Spritz: general relativistic magnetohydrodynamics with neutrinos

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in collaboration with

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and

TCAN[+] collaboration

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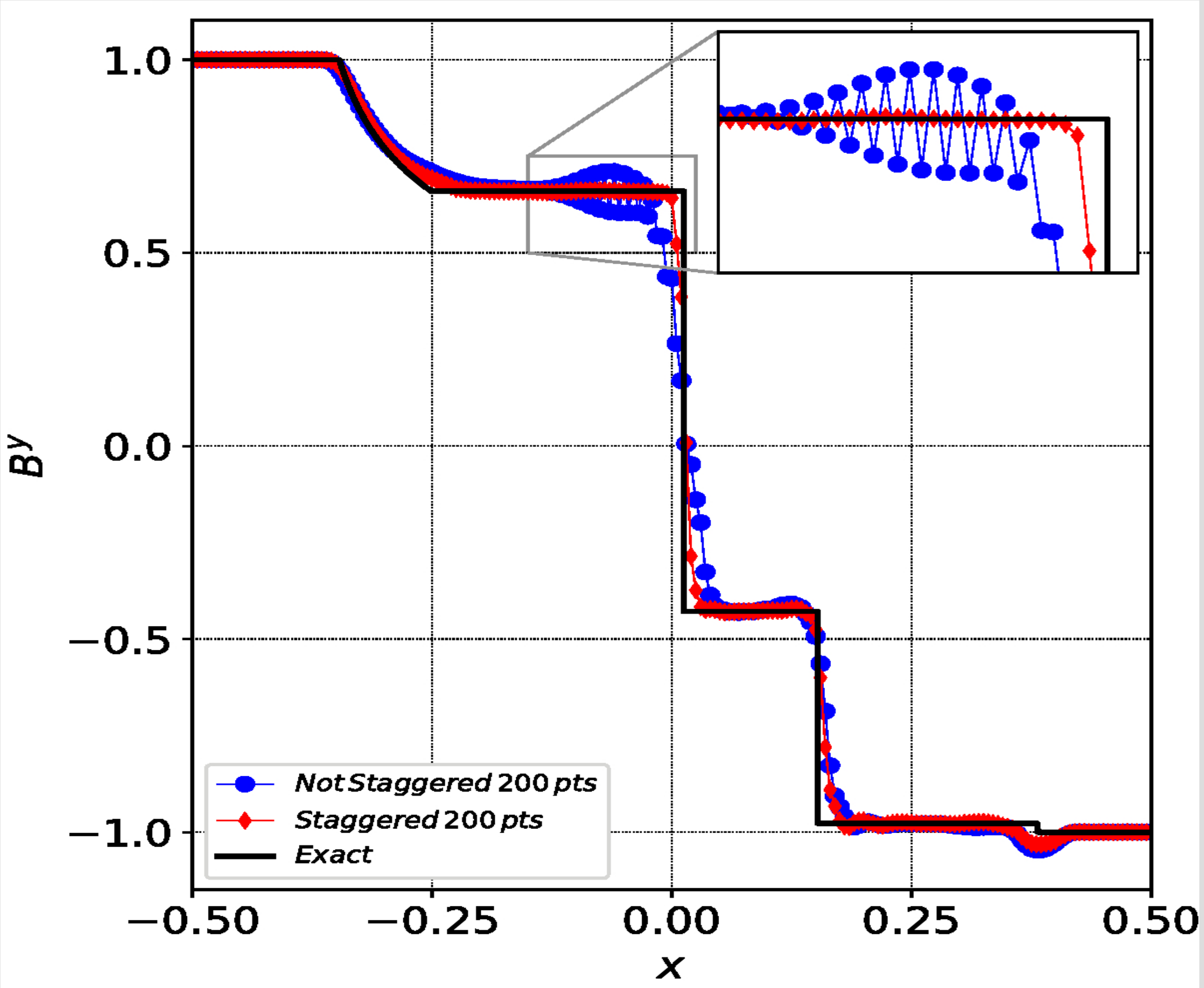
1st milestone in new GRMHD + neutrinos code development

Cipolletta et al (2020), Classical and Quantum Gravity 37.13 (2020): 135010

- **STAGGERED Avec:** Accurate evolution of magnetic field
- **Reconstruction orders:** minmod, PPM, WENO-z *Cipolletta et al (2021), under review*
- **EOS_Omni thorn:** Allows implementation of “general” EOS
- **Extensive testing:** 1D, 2D, 3D
- **2nd- order convergence**

- BALASARA 1 ShockTube
- PPM + HLLE
- Postshock oscillations avoided



Tabulated EOSs and neutrino leakage

Cipolletta et al (2021), under review

- Tabulated EOS: *https://compose.obspm.fr/home/* $\longrightarrow \quad P = P\left(\rho, T, Y_e\right)$
- Need to select EOS's "slices" for ID: const. T or S slices
- Code for producing and reading ID: Lorene - *https://lorene.obspm.fr/*
- Code for setting Beta equilibrium
- C2P which support "evolving" T and S: PalenzuelaID – *Siegel et al, ApJ (2018)*
- Code for neutrino leakage: ZelmaniLeak - *Ott et al, PRD (2012)*

ZelmaniLeak - Neutrino Leakage

1. *Dominant processes:* *Electron Capture, Positron Capture, Pair Annihilation, Plasmon Decay*

2. *Optical Depth:* **Isotropic Neutrino Radiation** $\rightarrow \tau(\mathbf{x})$

3. *Neutrino Energy Balance*

   3.1. *Diffusive Regime (Absorption) -* $\rho > \mathbf{10^{12} g\, cm^{-3}}$ *- Sources of opacity*

   3.2. *Free-streaming Regime (Emission) -* $\rho < \mathbf{10^{12} g\, cm^{-3}}$ *- 1.* ***+ bremss.***

   $\Rightarrow Q^{\mathrm{ef}}_{\nu_i}, R^{\mathrm{ef}}_{\nu_i} \Rightarrow L_{\nu_i}$

   3.3. *Neutrino Re-absorption – Heating:* $Q^{\mathrm{heat}}_{\{\nu_e,\bar{\nu}_e\}}$ *that modifies* $Q^{\mathrm{ef}}_{\nu_i}, R^{\mathrm{ef}}_{\nu_i}$

4. *Neutrino Pressure Handling:* $\rho > 10^{12} \frac{\mathrm{g}}{\mathrm{cm}^3} \Rightarrow P_\nu$ added to $T^{\alpha\beta}$ source terms

5. *Ray-by-ray approach:* $(x, y, z) \rightarrow (r, \theta, \phi) \rightarrow (x, y, z)$

6. *Operator-split:* Y_e and ϵ should be updated at each time-step via P2C

TOV Tests

ID	GRMHD	symmmetry	Beta-equilibrium	T-Evolution	Max B-Field	Neutrino-Leakage
00	Spritz	*Octant*	T-slice	X	-	*Disabled*
01	Spritz	Full 3D	S-slice	V	-	*Disabled*
02	GRHydro	*Octant*	S-slice	V	-	*Disabled*
03	Spritz	*Octant*	S-slice	V	-	*Disabled*
04	Spritz	Full 3D	S-slice	V	-	*Enabled*
05	GRHydro	*Octant*	S-slice	V	-	*Enabled*
06	Spritz	*Octant*	S-slice	V	-	*Enabled*
07	GRHydro	*Octant*	T-slice	V	-	*Disabled*
08	Spritz	*Octant*	T-slice	V	-	*Disabled*
09	Spritz	*Octant*	T-slice	V after 2 ms	-	*Disabled*
10	GRHydro	*Octant*	T-slice	V	-	*Enabled*
11	Spritz	*Octant*	T-slice	V	-	*Enabled*
12	Spritz	*Octant*	T-slice	V after 2 ms	-	*Enabled* after t = 3 ms
13	Spritz	Full 3D	S-slice	V	10^{16} G	*Disabled*
14	Spritz	Full 3D	S-slice	V	10^{16} G	*Enabled*
15	Spritz	Full 3D	T-slice	V	10^{16} G	*Disabled*
16	Spritz	Full 3D	T-slice	V	10^{16} G	*Enabled* after t = 3 ms

Cipolletta et al (2021), under review

RESULTS

- LS220 EOS
- 5 refinement levels
- $dx_{min} = 0.12 \rightarrow$ 60 pts per r_{NS}
  resolution of 180m for NS interior
- Constant S or T initial slice
- Consider or not the heating

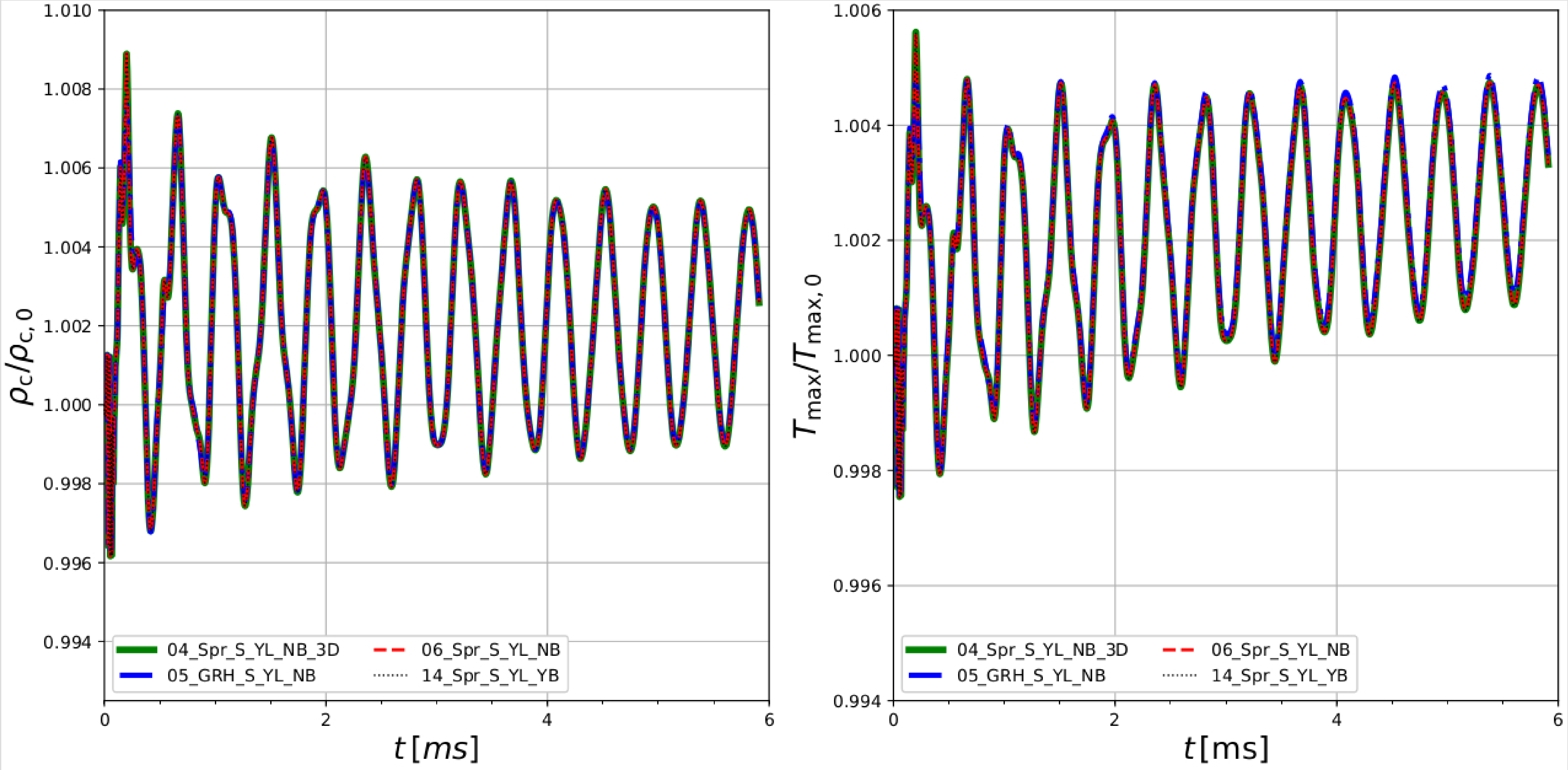
Maximum Rest mass Density

Maximum Temperature

Maximum norm of B

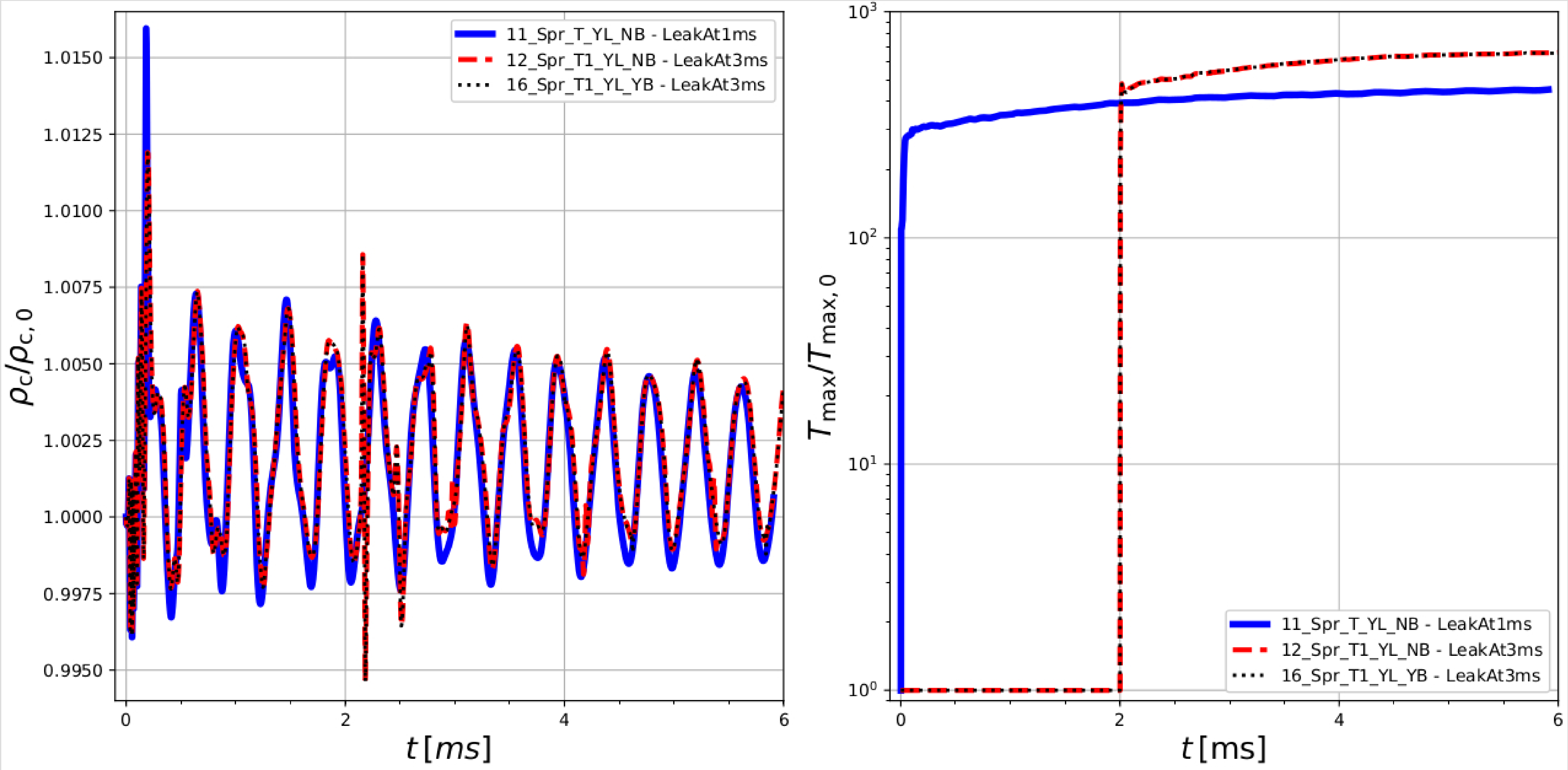
Luminosity of neutrinos

RESULTS – const S id with leakage



Maximum of T at NS center

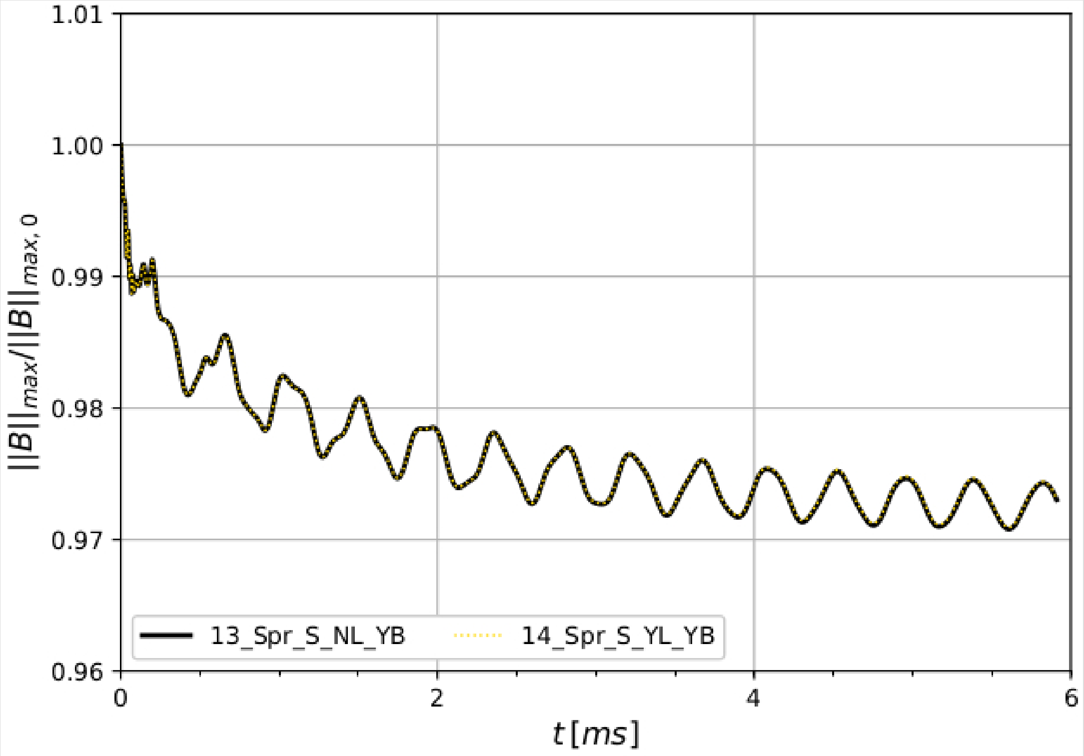
RESULTS – const T id with leakage



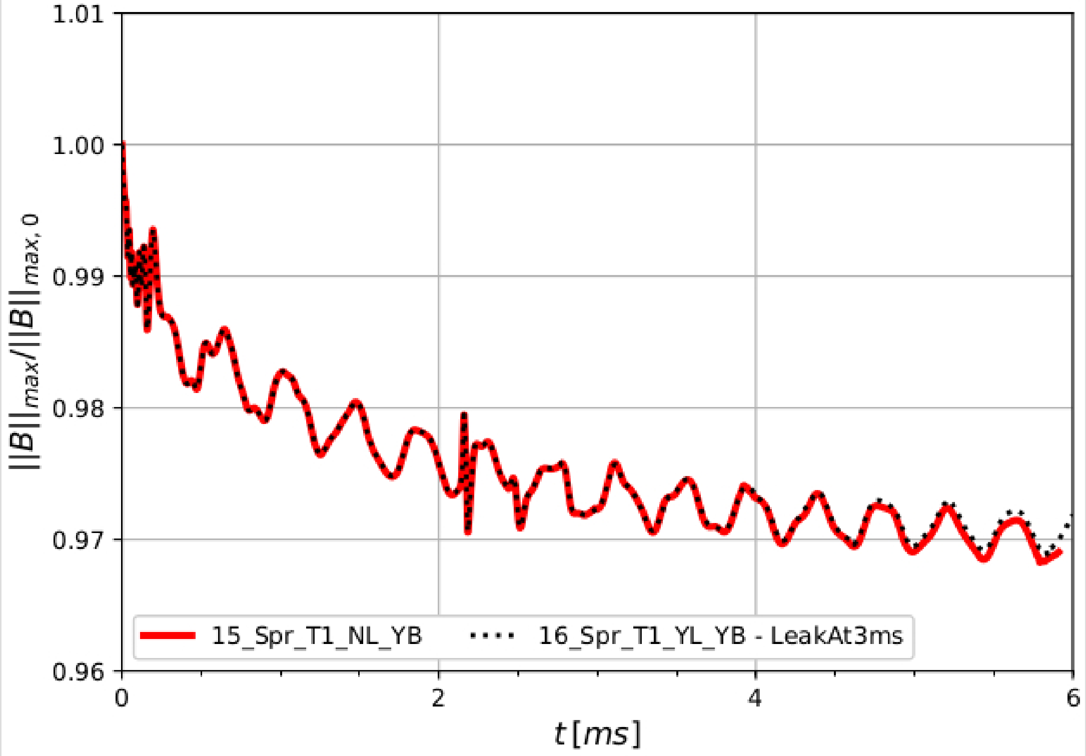
Maximum of T at NS surface (!!!)

RESULTS – B norm max

Const S id



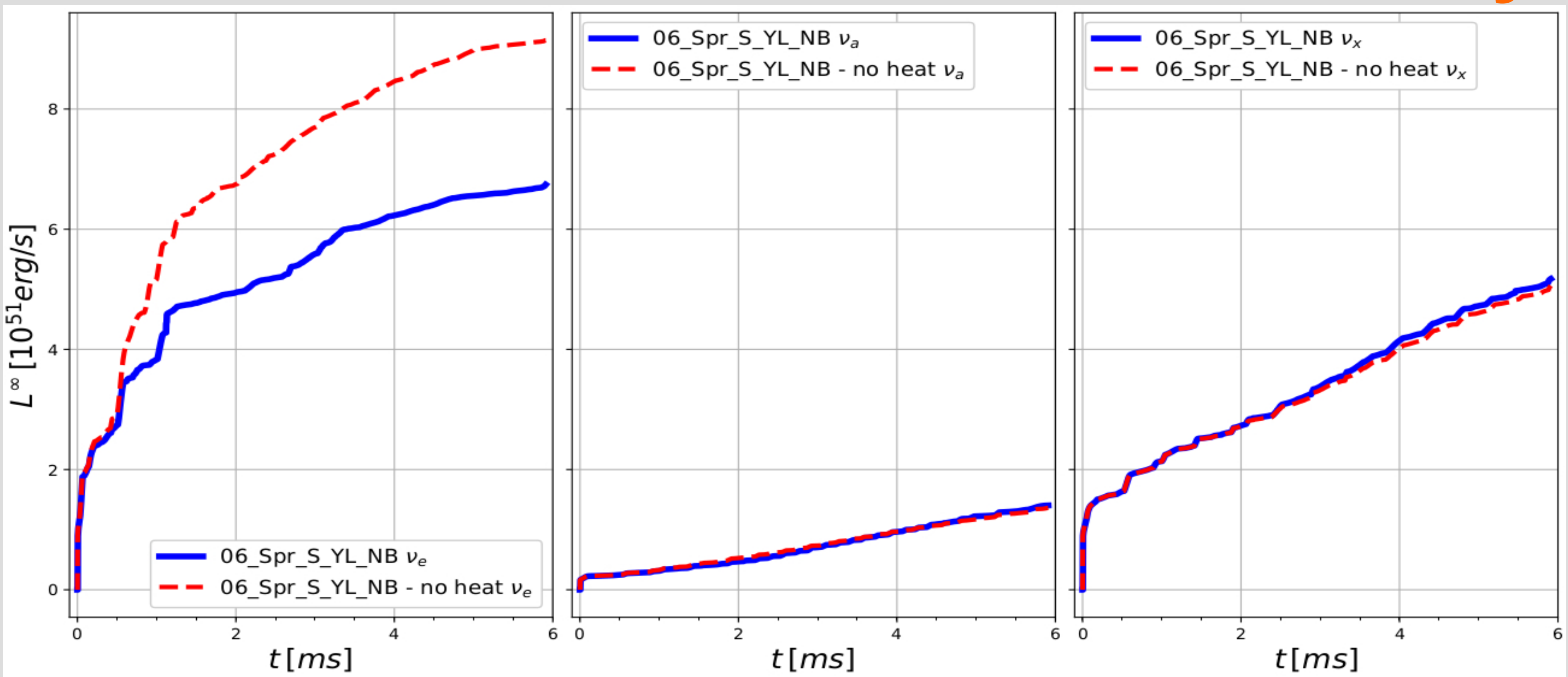
Const T id



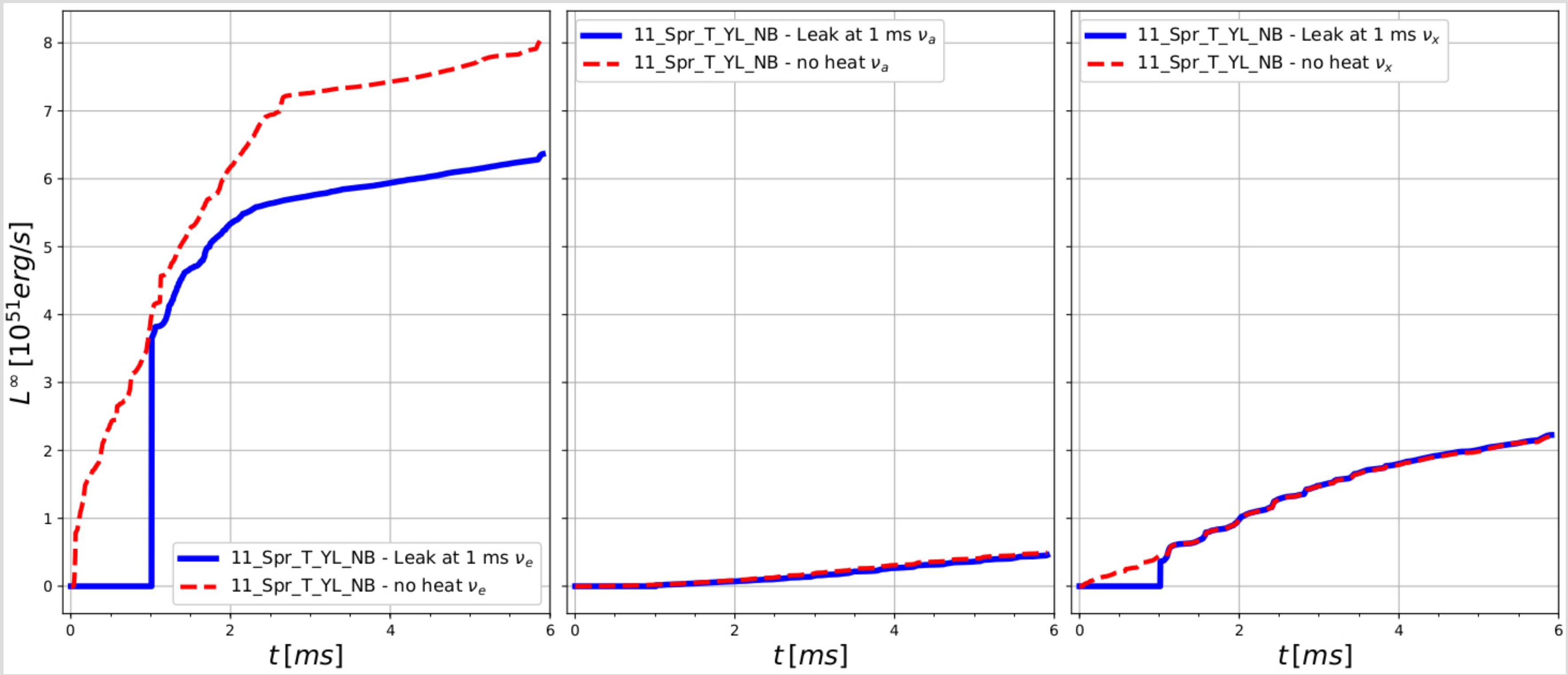
Lekage activation does not alter the maximum B-field evolution

RESULTS – neutrino Luminosity

Const S id



Const T id



Heating may considerably affect the neutrino luminosity observed

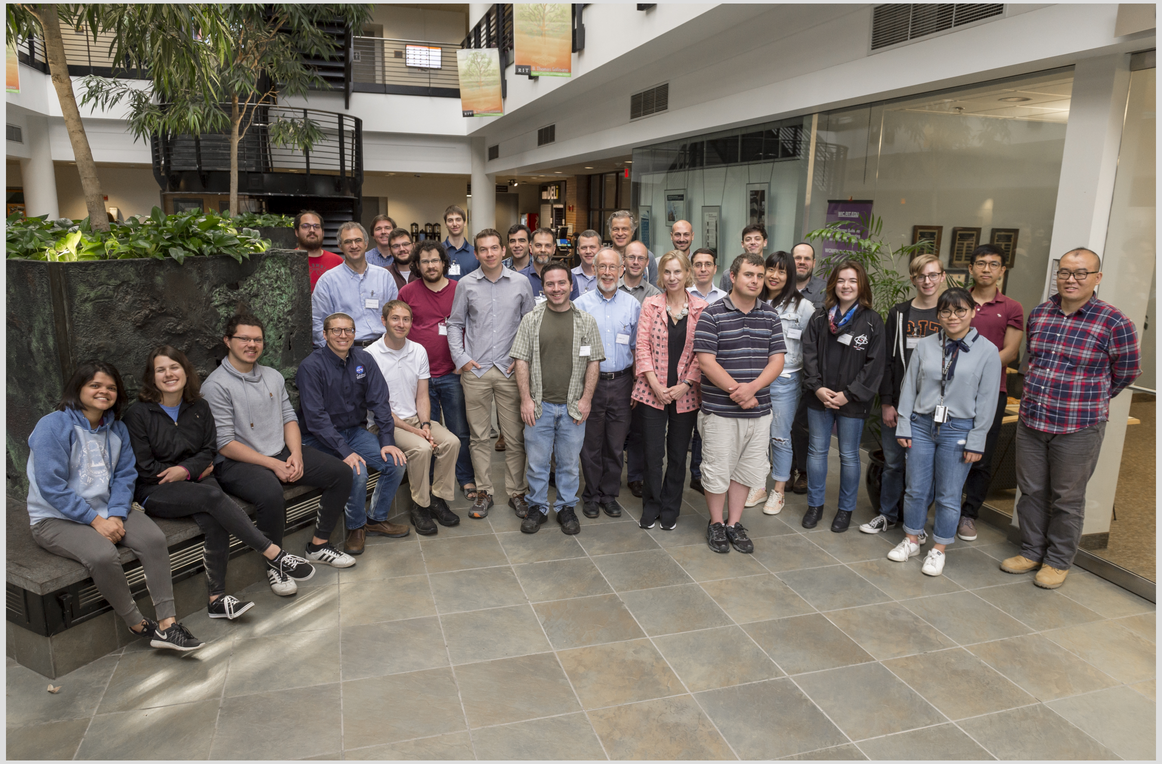
Heating effects need to be handled with care

Sprtiz code in the TCAN collaboration

Theory and Computational Network on Neutron Star Mergers

Advancing Computational Methods to Understand the Dynamics of Ejections, Accretion, Winds and Jets in Neutron Star Mergers

TCAN

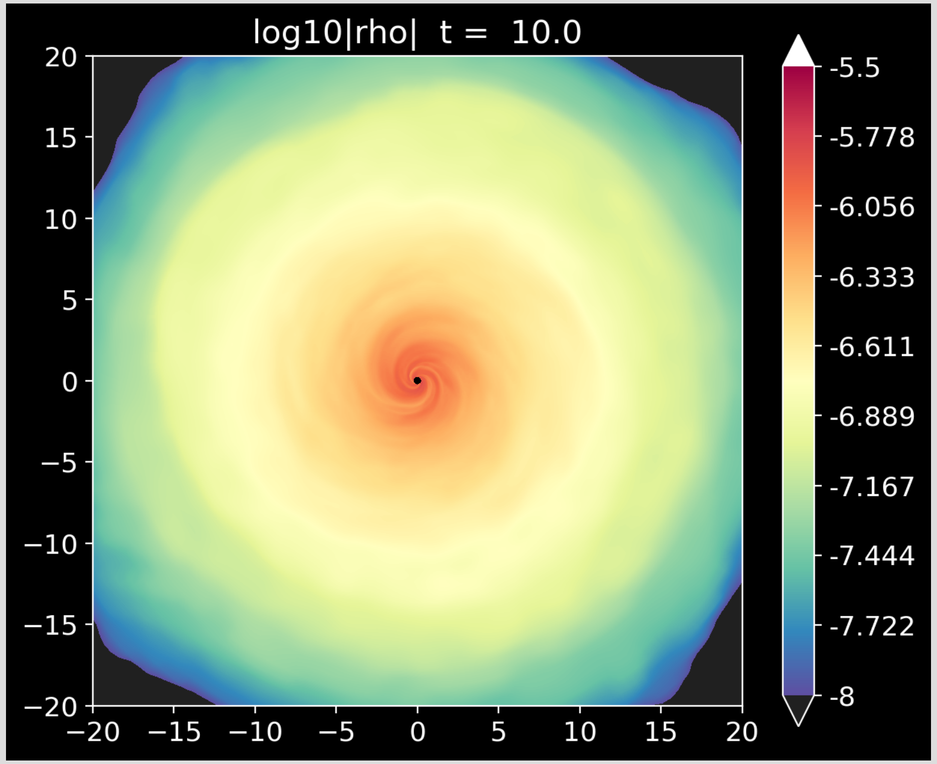


Goal: <u>long-term BNS simulations with:</u>

- Dynamical GR-MHD
- Nuclear and Neutrino Physics, EOS
- Neutrino/photon transport
- R-processes/nucleosynthesis

Take advantage of the strength of each code:

- absence of symmetry → *CARTESIAN* coordinates
- axial symmetry → *SPHERICAL* coordinates



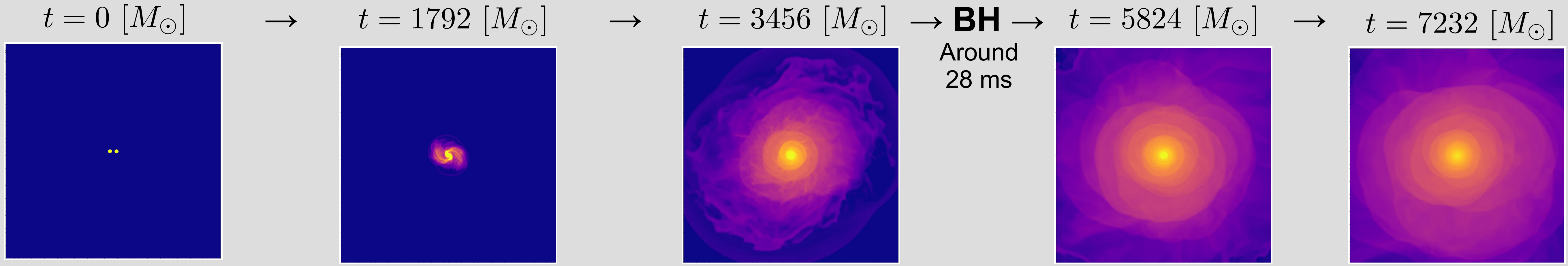
Work in progress:
<u>Armengol-Lopez et al.</u>

Hand-off from BNS simulation in Cartesian coordinates (**IGM**) to postmerger simulations in spherical coords (**HARM3D**)

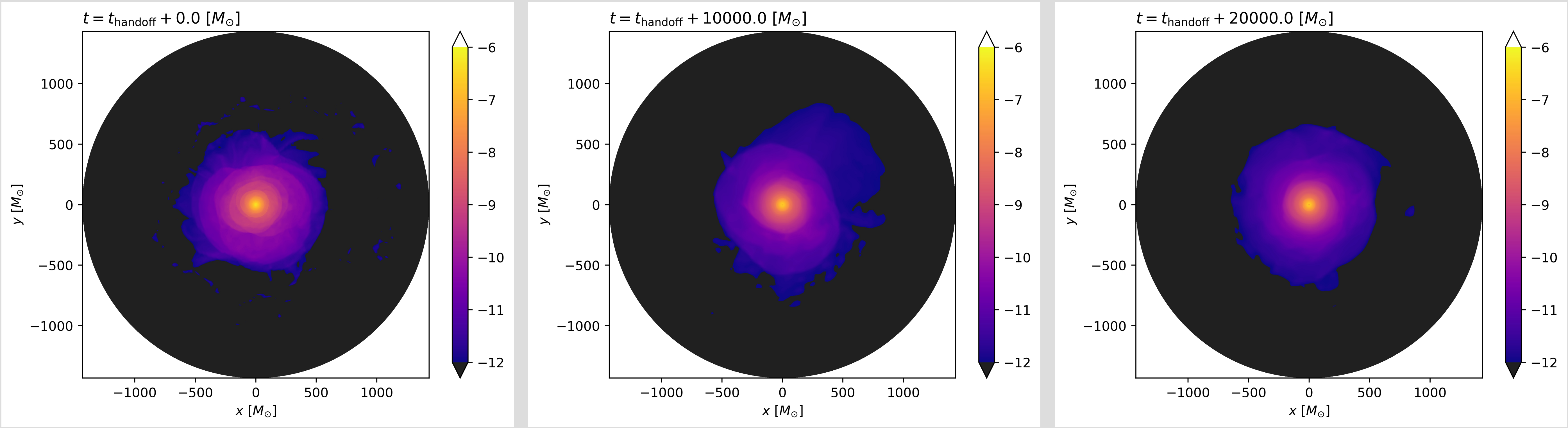
Visit *compact-binaries.org*

PURE HYDRO BNS MERGER (the "Missing Link") + HANDOFF

SPRITZ



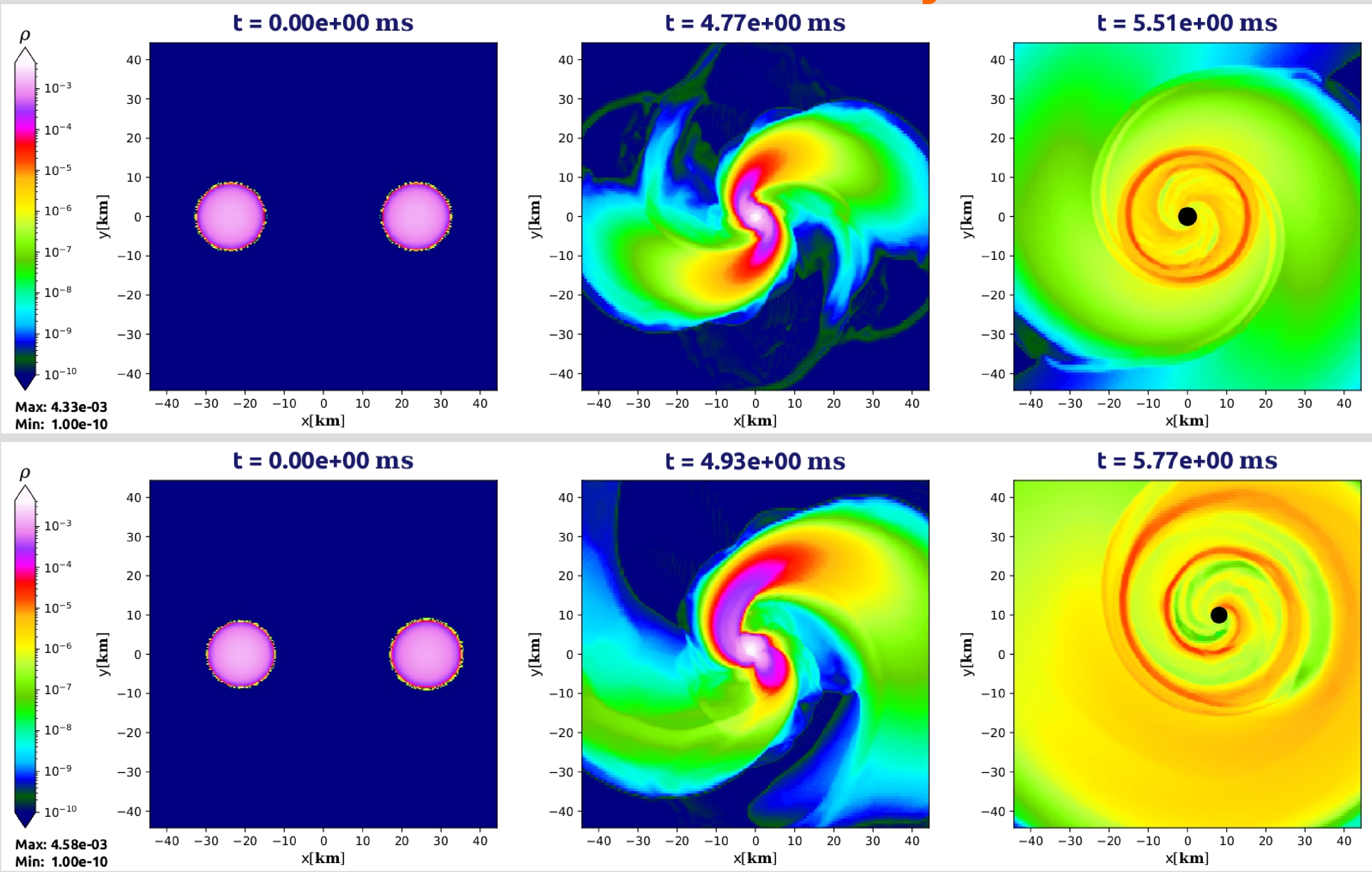
HARM3D



Images for HARM3D: credits to **Federico G. L. Armengol @RIT**

PRELIMINARY TESTS FOR BNS WITH SLy4 EOS

- SLy4 EOS
- 6 refinement levels
- dx_{min} = 0.24 ~ 354 m
- Cold initial data



Images: courtesy of **Lorenzo Ennoggi @UniMIB**