The MagBURST project: Magnetar birth as engine of extreme stellar explosions

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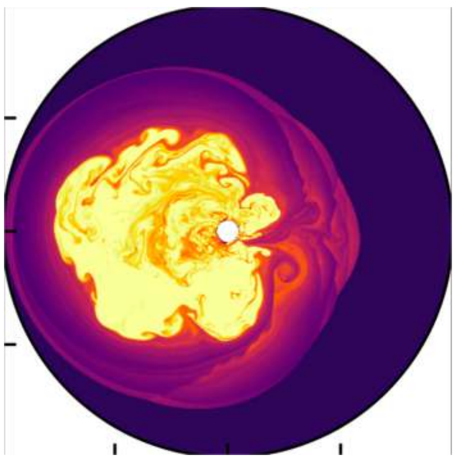
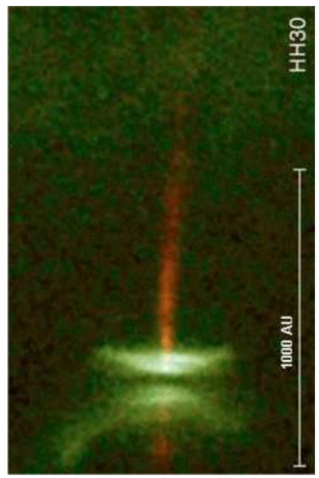
My journey to magnetars

Different objects but similar physical ingredients: (magneto)hydrodynamical instabilities



Thèse de B. Pagani



Normal supernovae	Accretion disks & jets	Magnetars, hypernovae & GRBs	
2007 PhD	2010 postdoc	2013 postdoc	2017 ERC
CEA Saclay Directeur: Thierry Foglizzo	University of Cambridge (UK)	MPA Garching (Germany)	CEA Saclay

Plan of the talk

1 Introduction : why and how to form magnetars ?

2 Magnetorotational instability

Alexis Reboul-Salze

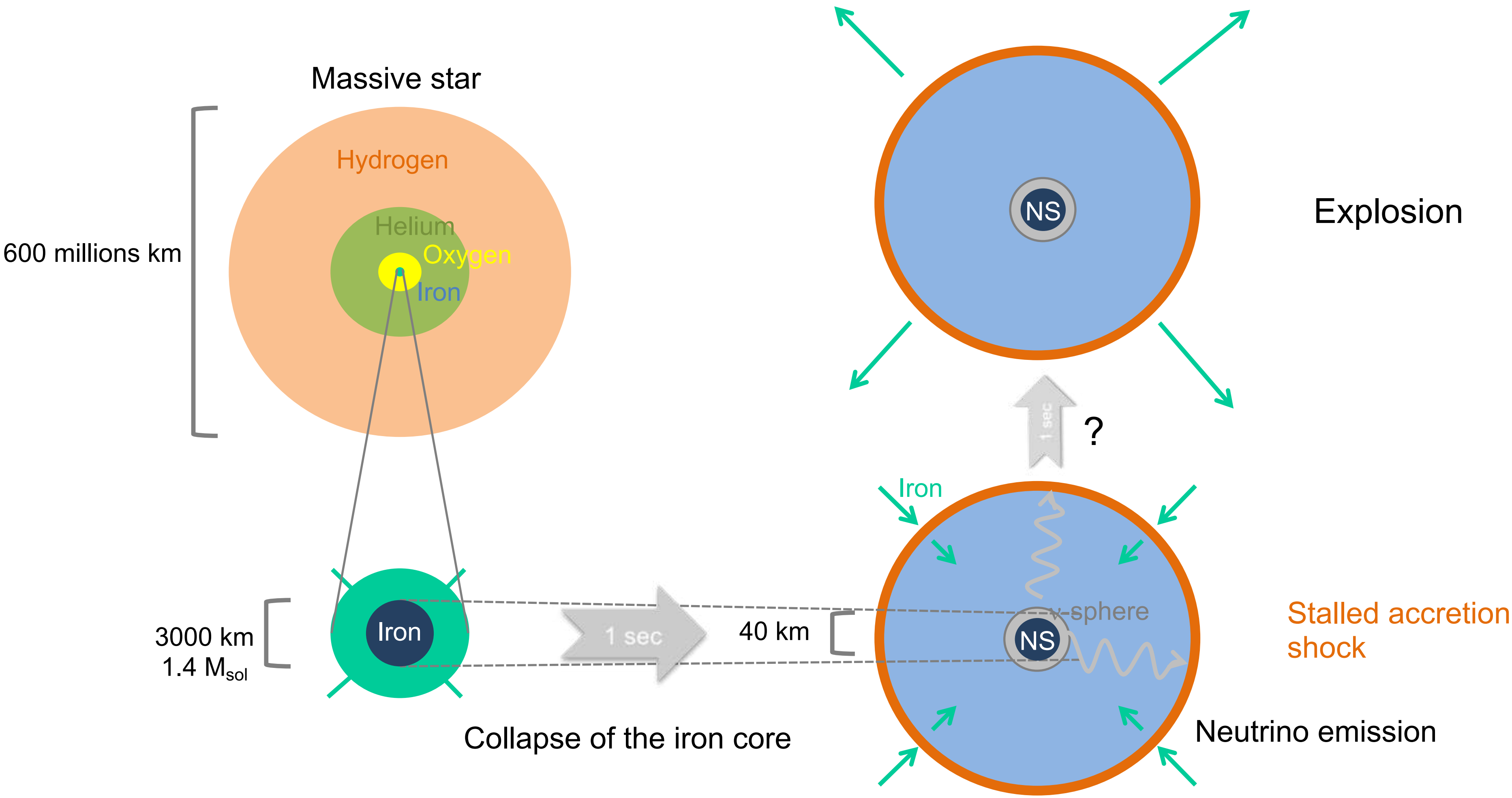
3 Convective dynamo

Raphaël Raynaud

4 Magnetorotational explosions

Matteo Bugli

Core collapse: formation of a neutron star



Core collapse supernovae: a multi-physics problem

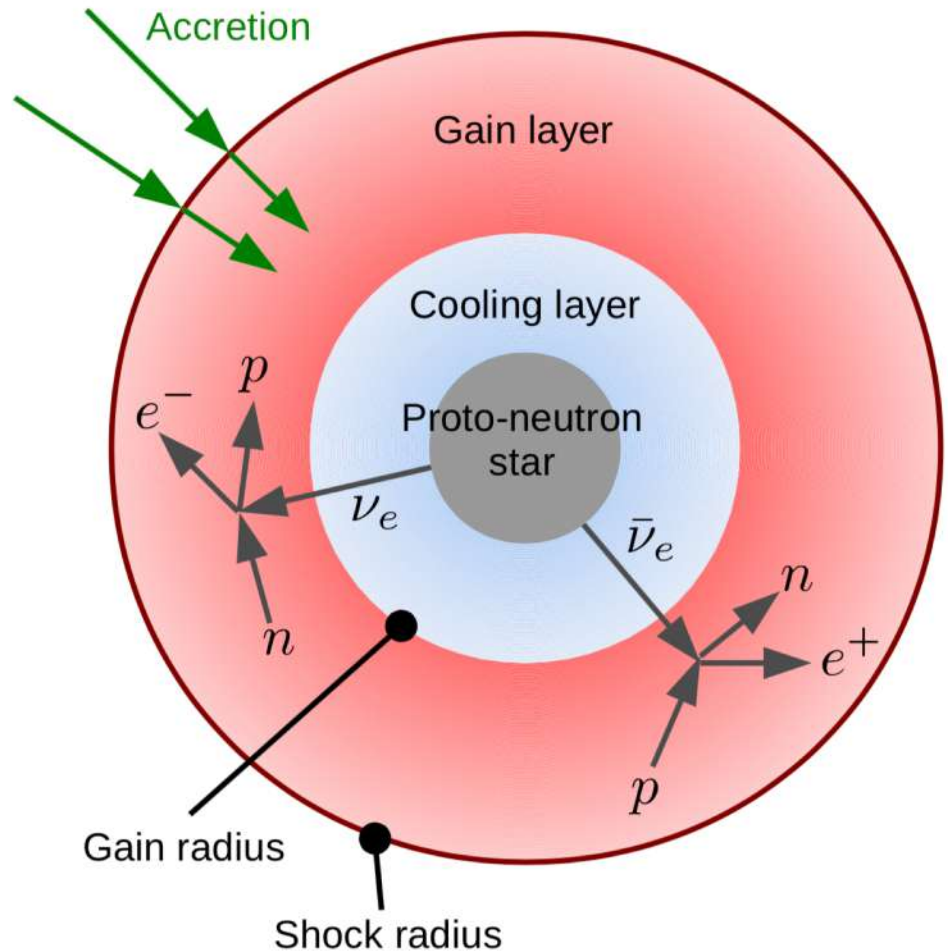
- Multi-dimensional hydrodynamics (instabilities, turbulence..)

- Neutrino-matter interactions
  sophisticated transport schemes

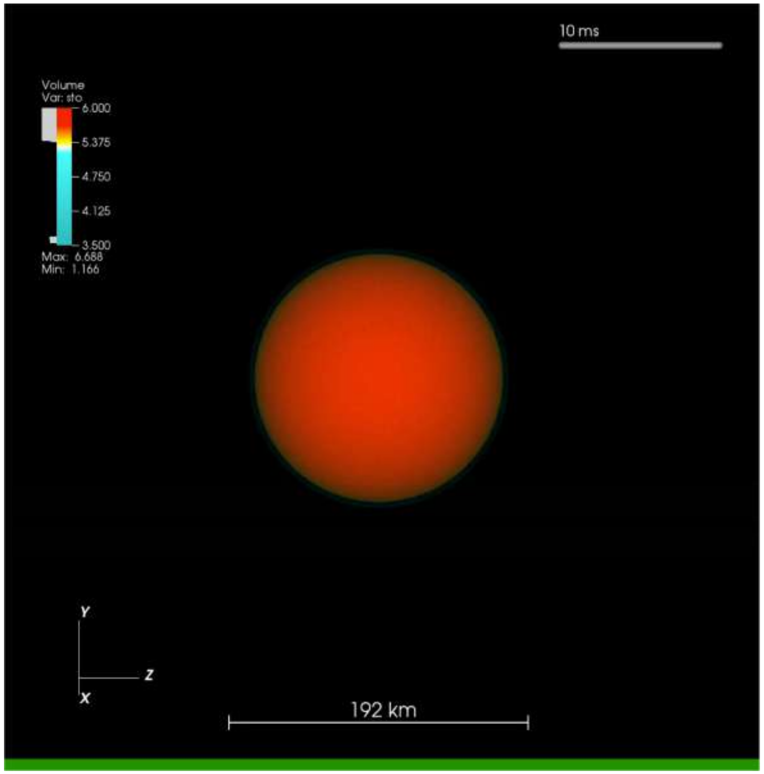
- Ultra-high density equation of state

- General relativity

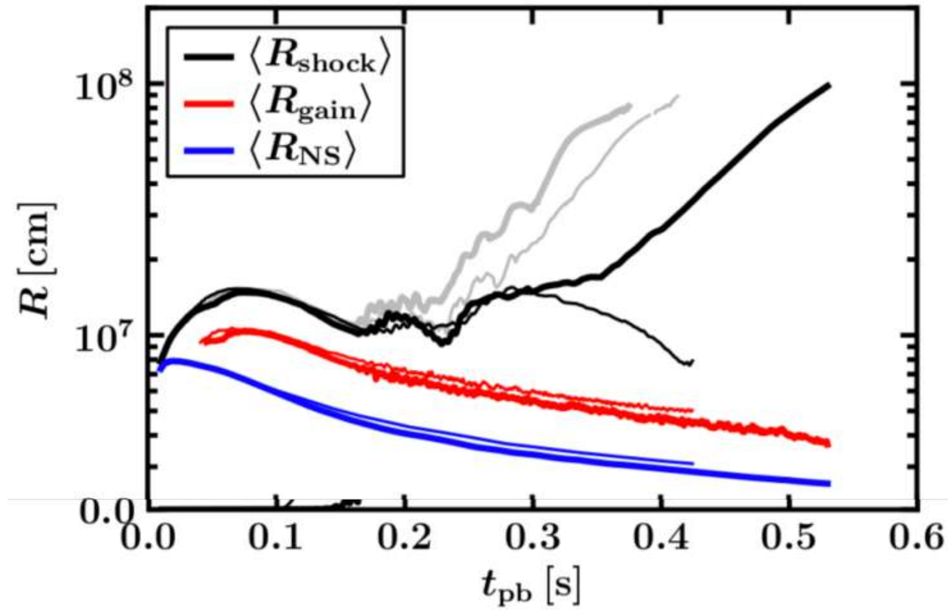
- Magnetic field



Standard supernovae: neutrino-driven explosions ?



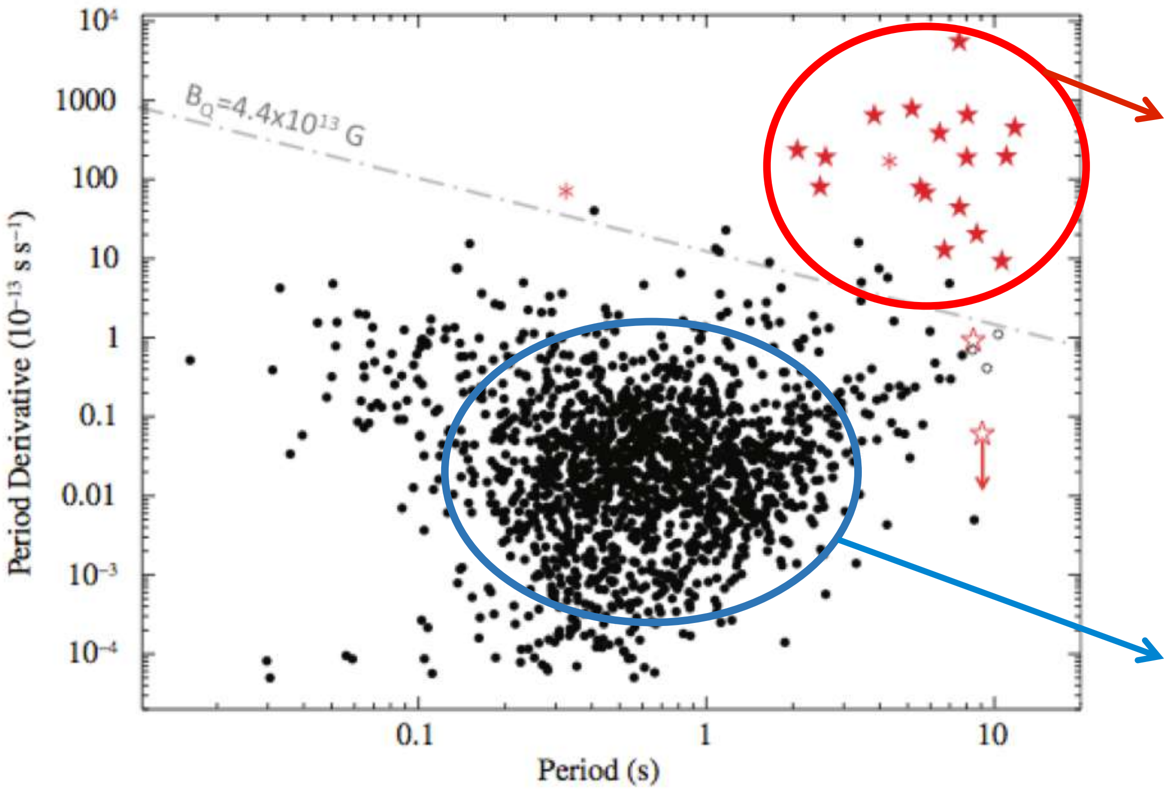
Movie from Garching group



Melson et al 2015

Explosion in 2D and 3D simulations ? Yes but only for some progenitors

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

Galactic magnetars: observational constraints

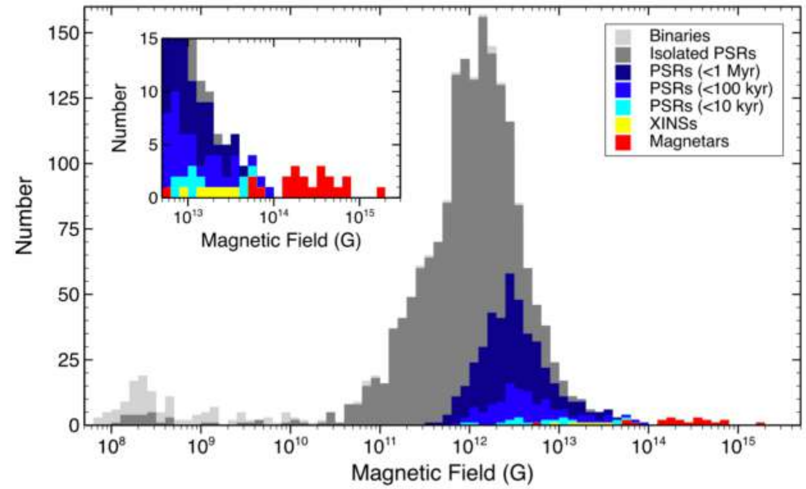
25 magnetars in Galaxy and magellanic clouds

Slow rotation P ~1 - 10 s

-> Rotation at birth unknown !

Magnetic dipole B_{dip} ~ 10^{14} - 10^{15} G

Some weak field magnetars => stronger multipolar/toroidal field ?



Olausen & Kaspi 2014

Young: typically 10^4 - 10^5 years old

Birth rate : ~10% of core-collapse SNe/neutron star birth

~10 magnetars associated to a supernova remnants

=> Normal explosion kinetic energy => P > 5 ms

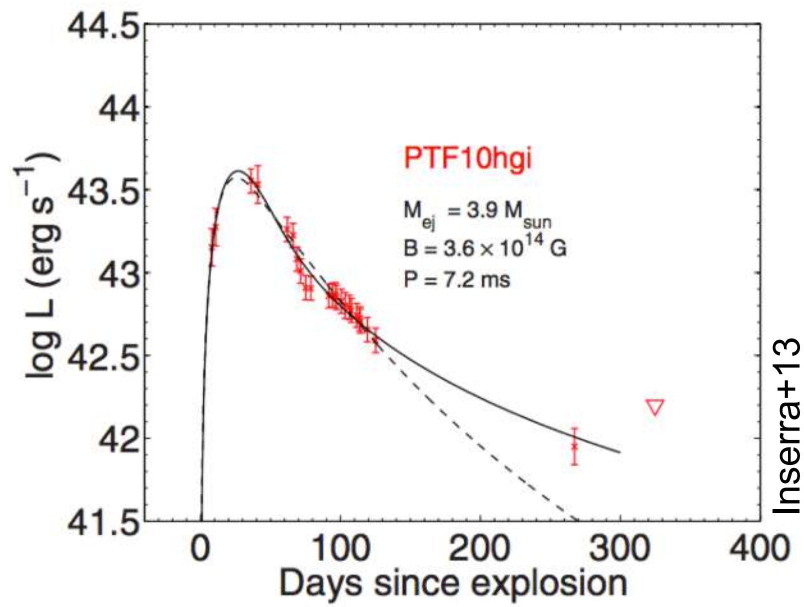
Which supernovae are associated to magnetar birth ?

Superluminous supernovae

Total luminosity :

→ Typical supernova 10^{49} ergs

→ Superluminous supernovae 10^{51} ergs



Light curves can be fitted by millisecond magnetar

- strong dipole magnetic field: B ~ 10^{14}-10^{15} G
- fast rotation: P ~ 1-10 ms

e.g. Kasen+10, Dessart+12, Nicholl+13, Inserra+13

Hypernovae & Long GRBs

Explosion kinetic energy :

→ Typical supernova 10^{51} ergs

→ Rare hypernova (& GRB) 10^{52} ergs

→ Neutrino driven explosions ?

→ Millisecond magnetar ?

e.g. Burrows+07, Takiwaki+09,11
Bucciantini+09, Metzger+11, Obergaulinger+17

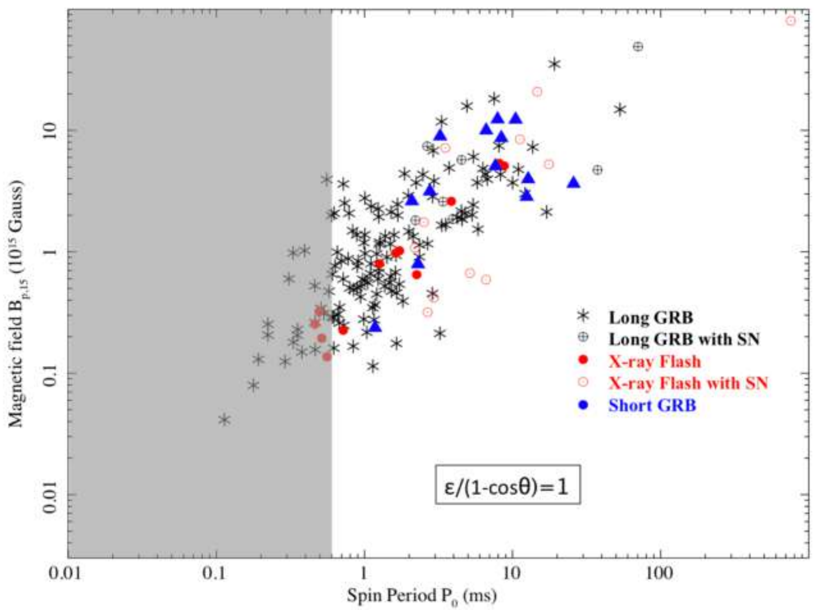
X-ray plateau can be fitted by magnetar model

Rea+2015:

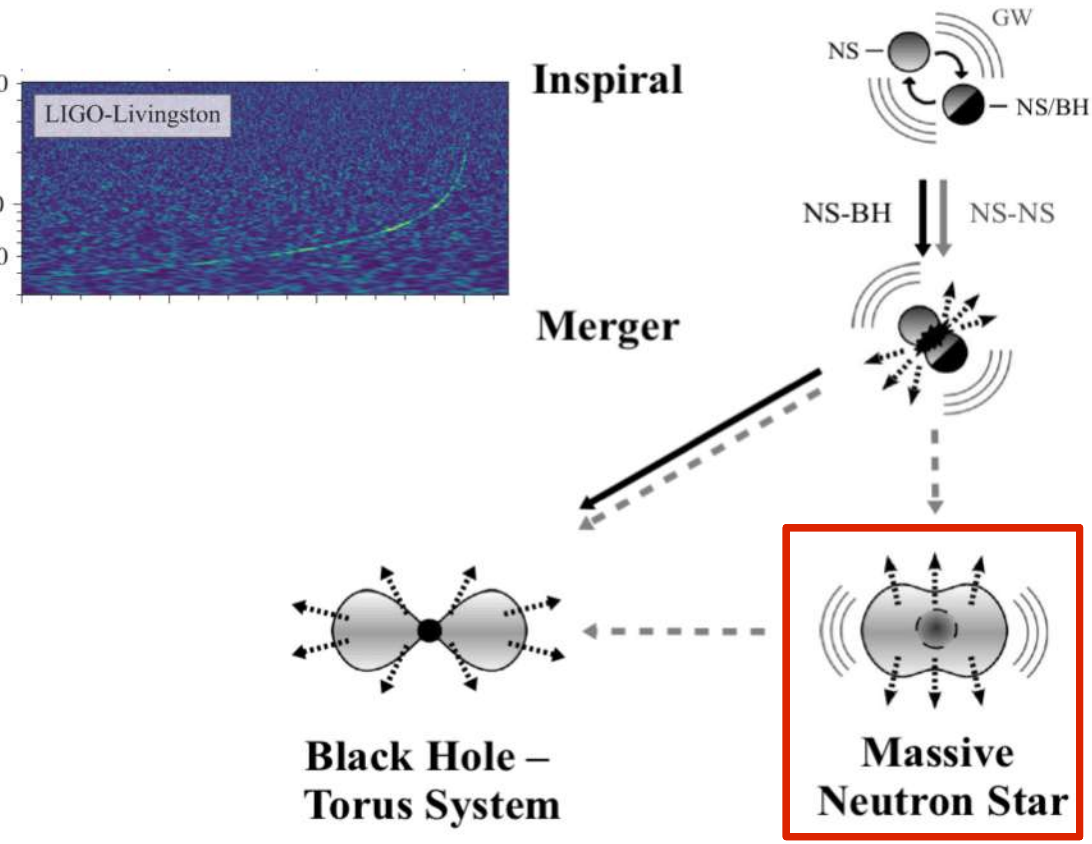
GRB magnetars are « supermagnetars »

Stronger magnetic fields than normal magnetars

$B_{dip} \sim 10^{15} - 10^{16}$ G



A magnetar formed in NS mergers ?



3 possibilities :

- direct collapse to a black hole
- hypermassive NS stabilized by rotation : delayed collapse
- stable neutron star

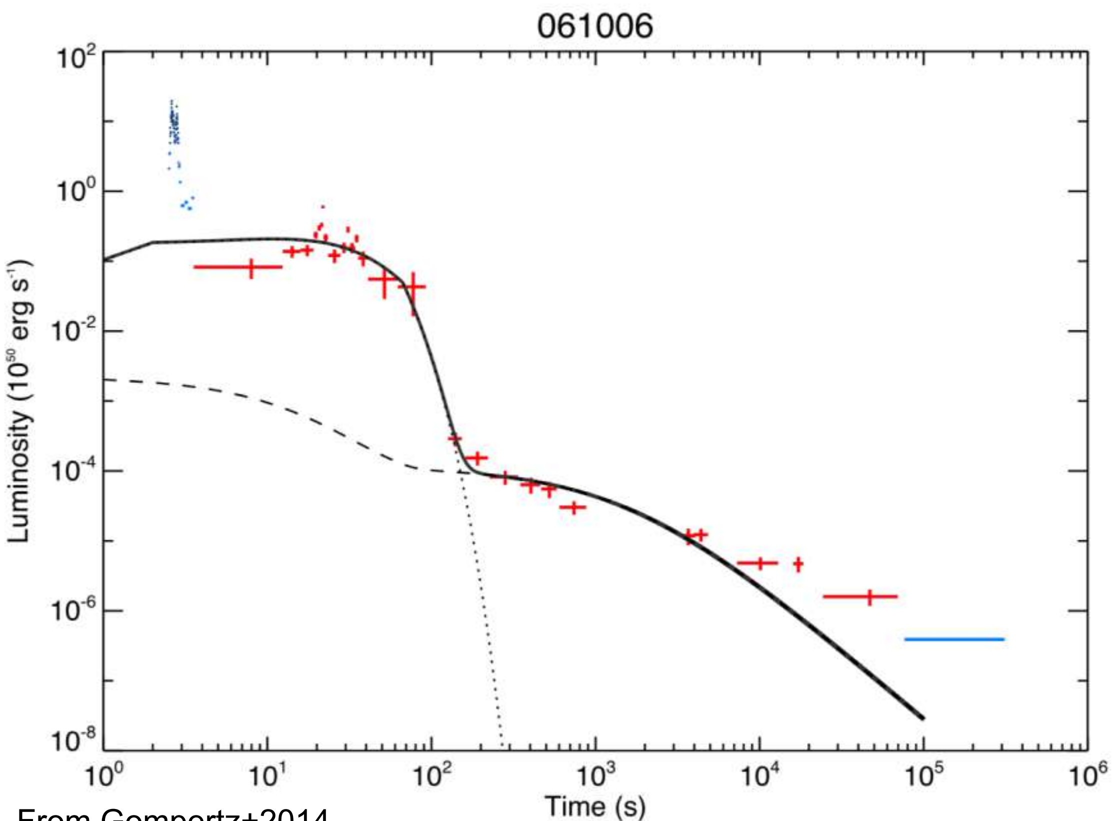
Formation of a magnetar ?

Signature in future joint gravitational wave – electromagnetic obervations ?

SVOM

Launch : end of 2021

GRBs: Extended emission and X-ray plateaus from magnetars ?



From Gompertz+2014

Extraction of the magnetar rotation energy (up to 10^{53} erg):

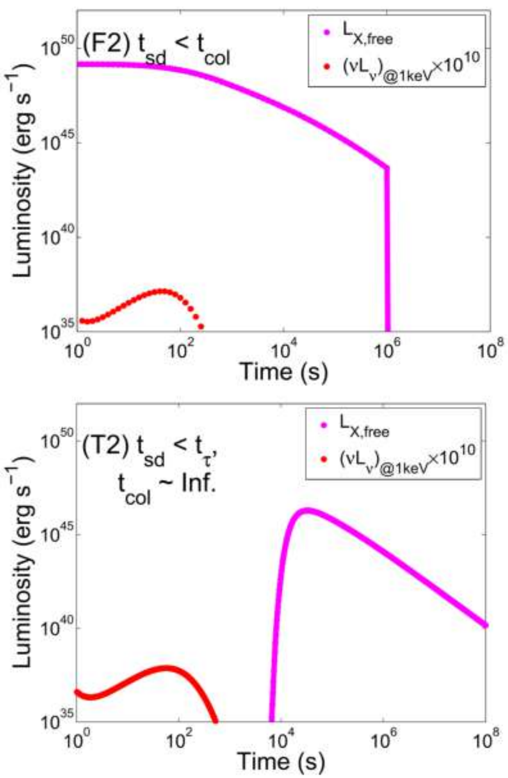
- Dipole spin-down in vacuum

T_{sd} ~ 2×10^3 s $(B/10^{15}G)^{-2}$ $(P/1ms)^2$

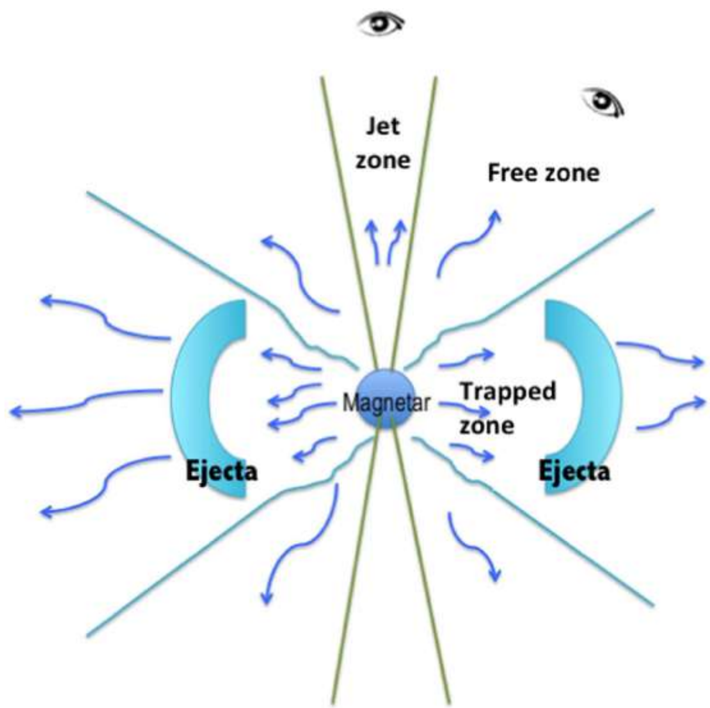
L_{dip} ~ 10^{49} erg/s $(B/10^{15}G)^2$ $(P/1ms)^{-4}$ $\times(1 + t/T_{sd})^{-2}$

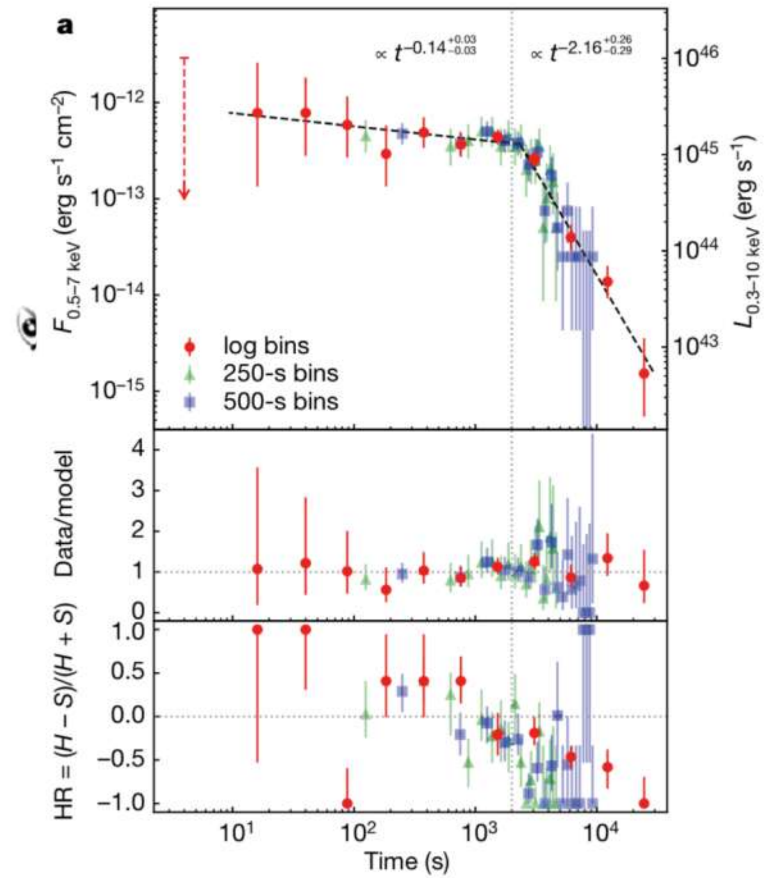
Zhang+2001, Fan&Xu2006, Metzger+2008, Rowlinson+2010, 2013, Gompertz+2013,2014, Lu+2015, Gao+2016

Off-axis counterpart of GW from a magnetar ?



Zhang 2013, Sun+2017

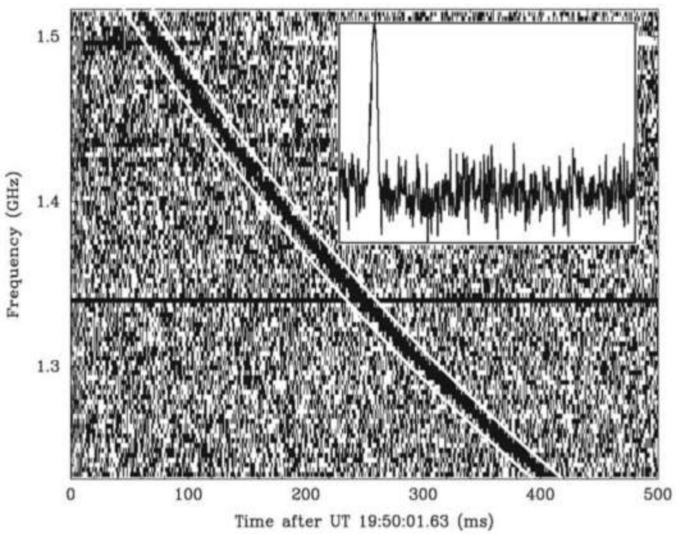




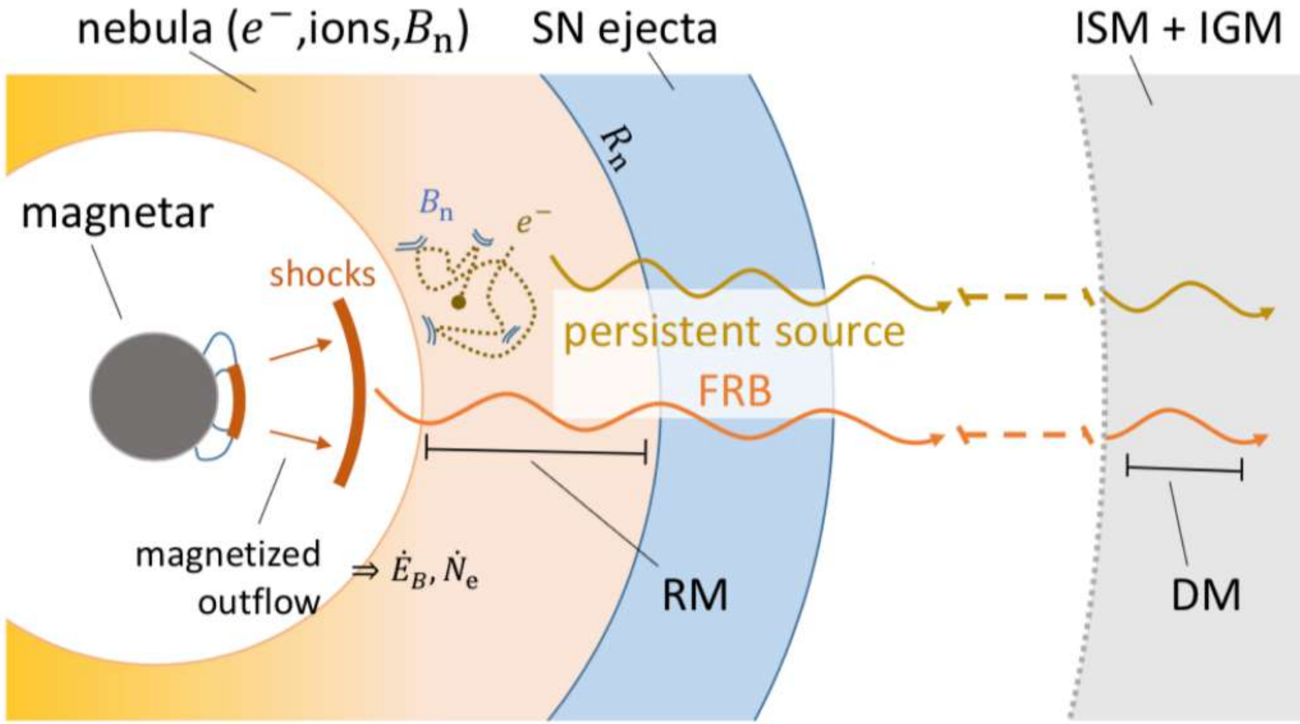
Xue+2019

Collaboration with Diego Gotz
Matteo Bugli, Raphael Raynaud

Fast radio bursts from young magnetar ?



Lorimer et al 2007



Margalit & Metzger 2018

Collaboration with Christian Gouiffes, Emeric Le Floch et al

Impact of a strong magnetic field on the explosion

Strong magnetic field: B ~ 10^{15} G

+ fast rotation (period of few milliseconds)

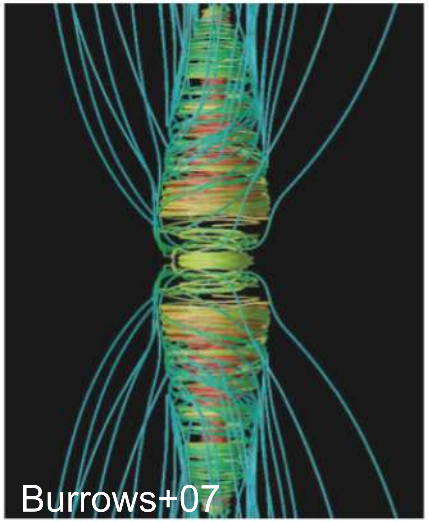
=> powerful jet-driven explosions !

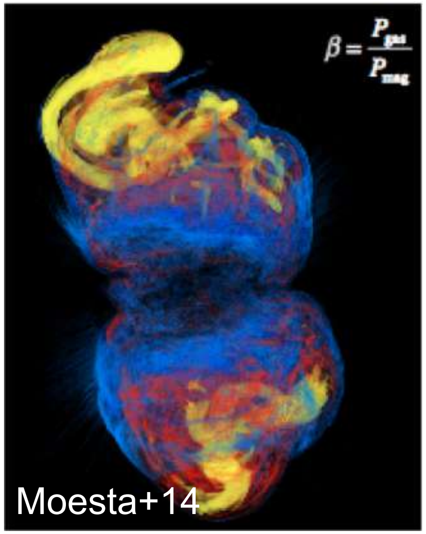
e.g. Shibata+06, Burrows+07, Dessart+08, Takiwaki+09,11, Kuroda+10, Winteler+12, Obergaulinger+17

But in 3D, jets may be unstable to kink instability

Moesta+2014

Caveat: origin of the magnetic field is not explained





Theoretical open question: magnetic field origin

Compression of stellar field in core collapse supernovae: <10^{12}-10^{13} G (?)

Magnetic field of NS before merger: 10^{8}-10^{12} G

Magnetar: 10^{15} G

Amplification mechanism ?

Magnetorotational instability

Similar to accretion disks

Convective dynamo

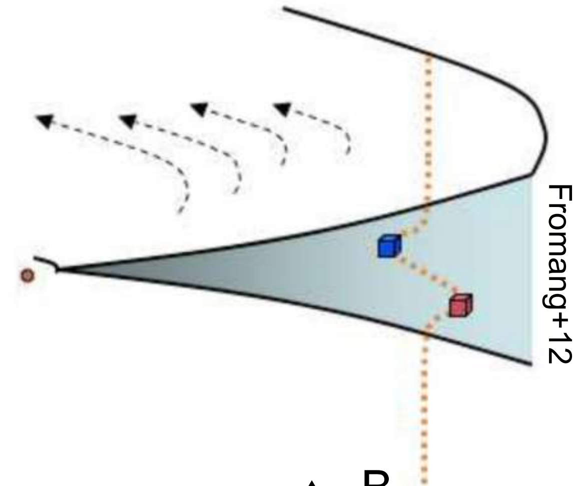
Similar to planetary & stellar dynamos

Plan of the talk

The magnetorotational instability (MRI)

In ideal MHD (i.e. no resistivity or viscosity) :

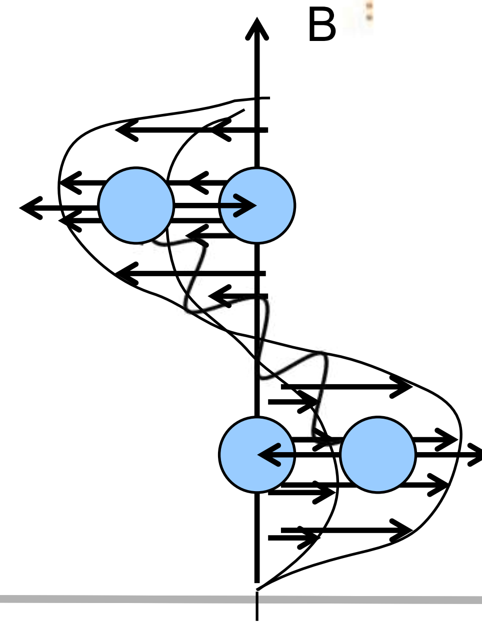
Condition for MRI growth $\frac{\mathrm{d}\Omega}{\mathrm{d}r} < 0$



Growth rate : $\sigma = \frac{q}{2}\Omega$

with $\Omega \propto r^{-q}$

→ Fast growth for fast rotation



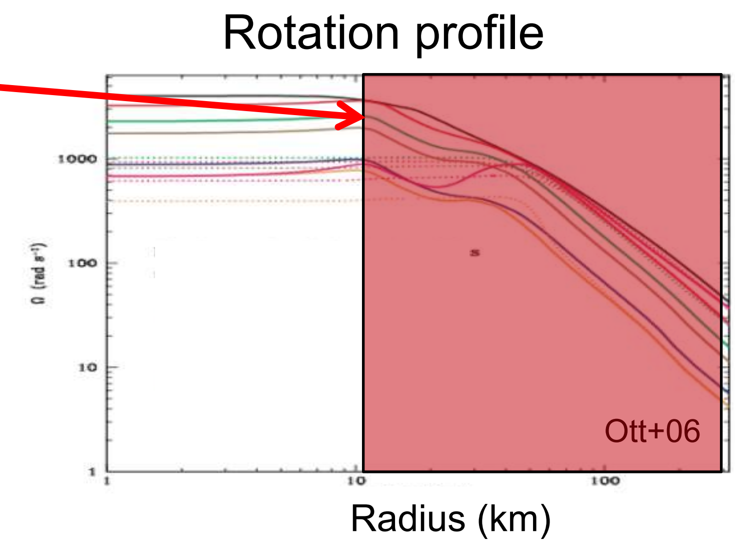
Wavelength : $\lambda \propto \frac{B}{\Omega\sqrt{\rho}}$

→ Short wavelength for weak magnetic field

Proto-neutron stars vs disks conditions

MRI unstable differential rotation
at radii > 10 km

Akiyama+2003, Obergaulinger+2009

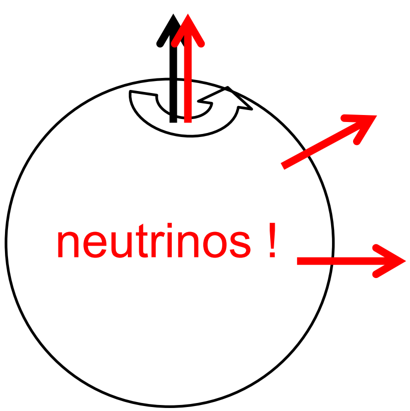


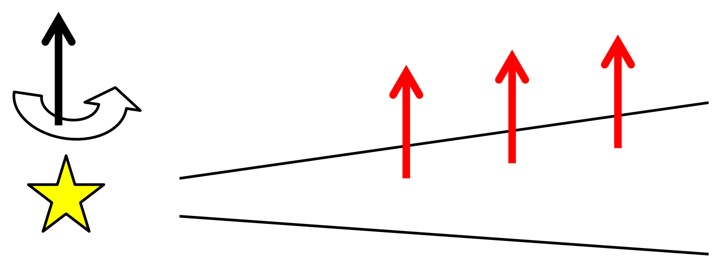
Impact of conditions specific to neutron stars ?

→ neutrinos

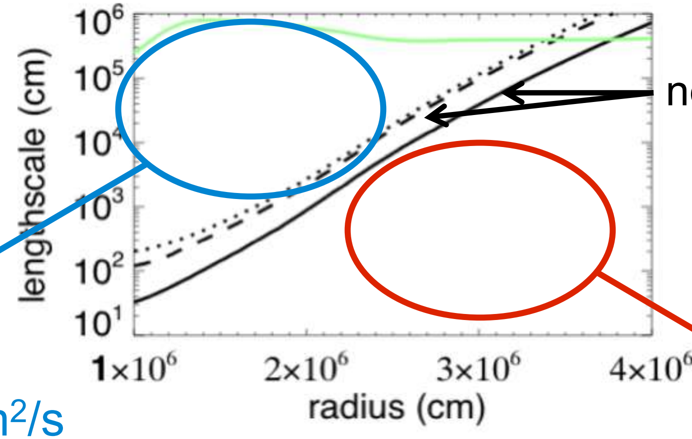
→ buoyancy (entropy & composition gradients)

→ spherical geometry



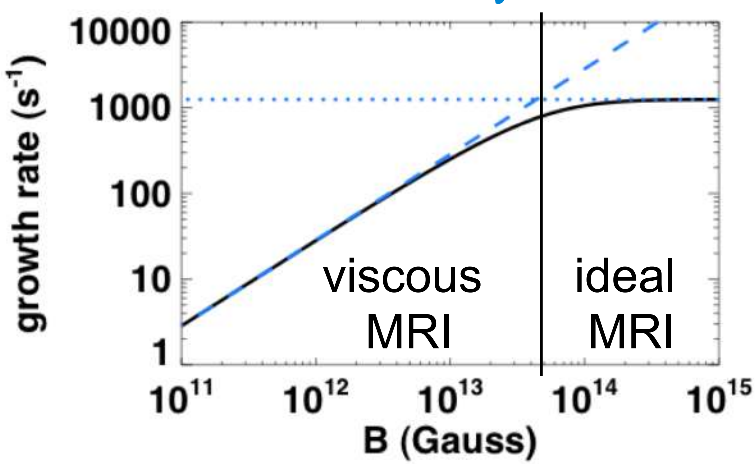


Impact of neutrinos on the MRI: growth rate

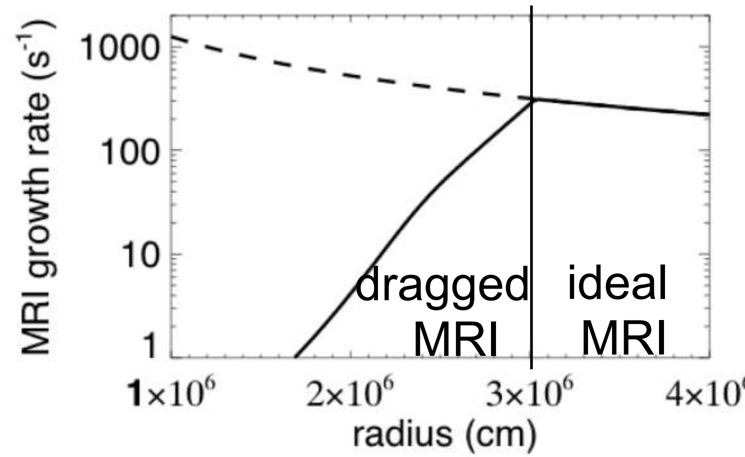


neutrino mean free path

Diffusive regime:
Neutrino viscosity 10^{11} cm^2/s



Neutrino drag regime

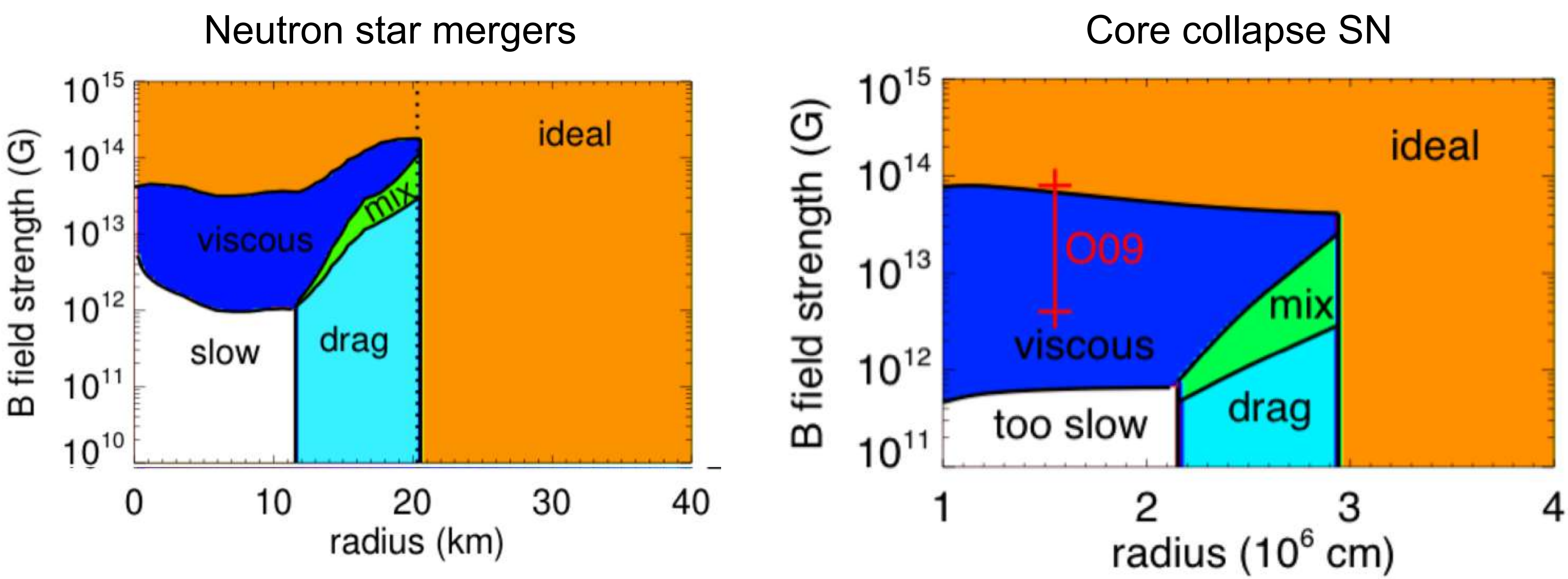


Slow growth for weak initial magnetic field < 10^{12} G

Fast growth near surface independently of field strength

Guilet et al (2015), Guilet et al (2017)

Comparing supernovae & neutron star mergers



=> Very similar physical conditions in NS mergers and supernovae

Guilet+2015, 2017

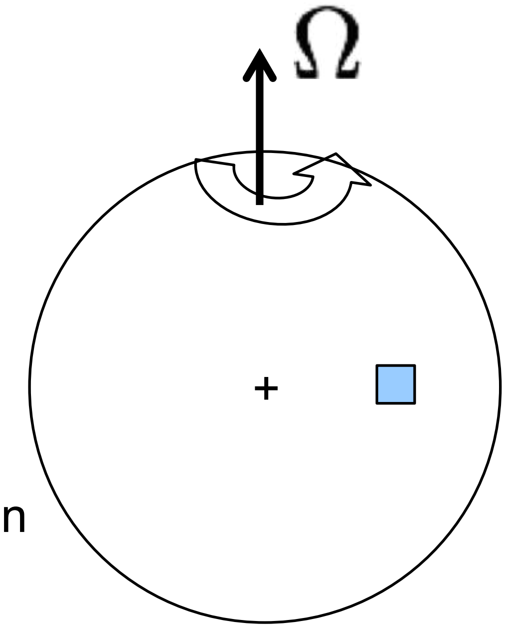
Numerical simulations: local models

- Small box : at a radius r = 20 km
  size 4×4×1 km

- Differential rotation
  => shearing periodic boundary conditions

- Entropy/composition gradients in Boussinesq approximation

Code: Snoopy (G. Lesur)

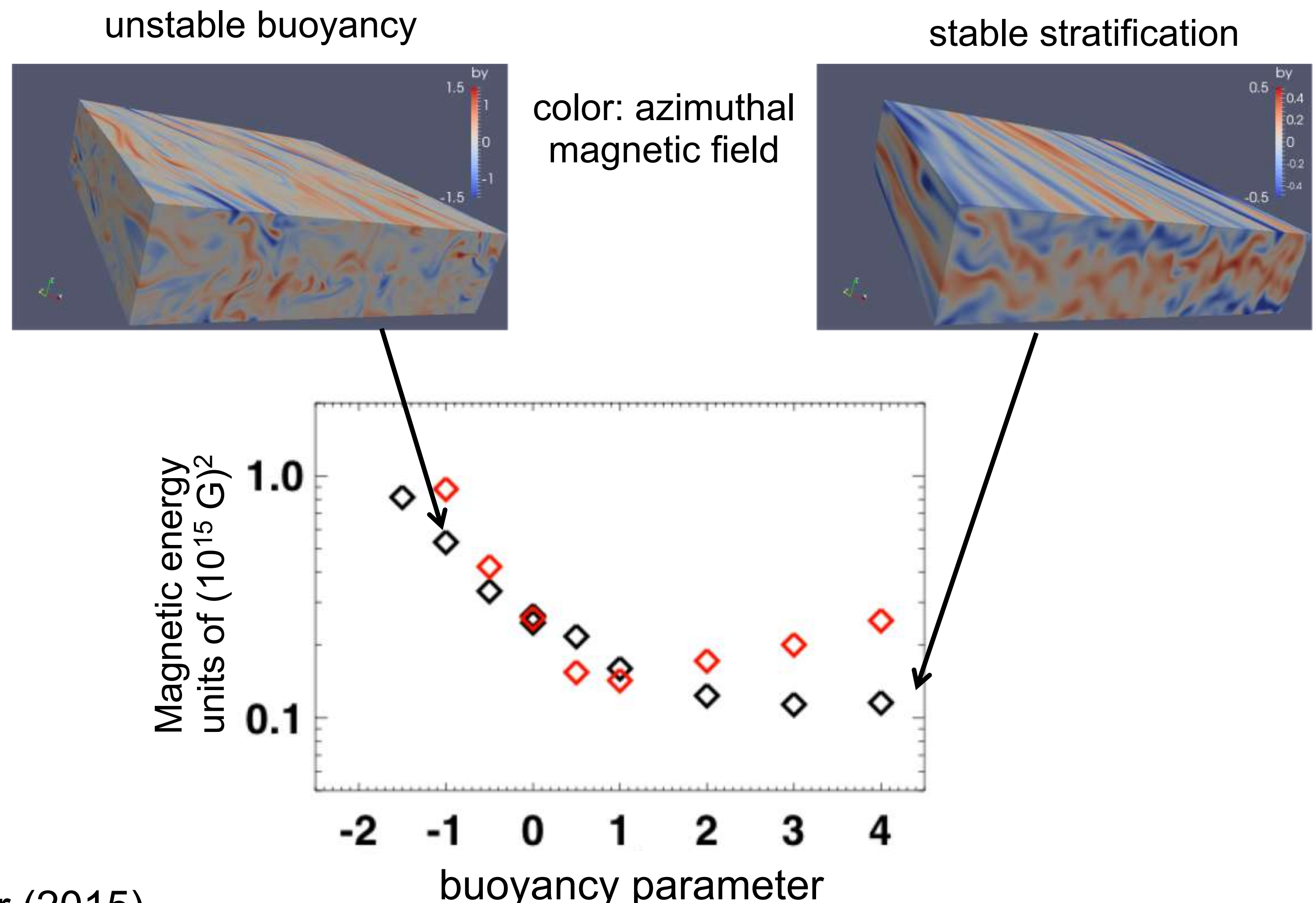


Obergaulinger+2009, Masada+2012,
Guilet+2015, Rembiasz+2015,2016

Fiducial parameters :

$$\rho = 10^{13}\,\mathrm{g.cm}^{-3}$$
$$B = 2\times 10^{13}\,\mathrm{G}$$
$$\Omega = 2\times 10^{3}\,\mathrm{s}^{-1}$$
$$\nu = 2\times 10^{10}\,\mathrm{cm}^{2}.\mathrm{s}^{-1}$$

Impact of stratification on the MRI



Guilet & Müller (2015)

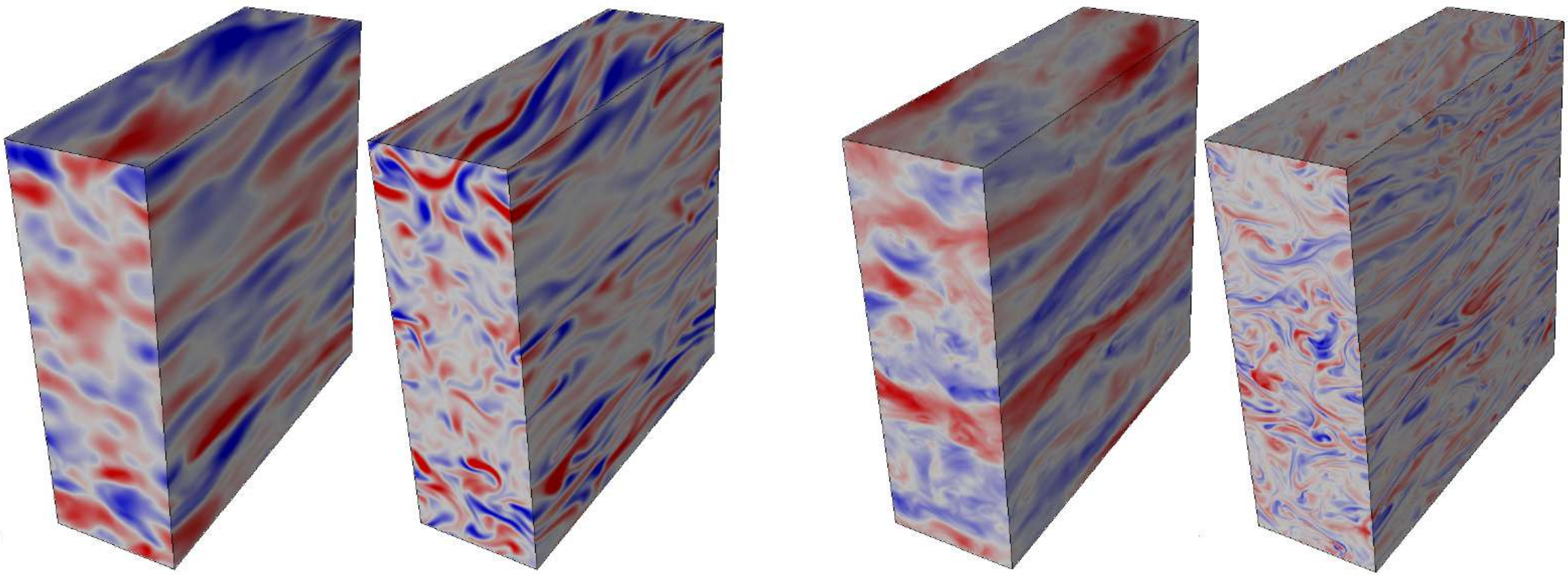
Dependence on diffusion processes: large Pm

In a protoneutron star: $Pm = 10^{13}$!

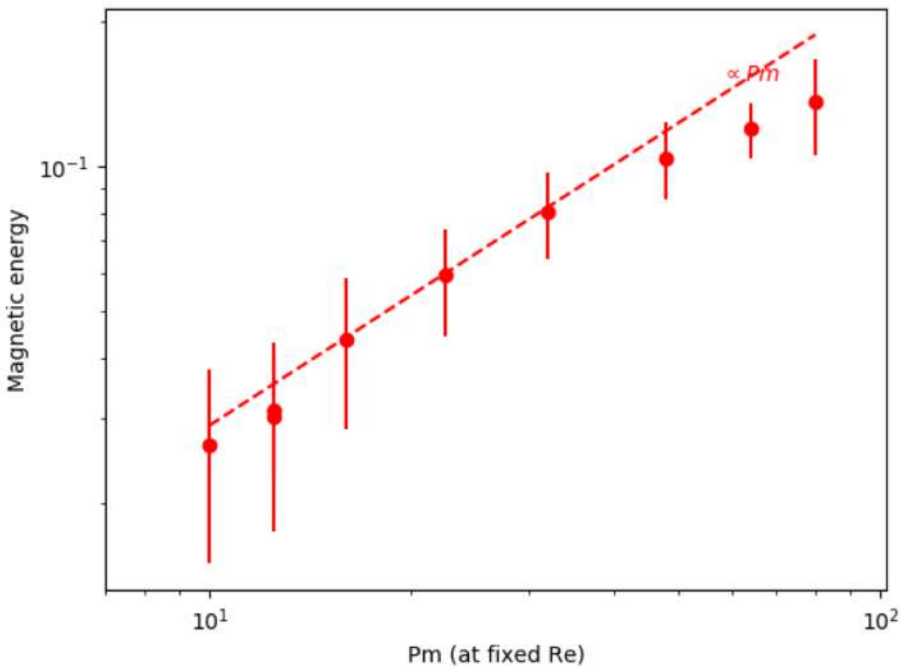
Pm = viscosity/resistivity

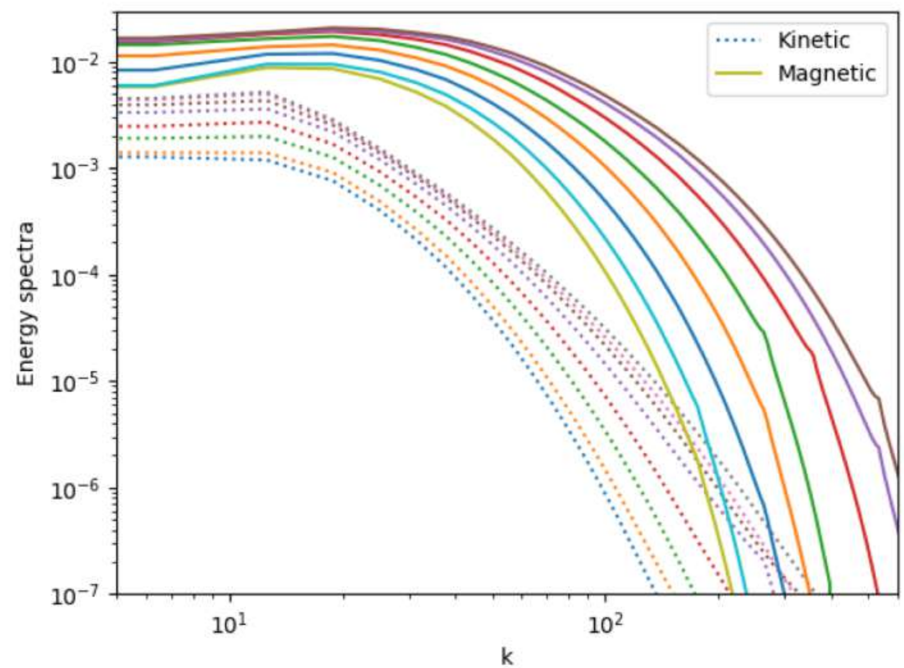
Pm = 12.5 — Velocity, B field

Pm = 80 — Velocity, B field



Dependence on diffusion processes: large Pm





Plateau at large magnetic Prandtl number Pm ?

See also for low Pm:
Fromang+2007, Lesur+2007,
Meheut+2015, Potter+2017

A simple setup for global MRI

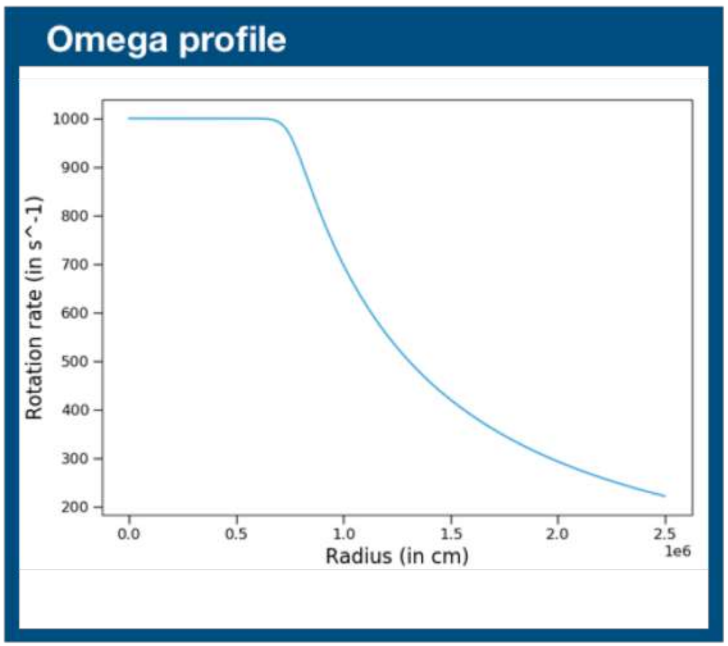
Simplest model : Incompressible ; resolution = 256x512x1024

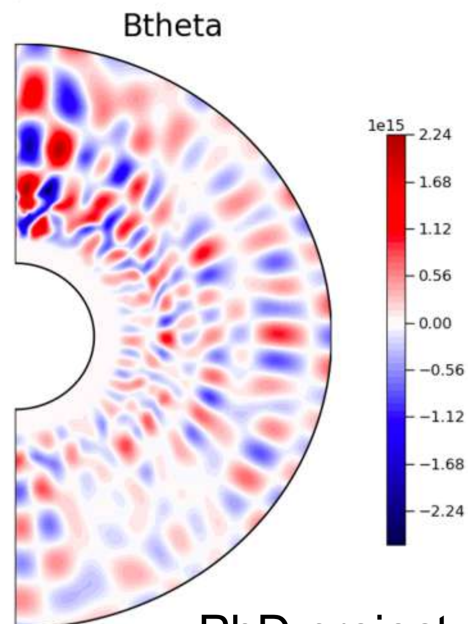
Public pseudo-spectral code : MagIC Gastine & Wicht 2012 https://github.com/magic-sph/magic

Differential rotation imposed at the outer boundary

Typical parameters values : Pm = 16 and Re = 5000

$$\Omega = 10^3\ \mathrm{s}^{-1},\ \nu = 8 \cdot 10^{11}\ \mathrm{cm}^2\mathrm{s}^{-1},\ \eta = 5 \cdot 10^{10}\ \mathrm{cm}^2\mathrm{s}^{-1},\ r = 25\ \mathrm{km},\ B_{mean} = 8.97 \cdot 10^{14}$$

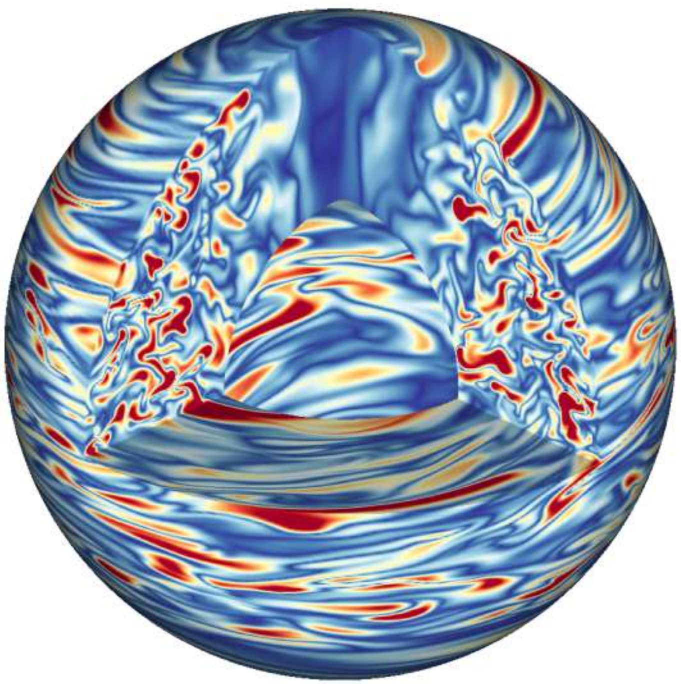


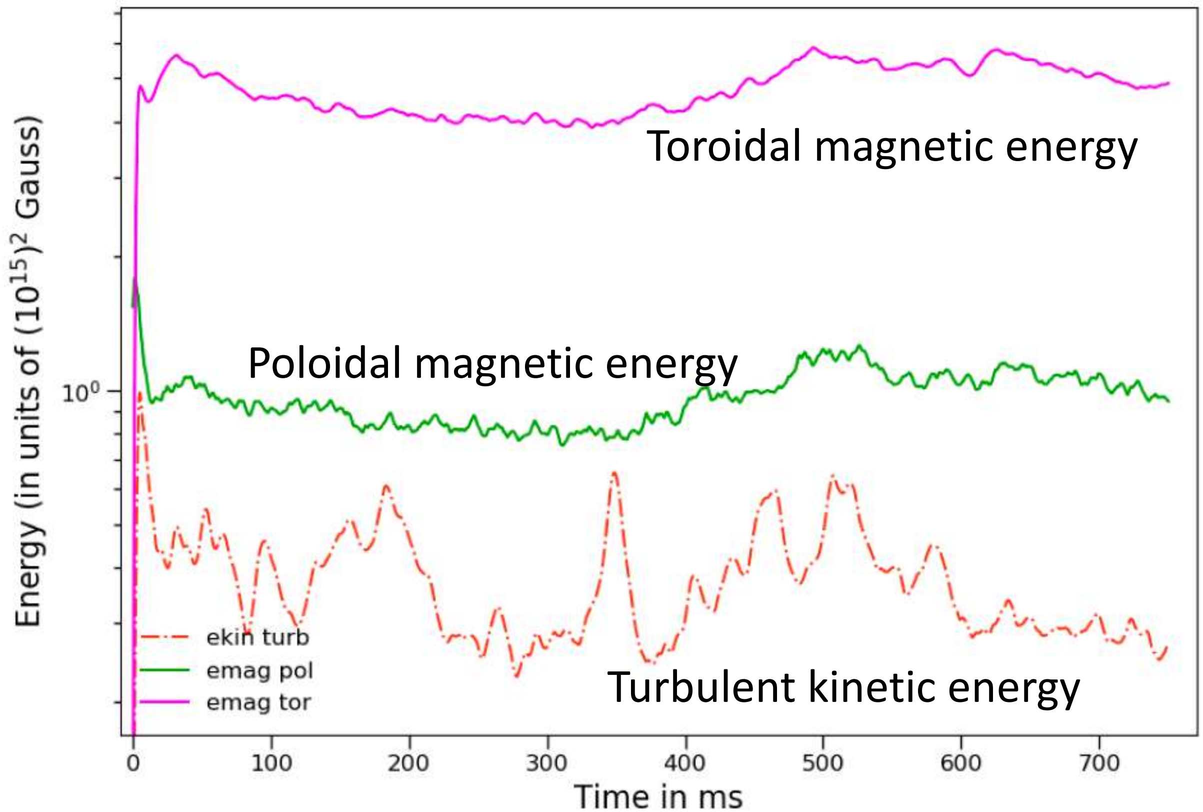


Initial B field:
small scales
~ local models

PhD project of Alexis Reboul-Salze

Global model of MRI: geometry of the magnetic field ?

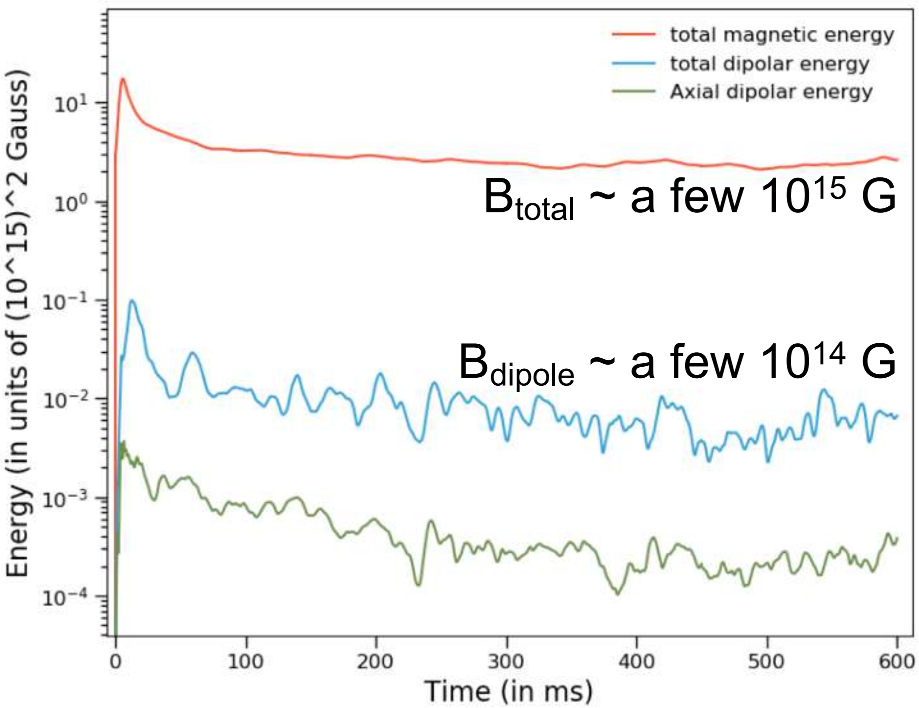




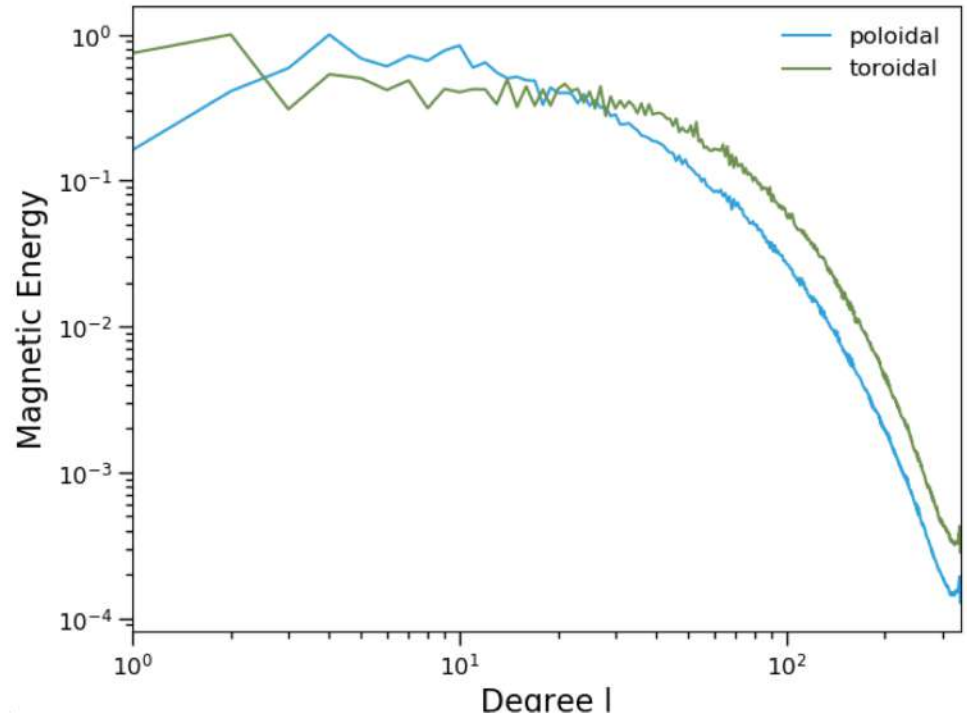
Reboul-Salze, Guilet, Raynaud & Bugli 2019, in prep

A subdominant but significant dipole

Magnetic energy evolution



Magnetic energy spectrum



Equatorial dipole as strong as a (weak) magnetar ☺

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Alexis Reboul-Salze

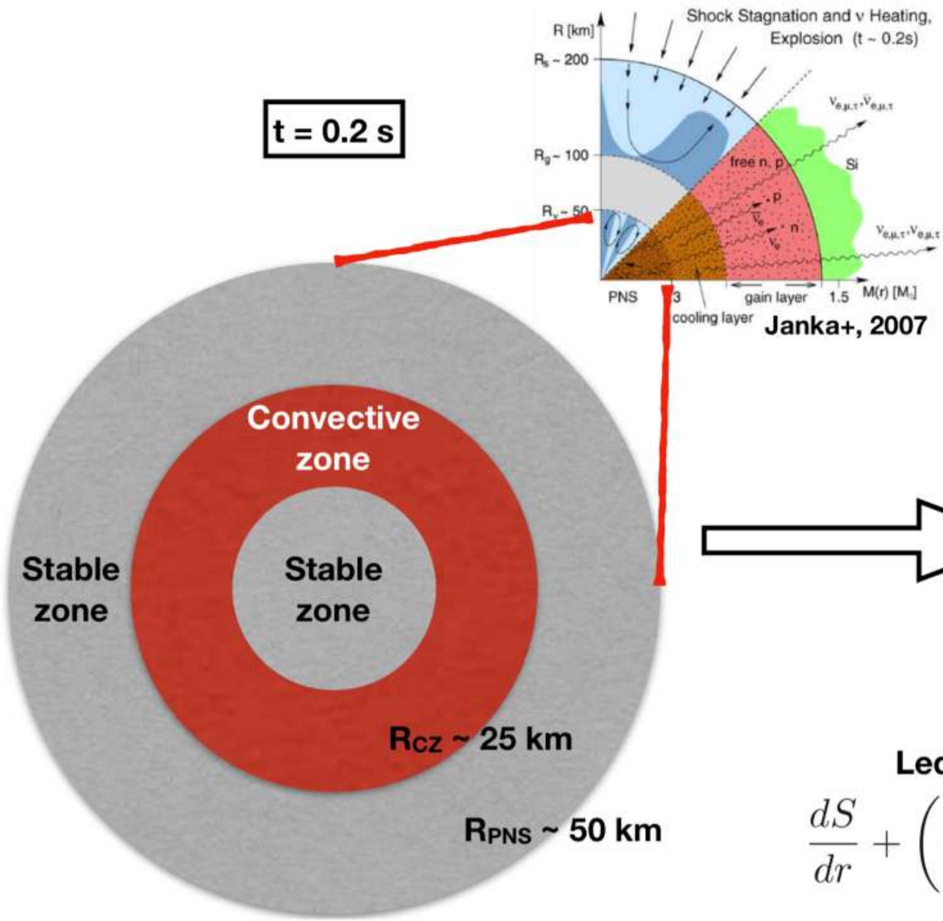
3 Convective dynamo

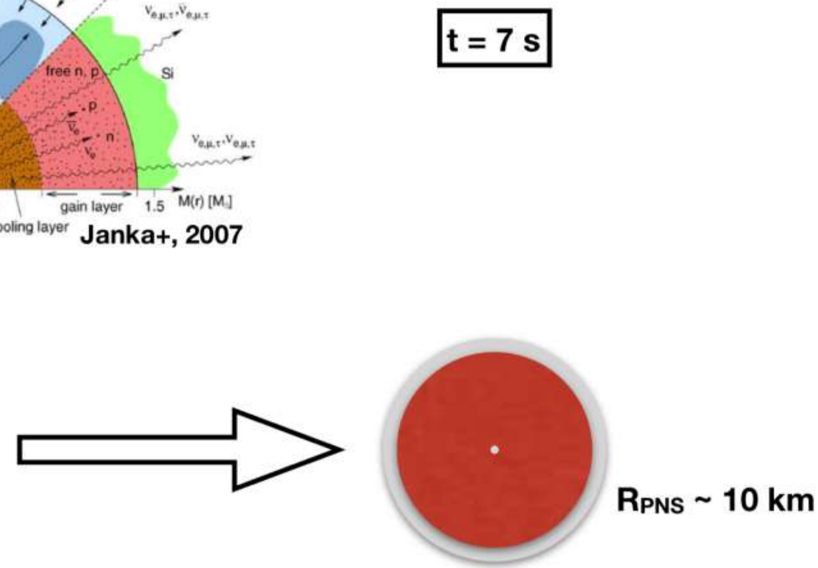
Raphaël Raynaud

4 Magnetorotational explosions

Matteo Bugli

Convective zone in a proto-neutron star





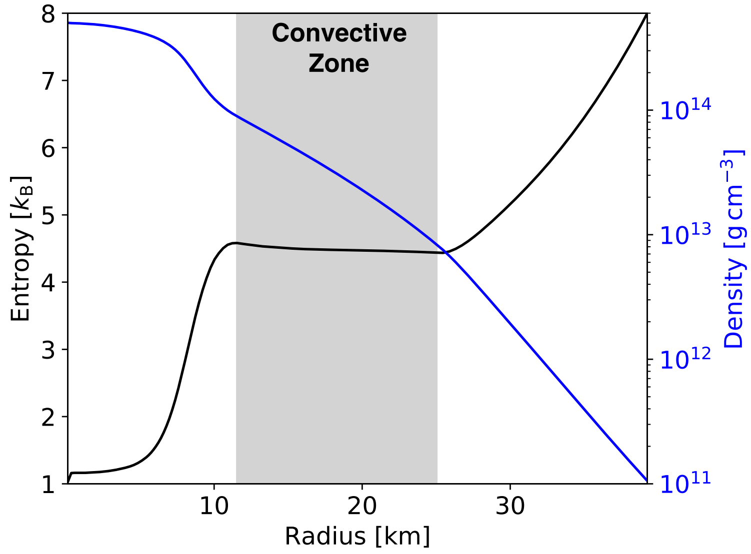
Ledoux criterion

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

Magnetars from convective dynamo ? Thompson & Duncan 1993

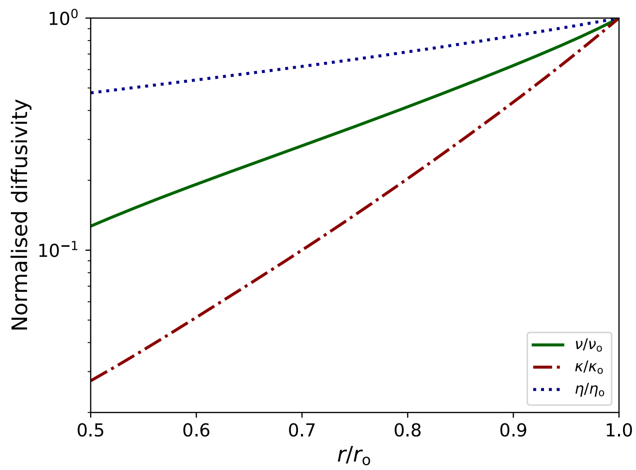
First simulations of a convective dynamo in proto-neutron stars

Physics included:
- PNS structure from 1D model by Garching group
- Equation of state: LS220
- Progenitor: 27 Msun
- Only the convective zone: r = 12-25 km
- Anelastic approximation (soundproof)

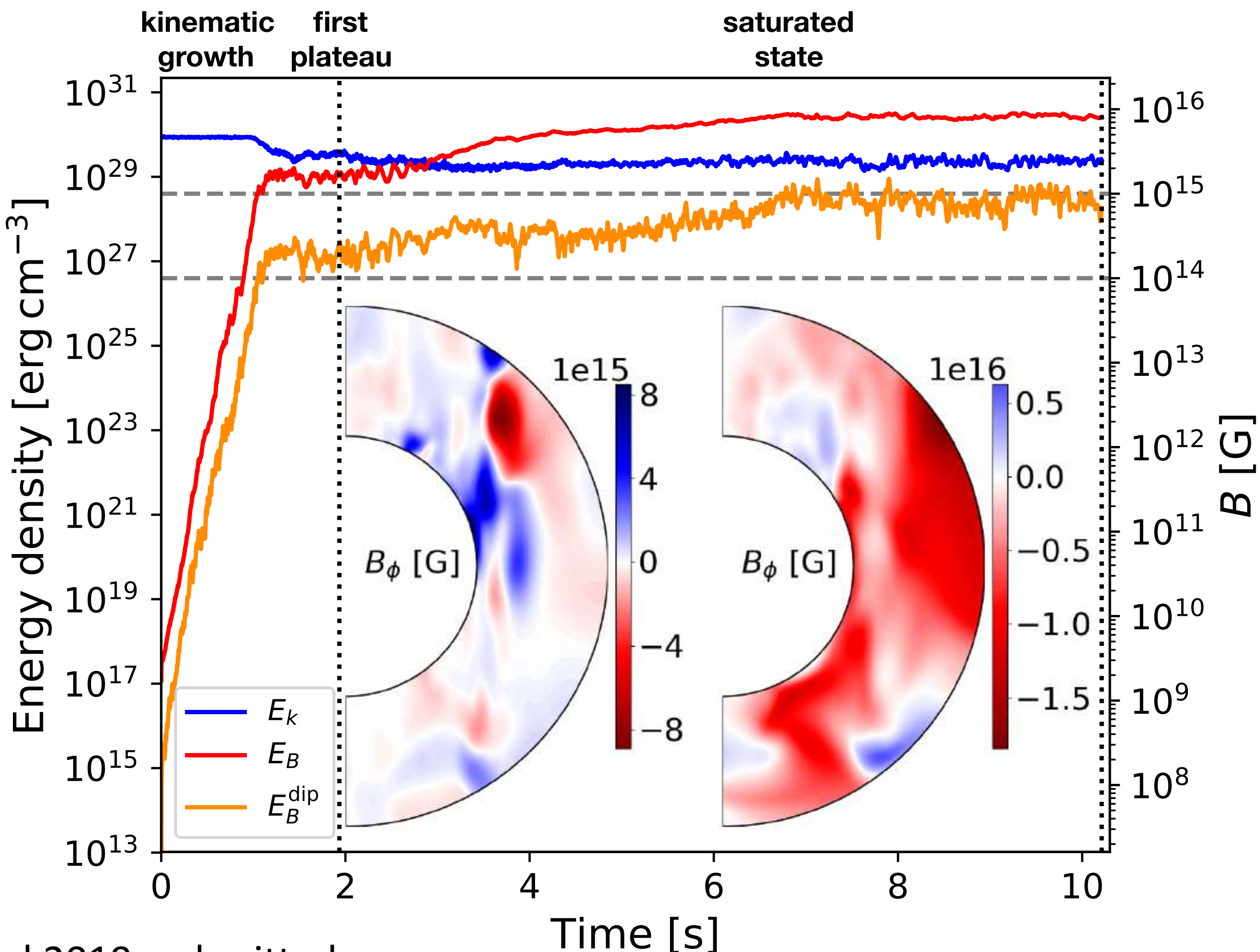


Explicit diffusivities:
- viscosity & thermal diffusion due to neutrinos
- resistivity

PNS	Simulation
$\nu_o \sim 10^{10}\,\mathrm{cm^2\,s^{-1}}$	$\nu_o \sim 10^{12}\,\mathrm{cm^2\,s^{-1}}$
$\kappa_o \sim 10^{12}\,\mathrm{cm^2\,s^{-1}}$	$\kappa_o \sim 10^{13}\,\mathrm{cm^2\,s^{-1}}$
$\eta_o \sim 10^{-5}\,\mathrm{cm^2\,s^{-1}}$	$\eta_o \sim 10^{12}\,\mathrm{cm^2\,s^{-1}}$



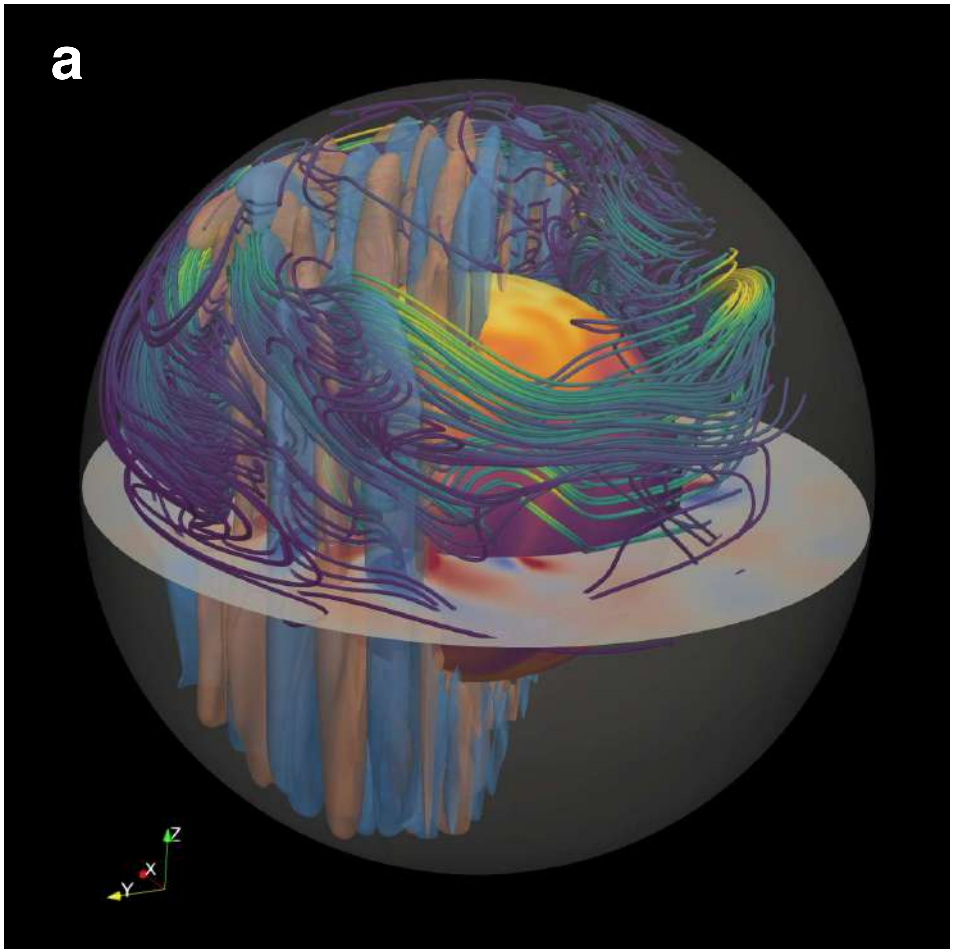
Typical B field time evolution for fast rotation



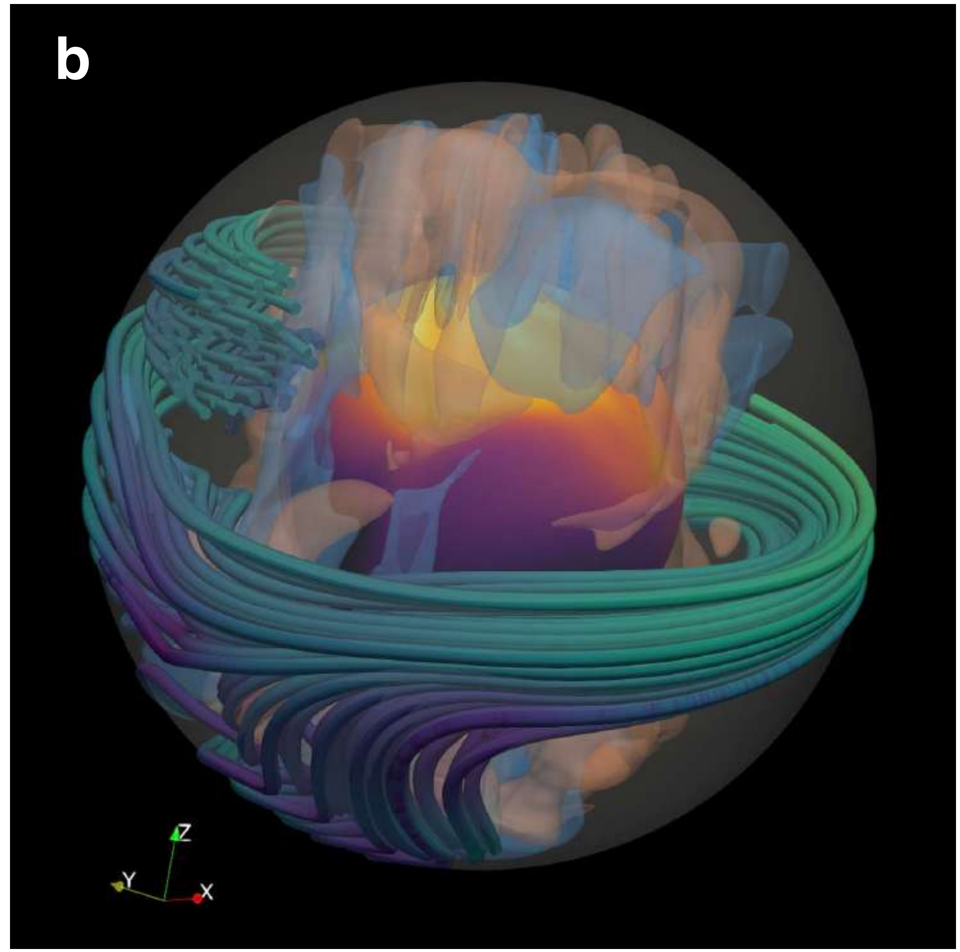
Raynaud, Guilet et al 2019, submitted

Flow & B field morphology

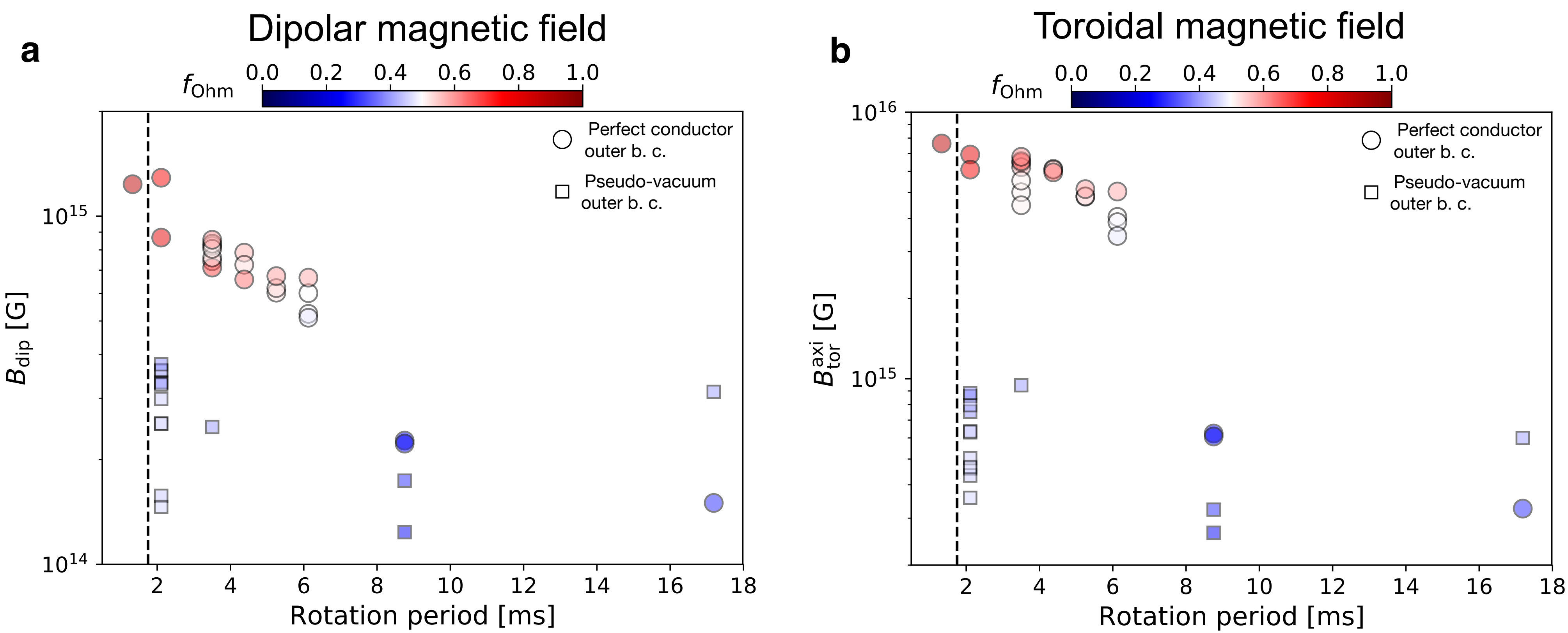
First plateau



Saturated state



Magnetic field strength



up to 10^{15} G ! ☺

up to 10^{16} G !

Compatible with magnetar model for GRBs

Delayed strong dynamo action ?

Rossby number decreases with time as the PNS cools and shrinks:

$$Ro = U/(\Omega d)$$
$$Ro \propto (\Phi_o R^4/M)^{1/3}/j$$

Very fast rotation: P < 2.5 ms
prompt strong dynamo

=> hypernova & GRB ?

Intermediate rotation: 2.5 ms < P < 10 ms
delayed strong dynamo

- somewhat weaker field
- less rotation kinetic energy

=> superluminous SNe & magnetars associated with normal SNe ?

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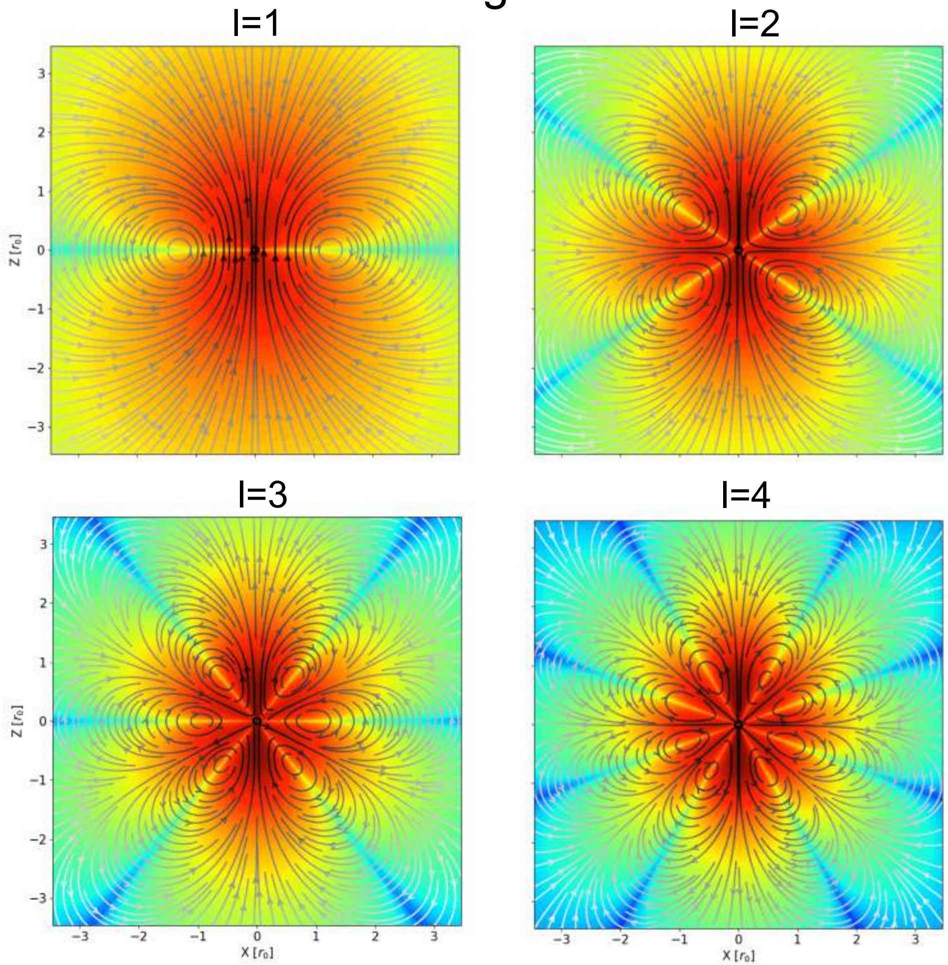
Matteo Bugli

Magnetorotational explosions

Initial magnetic field



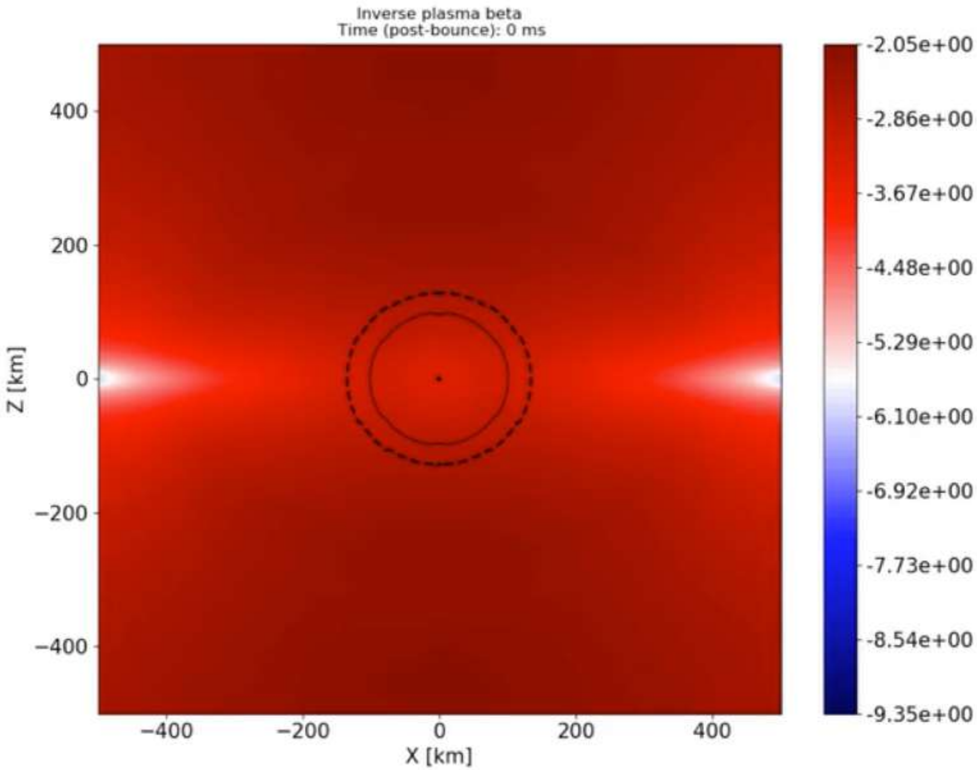
Physics included:
- Fully compressible MHD
- Special relativity
- Neutrino transport
- Realistic equation of state
- 2D

B field amplification not described:
-> test the influence of initial B field
geometry & intensity

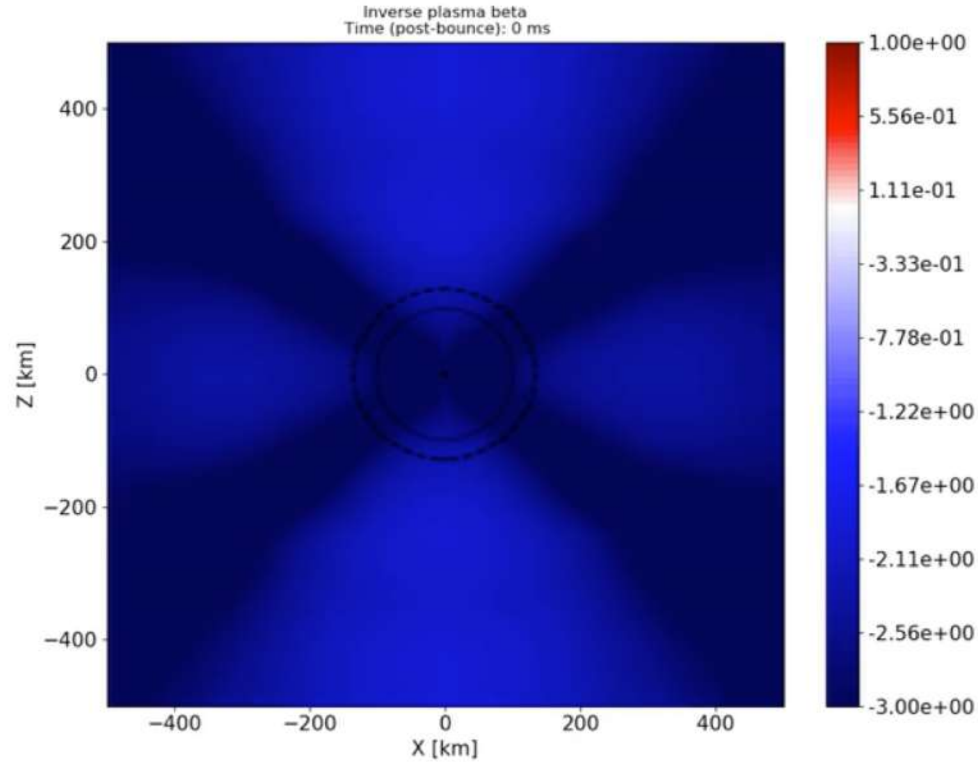
Matteo Bugli (postdoc at CEA Saclay), collaboration with Martin Obergaulinger (Darmstadt)

Magnetorotational explosions: dipole versus quadrupole

Dipole B field



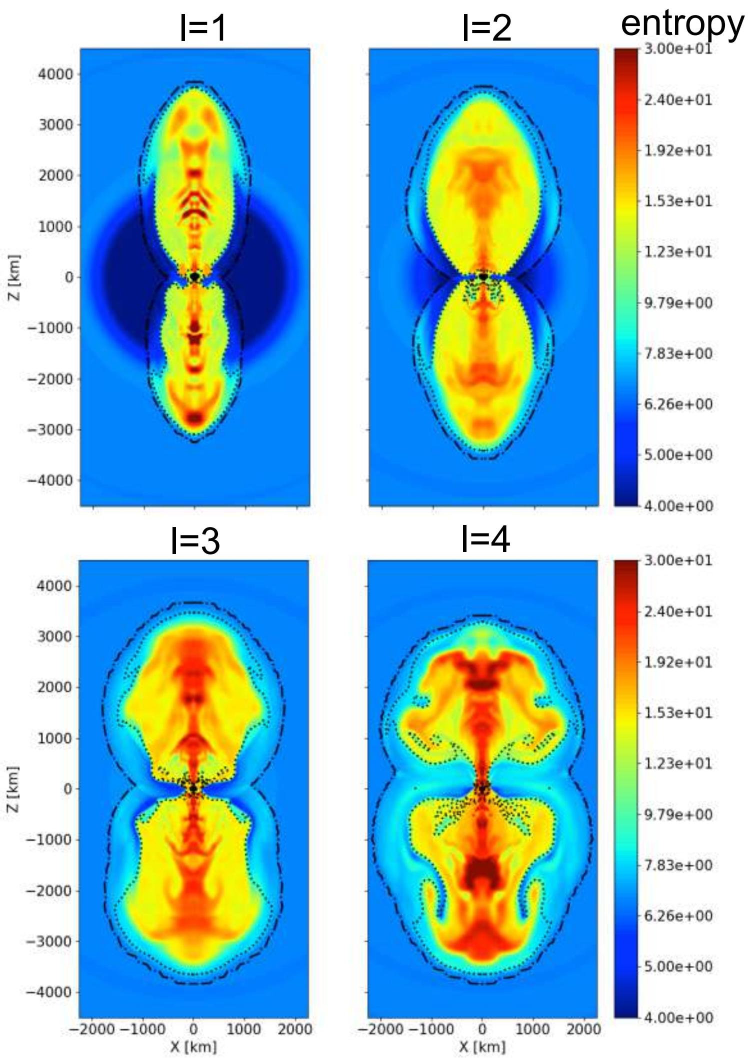
Quadrupole B field

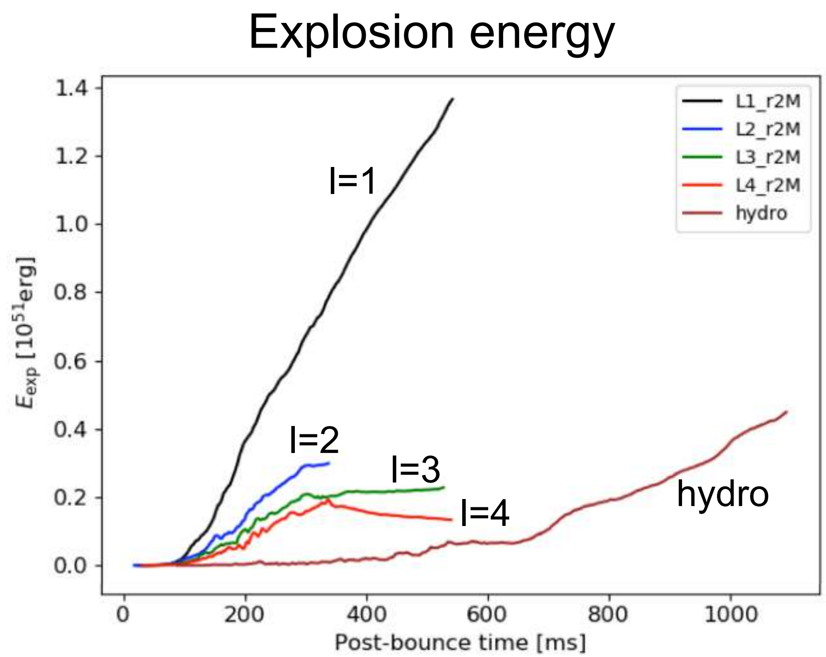


Color code = magnetic pressure/thermal pressure

Dipole B field more efficient at launching an explosion

Magnetorotational explosions as a function of multipolar order





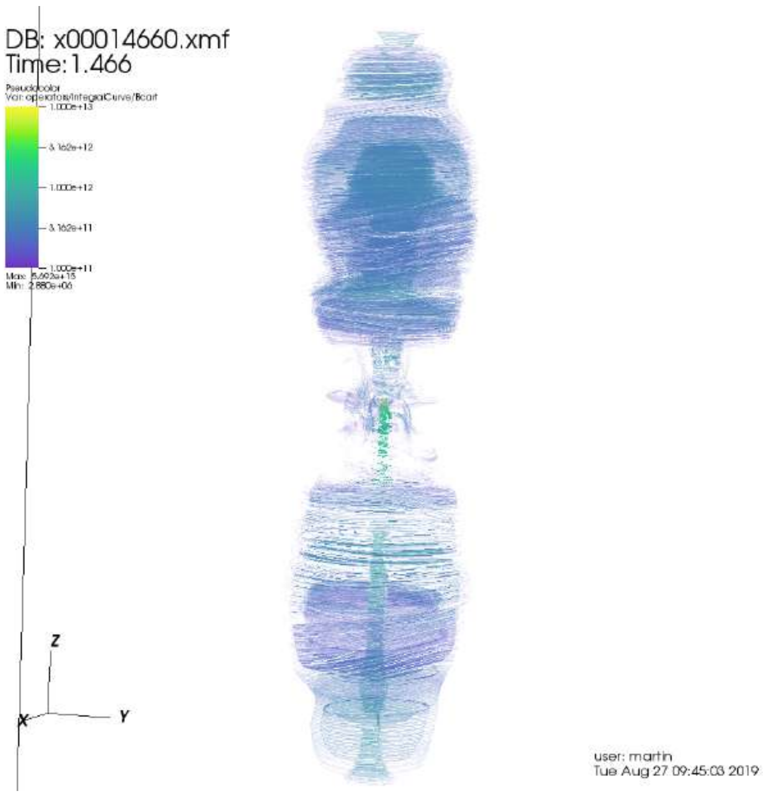
Higher multipoles also launch explosions but:

- Less collimated
- Less energetic

Bugli, Guilet et al 2019 (submitted)

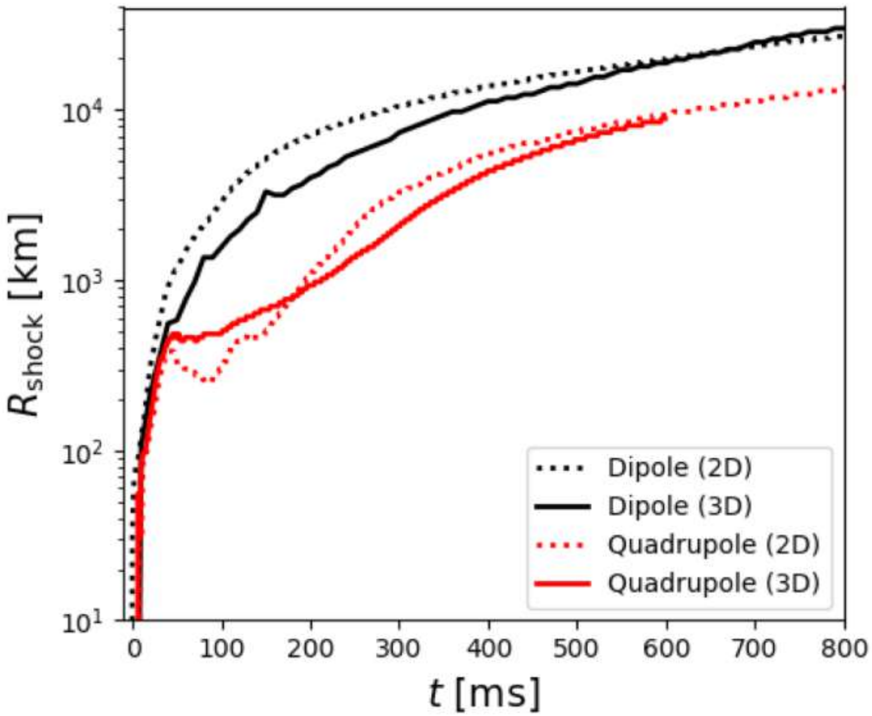
Magnetorotational explosions: 3D simulations

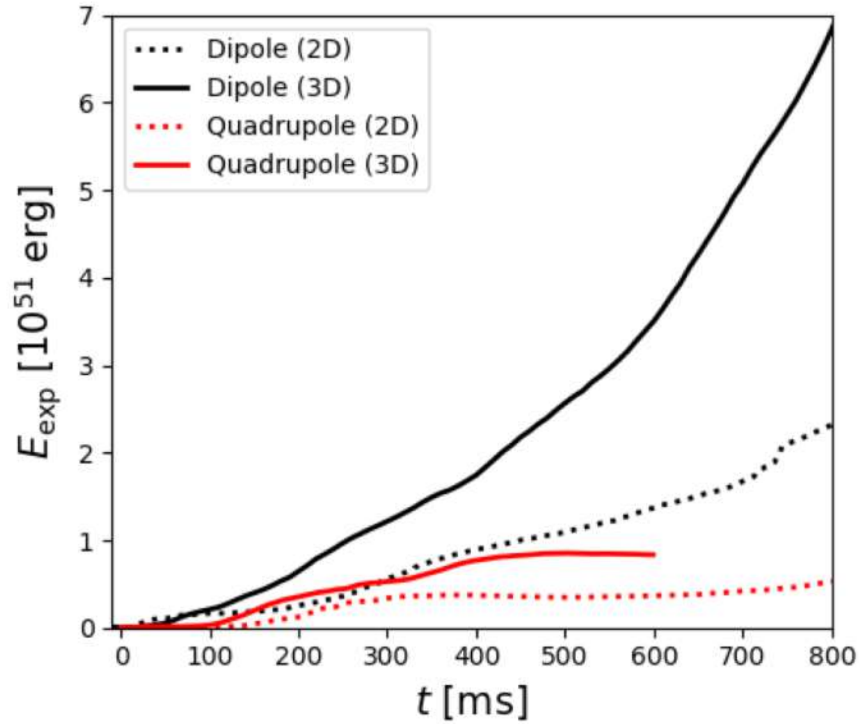
Dipole (l=1)



Quadrupole (l=2)

Magnetorotational explosions: 2D vs 3D simulations





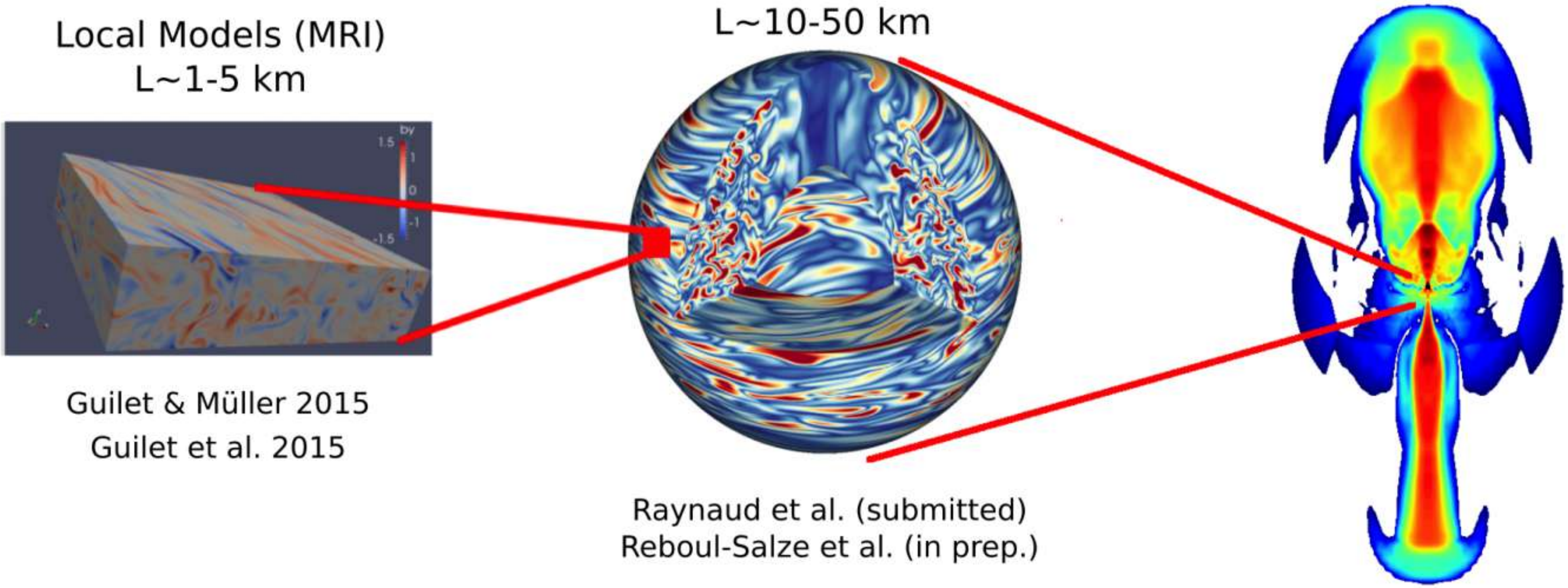
Qualitatively confirms dependence on
multipolar order, quantitatively different

Still a long way to go: from the small to the 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)

Amplification & saturation ?

High Pm regime? Drag force?

Magnetic field geometry ?

MRI vs convective dynamo

Explosion diversity ?

Energy, jet properties etc.

GW & neutrinos signature ?

Thanks !