Microphysical simulations of neutron star merger's remnants

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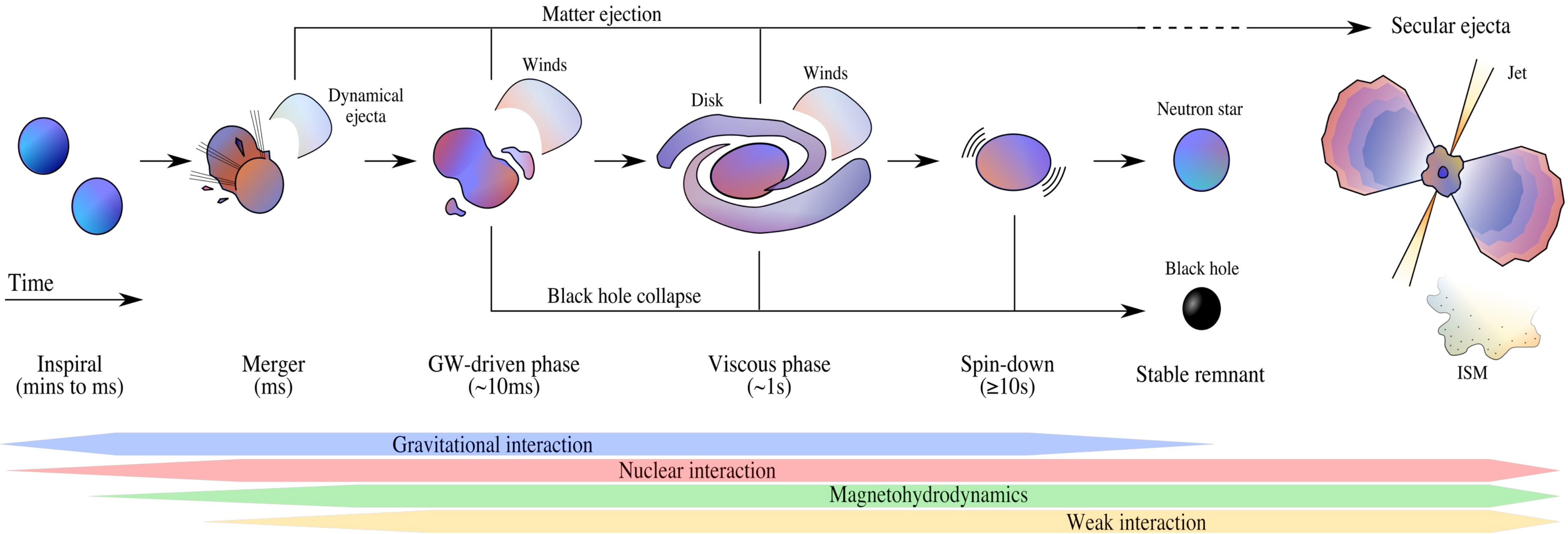
Exploring remnants in the viscous phase



Viscous phase dominated by neutrino losses and turbulence:

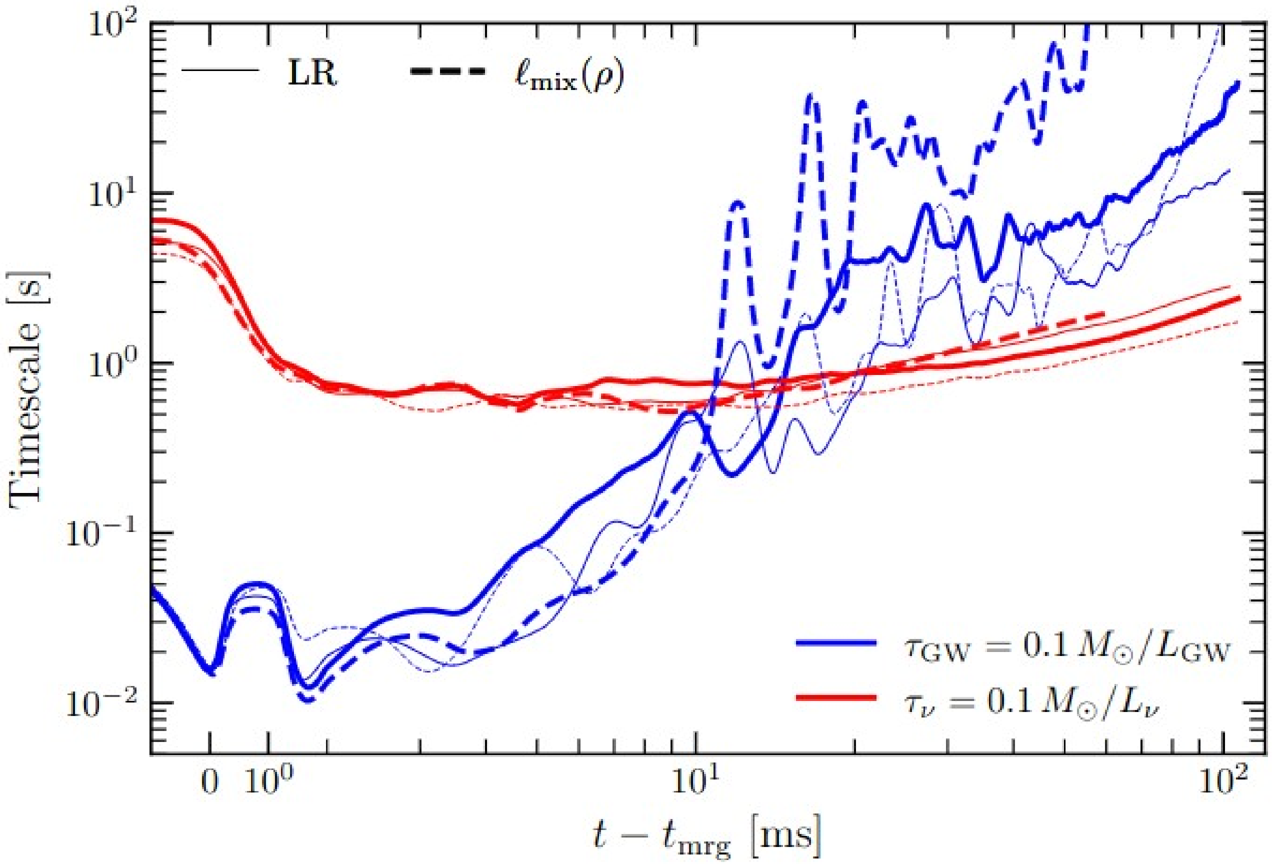
$$t_{\rm rem} \simeq \alpha^{-1}\ R^2_{\rm rem}\ \Omega_{\rm rem}\ c_s^{-2} \simeq 0.56\ {\rm s}\left(\frac{\alpha}{0.001}\right)^{-1}\left(\frac{R_{\rm rem}}{15{\rm km}}\right)^2\left(\frac{\Omega_{\rm rem}}{10^4{\rm kHz}}\right)\left(\frac{c_s}{0.2c}\right)^{-2}$$

$$t_{\rm diff} \simeq \frac{\tau_\nu R_{\rm rem}}{c} \simeq 4.28\ {\rm s}\left(\frac{R_{\rm rem}}{15\ {\rm km}}\right)^{-1}\left(\frac{M_{\rm rem}}{2.5{\rm M}_\odot}\right)\left(\frac{T_{\rm rem}}{20\ {\rm MeV}}\right)^2$$

~hundreds of GR simulations w/ microphysics (mass, mass ratio, EOS, etc) to ~100ms and multiple resolutions

No quantitative models yet

Reviews [https://arxiv.org/abs/2002.03863] [https://arxiv.org/abs/2002.03863]

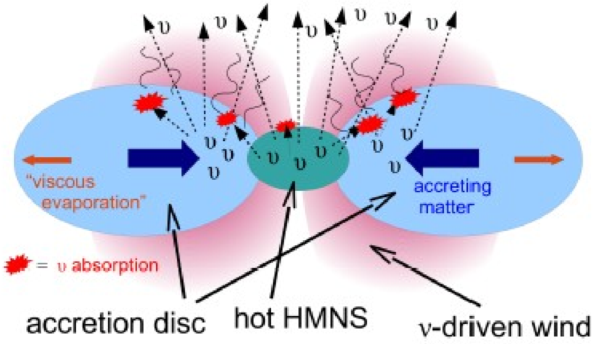


Viscous phase GR simulation w/ M1 and LES subgrid model
Radice&SB [https://arxiv.org/abs/2306.13709]

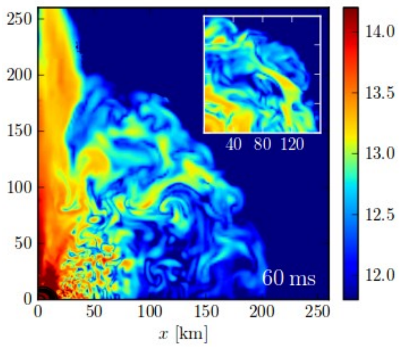
Remnants after the GW-dominated phase

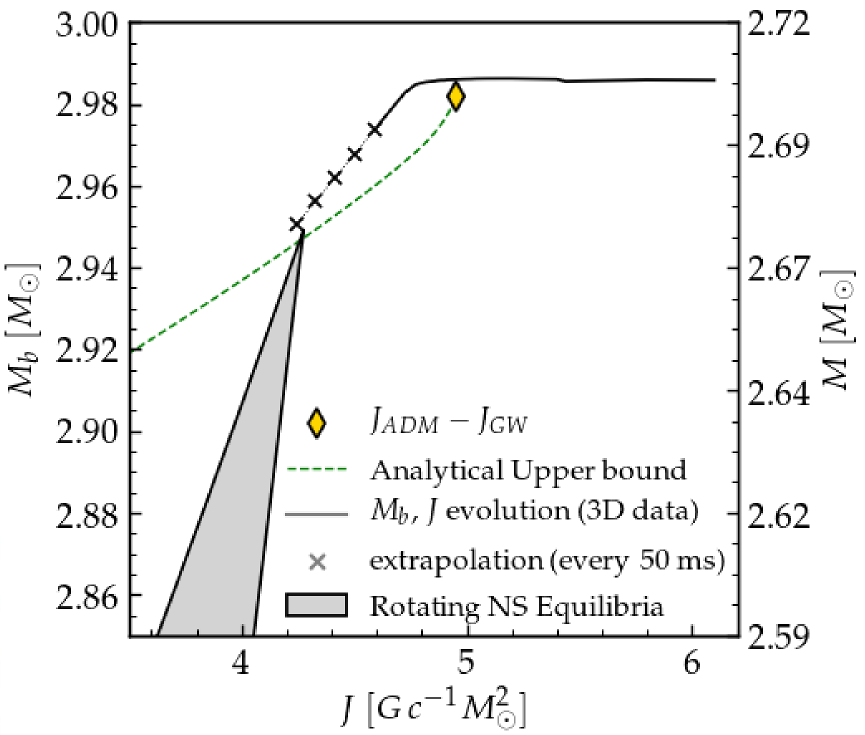
- Angular momentum ("super-Keplerian") and mass in excess
- Evolution governed by neutrino cooling and viscous processes (magnetic turbulence & stresses, neutrino heating, etc)
- Discs <~ 0.1Mo: Nuclear recombination → Massive winds

[Perego+ 2014]



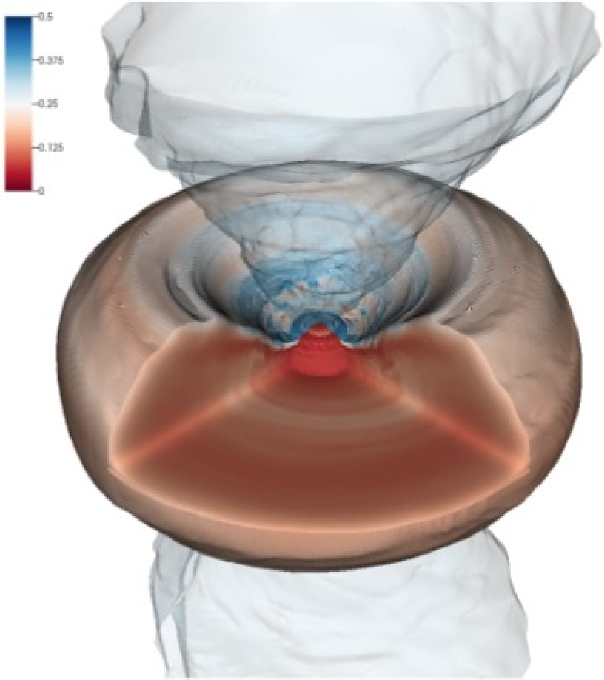
[Siegel+ 2014]



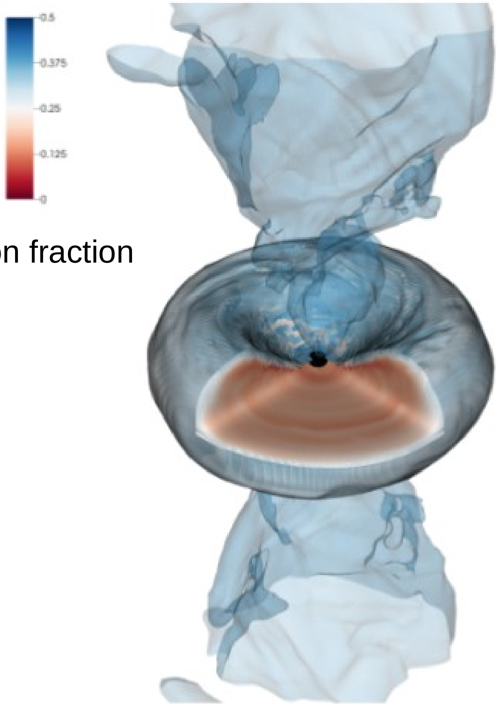


Radice, Perego, SB, Zhang [https://arxiv.org/abs/1803.10865]
Nedora, SB+ [https://arxiv.org/pdf/2008.04333]

Discs around NS and BH remnants



Electron fraction



Perego, SB, Radice [https://arxiv.org/abs/1903.07898]

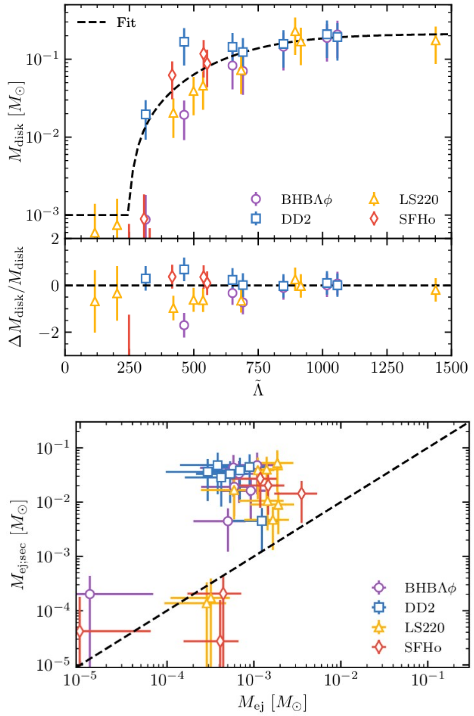
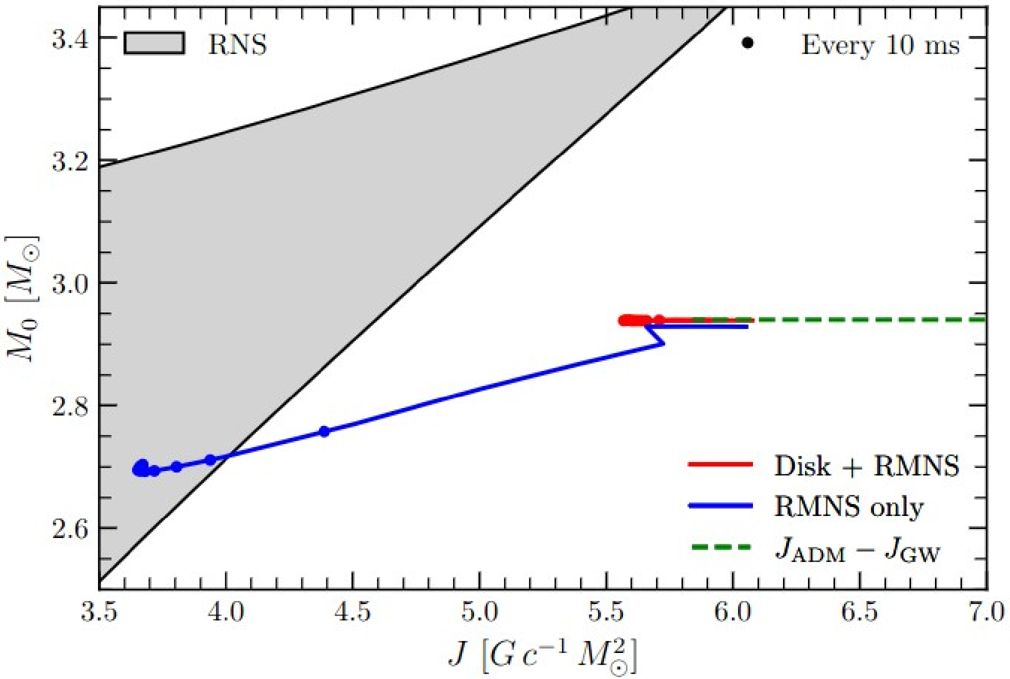


Figure 16. Dynamical ejecta $M_{\rm ej;dyn}$ versus secular ejecta masses $M_{\rm ej;sec}$. With the exception of the prompt BH formation cases that are able to expel at least a few $10^{-4}\,M_\odot$ in dynamical ejecta, the secular ejecta dominate over the dynamical ejecta.

[https://arxiv.org/abs/1809.11161]

Mass, compactness, composition depends on binary parameters and central remnant
Disc masses can be estimated from the reduced tidal parameter Λ (EOS-insensitive relation)
Disc winds significantly more massive than dynamical ejecta

Long-lived NS Remnants



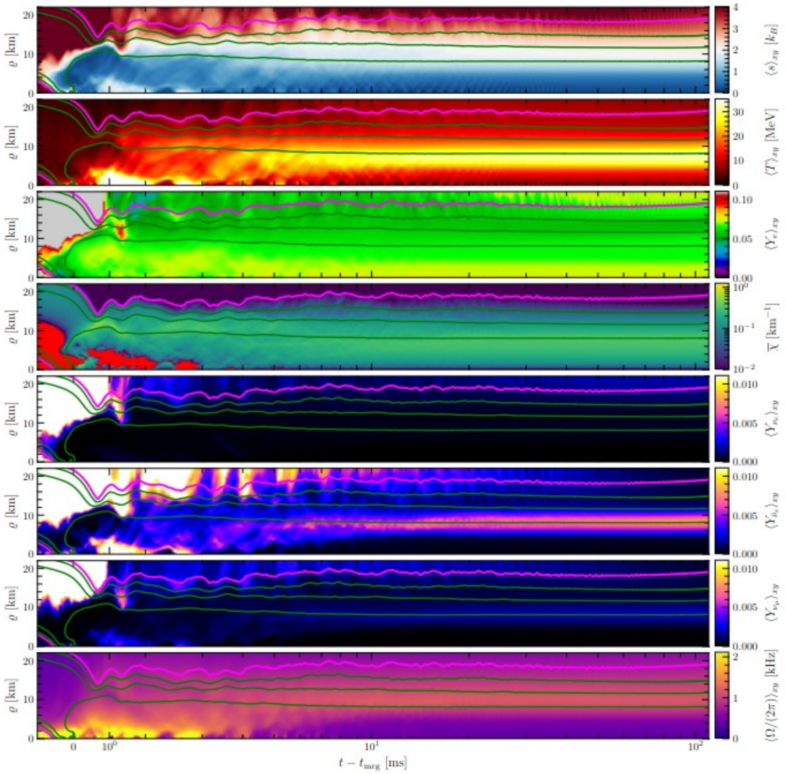


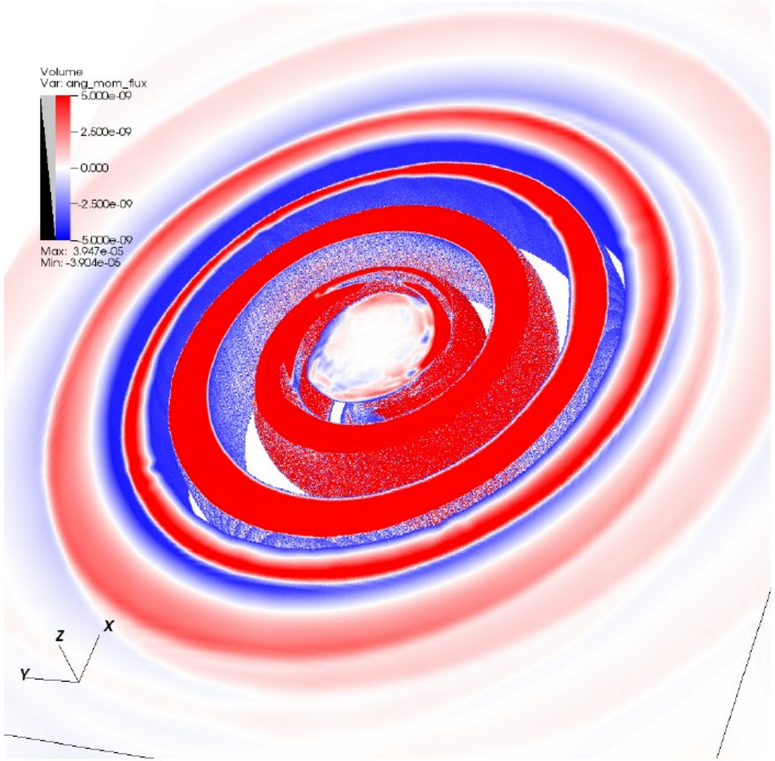
Figure 3. Angularly averaged profiles of entropy s, electron fraction Y_e, convection instability criterion χ, neutrino fractions Y_{ν_e}, $Y_{\bar{\nu}_e}$, and Y_{ν_μ}, and angular frequency Ω on the equatorial plane for the $\ell_{\rm mix} = 0$ SR binary. The profiles are shown as a function of cylindrical radius ϱ and time from merger $t - t_{\rm mrg}$. The purple contour denotes $\rho = 10^{13}$ g · cm^{-3}, while the green contours are $\rho = 10^{13.5}, 10^{14}$, and $10^{14.5}$ g · cm^{-3}.

Ledoux criterion → remnant stably stratified → no convection
Differential rotation persists w/ Omega peak at "surface"
→ core is MRI stable

Radice&SB [https://arxiv.org/abs/2306.13709]

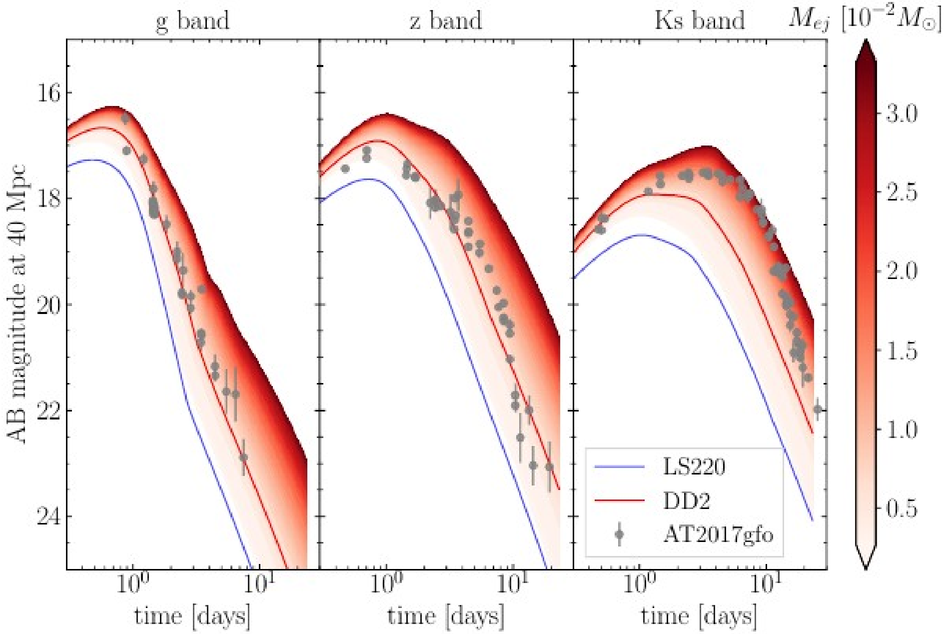
~100 ms 3D ab-inito evolutions with microphysics, M1 and GRLES (turbulent viscosity)

Long-lived Remnants: spiral-wave winds



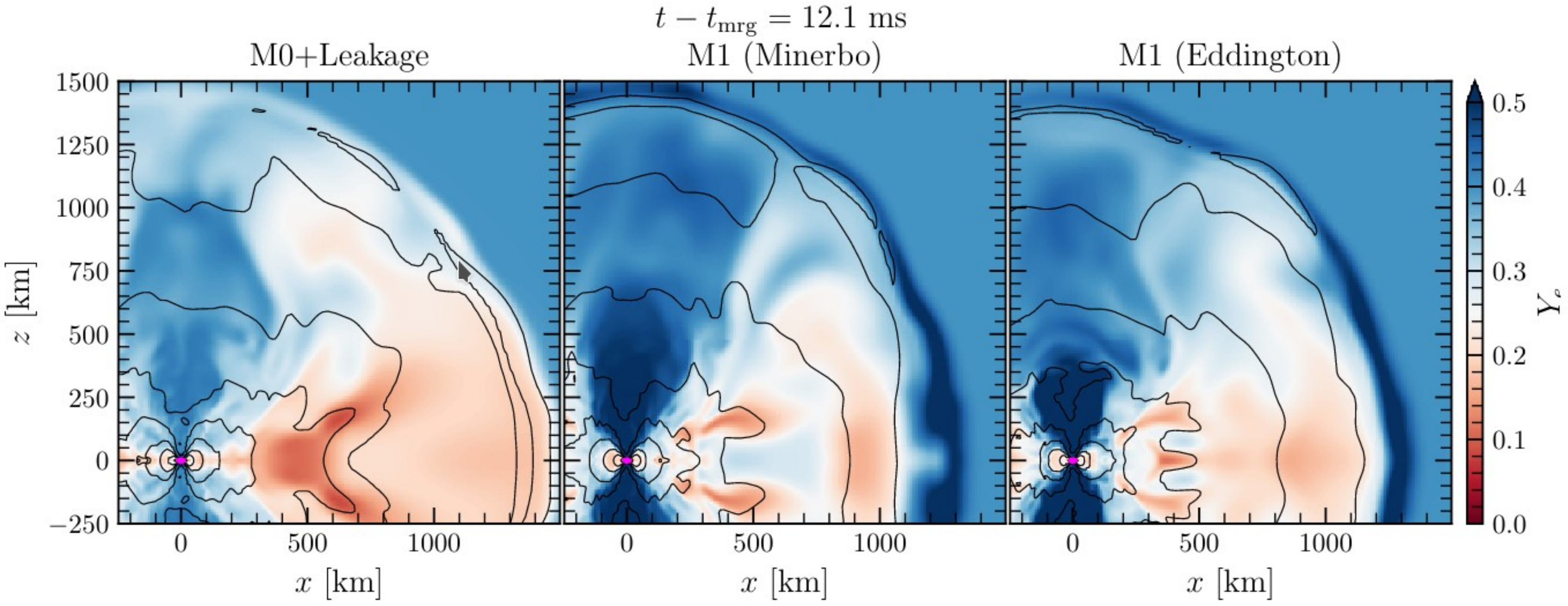
Nedora, SB+ [https://arxiv.org/abs/1907.04872]

Timescale ~ 10s ms postmerger (to collapse)
Mass ~ 0.01Mo (to 100ms)
Generic mechanism boosted by neutrino heating/MHD component



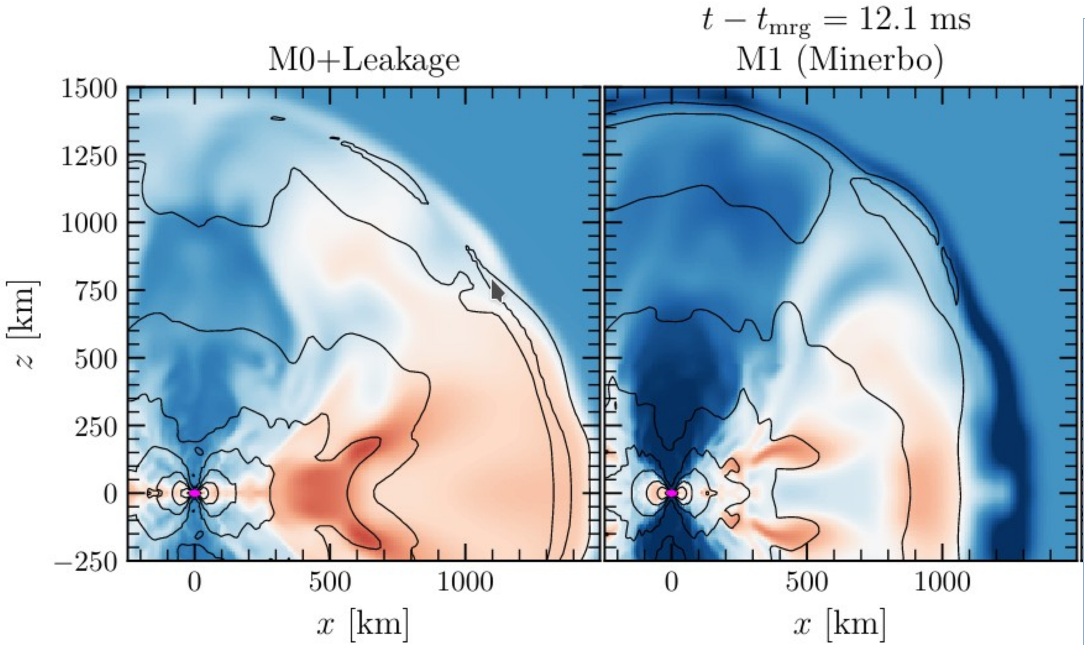
~100 ms 3D ab-inito evolutions with microphysics, M0 and GRLES (turbulent viscosity)

Neutrino transport scheme ...



M1: neutrinos from RMNS (+50% energies; polar) and disc (larger area; equatorial) → increase Ye differences and anisotropy
M1 (cf. M0): RMNS has neutrino trapped gas (dT/T ~ - few %; Perego+ 2018); but no effects on GWs!
M1: Ye close to equilibrium values above the remnant
M0 (cf. M1): transport happens only radially
M1 Eddington vs Minerbo: free streaming nus are slower ~1/sqrt(3) and interact further out

… ejecta composition …



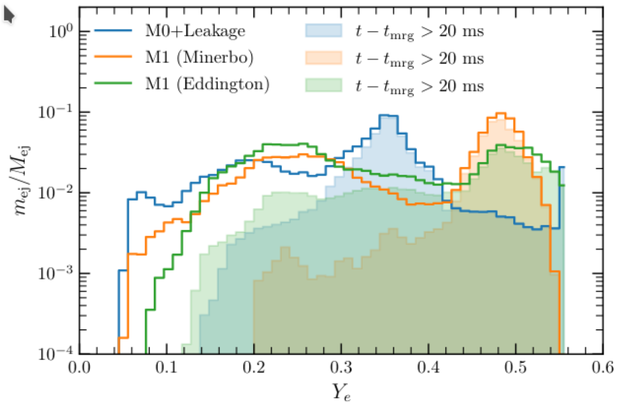
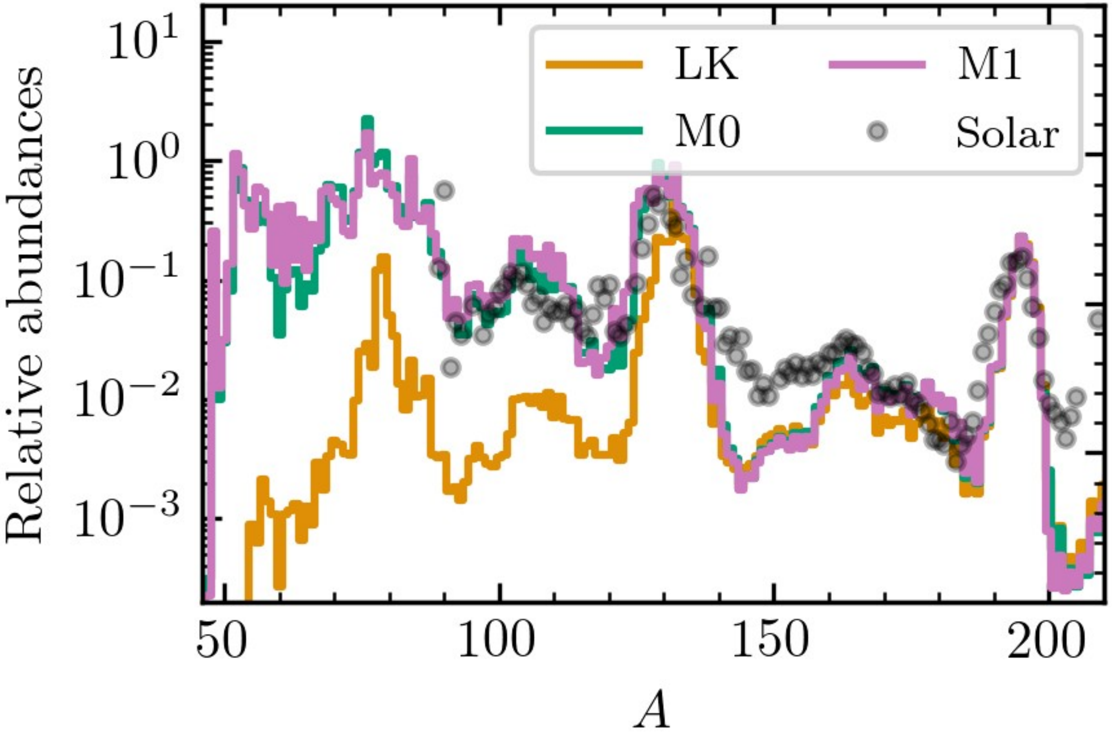


Figure 26. Ejecta Y_e for the SLy $1.3\,M_\odot - 1.3\,M_\odot$ binary. The shaded regions show the contributions to the Y_e histogram due to the material ejected after the first 20 ms of the merger. The ejecta distribution peaks at significantly larger Y_e in the M1 runs. The Eddington and Minerbo results 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.

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

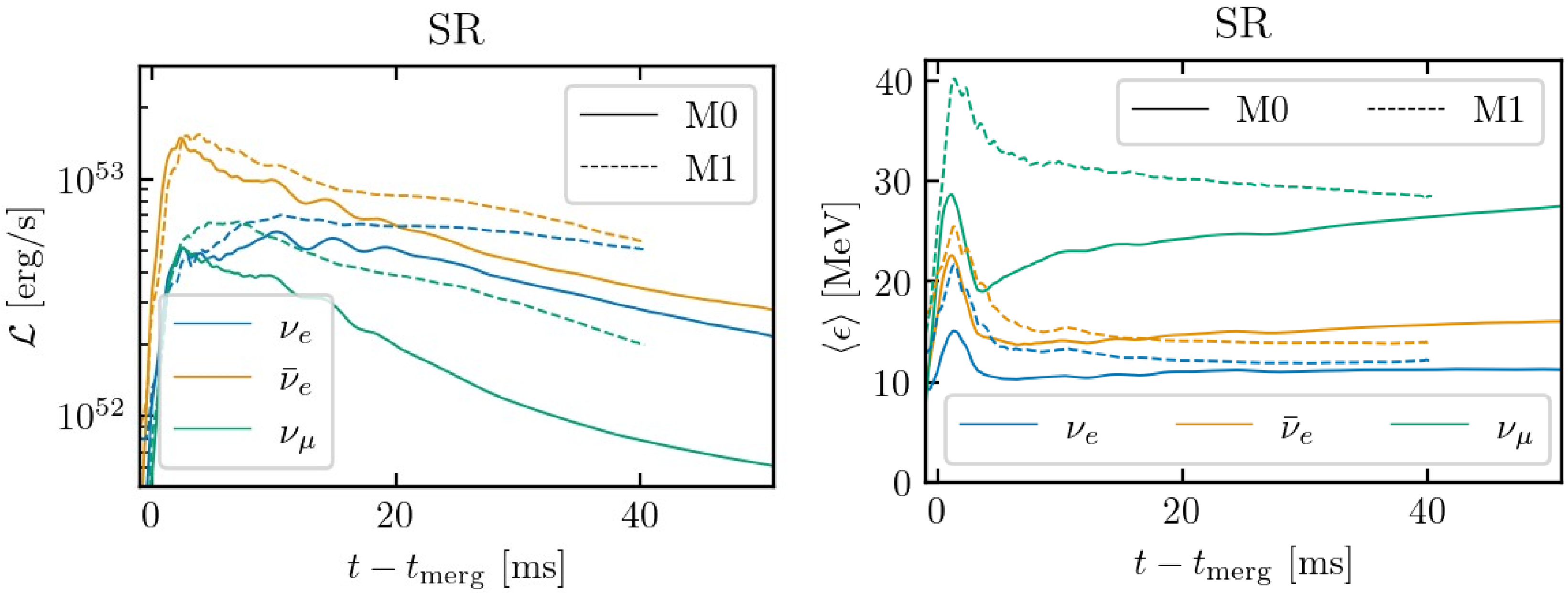
... nucleosynthesis ...



M1 vs M0 differences are smaller than diffs due to EOS and mass ratio variability
Leakage only under-produces A<120 cf. M[01] (Ye<~0.35 and less mass)→ need heating effect!

Systematic study of remnant and ejecta properties: neutrino schemes and mesh resolutions Zappa, SB, Radice, Perego [https://arxiv.org/abs/2210.11491]

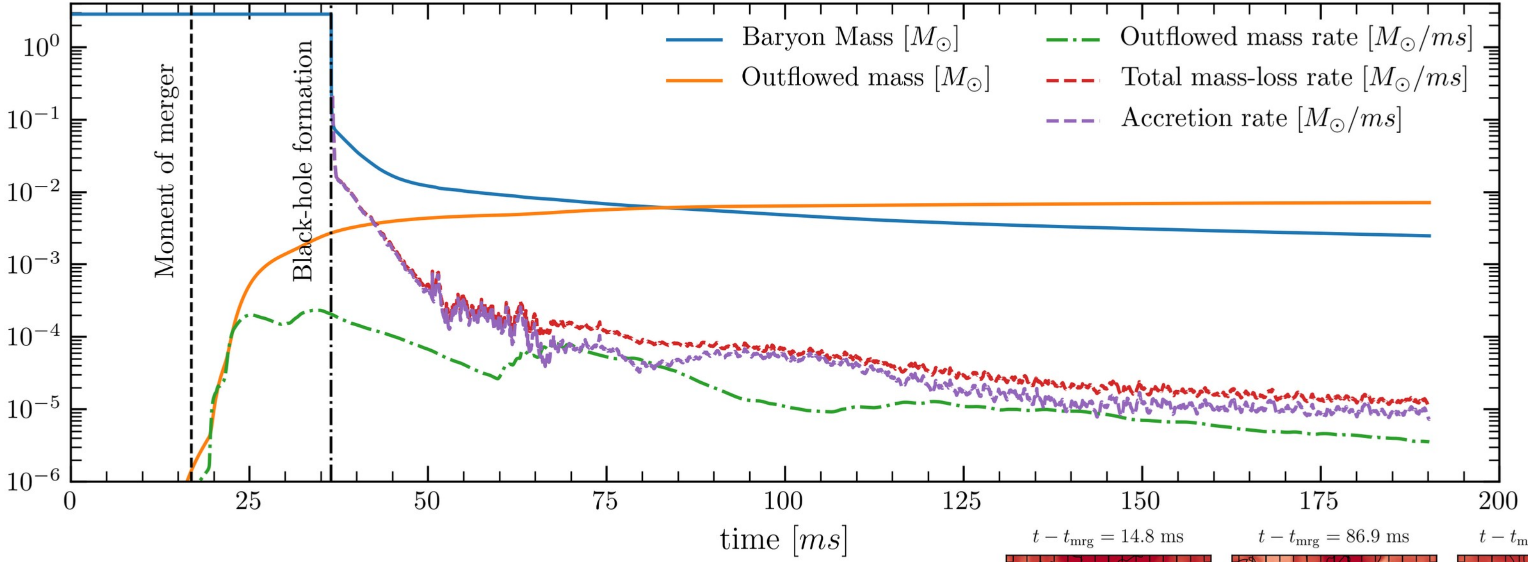
… and neutrino luminosities & energies

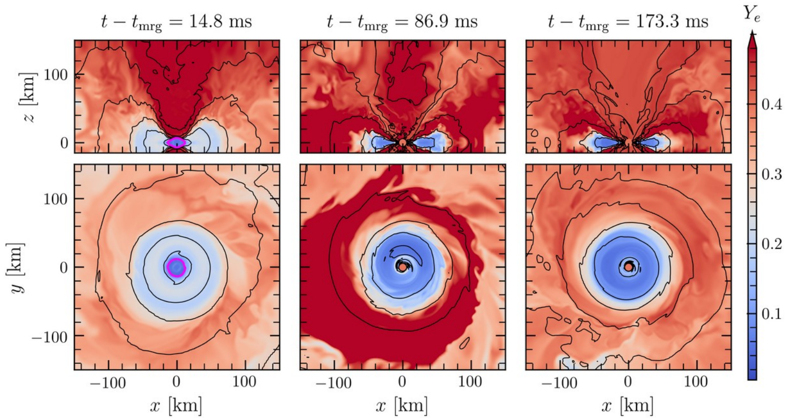


Peaks at ~2-3 ms postmerger
“protonization” of decompressed and heated neutron-rich material → Hierarchy: L(anue) > L(nue) > L(nuX)
Averaged energy hierarchy: E(nuX) > E(anue) > E(nue)
M1 luminosities (energies) systematically larger of <~50% (<~30%) w.r.t. M0+leakage
Energies affected by neutron diffusion and thermalization near neutrinospheres

Systematic study of remnant and ejecta properties: neutrino schemes and mesh resolutions Zappa, SB, Radice, Perego [https://arxiv.org/abs/2210.11491]

Short-lived remnants





Collapse shuts off remnant dynamics and spiral-wave winds
Accretion rate dominates over outflow rate
Neutrino cooled disc (caveat: no MHD, but true w/ LES)

GR simulation w/ M1

(Yet another) GR M1 gray+ scheme

- Follow M1+ of Foucart+ 2016, but
- Complete matter-radiation sources in GR (all v/c terms, etc)

  Necessary even for simple tests!
- Flux-limiter approach with 2nd order asymptotically preserving scheme

  Avoid ill-posed "heat equation" fluxes

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

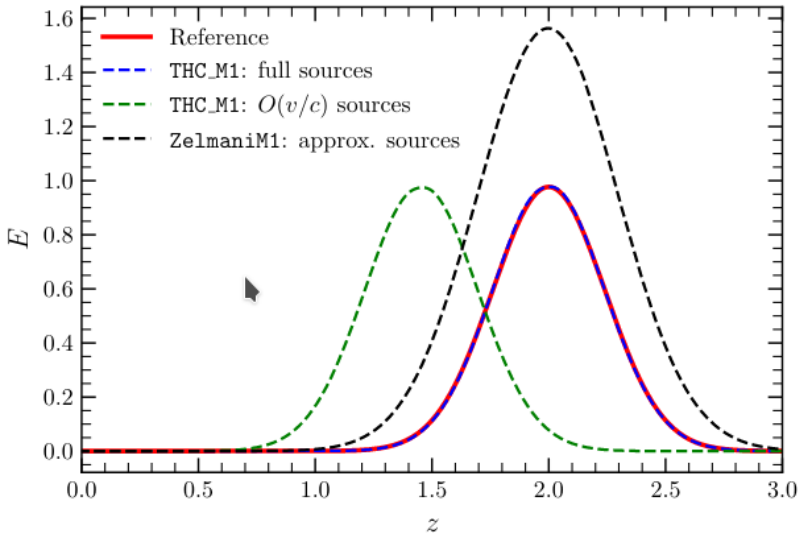


Figure 3. Diffusion and advection of Gaussian pulse of radiation in a purely scattering moving medium. The medium is moving with velocity $v = 0.5$. The reference profile is a translated semi-analytic solution of the diffusion equation. Our results show that it is essential to properly treat all of the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

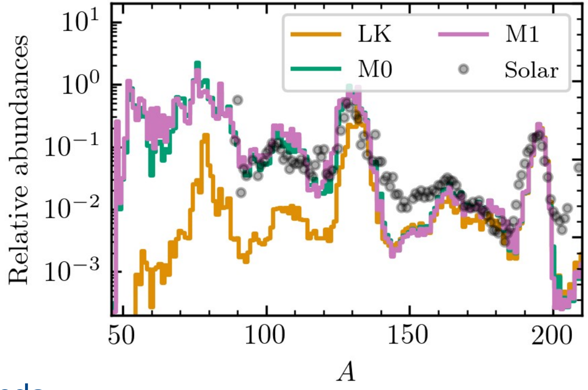
Conclusion

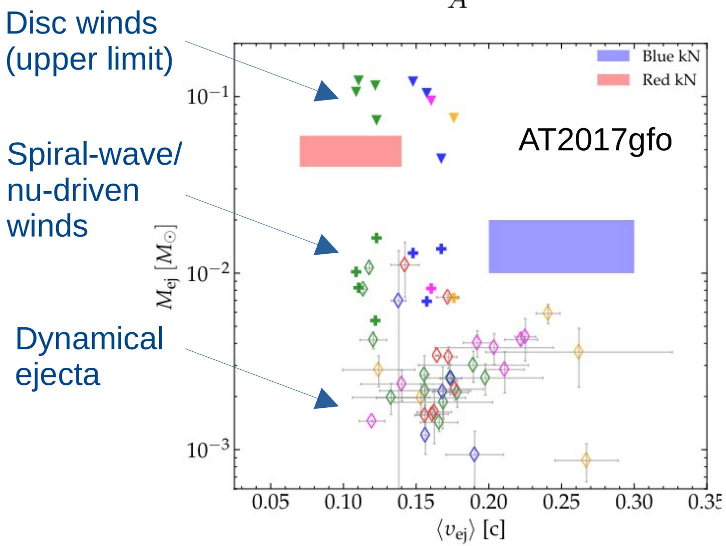
NS remnant produced with angular momentum ("super-Keplerian") and mass in excess → massive winds developing on viscous timescales

NS remnants are stable against convection and MRI. Evolution to uniform rotation? How magnetic field breaks out of the star?

Neutrino transport impacts remnants, ejecta and nucleosynthesis (→ kilonova light curves.) "ab-initio", "self-consistent" etc simulations must, at very least, include neutrino heating.

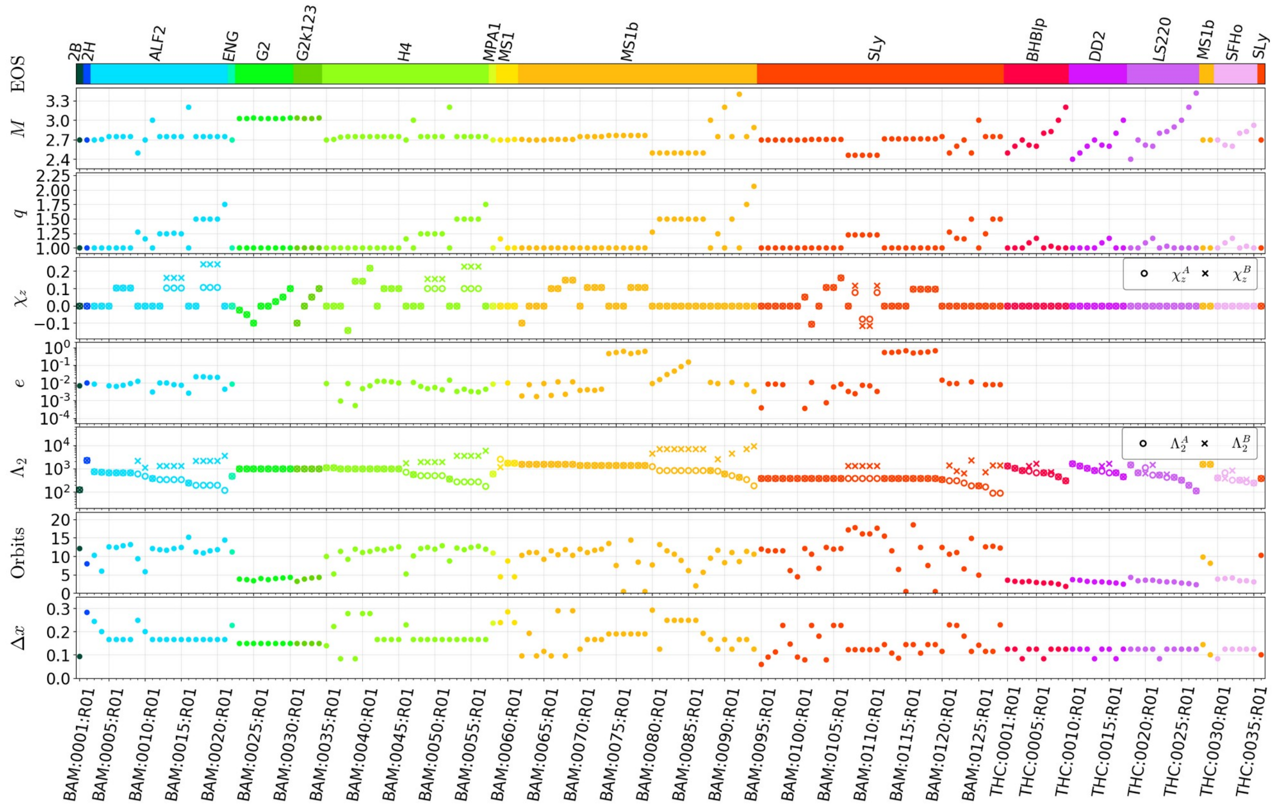
Simulations point to anisotropic, multi-component (different mechanisms) ejecta to explain AT2017gfo; they require, in particular, spiral-wave *and* disc winds.

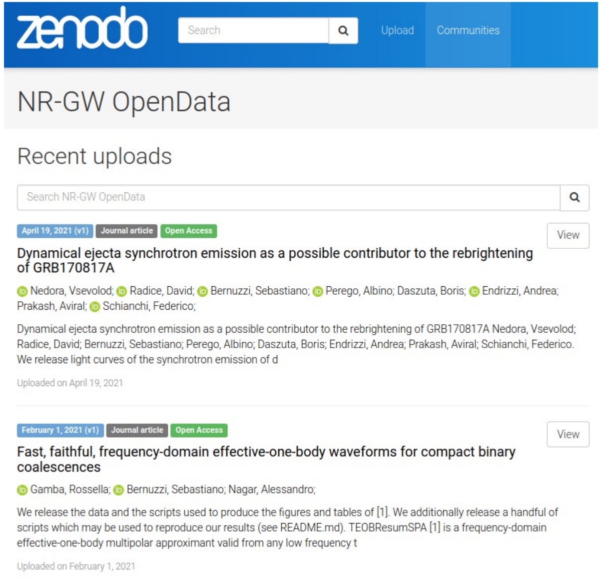




Backup slides

Public data release





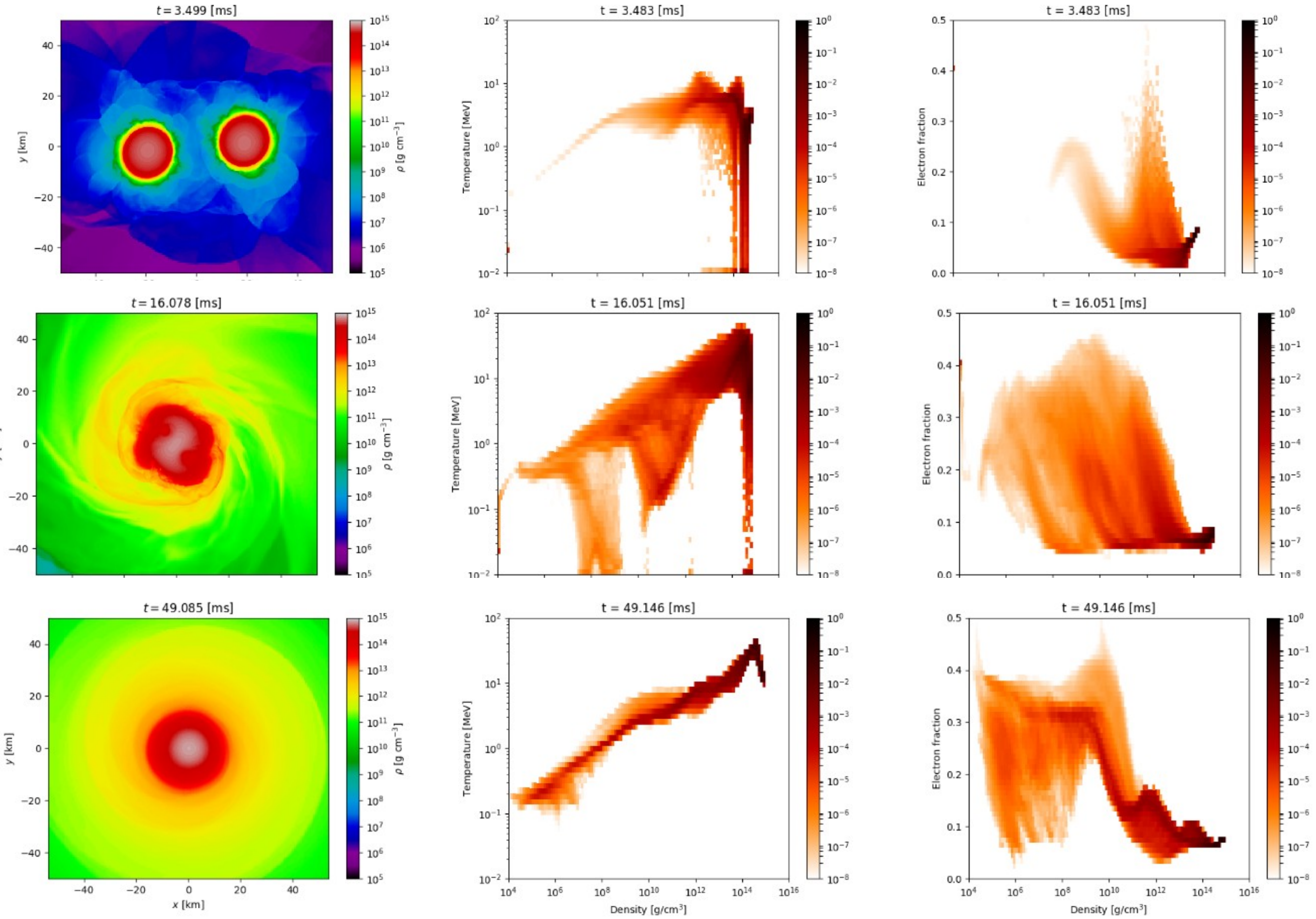
CoRe www.computational-relativity.org

Extreme Matter in BNSM

(Late-) Inspiral phase

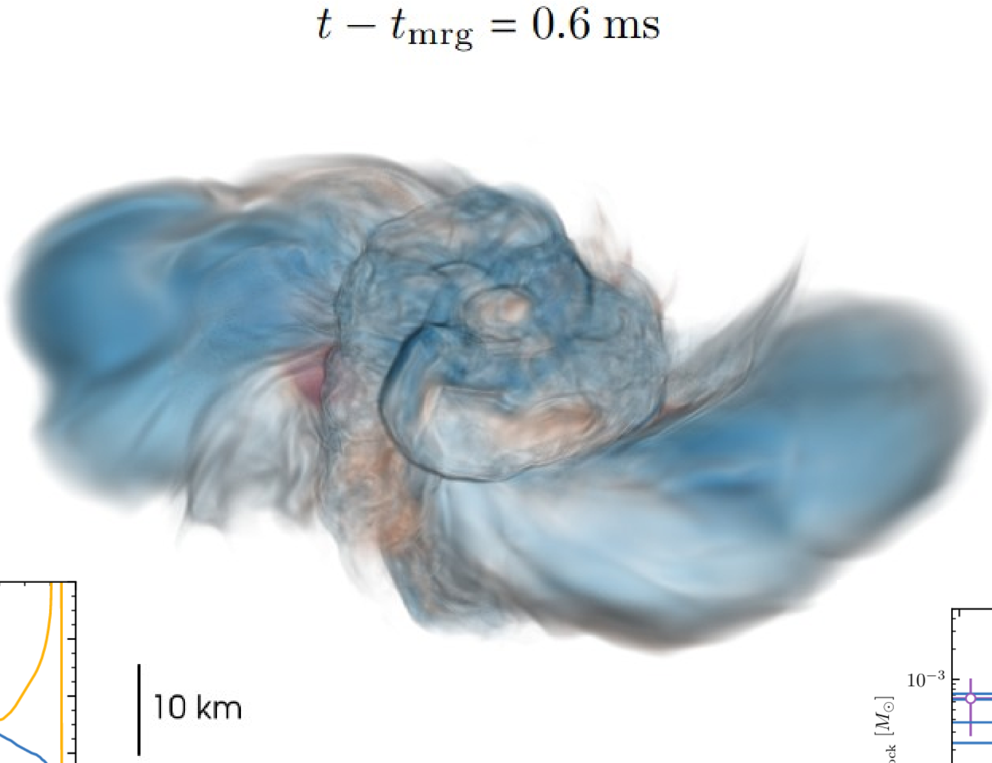
GW-driven phase

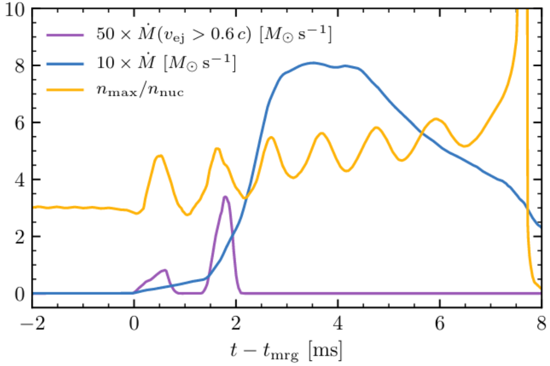
(Early-) viscous phase



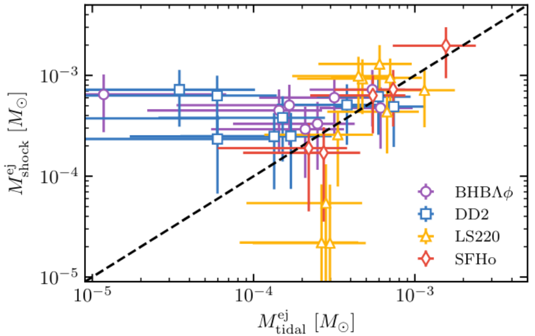
Perego, SB, Radice [https://arxiv.org/abs/1903.07898]

Dynamical ejecta

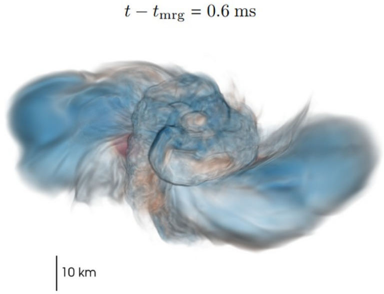


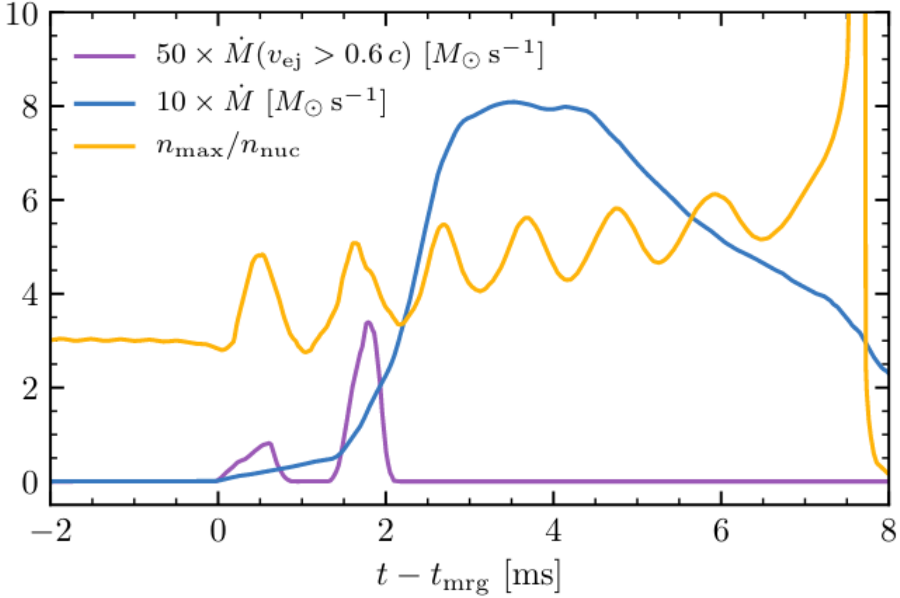


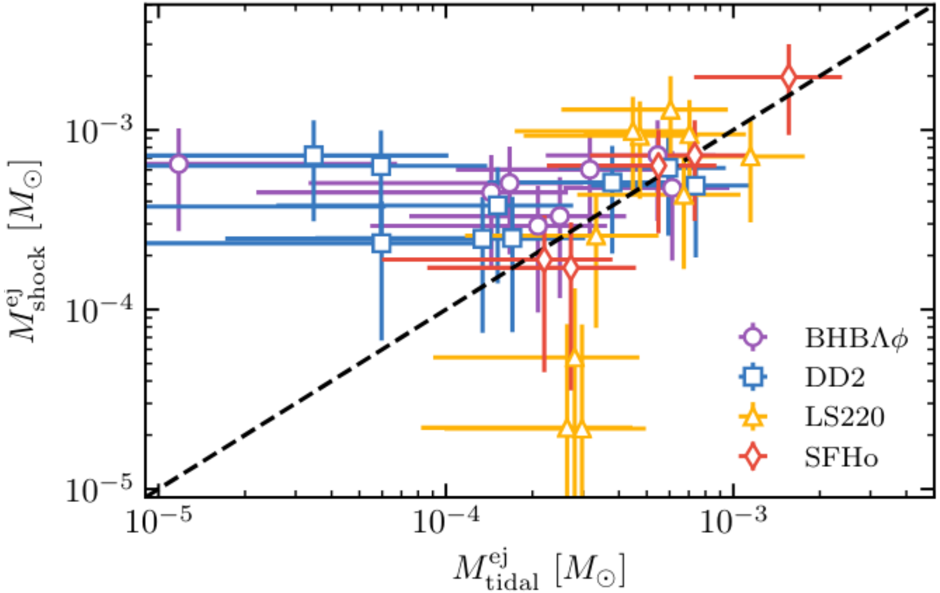
Radice+ [https://arxiv.org/abs/1809.11161]



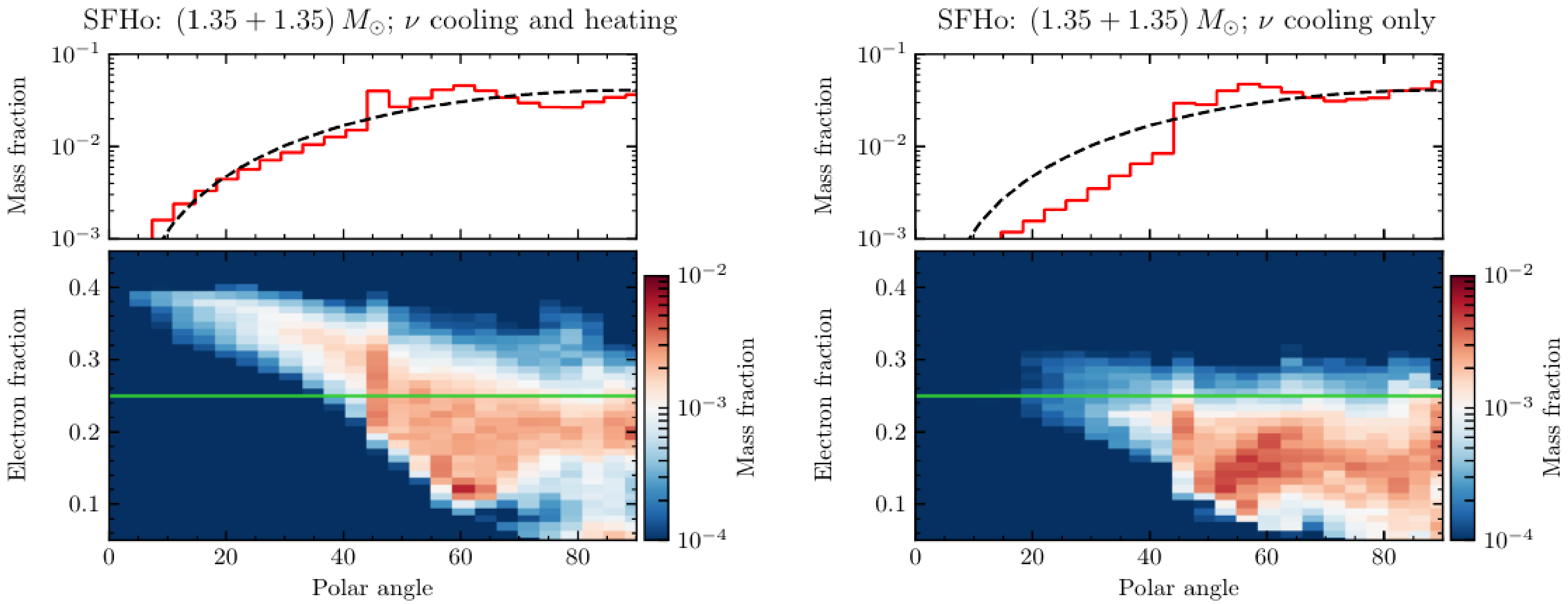
Dynamical ejecta







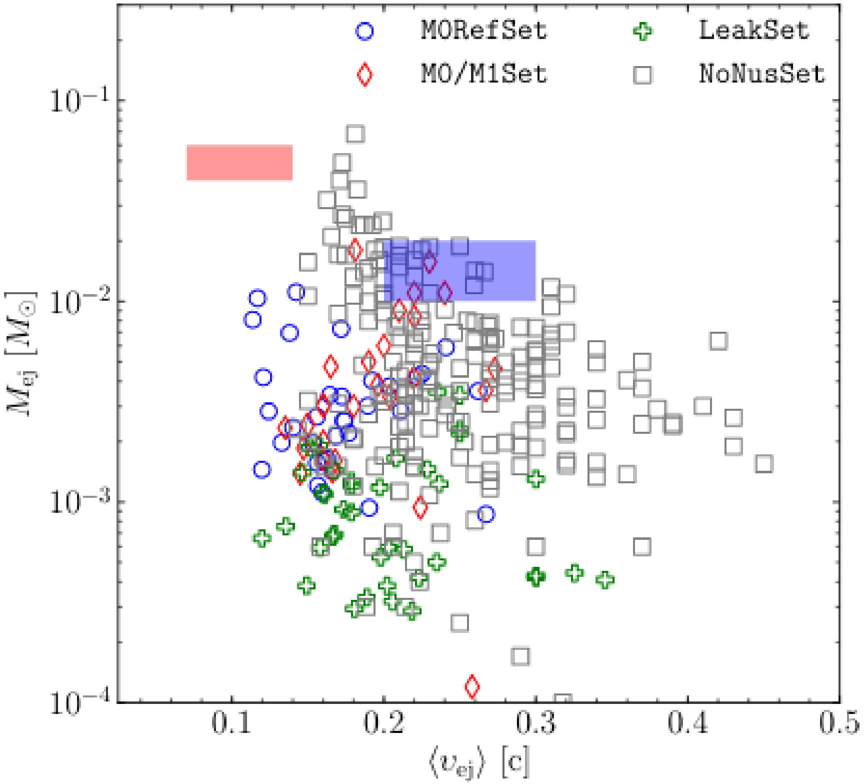
Weak interactions in the dynamical ejecta



Neutrino absorption determines both composition and kinetic properties !

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

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]

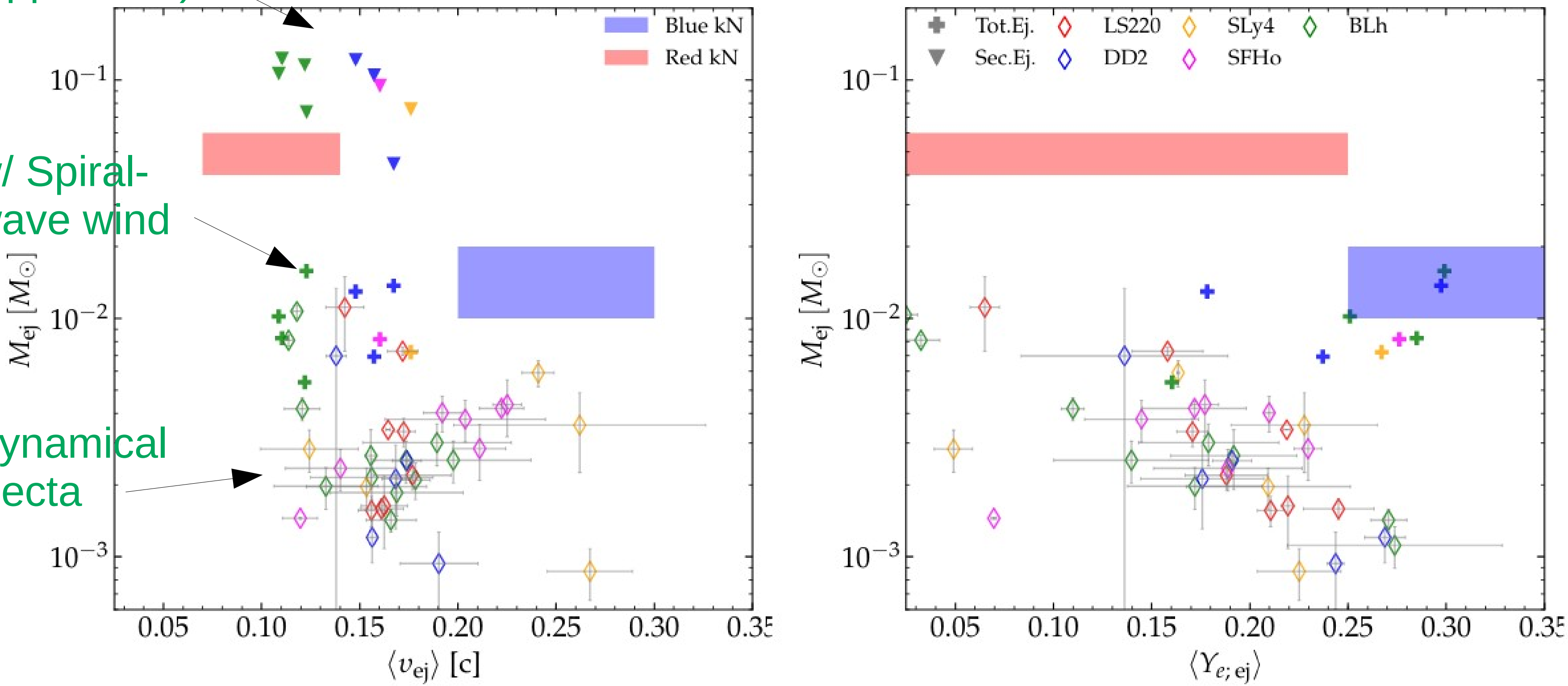
* $\overline{\Lambda}$ (or κ^T_2) = coupling constant of tidal interactions at leading Newtonian order.

AT2017gfo & targeted simulations

Disc wind (upper limit)

w/ Spiral-wave wind

Dynamical ejecta



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

Systematic study of ejecta properties: neutrino schemes and mesh resolutions

Zappa, SB, Radice, Perego [https://arxiv.org/abs/2210.11491]