Analytical and numerical modeling of precessing binary black holes

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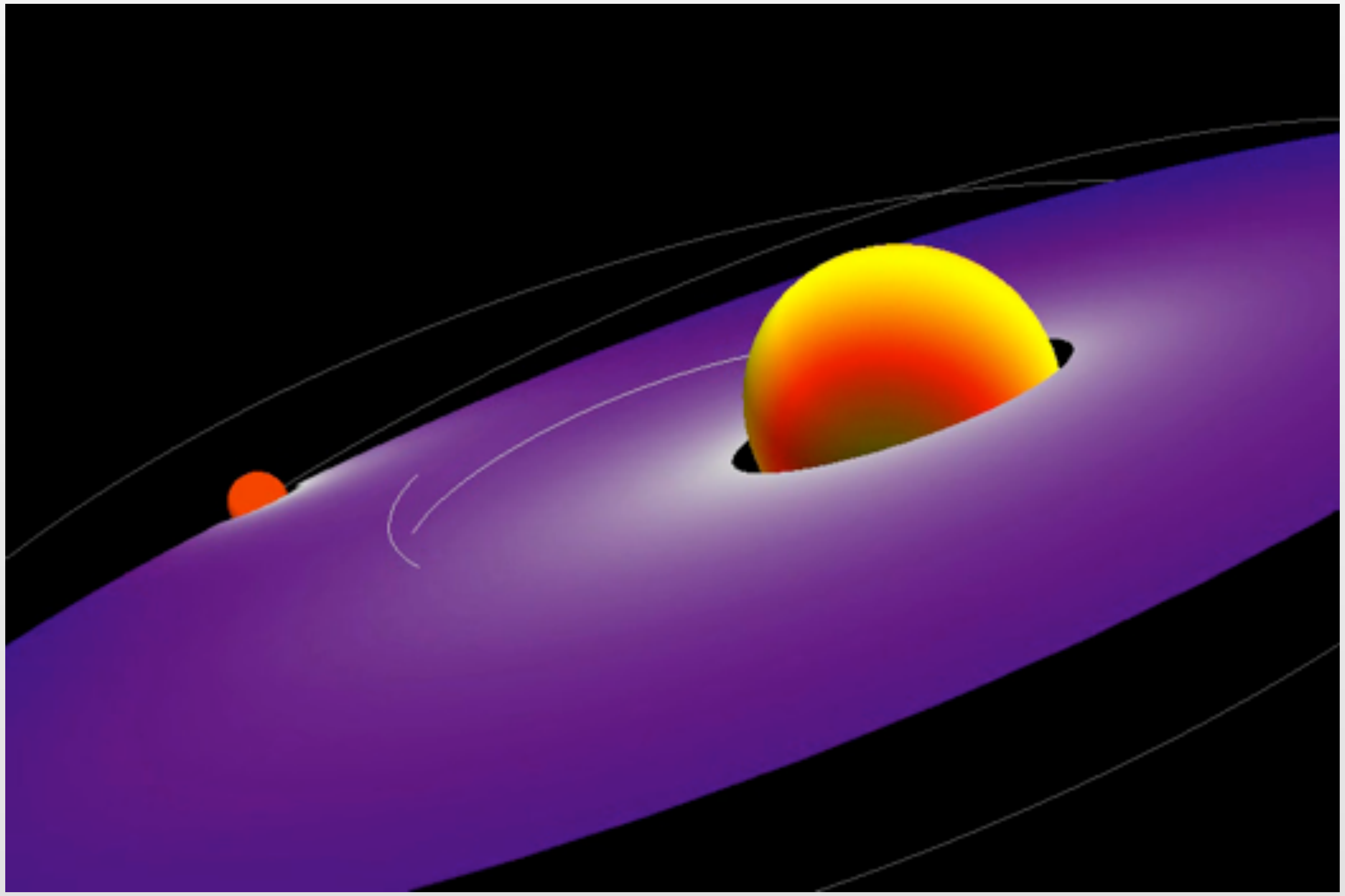
CAP Congress, Sudbury, June 16-20, 2014

Simulations of Extreme Spacetimes (SXS) collaboration

Buonanno group

Precessing compact object binaries

- Spin ***not*** parallel to orbital angular momentum
- Spin-spin and spin-orbit angular momentum exchange
- Orbital plane & spins precess



BH-BH binary
visualization by U of T ugrad Patrick Fraser

Motivation: LIGO

- ❖ Advanced LIGO nearly complete, first science run planned for 2015
- ❖ LIGO talks tomorrow:
  - Gaby Gonzalez 10:30-11:15
  - Kipp Cannon 13:35-14:15
  - Riccardo Bassiri 14:15-14:45
- ❖ Most likely GW source: Stellar mass compact object binaries

LIGO's many waveform needs

❖ Signal detection by matched filtering

- Template banks covering parameter-space targeted in searches

  aligned spin, non-eccentric

❖ Constrain event-rates with non-detection

- Some waveforms elsewhere in parameter space

  precessing systems; eccentric systems

❖ Parameter estimation (sky location!)

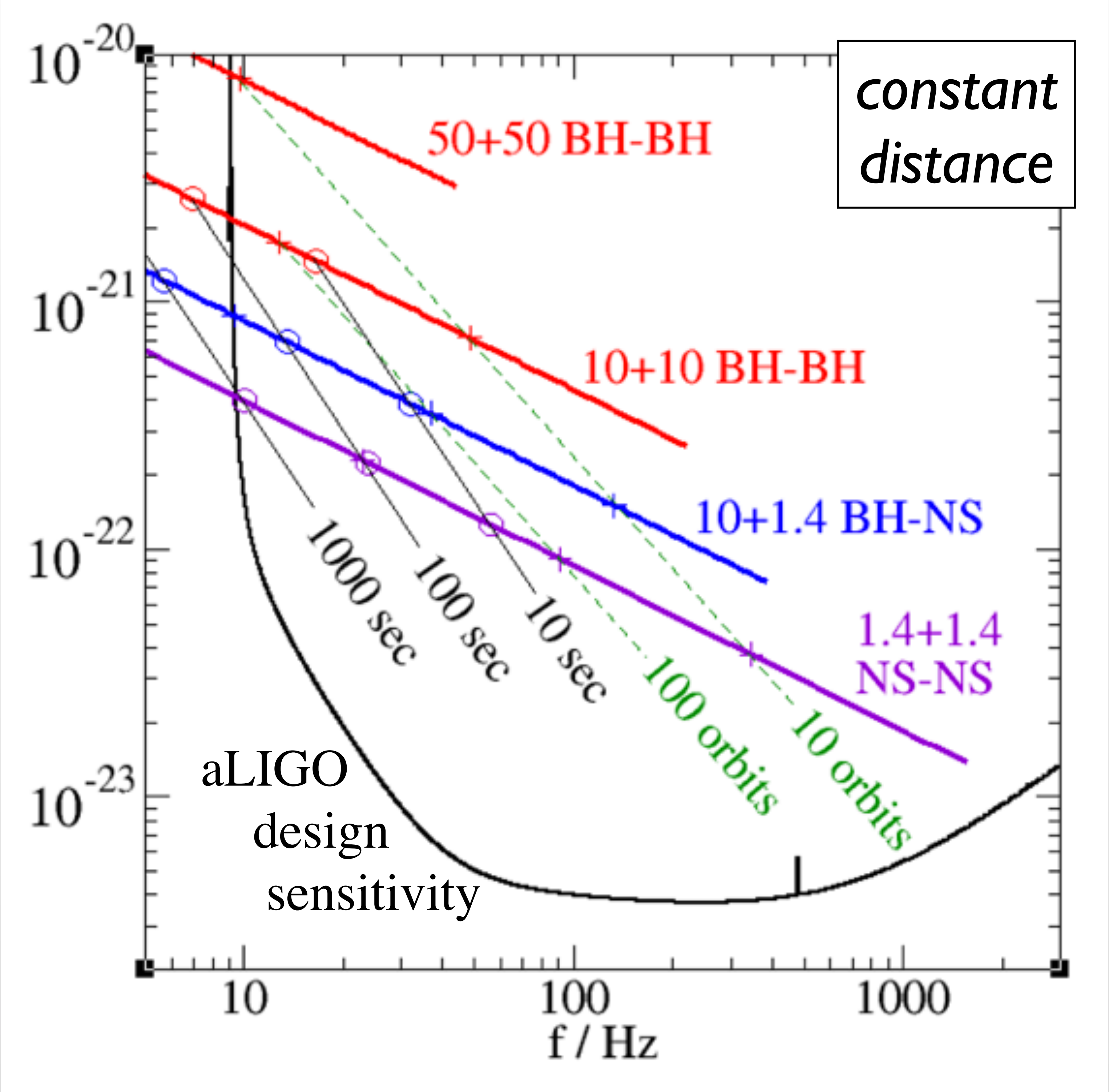
- ***Accurate*** waveforms **continuous** in ***all*** parameters

$$M_1, M_2, \vec{S}_1, \vec{S}_2;\ \ e, \omega_0;\ \ i, \beta;\ \ \mathrm{RA}, \mathrm{dec}$$

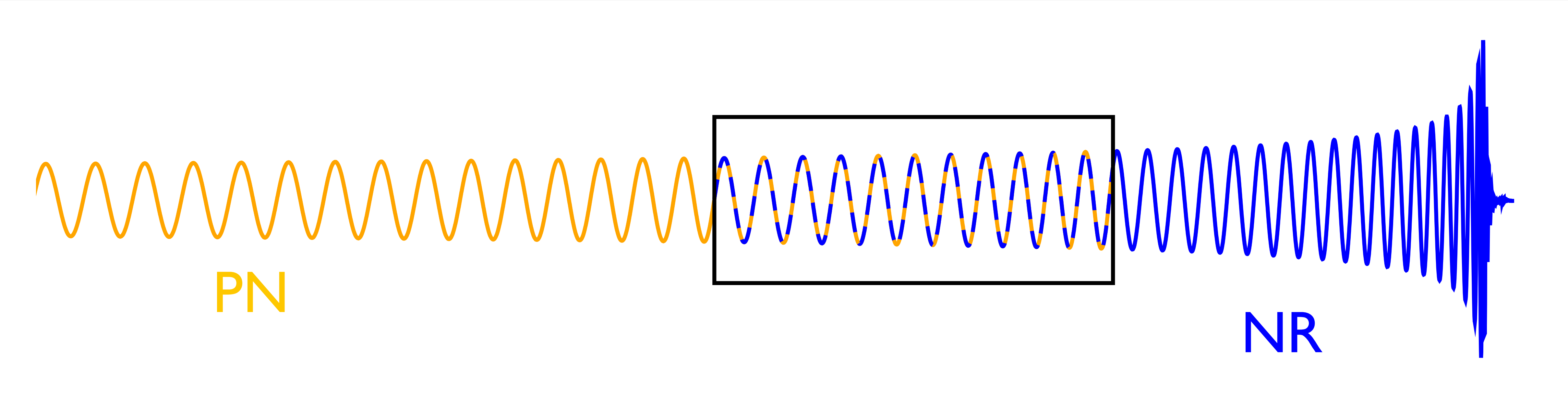
current goal: quasi-circular

Compact object binary characteristics

- BH-BH, BH-NS or NS-NS
- NS-NS merge at very high frequencies
  - inspiral waveforms sufficient
- BH-NS, BH-BH merge in LIGO's most sensitive frequency band
  - Require waveforms for last 100's of orbits, merger and ringdown



Tools for computing waveforms



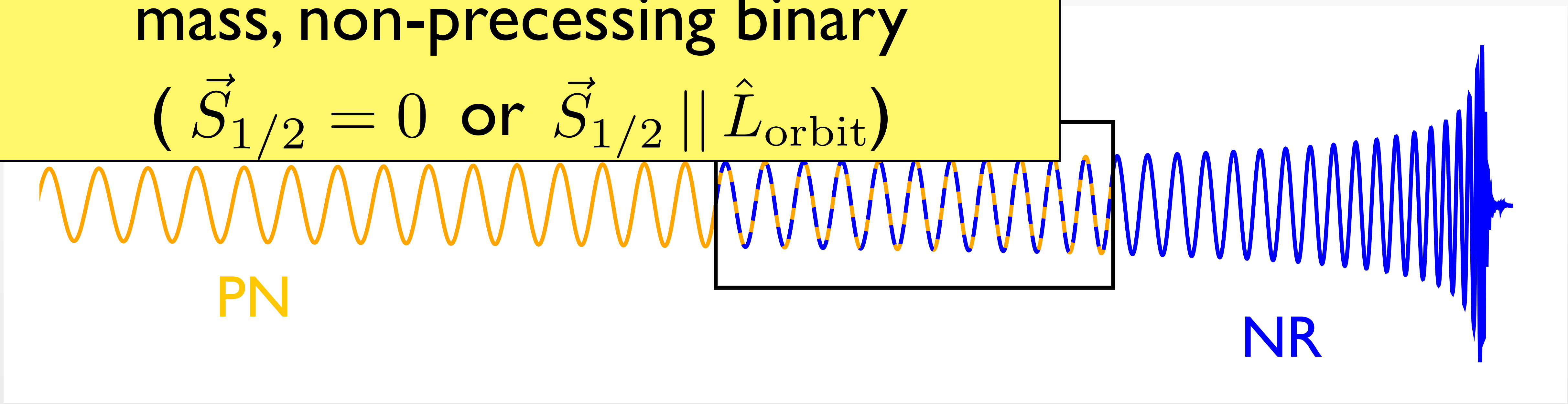
❖ Early inspiral
- Post-Newtonian
- Perturbative expansion in v/c

❖ Late inspiral+merger
- Numerical relativity
- State of the art:
  - 30 orbits,
  - 100,000 CPU-hours

❖ Ringdown
- Perturbation theory
- Numerical relativity

Tools for computing waveforms

Simple chirp waveform of an equal mass, non-precessing binary ($\vec{S}_{1/2} = 0$ or $\vec{S}_{1/2} \,||\, \hat{L}_{\rm orbit}$)



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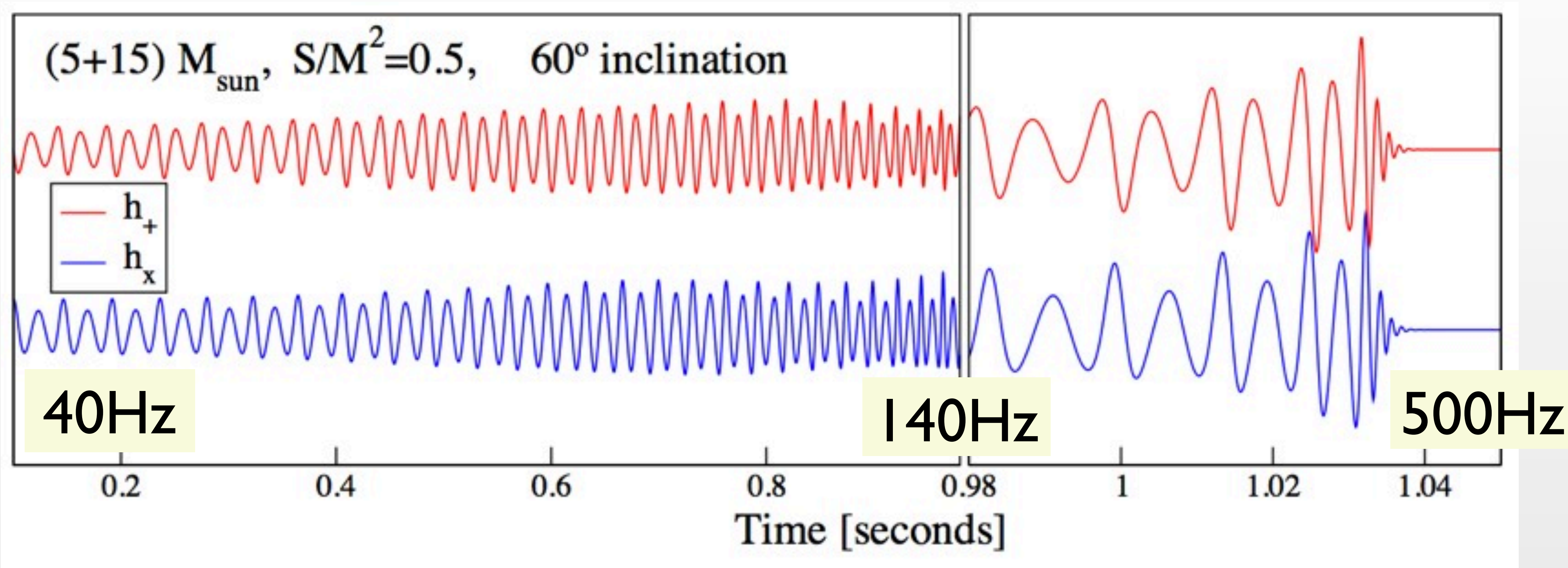
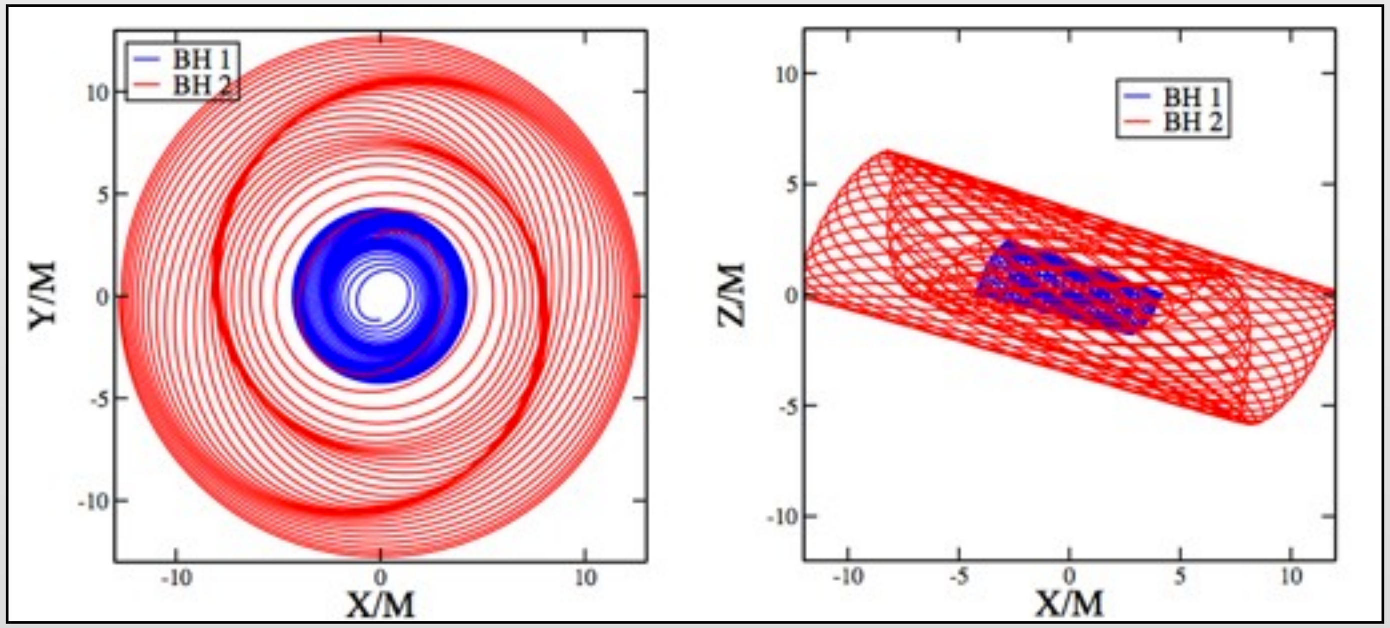
Precessing BH-BH

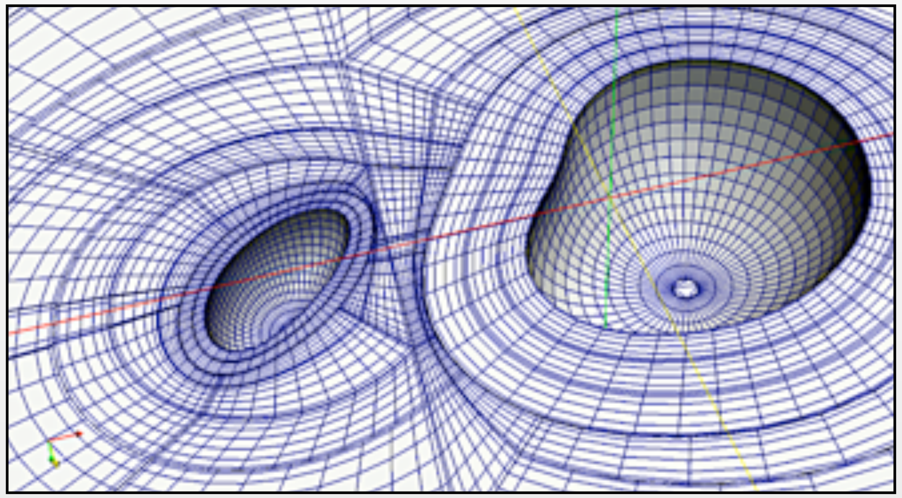


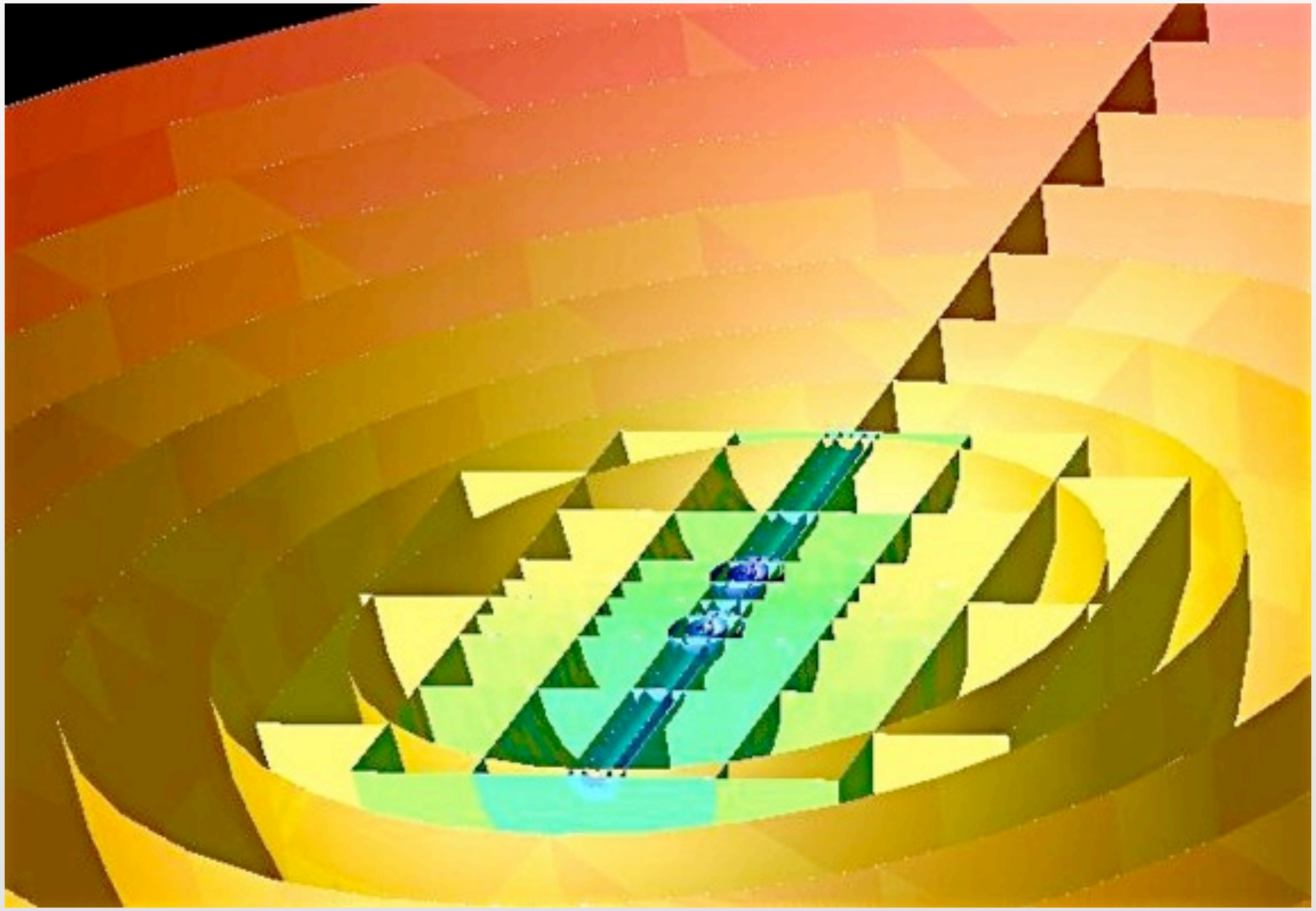
- Modulated amplitude
- Temporal harmonics
- Dependence on inclination
- Modified phasing



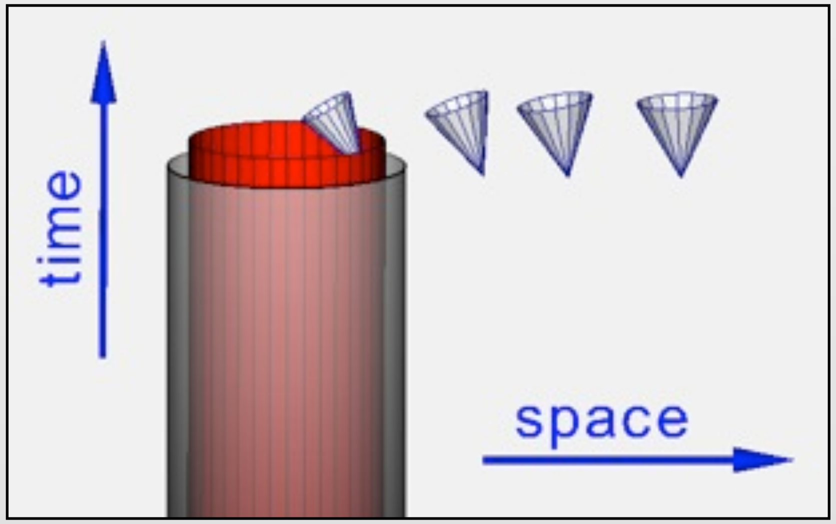
Spectral Einstein Code (SpEC)

- ❖ Multi-domain spectral adaptive mesh refinement





- ❖ BH excision



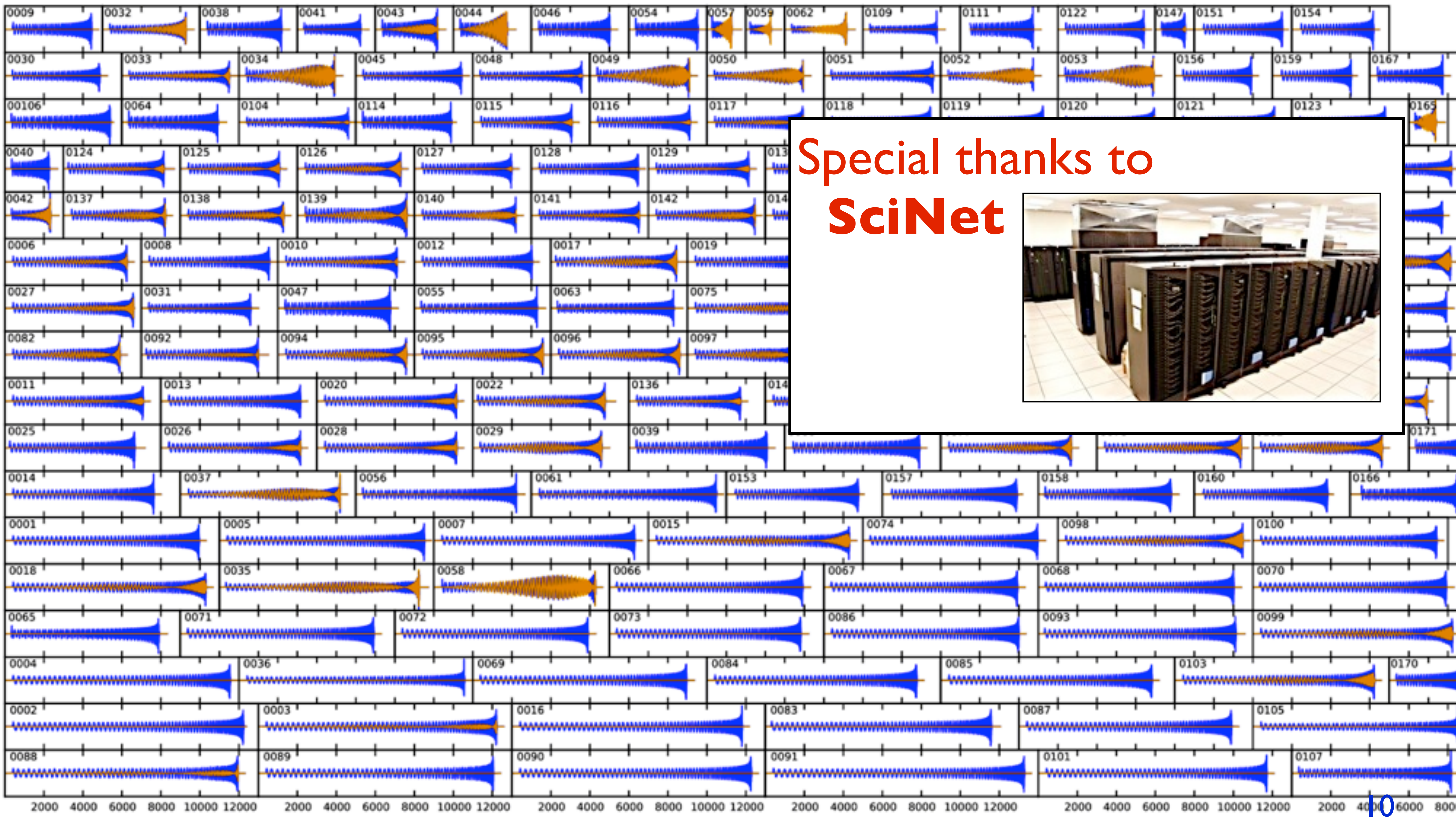
- ❖ High efficiency and accuracy enables very long simulations

www.black-holes.org/SpEC.html

e.g. HP ea 04, Scheel ea 06, Boyle ea 07, Lovelace ea 08, Hemberger ea 13, Mroue ea 13, Szilagyi 14

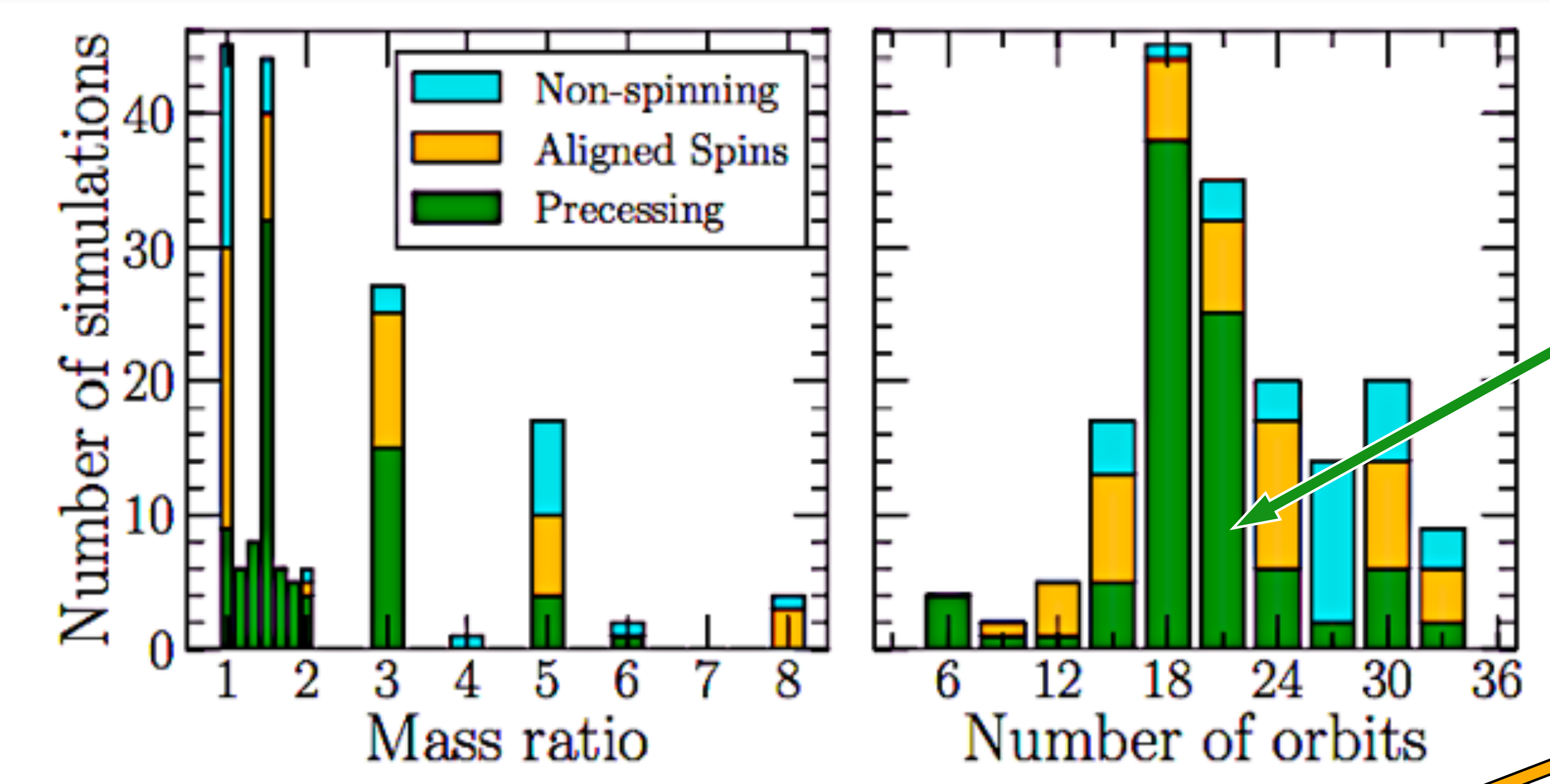
SXS numerical waveform catalog

A. Mroue, M.Scheel, B.Szilagyi, HP et al, 1304.6077, PRL 2013
Data publicly available www.black-holes.org/waveforms



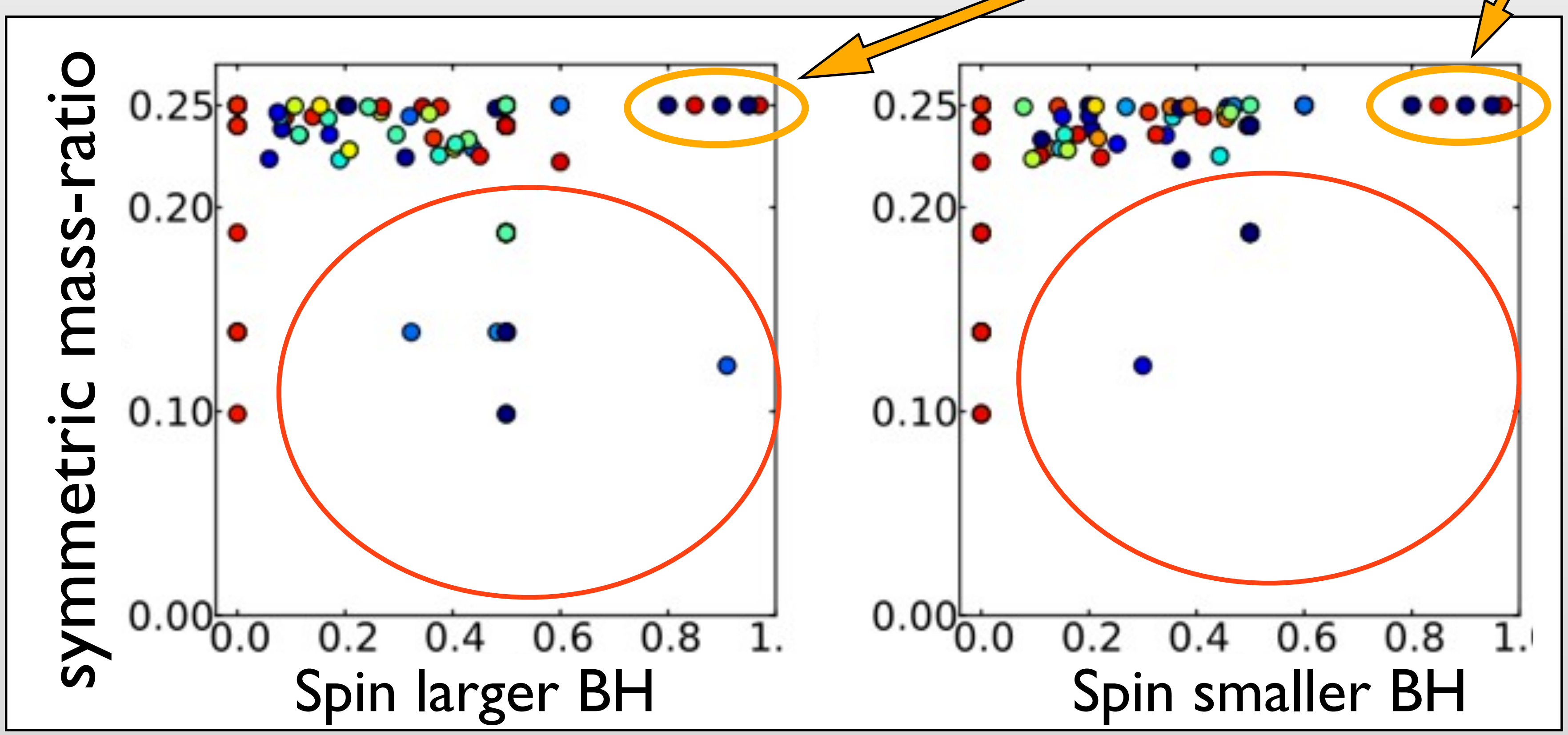
Special thanks to
SciNet

SXS catalog: parameter space coverage



91 precessing binaries

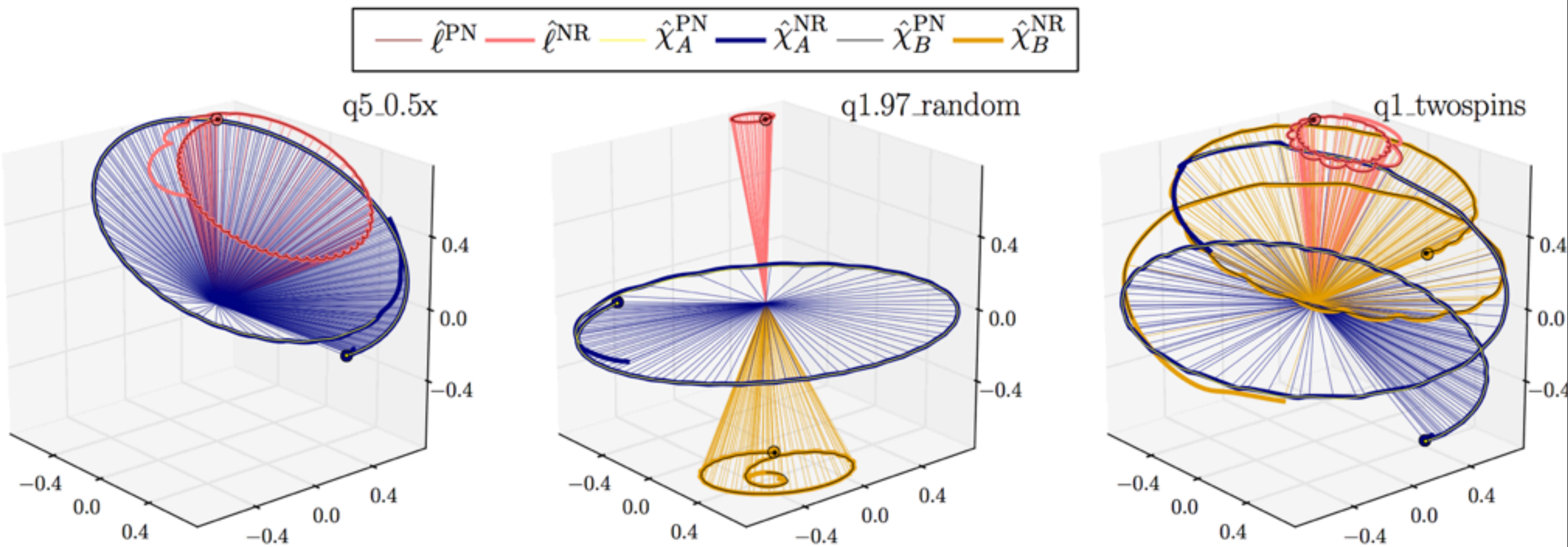
Max aligned spin 0.98



Few unequal-mass systems with spin

Investigate precession dynamics

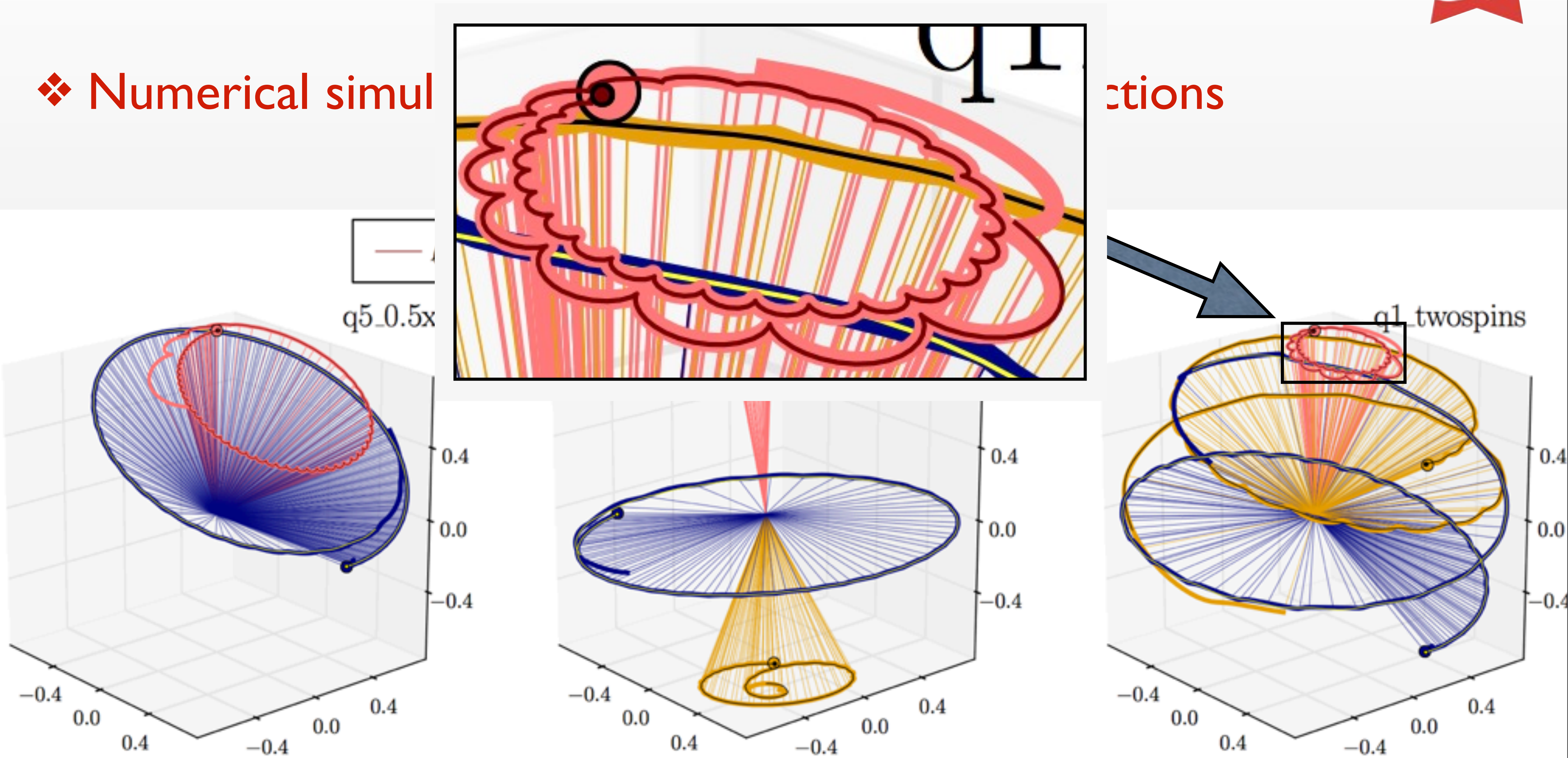
❖ Numerical simulations & post-Newtonian predictions



Ossokine ea, in prep

Numerics (red) agree w/ post-Newtonian (black)

❖ Numerical simul ... ctions

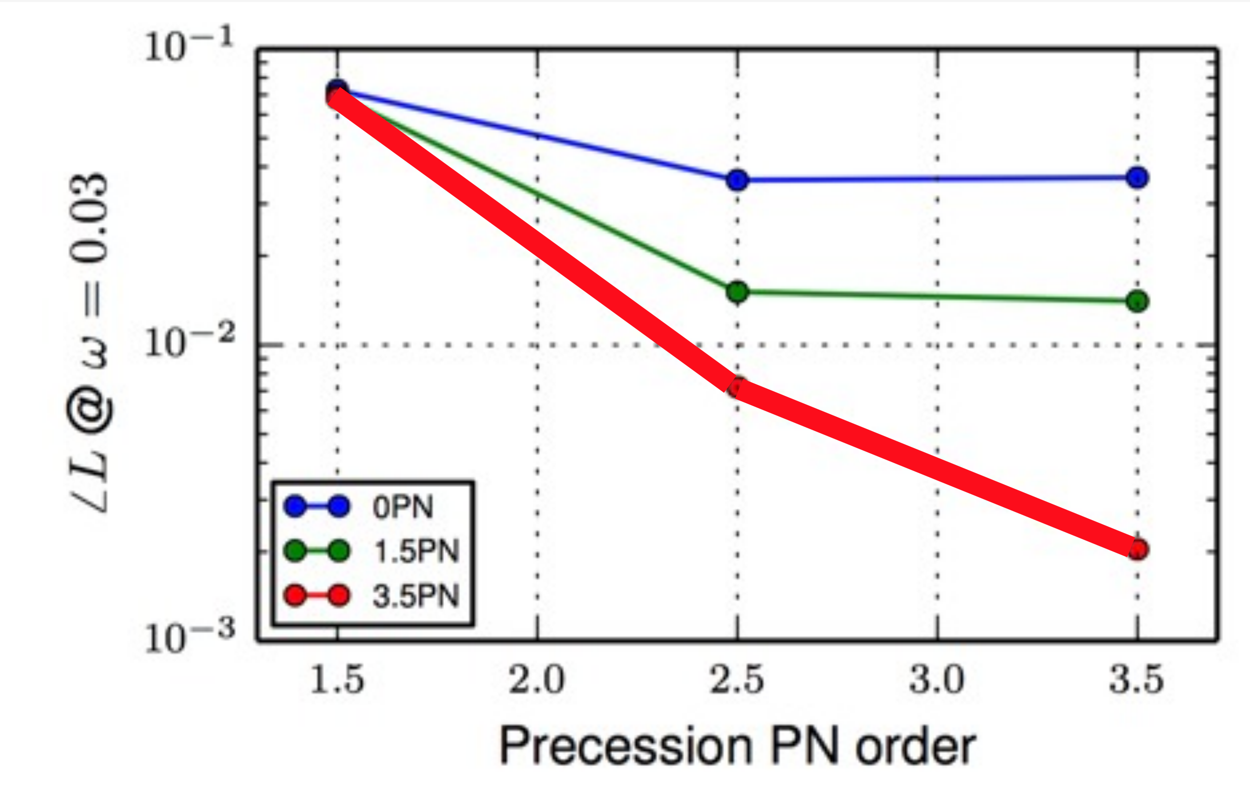


Ossokine ea, in prep

Convergence of precessing PN

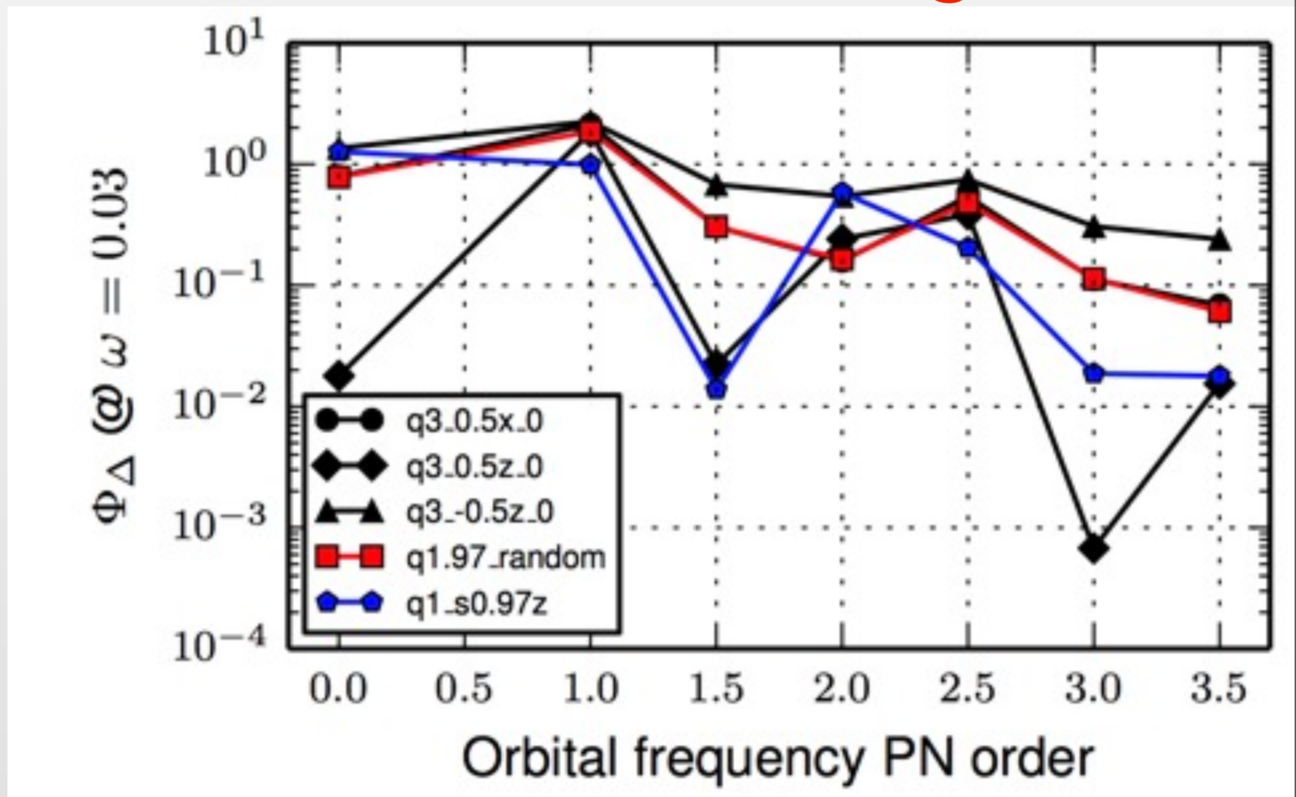
orbital plane precession

quick, monotonic convergence



orbital phase

slow, erratic convergence



Ossokine ea, in prep

As bad as non-precessing PN requires many-orbit NR & careful modeling

Analytical waveform modeling

❖ Effective one body

- Buonanno, Damour 1999; many papers since
- Effective Hamiltonian to capture conservative dynamics

$$H = \mu\sqrt{p_r^2 + A(r)\left[1 + \frac{p_r^2}{r^2} + 2(4-3\nu)\nu\frac{p_r^4}{r^2}\right]}, \qquad A(r) = \sum_{k=0}^{4}\frac{a_k(\nu)}{r^k} + \frac{a_5(\nu)}{r^5}$$

- Radiation reaction terms

$$\frac{dp_r}{dt} = -\frac{\partial H}{\partial p_r} + a^r_{\rm RR}\frac{\dot r}{r^2\Omega}\widehat{\mathcal{F}}_\phi$$

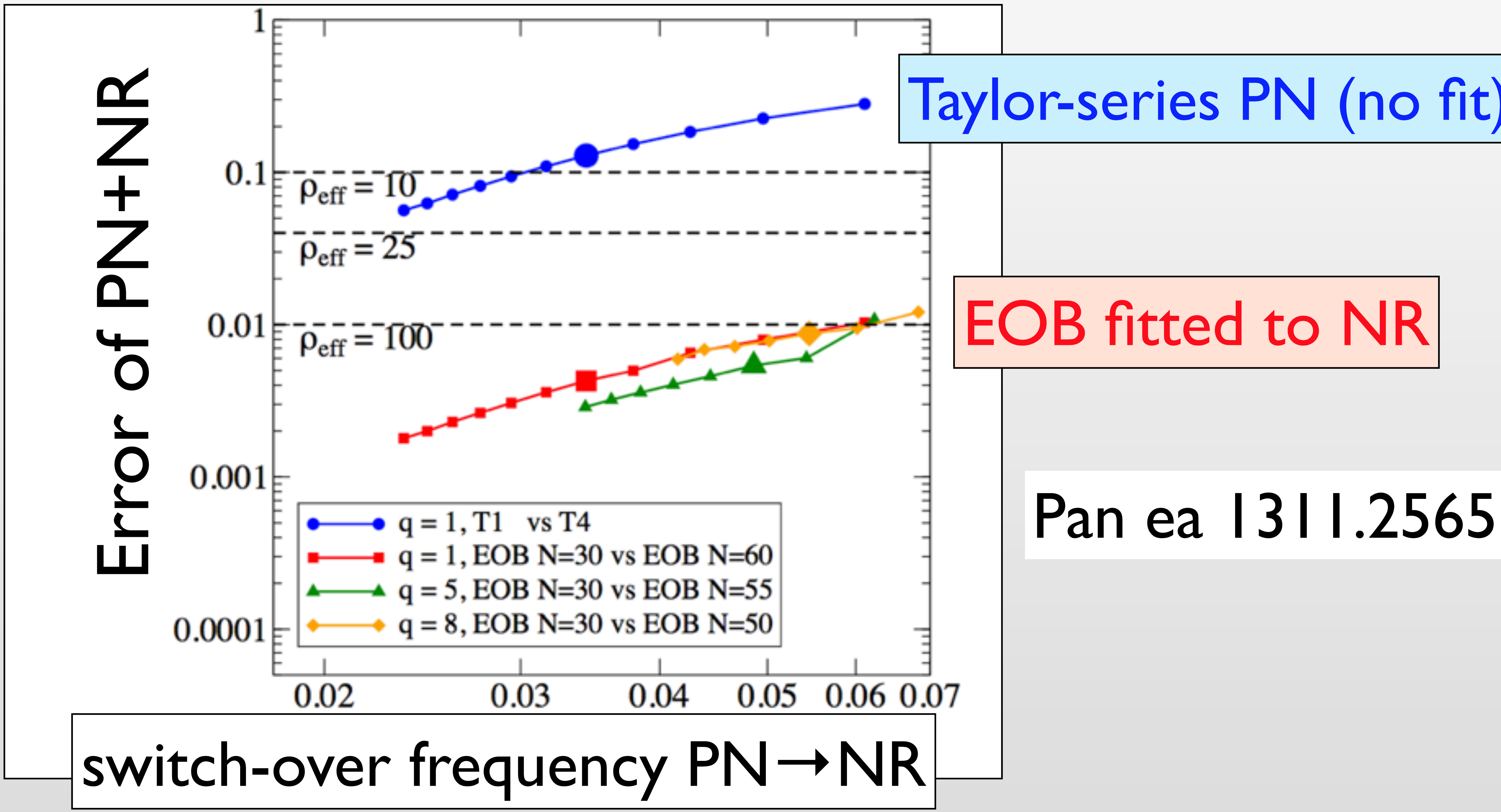
$$\frac{dp_\varphi}{dt} = = 0 - \frac{v_\Omega^3}{\nu V_\phi^6}F_4^4(V_\phi;\nu, v_{\rm pole}), \quad \text{using 4-PN term } \mathcal{F}_{8,\nu=0} + \nu A_8$$

- Attach BH ringdown modes

★ Fit free parameters to NR simulations

EOB progress (1)

❖ Non-spinning case: ***Error-estimate*** of EOB fit



Pan ea 1311.2565

EOB progress (2)

❖ Aligned-spin case: Spin-magnitudes ***up to extremal***

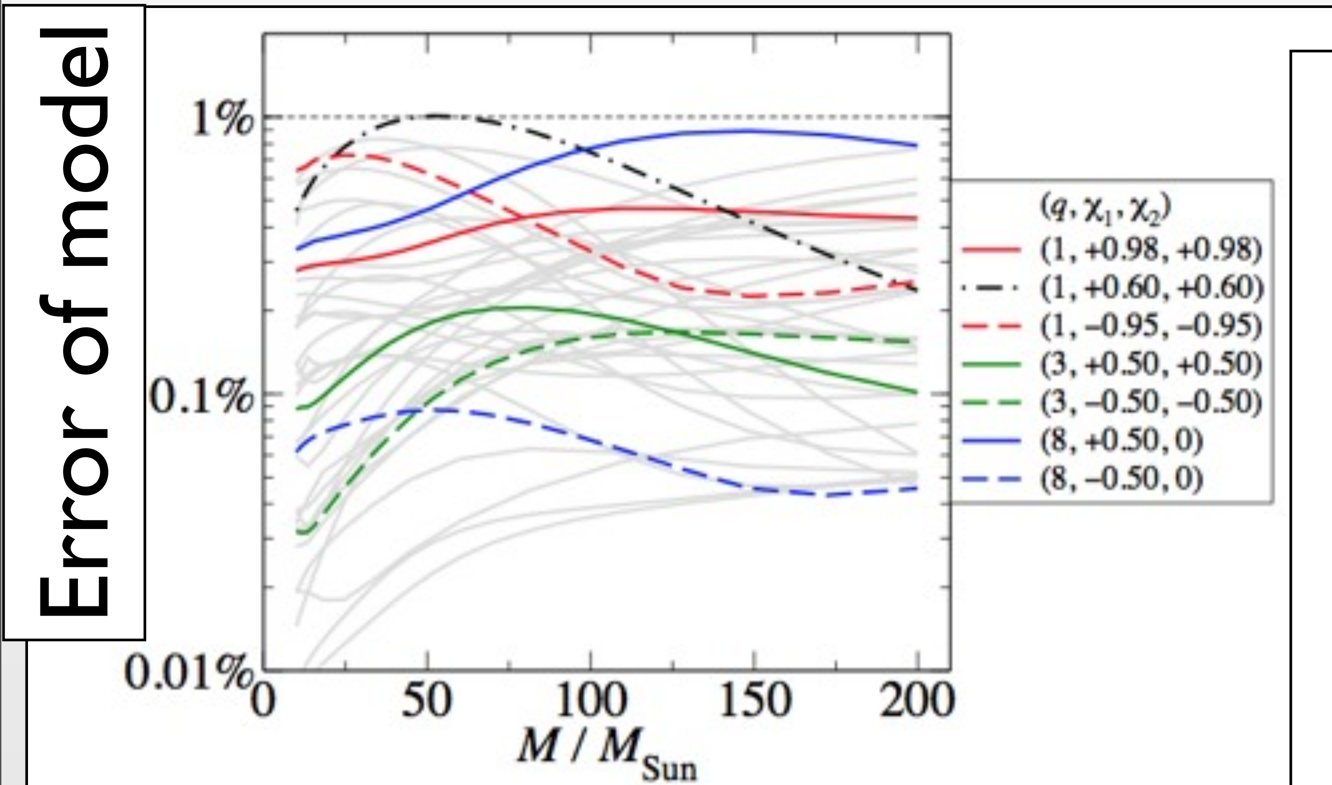
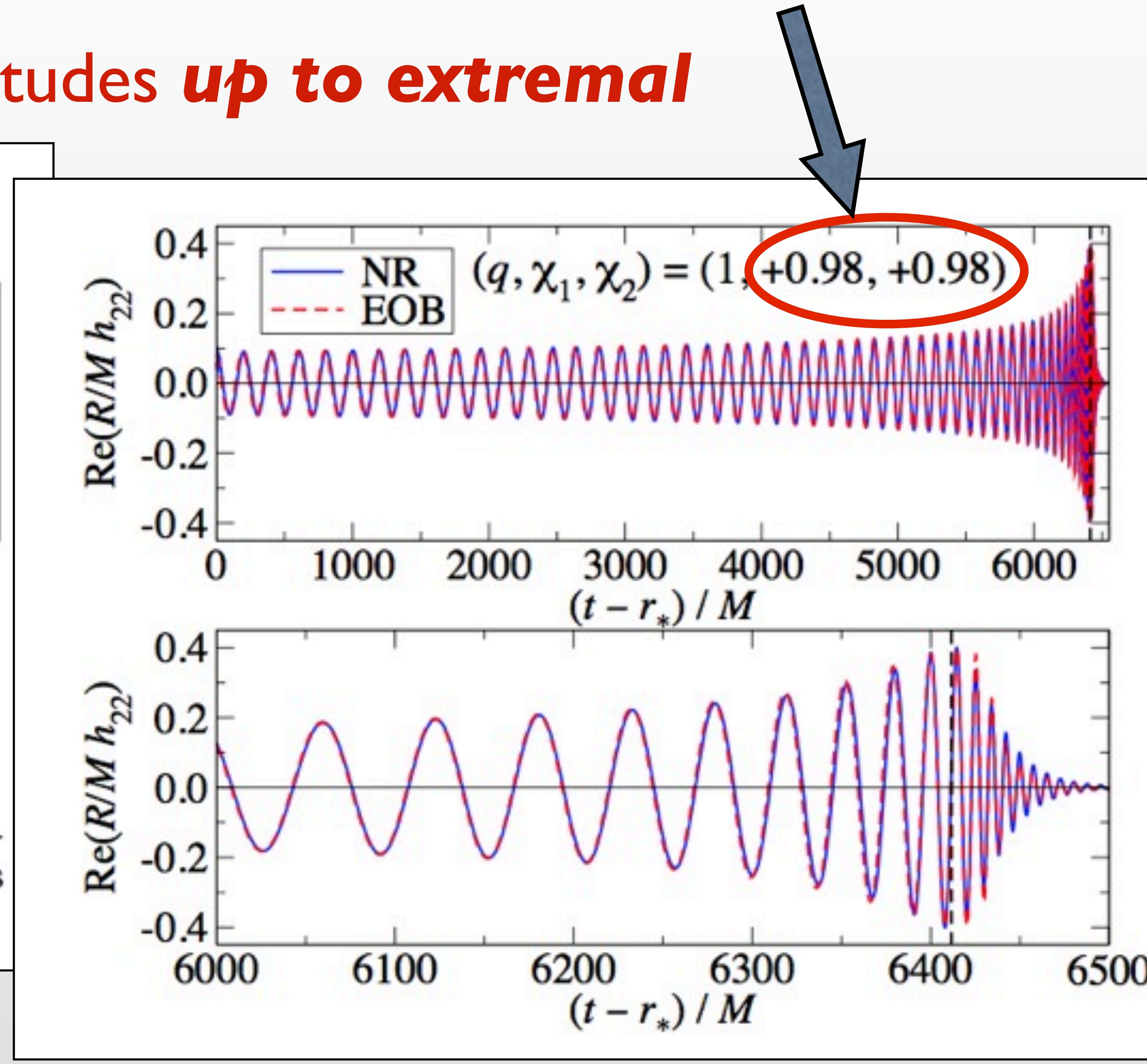


FIG. 1. Unfaithfulness of (2,2) EOB waveforms for *all* the 38 non-precessing BH binaries in the SXS catalog. Only a few selected cases are labeled in the legend.

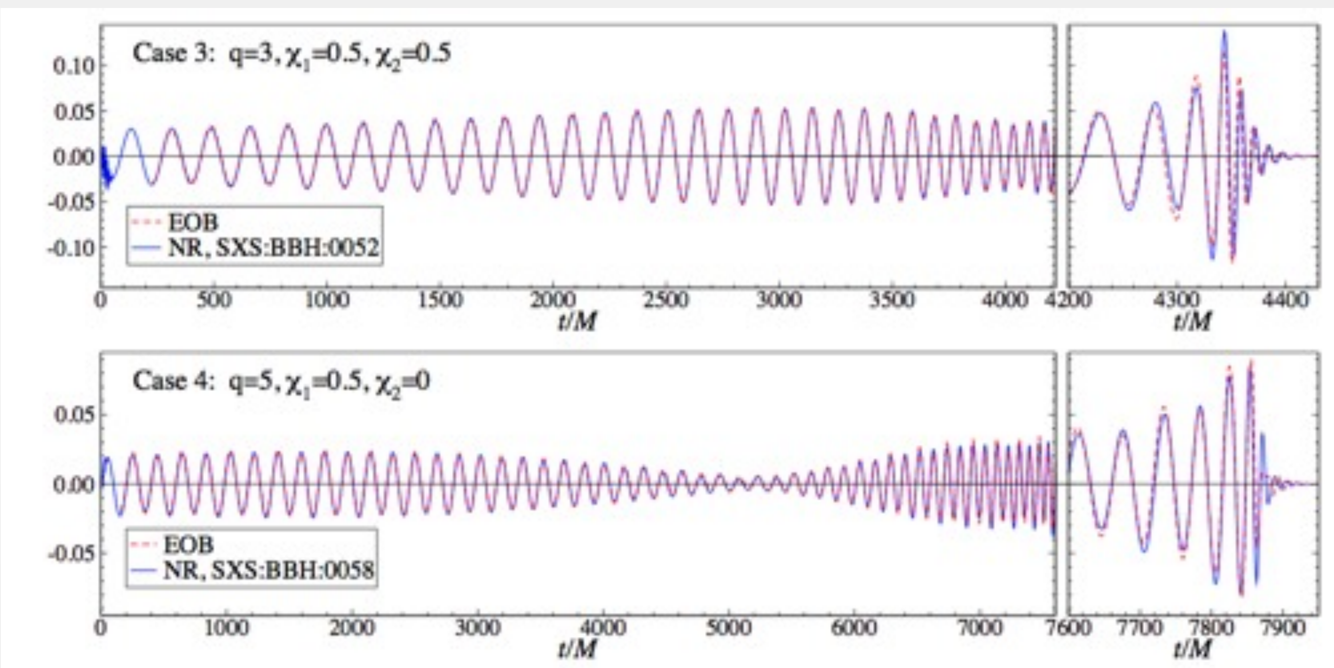


Taracchini ea, 1311.2544

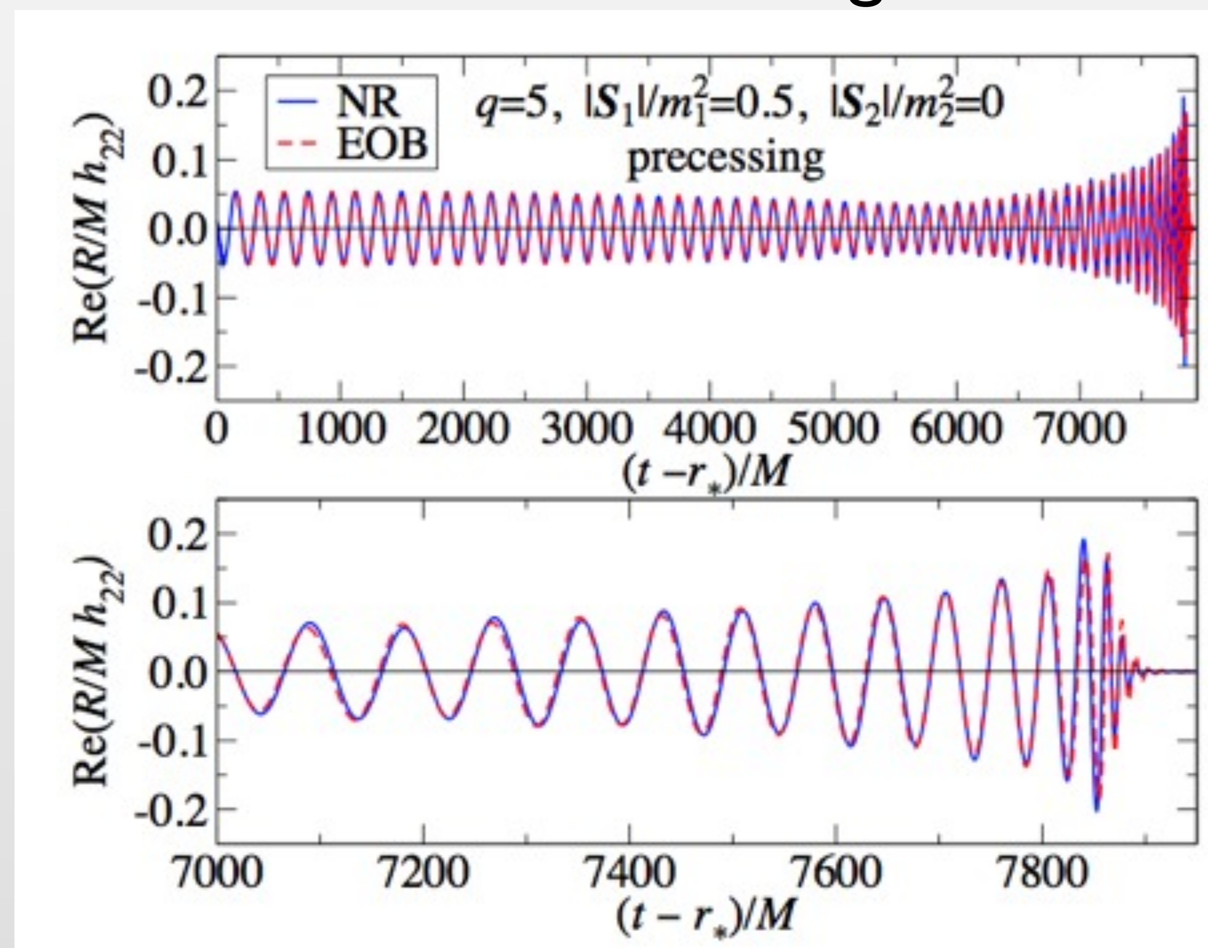
EOB progress (3)

❖ <u>Precessing case:</u> ***First generic, precessing EOB models***

- Idea (Buonanno ea 2005, Hannam ea 1308.3271)
- Start with aligned-spin waveforms
- Apply time-dependent rotation to account for orientation change of orbital plane



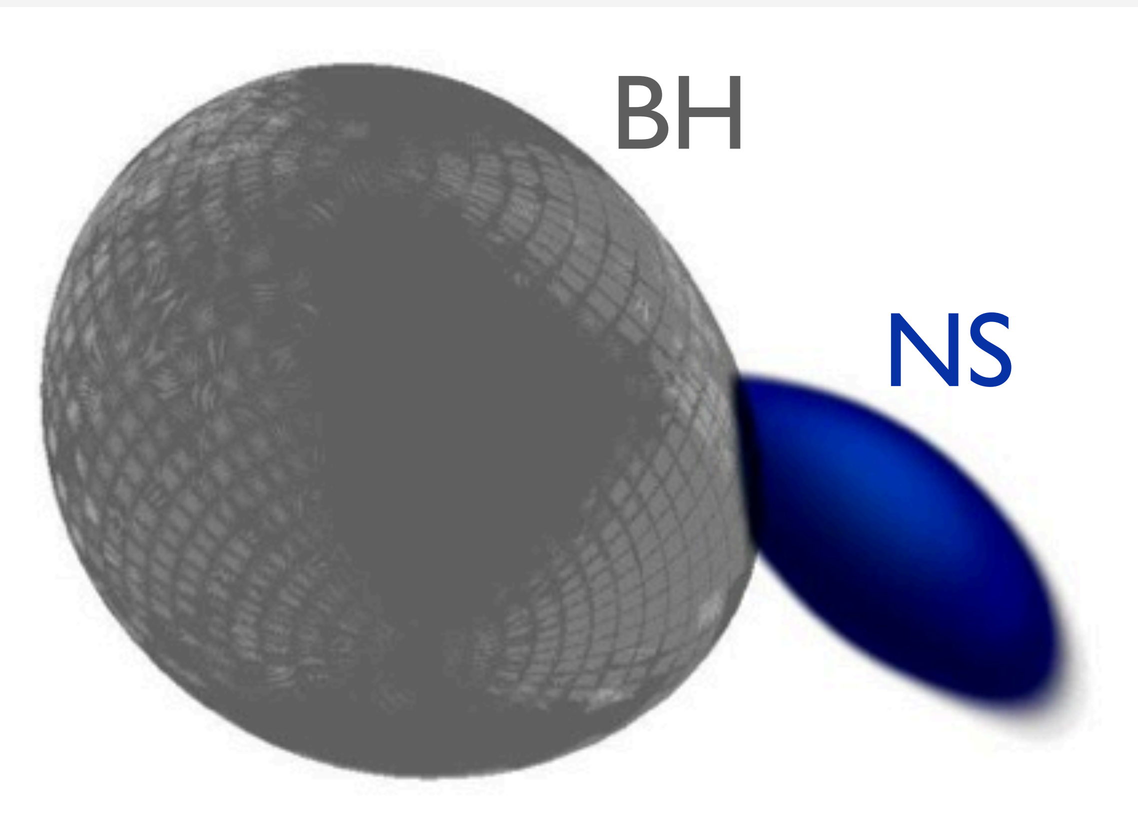
Pan ea, 1307.6232



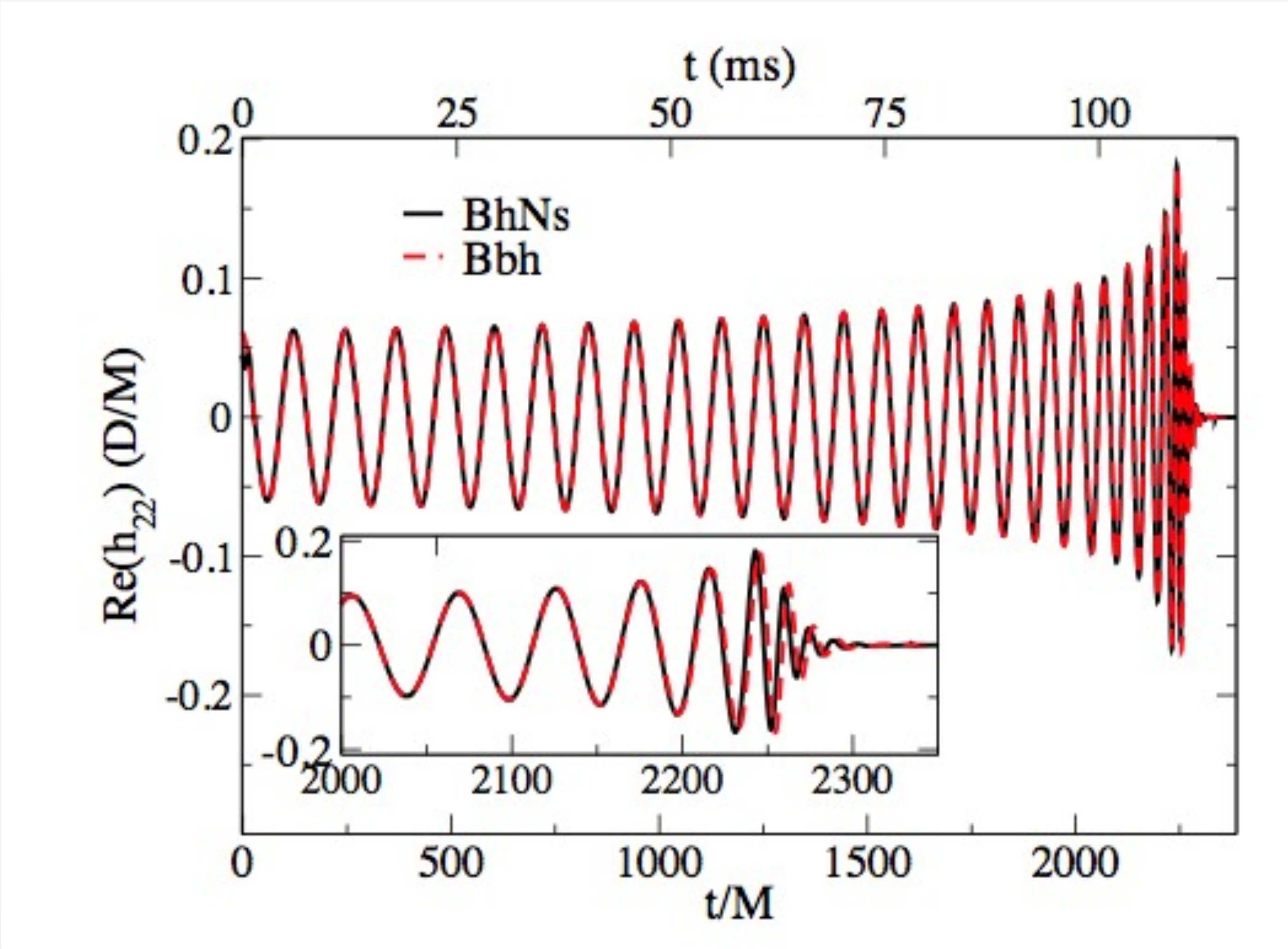
Taracchini ea, 1311.2544

Mixed BH-NS binaries

❖ For high mass-ratio, low-spin: ***BH-NS ≡ BH=BH***
  - NS eaten by BH in one piece, no disruption

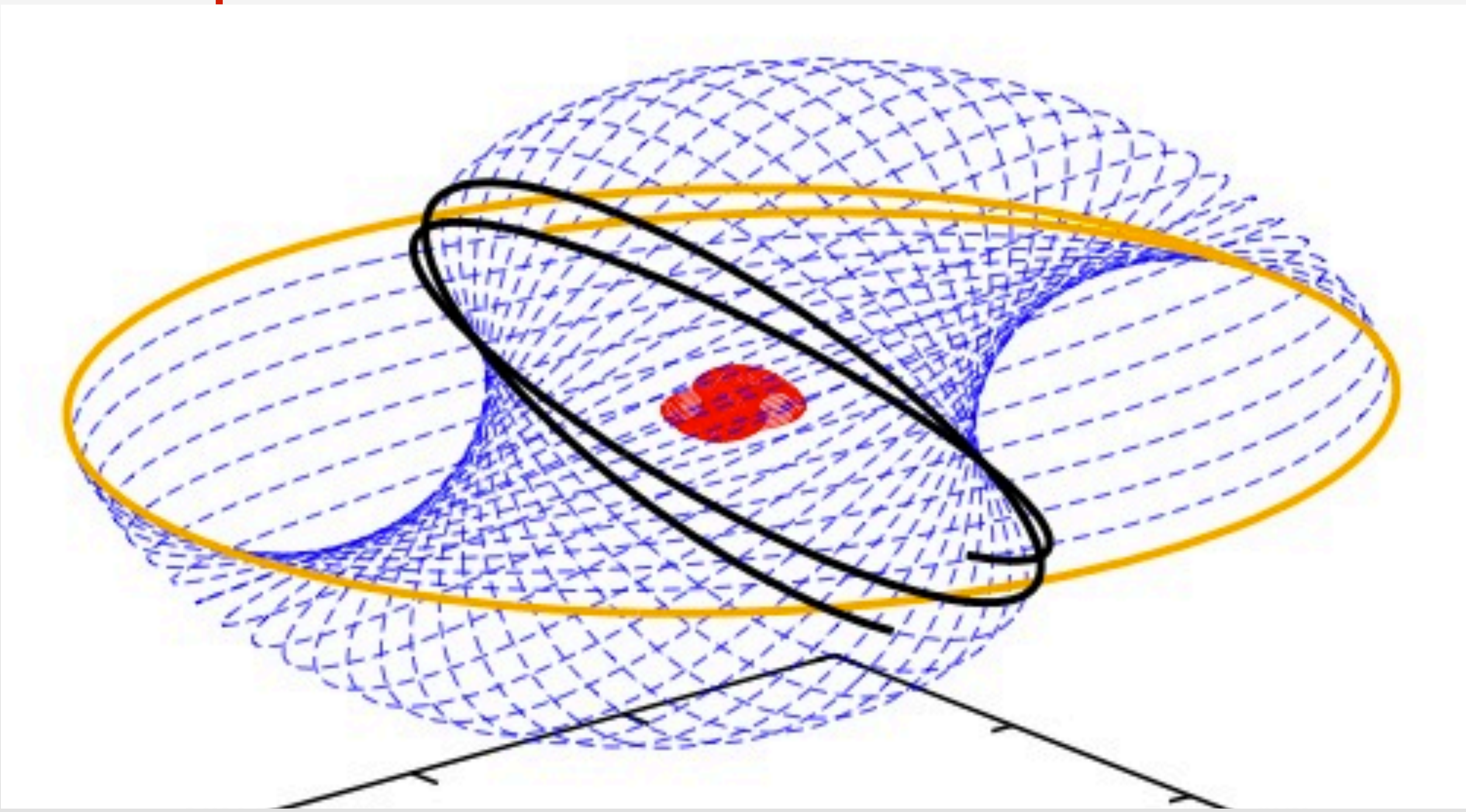


Foucart ea, 1311.2544



Highly precessing BH-BH

- q=9.5, Spin 0.5, mimicks a 13Msun + 1.4Msun BH-NS
- orbital plane flips over

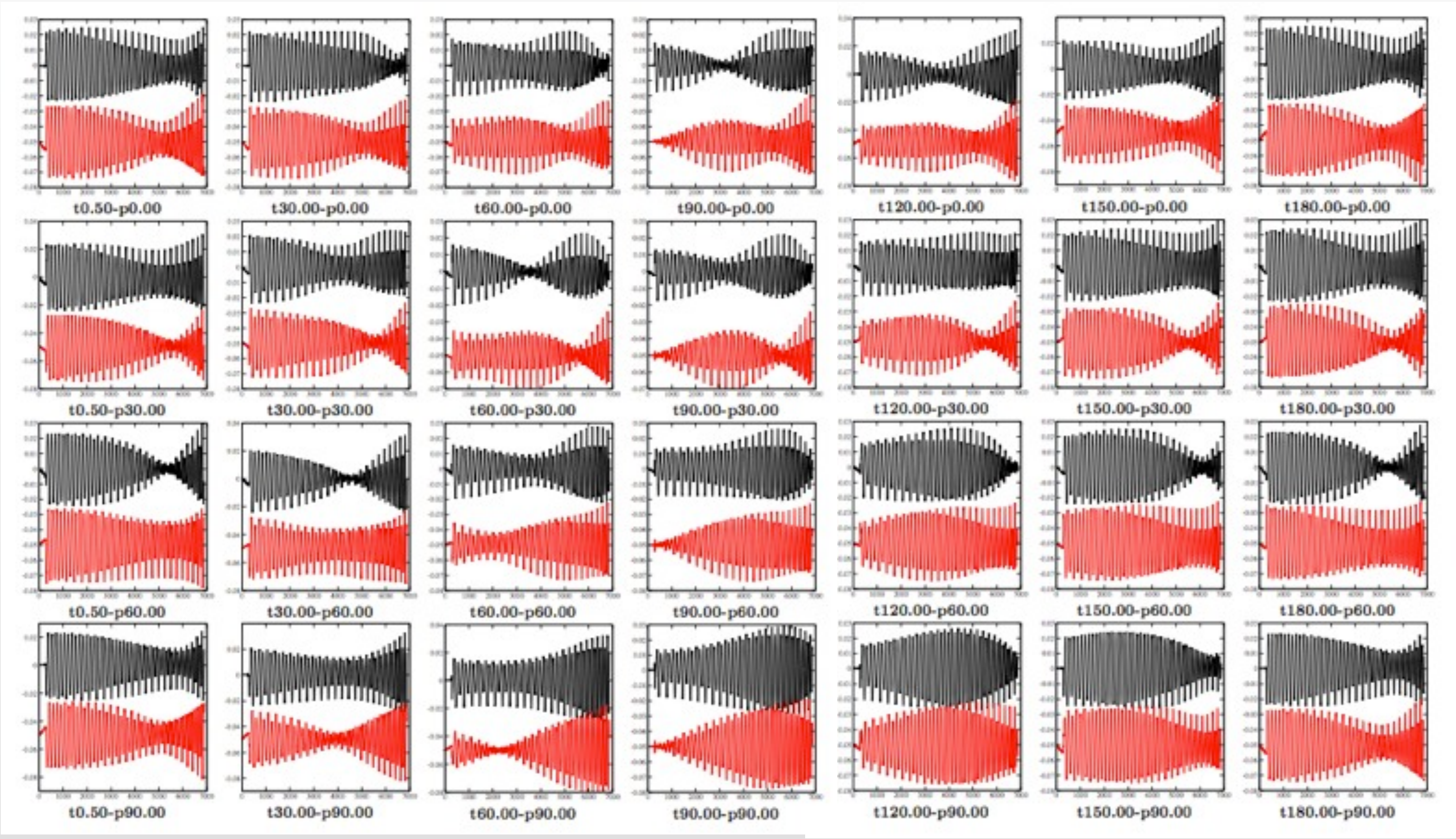


Ossokine, HP & SXS

One system, many emission directions

change inclination

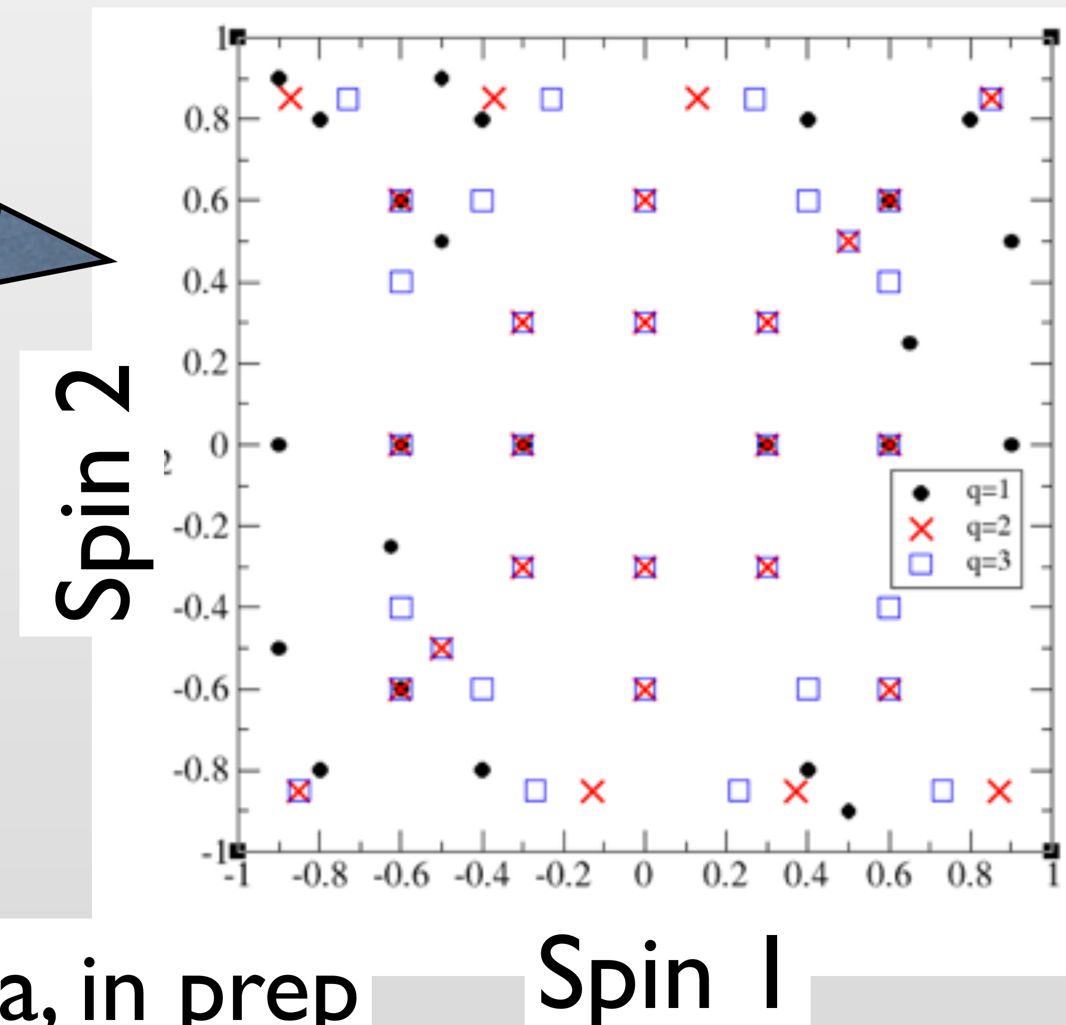
change orbital phase



S. Ossokine, HP + SXS

Summary

- ❖ Advanced LIGO on track for searches in 2015
- ❖ Vast progress in waveform modeling
  - 100's of NR simulations
  - first precessing BBH models
  - complete knowledge of precessing BH-BH appears feasible
- ❖ Future work
  - Validation everywhere in spin-space
  - **mass-ratio≳4 w/ spins**
    - PN least reliable in that region
  - BH-NS with NS disruption
  - eccentric systems



Chu ea, in prep