Modelling extreme explosions in the millisecond magnetar scenario: protoneutron star dynamos

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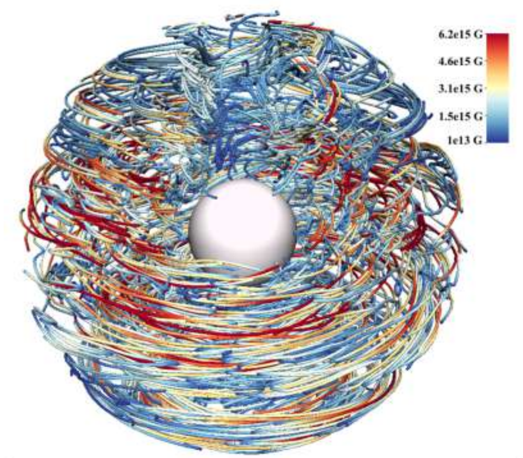

ERC MagBURST team:

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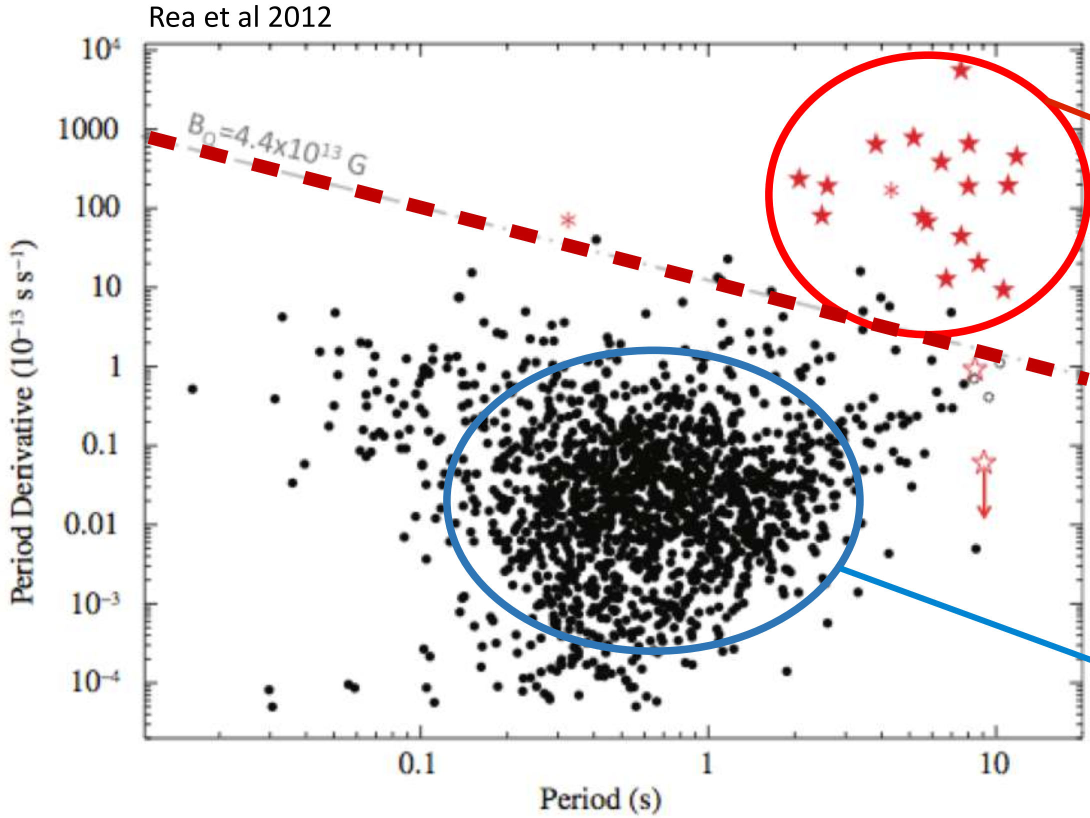
Paul barrère
Raphaël Raynaud
Matteo Bugli




October 26, 2023

Magnetars: the most intense known magnetic fields



$$B_{\rm dip} \propto \sqrt{P\dot{P}} \sim 10^{14} - 10^{15}\,{\rm G}$$

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

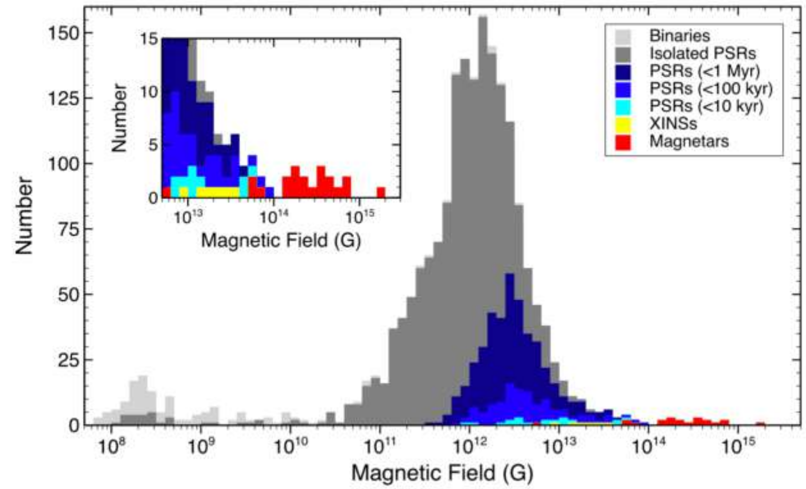
Galactic magnetars: observational constraints

30 magnetars in Galaxy and magellanic clouds

Magnetic dipole $B_{dip} \sim 10^{14} - 10^{15}$ G

Indications of stronger multipolar/toroidal field

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



Olausen & Kaspi 2014

Birth rate : ~10-40 % of core-collapse SNe/neutron star birth

Slow rotation P ~1 - 10 s

-> But rotation at birth unknown !

~10 magnetars associated to a supernova remnants

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

Which supernovae are associated to magnetar birth ?

Outstanding stellar explosions: millisecond magnetars ?

Explosion kinetic energy :

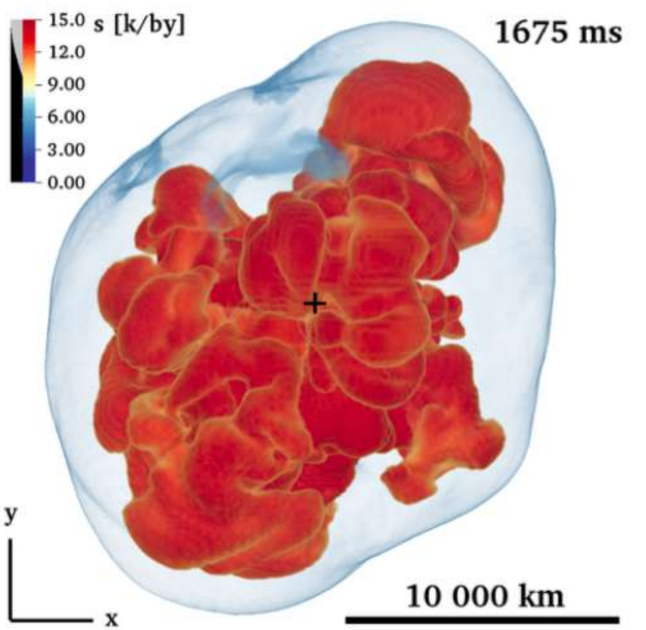
Typical supernova: 10^{51} erg

→ Neutrino driven explosions ?

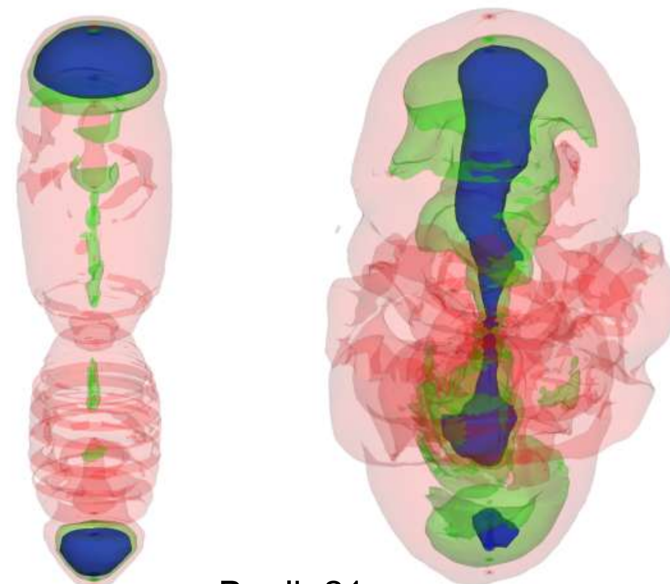
Rare hypernova & long GRB: 10^{52} erg

aka type Ic BL

→ Magnetorotational explosion ?



Bollig+20



Bugli+21

e.g. Burrows+07, Takiwaki+09,11, Moesta+14, Obergaulinger+17,20, Kuroda+20

Outstanding explosions: millisecond magnetars ?

Total luminosity :

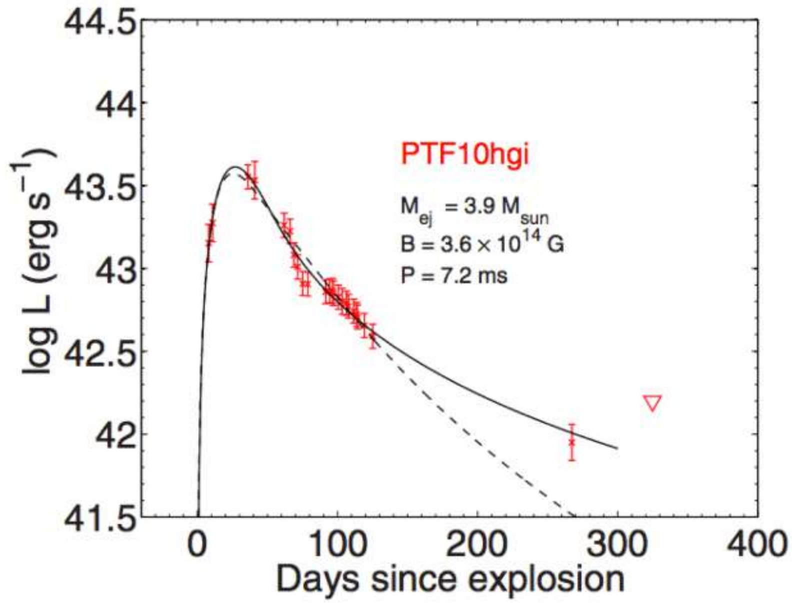
→ Typical supernova 10^{49} erg

→ Superluminous supernovae 10^{51} erg

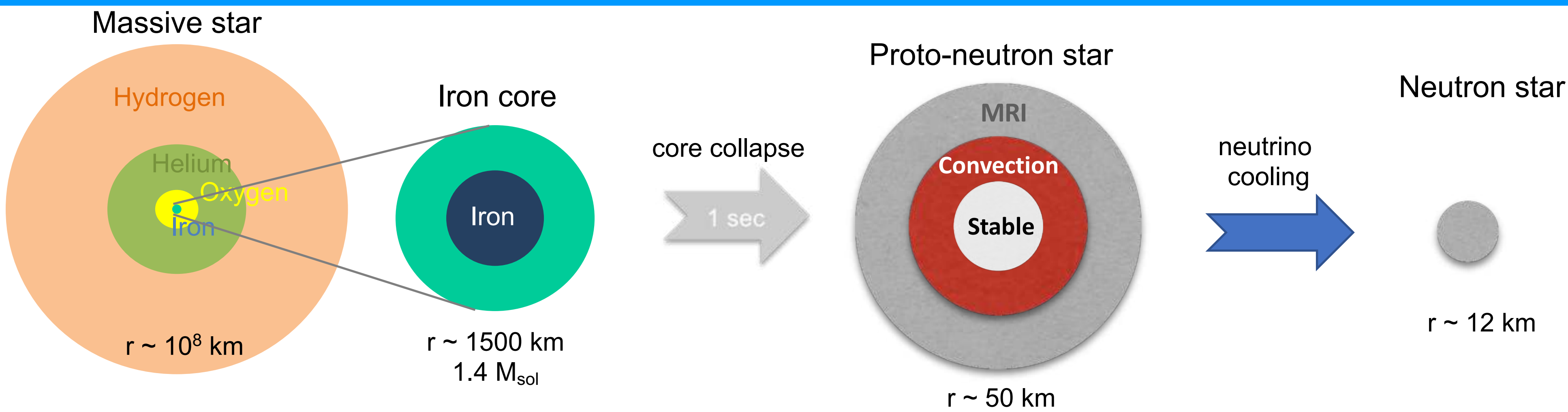
Light curves can be fitted by millisecond magnetar

- 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



Different scenarios for magnetar formation



Compression of stellar magnetic field :

Amplification by a few ~10^4 during core collapse
Very magnetised stars on surface (B >1 kG) : also need a 10^{10}-10^{11} G in the iron core

Protoneutron star dynamos

Magnetorotational instability

Similar to accretion disks

Convective dynamo

Similar to planetary & stellar dynamos

Tayler-Spruit dynamo

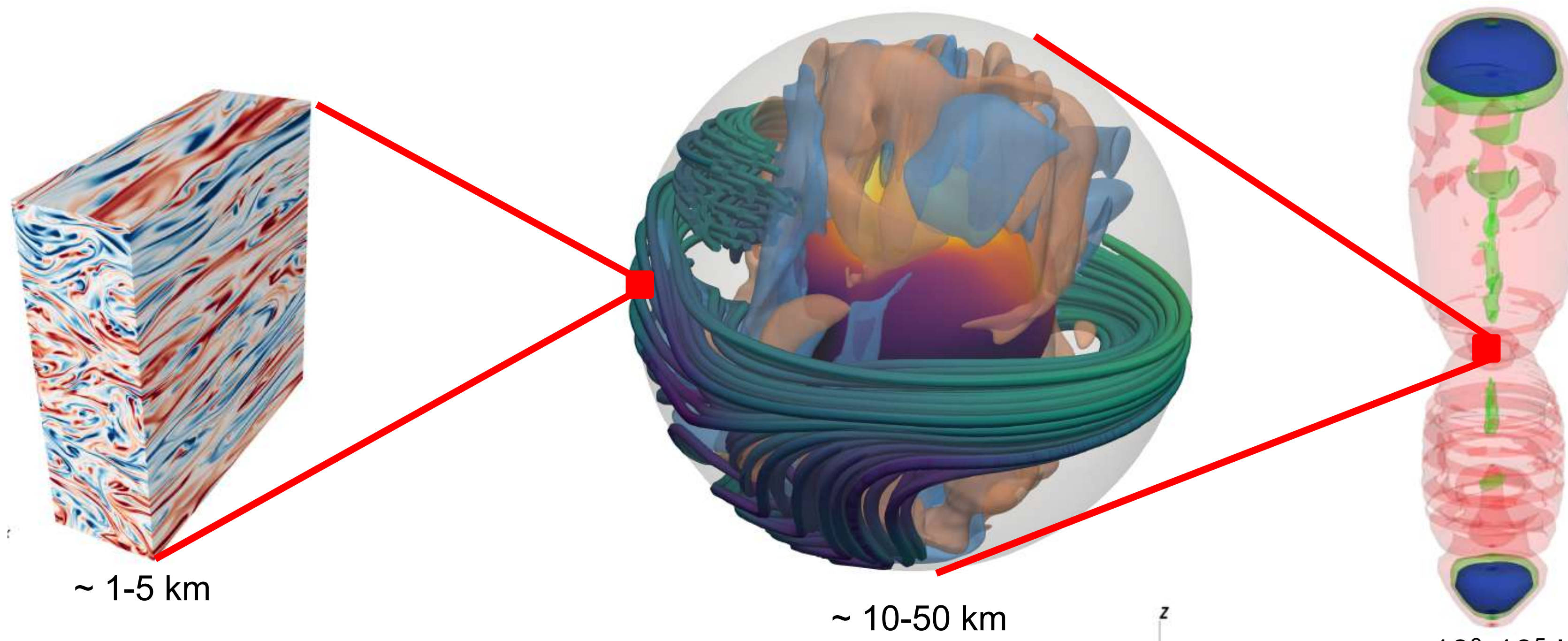
Similar to stellar radiative zones
Talk by Paul Barrère last week

Simulating different spatial scales

Small turbulent scales
Code snoopy
(Lesur & Longaretti 2005)

Protoneutron star dynamo
MagIC code :
https://github.com/magic-sph/magic

Magnetorotational explosions
Code ALCAR,
Martin Obergaulinger



~ 1-5 km

~ 10-50 km

~ 10^3-10^5 km

Guilet et al 2022

Raynaud et al. 2020

Bugli et al. 2021

ERC project MagBURST

Modelling protoneutron star dynamo in spherical geometry

Classical MHD equations

Sound-proof approximations :
Boussinesq, anelastic

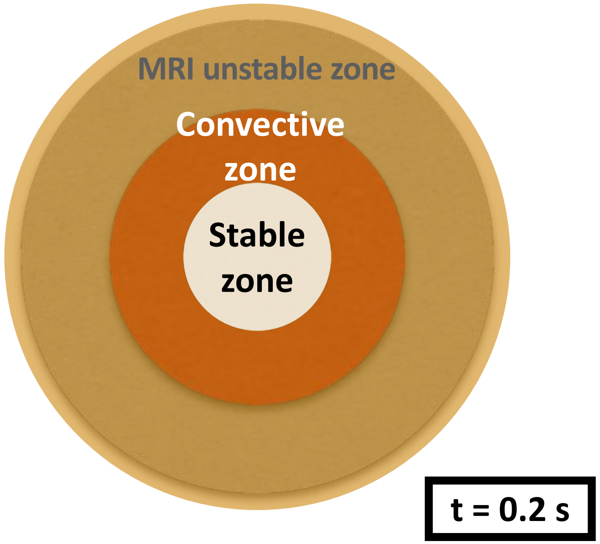
Large viscosity due to neutrino diffusion

High-density equation of state

Spherical geometry

Numerical techniques : pseudo-spectral
Spherical harmonics and Chebychev polynomials

Thermodynamic state from 1D supernova models
(From Garching's group)



MagIC code :
https://github.com/magic-sph/magic
Wicht+ 2002, Gastine+ 2012

The magnetorotational instability (MRI)

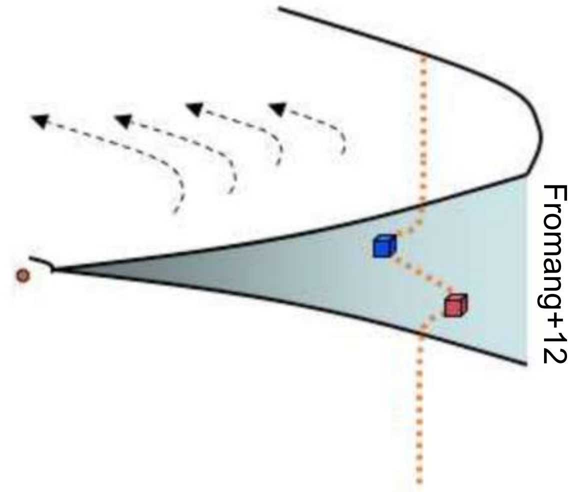
In ideal MHD (i.e. no resistivity or viscosity) :

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

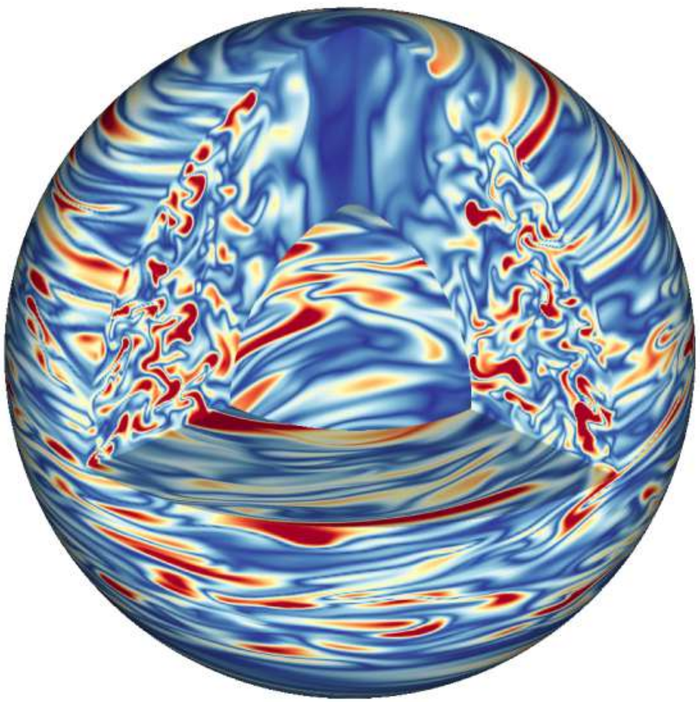


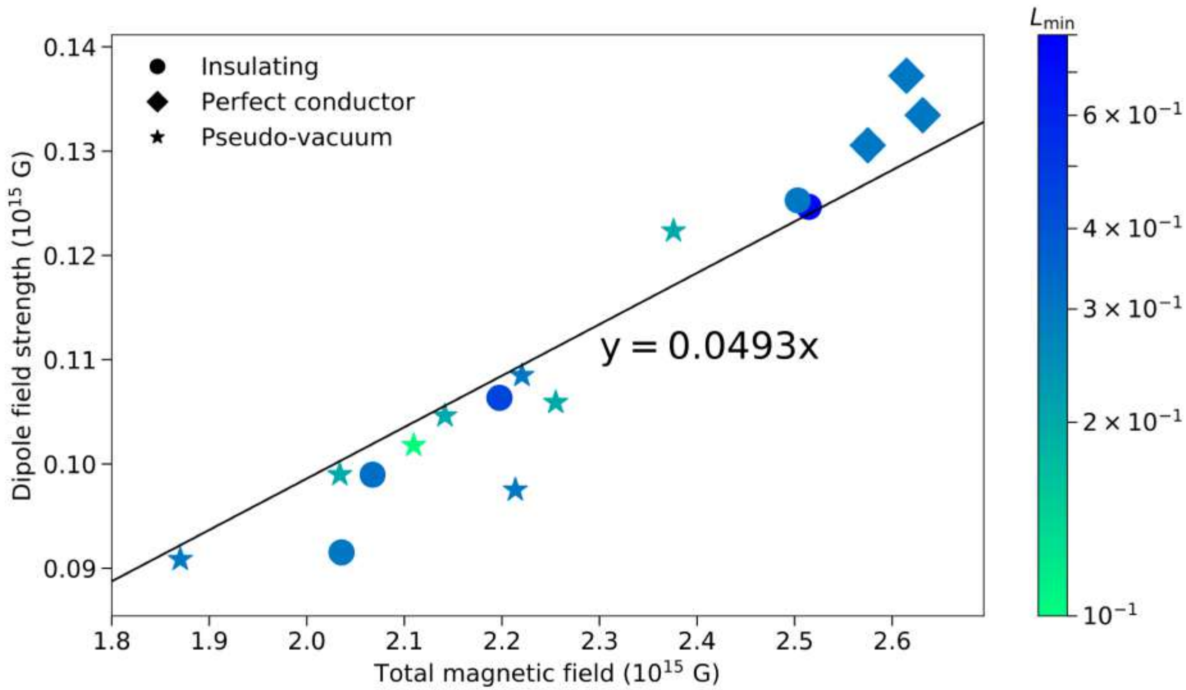
Wavelength : $\lambda \propto \frac{B}{\sqrt{\rho\Omega}}$

→ Short wavelength for weak magnetic field

Akiyama+03, Obergaulinger+09, Masada+12, Guilet+15,22, Moesta+15, Rembiasz+16, Reboul-Salze+21,22

MRI in spherical geometry: dipole generation



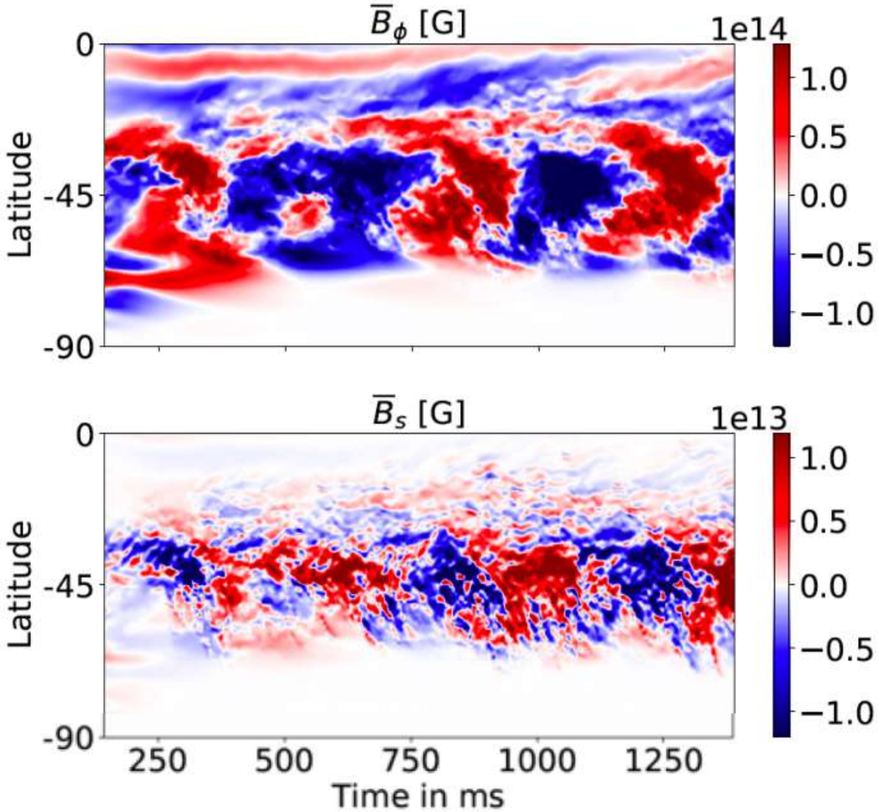


Equatorial dipole (dipolar angle ~ 80°)

Reboul-Salze+2021

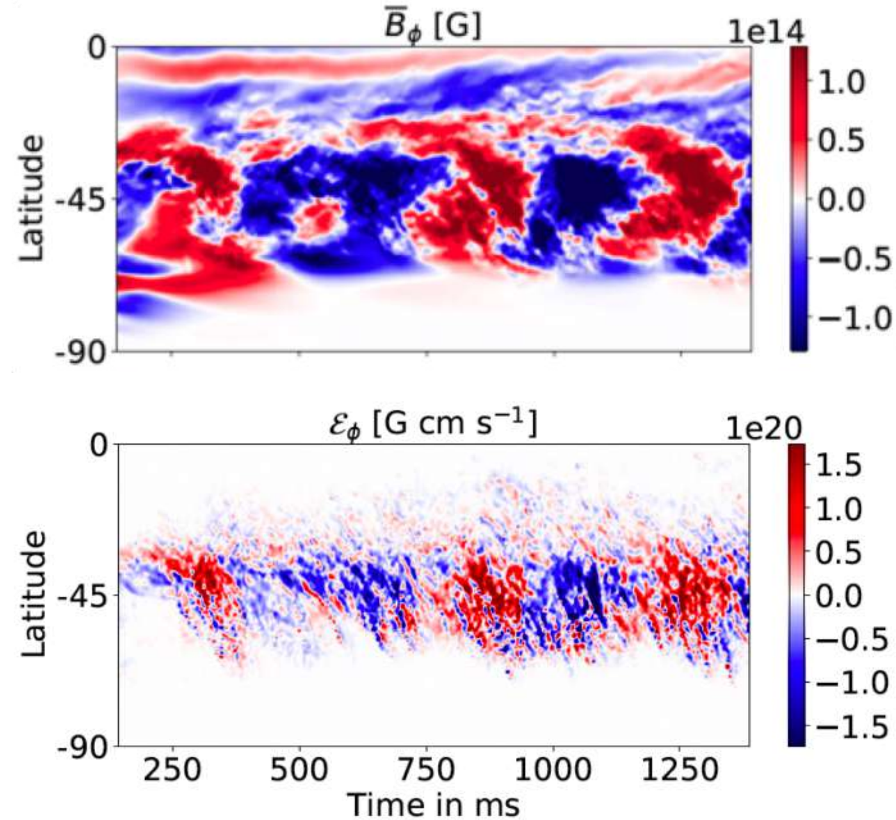
Mean field dynamo oscillations

Omega effect



$$\frac{\partial \overline{B}_\phi}{\partial t} = s\overline{B}_s \frac{d\Omega}{ds}$$

Alpha effect



$$\mathcal{E}_\phi = \alpha_{\phi\phi}\overline{B}_\phi$$

Reboul-Salze+2022

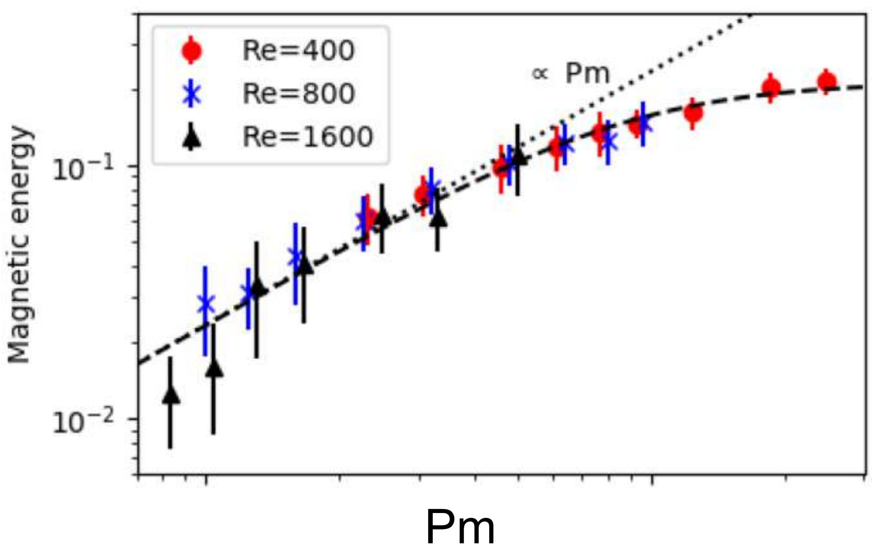
Dependence on diffusion processes: large magnetic prandtl numbers (Pm)

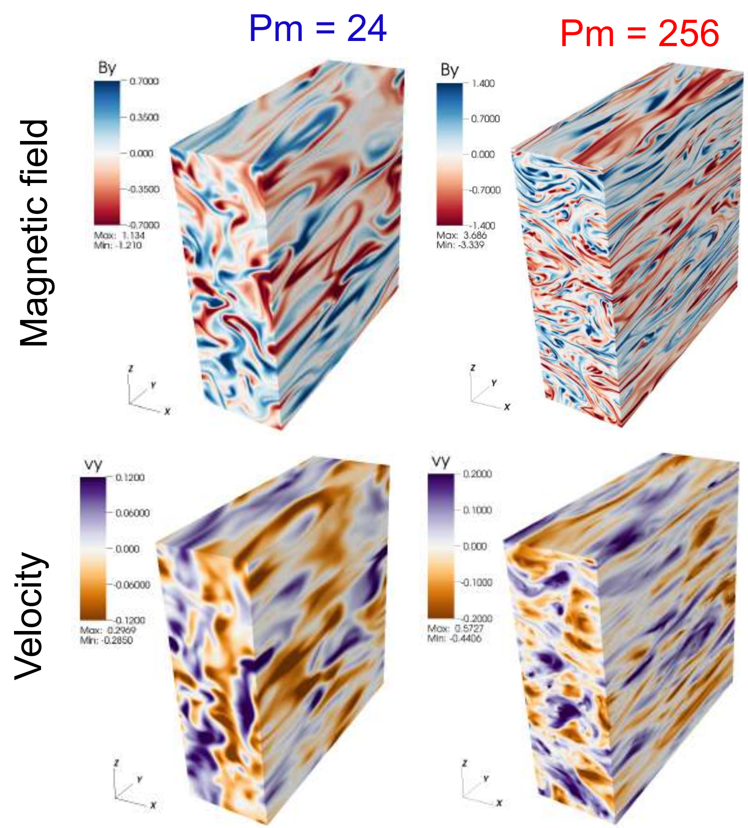
Are high Pm dynamos efficient to generate large-scale magnetic fields ?

See Lander 2022

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

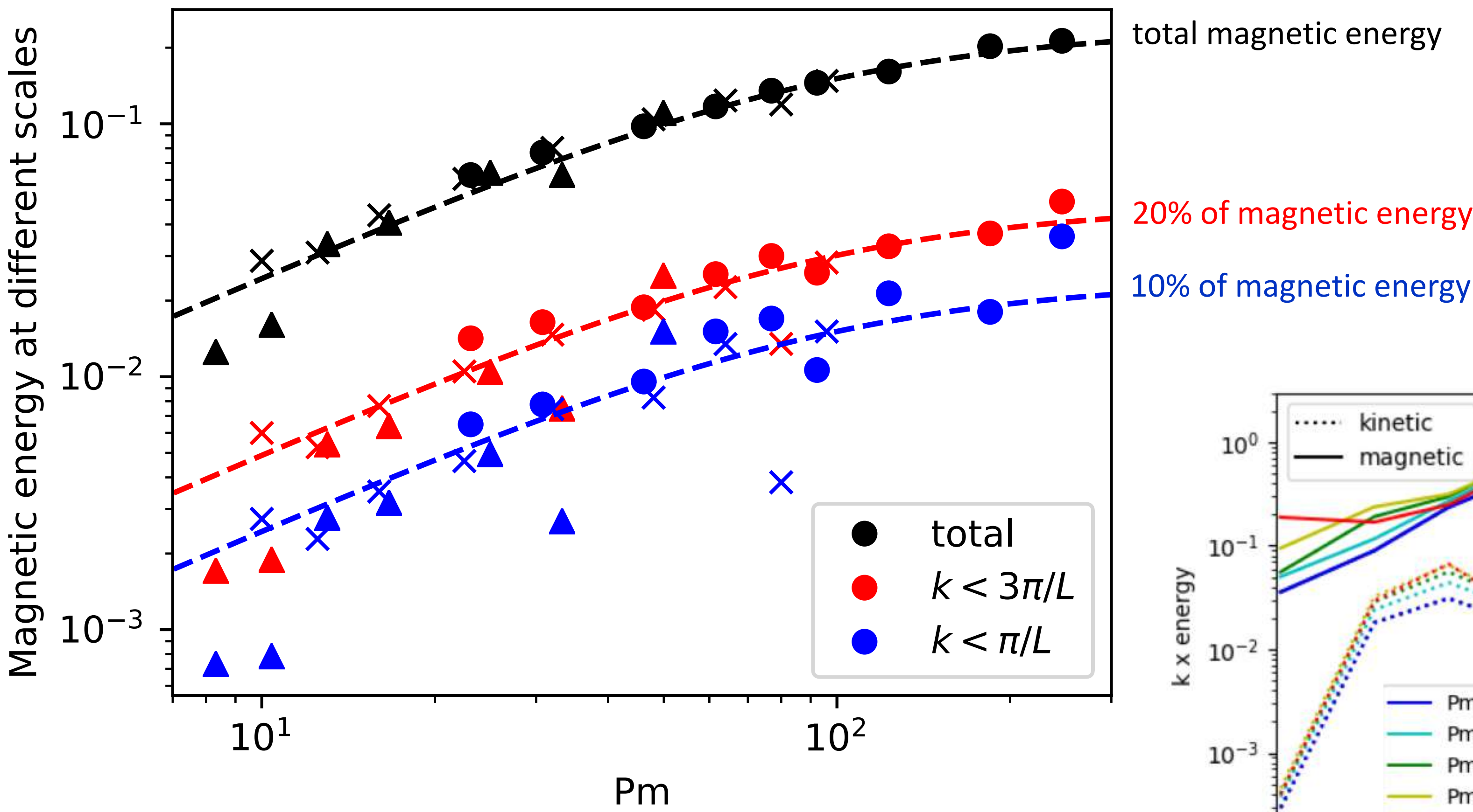
Pm = viscosity/resistivity

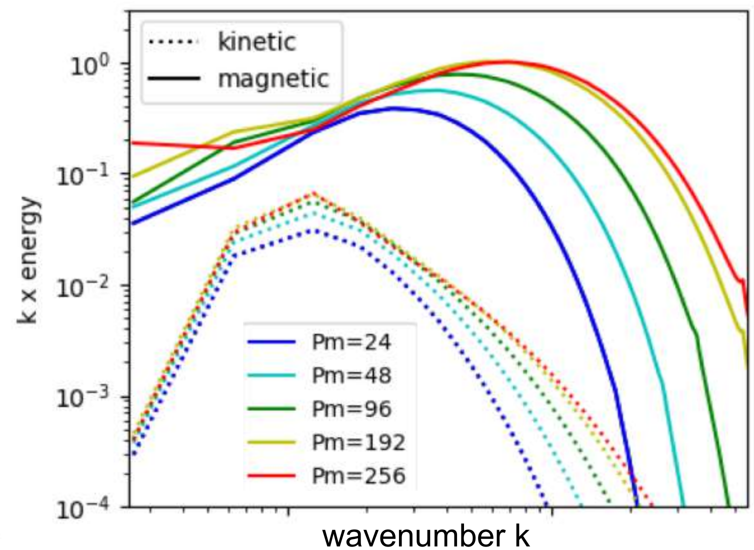




Guilet et al 2022 (see also Held et al 2022)

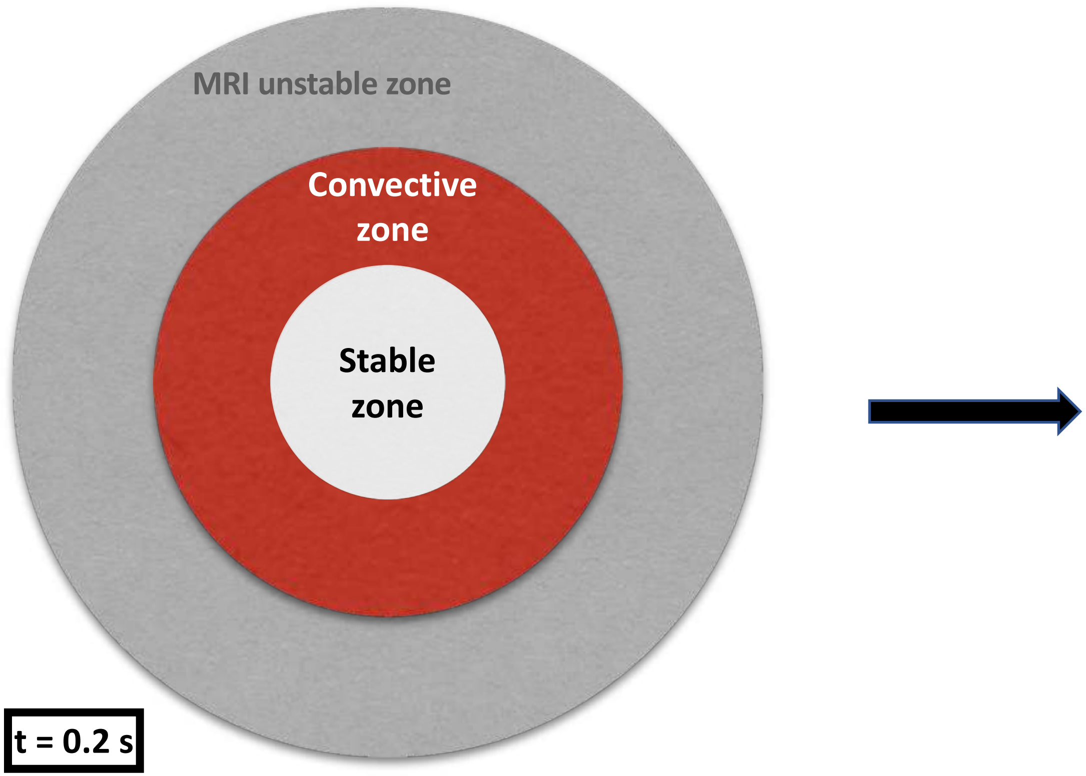
Large-scale dynamo at large Pm





Guilet et al 2022

Convective dynamo

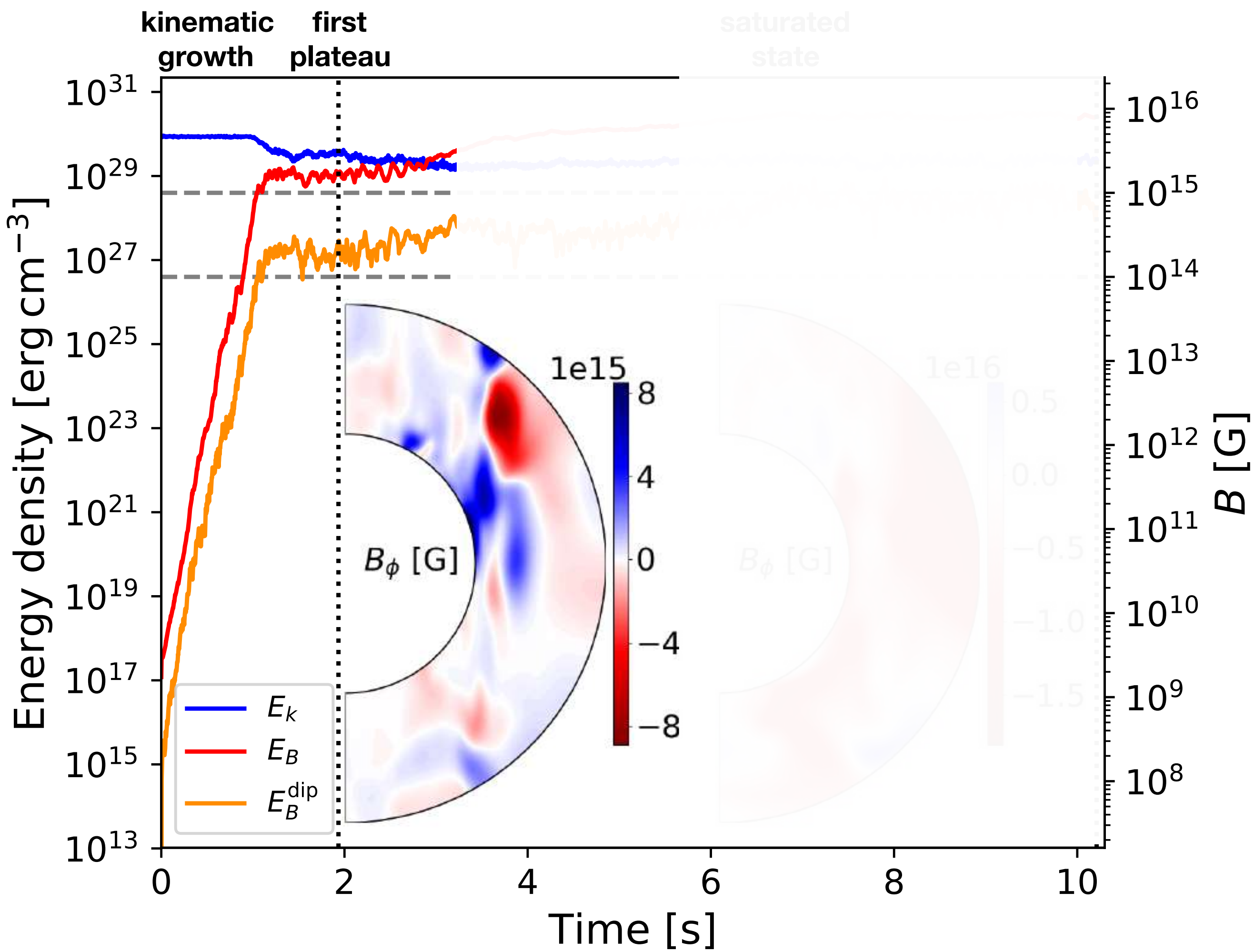


Thermodynamic state from 1D CCSN models from Garching's supernova group

Raynaud et al 2020, 2022

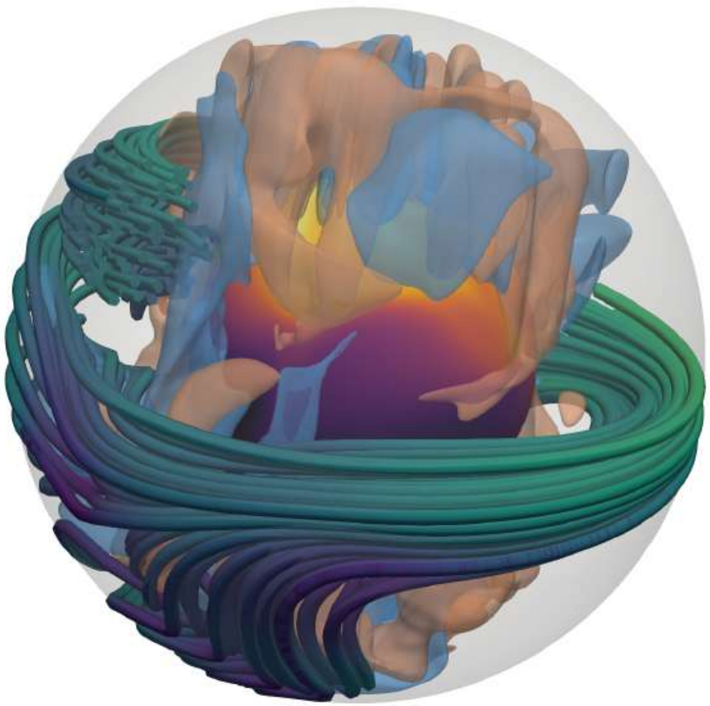
See also Masada et al 2021

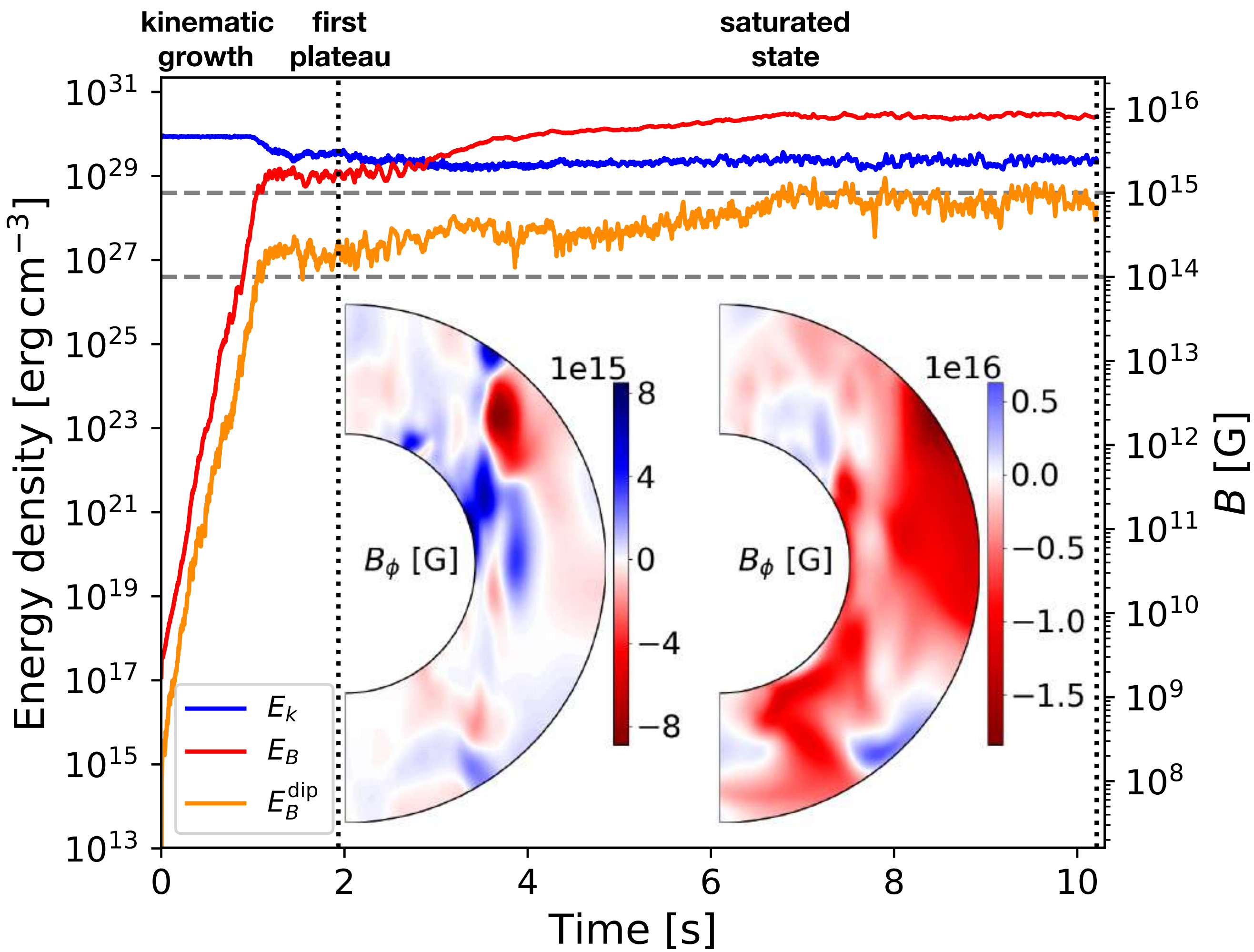
Convective dynamo in a protoneutron star



Raynaud et al 2020

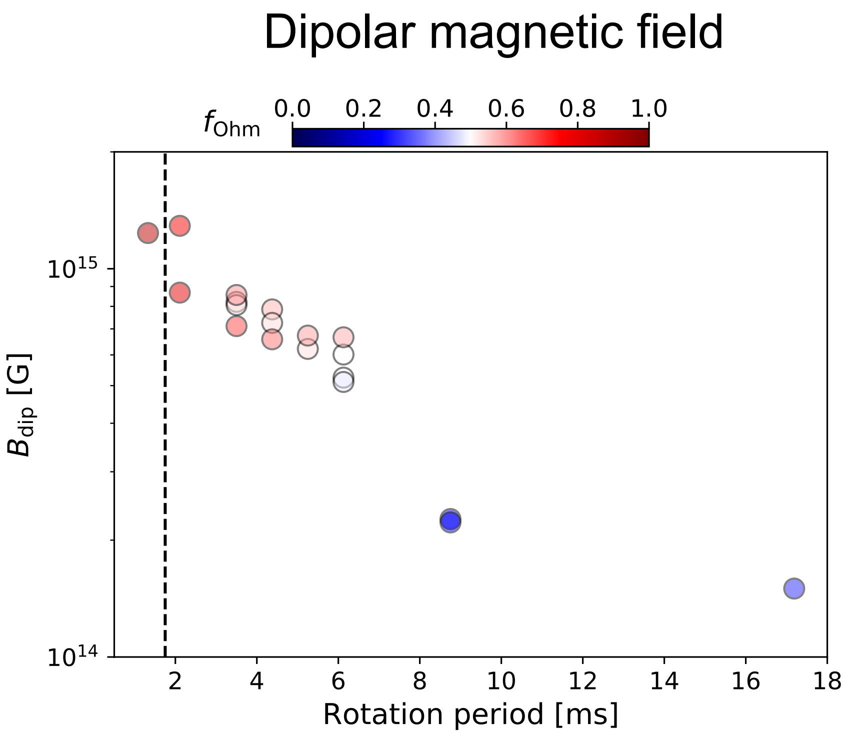
Convective dynamo in a protoneutron star

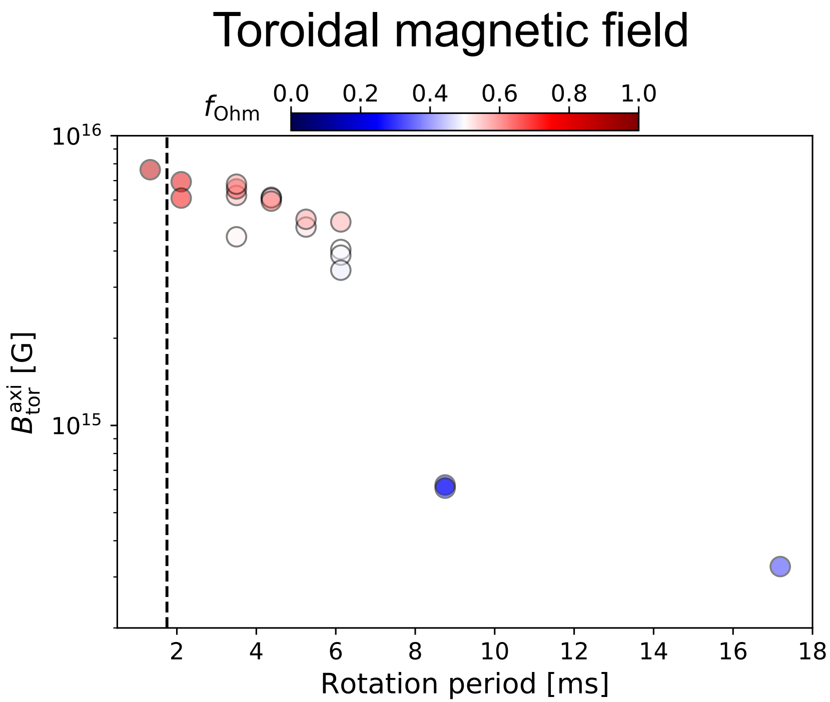




Raynaud et al 2020

Magnetic field strength





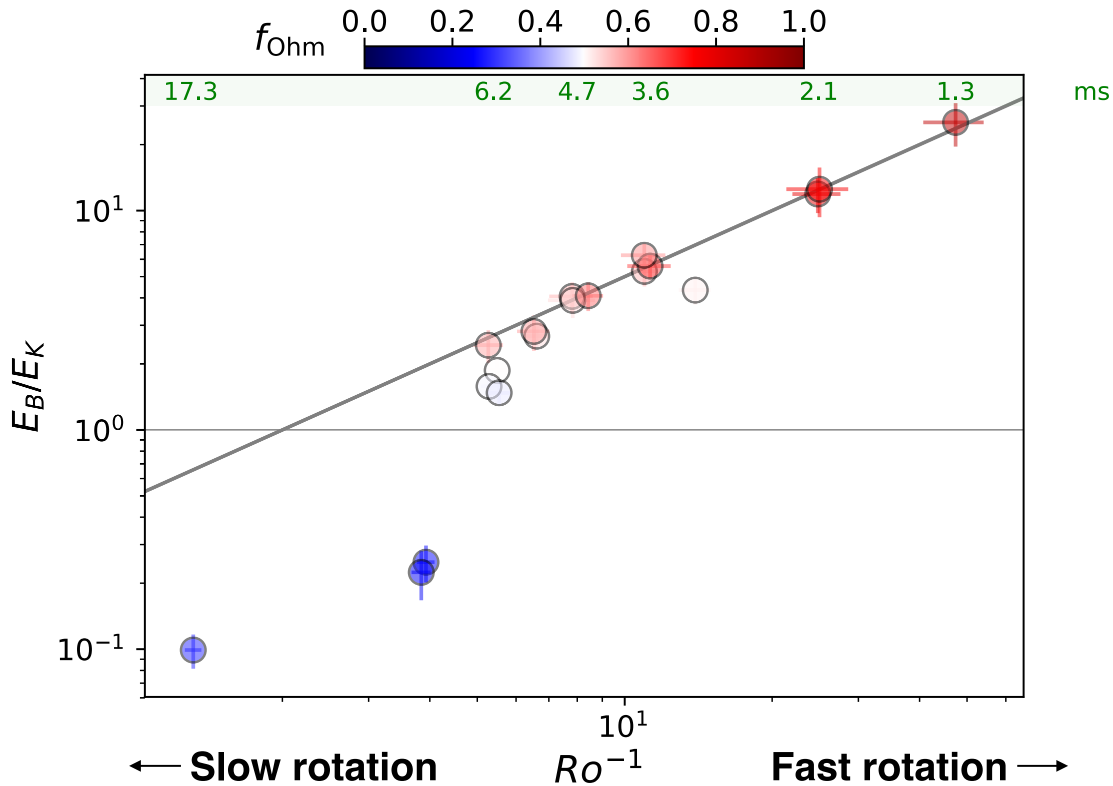
Raynaud et al 2020

Scaling: strong field regime

Magnetostropheric force balance:
Lorentz ~ Coriolis

$$B^2 \propto \Omega \mu \varrho U d \implies \frac{E_B}{E_{kin}} \propto Ro^{-1}$$

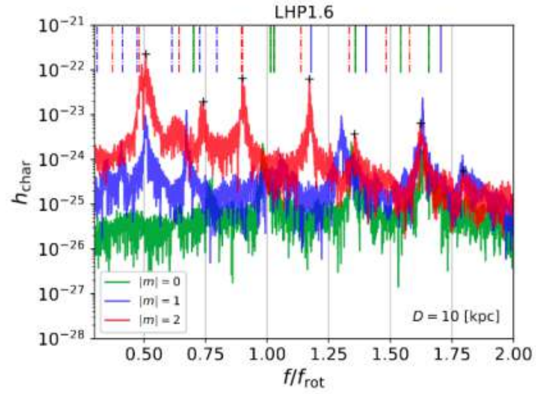
Rossby number: $Ro = U/(\Omega d)$



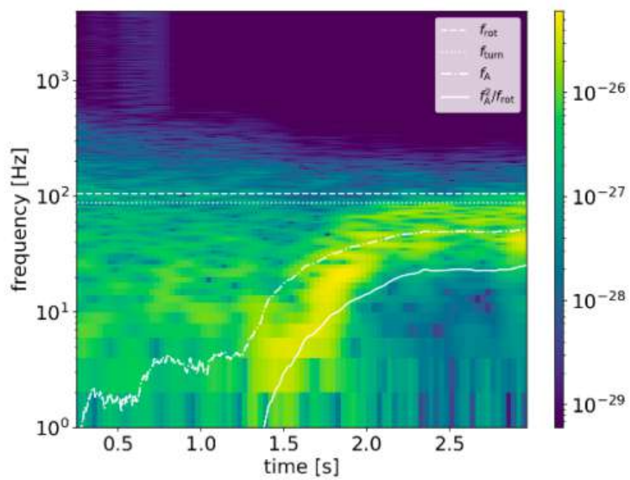
Raynaud+20, see also Roberts78,88 ; Dormy 16 ; Augustson+16 Seshasayanan+19

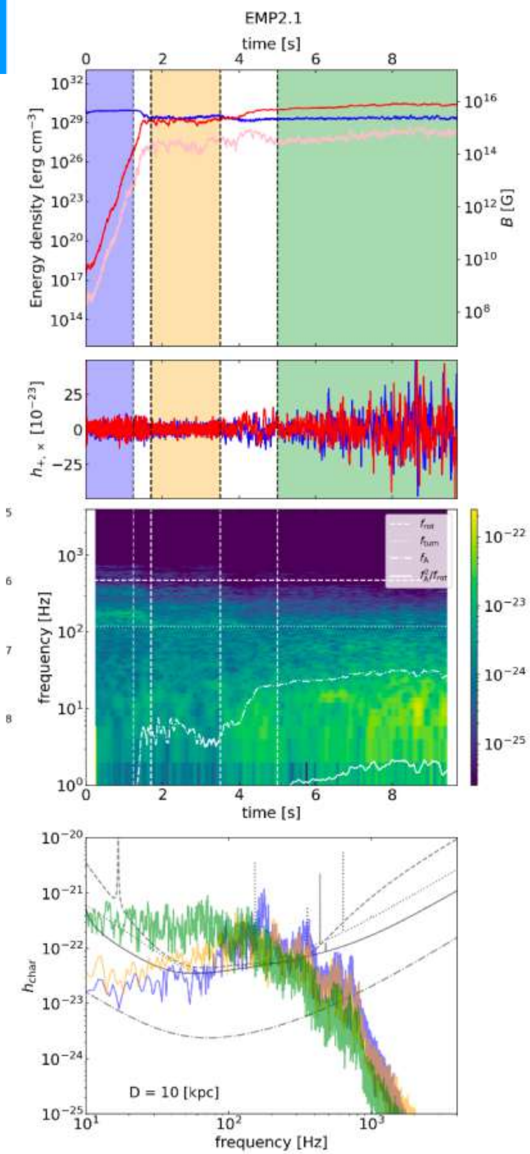
Gravitational waves from the convective dynamo

Peaks from inertial modes



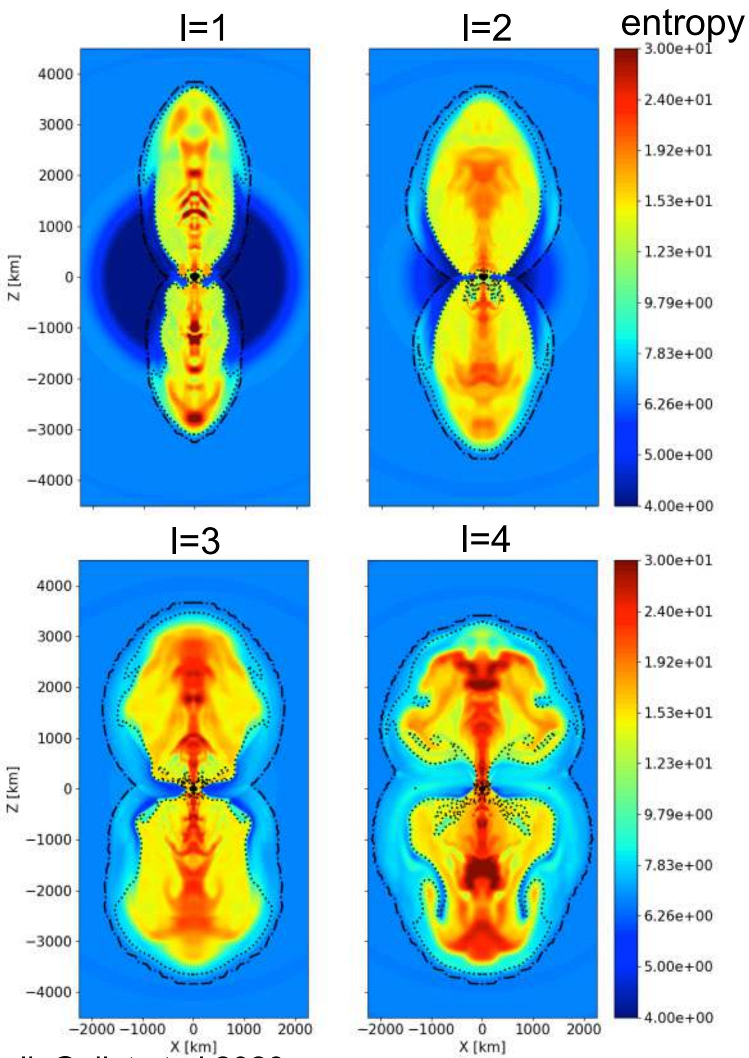
Low-frequency excess : a signature of the strong field dynamo ?



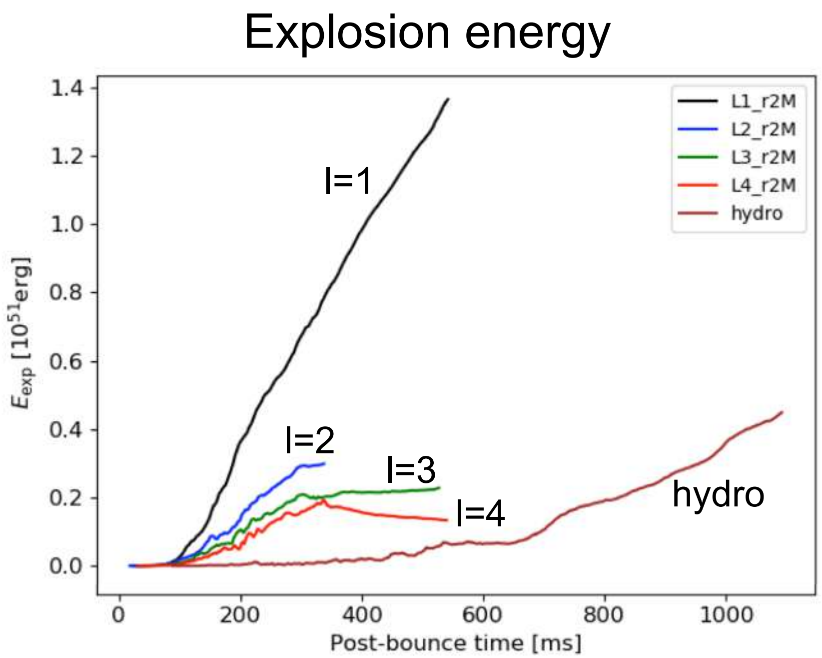


Raynaud et al 2021

Magnetorotational explosions as a function of multipolar order



Bugli, Guilet et al 2020



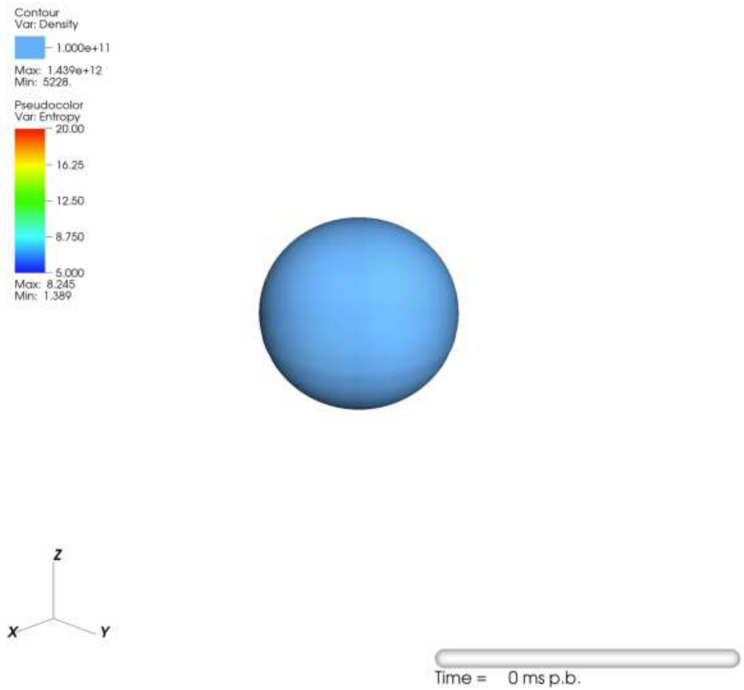
Higher multipoles also launch explosions but:

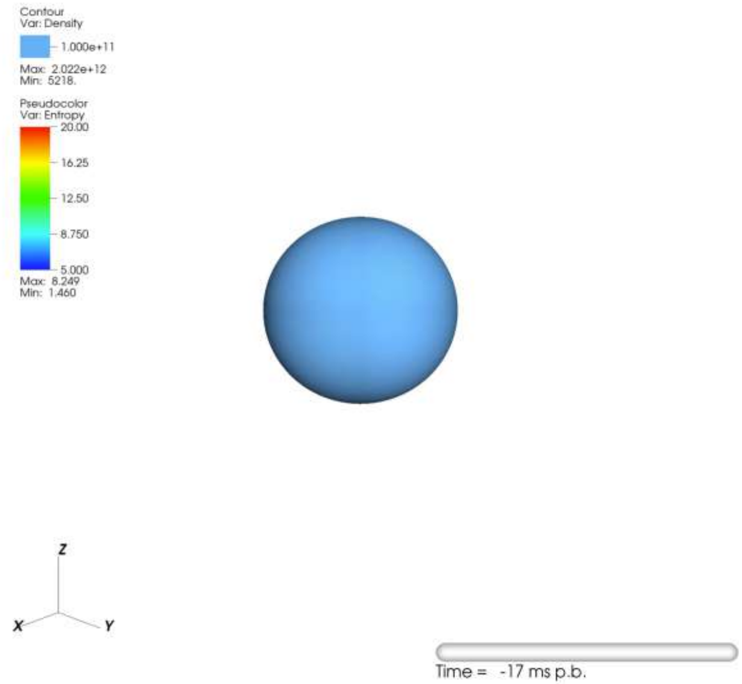
- Less collimated
- Less energetic

Magnetorotational explosions: inclined dipole

Aligned dipole

Equatorial dipole





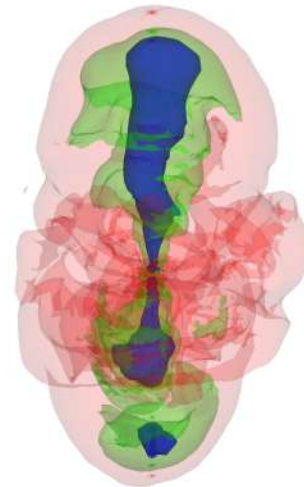
Color code = entropy

Inclined dipole: slower and more spherical explosion but jet also present

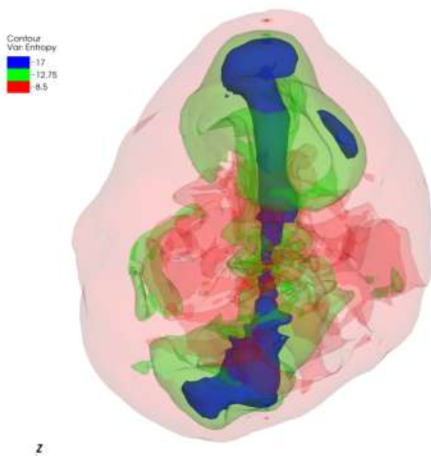
Magnetorotational explosions: 3D simulations

Aligned dipole

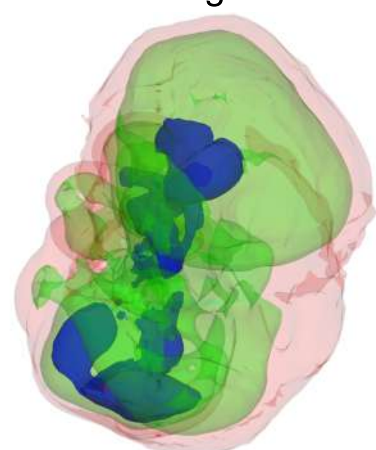
Quadrupole



Inclined dipole



Non-magnetised



Bugli+ 2021

Conclusions

Current models of protoneutron star dynamo predict :

- Magnetar-like dipolar fields (10^{14}-10^{15} G) can be generated for fast enough rotation
- Even stronger non-dipolar magnetic fields reaching 10^{16} G
- 3 different possible dynamo mechanisms

The properties of the explosion depend sensitively on the magnetic field geometry

Open questions :

- Extrapolation to large magnetic Prandtl numbers
- Relaxation onto a stable equilibrium & evolution on longer timescales
- Subgrid dynamo models in magnetorotational explosion simulations

Thank you !