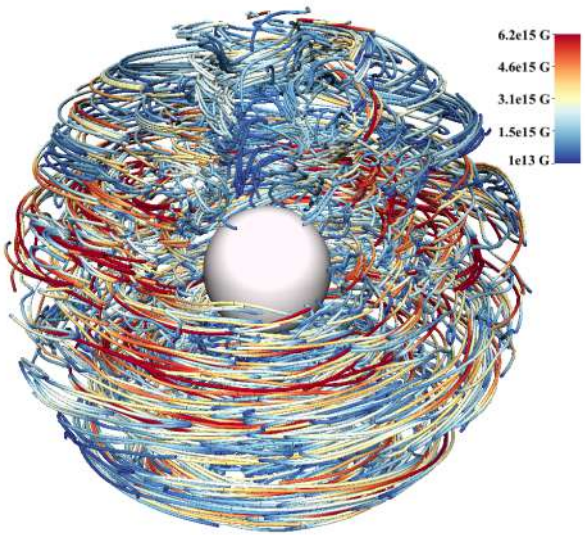
Modelling stellar explosions and compact objects

instabilities and magnetic field



Jérôme Guilet
(CEA Saclay)

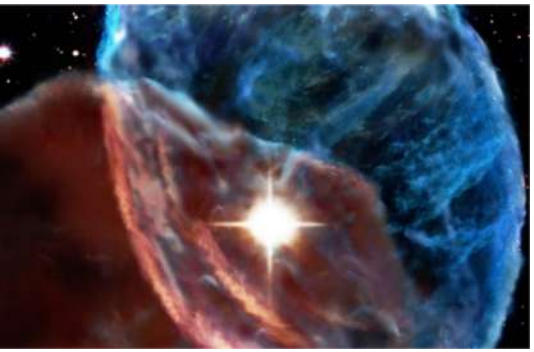
Saclay group members:

Anne-Cécile Buellet (2nd year PhD)
Matteo Bugli (postdoc)
Thierry Foglizzo (chercheur CEA)
Raphaël Raynaud (maitre de conférence)
Alexis Reboul-Salze (3rd year PhD)

Journées PNHE
14 septembre 2021

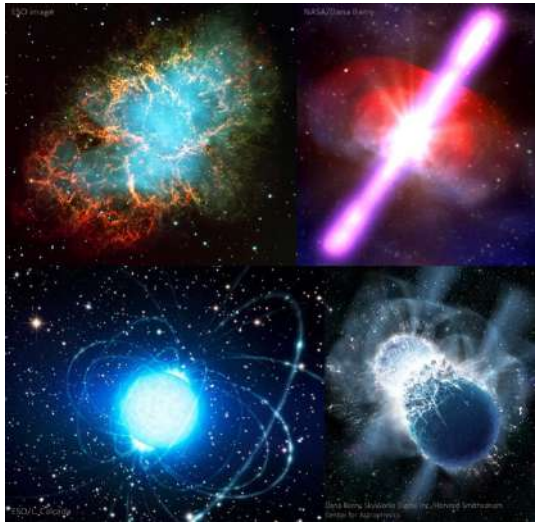
Importance of stellar explosions and compact objects

Kinetic energy injection

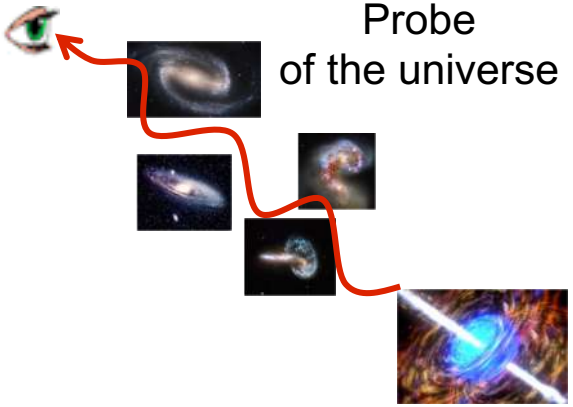


Cosmic ray acceleration

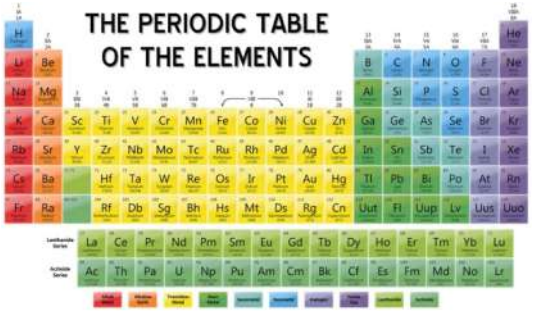
Transient sky



Probe
of the universe

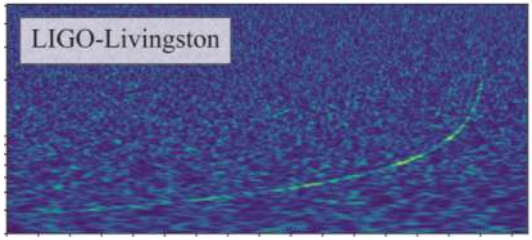


Source of heavy elements



Multimessenger signals

Birth and merger of
compact objects



Core collapse supernovae: a multi-physics problem

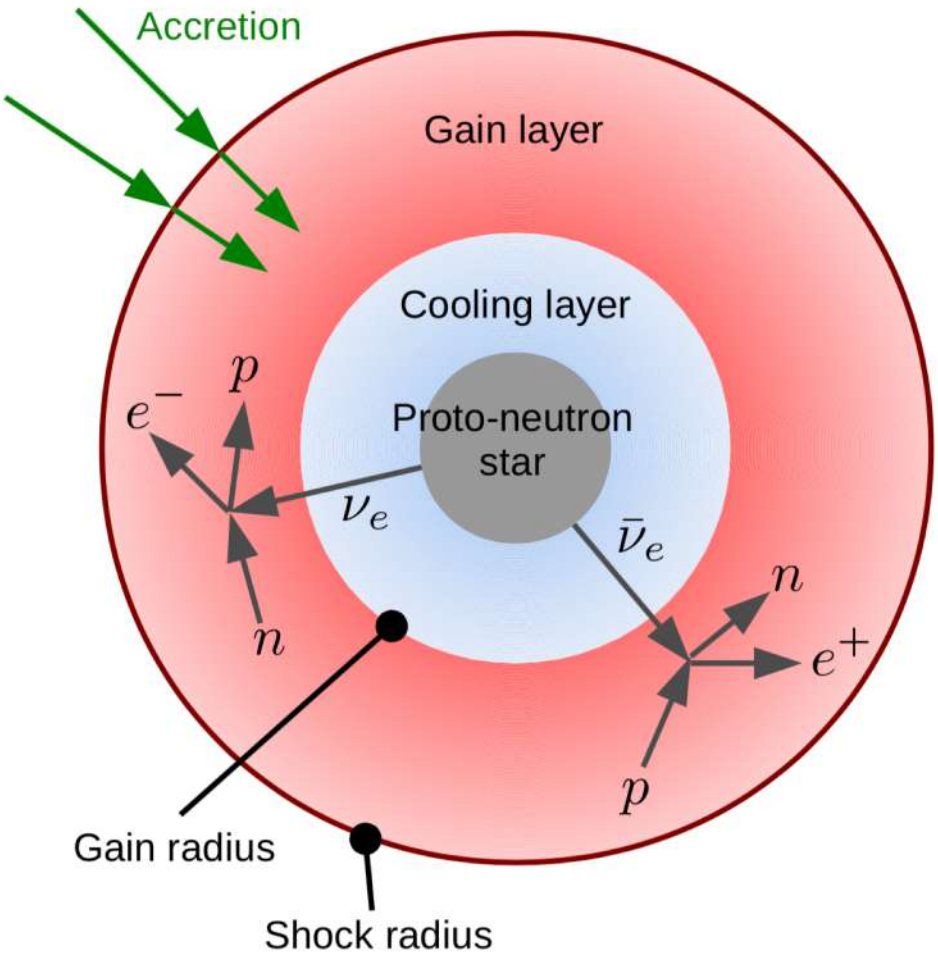
- Multi-dimensional hydrodynamics (instabilities, turbulence..)

- Magnetic field

- Neutrino-matter interactions
  sophisticated transport schemes

- Ultra-high density equation of state

- General relativity

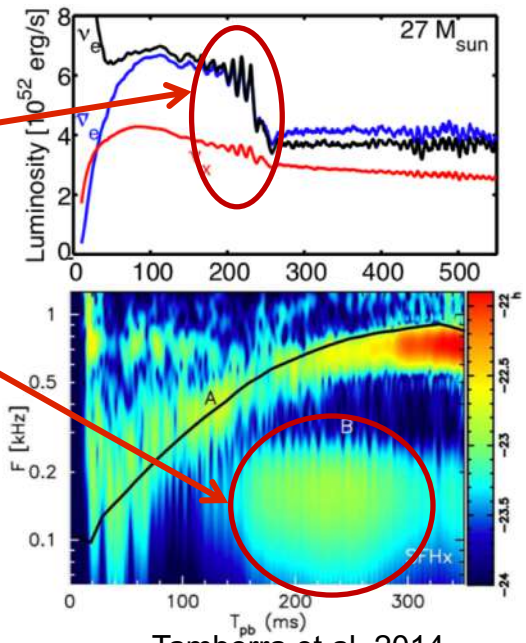


Key questions & importance of hydrodynamical instabilities

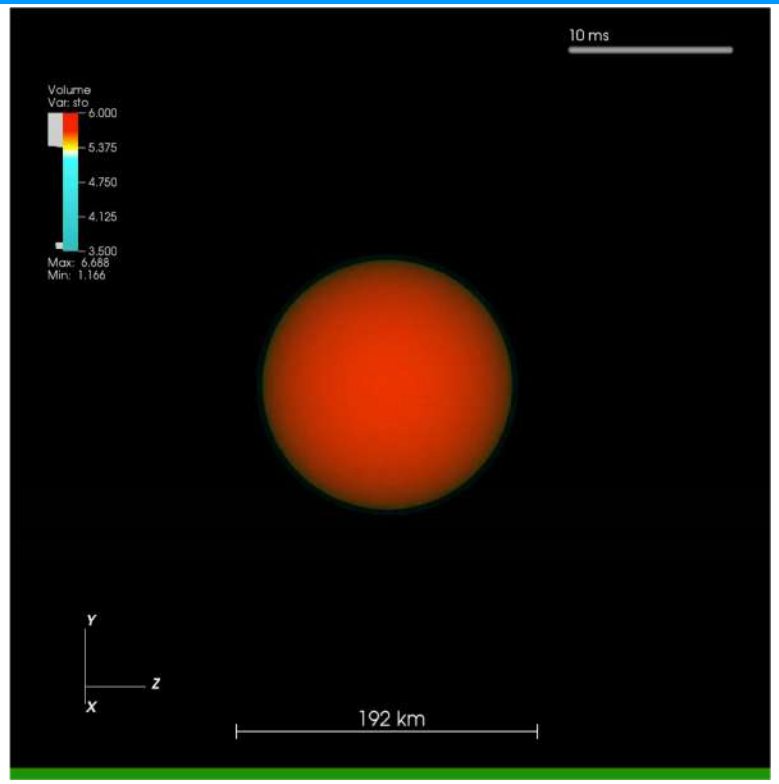
Which stars explode ? Which stars fail ?

Properties of the compact object:
- Mass: black hole or neutron star ?
- Kick, spin ?

Multimessenger signal:
- Modulation of neutrinos
- Gravitational waves

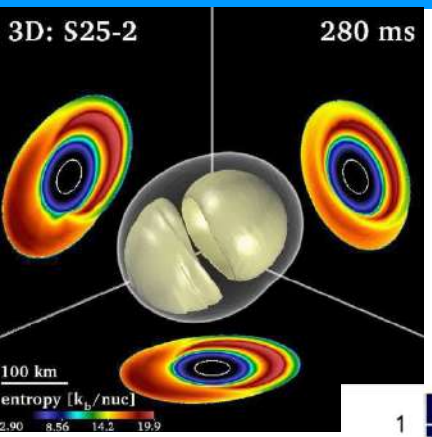


Tamborra et al 2014
Kuroda et al 2016



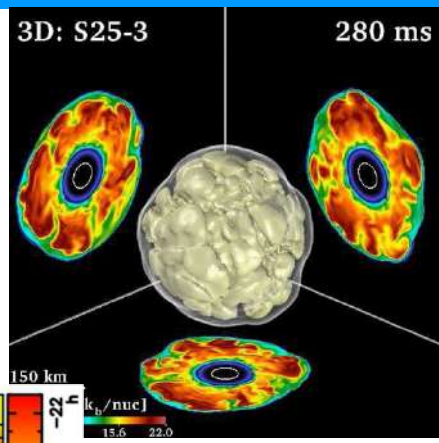
Simulation from the Garching group

Gravitational wave signatures of hydrodynamical instabilities

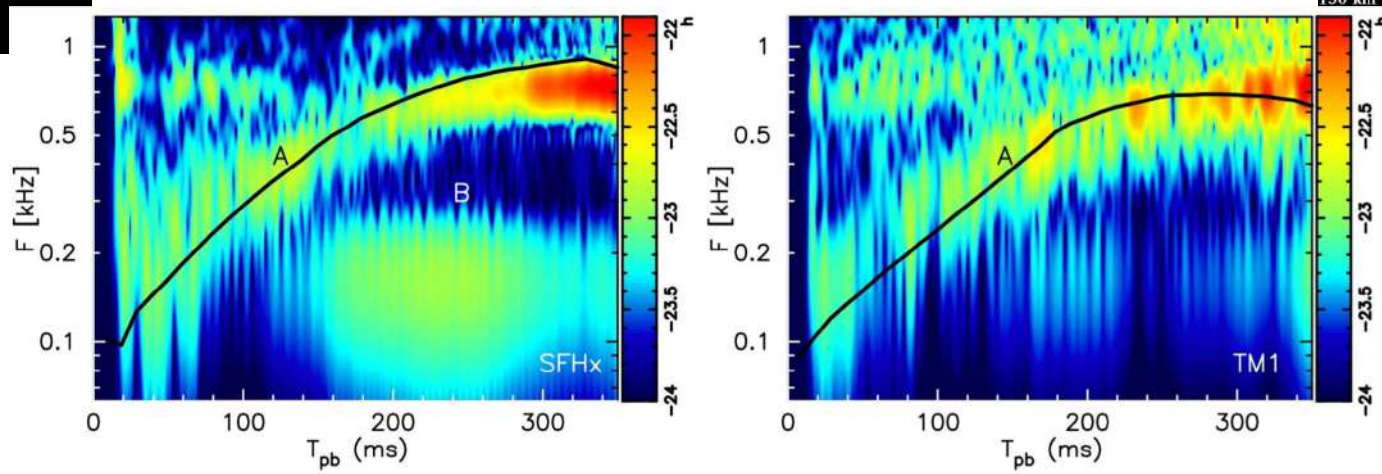


Standing accretion shock instability (SASI)

Neutrino-driven convection



Hanke+2013



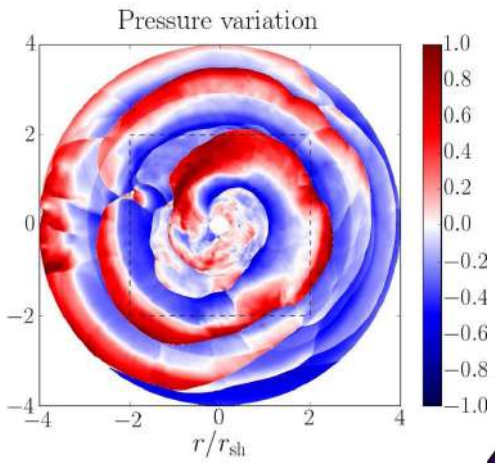
Hanke+2013

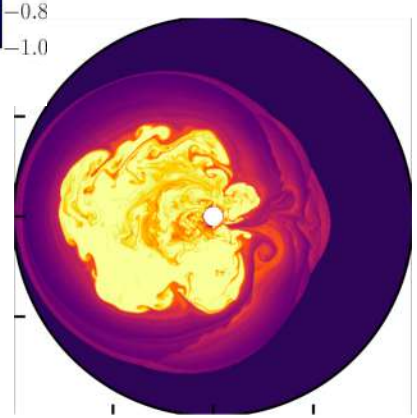
Kuroda+2016

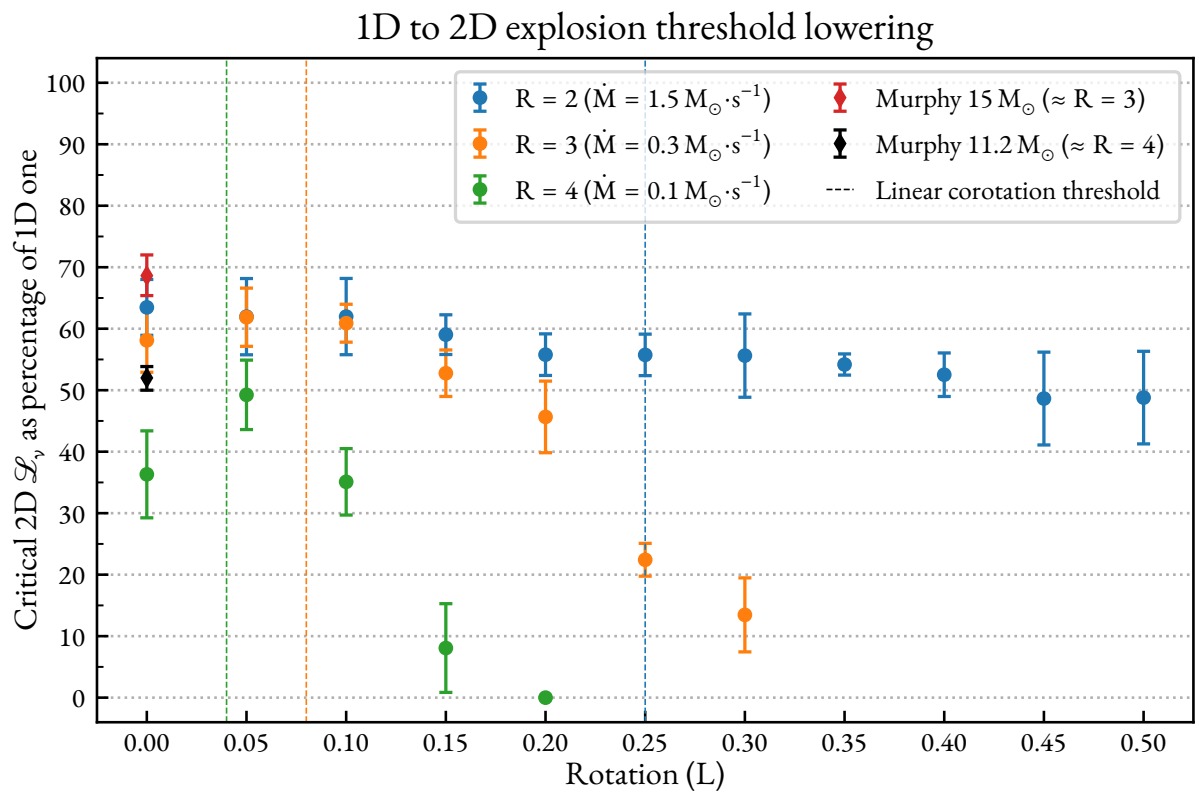
Which instability dominates ? Physical understanding and analytical description, PhD thesis of Anne-Cécile Buellet

Influence of rotation on the explosion ?

More than 500 2D simplified simulations



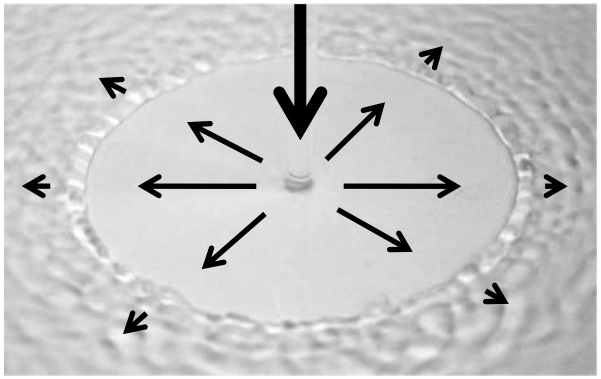




Kazeroni et al 2017, Pagani et al in prep

Confronting theory with laboratory experiments

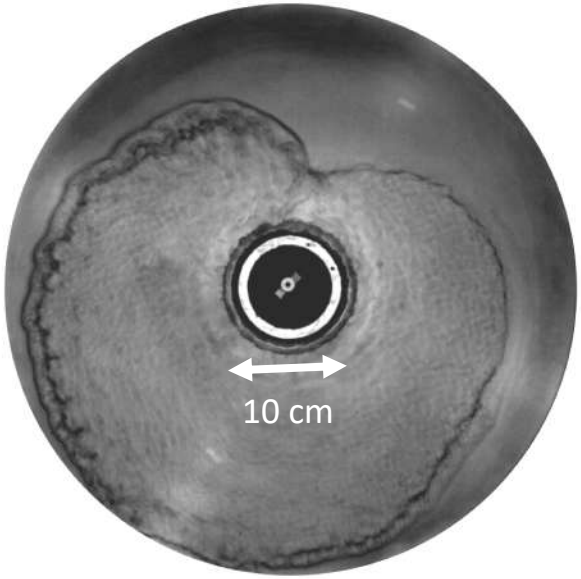
Kitchen sink hydraulic jump



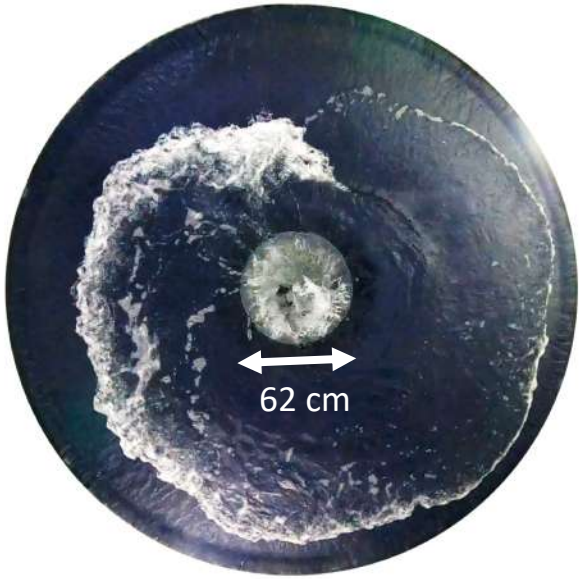
Physical analogy

acoustic waves shock wave pressure	↔	surface waves hydraulic jump depth

First experiment



New experiment :
turbulent regime



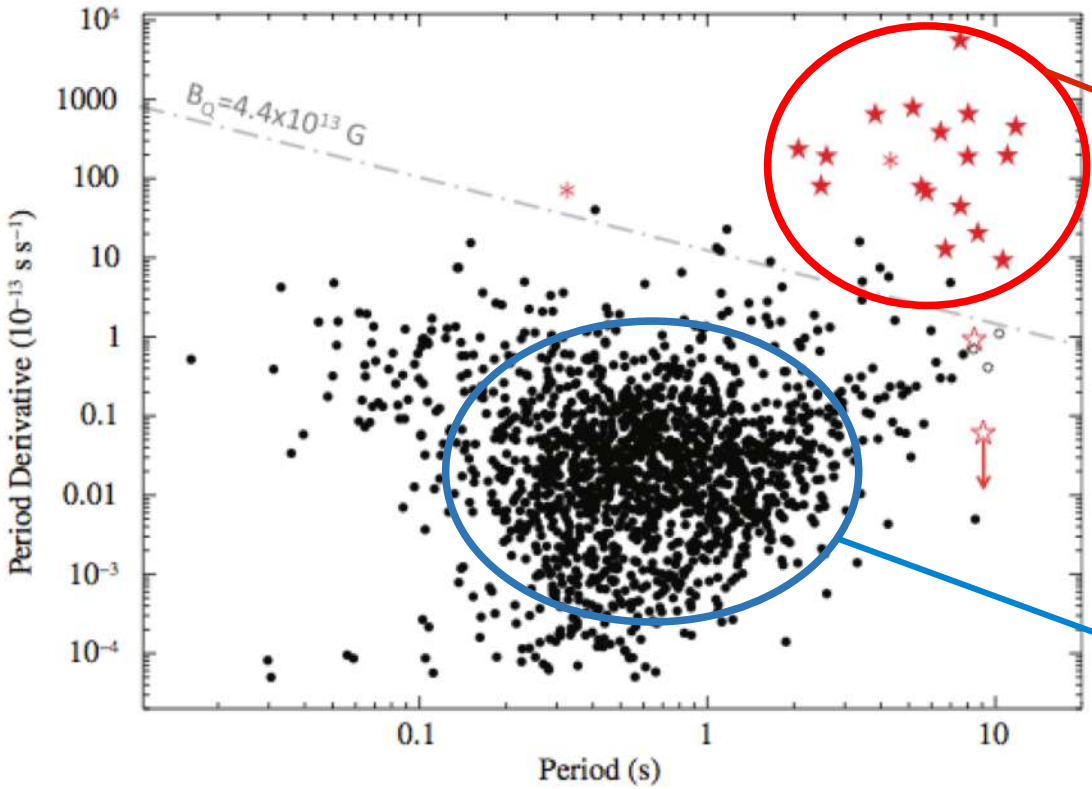
Foglizzo et al 2012, Foglizzo et al 2015

What about magnetic fields ?

Magnetar formation & extreme explosions

Magnetars: the most intense known magnetic fields

Rea et al 2012



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

Outstanding explosions: millisecond magnetars ?

Explosion kinetic energy :

→ Typical supernova 10^{51} erg

→ **Hypernova & GRB** 10^{52} erg

aka type Ic BL

Total luminosity :

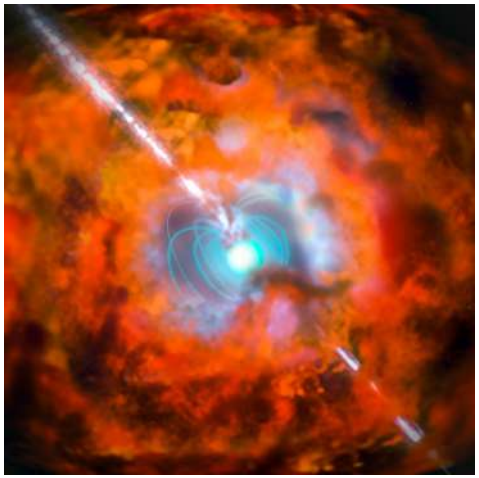
→ Typical supernova 10^{49} erg

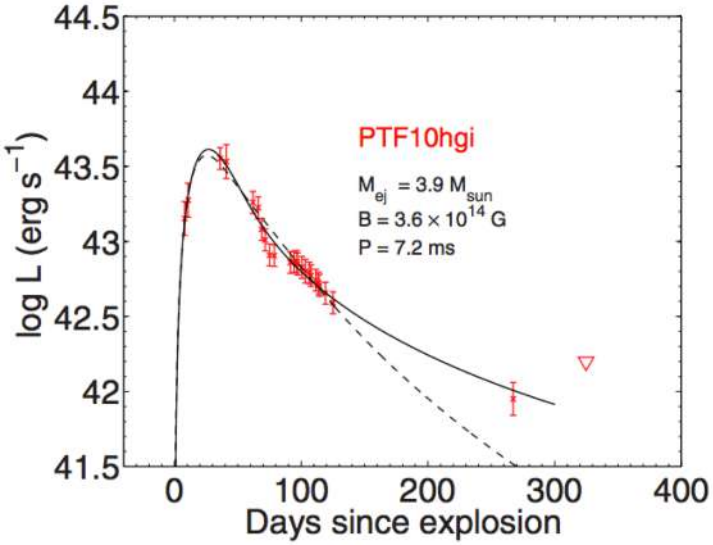
→ **Superluminous supernovae** 10^{51} erg

Large kinetic energy reservoir if fast rotation

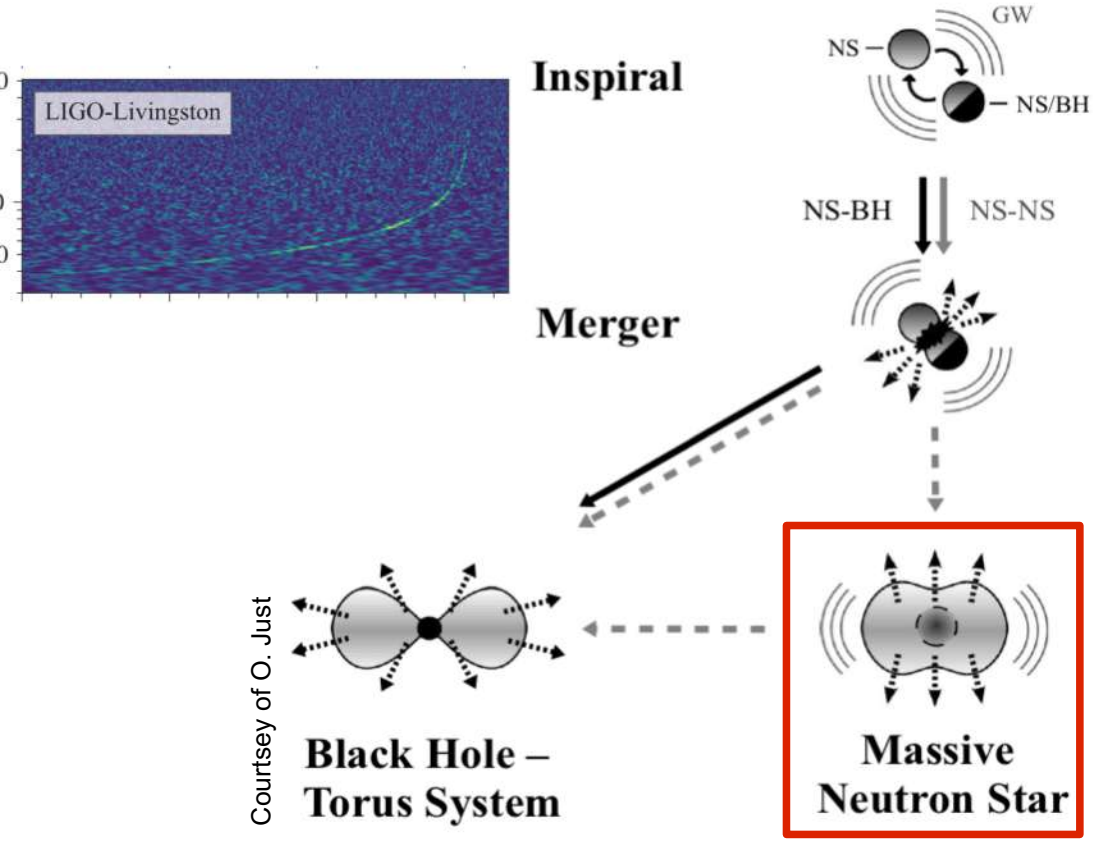
Strong magnetic field to extract this energy

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





A magnetar formed in NS mergers ?

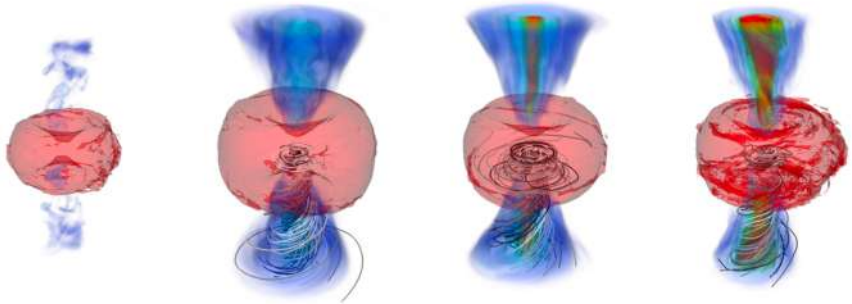


Courtsey of O. Just

3 possibilities :

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

Formation of a magnetar ?

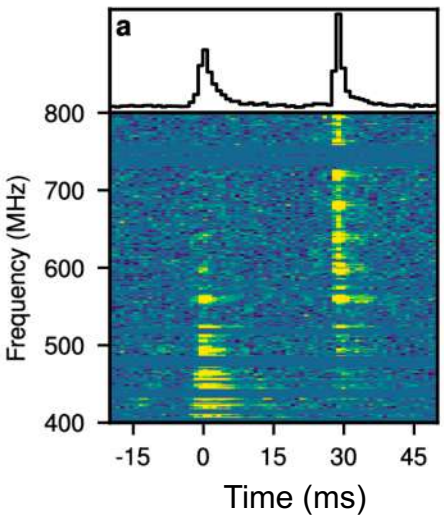


Moesta+2020

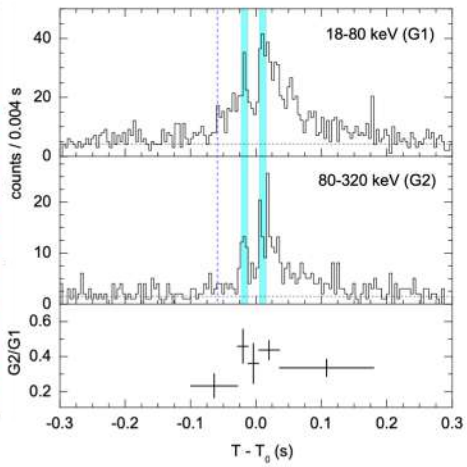
Fast radio bursts from magnetars

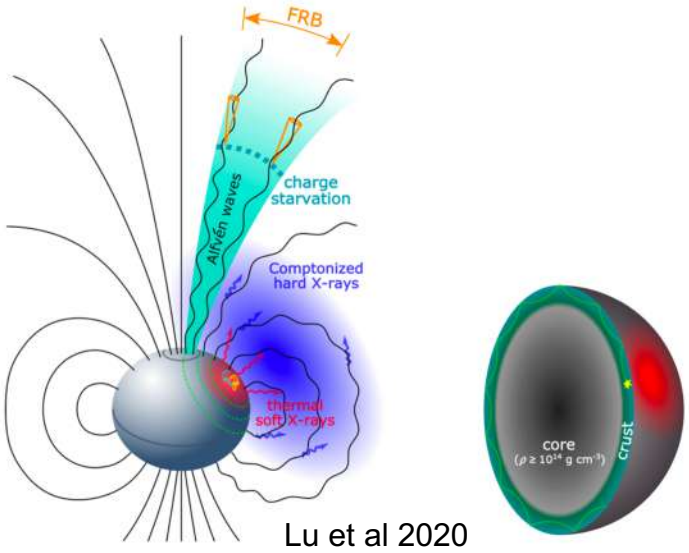
2 (faint) FRBs detected from a galactic magnetar
in coincidence with X-ray bursts

Chime 2020



Ridnaia+ 2020



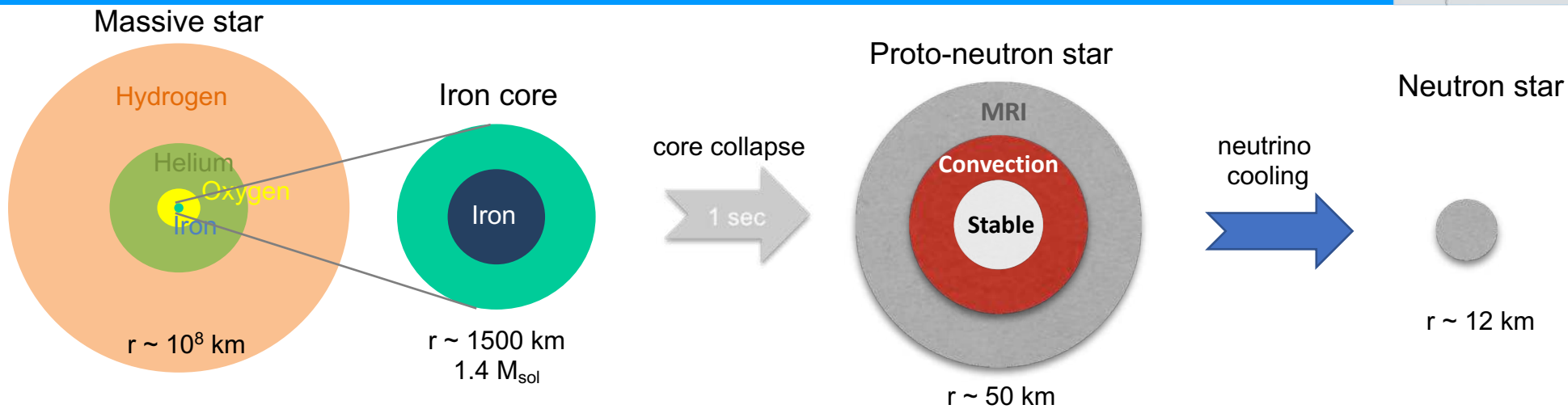


Lu et al 2020

French observing effort lead by Christian Gouiffes

Fast radio bursts as a probe of extragalactic magnetar formation ?

Magnetic field origin : different scenarios



Compression of stellar magnetic field :

Amplification by a few ~10^4 during core collapse

Very magnetised stars on surface (B >1 kG) : also need a 10^{10}-10^{11} G in the iron core

Protoneutron star dynamos

Magnetorotational instability

Similar to accretion disks

Convective dynamo

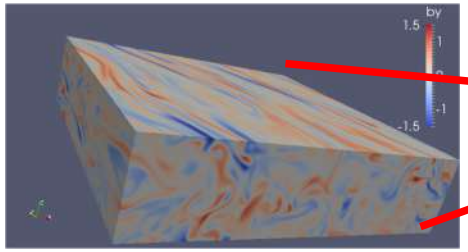
Similar to planetary & stellar dynamos

Magnetar as central engine of extreme explosions

Small turbulent scales
Code snoopy
(Lesur & Longaretti 2005)

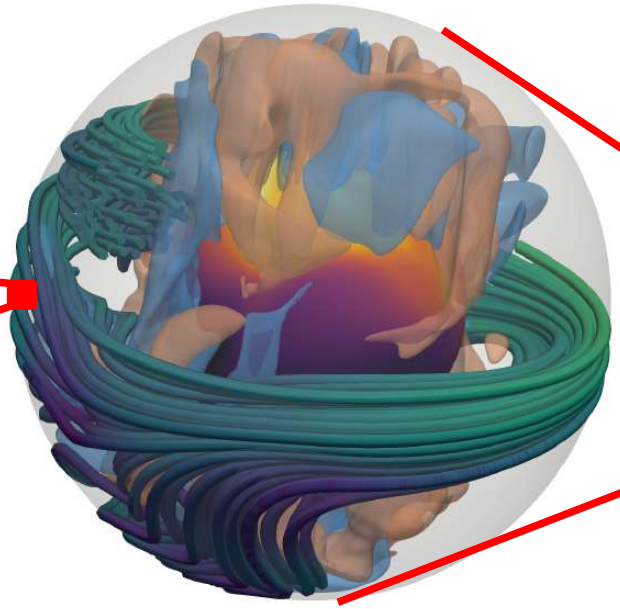
Protoneutron star dynamo
MagIC code : https://github.com/magic-sph/magic

Magnetorotational explosions
Code ALCAR,
Martin Obergaulinger

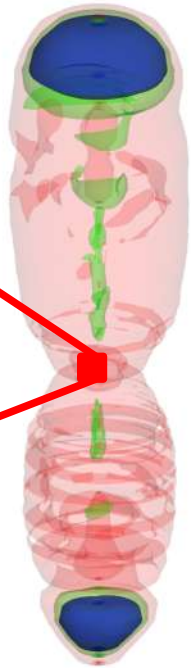


~ 1-5 km

Guilet et al. 2015, 2021



~ 10-50 km
Raynaud et al. 2020, 2021
Reboul-Salze et al. 2021

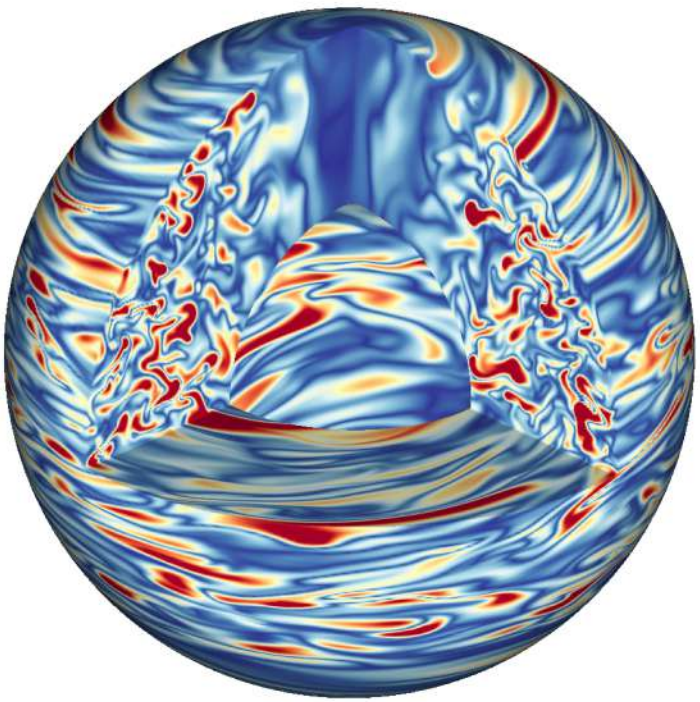


~ 10^3-10^5 km

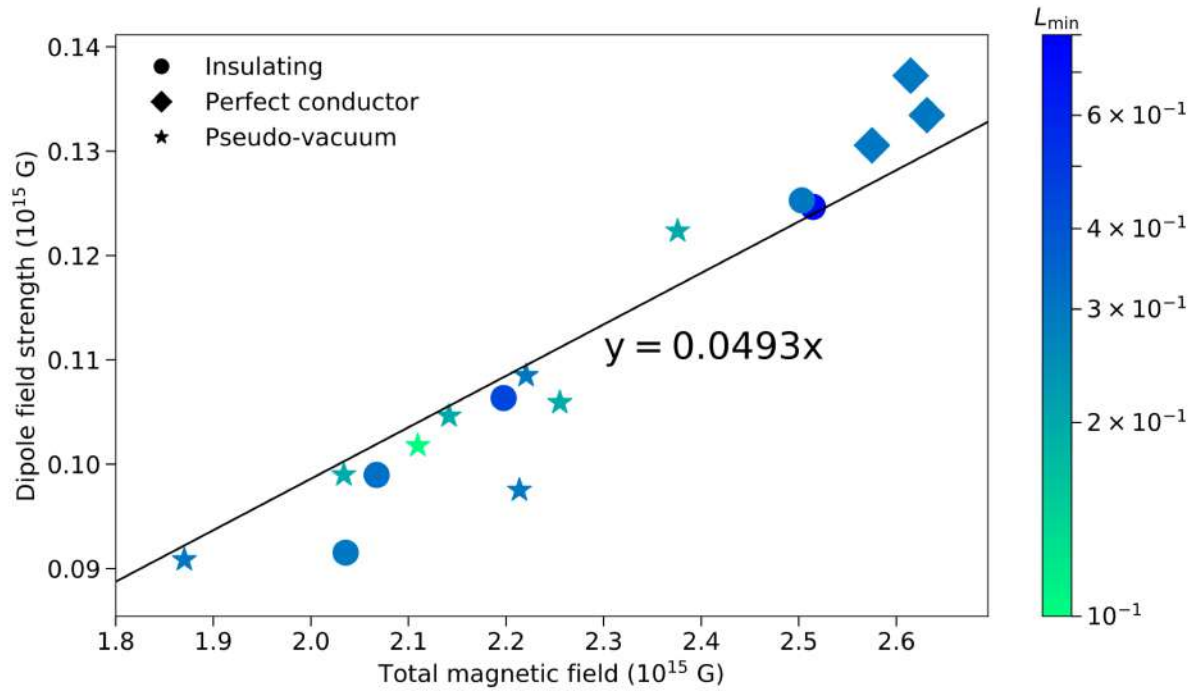
Bugli et al. 2020, 2021

ERC starting grant MagBURST (PI : Jérôme Guilet)

Magnetorotational instability



Reboul-Salze+2021



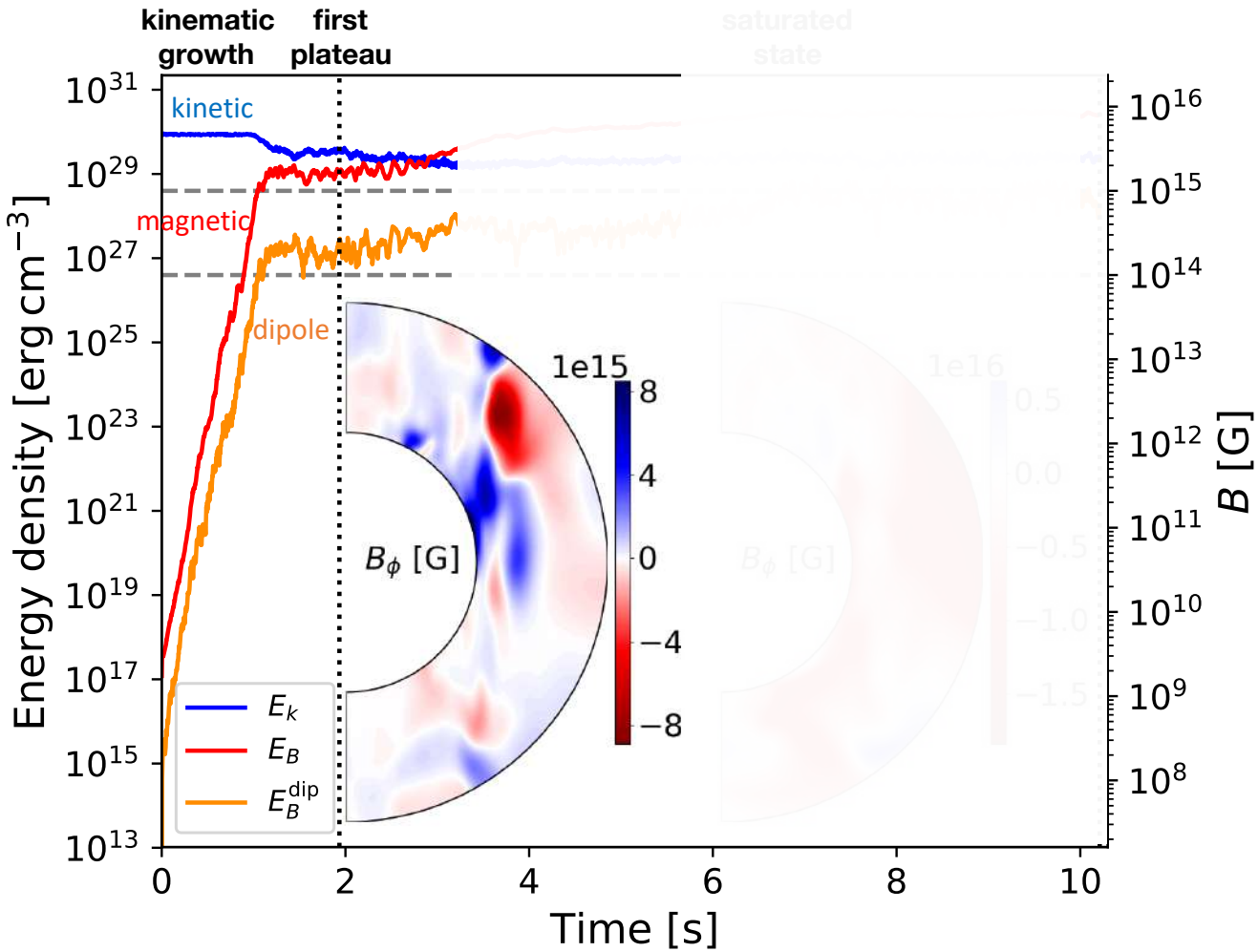
Magnetar strength dipole

Inclined toward the equator (dipolar angle ~ 80°)

Oscillatory dynamo cycles

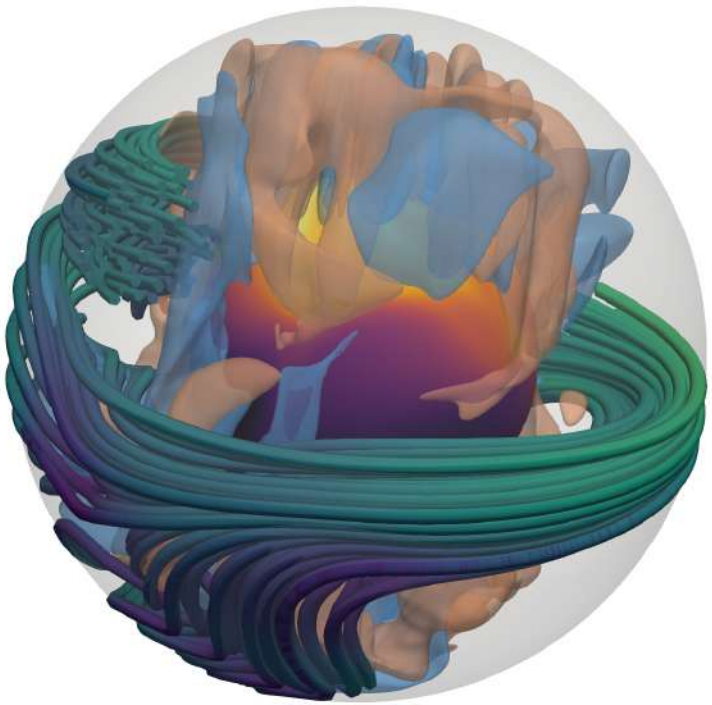
PhD thesis of Alexis Reboul-Salze

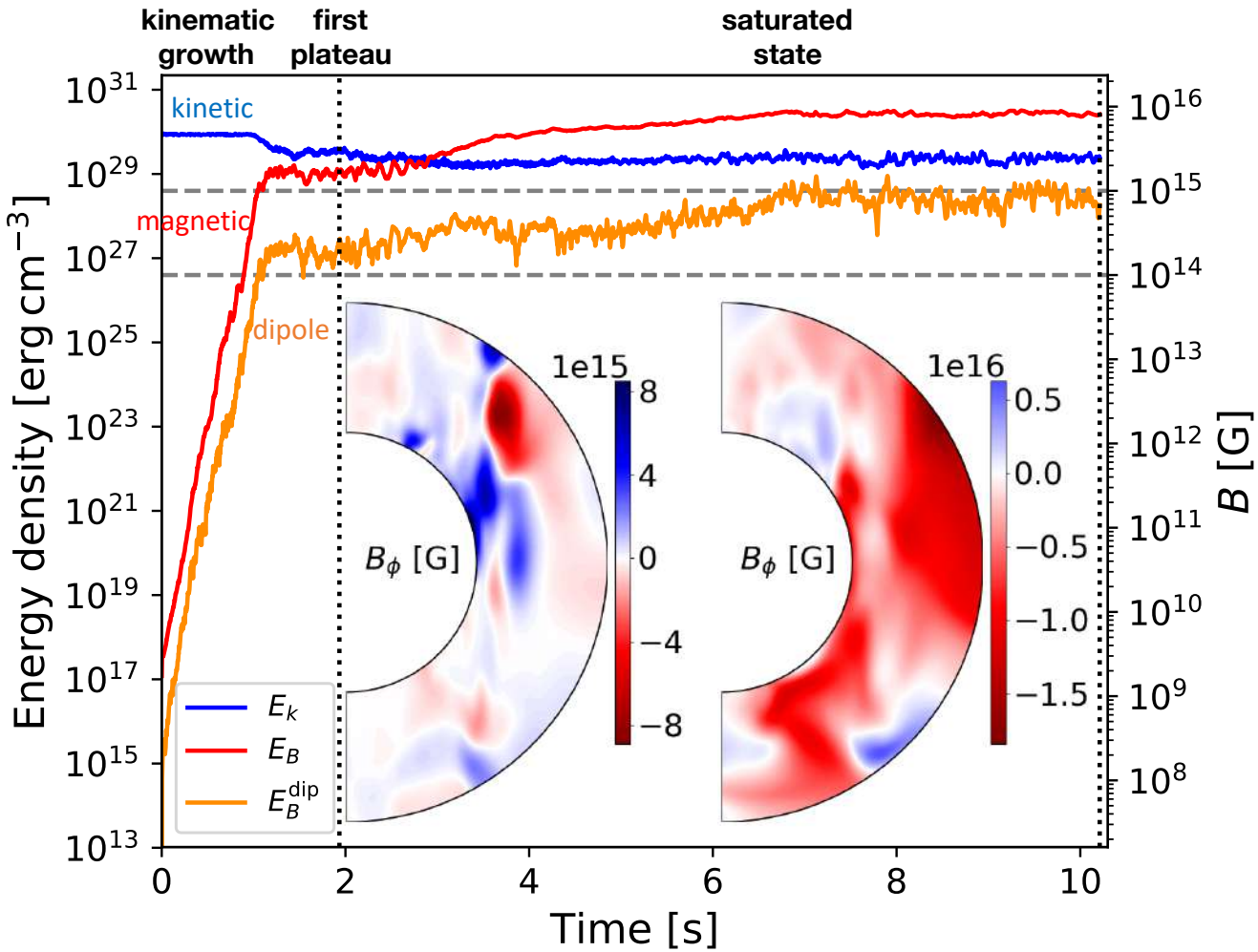
Convective dynamo



Raynaud et al 2020

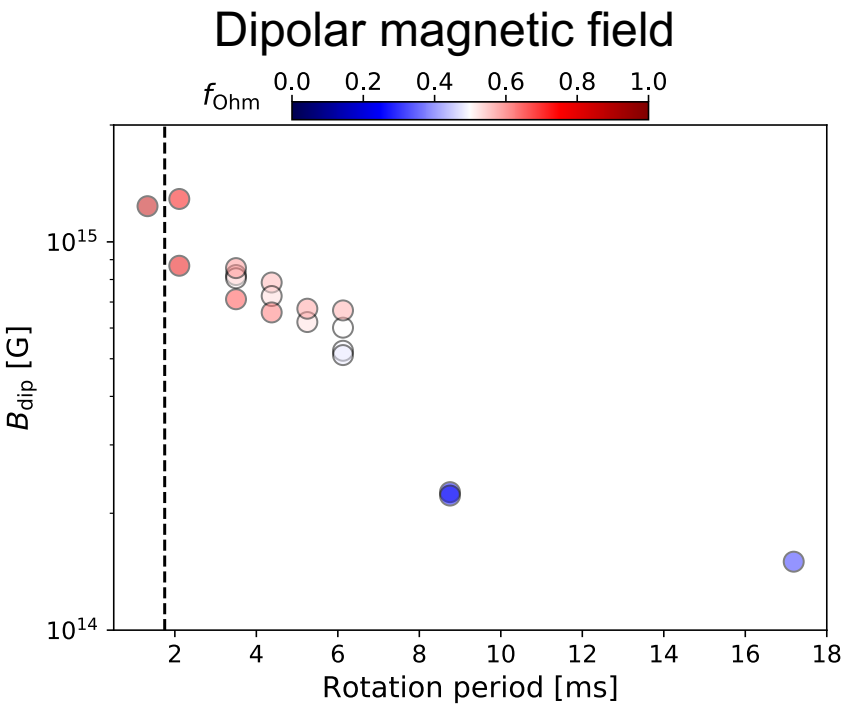
Convective dynamo in a protoneutron star

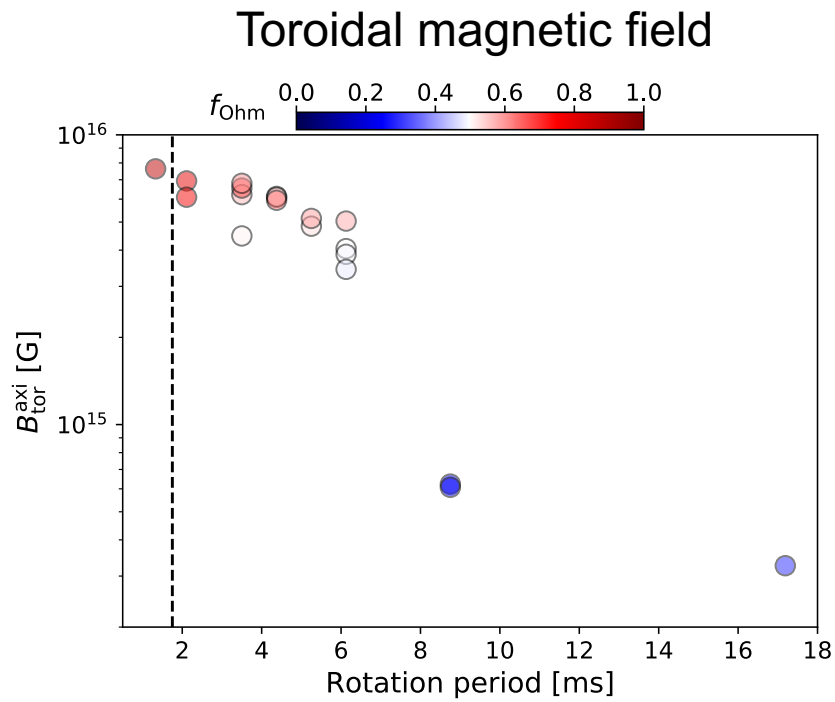




Raynaud et al 2020

Magnetic field strength





Very fast rotation: P < 2.5 ms

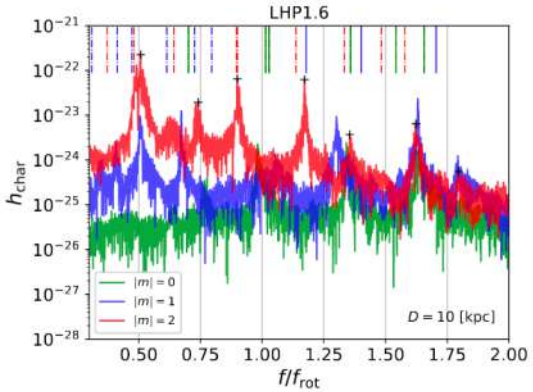
prompt strong dynamo => « supermagnetar » associated to hypernova & GRB ?

Intermediate rotation: 2.5 ms < P < 10-20 ms

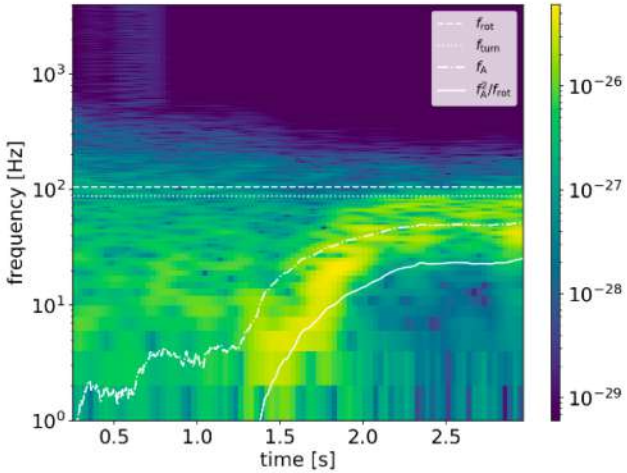
delayed strong dynamo => normal magnetar with superluminous SNe & normal SNe ?

Gravitational waves from the convective dynamo

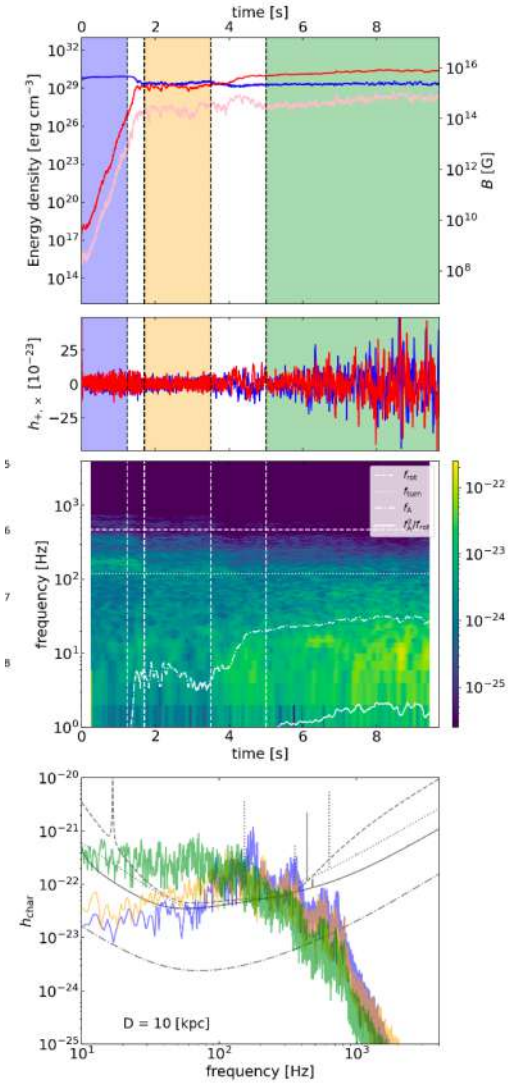
Peaks from inertial modes



Low-frequency excess : a signature of the strong field dynamo ?



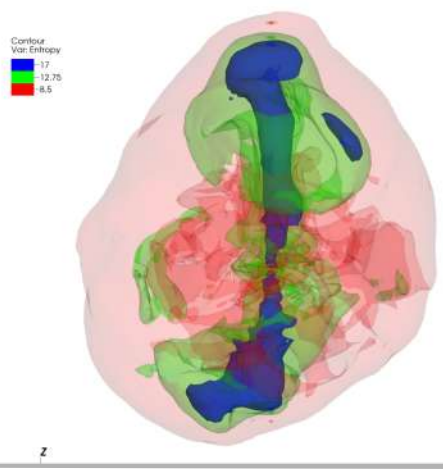
Raynaud et al 2021



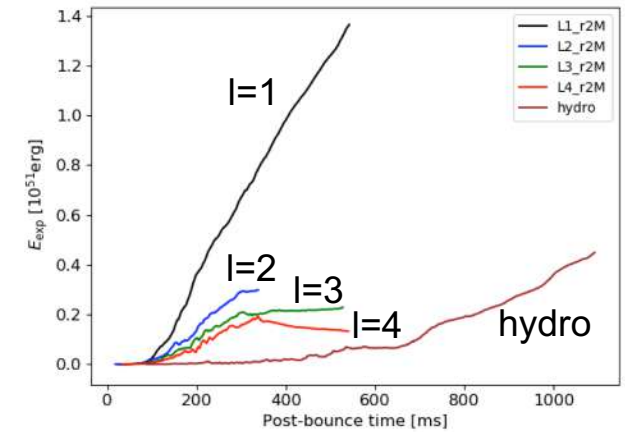
Magnetorotational explosions as extreme explosions ?

Aligned dipole

Inclined dipole



Explosion energy



Key questions :

Explosion energy ?

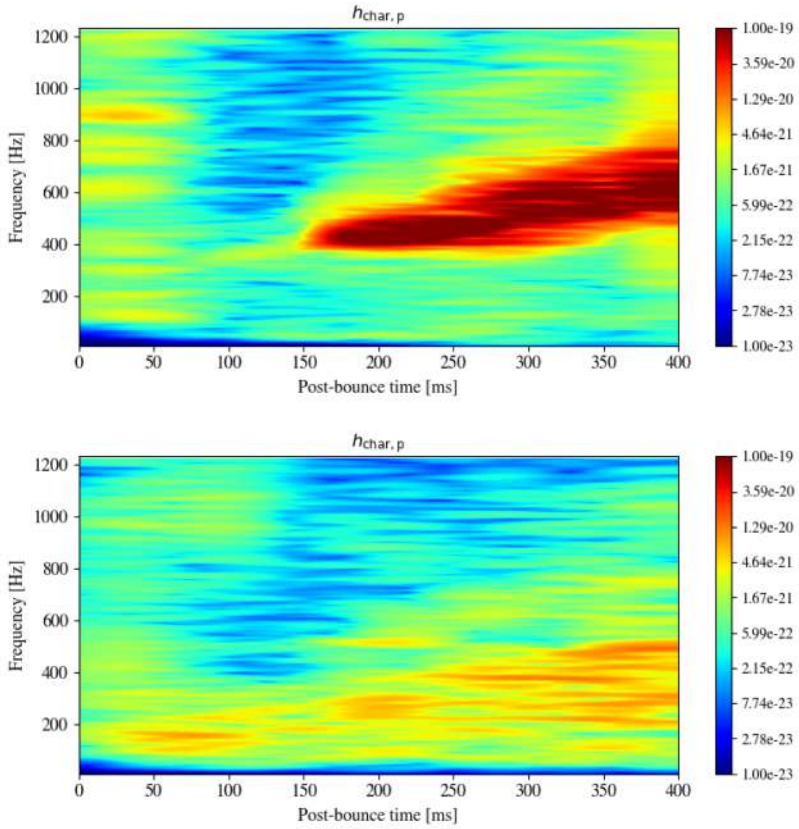
Collimated jet ?

=> Diversity of explosions

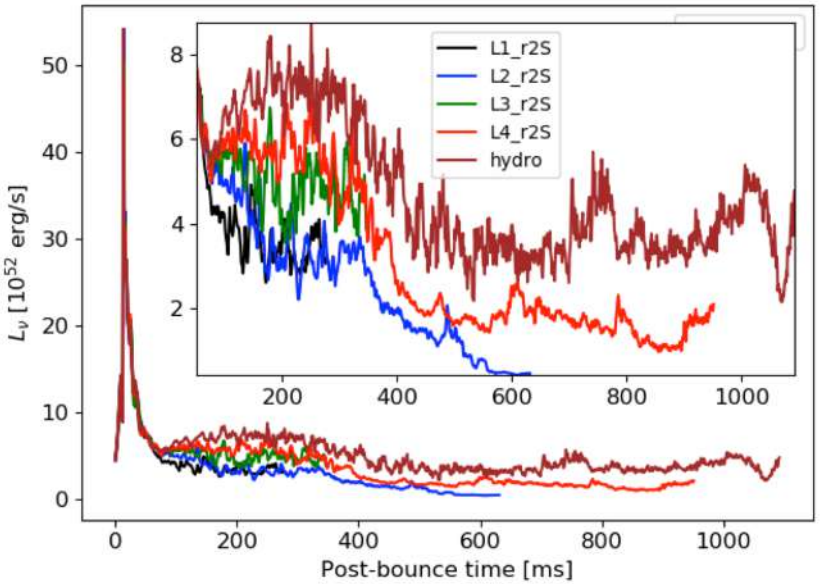
Bugli, Guilet et al 2020, 2021

Multimessenger signatures

Gravitational waves from corotation instability



Neutrino signature



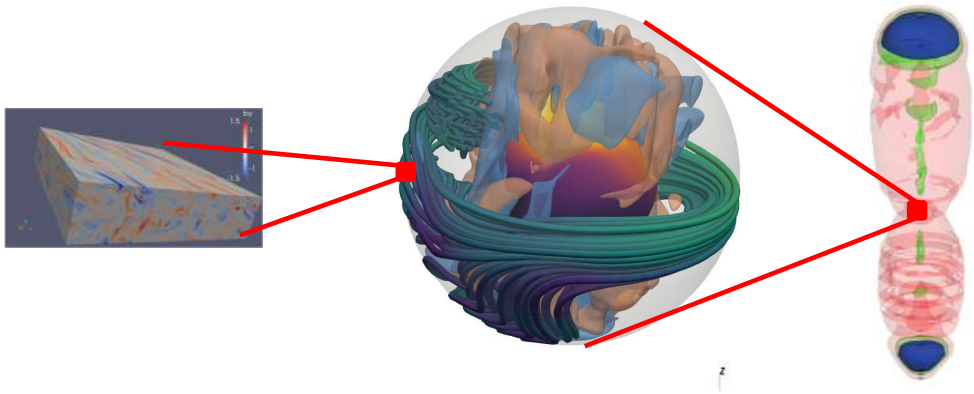
Bugli et al 2020

Detectability by current detectors

LEAK labex project

Bugli et al, in prep

Still a long way to go



Modelling prospects :

- Physics of turbulence (at large magnetic Prandtl numbers)
- Subgrid-scale modelling of magnetic field amplification
- Evolution on longer timescales to compare with electromagnetic observations

→ Couple ab initio simulations and emission models

Prospects in the multimessenger era

Gravitational wave & neutrinos signature of core-collapse supernovae

→ Convection, SASI and corotation instability

→ Signature of dynamo action : measure rotation and magnetic field ?

LIGO/VIRGO, Einstein telescope

Consequences for binary formation & population

→ Bin2grav labex project lead by Sylvain Chaty

Diversity of electromagnetic transients driven by magnetar formation ?

→ Couple ab initio simulations and emission models

→ Electromagnetic counterpart to neutron star mergers ?