Core collapse supernovae & neutron star formation : impact of the progenitor structure, rotation and magnetic field

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Plan of the talk

1. Typical supernovae : asymmetric neutrino driven explosions ?
2. Rotation
3. Magnetic field (& rotation)
4. Conclusion

A diversity of supernovae

Observational constraints on explosion energy :

→ Sub-energetic supernova : 10^{50} ergs

→ Typical supernova : 10^{51} ergs

→ Rare « hypernovae » : 10^{52} ergs

→ Neutrino driven explosions ?

e.g. Hanke+13, Bruenn+14, Melson+15, Lentz+15

→ Magnetorotational explosions ?

e.g. Burrows+07, Takiwaki+09,11

Observational constraints on total luminosity :

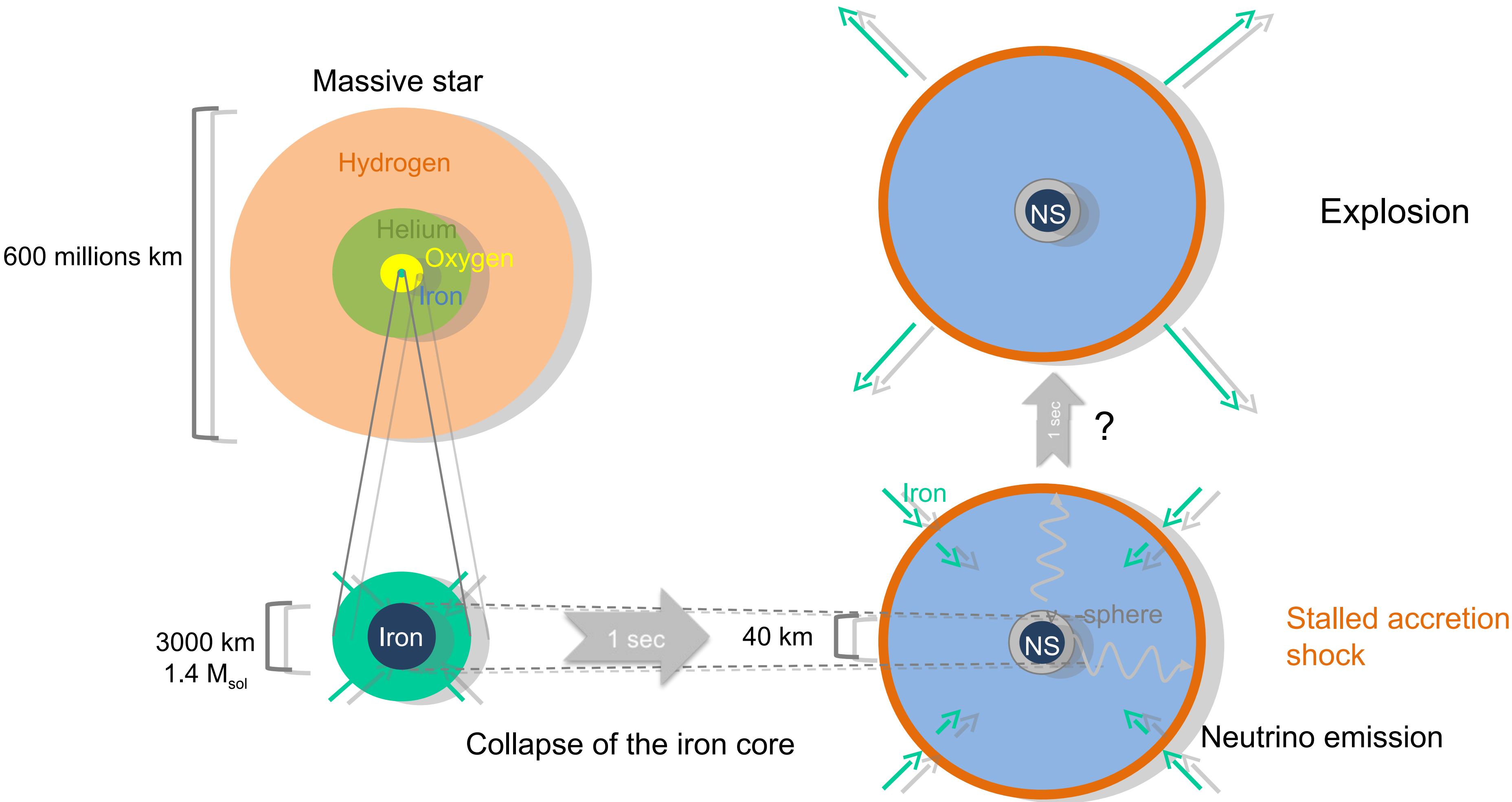
→ Typical supernova : 10^{49} ergs

→ Superluminous supernovae : 10^{51} ergs

→ Millisecond magnetar ?

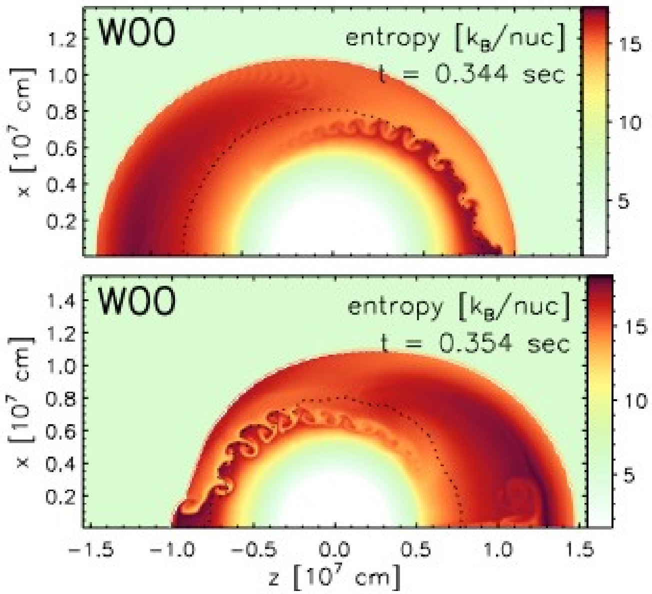
e.g. Woosley+10, Dessart+12

Core collapse: formation of a neutron star



Asymmetry : SASI and/or convection

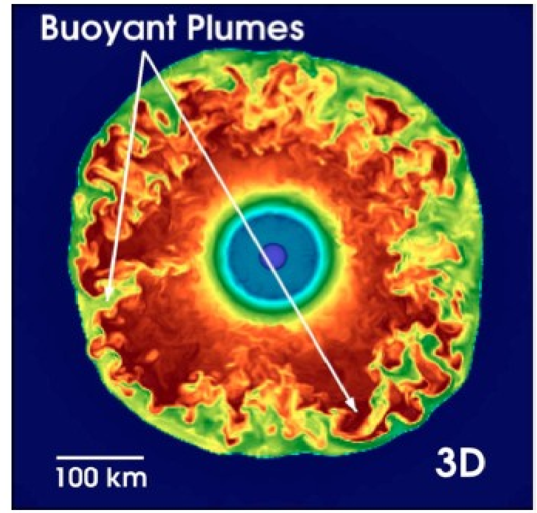
Standing Accretion Shock Instability (SASI)



Scheck et al 2008

Large scale shock oscillations

Neutrino-driven convection



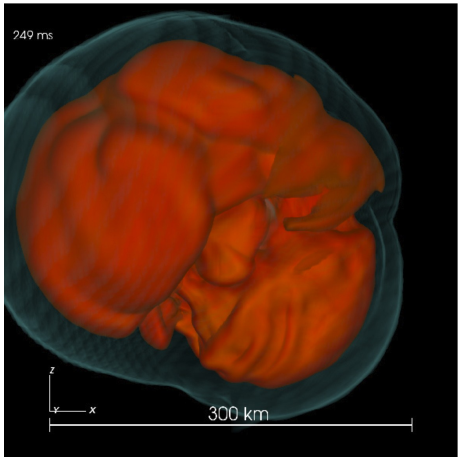
Murphy et al 2013

Convective plumes

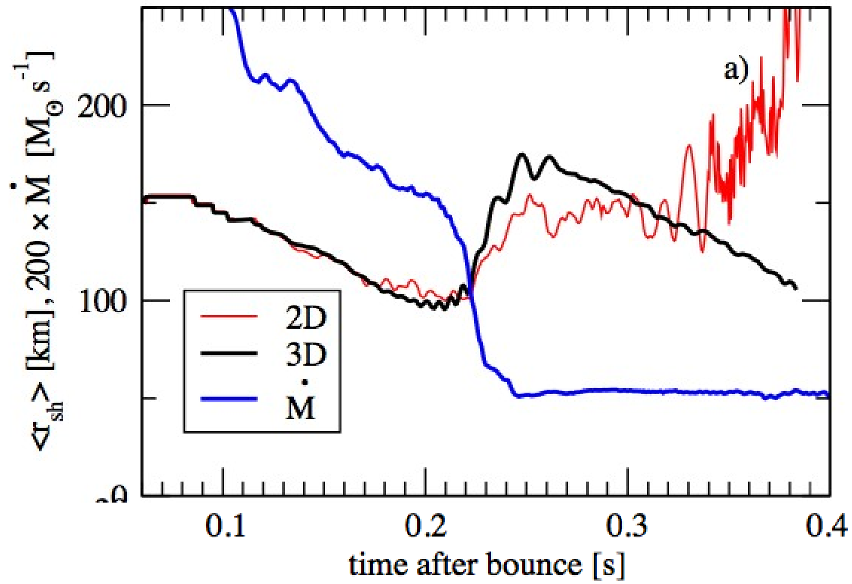
Global asymmetry of the explosion !

Introduction

Asymmetric neutrino driven explosions ?



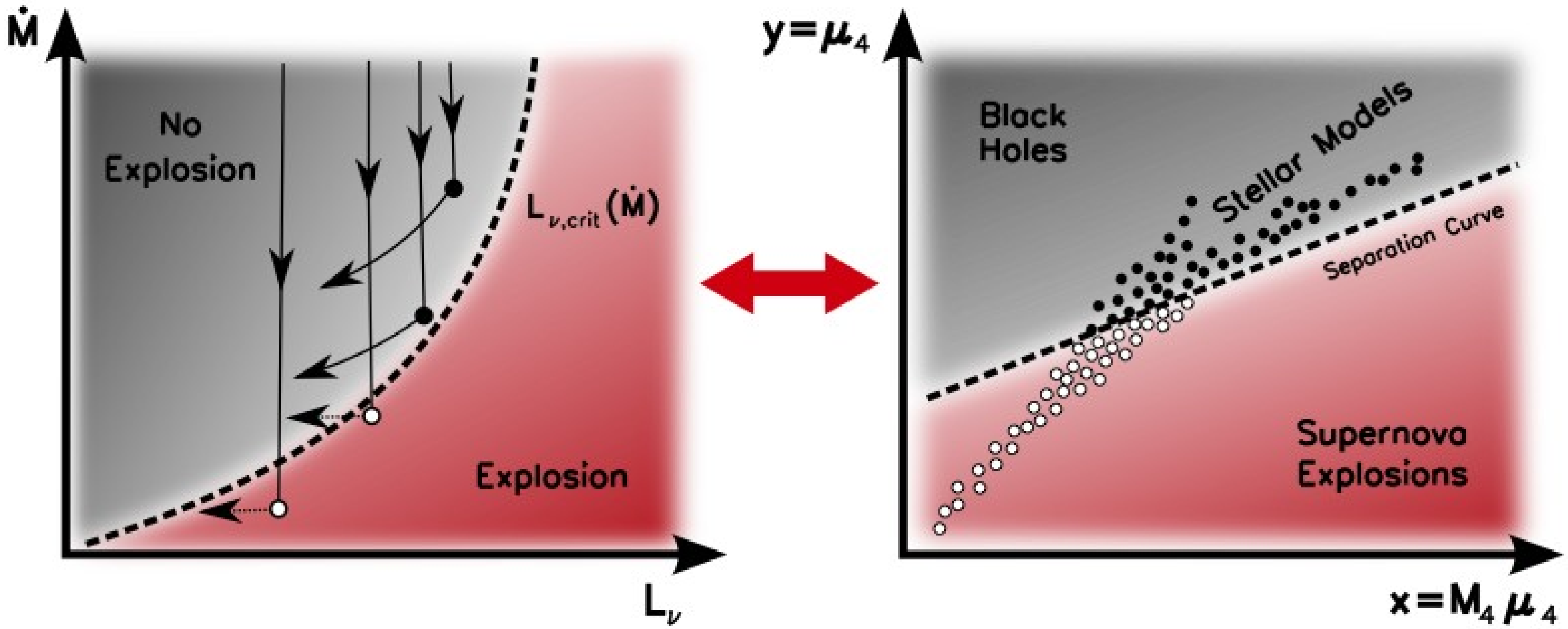
Hanke et al (2013)



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

Oak ridge group : explosions in 2D and 3D
Garching group : explosions in 2D but not in 3D
Princeton group : no explosion in 2D

Dependence on progenitor density structure



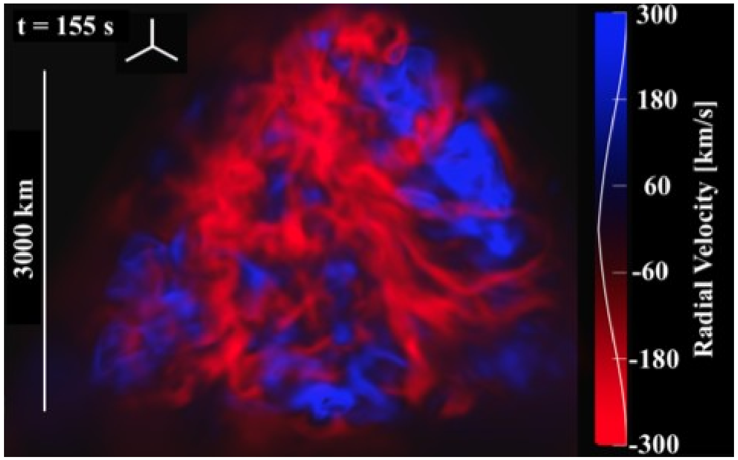
Criterion for explosion as a fonction of progenitor structure (Ertl et al 2015)

Two parameters :

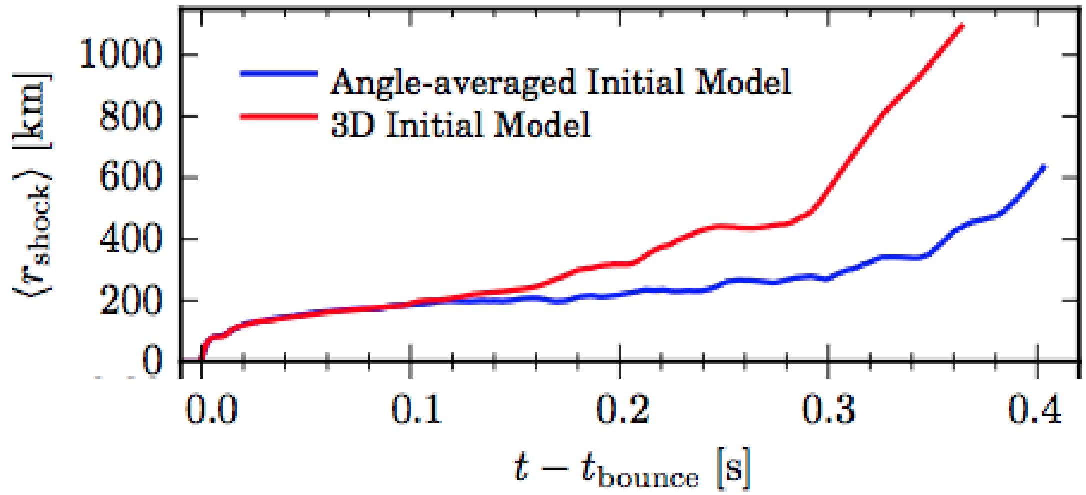
$$M_4 \equiv m(s=4)$$

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

Importance of initial asymetries ?



Couch et al 2015



Asymetries in the progenitor help the onset of explosion

Couch & Ott 2013, Mueller & Janka 2015, Couch et al 2015

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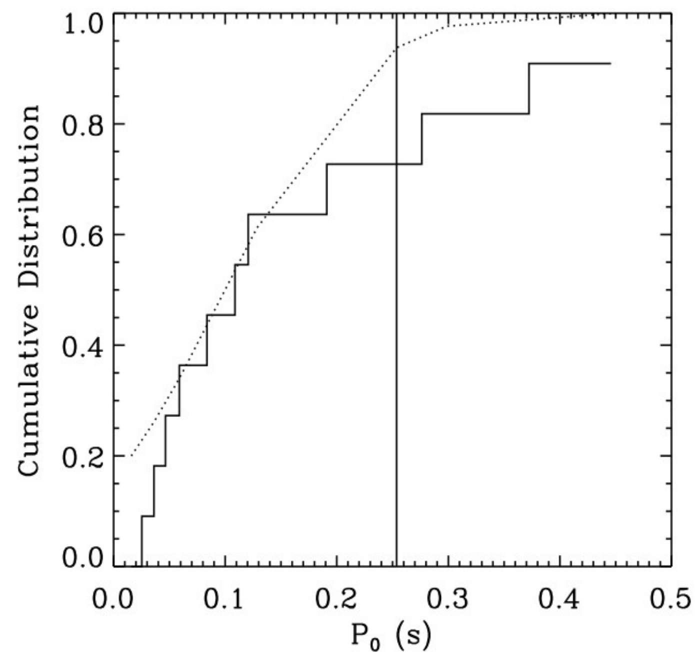
Spin of neutron stars

Observations of neutron stars rotation at birth :

- few good measures (uncertain age and extrapolation)
- range from 10 to a few 100 of ms

Initial rotation period of neutron stars



From Popov & Turolla 2012

Rotation

Origin of neutron star's spin ?

Angular momentum conservation :

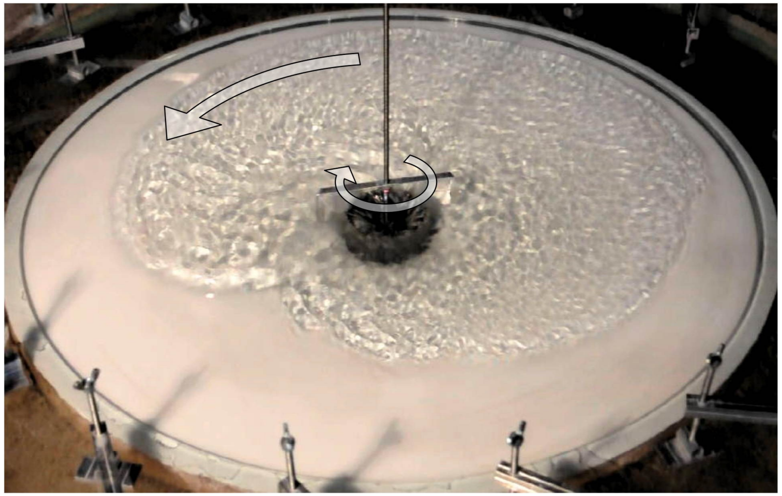
→ iron core periods of 100 to 1000 s

→ need for efficient angular momentum transport to slow down the core

Angular momentum redistribution :
SASI can spin up (or down) the neutron star !

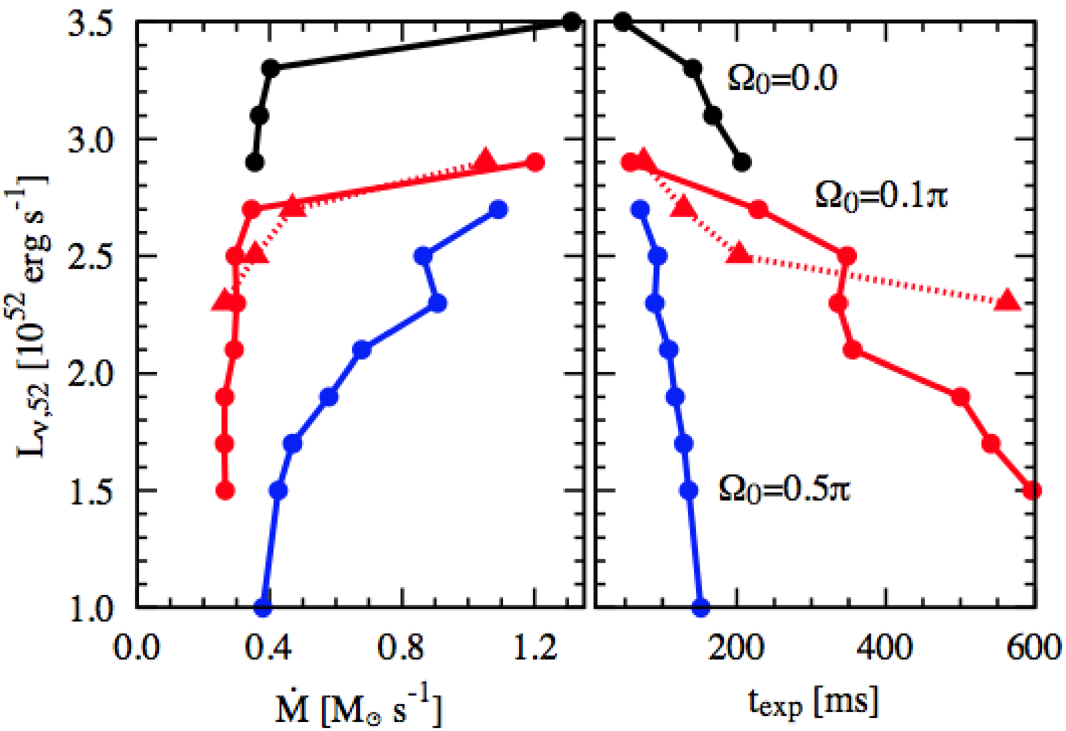
→ neutron star periods of ~50 ms to several 100 ms are possible

Blondin & Mezzappa 2007, Guilet & Fernandez 2014



Foglizzo et al 2012

Rotation aiding the explosion ?



Nakamura et al 2014

Easier explosions with fast rotation (NS period of a few milliseconds)

→ Effect of moderate rotation ? Impact on SASI ? (Yamasaki & Foglizzo 2008)

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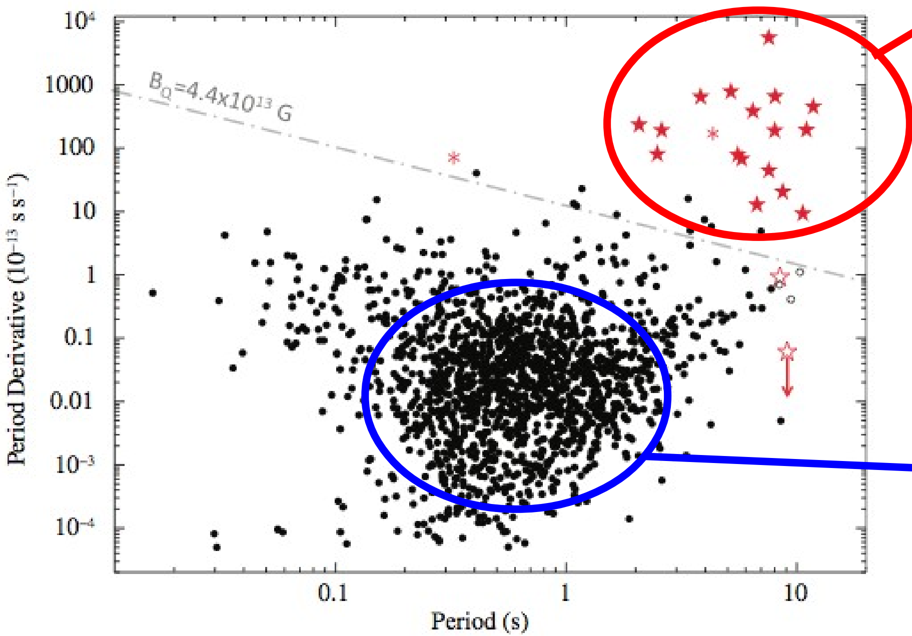
What about the magnetic field ?



Magnetars

Anomalous X-ray pulsars (AXP)

Soft gamma repeater (SGR)

Dipole magnetic field :

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

Normal pulsars

Dipole magnetic field :

B ~ 10^{12} G

Origin of magnetic field ?

1. Fossil magnetic field : magnetic flux conservation

   → Need B ~ 10^{11}G to form a magnetar

2. Magnetic field amplification during neutron star formation ?

   With fast rotation (ms period)

   → Magnetorotational instability (MRI) ?

   → Convective dynamo (with fast rotation) ?

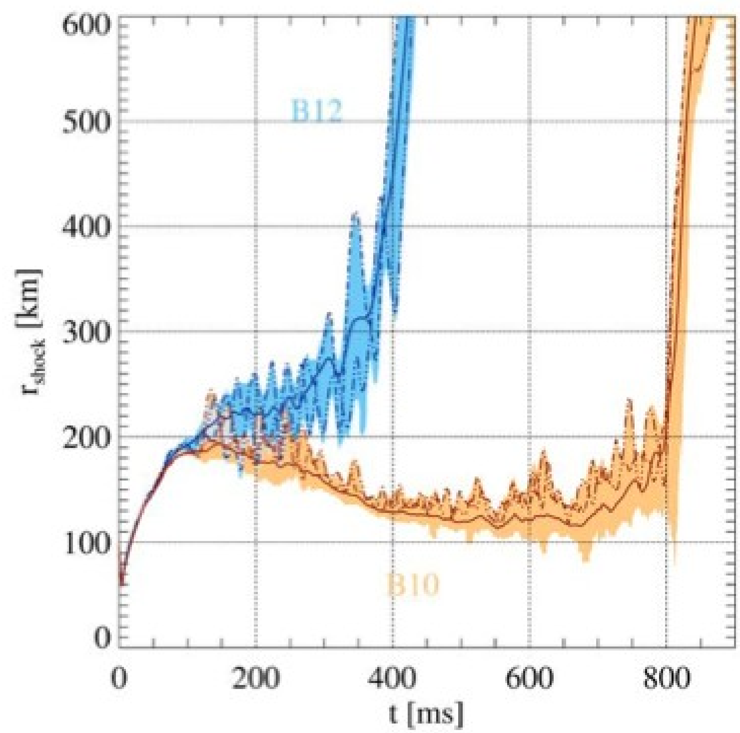
Magnetic field

Strong fossil magnetic field

Impact on SASI
Guilet & Foglizzo 2010, Endeve et al 2010, 2012

Alfven surface
Guilet et al 2011

Magnetically supported explosion
Obergaulinger et al 2014



Obergaulinger et al (2014)

Magnetic field amplification with fast rotation

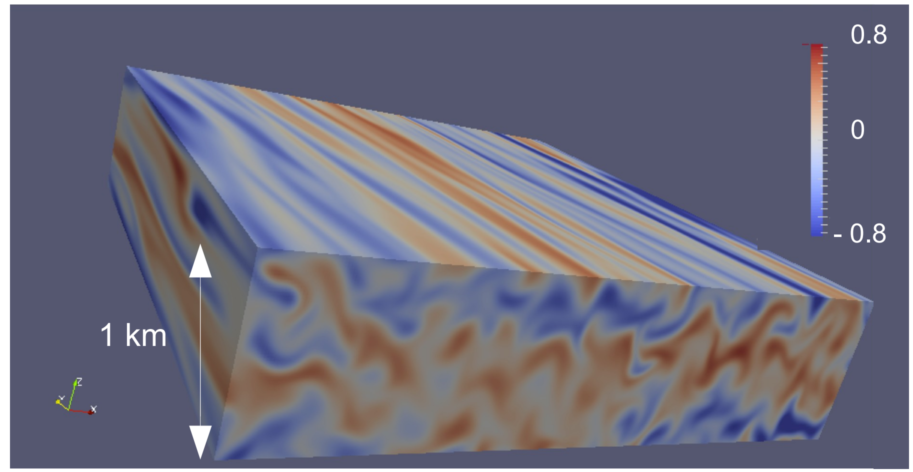
The magnetorotational instability can grow with fast rotation

Akiyama et al 2003, Masada et al 2007, Guilet et al 2015

Local 3D models :
Amplification up to B ~ 10^{15} G

Obergaulinger et al 2009, Guilet & Mueller 2015

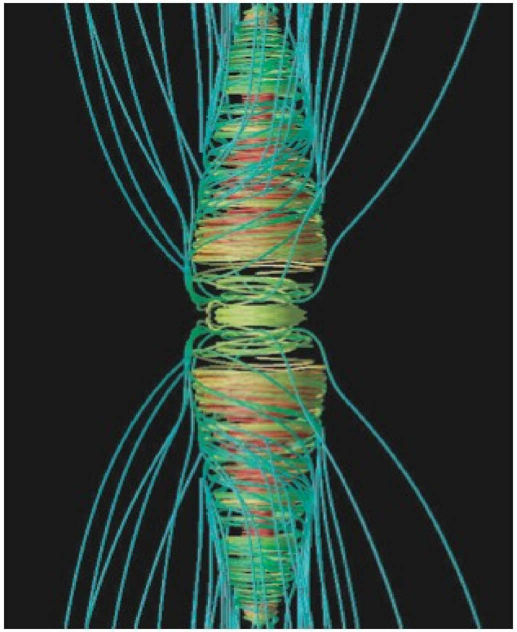
Champ magnétique (10^{15} G)



Guilet & Mueller 2015

Magneto-rotational explosions ?

Jet driven explosion



Burrows et al (2007)

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

+ fast rotation (period of few milliseconds)

=> powerful jet driven explosions !

Potential explanation for :

- hypernovae
- long GRBs (millisecond magnetar engine)
- some superluminous supernovae
- r-process nucleosynthesis

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Conclusions

Progenitor properties can impact supernovae in many ways :

- density profile
- initial asymmetries
- rotation
- magnetic field

(Much) more work is needed in stellar evolution and supernova theory to describe the diversity of supernovae and neutron stars.

Thanks !