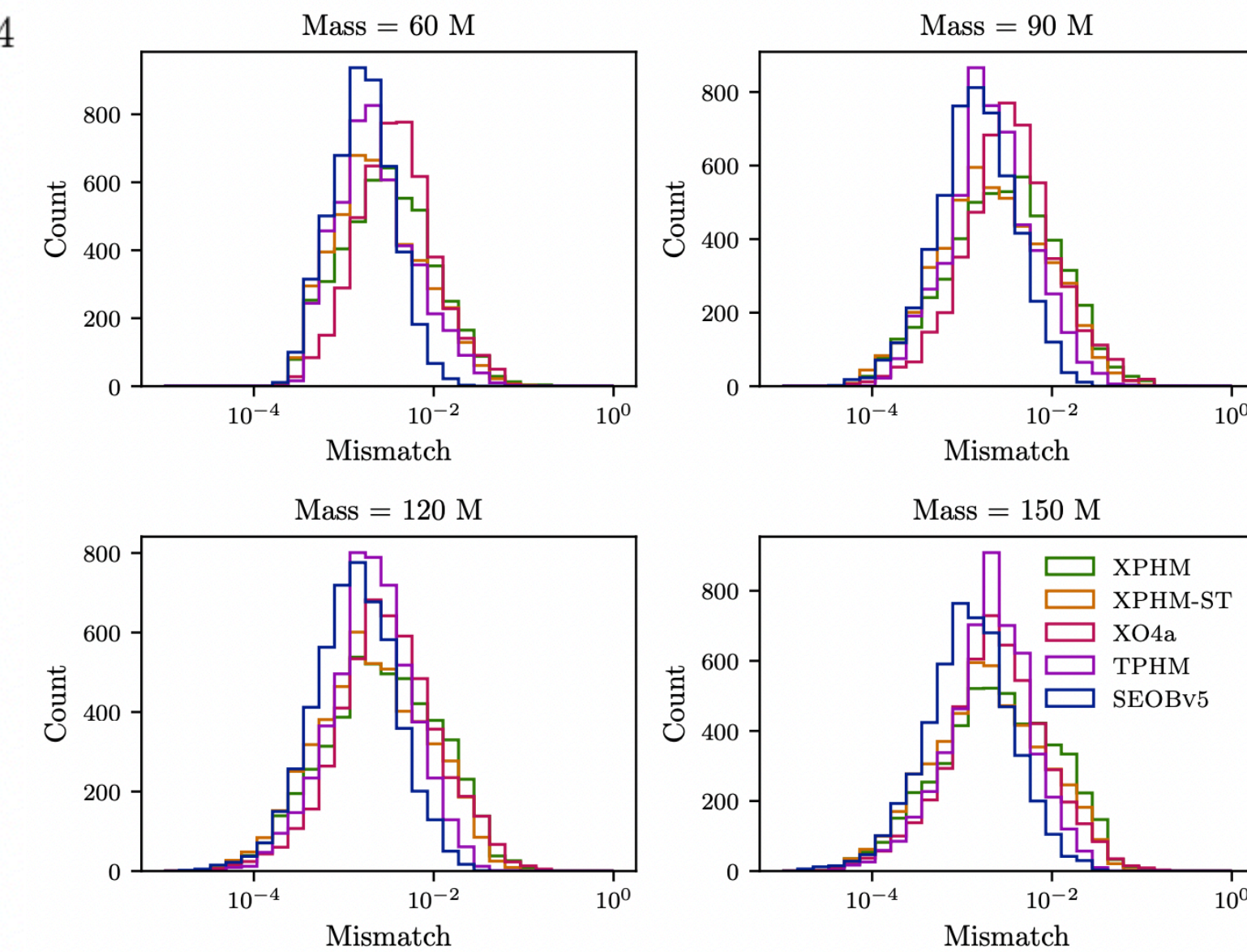
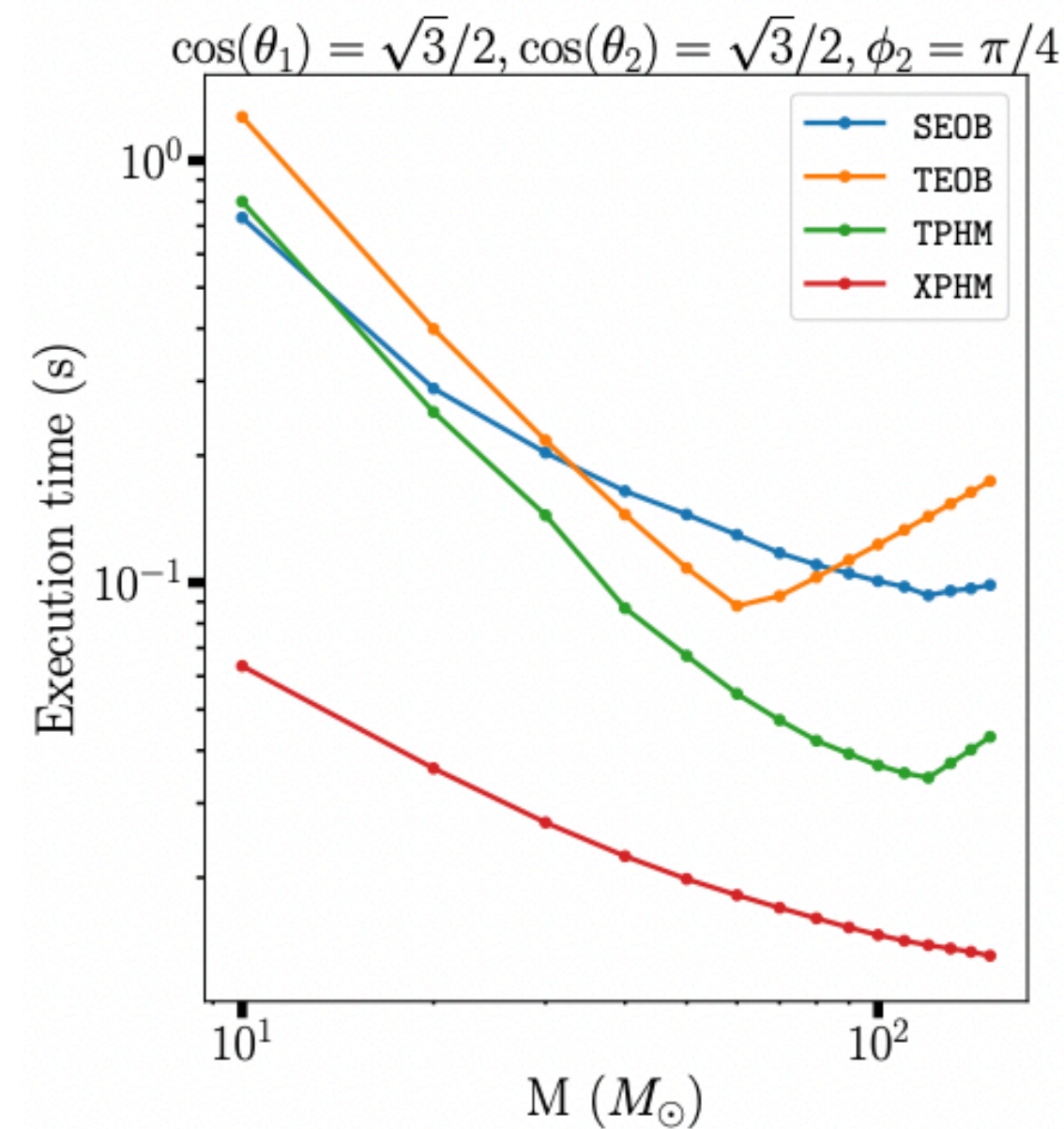
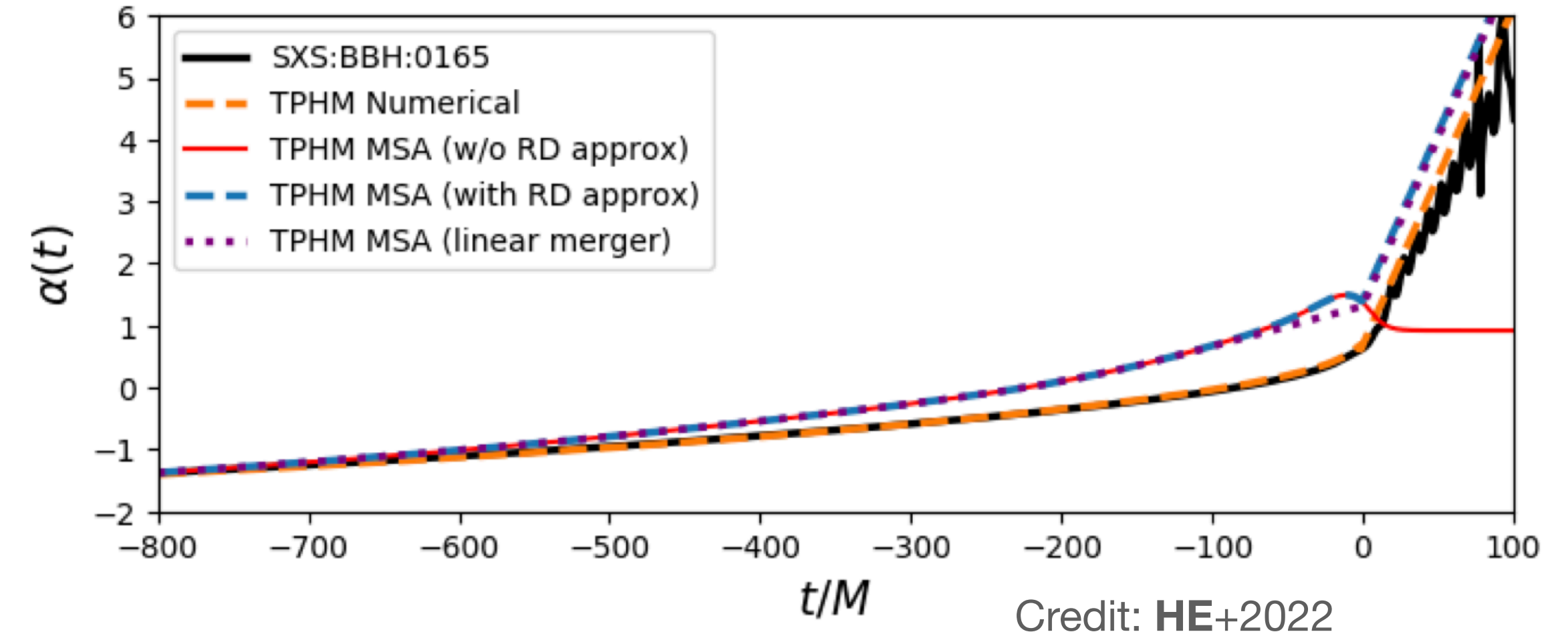
$$h_+(t) - ih_\times(t) = e^{i\alpha(t)} \sum_{\ell m} A_{\ell m}(t) e^{im\phi_{\ell m}(t)} {}_{-2}Y_{\ell m}[\beta(t), \gamma(t)]$$

- **IMRPhenomTPHM** [HE+, PRD 105, 084040 (2022)]:

- Numerical evolution of spin-precession (more accurate than closed-form expressions, allowed the development of XPHM-SpinTaylor)
- Improved merger-ringdown description of spin-precessing systems.
- Fastest state-of-the-art time-domain model.

Recent improvements and extensions:

- **IMRPhenomT(P)HM_20** [Rosselló+, PRD 110, 084074 (2024); Rosselló&Husa arXiv:2506.08888 (2025)]: inclusion of non-linear displacement memory and (2,0,0) QNM excitation.
- **IMRPhenomTEHM** [Planas+(incl. HE), arXiv:2503.13062 (2025)]: Model for systems in mild eccentric orbits.
- New efficient implementation in **phenomxpy** [García-Quirós+2025] with GPU support: employed for MBHB signals in LISA DDPC Mojito data challenge.



Modeling eccentric systems: IMRPhenomTEHM

IMRPhenomTEHM [Planas+(incl. HE), arXiv:2503.13062 (2025)]:
Adding eccentric correction to IMRPhenomTHM (aligned-spin systems)

Orbital motion evolved with secular equations with eccentric corrections at 3PN:

- Quasi-circular limit from IMRPhenomTHM, calibrated to NR simulations

$$\dot{\Omega}(\Omega, e) = \dot{\Omega}^{\text{THM}}(\Omega) + \dot{\Omega}_{e \neq 0}^{3\text{PN}}(\Omega, e),$$

$$\dot{e}(\Omega, e) = \dot{e}^{3\text{PN}}(\Omega, e),$$

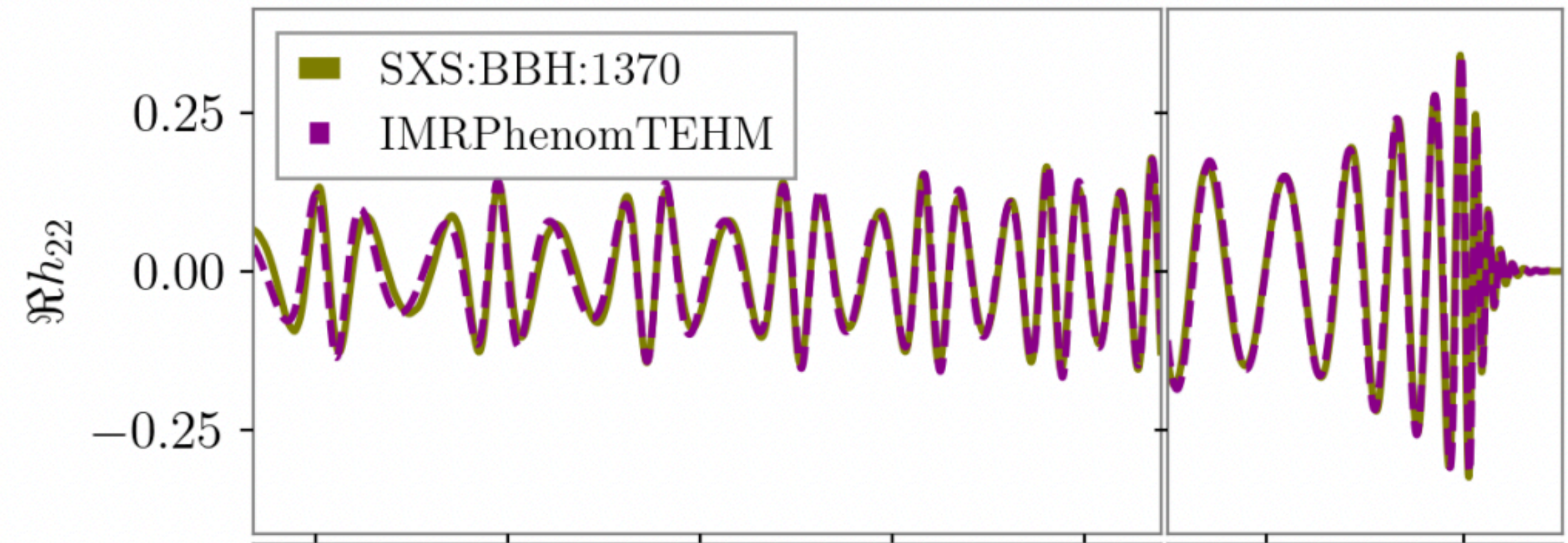
$$\dot{l}(\Omega, e) = \dot{l}^{3\text{PN}}(\Omega, e)$$

Eccentric corrections in waveform modes at 3PN non-spinning [Ebersold+2019] and 2PN spinning [Henry&Khalil 2023] (expanded to e^6):

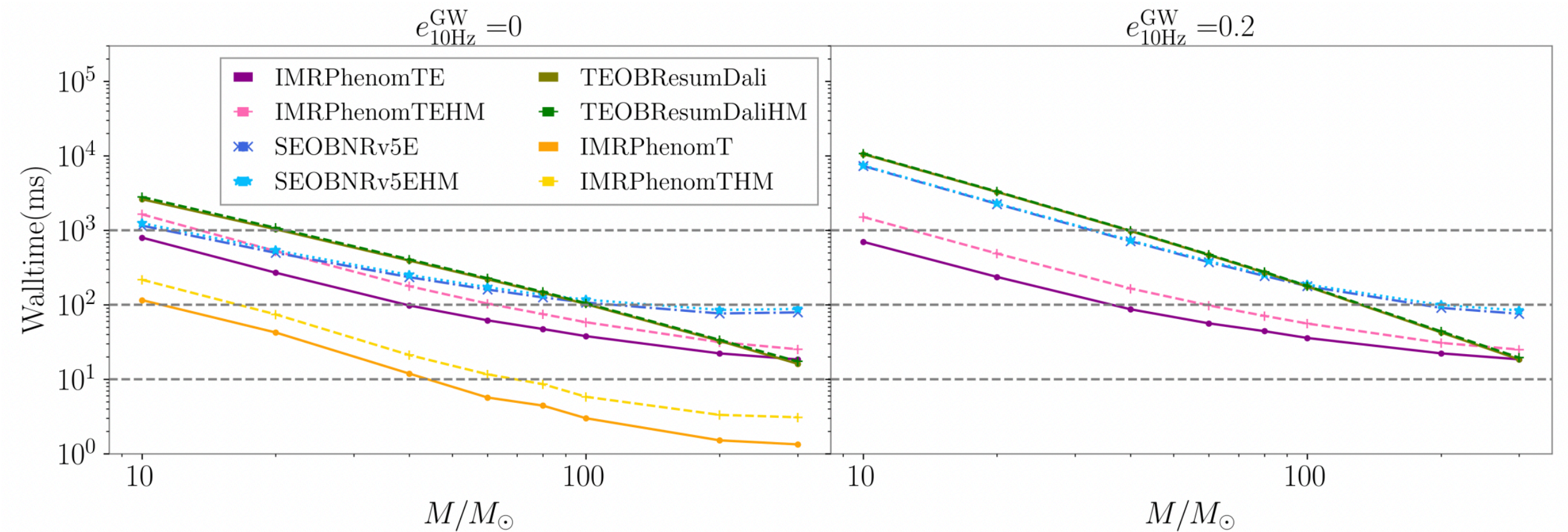
$$h_{lm}^{\text{TEHM}} = \left(\tilde{h}_{lm}^{\text{THM}} + \frac{8GM\eta}{c^2 R} \sqrt{\frac{\pi}{5}} [x H^{lm}(x, e, l) - x^{e=0} H_{e=0}^{lm}(x^{e=0})] e^{-im\lambda} \right) e^{-imW(l)}$$

Accurate for mild eccentricities

Most efficient eccentric IMR waveform model.



From Planas+2025a



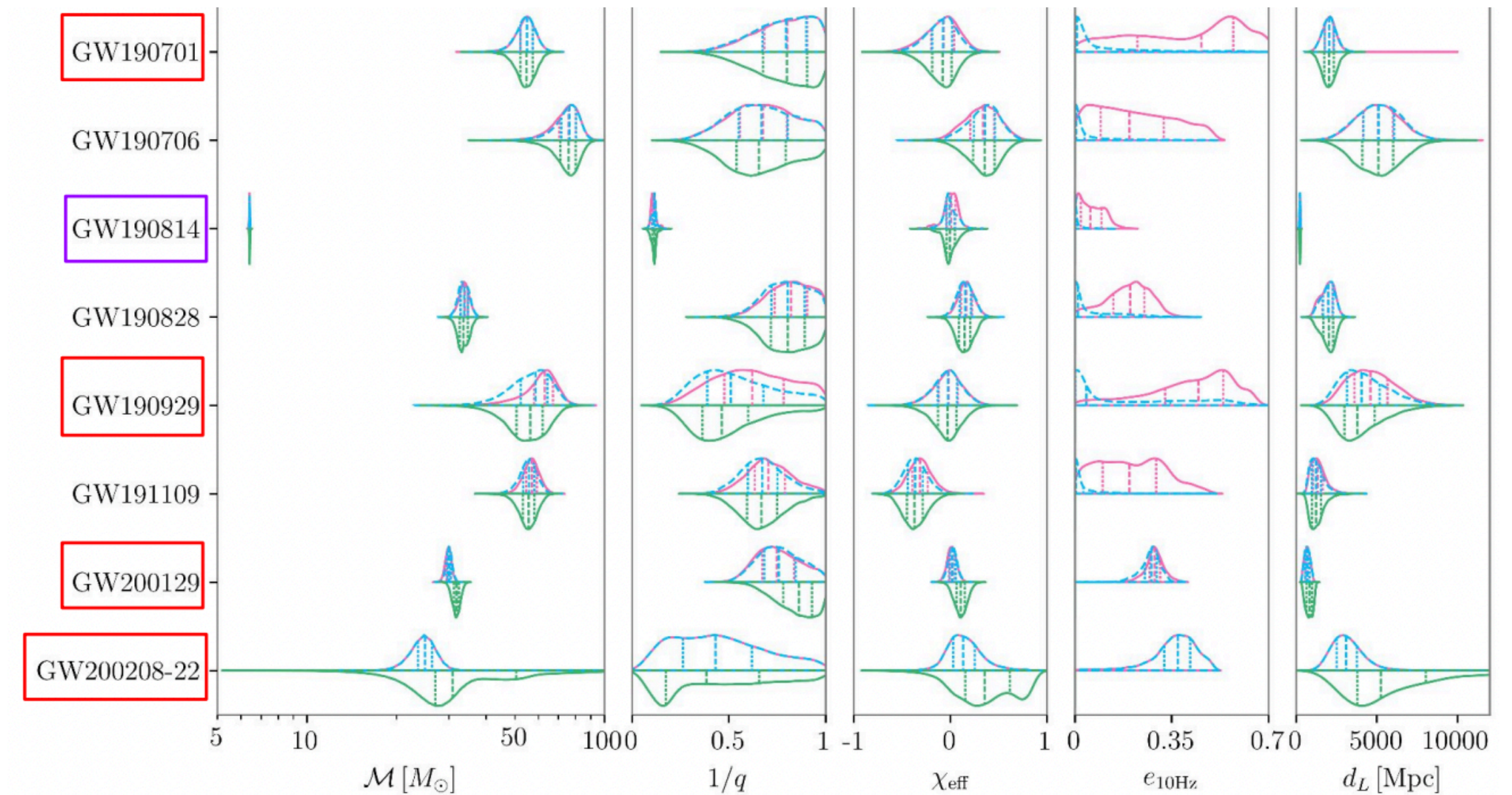
From Planas+2025a

Modeling eccentric systems: IMRPhenomTEHM

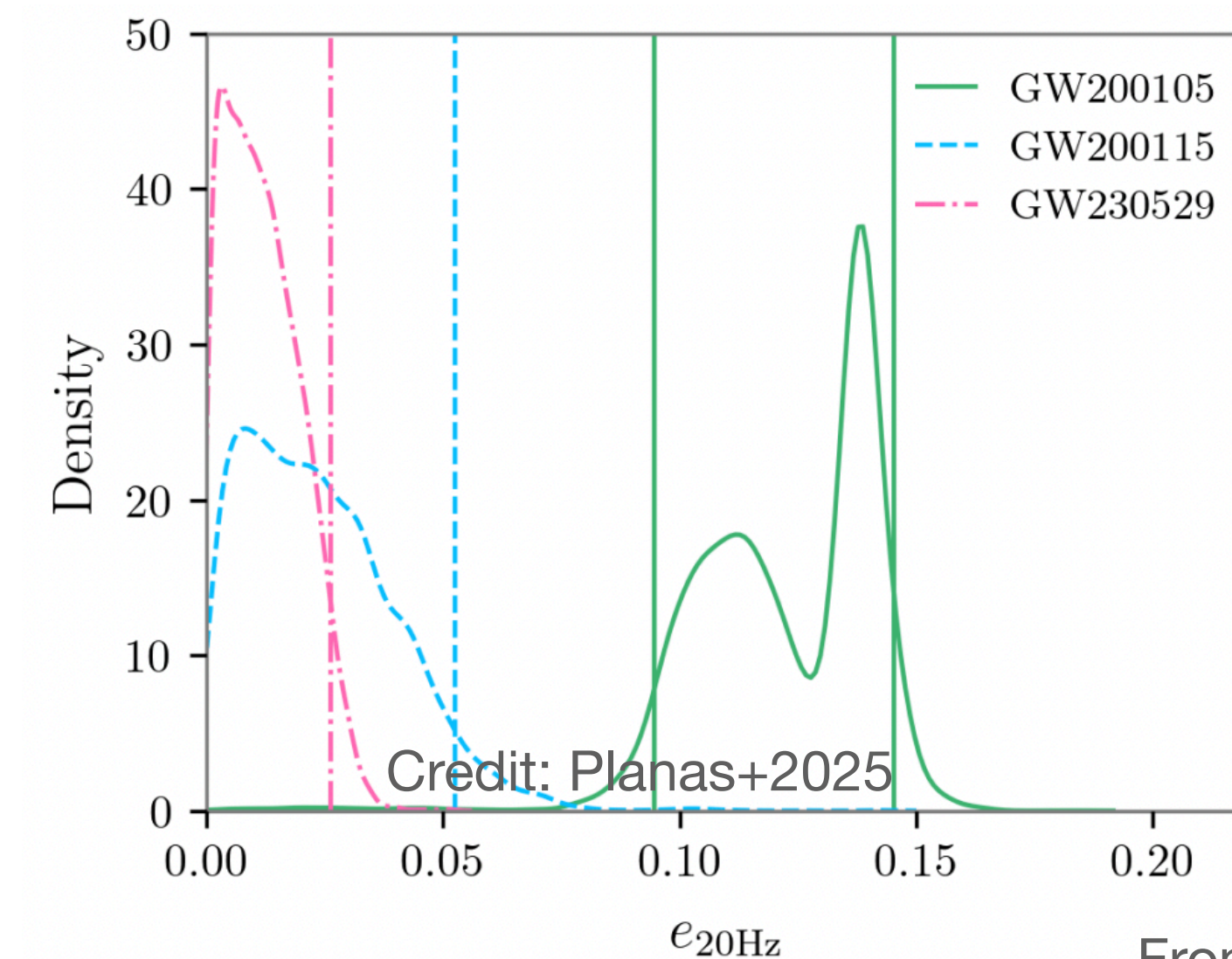
Eccentric re-analysis of GWTC-3 [Planas+(incl. HE), arXiv:2504.15833 (2025)]:

- BBH results consistent with [Gupta+2024], find 3 classes of events:
 - Compatibles with quasi-circular binaries (railing against $e=0$).
 - (GW190701, GW190929): PE prefers eccentricity, but high mass, short waveform, ... -> no claim of eccentric binary
 - GW200208_22: Low SNR, Uniform prior supports eccentricity, LogUniform lower support... No strong evidence.
- GW200129: eccentricity is strongly preferred over precession claim
 - Bayes factors vs QC (log10): 1.3-4.0, vs NRSur: 0.13-1.87
 - Eccentricity robustly favored for different glitch subtractions.

Evidence for eccentricity in NSBH event GW200105 [Planas+, arXiv:2506.01760 (2025)] (confirming [Morras+2025])



From Planas+2025b



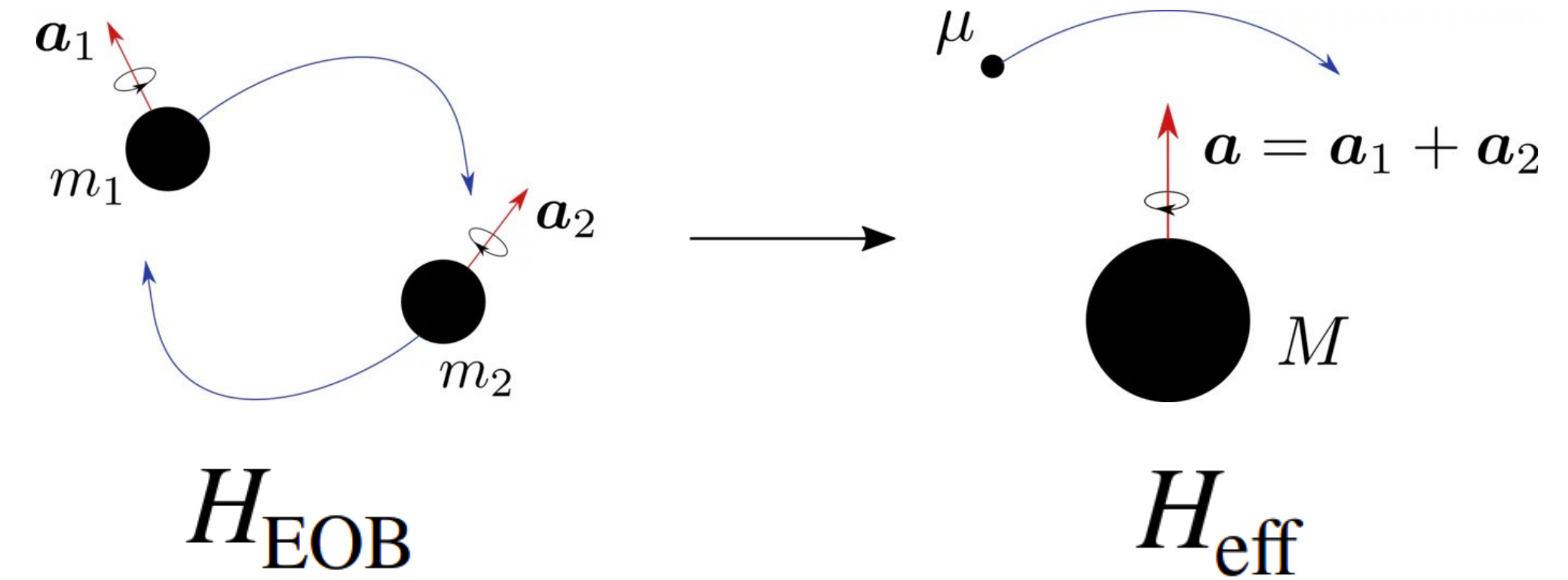
From Planas+2025c

Effective-One-Body (EOB)

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

Main ingredients of EOB waveforms:

1. **EOB Hamiltonian** describing the conservative binary dynamics
2. **Radiation reaction (RR) force** to account for loss of energy and angular momentum via emission of GWs
3. **Gravitational waveform modes** for inspiral, merger, and ringdown



Credit: Lorenzo Pompili

EOB Hamiltonian

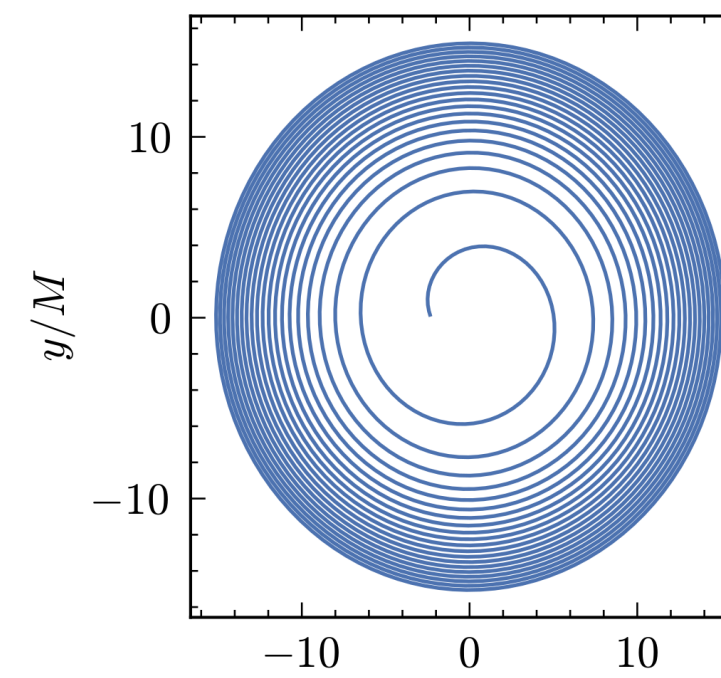
$$H^{\text{EOB}} = M \sqrt{1 + 2\nu \left(\frac{H_{\text{eff}}}{\mu} \right)}$$

Equations of motion
(ODE)

$$\begin{aligned} \dot{\vec{r}} &= \frac{\partial H^{\text{EOB}}}{\partial \vec{p}} \\ \dot{\vec{p}} &= -\frac{\partial H^{\text{EOB}}}{\partial \vec{r}} + \vec{\mathcal{F}} \end{aligned}$$

Orbital dynamics

$$\Rightarrow \vec{r}, \vec{p} \Rightarrow$$



Waveform modes

$$h_{\ell m}^{\text{insp-plunge}} = h_{\ell m}^{\text{Newt}} S_{\text{eff}} T_{\ell m} f_{\ell m} e^{i\delta_{\ell m}} h_{\ell m}^{\text{NQC}}$$

$$h_{\ell m}^{\text{merg-RD}} \tilde{A}_{\ell m} e^{i\tilde{\phi}_{\ell m}} e^{-i\sigma_{\ell m 0}(t-t_{\text{peak}}^{22})}$$

$$h_{\ell m} = \begin{cases} h_{\ell m}^{\text{insp-plunge}}, & t < t_{\text{peak}}^{22}, \\ h_{\ell m}^{\text{merg-RD}}, & t > t_{\text{peak}}^{22}. \end{cases}$$

Radiation-reaction force

$$\mathcal{F} = \frac{\Omega}{16\pi} \frac{p}{L} \sum_{\ell, m} m^2 |h_{\ell m}|^2$$

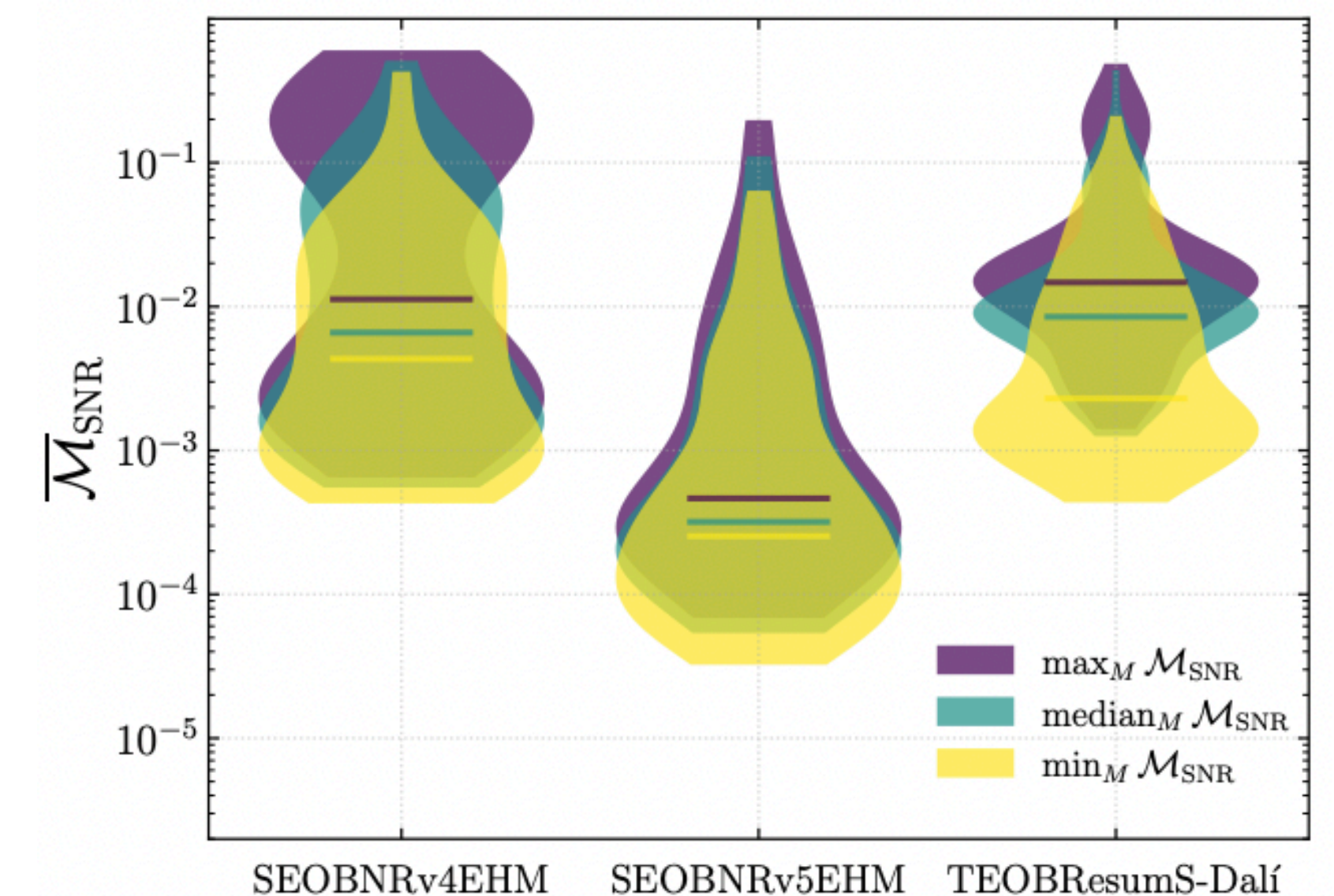
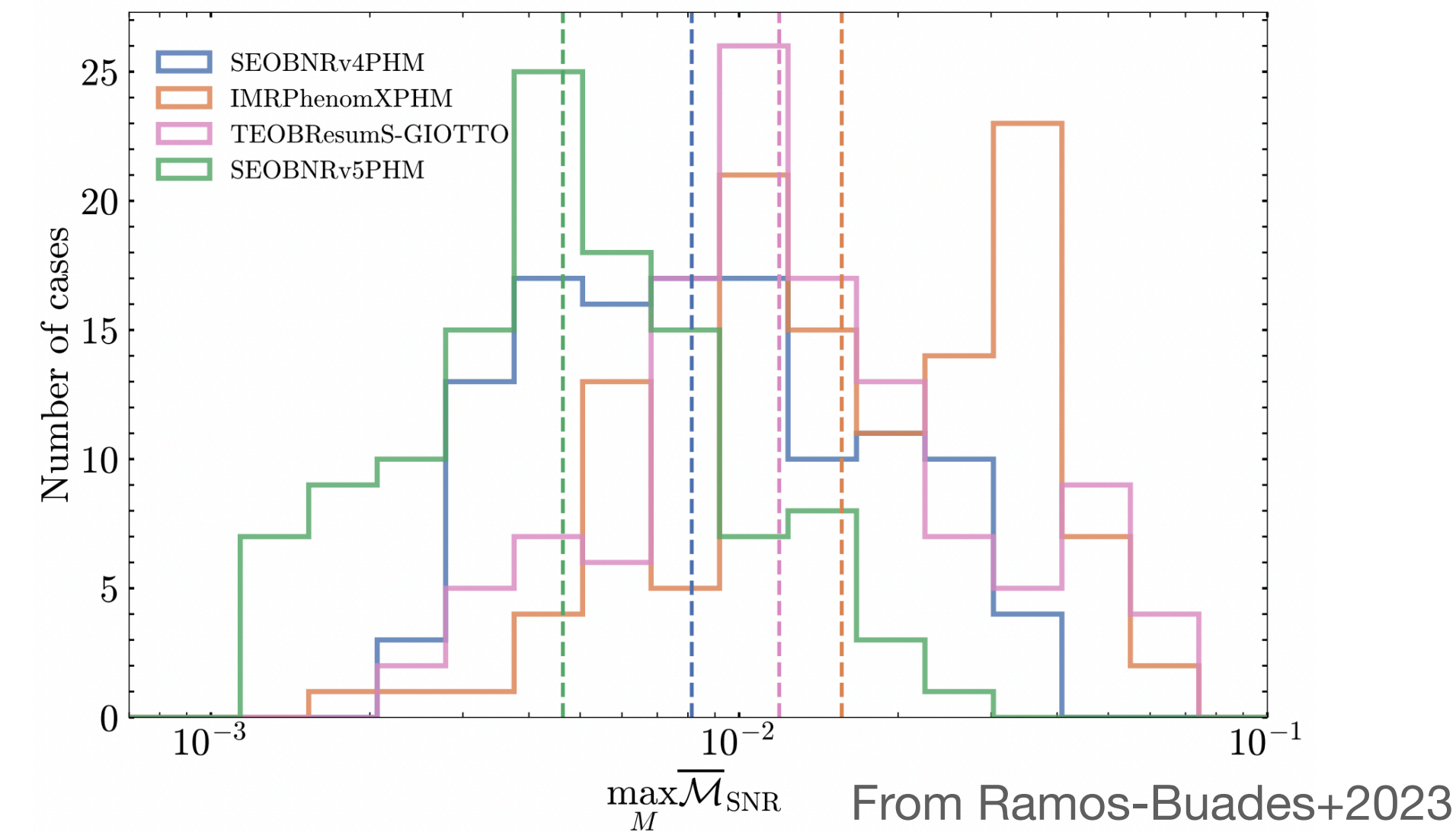
Effective-One-Body (EOB)

SEOBNRv5PHM: Latest generation of SEOBNR models for quasi-circular systems

- Updated PN information in the fluxes, waveform modes and Hamiltonian [Khalil+(incl. HE), PRD 108, 124036 (2023)]
- Inclusion of 2nd-order self-force results in the waveform modes [van de Meent+, PRD 108, 124038 (2023)]
- Fast spin evolution using Taylor-expanded PN equations (as in IMRPhenomTPHM) [Ramos-Buades+(incl. HE), PRD 108, 124037 (2023)]
- Efficient python implementation [Mihaylov+(incl. HE), Soft.X 30, 102080 (2025)]
- Inclusion of calibrated equatorial-asymmetric effects in the waveform modes [HE+, arXiv:2506.19911 (2025)]

SEOBNRv5EHM: Highly accurate aligned-spin model for systems on eccentric orbits [Gamboa+(incl. HE), PRD 112, 044038 (2025)]

- Eccentric effects up to 3PN in radiation-reaction and waveform modes
- High accuracy against eccentric NR simulations (despite lack of calibration)



From Gamboa+2025

Adding equatorial-asymmetric effects in SEOBNRv5PHM

Equatorial symmetry broken for spin-precessing systems [Boyle+2014]

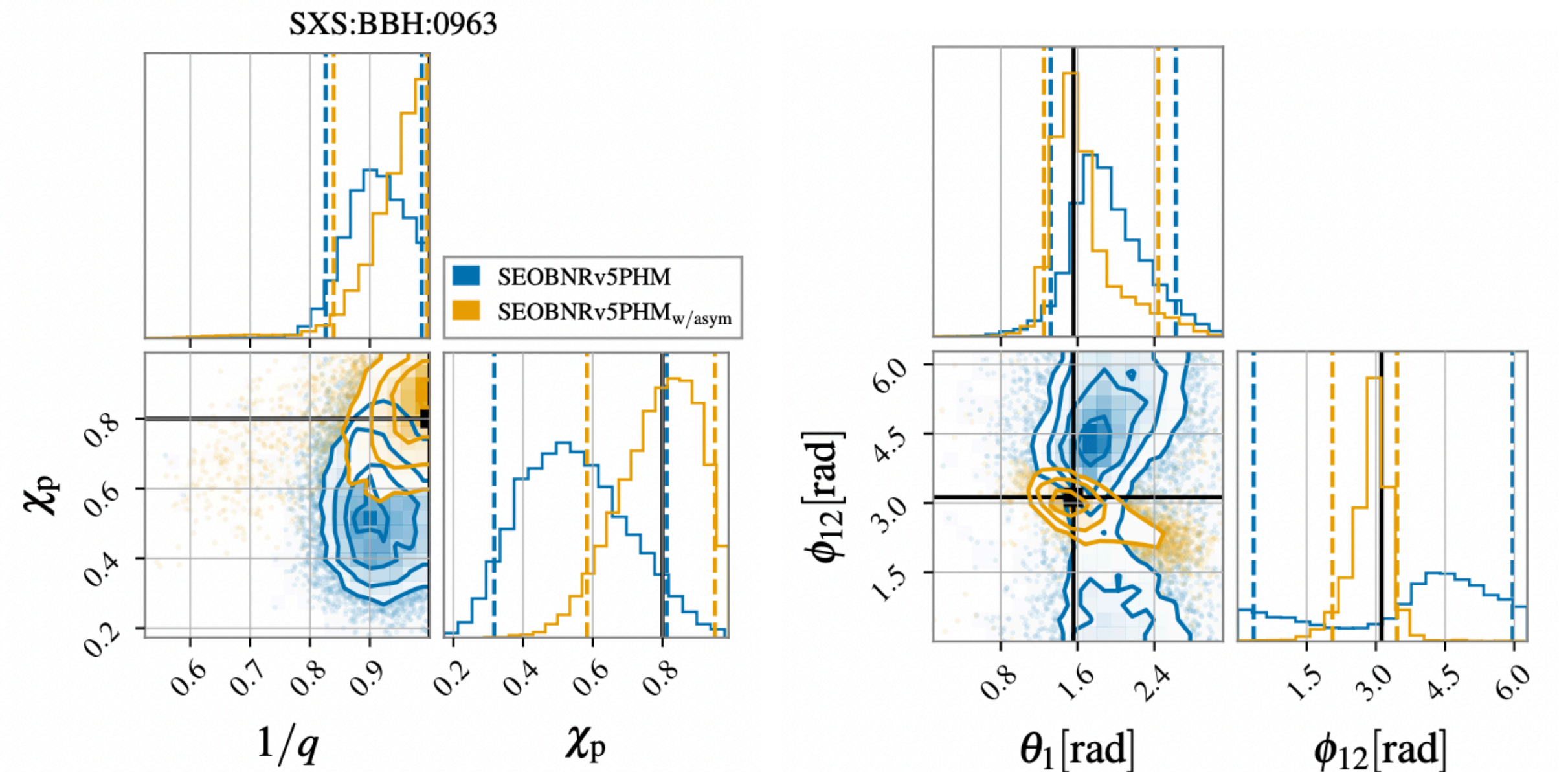
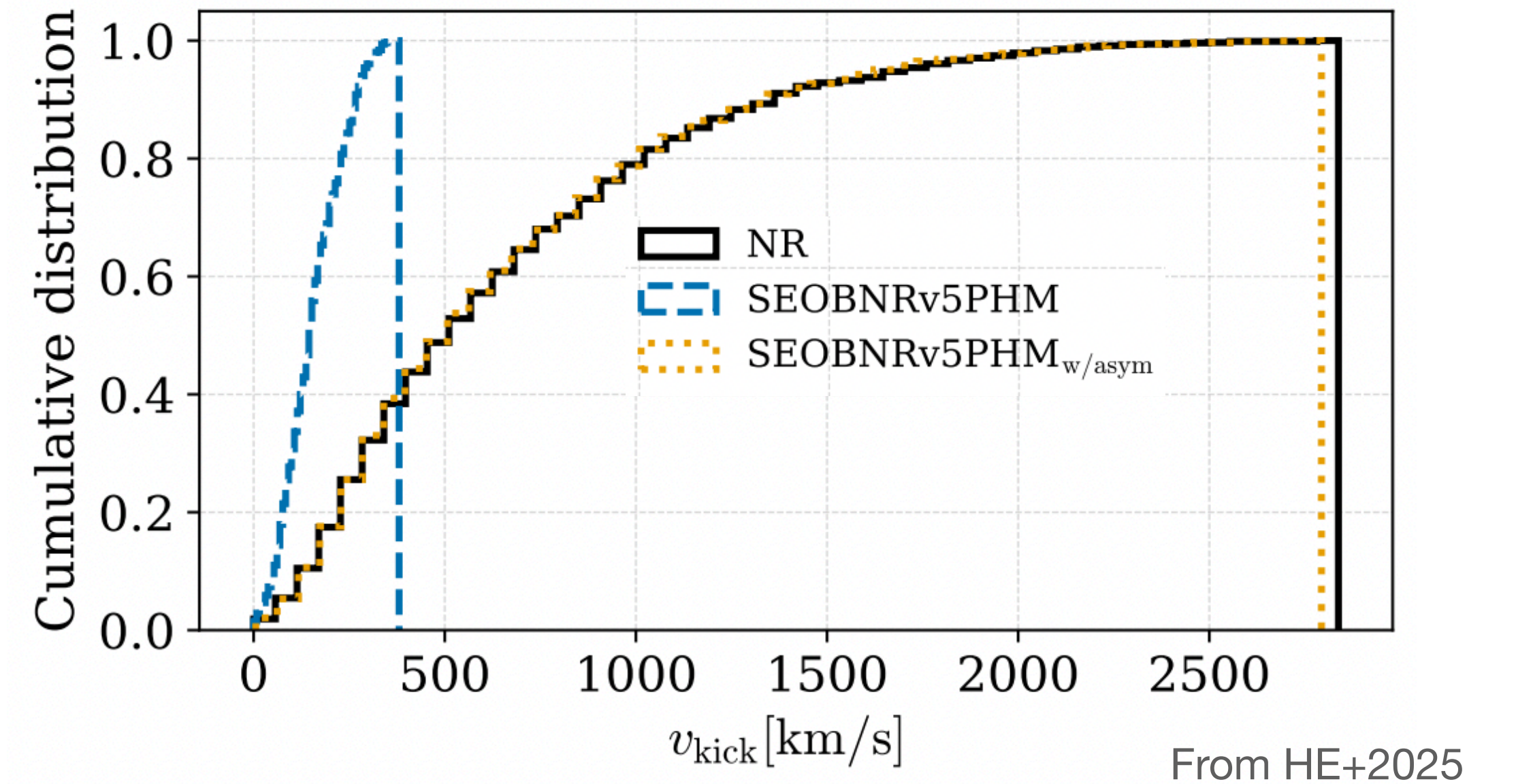
Antisymmetric contribution: asymmetry between positive and negative m-modes in the co-precessing frame.

$$h_{lm}^{\text{asymm}} = \frac{h_{l,+m}^{\text{cop}} - (-1)^l h_{l,-m}^{\text{cop}}}{2}$$

We recently included [HE+, arXiv:2506.19911 (2025)] this contribution in SEOBNRv5PHM for the $\ell = m$ harmonics:

- **Calibrated** with ~1500 spin-precessing NR simulations and ~3000 Teukolsky geodesic waveforms
- **50% improvement of model accuracy** for face-on systems.
- **Crucial to explain high recoil velocities:** good agreement with NR distribution.
- **Reduction of inference biases** in spin and mass parameters.

It will be employed for next catalog version GWTC-5.0



Modeling the BBH signal space

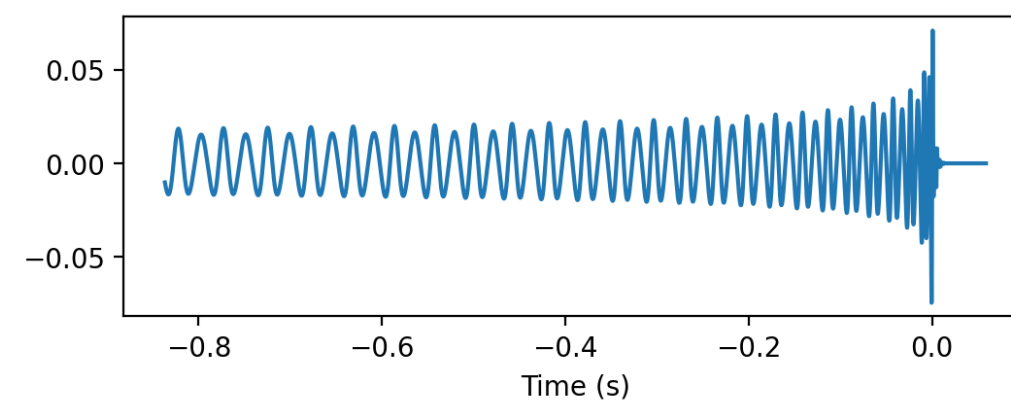
Spin-precessing

Quasi-circular orbits

Spin-aligned

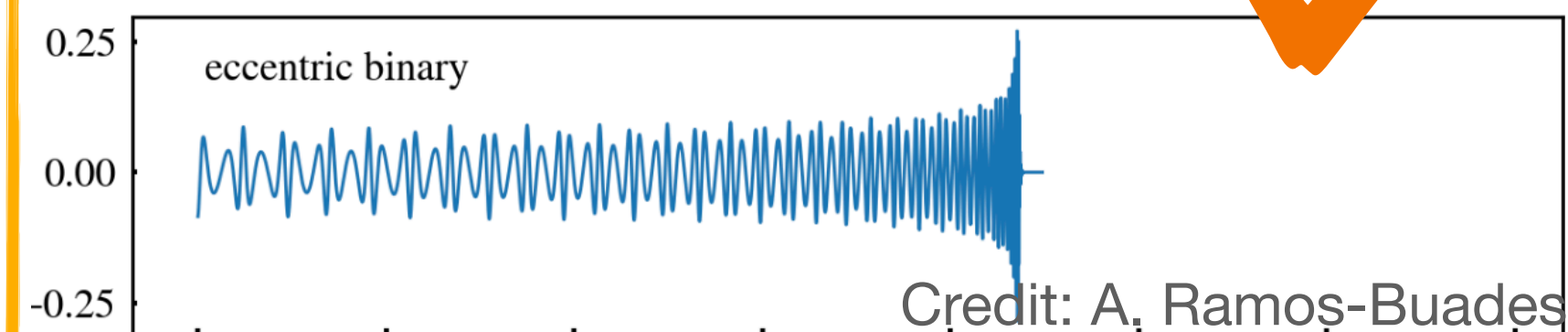
Well-established models:

HMs, full calibration to NR and TPL, accurate orbital evolution, systematics bw models only in corners of parameter space



Recently developed:

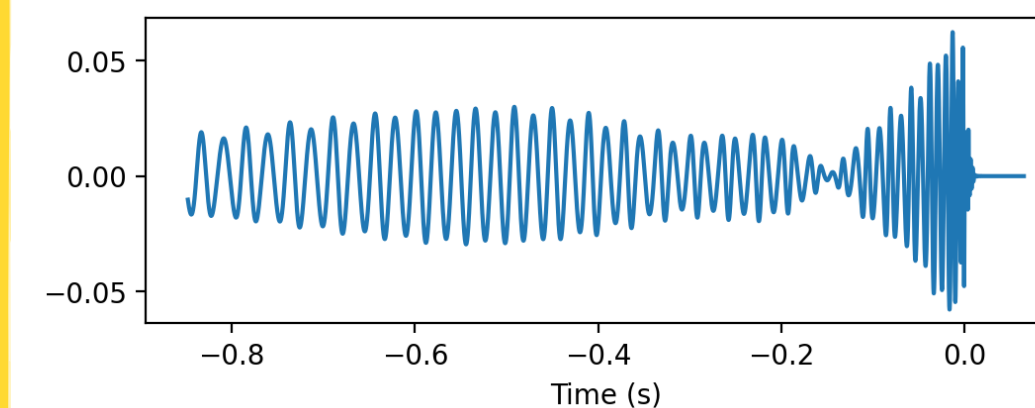
Valid up to moderate eccentricities, HMs included, **assume quasi-circular final state, lack of calibration with eccentric NR, unknown systematics**



Eccentric orbits

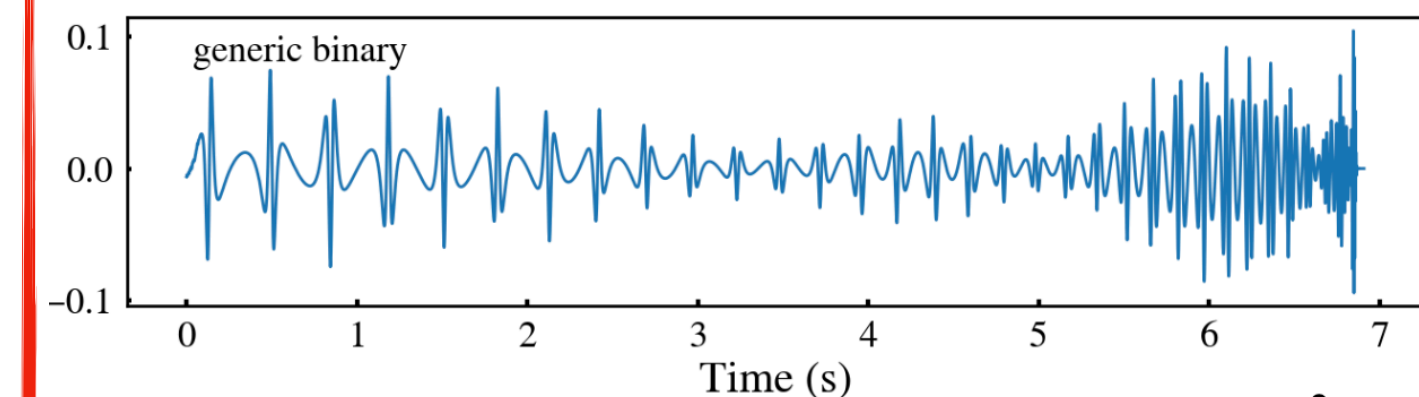
Mature models:

Accurate inspiral description of spin dynamics, **lack of NR precessing calibration in some models, others with approximations (single-spin), missing physical effects in some models (equatorial asymmetry). Model systematics present even at moderate spins.**



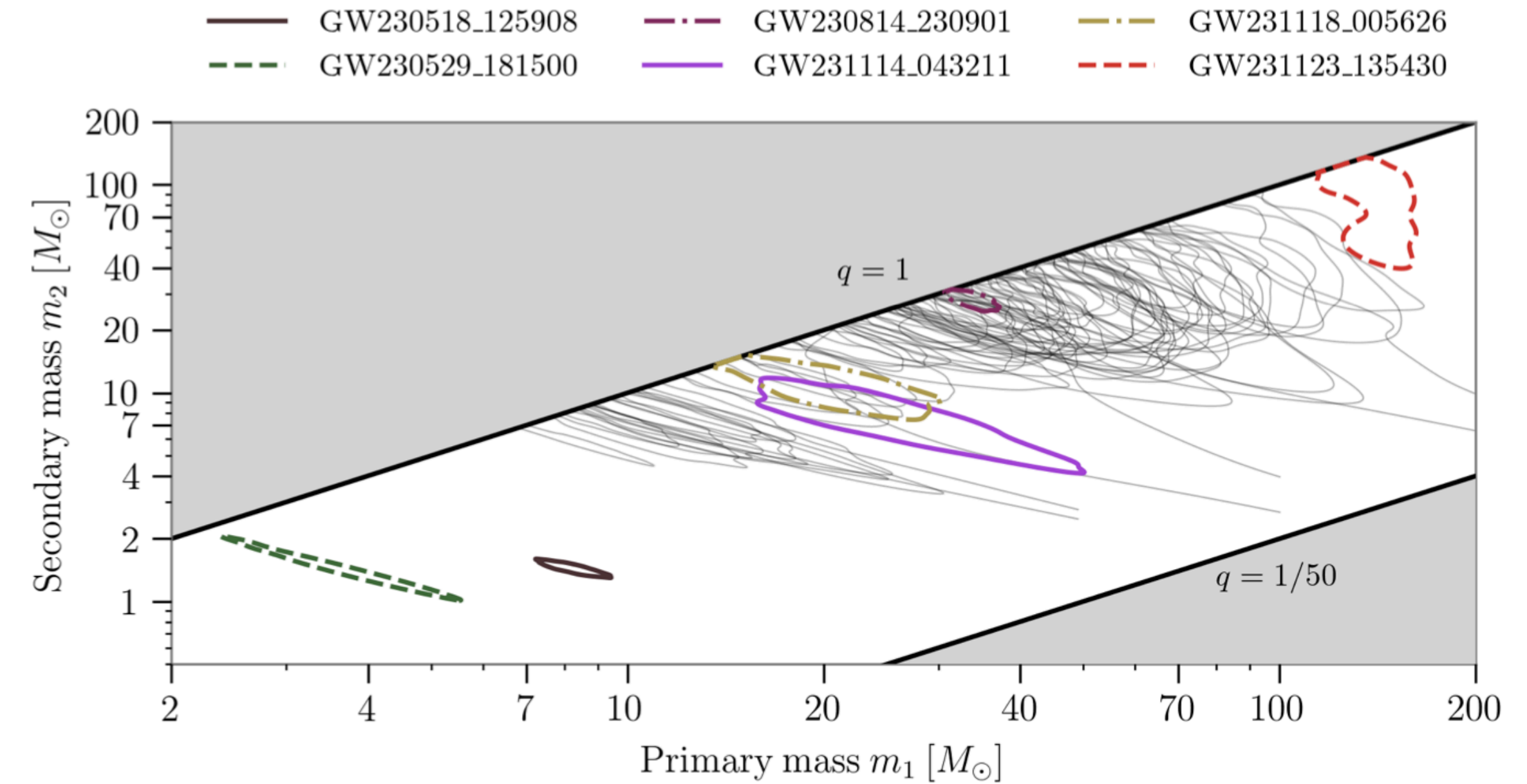
Starting to be investigated:

Initial studies on how to build these models, some proof-concept models presented.

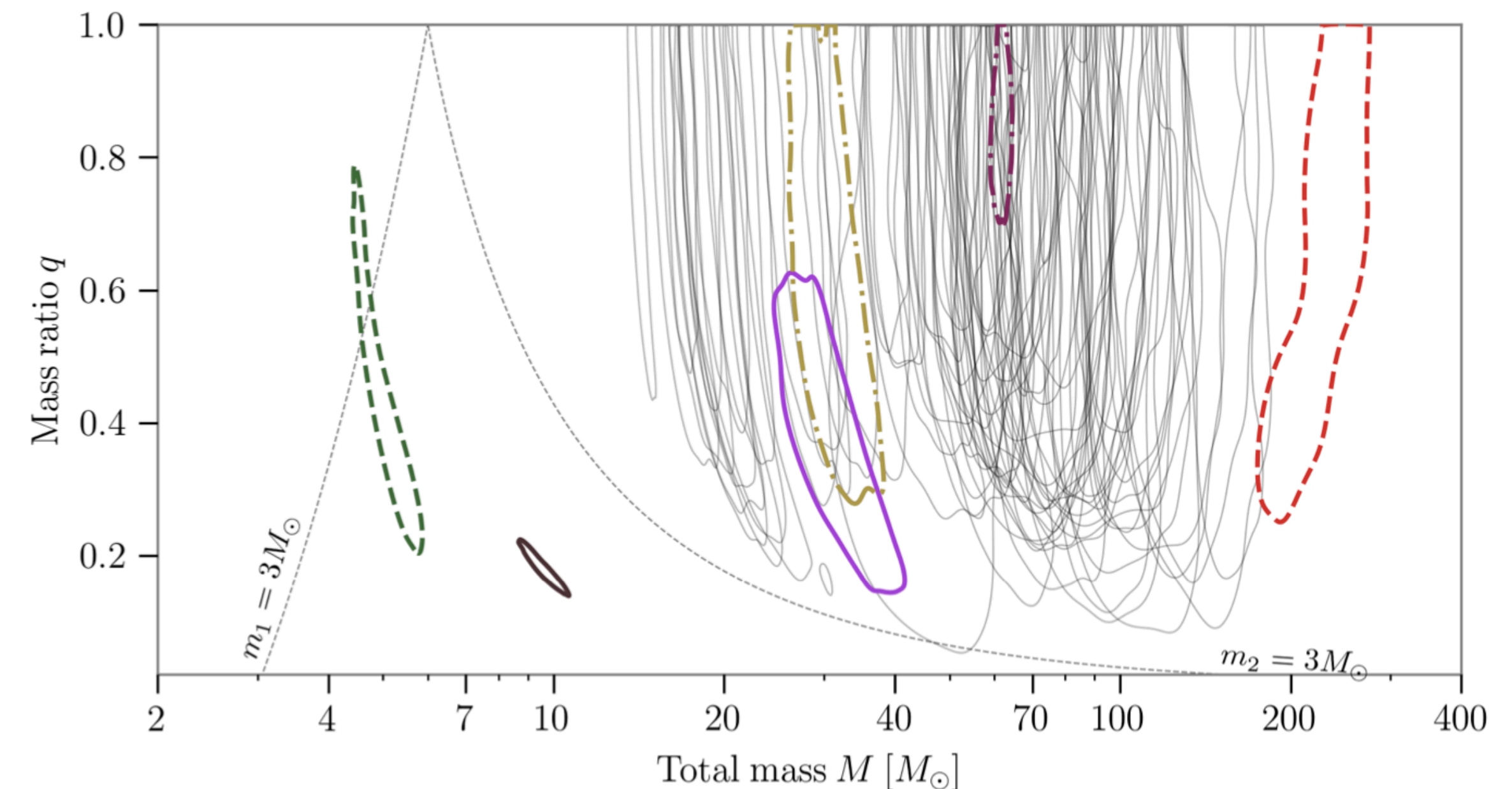


New update of the Gravitational Wave Transient Catalog (GWTC) with signals detected during the O4a observing run (May 23 - Jan 24)

- 128 new candidates with $p_{\text{astro}} > 0.5$
- 86 with full inference of source parameters
- 2 NSBH candidates:
 - GW230518_125908
 - GW230529_181500 ($m_1 < 5M_\odot$ at 99% CL)
- 84 confident BBH candidates
 - Mass range $M \in [14, 238]M_\odot$
 - Highest mass BBH to date: GW231123_135430 ($M = 238^{+28}_{-49}M_\odot$)



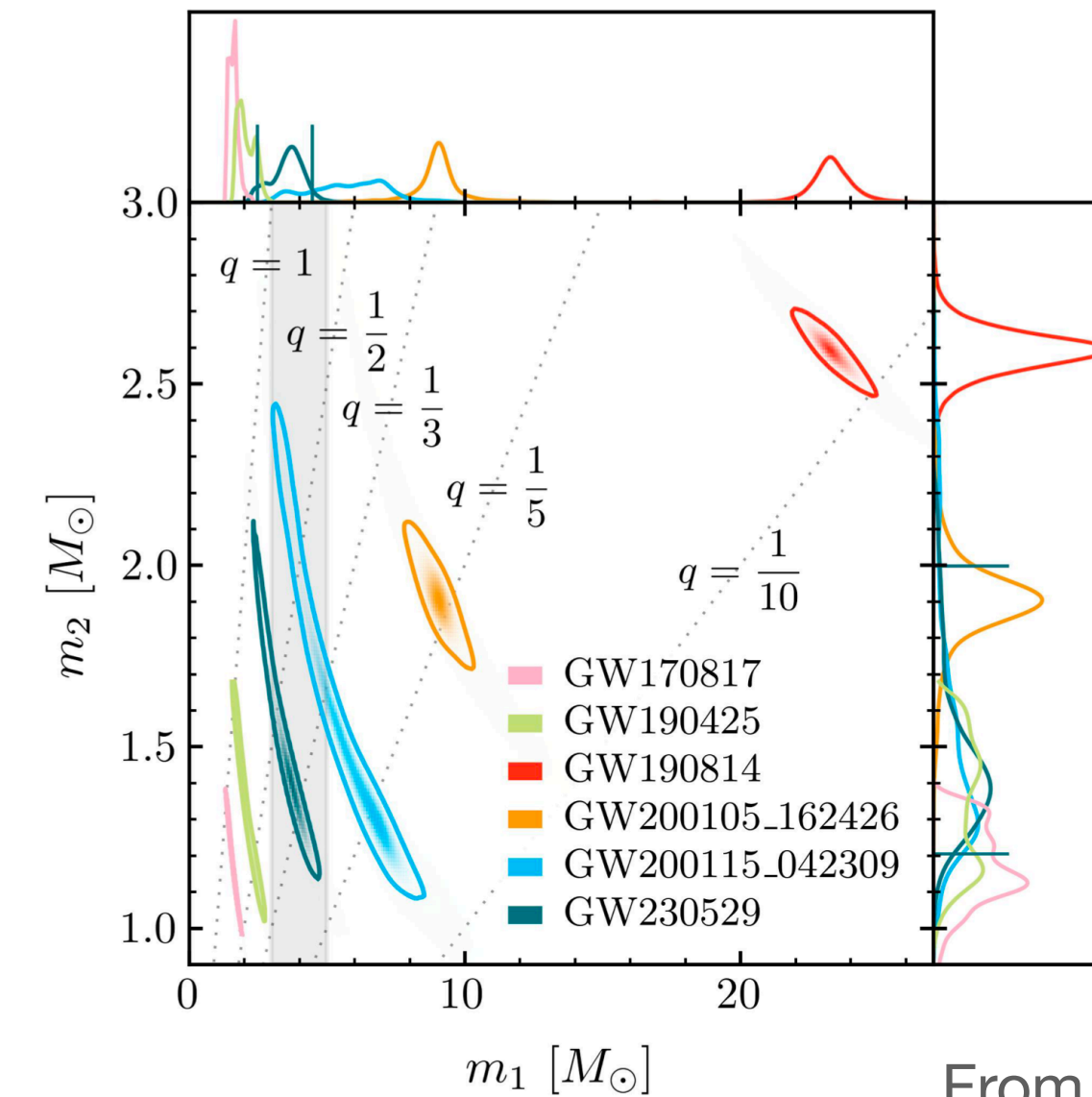
From LVK+2025: GWTC-4.0 Results



Special events from O4: filling the mass gaps

GW230518_125908:

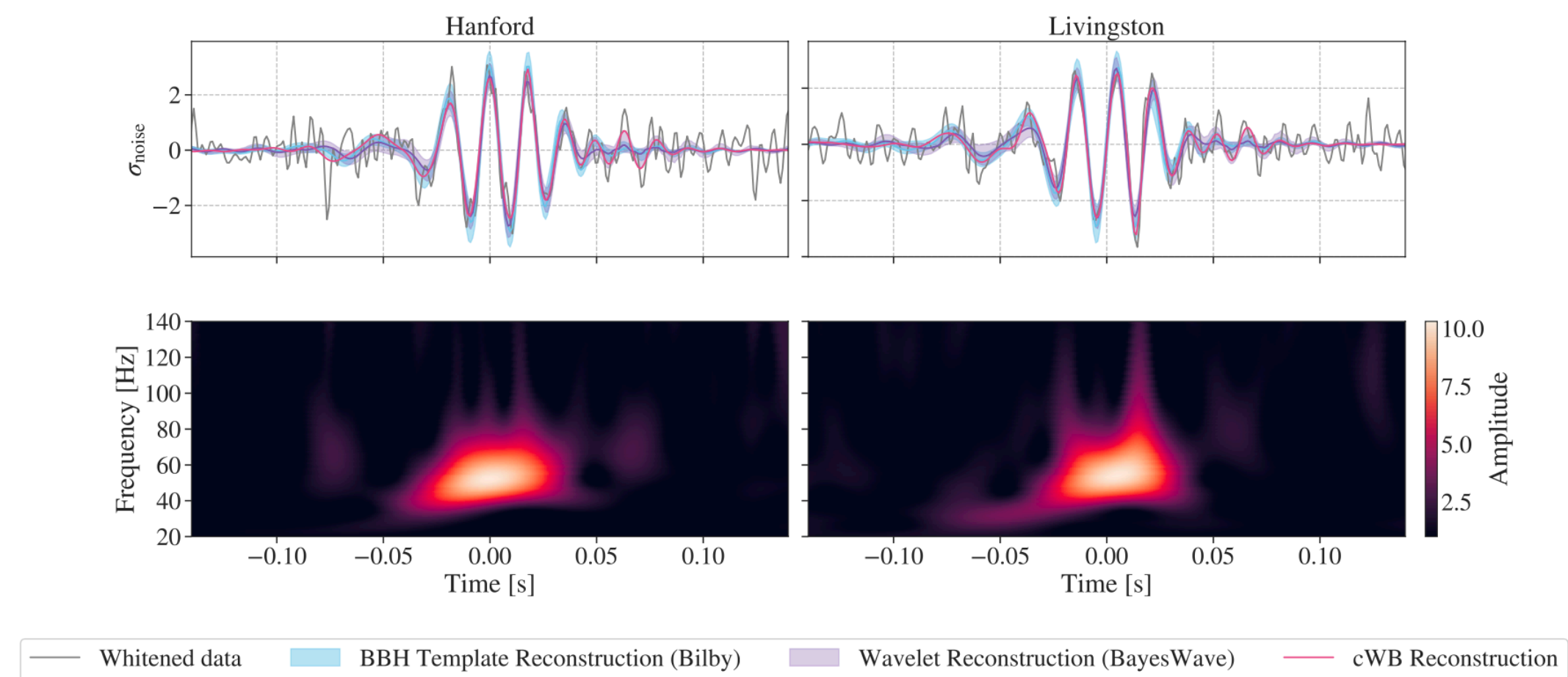
- NSBH with BH in the “low-mass gap” ($m_1 < 5M_\odot$ at 99% CL)
- Comparable masses ($q \sim 0.4$), increased prospects for EM counterpart (but none observed).
- Increased rates of NSBH systems, systems with object in the low-mass gap, and EM bright NSBH systems.



From LVK+2025: GW230529

GW231123_135430:

- Very short signal (≈ 0.1 s, ~ 5 cycles)-> **ringdown dominated** morphology.
- Heaviest BBH to date. Inferred source:
 $m_1 = 137^{+22}_{-17}M_\odot$, $m_2 = 103^{+20}_{-52}M_\odot$, $\chi_1 \approx 0.9$, $\chi_2 \approx 0.8$
- Masses lie in or across the **pair-instability-supernova** (PISN) mass-gap.
- **High component spins** -> herarchical-merger candidate?

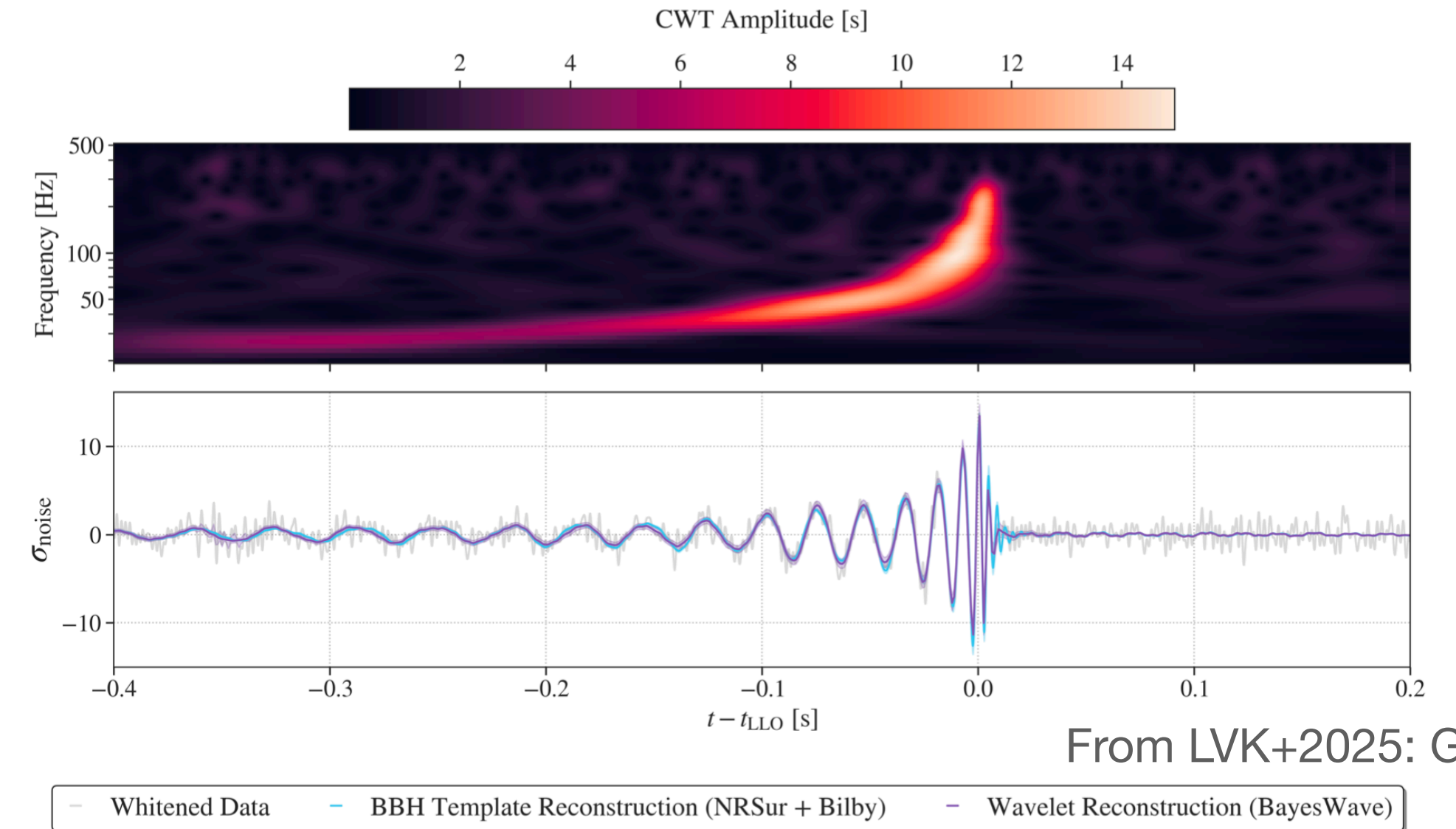


From LVK+2025: GW231123

Special events from O4: testing fundamental physics with loud events

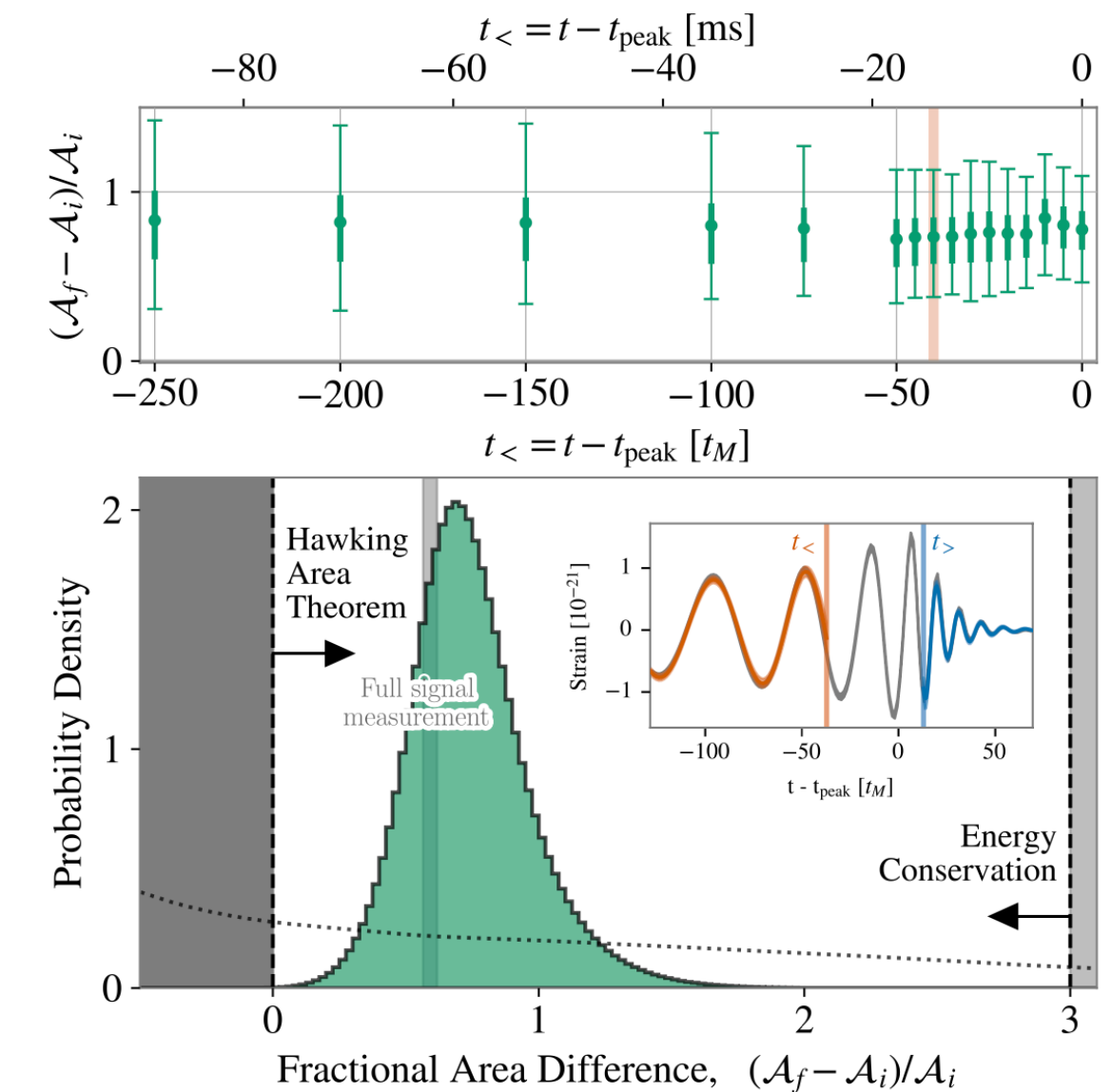
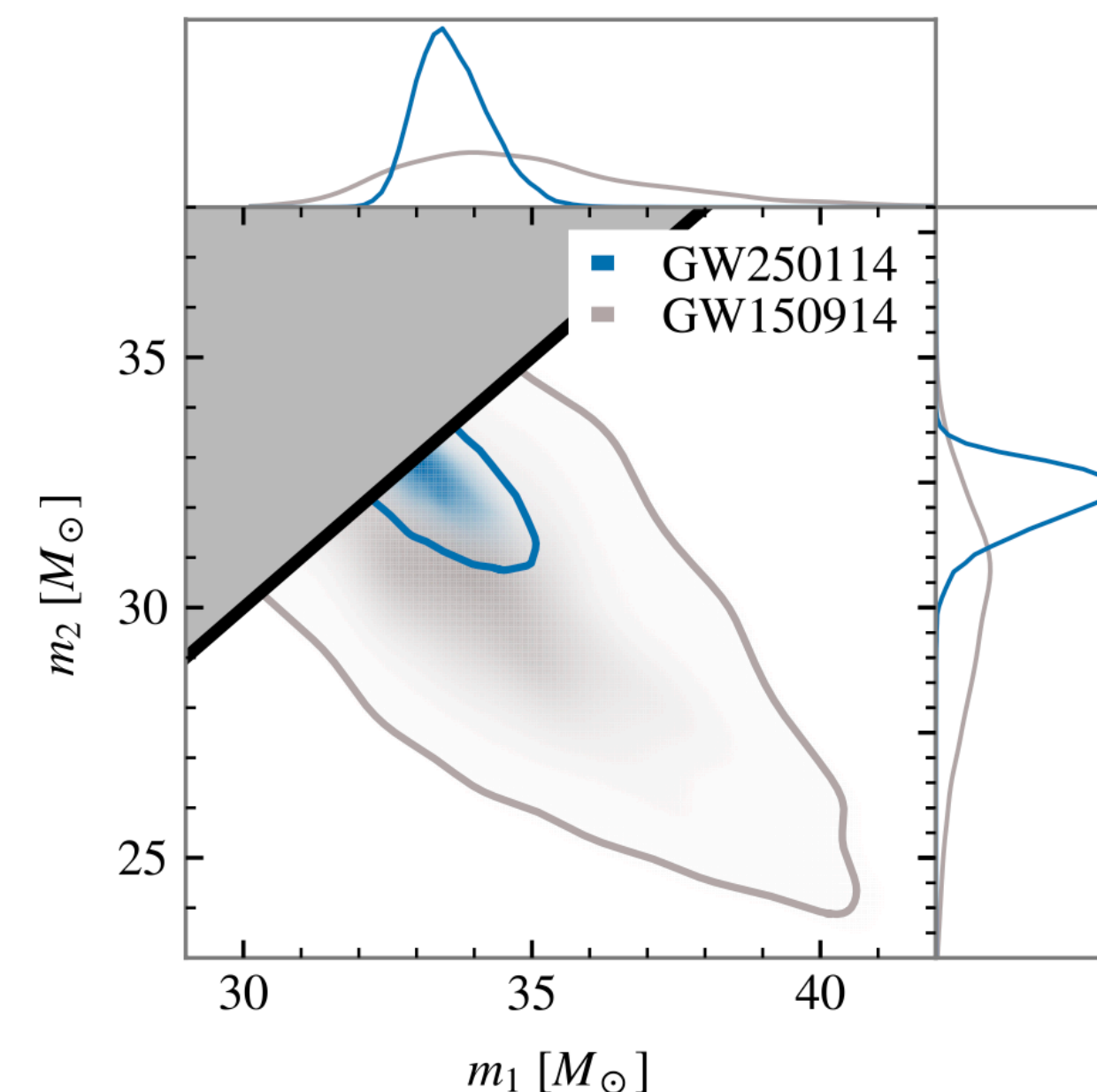
GW230814_23090:

- Highest SNR of O4a: $\rho = 42.13^{+0.07}_{-0.11}$
- Orientation likely edge-on, allowing subdominant mode visibility -> First confident detection of $\ell=4$ harmonic ($\rho_{\ell=4} \approx 3.3$)
- BH spectroscopy with ringdown signal -> mild deviation from GR observed, but attributed to noise and waveform systematics.



GW250114_082203:

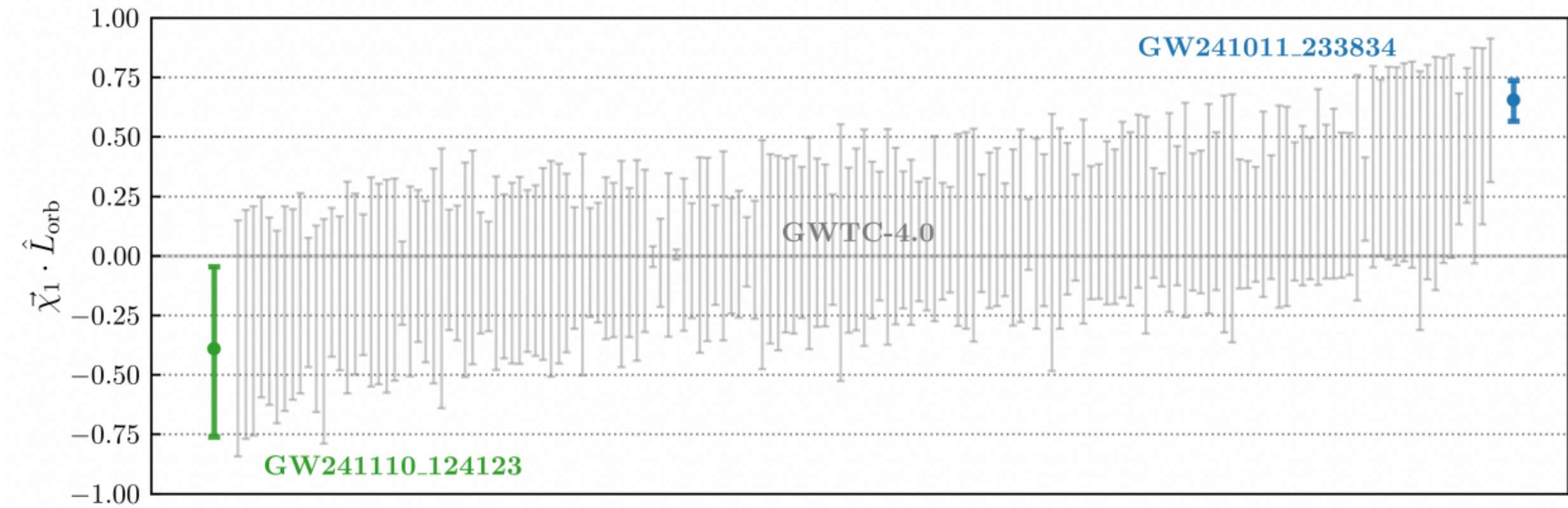
- **SNR:** total ≈ 77 (network); ≈ 53 (LHO), ≈ 60 (LLO) -> Loudest GW signal to date!
- **Source:** near-equal-mass binary $m_1 \approx 34M_{\odot}$, $m_2 \approx 34M_{\odot}$, $\chi_{\text{eff}} \approx 0$. GW150914-like with today's sensitivity!
- Black-hole spectroscopy (detect overtone $n = 1$),
- Test of Hawking's area theorem.



Special events from O4: highly-spinning & asymmetric

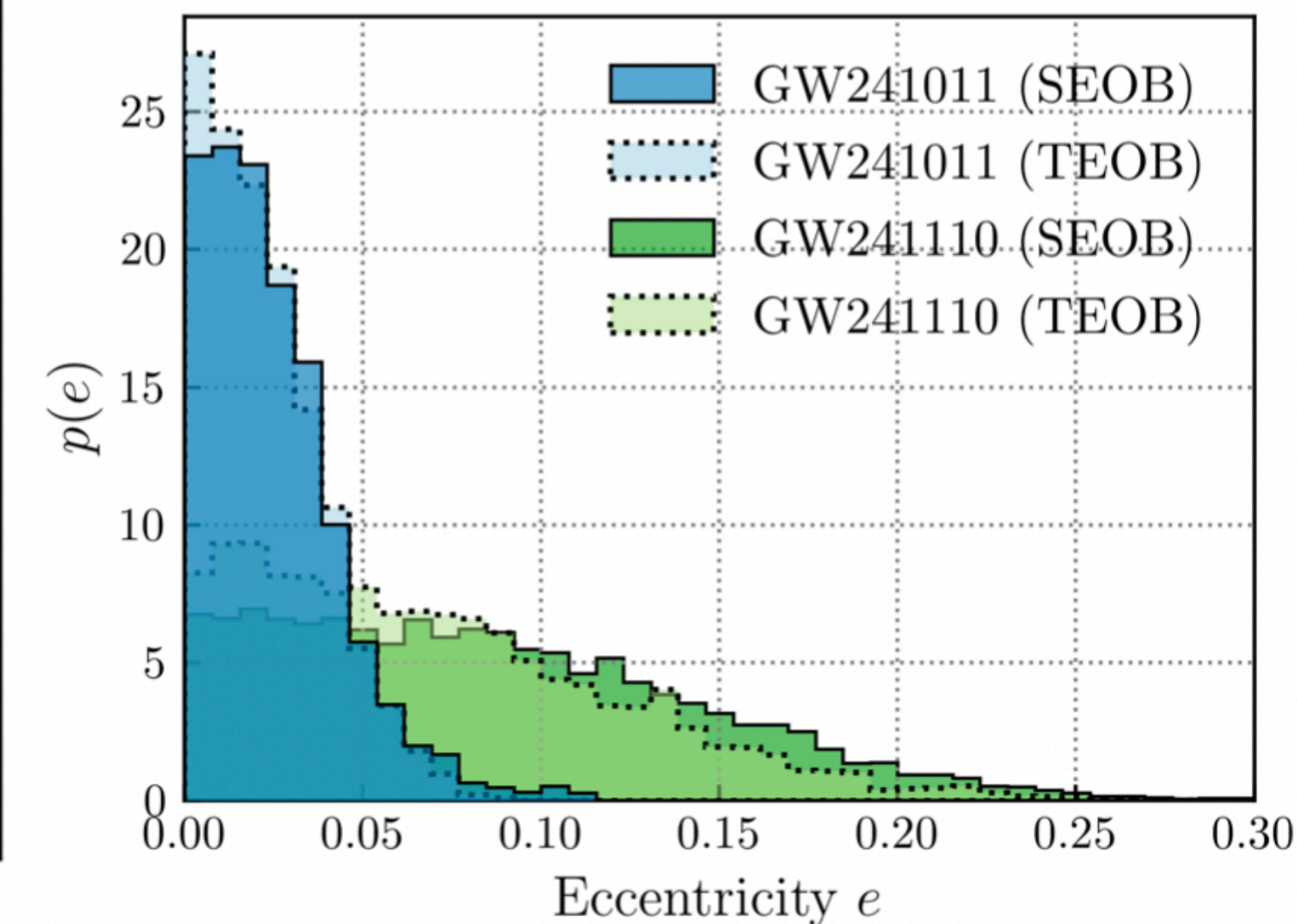
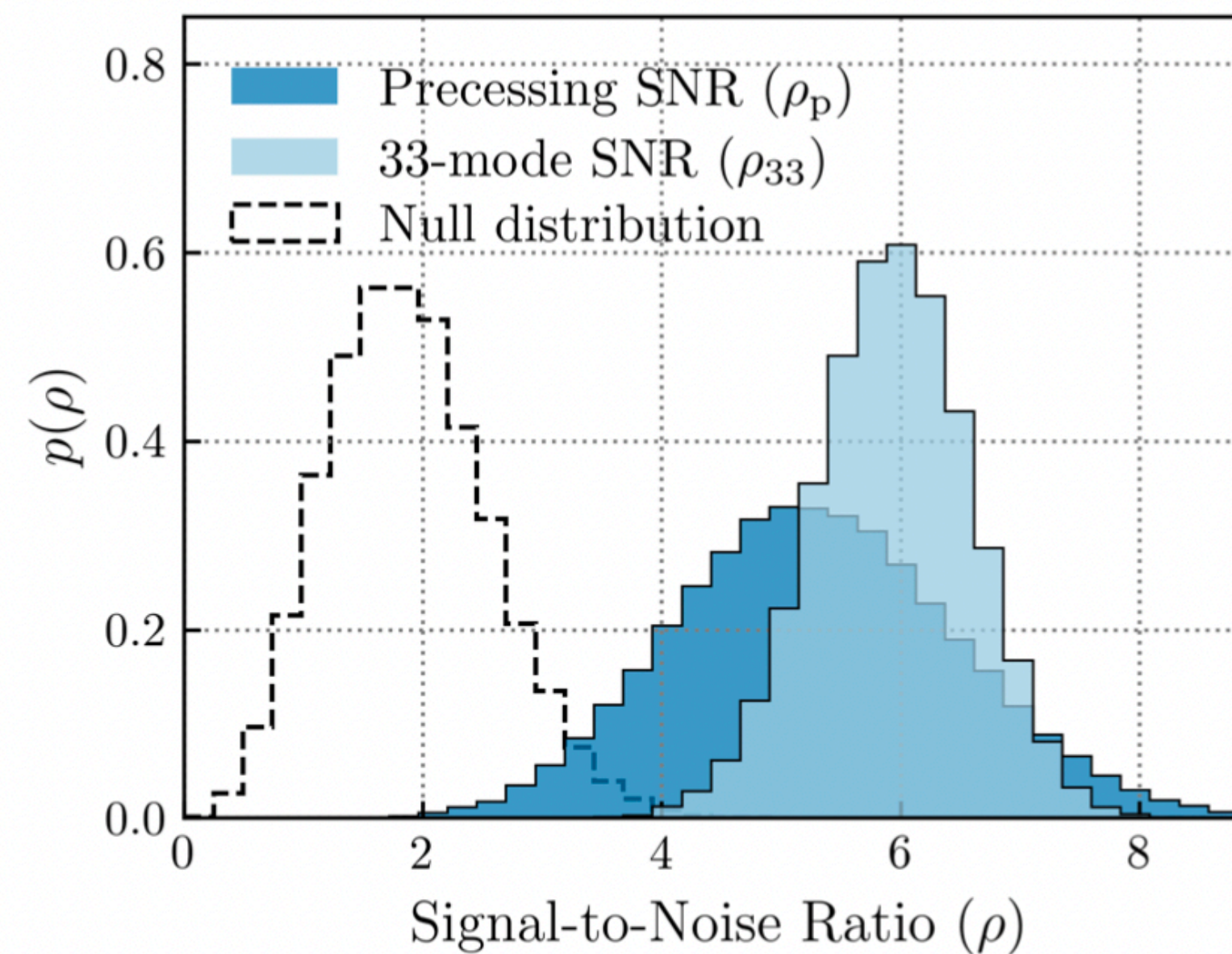
GW241011_233834 &
GW241110_124123:

- Highly spinning, mass asymmetric BBHs. -> Candidate hierarchical mergers
- Measurement of spin-induced quadrupole moment
- Evidence of higher harmonics in the inspiral (33-mode) and spin-precession
- Eccentric analysis constrains orbital eccentricity of the systems.
- Measurement of spin-induced quadrupole moment -> three orders of magnitude improvement in the constraint of deviations from GR.



Compact Binary Detections

From LVK+2025: GW241011&GW241110



Models employed in GWTC-4.0: systematic differences

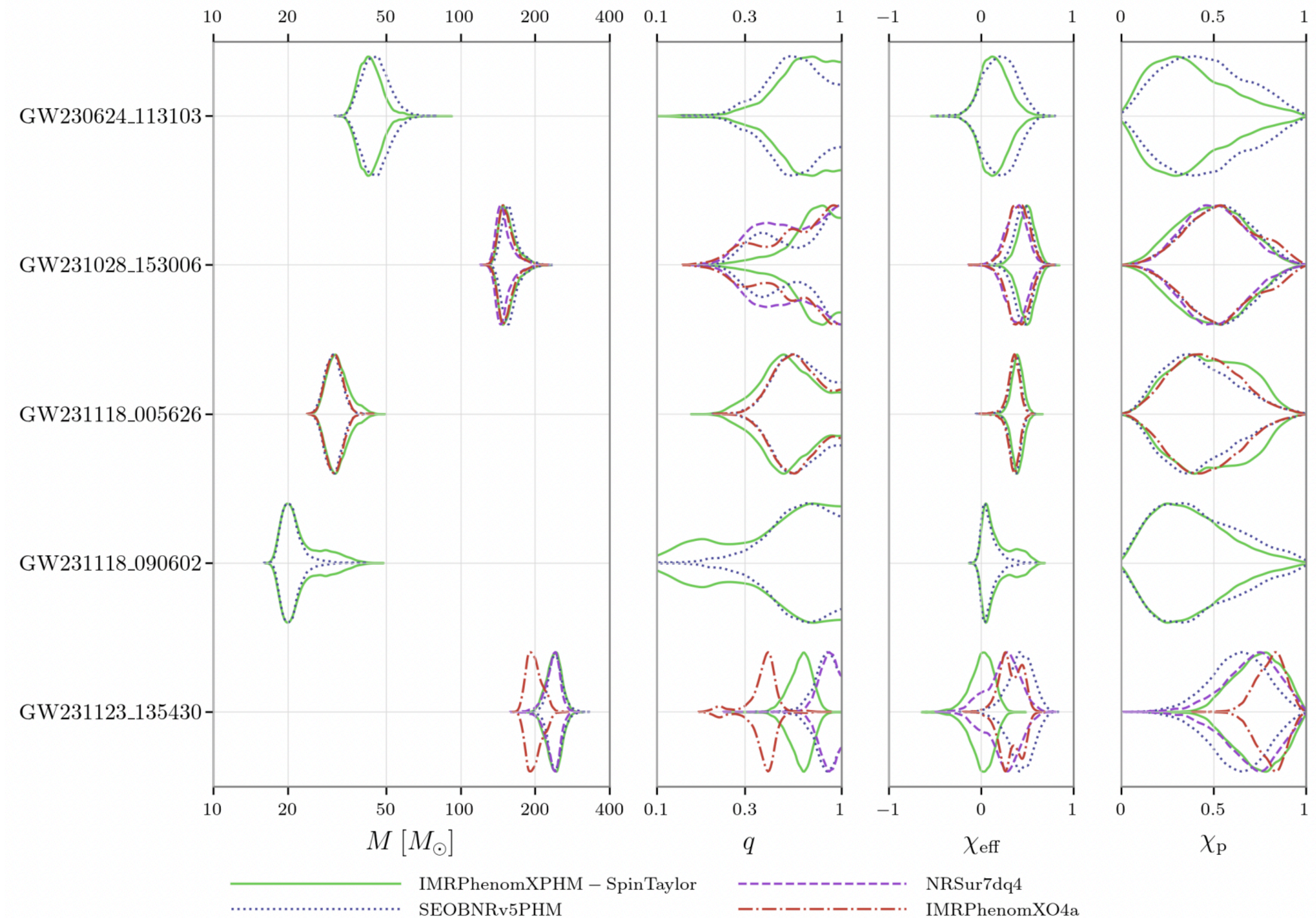
Waveform models employed in GWTC-4.0:

- IMRPhenomXPHM-SpinTaylor (all events)
- SEOBNRv5PHM (all events)
- NRSur7dq4 (events in its applicability region)
- IMRPhenomXO4a (high SNR, measurement of χ_p , or hints of systematic effects)
- IMRPhenomTPHM (for GW231123)

Most events show **very consistent results for different models**

But some show **systematic differences due to model inaccuracies**.

- High mass systems (hard for FD models)
- Unequal masses and/or high spins (limited calibration of the models)
- High SNR: shrink statistical error, while keeping systematic error.

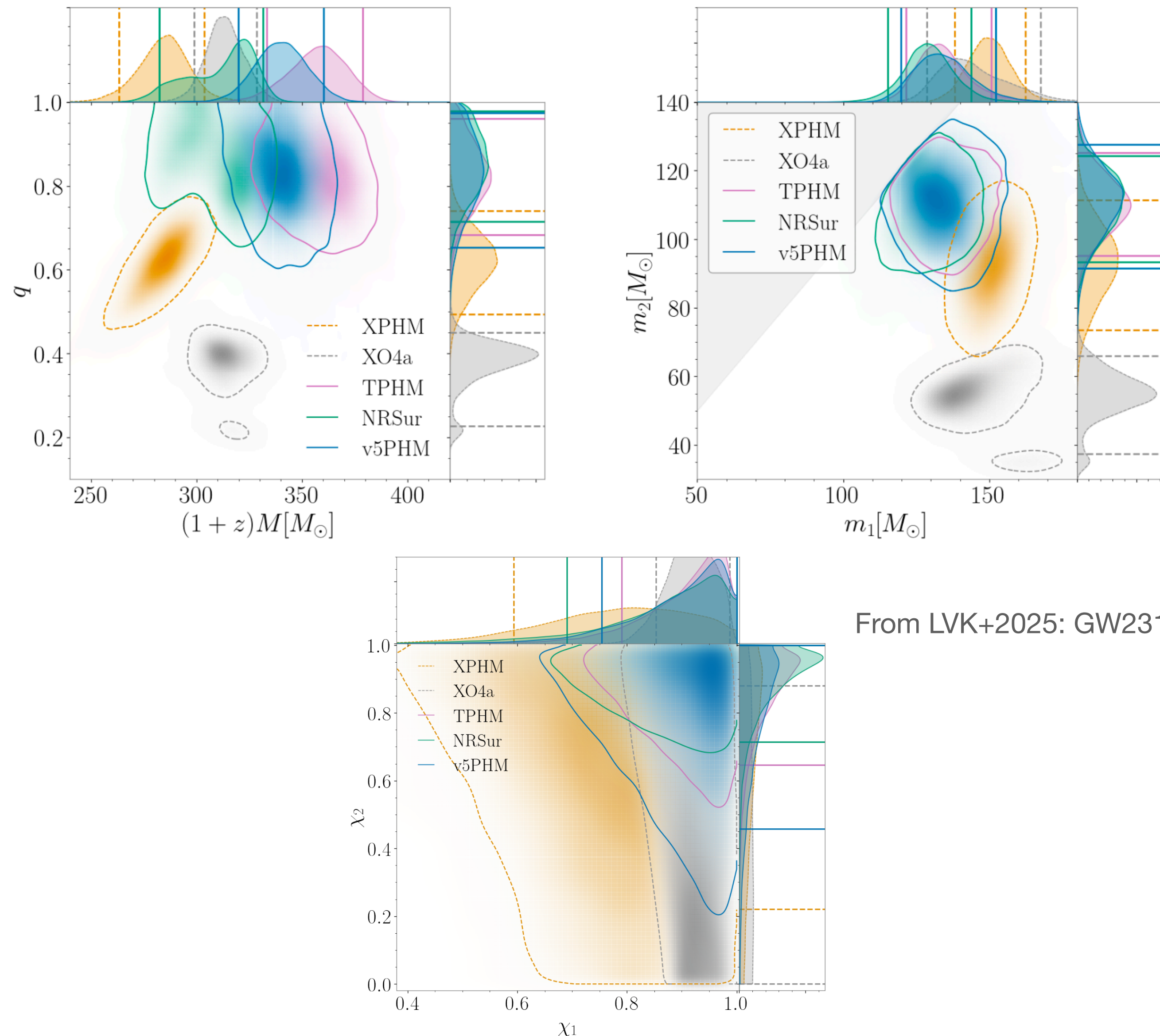


From LVK+2025: GWTC-4.0 Results

Systematics in challenging events

GW231123_135430

- **Challenging region of parameter space:**
 - Very high total mass (only merger-ringdown observed)
 - Large spins (Lack of NR simulations to inform models)
- **Significant disagreement** between models in **total mass**.
- **Mass-ratio differences** between time-domain models (near-equal-mass systems) and frequency-domain models (asymmetric masses).
- IMRPhenomXPHM not suited for this kind of event due to its approximations.

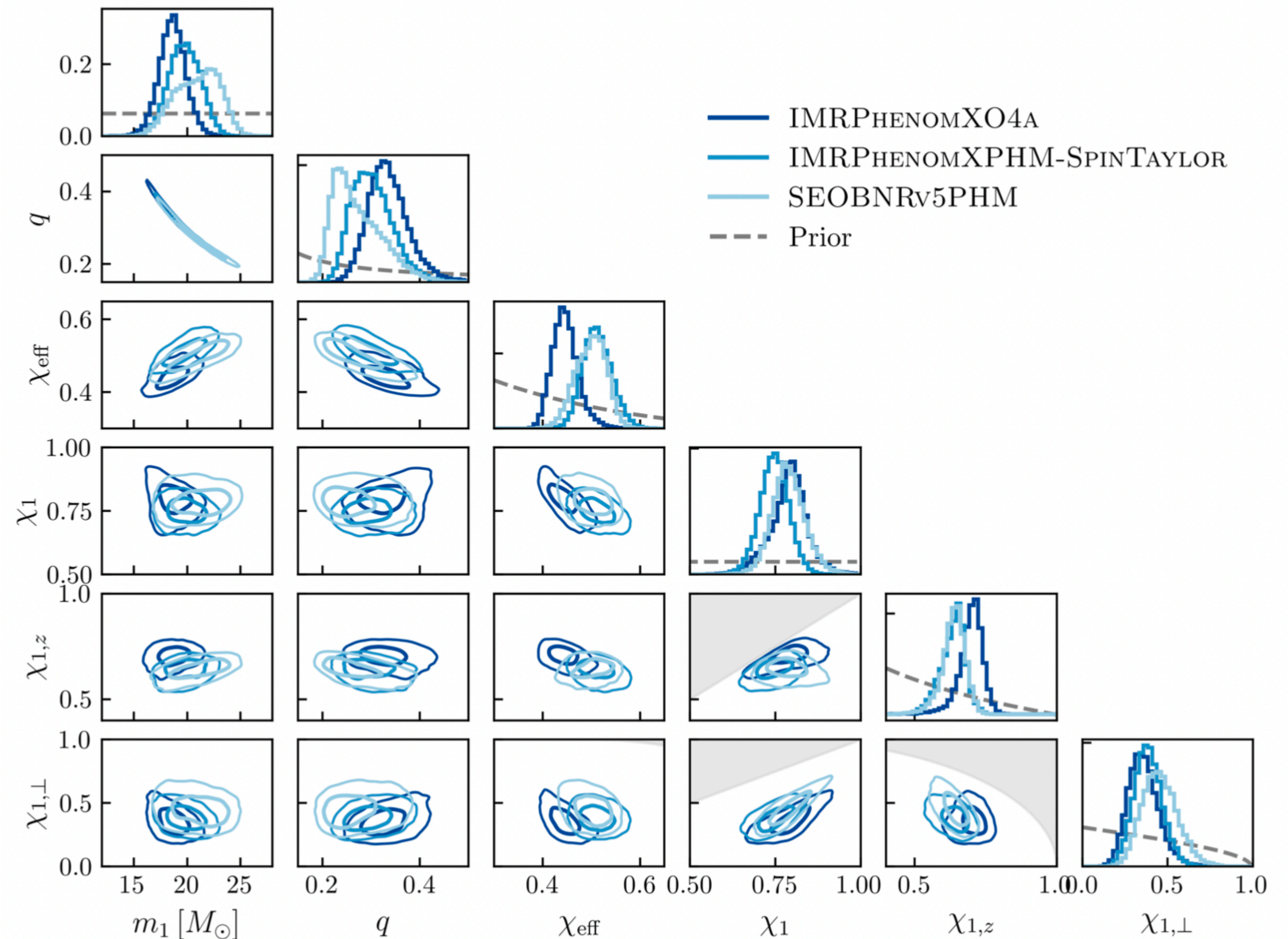


From LVK+2025: GW231123

Systematics in challenging events

GW241011_233834

- Challenging region of parameter space:
 - Unequal masses
 - Large spins (Lack of NR simulations to inform models)
 - Spin-precession
- **Slight disagreement** between models in **primary mass, primary spin and mass-ratio**
- Different descriptions of spin-precession are probably the reason

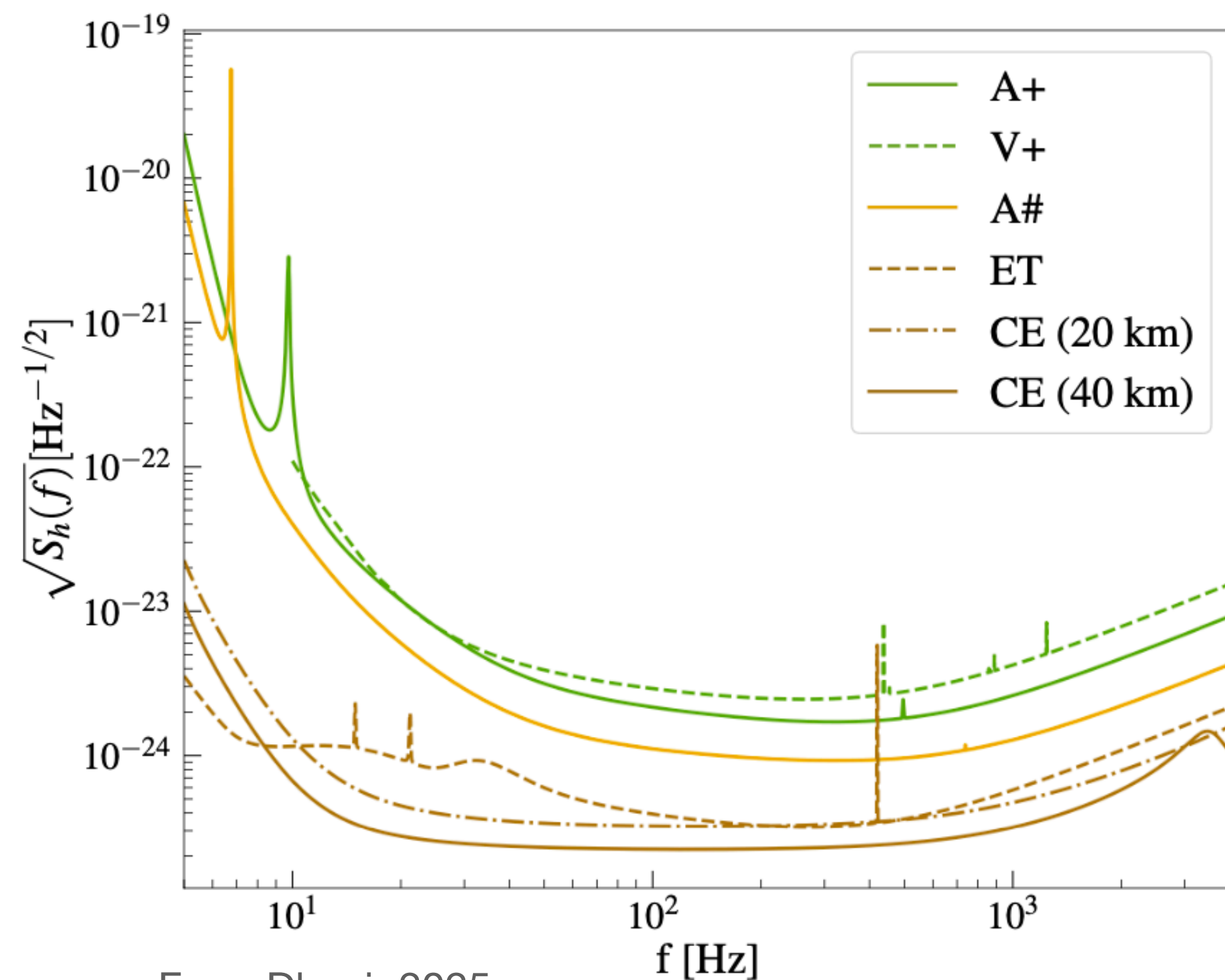


From LVK+2025: GW241011&GW241110

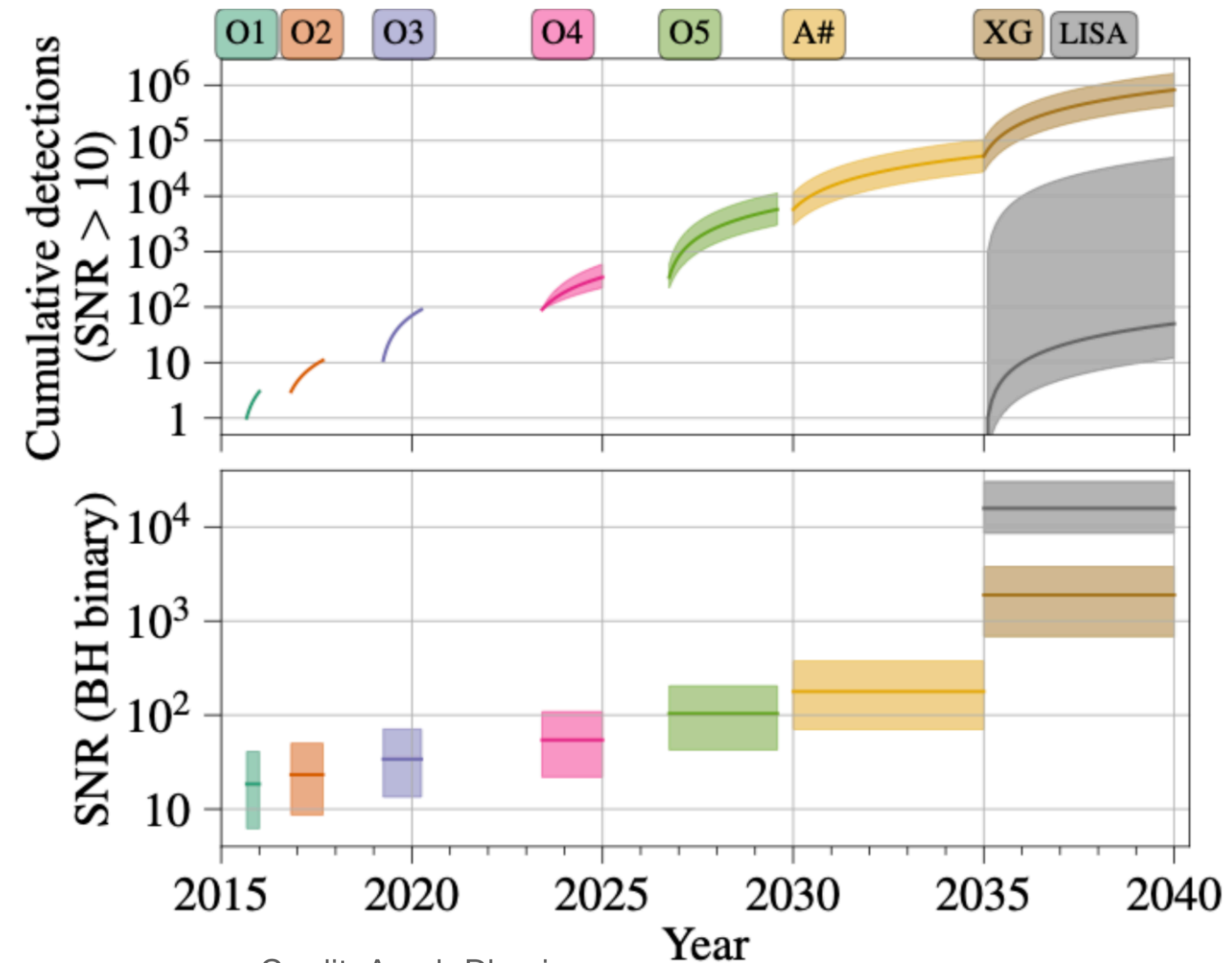
Accuracy challenge for next-generation detectors

Expected sensitivity improvements in current and future facilities:

- Dramatic increase in the number of events
- Higher SNR distribution: reduction of statistical uncertainty
- Will the systematic error due to inaccuracies in current waveform models bias the science outcomes?



From Dhani+2025



Credit: Arnab Dhani

Systematic biases due to inaccurate waveform models

PHYSICAL REVIEW X **15**, 031036 (2025)

Study **systematic biases** using two **state-of-the-art** waveform models for **spin-precessing** systems:

- Signal: **SEOBNRv5PHM**
- Inference: **IMRPhenomXPHM**

1 - Biases across parameter space:

- **Linear-signal-approximation** for inference
- Three **detector networks**: **O5** (2 aLIGO, aVirgo), **A#** (2 a#LIGO, aVirgo), **XG** (ET, 2 CE)
- Effect on **population inference** for an **LVK-like** mock population
- Bias **horizon distance** across parameter space

2 - Effect on science cases with “Golden” binaries:

- Full **Bayesian analysis** for selected cases
- **Distance** and **sky-location** biases: **Hubble constant** inference
- **Primary-mass** bias: **Upper mass-gap** limits
- **Secondary-mass** bias: Maximum **NS** mass

Systematic Biases in Estimating the Properties of Black Holes Due to Inaccurate Gravitational-Wave Models

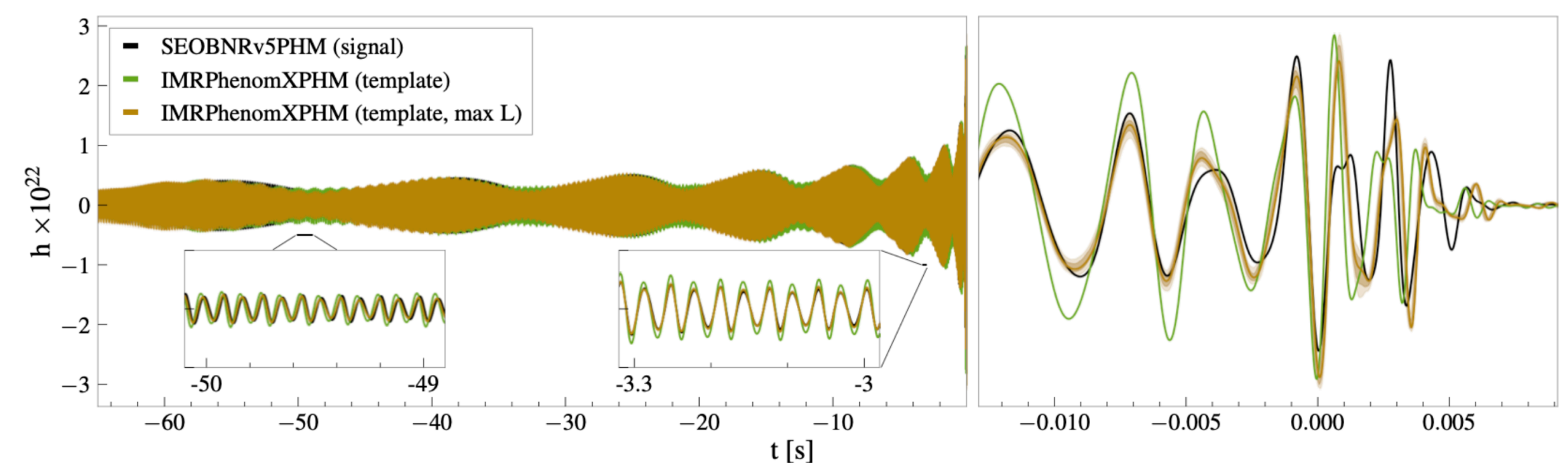
Arnab Dhani^{1,*}, Sebastian H. Völkel¹, Alessandra Buonanno^{1,2}, Hector Estelles¹, Jonathan Gair¹,
Harald P. Pfeiffer¹, Lorenzo Pompili¹ and Alexandre Toubiana¹

¹*Max Planck Institute for Gravitational Physics (Albert Einstein Institute),
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²*Department of Physics, University of Maryland, College Park, Maryland 20742, USA*

GW190814-like, but **strongly precessing**: $q = m_1/m_2 \sim 10$, $\chi_{\text{eff}} = 0.51$, $\chi_p = 0.45$

SNR (O5): ~ 75 , **mismatch**(signal,template) $\sim 4\%$, **Biases**: $\delta\chi_p \sim 13\%$, $M \sim 3\%$, $q \sim 6\%$



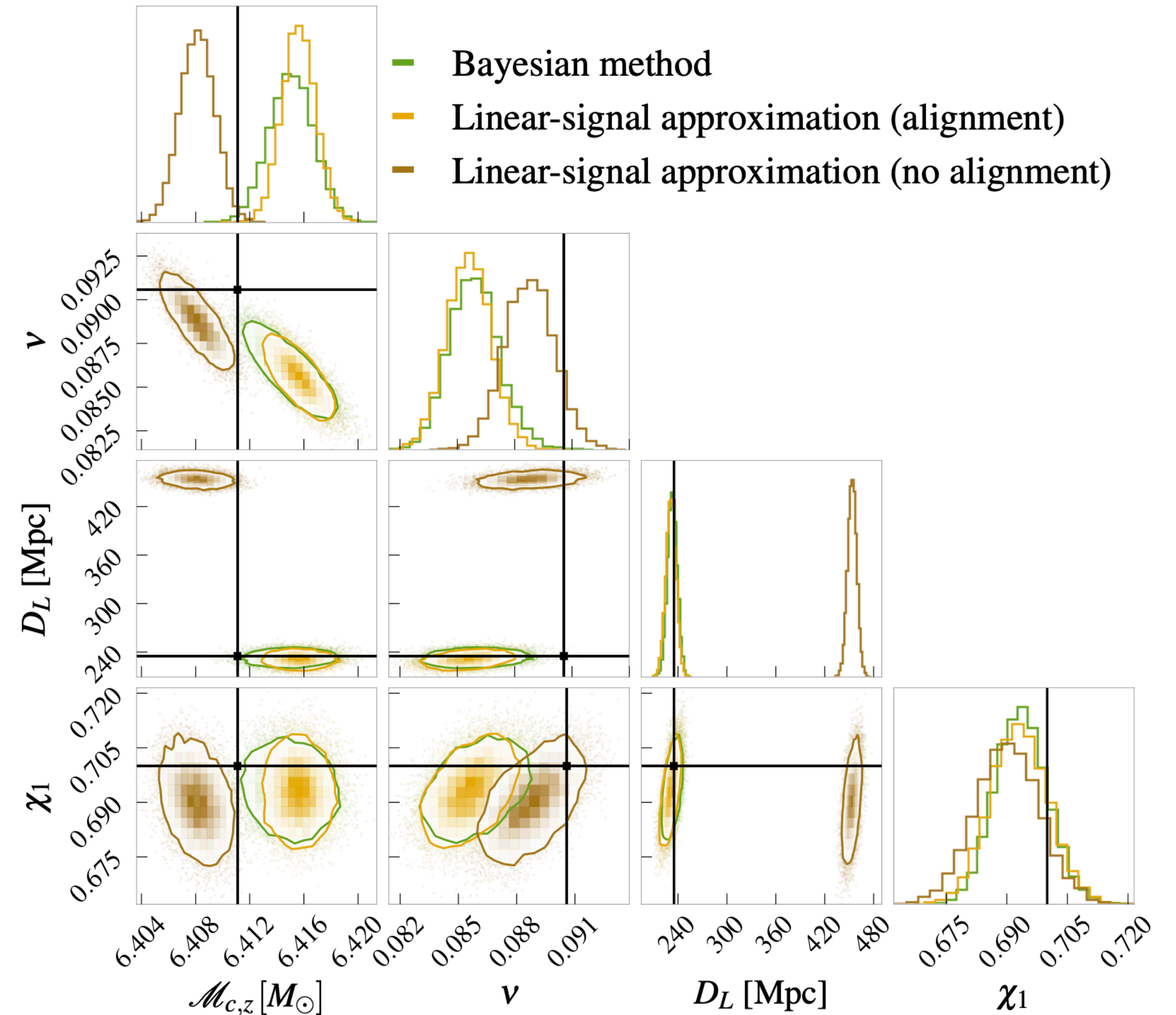
Linear signal approximation

- Fisher matrix: $F_{ij} = (\partial_{\theta_i} h(\boldsymbol{\theta}) | \partial_{\theta_j} h(\boldsymbol{\theta}))$
- Covariance matrix: $C_{ij} = (F_{ij})^{-1}$
- Statistical uncertainty: $\Delta\theta_i = \sqrt{C_{ii}}$
- Parameter bias: $\delta\theta_i = C^{ij}(\partial_{\theta_i} h(\boldsymbol{\theta}) | \delta h)$

Flanagan-Hughes+98 Cutler-Vallisneri +07

Some **extrinsic** parameters do not agree completely between waveform models: **alignment needed**

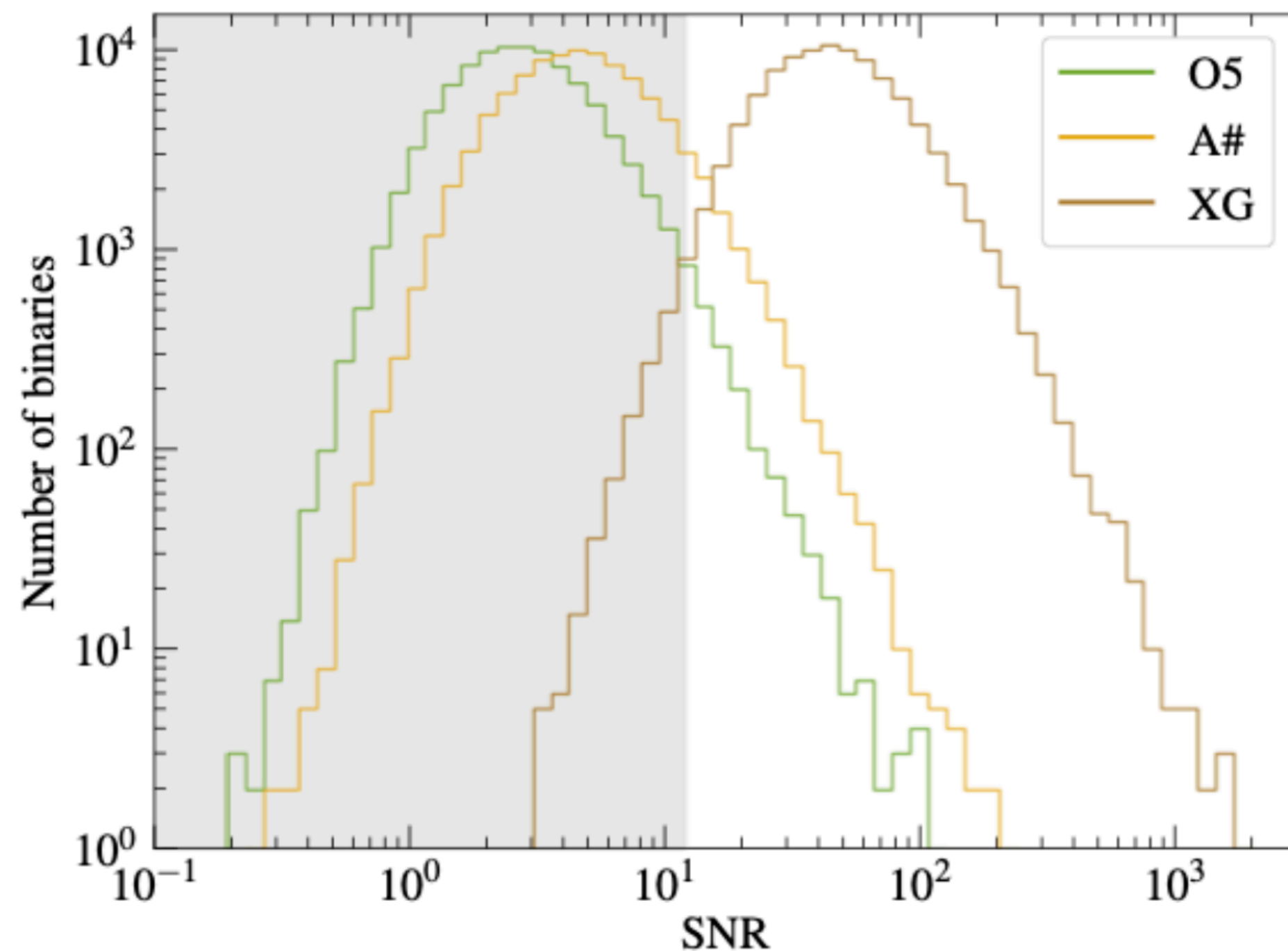
$$\delta h \equiv \min_{t_c, \phi_{\text{ref}}, \psi, \phi_{\text{JL}}} (h_s - h)$$



Systematic biases in LVK-like population

Synthetic population

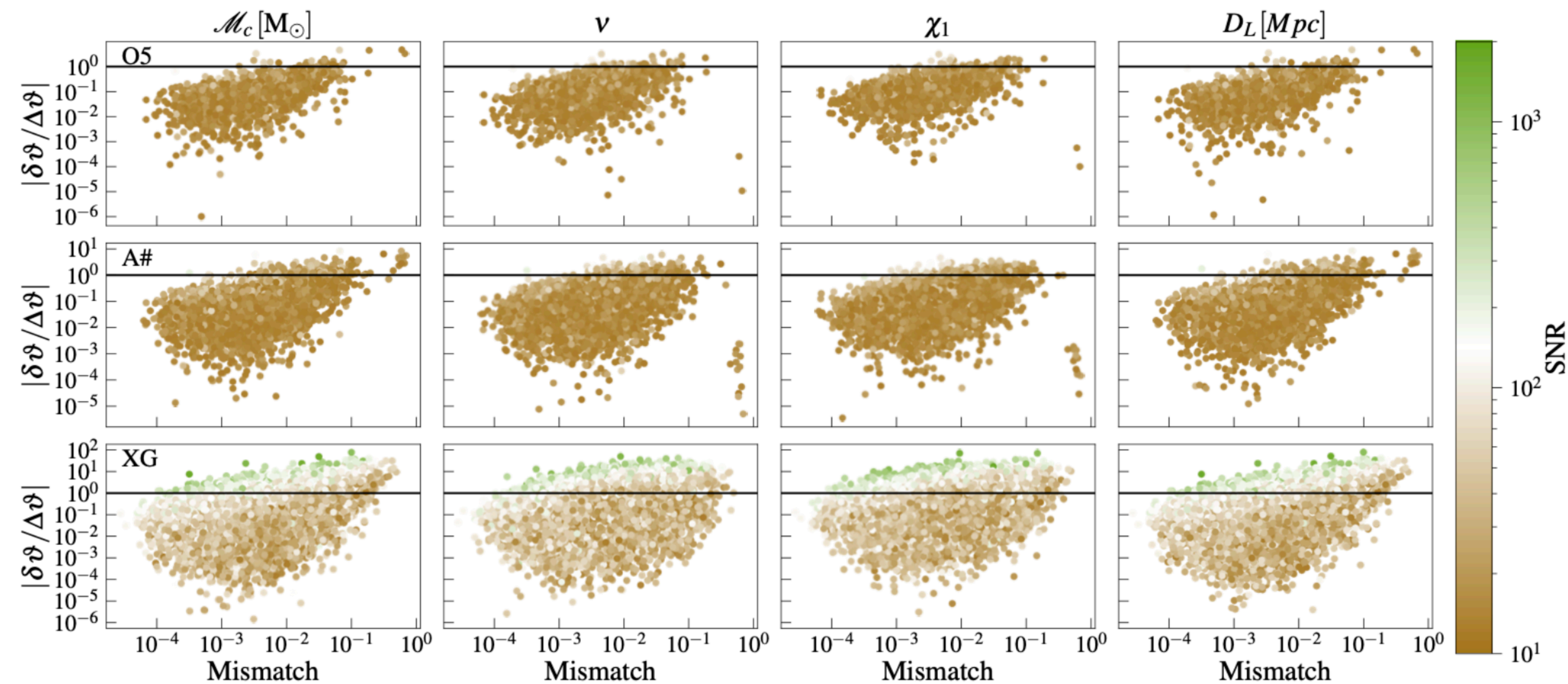
- **Mass distribution:** LVK GWTC-3
- **Spin distribution:** uniform magnitudes and isotropic directions
- **Redshift:** $z \in [0,3]$



$|\delta\theta/\Delta\theta| > 1$: Systematic bias greater than statistical error - **parameter biased.**

Percent biased:

- O5/A#: 2-3%
- **XG: 10-25%**
- Correlation with mismatch btw signal and template



Systematic biases across parameter space

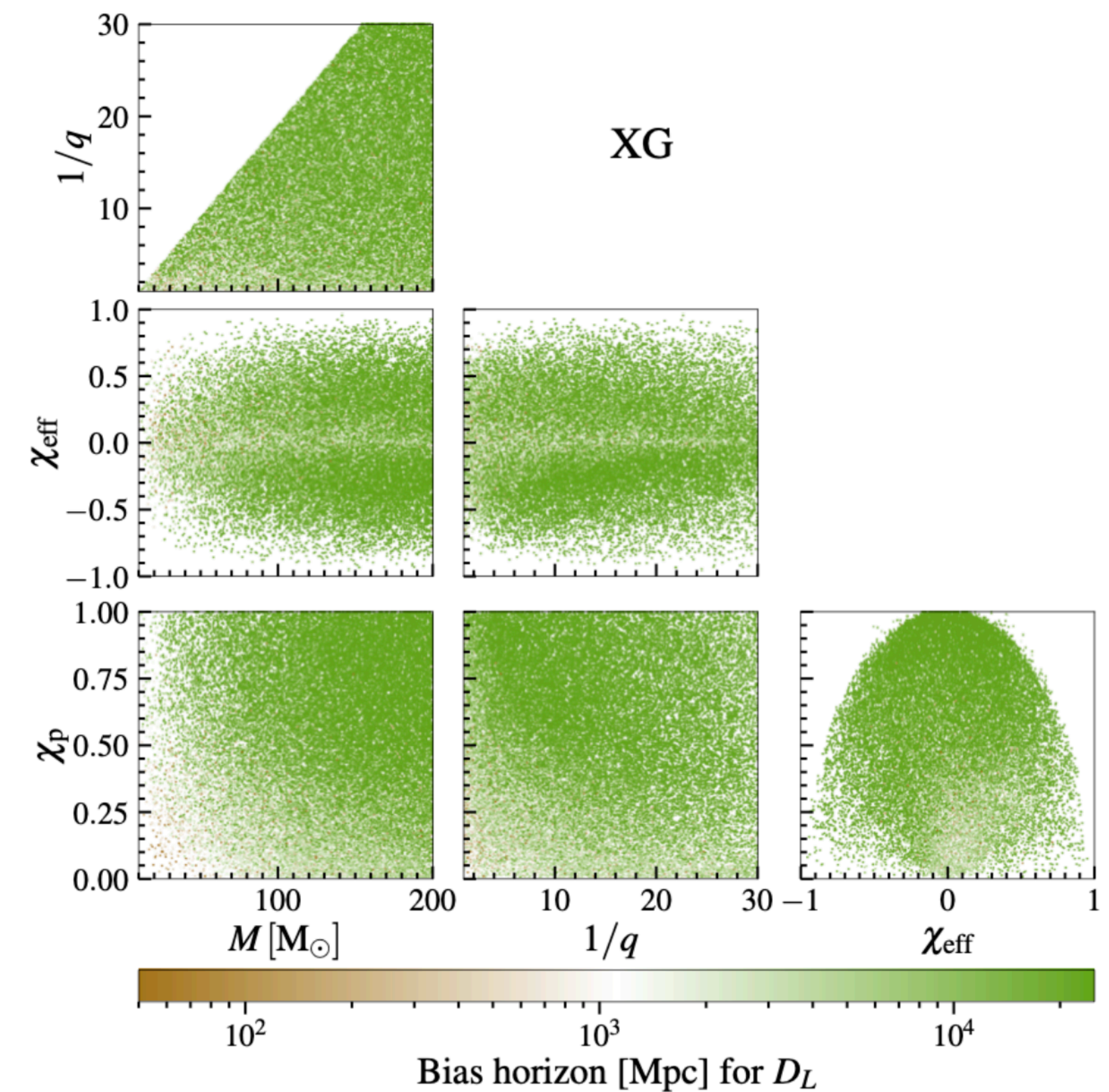
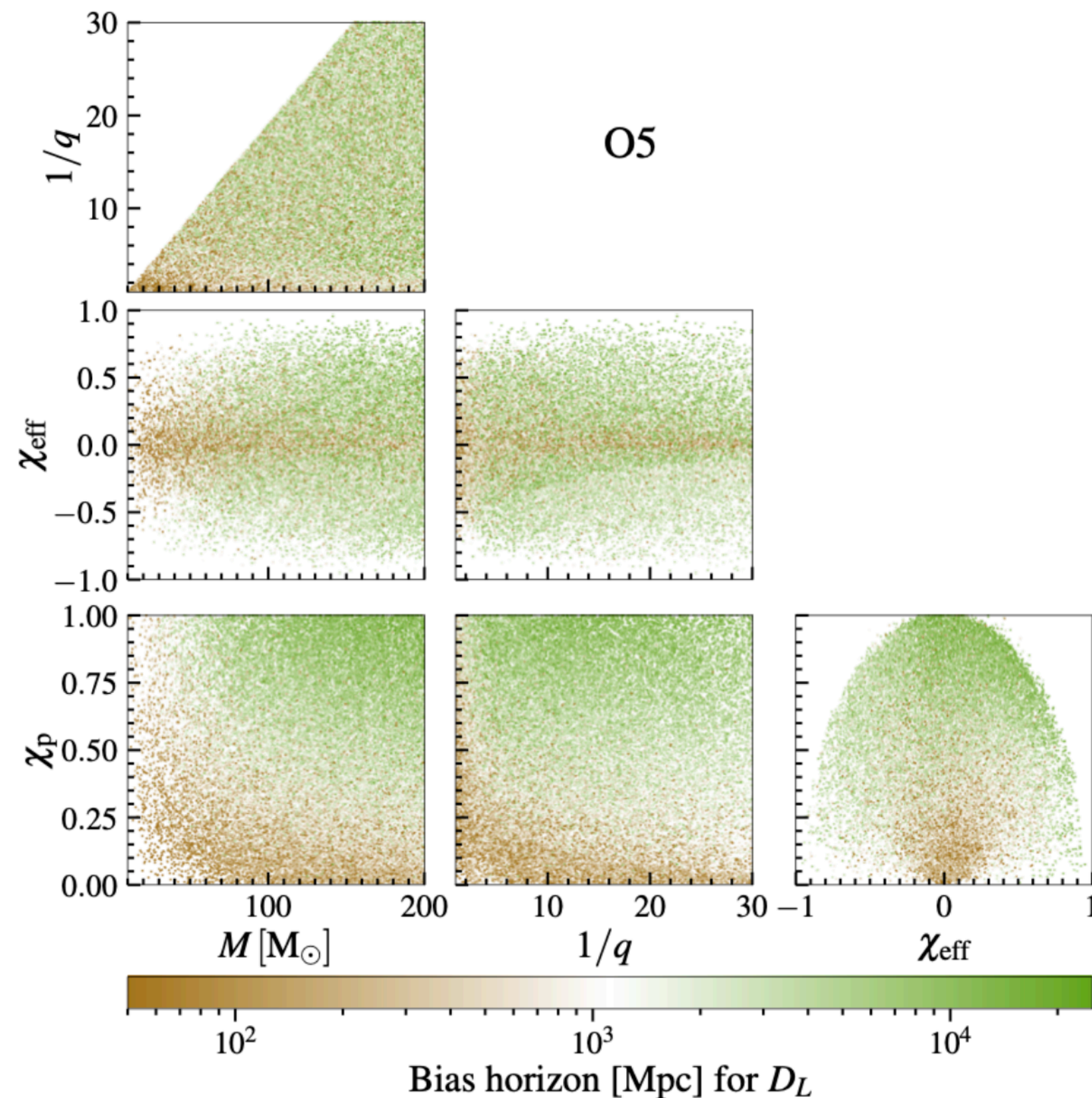
Goal: study biases across broader parameter space. **Individual interesting binaries might be in challenging regions.**

Unphysical population

- **Uniform distribution:** $q = m_1/m_2 \leq 30$
- **Uniform distribution:** $\chi_p \in [0,1]$

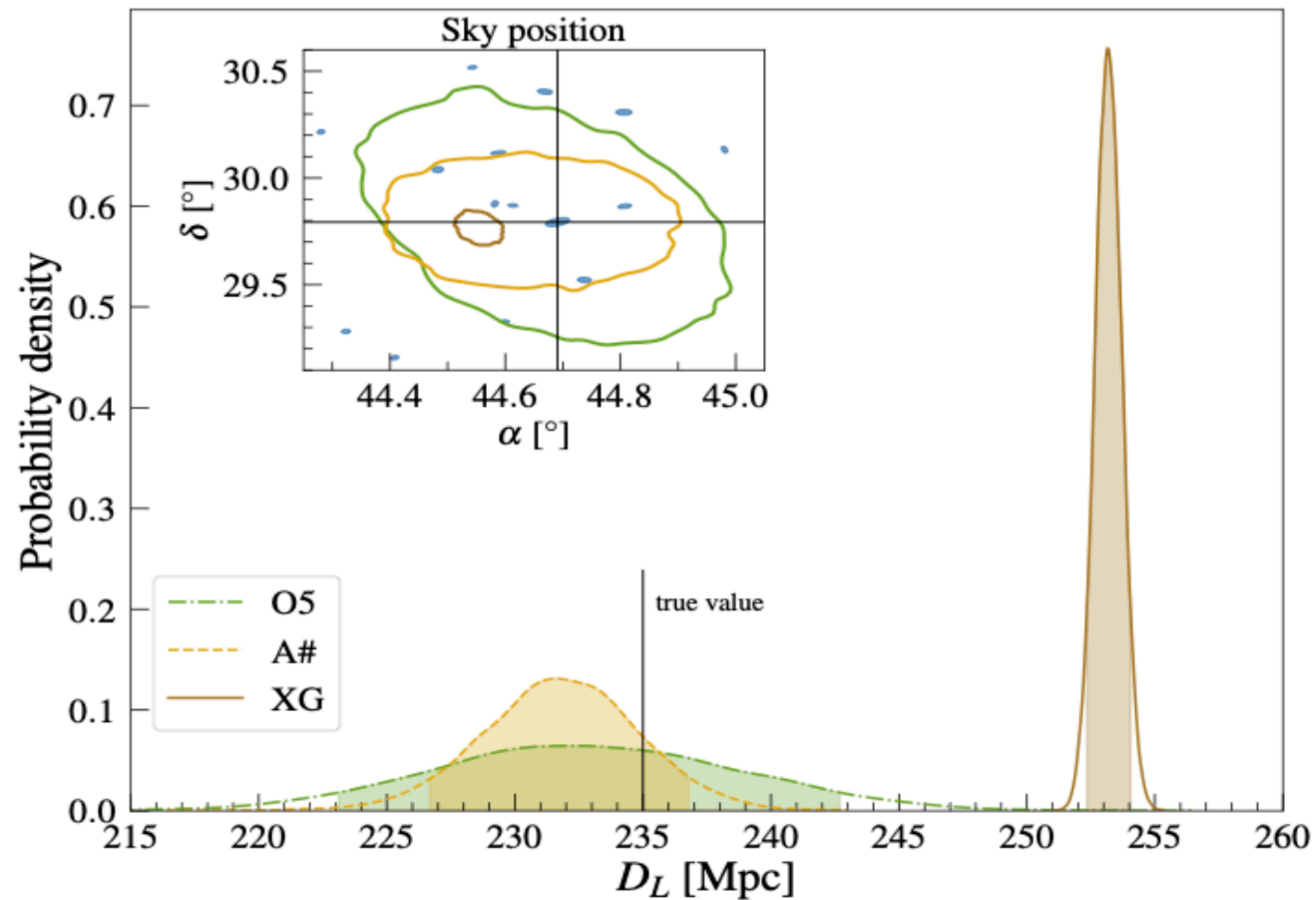
Bias horizon: minimum distance at which a given parameter is biased ($|\delta\theta/\Delta\theta| > 1$) (**larger is worse - systematics appearing at lower SNRs**)

Less systematics for smaller spins: **improvements in spin-precession still needed**



Effect on science goals: biased distance and sky-location

- ❖ $m_1 = 23.2M_\odot, m_2 = 2.6M_\odot$
- ❖ $\chi_{eff} = 0.51, \chi_p = 0.45$
- ❖ $SNR_{O5} = 75, SNR_{XG} = 1040$

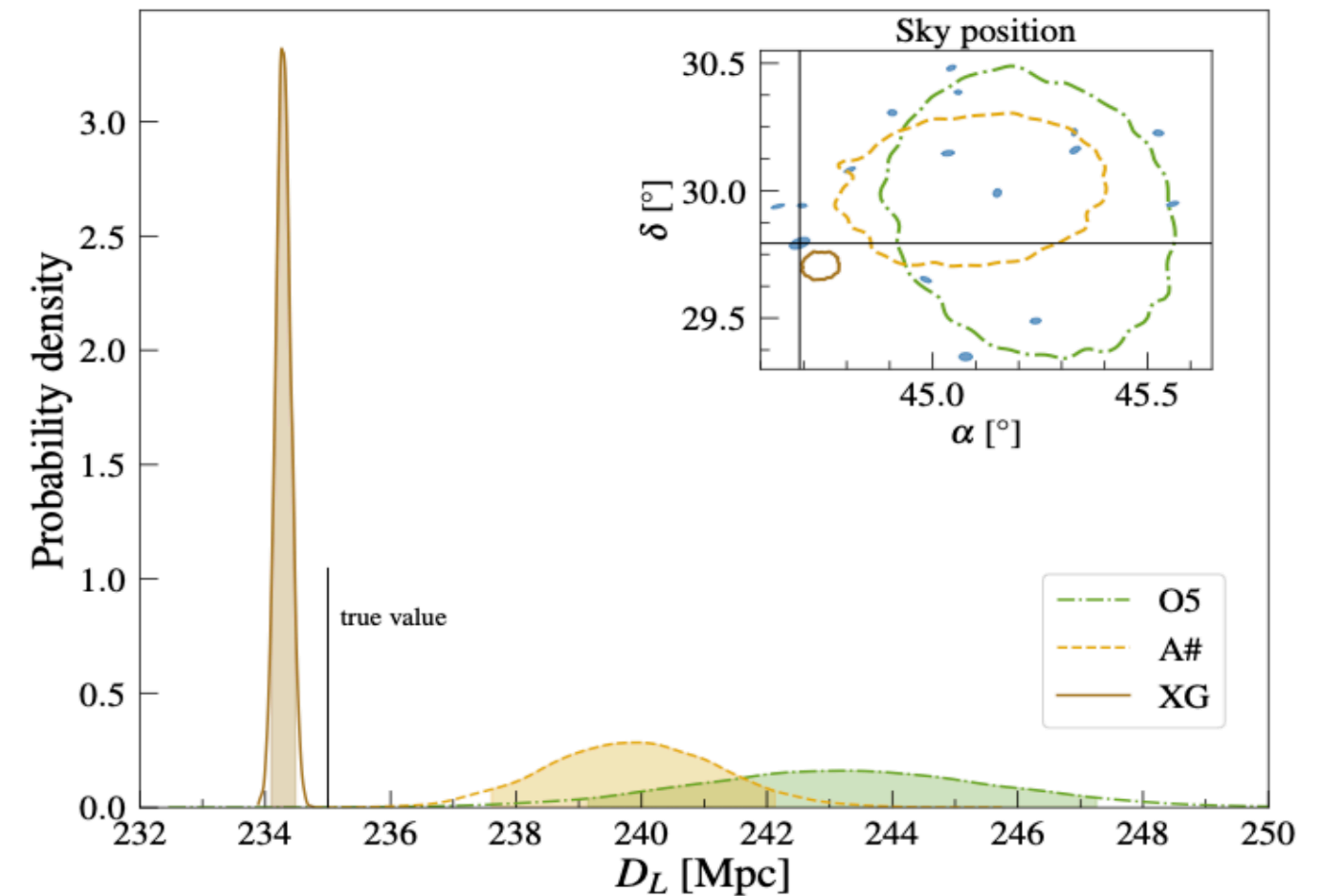


Spin-precessing NSBH:

distance and sky-location biased for XG

Can affect Hubble constant estimation and the identification of EM counter-parts.

- ❖ $m_1 = 61.8M_\odot, m_2 = 9.5M_\odot$
- ❖ $\chi_{eff} = -0.43, \chi_p = 0.77$
- ❖ $SNR_{O5} = 119, SNR_{XG} = 2490$

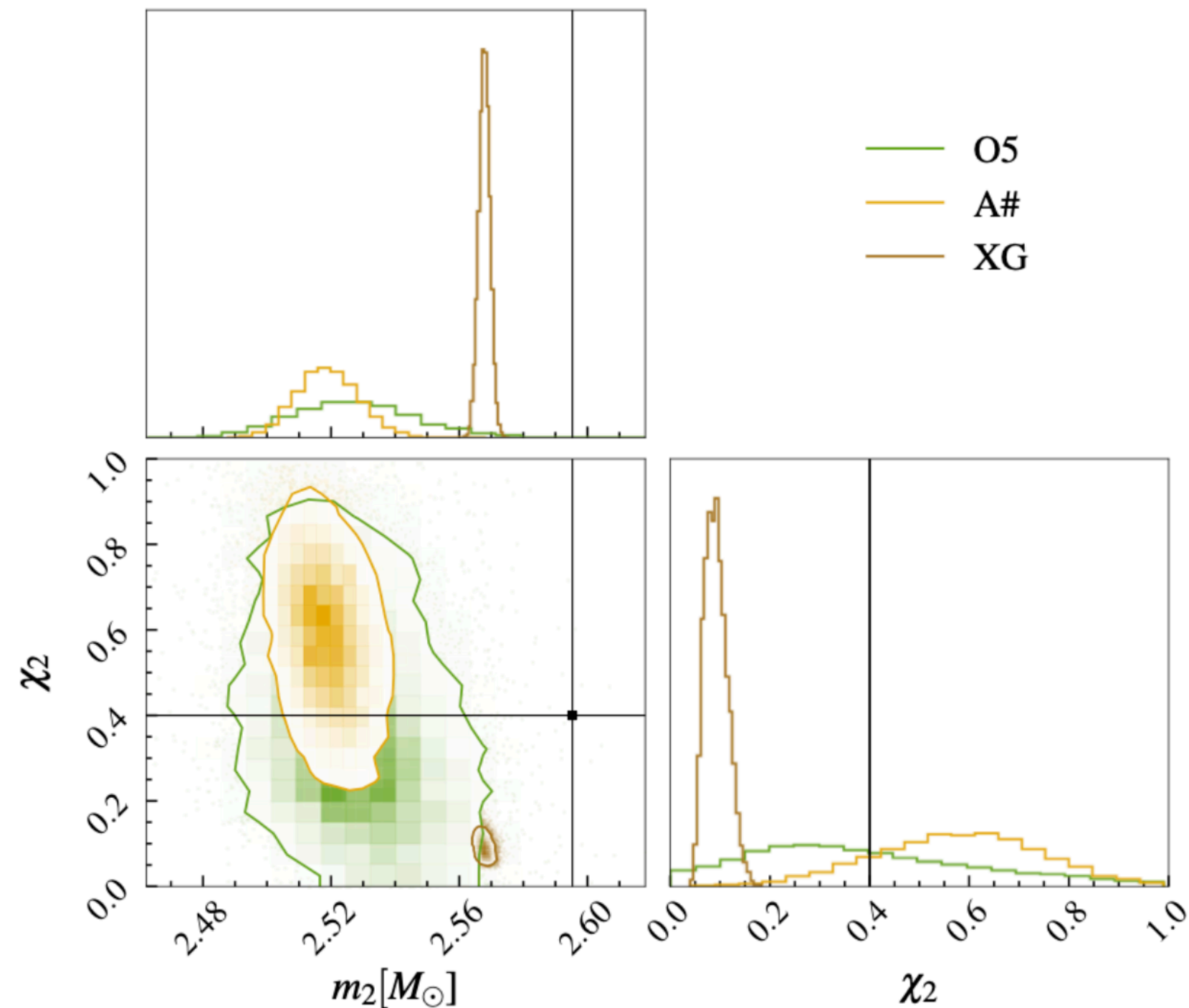


Highly asymmetric strongly precessing:

distance and sky-location biased even for O5

Effect on science goals: biased component masses

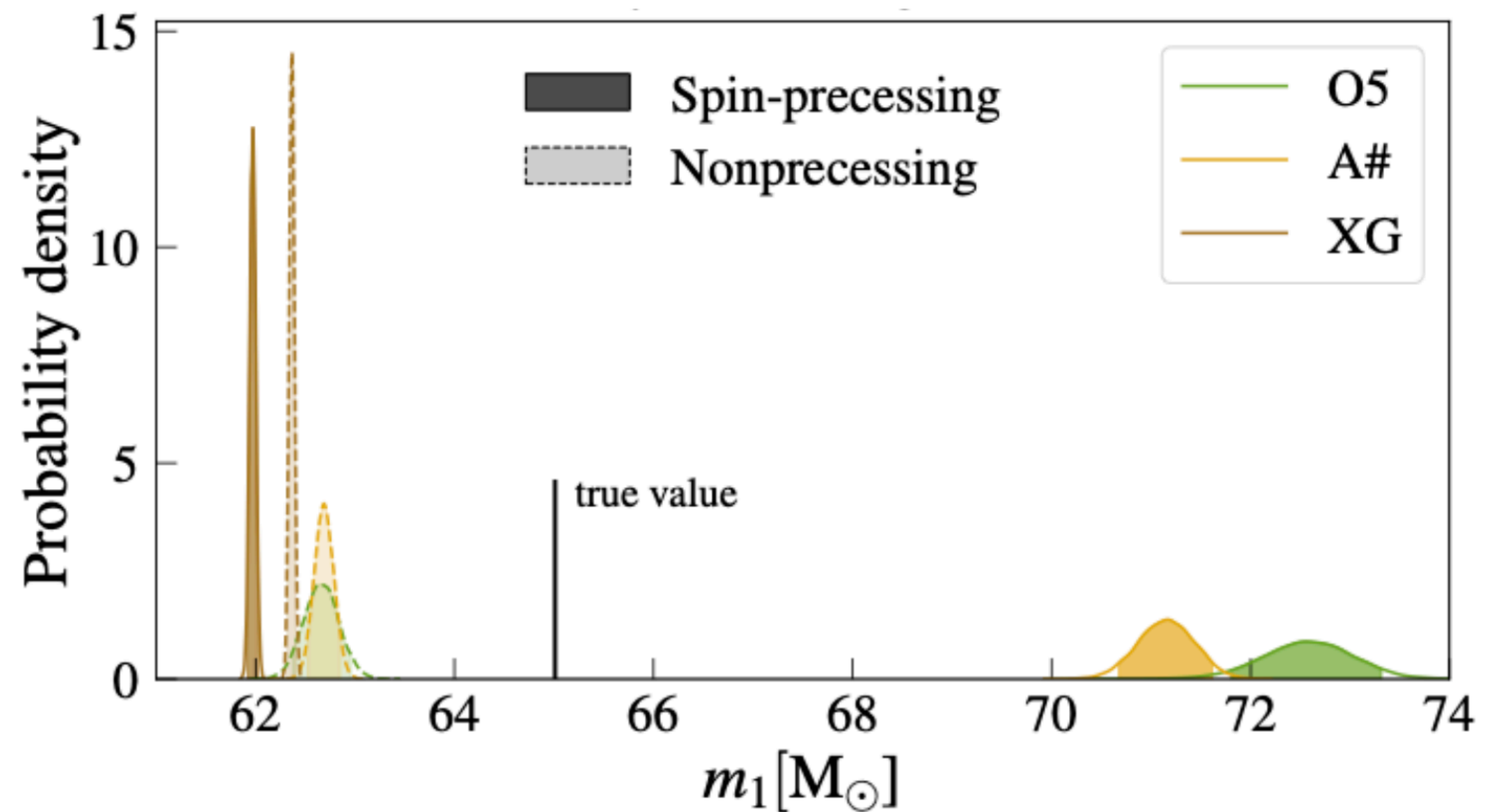
- ❖ $m_1 = 23.2M_\odot, m_2 = 2.6M_\odot$
- ❖ $\chi_{eff} = 0.51, \chi_p = 0.45$
- ❖ $SNR_{O5} = 75, SNR_{XG} = 1040$



Spin-precessing NSBH:
secondary-mass biased even for O5.

Can affect estimation of maximum NS mass.

- ❖ $m_1 = 61.8M_\odot, m_2 = 9.5M_\odot$
- ❖ $\chi_{eff} = -0.43, \chi_p = 0.77$ and $\chi_{eff} = 0.89, \chi_p = 0$
- ❖ $SNR_{O5} = 119, SNR_{XG} = 2490$



Highly asymmetric strongly precessing (and non-precessing!):
primary-mass biased

Can affect estimation of lower end of upper mass-gap.

- Active waveform development in the last years: **mature models for quasi-circular systems and first models for eccentric systems**
- **New GW observations are increasing the parameter space and the SNR of detected systems: exciting new science outcomes.**
- **Waveform inaccuracies are starting to show systematic effects in the results.**
- Current accuracy will not be enough for improve sensitivity of future detectors: **biases in population and science goals with “golden binaries”.**
- **More work needed to address the challenges of the future!**