The magneto-rotational instability in proto-neutron stars

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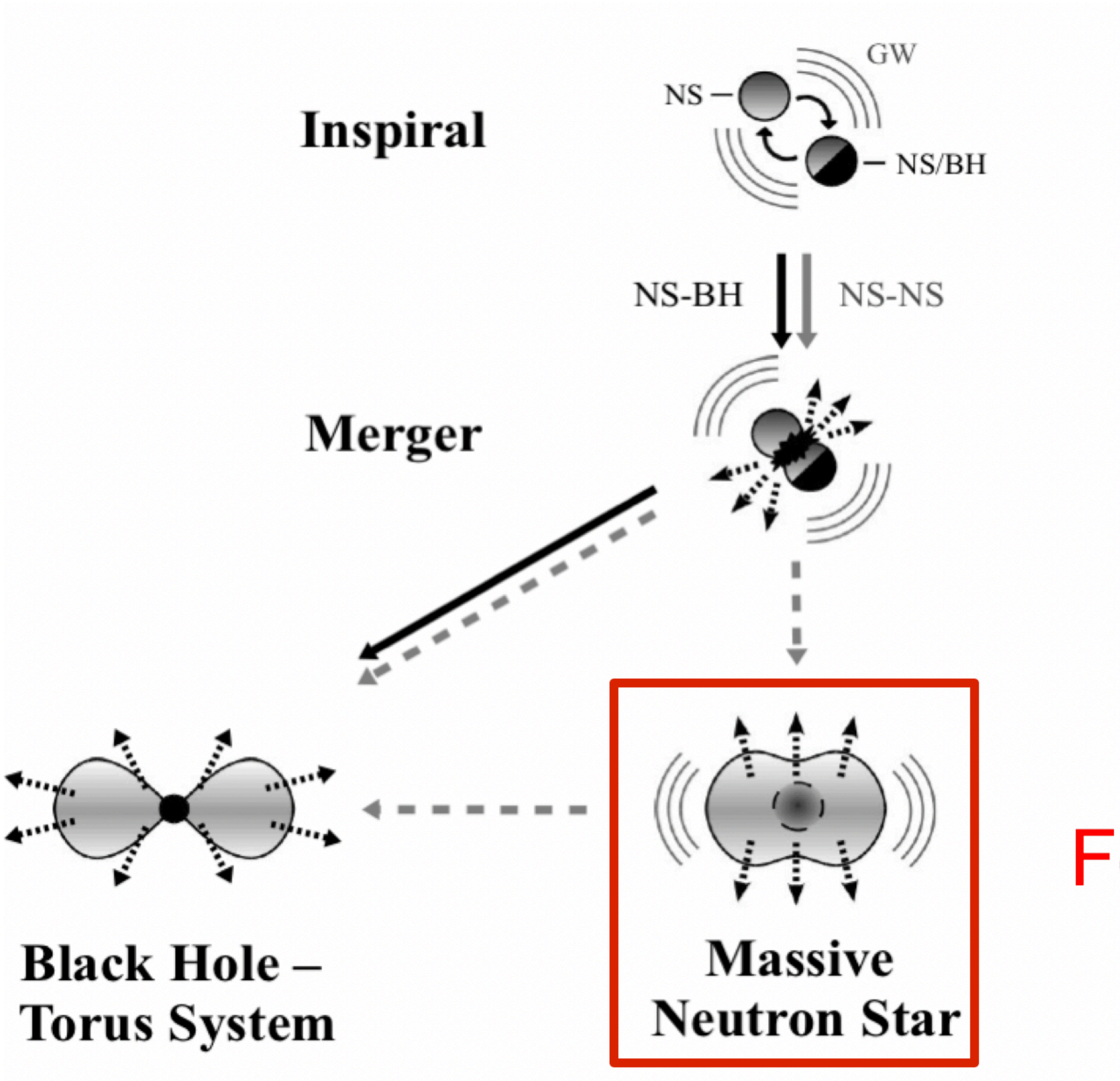
Neutron star merger context



3 possibilities :

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

Formation of a magnetar ?

Open theoretical question : magnetic field origin

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

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

Magnetar dipolar strength : ~ 10^{14}-10^{15} G

Amplification mechanism ?

Magnetorotational instability

Both SN & mergers

Similar to accretion disks

Convective dynamo

Both SN & mergers

Similar to planetary & stellar dynamos

Outline

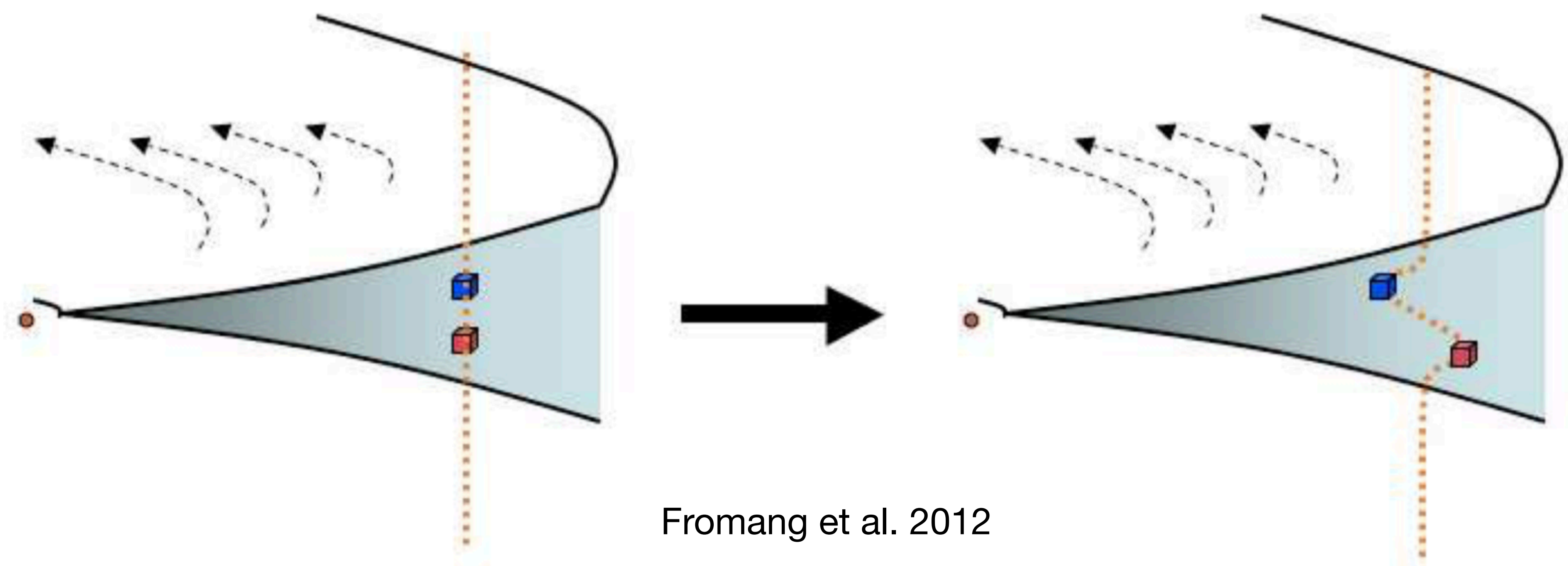
I- Presentation of the local models of the MRI

II- A global model of the MRI

III- Preliminary parameter study

Amplification mechanism : magneto-rotational instability (MRI)

MRI mechanism in a simple case :



Fromang et al. 2012

Instability criterion : $\frac{d\Omega}{dr} < 0$

Growth rate: $\sigma = \frac{q\Omega}{2}$ avec $(\Omega \propto r^{-q})$

-> Fast growth for fast rotation

Wavelength : $\lambda_{MRI} \propto \frac{B}{\rho\Omega}$

-> Short wavelength for weak magnetic fields

Local models in accretion disks

"Shearing box" models

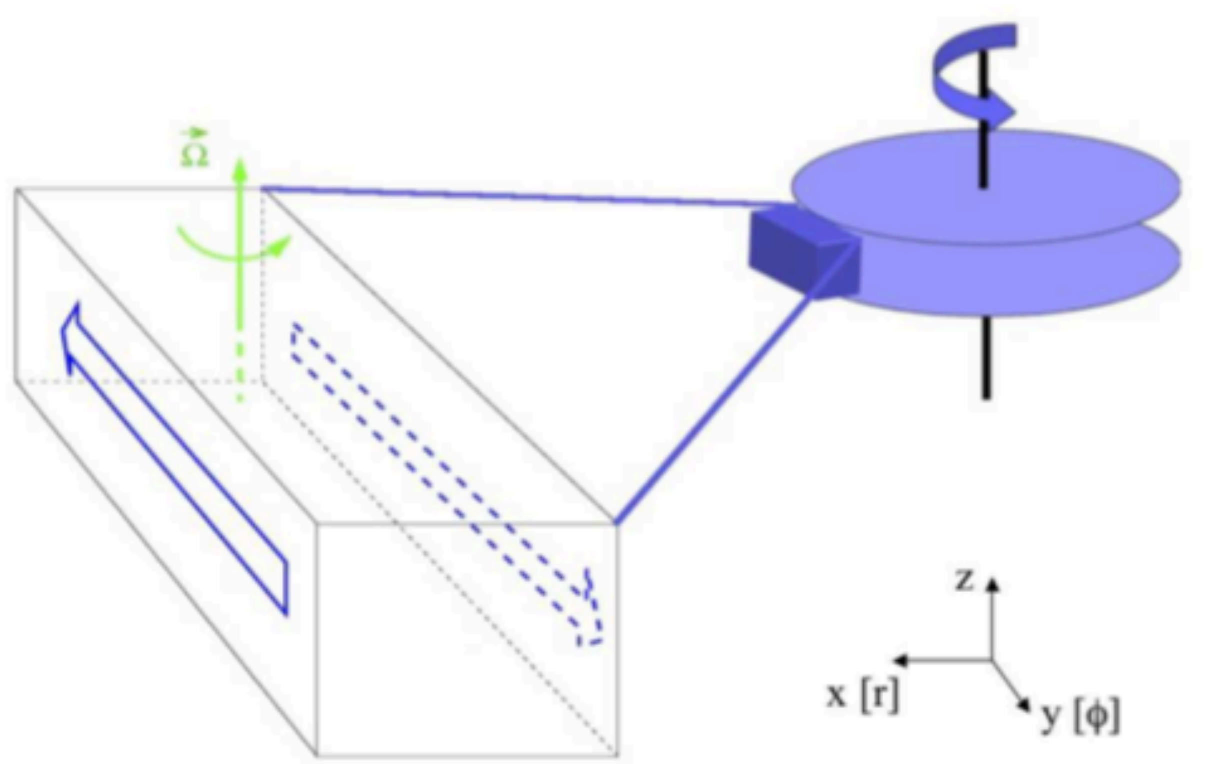
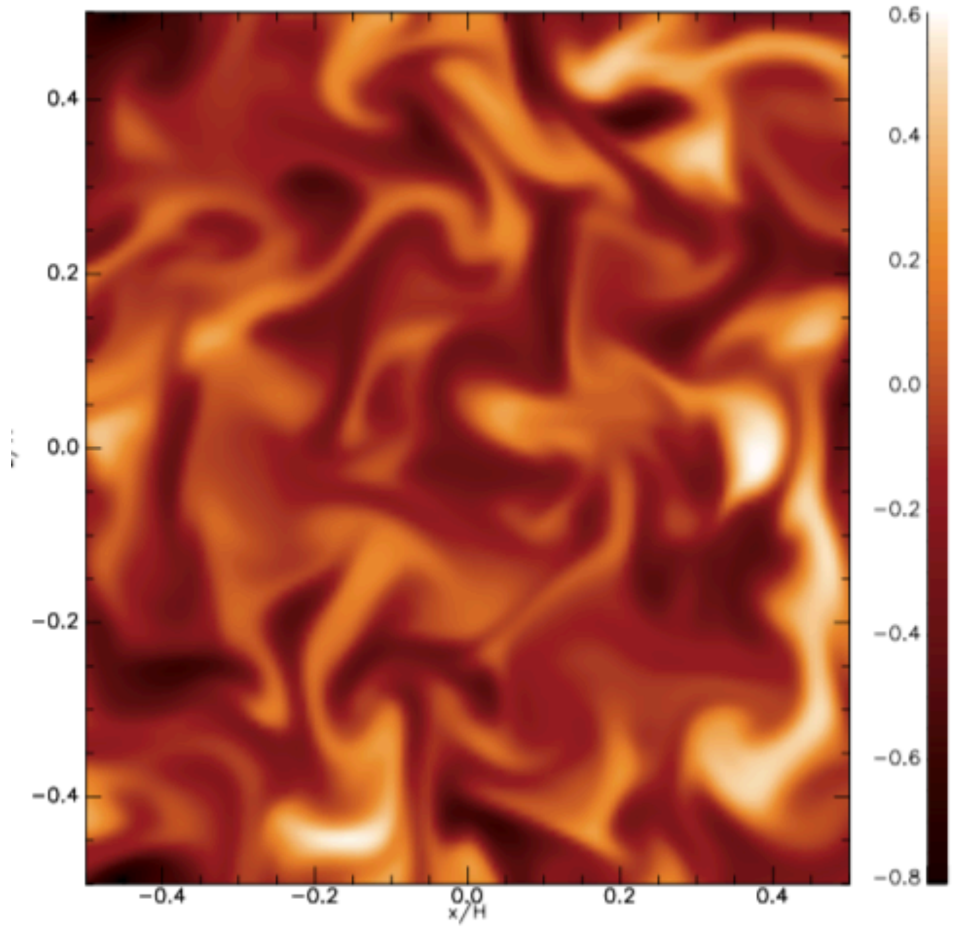


Figure courtesy :G. Lesur

Turbulence MHD : toroidal field



Fromang et al. 2007

Impact of conditions specific to neutron stars ?

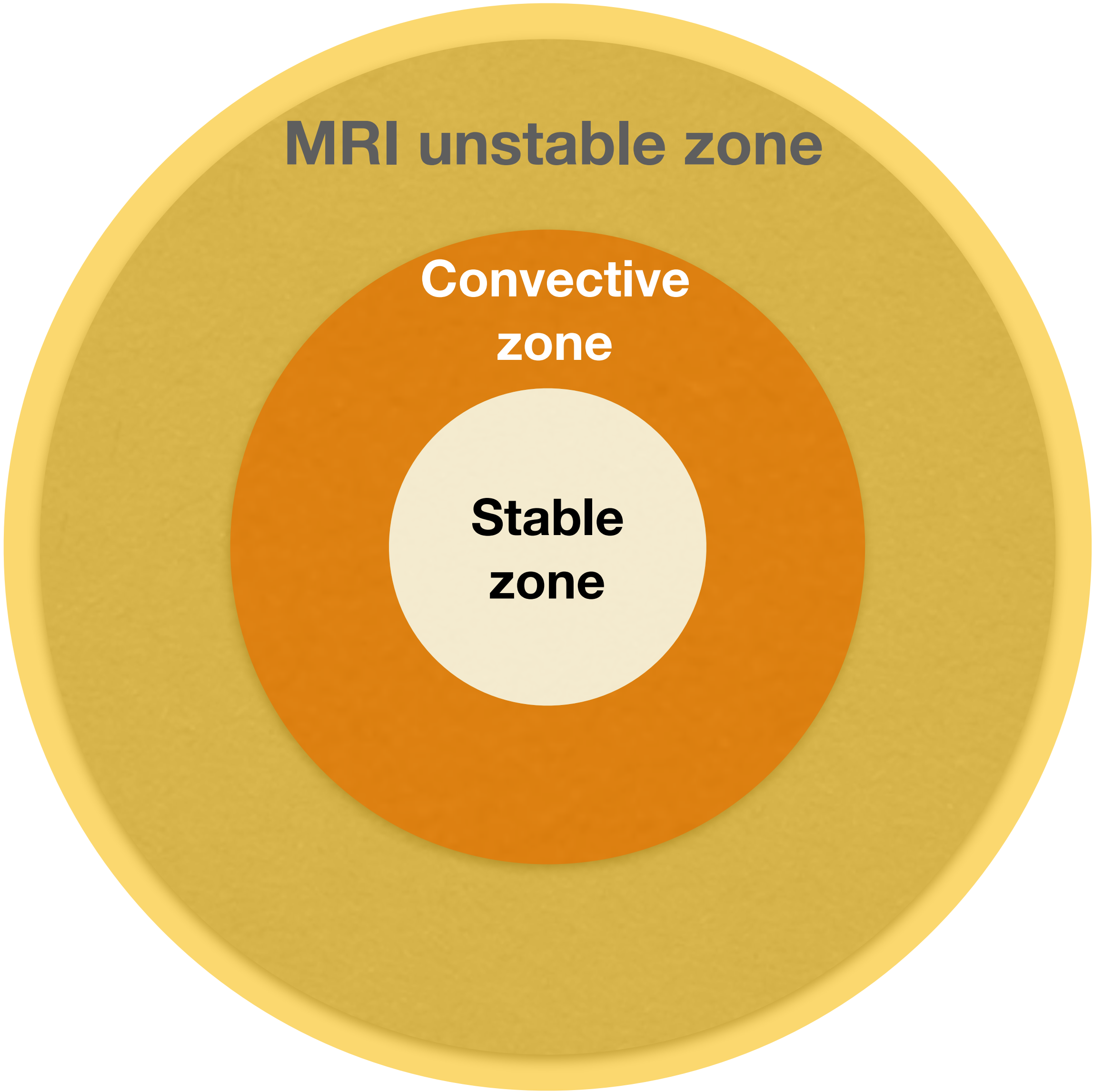
→ neutrinos

→ buoyancy (entropy & composition gradients)

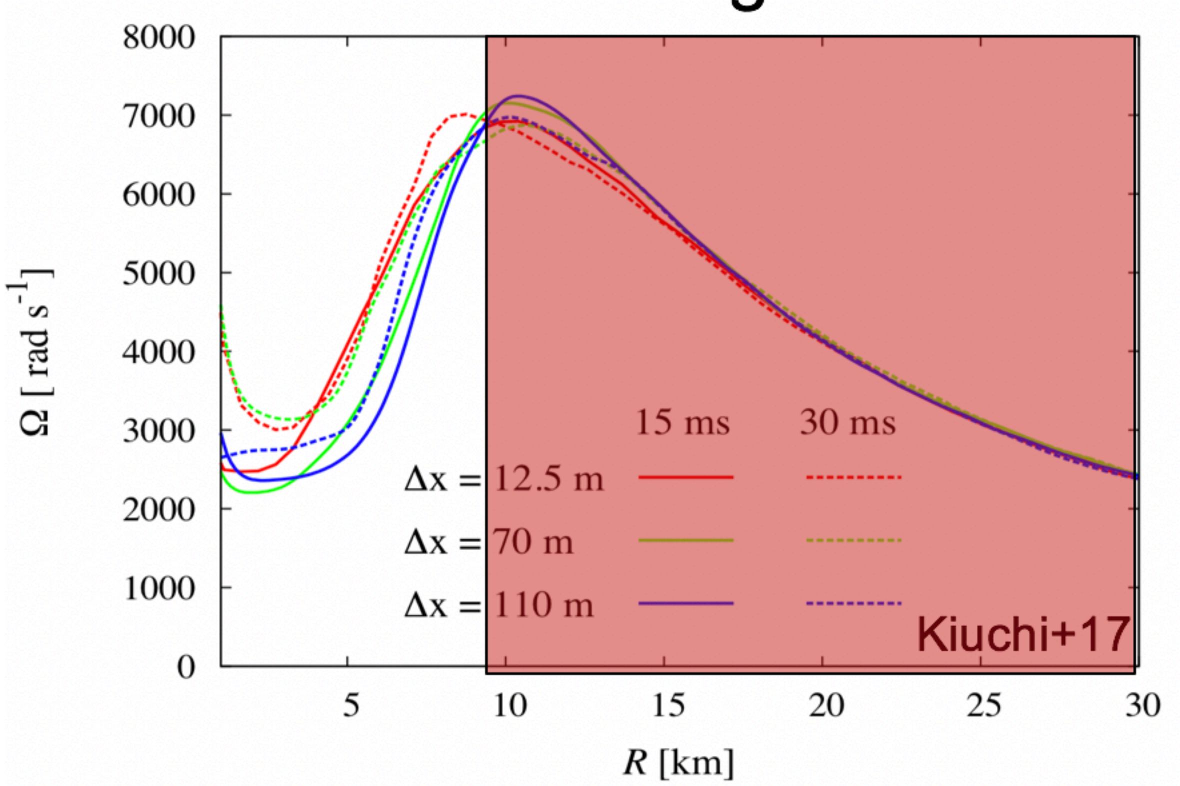
→ spherical geometry

MRI unstable zone vs convective zone

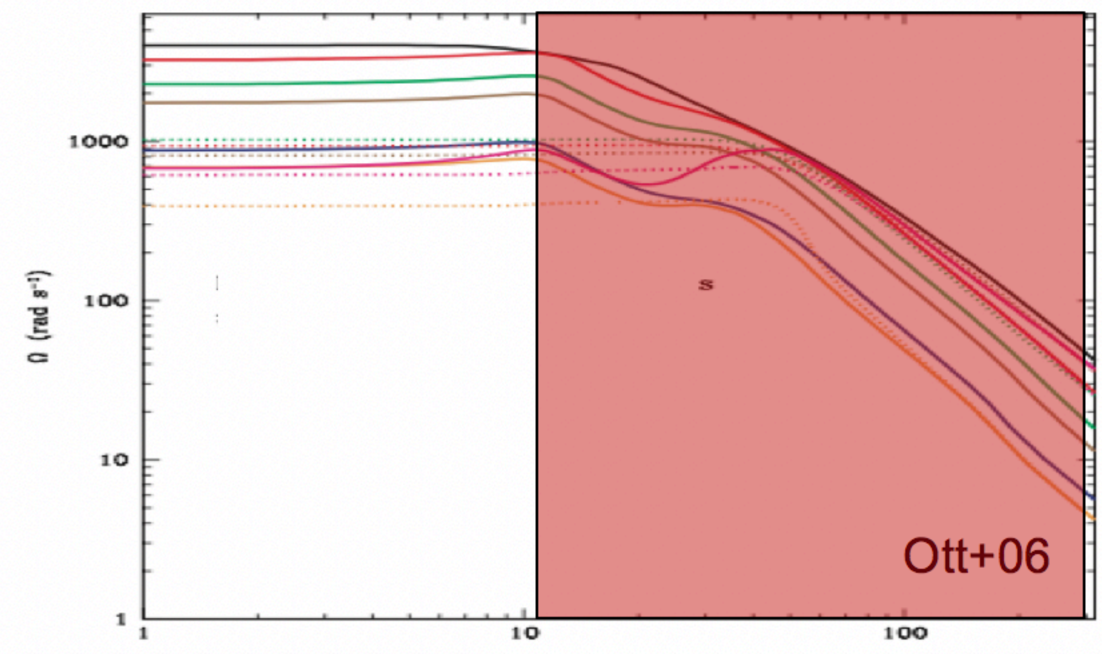
t = 0.2 s



NS merger



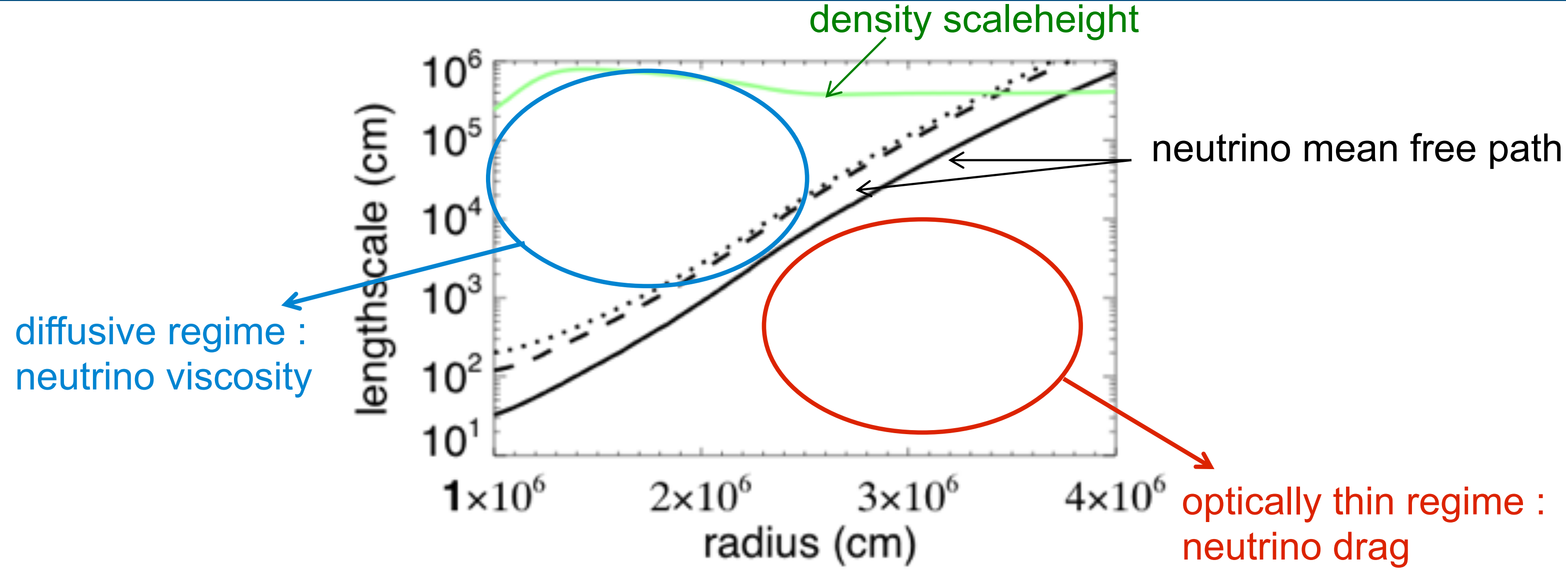
supernovae



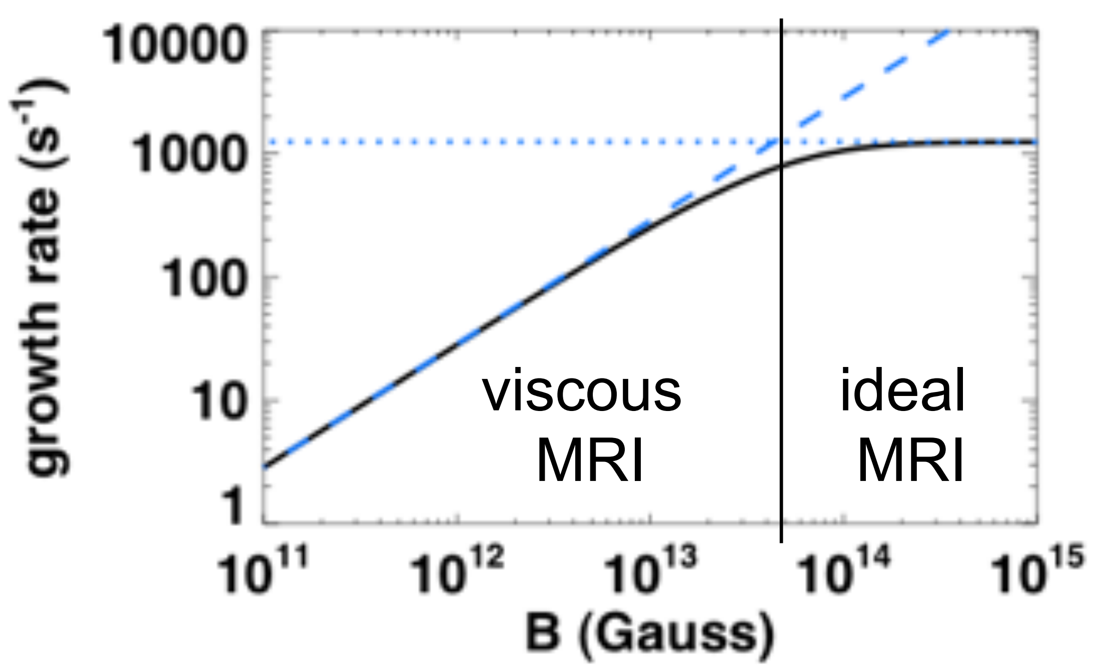
Radius (km)

Impact of neutrinos on the MRI :

Two regimes



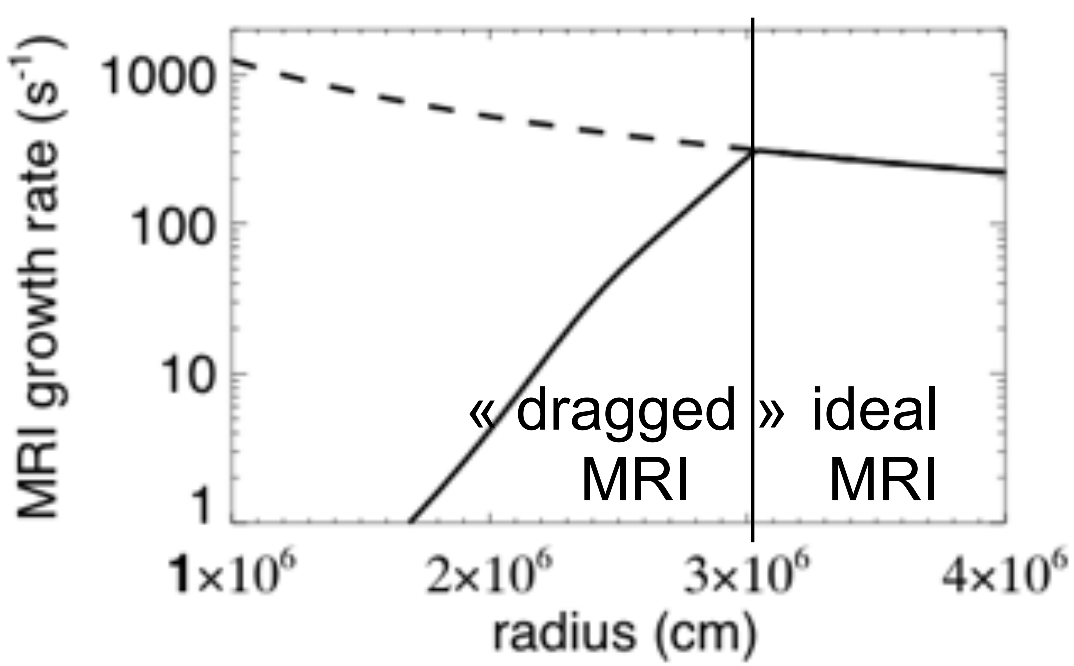
Viscous regime



Slow growth for weak initial magnetic field

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

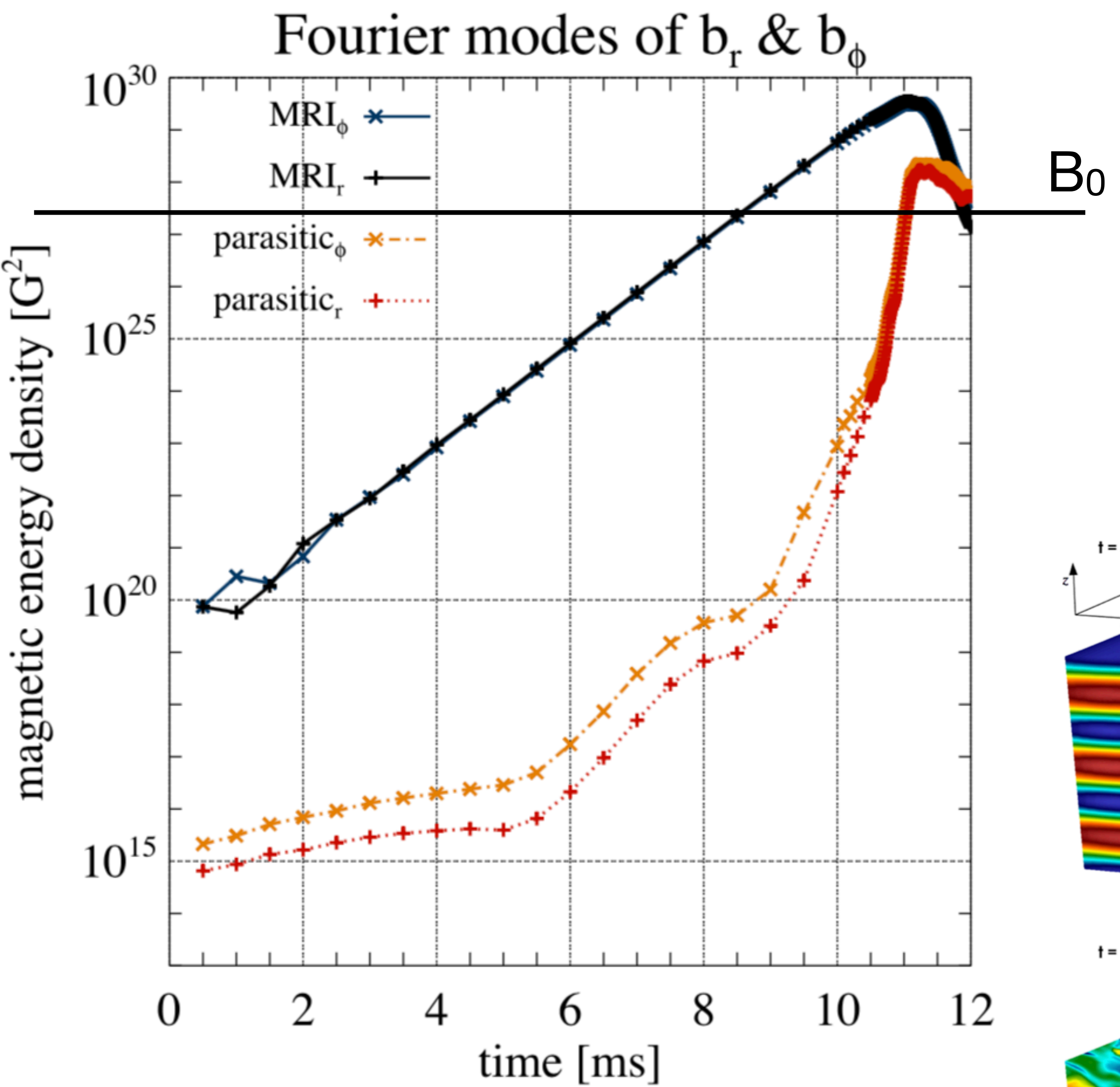
Neutrino drag regime



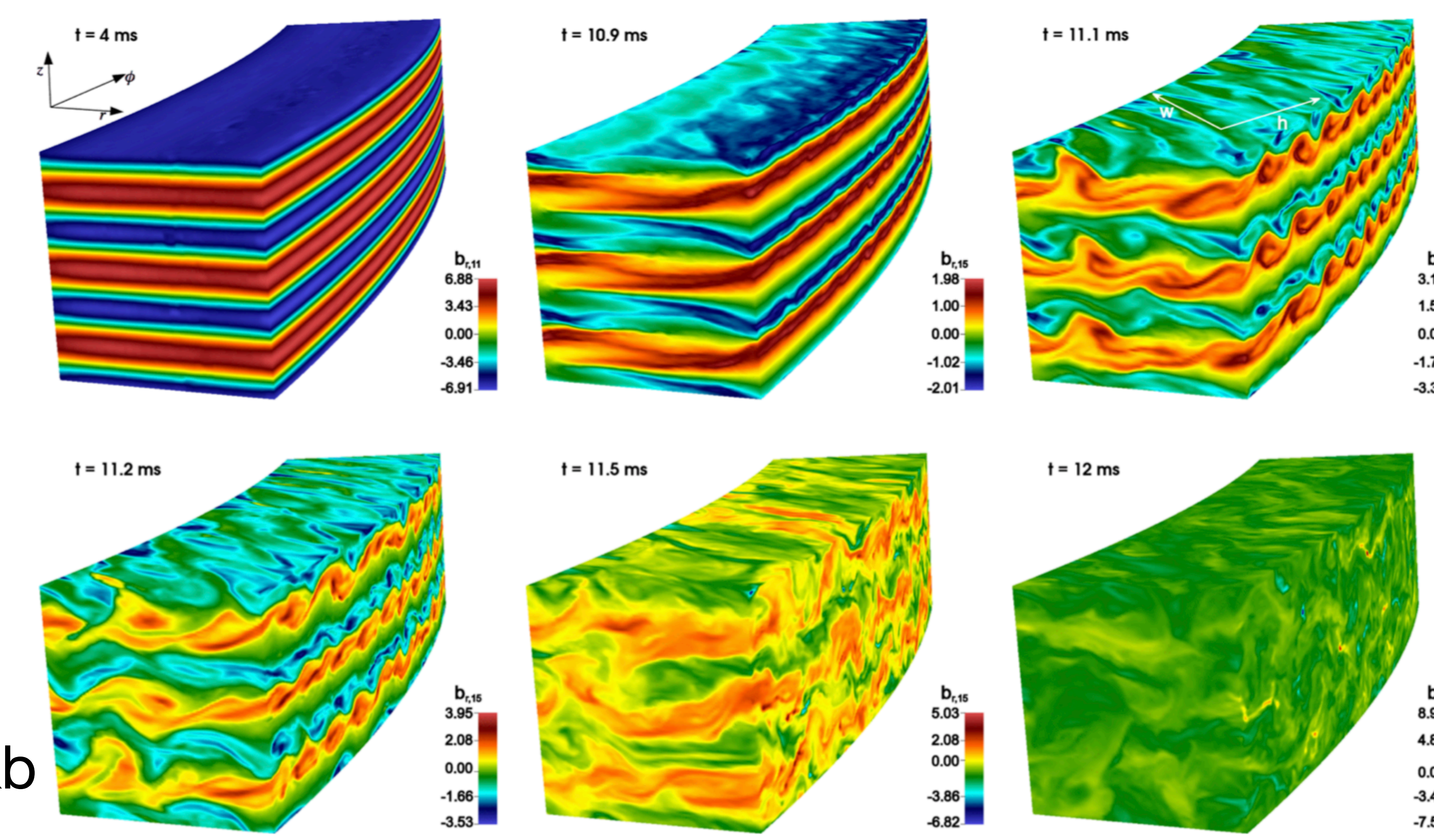
Fast growth near surface

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

Channel modes terminated by parasitic instabilities



b_r field at different times

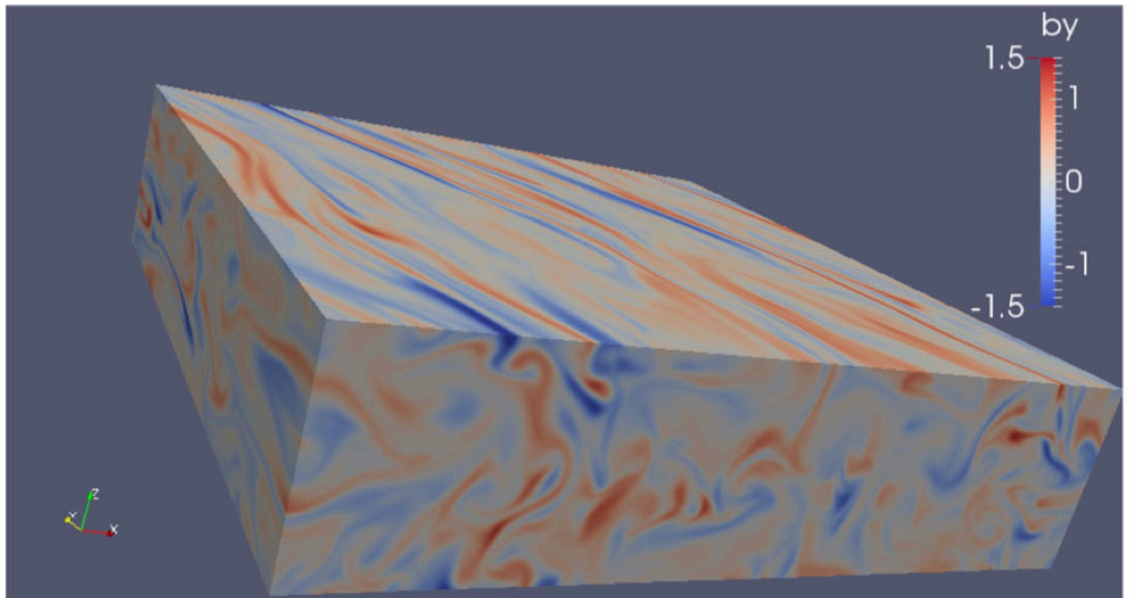


Rembiasz et al. 2016a&b

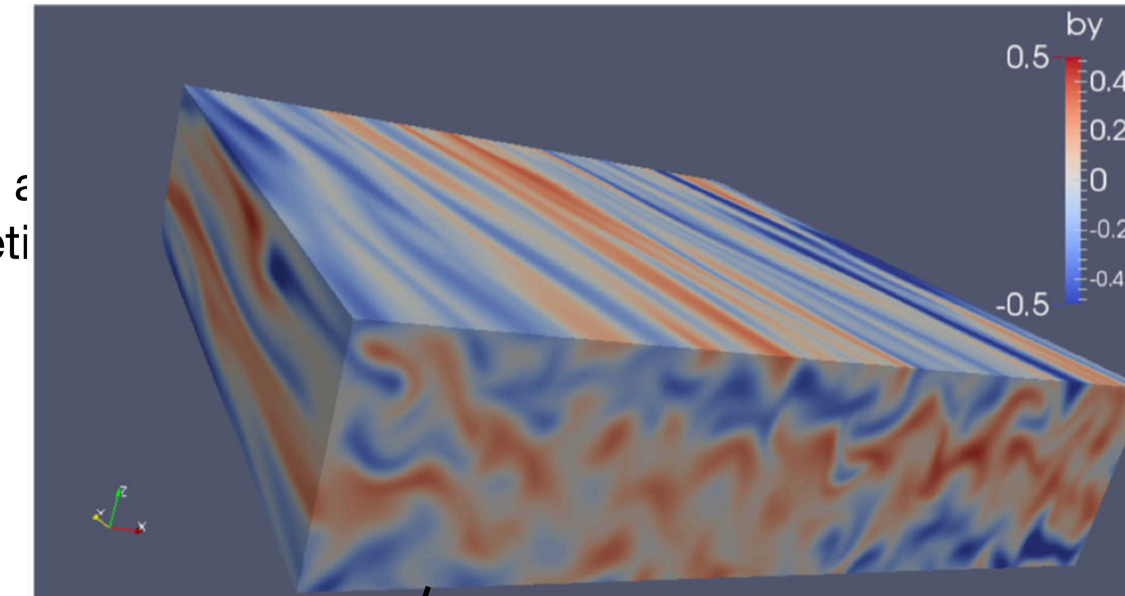
Impact of stratification on MRI

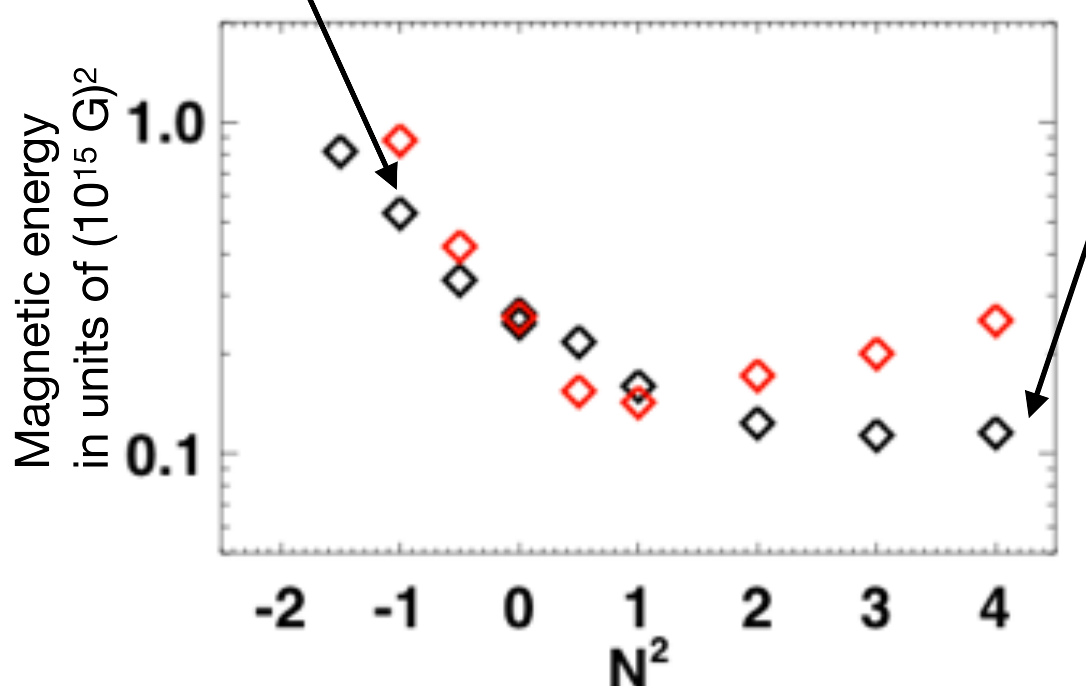
Unstable buoyancy

Stable stratification



Color : a
Magneti



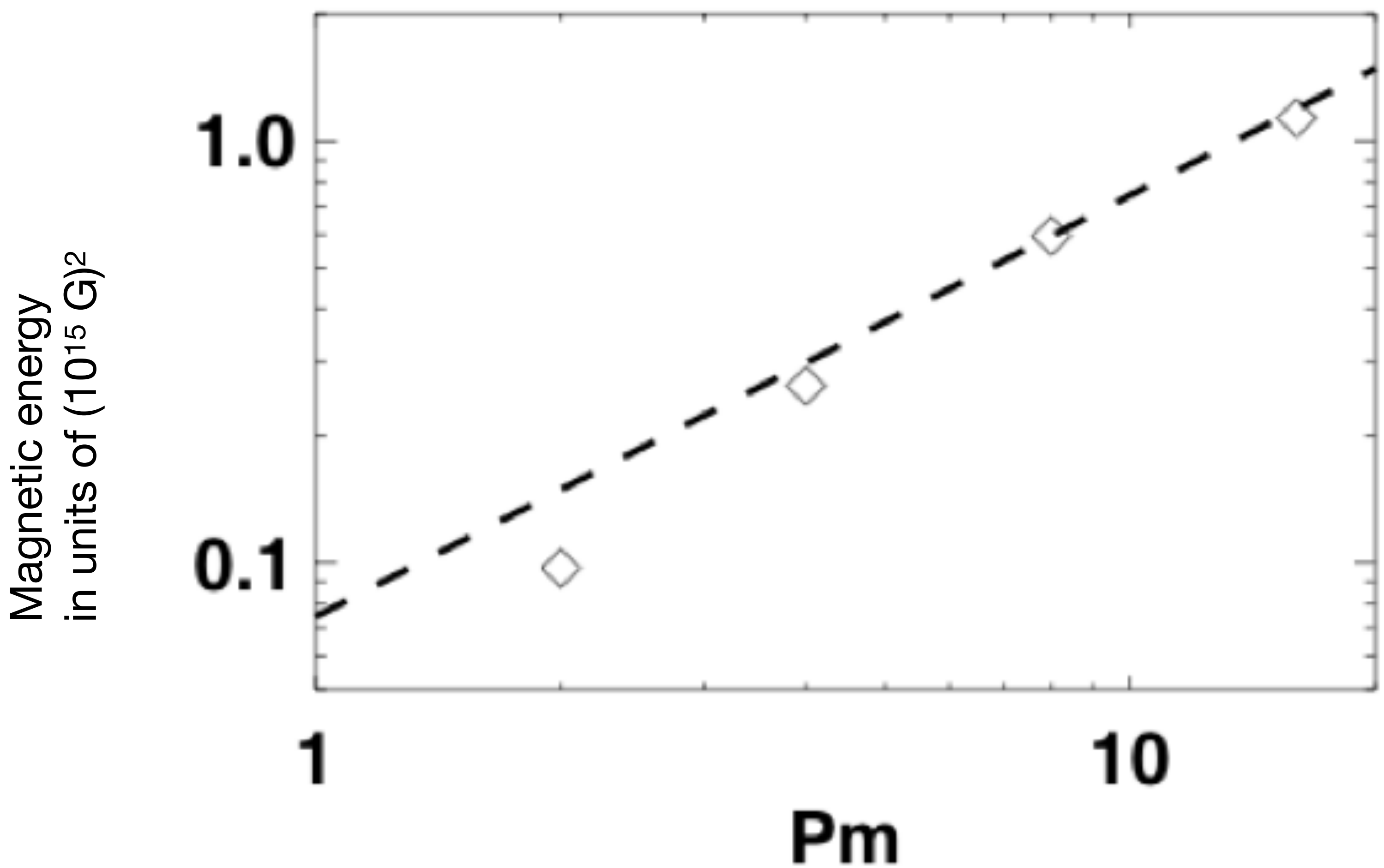


Guilet & Müller (2015)

Buoyancy parameter

Dependences on diffusion processes

$Pm = 10^{13}$!

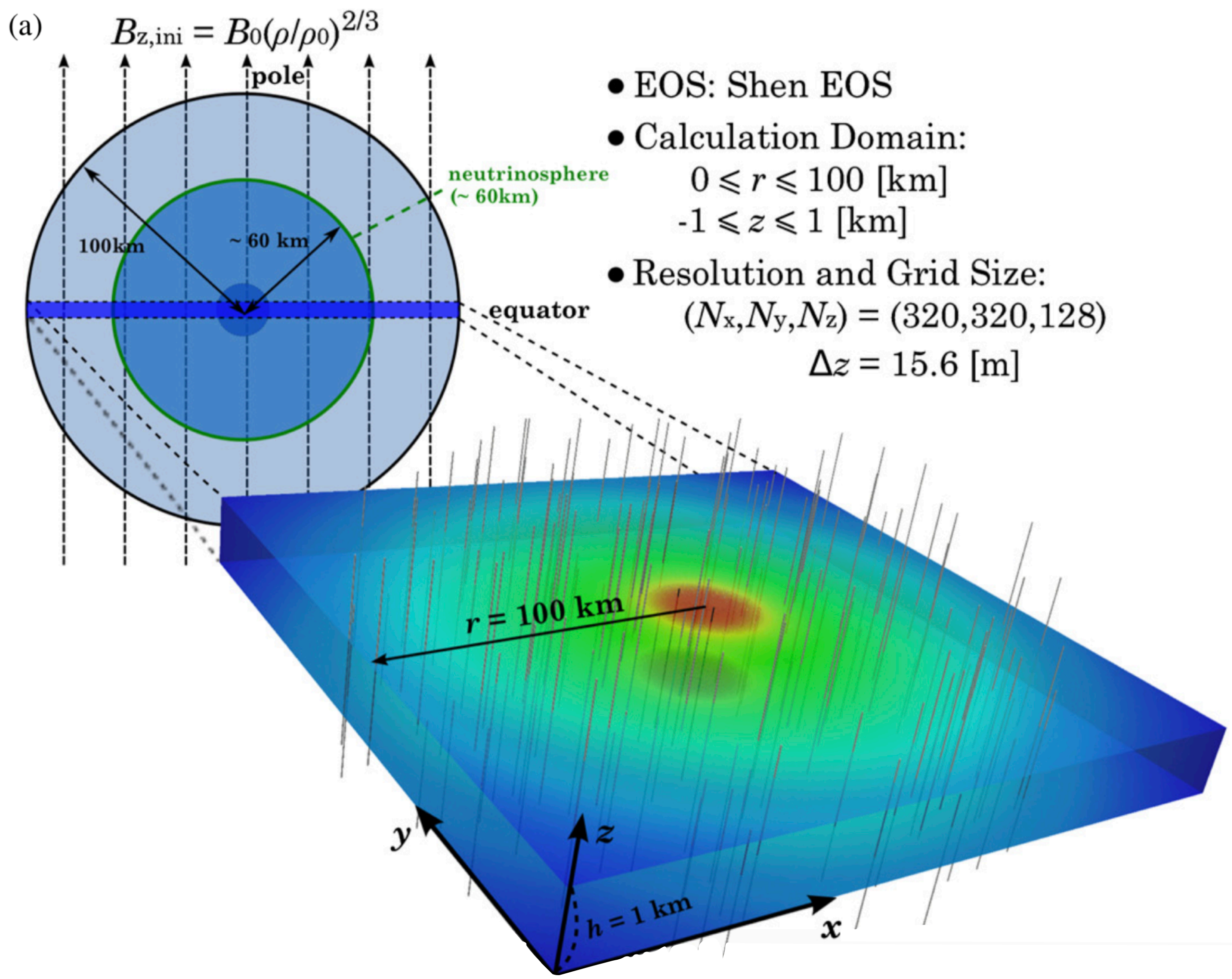


See also:
Fromang+2007, Lesur+2007,
Meheut+2015, Potter+2017

Pm = viscosity/resistivity

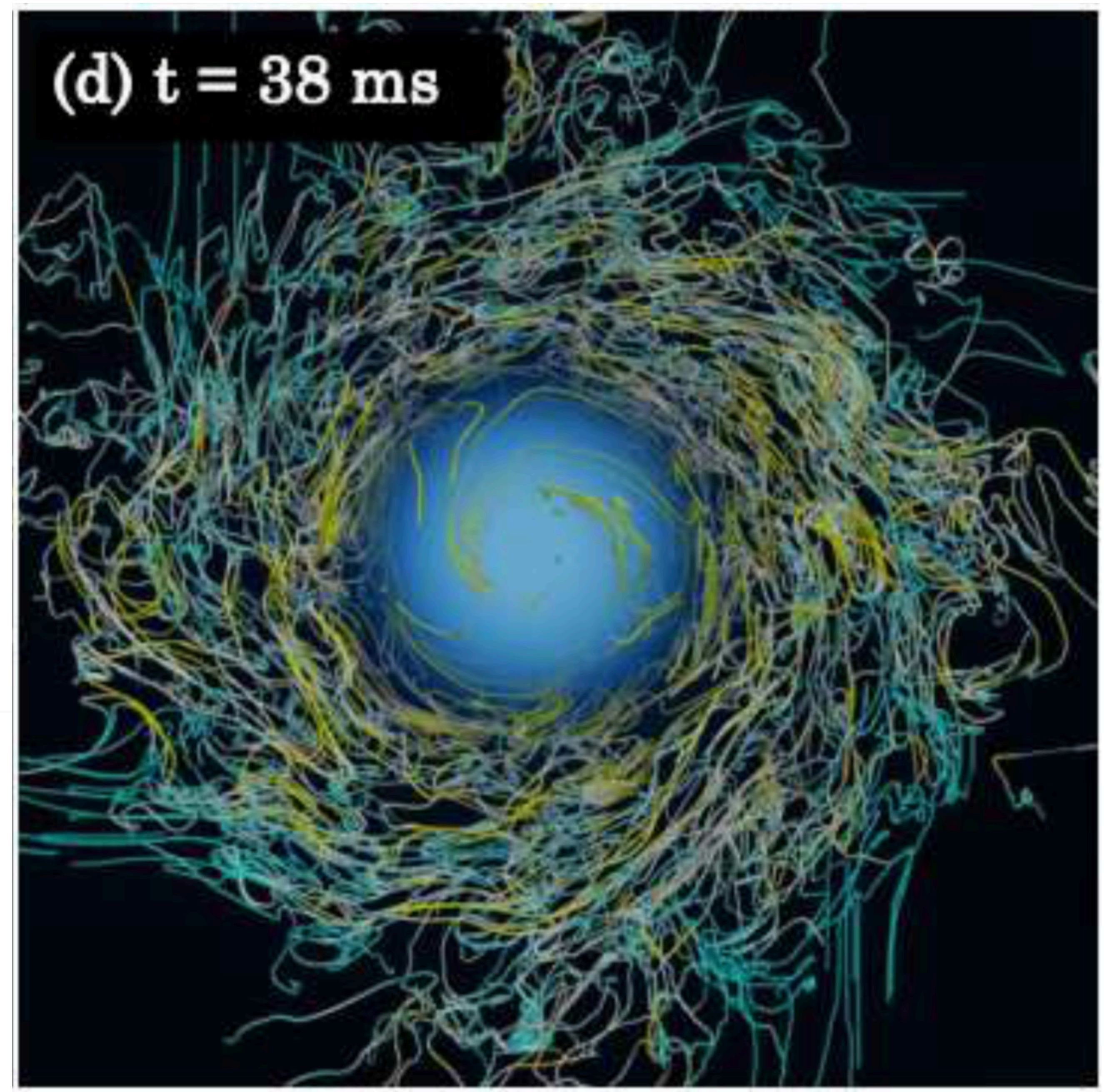
Behaviour at realistic values: very large magnetic Prandtl number ?

Global simulation in the equatorial plane



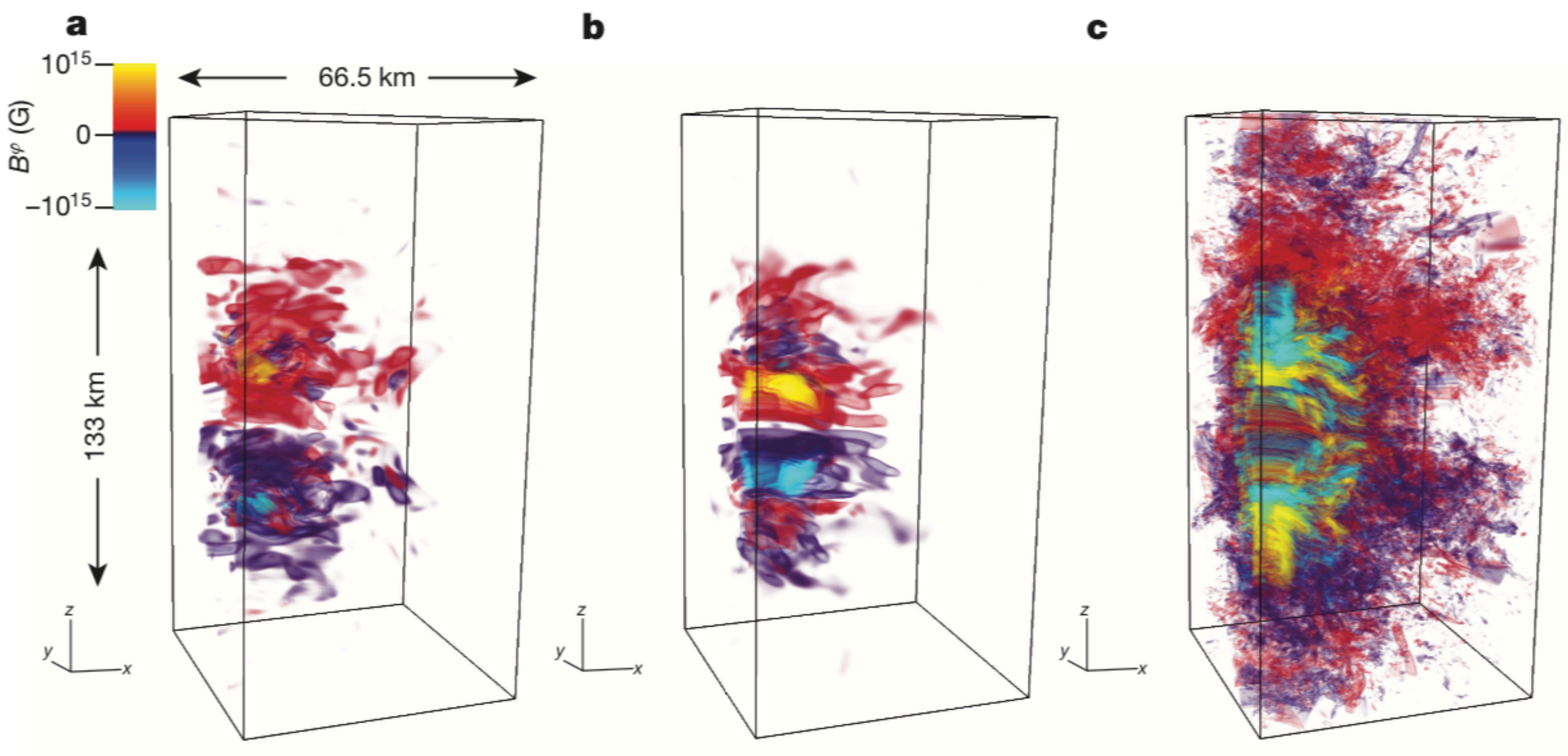
Masada et al. (2015)

Magnetic field lines



First attempt at a global model

Mösta et al 2015

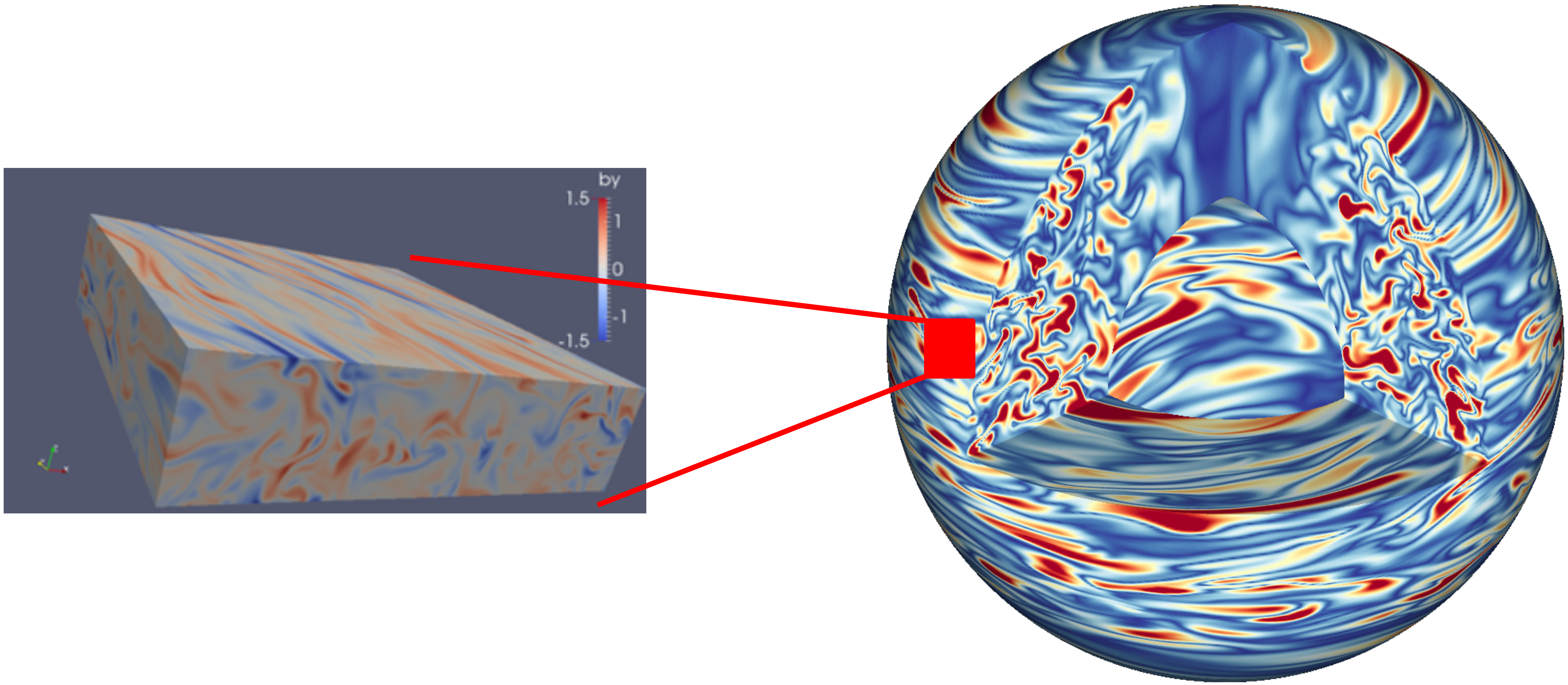


- First time high enough resolution
- Initial strong dipolar field
- High computational costs

From local models towards global models

Step 1 : Local model of the MRI

Step 2 : Global model of the MRI



Magnetic toroidal field

Outline

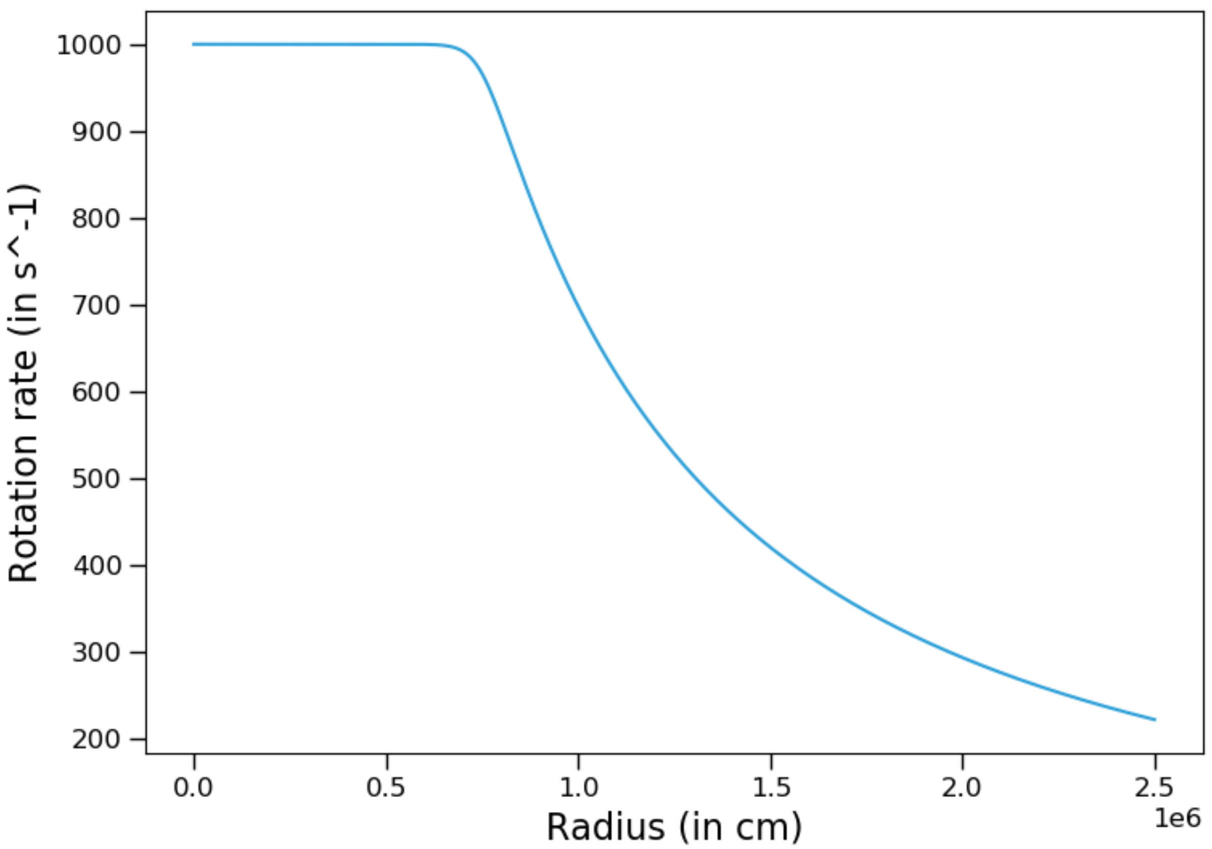
II- A global model of the MRI in a PNS

Our setup

- Simplest model : Incompressible, constant density
- Code : MagIc, 3D MHD spectral code
- Velocity force at the outer boundary

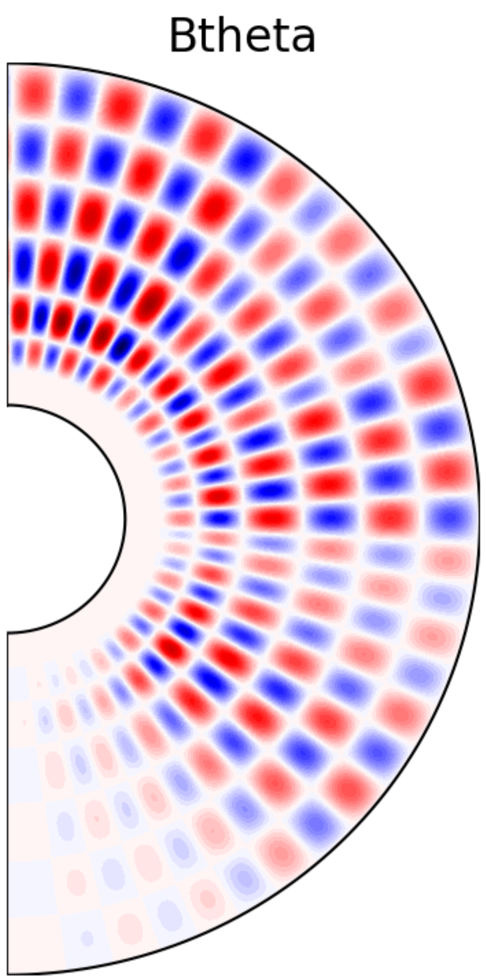
$$\Omega = 10^3 \text{ s}^{-1}, \nu = 8 \cdot 10^{11} \text{ cm}^2\text{s}^{-1}, \eta = 5 \cdot 10^{10} \text{ cm}^2\text{s}^{-1}, r = 25 \text{ km}, B_{mean} = 8.97 \cdot 10^{14}$$

Omega profile



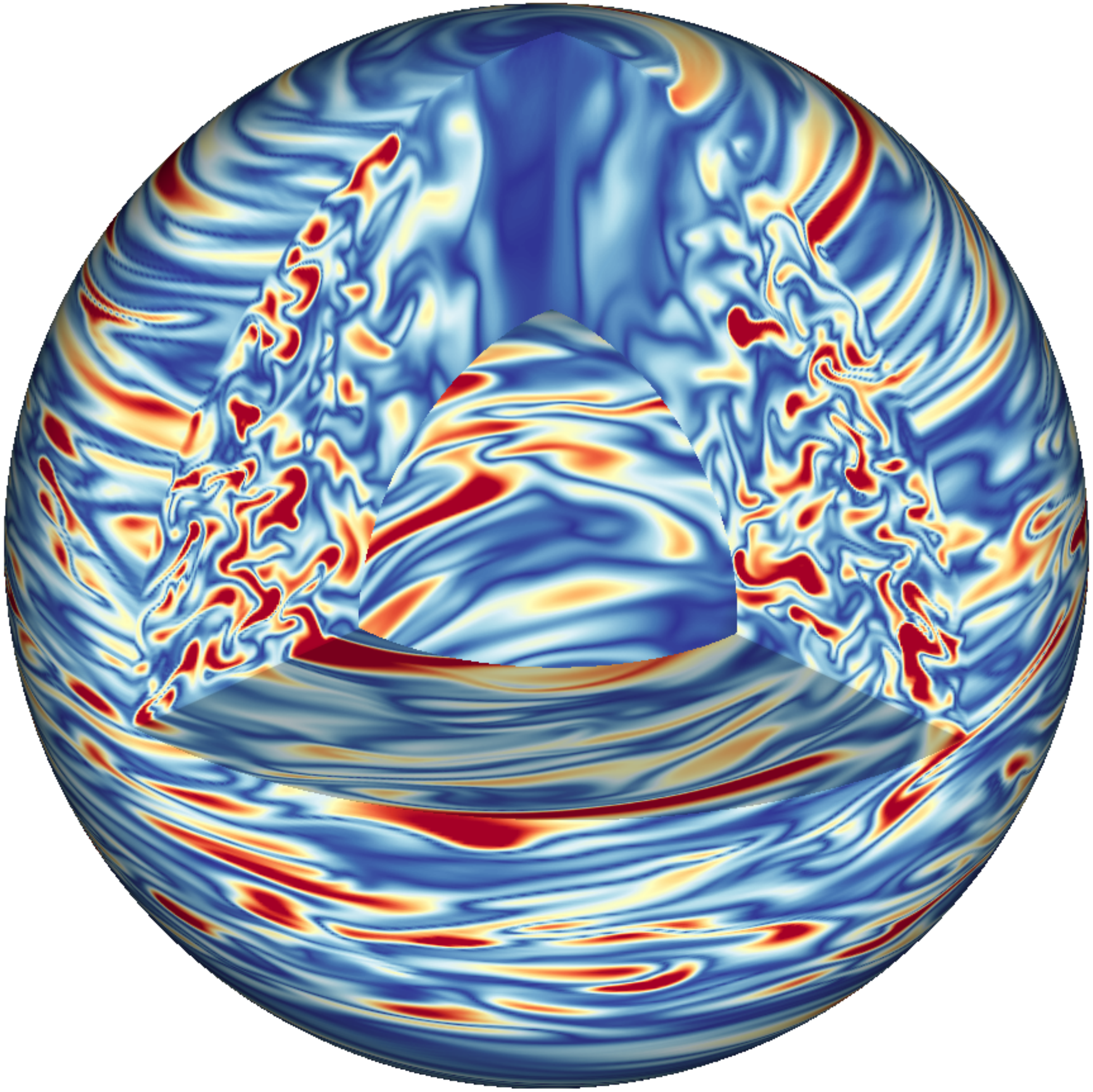
- Constant in cylinders

Magnetic field profile

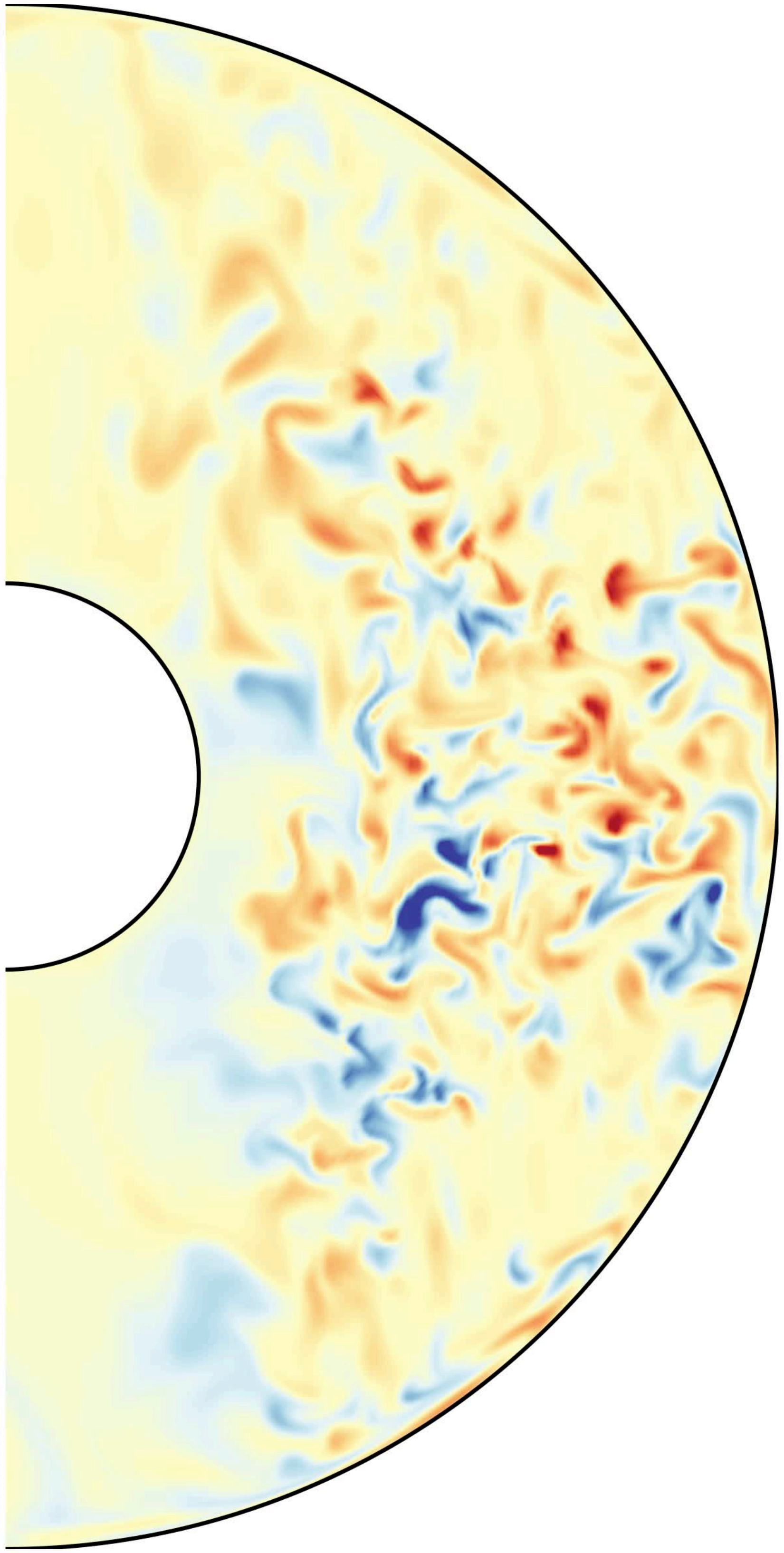


Small scales
~ Local models

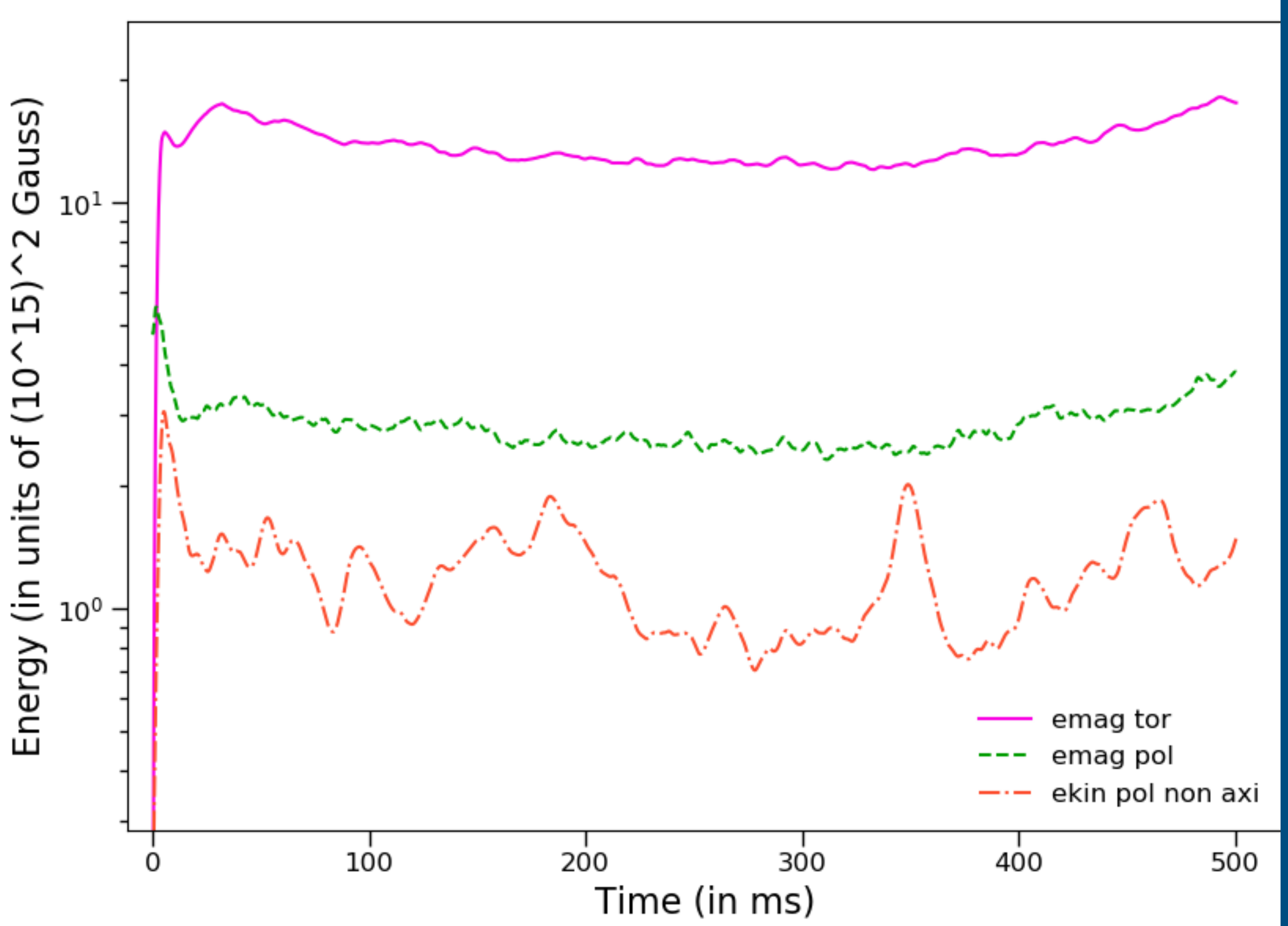
Amplitude of the magnetic field



Time evolution of the field

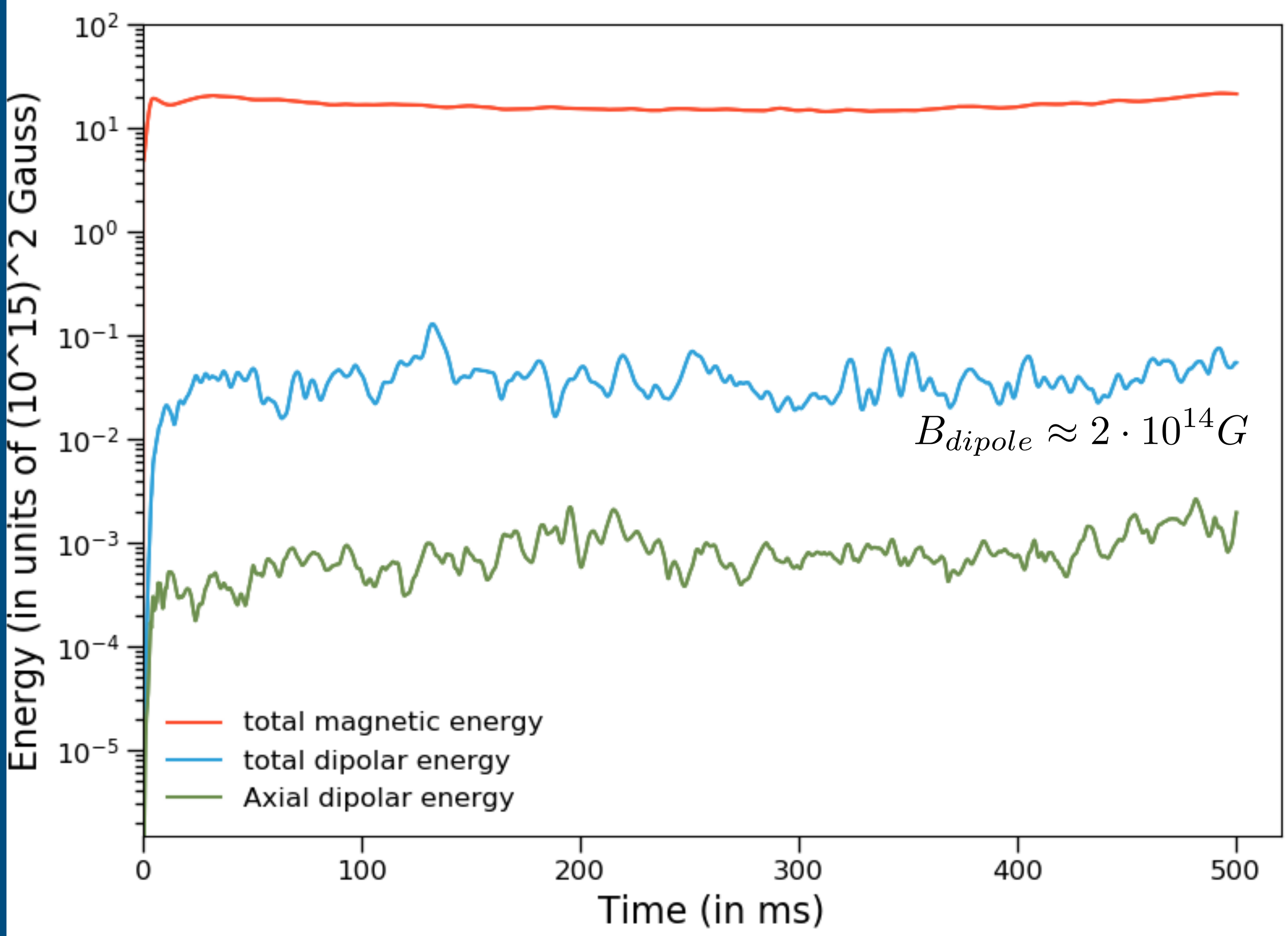


Time evolution of global quantities

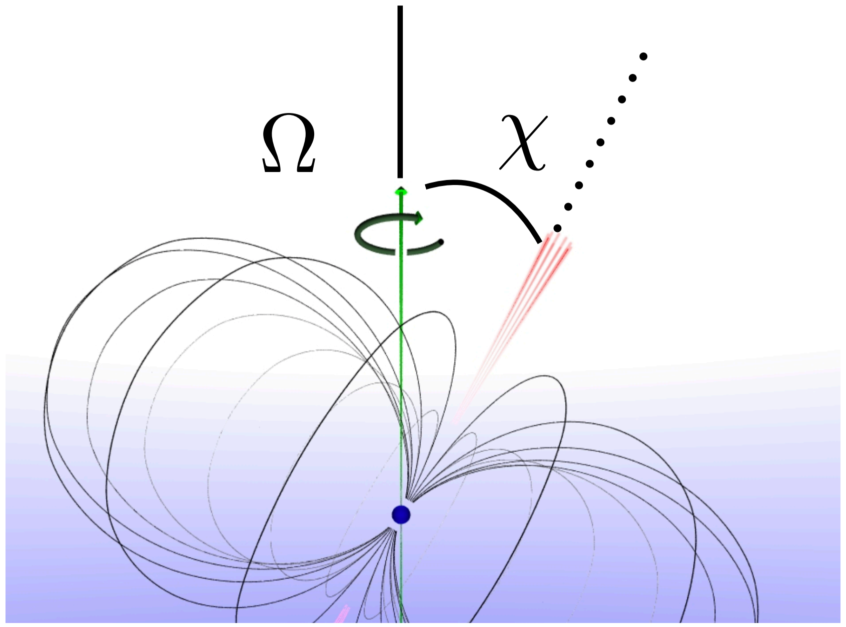


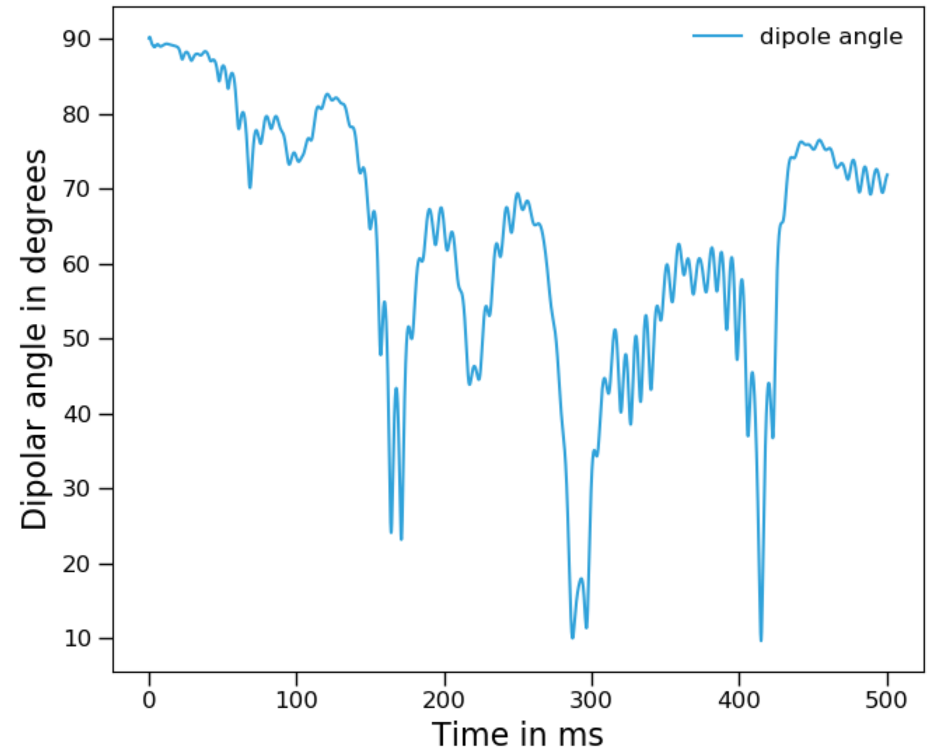
Preliminar results on the dipole

Time Evolution of dipolar energy



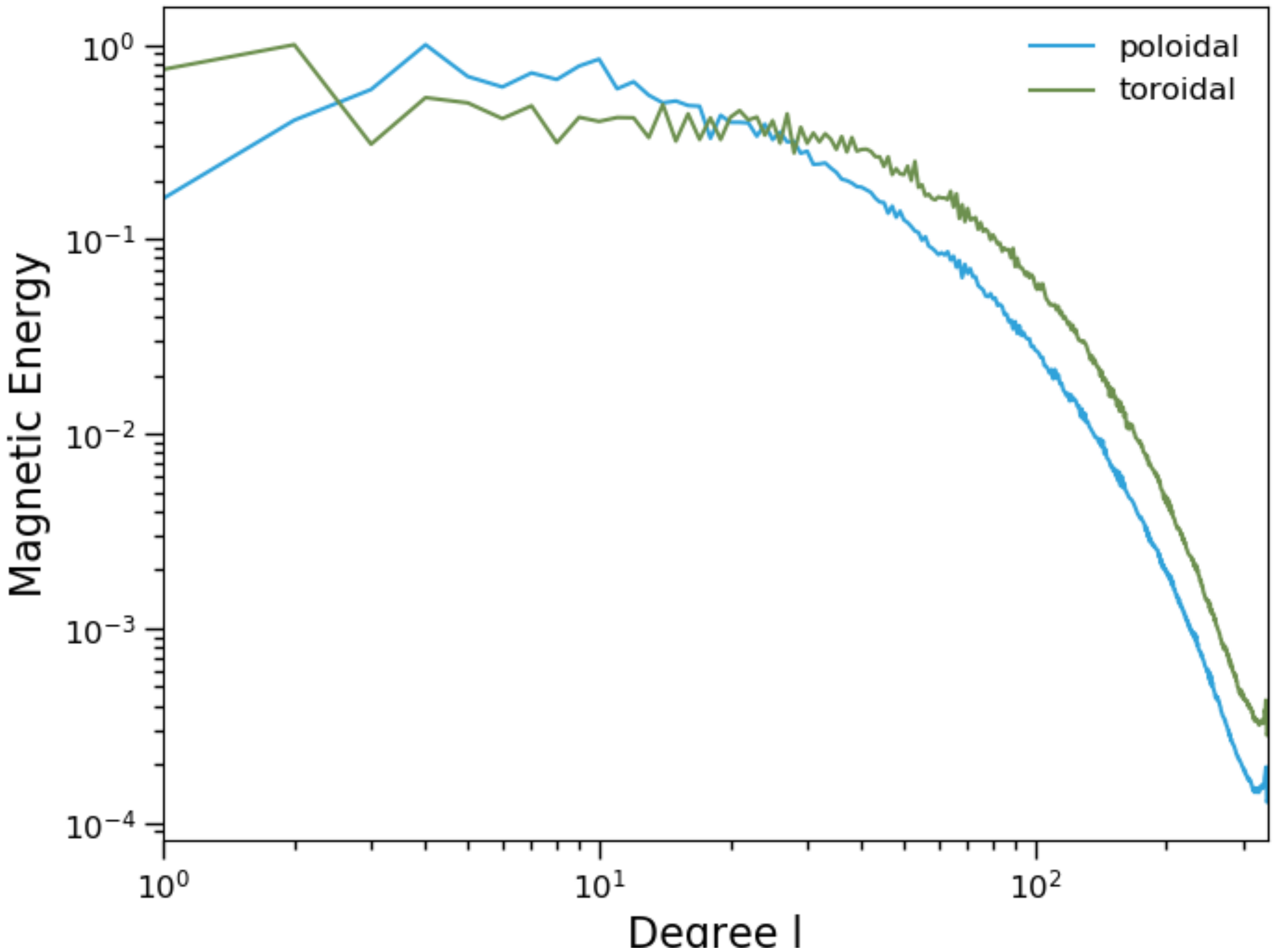
Dipolar angle





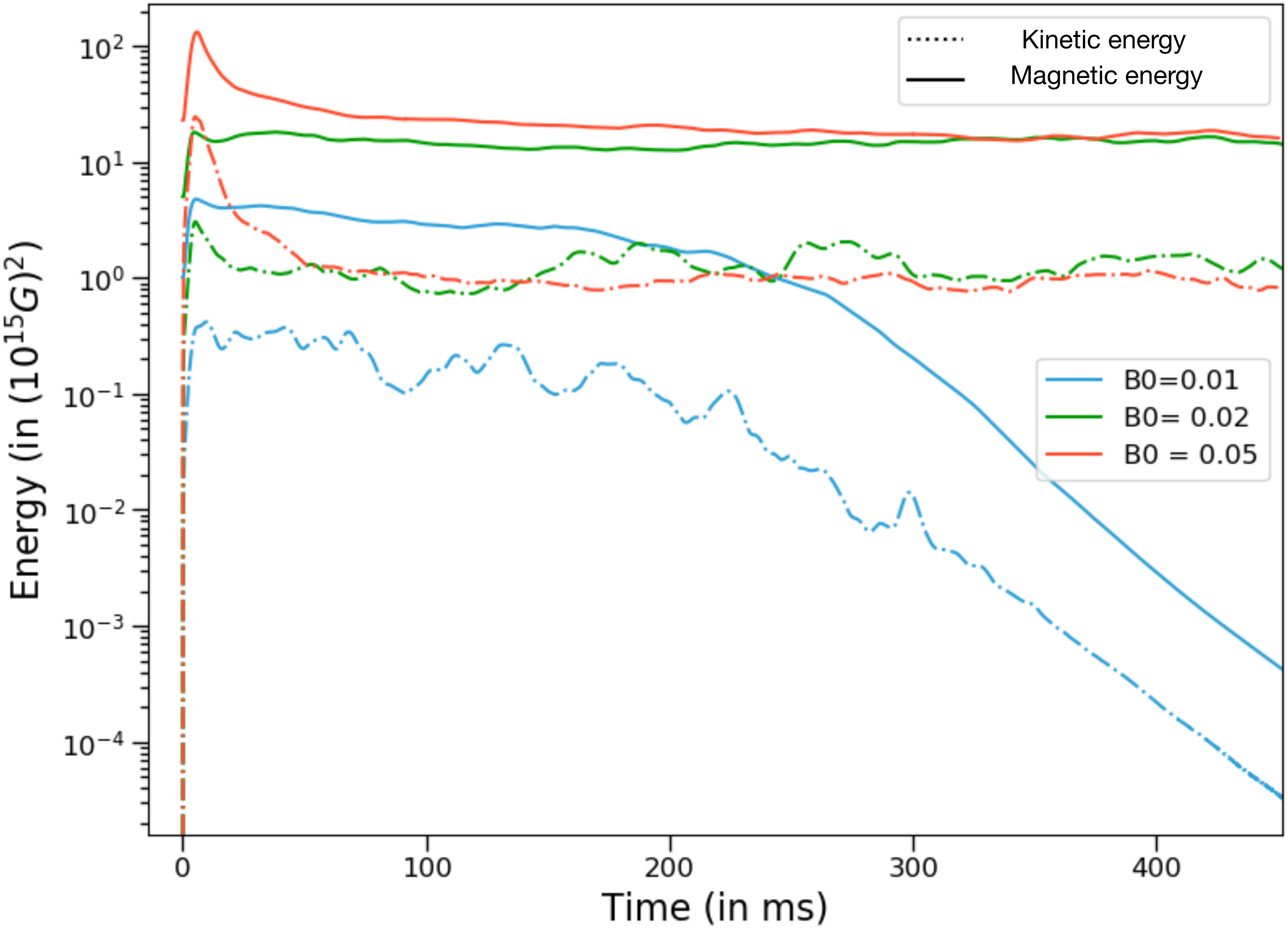
Magnetic energy spectrum

Spectrum at t = 600 ms



III-Preliminary parameter study

Influence of the initial magnetic field amplitude

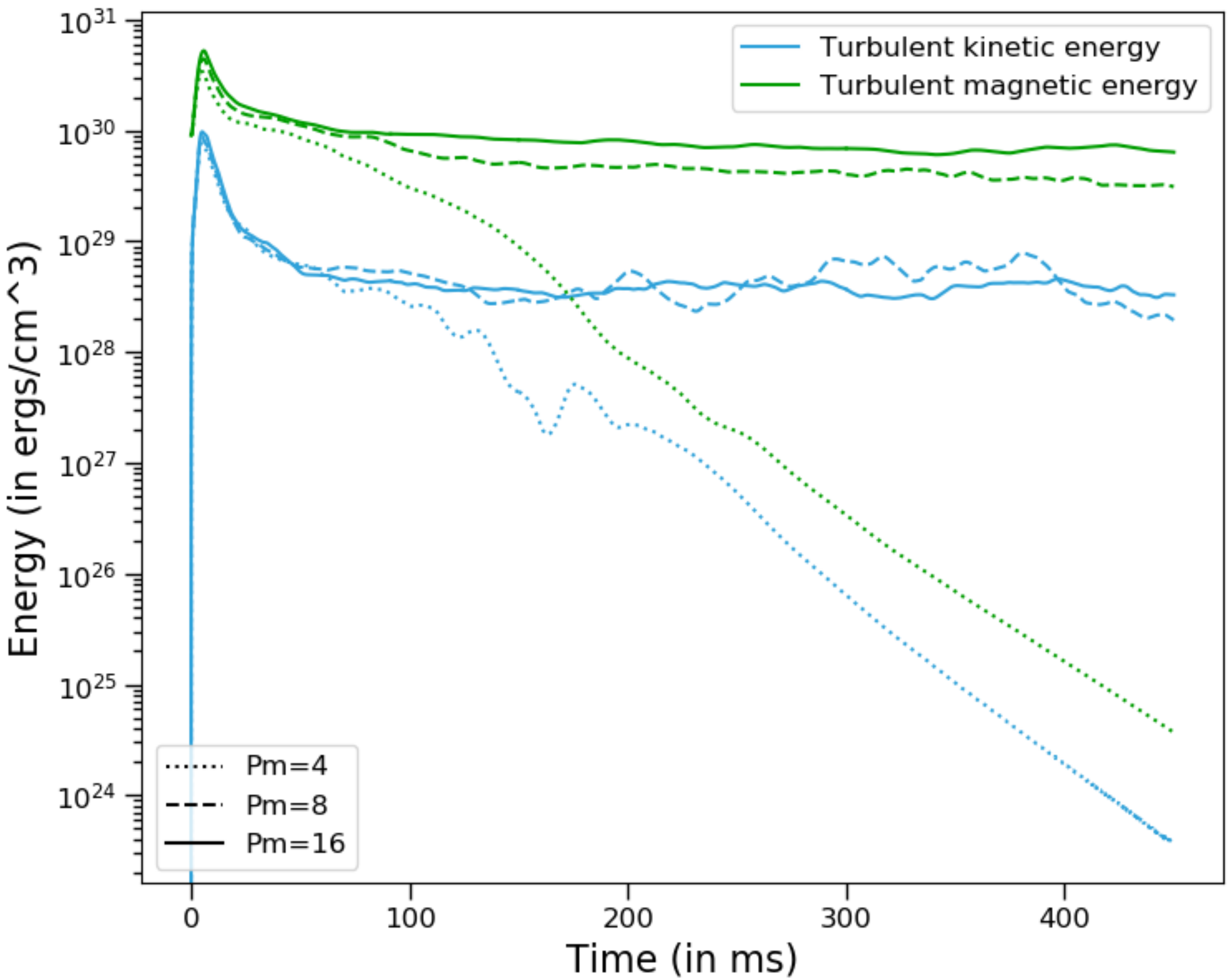


$B_0 = 4.48 \times 10^{14}$ G

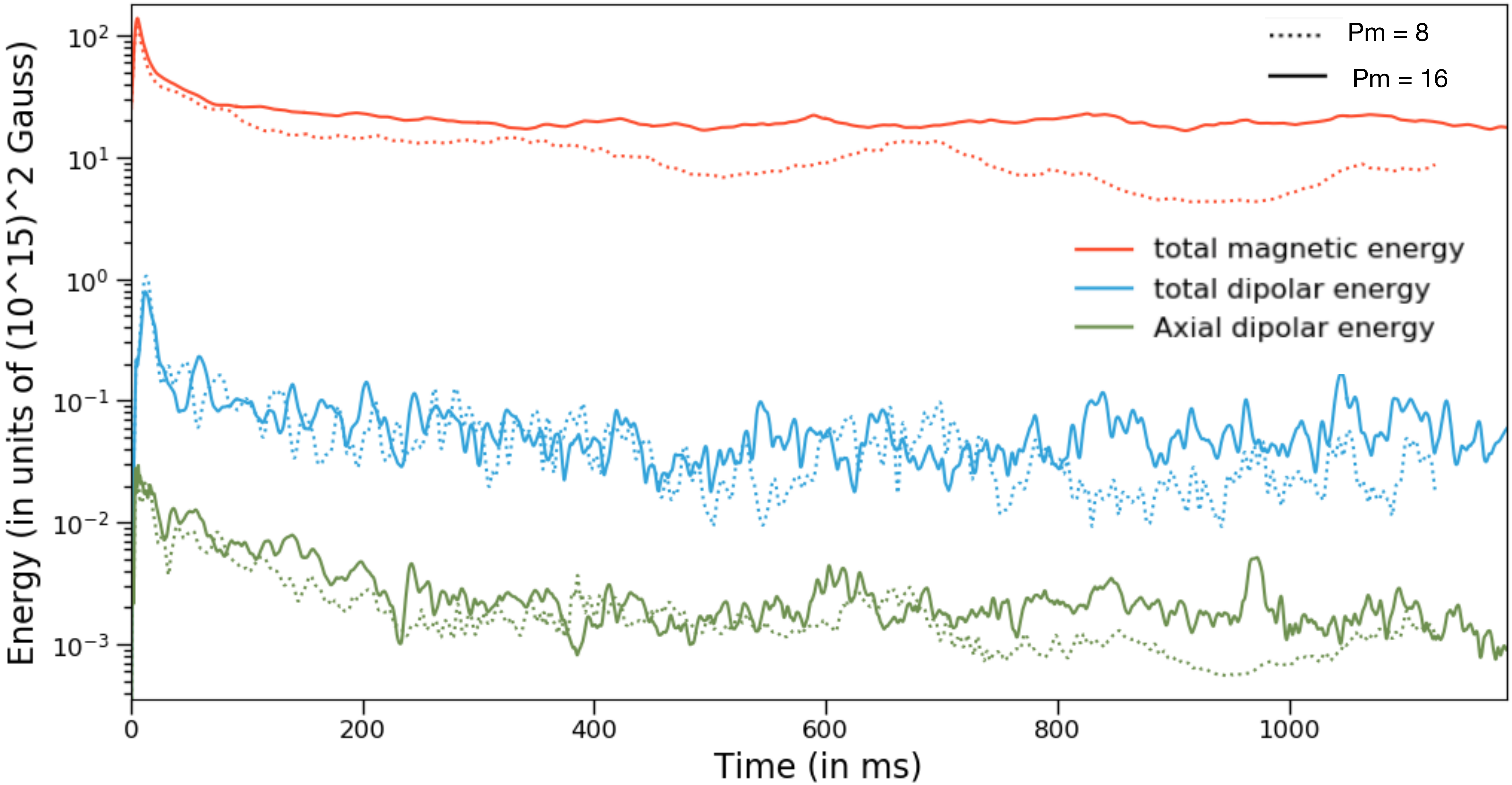
$B_0 = 8.97 \times 10^{14}$ G

$B_0 = 2.24 \times 10^{15}$ G

Influence of the Prandtl magnetic number



Influence of the Pm on the dipole



Summary and perspectives

- Magnetar-like magnetic field strength
- A dipole is generated by the small scales
- Further understanding of the physics

—> Influence of global flows on the dipole

- Influence of parameters

—> Towards more realistic values

- Implement a realistic EoS
- Interaction with a convective dynamo ?