How to form a millisecond magnetar ?

Magnetic field amplification in protoneutron stars

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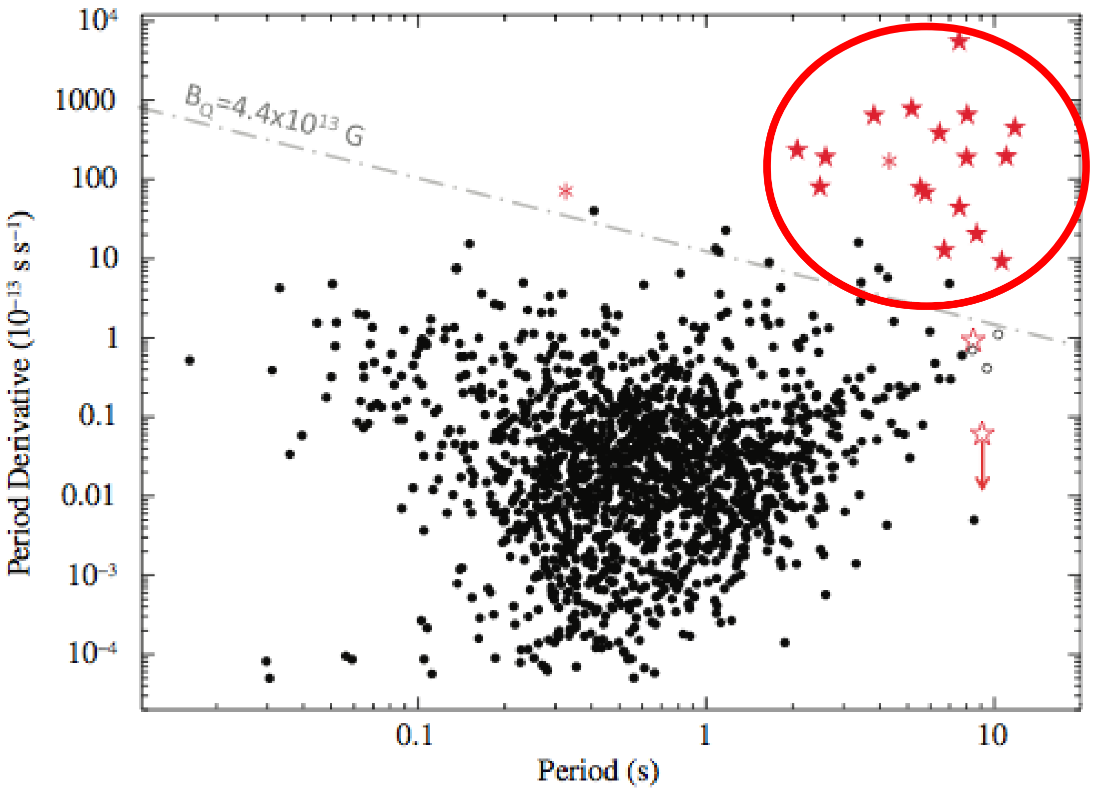
Galactic magnetars



Magnetars:

Anomalous X-ray pulsars (AXP)

Soft gamma repeater (SGR)

Strong dipole magnetic field:

B ~ 10^{14}-10^{15} G

Outstanding explosions: millisecond magnetars ?

Explosion kinetic energy :

→ Typical supernova 10^{51} ergs → Neutrino driven explosions ?

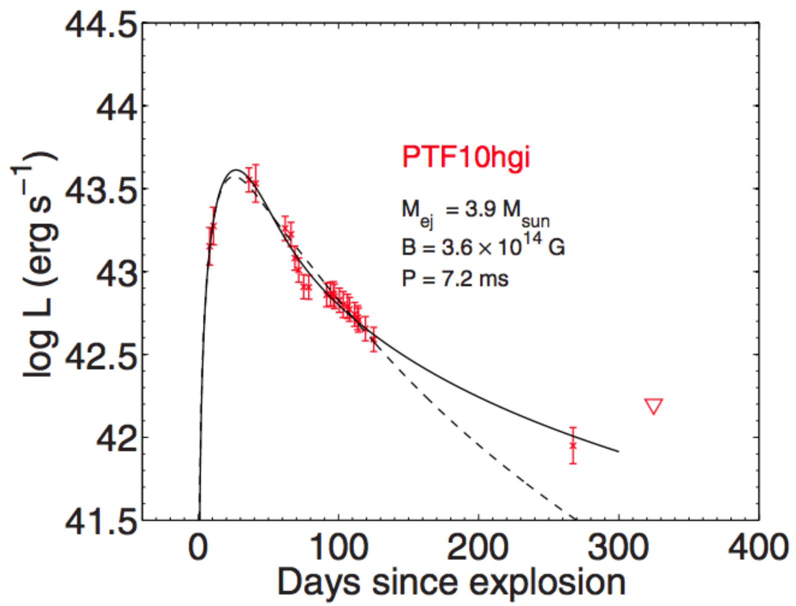
→ Rare hypernova (& GRB) 10^{52} ergs → Millisecond magnetar ?

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

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. Woosley+10, Dessart+12,
Nicholl+13, Inserra+13

Missing theoretical piece: magnetic field origin

Huge range of magnetic field strength :

→ Initially « weak » magnetic field : $\lesssim 10^9\,\mathrm{G}$ (?)

→ After compression by the core-collapse: $\lesssim 10^{12} - 10^{13}\,\mathrm{G}$ (?)

→ Magnetar strength : $\sim 10^{15}\,\mathrm{G}$

Amplification mechanism ?

Magnetorotational instability (MRI) ?

Similar to accretion disks
→ application to protoneutron stars

Convective dynamo ?

Similar to solar & planetary dynamos
→ need of numerical simulations for neutron stars

The magnetorotational instability (MRI)

MRI in its simplest form (ideal MHD):

Instability criterion $$\frac{\mathrm{d}\Omega}{\mathrm{d}r} < 0$$

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

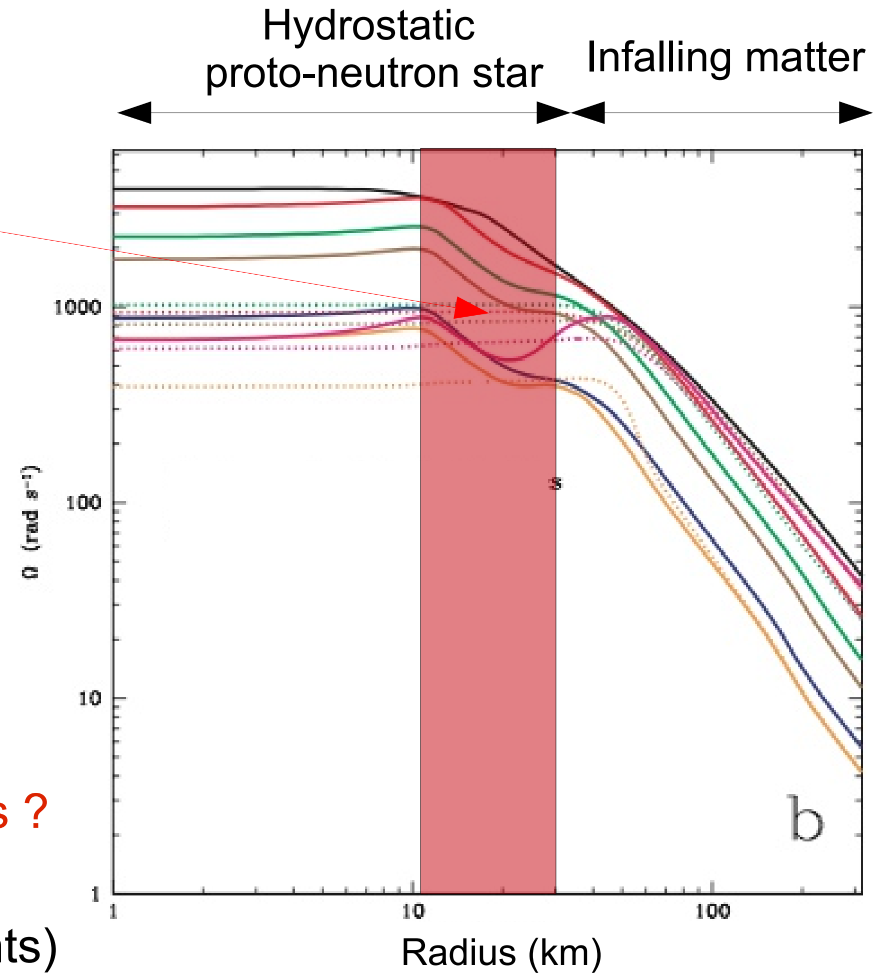
→ Fast growth for fast rotation

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

→ Short wavelength for weak magnetic field

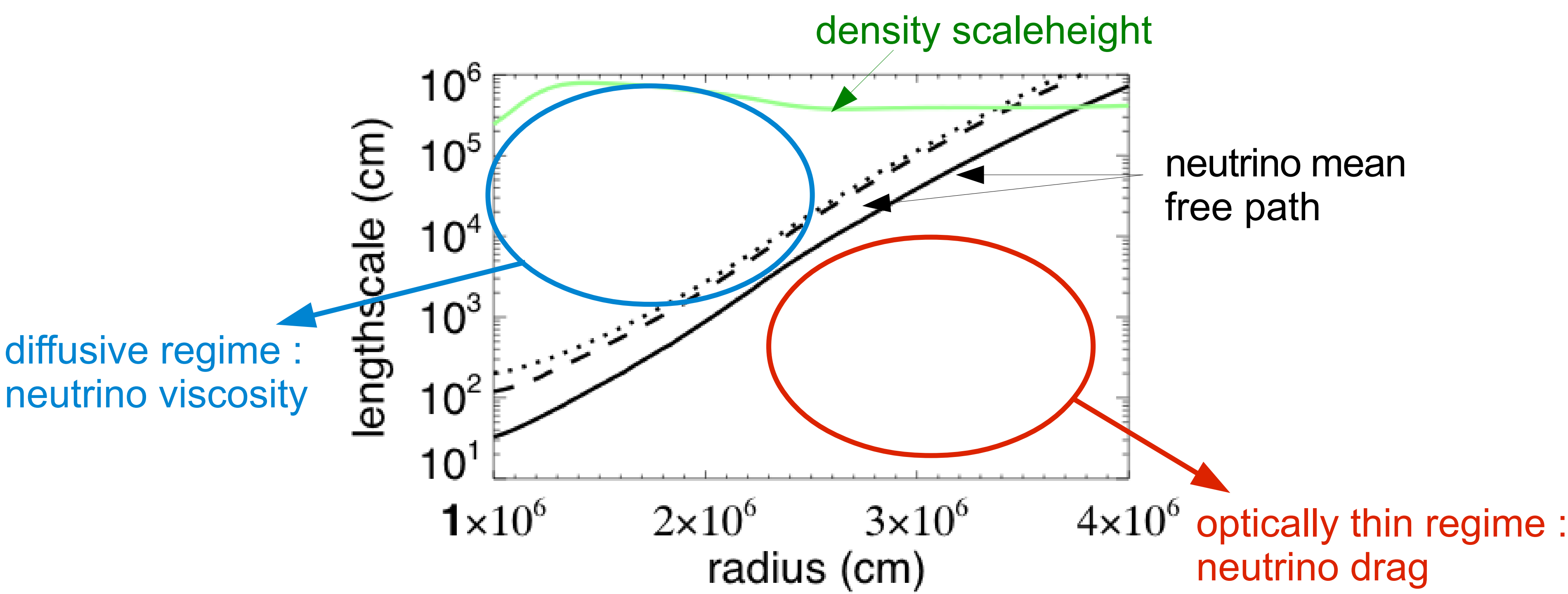
Impact of conditions specific to protoneutron stars ?

- → neutrinos
- → buoyancy (entropy & composition gradients)
- → spherical geometry



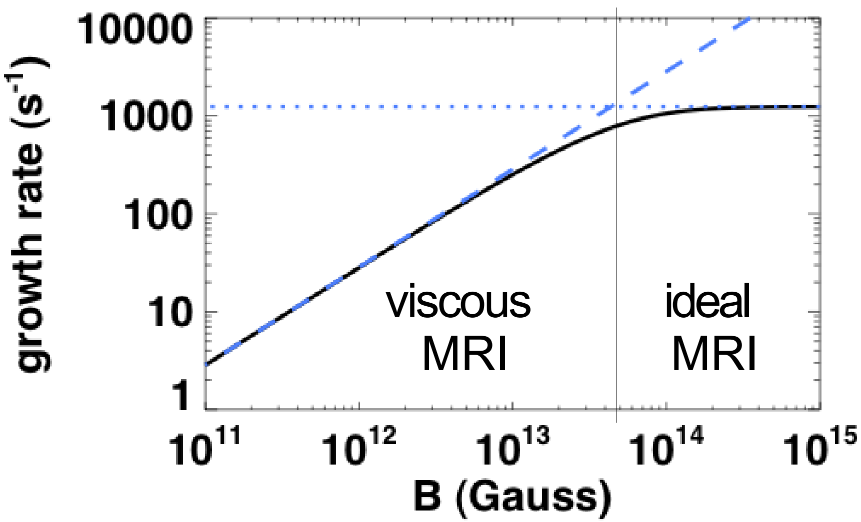
Ott et al (2006)

Impact of neutrinos on the MRI: two regimes



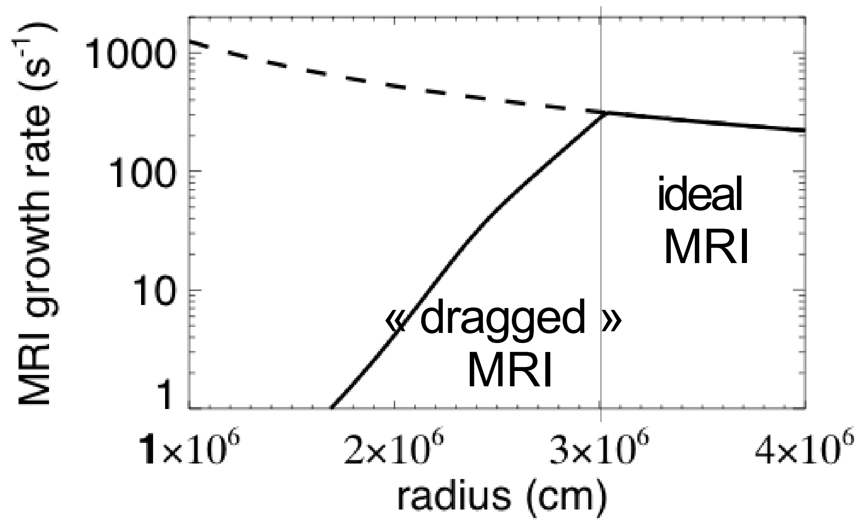
Impact of neutrinos on the MRI: growth rate

Viscous regime



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

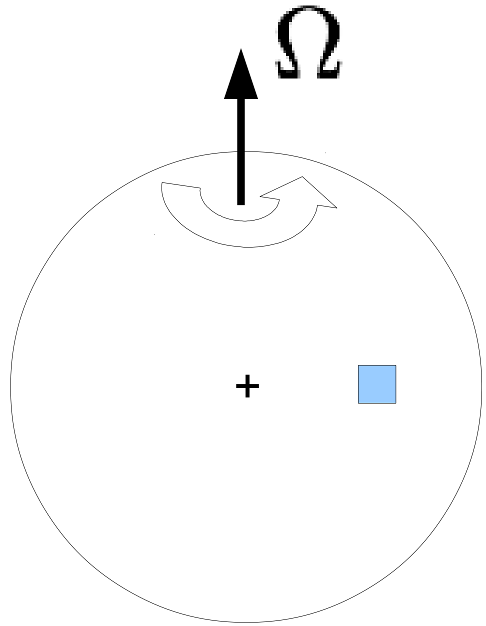
Neutrino drag regime



Fast growth near surface independently of field strength

Guilet et al (2015)

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

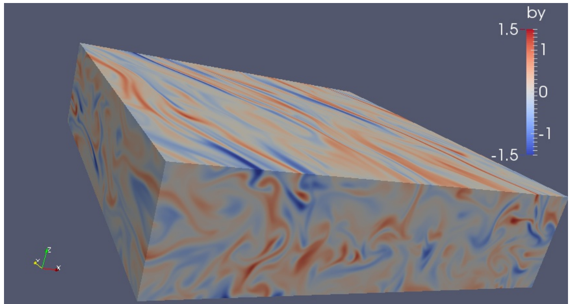
Obergaulinger+2009, Masada+2012,
Guilet+2015, Rembiasz+2015,2016

Fiducial parameters :

$$\rho = 10^{13}\,\mathrm{g.cm^{-3}}$$
$$B = 2\times10^{13}\,\mathrm{G}$$
$$\Omega = 2\times10^{3}\,\mathrm{s^{-1}}$$
$$\nu = 2\times10^{10}\,\mathrm{cm^2.s^{-1}}$$

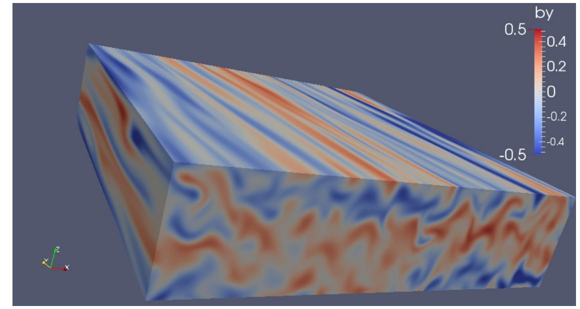
Impact of stratification on the MRI

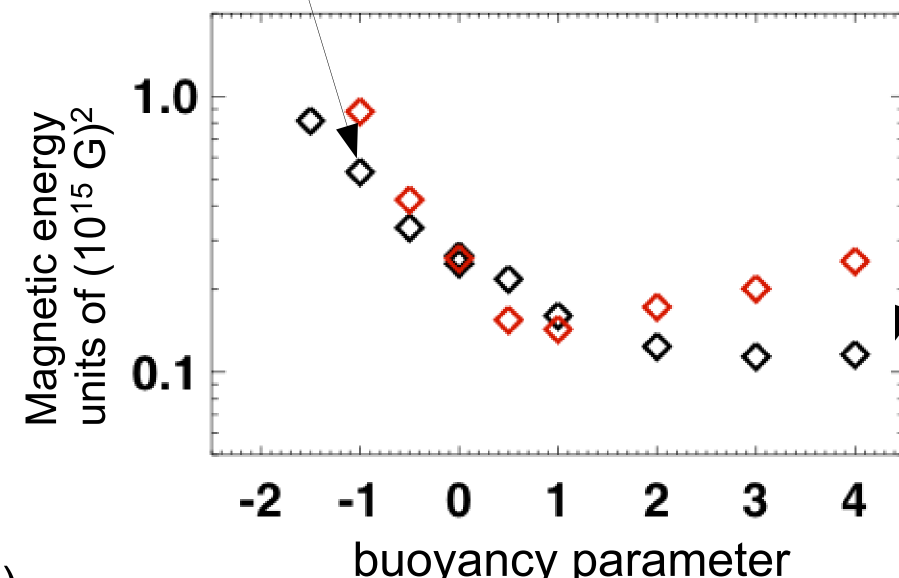
unstable buoyancy



color: azimuthal magnetic field

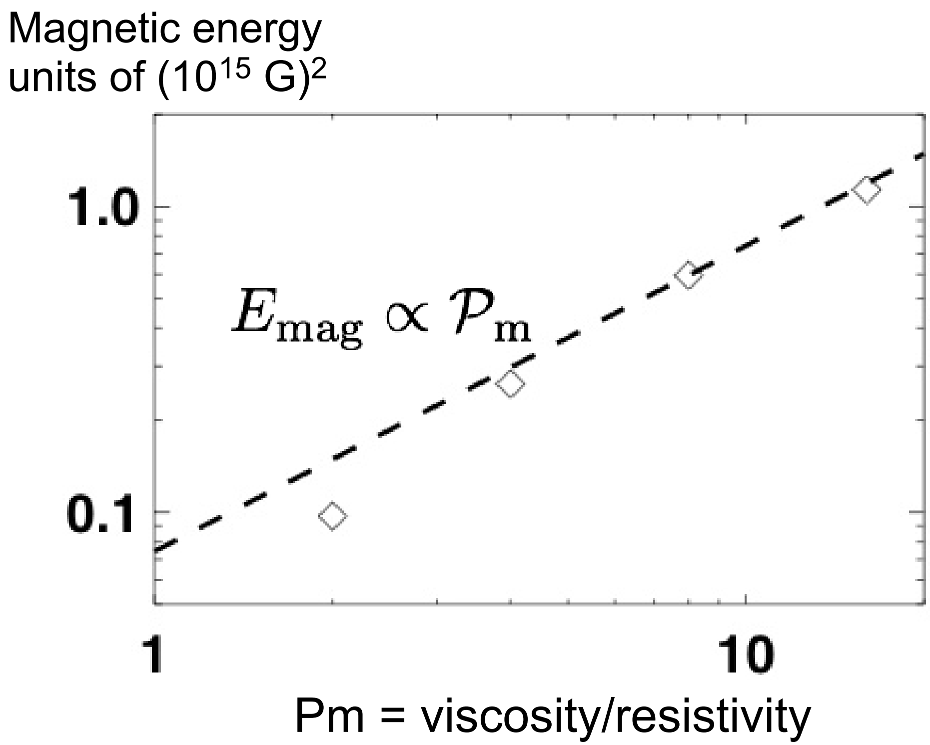
stable stratification





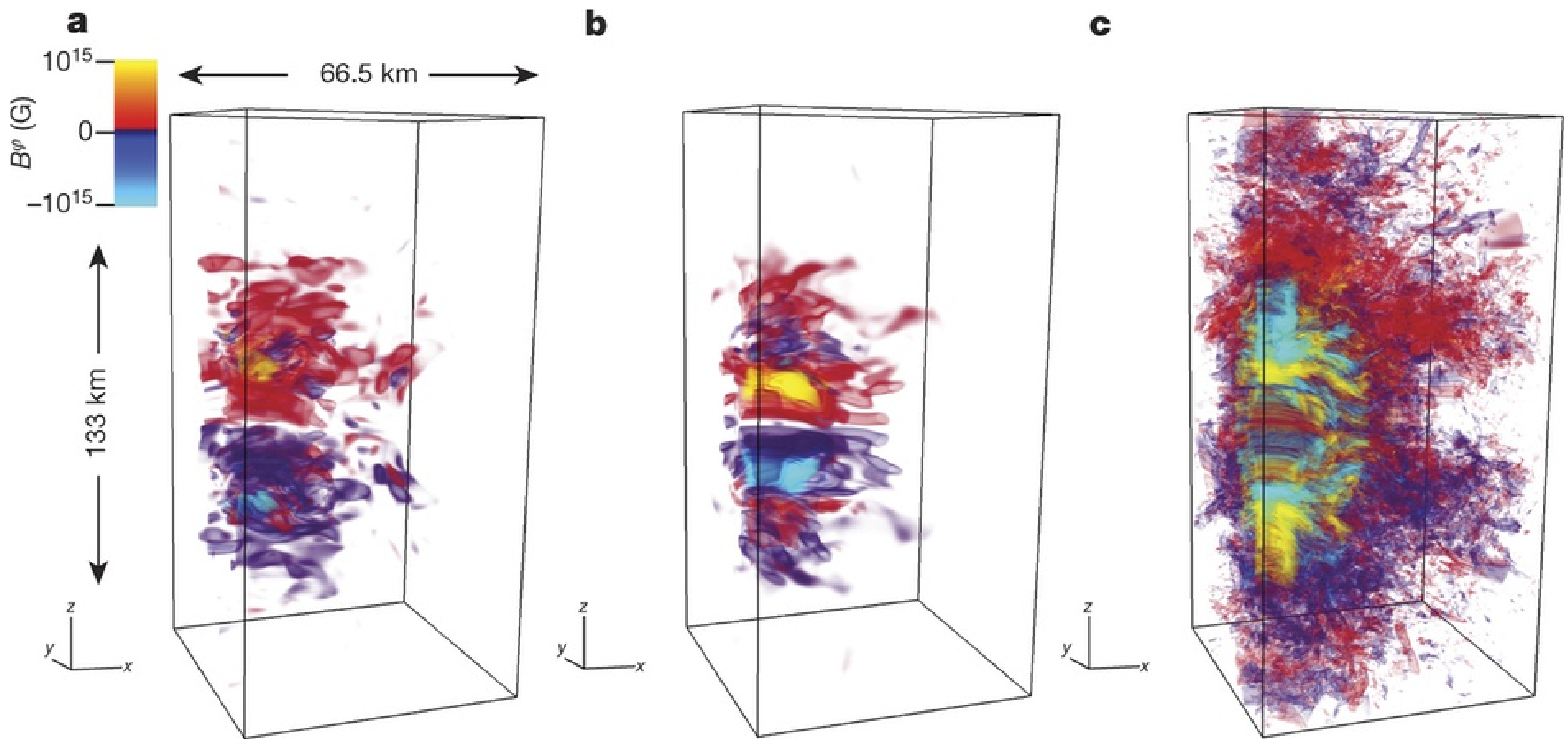
Guilet & Müller (2015)

Dependence on diffusion processes



Behaviour at realistic values: very large Pm ?

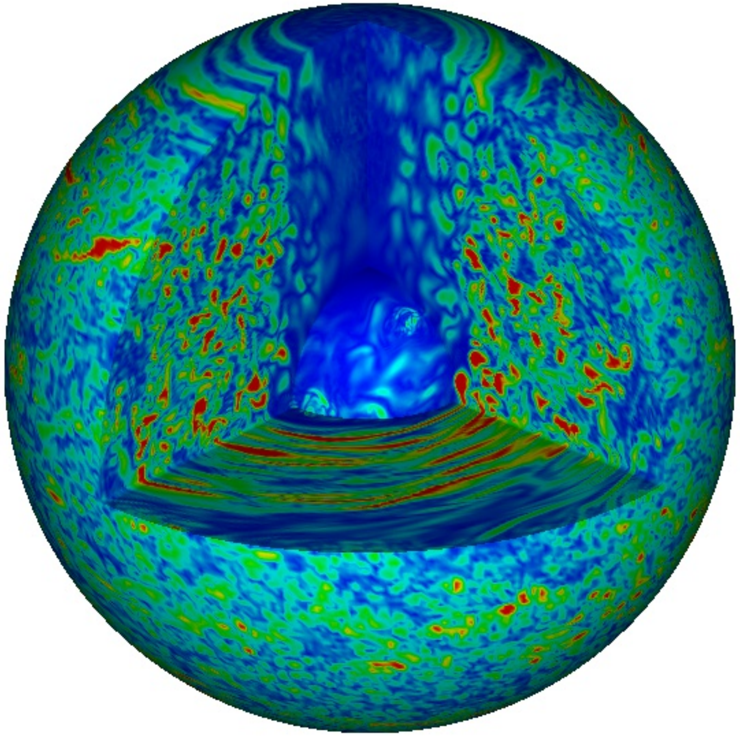
Global models: geometry of the magnetic field ?

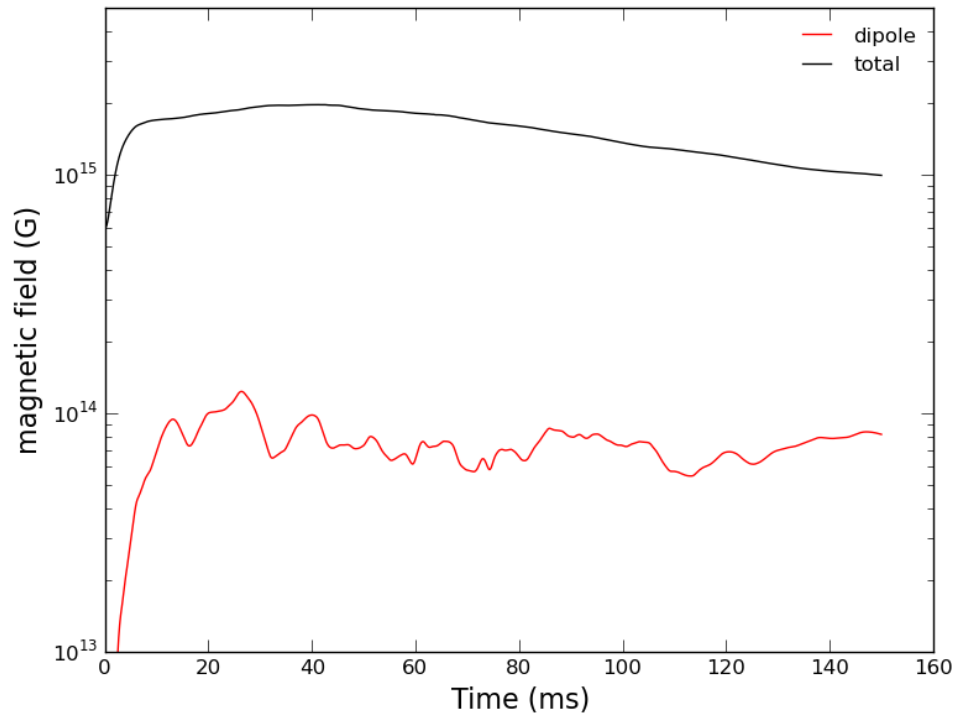


Moesta+2015 : first simulation with large-scale magnetic field generation..
but started with magnetar strength dipolar field

Global models: geometry of the magnetic field ?

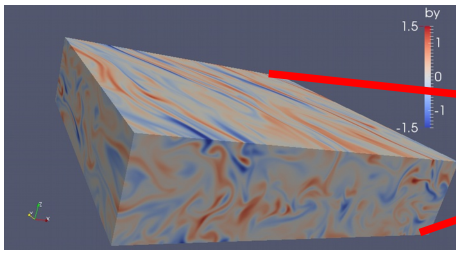
Preliminary simulations of a very simplified model of full neutron star
→ incompressible approximation
→ start with a small-scale field of ~5.10^{14} G





Still a long way to go: from the small to the large scales

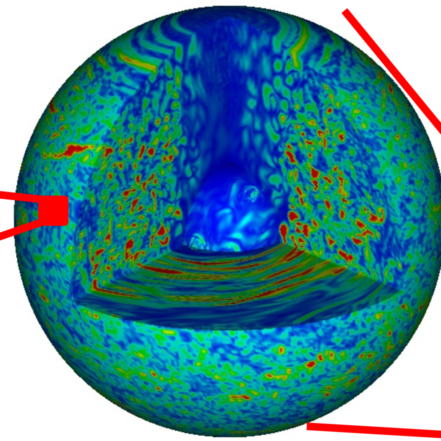
Step 1: local MRI model



Guilet+15

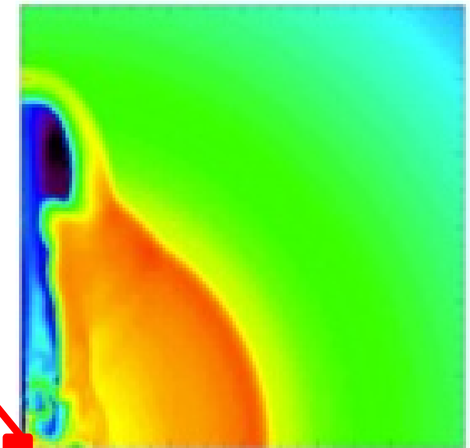
~ 1-5 km

Step 2: global simulations



~ 10-50 km

Step 3: hypernova & GRB jet



Bucciantini+09

~ 10^5-10^6 km

High Pm regime ?

Neutrino drag regime ?

Magnetic field geometry ?

MRI vs convective dynamo

Explosion diversity ?

Energy, jet properties, nucleosynthesis, luminosity etc..

Thanks !