A global model of the magneto-rotational instability in proto-neutron stars

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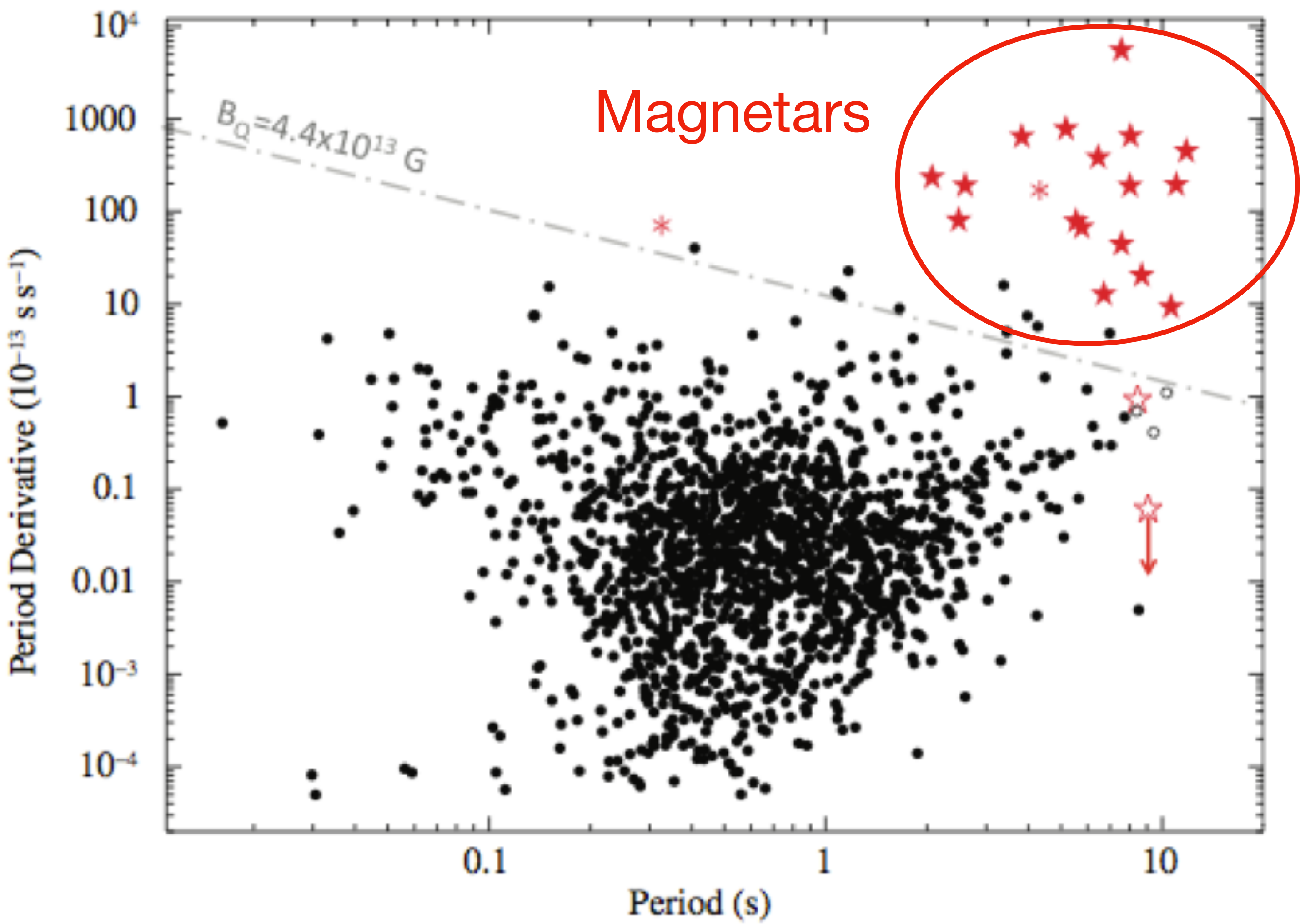
1 : AIM, CEA Paris-Saclay

Motivation : Magnetars

$P - \dot{P}$ diagram



Crédit : Rea et al. 2012

- Hard X-Ray and Soft Gamma observations
  -> Anomalous X-Ray Pulsar
  -> Soft Gamma Repeater
- Radio Observations

How to measure the B field
-> Period + Spin down measurement

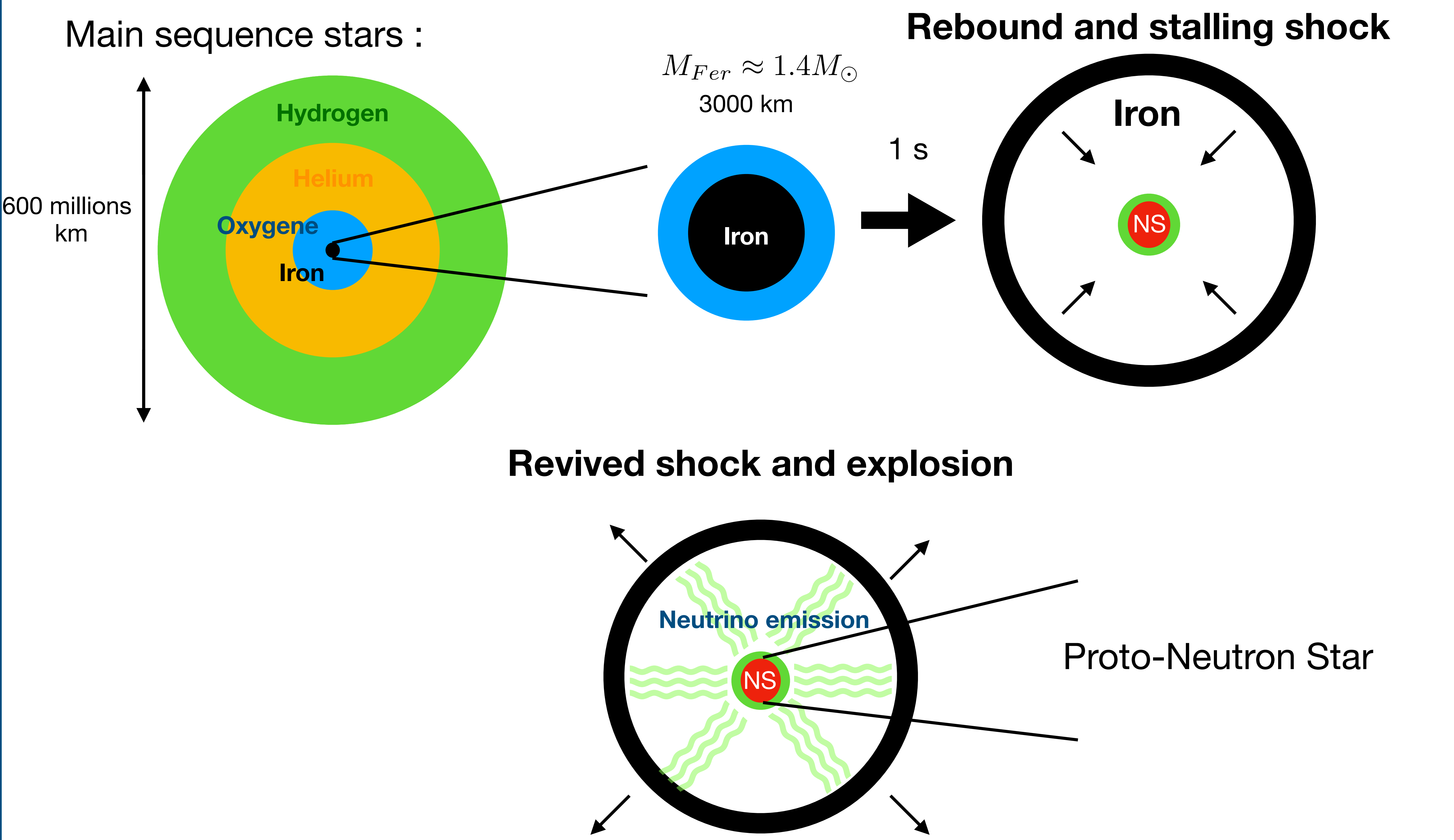
$$B_{dip} = 10^{14}\left(\frac{P}{5\ s}\right)^{\frac{1}{2}}\left(\frac{\dot{P}}{10^{-11}\ s\ s^{-1}}\right)^{\frac{1}{2}} \quad \mathrm{G}$$

- Dipolar magnetic field strength of magnetars :

-> $B_{magnetar} \approx 10^{14} - 10^{15} G$

Neutron star formation

Core-Collapse Supernova



Supernova observations

Outstanding explosions : millisecond magnetars ?

Kinetic energy of the explosion

→ Classic Supernova 10^{51} ergs → Neutrino-driven mechanism

→ Hypernova (rare) (<1 %) 10^{52} ergs → Magneto-rotational

See Phillips Moesta's talk
and Matteo Bugli's talk

Luminosity of the supernova :

→ Classic Supernova 10^{49} ergs

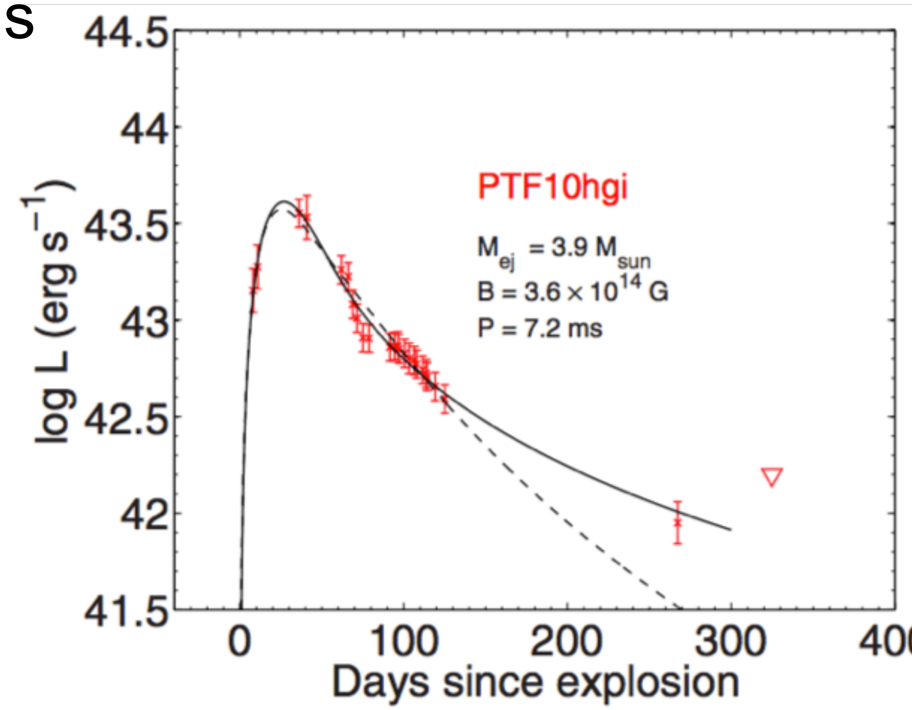
→ Super-Luminous Supernova (<0.1%) 10^{51} ergs

Luminosity curves fitted by a magnetar model with:

-> Strong dipole field : $B \approx 10^{14} - 10^{15} G$

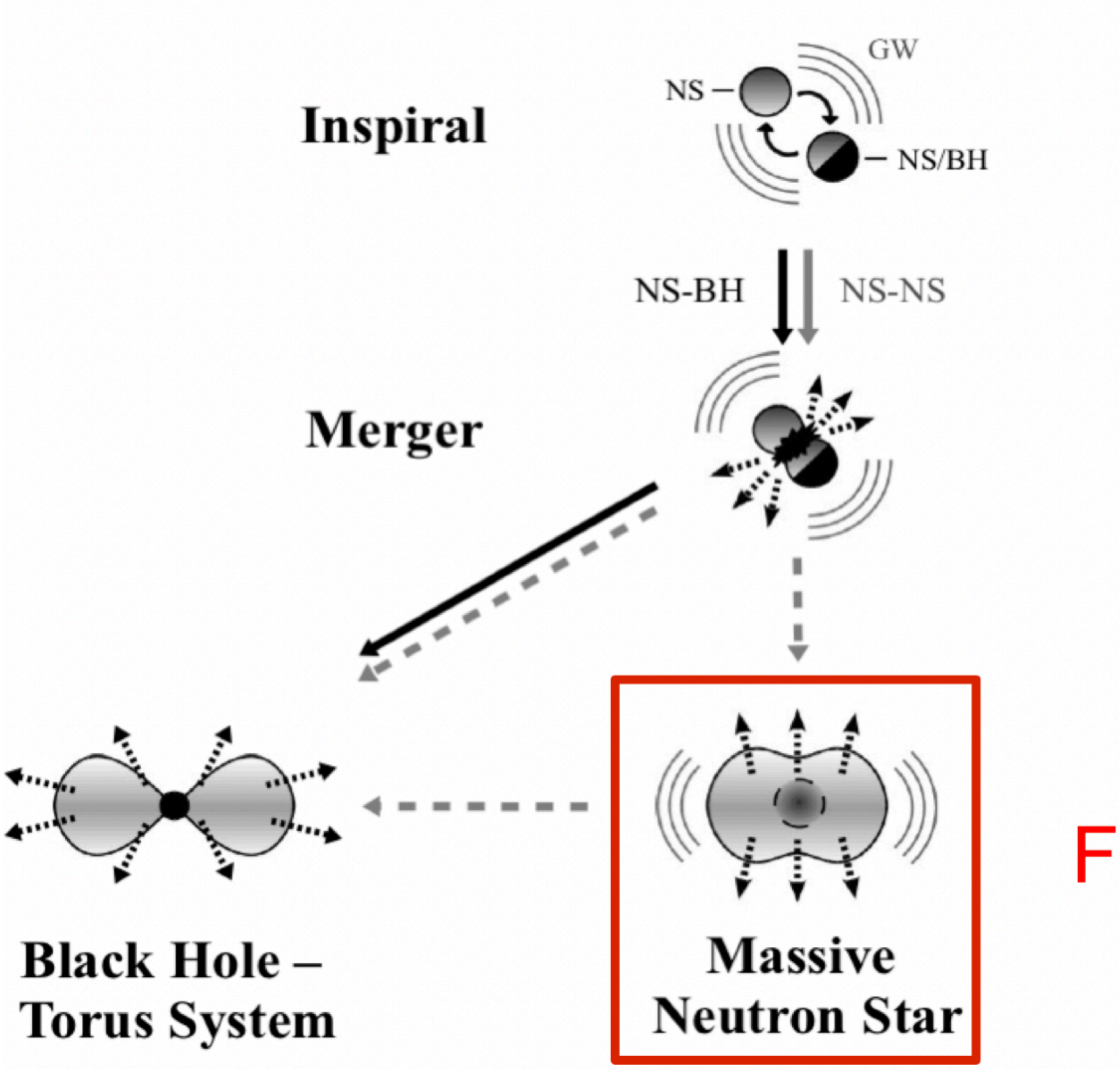
-> Fast Rotation : P ~ 1-10 ms

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



Inserra+13

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

SN (& mergers ?)

Similar to planetary & stellar dynamos

See Raphael Raynaud's talk

Outline

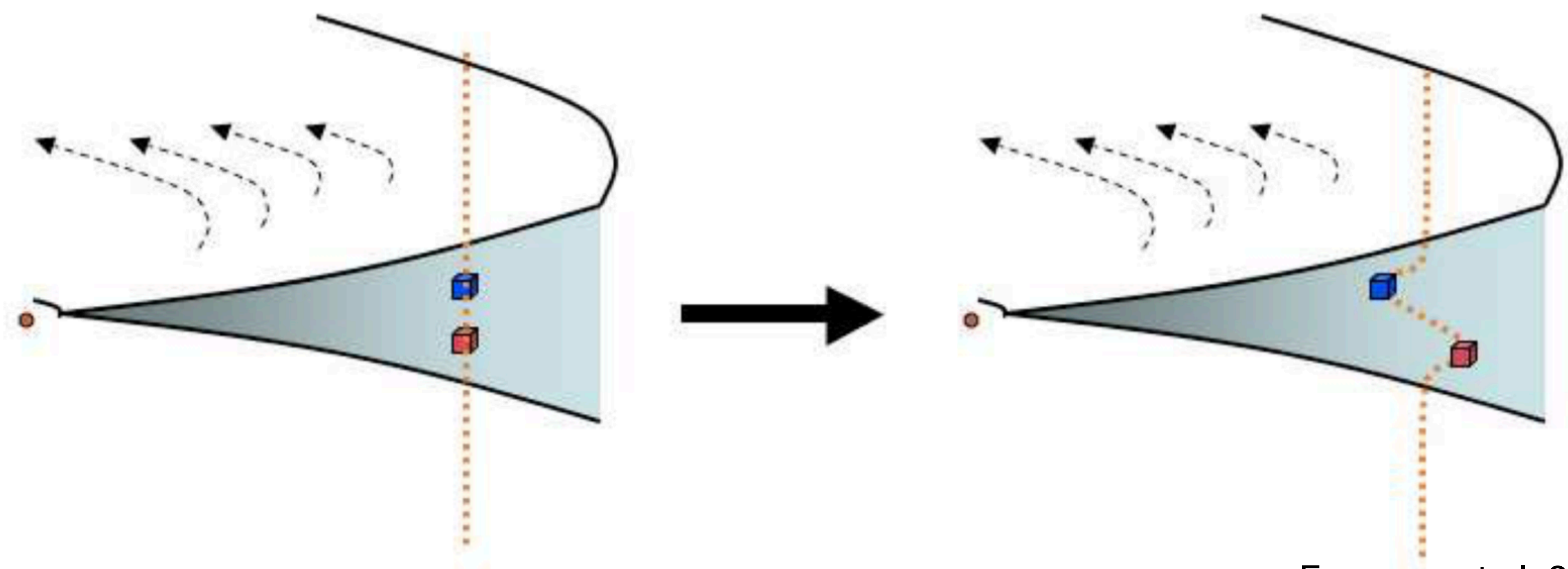
I- Presentation of the local models of the MRI

II- A global model of the MRI

III- 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: $\sigma = \frac{q\Omega}{2}$ with $\Omega \propto r^{-q}$

-> Fast growth for fast rotation

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

-> Short wavelength for weak magnetic fields

Local models in accretion disks

"Shearing box" models

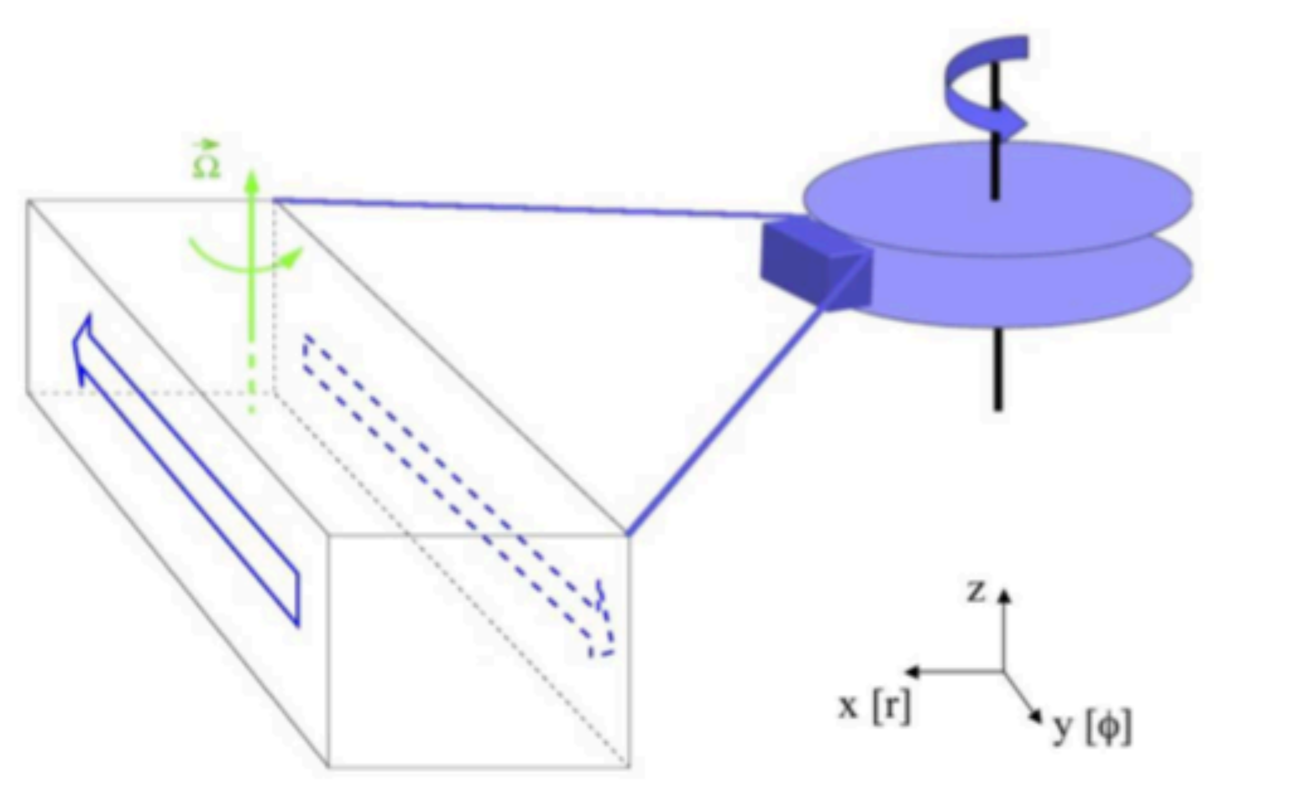
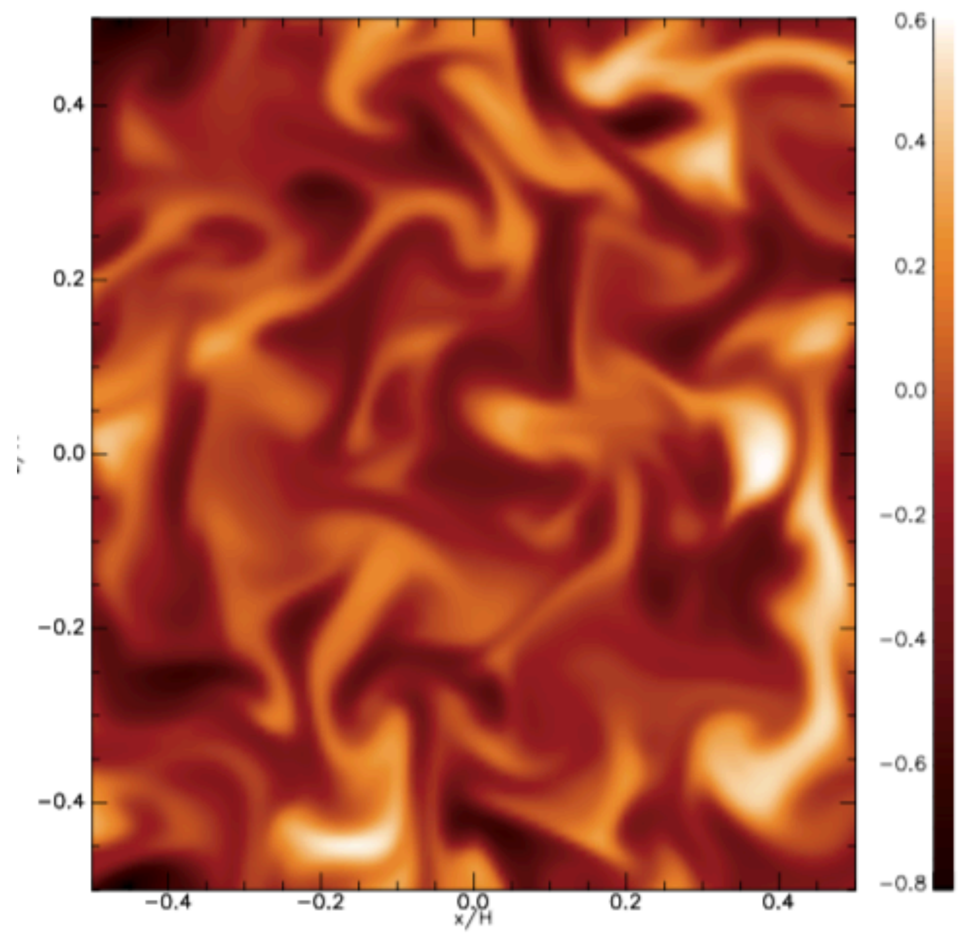


Figure courtesy :G. Lesur

Turbulence MHD : toroidal field



Fromang et al. 2007

Impact of conditions specific to neutron stars ?

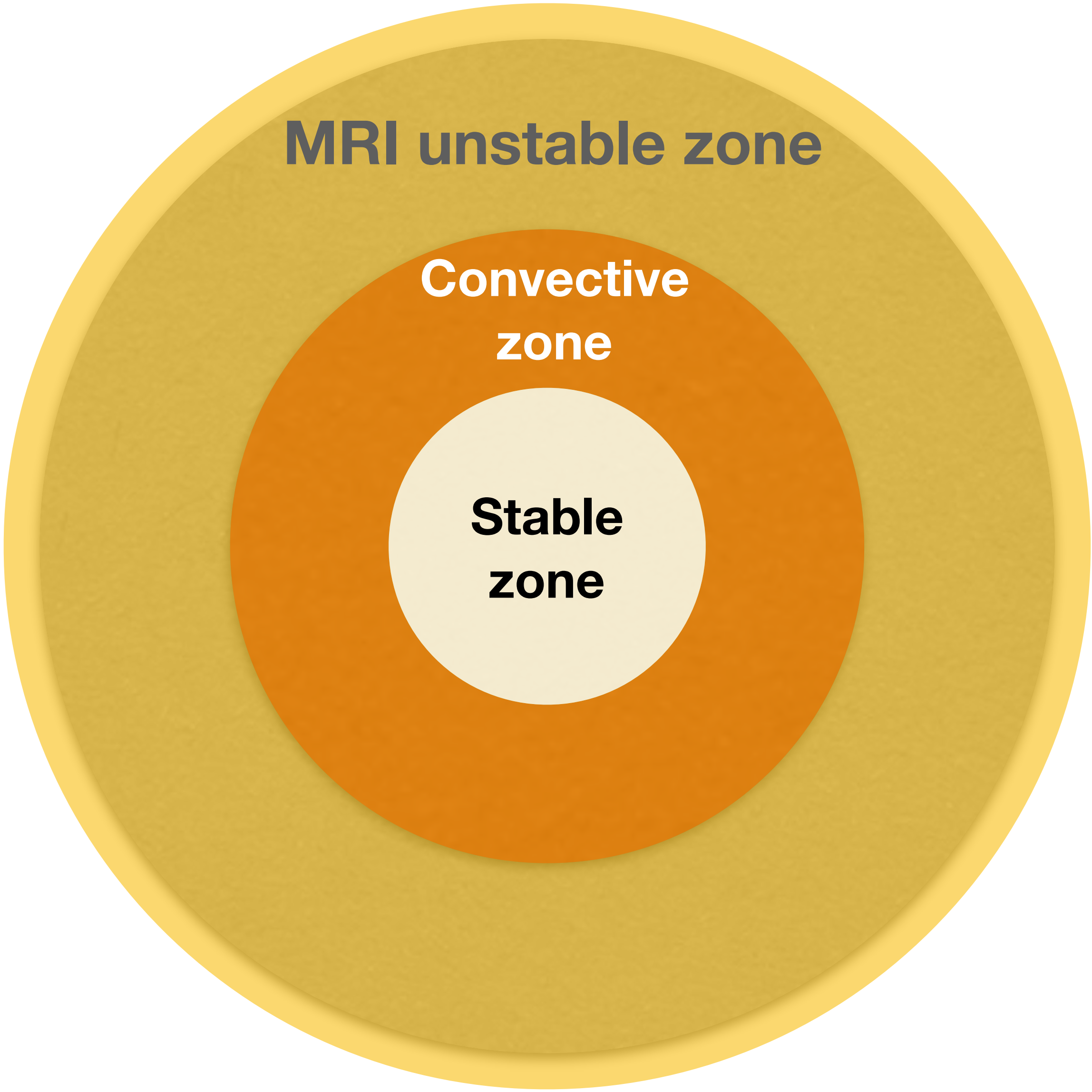
→ neutrinos

→ buoyancy (entropy & composition gradients)

→ spherical geometry

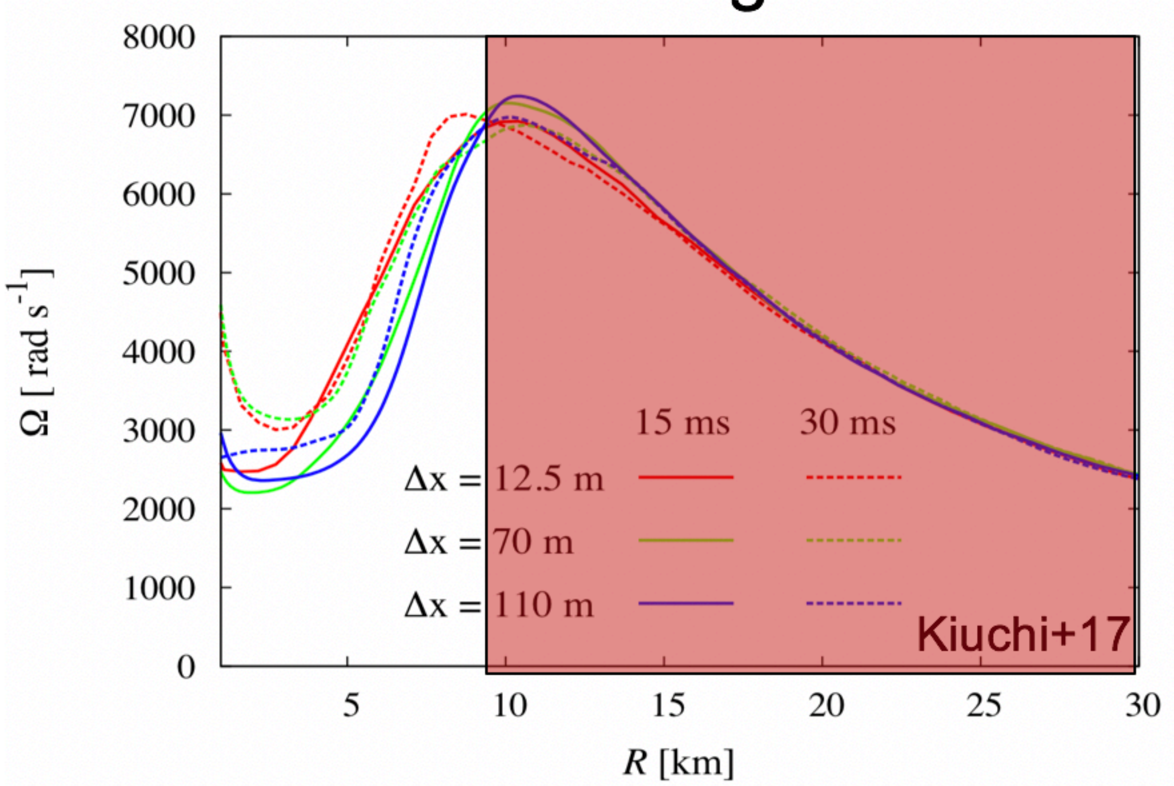
MRI unstable zone vs convective zone

t = 0.2 s

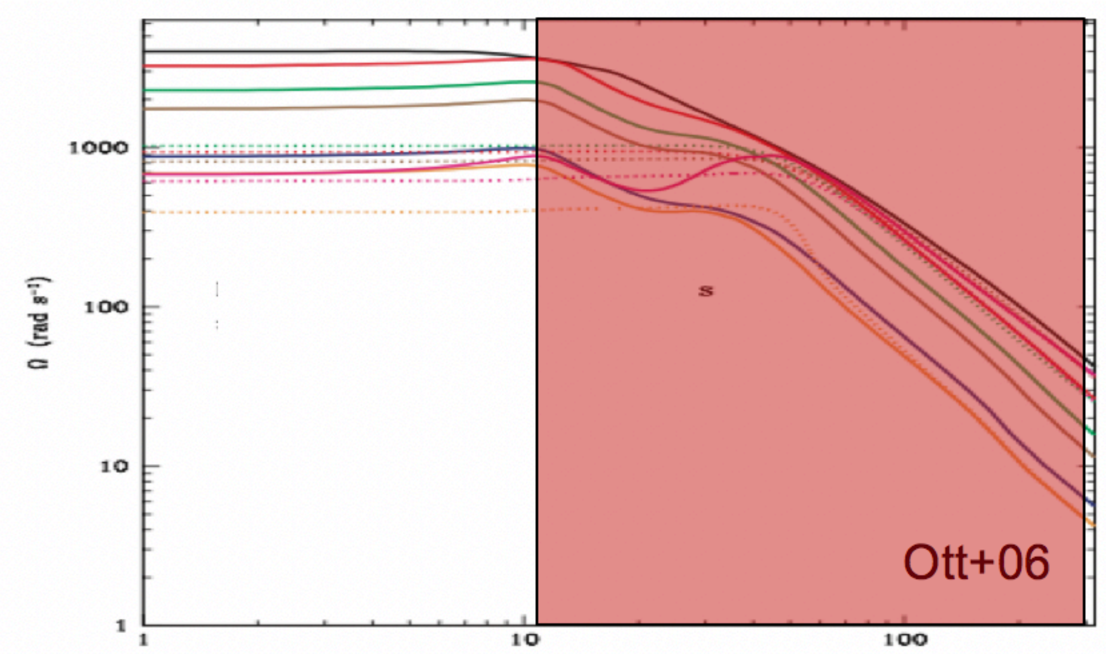


See Raphael Raynaud's talk

NS merger



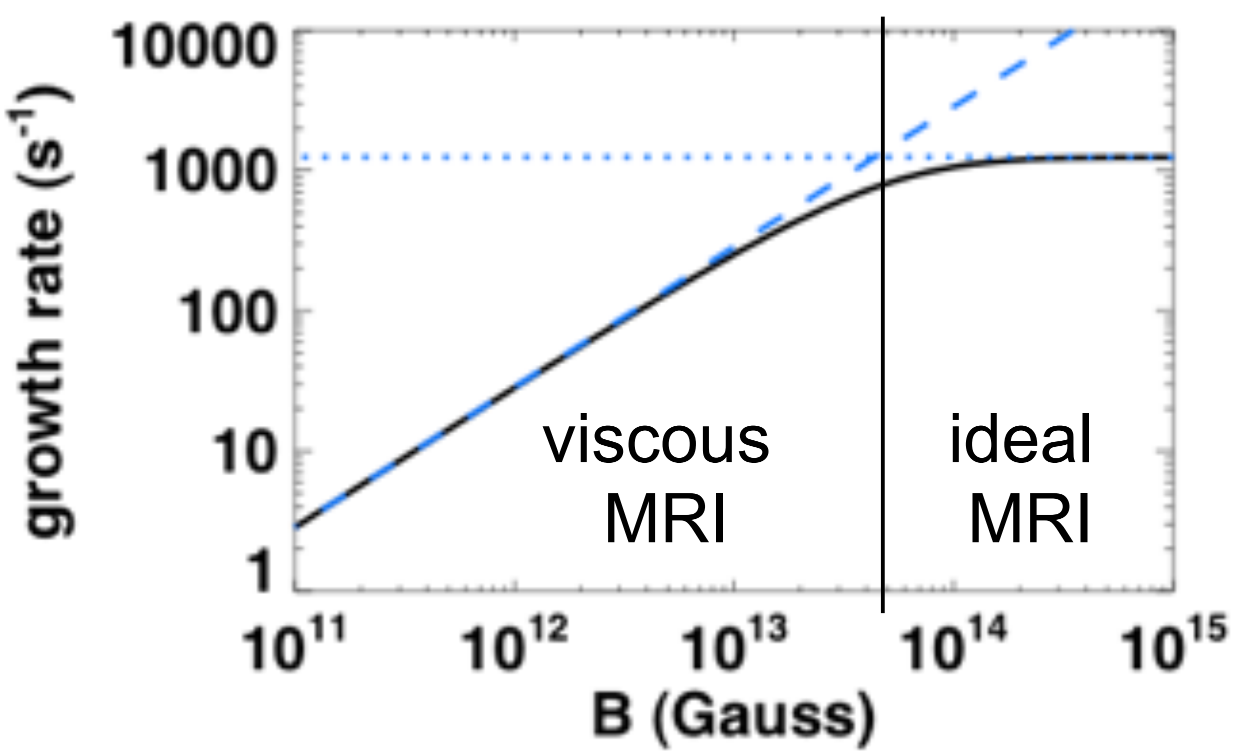
supernovae



Impact of neutrinos on the MRI

Viscous regime

$$\lambda_{MRI} > l_{neutrino}$$

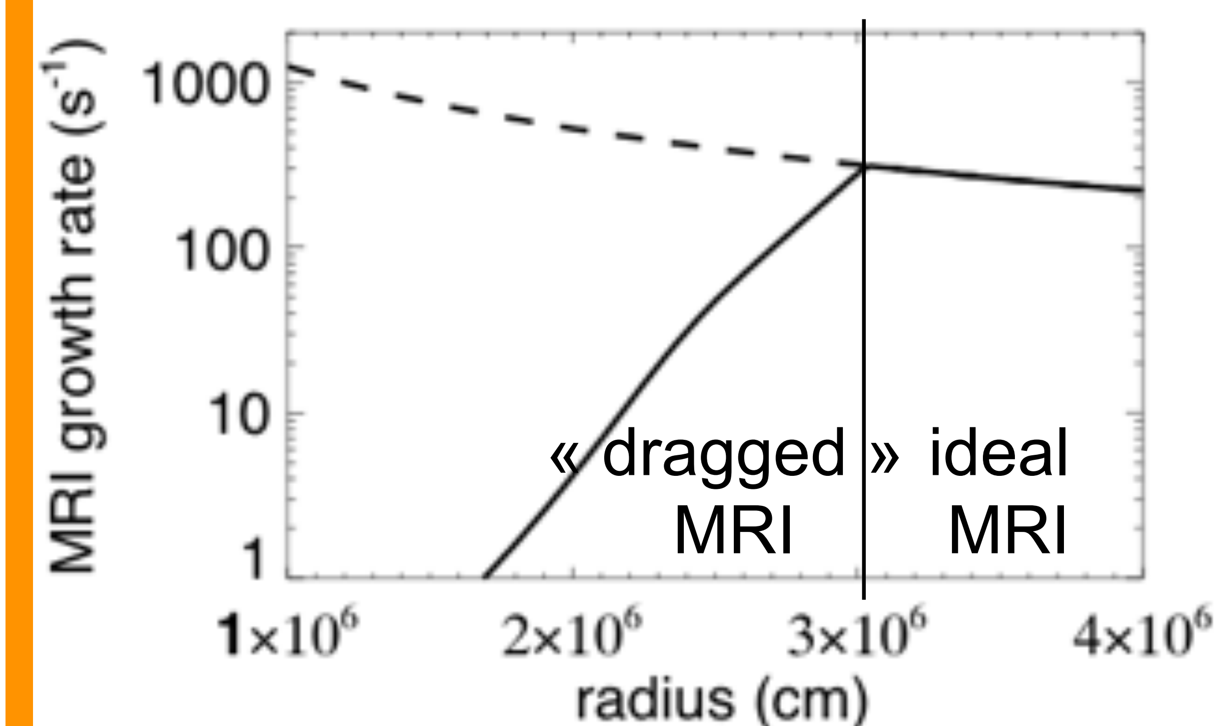


Slow growth for weak initial magnetic field

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

Neutrino drag regime

$$\lambda_{MRI} < l_{neutrino}$$

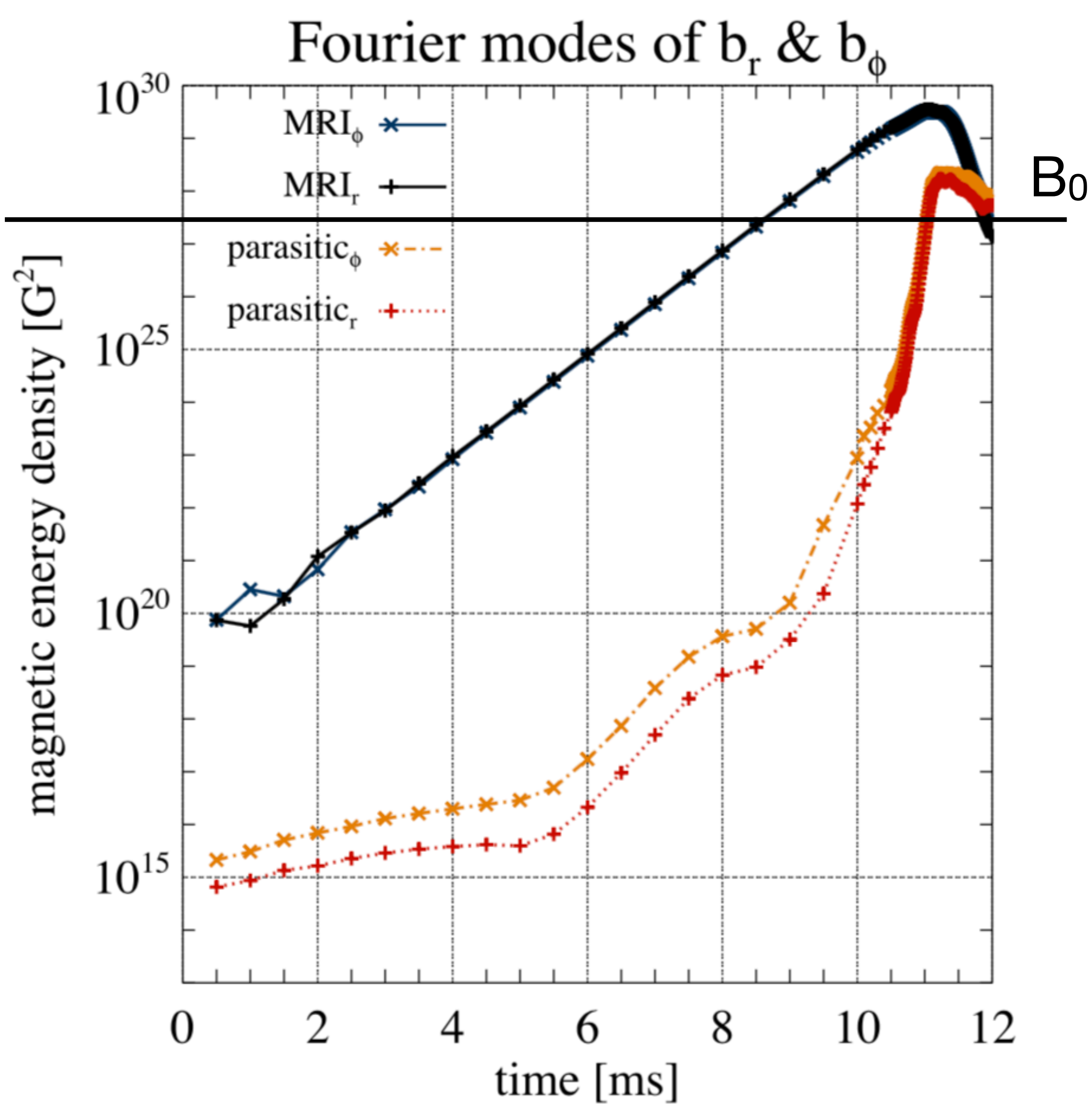


Fast growth near surface

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

Magnetic field amplification in local models

Amplification and saturation study

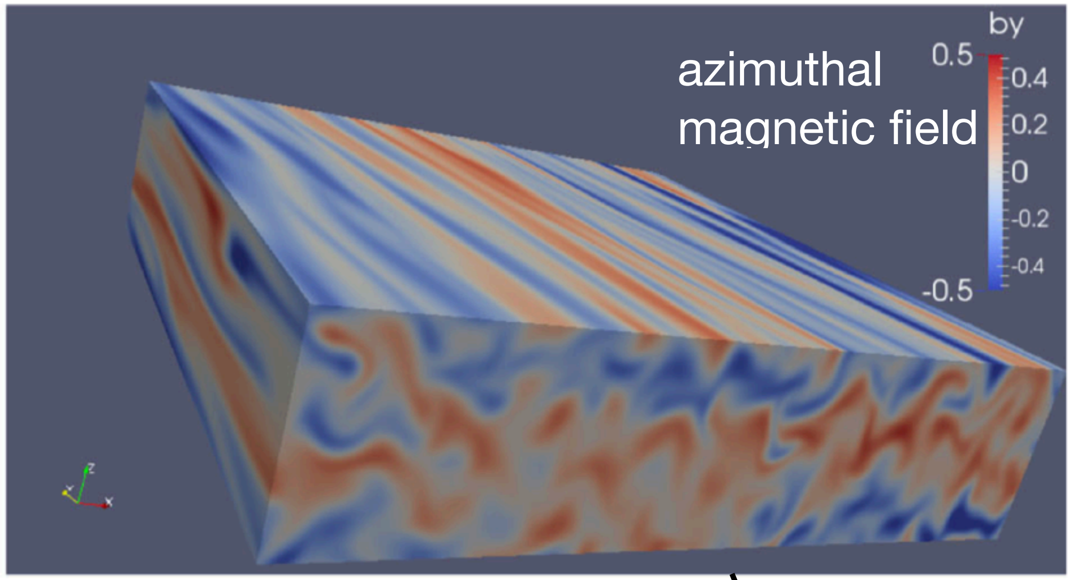


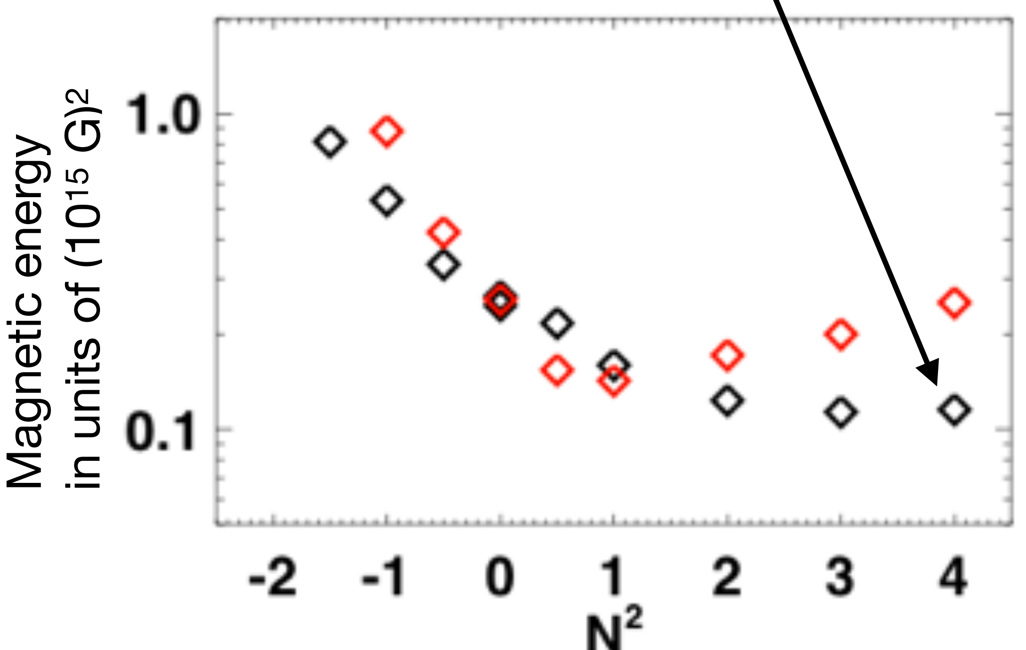
Crédit : Rembiaz et al. 2016

See also :
Obergaulinger 2009,Masada 2015

Study of the buoyancy impact

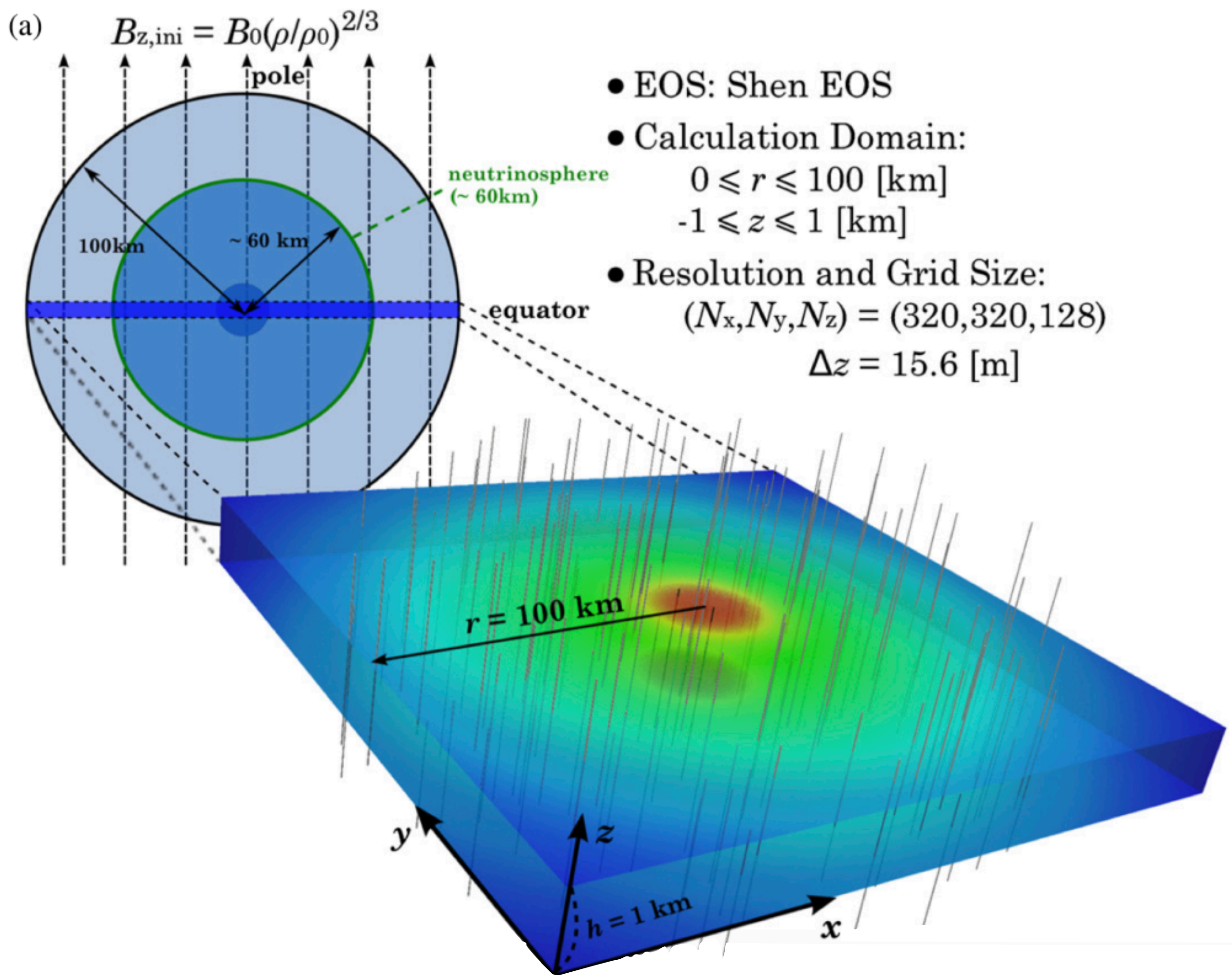
Stable stratification





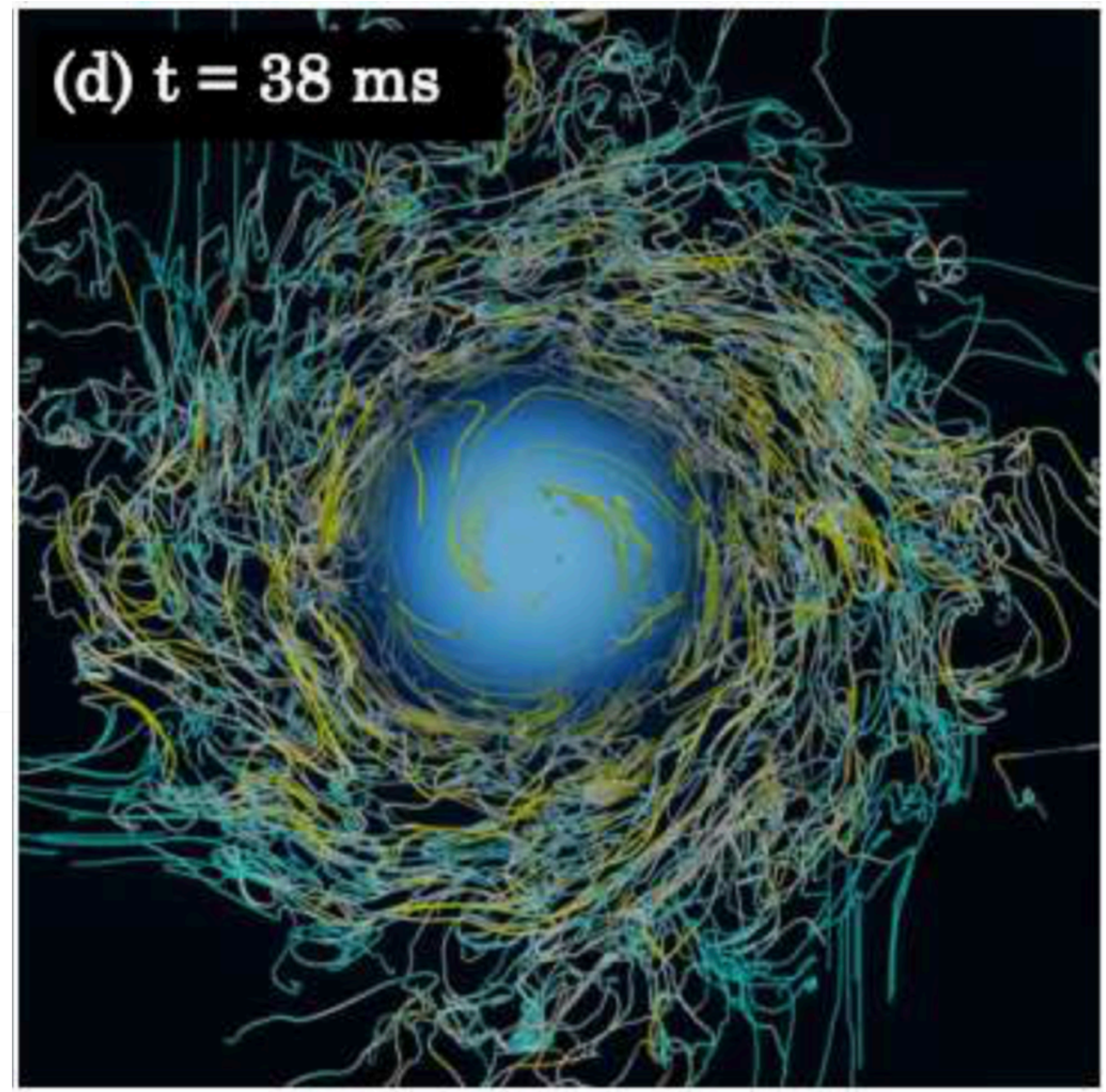
Crédit : Guilet and Müller. 2016

Global simulation in the equatorial plane



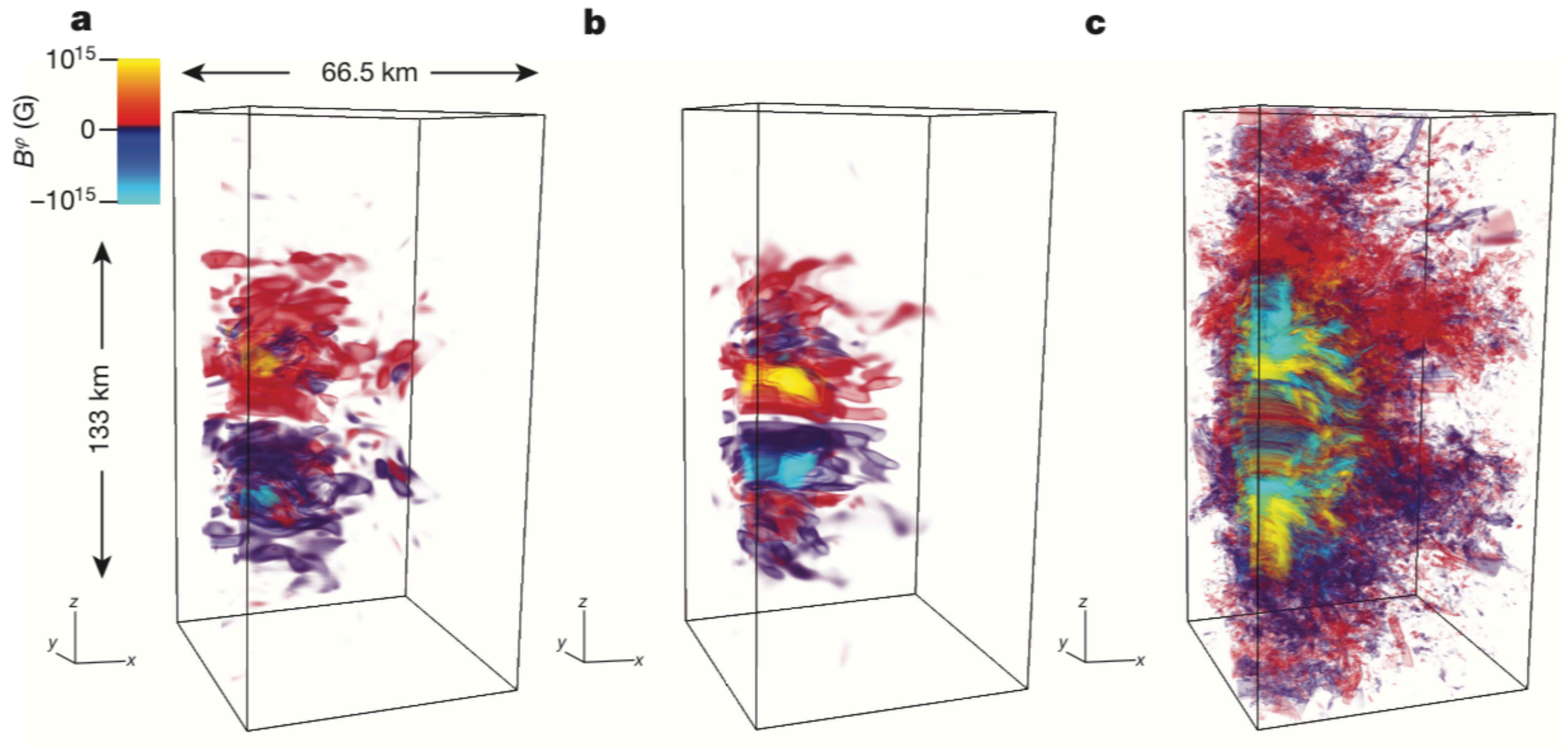
Masada et al. (2015)

Magnetic field lines



First attempt at a global model

Moesta et al 2015



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

Outline

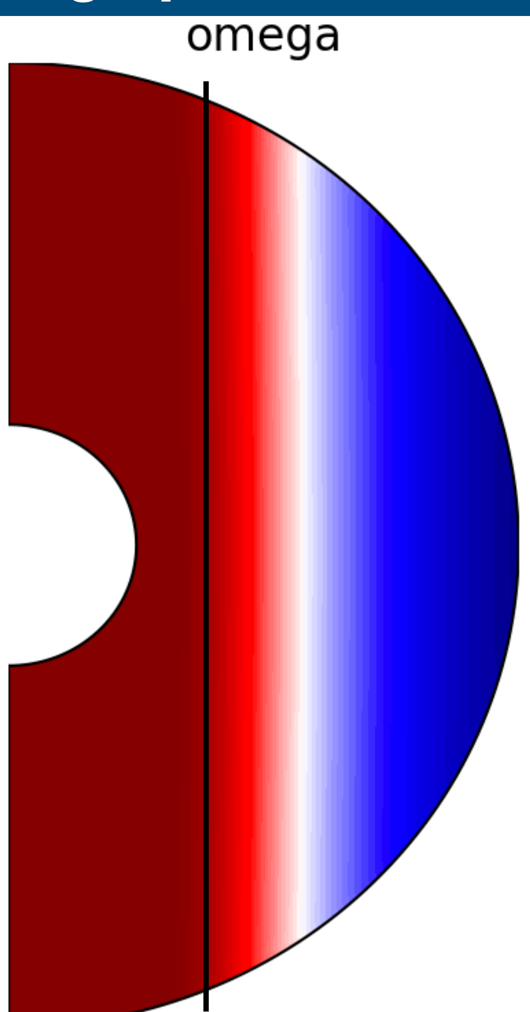
II- A global model of the MRI in a PNS

Our setup

- Simplest model : Incompressible $\longrightarrow$ $N_r = 256$, $N_{theta} = 512$, $N_{phi} = 1024$
  -> 3D pseudo-spectral MHD code, MagIC
- Initial velocity is fixed at the outer boundary
- Typical parameters values : $B_0 = 9 \times 10^{14}$, Pm = 16 and Re = 5000

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

Omega profile

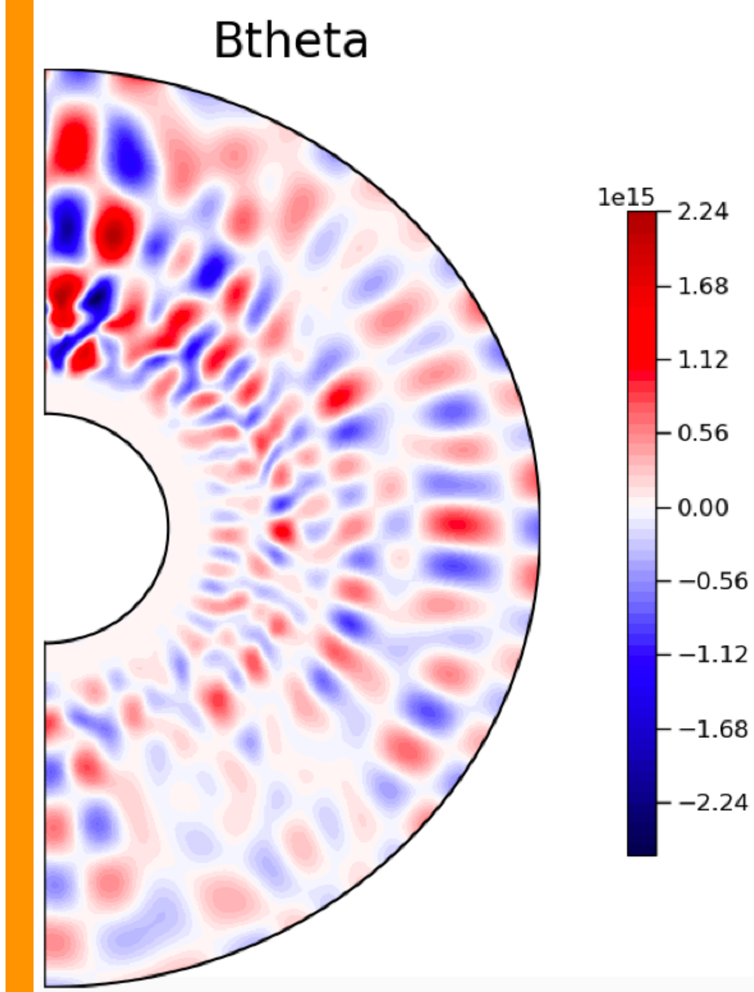


Core in solid body rotation

Then :

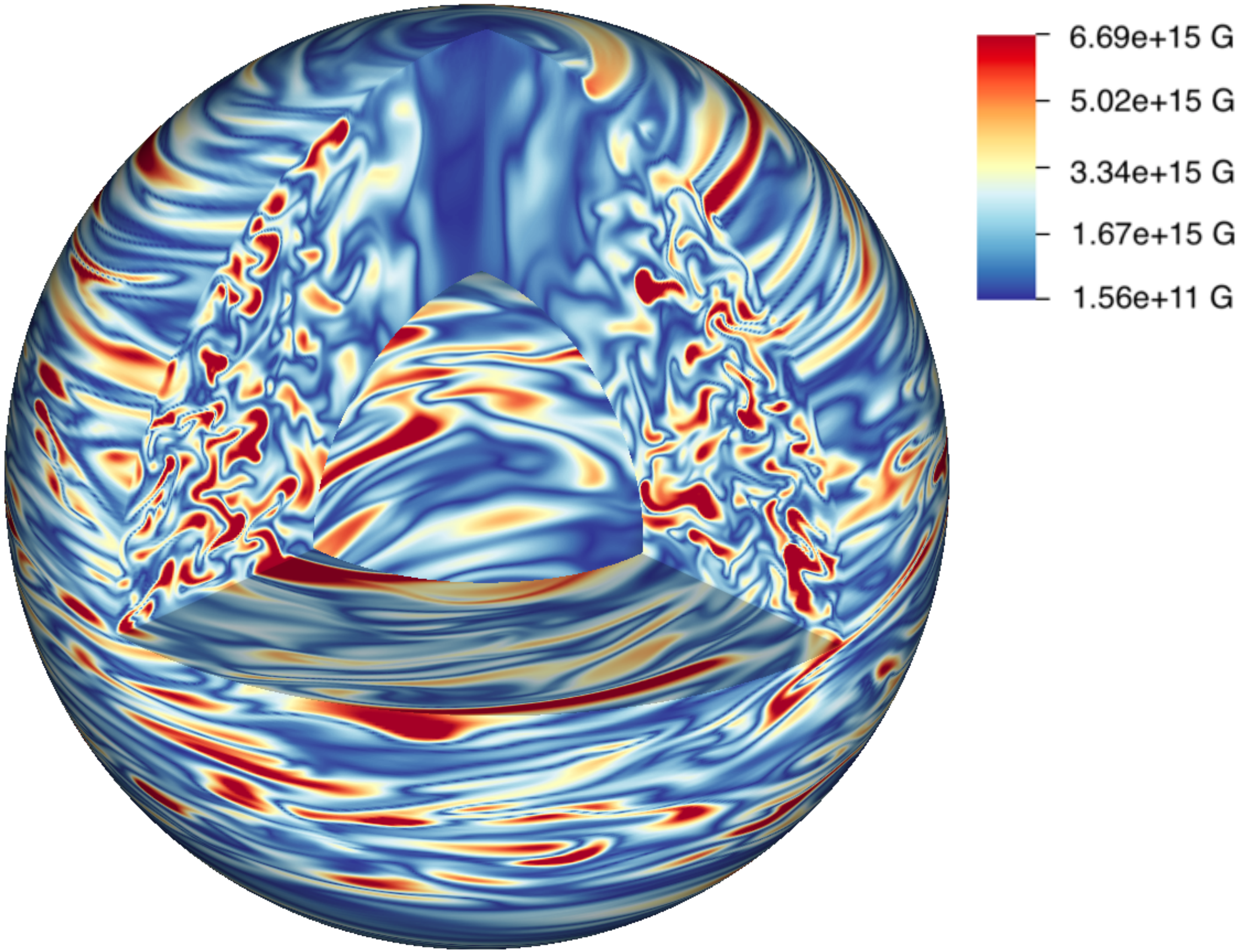
$$\propto \ r^{-q}$$

Magnetic field profile

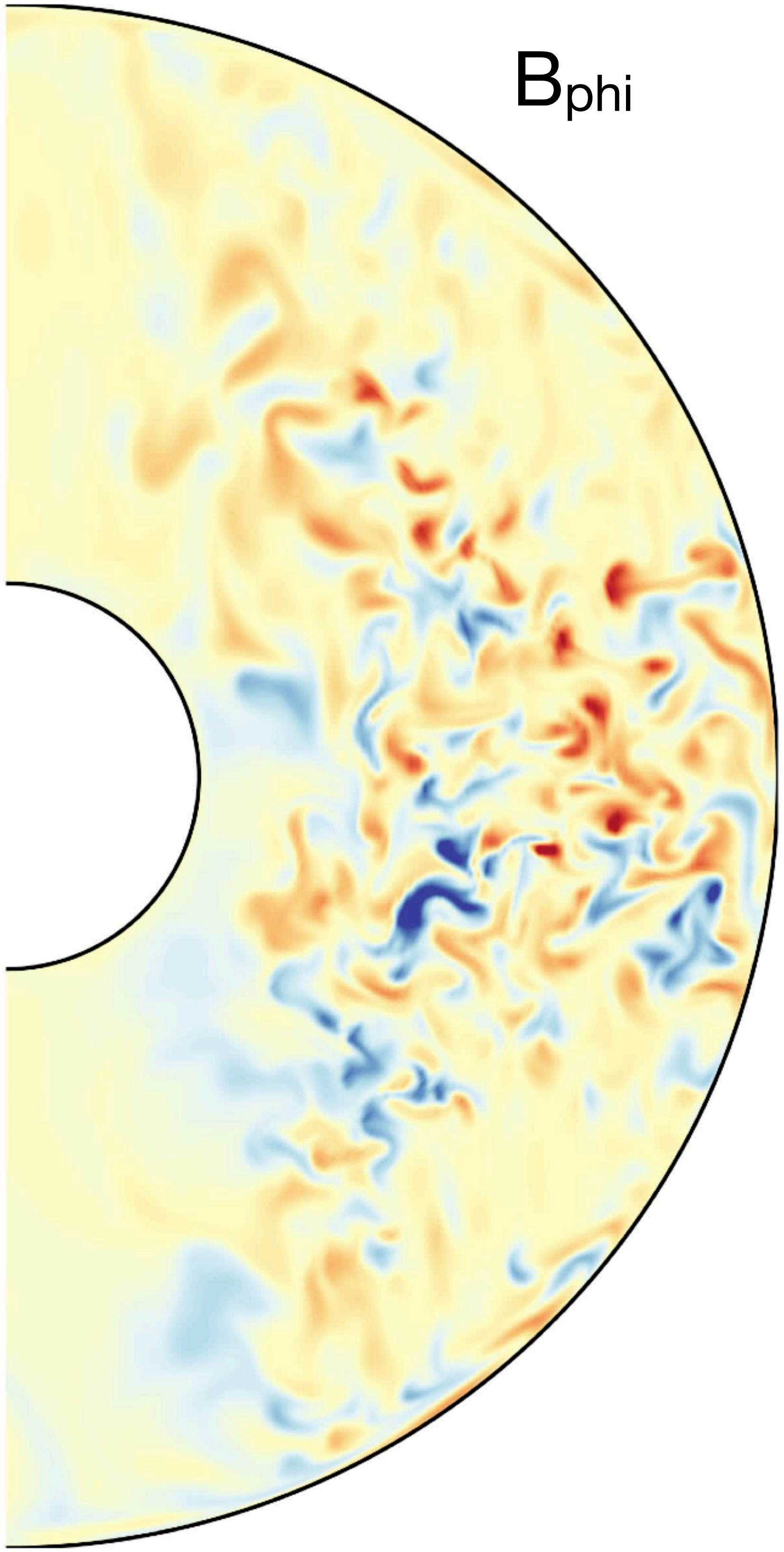


Small scales
~ Local models

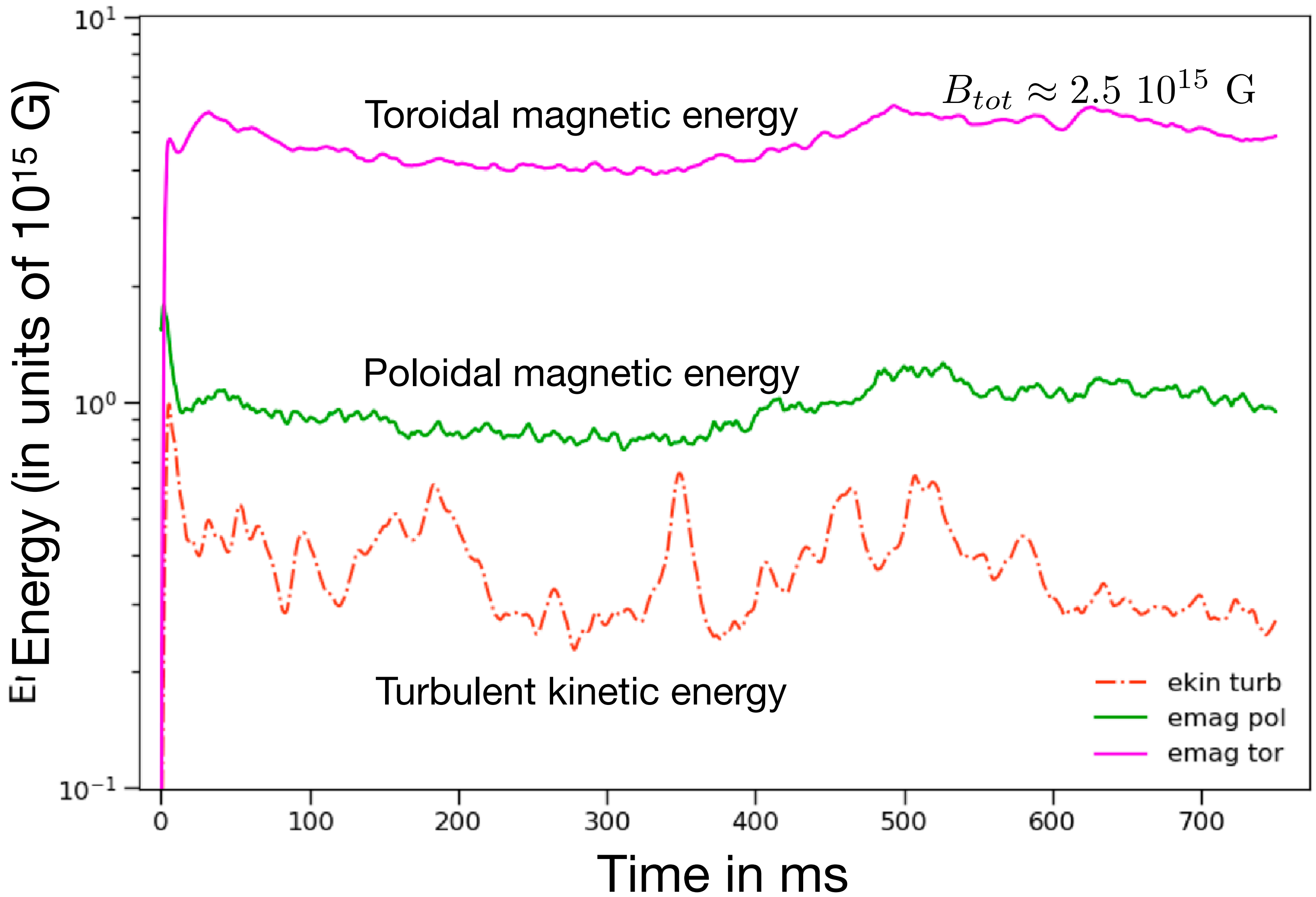
Amplitude of the magnetic field



Time evolution of the field

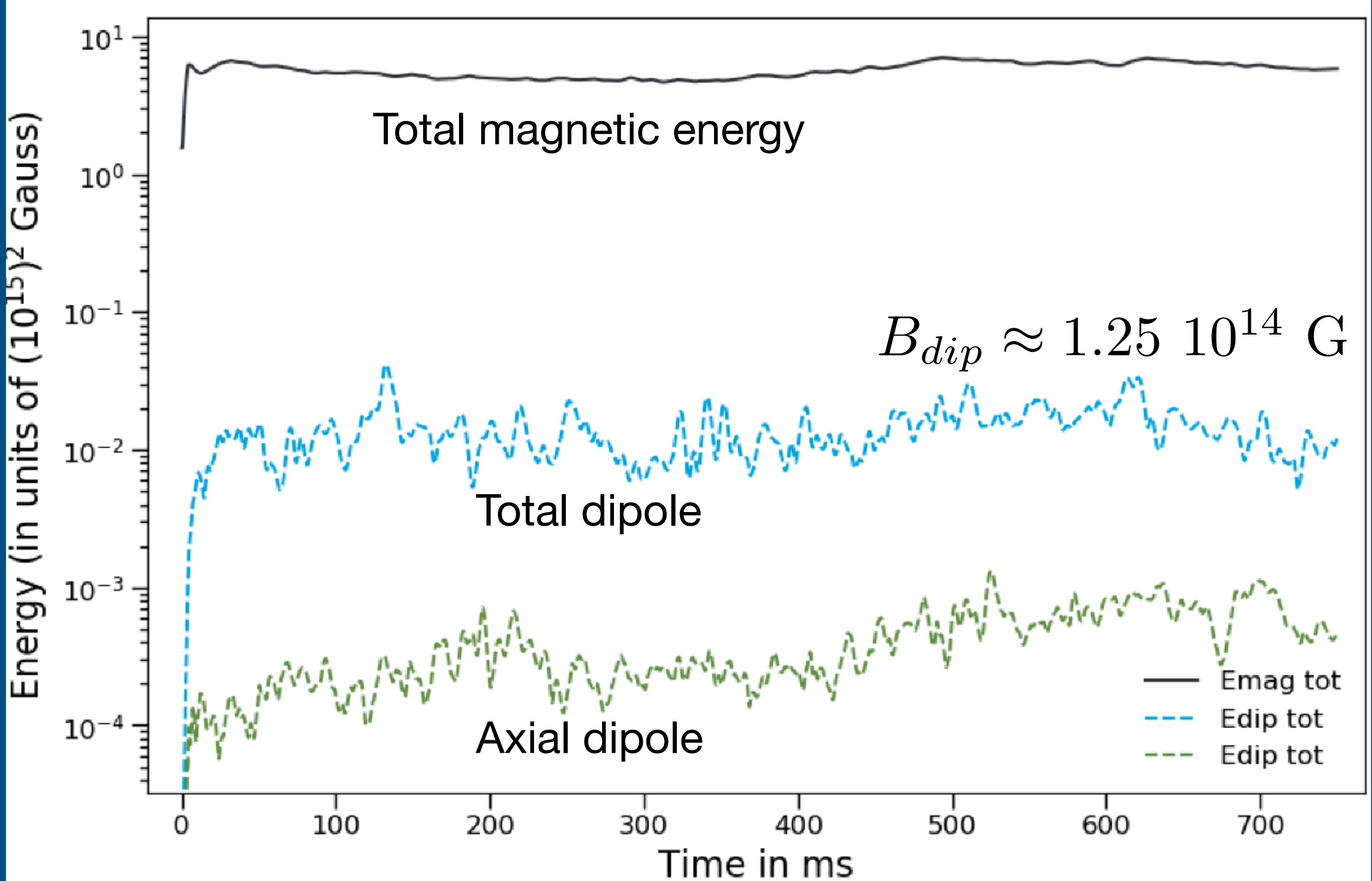


Time evolution of global quantities

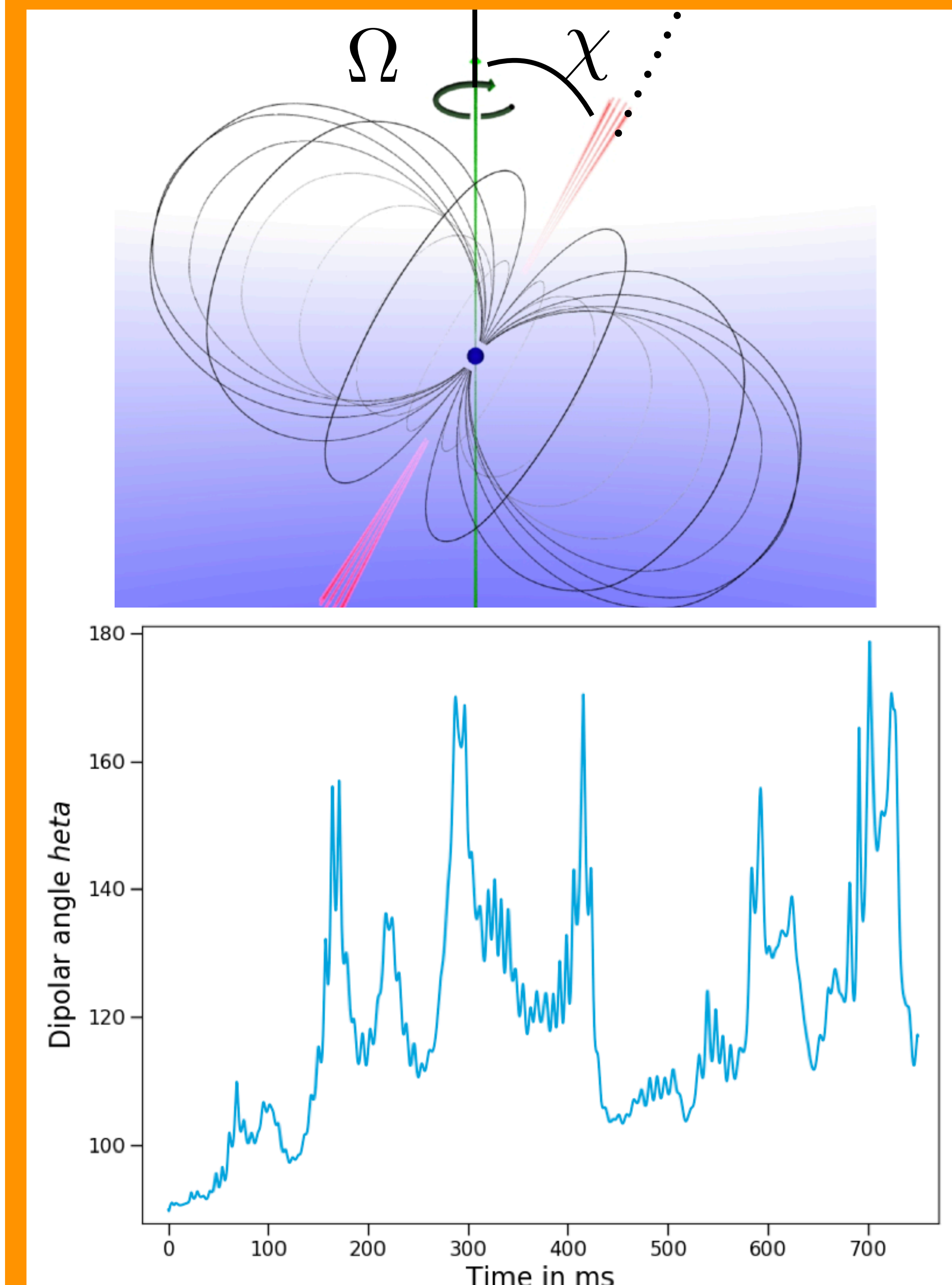


Results on the dipole

Time Evolution of dipolar energy

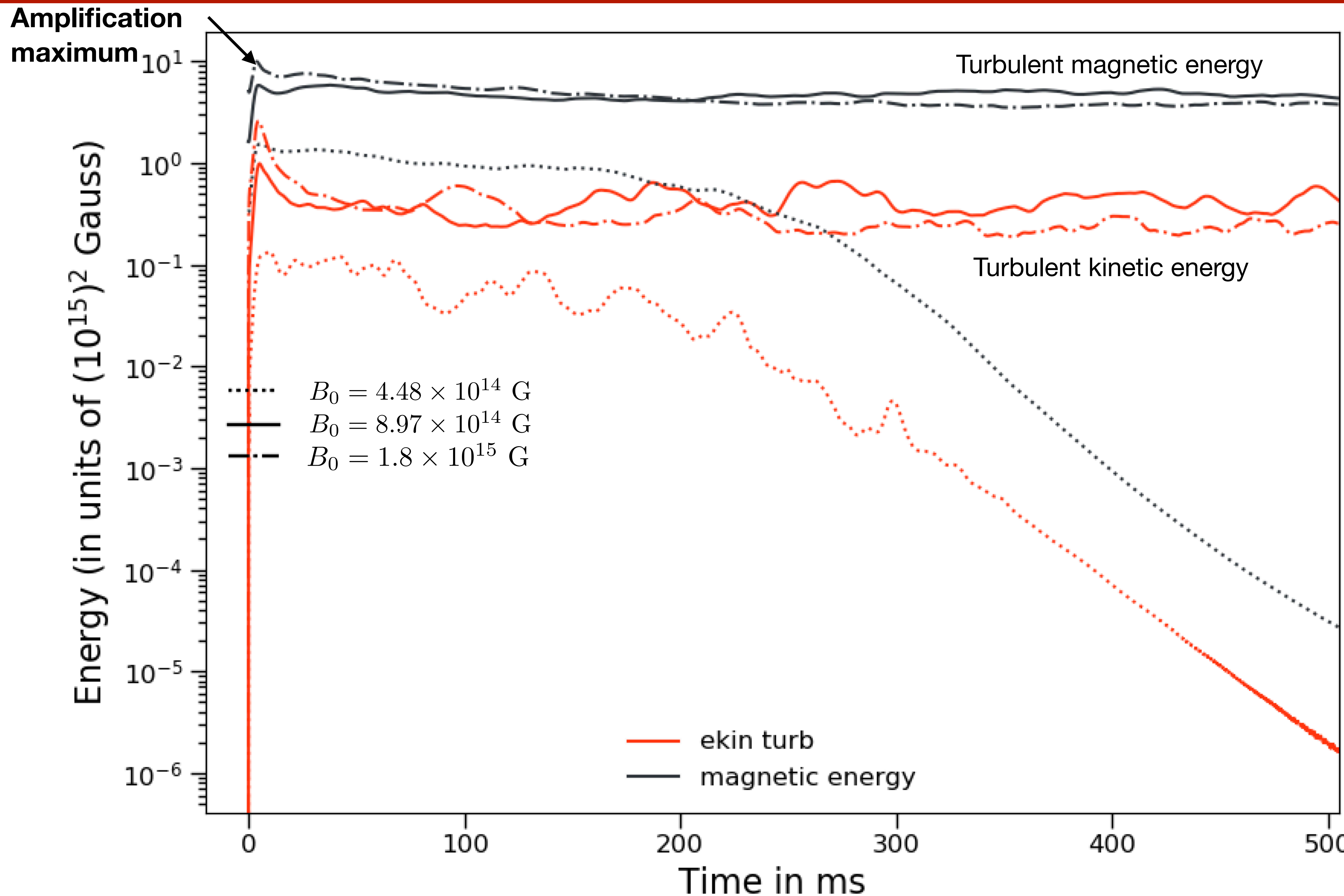


Dipolar tilt angle

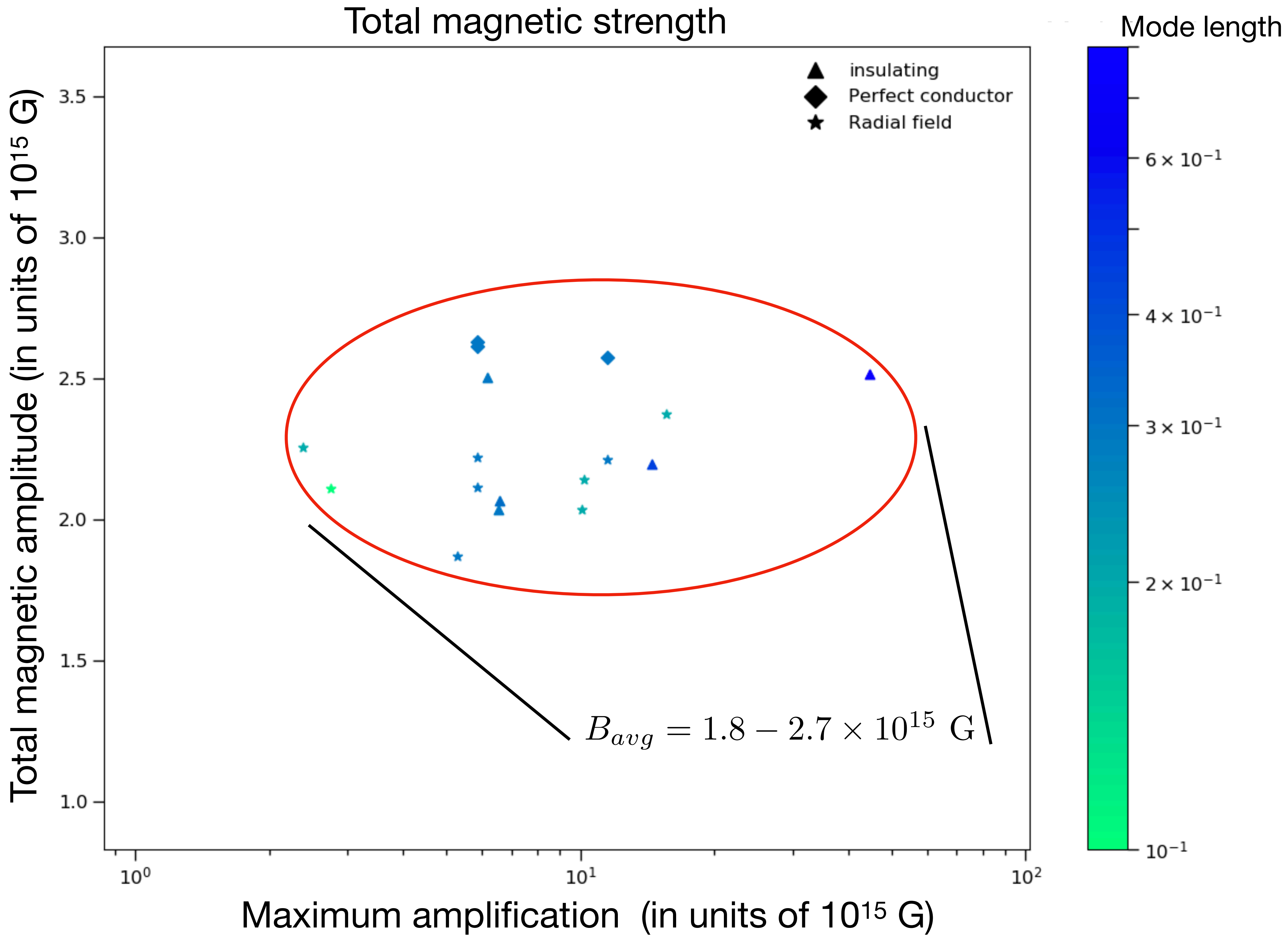


III- Parameter study

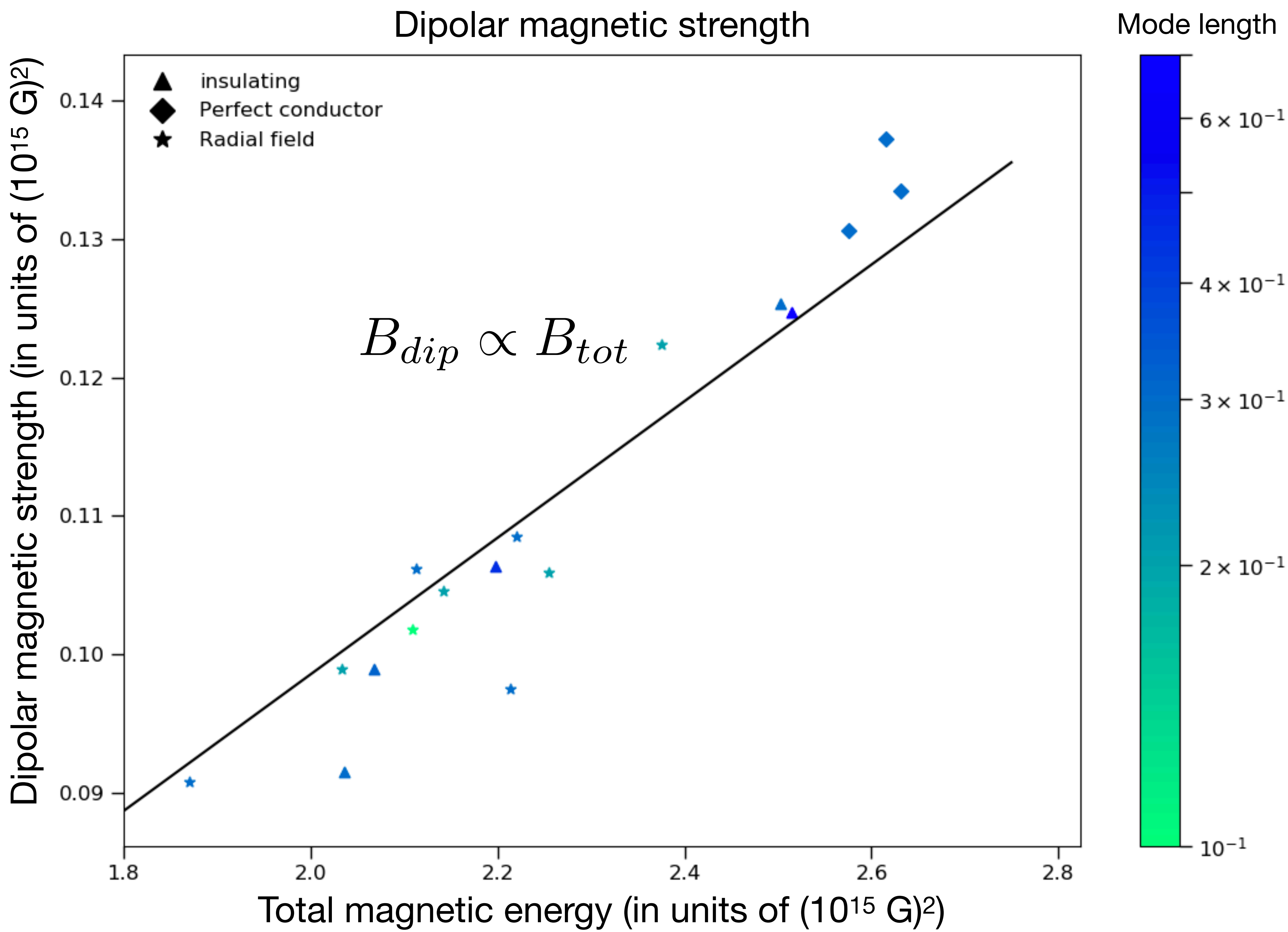
Initial magnetic field amplitude threshold



Small impact of initial conditions and boundary conditions



Dipole strength depends on total magnetic field



Summary and perspectives

- Summary :

  Turbulent magnetic field with subdominant but **magnetar-like** dipole

  A **non-aligned** dipole is robustly generated by the small scales

  ⟶ Reboul-Salze et al (in prep)

- Perspectives :

  Add the buoyancy force (stable stratification)

  Implement a realistic EoS and a background state

  Interaction with a convective dynamo

  Sub-grid modelling of the MRI for Magneto-rotational explosions

THANK YOU