3D MHD core-collapse supernovae code comparison: the impact of numerics on central engine simulations

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Abstract

Magneto-rotational supernovae are extreme core-collapse supernovae (CCSN) where the combination of fast rotation and strong large-scale magnetic fields leads to extraordinarily powerful explosions. The accreting central compact object (either a proto-magnetar or a black hole) can power-up energetic transients such as hypernovae and long gamma-ray bursts, as the rotational energy of the stellar core is extracted by the action of magnetic fields and used to launch polar outflows that propagate through the stellar progenitor. The properties of the explosion can depend crucially on the simulation's accuracy in reproducing quantities such as the extraction of rotational energy from the central proto-neutron star, the winding of magnetic field lines promoting the launch of polar outflows, and the onset of non-axisymmetric instabilities that could hinder the outward propagation of the jet. However, it remains still unclear to what extent models of magneto-rotational explosions depend on the numerical details of the specific tool used to produce them (such as the adoption of Cartesian or spherical coordinates, full general relativity or modified Newtonian gravity, multi-dimensional neutrino transport or simplified leakage schemes). We present results from an ongoing code-comparison project which considers, for the first time, the modeling of a prototypical 3D magneto-rotational explosion realized with various state-of-the-art CCSN numerical codes using different grid geometries, gravity treatment, and neutrino-matter interactions. All models consider the same stellar progenitor with a fast rotating core ($\simeq$ 1 rad/s) and a strong aligned dipolar magnetic field ($\simeq$ **10^{12}** G), where we imposed the same well-defined non-axisymmetric initial perturbation to seed the kink instability in the outflow. We show the impact that specific modeling choices have on the explosion dynamics, the properties of the central compact object, and the stability of the polar outflow, obtaining good overall agreement among different codes with some quantitative deviations.

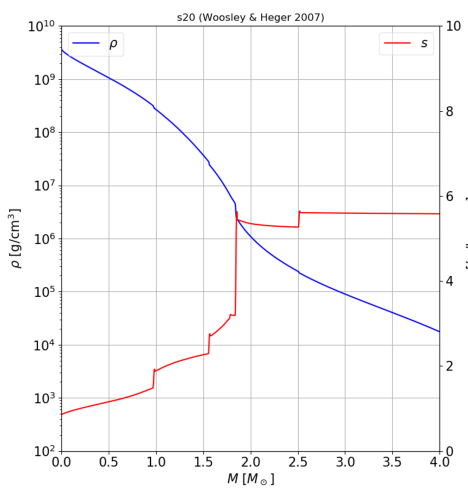
The numerical codes

Code Name	Grid Geometry	Neutrino Transport	Gravity
3DnSNe-IDSA [1]	(r,θ,ϕ)	IDSA	GR effective Φ [5]
AENUS-ALCAR [2]	(r,θ,ϕ)	M1	GR effective Φ [5]
CoCoNuT-FMT [3]	(r,θ,ϕ)	FMT	GR effective Φ [6]
FLASH-M1 [4]	(x,y,z)	M1	GR effective Φ [5]

The initial conditions

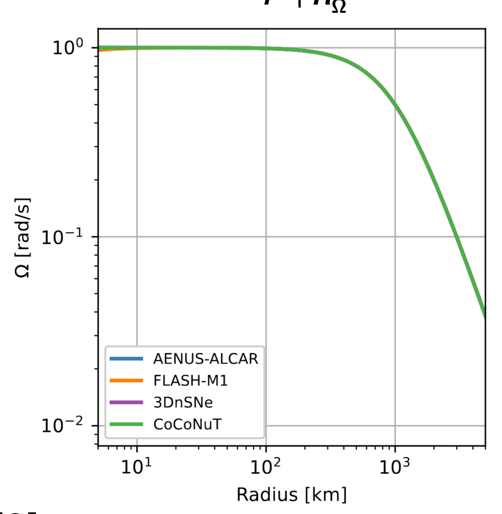
Stellar progenitor

- `s20`: $M_{ZAMS} = 20M_\odot$ with solar metallicity [7]
- Iron core with mass $M_{Fe} \simeq 1.85M_\odot$ and radius $R_{Fe} \simeq 2600$ km
- No rotation nor magnetic field from stellar evolution



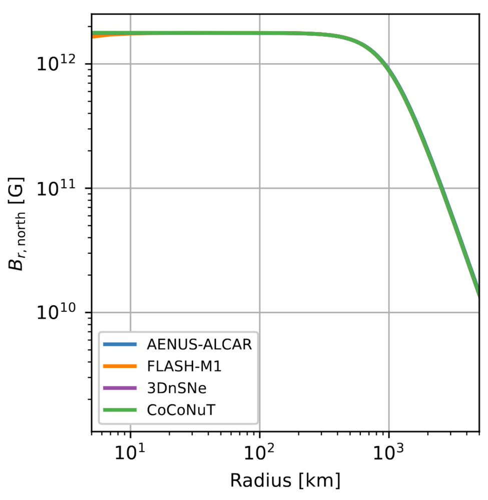
Rotation rate

- Inner core ($R_\Omega = 1000$ km) in solid body rotation ($\Omega_0 = 1$ rad/s)
- Constant specific angular momentum elsewhere with shellular differential rotation
- $\Omega(r) = \Omega_0 \frac{R_\Omega^2}{r^2+R_\Omega^2}$



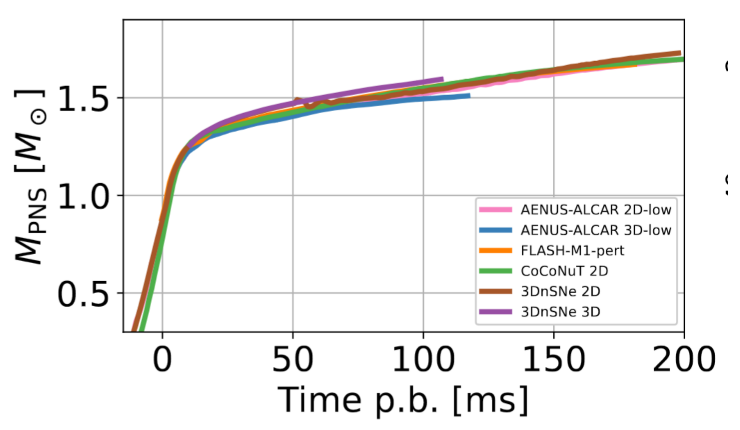
Magnetic field

- Modified aligned dipole: constant intensity $B_0 \simeq 1.77 \times 10^{12}$ G within $R_0 = 1000$ km.
- Azimuthal vector potential: $A^\phi = \frac{B_0}{2}\frac{R_0^3}{R_0^3+r^3} r \sin\theta$

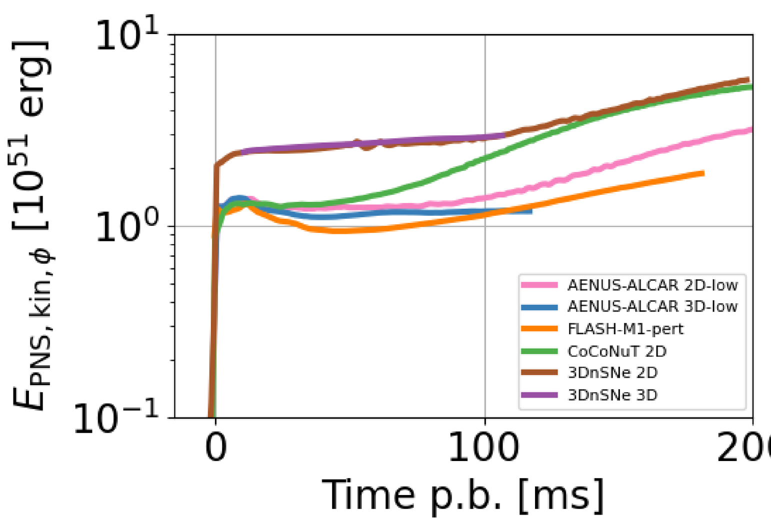


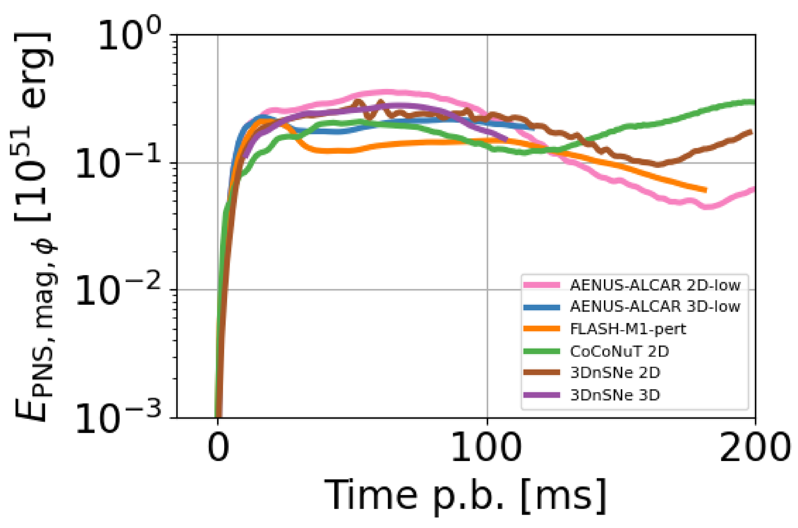
- Equation of state $\rightarrow$ SFHo [8]
- Non-axisymmetric density perturbation: $\delta\rho = \rho_0\epsilon \sin(2\theta)\cos\phi$ with $\epsilon = 0.01$
- Spectral ν-transport schemes with 20 bins up to 300 MeV

The proto-neutron star

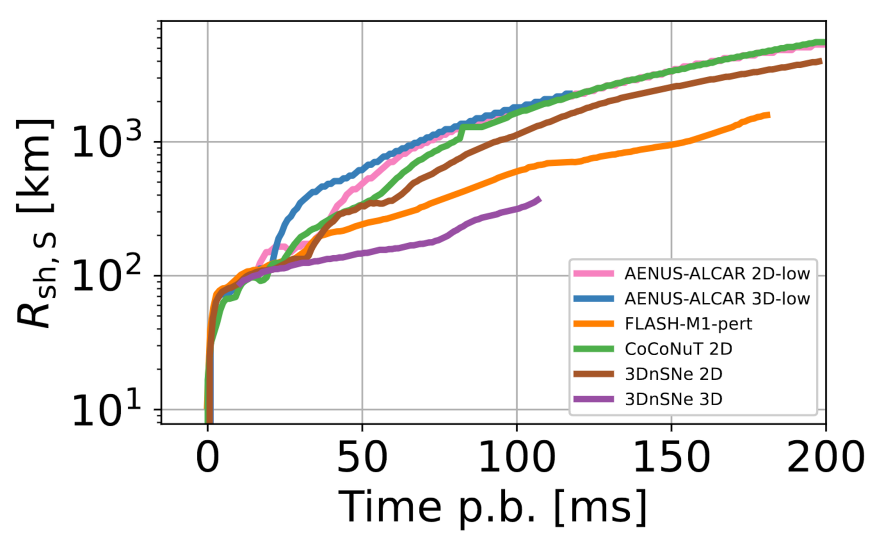


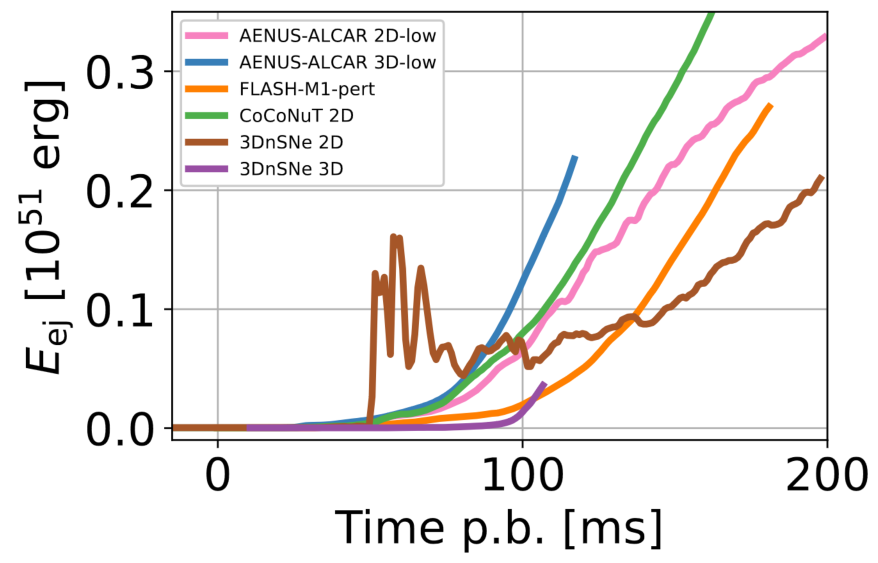
- PNS mass consistent among different codes
- Radial profiles for density, entropy, and the magnetic field's general structure in good agreement
- Deviations for rotational energy and toroidal magnetic fields after $\sim$ **150** ms p.b.





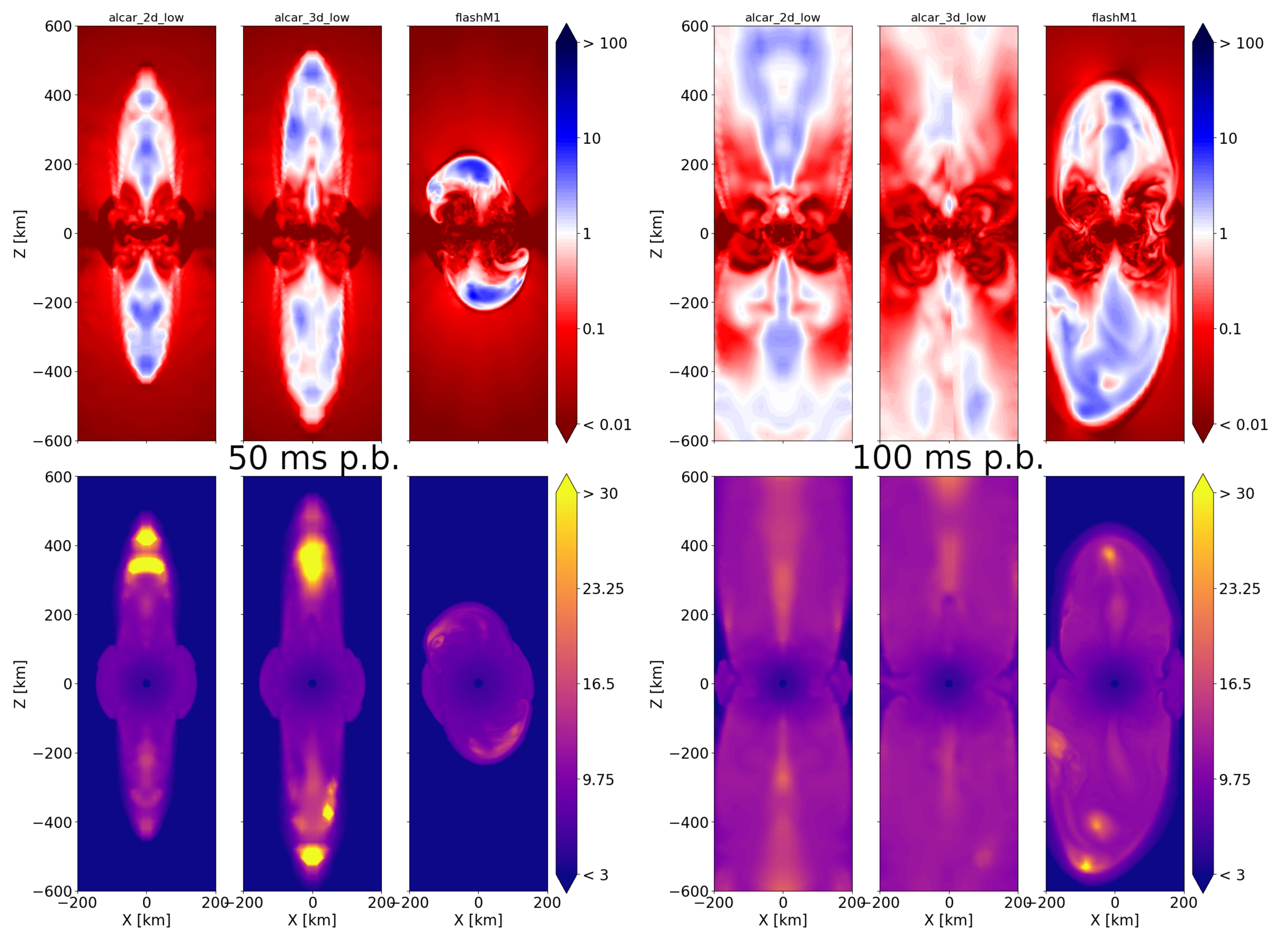
Explosion dynamics



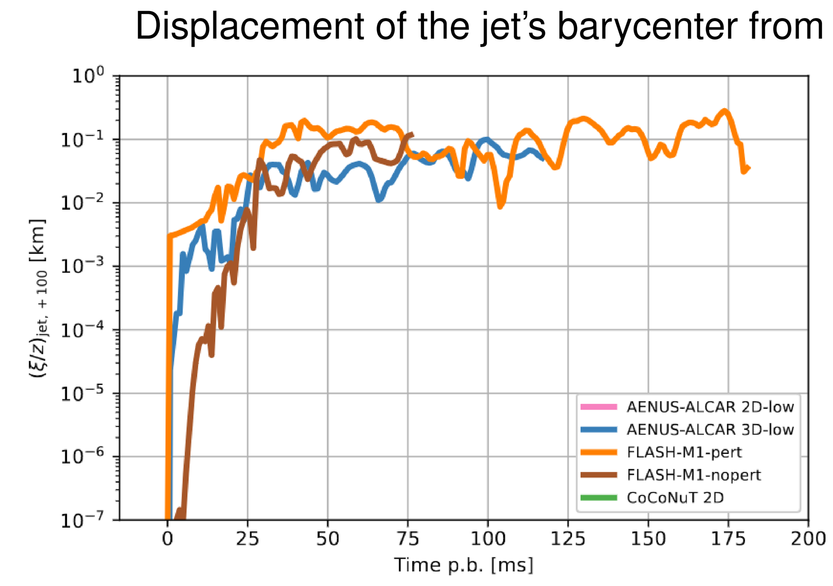


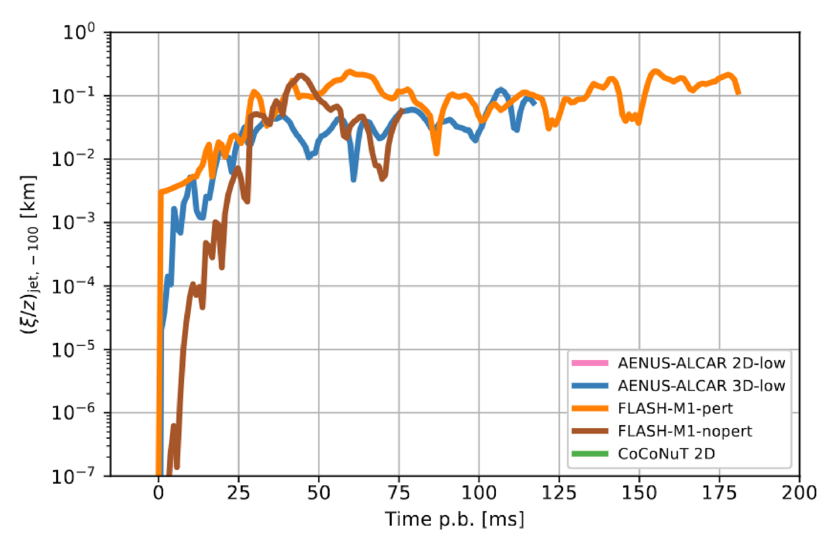
- Prompt explosion for all simulations, but with different efficiency.
- `AENUS-ALCAR` produces the strongest and most axisymmetric explosions.
- `FLASH-M1` 3D explosion is more structured, less powerful, and takes longer to expand.
- Onset of the kink instability, but no disruption of the general structure of the ejecta.

Inverse plasma beta (top panels) and specific entropy (bottom).



Displacement of the jet's barycenter from the rotational axis over time at $r = 100$ km.





Results and Future Perspectives

- ✓ Qualitative agreement among all different codes at the early stages of the explosion
- ✓ Quantitative deviations in the explosion efficiency and shock radius expansion within the first 100 ms
- ✓ Proto-neutron star mass consistently reproduced, but deviations in rotation rates and total angular momentum
- ✓ No disruption of the outflow by the kink instability, but significant differences in the azimuthal structure

- ○ Inclusion of more 2D and 3D models
- ○ Impact of resolution and convergence
- ○ Extension of models to later times
- ○ Analysis of multi-messenger signals

References

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