Neutrino reaction rates in BNS mergers

BNS_NURATES: AN OPEN-SOURCE PERFORMANT LIBRARY

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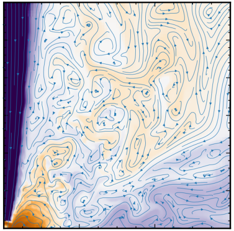
A. Perego, D. Radice

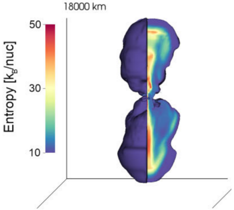
Phys. Rev. D 111, 063053 (2025)

sirEN Conference - Giulianova - 11/06/2025

R-PROCESS SITES AND ROLE OF NEUTRINOS

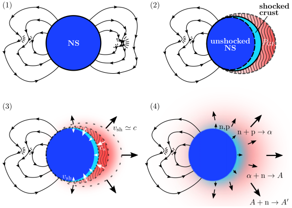


Accretion-induced collapse of WD *[Cheong et al., 2025]*



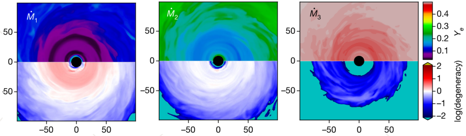
Magneto-rotational CCSNe

[Reichert et al., 2022]

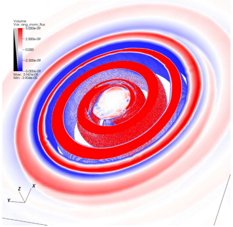


Magnetar Giant Flares

[Cehula et al., 2024]



Collapsars *[Siegel et al., 2019]*



BNS mergers

[Nedora et al., 2019]

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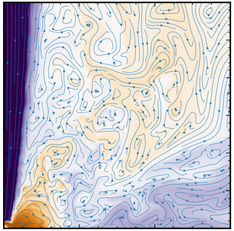

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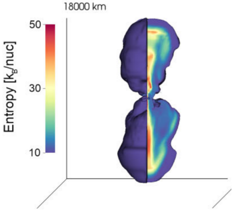

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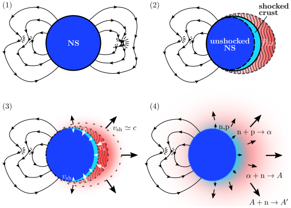

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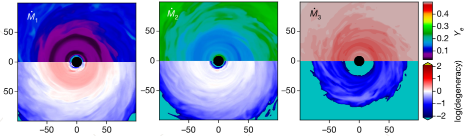
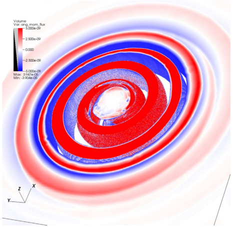


Collapsars *[Siegel et al., 2019]*

$$\frac{\partial f}{\partial t} + \frac{\mathbf{p}}{m} \cdot \nabla f + \mathbf{F} \cdot \frac{\partial f}{\partial \mathbf{p}} = \left(\frac{\partial f}{\partial t} \right)_{\text{coll}}$$



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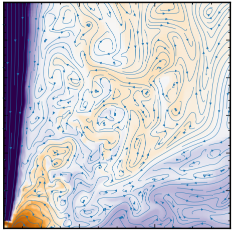

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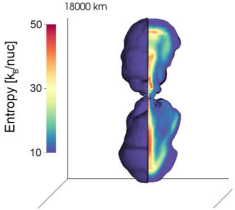

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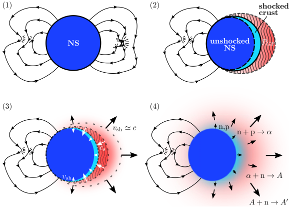

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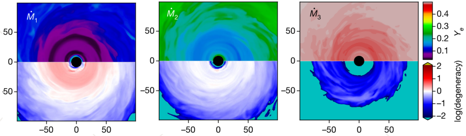

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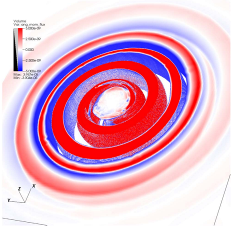

BNS mergers

[Nedora et al., 2019]

The bns_nurates library

Monopole term of energy-dependent kernels

β processes *[Bruenn, 1985]*

$p + e^- \leftrightarrow n + \nu_e$

$n + e^+ \leftrightarrow p + \bar{\nu}_e$

- weak-magnetism *[Horowitz, 2002]*
- in-medium effects *[Oertel et al., 2020]*
- (inverse) nucleon decay

Electron/positron annihilation

[Pons et al., 1998]

$e^- + e^+ \leftrightarrow \nu + \bar{\nu}$

Nucleon-nucleon Bremsstrahlung

[Hannestad and Raffelt, 1998]

$N + N \leftrightarrow N + N + \nu + \bar{nu}$

- in-medium effects *[Fischer, 2016]*

Elastic scattering on nucleons *[Bruenn, 1985]*

$N + \nu \leftrightarrow N + \nu$

- weak-magnetism *[Horowitz, 2002]*

Inelastic scattering on (anti-)electrons

[Mezzacappa and Bruenn, 1993]

$e^\pm + \nu \leftrightarrow e^\pm + \nu$

Gray emissivities/opactites

Integration of kernels with a highly tuned 1- and 2-dimensional custom Gauss-Legendre quadrature rule on a **generic neutrino distribution function**.

Reconstruction of neutrino distribution

$$f(\omega) = w_{\text{thick}} f_{\text{thick}}(\omega; a, b) + w_{\text{thin}} f_{\text{thin}}(\omega; c, d)$$

with parameters adn weights retrieved from neutrino number/energy densities and Eddington factors.

The bns_nurates library

Monopole term of energy-dependent kernels

β processes *[Bruenn, 1985]* $p + e^- \leftrightarrow n + \nu_e$ $n + e^+ \leftrightarrow p + \bar{\nu}_e$ ▶ weak-magnetism *[Horowitz, 2002]* ▶ in-medium effects *[Oertel et al., 2020]* ▶ (inverse) nucleon decay	*Electron/positron annihilation* *[Pons et al., 1998]* $e^- + e^+ \leftrightarrow \nu + \bar{\nu}$	*Nucleon-nucleon Bremsstrahlung* *[Hannestad and Raffelt, 1998]* $N + N \leftrightarrow N + N + \nu + \bar{nu}$ ▶ in-medium effects *[Fischer, 2016]*	*Elastic scattering on nucleons* *[Bruenn, 1985]* $N + \nu \leftrightarrow N + \nu$ ▶ weak-magnetism *[Horowitz, 2002]*	*Inelastic scattering on (anti-)electrons* *[Mezzacappa and Bruenn, 1993]* $e^\pm + \nu \leftrightarrow e^\pm + \nu$

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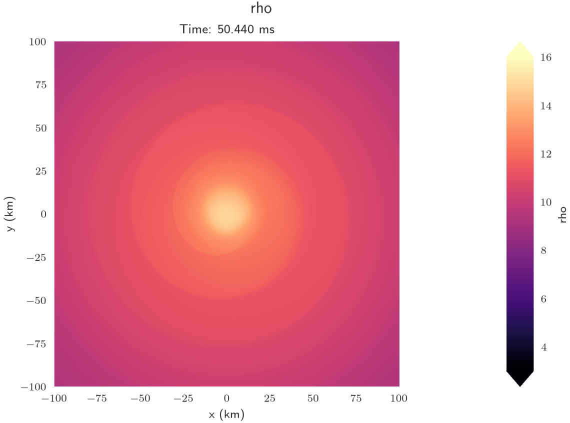
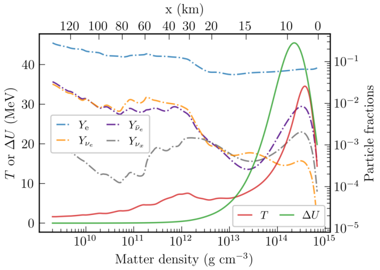
Reference simulation

Equal-mass, $M_{\rm NS}$=1.298 $M_\odot$, DD2 EOS



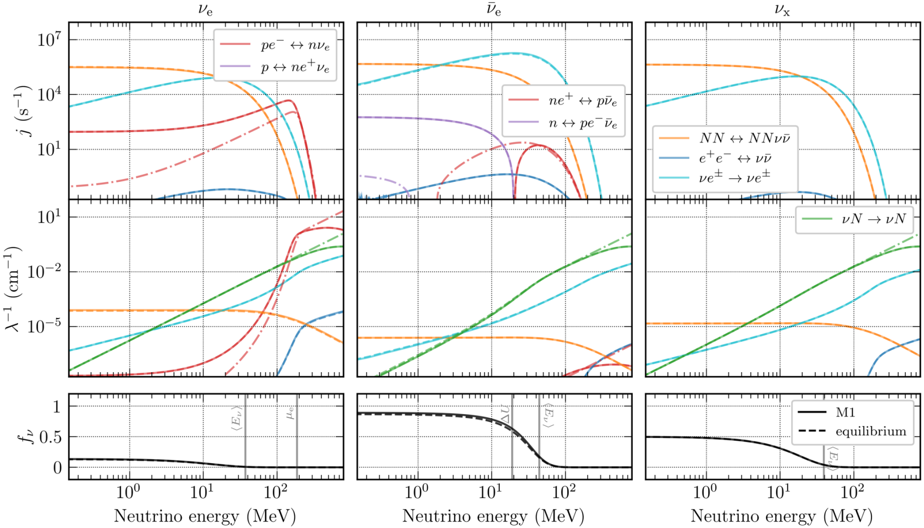
Rest-mass density on xy plane



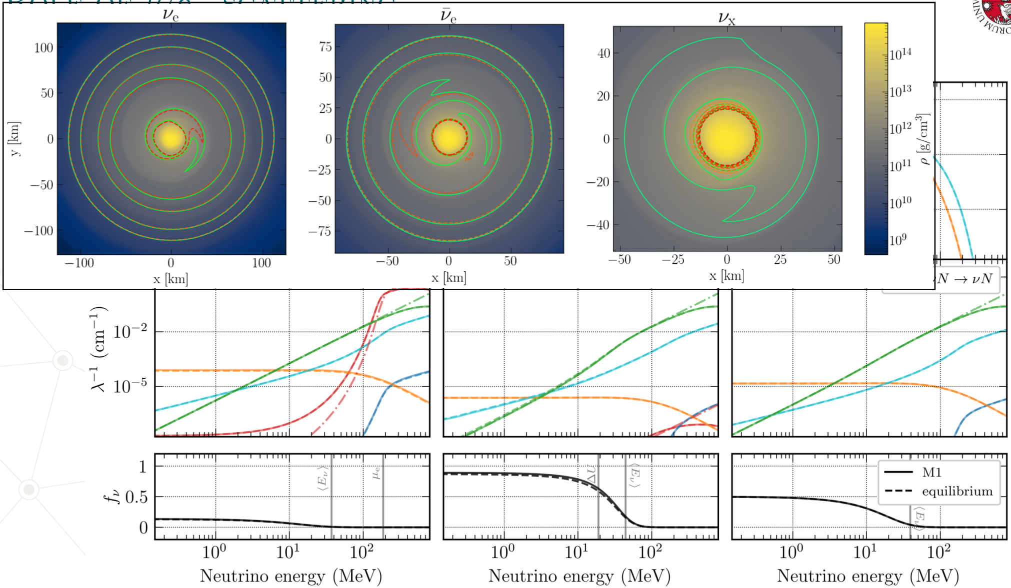
Thermodynamics conditions on x axis

#	ρ (g/cm^3)	T (MeV)	Y_e
A	$6.90 \cdot 10^{14}$	12.39	0.07
B	$9.81 \cdot 10^{13}$	16.63	0.06
F	$1.01 \cdot 10^{10}$	2.17	0.19

Role of ν/e^- scattering



Spectral emissisvity, inverse mean free path and distribution function for point A.



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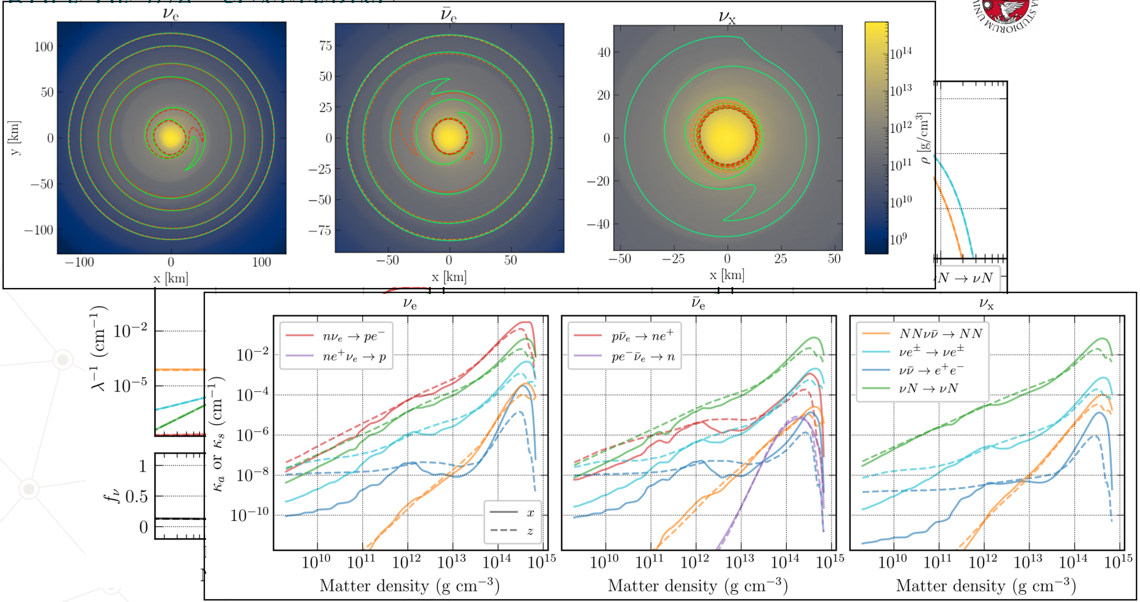
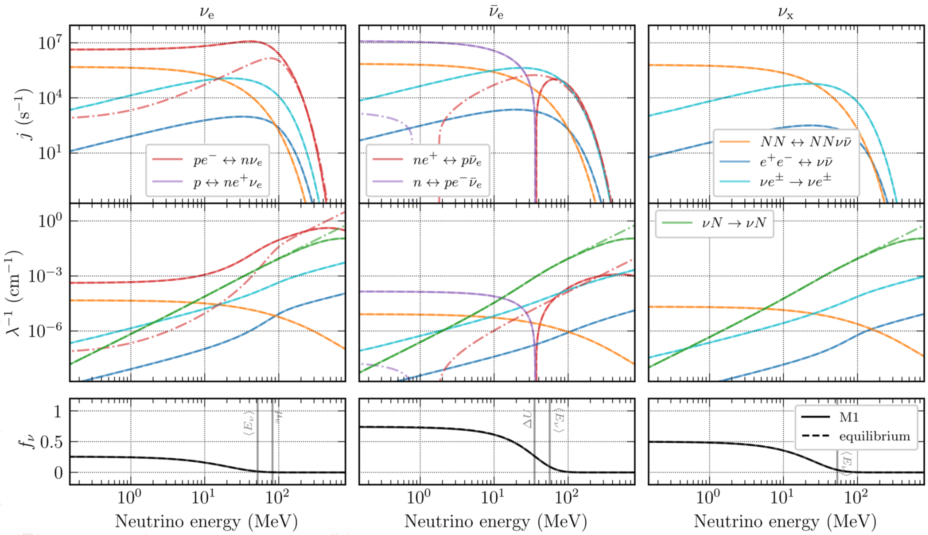


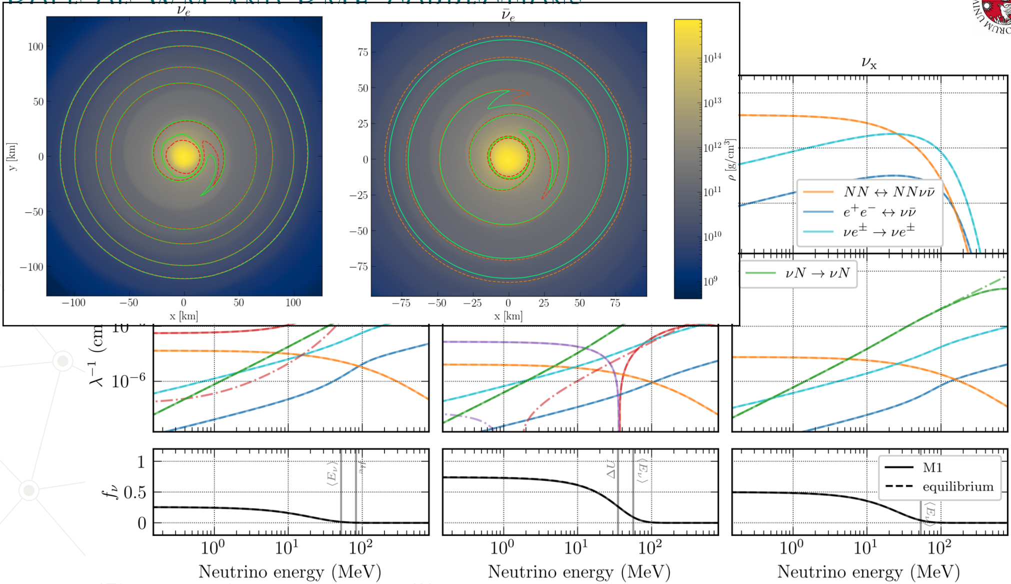
Spectral emissisvity, inverse mean free path and distribution function for point A.

Role of WM and RMF corrections



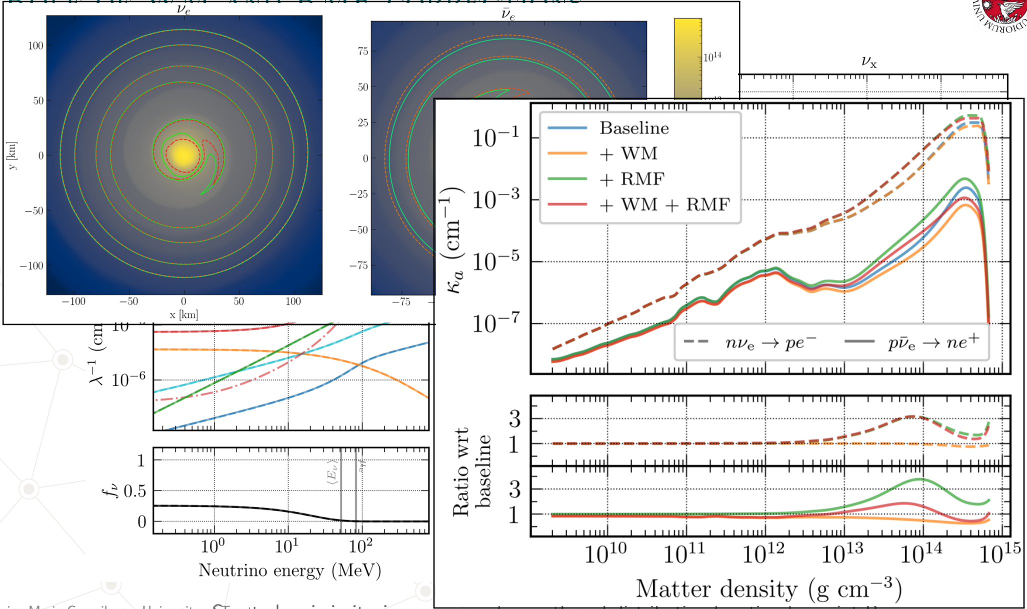
Spectral emissisvity, inverse mean free path and distribution function for point B.

Role of WM and RMF corrections



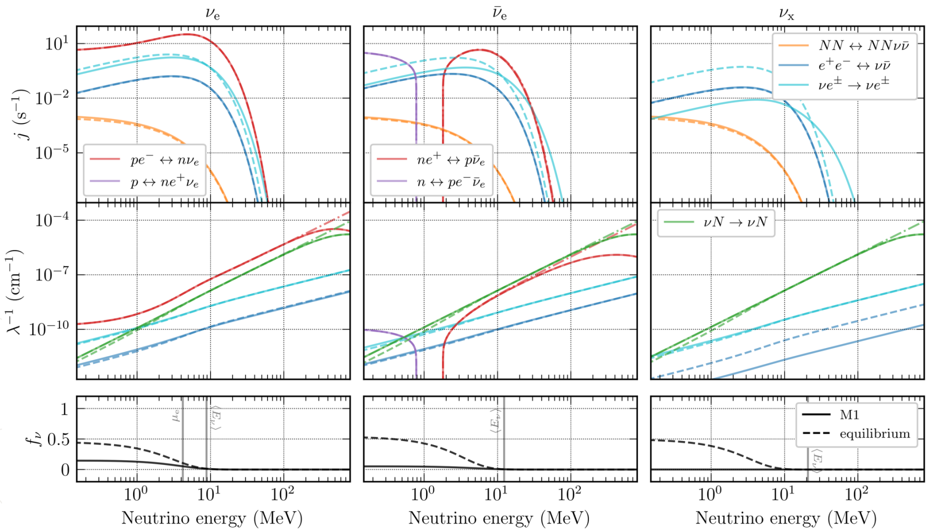
Spectral emissisvity, inverse mean free path and distribution function for point B.

Role of WM and RMF corrections



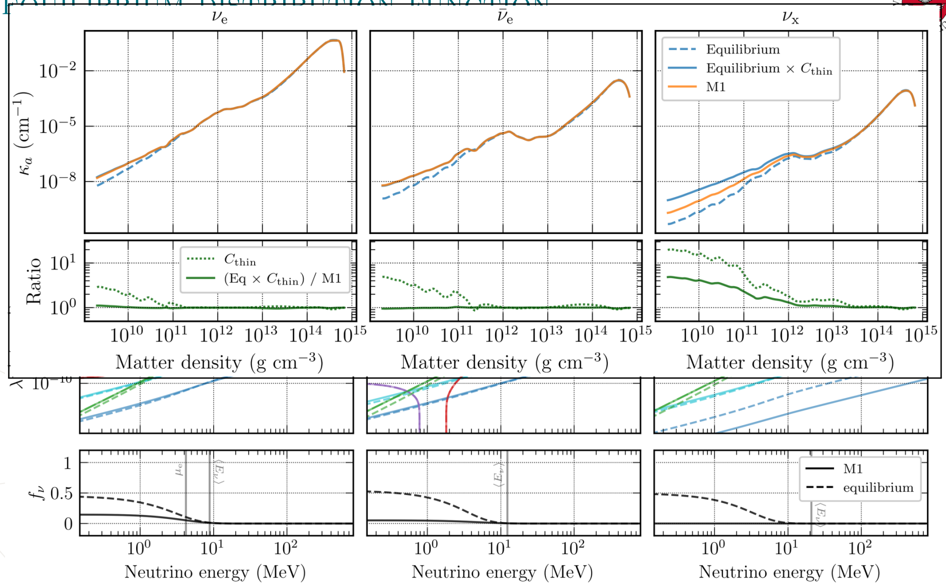
Spectral emissivity, inverse mean free path and distribution function for point B.

Non-equilibrium distribution function



Spectral emissisvity, inverse mean free path and distribution function for point F.

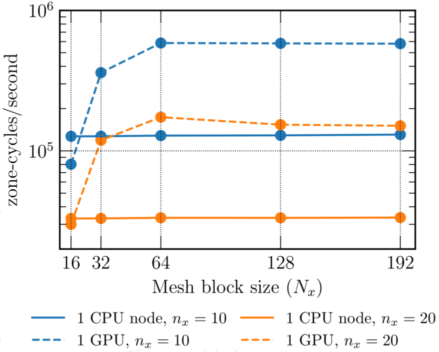
Non-equilibrium distribution function



Spectral emissivity, inverse mean free path and distribution function for point F.

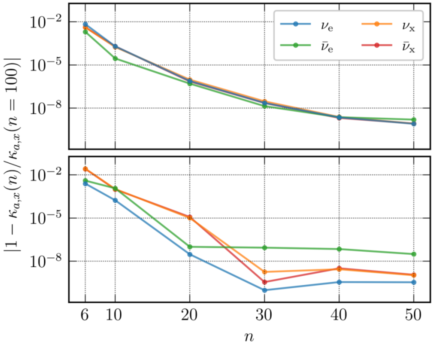
Numerical/computational considerations

Performance



Computation speed vs. grid size

Accuracy

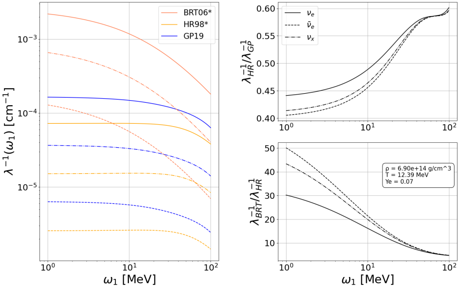


Accuracy vs. number of integration nodes.

Integration efforts into BNS evolution codes (`WhiskyTHC`, `GR-Athena++`, `AthenaK`) is ongoing and almost complete.

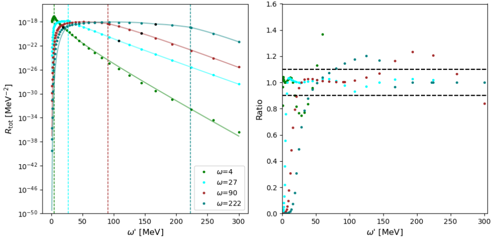
Ongoing developments

Better nucleon-nucleon Bremsstrahlung via the T-matrix formalism *[Guo and Martínez-Pinedo, 2019]*



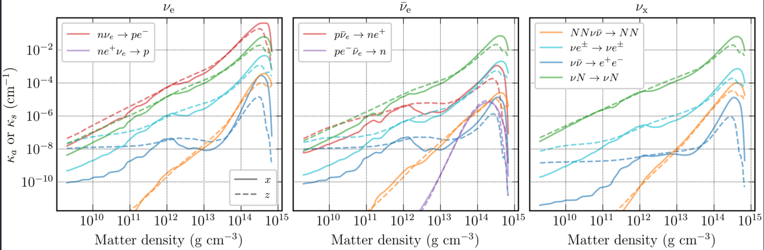
NN Bremsstrahlung opacity at point A (courtesy of Stefano Caldini).

Extension to scattering on *massive* leptons (muons)



μ/ν scattering kernel at $T = 11$ MeV and $\mu_\mu = 157$ MeV as function of outgoing neutrino energy (courtesy of Raffaele Ferrari).

Conclusions



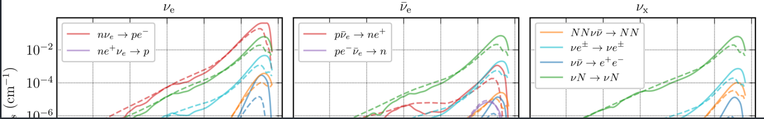
Gray opacities on BNS profiles

Reliable modelling of neutrino dynamics in BNS mergers requires a realistic yet performing treatment of their reactions. BNS_NURATES offers:

- Representative and growing set of ν reactions
- State of the art correction terms
- Reconstruction of the ν distribution
- Clean, well tested and preforming implementation

First simulations exploiting it are coming soon, so ...

Conclusions



References

L. Chiesa, M. Bhattacharyya, F. Mazzini, F. M. Guercilena, A. Perego, D. Radice, Phys. Rev. D 111, 063053 (March 2025)

`https://github.com/RelNucAs/bns_nurates`

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References

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