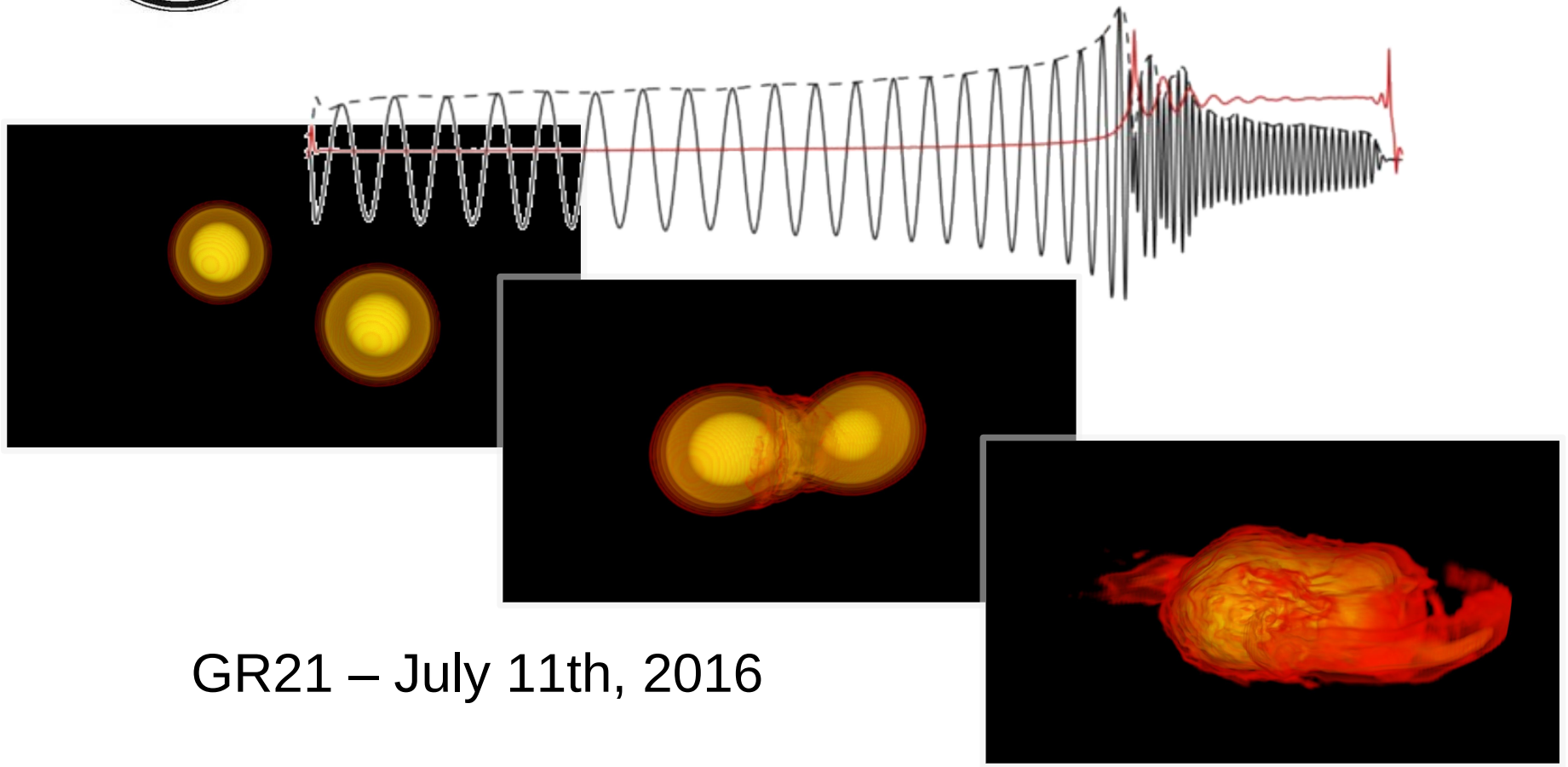
How loud are neutron star mergers in the gravitational-wave window?

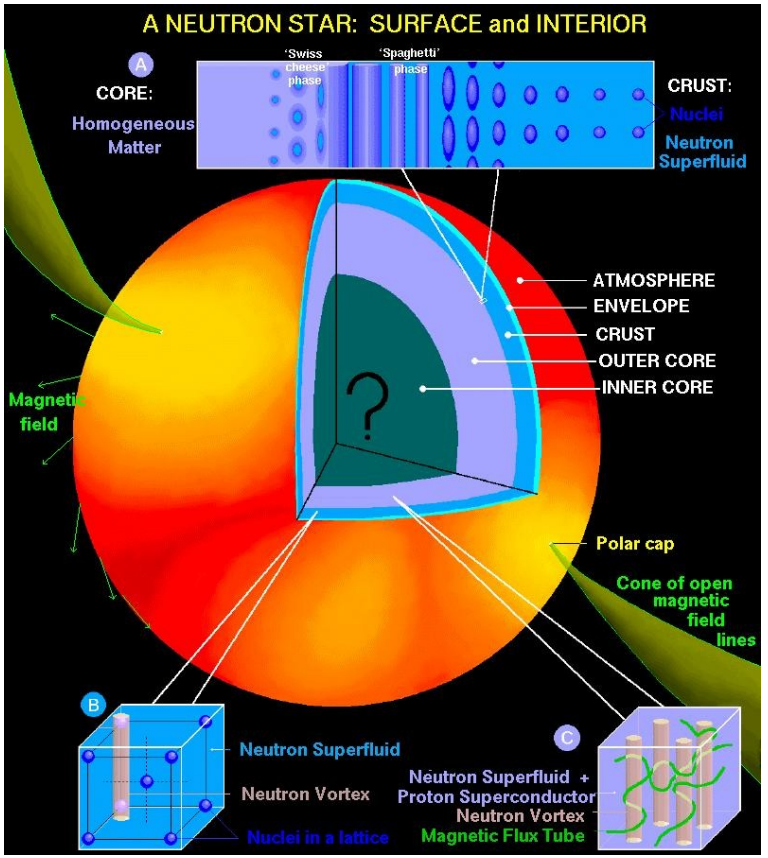
S.Bernuzzi* (Parma U & INFN)

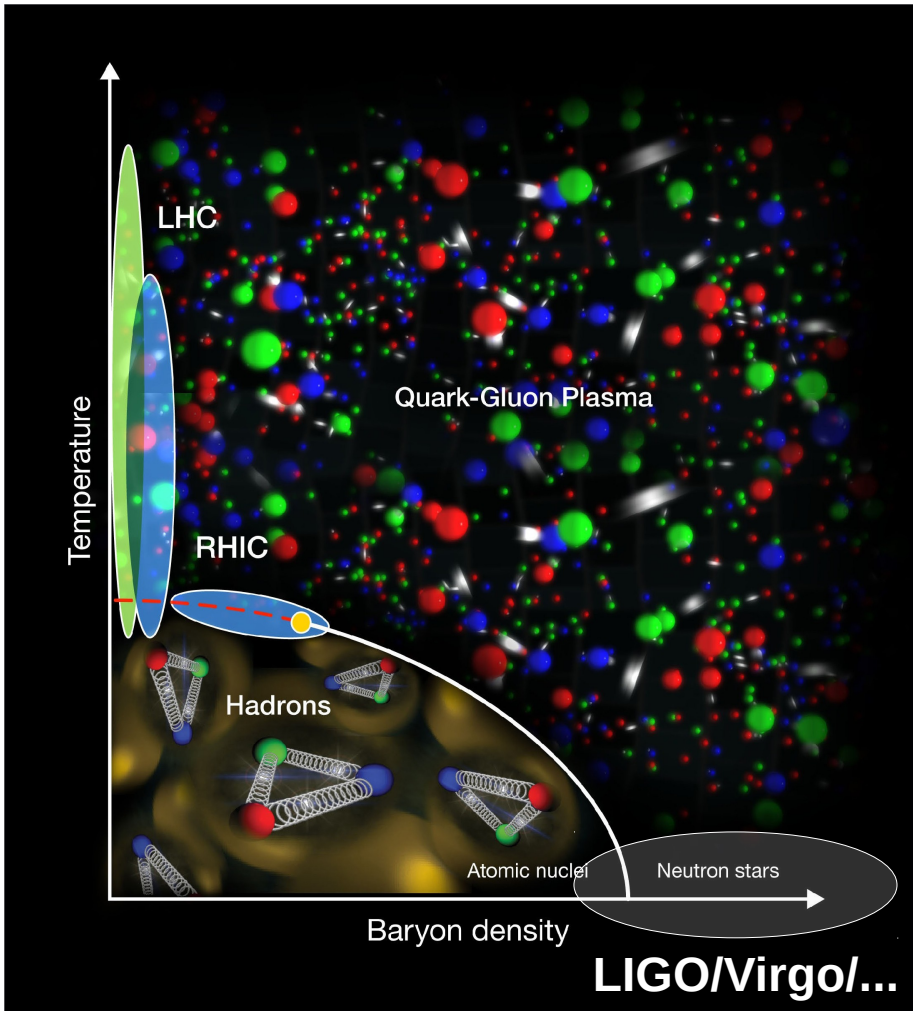
** Rita Levi Montalcini excellence fellow*



GR21 – July 11th, 2016

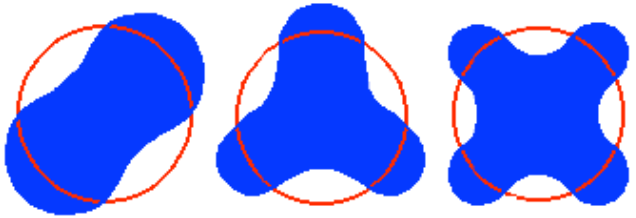
Neutron star matter, binaries, and GWs





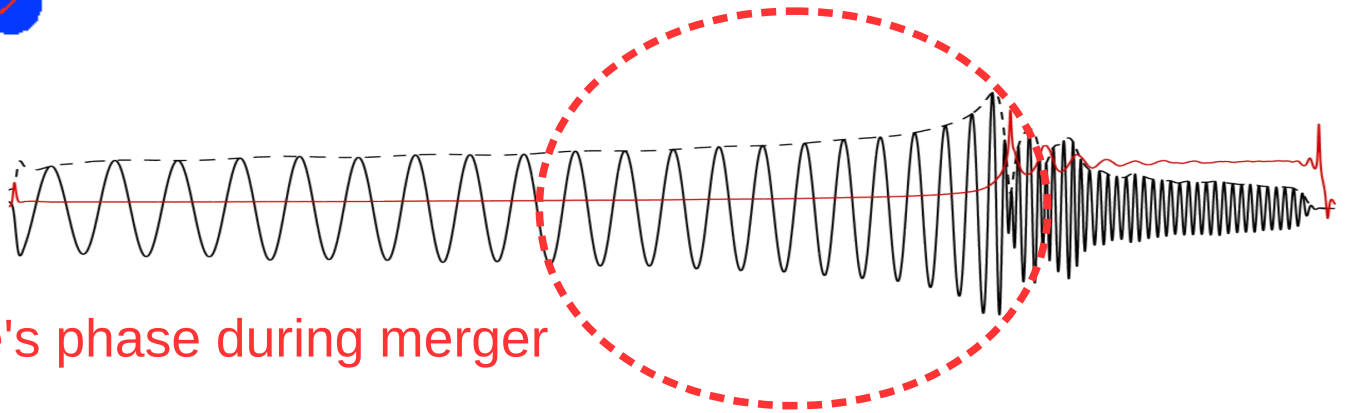
Binary neutron star mergers

GW observation of tidal effects tells us about the neutron star matter

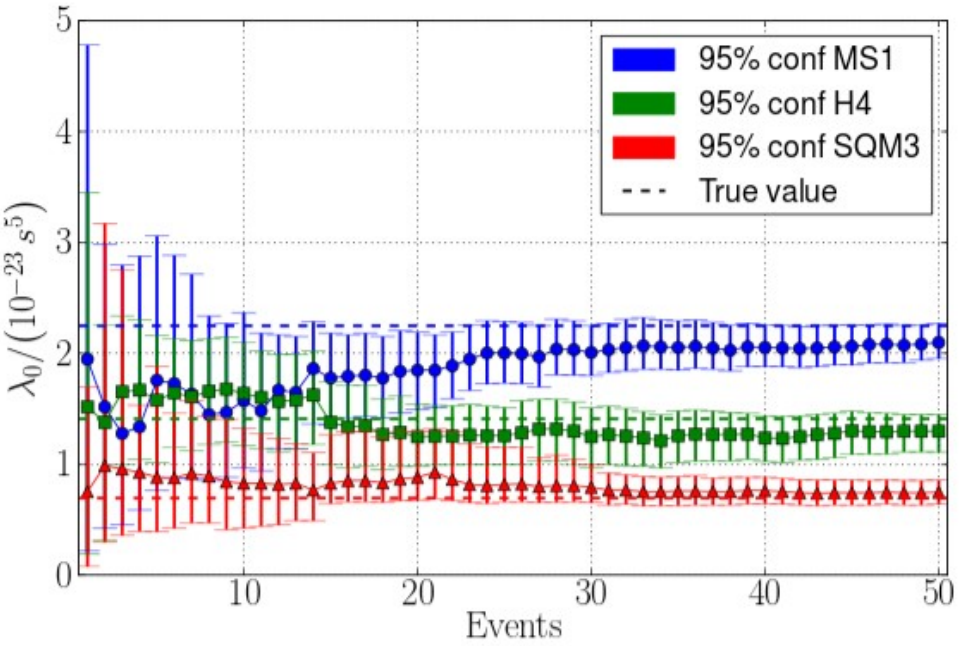


$$\lambda_2 \propto \frac{Q_{ij}}{\partial_{ij}\Phi_{ext}}$$

Tides depend crucially on EOS

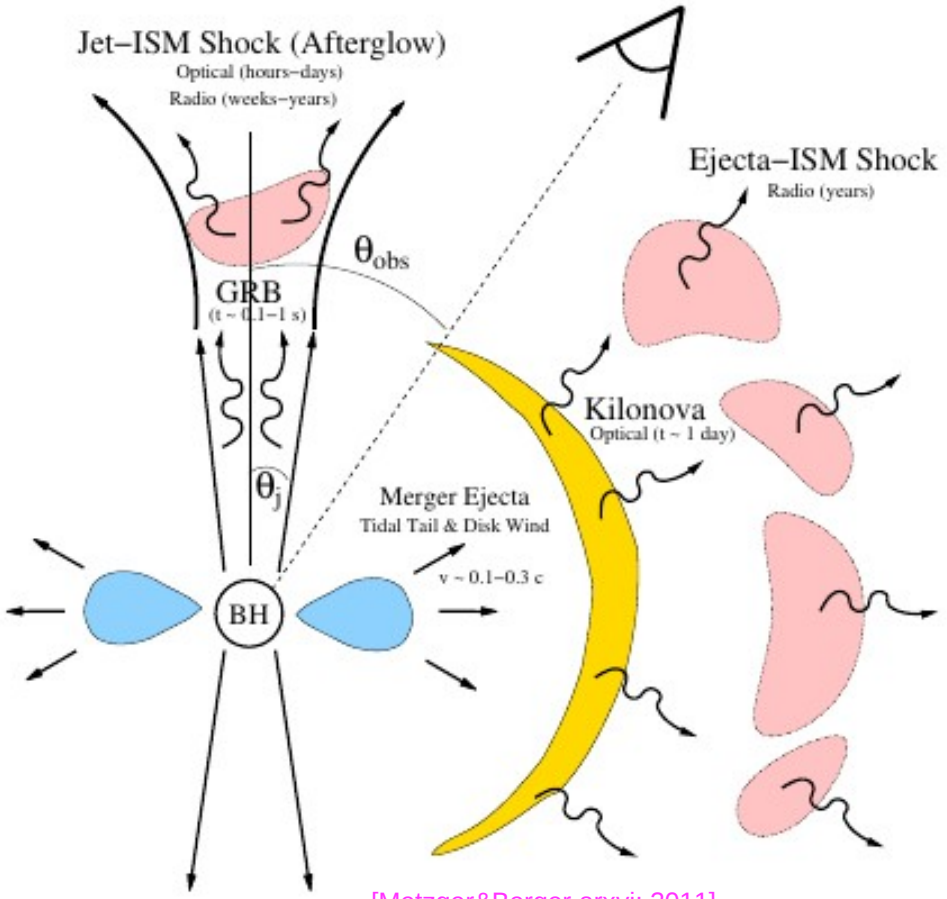


Tides determine the wave's phase during merger



e.g. [Del Pozzo+ arXiv:1307.8338, Lackey&Wade arXiv:1410.8866, Agathos+ arXiv:1503.05405]

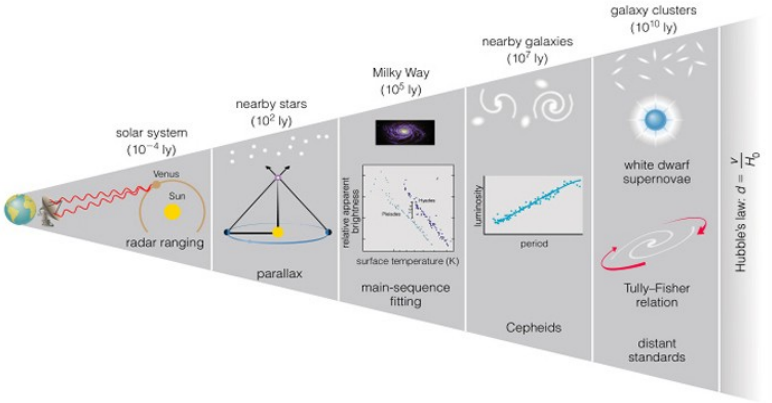
Multimessenger astrophysics and cosmography

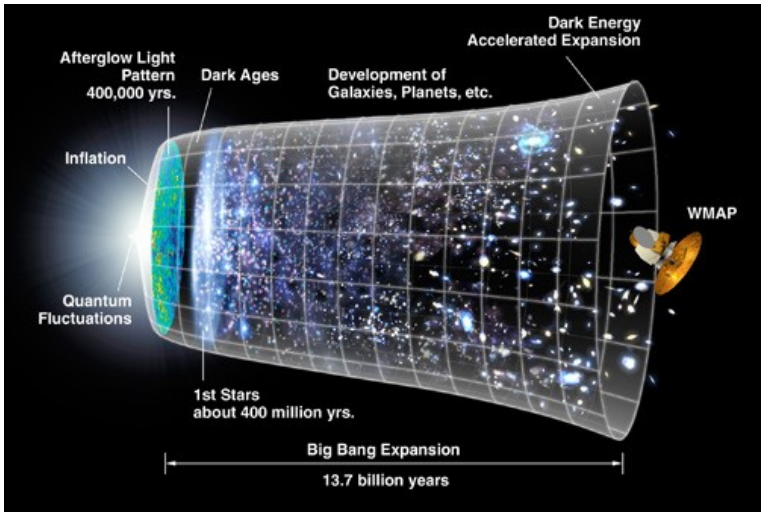


[Metzger&Berger arxvi: 2011]

EM counterparts “identification”

→ Branchesi, Shibata talks
→ Ciolfi, Liebling B2 talks
→ B1 Session

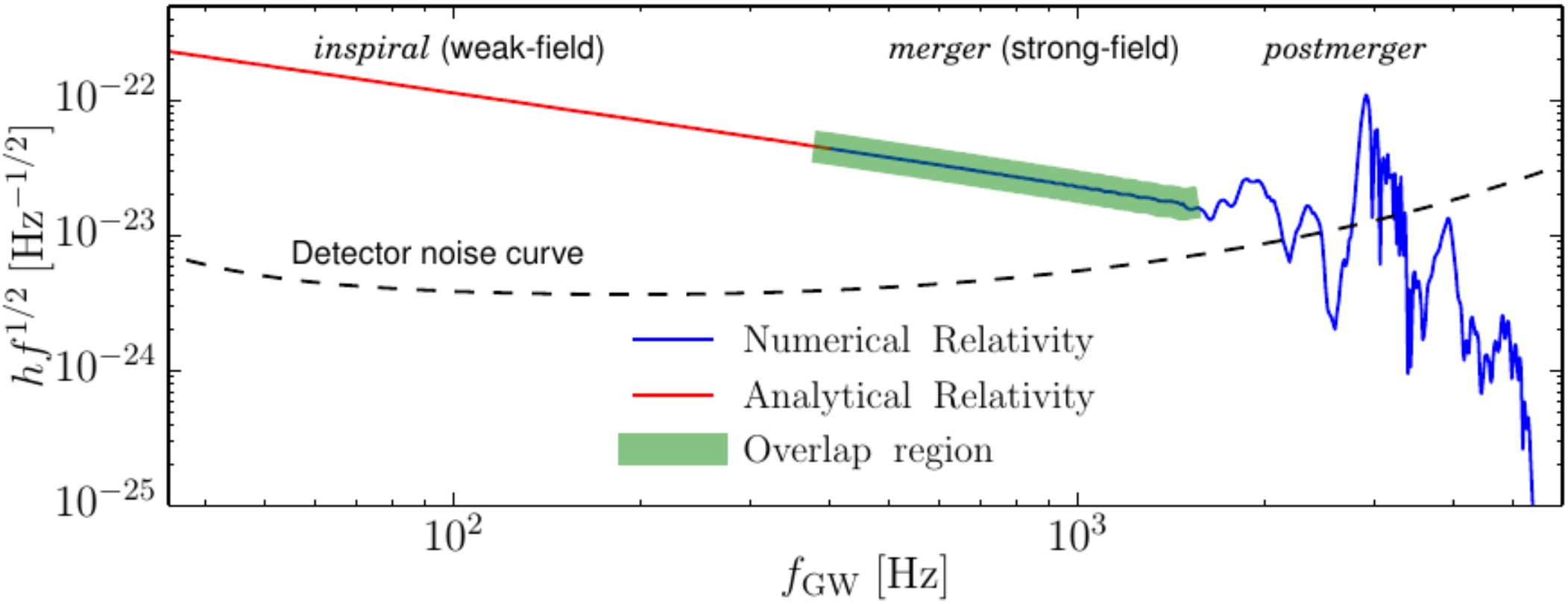




Cosmography, *Standard sirens*

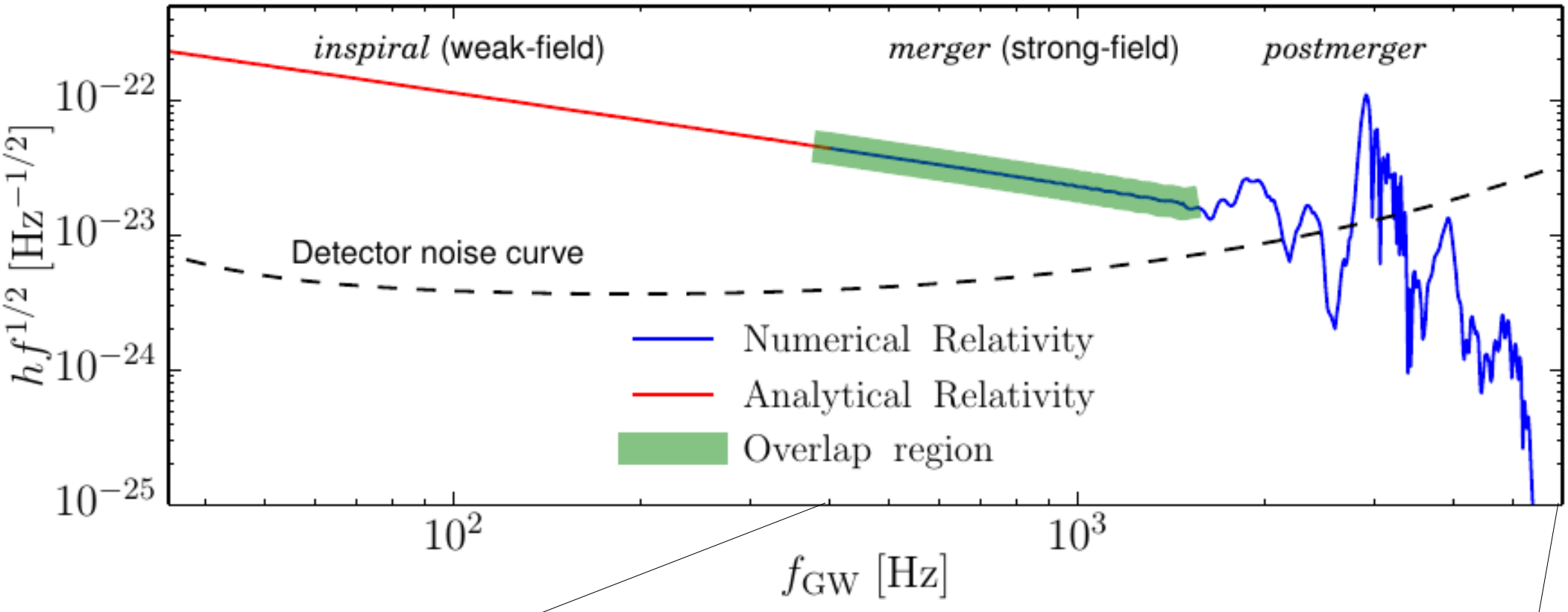
[Schutz 1986, Messenger&Read arXiv:1107.5725]

GW observations require detailed signal models

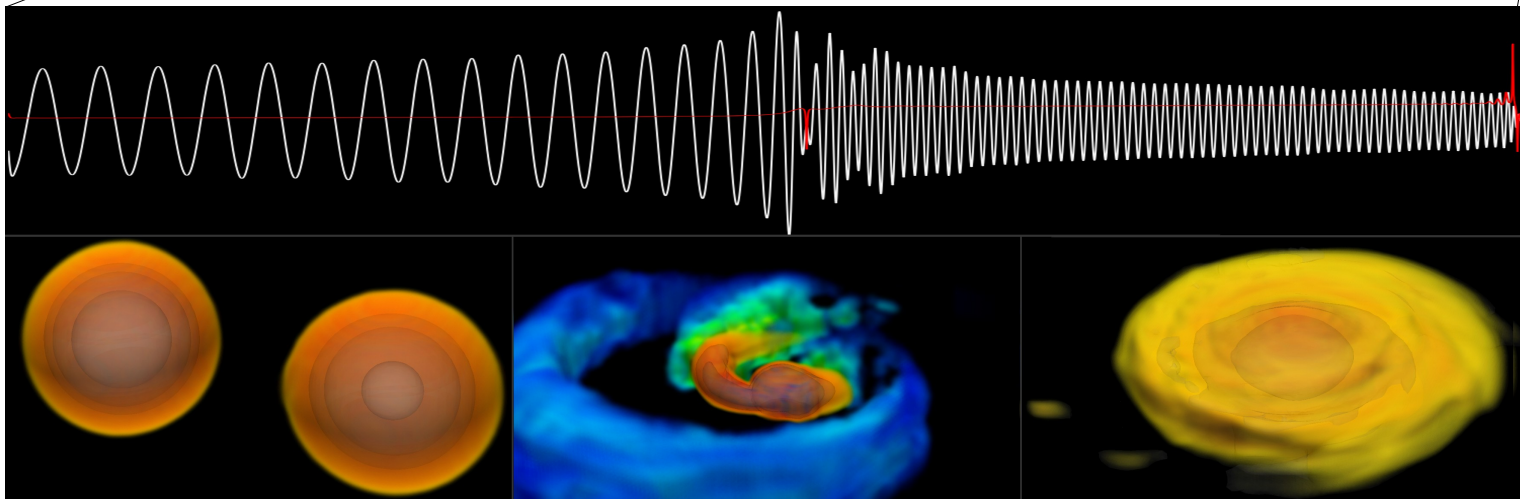


- GW energy, angular momentum, frequency
- Amplitude & phase GW “broad-band” model
- Binary parameter space: masses + spins + EOS

GW observations require detailed signal models

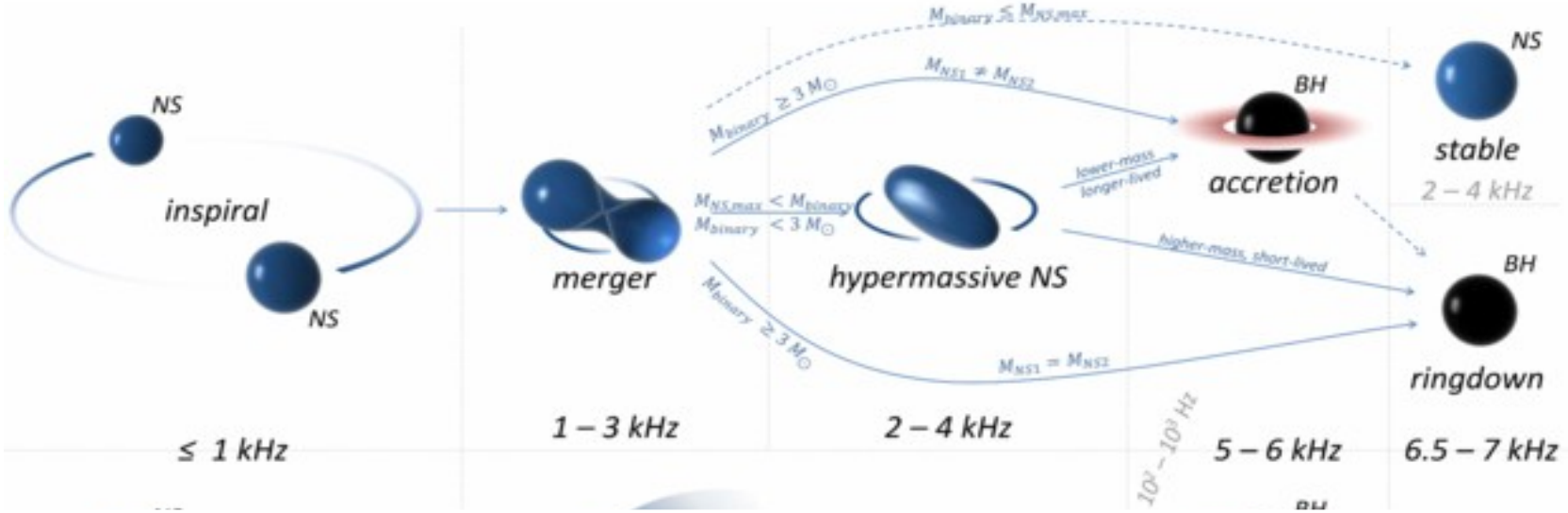


NR simulation

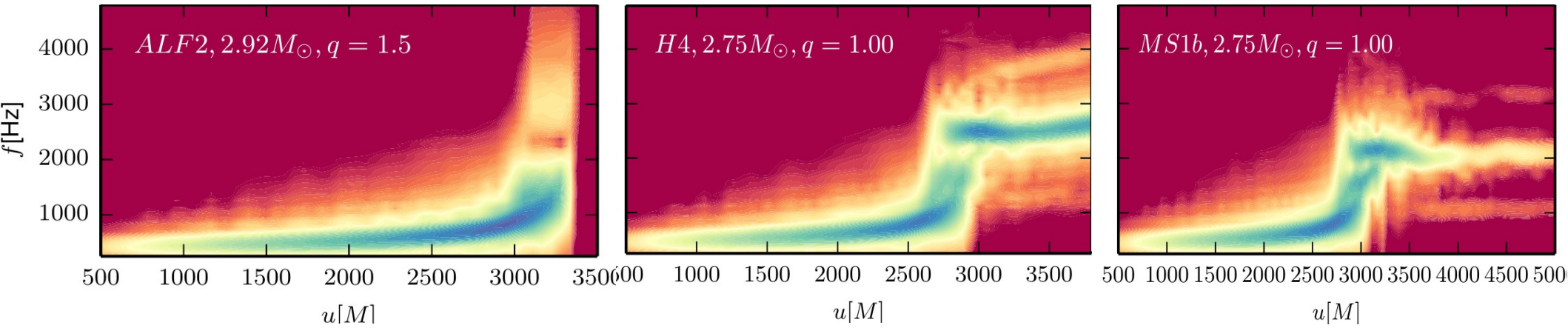


Broad features of merger well understood ...

Figure 1 from I Bartos et al 2013 Class. Quantum Grav. 30 123001

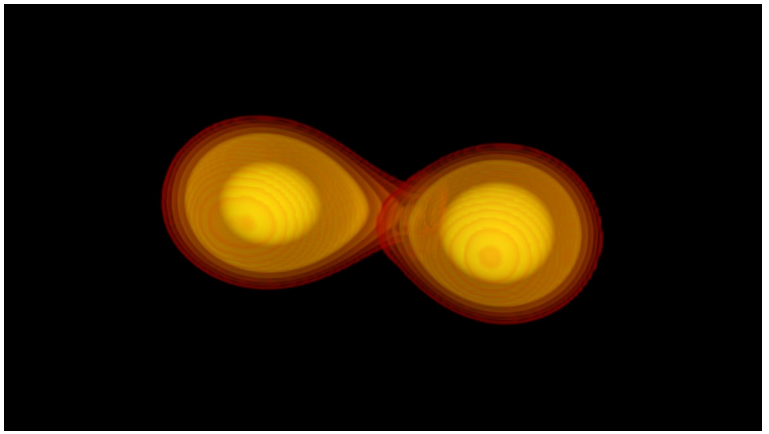


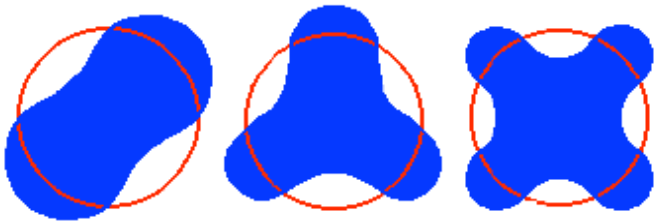
GW spectrograms [Dietrich+ (To appear)]



… detailed complete GW models still challening

Relativistic Tides





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

Love number
(electric-type)

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

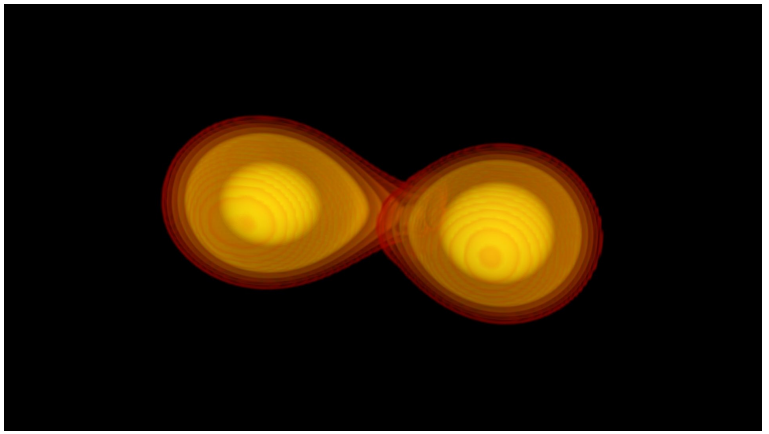
$$H_{\rm EOB} \approx Mc^2 + \frac{\mu}{2}\left(\mathbf{p}^2 + A(r) - 1\right)$$
$$A(r) = 1 - 2/r - \kappa_2^T(\lambda_2)/r^6$$

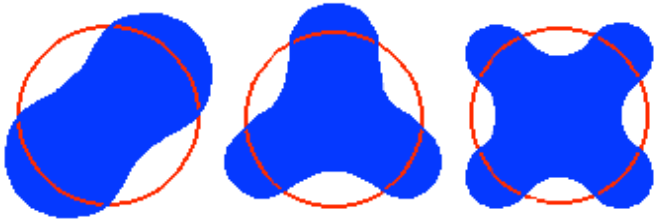
Tidal contribution to post-Newtonian dynamics and waveform

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

[DamourSoffelXu 1992, Flanagan&Hinderer arXiv:0709.1915, Damour&Nagar arXiv:0911.5041, …]

Relativistic Tides





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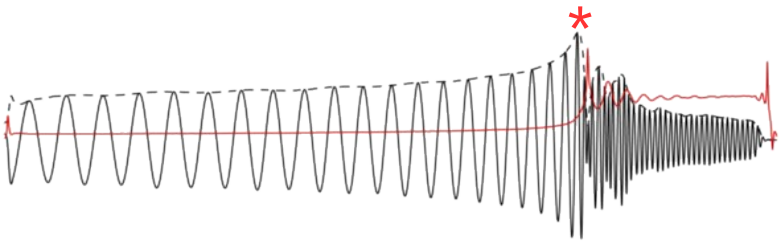
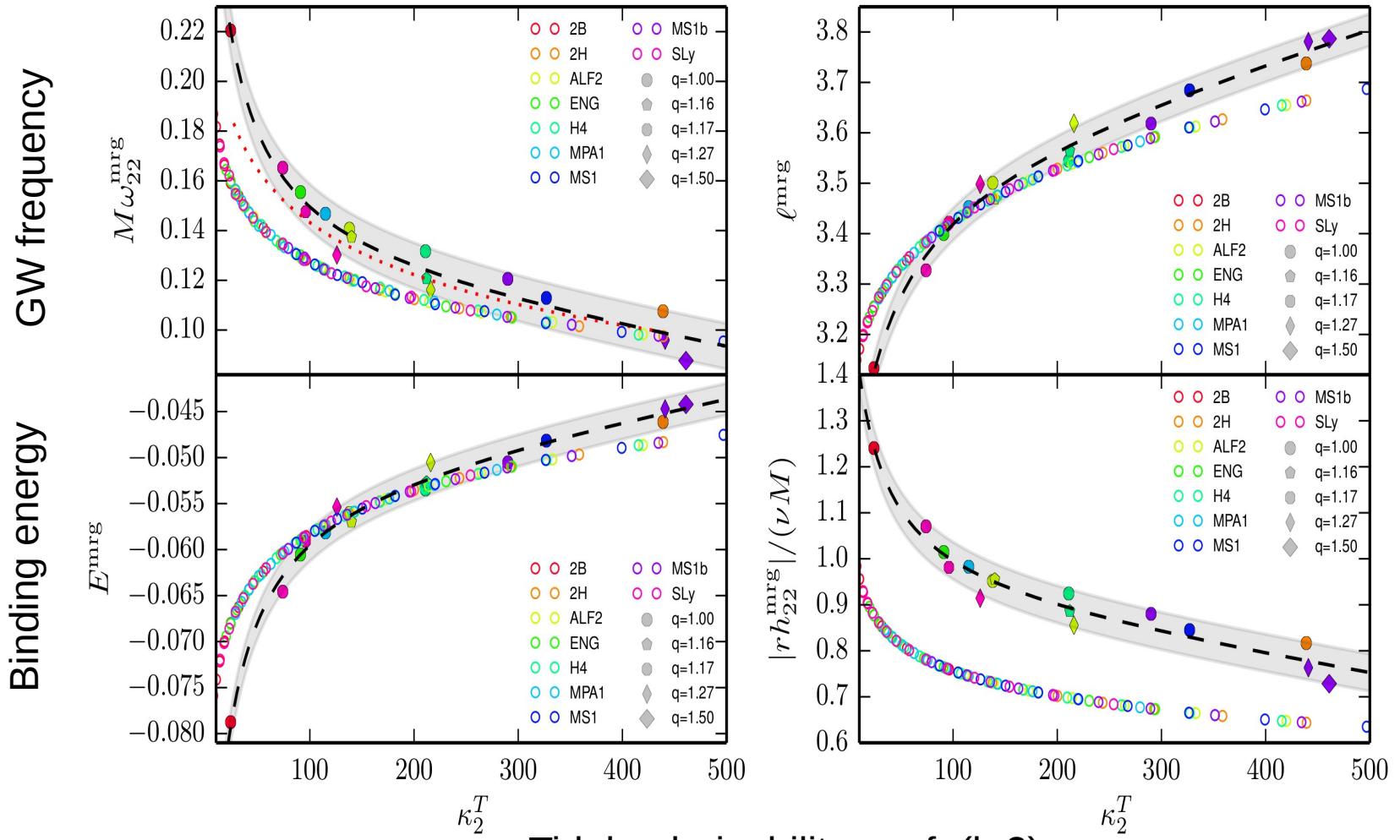
Parametrizing the BNS merger dynamics

"Universality of merger dynamics"
[SB,Nagar,Balmelli,Dietrich,Ujevic arxiv:1402.6244]



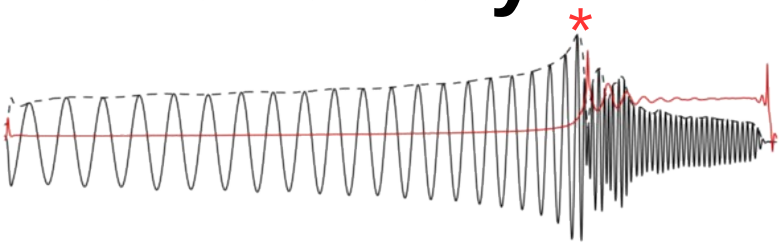
end of chirp signal



Tidal polarizability coef. (l=2)

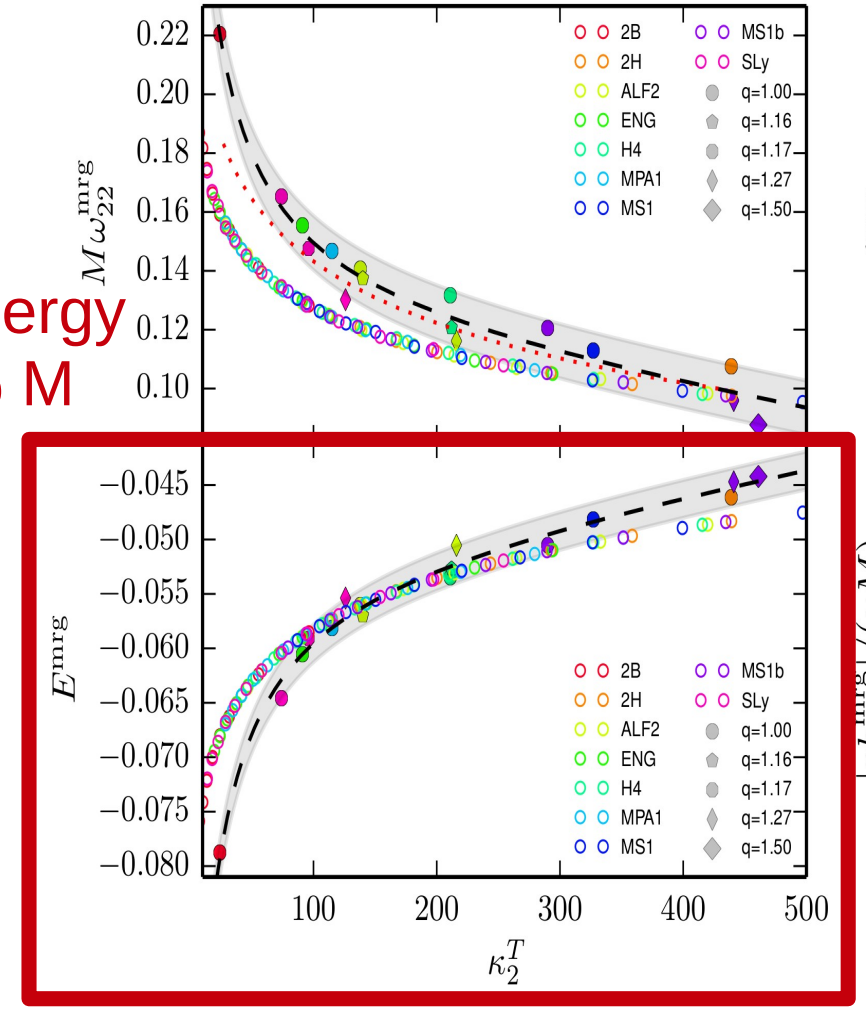
Energy emitted in GW “up to merger” for any irrotational binary

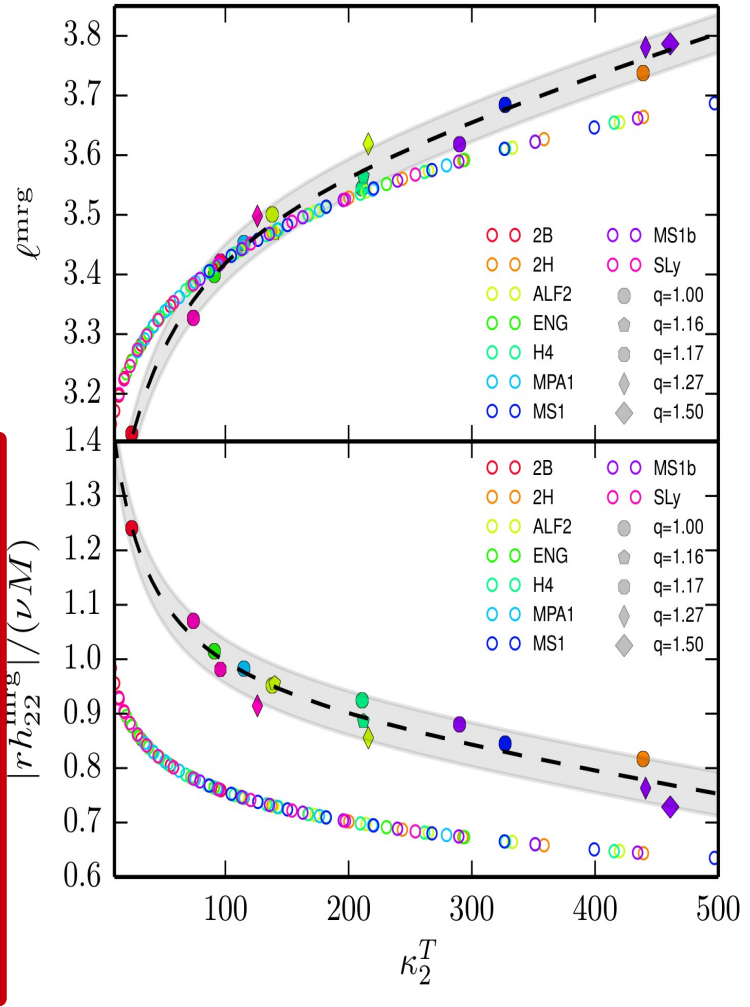
“Universality of merger dynamics”
[SB+ arxiv:1402.6244]



end of chirp signal

GW energy
1-2% M

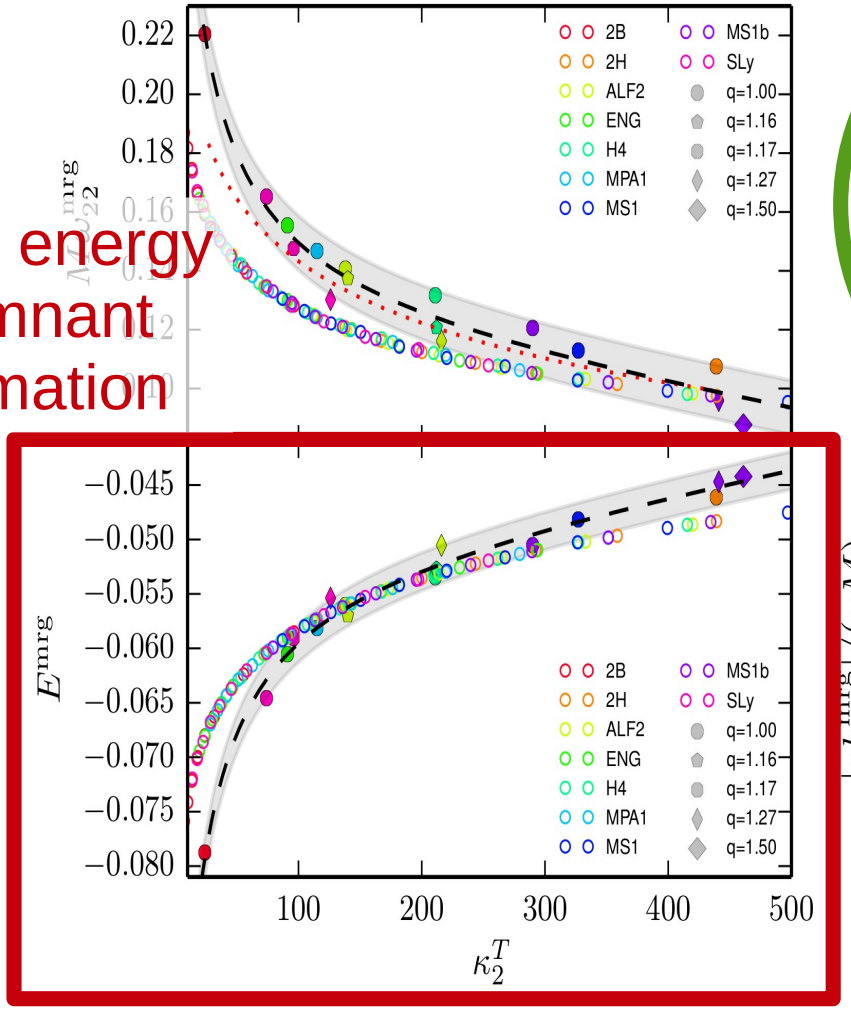




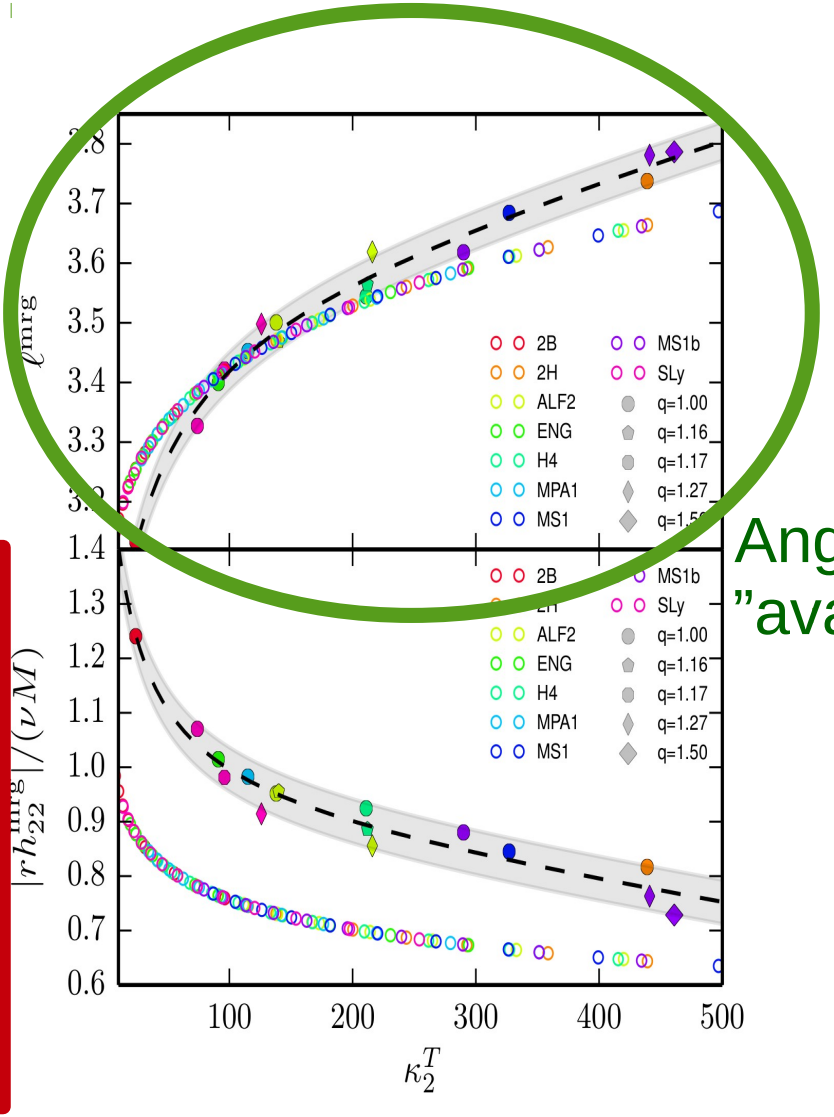
Merger remnant and outcome

"Universality of merger dynamics"
[SB+ arxiv:1402.6244]

Binding energy of remnant at formation

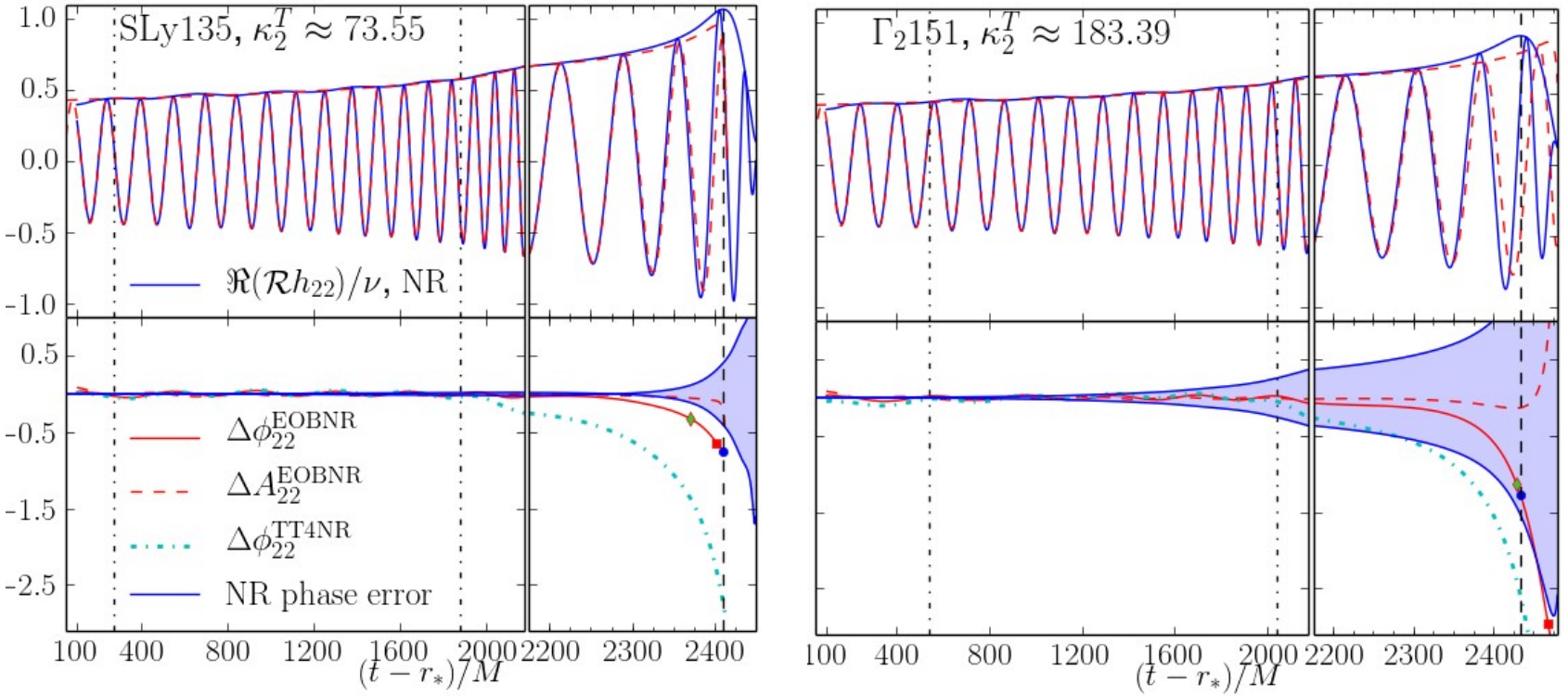


Ang.Mom. "available"



TEOBResum:
Model of dynamics and GWs up to merger

[SB,Nagar,Dietrich,Damour arXiv:1412.4553]

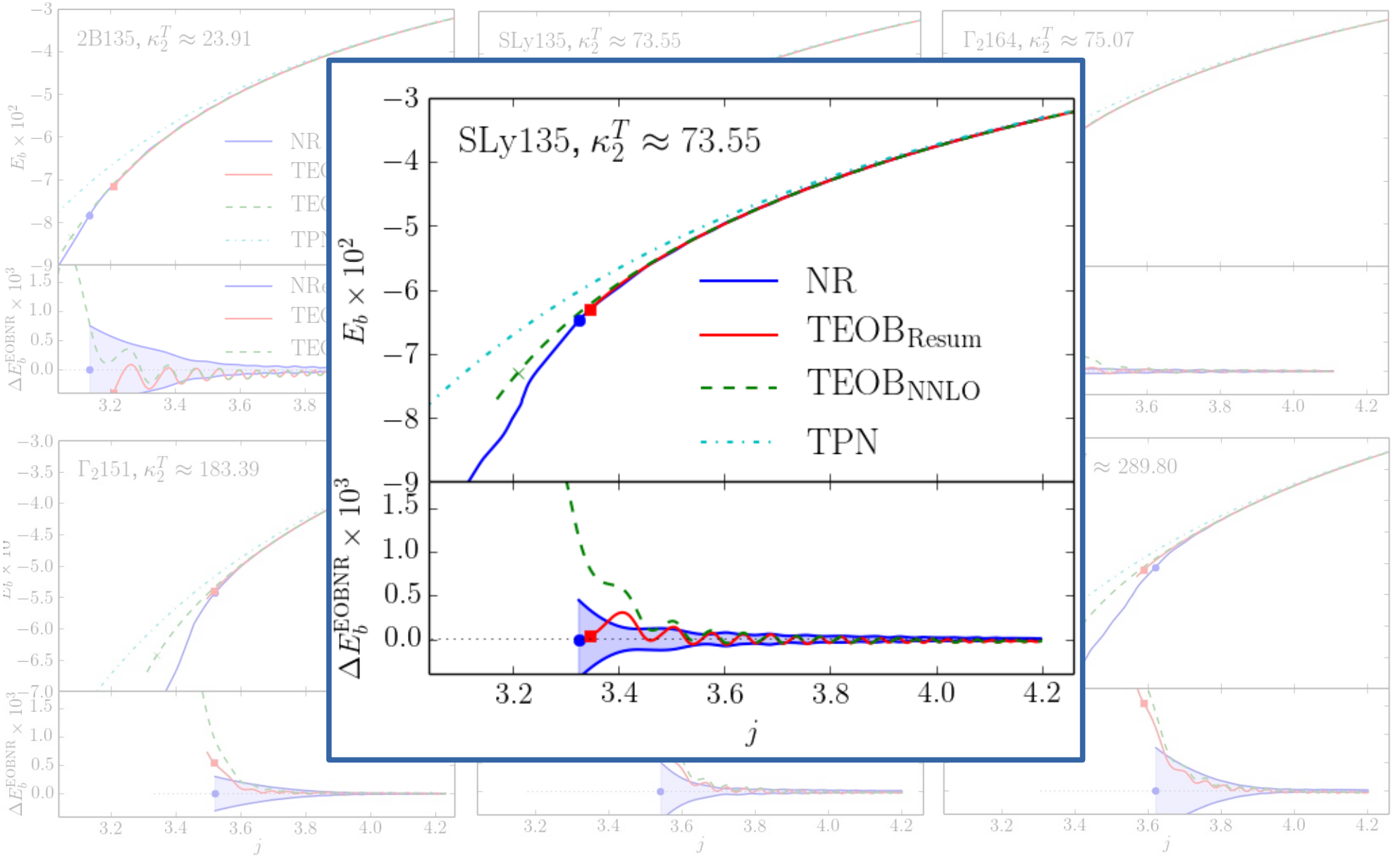


- Improve significantly the previous TEOB NNLO [SB+ arXiv:1205.3403]
- Predicts rather well NR waveforms

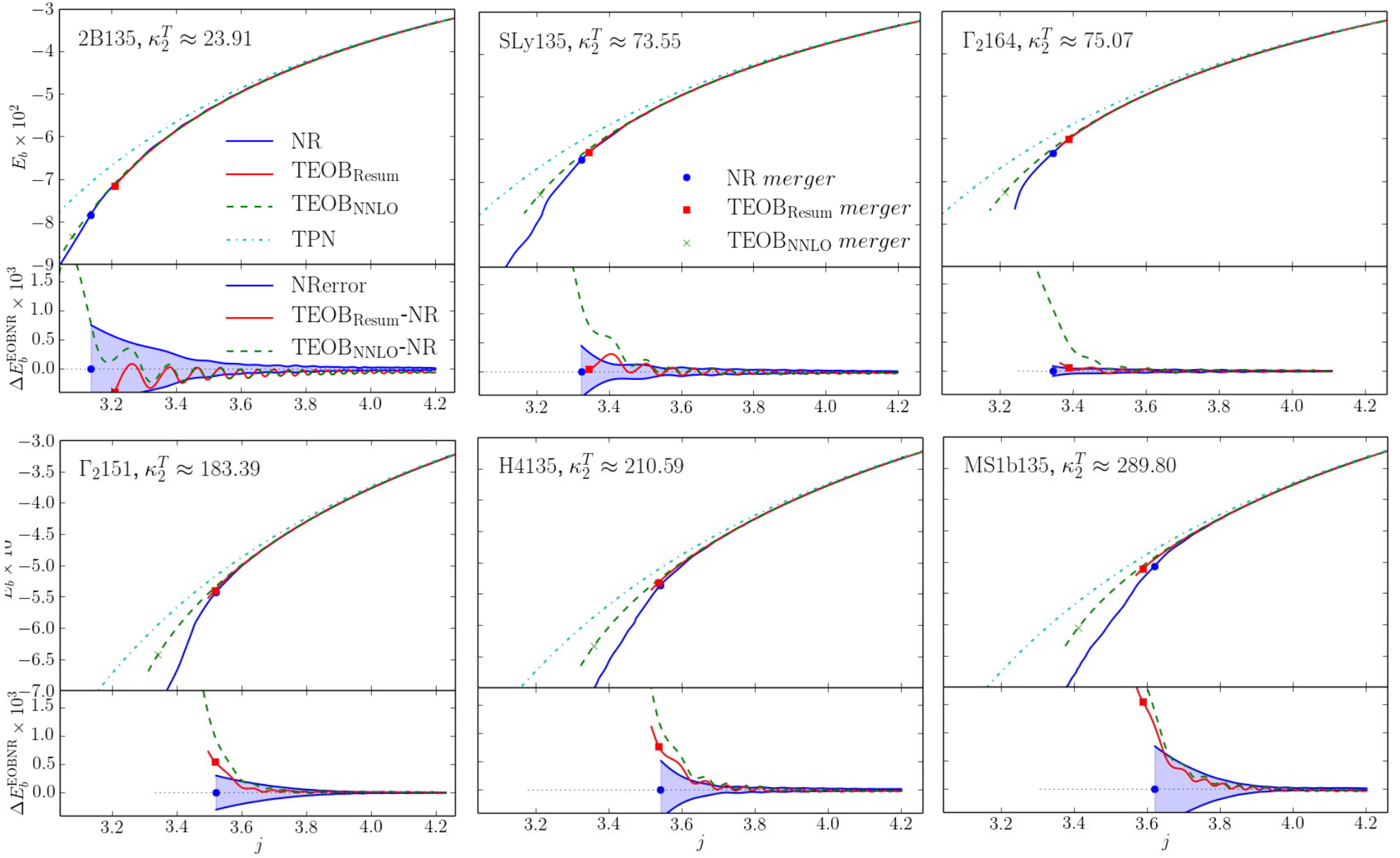
Publicly available EOB dev code
https://eob.ihes.fr

ROM → Lackey, Galley, SB
In LAL → Meidam, Van den Broeck

TEOBResum: BNS dynamics



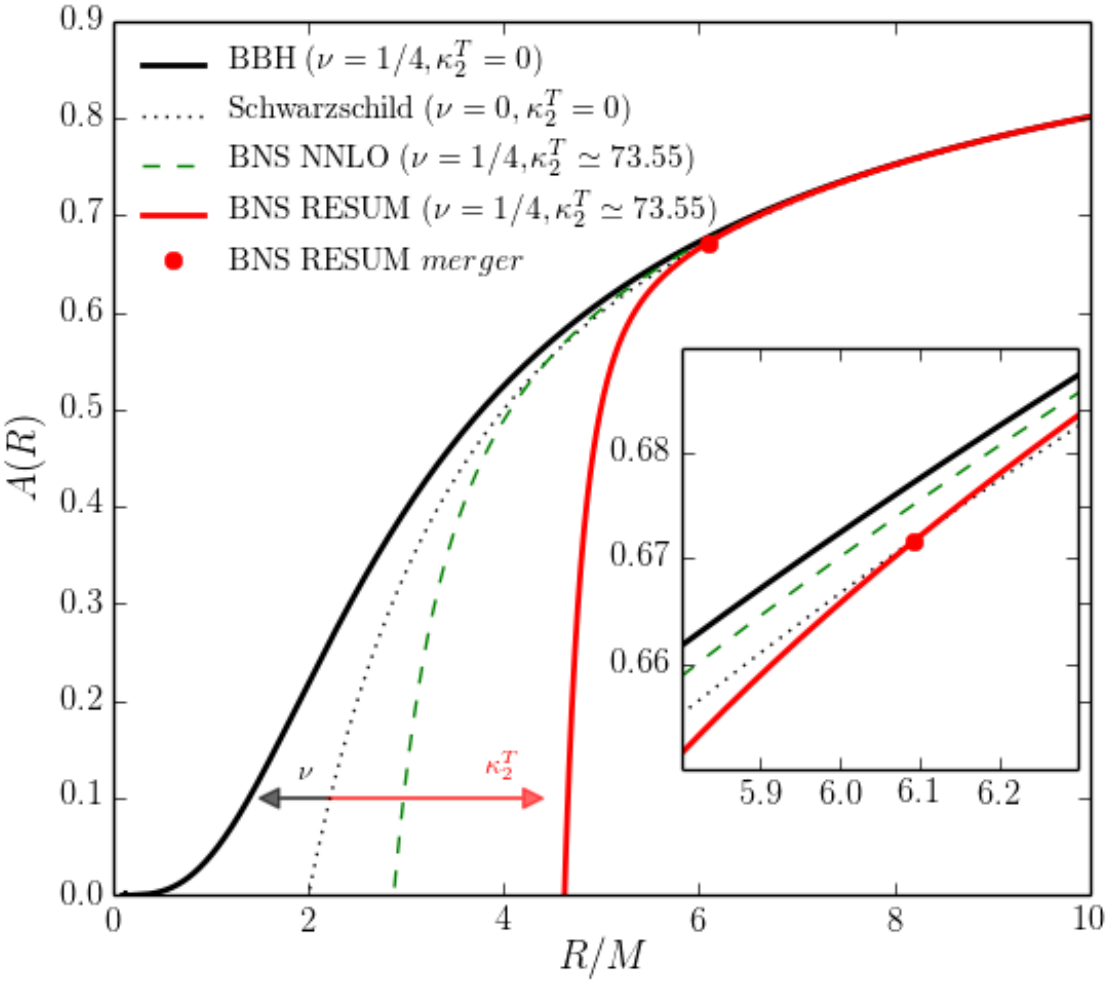
TEOBResum: BNS dynamics



TEOBResum: The GSF-Resummed A(R) potential

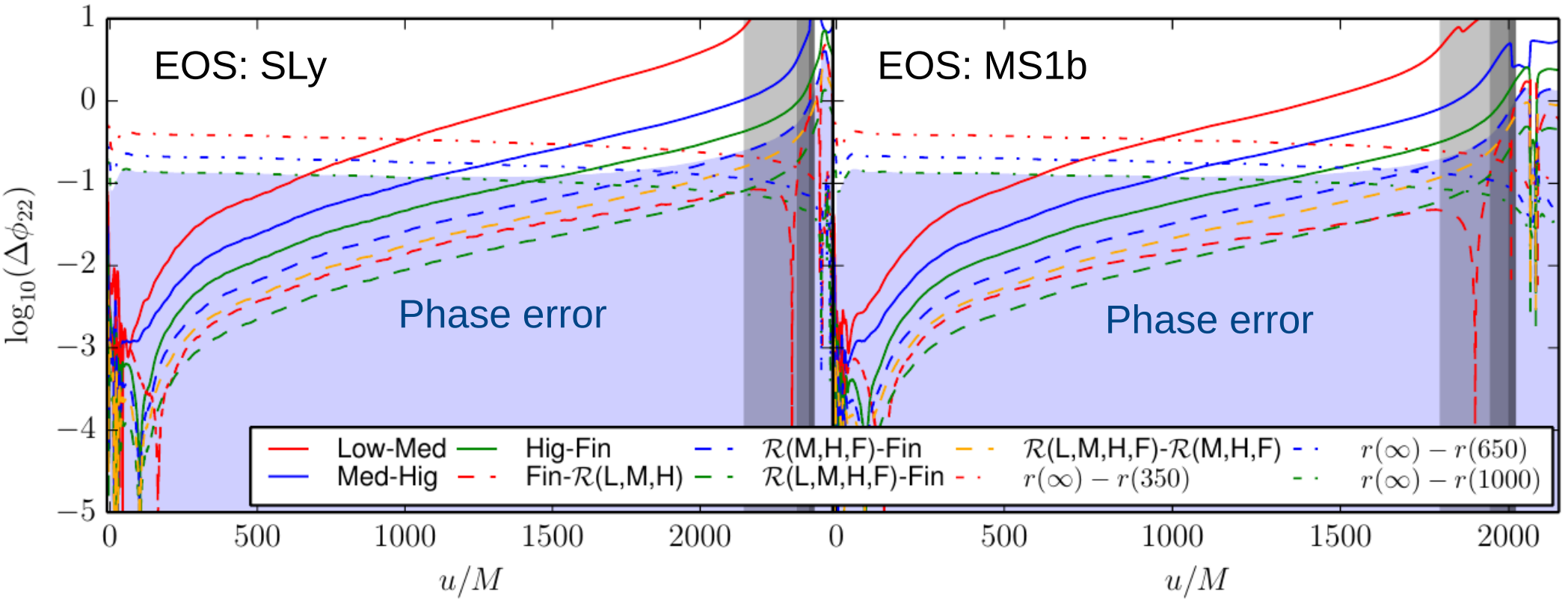
$$H_{\rm EOB} \approx Mc^2 + \frac{\mu}{2}\left(\mathbf{p}^2 + A(r) - 1\right)$$
$$A(r) = 1 - 2/r - \kappa_2^T(\lambda_2)/r^6$$

[Bini&Damour arXiv:1409.6933]



Improved NR GW with high-order WENO schemes

[SB&Dietrich arxiv:1604.07999]



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

See also [Radice+ arxiv:1306.6052]

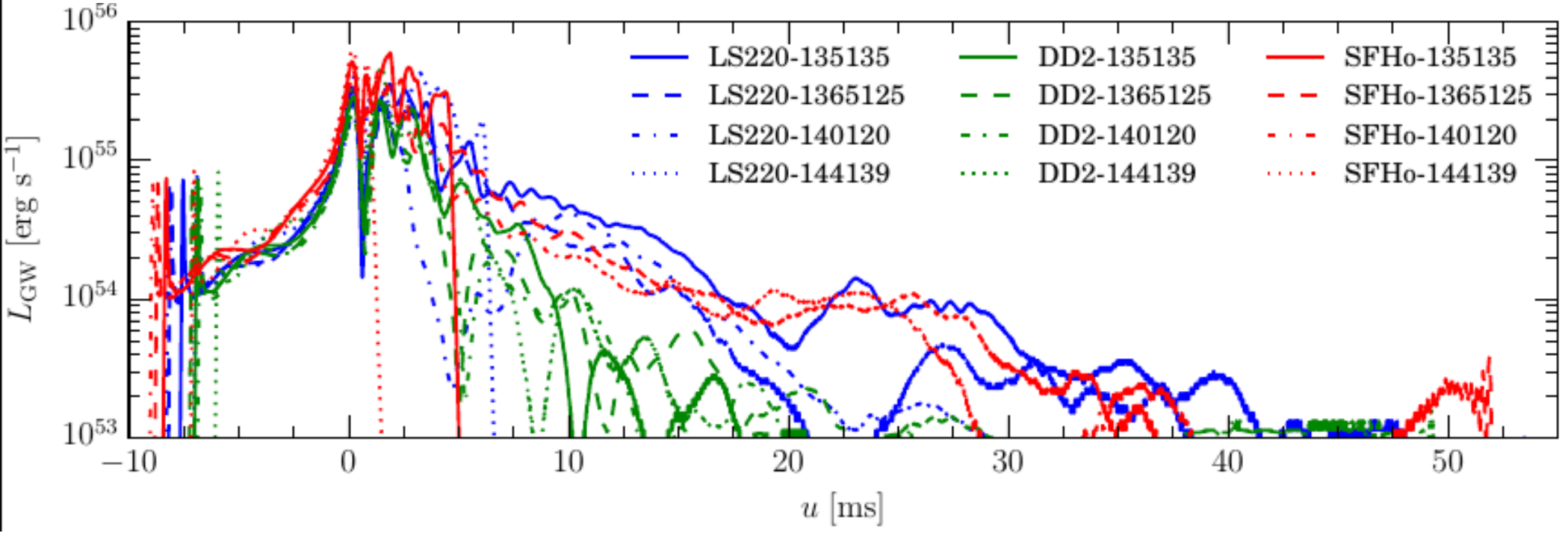
Subcell WENO-DG → Bruegmann talk

Remnant HMNS is the loudest GW emitter

[SB+, Radice, Ott, Roberts, Moesta, Galeazzi arXiv:1512.06397]

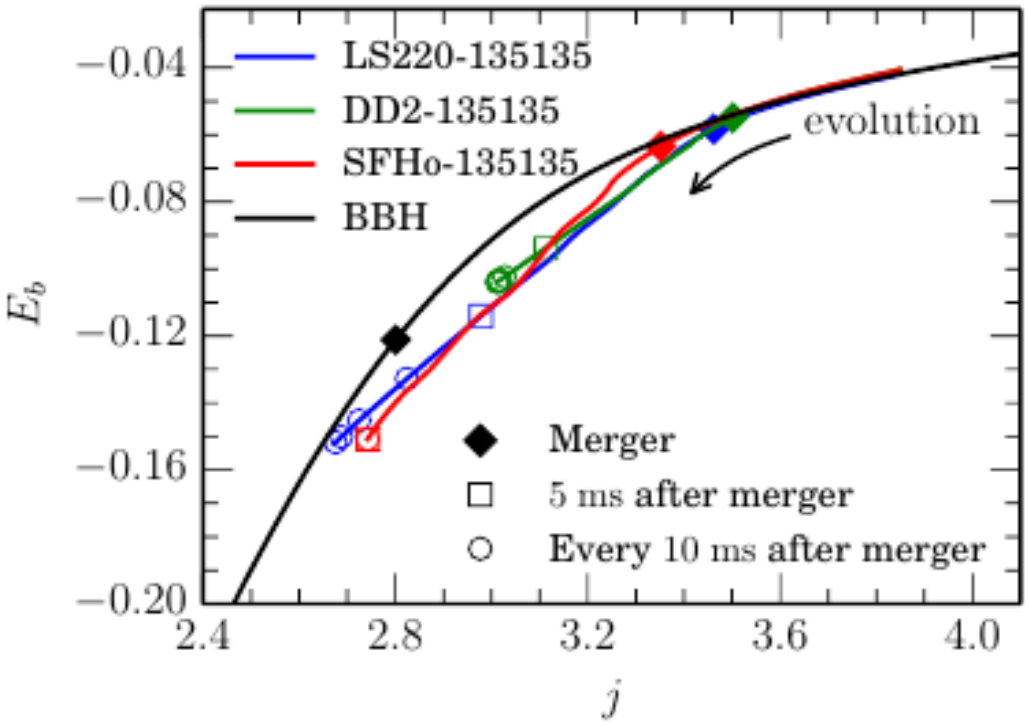
- Large BNS sample; 3 EOS w/ microphysics, neutrinos (leakage)
- HMNS emission is <u>fast:</u> timescale τ_{GW}~ 10-20 ms

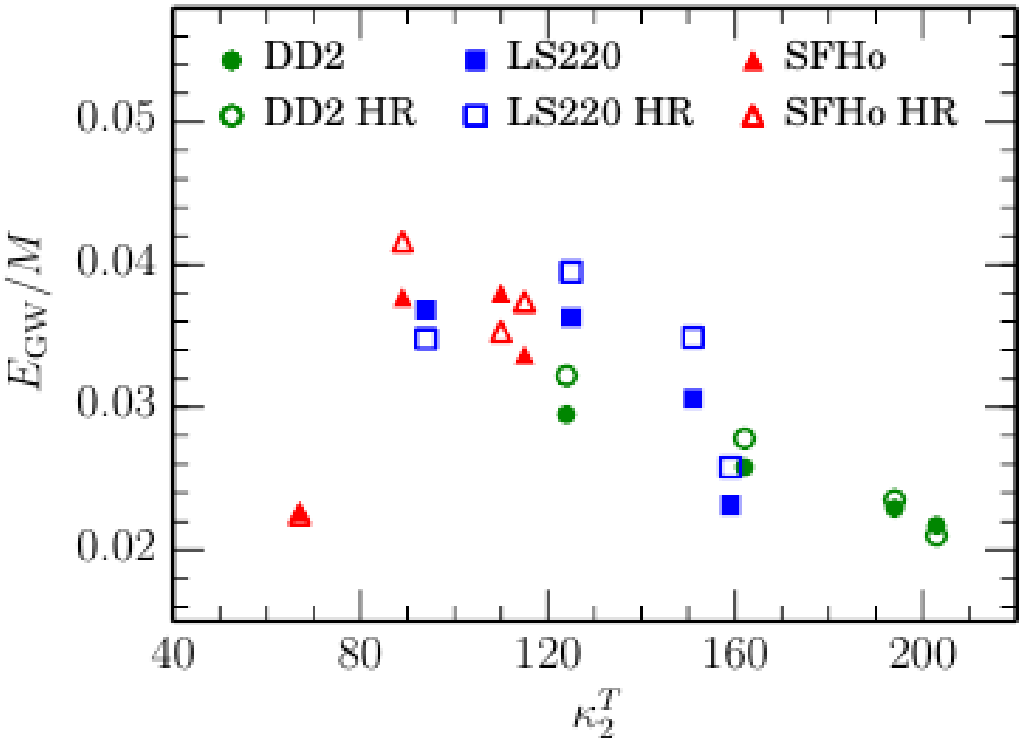
  τ_{GW} → 2x the GW energy of the inspiral+merger
- Hydrodynamics (**m=2**); other physics is <u>negligible</u>



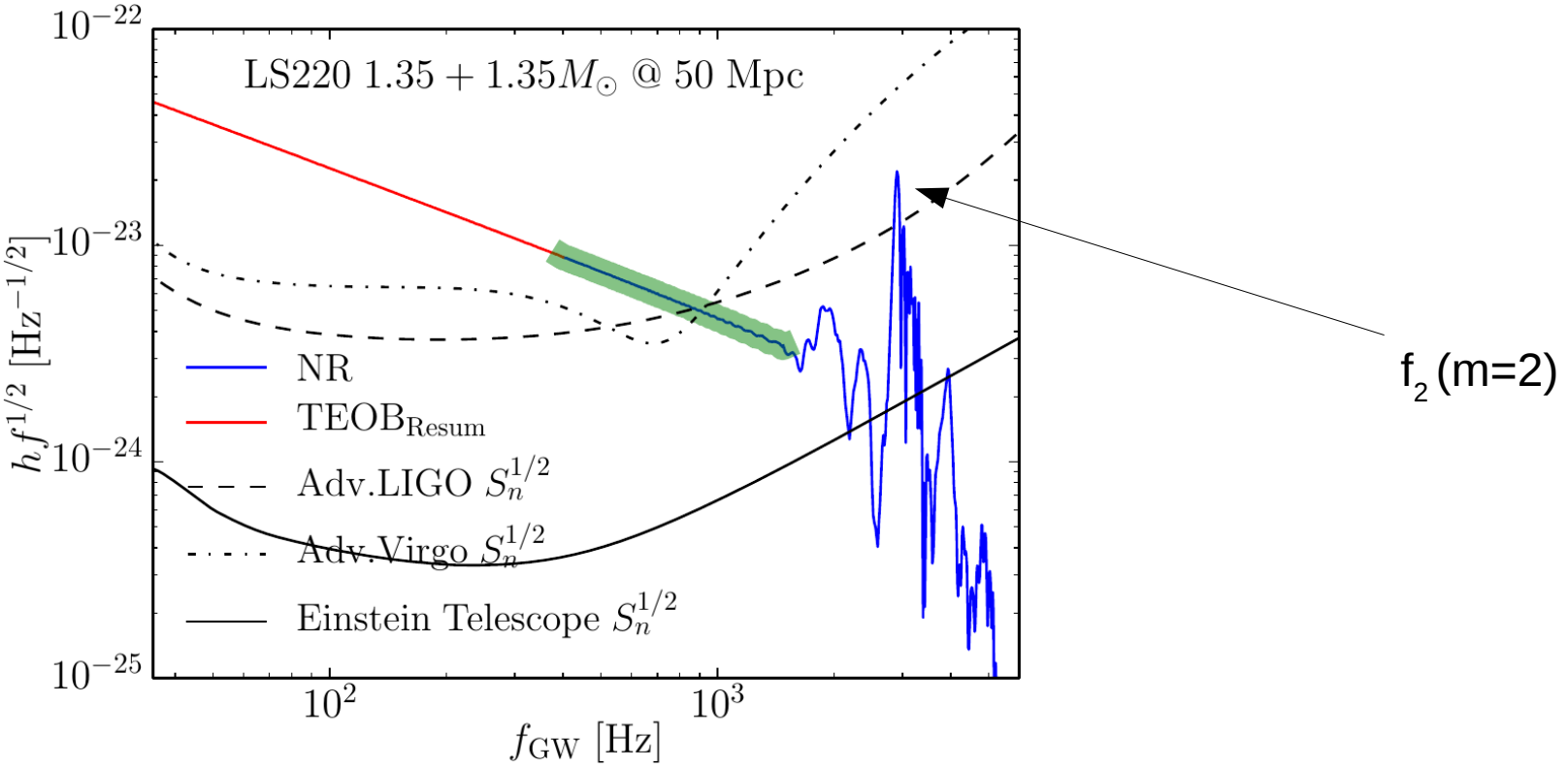
Remnant HMNS is the loudest GW emitter

- Largest emission from BNS w/ $70 < \kappa^T_2 < 150$
- E_{Rad}/M >~ BBH nonspinning inspiral-merger (no ringdown)
- High-frequencies observations challenging for aLIGO/Virgo





Postmerger spectrum peak frequencies

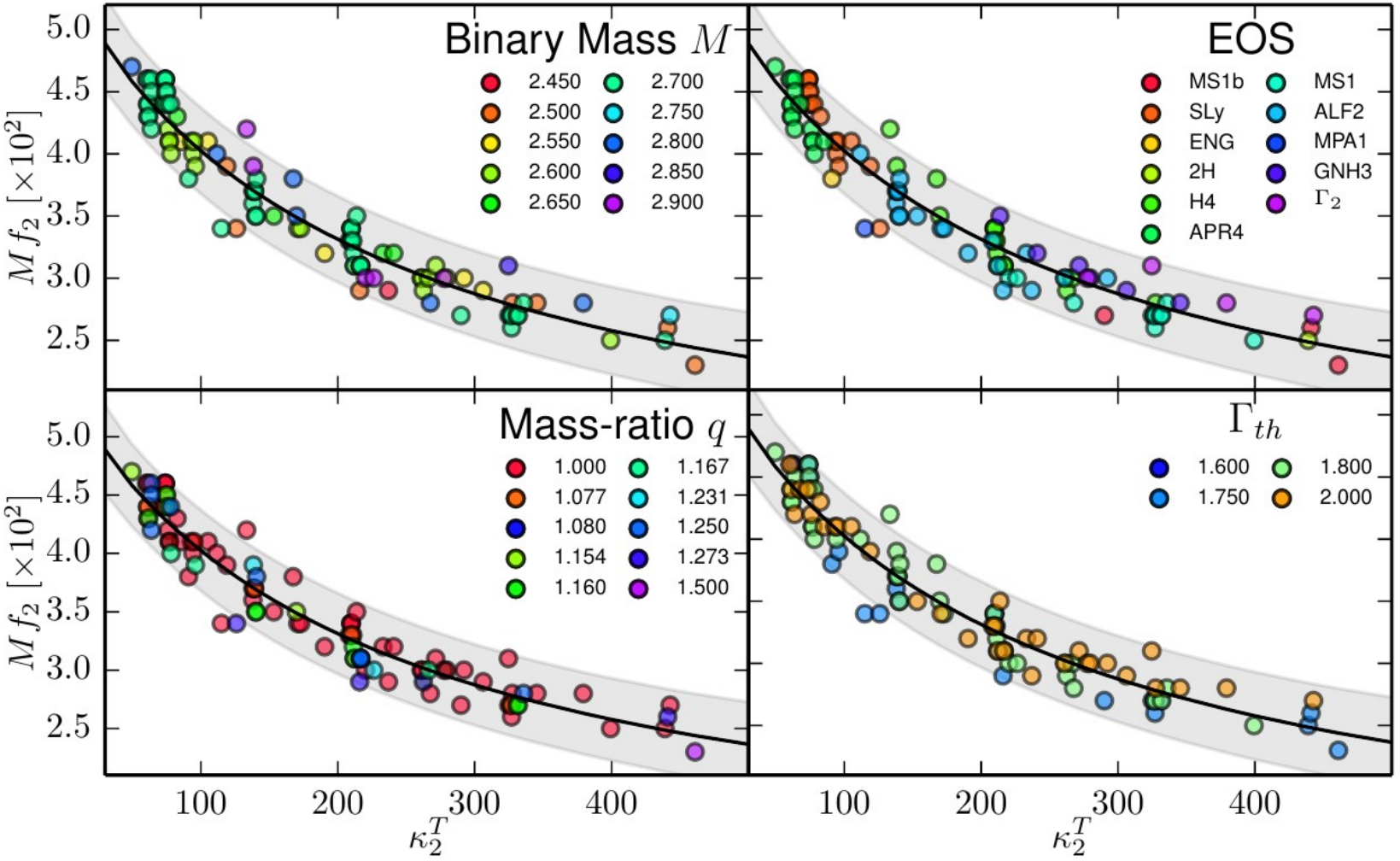


- Various models associating f_2 to isolated equil. star properties
- Conceptually indepedent on inspiral-merger models
- Possibility to extract “EOS-related info” (R_x,M_{max},...)

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

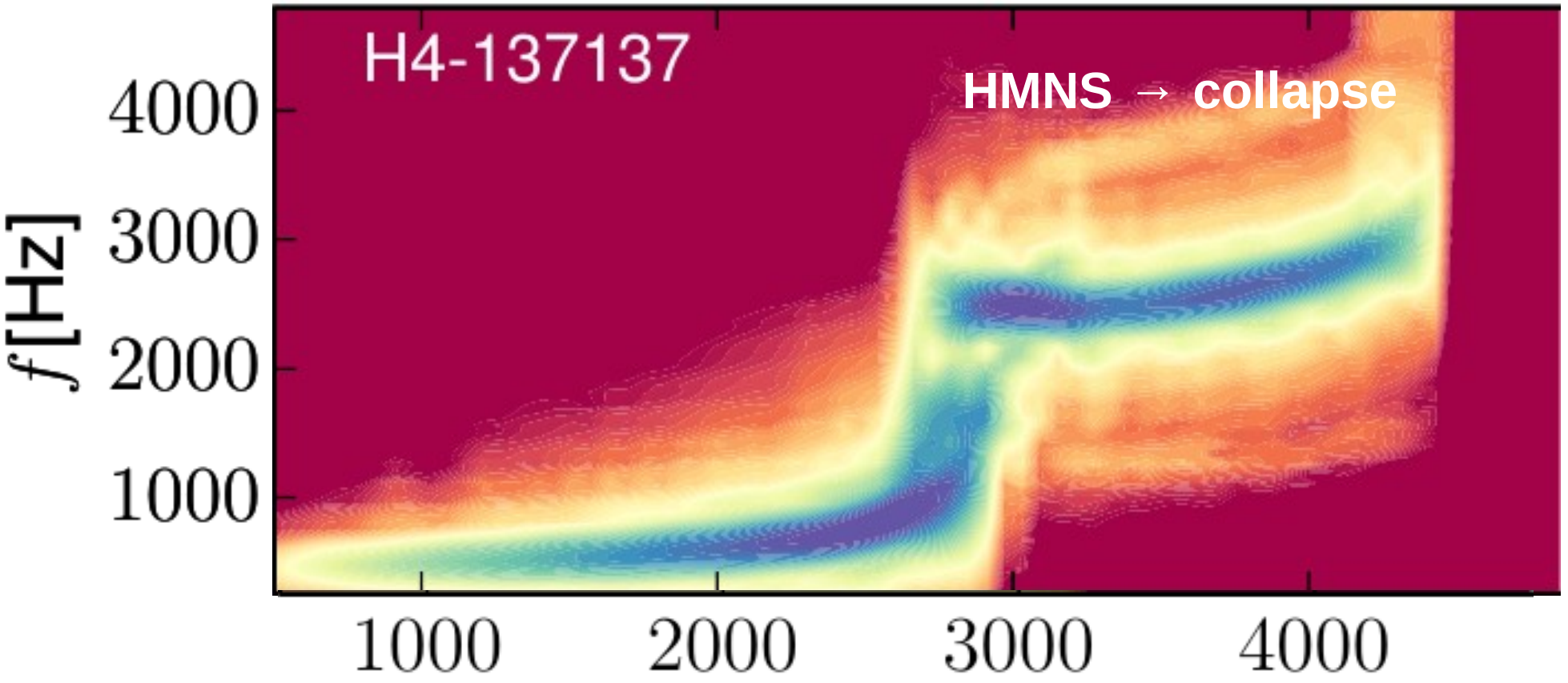
Peak frequency correlates to κ^T_2

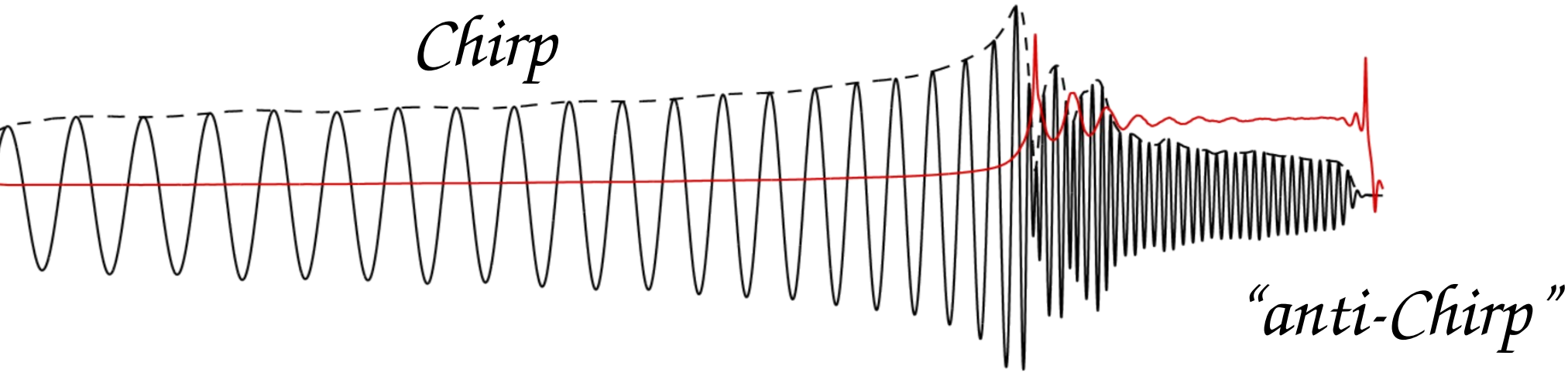
[SB, Dietrich, Nagar arXiv:1504.01764]



- Large NR dataset (~100, 3 codes) [Hotokezaka+ arXiv:1307.5888, Takami+ arXiv:1403.5672]
- Conceptually “compatible” with inspiral-merger (cf. TEOB)
- DA applications ? (WIP)

Is it really a peak ?





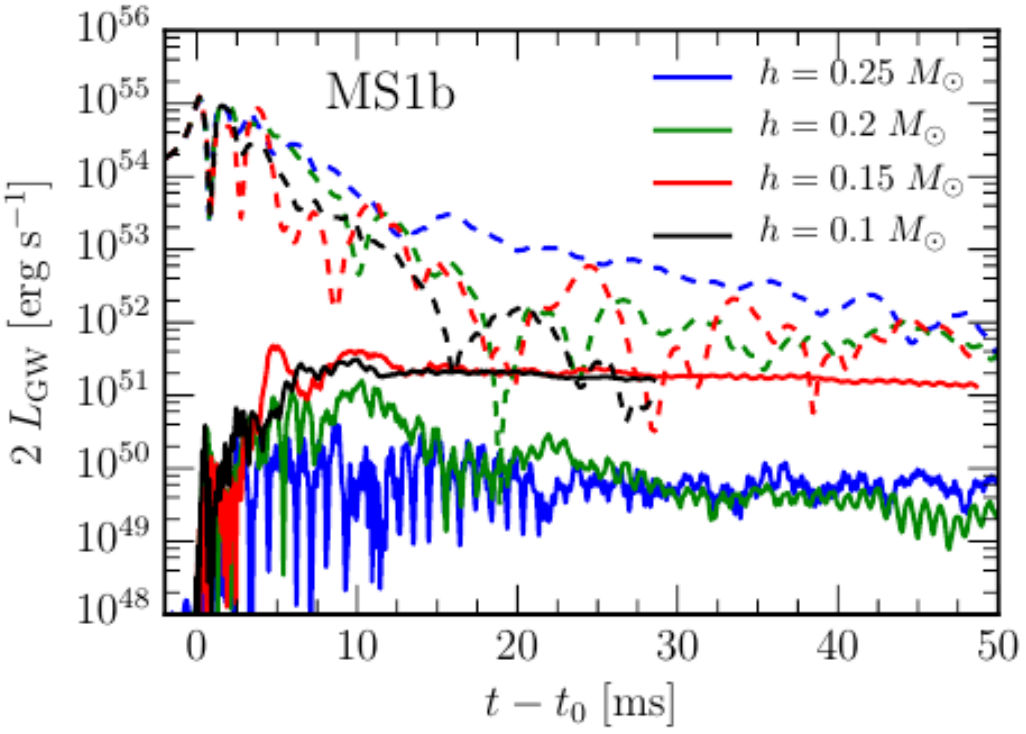
[SB, Dietrich, Nagar arXiv:1504.01764]

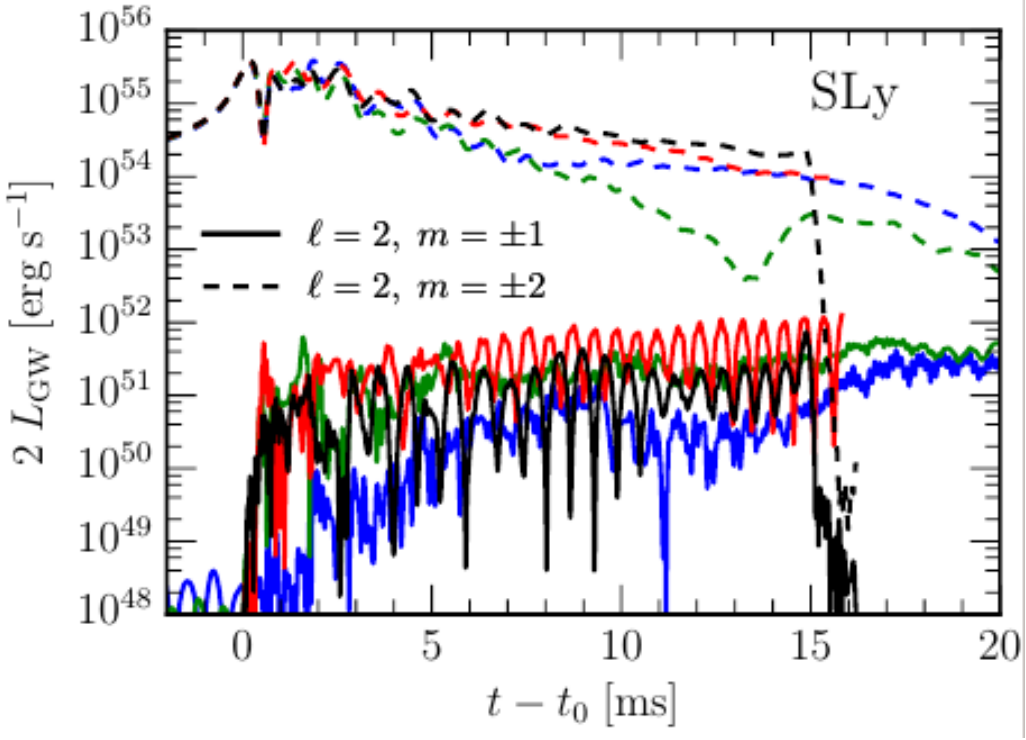
Example of other emission channels: One-armed spiral instability

[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

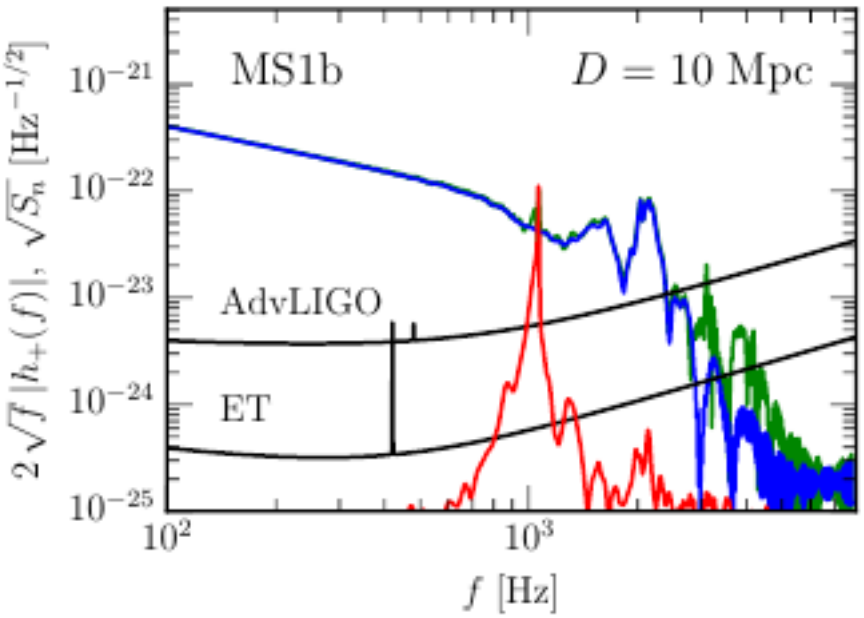


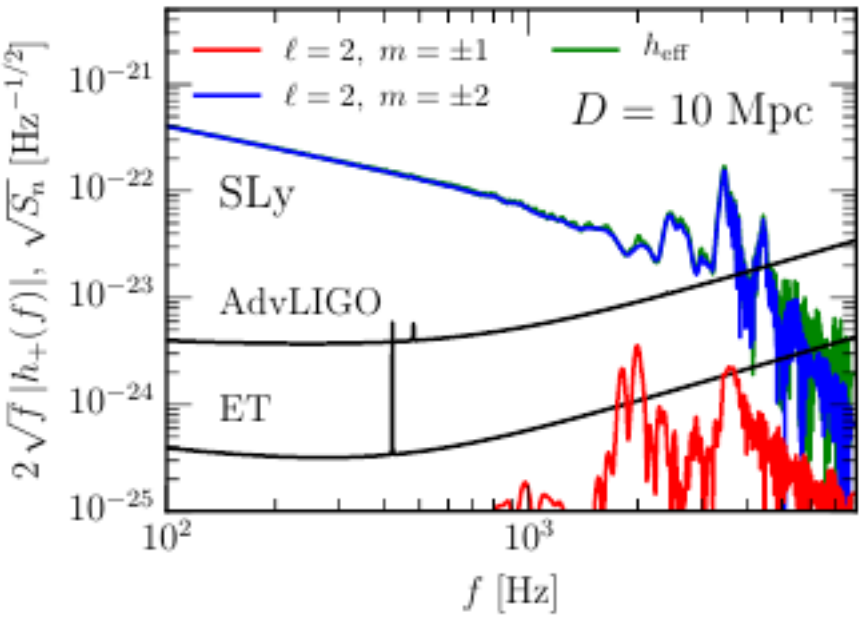


One-armed spiral instability: detectability

[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





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

Towards a complete GW spectrum model

- Combine numerical and analytical methods

  EOB → NR : identify key parameters, physical effects

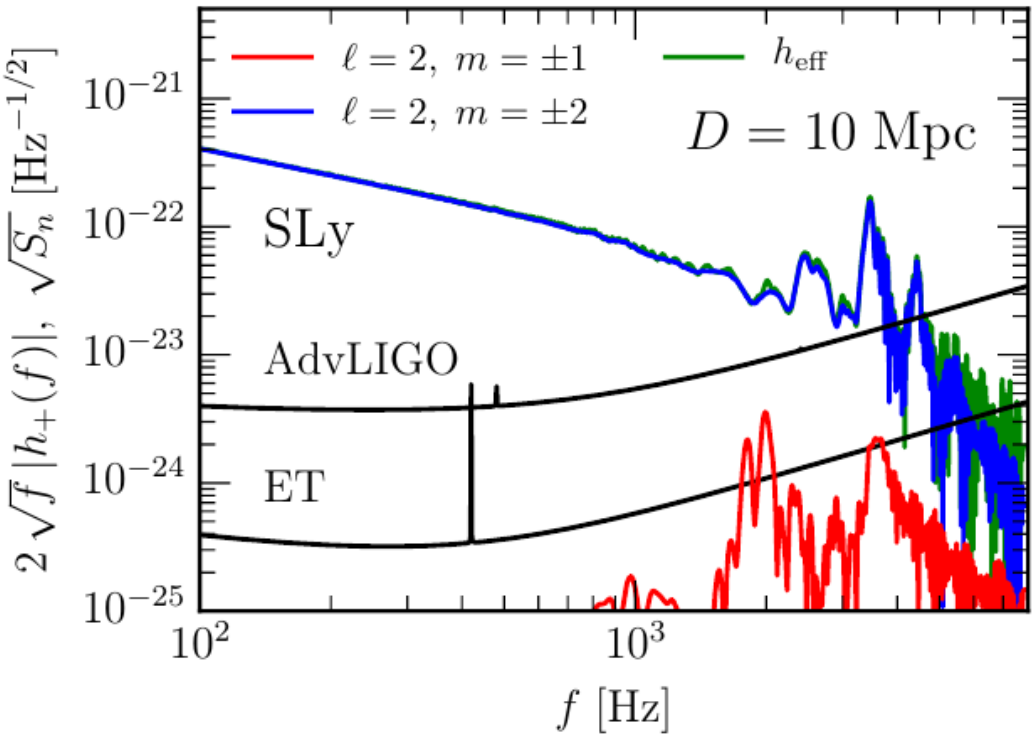
  EOB ←NR : inform about “nonlinear dynamics”

  Efficient representation of the model (e.g. ROM)
- Improve simulation's precision
- Include rotational (spin) effect (coupling w/ tides)

BNS Spin (+ parameter space) → Dietrich talk

Publicly available EOB code
https://eob.ihes.fr

Publicly available hybrid TEOBResum + NR waveforms
https://zenodo.org/record/46733#.VvCC7CaR4ll



Community collection

NR-GW OpenData

A collection of datasets from numerical relativity and gravitational waves modeling papers.

Title:
NR-GW OpenData

Curated by:
bernuzzi

Curation policy:
New uploads in this community must contain publicly distributable material related to gravitational waves modeling and numerical relativity papers.

Created:
2016-02-29

Harvesting API:
OAI-PMH Interface

Publicly available hybrid TEOBResum + NR waveforms

https://zenodo.org/record/46733#.VvCC7CaR4ll