Hydrodynamic instabilities

Thierry Foglizzo

CEA Saclay

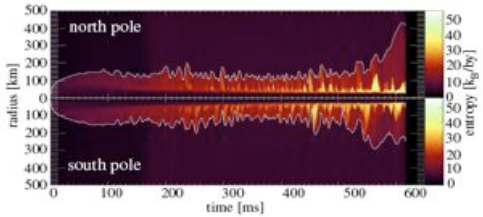
Hydrodynamic instabilities

Thierry Foglizzo

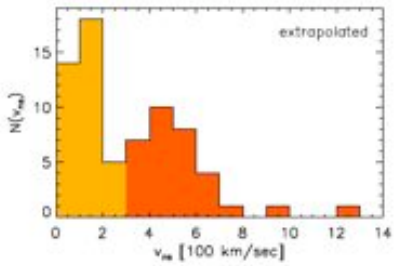
CEA Saclay

The possible consequences of hydro instabilities: SASI, buoyancy and shear

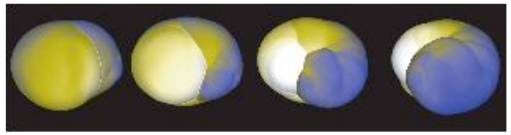
- successful explosion of $15M_{sol}$ driven by neutrino energy
  (Marek & Janka 09, Suwa+10, Müller+12)



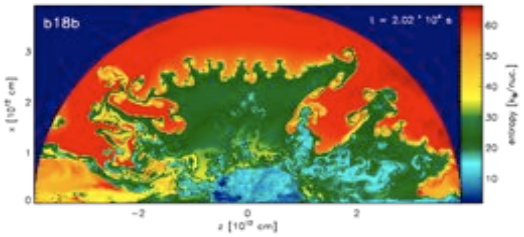
- pulsar kick
  (Scheck+04, 06, Nordhaus+10, **Wongwathanarat+10**)



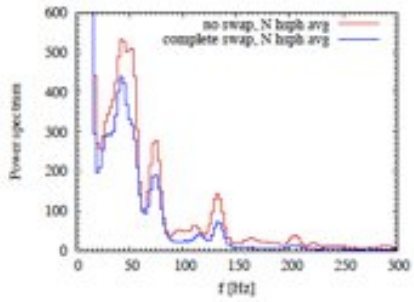
- pulsar spin ?
  (**Blondin & Mezzacappa 07**, Yamasaki & Foglizzo 08, **Iwakami+09**, **Fernandez 10**, **Rantsiou+11**)



- H/He mixing in SN1987A
  (Kifonidis+06, **Scheck 07**, **Hammer+09**)

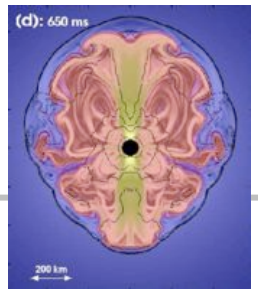


- gravitational waves
  (Ott+06,+08, Kotake+07,**+09**,**+11**, Marek+09, Murphy+09, **Müller+12**)



- neutrino signal
  (Marek+09, Lund+10, Brandt+11, **Müller+12**)

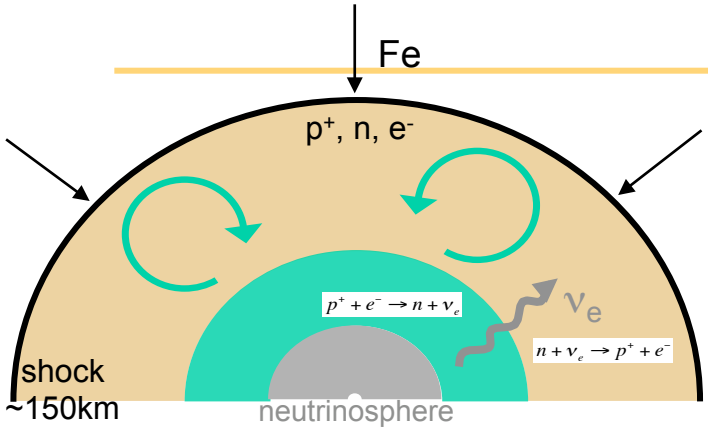
- magnetic field amplification
  (Endeve**+10**,**+12**, Guilet+11, Obergaulinger & Janka 11)



Outline

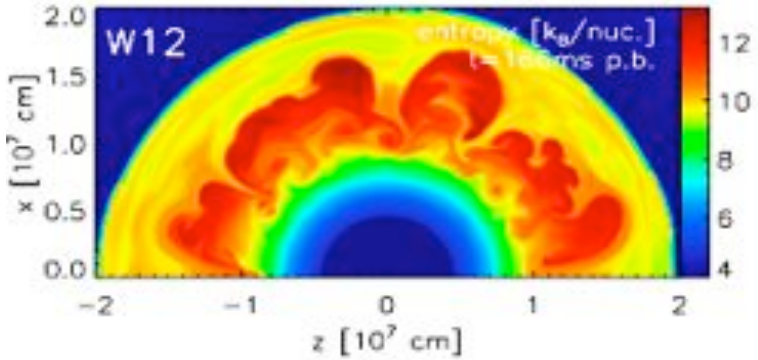
- What is SASI, what is ν-driven convection ?
- Can SASI be disentangled from ν-driven buoyancy ?
- What is left of SASI in 3D "realistic" simulations ?
- Connexion between SASI and ...
  - the ν-driven explosion mechanism ?
  - the acoustic mechanism ?
  - pulsar kick ?
  - pulsar spin ?
  - gravitational waves ?
  - ν-signature ?
  - explosion anisotropies, mixing ?

Instabilities during the phase of stalled accretion shock

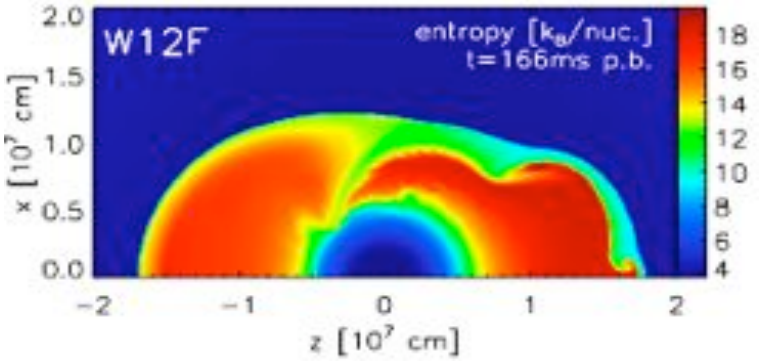


Foglizzo et al. 06, Müller et al. 12

neutrino driven convection
+
SASI



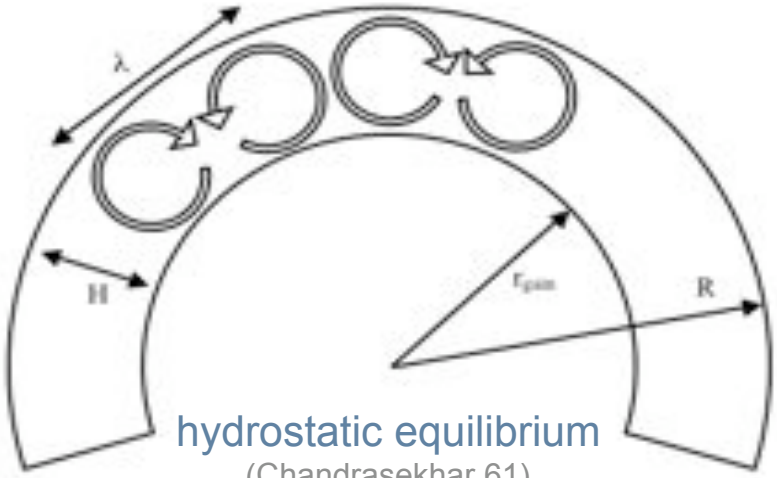
- Neutrino driven convection, l>5
  (Herant, Benz & Colgate 92, ...)



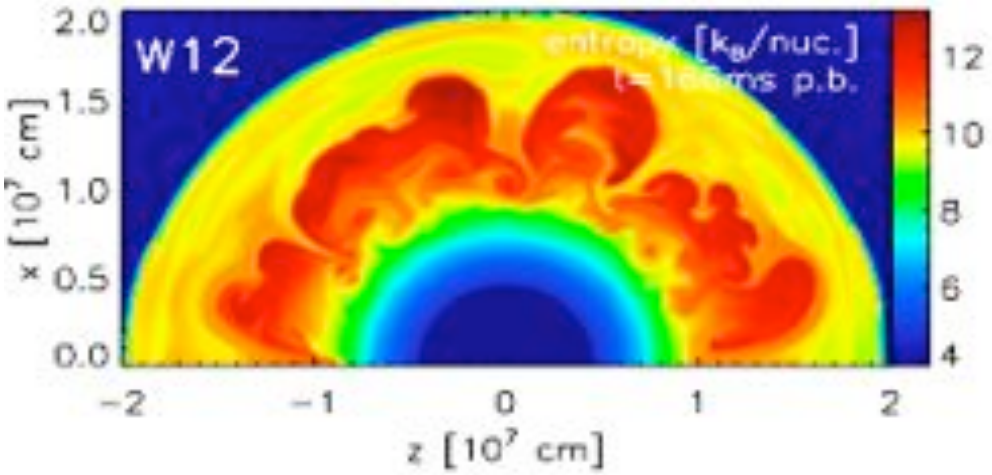
- SASI in an adiabatic flow l=1,2
  (Blondin et al. 03 ...)

What do we understand of convection and SASI ?

Contribution of the neutrino-driven convection to a mode l=1 ?



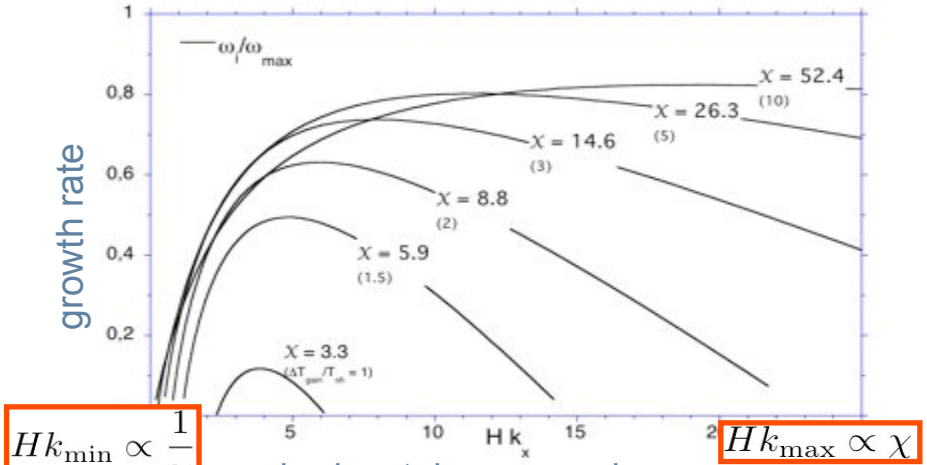
hydrostatic equilibrium
(Chandrasekhar 61)



Foglizzo, Scheck & Janka 06

$$\chi \equiv \frac{\tau_{\rm adv}}{\tau_{\rm buoy}} \sim \frac{H\omega_{\rm buoy}}{v} \sim \left(\frac{\mathcal{G}M}{r_{\rm sh}v_2^2}\right)^{\frac{1}{2}} \left(\frac{H}{r_{\rm sh}}\right)^{\frac{1}{2}} \sim 3.1 \left(\frac{v_1}{7v_2}\right) \left(\frac{H}{0.4r_{\rm sh}}\right)^{\frac{1}{2}}$$

!

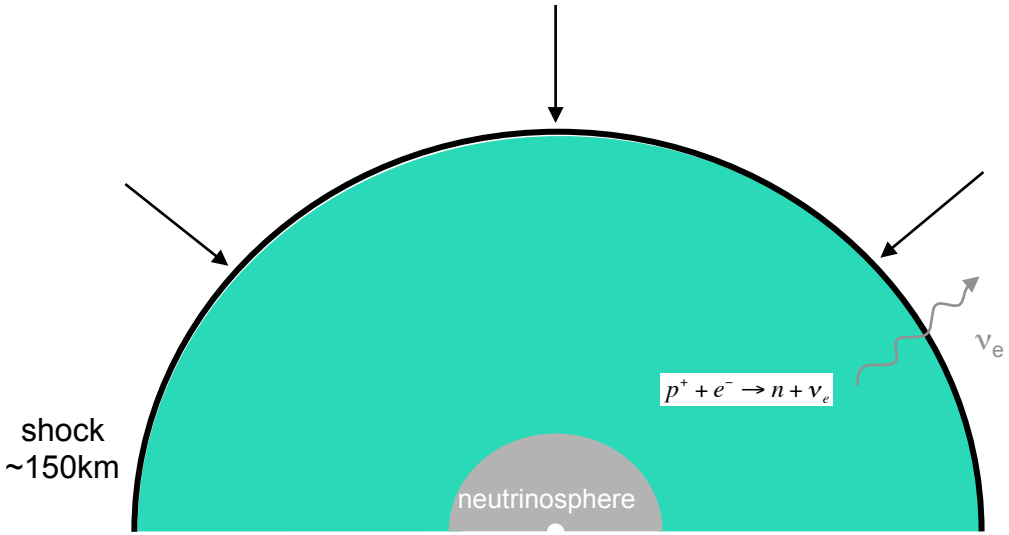


threshold $\chi \sim 3$

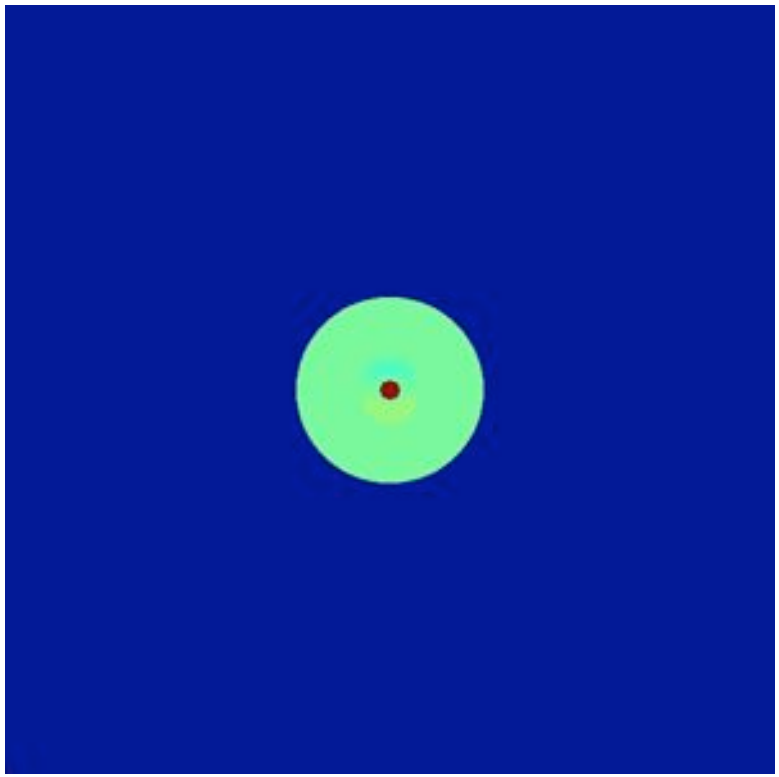
->the convective instability cannot be responsible for large scale oscillations (also Yamasaki & Yamada 07)

but non linear buoyancy may drive turbulence
(Scheck et al. 08, Fernandez & Thompson 09)

Stationary Accretion Shock Instability : SASI



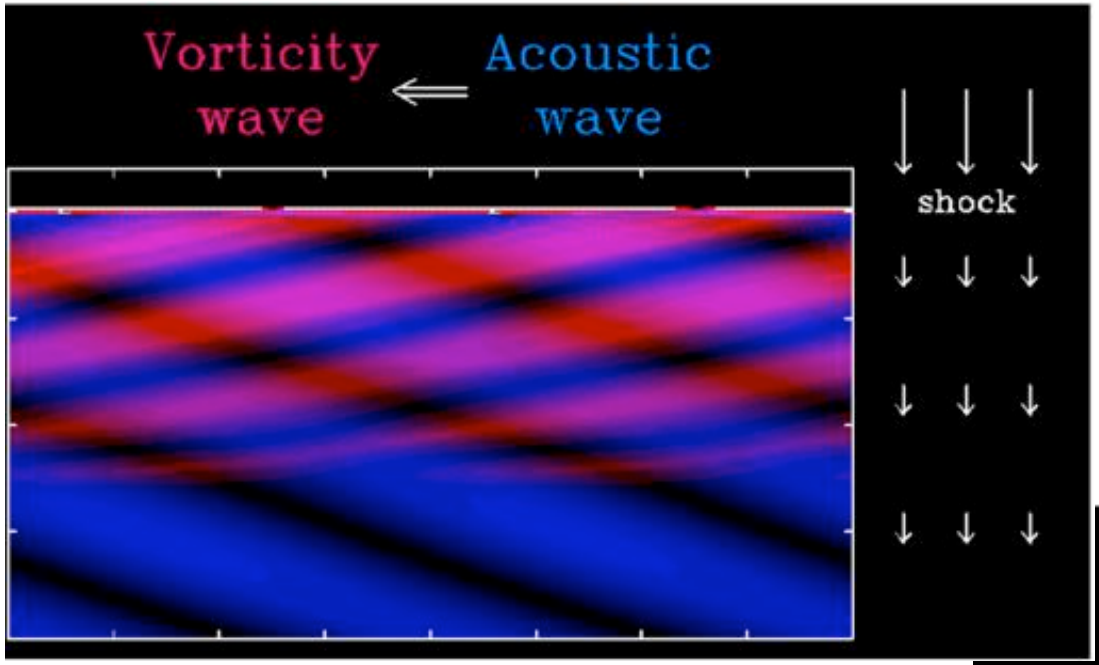
Blondin et al. 03

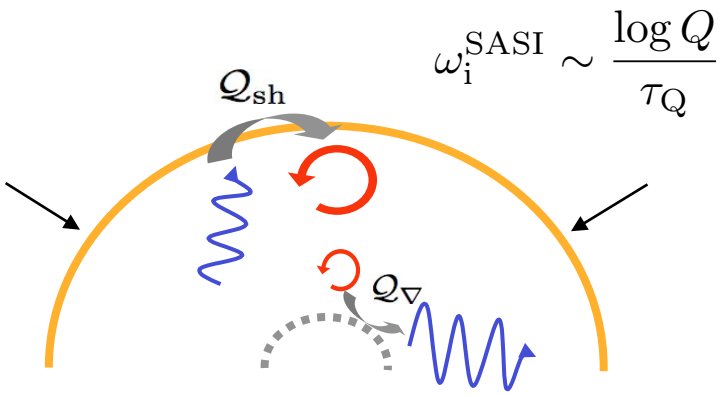


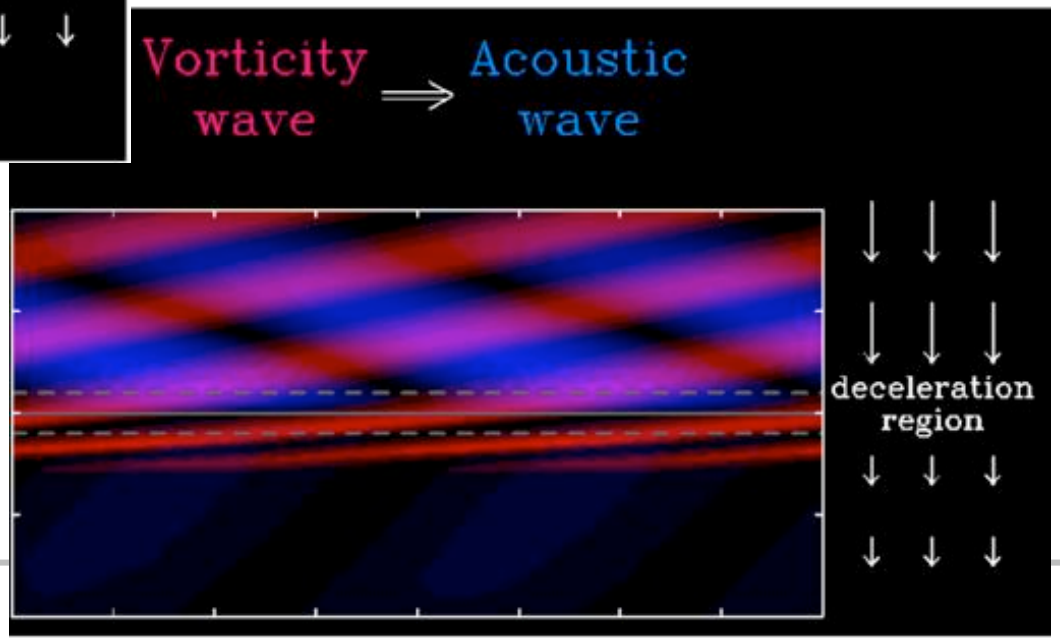
No neutrino heating
=
No confusion with neutrino-driven convection
(not an explosion model)

Linear coupling between the acoustic wave and the entropy/vorticity wave

(Sato, Foglizzo & Fromang 09)

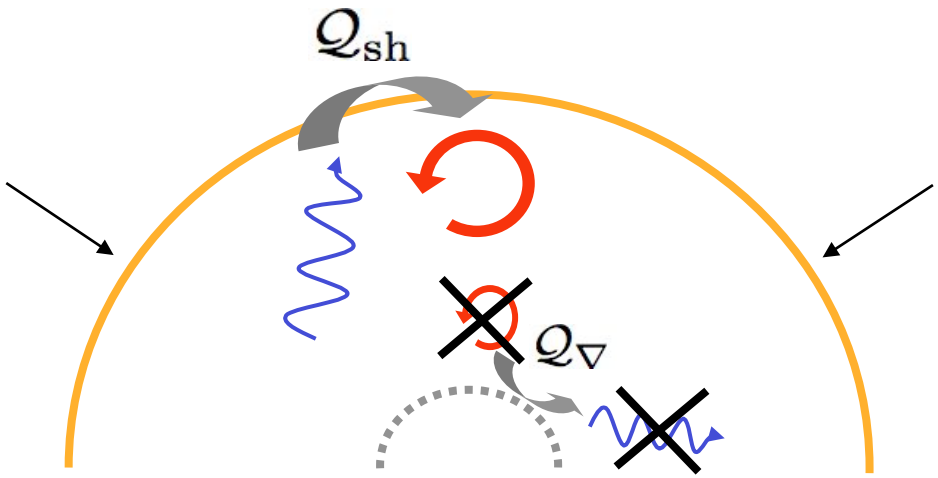


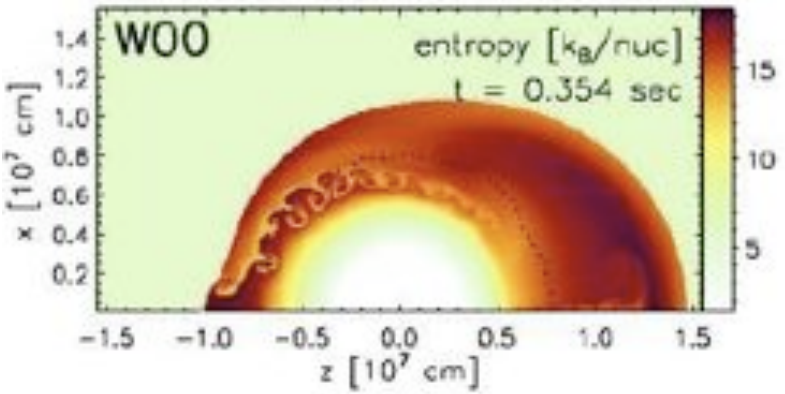




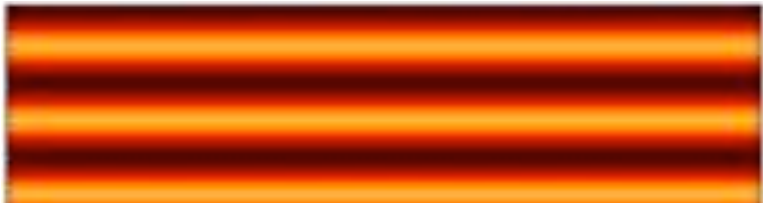
The saturation of SASI by parasitic instabilities

Guilet et al. 2010

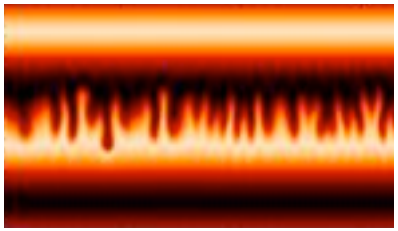




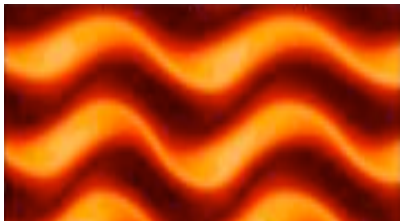
entropy-vorticity wave



Rayleigh-Taylor

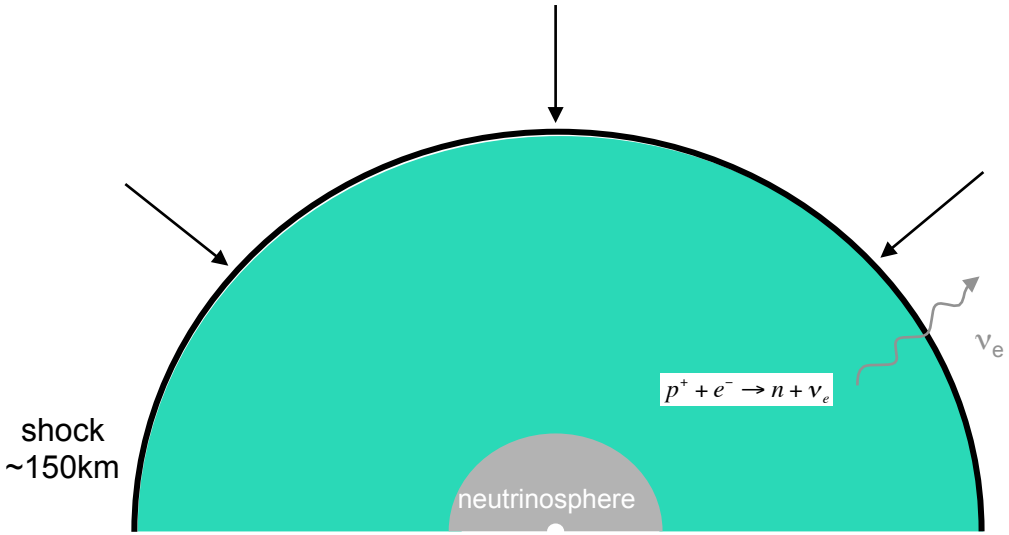


Kelvin-Helmhotz

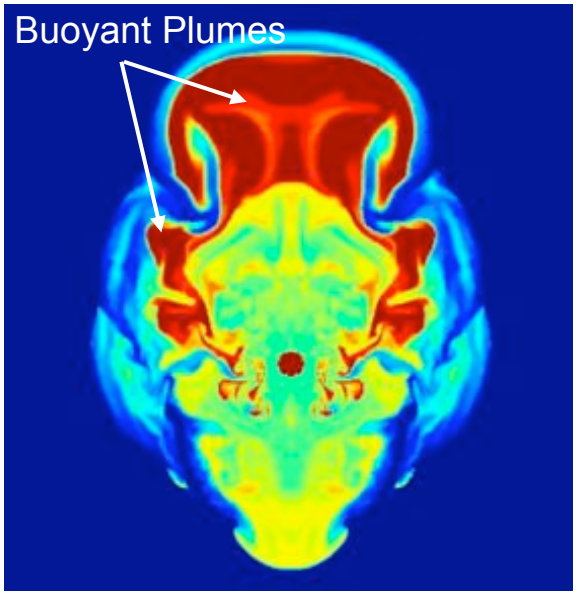


stabilisation if the local parasitic instabilities
- propagate against the flow
- grow as fast as SASI

Can SASI be disentangled from ν-driven convection ?



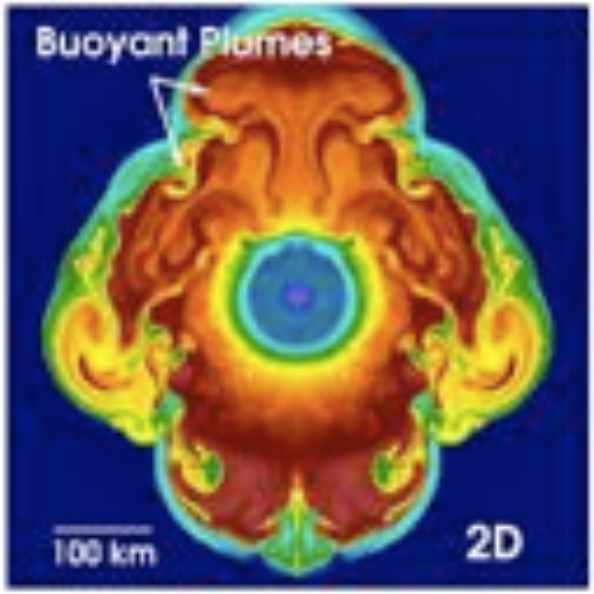
Blondin et al. 03



No neutrino heating
=
No confusion with neutrino-driven convection

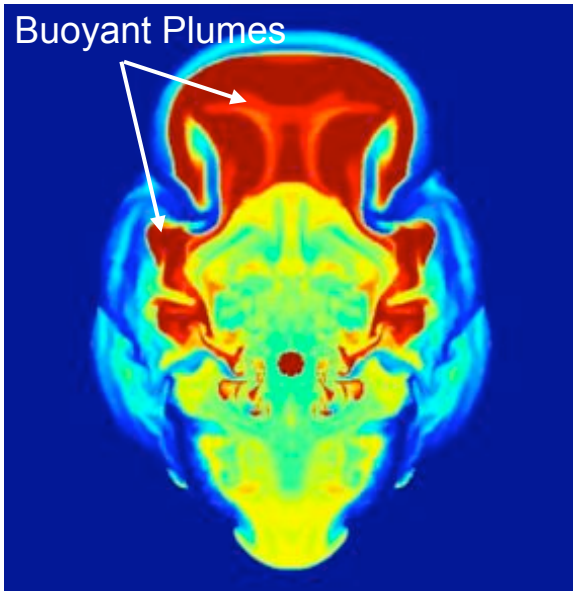
But still, some nonlinear buoyancy effects
Guilet+12

Can SASI be easily disentangled from ν-driven convection ?



Murphy+12

With neutrino heating
=
SASI + neutrino-driven convection



Blondin+03

No neutrino heating
=
SASI alone

What are the properties of SASI driven turbulence ?
(e.g. Endeve+12)

Instabilities and the explosion threshold

SASI amplitude seems weaker in 3D compared to 2D (Hanke+12, Burrows+12),
but the explosion threshold is unchanged (even slightly easier in 3D)

-> influence of SASI on the explosion ?

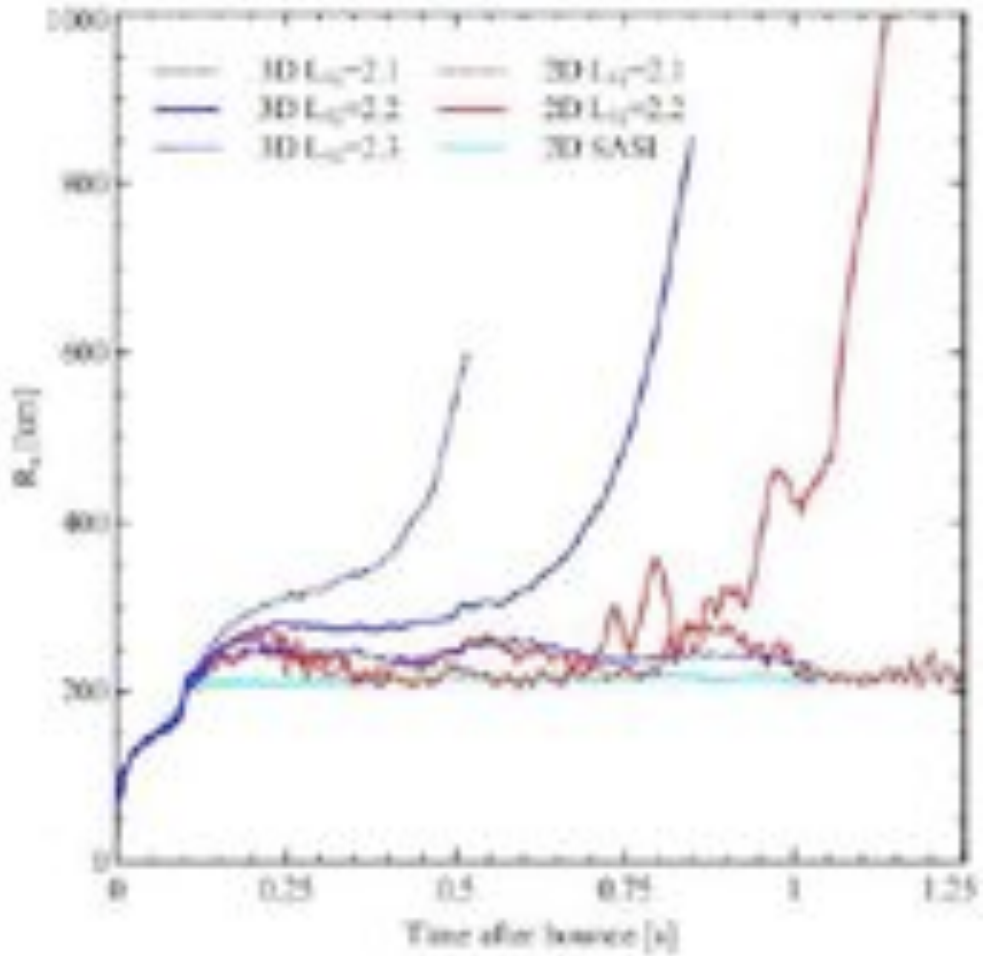
-> is the 3D turbulence triggered by SASI ?

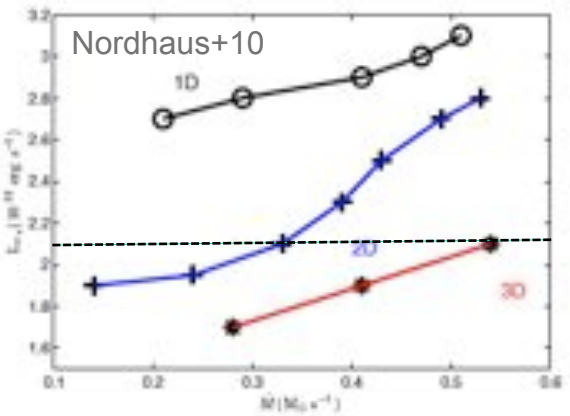
-> 3D explosion of the $27M_{sol}$ progenitor ?

-> Expected spiral SASI mode ? With rotation ?

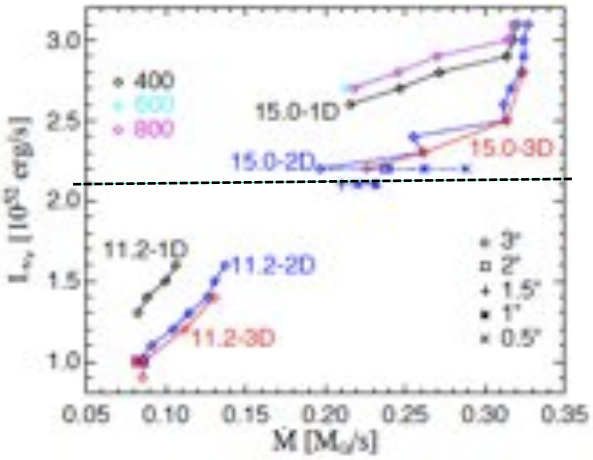
Drawing conclusion from a single model ? Nordhaus+10 vs Burrows+12

Burrows+12



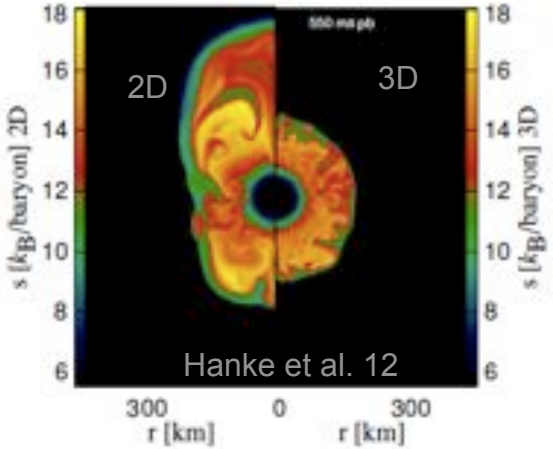


Hanke+12



nonlinear interplay of SASI and buoyancy in 2D/3D (in preparation)

If neutrino heating is strong enough to drive turbulence in the gain region (l>5)



> stabilisation of the advective-acoustic mode by turbulent damping

$$\nu_{\rm turb} \equiv \alpha \, \frac{\omega_{\rm BV}}{k^2_{\rm gain}}$$

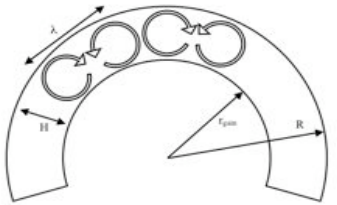
of vorticity waves (turbulent viscosity)
and entropy waves (turbulent diffusion of heat)

$$\omega_{\rm i}^{\rm turb} \sim -\nu_{\rm turb} k^2_{\rm SASI}$$

$$\chi \equiv \omega_{\rm BV} \, \tau_{\rm gain}$$

$$\omega_{\rm i}^{\rm SASI} \equiv \frac{\log Q}{\tau_{\rm Q}}$$

$$\chi > \left(\frac{\tau_Q}{\tau_{\rm gain}} \right)^2 \frac{\log Q}{\alpha}$$

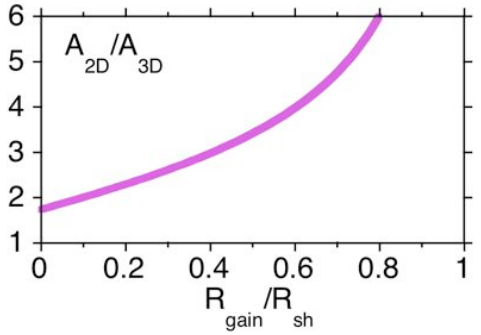


> stochastic excitation of the stable advective-acoustic mode: random walk (e.g. solar p-modes)

$$E_{nlm}(t) \sim \left| \sum_{0<t-t_k<\tau_{\rm d}} a^k_{nlm} e^{i\Phi^k_{nlm}} \right|^2$$

(e.g. Foglizzo 98)

$$\frac{A_{\rm 2D}}{A_{\rm 3D}} \sim \frac{N_{\rm 2D}^{\frac{1}{2}} < a_{\rm 2D} >}{N_{\rm 3D}^{\frac{1}{2}} < a_{\rm 3D} >} \propto \left(1 - \frac{R_{\rm gain}}{R_{\rm sh}} \right)^{-\frac{1}{2}}$$

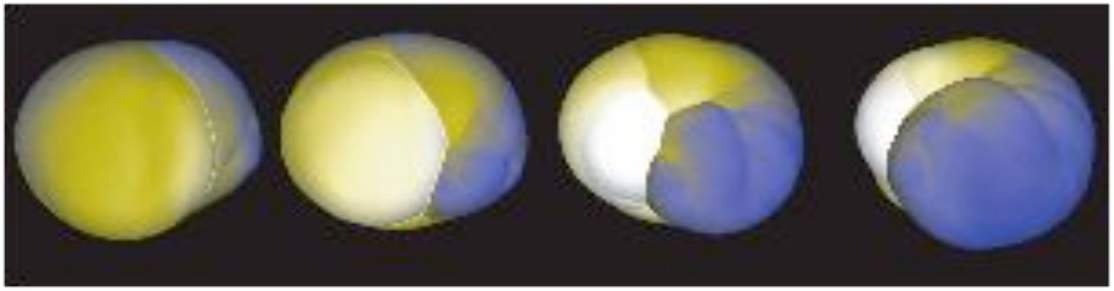


consequences
- stochastic direction of oscillation (Kotake+09)
- larger SASI amplitude in 2D vs 3D (Iwakami+09, Hanke+12)
- the interplay of SASI and buoyancy depends on the core structure (Müller+12)

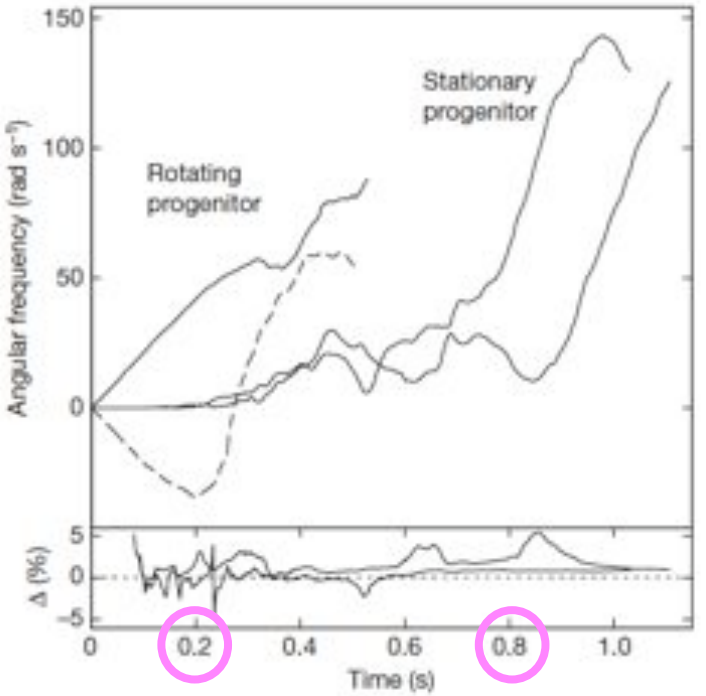
-> Need to characterize the linear strengths of buoyancy (χ) and SASI (Q) in the collapsing core (~1D)

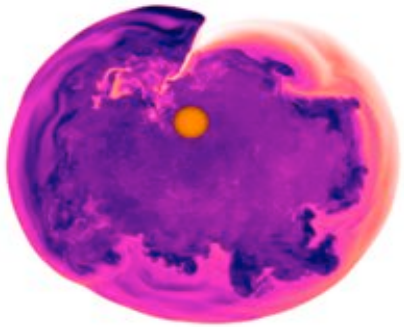
The spiral mode of SASI in 3D

Blondin & Mezzacappa 07
Fernandez 10,
Blondin & Shaw 07, TF+12



A spiral mode dominates the nonlinear evolution: why so robust ?





Timescale for symmetry breaking ?

-too slow for slow rotators ?
(Iwakami+08, Wongwathanarat+10, Rantsiou+11,
Hanke+12, Burrows+12)

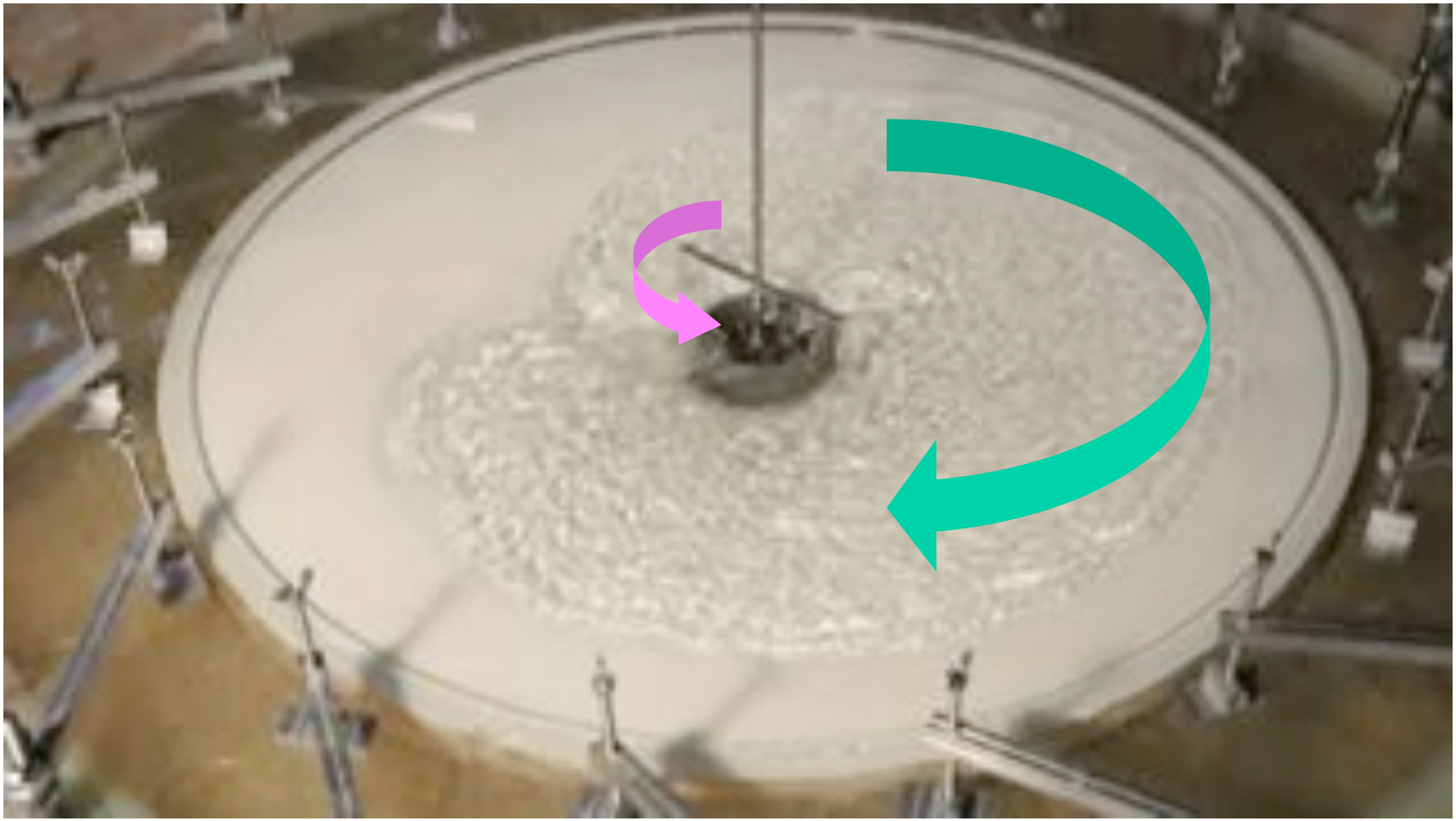
- how is SASI destabilized by rotation ?
Blondin & Mezzacappa 07, Yamasaki & Foglizzo 08

→ Need more 3D simulations with a rotating progenitor
(Iwakami et al. 09, Kotake 12?)

- quadratic centrifugal force r Ω^2,
- linear Doppler shift of the frequency ω-mΩ

Angular momentum budget

rotating wave + advected vorticity = 0



Angular momentum budget

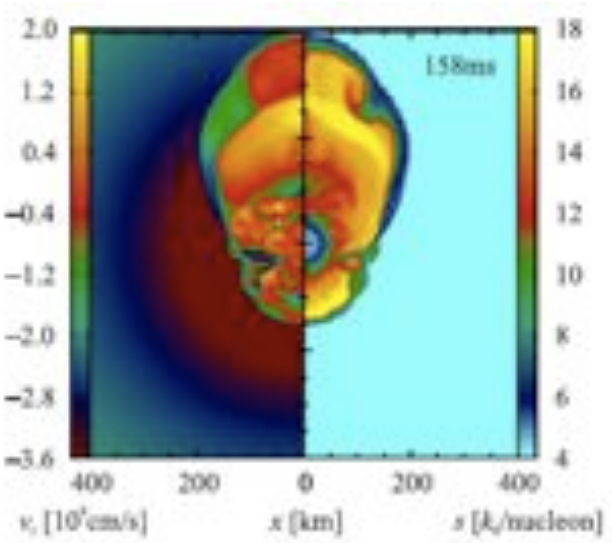
rotating wave + advected vorticity = 0

Diversity of progenitors: 8.1, 11.2, 15, 27 M_{sol} (e.g. Ugliano+12, Müller+12)

-> no direct generalization (e.g. Burrows+12, Murphy+12?)

-> 3D simulations are still too few (dM/dt, rotation)

e.g. $27M_{sol}$ in 3D ? with rotation ?



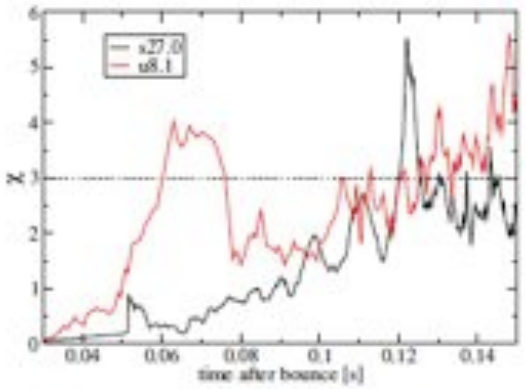
$27M_{sol}$ in 2D (Müller+12)

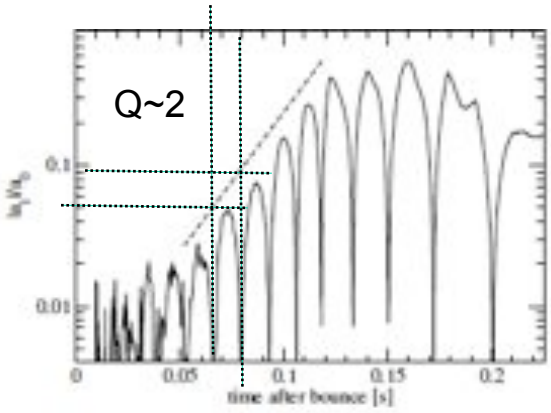
Some parameters can help characterize the hydro properties

-strength of ν-driven buoyancy (χ parameter)

-strength of SASI (Q parameter)

-others ?





->dependence on rotation, EOS ?

->stabilization of spiral SASI by turbulence: Ω(χ) ?

->explosion threshold $\chi(L_\nu, dM/dt)$?

Thanks for this stimulating program