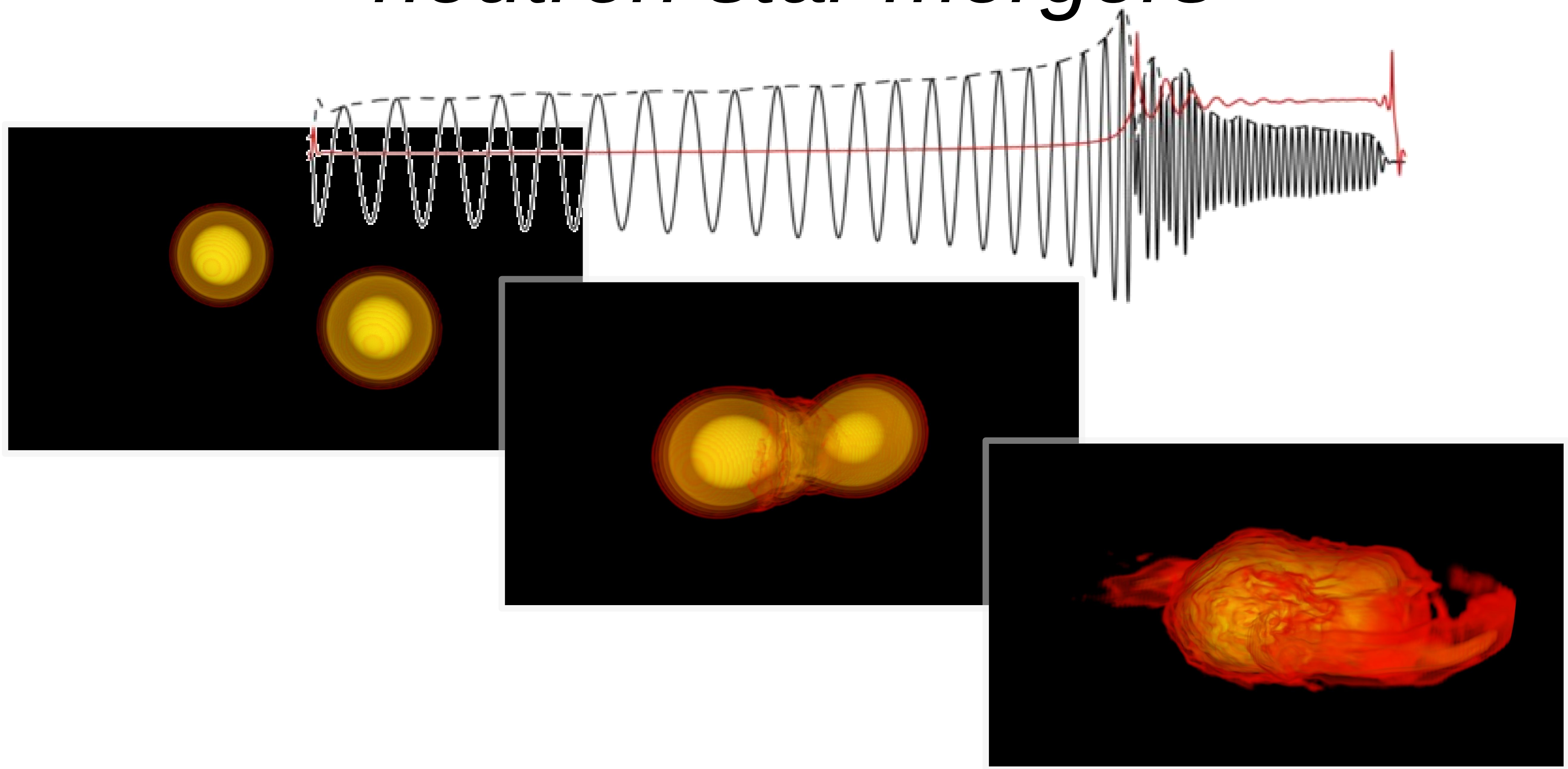
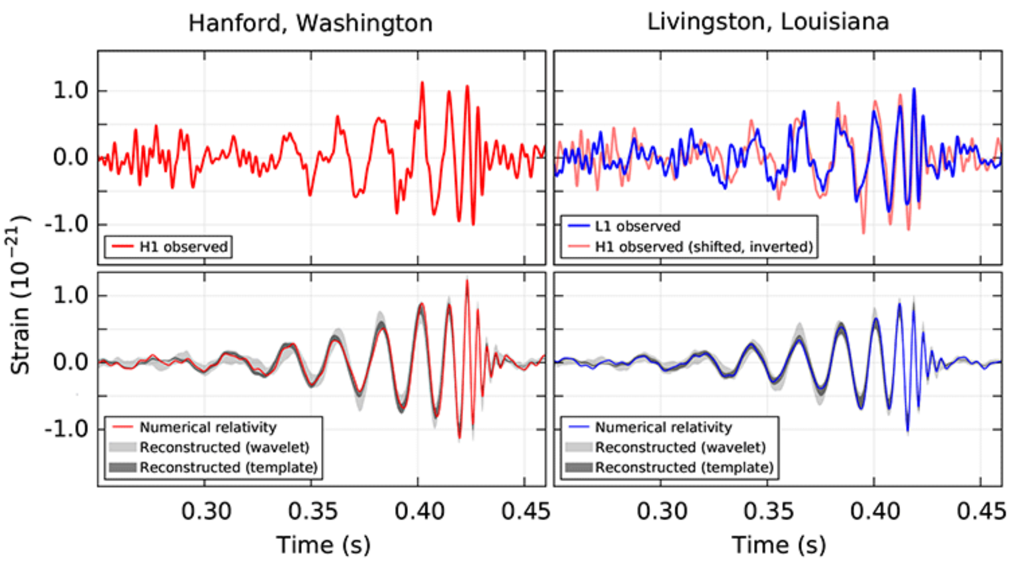
S.Bernuzzi Pisa, June 28th, 2017
UNIVERSITÀ DI PARMA
INFN

Constraints on extreme density matter from GW observation of neutron star mergers



GW150914 : GW astronomy has started

September, 14th 2015, 09:50:45 UT



Key source:

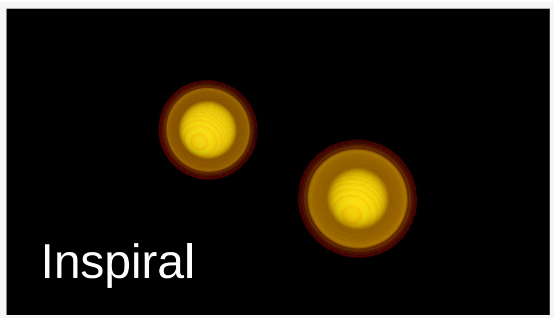
neutron stars binaries

- First ("indirect") evidence, Hulse&Taylor pulsar
- Expected 1-100 events/year in LIGO/Virgo band by 2019
- GW measurements <u>require</u> precise waveform models

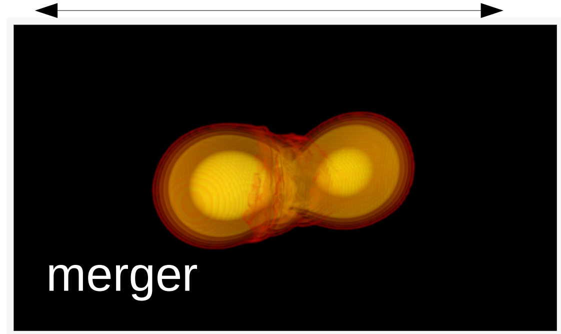
GWs: Tiny signatures of extreme events

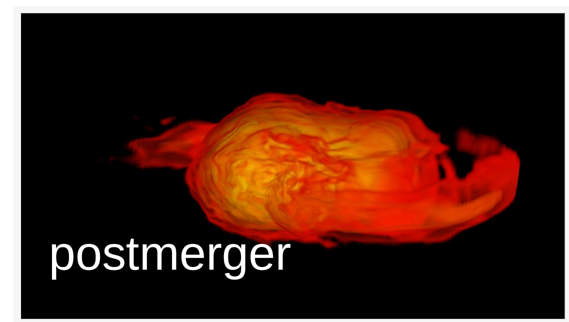
Collision of neutron stars [Mass~1.4 Msun, Radius~10 km]:

d ~ 150 km



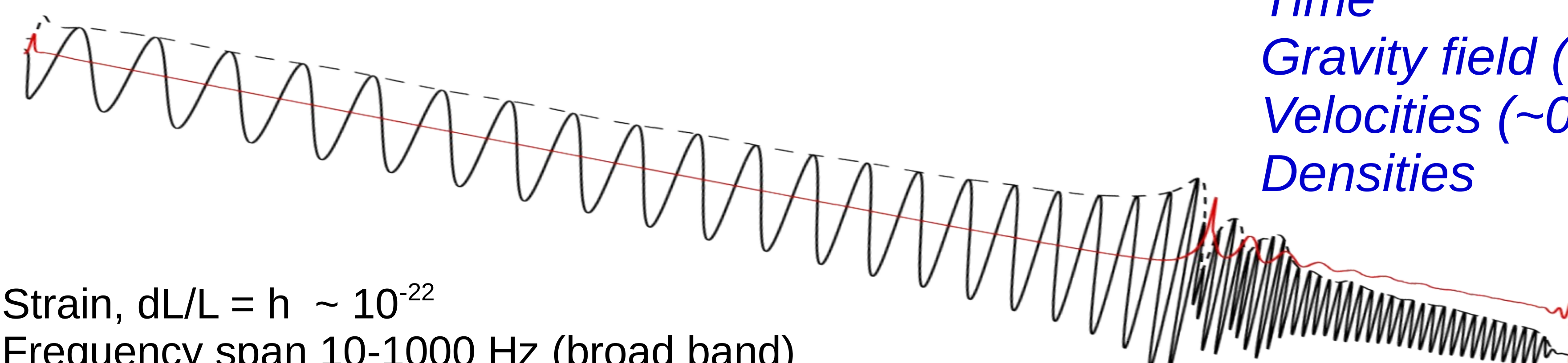
d ~ 50 km





D~200 Mpc (“far away”) from the source:

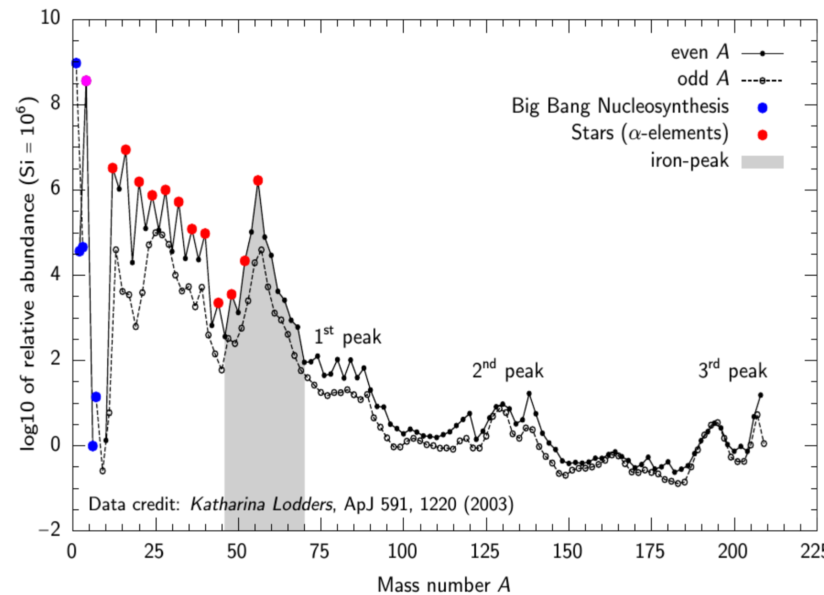
Time
Gravity field (~M/d)
Velocities (~0.1 c)
Densities

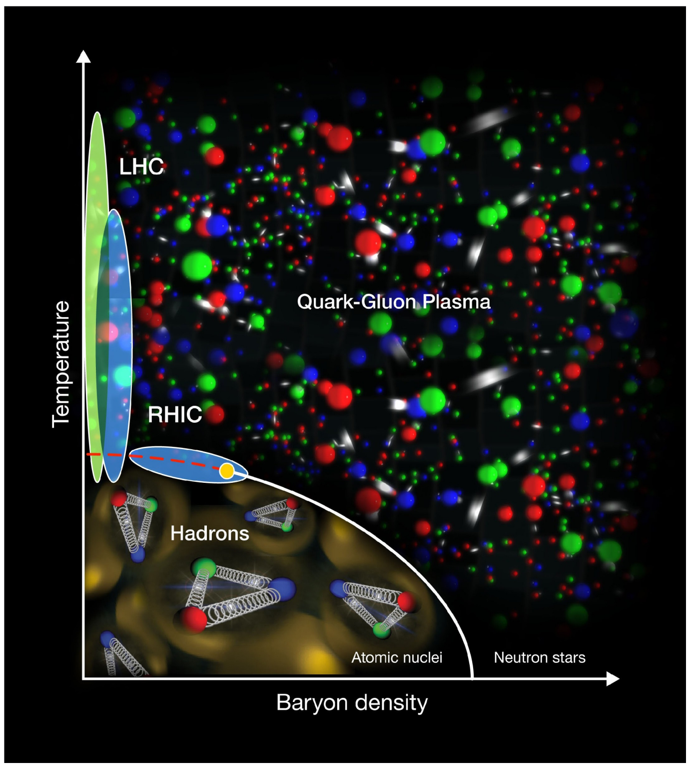


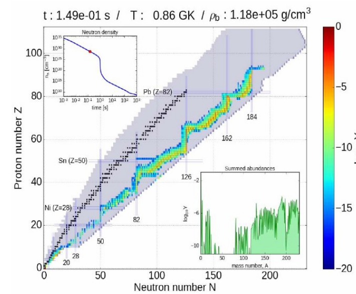
Strain, dL/L = h $\sim 10^{-22}$
Frequency span 10-1000 Hz (broad band)

What can we learn from neutron star mergers?

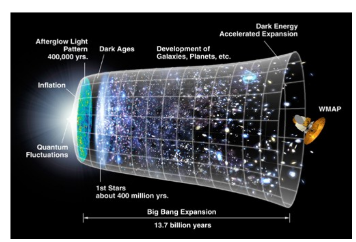
FUNDAMENTAL PHYSICS
Strong-field tests GR (dynamics)
Structure of bulk matter at supranuclear densities
Heavy elements nucleosynthesis

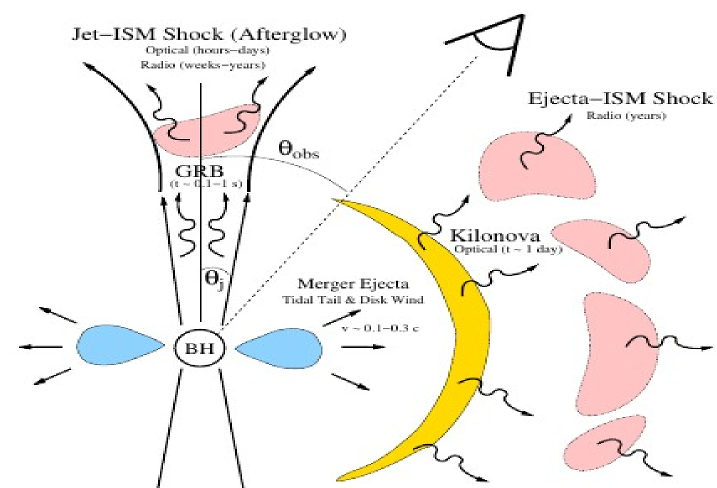






ASTROPHYSICS (Multi-messenger)
Origin of gamma-ray burst
Origin of kilonovae, site for r-processes

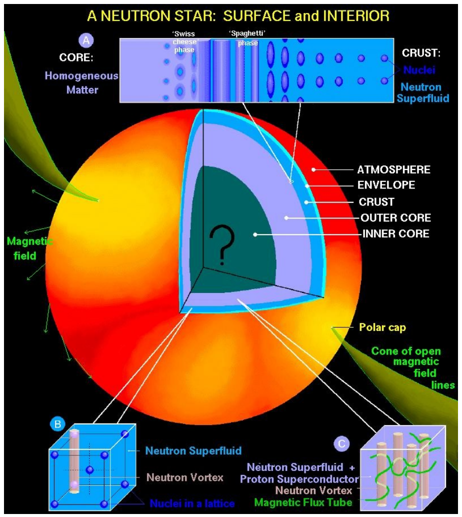




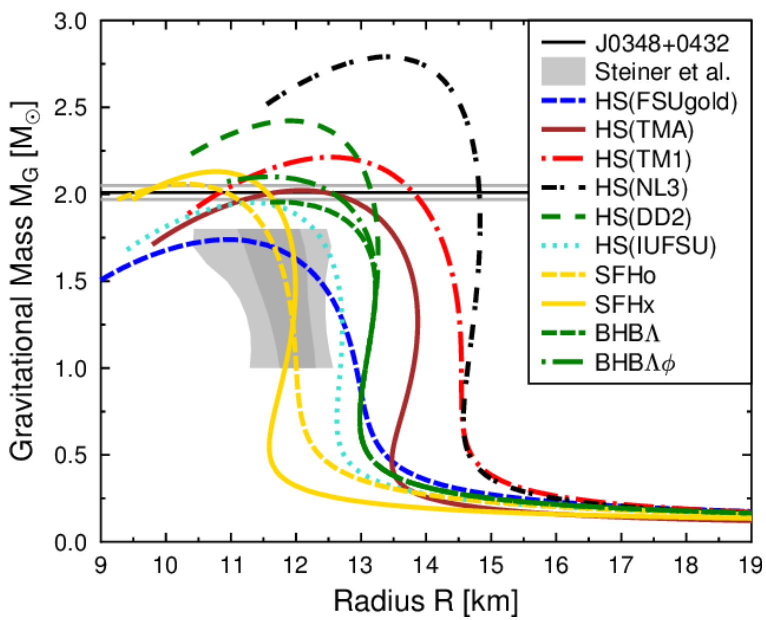
COSMOGRAPHY
Measure Hubble constant
Standard sirens, Calibrate cosmic distance ladder

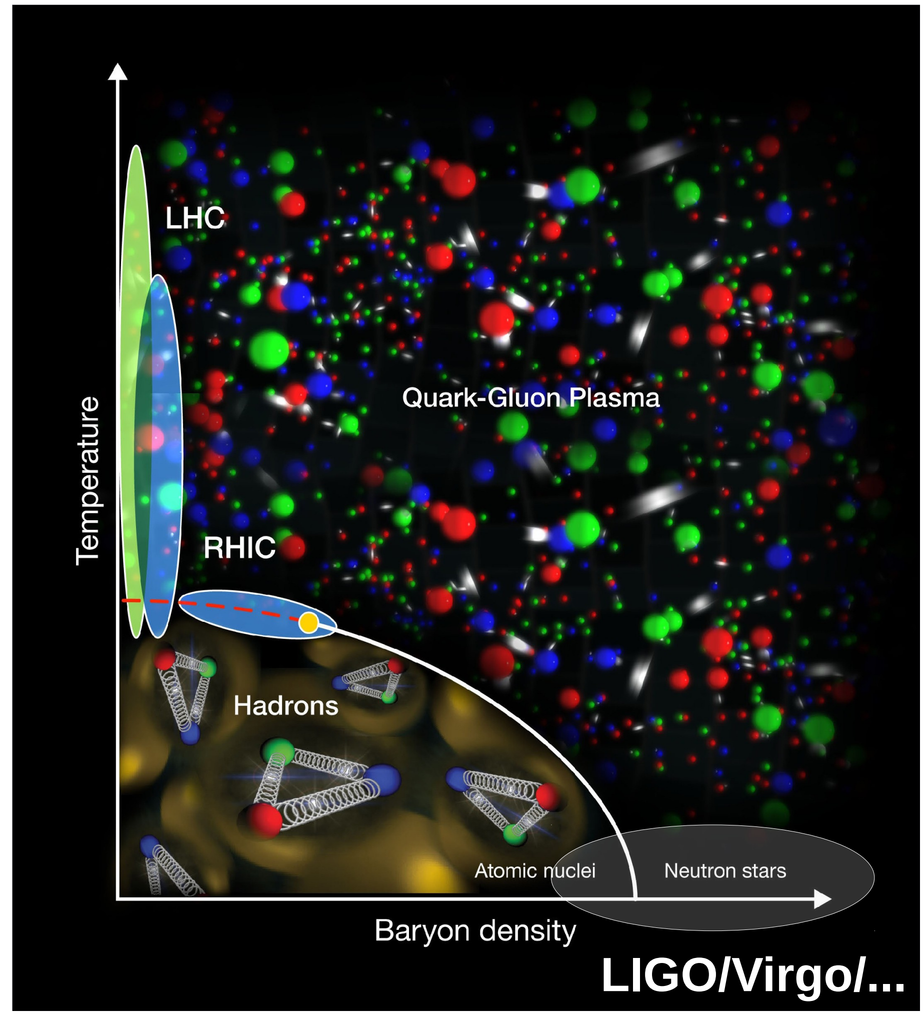
Fundamental physics

Constraining the Equation of State of matter at supranuclear densities



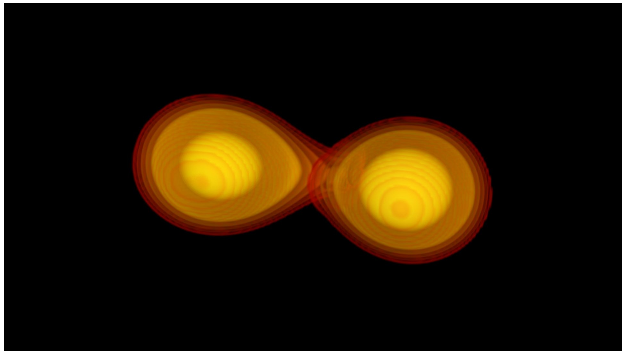
Different EOS → different star's structure

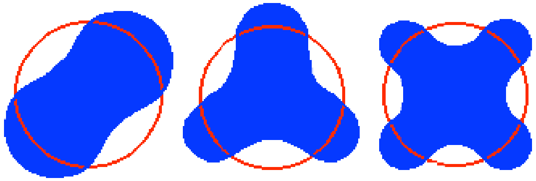




Binary neutron star mergers

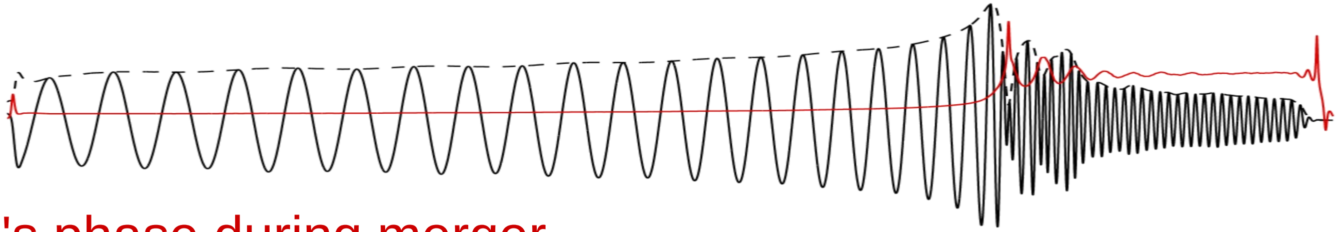
Example: observing tidal effects in GWs tells us about the neutron star matter





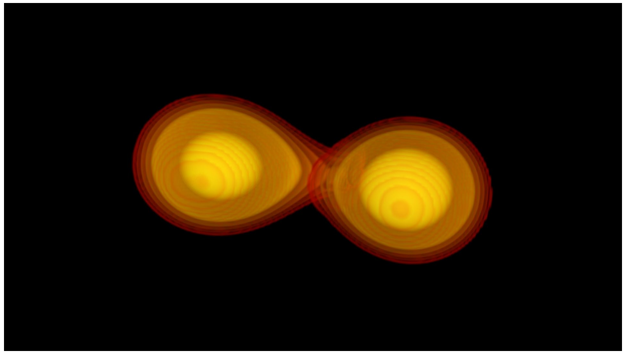
Tides depend critically on EOS

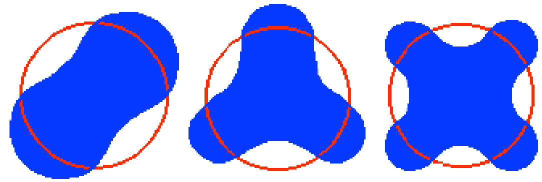
$$\lambda_2 \propto \frac{Q_{ij}}{\partial_{ij}\Phi_{ext}}$$



Tides determine the wave's phase during merger

Example: observing tidal effects in GWs tells us about the neutron star matter





Tides depend crucially on EOS

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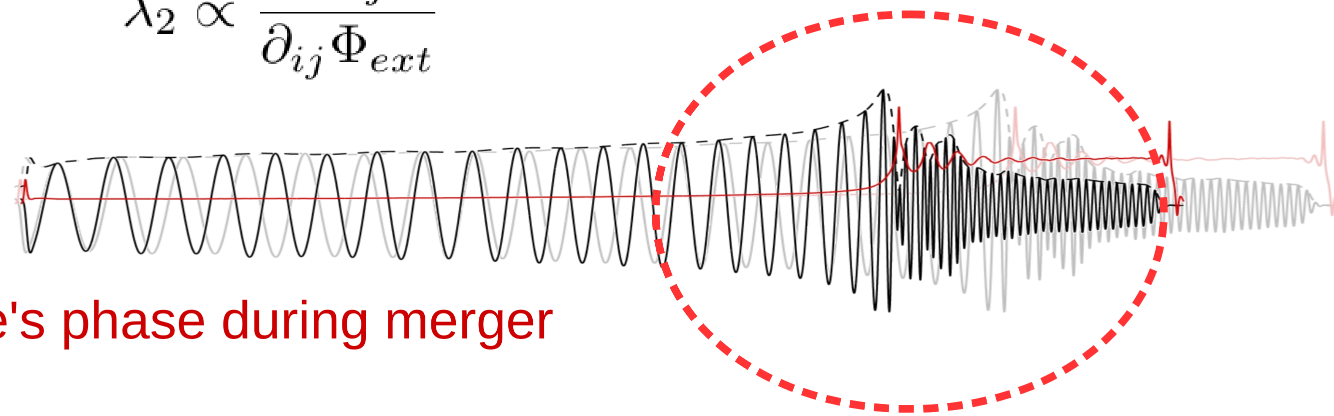
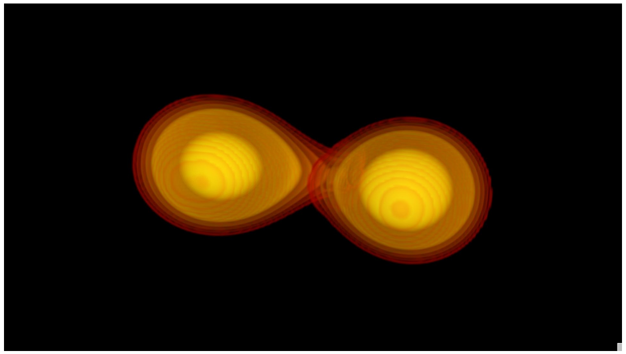
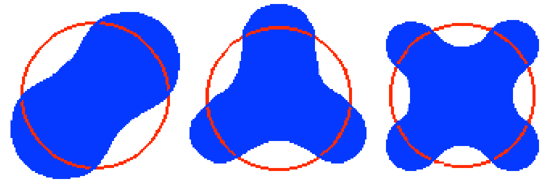


Tides determine the wave's phase during merger

Example: observing tidal effects in GWs tells us about the neutron star matter





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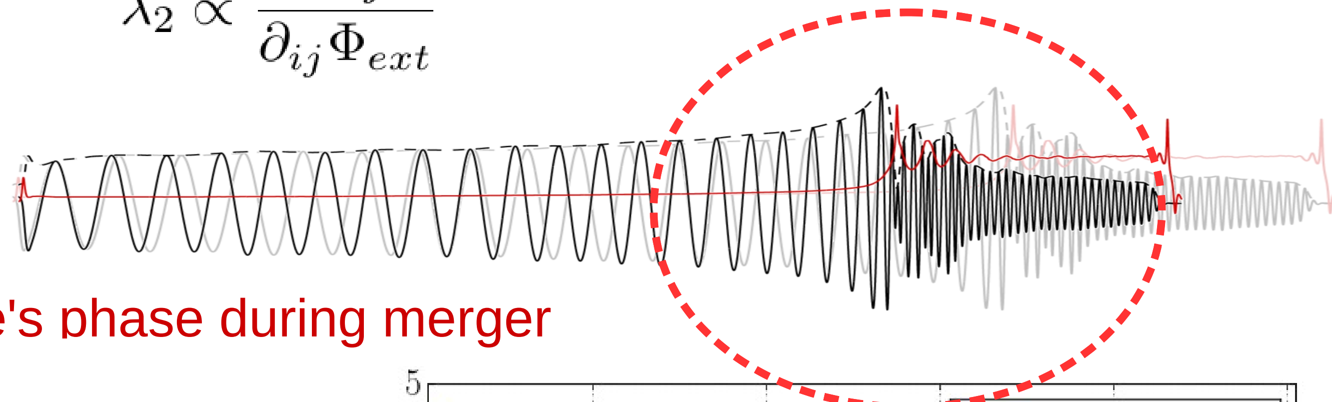
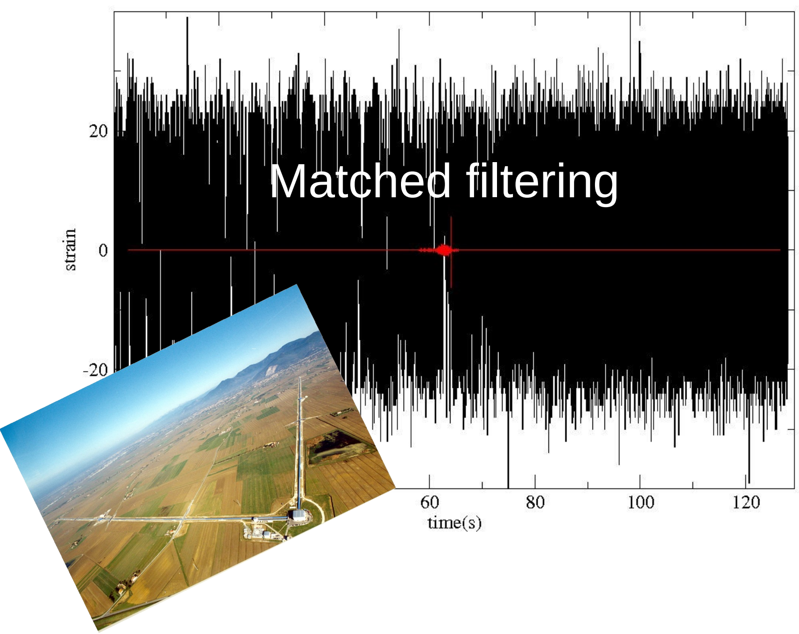
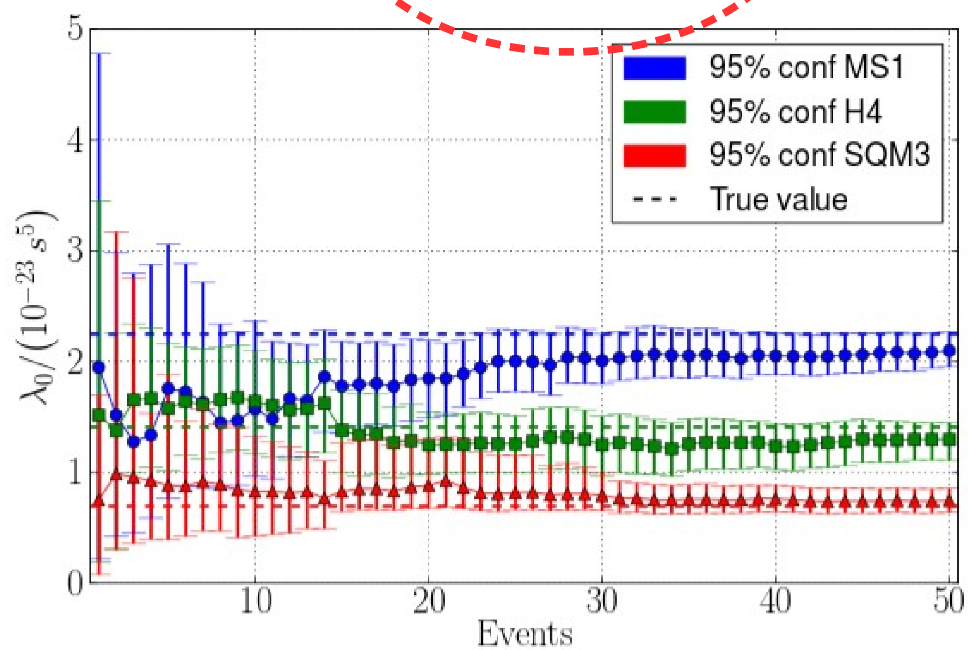


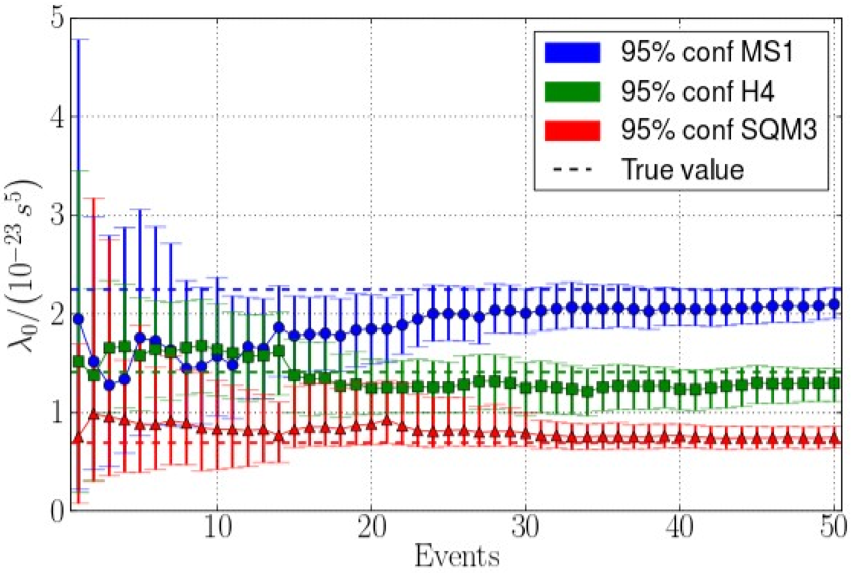
Tides determine the wave's phase during merger





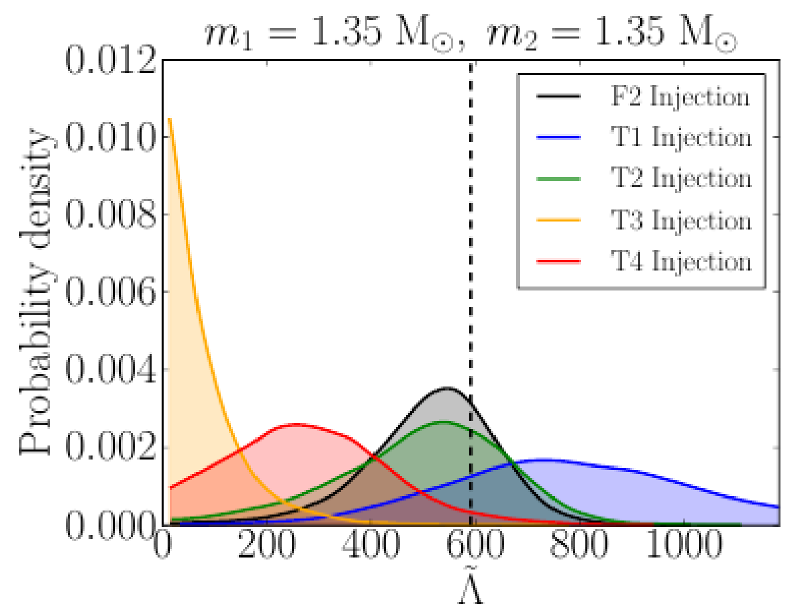
[Del Pozzo+ PRL 111 (2013)]

Data-analysis status

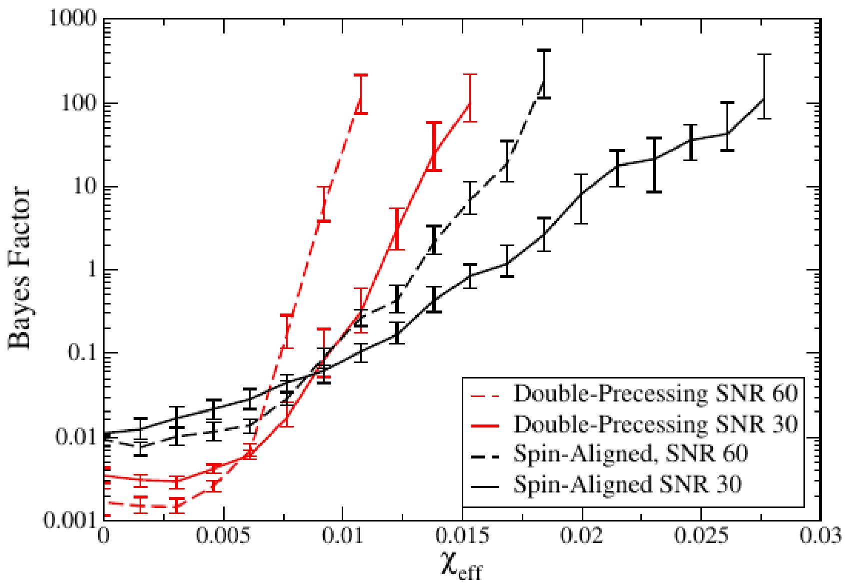


[Del Pozzo+ arXiv:1307.8338]
Tidal parameters can be constrained by LIGO/Virgo using multiple observations

[Agathos+ arXiv:1503.05405]
Mass-prior effect is crucial
(confirm biases due to waveform systematics)



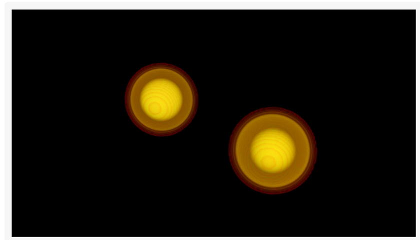
[Wade+ arXiv:1402.5156, Lackey+ arXiv:1410.8866]
Uncertainties in the waveform models lead to systematic errors in EOS ~ statistical errors

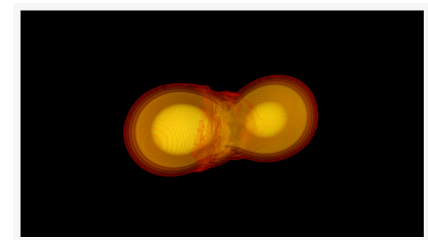


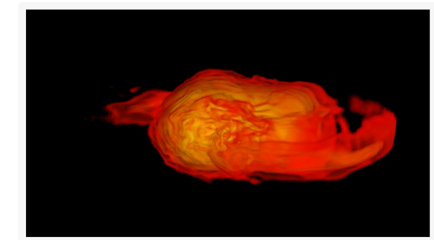
[Chatziioannou+ arXiv:1404.3108]
SNR>~30, large biases on masses and spins if precessing spin effects not modeled (small spins <0.2)

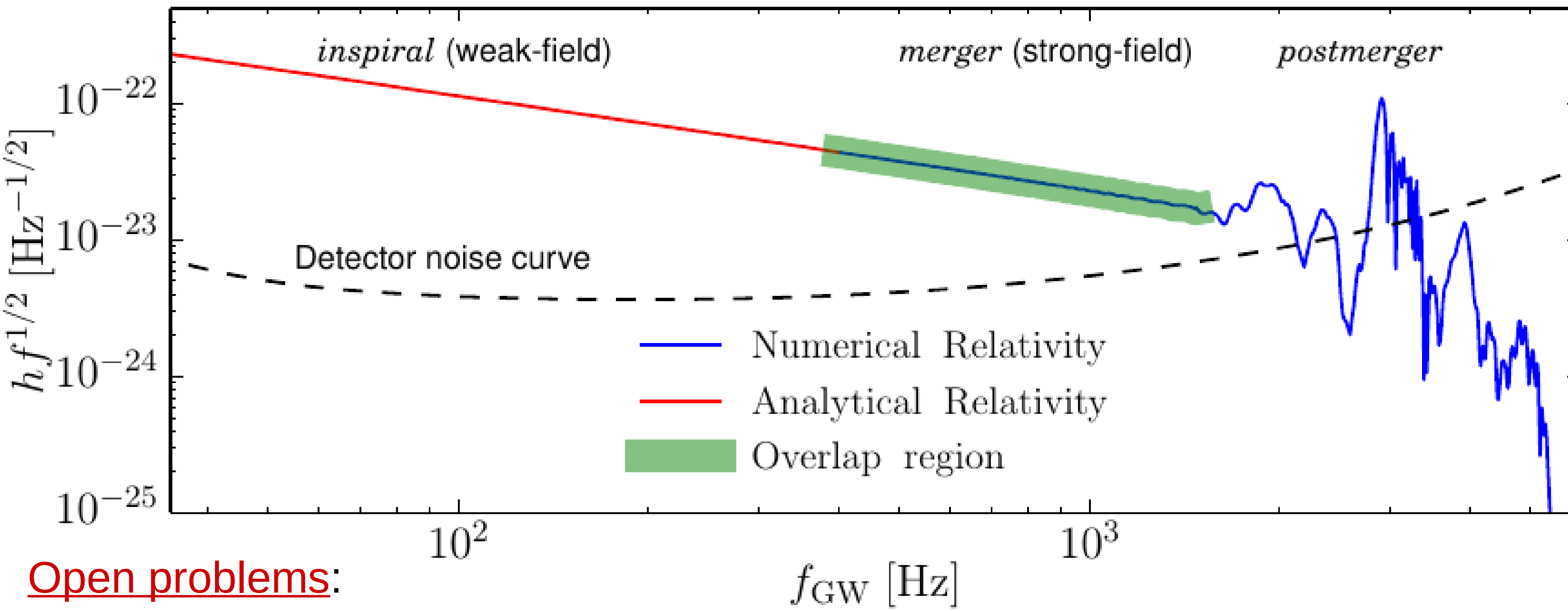
See also [Read+ arXiv:0901.3258, Hinderer+ arXiv:0911.3535, Damour+ arXiv:1203.4352]

The GW spectrum of binary neutron stars







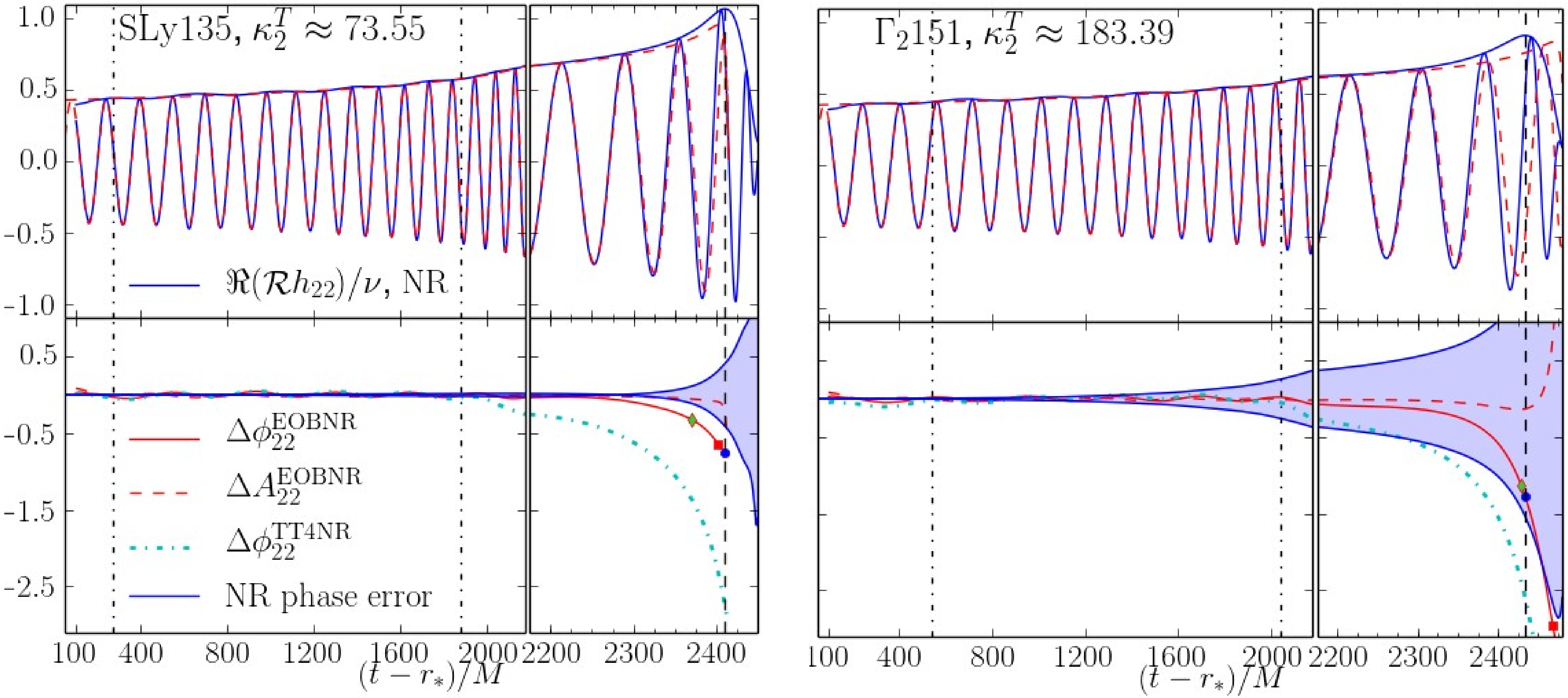


Open problems:

- Faithful and **complete waveform model** (*inspiral*+*merger*+*postmerger*)
- Coverage of the **parameter space** (mass, spins, EOS, …)
- Precise prediction of the merger remnant (e.g. collapse, black hole)

First waveform model for inspiral → merger

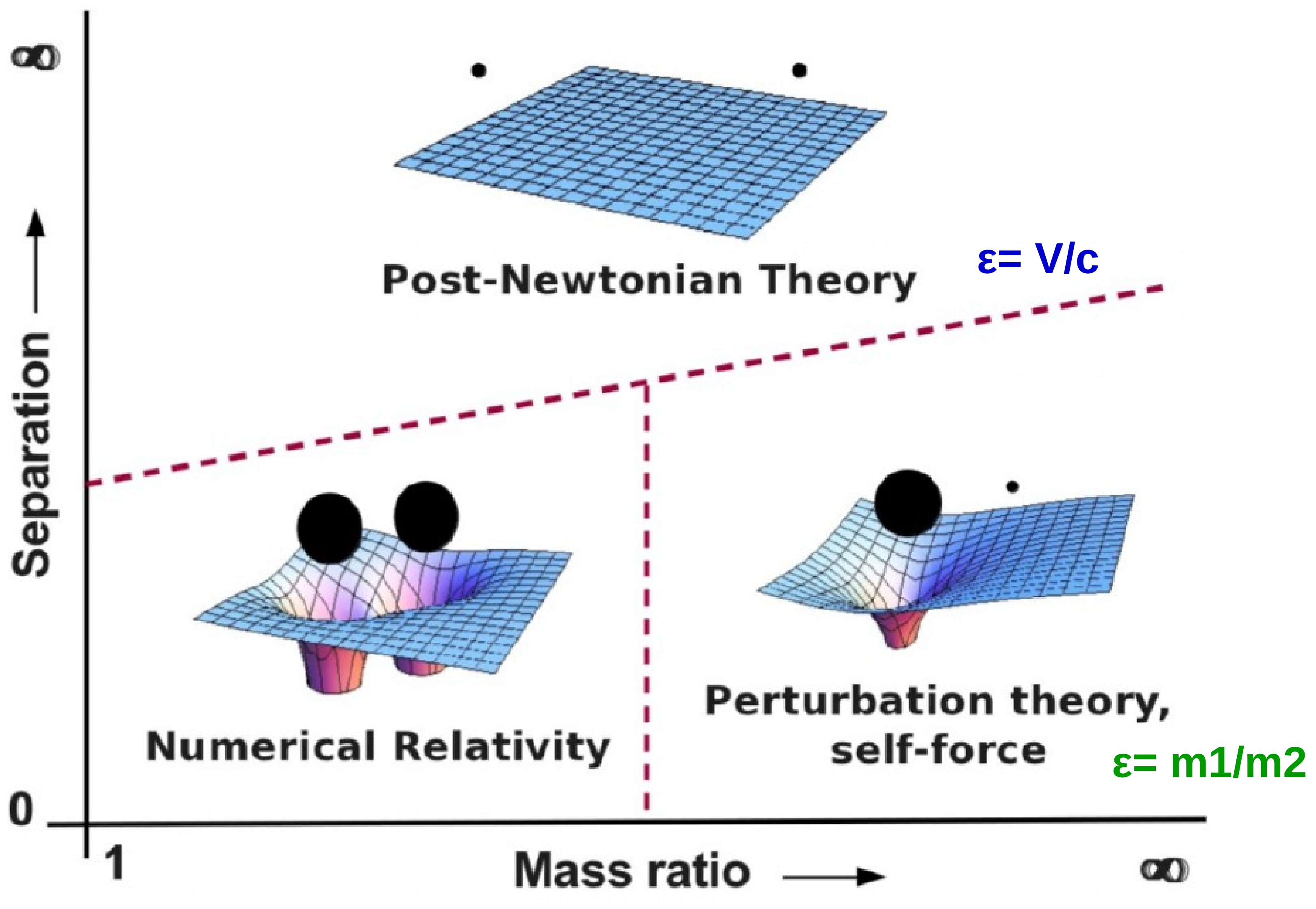
[SB,Nagar,Dietrich,Damour PRL 114 (2015)]



- 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!)

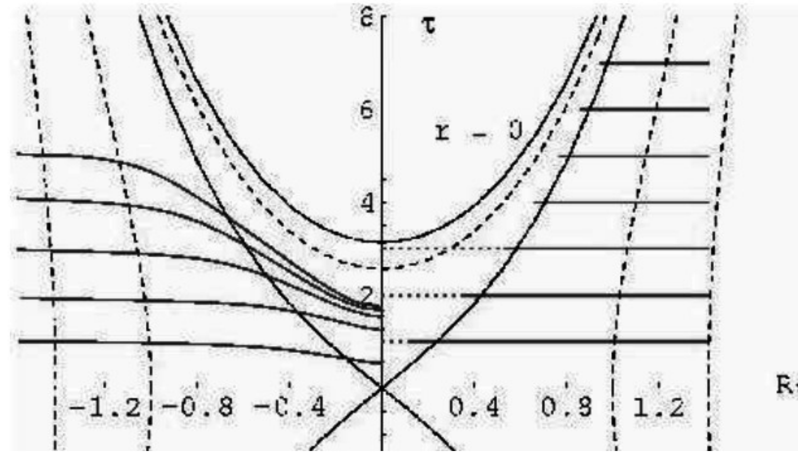
See [Hinderer+ PRL 116 (2016)] for an alternative approach

Methods for the GR 2-body problem



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

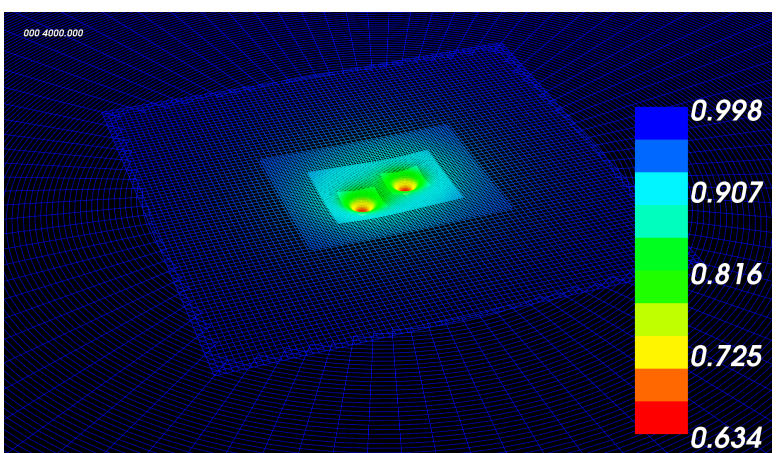
GR Formulation and Cauchy problem
+ GR hydrodynamics



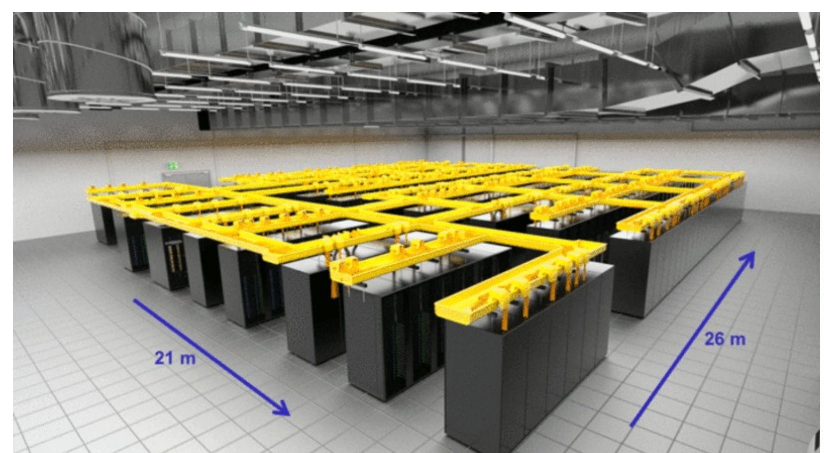
Coordinates and Singularities

Numerical relativity in a nutshell

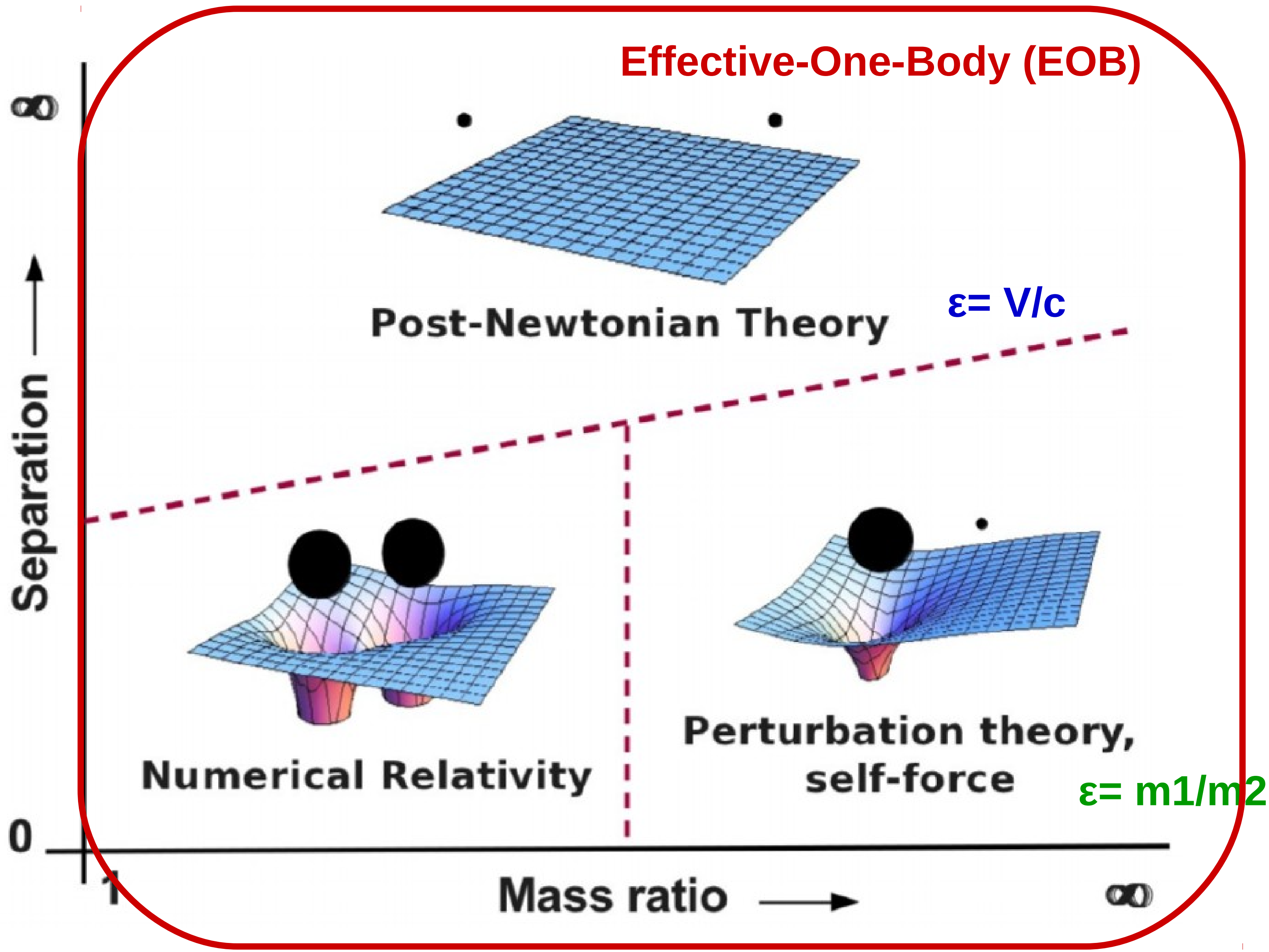
Numerical methods for PDEs on adaptive grids



High-performance-computing (HPC)

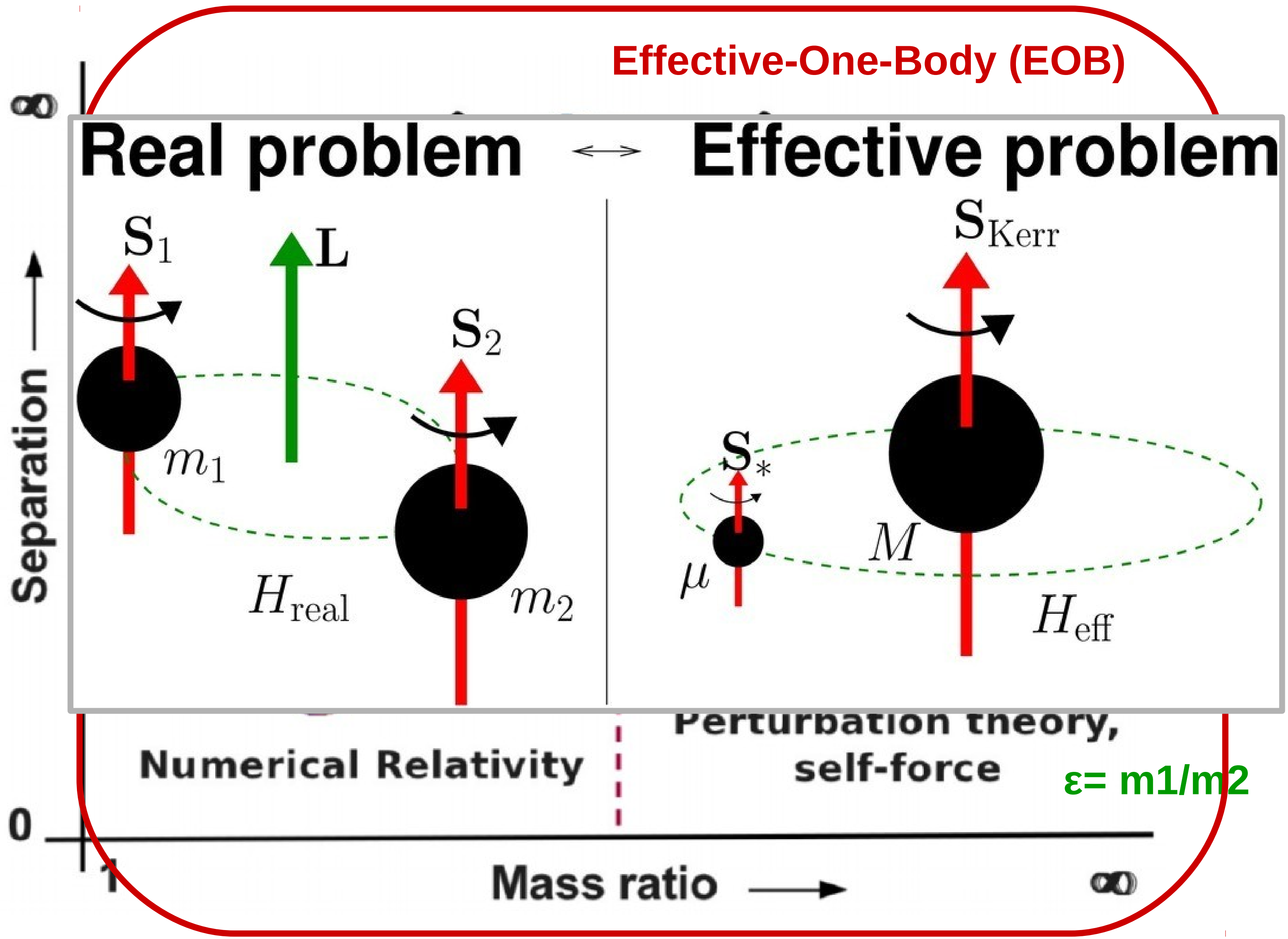


Methods for the GR 2-body problem



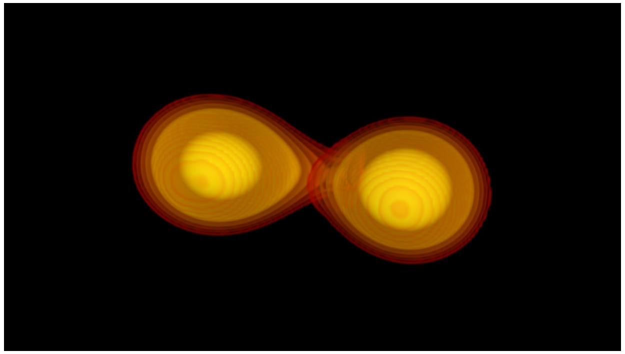
[Buonanno&Damour arXiv:gr-qc/9811091, Damour,Iyer,Nagar arXiv:0811.2069, Damour&Nagar arXiv:0911.5041]

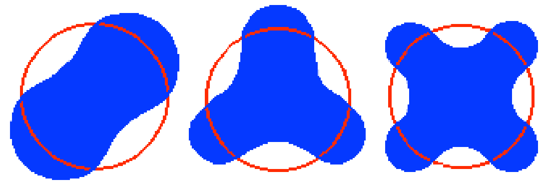
Methods for the GR 2-body problem



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

Relativistic Tides in EOB





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

[Damour&Nagar arXiv:0911.5041]

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

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:

$$h \sim Af^{-7/6}e^{-i\Psi(f)} \approx Af^{-7/6}e^{-i\Psi_{PP}(f) + i39/4\kappa_2^T x(f)^{5/2}}$$

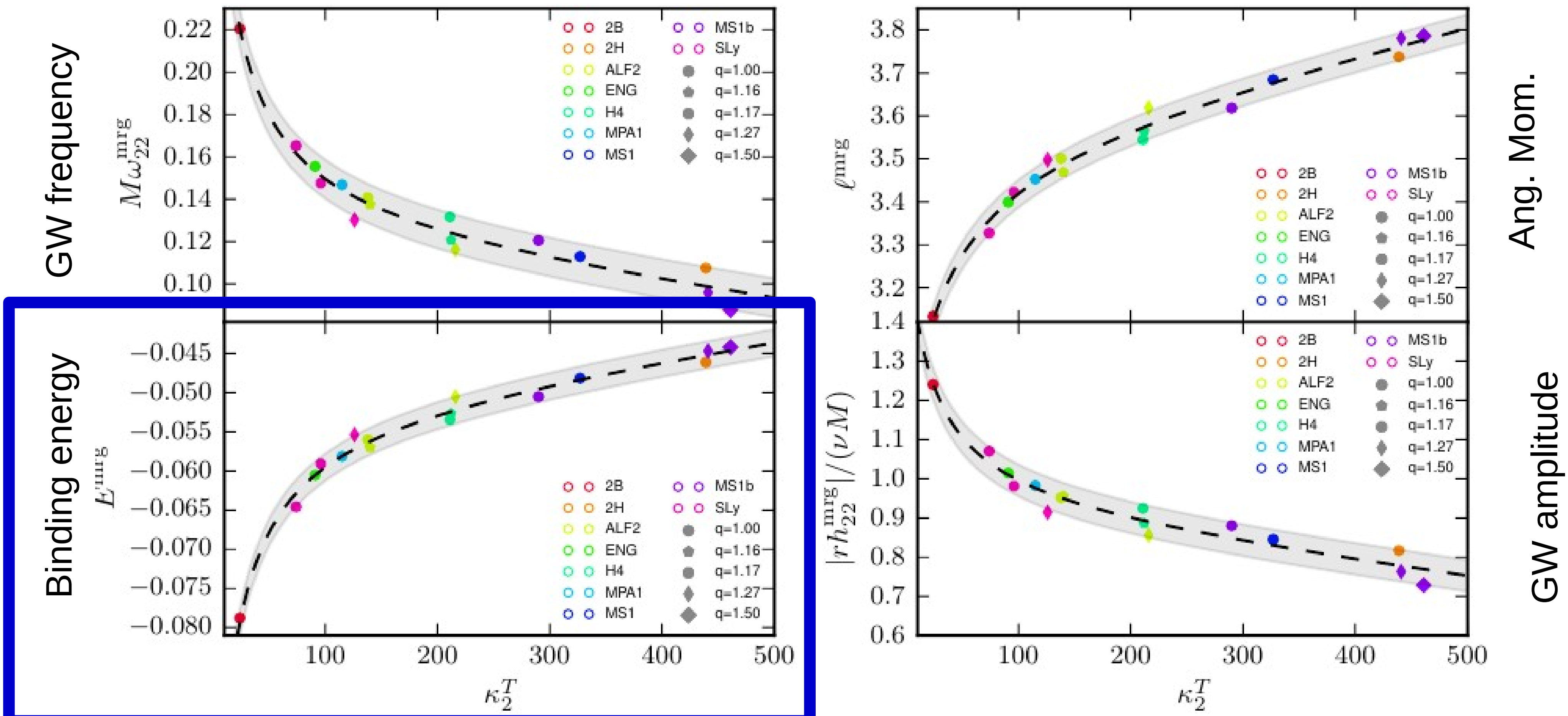
Key point: No other binary parameter (mass, radii, etc) enter separately the formalism

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)

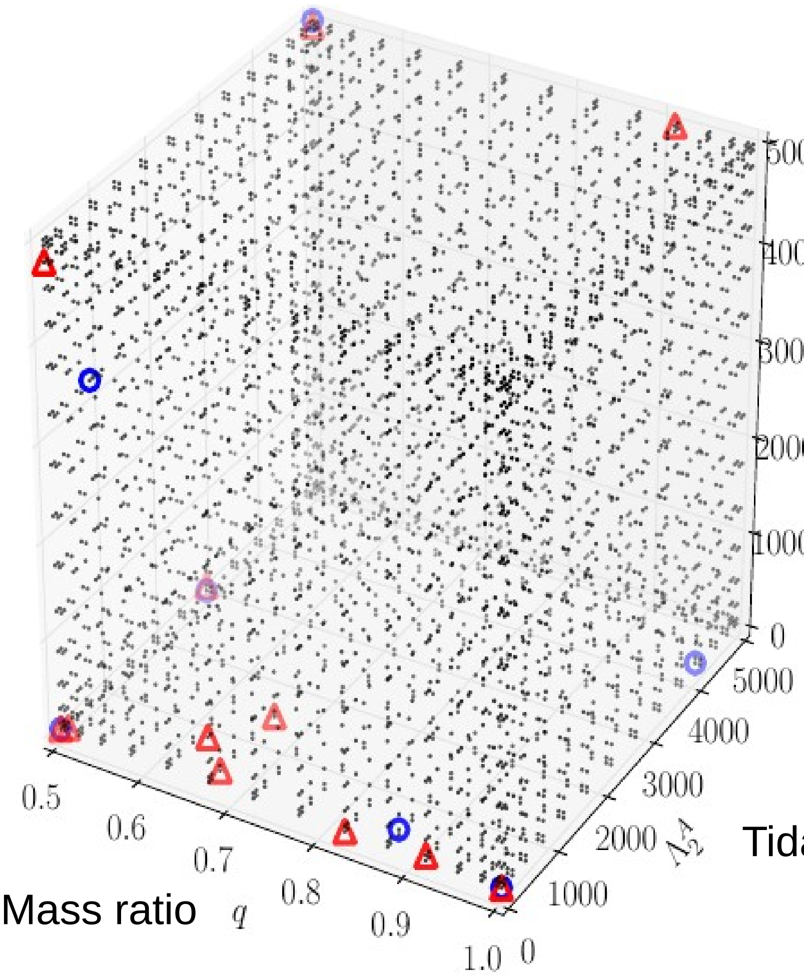
Predict energy emitted for given binary by specifying solely the kappa value

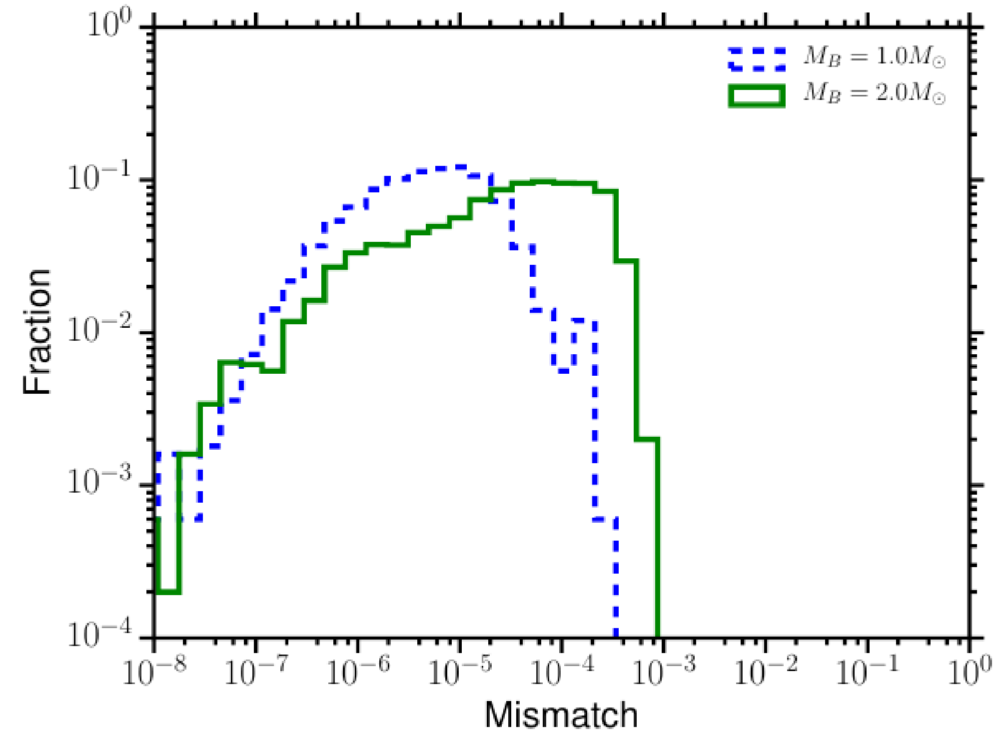


Tidal polarizability coef. (l=2)

Fast templates for GW data-analysis of BNS

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





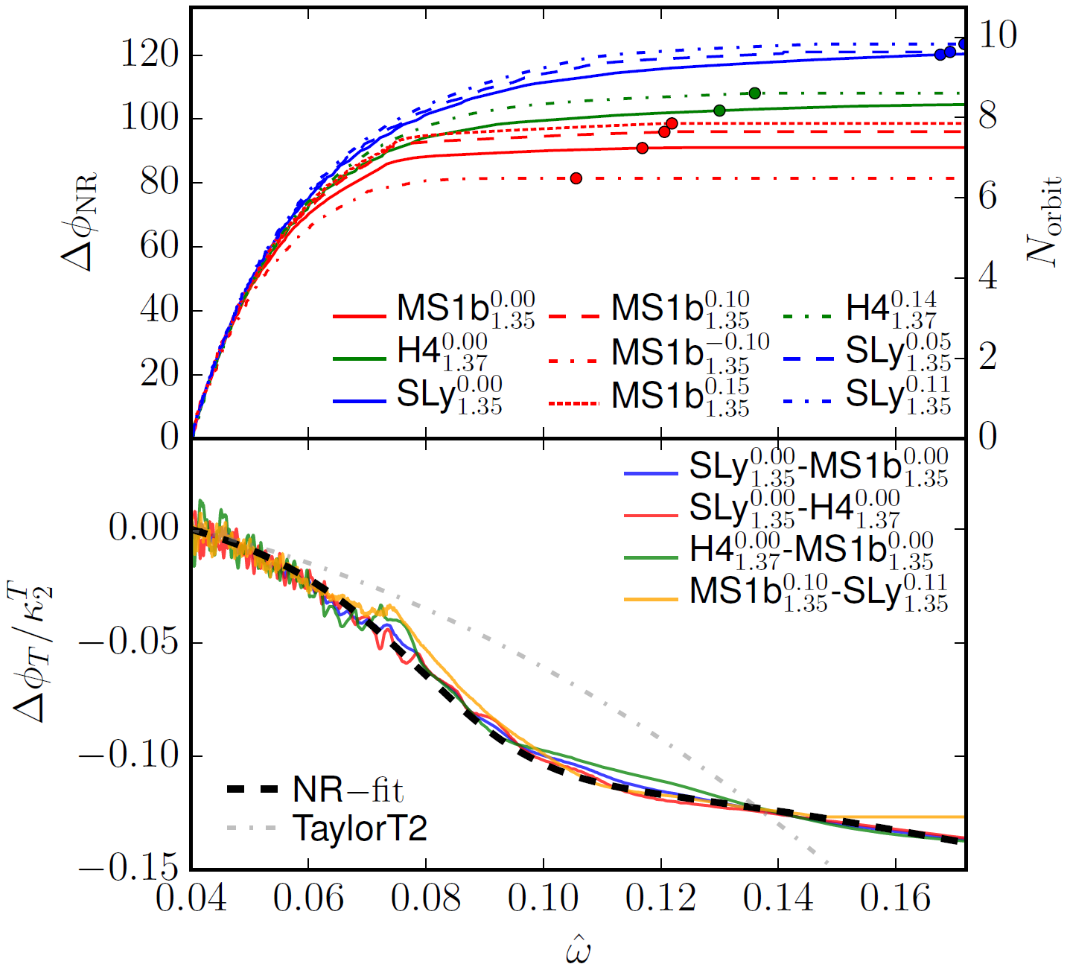
First model accurate to merger available in LIGO/Virgo library

- **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)

NR-based tidal approximants in closed-form

[Dietrich, SB, Tichy arXiv:1706.02969]

NEW



1. Extract strong-field tidal phase from *ansatz*

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

2. Combine with low-frequency post-Newtonian results in effective resummed expression

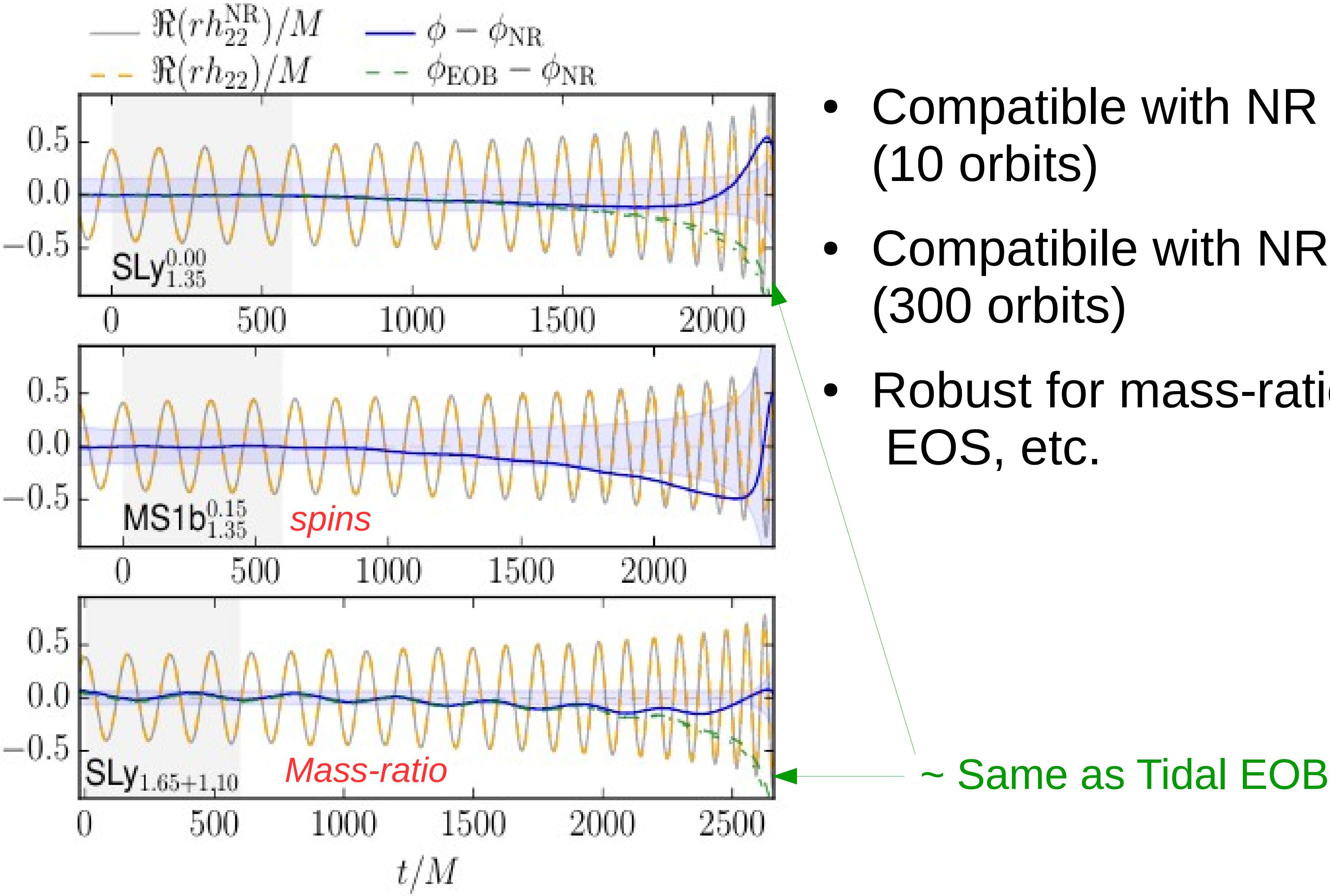
$$\phi_T = -\kappa_2^T \frac{c_{\rm Newt}}{X_A X_B} x^{5/2} \times \frac{1 + n_1 x + n_{3/2} x^{3/2} + n_2 x^2 + n_{5/2} x^{5/2} + n_3 x^3}{1 + d_1 x + d_{3/2} x^{3/2}}$$

3. Use with ANY BBH baseline, in time or frequency domain

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

Performances

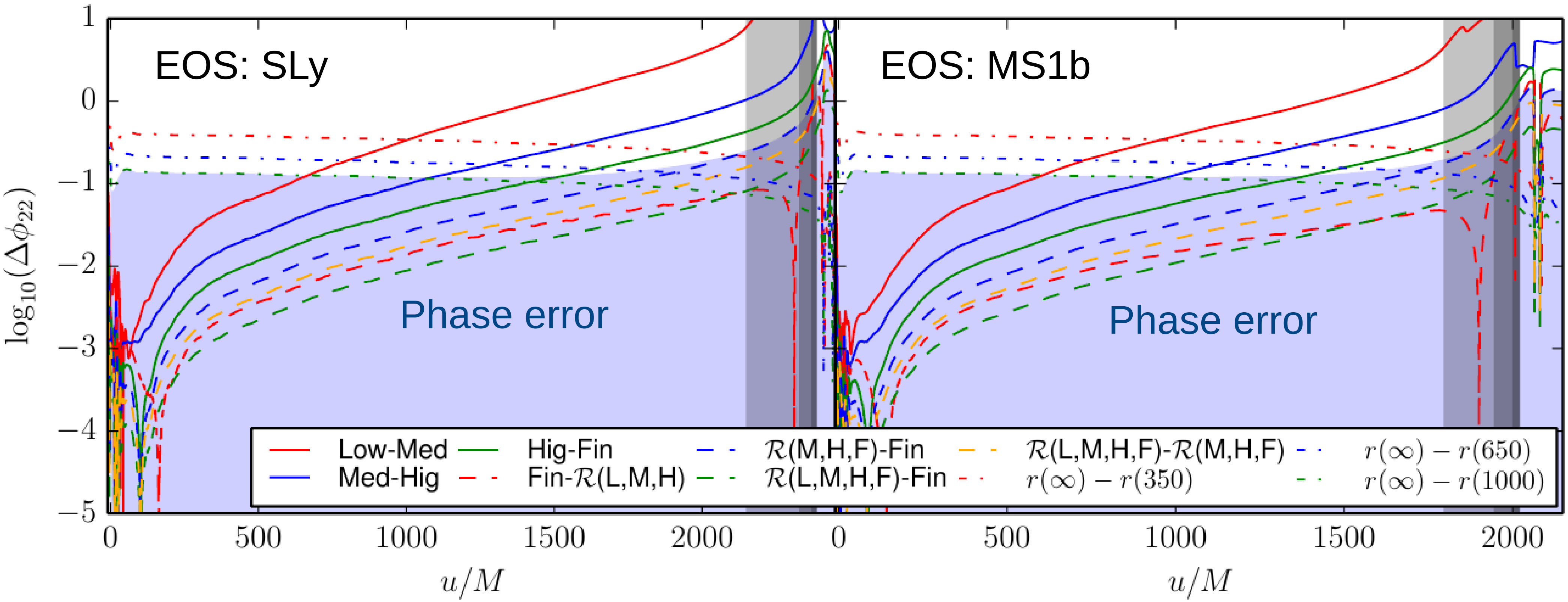
[Dietrich, SB, Tichy arXiv:1706.02969]



- Compatible with NR (10 orbits)
- Compatibile with NR-hybrids (300 orbits)
- Robust for mass-ratio, spins, EOS, etc.

Improved NR GW with high-order WENO schemes

[SB,Dietrich PRD94 064062 (2016)]



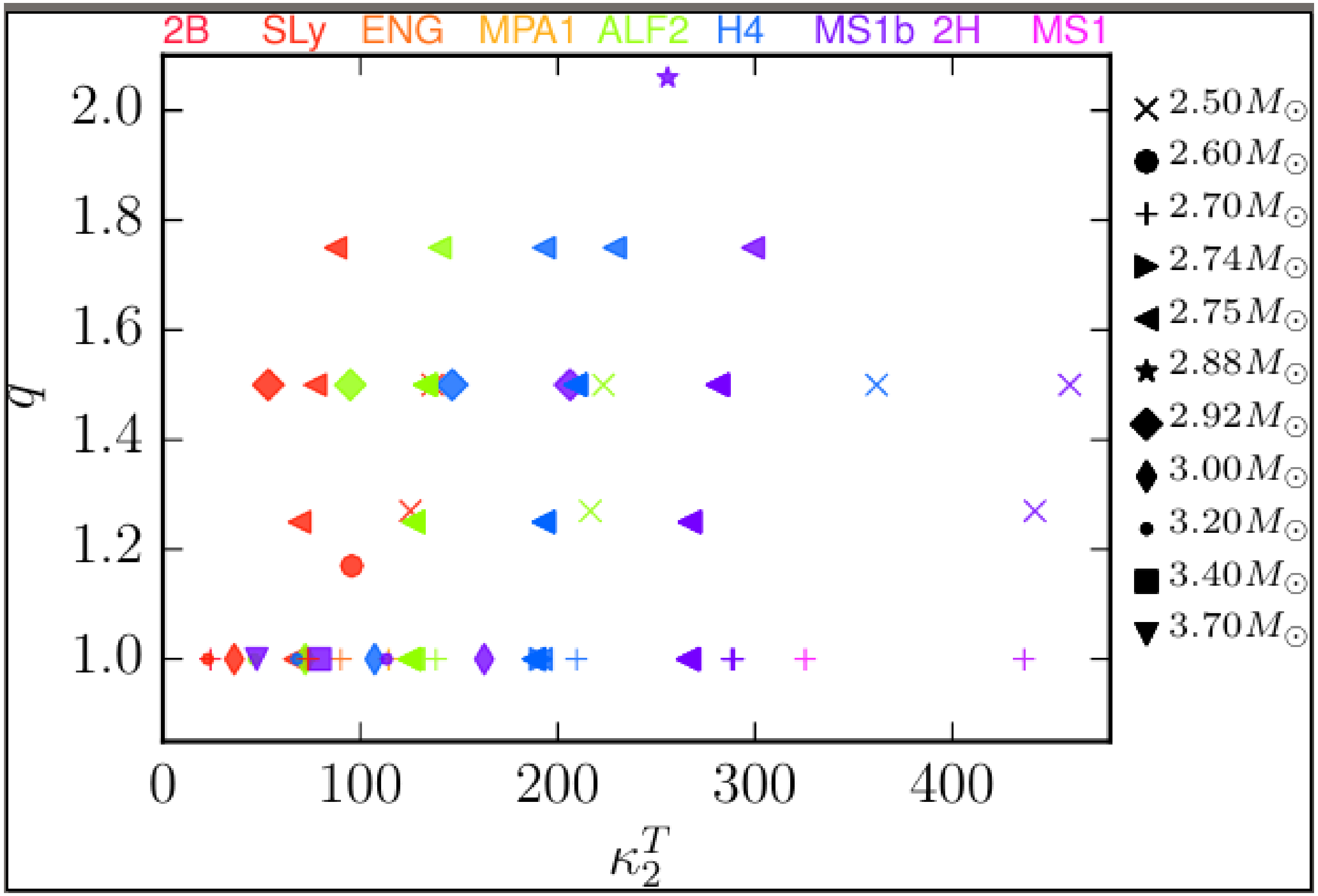
- Robust convergence assessment
- Large resolution span (64^3-192^3), no alignment
- Detailed error budget (truncation errors, wave extraction systematics, eccentricity, junk radiation, etc)

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

Exploring the BNS parameter space

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

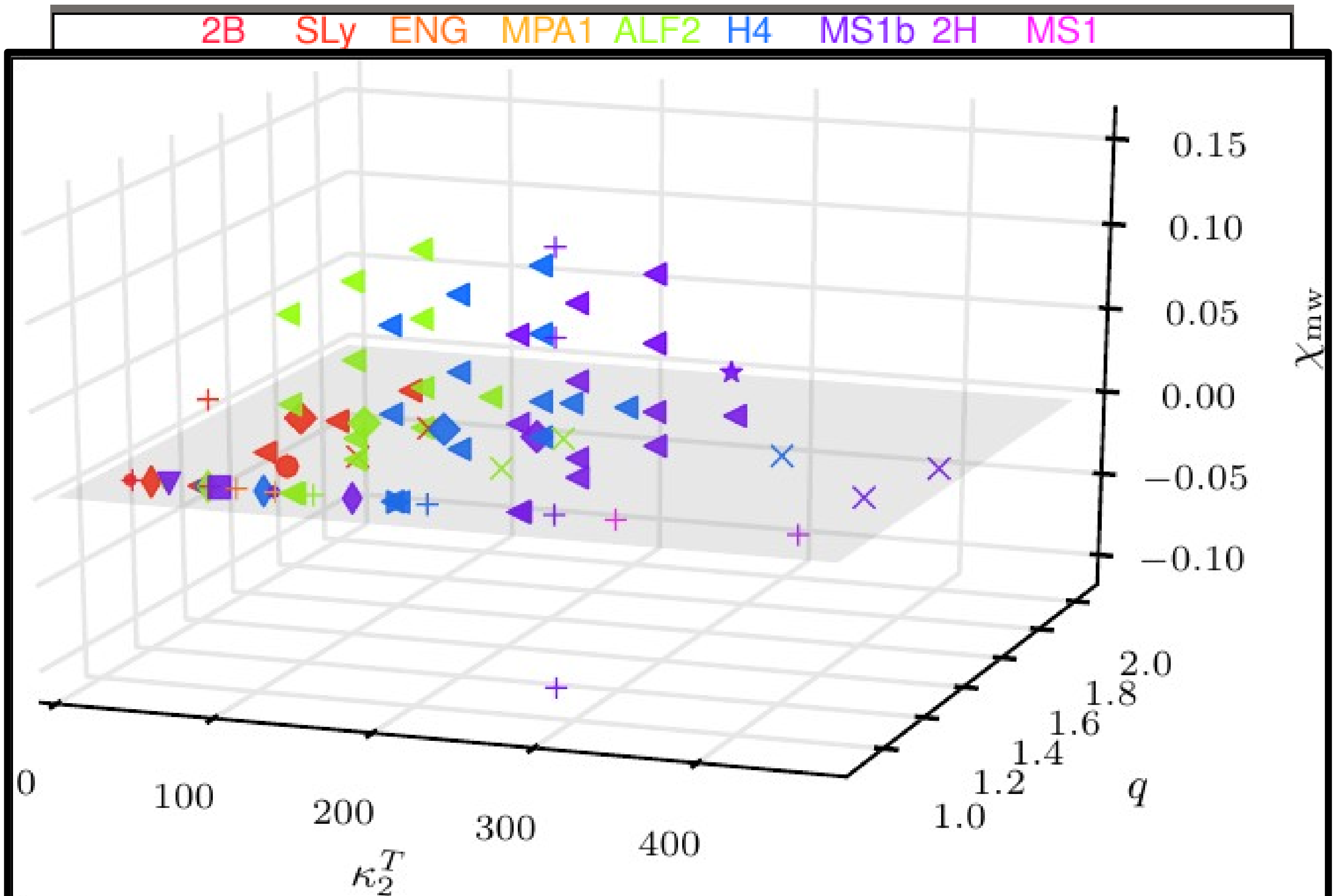
Mass ratio



Tidal coupling constant (EOS)

Exploring the BNS parameter space

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

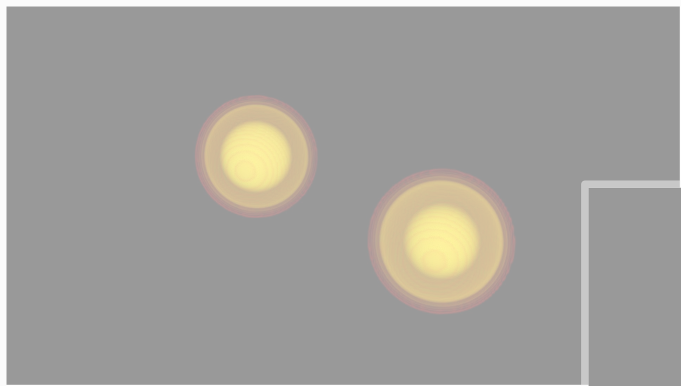


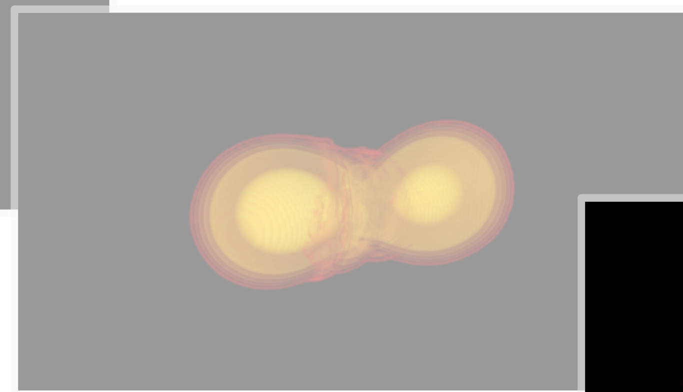
Effective Spin

Tidal coupling constat (EOS)

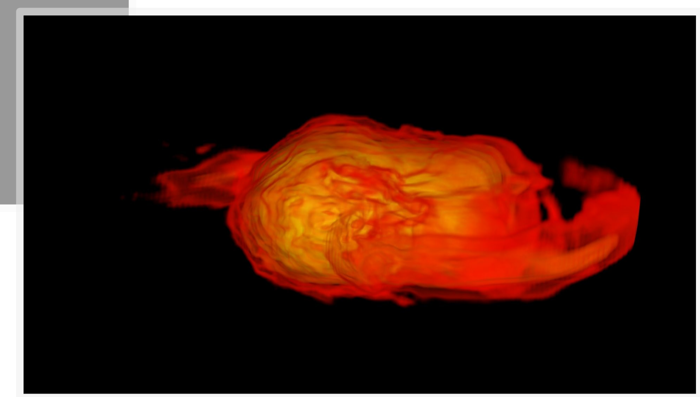
Mass ratio

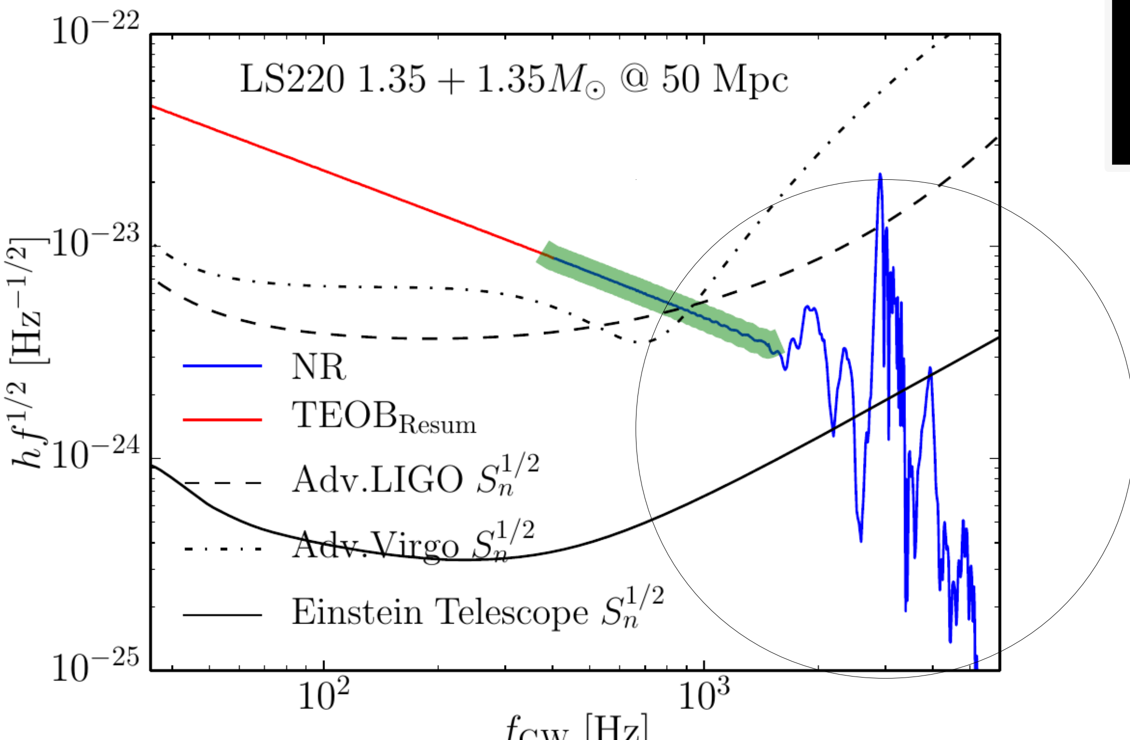
Results: postmerger





Challenges:
- no analytical information
- multiphysics simulations





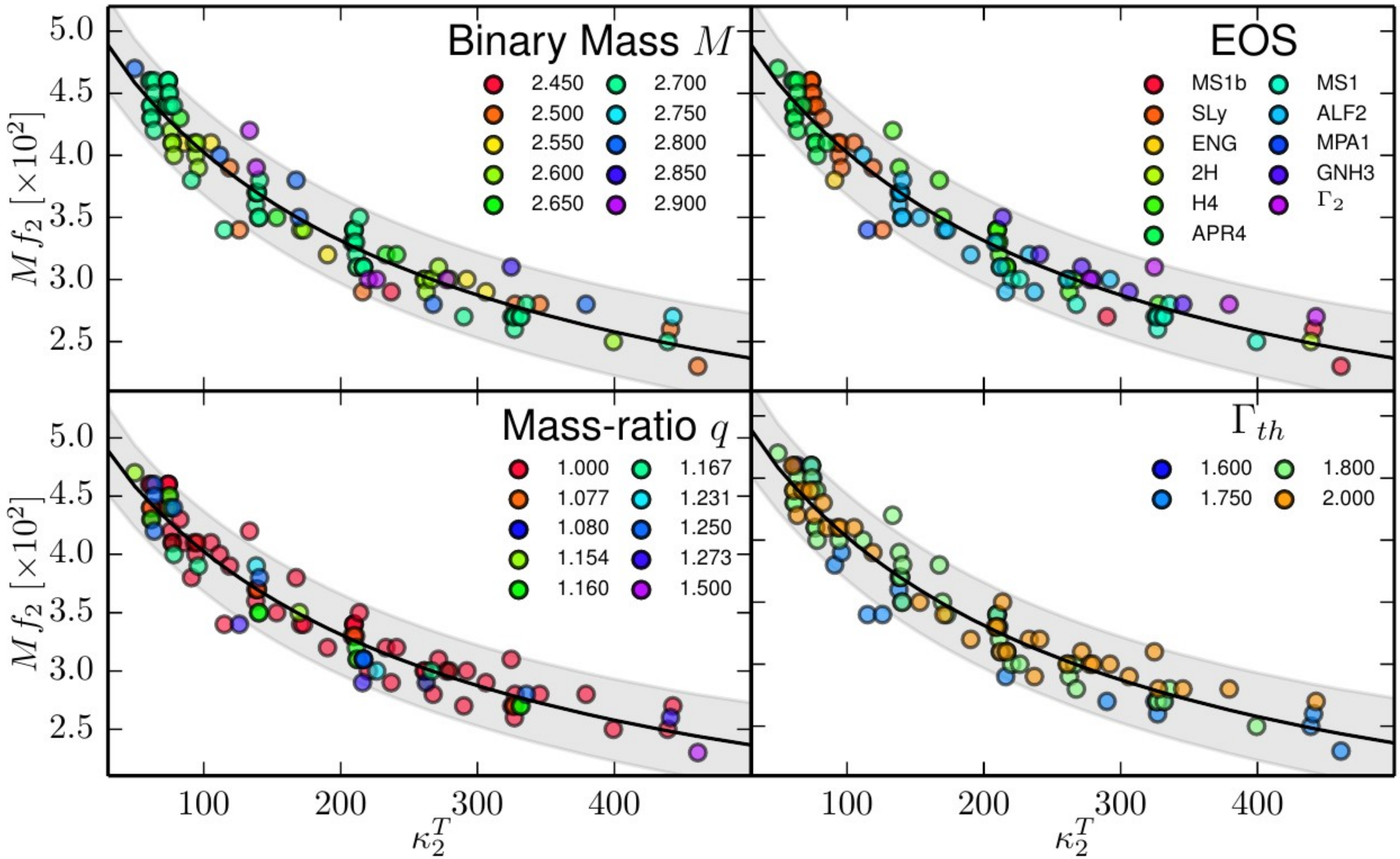
Rich frequency content

Main peak freq called f_2
(Rotational freq. of remnant)

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

Peak frequency correlates to tidal parameter

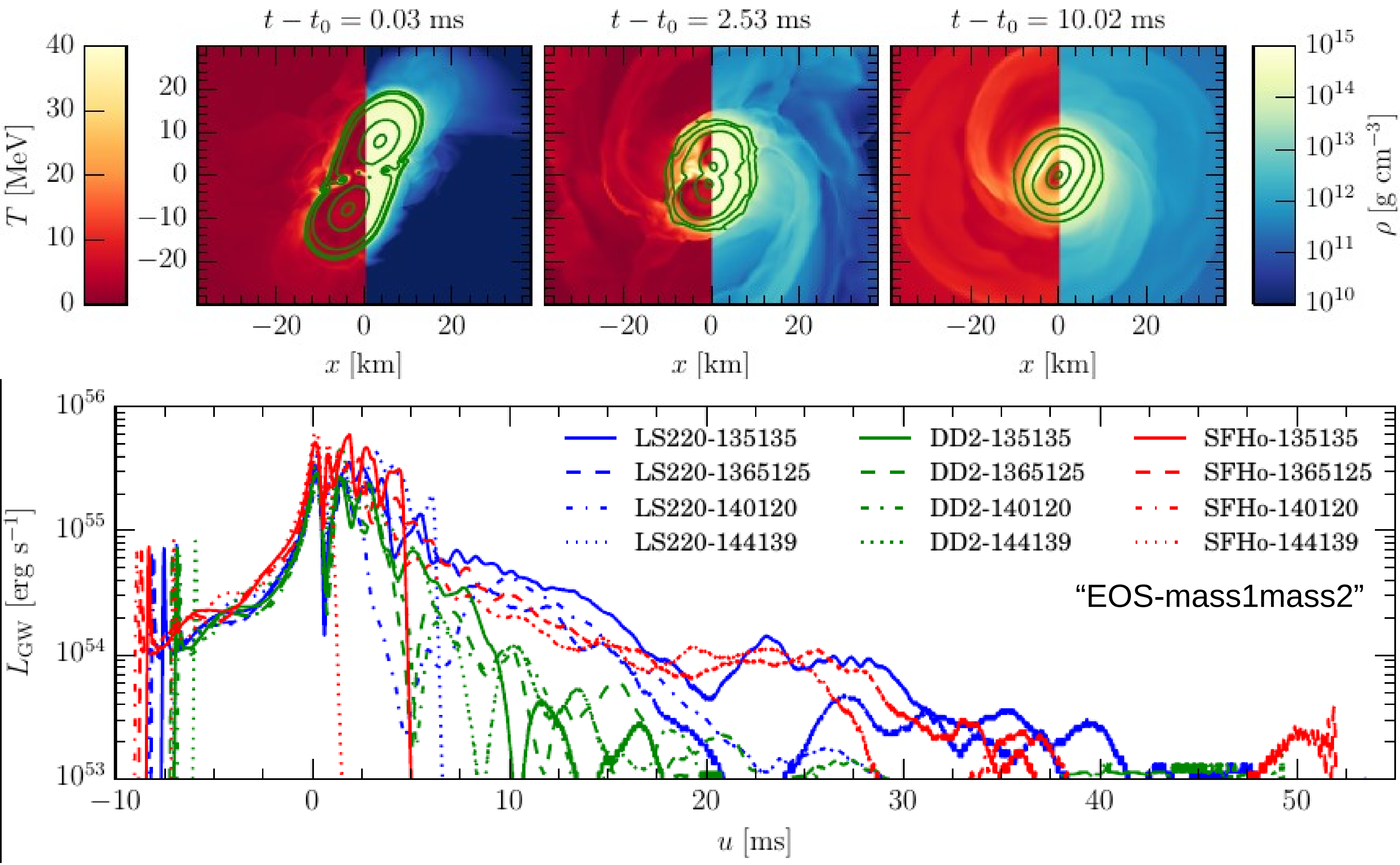
[SB, Dietrich, Nagar PRL 115 (2015)]



- 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)]



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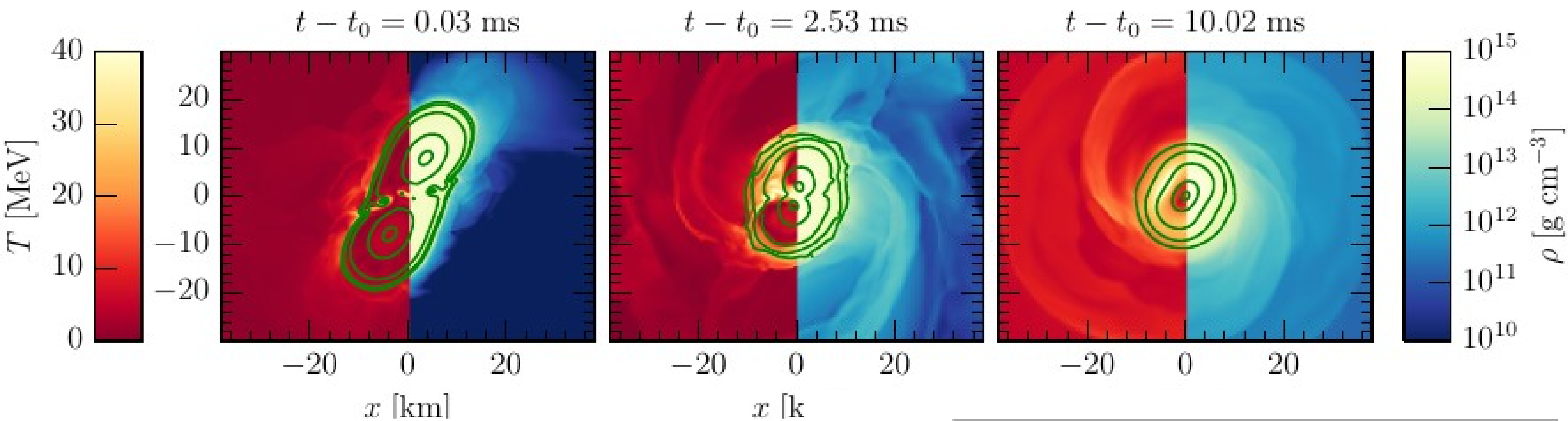
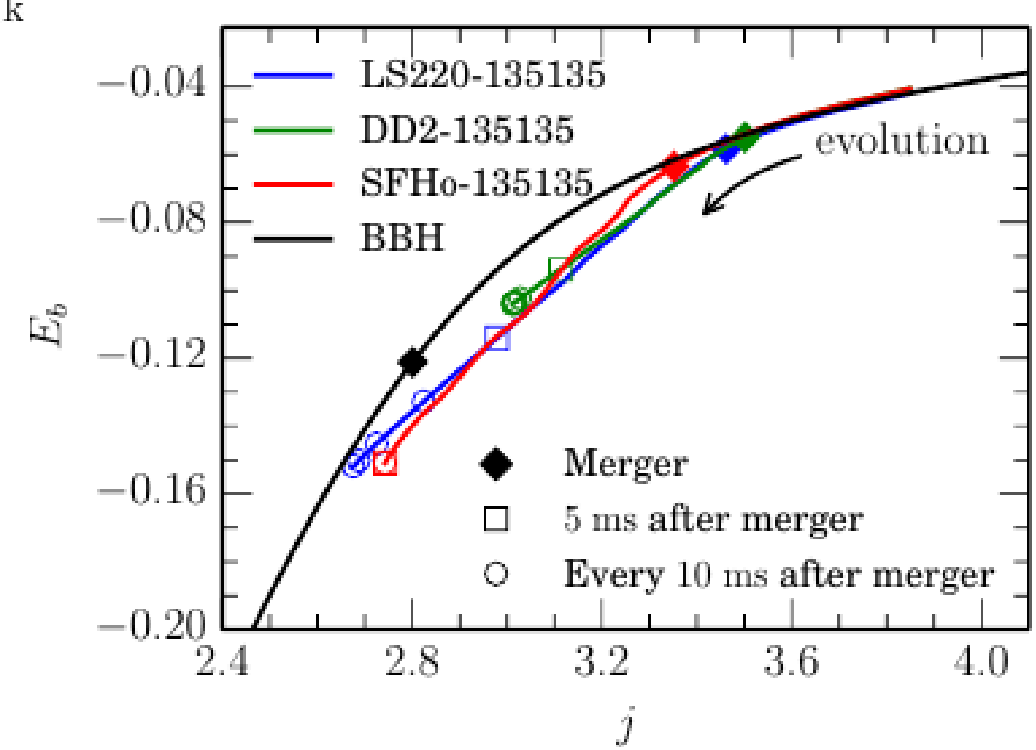


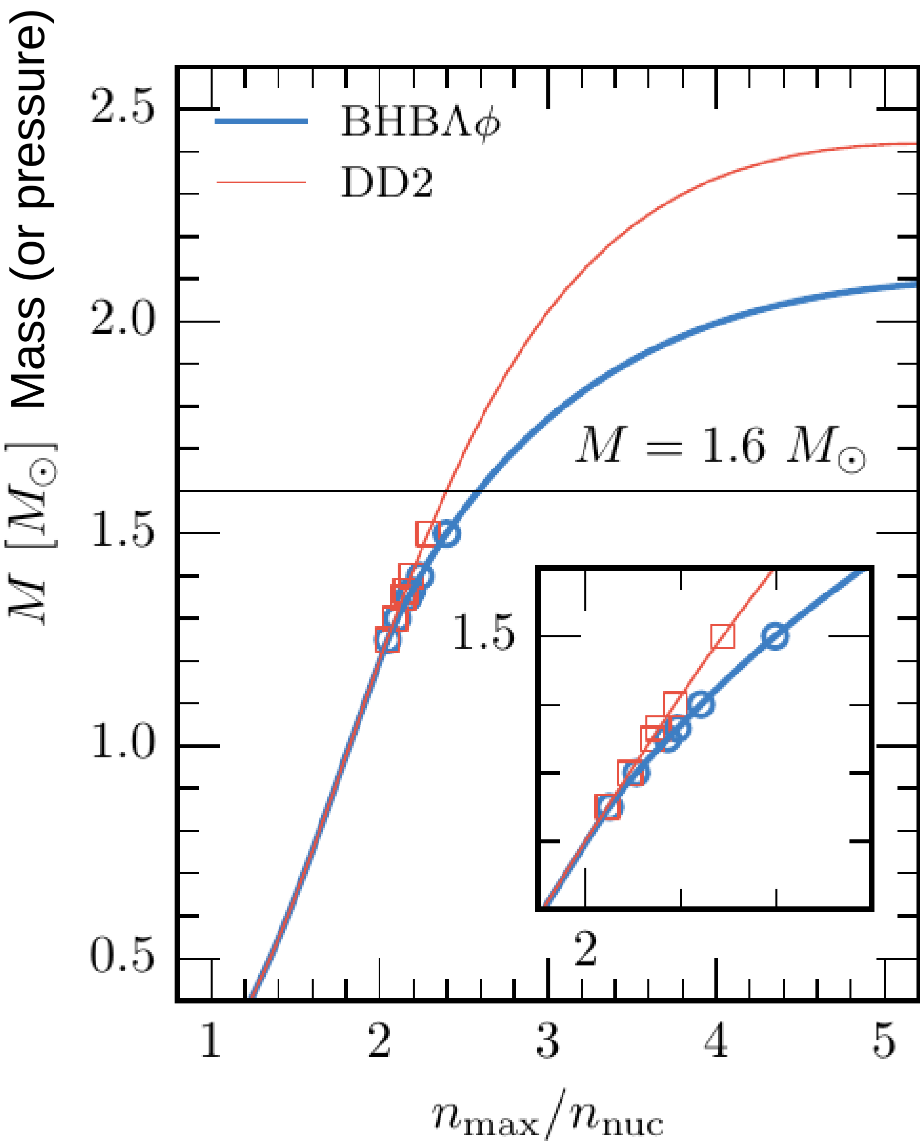
- Emission is FAST: $\tau_{GW} \sim 20$ ms
- Emission is LOUD: E(HMNS) ~ 2x E(merger)
- Note: explain the $f_2(\kappa_2)$ correlation



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

Merger remnant reaches extreme densities

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



Baryon number density

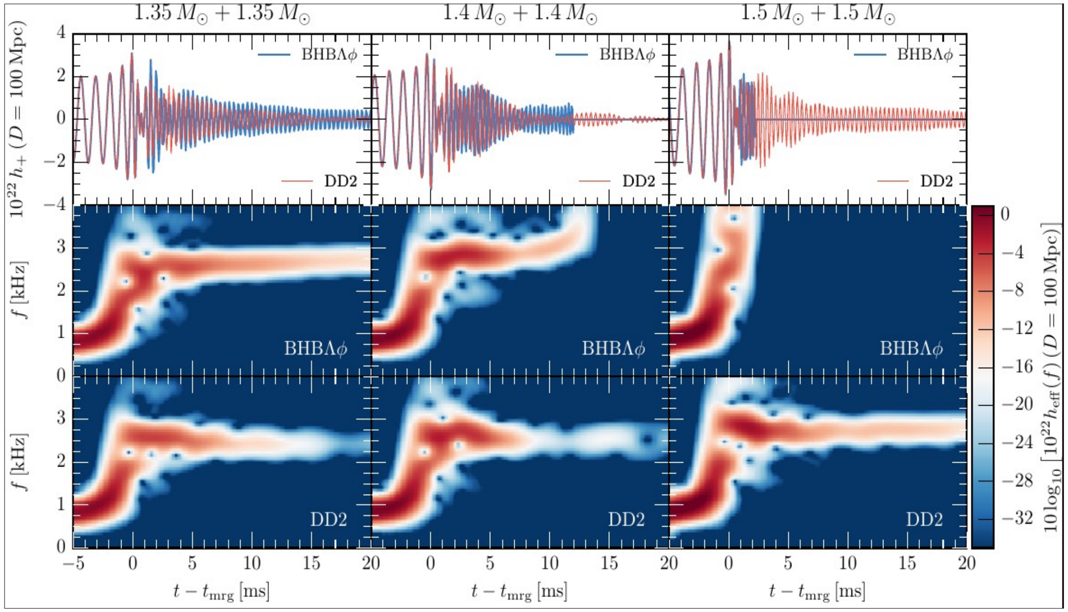
- Baryon number density **n ~ 3-5 n_{nuc}**
- Extra DOF/phase transitions?
- Specific model: Λ-hyperons

  [Banik+ arxiv:1404.6173]

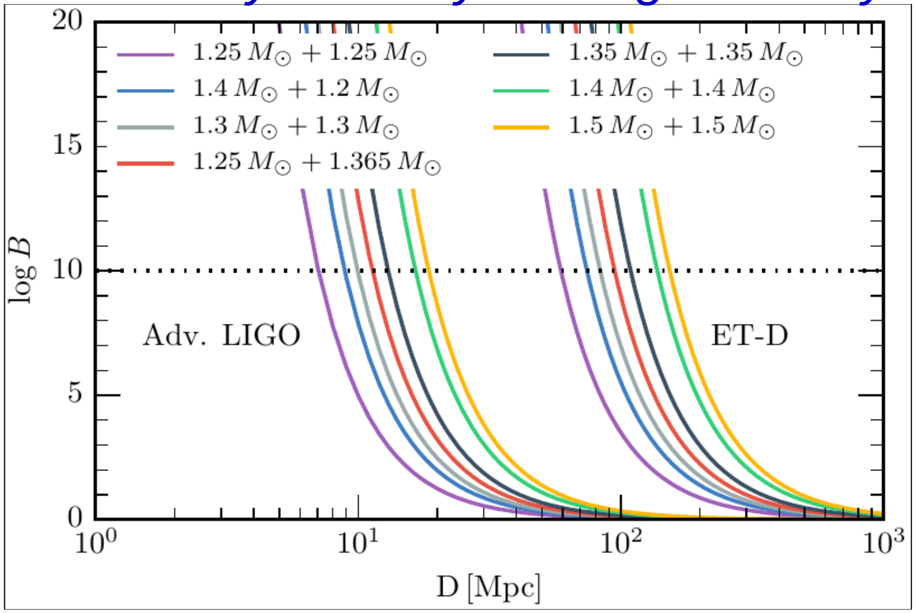
  Microphysical EOS compatibile with astro and nuclear phys constraints
- In general: “softness” effects

GWs could probe such “softness effects”

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



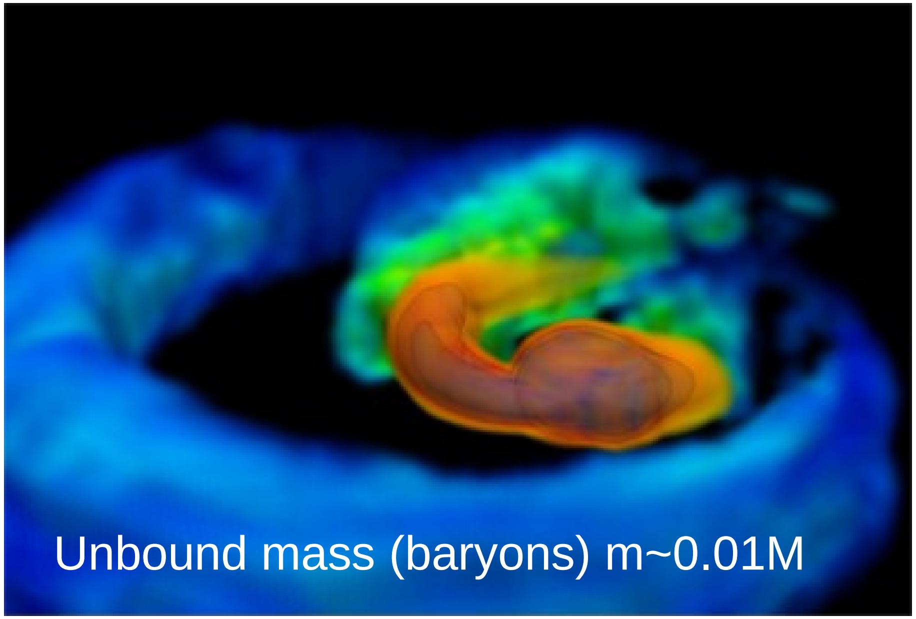
Data-analysis study: distinguishablity

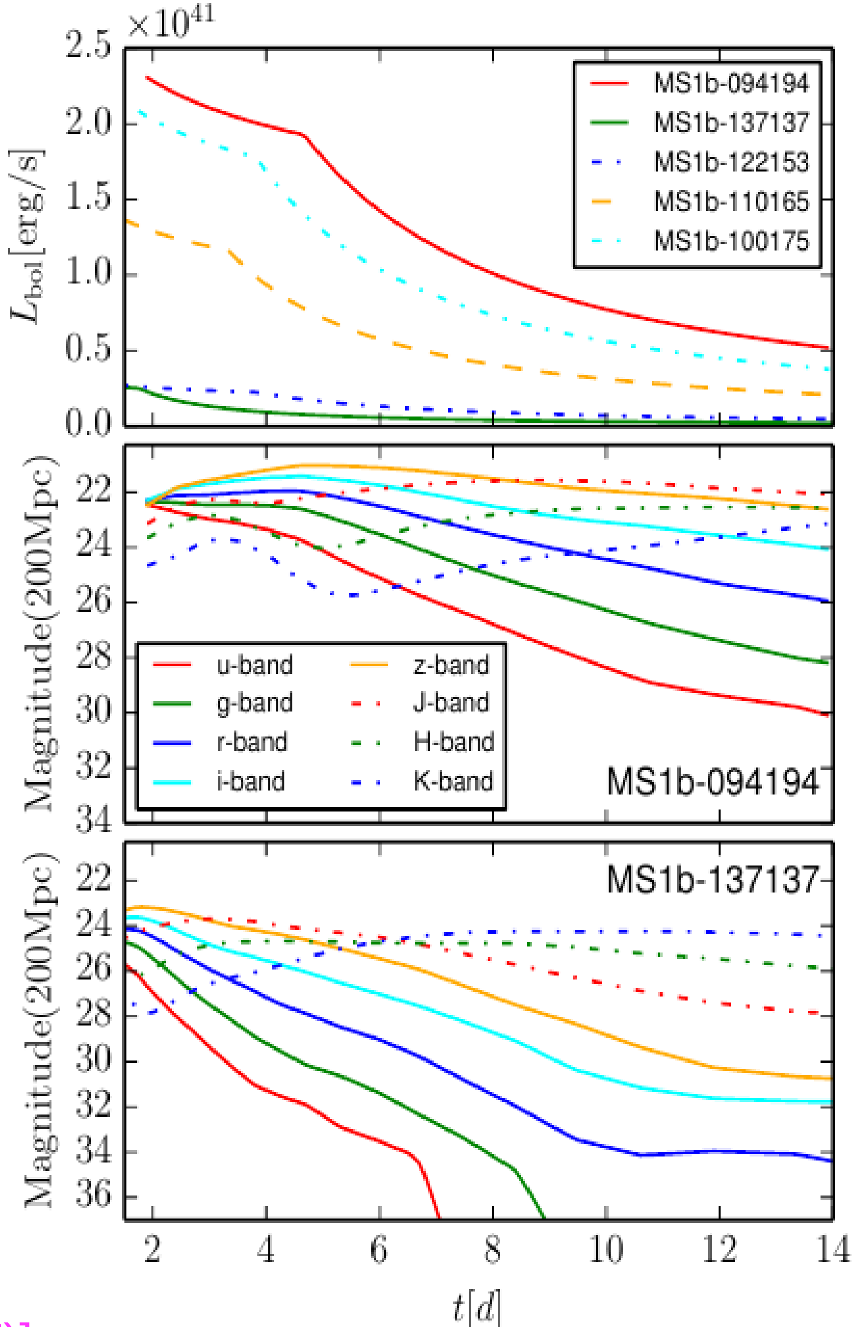


log(Bayes factor) vs. Source distance

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

Dynamical ejecta and kilonova properties





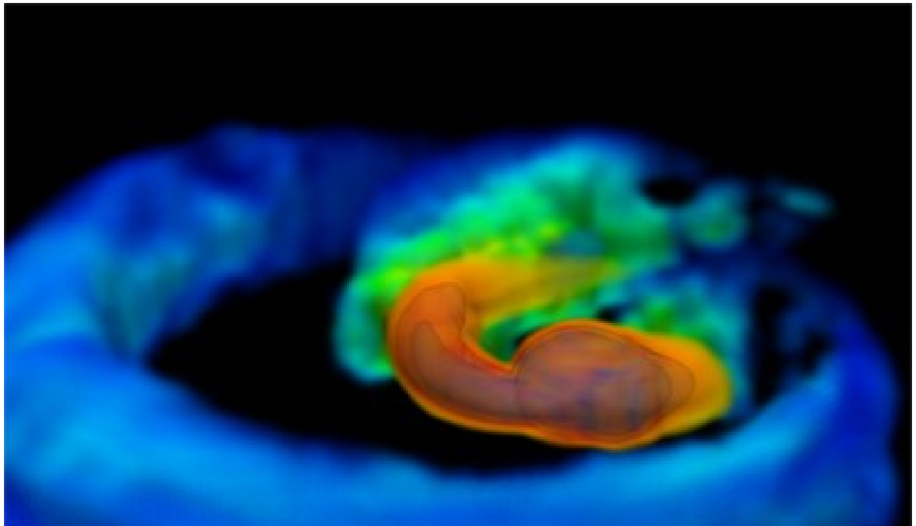
- Two Mechanisms: tidal tidal vs. shocks
- Neutron-rich →r-processs nucleosynthesis of heavy elements (>Fe)
- Decay r-process nuclei → EM emission

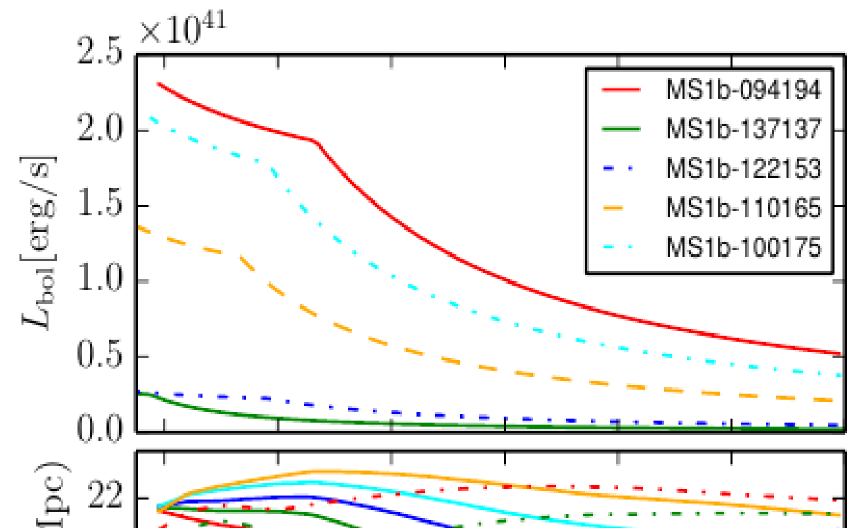
  Simplified models [Grossmann+ (2014)] [Kawaguchi+ (2016)]

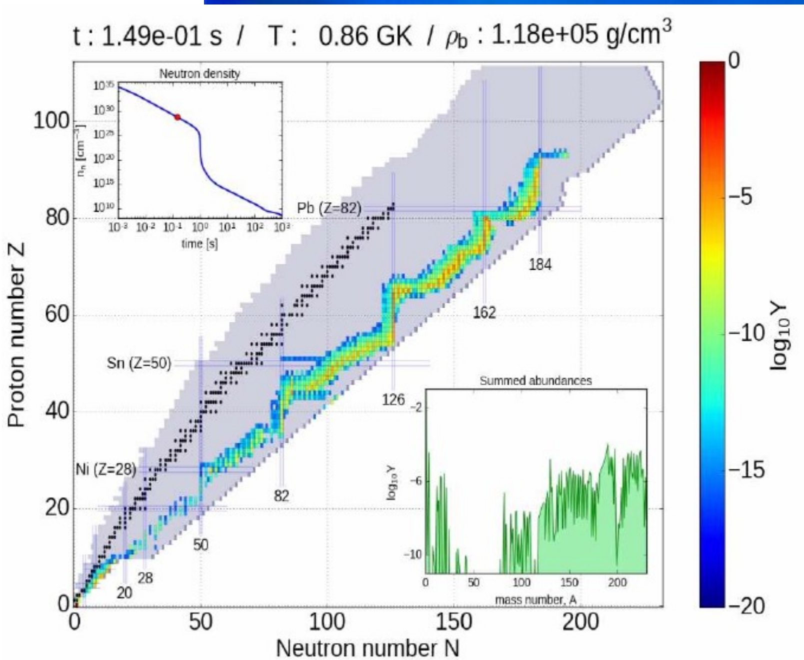
- Strong-field input from GR simulations (mass, kinetic energy) is essential !
- Example: Light curves, dependence on mass-ratio

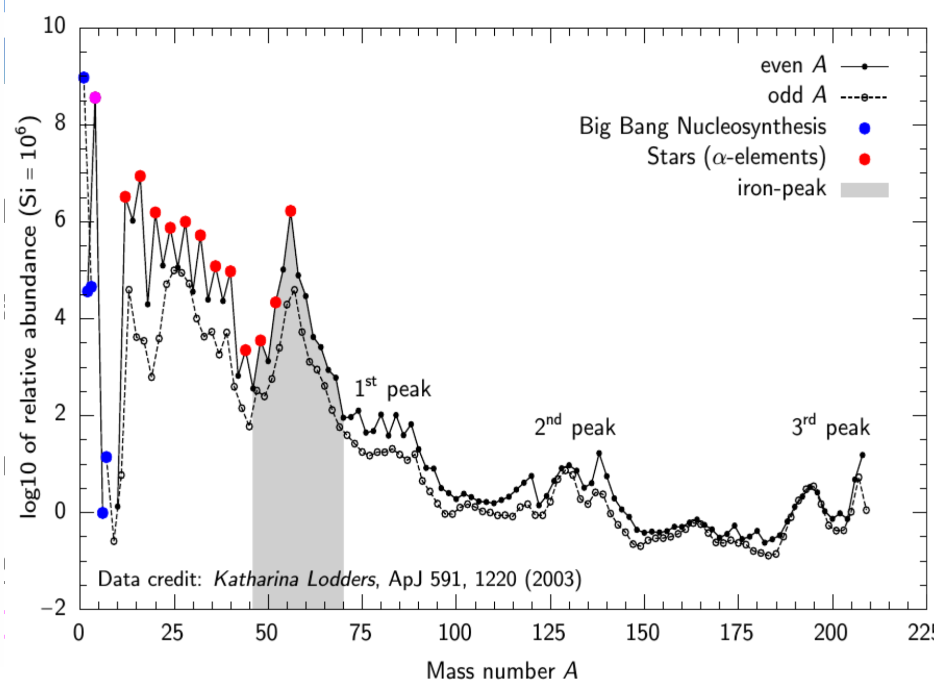
[Dietrich, Ujevic, SB+ (2017), Dietrich, SB, Ujevic+ (2017)]

Dynamical ejecta and nucleosynthesis









- Strong-field input from GR simulations (mass, kinetic energy) is essential !

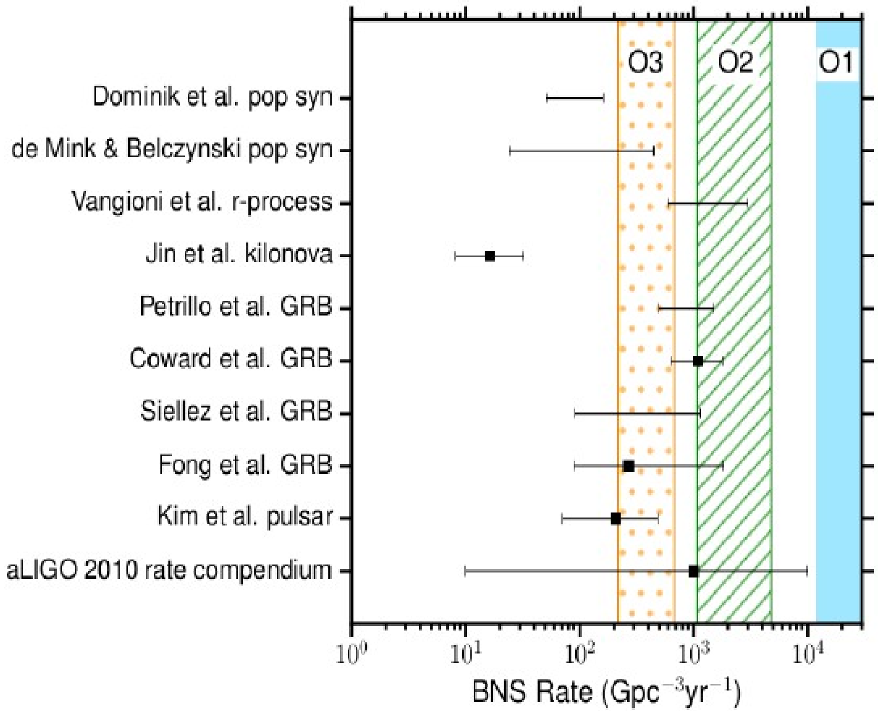
Days (after merger)

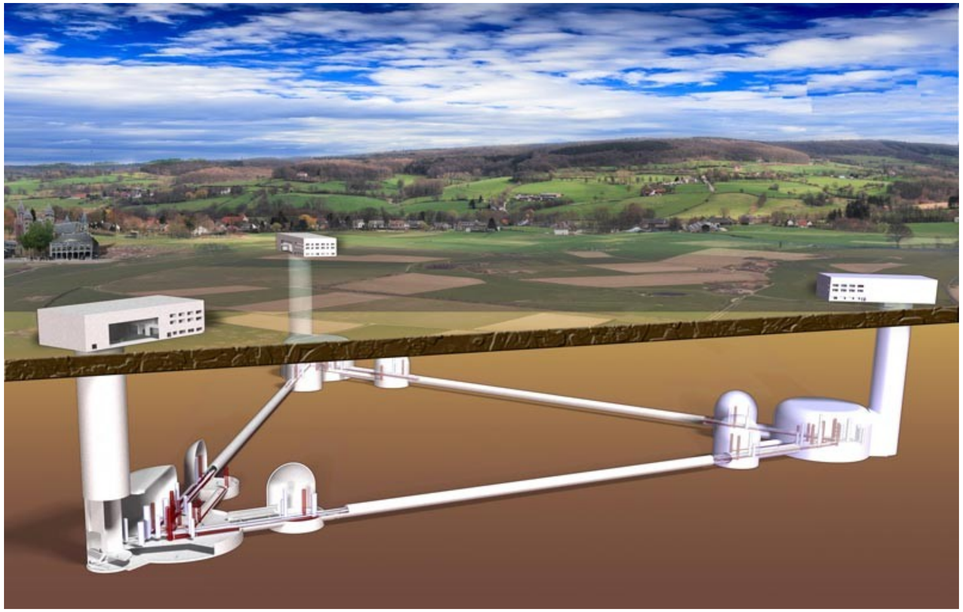
Future goals

- Model(s) for complete GW spectrum (generic spin, postmerger, etc)
- Interface with GW data-analysis and prepare for first detection
- Connect strong-field dynamics and GW signals to EM signatures

  [Dynamical ejecta, EOS & Microphysics, radiative aspects in simulations]
- Prepare next challenges: Einstein Telescope (LISA)

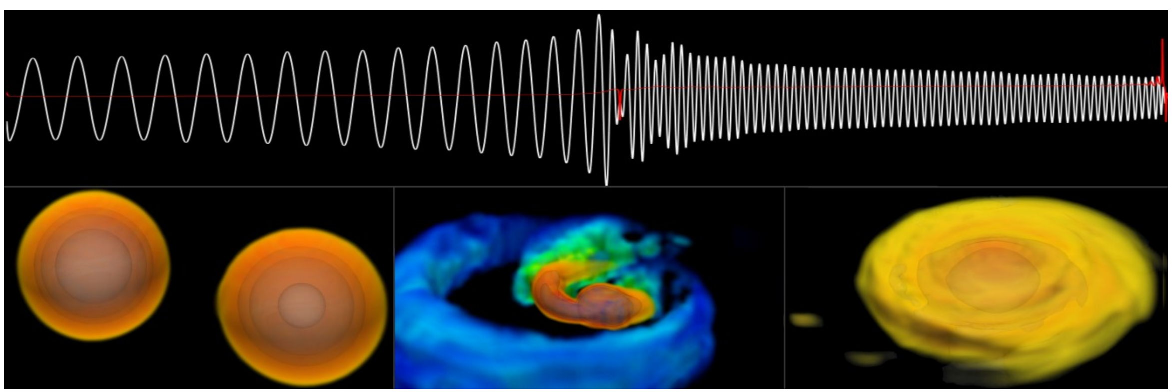
  [Accuracy, parameter space; new methods AR/NR]

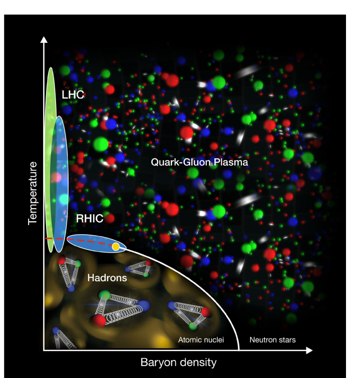


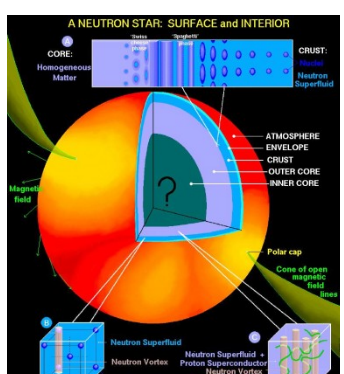


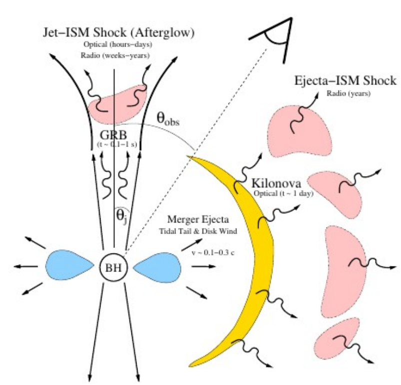
Summary

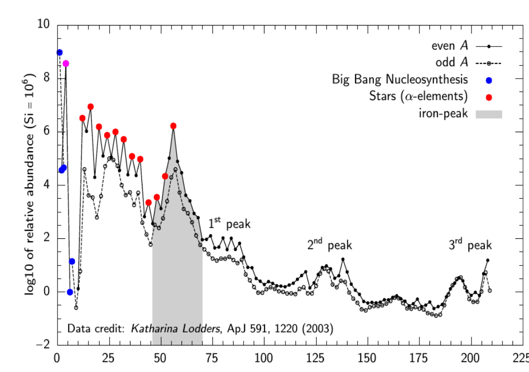
- Binary neutron stars key sources for GW astronomy
- Unique info about extreme matter
- GW measurements <u>require</u> precise waveform models
- Building GW models: interface analytical and numerical relativity method
- Strong-field GR-dynamics crucial input for electromagnetic emission models











Summary (waiting for detection...)

- Binary neutron stars key sources for GW astronomy
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- Building GW models: interface analytical and numerical relativity method
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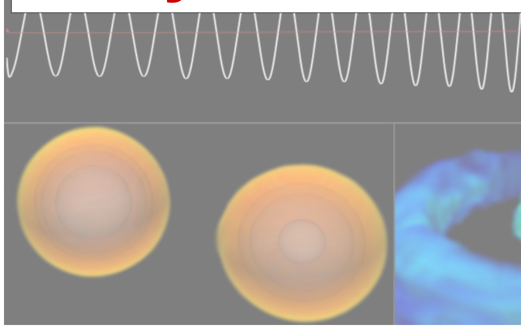
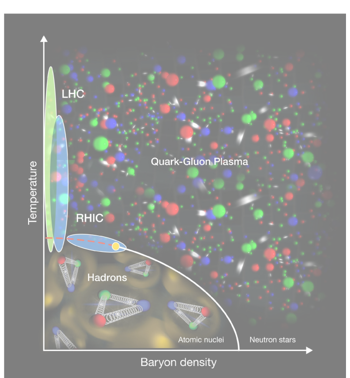
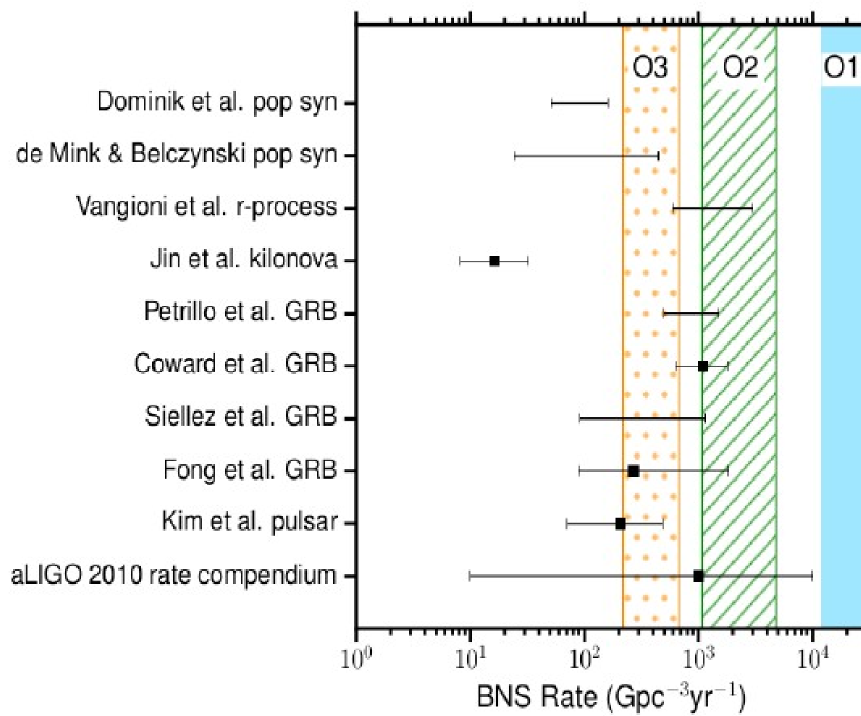
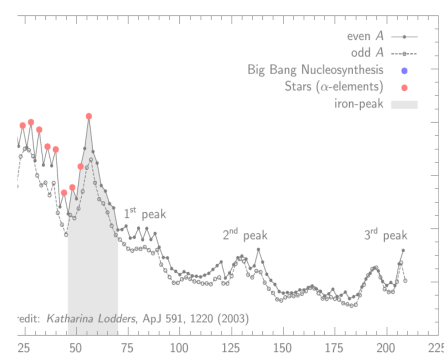
very exciting years for GR and GW science!

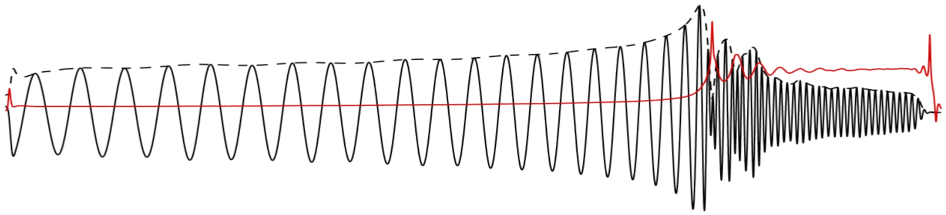








Next: a deeper connection to fundamental physics



Source parameters (event interpretation) - EQUATION OF STATE

?

nn - nnn interactions, QCD constraints, *and all that ...*