Numerical models of magneto-rotational supernovae: dynamics, multi-messenger signals, and nucleosynthesis

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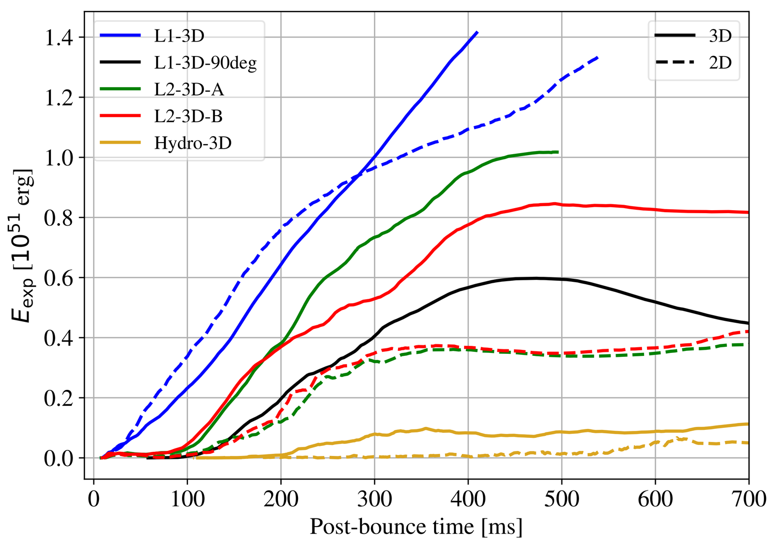
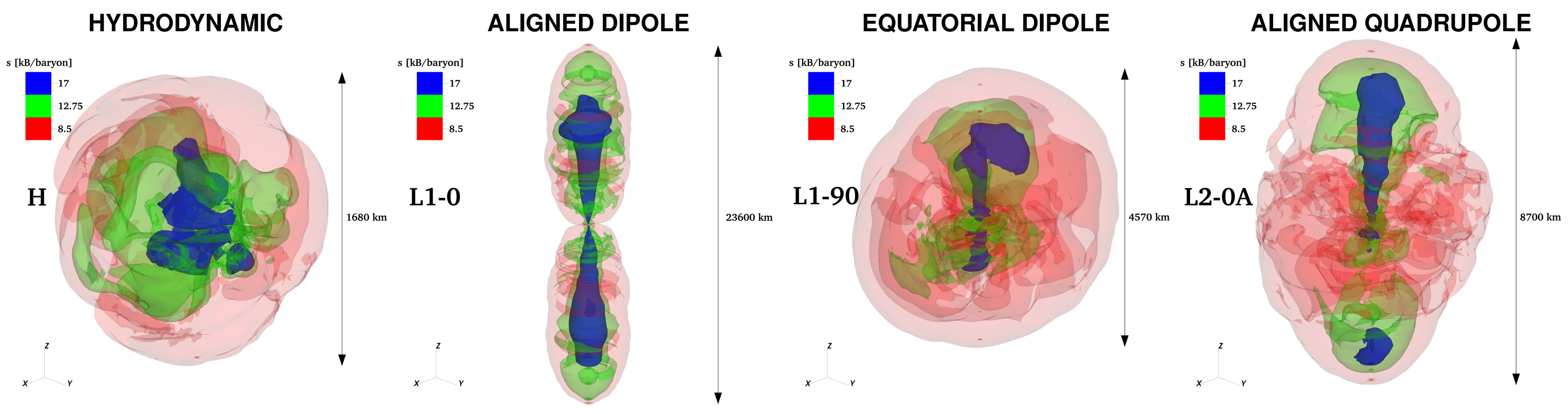
Abstract

The gravitational collapse of a massive star with a fast-rotating core sets the stage for the onset of magneto-rotational core-collapse supernovae (CCSN). The accreting central compact object (either a black hole or a proto-magnetar) is believed to be the central engine that can power up outstanding stellar explosions such as hypernovae and long gamma-ray bursts (GRBs). Current magnetohydrodynamic models allow one to make quantitative predictions on the properties of the compact remnant, the multi-messenger signatures of the explosion, the launching conditions of the jet, and the nucleosynthesis of new heavy elements contributing to the chemical evolution of galaxies. We present the results obtained by recent **3D magneto-rotational supernova models** that aim at characterizing the multi-faceted dynamics of the outstanding stellar explosion. We show how **different magnetic field configurations** during the gravitational collapse affect not only the explosion dynamics and the compact remnant properties, but also the associated multi-messenger emission. We also present recent **state-of-the-art explosive nucleosynthesis calculations** based on the 3D CCSN models, demonstrating the profound impact of magnetic field topology in determining the efficiency of r-processes during the explosion, the production of heavy elements, and thus the chemical evolution of galaxies. In particular, only for aligned dipolar magnetic fields the supernova ejecta are sufficiently neutron-rich to produce elements beyond atomic number A∼130. Moreover, **the impact of the magnetic field's dynamics dominates over the uncertainties related to nuclear physics inputs** used for the nucleosynthesis calculations, demonstrating the paramount importance of accurately modeling the dynamics of central engine.

Progenitor and explosion dynamics [3]

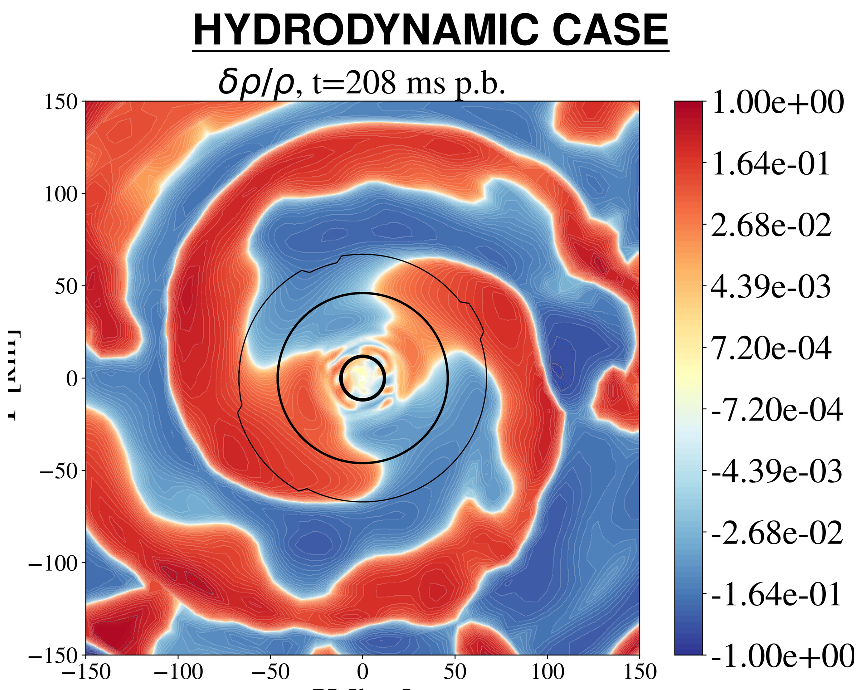
- $M_{\rm ZAMS} = 35M_\odot$, Iron core of $\sim 2.1M_\odot$ [1]
- 3D relativistic MHD simulations with the `AENUS-ALCAR` code [2]
- Rapid rotation from stellar evolution, different magnetic configurations
- Stronger explosions for lower multipoles
- Misaligned configurations are less efficient
- 3D generally more energetic than corresponding 2D models



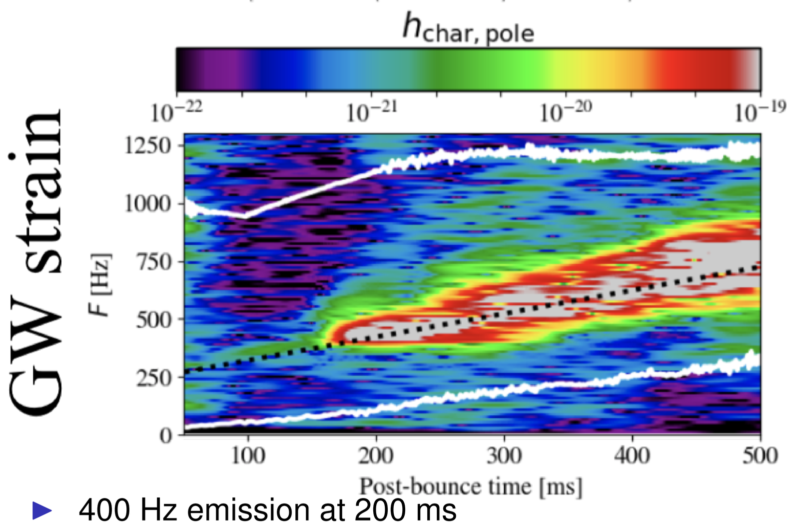


Gravitational waves [5]

Hydrodynamic case

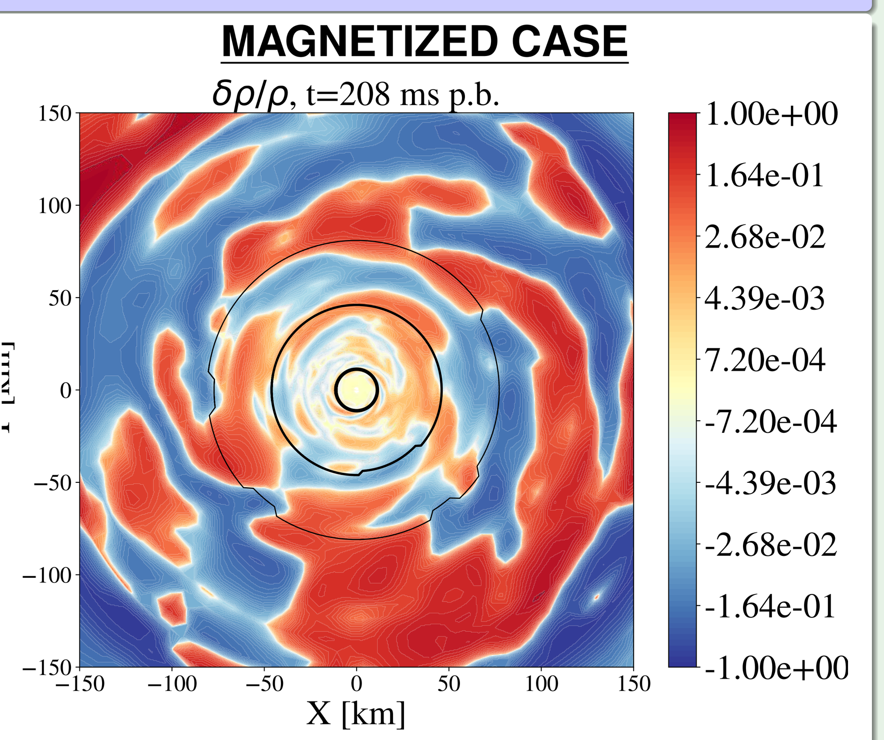


- Spiral structures forming with fast rotation
- Onset of the low $T/|W|$ instability
- Observed for different progenitors/rotation profiles [4]

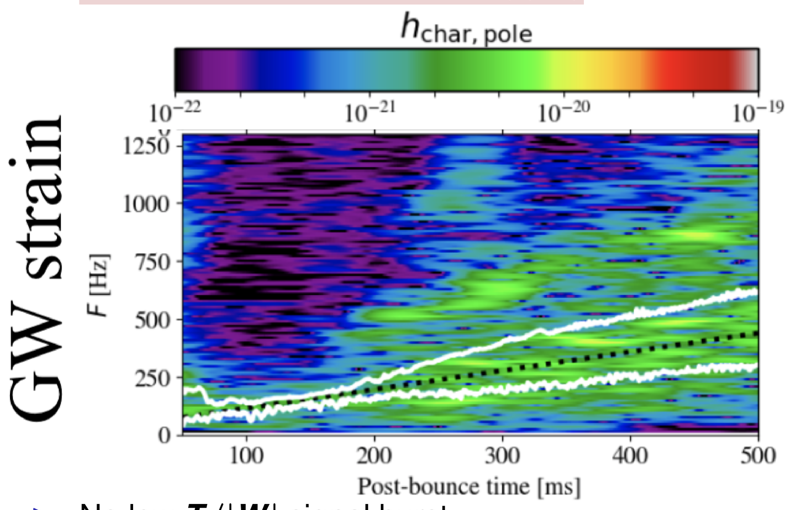


- 400 Hz emission at 200 ms
- $h \sim 10^{-20}$ for $D = 10$ kpc
- Strong correlation with PNS modes

Magnetized case

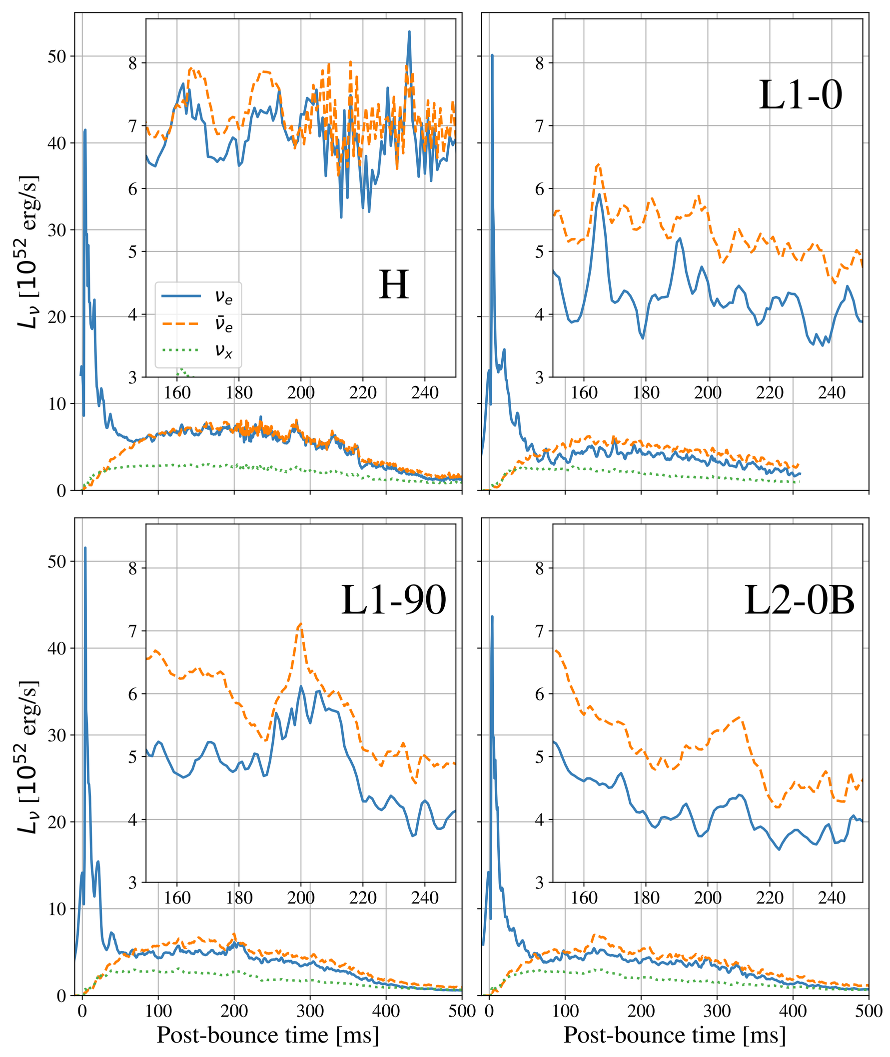


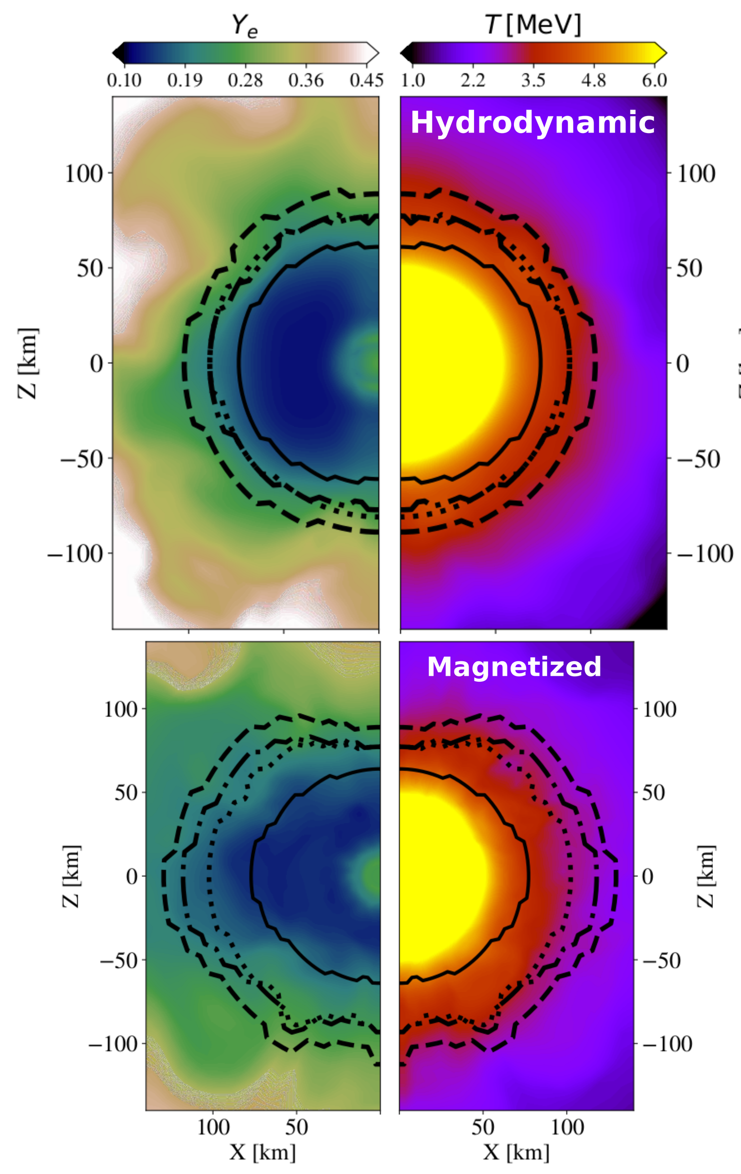
- No large-scale spiral structures
- Smaller-scale density perturbations
- Weak dependence on magnetic field
- B field stabilizes against low $T/|W|$



- No low $T/|W|$ signal burst
- $h \sim 5\times10^{-22}$ for $D = 10$ kpc
- Magnetic transport of angular momentum

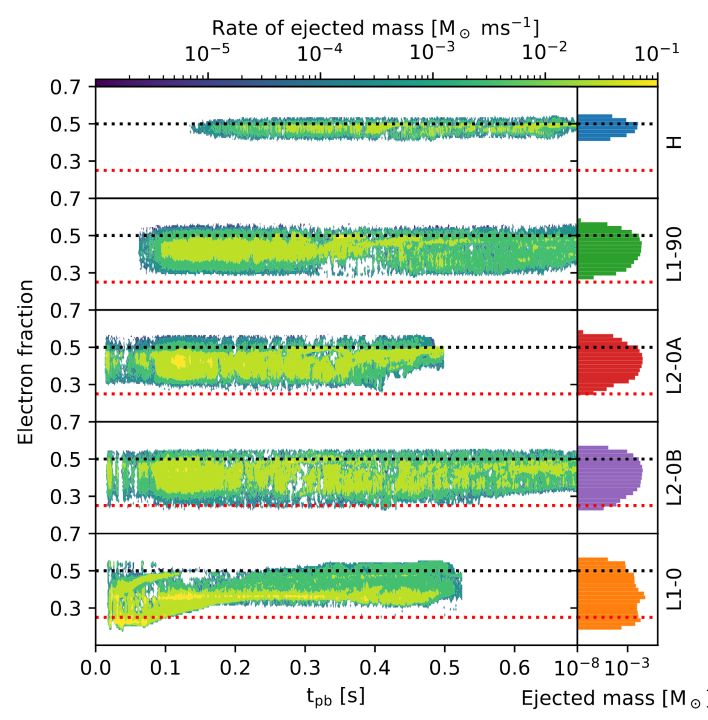
Neutrino emission [5]

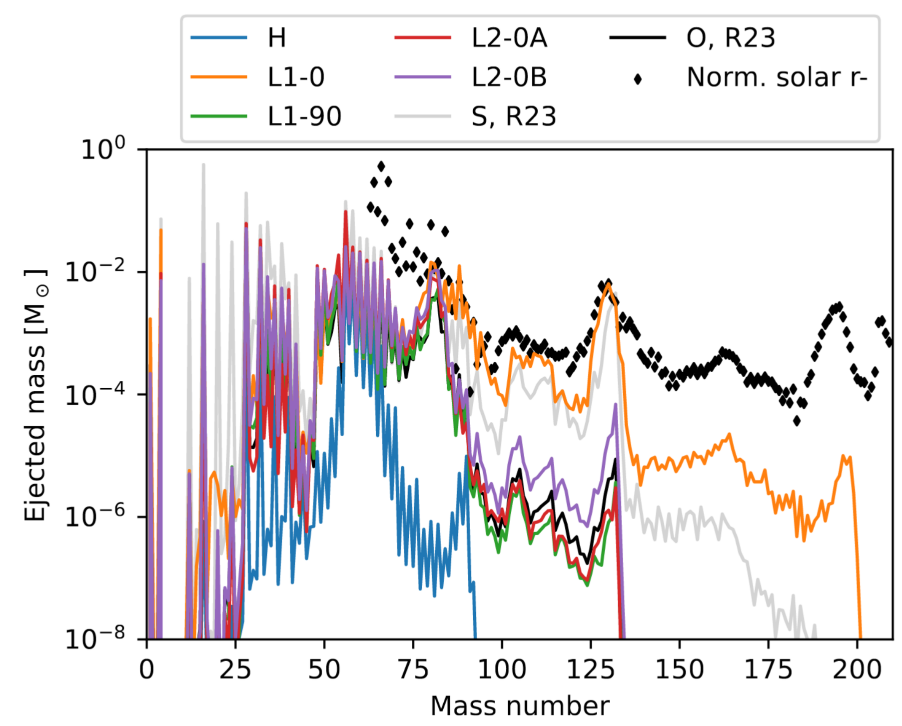




- Systematic lower neutrino luminosity in magnetized models along the equator (detectable by current neutrino detectors [6])
- More compact PNS without magnetic fields ⇒ neutrino decouple at higher temperatures ⇒ higher mean energies
- ν_e-$\bar\nu_e$ asymmetry in magnetized models (higher luminosity for $\bar\nu_e$)
- Outward transport of angular momentum ⇒ lower Y_e ⇒ contraction of $\bar\nu_e$ neutrinosphere.

Explosive nucleosynthesis [7]





- Calculations performed with WinNet nuclear reaction network using $\sim$ **6500** nuclei [8]
- More neutron-rich material for magnetized models (expelled promptly by the magnetorotational mechanism)
- All magnetized models produce 1st r-process peak elements, but lowest Y_e for aligned dipolar fields
- 2nd peak and some 3rd peak elements produced only for most powerful explosions (aligned dipole), but still no actinides
- Consistent with previous 3d models [9] but lower r-process elements production compared to 2d models [10]
- Uncertainties on the network nuclear physics are only marginally impactful

Results and Future Perspectives

- ✓ Non-dipolar magnetic field produce weaker explosions and more massive PNS
- ✓ Intense magnetic fields quench strong GW bursts coming from corotational hydrodynamic instabilities
- ✓ Neutrino signals impacted by the magnetic transport of angular momentum
- ✓ Only with strong dipolar magnetic fields very heavy elements (A≳150) are synthesized

- ○ Extension to progenitors with moderate rotation and magnetic fields
- ○ Assess impact of state-of-the-art nuclear equations of state
- ○ Analysis of GW-neutrino correlations and their detectability
- ○ Explore the impact of magnetic fields from PNS dynamo scaling relations

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