The formation of Magnetars: from protoneutron star dynamos to core-collapse supernovae central engines

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Outline

Introduction
Magnetars and supernovae
Modeling

Magnetorotational instability
Characteristics of the MRI
Numerical models

Convective dynamo
Convection in proto-neutron stars
Numerical results

Magnetorotational explosions
Non-dipolar magnetic fields
Numerical models

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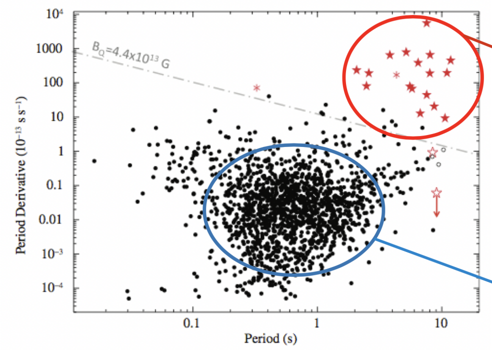
Magnetars: the most intense known magnetic fields



Magnetars

Anomalous X-ray pulsars (AXP)

Soft gamma repeater (SGR)

Strong dipole magnetic field:

$B \sim 10^{14} - 10^{15}$ G

Pulsars

$B \sim 10^{12} - 10^{13}$ G

Which supernovae are associated with magnetars?

Outstanding explosions and magnetic fields

Explosion kinetic energy

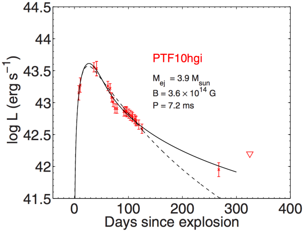
- Typical supernova: 10^{51} erg
- Rare hypernovae and GRB: 10^{52} erg

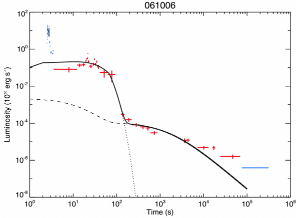
Total luminosity

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

Lightcurves and X-ray plateaus

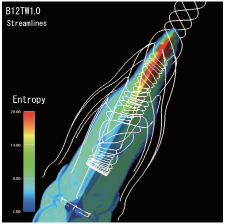
- Strong dipolar magnetic field: $B \sim 10^{14} - 10^{15}$ G
- Fast rotation: $P \sim 1 - 10$ ms
- Kasen and Bildsten (2010); Dessart et al. (2012); Nicholl et al. (2013); Inserra et al. (2013); Zhang and Mészáros (2001); Metzger et al. (2008); Lü et al. (2015); Gao et al. (2016)



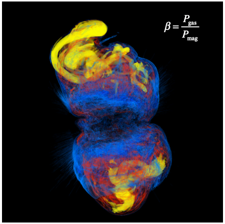


Impact of strong magnetic fields

- Strong magnetic fields ($B \sim 10^{15}$ G) and fast rotation ($P \sim$ few ms)
- Powerful jet-driven explosions (Shibata et al., 2006; Burrows et al., 2007; Dessart et al., 2008; Takiwaki et al., 2009; Kuroda and Umeda, 2010; Winteler et al., 2012; Obergaulinger and Aloy, 2017)
- In 3D the jet might be destroyed by kink instability (Mösta et al., 2014a)
- Big uncertainties on the initial magnetic field



Takiwaki et al. 2009



Moësta et al. 2014

Open question: origin of the magnetic field

- Compression of progenitor field in CCSN: $10^{12} - 10^{13}$ G (?)
- Magnetic field of NS before merger: $10^{8} - 10^{12}$ G (but see Schneider et al. 2019)
- Magnetar: 10^{15} G

What is the amplification mechanism?

Possible dynamics within the PNS:

Magnetorotational Instability | Convective dynamo

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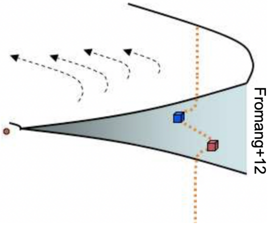
The magnetorotational instability (MRI)

In ideal MHD (no resistivity or viscosity)

- Instability onset: $\frac{\mathrm{d}\Omega}{\mathrm{dr}} < 0$
- Growth rate: $\sigma = \frac{q}{2}\Omega$ with $\Omega \propto r^{-q}$
- Fast growth for fast rotation
- Wavelength: $\lambda \propto \frac{B}{\sqrt{\rho\Omega}}$
- Short wavelength for weak magnetic fields



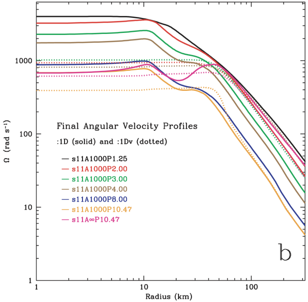
Proto-neutron stars vs. accretion disks

MRI unstable profile at $r > 10$ km

(Akiyama et al., 2003; Obergaulinger et al., 2009)

Conditions specific to PNS:

- neutrinos
- buoyancy
- spherical geometry

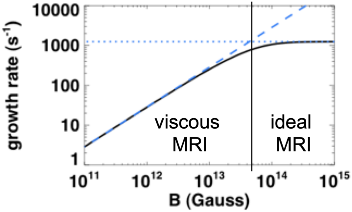


Ott et al. (2006)

The impact of neutrinos on the MRI (Guilet et al., 2015, 2017)

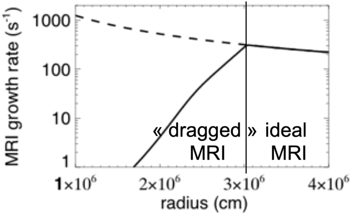
Viscous regime

- $\lambda_{\rm MRI} > l_\nu$
- Slow growth for weak fields



ν-drag regime

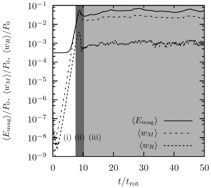
- $\lambda_{\rm MRI} < l_\nu$
- Fast growth near the surface

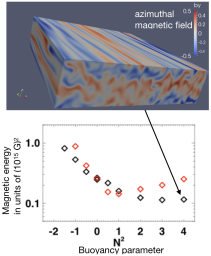


Numerical simulations: local models

- Shearing box simulations
- Differential rotation with shearing boundary conditions
- Entropy/composition gradients
- Efficient amplification of the magnetic field, but no large-scale component
- Obergaulinger et al. (2009); Masada et al. (2012); Guilet et al. (2015); Rembiasz et al. (2016a,b)

Masada et al. 2012

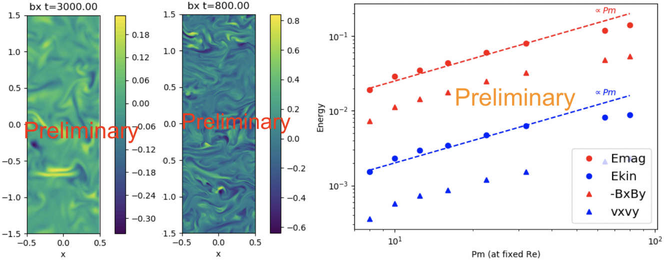




Guilet et al. 2015

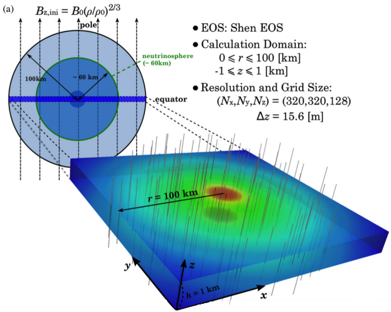
Dependence on diffusion process

- Magnetic Prandtl number: $Pm = \nu/\eta$
- Proto-neutron star: $Pm \sim 10^{13}$
- Numerical simulations: $Pm \sim 1$
- Is there a plateau at large Pm?

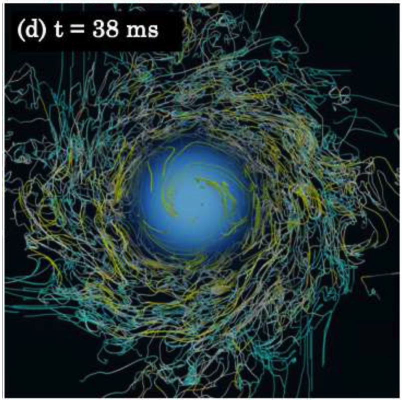


Pm=12.5 Pm=80

Global models in the equatorial plane (Masada et al., 2015)

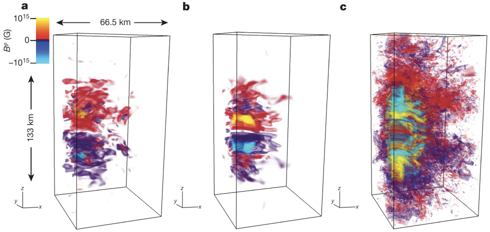


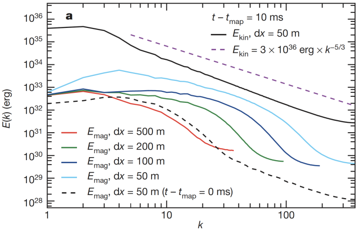
Magnetic field lines



First attempt at a global model (Mösta et al., 2015)

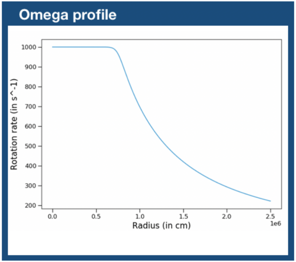
- Global high-resolution (up to 50 m)
- Generation of large scale components
- Initial field: strong dipole

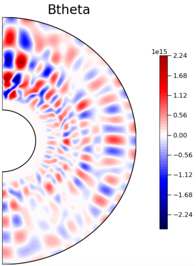




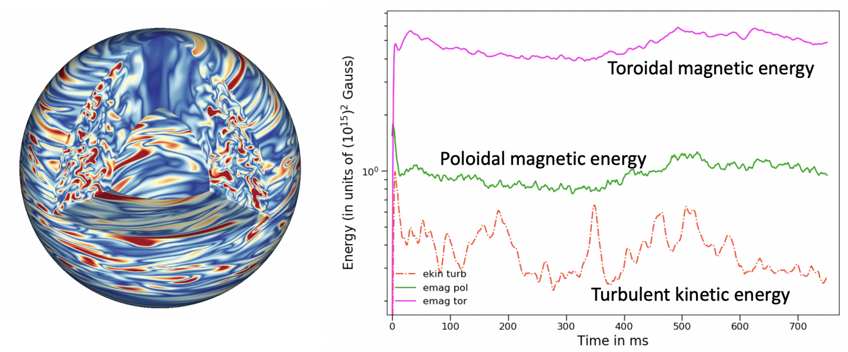
A simple setup for global MRI (Reboul-Salze et al., in prep.)

- Incompressible fluid
- Resolution: $256 \times 512 \times 1024$
- Typical parameters:
  - $Pm = 16$ and $Re = 5000$
  - $\Omega = 10^3\ \mathrm{s}^{-1}$
  - $\nu = 8 \cdot 10^{11}\ \mathrm{cm^2 s^{-1}}$
  - $\eta = 5 \cdot 10^{10}\ \mathrm{cm^2 s^{-1}}$
  - $r = 25$ km
  - $B_{\mathrm{mean}} = 8.97 \cdot 10^{14}$ G



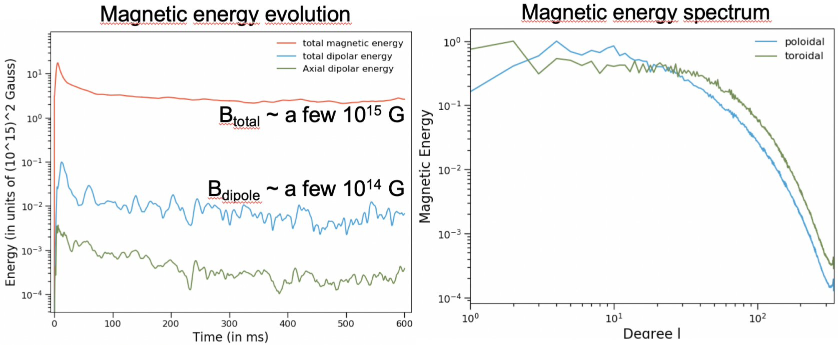


Geometry of the magnetic field



A. Reboul-Salze, J. Guilet, R. Raynaud & M. Bugli 2019, in prep.

A subdominant but significant dipole



MRI saturated state independent of the initial magnetic field

Non-aligned dipole as strong as a (weak) magnetar

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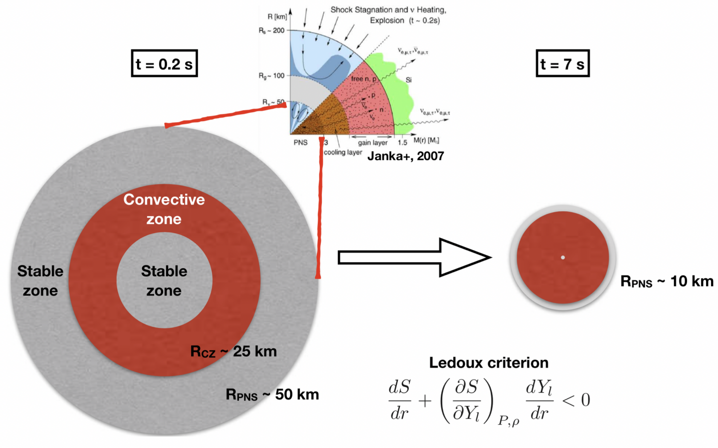
Convective zone in a proto-neutron star



Ledoux criterion

$$\frac{dS}{dr} + \left(\frac{\partial S}{\partial Y_l}\right)_{P,\rho} \frac{dY_l}{dr} < 0$$

Interior model and assumptions (Raynaud et al., submitted)

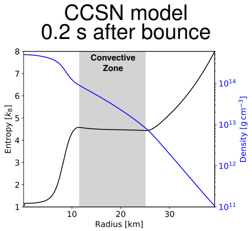
- PNS structure from 1D model by the Garching group
- Equation of state: LS220
- Progenitor: 27 $M_\odot$
- Only convective zone: 12-25 km
- Anelastic approximation (soundproof)
- Viscosity and thermal diffusion by neutrinos
- Resistivity by electrons

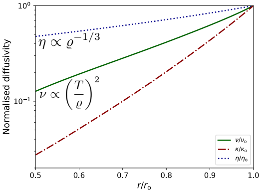
PNS

- $\nu_0 \sim 10^{10}$ cm^{2}s^{-1}
- $\kappa_0 \sim 10^{12}$ cm^{2}s^{-1}
- $\eta_0 \sim 10^{-5}$ cm^{2}s^{-1}

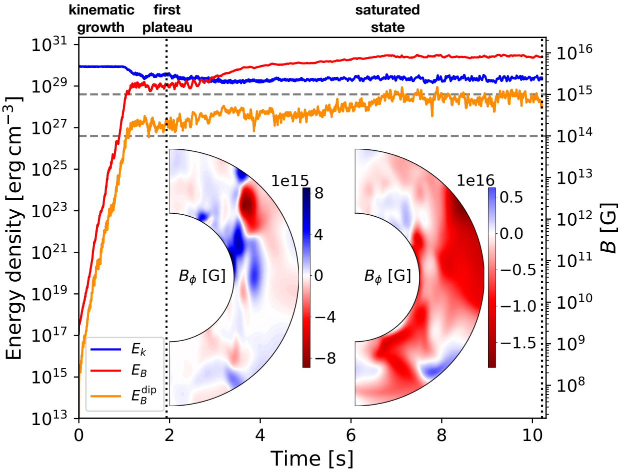
Simulation

- $\nu_0 \sim 10^{12}$ cm^{2}s^{-1}
- $\kappa_0 \sim 10^{13}$ cm^{2}s^{-1}
- $\eta_0 \sim 10^{12}$ cm^{2}s^{-1}





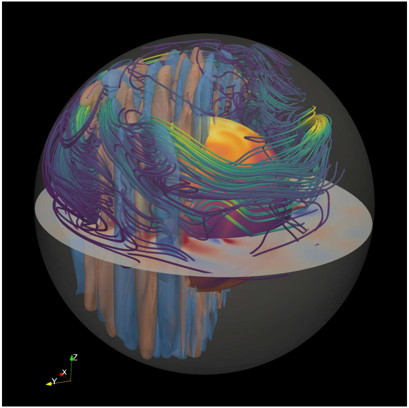
Typical time serie for fast rotating model ($P_{rot} = 2\mathrm{ms}$)

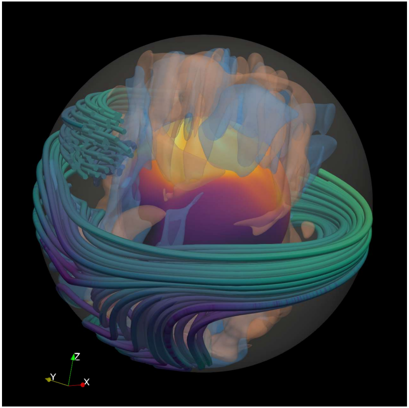


Flow and magnetic field structure

first plateau
$t \sim 2$ s

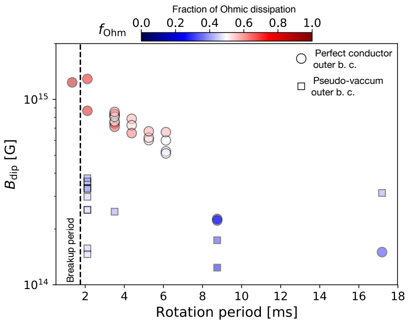
saturated state
$t \geq 6$ s



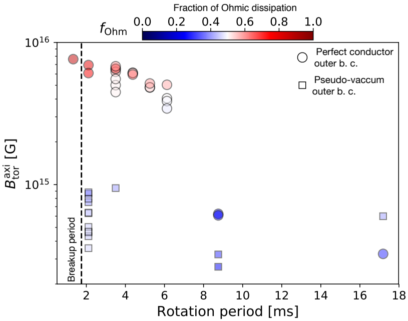


Magnetic field strength

$B_{\rm dip}$ up to $\sim 10^{15}$G

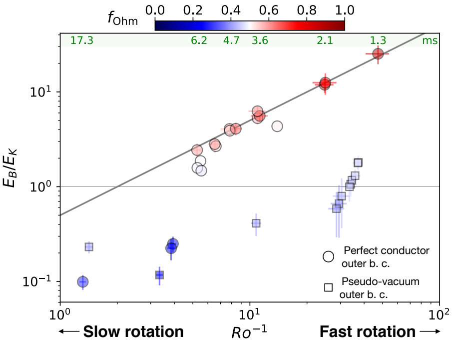


$B_{\rm tor}$ up to $\sim 10^{16}$G



Values compatible with magnetar model for GRB

Understanding the dynamo saturation



Magnetostrophic balance: Lorentz-Coriolis

$$B^2 \propto \Omega \mu \varrho U d$$

$$\Downarrow$$

$$\frac{E_B}{E_{kin}} \propto Ro^{-1} = \frac{\Omega d}{U}$$

Delayed strong dynamo action?

- The PNS shrinks and cools down: higher spin, slower convective motions
- Rossby number *Ro* decreases: possible transition to strong field regime

Fast rotation

- $P < 2.5$ ms
- Prompt strong dynamo
- Hypernovae? GRBs?

Intermediate rotation

- $2.5 \text{ ms} < P < 10$ ms
- Delayed strong dynamo
- SLSN? Magnetars in normal SNe?

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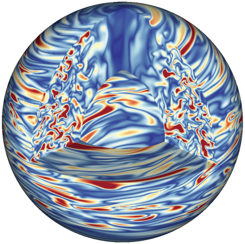
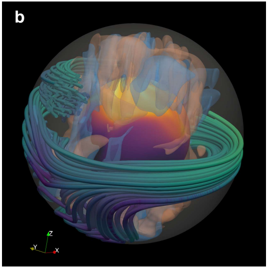
Connecting small and large scales

- 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?





Initial magnetic field: pure dipole?

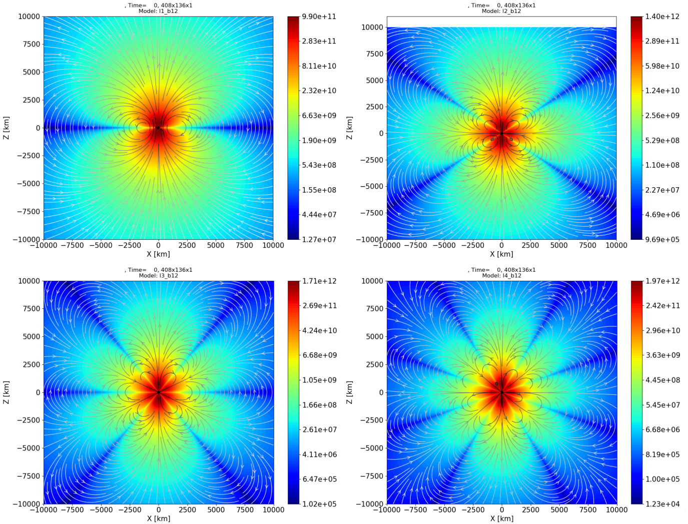
- Poor constraints from both observations and evolutionary models on the initial field.
- Quasi-uniform field up to $r_0 \sim 10^3$km, then magnetic dipole (Suwa et al., 2007):

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

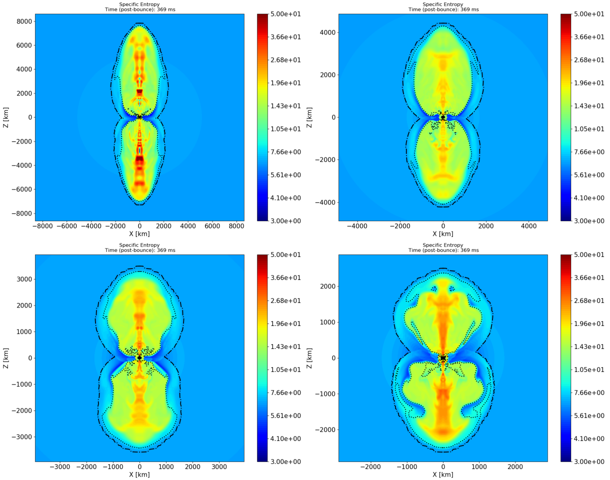
- Progenitor *original* field from 1D stellar evolution (Woosley and Heger, 2006)
- Superimposed toroidal field (Obergaulinger and Aloy, 2017):

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

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

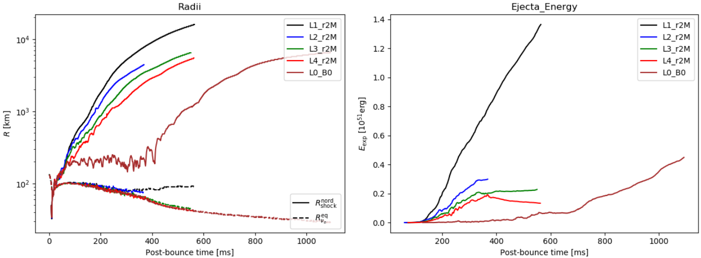


Onset of the explosion ($r_0 = 2.9 \times 10^8$cm, $B_0 = 8 \times 10^{10}$G)

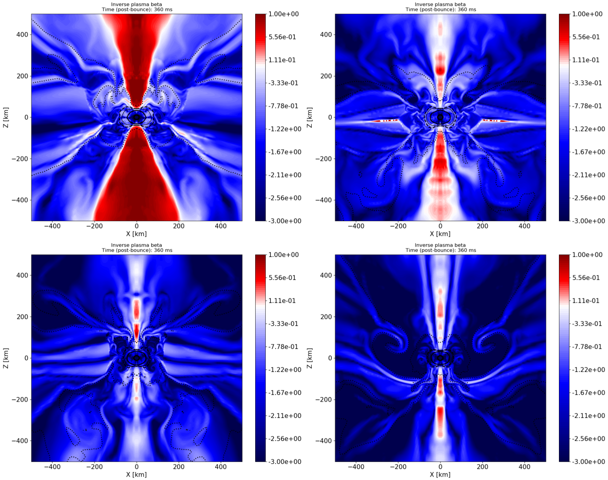


Shock radii - Explosion energies ($r_0 = 2.9 \times 10^8$cm, $B_0 = 8 \times 10^{10}$G)

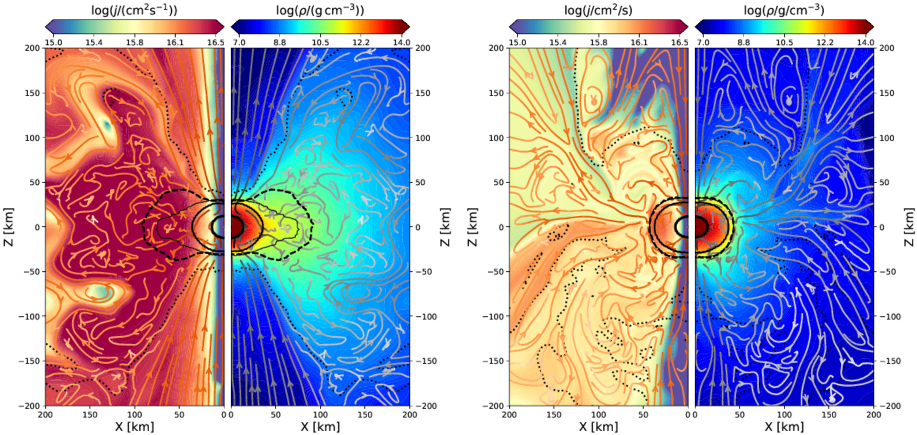
- Onset of explosion at the same time
- Slower expansion for higher multipoles
- Less energetic explosion and shallower increase of energy for higher multipoles



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



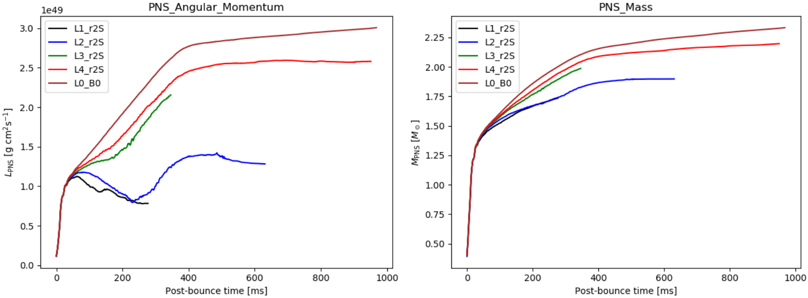
$l = 1$ vs $l = 4$ ($r_0 = 2.9 \times 10^8$cm, $B_0 = 8 \times 10^{10}$G)



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

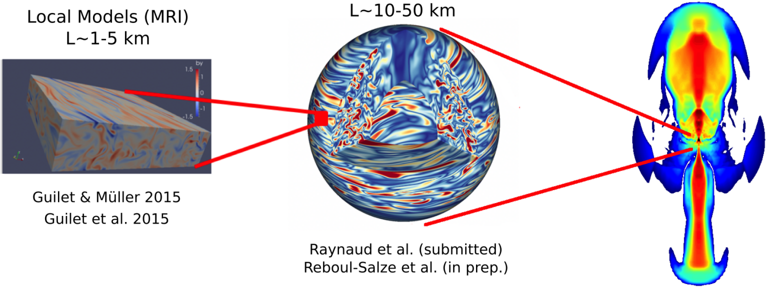


Still a long way to connect small and large scales!

Local Models (MRI)
L~1-5 km

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

Magneto-rotational
supernova explosion
L~100-10000 km



Guilet & Müller 2015
Guilet et al. 2015

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

Bugli et al. (submitted)

Conclusions

Magnetorotational instability

- Turbulent magnetic field with sub-dominant (but magnetar-like) dipole.
- Non-aligned dipole robustly generated from small scales.
- Buoyancy? Interaction with the convective dynamo?

Convective dynamos

- Amplification of seed fields to magnetar values.
- Clear dependence on the PNS rotation, possible transition in time to strong field regime.
- More dynamic evolution? Interaction with MRI unstable layer?

MHD-driven explosions

- Different topologies affect explosion dynamics and PNS formation.
- Lower multipoles produce more energetic explosions, slower and less massive PNS.
- 2D vs. 3D? Dynamo subgrid modeling?

ご清聴
ありがとう ございました!

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