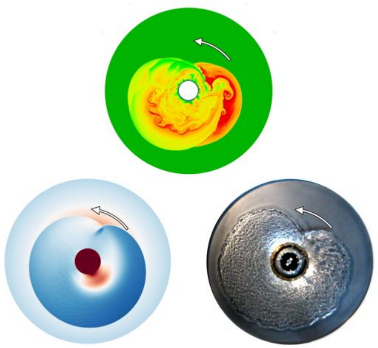
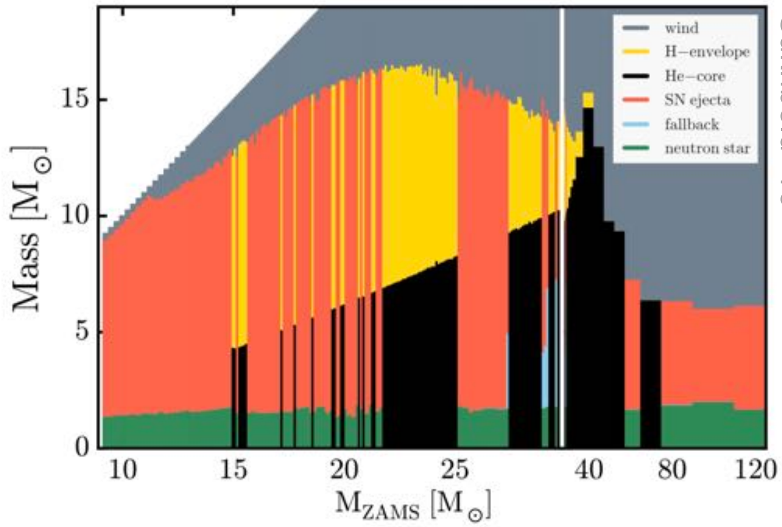
The impact of stellar parameters on the mechanism of stellar explosions



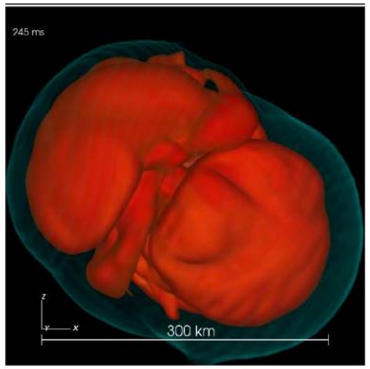
Thierry Foglizzo
CEA Saclay



Sukhbold+16

the main parameters of "standard" core-collapse

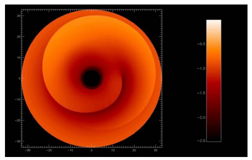
- -ZAMS mass M_{ZAMS}, compacity $\xi_{2.5}$
- -neutrino driven convection & SASI χ, Q_{SASI}, r_{sh}/r_{NS}
- -explosion threshold M_4, μ_4
- -precollapse inhomogeneities Ma_{conv}, l_{conv}
- -angular momentum in the stellar core j_{core}

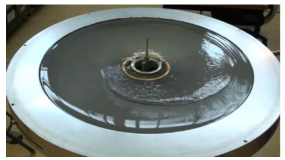


Hanke+13

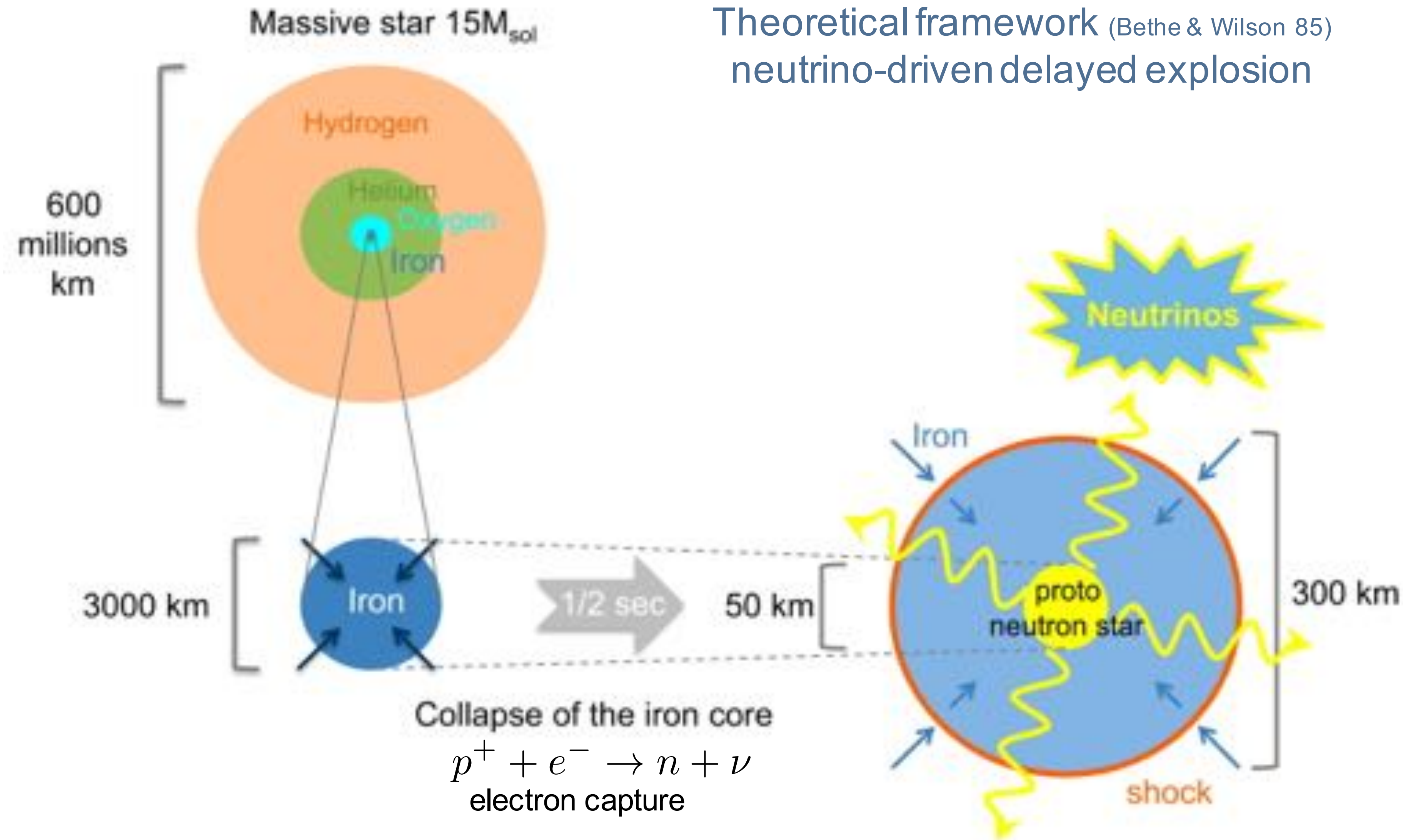
their impact on the explosion

their relation to the stellar structure





Theoretical framework (Bethe & Wilson 85)
neutrino-driven delayed explosion



Collapse of the iron core

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

electron capture

$$\frac{GM_{\rm ns}^2}{R_{\rm ns}} \sim 2\times 10^{53}{\rm erg}\left(\frac{30{\rm km}}{R_{\rm ns}}\right)\left(\frac{M_{\rm ns}}{1.5M_{\rm sol}}\right)^2$$

modest energy in differential rotation: $E_{\rm diff} < E_{\rm rot} \sim 2.4\times 10^{50}{\rm erg}\left(\frac{M_{\rm ns}}{1.5M_{\rm sol}}\right)\left(\frac{R_{\rm ns}}{10{\rm km}}\right)^2\left(\frac{10{\rm ms}}{P_{\rm ns}}\right)^2$

Towards ab initio simulations in 3D (MPA Garching)

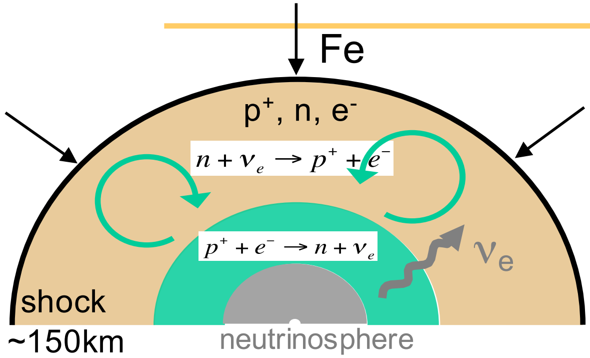
Hanke+13

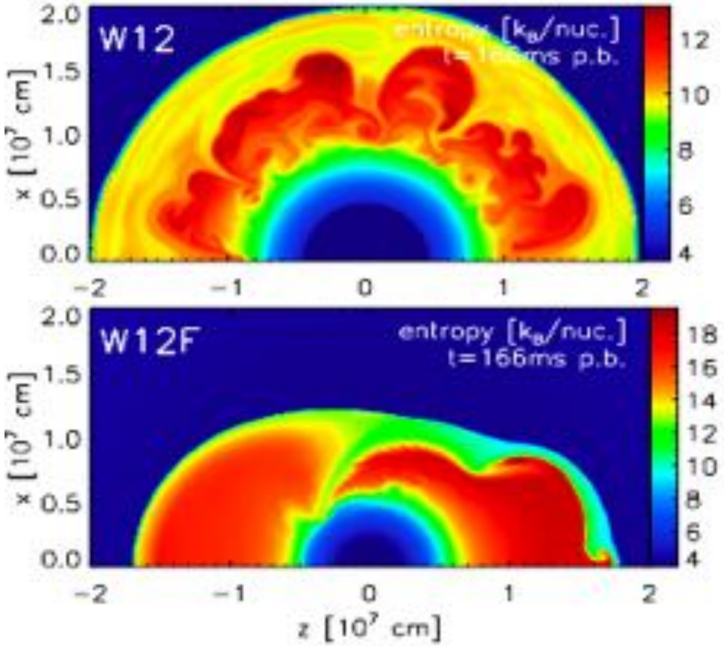
project PRACE 150 millions hours
16.000 processors, 4,5 months/model

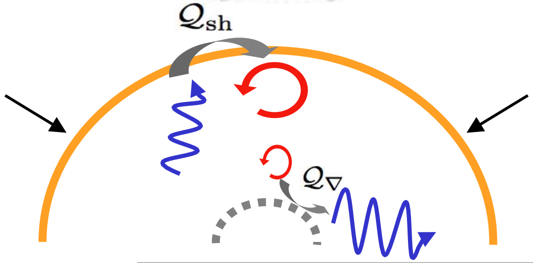
evolution time : 500ms
diameter: 300km

$27M_{sol}$

2 instabilities during the phase of stalled accretion shock







Neutrino-driven convection (Herant+92, ...)

- entropy gradient fed by neutrino absorption
- inhibited if the advection time is too short

(Foglizzo+06)

$$\chi \equiv \int_{\rm sh}^{\rm gain} \omega_{\rm BV} \frac{{\rm d}r}{v_r} < 3$$

SASI: Standing Accretion Shock Instability

(Blondin+03 ...)

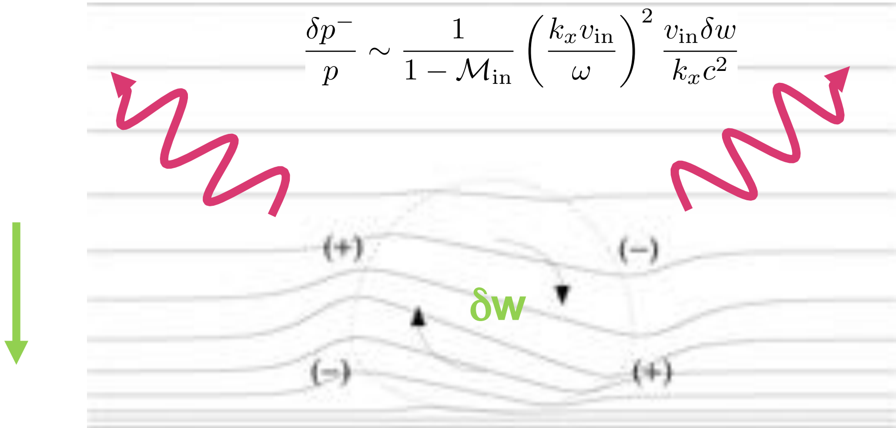
- advective-acoustic cycle
- oscillatory, large angular scale l=1,2:

  pulsar kick, nucleosynthesis imprint

  gravitational waves & neutrino direct signatures

Efficiency of the advective-acoustic feedback from adiabatic gradients

Foglizzo 09

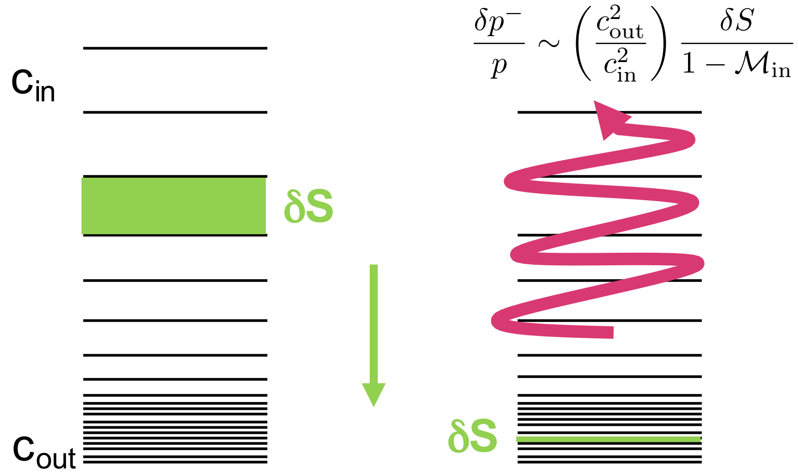


Vortical-acoustic coupling

advected vorticity → pressure feedback

Entropic-acoustic coupling

advected entropy → pressure feedback



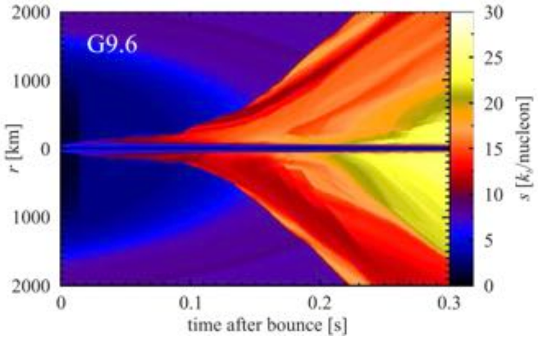
Progress of ab initio simulations: understandable diversity

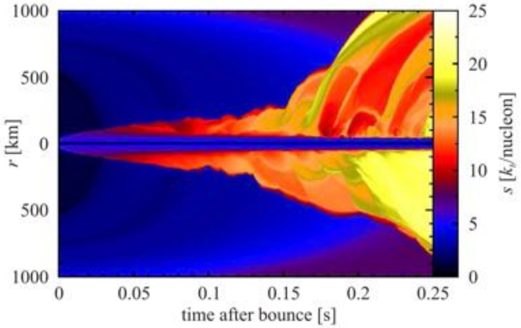
-axisymmetric explosions from first principles

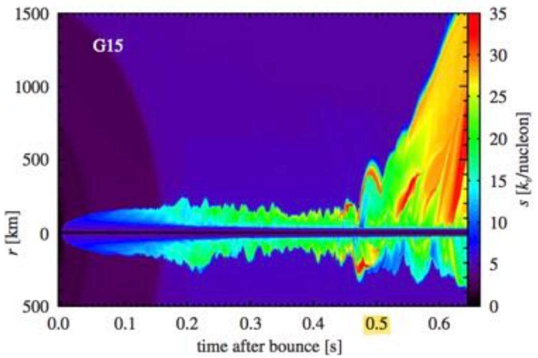
8.1, 9.6 ,11.2, 15, 27M_{sol} (MPA)

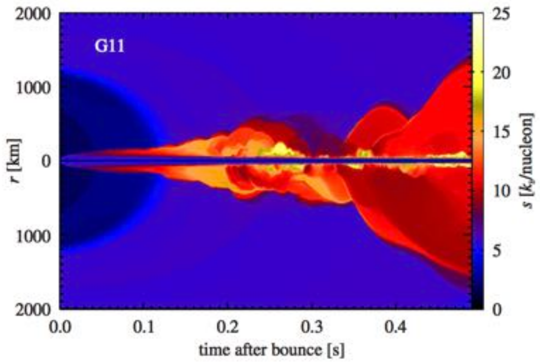
12, 15, 20, 25 M_{sol} (ORNL)

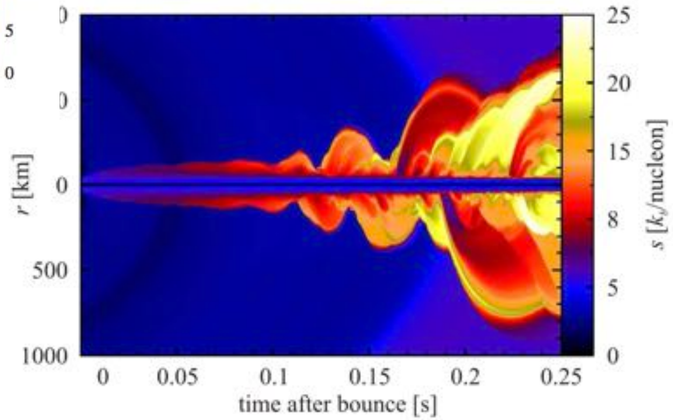
(Müller+12a,b,+13, Bruenn+13)











-depending on the progenitor, the dynamical evolution can be dominated by neutrino driven buoyancy (11.2M_{sol}) or by SASI (27M_{sol}) or by both (15M_{sol})

--competition between advection and buoyancy

(Foglizzo+06, Fernandez+13)

$$\chi \equiv \int_{\rm sh}^{\rm gain} \omega_{\rm BV} \frac{{\rm d}r}{v_r} < 3$$

-weakish explosion energy < 10^{51} erg

-lack of convergence between the numerical models (Bruenn+13)

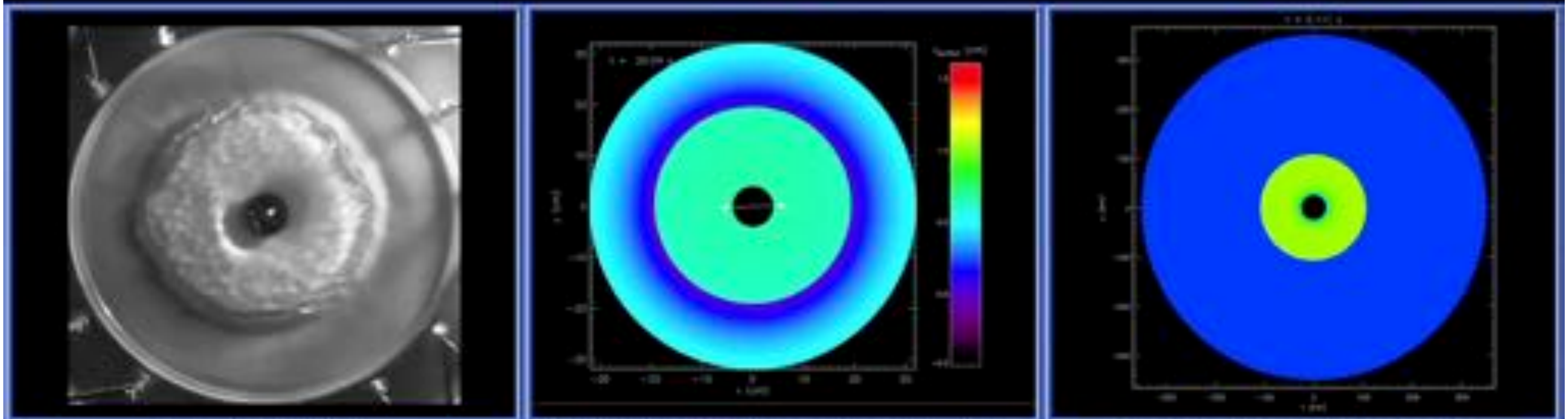
-neutrino transport questioned by Dolence+15

Dynamics of water in the fountain

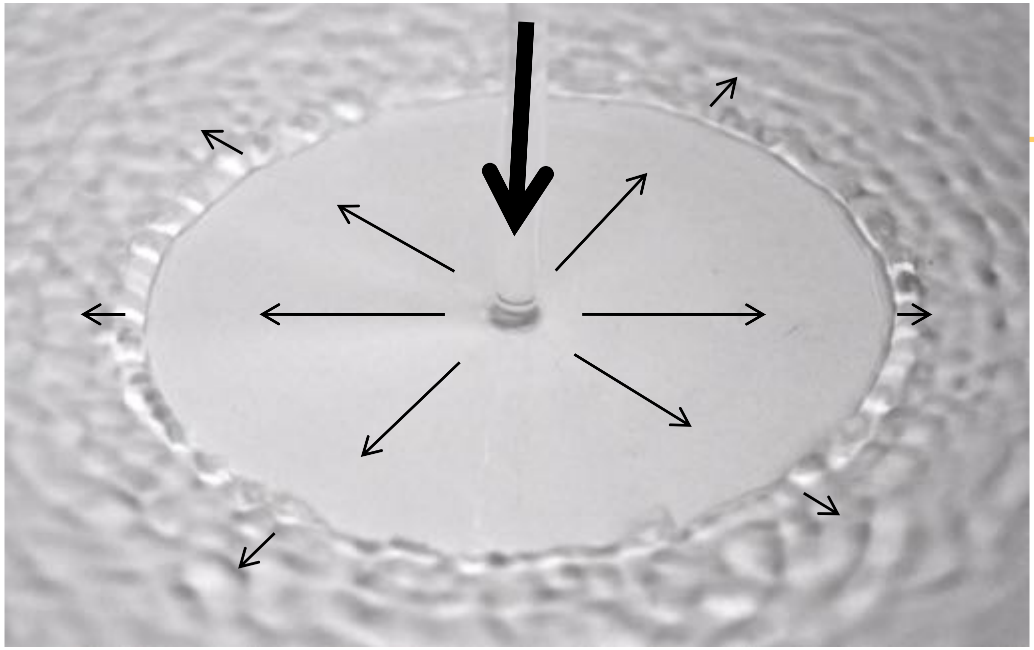
Dynamics of the gas in the supernova core

diameter 40cm ← 1 000 000 x bigger → diameter 400km

3s/oscillation ← 100 x faster → 0.03s/oscillation

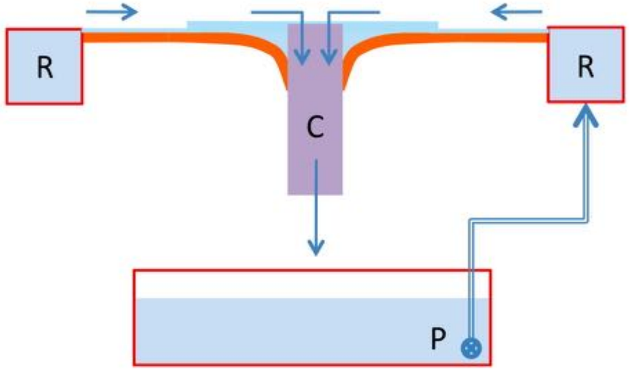


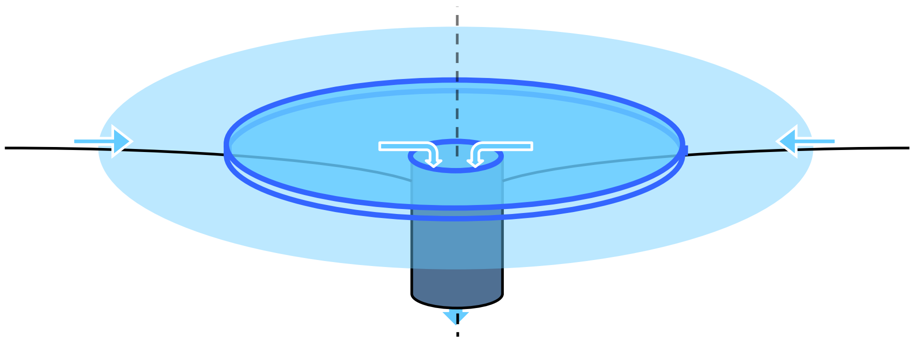
Expérience hydraulique | *Simulation numérique de l'expérience hydraulique* | *Simulation numérique de l'onde de choc dans le coeur de la supernova*



SWASI: an experimental analogue of SASI

Shallow Water Analogue of a Shock Instability

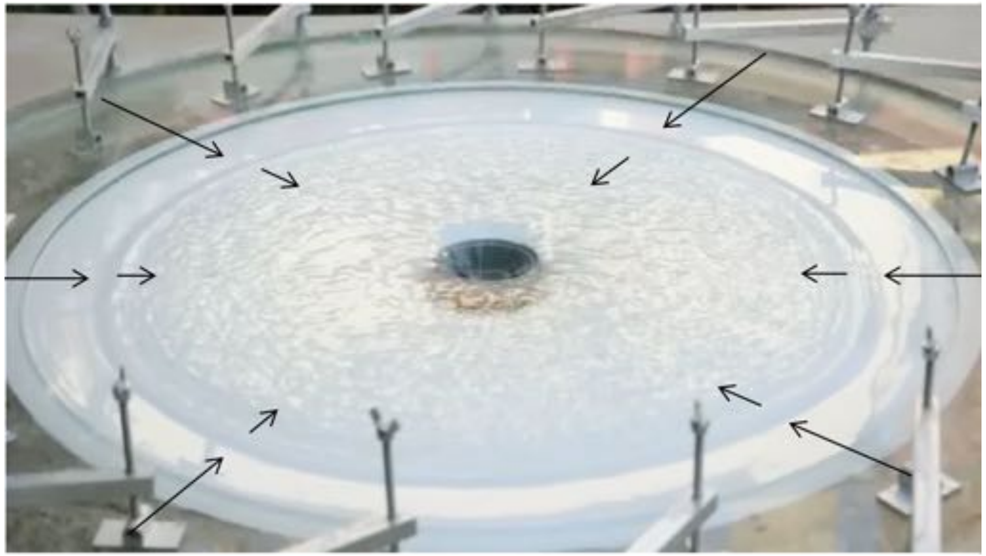




acoustic waves
shock wave
pressure

↔

surface waves
hydraulic jump
depth



Formal similarity between SASI and SWASI

accretion of gas (on a cylinder)

density ρ, velocity v, sound speed $c \propto \rho^{\frac{\gamma-1}{2}}$

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho v) = 0$$

$$\frac{\partial v}{\partial t} + w \times v + \nabla \left(\frac{v^2}{2} + c^2 \log \frac{\rho}{\rho_0} + \Phi \right) = 0$$ isothermal

$$\frac{\partial v}{\partial t} + w \times v + \nabla \left(\frac{v^2}{2} + \frac{c^2}{\gamma - 1} + \Phi \right) = \frac{c^2}{\gamma} \nabla S$$ adiabatic

inviscid shallow water accretion

depth H, velocity v, wave speed $c = (gH)^{\frac{1}{2}}$

$$\Phi = gz$$

$$c^2 = gH$$

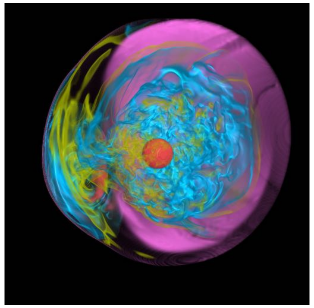
$$\frac{\partial H}{\partial t} + \nabla \cdot (Hv) = 0$$

$$\frac{\partial v}{\partial t} + w \times v + \nabla \left(\frac{v^2}{2} + c^2 + \Phi \right) = 0$$

- Inviscid shallow water: analogue to an isentropic gas γ=2

(intermediate between "isothermal" and "γ=2 without entropy")

3D spherical
γ=4/3



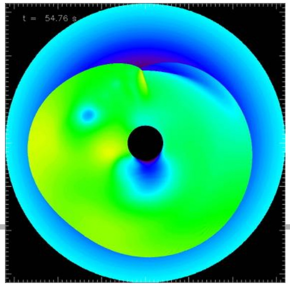
Blondin & Mezzacappa 07

expected scaling $\frac{t_{\rm ff}^{\rm sh}}{t_{\rm ff}^{\rm jp}} \equiv \left(\frac{r_{\rm sh}}{r_{\rm jp}} \right) \left(\frac{r_{\rm sh} g H_{\rm jp}}{G M_{\rm NS}} \right)^{\frac{1}{2}} \sim 10^{-2}$

shock radius $\times 10^{-6}$ 200 km → 20 cm

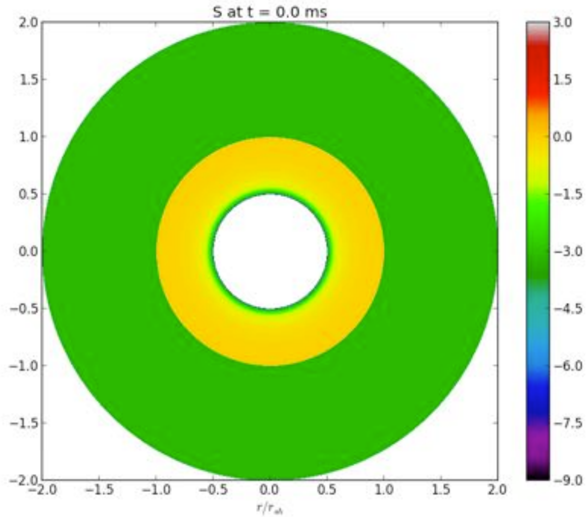
oscillation period $\times 10^{2}$ 30 ms → 3 s

2D cylindrical
γ=2 isentropic

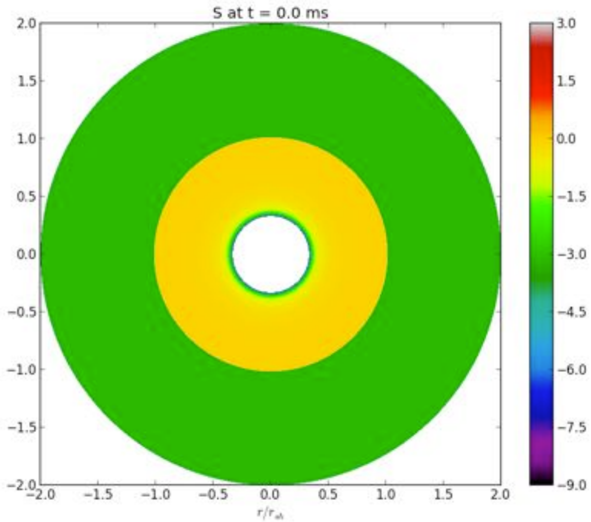


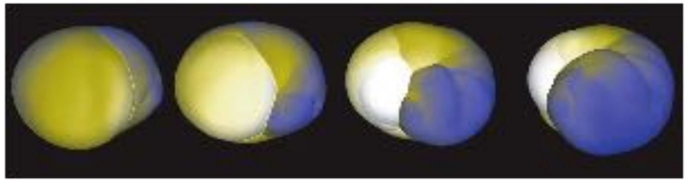
Spin up uf the neutron star induced by the spiral mode of SASI

$r_{sh}/r_{NS} = 2$



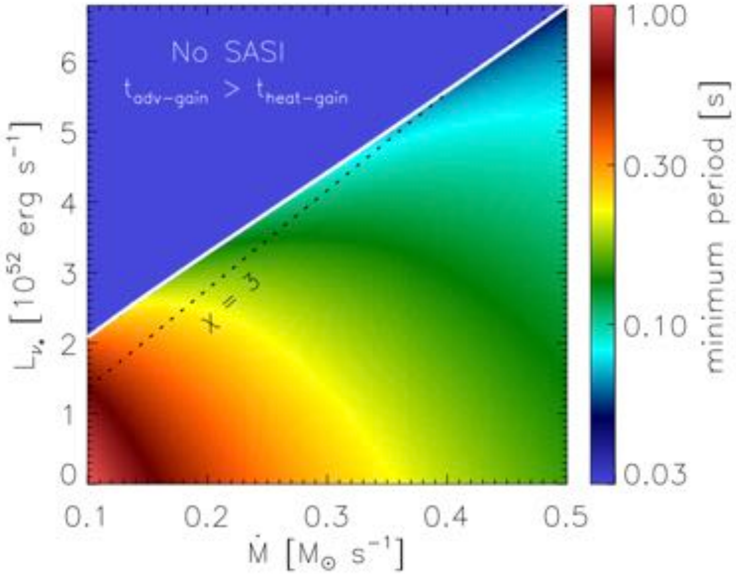
$r_{sh}/r_{NS} = 3$

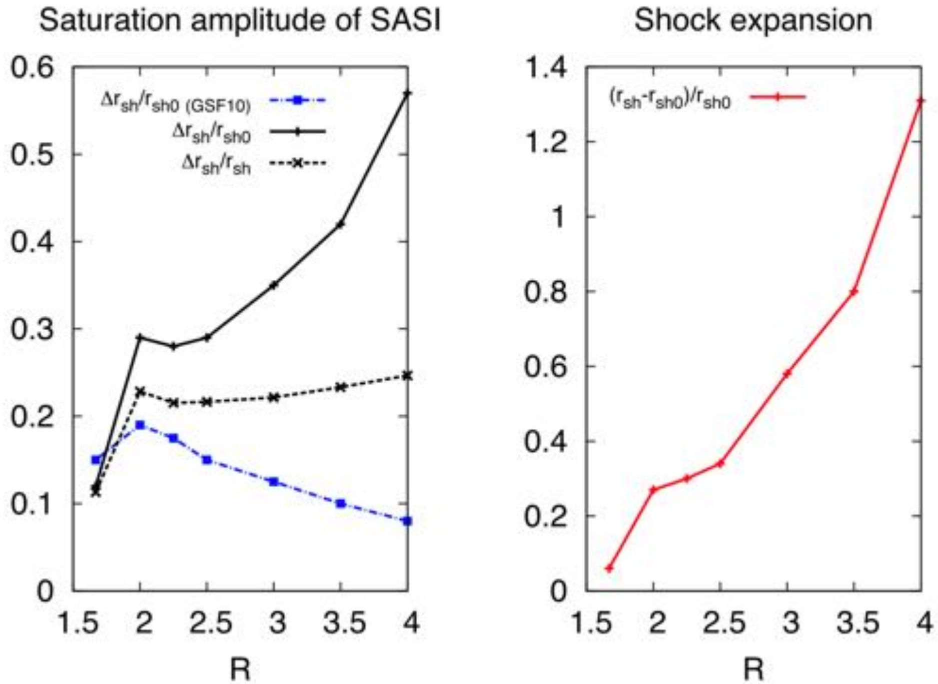




Blondin & Mezacappa 07

Guilet & Fernandez 14





Kazeroni+16

-the strength of SASI increases with the radius ratio $R = r_{sh}/r_{NS}$
-unexpected stochasticity

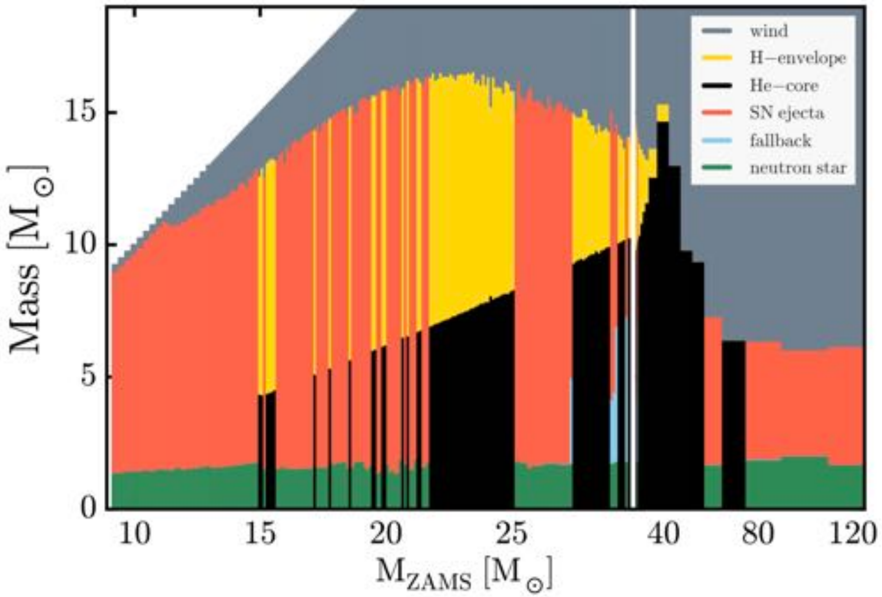
« Islands of explodability in a sea of black hole formation »

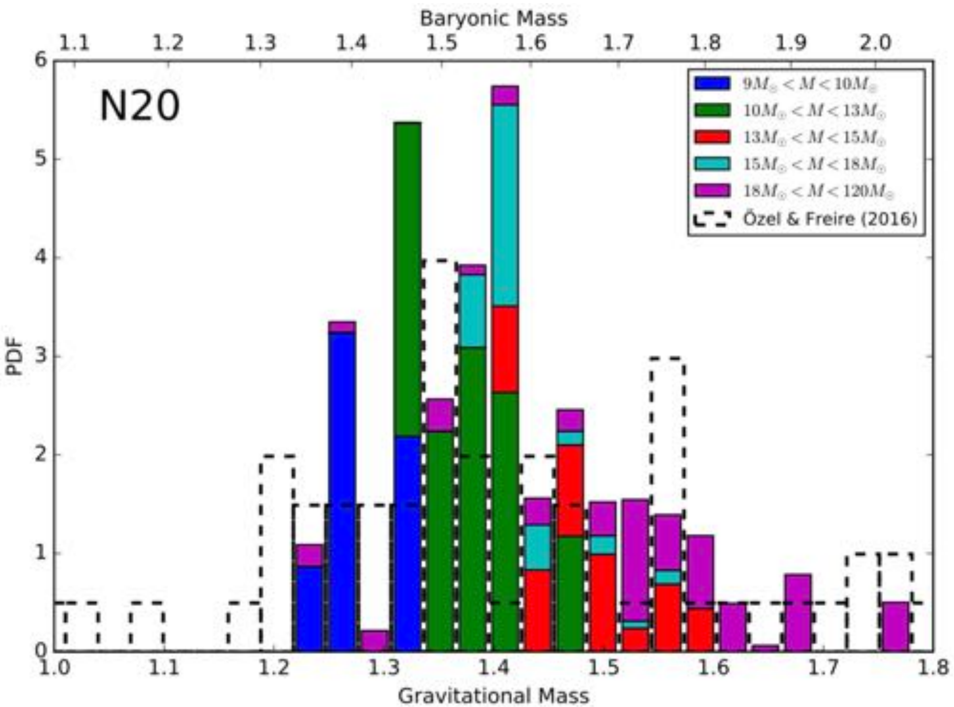
Sukhbold+16

1-D models calibrated with SN1987A (~18M_{sol}) and the Crab (~10M_{sol})

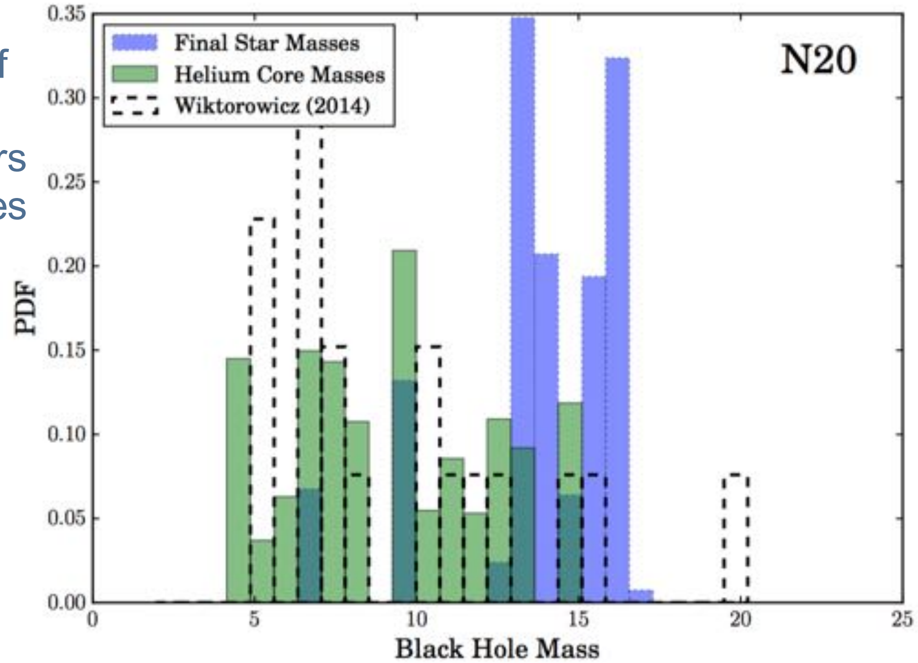
but -SN1987A was peculiar (Morris & Podsiadlowski 07)
-the SASI/convective multi-D diversity is ignored

also -single star evolution: binarity is ignored (Sana+12)
-rotation is neglected



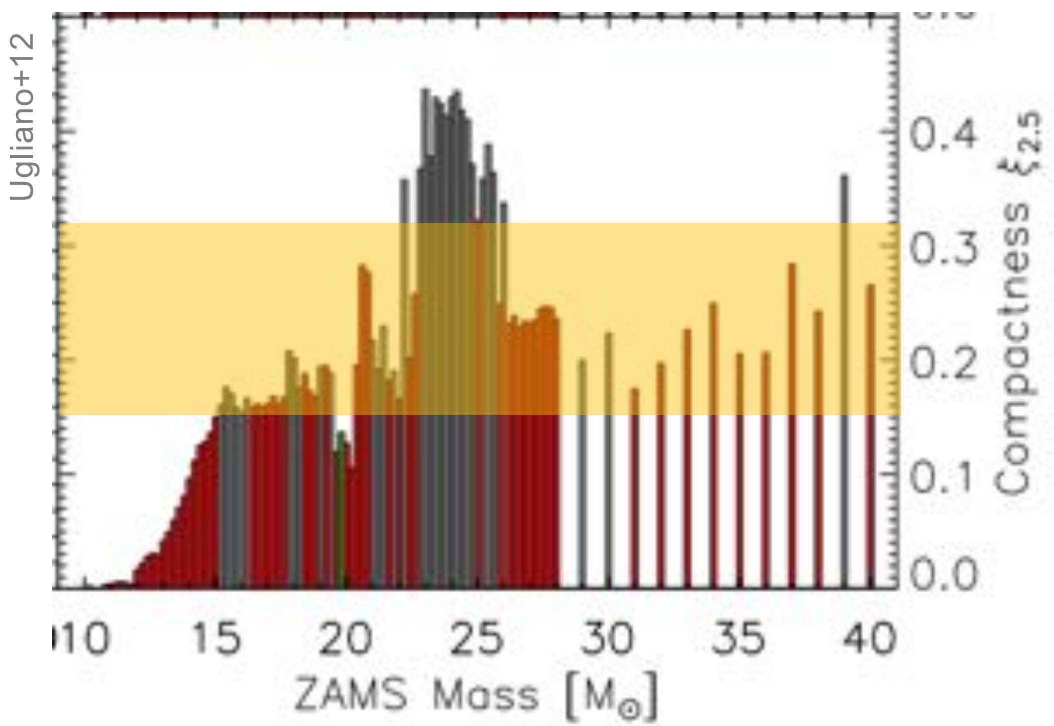


distribution of masses of neutron stars and black holes



The compactness captures a large fraction of the explosion threshold

(Ugliano+12, Ertl+16, Sukhbold+16)



$$\xi_M \equiv \frac{M}{M_{\rm sol}} \frac{1000{\rm km}}{R(M)}$$
$$\sim 3\times 10^{-3} \frac{R_{\rm Schw}(M)}{R(M)}$$

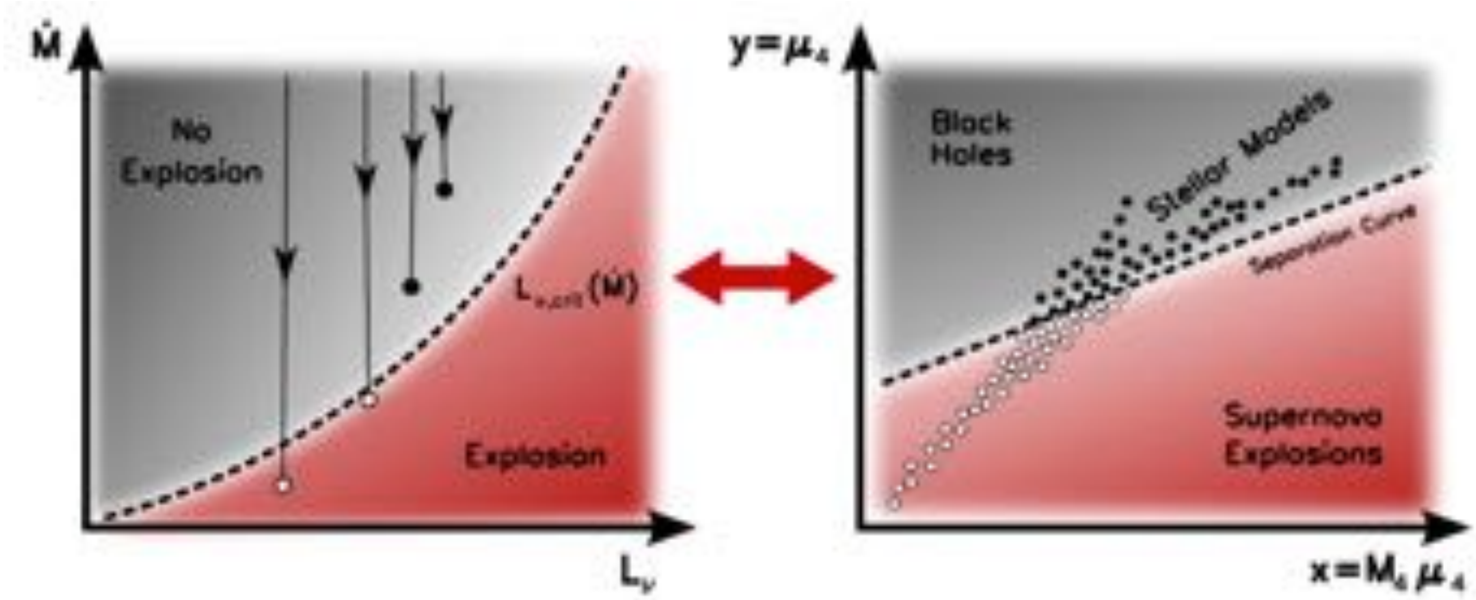
SN/BH threshold

ξ=0.45 ? (O'Connor & Ott 11)
ξ=0.2 ? (Horiuchi+14)

inconclusive for $0.15<\xi<0.32$ (Ugliano+12)

A two-parameter criterion for the explosion?

from Burrows & Goshy 93 to Ertl+16



$$M_4 \equiv \frac{m(s=4)}{M_{\rm sol}}$$

$$\mu_4 \equiv \frac{1000\mathrm{km}}{M_{\rm sol}} \frac{dm}{dr}\Big|_{s=4}$$

structural parameters measured **before collapse**, when $\rho(r=0)=5\times10^{10}$g/cm^3

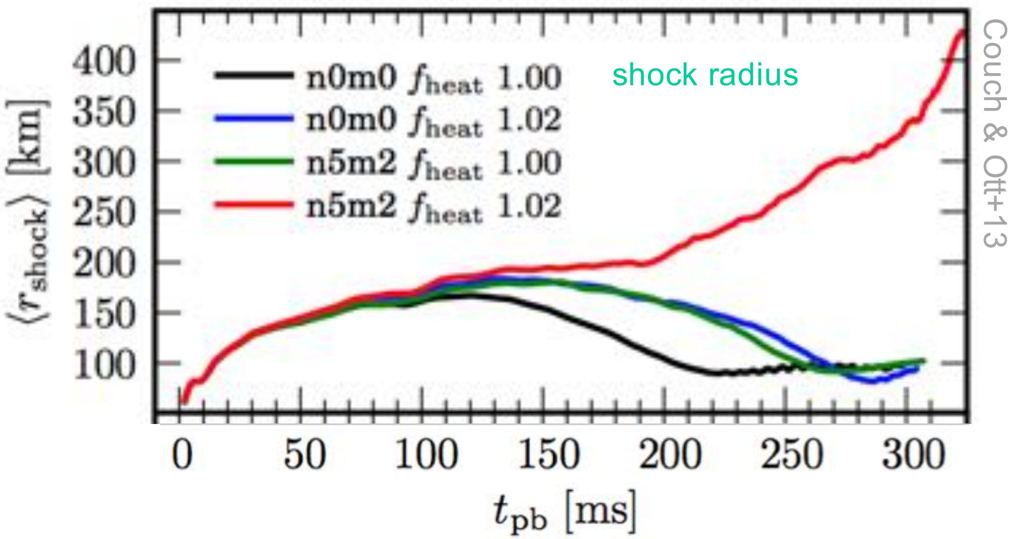
- s=4 ~ base of the oxygen shell
- M_4 ~ accretor mass
- μ_4 ~ mass accretion rate
- $M_4\,\mu_4$ ~ neutrino luminosity

Effect of the missing parameters ?

– advective stabilisation of advection
- SASI efficiency
- precollapse asymmetries
- angular momentum

The explosion is sensitive to precollapse convective asymmetries

(Couch & Ott+13, 15, Müller & Janka 15, Couch+15, Abdikamalov+16, Müller+16)



$\Delta L_\nu/L_\nu$~2-3% (15M_{sol})
Couch+Ott+13

$\Delta L_\nu/L_\nu$~12-24% (18M_{sol})
Müller+16

Müller+16: Oxygen burning during the last 5mn before the core-collapse of a 18M_{sol} progenitor

-increase of the convective Mach number up to Ma_{conv}~0.1

-impact of the **radial size Δr of the convective O shell**: final emergence of a **large scale** mode **l~ πr/Δr ~**2 due to the fast contraction of the Si-Fe core

-reduction of the critical neutrino luminosity by 12-24% (18M_{sol} is a favourable case)

How to relate the explosion parameters to the stellar parameters ?

NS, BH ←→	collapse/explosion dynamics ←→	precollapse structure ←→	RSG/BSG phase ←→	MS evolution ←→	ZAMS
R_{NS}~10km	R_{PNS}~50km	R_{Fe}~1500km			
	mass accretion rate ν luminosity	$\xi_{2.5}$ <0.15-0.35 compactness M_4, μ_4 (Ertl+16)	Si/O interface		M_{ZAMS}
NS kick V_{NS} ~ 0-10^4km/s	χ>3 ν-driven convection Q_{SASI}>1, r_{sh}/r_{NS} >2 SASI				11.2, 15M_{sol} 15, 27M_{sol}
	turbulent pressure low l=2 forcing	size of convective O, Si inhomogeneities			
P_{NS} ~ 10-100ms j_{NS}~6x10^{13-14}cm^2/s (Popov & Turolla 12)	j(r,θ,t) angular momentum	j_{core} (r,θ) ~4x10^{14}cm^2/s with B (Heger+05) ~10^{13-14}cm^2/s with IGW (Fuller+15)	RG hints (Cantiello+14)		
j_{NS}<6 10^{15}cm^2/s P_{NS} > 1ms	low T/W instab. j_{NS}>10^{15}cm^2/s ?				