The long-time evolution of the Accretion-Induced Collapse of White Dwarfs to Neutron Stars

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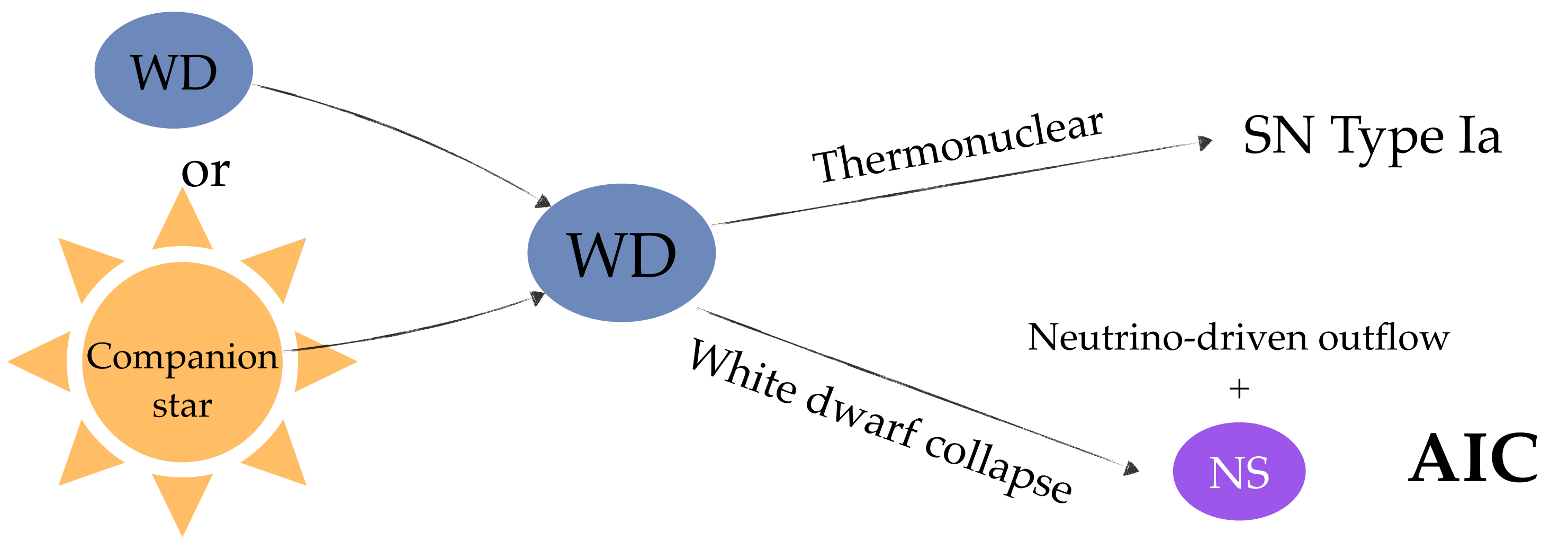
INTRODUCTION



- The Accretion-Induced Collapse (AIC) of white dwarfs (WDs) is an alternative scenario to neutron star (NS) formation apart from massive stellar collapse.
- Accretion of mass and angular momentum from a companion star or a WD-WD merger can push WDs to reach their Chandrashekar mass limit.
- Electron capture at sufficiently high densities in the interior of the Chandrasekhar-mass WD makes it gravitationally unstable and triggers the collapse of the WD to a NS in an AIC scenario.
- There is no confirmed observation of an AIC yet!
- To determine the nucleosynthetic output and the observational properties of such events, it is crucial to model the AIC from the onset of the WD collapse and follow the neutrino-driven outflow to the homologous expansion of the ejecta.
- ‣ *We simulate the long-time evolution of AICs from a representative set of progenitor systems with different masses and rotational profiles.*

METHODS

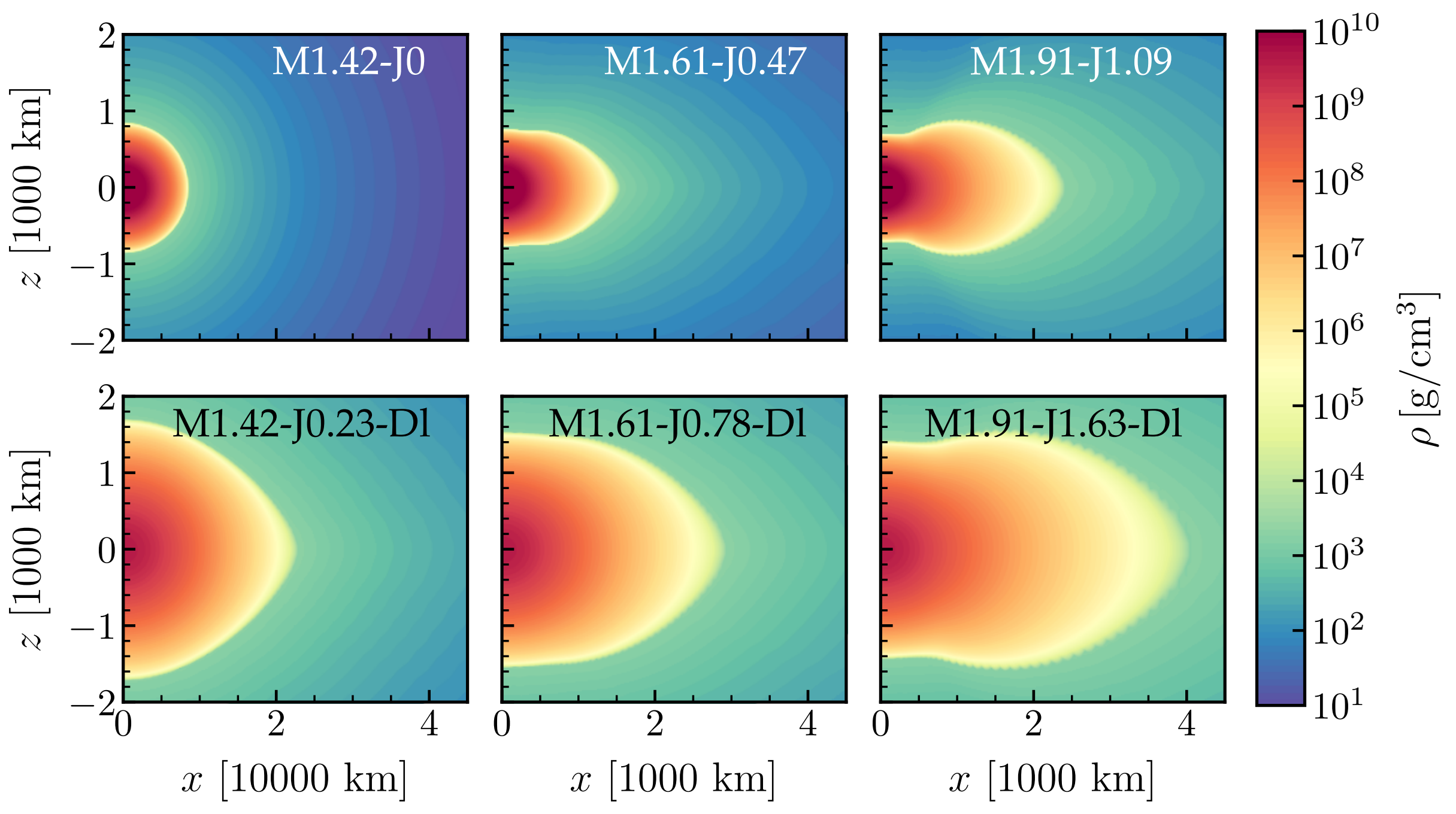


Figure 1: Color-coded density of each AIC progenitor in the xz plane. From left to right, the upper left model has a mass of 1.42 $M_\odot$, high central density, and no rotation, i.e. the model M1.42-J0, the bottom left one is the M1.42-J0.23-Dl with the same mass and slow rotation on the surface. The middle panels show the rotating progenitors with 1.61 $M_\odot$, i.e., M1.61-J0.47 (middle top) and M1.61-J0.78-Dl (middle bottom). The right panels show the rotating progenitors with 1.91 $M_\odot$, i.e., M1.91-J1.09 (right top) and M1.91-J1.63-Dl (right bottom). Mass and rotation increase towards the right panels. The models are embedded in a CSM with radially decreasing density and temperature profiles.

- We perform, for the first time, the long-time evolution of the AICs from the onset of the WD collapse and follow the ejecta for several seconds.
- We use the radiation-hydrodynamics code ALCAR [1].
- Our modeling employs fully multi-dimensional, multi-energy-group neutrino transport (by a two-moment treatment) with a state-of-the-art description of the neutrino interactions and a modern nuclear equation of state [2].
- Axisymmetric simulations for six AIC models with masses between 1.42-1.91 $M_\odot$ and different rotational profiles [3],[4].

RESULTS

Non-Rotating model

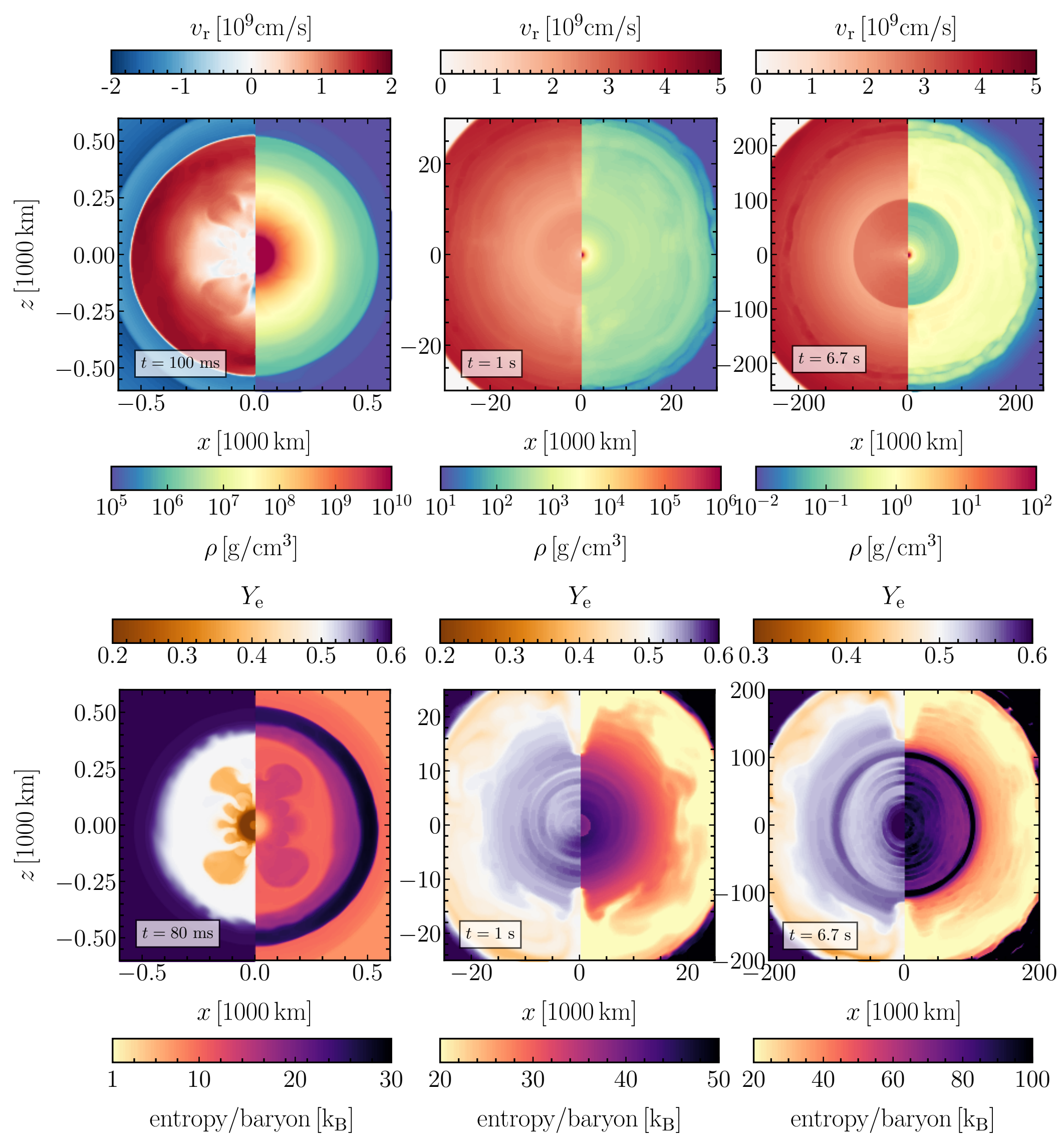


Figure 2: Series of color-coded cross-sections for different quantities at three different times of evolution for the non-rotating model **M1.42-J0**. The top row shows the radial velocity (left half panels) and the density in logarithmic scale (right half panels). The bottom row displays the electron fraction Y_e (left half panels) and entropy (right half panels).

Fast-Rotating model

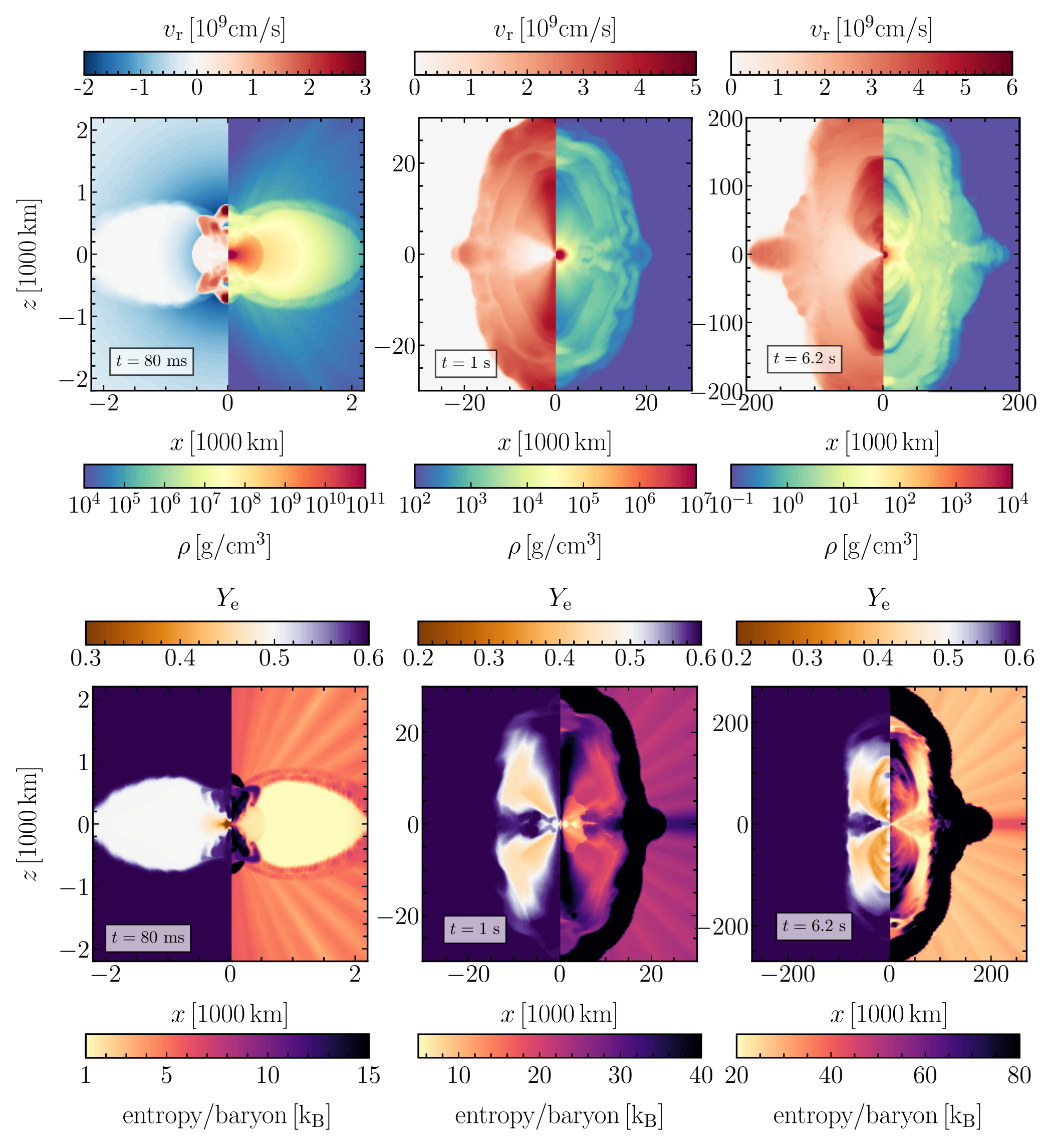


Figure 3: Series of color-coded cross-sections for different quantities at three different times of evolution for the fast-rotating model **M1.91-J1.09**. The top row shows the radial velocity (left half panels) and the density in logarithmic scale (right half panels). The bottom row displays the electron fraction Y_e (left half panels) and entropy (right half panels).

- The *non-rotating* AIC model shows a spherically symmetric neutrino-driven outflow.
- Initial mass ejecta are neutron-rich (orange regions) coming from electron captures.
- Later mass ejecta are proton-rich (purple regions) due to electron neutrino absorptions ($\nu_e + n \rightarrow p + e^-$).

- The outflow develops in the polar direction in all the *rotating models*.
- The initial angular momentum profile defines the shape of the outflow by constraining the mass that stays in a rotationally supported disk around the NS and the ejecta mass.
- Rapidly rotating neutron stars are formed in rotating pre-collapse models surrounded by a rotationally supported disk.

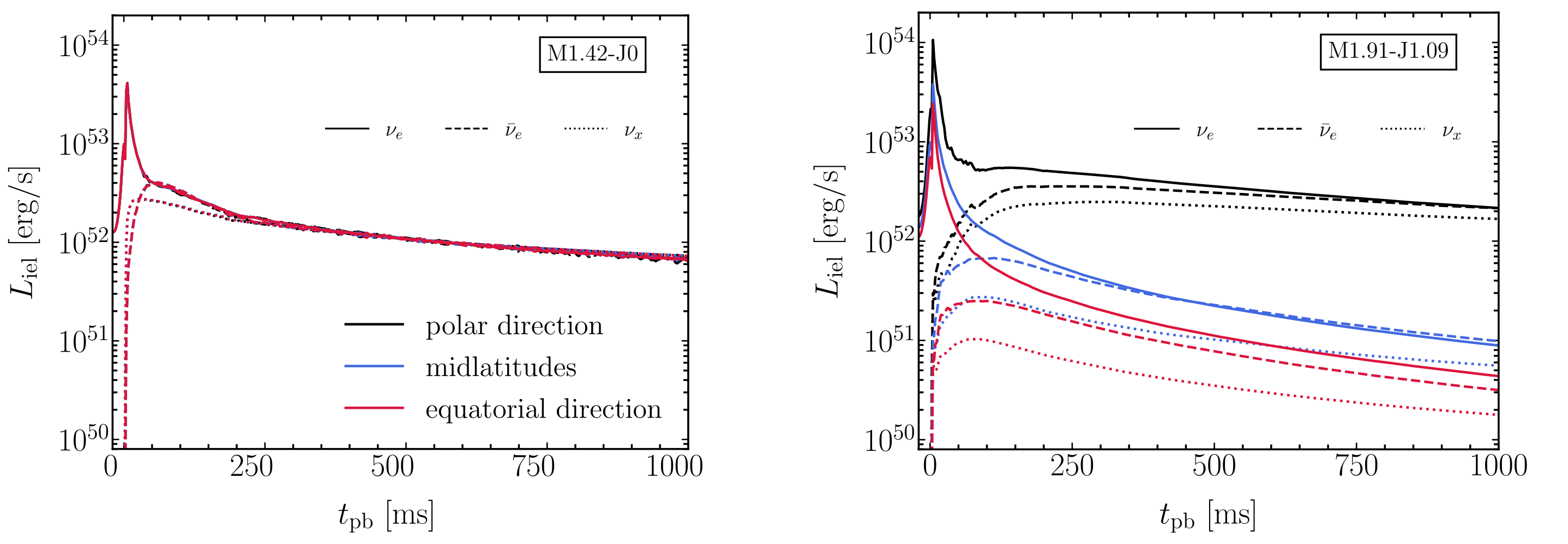


Figure 4: Luminosity as a function of post-bounce time along different directions for electron neutrinos (solid lines), electron antineutrinos (dashed lines), and heavy-lepton neutrinos (dotted lines). The black lines show the luminosity along the *poles*, the blue lines correspond to *mid-latitudes*, and the red lines show the luminosity in the *equatorial* direction. The luminosities are evaluated at a distance of 3500 km and transformed at the lab frame.

- In *the non-rotating* AIC model, the neutrino luminosities are spherically symmetric.
- In the *rotating models*, the neutrino luminosities show a large spread across the polar θ angle.
- Higher luminosity towards the poles.
- Ejecta properties vary along the polar angle as a result of the asymmetric neutrino luminosity (see bottom part of Fig. 3 and Fig. 4).

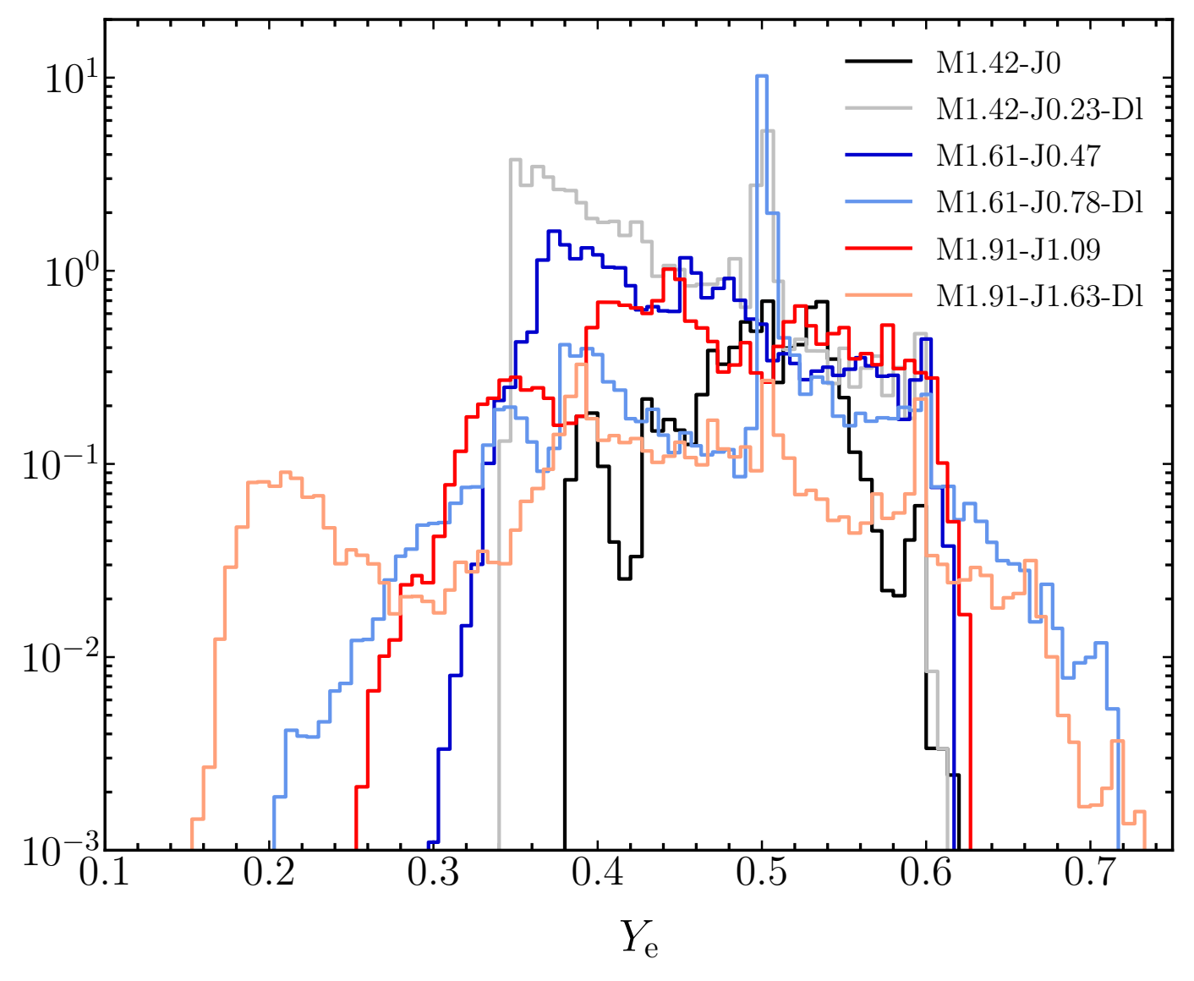


Figure 5: Ejecta mass as a function of the electron fraction.

- Ejecta masses ~ $10^{-2}\,M_\odot$.
- Material with low Y_e could produce r-process nuclei, but only in fast-rotating collapsing WDs.
- *Non-rotating model*: ejecta distribution similar to ECSN.
- *Rotating models*: early-time ejecta that originate from the poles are proton-rich (high Y_e), and late-time ejecta, mostly originating from the mid-latitudes and equator, are neutron-rich (low Y_e).

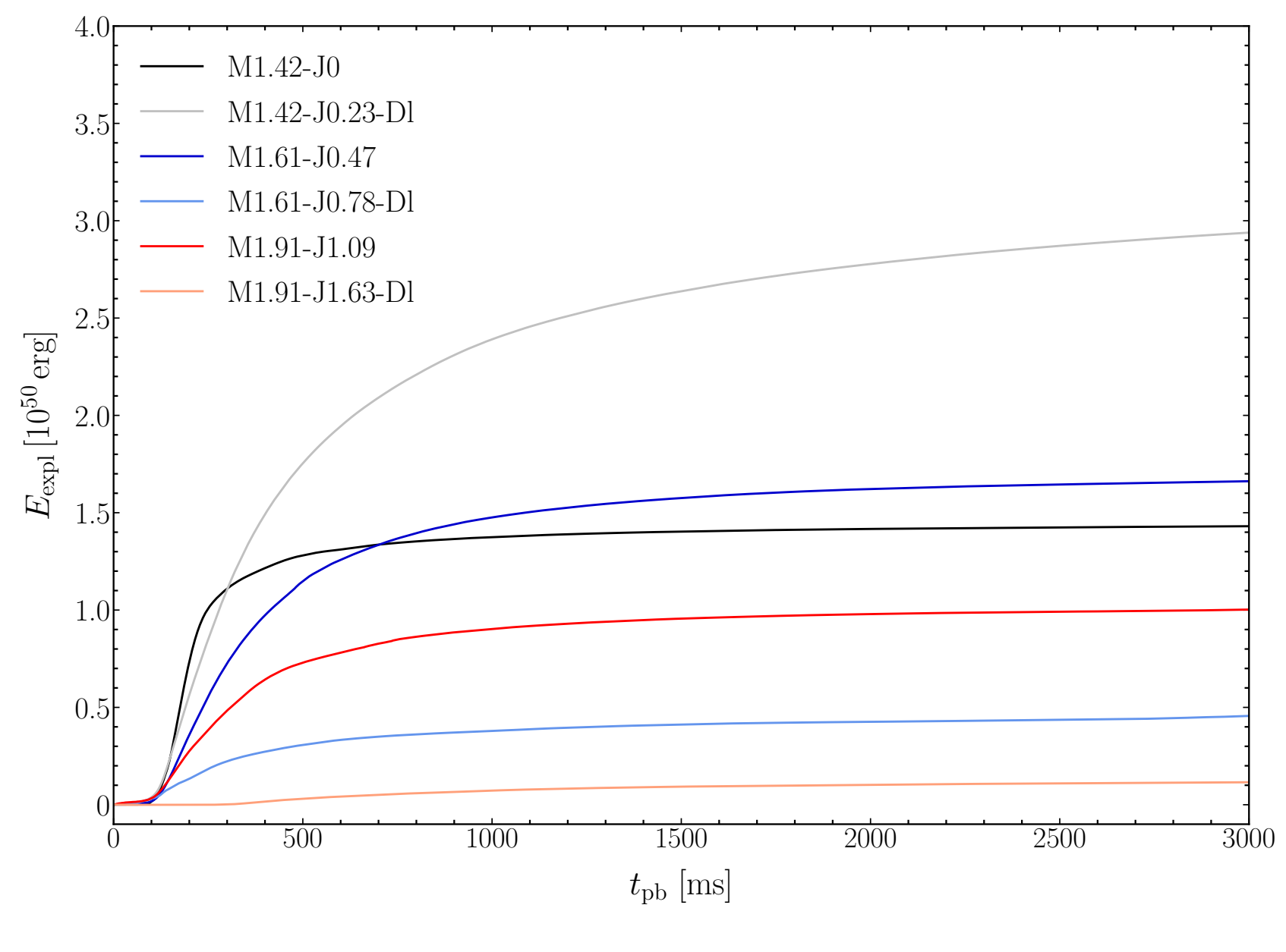


Figure 6: Explosion Energy of the outflow as a function of post-bounce time.

- AICs yield low-energetic outflows.
- Explosion energies ~ 10^{50} erg .
- $E_{\rm expl}$ depends on the ejecta mass, which is strongly correlated to the initial angular momentum of the model.
- High angular momentum models develop heavy disks and low ejecta mass, showing low explosion energy.

SUMMARY AND CONCLUSIONS

- We simulate the long-time evolution of AICs for a representative set of progenitor models with different masses and degrees of rotation.
- All models show neutrino-driven outflows. The non-rotating model develops a spherically symmetric outflow. The rotating models are significantly affected by the initial angular momentum budget. They form neutron stars surrounded by disks.
- Neutron stars formed with masses ~1-1.4 $M_\odot$ and millisecond periods in the rotating models.
- Low-energetic, low-mass ejecta outflows that are mainly determined by the initial rotational profile.
- Neutron-rich material is produced that could be forming r-process nuclei in some cases.
- Our models can be used for detailed nucleosynthesis calculations and light curve modeling.

REFERENCES

[1] Just, O., Obergaulinger, M., & Janka, H.-T. (2015), A new multidimensional, energy-dependent two-moment transport code for neutrino-hydrodynamics, *MNRAS* 453(4):3386–3413.
[2] Steiner, A. W., Hempel, M., & Fischer, T. (2013), Core-collapse supernova equations of state based on neutron star observations, *ApJ* 774(1):17.
[3] Abdikamalov, E., Ott, C. D., Rezzolla, L., et al. (2010), Axisymmetric general relativistic simulations of the accretion-induced collapse of white dwarfs, *Phys. Rev. D*, 81(4):044012.
[4] Ehring, J., Batziou E., Janka, H.-T. et al. (in prep.)
[5] Batziou, E., Glas, R., Janka, H.-T. et al. (to be submitted in ApJL)
[6] Batziou, E., Janka, H.-T., Glas, R., Ehring, E. et al. (in prep.)

Stay in touch!

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