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

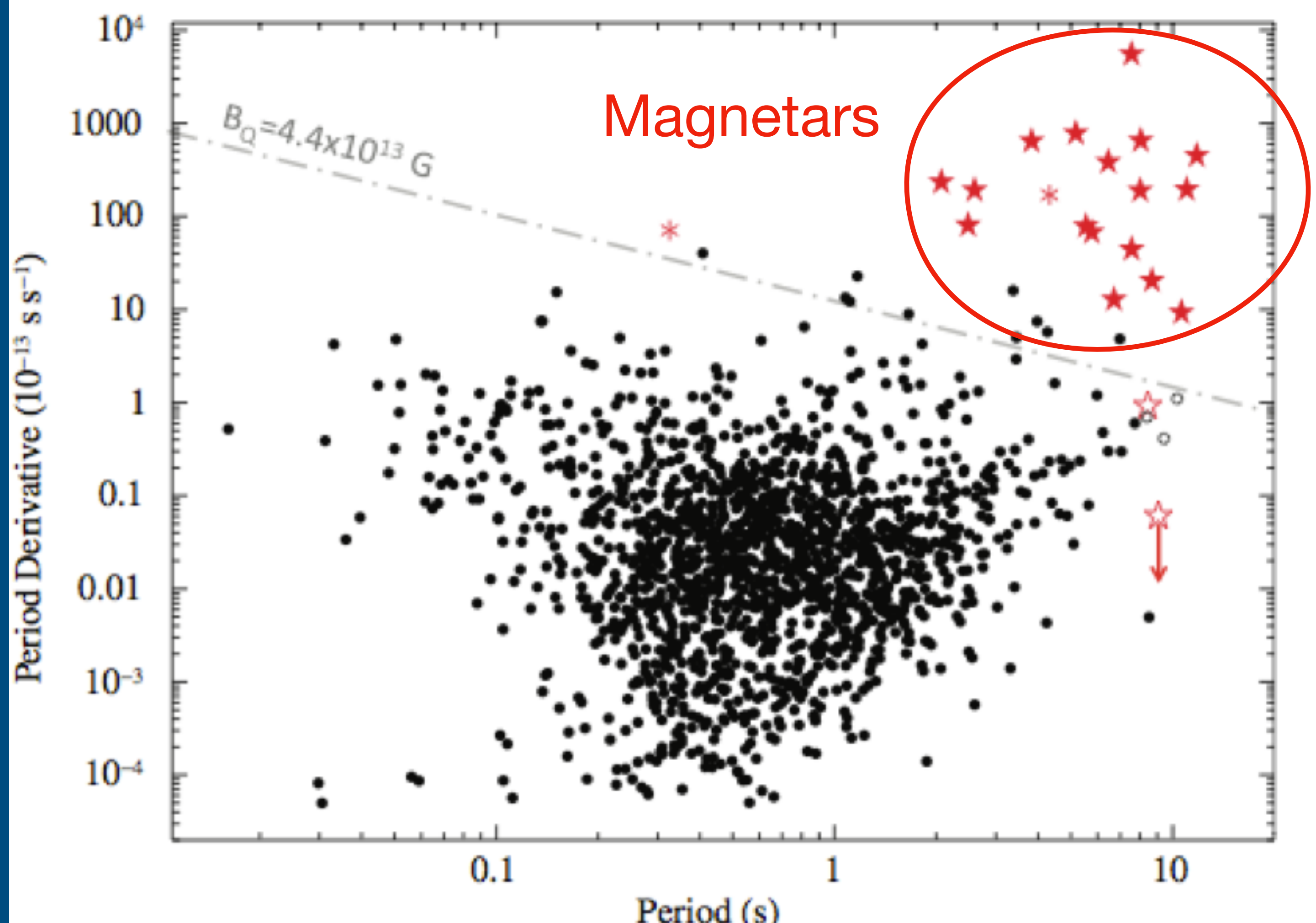
Alexis Reboul-Salze [1]

J. Guilet [1], R. Raynaud [1], M. Bugli [1]

1 : AIM, CEA Paris-Saclay

Motivation : Magnetars

$P - \dot{P}$ diagram   See Marta Burgay's talk and Diego Gotz's talk



Crédit : Rea et al. 2012

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

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

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

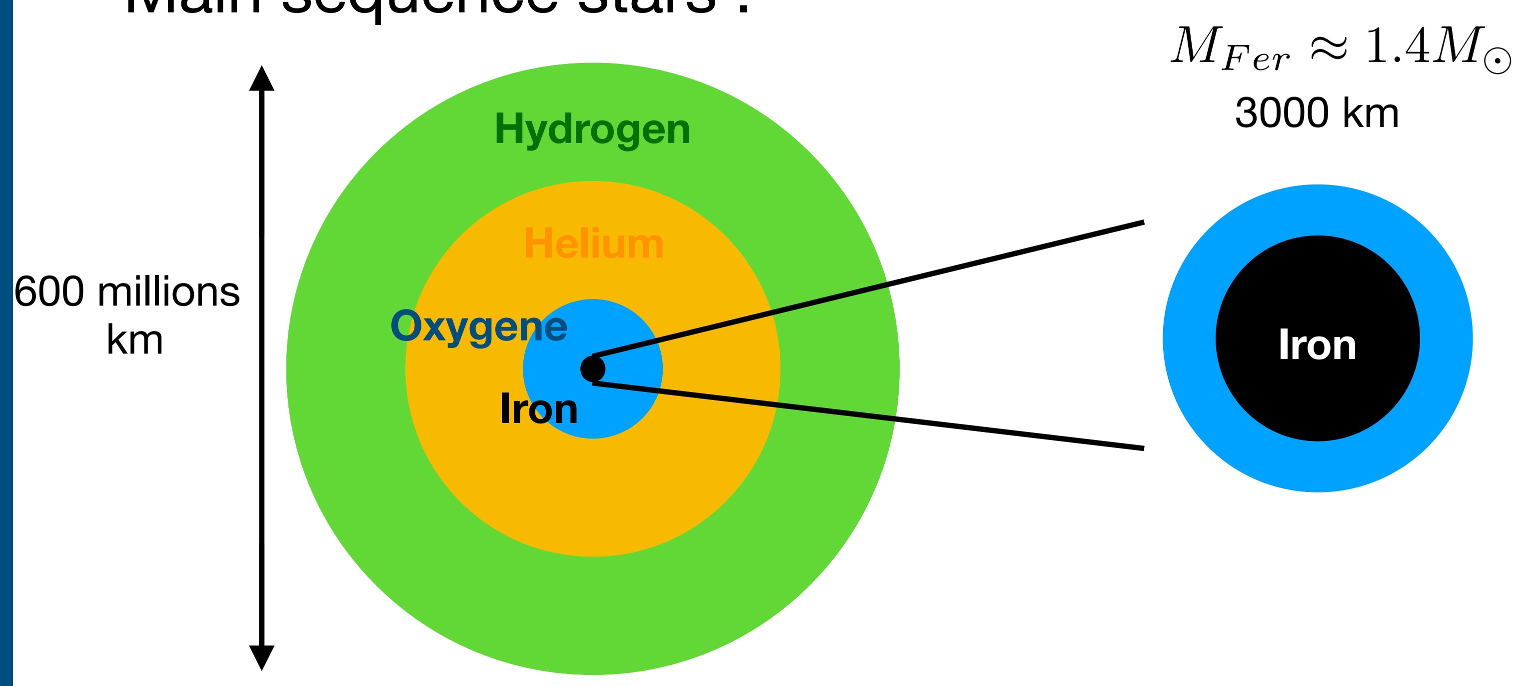
- Dipolar magnetic field strength of magnetars :

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

Neutron star formation

Core-Collapse Supernova See Jacco Vink's talk

Main sequence stars :

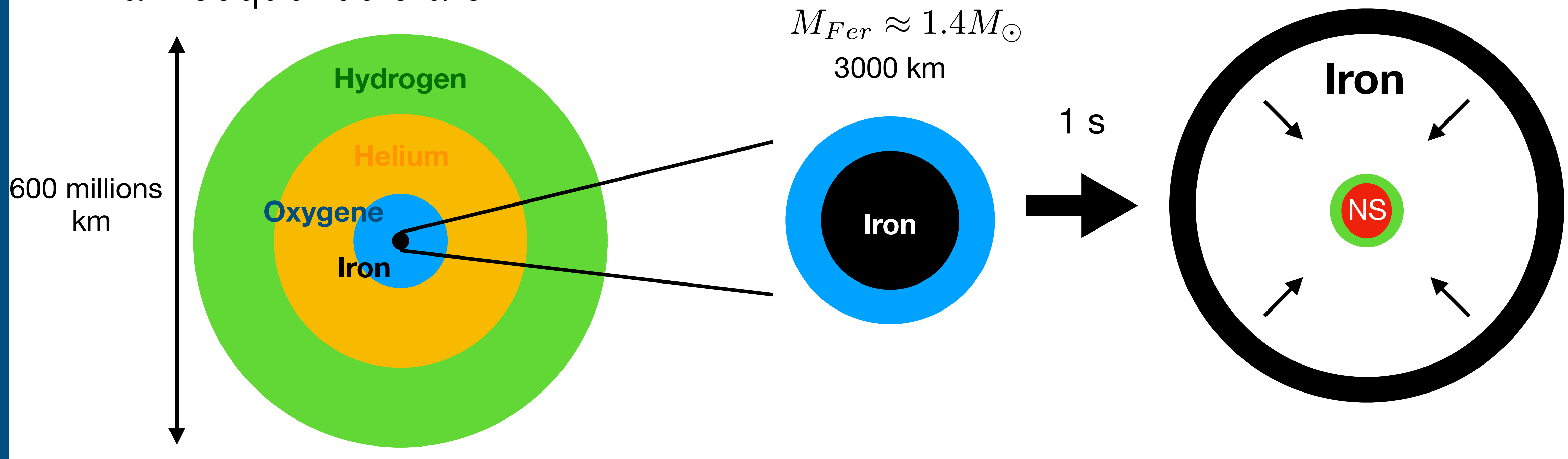


Neutron star formation

Core-Collapse Supernova See Jacco Vink's talk

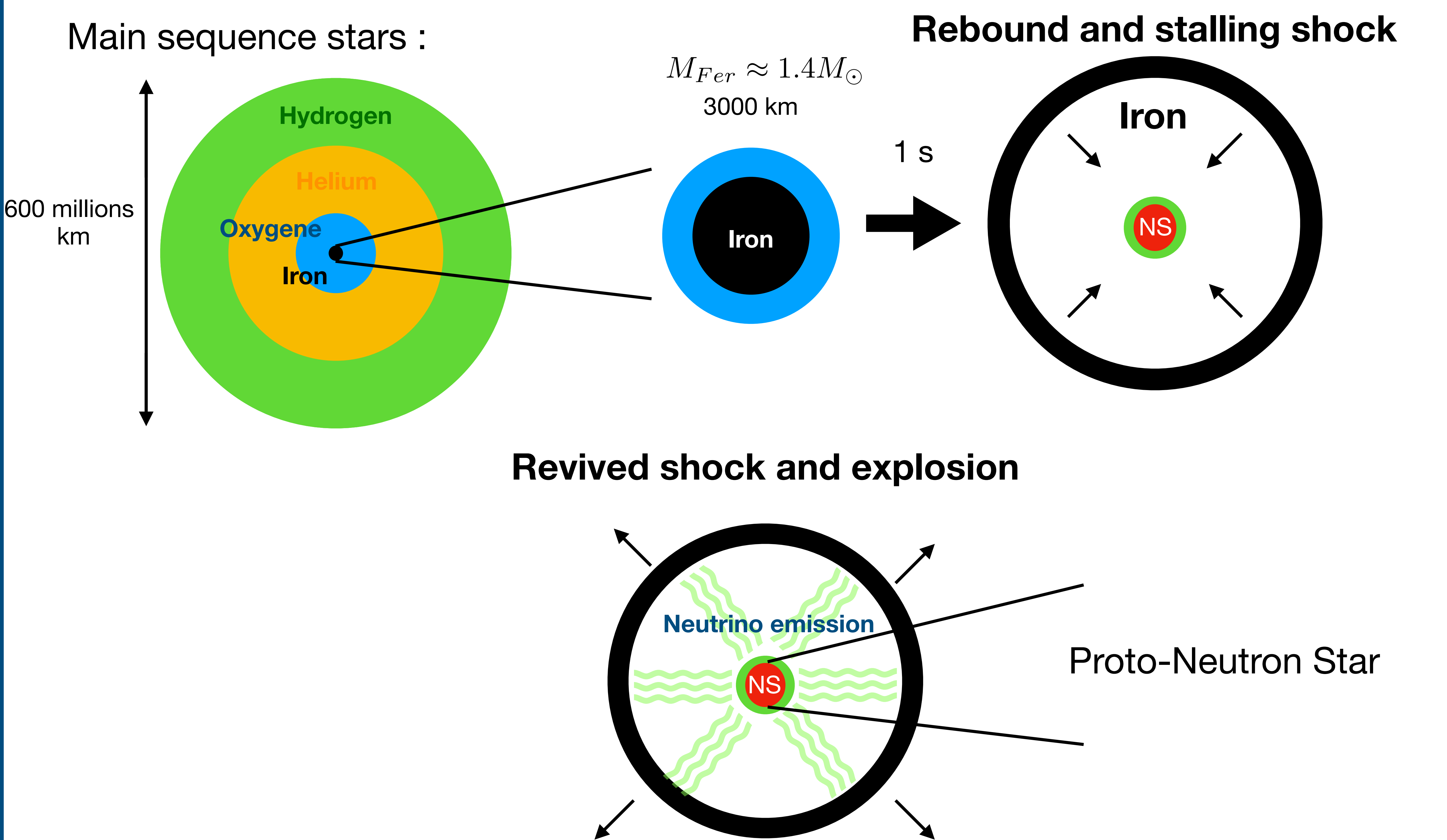
Main sequence stars :

Rebound and stalling shock



Neutron star formation

Core-Collapse Supernova See Jacco Vink's talk



Supernova observations

Outstanding explosions : millisecond magnetars ?

Kinetic energy of the explosion
→ Classic Supernova 10^{51} ergs
→ Hypernova (rare) (<1 %) 10^{52} ergs

Luminosity of the supernova :
→ Classic Supernova 10^{49} ergs
→ Super-Luminous Supernova (<0.1%) 10^{51} ergs

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

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

Luminosity of the supernova :

→ Classic Supernova 10^{49} ergs

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

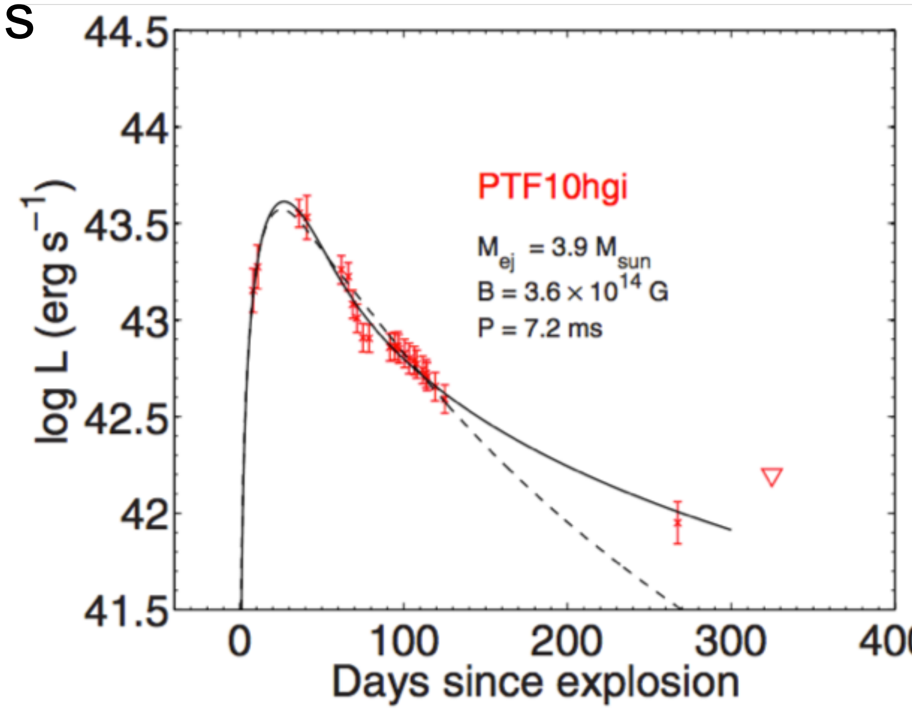
Supernova observations

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

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

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

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

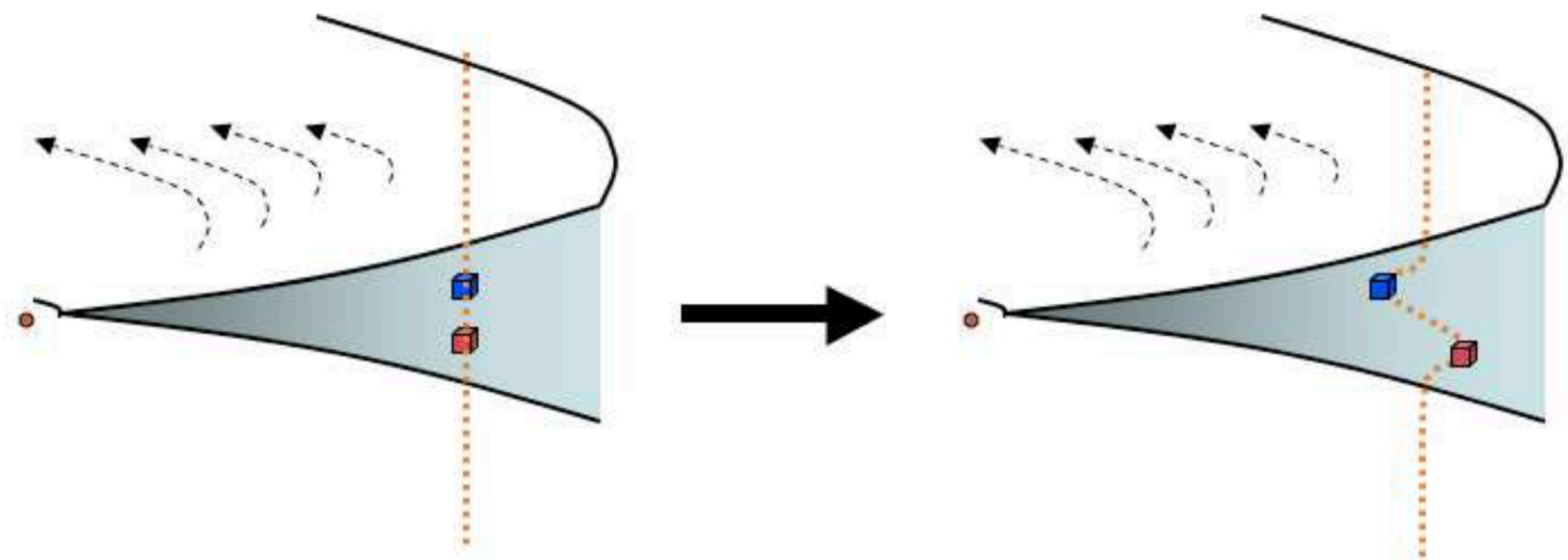
I- Presentation of the local models of the MRI

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

-> 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

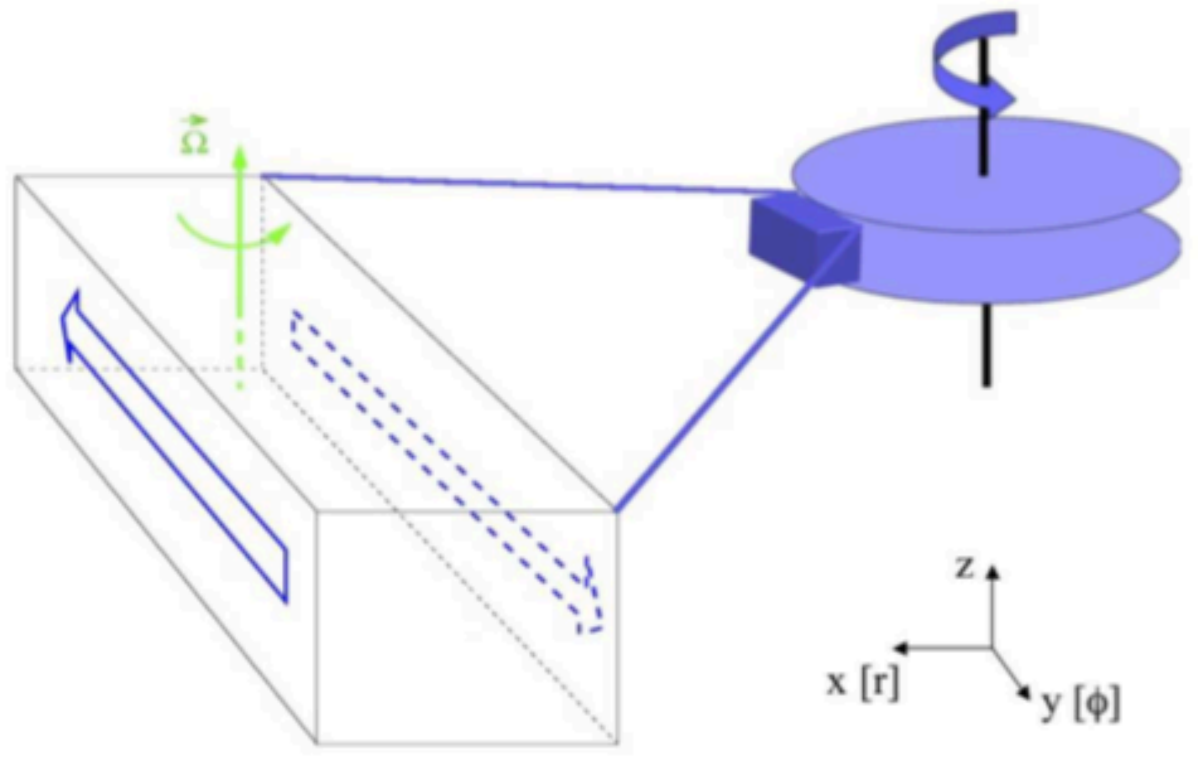
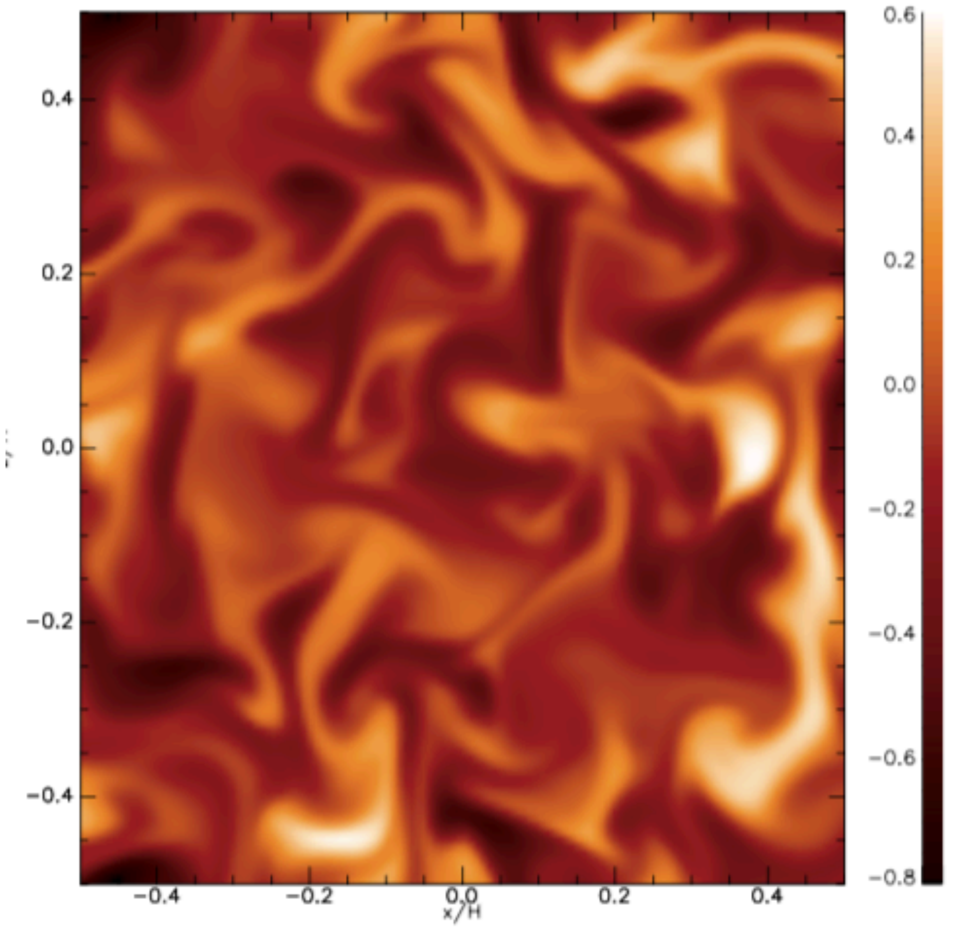


Figure courtesy : G. Lesur

Turbulence MHD : toroidal field



Fromang et al. 2007

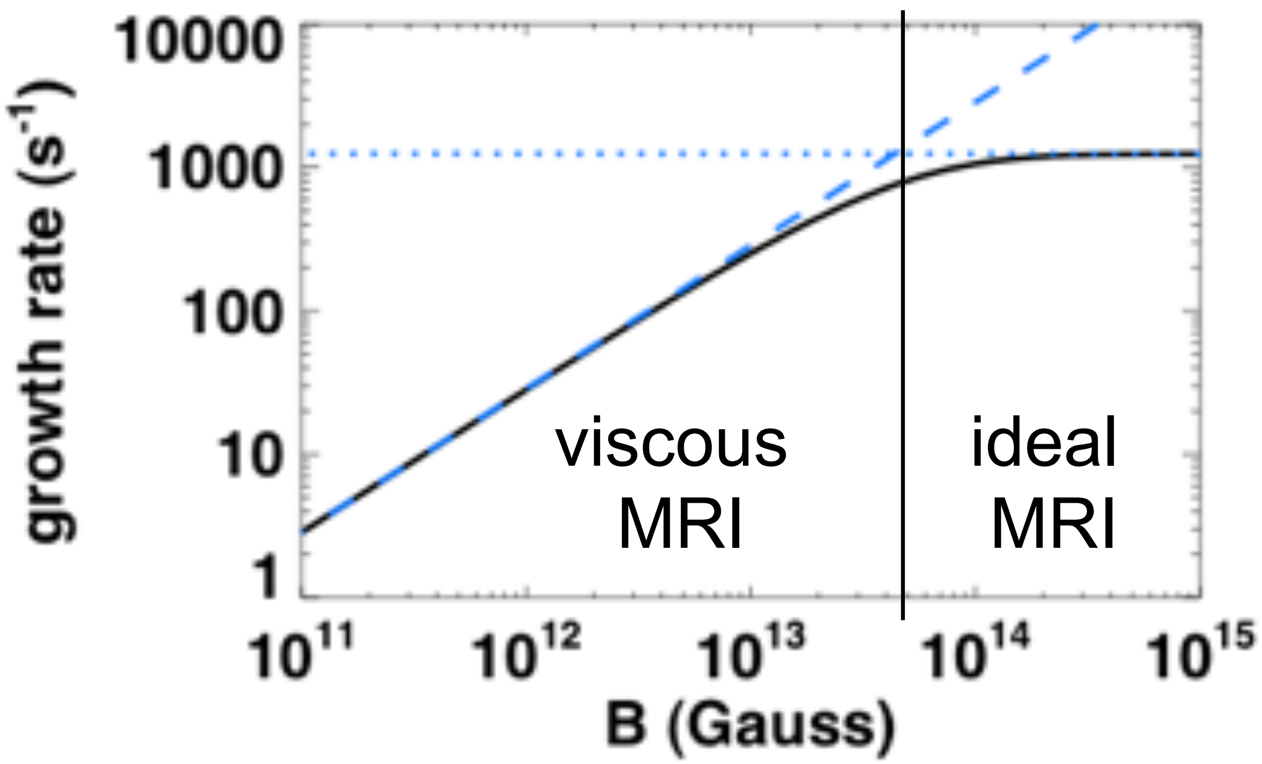
Impact of conditions specific to neutron stars ?

- → neutrinos → Guilet et al. 2015
- → buoyancy (entropy & composition gradients) → Guilet & Müller 2015
- → spherical geometry

Magnetic field amplification in local models

Neutrino Impact

Two regimes : Focus on the viscous regime

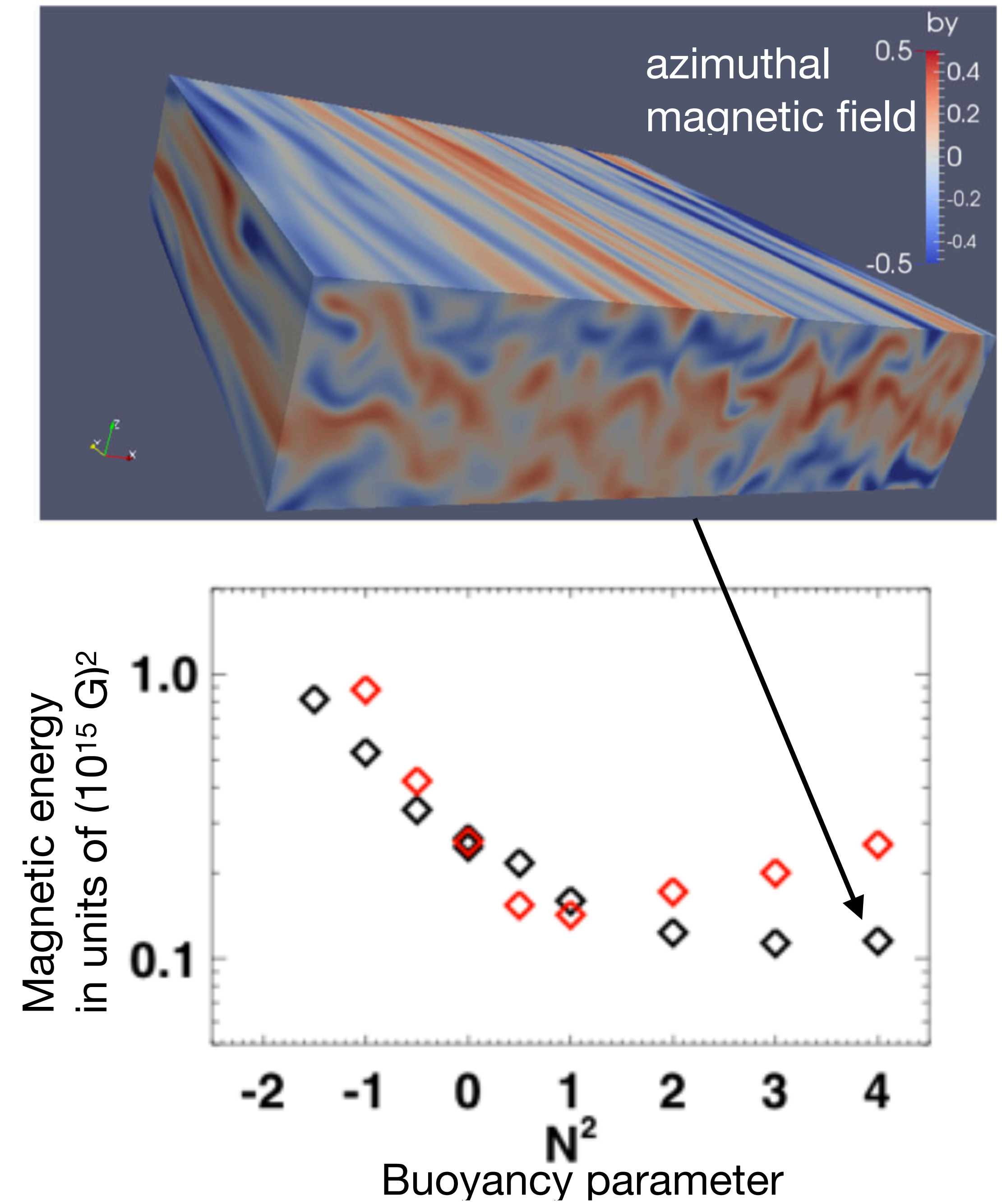


Guilet et al. (2015), Guilet et al. (2017)

Slow growth for weak initial magnetic field

Buoyancy impact

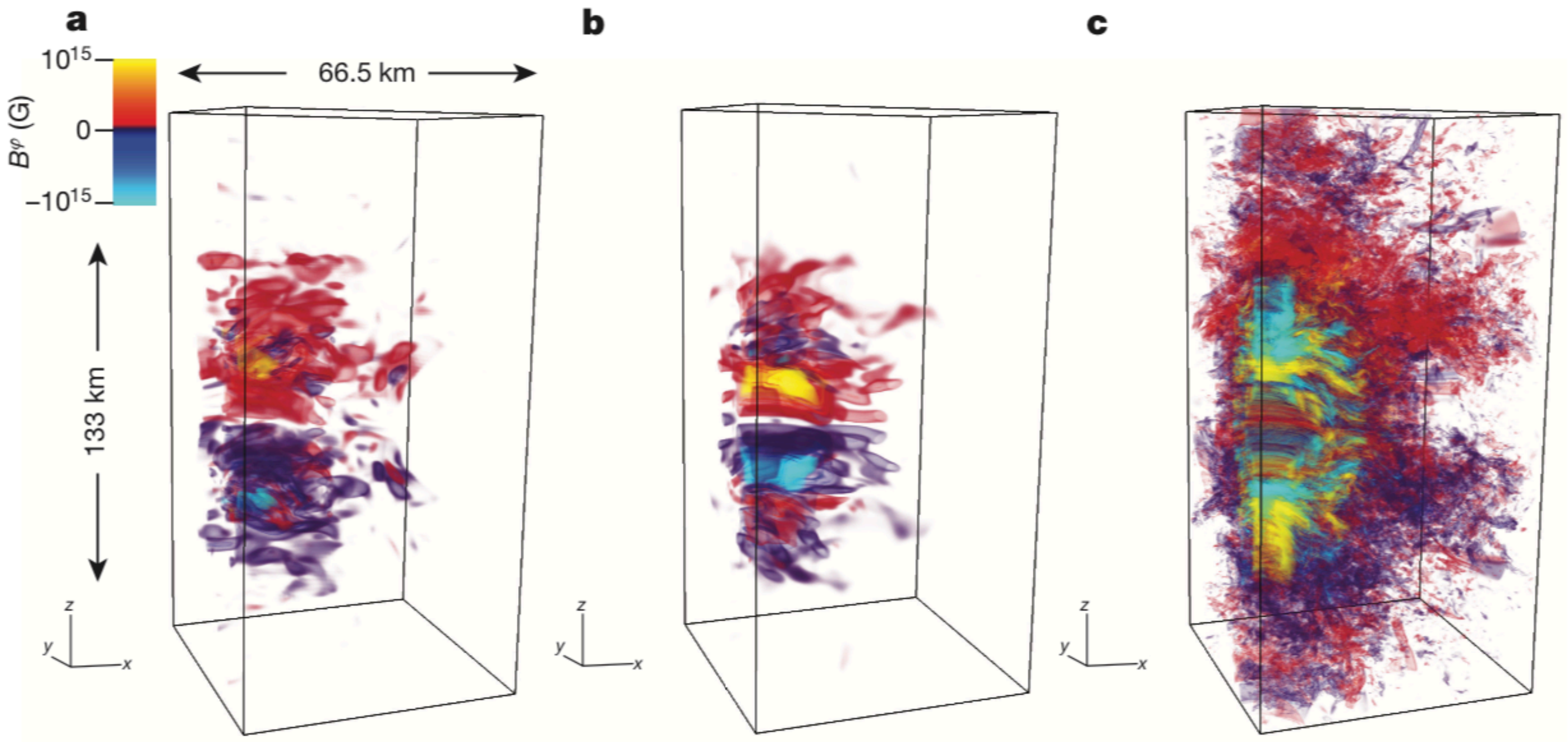
Stable stratification



Crédit : Guilet and Müller. 2016

First attempt at a global model

Mösta et al 2015



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

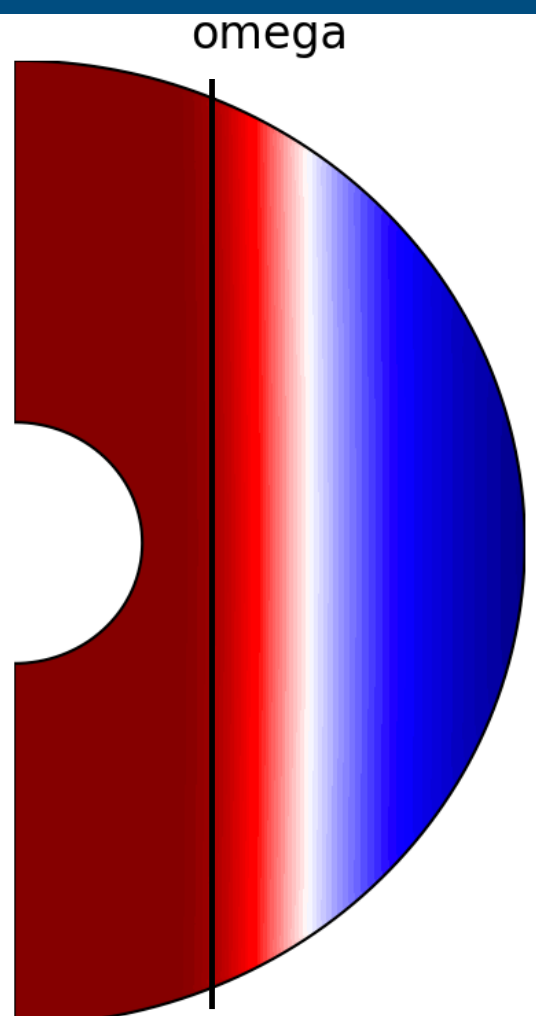
II- A global model of the MRI in a PNS

Our setup

- Simplest model : Incompressible → $N_r = 256$, $N_{theta} = 512$, $N_{phi} = 1024$
- Initial velocity is fixed at the outer boundary
- Typical parameters values : $B_0 = 9\mathrm{x}10^{14}$, 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

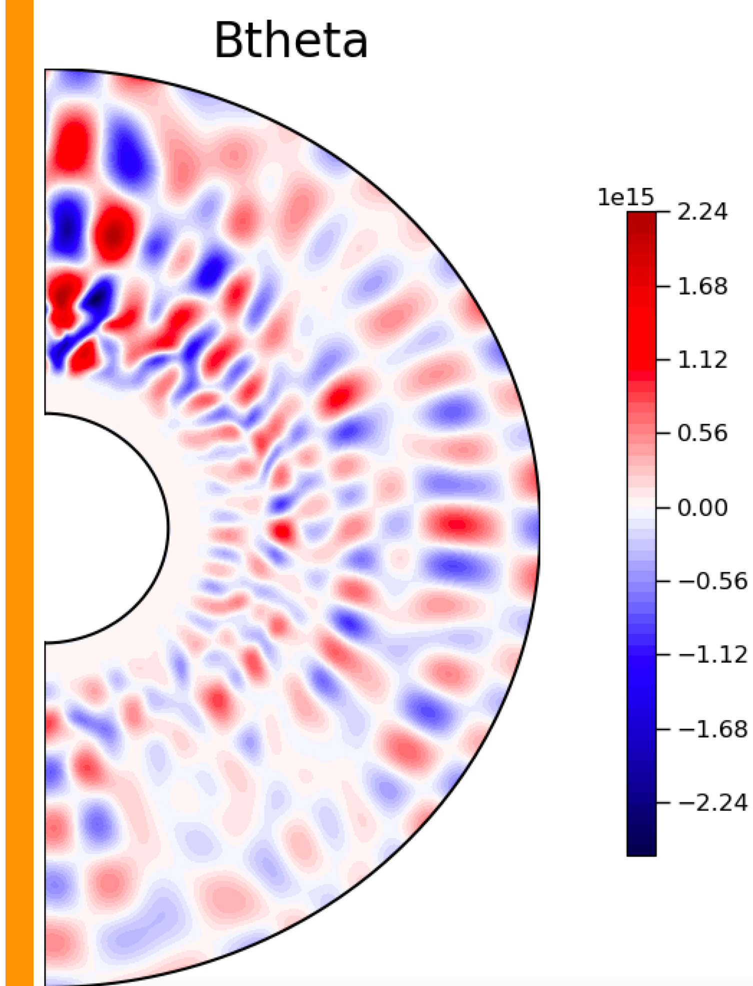


Core in solid body rotation

Then :

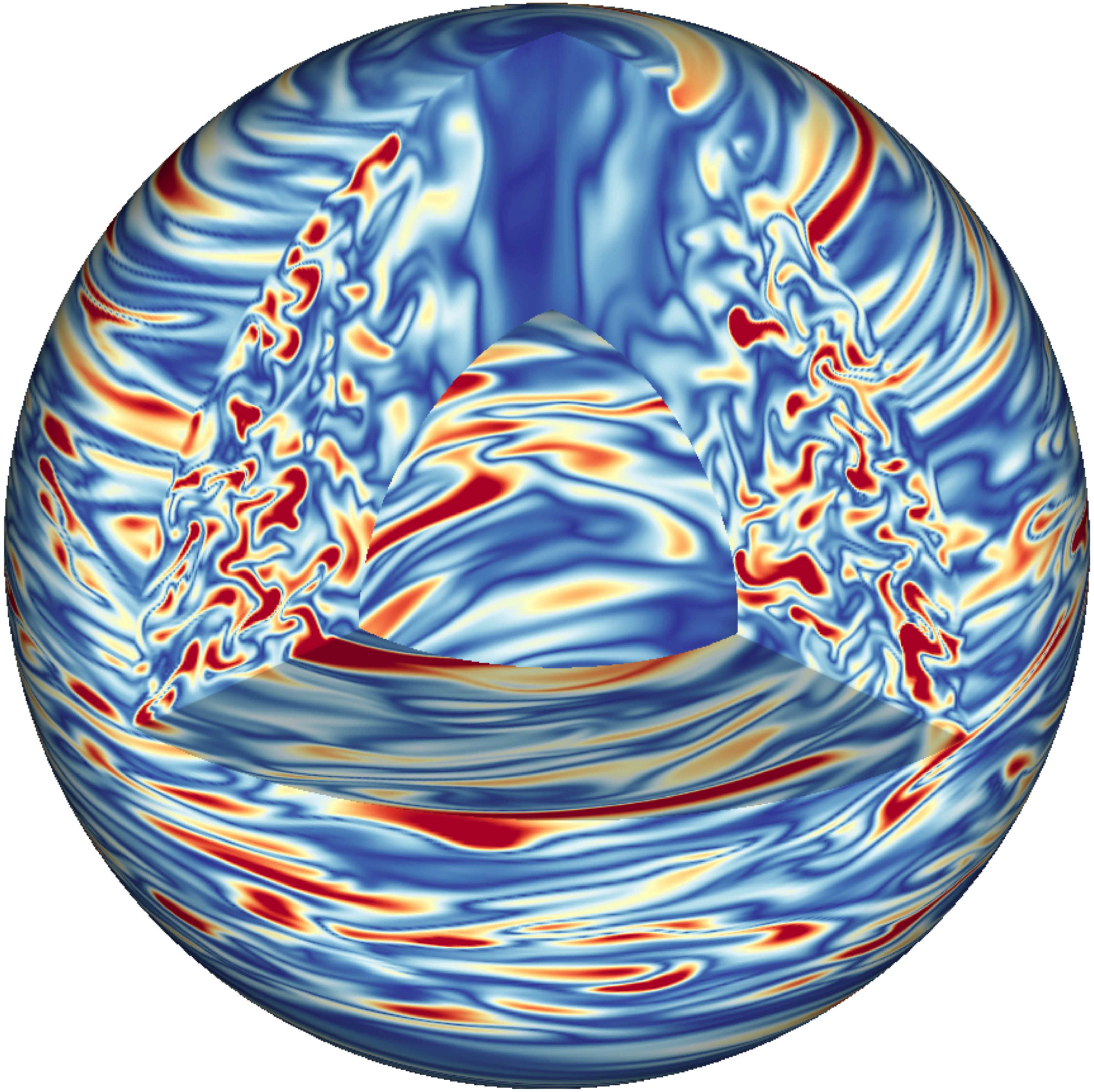
$$\propto\ r^{-q}$$

Magnetic field profile



Small scales
~ Local models

Amplitude of the magnetic field

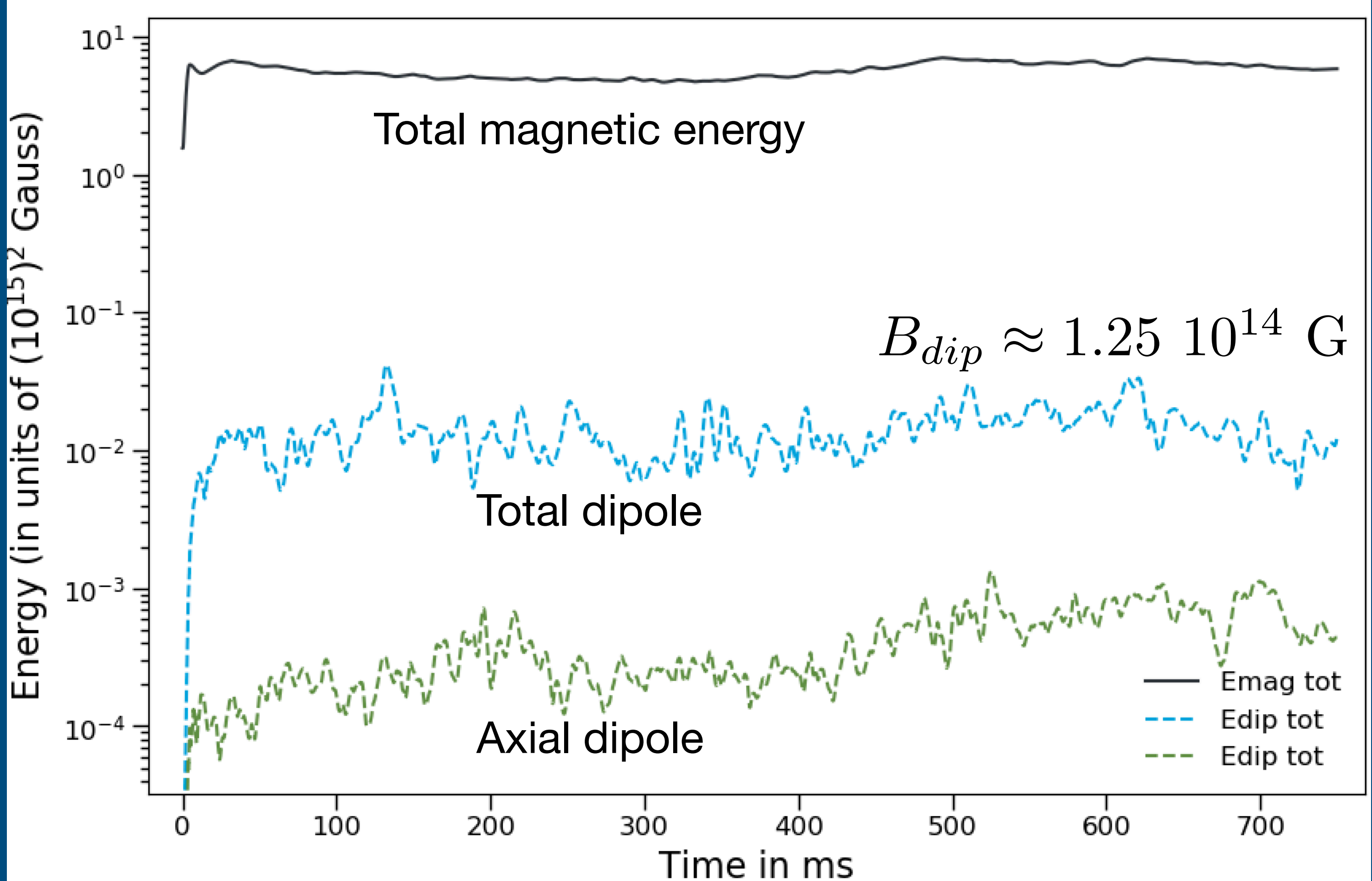


Results on the magnetic and dipole energies

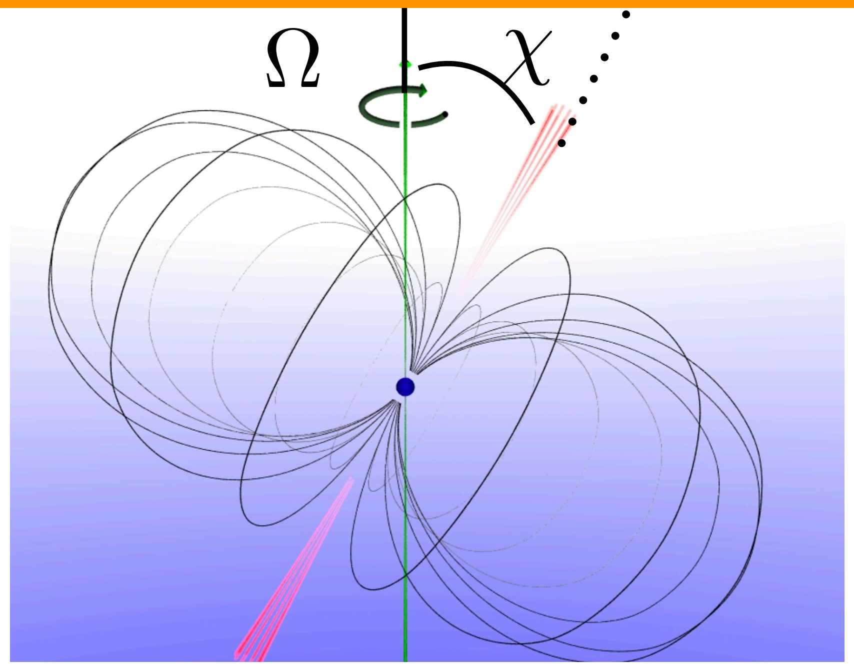
Time Evolution of dipolar energy

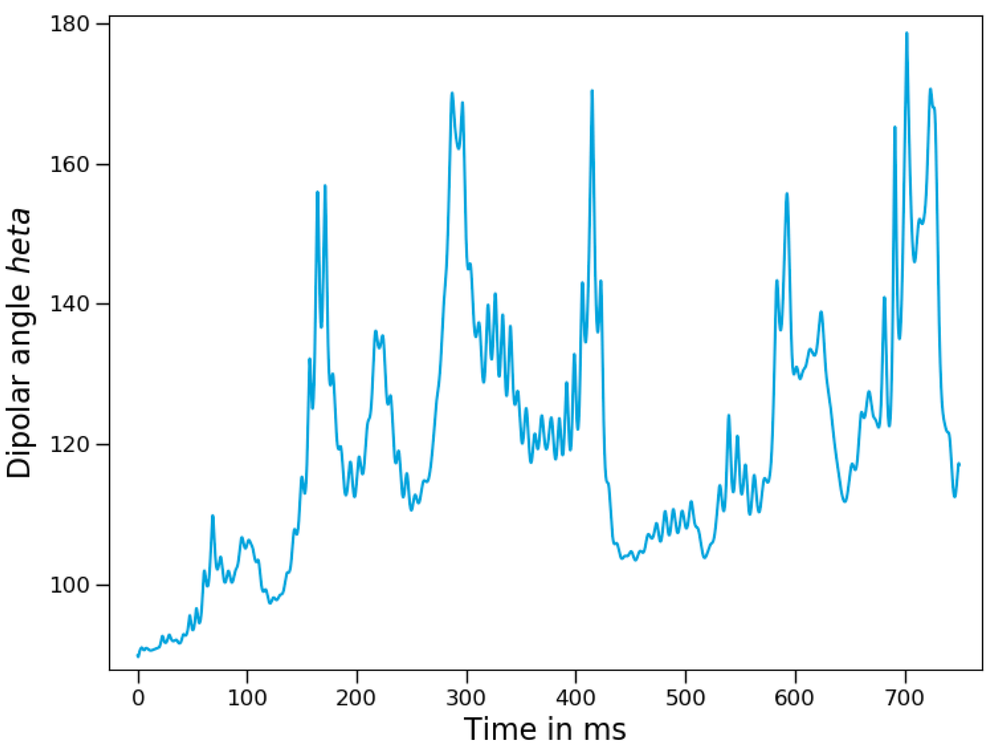
$$B_{tot} \approx 2.5\ 10^{15}\ \mathrm{G}$$

$$B_{dip} \approx 1.25\ 10^{14}\ \mathrm{G}$$



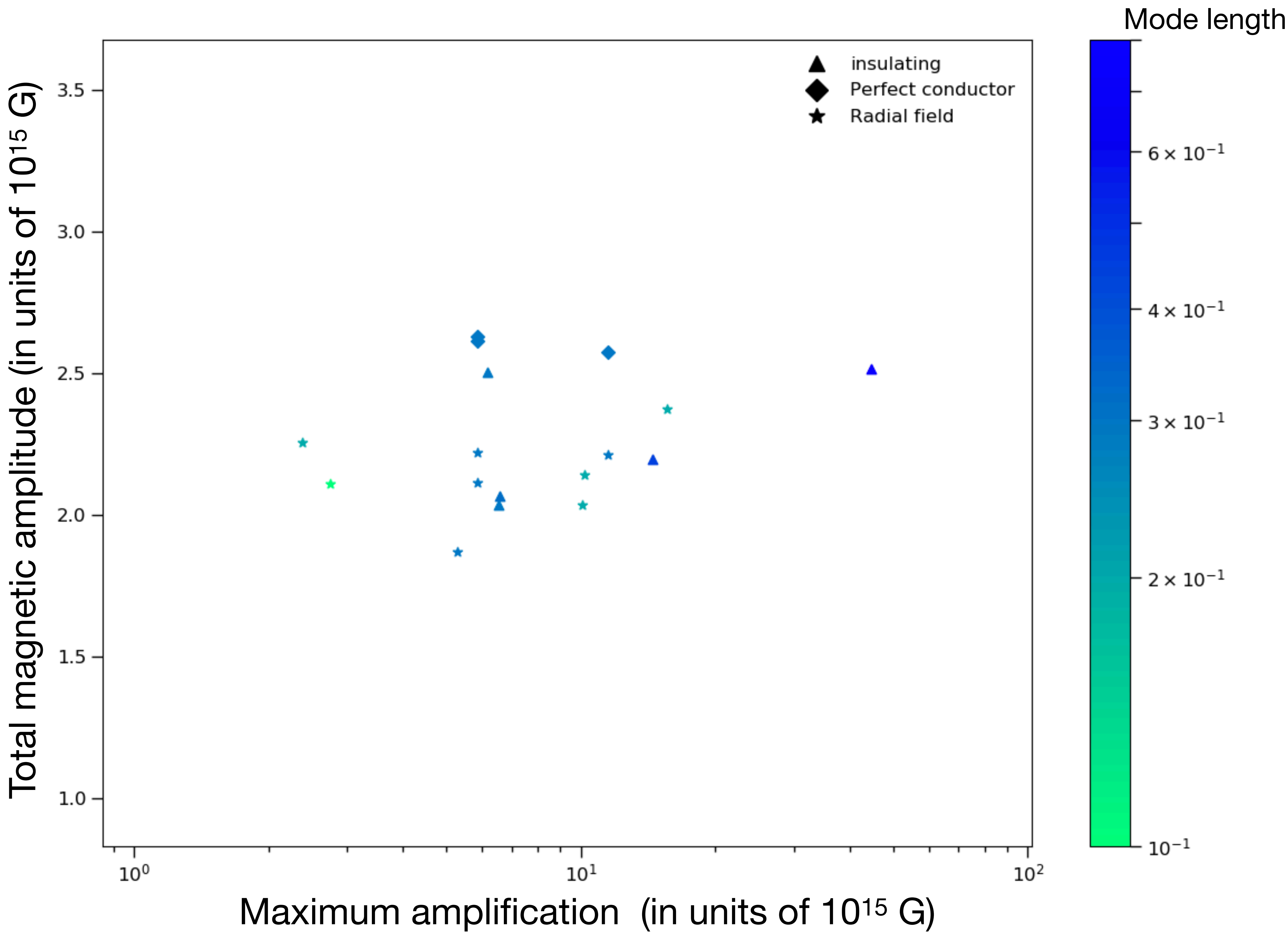
Dipolar tilt angle



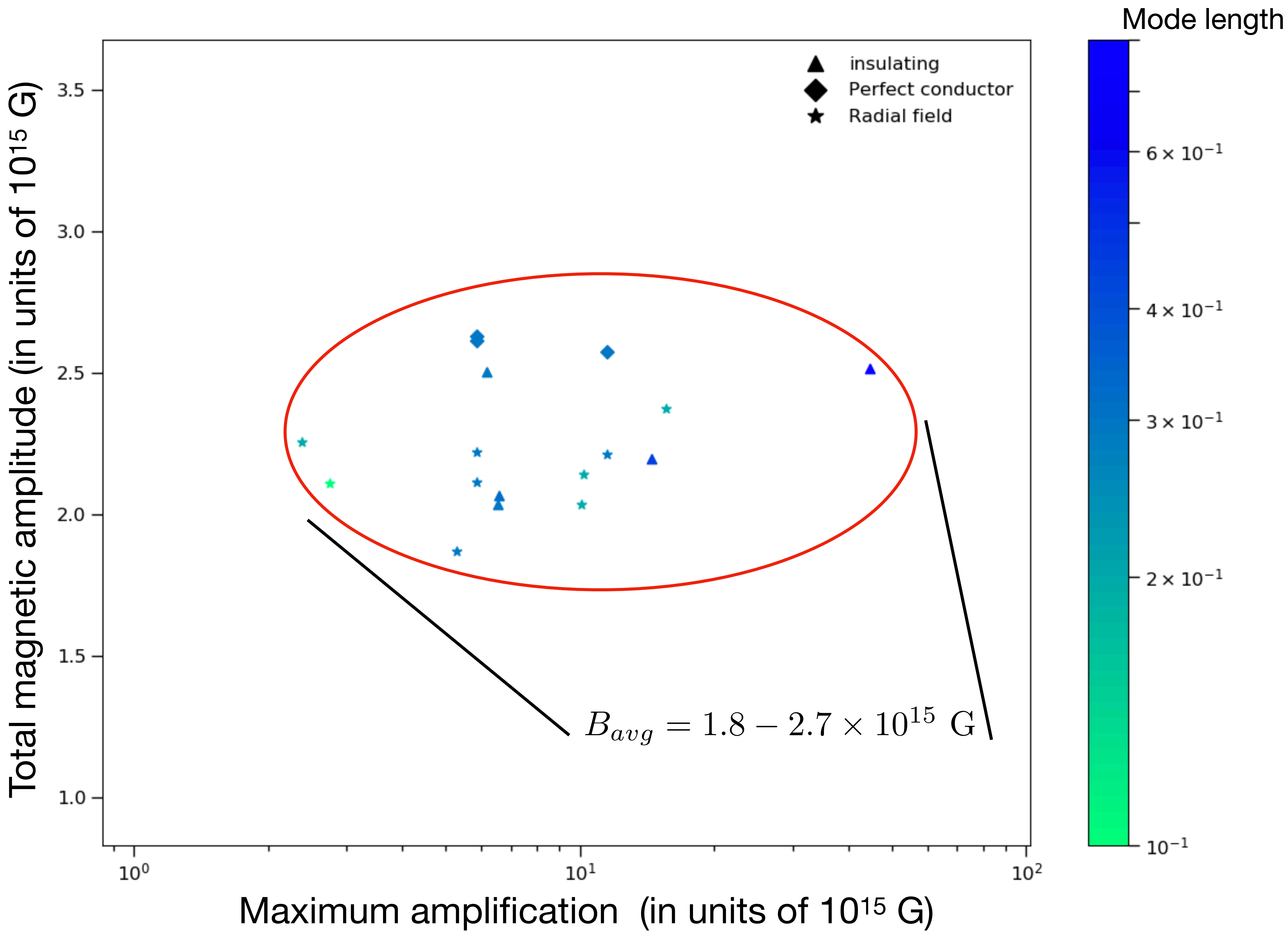


III-Preliminary parameter study

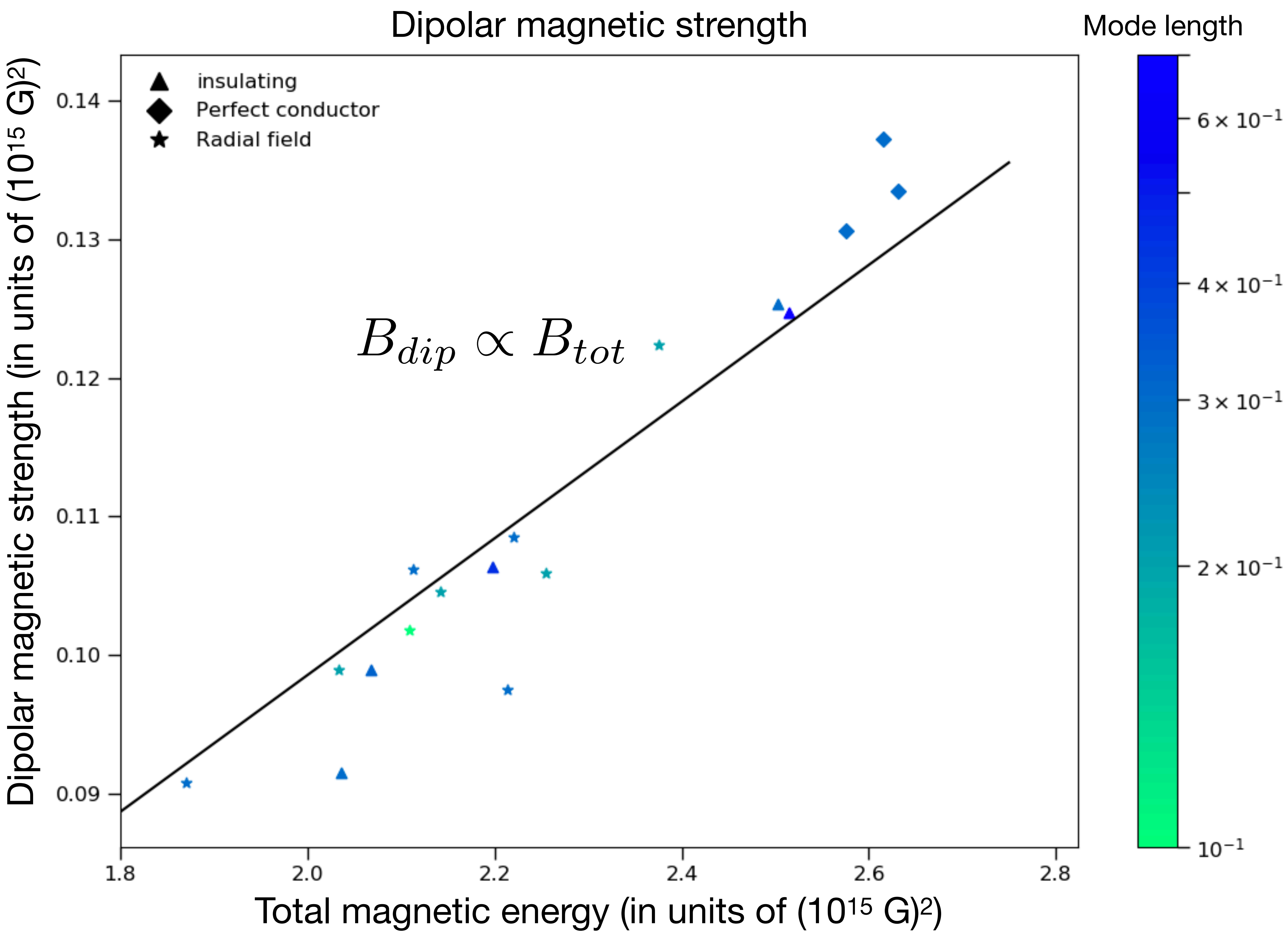
Small impact of initial conditions and boundary conditions



Small impact of initial conditions and boundary conditions



Dipole strength depends on total magnetic field



Summary and perspectives

- Summary :

  Magnetar-like magnetic field strength

  A dipole is robustly generated by the small scales

- Perspectives :

  Influence of diffusion processes
  —> Towards more realistic values in models

  Add the buoyancy force (stable stratification)

  Implement a realistic EoS

  Interaction with a convective dynamo ?

  Sub-grid modelling of the MRI for Magneto-rotational Explosions ?

THANK YOU

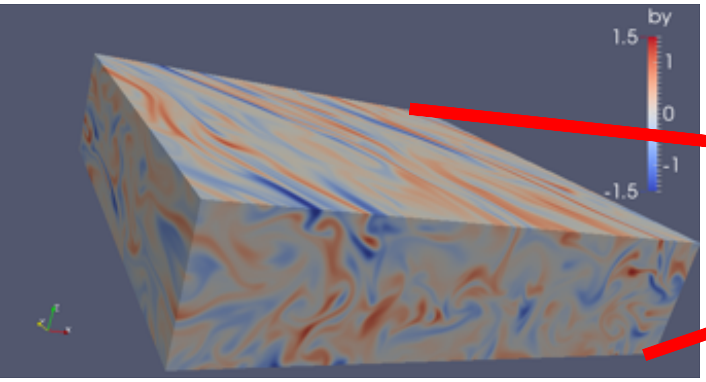
ERC Magburst

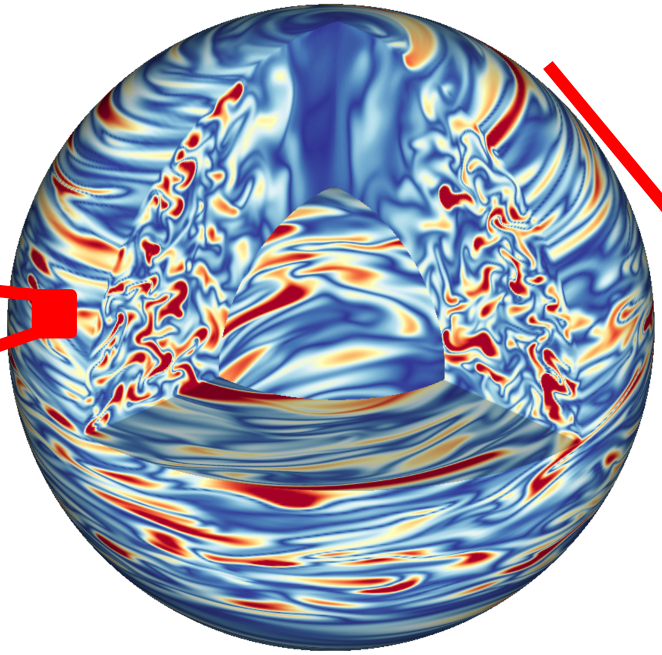
See Matteo Bugli's talk

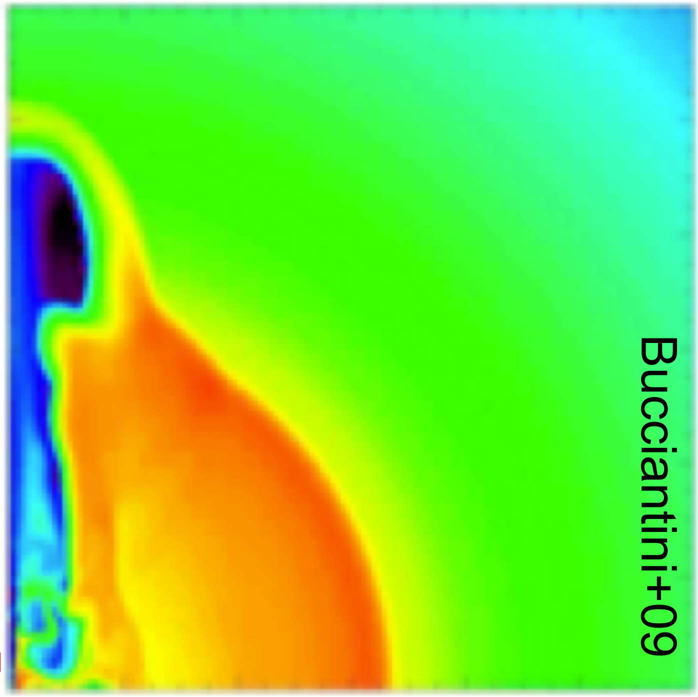
Step 1 : Local model of the MRI

Step 2 : Global model

Etape 3 : Hypernova







~ 1-5 km

~ 10-50 km

~ 10^5-10^6 km

Jérôme Guilet

Alexis Reboul-Salze & Raphaël Raynaud (Convective dynamo)

Matteo Bugli

THANK YOU