How to form a millisecond magnetar ?

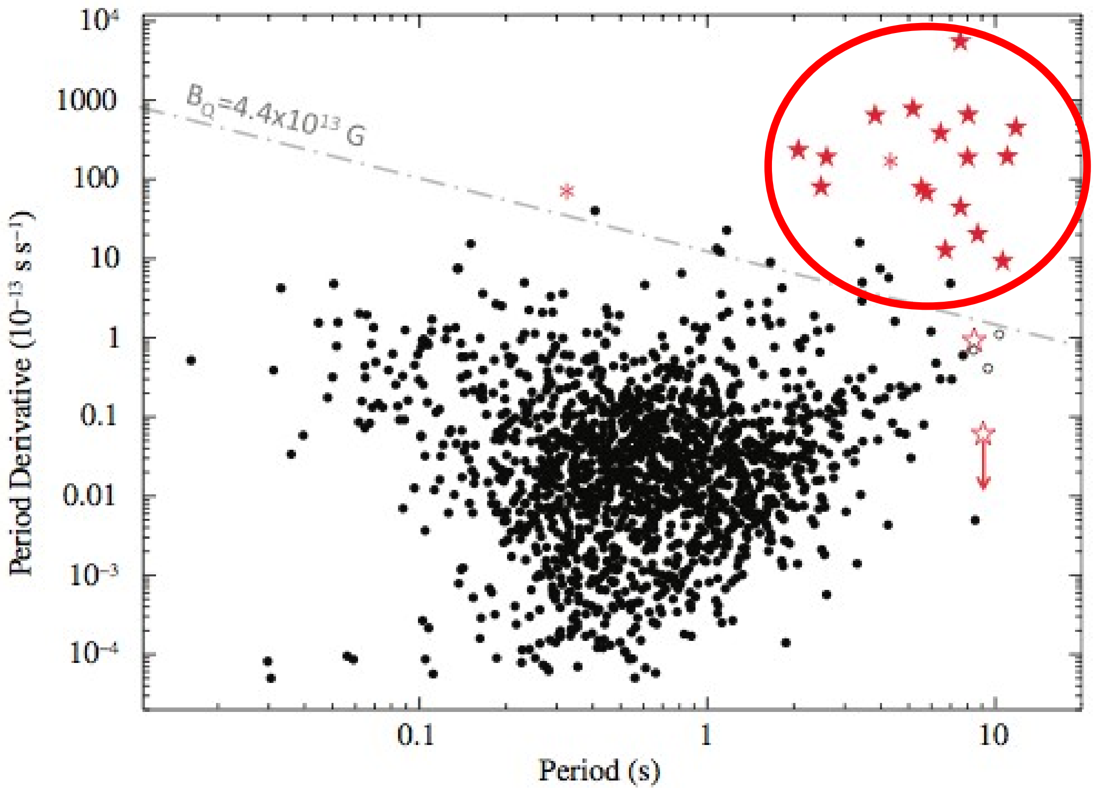
Magnetic field amplification in protoneutron stars

Jérôme Guilet
(CEA Saclay)

collaborators Ewald Müller, Thomas Janka, Oliver Just (MPA Garching)

Tomasz Rembiasz, Martin Obergaulinger, Pablo Cerda-Duran,
Miguel-Angel Aloy (Valencia)

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

→ 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 :

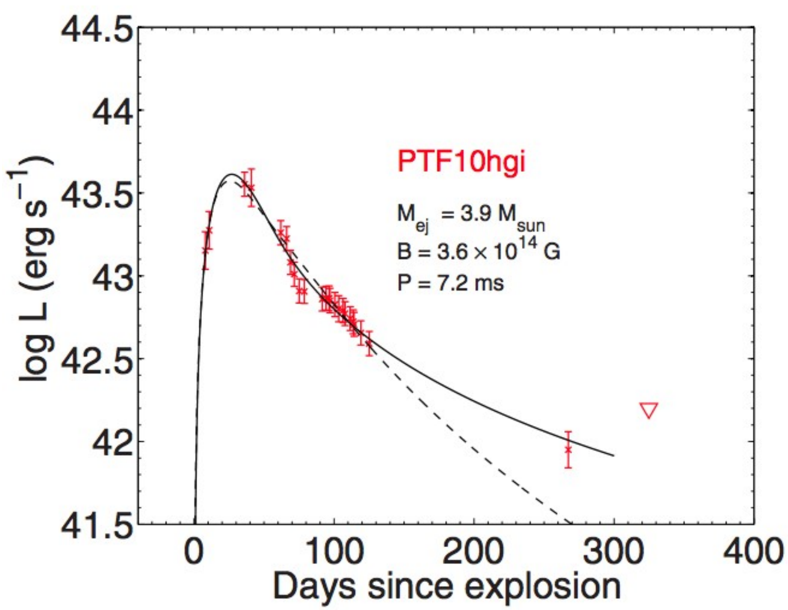
→ Typical supernova 10^{49} ergs

→ 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 ~ 10^{15} G

+ fast rotation (period of few milliseconds)

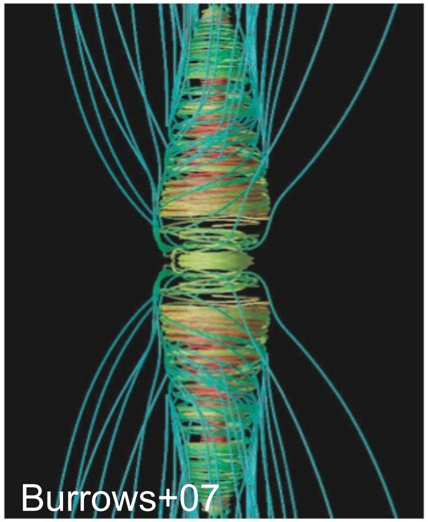
=> powerful jet-driven explosions !

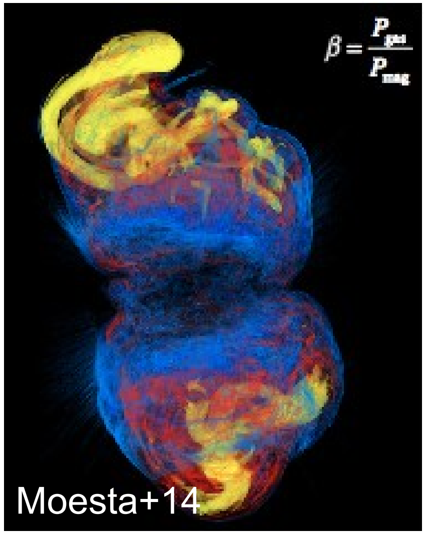
e.g. Sibata+06, Burrows+07, Dessart+08, Takiwaki+09,11, Winteler+12, Obergaulinger+17

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

Moesta+2014

Caveat: origin of the magnetic field is not explained


Burrows+07


Moesta+14

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 for numerical simulations of 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 : $\lambda \propto \frac{B}{\sqrt{\rho\Omega}}$

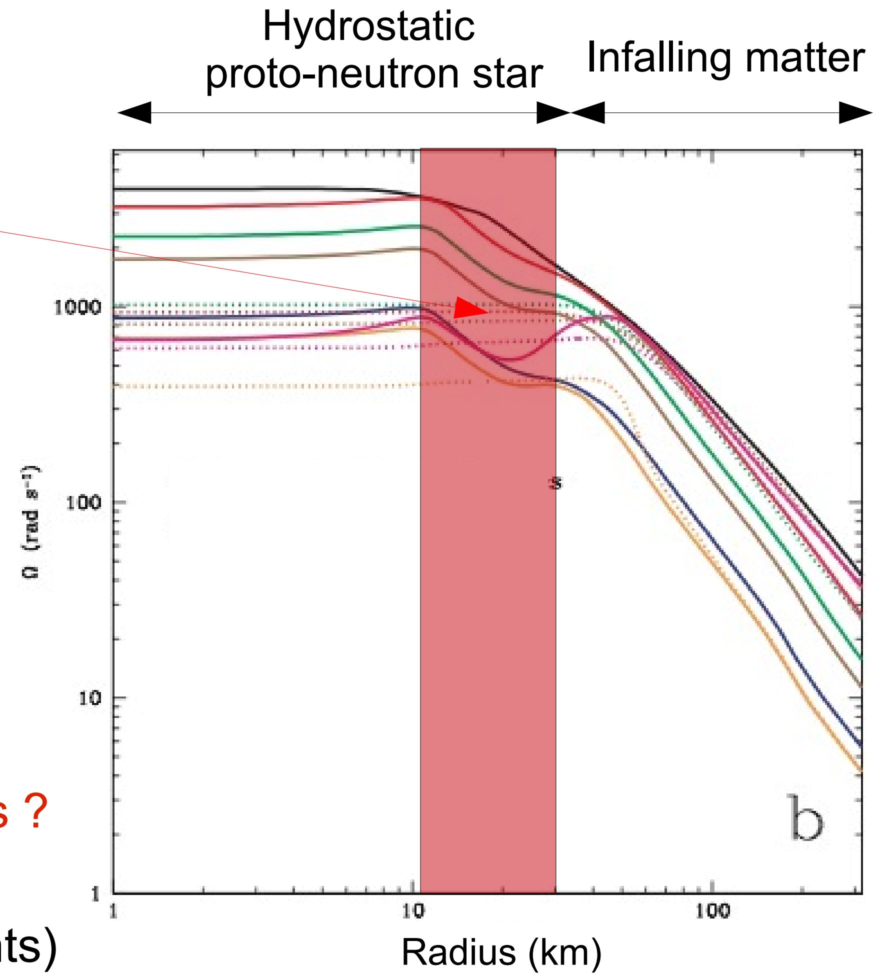
→ Short wavelength for weak magnetic field

Impact of conditions specific to protoneutron stars ?

→ neutrinos

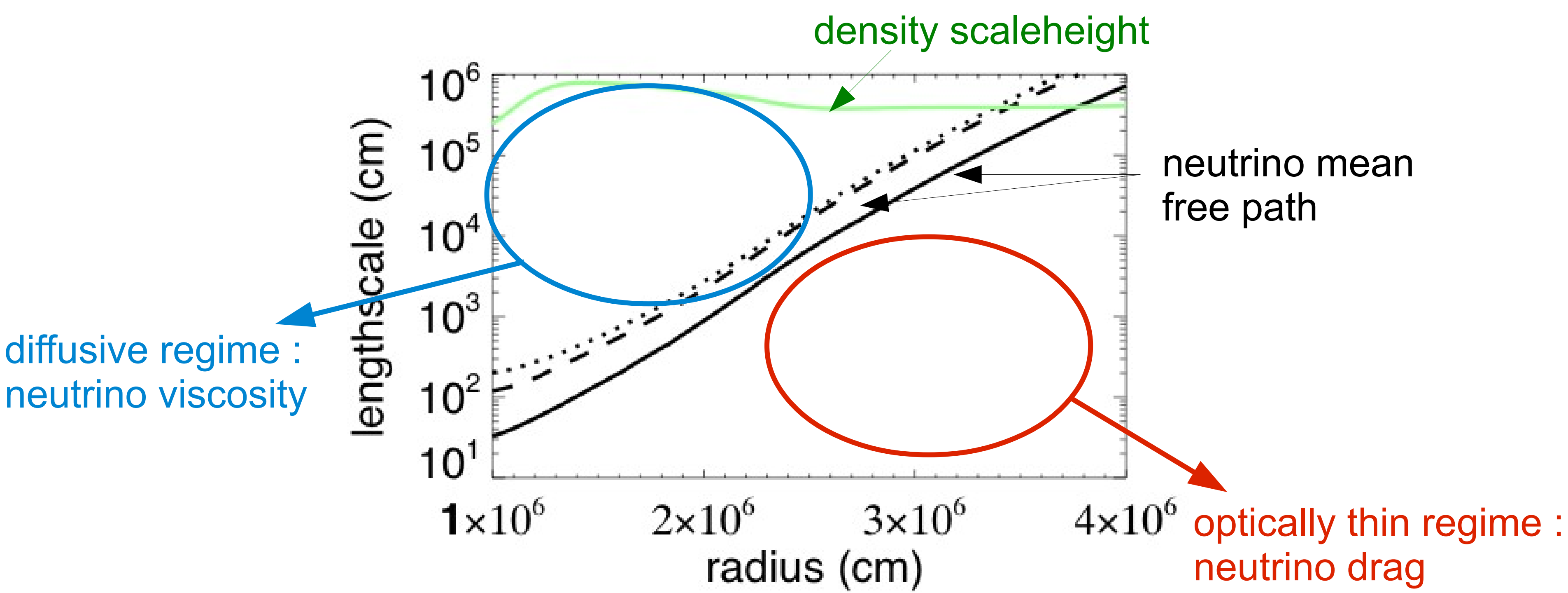
→ buoyancy (entropy & composition gradients)

→ spherical geometry



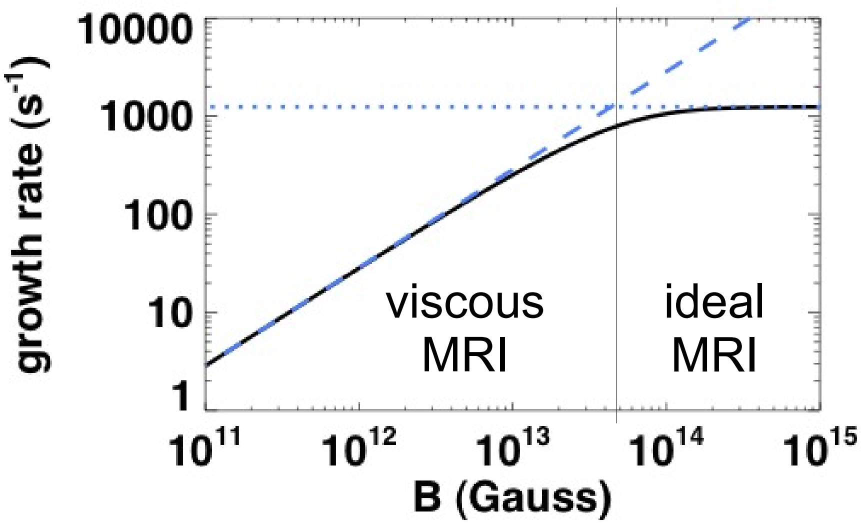
Ott et al (2006)

Impact of neutrinos on the MRI: two regimes

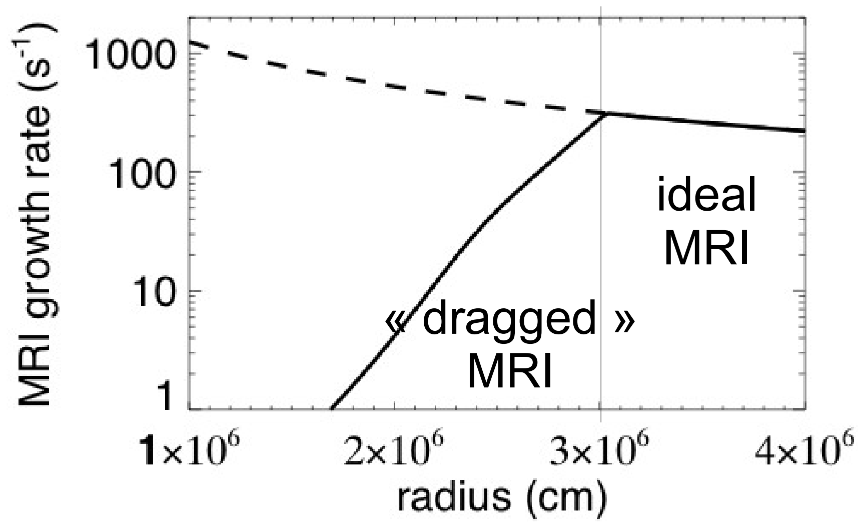


Impact of neutrinos on the MRI: growth rate

Viscous regime



Neutrino drag regime

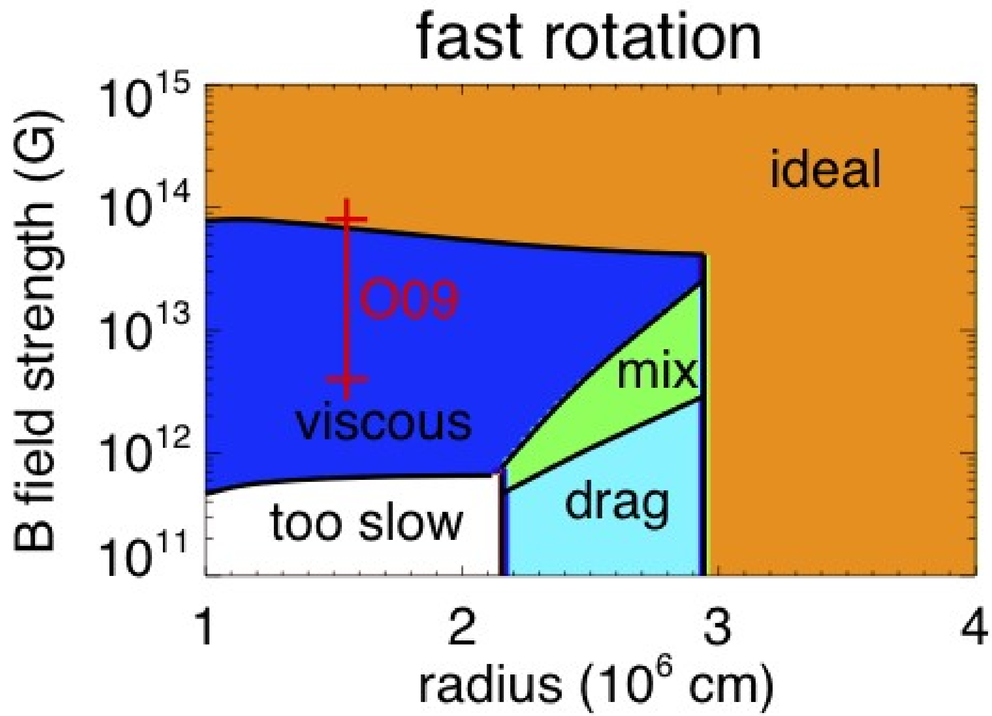


Slow growth for weak initial magnetic field < 10^{12} G

Fast growth near surface independently of field strength

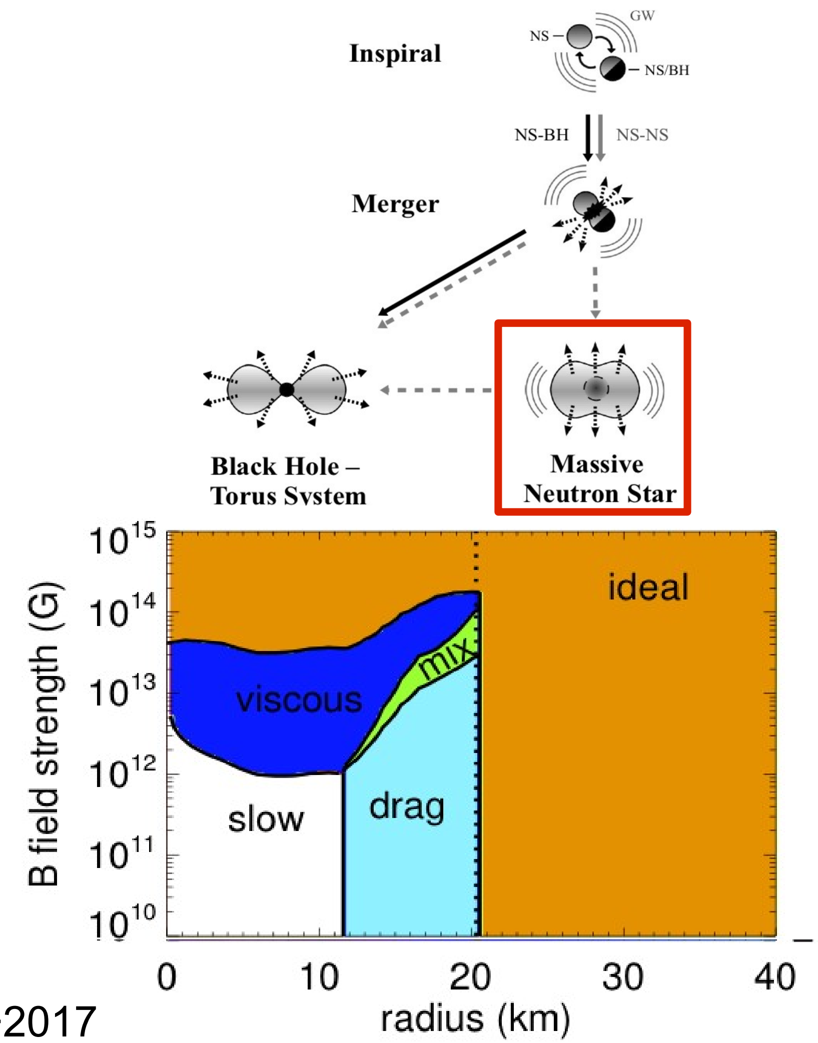
Guilet et al (2015)

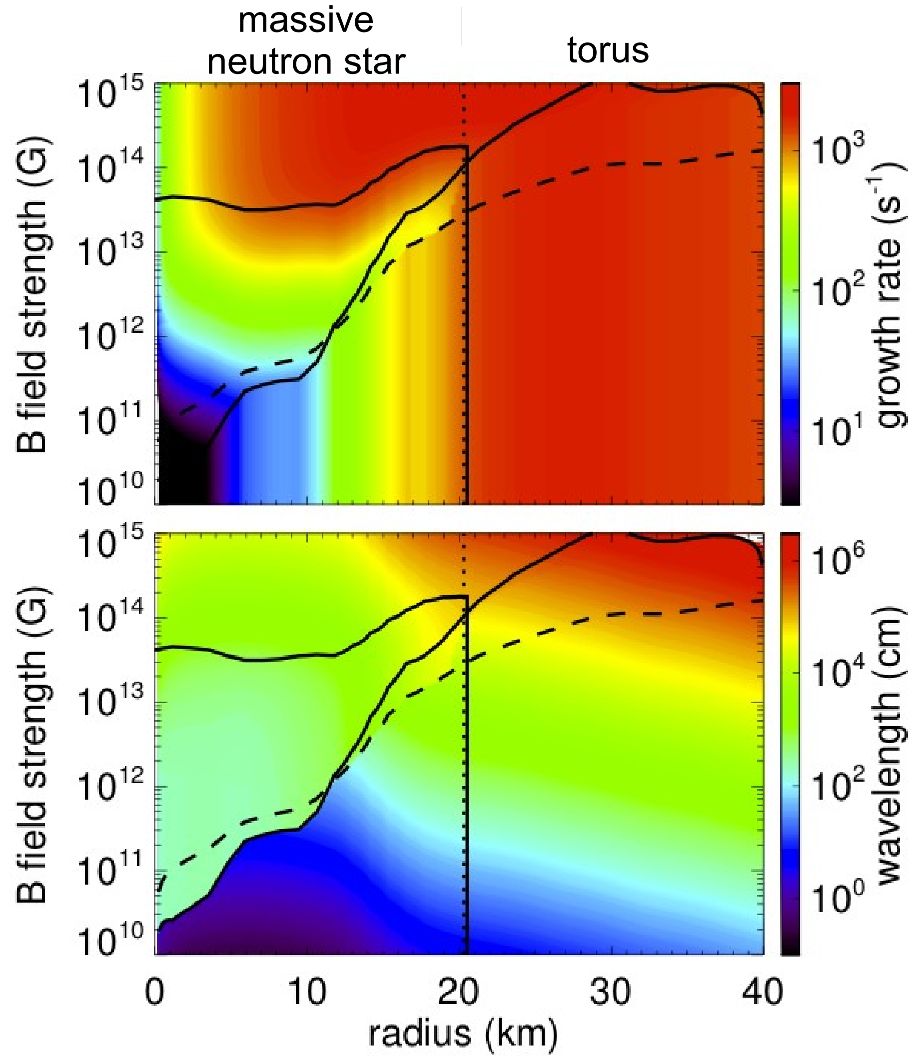
MRI growth: different regimes



Guilet et al (2015)

Application to neutron star mergers





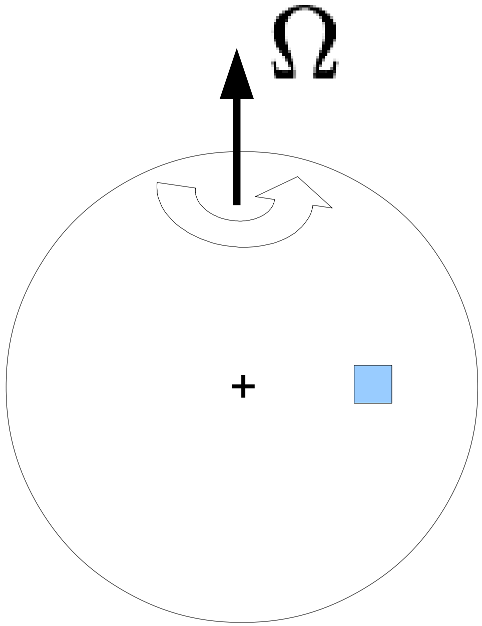
Guilet+2017

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 :

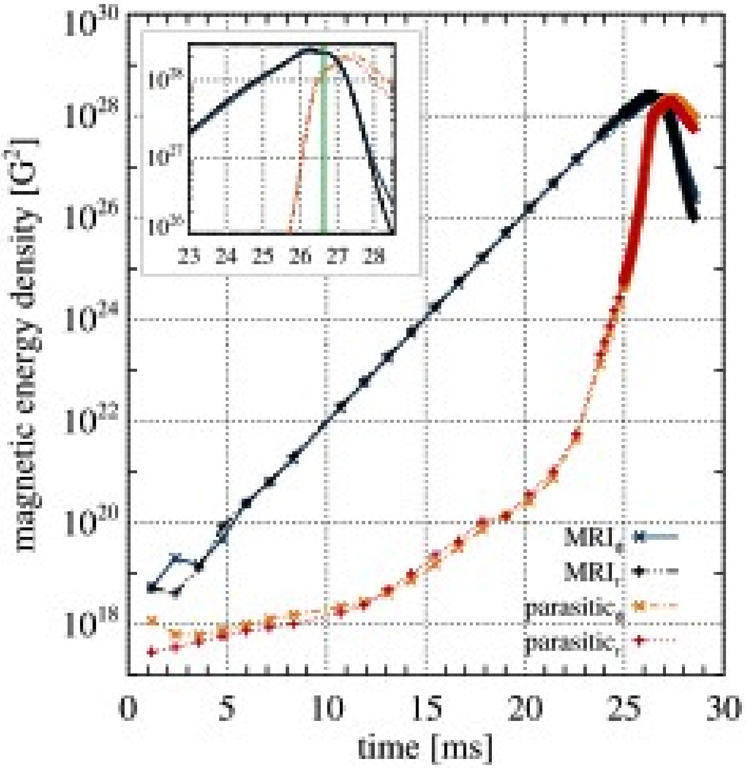
$\rho = 10^{13}\,\mathrm{g.cm^{-3}}$

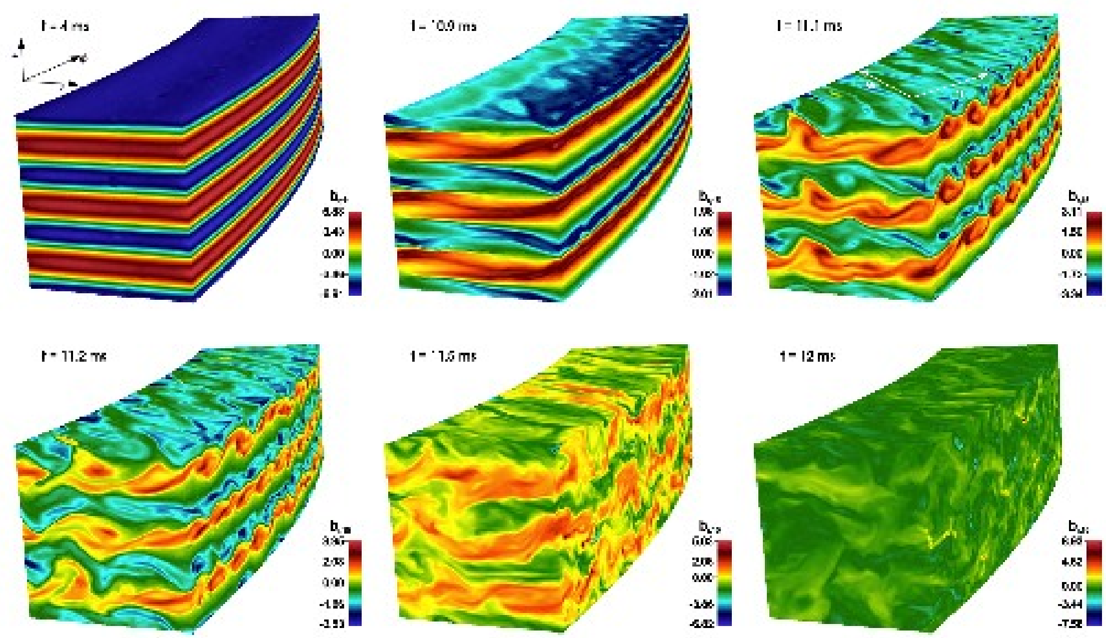
$B = 2\times10^{13}\,\mathrm{G}$

$\Omega = 2\times10^{3}\,\mathrm{s^{-1}}$

$\nu = 2\times10^{10}\,\mathrm{cm^2.s^{-1}}$

Channel mode growth & termination

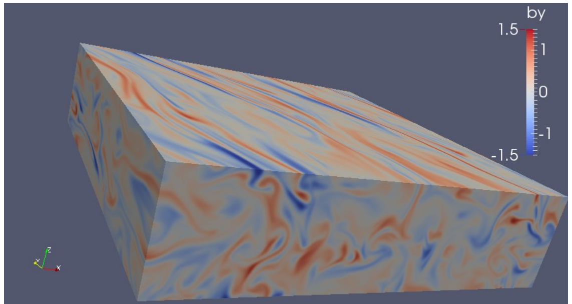




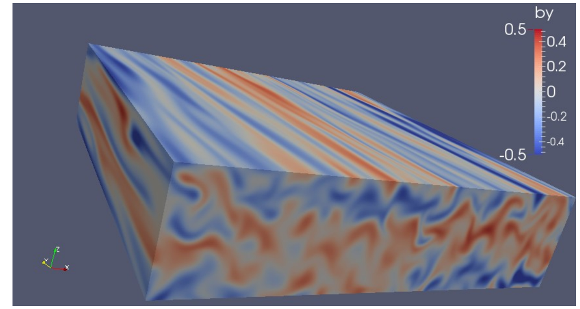
Rembiasz et al. 2016a&b

Impact of stratification on the MRI

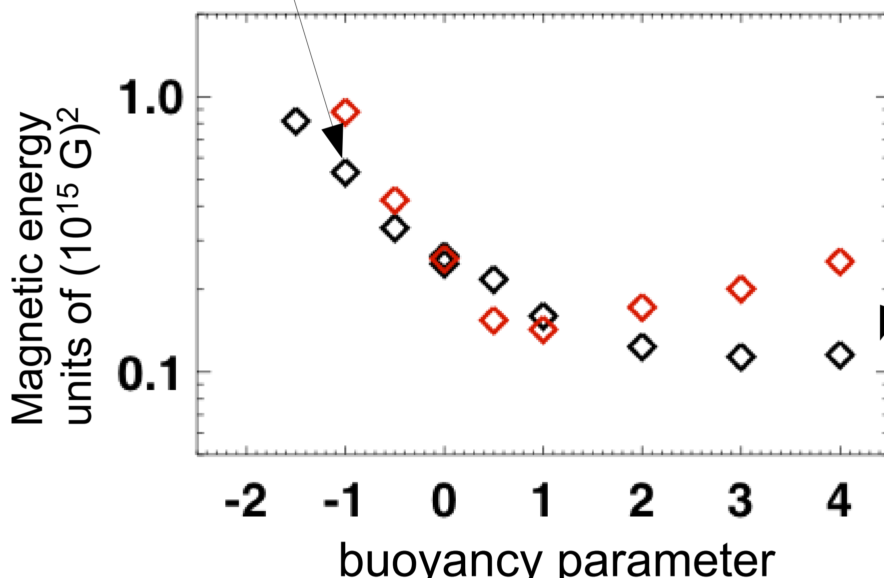
unstable buoyancy



stable stratification

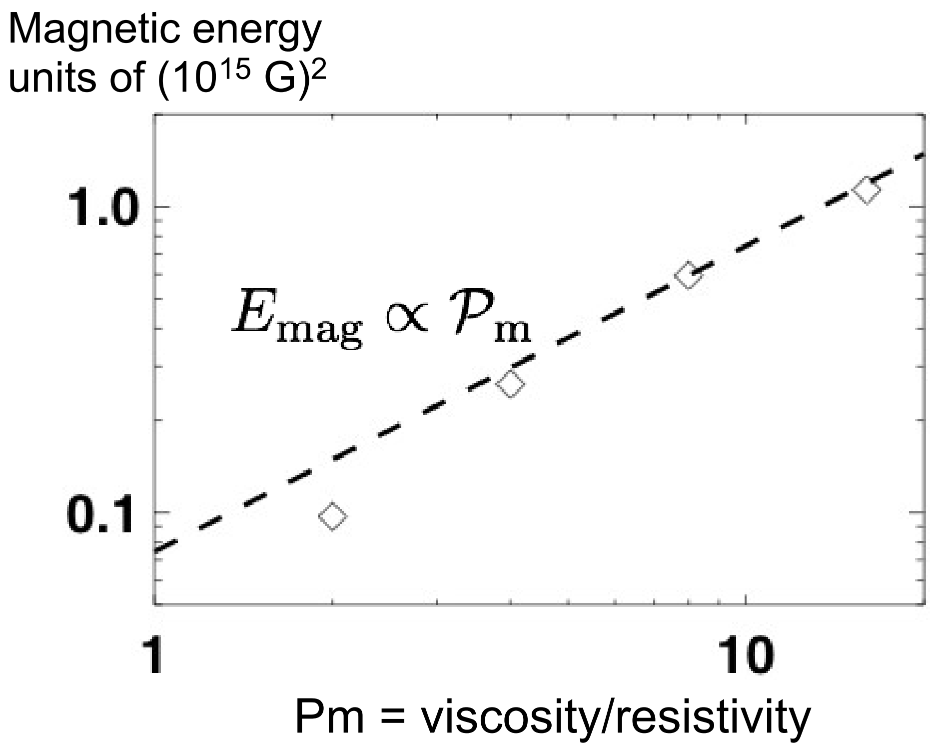


color: azimuthal magnetic field



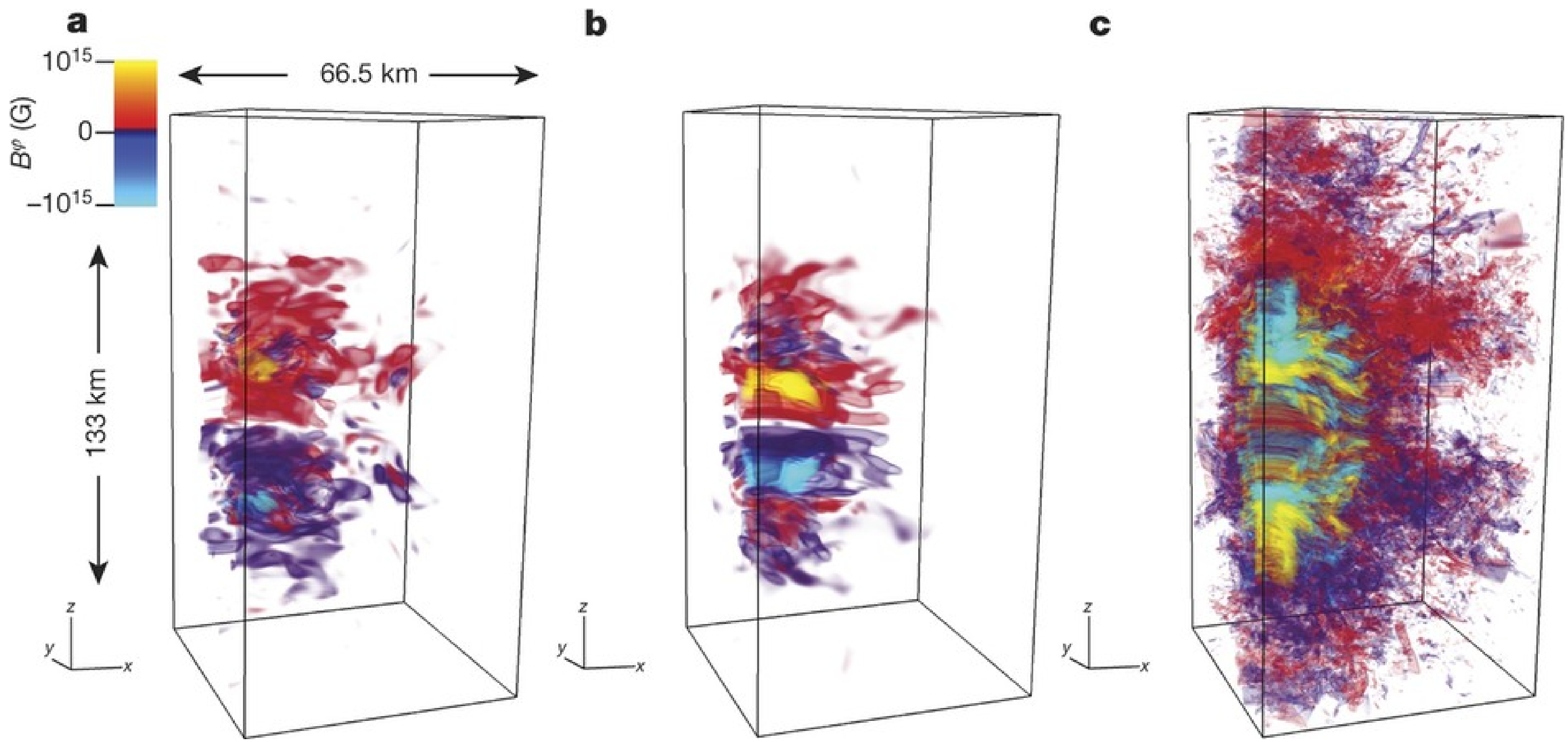
Guilet & Müller (2015)

Dependence on diffusion processes



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

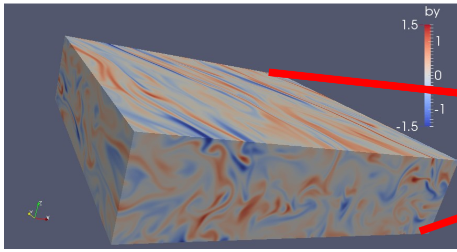
Global models: geometry of the magnetic field ?



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



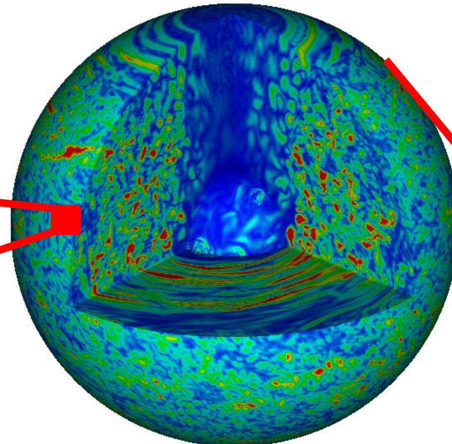
Guilet+15

~ 1-5 km

High Pm regime ?

Neutrino drag regime ?

Step 2: global simulations

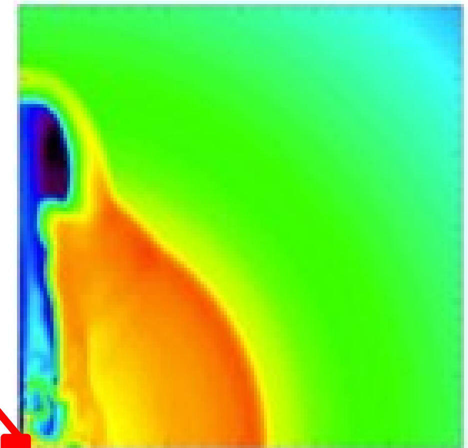


~ 10-50 km

Magnetic field geometry ?

MRI vs convective dynamo

Step 3: hypernova & GRB jet



Bucciantini+09

~ 10^5-10^6 km

Explosion diversity ?

Energy, jet properties etc.

ERC project MagBURST

erc

Raphaël Raynaud

Matteo Bugli

Thanks !