Numerical models of magnetorotational core-collapse supernovae explosions

Dynamics, gravitational waves, neutrinos, and explosive nucleosynthesis

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Core-collapse Supernovae

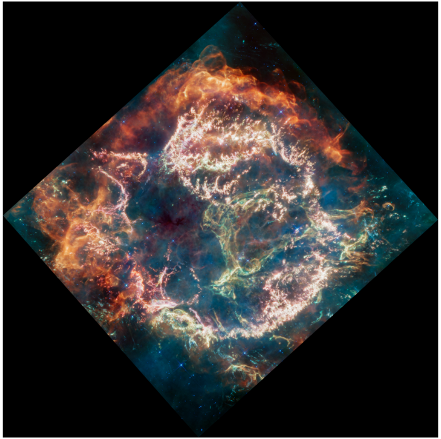
- Explosive end-of-life product of massive stars ($M \gtrsim 8 M_\odot$)
- Formation of stellar compact objects
- Dynamical feedback on galaxy evolution
- Explosive nucleosynthesis $\Rightarrow$ chemical evolution
- Sources of gravitational waves and neutrinos

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

Neutrinos ($\sim 99\%$)

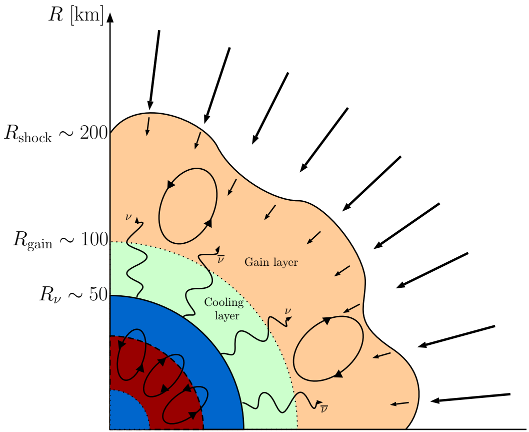
Ejecta ($\sim 1\%$)

Gravitational waves ($\sim 10^{-8}$)



Credit: NASA, ESA, CSA

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

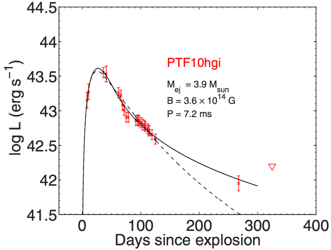
Total luminosity

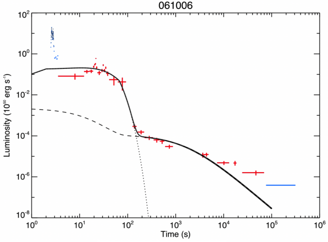
- Typical supernova: 10^{49} erg
- Superluminous SN: 10^{51} erg

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

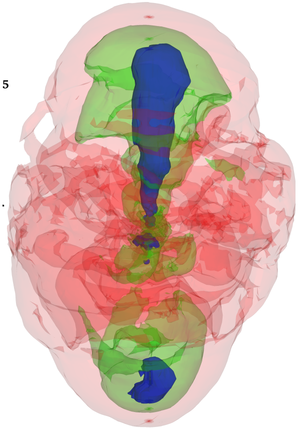
Main mechanism

- 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)

How does the magnetic field topology affect the explosion?



Bugli et al. (2021)

3D MHD explosion models

(Bugli et al. 2021)

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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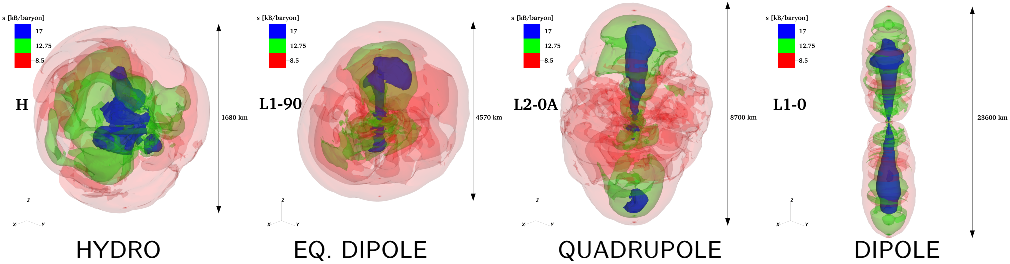
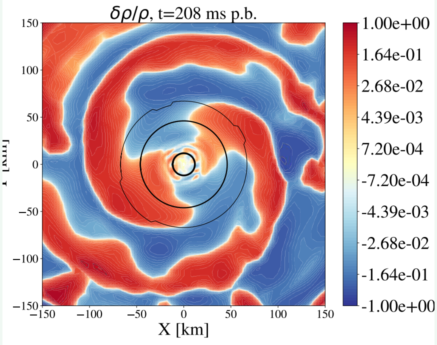


More magnetic flux at the poles $\Rightarrow$ **stronger explosions** and faster shocks

Corotational instabilities

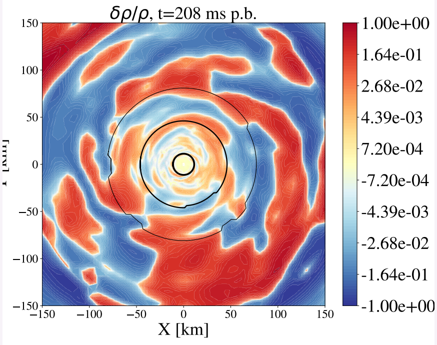
(Bugli et al. 2023)

Hydrodynamic case



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

Magnetized case

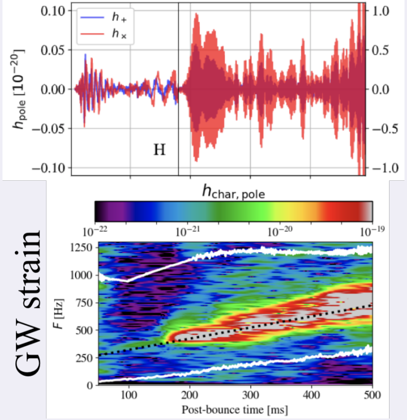


- No large-scale spiral structures
- Turbulent density perturbations
- Weak dependence on magnetic field

GW emission

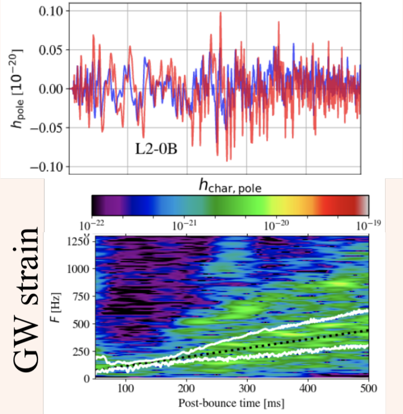
(Bugli et al. 2023)

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)

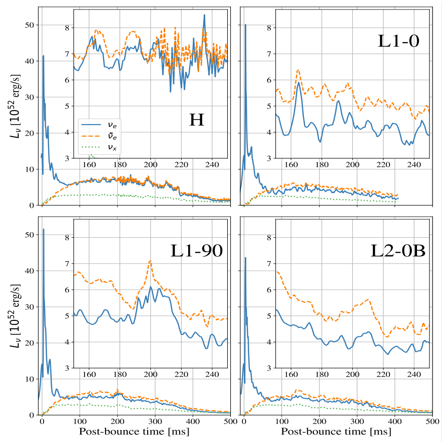


- No low $T/|W|$ burst, broad-band emission
- $h \sim 5 \times 10^{-22}$ for $D = 10$ kpc
- Strong transport of angular momentum

Neutrino emission

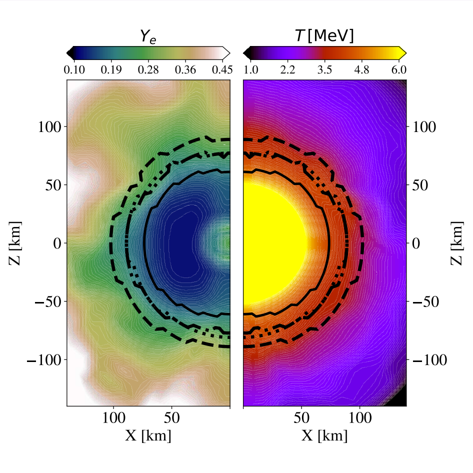
(Bugli et al. 2023)

Lightcurves (equator)



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

Y_e distribution (hydro)



- More compact PNS ⇒ higher mean energies

Neutrino emission

(Bugli et al. 2023)

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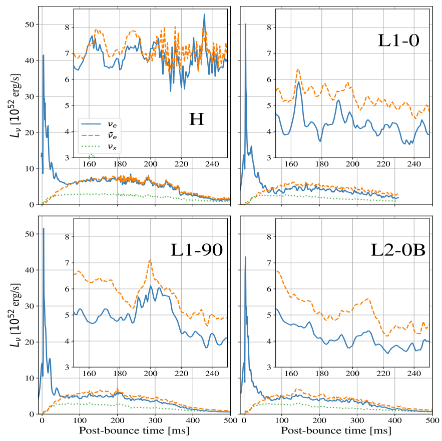

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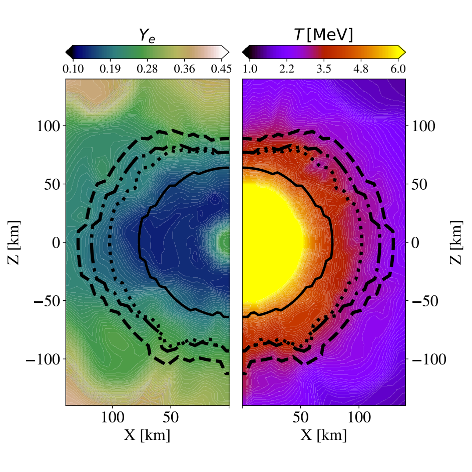
Y_e distribution (magnetized)



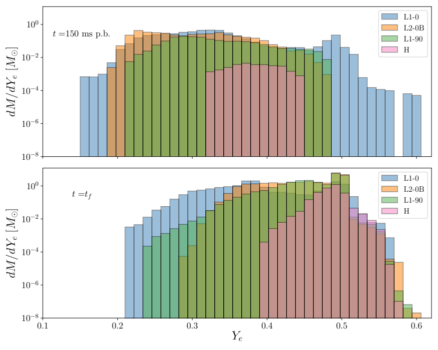
- Outward transport of a.m. $\Rightarrow$ lower Y_e

Explosive nucleosynthesis

(Reichert,Bugli et al. 2024)

Ejecta composition

- More neutron-rich material for magnetized models
- Lowest Y_e for dipolar fields
- Neutron-rich material is expelled promptly only for strong MR explosions



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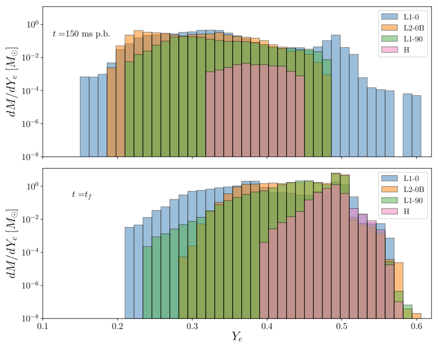
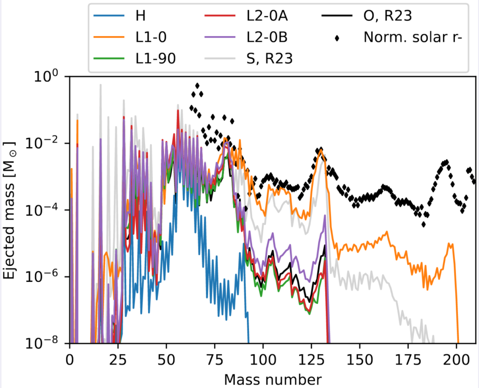
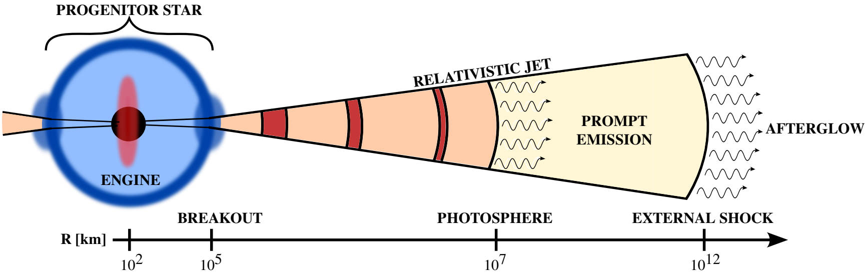


- All magnetized models produce 1st r-process peak elements
- 2nd peak reproduced only for the aligned dipole
- No actinides, consistent with recent 3d models (Reichert et al., 2023) and 2d models (Reichert et al., 2021)



The modeling of collapsar GRBs



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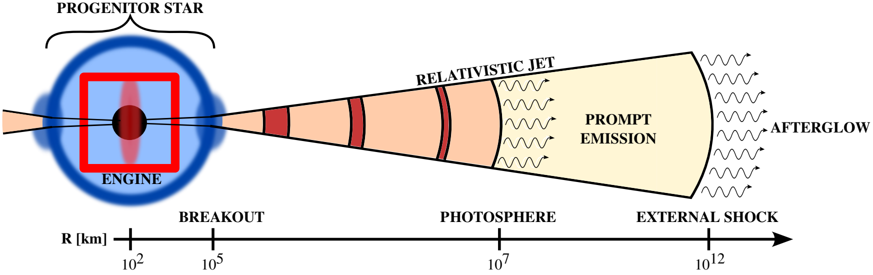

Central engine

- Stellar evolution models with range of masses and rotation
- (GR)MHD models, ν transport, nuclear EoS
- Up to $\sim$ seconds (Siegel and Metzger, 2018; Powell et al., 2023; Shibagaki et al., 2024)

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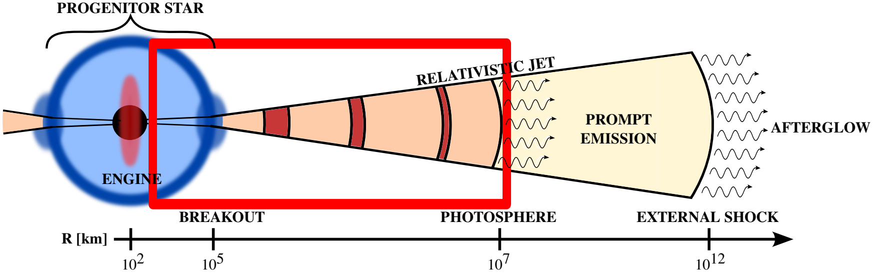

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Relativistic jet

- Jet propagation models with energy injection (Mattia et al., 2023)
- (G)RMHD models (?)
- Up to $\sim$ 10s seconds
- GPU+GRMHD $\Rightarrow$ BH+jet models (Gottlieb et al., 2021, 2022)

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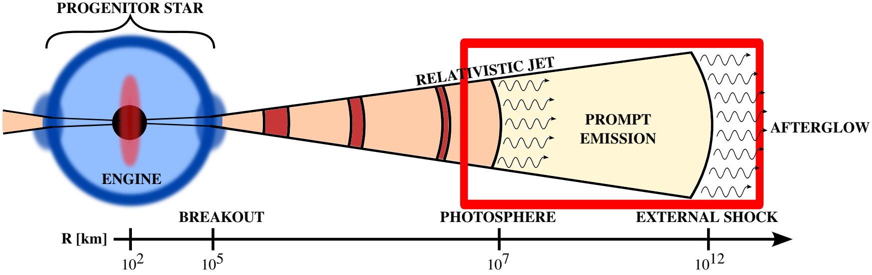

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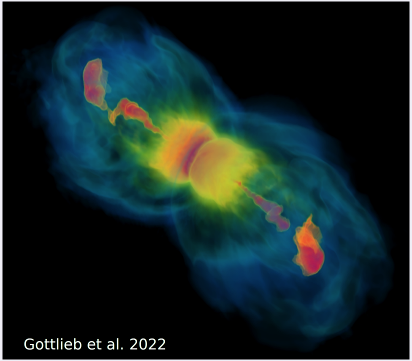
Observations

- Semi-analytical emission models (prompt, afterglow)
- Simplified assumptions on jet and engine's dynamics
- Radiative R(M)HD (Duffell and MacFadyen, 2013; Duffell, 2016; Ayache et al., 2022)

Tackling the large scale-separation problem

Ab-initio jet models

- First black hole-powered collapsar jets up to photosphere (Gottlieb et al., 2021, 2022)
- Self-consistent central engine formation?
- State-of-the-art GRB stellar progenitors?



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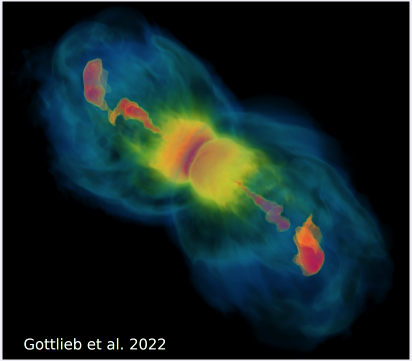
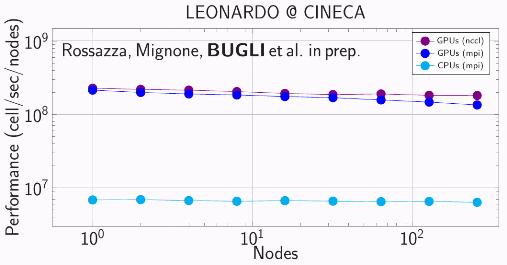


Enhancing code efficiency

- GPU-accelerated codes qualitatively impact the modeling (Liska et al., 2022; Lesur et al., 2023)
- High-order schemes increase the effective grid resolution (Berta et al., 2024; Mignone et al., 2024)
- GPU resistive GRMHD module for the `PLUTO` code (Bugli et al., in prep.)

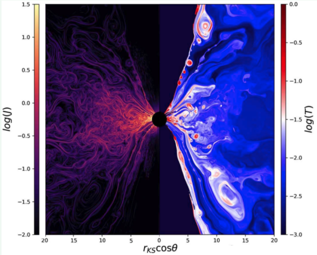


Dissipation and reconnection in accreting compact objects

- Magnetic reconnection ⇒ relativistic e^- ⇒ synchrotrone/IC
- Flares from Blazar jets (Sobacchi et al., 2023), disk coronal emission (Sironi and Beloborodov, 2020; Hakobyan et al., 2024), FRBs (Most and Philippov, 2022), GRBs (Zhang and Yan, 2011; Most et al., 2024)

Resistive GRMHD

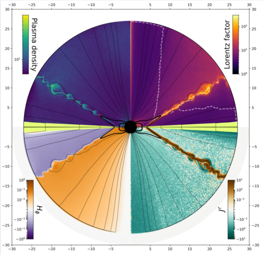
- Large temporal and spatial scales
- Accretion-ejection modeling
- No self-consistent magnetic dissipation



Ripperda et al. (2020)
(Qian et al., 2017; Ripperda et al., 2019; Mattia et al., 2023)

GR-PIC

- First-principles particle-fields coupling
- Self-consistent dissipation of magnetic energy
- Still challenging to model the large scales



El Mellah et al. (2022)
(Parfrey et al., 2019; Crinquand et al., 2021, 2022)

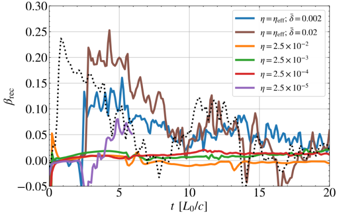
Effective resistivity model

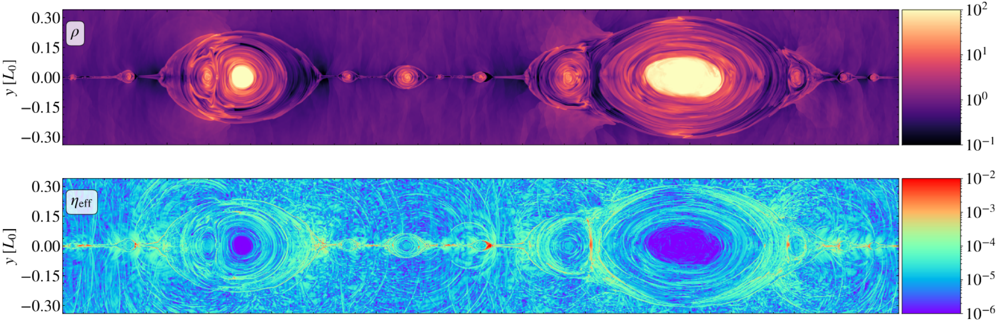
(Bugli et al., submitted)

- Direct measurement of resistivity from PIC simulations (Selvi et al., 2023)
- Formulation in terms of fluid quantity in the ResRMHD framework:

$$\eta_{\rm eff} = \frac{\bar{\delta}}{\bar{\rho}} \sqrt{\left(\bar{\delta}\partial_{\bar{y}} \bar{v}_y\right)^2 + \bar{e}_z^2} \ .$$

- Fast reconnection in quantitative agreement with kinetic models





Conclusions

- ✓ Qualitative impact of magnetic field topology on magnetorotational explosions
- ✓ 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
- ✓ Developments in bridging small and large scales (GPUs, kinetic closures for dissipation)

Perspectives

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Grazie della vostra attenzione!

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