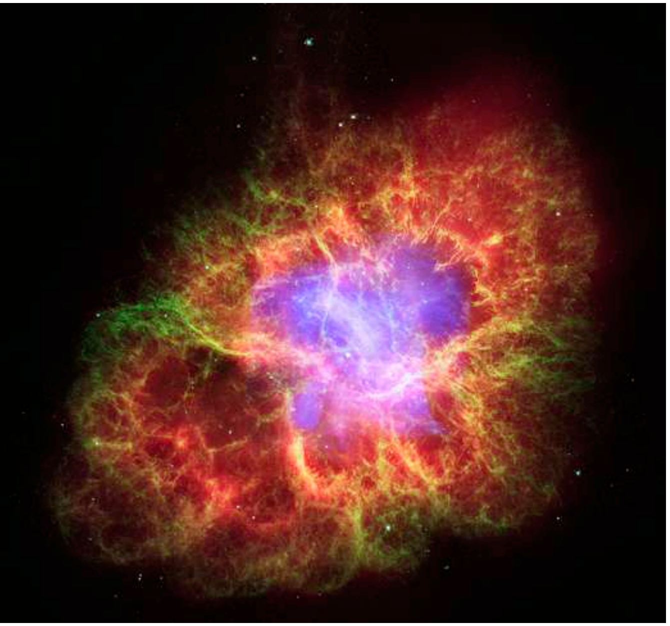
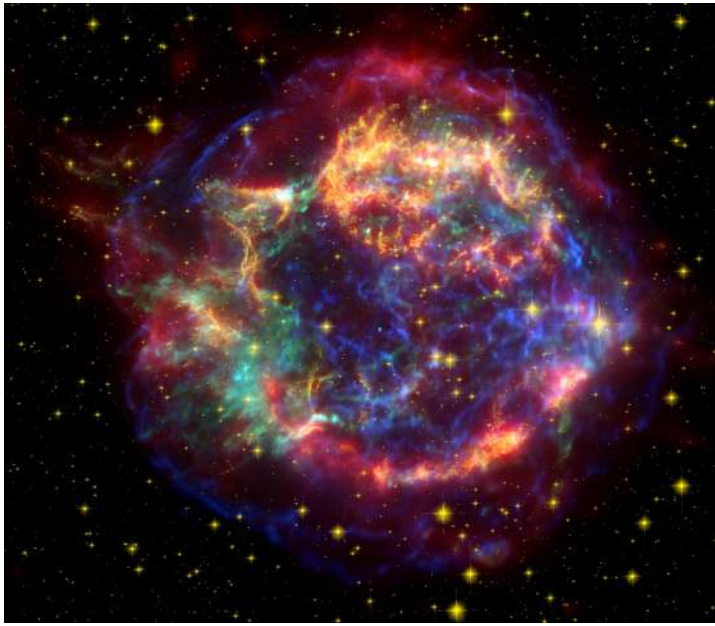
Multidimensional dynamics in core collapse supernovae



Crab

Jérôme Guilet
(IRFU/DAp)



Cassiopeia A

Core collapse supernovae

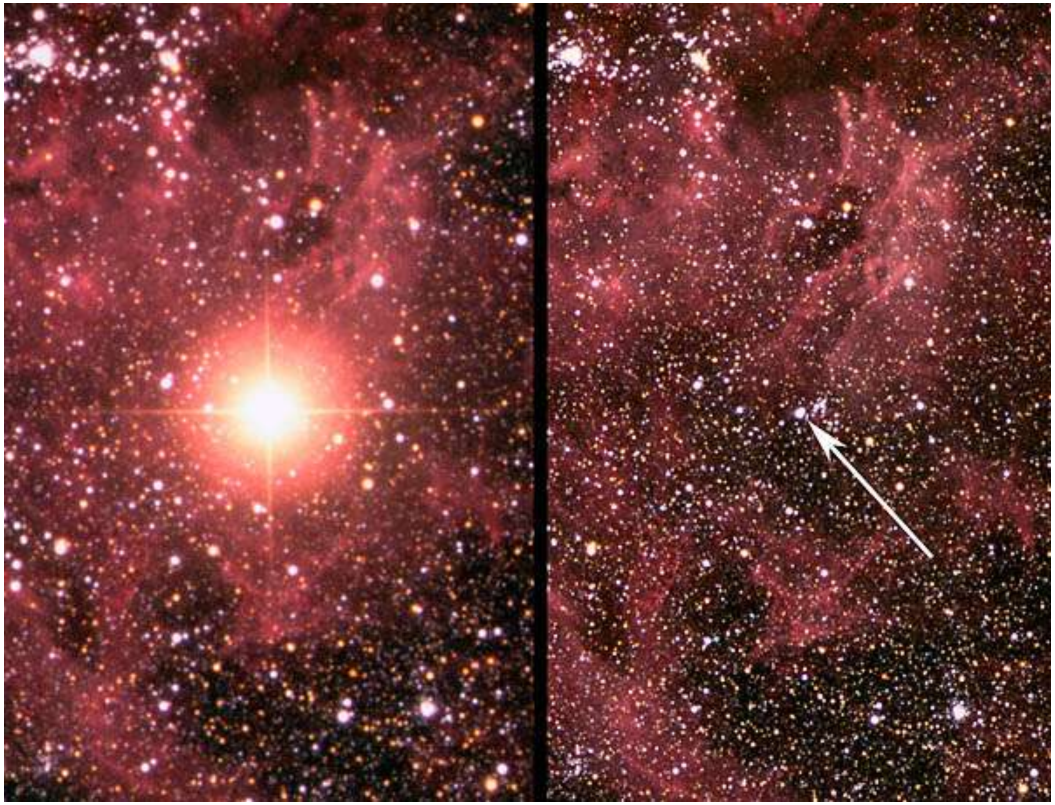
Core collapse supernovae: type II, Ib & Ic

Not discussed here: SN Ia (thermonuclear)

Electromagnetic waves are emitted days after the explosion:

-> the central engine is difficult to constrain

Gravitational waves and neutrinos (would) give a view of the instant of explosion



SN1987A: last (almost) galactic SN (LMC)
25 neutrinos detected

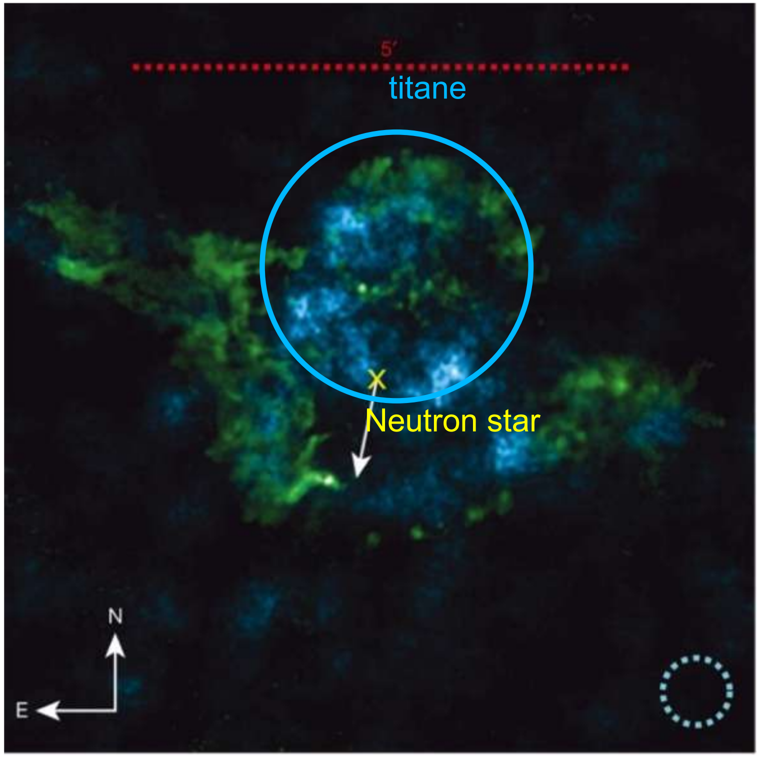
Observational evidence for asymmetry

Morphology of supernova remnants

Neutron star kicks: several 100 km/s
=> accelerated at birth

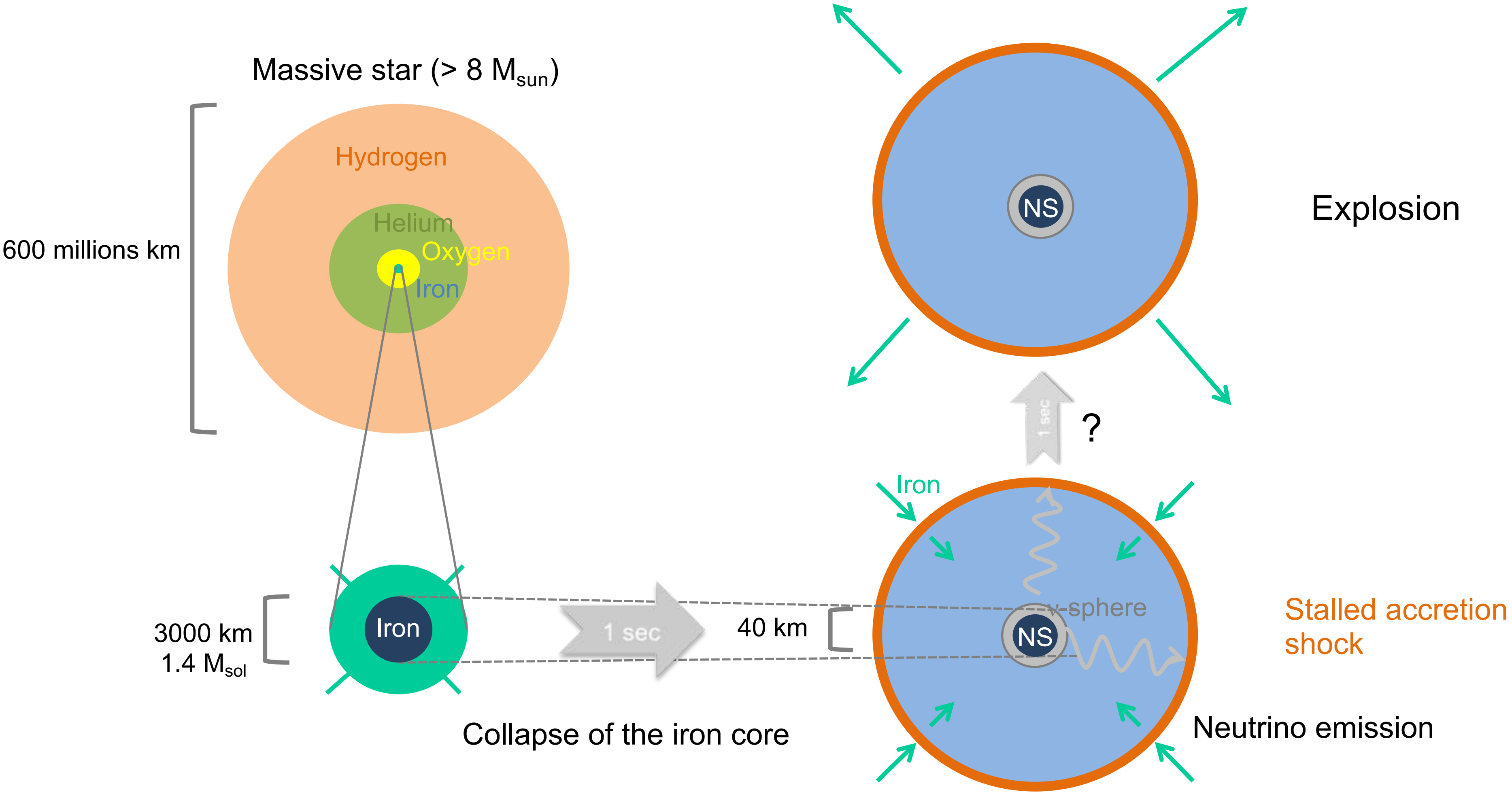
Polarisation of SN light:
inner ejecta are asymmetric

Observation of Cas A



Grefenstette et al 2014

Core collapse: formation of a neutron star



Neutrino-driven mechanism: a multi-physics problem

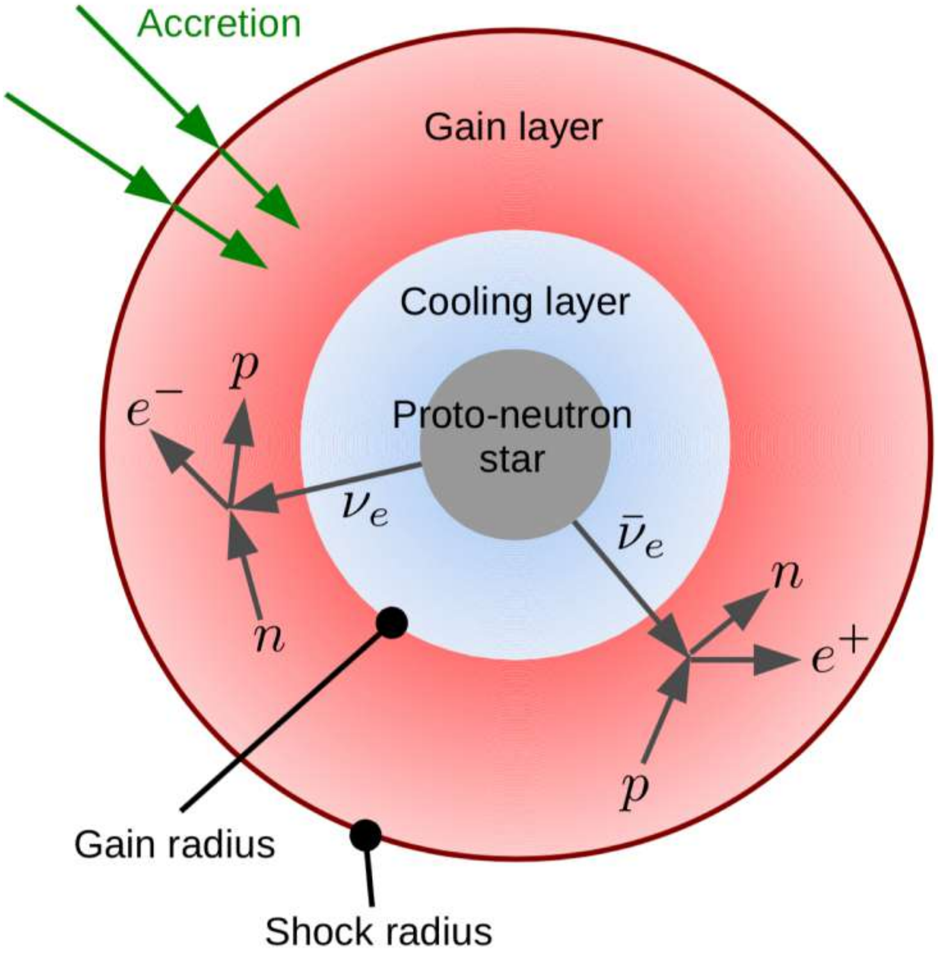
- Multi-dimensional hydrodynamics (instabilities, turbulence..)

- General relativity

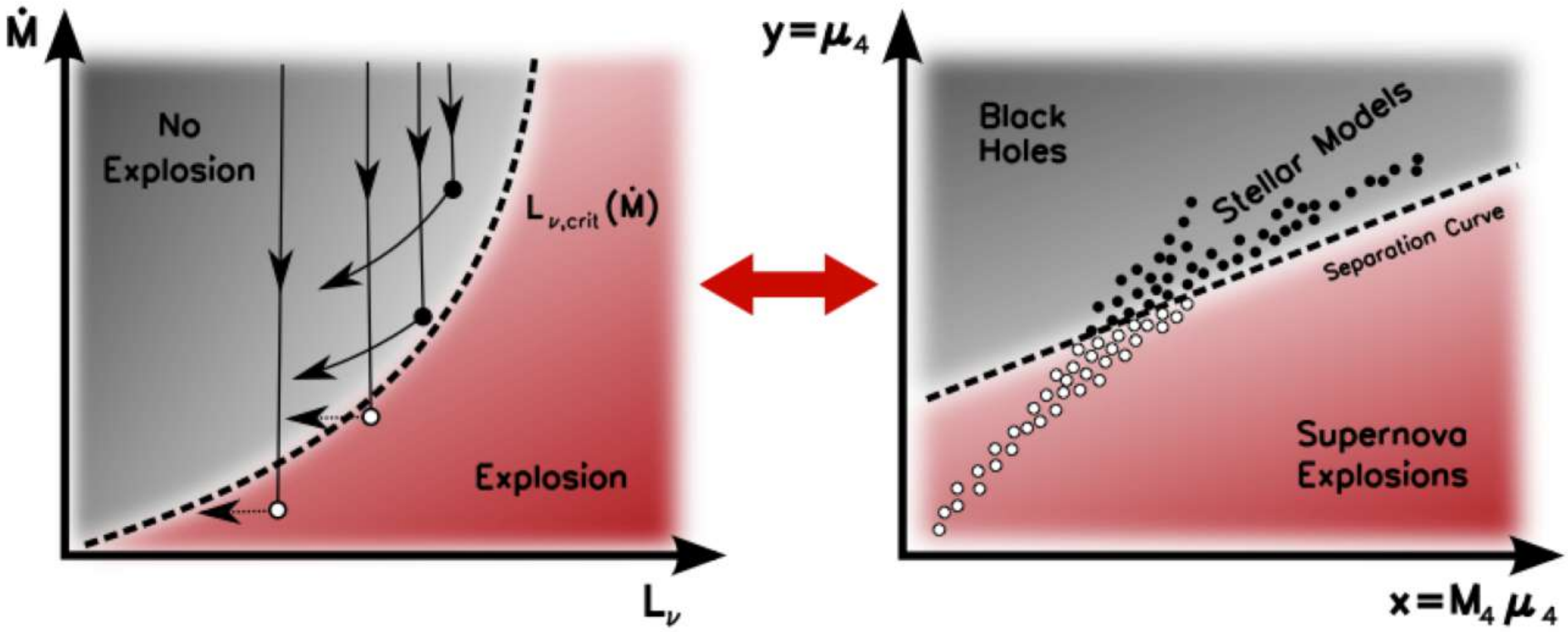
- Neutrino-matter interactions
  sophisticated transport schemes

- Ultra-high density equation of state

- Magnetic field



Critical neutrino luminosity



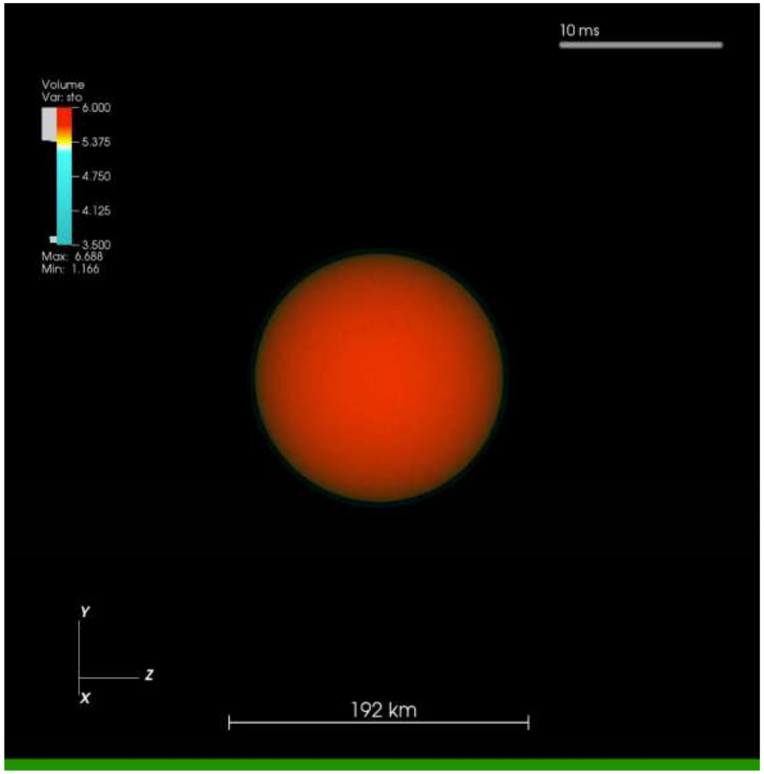
Criterion for explosion as a fonction of progenitor structure (Ertl et al 2015)

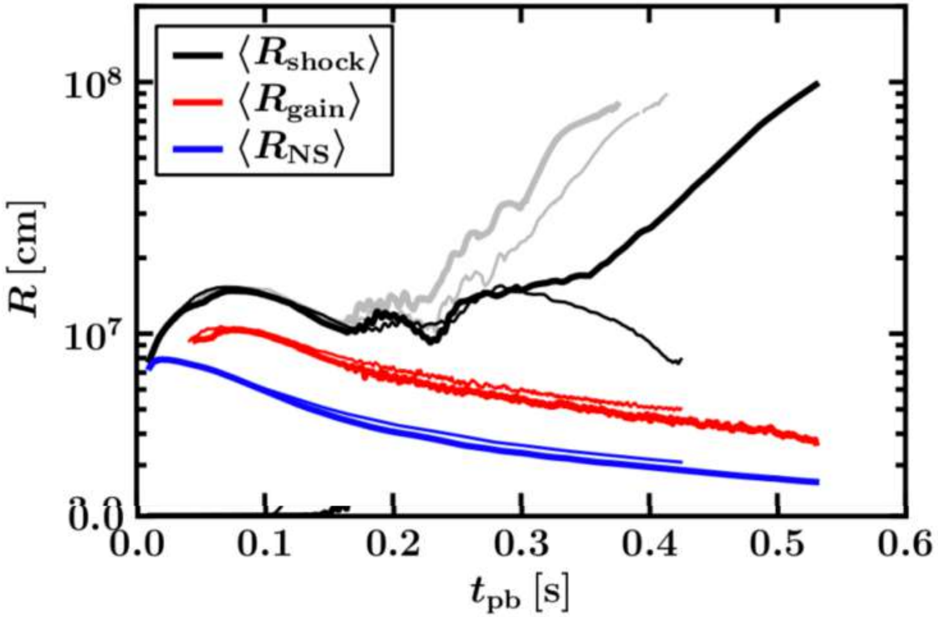
Two parameters :

$$M_4 \equiv m(s=4)$$

$$\mu_4 \equiv \left.\frac{\mathrm{d}m}{\mathrm{d}r}\right|_{s=4}$$

Sophisticated 3D simulations are necessary



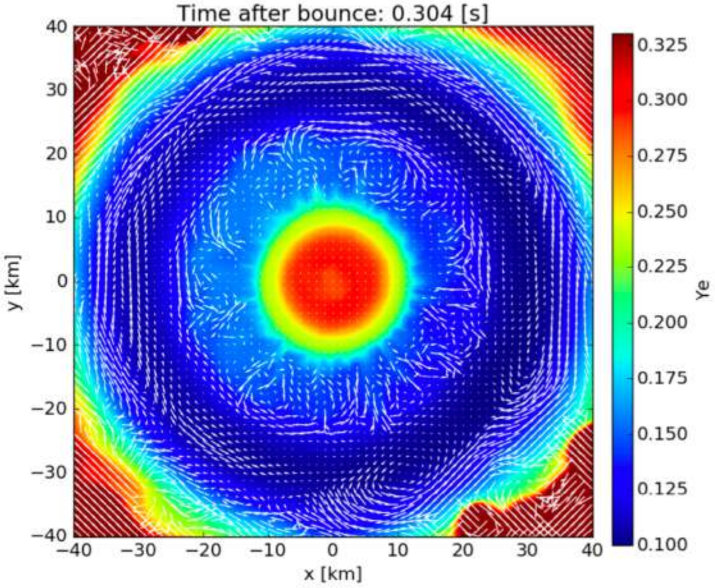


Explosion in 2D and 3D simulations ? No consensus yet..

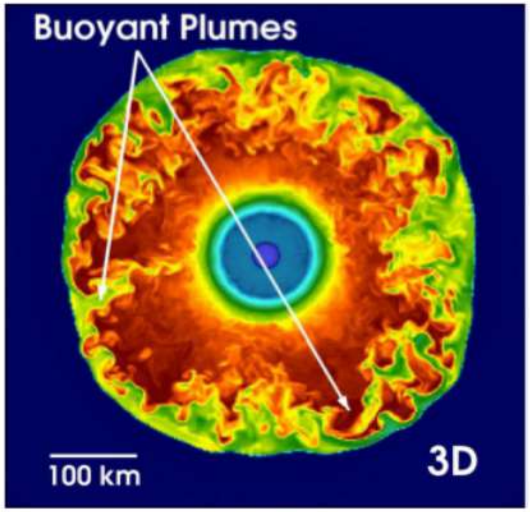
Oak ridge & japanese groups : explosions in 2D and 3D
Garching group : explosions in 2D, only for low mass in 3D with standard physics
Princeton group : first 3D explosion last month

Hydrodynamic instabilities

Protoneutron star convection

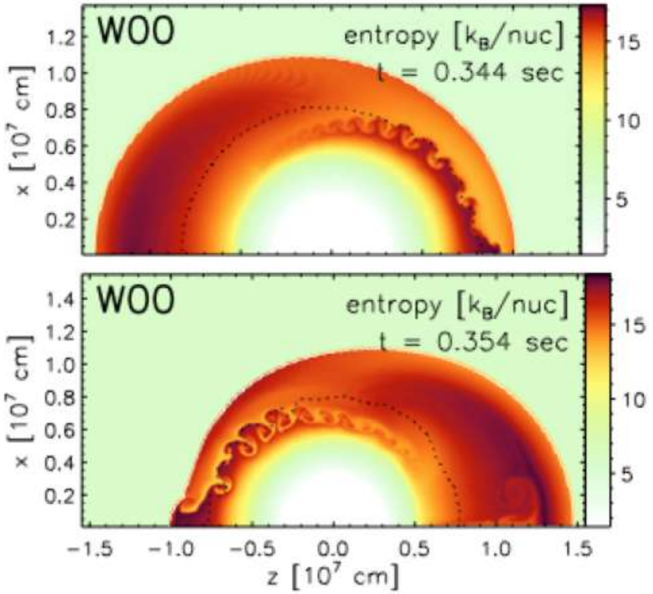


Neutrino-driven convection



Murphy et al 2013

Standing Accretion Shock Instability (SASI)



Scheck et al 2008

Global asymmetry of the explosion

Proto-neutron star convection

Ledoux criterion

$$\omega^2 = -\frac{g}{\gamma_{n_B}}\left(\gamma_s \nabla \ln(s) + \gamma_{Y_L} \nabla \ln(Y_L)\right),$$

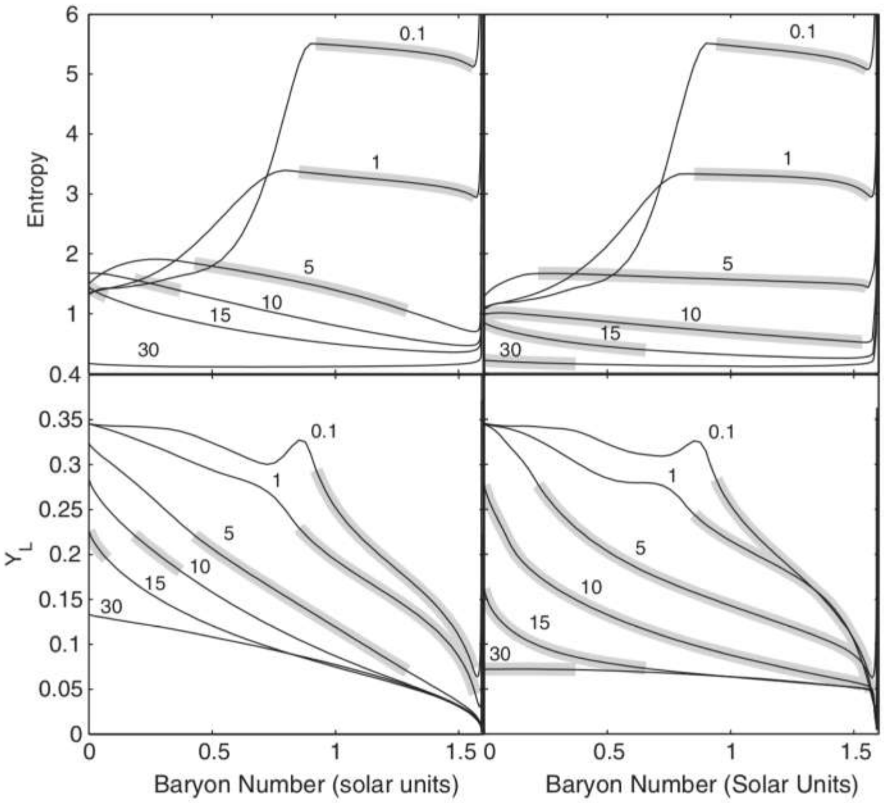
entropy

electron fraction

$$\gamma_{n_B} = \left(\frac{\partial \ln P}{\partial \ln n_B}\right)_{s,Y_L},$$

$$\gamma_s = \left(\frac{\partial \ln P}{\partial \ln s}\right)_{n_B,Y_L},$$

$$\gamma_{Y_L} = \left(\frac{\partial \ln P}{\partial \ln Y_L}\right)_{n_B,s},$$



Roberts+2012

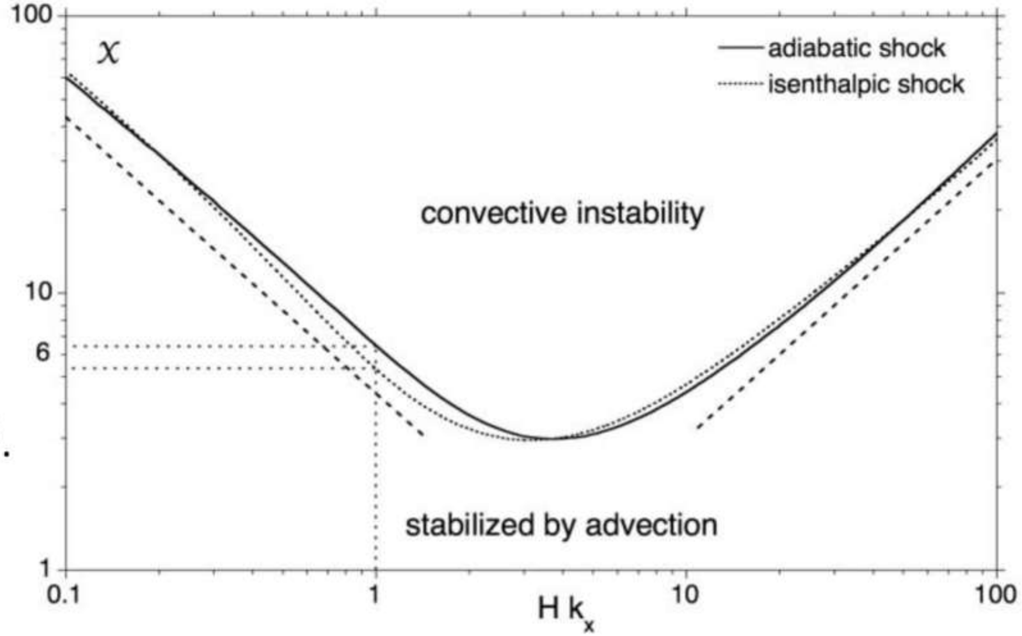
Consequence: faster cooling of the protoneutron star

Neutrino-driven convection: heating vs advection

Parameter controling stability:

$$\chi \equiv \int_{\mathrm{gain}}^{\mathrm{shock}} \omega_{\mathrm{buoy}}(z)\, \frac{dz}{v}.$$

$$\chi \sim \left(\frac{G\Delta S}{H}\right)^{1/2} \frac{H}{v} \sim \left(\frac{GH}{v^2}\right)^{1/2} (\Delta S)^{1/2} \propto \mathrm{Fr}^{-1/2}.$$

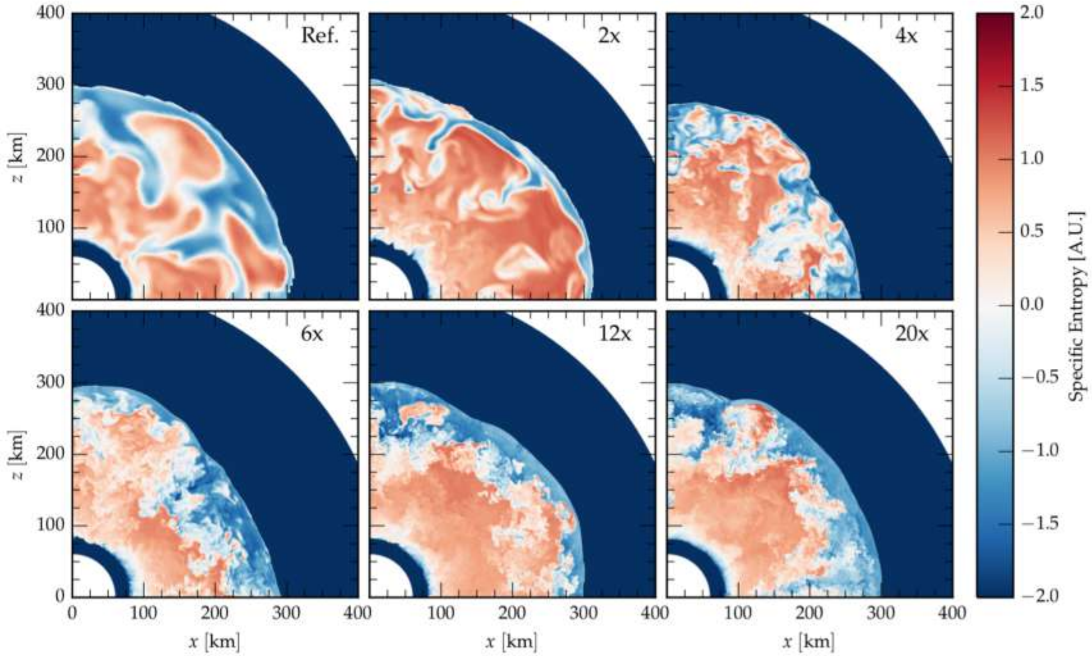


Foglizzo+2006

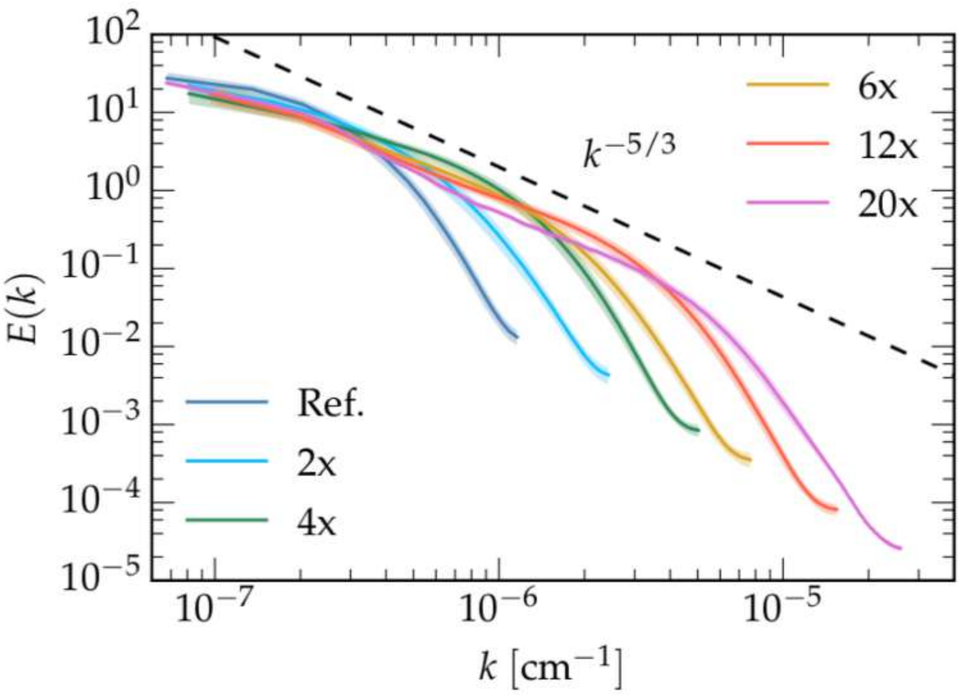
Linear instability for chi > 3

For chi < 3, convection can be non-linearly excited but not self-sustained
Kazeroni+2018

Neutrino-driven convection: heating vs advection



Radice+2016



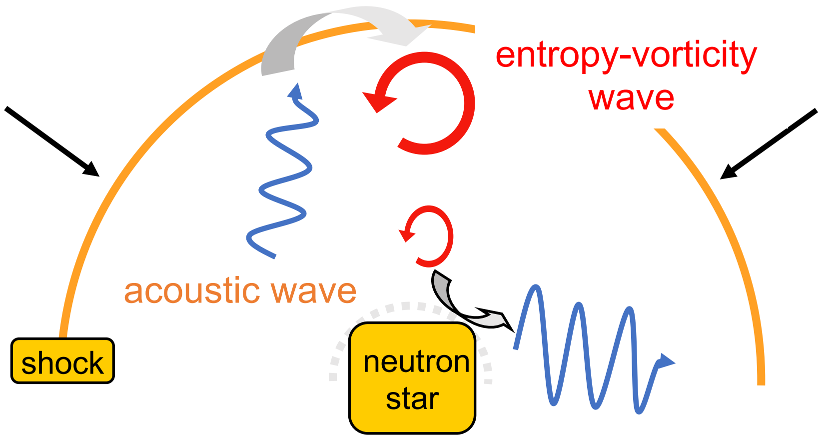
Convection helps explosion:

- Turbulence pressure pushes shock
- Increases heating efficiency

The Standing Accretion Shock Instability (SASI)

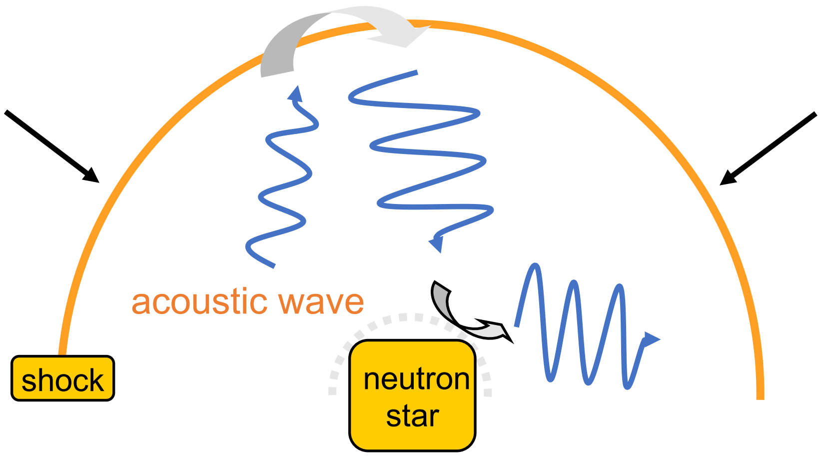
Advective-acoustic cycle

Foglizzo *et al* 2007



Purely acoustic mechanism

Blondin & Mezzacappa 2006



Advective-acoustic cycle favored by a WKB analysis (Foglizzo+2007, Guilet+12) & frequencies of unstable modes (Guilet+12)

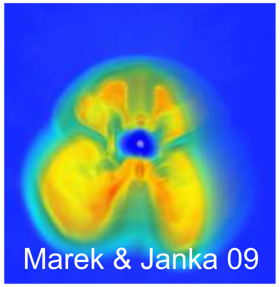
SASI in models with different degree of realism

realism & complexity

simplicity & understanding

Complex comprehensive simulations

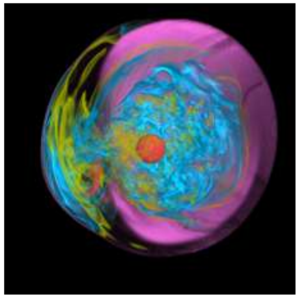
(Marek & Janka 09, Burrows et al. 06,
Wongwathanarat 10, Suwa et al. 10,
Müller et al. 12, Kuroda et al. 12,
Sumiyoshi & Yamada 12)



progenitor structure + nuclear EOS
+ neutrino "transport" & interactions
+ "GR" + "multi-D" hydro
(no magnetic field)

Multi-D hydro processes only

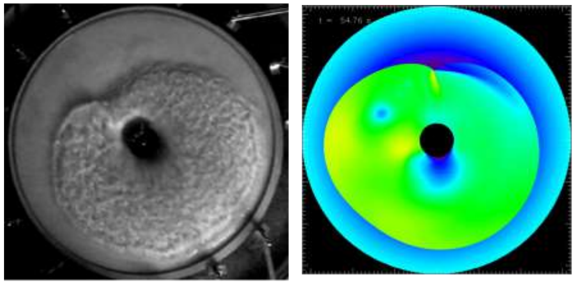
Blondin & Mezzacappa 07
Fernandez+2010
Kazeroni+2016,2017



stationary accretion,
ideal gas,
3D adiabatic

SWASI experiment

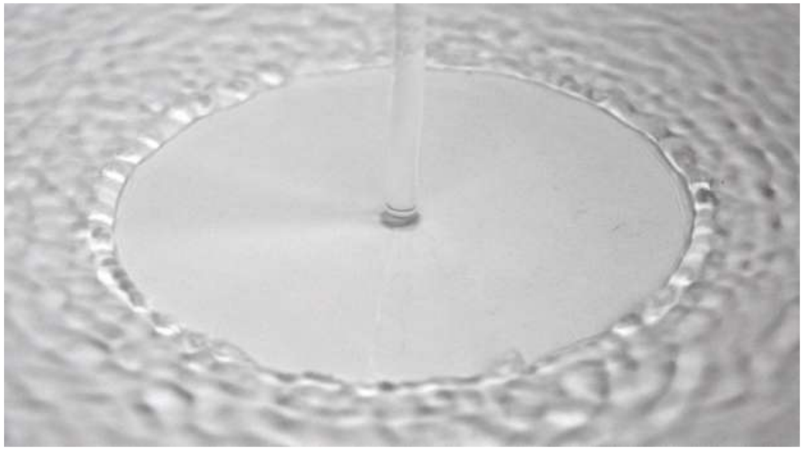
Foglizzo et al. 12

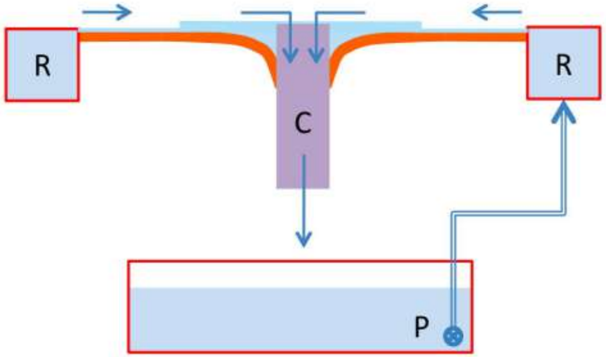


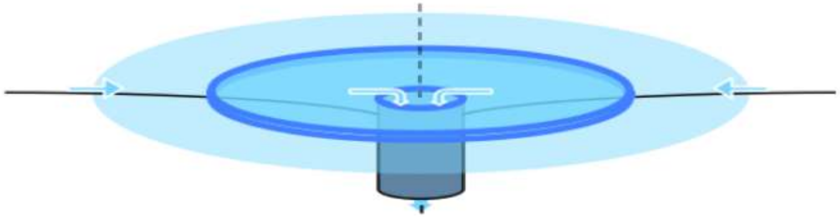
- 2D shallow water
  inviscid

SWASI : Shallow Water Analogue of a Shock Instability

Kitchen sink hydraulic jump

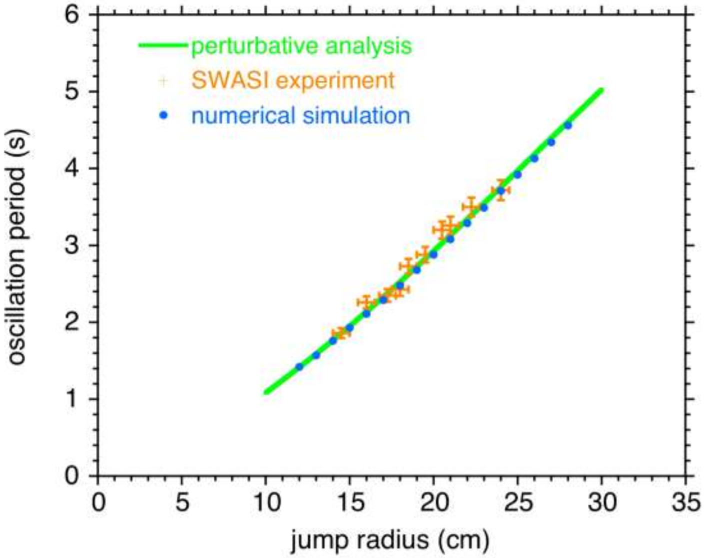






	↔	
acoustic waves		surface wave
shock wave		hydraulic jump
pressure		depth

SWASI : Shallow Water Analogue of a Shock Instability



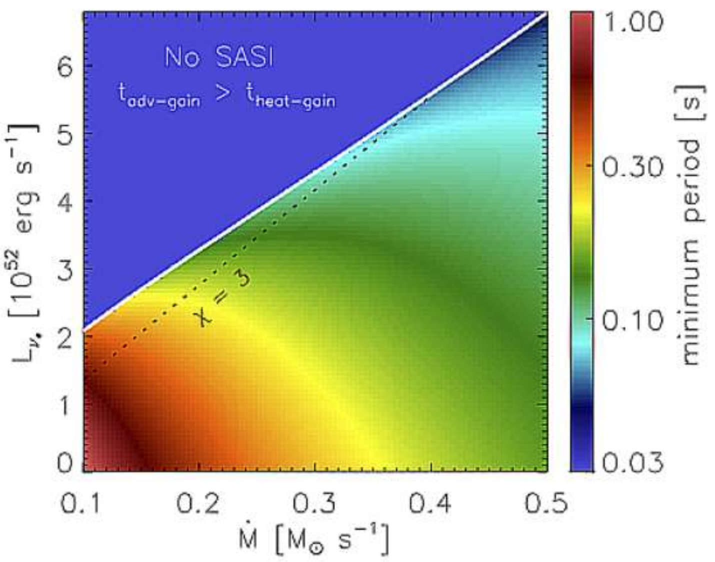
Angular momentum redistribution & neutron star spins

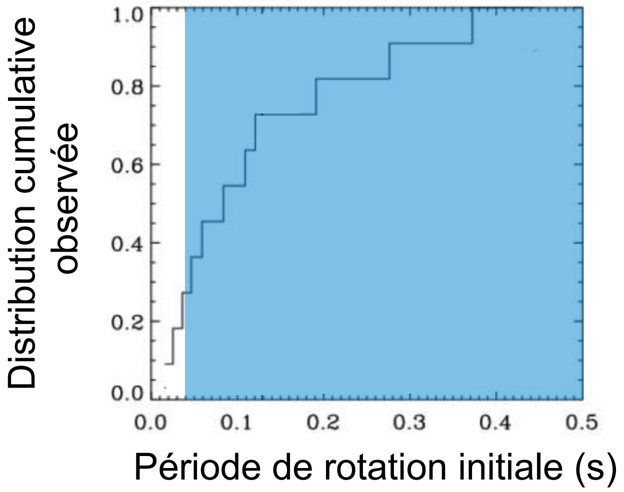
Consequences for the spin of neutron stars

Approximate expression for the neutron star period
Guilet+14

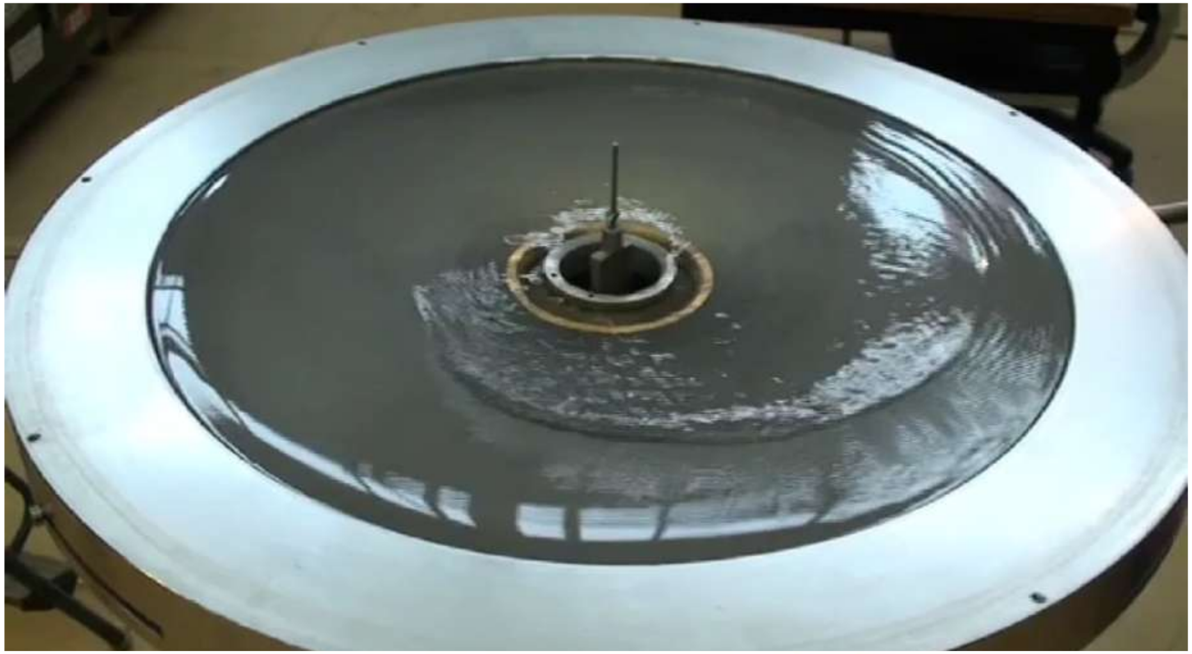
$$P \simeq 290\, I_{45} \left(\frac{10}{\kappa}\right) \left(\frac{P_{sasi}}{50\,\mathrm{ms}}\right) \left(\frac{120\,\mathrm{km}}{r_{\mathrm{sh}} - r_*}\right) \left(\frac{v_{\mathrm{sh}}}{3000\,\mathrm{km.s^{-1}}}\right) \left(\frac{0.3\,\mathrm{M_\odot.s^{-1}}}{\dot M}\right) \left(\frac{150\,\mathrm{km}}{r_{\mathrm{sh}}}\right)^2 \left(\frac{r_{\mathrm{sh}}}{3\Delta r}\right)^2 \mathrm{ms}$$

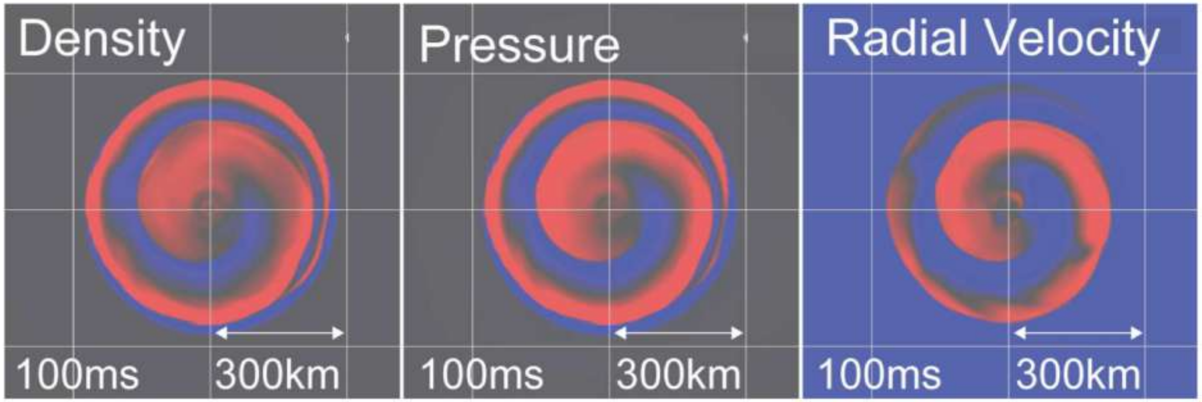
=> SASI has the potential to explain the rotation of most (but not all) neutron stars

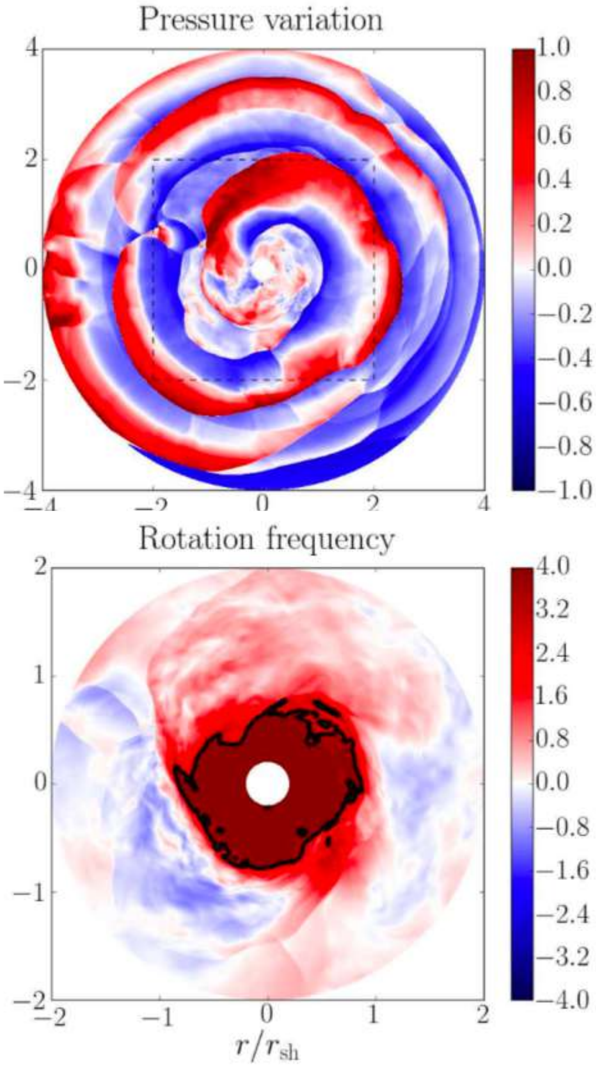




Fast rotators: corotation instability

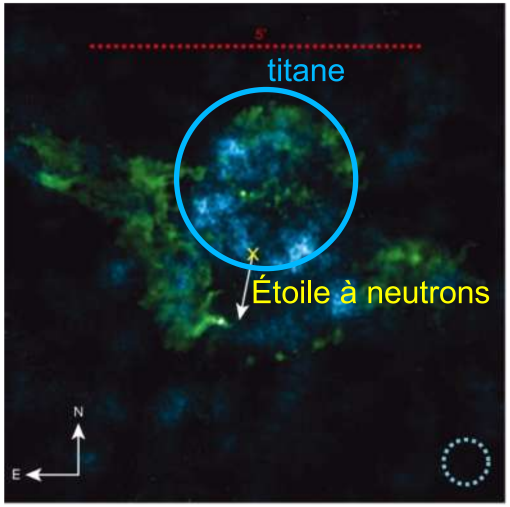






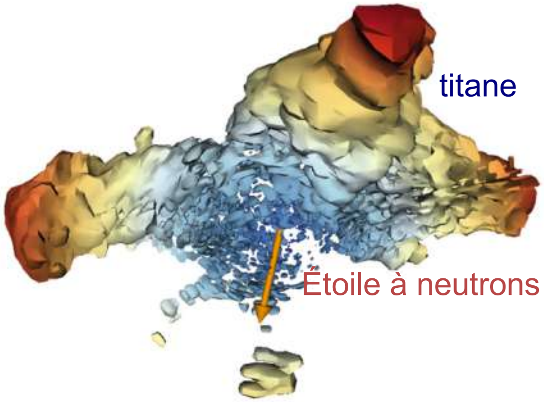
Explosion morphology revealed by nucleosynthesis

Observation of Cas A



Grefenstette et al 2014

Numerical simulation

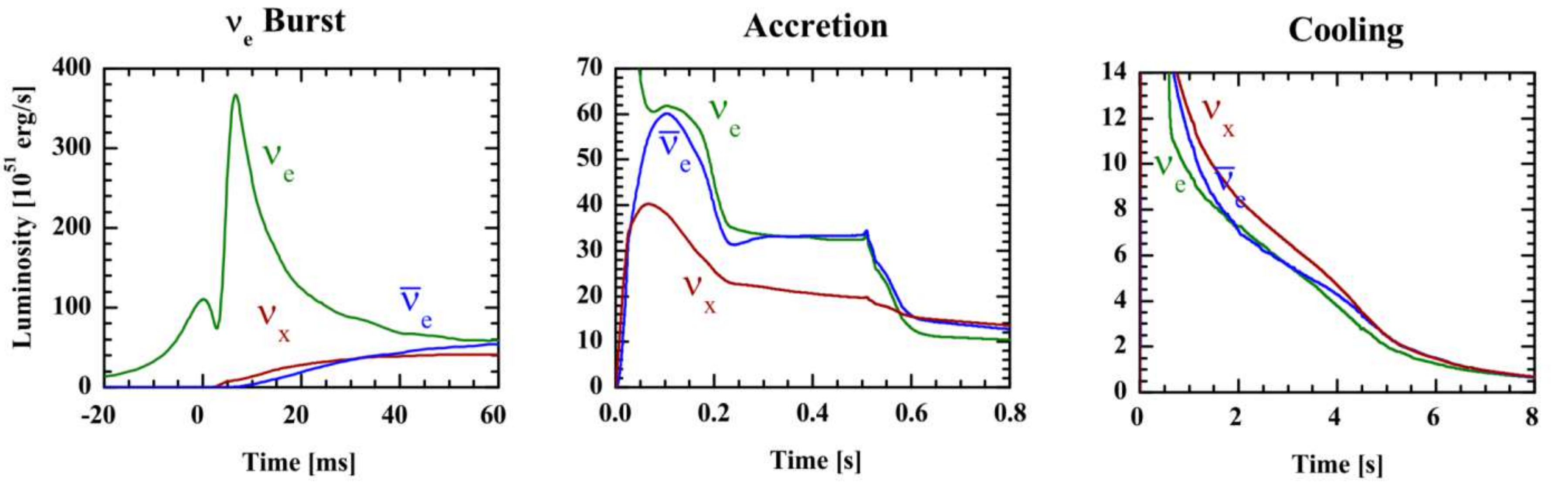


Wongwathanarat et al 2016, 2018

Titanium nucleosynthesis is a tracer of explosion asymetry

sensitive to electron fraction Ye

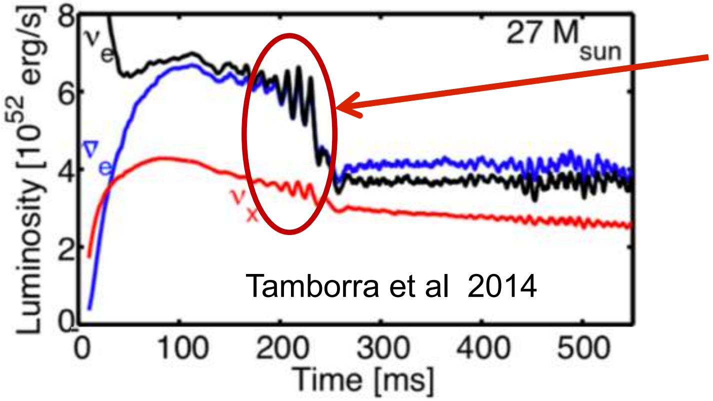
Neutrino signatures



test oscillation physics

probes SN astrophysics

probes nuclear physics
& PNS convection



Tamborra et al 2014

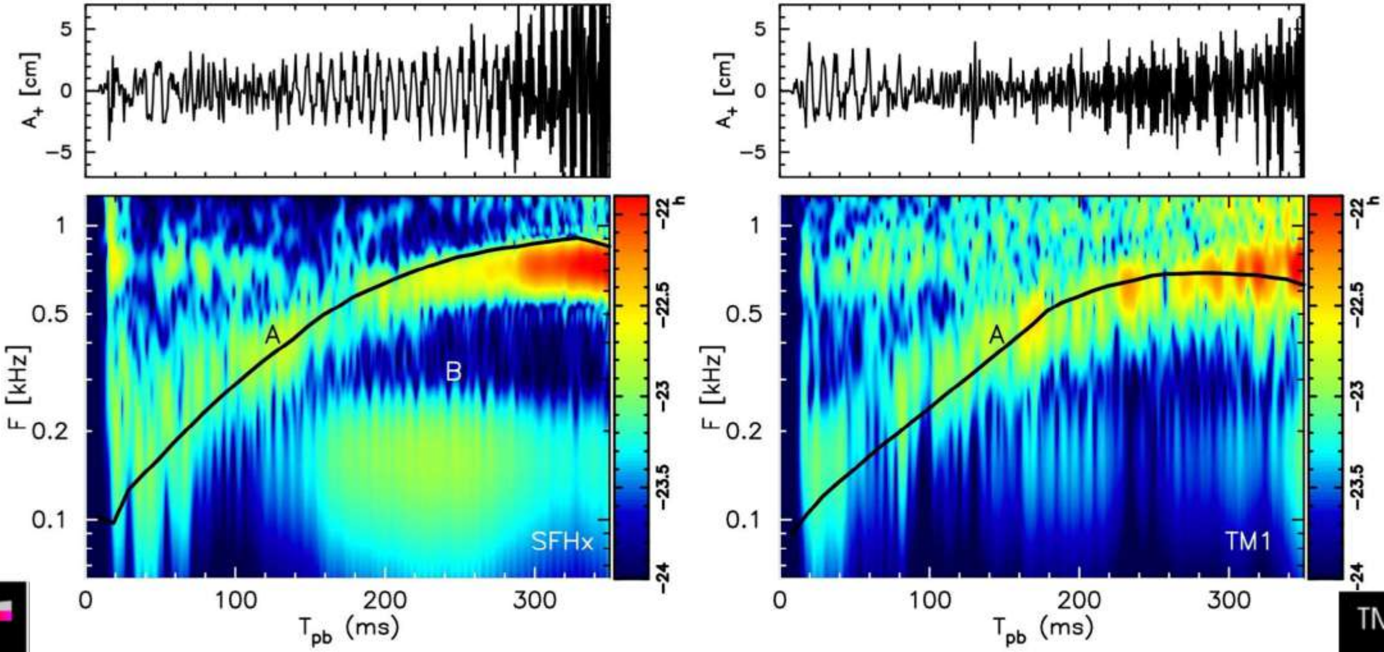
hydrodynamic instabilities

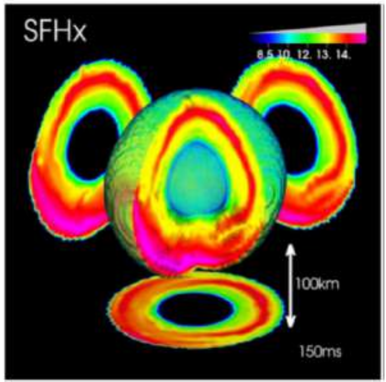
EOS & mass dependance

Gravitational wave signature

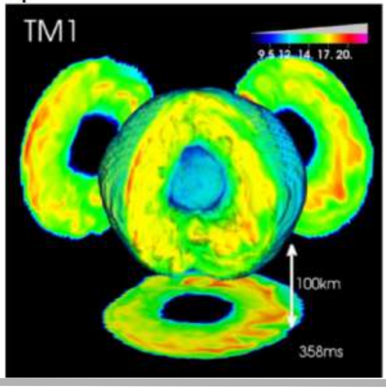
Softer EOS
(SFHx, Steiner+13)

Stiffer EOS
(TM1, Hempel+10)





Kuroda+2016



Outstanding explosions: magnetorotational explosions ?

Explosion kinetic energy :

→ Typical supernova 10^{51} erg

→ Rare hypernova & GRB 10^{52} erg

aka type Ic BL

Total luminosity :

→ Typical supernova 10^{49} erg

→ Superluminous supernovae 10^{51} erg

Light curves can be fitted by millisecond magnetar

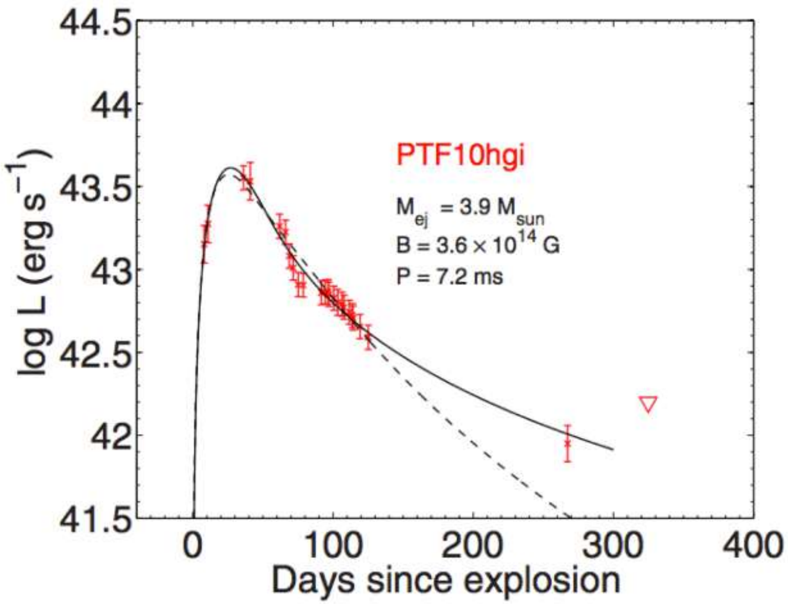
- strong dipole magnetic field: $B \sim 10^{14}$-10^{15} G
- fast rotation: $P \sim 1$-10 ms

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

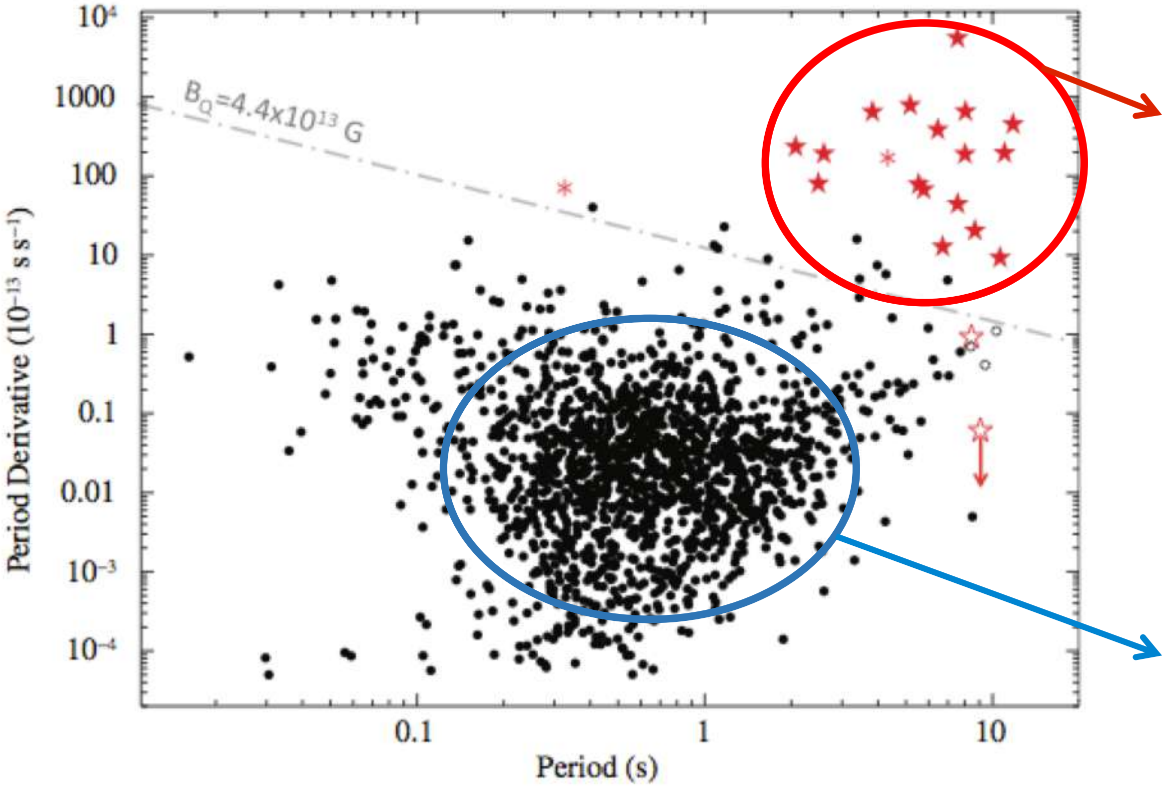
→ Neutrino driven explosions ?

→ Magnetorotational explosion ?

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



Magnetars: the most intense known magnetic fields



Magnetars

Anomalous X-ray pulsars (AXP)

Soft gamma repeater (SGR)

Strong dipole magnetic field:

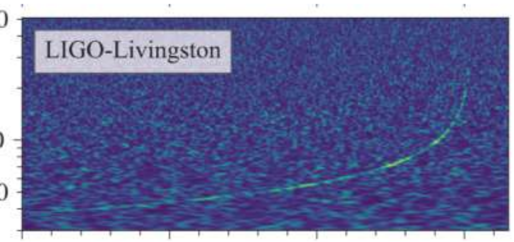
$B \sim 10^{14} - 10^{15}$ G

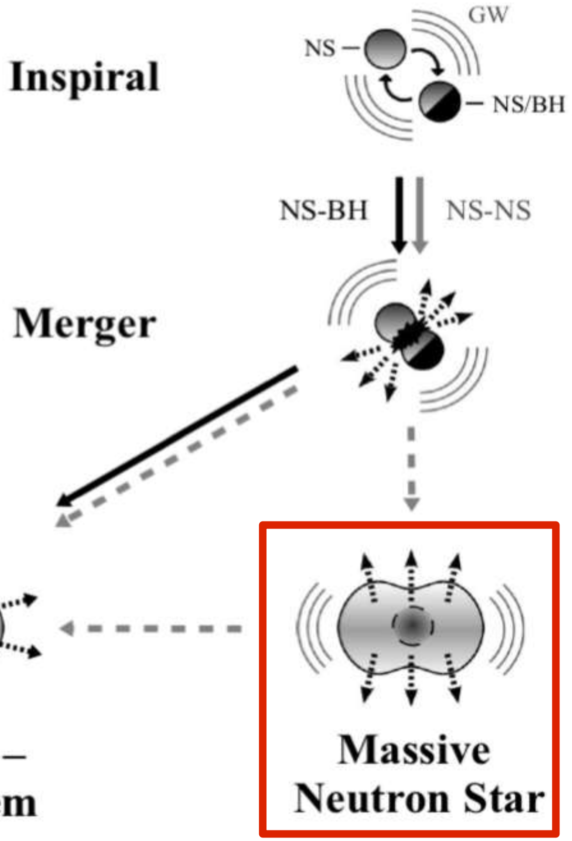
Pulsars

$B \sim 10^{12} - 10^{13}$ G

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

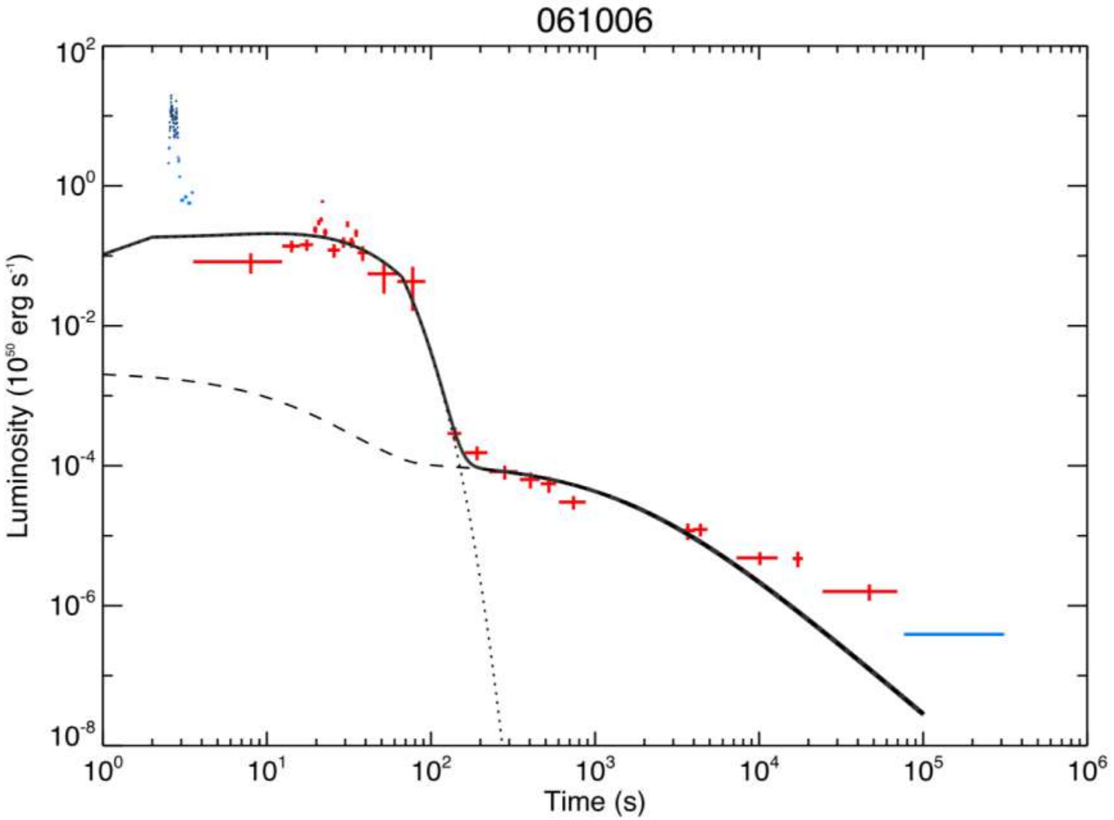
Formation of a magnetar ?

Signature in future joint gravitational wave – electromagnetic obervations ?

SVOM

Launch : end of 2021

GRBs: 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

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

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

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

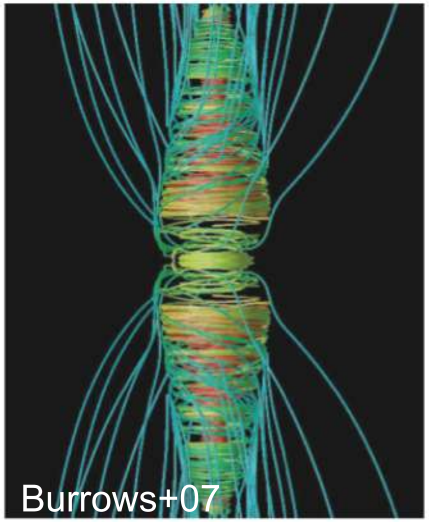
Impact of a strong magnetic field on the explosion

Strong magnetic field: B ~ 10^{15} G

+ fast rotation (period of few milliseconds)

=> powerful jet-driven explosions !

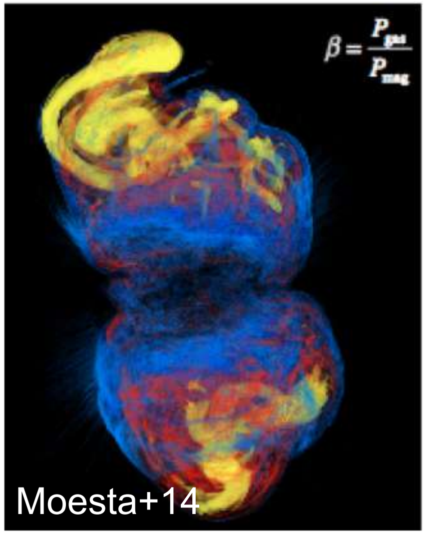
e.g. Sibata+06, Burrows+07, Dessart+08, Takiwaki+09,11, Winteler+12, Obergaulinger+17



Burrows+07

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

Moesta+2014



Moesta+14

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}-10^{13} G (?)

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

Magnetar: 10^{15} G

Amplification mechanism ?

Magnetorotational instability

Similar to accretion disks

Convective dynamo

Similar to planetary & stellar dynamos

The magnetorotational instability (MRI)

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

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

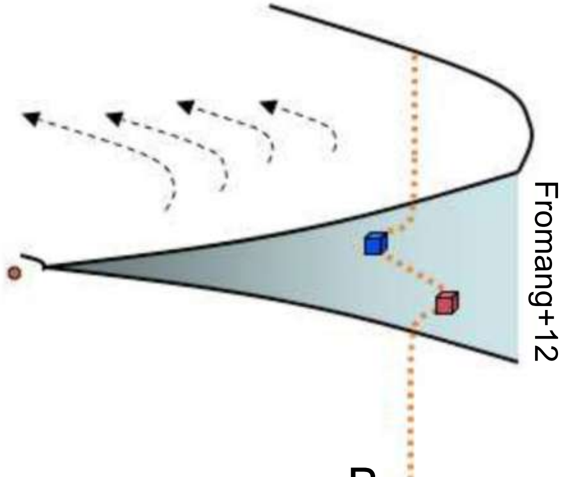
Growth rate : $\sigma = \frac{q}{2}\Omega$

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

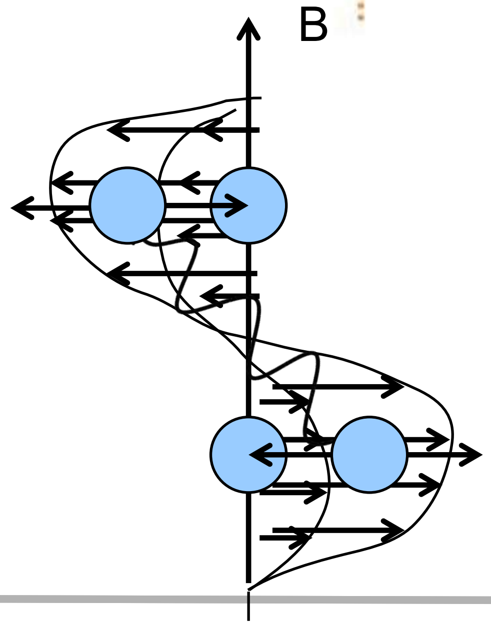
→ Fast growth for fast rotation

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

→ Short wavelength for weak magnetic field



Fromang+12

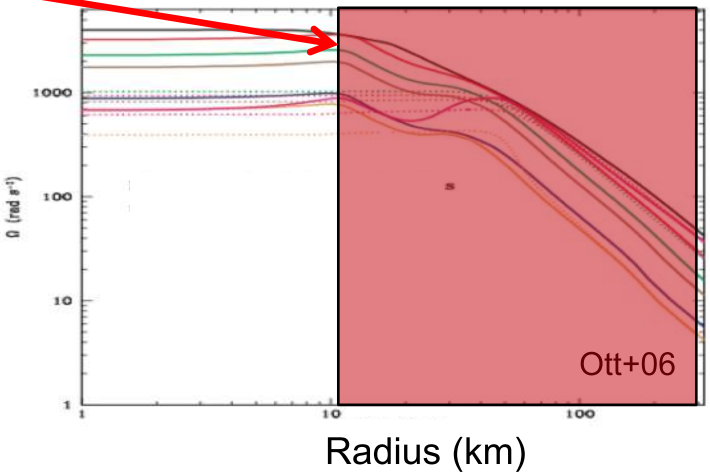


Proto-neutron stars vs disks conditions

MRI unstable differential rotation
at radii > 10 km

Akiyama+2003, Obergaulinger+2009

Rotation profile

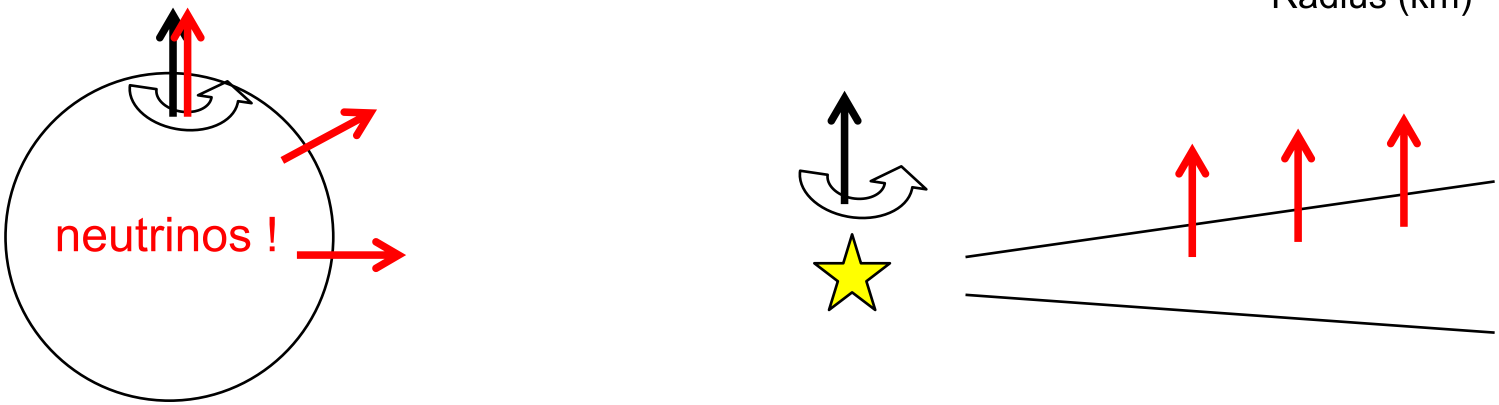


Impact of conditions specific to neutron stars ?

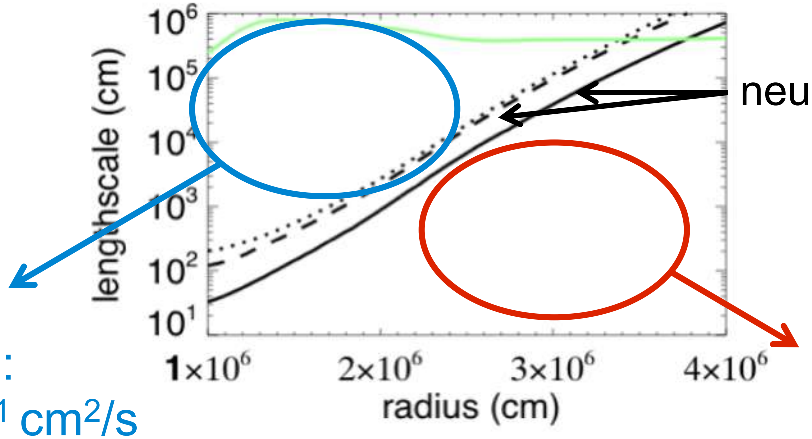
→ neutrinos

→ buoyancy (entropy & composition gradients)

→ spherical geometry

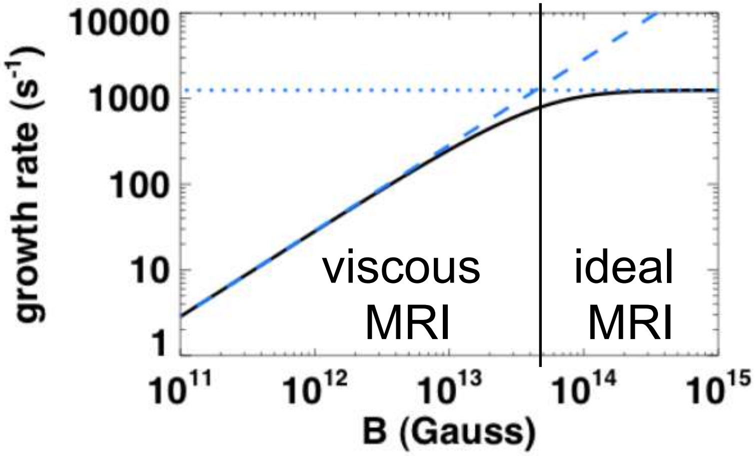


Impact of neutrinos on the MRI: growth rate

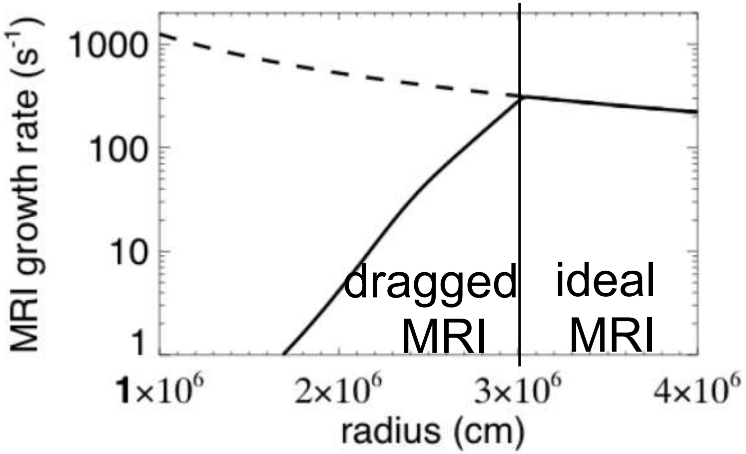


neutrino mean free path

Diffusive regime:
Neutrino viscosity 10^{11} cm^2/s



Neutrino drag regime



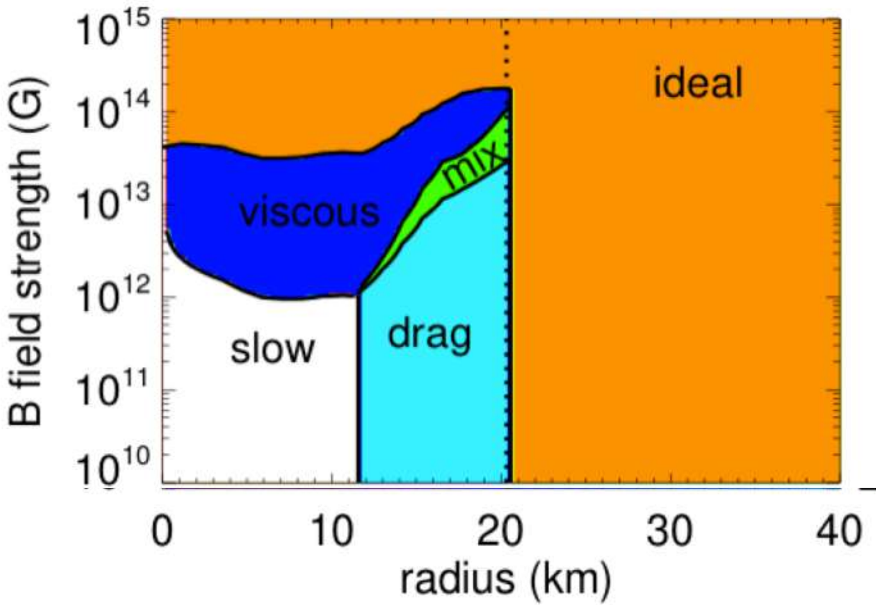
Slow growth for weak initial magnetic field < 10^{12} G

Fast growth near surface independently of field strength

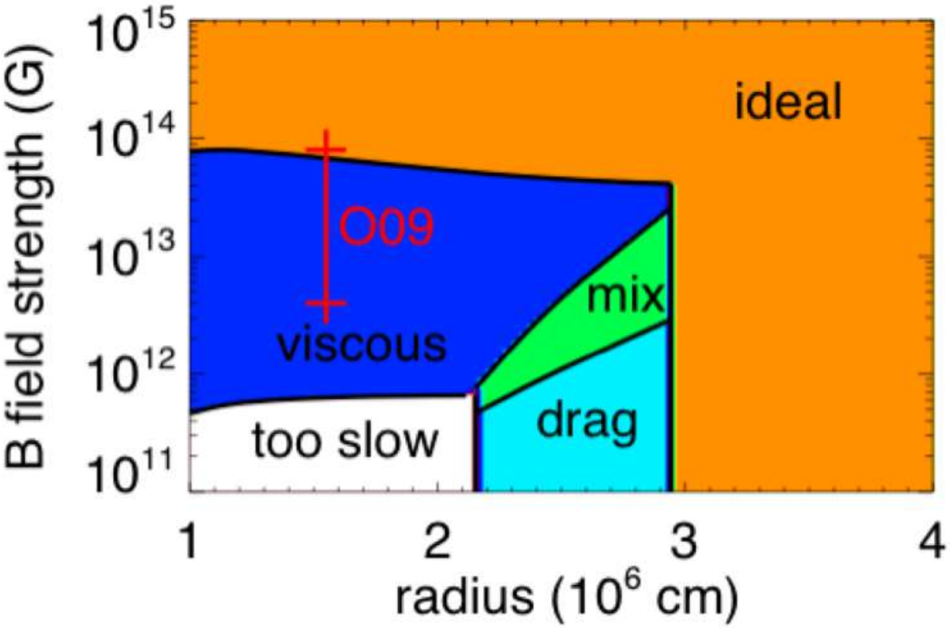
Guilet et al (2015), Guilet et al (2017)

Comparing supernovae & neutron star mergers

Neutron star mergers



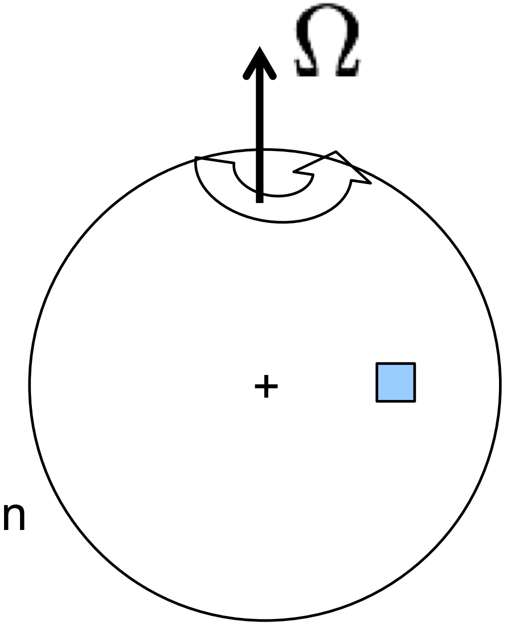
Core collapse SN



=> 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

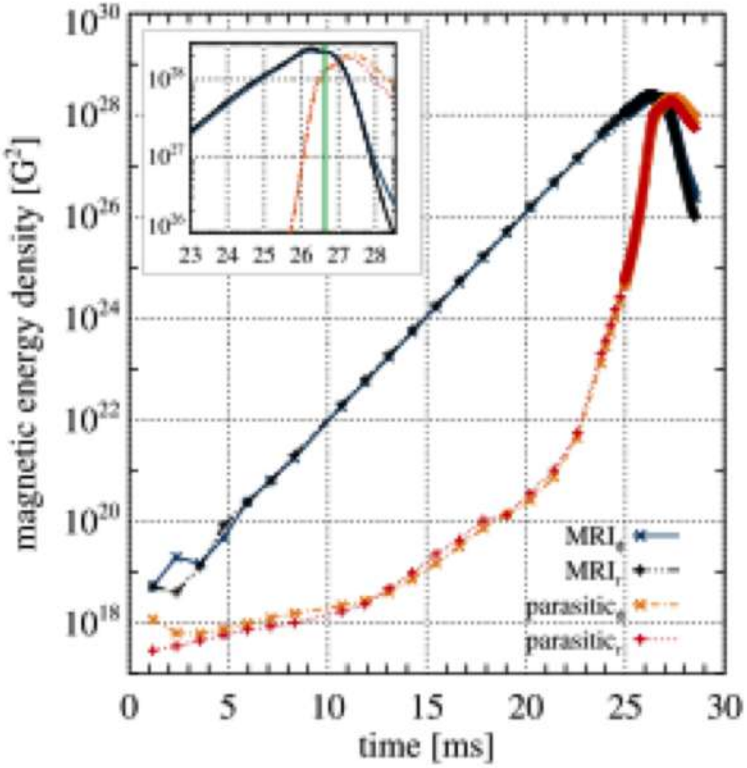
Code: Snoopy (G. Lesur)

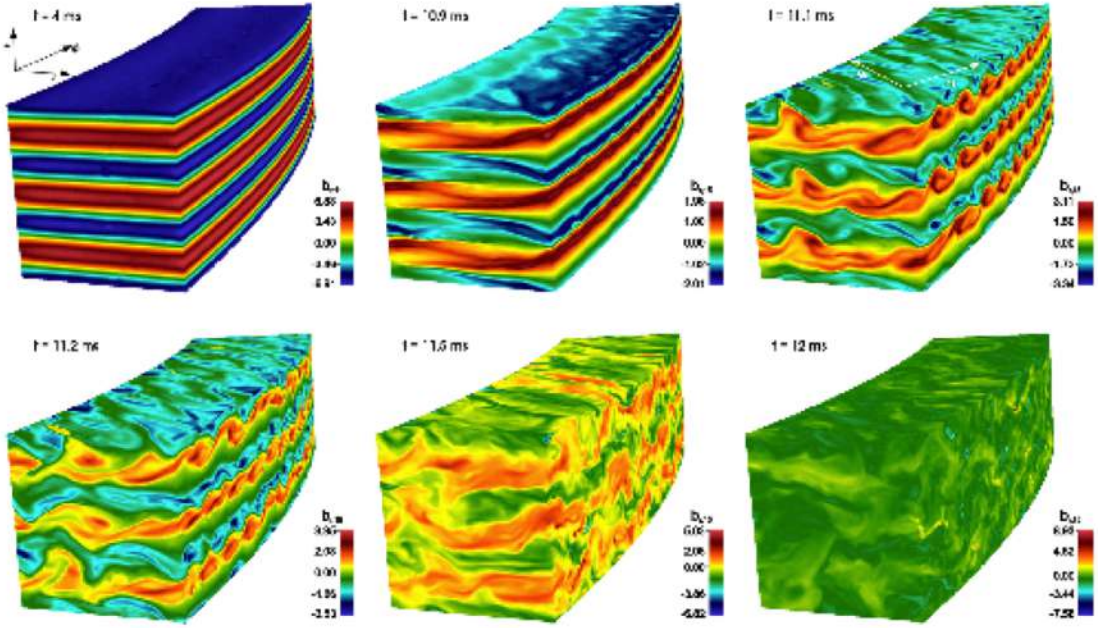
Obergaulinger+2009, Masada+2012,
Guilet+2015, Rembiasz+2015,2016

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 termination by parasitic instabilities





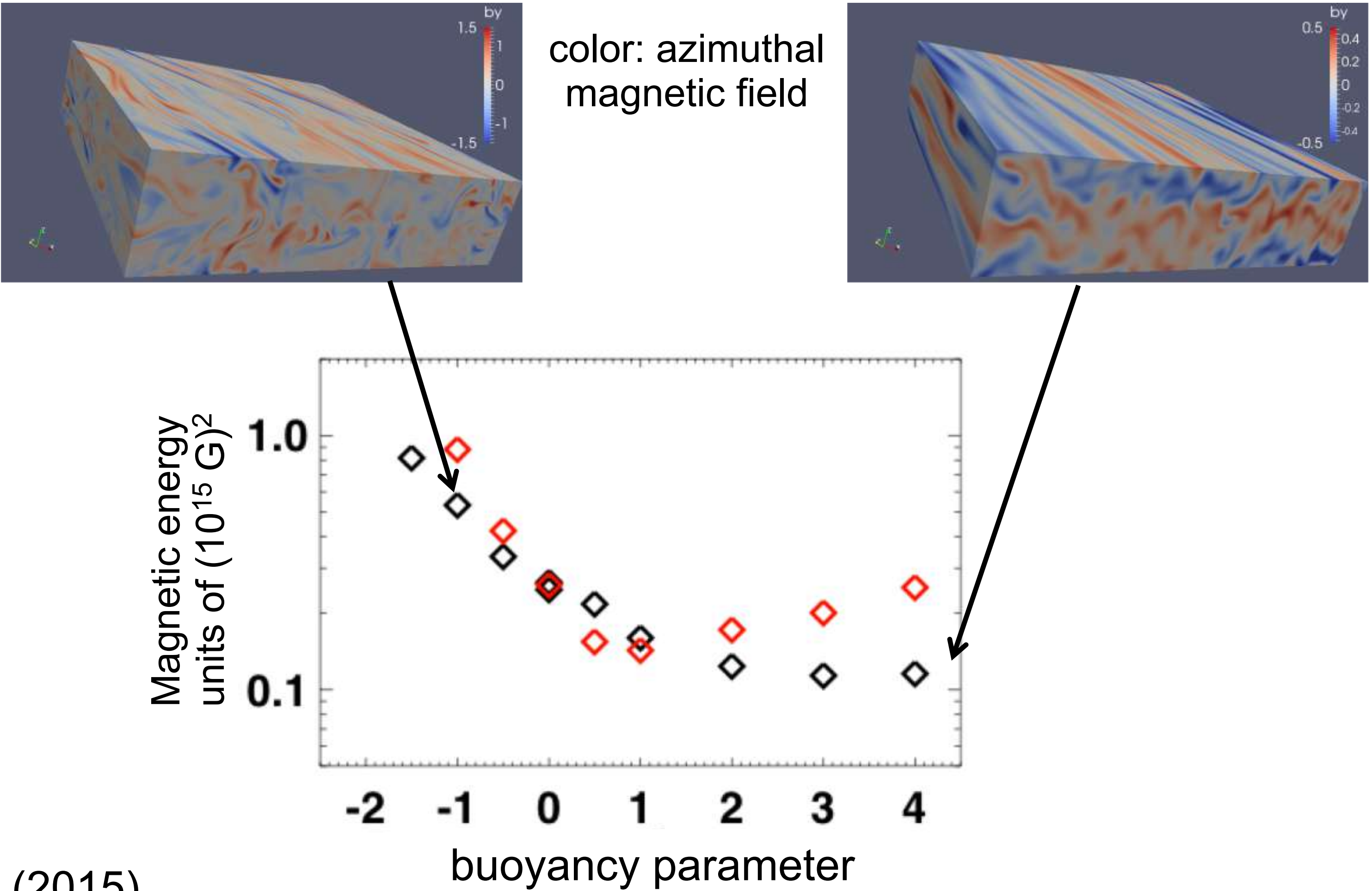
Rembiasz et al. 2016a&b

Impact of stratification on the MRI

unstable buoyancy

stable stratification

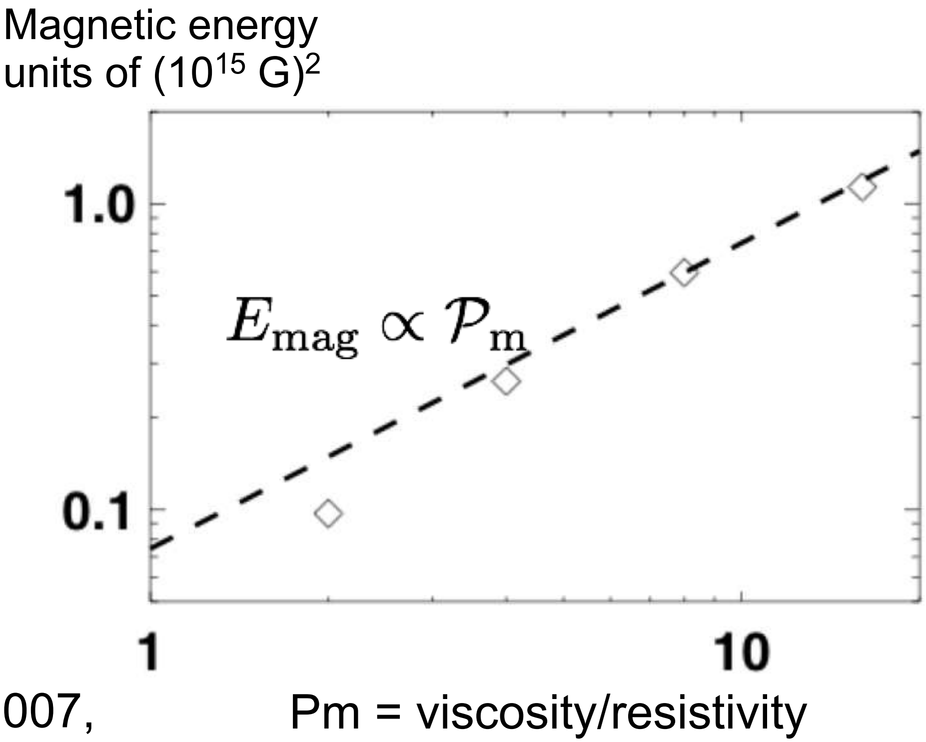
color: azimuthal magnetic field



Guilet & Müller (2015)

Dependence on diffusion processes

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

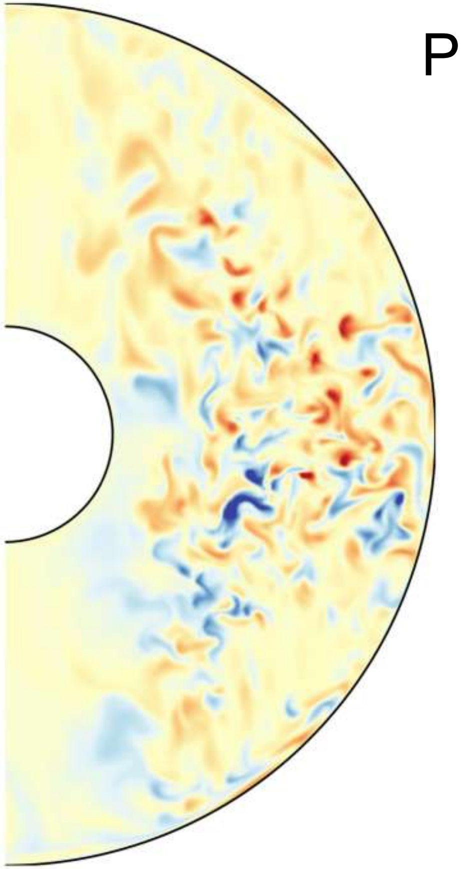


See also:
Fromang+2007, Lesur+2007,
Meheut+2015, Potter+2017

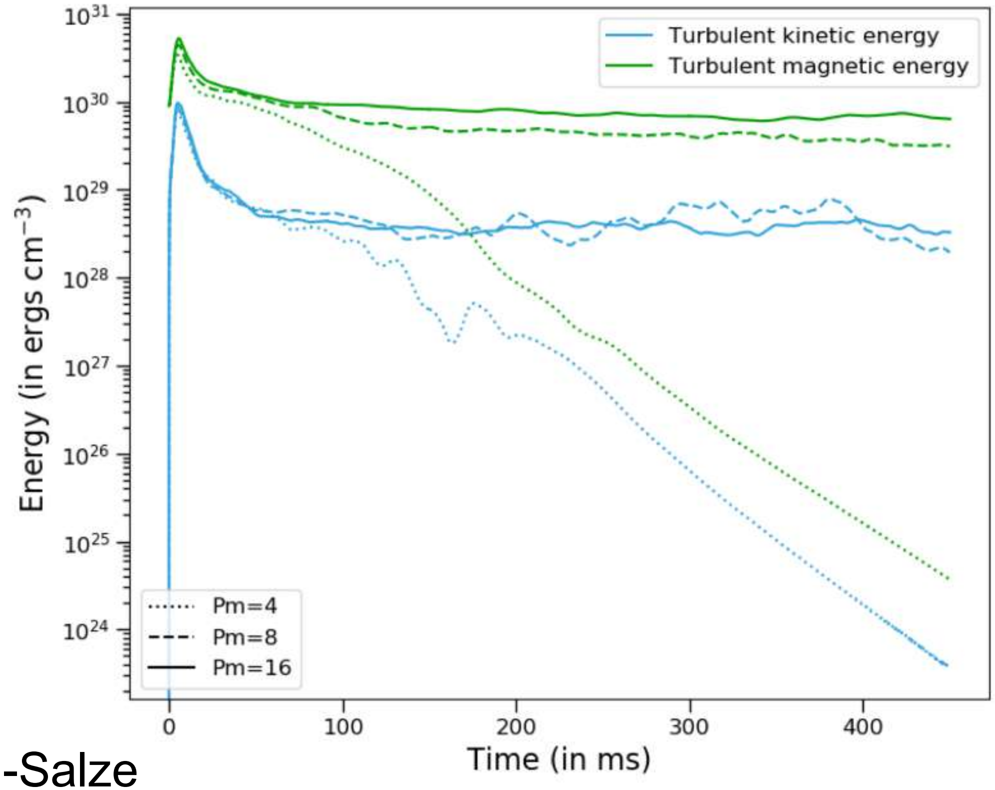
Behaviour at realistic values: very large magnetic Prandtl number Pm ?

Global model of MRI: geometry of the magnetic field ?

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



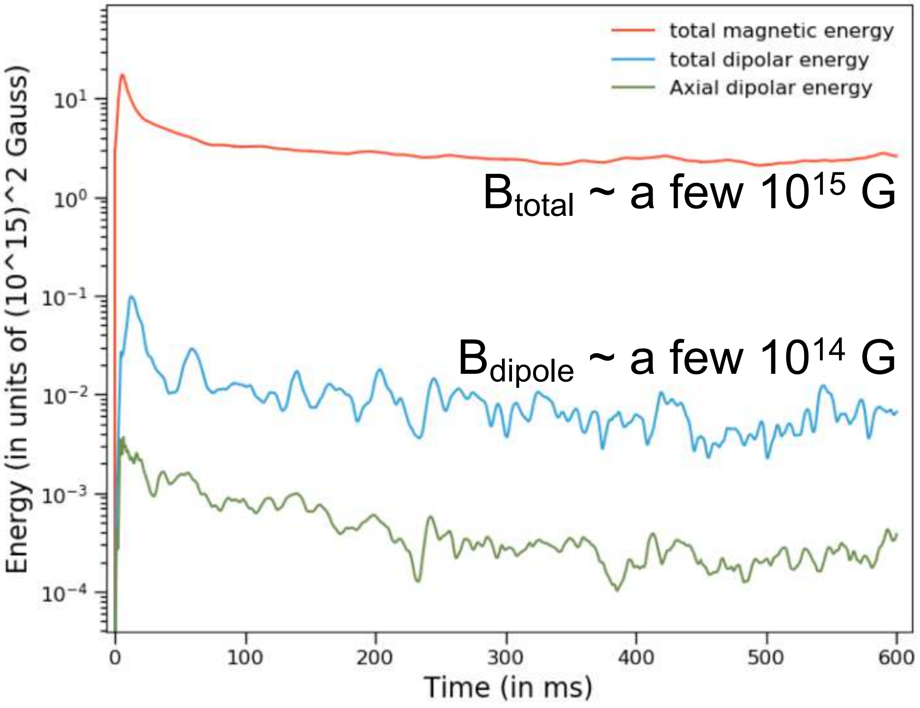
Pseudo-spectral code : MagIC Wicht (2002), Gastine & Wicht (2012)



Projet de thèse d'Alexis Reboul-Salze

Global models: strength of dipole magnetic field

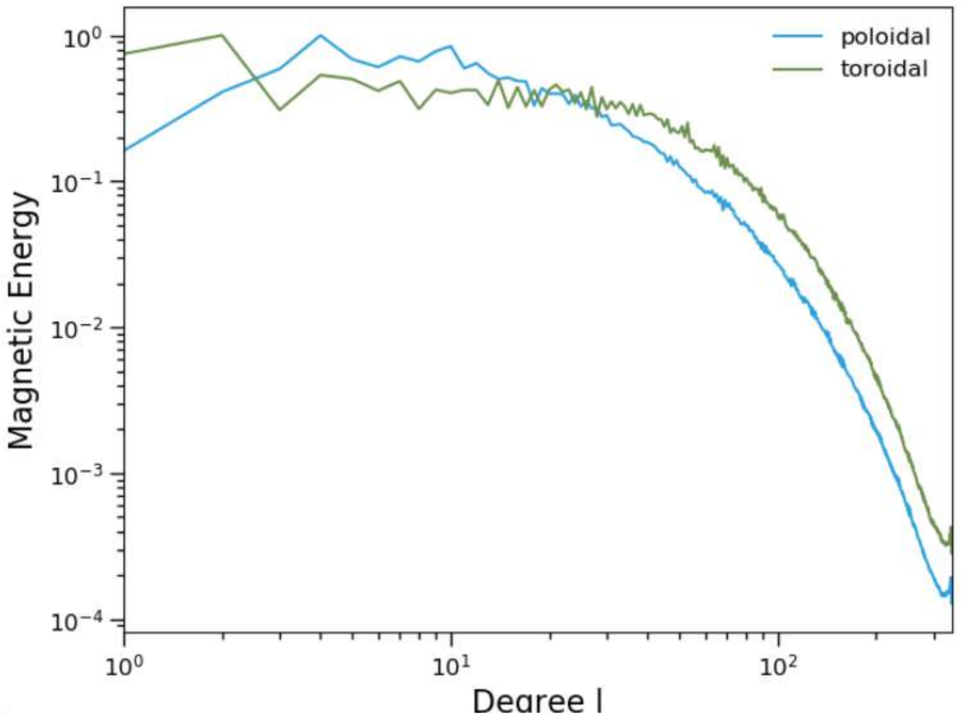
Magnetic energy evolution



B_{total} ~ a few 10^{15} G

B_{dipole} ~ a few 10^{14} G

Magnetic energy spectrum

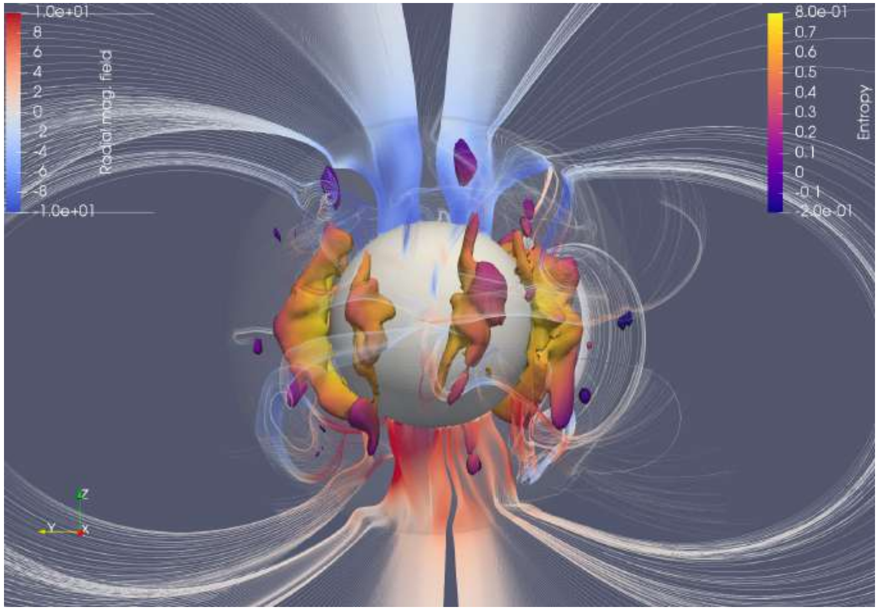


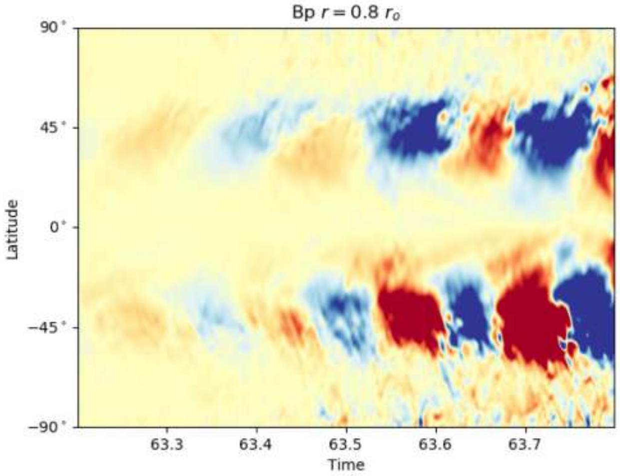
Equatorial dipole as strong as a magnetar ☺

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

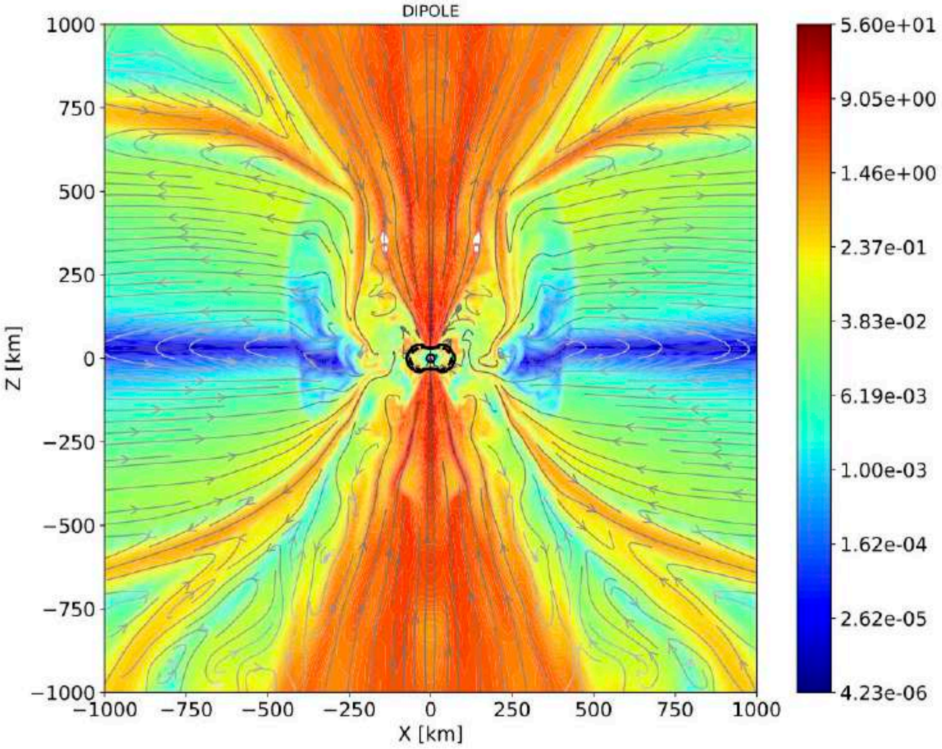




Is a regime with strong dipolar magnetic field possible ?

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)

Conclusions

Very rich and complex multidimensional fluid dynamics:

- PNS convection + dynamo
- Neutrino-driven convection
- Standing Accretion Shock Instability (SASI)
- Corotation instability (low-T/W)
- Magnetorotational instability (MRI)

Big impact on core collapse supernovae

- Success of explosion
- Asymmetry: neutron star kick and spin, SNR morphology
- Neutrino & gravitational wave signatures
- Magnetic fields & extreme supernovae

Multi-messenger observations will be essential to constrain all this physics

Thank you !