The physics of magnetar formation

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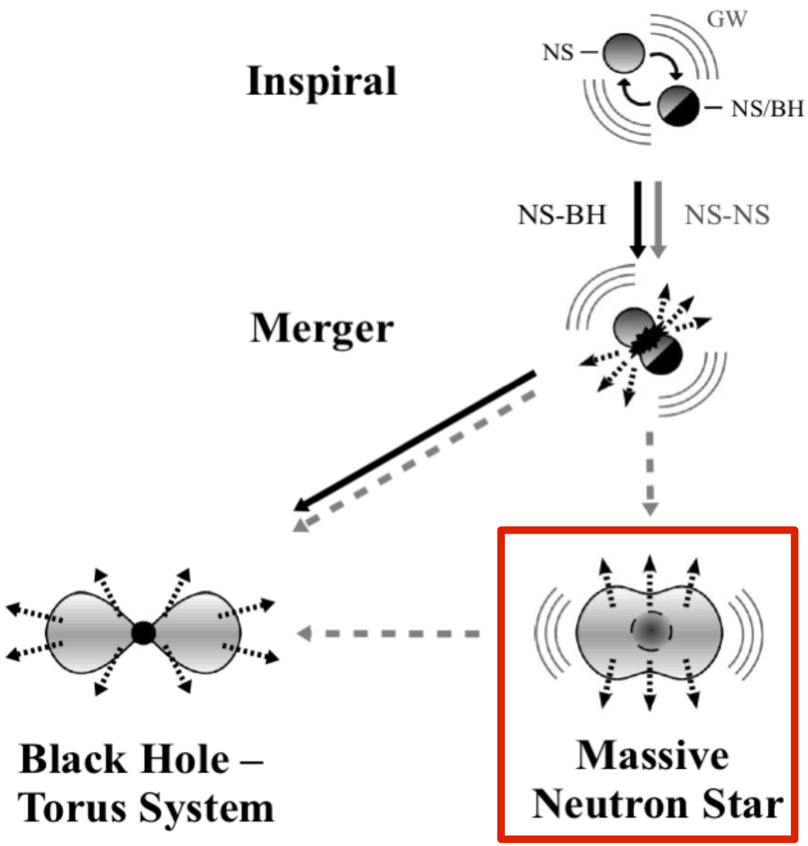
Nature of the compact object formed in NS mergers ?

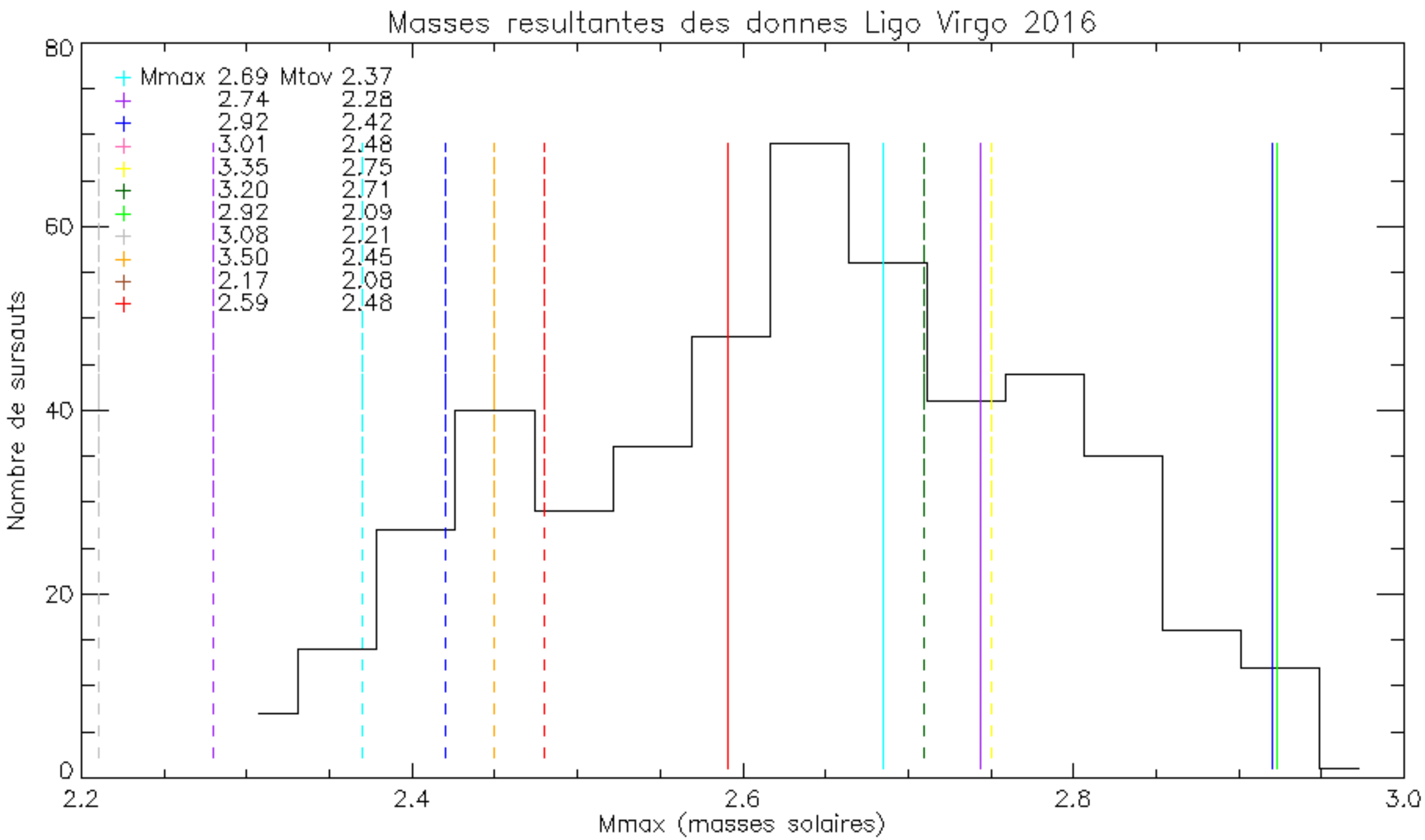


3 possibilities :

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

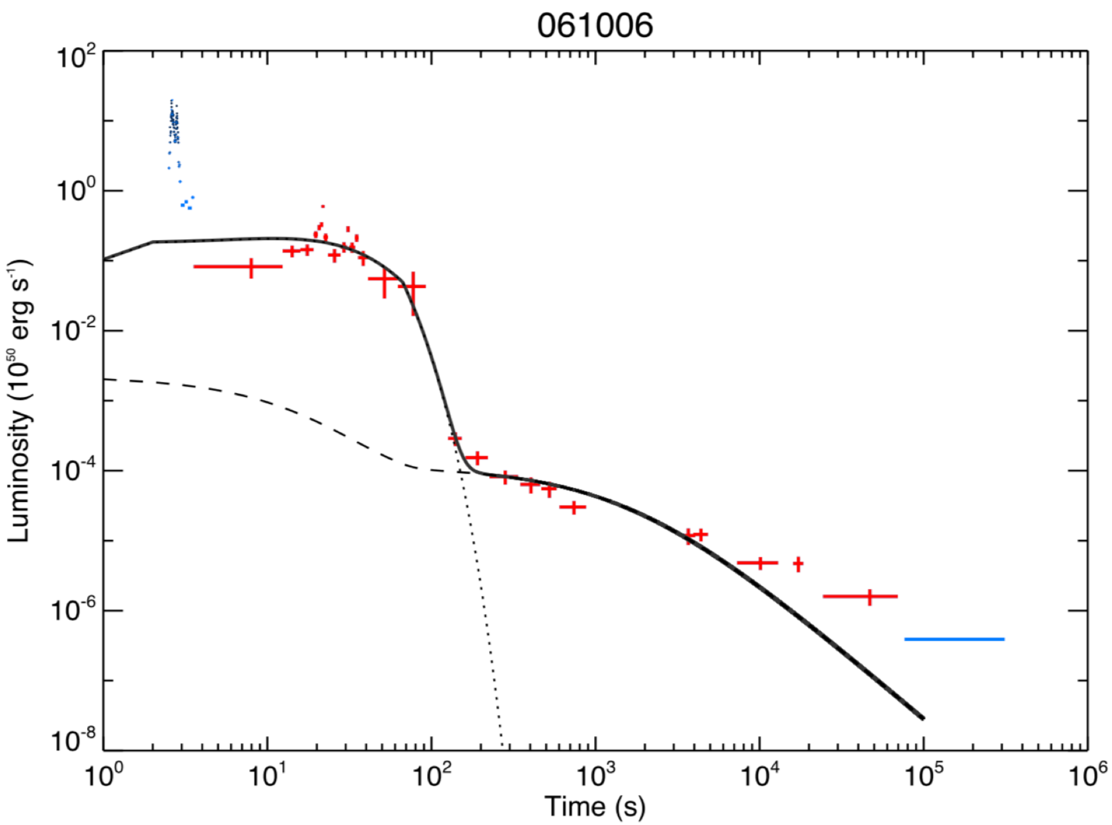
Formation of a magnetar ?

Illustrative mass distribution of remnants



Kindly provided by Laura Gosset based on
Singer+2014 & Shunke+2018

Extended emission and X-ray plateaus from magnetars ?



From Gompertz+2014

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

- Dipole spin-down in vacuum

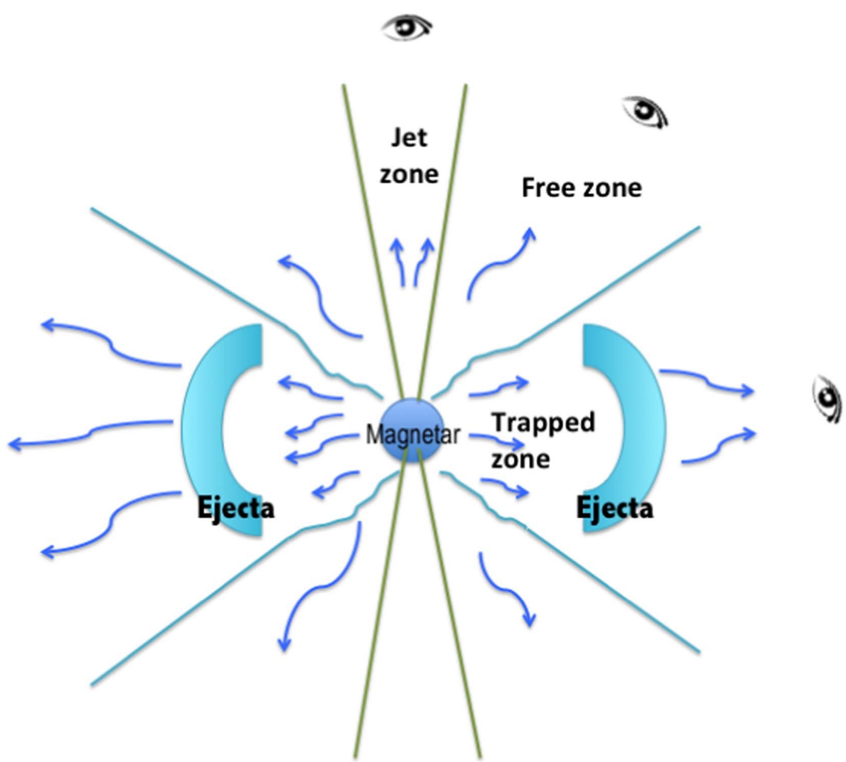
$T_{sd} \sim 2 \times 10^{3}$ s $(B/10^{15}G)^{-2}$ $(P/1ms)^{2}$

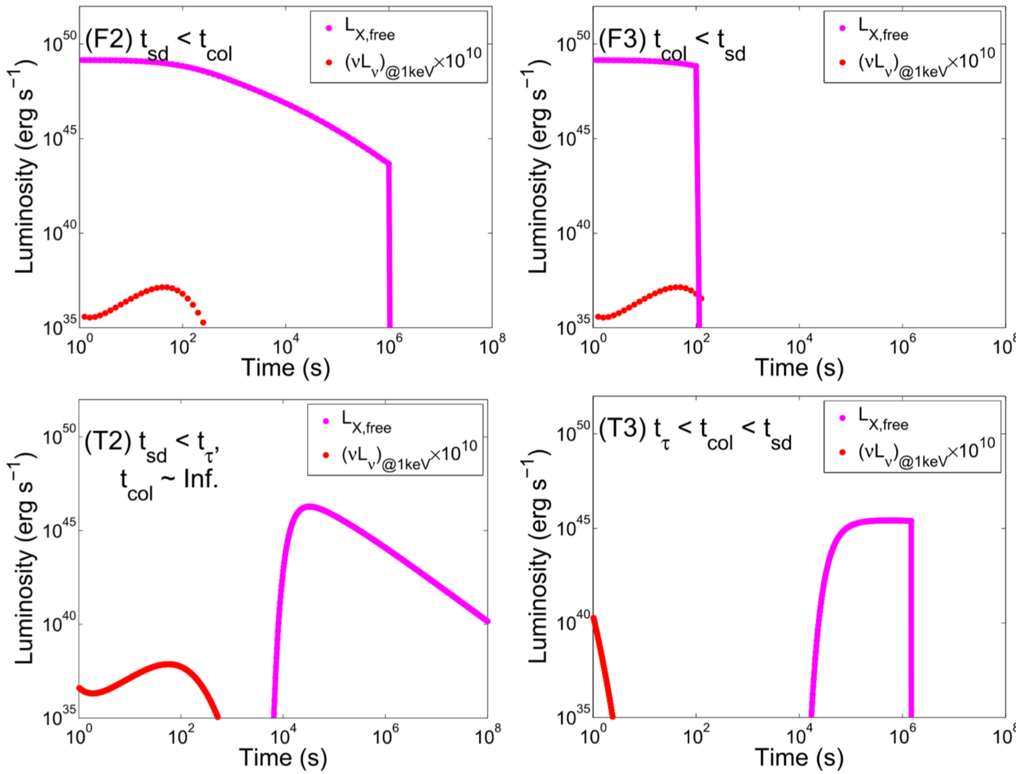
$L_{dip} \sim 10^{49}$ erg/s $(B/10^{15}G)^{2}$ $(P/1ms)^{-4}$ $\times(1 + t/T_{sd})^{-2}$

- Propeller with fall-back disk for the extended emission?

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

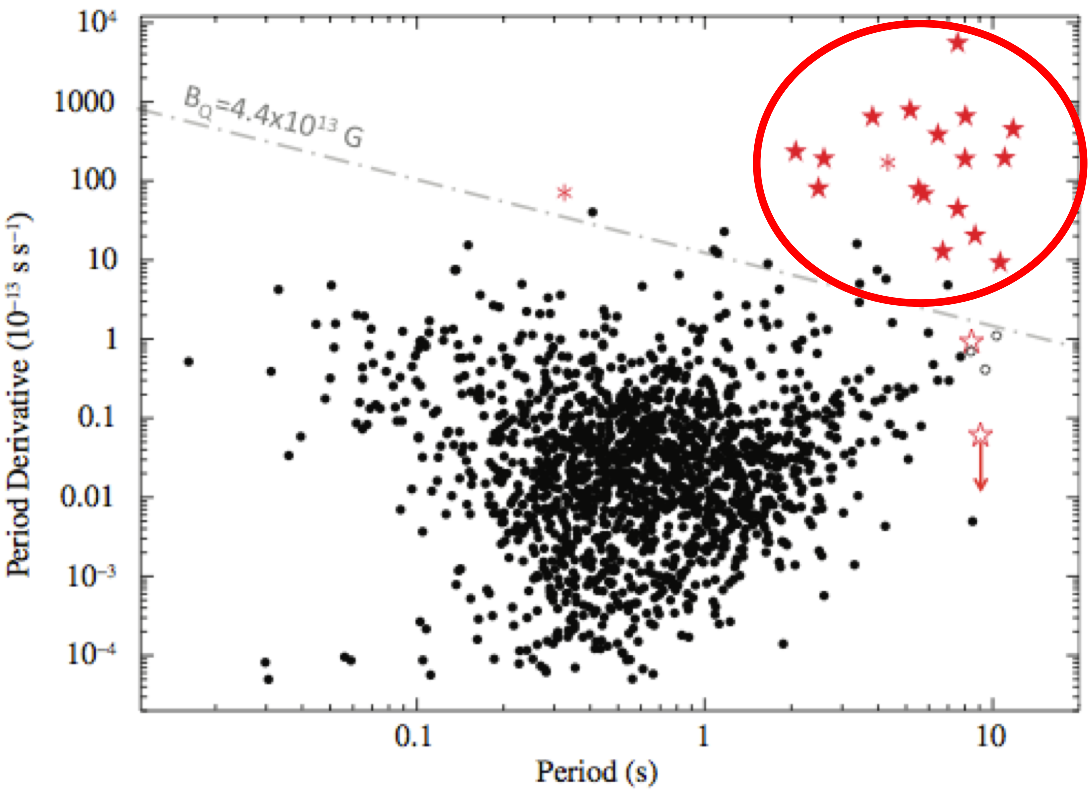
Off-axis counterpart of GW from a magnetar





Zhang 2013, Sun+2017

Galactic magnetars



Galactic magnetars:

Anomalous X-ray pulsars (AXP)

Soft gamma repeater (SGR)

Strong dipole magnetic field:

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

Slow rotation (expected from spin-down) but may be born as fast rotators

Birth rate ~10% of core-collapse supernovae

=> much more than NS mergers

Outstanding stellar explosions: millisecond magnetars ?

Explosion kinetic energy :

→ Typical supernova 10^{51} ergs

→ Rare hypernova & long GRB 10^{52} ergs

→ Neutrino driven explosions ?

→ Millisecond magnetar ?

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

Total luminosity :

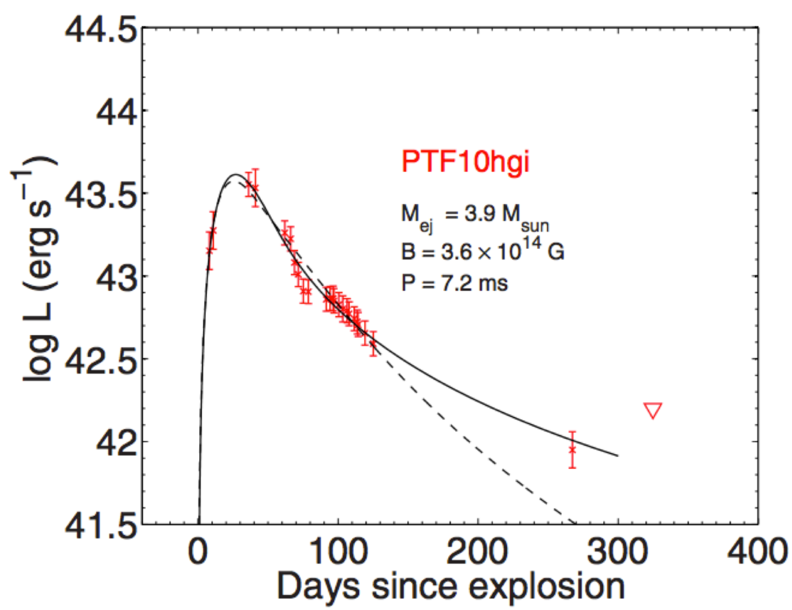
→ Typical supernova 10^{49} ergs

→ Superluminous supernovae 10^{51} ergs

Light curves can be fitted by millisecond magnetar

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

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



Theoretical open question: magnetic field origin

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

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

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

Amplification mechanism ?

Magnetorotational instability

Both SN & mergers

Similar to accretion disks

Convective dynamo

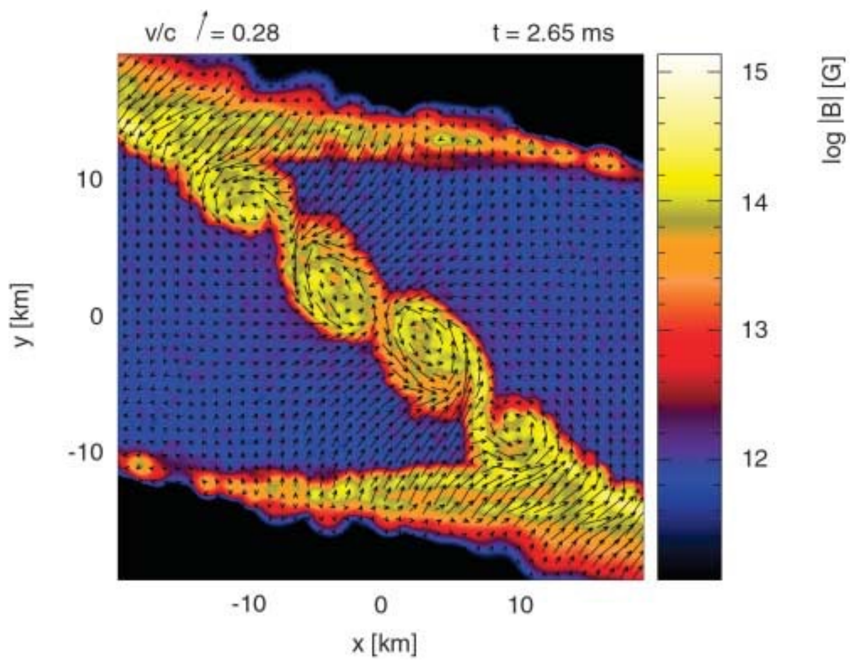
Both SN & mergers

Similar to planetary & stellar dynamos

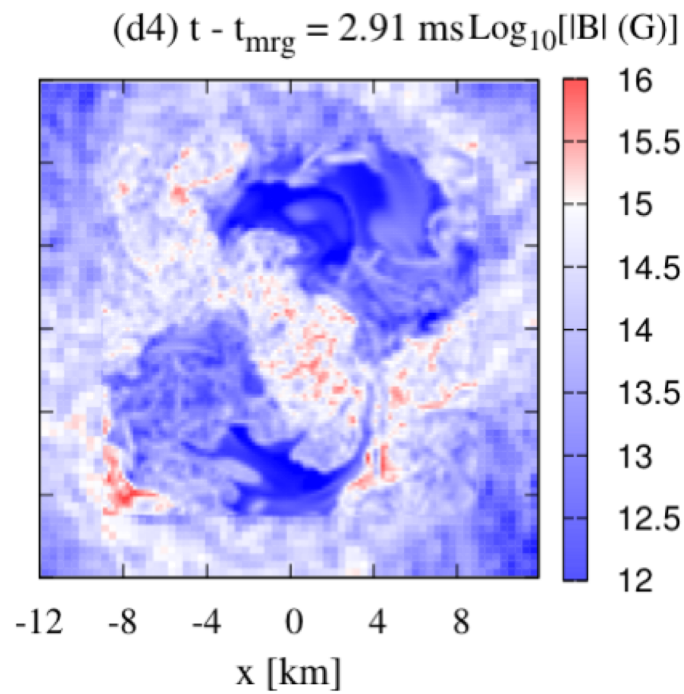
Shear instability

Only in mergers

Amplification mechanism: shear instability



Price & Rosswog 2006



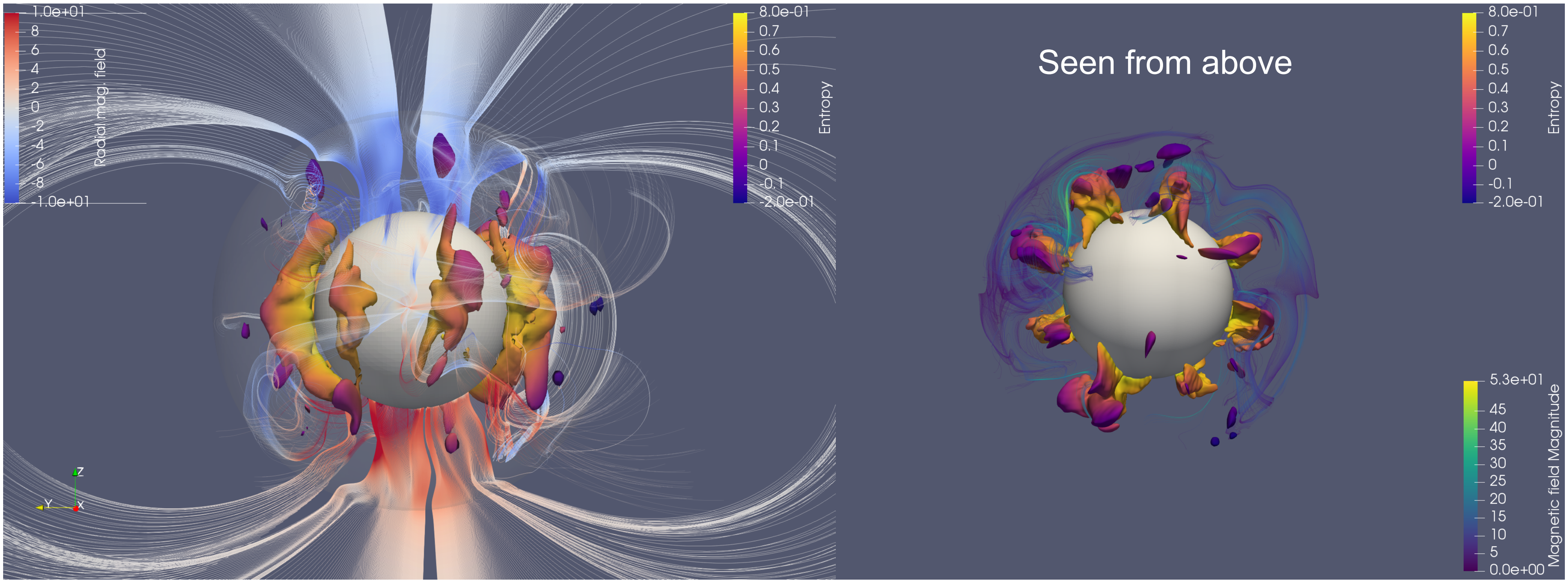
Kiuchi+2015

Generation of strong magnetic field but at small scales only (no dipole)

Amplification mechanism: convective dynamo

Thompson & Duncan 1993 predicted 10^{15}G dipole magnetic based on very simple scaling arguments

Preliminary simulations of convective dynamo in a protoneutron star
by Raphaël Raynaud



Amplification mechanism: magnetorotational instability (MRI)

MRI in its simplest form (ideal MHD):

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

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

→ Fast growth for fast rotation

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

→ Short wavelength for weak magnetic field

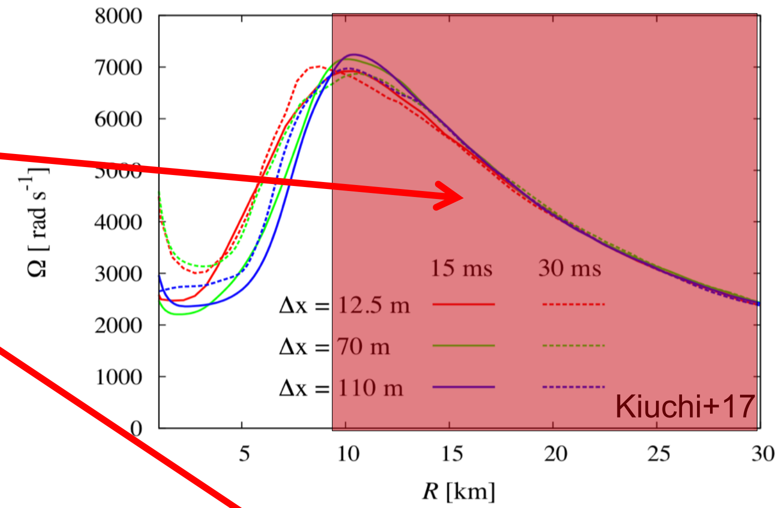
Impact of conditions specific to neutron stars ?

→ neutrinos

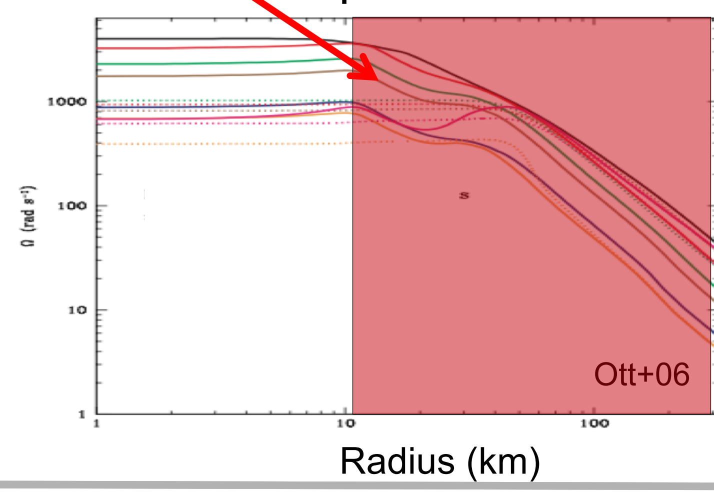
→ buoyancy (entropy & composition gradients)

→ spherical geometry

NS merger



supernovae

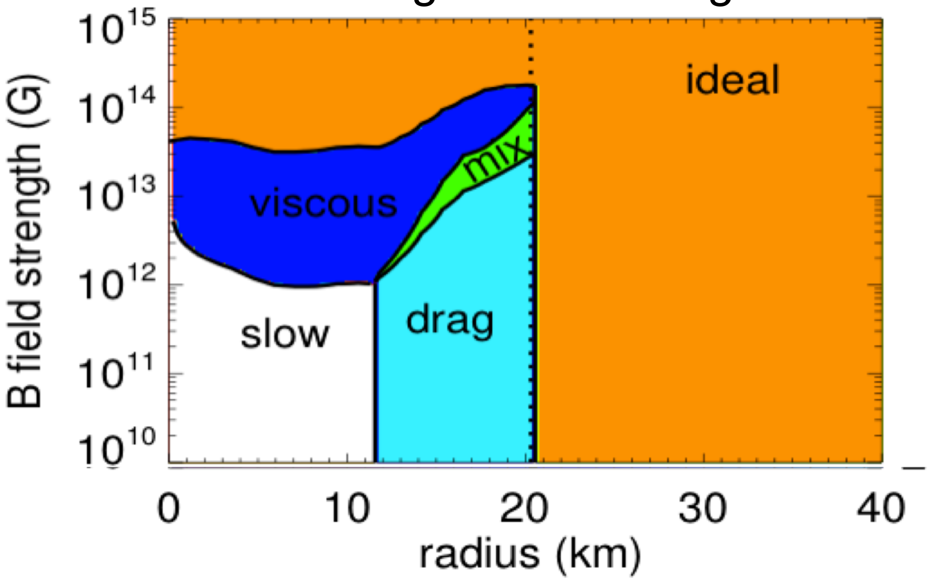


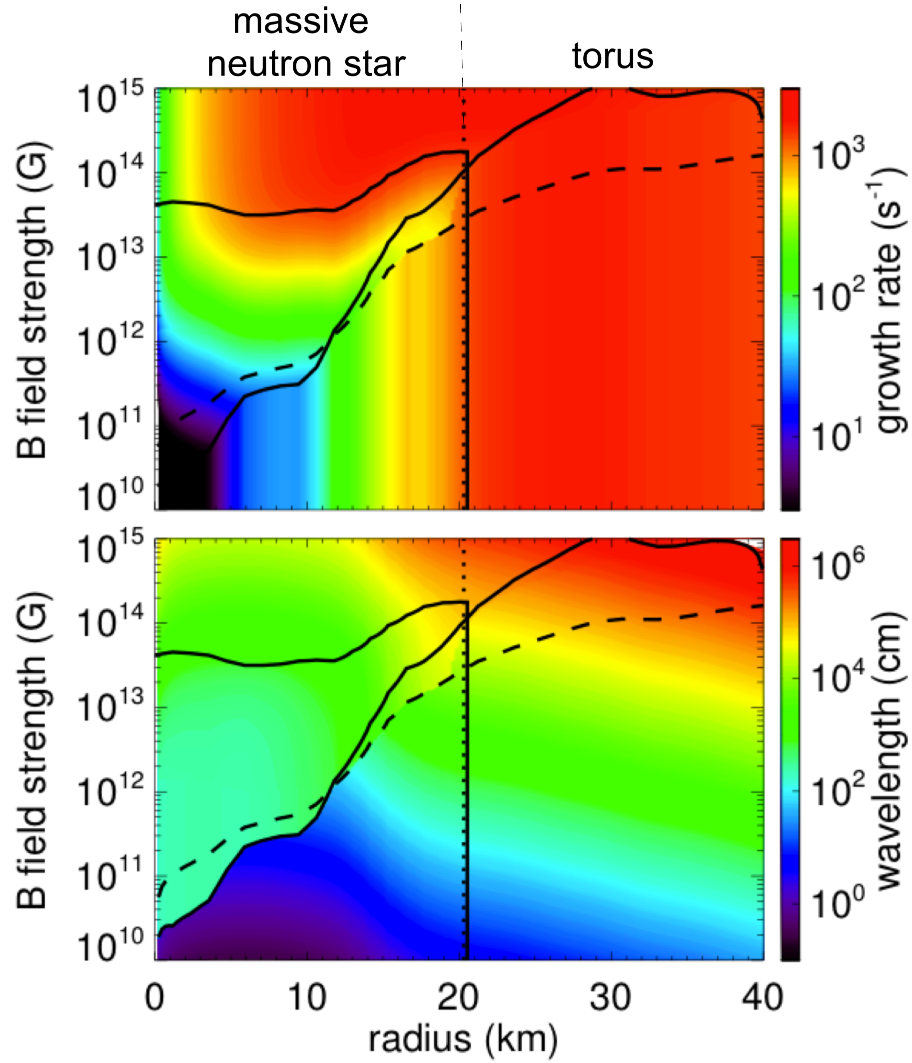
How fast does the MRI grow ? Impact of neutrinos

Analytical description of MRI growth in the linear phase in the presence of neutrinos

Guilet+2015, 2017

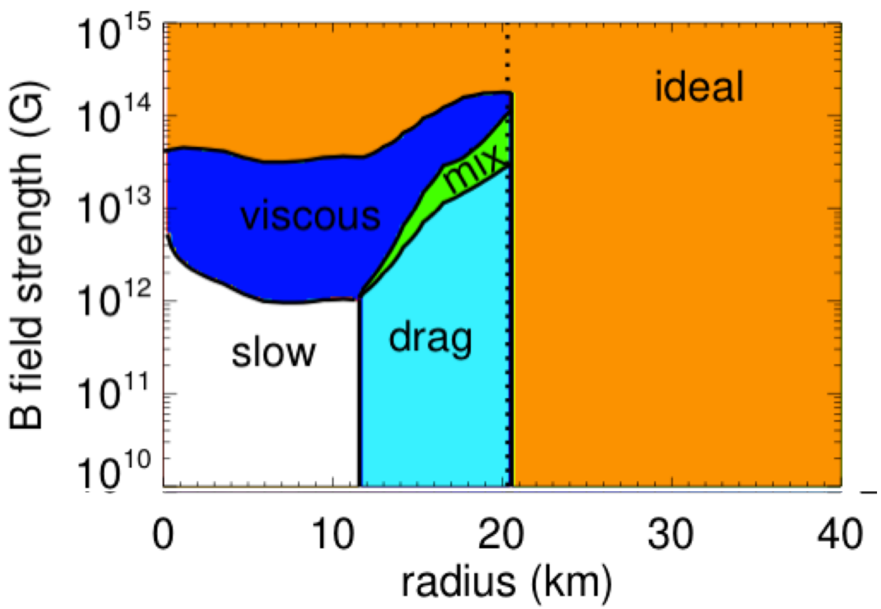
Different regimes of MRI growth



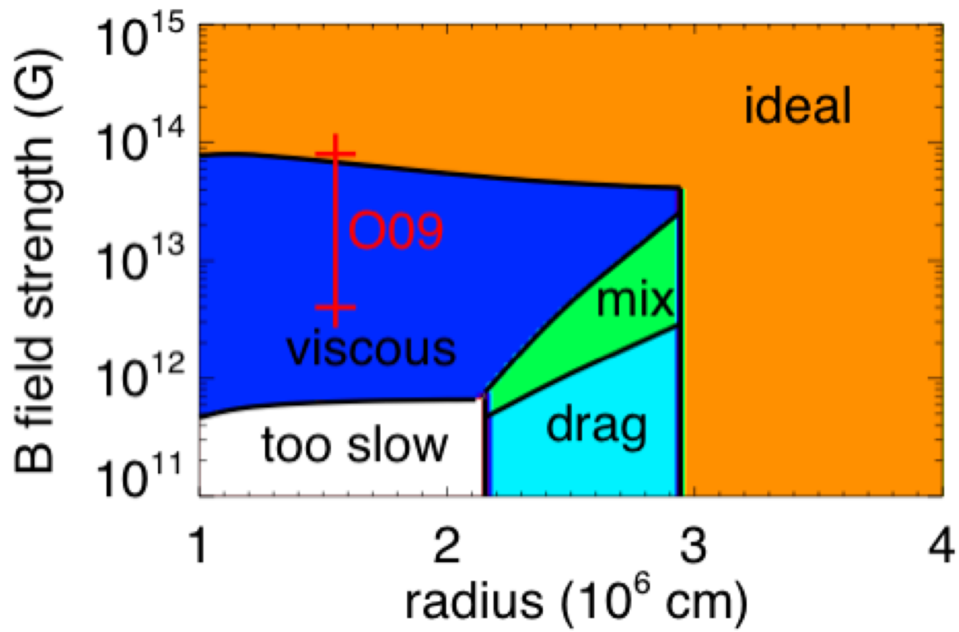


Comparing supernovae & neutron star mergers

Neutron star mergers



Core collapse SN



=> Very similar physical conditions in NS mergers and supernovae

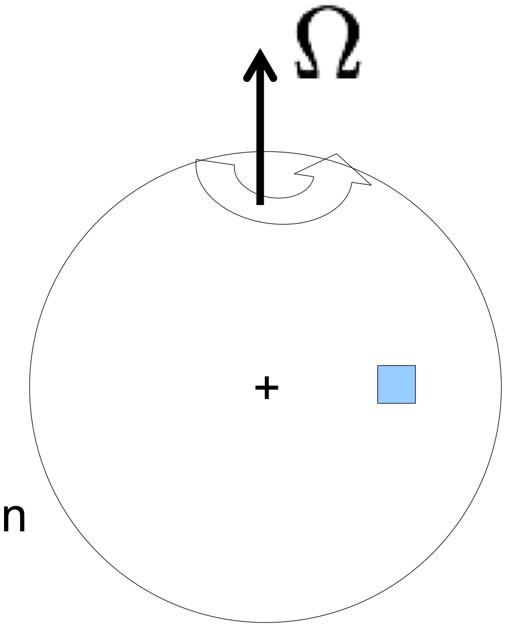
Guilet+2015, 2017

Numerical simulations: local models

- Small box : at a radius r = 20 km
  size 4×4×1 km

- Differential rotation
  => shearing periodic boundary conditions

- Entropy/composition gradients in Boussinesq approximation

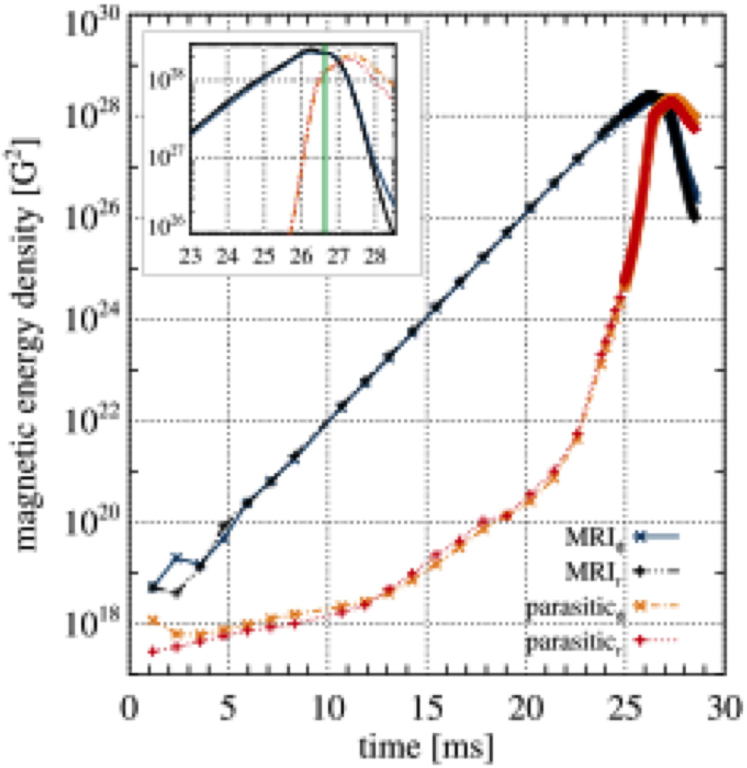


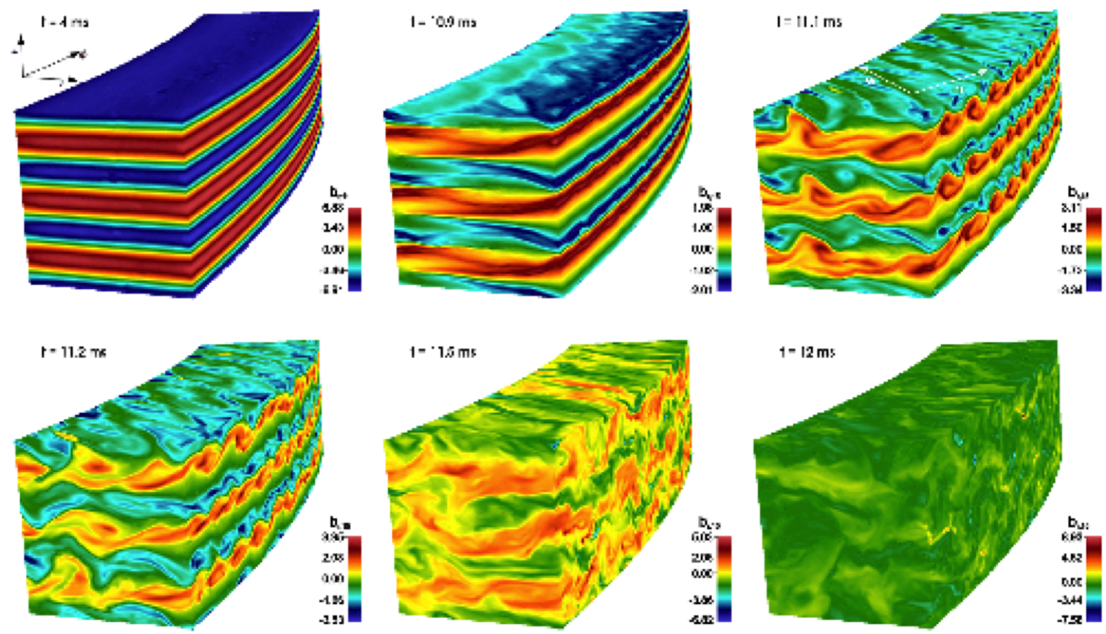
Obergaulinger+2009, Masada+2012,
Guilet+2015, Rembiasz+2015,2016

Fiducial parameters :

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

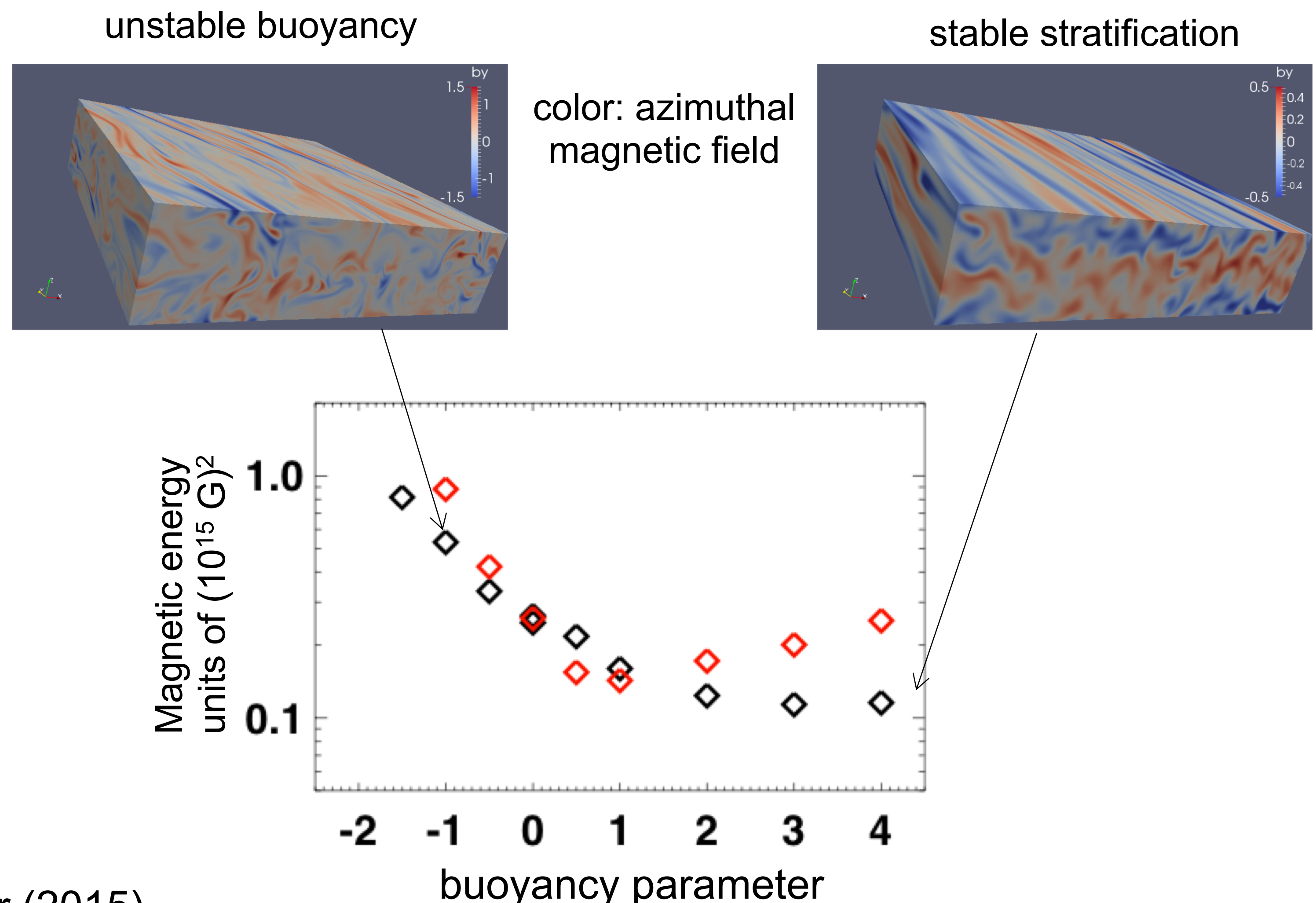
Channel mode growth & termination





Rembiasz et al. 2016a&b

Impact of stratification on the MRI

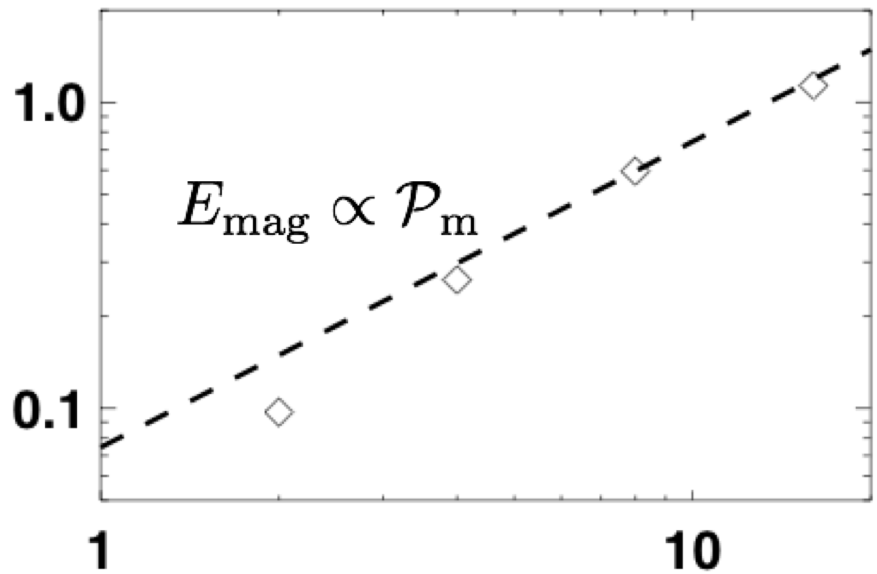


Guilet & Müller (2015)

Dependence on diffusion processes

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

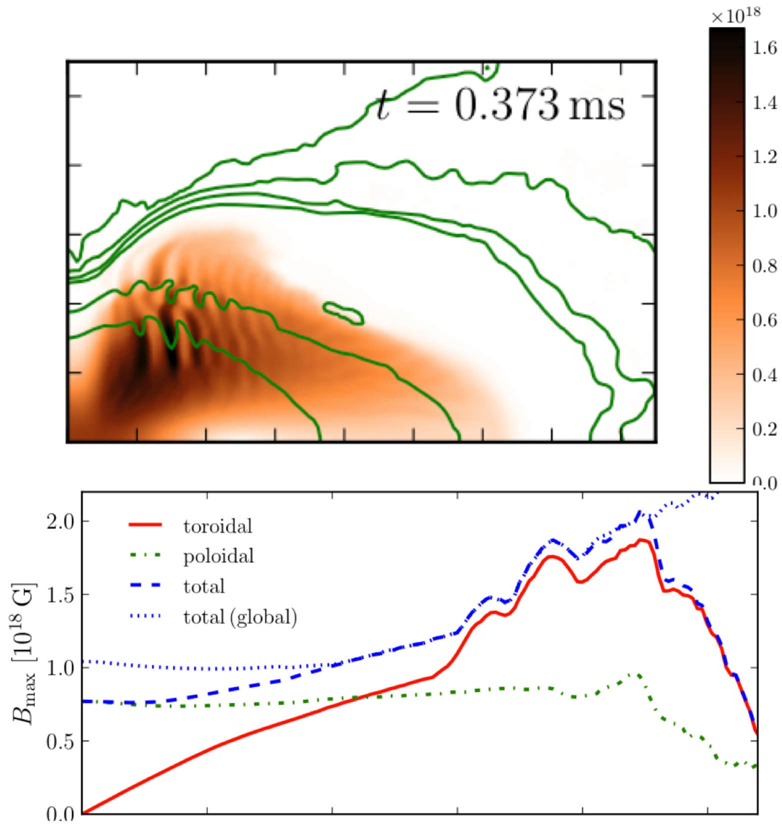
Magnetic energy
units of $(10^{15}\ G)^2$



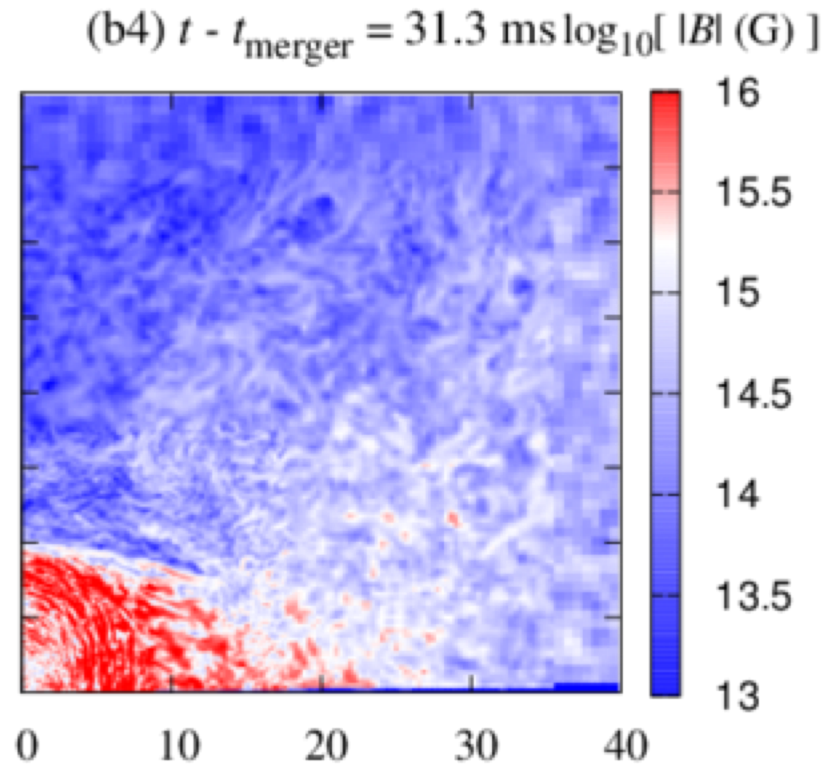
Pm = viscosity/resistivity

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

MRI in global models of NS mergers



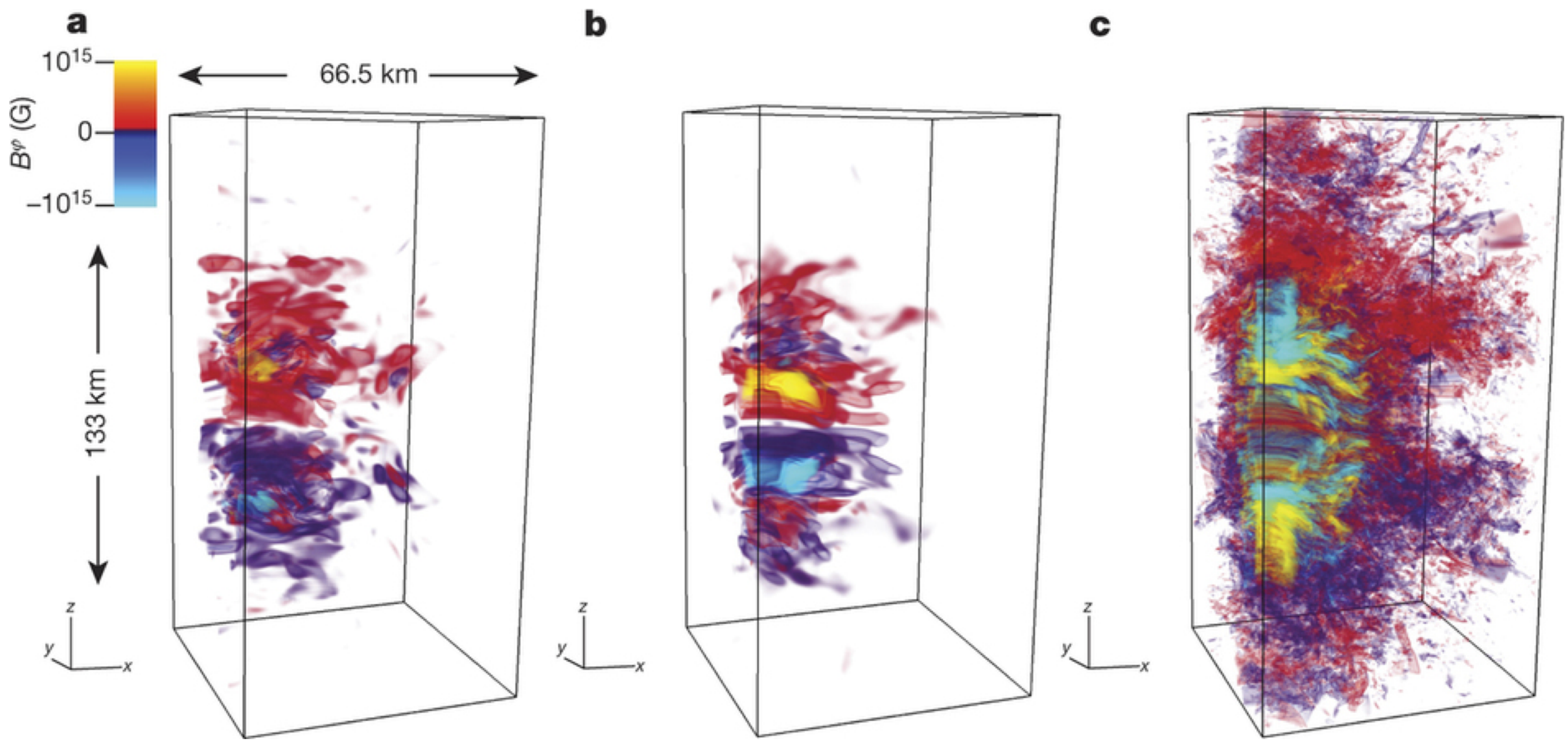
Siegel+2013



Kiuchi+2015

Generation of large-scale/dipole magnetic field is still an open question

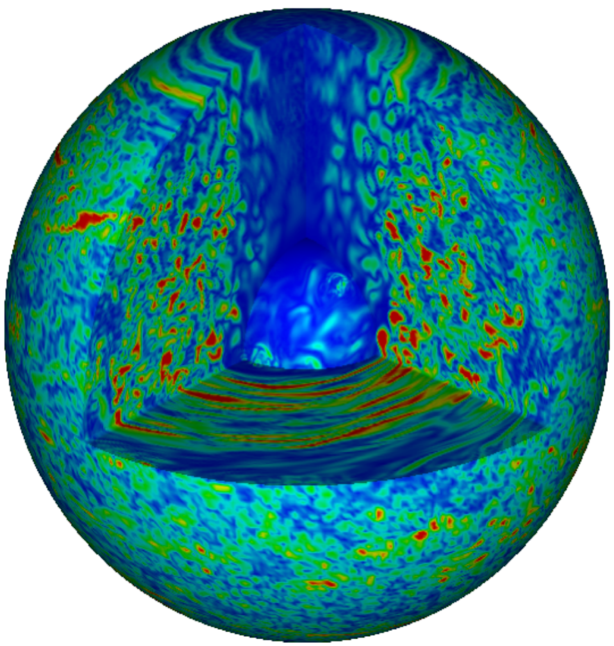
Global models: geometry of the magnetic field ?



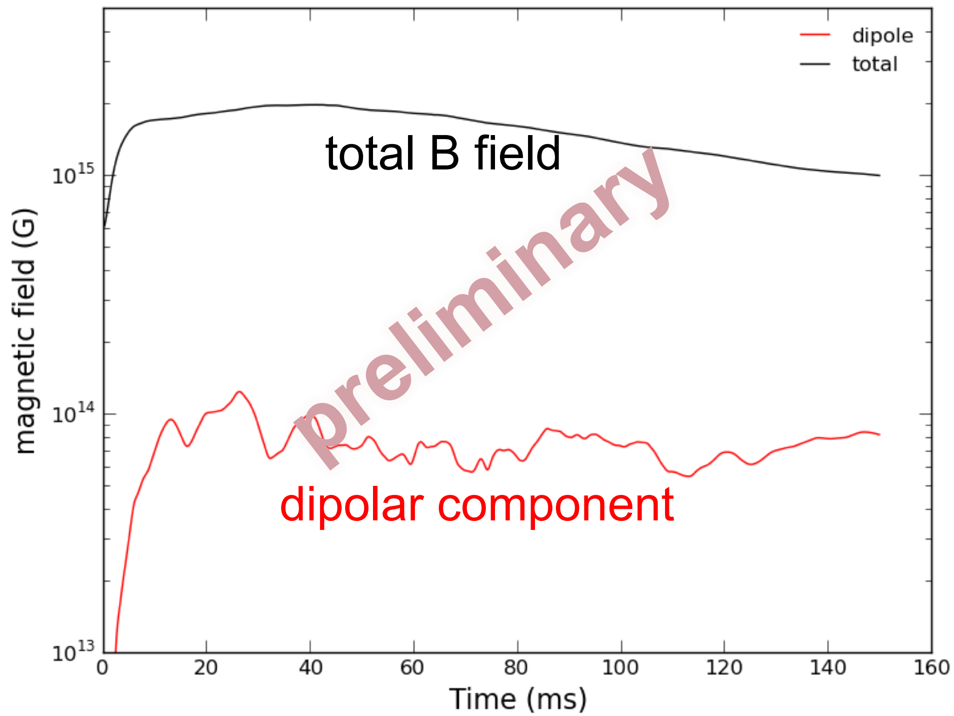
Moesta+2015 : first simulation with large-scale magnetic field generation..
but started with magnetar strength dipolar field

Global models: geometry of the magnetic field ?

Code: MAGIC
(https://github.com/magic-sph/magic)
Wicht (2002, PEPI, 132, 281-302)
Gastine & Wicht (2012, Icarus, 219, 428-442)



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

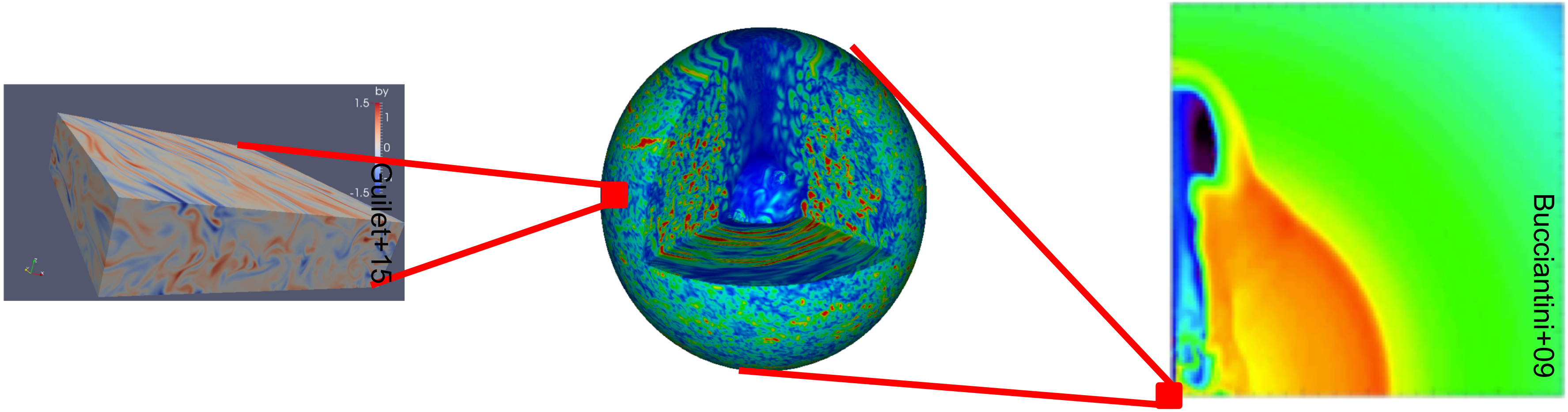


Towards an ab initio description of the central engine

Step 1: local MRI model

Step 2: magnetar formation

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 etc.

ERC project MagBURST
PI : Jerome Guilet

Raphaël Raynaud
Alexis Reboul-Salze

Matteo Bugli

Conclusion

Need for an ab initio description of the central engine

→ origin & evolution of the magnetic field

generation of a dipolar magnetic field is still an open question

→ converging efforts in supernovae & NS mergers

Observational signature of the birth of a magnetar ?

→ delay for jet formation due to magnetic field amplification timescale ?

→ extended emission/X-ray plateau associated to short GRBs
smoking gun with pulsations ?

→ off-axis counterparts to GW in X-ray (or other wavelength?)

What would SVOM/MXT detect ? (on-going effort with Laura Gosset & Diego Gotz)

Thanks !