How to form a millisecond magnetar ? Magnetic field amplification in protoneutron stars

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Plan of the talk

1. Introduction : Magnetic fields in core collapse supernovae

2. Can the magnetorotational instability grow ? Linear analysis

   → Effects of neutrino radiation

3. How strong is the final magnetic field ? Numerical simulations

   → Channel mode termination

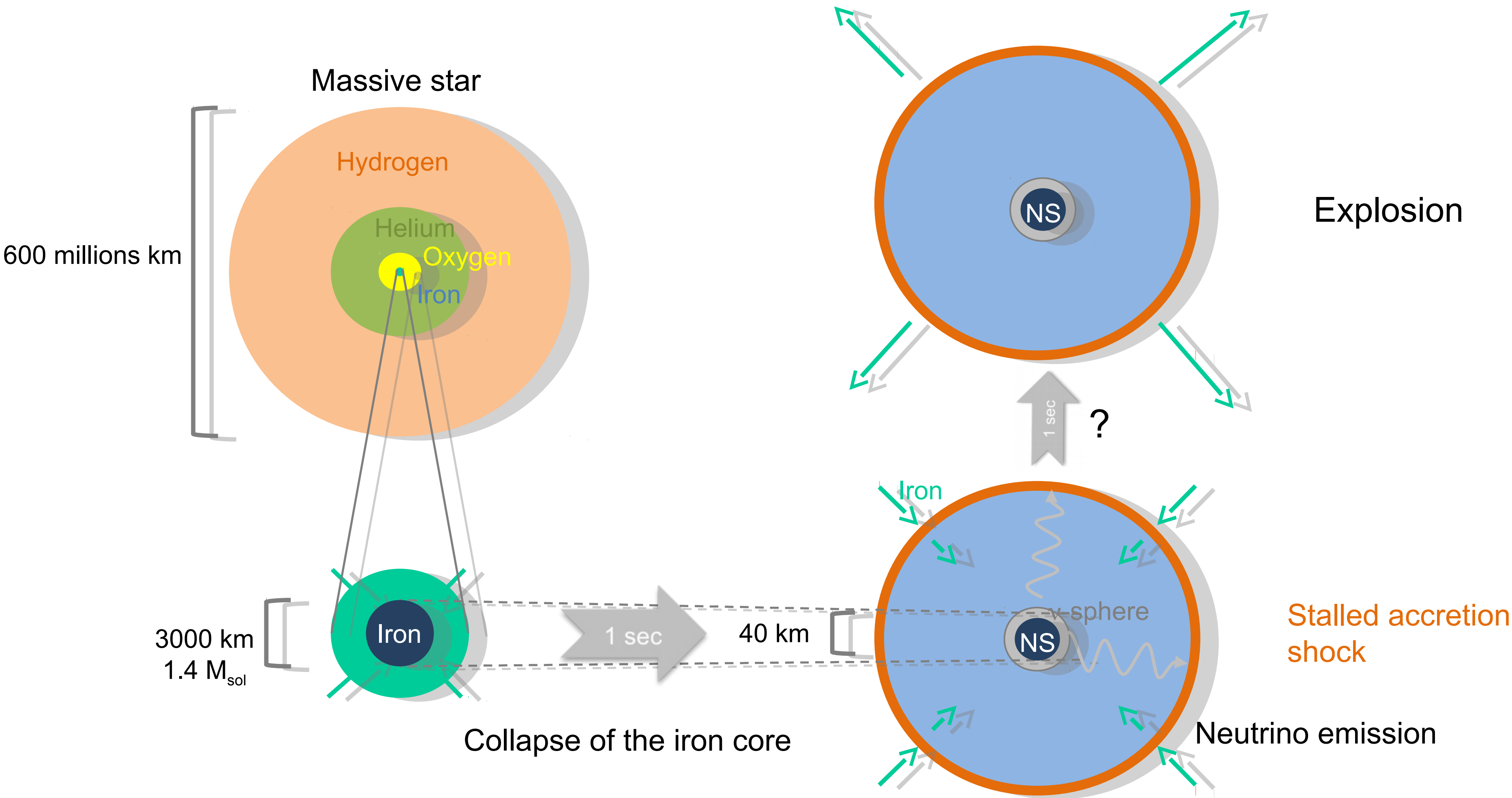
   → Influence of buoyancy

   → Dependence on the magnetic Prandtl number

   → The dawn of global simulations

4. Conclusion & perspectives

Core collapse: formation of a neutron star



A diversity of explosions

Explosion kinetic energy :

→ Typical supernova 10^{51} ergs → Neutrino driven explosions ?
e.g. Bruenn+14, Melson+15

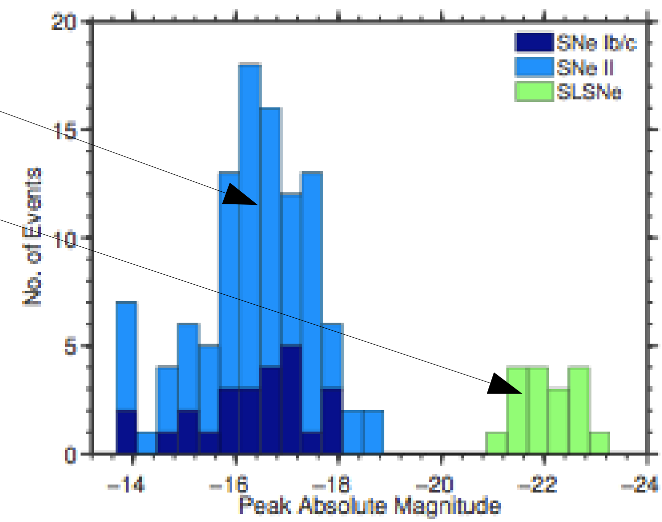
→ Rare hypernova (& GRB) 10^{52} ergs → Millisecond magnetar ?
e.g. Burrows+07, Takiwaki+09,11
Bucciantini+09, Metzger+11

Total luminosity :

→ Typical supernova 10^{49} ergs

→ Superluminous supernovae 10^{51} ergs

→ Millisecond magnetar ?
e.g. Woosley+10, Dessart+12,
Nicholl+13, Inserra+13

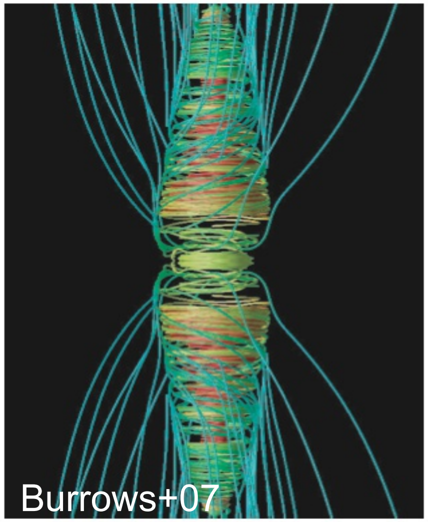


Magnetic explosions ?

Strong magnetic field: B ~ 10^{15} G
+ fast rotation (period of few milliseconds)

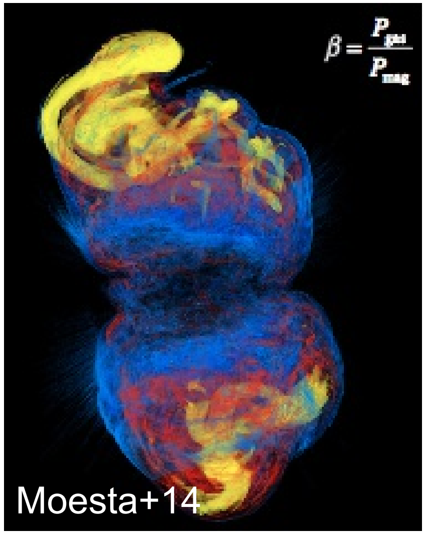
=> powerful jet-driven explosions !

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



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

Moesta+2014



Open question:
Can magnetic explosions explain hypernovae ?

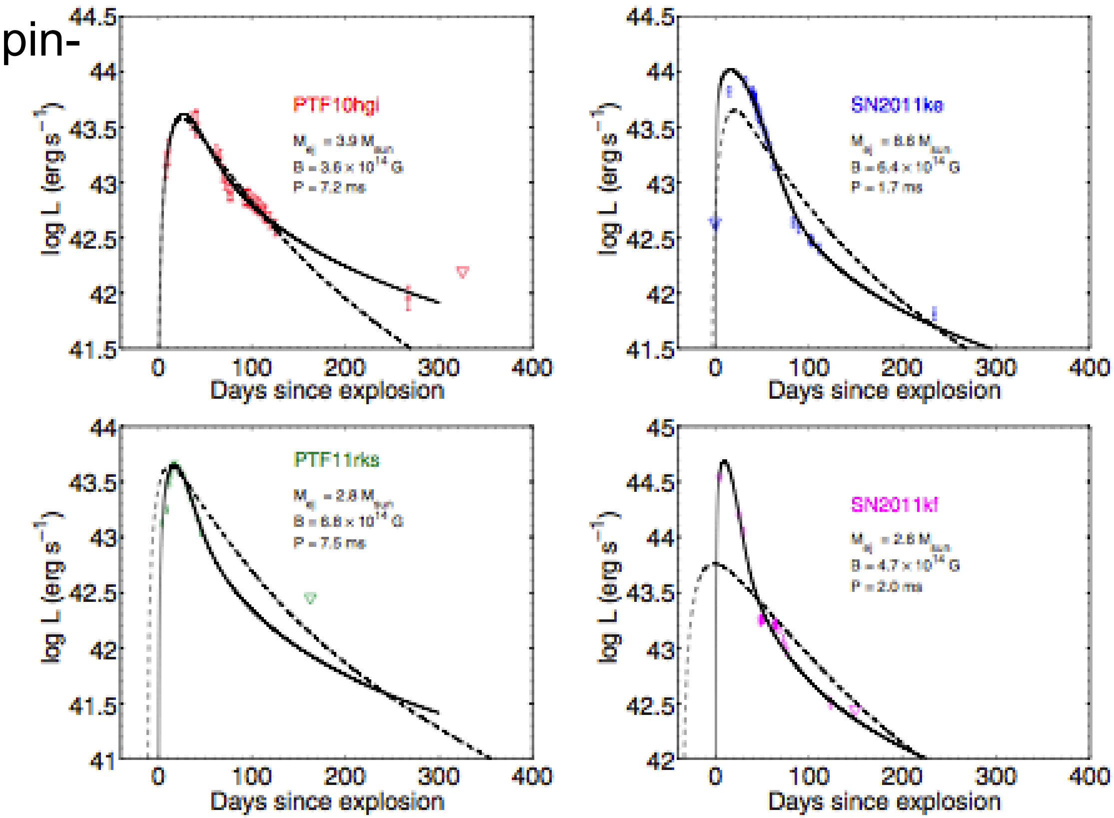
Are millisecond magnetars powering superluminous supernovae ?

Delayed energy injection by magnetar spin-down on timescale of weeks-months

=> very high luminosity

Light curves can be fitted by:

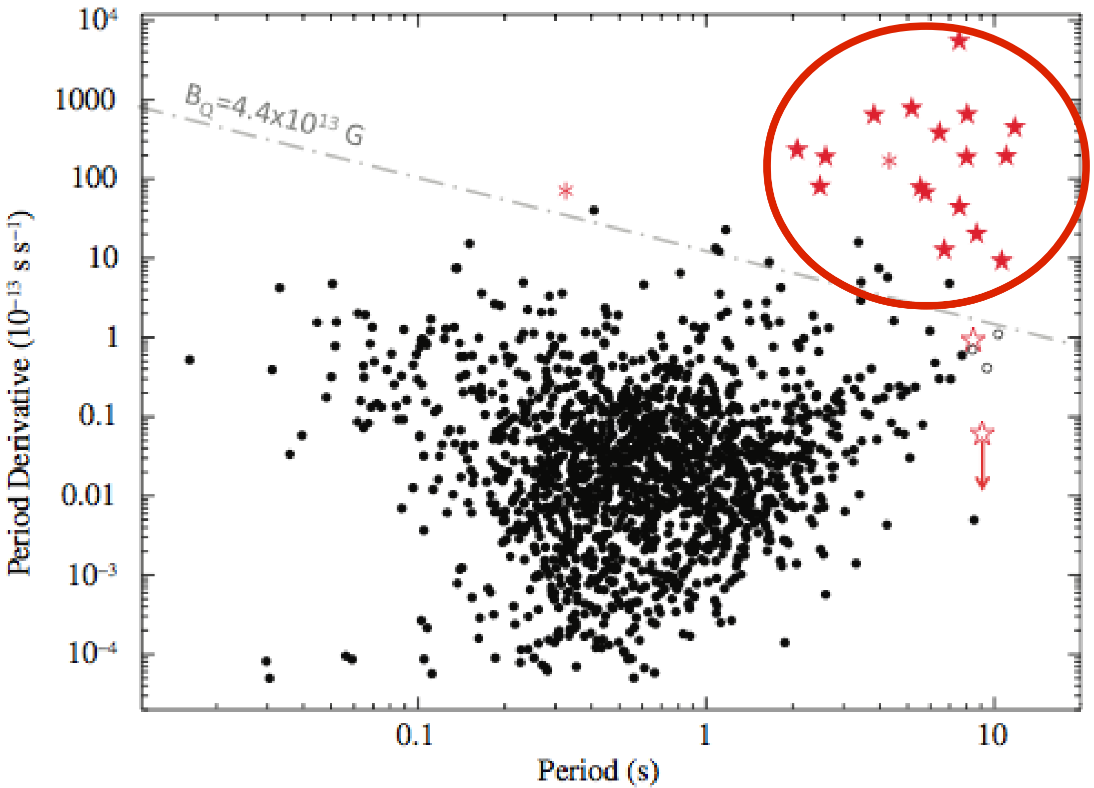
- strong dipole magnetic field:
  $B \sim 10^{14}\text{-}10^{15}$ G
- fast rotation:
  $P \sim 1\text{-}10$ ms



Inserra+2013

Talk by Ken Chen last week

Galactic magnetars



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

Strong dipole magnetic field:

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

Slow rotation:

$P \sim 1$-10 s

Typical age:
10^4-10^5 years

Talks by Michael Gabler & Pablo Cerda-Duran

Rotation at birth unknown: were some or all of them born as millisecond magnetars ?

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)

In ideal MHD (i.e. no resistivity or viscosity) :

Condition for MRI growth $\frac{\mathrm{d}\Omega}{\mathrm{d}r} < 0$

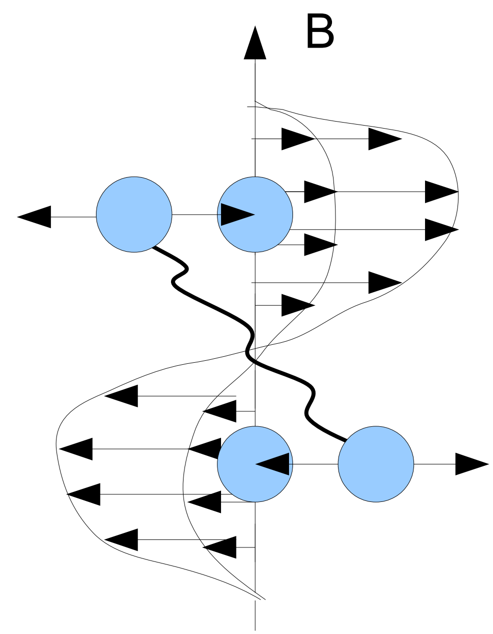
Growth rate : $\sigma = \frac{q}{2}\Omega$

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

→ Fast growth for fast rotation

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

→ Short wavelength for weak magnetic field

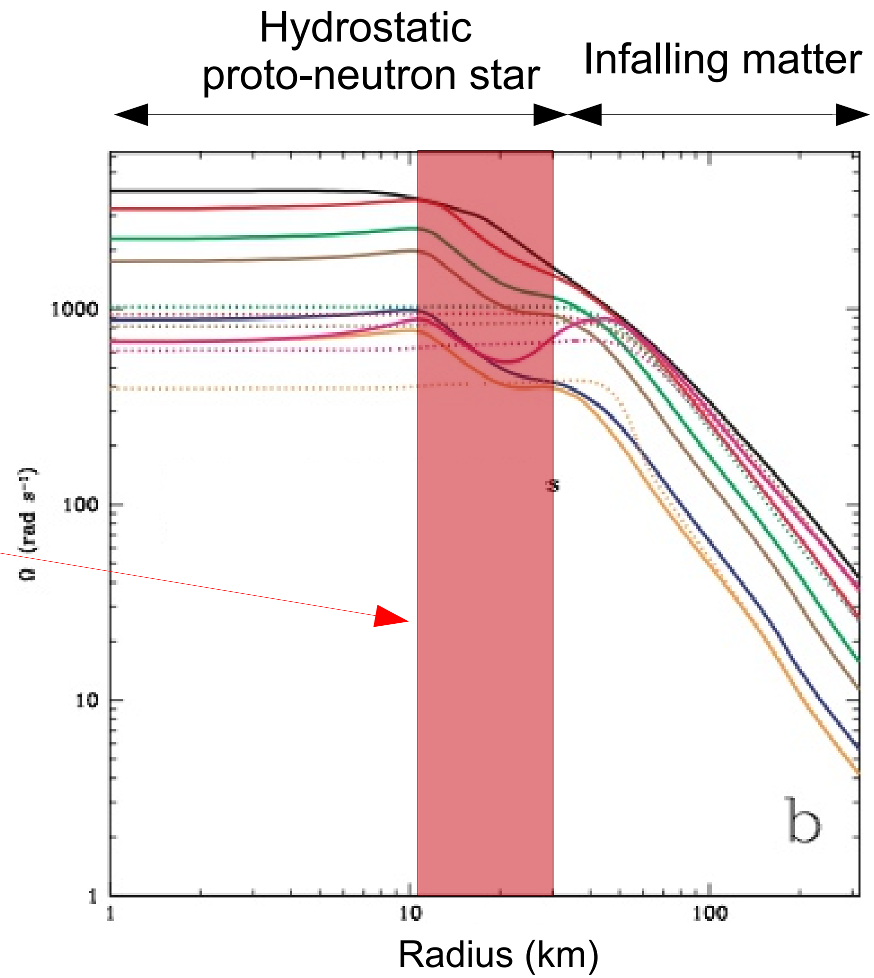


Rotation profile in the proto-neutron star

Rotation frequency profile :
→ Differential rotation at radii > 10 km

Rotation frequency decreases with radius : => MRI unstable !

Akiyama et al (2003)
Obergaulinger et al (2009)



Ott et al (2006)

Proto-neutron stars vs disks conditions

Main differences between proto-neutron stars and accretion disks:

→ Neutrinos: viscosity and drag

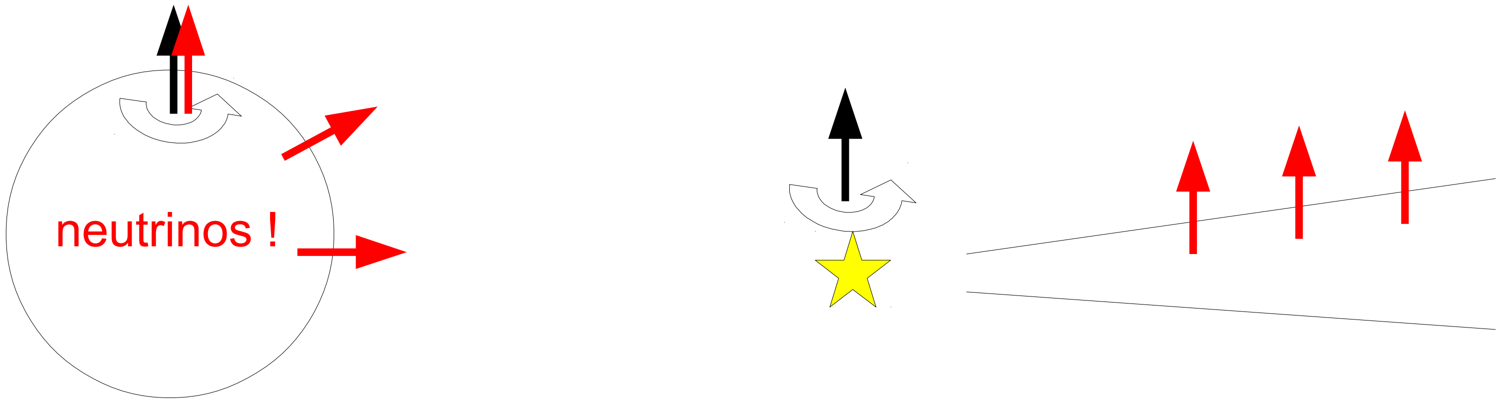
→ Prevent MRI growth ?

→ Buoyancy: radial entropy and composition gradients

→ Impact on magnetic field amplification by MRI ?

→ Geometry: spherical vs thin disk

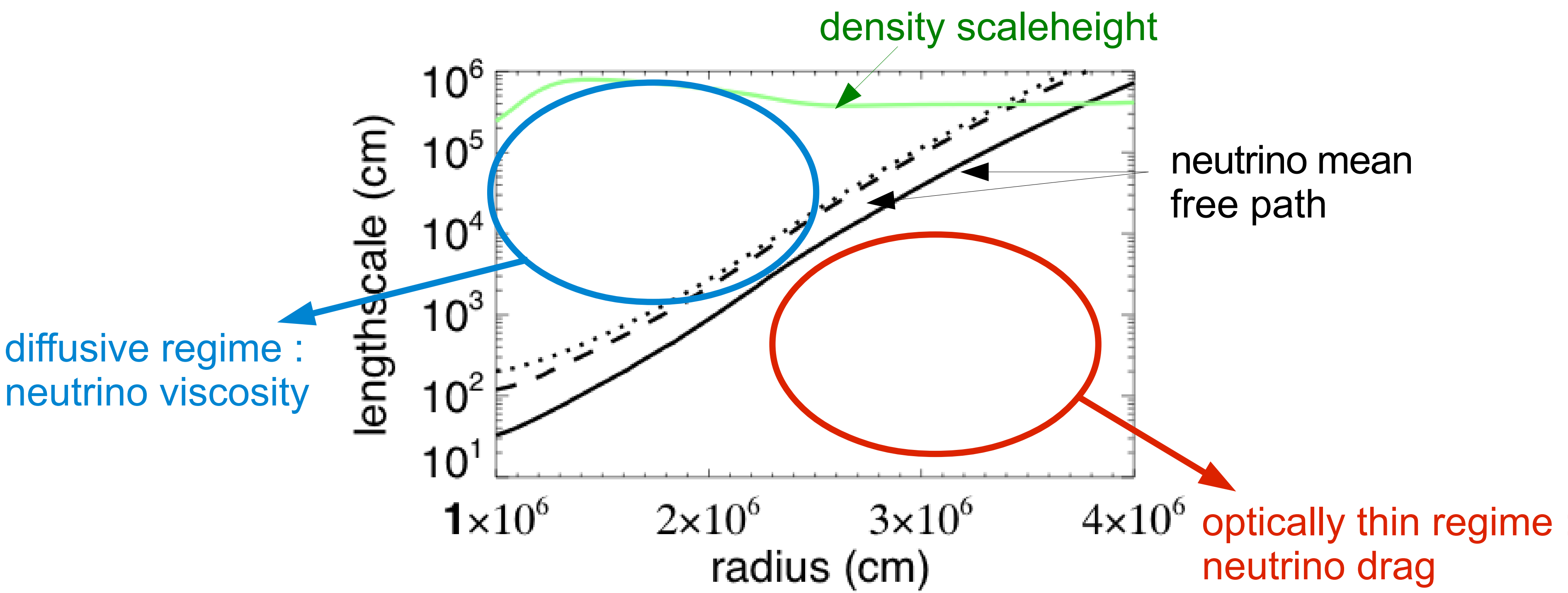
→ Help global coherence ?



2. Can the magnetorotational instability (MRI) grow ?

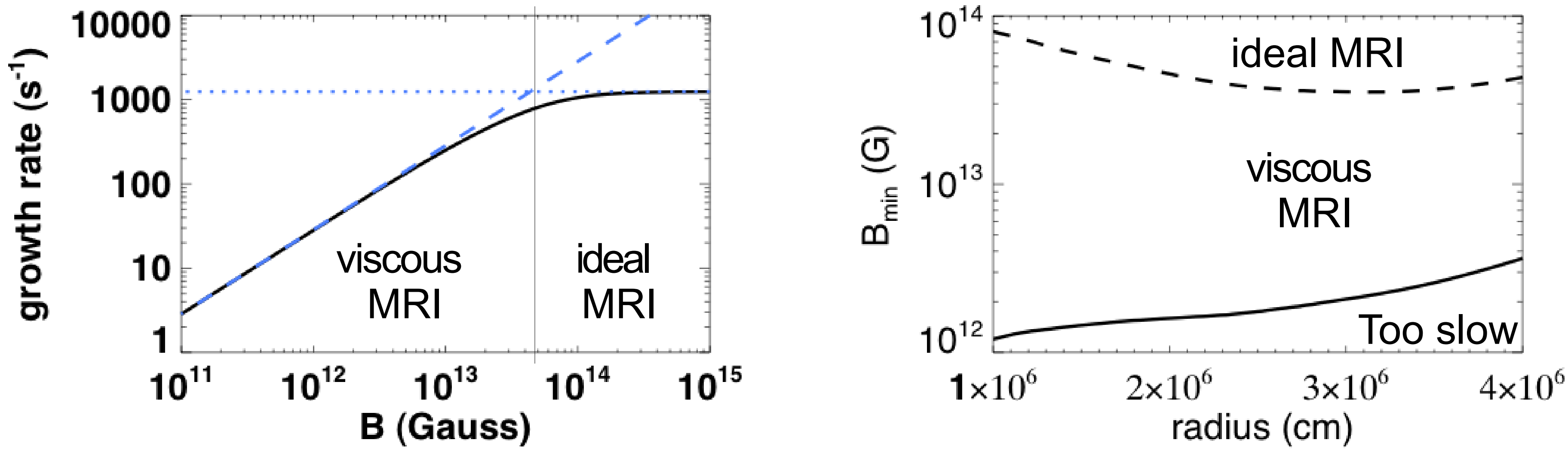
Effects of neutrino radiation

Effects of neutrino radiation : two regimes



Neutron star structure from a simulation by Hanke et al (2013)

MRI with neutrino viscosity

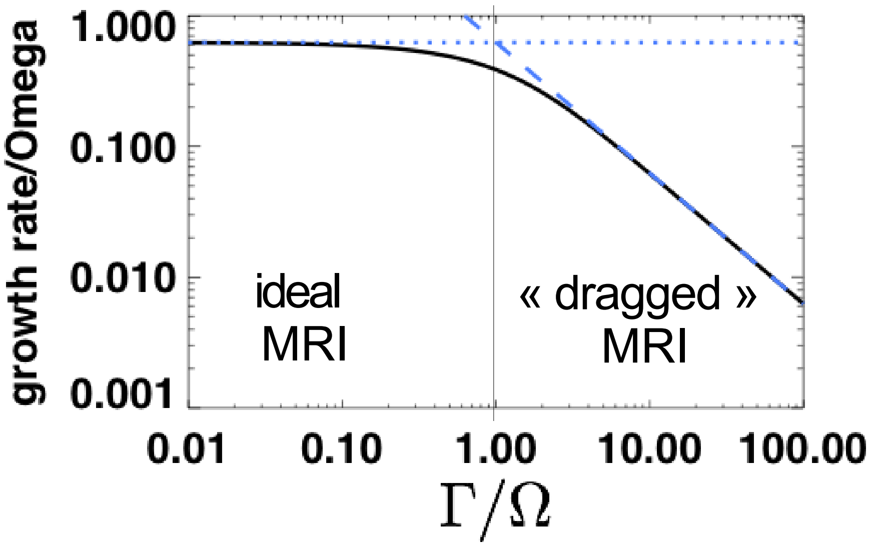


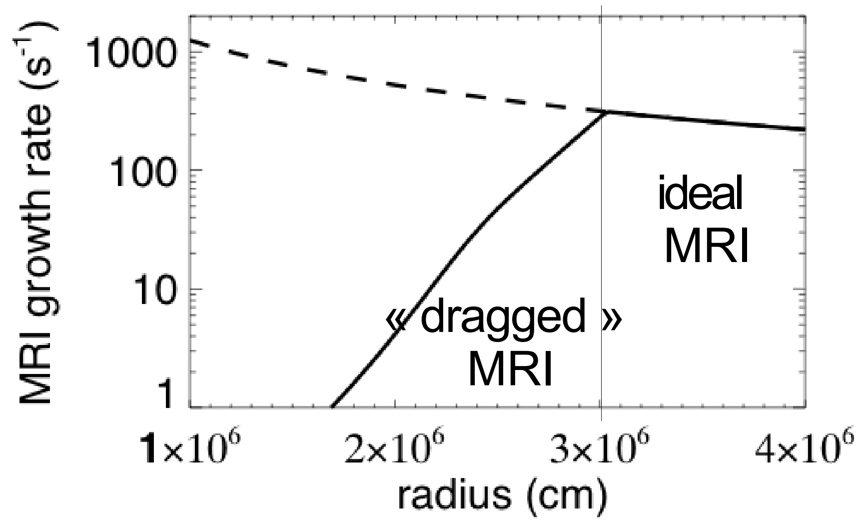
Dimensionless number : $E_\nu \equiv \frac{v_A^2}{\nu\Omega} \sim 0.02 \left(\frac{B}{10^{13}\,\mathrm{G}}\right)^2 \left(\frac{\rho}{10^{13}\,\mathrm{g.cm^{-3}}}\right)^{-1} \left(\frac{\Omega}{2000\,\mathrm{s^{-1}}}\right)^{-1} \left(\frac{\nu}{2\times10^{10}\,\mathrm{cm^2.s^{-1}}}\right)^{-1}$

e.g. Pessah & Chan (2008)

MRI growth requires a minimum initial magnetic field strength of > 10^{12} G...

MRI with neutrino drag

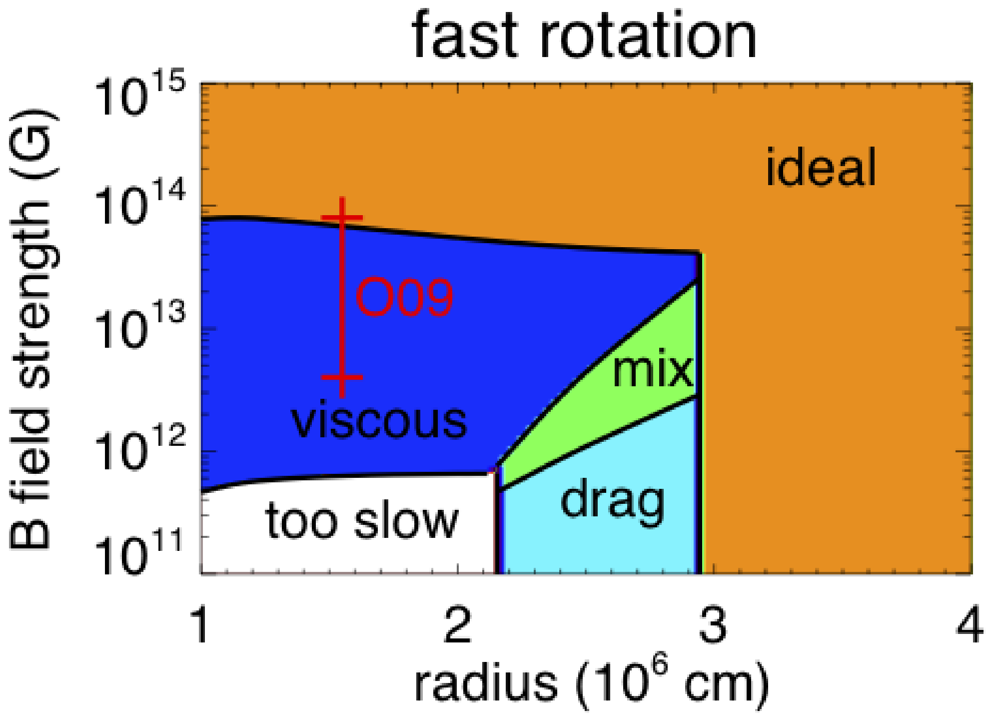




Neutrino drag : $-\Gamma \mathbf{v}$, with damping rate : $\Gamma = \frac{4}{3} \frac{E_\nu}{l_\nu \rho c}$

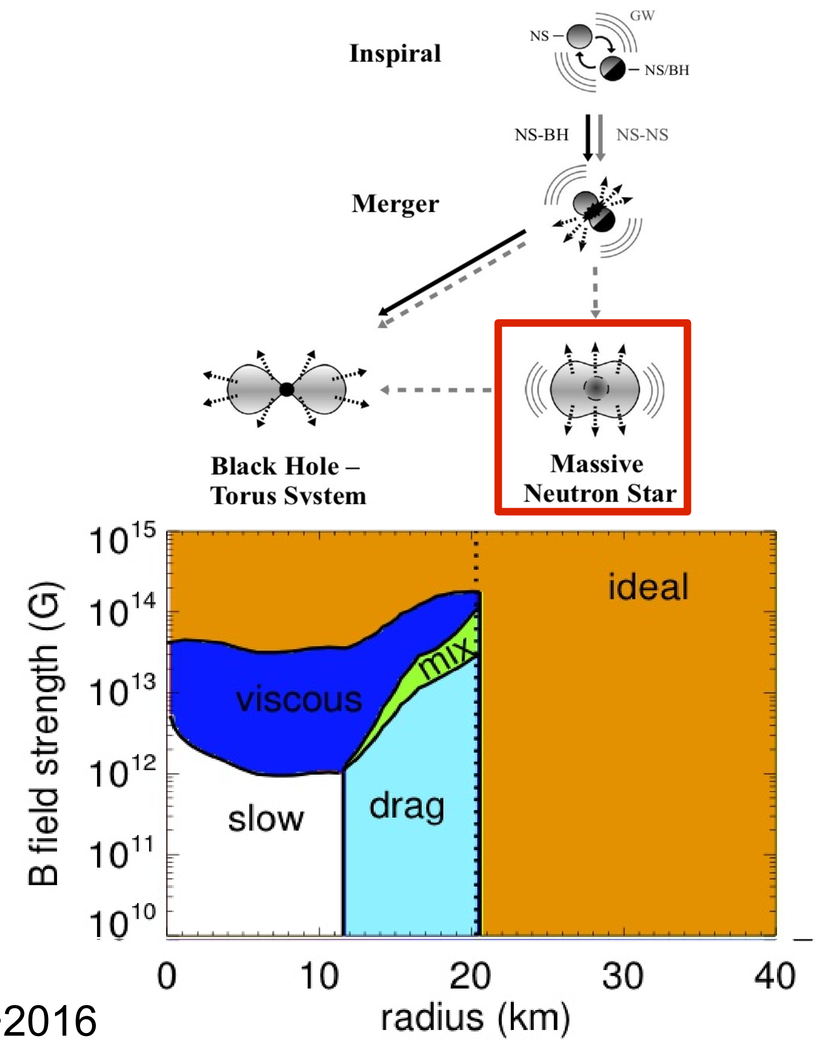
The MRI can grow near the PNS surface from any weak field strength !

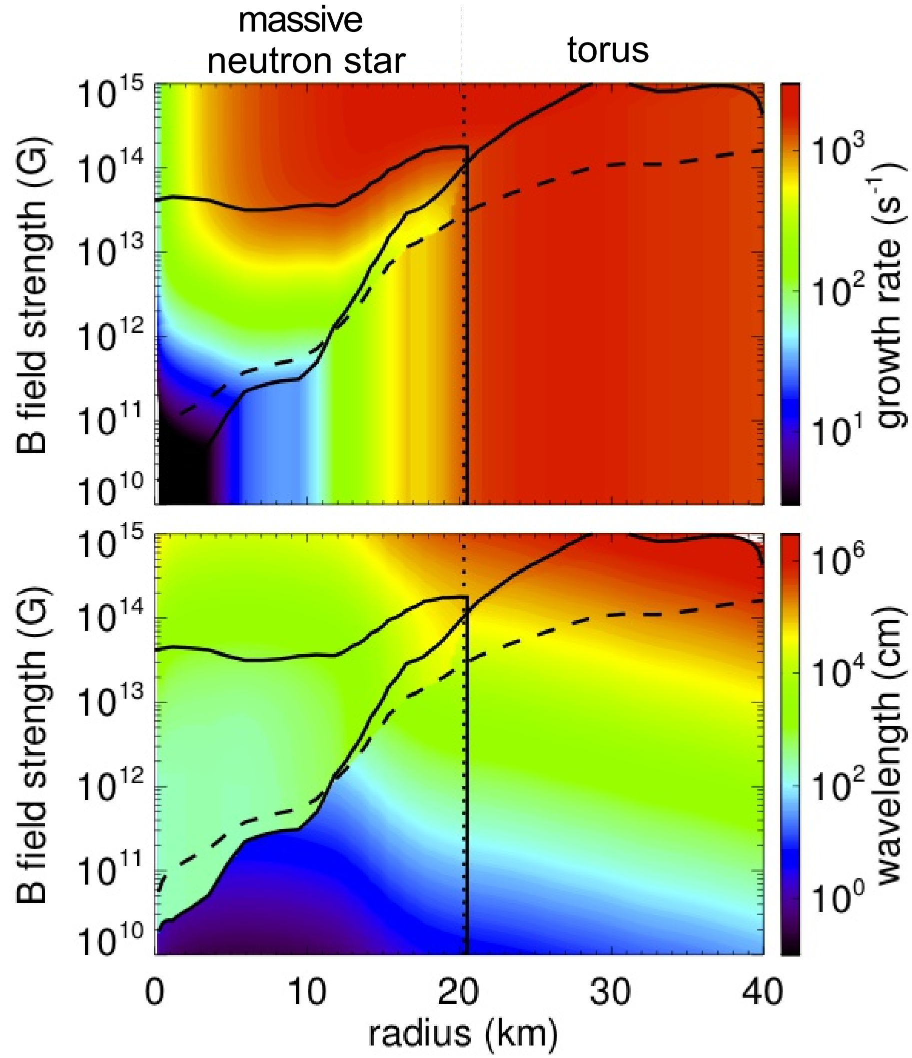
MRI growth: different regimes



Guilet et al (2015)

Application to neutron star mergers





Guilet+2016

3. How strong is the final magnetic field ?

→ Channel mode termination

→ Influence of buoyancy

→ Dependence on the magnetic Prandtl number

→ The dawn of global simulations

Numerical simulations: local models

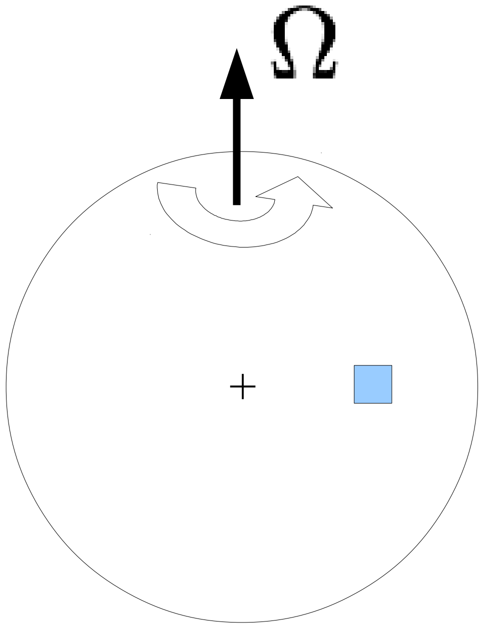
- Small box : ~km size at a radius r ~ 20-40 km

- Differential rotation
  => shearing periodic boundary conditions

- Entropy/composition gradients

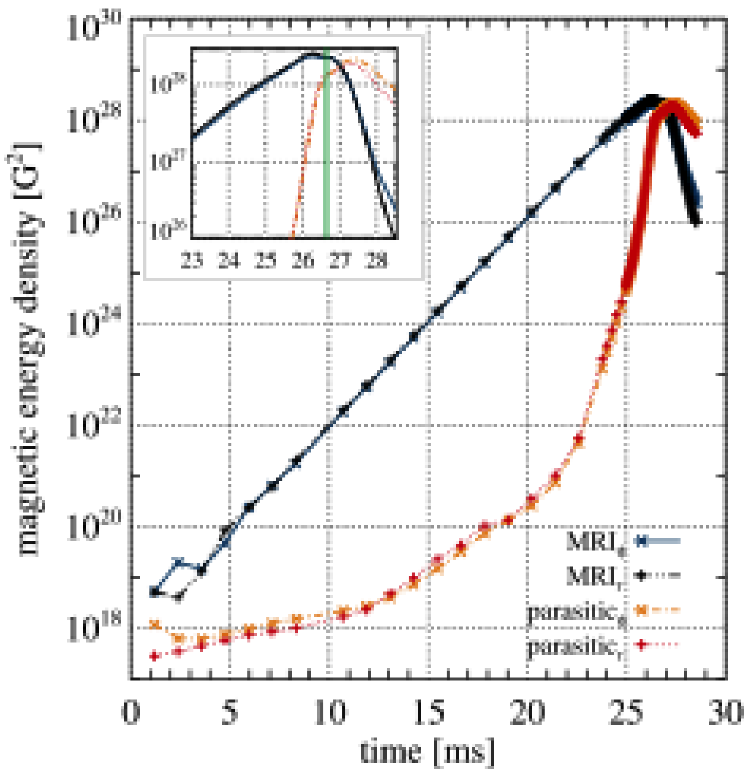
- Different numerical methods : spectral or finite volume

- Fully compressible or quasi-incompressible approximation

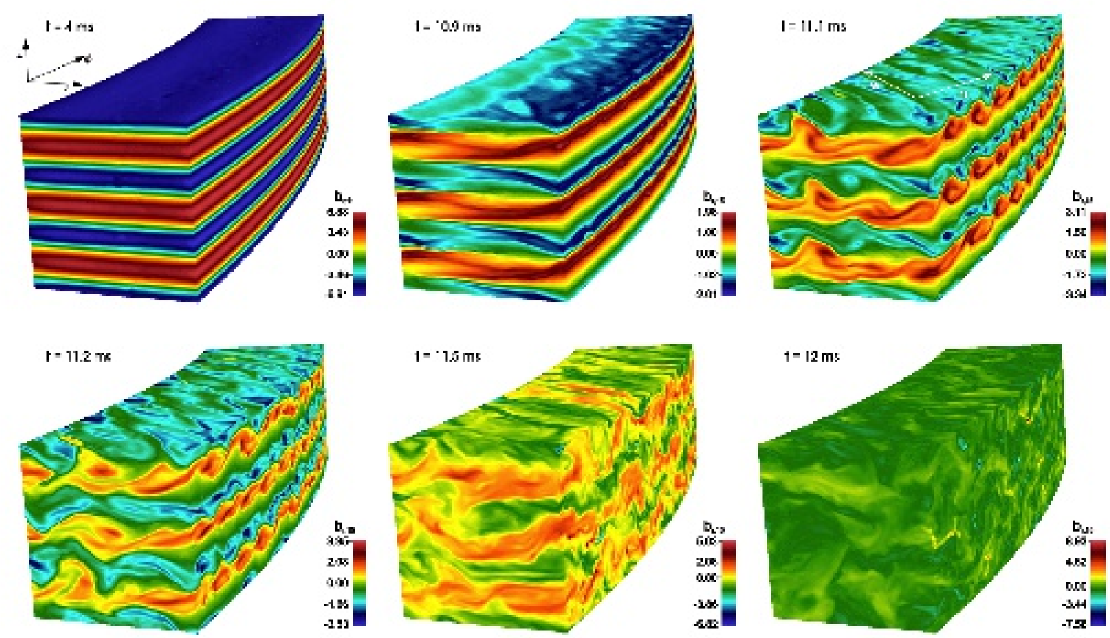


Obergaulinger+2009, Masada+2012,
Guilet+2015, Rembiasz+2016a,b

Channel mode termination by parasitic instabilities



Rembiasz et al. 2016a&b



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Buoyancy from entropy and lepton fraction gradients

Brünt-Väisälä frequency :

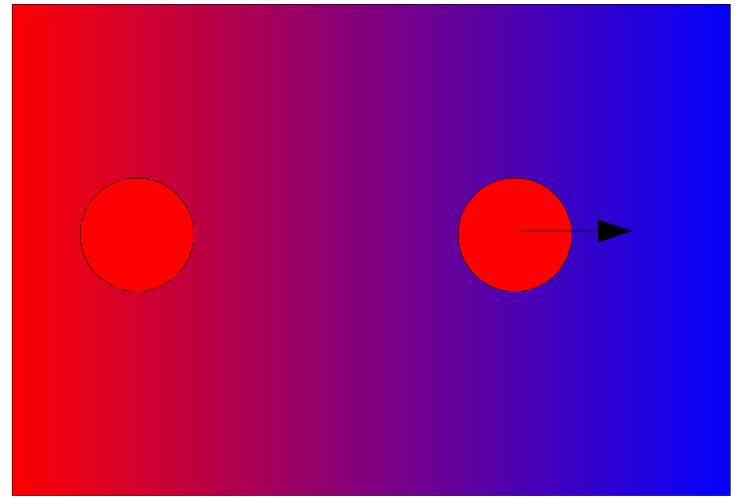
$$N^2 \equiv -\frac{g}{\rho}\left[\frac{\partial\rho}{\partial S}|_{P,Y_e}\frac{\mathrm{d}S}{\mathrm{d}r} + \frac{\partial\rho}{\partial Y_e}|_{P,S}\frac{\mathrm{d}Y_e}{\mathrm{d}r}\right]$$

Linear analysis of MRI with buoyancy :

stable buoyancy can stabilise the MRI

But : thermal diffusion allows the growth

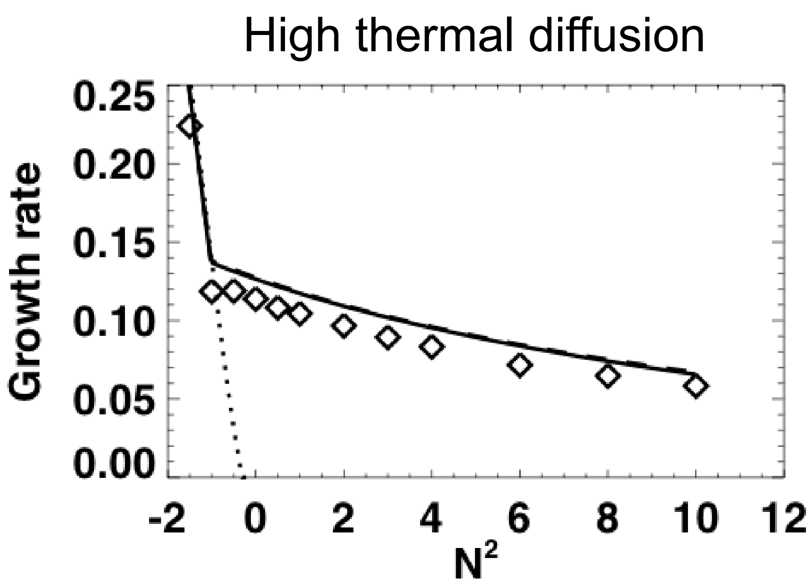
Balbus & Hawley (1994), Menou et al (2003), Masada et al (2007)

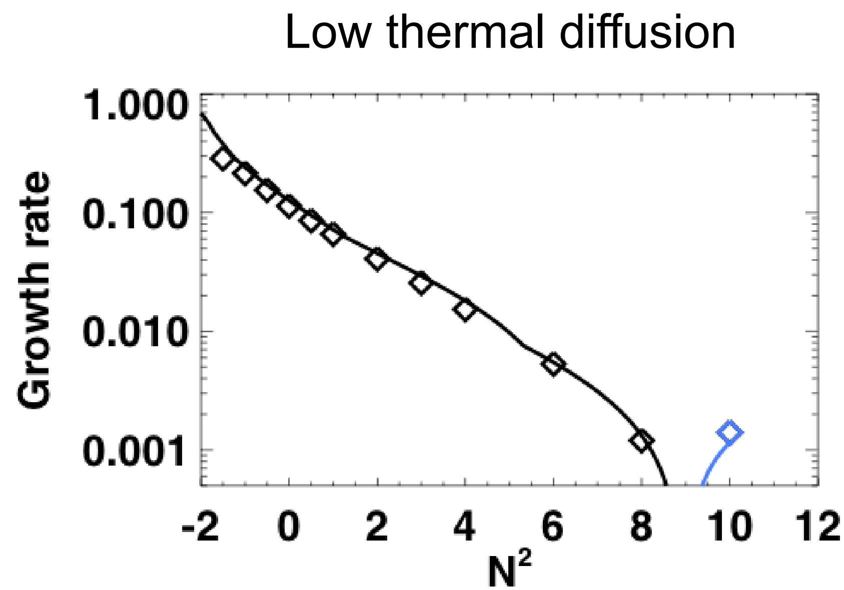


$N^2 \lessgtr 0$

radial displacement favored / suppressed

Linear MRI growth with buoyancy



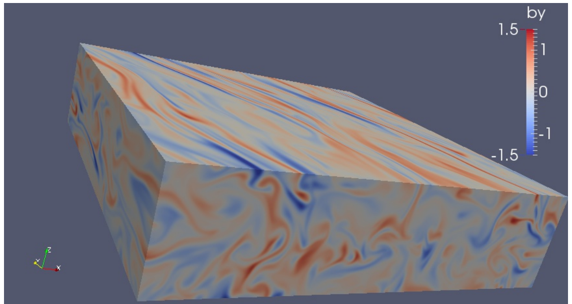


Confirms linear analysis :

thermal diffusion by neutrinos allows fast MRI growth

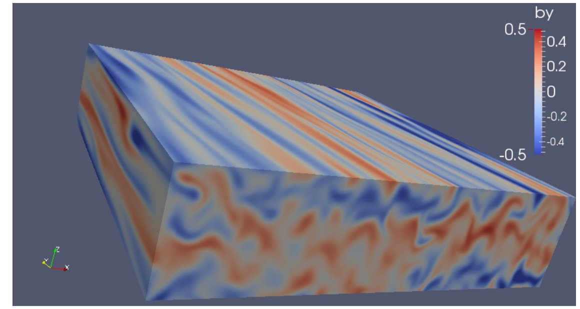
Impact of stratification on the MRI

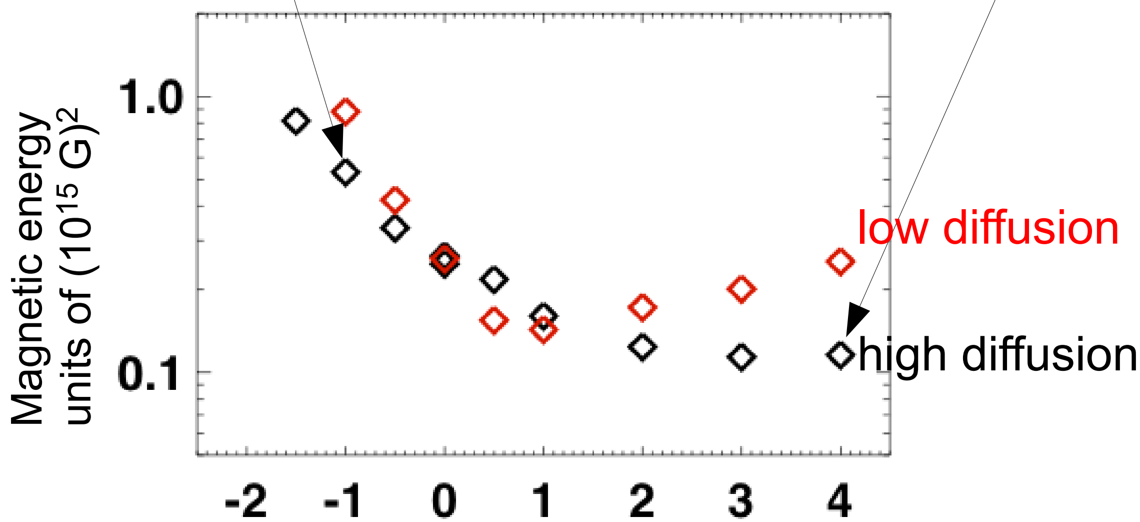
unstable buoyancy



color: azimuthal magnetic field

stable stratification





buoyancy parameter

Guilet & Müller (2015)

3. How strong is the final magnetic field ?

→ Channel mode termination

→ Influence of buoyancy

→ Dependence on the magnetic Prandtl number

→ The dawn of global simulations

Dependence on the magnetic Prandtl number

Neutrino viscosity : $\nu \sim 10^{10}\,\mathrm{cm}^2.\mathrm{s}^{-1}$

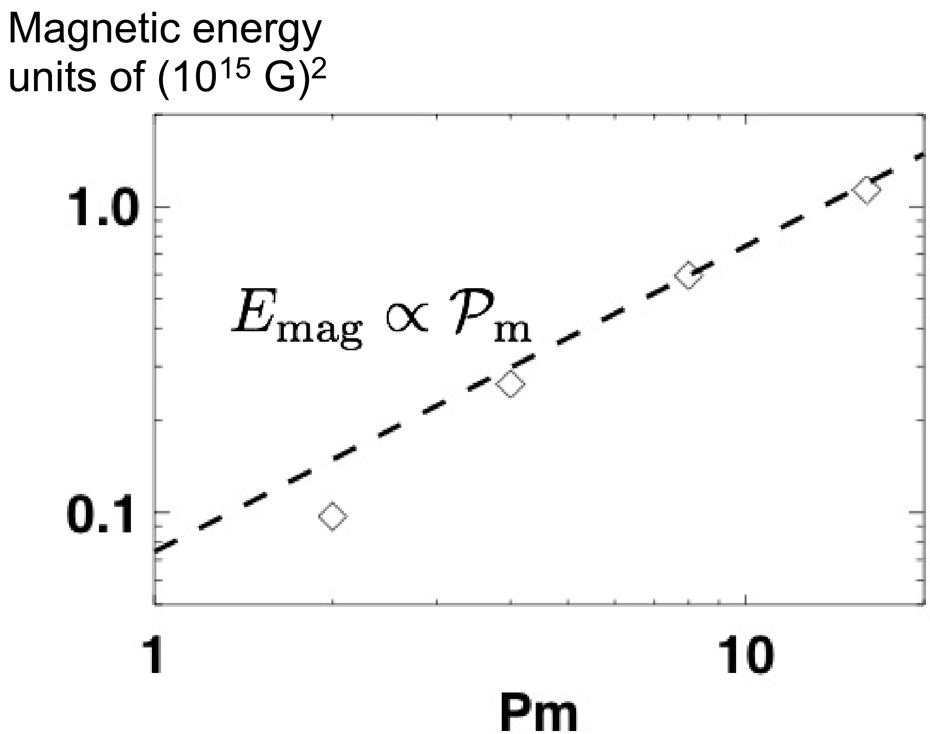
Resistivity : $\eta \sim 10^{-3}\,\mathrm{cm}^2.\mathrm{s}^{-1}$

Magnetic Prandtl number : $\mathcal{P}_m \equiv \frac{\nu}{\eta} \simeq 10^{13}$

Previous simulations used : $\mathcal{P}_m = 4$

Behaviour at very large magnetic Prandtl number ?

Dependence on the magnetic Prandtl number



Behaviour at very large magnetic Prandtl number ?

3. How strong is the final magnetic field ?

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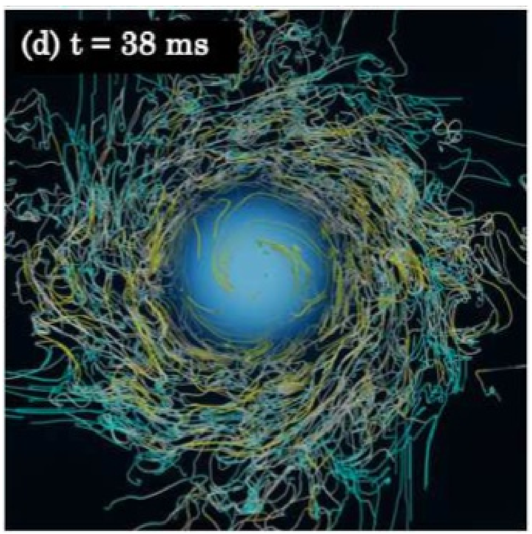
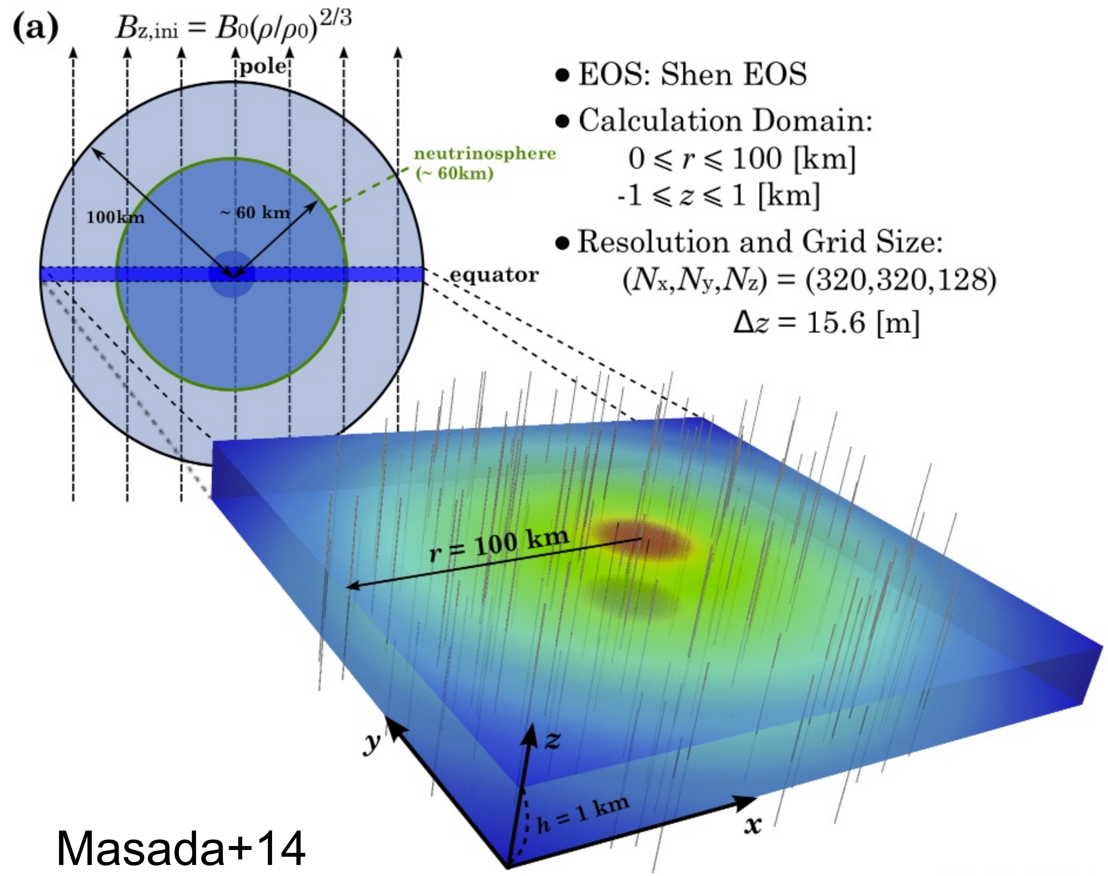
Semi-global simulations

Local in vertical direction
global in horizontal direction

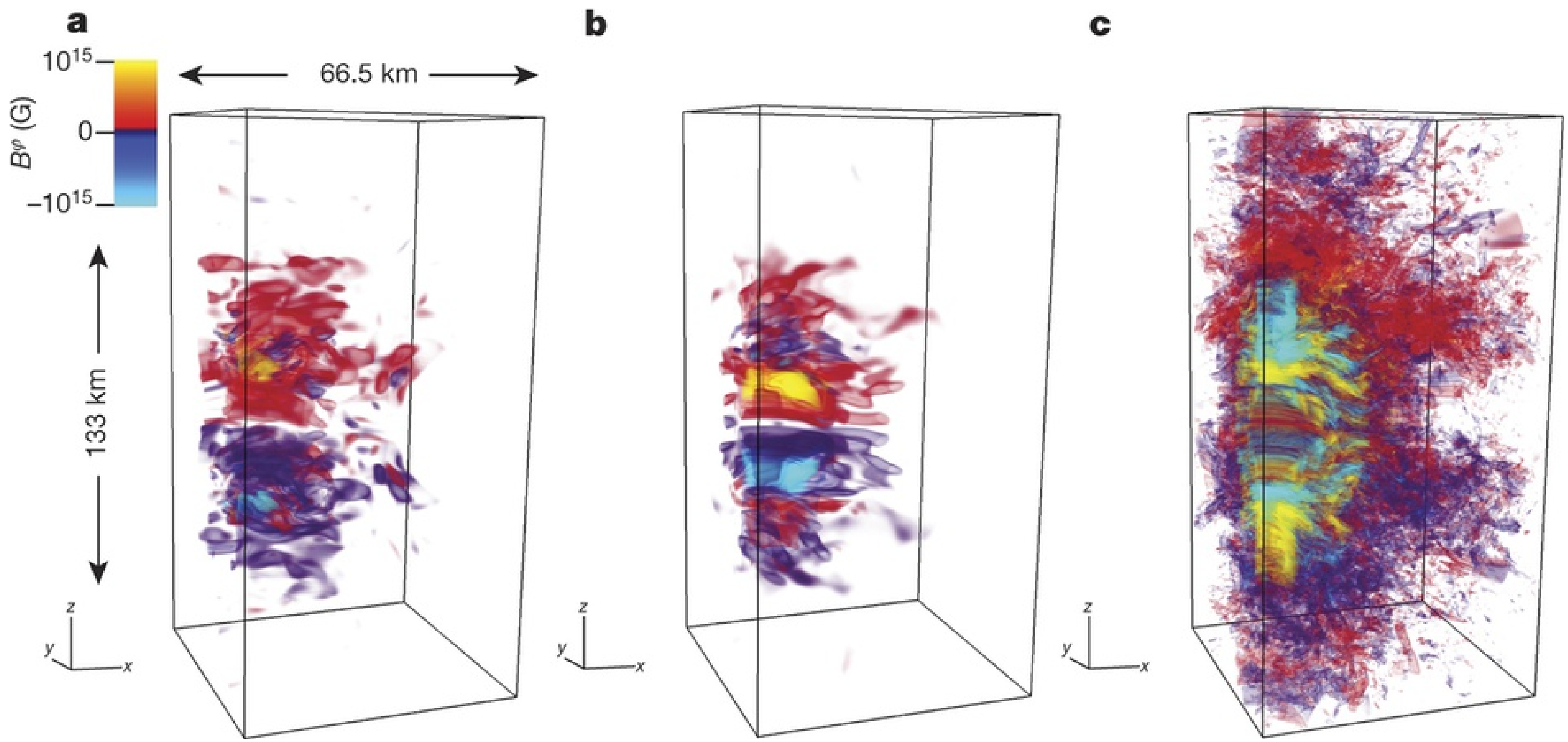
Good vertical resolution
but low horizontal resolution





Masada+14

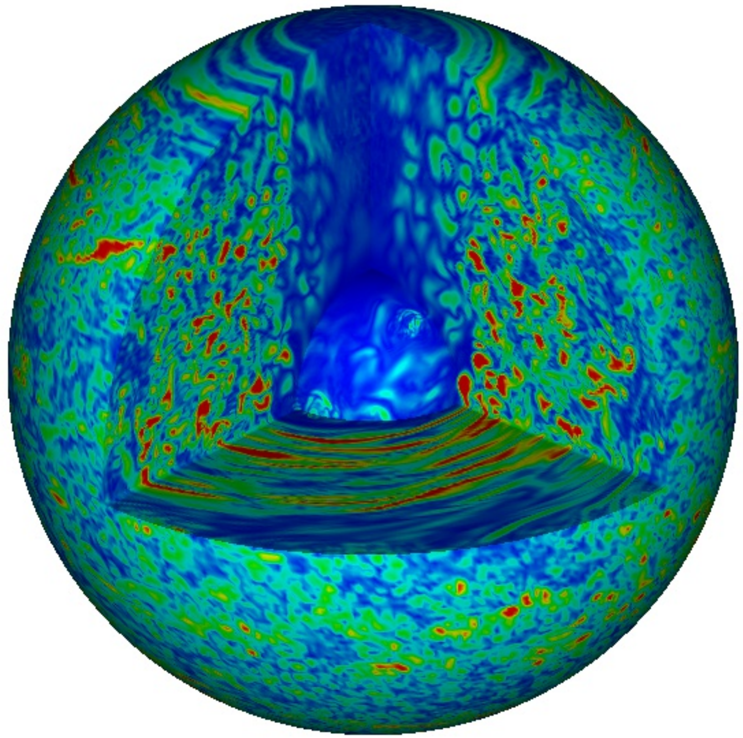
Global models



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

A simplified full-sphere MRI simulation

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



Summary

1. The MRI can grow in two different regimes :

   - Viscous regime deep inside the proto-neutron star :

     → requires a minimum initial magnetic field of ~10^{12} G

   - Neutrino drag near the surface of the proto-neutron star

2. Final magnetic field strength :

   - Stratification matters : sub-magnetar strength in stable regions

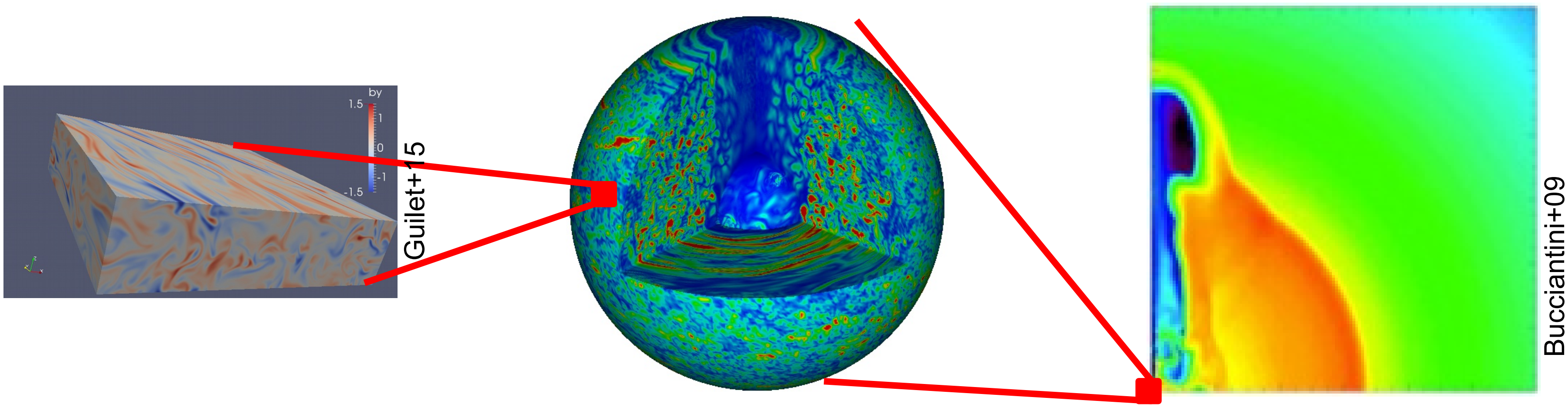
   - Strong dependence on the magnetic Prandtl number

     → MRI may be more efficient than simulations suggest !

   - Generation of a dipolar magnetic field is still an open question

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

Step 1 : local MRI model — Step 2 : global simulations — Step 3 : hypernova & GRB jet



~ 1-5 km — ~ 10-50 km — ~ 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 !