The role of magnetic field topology in core-collapse supernovae simulations

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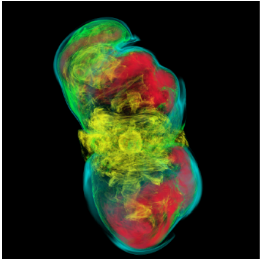
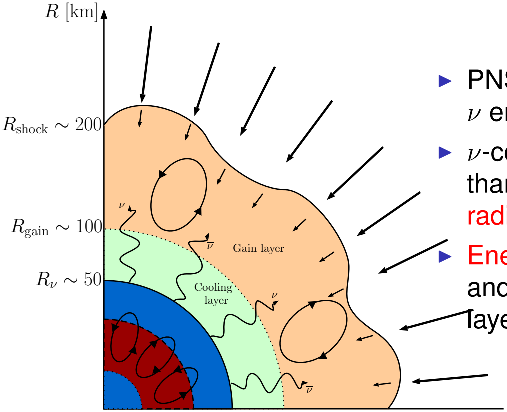
Core-collapse Supernovæ

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



Mösta et al. (2014)

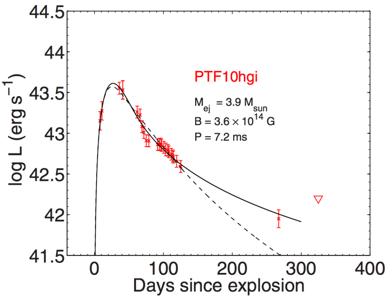
Neutrino-heating mechanism



- PNS contraction $\Rightarrow$ higher ν energies
- ν-cooling rate drops faster than ν-heating $\Rightarrow$ Gain radius
- Energy deposition by ν_e and $\bar{\nu}_e$ absorption in gain layer

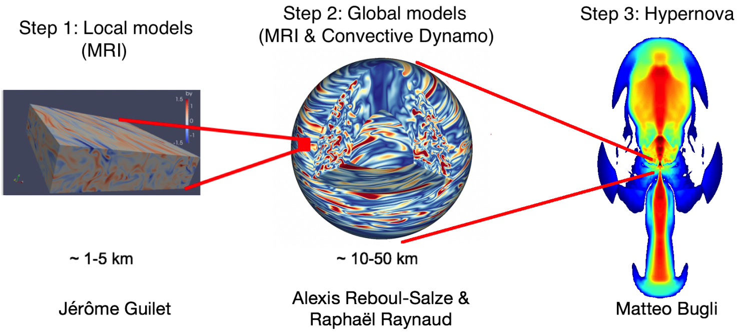
CCSN and magnetic fields

- 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 pulsar? (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)

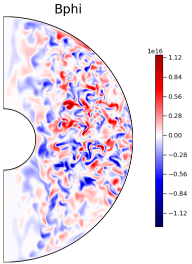
The MagBurst project

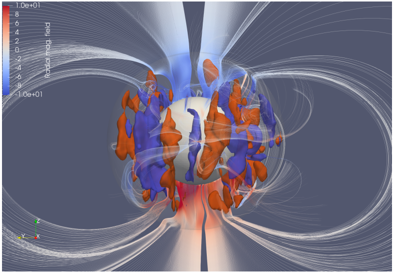


- Amplification of magnetic field and magnetar formation
- Multi-scale problem, interconnected steps
- How does the PNS dynamo affect the explosion properties?

Sub-grid modeling of the PNS dynamo

- 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?





Initial magnetic field: pure dipole?

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

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

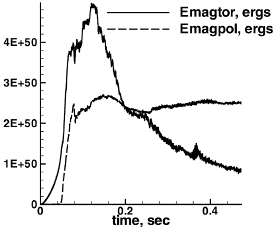
- Progenitor *original* field from 1D stellar evolution (Woosley and Heger, 2006)
- Superimposed toroidal field (Obergaulinger and Aloy, 2017):

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

Quadrupole in the literature: contradicting results

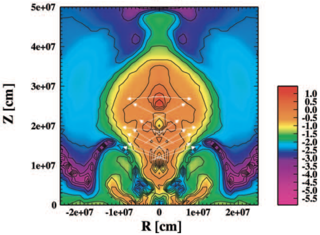
Ardeljan et al. (2005)

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



Sawai et al. (2005)

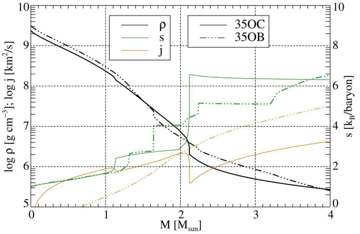
- Pre-collapse magnetic field
- Explosion energy: $(0.24 - 0.59) \times 10^{51}$ ergs
- More collimated and faster polar outflows

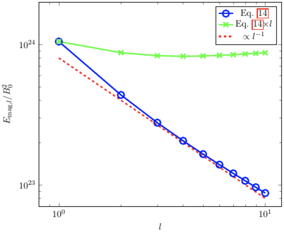


The progenitor: 35OC (Woosley and Heger, 2006)

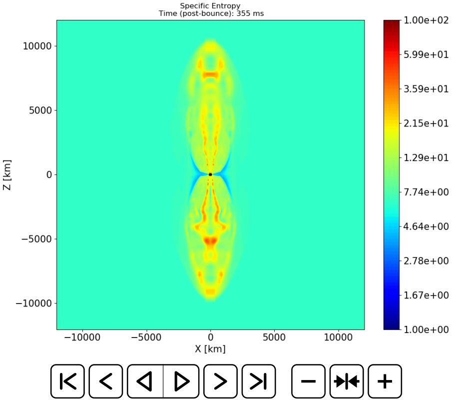
- SRMHD code with ν transport (Just et al., 2015).
- $M_{\rm ZAMS} = 35 M_\odot$, mass at collapse $\sim 28 M_\odot$
- Stellar evolution with rotation and magnetic fields (Spruit, 2002)
- Axisymmetric models, rapid rotation at collapse
- Generalized multipolar expansion:

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

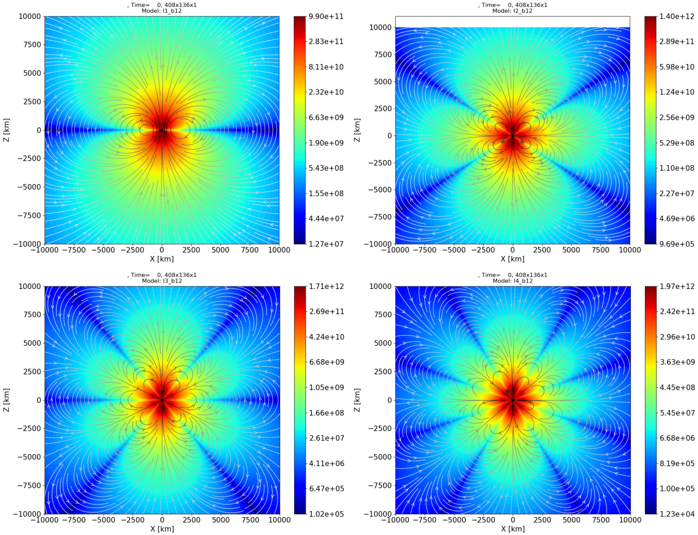




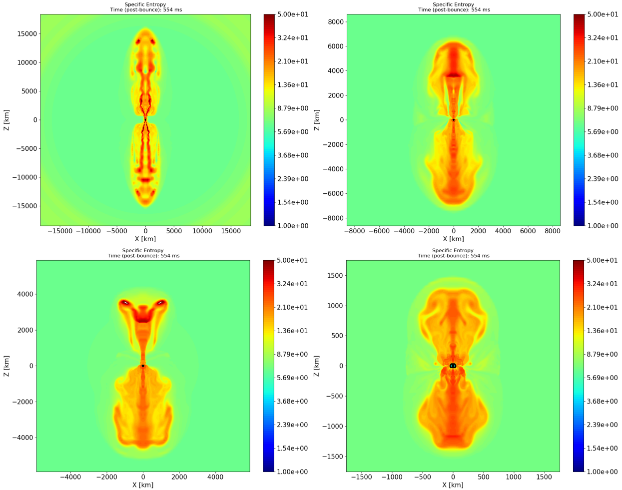
Strong dipole: standard magnetorotational explosion



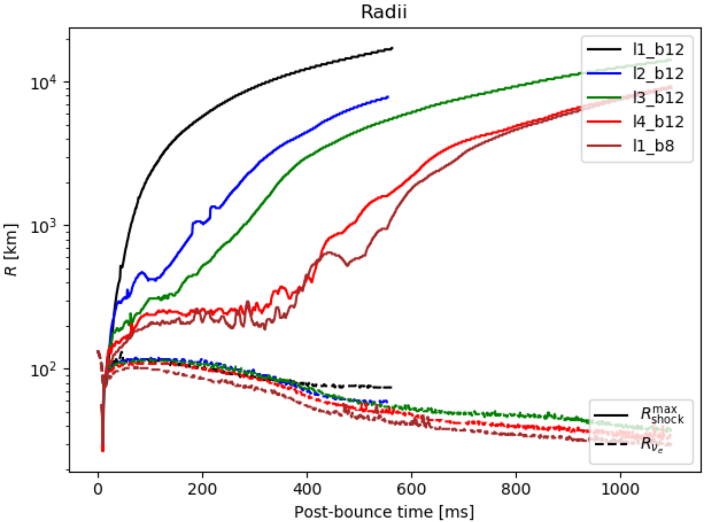
Comparison: different multipoles



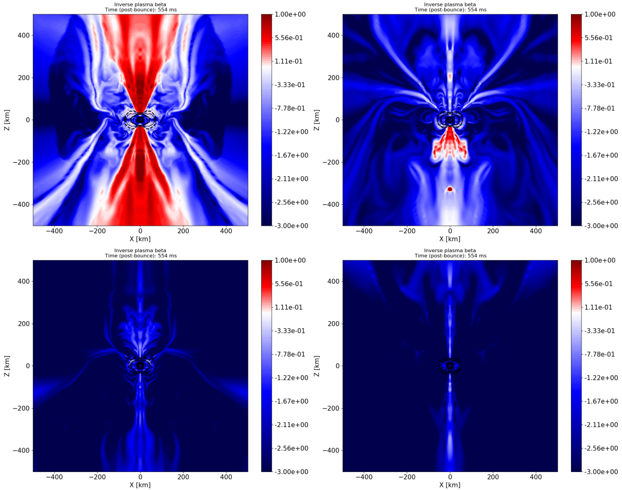
Onset of the explosion



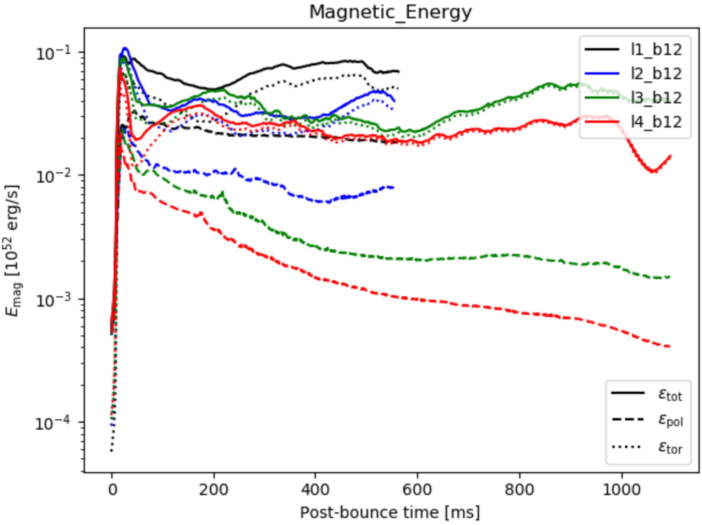
Shock radii (preliminary!)



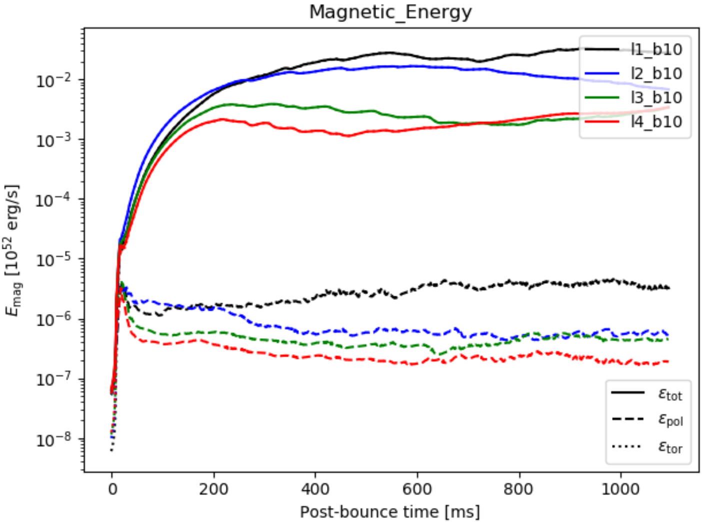
Magnetic/thermal pressure



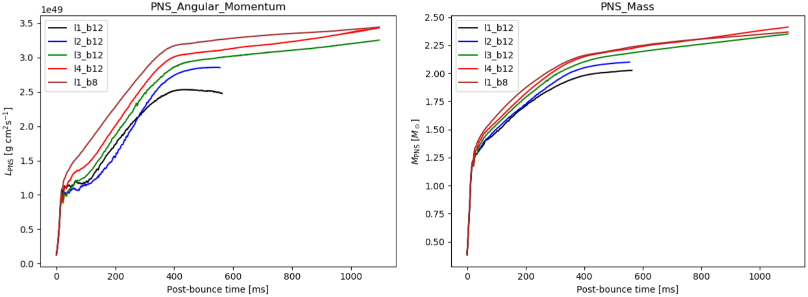
Total magnetic energy (preliminary!)



Total magnetic energy (preliminary!)



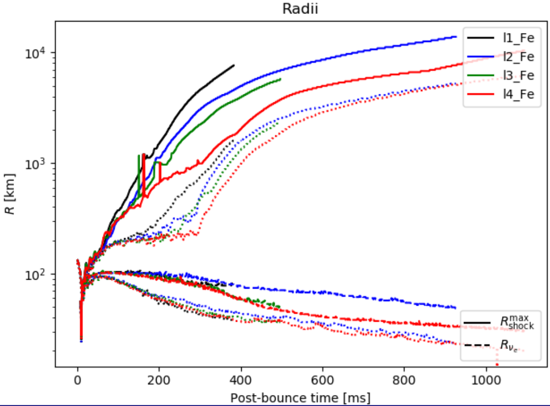
PNS mass and spin (preliminary!)



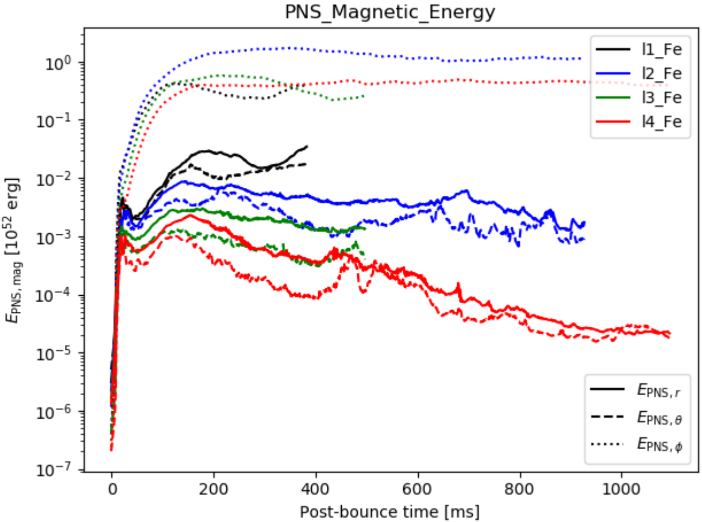
Different normalization (preliminary!)

Fixed B at the poles at the iron core interface:

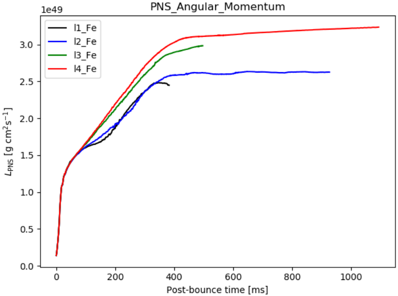
$$B_l^{\text{poles}} = \sqrt{l}\frac{B_0}{1+(r/r_0)^{l+2}}; \quad r_0 = R_{\text{Fe}}$$

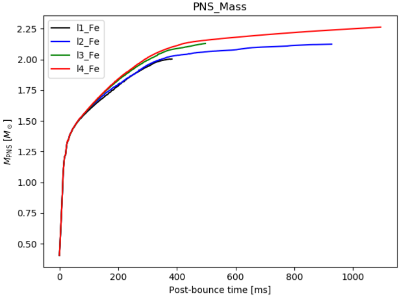


PNS magnetic energy (preliminary!)



PNS mass and spin (preliminary!)





Conclusions

- Impact of different multipolar configurations on the onset of explosion, PNS mass accretion and spin evolution.
- Fixed total magnetic energy: later explosions and higher mass and spin of the PNS for higher multipoles.
- Fixed polar field at iron core: simultaneous explosions, but slower outflows

Perspectives

- Extension to later times, further analysis of the dissipation mechanism
- Extension to 3D using the axisymmetric models as guiding line
- Subgrid modeling of the unresolved dynamo in the PNS (mean-field approach)

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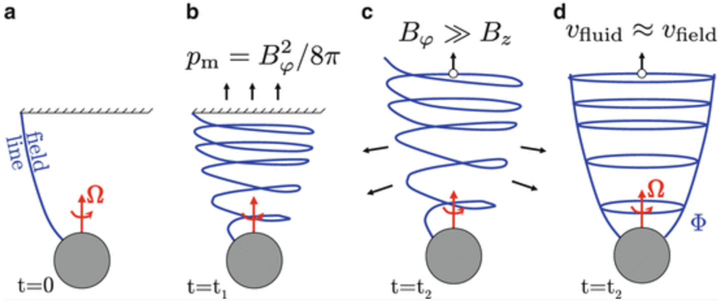
Relativistic outflows

- Magnetic fields are crucial in the launch and collimation of relativistic outflows (Blandford and Znajek, 1977; Tchekhovskoy et al., 2011; Liska et al., 2018).
- Key parameters: central object rotation, radial magnetic field flux.



(Tchekhovskoy, 2015)