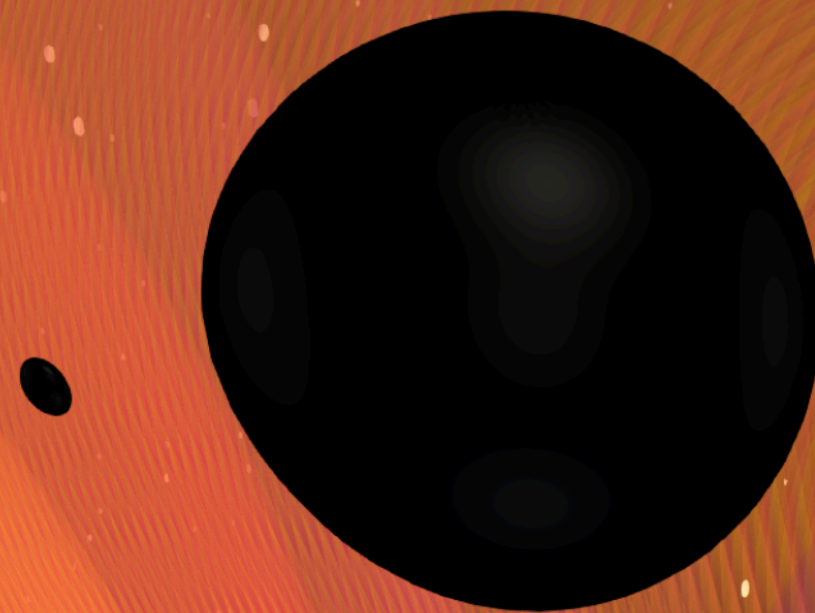


Modeling Astrophysical Sources of Gravitational Waves



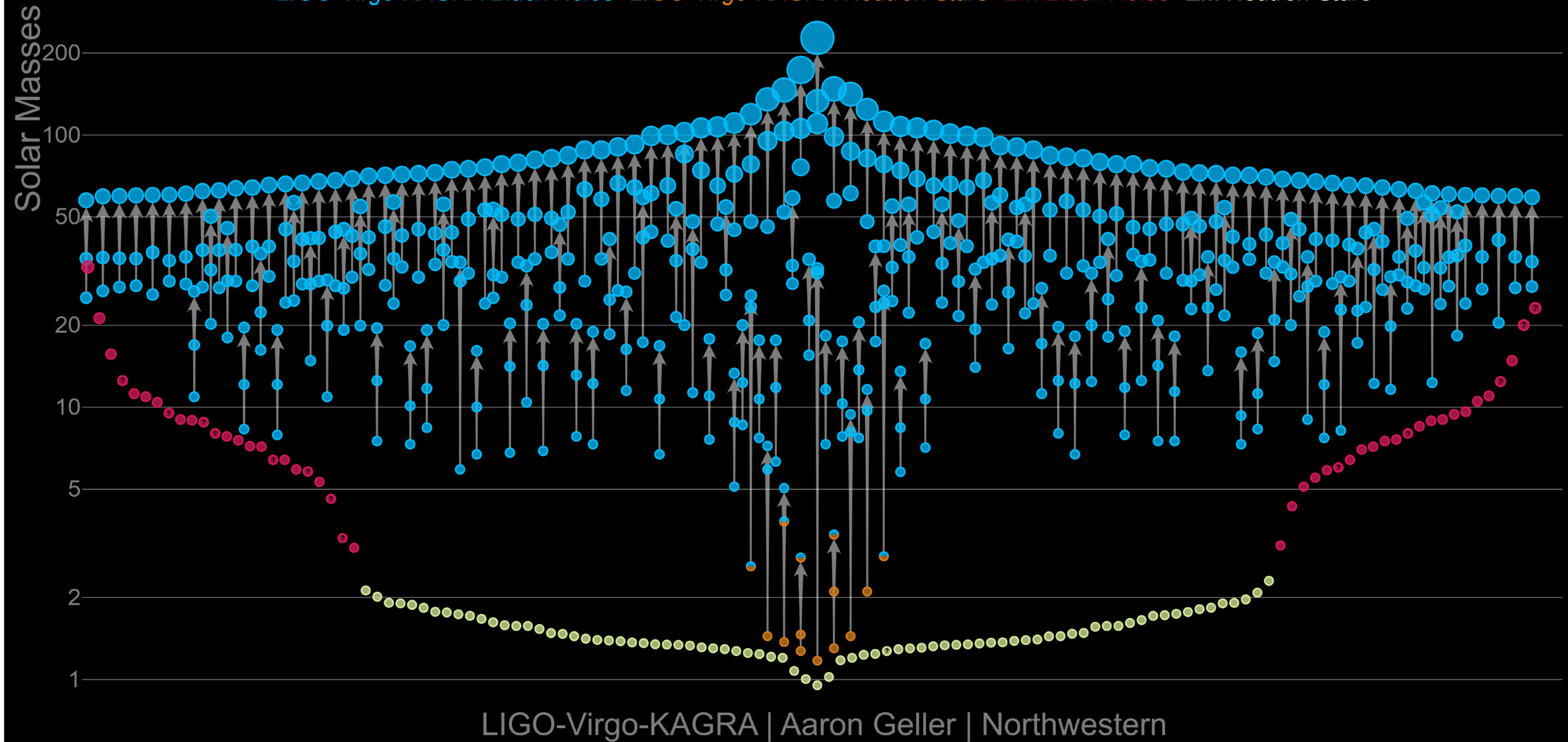
Harald Pfeiffer
MPI for Gravitational Physics
Future of GW Astronomy
ICTS, Bengaluru
Oct 28, 2025

GW astronomy spectacularly successful



Masses in the Stellar Graveyard

LIGO-Virgo-KAGRA Black Holes *LIGO-Virgo-KAGRA Neutron Stars* *EM Black Holes* *EM Neutron Stars*

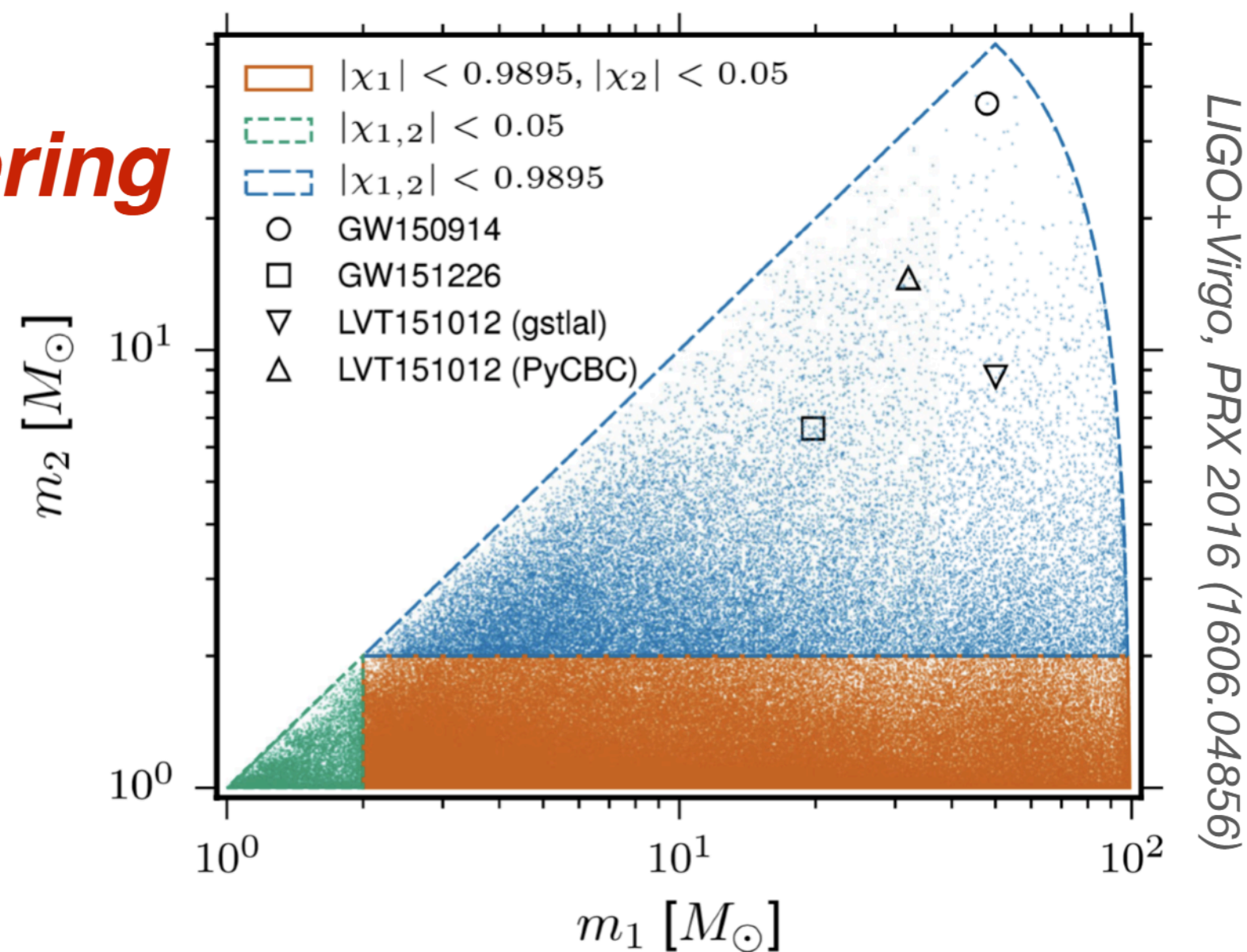


LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

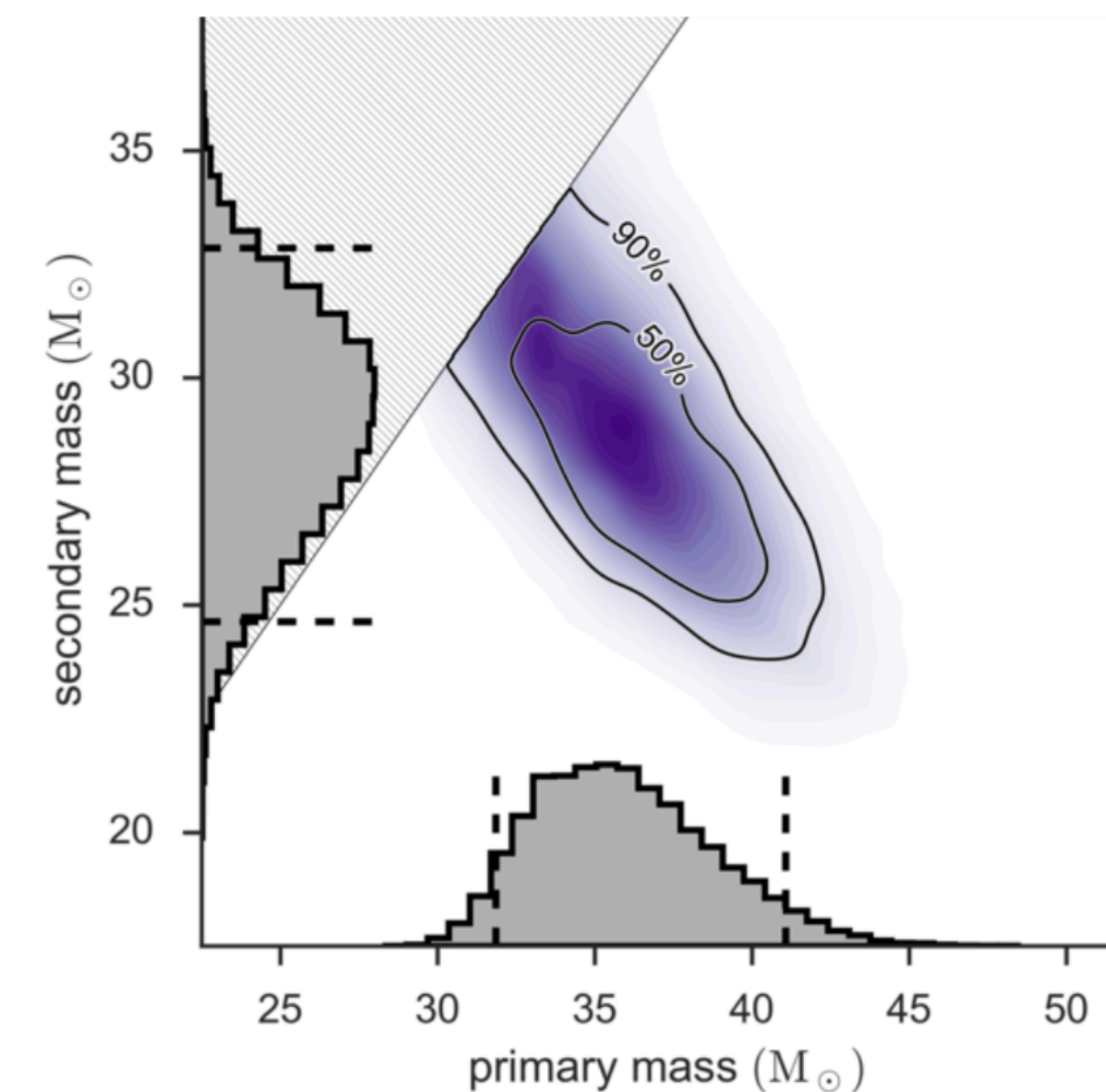
Waveform knowledge essential for GW astronomy



Detection by matched filtering

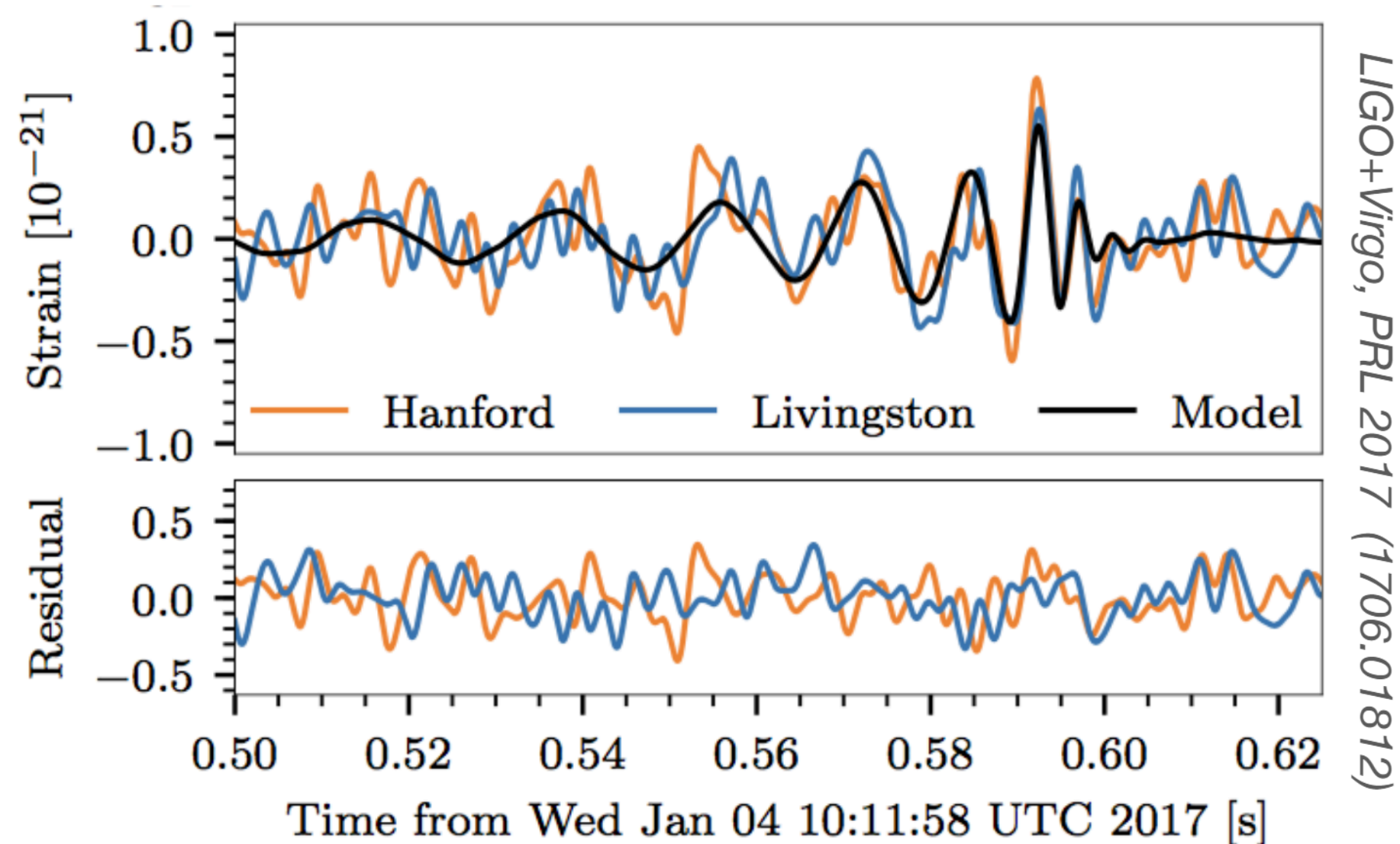


Parameter estimation

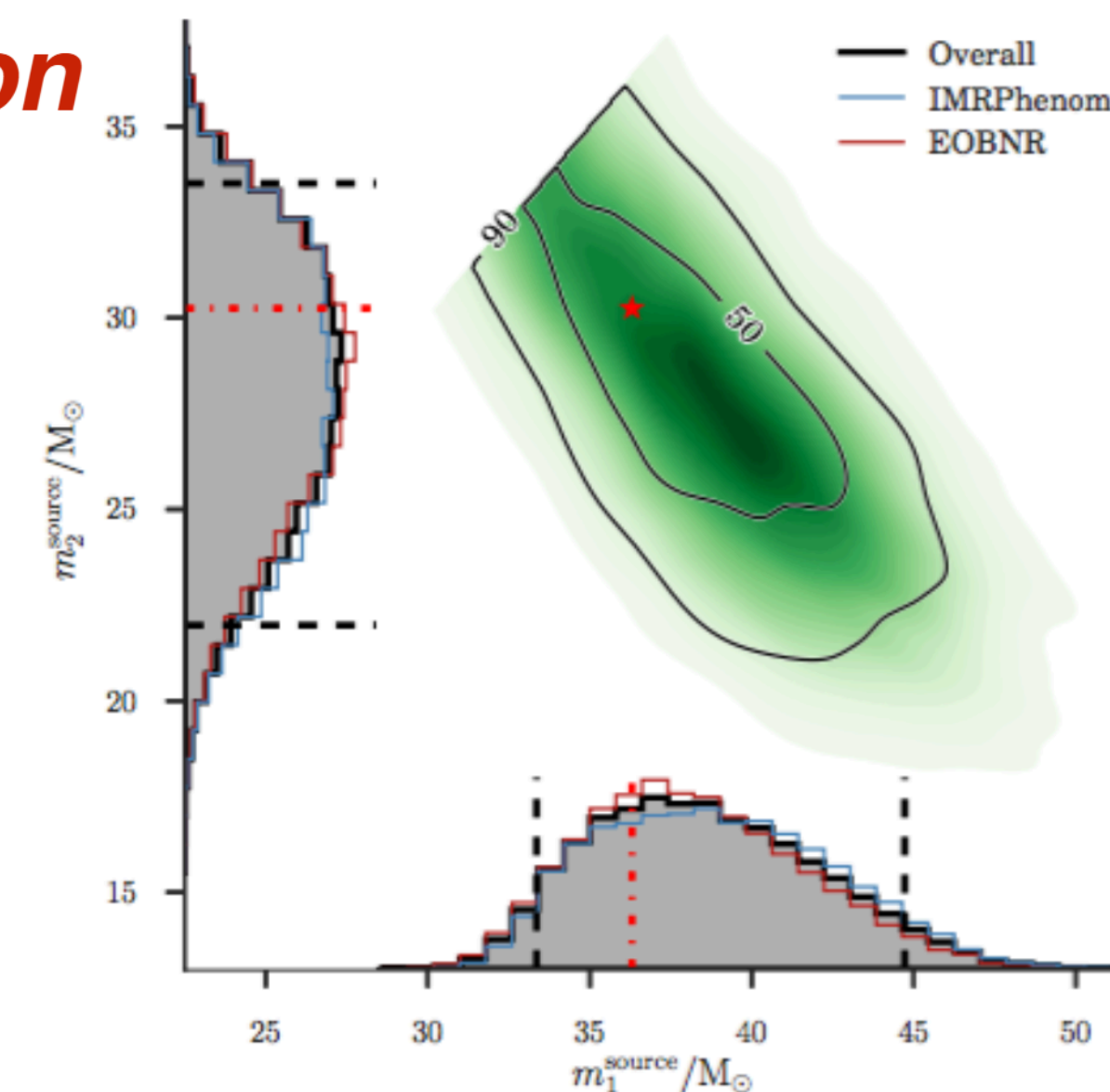


"GW150914" Abbott+ PRL 12016

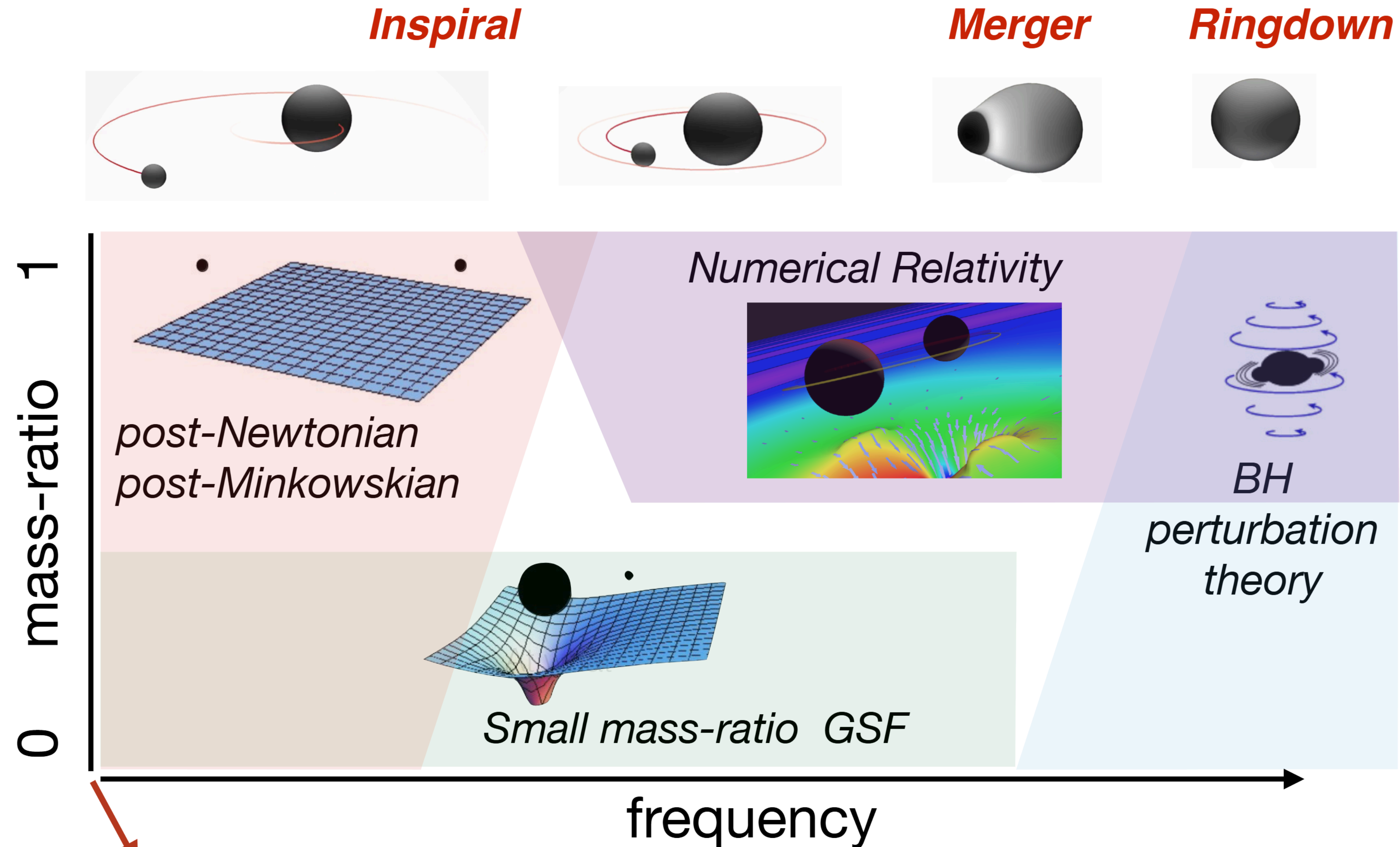
Testing GR



Validation



Methods for modeling compact object binaries



masses, spins, eccentricity, tides, EOS, environments, beyond GR

Waveform model



- **Combines results from "Methods"** to achieve ...

- **inspiral-merger-ringdown**
- **continuous in parameters**

$$\theta = (m_1, m_2, \vec{\chi}_1, \vec{\chi}_2; e, \ell; \text{EOS}; \text{environment}; \text{beyondGR})$$

- **fast**
- **accurate**

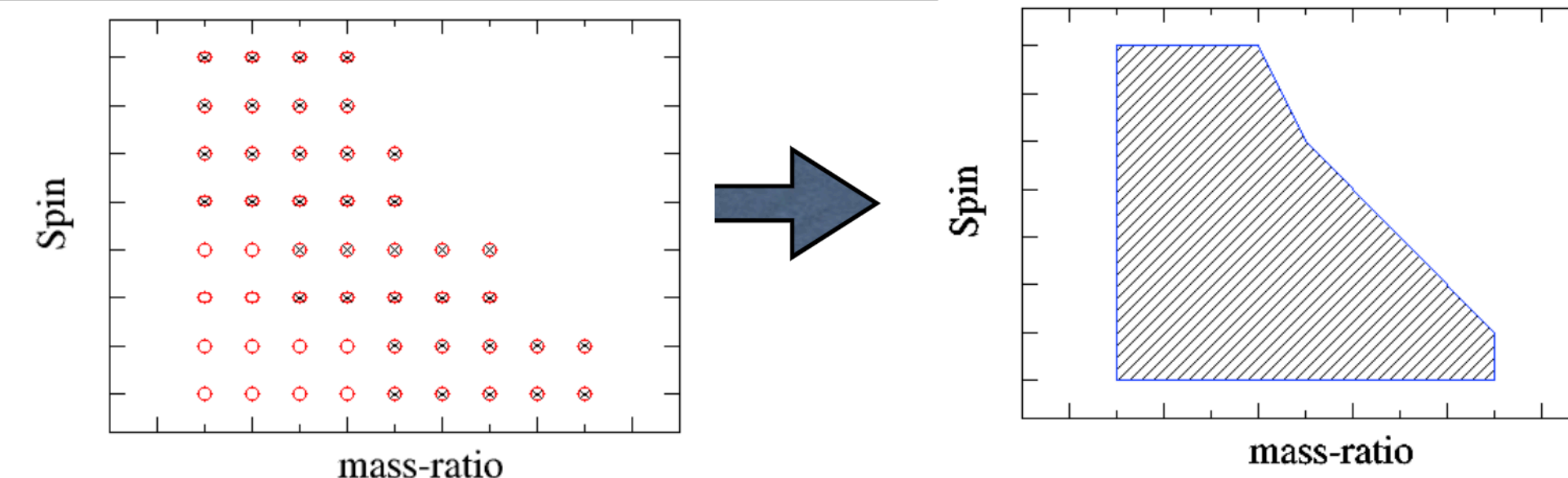
- includes also def'n of BMS frame, spin-directions, eccentricity

- **ever more physical effects**

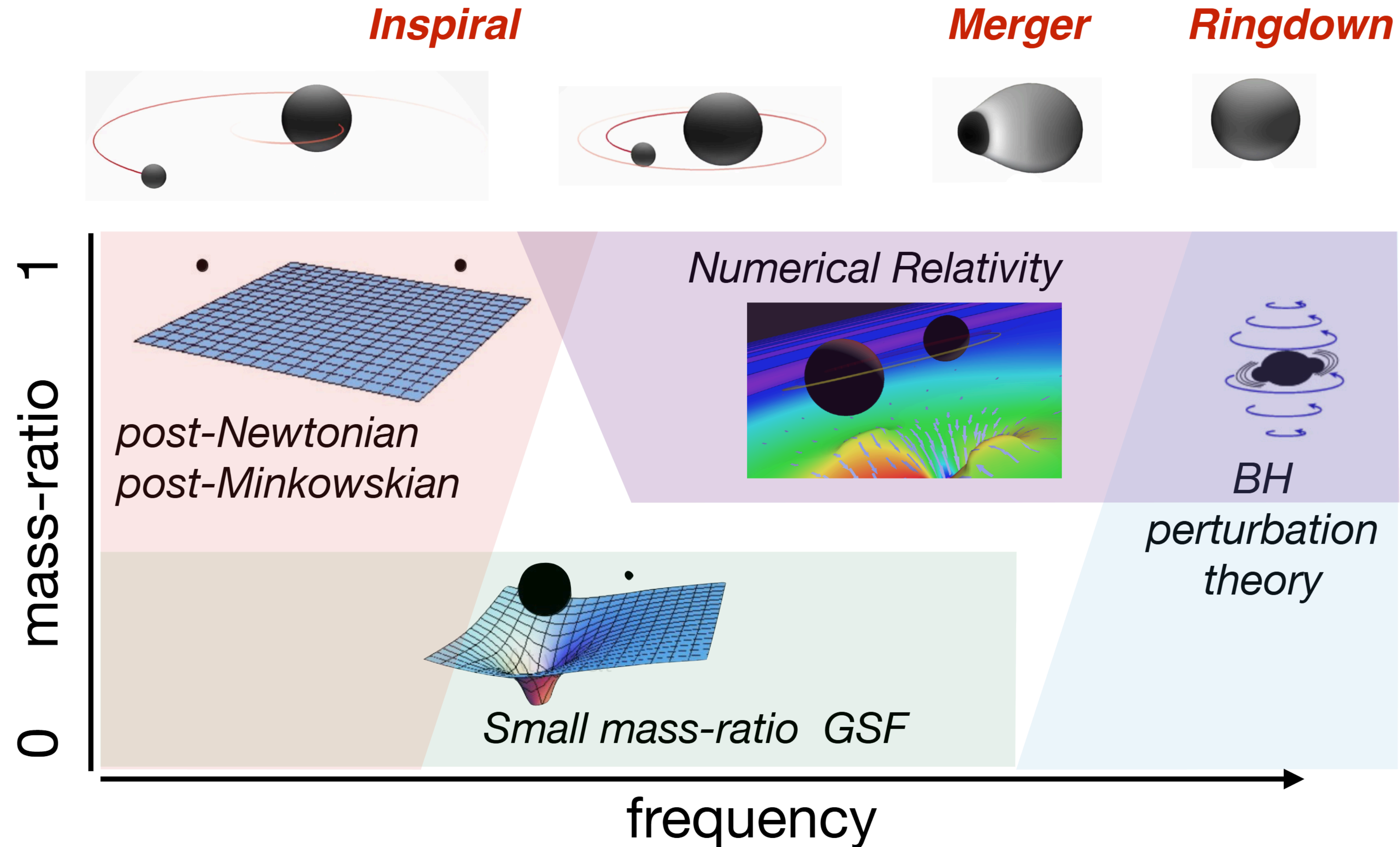
- spin-precession ✓, eccentricity ✓, both
- EOS ✓, tides ✓, disruption
- higher-order modes ✓, GW memory, GW ringdown tails
- BH kicks, orbital resonances
- environmental effects (perturbing bodies, accretion disks, grav. lensing of propagating GWs)
- beyondGR effects: parameterized deviations ✓; solutions in concrete alternative theories (✓)

- **for ever larger portion of parameter space**

- mass-ratio, spins, eccentricity, EOS, beyond-GR



Methods for modeling compact object binaries



Inspiral-merger-ringdown BH-BH waveform models



Effective one body (EOB)

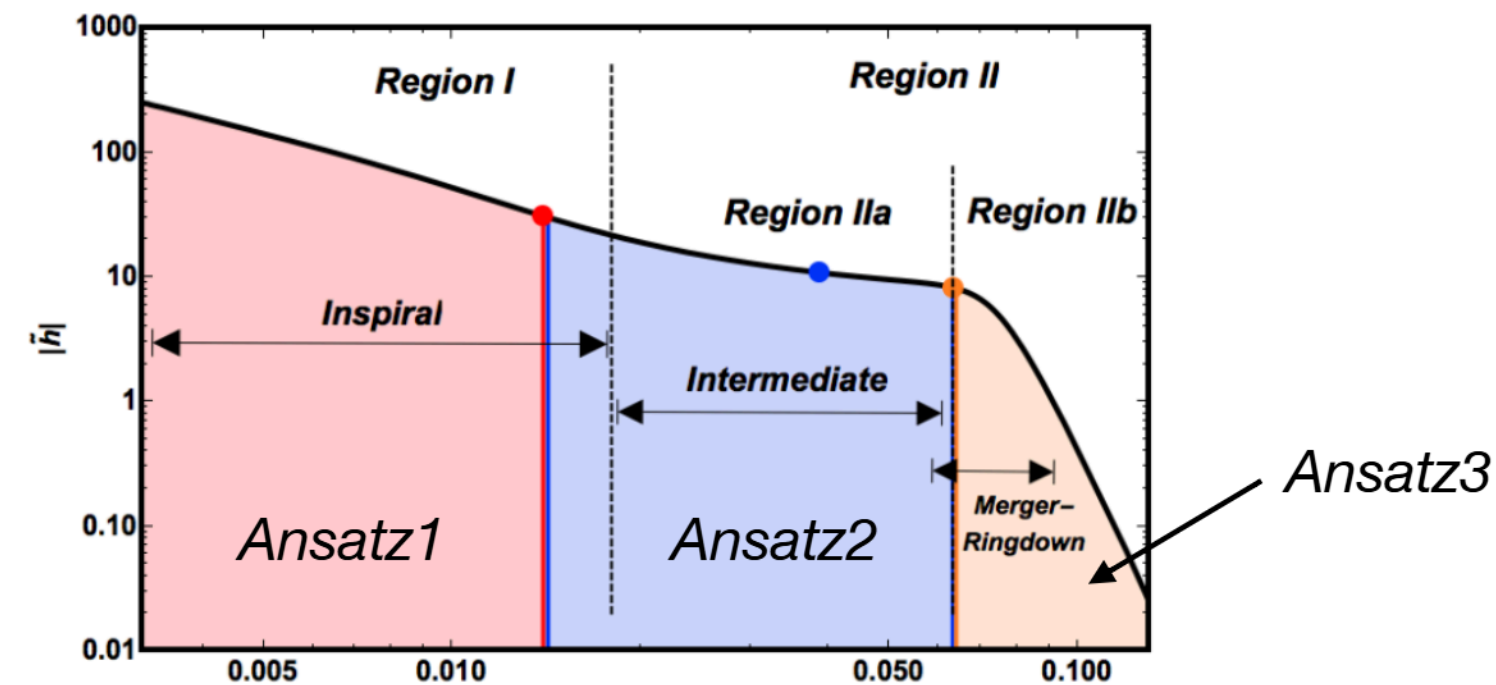
$$H = \mu \sqrt{p_r^2 + A(r) \left[1 + \frac{p_r^2}{r^2} + 2(4 - 3\nu)\nu \frac{p_r^4}{r^2} \right]}$$

Hamiltonian dynamics
dynamics $\Rightarrow h_{lm}(\theta; t)$

Fit free parameters against numerical simulations

Buonanno, Damour 99
EOBNR Buonanno+ 09, Pan+11
SEOBNR (aligned spins) Taracchini+ 12
SEOBNRv3 (precessing) Pan+ 14, Taracchini+14,
SEOBNRv4 {HM, P, PHM, HM_ROM} Bohe+ 17, Cotesta+ 18, Cotesta+
20, Ossokine+ 20
TEOBResumS{Dali,Giotto} TEOBResumSM Nagar+ 18, 20, Albanesi+
25, Gamba+24
SEOBNRv5{HM,P,PHM,E,PEHM} Pompili+ 23, Ramos-Buades+ 23,
Gamboa+ 25

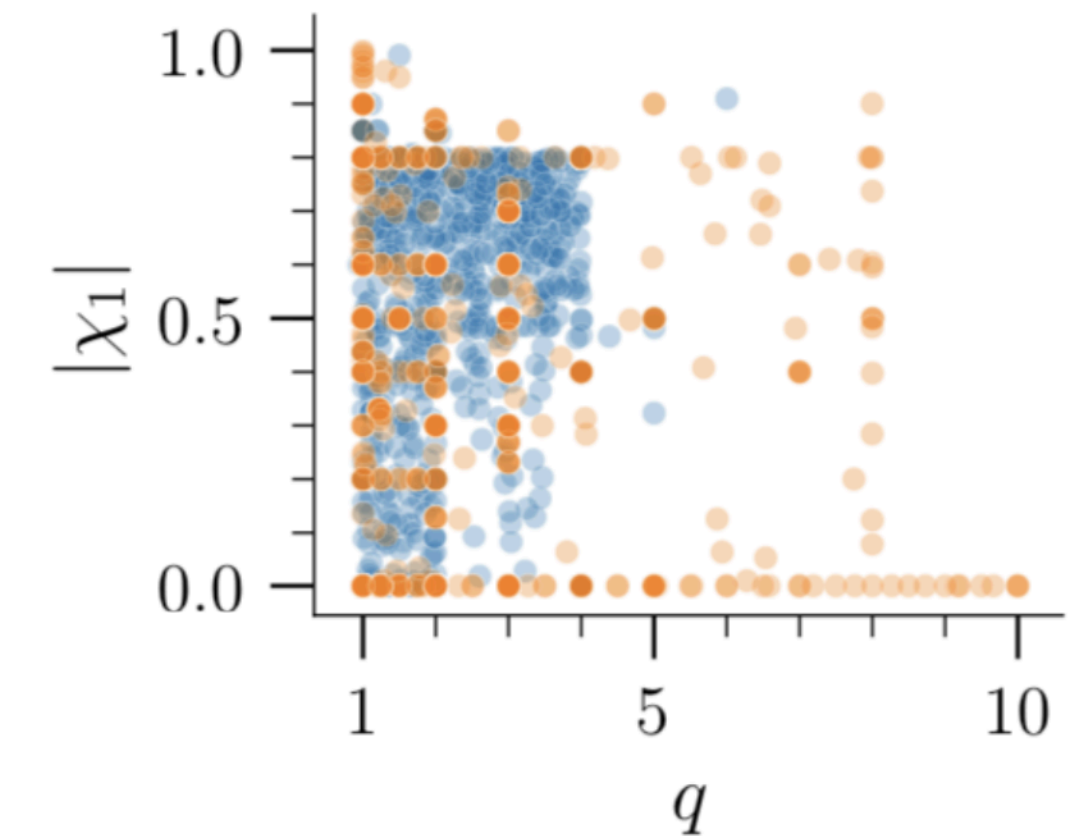
Phenomenological (Phenom)



Power-series for
 $\tilde{h}_{lm}(\theta; f)$

Phenom Ajith+ 08
Phenom{B,C} (aligned spins) Ajith+ 11, Santamaria+ 10
PhenomD Husa+ 15, Khan+ 15
PhenomHM London+ 18
Phenom{P, Pv2} (precessing) Hannam+ 13
Phenom{Pv3, Pv3HM} Khan+ 19, Khan+ 20
PhenomX{AS, HM, P, PHM} Pratten+ 20,
Garcia-Quiros+ 20ab, Pratten+ 21
PhenomPNR Hamilton+ 21
PhenomX_{O4a, Taylor} Thompson+24, Colleoni+25
PhenomTE Lluc-Planas+ 25

NR surrogate Models



Direct interpolation
in parameters θ

Field+ 13
Blackman+ 15,17,18 precessing-spins
Varma+ 18,19 precessing-spins
Yoo+ 22, Islam+ 22,23 (high q)
Walker+ 23 (extreme spins)
Yoo+ 23 (GW memory + hybridization)
Islam+ 21, Maurya+ 25, Nee+ 25 (eccentricity)

EOB models: physics content & version history



Tables from LISA waveform whitepaper
Living Reviews Relativity (arXiv:2311.01300)

SEOBNR

family	waveform model	spins	ecc./hyper.	NR & Teukolsky calib. region	CP-frame modes
1 st	*EOBNRv1 [1434]			$q \leq 4$	
2 nd	EOBNRv2 [1469]			$q \leq 3$	(2, 2)
	SEOBNRv0 [1472]			$q = 1, \chi_{1,2} = \pm 0.4$	
	*EOBNRv2HM [1435]			$q \leq 6$	(2, 2), (2, 1), (3, 3), (4, 4), (5, 5)
	*EOBNRv2HM_ROM [504]				
	*SEOBNRv1 [1424]			$q \leq 6, \chi_{1,2} = \pm 0.4$	
3 rd	*SEOBNRv1_ROM [1455]	✓			(2, 2)
	*SEOBNRv2 [1425]				
	*SEOBNRv2_ROM [1456]			NR: $q \leq 8, \chi_{1,2} \leq 0.98$ Teuk.: $q = 1000, \chi_{1,2} \leq 0.99$	
	SEOBNRv2P [1251]	✓✓			(2, 2), (2, 1)
	*SEOBNRv3P [1425, 1437]				
	*SEOBNRv4 [754]	✓			(2, 2)
4 th	*SEOBNRv4_ROM [754]	✓✓			(2, 2), (2, 1)
	*SEOBNRv4P [756]				
	*SEOBNRv4HM [1428]	✓		NR: $q \leq 8, \chi_{1,2} \leq 0.995$ Teuk.: $q = 1000, \chi_{1,2} \leq 0.99$	(2, 2), (2, 1), (3, 3), (4, 4), (5, 5)
	*SEOBNRv4HM_ROM [1459]	✓✓			
	*SEOBNRv4PHM [756]	✓			
	*SEOBNRv4PHM_surr [1460]	✓			
	*SEOBNRv4EHM [758]	✓✓	✓		(2, 2), (2, 1), (3, 3), (4, 4)
	*SEOBNRv4PHM_4dq2 [1463]				
5 th	*SEOBNRv5 [1429]	✓		NR: $q \leq 20, \chi_{1,2} \leq 0.998$ Teuk.: $q = 1000, \chi_{1,2} \leq 0.99$	(2, 2)
	*SEOBNRv5_ROM [1429]				
	*SEOBNRv5HM [1429]	✓✓			(2, 2), (2, 1), (3, 2), (3, 3), (4, 3), (4, 4), (5, 5)
	*SEOBNRv5PHM [1441]				
✓ aligned spin, ✓✓ arbitrary spin orientations. * implemented in LALsuite, and for the latest version (v5) in the open-source Python package pySEOBNR [1490].					

TEOBResumS

Physical content		GIOTTO	DALI
Analytic information	$A(r)$	Pseudo 5PN, resummed	Pseudo 5PN, resummed
	$D(r)$	3PN, resummed	5PN, resummed
	$Q(r, pr_*)$	3PN	5PN (local)
	G_S, G_{S*}	3.5PN	3.5PN
	r_c	NLO	NLO
NR information	a_c^6	Effective parameter in $A(r)$	
	c_{N3LO}	Effective parameter in G_S, G_{S*}	
	NQCs	Ensure correct transition between plunge and merger	
	Ringdown	Phenomenological model, quasi-circular	
	BBH NR Validation region	$q \geq 10$ and test-mass with $ \chi_{1,2} \geq 0.99$; $10 < q < 128$ no-spins	
Spins	Aligned	✓	✓
	Precessing	✓	-
Orbital dynamics		Circular	Generic (bound & open)
Subdominant CP modes	Inspiral to merger	$(\ell, m) \leq 8$	
	Merger/ringdown	$(\ell, m) = (2, 1), (2, 2), (3, 2), (3, 3), (4, 2), (4, 4), (5, 5)$	

Table 11. Current/default physics incorporated in TEOBResumS. TEOBResumS is developed open source and publicly available at https://bitbucket.org/eob_ihes/teobresums/. Symbols are defined in the text. Historical milestones in the model developments and the associated references can be found in the Wiki page of the repository. Robustness tests and the detailed parameter space coverage can be found in the Wiki page and are continuously updated. TEOBResumS can also be installed via `pip install teobresums`. The code is interfaced to state-of-art GW data-analysis pipelines, including bilby and pycbc. The code uses semantic versioning since the deployment of the GIOTTO version. Earlier versions of TEOBResumS are implemented in LAL Simulation and reviewed by LVK.



Table from LISA waveform whitepaper
Living Reviews Relativity (arXiv:2311.01300)

Waveform Family	Domain	Waveform Model	Spins	Mode Content		Eccentricity	Calibration Region	
1st generation	FD	IMRPhenomA	✗		(2,±2)	no	q ≤ 4	
2nd generation		IMRPhenomB	✓				CP	NR calibration: q ≤ 4, χ _{1/2} ≤ 0.75 χ _{1/2} ≤ 0.85 (for q = 1)
		IMRPhenomC	✓					
		IMRPhenomP	✓✓					
3rd generation		IMRPhenomD	✓		(2,±2),(2,±1),(3,±3), (4,±3),(4,±4)	NR calibration: q ≤ 18, χ _{1/2} ≤ 0.85 -0.95 ≤ χ _{1/2} ≤ 0.98 (for q = 1)		
		IMRPhenomPv2	✓✓	CP				
		IMRPhenomPv3	✓✓					
		IMRPhenomHM	✓					
		IMRPhenomPv3HM	✓✓	CP				
4th generation		IMRPhenomXAS	✓		(2,±2)	in development	NR calibration: q ≤ 18, χ _{1/2} ≤ 0.99 Teukolsky calibration: q ≤ 1000	
	IMRPhenomXP	✓✓	CP					
	IMRPhenomXHM	✓		(2,±2),(2,±1),(3,±2), (3,±3),(4,±4)				
	IMRPhenomXPHM	✓✓	CP					
	TD	IMRPhenomT	✓		(2,±2)	in development <i>Lluc-Planas+ 25</i>	NR calibration: q ≤ 18, χ _{1/2} ≤ 0.99 Teukolsky calibration: q ≤ 1000	
		IMRPhenomTP	✓✓	CP				
		IMRPhenomTHM	✓		(2,±2),(2,±1),(3,±3), (4,±4),(5,±5)			
		IMRPhenomTPHM	✓✓	CP				
✗ no spins ✓ spins aligned with orbital angular momentum ✓✓ precessing spins CP mode content in co-precessing frame								

Table 12. Progress in the development of phenomenological waveform models in frequency domain (FD) and time domain (TD).

Surrogate construction: 1-D example for $\{q\}$



1. Choose data decomposition: $h(t) = A(t)e^{i\phi(t)}$

2. Construct reduced basis

$$A(q_i, t) = \sum_j c_j(q_i) \hat{e}_j(t)$$

3. Empirical time-interpolation

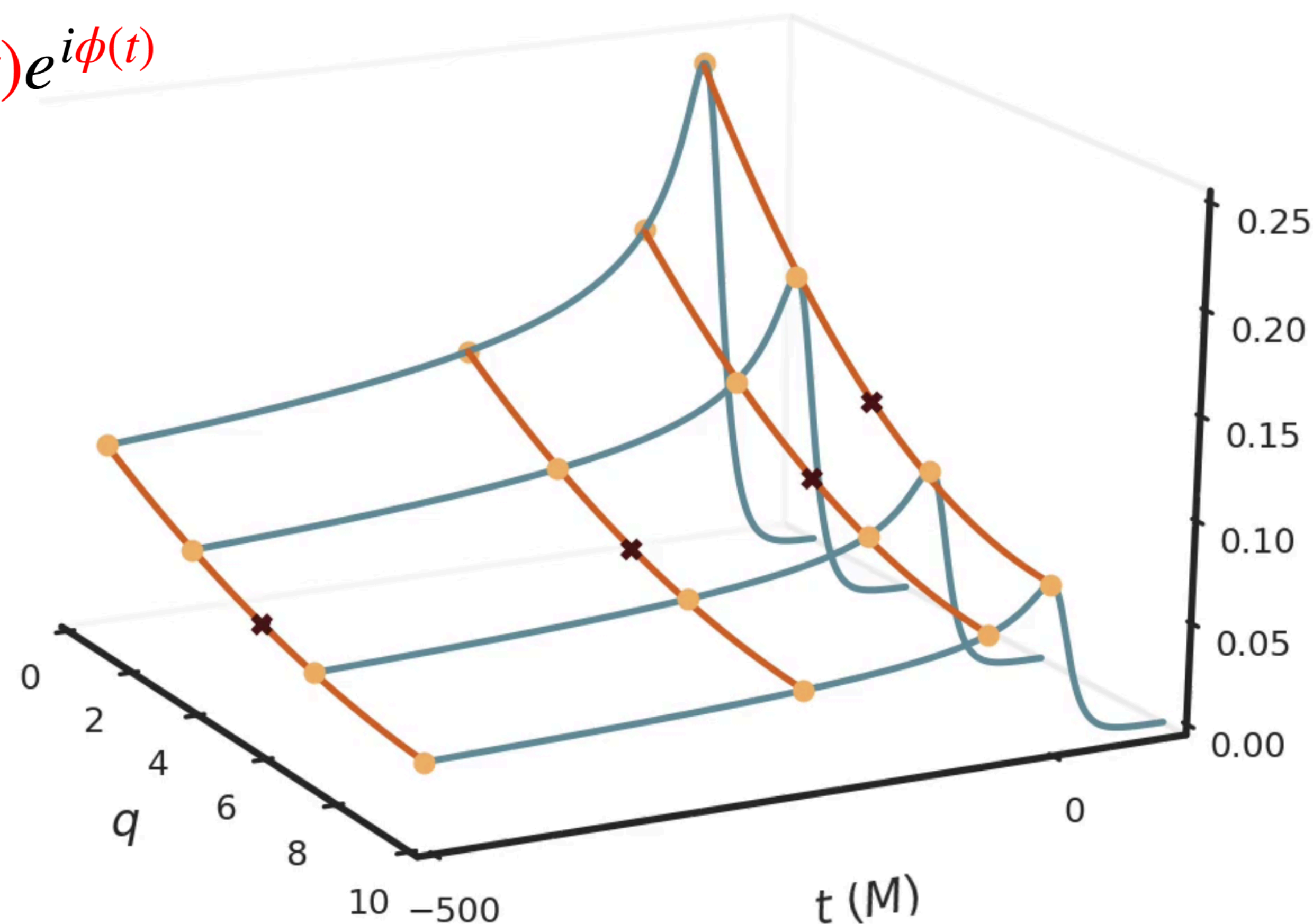
$$A(q_i, \{t_k\}) \Rightarrow c_j(q_i) = c_j[A(q_i, \{t_k\})]$$

4. Parameter-interpolation

$$\Rightarrow A(q, t_k) \text{ (function of continuous } q\text{)}$$

5. to compute the waveform at some q :

$$A(q, t) = \sum_j c_j[A(q, \{t_k\})] \hat{e}_j(t)$$



visualisations courtesy Vijay Varma

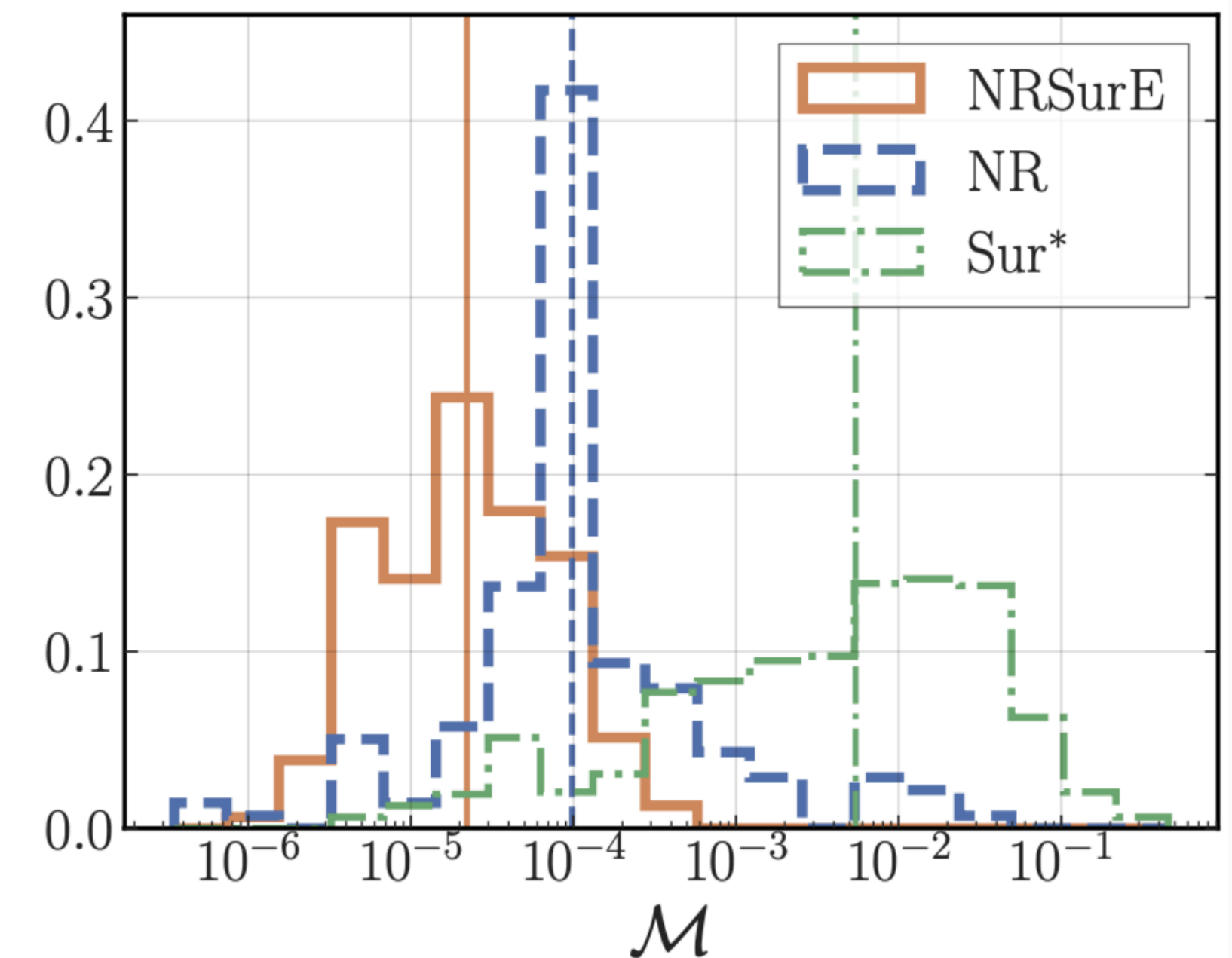
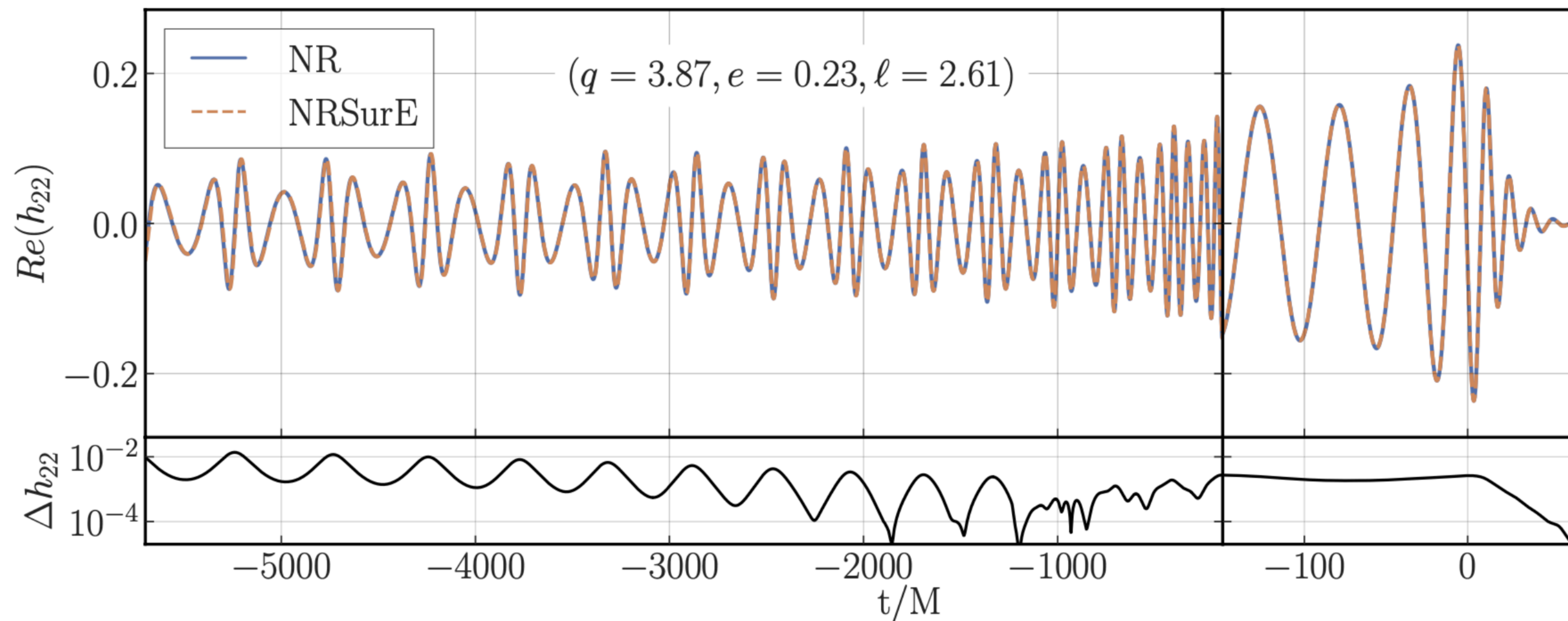
Surrogate construction: validation



- **Leave-k-out cross validation**

- construct surrogate from $N - k$ NR-waveforms
- use remaining k waveforms to test accuracy
- repeat for different sets of k waveforms

NR-surrogates limited by NR-capabilities (length, parameter space coverage). But can also 'surrogate' other models.

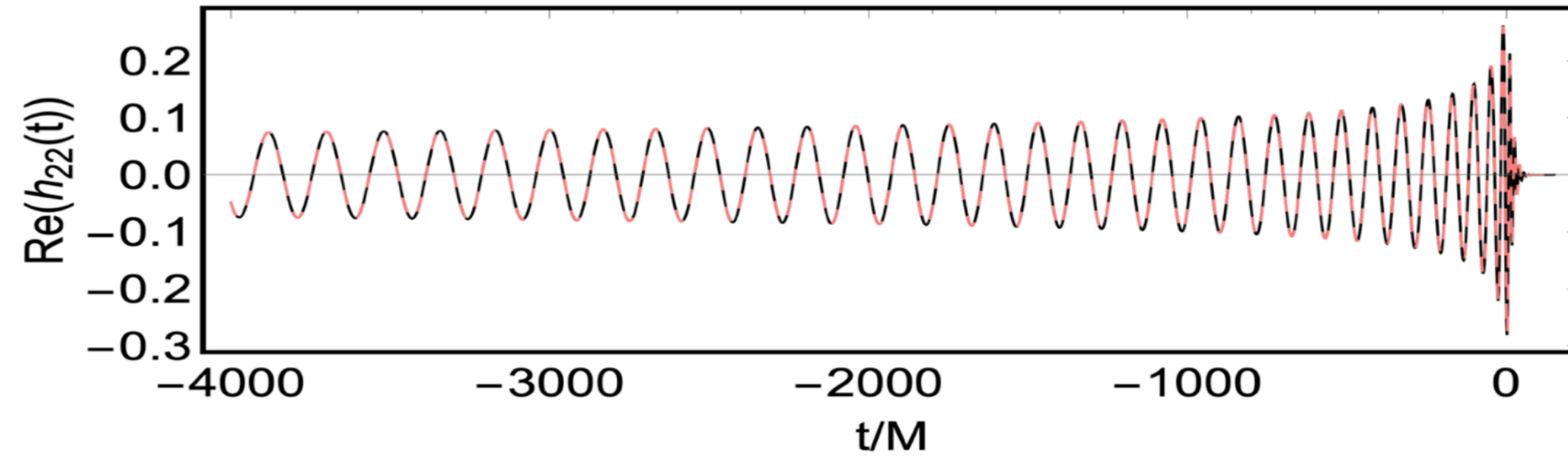


Example: Nee+ [arXiv:2510.00106](https://arxiv.org/abs/2510.00106)

Waveform models: Some example plots

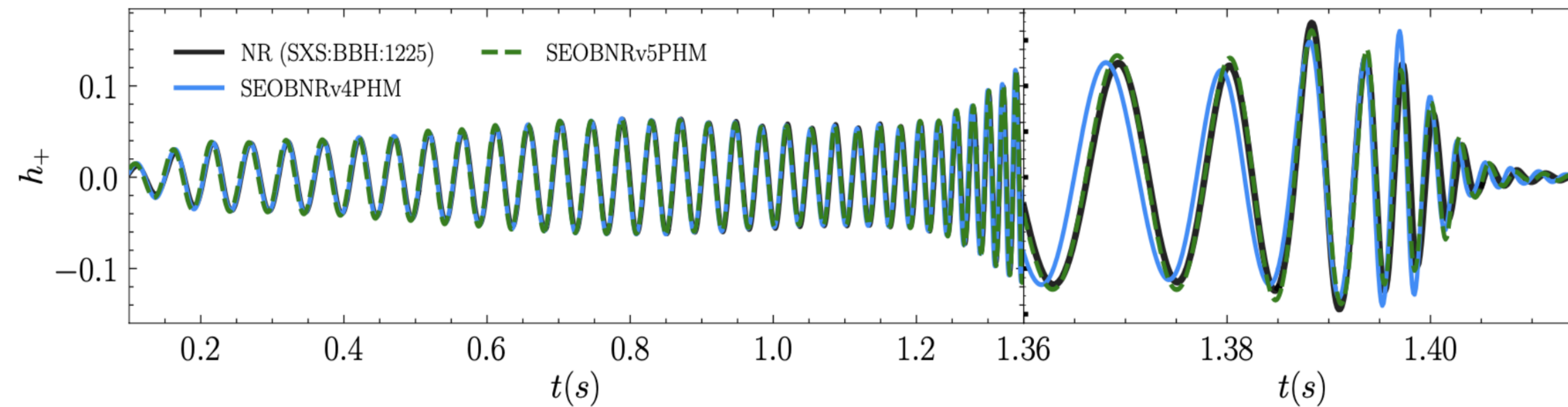


*aligned-spin
(no precession)*



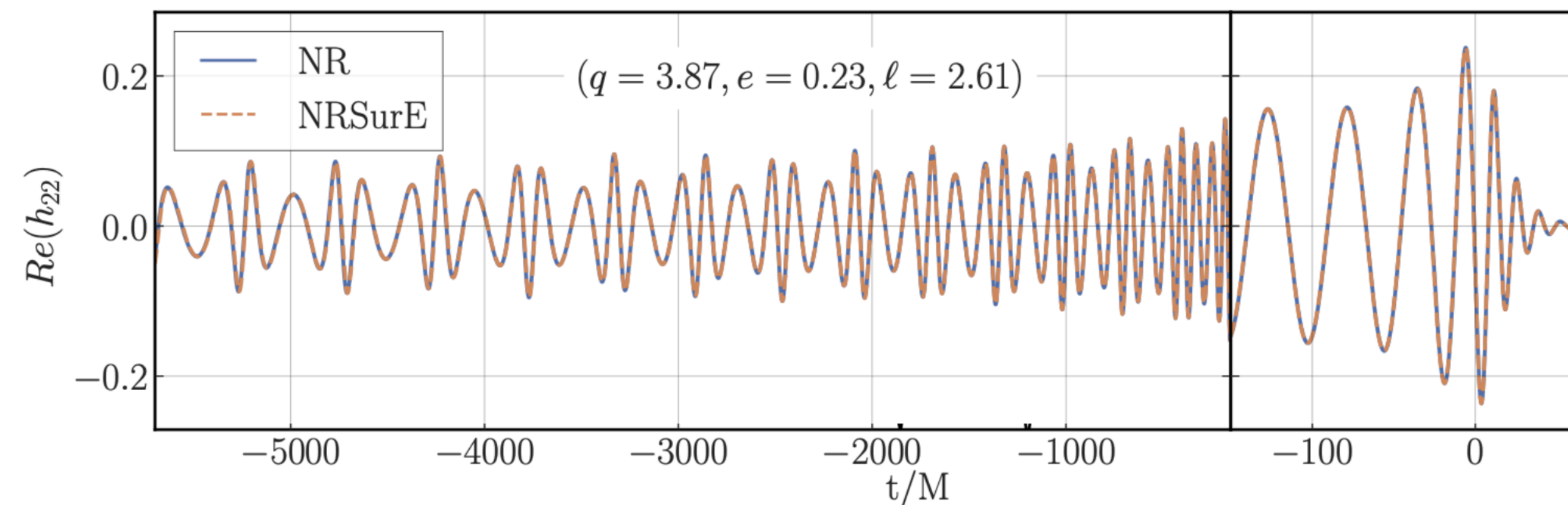
*IMRPhenomT
Estelles+ 20*

*generic spin
(orbital plane precession)*



*SEOBv5PHM
Ramos-Buades+ 23*

non-precessing eccentric



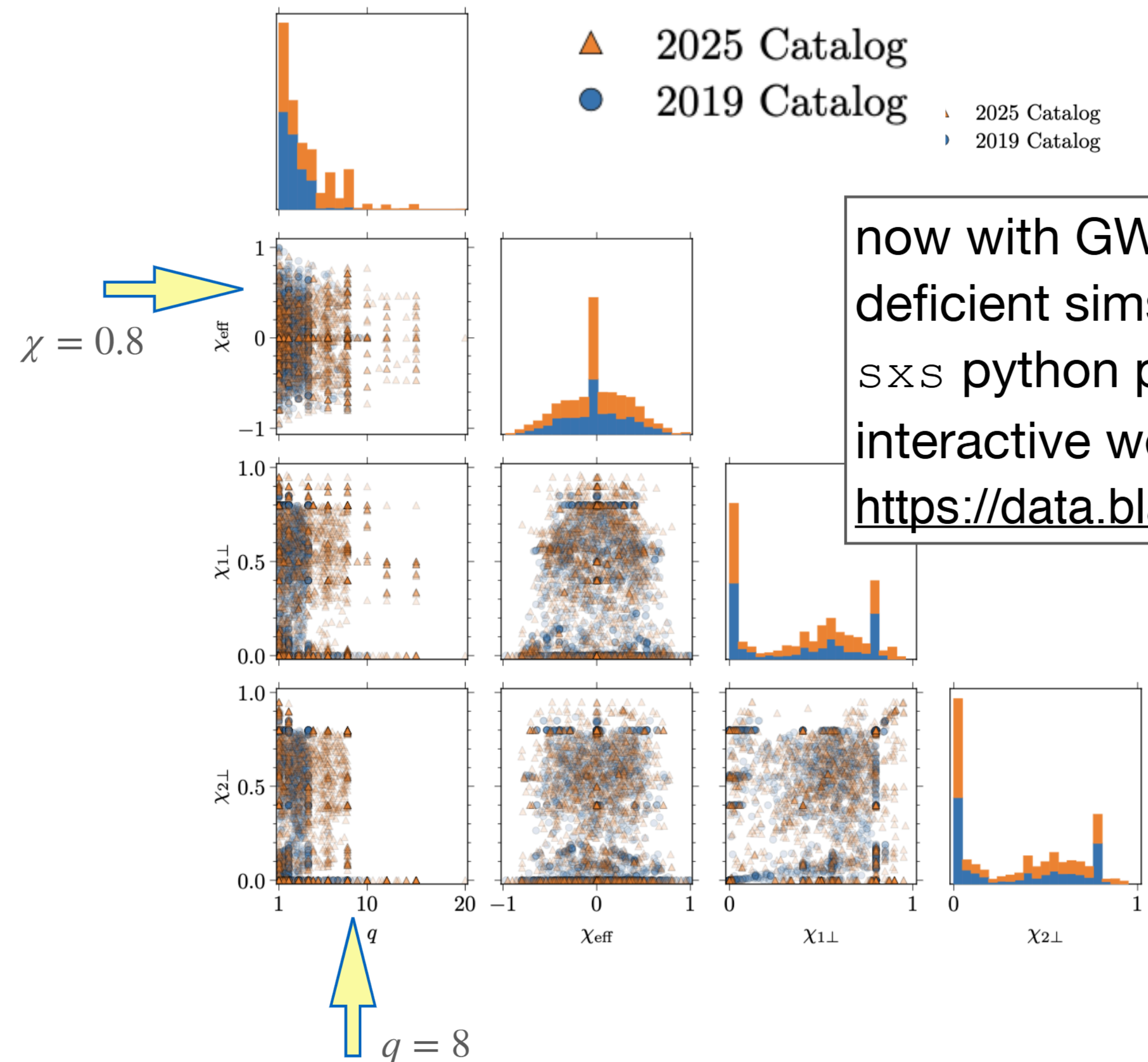
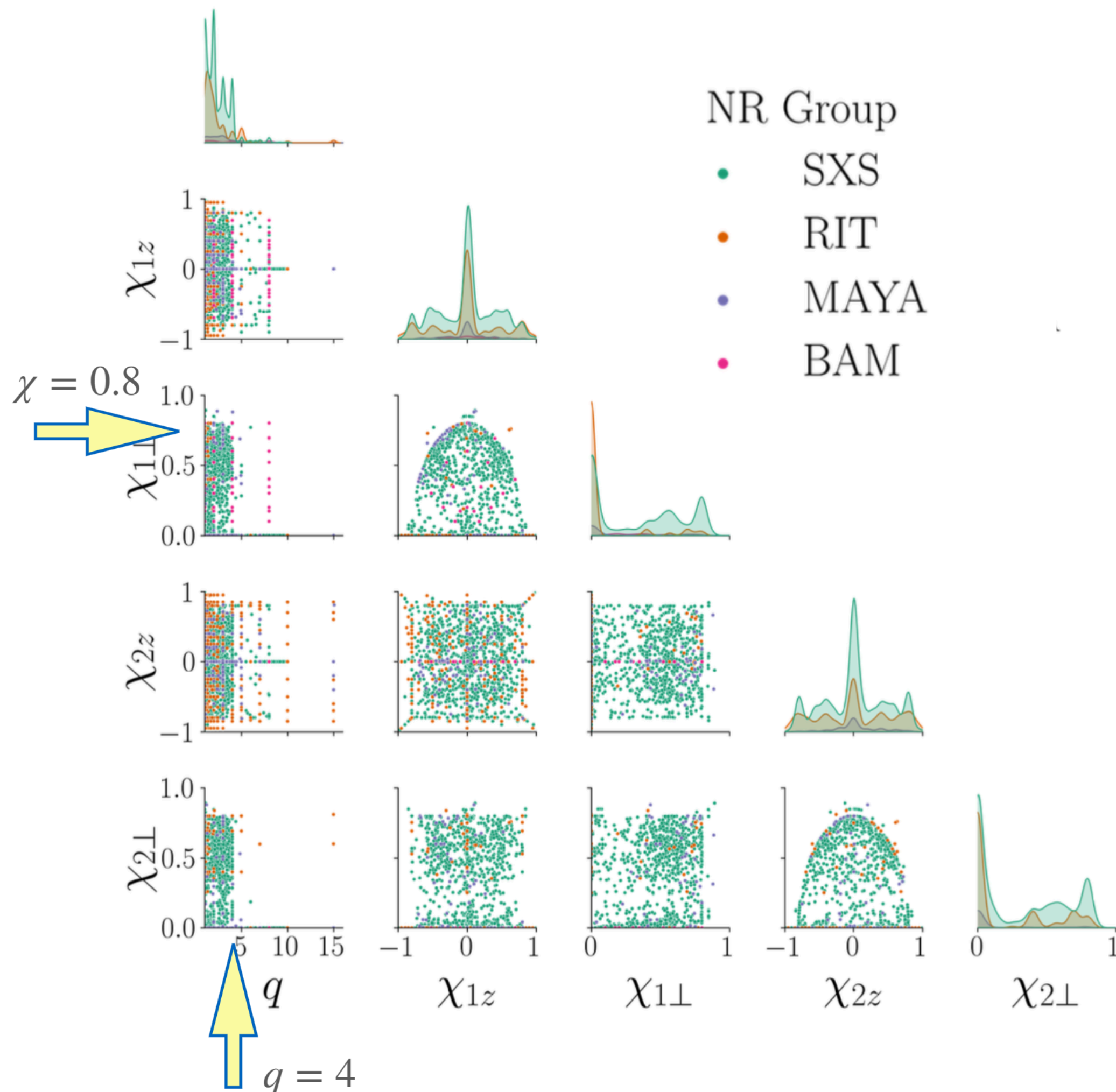
*NRSurE
Nee+ 25*

Numerical relativity: parameter space coverage



*LISA waveform whitepaper
Living Reviews Relativity
(arXiv:2311.01300)*

*SXS Catalog update
Scheel+ (CQG 2025) arXiv:2505.13378*



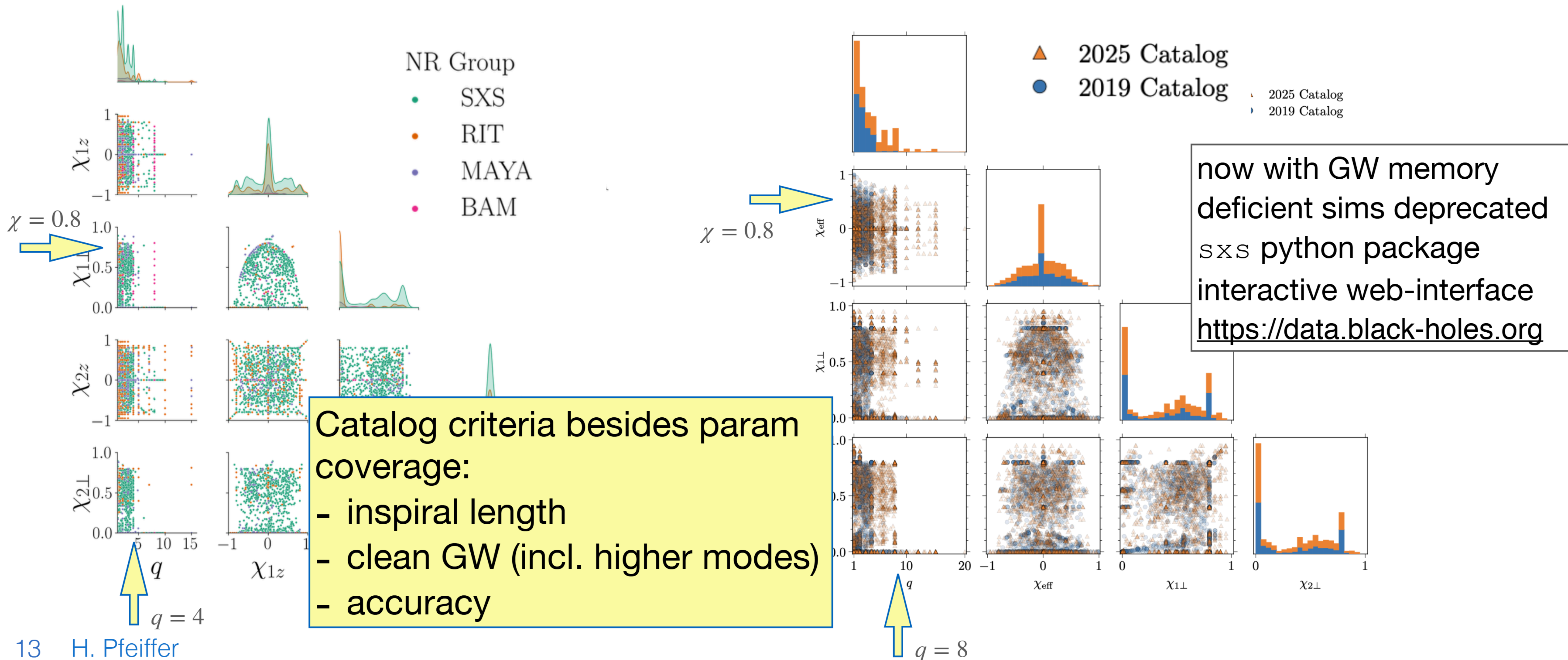
now with GW memory
deficient sims deprecated
SXS python package
interactive web-interface
<https://data.black-holes.org>

Numerical relativity: parameter space coverage



LISA waveform whitepaper
Living Reviews Relativity
(arXiv:2311.01300)

SXS Catalog update
Scheel+ (CQG 2025) arXiv:2505.13378

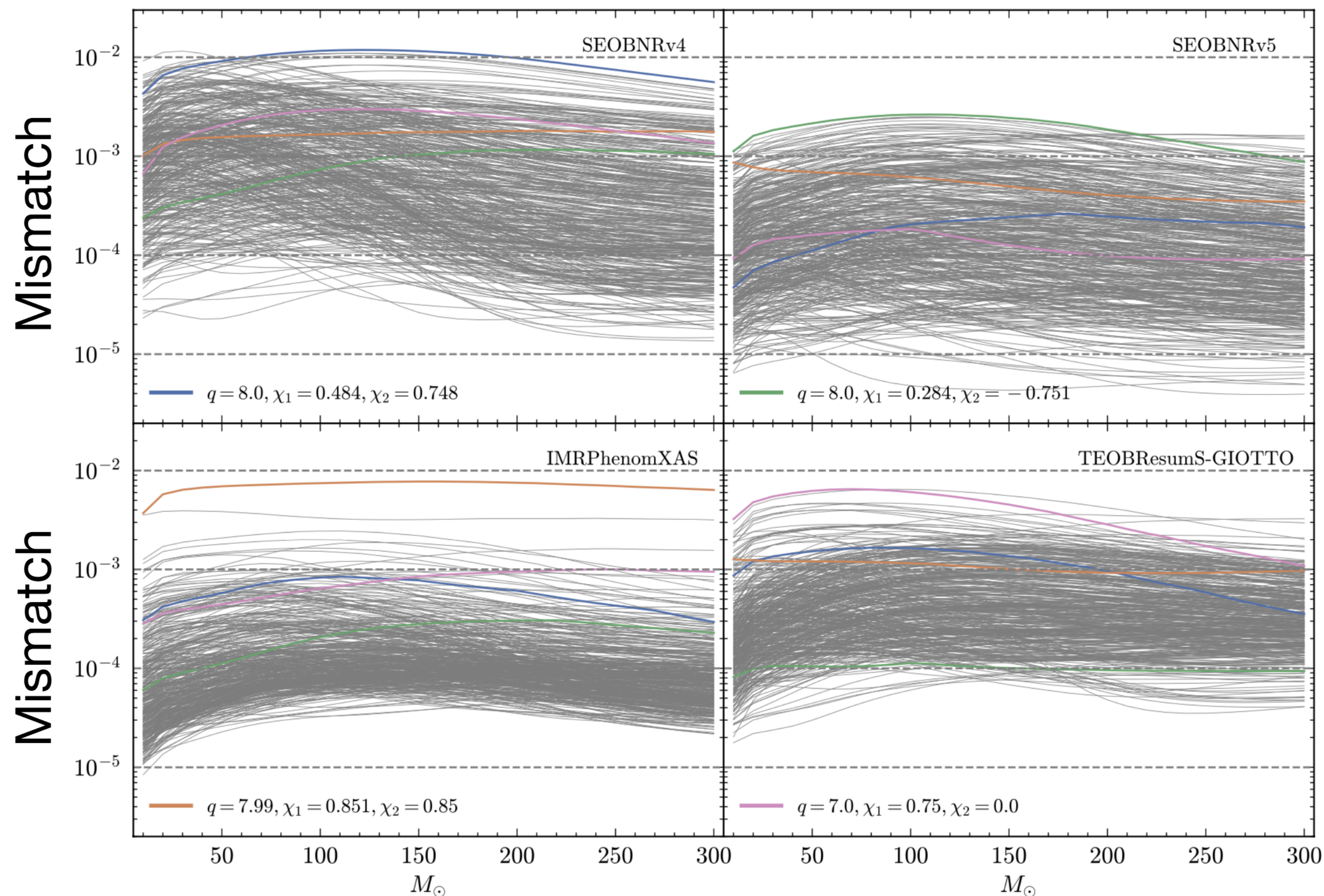


NR role in waveform model development



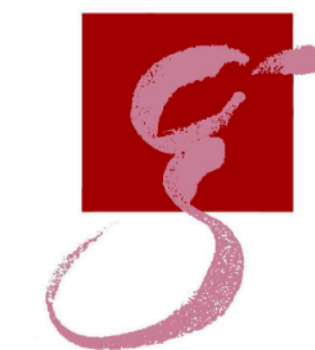
- **Assess accuracy** of waveform models
- Determine **importance of improvements**
 - higher order
 - additional physics
 - higher modes, precession, memory
- **Calibrate model-parameter** for improved agreement
 - GW modes & fluxes
 - merger dynamics
 - ringdown attachment
 - ...
- $\Rightarrow$ generations of models

Errors in 4 waveform models as compared to 442 NR simulations



As example: Pompili+ 2303.18039

Models used by LVK...



Catalog release	Data analysed	Search templates	Sensitivity estimates	Parameter estimation
GWTC-1.0 (Abbott et al. 2019a)	O1, O2	SEOBNRv4_ROM, TAYLORF2	-	IMRPHENOMPv2, IMRPHENOMPv2_NRTIDAL, SEOBNRv3, SEOBNRv4_ROM_NRTIDAL, SEOBNRv4T, TAYLORF2, TEOBRESUMS
GWTC-2.0 (Abbott et al. 2021a)	O3a	SEOBNRv4_ROM, TAYLORF2	SEOBNRv4_OPT	IMRPHENOMD, IMRPHENOMD_NRTIDAL, IMRPHENOMHM, IMRPHENOMPv2, IMRPHENOMPv2_NRTIDAL, IMRPHENOMPv3HM, IMRPHENOMNSBH, NRSUR7DQ4, SEOBNRv4_ROM_NRTIDALV2_NSBH, SEOBNRv4_ROM, SEOBNRv4HM_ROM, SEOBNRv4P, SEOBNRv4PHM, SEOBNRv4T_SURROGATE, TAYLORF2, TEOBRESUMS
GWTC-2.1 (Abbott et al. 2024)	O1–O3a	SEOBNRv4_OPT, SEOBNRv4_ROM, SPINTAYLORT4, TAYLORF2	SEOBNRv4P, SEOBNRv4PHM, SPINTAYLORT4	IMRPHENOMPv2_NRTIDAL, IMRPHENOMXPHM, SEOBNRv4PHM,
GWTC-3.0 (Abbott et al. 2023a)	O3b	SEOBNRv4_OPT, SEOBNRv4_ROM, SPINTAYLORT4, TAYLORF2	SEOBNRv4P, SEOBNRv4PHM, SPINTAYLORT4	IMRPHENOMNSBH, IMRPHENOMXPHM, SEOBNRv4_ROM_NRTIDALV2_NSBH, SEOBNRv4PHM
GWTC-4.0 (Abac et al. 2025b)	O4a	IMRPHENOMD, SEOBNRv4_OPT, SEOBNRv4_ROM, SEOBNRv5_ROM, SPINTAYLORT4, TAYLORF2	IMRPHENOMXPHM	IMRPHENOMNSBH, IMRPHENOMPv2_NRTIDALV2, IMRPHENOMXO4A IMRPHENOMXPHM_SPINTAYLOR, NRSUR7DQ4, SEOBNRv4_ROM_NRTIDALV2_NSBH, SEOBNRv5PHM

... and their physics content



Model	Precession	Multipoles (ℓ , $ m $)	Matter	Reference
SPINTAYLORT4	✓	$\ell \leq 4$	✓	Isoyama et al. (2020)
TAYLORF2	×	(2, 2)	✓	Damour et al. (2001)
IMRPHENOMD	×	(2, 2)	×	Khan et al. (2016)
IMRPHENOMD_NRTIDAL	×	(2, 2)	✓	Dietrich et al. (2019b)
IMRPHENOMHM	×	(2, 2), (2, 1), (3, 3), (3, 2), (4, 4), (4, 3)	×	London et al. (2018)
IMRPHENOMNSBH	×	(2, 2)	✓	Thompson et al. (2020)
IMRPHENOMPv2	✓	(2, 2)	×	Bohé et al. (2016)
IMRPHENOMPv2_NRTIDAL	✓	(2, 2)	✓	Dietrich et al. (2019b)
IMRPHENOMPv2_NRTIDALV2	✓	(2, 2)	✓	Dietrich et al. (2019a)
IMRPHENOMPv3HM	✓	(2, 2), (2, 1), (3, 3), (3, 2), (4, 4), (4, 3)	×	Khan et al. (2020)
IMRPHENOMXPHM	✓	(2, 2), (2, 1), (3, 3), (3, 2), (4, 4)	×	Pratten et al. (2021)
IMRPHENOMXPHM_SPINTAYLOR	✓	(2, 2), (2, 1), (3, 3), (3, 2), (4, 4)	×	Colleoni et al. (2025b)
IMRPHENOMXO4A	✓	(2, 2), (2, 1), (3, 3), (3, 2), (4, 4)	×	Thompson et al. (2024)
NRSUR7DQ4	✓	$\ell \leq 4$	×	Varma et al. (2019a)
SEOBNRv3	✓	(2, 2), (2, 1)	×	Pan et al. (2014)
SEOBNRv4_OPT	×	(2, 2)	×	Devine et al. (2016)
SEOBNRv4_ROM	×	(2, 2)	×	Bohé et al. (2017)
SEOBNRv4HM_ROM	×	(2, 2), (2, 1), (3, 3), (4, 4), (5, 5)	×	Cotesta et al. (2020)
SEOBNRv4_ROM_NRTIDAL	×	(2, 2)	✓	Dietrich et al. (2019b)
SEOBNRv4_ROM_NRTIDALV2_NSBH	×	(2, 2)	✓	Matas et al. (2020)
SEOBNRv4P	✓	(2, 2), (2, 1)	×	Ossokine et al. (2020)
SEOBNRv4PHM	✓	(2, 2), (2, 1), (3, 3), (4, 4), (5, 5)	×	Ossokine et al. (2020)
SEOBNRv4T	×	(2, 2)	✓	Steinhoff et al. (2016)
SEOBNRv4T_SURROGATE	×	(2, 2)	✓	Lackey et al. (2019)
SEOBNRv5_ROM	×	(2, 2)	×	Pompili et al. (2023)
SEOBNRv5PHM	✓	(2, 2), (2, 1), (3, 3), (3, 2), (4, 4), (4, 3), (5, 5)	×	Ramos-Buades et al. (2023)
TEOBRESUMS	×	(2, 2), (2, 1), (3, 3), (3, 2), (3, 1)	✓	Akcay et al. (2019)

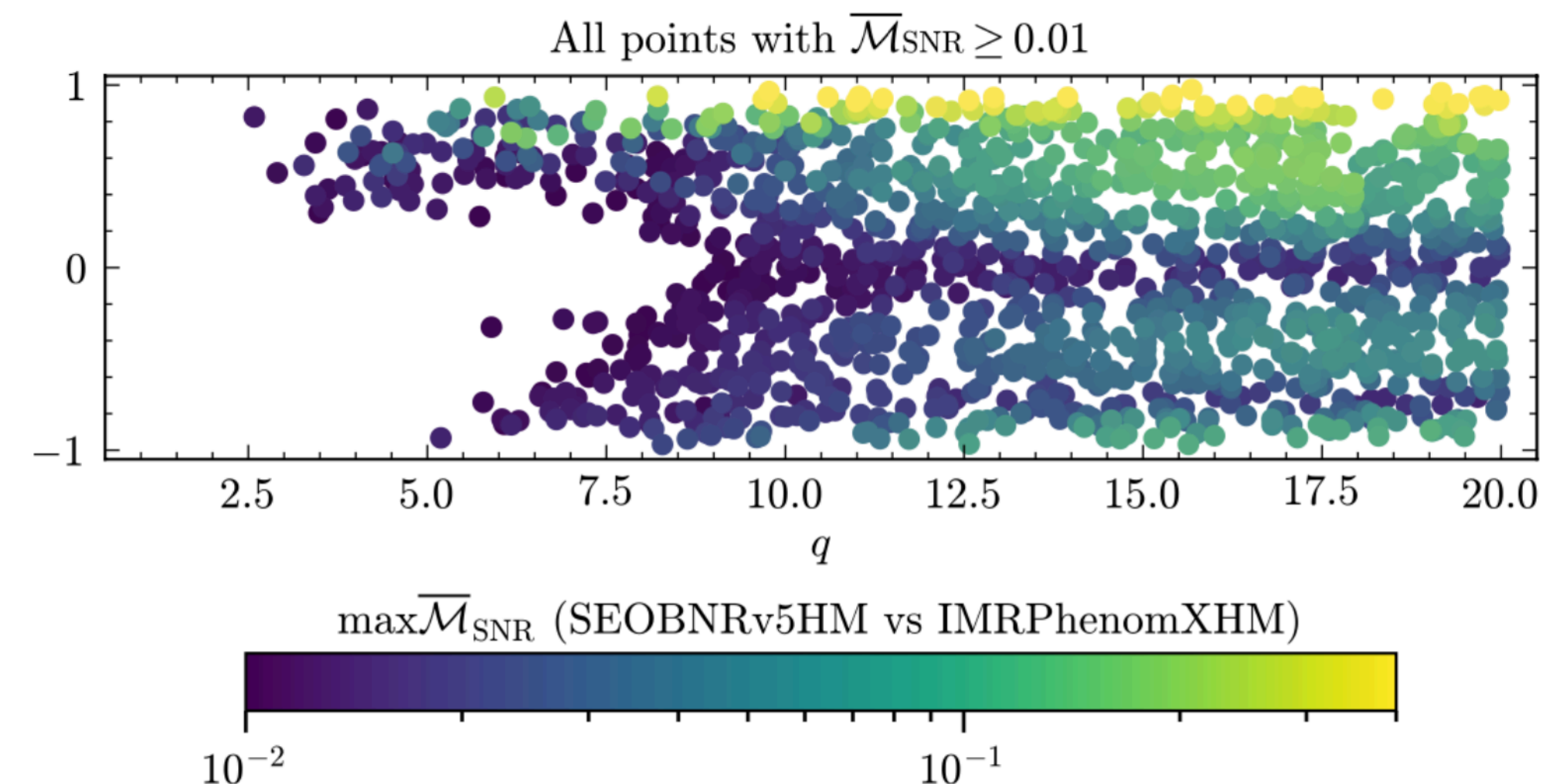


- **BBH quasi-circular:**
 - precessing spins & higher modes are standard
 - IMRPhenom{XO4a,XPHM,XPHM_SpinTaylor}, NRsur_7dq4, SEOBNRv5PHM, TEOBResumS-Giotto
- **BBH - eccentric**
 - non-spinning or aligned-spin, higher modes
 - ESIGMAHM, IMRPhenomTEHM, SEOBNRv4E, SEOBNRv5EHM, TEOBResumS-Dali
- **BNS**
 - at most one of {precession, HM} (except SpinTaylorT4)
 - IMRPhenomPv2_Tidalv2 (extensive tidal fits to NR), SEOBNRv4T (resonant tides)
- **BH-NS**
 - aligned spin, 22
 - IMRPhenomNSBH, SEOBNRv4_ROM_NRTidalv2_NSBH

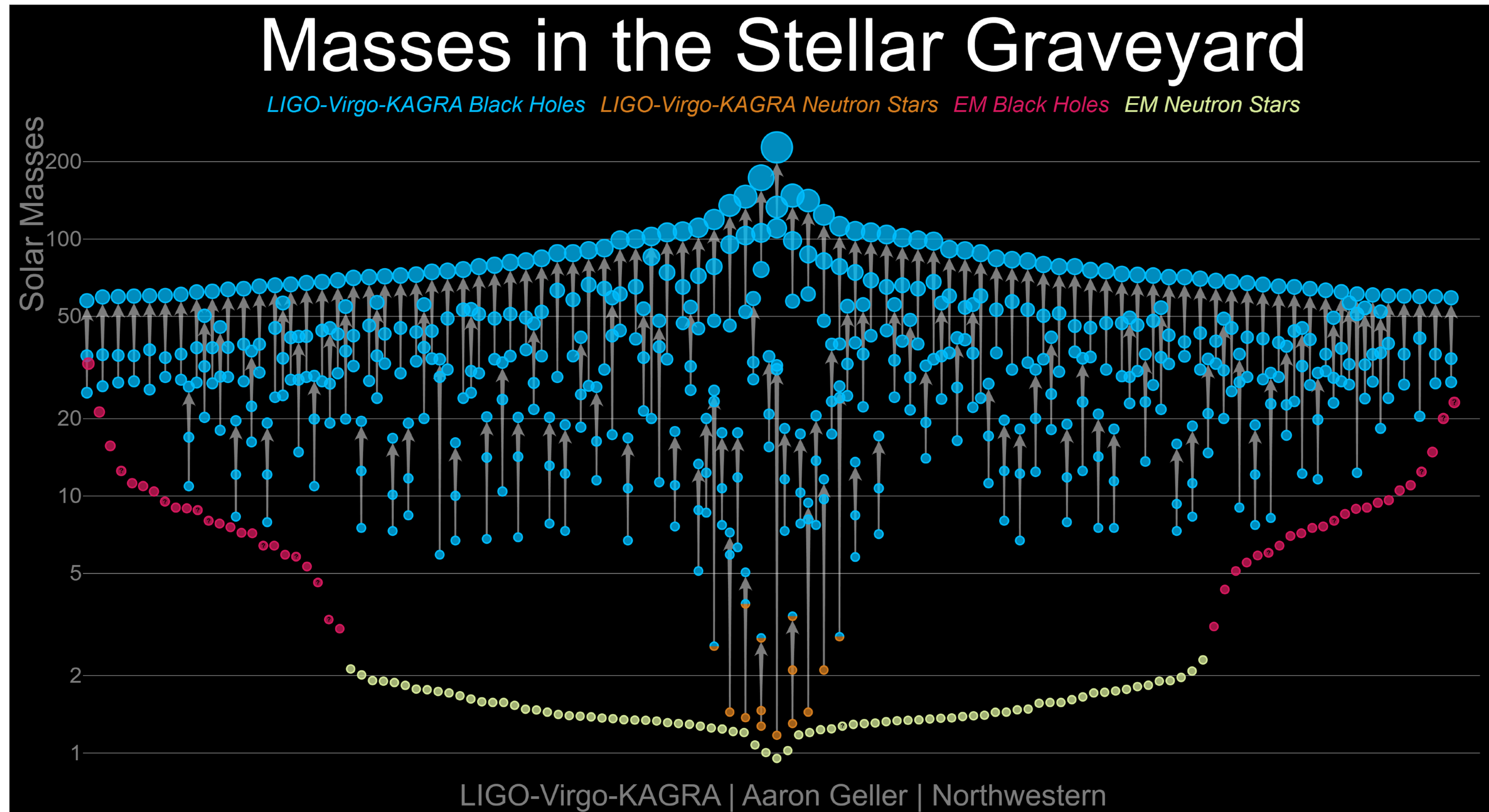
Parameter space coverage



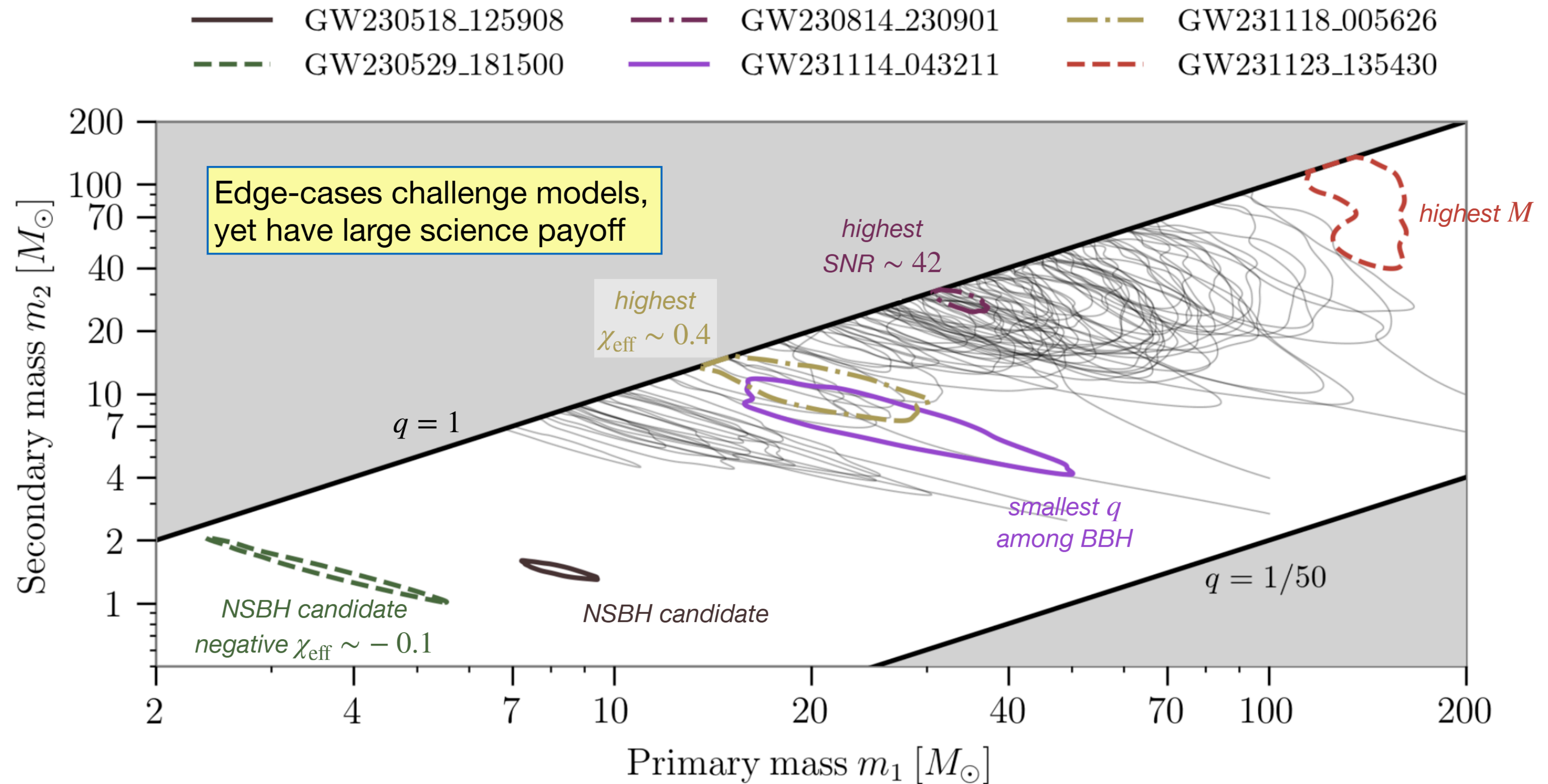
- **BBH**: models can be evaluated for a rather large range of q, χ_i .
They become **less accurate/reliable** for $q \gtrsim 8$ or $\chi_i \gtrsim 0.8$ (lack of NR simulations)
- **BNS**: reasonable NR coverage. Low mass pushes merger out of (today's) detector band. Comparable mass & low spins reduce precession
- **BH-NS**:
 - **strong precession** (large q and large χ_{BH})
 - **disruption** can be in band
 - **lack of NR simulations**
 - No systematic explorations of precession, nor of anti-aligned BH-spins, nor of disruption.
 - GW2001{05,15} analysis:
 - a) compare aligned-spin BH-NS to aligned-spin BBH to argue 'matter unimportant'.
 - b) then use precessing BBH waveforms for PE.



Pompili+, *PRD* 108,124035 (2023), *arXiv*:2303.18039



Events in O4a

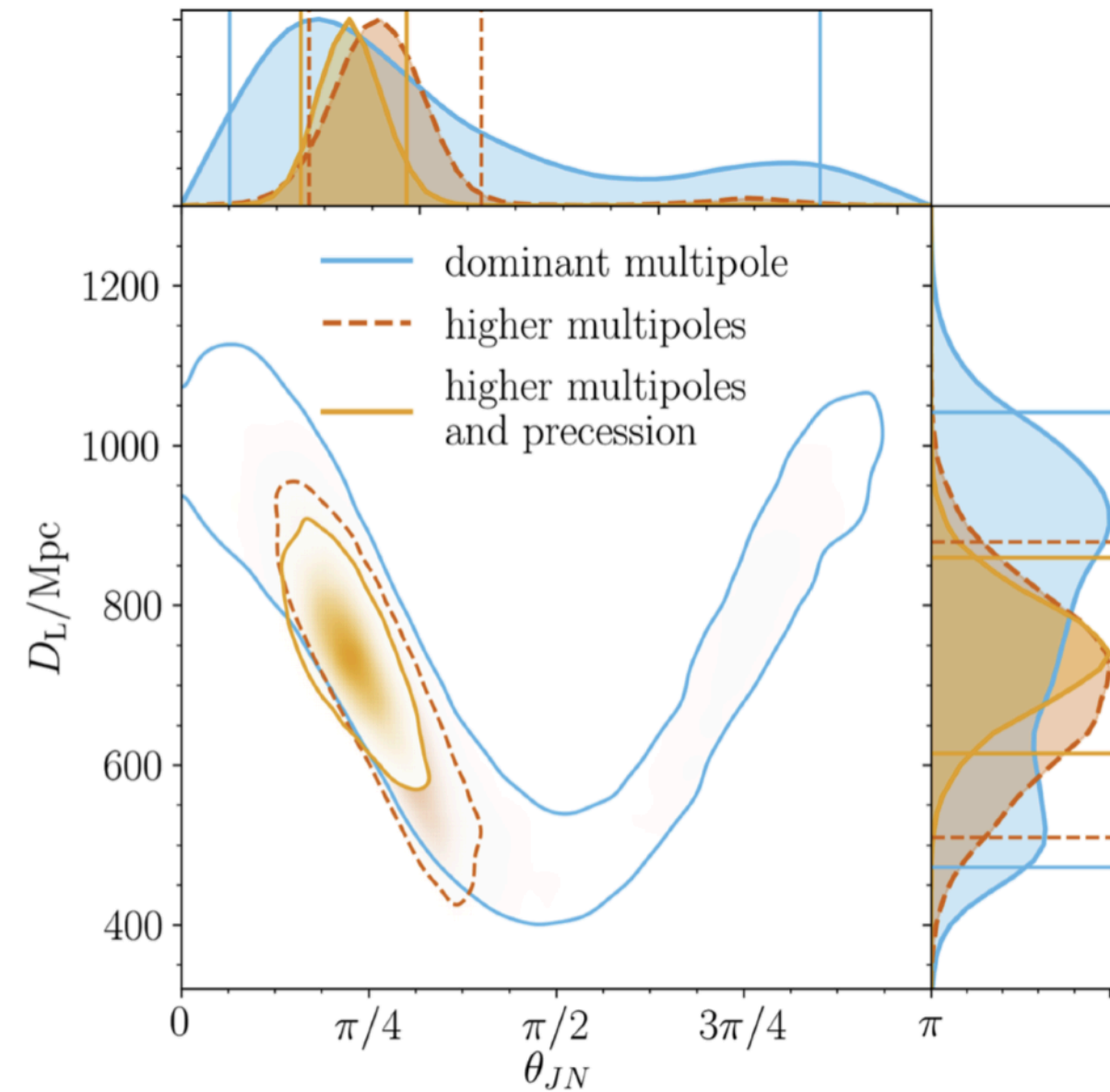


GWTC-4 results (2508.18082)

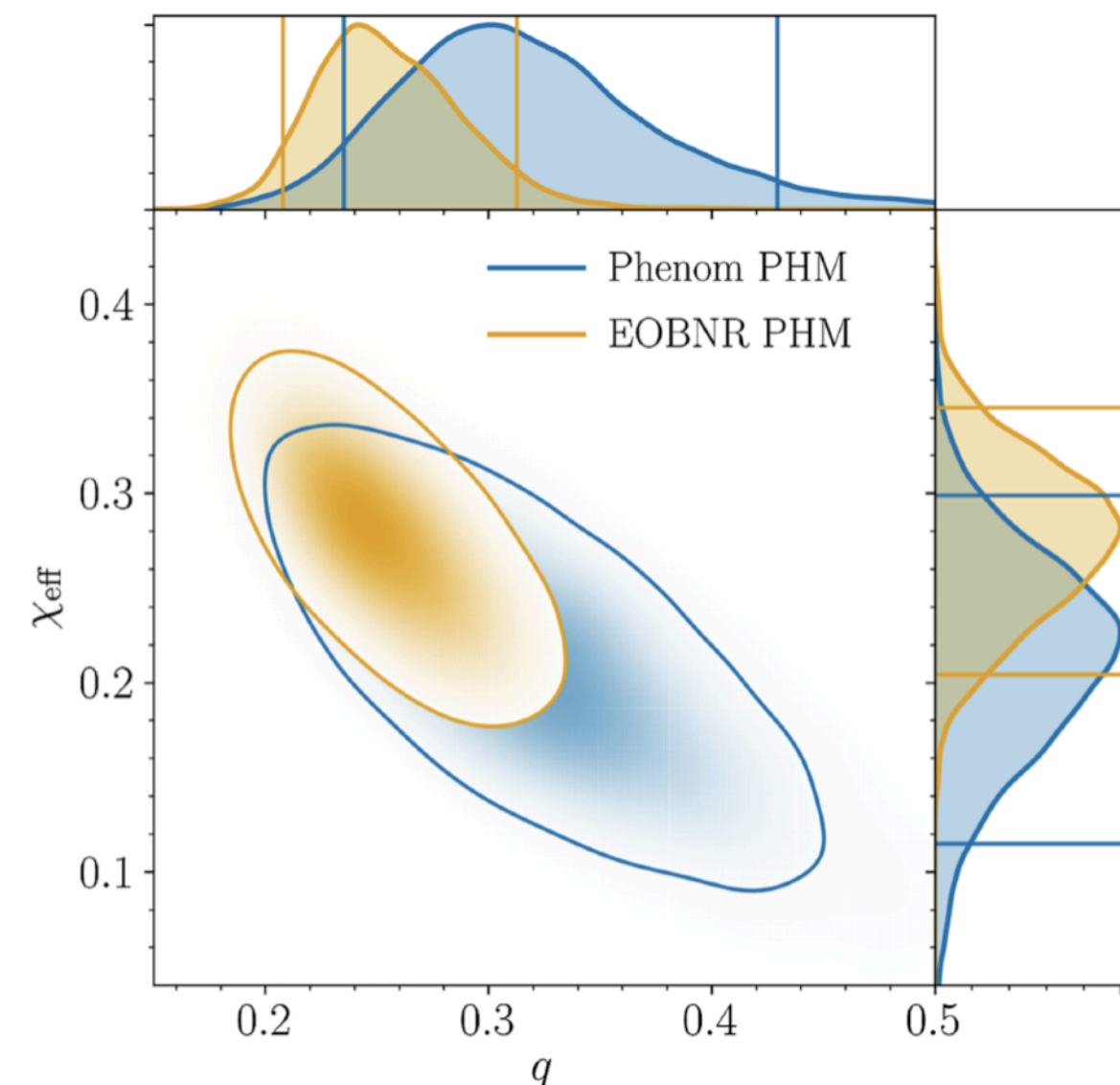
Case study: GW190412 $(30 + 8)M_{\odot}$ at SNR=19



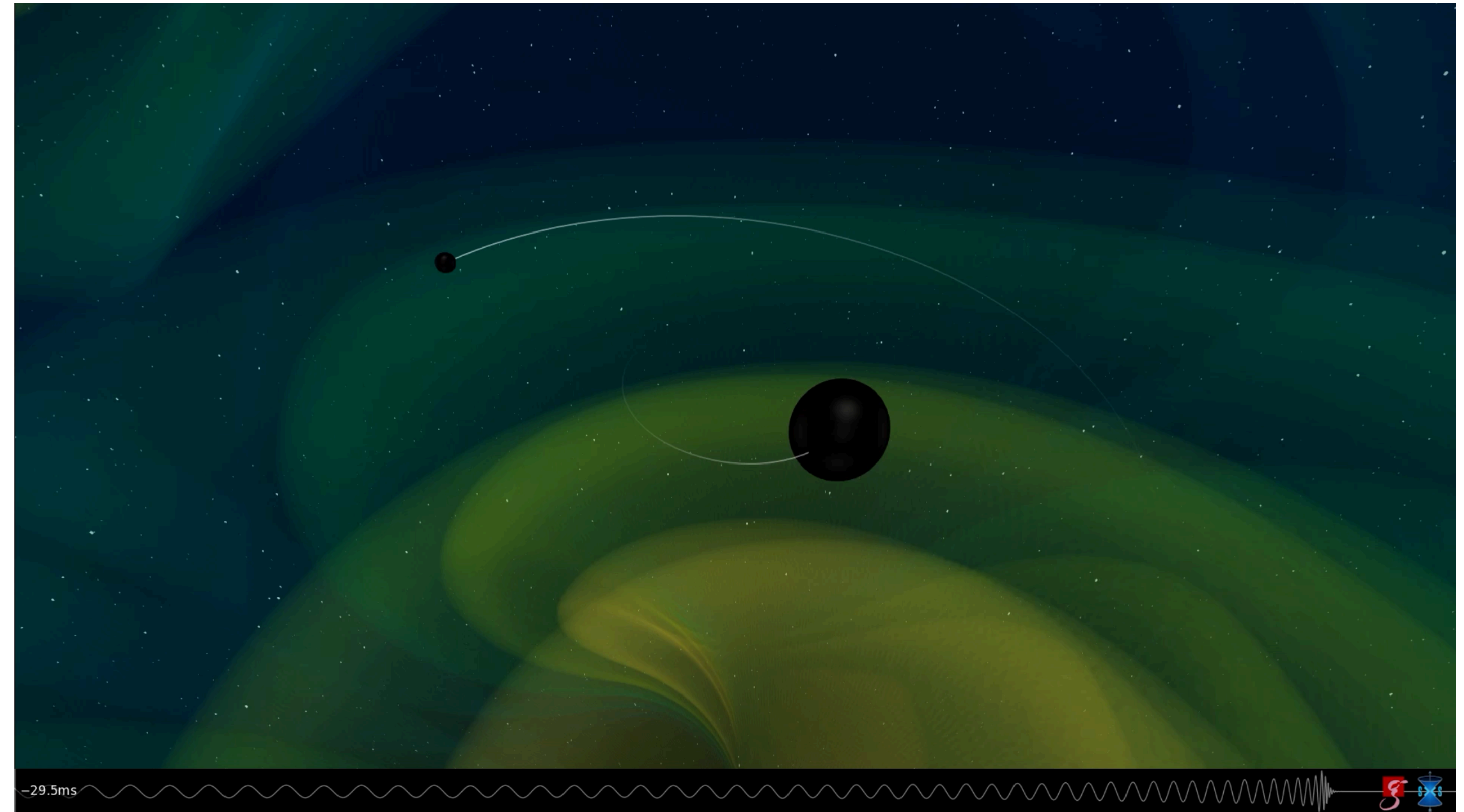
higher-modes break degeneracies



Abbott et al,
PRD 102 043015 (2020)



IMRPhenomPv3HM Khan+ 19; 20
SEOBNRv4PHM Ossokine+ 20



N. Vu, HP

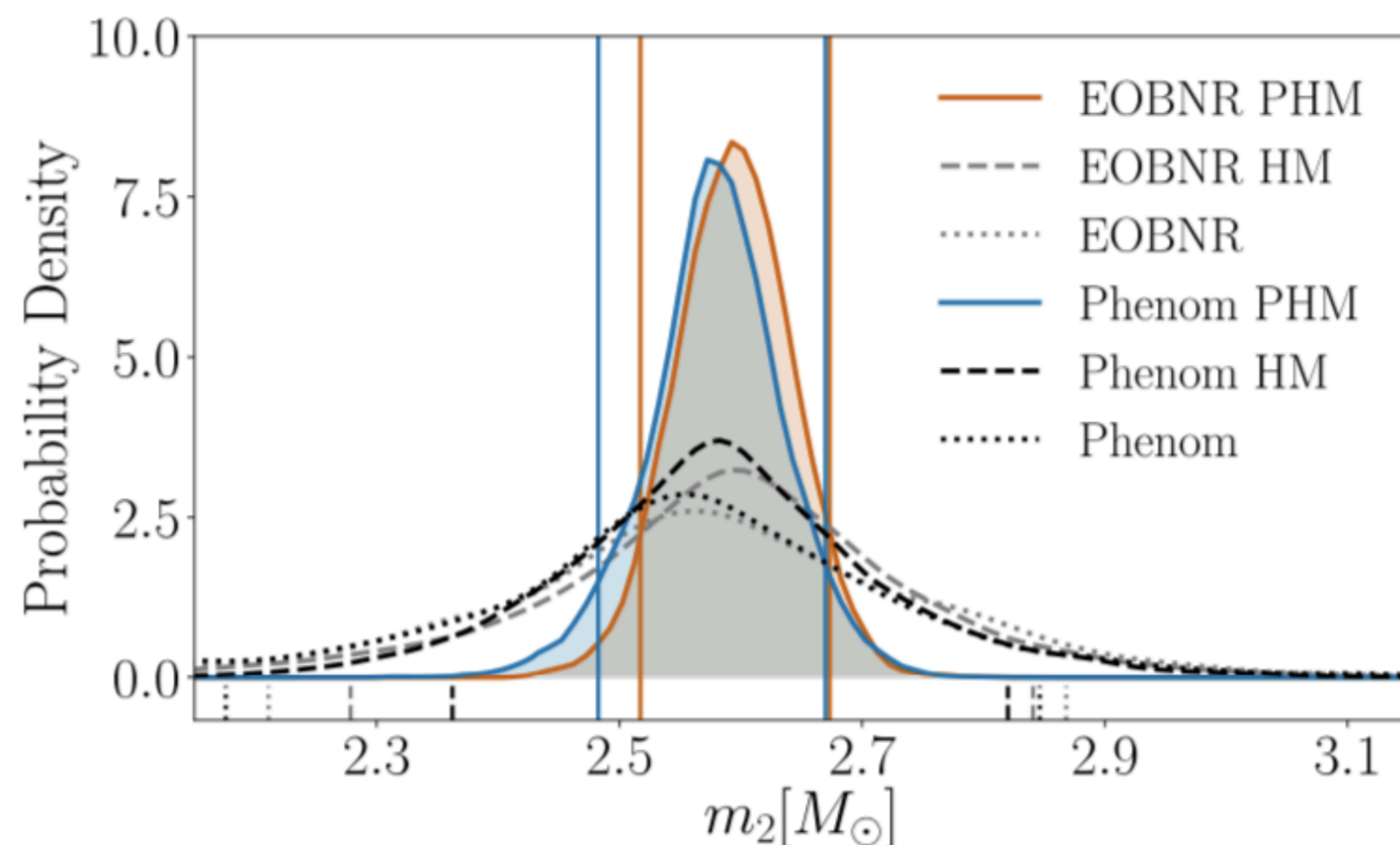
- Adding "physics" to models paid off
- Encouragement to improve accuracy

GW190814 - most unequal masses

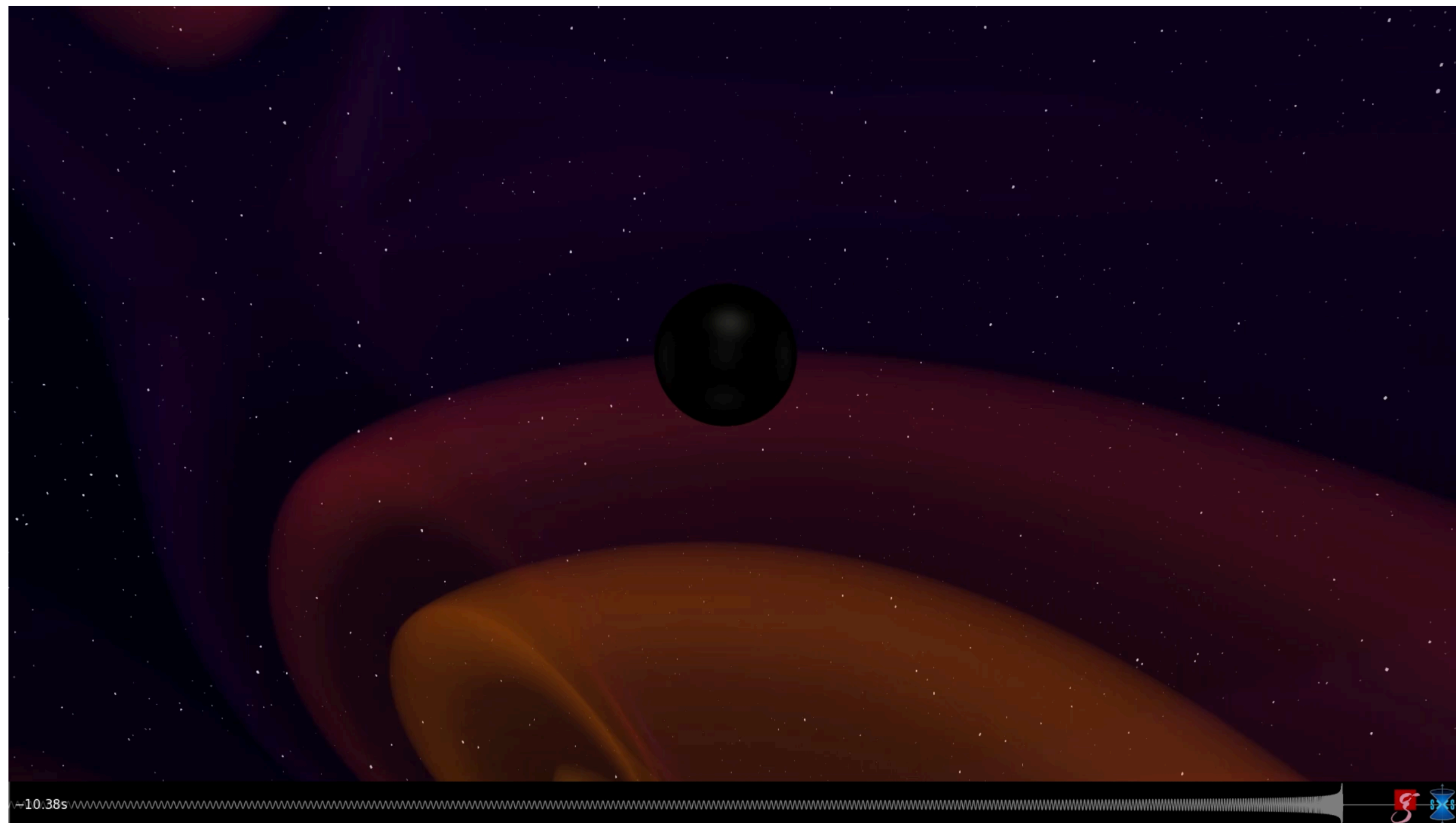


$(23 + 2.6)M_{\odot}$, SNR = 23

higher-modes & precession
sharpen measurements



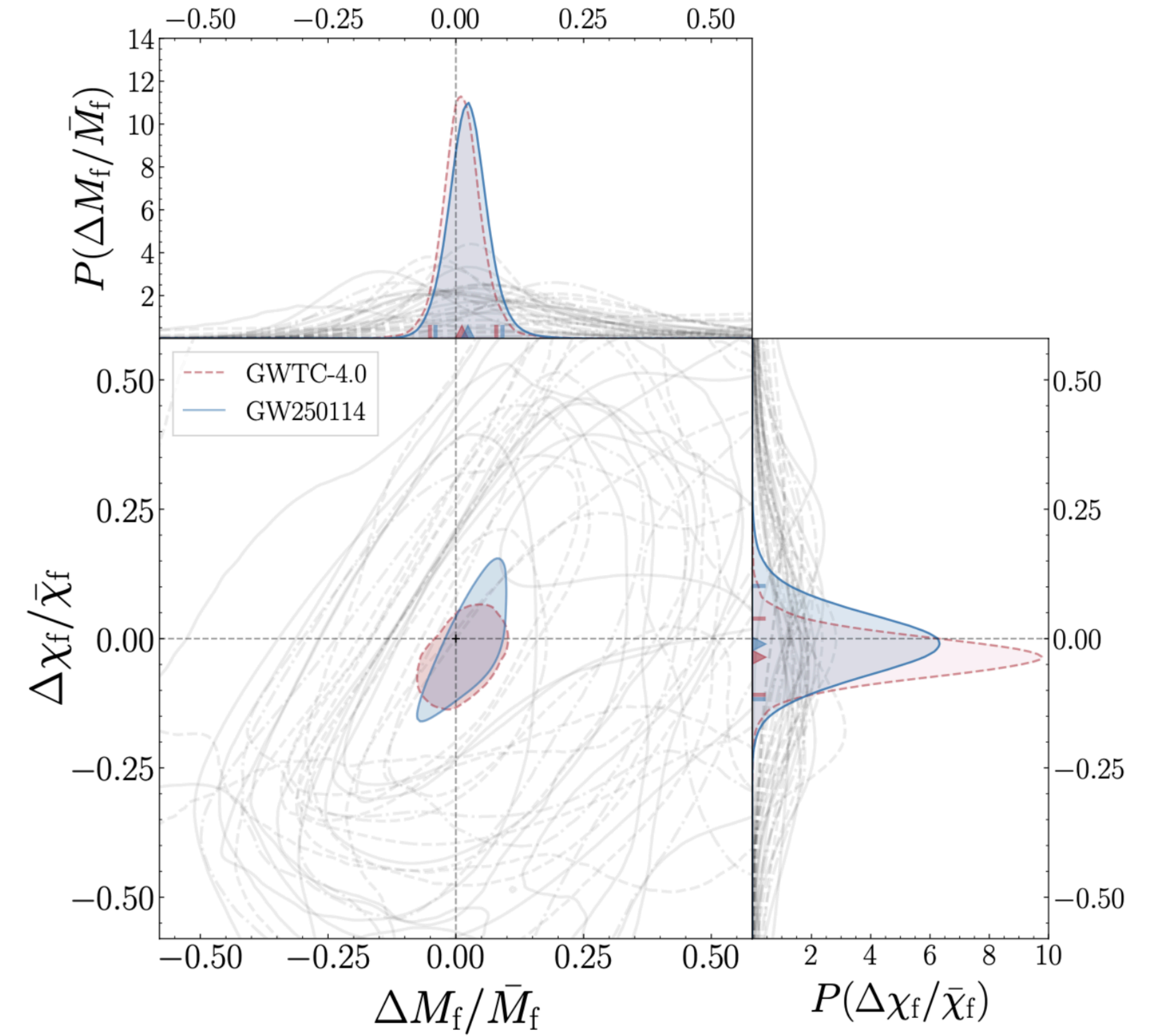
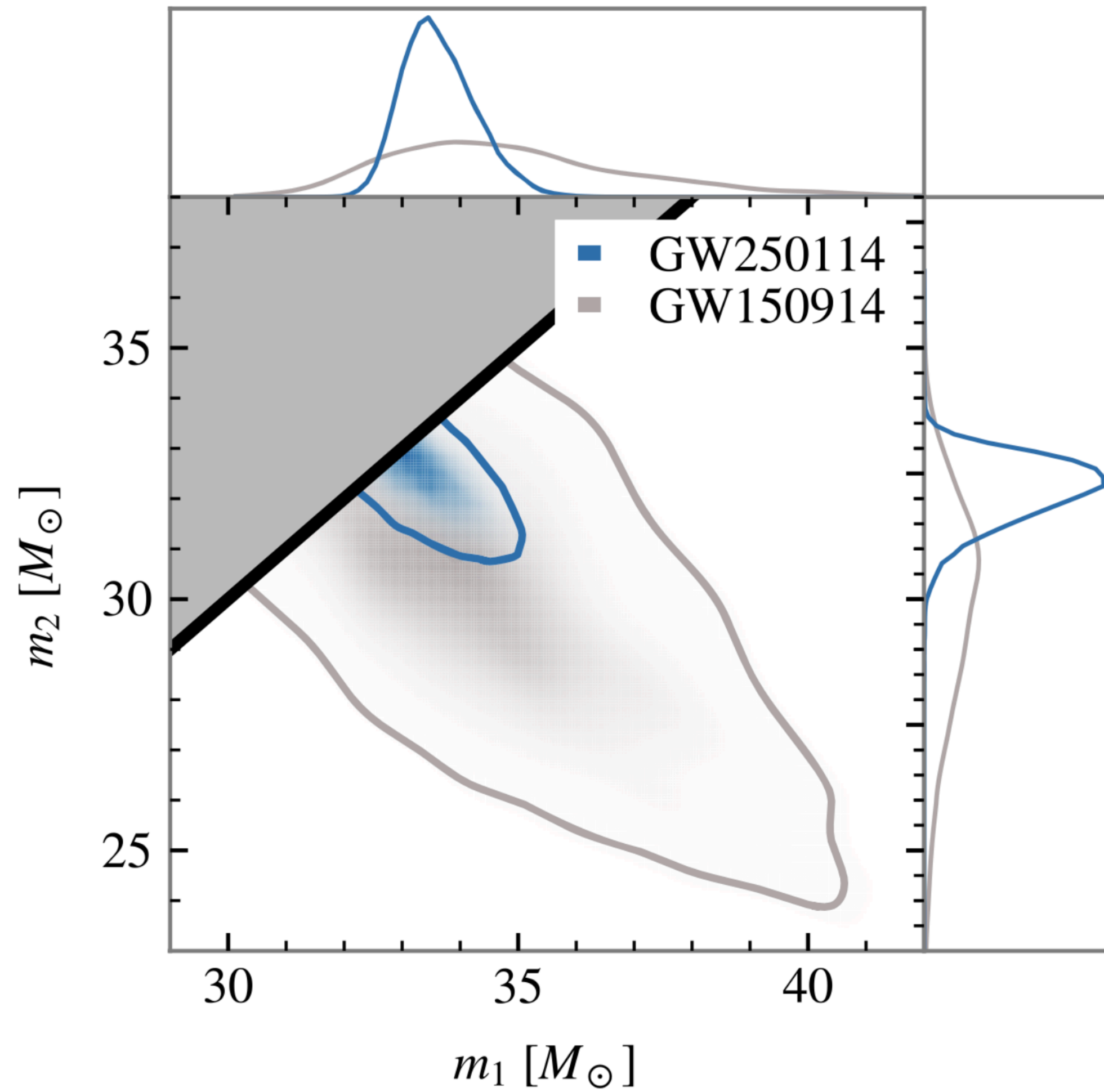
Abbott et al,
ApJL 892 L3 (2020)



- Needed precessing models at $q \sim 0.1$
- Triggered extra NR work up to $q = 1/15$
- Luckily, $\chi_1 \sim 0$, where waveforms are good

N. Vu, HP

GW250114: waveform models work confidently at SNR~80 (!)

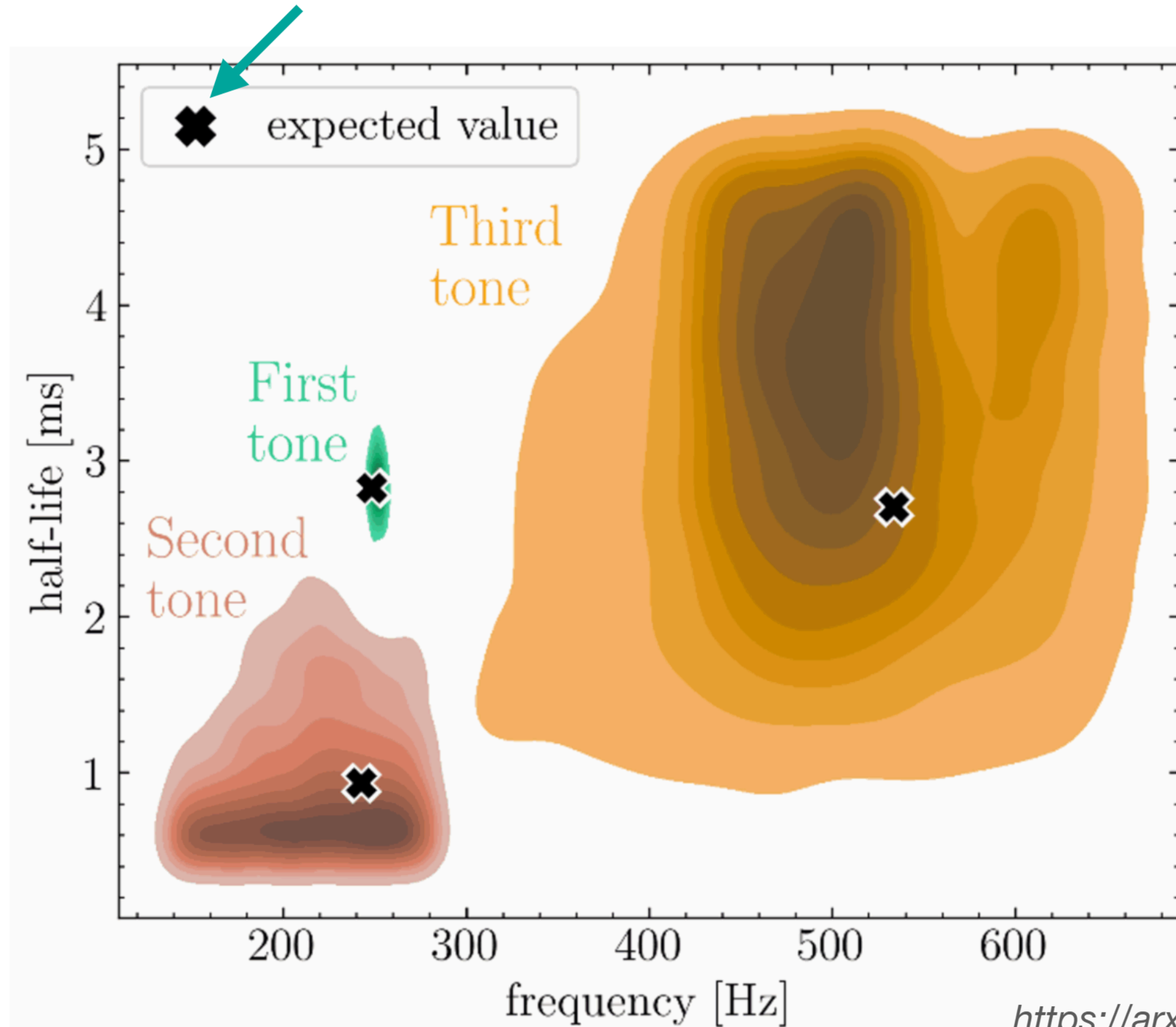


Phys. Rev. Lett. 135, 111405 (2025);
arXiv:2509.08099

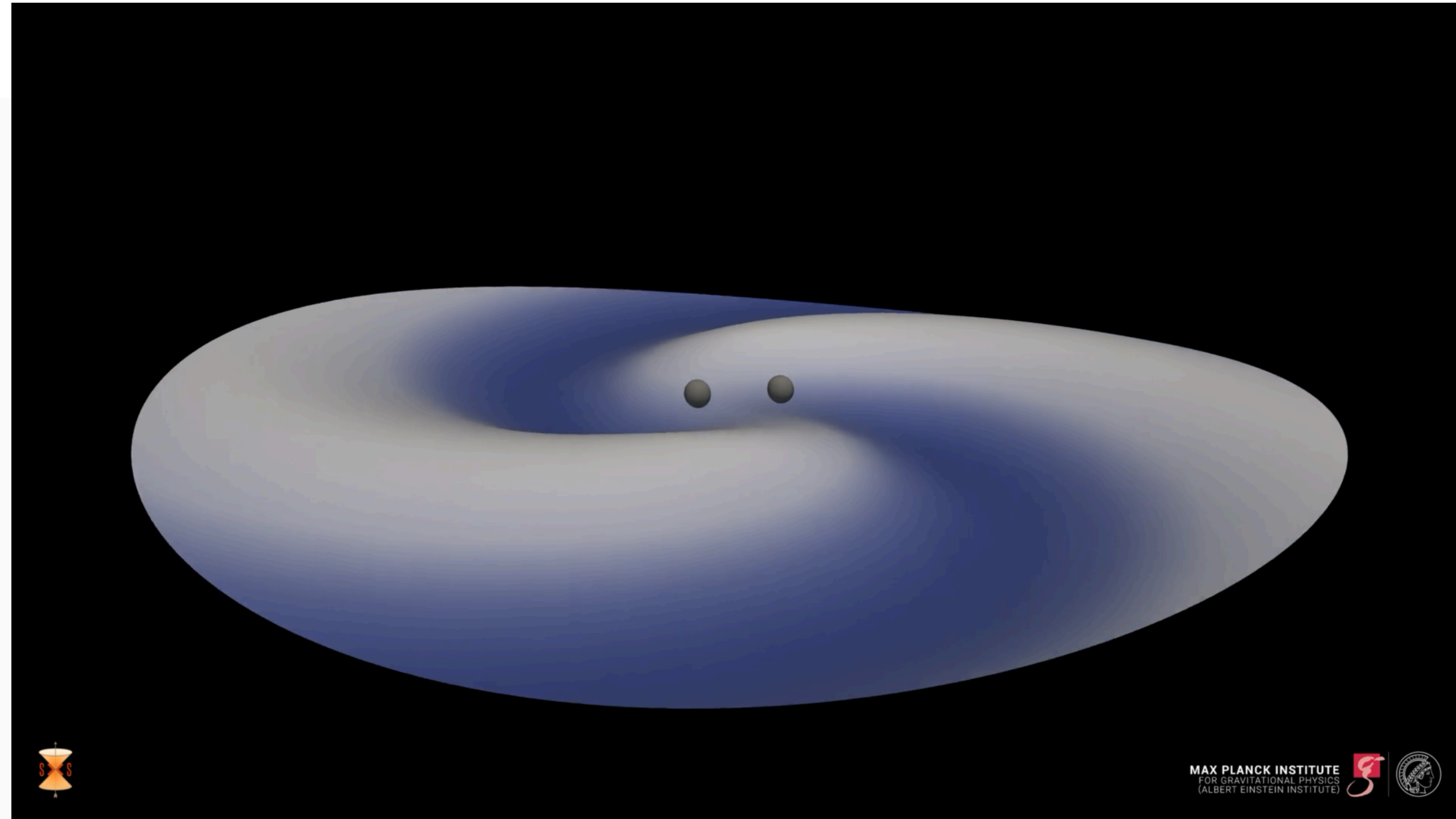
GW250114: ringdown analysis



from IMR analysis (using
waveform model NRsur_7dq4)



<https://arxiv.org/abs/2509.08099>



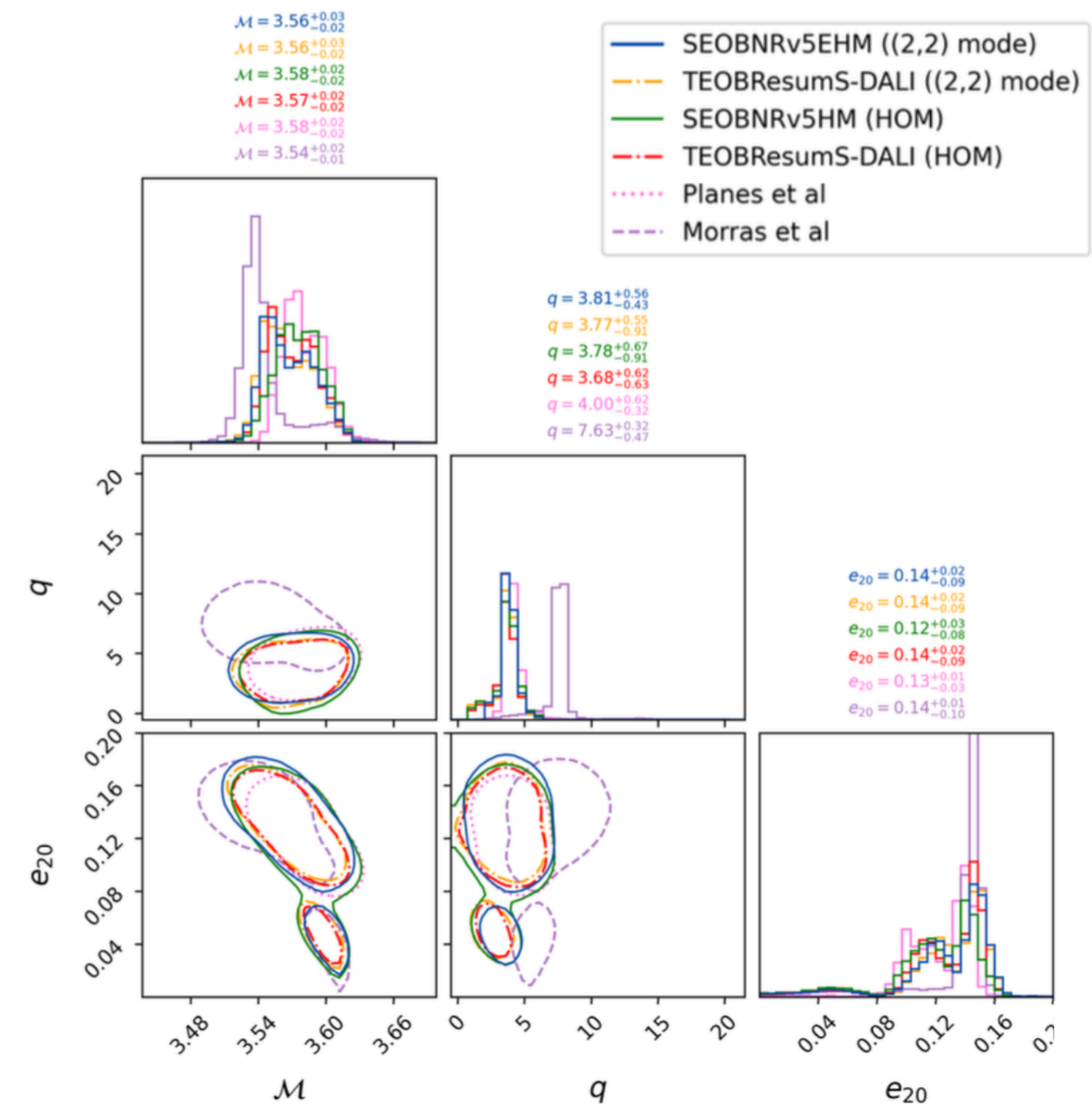
HP, A. Buonanno, K. Mitman

https://ligo.org/science-summaries/GW250114_TGR/



- several BBH waveform models now incorporate eccentricity
- identification of **a few GW events as eccentric**
 - For BBH
 - Romero-Shaw+ 2206.14695, Gupte+ 2404.14286, Lluc-Planas+ 2504.15833
 - **Caveats**: glitches, use of "quasi-circular mergers", impact of priors, low Bayes-factors
 - BH-NS GW200105 found to be eccentric in several studies with several waveform models
 - Morras+ 2503.15393, Planas+ 2506.01760, Kacanja+ 2508.00179, Jan+ 2508.12460
 - **Caveats**: low SNR event, single detector, high FAR
- next goals:
 - eccentric+precession
 - eccentricity & radial phase dependence of merger

BH-NS GW200105 analysis (Kacanja+ 2508.00179)



Eccentricity



**NR: $\max(A_{22})$ & t_{peak}
change with radial phase**

- several BBH wave eccentricity

- identification of ϵ

- For BBH

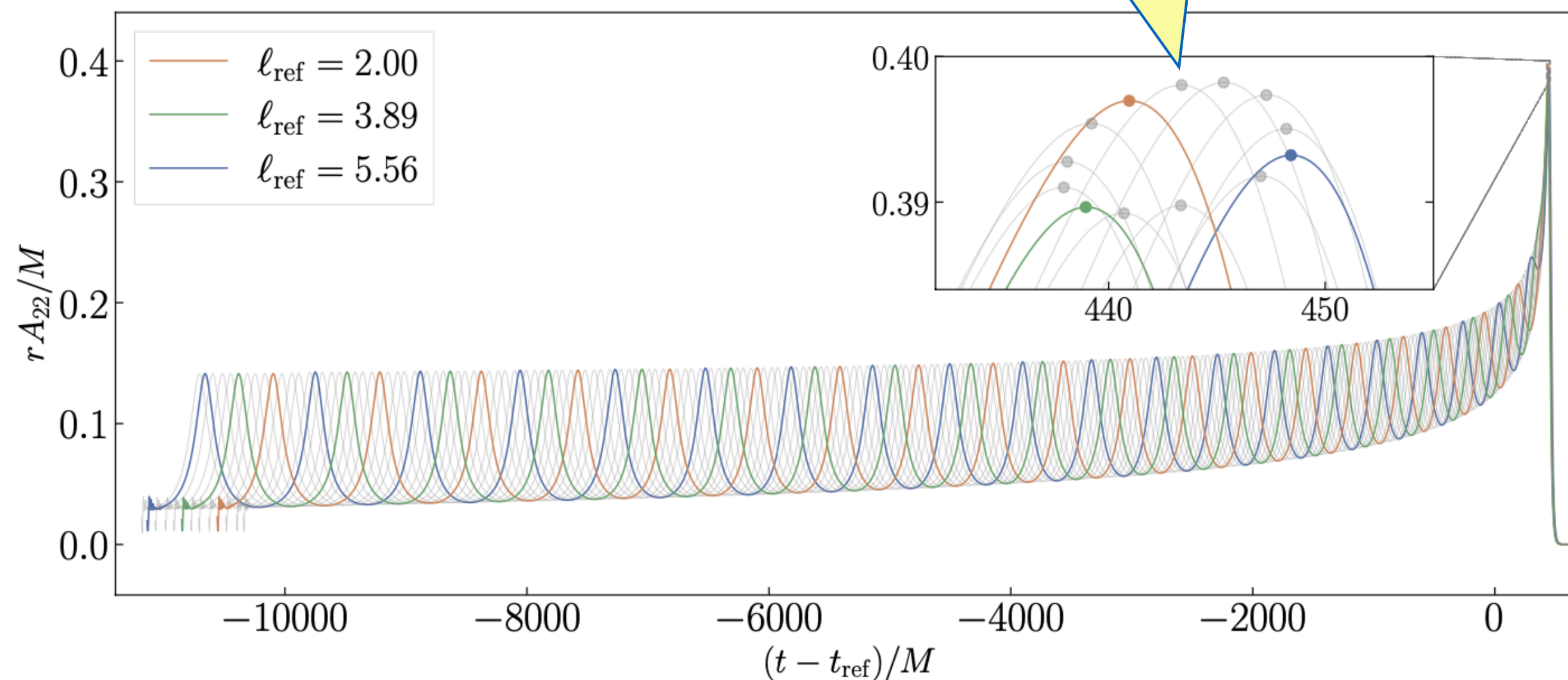
- Romero-Shaw 2504.15833

- **Caveats:** glitch low Bayes-factor

- BH-NS GW200109 studies with sev

- Morras+ 2503
 - Kacanja+ 2508

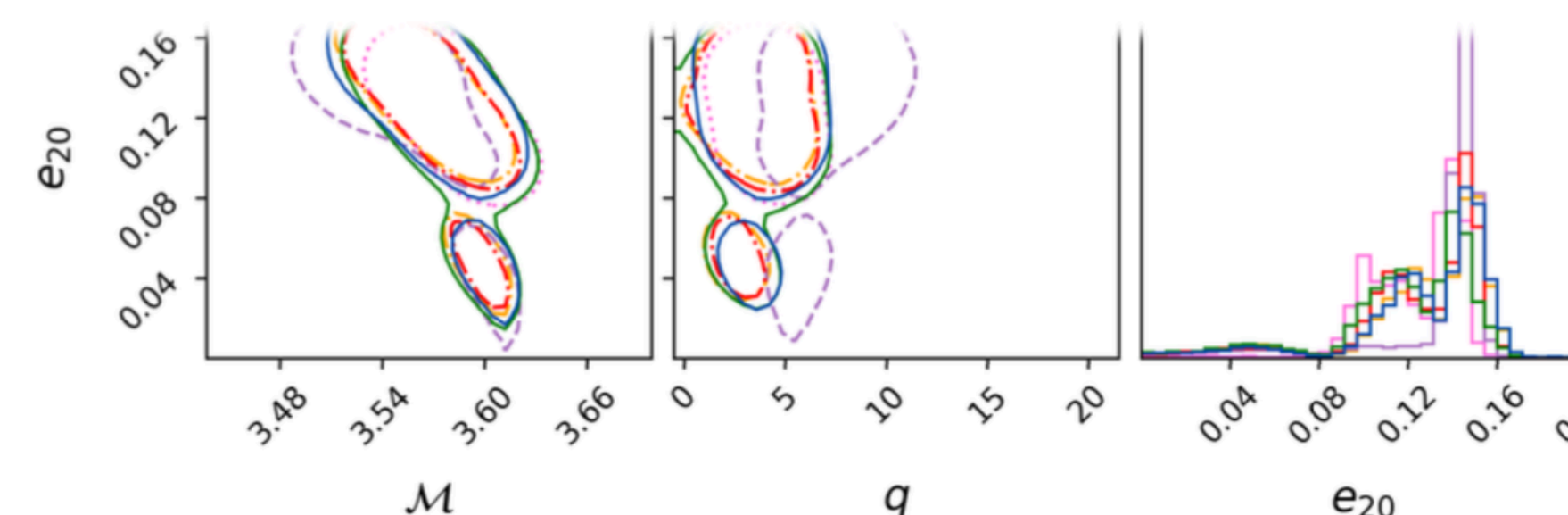
- **Caveats:** low



- next goals:

- eccentric+precession

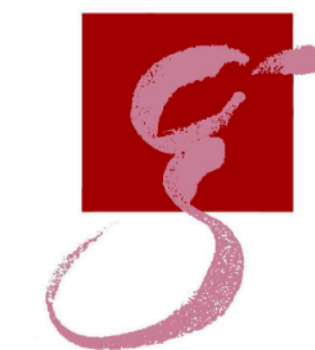
- **eccentricity & radial phase dependence of merger**



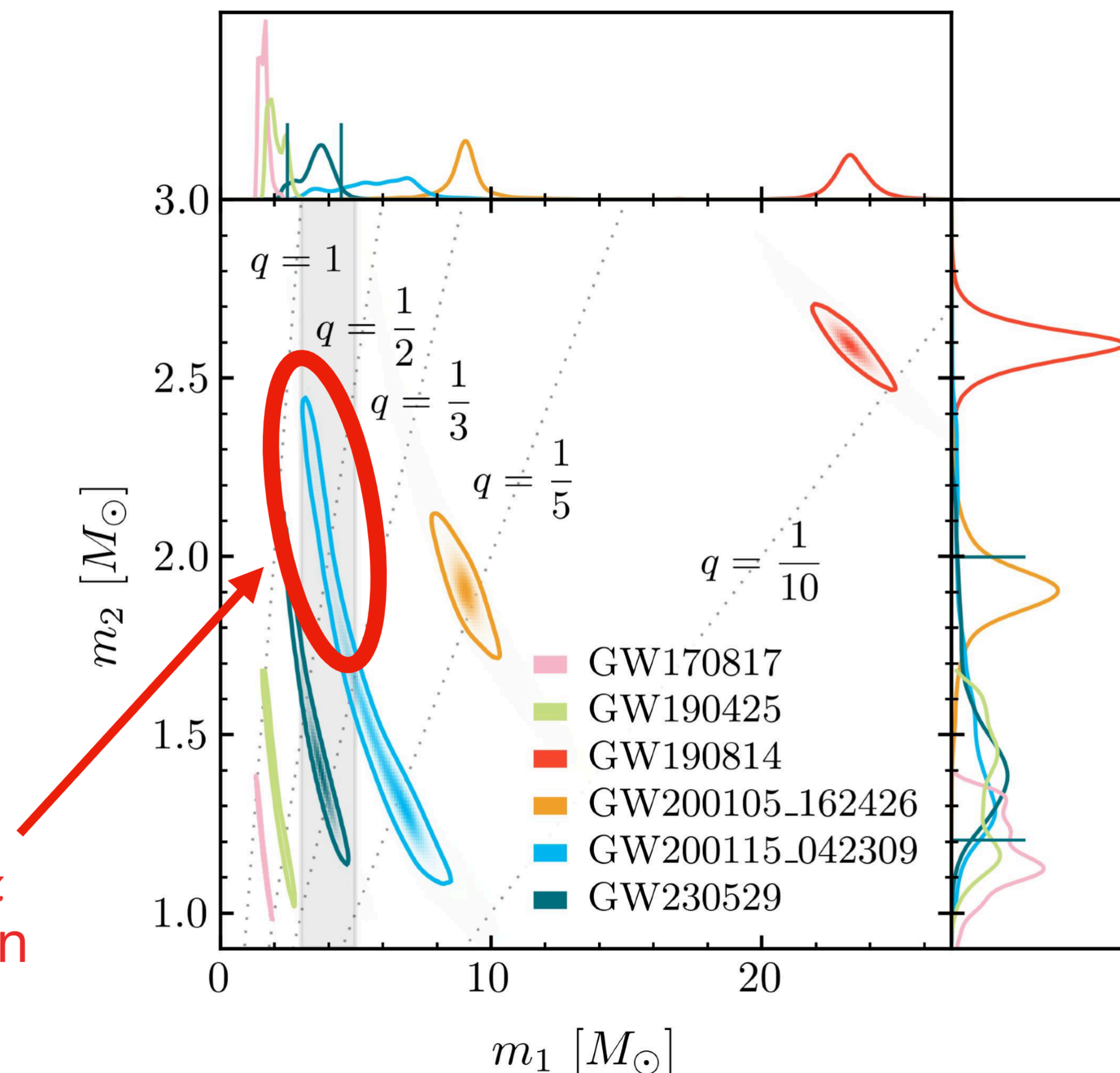


- The overall good GW results using waveform models required many types of advances
- **Towards higher accuracy**
 - better matching to more NR
 - more PN information
 - more physical effects (eccentricity!)
- **Also essential**
 - **faster** evaluation
 - comprehensive model-model and model-NR **validation (e.g. LVK reviews!)**
 - improved **smoothness** across parameters space
 - **conventions**
 - increased **robustness**

Shortcomings I: NS-BH systems

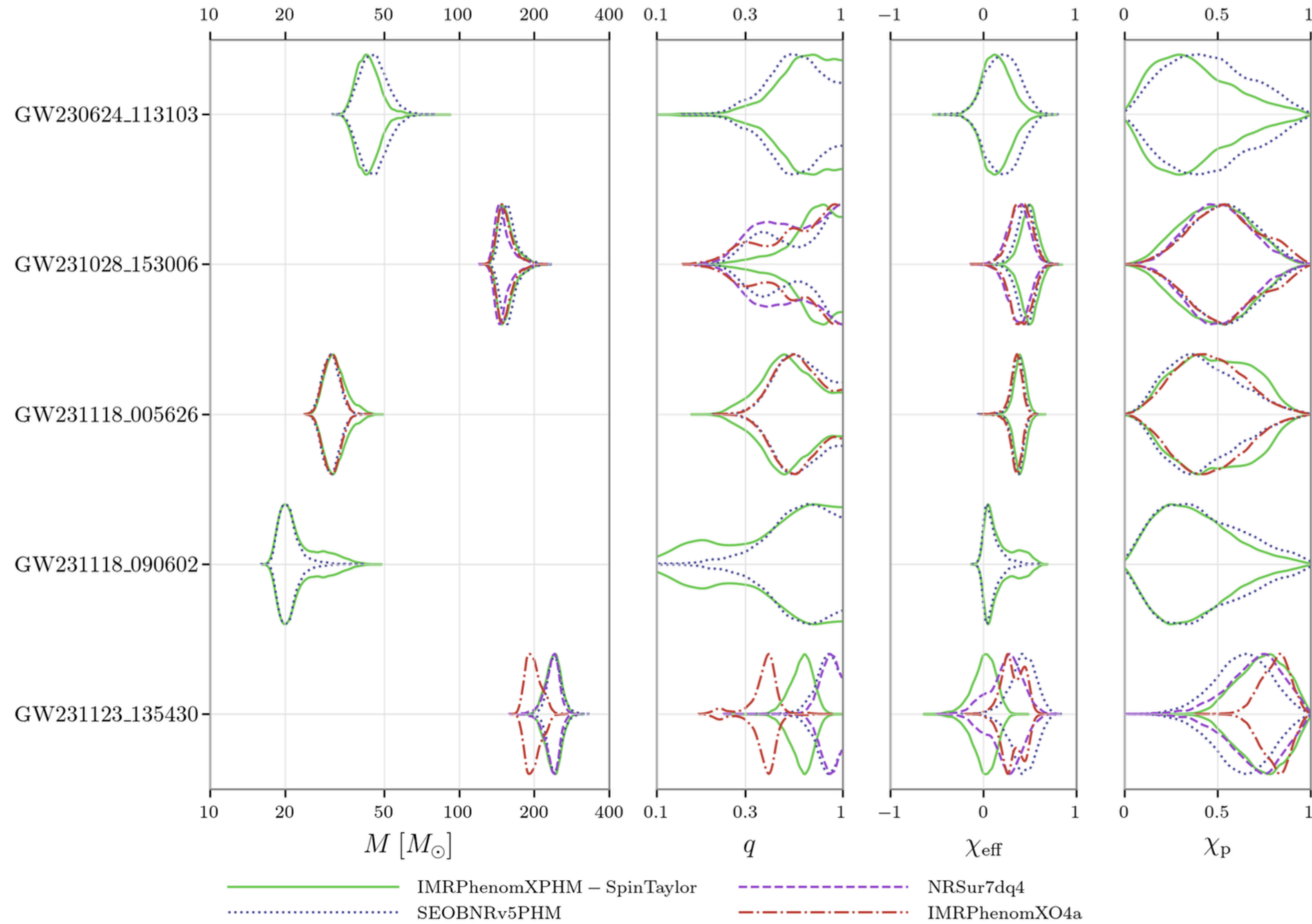


- Lack of precessing NS-BH waveform models
- Lack of NR information. Especially for
 - negative $\chi_{\text{BH},z}$
 - NS-disruption
 - EOS dependence (max NS mass)



Tail toward $m_1 \approx m_2$ and negative $\chi_{\text{BH},z}$
Probably not real, but waveforms uncertain

Shortcomings II: O4a Events with waveform systematics

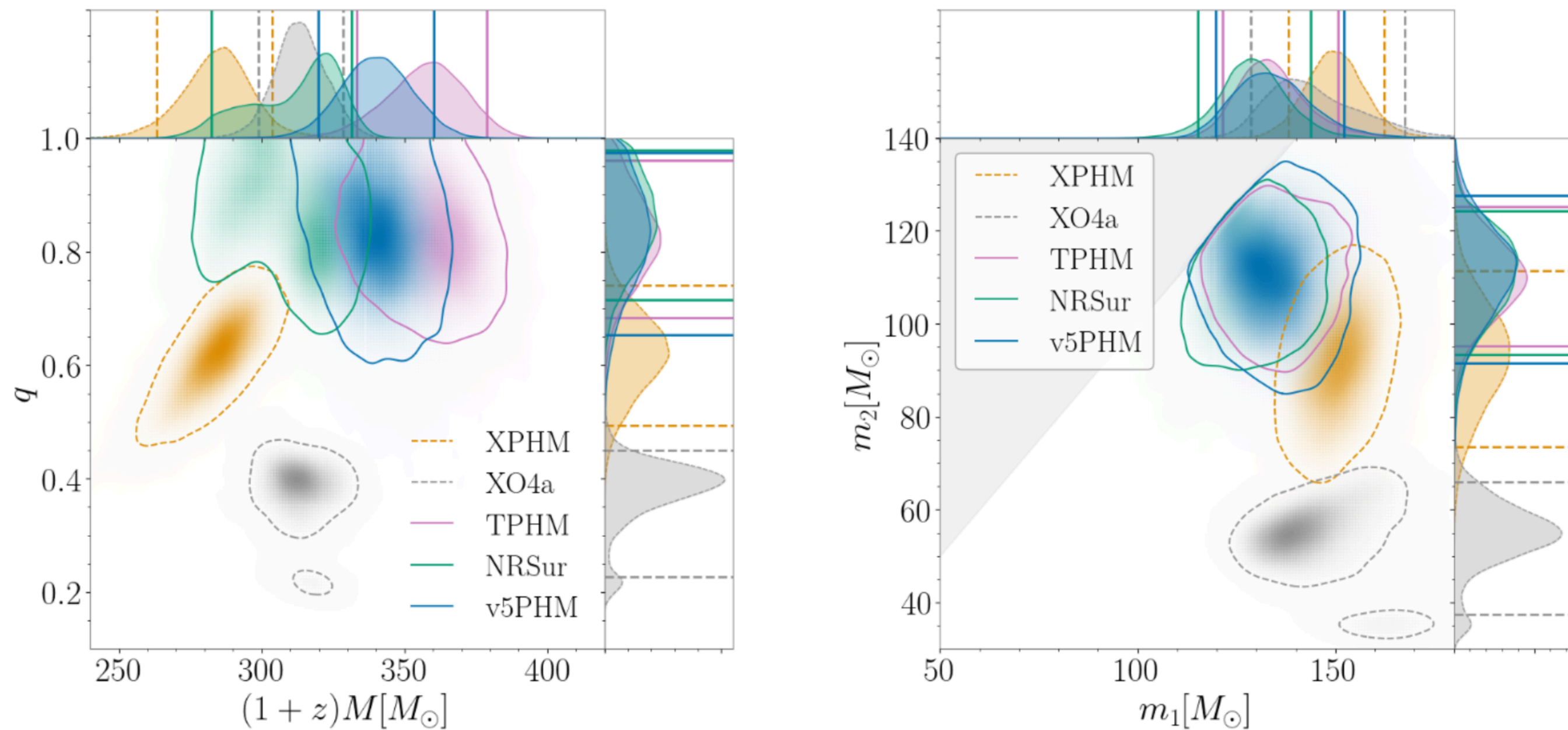


Not perfect, but not that bad. ...except for GW231123...

Shortcomings III: High-mass, high-spin systems

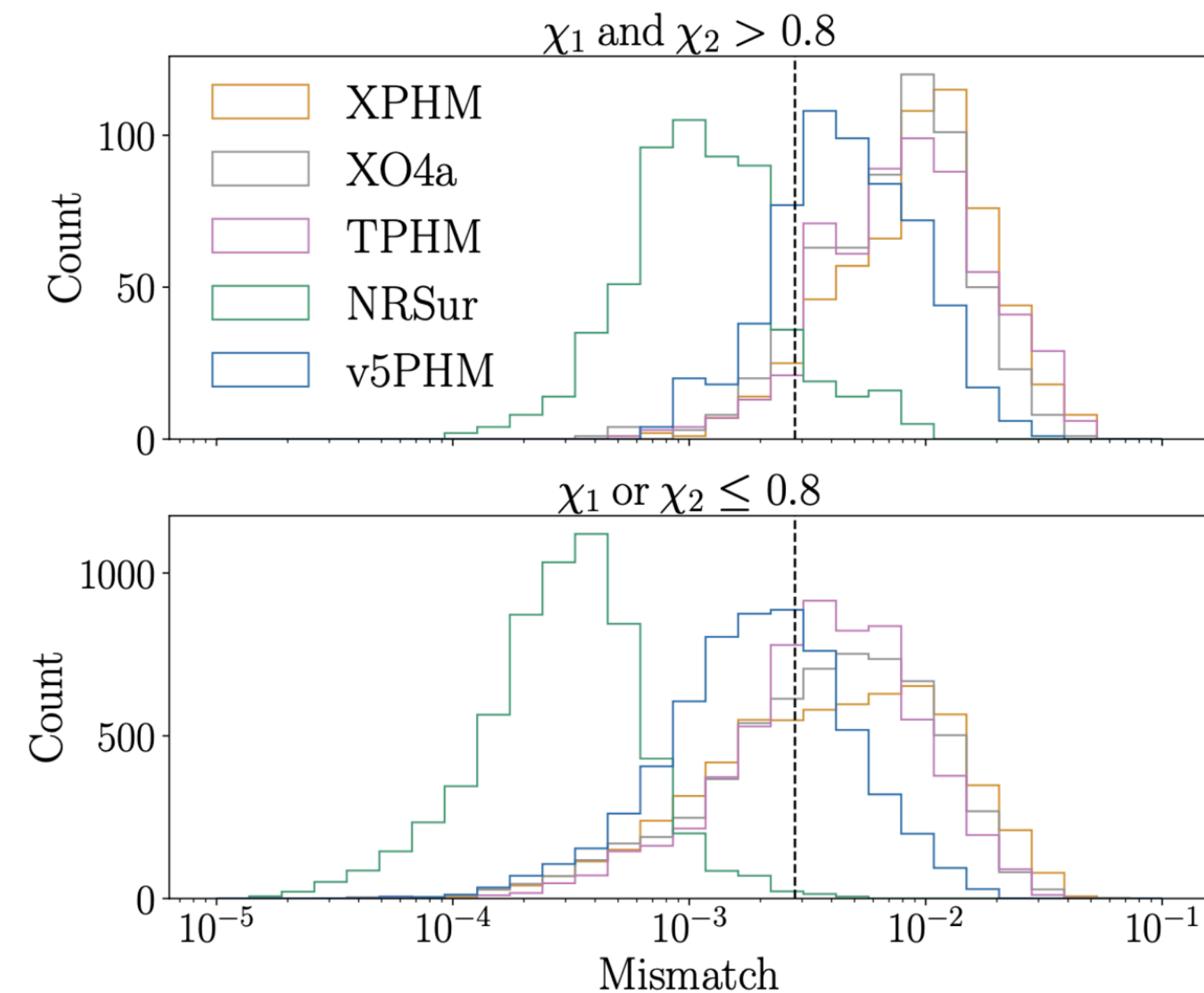


- GW231123: Systematics study with attached GW signal



The estimate **systematic error $\sim \Delta(\text{models})$** assumes all models are similarly accurate. How would we know this?

Waveform-validation study against NR: loss of accuracy for $\chi > 0.8$



Shortcomings III: High-mass, high-spin systems

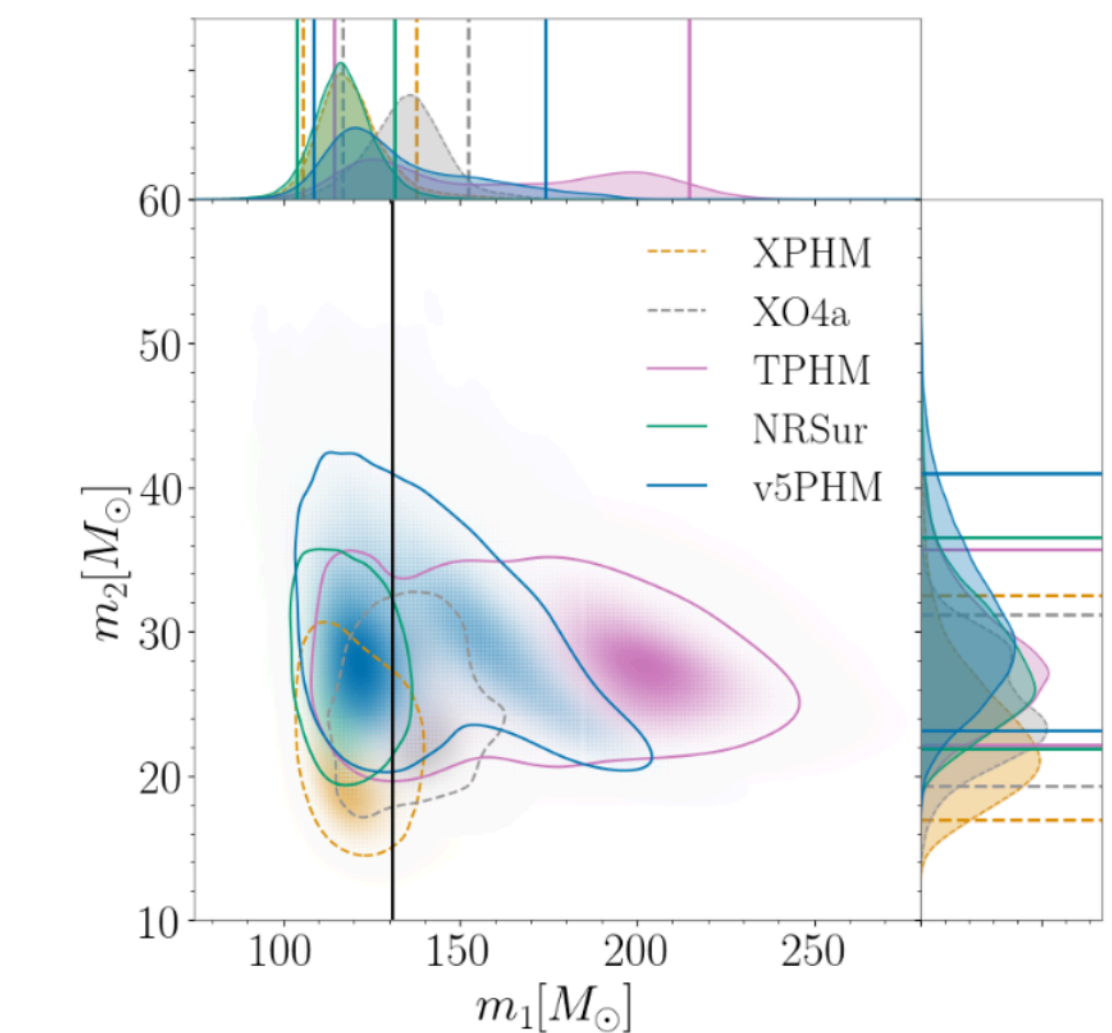
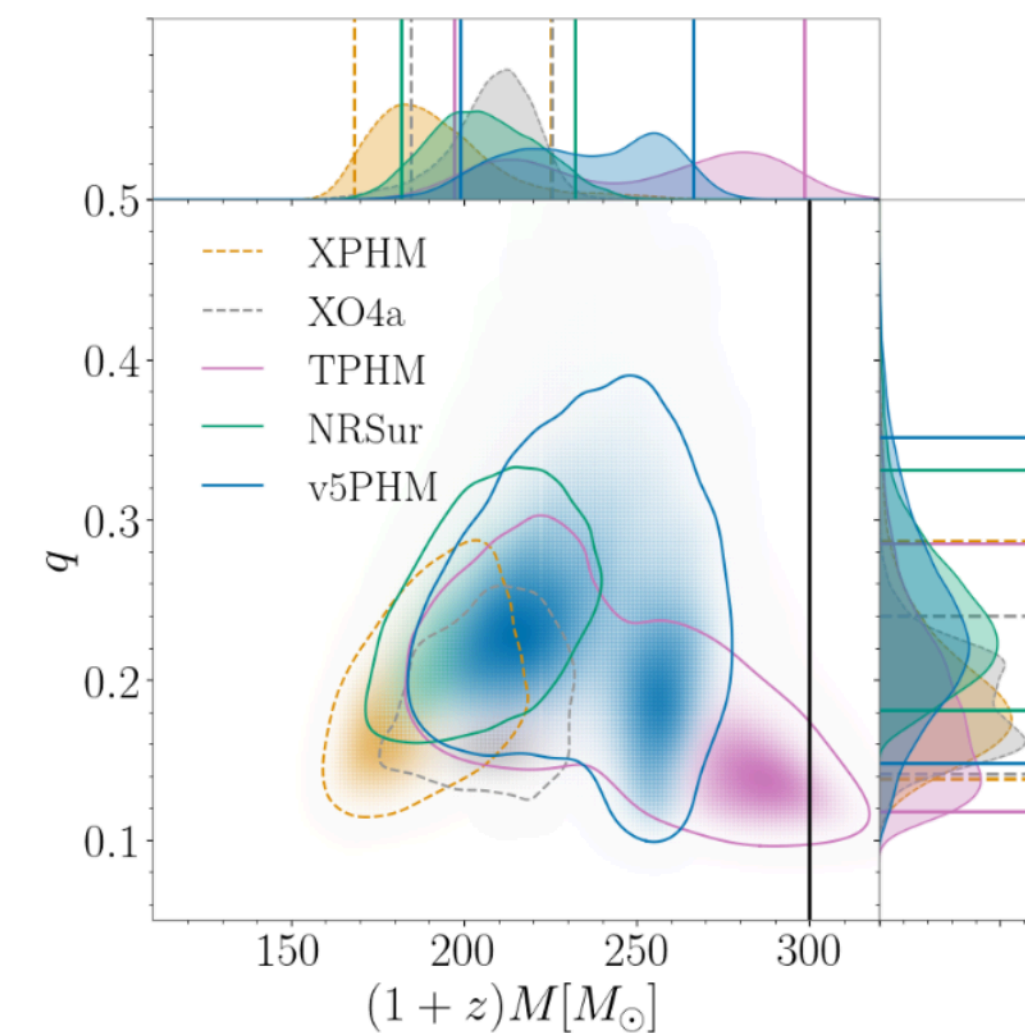
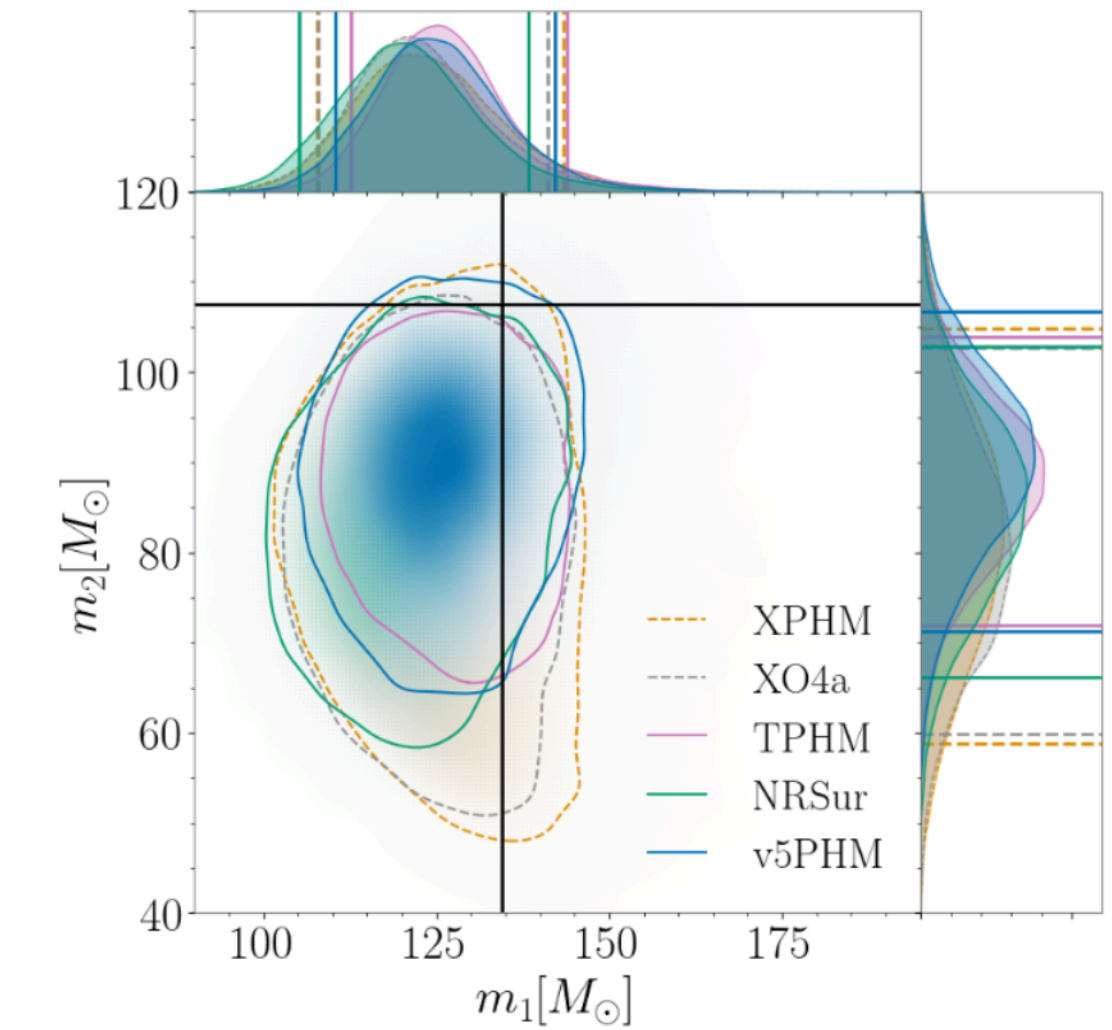
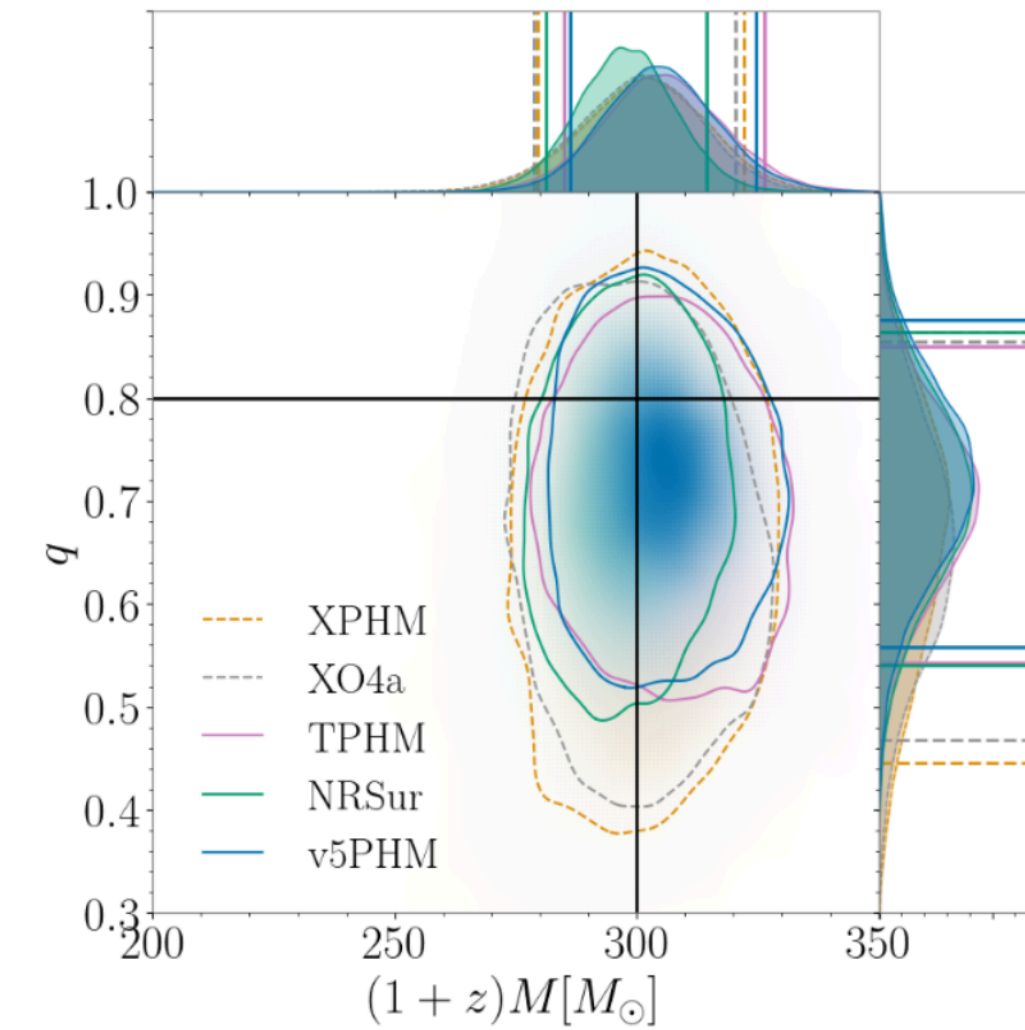


- *still* GW231123,
now NR-injection study
 - often good PE results
 - sometimes abysmal

NR-injection has
equal mass ($q = 1!!$)



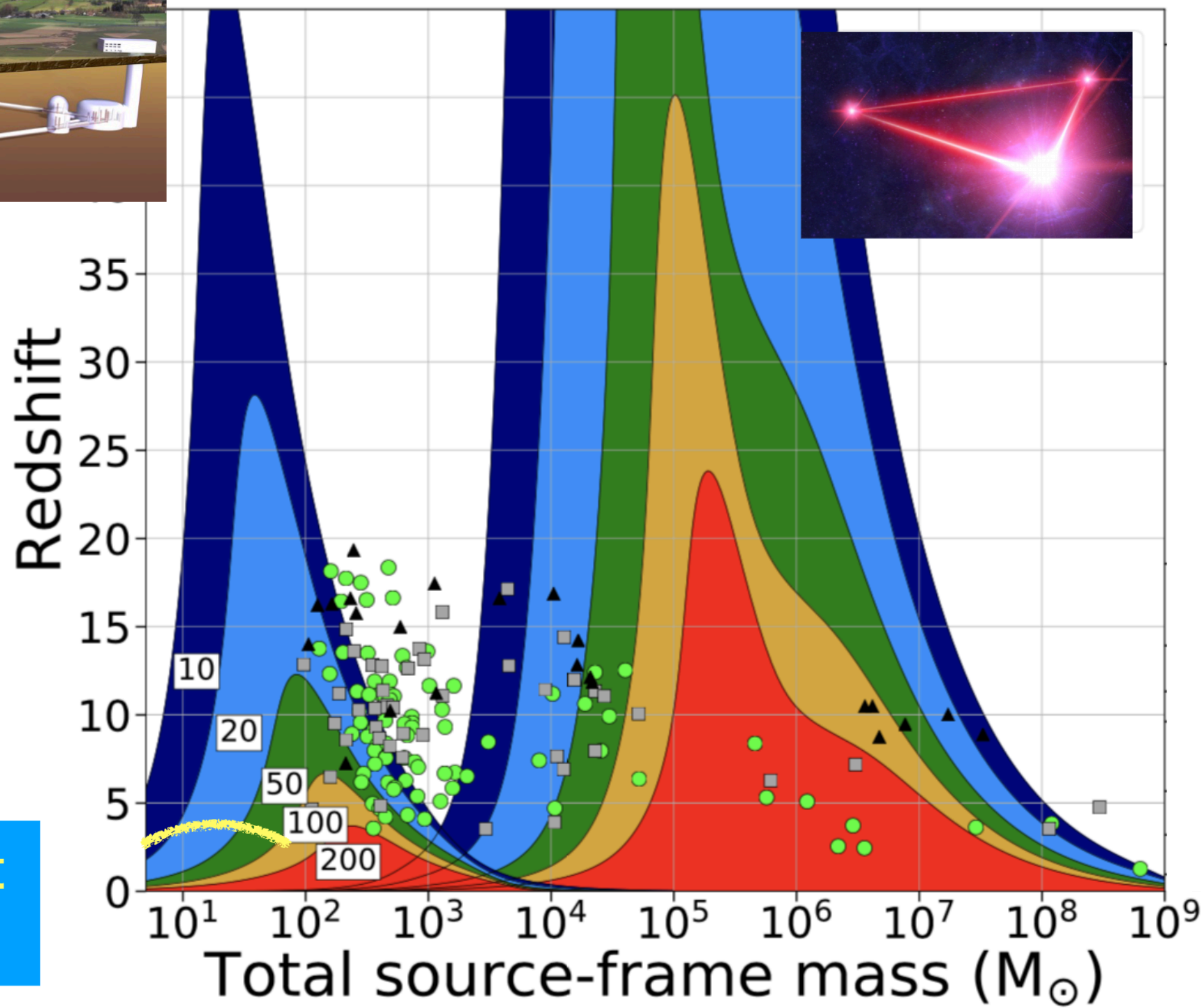
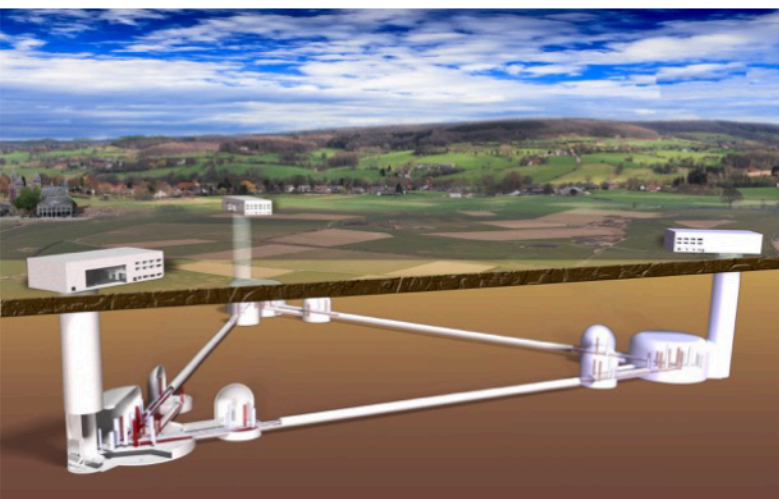
GW231123 *arXiv:2507.0821*



In future, more diverse systems at much higher SNR

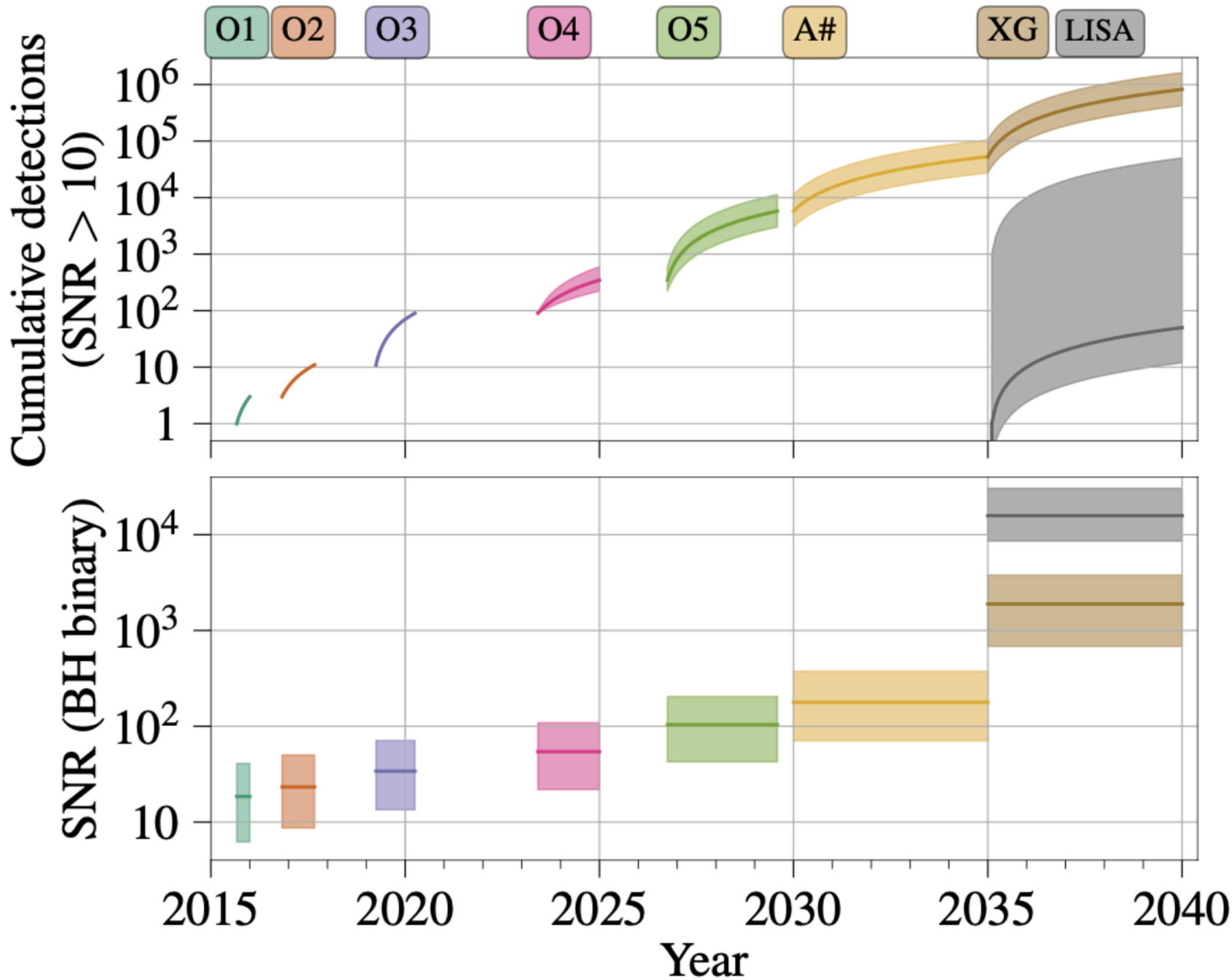


LISA, Cosmic Explorer, Einstein Telescope:
SNRs of 1000's (instead of 10's)
needed accuracy $\sim 1/\text{SNR}$



Current
LVK

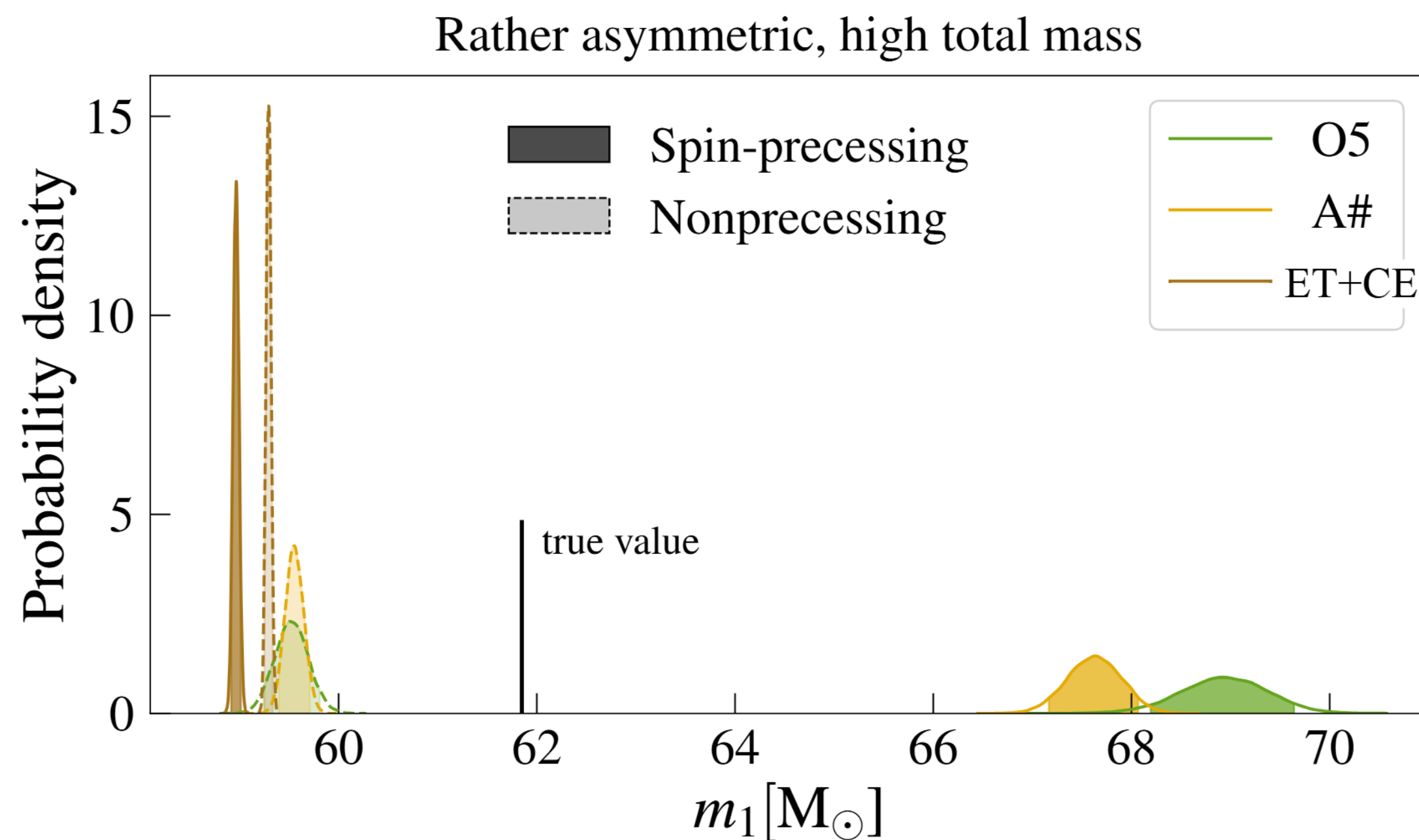
GWIC, 3G Science Case



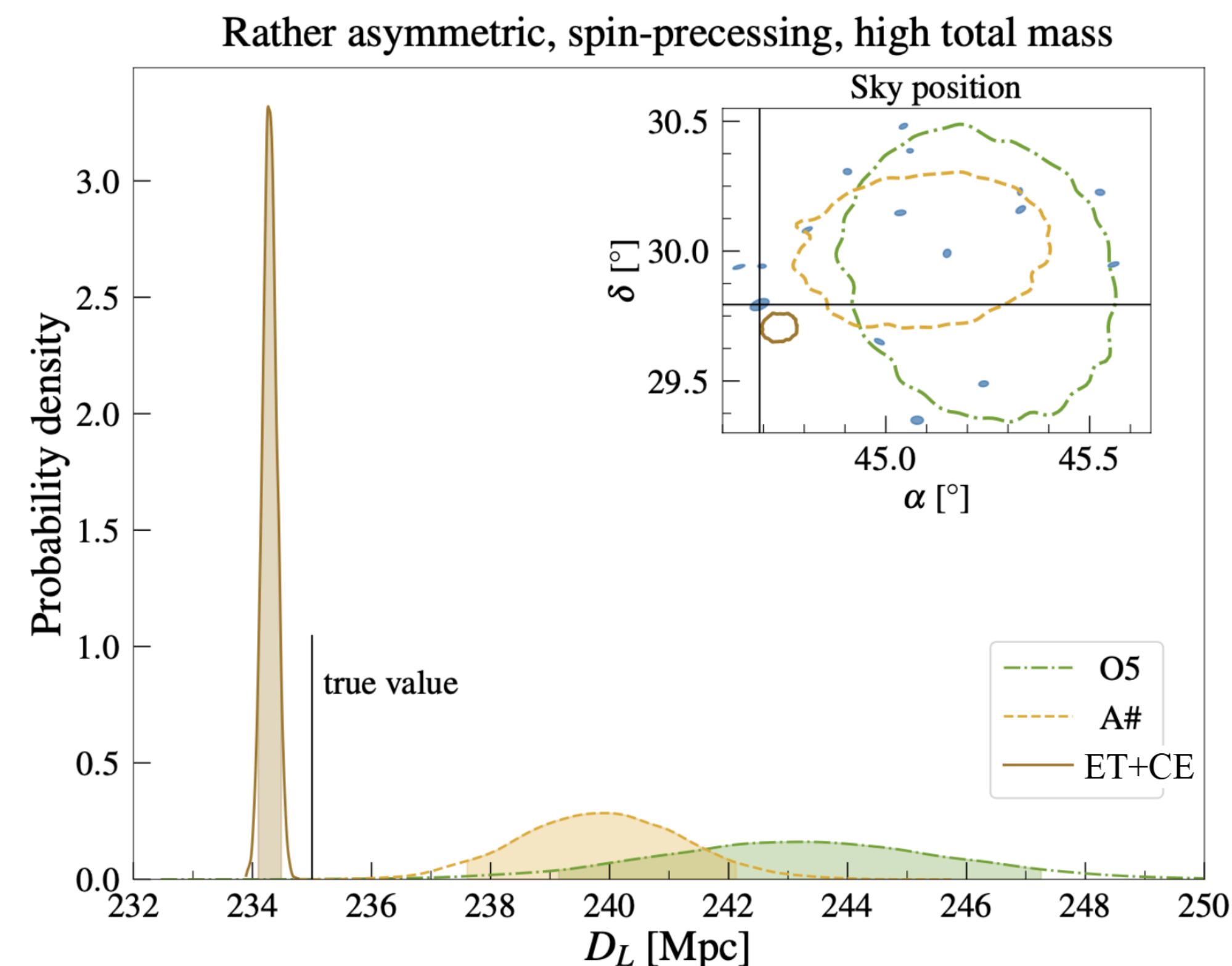
Scary example



- $m_1 = 61.8M_\odot$, $m_2 = 9.5M_\odot$, quasi-circular, large spins ($\chi_{eff} = -0.43$, $\chi_p = 0.77$)
- **Nothing estimated correctly. Not even at O5 sensitivities. Not even aligned-spin.**

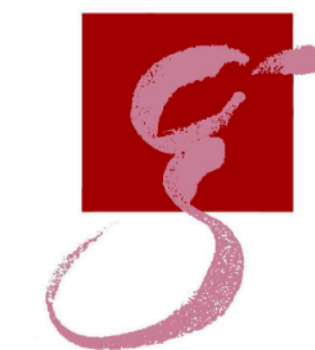


Dhani, Völkel+ *PRX* (2025), (2404.05811)





- At sufficiently high SNR, imprints of astrophysics will surface
 - perturbing matter near binary
 - 3rd body, Kozai resonances, etc.
 - gas / accretion disk
 - gravitational lensing of propagating gravitational waves
 - strong - multiple "images" (i.e. signals)
 - weak - deformation of waveform, possibly in wave-optics regime
 - superposed GW events
- Immense opportunity to learn about our astrophysical universe
 - cf. for CMB: SZ-effect finds galaxies. Extinction teaches us about dust in Milky Way
- But also challenge for parameter estimation, testing GR



- Waveform modeling is a **successful pillar of GW astronomy** since its inception
 - often overlooked the importance of 'tedious' work (reviews, conventions, smoothness, speed)
- It has **mostly kept up with increasing demands of more sensitive detectors**
- To continue to extract the most physics/astro-physics/beyond-GR information from the most interesting events in the future **will require immense improvements:**
 - standard vacuum-GR
 - BH-NS, BNS
 - more detailed beyond GR
 - astrophysical imprints