FRIEDRICH-SCHILLER-UNIVERSITÄT JENA

erc
European Research Council
Established by the European Commission

www.computational-relativity.org

Public database of NR BNS waveforms
https://core-gitlfs.tpi.uni-jena.de/core_database
and ejecta profiles
https://zenodo.org/communities/nrgw-opendata

Numerical Relativity Modeling for EOS Constraints

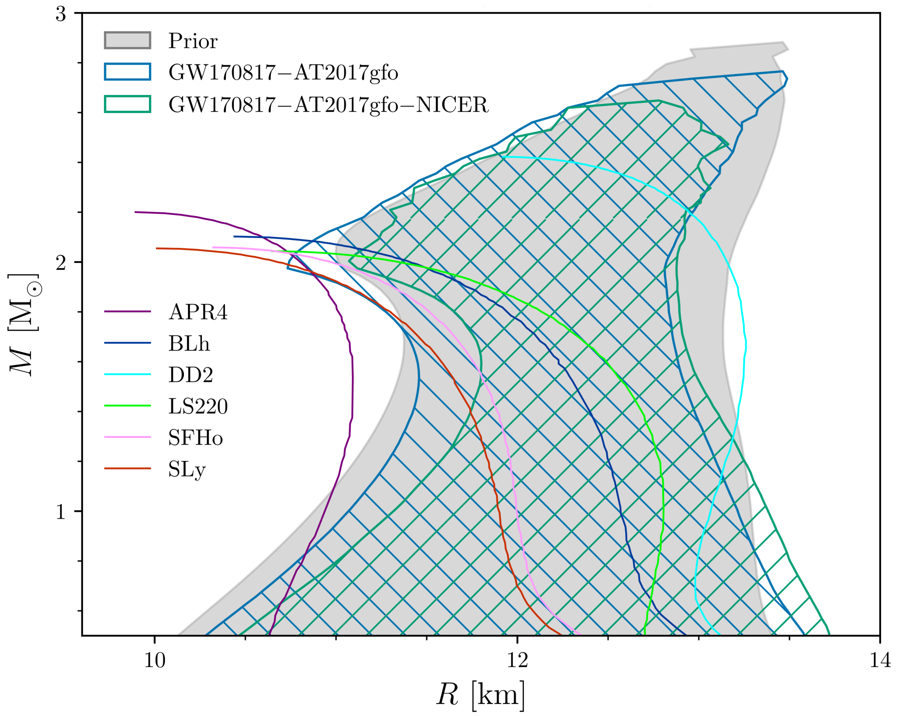
S.Bernuzzi

ETC*
“Neutron stars as multi-messenger laboratories for dense matter”

June 2022

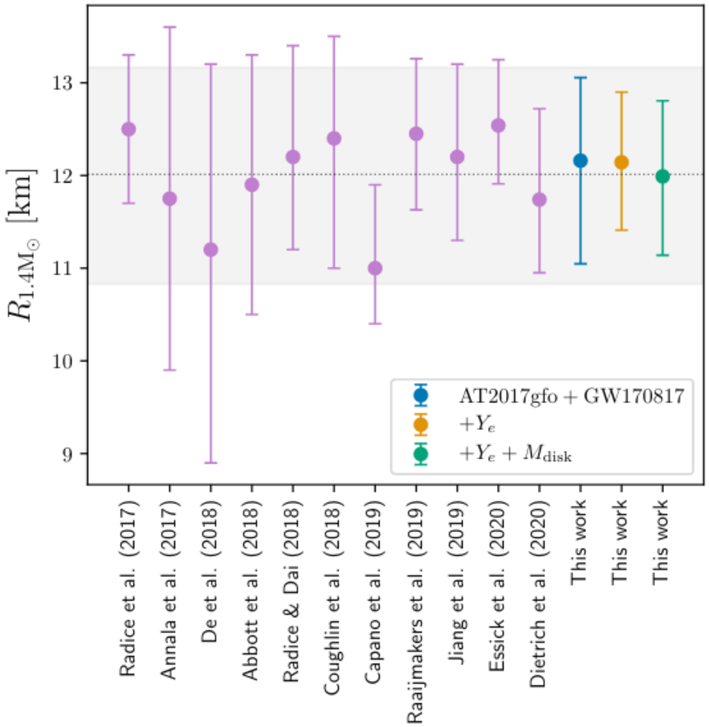
Constraints on EOS after GW170817

Breschi+ [https://arxiv.org/abs/2101.01201]



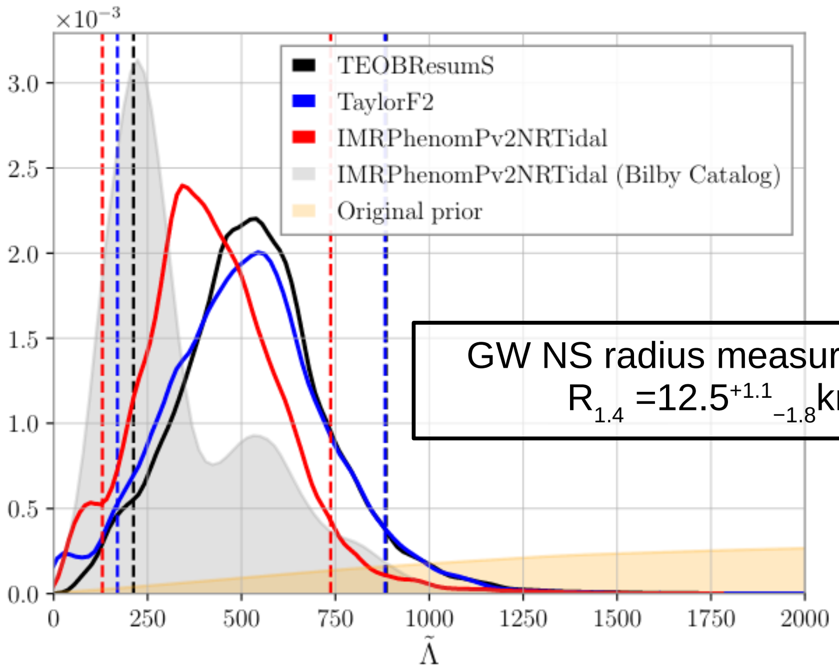
NS radius measurement w/ NICER
$R_{1.4} = 12.3^{+0.7}_{-0.7}$ km

NS radius GW170817+AT2017gfo
$R_{1.4} = 12.2^{+0.5}_{-0.5}$ km



GW170817 inference of tidal parameters

Gamba, Breschi, SB+ [https://arxiv.org/abs/2009.08467]



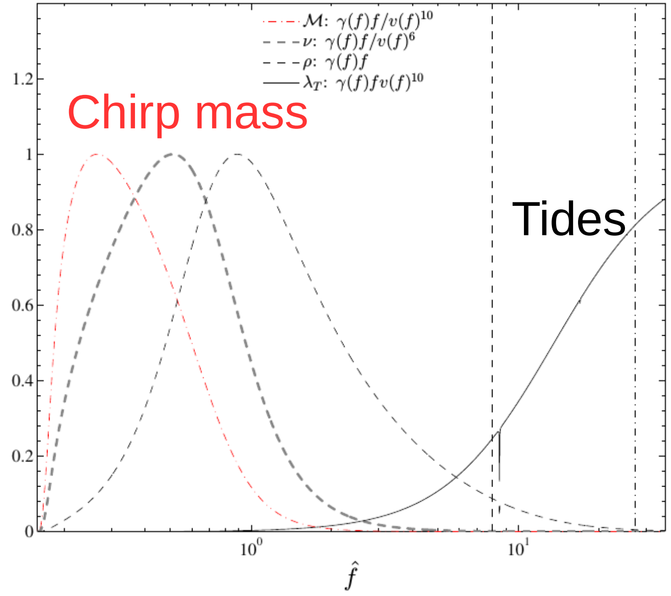
GW NS radius measurement:
$R_{1.4} = 12.5^{+1.1}_{-1.8}$ km

PHYSICAL REVIEW D 85, 123007 (2012)

Measurability of the tidal polarizability of neutron stars in late-inspiral gravitational-wave signals

Thibault Damour and Alessandro Nagar
Institut des Hautes Etudes Scientifiques, 91440 Bures-sur-Yvette, France ICRANet, 65122 Pescara, Italy

Loïc Villain
Laboratoire de Mathématiques et de Physique Théorique, Univ. F. Rabelais—CNRS (UMR 7350), Féd. Denis Poisson, 37200 Tours, France
(Received 20 March 2012; published 15 June 2012)



GW170817: no significant wvf systematics BUT $\bar{\Lambda}$ "double peaked" posteriors …
1kHz cut-off removes double peaks, less wvf baises and shifts to larger $\bar{\Lambda}$ (larger radii) for comparable log-like.
Estimated <10% SNR above f > 1kHz. High-frequencies issues in $\bar{\Lambda}$-inference? [Dai+ 2018, Narikawa+ 2019]

Systematics & waveform accuracy

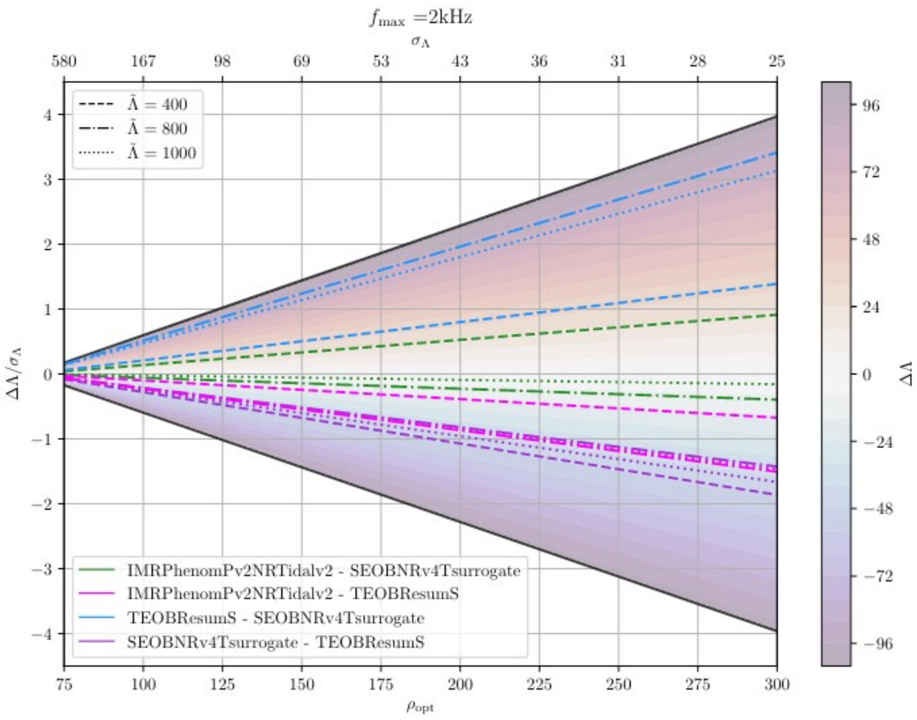
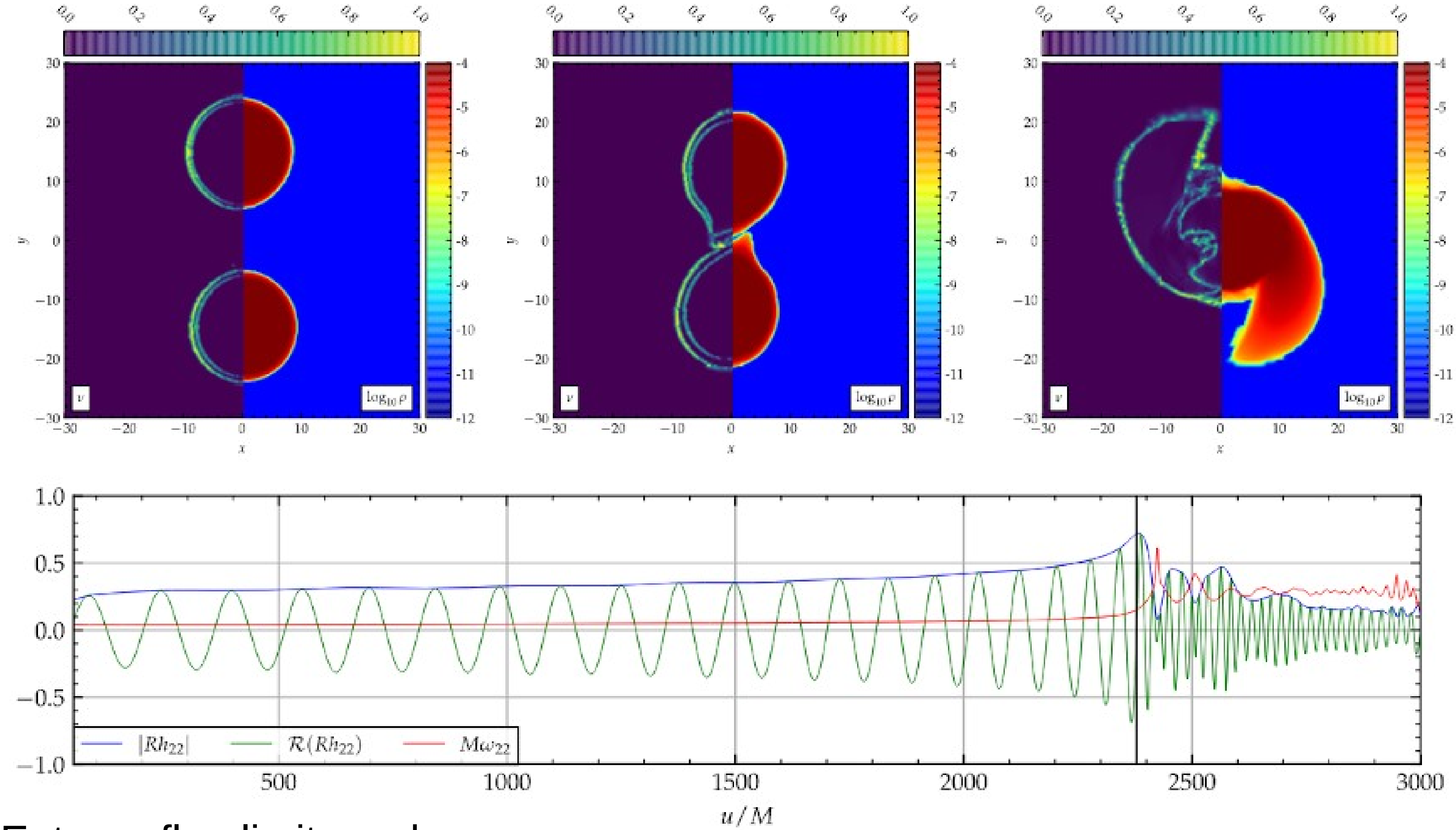


TABLE V. Faithfulness values $\mathcal{F}$ computed considering frequencies from f_{low} to f_{mrg} between simulations with the same intrinsic parameters and two different resolutions, extracted at $r/M = 1000$. The source is situated in the same sky location as GW170817, and the waveform polarizations h_+ and $h_\times$ are computed and projected on the Livingston detector. We employ the `aLIGODesignSensitivityP1200087` [22] PSD from `pycbc` [110] to compute the matches, and compare the values obtained to the thresholds $\mathcal{F}_{thr}$ calculated with Eq. 19 with $\epsilon^2 = 1$ or $\epsilon^2 = N$. A tick ✓ indicates that $\mathcal{F} > \mathcal{F}_{thr}$. Conversely, a cross ✗ indicates that $\mathcal{F} < \mathcal{F}_{thr}$.

Sim	n[a]	$\mathcal{F}$	SNR 14 $N=6$	SNR 14 1	SNR 30 $N=6$	SNR 30 1	SNR 80 $N=6$	SNR 80 1
BAM:0011	[96, 64]	0.991298	✓	✗	✗	✗	✗	✗
BAM:0017	[96, 64]	0.985917	✓	✗	✗	✗	✗	✗
BAM:0021	[96, 64]	0.957098	✗	✗	✗	✗	✗	✗
BAM:0037	[216, 144]	0.998790	✓	✓	✓	✗	✗	✗
BAM:0048	[108, 72]	0.983724	✗	✗	✗	✗	✗	✗
BAM:0058	[64, 64]	0.999127	✓	✓	✓	✗	✗	✗
BAM:0064	[240, 160]	0.997427	✓	✗	✓	✗	✗	✗
BAM:0091	[144, 108]	0.997810	✓	✓	✓	✗	✗	✗
BAM:0094	[144, 108]	0.996804	✓	✗	✓	✗	✗	✗
BAM:0095	[256, 192]	0.999550	✓	✓	✓	✓	✓	✗
BAM:0107	[128, 96]	0.995219	✓	✗	✗	✗	✗	✗
BAM:0127	[128, 96]	0.999011	✓	✓	✓	✗	✗	✗

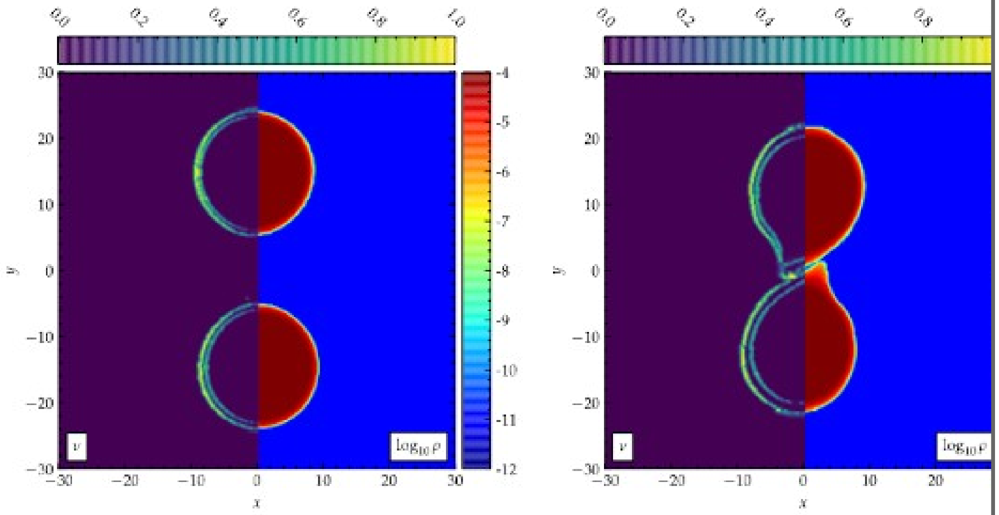
[a] Number of grid point (linear resolution) of the finest grid refinement, roughly covering the diameter of one NS

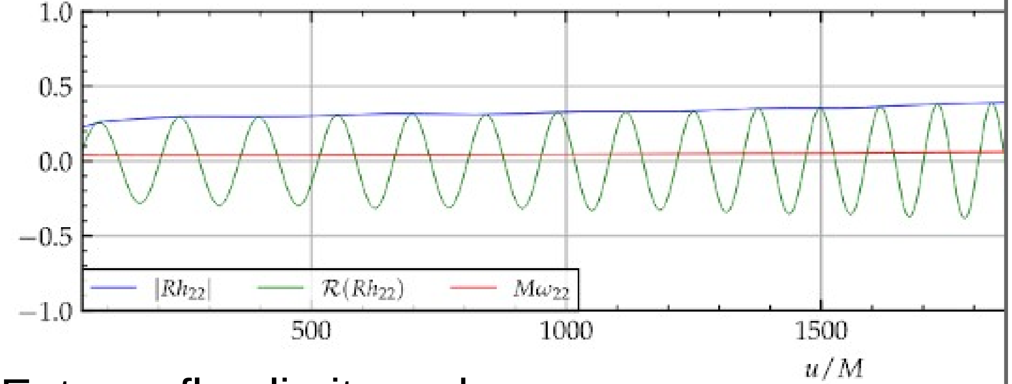
Gamba,Breschi,SB+ [https://arxiv.org/abs/2009.08467]



Entropy flux-limiter scheme

Doulis,Atteneder,SB,Bruegmann [https://arxiv.org/abs/2202.08839] (see also work by Guercilena+)





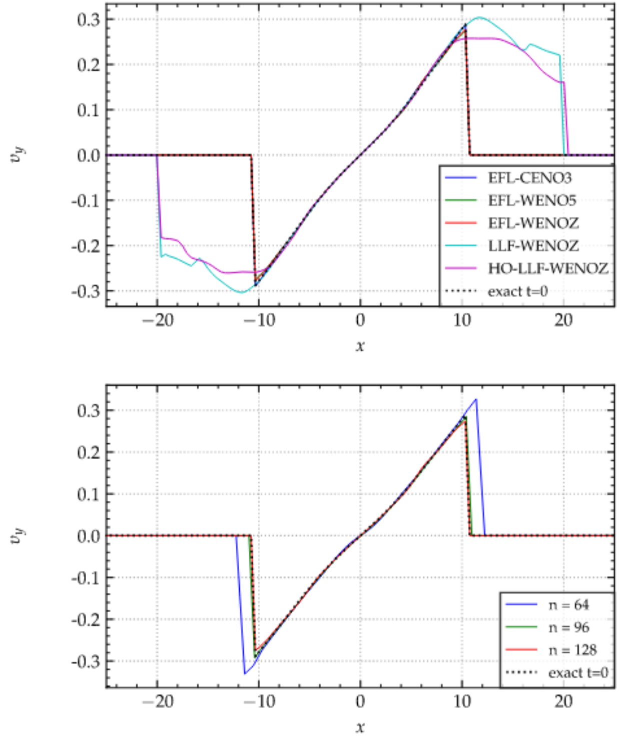


FIG. 9. Velocity profile of a stationary rotating neutron star in a dynamical spacetime with Γ-law EoS. Top: One-dimensional profile of the velocity component v_y along the x-direction at time $t = 1000$ (four periods) with $n = 128$. Bottom: The v_y profile of the WENO5 scheme with increasing resolution.

Entropy flux-limiter scheme

Doulis,Atteneder,SB,Bruegmann [https://arxiv.org/abs/2202.08839]

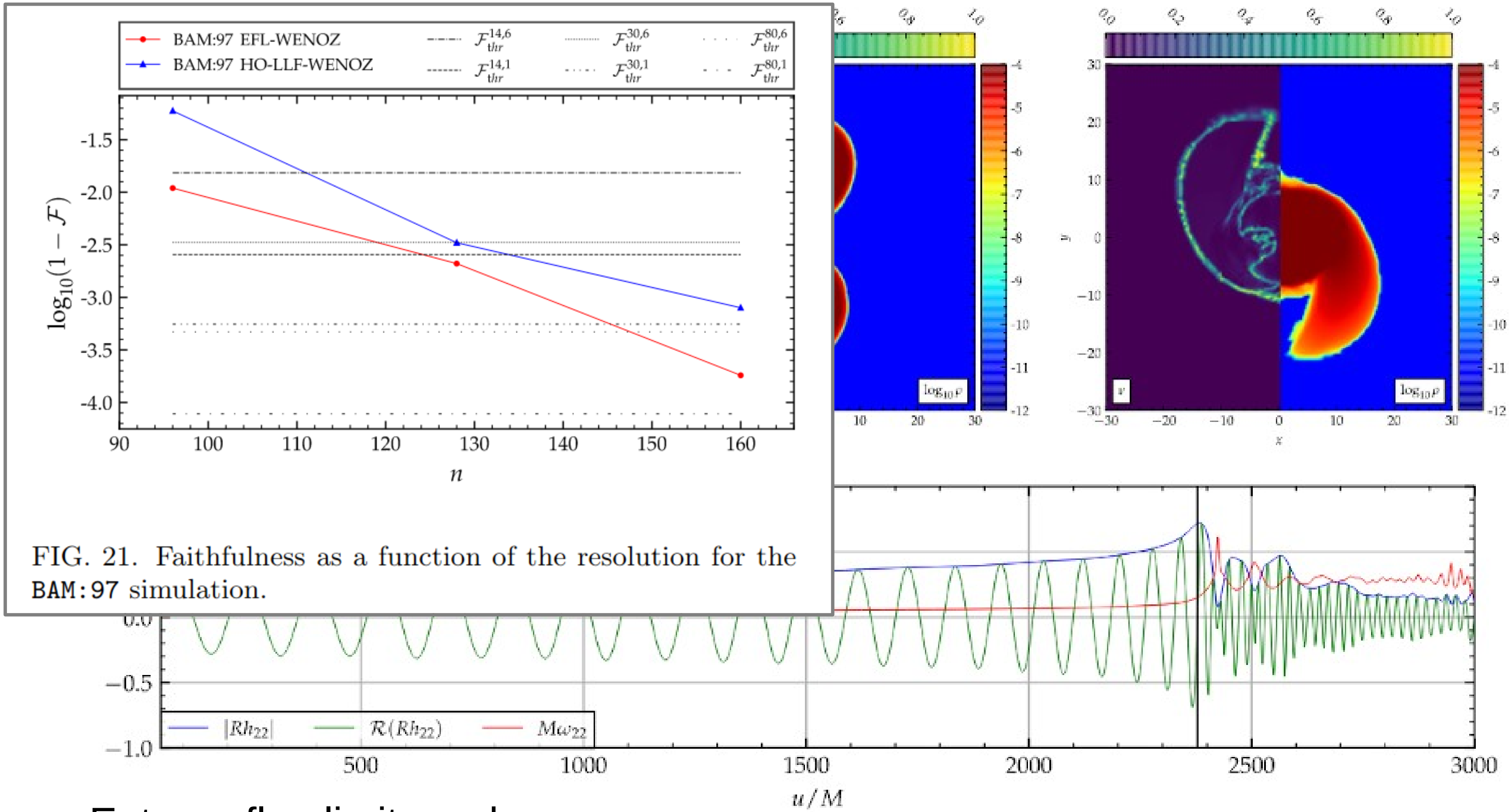
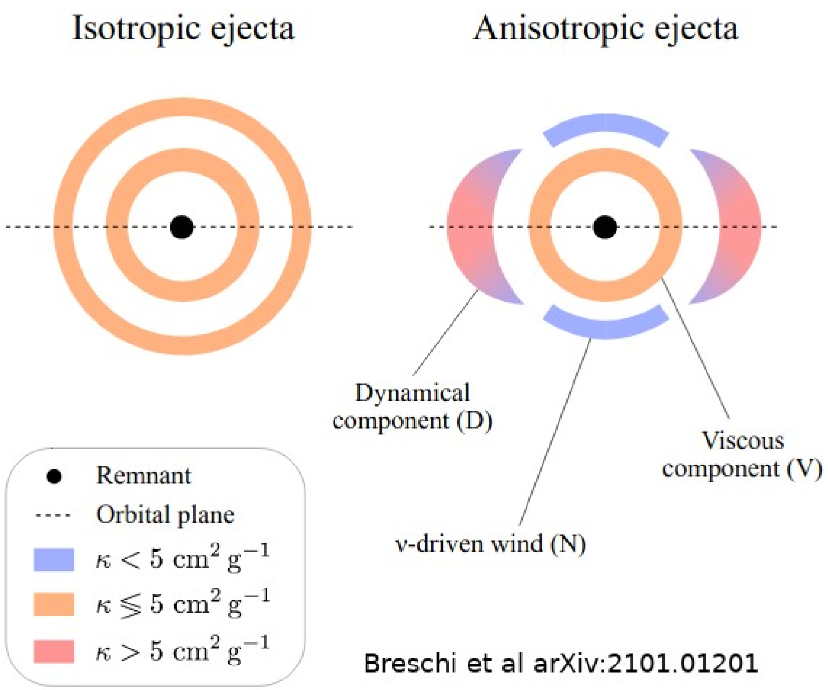


FIG. 21. Faithfulness as a function of the resolution for the BAM:97 simulation.

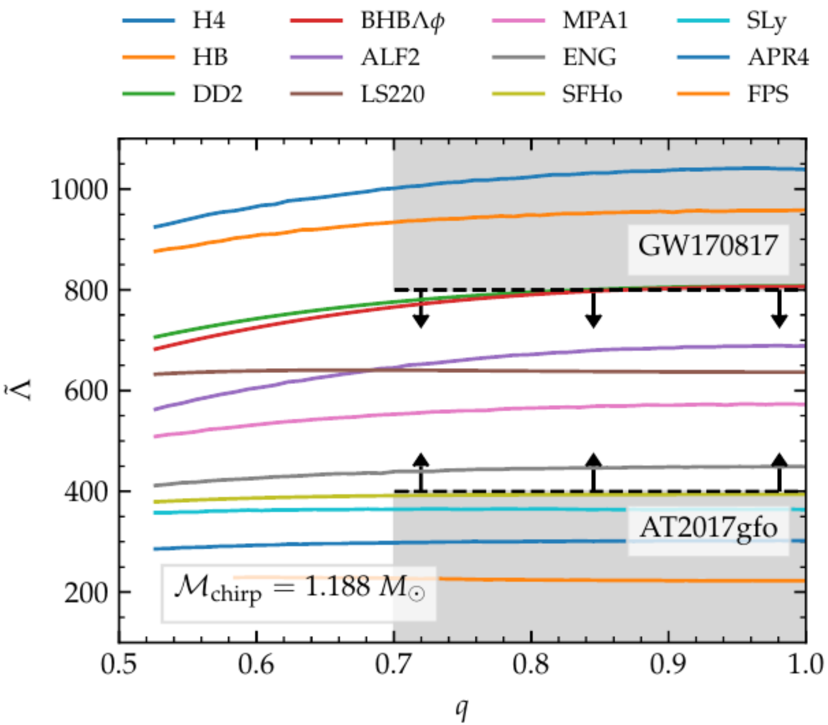
Entropy flux-limiter scheme

Doulis,Atteneder,SB,Bruegmann [https://arxiv.org/abs/2202.08839]

AT2017gfo inference: tidal par & mass ratio

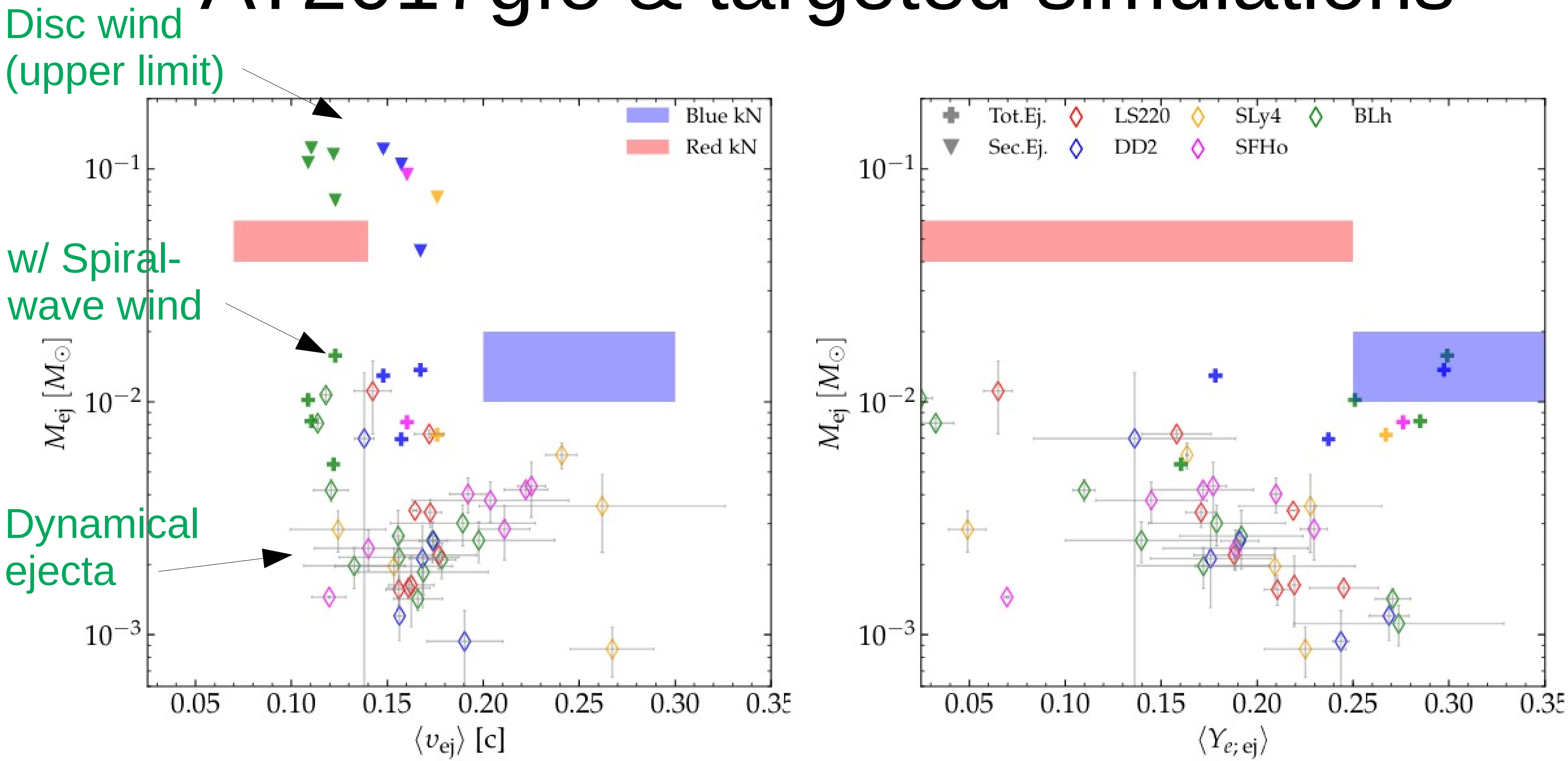


Breschi et al arXiv:2101.01201



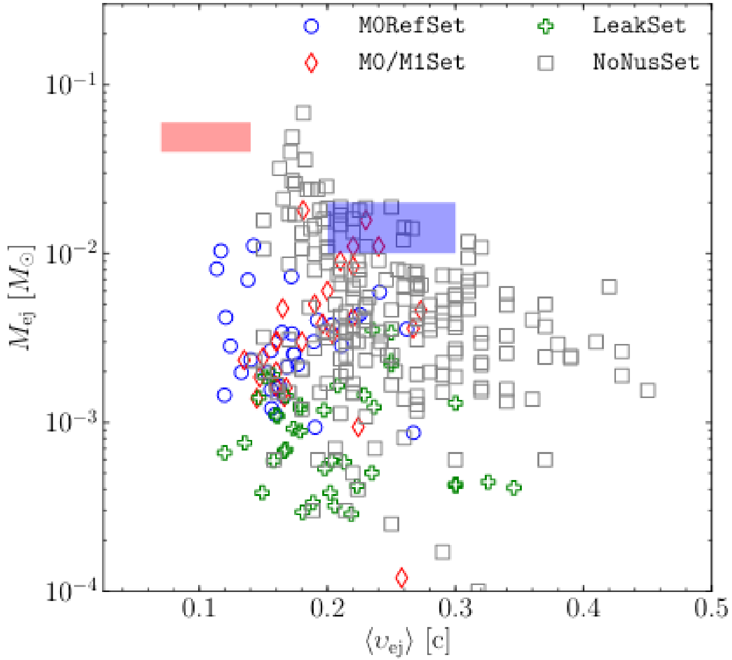
- $\bar\Lambda$ & q from color/disk/ejecta mass (Radice,Perego,Zappa,SB [https://arxiv.org/abs/1711.03647])
- NR-informed semi-analytical kN models (Perego+ [https://arxiv.org/abs/1711.03982])
- Model selection: 3-components + anisotropic models preferred [https://arxiv.org/abs/2101.01201]

AT2017gfo & targeted simulations



- Need at least two components high/low opacities (tentatively ~ dynamical ejecta+ winds ?)
- Spherical two-component models are incompatibile with NR ejecta

Weak interactions in the dynamical ejecta



- Dynamical averaged properties are captured by the reduced tidal parameter* and the mass ratio

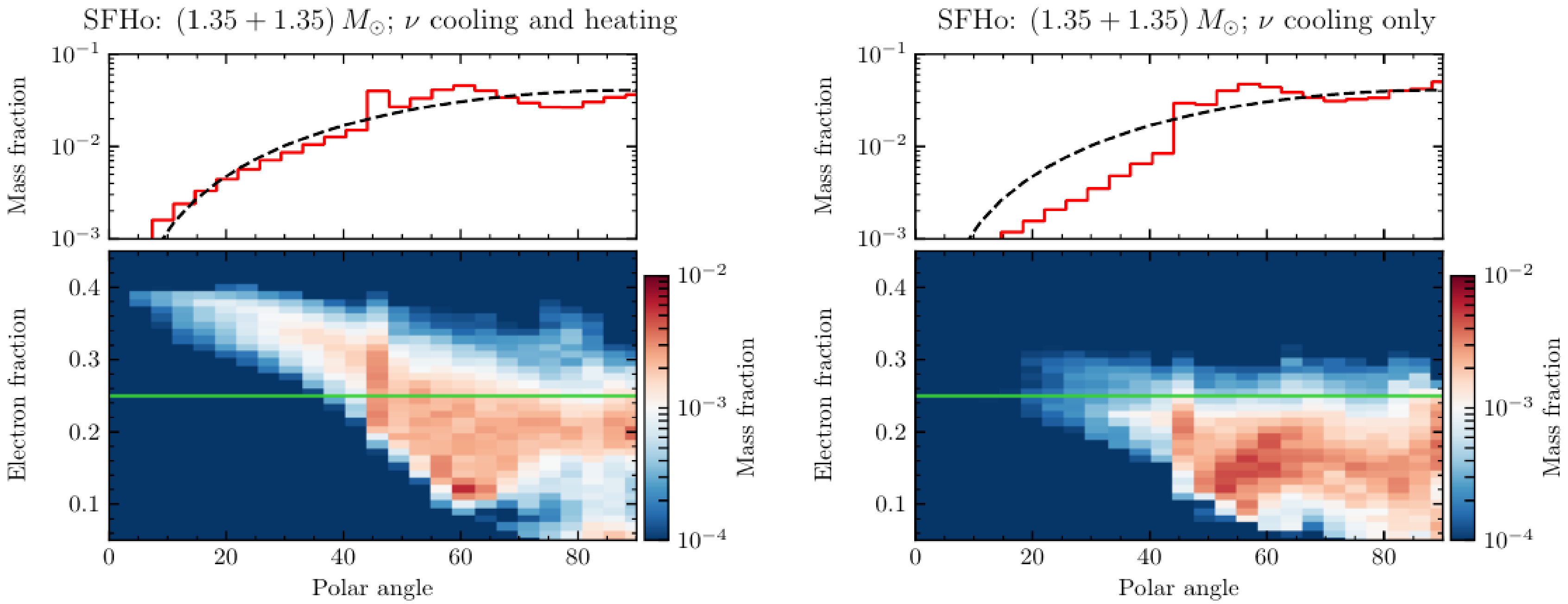
  (EOS-insensitive relations)

- Large uncertainties related to different neutrino transport schemes employed in simulations

  [Nedora+ https://arxiv.org/abs/2011.11110]

* $\bar{\Lambda}$ (or κ^T_2) = coupling constant of tidal interactions at leading Newtonian order.

Weak interactions in the dynamical ejecta

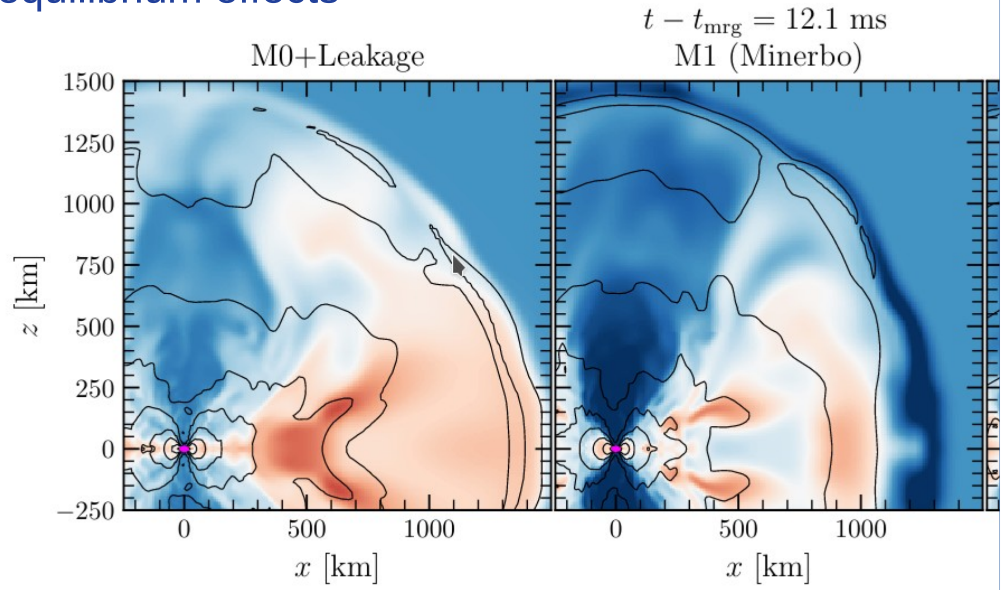


Neutrino absorption determines composition and kinetic properties

[Perego,Radice,SB ApJL 2017]   See also [Wanajo+ 2014, Sekiguchi+ 2016, Foucart+ 2017/2018]

Leakage+M0 vs M1 gray+

Optically thick sources on long timescales
Out-of-equilibrium effects



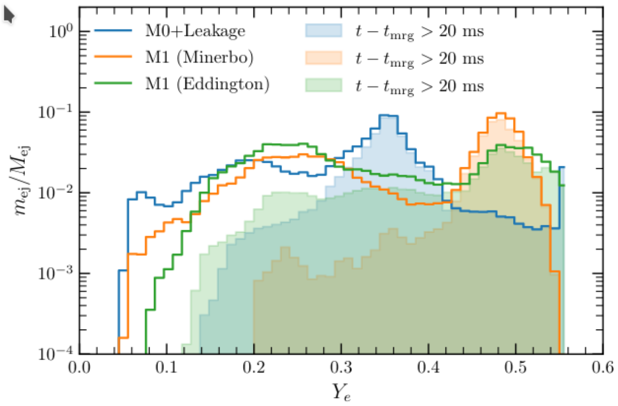


Figure 26. Ejecta Y_e for the SLy 1.3 $M_\odot - 1.3\ M_\odot$ binary. The shaded regions show the contributions to the Y_e histogram due to the material ejected after the first 20 ms of the merger. The ejecta distribution peaks at significantly larger Y_e in the M1 runs. The Eddington and Minerbo results are in good agreement, but the Eddington simulations produce a smaller amount of very neutron rich ejecta ($Y_e \sim 0.1$).

Figure 18. Electron fraction (color) of the dynamical ejecta cloud formed for the SLy 1.3 $M_\odot$ – 1.3 $M_\odot$ binary. The black lines are isodensity contours of $\rho = 10^5, 10^6, 10^7, 10^8, 10^9, 10^{10}, 10^{11}$, and 10^{12} g cm^{-3}. The purple contour shows corresponds to $\rho = 10^{13}$ g cm^{-3} and denotes the approximate location of the surface of the merger remnant. M0 and M1 results are in good qualitative agreement, but M1 predicts higher electron fractions for both the polar and equatorial ejecta.

+ lower nu luminosities

Radice,SB,Perego,Haas [https://arxiv.org/abs/2111.14858]

M1 gray+ scheme

Radice,SB,Perego,Haas 2021
[https://arxiv.org/abs/2111.14858]

Compare Foucart+ 2016 and Zelmani codes:

* diffusion limit : 2nd order asymptotically preserving scheme.

Avoids ill-posed heat equation.

* complete sources : appear necessary even for simple tests

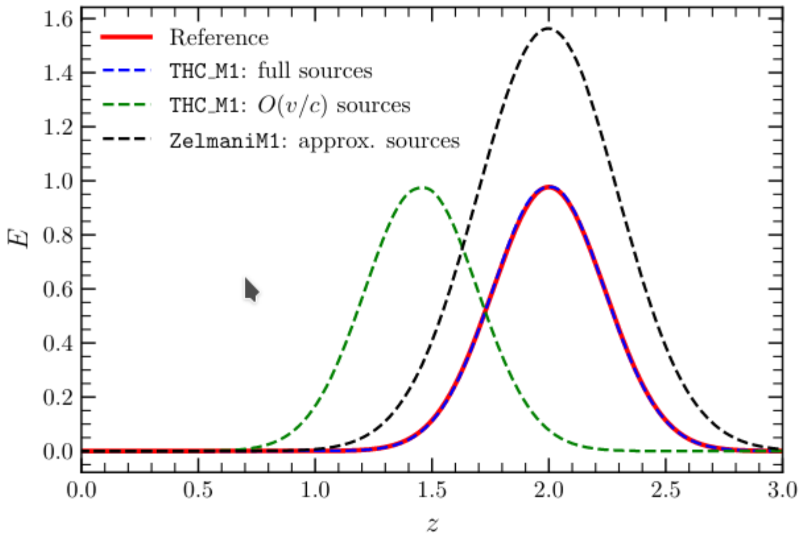
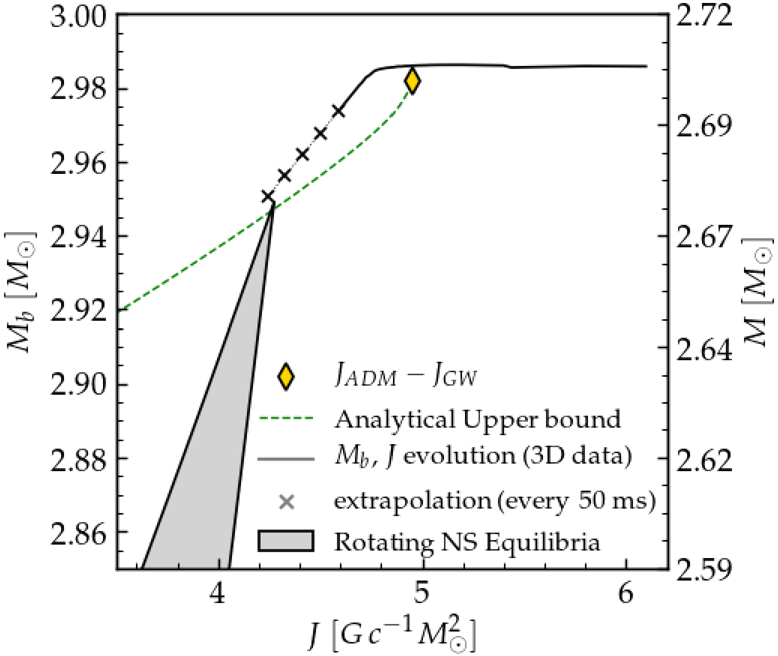


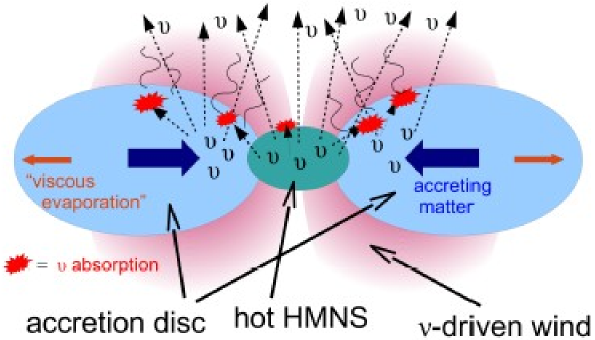
Figure 3. Diffusion and advection of Gaussian pulse of radiation in a purely scattering moving medium. The medium is moving with velocity $v = 0.5$. The reference profile is a translated semi-analytic solution of the diffusion equation. Our results show that it is essential to properly treat all of the source terms in the M1 equations to correctly capture the advection of trapped radiation.

Remnant evolution on viscous timescale

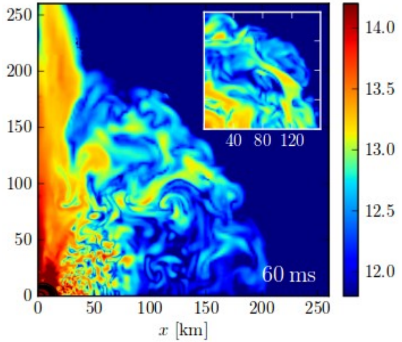
- Angular momentum (“super-Keplerian) and mass in excess
- Evolution governed by neutrino cooling and viscous processes (magnetic turbulence & stresses, neutrino absorption, etc)
- Nuclear recombination → Massive winds



[Perego+ 2014]



[Siegel+ 2014]

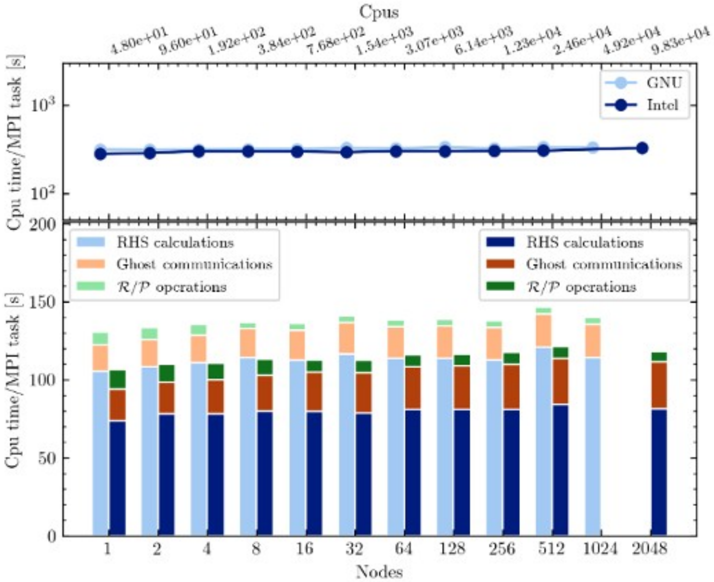


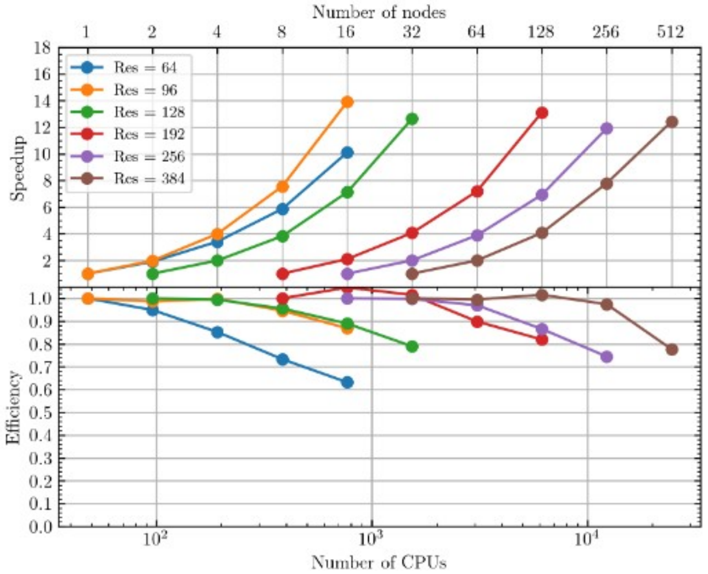
[Radice, Perego, SB, Zhang MNRAS 2018]
[Nedora, SB+ https://arxiv.org/pdf/2008.04333]

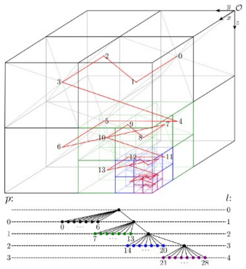
Need comprehensive approach !

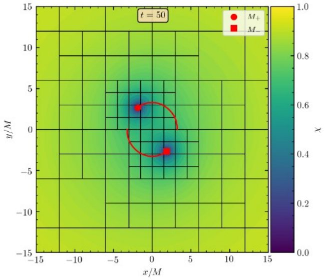
Towards exascale numerical relativity

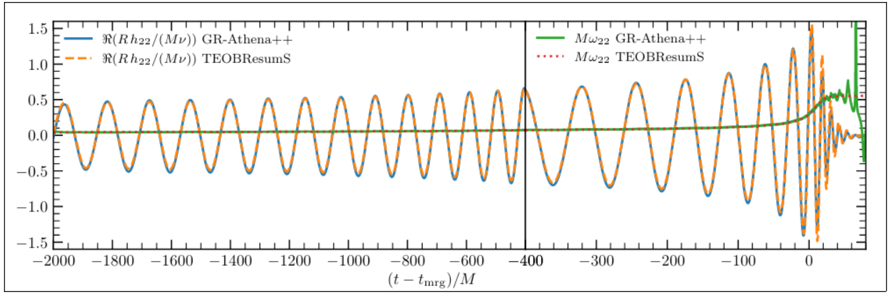
GR-Athena++ [Daszuta+ 2021] based on Athena++ (Stone+)



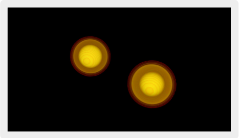




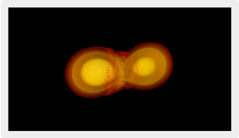


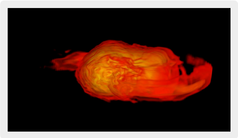


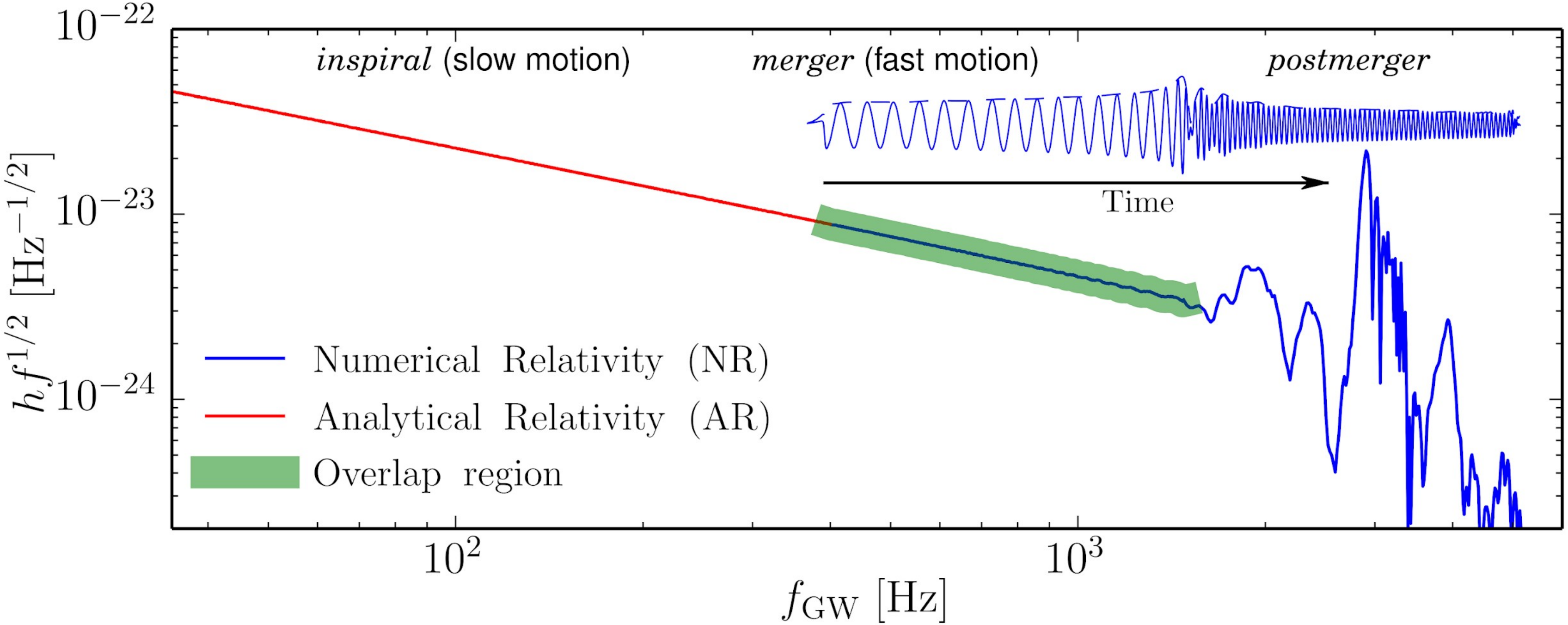
Complete GW spectrum model



SB+ [https://arxiv.org/abs/1504.01764]
Breschi,SB+ [https://arxiv.org/abs/1908.11418]
Breschi,SB+ [https://arxiv.org/abs/2205.09112]



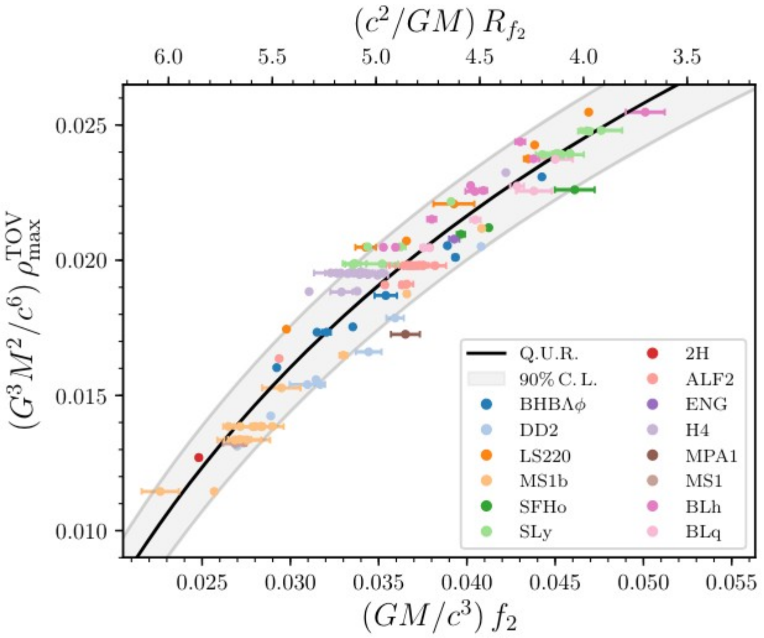




Full-spectrum constraints on M-R diagram

Full-spectrum (mock) analysis using ET @ minimum SNR threshold for a PM detection
NS maximum density to 15% and maximum mass to 12% (90% conf. Lev.)
Recalibration parameters: account for theoretical uncertainties in EOS-insensitive rel.

Breschi, SB+ [https://arxiv.org/abs/2110.06957]



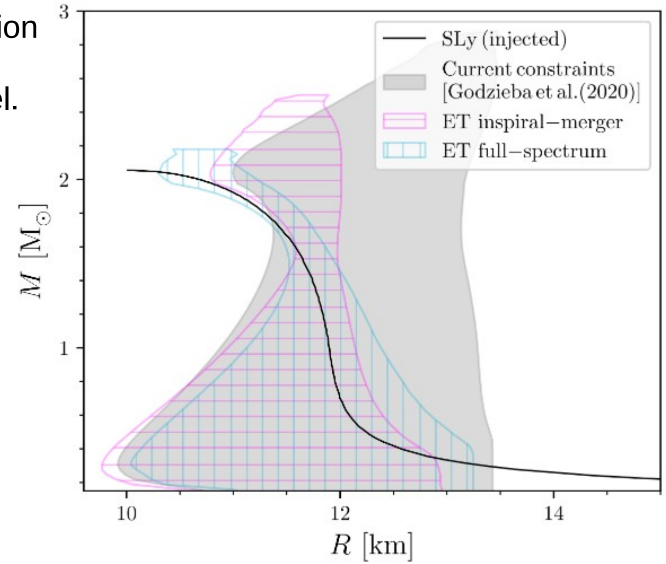
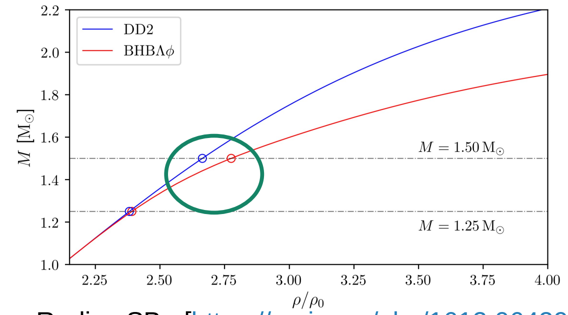
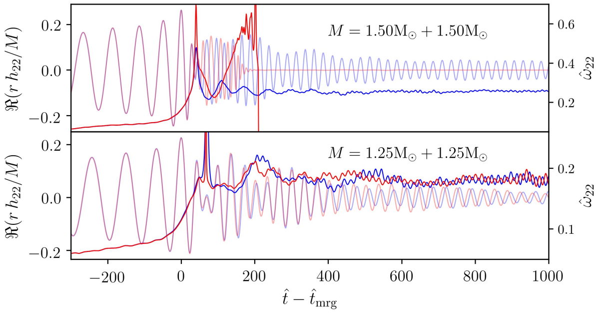


FIG. 4. Mass-radius diagram constraints from a single full-spectrum Einstein Telescope (ET) BNS observation with PM SNR 10 (total SNR 180). The gray area (prior) corresponds to the two-million EOS sample of Ref. [69]. The magenta and cyan areas are the 90% credibility regions given by inspiral-merger and inspiral-merger-PM inferences respectively. The full-spectrum (cyan) posterior agrees with the injected EOS (black).

EOS softening from model deviations



Radice,SB+ [https://arxiv.org/abs/1612.06429]



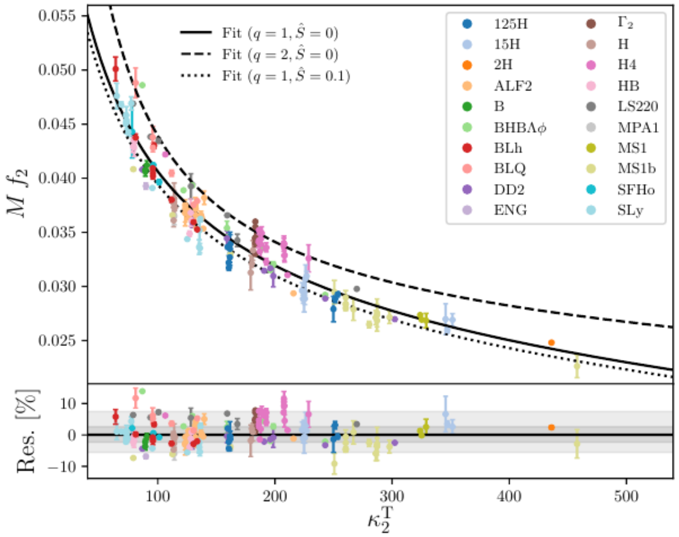
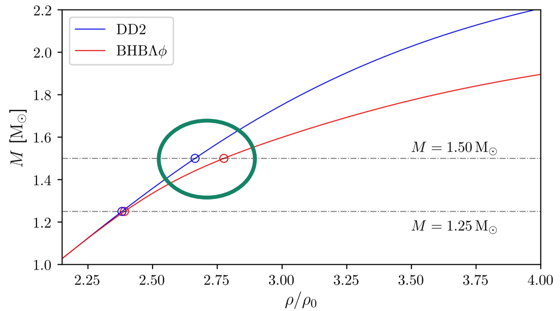


FIG. 3. Quasi-universal relation for the PM peak frequency f_2 as function of the tidal polarizability κ_2^T. Top panel: calibrated relations (black lines) compared to NR data (colored dots) extracted from the CoRe and the SACRA databases. Each color corresponds to a different EOS. NR medians and error-bars are reported averaging over different numerical resolutions (when available) for the same binary configuration. Bottom panel: Relative residuals between the calibrated relation and the NR data validation set. The gray areas show the 50% (dark) and 90% (light) credible regions of the residuals.

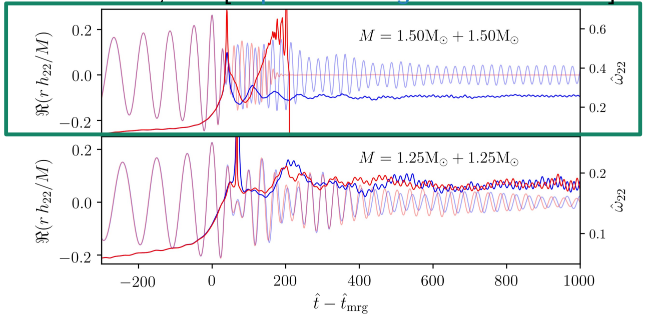
Small “window” of binary parameters (EOS dependent)
Frequency vs collapse time?
Recalibration parameters: are critical here 1,2,...N-sigma (?!)

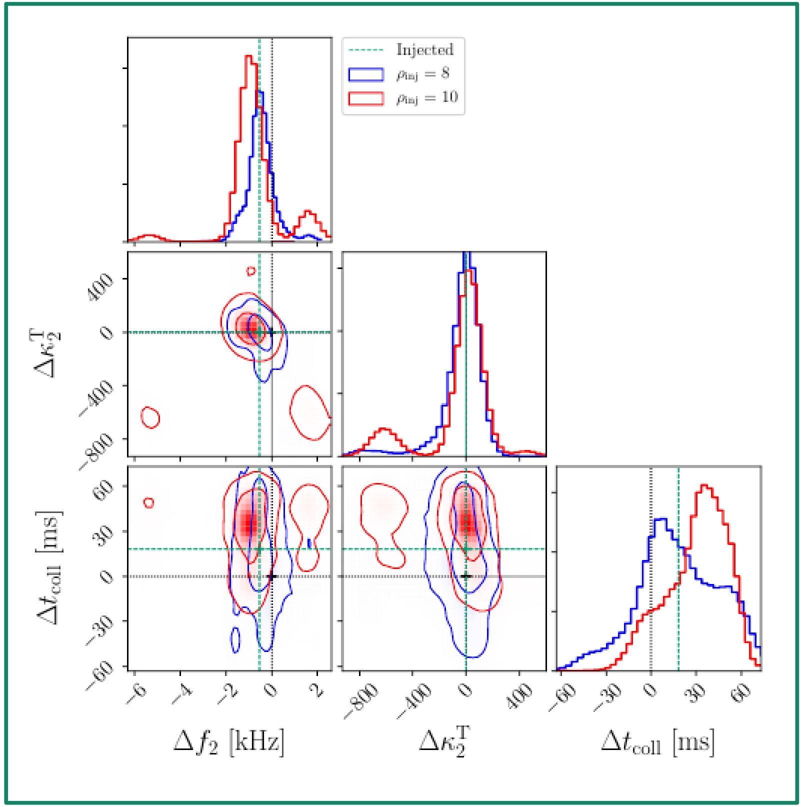
Breschi,SB+ [https://arxiv.org/abs/1908.11418]
Breschi+ [https://arxiv.org/abs/2205.09979]

EOS Softening from model deviations



Radice,SB+ [https://arxiv.org/abs/1612.06429]



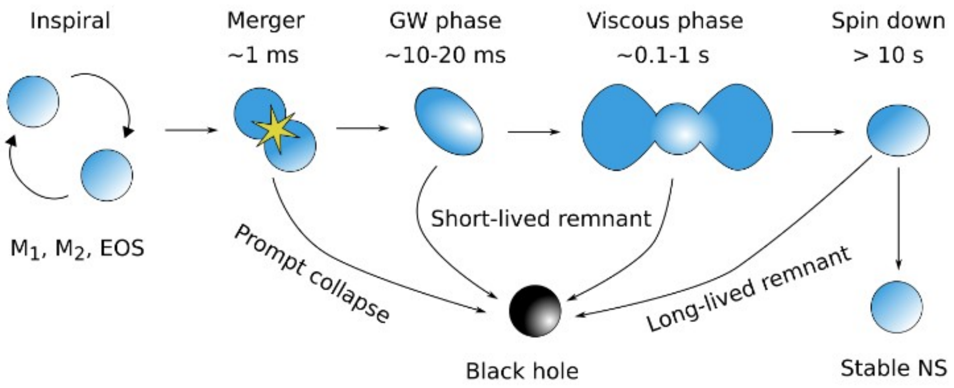


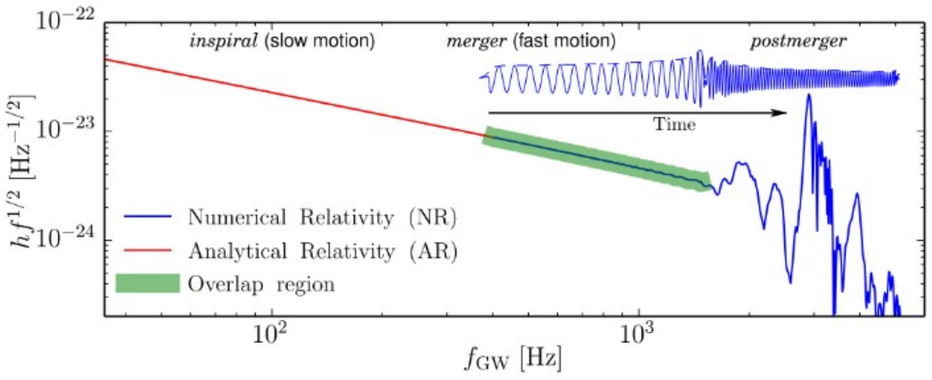
Small "window" of binary parameters (EOS dependent)
Frequency vs collapse time
Recalibration parameters: are critical here 1,2,...N-sigma (?!)

Be careful concluding something about your favorite EOS model!

Breschi,SB+ [https://arxiv.org/abs/1908.11418]
Breschi+ [https://arxiv.org/abs/2205.09979]

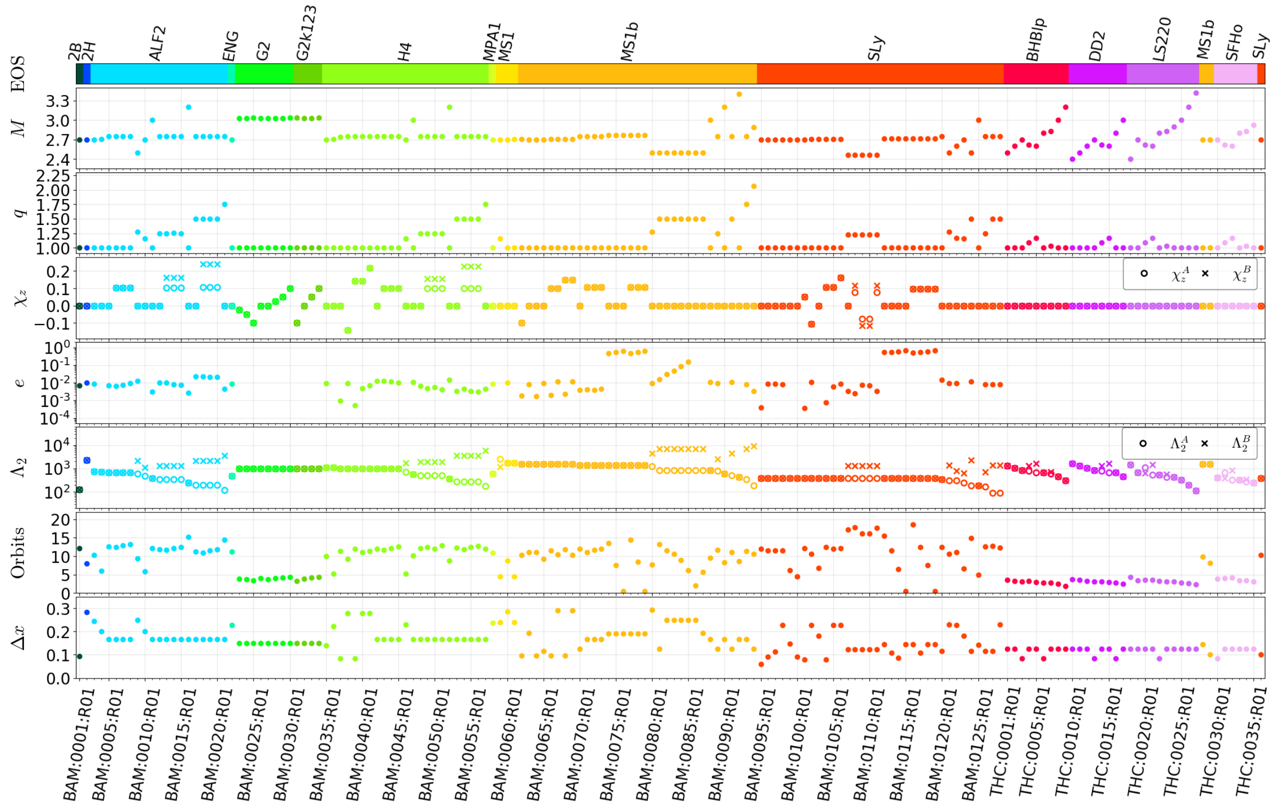
Where do we stand with the modeling?

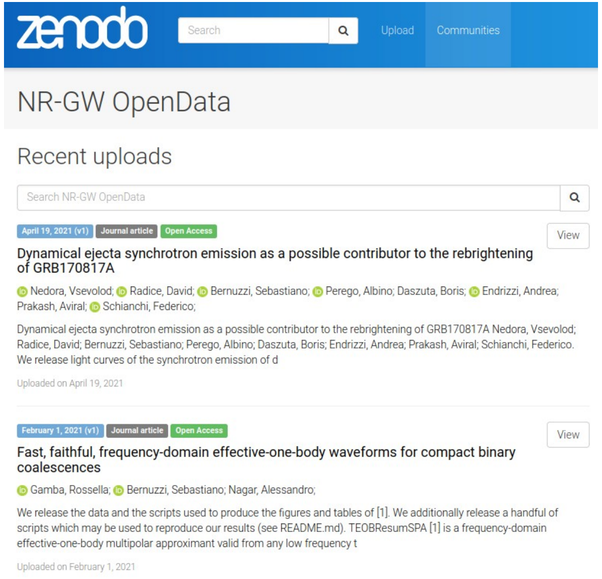




- Waveforms: NR not yet sufficient for high-SNR signals (and no alternatives)
- Waveforms: complete model exist now but accuracy to be improved
- Post-merger signals & inference: caveats!
- Prompt collapse inference to be improved by precise NR EOS-insensitive relations
- Dynamical ejecta: Neutrino heating cannot be neglected
- Remnant & winds ejecta: Need comprehensive approach to attack viscous timescales

Public data release





CoRe www.computational-relativity.org