

Supernovae extrêmes: hypernovae, sursauts gamma, supernovae superlumineuses

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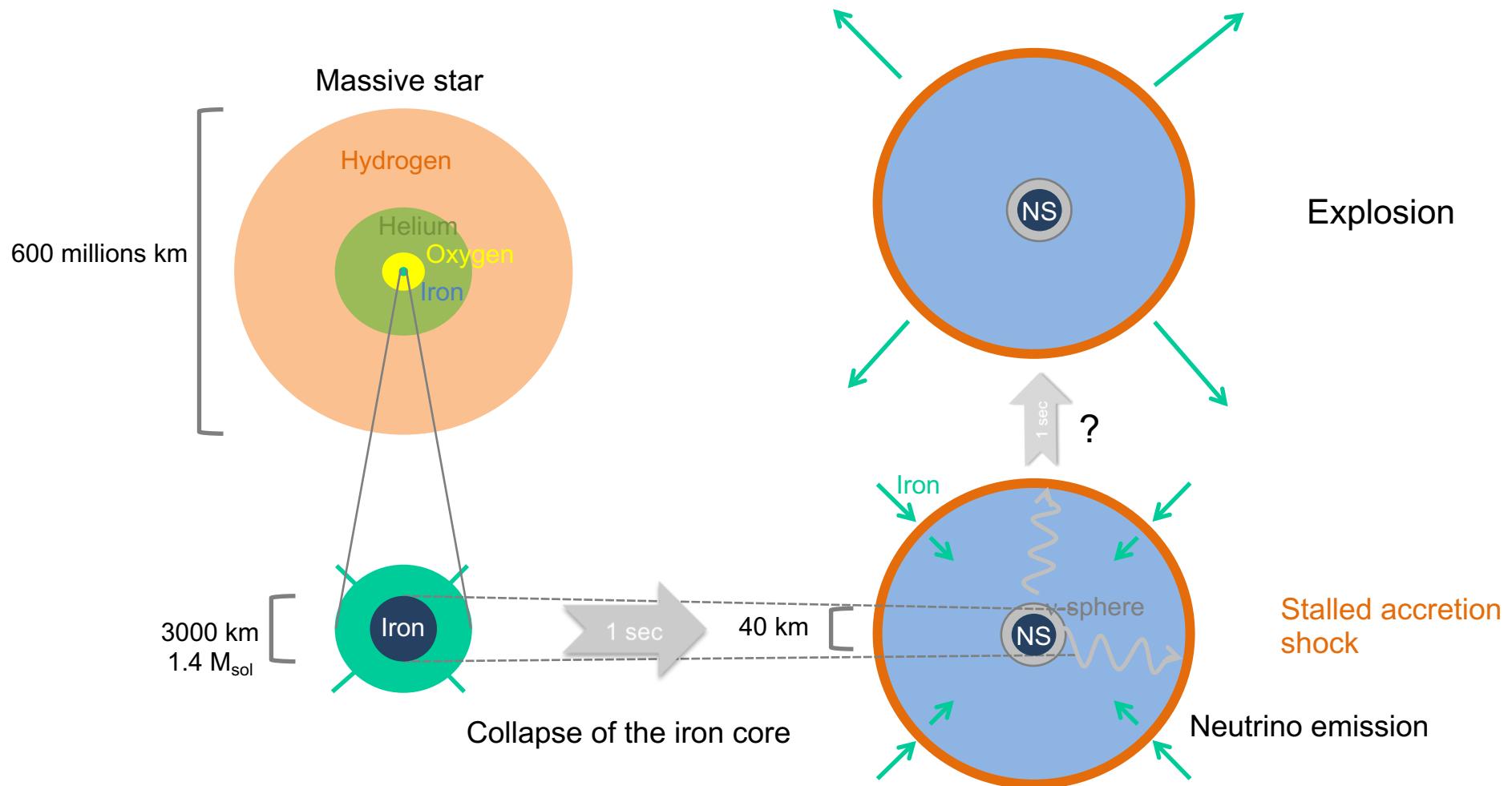
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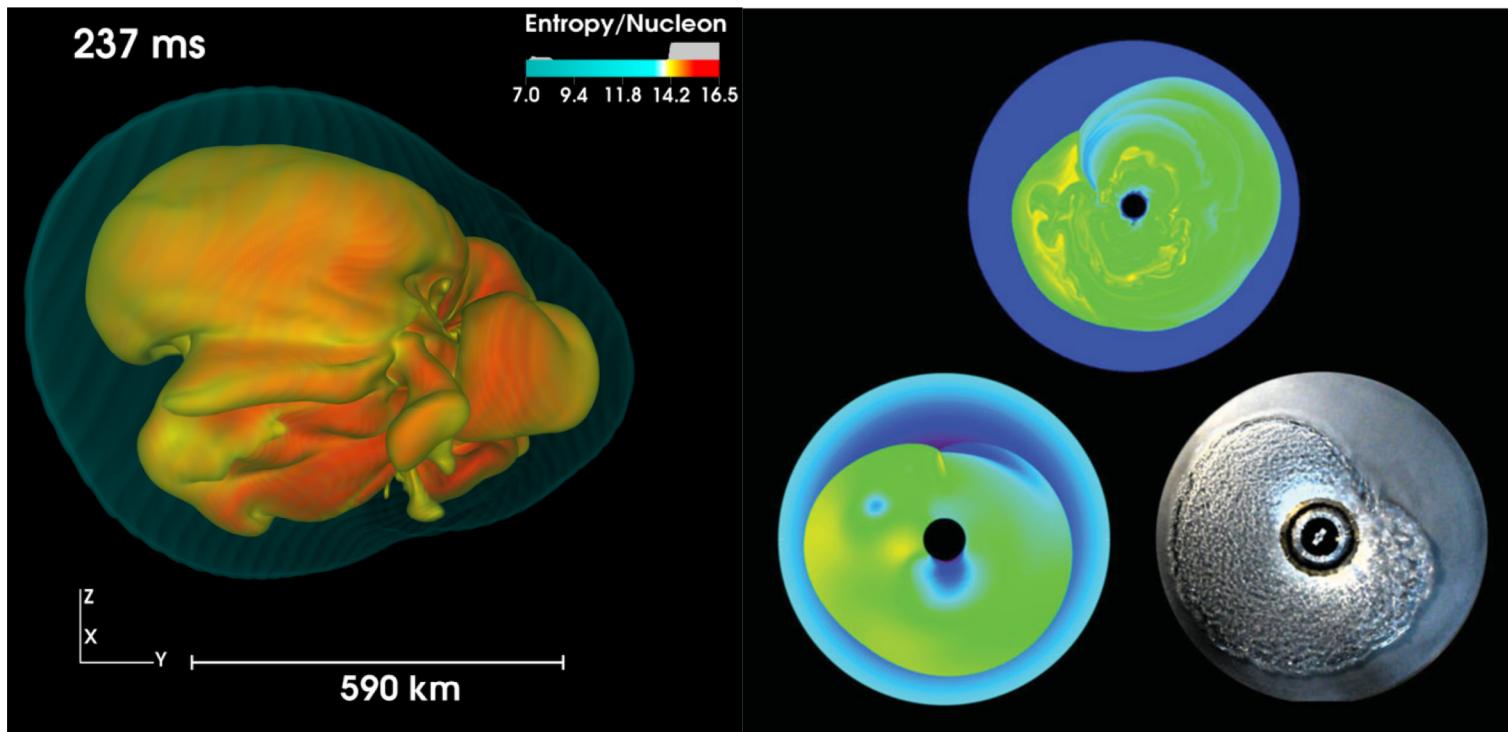
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Core collapse: formation of a neutron star



Normal supernovae: neutrino driven explosions aided by hydrodynamical instabilities ?



Summa et al (2018)

Foglizzo et al (2015)

Agreement on the crucial role of neutrinos and hydrodynamic instabilities but no consensus yet on detailed modelling

Outstanding explosions: magnetorotational explosions ?

Explosion kinetic energy :

- Typical supernova 10^{51} erg
- Rare hypernova & GRB aka type Ic BL 10^{52} erg

→ Neutrino driven explosions ?

→ Magnetorotational explosion ?

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

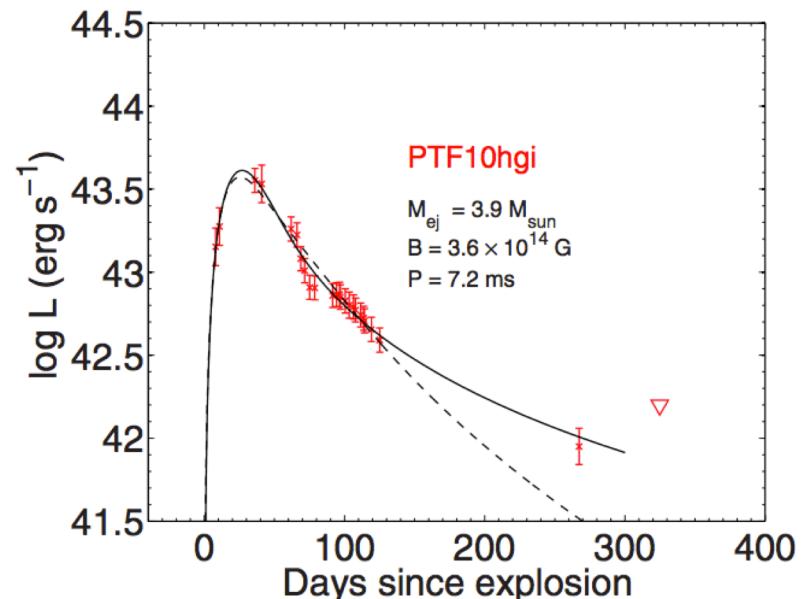
Total luminosity :

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

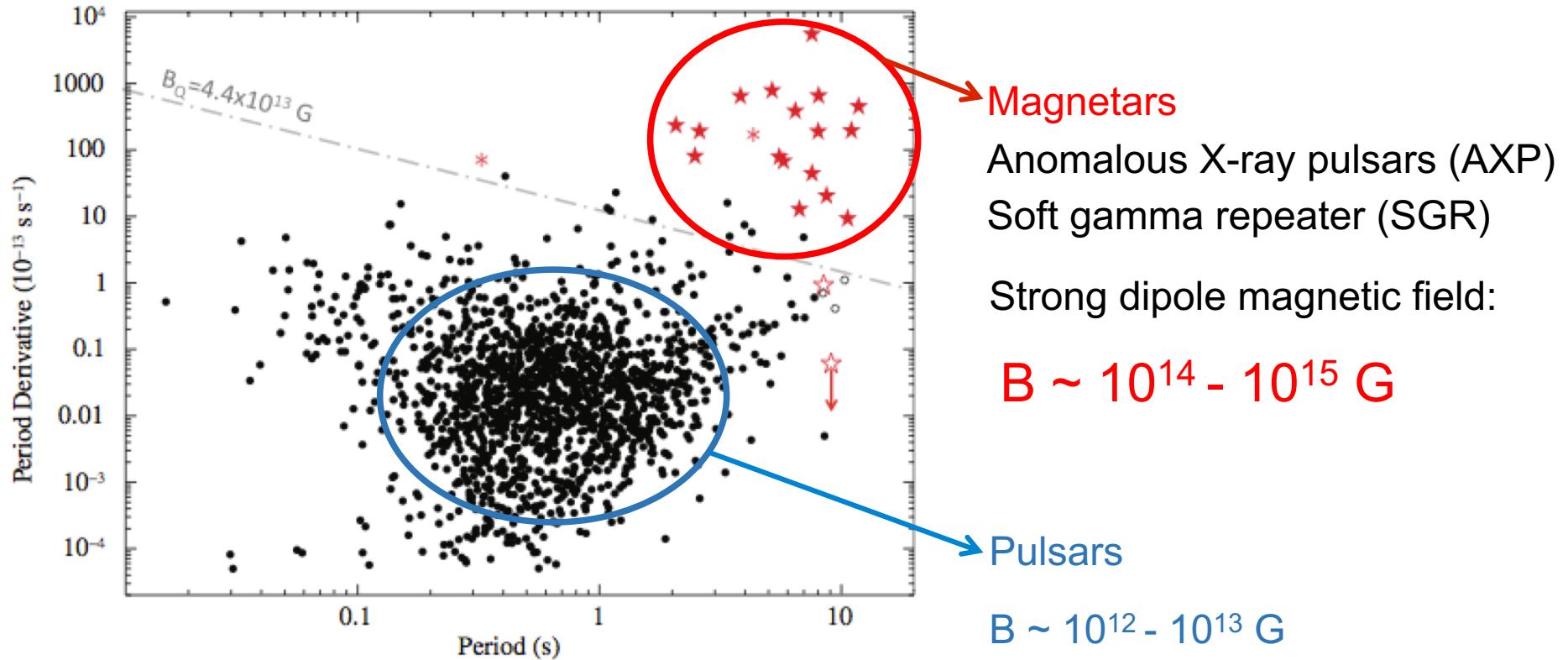
Light curves can be fitted by millisecond magnetar

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

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

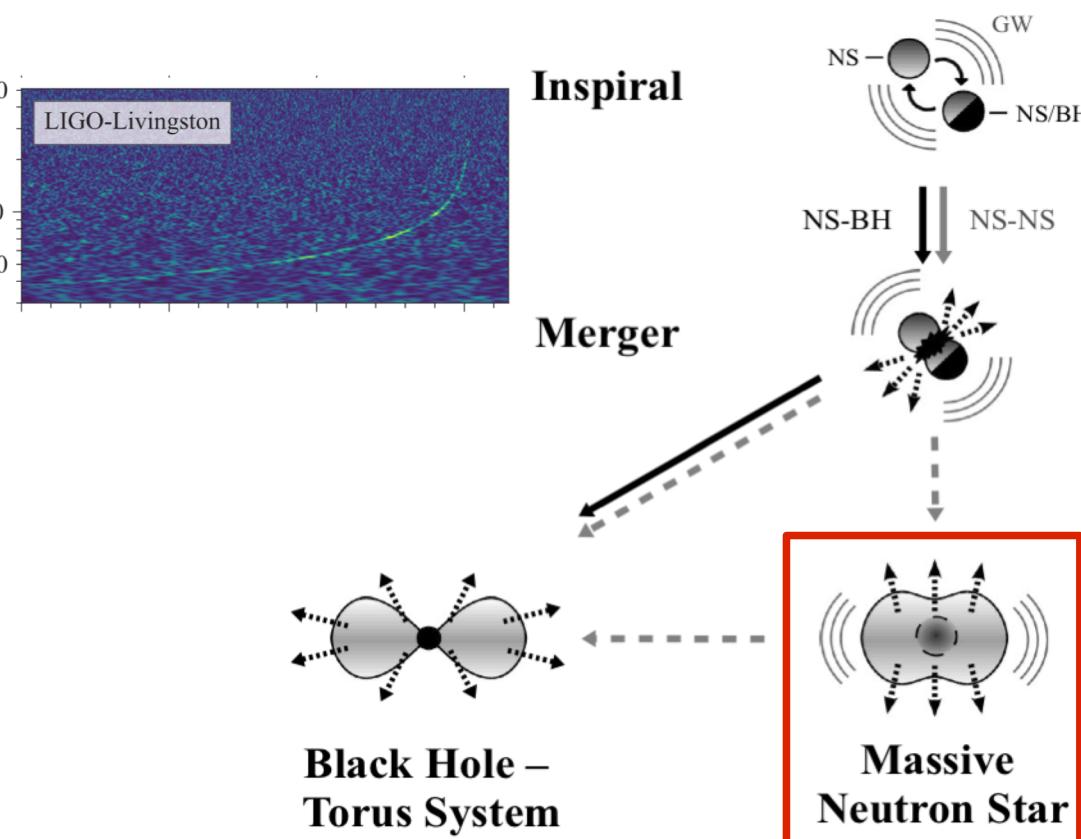


Magnetars: the most intense known magnetic fields



Which supernovae are associated to magnetar birth ?

A magnetar formed in NS mergers ?



3 possibilities :

- direct collapse to a black hole
- hypermassive NS stabilized by rotation : delayed collapse
- stable neutron star

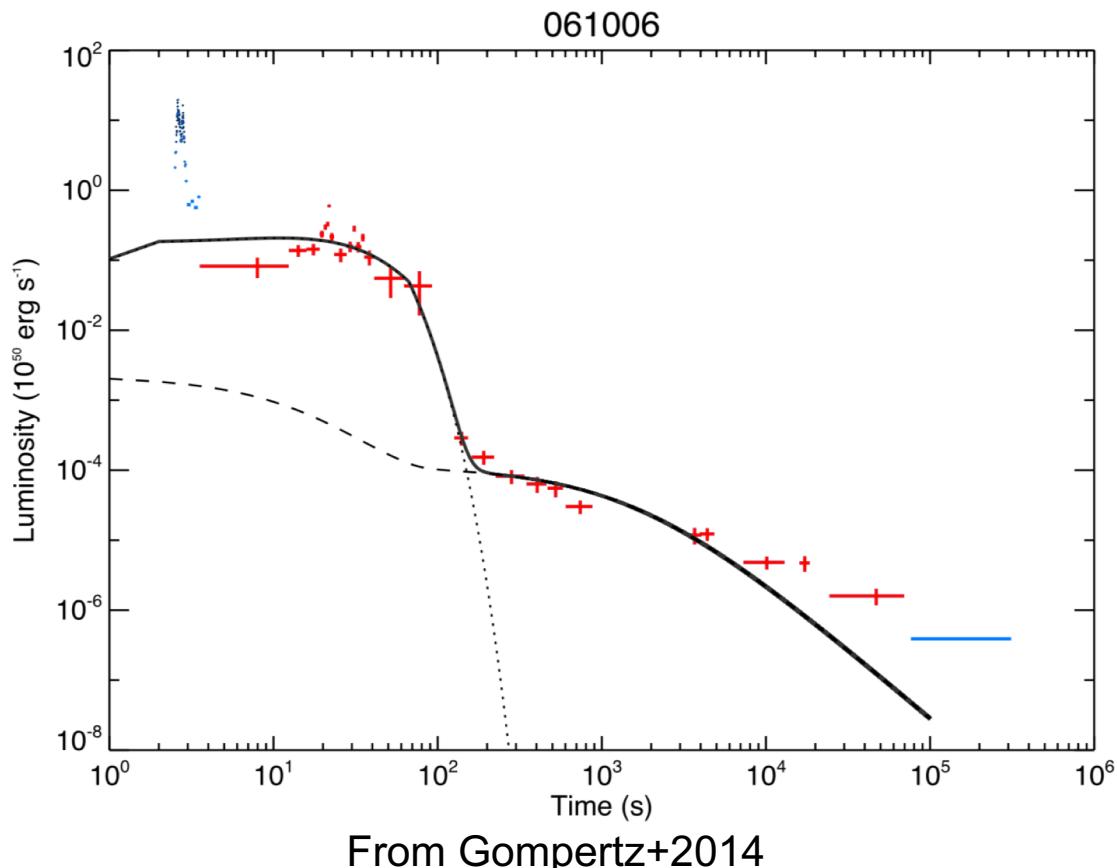
Formation of a magnetar ?

Signature in future joint gravitational wave – electromagnetic obervations ?



Launch : end of 2021

GRBs: Extended emission and X-ray plateaus from magnetars ?



Extraction of the magnetar rotation energy (up to 10^{53} erg):

- Dipole spin-down in vacuum

$$T_{\text{sd}} \sim 2 \times 10^3 \text{ s} (B/10^{15} \text{ G})^{-2} (P/1 \text{ ms})^2$$

$$L_{\text{dip}} \sim 10^{49} \text{ erg/s} (B/10^{15} \text{ G})^2 (P/1 \text{ ms})^{-4} \times (1 + t/T_{\text{sd}})^{-2}$$

Zhang+2001, Fan&Xu2006, Metzger+2008, Rowlinson+2010, 2013, Gompertz+2013,2014, Lu+2015, Gao+2016

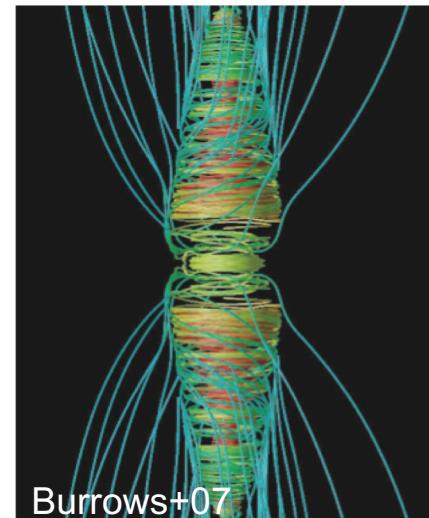
Impact of a strong magnetic field on the explosion

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

+ fast rotation (period of few milliseconds)

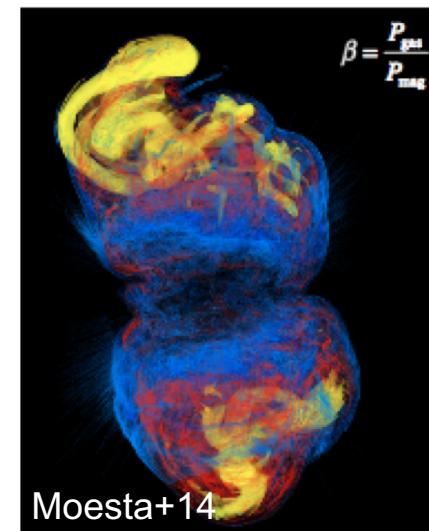
=> powerful jet-driven explosions !

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



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

Moesta+2014



Caveat: origin of the magnetic field is not explained

Theoretical open question: magnetic field origin



Compression of stellar field in core collapse supernovae: $< 10^{12}\text{-}10^{13}$ G (?)

Magnetic field of NS before merger: $10^8\text{-}10^{12}$ G

Magnetar: 10^{15} G

Amplification mechanism ?

Magnetorotational instability

Similar to accretion disks

Talks by Jean-Pierre Lasota
Nicolas Scepi
Antoine Riols

Convective dynamo

Similar to planetary & stellar dynamos

Amplification mechanism: magnetorotational instability (MRI)

MRI in its simplest form (ideal MHD):

Instability criterion

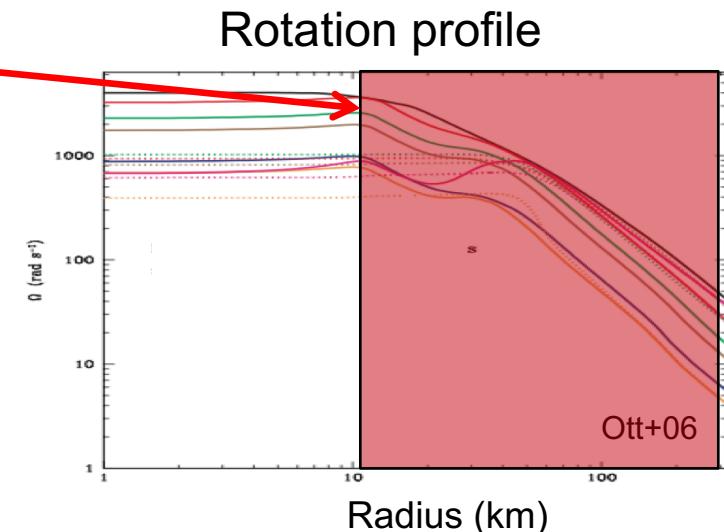
$$\frac{d\Omega}{dr} < 0$$

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



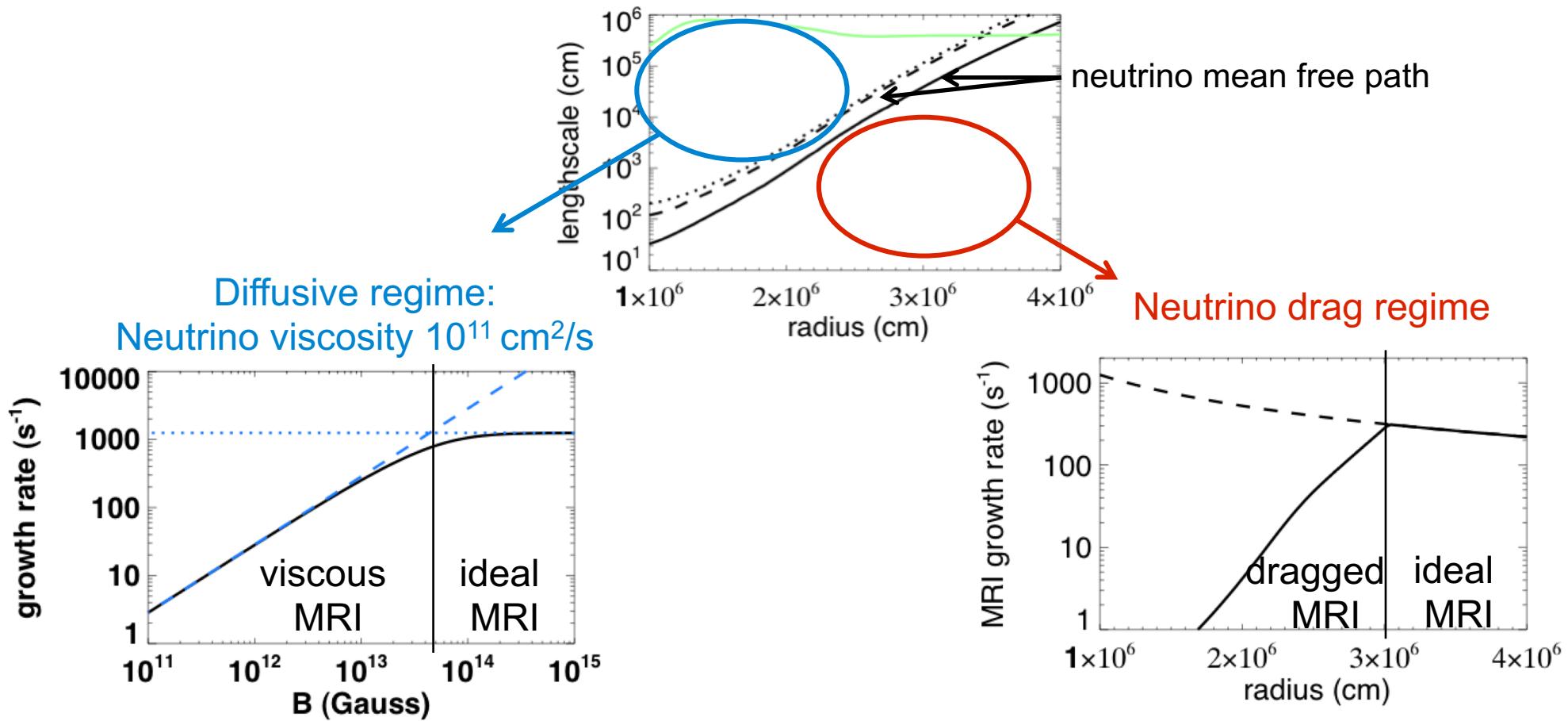
Impact of conditions specific to neutron stars ?

→ neutrinos

→ buoyancy (entropy & composition gradients)

→ spherical geometry

Impact of neutrinos on the MRI: growth rate

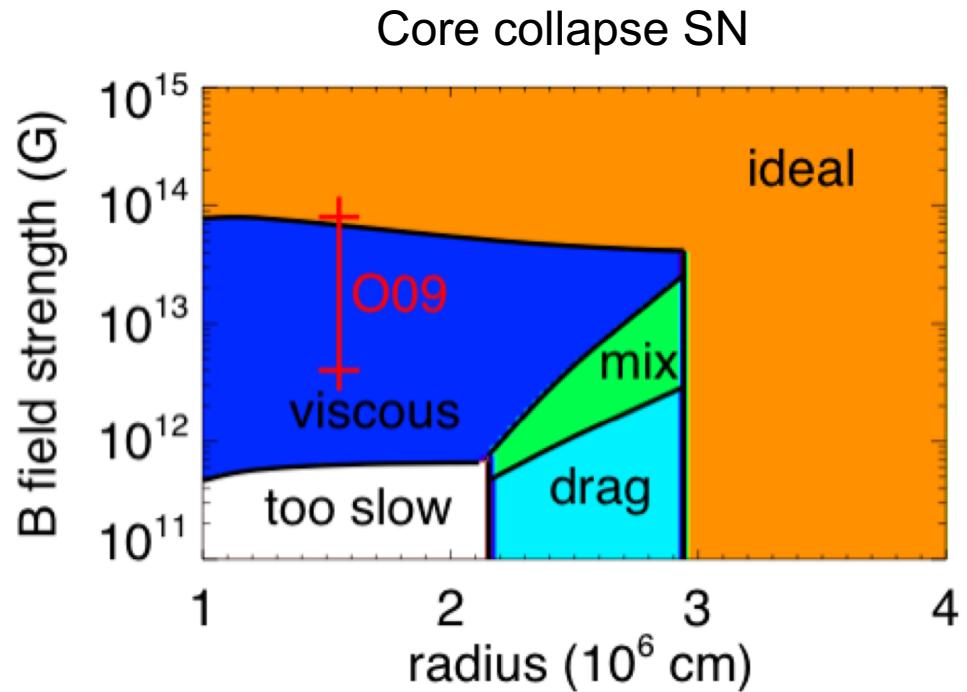
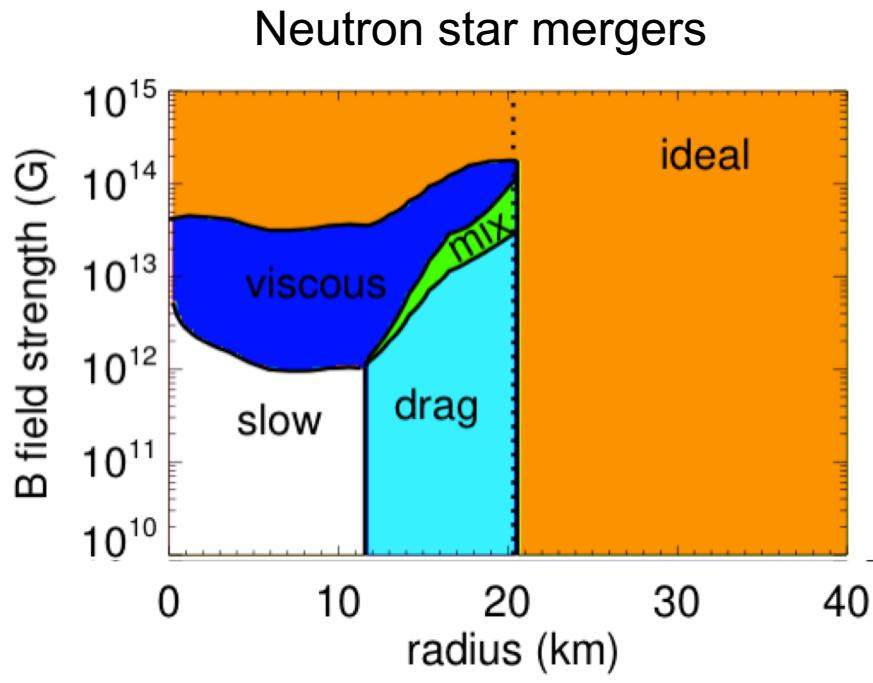


Slow growth for weak initial magnetic field $< 10^{12}$ G

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

Fast growth near surface
independently of field strength

Comparing supernovae & neutron star mergers



=> Very similar physical conditions in NS mergers and supernovae

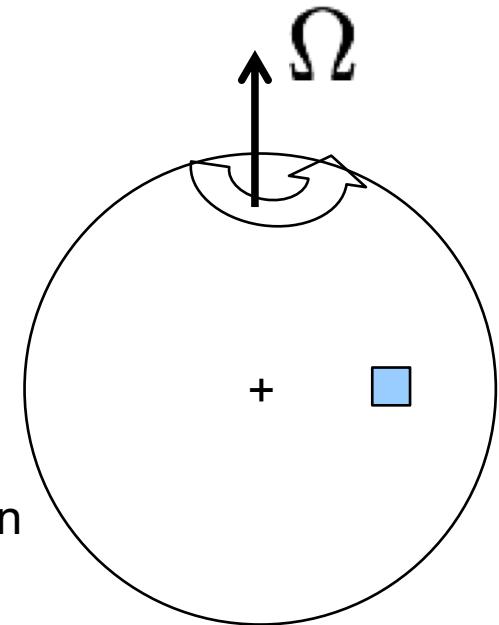
Guilet+2015, 2017

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 in Boussinesq approximation

Code: Snoopy (G. Lesur)

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



Fiducial parameters :

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

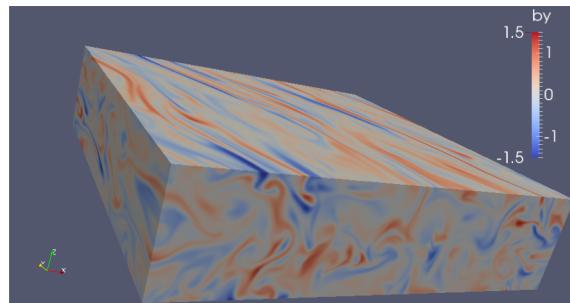
$$B = 2 \times 10^{13} \text{ G}$$

$$\Omega = 2 \times 10^3 \text{ s}^{-1}$$

$$\nu = 2 \times 10^{10} \text{ cm}^2 \cdot \text{s}^{-1}$$

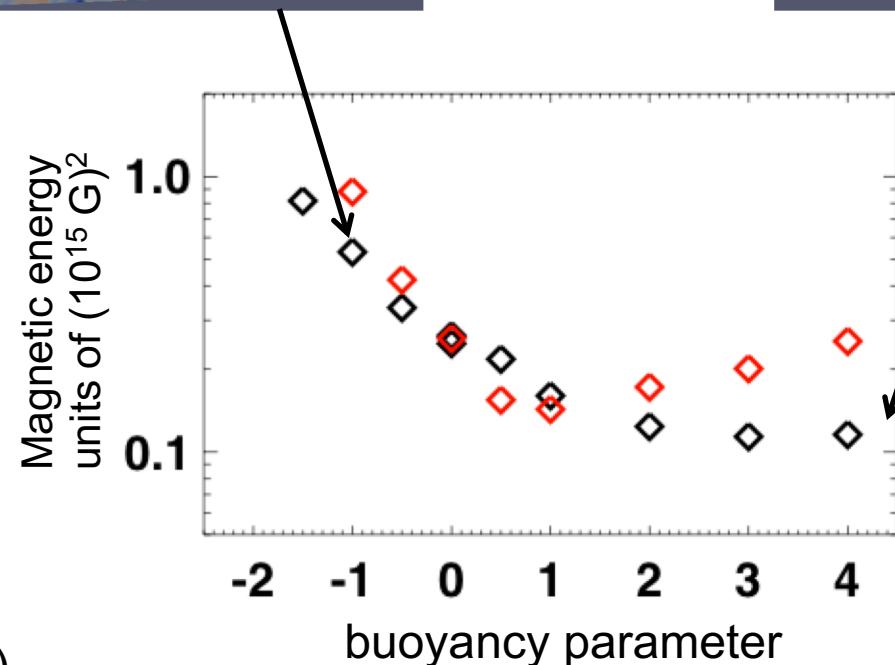
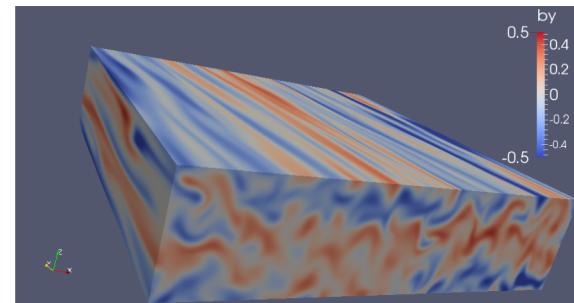
Impact of stratification on the MRI

unstable buoyancy



color: azimuthal
magnetic field

stable stratification

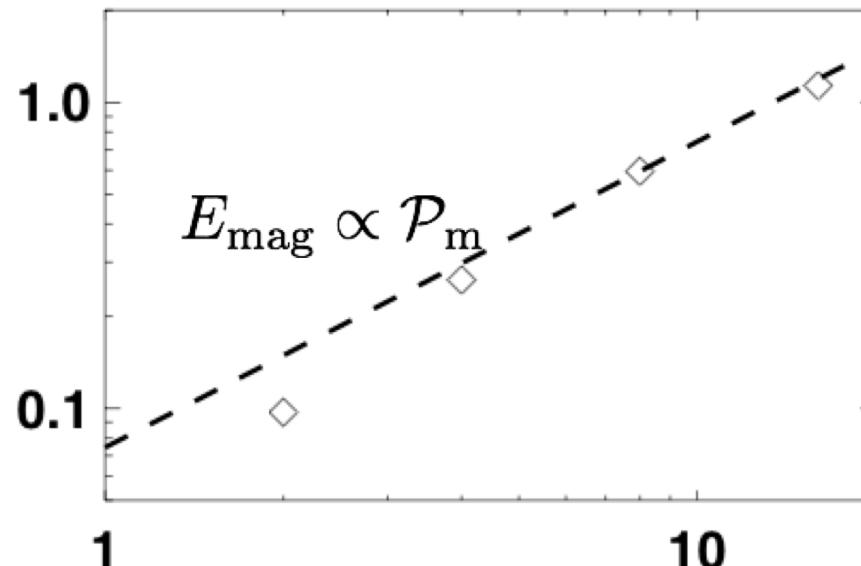


Guilet & Müller (2015)

Dependence on diffusion processes

$$Pm = 10^{13} !$$

Magnetic energy
units of $(10^{15} \text{ G})^2$



See also:

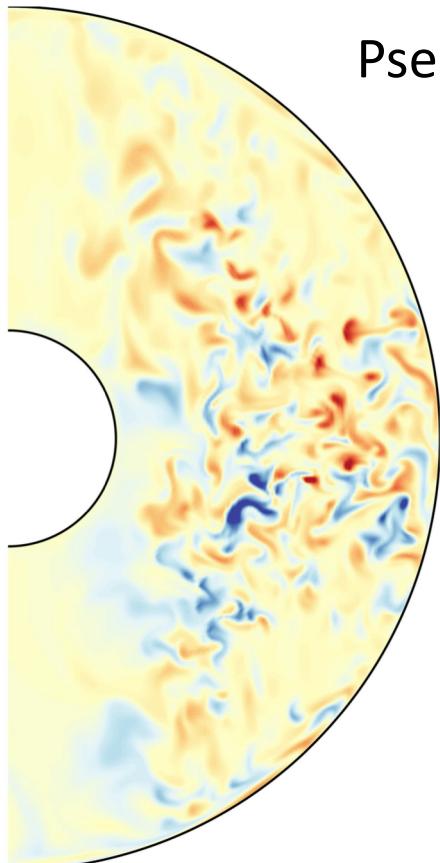
Fromang+2007, Lesur+2007,
Meheut+2015, Potter+2017

$Pm = \text{viscosity}/\text{resistivity}$

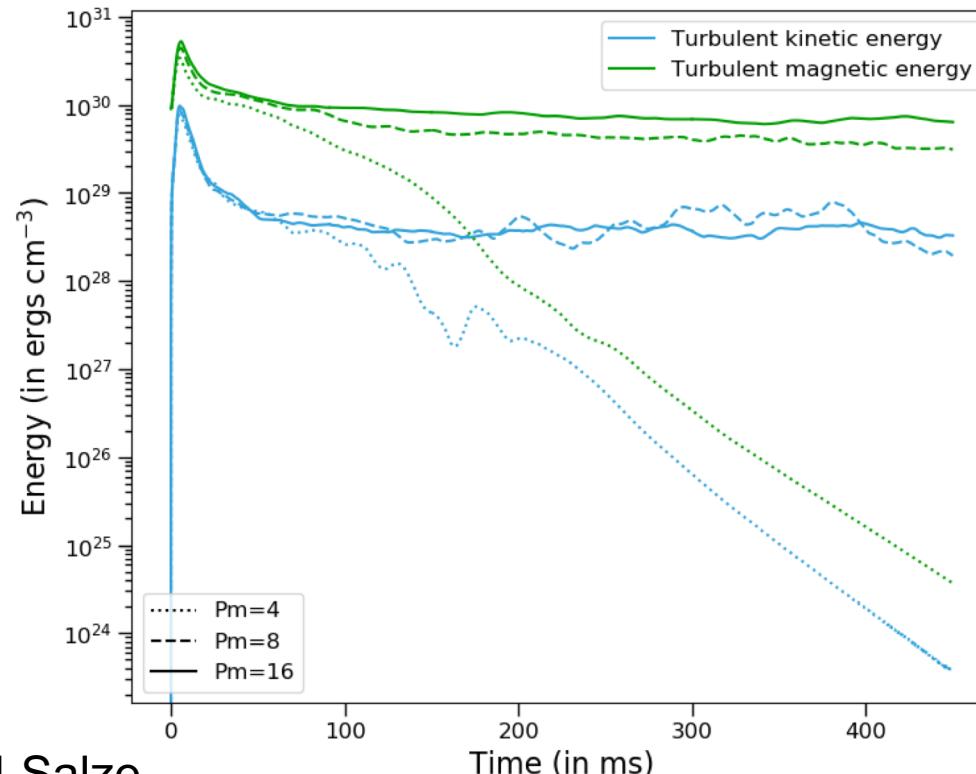
Behaviour at realistic values: very large magnetic Prandtl number Pm ?

Global model of MRI: geometry of the magnetic field ?

Simplest model of MRI in spherical geometry : incompressible, differential rotation profile forced at outer boundary



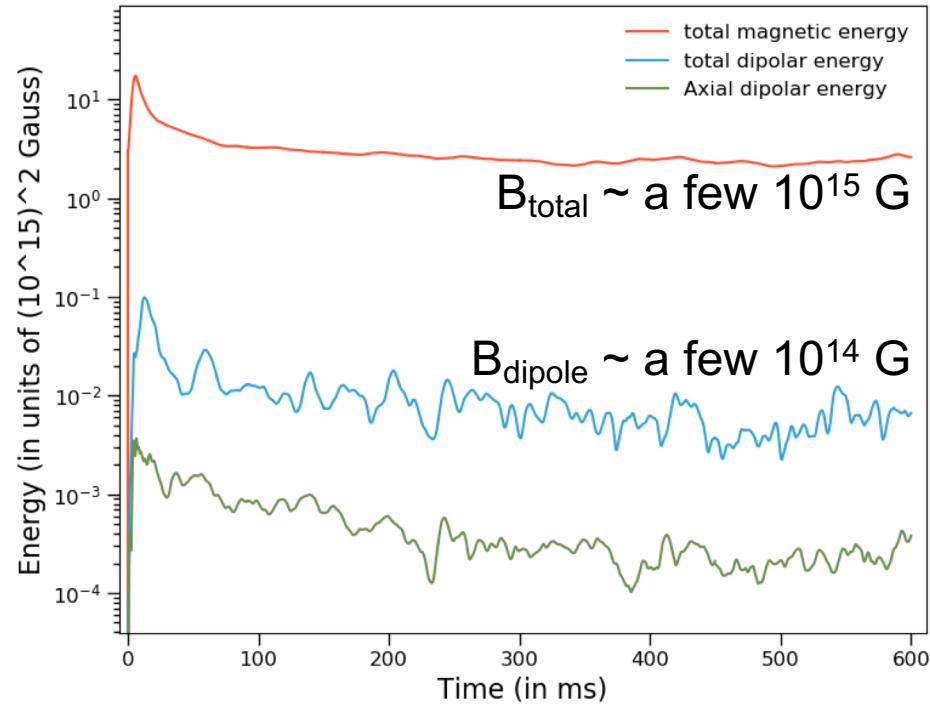
Pseudo-spectral code : MagIC Wicht (2002), Gastine & Wicht (2012)



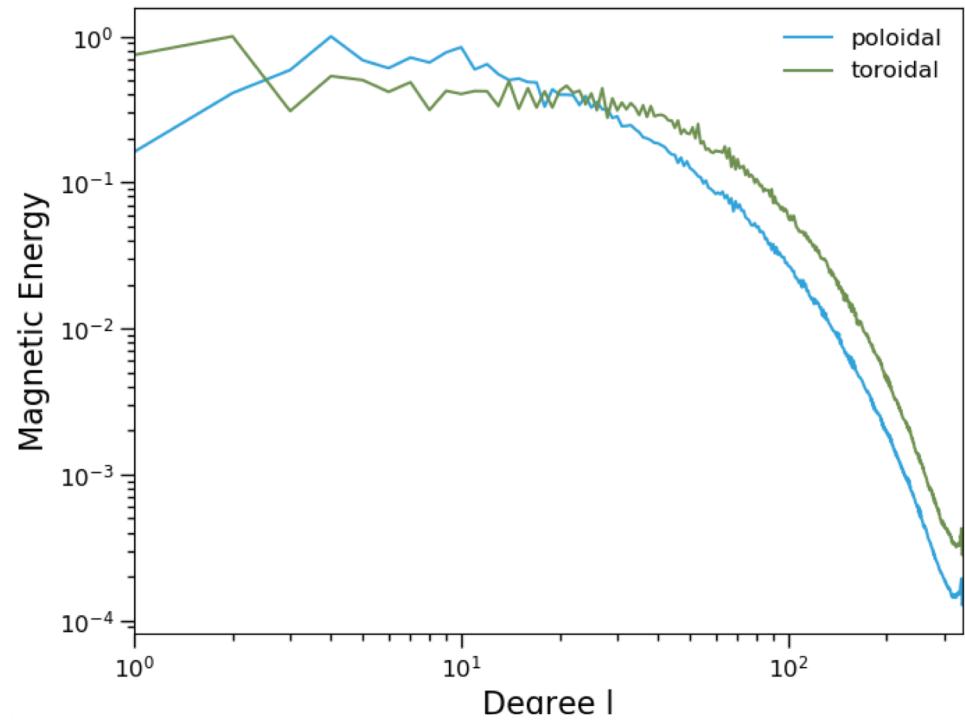
Projet de thèse d'Alexis Reboul-Salze

Global models: strength of dipole magnetic field

Magnetic energy evolution



Magnetic energy spectrum

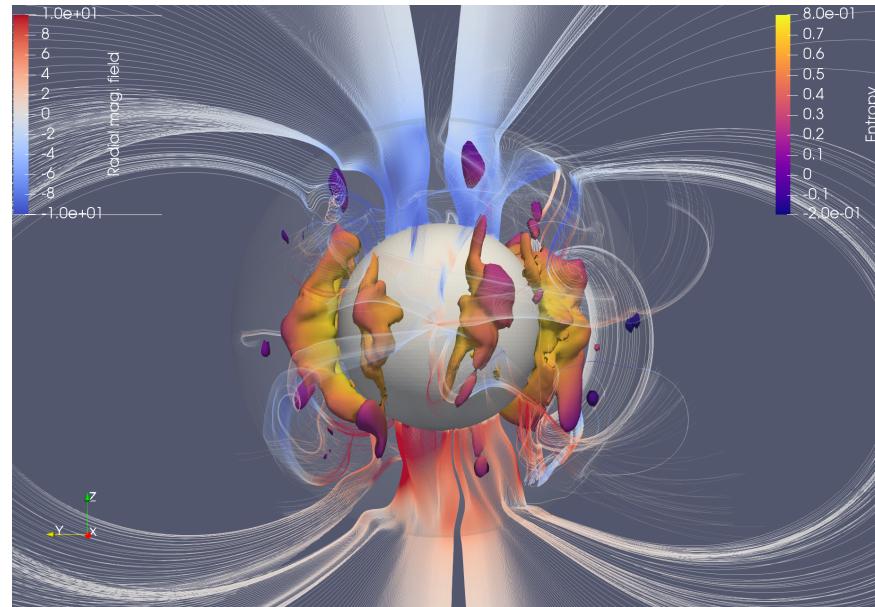
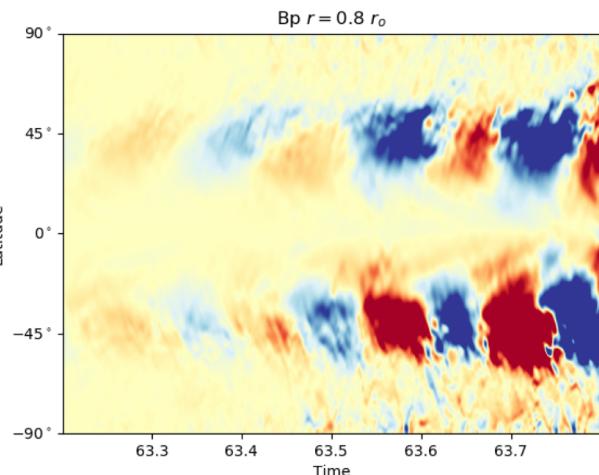


Equatorial dipole as strong as a magnetar ☺

First simulations of a convective dynamo in proto-neutron stars

Physics included:

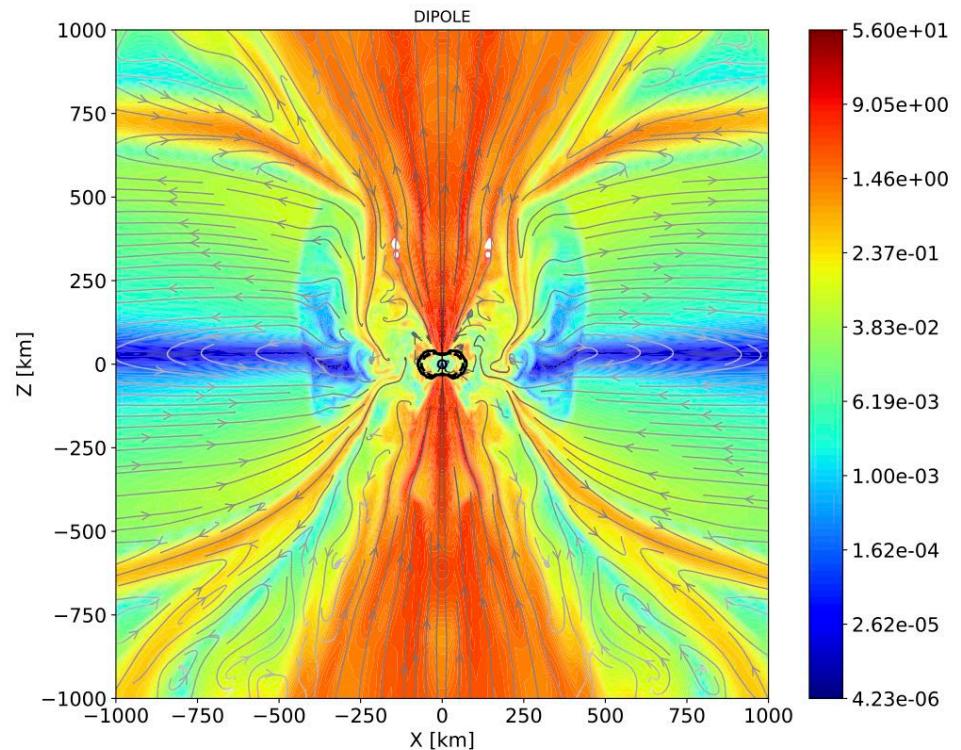
- Realistic equation of state & proto-neutron star structure
- Anelastic approximation
- Only the convective zone



Is a regime with strong dipolar magnetic field possible ?

Raphaël Raynaud

Magnetorotational explosions



Physics included:

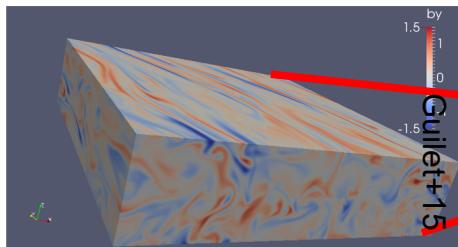
- Fully compressible MHD
- Special relativity
- Neutrino transport
- Realistic equation of state
- 2D

B field amplification not described:
-> test the influence of initial B field
geometry & intensity

Matteo Bugli, collaboration with Martin Obergaulinger (Valencia)

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

Step 1: local MRI model

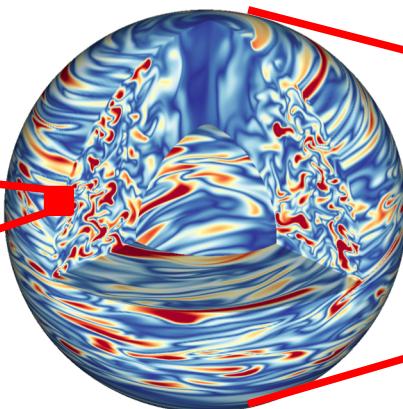


$\sim 1\text{-}5 \text{ km}$

Amplification & saturation ?

High Pm regime? Drag force?

Step 2: global simulations

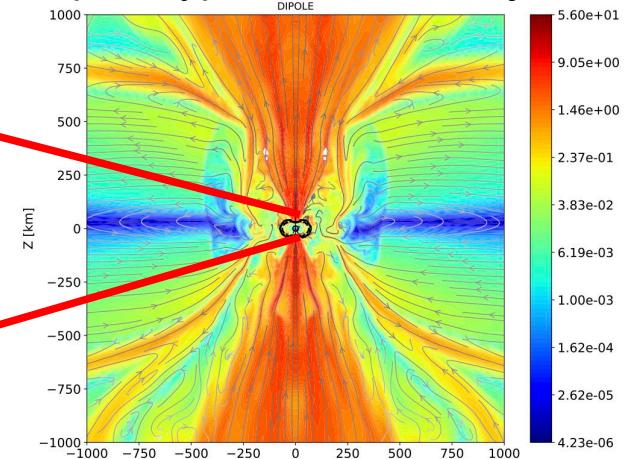


$\sim 10\text{-}50 \text{ km}$

Magnetic field geometry ?

MRI vs convective dynamo

Step 3: hypernova & GRB jet



$\sim 10^3\text{-}10^5 \text{ km}$

Explosion diversity ?

Energy, jet properties etc.

ERC project MagBURST
PI : Jerome Guilet



Raphaël Raynaud
Alexis Reboul-Salze

Matteo Bugli

Merci !