Explosive nucleosynthesis and multimessenger emission from extreme stellar explosions

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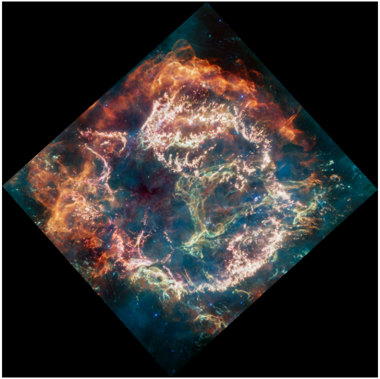
Assemblée générale GdR Ondes Gravitationnelles
Université Aix Marseille, Campus Luminy - 15/10/2024

Funded by the Horizon 2020 Framework Programme of the European Union

Introduction

Core-collapse Supernovae

- Explosive end-of-life product of massive stars ($M \gtrsim 8 M_\odot$)
- Formation of stellar compact objects
- Dynamical feedback on galaxy evolution
- Explosive nucleosynthesis ⇒ chemical evolution
- Sources of gravitational waves and neutrinos

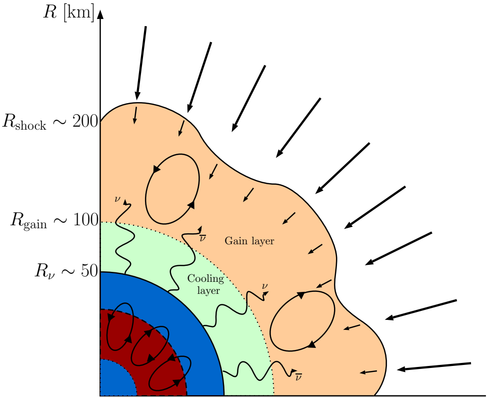


Where does the binding energy ($\sim 10^{53}$ erg) end up?

Neutrinos ($\sim$ 99%)
Ejecta ($\sim$ 1%)
Gravitational waves ($\sim 10^{-8}$)

Key aspect: how is the shock revived?

Standard neutrino-driven CCSN



- Collapse ⇒ nuclear densities ⇒ shock wave and Proto-Neutron Star (PNS)
- ν-cooling rate drops faster than ν-heating ⇒ Gain radius
- Energy deposition by ν_e and $\bar{\nu}_e$ absorption in gain layer
- Multi-D hydrodynamic instabilities crucial for the explosion:
- Convection (Janka, 2012)
- SASI (Standing Accretion Shock instability) (Foglizzo et al., 2015)

99% of core-collapse supernovae explode thanks to neutrinos

Extreme stellar explosions

Explosion kinetic energy

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

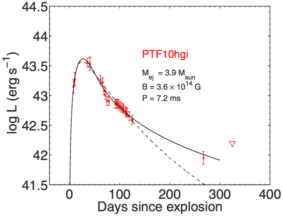
Total luminosity

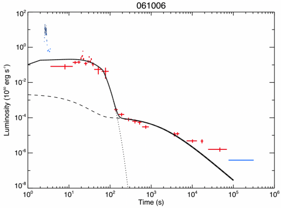
- Typical supernova: 10^{49} erg
- Superluminous SN: 10^{51} erg

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)

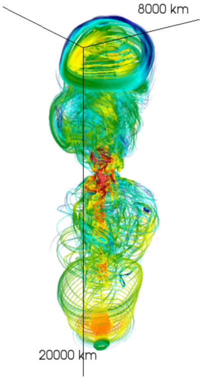
Magneto-rotational core-collapse supernovae

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; **Bugli** et al., 2020; Kuroda et al., 2020; Obergaulinger and Aloy, 2021; **Bugli** et al., 2021, 2023; 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, 2022; Barrère et al., 2022, 2023)



Obergaulinger and Aloy (2021)

Core-collapse numerical models

3D MHD explosion models

(Bugli et al. 2021)

How does the magnetic field topology affect the explosion?

3D MHD explosion models

(Bugli et al. 2021)

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The initial conditions

- Massive, fast rotating progenitor
  (Woosley and Heger, 2006)
- Different magnetic configurations : dipole (aligned and equatorial), quadrupole

The `AENUS-ALCAR` code

- Relativistic MHD with M1 ν-transport
  (Just et al., 2015; Obergaulinger and Aloy, 2020)
- GR corrections to gravity, nuclear EoS
- High-order reconstruction schemes, spherical grid with coarsened zones

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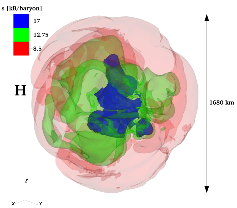
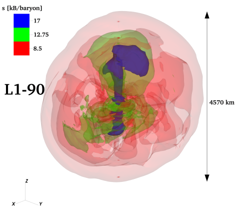
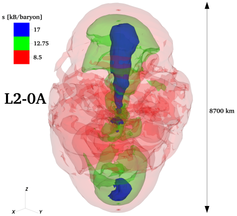


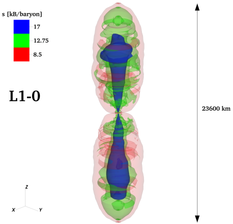
HYDRO



EQ. DIPOLE



QUADRUPOLE



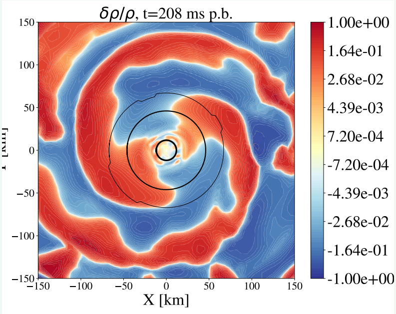
DIPOLE

More magnetic flux at the poles ⇒ **stronger explosions** and faster shocks

Corotational instabilities

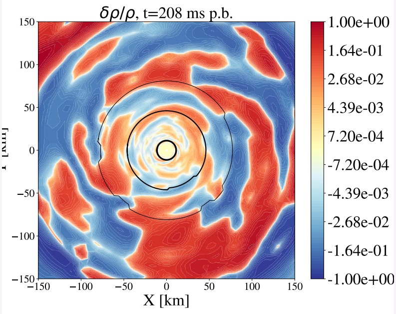
(Bugli et al. 2023)

Hydrodynamic case



- Spiral structures forming at $\sim$ 200 ms p.b.
- Observed for different progenitors/rotation profiles (Takiwaki et al., 2016, 2021)

Magnetized case

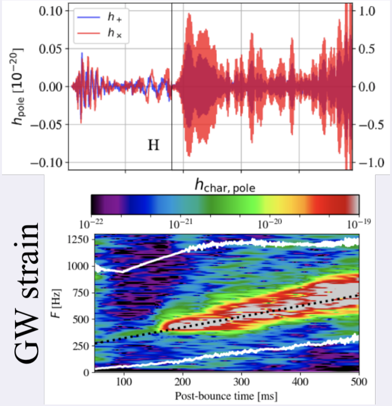


- No large-scale spiral structures
- Turbulent density perturbations
- Weak dependence on magnetic field

GW emission

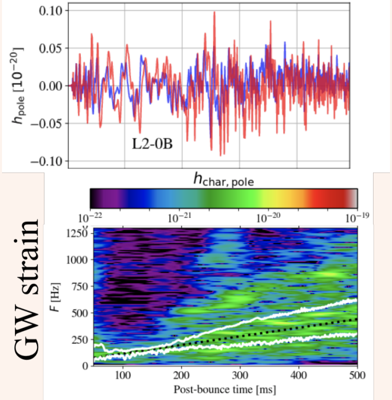
(Bugli et al. 2023)

Hydrodynamic case



- Intense 400 Hz emission at 200 ms
- $h \sim 10^{-20}$ for $D = 10$ kpc
- Strong correlation with PNS modes

Magnetized case (quadrupole)

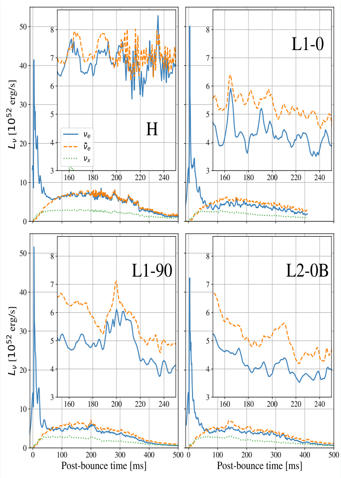


- No low $T/|W|$ burst, broad-band emission
- $h \sim 5 \times 10^{-22}$ for $D = 10$ kpc
- Strong transport of angular momentum

Neutrino emission

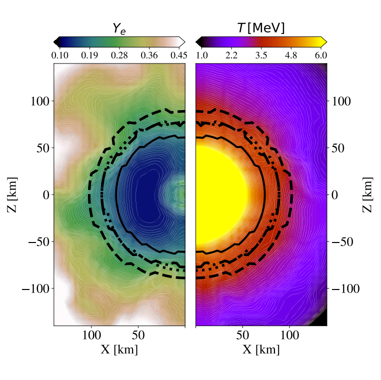
(Bugli et al. 2023)

Lightcurves (equator)



- Lower luminosity in magnetized models
- ν_e-$\bar{\nu}_e$ deviations not seen in hydrdynamic case

Y_e distribution (hydro)



- More compact PNS ⇒ higher mean energies

Neutrino emission

(Bugli et al. 2023)

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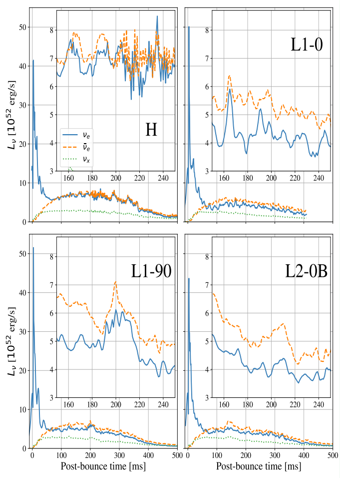

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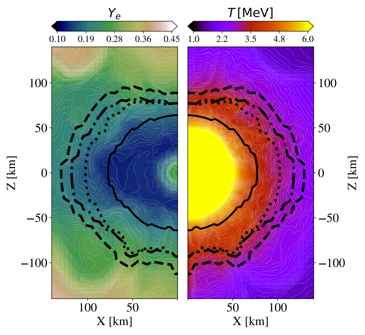

- Outward transport of a.m. ⇒ lower Y_e

Explosive nucleosynthesis

From CCSN models to nucleosynthetic yields

Nuclear reaction networks

- Large set of coupled ODEs tracking nuclear abundances over time
- NSE ($T \gtrsim 6$ GK) $\Rightarrow$ set of algebraic Saha equations
- Several 10^3 isotopes tracked in post-processing

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In-situ MHD-network coupling

- Isotopes advected by the flow ⇒ from ODEs to PDEs
- Direct feedback on the flow, direct thermodynamic conditions
- Highly expensive, typically ∼100 species (Harris et al., 2017; Sandoval et al., 2021)

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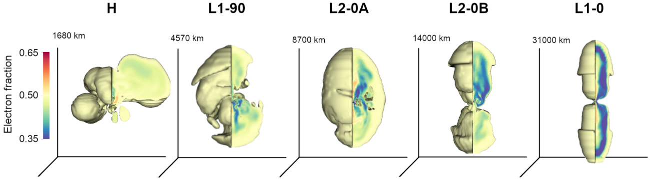
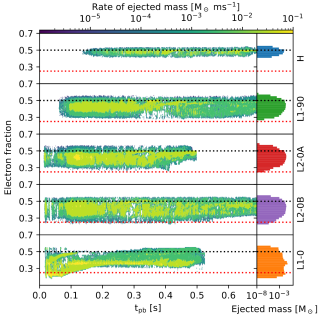
Input from CCSN models

- Lagrangian tracer particles providing density, temperature, electron fraction
- Accurate neutrino transport schemes are crucial!
- Nishimura et al. (2015); Bovard et al. (2017); Reichert et al. (2023)
- Recent review: Obergaulinger and Reichert (2023)

Nucleosynthesis and B field topology (Reichert, Bugli et al. 2024)

- Analysis of 3D MHD models with different B field configurations (**Bugli** et al., 2023)
- WinNet nuclear reaction network (Winteler et al., 2012; Reichert et al., 2023) ∼ 6500 nuclei

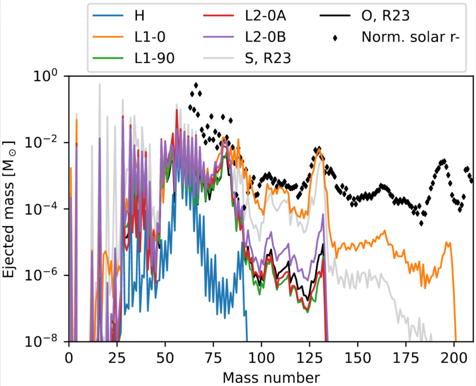




- More neutron-rich material for magnetized models
- Lowest Y_e for dipolar fields
- Neutron-rich material is expelled promptly only for strong MR explosions
- Rotation supports against the accretion onto the PNS
- Longer simulations required to reduce uncertainties

Ejecta composition

(Reichert, Bugli 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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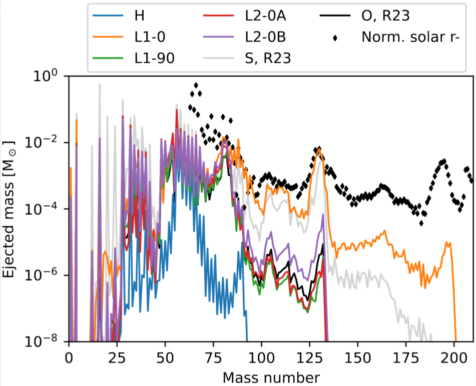

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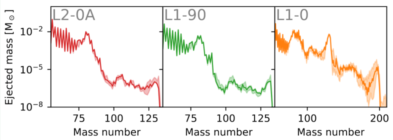
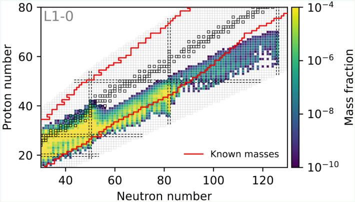
How do dynamical uncertainties compare to nuclear network details?

Nuclear physics uncertainties (I)

Nuclear masses

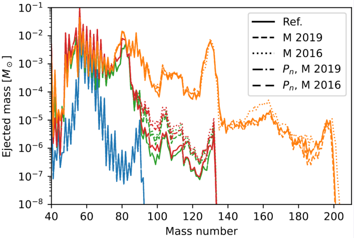
- Uncertain nuclear masses for neutron-rich isotopes
- 6 different energy density functionals (Martin et al., 2016)
- Biggest impact beyond known nuclear masses around r-process peaks
- Limited quantitative deviations





Beta-decay

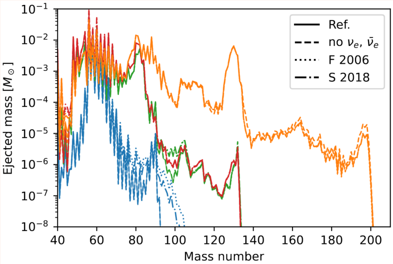
- Beta-decay rates set speed and amount of matter moving towards more stable nuclei
- Different sets tested (Möller et al., 2003; ?, 2019)
- Different half-lives, decay channels (n emitted)
- Increase of yields by at most a few times for L1-0 and L2-0A models



Nuclear physics uncertainties (II)

Neutrino reactions

- CC reactions affect the neutron-richness
- 4 different neutrino treatments:
    - CC only on nucleons (reference)
    - no ν-reactions
    - CC on nucleons and heavy nuclei (Fröhlich et al., 2006)
    - Same reactions with different rates (Sieverding et al., 2018)
- Impact on the hydrodynamic case ($80 < A < 100$), otherwise minor deviations

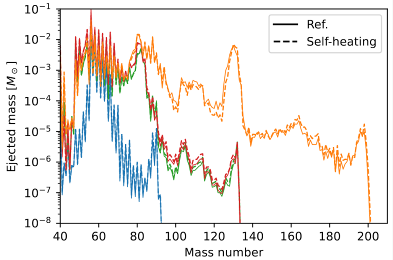


Self-heating

- Energetic feedback of reactions on the entropy
- First law of thermodynamics:

$$\Delta S = -\frac{1}{k_B T}\sum_i(\mu_i + Z_i\mu_e)\Delta Y_i - \dot{q}$$

- Negligible impact for all models



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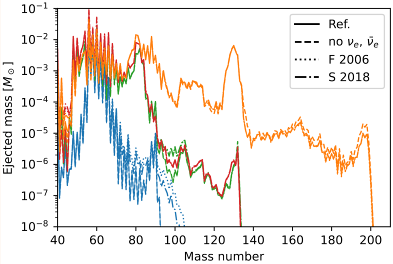

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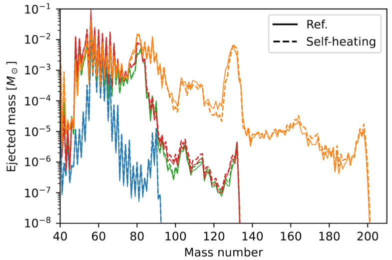

Dynamical uncertainties dominate over nuclear physics ones!

MR-CCSN code comparison

Explosion 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?

Code comparison project

(Bugli et al., in prep.)

Code Name	Grid Geometry	Neutrinos	Dimensions
3DnSNe-IDSA (Takiwaki et al., 2016)	(r, θ, ϕ)	IDSA	2D, 3D
AENUS-ALCAR (Just et al., 2015)	(r, θ, ϕ)	M1	2D, 3D
CoCoNuT-FMT (Müller and Janka, 2015)	(r, θ, ϕ)	FMT	2D
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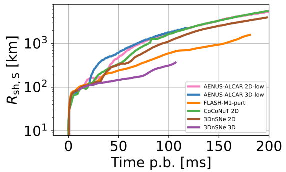
Shock expansion



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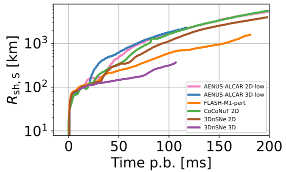
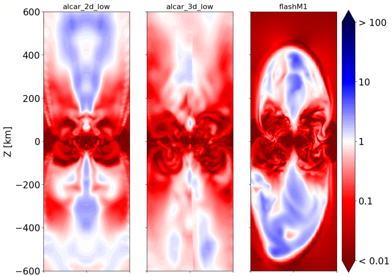


Magnetic pressure



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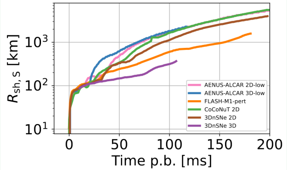

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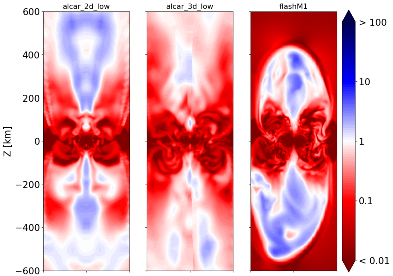
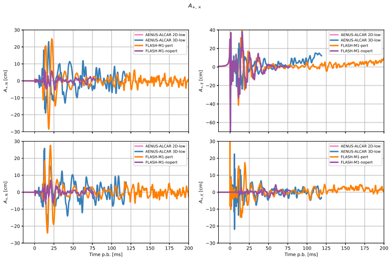


Gravitational waves



Conclusions

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- ✓ Distinctive signatures of rotation and strong magnetic fields on both GW and neutrinos
- ✓ Elements beyond the 2nd r-process peak produced only in the strongest 3D explosions
- ✓ Impact of nuclear physics uncertainties subdominant w.r.t. the magnetic field dynamics
- ✓ Preliminary results from MR-CCSN code comparison show some degree of agreement

Perspectives

- ○ More 3D models (progenitors, rotation, magnetic field)
- ○ Characterization of black hole/magnetar dichotomy
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Merci de votre attention !

Backup slides

The WinNet nuclear reaction network

(Reichert et al. 2023)

Main features

- Single-zone code
  (tracers do not interact with each other)
- Burning time scales much shorter that diffusive one

Full Nuclear Reaction Network ($T \lesssim 6$ GK)

$$\frac{DY_i}{Dt} = \sum_j N^i_j \lambda_j Y_j \qquad [1-\text{body}]$$

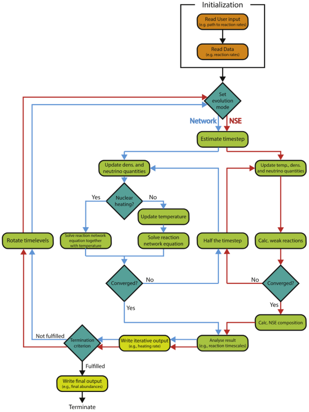
$$+ \sum_{jk} \frac{N^i_{j,k}}{1+\delta_{jk}} \rho N_A \langle \sigma v \rangle_{j,k} Y_j Y_k \qquad [2-\text{body}]$$

$$+ \sum_{jkl} \frac{N^i_{j,k,l}}{1+\Delta_{jkl}} \rho^2 N_A^2 \langle ijk \rangle Y_j Y_k Y_l \qquad [3-\text{body}]$$

sha

Nuclear Statistical Equilibrium ($T \gtrsim 6$ GK)

- Strong and e.m. interactions in equilibrium
- Saha equations in 2 unknown (Y_p, Y_n), ρ, T, Y_e taken from tracer particles
- Nuclear reaction network still used for weak interactions



Code comparison for MR-CCSN

(Bugli et al. in prep.)

The numerical codes

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

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Common settings

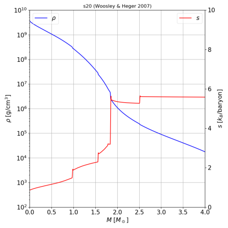
- Nuclear equation of state → SFHo (Steiner et al., 2013)
- Non-axisymmetric perturbation in density:

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

The initial conditions

PROGENITOR

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



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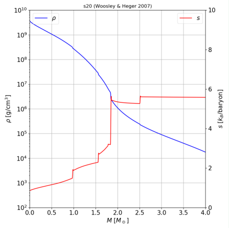
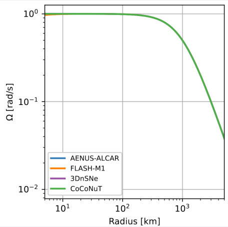


ROTATION RATE

- 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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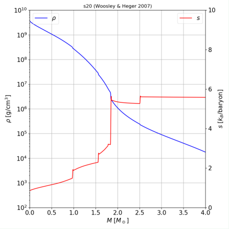

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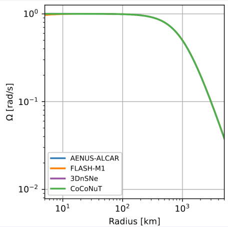
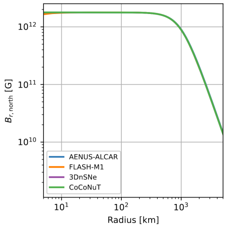


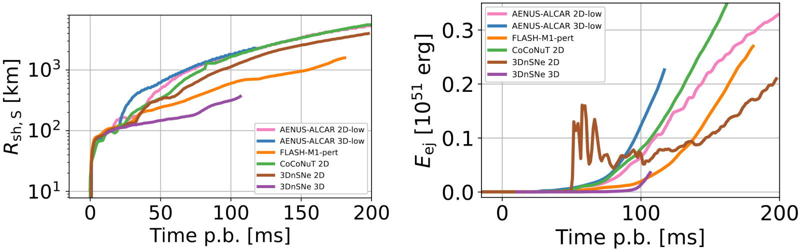
MAGNETIC FIELD

- 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

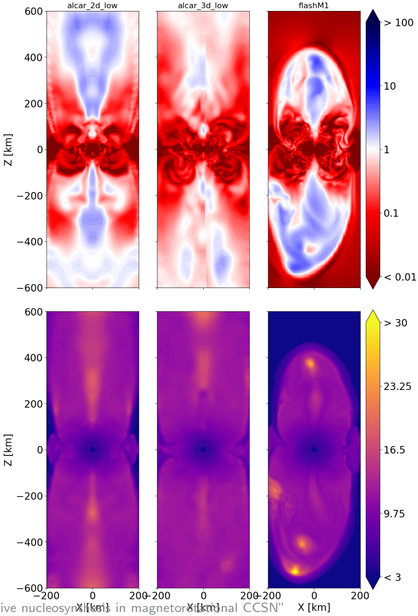


- Prompt explosion for all simulations, but with different efficiencies.
- `AENUS-ALCAR` (`3DnSNe-IDSA`) produces the fastest (slowest) shock expansion and the most (least) powerful explosion.
- 2D vs 3D: opposite trends between the codes

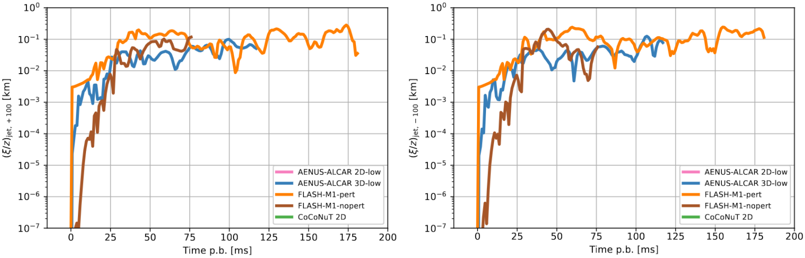
Explosion dynamics

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

Specific entropy



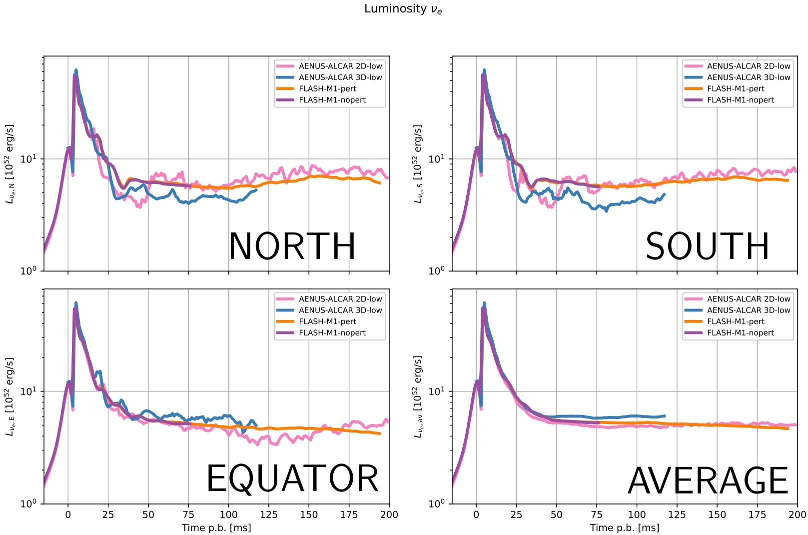
The kink instability



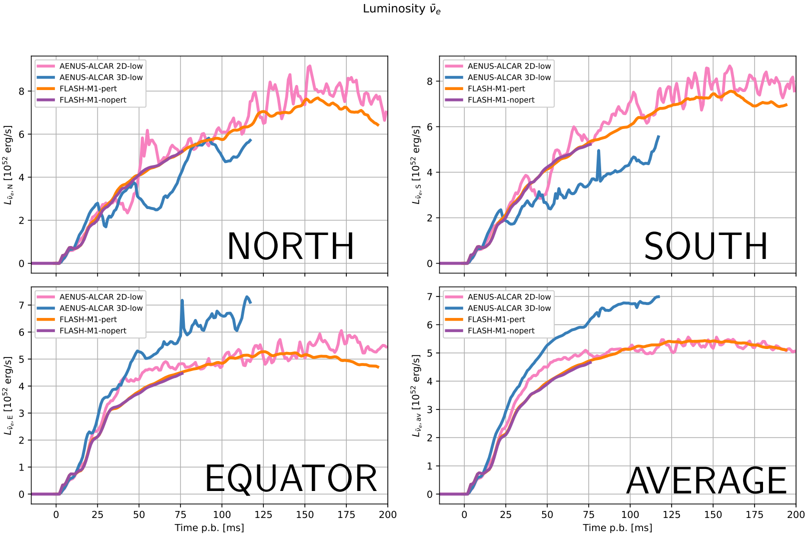
- Displacement of the jet's barycenter over time at $r = 100$ km
- Consistent saturation of the non-axisymmetric modes of the kink
- Coherence of the outflow with both Cartesian and spherical grids

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

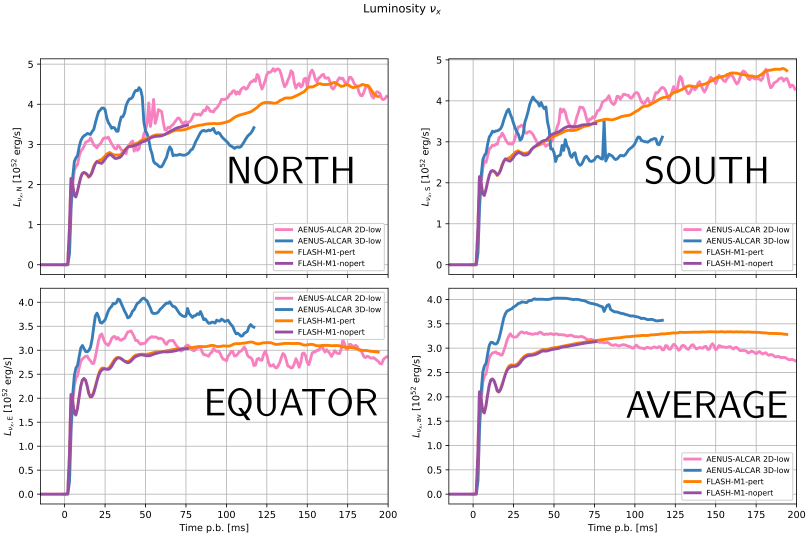
Neutrino emission: ν_e



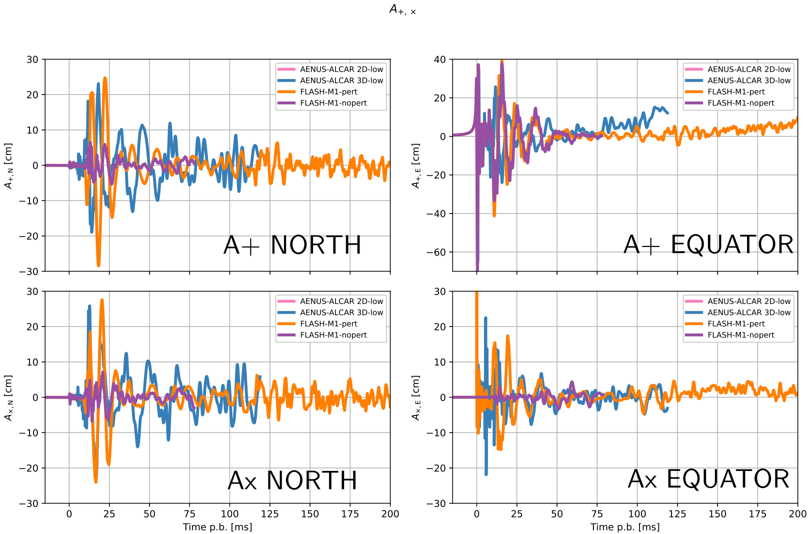
Neutrino emission: $\bar{\nu}_e$



Neutrino emission: ν_x



Gravitational waves



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