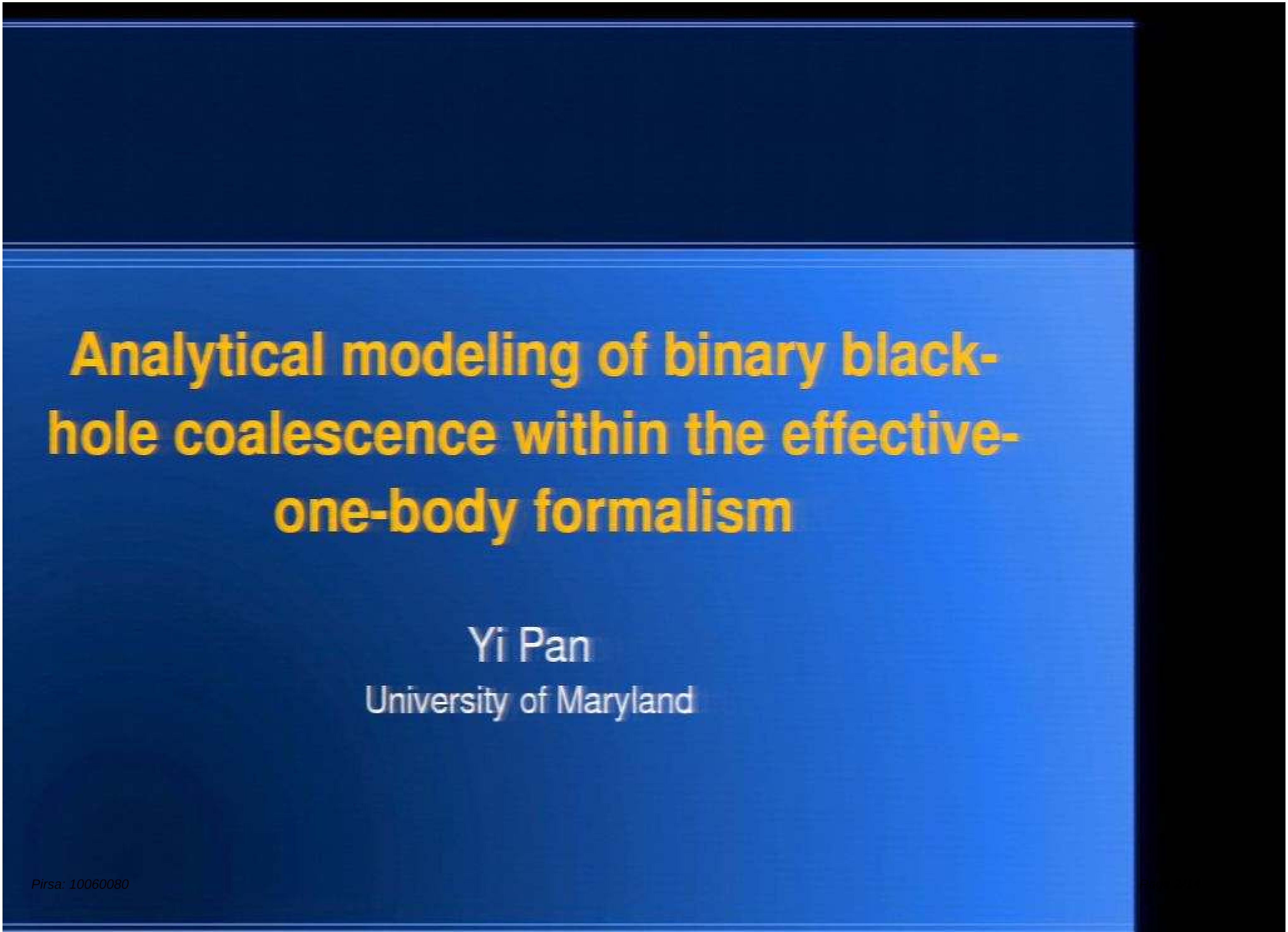
Title: Analytical modeling of binary black-hole coalescence within the effective-one-body formalism.

Date: Jun 25, 2010 05:10 PM

URL: http://pirsa.org/10060080

Abstract: I will review recent advances in the effective-one-body formalism aimed at describing the dynamics and gravitational-wave emission from coalescing black holes. I will discuss the implications of those advances for the search of gravitational waves from binary black holes and for the recoil velocity of black holes formed through merger.



Analytical modeling of binary black-hole coalescence within the effective-one-body formalism

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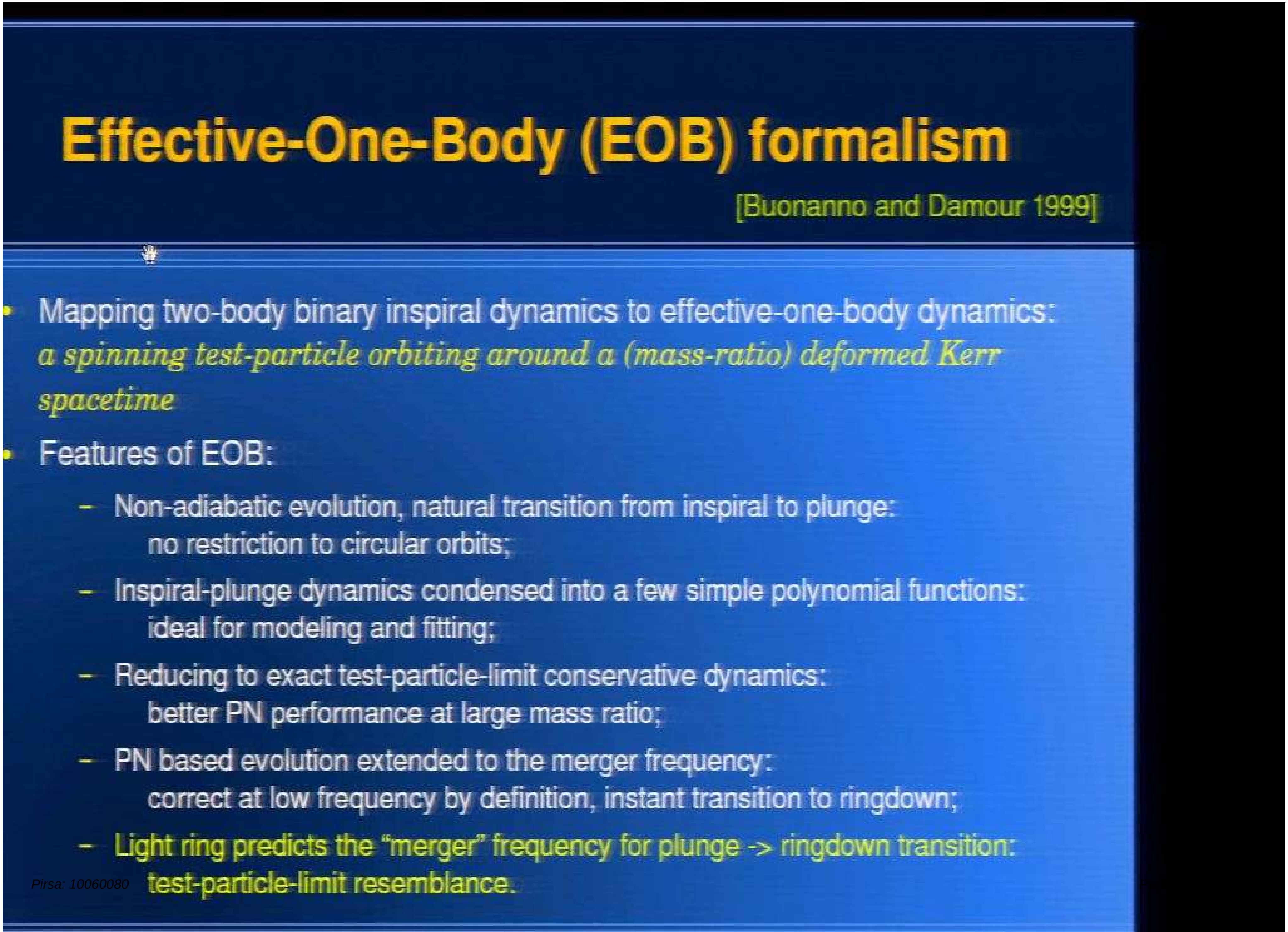
Collaborators and Motivation

- Collaborators: Alessandra Buonanno, Enrico Barausse, Etienne Racine, Andrea Taracchini, Ryuichi Fujita, Hideyuki Tagoshi, Nico Yunes, Scott Hughes, Cole Miller, NASA-Goddard NR Group, Caltech-Cornell-CITA NR Collaboration.
- Motivation: accurate analytical waveforms meeting the detection and measurement requirements for the observation of GW signals from coalescing BBH with laser interferometric GW detectors.
- We consider comparable-mass binaries on quasi-circular orbits (see N. Yunes' talk for EOB modeling of EMRI waveforms).
- Improvements made to the EOBNR model being used to generate templates for LIGO high-mass search: *better accuracy for non-spinning waveforms and development of spinning waveforms*



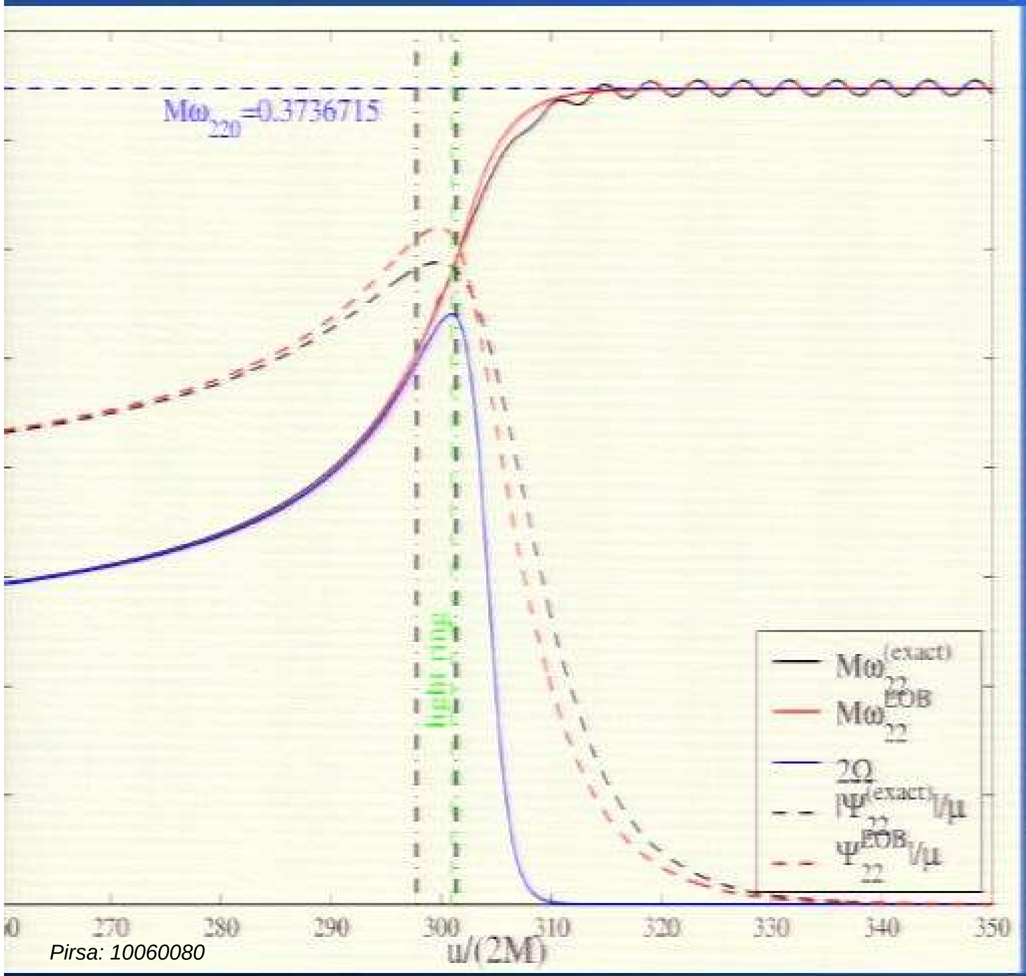
Effective-One-Body (EOB) formalism

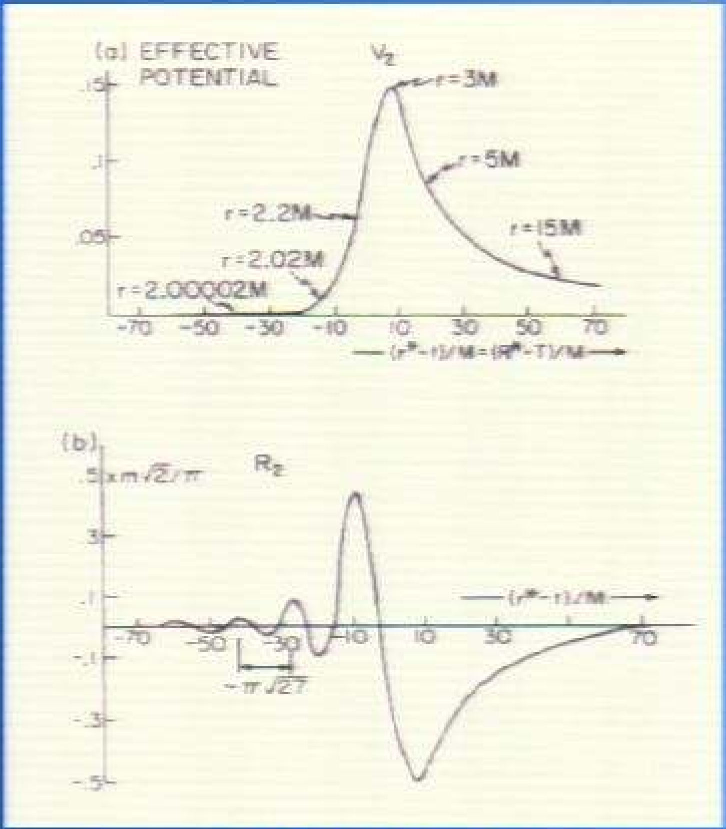
[Buonanno and Damour 1999]

- Mapping two-body binary inspiral dynamics to effective-one-body dynamics: *a spinning test-particle orbiting around a (mass-ratio) deformed Kerr spacetime*
- Features of EOB:
  - Non-adiabatic evolution, natural transition from inspiral to plunge: no restriction to circular orbits;
  - Inspiral-plunge dynamics condensed into a few simple polynomial functions: ideal for modeling and fitting;
  - Reducing to exact test-particle-limit conservative dynamics: better PN performance at large mass ratio;
  - PN based evolution extended to the merger frequency: correct at low frequency by definition, instant transition to ringdown;
  - Light ring predicts the “merger” frequency for plunge -> ringdown transition: test-particle-limit resemblance.

EOB in test particle limit

[Damour and Nagar 2007]





[press 1971; Davis, Ruffini, Press and Price 1971; Davis, Ruffini and Tionmo 1972]

EOB inspiral-plunge dynamics

- Hamilton equations with radiation reaction force (precessing evolutions)

$$\frac{dq^i}{dt} = \frac{\partial \mathcal{H}^{\rm EOB}}{\partial p_i} \qquad \frac{dp_i}{dt} = -\frac{\partial \mathcal{H}^{\rm EOB}}{\partial q^i} + \mathcal{F}_i$$

$$\frac{d\boldsymbol{S}_1}{dt} = \frac{\partial \mathcal{H}^{\rm EOB}}{\partial \boldsymbol{S}_1} \times \boldsymbol{S}_1 \qquad \frac{d\boldsymbol{S}_2}{dt} = \frac{\partial \mathcal{H}^{\rm EOB}}{\partial \boldsymbol{S}_2} \times \boldsymbol{S}_2$$

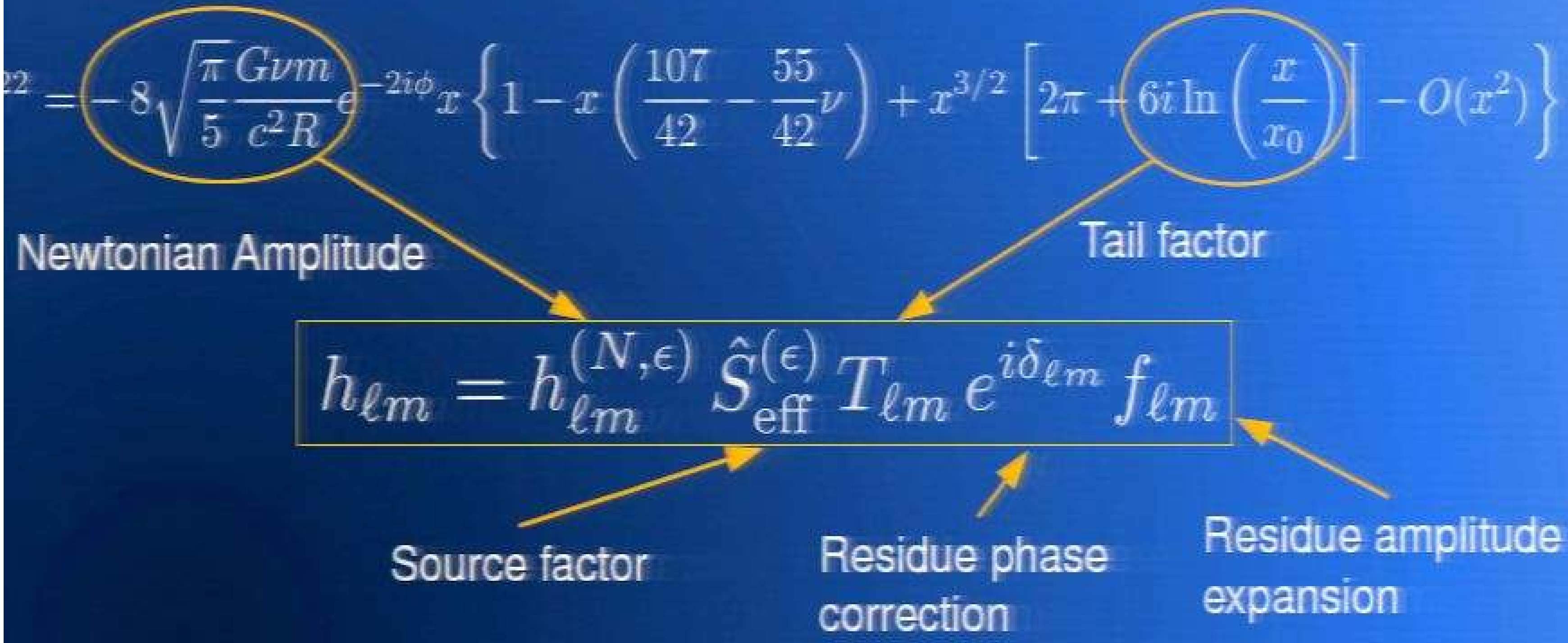
- RR force $\mathcal{F}_i$ matches known rates of energy and angular momentum loss for quasi-adiabatic orbits. GW energy flux can be replaced with a suitable resummation

$$\mathcal{F}_i \propto \frac{1}{16\pi} \sum_{\ell=2}^{8} \sum_{m=-\ell}^{\ell} \left| \dot{h}_{\ell m} \right|^2$$

Factorized resummed waveforms

[Damour, Iyer and Nagar 2008; Pan et al. 2010]

Factorized resummation: nonlinear higher order effects extracted into source and tail factors



$${}^{22} = -8\sqrt{\frac{\pi}{5}}\frac{G\nu m}{c^2 R}e^{-2i\phi}x\left\{1 - x\left(\frac{107}{42} - \frac{55}{42}\nu\right) + x^{3/2}\left[2\pi + 6i\ln\left(\frac{x}{x_0}\right)\right] - O(x^2)\right\}$$

Newtonian Amplitude

Tail factor

$$\boxed{h_{\ell m} = h_{\ell m}^{(N,\epsilon)}\,\hat{S}_{\text{eff}}^{(\epsilon)}\,T_{\ell m}\,e^{i\delta_{\ell m}}\,f_{\ell m}}$$

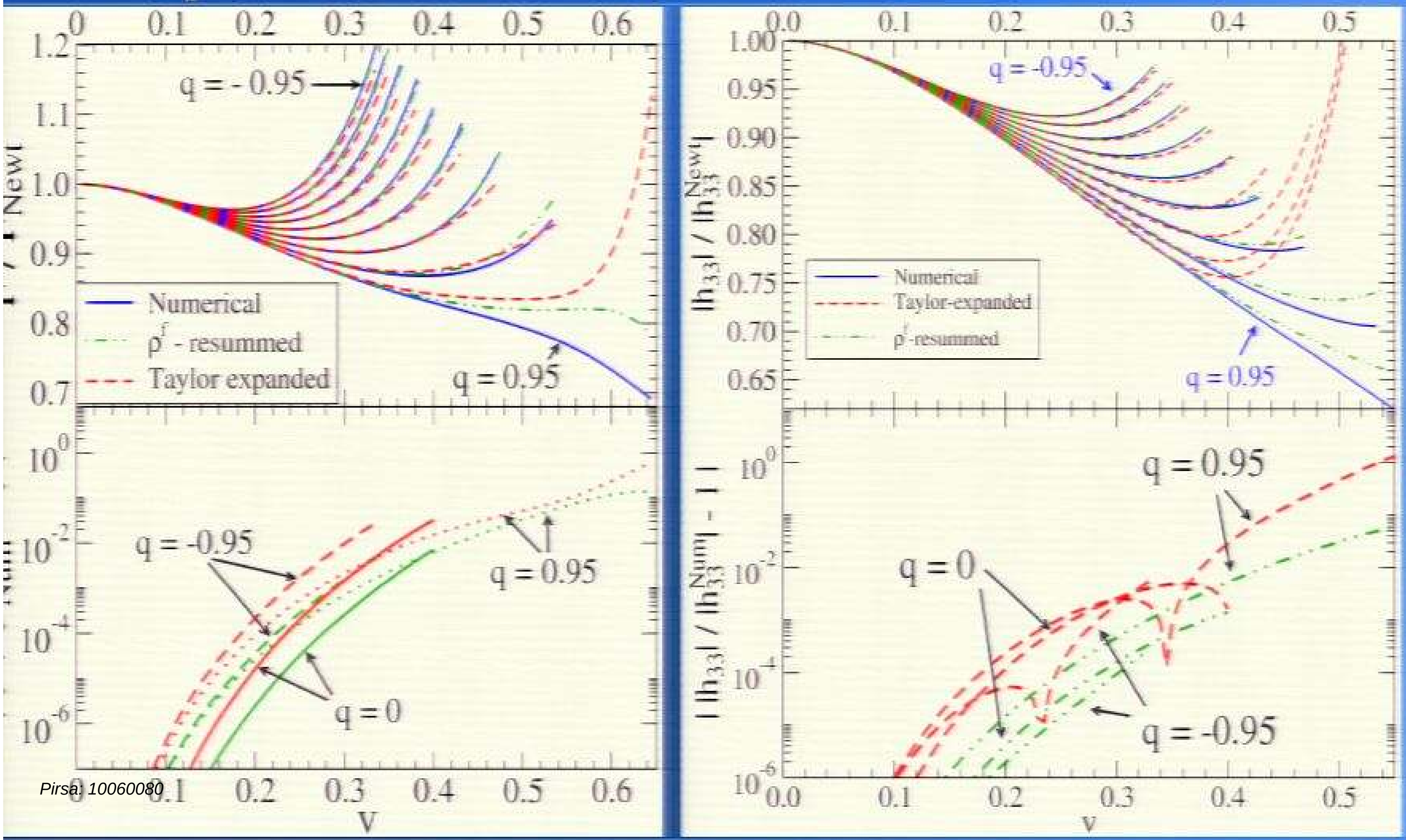
Source factor

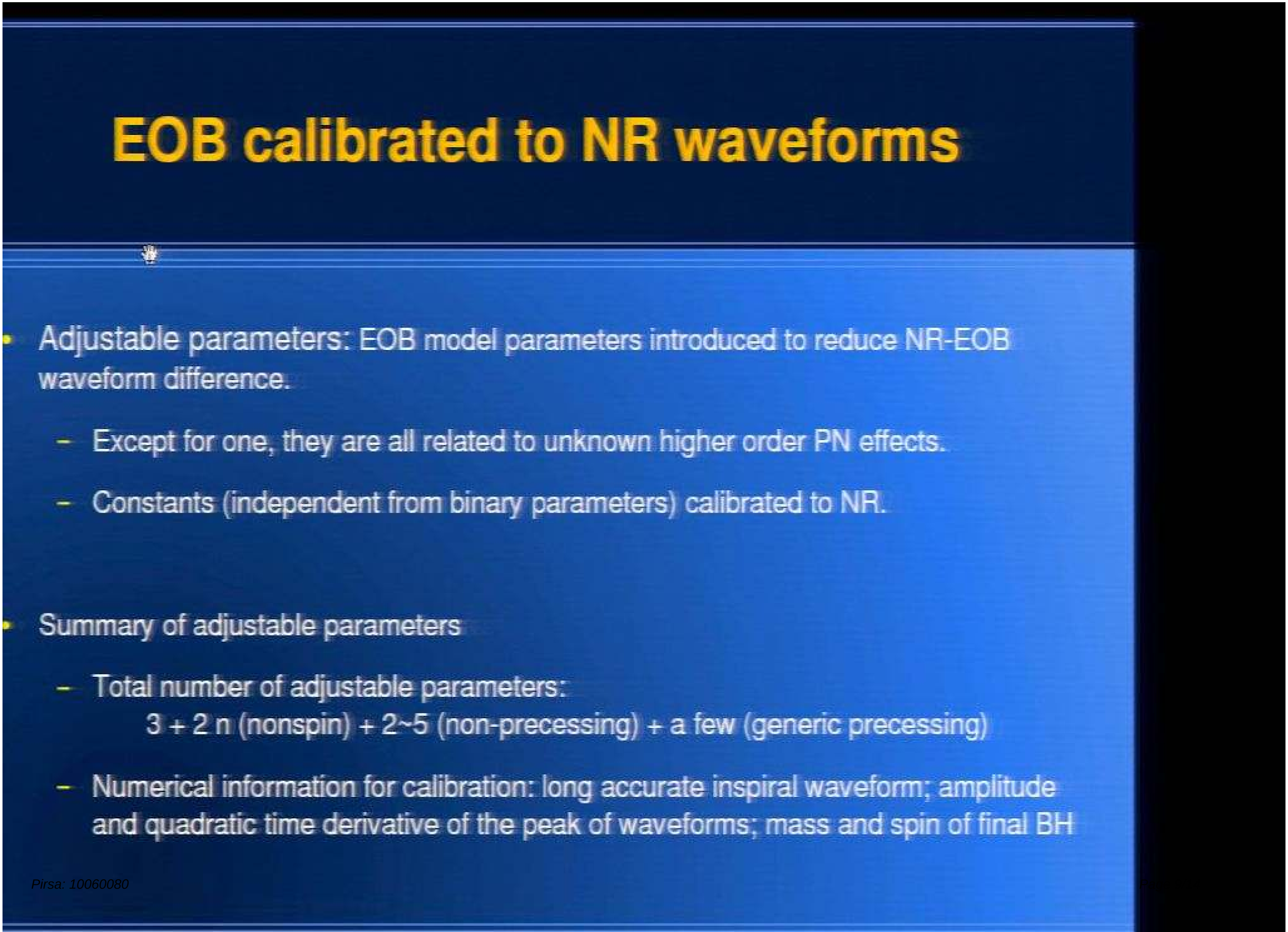
Residue phase correction

Residue amplitude expansion

Performance of factorized resummed waveforms (uncalibrated)

[Pan et al. 2010]



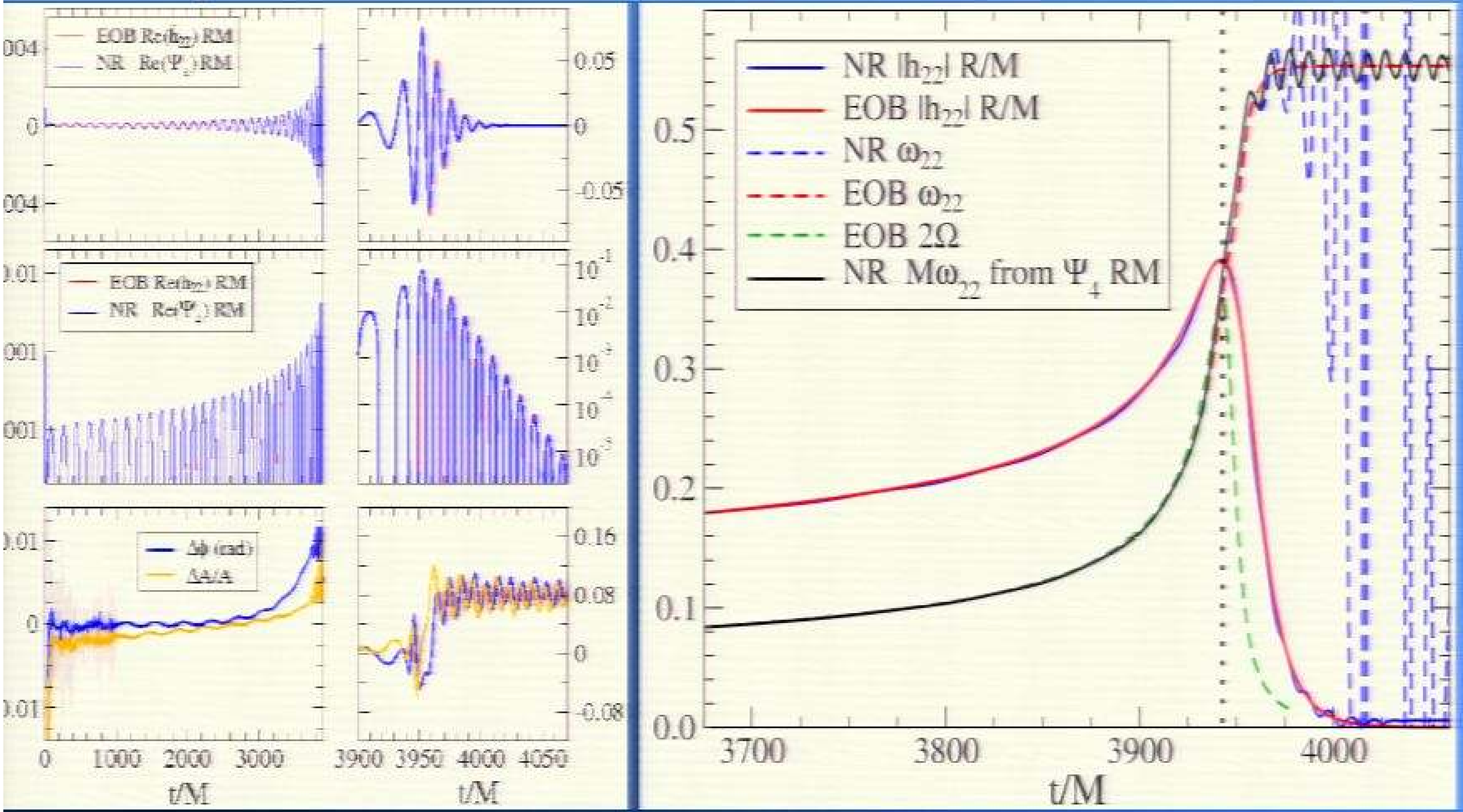


EOB calibrated to NR waveforms

- Adjustable parameters: EOB model parameters introduced to reduce NR-EOB waveform difference.
  - Except for one, they are all related to unknown higher order PN effects.
  - Constants (independent from binary parameters) calibrated to NR.
- Summary of adjustable parameters
  - Total number of adjustable parameters:
    3 + 2 n (nonspin) + 2~5 (non-precessing) + a few (generic precessing)
  - Numerical information for calibration: long accurate inspiral waveform; amplitude and quadratic time derivative of the peak of waveforms; mass and spin of final BH

EOB calibrated to NR: nonspin equal-mass waveforms

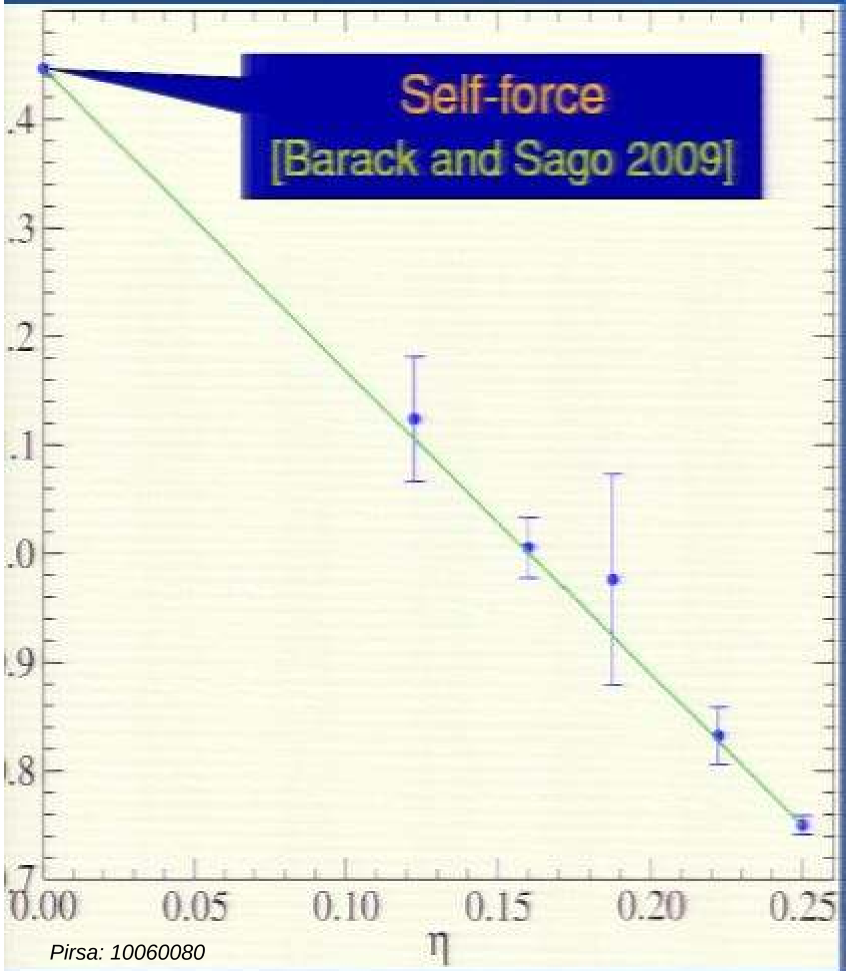
[Buonanno et al. 2009]

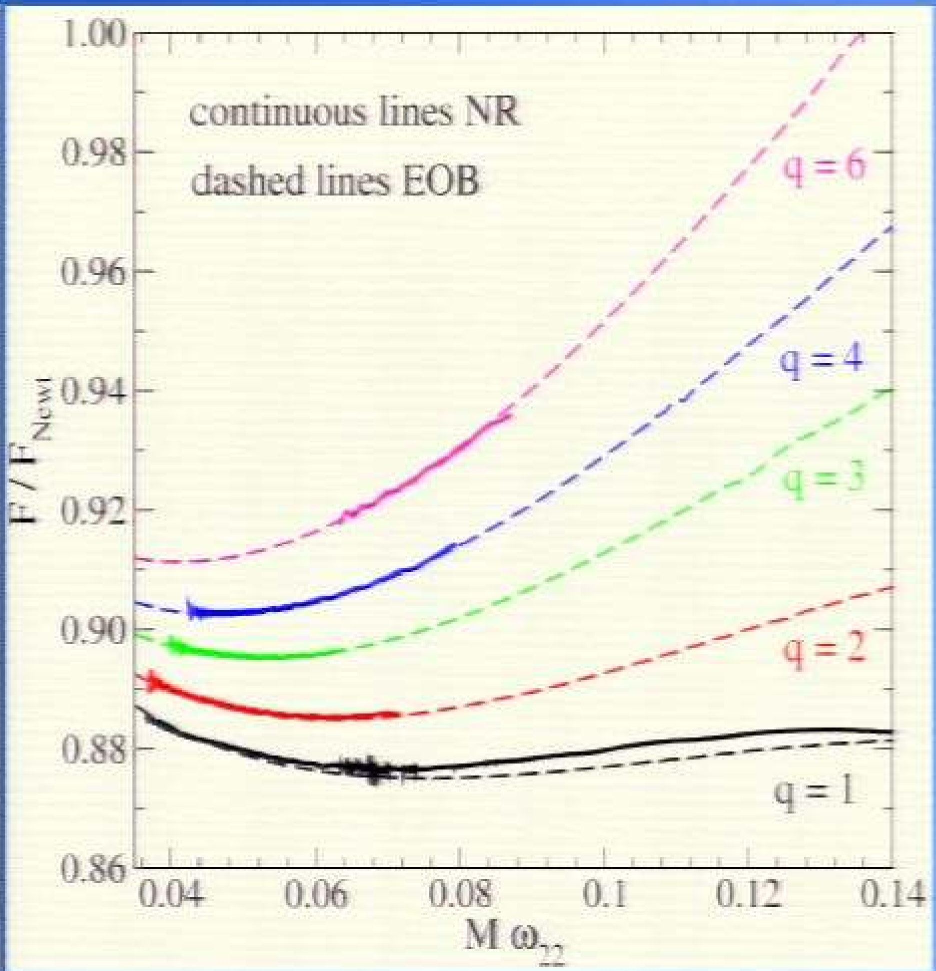


Phase and amplitude difference within numerical errors; Faithfulness > 0.9999

EOB calibrated to NR: nonspin unequal-mass dynamics

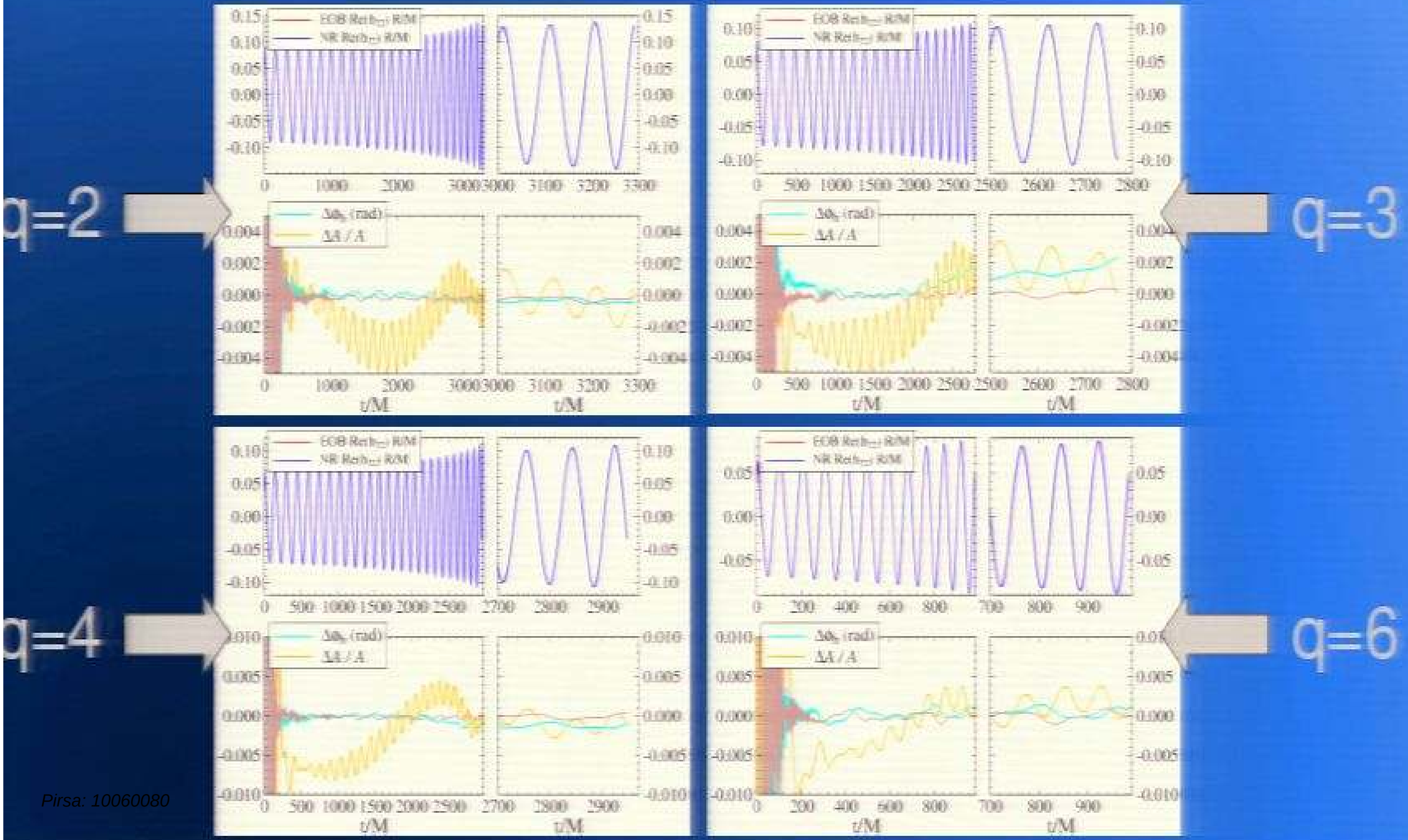
Courtesy Caltech-Cornell-CITA: M. Boyle, L. Buchmann, H. Pfeiffer, M. Scheel, Nick Taylor





EOB calibrated to NR: nonspin unequal-mass waveforms

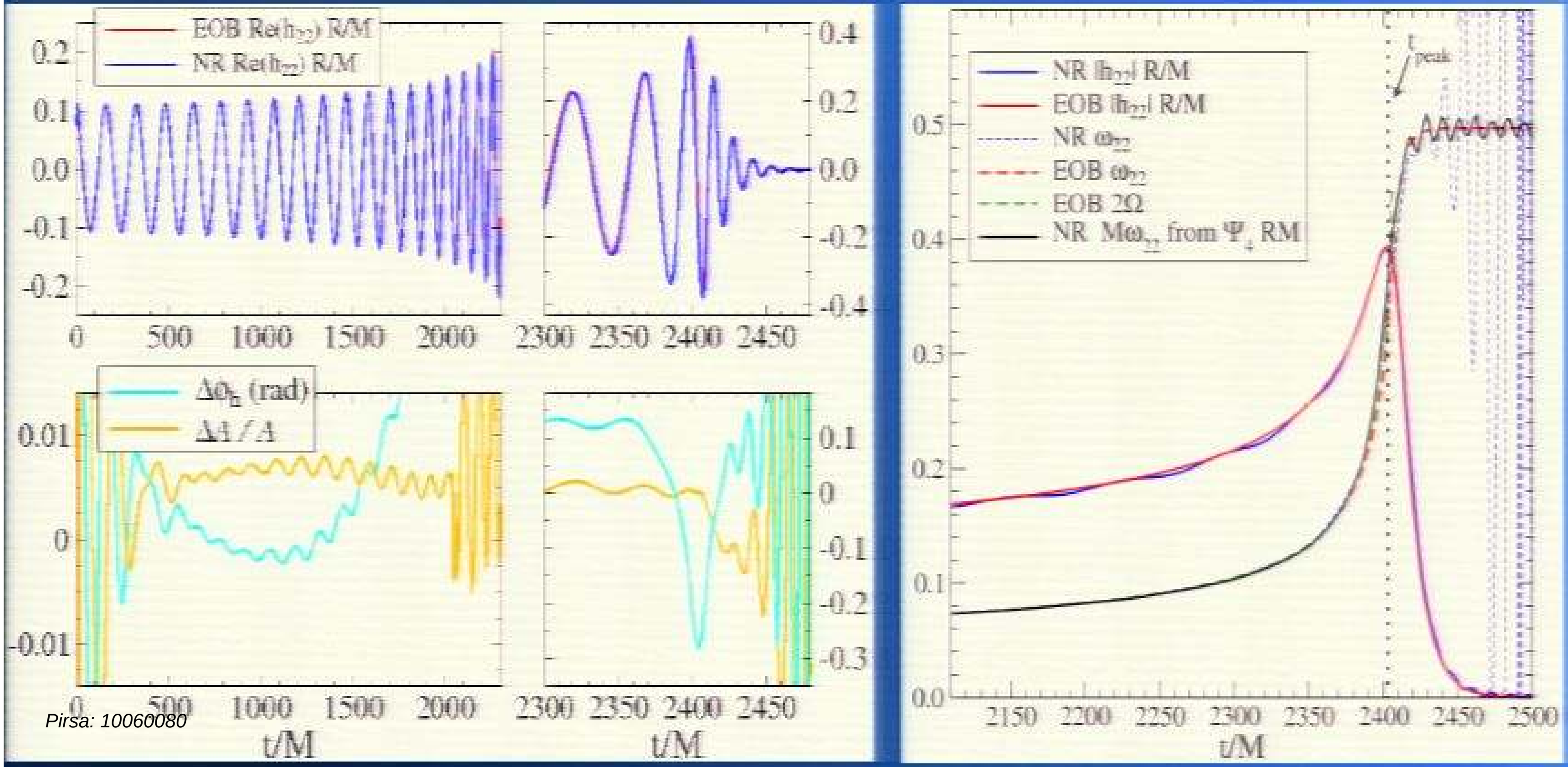
Courtesy Caltech-Cornell-CITA NR collaboration

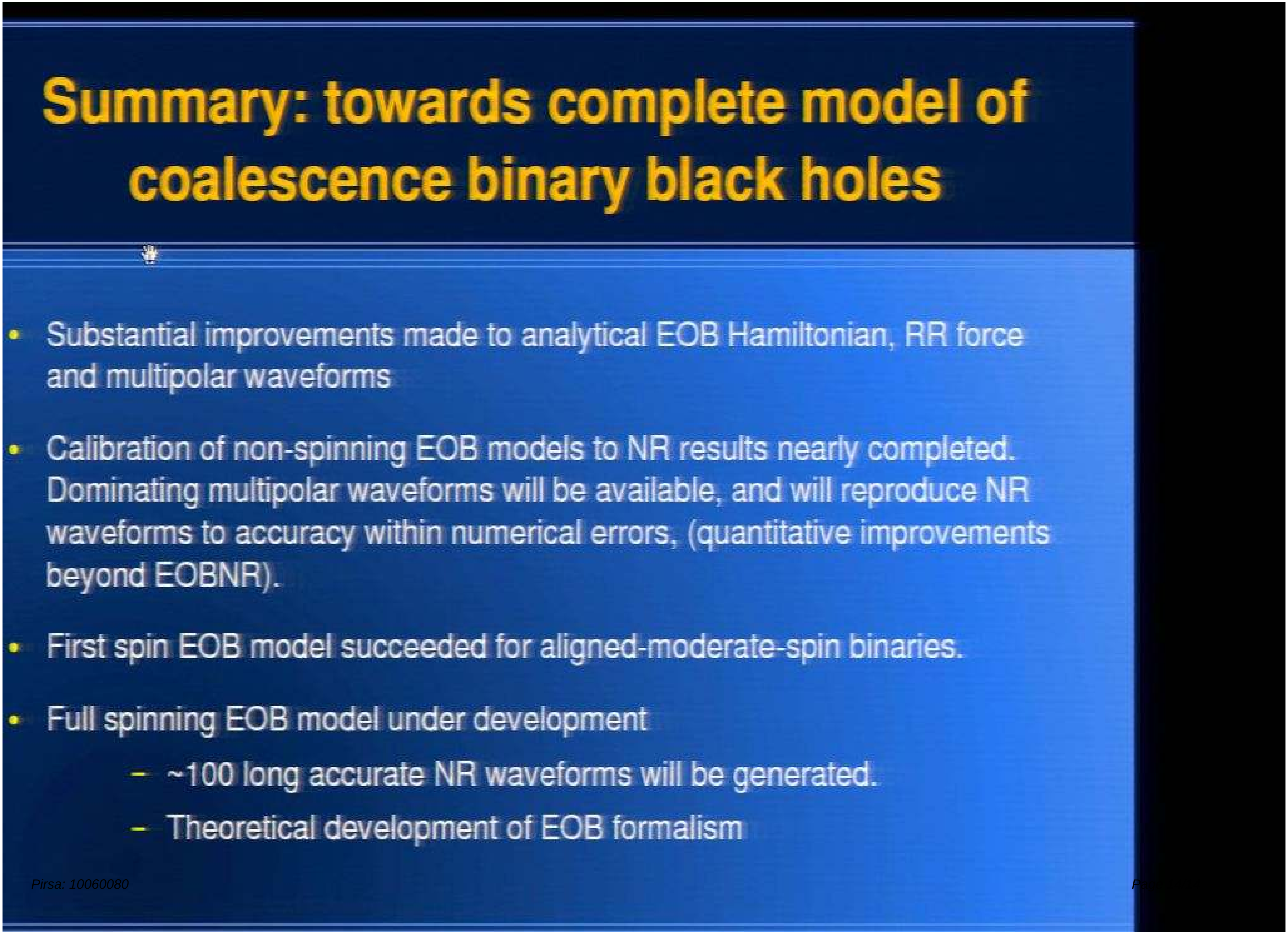


EOB calibrated to NR: aligned-spin waveforms

[Pan et al. 2009]

SpEC simulation of an equal-mass binary with equal-amplitude anti-aligned spins: $\chi_1 = \chi_2 = 0.43757$.   Faithfulness > 0.999





Summary: towards complete model of coalescence binary black holes

- Substantial improvements made to analytical EOB Hamiltonian, RR force and multipolar waveforms
- Calibration of non-spinning EOB models to NR results nearly completed. Dominating multipolar waveforms will be available, and will reproduce NR waveforms to accuracy within numerical errors, (quantitative improvements beyond EOBNR).
- First spin EOB model succeeded for aligned-moderate-spin binaries.
- Full spinning EOB model under development
  - ~100 long accurate NR waveforms will be generated.
  - Theoretical development of EOB formalism