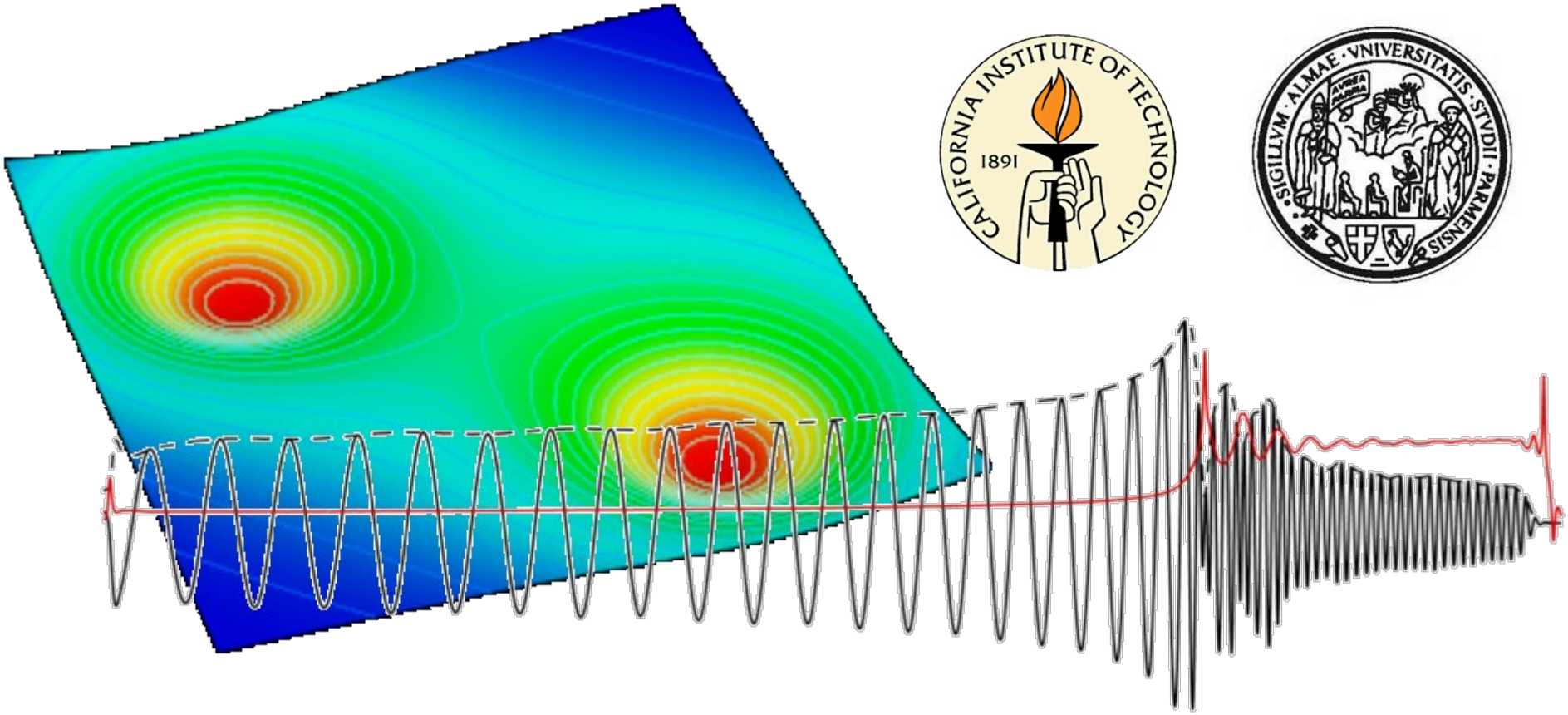
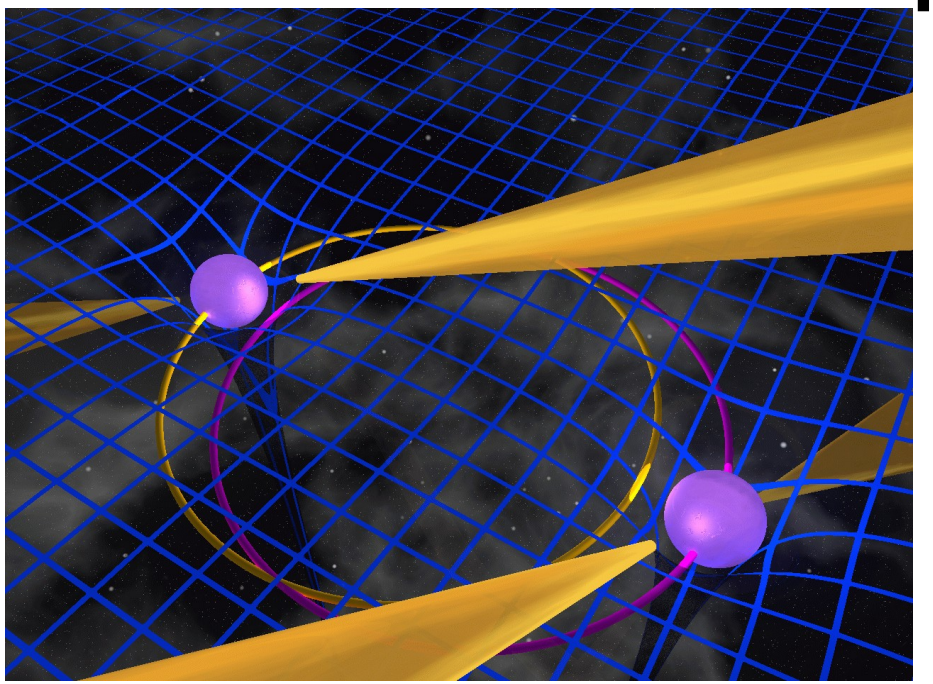
Modeling Gravitational Waves from Neutron Star Mergers

S.Bernuzzi

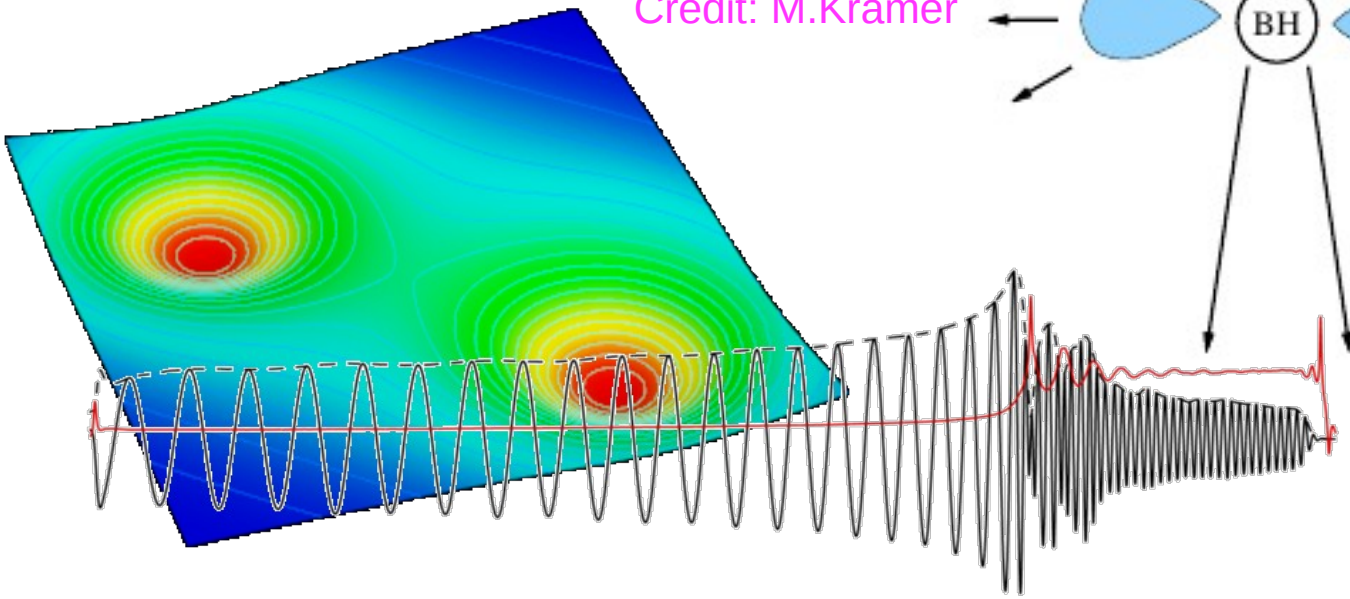


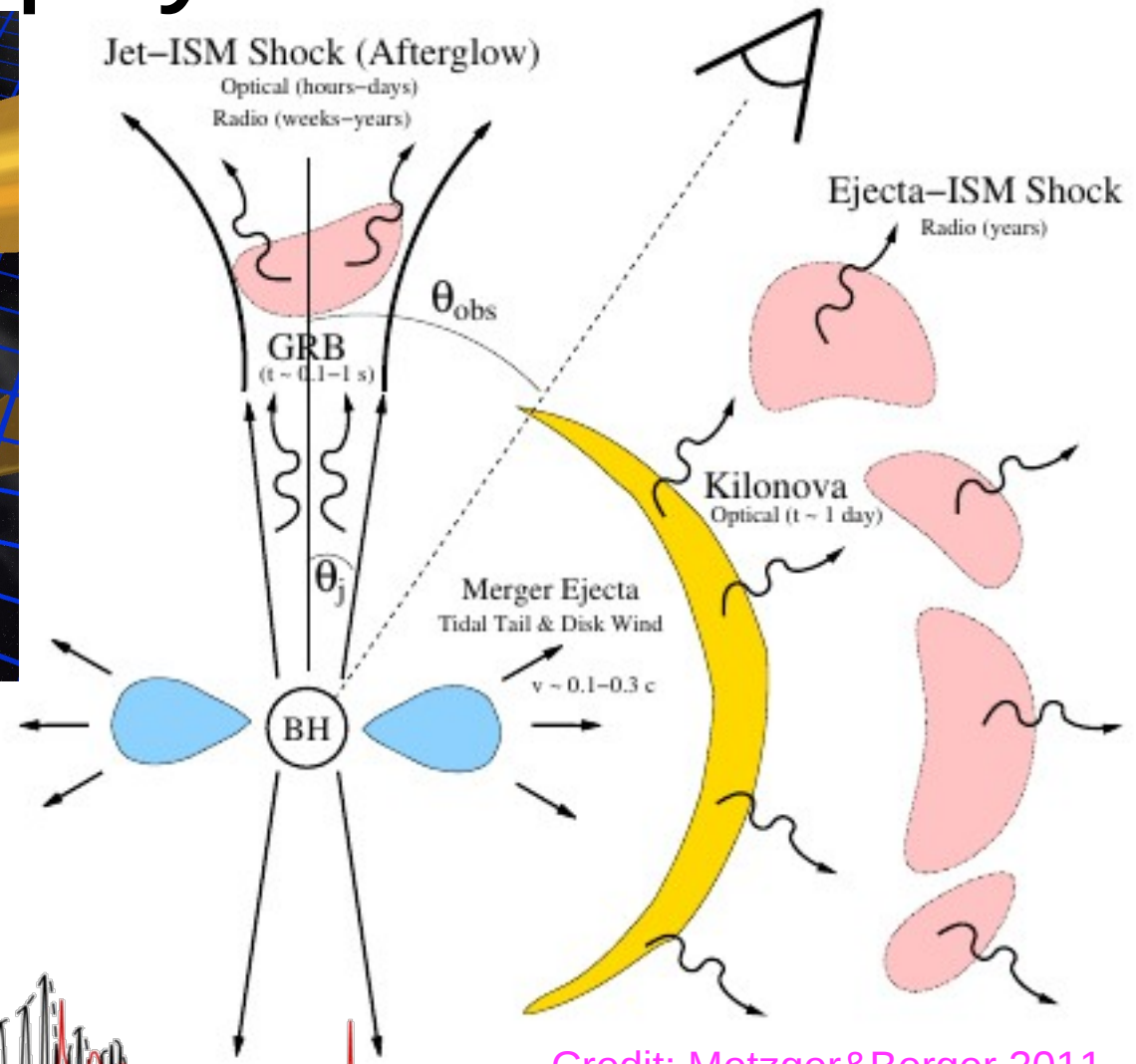
MICRA - August, 19th 2015

Neutron star mergers astrophysics



Credit: M.Kramer





Credit: Metzger&Berger 2011

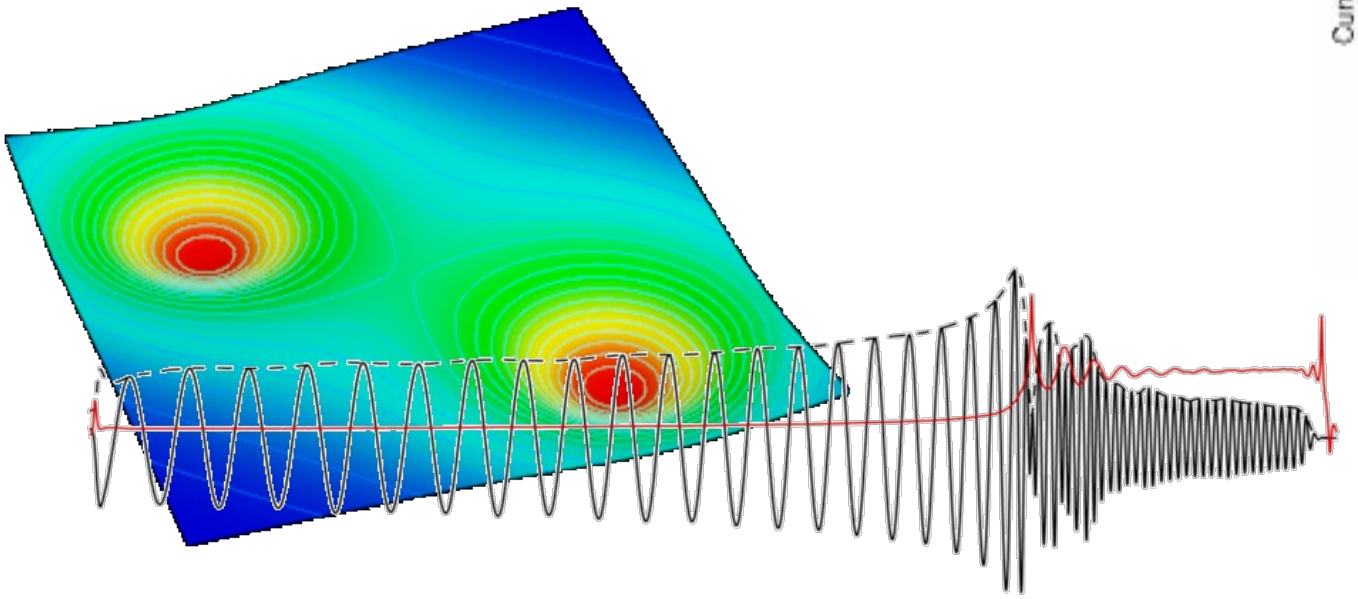
However ...

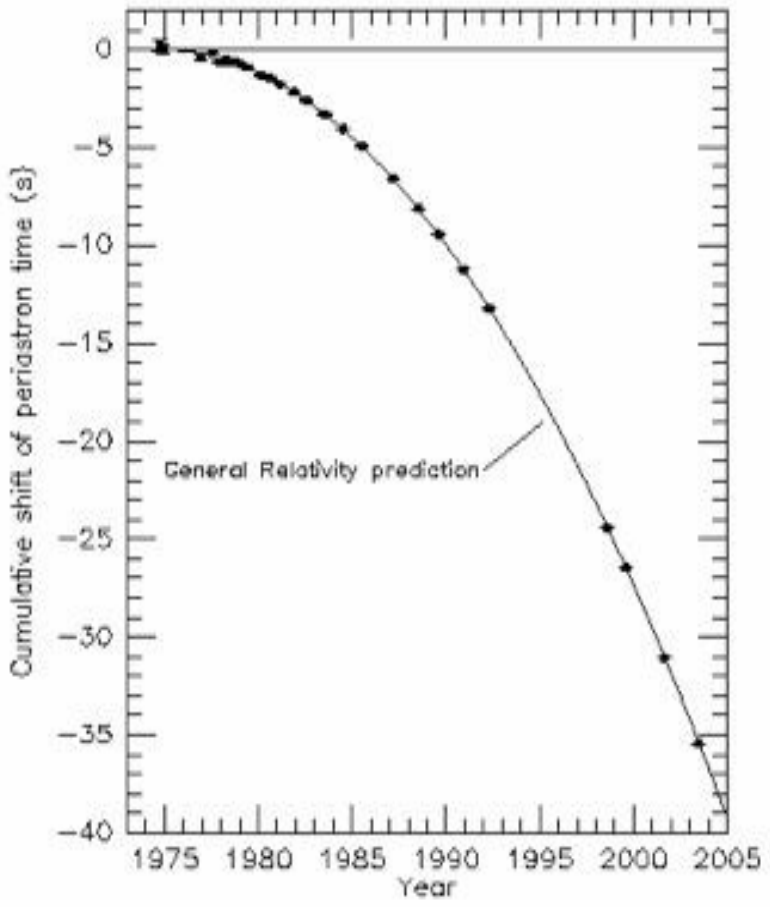
- Many uncertainties remains:
- Clear source/central engine identification requires Gravitational Wave observations
- Gravitational waves observations are crucial !

Binary neutron stars & GWs

- Strong-field tests GR
- Indirect evidence
- Direct obervations require **precise** theoretical knowledge of the late-inspiral-merger signal
- Theory: GR, Numerical Relativity,

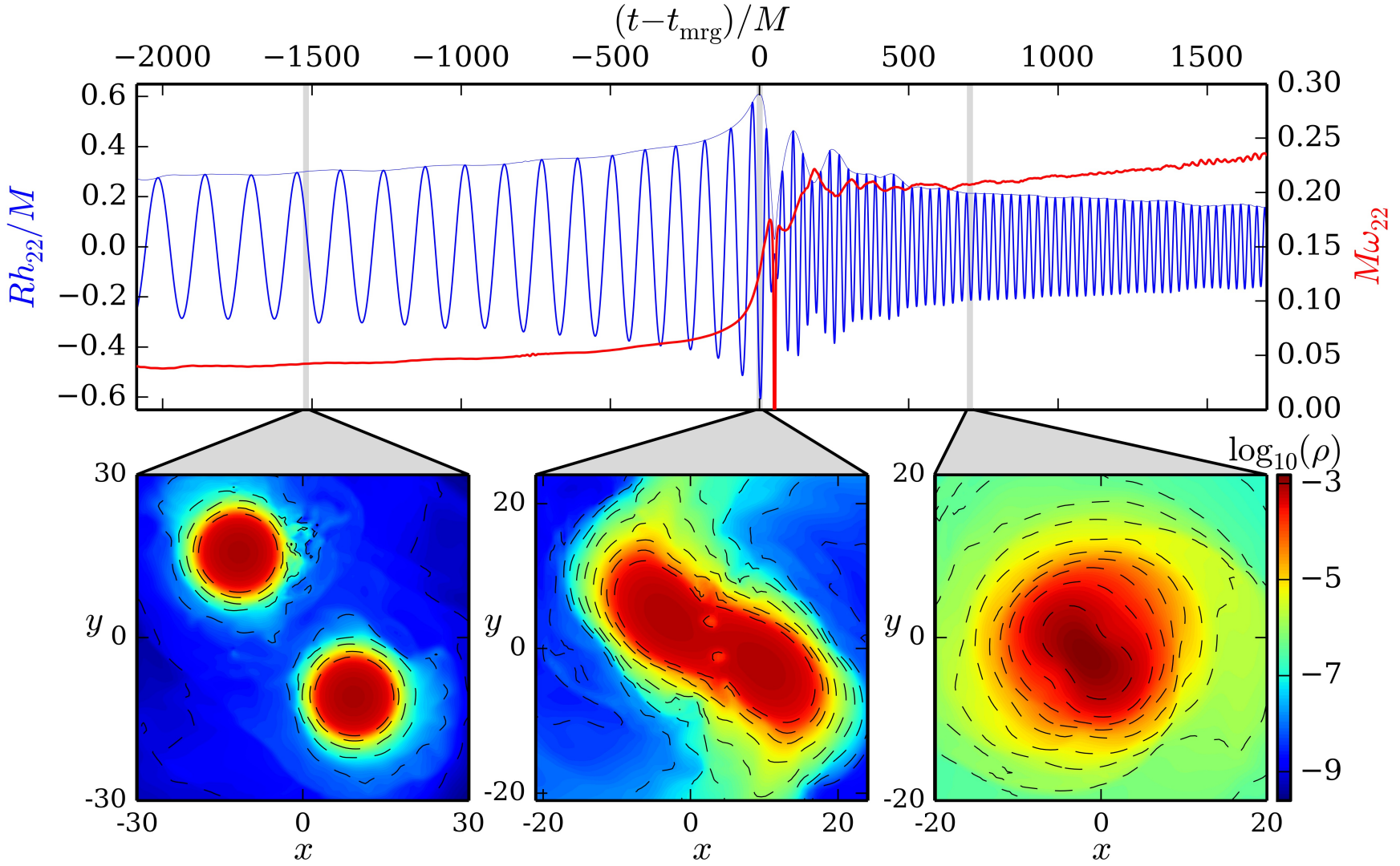
  <u>ONLY way to do it</u> !





[Hulse&Taylor Pulsar]

NS-NS merger waveform



- How dynamics depend on EOS, mass, mass-ratio, *etc* ?
- Can we model the waveform and the GW spectrum ?

How do we model tides during late-inspiral and merger ?

How dynamics depend on EOS, mass, mass-ratio, *etc ?*

Effective-one-body framework
[Sketch of the Hamiltonian]

[Buonanno&Damour PRD 2000, ...]

- Newton: 2-body problem, relative motion => motion of particle in 2-body potential
- Relativistic 2-body problem =>

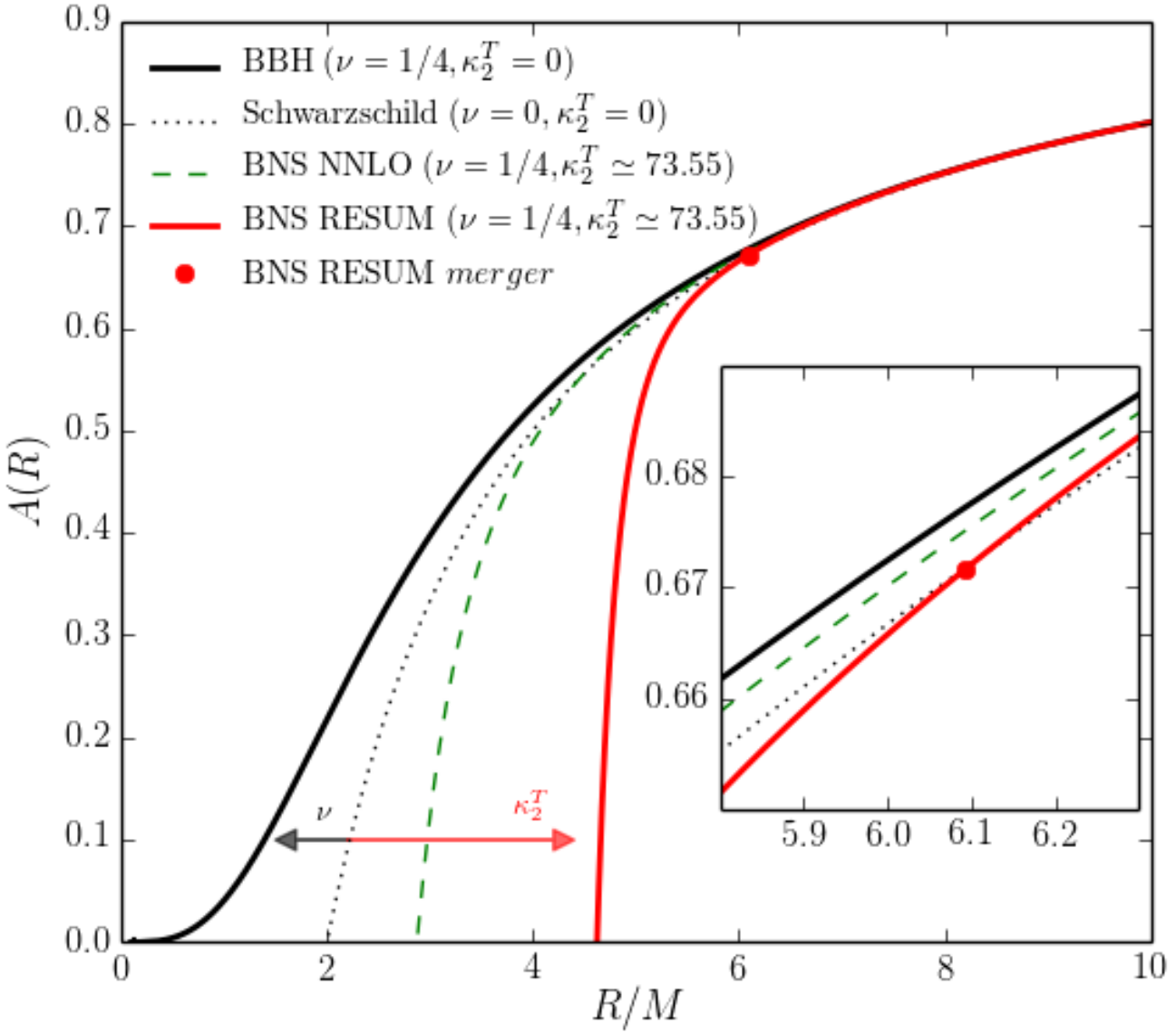
  motion of effective particle in effective metric (potential)
- Particle on Schwarzschild: $H \sim \mu\sqrt{A\,(1+p_\varphi^2 u^2)+p_{r*}^2}$
- Metric potential A(u)

$$A(u;\nu;\kappa_2^T) = A^0(u;\nu) + A^T(u;\nu;\kappa_2^T)$$

$$A^0(u;\nu) = 1 + 2u + \nu(... \qquad A^T(u;\nu;\kappa_2^T) = -\kappa_2^T u^6 - ..$$

[Damour&Nagar PRD 2009]

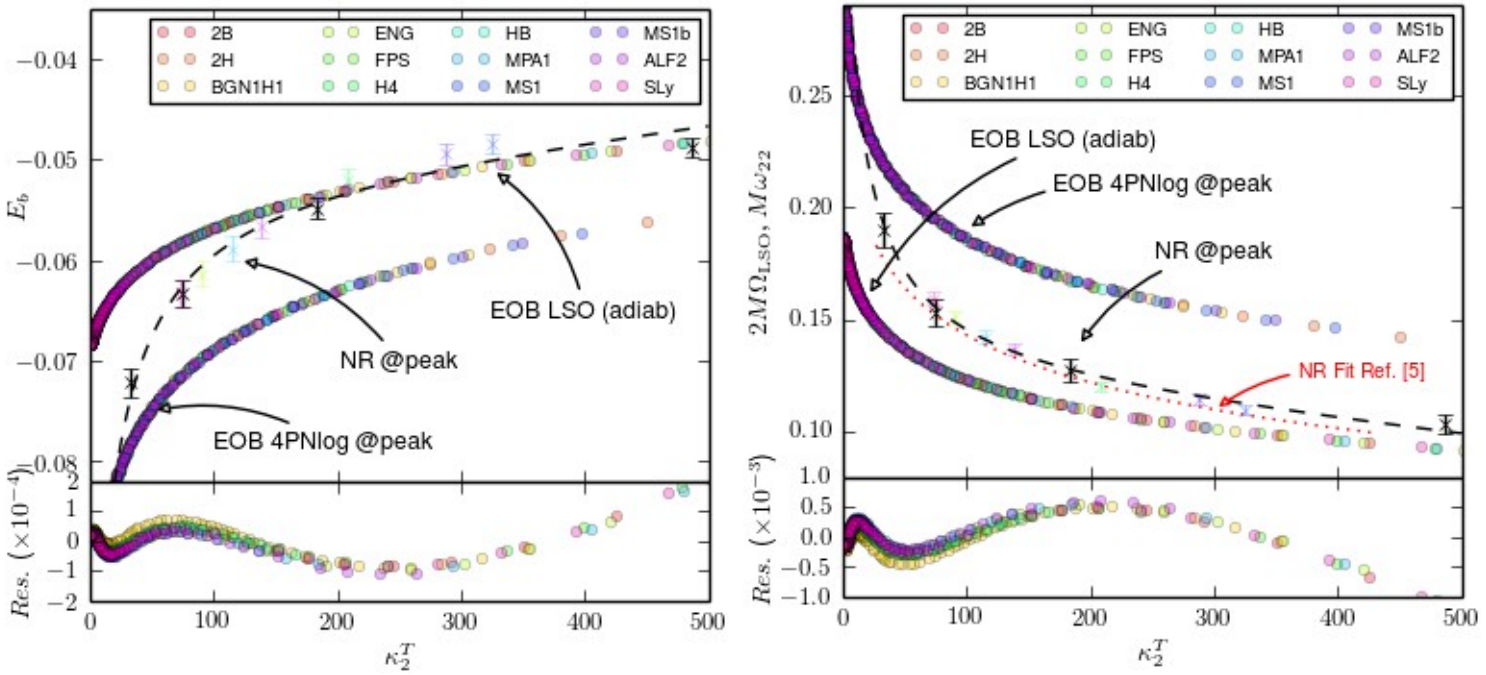
The A(r) potential with tides



[SB,Nagar,Dietrich,Damour PRL 2015]

Universal properties of merger

[SB,Nagar,Balmelli,Dietrich,Ujevic PRL 2014]



Dynamics of *every* irrotational binary (at small separations) is described only by

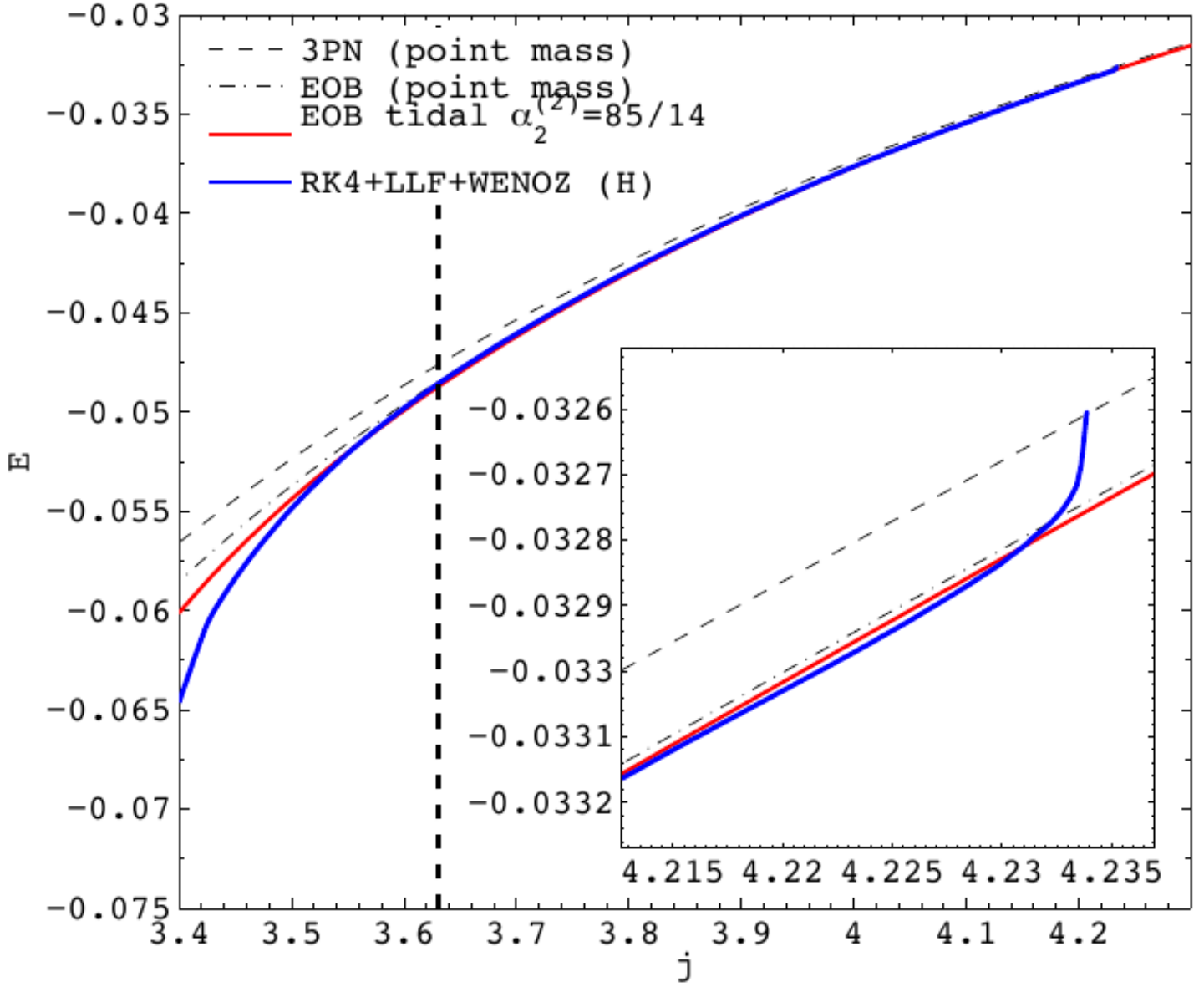
$$\kappa_\ell^T \equiv 2\left[\frac{1}{q}\left(\frac{X_A}{C_A}\right)^{2\ell+1} k_\ell^A + q\left(\frac{X_B}{C_B}\right)^{2\ell+1} k_\ell^B\right]$$

$$A_{\rm LO}^T(u) = -\kappa_2^T u^6$$

How do we extract meaningful gauge-invariant information from the simulations?

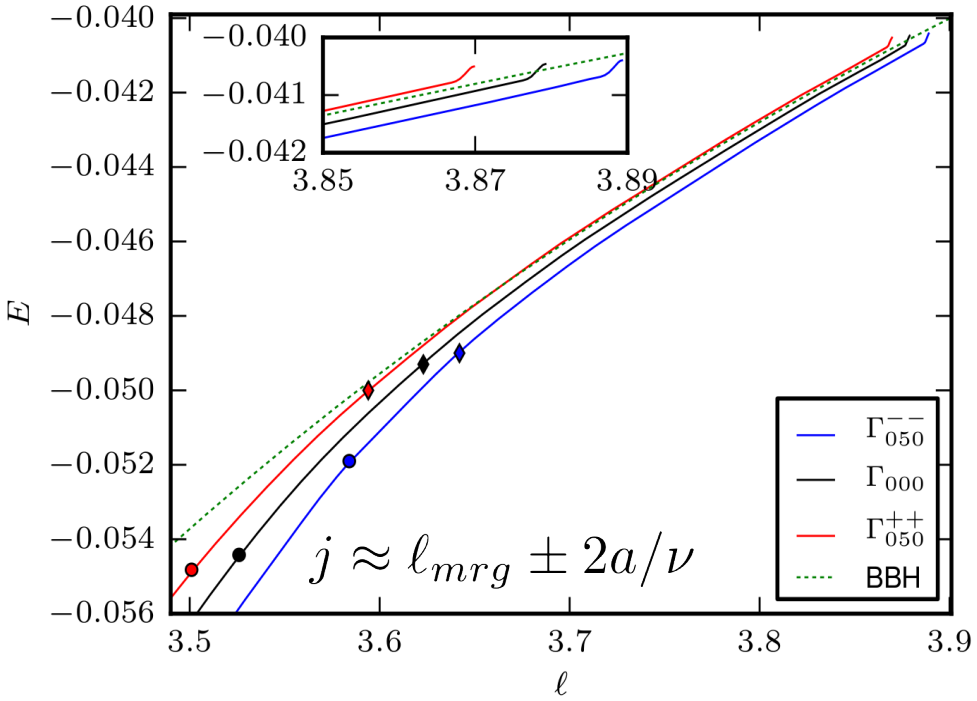
Gauge-invariant NS-NS dynamics

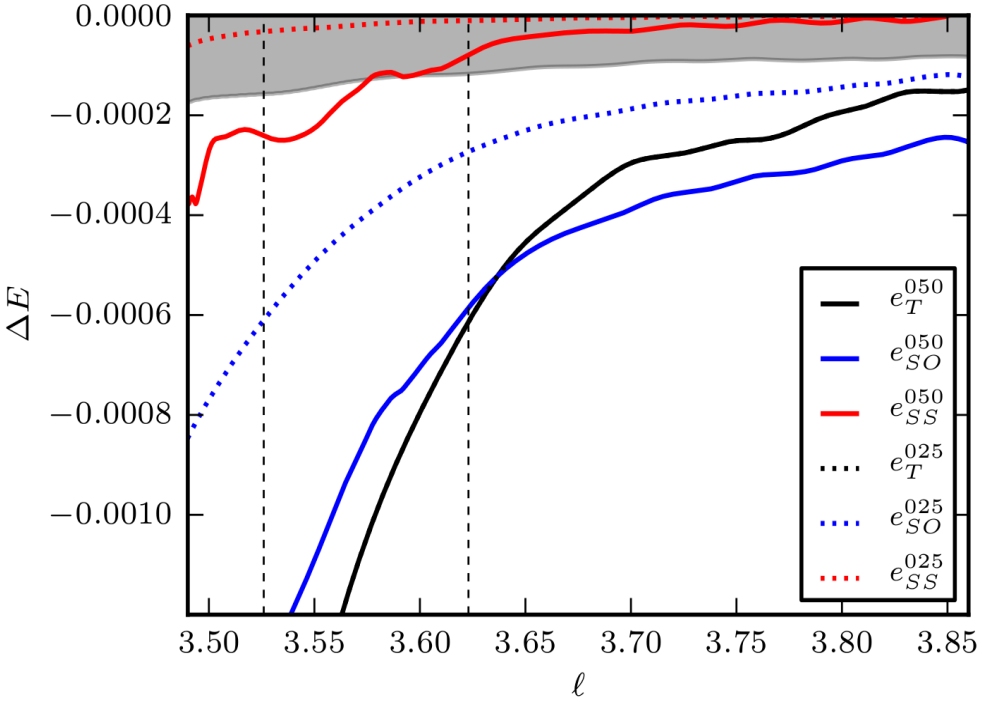
[SB,Nagar,Thierfelder,Bruegmann PRD 2012]



GR mergers with consistent spins

[SB,Dietrich,Tichy,Bruegmann PRD 2014]





$$E = E_{BBH} + E_{SO} + E_{SS} + E_T$$

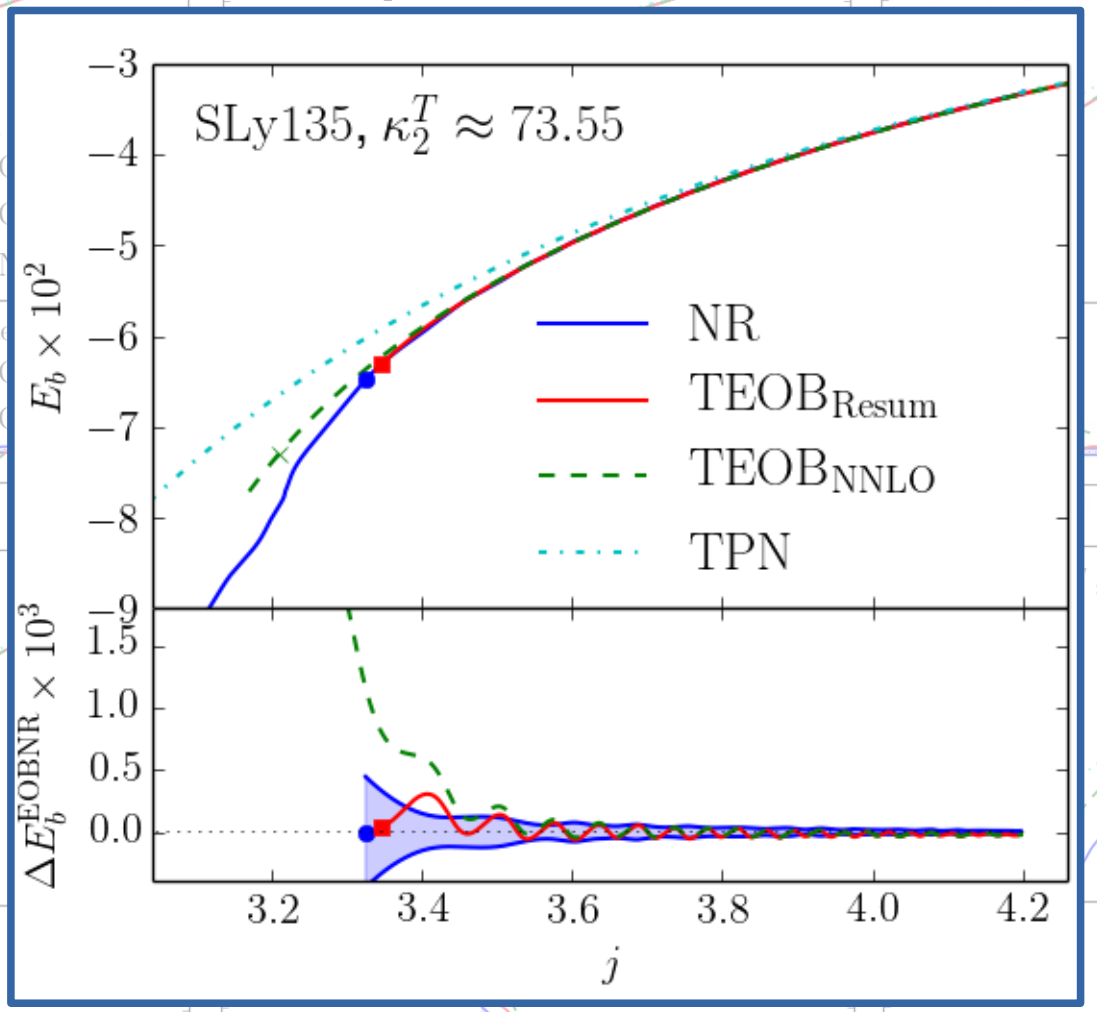
- 1st “realistic” NS-NS merger in GR (consistent initial data) [Tichy PRD 2010]
- Spin-orbit interaction in nonlinear GR !

  (Last-spherical-orbit [Damour PRD 2001], “hang-up” [Campanelli+ PRD 2006])
- 1st gauge-invariant comparison BHBH vs NSNS dynamcs
- a~0.05 => SO contribution >~ Tidal => CANNOT NEGLECT SPINS!

  (PN “hierarchy” holds up to strong-field / hydrodynamical regime)

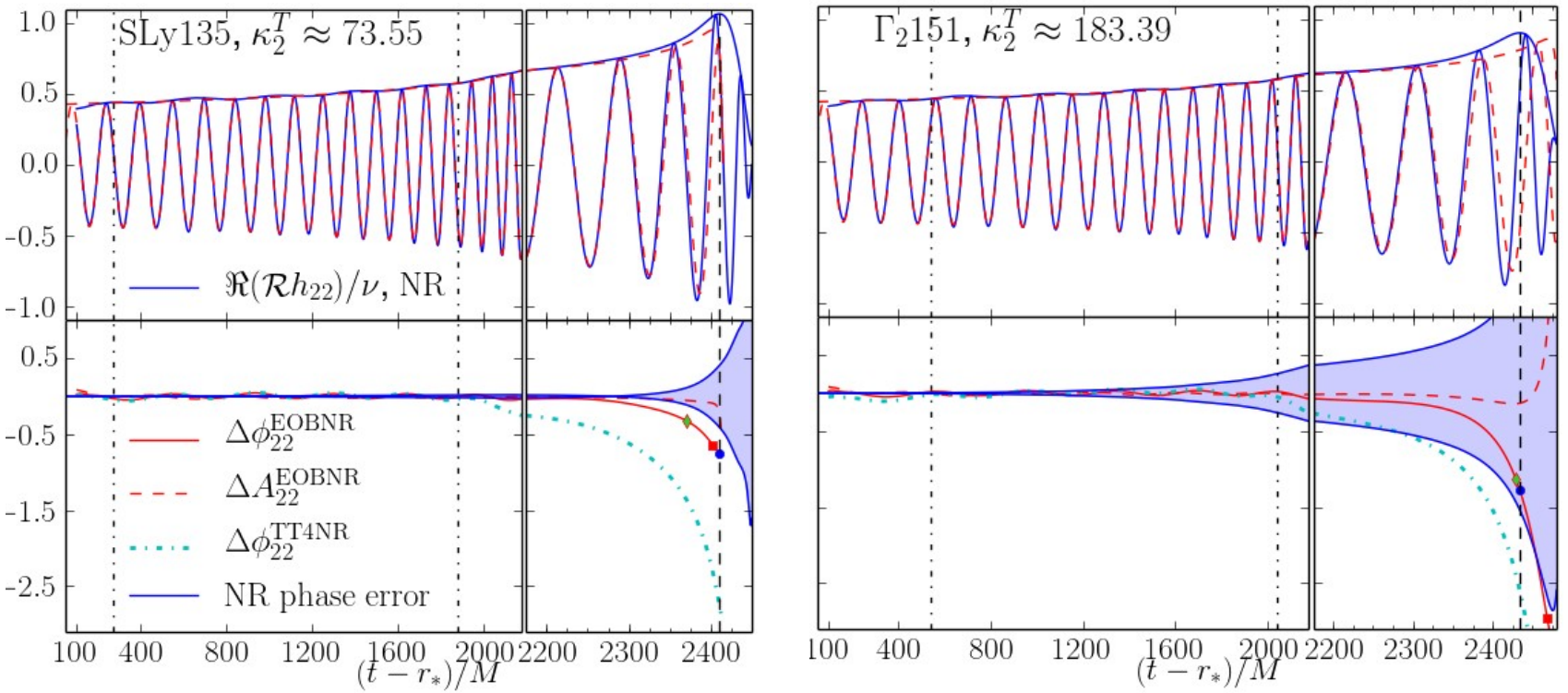
Modeling NS-NS dynamics

[SB,Nagar,Dietrich,Damour PRL 2015]



The merger waveform

[SB,Nagar,Dietrich,Damour PRL 2015]

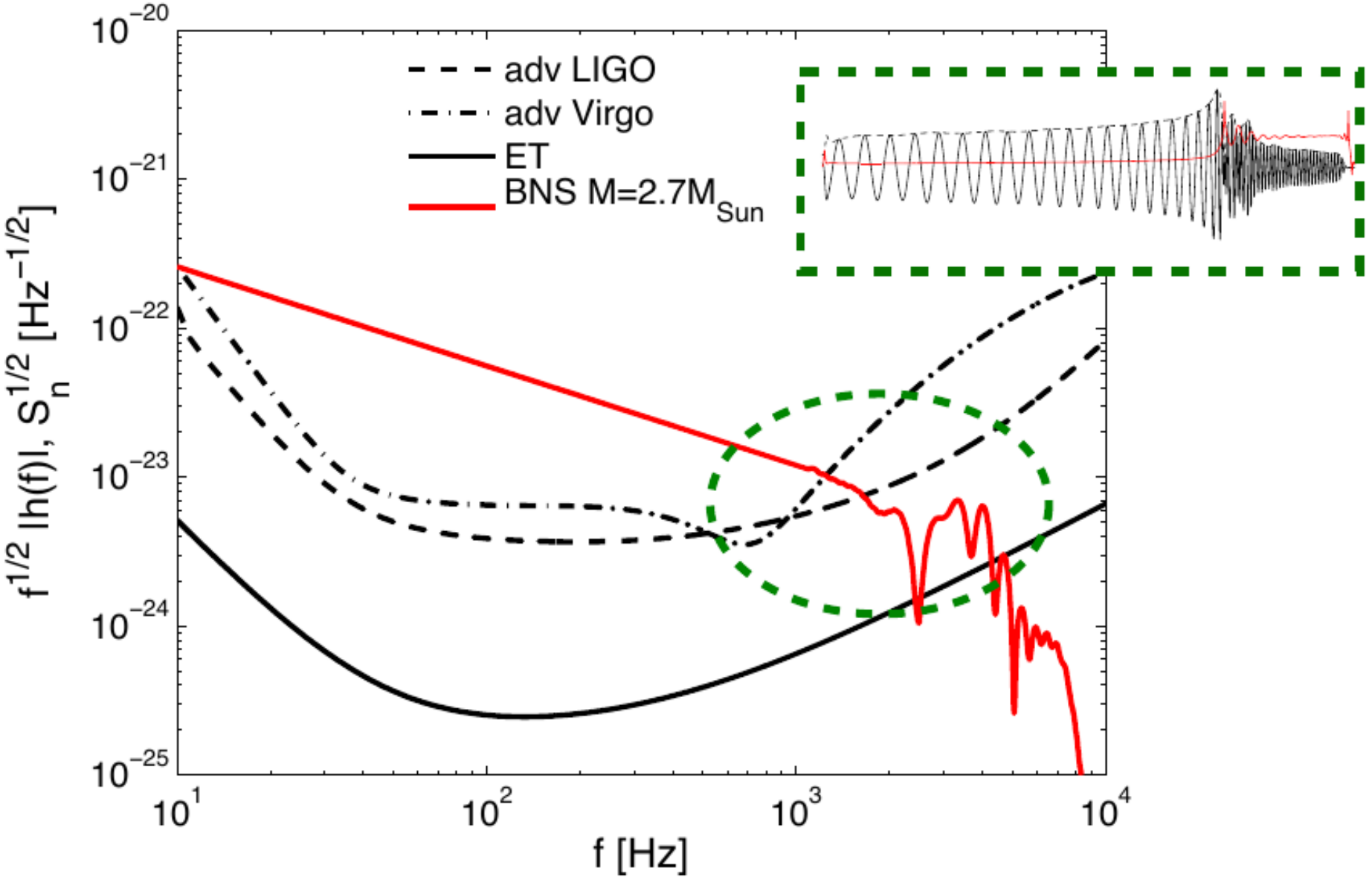


The model reproduces/predicts the NR waveform

NO TUNING/FITTING TO NR NS-NS DATA IS USED HERE !

Specifically we use:
- 1 NR-informed parameter (formally 5PN) for the BH-BH potential (SpEC data)
- Analytical frac. 2PN tidal corrections to the waveform
- Fix value of 1 unknown parameter (in its expected range) in the SF(2) function

GW Spectrum

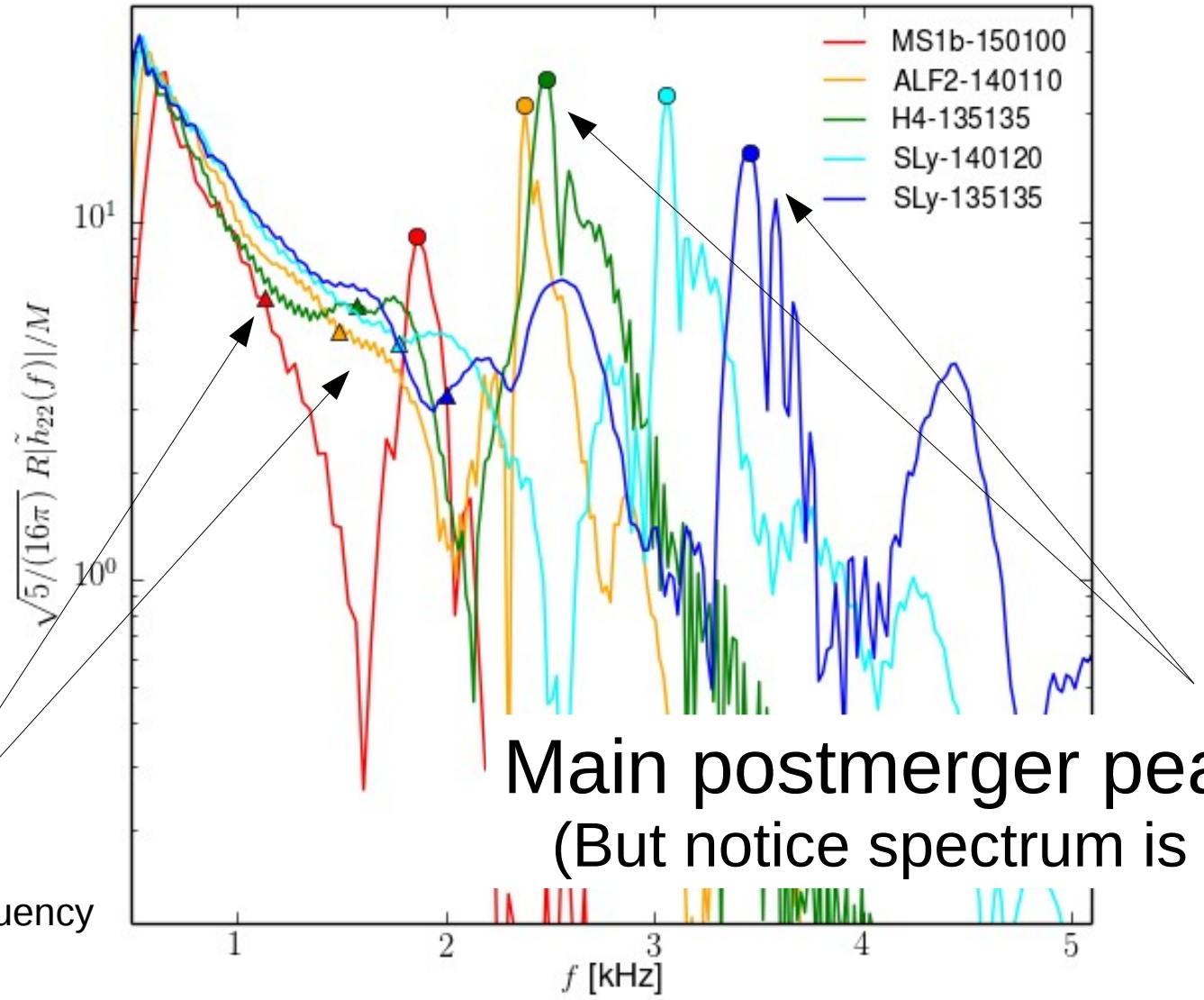

adv LIGO
adv Virgo
ET
BNS M=2.7M_Sun
f^1/2 |h(f)|, S_n^1/2 [Hz^-1/2]
f [Hz]
10^-20
10^-21
10^-22
10^-23
10^-24
10^-25
10^1
10^2
10^3
10^4

Can we model the complete spectrum ?

How about postmerger ?

Postmerger GW spectra

[SB,Dietrich,Nagar PRL 2015]

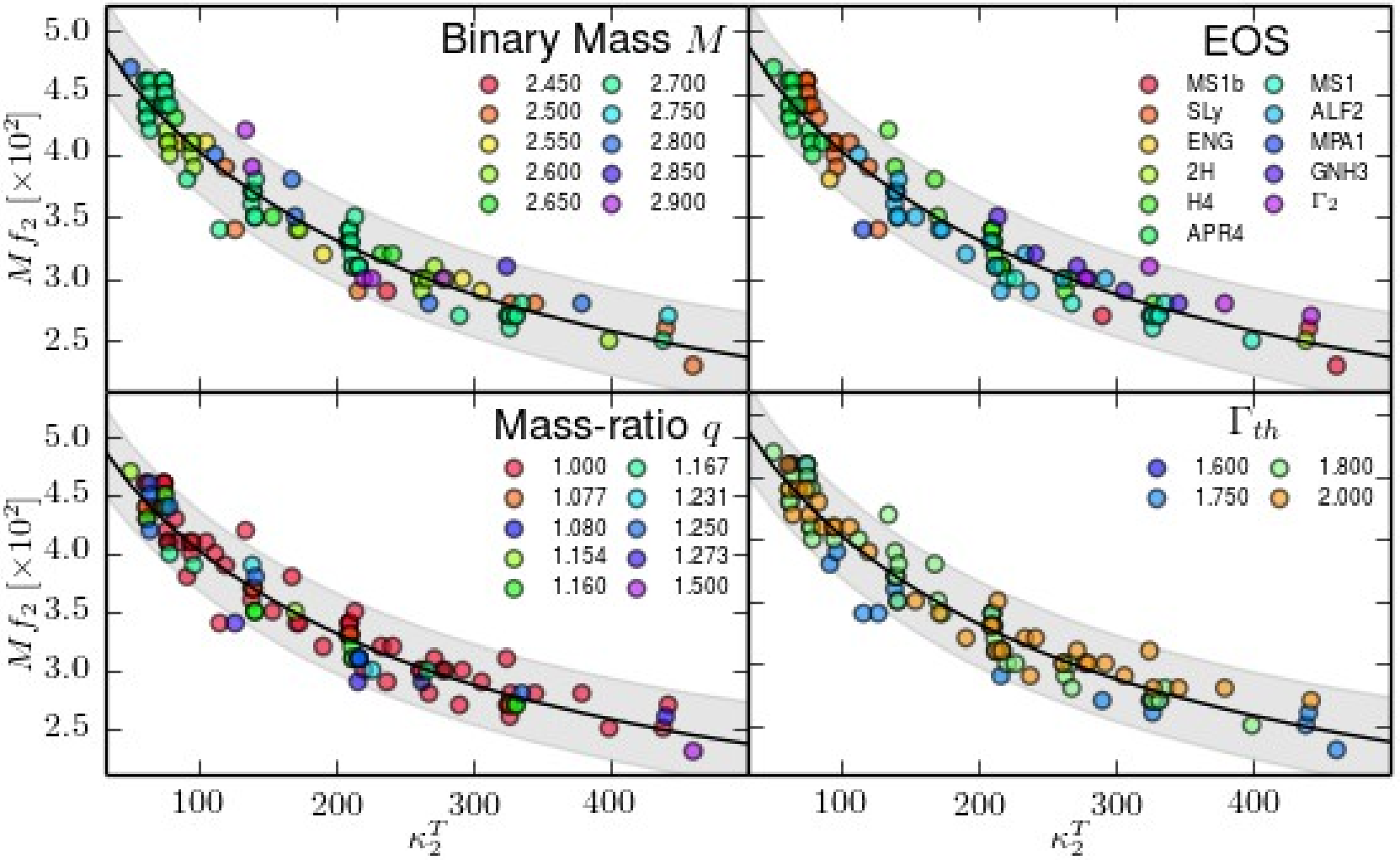


Main postmerger peak frequency

(But notice spectrum is continuous...)

Merger frequency

[SB,Dietrich,Nagar PRL 2015]



- Correlates to kappa for *every* binary !
- Simplified but robust description with a single tidal parameter
- A single parameter models inspiral-merger-postmerger !
- Does it help EOS extraction from GW observations ? [Li&SB, In Prep.]

Recent key achievements & Refs

- 1st proposal for a model of the complete GW spectrum of binary neutron stars, including both merger and postmerger

  [SB, Dietrich, Nagar PRL 2015, gr-qc:1504.01764]

- 1st semianalytical tidal EOB model able to capture dynamics and waveform up to merger

  [SB, Nagar, Dietrich, Damour PRL 2014, gr-qc:1412.4553]

- ``universal'' parametrization for neutron stars mergers dynamics, which uses a single key parameter for describing binaries with different equations of state, mass, and mass-ratio

  [SB, Nagar, Balmelli, Dietrich Ujevic PRL 2014, gr-qc:1402.6244]

- 1st mergers with realistic spins using constraint satisfying initial data

  [SB, Dietrich, Tichy, Bruegmann PRD 2014, gr-qc:1311.4443]

- EOB-NR analysis using gauge-invariant E(j) curves for dynamics

  [SB, Nagar, Thierfelder, Bruegmann PRD 2012, gr-qc:1205.3403]

Publicly available EOB code

EOB

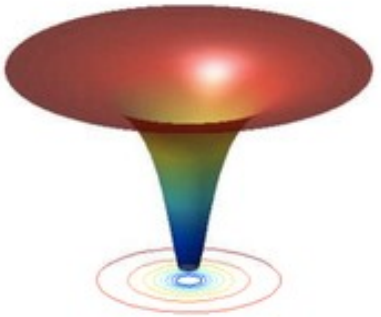
https://eob-new.ihes.fr

Search

EOB Code | About | Download | Documentation | Publications | Contact

About

The effective-one-body (EOB) model is a semi-analytical method for the description of the dynamics and the gravitational radiation emitted by coalescing binaries in general relativity. These web pages host the EOB code mainly developed at IHES. The code is written in Matlab and distributed under the GNU General Public License (GPL).



The original code for nonspinning black-hole binaries was written by Alessandro Nagar and Thibault Damour; it has been recently developed together with Sebastiano Bernuzzi. The model and the code are continuously under development: new versions, either including more physics or improvements in the implementation, will be periodically released.

People currently involved in the project: Sebastiano Bernuzzi, Tibault Damour, Alessandro Nagar.

Download

Please register before to access to the downloads section

This website is hosted by the Institut des hautes Études Scientifiques and maintained by Francois Bachelier.