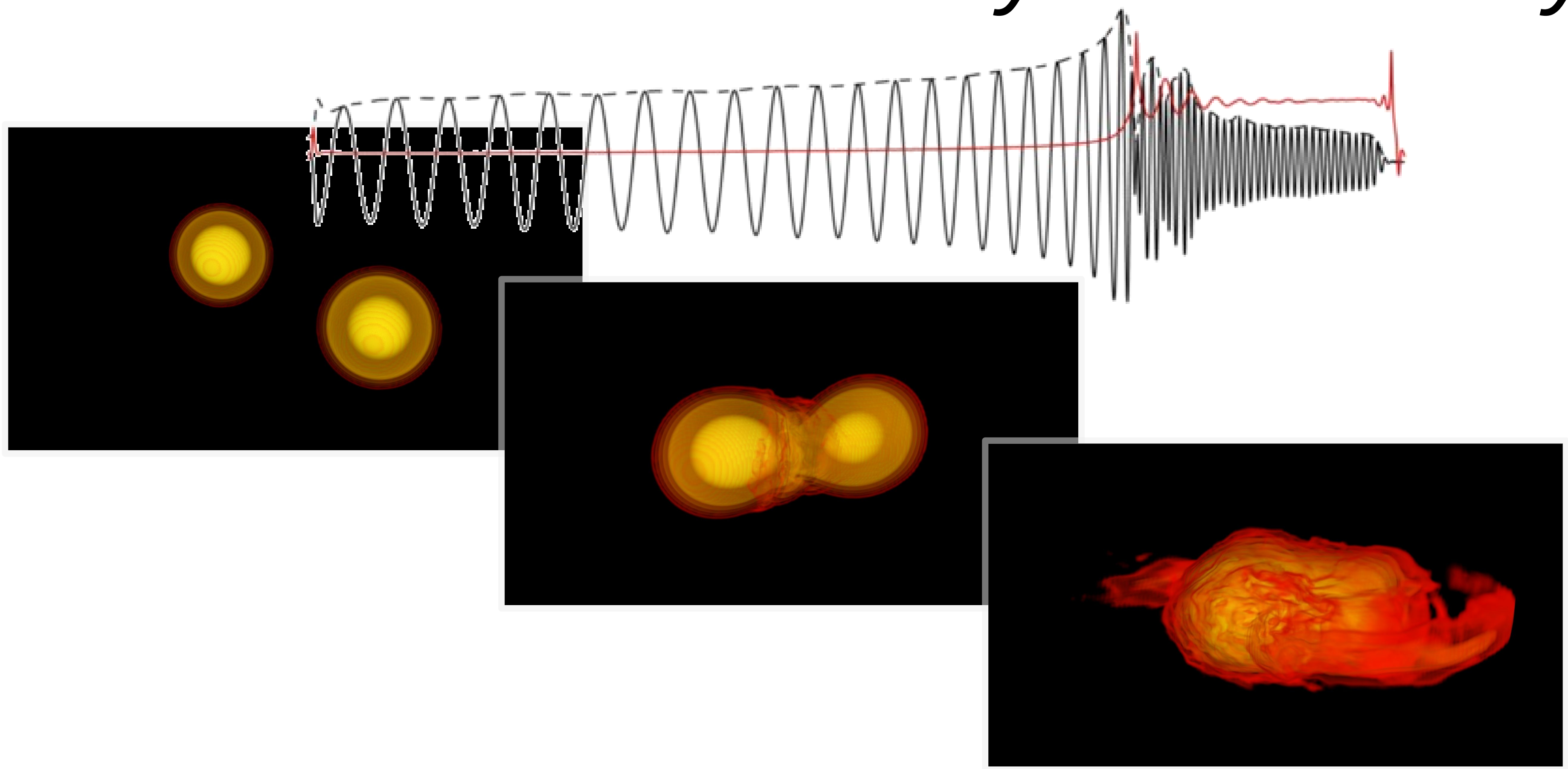
S.Bernuzzi Roma June, 20th 2017

Modeling GWs waves from NS mergers with numerical and analytical relativity

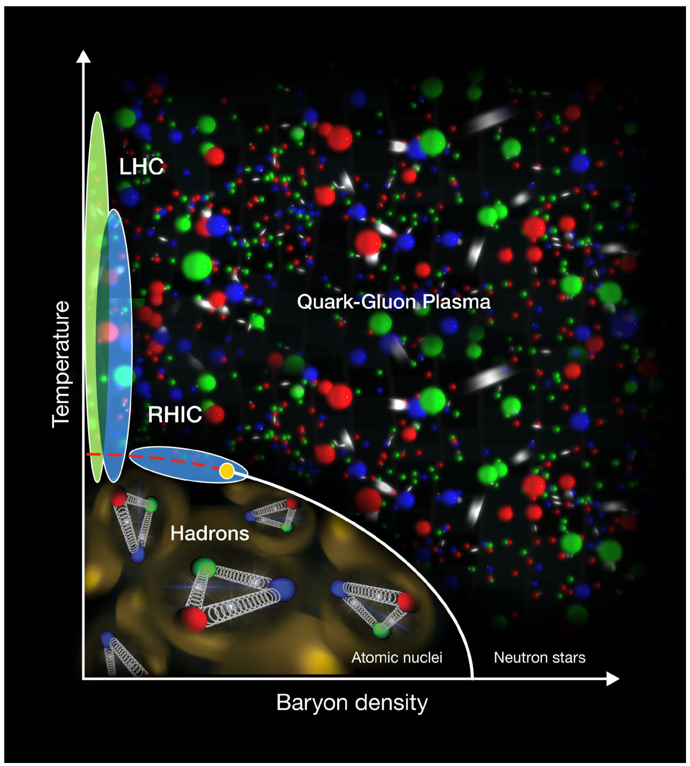


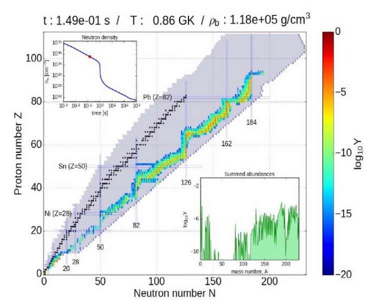
*** Outline ***

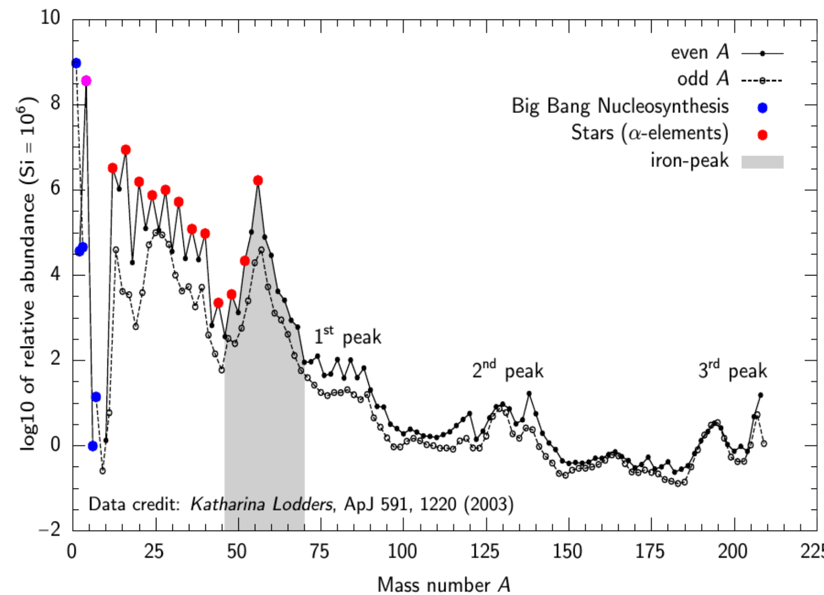
- Motivations
- Analytical/numerical techniques for waveform modeling in GR
- Parametrizing “the EOS”
- TEOBResum: a resummed tidal EOB model
- Fast and efficient representation of waveforms
- Closed-form tidal approximant from NR
- Parameter space studies
- Simulating NS with generic spin consistently
- Merger remnant: (an alternative) peak frequency characterization and emission energetics and timescale

What can we learn from neutron star mergers?

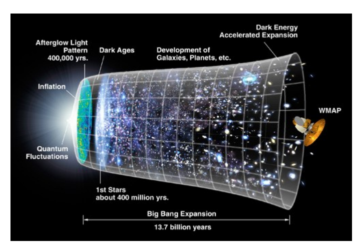
FUNDAMENTAL PHYSICS
Strong-field tests GR (dynamics)
Structure of bulk matter at supranuclear densities
Heavy elements nucleosynthesis

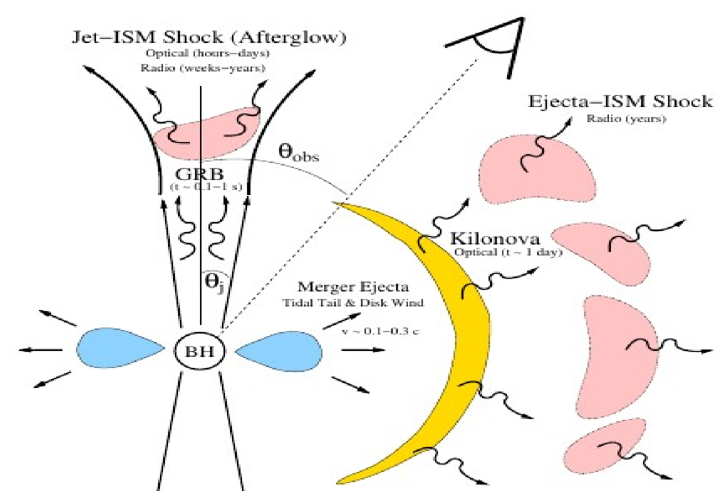






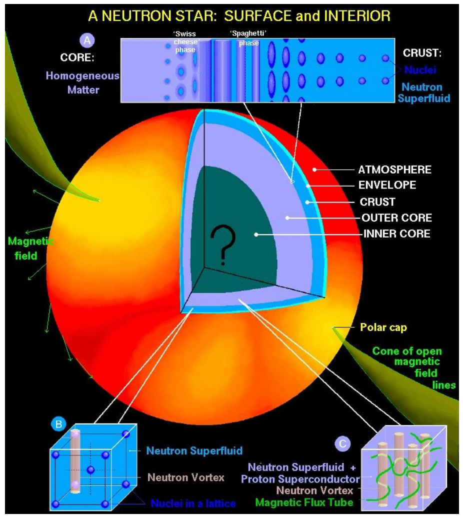
ASTROPHYSICS (Multi-messenger)
Origin of gamma-ray burst
Origin of kilonovae, site for r-processes



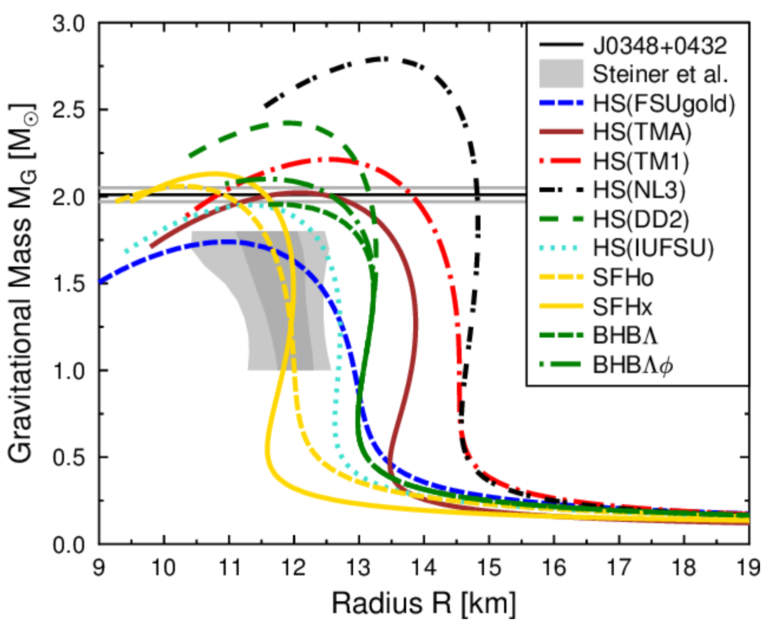


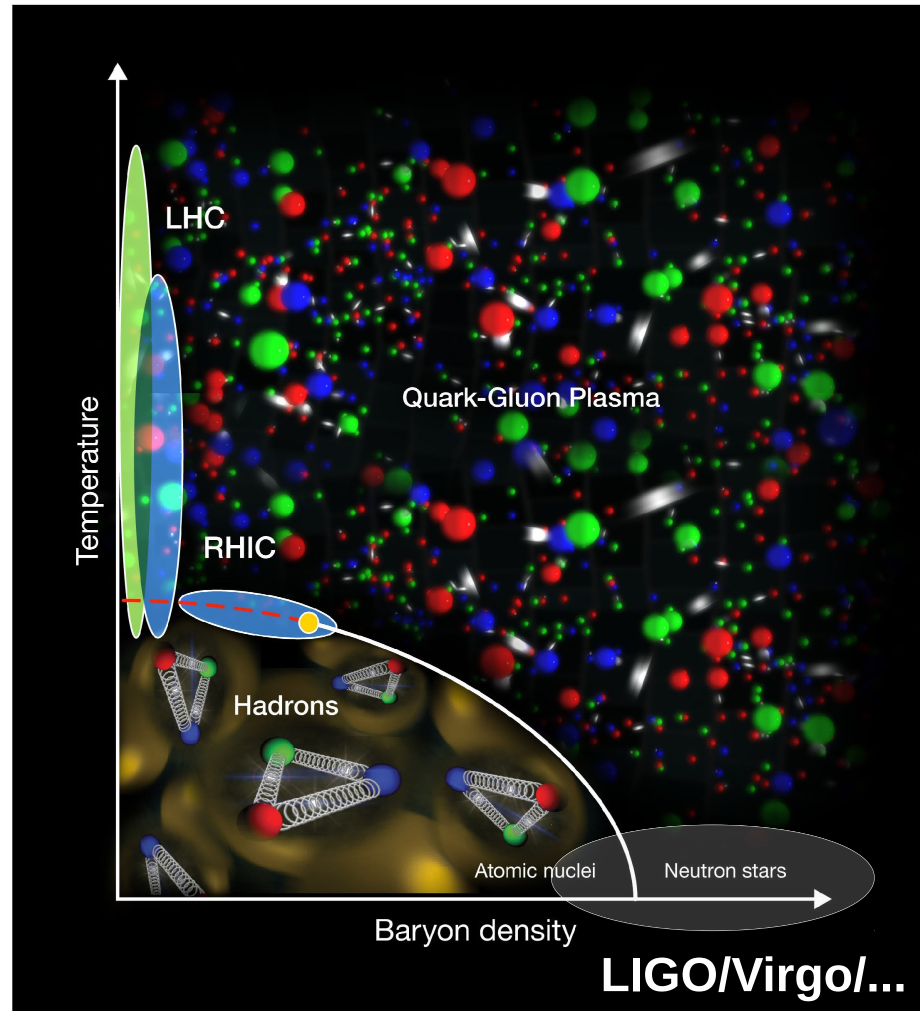
COSMOGRAPHY
Measure Hubble constant
Standard sirens, Calibrate cosmic distance ladder

Constraining the NS Equation of State



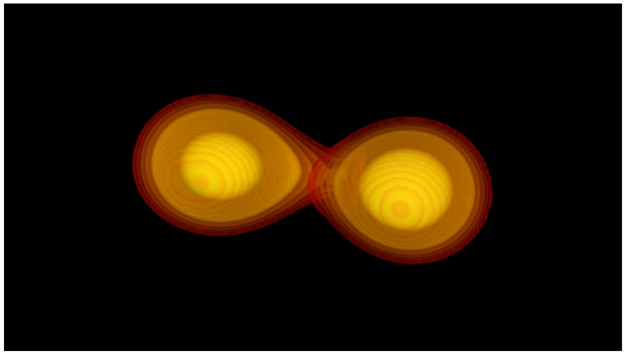
Different EOS → different star's structure

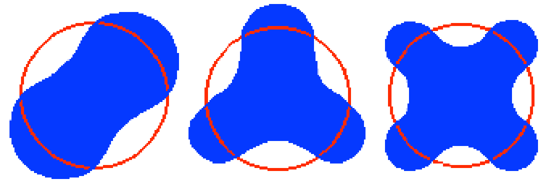




Binary neutron star mergers

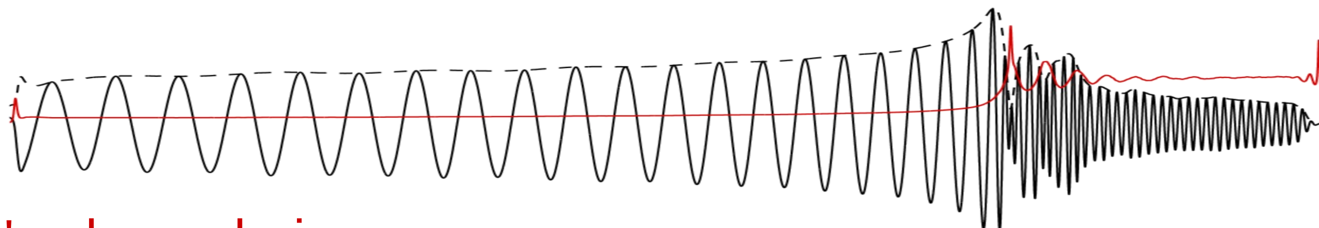
How to?





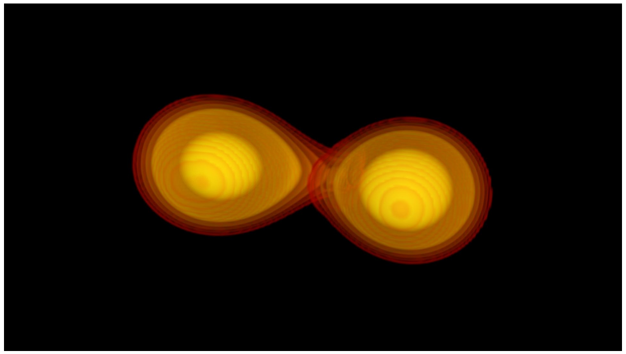
Tides depend critically on EOS

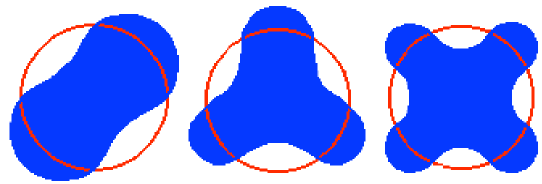
$$\lambda_2 \propto \frac{Q_{ij}}{\partial_{ij}\Phi_{ext}}$$



Tides determine the wave's phase during merger

How to?





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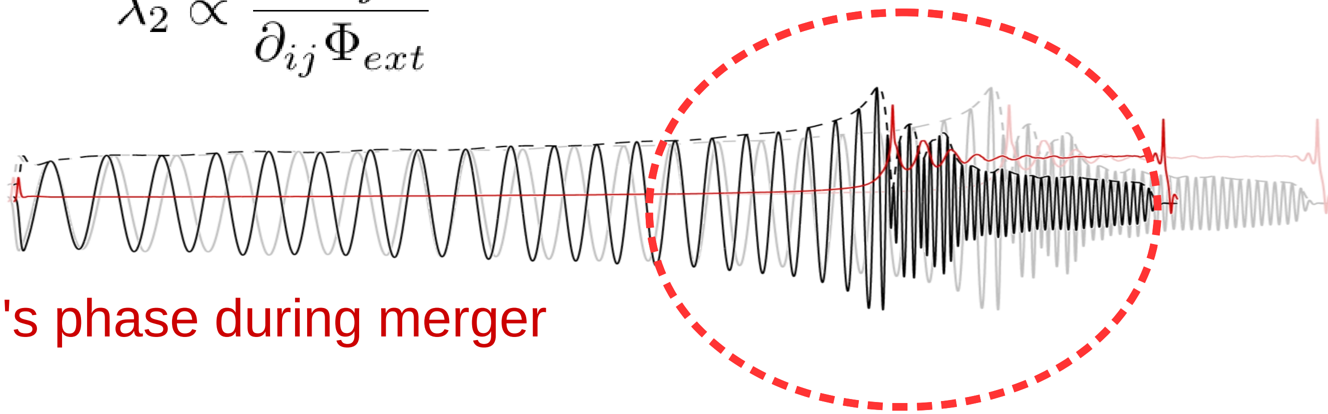
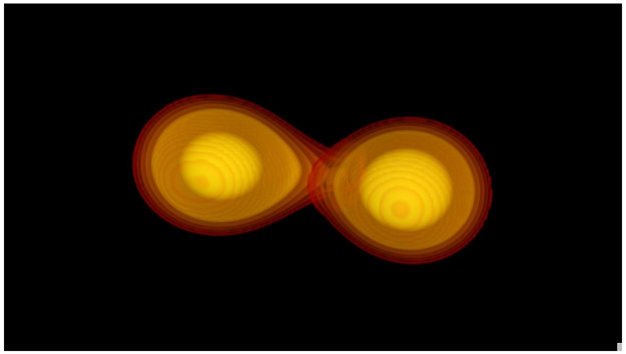
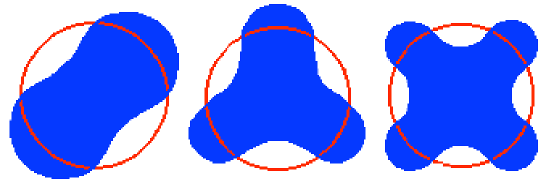
Tides depend crucially on EOS



Tides determine the wave's phase during merger

How to?





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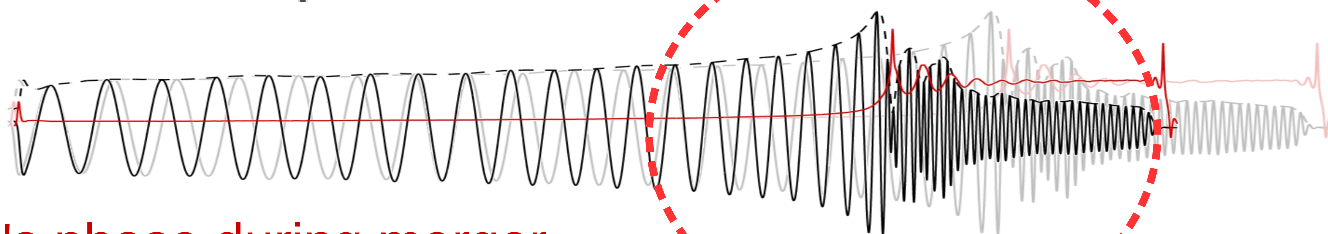
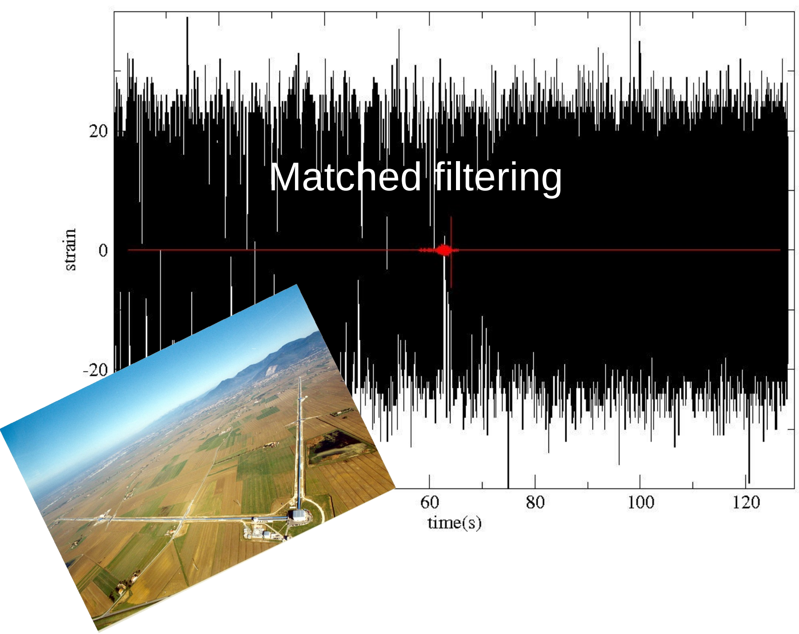
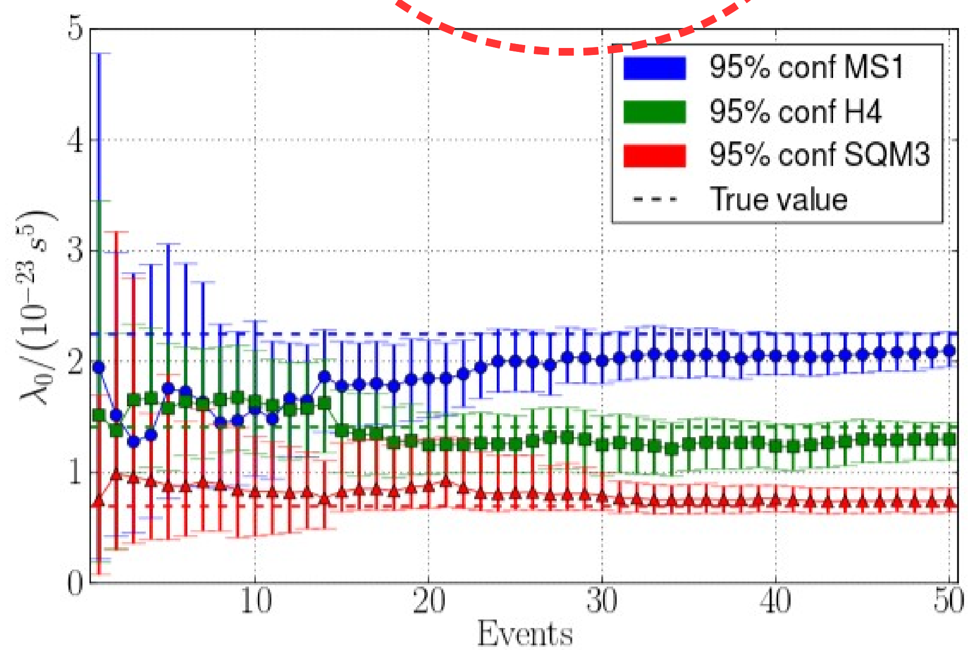


Tides determine the wave's phase during merger

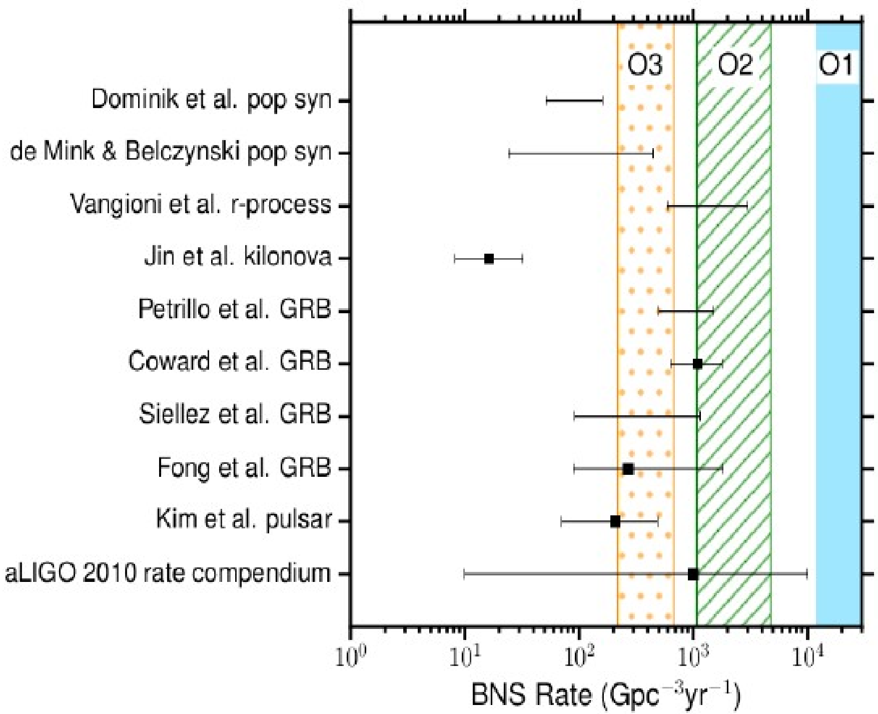


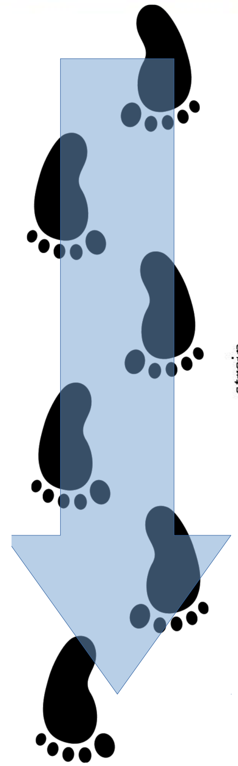


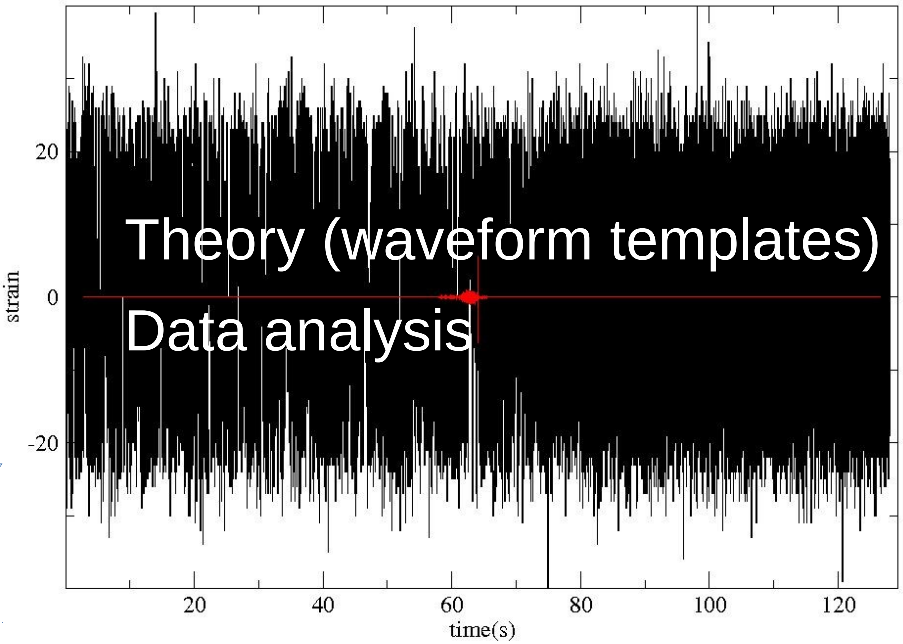
[Del Pozzo+ PRL 111 (2013)]

GW observations require detailed signal models

LIGO Lab/Virgo





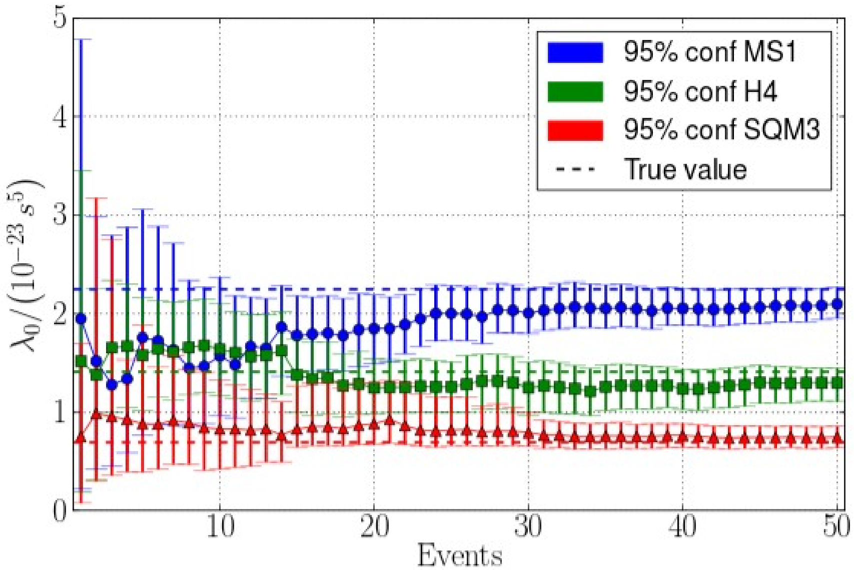


Theory (waveform templates)

Data analysis

Source parameters, interpretation ("science")

Data-analysis status

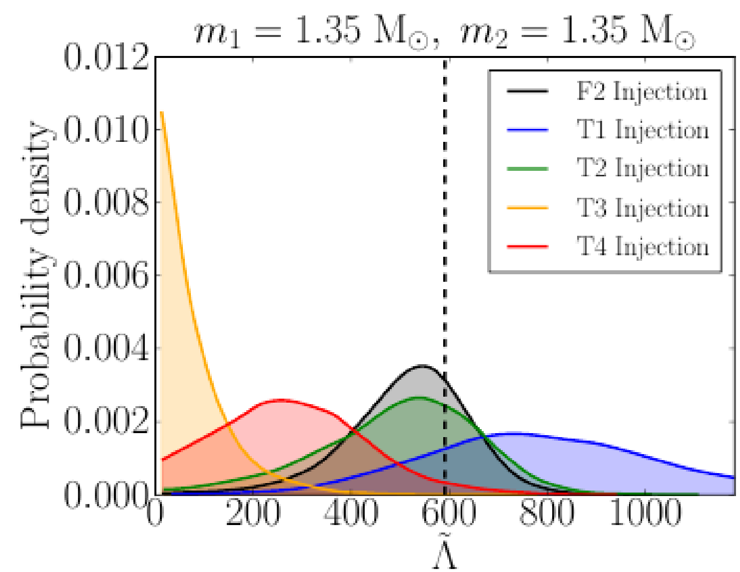


[Del Pozzo+ arXiv:1307.8338]

Tidal parameters can be constrained by LIGO/Virgo using multiple observations

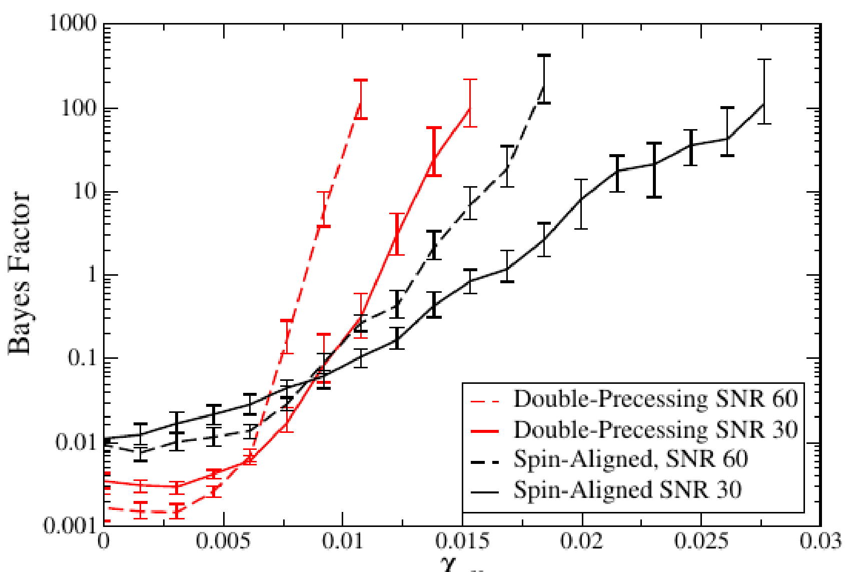
[Agathos+ arXiv:1503.05405]

Mass-prior effect is crucial (confirm biases due to waveform systematics)



[Wade+ arXiv:1402.5156, Lackey+ arXiv:1410.8866]

Uncertainties in the waveform models lead to systematic errors in EOS ~ statistical errors

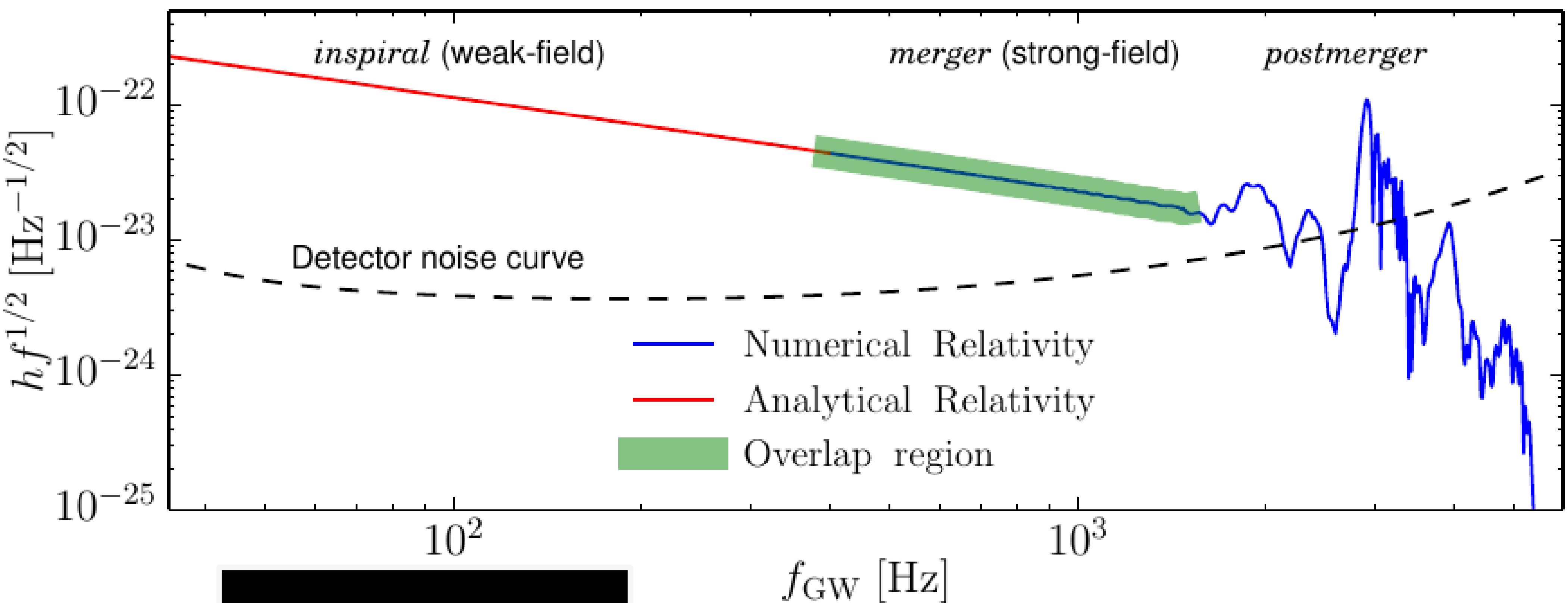


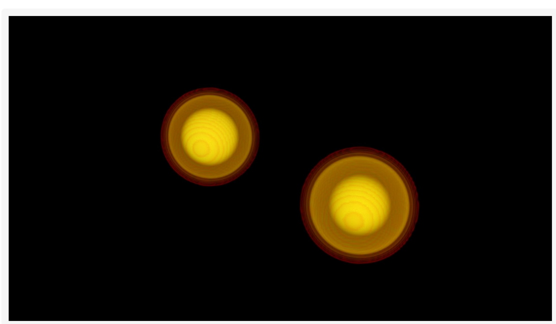
[Chatziioannou+ arXiv:1404.3108]

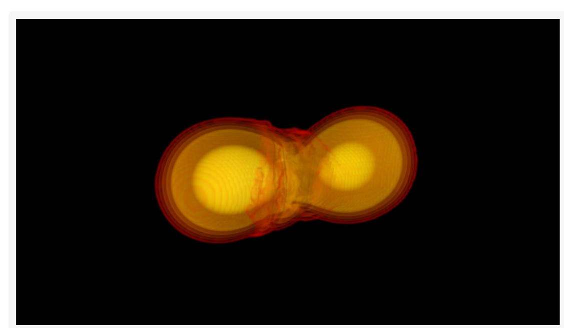
SNR>~30, large biases on masses and spins if precessing spin effects not modeled (small spins <0.2)

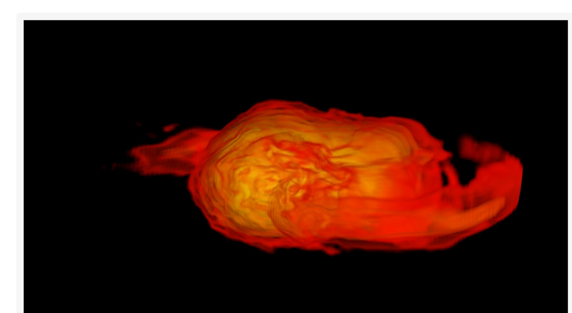
See also [Read+ arXiv:0901.3258, Hinderer+ arXiv:0911.3535, Damour+ arXiv:1203.4352]

The GW spectrum

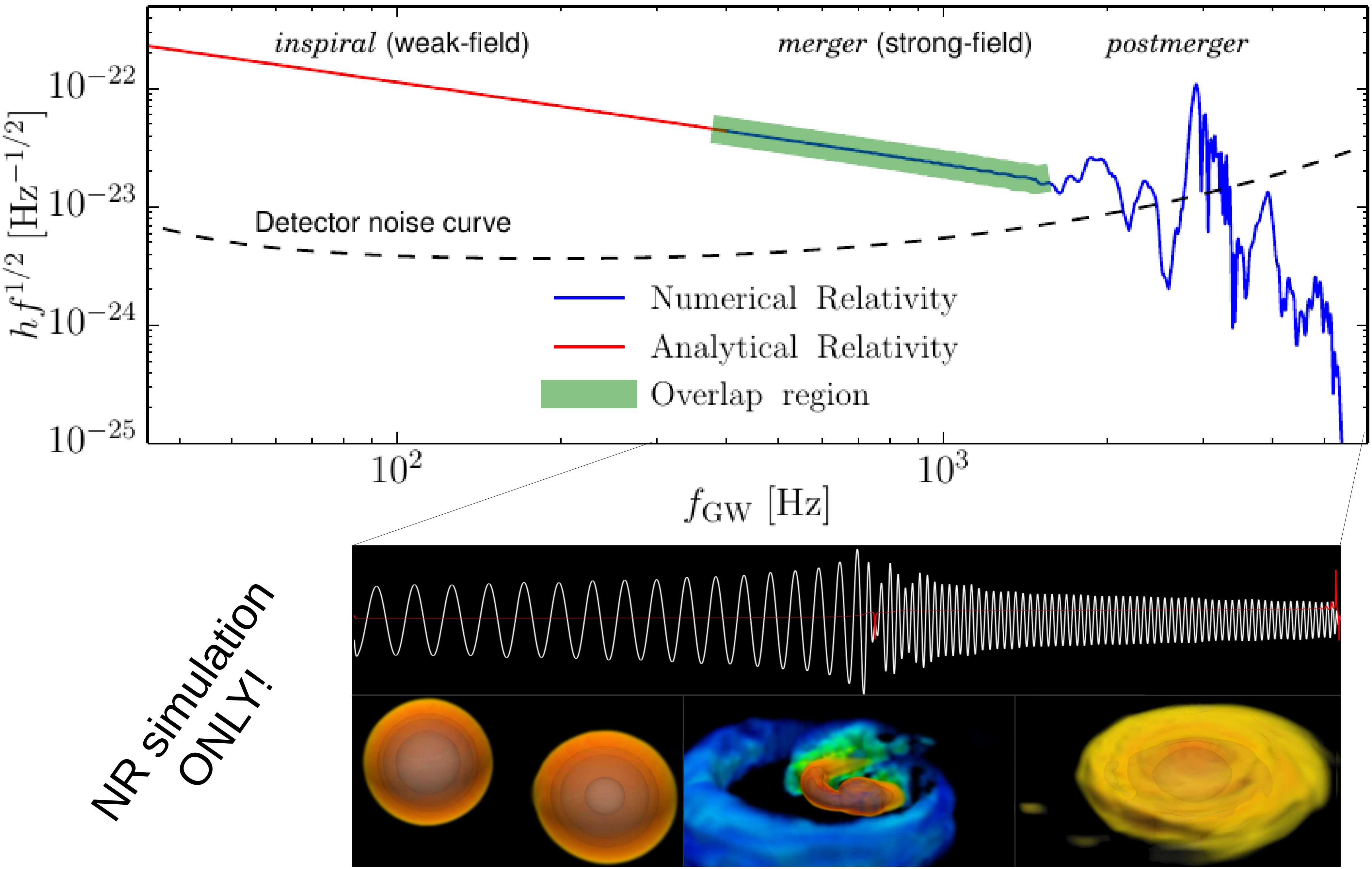








The GW spectrum

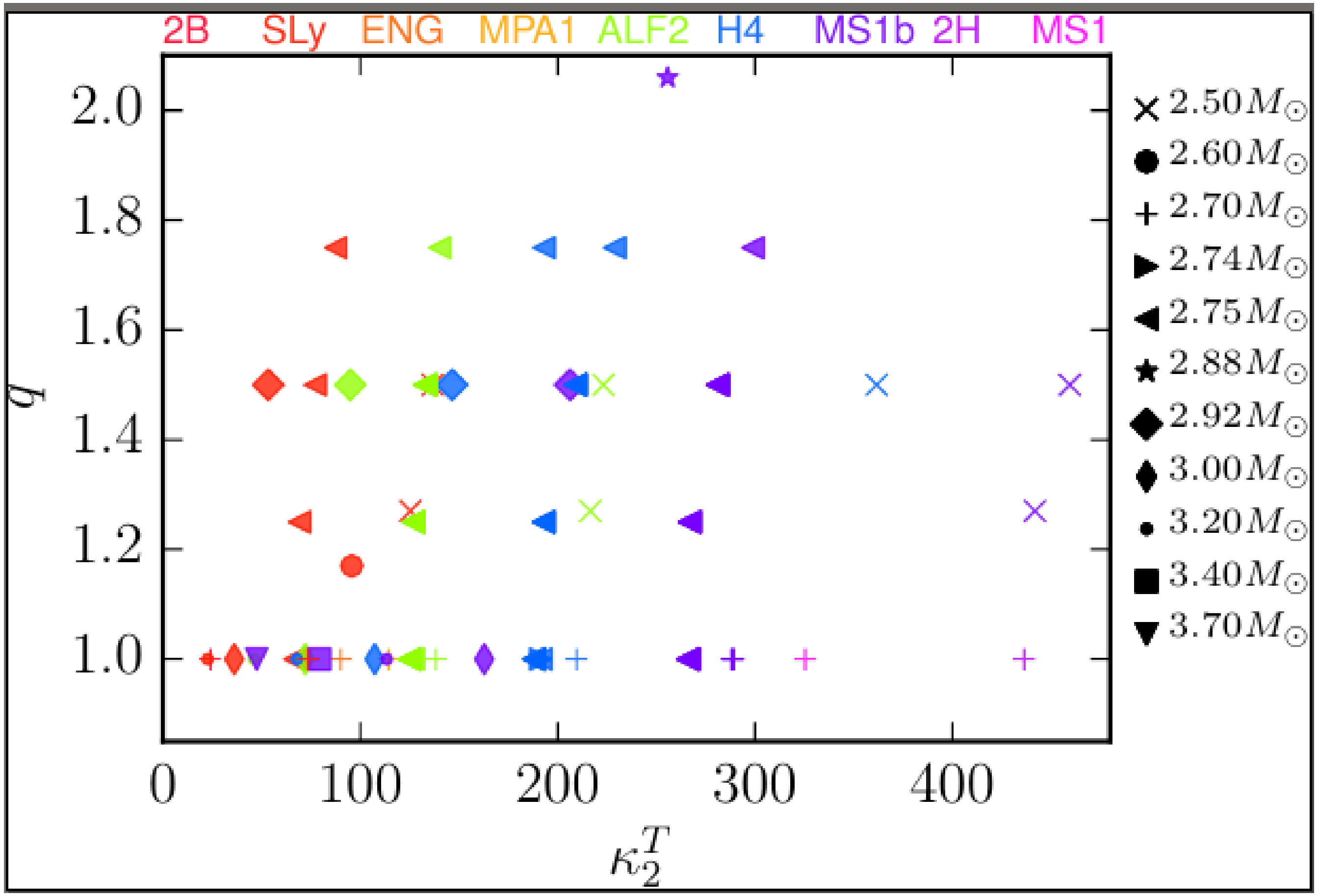


NR simulation ONLY!

Exploring the BNS parameter space

[Dietrich, Ujevic, SB, Tichy, Bruegmann PRD95 024029 (2017)]
[Dietrich, SB, Ujevic, Tichy PRD95 044045 (2017)]

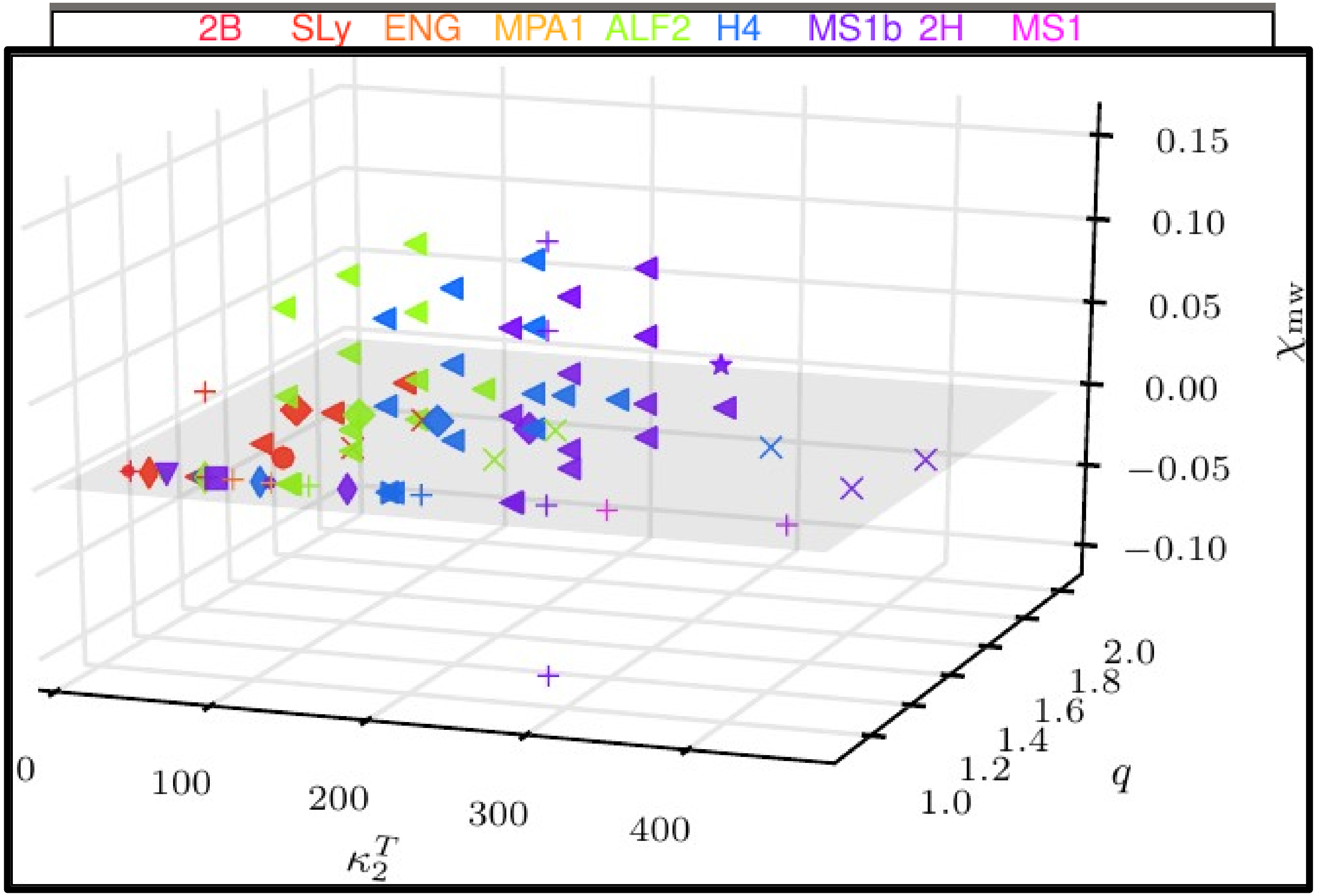
Mass ratio



Tidal coupling constant (EOS)

Exploring the BNS parameter space

Largest exploration of parameter space in strong-field regime available to date

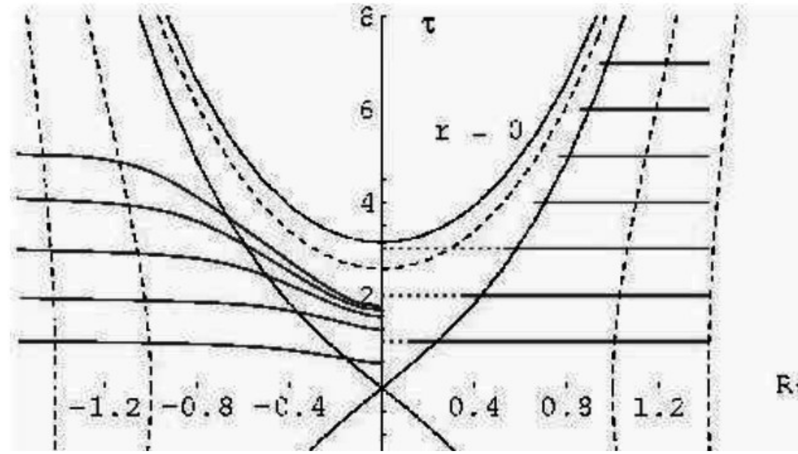


Effective Spin

Tidal coupling constat (EOS)

Mass ratio

$$
\begin{aligned}
\partial_t \tilde{\Gamma}^i = & -2\,\tilde{A}^{ij}\,\partial_j\alpha + 2\,\alpha\left[\tilde{\Gamma}^i{}_{jk}\,\tilde{A}^{jk} - \frac{3}{2}\,\tilde{A}^{ij}\,\partial_j \ln(\chi)\right.\\
& \left. -\frac{1}{3}\,\tilde{\gamma}^{ij}\,\partial_j(2\,\hat{K}+\Theta) - 8\,\pi\,\tilde{\gamma}^{ij}\,S_j\right] + \tilde{\gamma}^{jk}\,\partial_j\partial_k\beta^i\\
& + \frac{1}{3}\,\tilde{\gamma}^{ij}\partial_j\partial_k\beta^k + \beta^j\,\partial_j\tilde{\Gamma}^i - (\tilde{\Gamma}_{\rm d})^j\,\partial_j\beta^i\\
& + \frac{2}{3}\,(\tilde{\Gamma}_{\rm d})^i\,\partial_j\beta^j - 2\,\alpha\,\kappa_1\left[\tilde{\Gamma}^i - (\tilde{\Gamma}_{\rm d})^i\right],\\
\partial_t\Theta = & \frac{1}{2}\,\alpha\left[R - \tilde{A}_{ij}\,\tilde{A}^{ij} + \frac{2}{3}\,(\hat{K}+2\,\Theta)^2\right]\\
& -\alpha\left[8\,\pi\,\rho + \kappa_1\,(2+\kappa_2)\,\Theta\right] + \beta^i\partial_i\Theta\,,
\end{aligned}
$$



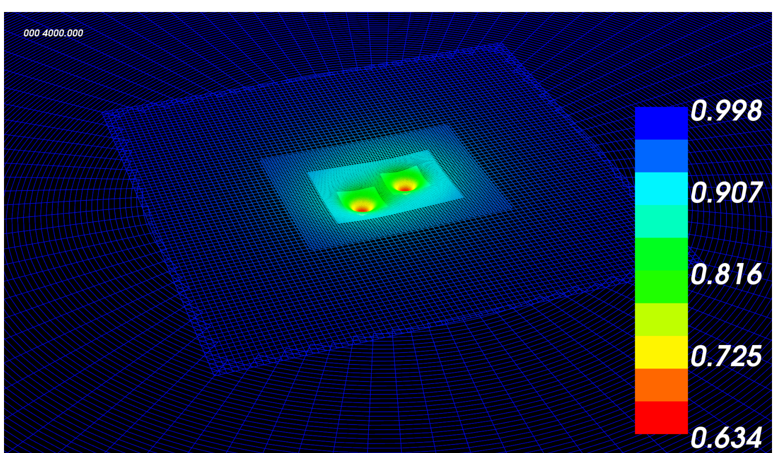
GR Formulation and Cauchy problem
+ GR hydrodynamics

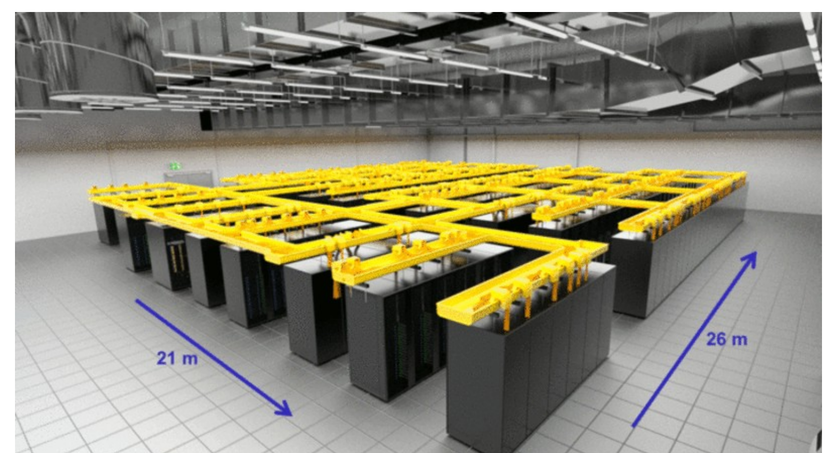
Coordinates and Singularities

Numerical relativity in a nutshell

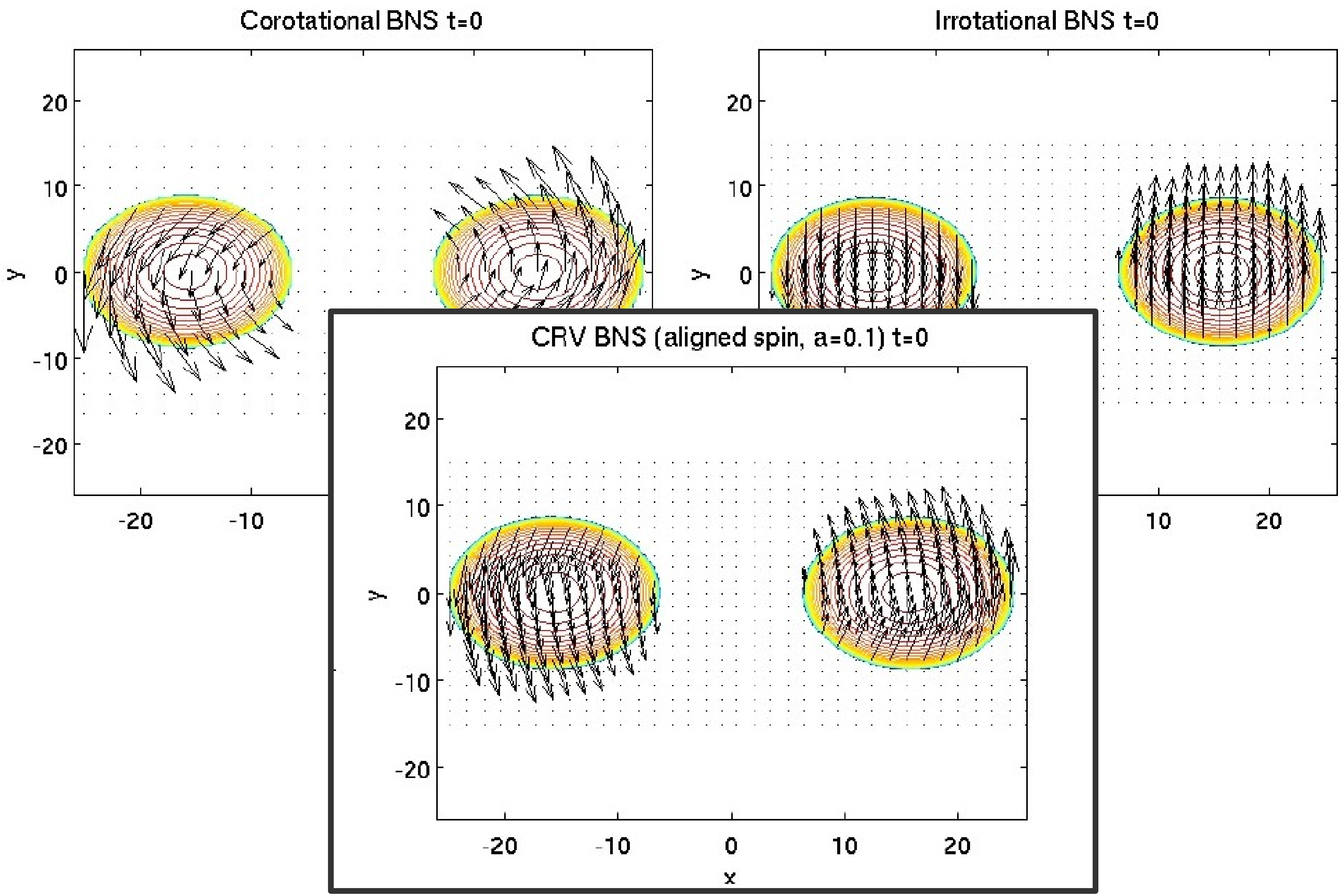
Numerical methods for PDEs on adaptive grids

High-performance-computing (HPC)





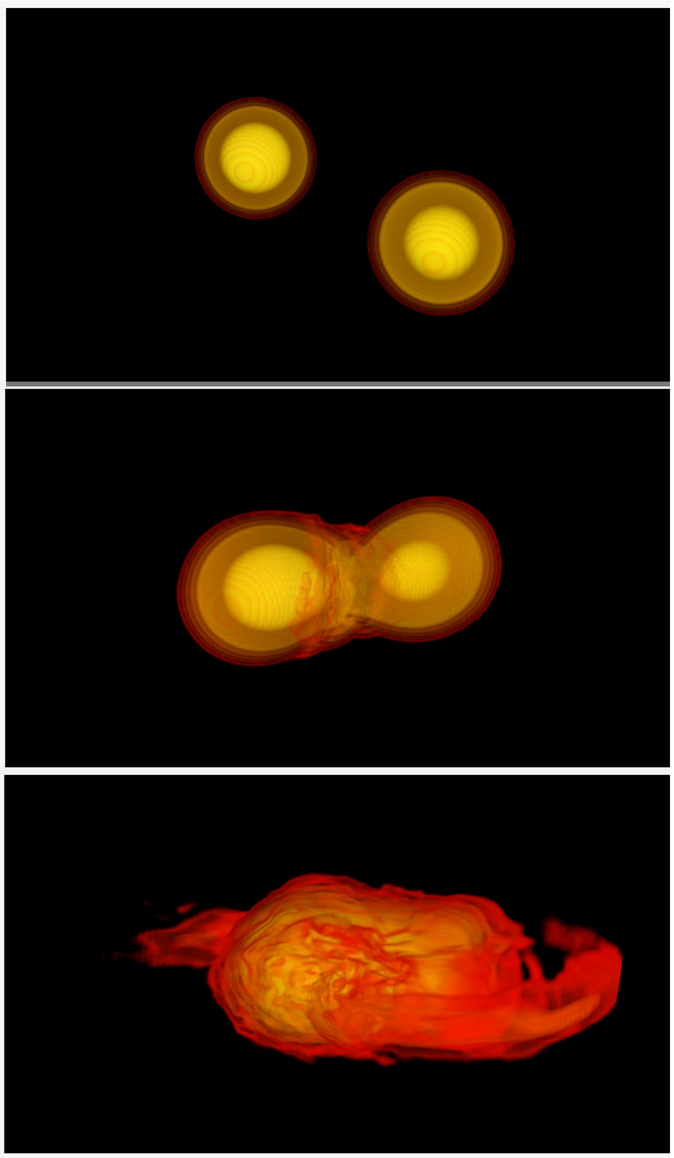
Quasiequilibrium circular initial data

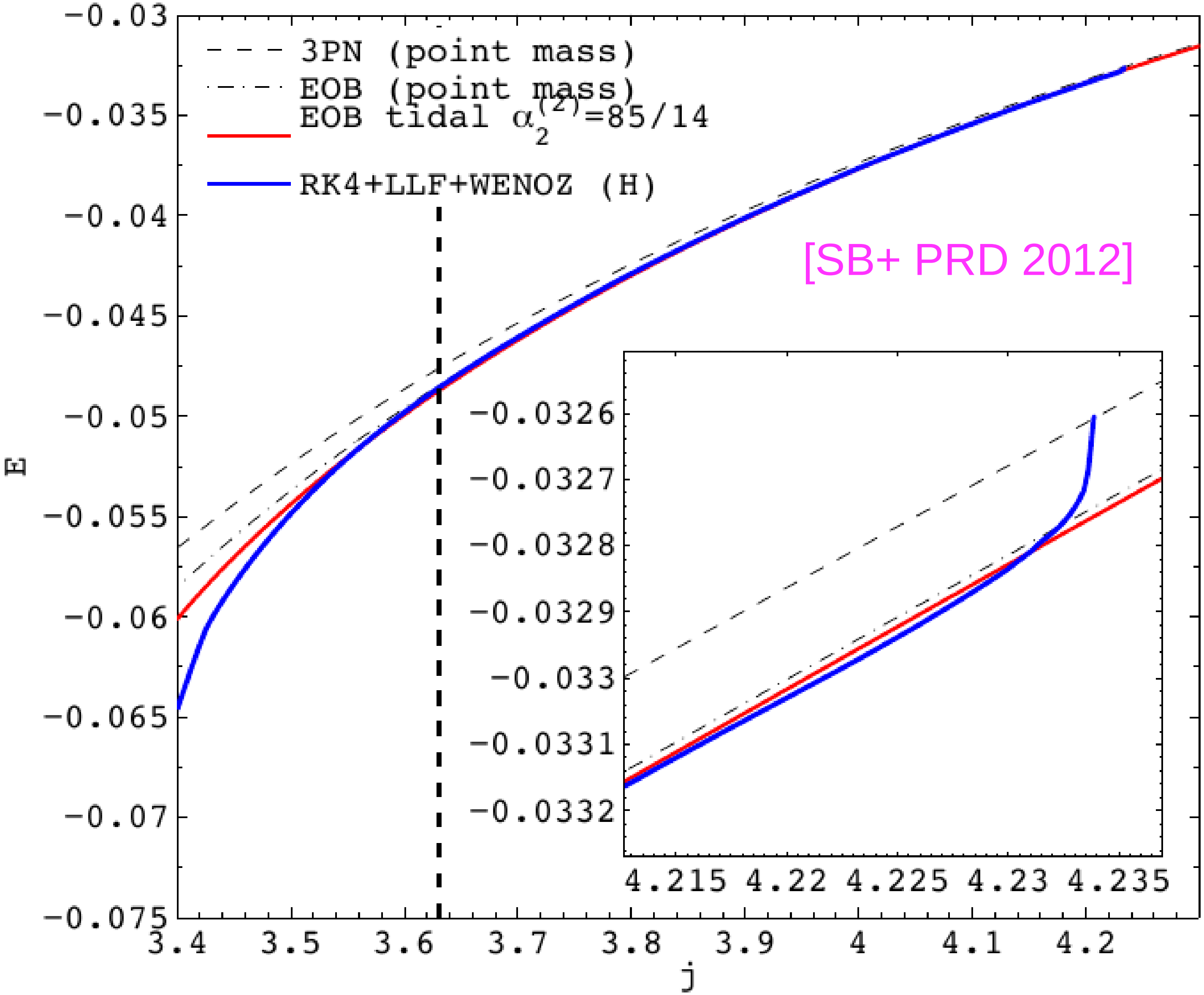


Constant Rotational Velocity approach

[Tichy arXiv:1209.5336, arXiv:1107.1440]

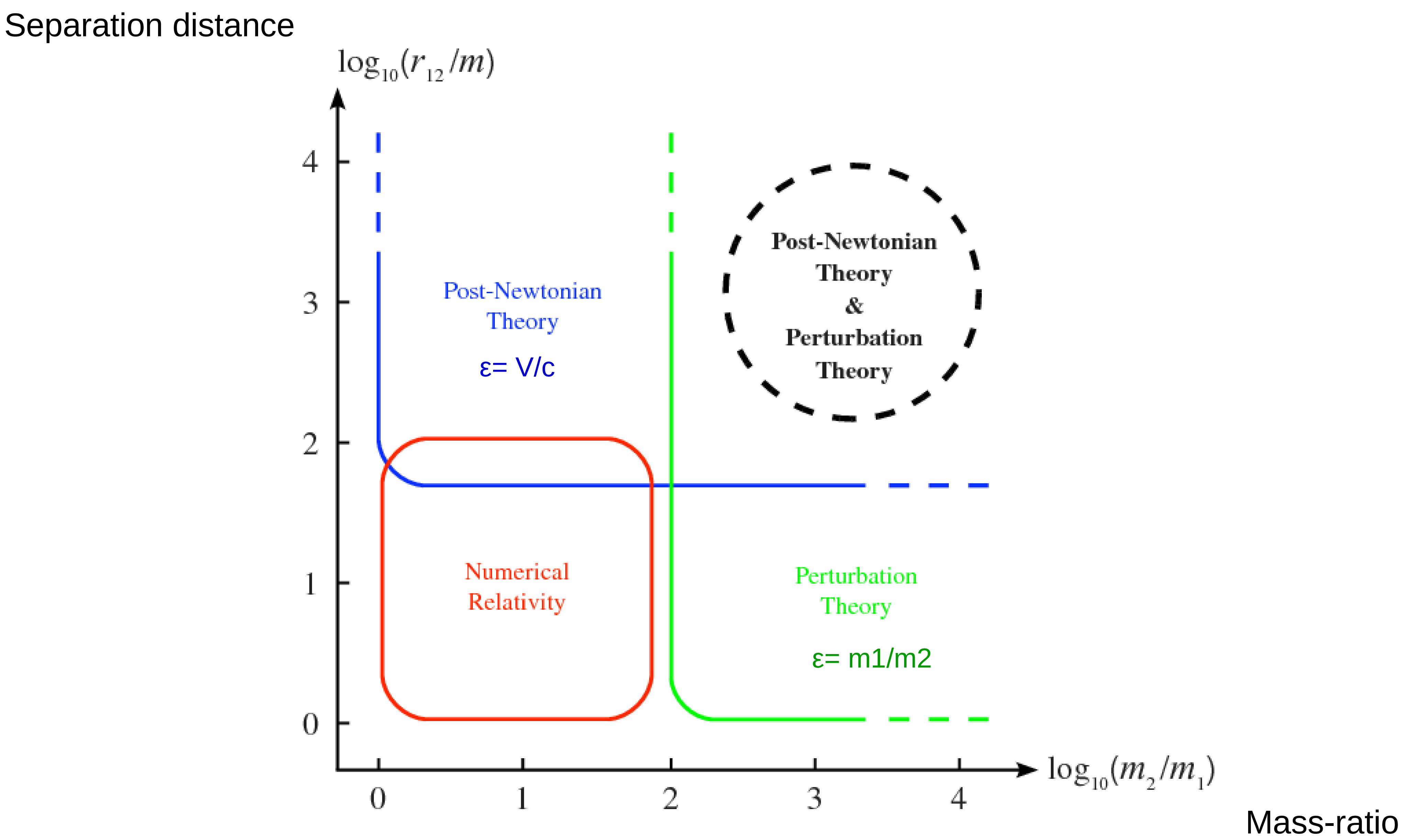
How to extract meaningful info from simulations?





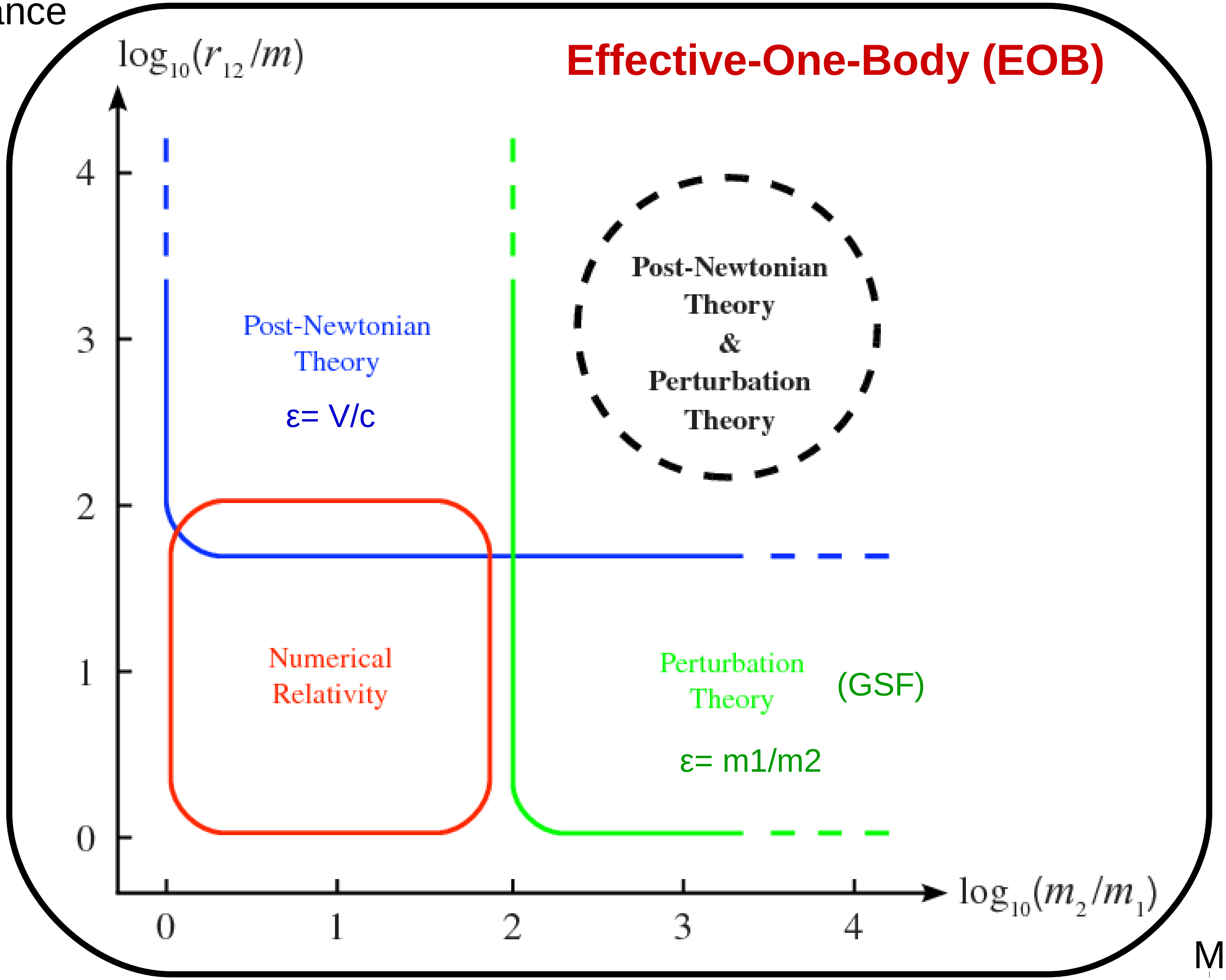
[Damour+ PRL 2012] → Probe conservative dynamics

Methods for the GR 2-body problem



Effective-One-Body framework

Separation distance

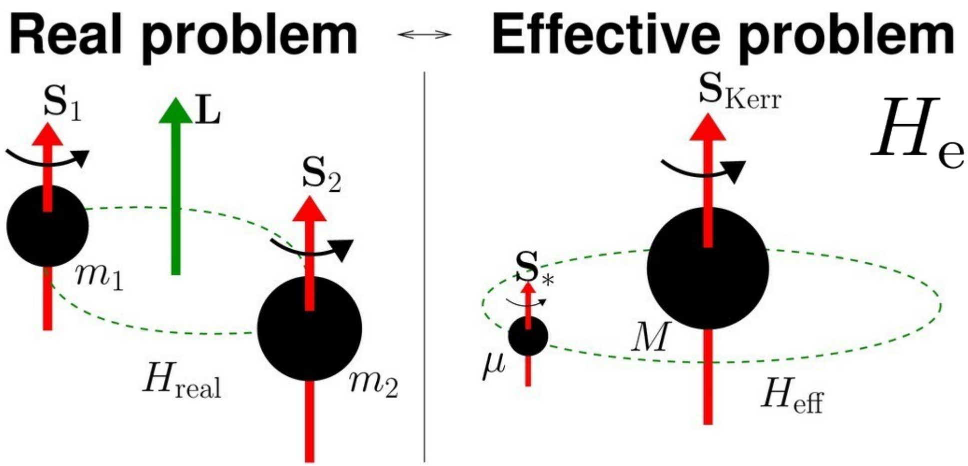


Mass-ratio

[Buonanno&Damour arXiv:gr-qc/9811091, Damour,Iyer,Nagar arXiv:0811.2069, Damour&Nagar arXiv:0911.5041]

Effective-One-Body

[Buonanno&Damour PRD 1999,2000]



Credit: A.Taracchini/AEI

$$H_{\rm eff} \sim \mu\sqrt{A(u)(1+p_\phi^2 u^2)+p_{r^*}^2}$$

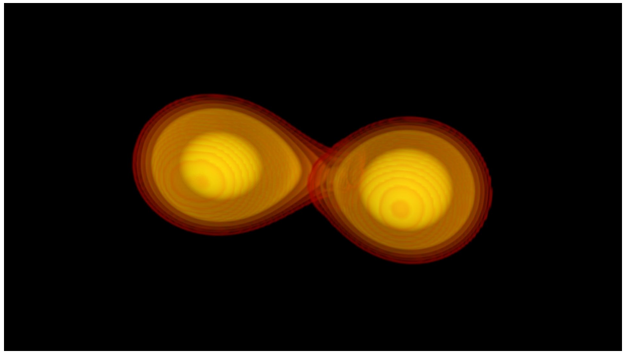
$$A(u;\nu;\kappa_2^T) = A^0(u;\nu) + A^T(u;\nu;\kappa_2^T)$$

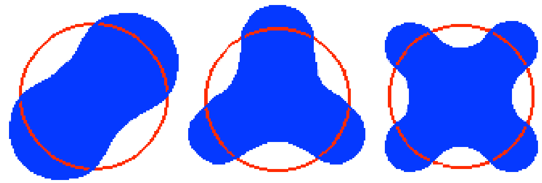
$$A^0(u;\nu) = 1 - 2u + \nu(\ldots$$

- Includes test-mass limit (i.e. particle on Schwarzschild)
- Includes post-Newtonian and self-force results
- Uses resummation techniques → predictive strong-field regime
- Includes tidal interactions (→ BNS) [Damour&Nagar PRD 2010]
- Flexible framework, can include NR results (“NR-informed”)
- <u>Most accurate framework to describe compact binary waveforms</u>

See e.g. [Taracchini+ PRD 2014][SB+ PRL 2015][Nagar+ PRD 2015][Hinderer+ 2016]

Relativistic Tides





$$\lambda_2 \propto \frac{Q_{ij}}{\partial_{ij}\Phi_{ext}}$$

[Hinderer arXiv:0711.2420, Damour&Nagar arXiv:0906.0096, Binnington&Poisson arXiv:0906.1366]

$$\kappa_2^T = 2\left[\frac{X_A}{X_B}\left(\frac{X_A}{C_A}\right)^5 k_2^A + \frac{X_B}{X_A}\left(\frac{X_B}{C_B}\right)^5 k_2^B\right]$$

[Damour&Nagar arXiv:0911.5041]

Tidal contribution to (post-) Newtonian dynamics and waveform:

Hamiltonian (Newtonian limit):

$$H_{\rm EOB} \approx Mc^2 + \frac{\mu}{2}\left(\mathbf{p}^2 + A(r) - 1\right)$$

$$A(r) = 1 - 2/r - \kappa_2^T(\lambda_2)/r^6$$

Tides are attractive and “act” at small separations

Tidal coupling constant

Waveform:

$$h \sim A f^{-7/6} e^{-i\Psi(f)} \approx A f^{-7/6} e^{-i\Psi_{PP}(f) + i 39/4 \kappa_2^T x(f)^{5/2}}$$

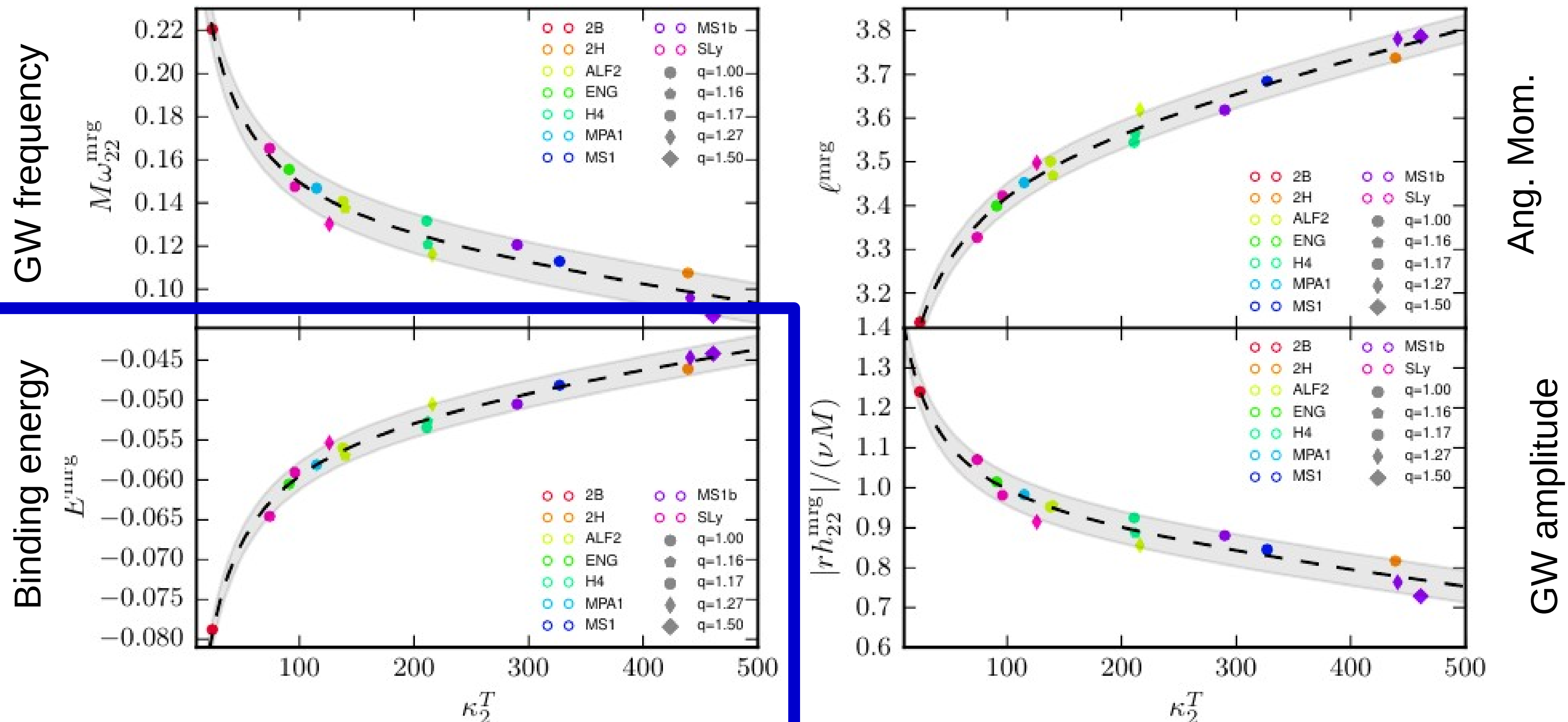
Key point: No other binary parameter (mass, radii, etc) enter separately the formalism

One parameter to characterize merger dynamics

[SB,Nagar,Balmelli,Dietrich,Ujevic PRL 112 (2014)]

Predict energy emitted in GW for all binaries, range 1-2% M
(all possible EOS, masses, mas-ratios)

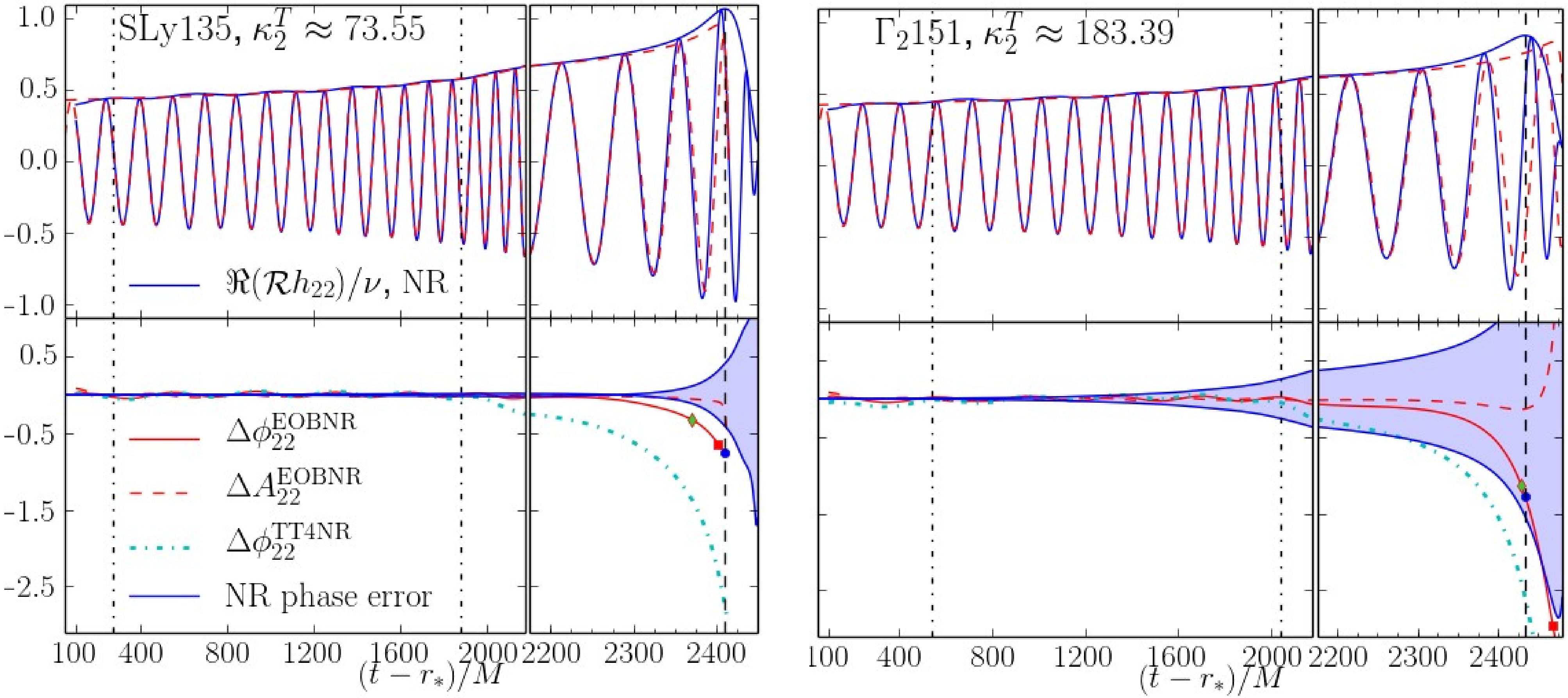
Predict energy emitted for given binary by specifying solely the kappa value



Tidal polarizability coef. (l=2)

First waveform model for inspiral → merger

[SB,Nagar,Dietrich,Damour PRL 114 (2015)]



- Effective-one-body model with tides, GSF Resummed approach [Bini+ 2014]
- Valid from low frequencies to merger, PREDICT the merger waveform
- Accuracy: uncertainties of the numerical data (improve simulations!)

See [Hinderer+ PRL 116 (2016)] for an alternative approach

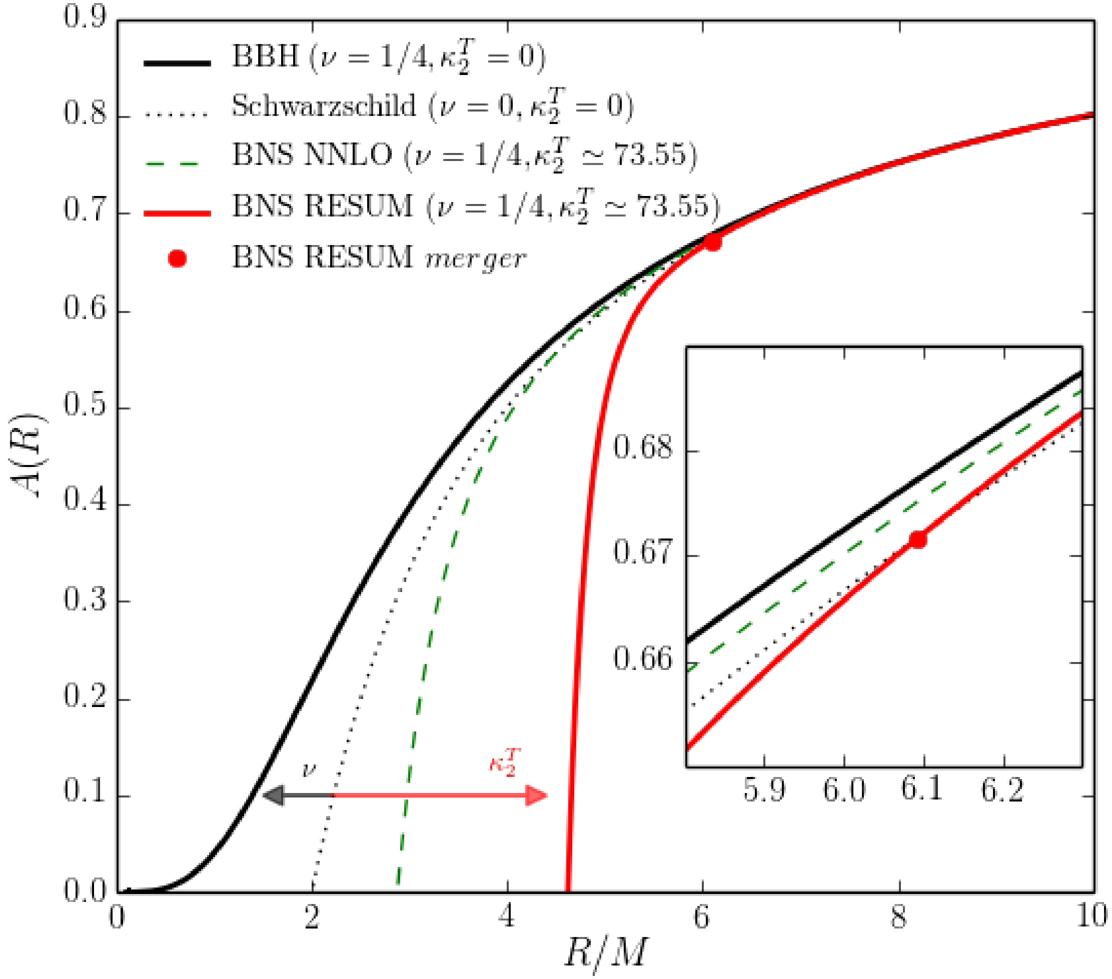
A GSF-based A(R) potential

$$H_{\rm EOB} \approx Mc^2 + \frac{\mu}{2}\left(\mathbf{p}^2 + A(r) - 1\right)$$

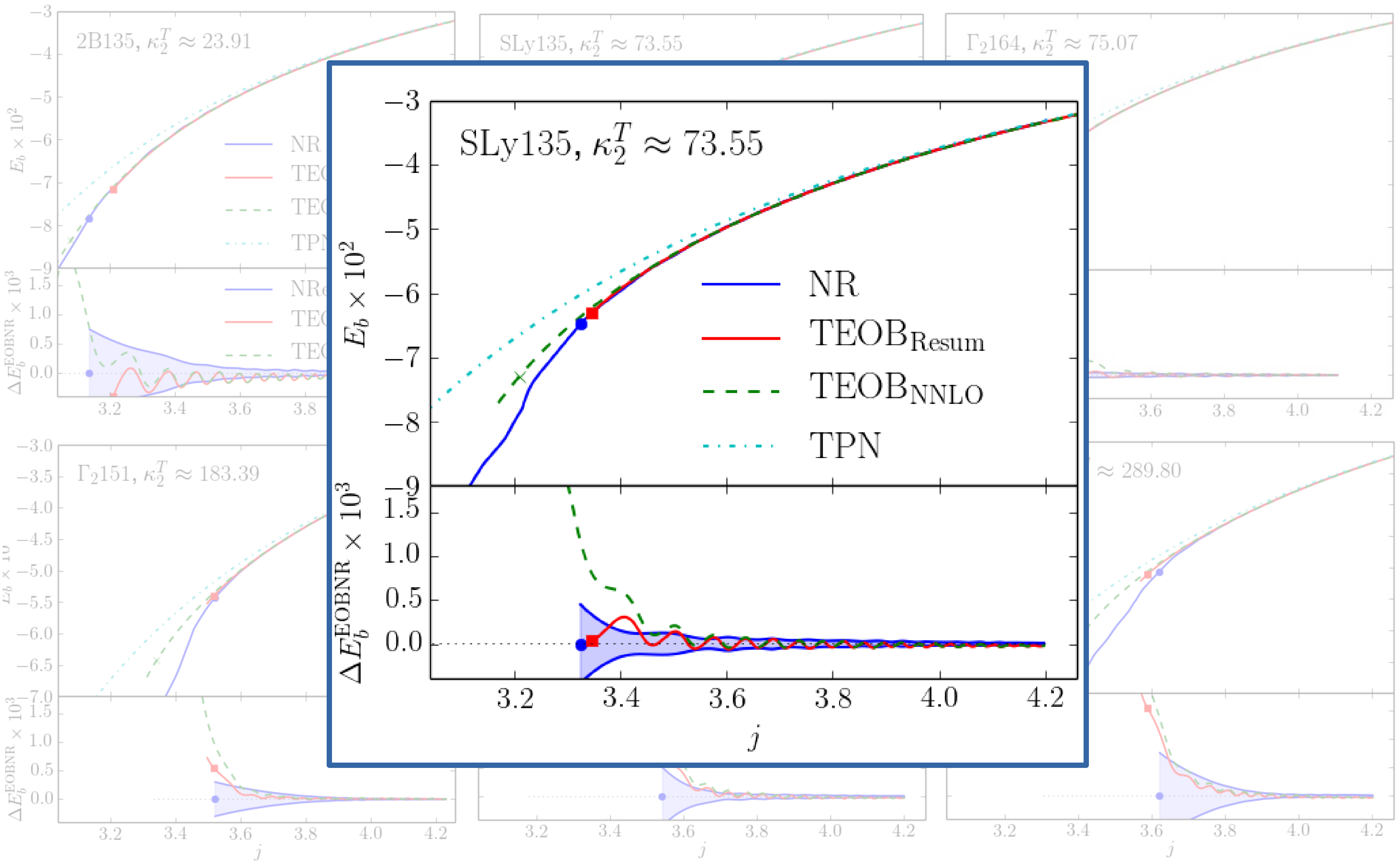
$$A(r) = 1 - 2/r - \kappa_2^T(\lambda_2)/r^6$$

[Bini&Damour PRD 2015]

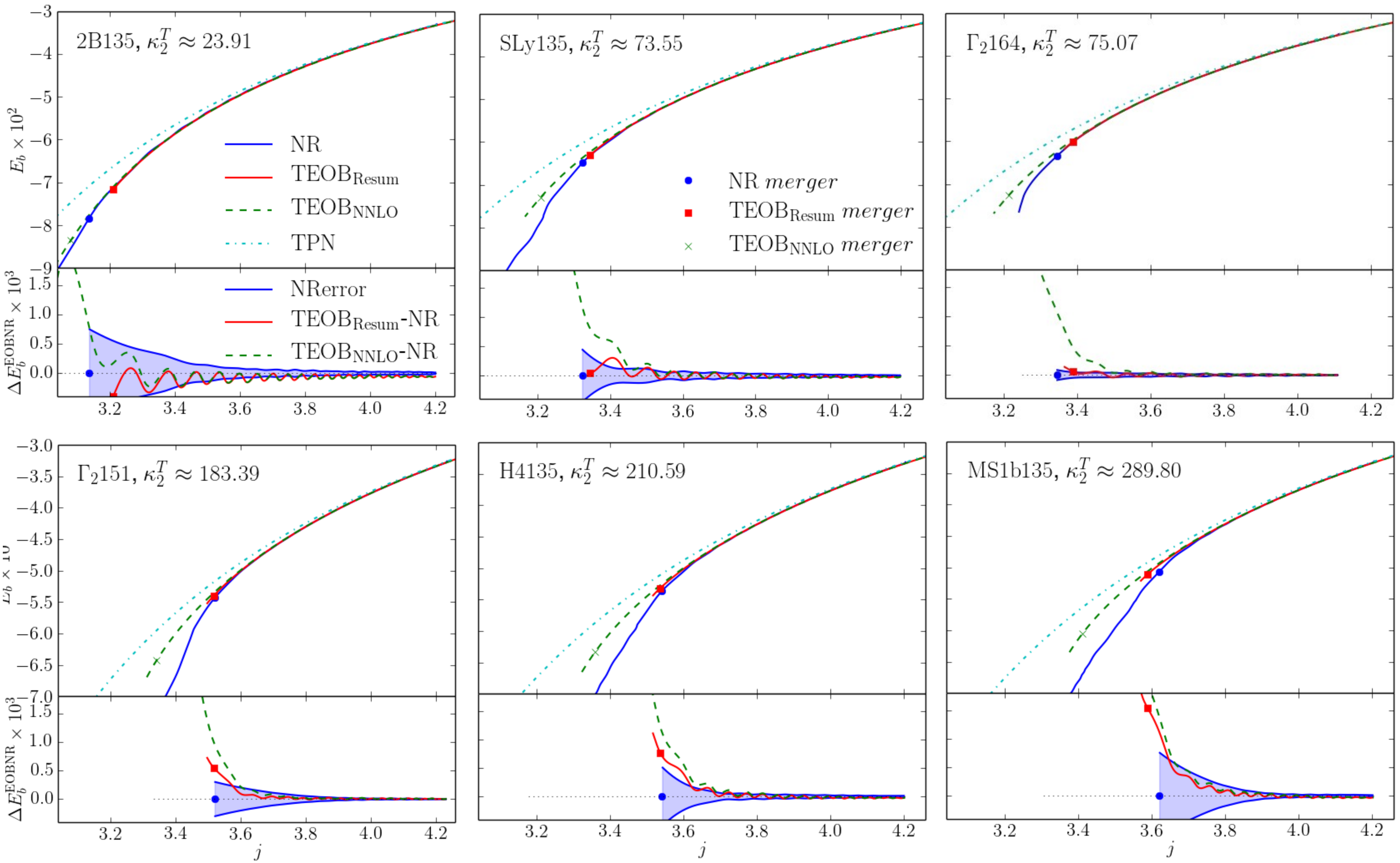
[SB,Nagar,Dietrich,Damour PRL 2015a]



Performance of the resummed tidal potential

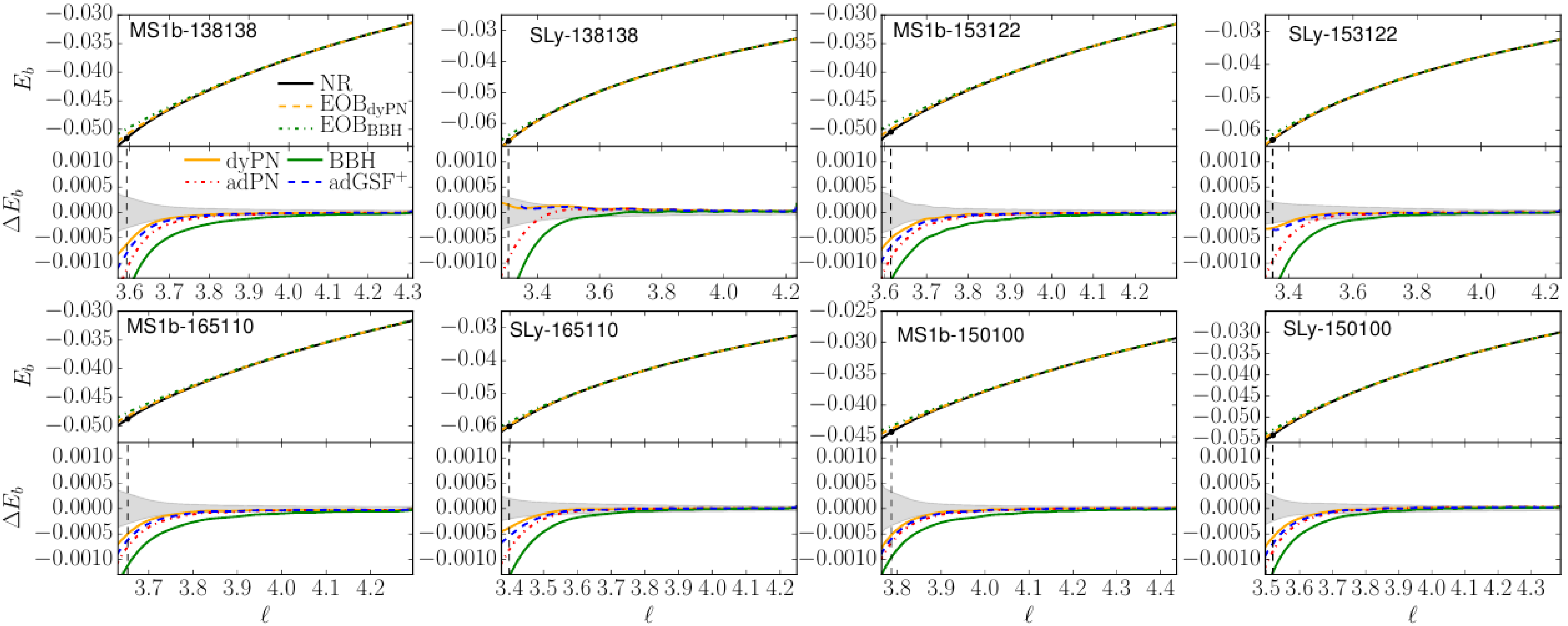


Performance of the resummed tidal potential



Comparison of EOB tidal models

[Dietrich&Hinderer arXiv:1702.02053]



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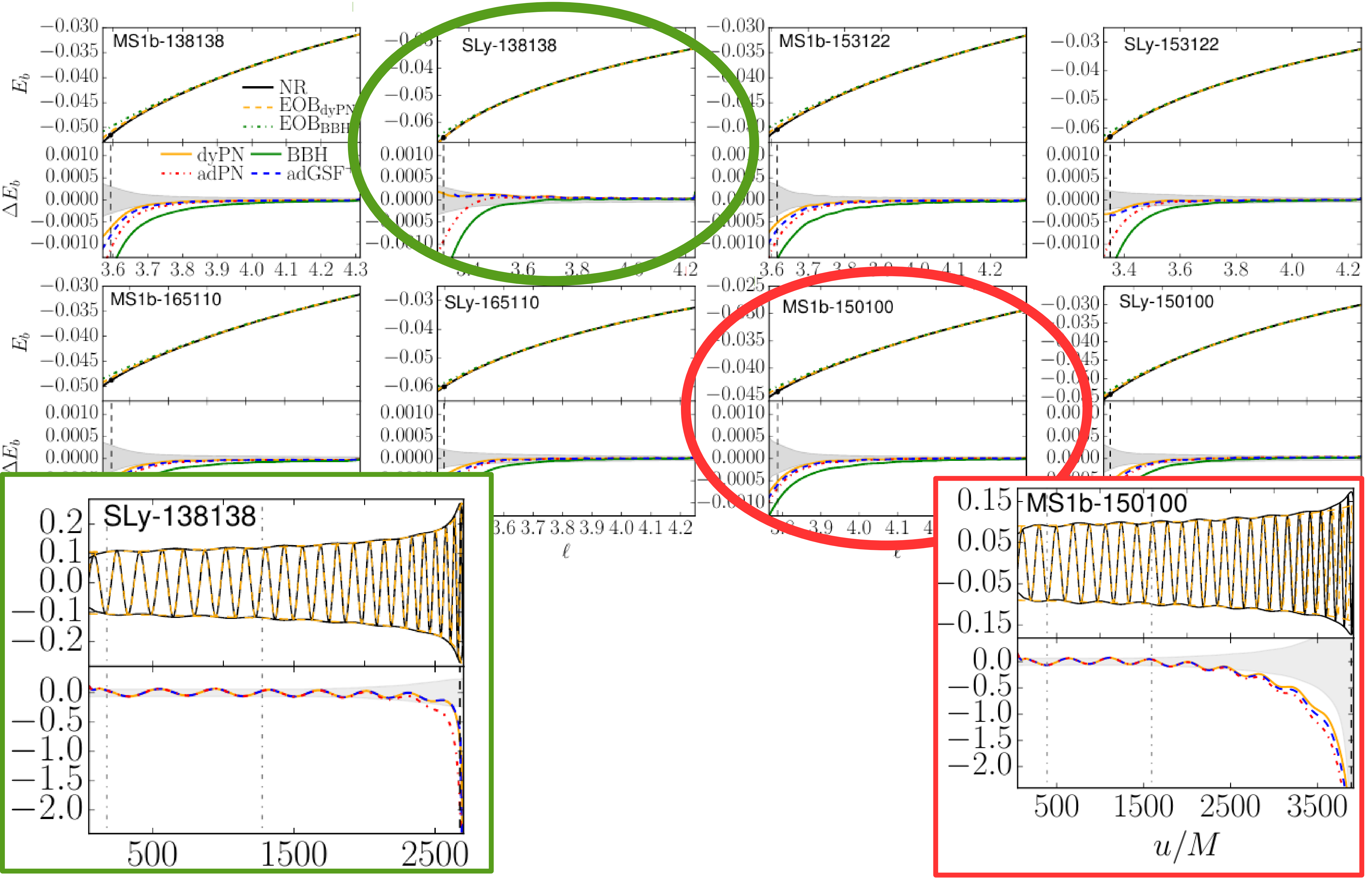
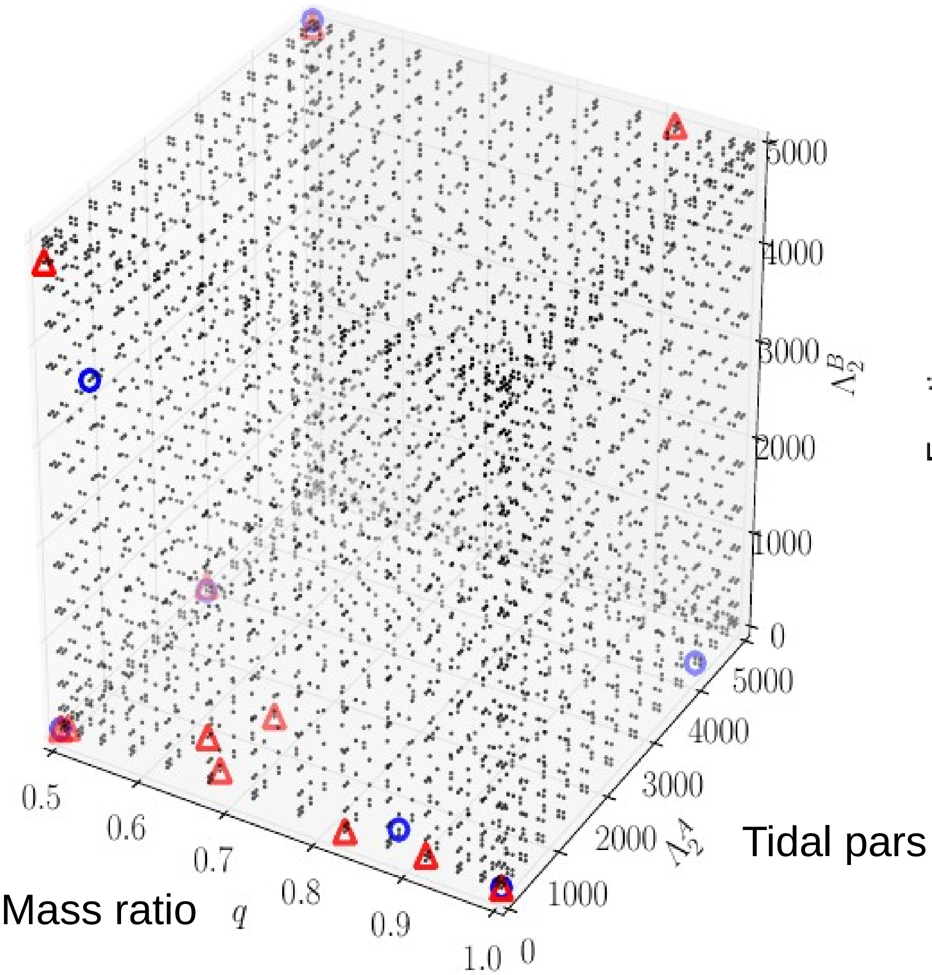
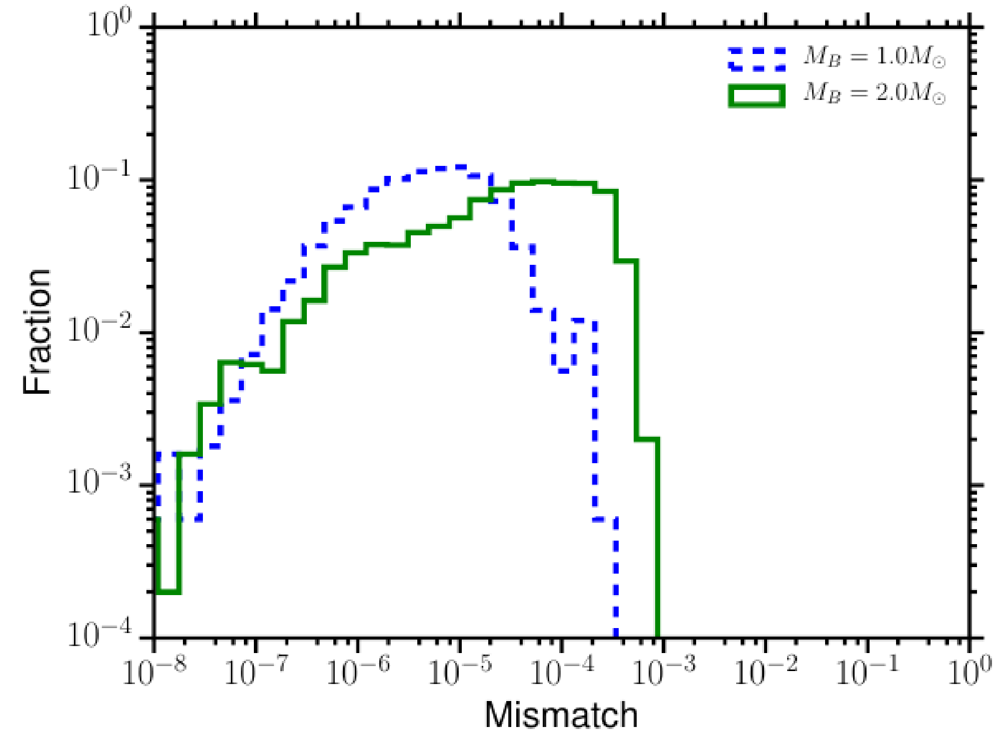


Fast templates for GW data-analysis of BNS

[Lackey, SB, Galley, Meidam, Van Den Broeck PRD (2017) – In Press]



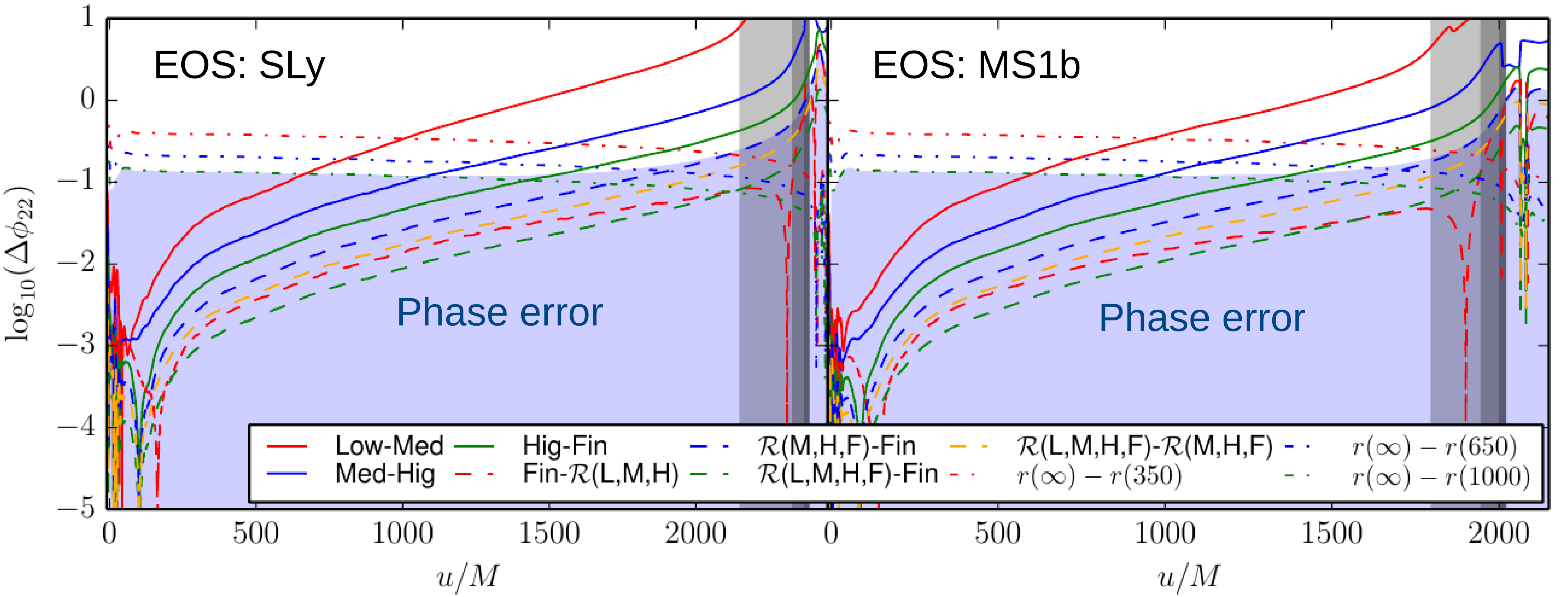


First model accurate to merger available in LIGO/Virgo library

- **SURROGATE** technique
- Training set in 3D par space: Chebyshev-Gauss-Lobatto 16^3 nodes.
- Basis #: 12 amplitude, 7 phase + Empirical interpolation
- Speed = ~0.07 s (30 Hz to mrg); ~ 0.8 s (10 Hz to mrg) → enable 10^7-10^ 8 evaluations (PE)

Improved NR GW with high-order WENO schemes

[SB,Dietrich PRD94 064062 (2016)]

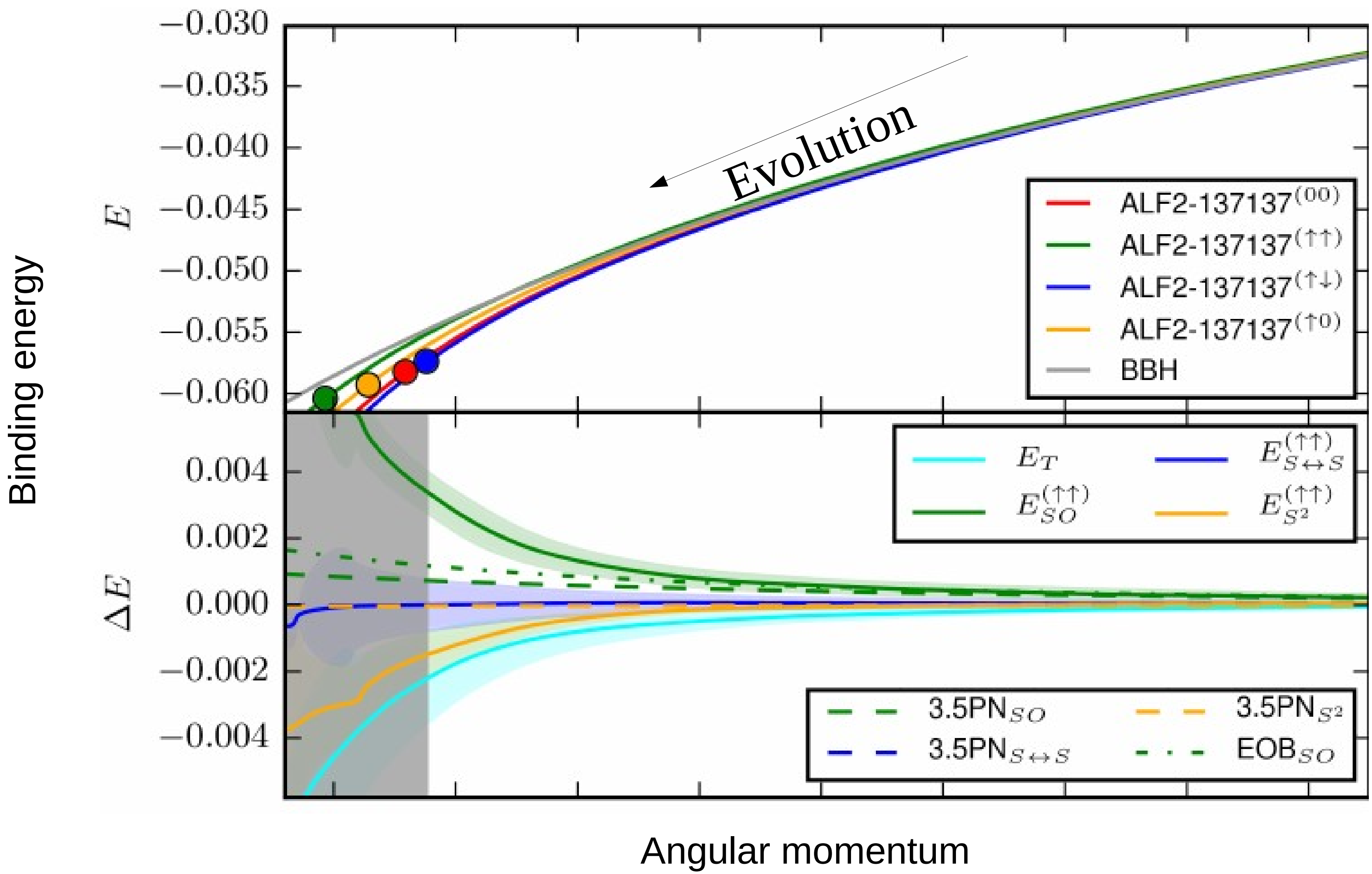


- Robust convergence assessment (although not 5th order)
- Large resolution span (64^3 -192^3), no alignment
- Error budget: significant improvement wrt FV schemes

See also [SB+ arXiv:1205.3403] [Radice+ arxiv:1306.6052]

Spins & tides during merger: energetics

[Dietrich, SB, Ujevic, Tichy PRD 95 (2017)]

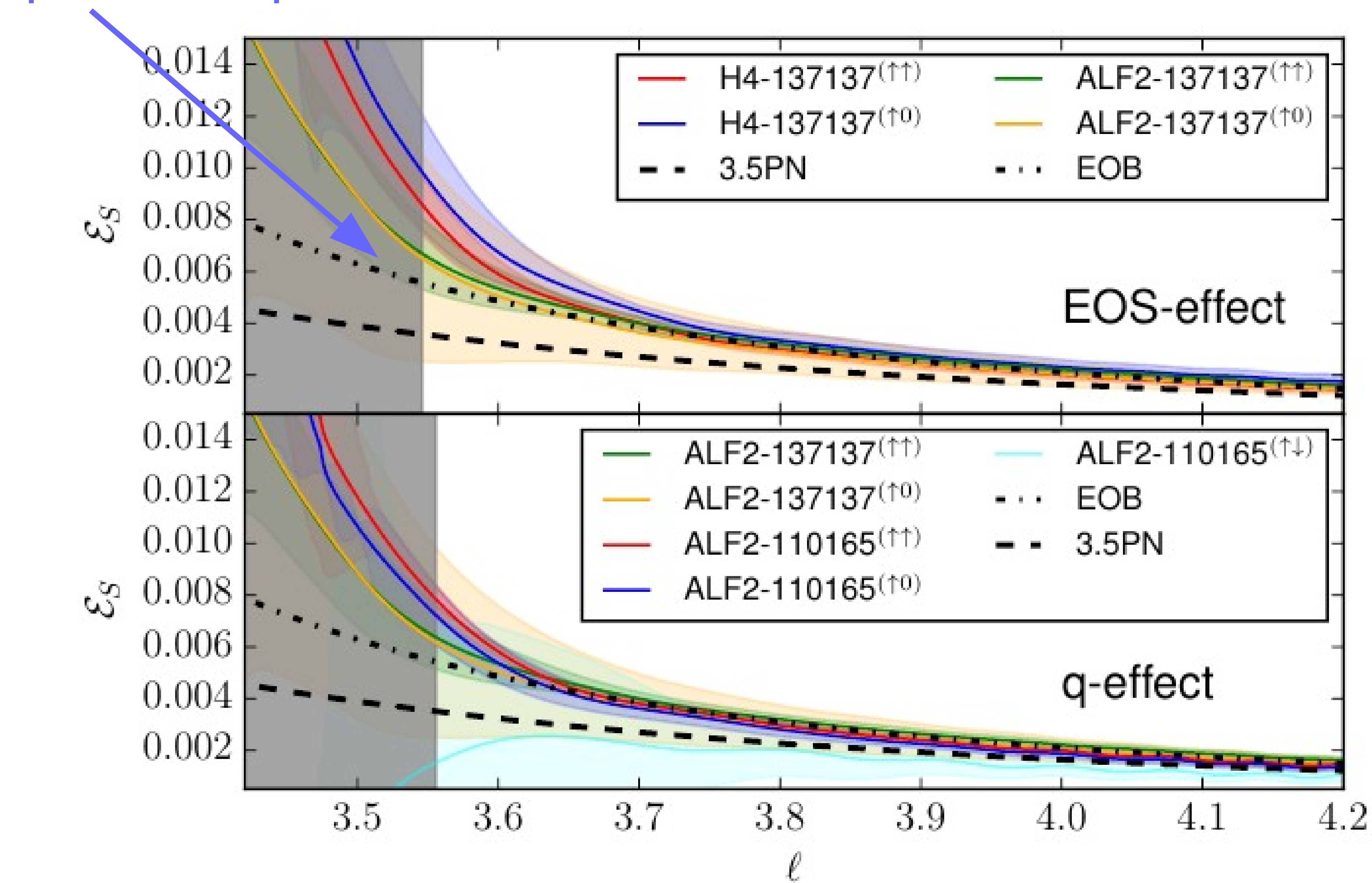


See also [SB, Dietrich, Tichy, Bruegmann arXiv:1311.4443]

Spins & tides during merger: energetics

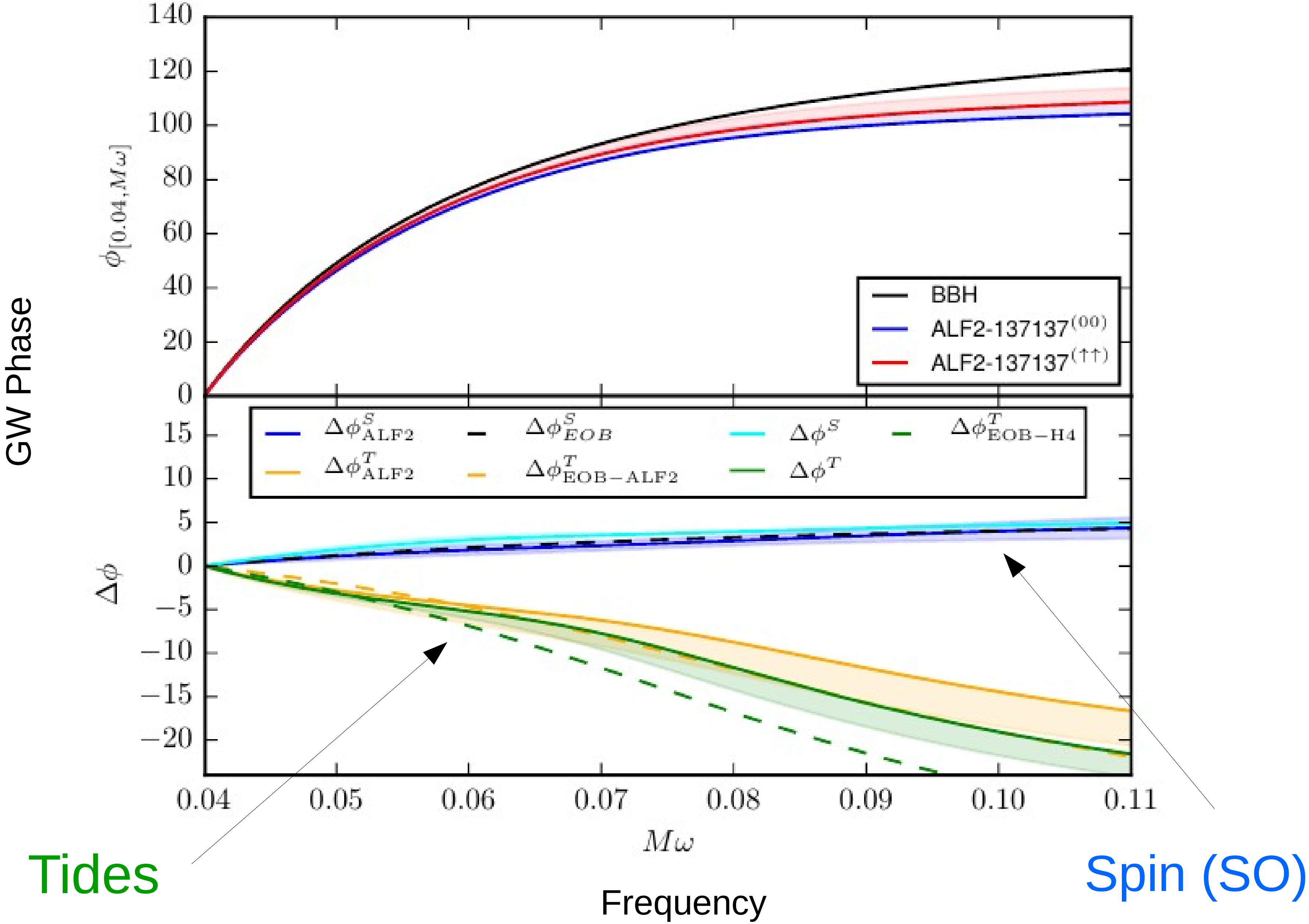
[Dietrich, SB, Ujevic, Tichy PRD 95 (2017)]

Spin-orbit and spin^2



Spins & tides during merger: phasing

[Dietrich, SB, Ujevic, Tichy PRD 95 (2017)]

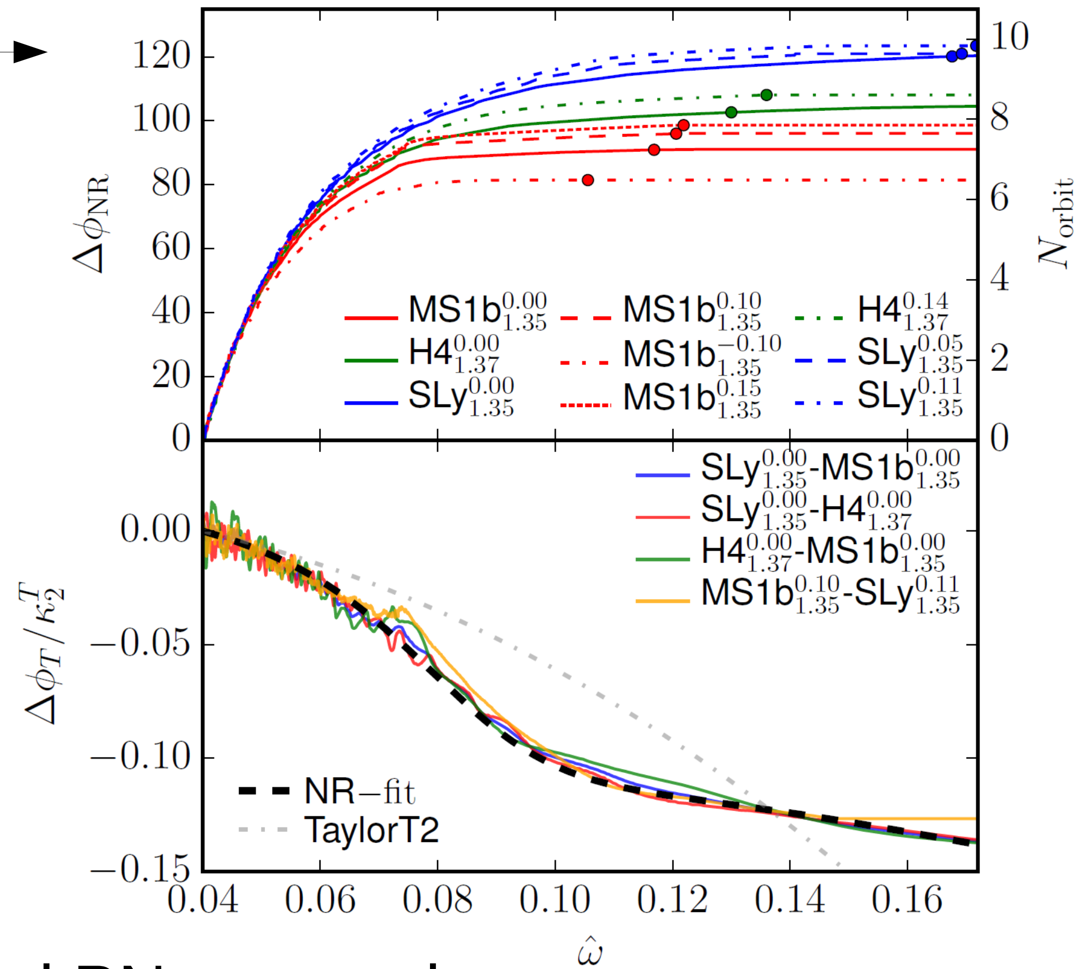


Closed-form tidal approximants from NR

[Dietrich, SB, Tichy arXiv:1706.02969] NEW

$$\phi(\hat{\omega}) \approx \phi_0(\hat{\omega}) + \phi_{SO}(\hat{\omega}) + \phi_T(\hat{\omega})$$

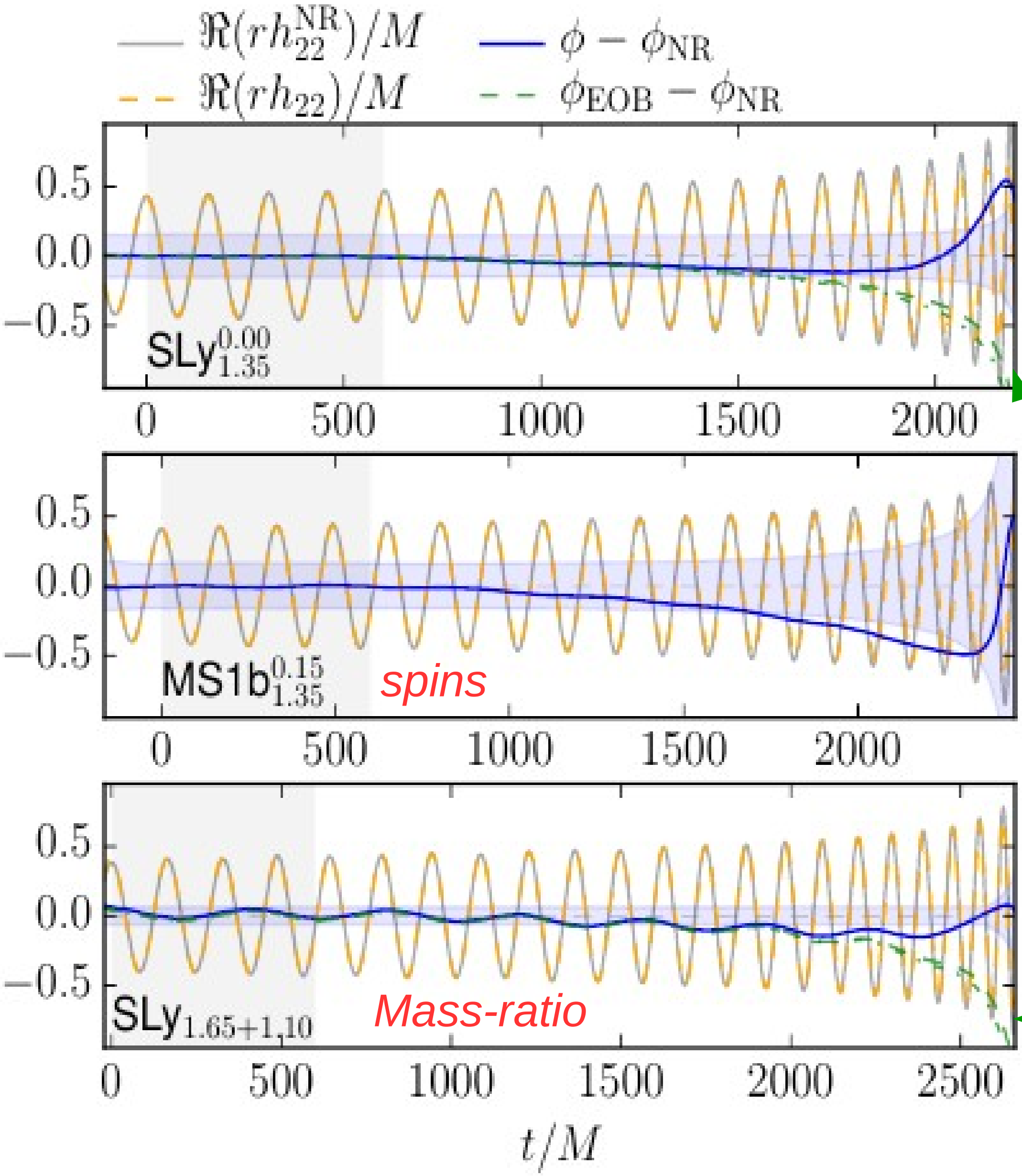
$$\phi_T = -\kappa_2^T \frac{c_{\rm Newt}}{X_A X_B} x^{5/2} \times \frac{1 + n_1 x + n_{3/2} x^{3/2} + n_2 x^2 + n_{5/2} x^{5/2} + n_3 x^3}{1 + d_1 x + d_{3/2} x^{3/2}}$$



1. Extract tidal phase
2. Fix coefs in effective resummed PN-expression
3. Use SPA and freq-domain expression
4. CAN BE USED WITH ANY BBH BASELINE!

Time-domain approximant

[Dietrich, SB, Tichy arXiv:1706.02969]



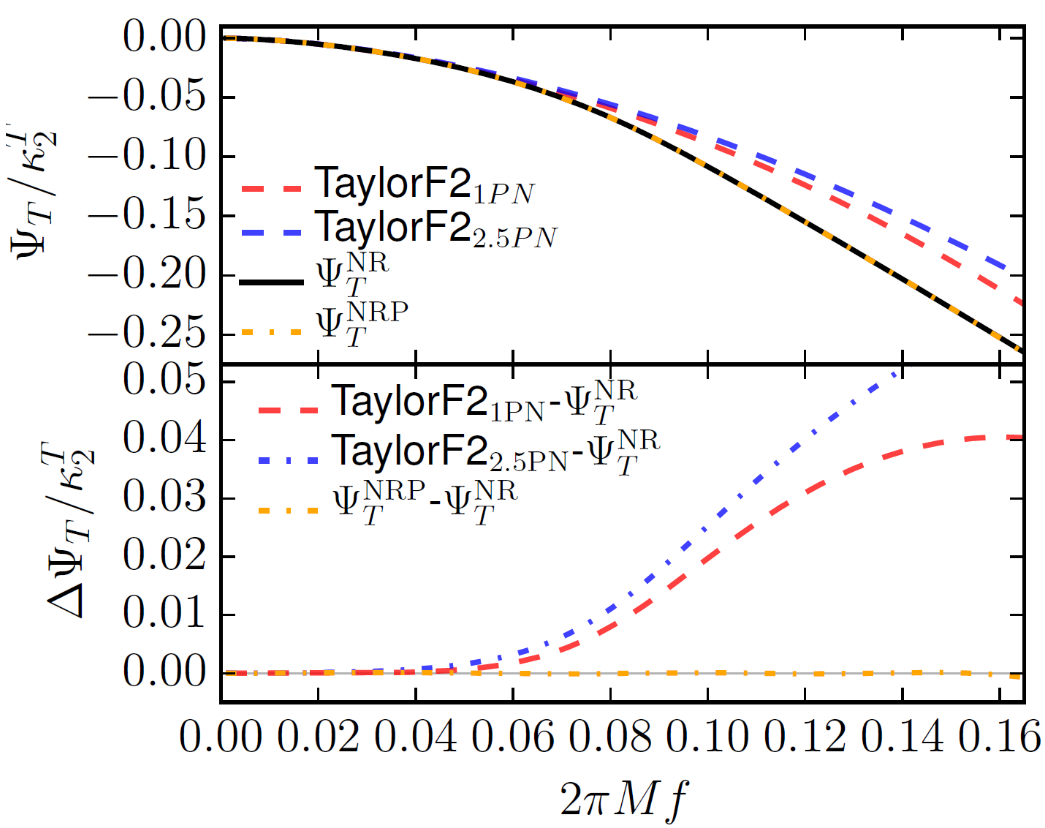
- Compatible with NR (10 orbits)
- Compatibile with NR-hybrids (300 orbits)
- Use with any BBH baseline

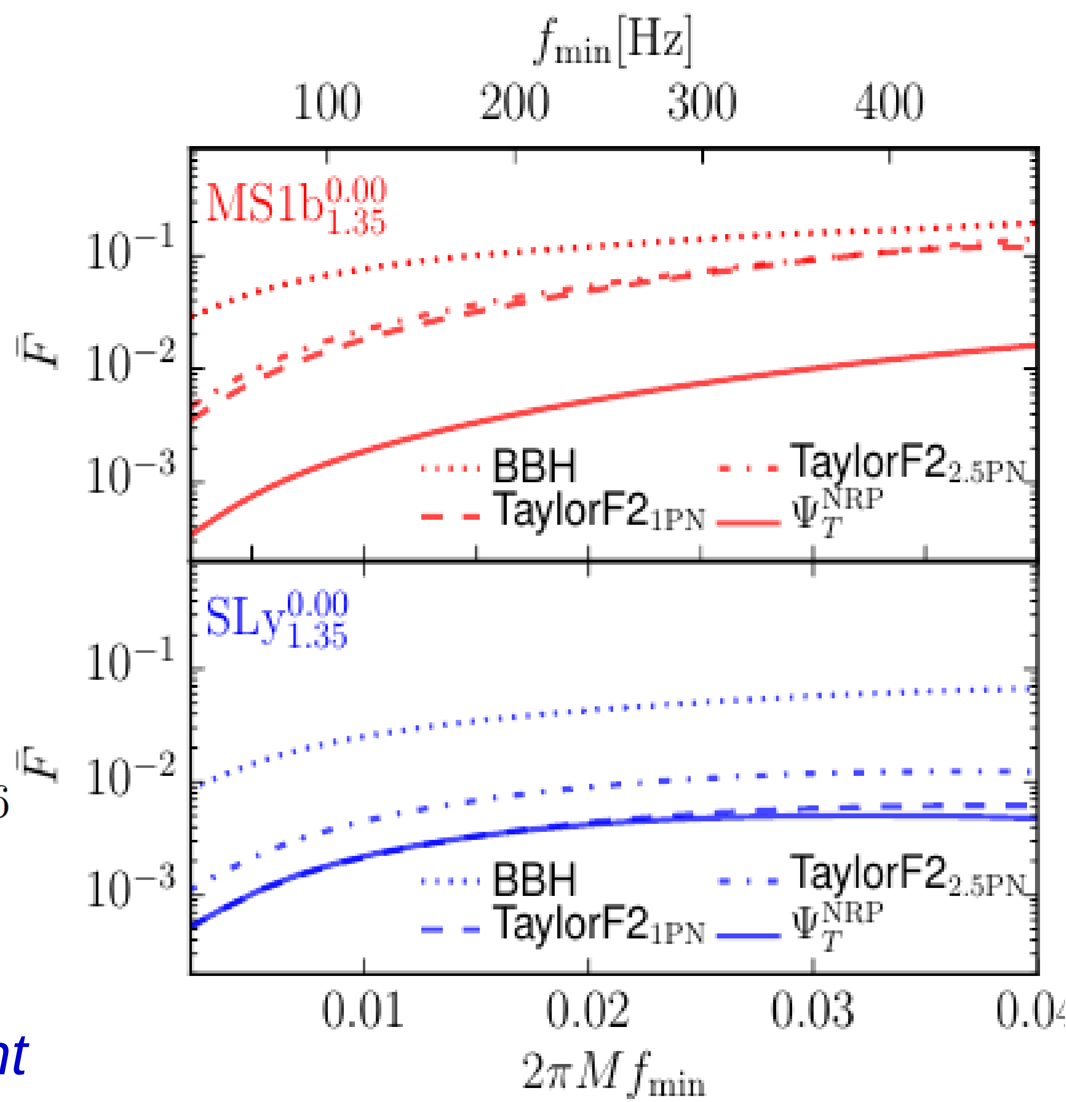
New error-controlled (4-5 resolutions) Eccentricity-reduced (e~1e-3) NR simulations

Same performances as Tidal EOB

Frequency-domain approximant

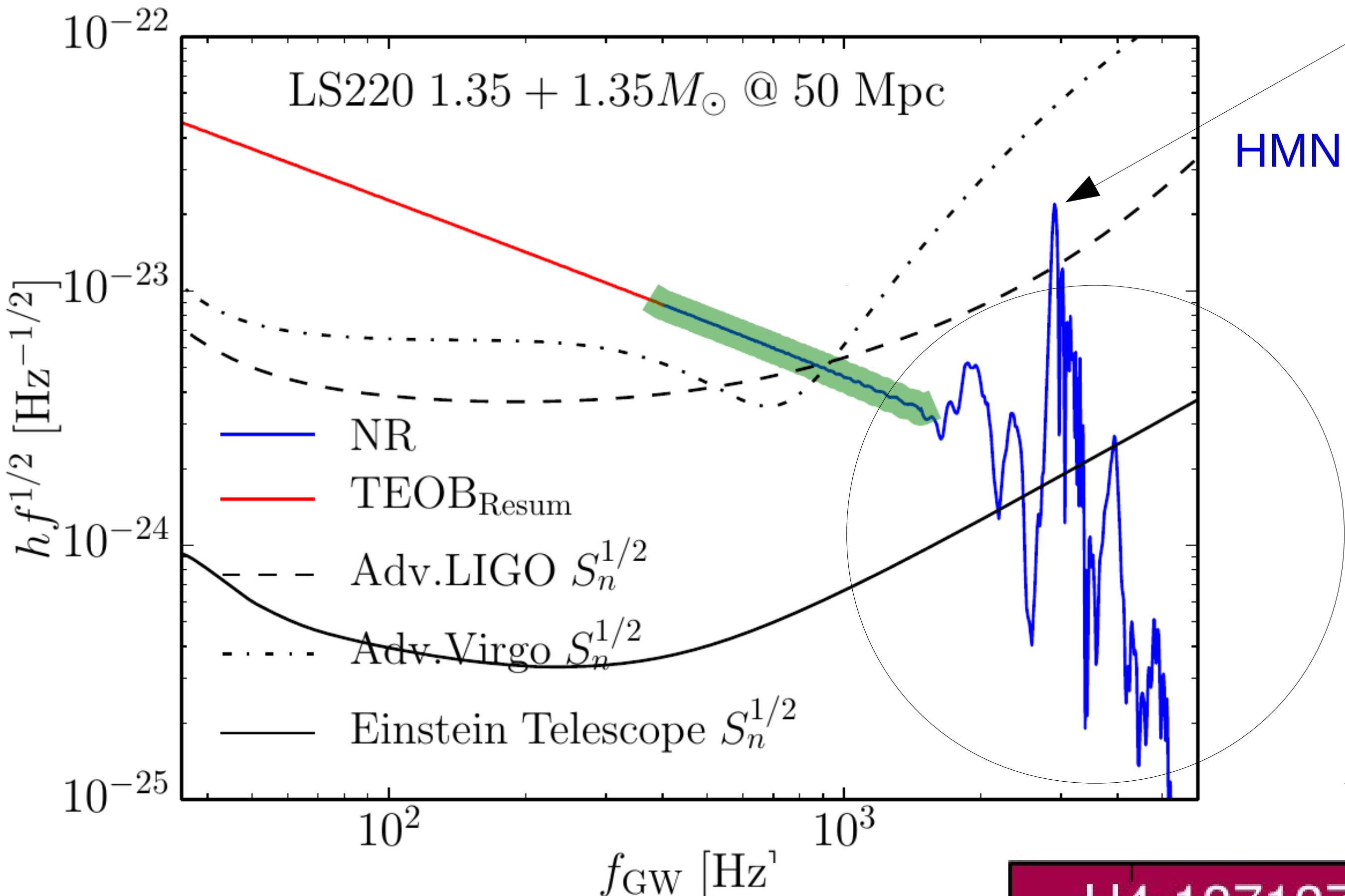
[Dietrich, SB, Tichy arXiv:1706.02969]





First NR-based tidal approximant
Fast, flexible, accurate

Postmerger spectrum



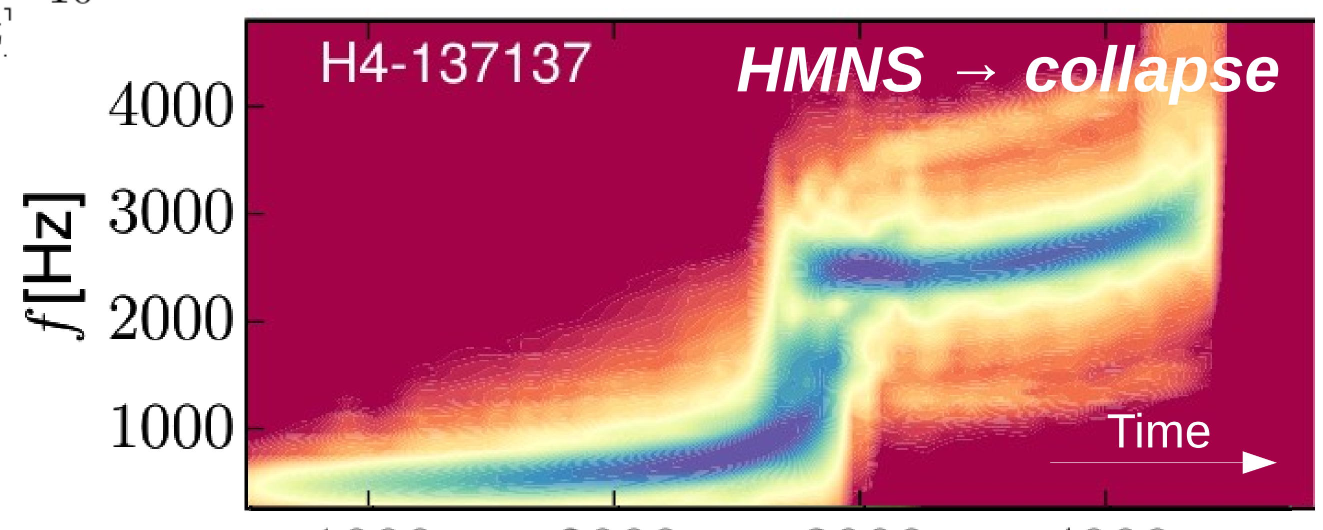
Rich frequency content

Main peak f_2 (m=2)

HMNS rot. freq at ~ peak luminosity

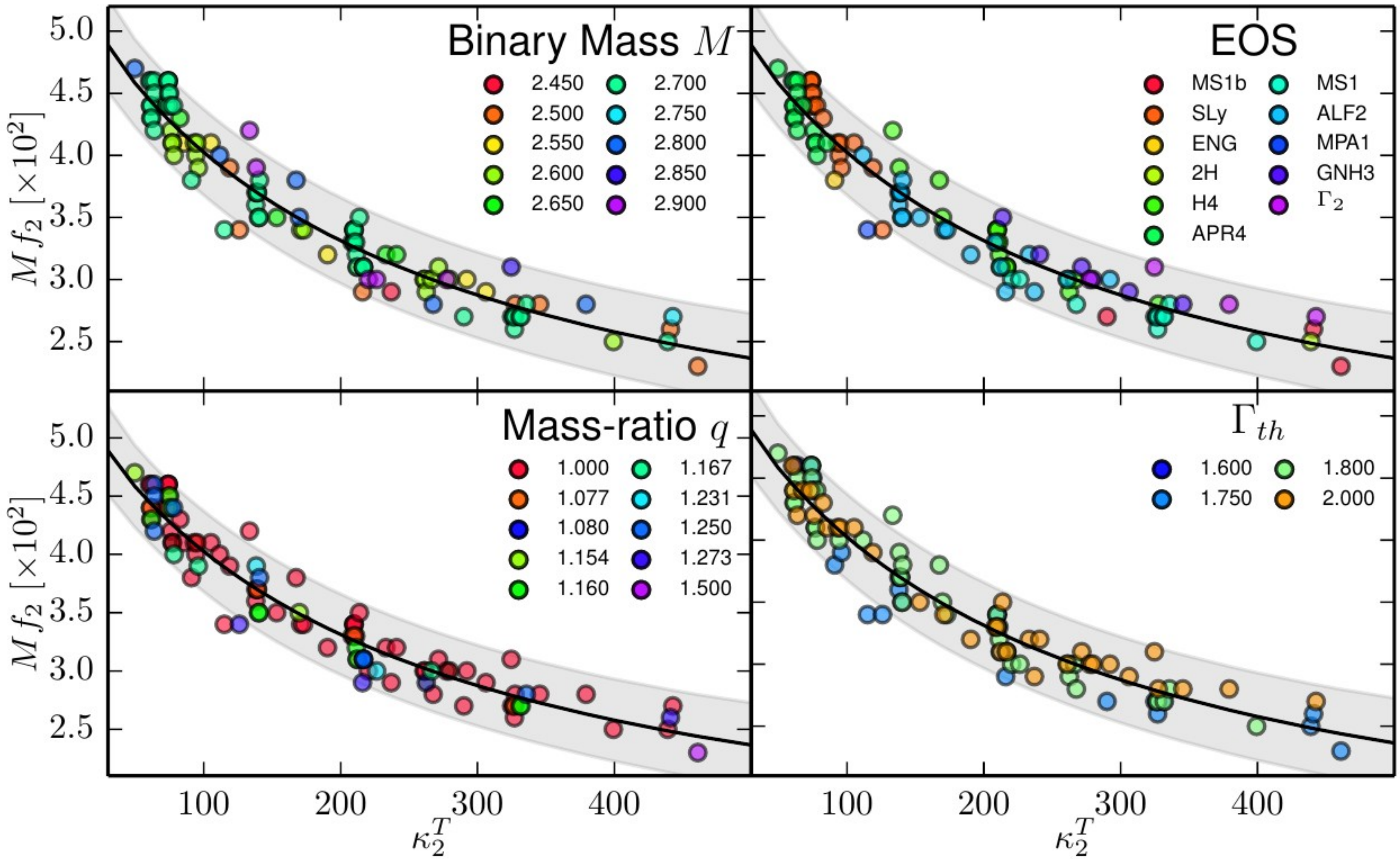
- Various models associate f_2 to isolated equil. star properties
- Possibility to extract “EOS-related info” (R_x,M_{max},...)
- Conceptually indepedent on inspiral-merger models

[Bauswein+ arXiv:1106.1616,
Hotokezaka+ arXiv:1307.5888,
Takami+ arXiv:1403.5672,
Clark+ arXiv:1509.08522, ...]



Peak frequency correlates to tidal parameter

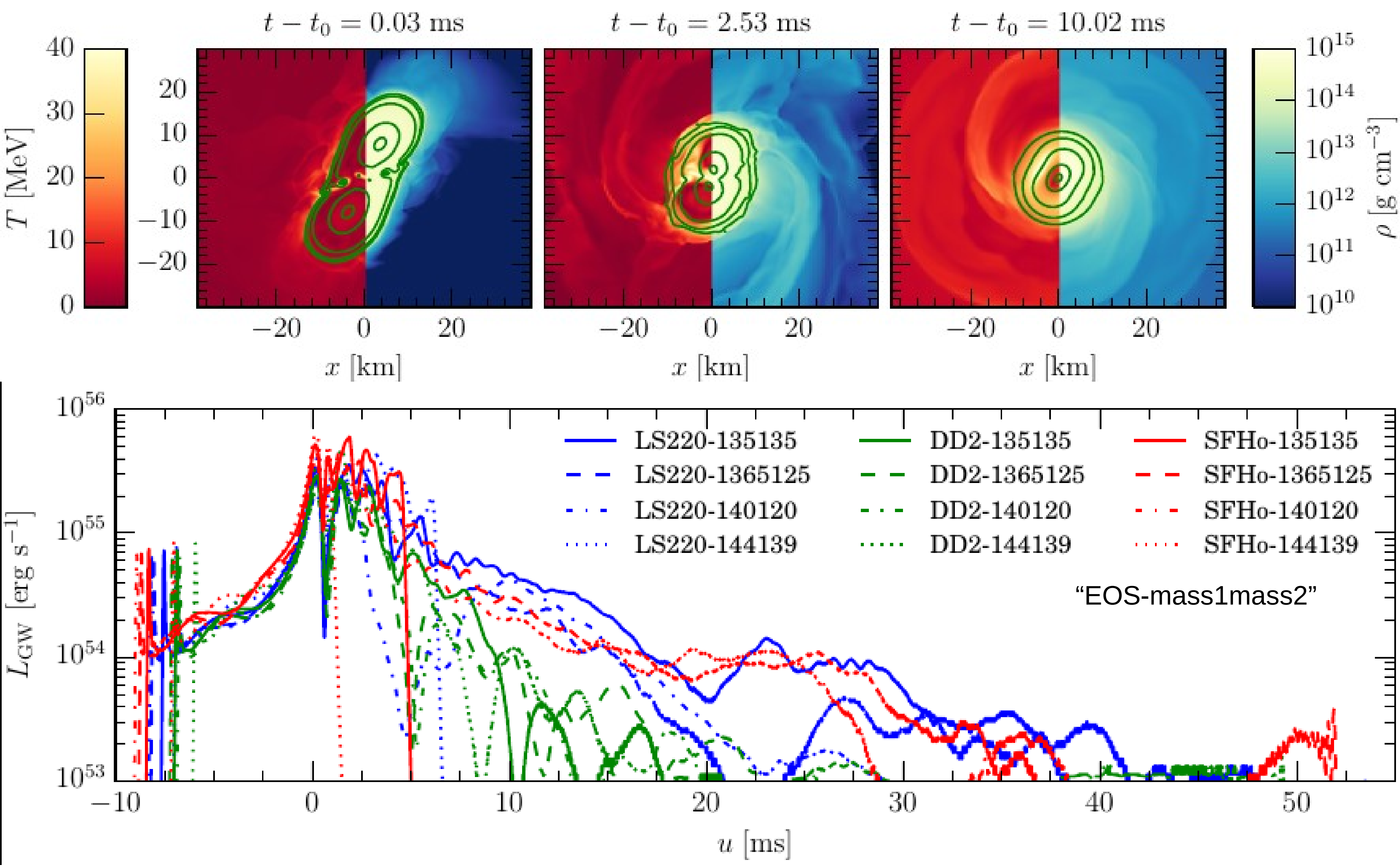
[SB, Dietrich, Nagar PRL 115 (2015)]



- Large NR dataset (~100, 3 codes) [+ Hotokezaka+ arXiv:1307.5888, Takami+ arXiv:1403.5672]
- Postmerger frequencies essentially determined by *merger* physics
- Conceptually “compatible” with inspiral-merger → Unified model !

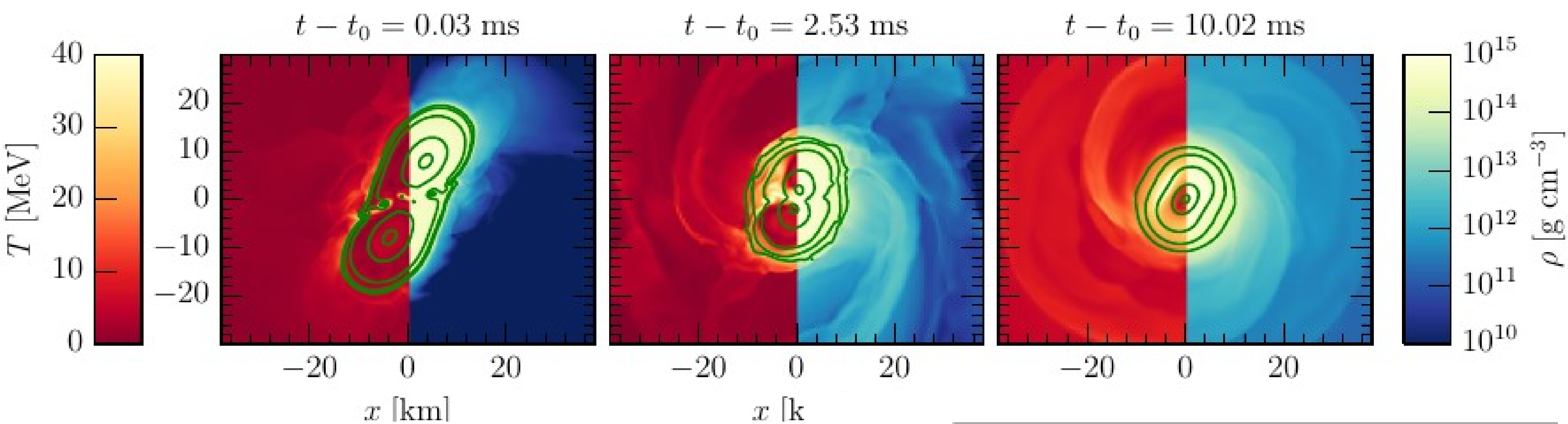
Remnant HMNS is the loudest GW phase

[SB, Radice, Ott, Roberts, Moesta, Galeazzi PRD94 024023 (2016)]



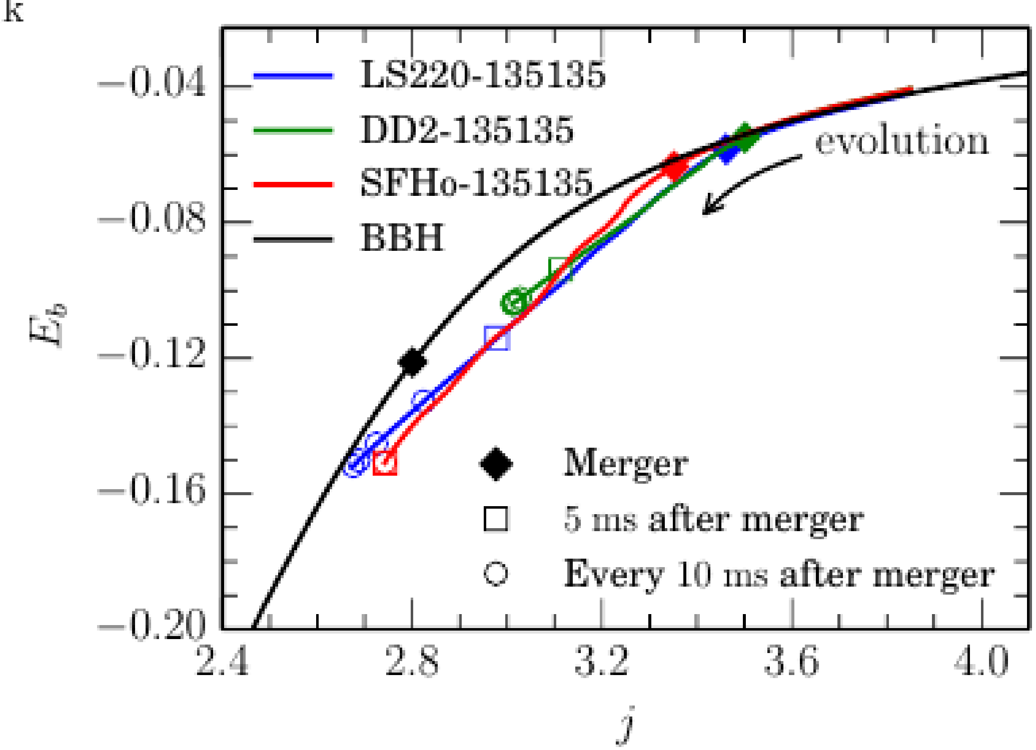
Remnant HMNS is the loudest GW phase

[SB, Radice, Ott, Roberts, Moesta, Galeazzi PRD94 024023 (2016)]



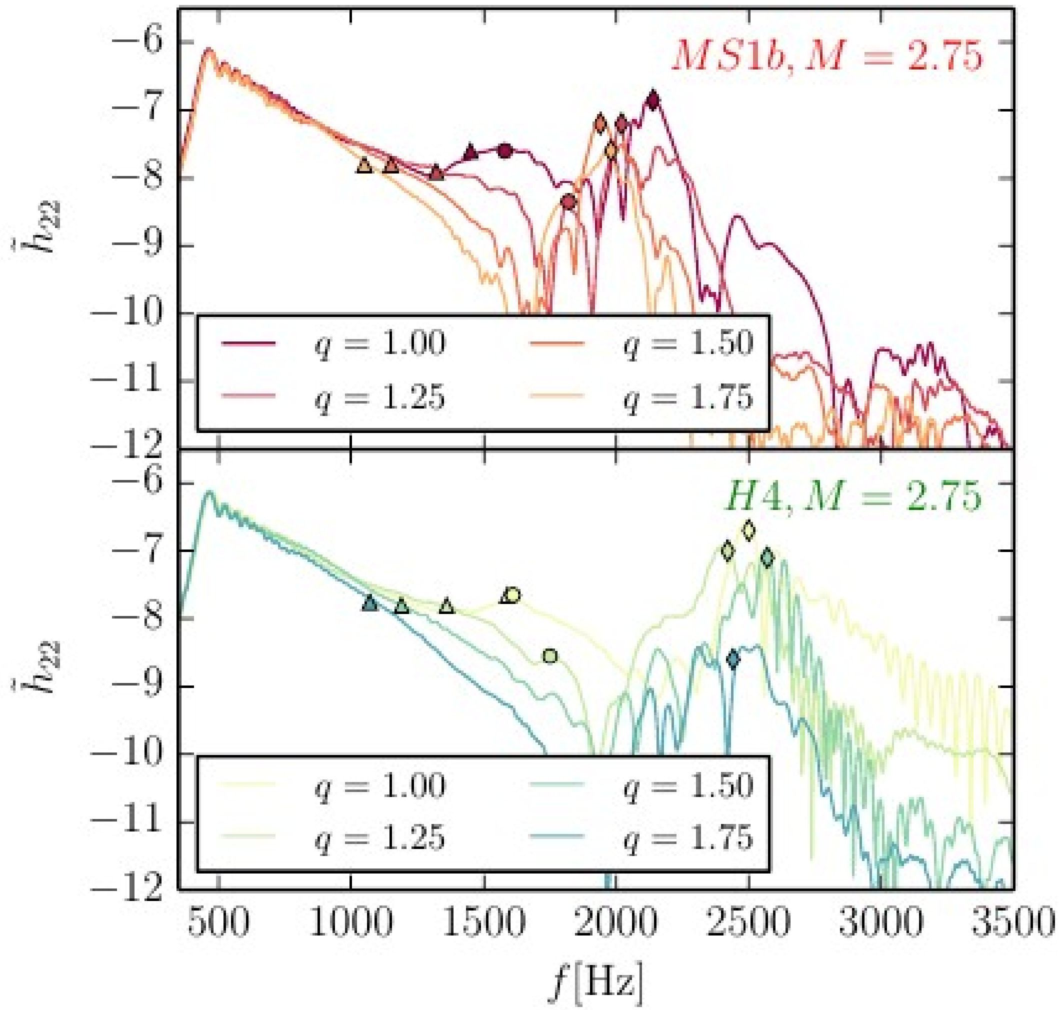
- Emission is FAST: $\tau_{GW} \sim 20$ ms
- Emission is LOUD: E(HMNS) ~ 2x E(merger)
- Note: explain the $f_2(\kappa_2)$ correlation

Simulations w/ microphysics & neutrinos
largest-to-date campaign

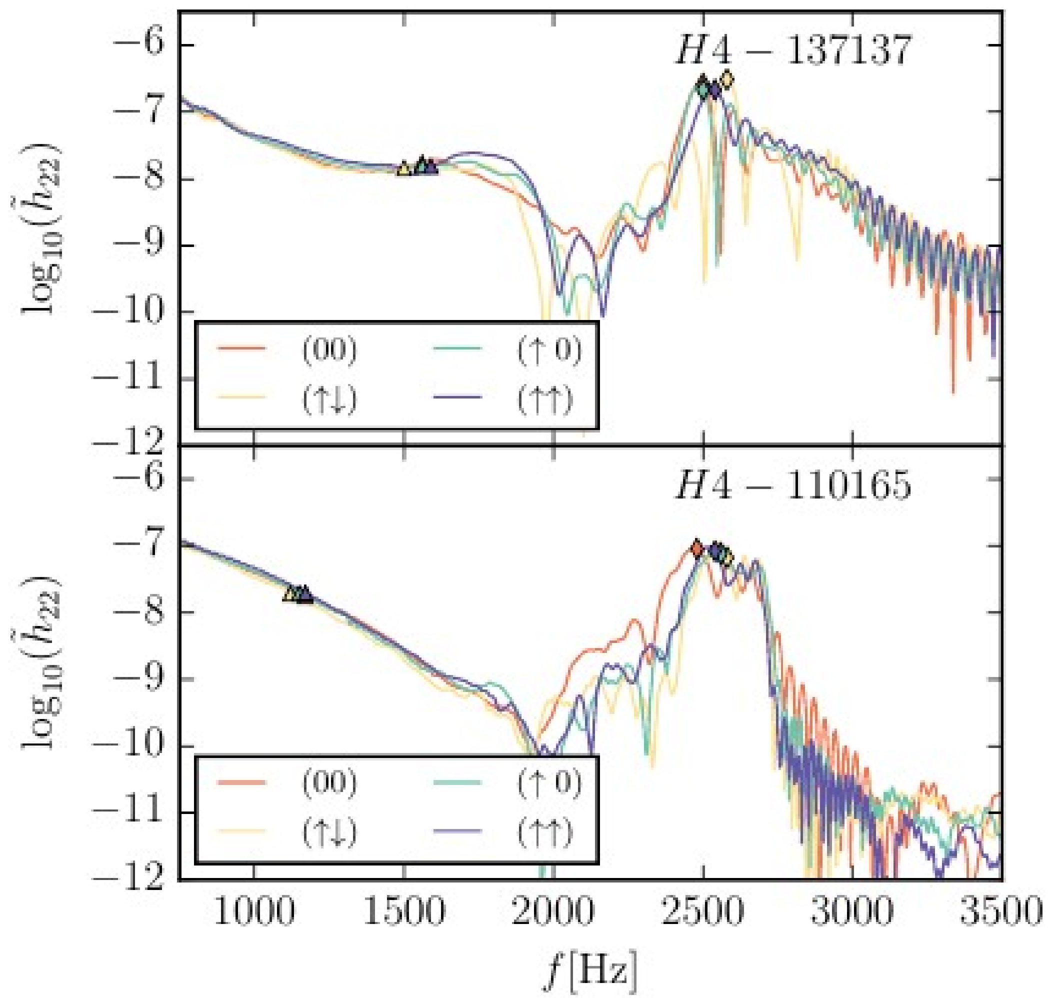


Postmerger spectrum

Mass-ratio effects



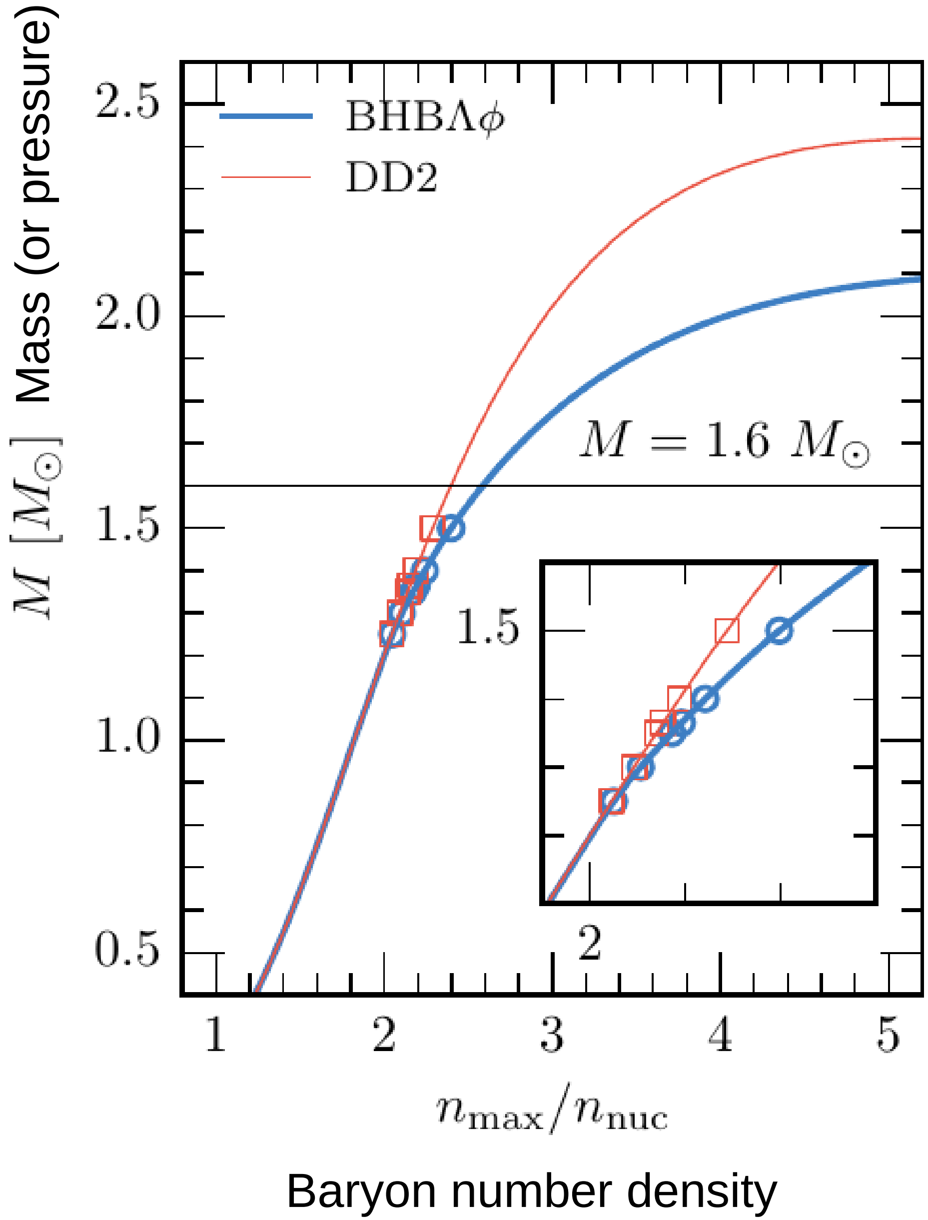
Spin effects



[Dietrich, Ujevic, SB, Tichy, Bruegmann arXiv:1607.06636]
[Dietrich, SB, Ujevic, Tichy arXiv:1611.07367]

Merger remnant reaches extreme densities

Can GW observations inform us about EOS changes at those densities?



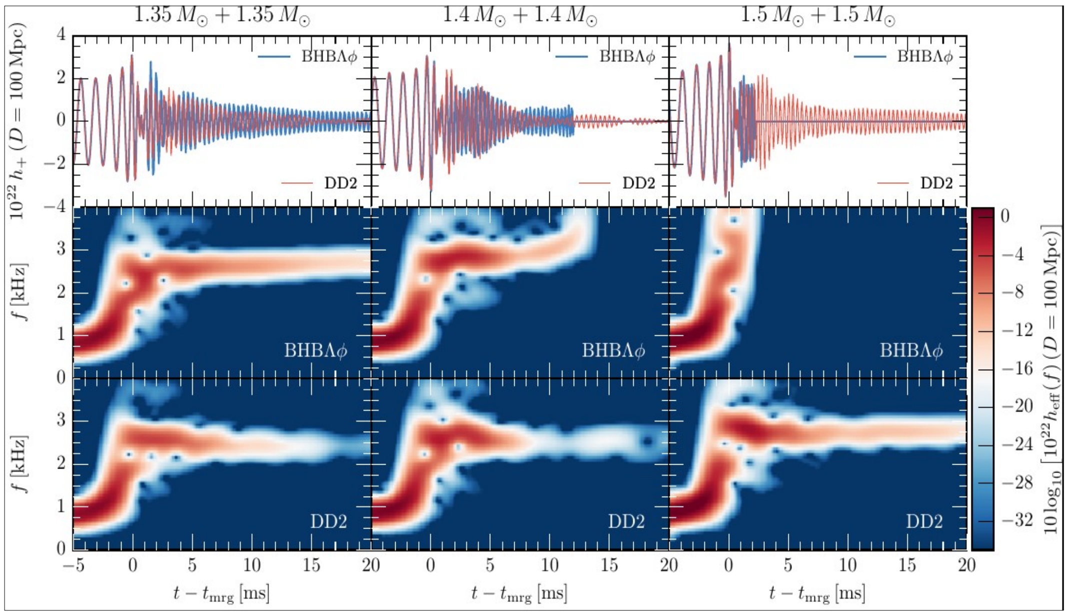
- Baryon number density **n ~ 3-5 n_{nuc}**
- Extra DOF/phase transitions?
- Specific model: Λ-hyperons

  [Banik+ arxiv:1404.6173]

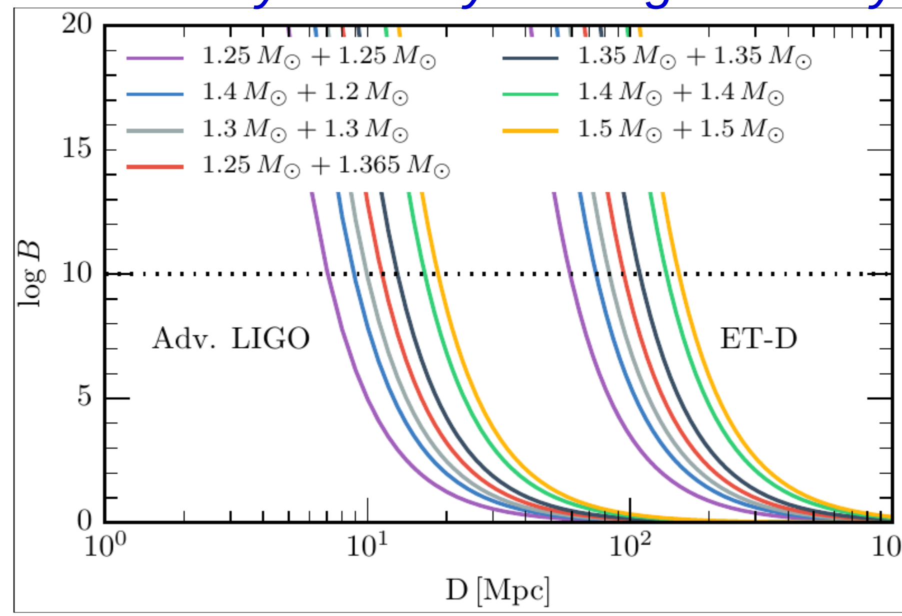
  Microphysical EOS compatibile with astro and nuclear phys constraints
- In general: “softness” effects

GWs could probe such “softness effects”

[Radice, SB, Del Pozzo, Ott, Roberts (2017) arXiv:1612.06429]



Data-analysis study: distinguishablity



log(Bayes factor) vs. Source distance

- Postmerger GW morfology contains unique info
- Detailed and generic models are necessary for DA studies
- High-freq. GW challenging to detect (→ Einstein telescope)

*** Summary ***

- The (leading order) tidal polarizability coupling constant parametrizes strong-field dynamics and EOS effects [SB+ arXiv:1402.6244]
- TEOBResum first tidal EOB model “up to merger” [SB+ arXiv:1412.4553]
- High-order methods help Improving NR simulations [SB+ arXiv:1205.3403, Radice+ arxiv:1306.6052, SB&Dietrich 1604.07999]
- Fast and efficient representation of waveforms [Lackey+ arXiv:1610.04742]
- Parameter space: masses, mass ratio, EOS, spins, microphysics [SB+ arXiv:1311.4443, Dietrich+ arXiv:1611.07367, Dietrich+ arXiv:1607.06636, SB+ arXiv:1512.06397, Radice+ arXiv:1612.06429]
- Energetics and waveforms with spins, first precessing simulation [SB+ arXiv:1311.4443, Dietrich+ arXiv:1507.07100, Dietrich+ arXiv:1611.07367]
- Postmerger peak frequency correlates with tidal coupling constant [SB+ arXiv:1504.01764]
- Postmerger emission is “fast and loud” [SB+ arXiv:1512.06397]