Numerical relativity for next-generation gravitational-wave observations

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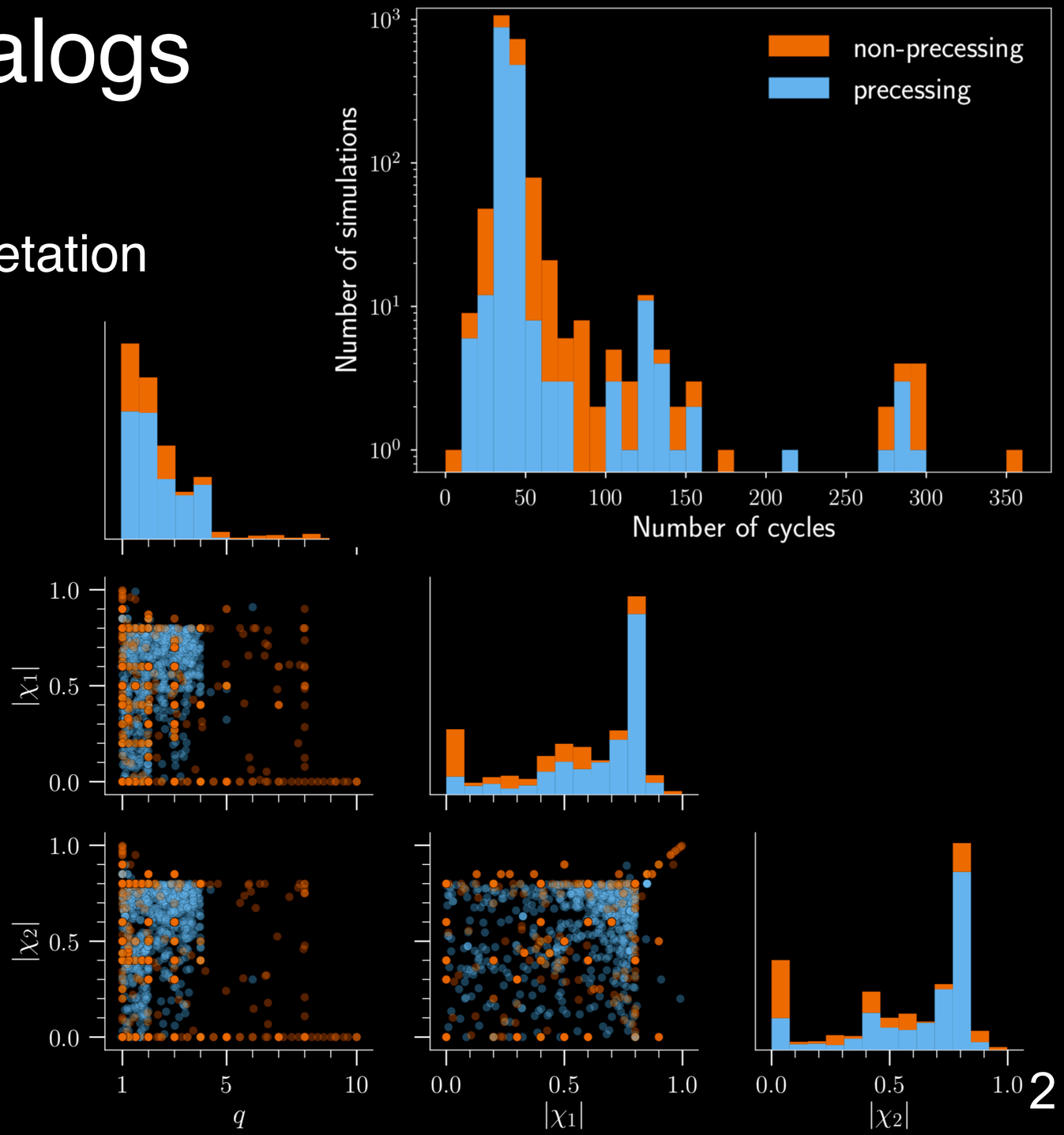
Numerical-relativity catalogs

- Tune & test waveform models for gravitational-wave observation, interpretation

- Binary black holes
  - Catalogs with 1000s of waveforms
- Mergers with neutron stars
  - Catalogs with 100s of waveforms

- **How accurate do these waves have to be?**



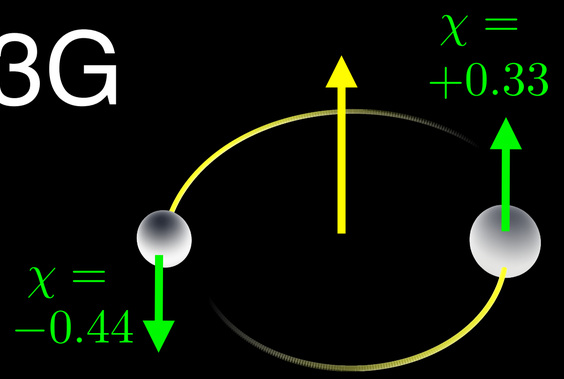
Figures courtesy Boyle+ arXiv:1904.04831

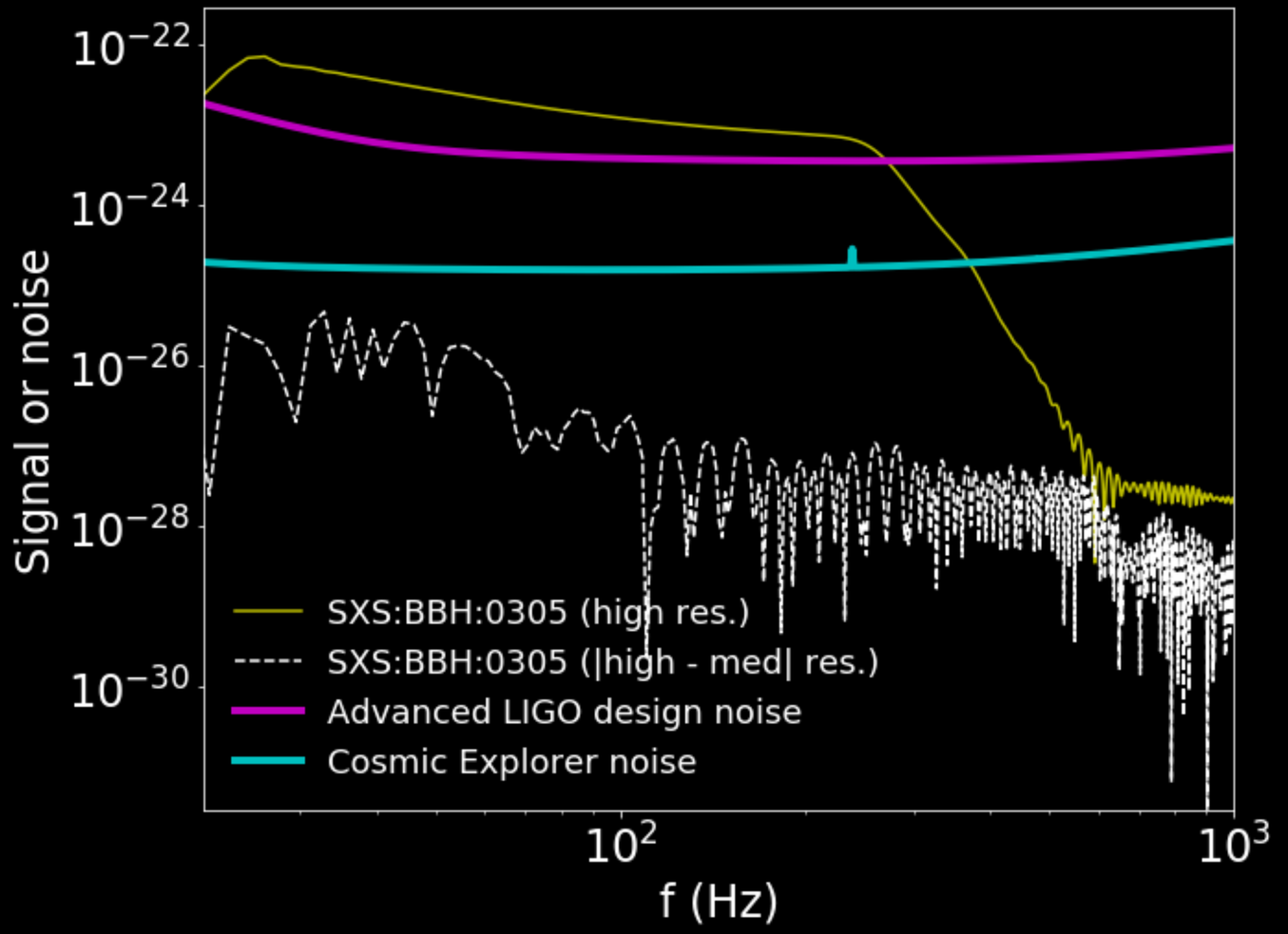
Accuracy for 3G

- Mismatch $\mathscr{M}$
  - Noise-weighted dot product
  - Two waveforms indistinguishable for SNR ρ

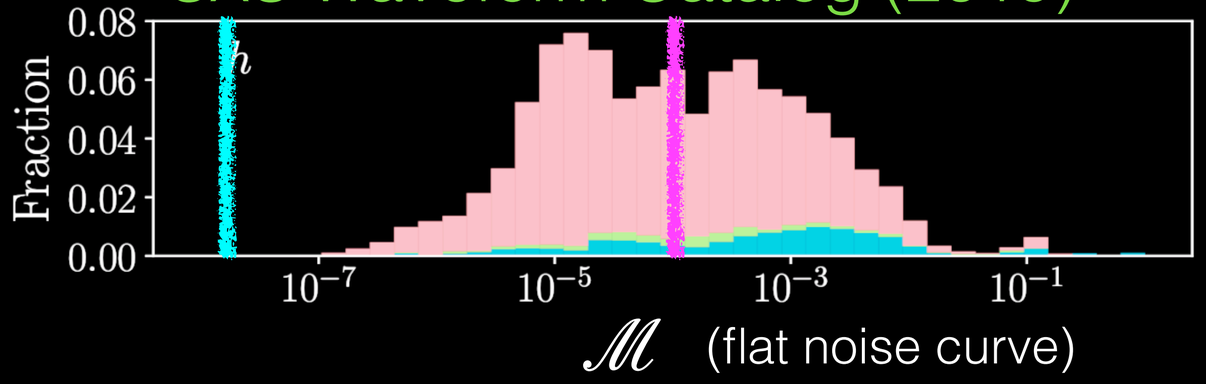
Lindblom+ PRD 78, 124020 (2008)

$$\mathscr{M} < \frac{1}{2\rho^2}$$





SXS Waveform Catalog (2019)



SXS:BBH:0305
NR high res.

$\rho^{NR}_{aLIGO} = 100$ $\rho^{NR}_{CE} = 3500$

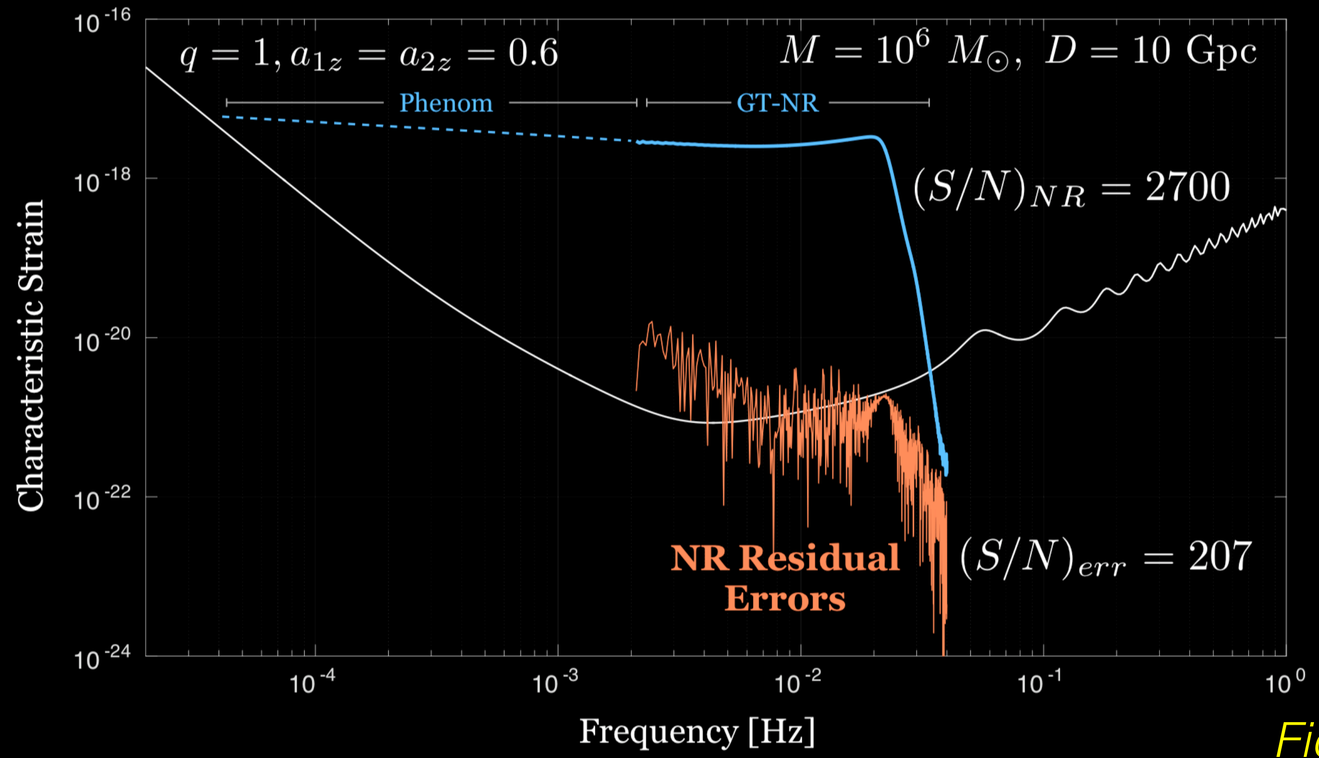
SXS:BBH:0305
NR errror

$\rho^{Err}_{aLIGO} = 0.05$ $\rho^{Err}_{CE} = 1.7$

Accuracy for LISA

- Must subtract loud signals…
  (massive black-hole mergers)

- …to see signals underneath them
  (e.g. extreme mass-ratio inspirals)



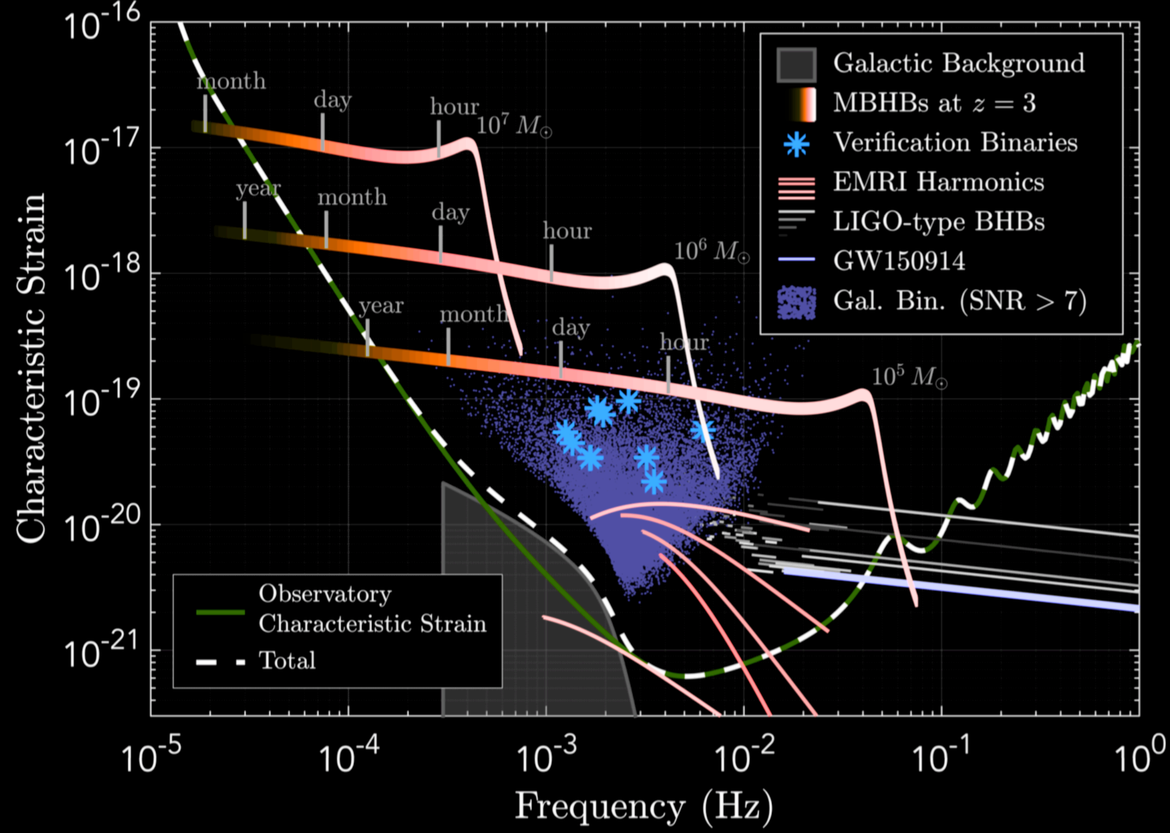
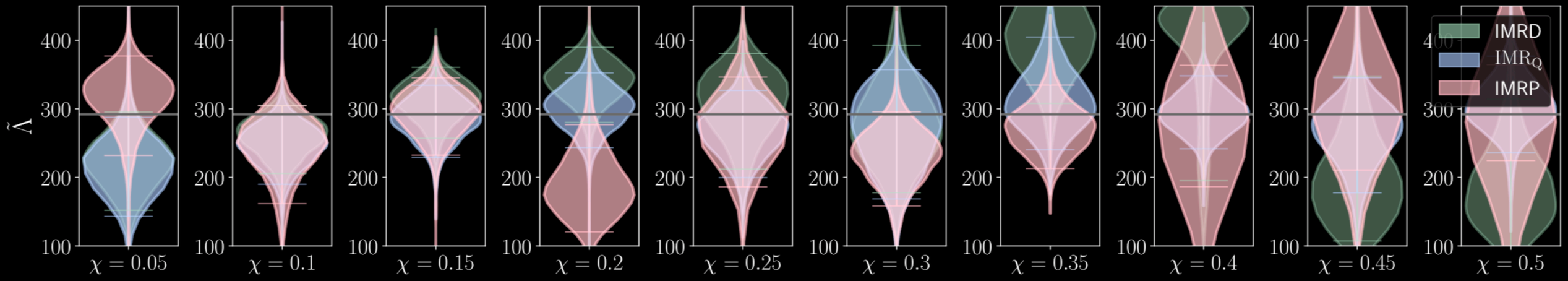


Figure 1 of LISA L3 Document

Figures courtesy LISA, Karan Jani, Deirdre Shoemaker

Accuracy for right now

- Binary neutron star waveform models with tides
  - –These models rely on numerical relativity
  - –Different state-of-the-art models recover different posteriors for injected binary neutron star waveforms

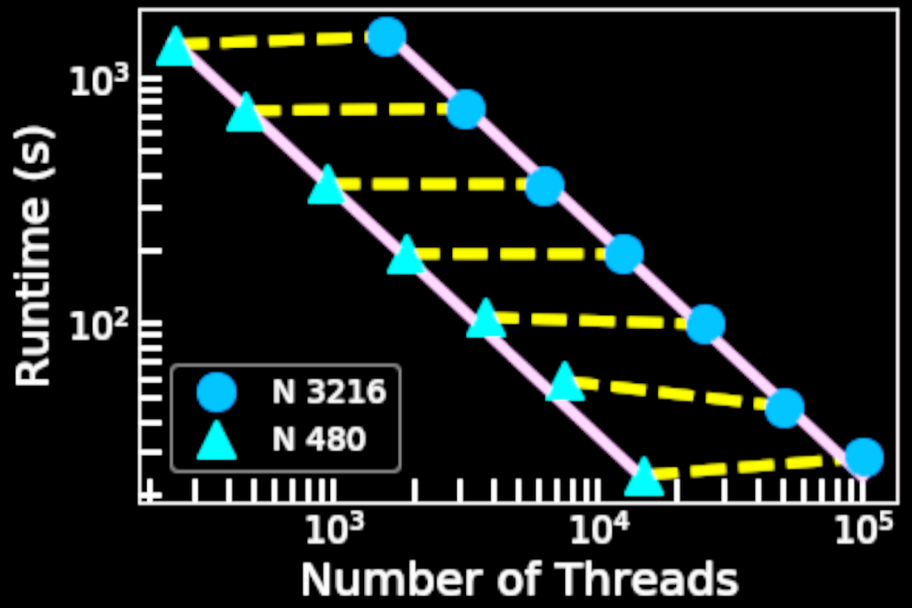


Figures courtesy Samajdar & Dietrich, arXiv:1905.03118

What does the next generation of NR look like?

- Might need orders-of-magnitude better waveforms for 3G, LISA

- How will numerical-relativity achieve this?
  - –Future is more (million+) cores, not faster cores
  - –We'll need next-generation NR
    - Efficient methods to maximize accuracy, minimize communication, handle shocks (e.g. Discontinous Galerkin)
    - Make sure all cores always busy (e.g. task-based parallelism)
    - One approach: spectre (spectre-code.org)



Figures courtesy SXS, Nils Deppe

The SXS Collaboration catalog of binary black hole simulations

Michael Boyle, Daniel Hemberger, Dante A.B. Iozzo, Geoffrey Lovelace, Serguei Ossokine, Harald P. Pfeiffer, Mark A. Scheel, Leo C. Stein, C.J. Woodford, Aaron B. Zimmerman, Nousha Afshari, Kevin Barkett, Jonathan Blackman, Katerina Chatziioannou, Tony Chu, Nicholas Demos, Scott E. Field, Nils L. Fischer, Evan Foley, Heather Fong, Alyssa Garcia, Matthew Giesler, Francois Hebert, Ian Hinder, Reza Katebi, Haroon Khan, Lawrence E. Kidder, Prayush Kumar, Kevin Kuper, Halston Lim, Maria Okounkova, Teresita Ramirez, Samuel Rodriguez, Hannes Rüter, Patricia Schmidt, Bela Szilagyi, Saul A. Teukolsky, Vijay Varma, and Marissa Walker

https://dcc.ligo.org/LIGO-P1900100

LIGO Waveforms Call
March 13, 2019

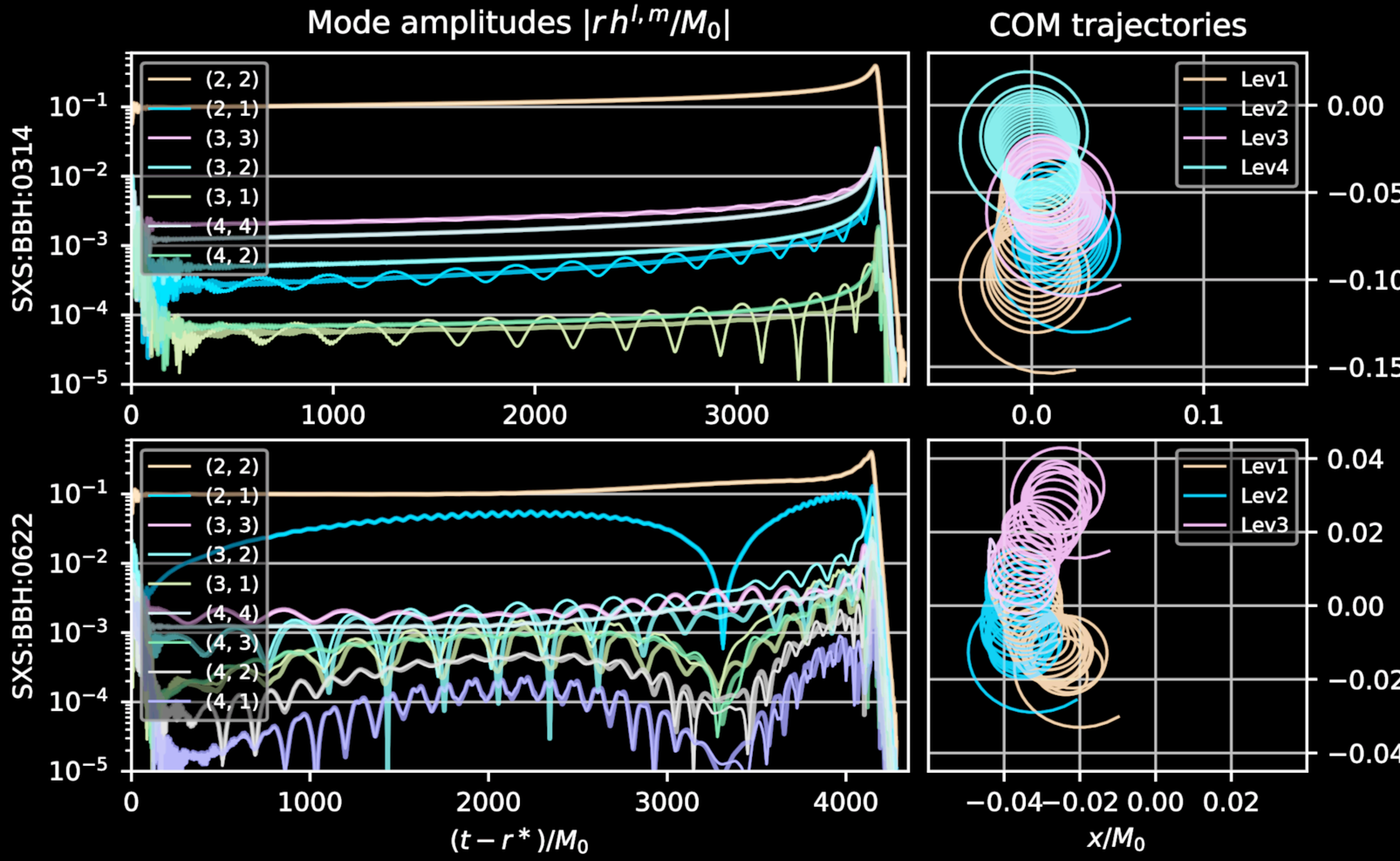
Introduction

- Numerical relativity (NR) models of binary black holes (BBHs)
  - Calibrate & validate waveform models for searches, parameter estimation
    - Need catalogs of many simulations
  - Reveal the nonlinear dynamics of warped spacetime
- This paper: major update to SXS Collaboration catalog

Catalog	Started	Updating?	Simulations	m_1/m_2 range	$\lvert\chi_1\rvert$ range	$\lvert\chi_2\rvert$ range	Precessing?	Median $N_{\rm cyc}$	Public?
NINJA [97,114]	2008	✗	63	1–10	0–0.95	0–0.95	✗	15	✗
NRAR [119]	2013	✗	25	1–10	0–0.8	0–0.6	✓	24	✗
Georgia Tech [121]	2016	✓	452	1–15	0–0.8	0–0.8	✓	4	✓
RIT (2017) [122]	2017	✓	126	1–6	0–0.85	0–0.85	✓	16	✓
RIT (2019) [123]	2017	✓	320	1–6	0–0.95	0–0.95	✓	19	✓
NCSA (2019) [124]	2019	✗	89	1–10	0	0	✗	20	✗
SXS (2018)	2013	✓	337	1–10	0–0.995	0–0.995	✓	23	✓
SXS (2019)	2013	✓	1936	1–10	0–0.998	0–0.998	✓	39	✓

Methods

- Spectral Einstein Code
  - –Quasilocal black-hole masses, spins, centers
  - –Waveforms
    - Extraction
    - Extrapolation
    - Center-of-mass correction
  - –Sign convention change
    - For consistency with common conventions
    - With this catalog release, the strain *h* has the opposite sign as before

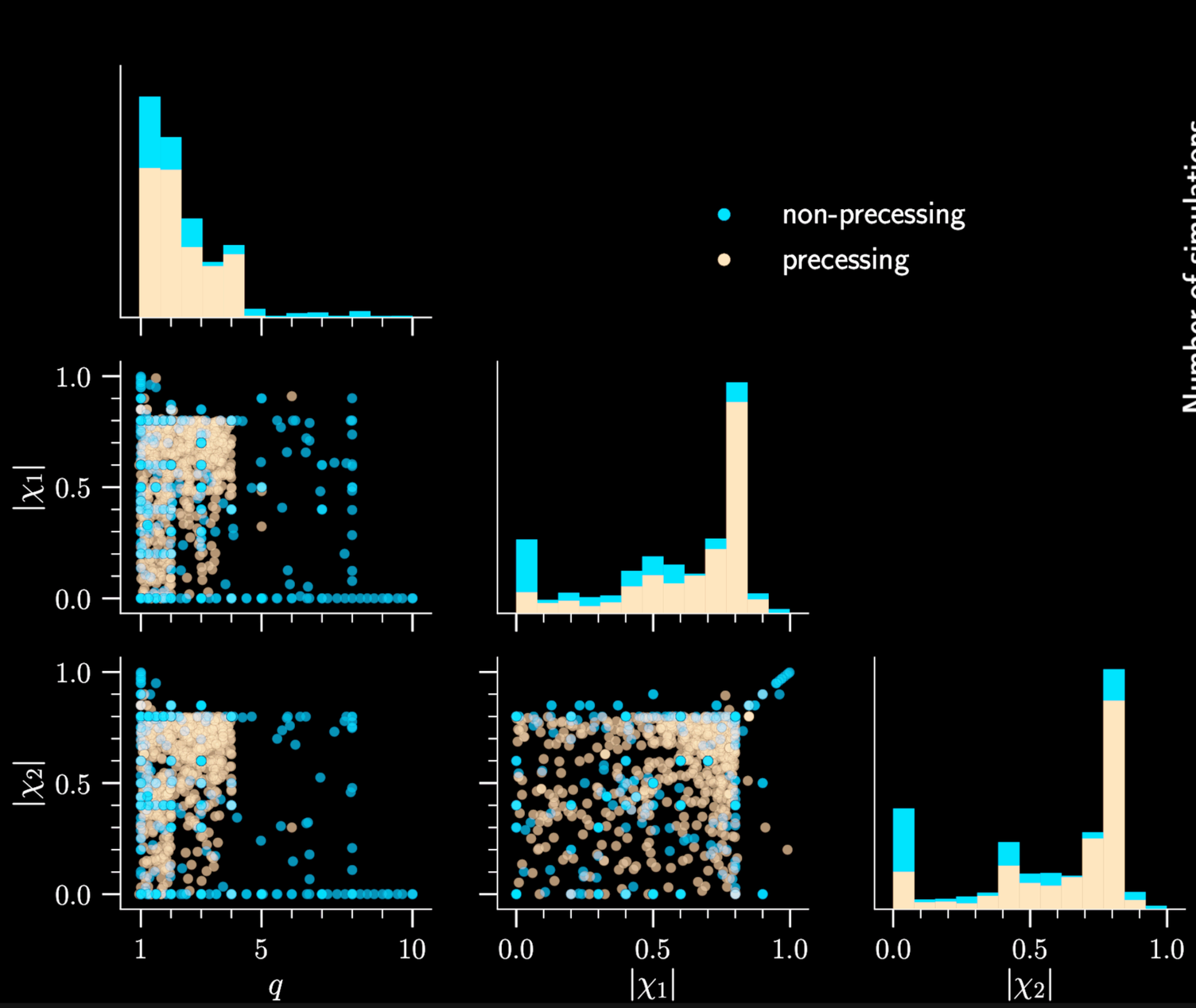


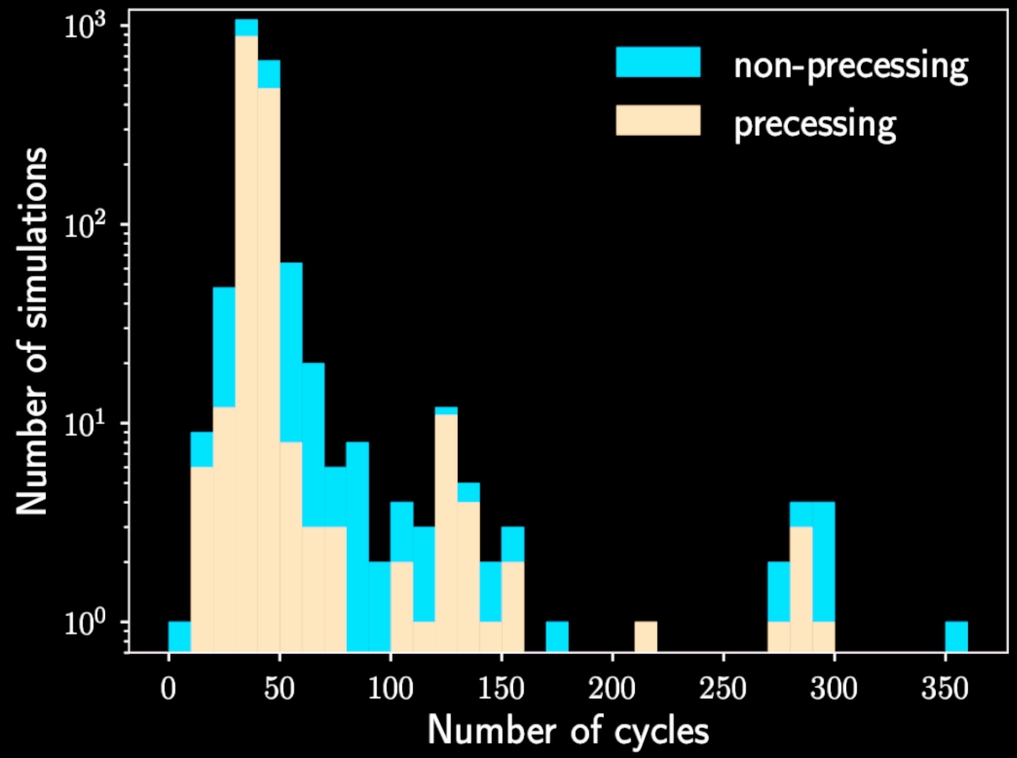
$$h_+ = \frac{1}{2}\left(h_{\hat{\theta}\hat{\theta}} - h_{\hat{\phi}\hat{\phi}}\right) ,$$

$$h_\times = h_{\hat{\theta}\hat{\phi}} ,$$

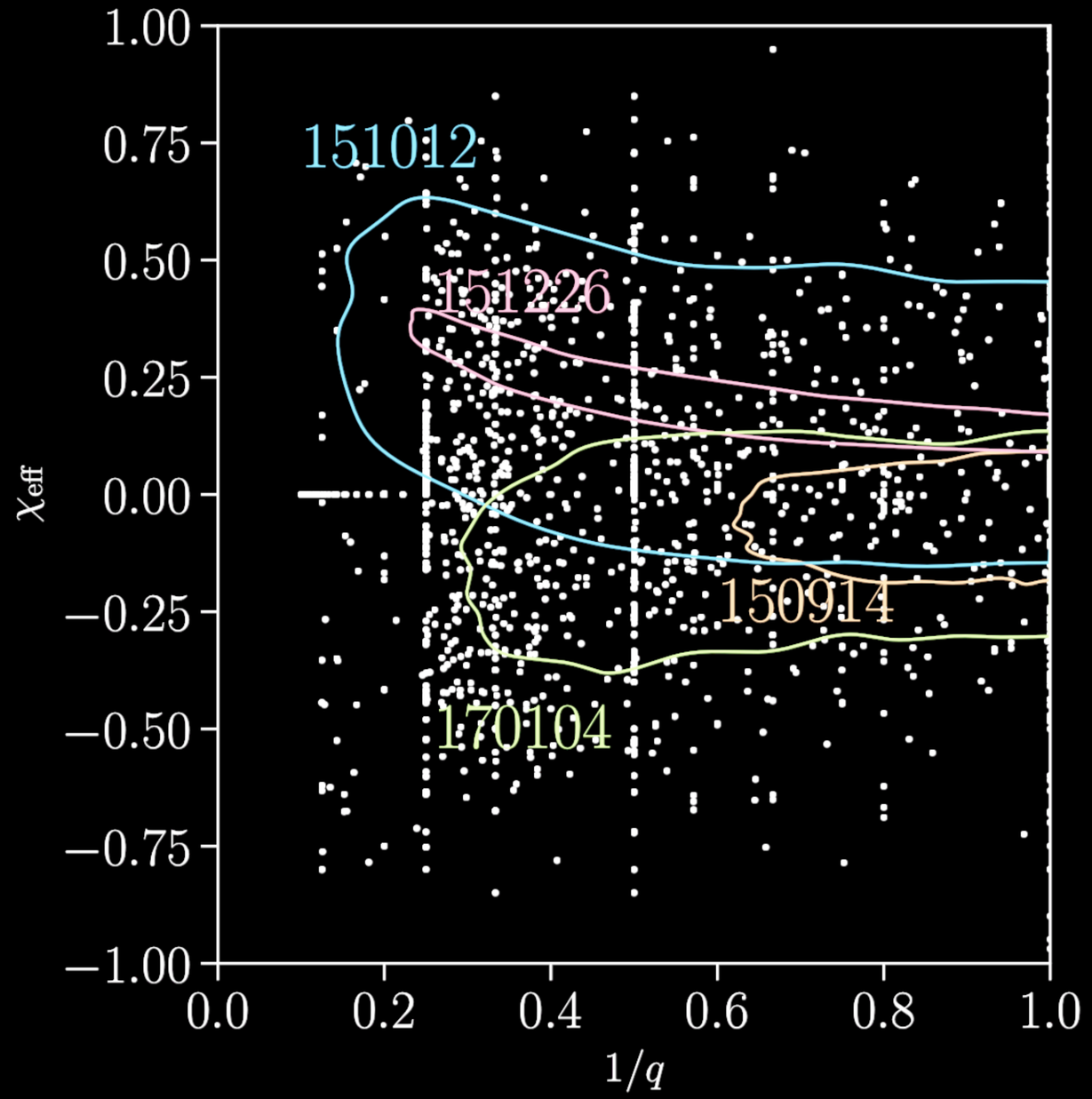
$$h = h_+ - i h_\times ,$$

Parameter space coverage

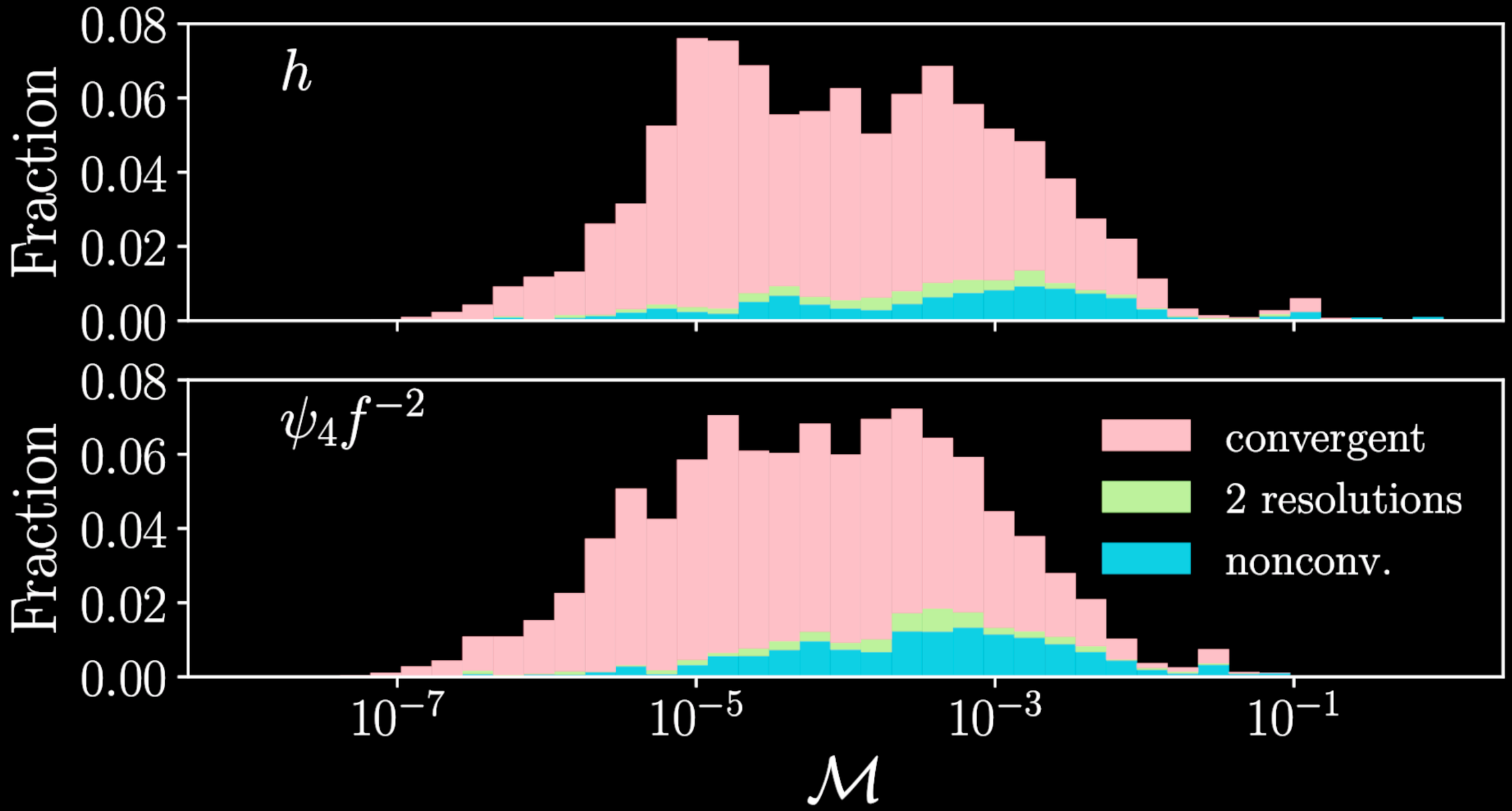




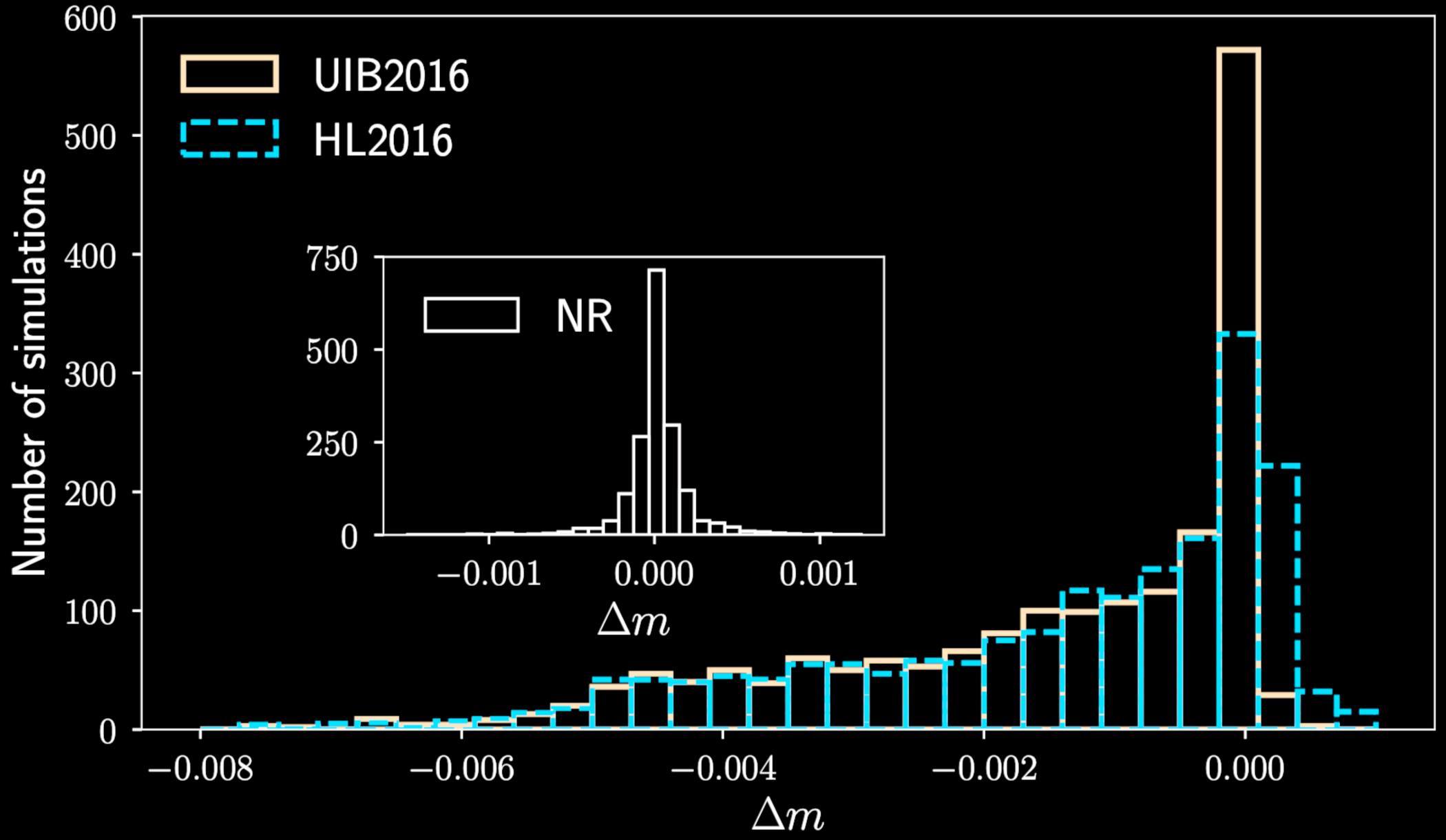
Parameter space coverage



Waveform quality



Remnant properties



Conclusion

- Substantial expansion of SXS Catalog of BBH waveforms

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- Availability
  - –With journal publication
    - black-holes.org/waveforms (SXS format, similar to NRAR format)
  - –Soon after publication
    - https://git.ligo.org/waveforms/lvcnr-lfs (LVC injection format)