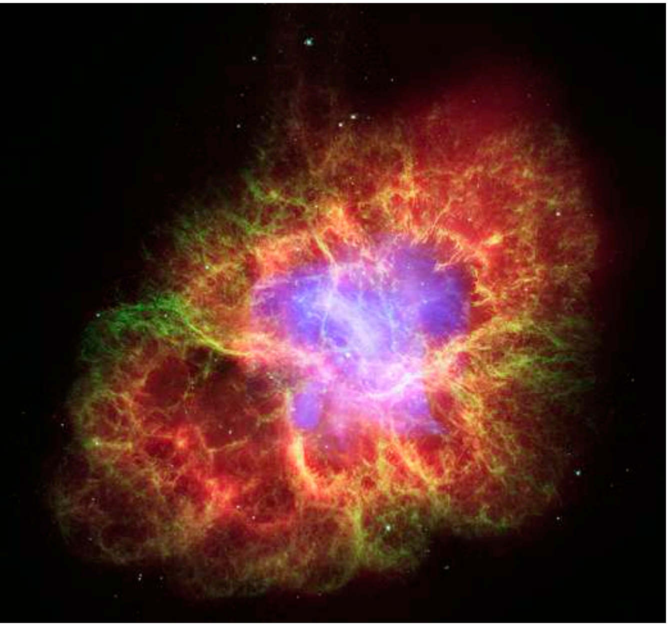
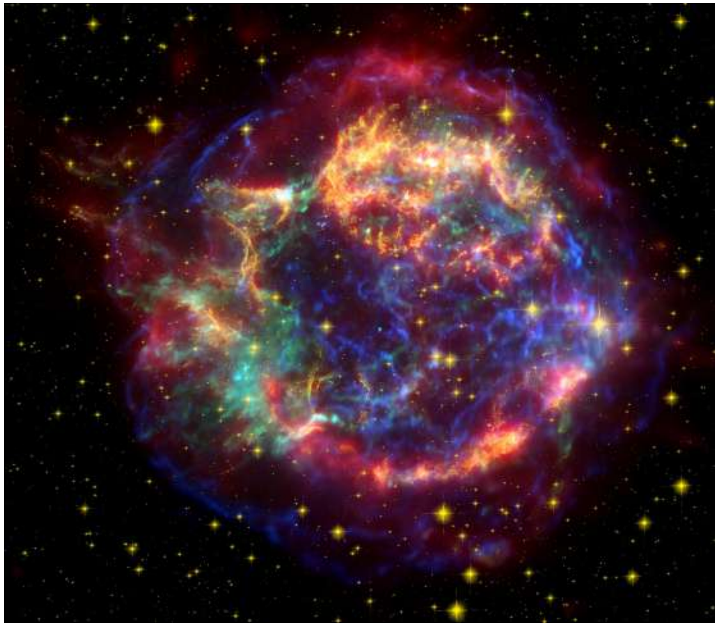
The physics of core collapse supernovae



Crab

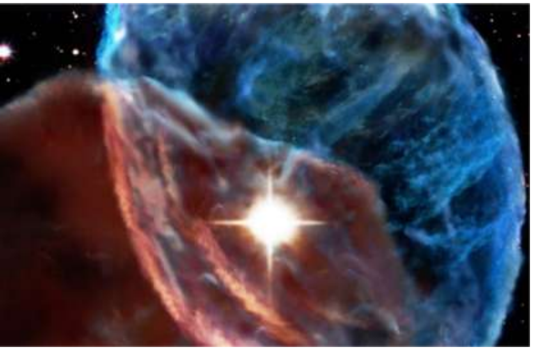
Jérôme Guilet
CEA Saclay,
Astrophysics Department



Cassiopeia A

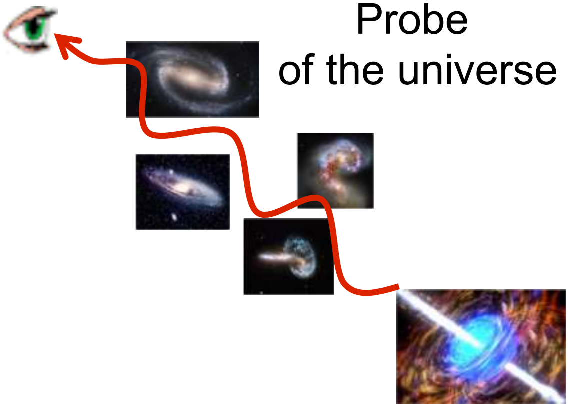
Importance of stellar explosions and compact objects

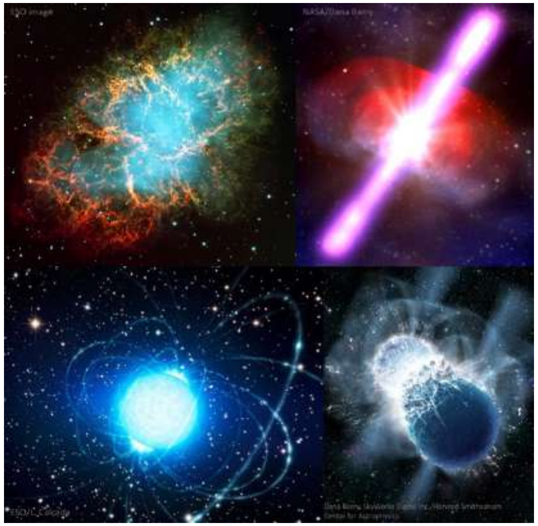
Kinetic energy injection in the instellar medium



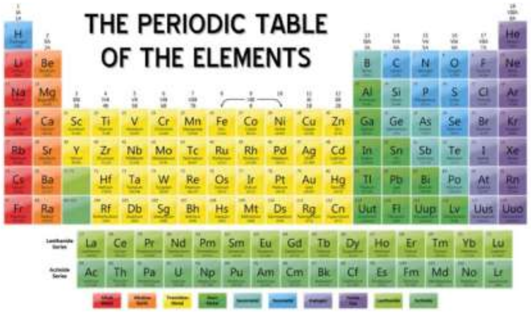
Cosmic ray acceleration

Probe
of the universe

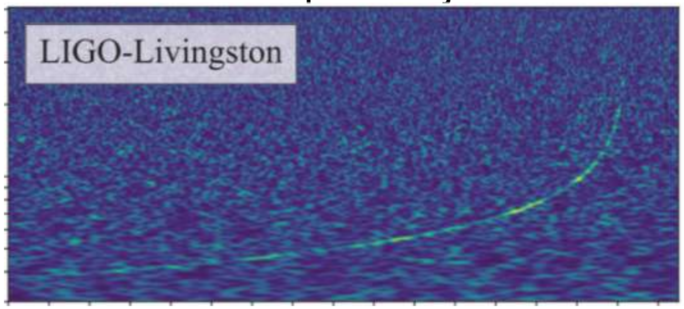




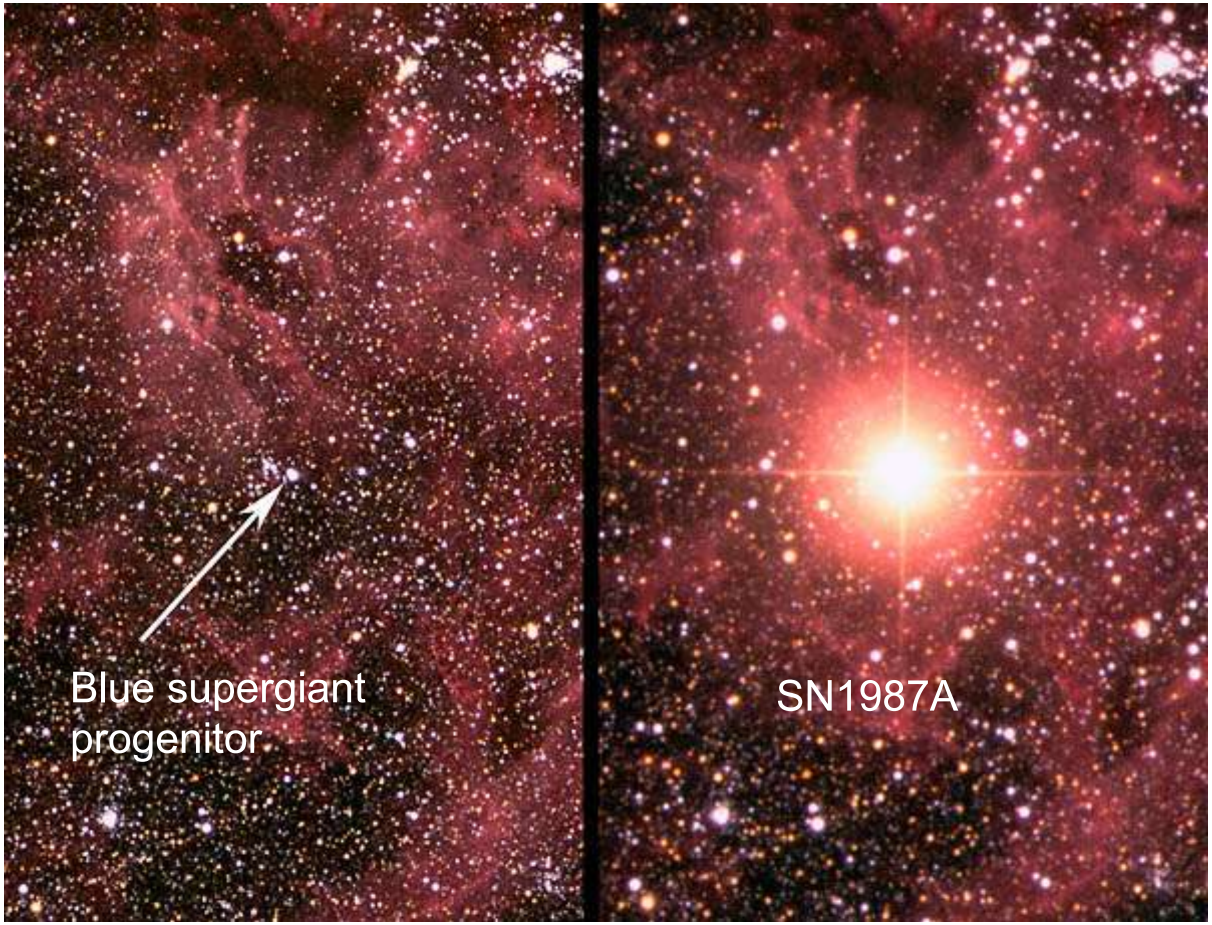
Source of heavy elements



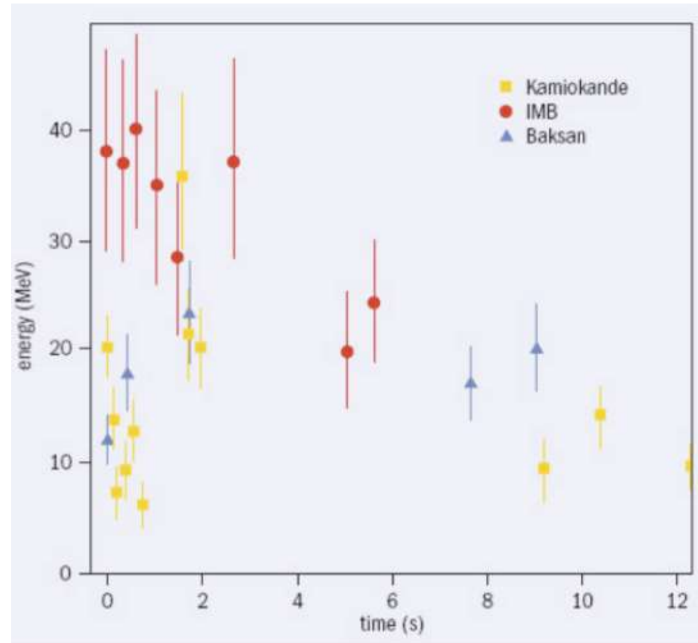
Birth and merger of
compact objects



Discovery of a supernovae



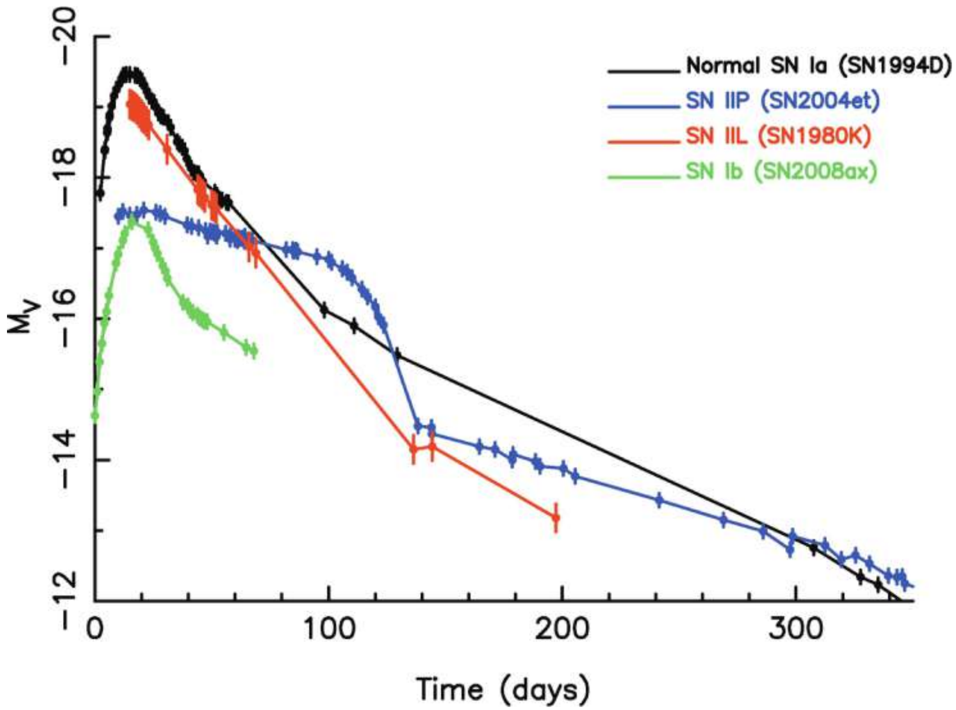
25 neutrinos detected



Nakahata 2007

SN1987A: last (almost) galactic SN (Large Magellanic Cloud)

Supernovae lighcurves

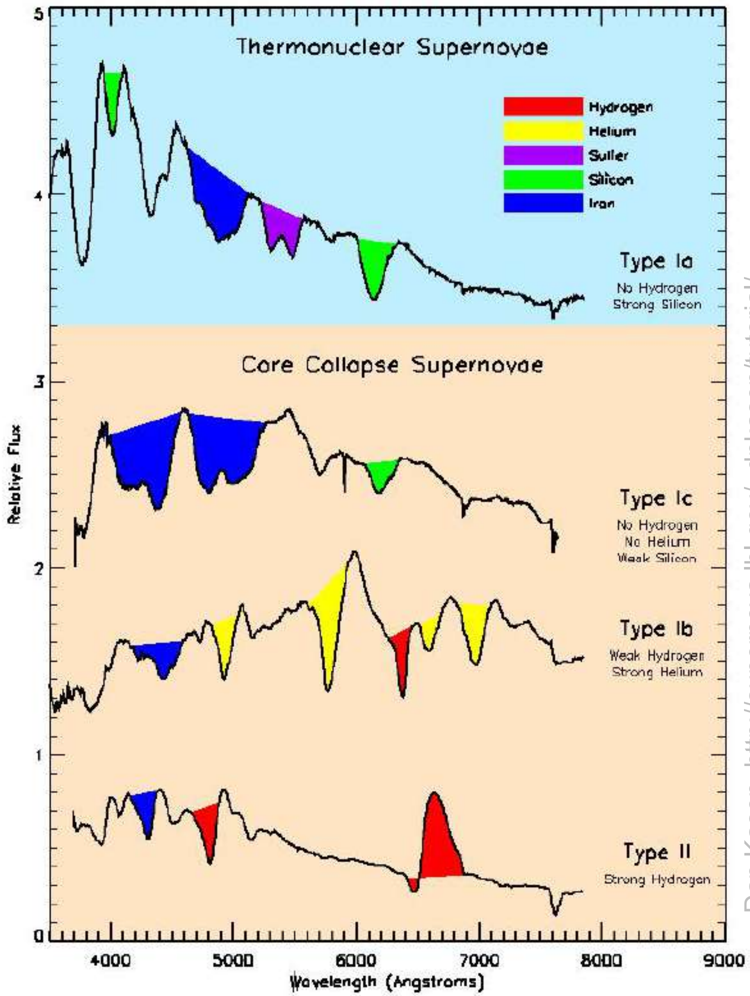


Vink 2020

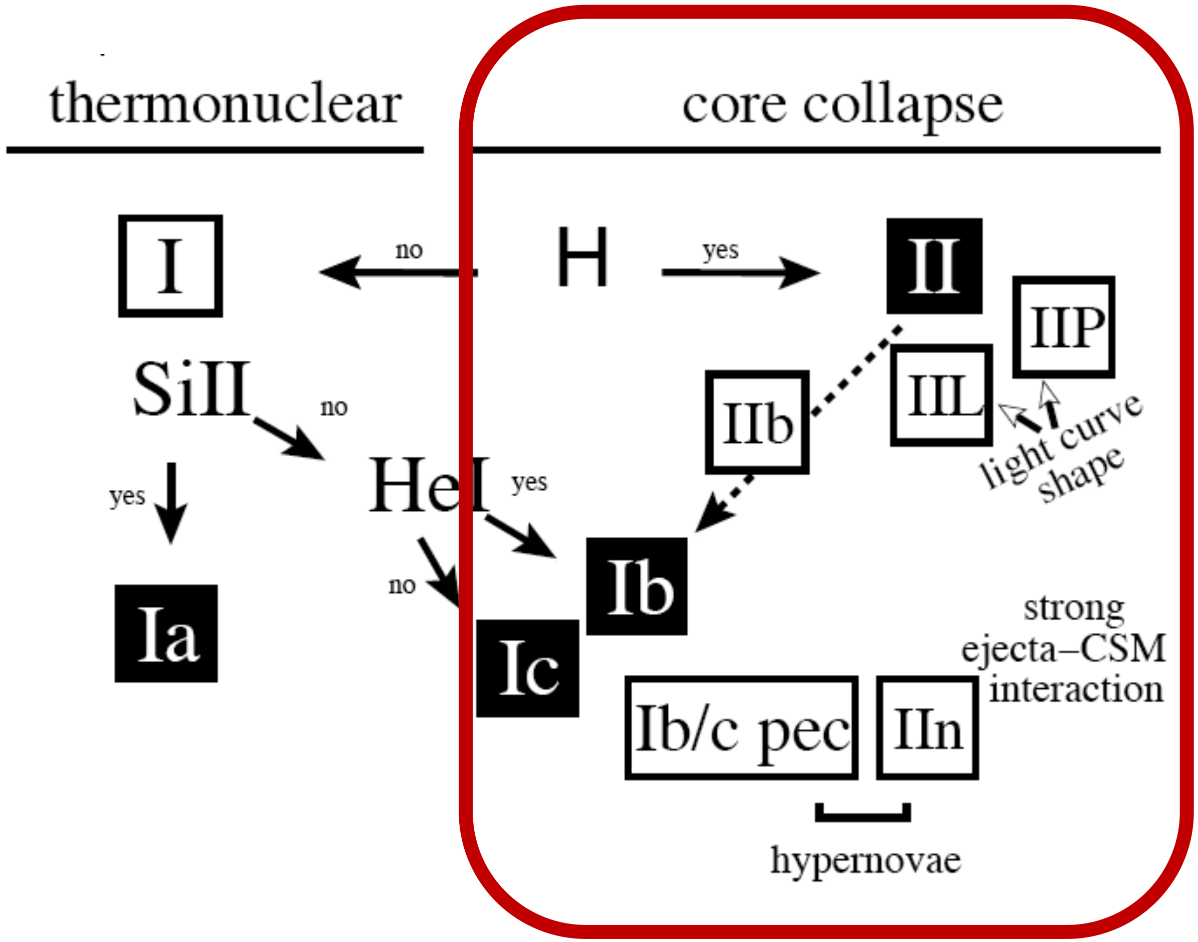
Energy injection by radioactive decay

$^{56}Ni \xrightarrow{6.1d} {}^{56}Co \xrightarrow{78.5d} {}^{56}Fe$

Supernova classification

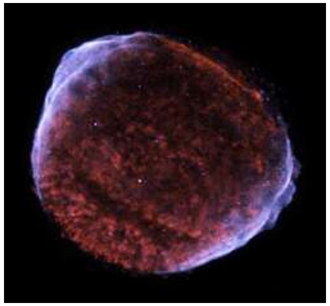


Dan Kasen, http://supernova.lbl.gov/~dnkasen/tutorial/

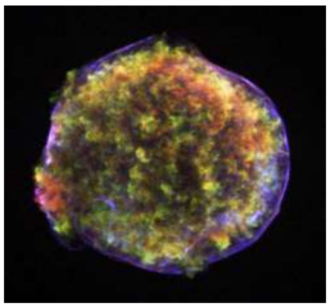


Turatto 2003

Supernovae remnants



SN 1006

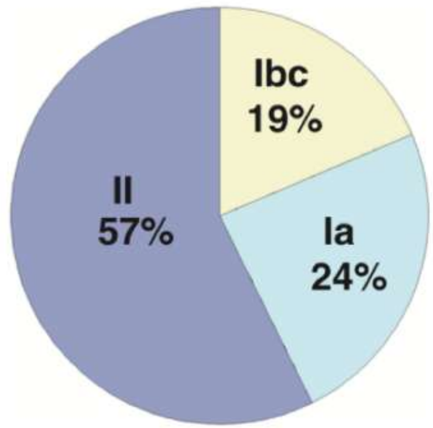


Tycho (1572)

Kepler (1604)

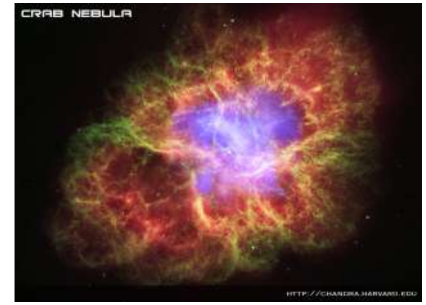
thermonuclear
supernovae
Ia

gravitational
supernovae
II, Ibc

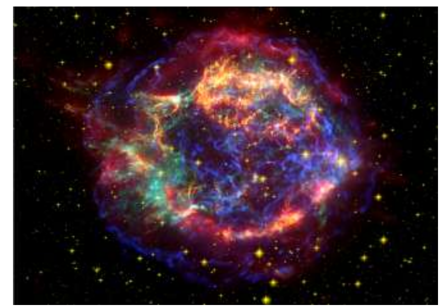


Volume distribution

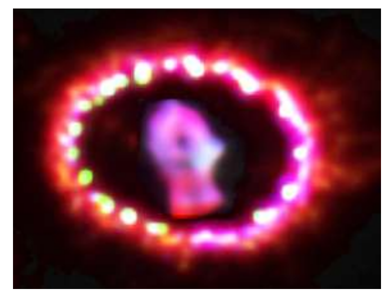
(Li+11)



Crab (1054)



Cassiopeia A (~1680)



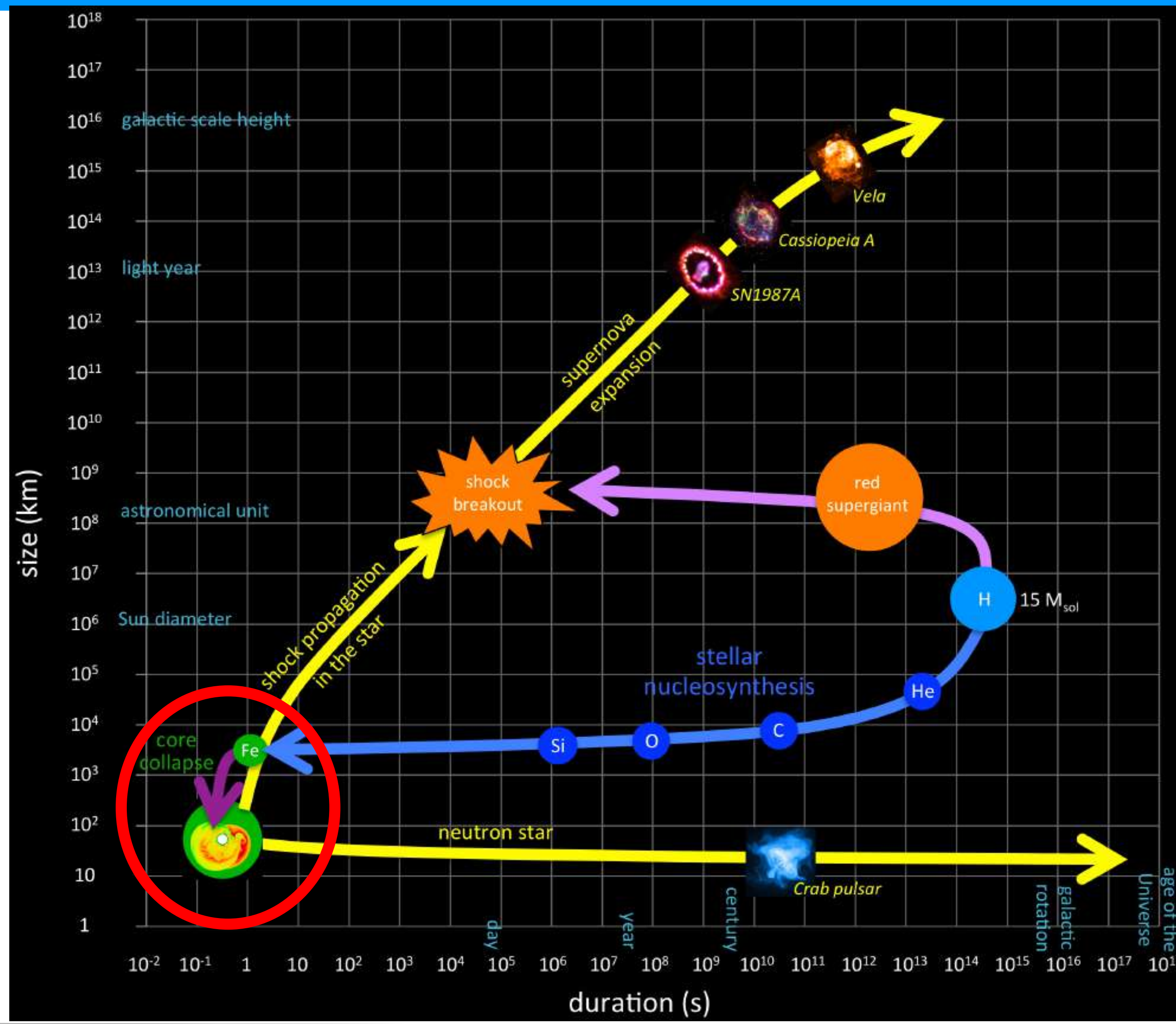
SN1987A

Life and death of a star: different time and spatial scales

Electromagnetic observations : days to centuries

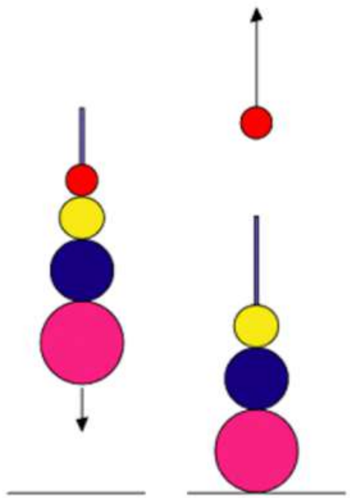
Explosion engine :~ 1 second

=> Direct probe with multimessenger observations : neutrinos & gravitational waves



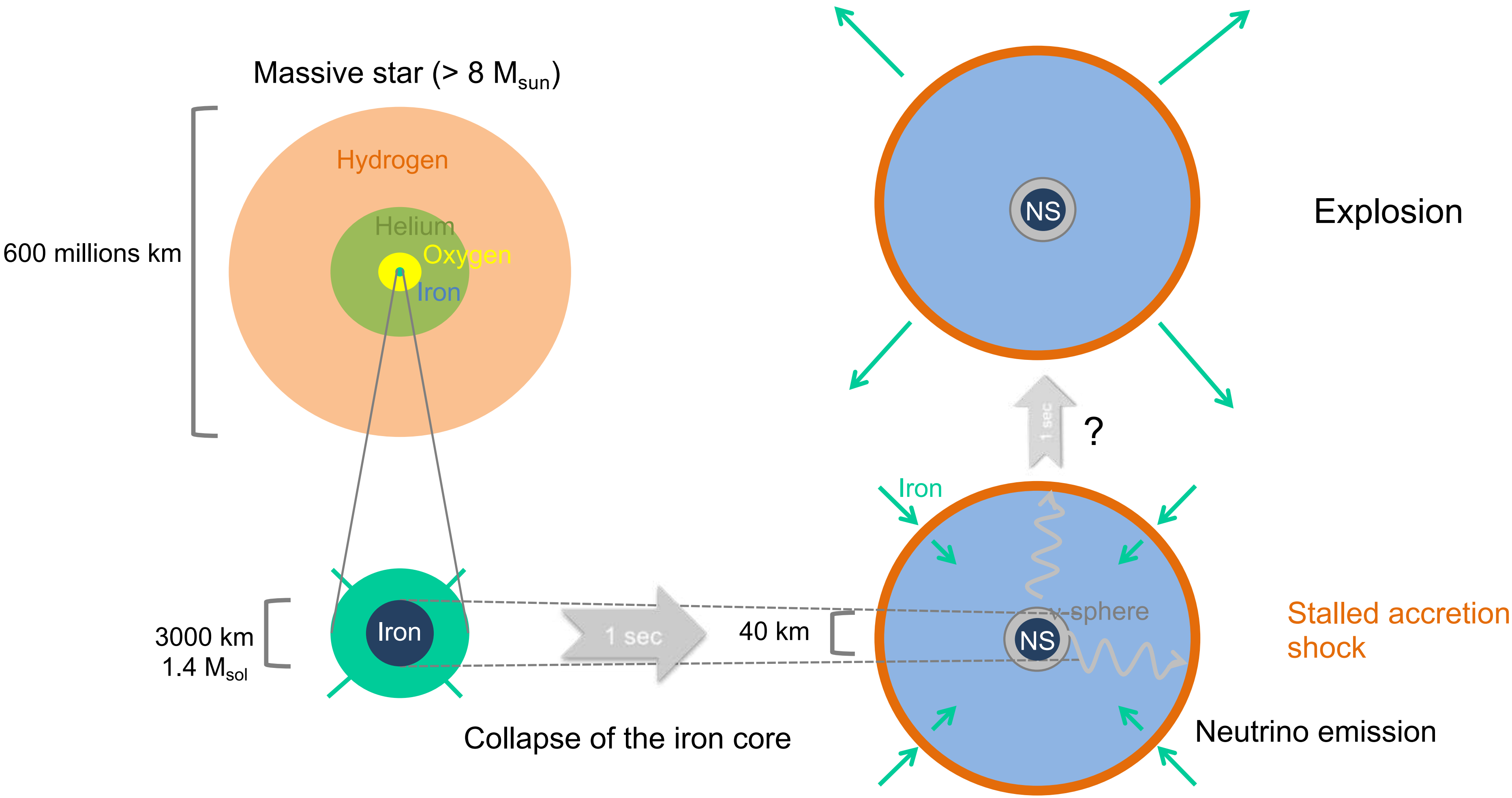
Courtesy of T Foglizzo

How can a collapse turn into an explosion ?



AstroBlaster
invented by
Stirling Colgate

Core collapse: formation of a neutron star



Proposed explosion mechanisms

Neutrino-driven explosions : favored mechanism for standard SNe

→ today's lecture (and start of tomorrow)

Magnetorotational explosions : need fast rotating progenitors ⇨ extreme events ?

→ tomorrow's lecture

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

A multi-physics problem

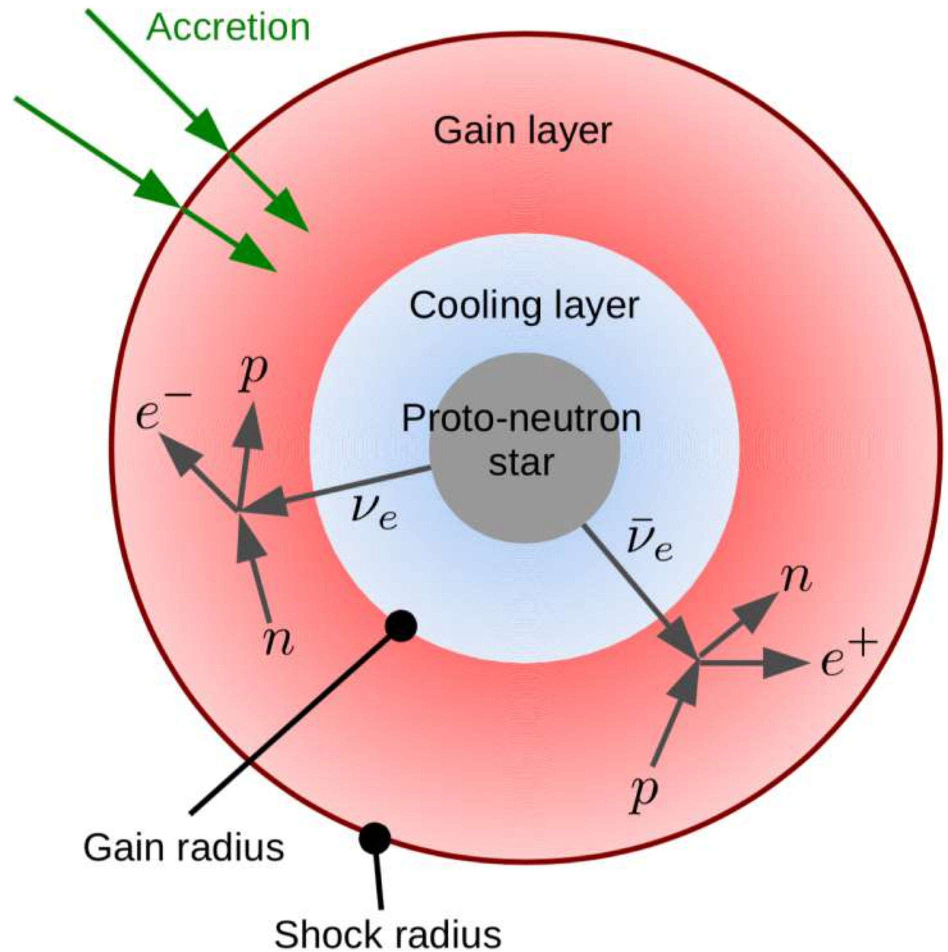
- General relativity

- Ultra-high density equation of state

- Neutrino-matter interactions
  sophisticated transport schemes

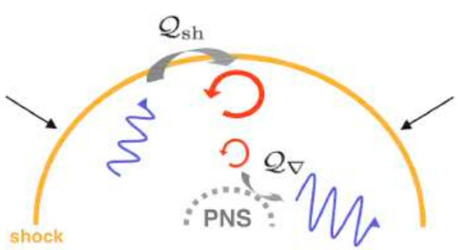
- Multi-dimensional hydrodynamics (instabilities, turbulence..)

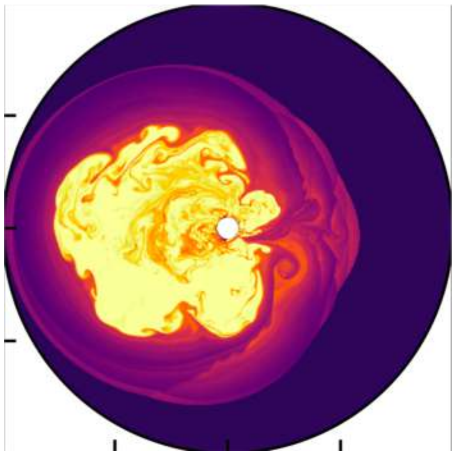
- Magnetic field



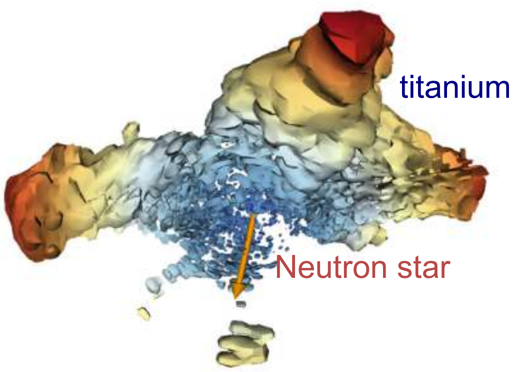
To simplify or not to simplify

Analytical studies	Simplified numerical simulations	« Realistic » numerical simulations	Observations

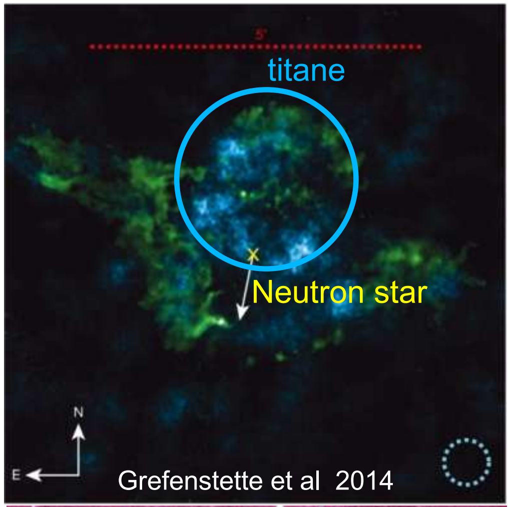


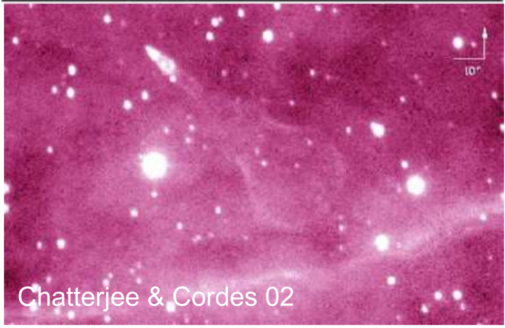


B. Pagani PhD thesis



Wongwathanarat et al 2016





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: $\mathrm{kT} \approx 10^5 - 10^7\ MeV$
- 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

Structure of the accretion flow before explosion

The composition of the infalling gas changes:

-across the shock, heavy nuclei are dissociated into nucleons

$$^{56}\mathrm{Fe} + 56 \times 8.8\mathrm{MeV} \rightarrow 26p + 30n + 26e$$

-in the gain region, neutrons and protons intercept some neutrinos

$$n + \nu_{\mathrm{e}} \rightarrow p^{+} + e^{-}$$

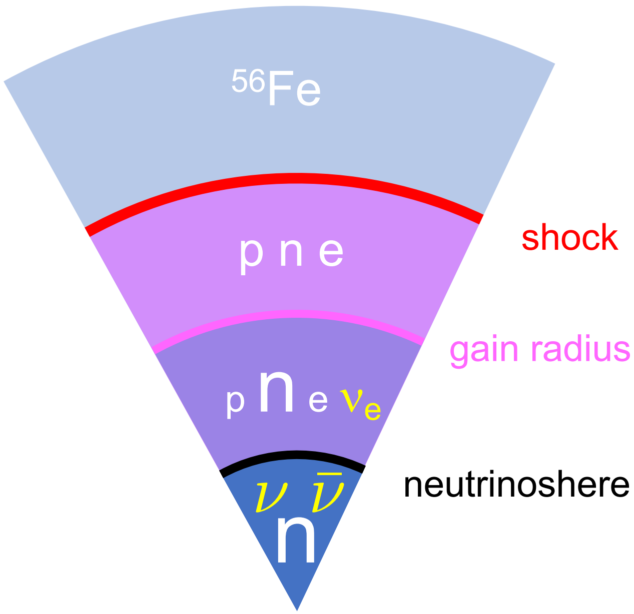
$$p^{+} + \bar{\nu}_{\mathrm{e}} \rightarrow n + e^{+}$$

-below the gain radius, protons & electrons turn into to neutrons & neutrinos near the proto-neutron star,

$$p^{+} + e^{-} \rightarrow n + \nu_{\mathrm{e}}$$

- inside the neutrinosphere, a thermal bath of neutrons, protons, neutrinos and anti-neutrinos

$$e^{-} + e^{+} \leftrightarrow \nu_{\mathrm{e}} + \bar{\nu}_{\mathrm{e}}$$



Criterion for neutrino-driven explosions

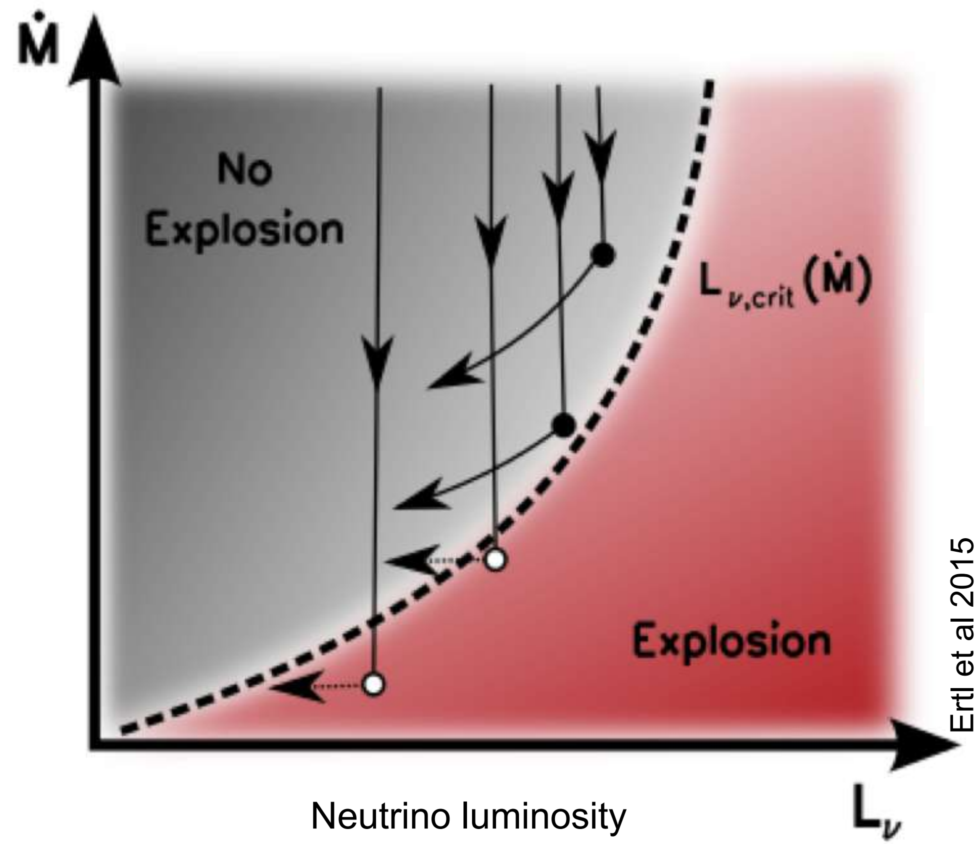
Explosion determined by a competition between
- neutrino heating
- ram pressure due to accretion

➡ Critical neutrino luminosity

Proposed explosion criterion:

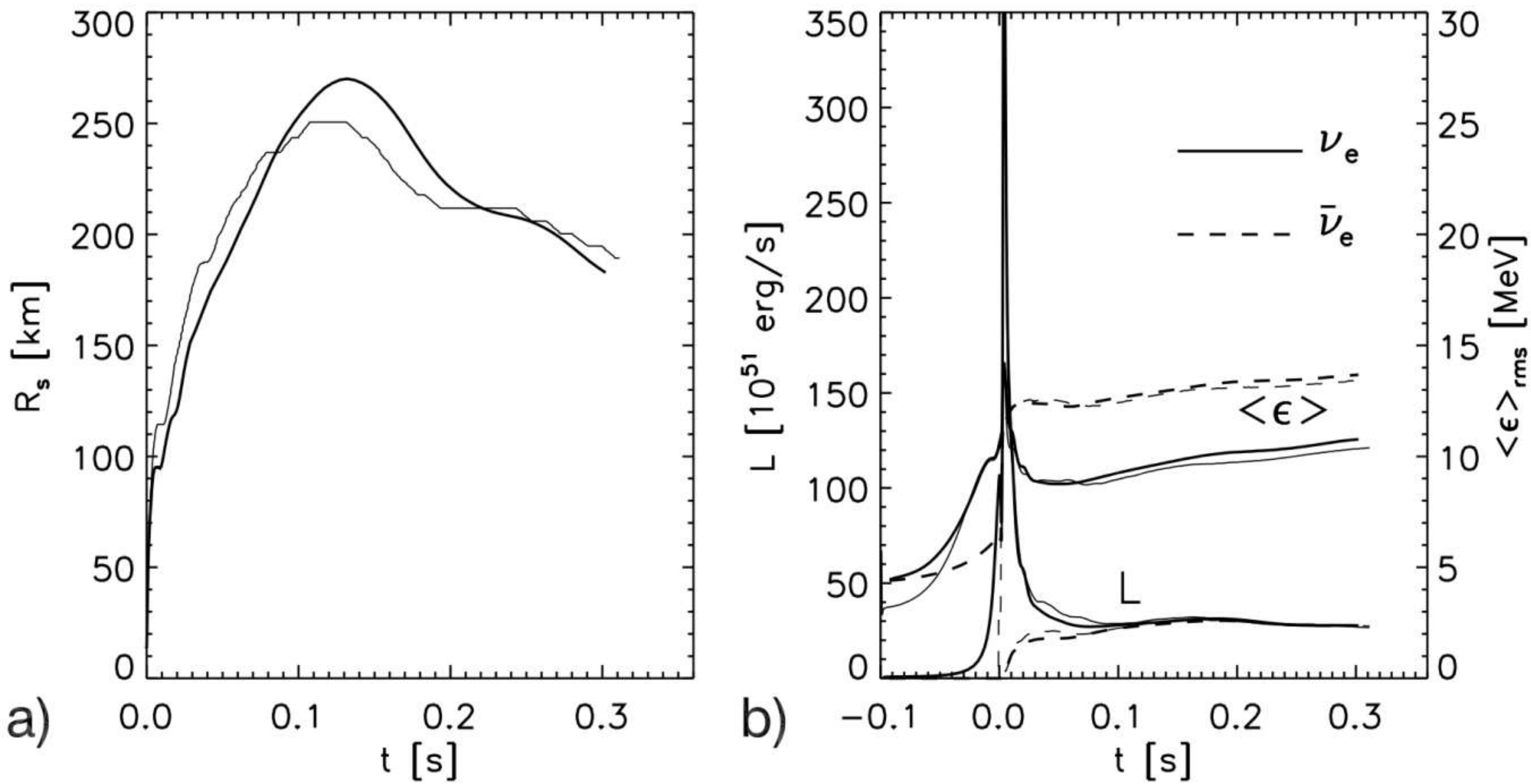
heating time < advection time

Mass accretion rate



Neutrino luminosity

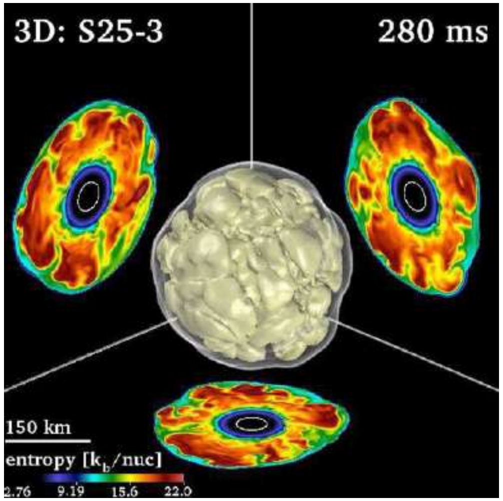
No explosion in 1D spherical symmetry



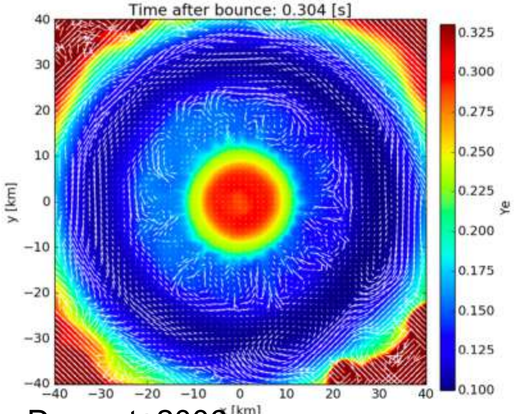
Liebendorfer et al 2005

Missing ingredient : hydrodynamic instabilities

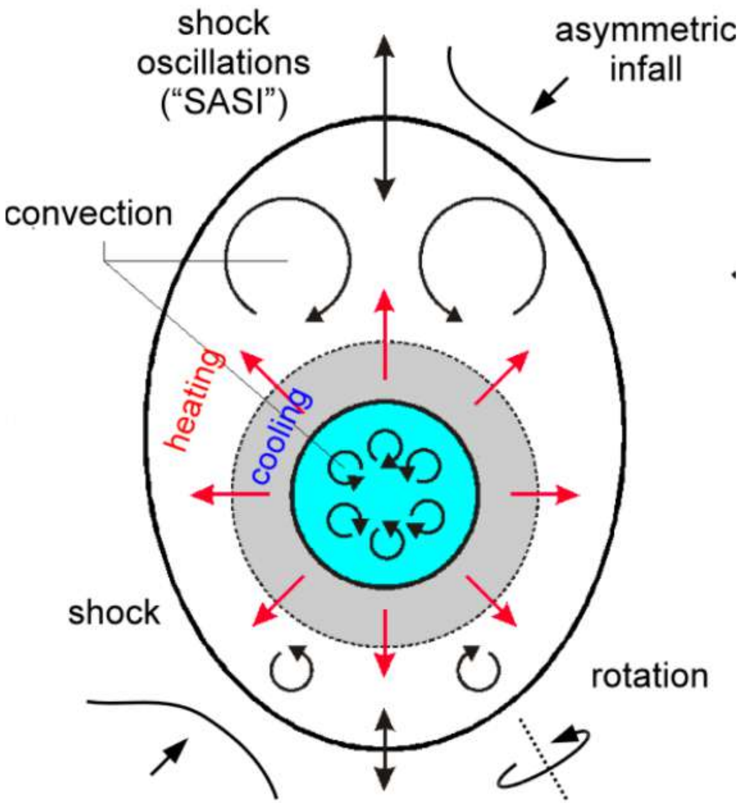
Neutrino-driven convection



Protoneutron star convection

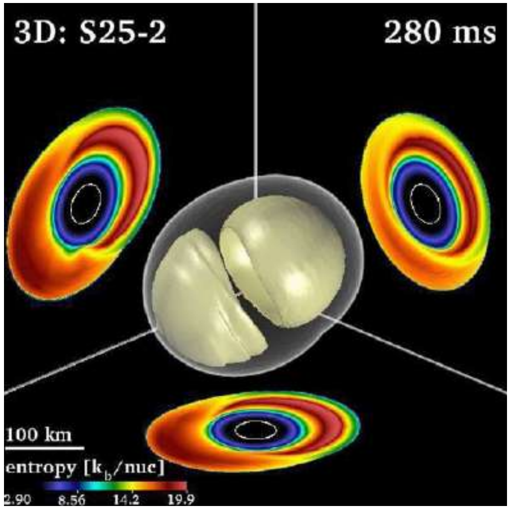


Dessart+2006



Mueller 2020

Standing Accretion Shock Instability (SASI)



Hanke+2013

Convection instability criterion

Ledoux criterion

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

entropy gradient

lepton fraction gradient

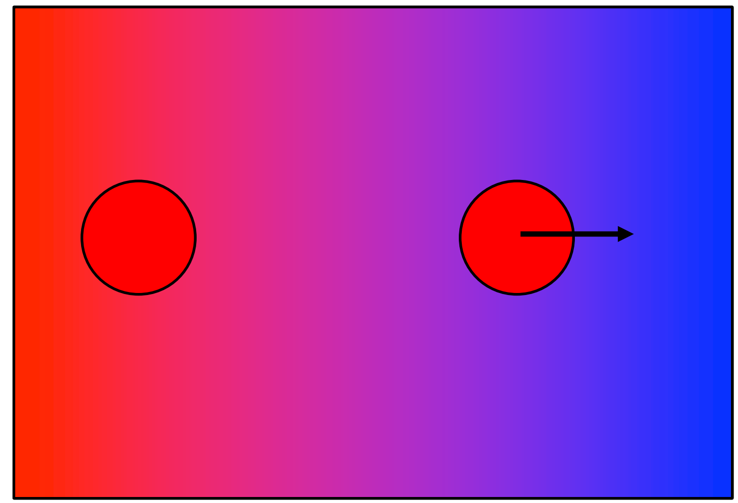
determined by neutrino transport (& turbulence)

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

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

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

determined by EOS



$N^2 \lessgtr 0$

radial displacement favored / suppressed

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

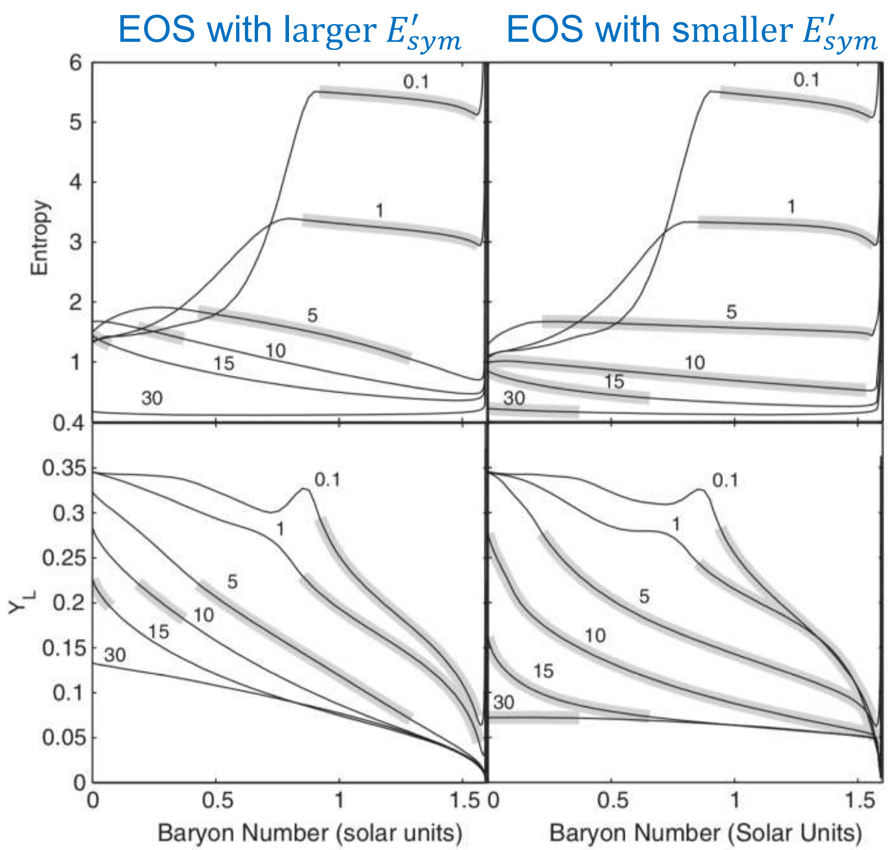
lepton fraction

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

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

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

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



Roberts+2012

Motions transport heat and leptons

=> faster cooling and deleptonization of the protoneutron star

Neutrino-driven convection: heating vs advection

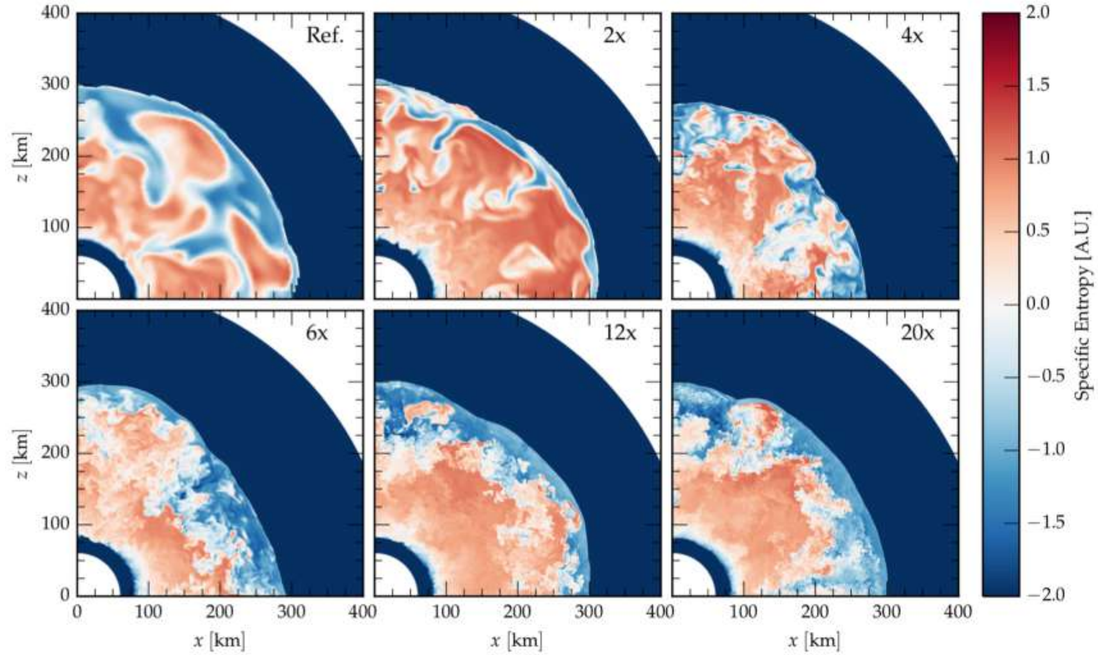
Unstable entropy gradient driven by neutrino heating

Advection tends to stabilize convection

New instability criterion:

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

Foglizzo+2006



Radice+2016

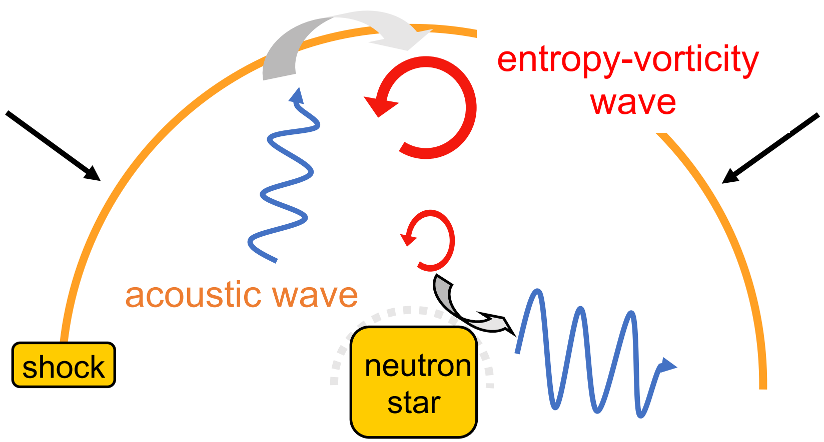
Linear instability for chi > 3

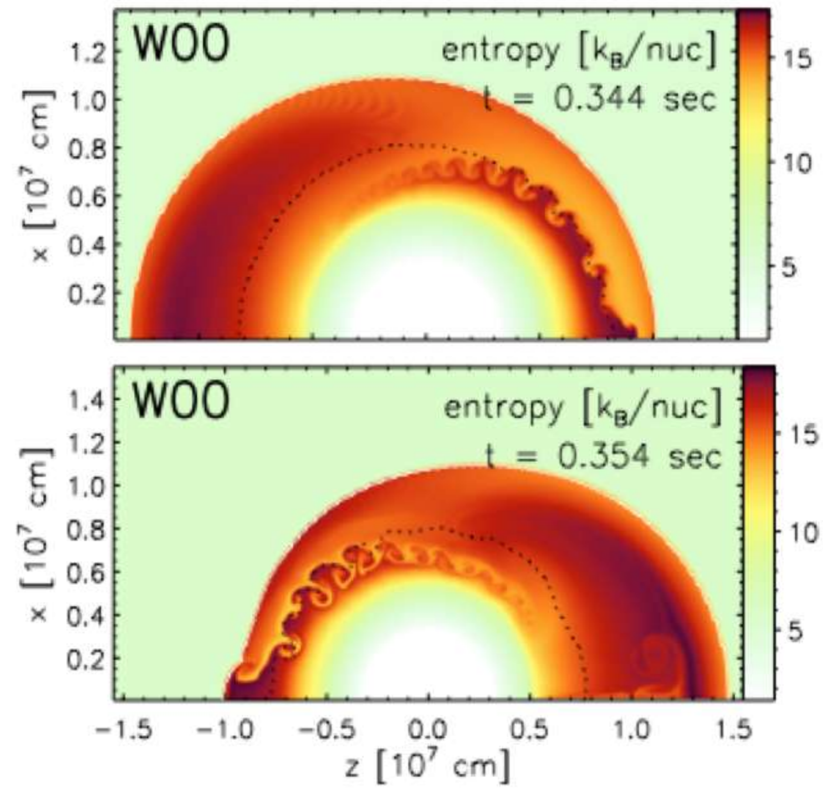
For chi < 3, convection can be non-linearly excited but not self-sustained
Kazeroni+2018

The Standing Accretion Shock Instability (SASI)

Advective-acoustic cycle

Foglizzo *et al* 2007, Guilet & Foglizzo 2012



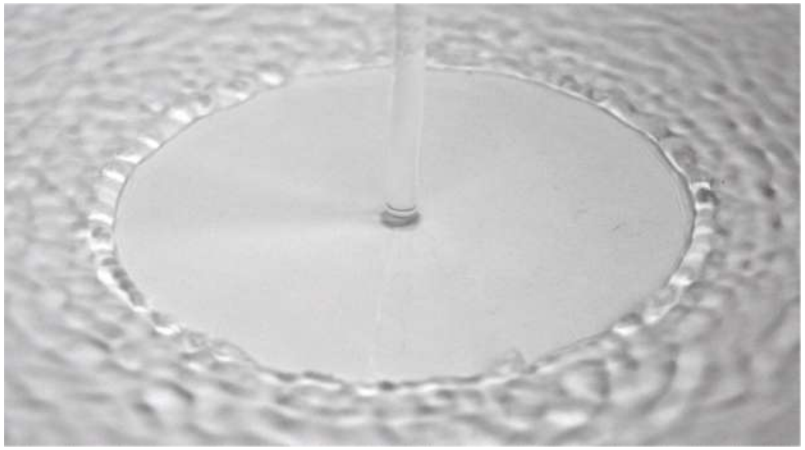


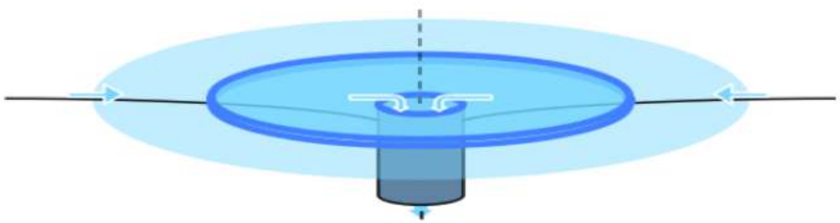
Scheck et al 2008

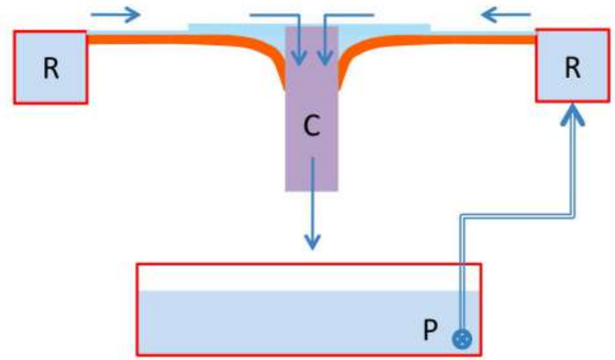
Large-scale shock oscillations : spherical harmonics l=1-2

SWASI : Shallow Water Analogue of a Shock Instability

Kitchen sink hydraulic jump







acoustic waves
shock wave
pressure

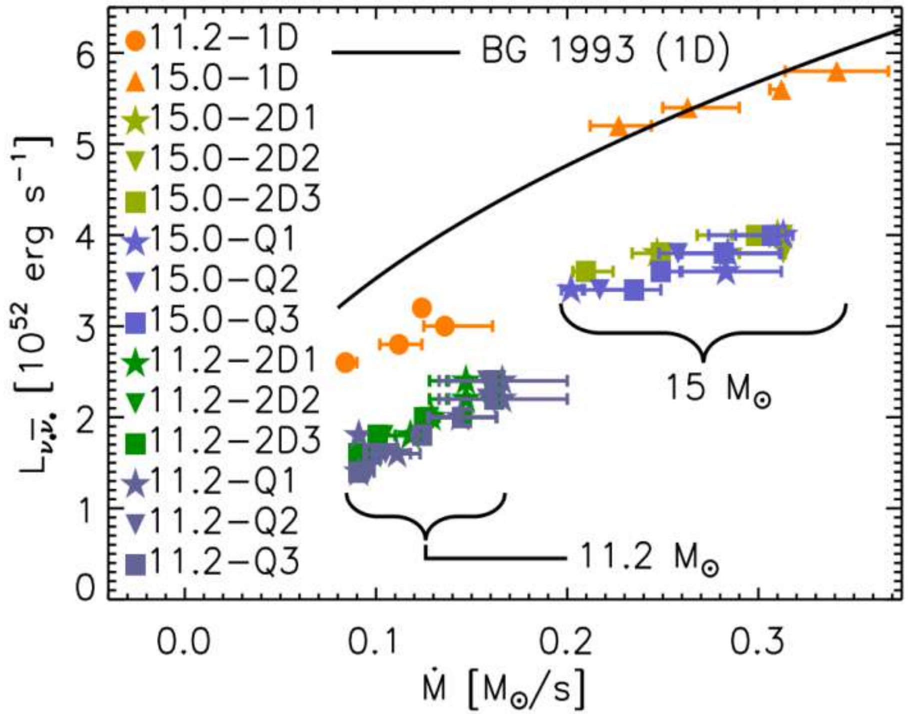
↔

surface wave
hydraulic jump
depth

Explosions are easier in multi-dimensions

Neutrino-driven explosions are aided by hydrodynamic instabilities:

Critical neutrino luminosity is lower than in 1D simulations

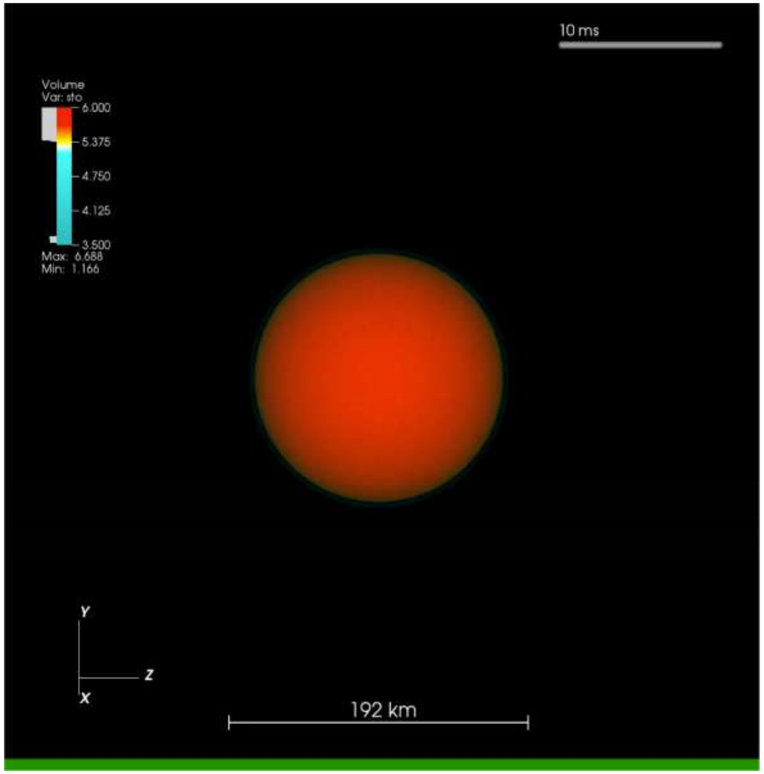


Murphy & Burrows 08

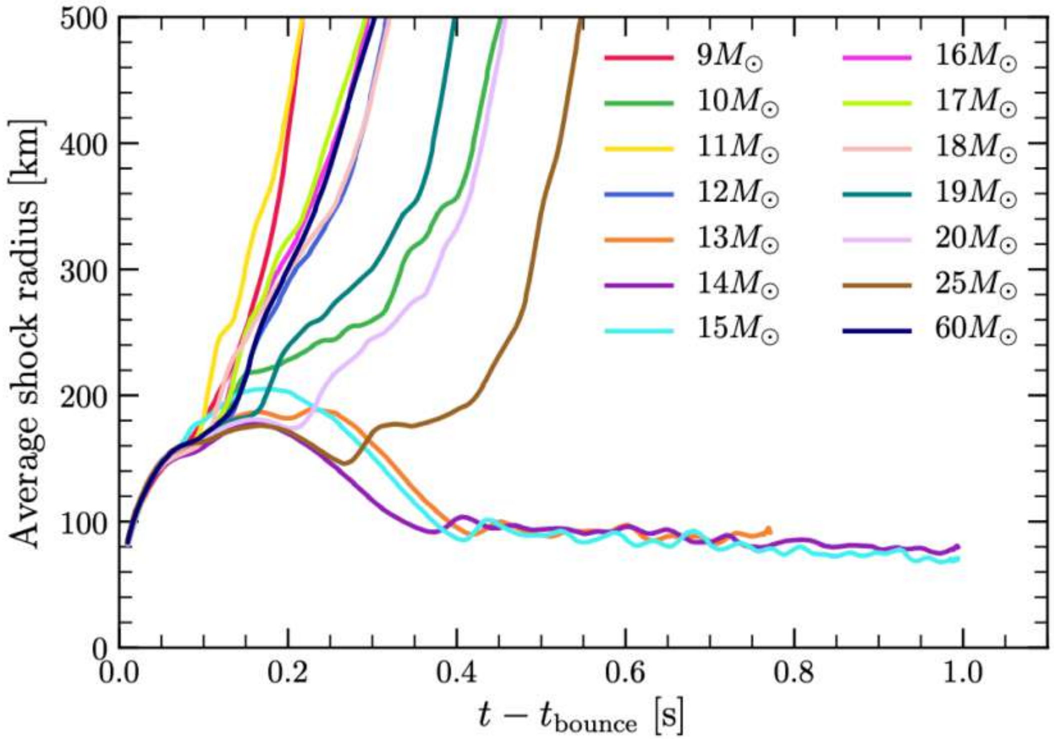
How SASI and convection help explosion:

- Turbulent pressure pushes the shock
- Increase of the heating efficiency: more time spent in the gain region

Successful explosions in 3D simulations (finally)



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



Burrows et al 2019

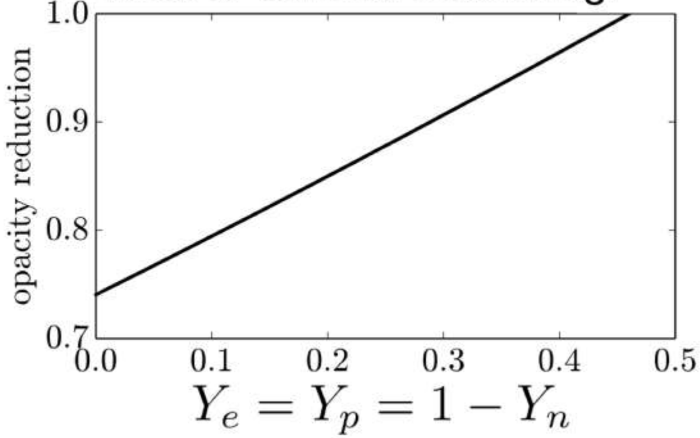
Obtaining robust explosions was a long standing difficulty
Now many groups commonly obtain 3D explosions

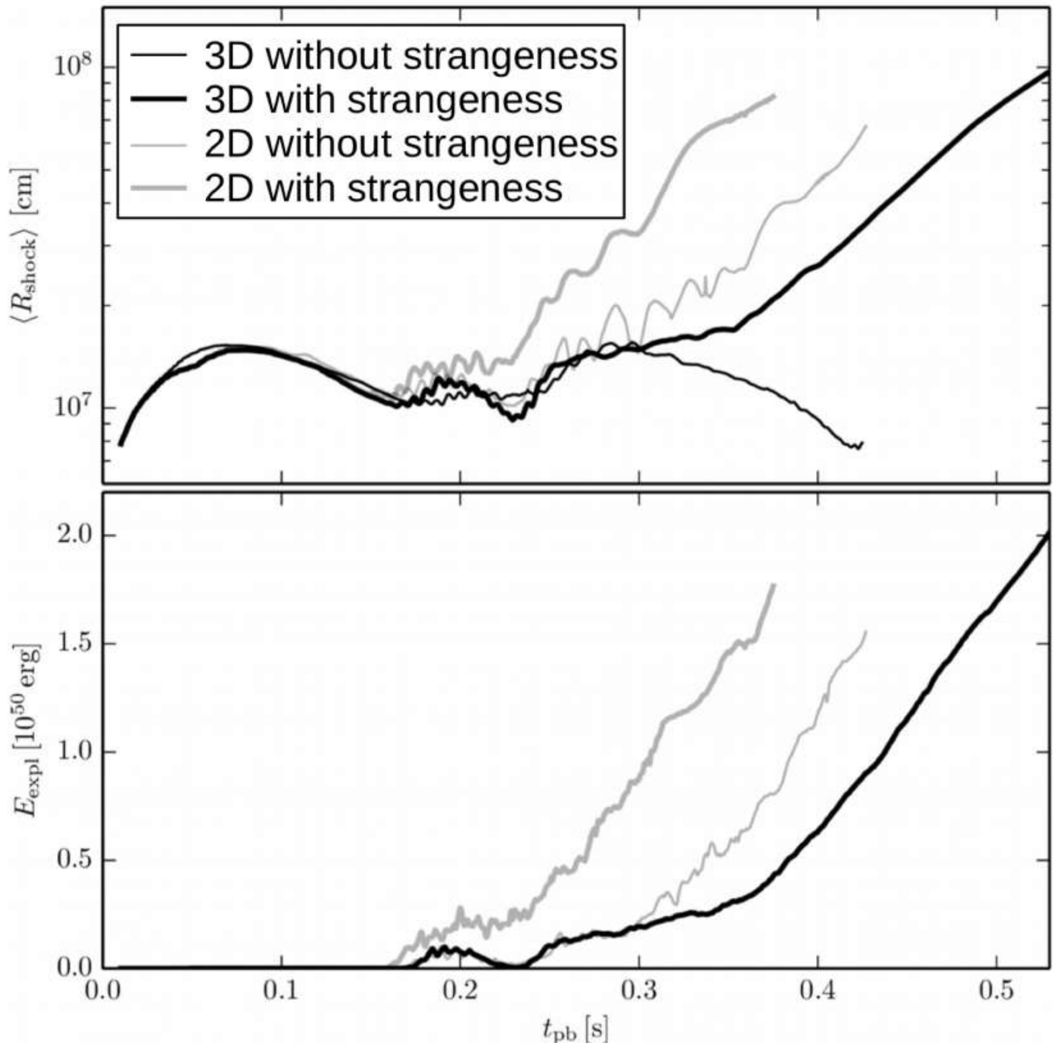
Sensitivity to neutrino-matter interactions

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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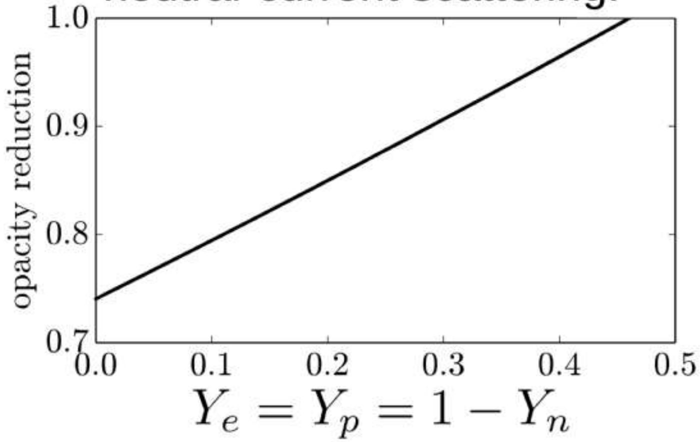
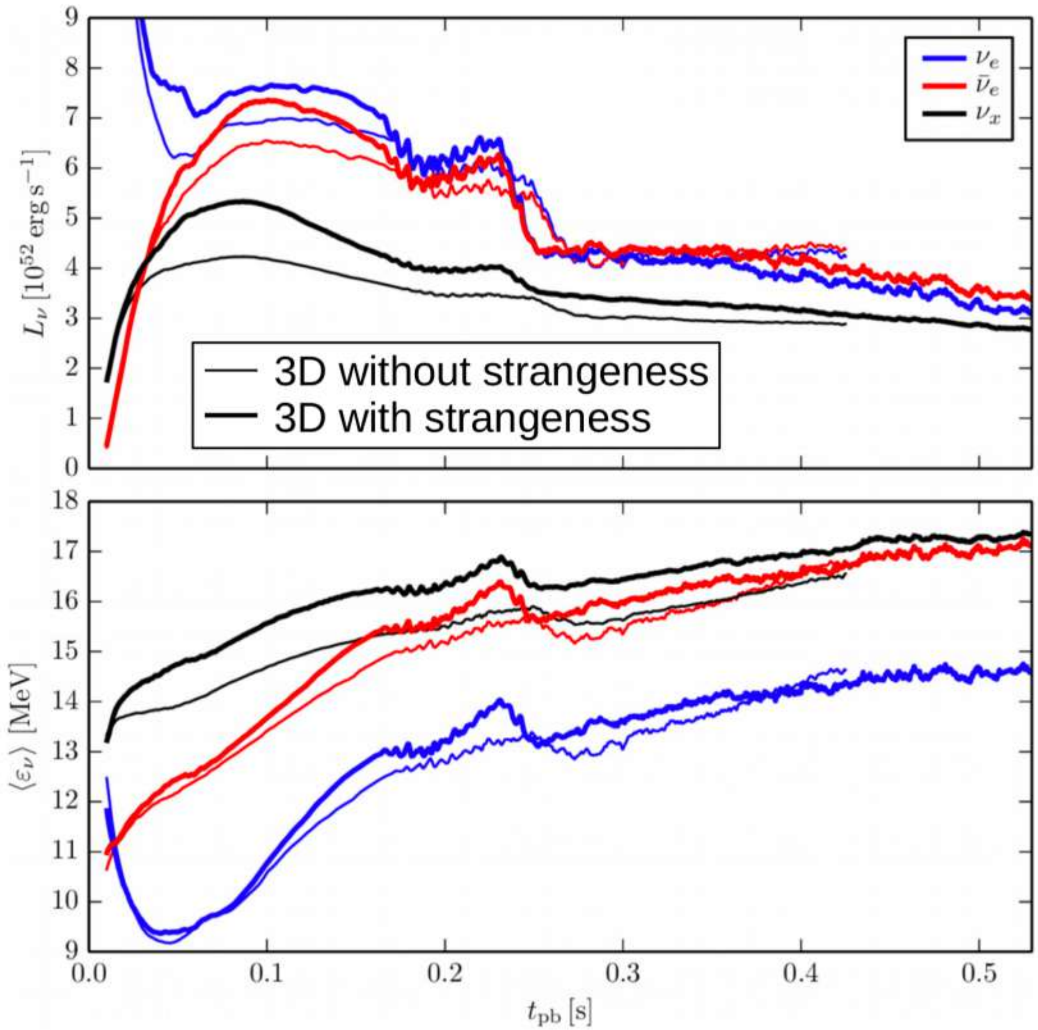


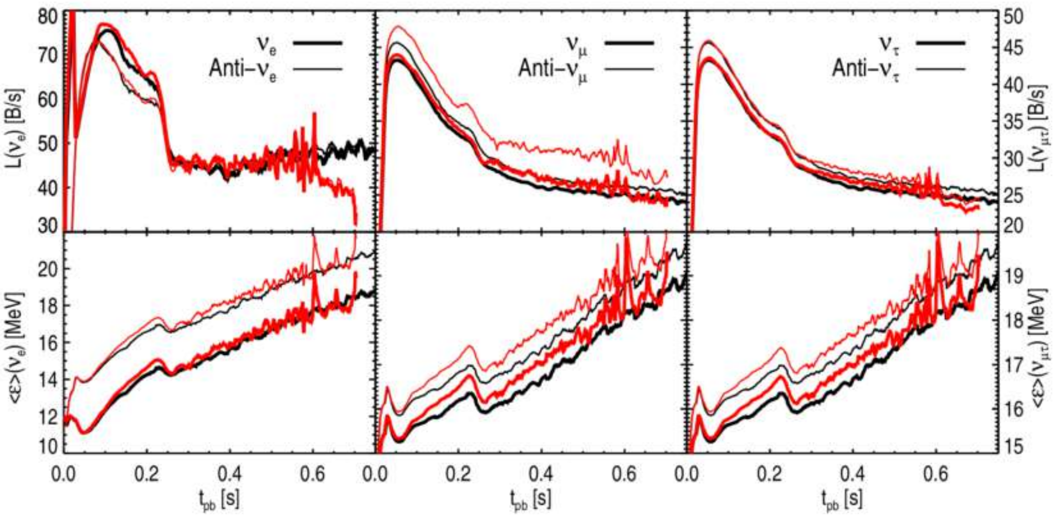


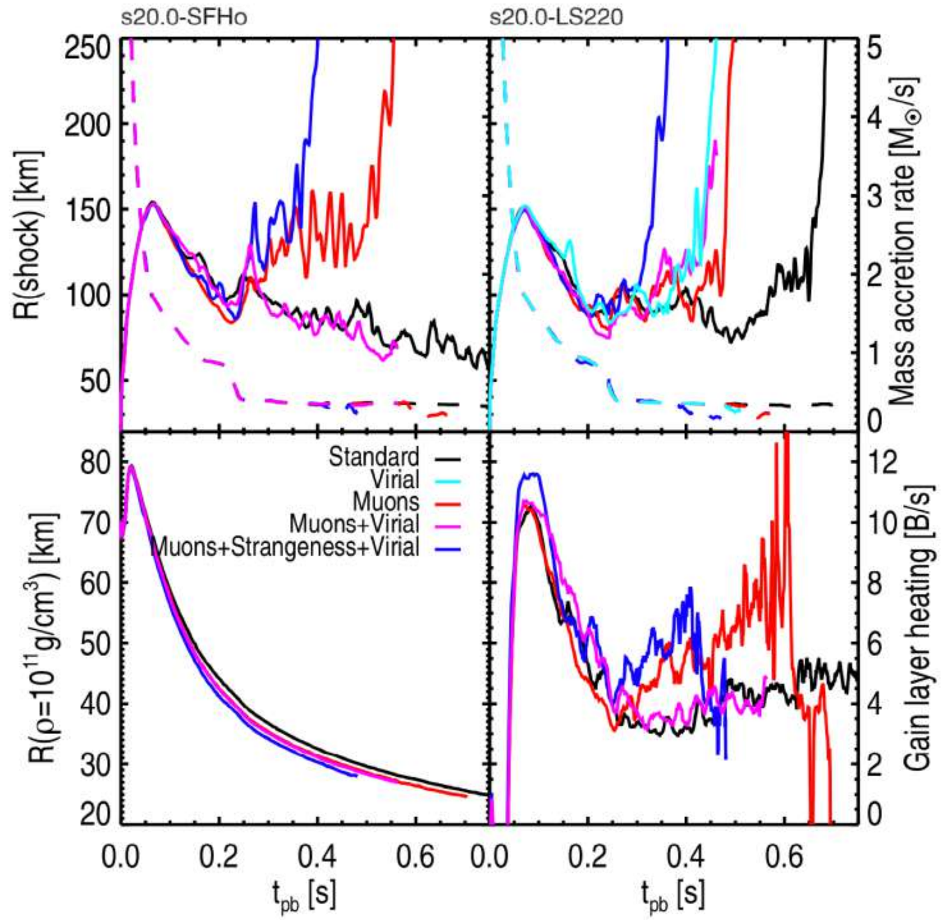
Melson et al (2015)

Sensitivity to neutrino-matter interactions: muons

Description of muon creation

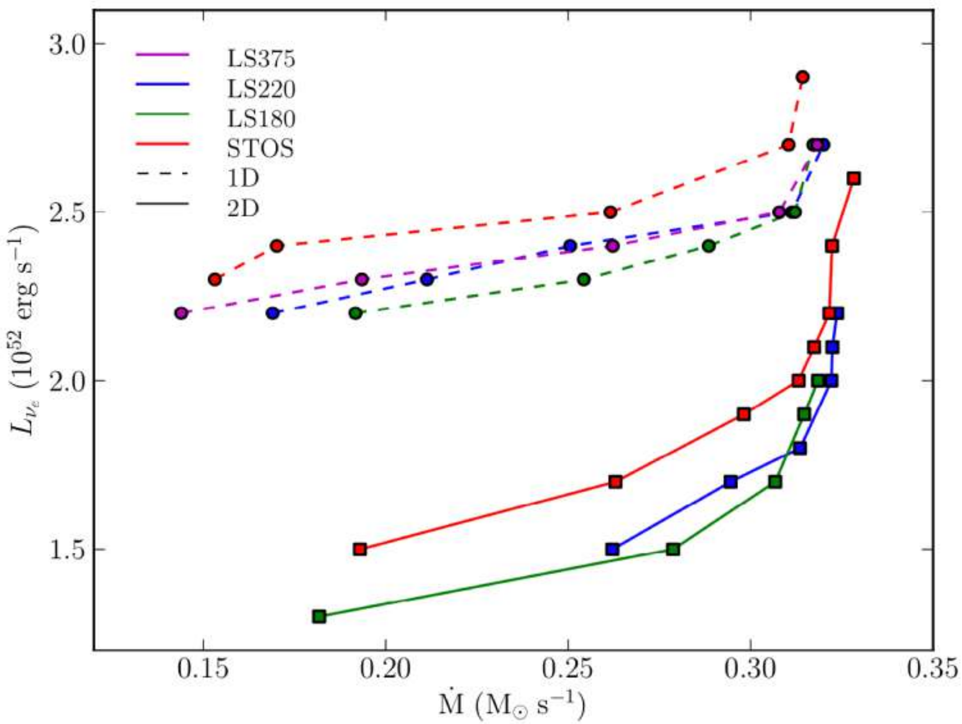
all six neutrino species described separately

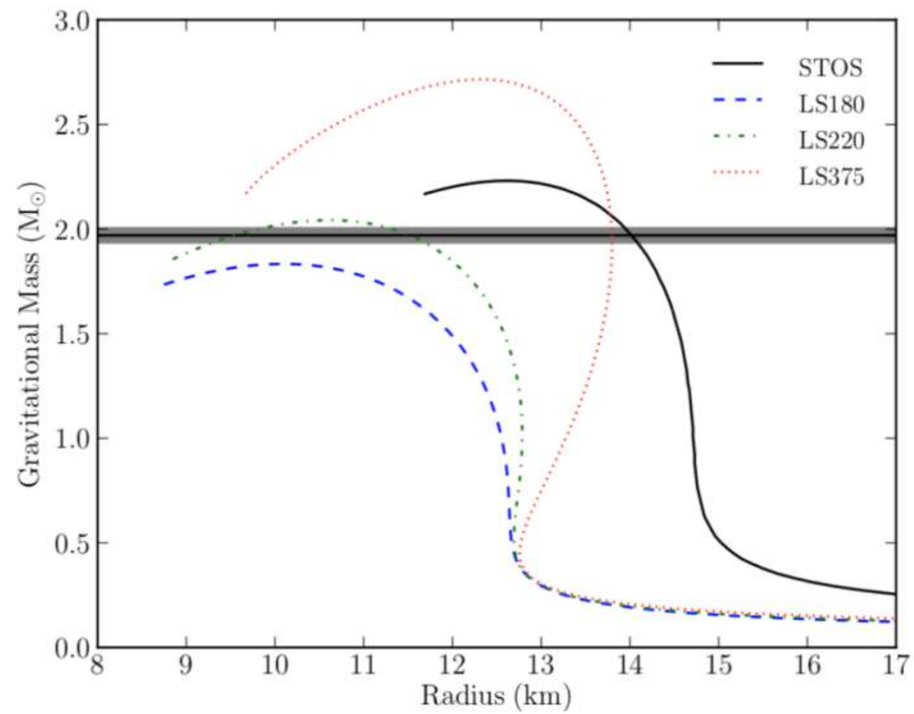




Bollig et al (2017)

Sensitivity to EOS stiffness





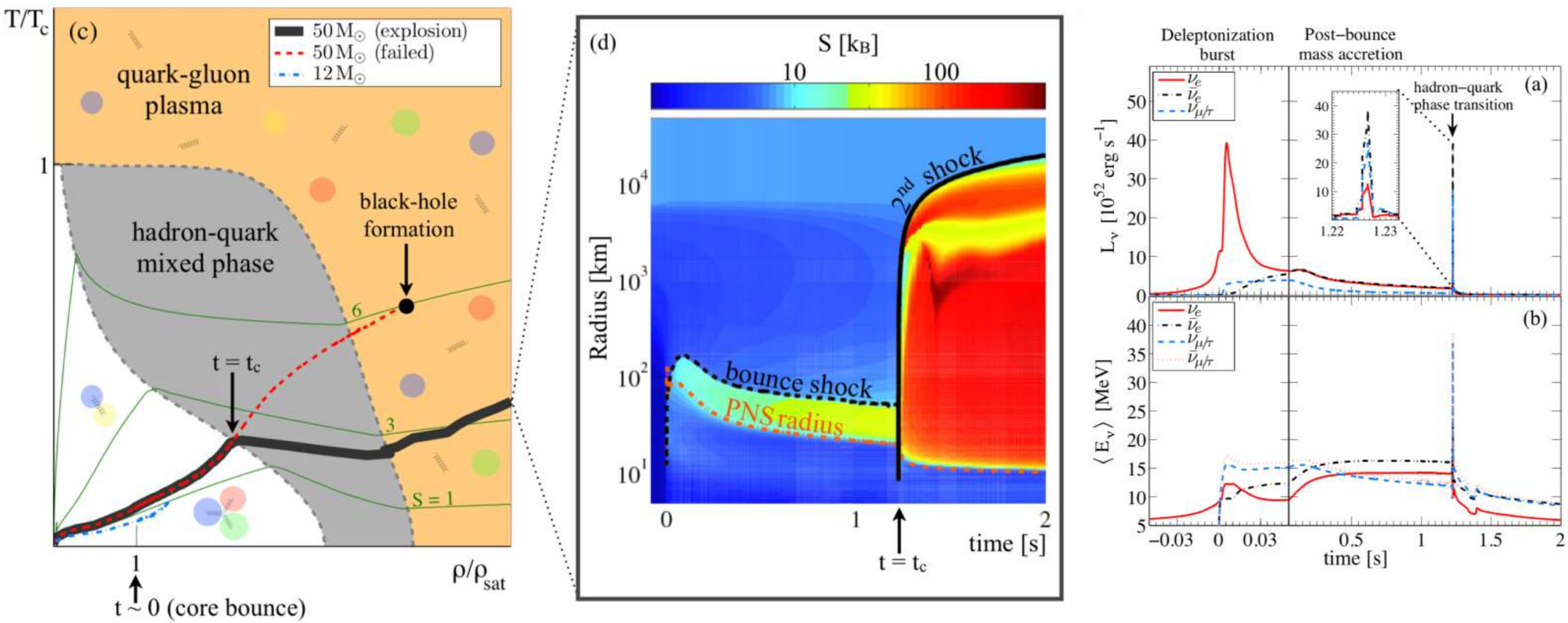
Softer EOS make explosions easier

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

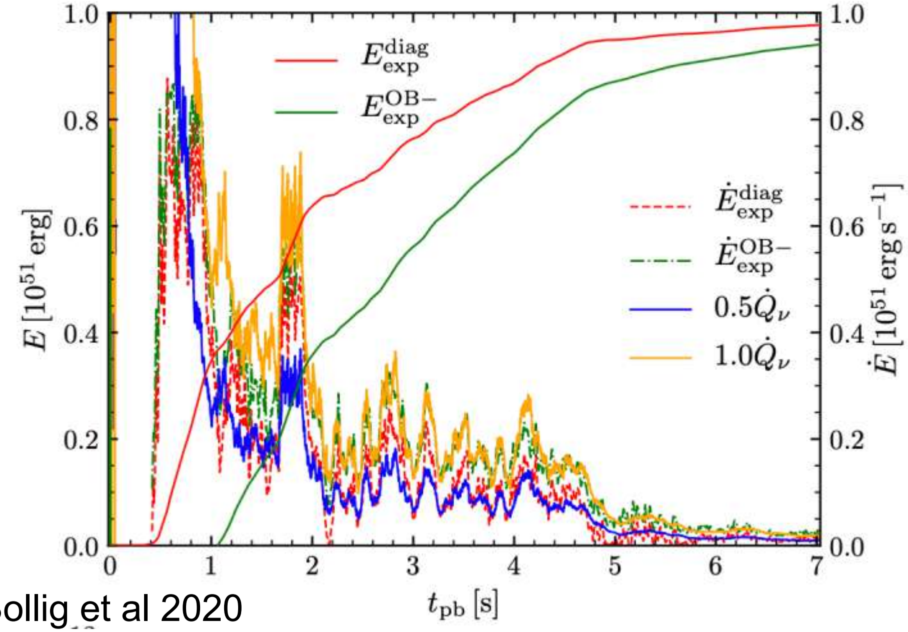


Fischer et al 2017

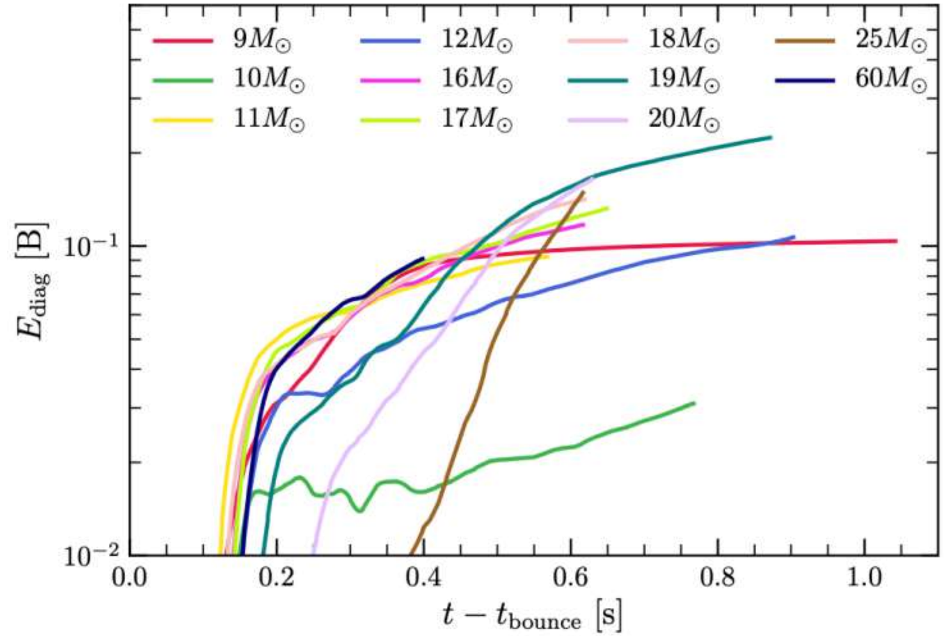
Comparing to observations: explosion energy

Observed range of explosion energies :
$\approx 10^{50}$ to a few 10^{51} erg

Median value : $\approx 5 \times 10^{50}$ erg



Bollig et al 2020

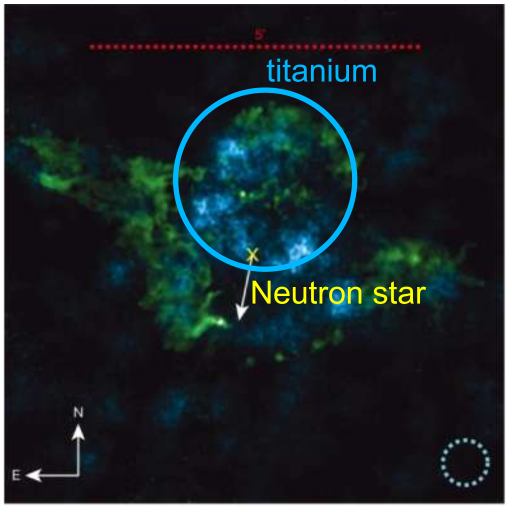


Burrows et al 2019

Explosion asymmetries account for observations

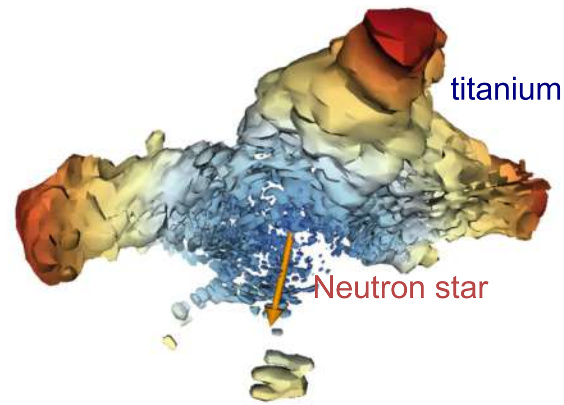
Titanium nucleosynthesis is a tracer of explosion asymetry

Observation of Cas A



Grefenstette et al 2014

Numerical simulation

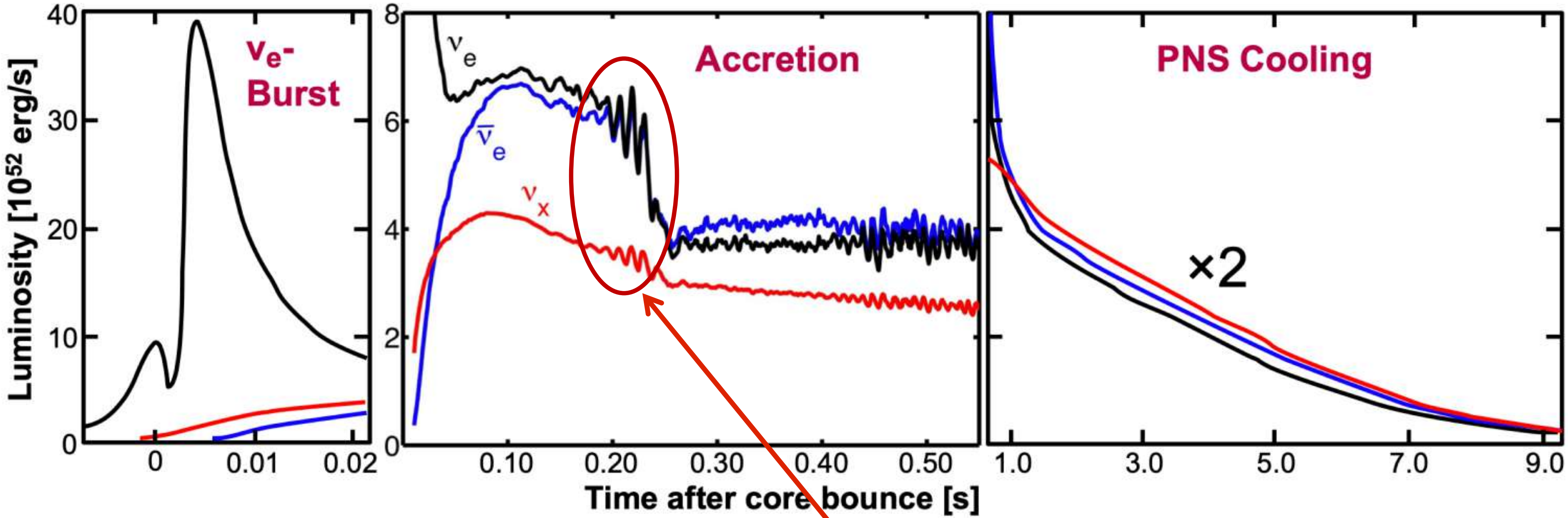


Wongwathanarat et al 2016, 2018

Other observational evidence of asymmetry:
Neutron star kicks: several 100 km/s => accelerated at birth

Polarisation of SN light: inner ejecta are asymmetric

Neutrino signatures



test oscillation physics

probes SN astrophysics

hydrodynamic instabilities

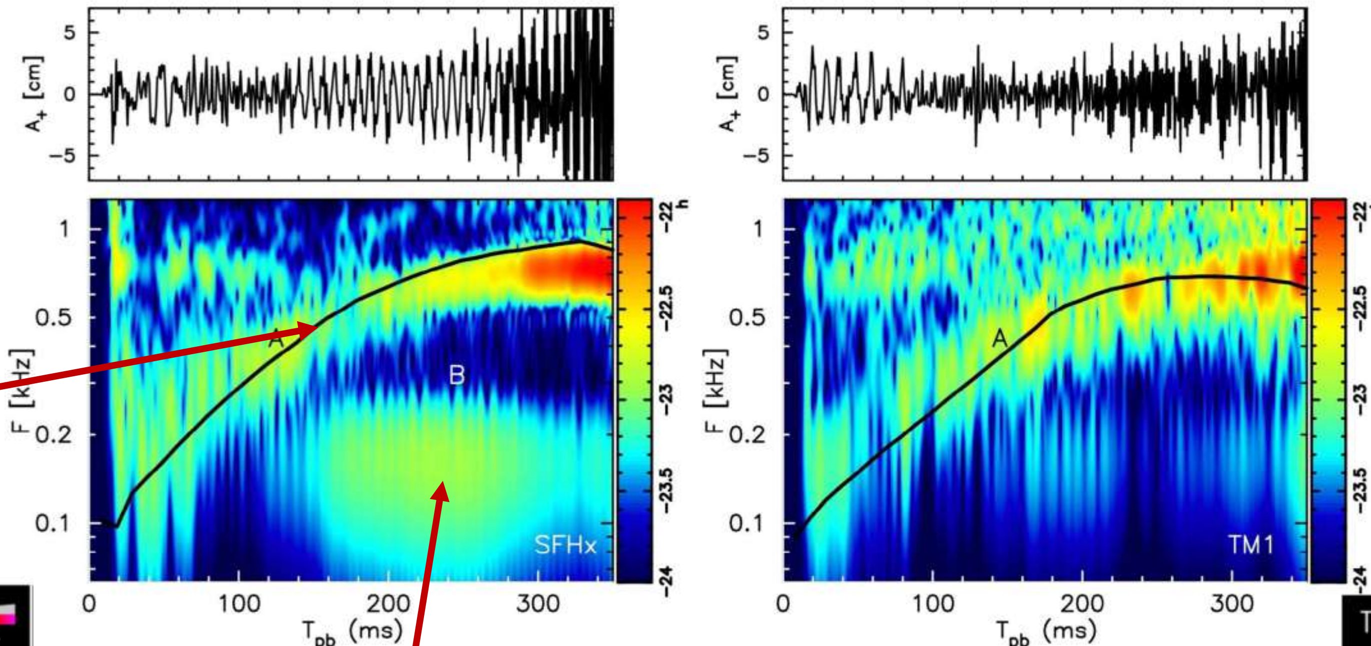
probes nuclear physics & PNS convection

EOS & mass dependance

Gravitational wave signature

Softer EOS
(SFHx, Steiner+13)

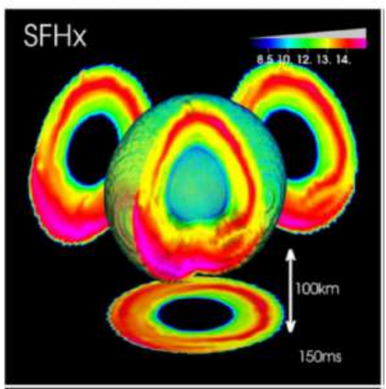
Stiffer EOS
(TM1, Hempel+10)

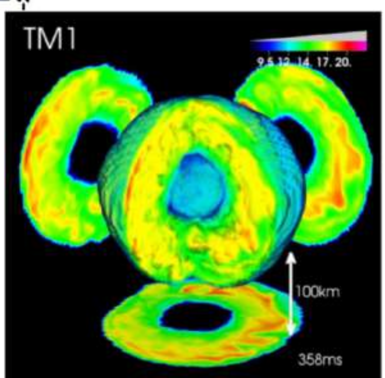


PNS surface oscillations

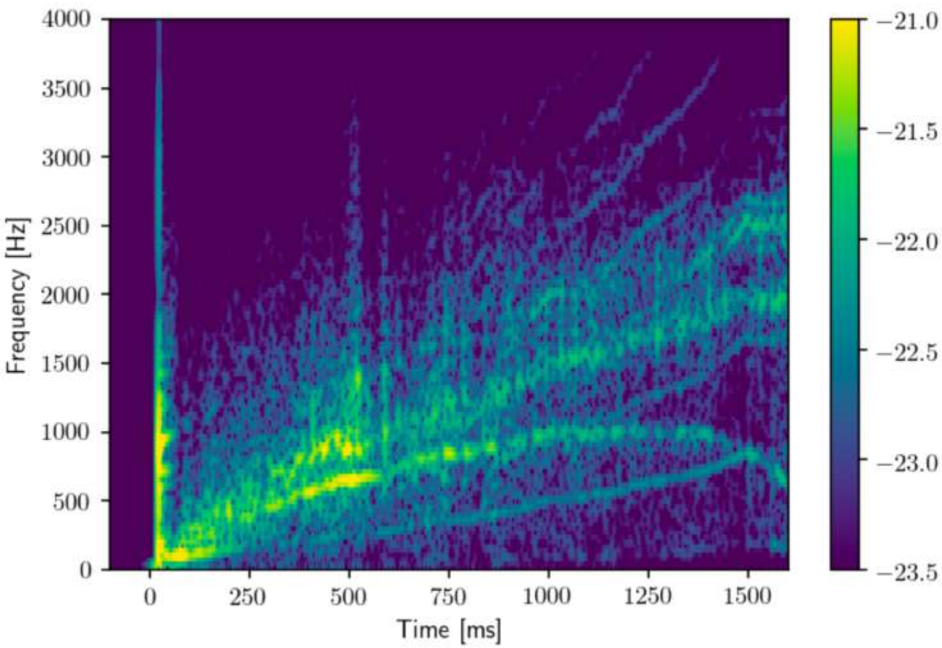
Signature of strong SASI activity

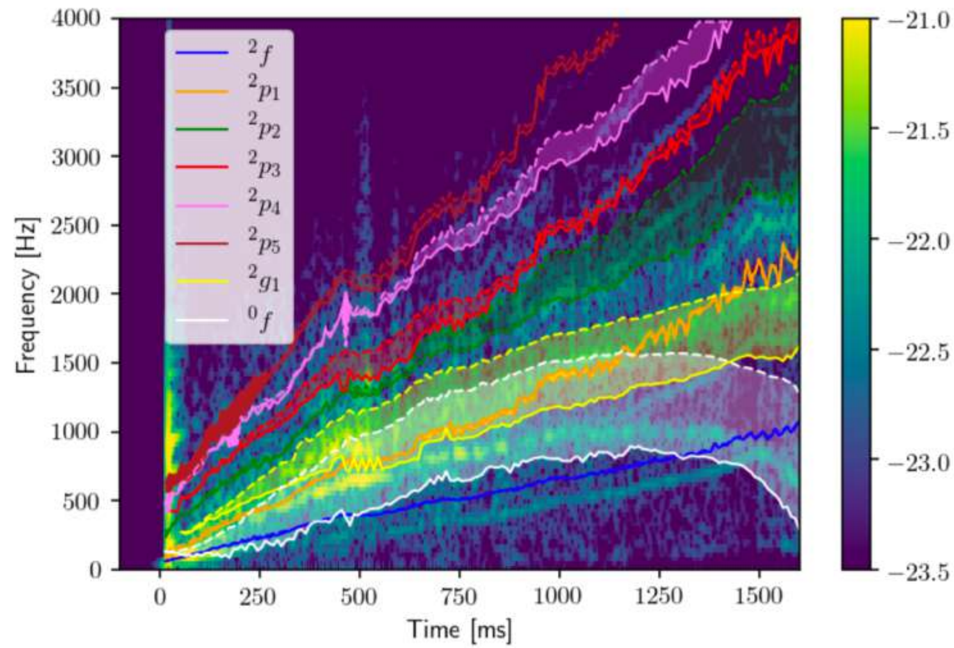
Kuroda+2016





Toward protoneutron star asteroseismology





Detection and identification of several oscillation modes
⇒ probe of protoneutron star structure

Torres-Forné+2018

Conclusion on standard supernovae

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

- Sound theoretical support: first principles & predictive
- Successful 3D explosions of many progenitors
- Reproduces the right order of magnitudes: explosion energy, nucleosynthesis, asymmetries, NS kicks

But many open questions/uncertainties to be solved for a more quantitative comparison to observations:

- Equation of state, neutrino interactions/transport, resolution dependence..
- Progenitor dependence

Direct probe of the dynamics with multimessenger observations: waiting for the next Galactic SN ☺

Outstanding explosions: magnetorotational explosions ?

Explosion kinetic energy :

- → Typical supernova 10^{51} erg
- → Rare hypernova & GRB 10^{52} erg
  aka type Ic BL

→ Neutrino driven explosions

→ Magnetorotational explosion ?
e.g. Burrows+07, Takiwaki+09,11
Bucciantini+09, Metzger+11, Obergaulinger+17

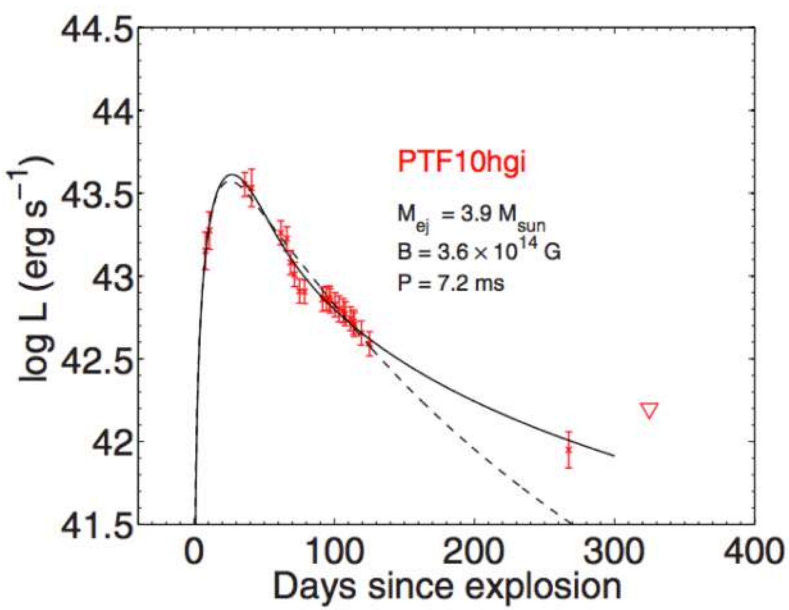
Total luminosity :

- → Typical supernova 10^{49} erg
- → Superluminous supernovae 10^{51} erg

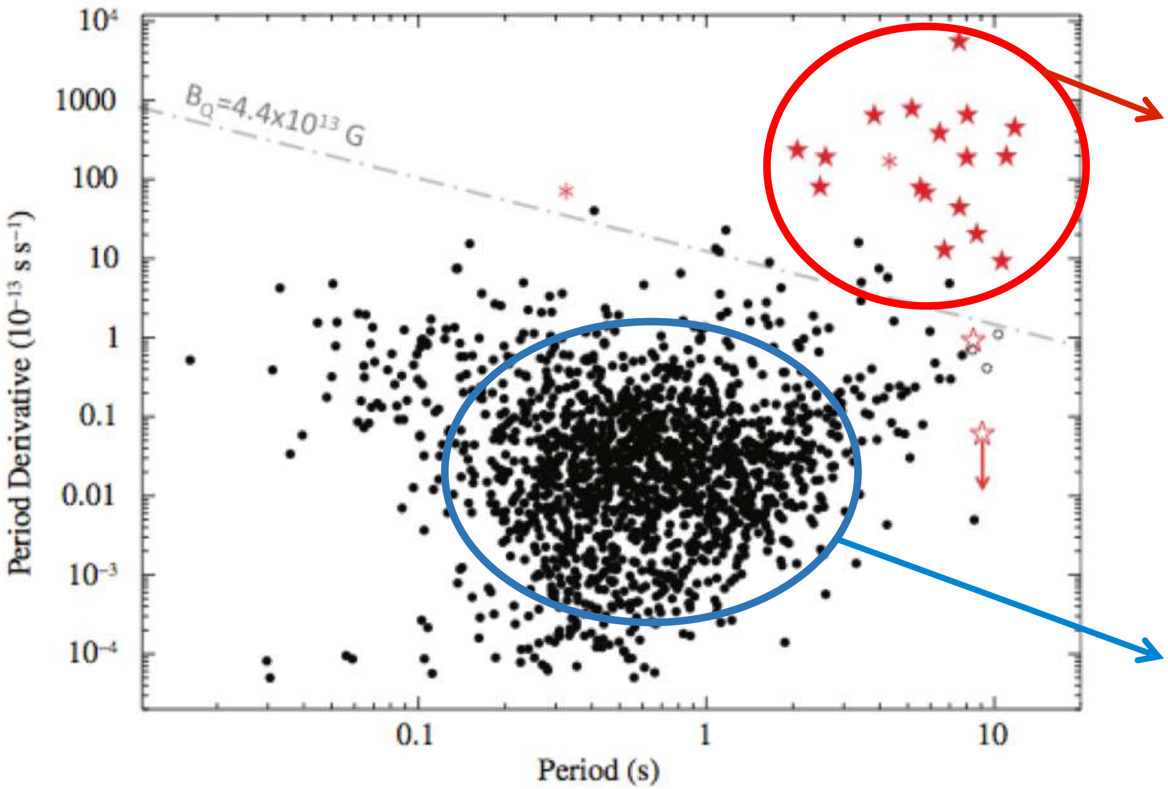
Light curves can be fitted by millisecond magnetar

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

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)

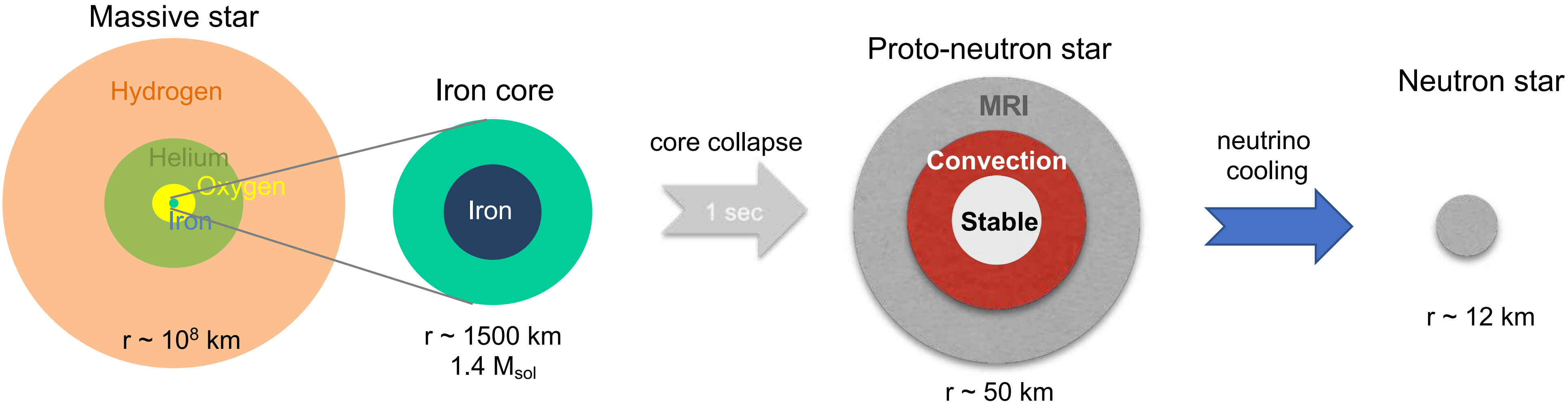
Strong dipole magnetic field:

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

Pulsars

B ~ 10^{12} - 10^{13} G

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

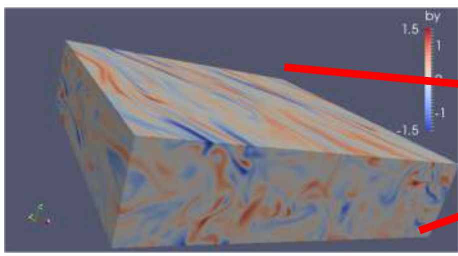
Similar to accretion disks

Convective dynamo

Similar to planetary & stellar dynamos

Simulating different spatial scales

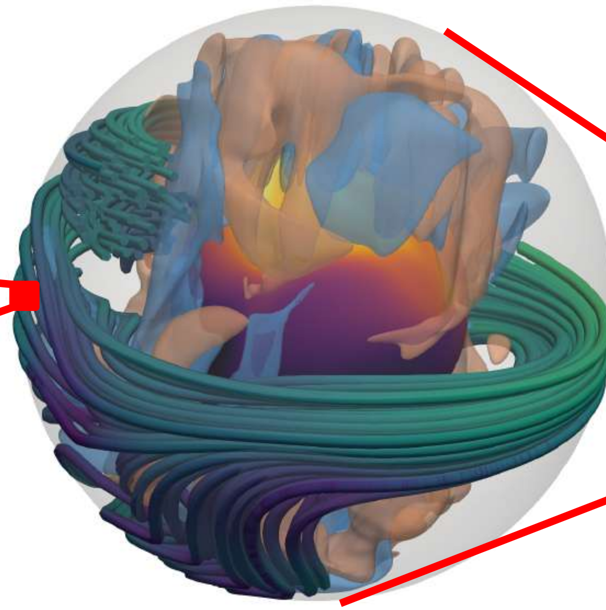
Small turbulent scales



~ 1-5 km

Guilet et al 2015, 2022

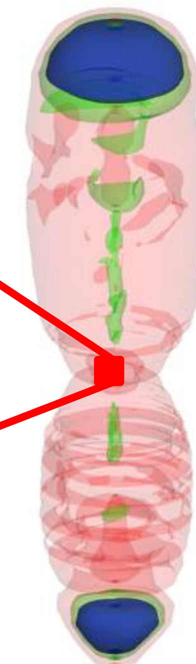
Protoneutron star dynamo



~ 10-50 km

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

Magnetorotational explosions



~ 10^3-10^5 km

Bugli et al. 2020

The magnetorotational instability (MRI)

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

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

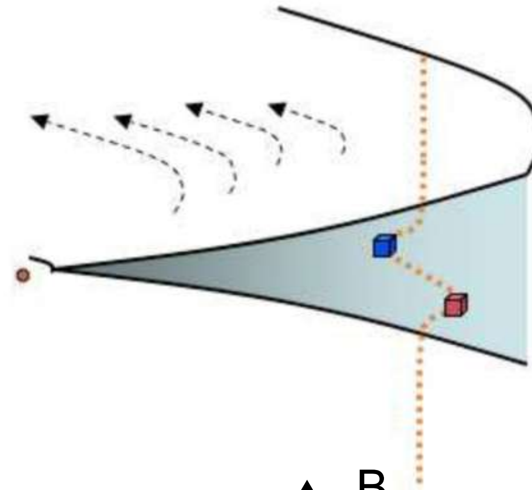
Growth rate : $$\sigma = \frac{q}{2}\Omega$$

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

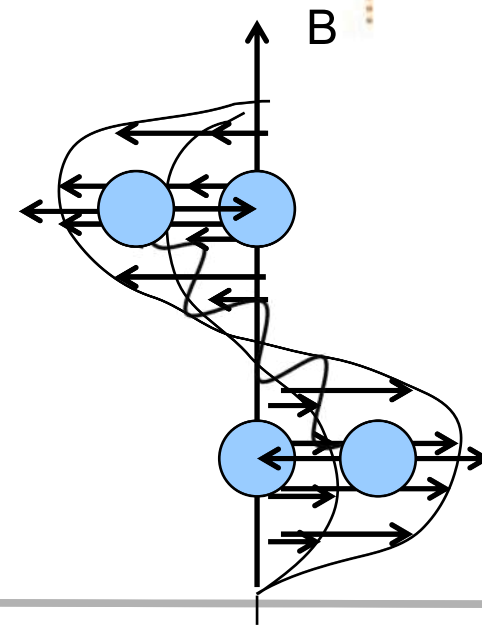
→ Fast growth for fast rotation

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

→ Short wavelength for weak magnetic field

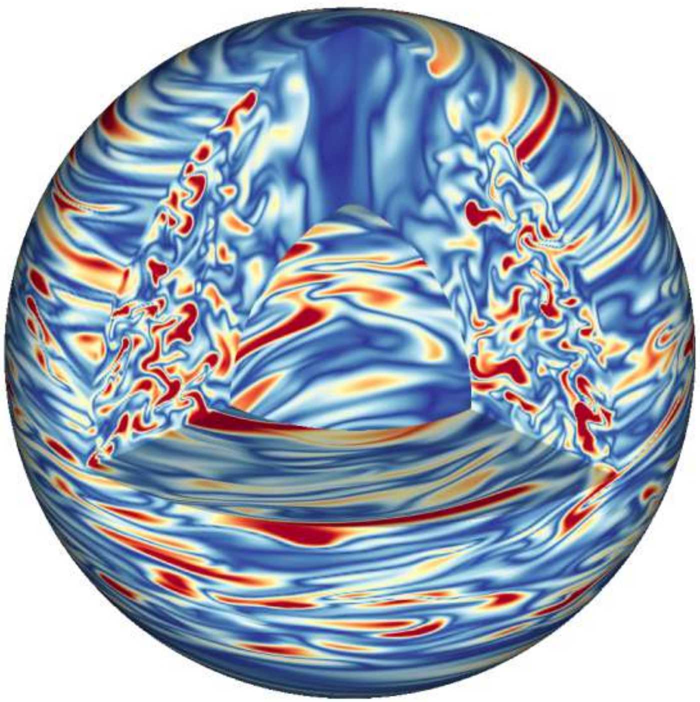


Fromang+12

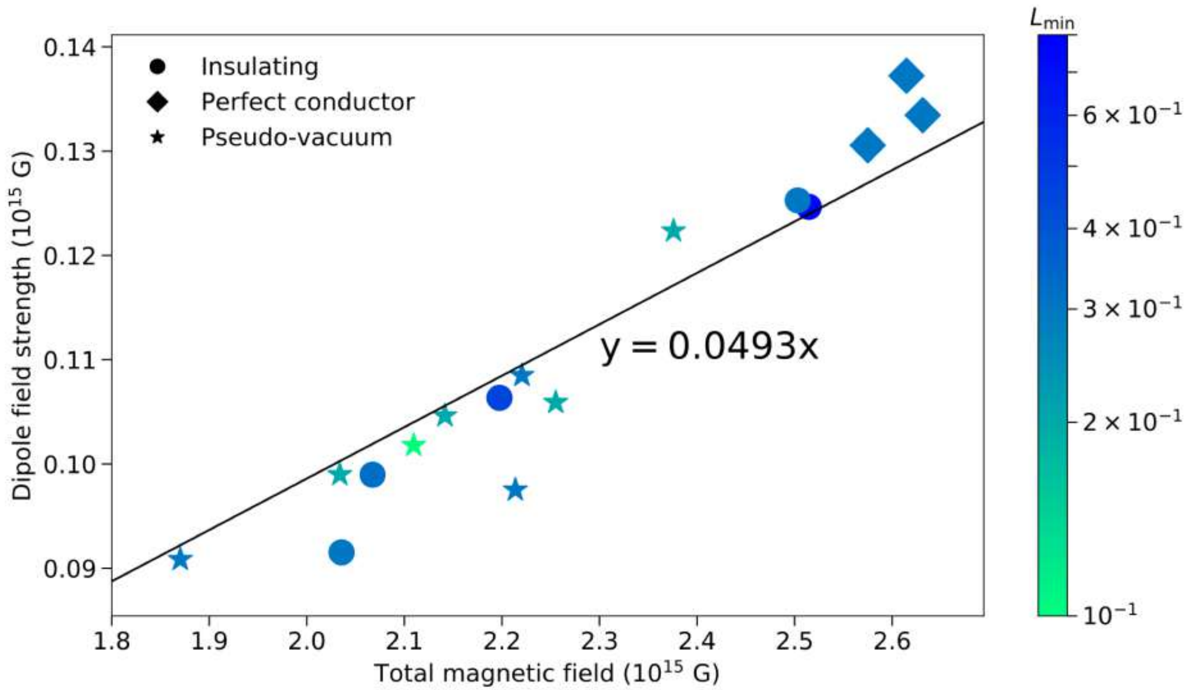


Magnetorotational instability in spherical geometry

PhD thesis of Alexis Reboul-Salze



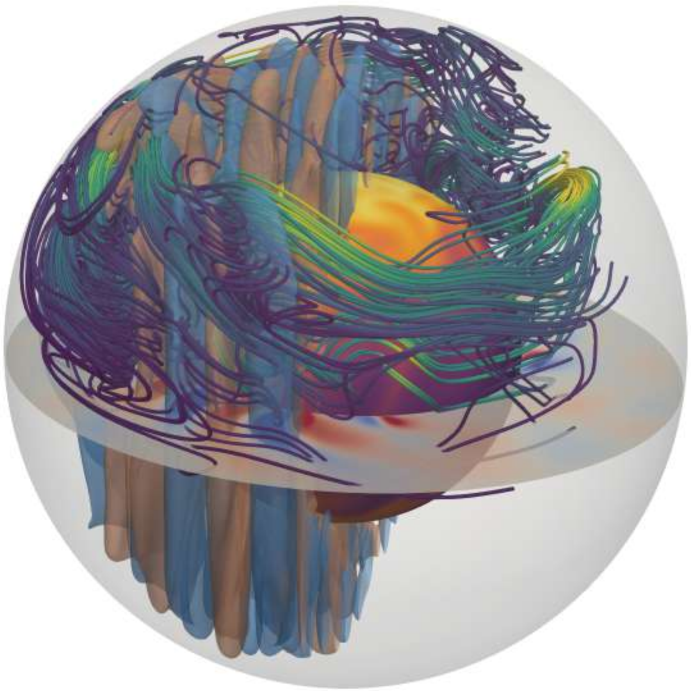
Reboul-Salze+2021

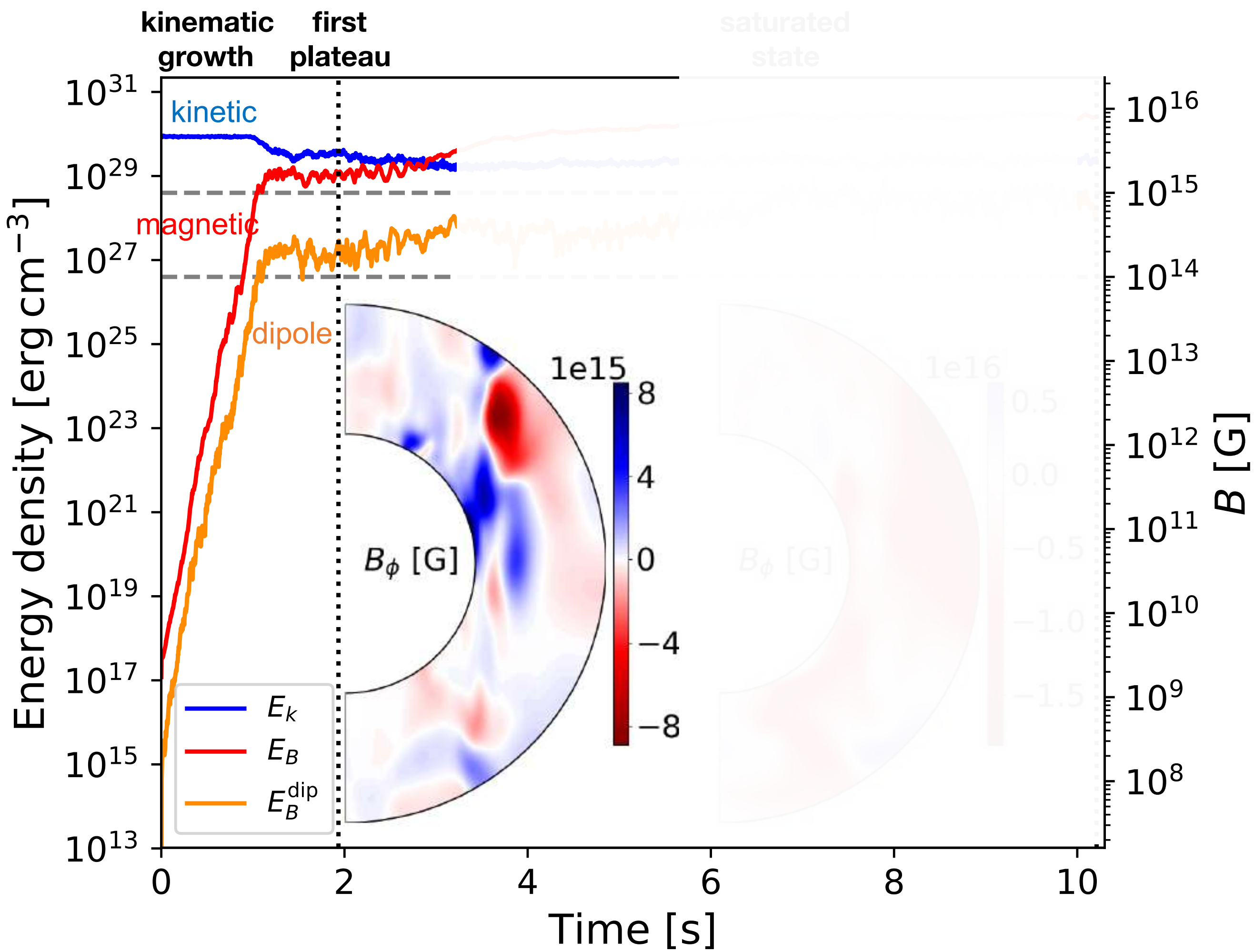


Magnetar strength dipole

Inclined toward the equator (dipolar angle ~ 80°)

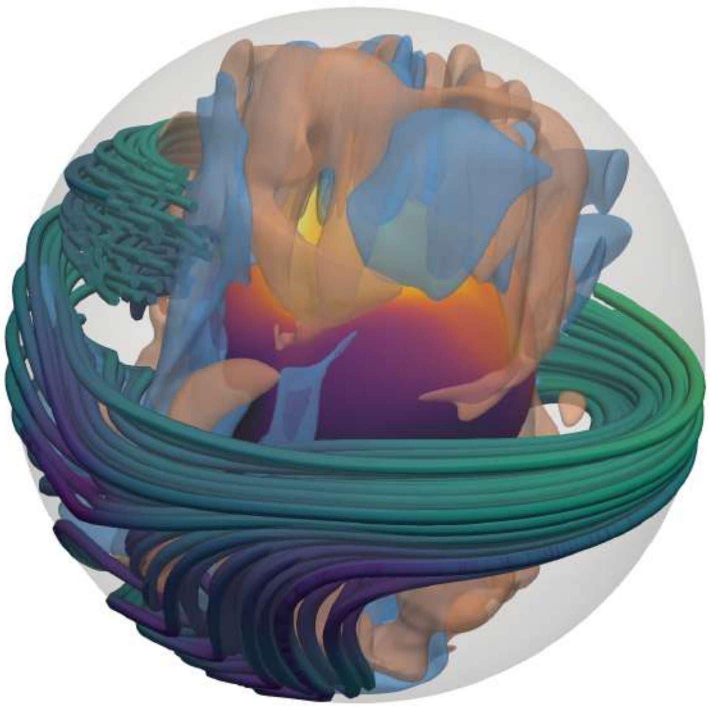
Convective dynamo in a protoneutron star

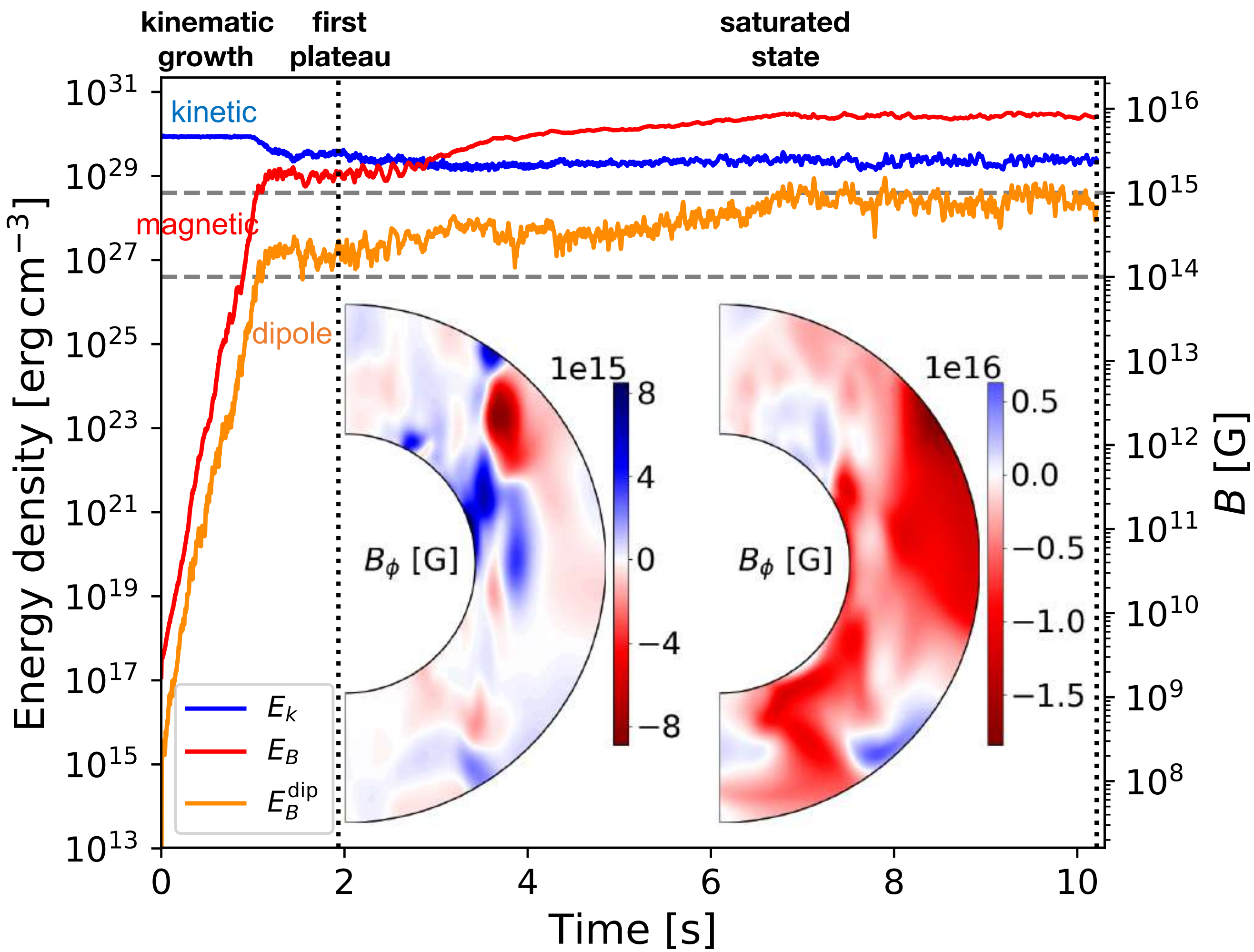




Raynaud et al 2020

Convective dynamo in a protoneutron star

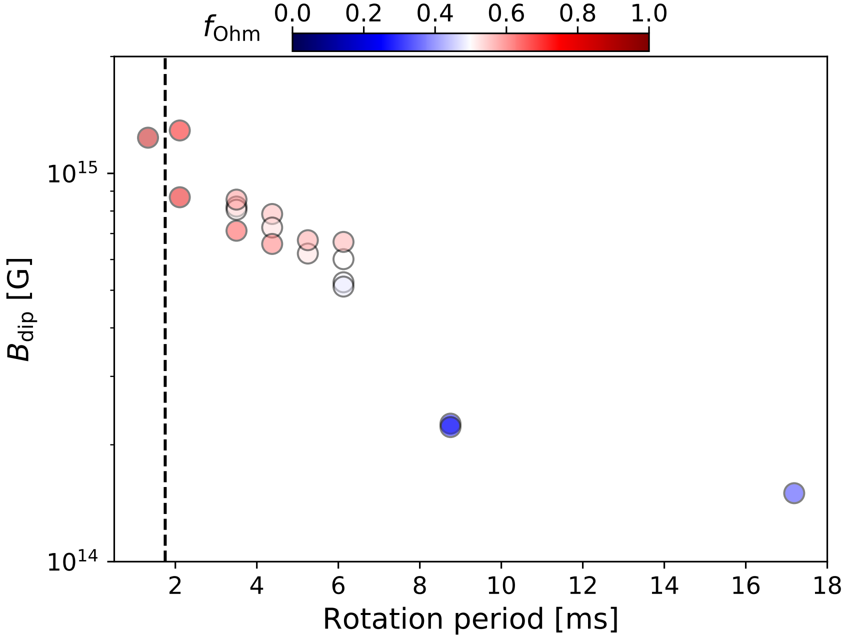




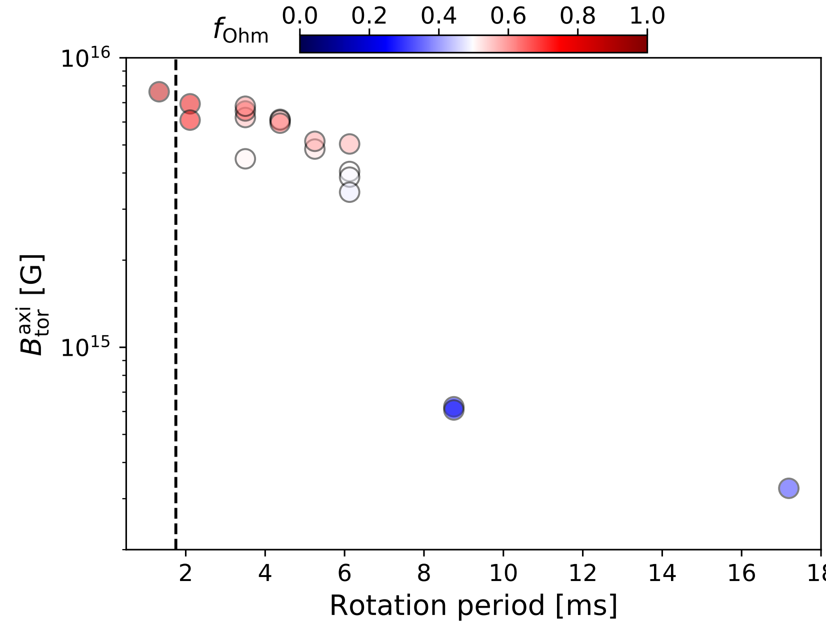
Raynaud et al 2020

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 ?

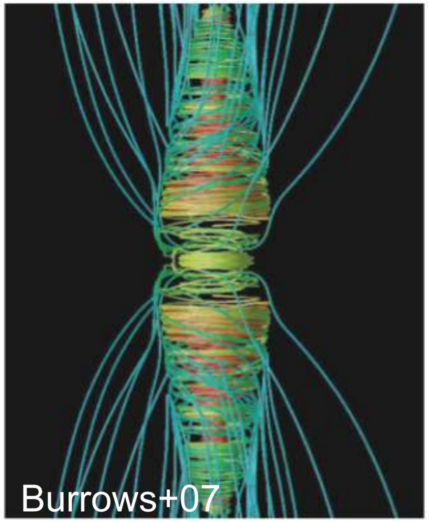
Magnetorotational explosions

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

+ fast rotation (period of few milliseconds)

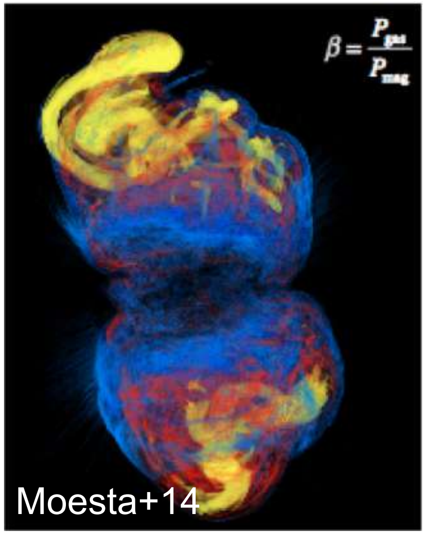
=> powerful jet-driven explosions

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



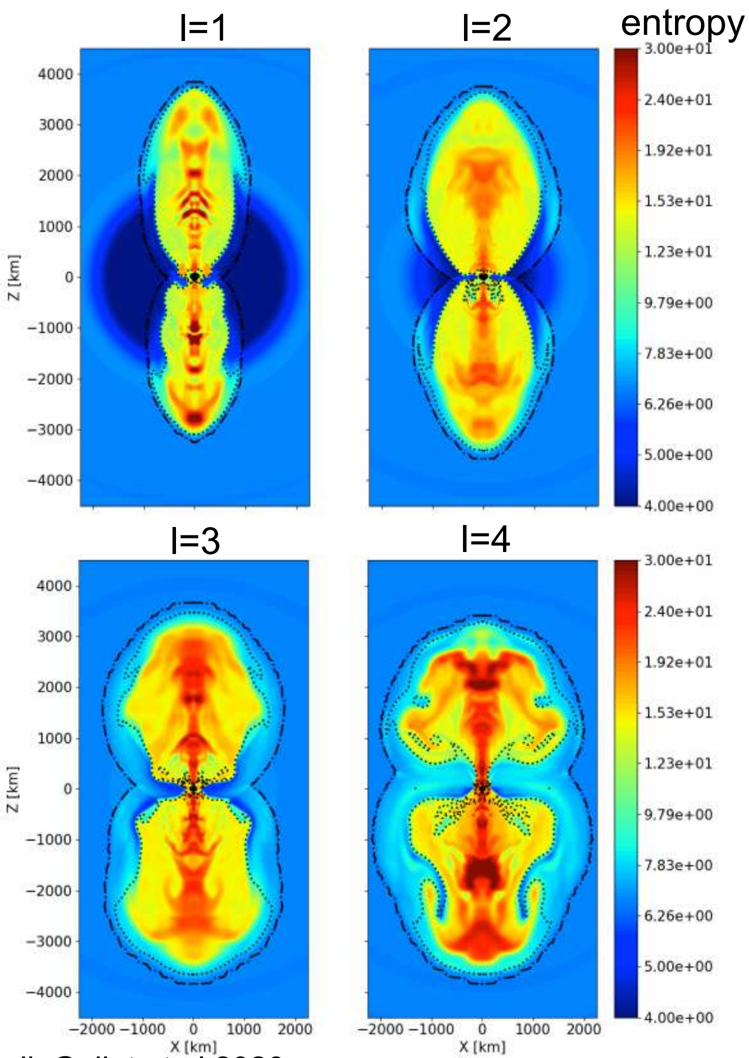
But in 3D, jets may be unstable to kink instability

Moesta+2014

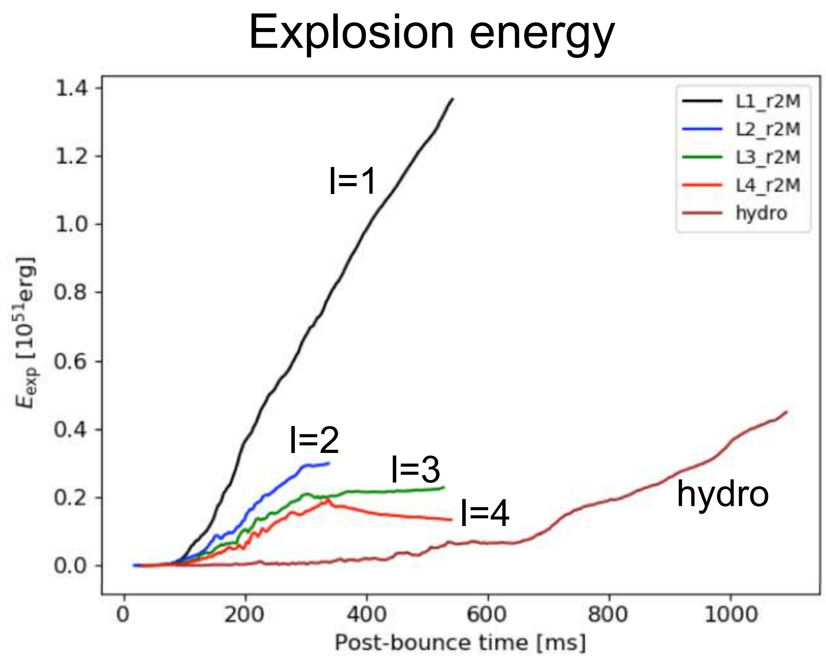


Caveat: strong dependence on the initial magnetic field

Magnetorotational explosions: dependence on magnetic field structure



Bugli, Guilet et al 2020



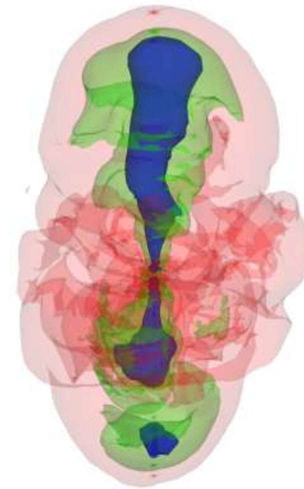
Higher multipoles also launch explosions but:

- Less collimated
- Less energetic

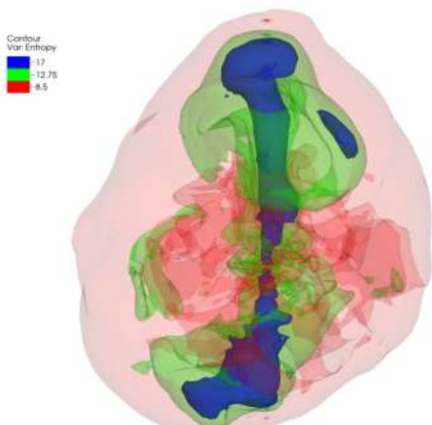
Magnetorotational explosions: 3D simulations

Aligned dipole

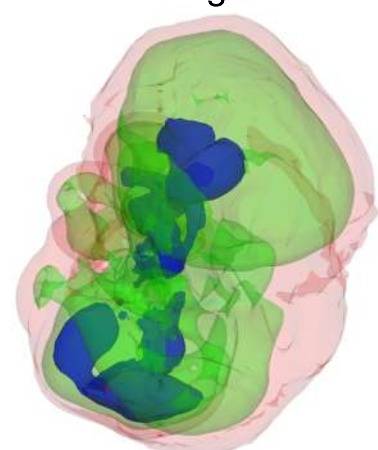
Quadrupole



Inclined dipole

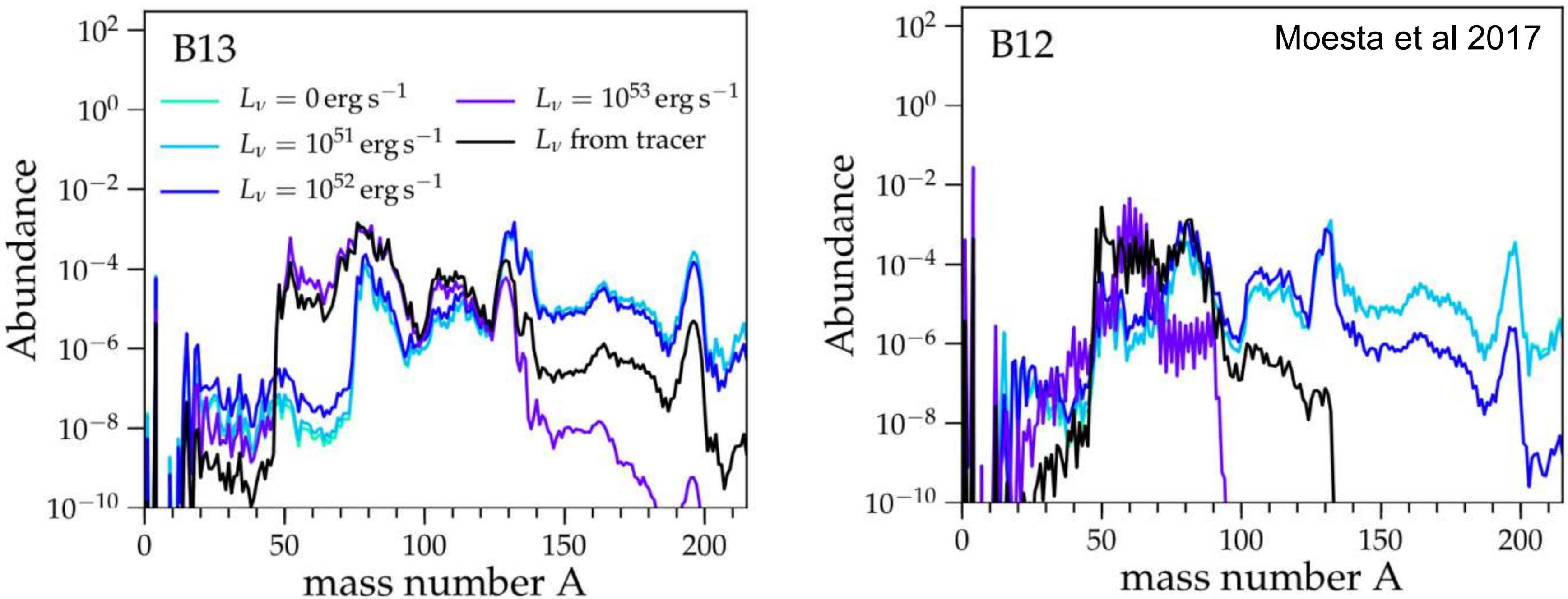


Non-magnetised



Bugli, Guilet et al 2021

R-process in magnetorotational explosions ?



Efficient r-process may be possible in magnetorotational supernovae
but need better description of neutrinos & magnetic field

Winteler+2012, Nishimura+2016, Moesta+2017, Halevi+2018

Conclusions on extreme explosions

Magnetorotational explosions from millisecond magnetar formation are a viable scenario for extreme explosions:

- Sufficient energy reservoir for fast rotation
- Dynamo models predict strong magnetic fields
- May be a source of r-process elements

But we are still far from a complete self-consistent picture:

- Dynamo models are sensitive to small scales
- Explosion simulations do not include the magnetic field amplification
- Longer simulations are needed to make a direct link to observations

Thank you !