# Numerical models of extreme core-collapse supernovae

## A comparison between state-of-the-art models

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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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- Coordinates singularities
- Riemann solvers, interpolations
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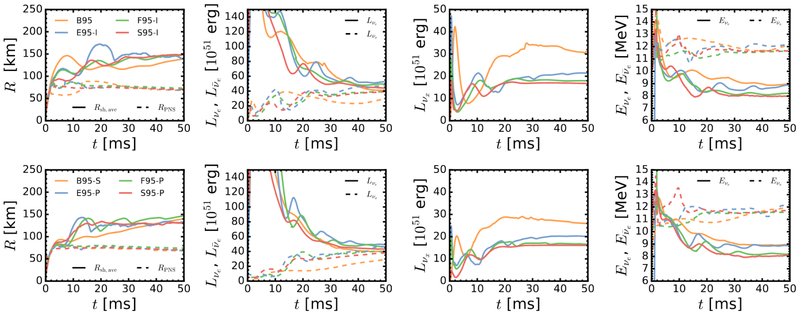
**Can different codes reproduce consistent results?**

# Hydrodynamic explosions

- Impact of $\nu$-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, $\nu$-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

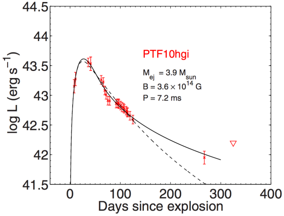
## Total luminosity

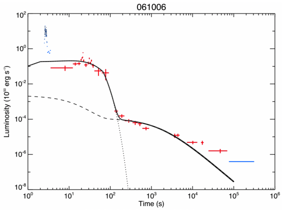
- Typical supernova: $10^{49}$ erg
- Superluminous SN: $10^{51}$ erg

## 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)

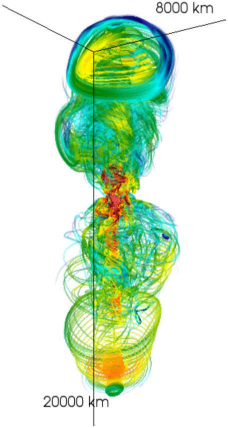
# Magneto-rotational core-collapse supernovae

## 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)

## 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)

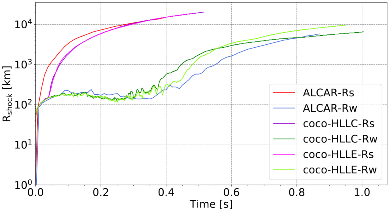


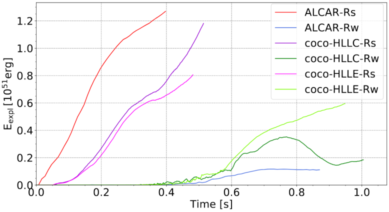

Obergaulinger and Aloy (2021)

# 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 ⇒ impact of angular momentum transport

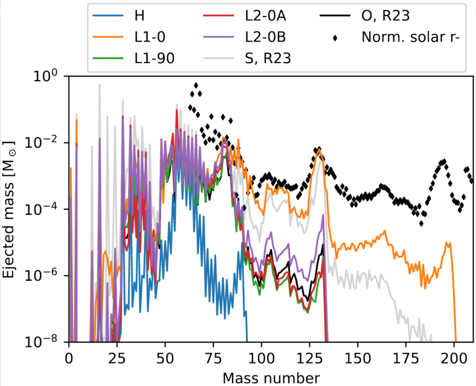



**How would more codes compare in 3D?**

# Ejecta composition

(Reichert, MB et al. 2024)




- All magnetized models produce 1st r-process peak elements
- 2nd peak reproduced only for the aligned dipole
- No 3rd peak nor actinides, consistent with recent 3d models (Reichert et al., 2023) and in contrast to 2d models (Reichert et al., 2021).
- Crucial estimates for chemical evolution models (Dvorkin et al., 2020)

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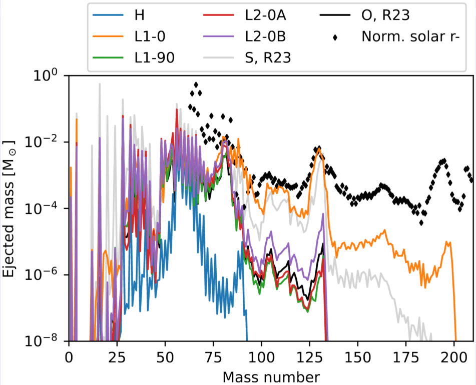


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## Weak dependence on nuclear physics

Neutron-rich nuclei masses
Beta-decay reaction rates
Charged-current reactions
Self-heating feedback on entropy

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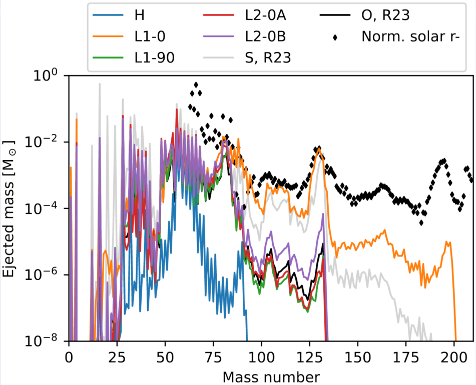


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Beta-decay reaction rates
Charged-current reactions
Self-heating feedback on entropy

**The explosion's efficiency directly affects nucleosynthesis yields**

# The 3D code comparison

(Bugli et al. in prep.)

The numerical codes

| Code Name | Grid Geometry | Neutrinos | Dimensions |
|---|---|---|---|
| **3DnSNe-IDSA** (Takiwaki et al., 2016) | $(r, \theta, \phi)$ | IDSA | 2D, 3D |
| **AENUS-ALCAR** (Just et al., 2015) | $(r, \theta, \phi)$ | M1 | 2D, 3D |
| **CoCoNuT-FMT** (Müller and Janka, 2015) | $(r, \theta, \phi)$ | FMT | 2D |
| **FLASH-M1** (O'Connor and Couch, 2018) | $(x, y, z)$ | M1 | 3D |

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## Common settings

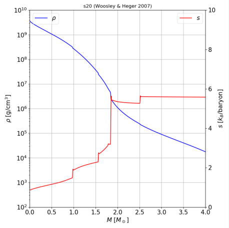
- Nuclear equation of state $\rightarrow$ SFHo (Steiner et al., 2013)
- Non-axisymmetric perturbation in density:

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

# The initial conditions

## PROGENITOR

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



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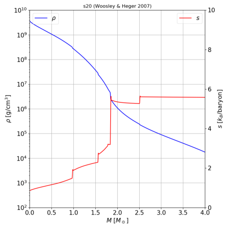
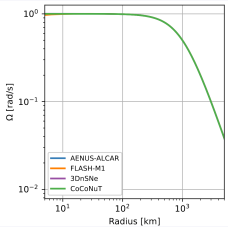



## ROTATION RATE

- 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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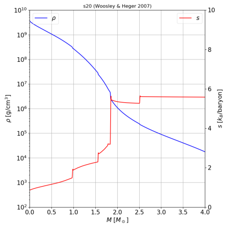


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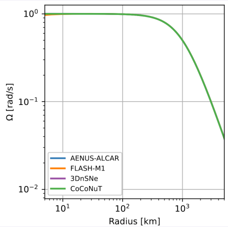
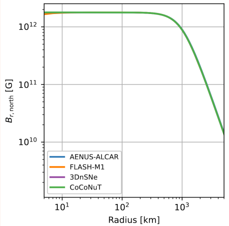


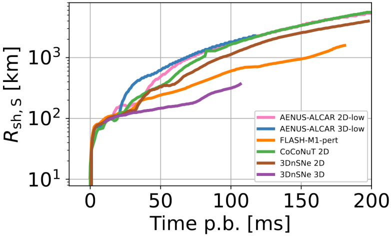

## MAGNETIC FIELD

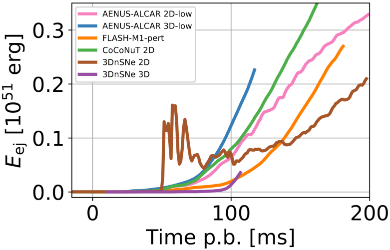
- Modified aligned dipole: constant intensity $B_0 \simeq 1.77 \times 10^{12}$ G within $R_0 = 1000$ km.
- Azimuthal vector potential:

$$A^\phi = \frac{B_0}{2} \frac{R_0^3}{R_0^3 + r^3} r \sin\theta$$



# Shock expansion and ejecta energy



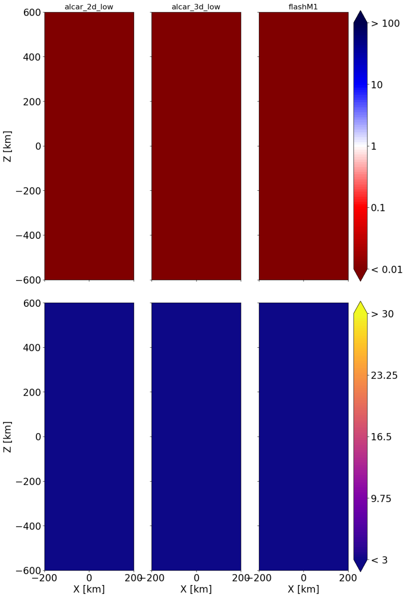




- Prompt explosion for all simulations, but with different efficiencies.
- AENUS-ALCAR (3DnSNe-IDSA) produces the fastest (slowest) shock expansion and the most (least) powerful explosion.
- 2D vs 3D: opposite trends between the codes

# Explosion dynamics

$p_{\mathrm{mag}}/p_{\mathrm{gas}}$

**Specific entropy**



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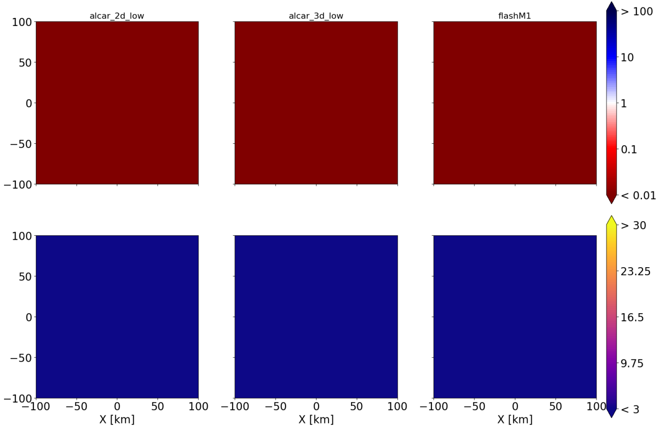
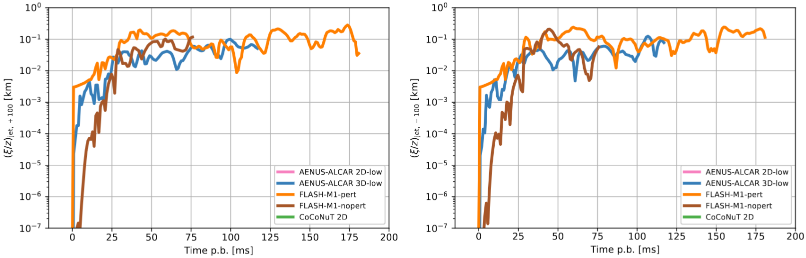


# Explosion dynamics

$p_{\mathrm{mag}}/p_{\mathrm{gas}}$

**Specific entropy**

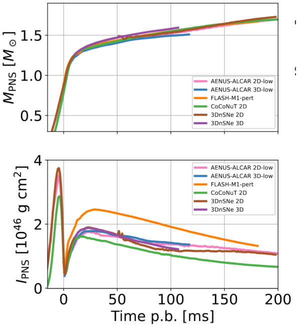
# The kink instability



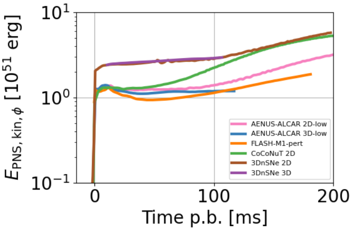

- Displacement of the jet's barycenter over time at $r = 100$ km
- Consistent saturation of the non-axisymmetric modes of the kink
- Coherence of the outflow with both Cartesian and spherical grids

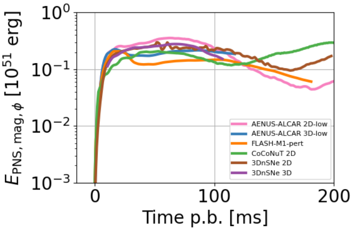
(Mösta et al., 2014; Kuroda et al., 2020)

# The proto-neutron star (I)

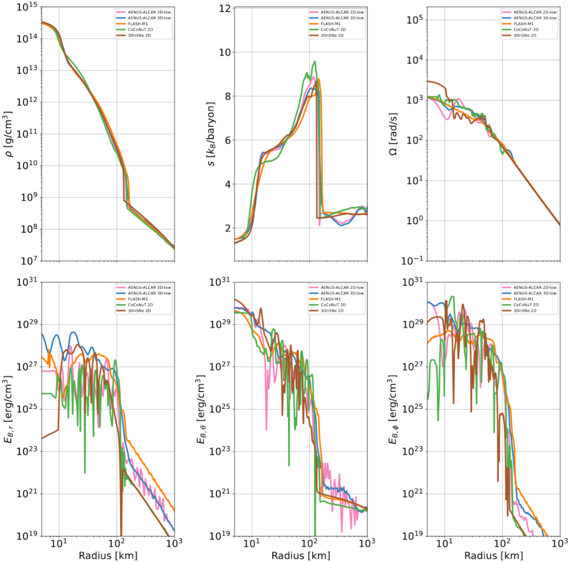



- PNS mass and moment of inertia consistent
- FLASH-M1 model significantly more oblate (possible effect from $\nu_x$ decoupling)
- Significant deviations in rotational energy, initial excess for 3DnSNe-IDSA models
- Toroidal magnetic energy consistent up to $t \sim 150$ ms p.b.



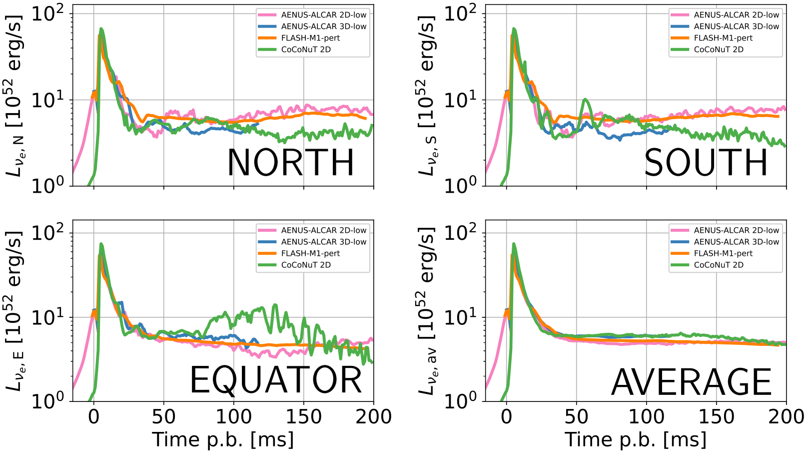
# The proto-neutron star (II)




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

# Neutrino emission: $\nu_e$

Luminosity $\nu_e$



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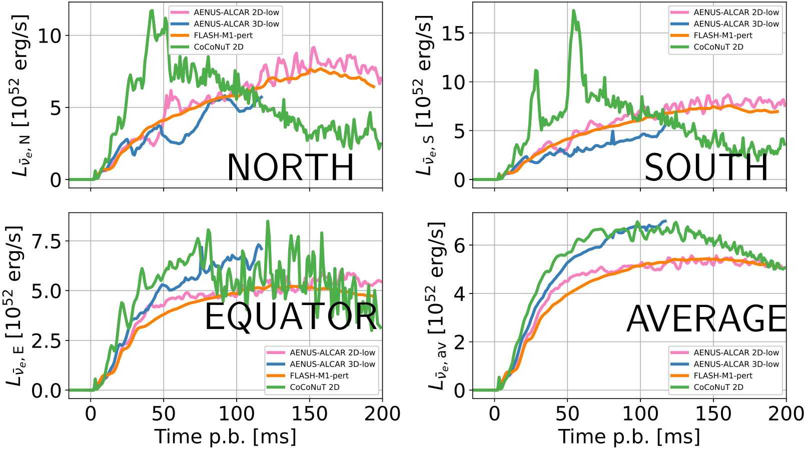
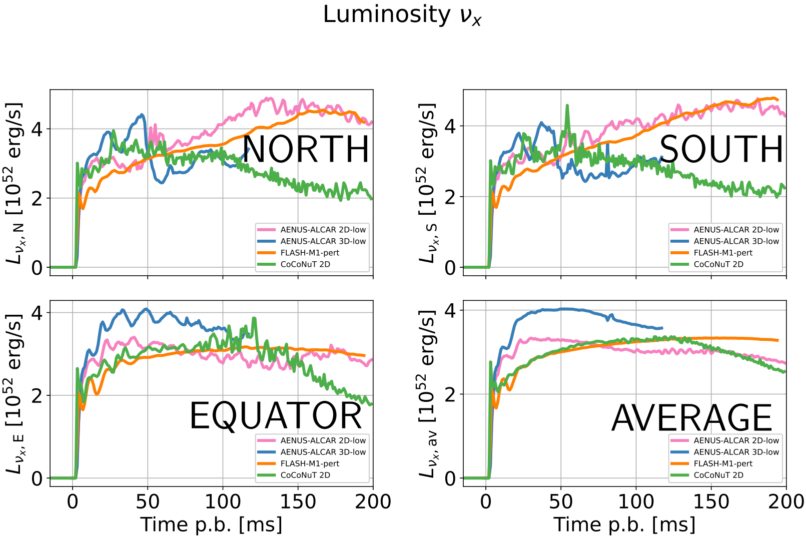
Luminosity $\bar{\nu}_e$

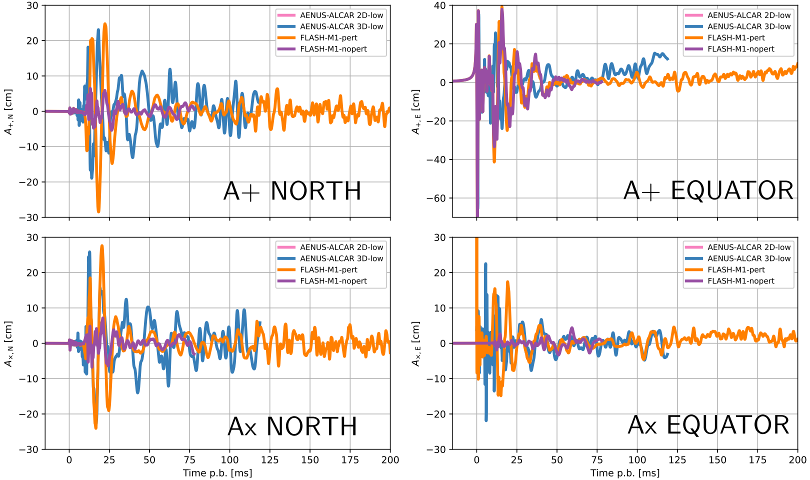


# Neutrino emission: $\nu_x$



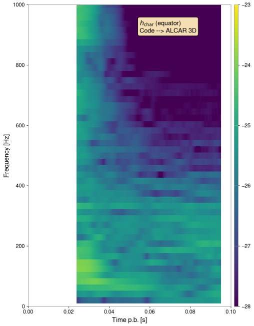
# Gravitational waves

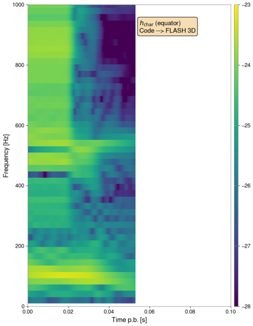
$A_{+,\times}$

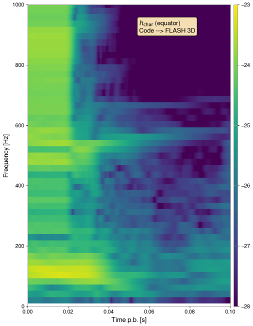


# Gravitational wave spectrograms

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



# 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

## Future goals

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

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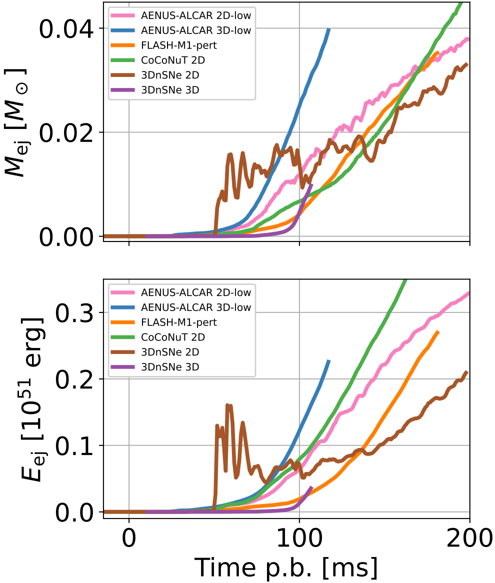
**Thank you for your attention!**

# Backup slides

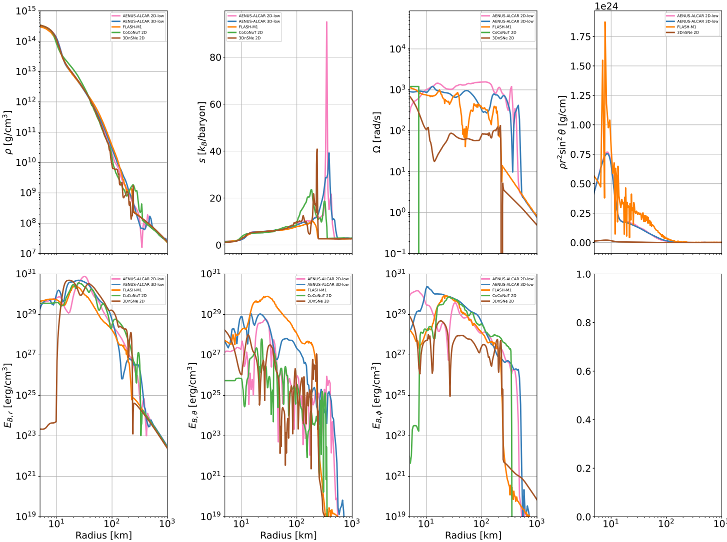
# Ejecta



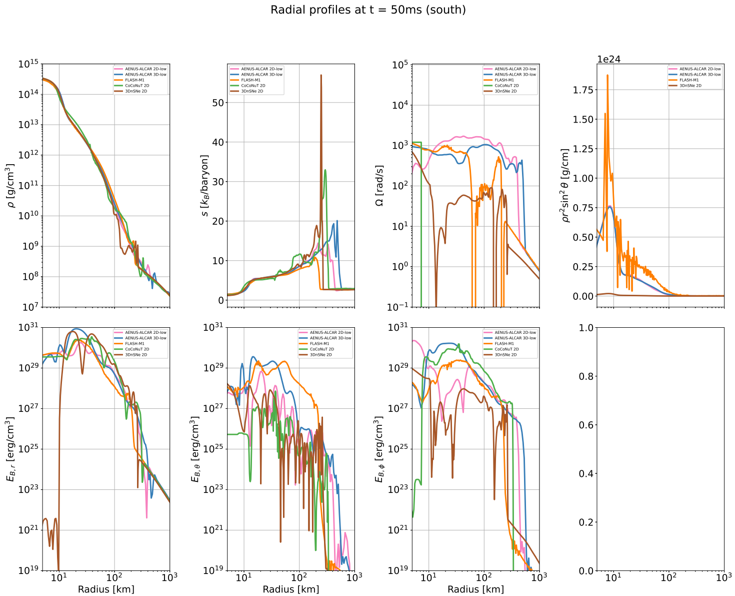
AENUS-ALCAR 2D-low
AENUS-ALCAR 3D-low
FLASH-M1-pert
CoCoNuT 2D
3DnSNe 2D
3DnSNe 3D
0.04
0.02
0.00
$M_{ej}$ [$M_\odot$]
0.3
0.2
0.1
0.0
$E_{ej}$ [$10^{51}$ erg]
0
100
200
Time p.b. [ms]

# Radial profiles (north)

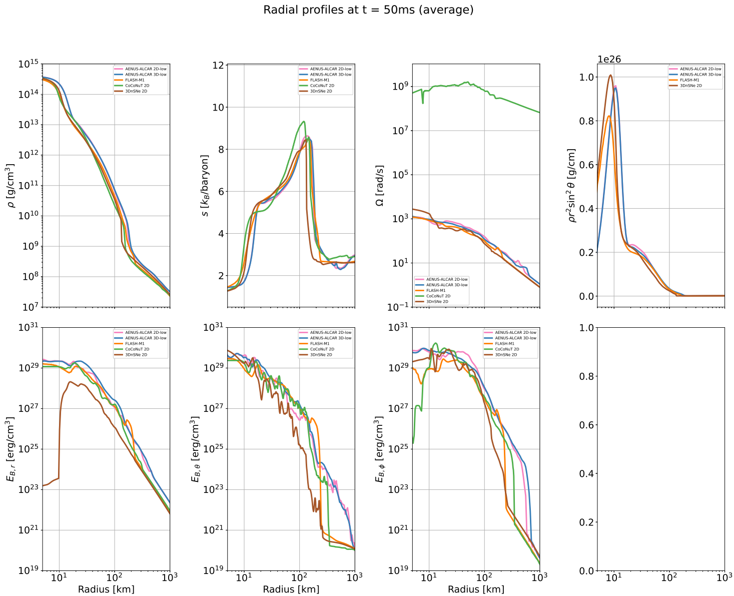
Radial profiles at t = 50ms (north)



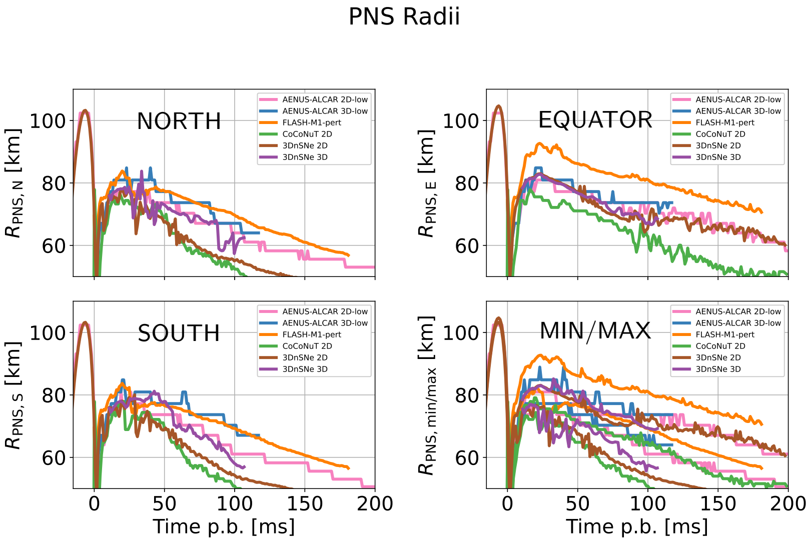
# Radial profiles (south)



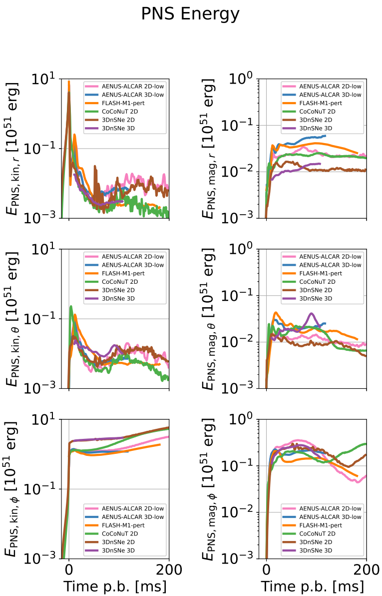
# Radial profiles (average)



# 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
$R_{PNS, N}$ [km]
$R_{PNS, E}$ [km]
$R_{PNS, S}$ [km]
$R_{PNS, min/max}$ [km]
100
80
60
0
50
100
150
200
Time p.b. [ms]

# PNS energies



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Barrère, P., Guilet, J., Reboul-Salze, A., Raynaud, R., and Janka, H.-T. (2022). A new scenario for magnetar formation: Tayler-Spruit dynamo in a proto-neutron star spun up by fallback. Astronomy & Astrophysics, Volume 668, id.A79, <NUMPAGES>14</NUMPAGES> pp., 668:A79.

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