Complex magnetic field topologies in core-collapse supernovae

Matteo Bugli[1]
Collaborators: J. Guilet[1], R. Raynaud[1], A. Reboul-Salze[1],
M. Obergaulinger[2,3], P. Cerdá-Durán[3], M. À. Aloy[3]

[1] Astrophysics Department, IRFU/CEA-Saclay, Gif-sur-Yvette, Paris
[2] Theoriezentrum, Technische Universität Darmstadt
[3] Departament d'Astronomia i Astrofisica, Universiat de València

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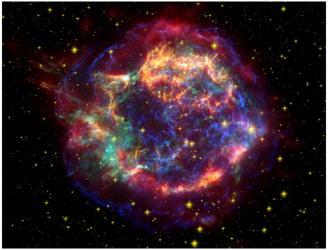
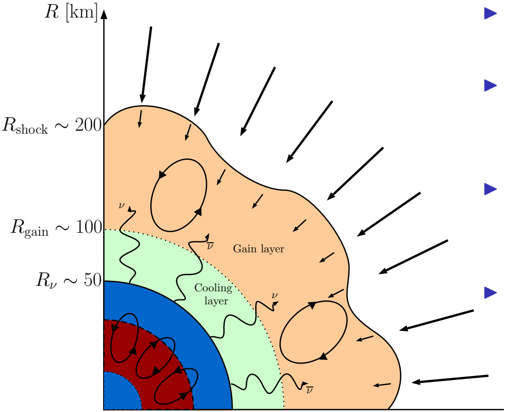
Core-collapse Supernovæ

- gravitational collapse of a massive star (unstable iron core)
- shock formation when nuclear densities are reached (stalling)
- shock expansion and ejection of unbound material (explosion)
- Key feature: revival of the stalling shock.



Credit: NASA/JPL-Caltech

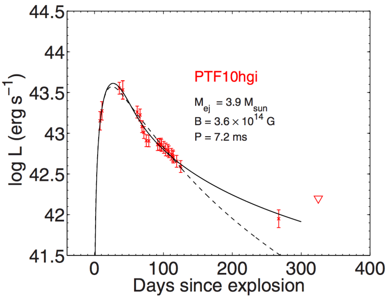
Neutrino-heating mechanism



- PNS contraction ⇒ higher ν energies
- 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 aid the explosion (i.e. convection, SASI)

CCSN and magnetic fields (see Philipp Mösta's talk)

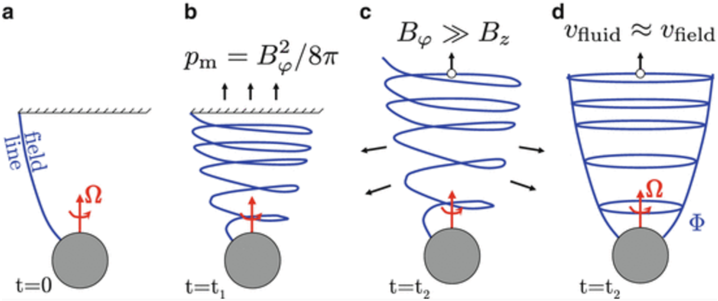
- Kinetic energies: 10^{51} ergs; rare Hypernovæ/LGRBs $\sim 10^{52}$ ergs
- Luminosities: 10^{49} ergs; Superluminous SN $\sim 10^{51}$ ergs.
- Need for extra energy reservoir $\Rightarrow$ rotation and magnetic fields of a millisecond magnetar? (Burrows et al., 2007; Bucciantini et al., 2009; Metzger et al., 2011; Takiwaki et al., 2009; Takiwaki and Kotake, 2011; Obergaulinger and Aloy, 2017)



(Inserra et al., 2013)

Relativistic outflows

- Magnetic fields are crucial in the launch and collimation of relativistic outflows (Blandford and Znajek, 1977; Uzdensky and MacFadyen, 2006; Tchekhovskoy et al., 2011).
- Key parameters: central object rotation, radial magnetic field flux.

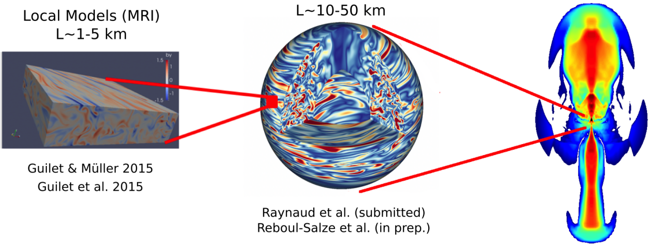


(Tchekhovskoy, 2015)

Magnetar vs Collapsar

- Two possible scenarios for magnetic energy extraction:
    - Millisecond magnetar (Metzger et al., 2011)
    - Collapsar (Woosley, 1993)
- Massive progenitors do not necessarily lead to direct collapse (Dessart et al., 2008; Obergaulinger and Aloy, 2017)
- Understanding the accretion dynamics onto the PNS is crucial
- Successful explosions and collapse to BH may not be mutually exclusive
- Many uncertainties on the characteristics of magnetic field at shock formation:
    - From stellar progenitor or forming PNS?
    - Dipolar? Complex topology?

The MagBurst project



Local Models (MRI)
L~1-5 km

Guilet & Müller 2015
Guilet et al. 2015

Global Models
(Convection and MRI)
L~10-50 km

Raynaud et al. (submitted)
Reboul-Salze et al. (in prep.)

Magneto-rotational
supernova explosion
L~100-10000 km

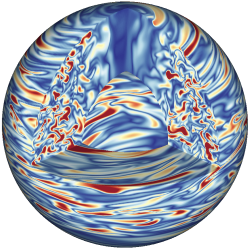
Bugli et al. (submitted)

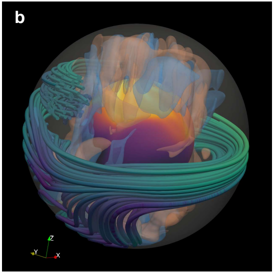
European Research Council
Established by the European Commission

- Amplification of magnetic field and magnetar formation
- Multi-scale problem, interconnected steps
- Impact of PNS dynamos on the explosion

Connecting small and large scales

- Fields amplified to magnetar-like strength ($10^{14} - 10^{15}$ G).
- Topology: non-dipolar fields produced by dynamos.
- Time evolution: delay between the bounce and the rise of the magnetic field.
- At what stages can the amplified field affect the shock revival?





MRI and convection driven dynamos (see Alexis' and Raphaël's talks)

Initial magnetic field: pure dipole?

- Poor constraints from both observations and evolutionary models on the initial field.
- Quasi-uniform field up to $r_0 \sim 10^3$km, then magnetic dipole (Suwa et al., 2007):

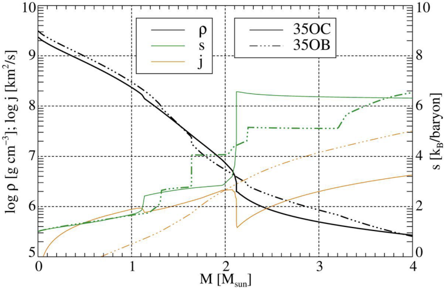
$$A_\phi = \frac{B_0}{2} \frac{r_0^3}{r^3 + r_0^3} r \sin\theta$$

- Progenitor *original* field from 1D stellar evolution (Woosley and Heger, 2006)
- Superimposed toroidal field (Obergaulinger and Aloy, 2017):

$$B_\phi = B_0 \frac{r_0^3}{r^3 + r_0^3} r \cos\theta$$

The progenitor: 35OC (Woosley and Heger, 2006)

- $M_{\rm ZAMS} = 35 M_\odot$, mass at collapse $\sim 28 M_\odot$
- Iron core of $\sim 2.1 M_\odot$, surrounded by $\sim 4 M_\odot$ of convective zone
- Original rotation profile from stellar evolution, rapid rotation



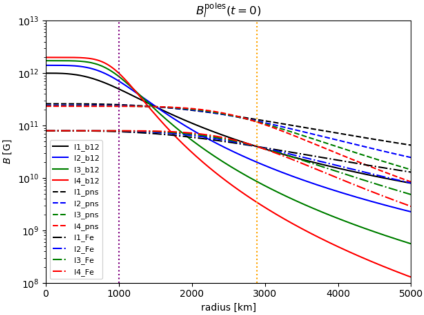
Initial magnetic field

- Generalized multipolar expansion:

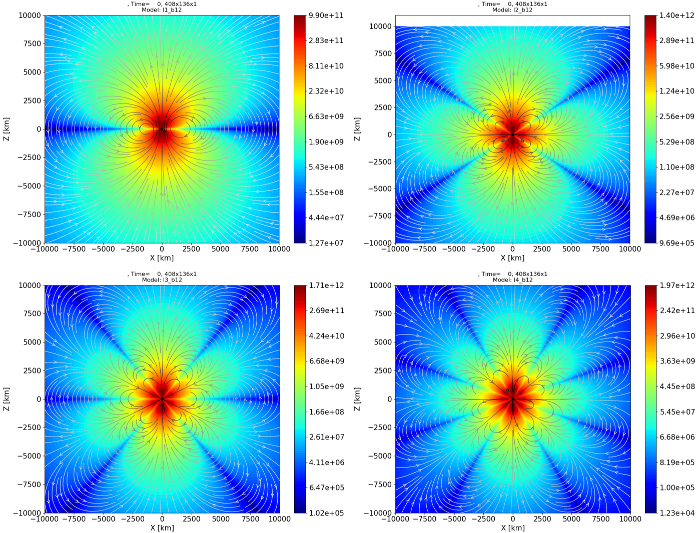
$$A_{\phi,l} = B_0 \frac{\sqrt{l}}{2l+1} \frac{r_0^{l+2}}{r^{l+2}+r_0^{l+2}} r \frac{P_{l-1}(\cos\theta) - P_{l+1}(\cos\theta)}{\sin\theta}$$

- Radial magnetic field strength at the poles:

$$|\boldsymbol{B}_l(r,\theta=0)| = \sqrt{l}\,\frac{B_0}{1+(r/r_0)^{l+2}}$$



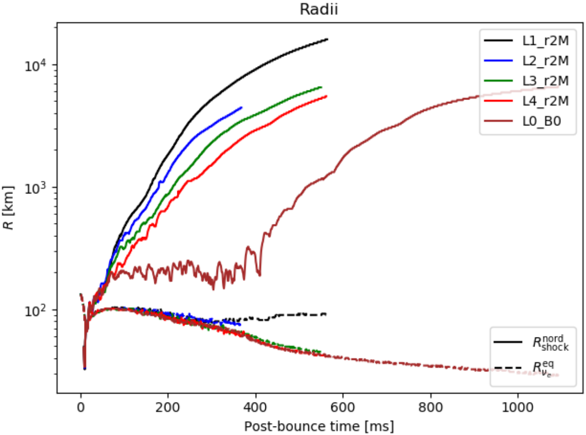
Comparison: different multipoles (Bugli et al., submitted)



Onset of the explosion $(r_0 = 2.9 \times 10^8\mathrm{cm},\ B_0 = 8 \times 10^{10}\mathrm{G})$

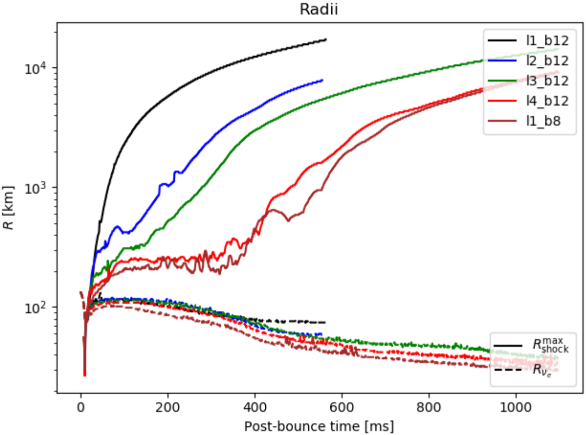
Shock radii - large r_0 ($r_0 = 2.9 \times 10^8$cm, $B_0 = 8 \times 10^{10}$G)

- Onset of explosion onset at the same time
- Slower expansion for higher multipoles



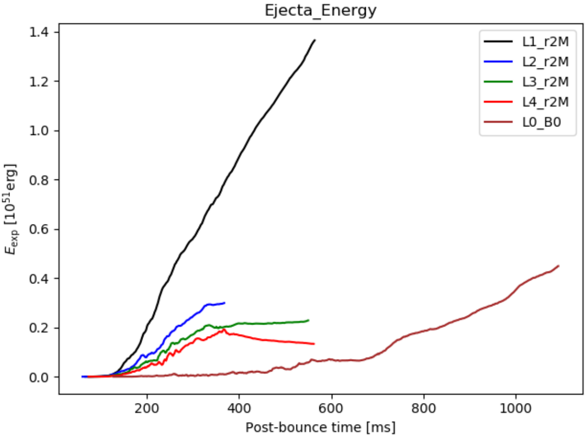
Shock radii - small r_0 ($r_0 = 10^8$cm, $B_0 = 10^{12}$G)

- Longer stalling phase for higher multipoles (faster radial decay)



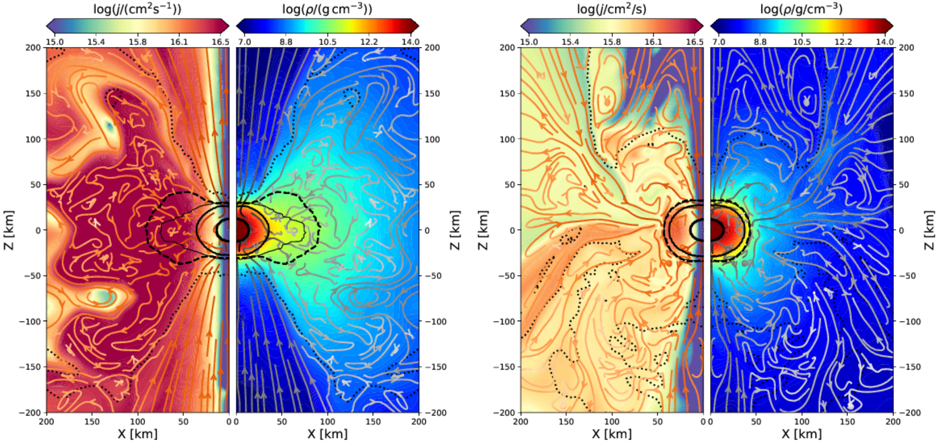
Explosion energy $(r_0 = 2.9 \times 10^8\text{cm}, B_0 = 8 \times 10^{10}\text{G})$

- Less energetic explosion and shallower increase of energy for higher multipoles

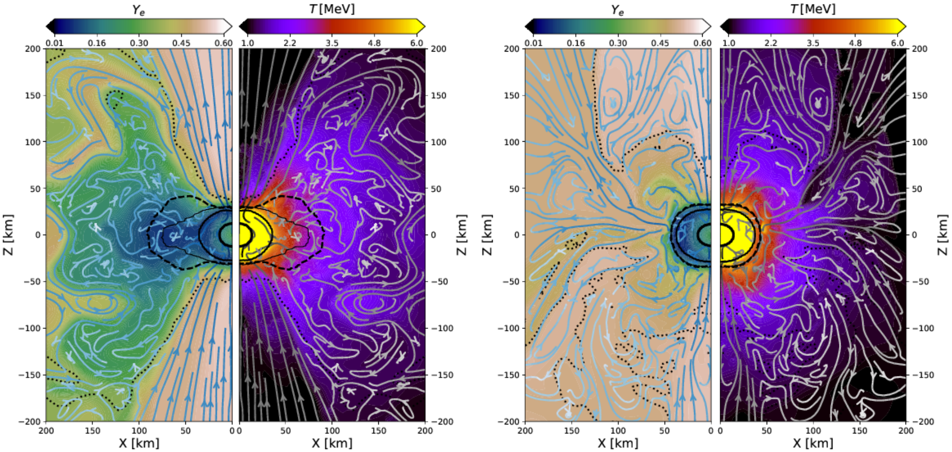


Magnetic/thermal pressure ($r_0 = 2.9 \times 10^8$cm, $B_0 = 8 \times 10^{10}$G)

$l = 1$ vs $l = 4$ ($r_0 = 2.9 \times 10^8$cm, $B_0 = 8 \times 10^{10}$G)

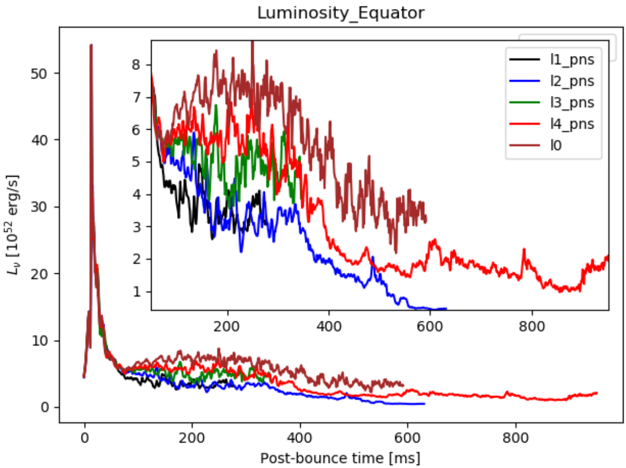


$l = 1$ vs $l = 4$ ($r_0 = 2.9 \times 10^8$cm, $B_0 = 8 \times 10^{10}$G)



Neutrino luminosities along equator

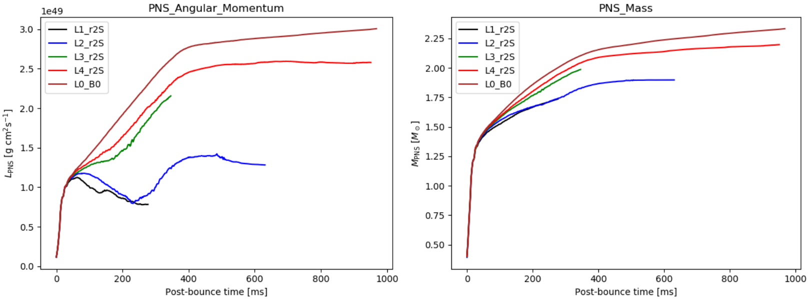
More oblate PNS $\Rightarrow$ lower surface temperature $\Rightarrow$ less energetic ν



PNS mass and spin ($r_0 = 2.9 \times 10^8$cm, $B_0 = 2.6 \times 10^{11}$G)

Higher multipole order $\Rightarrow$ closer to hydrodynamic limit:

- faster increase of total angular momentum (weaker magnetic braking)
- faster increase of total mass



Conclusions

- Different multipolar configurations have a strong impact on the explosion dynamics: higher $l \Rightarrow$ less energetic (delayed) explosion, less collimated ejecta
- Impact on the PNS formation:
  - less oblate surface, different Y_e distribution
  - shallower distribution of angular momentum
  - faster rotation, more massive PNS
- Radial extent of the magnetic field can also affect the dynamics (different degree of compression)

Perspectives

- Extension to later times: stable NS or collapse to BH?
- Extension to 3D: misaligned multipolar configurations, $m > 0$.
- Subgrid modeling of the unresolved dynamo in the PNS.

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ございました!

References I

Ardeljan, N. V., Bisnovatyi-Kogan, G. S., and Moiseenko, S. G. (2005). Magnetorotational supernovae. *Monthly Notices of the Royal Astronomical Society*, 359(1):333.

Blandford, R. D. and Znajek, R. L. (1977). Electromagnetic extraction of energy from Kerr black holes. *\mnras*, 179:433–456.

Bucciantini, N., Quataert, E., Metzger, B. D., Thompson, T. A., Arons, J., and Del Zanna, L. (2009). Magnetized relativistic jets and long-duration GRBs from magnetar spin-down during core-collapse supernovae. *Monthly Notices of the Royal Astronomical Society*, 396:2038–2050.

Burrows, A., Dessart, L., Livne, E., Ott, C. D., and Murphy, J. (2007). Simulations of Magnetically Driven Supernova and Hypernova Explosions in the Context of Rapid Rotation. *The Astrophysical Journal*, 664(1):416.

References II

Dessart, L., Burrows, A., Livne, E., and Ott, C. D. (2008). The Proto-Neutron Star Phase of the Collapsar Model and the Route to Long-Soft Gamma-Ray Bursts and Hypernovae. *\apjl*, 673:L43.

Inserra, C., Smartt, S. J., Jerkstrand, A., Valenti, S., Fraser, M., Wright, D., Smith, K., Chen, T.-W., Kotak, R., Pastorello, A., Nicholl, M., Bresolin, F., Kudritzki, R. P., Benetti, S., Botticella, M. T., Burgett, W. S., Chambers, K. C., Ergon, M., Flewelling, H., Fynbo, J. P. U., Geier, S., Hodapp, K. W., Howell, D. A., Huber, M., Kaiser, N., Leloudas, G., Magill, L., Magnier, E. A., McCrum, M. G., Metcalfe, N., Price, P. A., Rest, A., Sollerman, J., Sweeney, W., Taddia, F., Taubenberger, S., Tonry, J. L., Wainscoat, R. J., Waters, C., and Young, D. (2013). Super-luminous Type Ic Supernovae: Catching a Magnetar by the Tail. *The Astrophysical Journal*, 770(2):128.

References III

Just, O., Obergaulinger, M., and Janka, H.-T. (2015). A new multidimensional, energy-dependent two-moment transport code for neutrino-hydrodynamics. *\mnras*, 453:3386–3413.

Metzger, B. D., Giannios, D., Thompson, T. A., Bucciantini, N., and Quataert, E. (2011). The protomagnetar model for gamma-ray bursts. *Monthly Notices of the Royal Astronomical Society*, 413(3):2031.

Mösta, P., Richers, S., Ott, C. D., Haas, R., Piro, A. L., Boydstun, K., Abdikamalov, E., Reisswig, C., and Schnetter, E. (2014). Magnetorotational Core-collapse Supernovae in Three Dimensions. *The Astrophysical Journal*, 785:L29.

Obergaulinger, M. and Aloy, M. A. (2017). Evolution of the surface magnetic field of rotating proto-neutron stars. *Journal of Physics: Conference Series*, 932:012043.

References IV

Sawai, H., Kotake, K., and Yamada, S. (2005). Core-Collapse Supernovae with Nonuniform Magnetic Fields. *The Astrophysical Journal*, 631(1):446.

Suwa, Y., Takiwaki, T., Kotake, K., and Sato, K. (2007). Magnetorotational Collapse of Population III Stars. *Publications of the Astronomical Society of Japan*, 59(4):771–785.

Takiwaki, T. and Kotake, K. (2011). GRAVITATIONAL WAVE SIGNATURES OF MAGNETOHYDRODYNAMICALLY DRIVEN CORE-COLLAPSE SUPERNOVA EXPLOSIONS. *The Astrophysical Journal*, 743(1):30.

Takiwaki, T., Kotake, K., and Sato, K. (2009). Special Relativistic Simulations of Magnetically Dominated Jets in Collapsing Massive Stars. *The Astrophysical Journal*, 691(2):1360.

References V

Tchekhovskoy, A. (2015). Launching of Active Galactic Nuclei Jets. In Contopoulos, I., Gabuzda, D., and Kylafis, N., editors, *The Formation and Disruption of Black Hole Jets*, Astrophysics and Space Science Library, pages 45–82. Springer International Publishing, Cham.

Tchekhovskoy, A., Narayan, R., and McKinney, J. C. (2011). Efficient generation of jets from magnetically arrested accretion on a rapidly spinning black hole. *\mnras*, 418:L79–L83.

Uzdensky, D. A. and MacFadyen, A. I. (2006). Stellar Explosions by Magnetic Towers. *The Astrophysical Journal*, 647(2):1192.

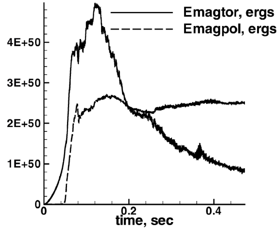
Woosley, S. E. (1993). Gamma-ray bursts from stellar mass accretion disks around black holes. *The Astrophysical Journal*, 405:273–277.

Woosley, S. E. and Heger, A. (2006). The Progenitor Stars of Gamma-Ray Bursts. *The Astrophysical Journal*, 637(2):914.

Quadrupole in the literature: contradicting results

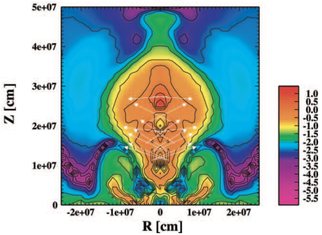
Ardeljan et al. (2005)

- Magnetic field "turned on" after bounce
- Explosion energy: 0.6×10^{51} ergs
- Strong ejection along the equator



Sawai et al. (2005)

- Pre-collapse magnetic field
- Explosion energy: $(0.24 - 0.59) \times 10^{51}$ ergs
- More collimated and faster polar outflows

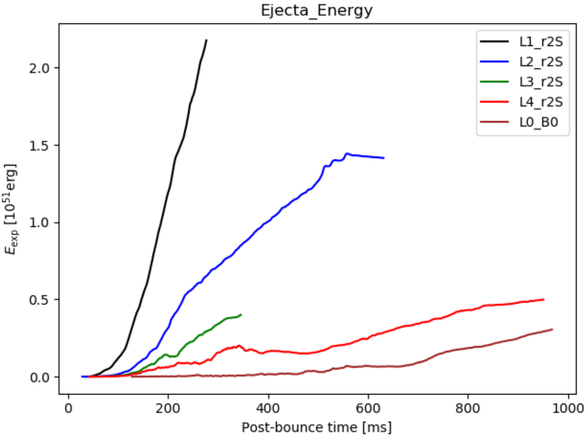


Numerical tool

- Multi-D relativistic MHD code ALCAR (Just et al., 2015)
- TOV gravity
- Multi-D spectral M1 ν-transport
- Equation of State:
    - High density ($\rho > 10^7$g/cm^3): LS220
    - Low density ($\rho < 10^7$g/cm^3): photons, relativistic and degenerate e^-/e^+, non-relativistic baryons (^{28}Si for $T < 0.44$MeV, ^{56}Ni otherwise)
- High-order reconstruction schemes, angular coarsening

Explosion energy $(r_0 = 2.9 \times 10^8\text{cm}, B_0 = 2.6 \times 10^{11}\text{G})$

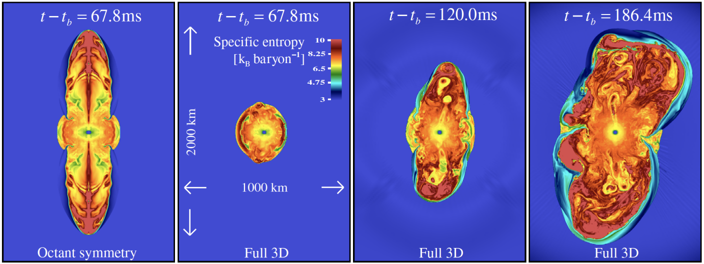
- Less energetic explosion and shallower increase of energy for higher multipoles



3D models

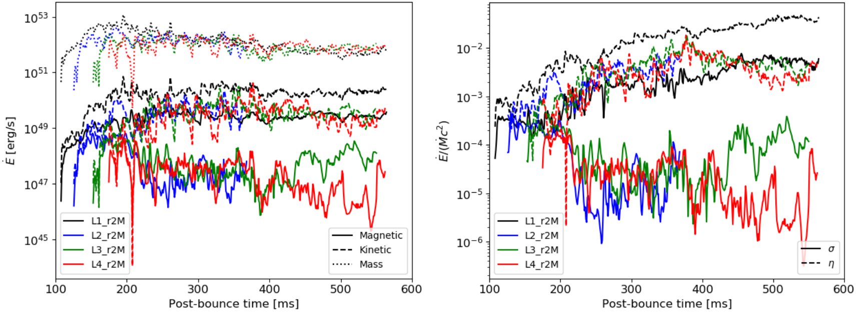
Qualitative differences between 2D and 3D magnetized models:

- wrong hydrodynamic turbulent cascade
- inhibition of non-axisymmetric instabilities: kink modes (Mösta et al., 2014)
- Cowling's anti-dynamo theorem

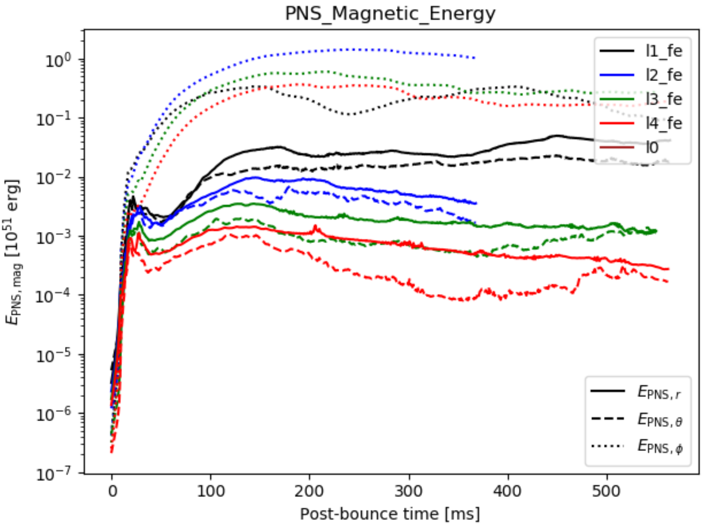


Y_e: $(l = 1)$ vs. $(l = 4)$ $(r_0 = 2.9 \times 10^8\text{cm}, B_0 = 8 \times 10^{10}\text{G})$

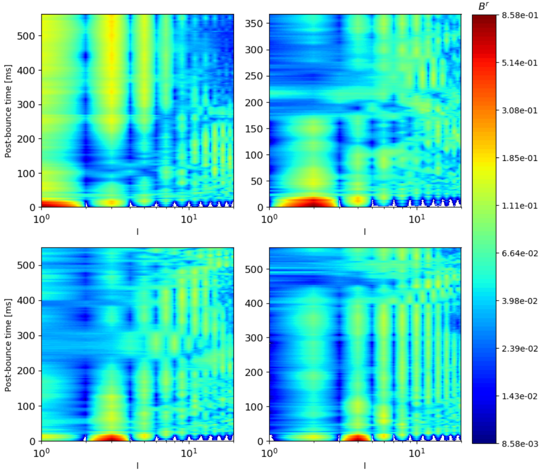
Baryon loading parameter - Magnetisation ($r_0 = 2.9 \times 10^8$cm, $B_0 = 8 \times 10^{10}$G)



PNS magnetic energy ($r_0 = 2.9 \times 10^8$cm, $B_0 = 8 \times 10^{10}$G)

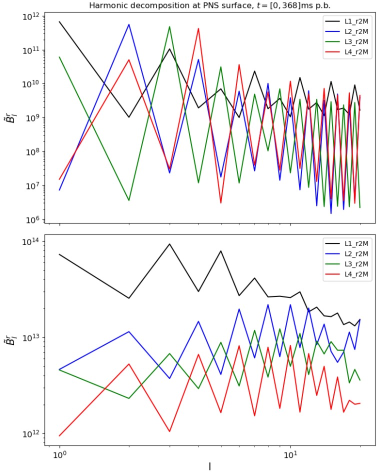


Harmonic distribution at $R_{\rm PNS}$ ($r_0 = 2.9 \times 10^8$cm, $B_0 = 8 \times 10^{10}$G)



Radial magnetic field (time vs. multipole order)

Harmonic distribution at $R_{\rm PNS}$ ($r_0 = 2.9 \times 10^8$cm, $B_0 = 8 \times 10^{10}$G)



Radial magnetic field spectra