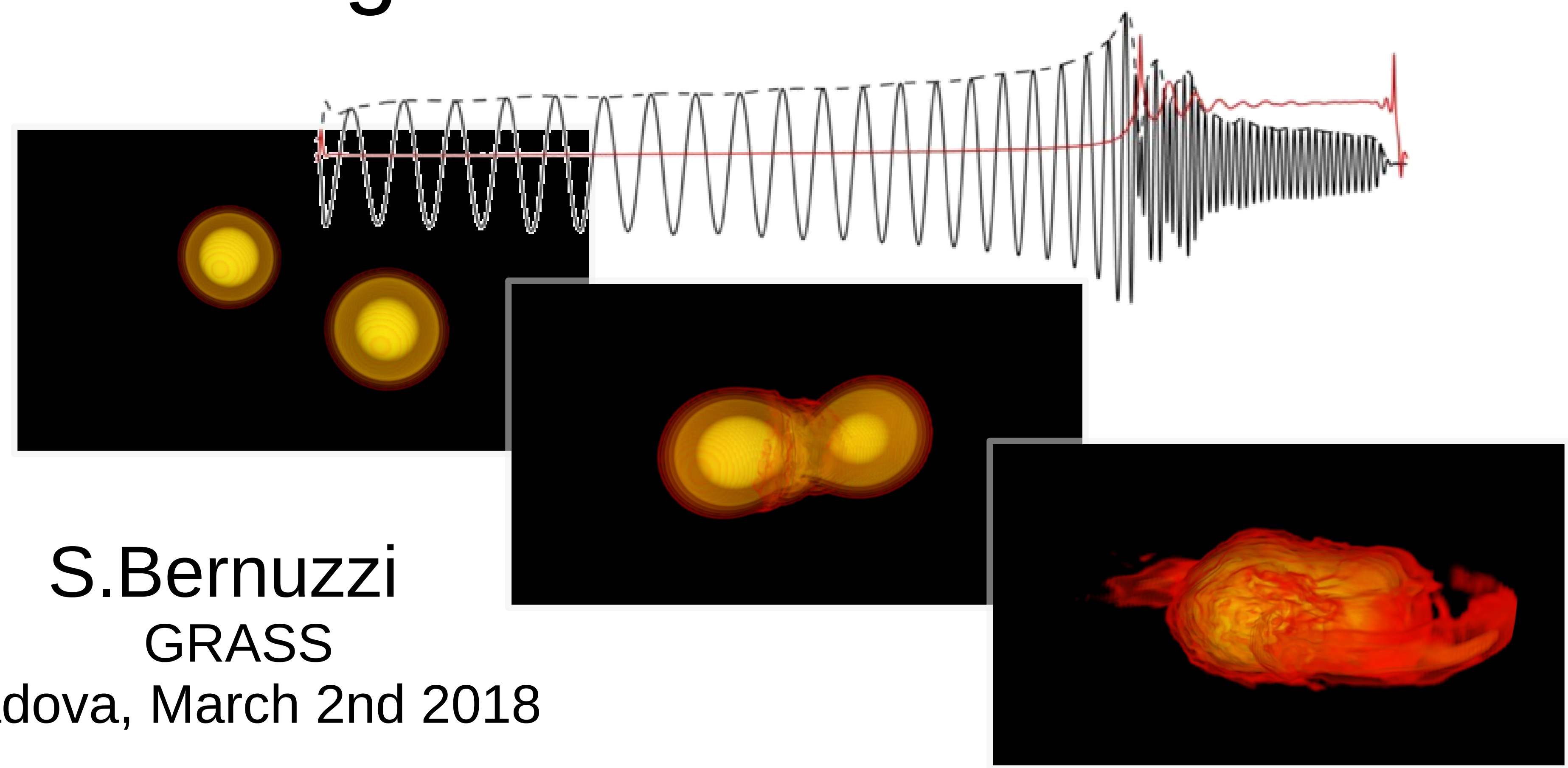
UNIVERSITÀ DI PARMA

INFN Istituto Nazionale di Fisica Nucleare

VIRGO

LIGO

Constraining extreme matter with gravitational waves



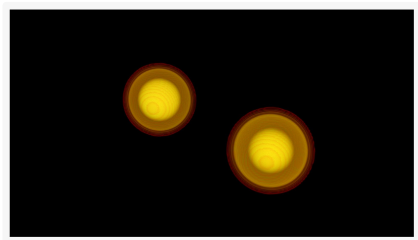
S.Bernuzzi

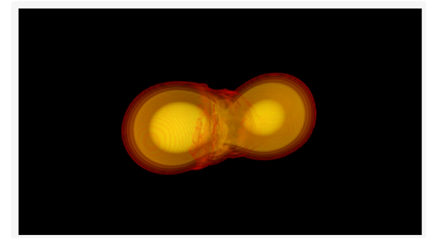
GRASS

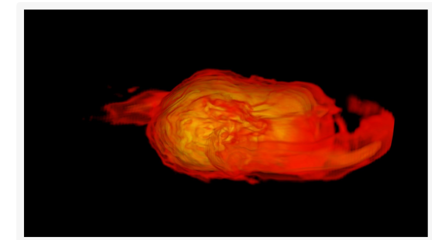
Padova, March 2nd 2018

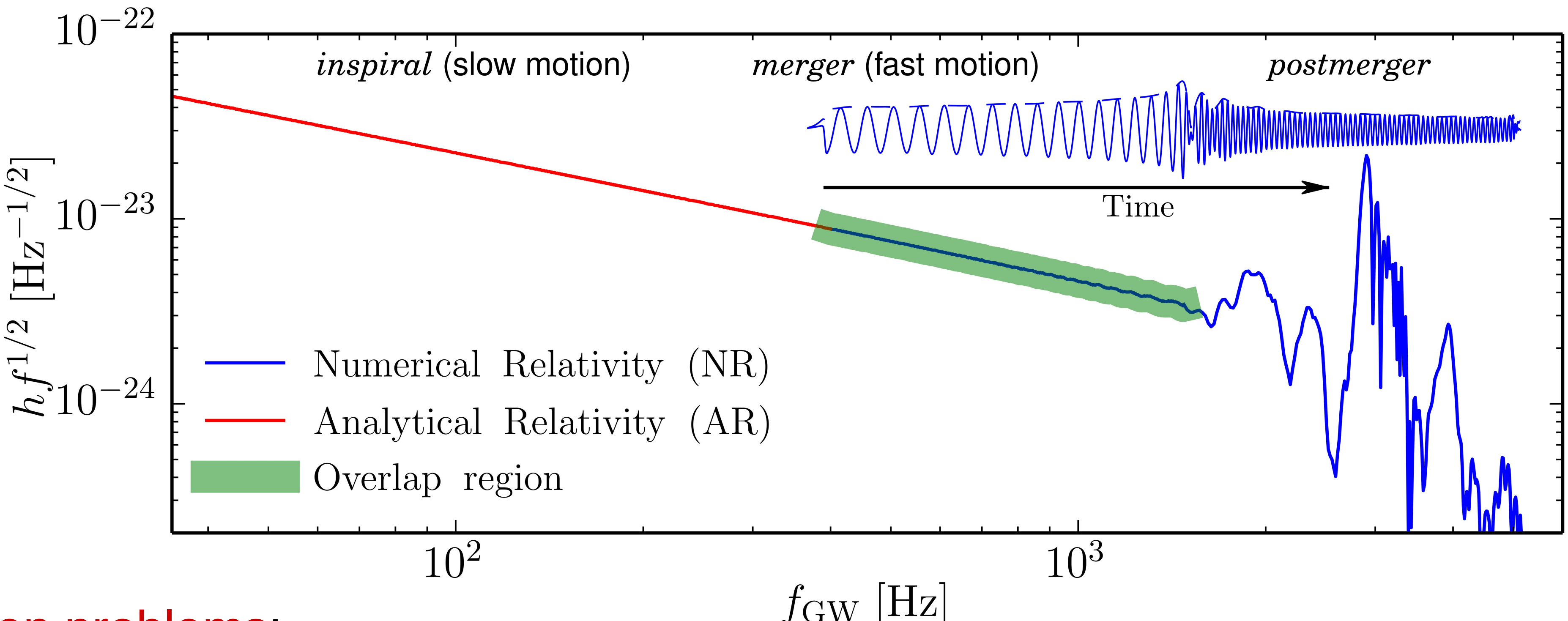
Note: [LVC] = Plots/figures from LIGO&Virgo collaboration

The GW spectrum of binary neutron stars





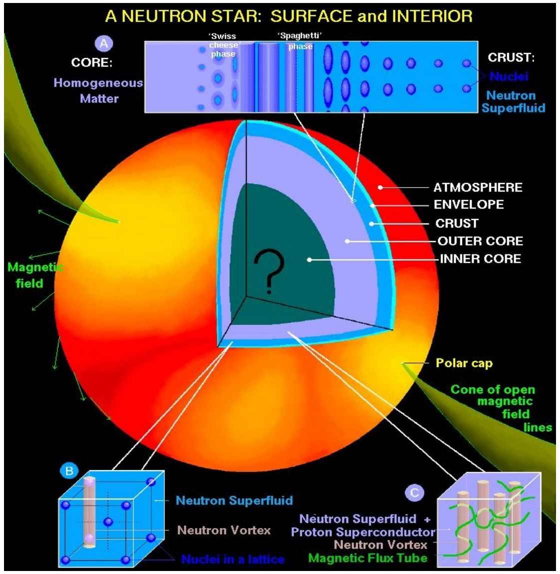




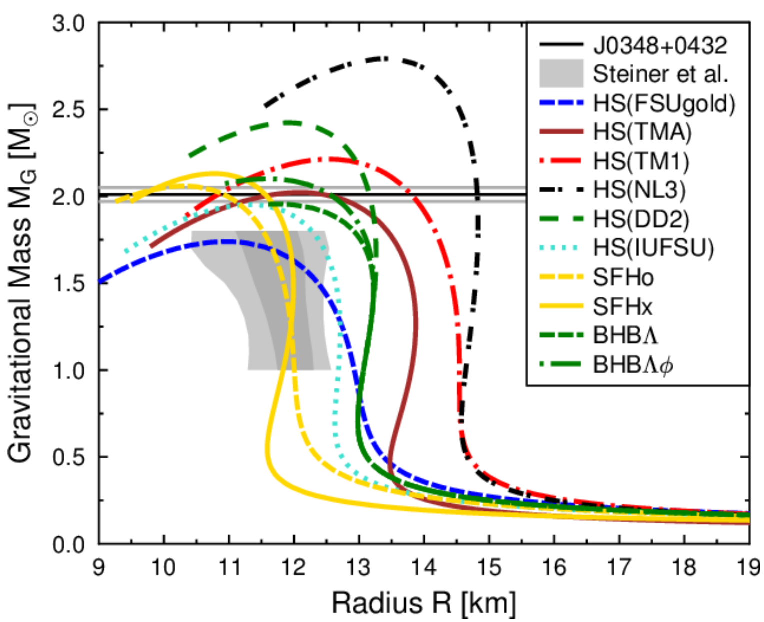
Open problems:

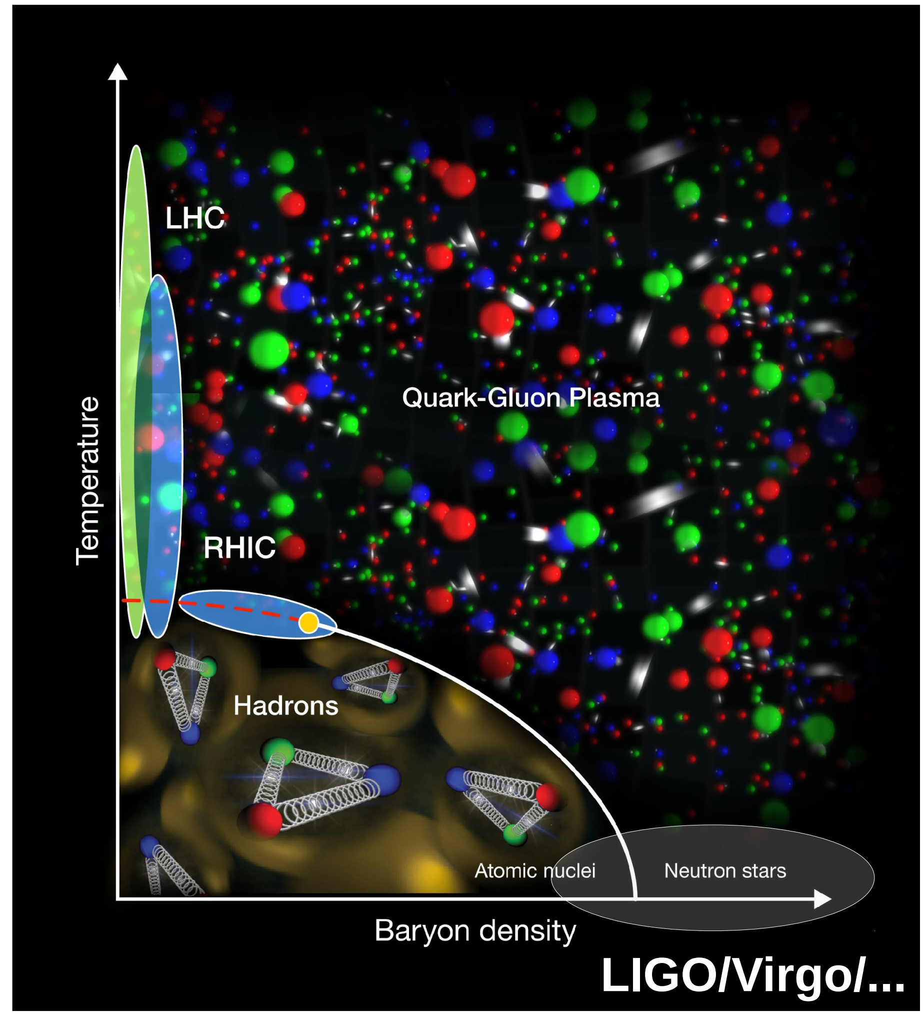
- Faithful and **complete waveform model** (*inspiral+merger+postmerger*)
- Coverage of the **parameter space** (mass, spins, EOS, …)
- Precise prediction of the merger remnant

What can we say about neutron star matter?



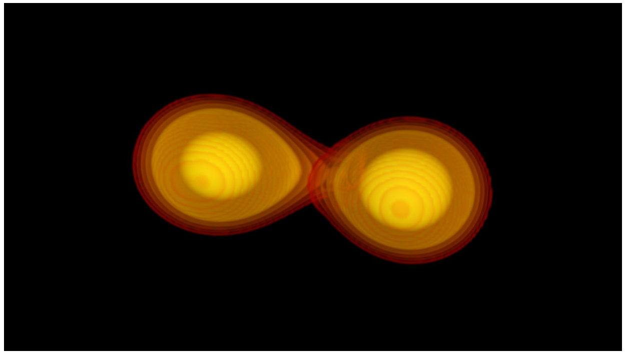
Different EOS → different star's structure

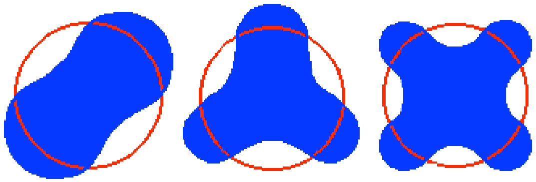




Binary neutron star mergers

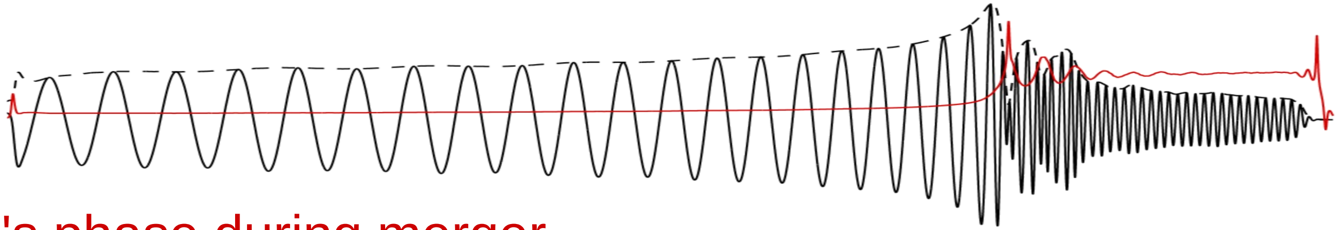
Observing tidal effects in GWs tells us about the neutron star matter





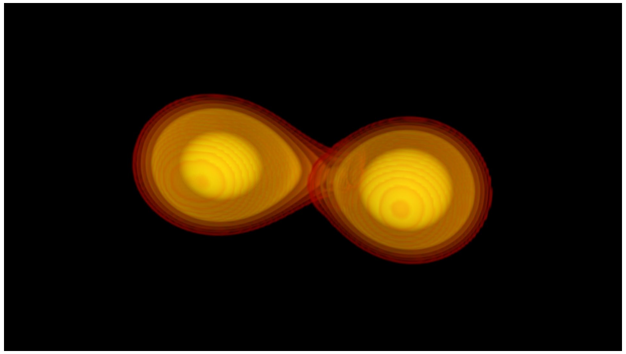
Tides depend critically on EOS

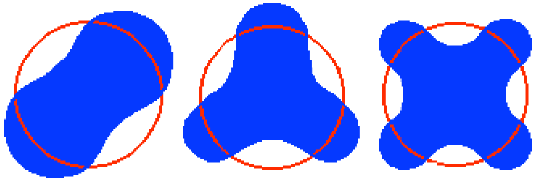
$$Q_{ij} = \lambda_2 G_{ij} \sim \lambda_2 \partial_i \partial_j \phi$$



Tides determine the wave's phase during merger

Observing tidal effects in GWs tells us about the neutron star matter





Tides depend crucially on EOS

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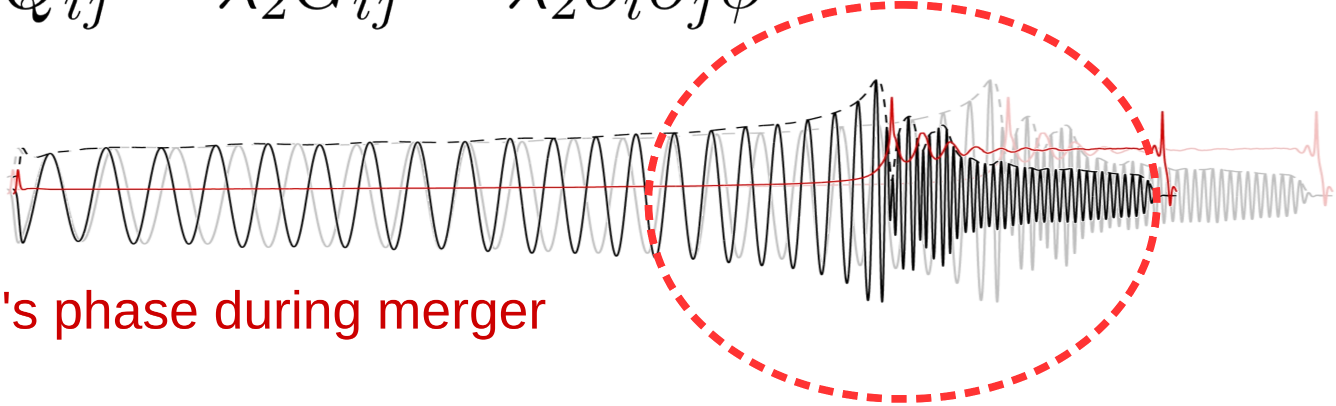

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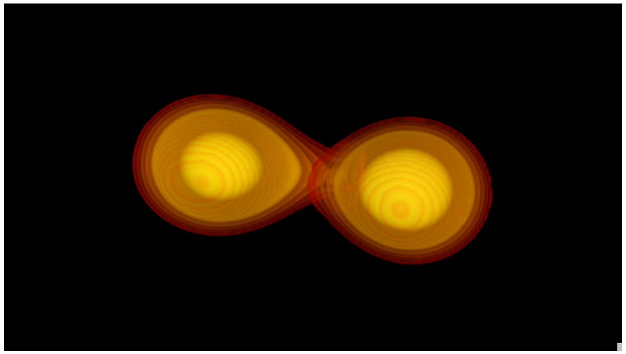
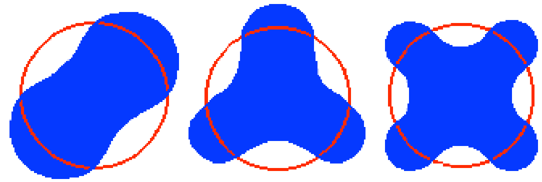
Observing tidal effects in GWs tells us about the neutron star matter





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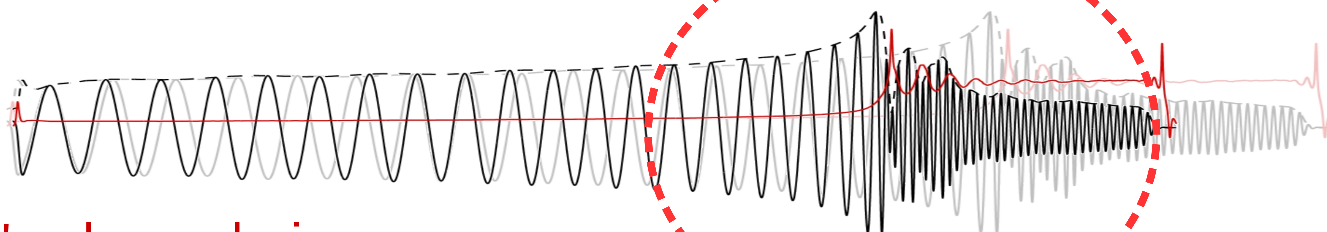
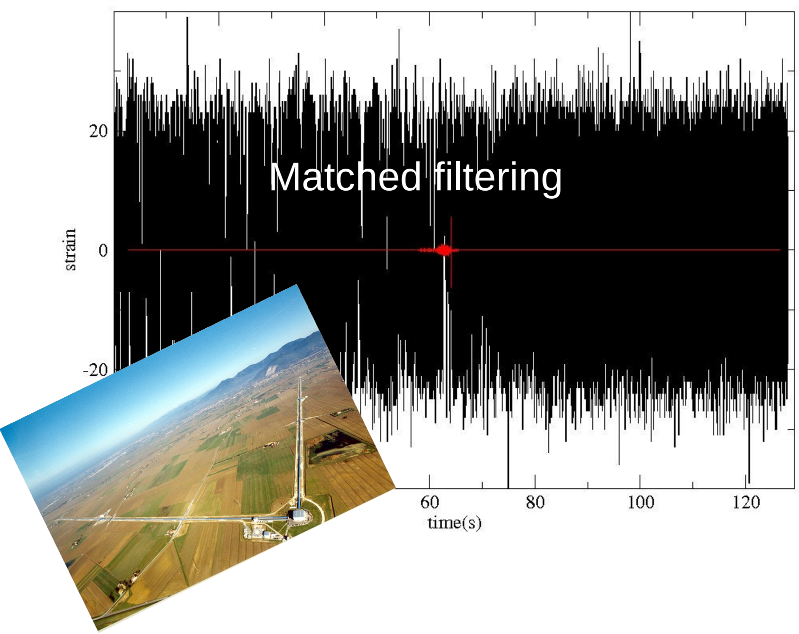
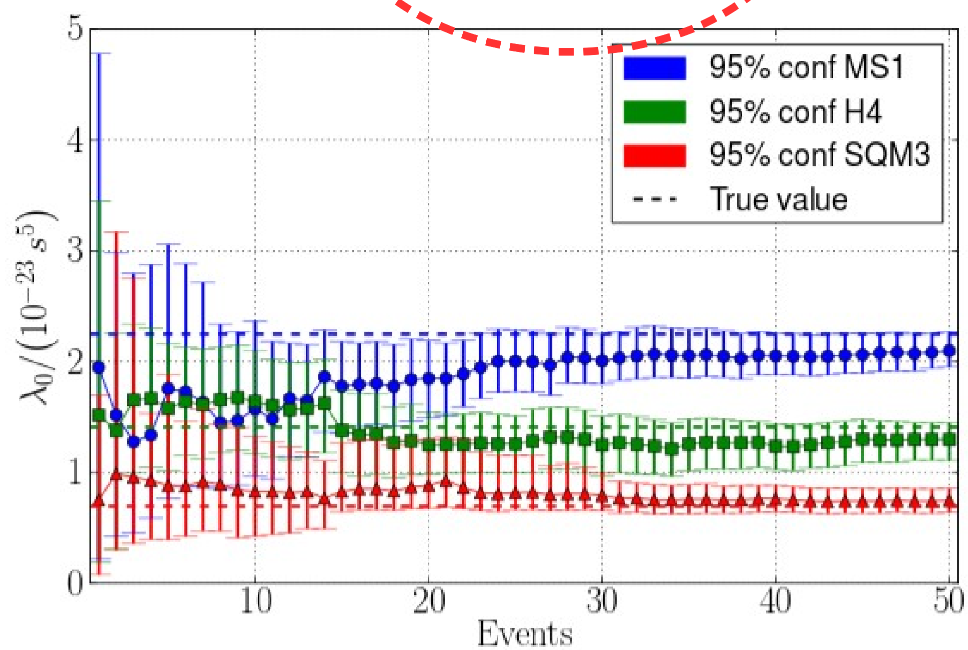
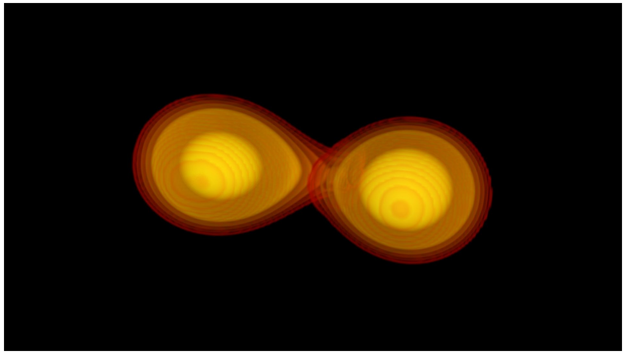


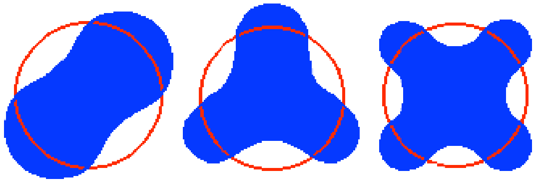
Tides determine the wave's phase during merger



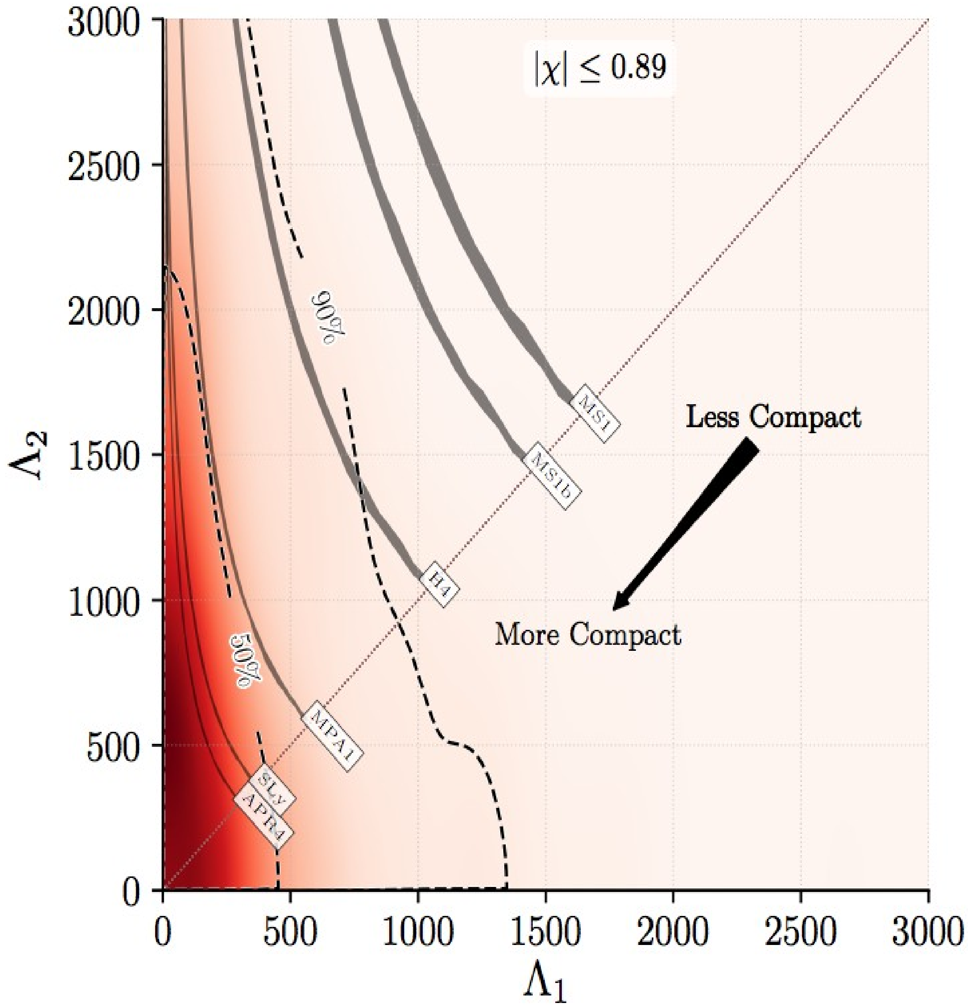


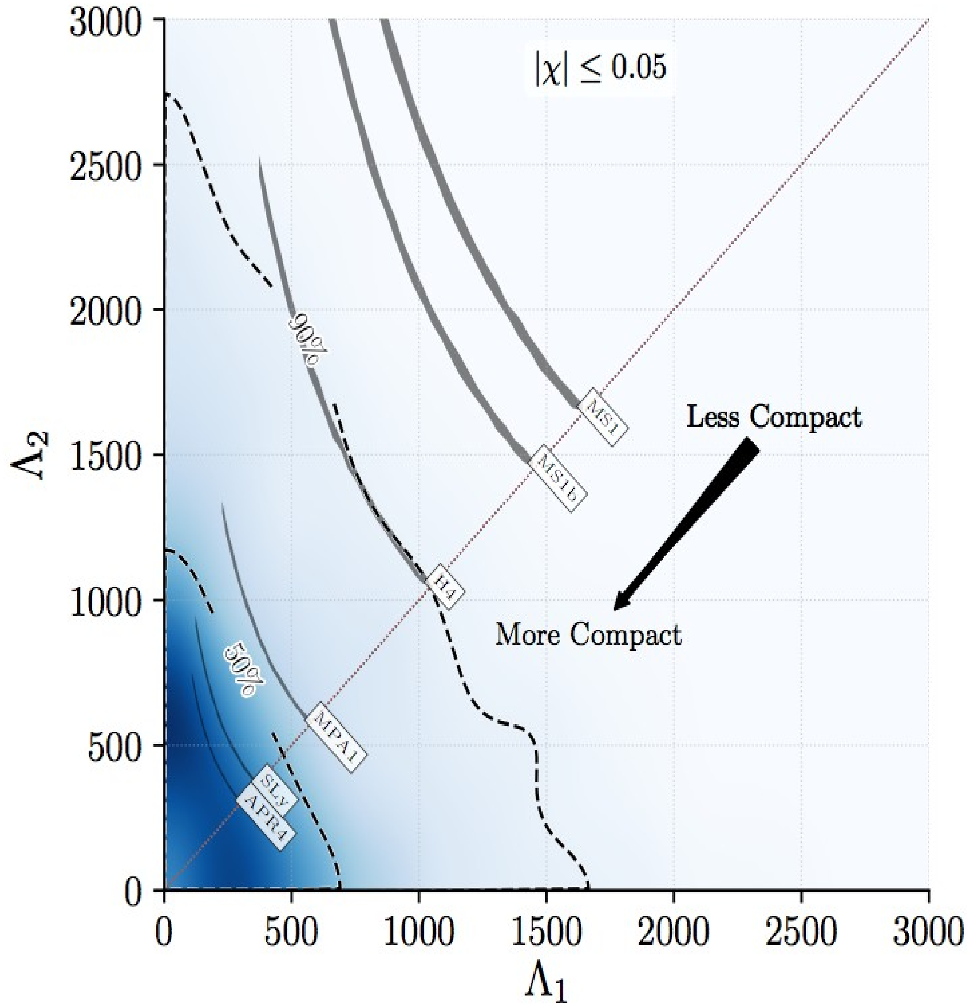
[Del Pozzo+ PRL 111 (2013)]





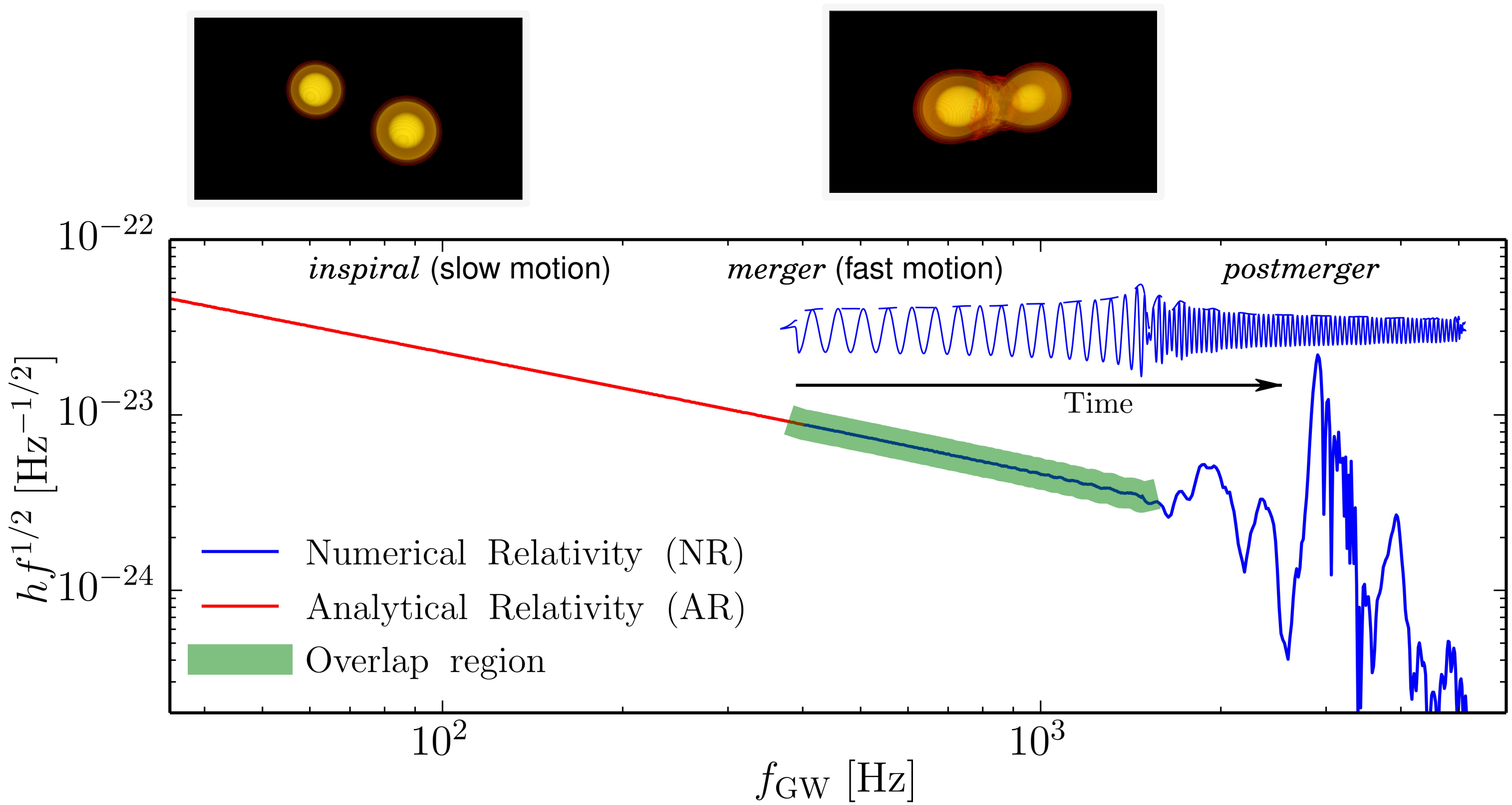
$$\lambda_2 \propto \frac{Q_{ij}}{\partial_{ij}\Phi_{ext}}$$



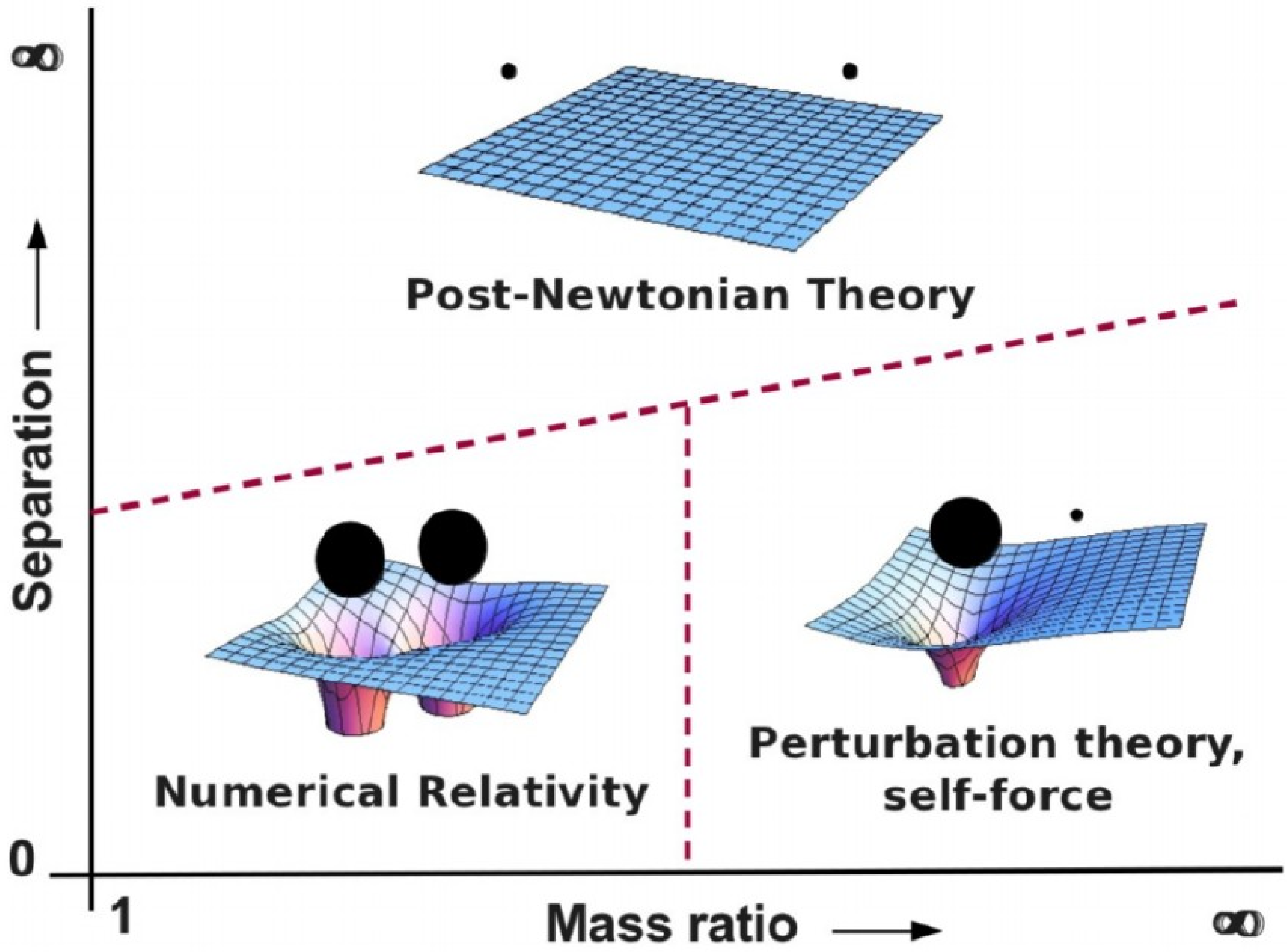


[LIGO&Virgo collab. Phys. Rev. Lett. 119, 161101 (2017)]

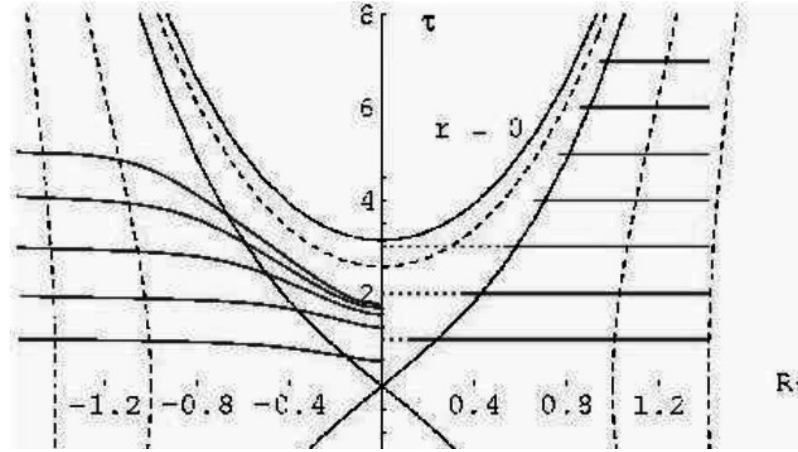
inspiral → merger - postmerger



Methods for the GR 2-body problem



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



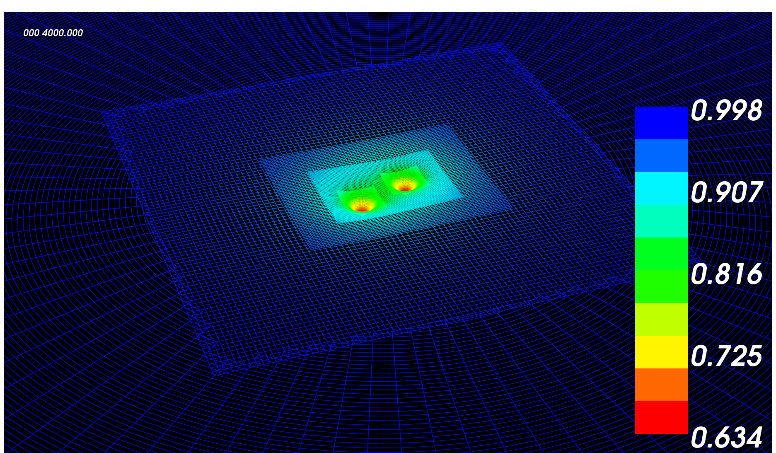
GR Formulation and Cauchy problem
+ GR hydrodynamics

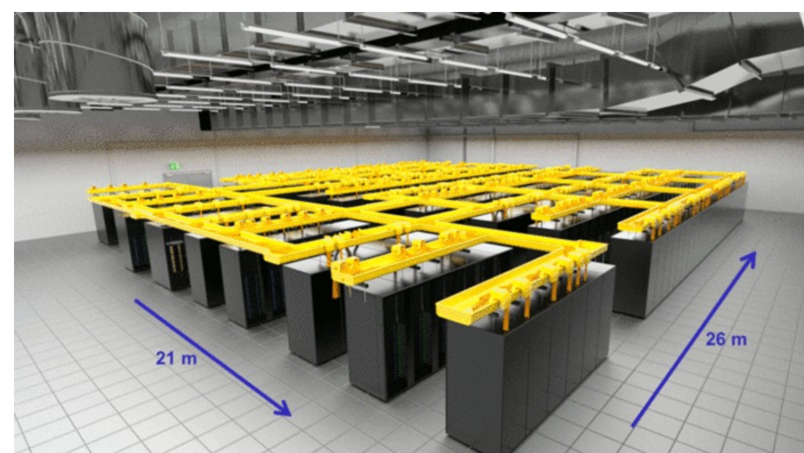
Coordinates and Singularities

Numerical relativity in a nutshell

Numerical methods for PDEs on adaptive grids

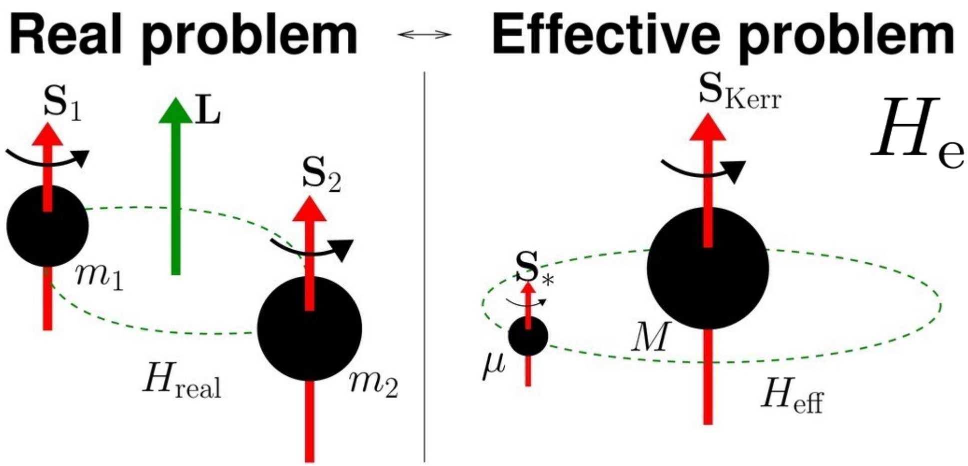
High-performance-computing (HPC)





Effective-One-Body

[Buonanno&Damour PRD 1999,2000]



Credit: A.Taracchini/AEI

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

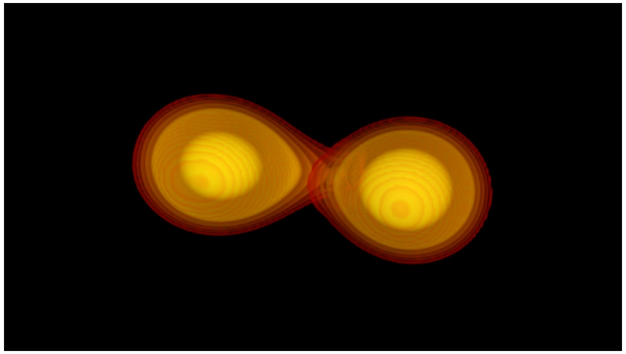
$$A(u;\nu;\kappa_2^T) = A^0(u;\nu) + A^T(u;\nu;\kappa_2^T)$$

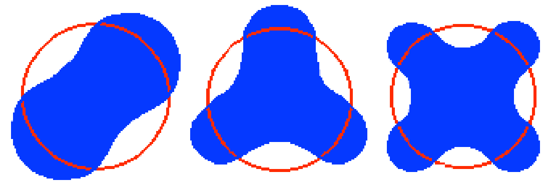
$$A^0(u;\nu) = 1 - 2u + \nu(\ldots$$

- 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:

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

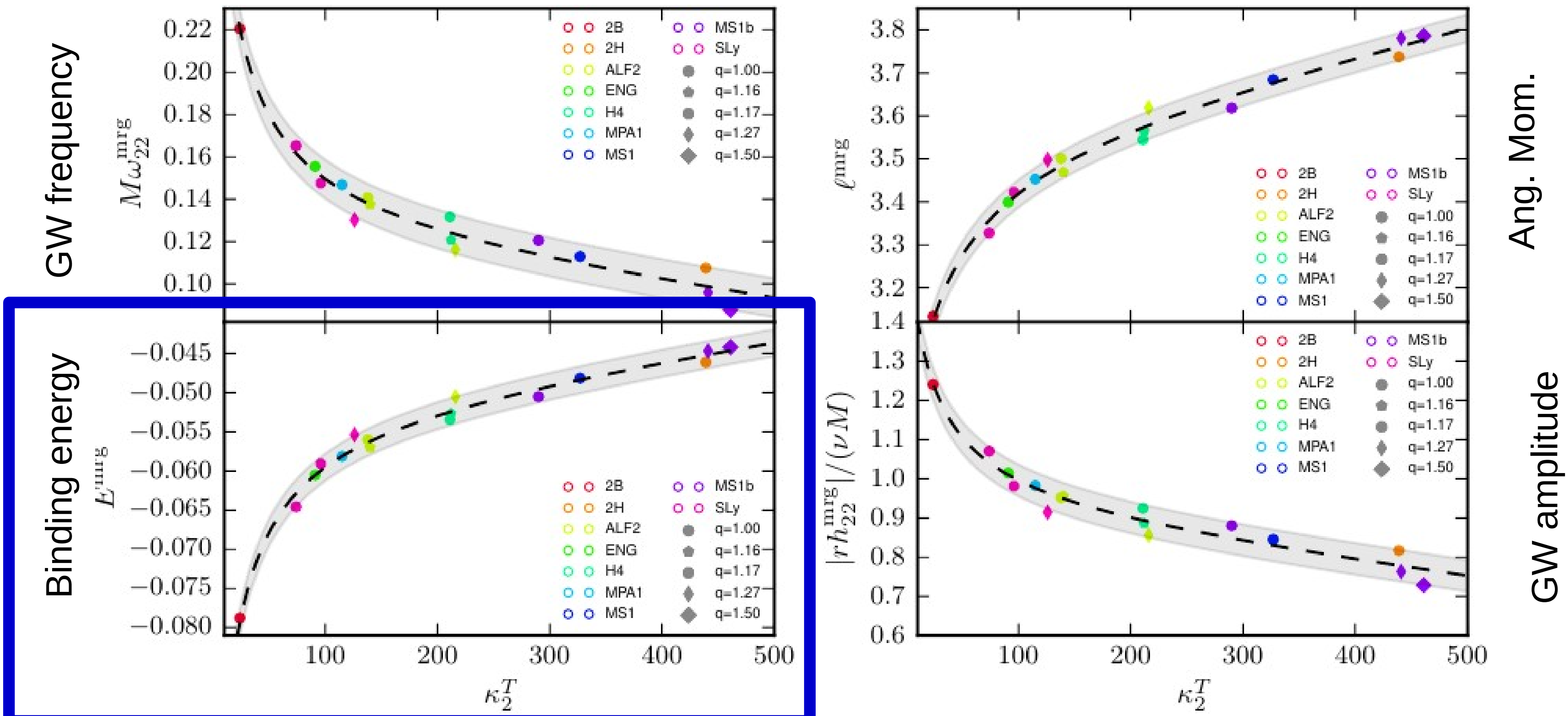
Key point: No other binary parameter (mass, radii, etc) enter separately the formalism

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)

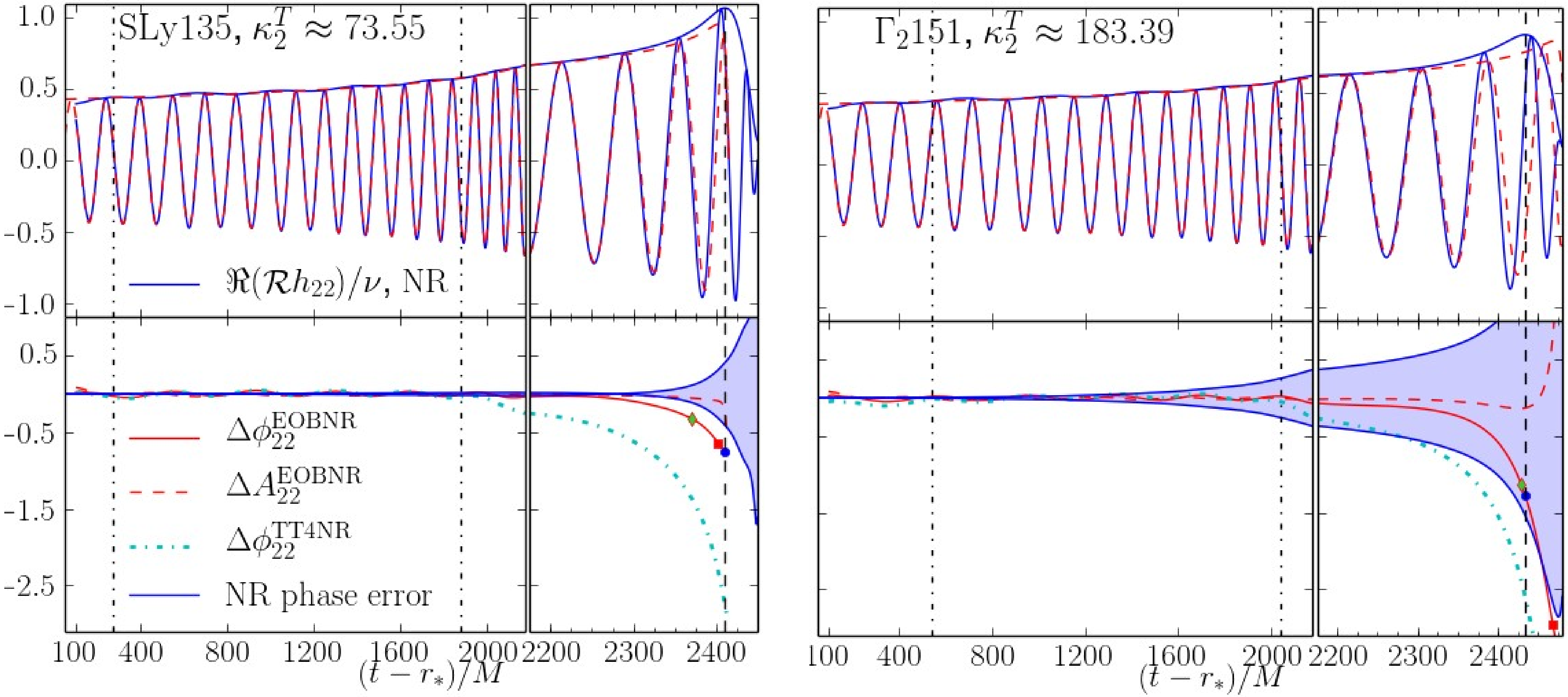
Predict energy emitted for given binary by specifying solely the kappa value



Tidal polarizability coef. (l=2)

First waveform model for inspiral → merger

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

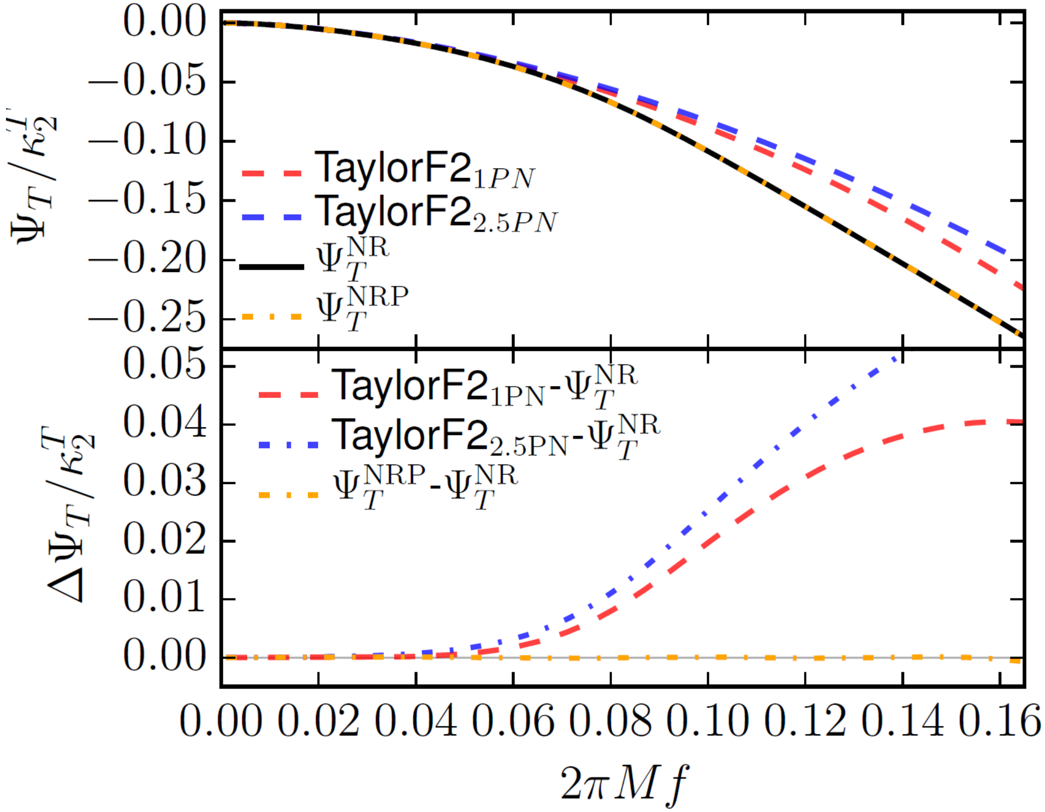


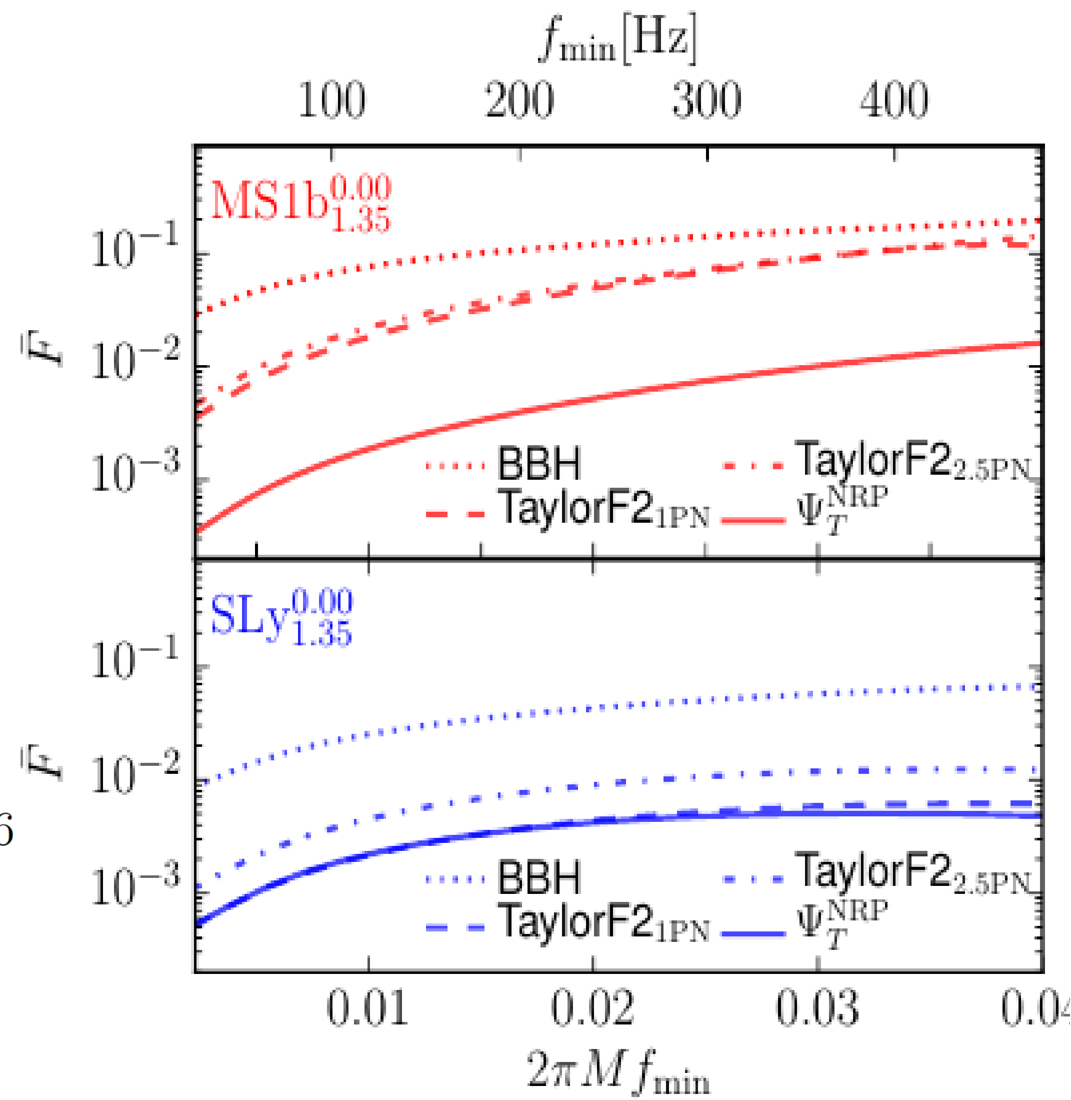
- Effective-one-body model with tides, GSF Resummed approach [Bini+ 2014]
- Valid from low frequencies to merger, PREDICT the merger waveform
- Accuracy: uncertainties of the numerical data (improve simulations!)

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

Closed-form tidal approximants PN+EOB+NR

[Dietrich, SB, Tichy PRD 96 121501 (2107)]

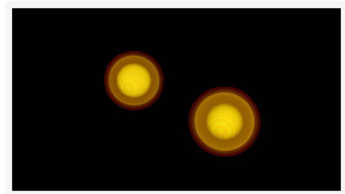


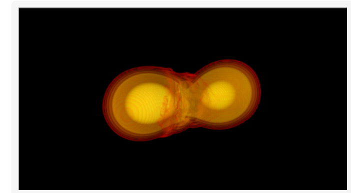


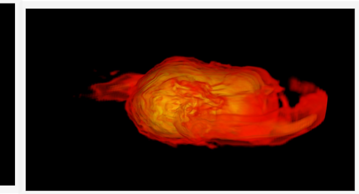
First NR-based tidal approximant
Fast, flexible, accurate

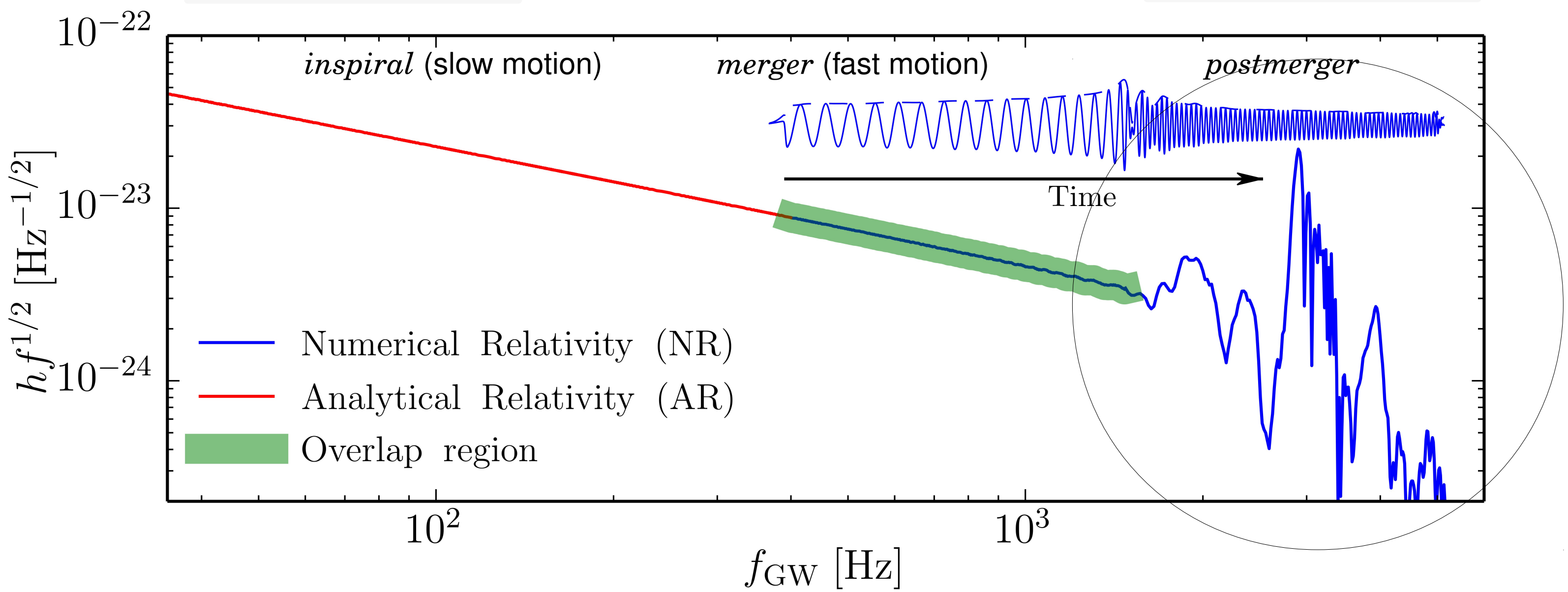
Used for GW170817 analysis

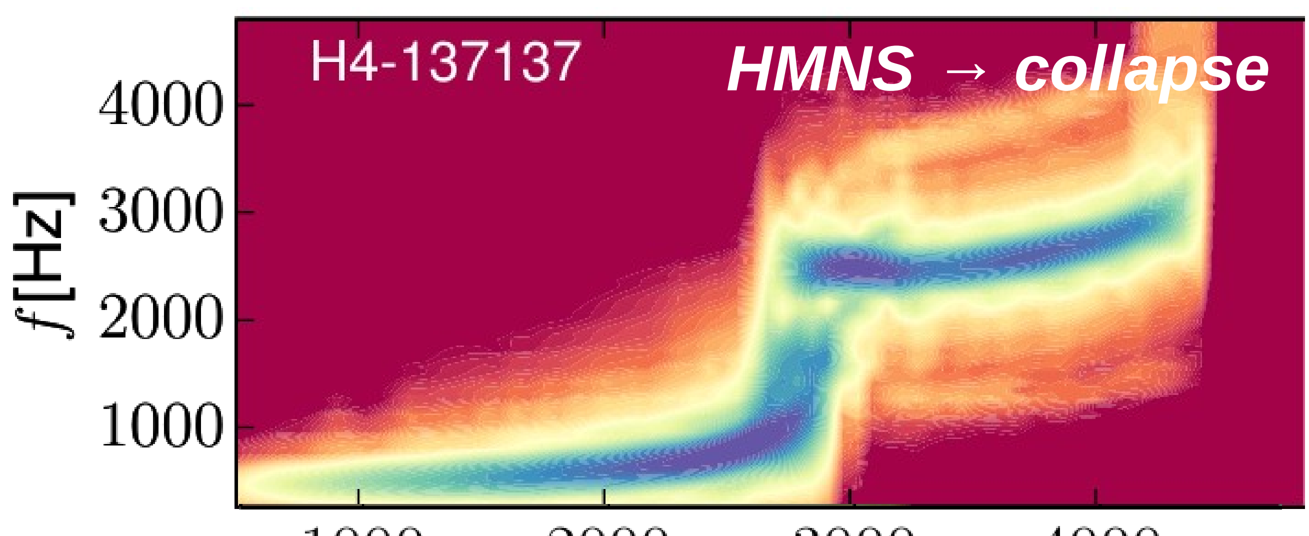
Inspiral - merger → postmerger





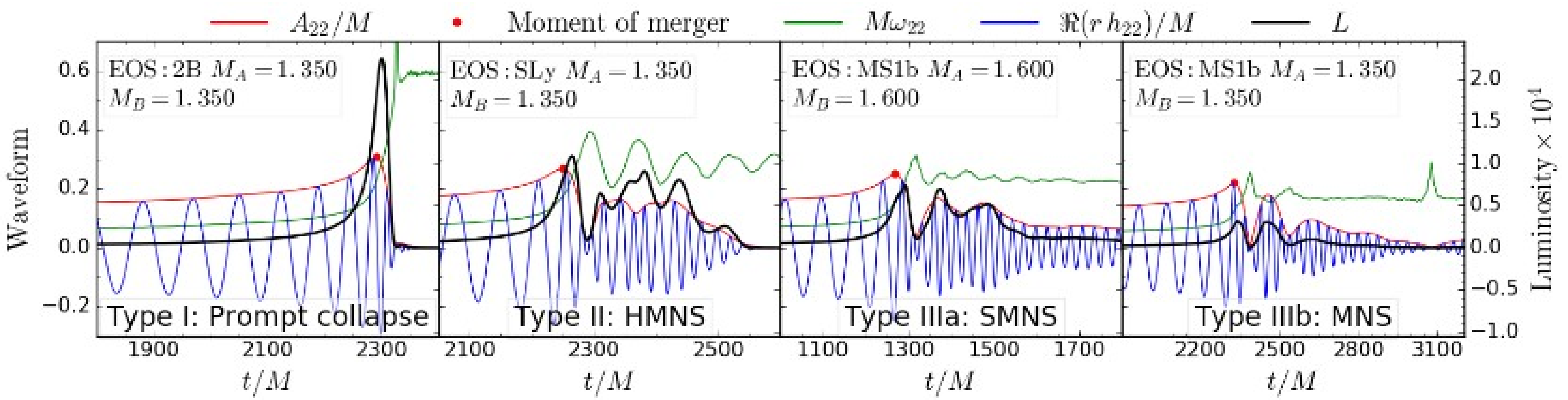




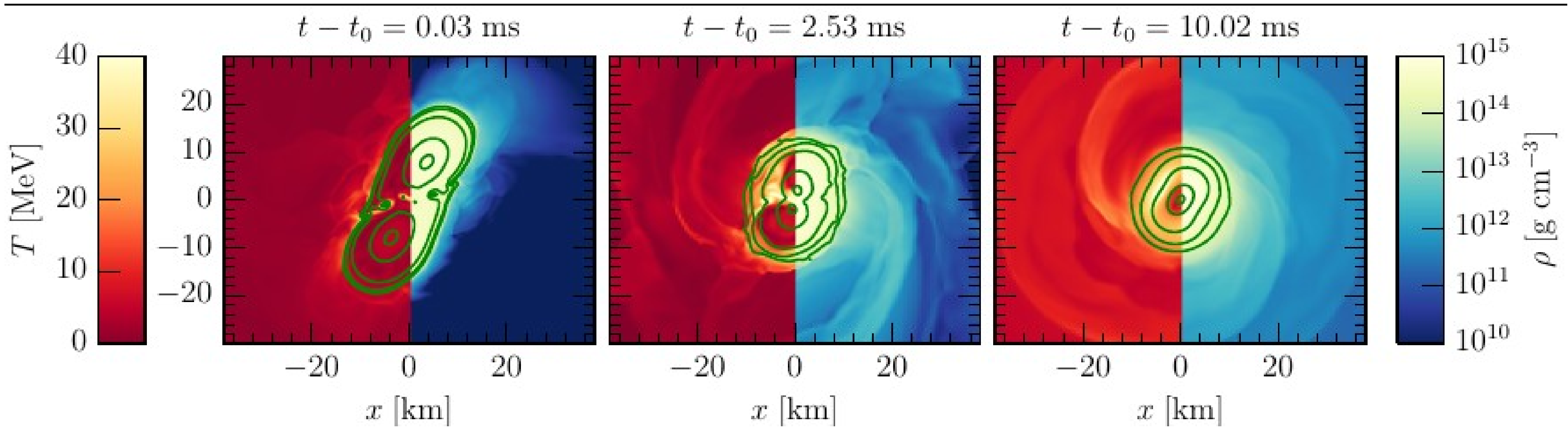


Remnant HMNS is the loudest GW phase

[Zappa, SB, Radice, Perego, Dietrich arxiv:1712.04267]

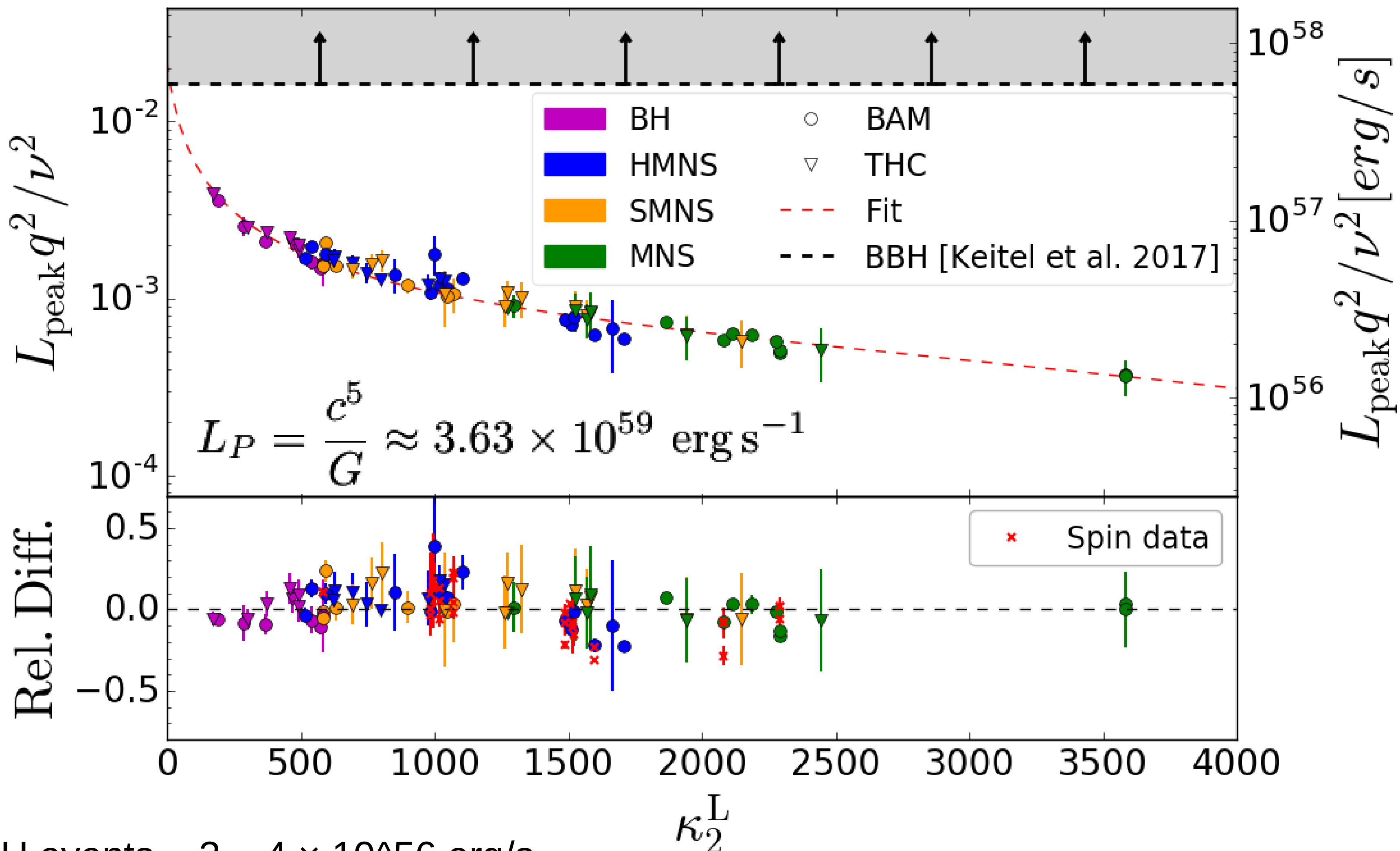


[SB, Radice, Ott, Roberts, Moesta, Galeazzi PRD94 024023 (2016)]



Compact binaries are the most luminous events

[Zappa, SB, Radice, Perego, Dietrich arxiv:1712.04267]

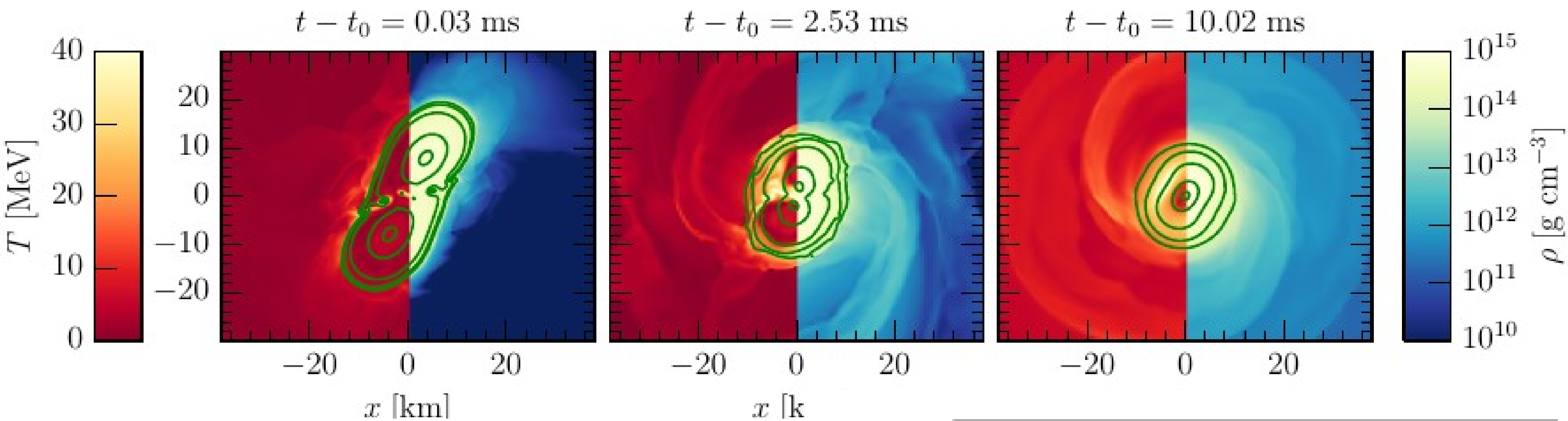


- BBH events ~ 3 − 4 × 10^56 erg/s
- Simple description of all simulated BNS based on tidal parameter
- Estimate for GW170817:

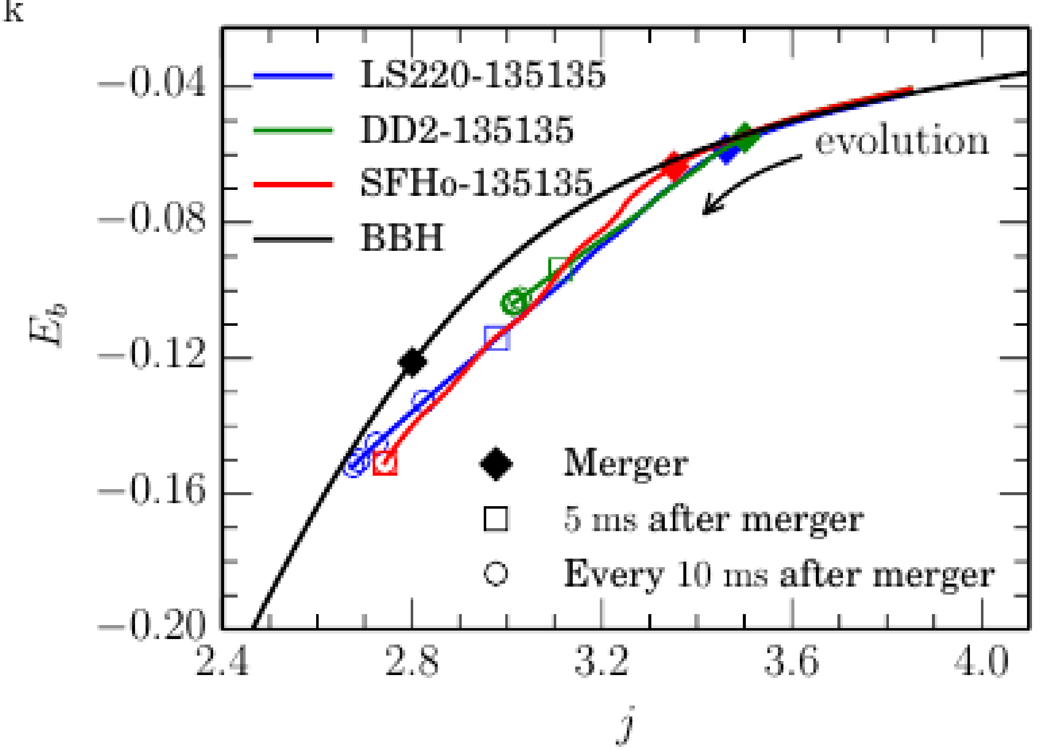
$$9.896 \times\ 10^{54}\mathrm{erg/s} \lesssim L_{\rm peak} \lesssim 4.940 \times\ 10^{56}\ \mathrm{erg/s}$$

Remnant HMNS is the loudest GW phase

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



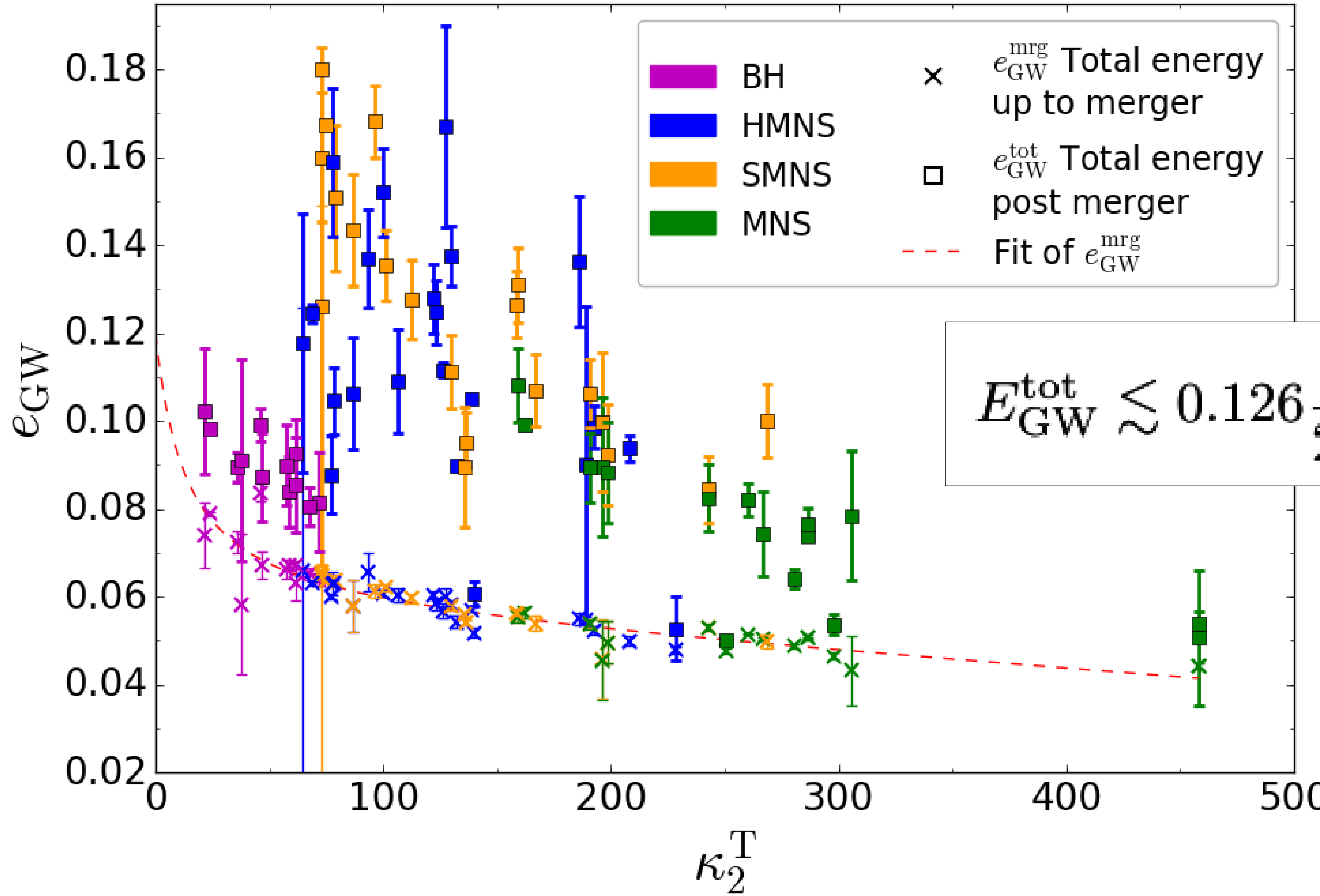
- Emission is FAST: τ_{GW}~ 20 ms
- Emission is LOUD: E(HMNS) ~ 2x E(merger)
- Most of the power is emitted at frequency ~ 2 x (Rotational frequency @ formation)



Simulations w/ microphysics & neutrinos

Upper limit on total energy emitted

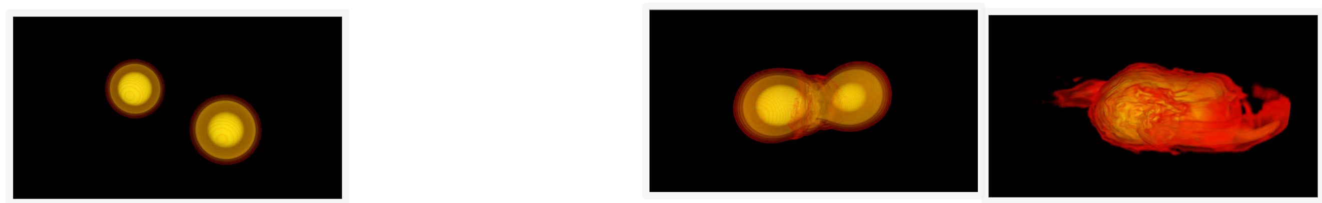
[Zappa, SB, Radice, Perego, Dietrich arxiv:1712.04267]

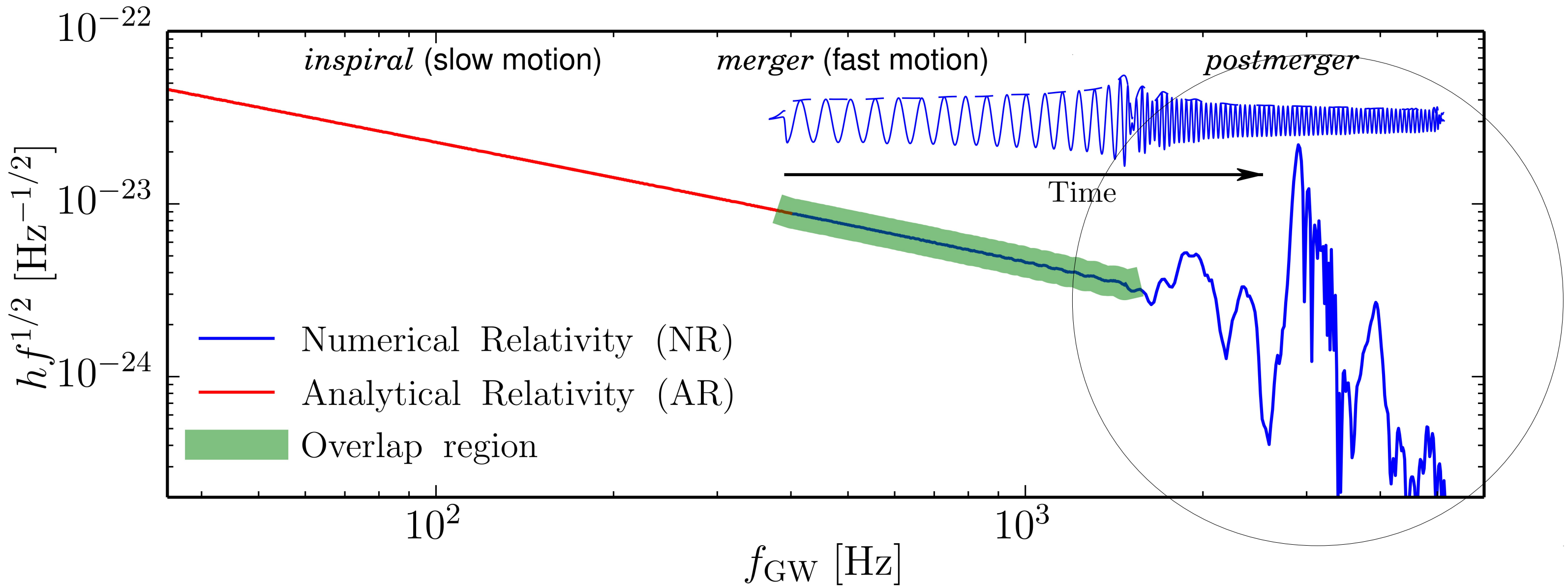


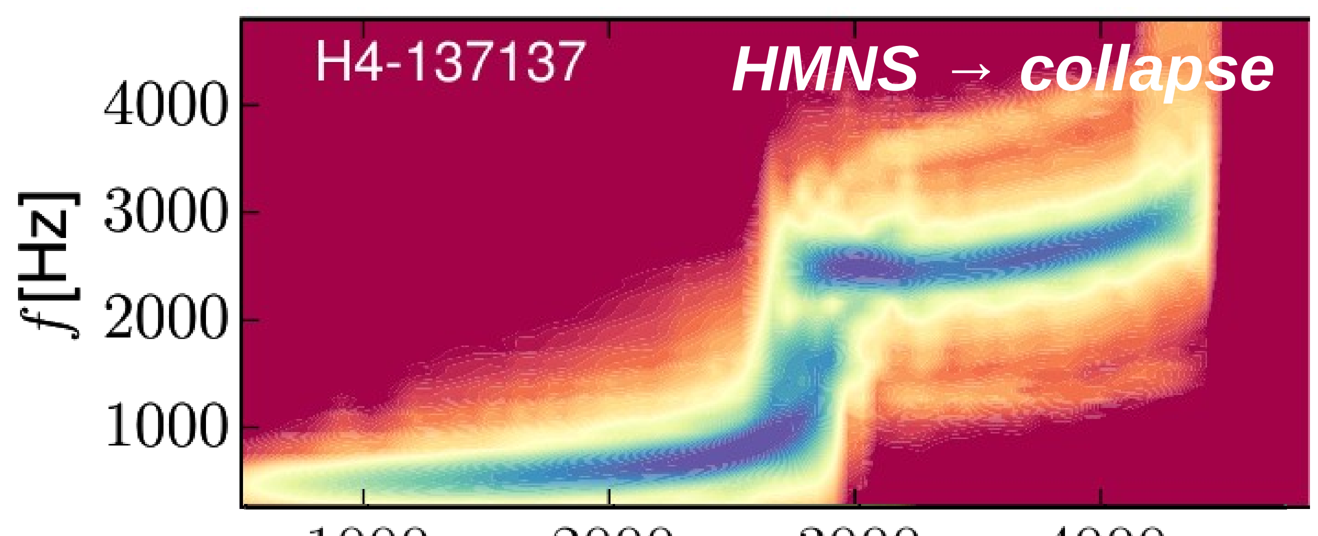
$$E_{\rm GW}^{\rm tot} \lesssim 0.126 \frac{M}{2.8} \ \mathrm{M_\odot c^2}$$

- Merger energy simple description based on tidal parameter [SB+ PRL 2014]
- Upper limit on total energy → postmerger is not detectable by LIGO/Virgo
- BBH events ~ 1-3 Msun c^2

Inspiral - merger → postmerger

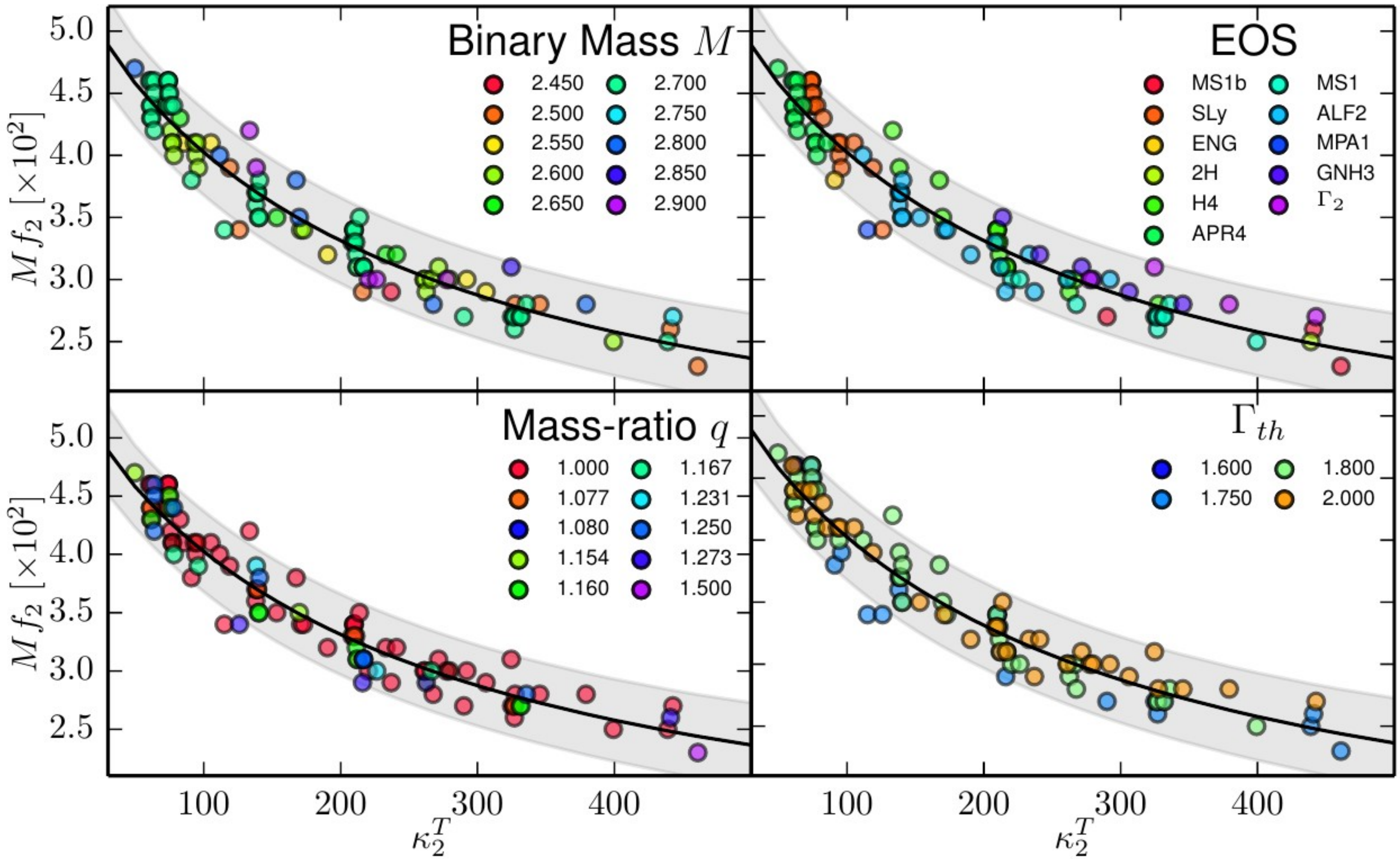






Peak frequency correlates to κ^T_2

[SB, Dietrich, Nagar PRL 115 091101 (2015)]



- Large NR dataset (~100, 3 codes) [Hotokezaka+ arXiv:1307.5888, Takami+ arXiv:1403.5672]
- Conceptually “compatible” with inspiral-merger (cf. TEOB)
- Postmerger frequencies essentially dependend on *merger* physics

One-armed instability

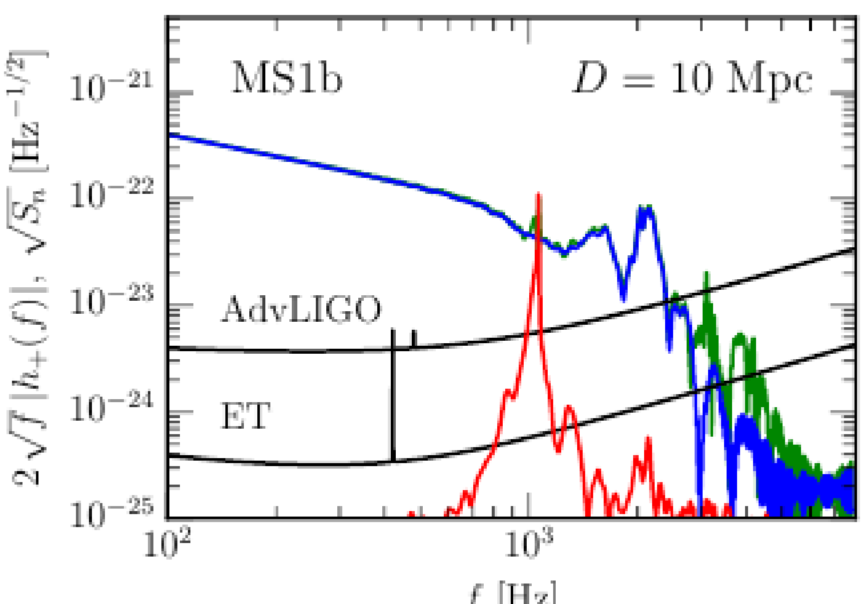
- m=1, Generic: single stars, supernovae cores, eccentric mergers

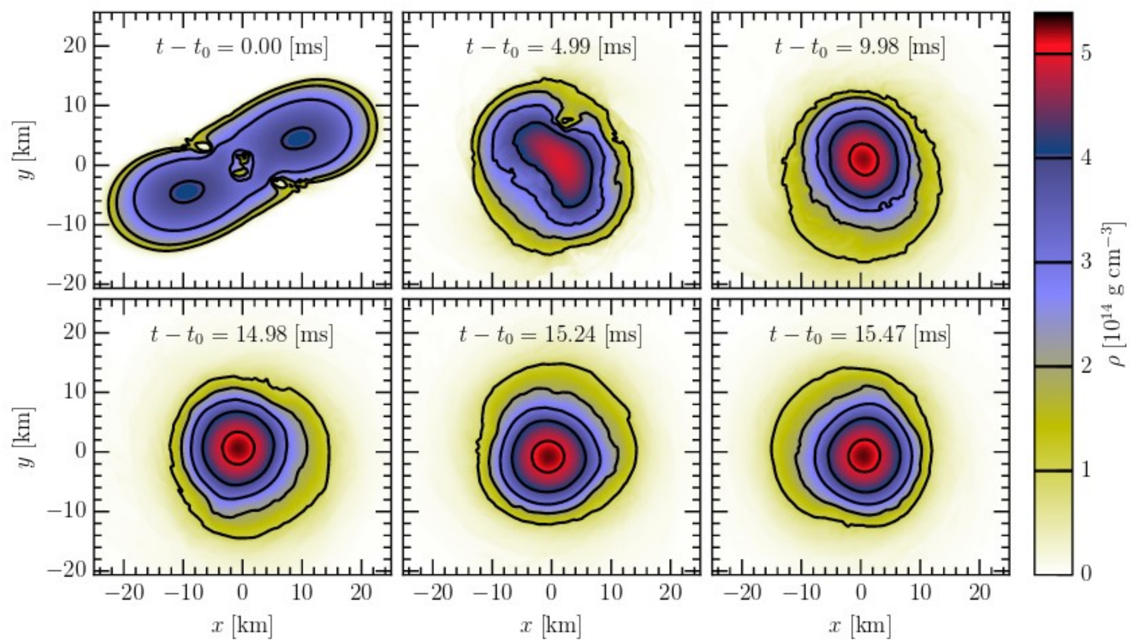
  e.g. […,Paschalidis, East+ 2015 arXiv:1511.01093, Radice+, arXiv:1603.05726, Lehner+ arXiv:1605.02369]

- **Not an efficient GW emitter**
- Inspiral-triggered search might improve [Lehner+ arXiv:1605.02369]

Detector	Binary	SNR	$\mathrm{SNR}_{2,1}$	$\mathrm{SNR}_{2,2}^{f\geq 1\,\mathrm{kHz}}$
Adv. LIGO	MS1b-M135-Q1	169.4	1.6	5.4
Adv. LIGO	SLy-M135-Q1	169.5	0.1	6.9
ET	MS1b-M135-Q1	2460.5	14.4	47.4
ET	SLy-M135-Q1	2461.6	1.0	61.3

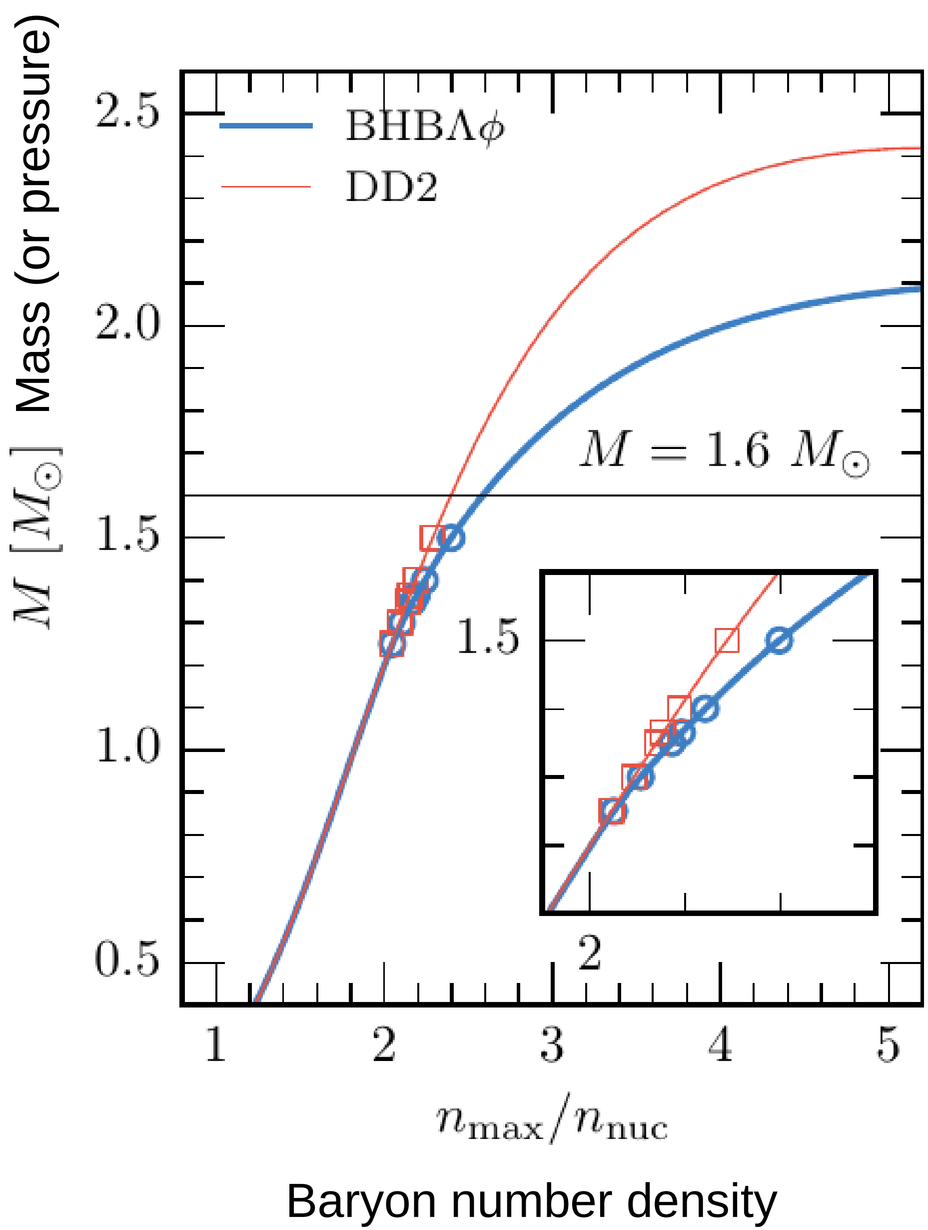
[Radice, SB, Ott, arXiv:1603.05726]





Merger remnant reaches extreme densities

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



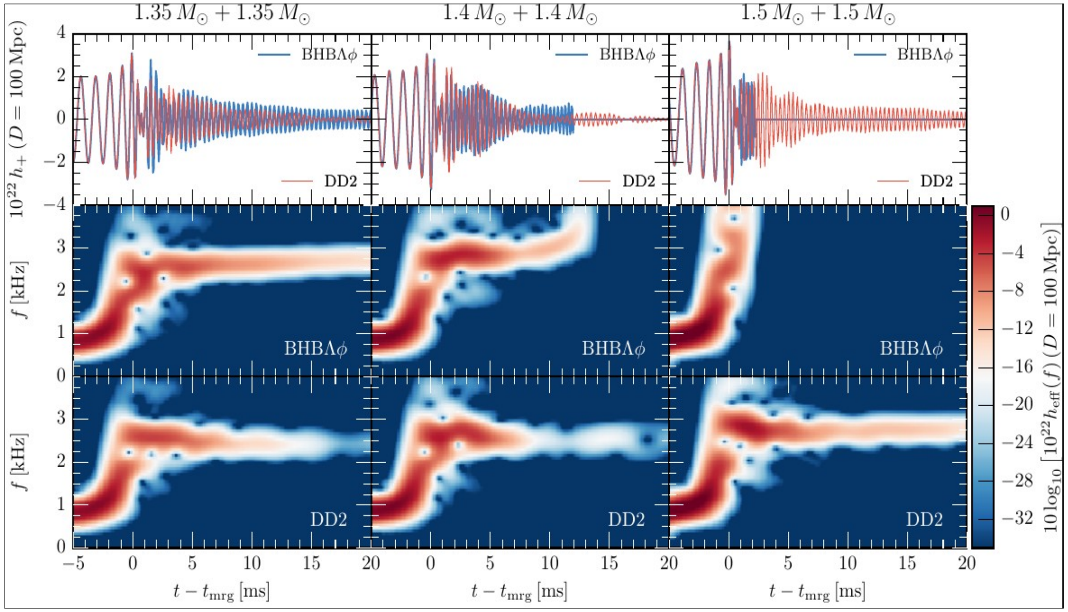
- Baryon number density **n ~ 3-5 n$_{\mathrm{nuc}}$**
- Extra DOF/phase transitions?
- Specific model: Λ-hyperons

  [Banik+ arxiv:1404.6173]

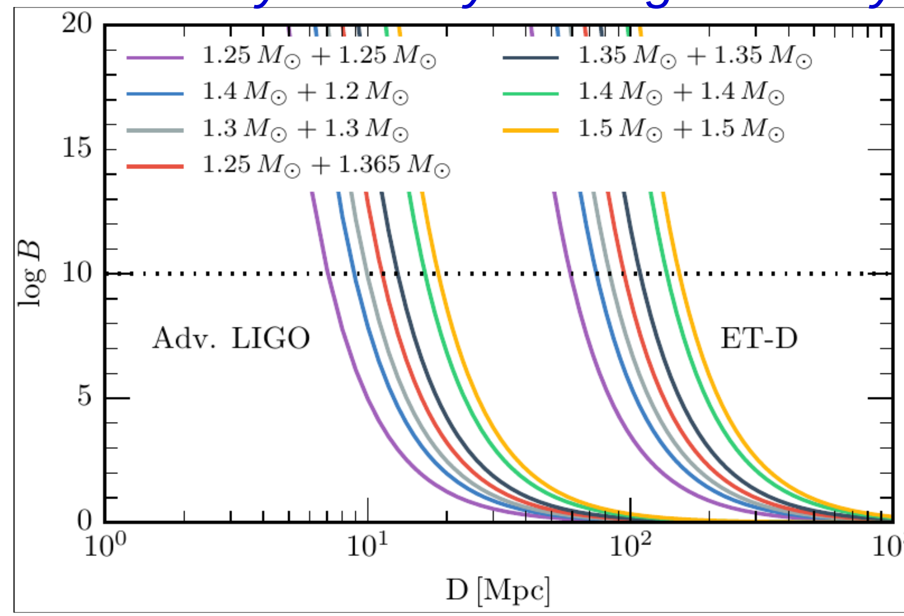
  Microphysical EOS compatibile with astro and nuclear phys constraints
- In general: “softness” effects

GWs could probe such "softness effects"

[Radice, SB, Del Pozzo, Ott, Roberts ApJL (2017)]



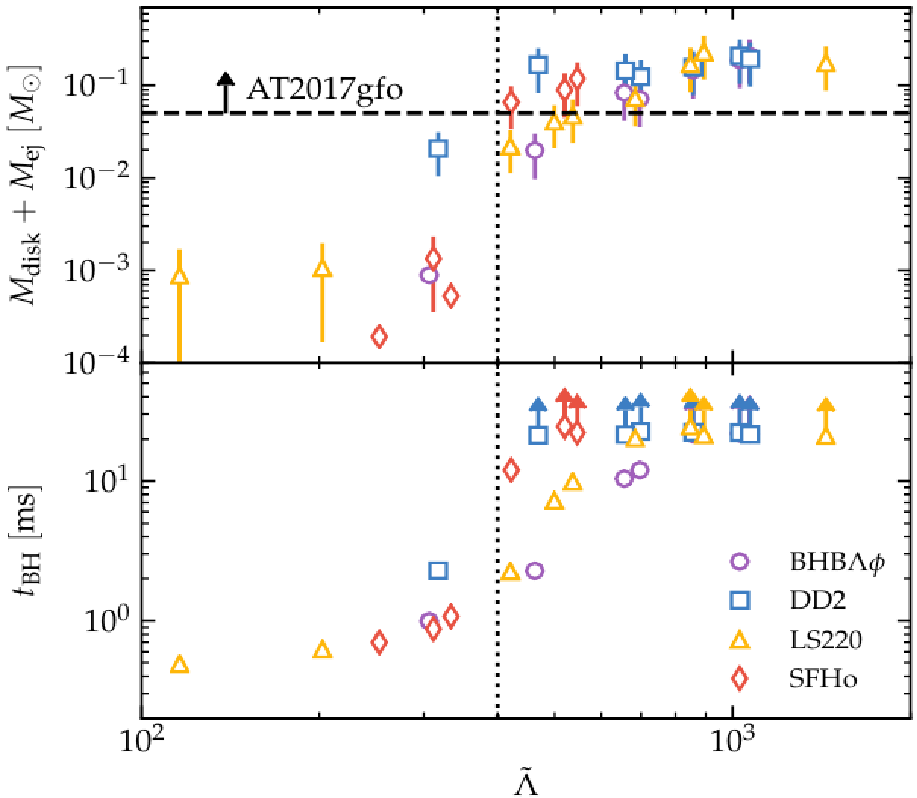
Data-analysis study: distinguishablity



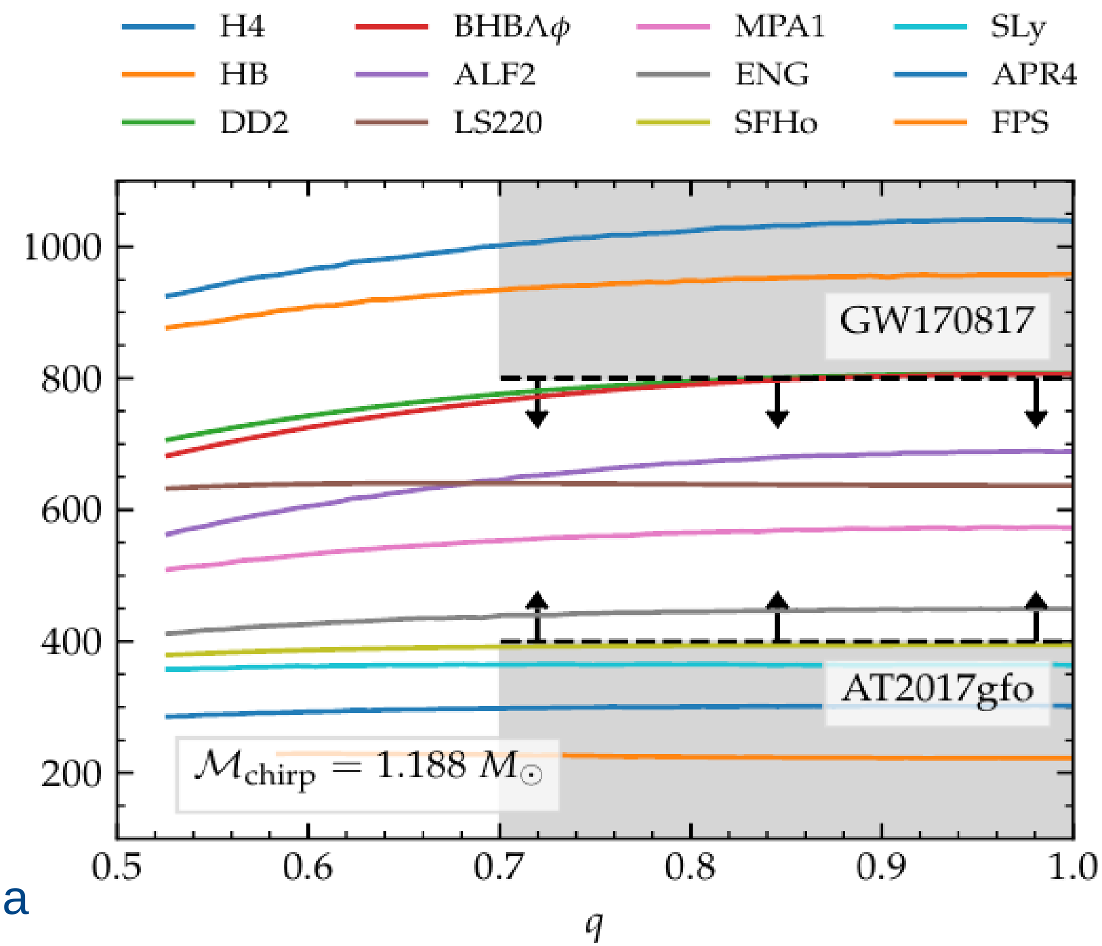
log(Bayes factor) vs. Source distance

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

Joint constraint on the neutron star equation of state from multimessenger observations



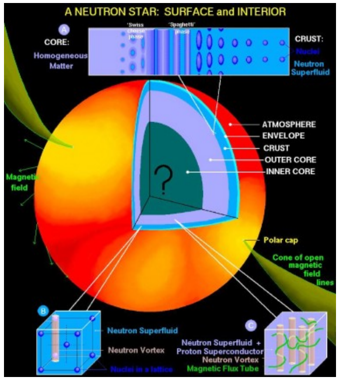
[Radice, Perego, Zappa, SB ApJL (2018)]

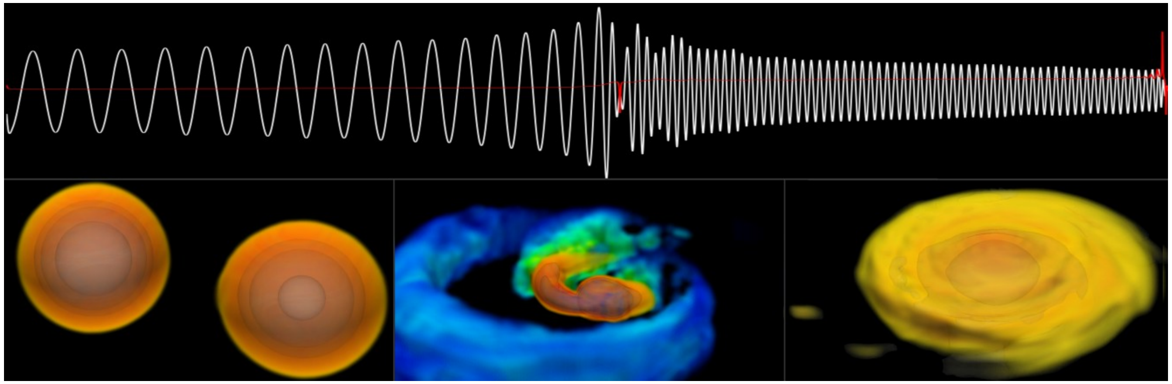


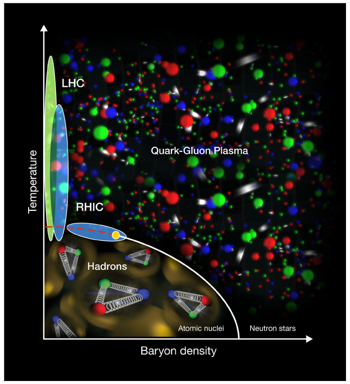
- kN model → lower bound on Mdisk
- Numerical relativity → Mdisk(Lambda)
- EM+NR analysis → lower bound on Lambda
- GW analysis → upper bound on Lambda

Summary

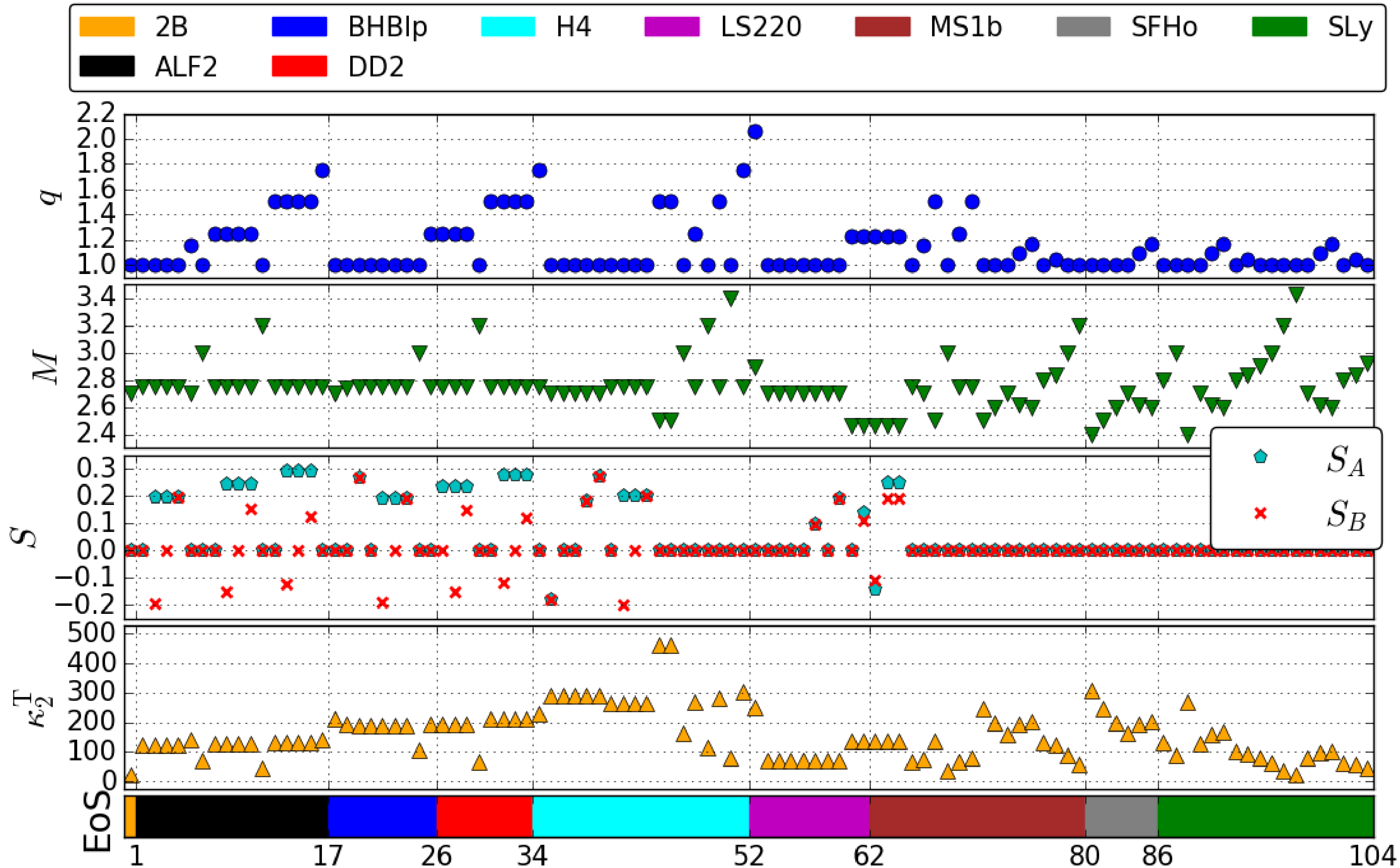
- Unique info about extreme matter
- But GW measurements require precise waveform models
- Inspiral → merger : EOS constraints from tidal parameters
- Detailed waveforms with tidal and spin interaction (urgent!)
- Merger → postmerger : explore even higher density regime
- Modeling is simplistic and not ready, but target is 3G







Exploring the BNS parameter space

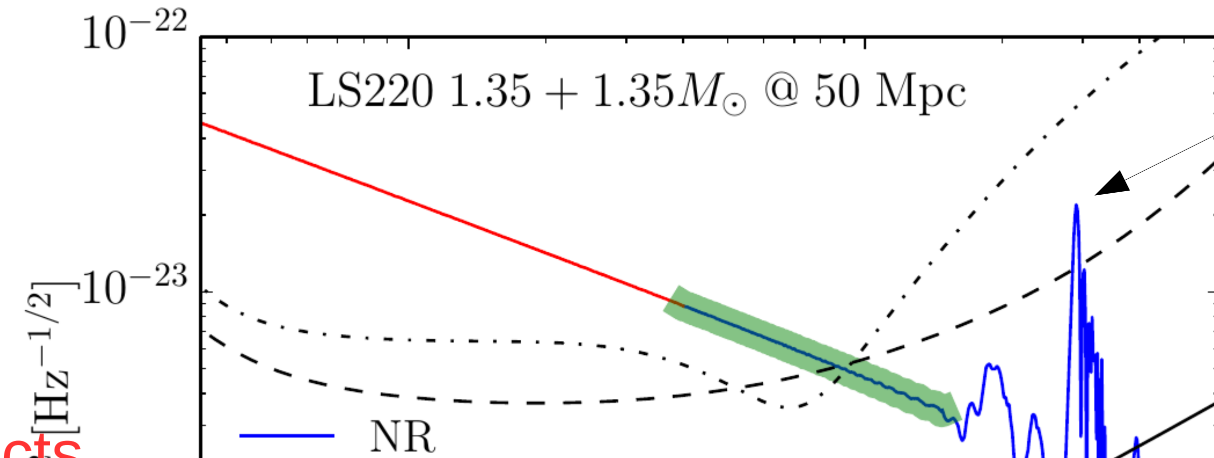


- 130 BNS, 330 dataset
- Multiple resolutions
- Multiorbits + post merger
- Variation of input physics

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

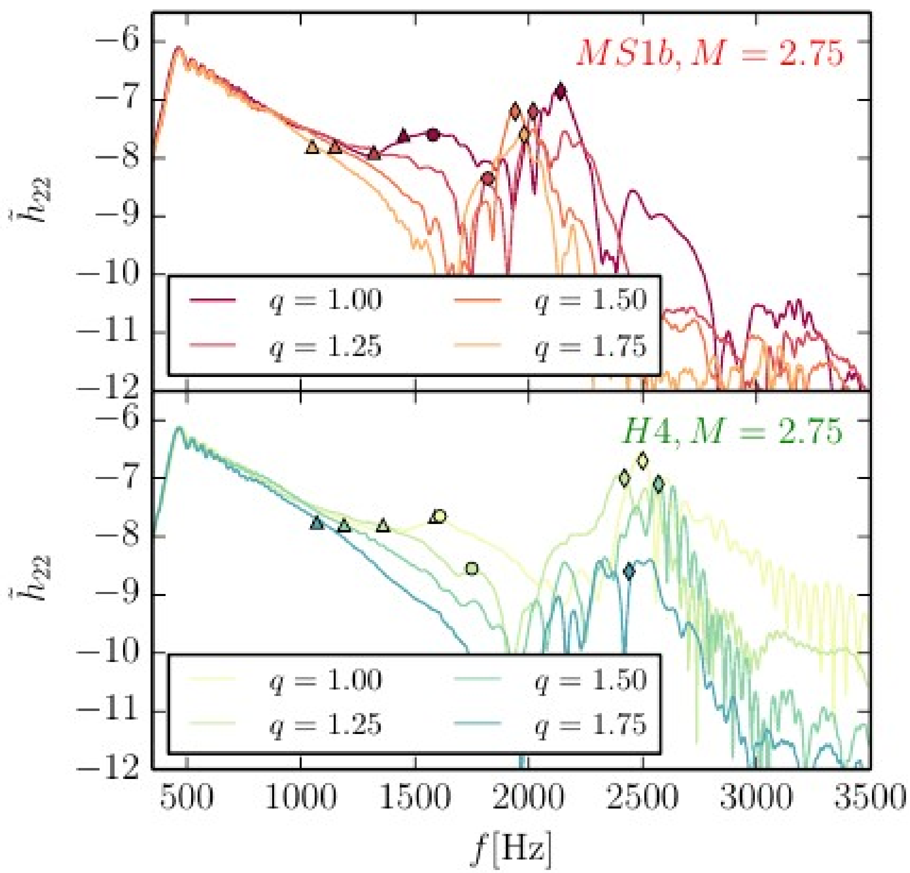
[Bernuzzi+ PRL (2015), Dietrich+ PRD91 (2015), SB+ PRD94 (2016), Radice+ PRD94 (2016), SB&Dietrich PRD94 (2016), Dietrich+ PRD95 024029 (2017), Radice+ ApJL 842 (2017), ….]

Postmerger spectrum

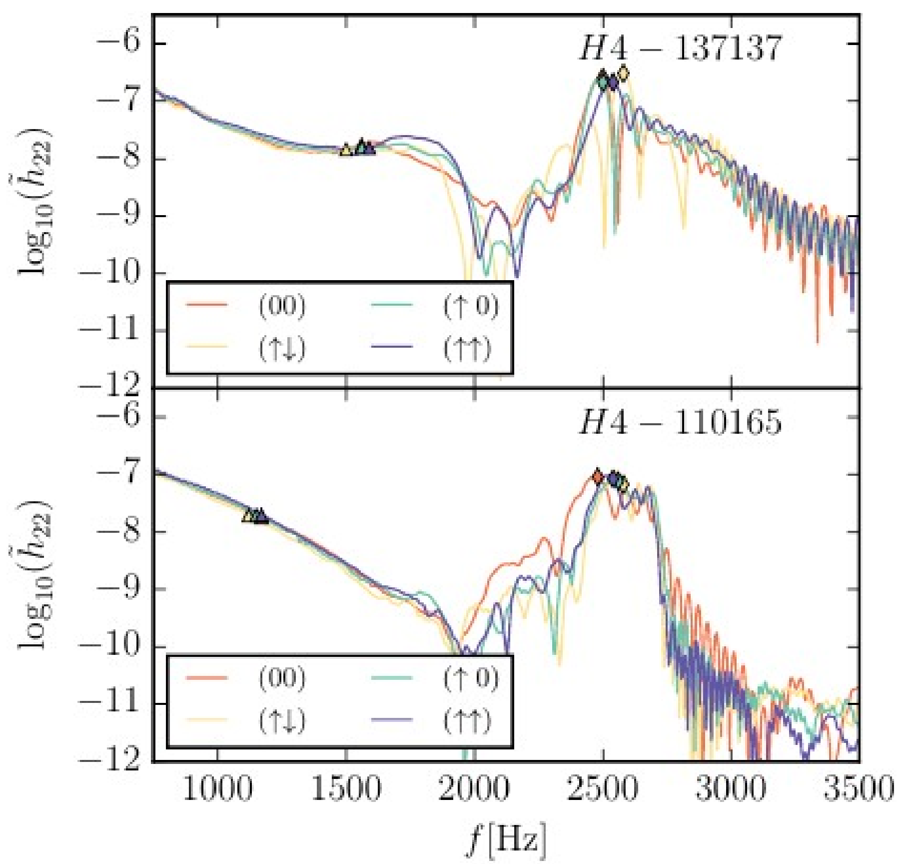


Main broad peak f_2 (m=2)

Mass-ratio effects

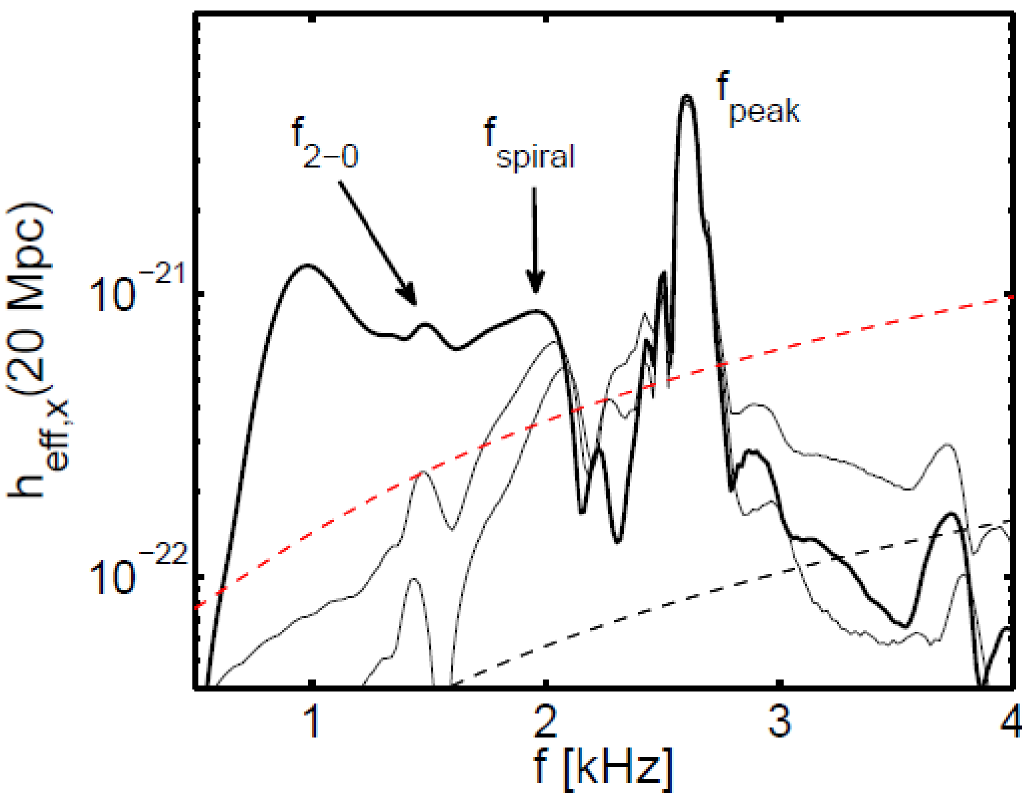


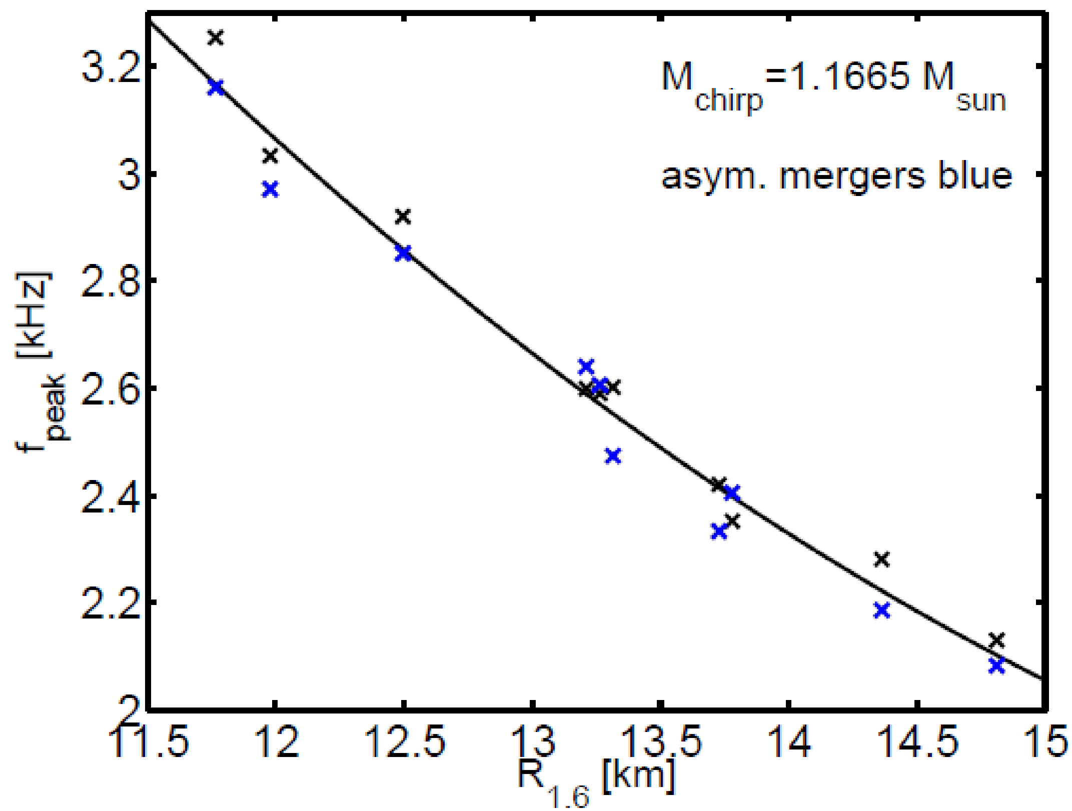
Spin effects



Postmerger spectrum: peak frequency

[Bauswein+ arxiv:1006.3315]





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

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

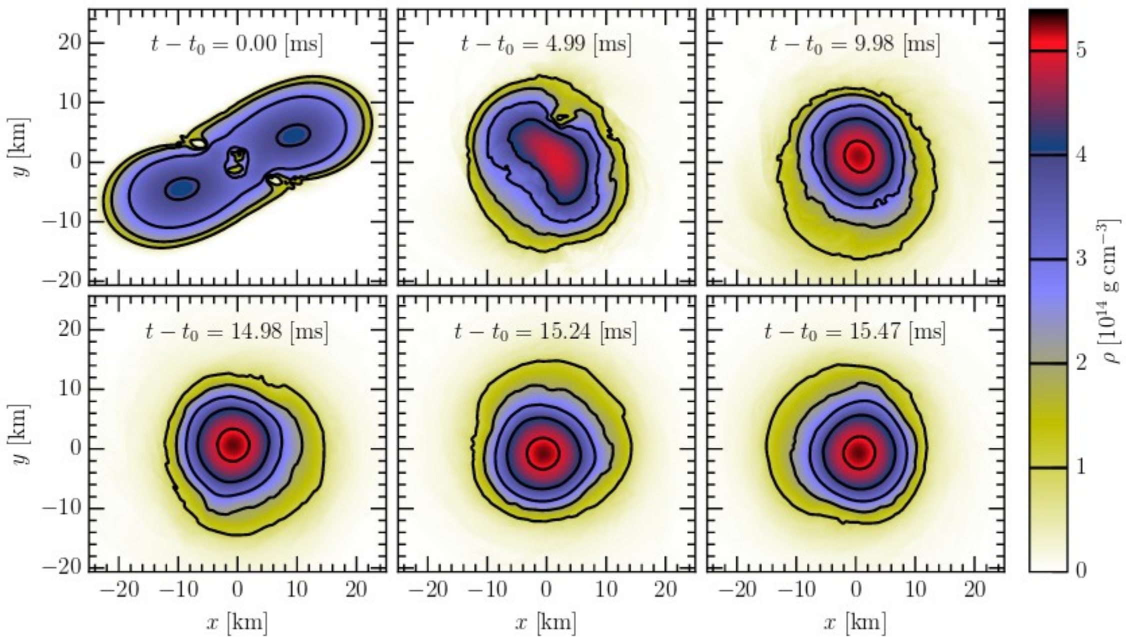
Example of other emission channels: One-armed spiral instability

[Radice, SB, Ott, arXiv:1603.05726]

- **m=1** dynamical instability; long-term (>~50 ms)
- Generic, e.g. single stars, supernovae cores, eccentric mergers.

See e.g. [Paschalidis, East+ 2015 arXiv:1511.01093] [Lehner+ arXiv:1605.02369]

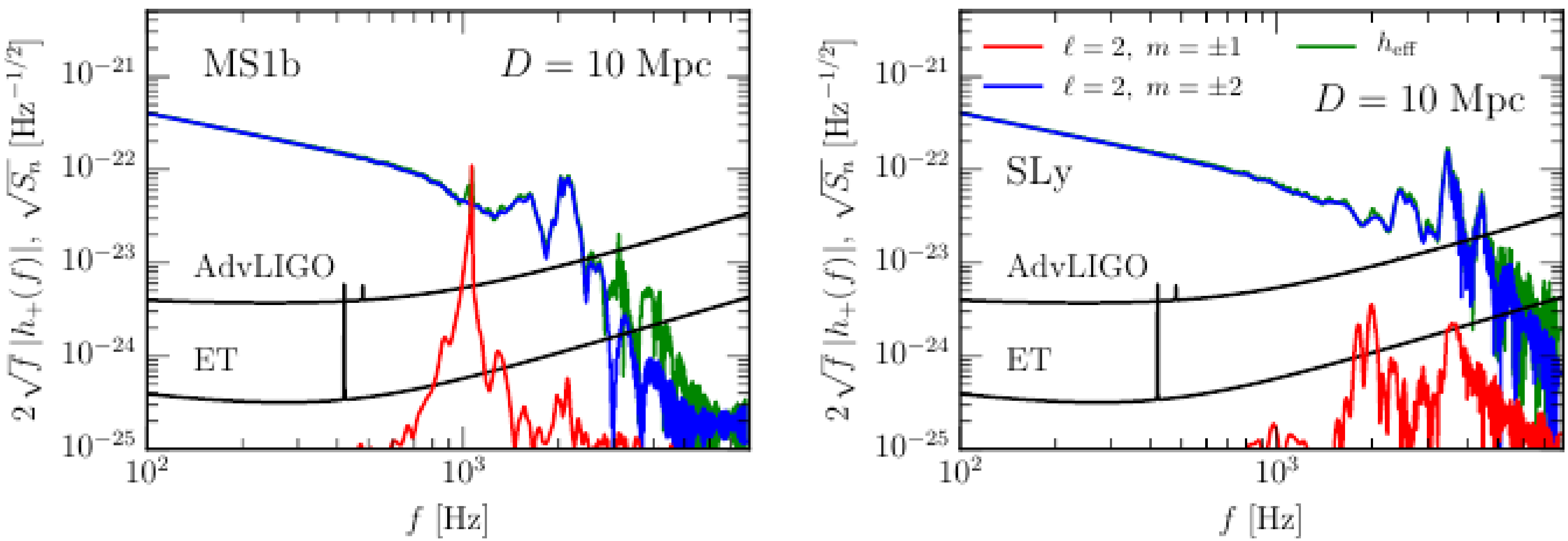
- Not an efficient GW emitter, although persistent



One-armed spiral instability: difficult detection

[Radice, SB, Ott, arXiv:1603.05726]

- Hybrid complete waveform from 10 Hz: effective-one-body with tides (TEOBResum) + long-term high-resolution NR data
- Full SNR analysis, optimal source orientation
- Inspiral-triggered search might improve [Lehner+ arXiv:1605.02369]



Detector	Binary	SNR	$SNR_{2,1}$	$SNR_{2,2}^{f \geq 1\,kHz}$
Adv. LIGO	MS1b-M135-Q1	169.4	1.6	5.4
Adv. LIGO	SLy-M135-Q1	169.5	0.1	6.9
ET	MS1b-M135-Q1	2460.5	14.4	47.4
ET	SLy-M135-Q1	2461.6	1.0	61.3

Publicly available hybrid waveforms
https://zenodo.org/record/46733#.VvCC7CaR4lI