Simulations
de supernovae gravitationnelles
et de coalescence d'étoiles à neutrons

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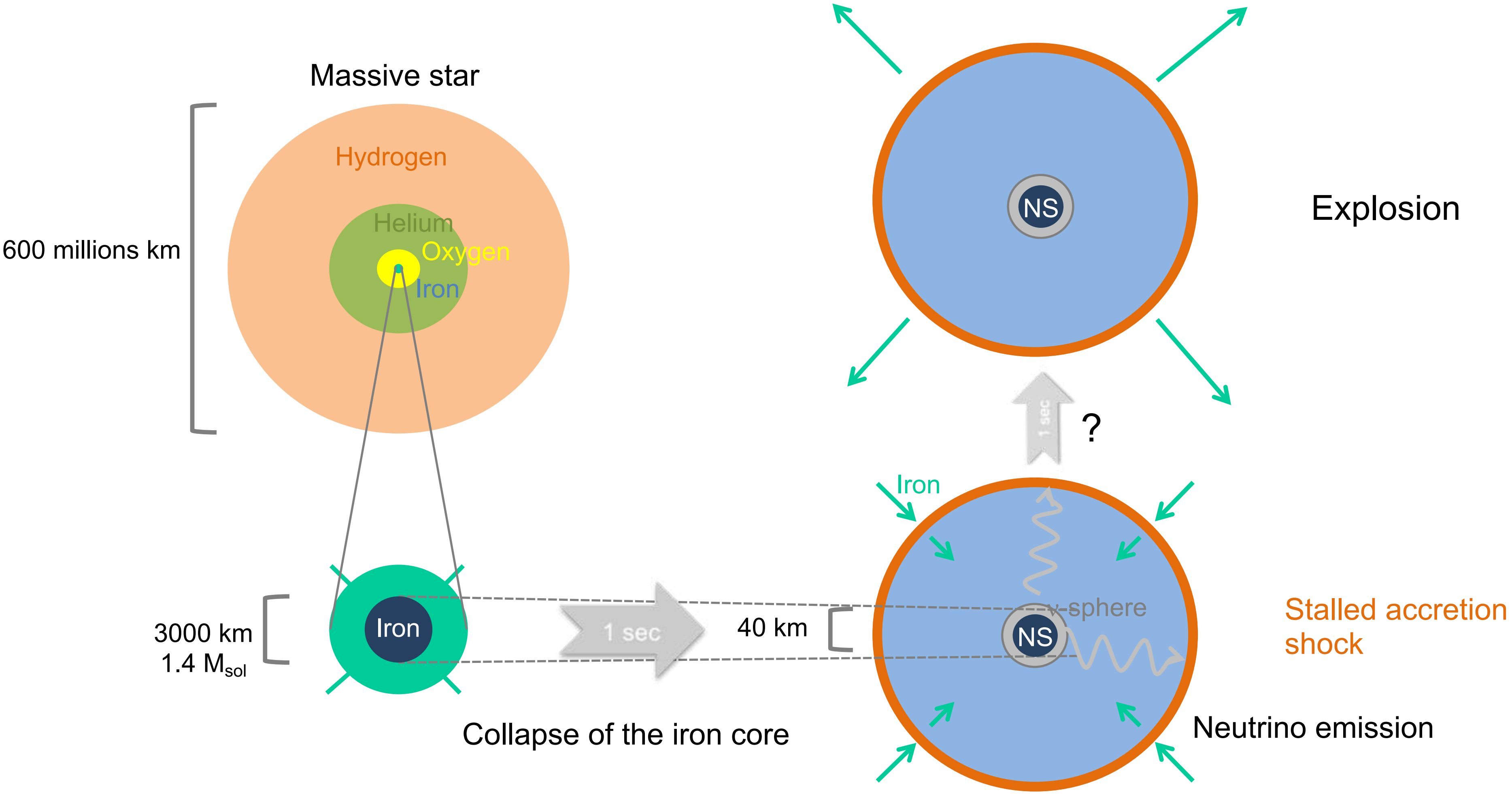
(IRFU/DAp)

Core collapse: formation of a neutron star



Proposed explosion mechanisms

Neutrino-driven explosions : favored mechanism for standard SNe

Magnetorotational explosions : need fast rotating progenitors ⇨ extreme events ?

Quark matter transition : uncertain physics, only very massive stars ?

Acoustic mechanism (Burrows+ 2006, 2007) : not confirmed by later studies or other groups

Jittering jets (Soker+) : weak physical motivation for the driving of the jets

Neutrino-driven mechanism: a multi-physics problem

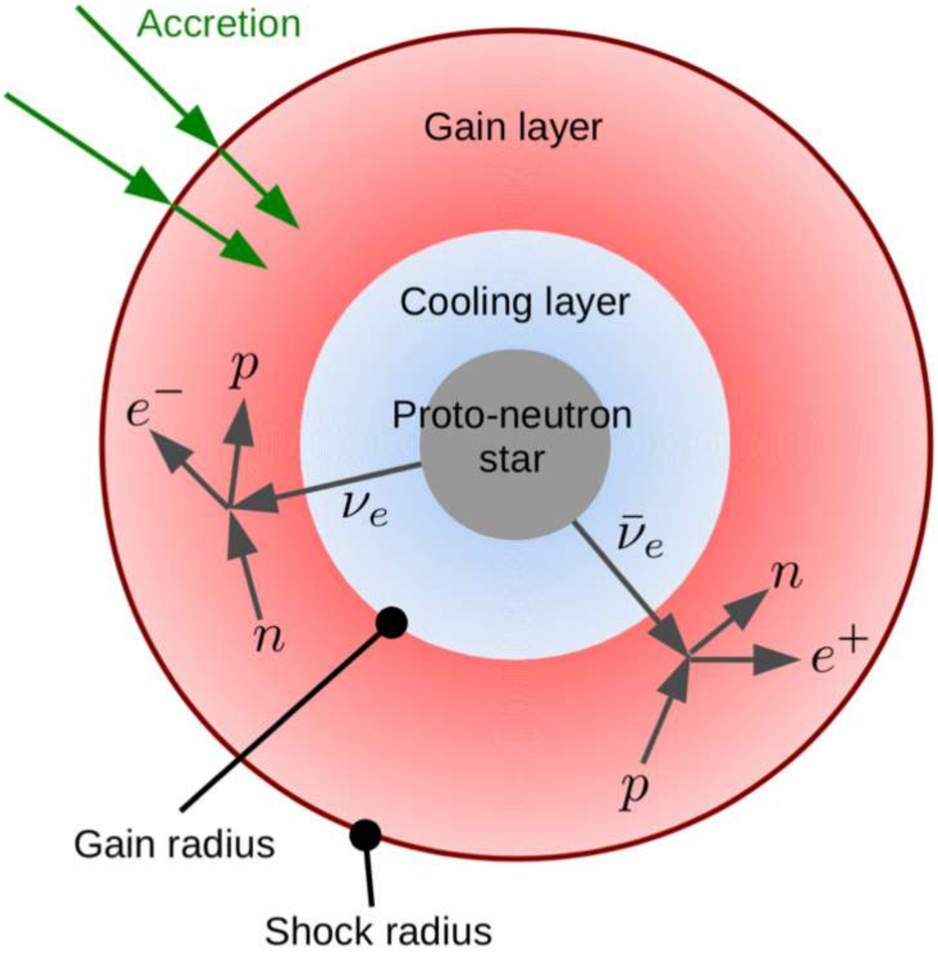
- Multi-dimensional hydrodynamics (instabilities, turbulence..)

- Magnetic field

- General relativity

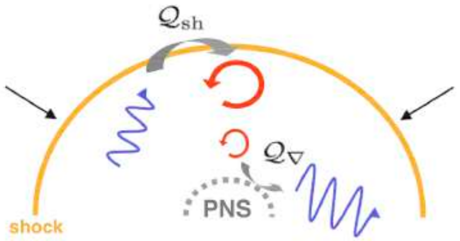
- Neutrino-matter interactions
    - sophisticated transport scheme
    - accurate cross sections

- Ultra-high density equation of state

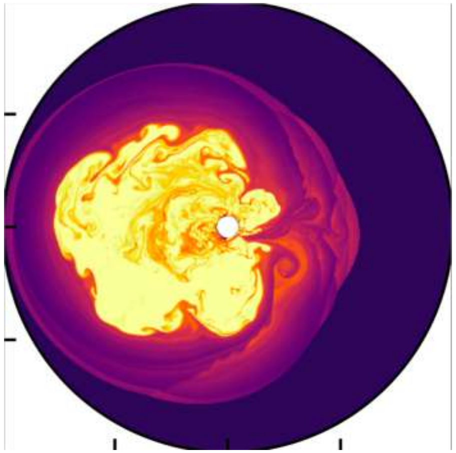


To simplify or not to simplify

Analytical studies

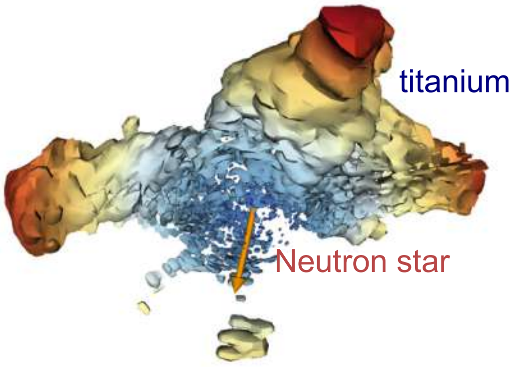


Simplified numerical simulations



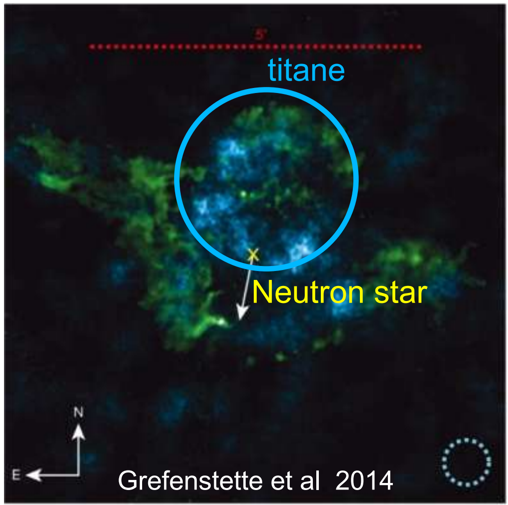
B. Pagani PhD thesis

« Realistic » numerical simulations

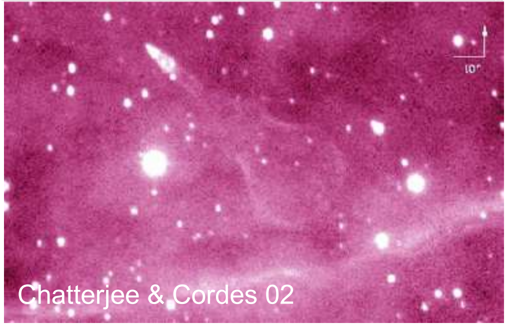


Wongwathanarat et al 2016

Observations



Grefenstette et al 2014



Chatterjee & Cordes 02

Realism

Physical understanding

General relativity

Compactness parameter : $\frac{GM}{rc^2}$

- Neutron star : $r \approx 12\ km, \frac{GM}{rc^2}$ ~ 0.2
- Protoneutron star : $r \approx 40\ km, \frac{GM}{rc^2}$ ~ 0.05

Approximations of general relastivistic effects:

- Full general relativity

  e.g. Kuroda et al 2012

- CFC approximation (conformal flatness condition)

  e.g. CoCoNut code, Müller et al 2010, 2012

- Pseudonewtonian potential

  e.g. Marek et al 2006

good approximation for SNe

approximate but incorporates the main effect of a more compact PNS

Ultra-high density equation of state

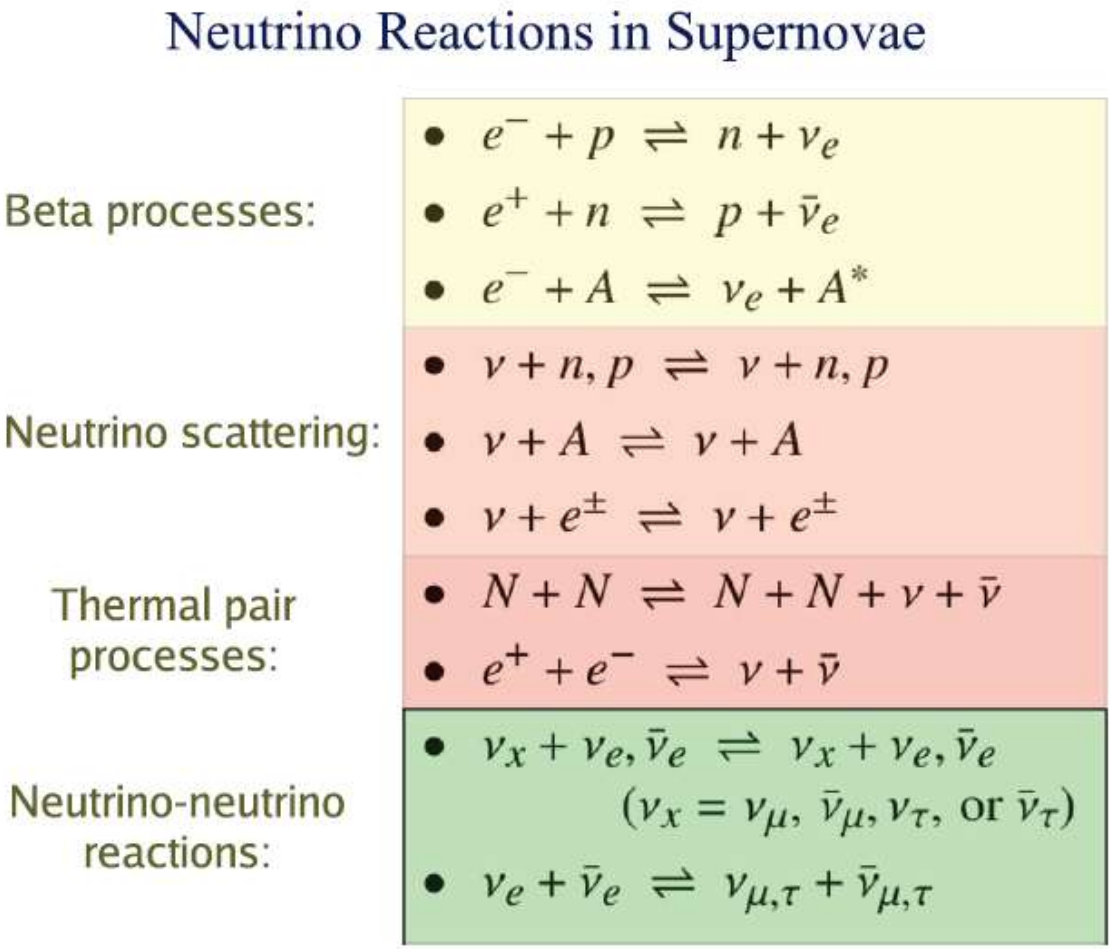
A supernova equation of state needs to cover a wide parameter space:

- High to ultra-high densities: $\approx 10^{7} - 10^{15}\ gcm^{-3}$
- High temperatures: $\mathrm{kT} \approx 10^{5} - 10^{7}\ eV$
- Electron fraction: $Y_e \approx 0.05 - 0.5$
- Account for nuclei (sometimes in the single nucleus approximation)

Common tabulated equations of state:

- Lattimer & Swesty 1992: compressible liquid drop model
  - e.g. LS220 with incompressibility $K = 220MeV$
- Steiner et al 2013 : relativistic mean field model
  - e.g. SFHo
- & many others…

Neutrino interactions



Neutrino Reactions in Supernovae

Beta processes:	$e^- + p \rightleftharpoons n + \nu_e$ $e^+ + n \rightleftharpoons p + \bar{\nu}_e$ $e^- + A \rightleftharpoons \nu_e + A^*$
Neutrino scattering:	$\nu + n, p \rightleftharpoons \nu + n, p$ $\nu + A \rightleftharpoons \nu + A$ $\nu + e^\pm \rightleftharpoons \nu + e^\pm$
Thermal pair processes:	$N + N \rightleftharpoons N + N + \nu + \bar{\nu}$ $e^+ + e^- \rightleftharpoons \nu + \bar{\nu}$
Neutrino-neutrino reactions:	$\nu_x + \nu_e, \bar{\nu}_e \rightleftharpoons \nu_x + \nu_e, \bar{\nu}_e$ $(\nu_x = \nu_\mu, \bar{\nu}_\mu, \nu_\tau, \text{or } \bar{\nu}_\tau)$ $\nu_e + \bar{\nu}_e \rightleftharpoons \nu_{\mu,\tau} + \bar{\nu}_{\mu,\tau}$

Dominant heating and cooling reactions

Heating by neutrino absorption in the gain region:

$$n + \nu_e \rightarrow p + e^-$$

$$p + \bar{\nu}_e \rightarrow n + e^+$$

Cooling by electron capture above the neutrinosphere:

$$p + e \rightarrow n + \nu_e$$

Cooling by thermal processes: neutrinos leaking out the PNS at the neutrinosphere

Neutrino transport schemes

3 species approximation :
- electron neutrino
- electron antineutrino
- 1 species for the 4 heavy lepton neutrinos (muon and tau)

Different approximations :

- Leakage scheme
- IDSA : isotropic diffusion source approximation
- Flux-limited diffusion

cheap but not very accurate

- Ray-by-ray approximation (e.g. Garching group)
- Moment method (M1)

state of the art

- Full Boltzman transport

accurate but too expensive for 3D simulations

Criterion for neutrino-driven explosions

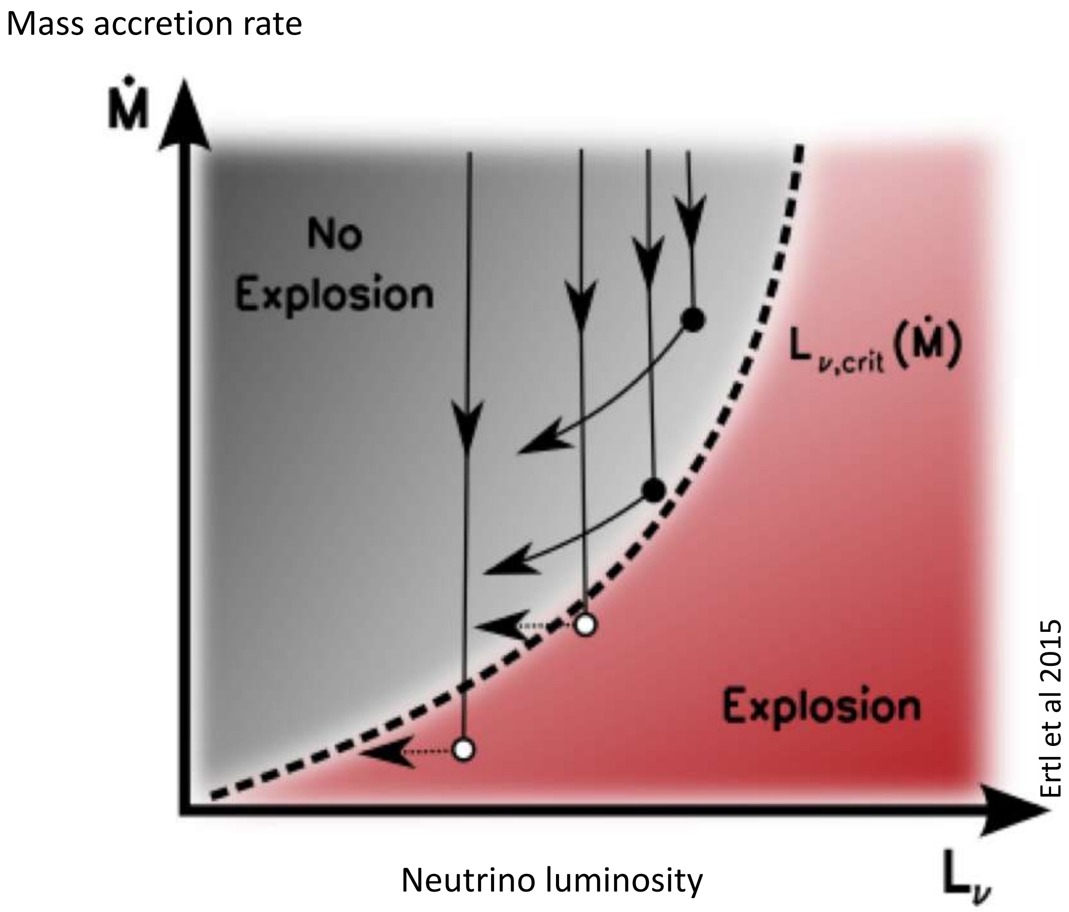
Explosion determined by a competition between

- ➢ neutrino heating
- ➢ ram pressure due to accretion

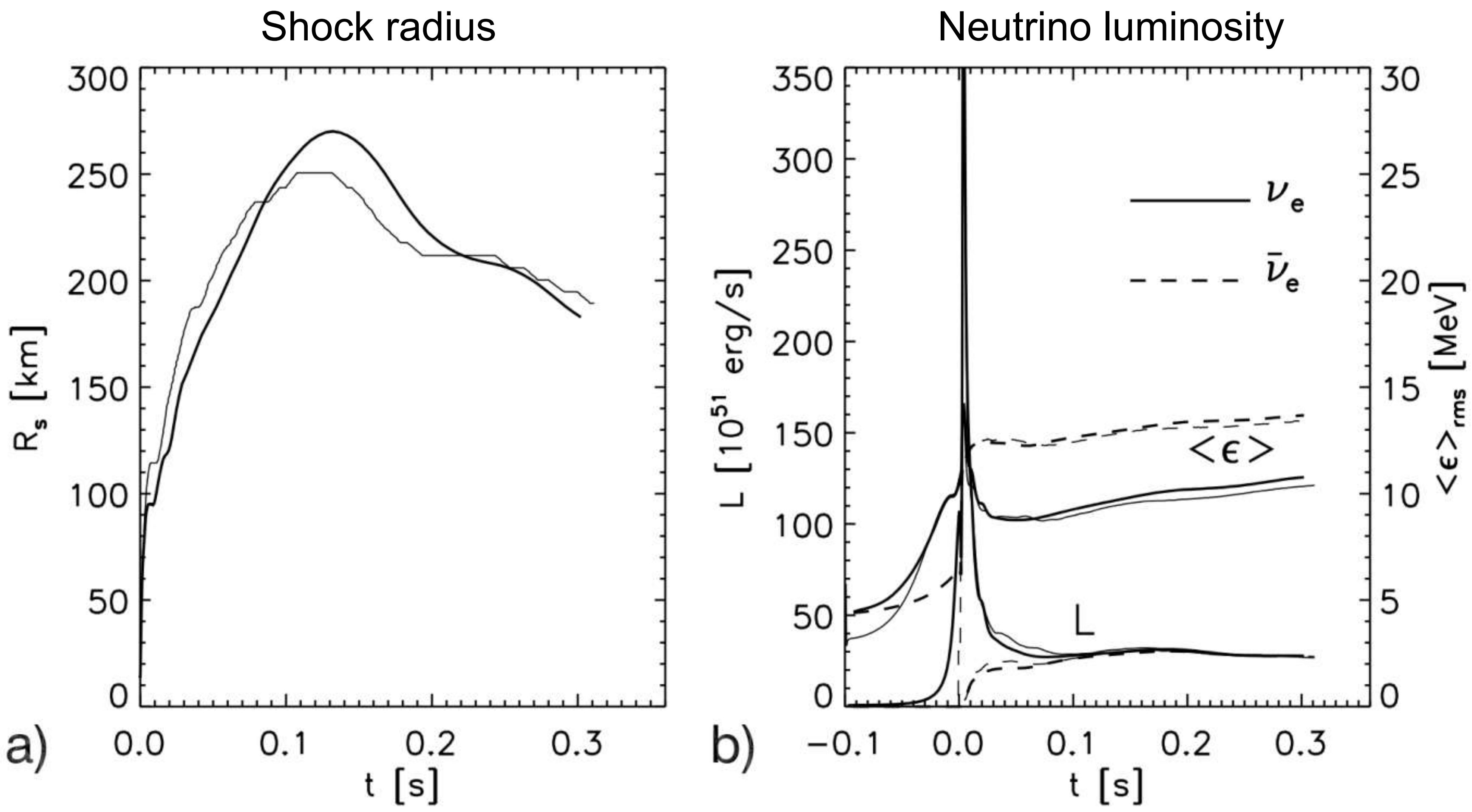
➡ Critical neutrino luminosity

Proposed explosion criterion:

heating time < advection time



No explosion in 1D spherical symmetry

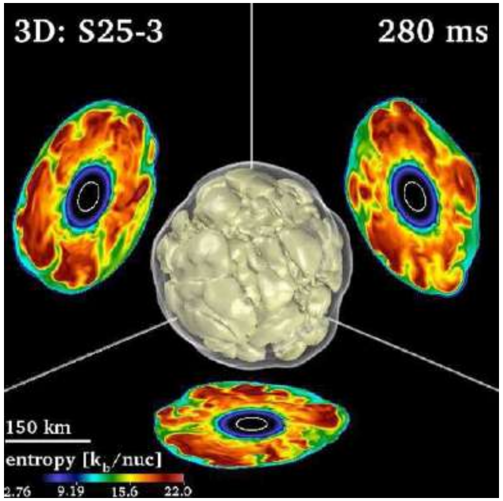

Shock radius

Neutrino luminosity

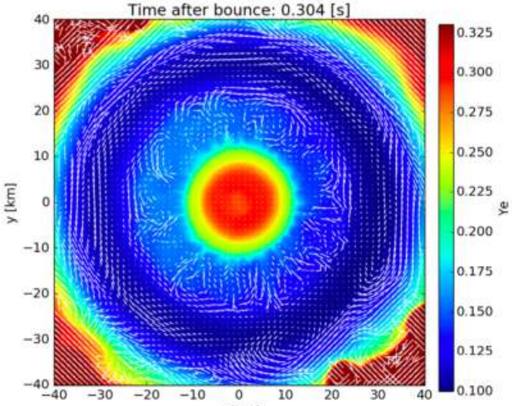
Liebendorfer et al 2005

Missing ingredient : hydrodynamic instabilities

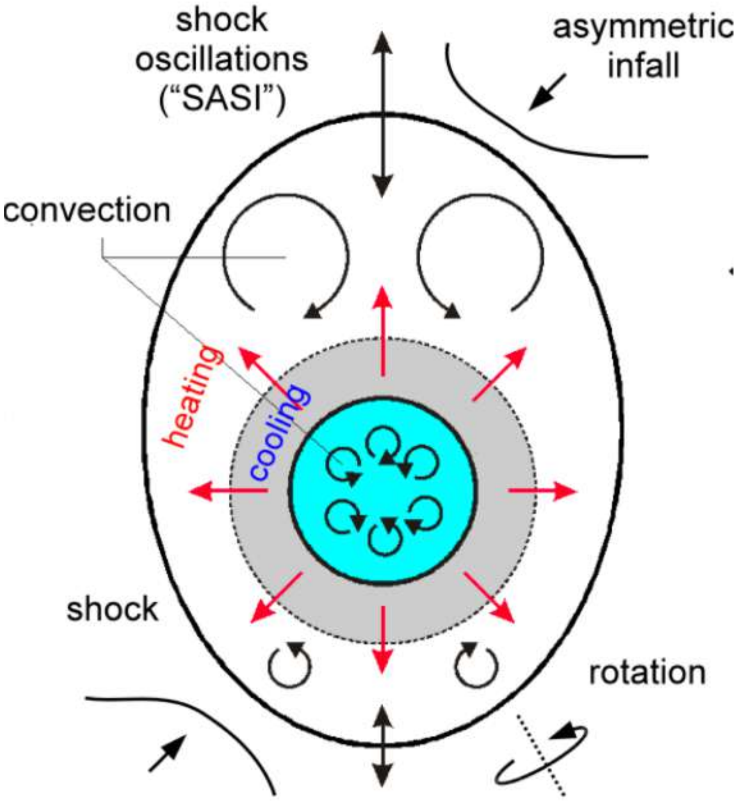
Neutrino-driven convection



Protoneutron star convection



Dessart+2006



shock oscillations ("SASI")

asymmetric infall

convection

heating

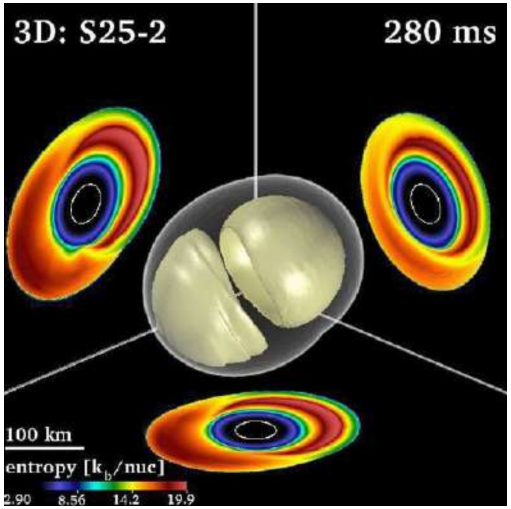
cooling

shock

rotation

Mueller 2020

Standing Accretion Shock Instability (SASI)

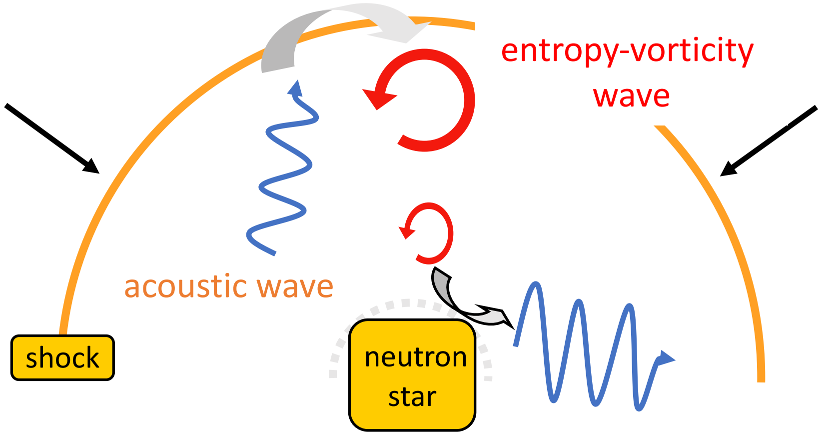


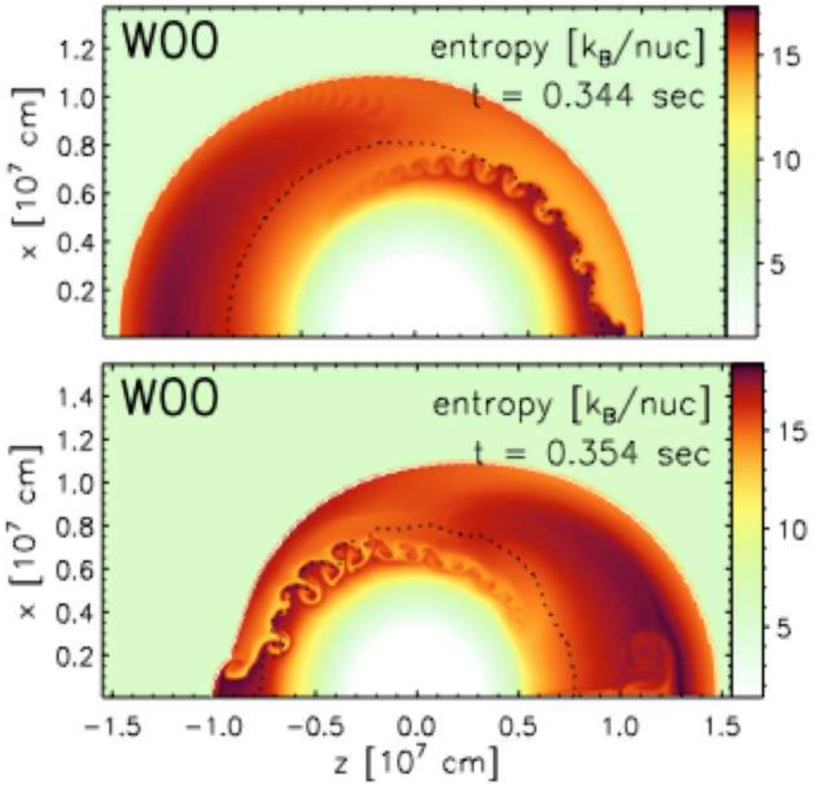
Hanke+2013

The Standing Accretion Shock Instability (SASI)

Advective-acoustic cycle

Foglizzo *et al* 2007, Guilet & Foglizzo 2012



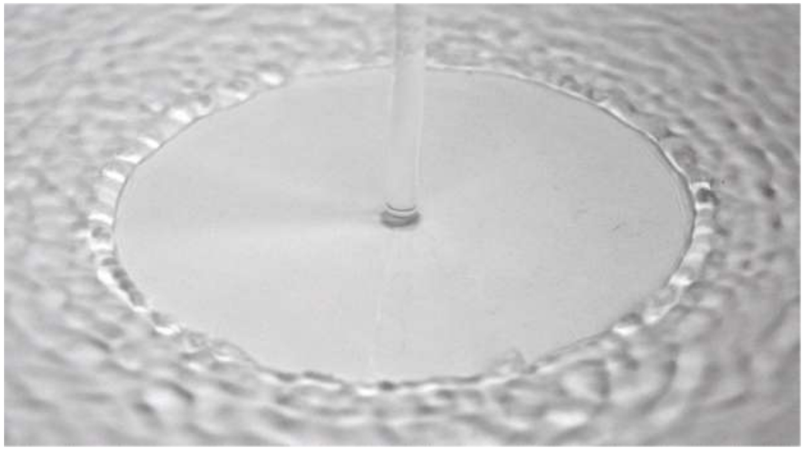


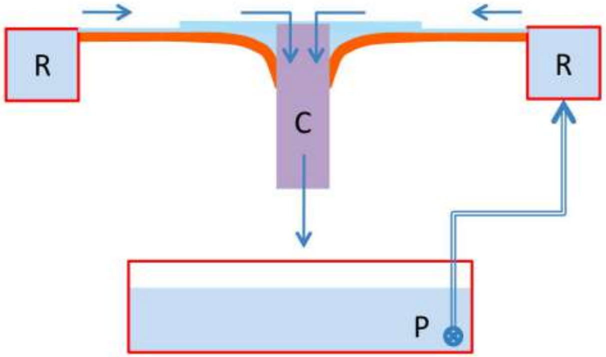
Scheck et al 2008

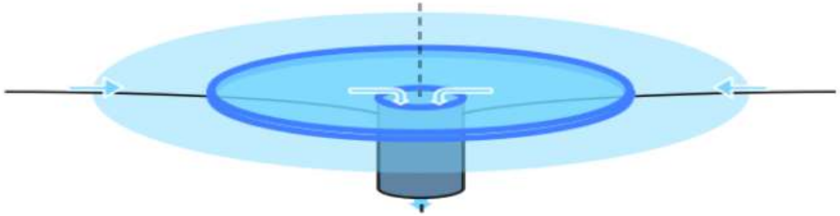
Large-scale shock oscillations : spherical harmonics l=1-2

SWASI : Shallow Water Analogue of a Shock Instability

Kitchen sink hydraulic jump



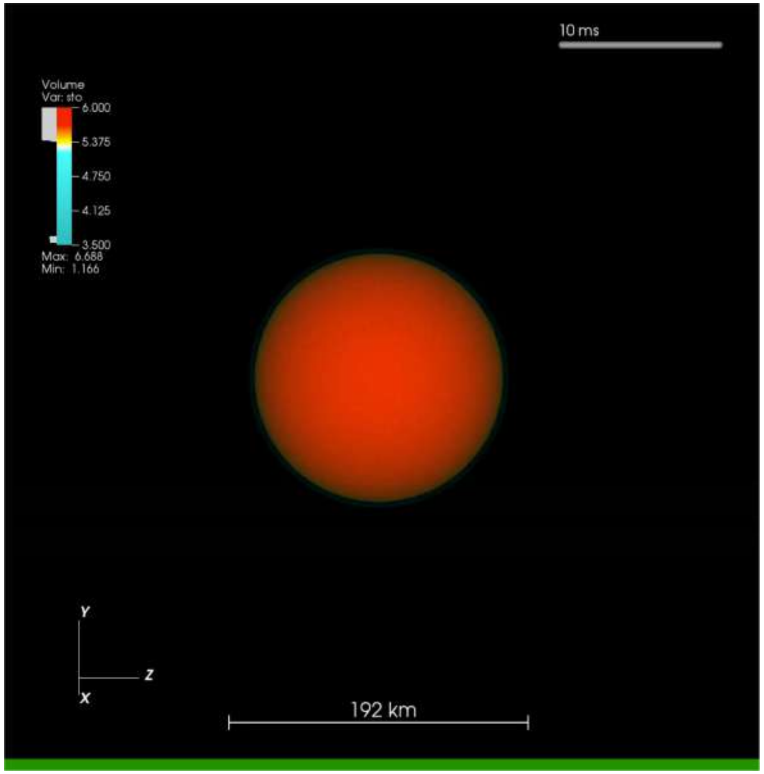




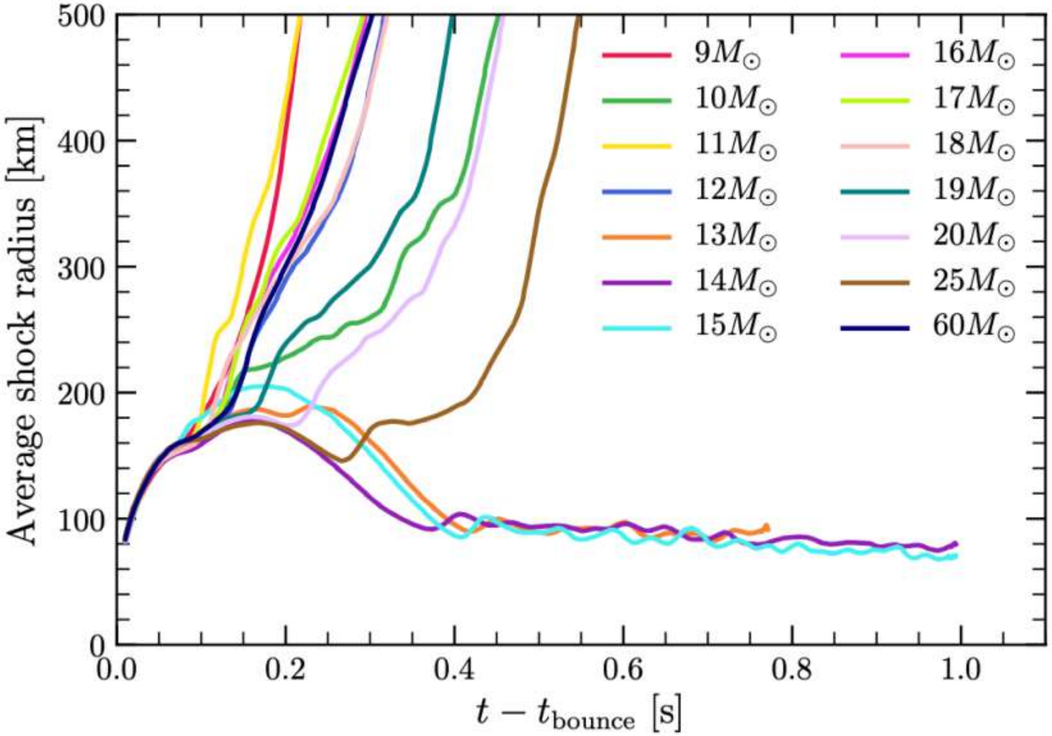
acoustic waves	⟷	surface wave
shock wave		hydraulic jump
pressure		depth

Foglizzo *et al* 2012

Successful explosions in 3D simulations (finally)



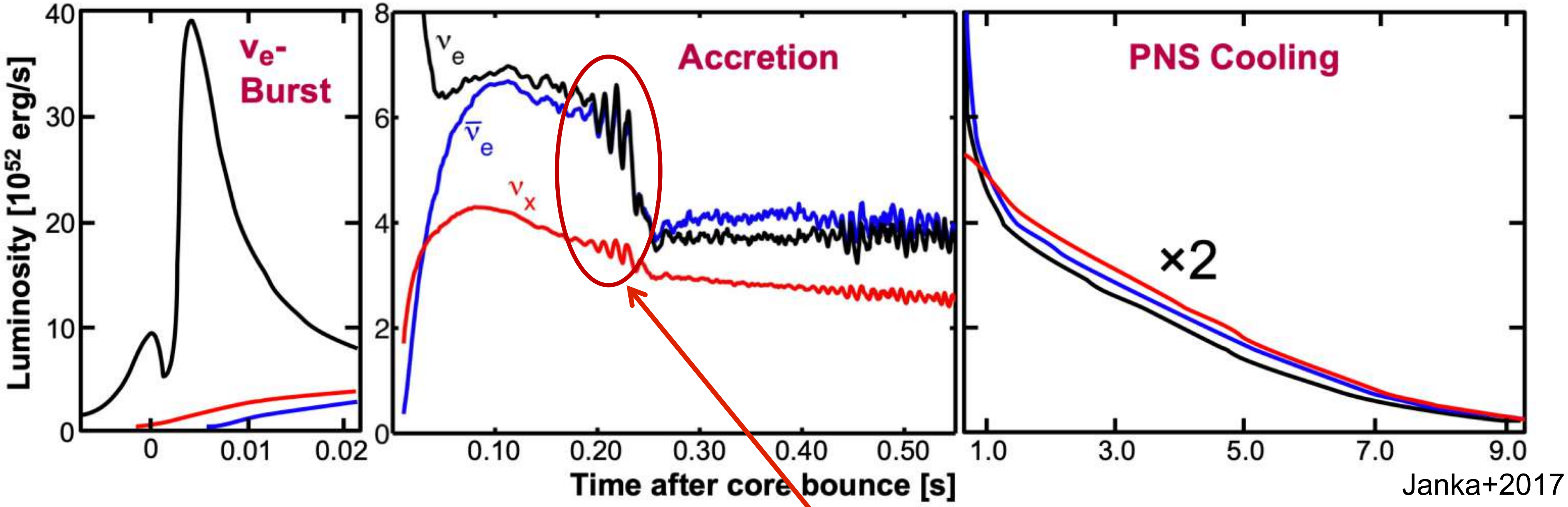
One of the first 3D explosions obtained by the Garching group



Burrows et al 2019

Obtaining robust explosions was a long standing difficulty
Now many groups commonly obtain 3D explosions

Neutrino signatures



Janka+2017

test oscillation physics

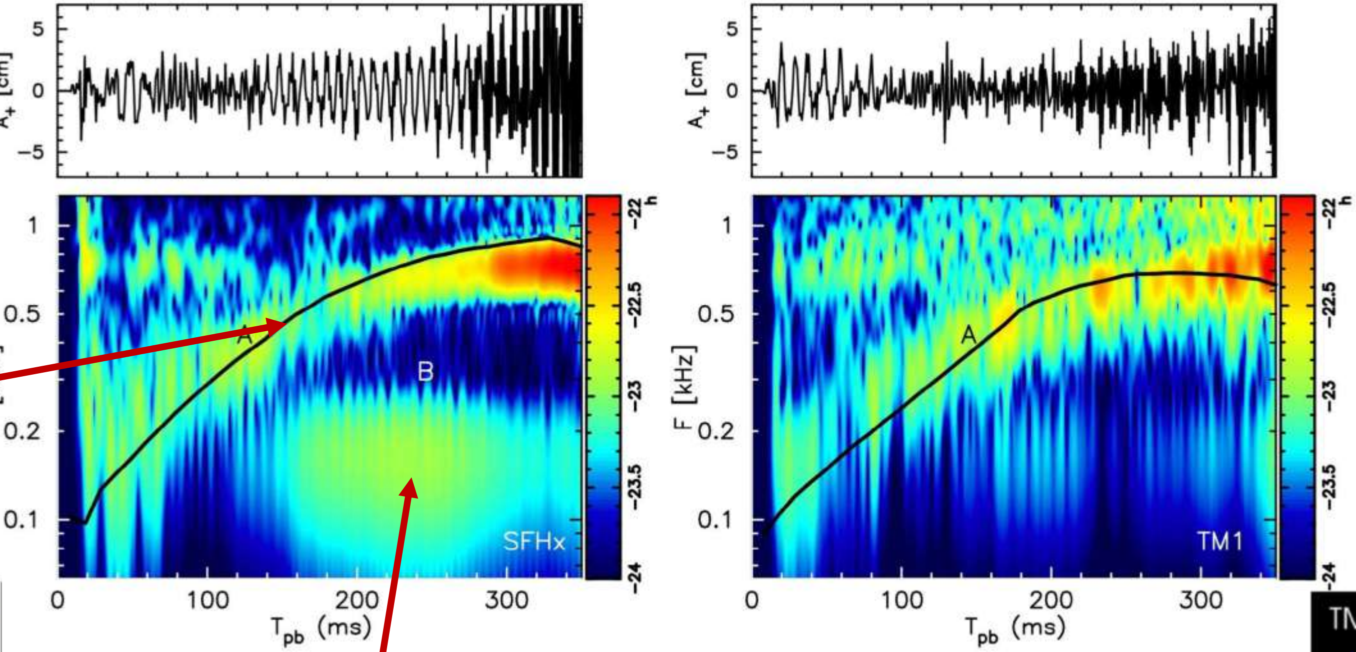
probes SN astrophysics

hydrodynamic instabilities

probes nuclear physics
& PNS convection

EOS & mass dependance

Gravitational wave signature

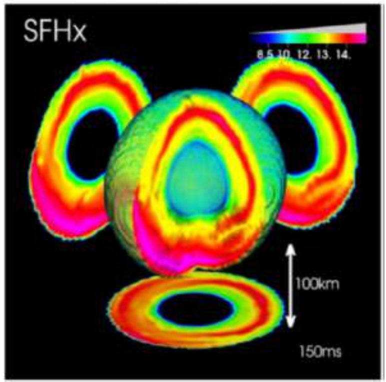


Softer EOS
(SFHx, Steiner+13)

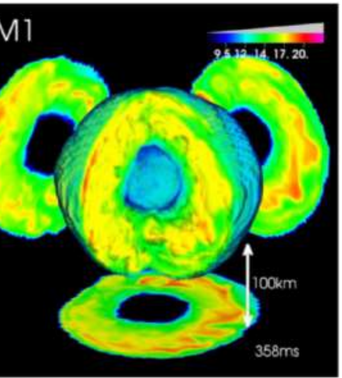
Stiffer EOS
(TM1, Hempel+10)

PNS surface oscillations

Kuroda+2016



Signature of strong SASI activity

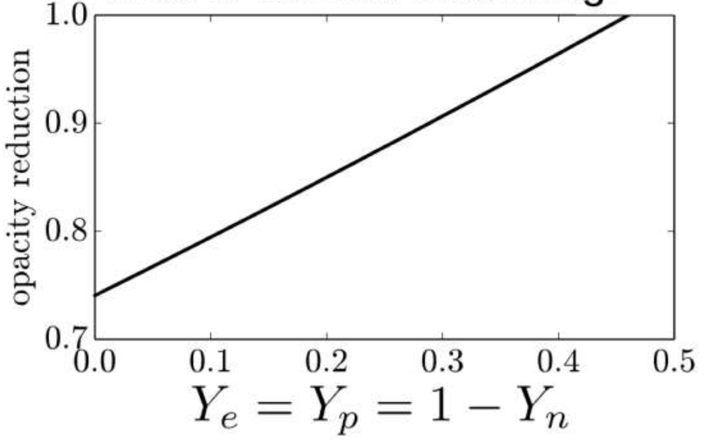


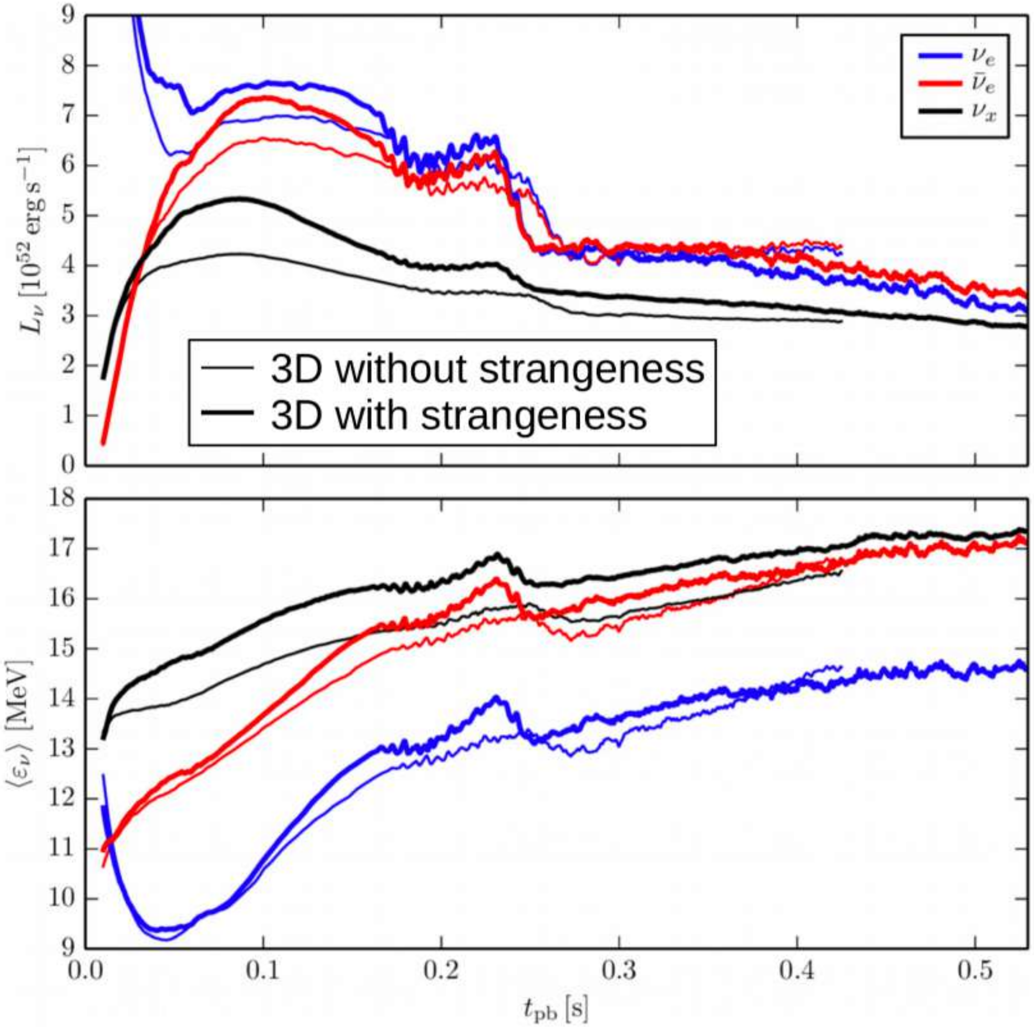
Sensitivity to neutrino-matter interactions

Strange quark correction to the nucleon spin

-> reduces neutral current scattering of neutrinos by 10-20%

Opacity reduction for neutral-current scattering:





Melson et al (2015)

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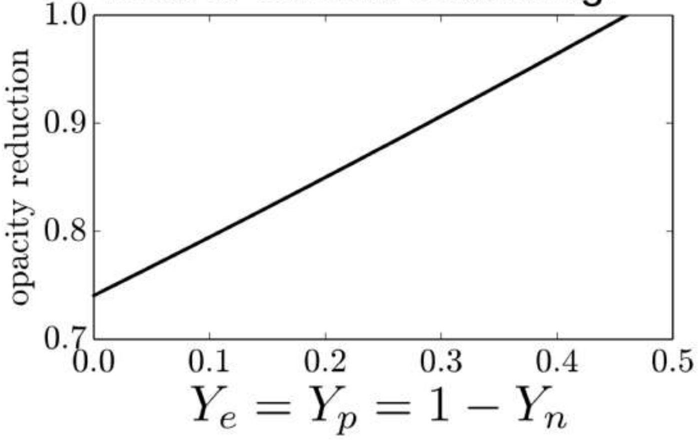
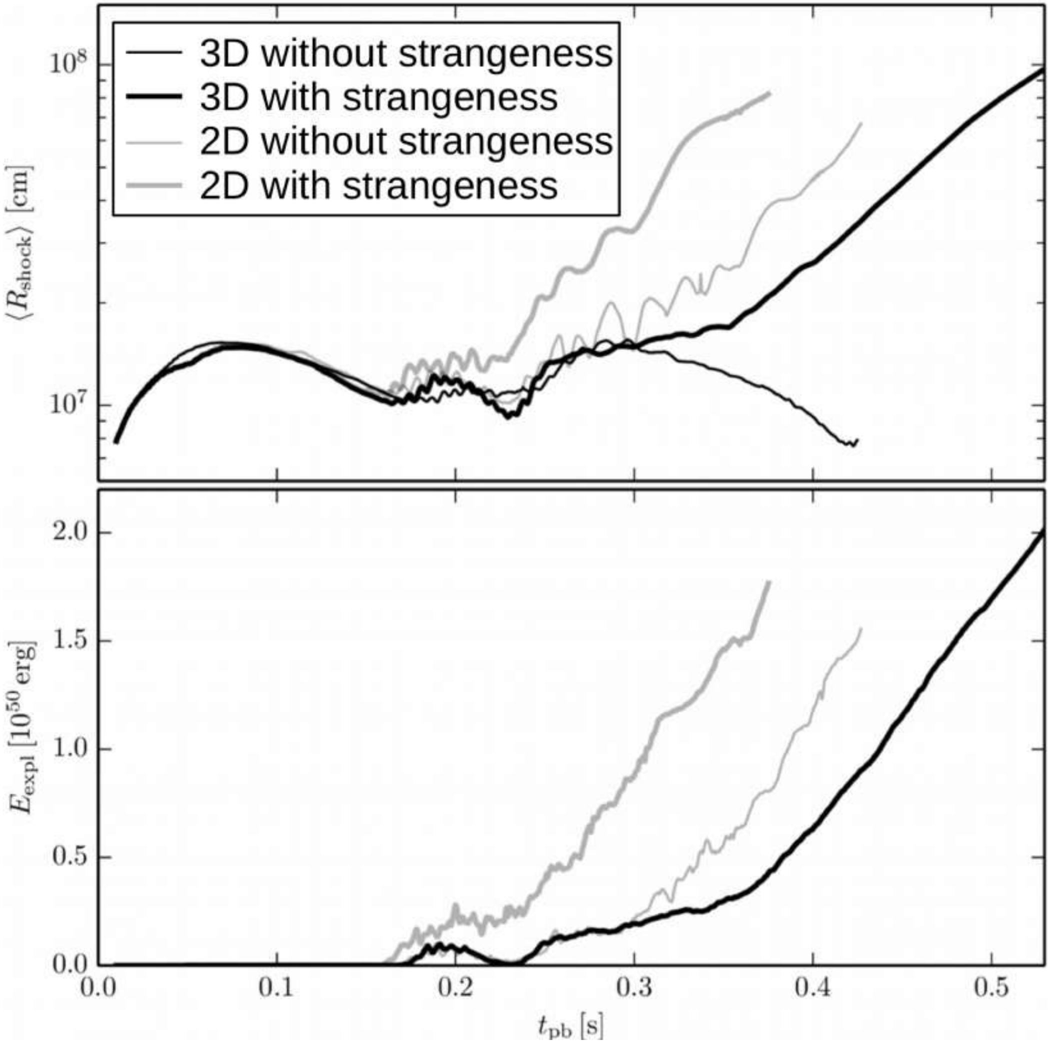
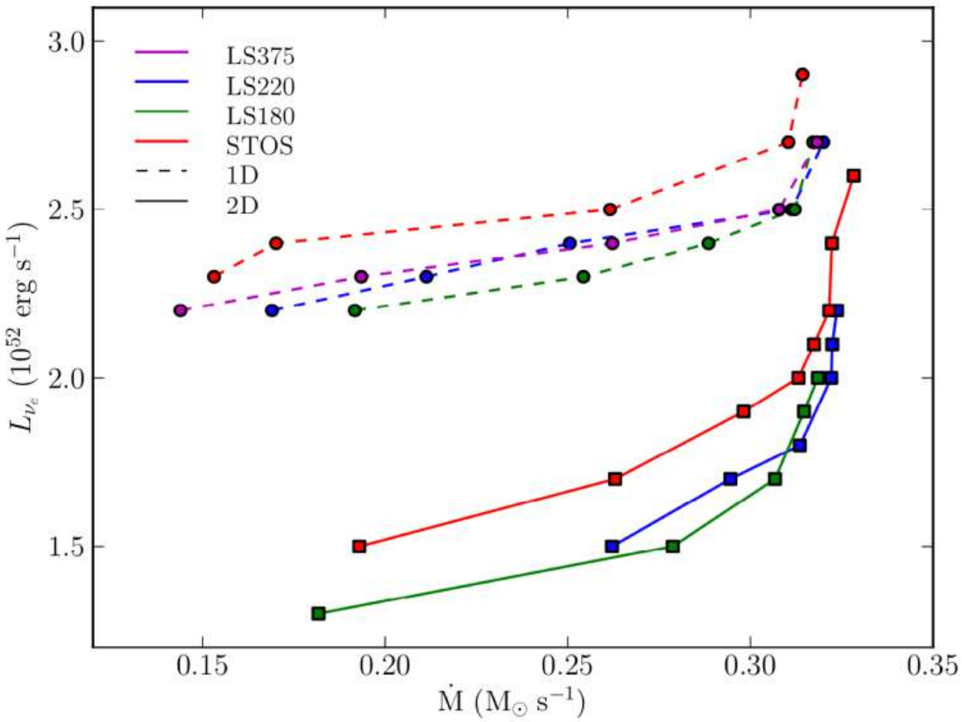
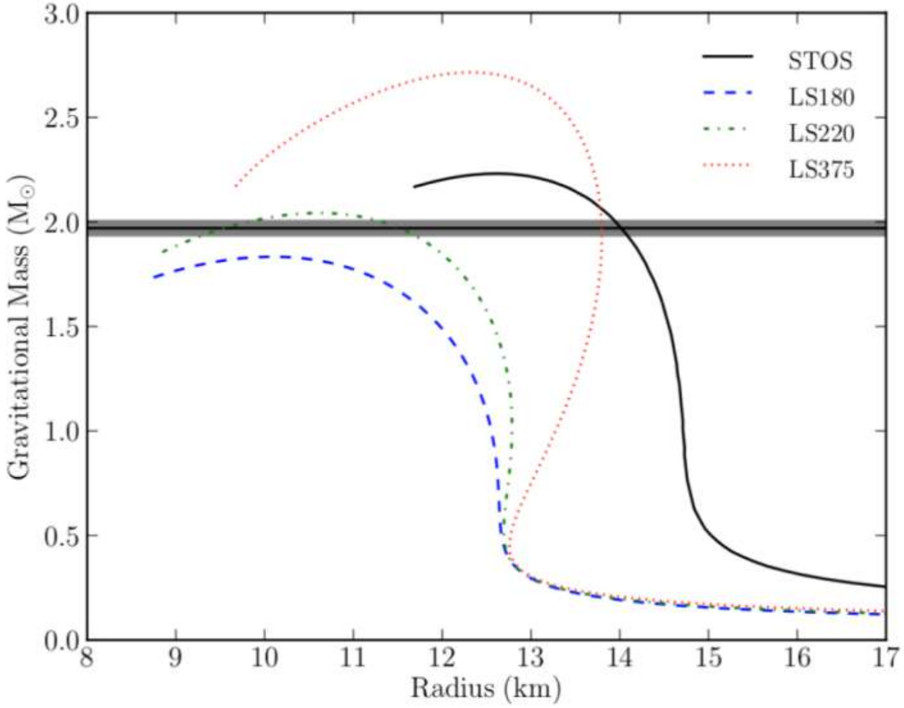




Melson et al (2015)

Sensitivity to EOS stiffness





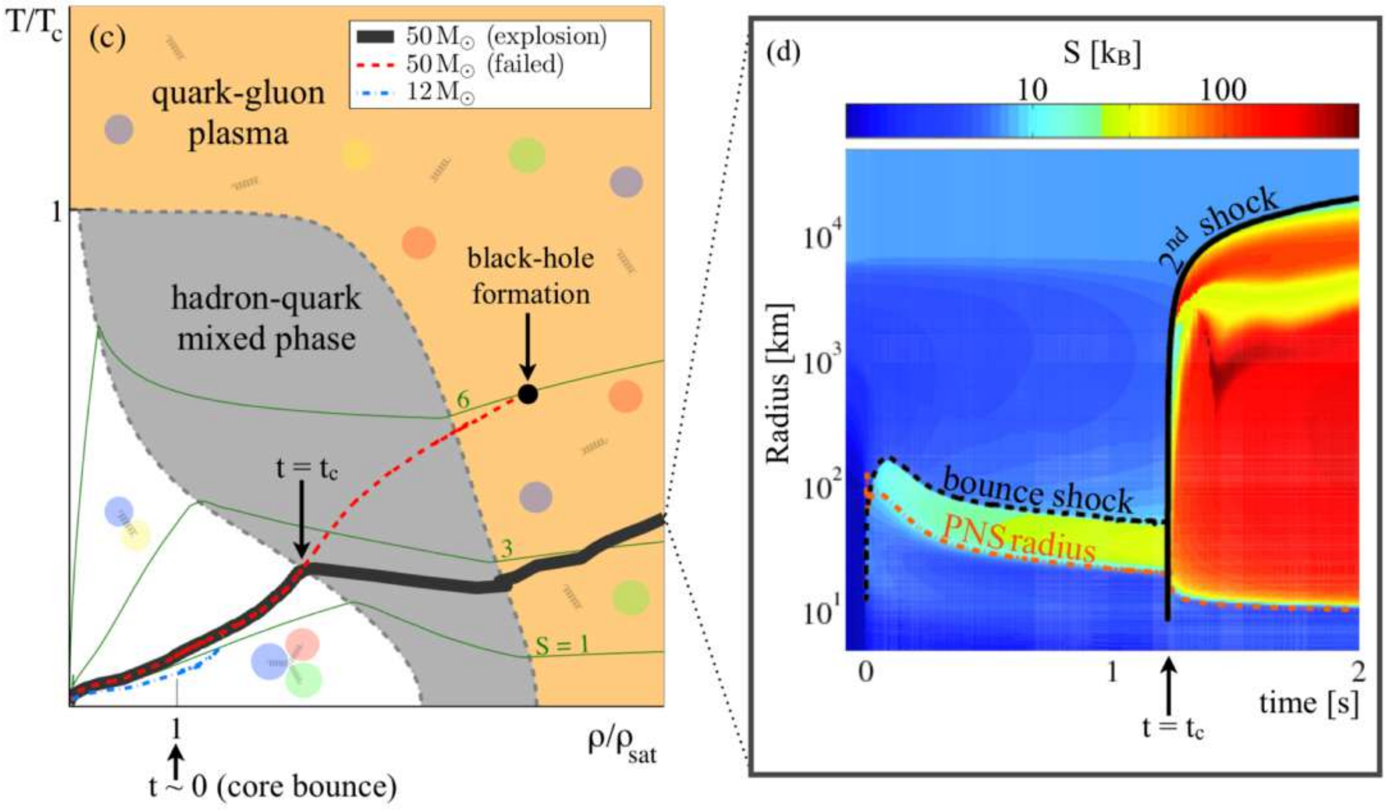
Softer EOS make explosions easier

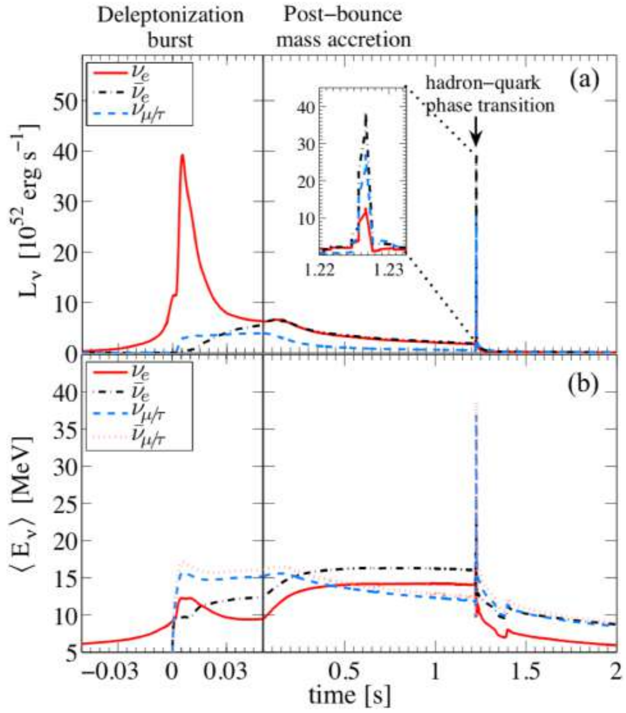
Couch 2013, Suwa et al 2013, Pan et al 2018

Phase transition to quark-gluon plasma ?

Strong explosion of high mass progenitor triggered by phase transition

Second peak of neutrino emission





Fischer et al 2017

Outstanding explosions: millisecond magnetars ?

Explosion kinetic energy :

→ Typical supernova 10^{51} erg

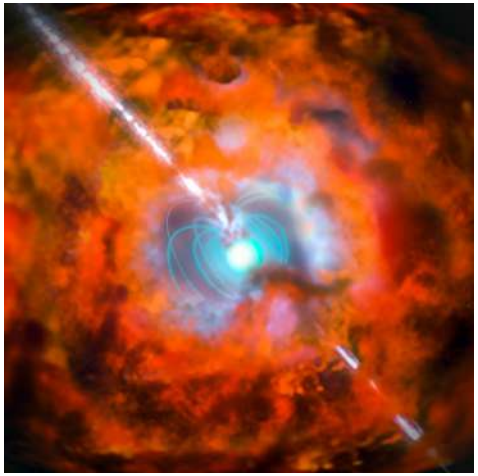
→ **Hypernova & GRB** 10^{52} erg

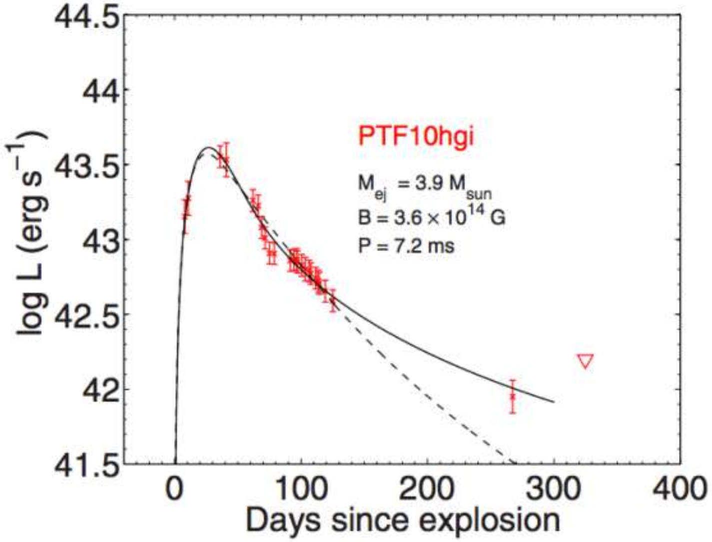
aka type Ic BL

Total luminosity :

→ Typical supernova 10^{49} erg

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



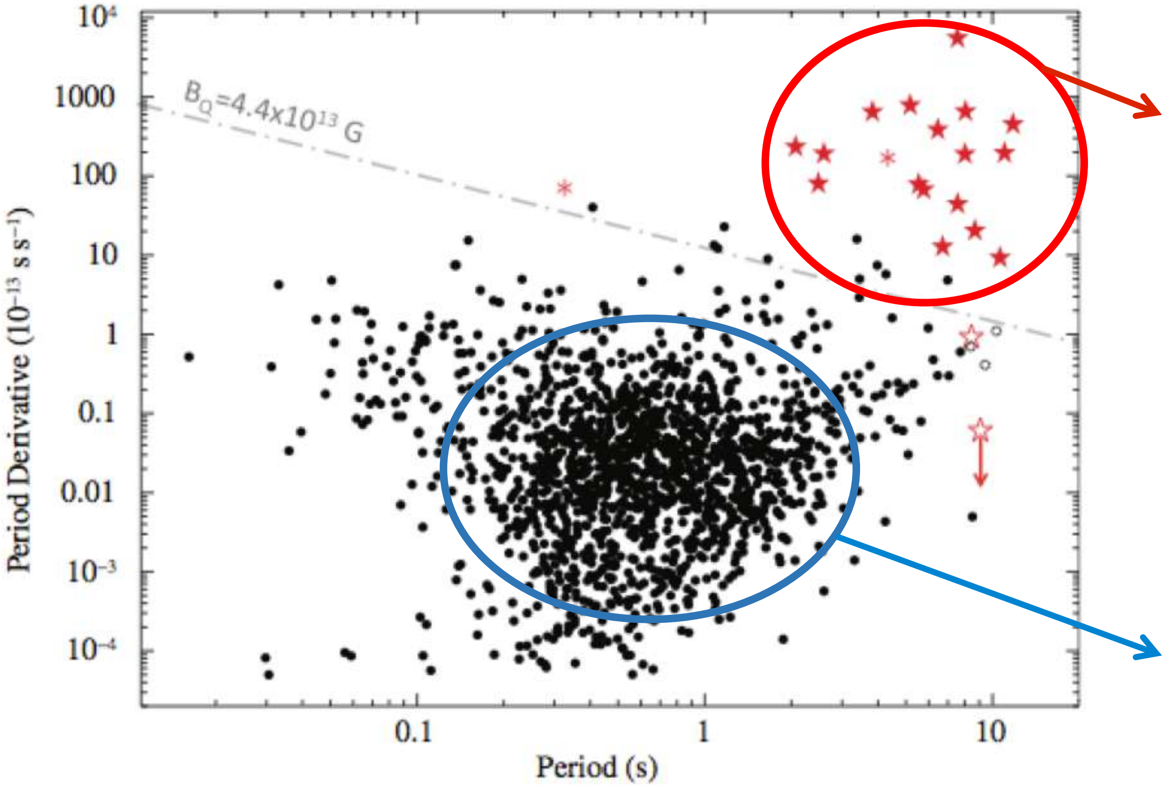


Large kinetic energy reservoir if fast rotation

Strong magnetic field to extract this energy

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

Magnetars: the most intense known magnetic fields



Magnetars

Anomalous X-ray pulsars (AXP)

Soft gamma repeater (SGR)

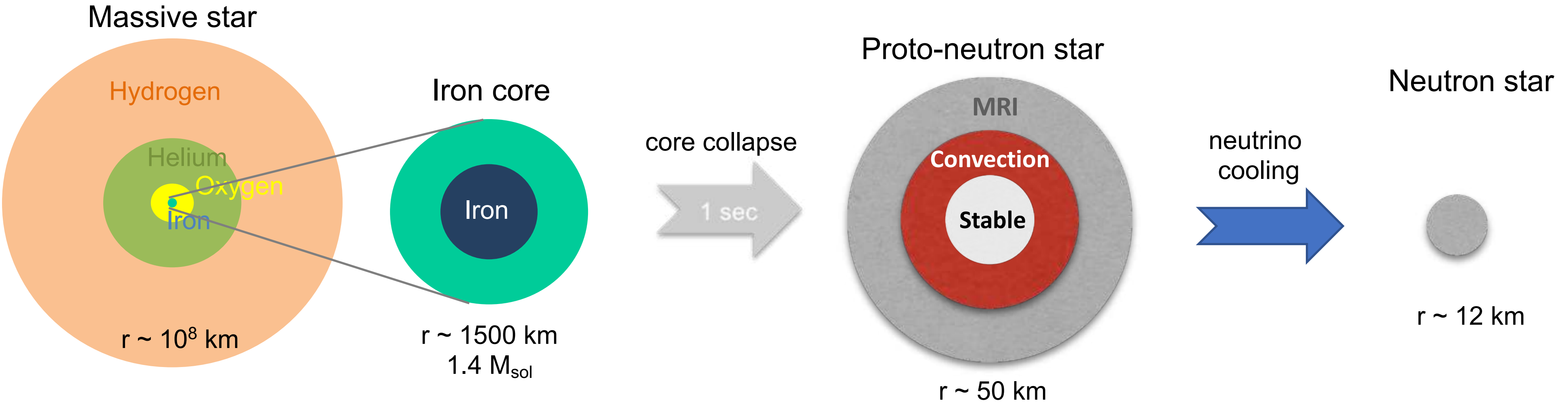
Strong dipole magnetic field:

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

Pulsars

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

Different scenarios for magnetar formation



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

Reboul-Salze+2021,2022, Guilet+2022

Convective dynamo

Similar to planetary & stellar dynamos

Raynaud+2020,2021

Tayler-Spruit dynamo

Similar to stellar radiative zones

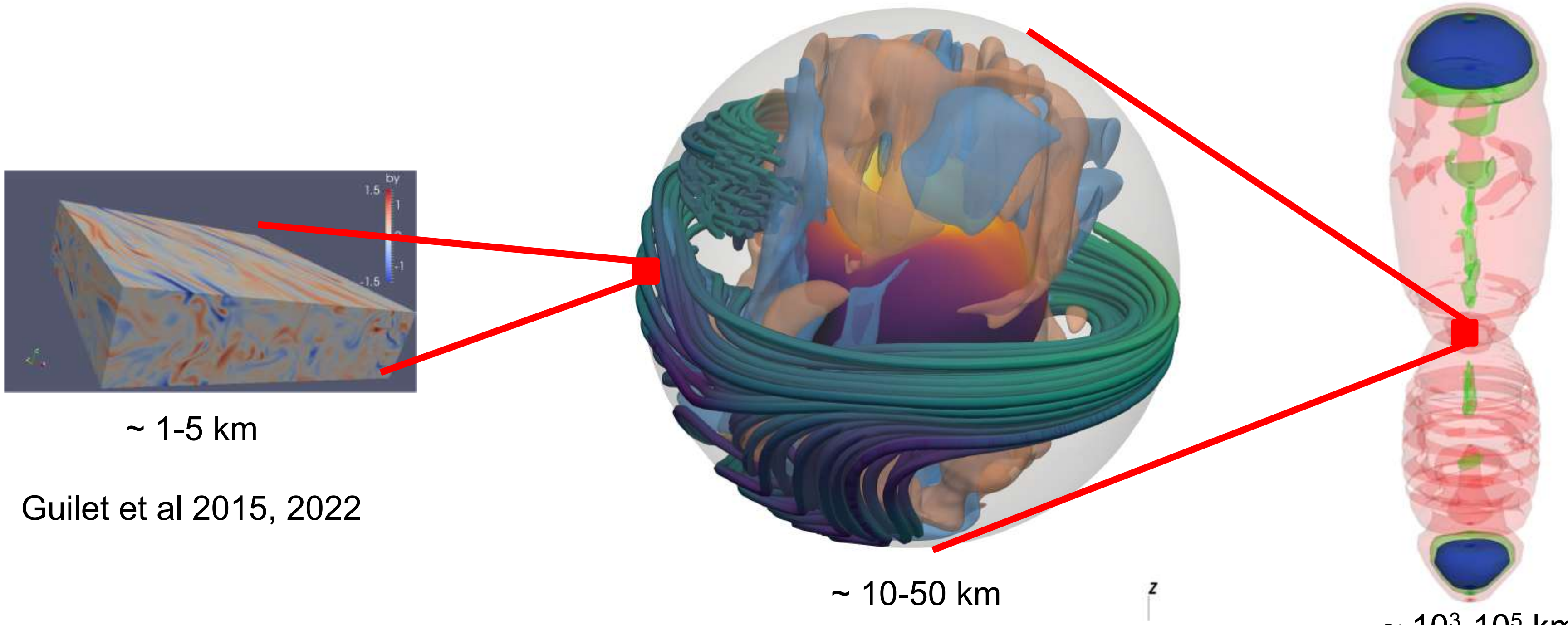
Barrère+2022

Simulating different spatial scales

Small turbulent scales

Protoneutron star dynamo

Magnetorotational explosions



~ 1-5 km

Guilet et al 2015, 2022

~ 10-50 km

Raynaud et al. 2020, 2022
Reboul-Salze et al. 2021,2022

~ 10^3-10^5 km

Bugli et al. 2020

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

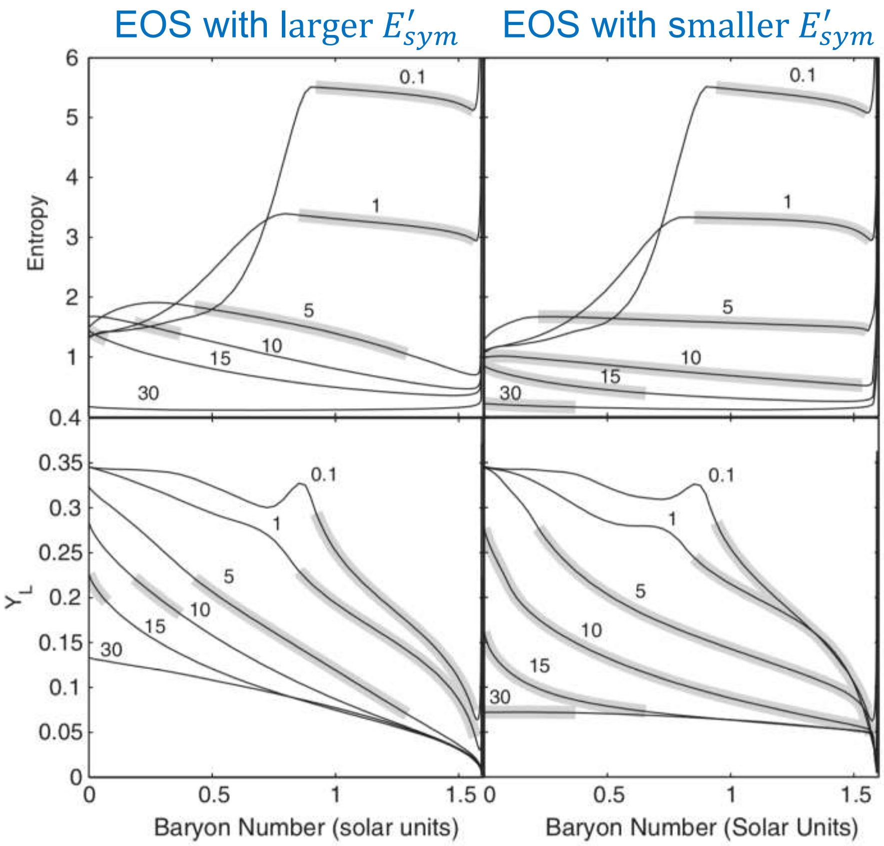
lepton fraction

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

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

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

Sensitive to the EOS through the slope of the symmetry energy E'_{sym}

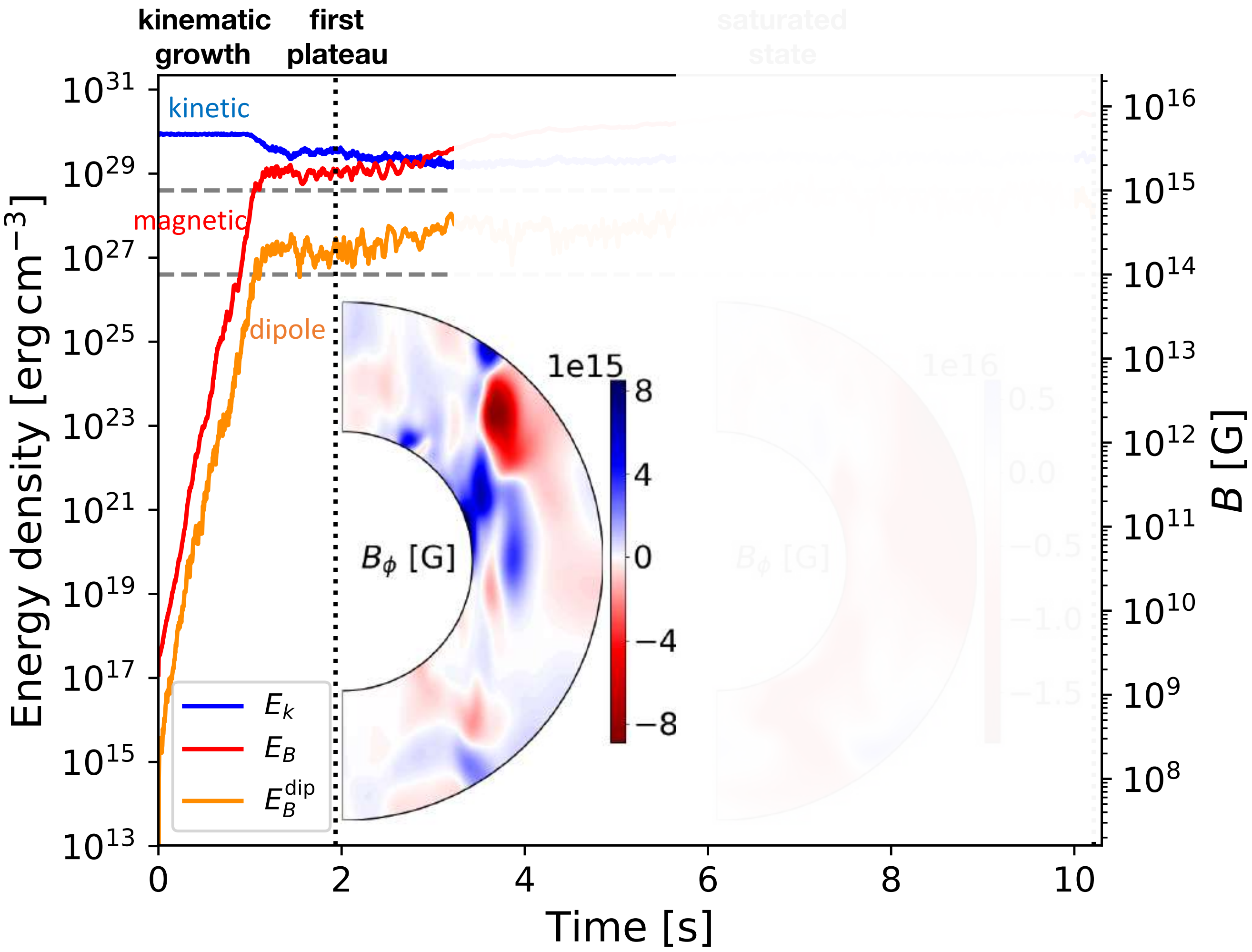

EOS with larger E'_{sym} EOS with smaller E'_{sym}

Roberts+2012

Motions transport heat and leptons

=> faster cooling and deleptonization of the protoneutron star

Convective dynamo in a protoneutron star



Raynaud et al 2020

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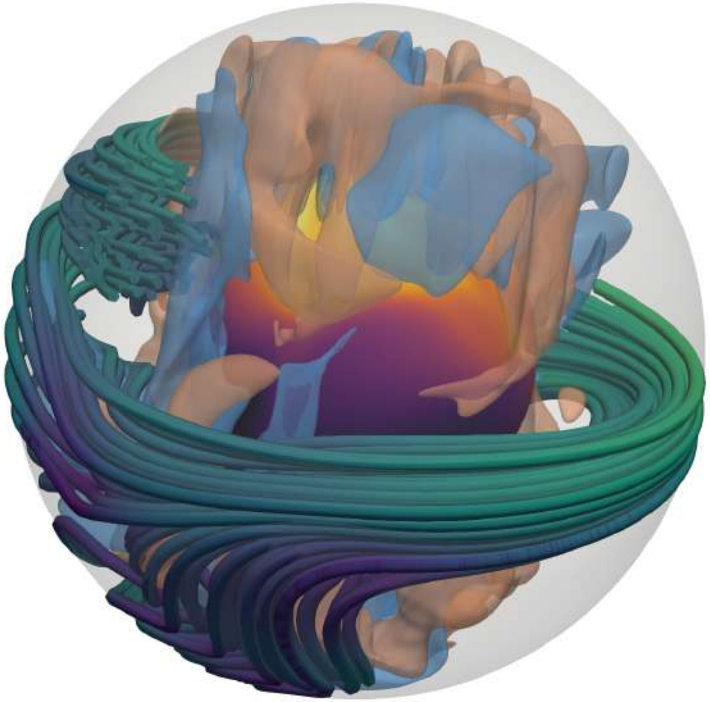
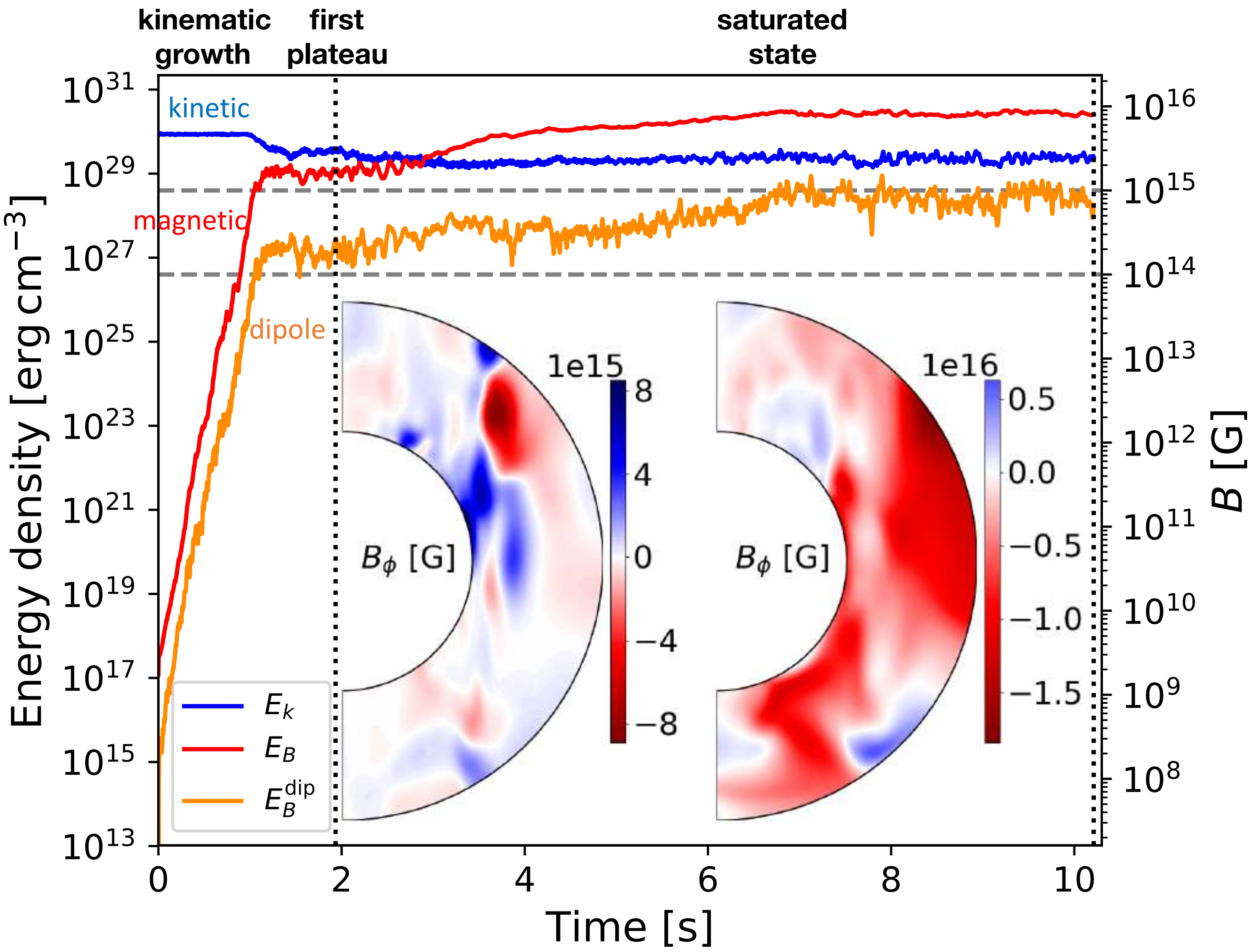
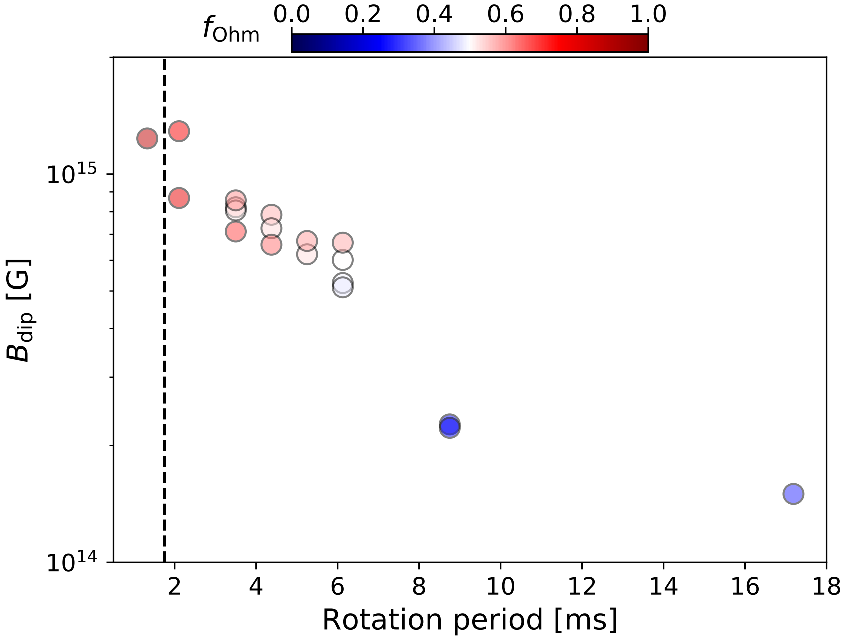




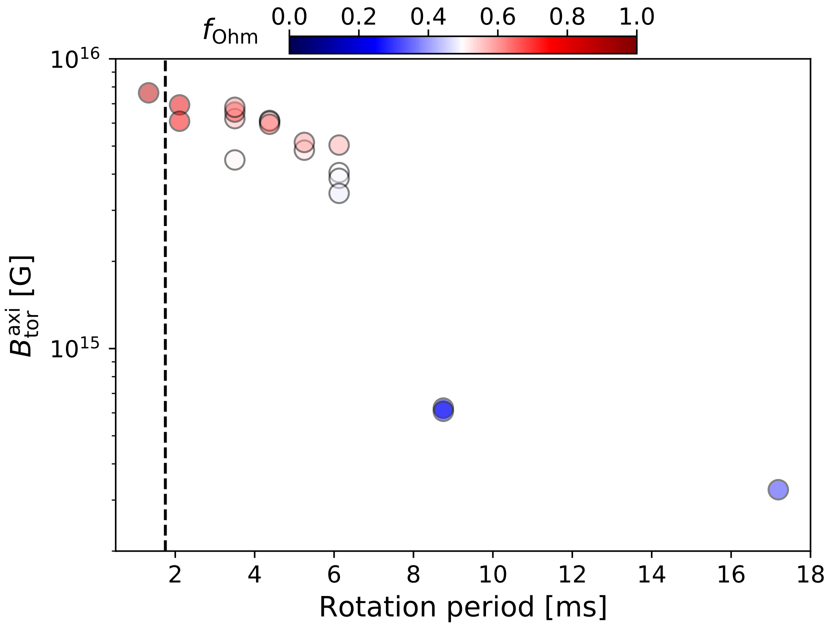
Raynaud et al 2020

Magnetic field strength

Dipolar magnetic field



Toroidal magnetic field



Very fast rotation: $P < 2.5$ ms

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

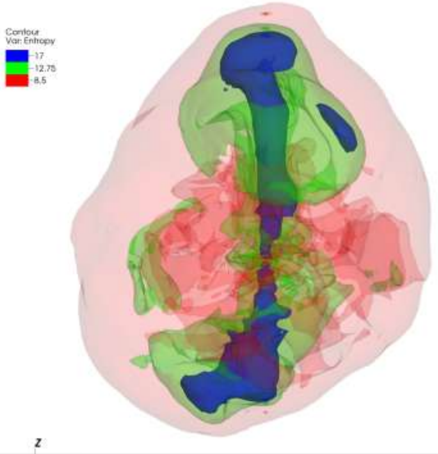
Intermediate rotation: 2.5 ms $< P <$ 10-20 ms

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

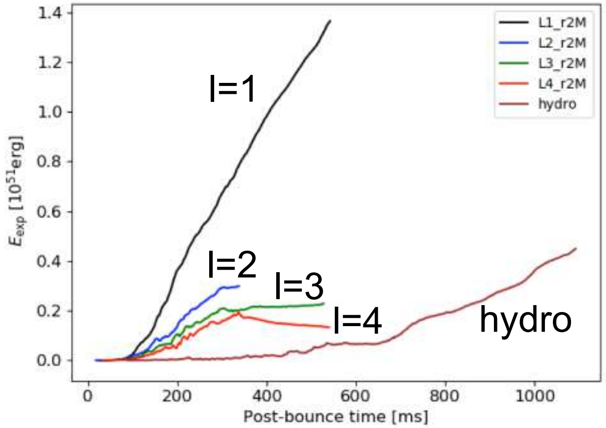
Magnetorotational explosions as extreme explosions ?

Aligned dipole

Inclined dipole



Explosion energy



Key questions :

Explosion energy ?

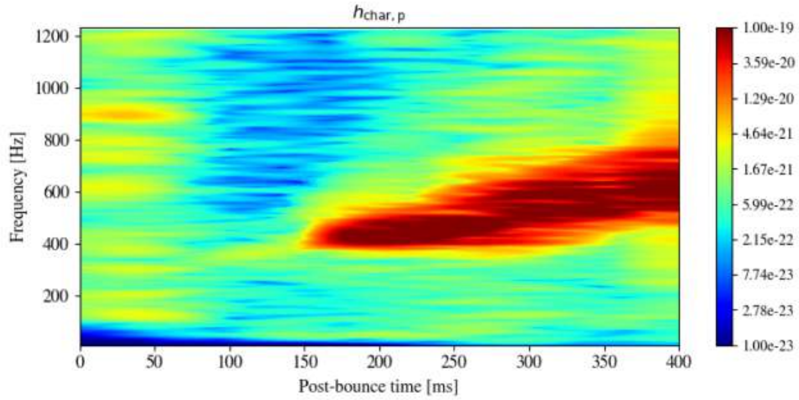
Collimated jet ?

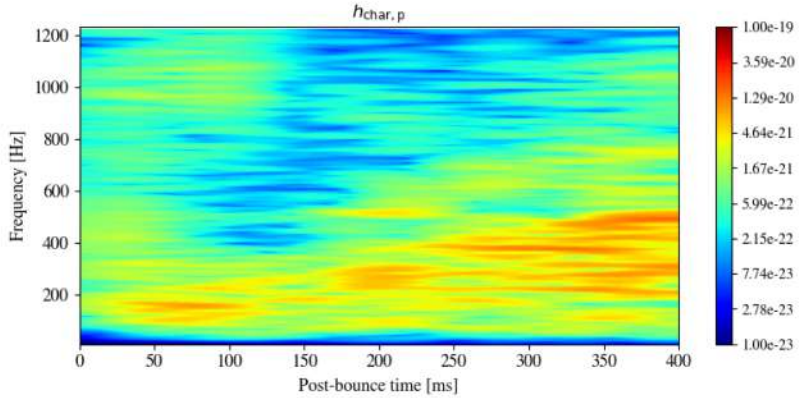
=> Diversity of explosions

Bugli, Guilet et al 2020, 2021

Multimessenger signatures

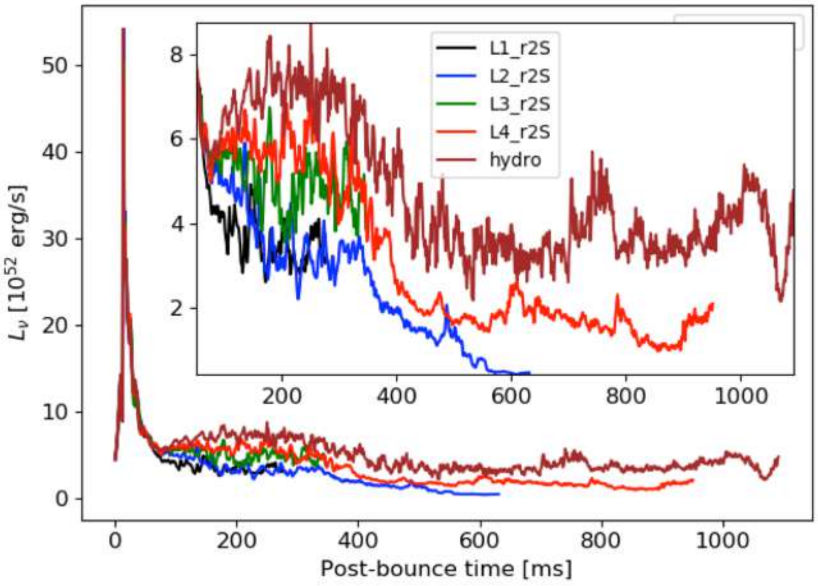
Gravitational waves from corotation instability





Bugli et al, in prep

Neutrino signature

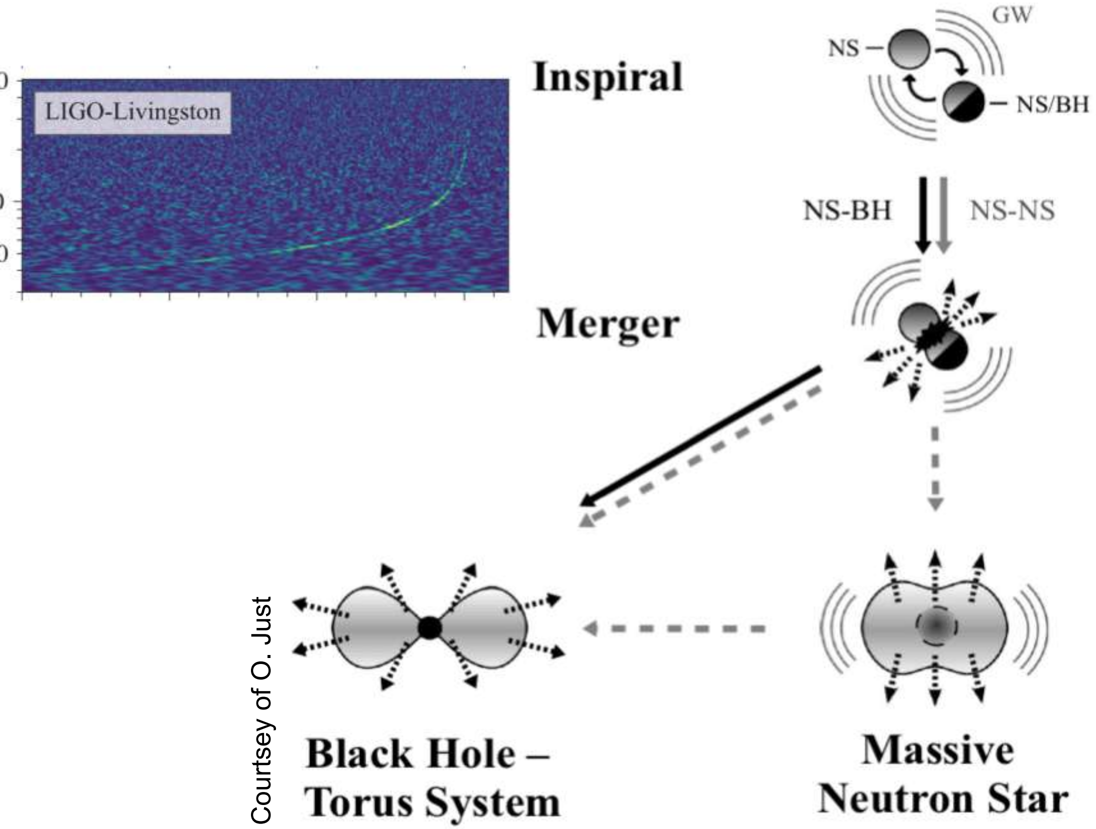


Bugli et al 2020

Detectability by current detectors

LEAK labex project

Neutron star mergers



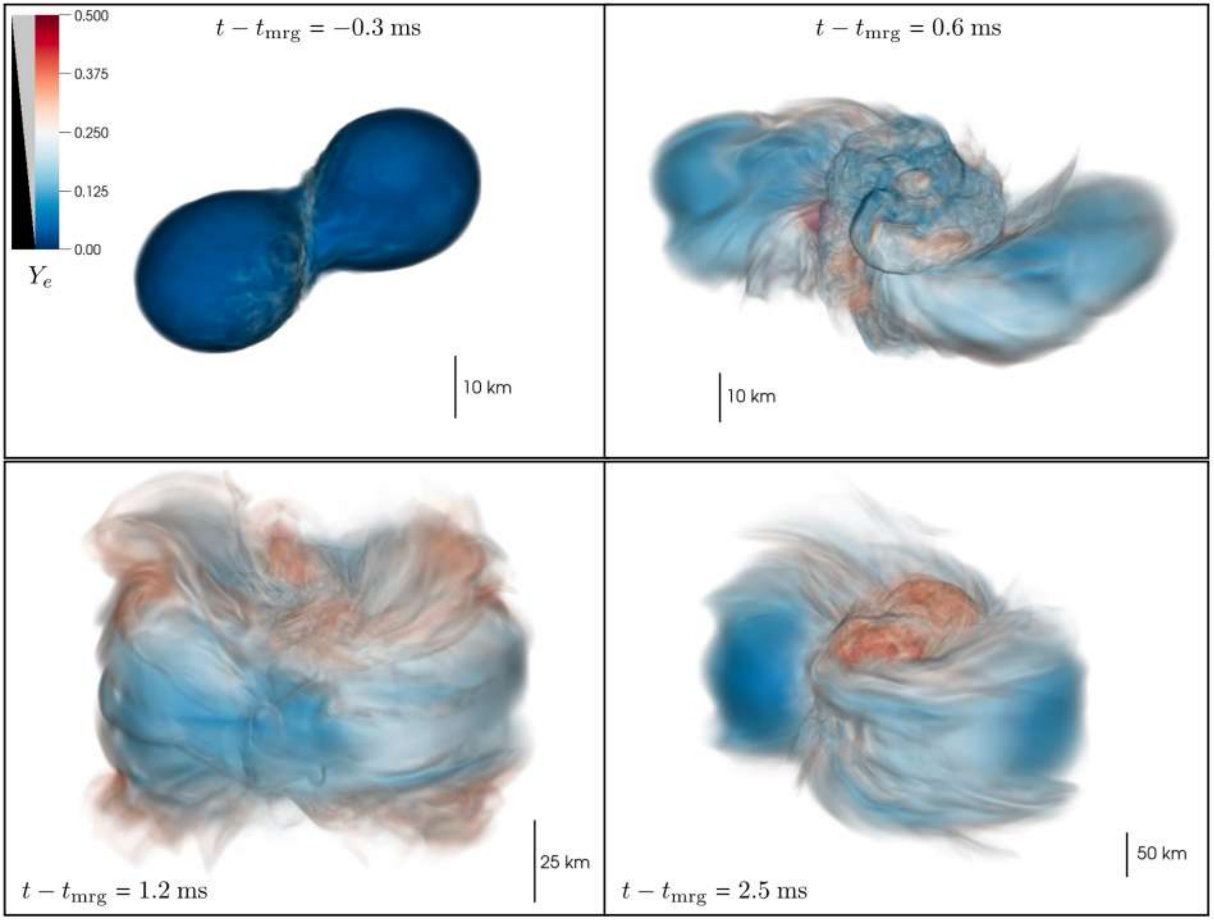
Courtsey of O. Just

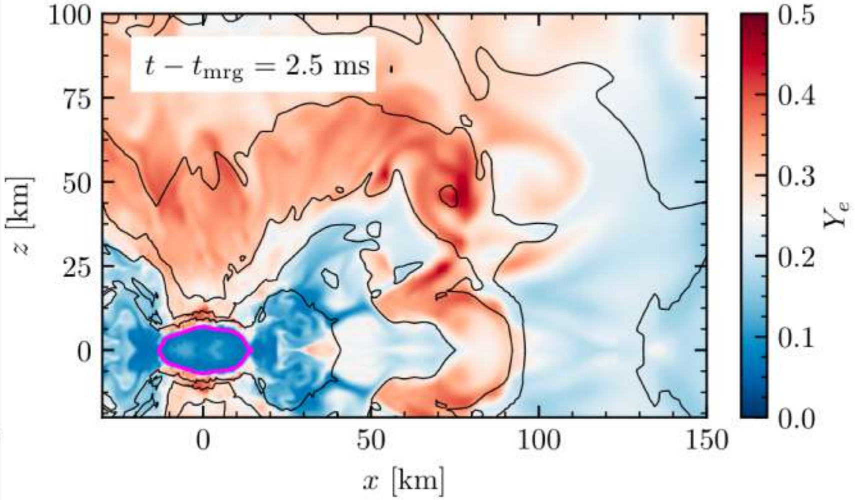
Same physical ingredients as in SN..
..but stronger general relativitic effects

3 possibilities :

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

Neutron star mergers: dynamics and ejecta



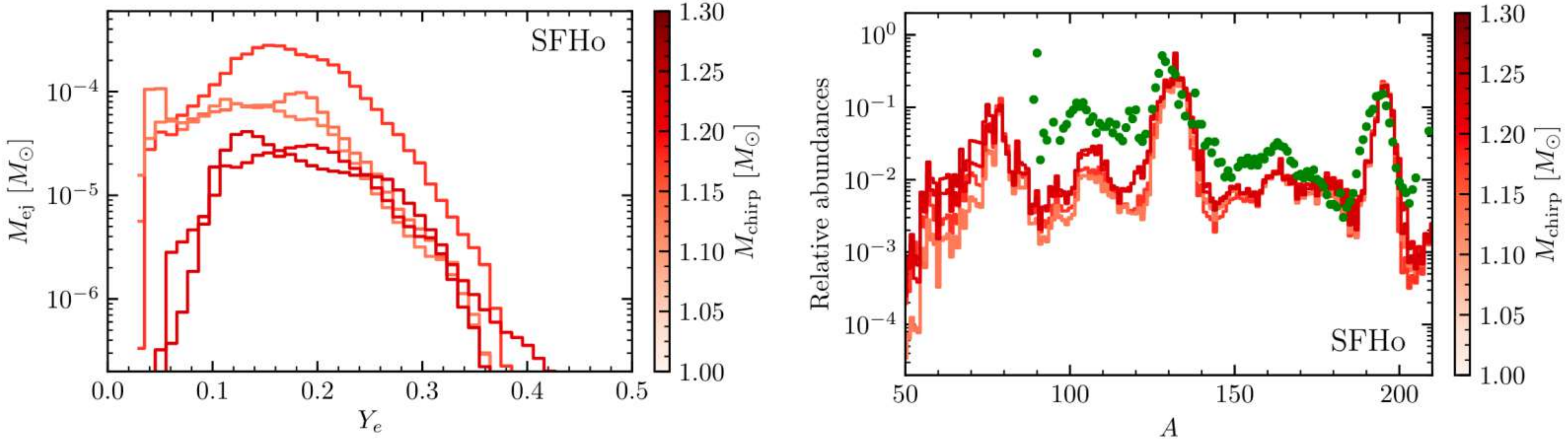


Several types of ejecta:

- Dynamical ejecta (low Ye)
- Neutrino/magnetic winds from disk or hypermassive neutron star (higher Ye)

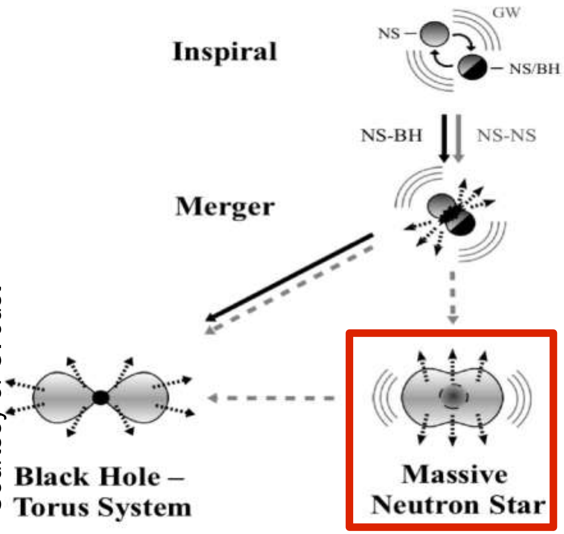
Radice+ 2018

Ejecta & nucleosynthesis



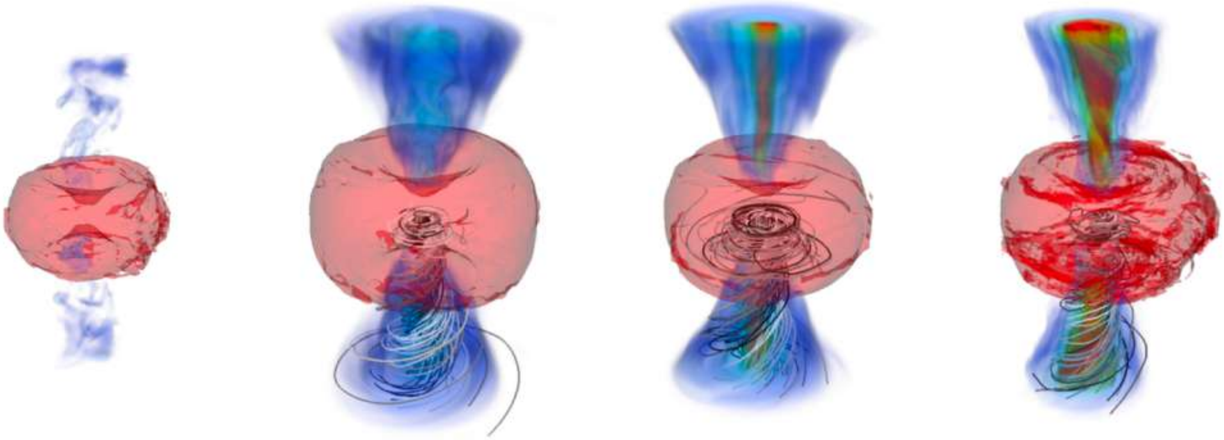
Radice+ 2018

A magnetar formed in NS mergers ?



Courtsey of O. Just

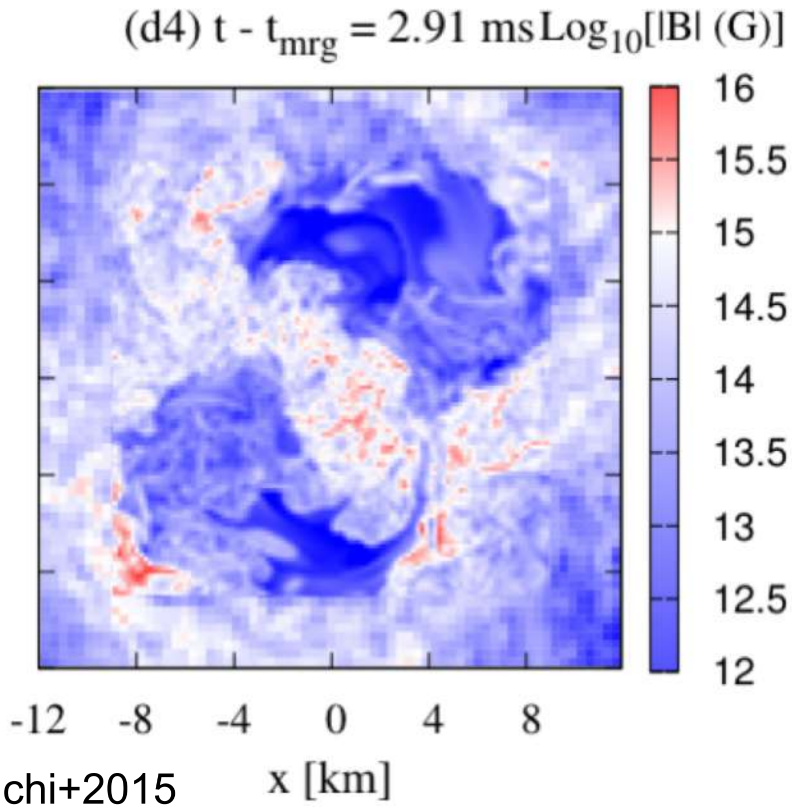
A magnetar as a central engine of short GRBs ?



Moesta+2020

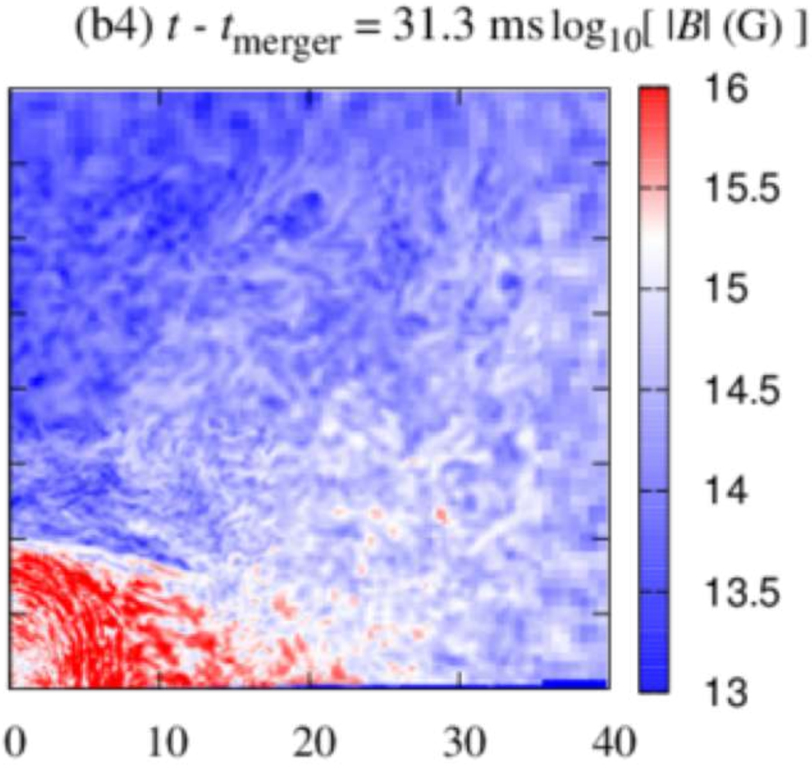
Magnetic field amplification => magnetar ?

Shear instability at interface



Kiuchi+2015

Magnetorotational instability



Big uncertainty: can this generate a strong large-scale magnetic field ?

Conclusions

Very rich and complex physics governs core collapse supernovae & neutron star mergers: MHD, general relativity, equation of state, neutrino cross sections, nucleosynthesis..

The neutrino-driven mechanism is the favored scenario to explain standard CCSN

Magnetorotational explosions are good candidate for extreme explosions

Neutron star mergers:

- robust source of r-process elements
- Magnetar or black hole as GRB central engine ?

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

Thank you !