The MHD-CCSN code comparison project

Matteo Bugli
(IAP)

Collaborators: E. O'Connor, T. Takiwaki, B. Müller, P. Mösta, J.Guilet, K. Kotake, L. Kovalenko, J. Matsumoto, M. Obergaulinger, V. Varma, A. Celati, L. Del Zanna

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CCSN models: an heterogeneous landscape

Initial conditions

- Progenitor/core mass, mixing, wind losses
- Rotation rate, transport of angular momentum
- Magnetic fields, dynamo processes
- Pre-collapse dynamics, turbulence

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- Gravity treatment (full GR, pseudo-Newtonian)
- Neutrino treatment (M1, IDSA, FMT)
- High-density nuclear equation of state (LS220, SFHo, SFHx, . . .)

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- Grid geometry (Cartesian,spherical)
- Refinement and coarsening
- Coordinates singularities
- Riemann solvers, interpolations
- Resolution and dissipation

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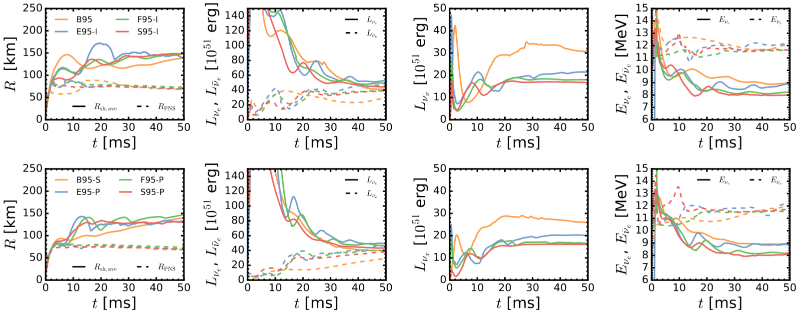
Can different codes reproduce consistent results?
(See Bernhard's lecture)

Hydrodynamic explosions

- Impact of ν-transport scheme in 1D (Liebendörfer et al., 2005; O'Connor et al., 2018), 2D (Just et al., 2018), and 3D (Glas et al., 2019)
- 3D hydro models with different rotation, gravity, ν-scheme (Cabezón et al., 2018)
- Main impact on PNS compression and heating efficiency



Cabezón et al. (2018)

Extreme stellar explosions

Explosion kinetic energy

- Typical supernova: 10^{51} erg
- Rare hypernovae and GRBs: 10^{52} erg

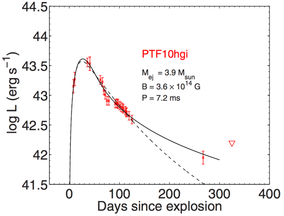
Total luminosity

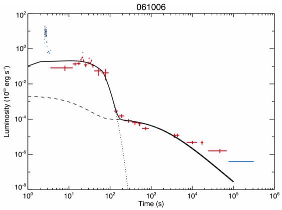
- Typical supernova: 10^{49} erg
- Superluminous SN: 10^{51} erg

Lightcurves and X-ray plateaus

- Strong dipolar magnetic field: $B \sim 10^{14} - 10^{15}$ G
- Fast rotation: $P \sim 1 - 10$ ms
- Kasen and Bildsten (2010); Dessart et al. (2012); Nicholl et al. (2013); Zhang and Mészáros (2001); Metzger et al. (2008); Lü et al. (2015); Gao et al. (2016)

Inserra et al. (2013)





Gompertz et al. (2014)

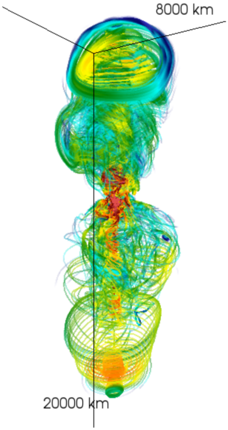
Magneto-rotational core-collapse supernovae

Main mechanism

- Rotation ⇒ energy reservoir
- Magnetic fields ⇒ means to extract that energy through magnetic stresses
- Powerful jet-driven explosions (Shibata et al., 2006; Burrows et al., 2007; Dessart et al., 2008; Winteler et al., 2012; Obergaulinger and á. Aloy, 2017; Kuroda et al., 2020; Obergaulinger and Aloy, 2021; Bugli et al., 2021; Powell et al., 2023; Shibagaki et al., 2024) (See Lyubov's poster, Martin's and Gerardo's talks tomorrow)

Origin of the magnetic field

- Progenitor (Woosley and Heger, 2006; Aguilera-Dena et al., 2020)
- Stellar mergers (Schneider et al., 2019)
- PNS dynamos (Raynaud et al., 2020; Reboul-Salze et al., 2021; Reboul-Salze et al., 2022; Barrère et al., 2022, 2023)

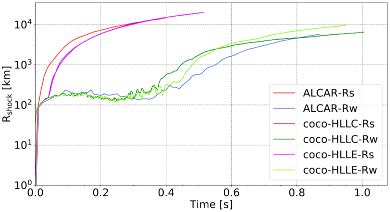


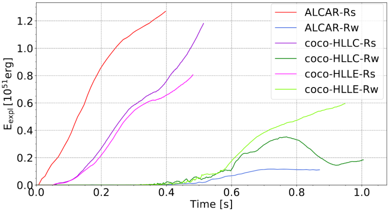
Obergaulinger and Aloy (2021)

2D MHD comparison

(Varma & Müller 2021)

- Progenitors: 35OC (Woosley and Heger, 2006), fast rotation with strong (S) or weak (W) magnetic field
- Qualitatively similar onset of the explosions, quantitative deviations
- Main sources of differences: central grid treatment, numerical dissipation $\Rightarrow$ impact of angular momentum transport





How would more codes compare in 3D?

The 3D code comparison

(MB et al. in prep.)

The numerical codes

Code Name	Grid Geometry	Neutrinos	Dimensions	Gravity
3DnSNe-IDSA (Takiwaki et al., 2016)	(r, θ, ϕ)	IDSA	2D, 3D	Pseudo-Newtonian
AENUS-ALCAR (Just et al., 2015)	(r, θ, ϕ)	M1	2D, 3D	Pseudo-Newtonian
CoCoNuT-FMT (Müller and Janka, 2015)	(r, θ, ϕ)	FMT	2D	Pseudo-Newtonian
FLASH-M1 (O'Connor and Couch, 2018)	(x, y, z)	M1	3D	Pseudo-Newtonian
GRaM-X (Shankar et al., 2023)	(x, y, z)	M0	3D	Full GR

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Common settings

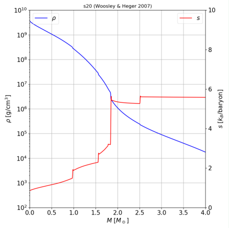
- Nuclear equation of state → SFHo (Steiner et al., 2013)
- Non-axisymmetric perturbation in density:

$$\delta\rho = \rho_0 \epsilon \sin(2\theta) \cos\phi \quad \text{with} \quad \epsilon = 0.01$$

The initial conditions

PROGENITOR

- s20: $M_{ZAMS} = 20M_{\odot}$ with solar metallicity (Woosley and Heger, 2007)
- Iron core with mass $M_{\mathrm{Fe}} \simeq 1.85M_{\odot}$ and radius $R_{\mathrm{Fe}} \simeq 2600$ km
- No rotation nor magnetic field from stellar evolution



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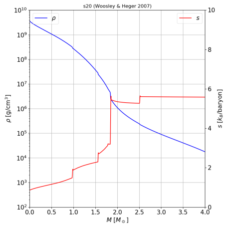
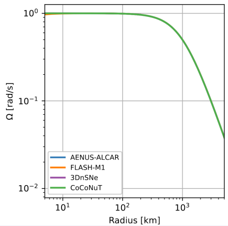


ROTATION RATE

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



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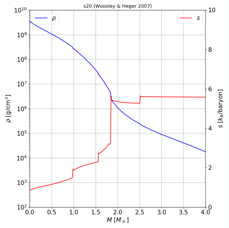

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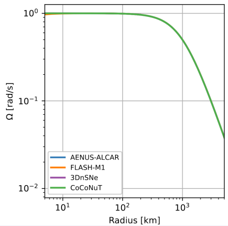
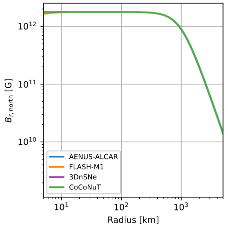
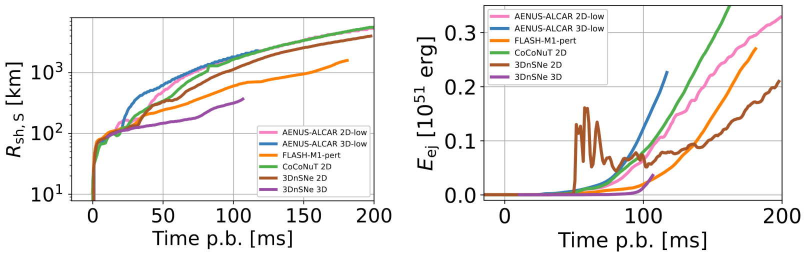


MAGNETIC FIELD

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

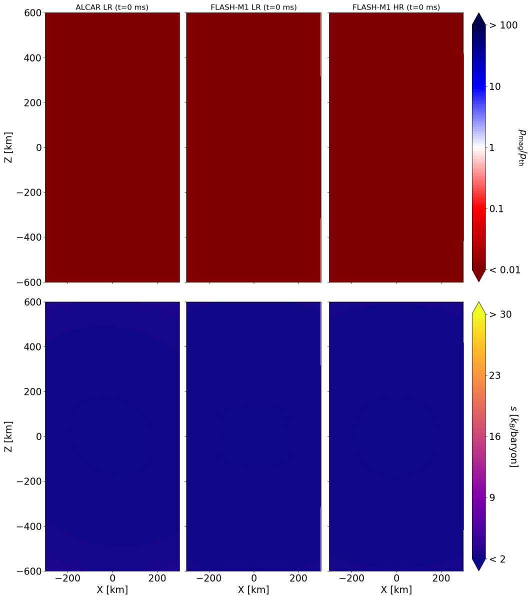


Shock expansion and ejecta energy



- Prompt explosion for all simulations, but with different efficiencies.
- AENUS-ALCAR (3DnSNe-IDSA) produces the fastest (slowest) shock expansion and the most (least) powerful explosion.
- 2D vs 3D: opposite trends between the codes

Explosion dynamics



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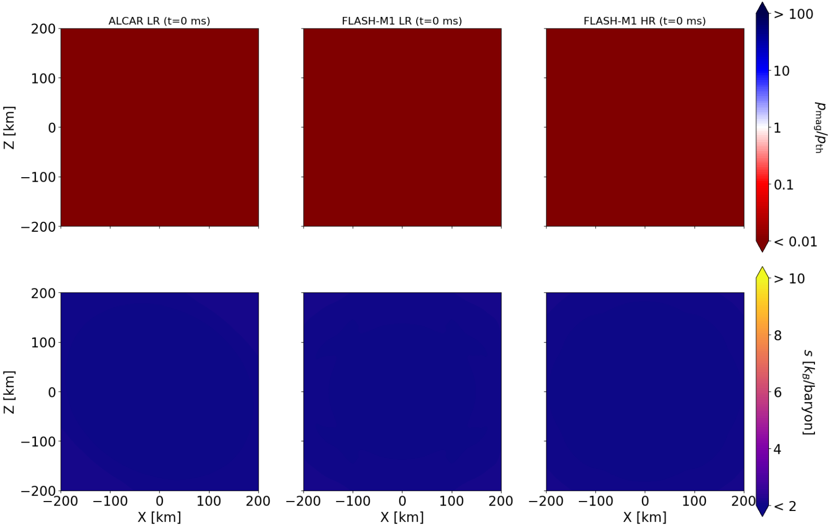
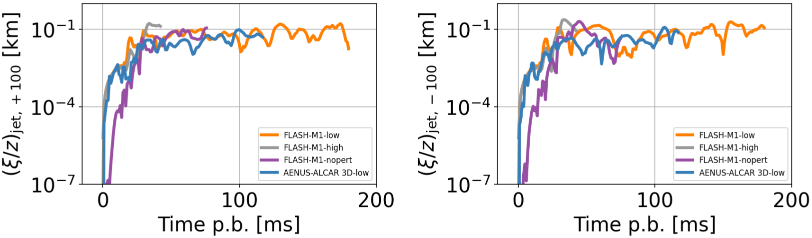


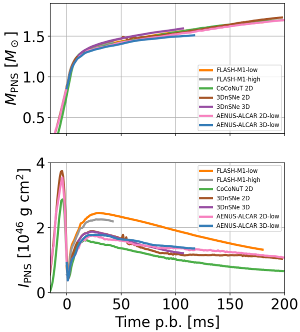
The kink instability



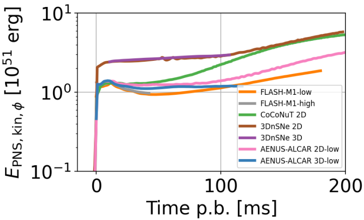
- Displacement of the jet's barycenter over time at $r = 100$ km
- Consistent saturation of the non-axisymmetric modes of the kink
- Coherence of the outflow with both Cartesian and spherical grids

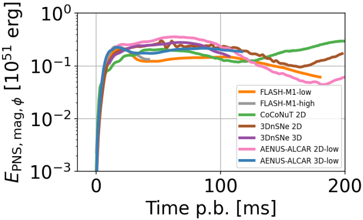
(Mösta et al., 2014; Kuroda et al., 2020)

The proto-neutron star (I)

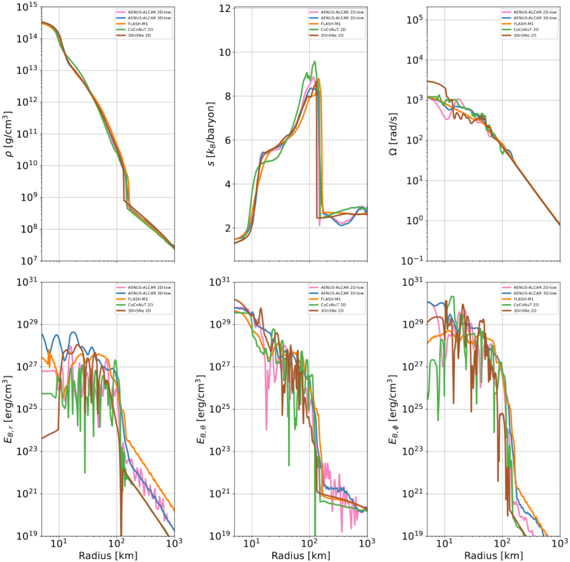


- PNS mass and moment of inertia consistent
- FLASH-M1 model significantly more oblate (higher resolution decreases the effect)
- Significant deviations in rotational energy, initial excess for 3DnSNe-IDSA models
- Toroidal magnetic energy consistent up to $t \sim 150$ ms p.b.



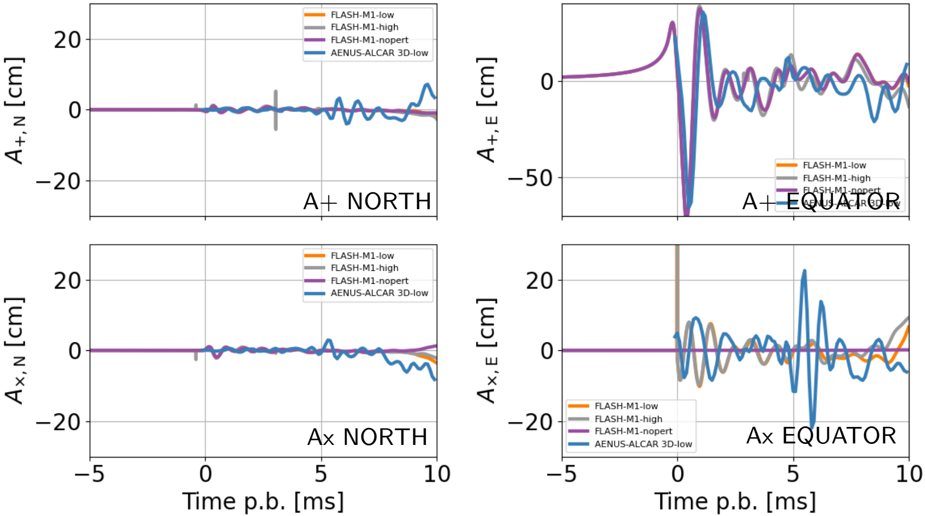


The proto-neutron star (II)



Radial profiles for density, entropy, and the magnetic field in good agreement

Gravitational waves



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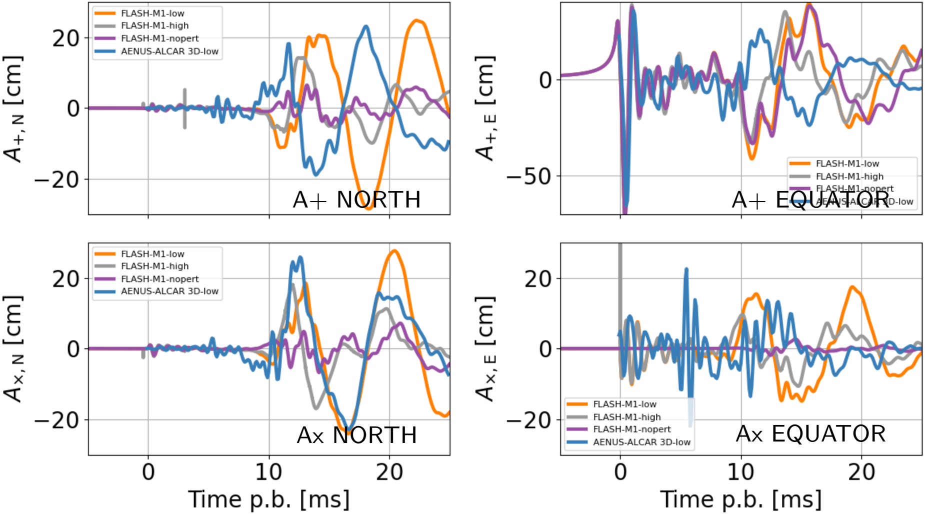

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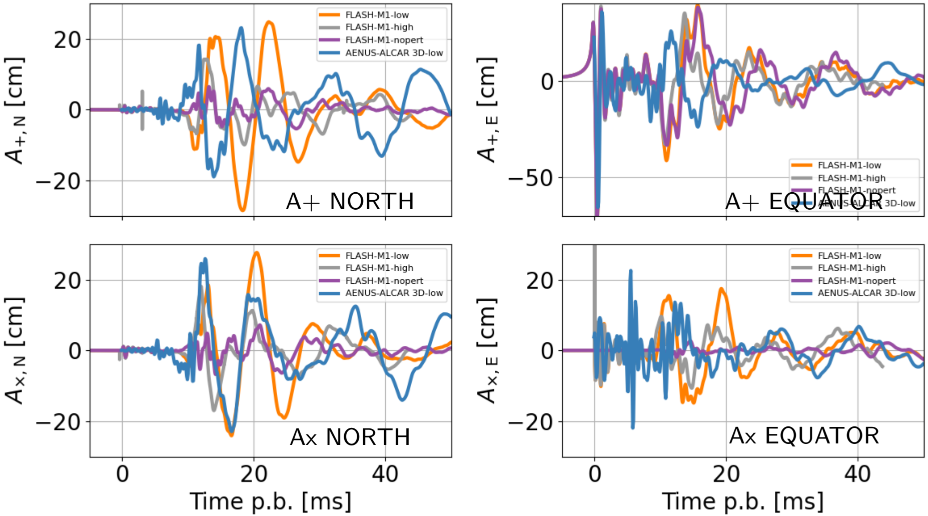

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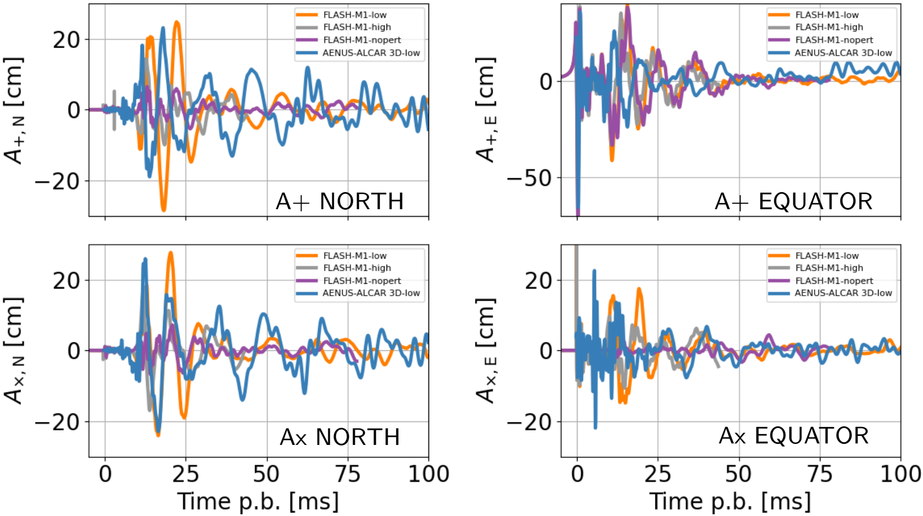
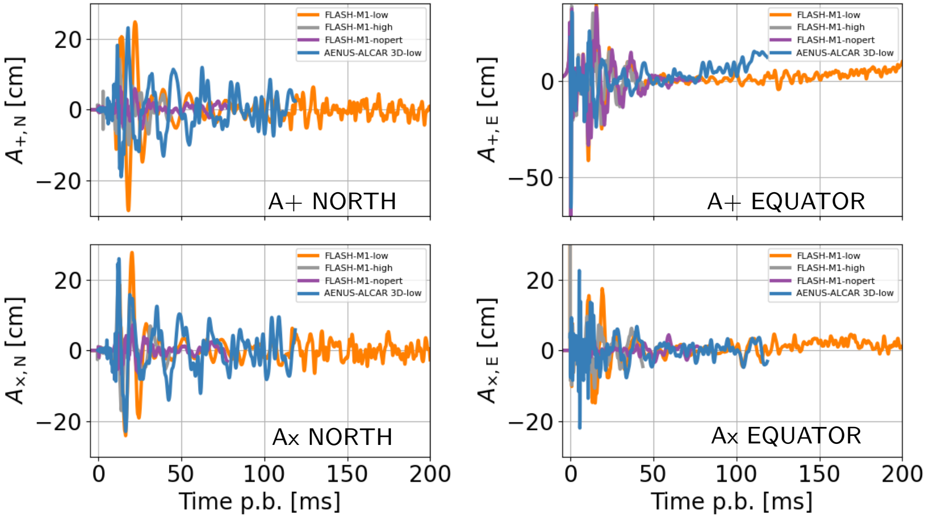


Gravitational waves



Conclusions

- ✓ 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 toroidal magnetic field
- ✓ No disruption of the outflow by the kink instability, but significant differences in the azimuthal structure

Upcoming work

- Impact of gravity and resolution
- Extension of models to later times
- More multi-messenger signal analysis: polarization, ν-GW correlations (see Shota's talk tomorrow)

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Dziekujemy za uwage!

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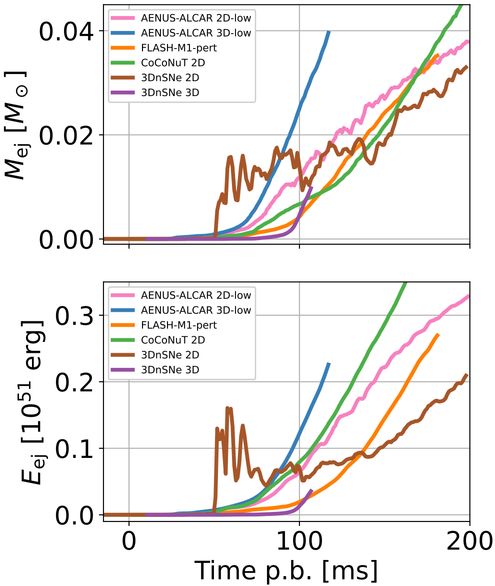
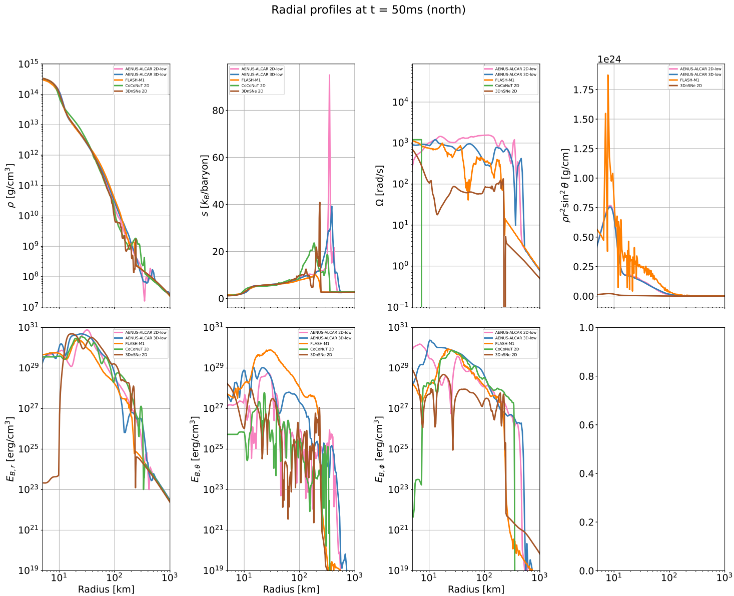
Backup slides

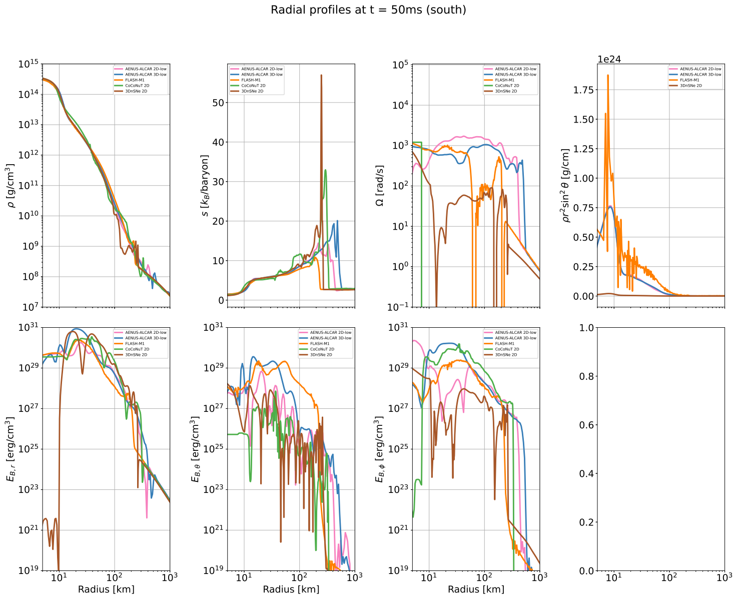
Ejecta


AENUS-ALCAR 2D-low
AENUS-ALCAR 3D-low
FLASH-M1-pert
CoCoNuT 2D
3DnSNe 2D
3DnSNe 3D
M_{ej} [$M_\odot$]
0.04
0.02
0.00
E_{ej} [10^{51} erg]
0.3
0.2
0.1
0.0
0
100
200
Time p.b. [ms]

Radial profiles (north)

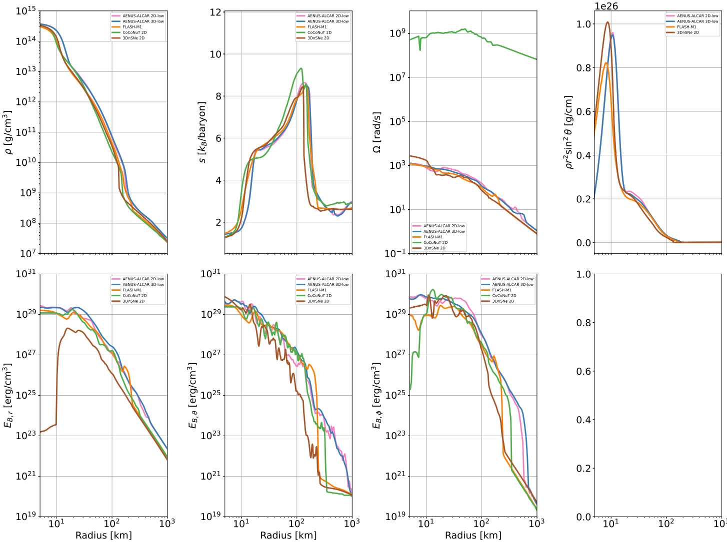


Radial profiles (south)

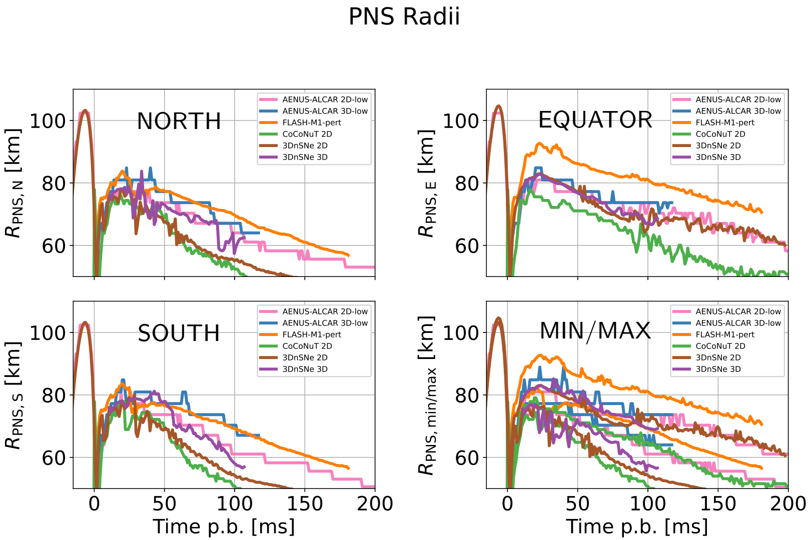


Radial profiles (average)

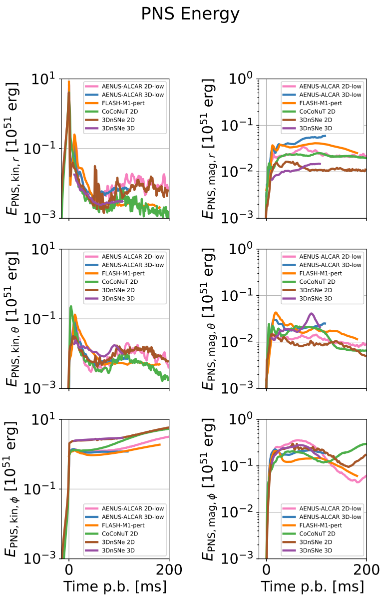
Radial profiles at t = 50ms (average)



PNS radius

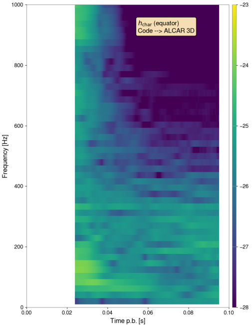

PNS Radii
NORTH
EQUATOR
SOUTH
MIN/MAX
AENUS-ALCAR 2D-low
AENUS-ALCAR 3D-low
FLASH-M1-pert
CoCoNuT 2D
3DnSNe 2D
3DnSNe 3D
$R_{\mathrm{PNS,N}}$ [km]
$R_{\mathrm{PNS,E}}$ [km]
$R_{\mathrm{PNS,S}}$ [km]
$R_{\mathrm{PNS,min/max}}$ [km]
Time p.b. [ms]

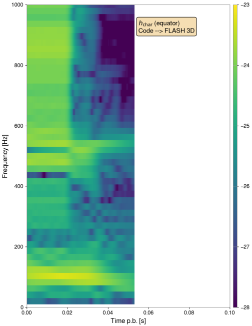
PNS energies

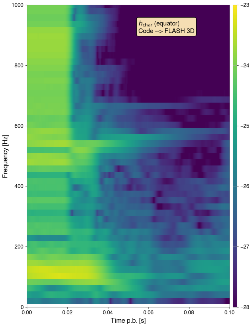


Gravitational wave spectrograms

Aenus-ALCAR 3D	FLASH-M1 3D (no pert.)	FLASH-M1 3D

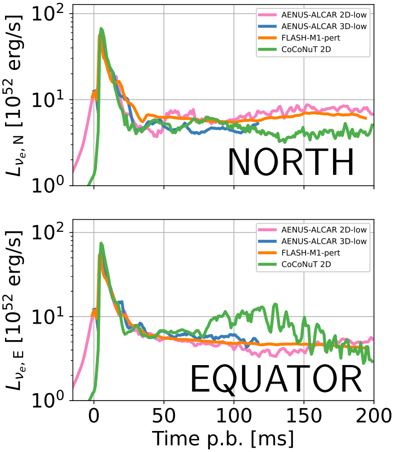




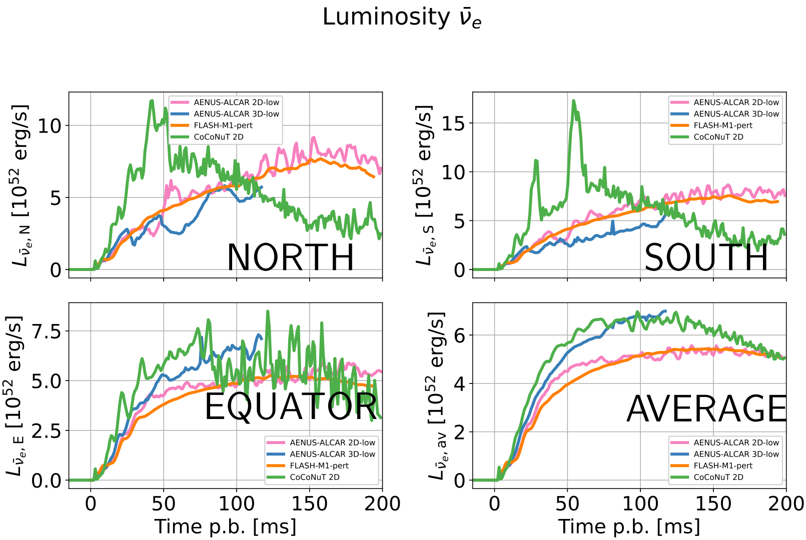


Neutrino emission: ν_e

Luminosity ν_e

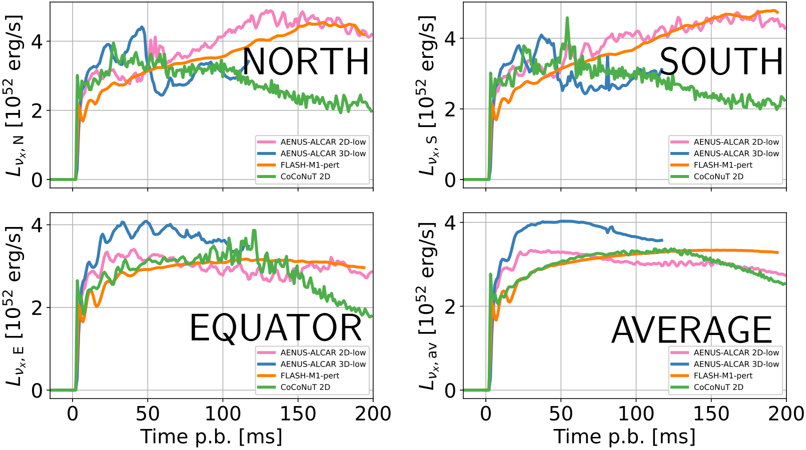


Neutrino emission: $\bar{\nu}_e$



Neutrino emission: ν_x

Luminosity ν_x



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