

How to form a millisecond magnetar ?

Magnetic field amplification in protoneutron stars

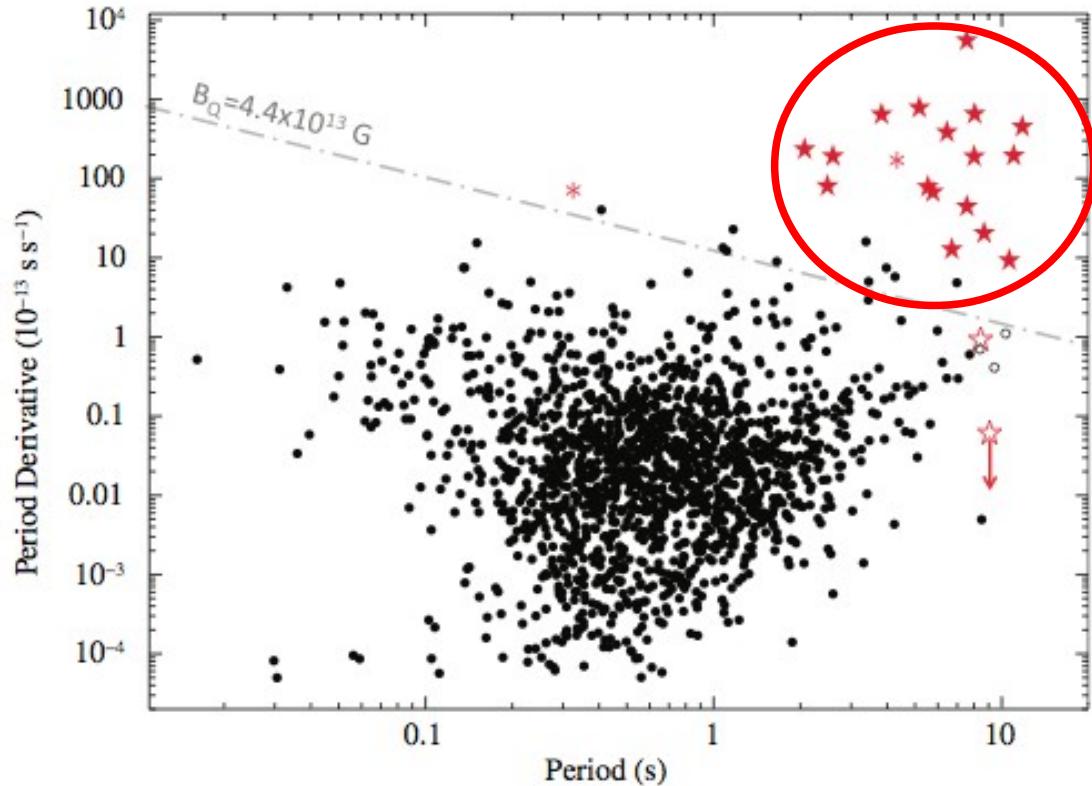
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Galactic magnetars



Magnetars:

Anomalous X-ray pulsars (AXP)
Soft gamma repeater (SGR)

Strong dipole magnetic field:

$$B \sim 10^{14}\text{-}10^{15} \text{ G}$$

Outstanding explosions: millisecond magnetars ?

Explosion kinetic energy :

- Typical supernova 10^{51} ergs
- Rare hypernova (& GRB) 10^{52} ergs

→ Neutrino driven explosions ?

→ **Millisecond magnetar ?**

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

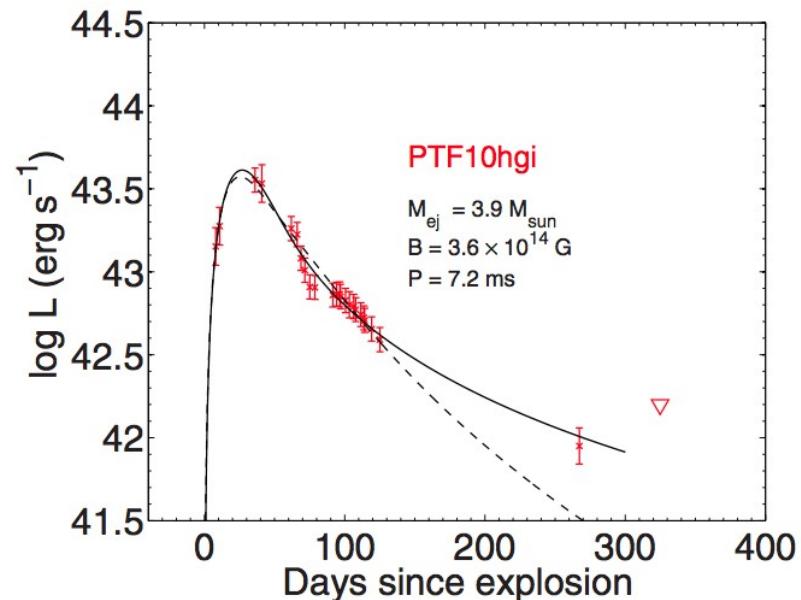
Total luminosity :

- Typical supernova 10^{49} ergs
- Superluminous supernovae 10^{51} ergs

Light curves can be fitted by millisecond magnetar

- strong dipole magnetic field: $B \sim 10^{14}-10^{15}$ G
- fast rotation: $P \sim 1-10$ ms

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



Impact of a strong magnetic field on the explosion

Strong magnetic field: $B \sim 10^{15}$ G

+ fast rotation (period of few milliseconds)

=> powerful jet-driven explosions !

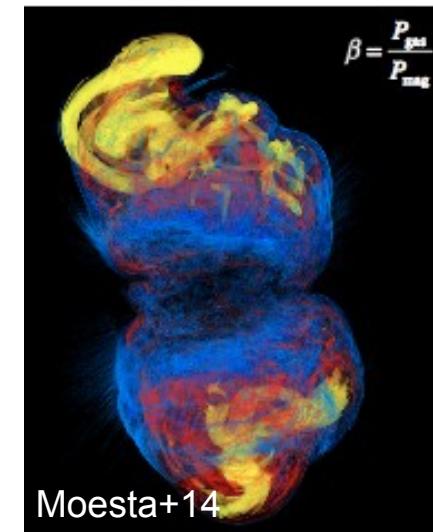
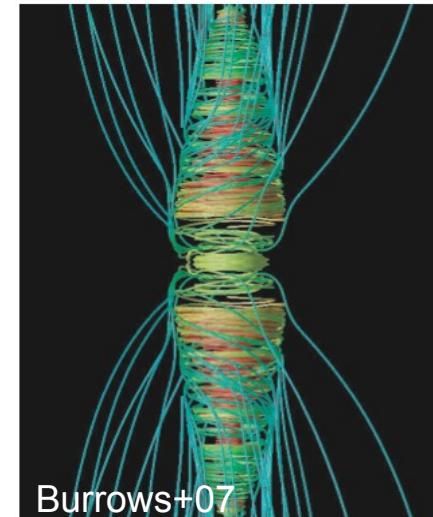
e.g. Sibata+06, Burrows+07, Dessart+08,
Takiwaki+09,11, Winteler+12, Obergaulinger+17

See talk by Martin Obergaulinger

But in 3D, jets can be unstable to kink instability

Moesta+2014

Caveat: origin of the magnetic field is not explained



Missing theoretical piece: magnetic field origin



Huge range of magnetic field strength :

- Initially « weak » magnetic field : $\lesssim 10^9$ G (?)
- After compression by the core-collapse: $\lesssim 10^{12} - 10^{13}$ G (?)
- Magnetar strength : $\sim 10^{15}$ G

Amplification mechanism ?

Magnetorotational instability (MRI) ?

Similar to accretion disks

- application to protoneutron stars

Convective dynamo ?

Similar to solar & planetary dynamos

- need for numerical simulations of neutron stars

The magnetorotational instability (MRI)

MRI in its simplest form (ideal MHD):

Instability criterion

$$\frac{d\Omega}{dr} < 0$$

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

→ Fast growth for fast rotation

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

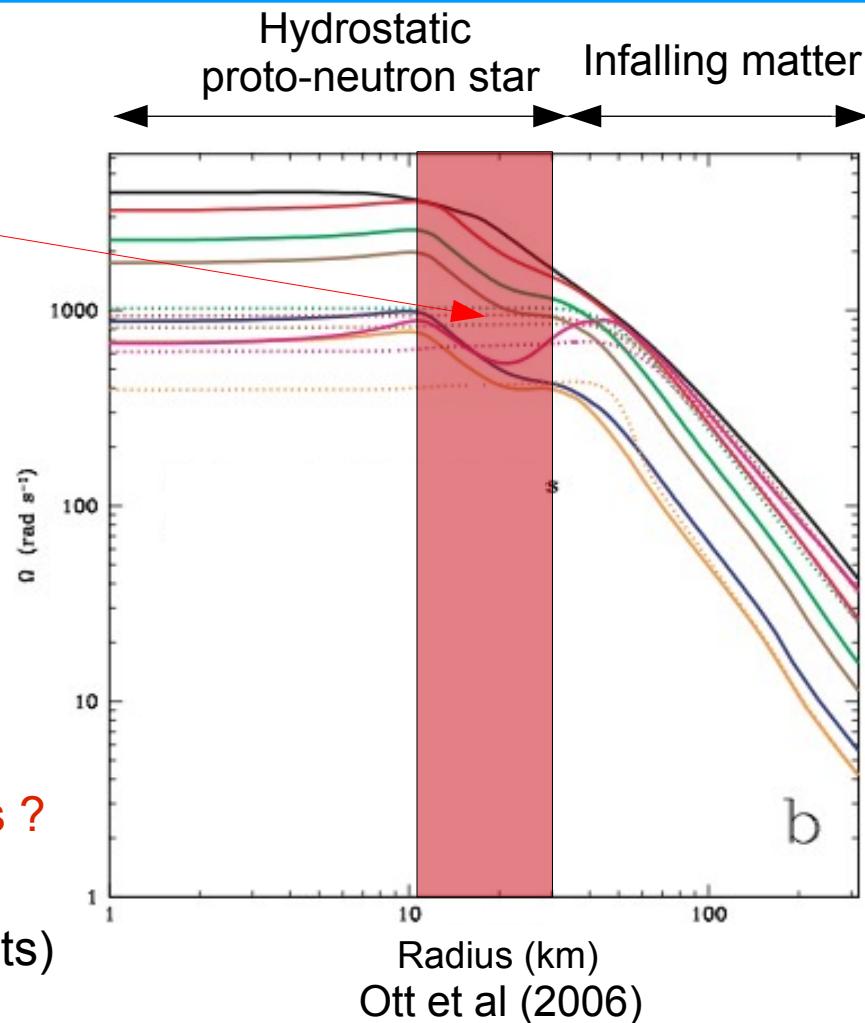
→ Short wavelength for weak magnetic field

Impact of conditions specific to protoneutron stars ?

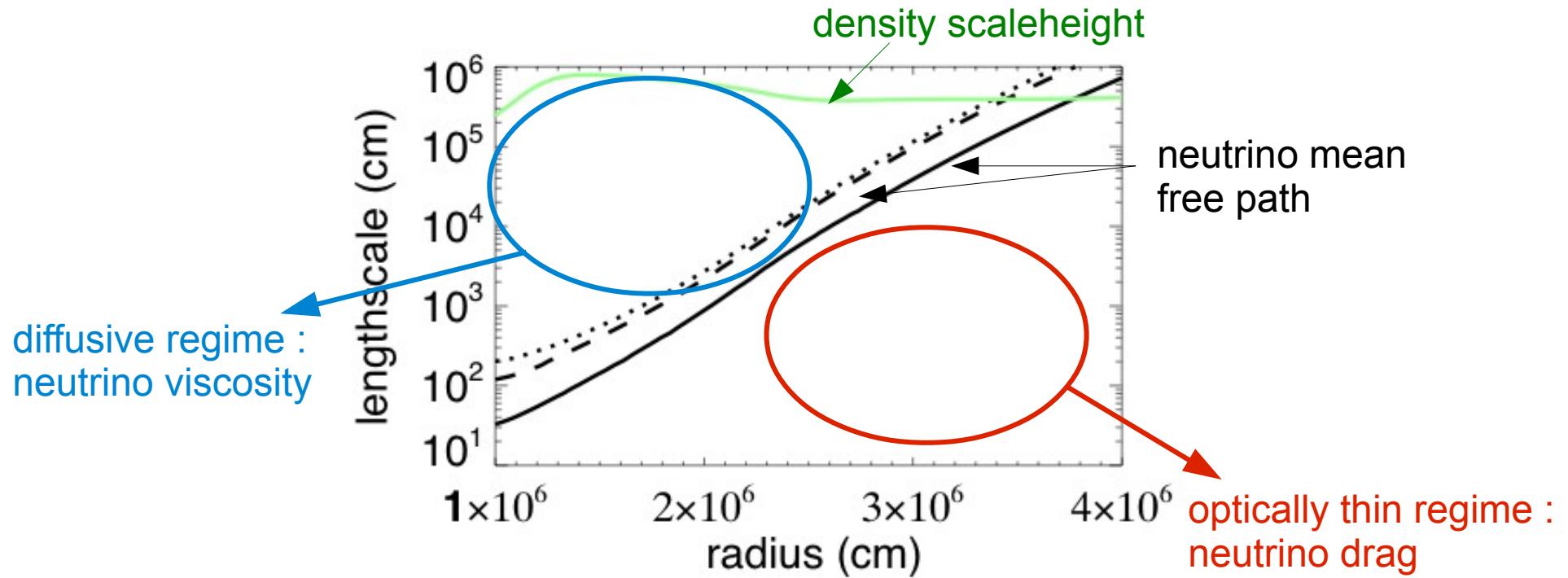
→ neutrinos

→ buoyancy (entropy & composition gradients)

→ spherical geometry

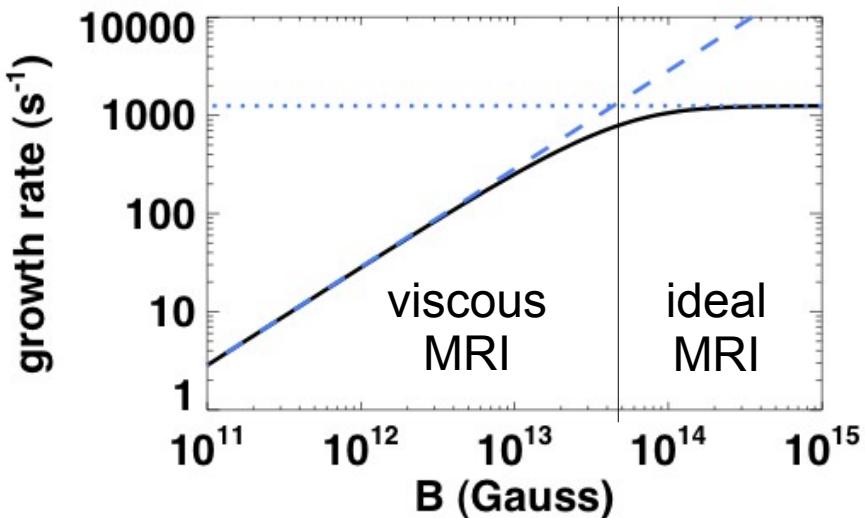


Impact of neutrinos on the MRI: two regimes



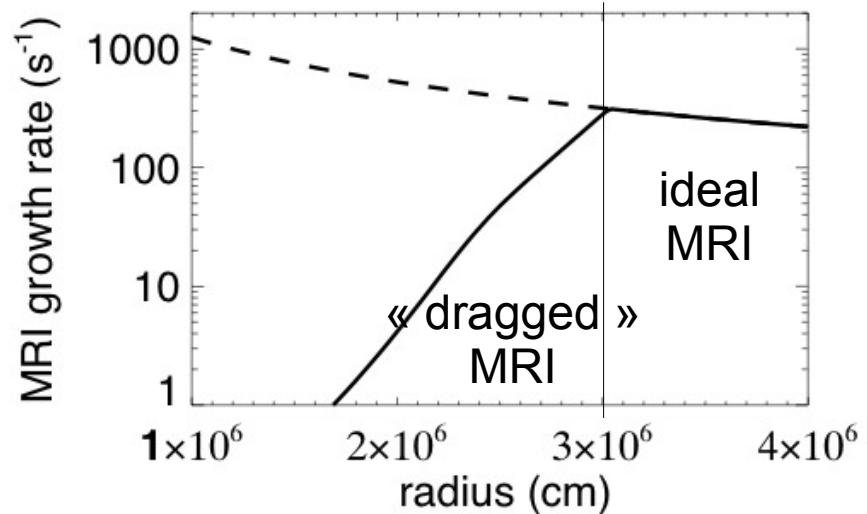
Impact of neutrinos on the MRI: growth rate

Viscous regime



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

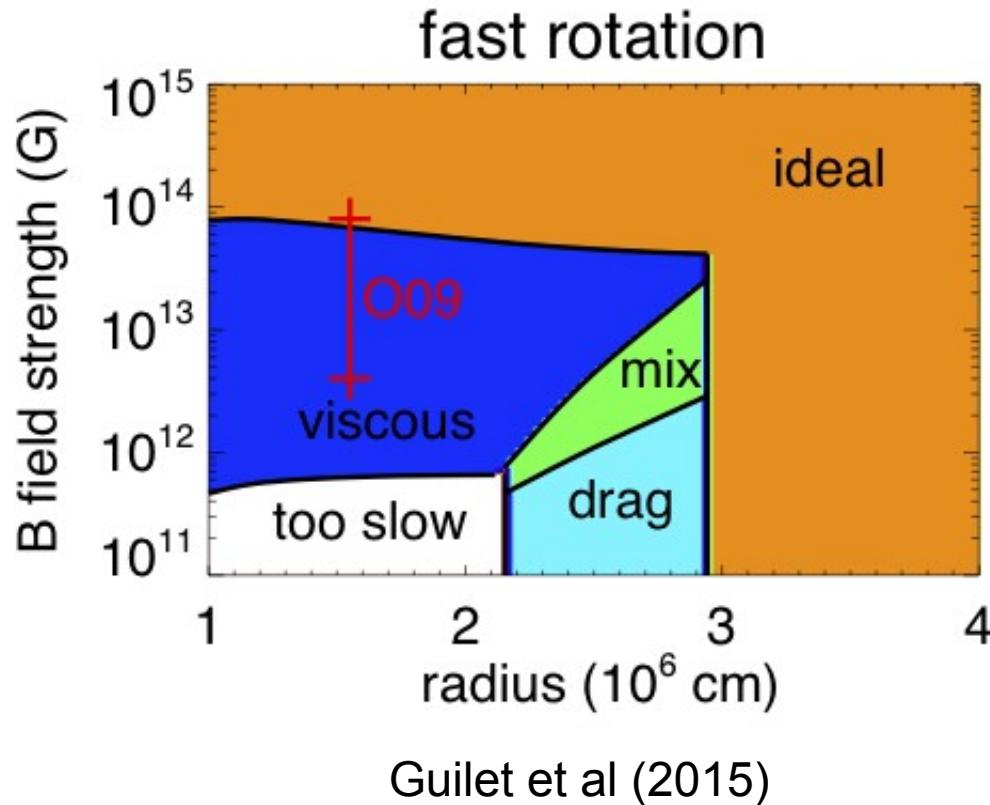
Neutrino drag regime



Fast growth near surface independently of field strength

Guilet et al (2015)

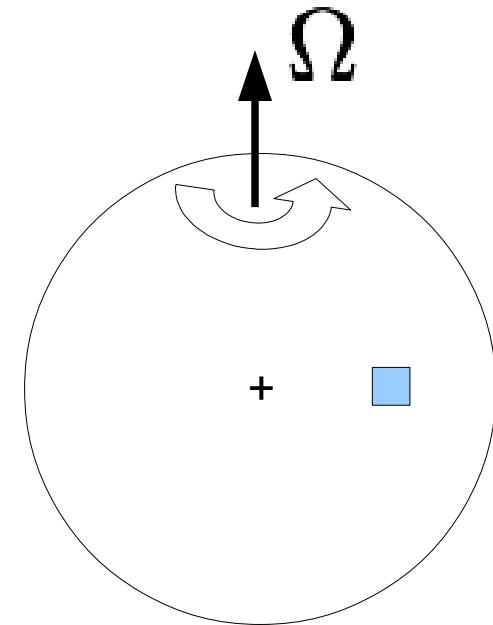
MRI growth: different regimes



Application to neutron star mergers : similar effects of neutrinos (Guilet et al 2017)

Numerical simulations: local models

- Small box : at a radius $r = 20$ km
size $4 \times 4 \times 1$ km
- Differential rotation
=> shearing periodic boundary conditions
- Entropy/composition gradients

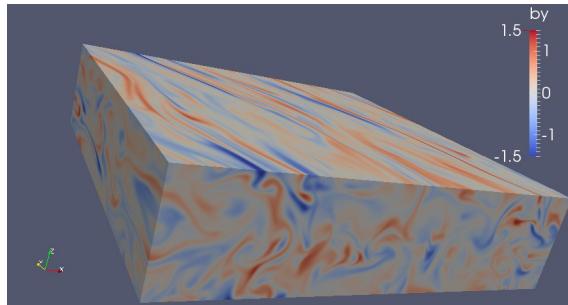


Obergaulinger+2009, Masada+2012,
Guilet+2015, Rembiasz+2015,2016

Fiducial parameters :
 $\rho = 10^{13} \text{ g.cm}^{-3}$
 $B = 2 \times 10^{13} \text{ G}$
 $\Omega = 2 \times 10^3 \text{ s}^{-1}$
 $\nu = 2 \times 10^{10} \text{ cm}^2 \cdot \text{s}^{-1}$

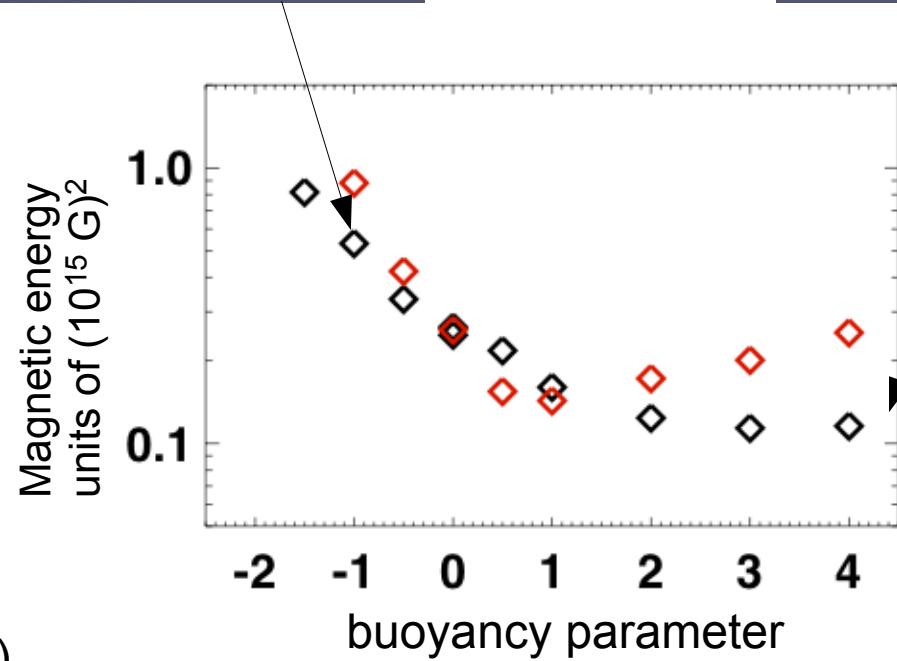
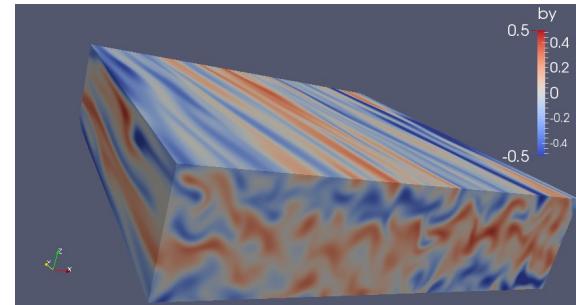
Impact of stratification on the MRI

unstable buoyancy



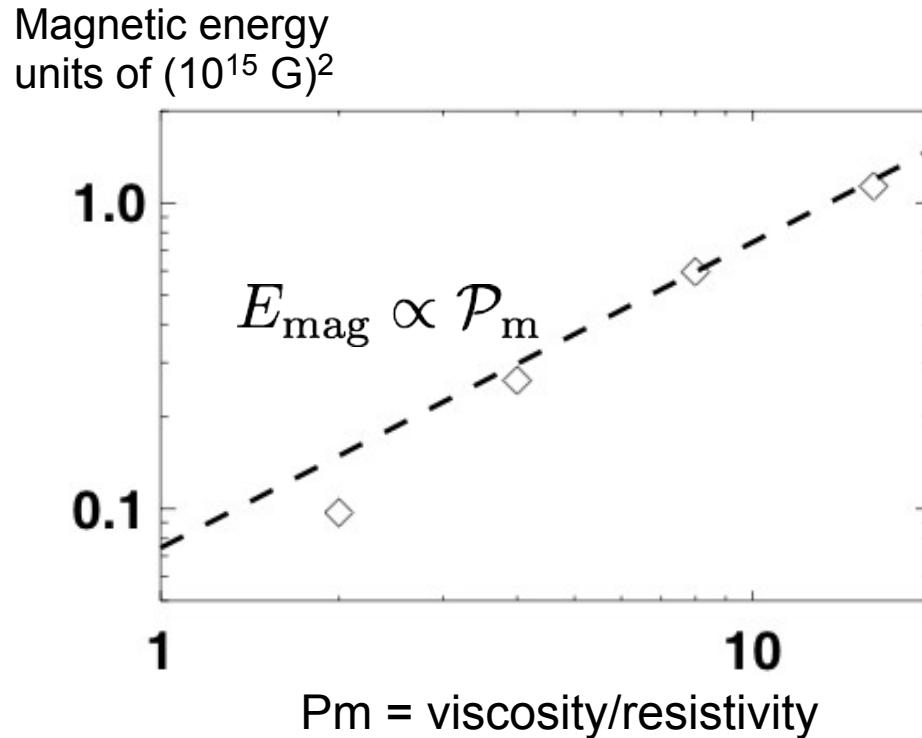
color: azimuthal
magnetic field

stable stratification



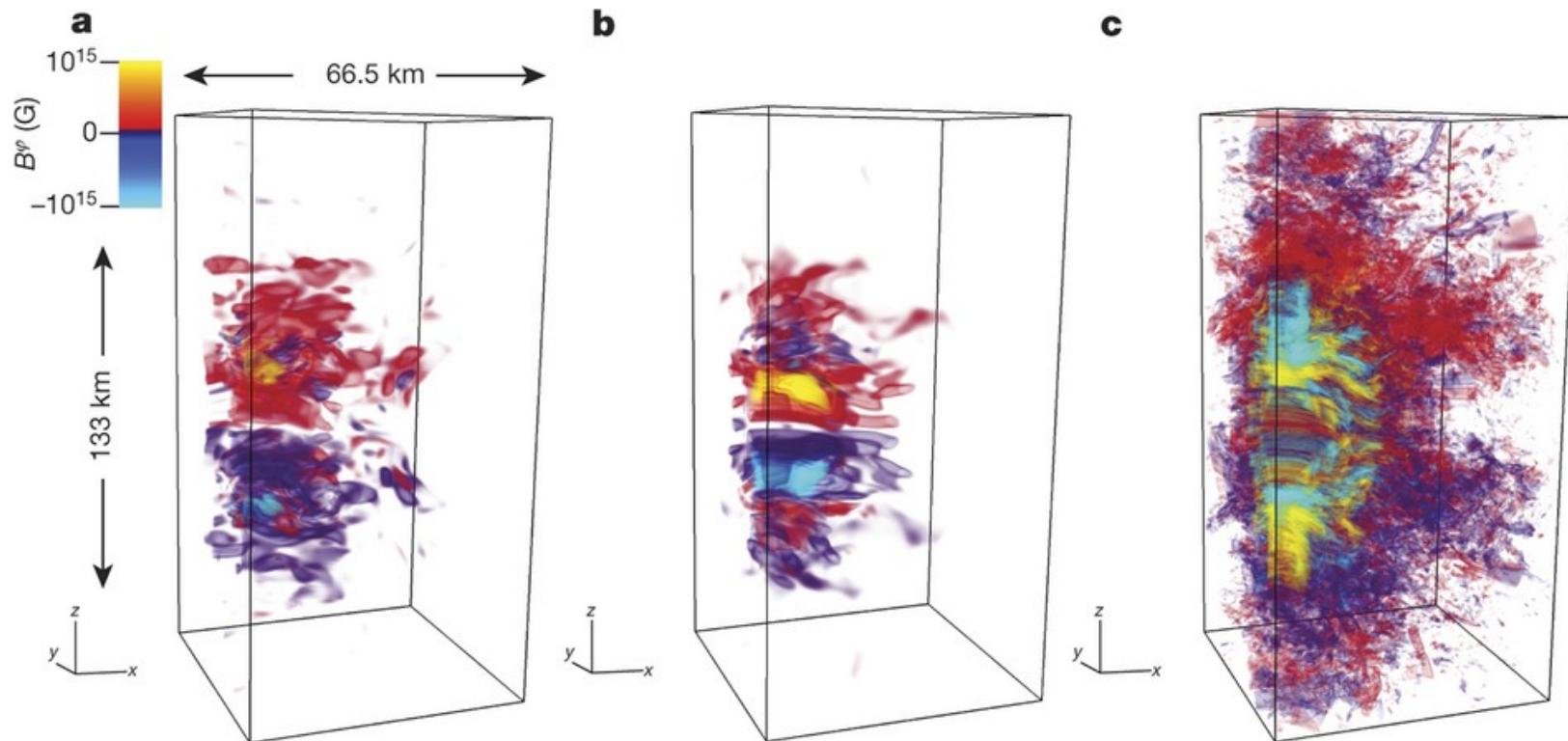
Guilet & Müller (2015)

Dependence on diffusion processes



Behaviour at realistic values: very large magnetic Prandtl number Pm ?

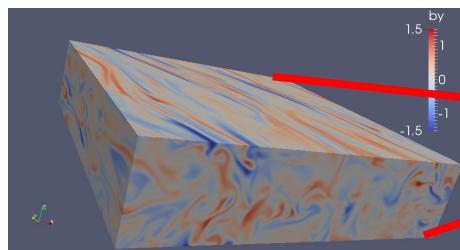
Global models: geometry of the magnetic field ?



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

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

Step 1: local MRI model



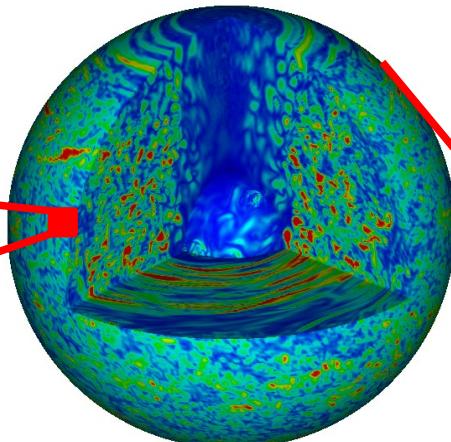
$\sim 1\text{-}5 \text{ km}$

High Pm regime ?

Neutrino drag regime ?

ERC project MagBURST

Step 2: global simulations



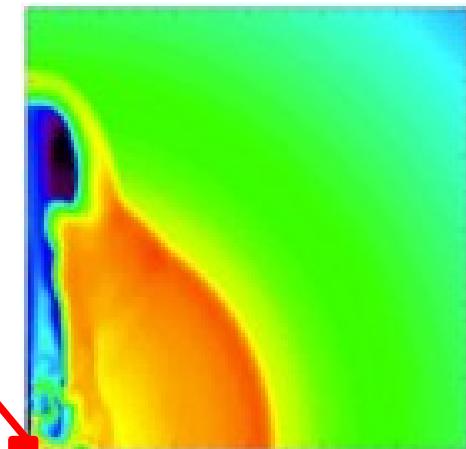
$\sim 10\text{-}50 \text{ km}$

Magnetic field geometry ?

MRI vs convective dynamo

Raphaël Raynaud

Step 3: hypernova & GRB jet



$\sim 10^5\text{-}10^6 \text{ km}$

Explosion diversity ?

Energy, jet properties etc.

Matteo Bugli



Thanks !