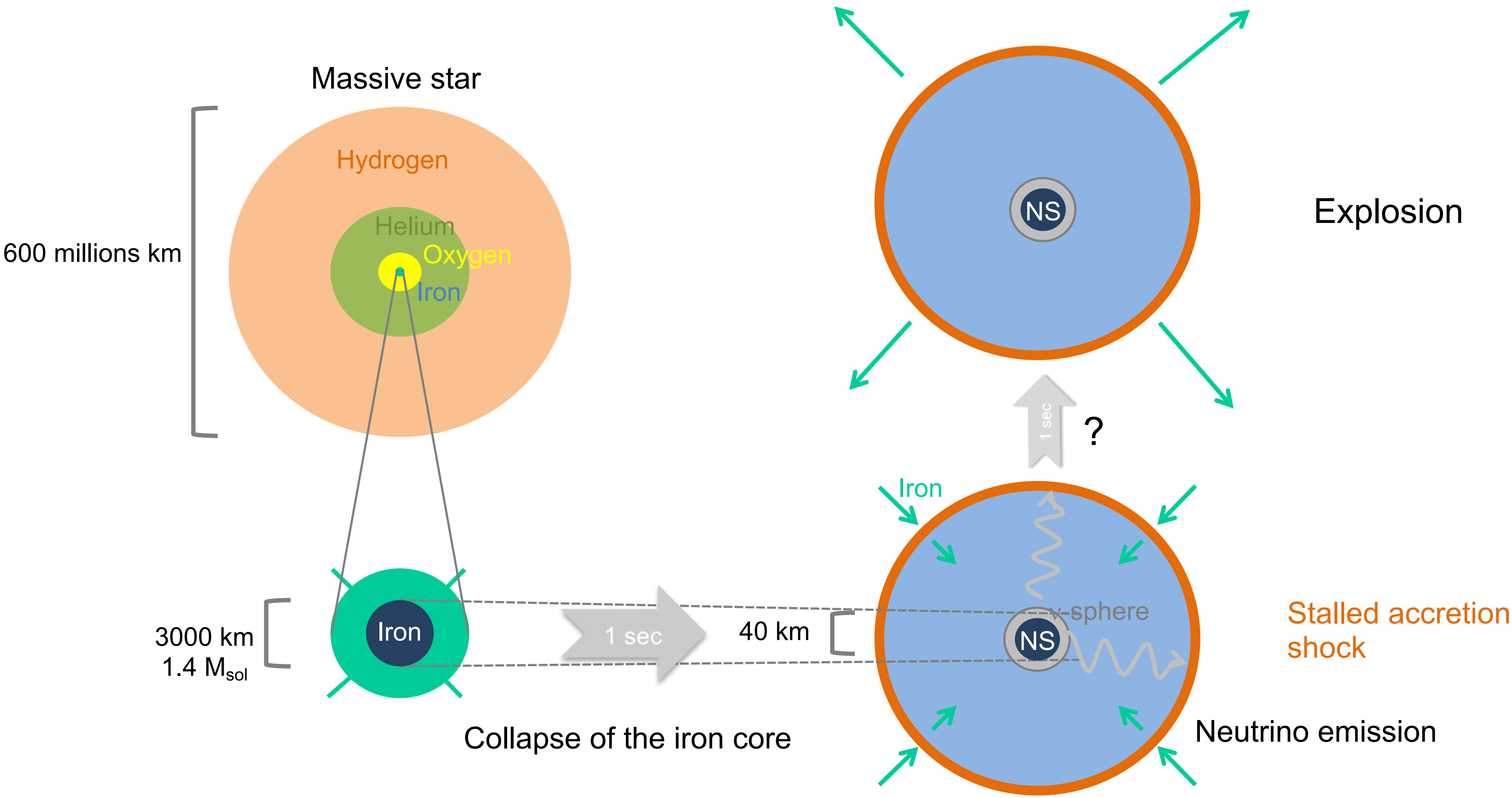
Modelling core collapse supernovae

Jérôme Guilet
(IRFU/DAp)

Core collapse: formation of a neutron star



Neutrino-driven mechanism: a multi-physics problem

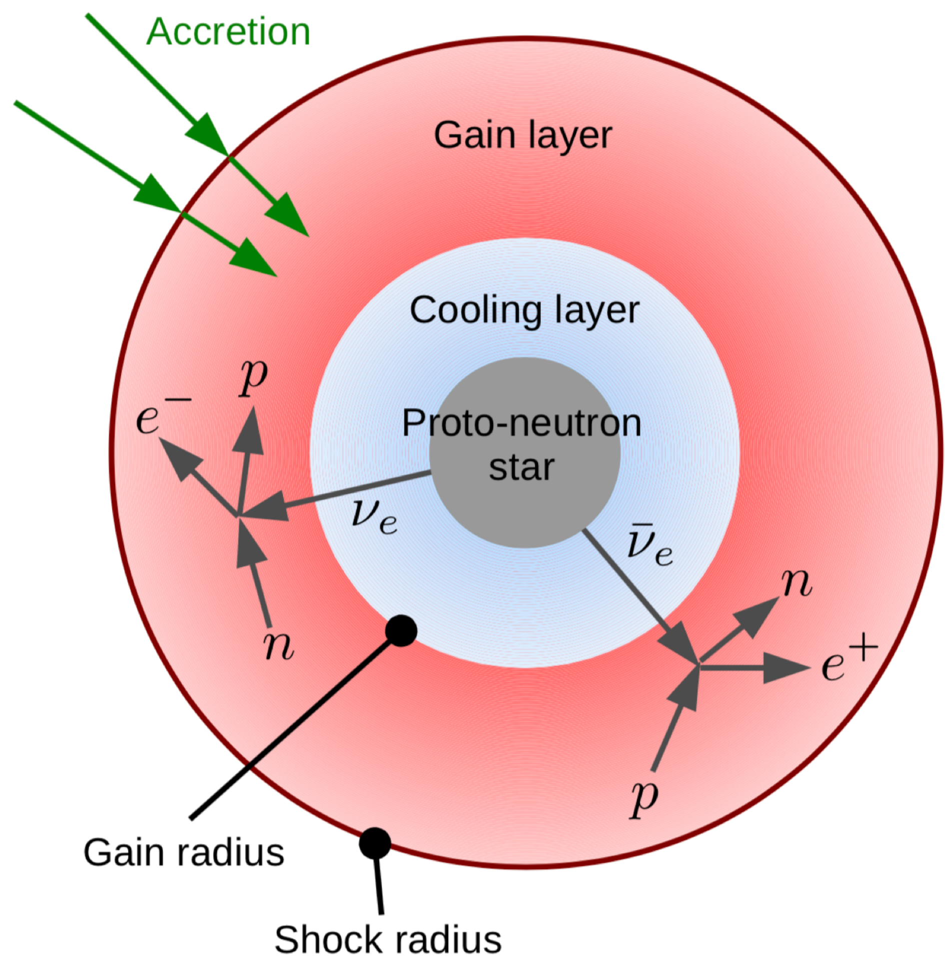
- Multi-dimensional hydrodynamics (instabilities, turbulence..)

- General relativity

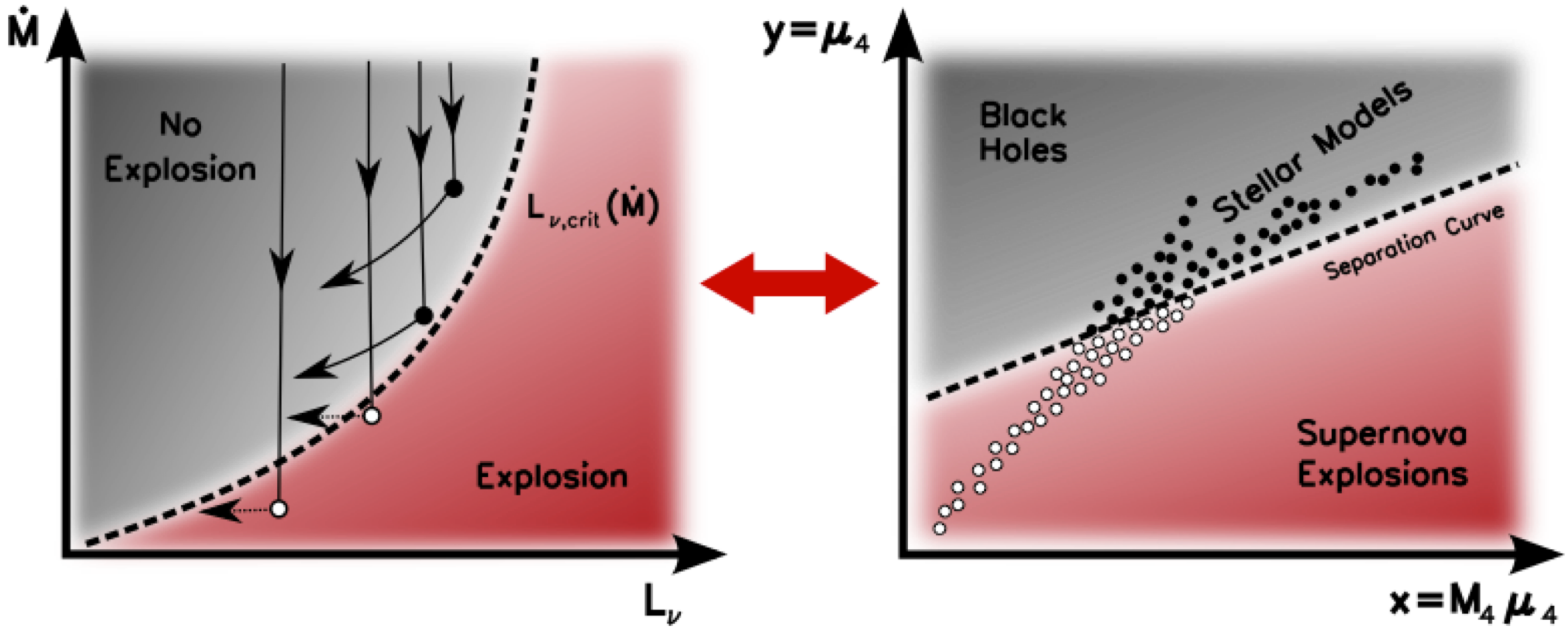
- Neutrino-matter interactions
  sophisticated transport scheme
  accurate cross sections

- Ultra-high density equation of state

- Magnetic field



Critical neutrino luminosity



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

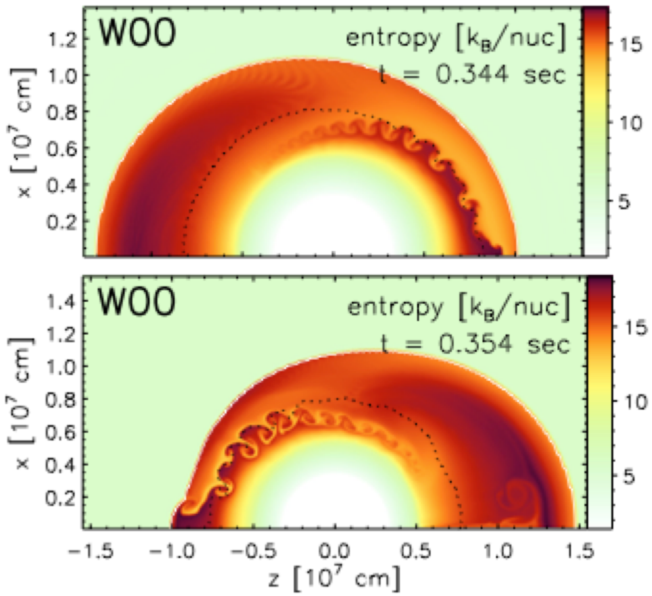
Two parameters :

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

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

Hydrodynamic instabilities

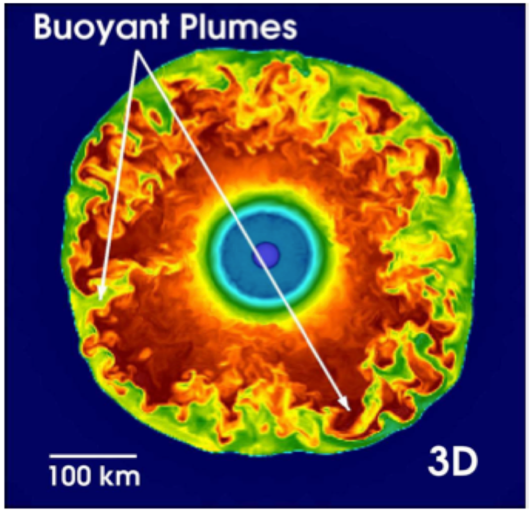
Standing Accretion Shock Instability (SASI)



Scheck et al 2008

Large scale shock oscillations

Neutrino-driven convection

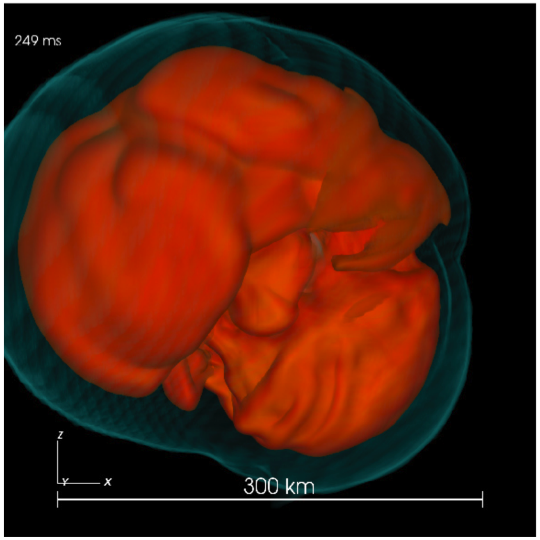


Murphy et al 2013

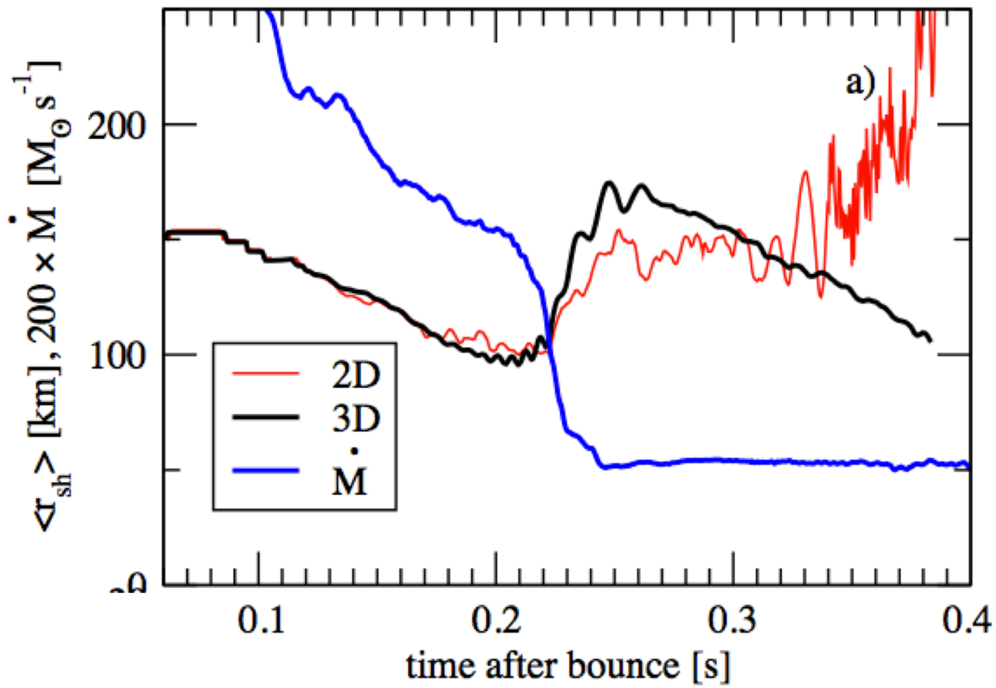
Convective plumes

Global asymmetry of the explosion

Sophisticated 3D simulations are necessary



Hanke et al (2013)



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

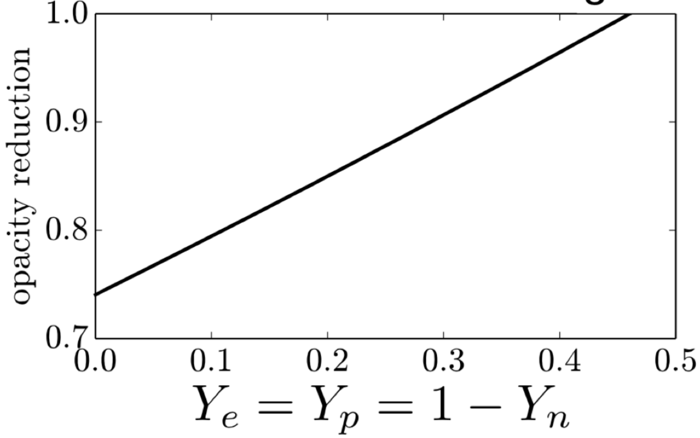
Oak ridge group : explosions in 2D and 3D
Garching group : explosions in 2D, only for low mass in 3D with standard physics
Princeton group : first 3D explosion last week

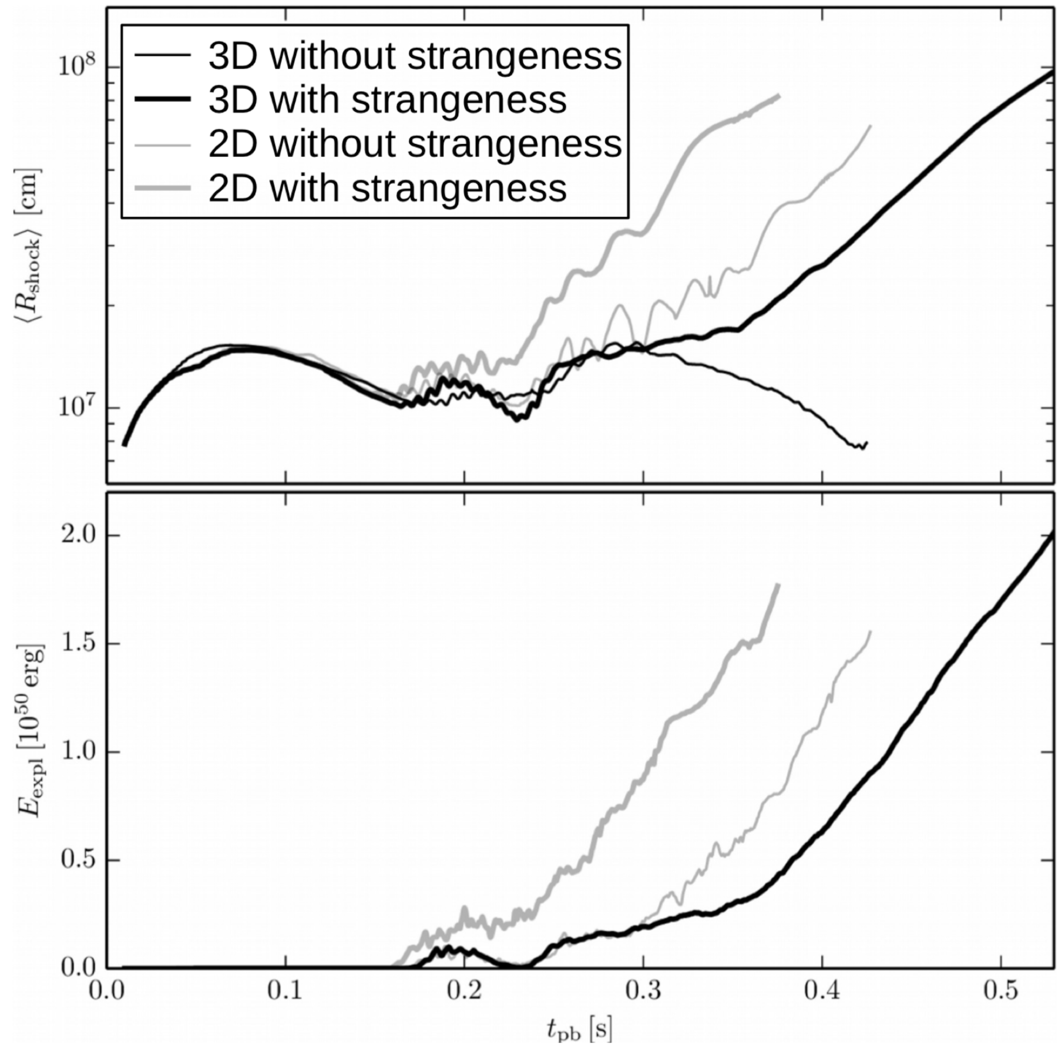
Sensitivity to neutrino-matter interactions

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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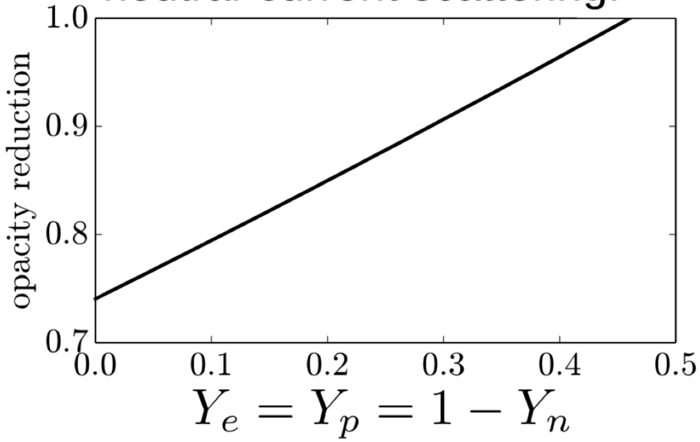
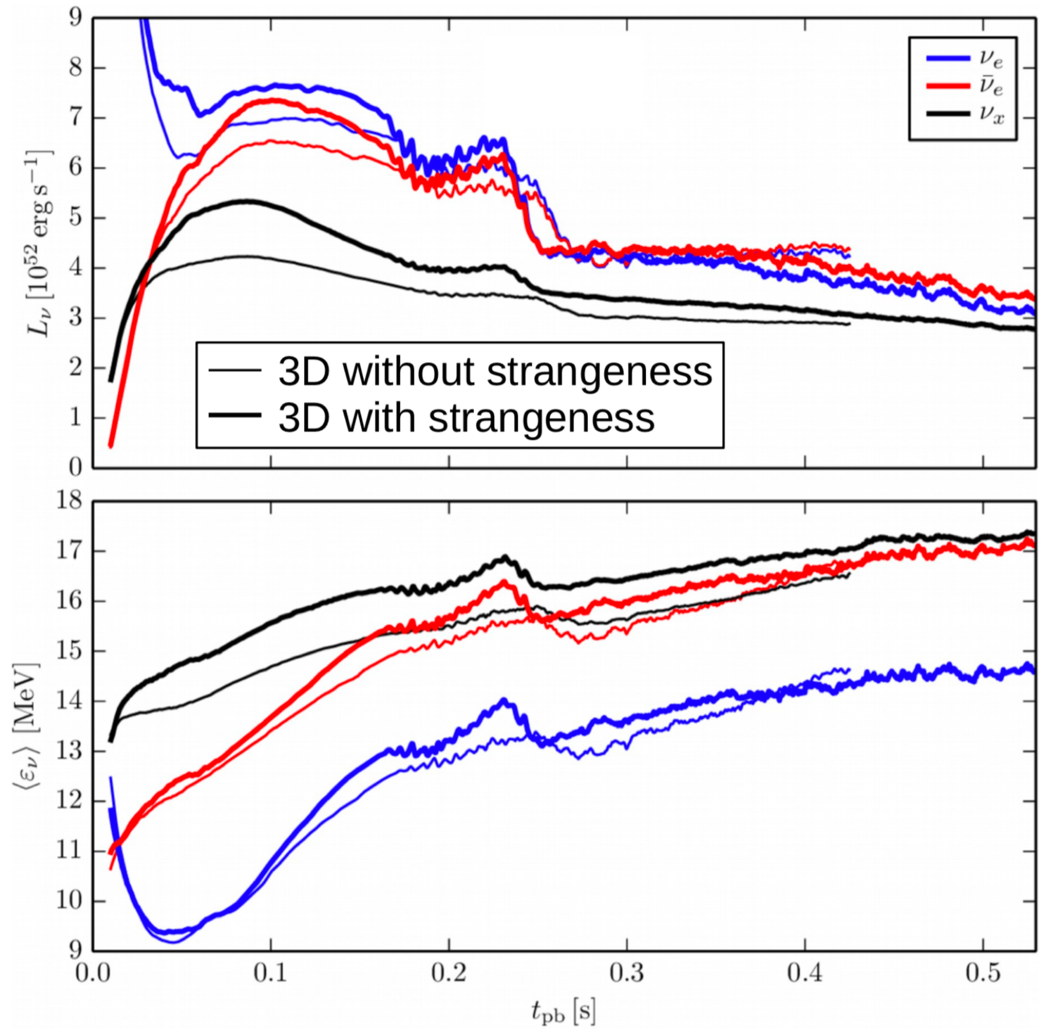


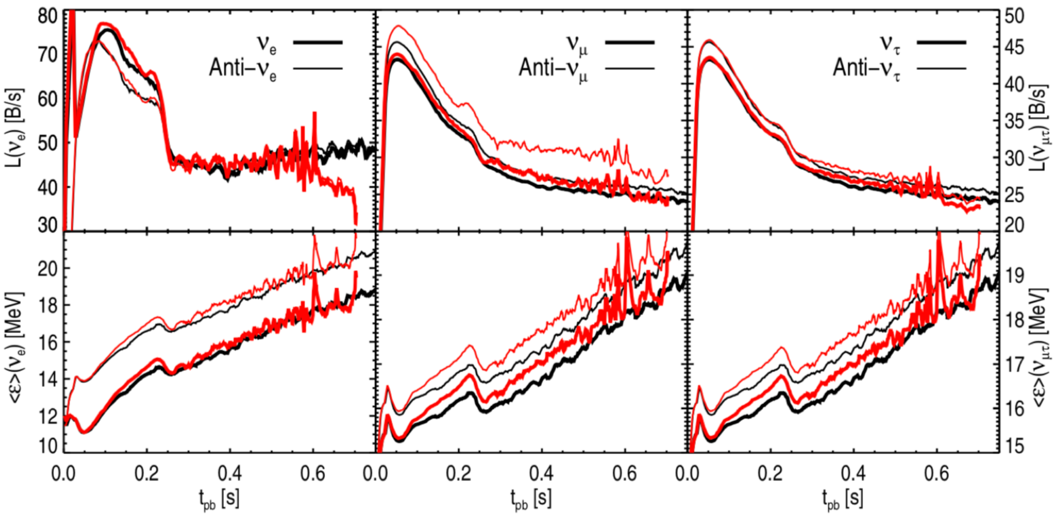


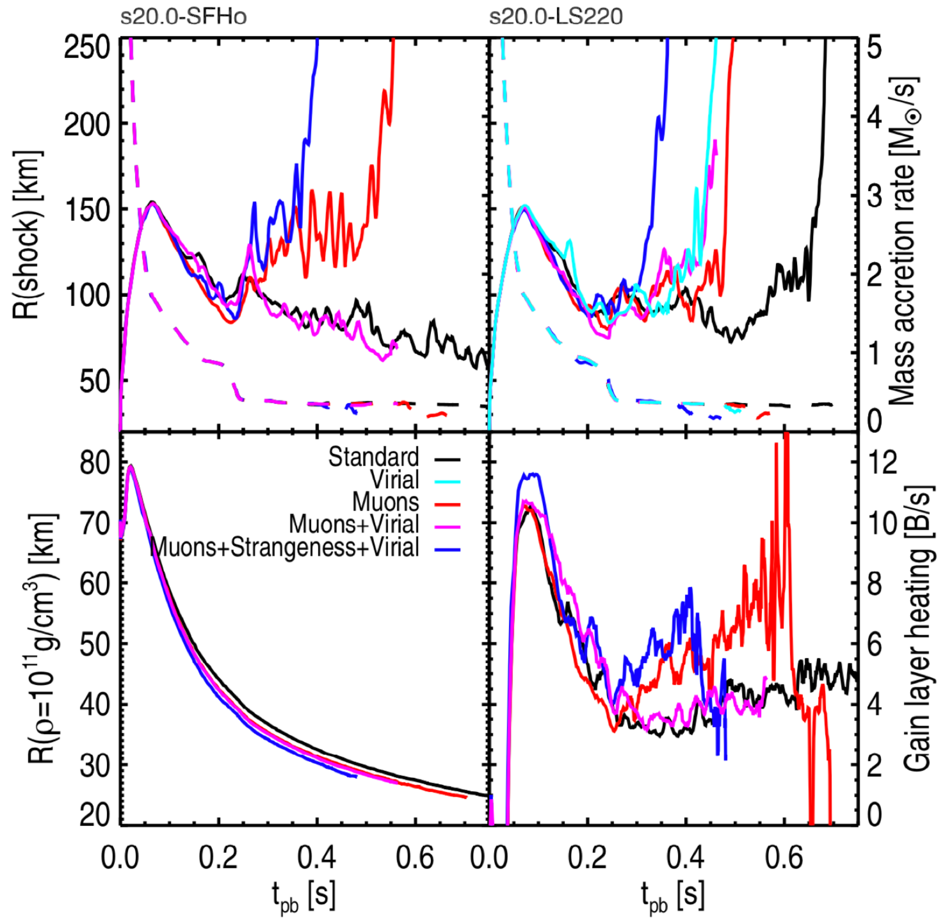
Melson et al (2015)

Sensitivity to neutrino-matter interactions: muons

Description of muon creation

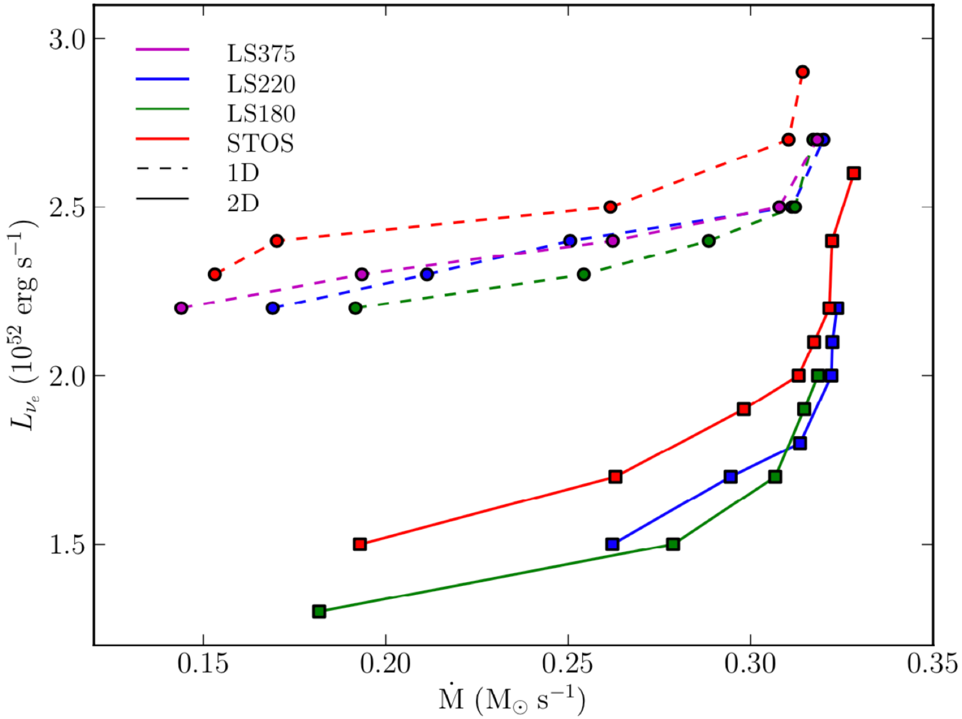
-> all six neutrino species described separately

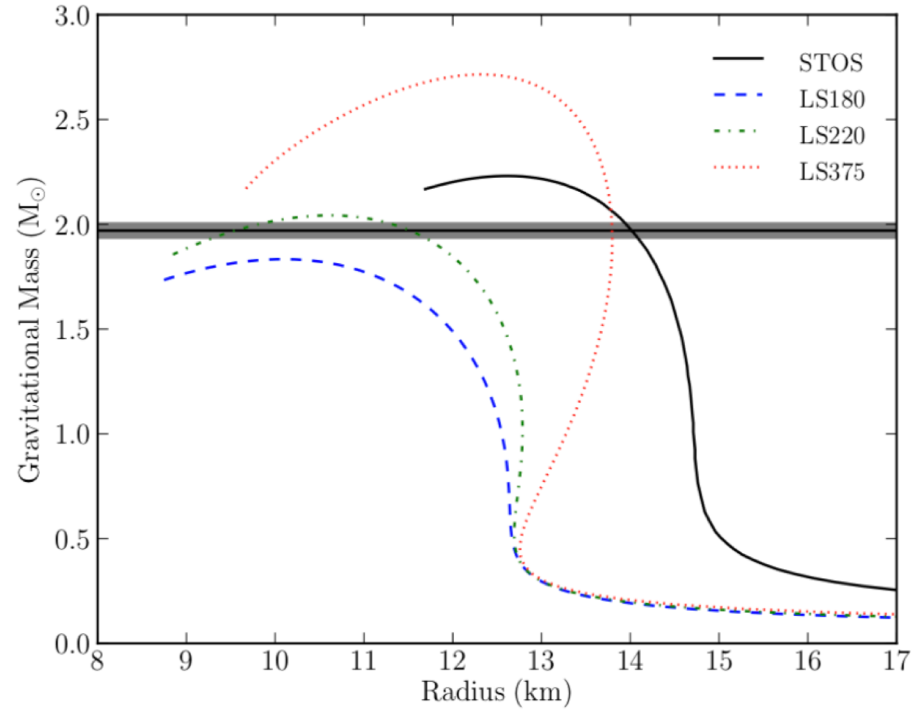




Bollig et al (2017)

Sensitivity to EOS stiffness



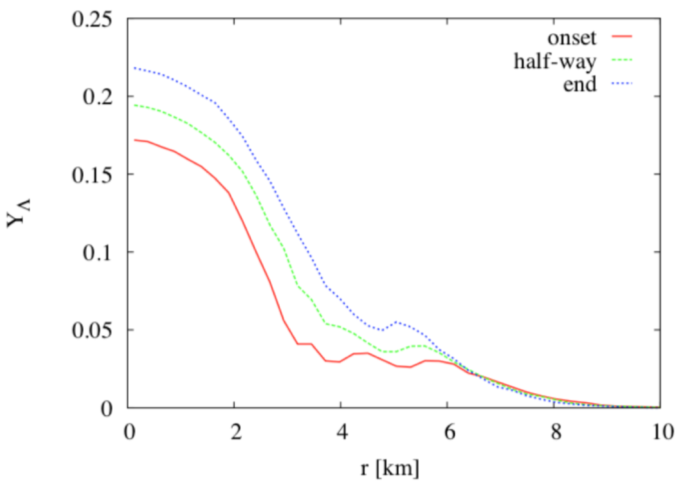


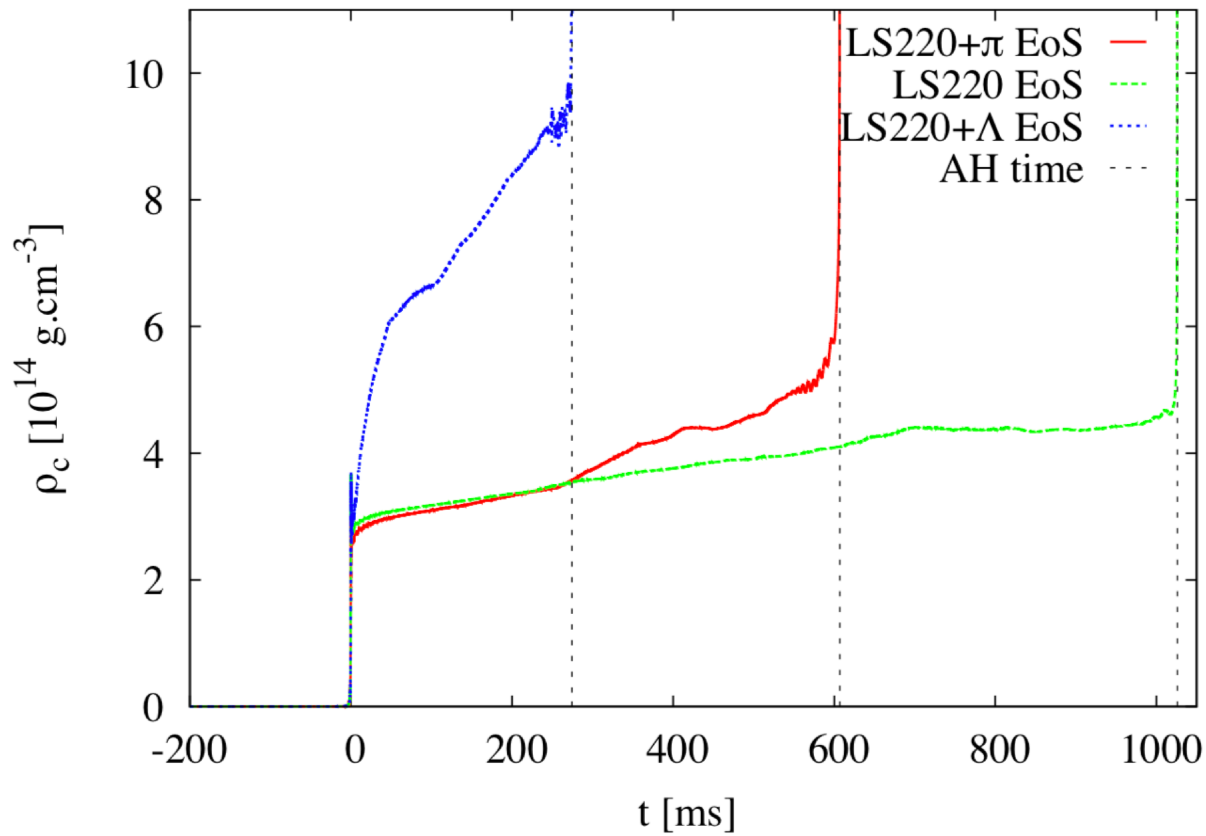
Softer EOS make explosions easier

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

Sensitivity to EOS: pions and hyperons

EOS including pions and hyperons



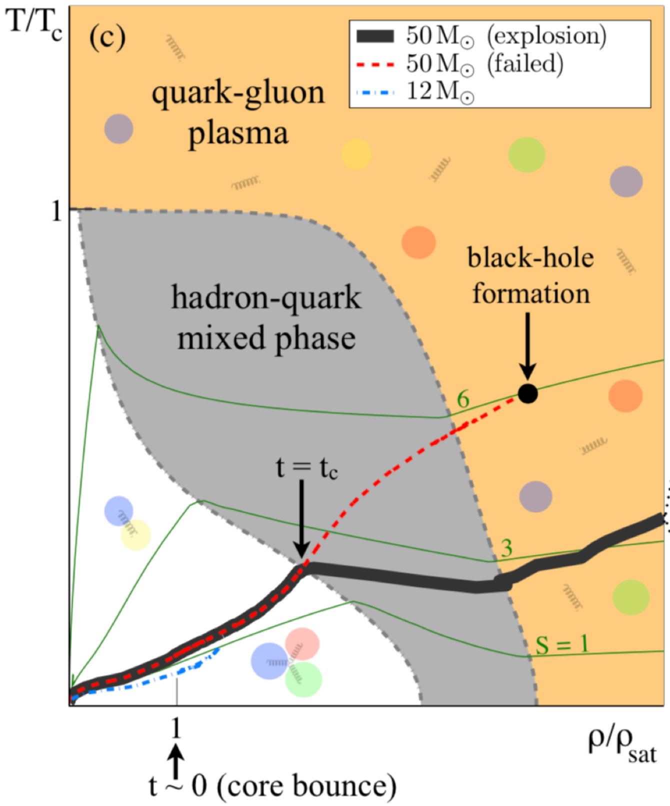


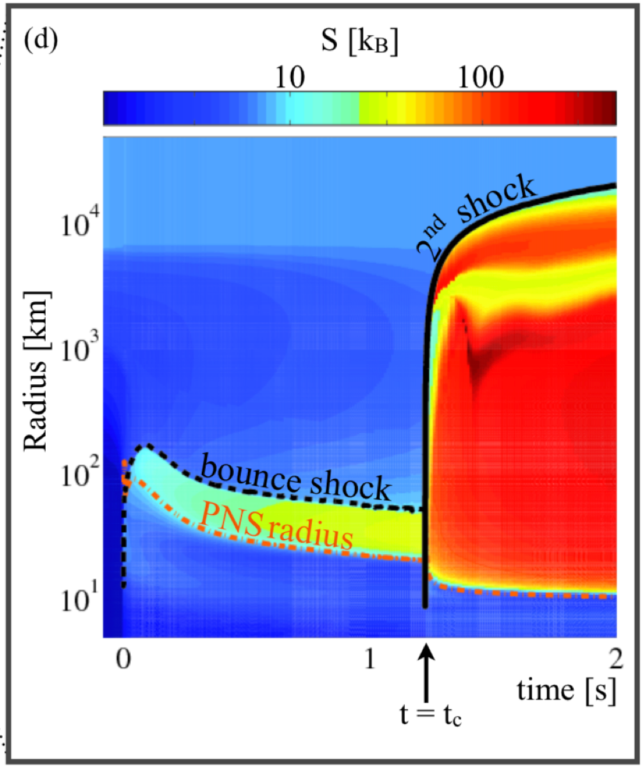
Peres et al 2013

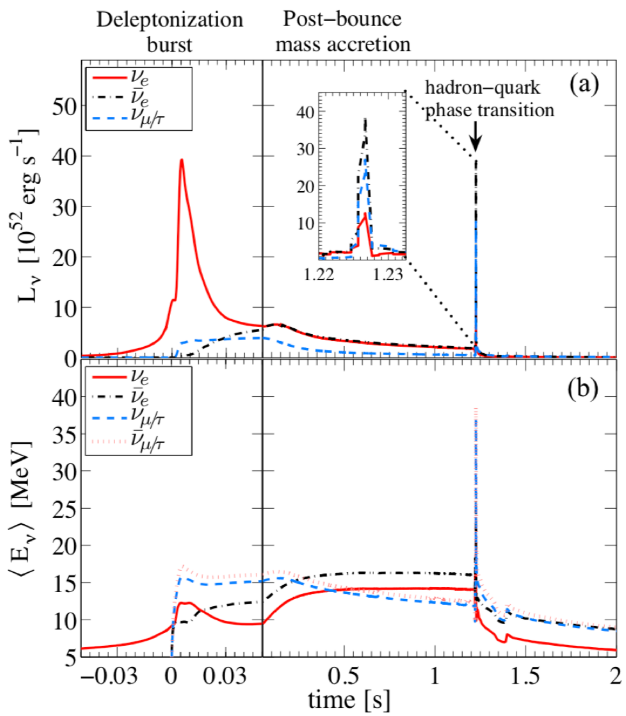
Phase transition to quark-gluon plasma ?

Strong explosion of high mass progenitor triggered by phase transition

Second peak of neutrino emission



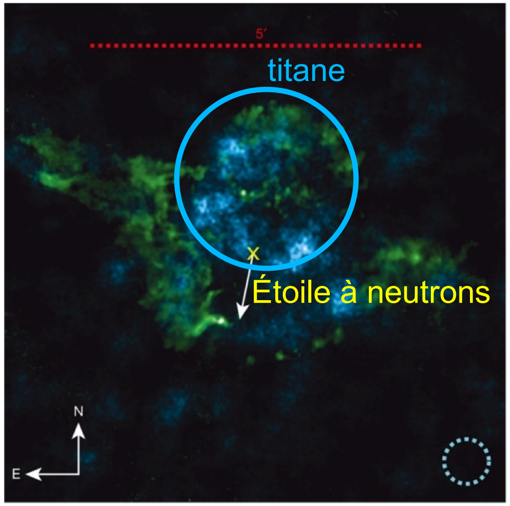




Fischer et al 2017

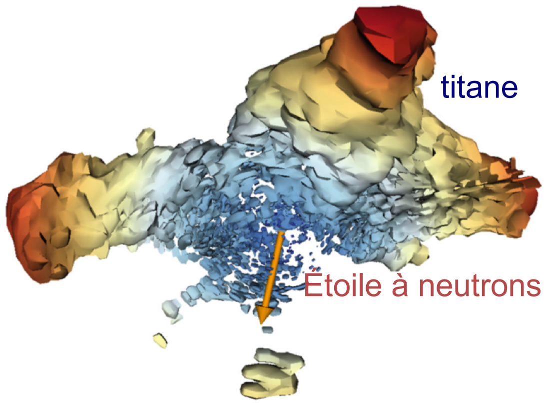
Explosion morphology revealed by nucleosynthesis

Observation of Cas A



Grefenstette et al 2014

Numerical simulation

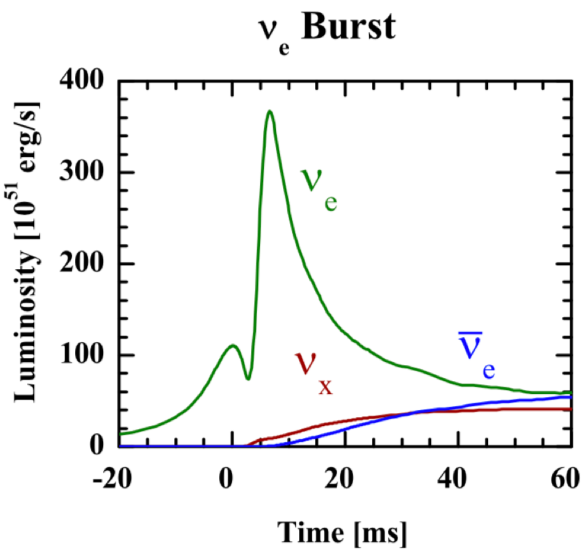


Wongwathanarat et al 2016, 2018

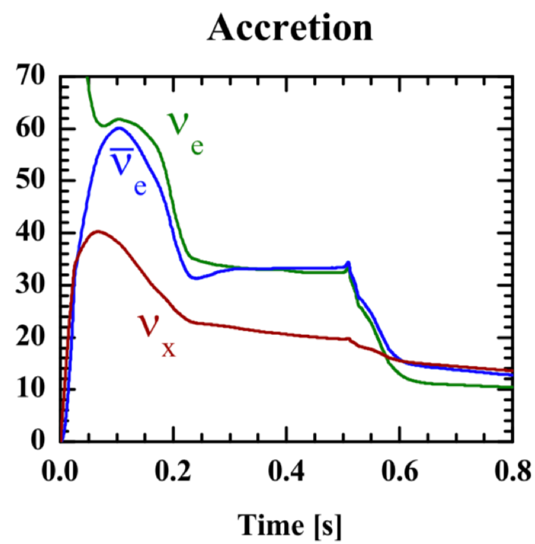
Titanium nucleosynthesis is a tracer of explosion asymetry

sensitive to electron fraction Ye

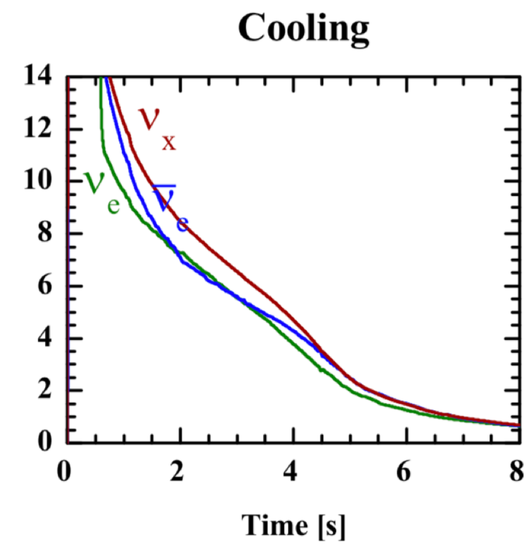
Neutrino signatures



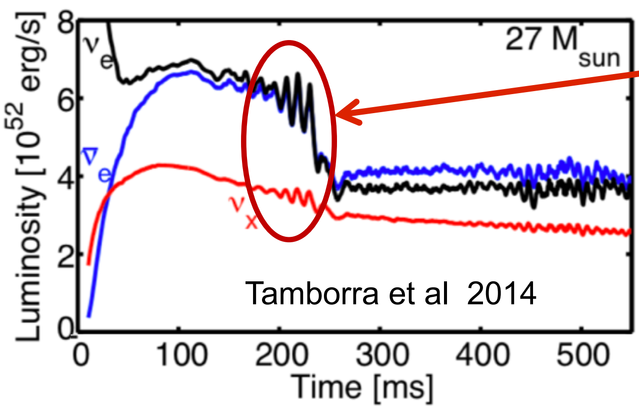
test oscillation physics



probes SN astrophysics



probes nuclear physics

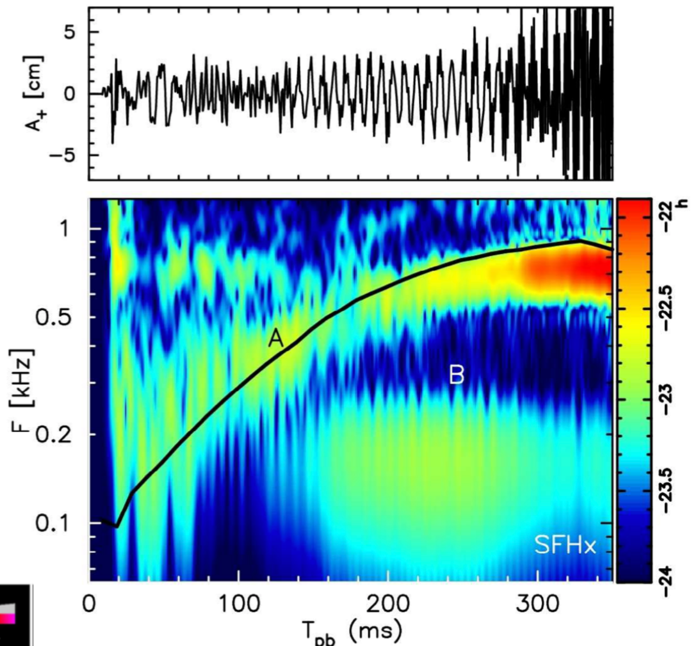


hydrodynamic instabilities

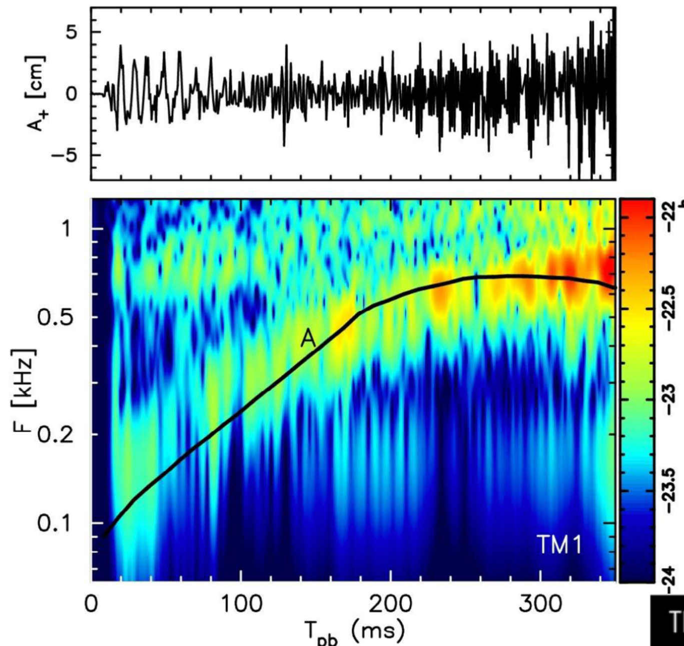
EOS & mass dependance

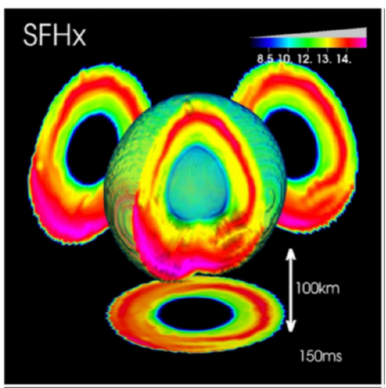
Gravitational wave signature

Softer EOS
(SFHx, Steiner+13)

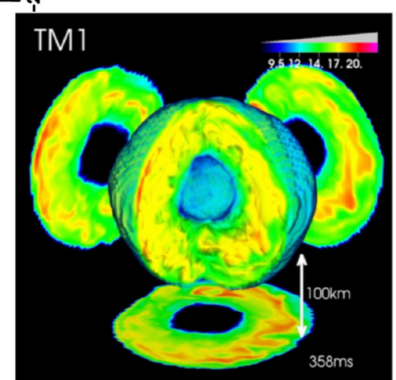


Stiffer EOS
(TM1, Hempel+10)





Kuroda+2016



Outstanding explosions: millisecond magnetars ?

Explosion kinetic energy :

→ Typical supernova 10^{51} J

→ Rare hypernova & GRB 10^{52} J
aka type Ic BL

→ Neutrino driven explosions ?

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

Total luminosity :

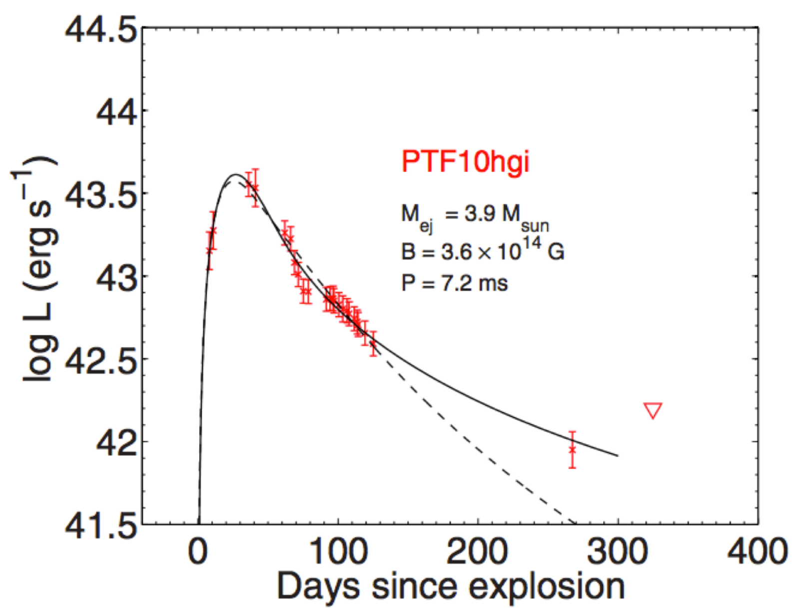
→ Typical supernova 10^{49} J

→ Superluminous supernovae 10^{51} J

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



Impact of a strong magnetic field on the explosion

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

+ fast rotation (period of few milliseconds)

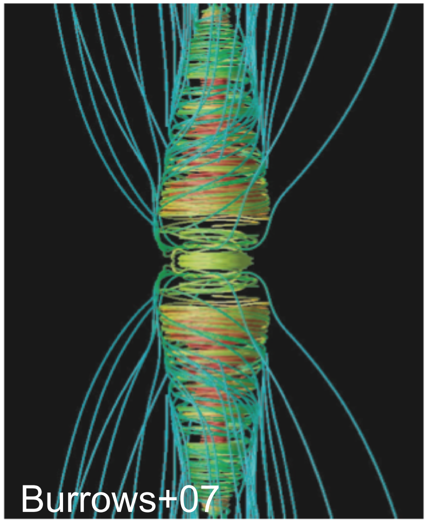
=> powerful jet-driven explosions !

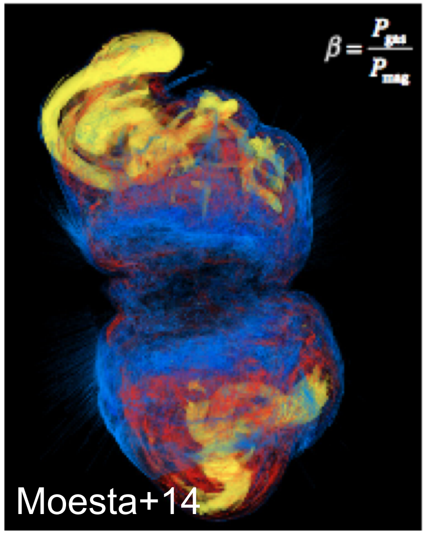
e.g. Sibata+06, Burrows+07, Dessart+08, Takiwaki+09,11, Winteler+12, Obergaulinger+17

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

Moesta+2014

Caveat: origin of the magnetic field is not explained

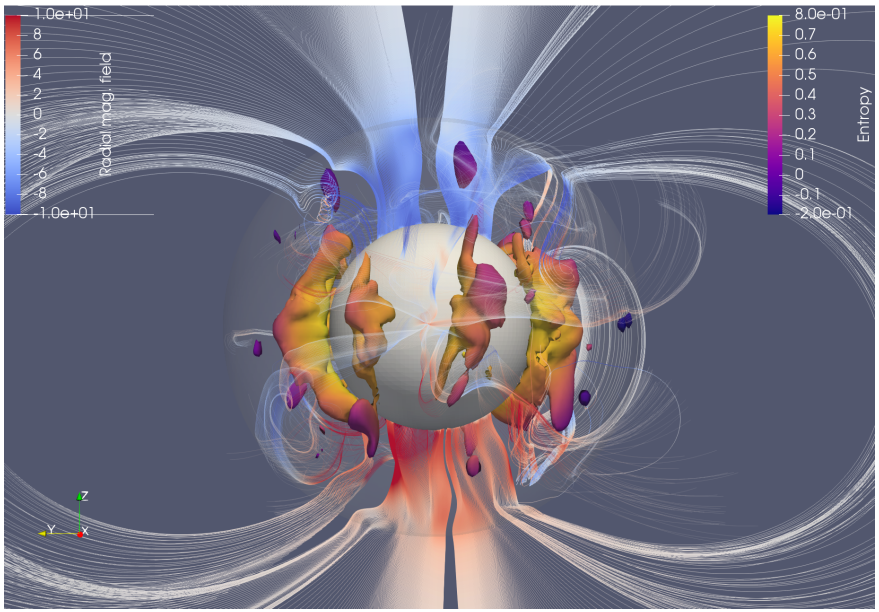

Burrows+07



Moesta+14

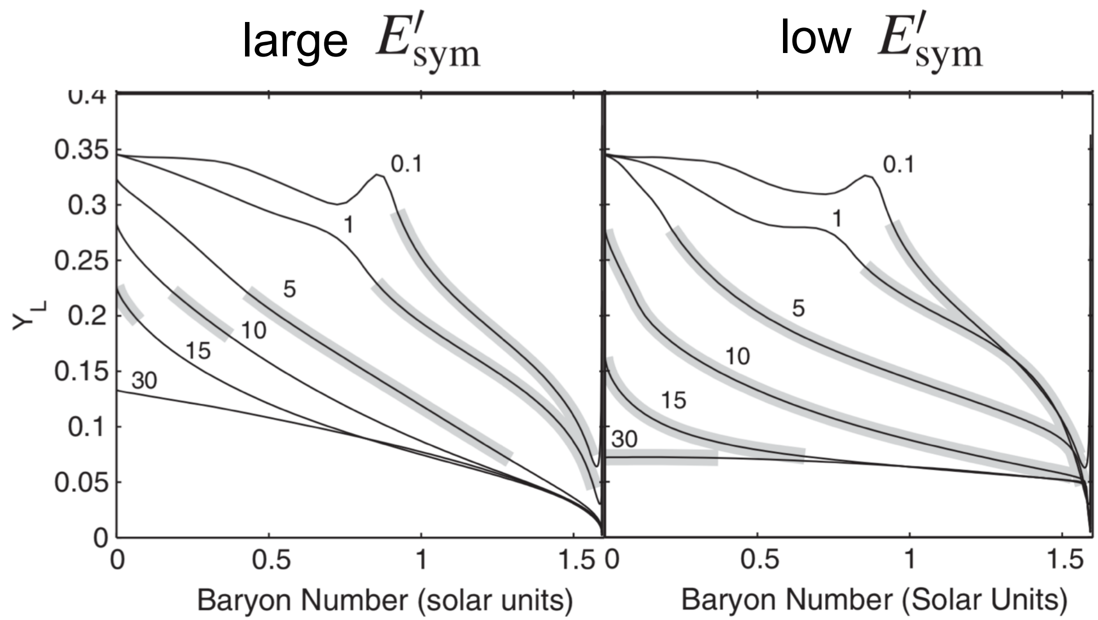
Magnetic field amplification

Dynamo with protoneutron star convection can generate a strong magnetic field



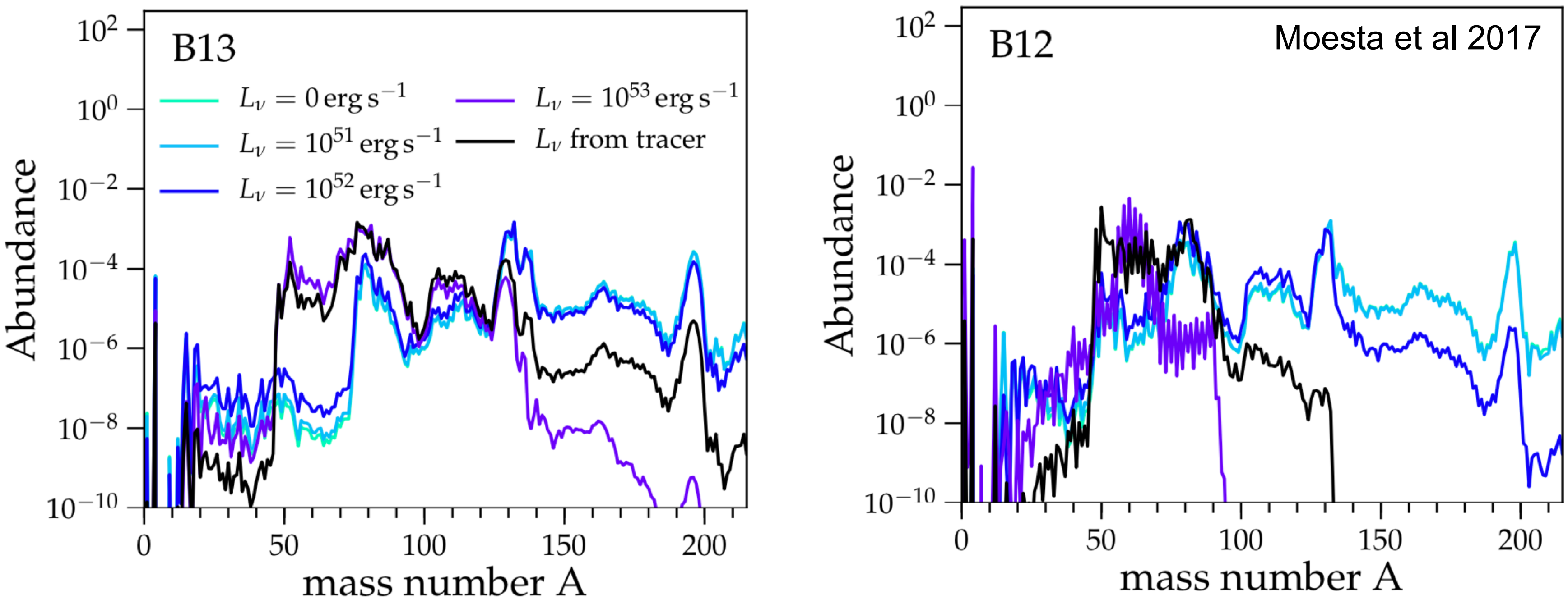
Raynaud & Guilet in prep

PNS convection depends strongly on EOS through slope of symmetry energy



Roberts et al 2012

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

Very rich and complex physics governs core collapse supernovae

Nuclear physics plays an important role in many aspects of supernovae

-> Equation of state

-> neutrino cross sections

-> nucleosynthesis

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

Thank you !