Binary neutron star merger simulations with realistic neutrino interaction rates

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Mass Ejection and r-process in GW170817

- kilonova AT170817 has red and blue components
- neutron-rich → lanthanide rich → red kilonova
- neutron-poor → lanthanide poor → blue kilonova
- thus, leptonization through neutrino interactions is important

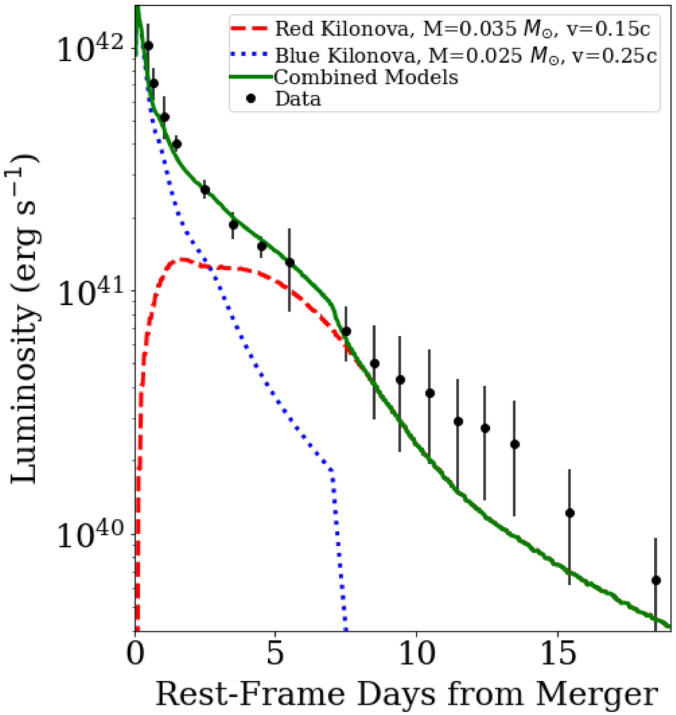

Fig.: Kilpatrick et al. 2017

Neutrinos in Numerical Relativity

Leakage | **Truncated Moments** | **Monte-Carlo**

$$S^{\mu} = (\eta - \kappa_a J) u^{\mu} - (\kappa_a + \kappa_s) H^{\mu}$$

- collisional source term is stiff
- requires implicit treatment → implicit-explicit (IMEX) time evolution
- interaction rates are not evolved quantities
- computed beforehand and provided in tables

Standard Interaction Rates in BNS Mergers

- **Commonly included reactions:**

Reactions	References		
Charged-Current	HAO	NuLib	Ruffert
$\nu_e + n \leftrightarrow p + e^-$ $\bar{\nu}_e + p \leftrightarrow n + e^+$	(1)	(2)	(3)
Pair-Processes			
$e^- + e^+ \rightarrow \nu_x + \bar{\nu}_x$ $N + N \rightarrow N + N + \nu_x + \bar{\nu}_x$	(2,4)		(3)
$\gamma \rightarrow \nu_x + \bar{\nu}_x$	–		
Elastic Scattering			
$\nu + p \rightarrow \nu + p$ $\nu + n \rightarrow \nu + n$	(2,4)		(3)
$\nu + A \rightarrow \nu + A$			(5)
$\nu + \alpha \rightarrow \nu + \alpha$			–

(1) G. Guo et al. 2020, PRD

(2) E. O'Connor et al. 2015, APJS

(3) M. H. Ruffert et al. 1996, A&A

(4) A. Burrows et al. 2006, Nucl. Phys. A

(5) F. Galeazzi et al. 2013, PRD

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Elastic Scattering			
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Different Charged-Current Prescriptions

"Ruffert" (1)

Elastic approximation (2)

Averaged lepton blocking factor

Analytical nucleon phase-space integral

$$Y_{12}=\frac{n_2-n_1}{\exp\left(\left[\mu_2-\mu_1+Q\right]/T\right)-1}$$

$$\kappa_a(\epsilon)=\frac{\sigma_0}{\left(m_e c^2\right)}\frac{\left(g_V^2+3g_A^2\right)}{4}(\epsilon+Q)^2\sqrt{1-\frac{m_l c^2}{\epsilon+Q}}\cdot\left(1-f_l(\epsilon+Q)\right)Y_{12}$$

(1) M. H. Ruffert et al. 1996, A&A

(2) S. W. Bruenn 1985, APJS

Different Charged-Current Prescriptions

"Ruffert" [1]	"NuLib" [3]
Elastic approximation [2]	Weak-magnetism / recoil
Averaged lepton blocking factor	Stimulated absorption
Analytical nucleon phase-space integral	Energy dependent lepton blocking factor

$$Y_{12} = \frac{n_2 - n_1}{\exp([\mu_2 - \mu_1 + Q]/T) - 1}$$

$$\kappa_{\mathrm{a}}^{*}(\epsilon) = \frac{W_{\mathrm{WM\,/\,Recoil}}(\epsilon)}{1 - f_{\nu}^{\mathrm{eq}}(\epsilon, \mu_{\nu}, T)} \cdot \kappa_{a}(\epsilon)$$

(1) M. H. Ruffert et al. 1996, A&A

(2) S. W. Bruenn 1985, APJS

(3) E. O'Connor et al. 2015, APJS

Different Charged-Current Prescriptions

"Ruffert" [1]	**"NuLib"** [3]	**"HAO"**
Elastic approximation [2]	Weak-magnetism / recoil	Full kinematics [4]
Averaged lepton blocking factor	Stimulated absorption	Microscopic corrections to hadronic current
Analytical nucleon phase-space integral	Energy dependent lepton blocking factor	Non-analytic phase-space integral

$$Y_{12}=\frac{n_2-n_1}{\exp([\mu_2-\mu_1+Q]/T)-1}$$

$$\kappa_a^*(\epsilon)=\frac{W_{\mathrm{WM\,/\,Recoil}}(\epsilon)}{1-f_\nu^{\mathrm{eq}}(\epsilon,\mu_\nu,T)}\cdot\kappa_a(\epsilon)$$

$$E_N^*=\sqrt{|\boldsymbol{p}_N|+(m_N^*)^2}+U_N$$

(1) M. H. Ruffert et al. 1996, A&A

(3) E. O'Connor et al. 2015, APJS

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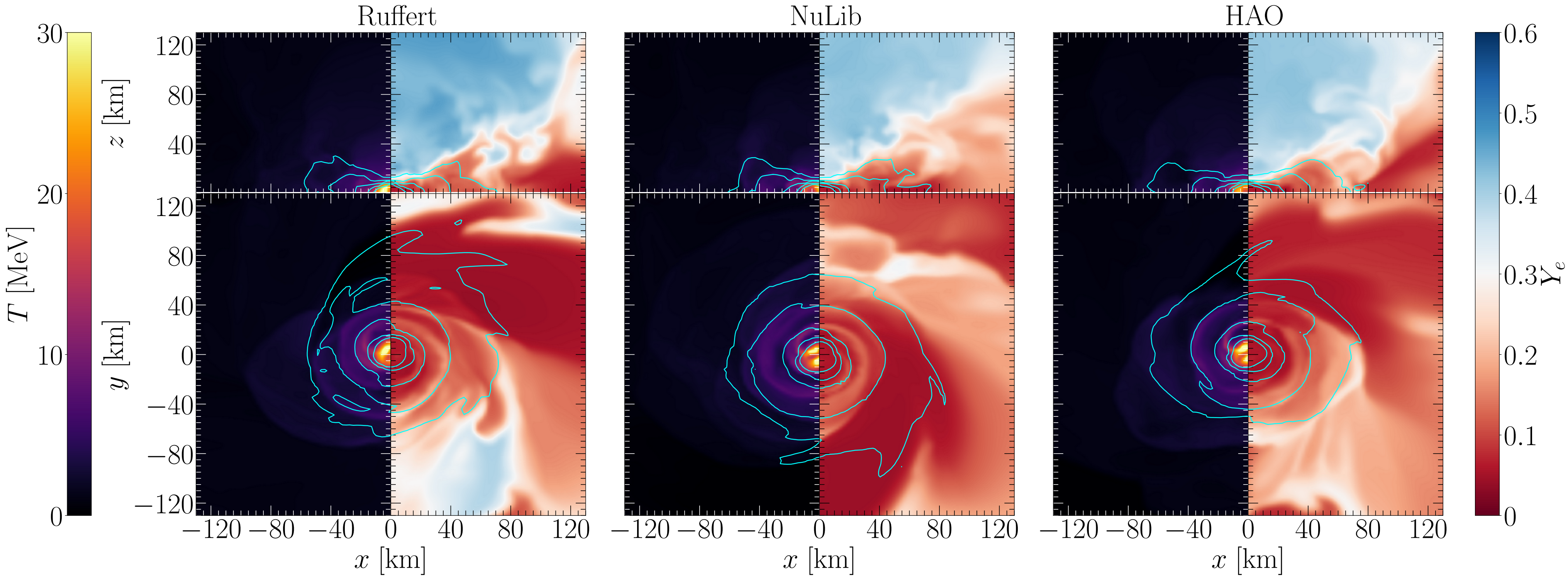
Do the more realistic prescriptions for Charged-Current reactions leave an imprint BNS merger simulations?

Simulation setup

Equal masses, total: 2.4 M
Equation of state: SFHo



* R. Jaeger et al. 2026 [in prep.]

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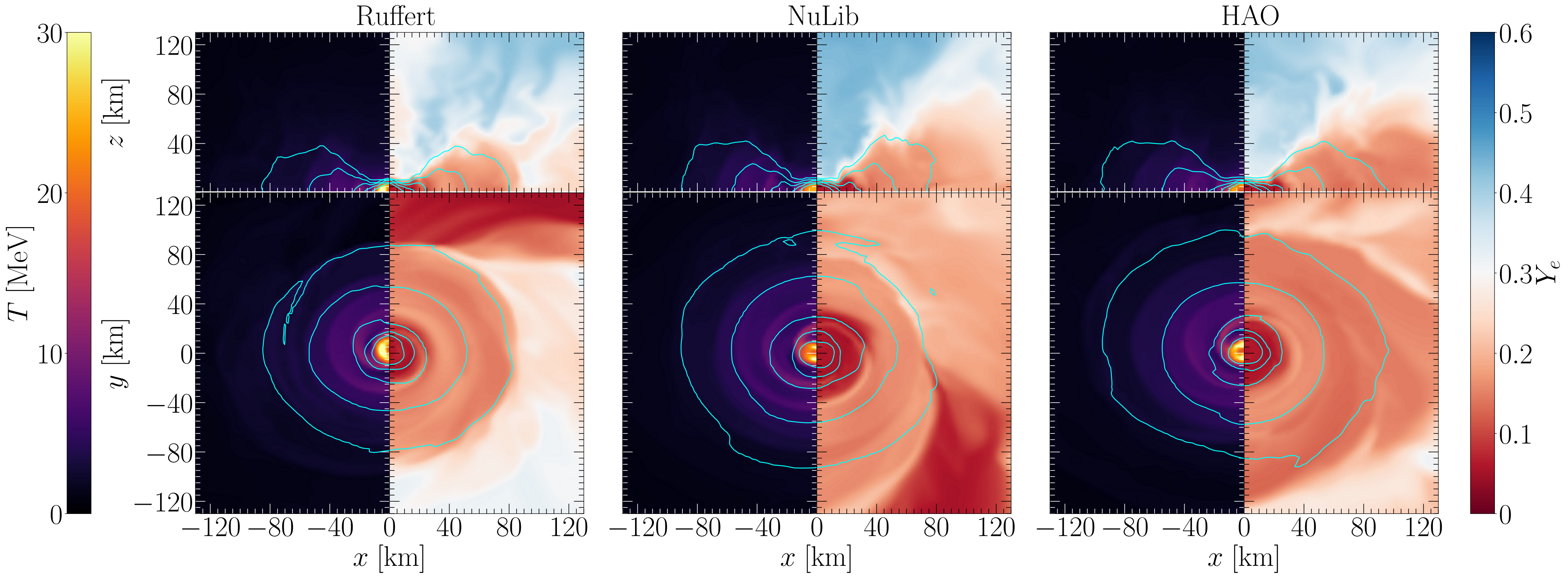

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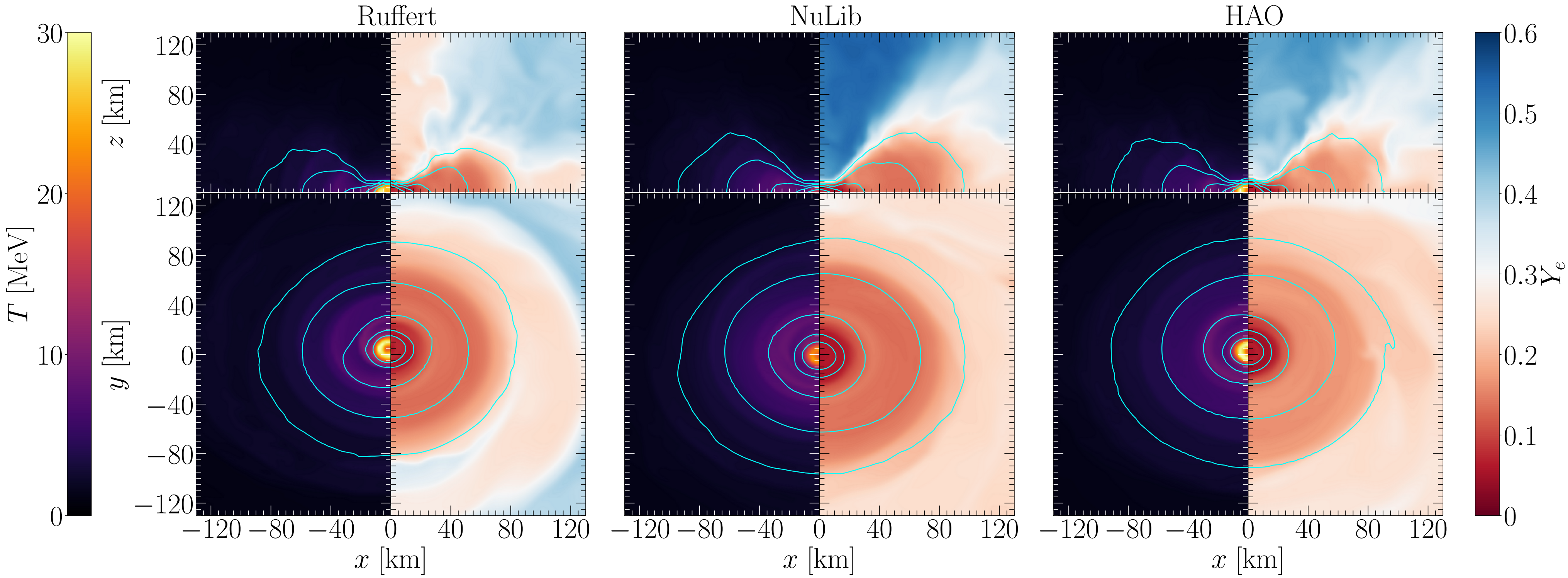

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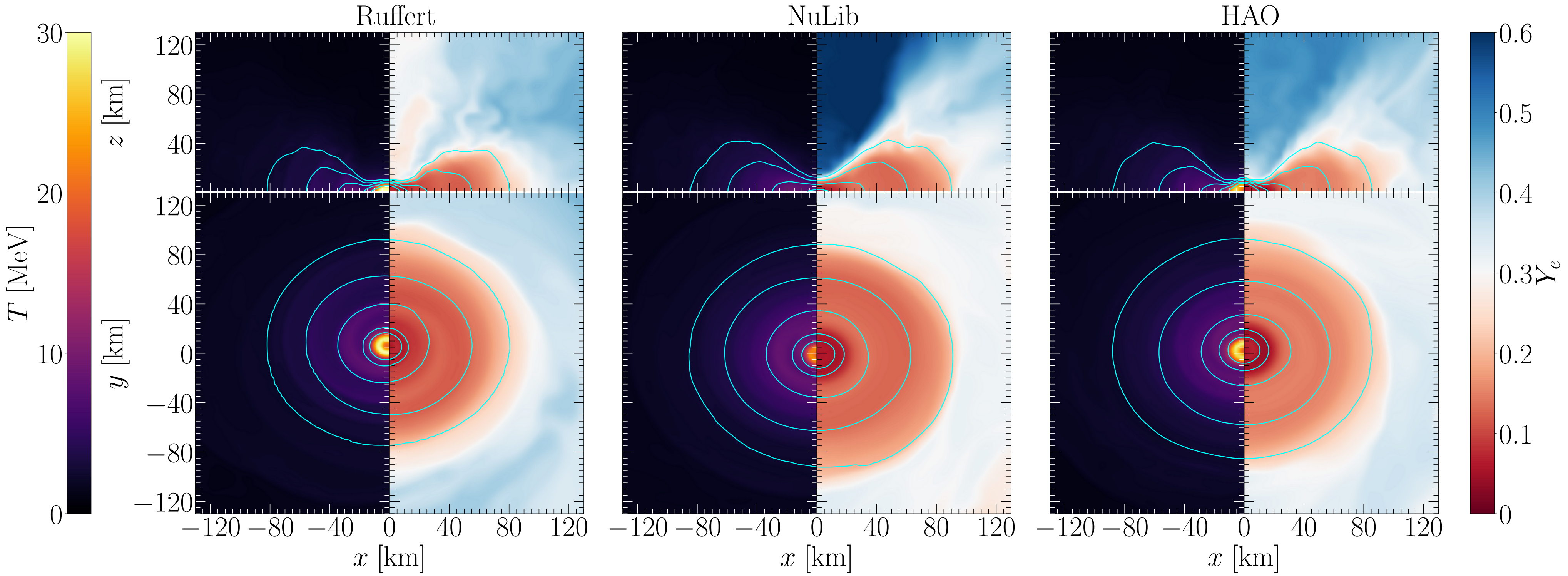

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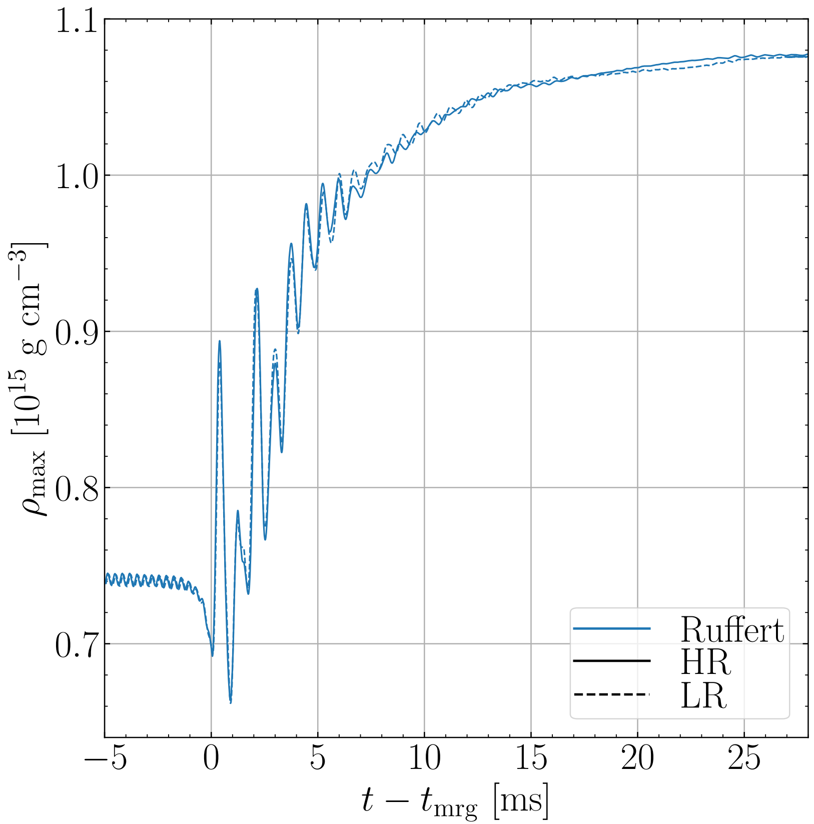
Simulation Monitors



- Ruffert : agreement across resolution

$$M_{\mathrm{rem}}^{\mathrm{HR}} = 2.449 \qquad \left(M_{\mathrm{rem}}^{\mathrm{LR}} = 2.448\right)$$

* R. Jaeger et al. 2026 [in prep.]

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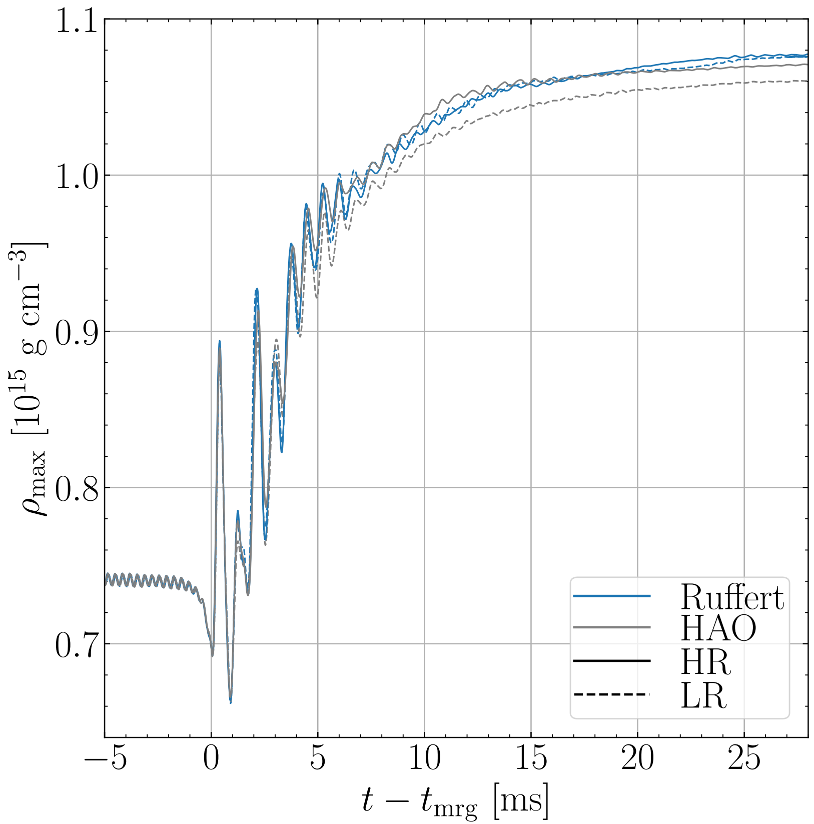

- Ruffert : agreement across resolution

  $$M^{\rm HR}_{\rm rem} = 2.449 \quad \left(M^{\rm LR}_{\rm rem} = 2.448\right)$$

- HAO : approach Ruffert for HR

  $$M^{\rm HR}_{\rm rem} = 2.424 \quad \left(M^{\rm LR}_{\rm rem} = 2.418\right)$$

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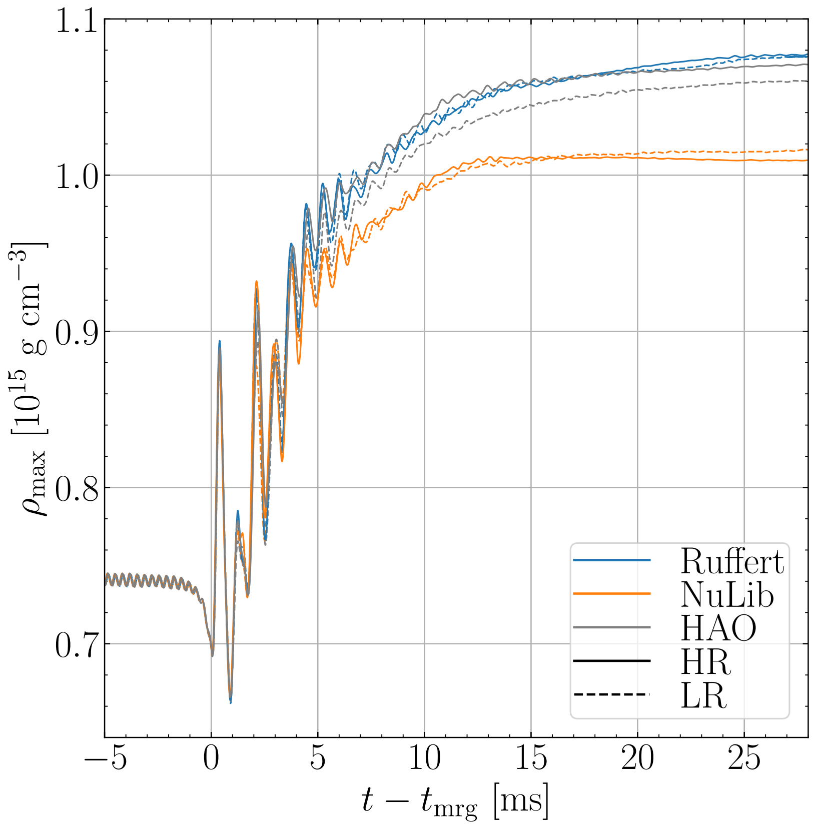

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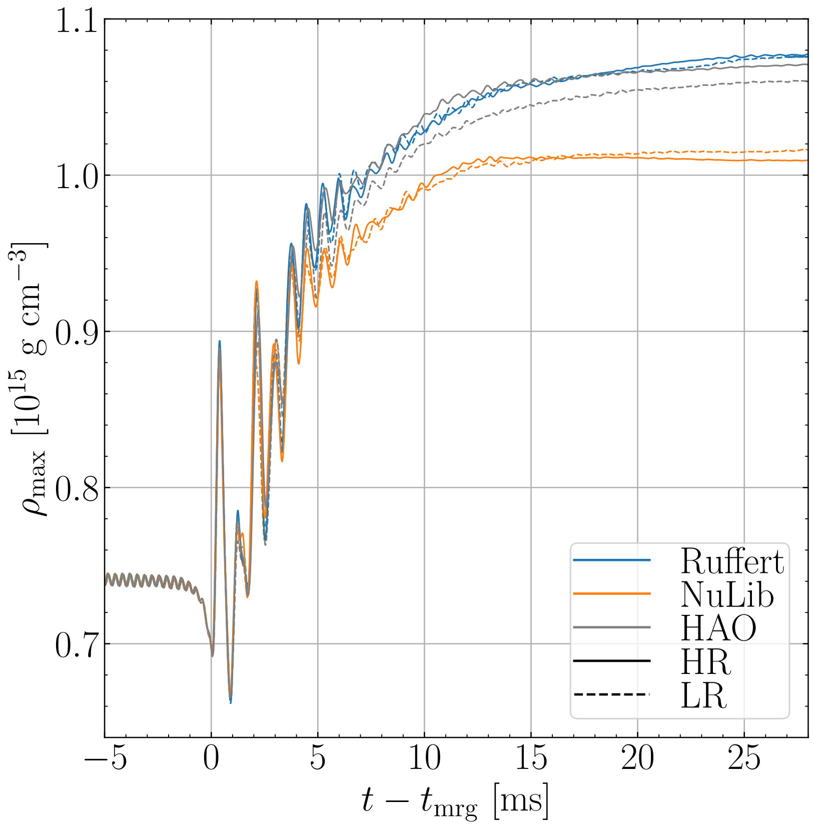
$$M_{\rm rem}^{\rm HR} = 2.424 \quad \left(M_{\rm rem}^{\rm LR} = 2.418\right)$$

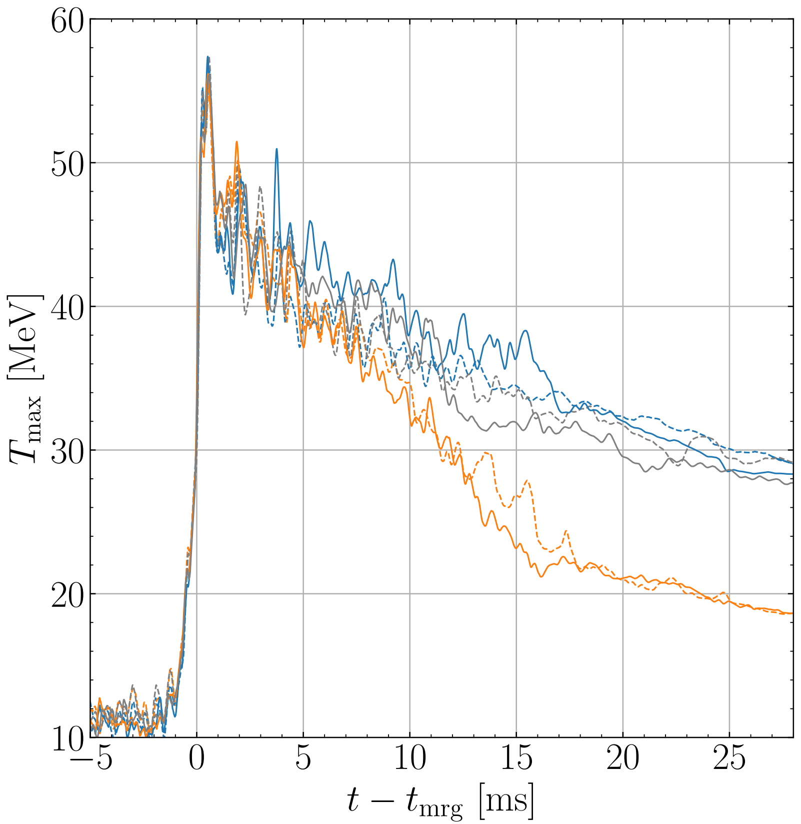
- NuLib : strong post-merger drift

$$M_{\rm rem}^{\rm HR} = 2.370 \quad \left(M_{\rm rem}^{\rm LR} = 2.392\right)$$

* R. Jaeger et al. 2026 [in prep.]

Simulation Monitors

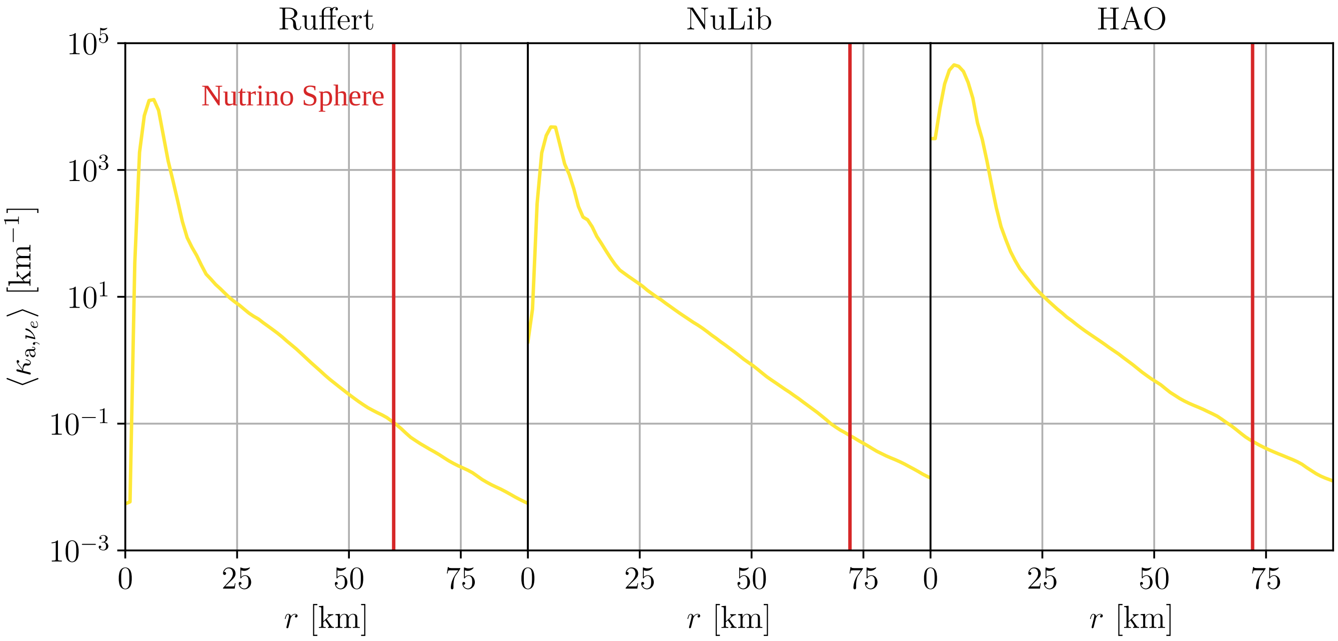


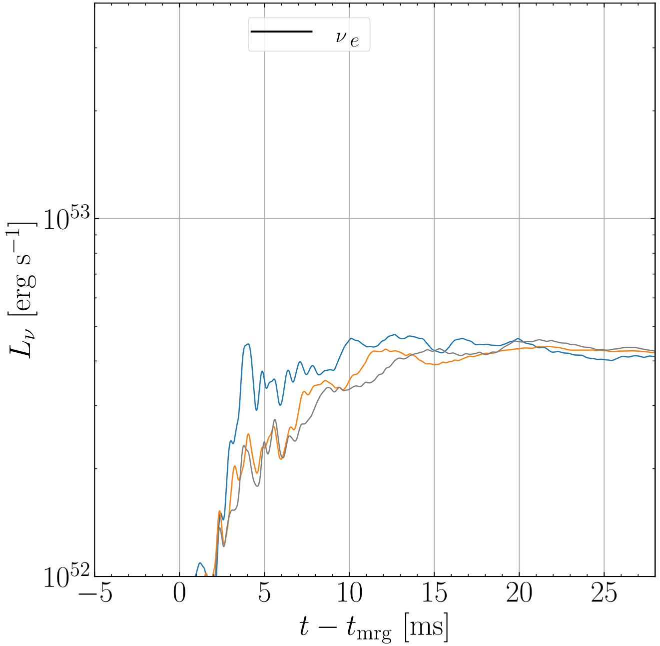


(P. Hammond et al. 2021, PRD)

* R. Jaeger et al. 2026 [in prep.]

Opacities + Neutrino Spheres





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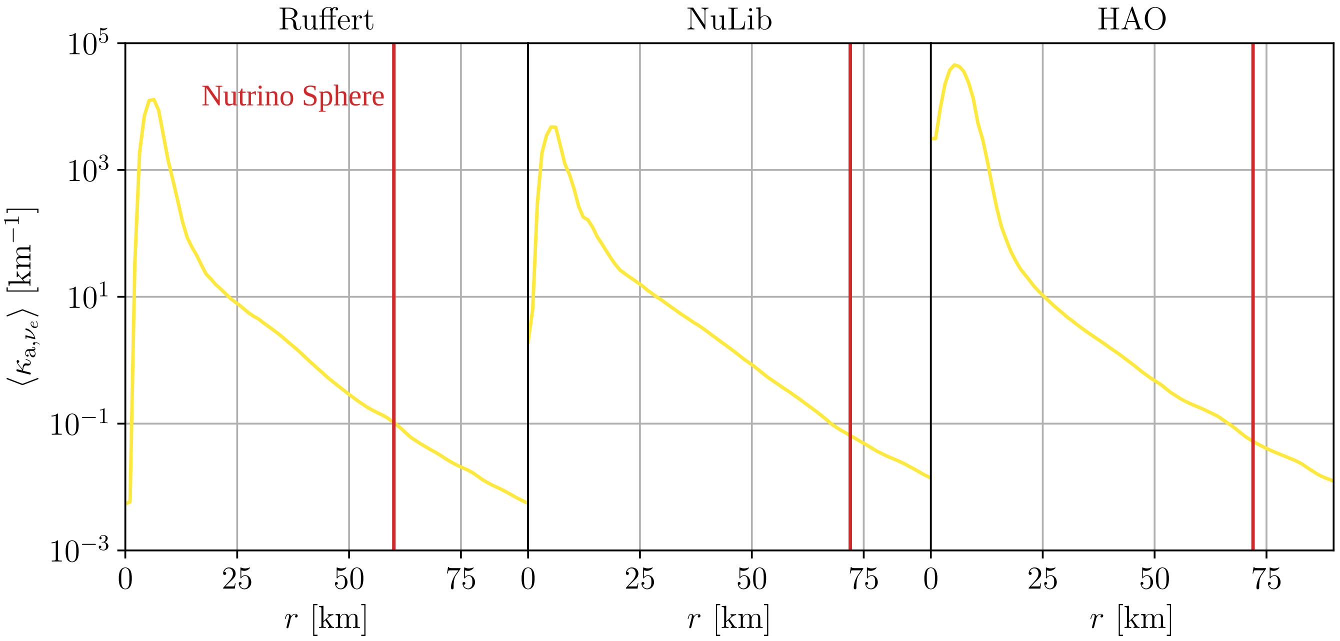

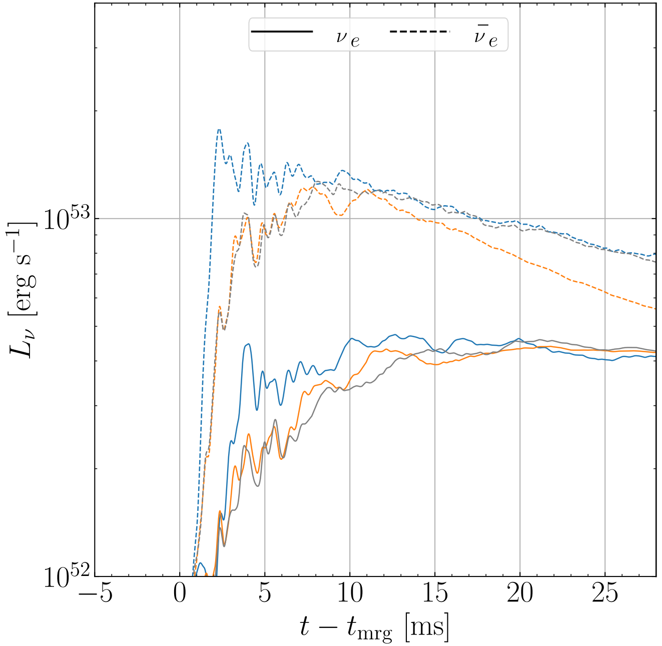

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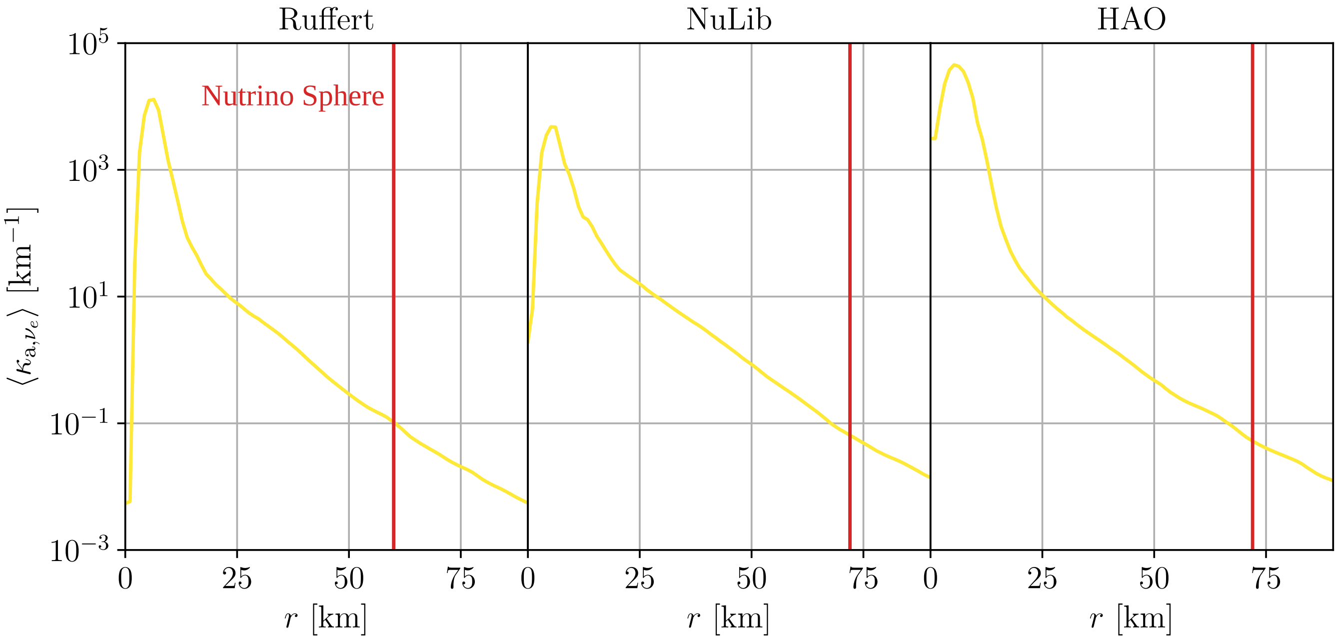
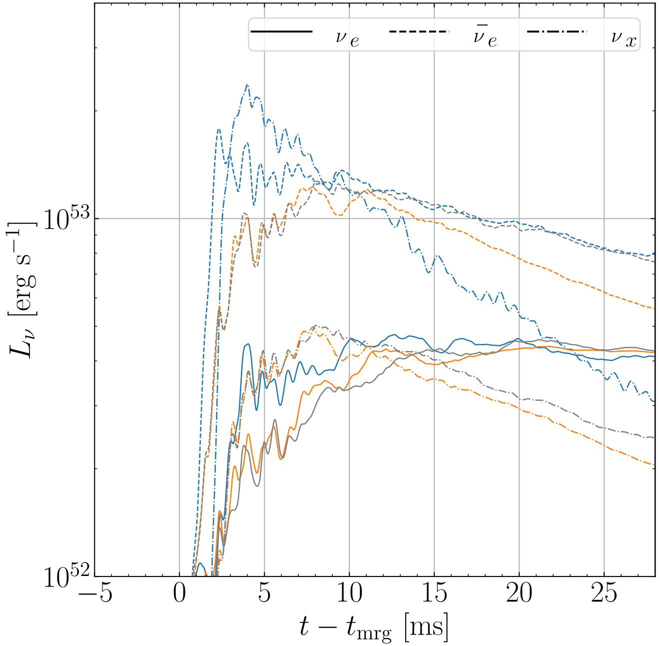
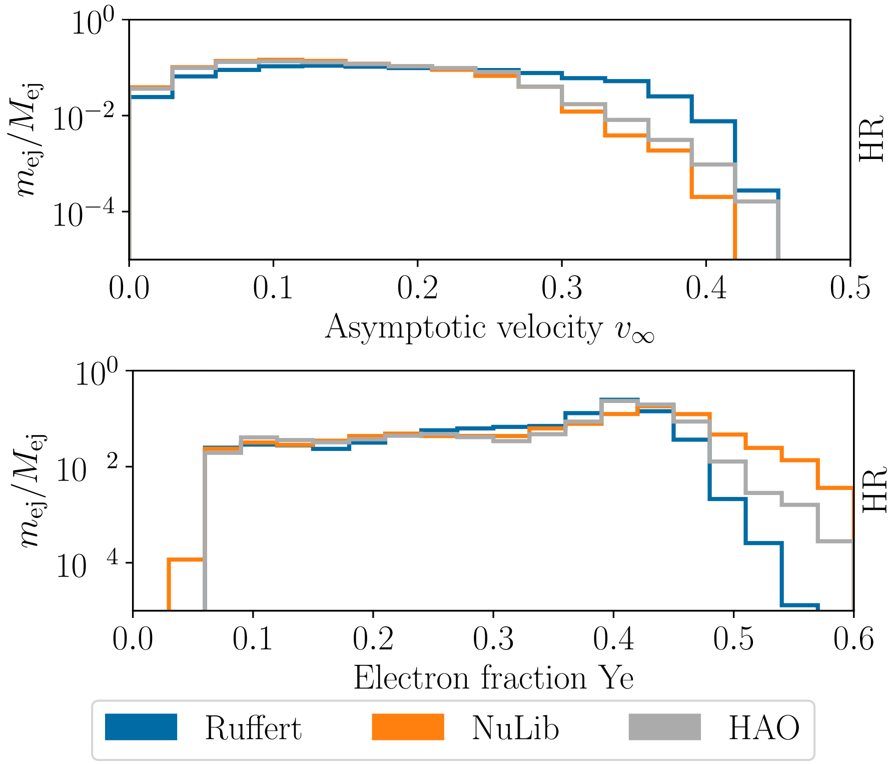




Simulation Ejecta and Remnant Properties

- **Ruffert**
  - Underestimated emissivities at low densities
  - Consistently higher ejecta masses
  - Larger ejecta velocities
  - Lower ejecta electron fraction
- **NuLib**
  - Lowest ejecta mass, close to **HAO**
  - Lowest velocities
  - Largest electron fraction ($\bar{\nu}_e$ luminosity decreases with T => more ν_e irradiation)



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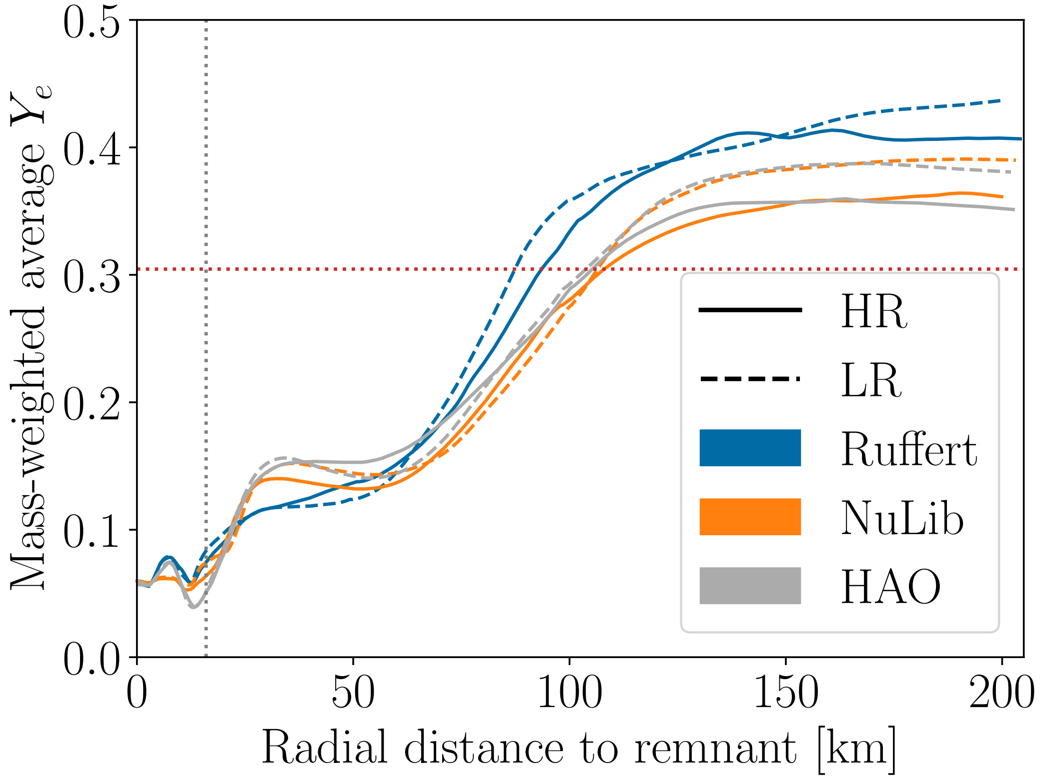
Remnant Disk and Neutrino Winds

- **Ruffert** : increased electron fraction in the (less dense) outer disk
  - Secular ejecta from the disk likely more protonized
  - Suppression of r-process
- **HAO** : increased electron fraction in inner disk (stronger neutrino irradiation from remnant)



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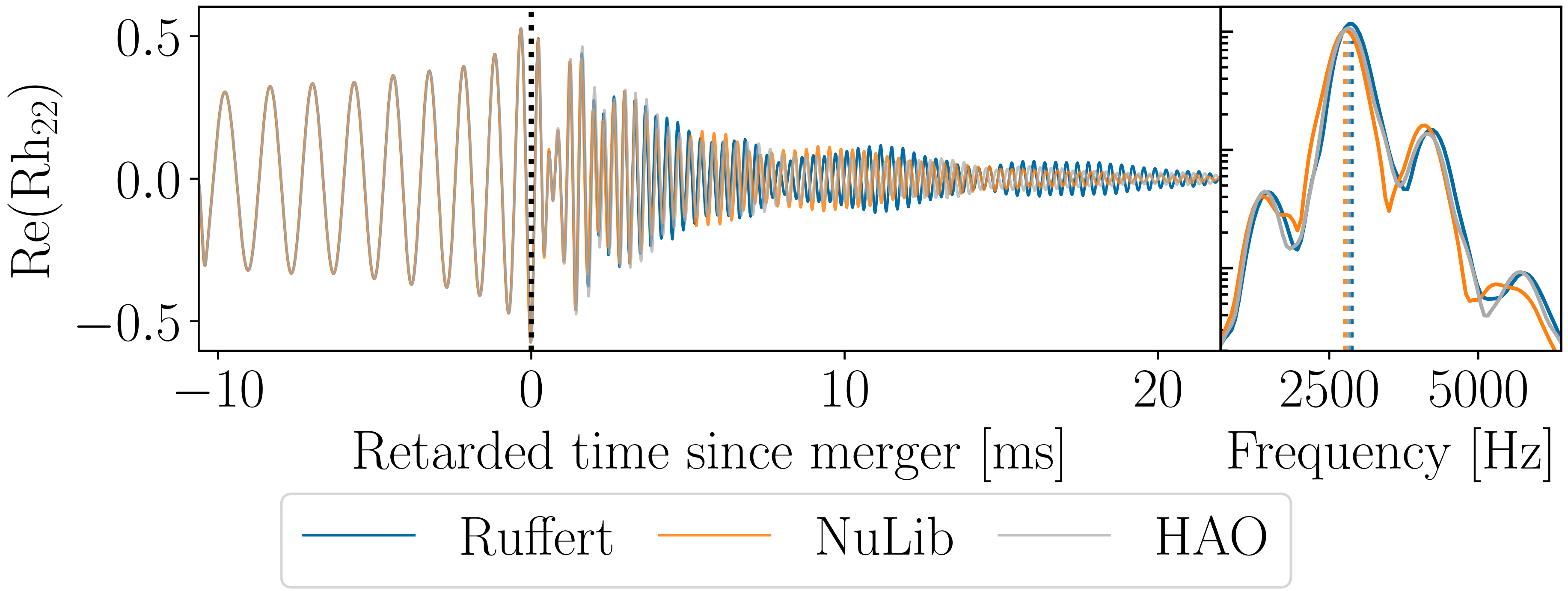
Gravitational Waves



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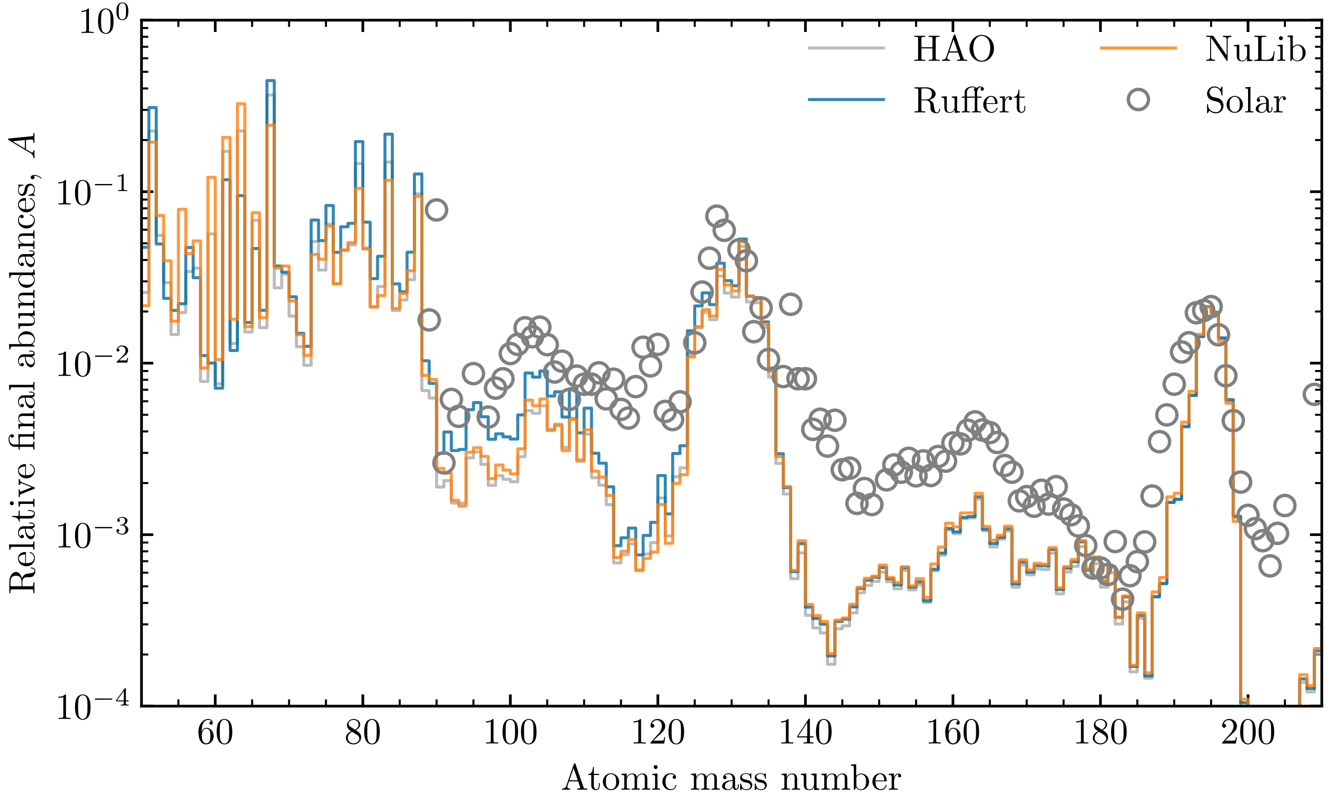
r-process Yields



Computed with `SkyNet`
J. Lippuner 2017, APJS

* R. Jaeger et al. 2026 [in prep.]

Summary

In comparison to Ruffert, more realistic interaction rates show:

- Potentially lower ejecta masses
- Reduced velocities of dynamical ejecta
- Increased electron fraction of dynamical ejecta
- Thicker disks (reduced disk electron fraction)
- No impact on post-merger gravitational waves
- Sligtly different r-process abundance patterns (for dynamical ejecta)

Thank you for listening

Questions

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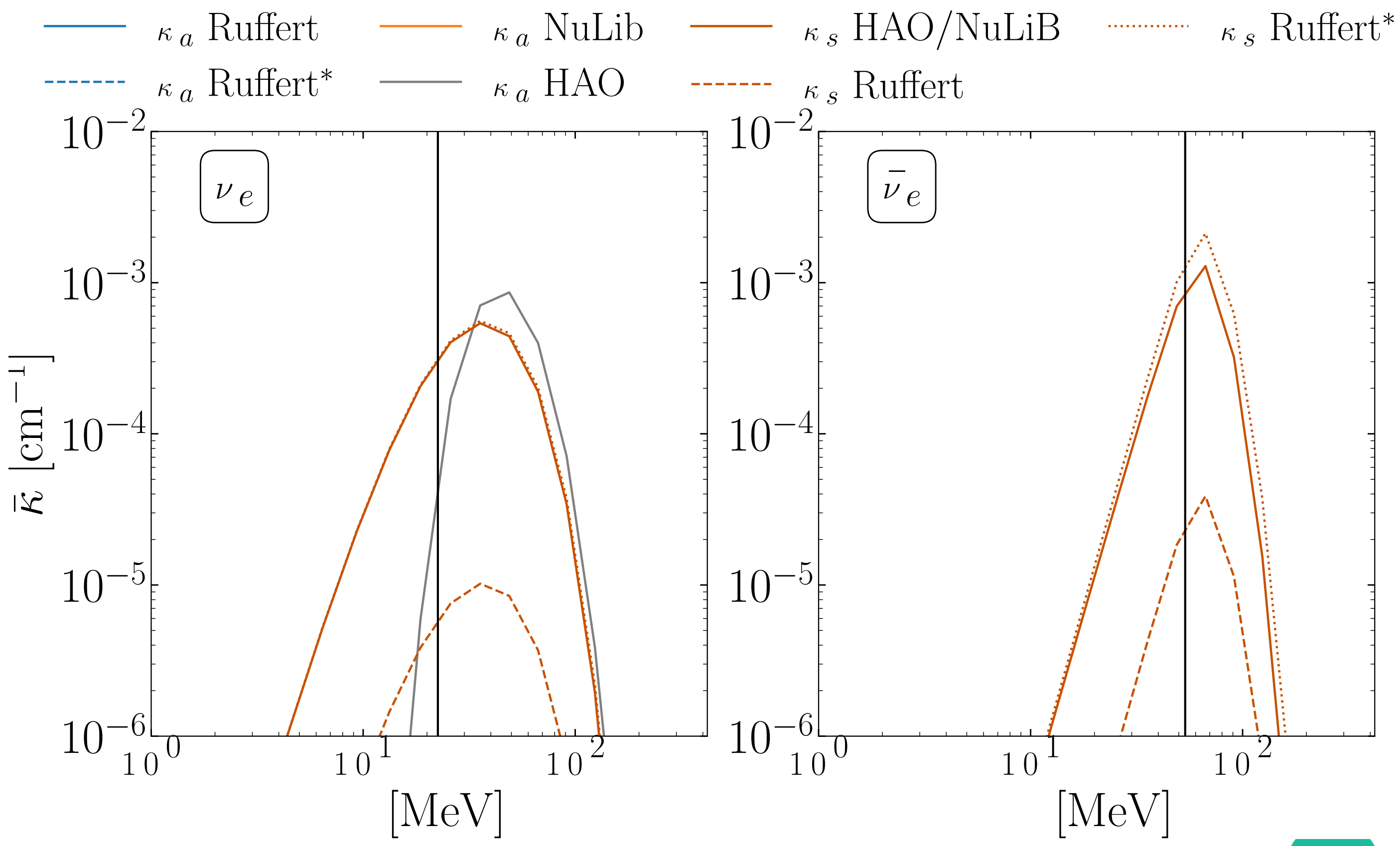
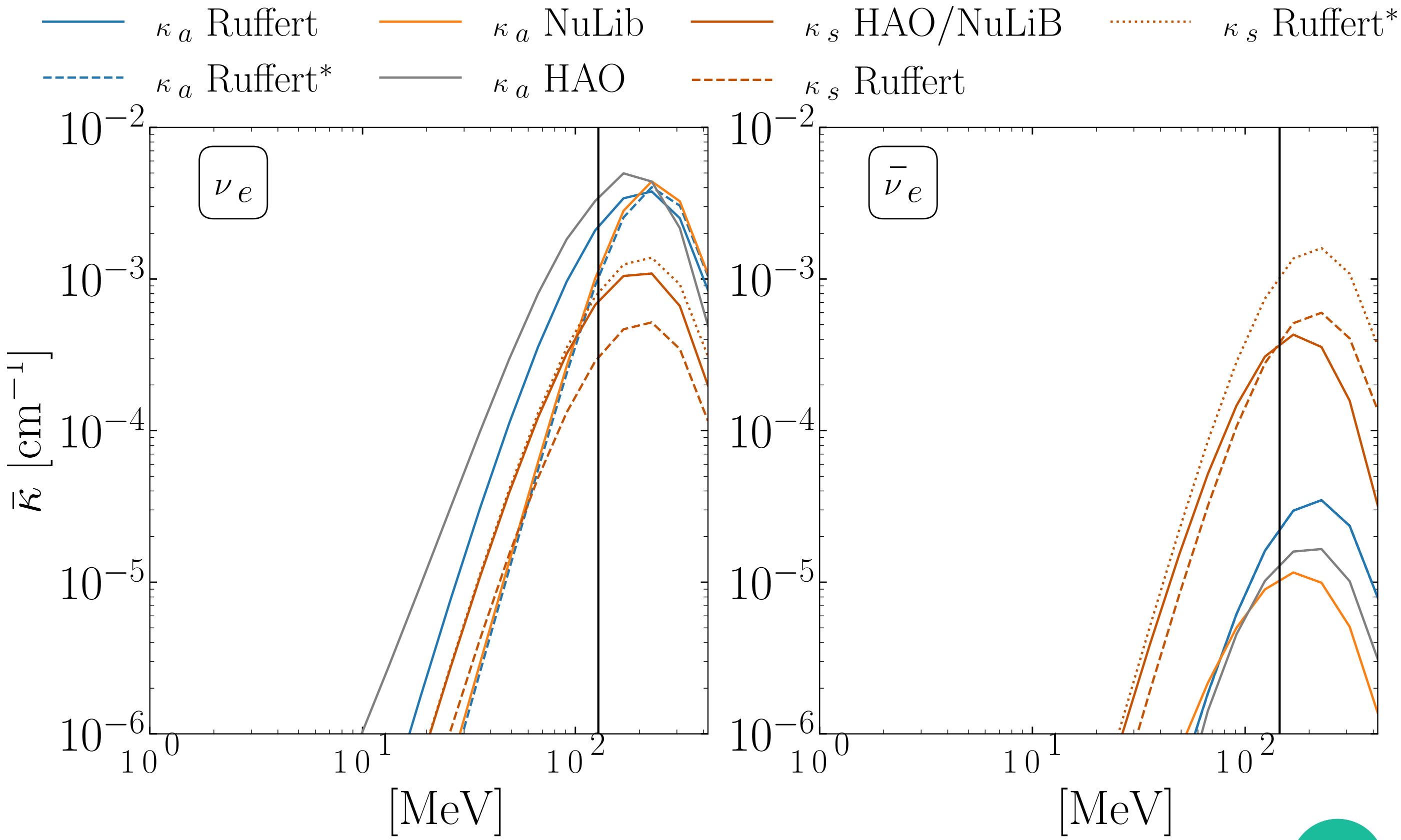
Opacities comparison – NS core

$T\,[\mathrm{MeV}]$	7.50
$\rho\,[\mathrm{g\ cm^{-3}}]$	$1.44\cdot10^{15}$
Y_e	0.05
$\hat{\mu}$	276.9
μ_e	213.6
$U_n\,[\mathrm{MeV}]$	910.2
$U_p\,[\mathrm{MeV}]$	906.0
$m_n^*\,[\mathrm{MeV}]$	319.0
$m_p^*\,[\mathrm{MeV}]$	317.7



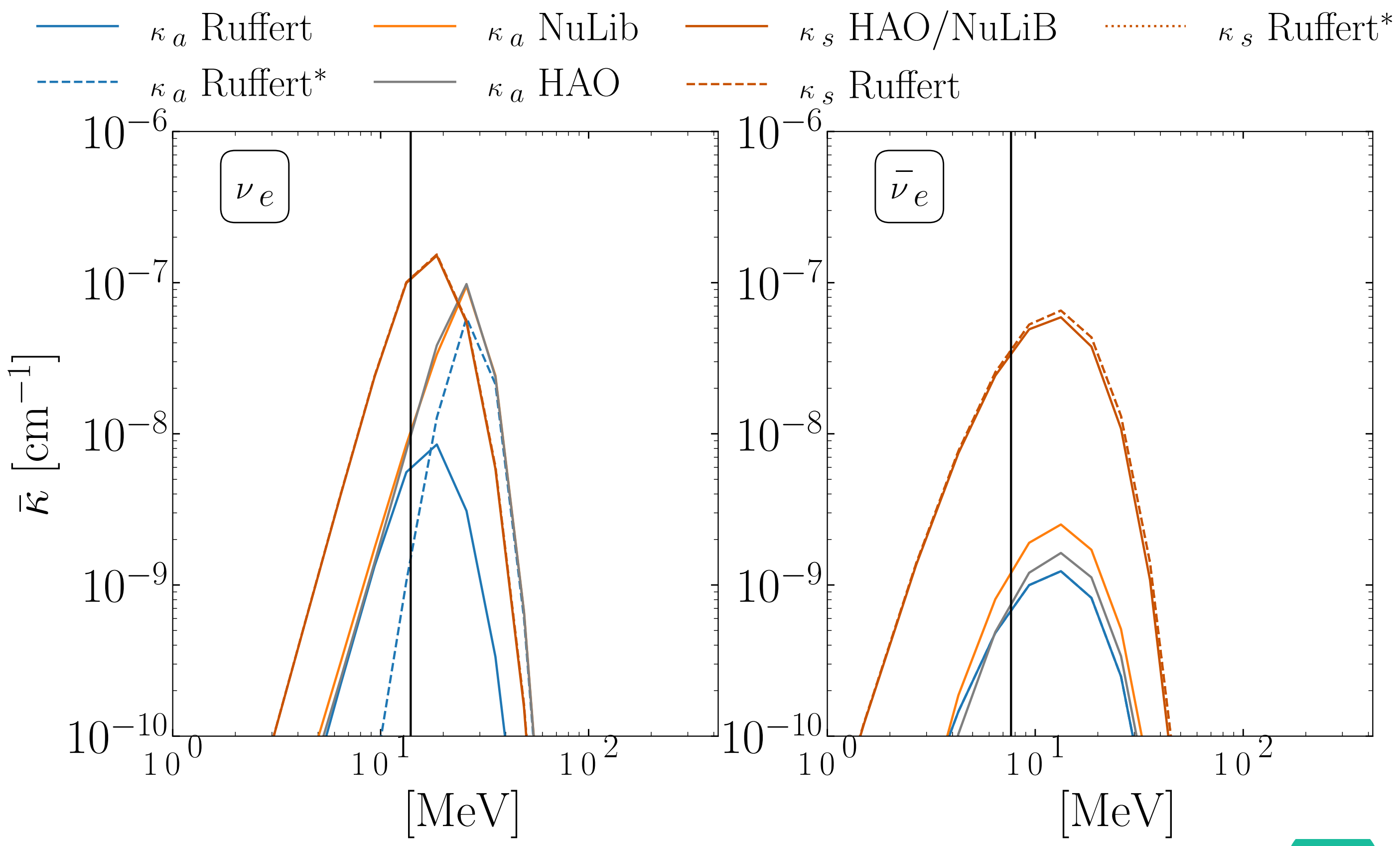
Opacities comparison – Hot regime

$T\,[\mathrm{MeV}]$	42.2
$\rho\,[\mathrm{g\ cm^{-3}}]$	$6.32\cdot10^{14}$
Y_e	0.07
$\hat{\mu}$	212.8
μ_e	150.8
$U_n\,[\mathrm{MeV}]$	395.4
$U_p\,[\mathrm{MeV}]$	352.2
$m_n^*\,[\mathrm{MeV}]$	534.1
$m_p^*\,[\mathrm{MeV}]$	532.8

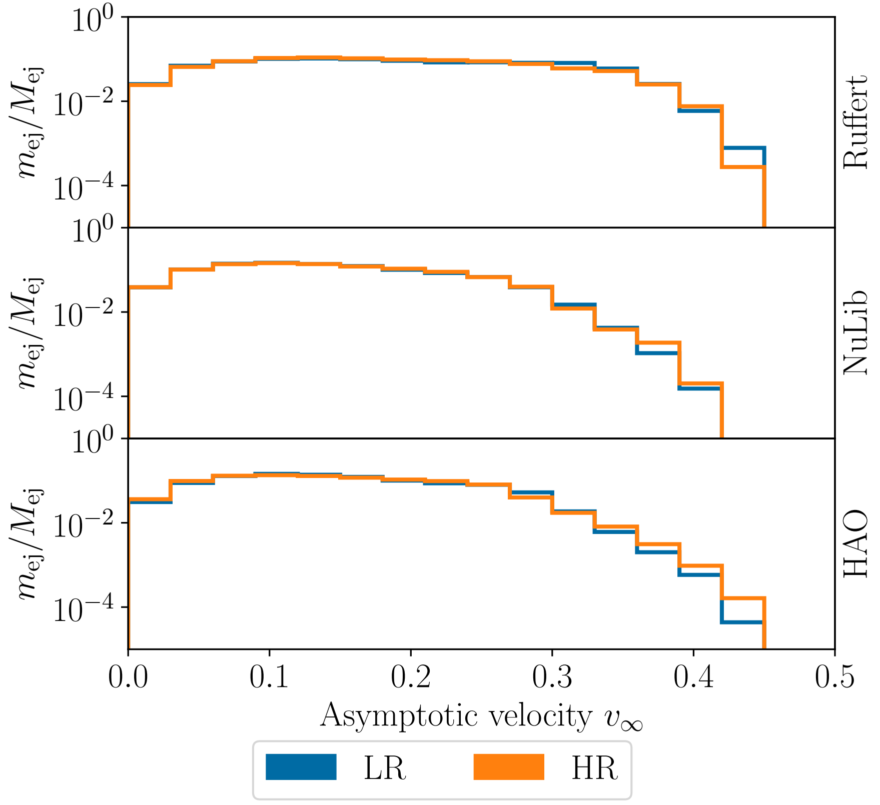


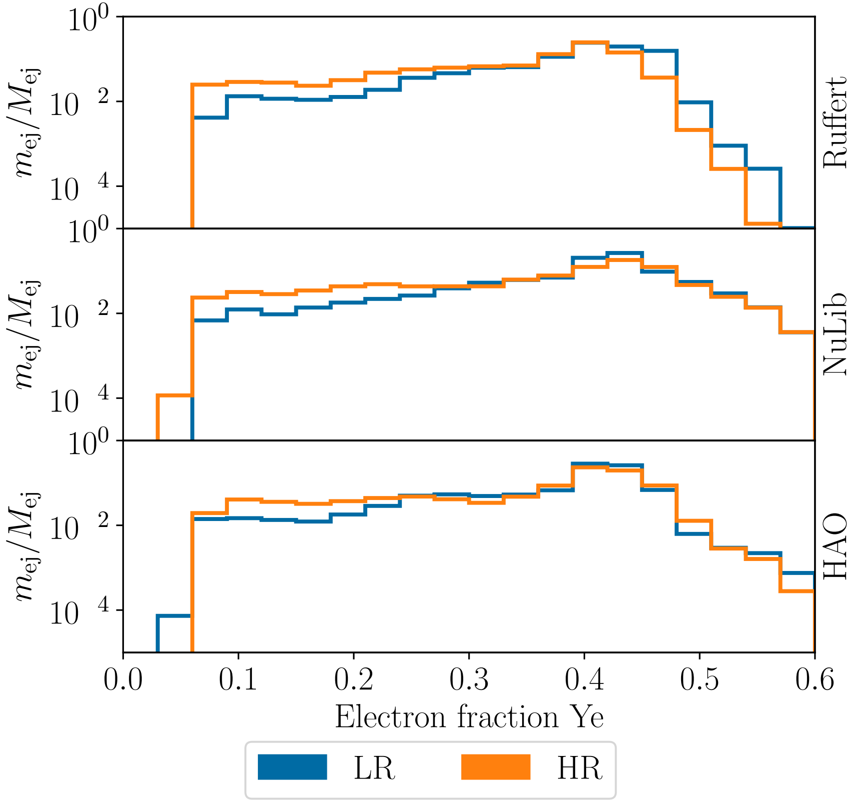
Opacities comparison – Disk

$T\,[\mathrm{MeV}]$	2.55
$\rho\,[\mathrm{g\ cm^{-3}}]$	$8.87 \cdot 10^{11}$
Y_e	0.20
$\hat{\mu}$	13.46
μ_e	28.24
$U_n\,[\mathrm{MeV}]$	0.38
$U_p\,[\mathrm{MeV}]$	0.08
$m_n^*\,[\mathrm{MeV}]$	939.0
$m_p^*\,[\mathrm{MeV}]$	937.7



Ejecta resolution comparison





Numbers

		Ruffert		NuLib		HAO	
		LR	HR	LR	HR	LR	HR
M_{rem}	$[\mathrm{M}_\odot]$	2.448	2.449	2.392	2.370	2.418	2.424
M_{disc}	$[10^{-1}\,\mathrm{M}_\odot]$	1.529	1.528	2.101	2.315	1.832	1.780
M_{ej}	$[10^{-3}\,\mathrm{M}_\odot]$	2.765	2.275	2.224	2.014	2.355	2.059

Disk properties