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Leibniz Supercomputing Centre

Binary neutron star merger (BNSM) simulations for multi-messenger astrophysics

pn68wi (completed), pn36ge, pn36jo (ongoing)

| 9-11 June 2023 | S.Bernuzzi (FSU Jena)

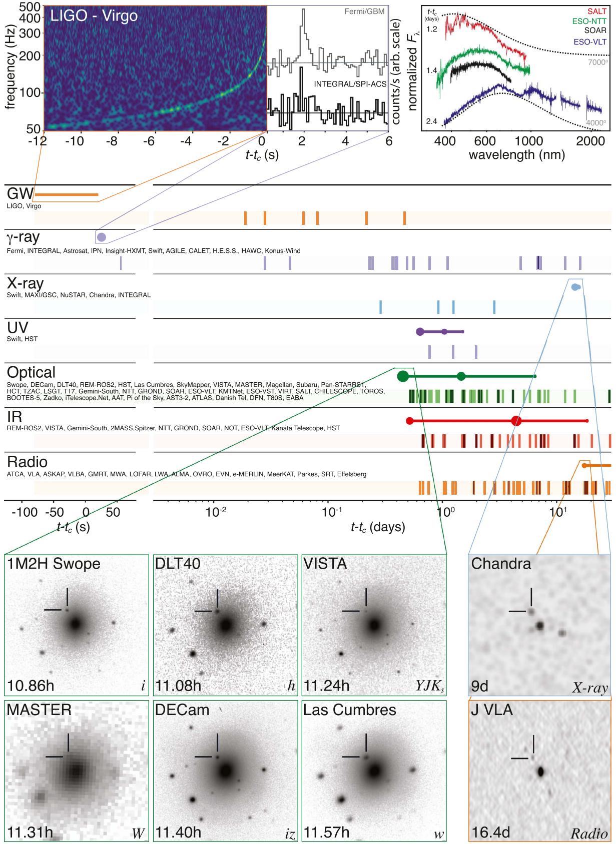
N.B. This document contains hyperlinks to various references

www.computational-relativity.org

FRIEDRICH-SCHILLER-UNIVERSITÄT JENA

European Research Council
Established by the European Commission

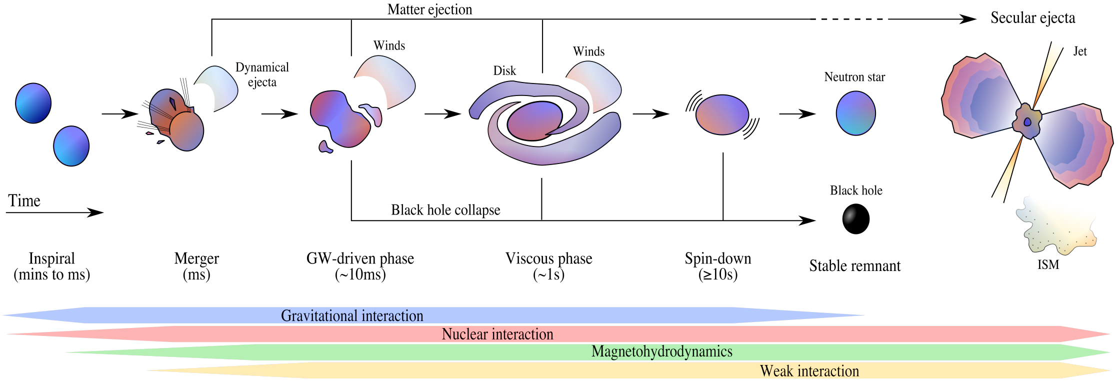
First-principles models of multi-messenger signals



GW170817 August, 17th 2017, 12:41:01 UTC

WANT: Quantitative predictions!

Outstanding issues in multi-scales & multi-physics BNSM modeling



Recent reviews: [Radice,SB,Perego 2020, SB 2020]

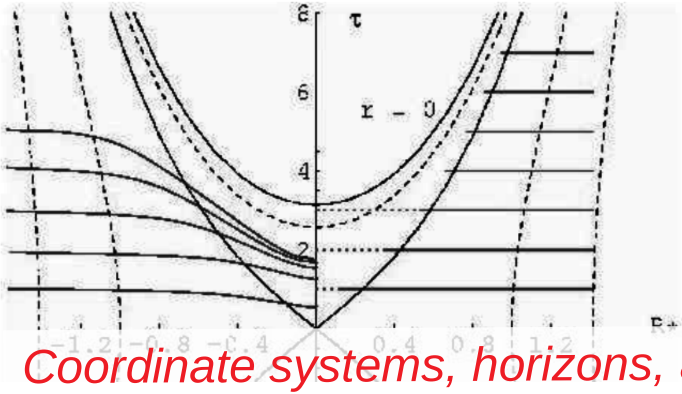
In-house developed production codes:

BAM (Jena) Bruegmann, SB+
THC (PSU) Radice+ (based on Einstein Toolkit)
GR-Athena++ (Jena/PSU) Daszuta+ (based on Athena++; IAS)

$$\partial_t \tilde{\Gamma}^i = -2\,\tilde{A}^{ij}\,\partial_j \alpha + 2\,\alpha\left[\tilde{\Gamma}^i{}_{jk}\,\tilde{A}^{jk} - \frac{3}{2}\,\tilde{A}^{ij}\,\partial_j \ln(\chi) - \frac{1}{3}\,\tilde{\gamma}^{ij}\,\partial_j(2\,\hat{K} + \Theta) - 8\,\pi\,\tilde{\gamma}^{ij}\,S_j\right] + \tilde{\gamma}^{jk}\,\partial_j\partial_k\beta^i + \frac{1}{3}\,\tilde{\gamma}^{ij}\partial_j\partial_k\beta^k + \beta^j\,\partial_j\tilde{\Gamma}^i - (\tilde{\Gamma}_d)^j\,\partial_j\beta^i + \frac{2}{3}\,(\tilde{\Gamma}_d)^i\,\partial_j\beta^j - 2\,\alpha\,\kappa_1\left[\tilde{\Gamma}^i - (\tilde{\Gamma}_d)^i\right],$$

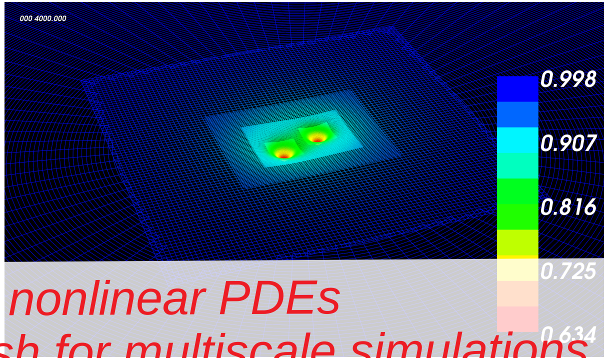
$$\partial_t \Theta = \frac{1}{2}\,\alpha\left[R - \tilde{A}_{ij}\,\tilde{A}^{ij} + \frac{2}{3}\,(\hat{K} + 2\,\Theta)^2\right]$$

GR formulations and Cauchy problem + hydrodynamics & radiation



Coordinate systems, horizons, and singularities

Numerical relativity in a nutshell

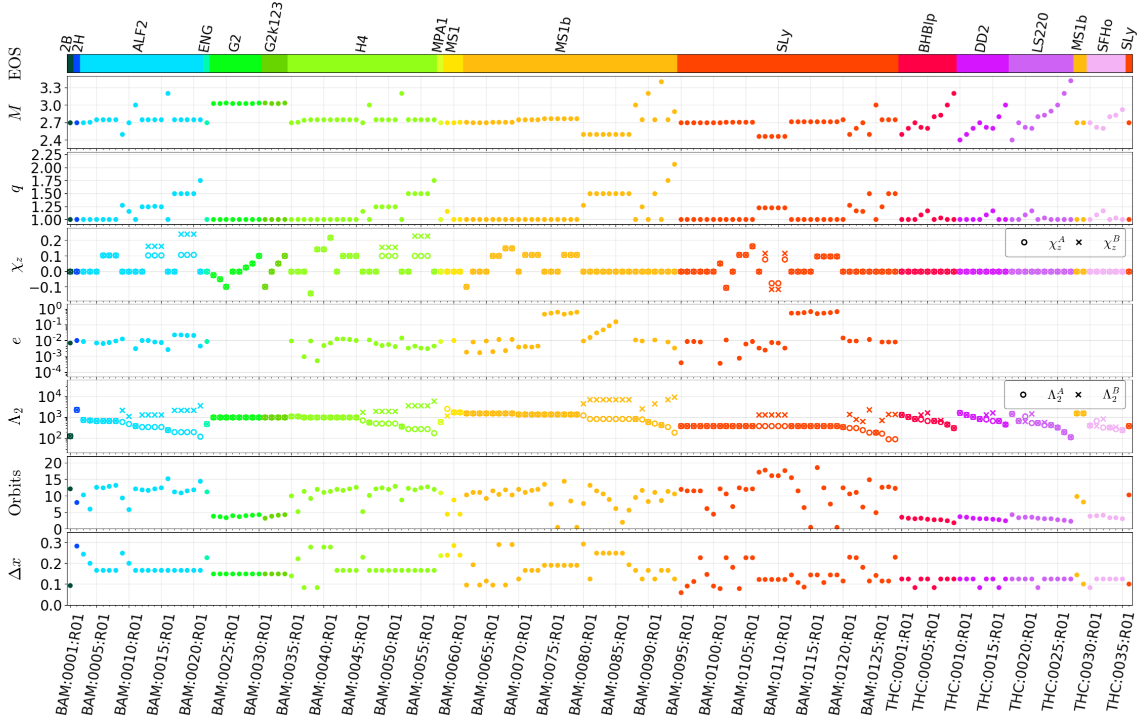


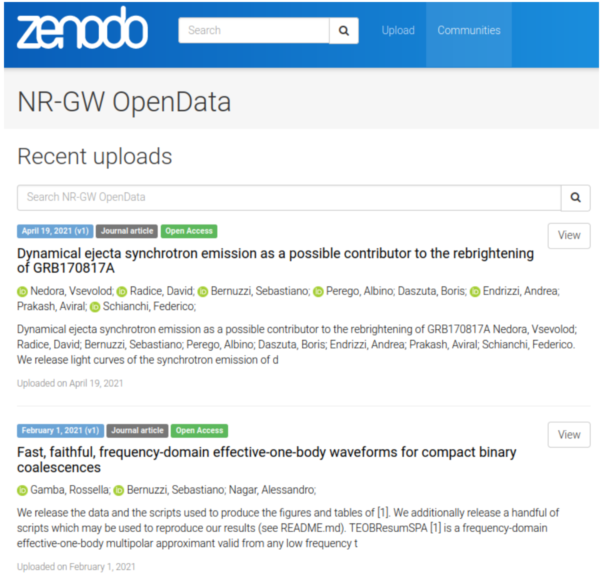
Numerics for nonlinear PDEs
Adaptive mesh for multiscale simulations

High-performance computing (hardware, exascale computing)

Public data release

Largest public catalog of gravitational waveforms from binary neutron star simulations [Gonzalez+ 2022]





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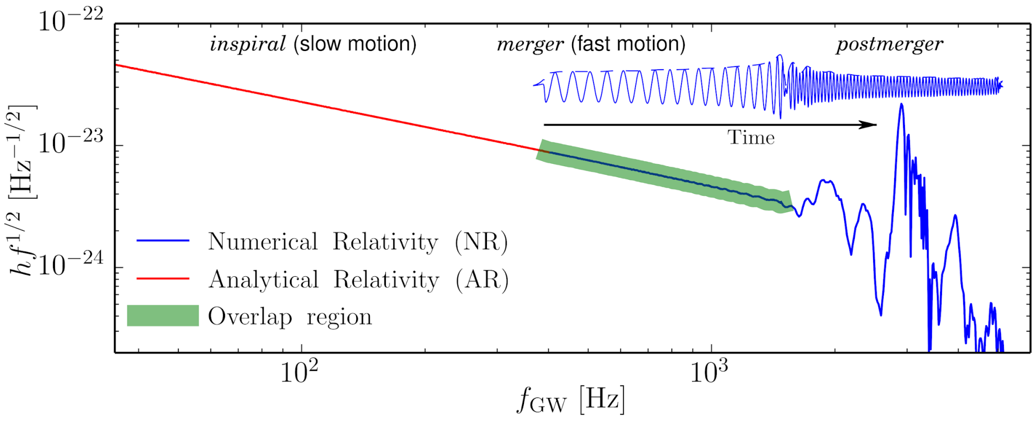
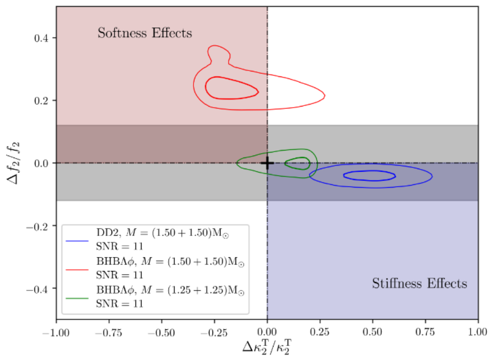
High-precision gravitational waves models



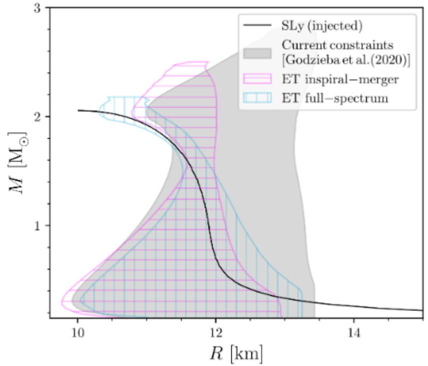
First model of the **complete BNSM spectrum** constructed with a data-driven approach to complete advanced inspiral-merger analytical models [Breschi+ 2019, 2022, 2022]

Bayesian inference applications:

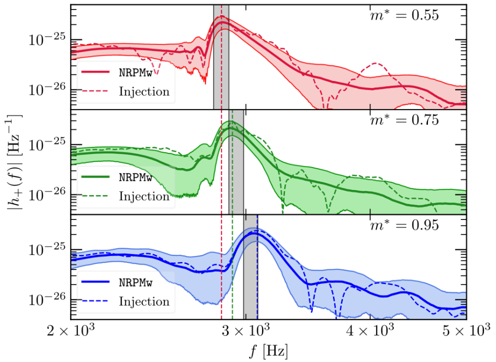
Softness constraints on extreme remnant matter (Quarks, hyperons, etc) [Breschi,SB+ 2019]

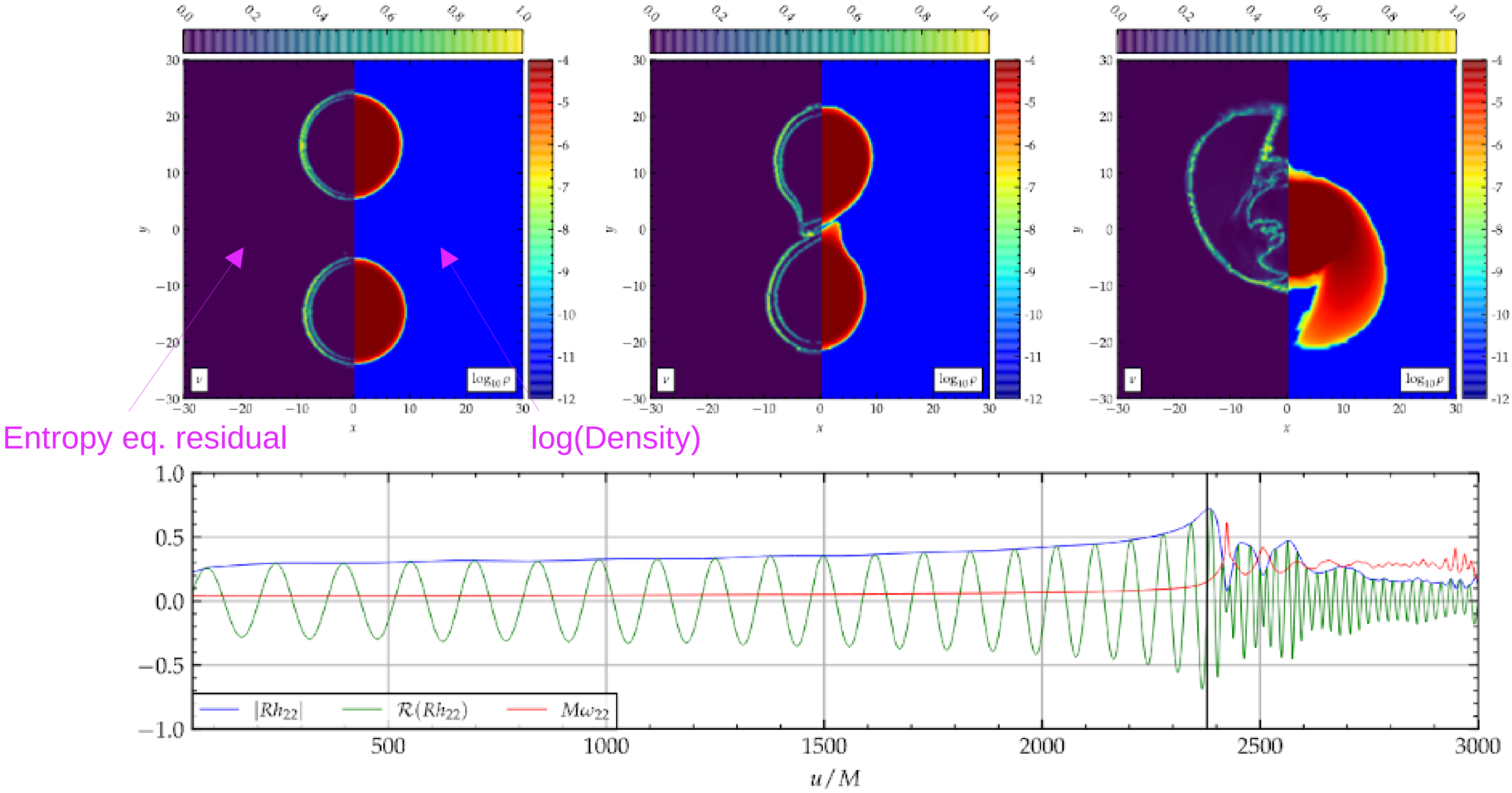


Constraints on neutron-mass radius diagram with Einstein Telescope observations [Breschi,SB+ 2021]



Sensitivity of Einstein Telescope to effective nucleon mass [Fields+ 2023]





Entropy flux-limiter scheme: accurate and 4th order convergence waveforms
[Doulis,Atteneder,SB,Bruegmann 2022]

Waveform systematic effects in gravitational-wave analyses of ground-based experiments (LIGO-Virgo, Einstein Telescope) e.g. constraints on the neutron star’s **equation of state** [Gamba+ 2020] [Doulis,Atteneder,SB,Bruegmann 2022]

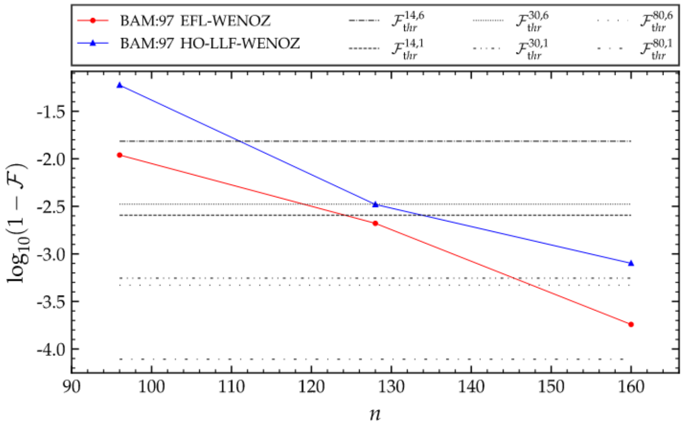
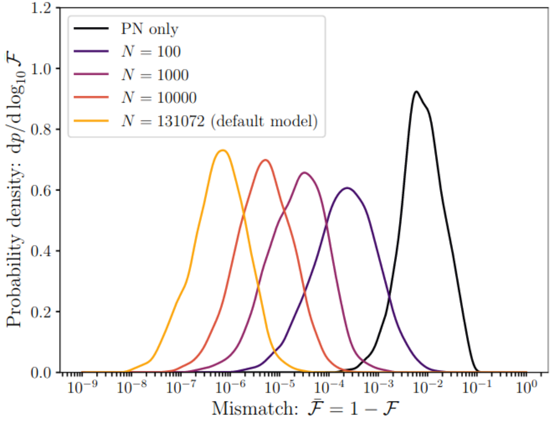
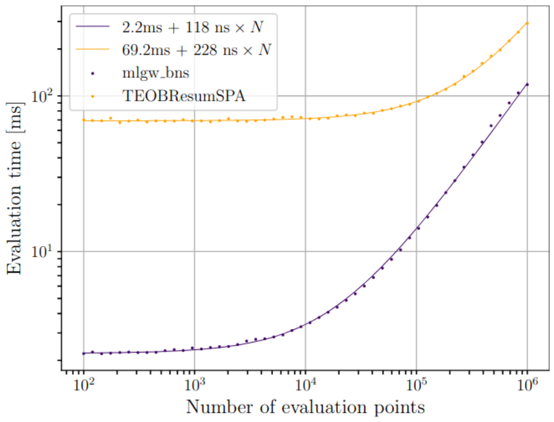


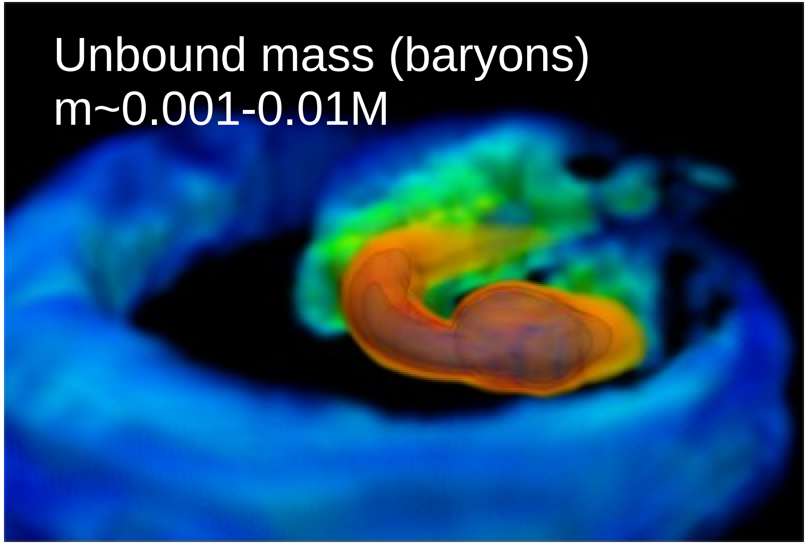
FIG. 21. Faithfulness as a function of the resolution for the BAM:97 simulation.



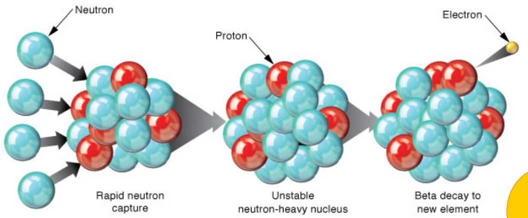


Machine learning simulation-generated (hybrid) waveform for efficient data analysis [Tissino+ 2023]

Mass ejecta, nucleosynthesis & kilonova



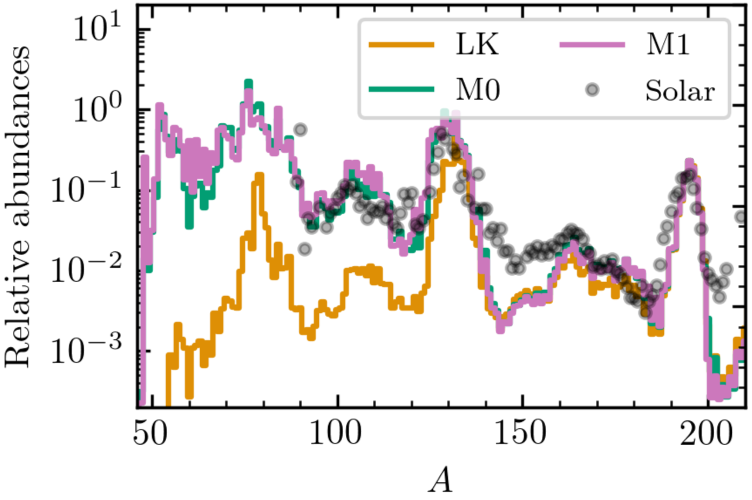
Exploring **neutrino driven winds** from the merger remnant
i) ab-initio long-term microphysics simulation reaching the viscous phase and
ii) a state-of-art general-relativistic neutrino transport scheme (M1). [Radice,SB+ 2022, Zappa,SB+ 2023]



R-process heavy elements production

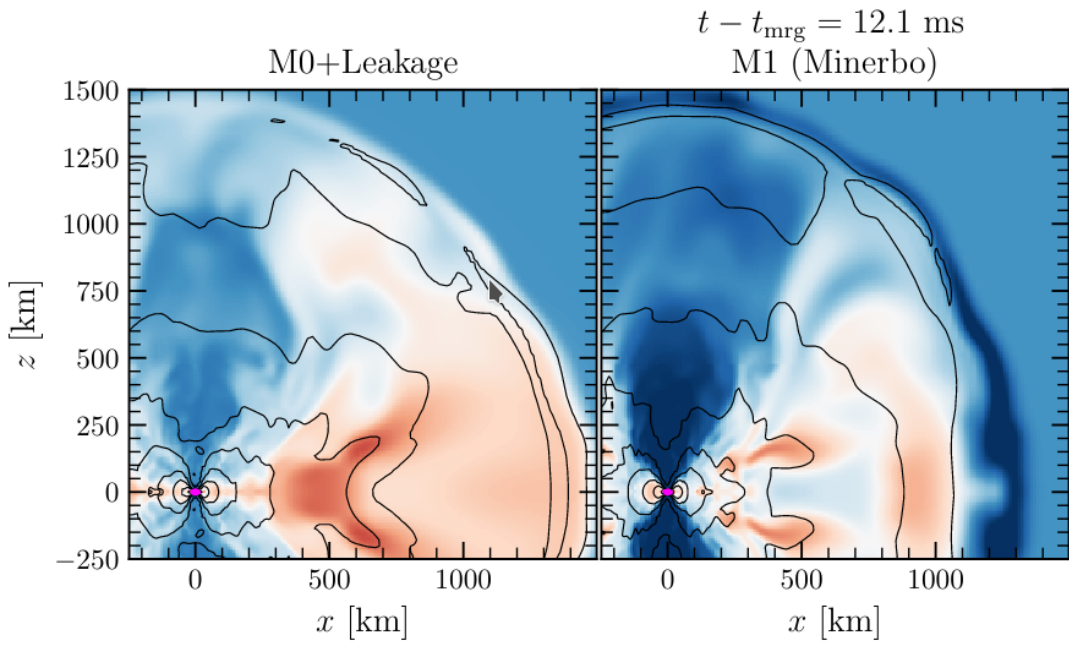
KILONOVA

Radioactive heating & thermalization (β-decays, α-decays, fission)



Microphysics and advanced neutrino transport

New Two-Moment (M1) General-Relativistic scheme:
Asymptotically preserving flux scheme; complete radiation-matter source terms (all v/c terms)



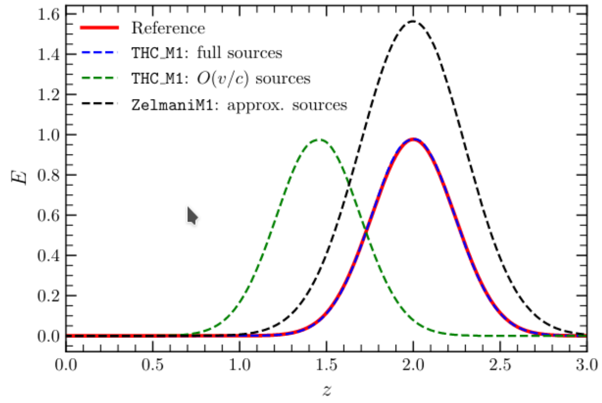
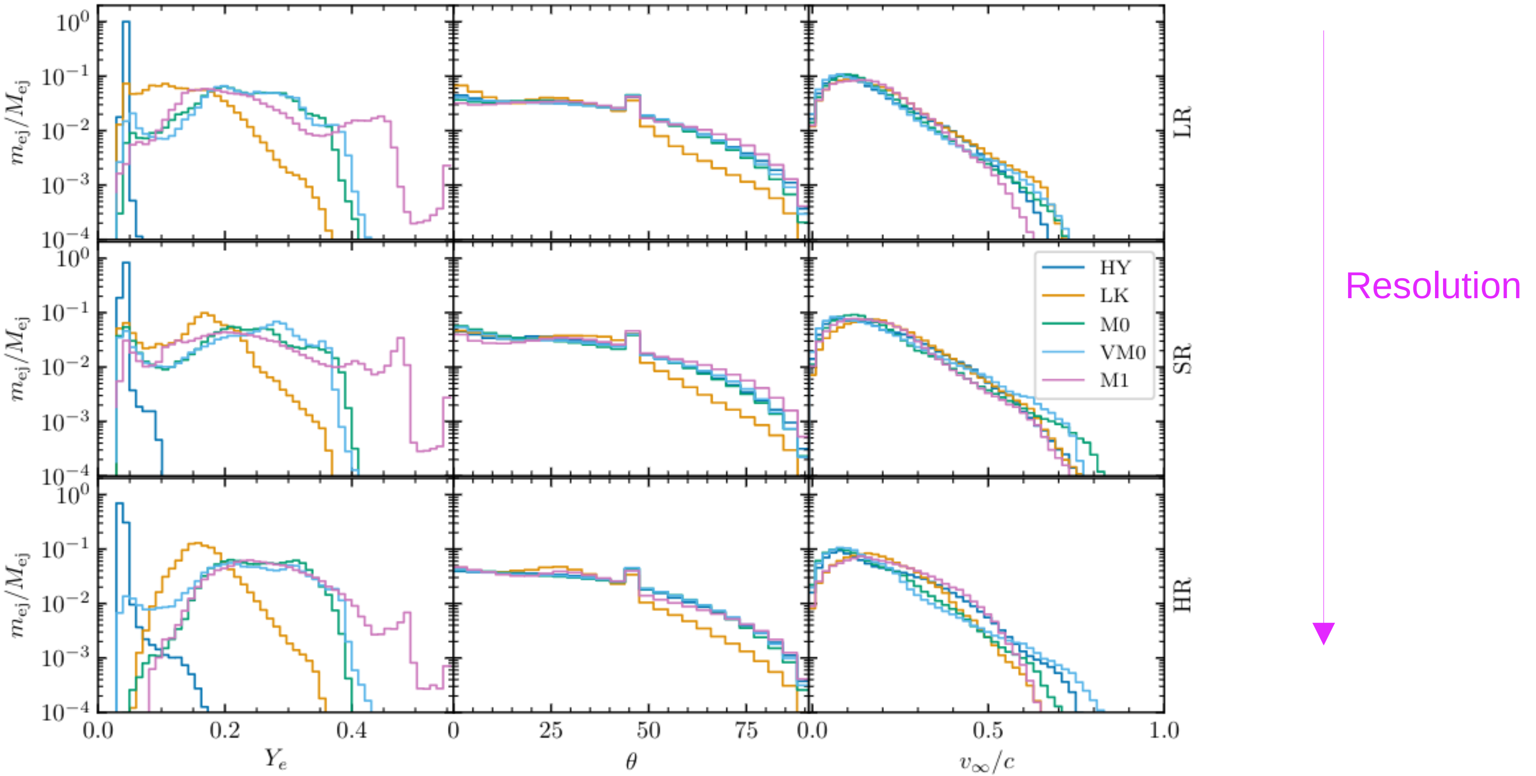


Figure 3. Diffusion and advection of Gaussian pulse of radiation in a purely scattering moving medium. The medium is moving with velocity $v = 0.5$. The reference profile is a translated semi-analytic solution of the diffusion equation. Our results show that it is essential to properly treat all of the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

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.

[Radice,SB+ 2022]

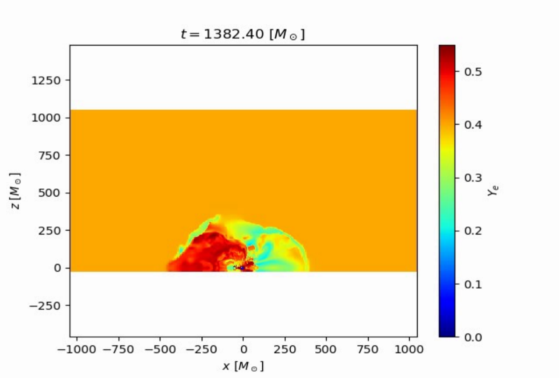
Systematic study of ejecta properties: neutrino schemes and mesh resolutions

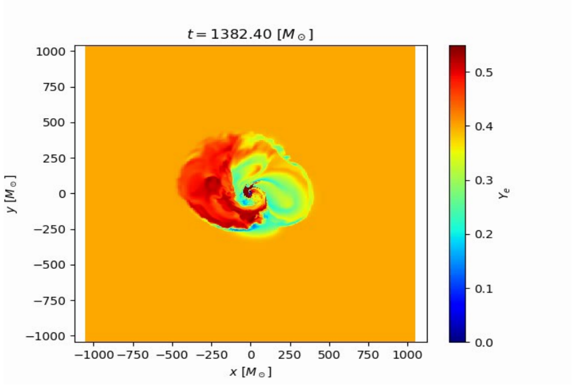


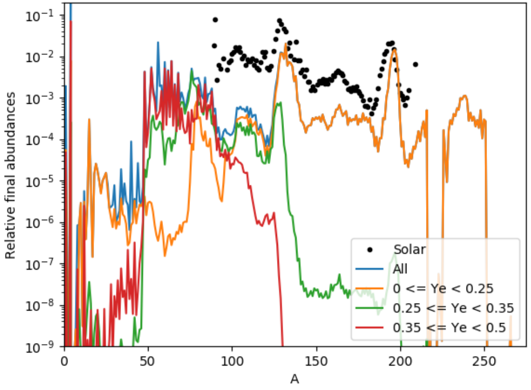
~20M core-hrs
on SuperMUC-NG
(pn68wi)

[Zappa,SB+ 2023]

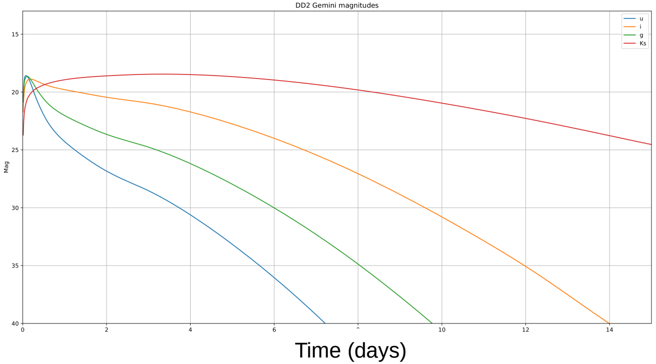
Exploring the viscous phase of the remnant ...



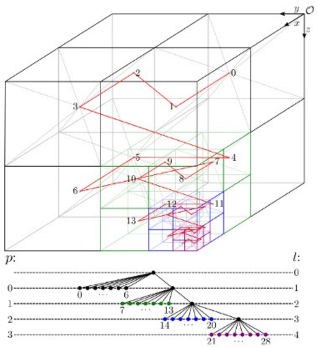


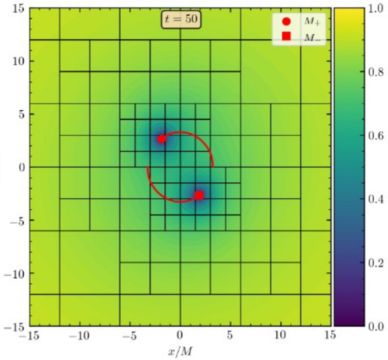


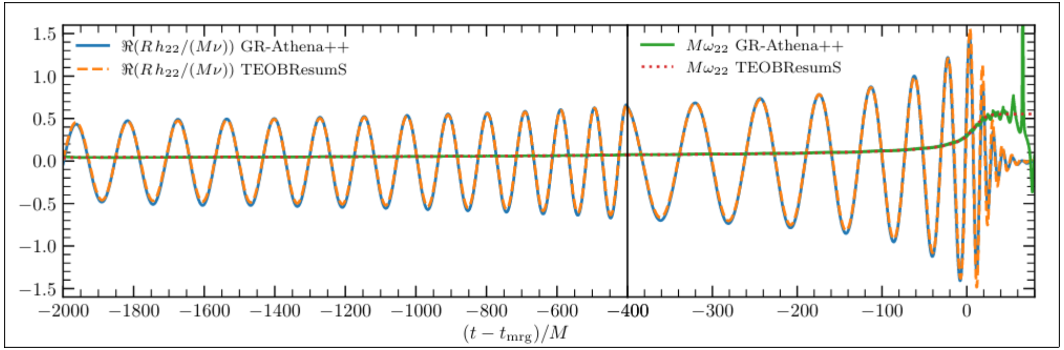
… nucleosynthesis, and kilonova light curves:



GR-Athena++: Towards exascale NR



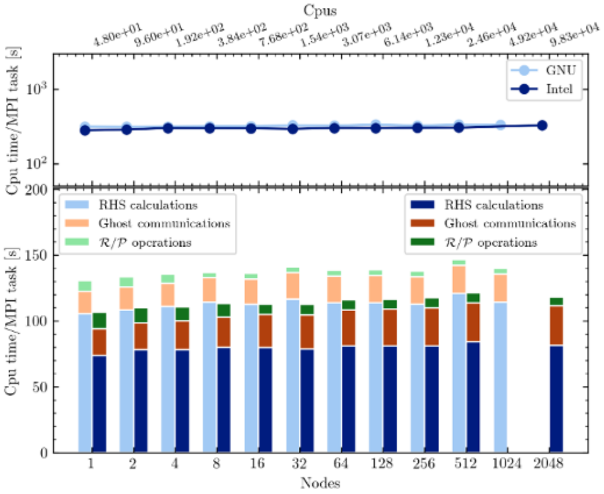


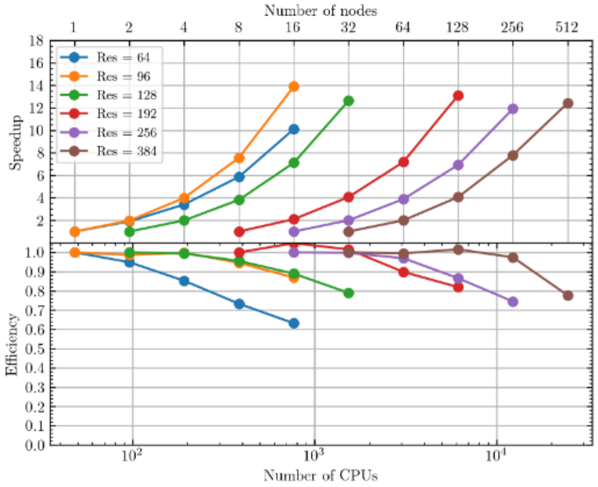


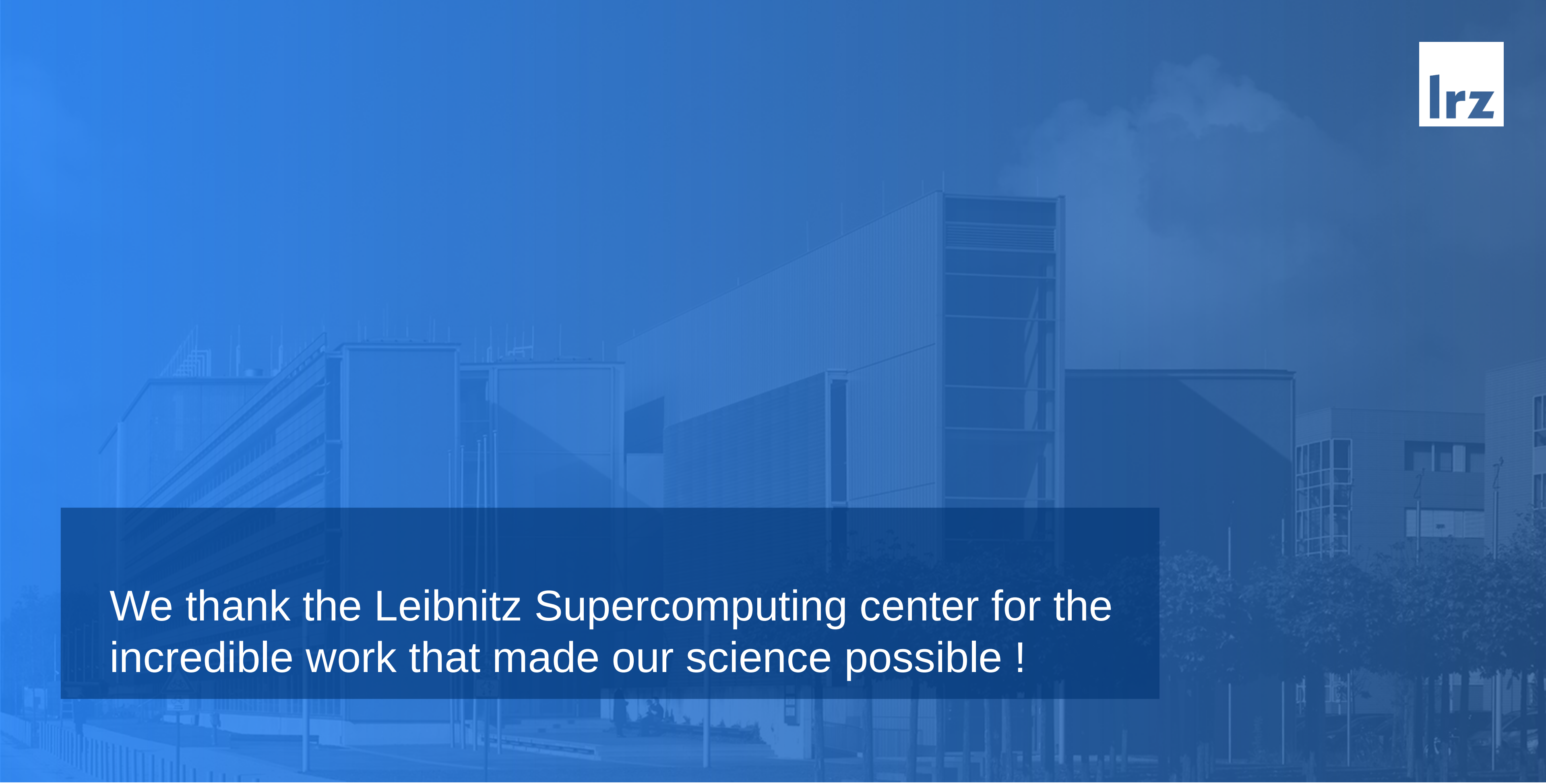
GR and vertex-center oct-tree AMR extension of the Athena++ codebase [Daszuta+ 2021]

Binary black hole & neutron stars simulations

A kokkos version under development w/ Stone (IAS) & Radice (PSU) groups







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We thank the Leibnitz Supercomputing center for the incredible work that made our science possible !

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