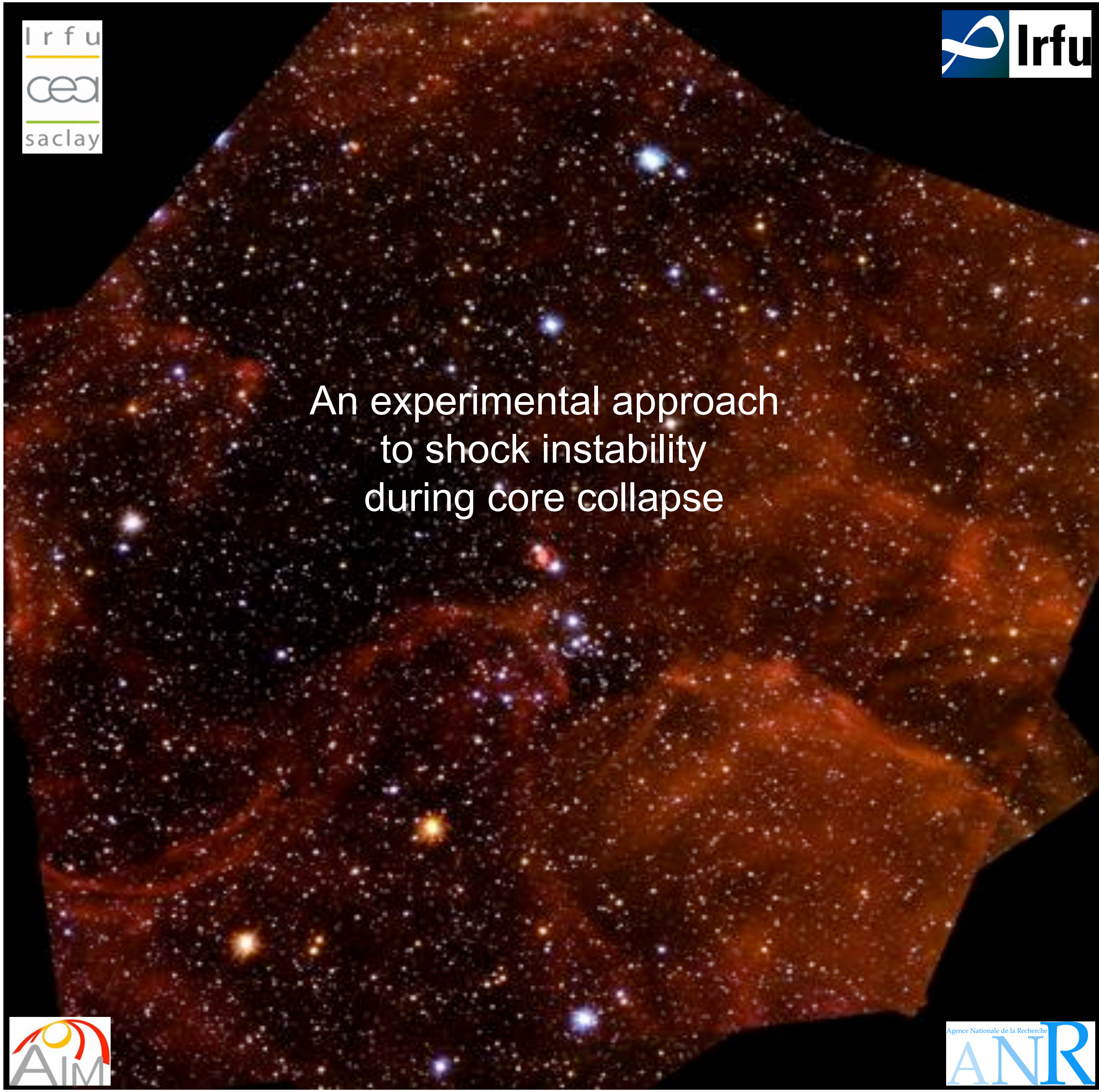
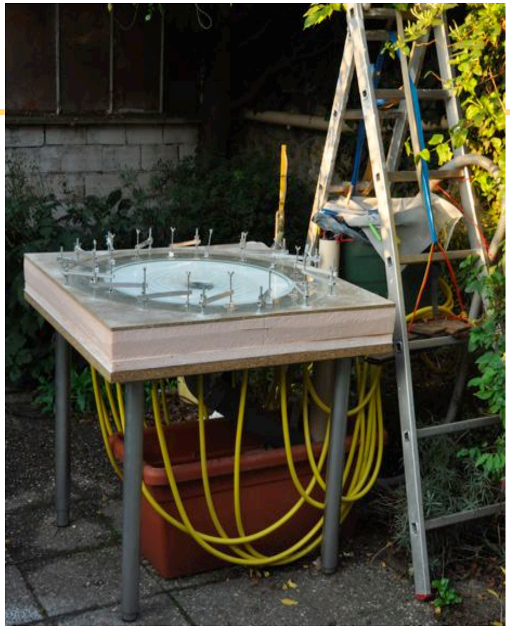
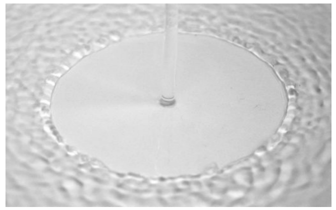


An experimental approach to shock instability during core collapse





Thierry Foglizzo

Frédéric Masset
Jérôme Guilet
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CEA Saclay,
UNAM, DAMTP

Outline

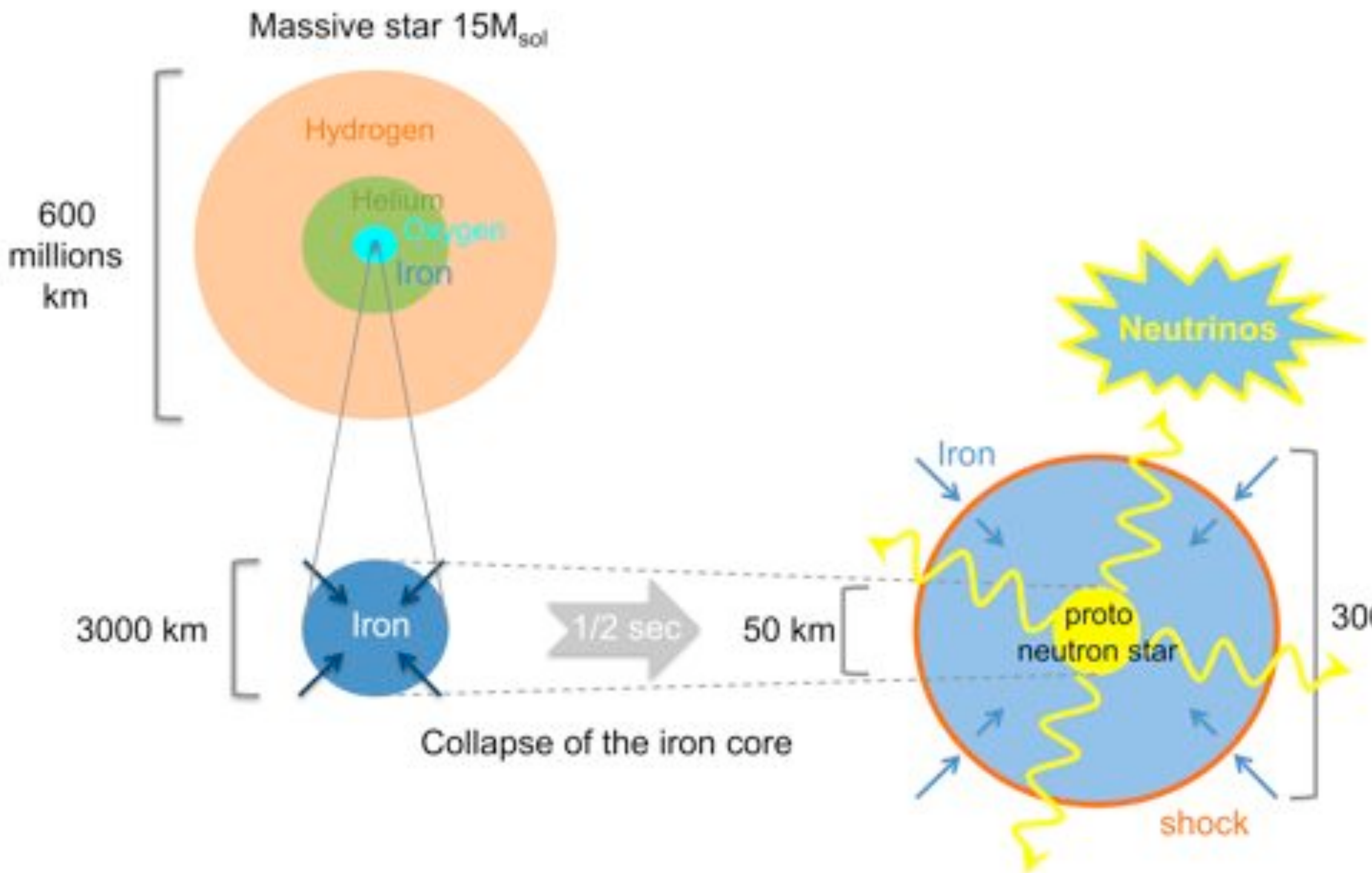
1- neutrino driven convection and the SASI: linear theory

2- a shallow water analogue of SASI, first experimental results

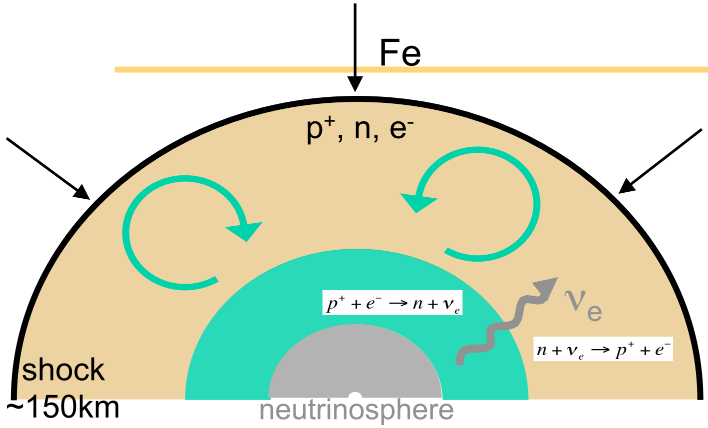
3- nonlinear interaction between SASI and buoyancy, 2D vs 3D

Theoretical framework (Bethe & Wilson 85)

neutrino-driven delayed explosion



Instabilities during the phase of stalled accretion shock

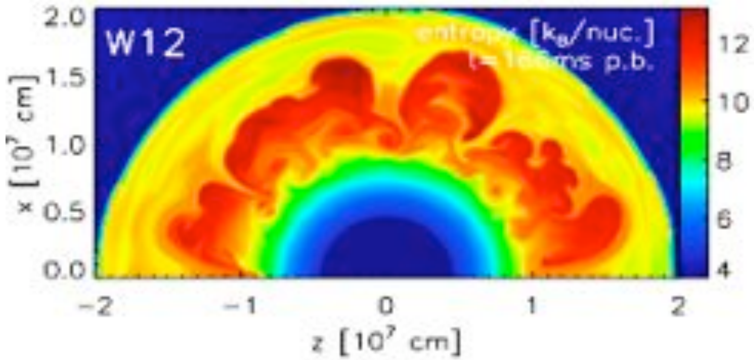


Foglizzo et al. 06, Müller et al. 12

neutrino driven convection

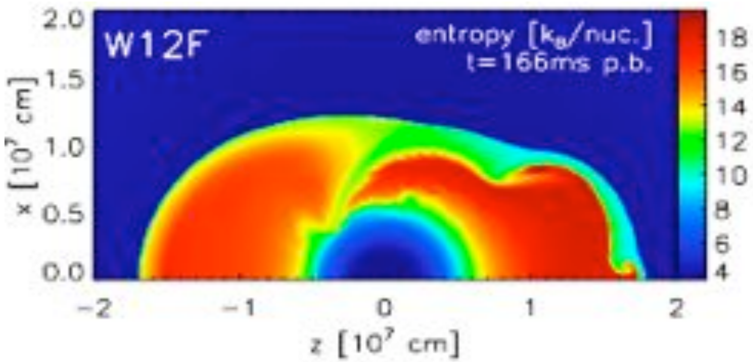
+

SASI



- Neutrino driven convection, l>5

(Herant, Benz & Colgate 92, ...)

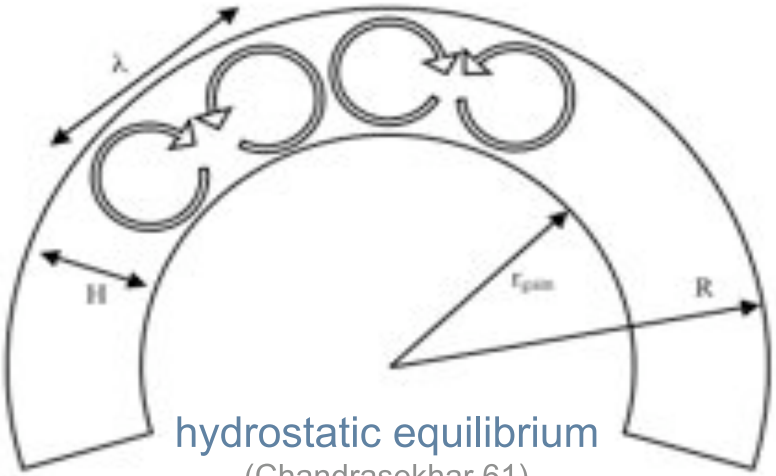


- SASI in an adiabatic flow l=1,2

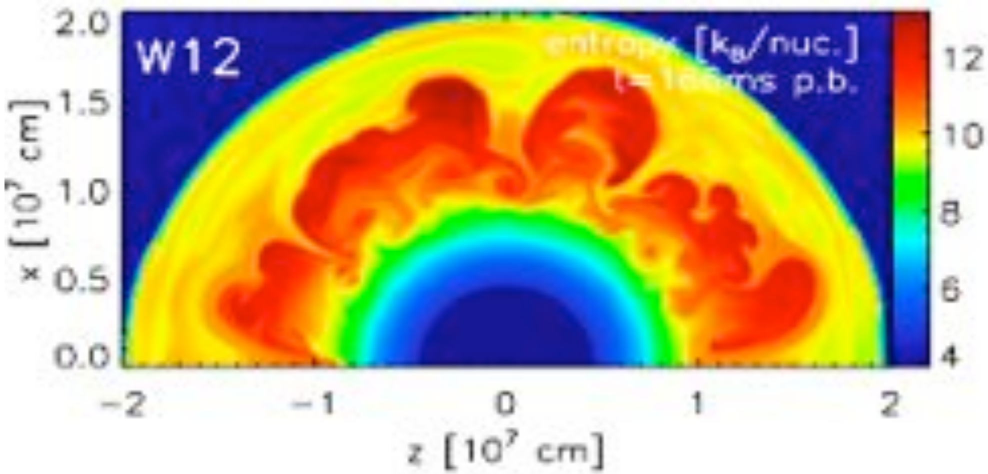
(Blondin et al. 03 ...)

What do we understand of convection and SASI ?

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



hydrostatic equilibrium
(Chandrasekhar 61)

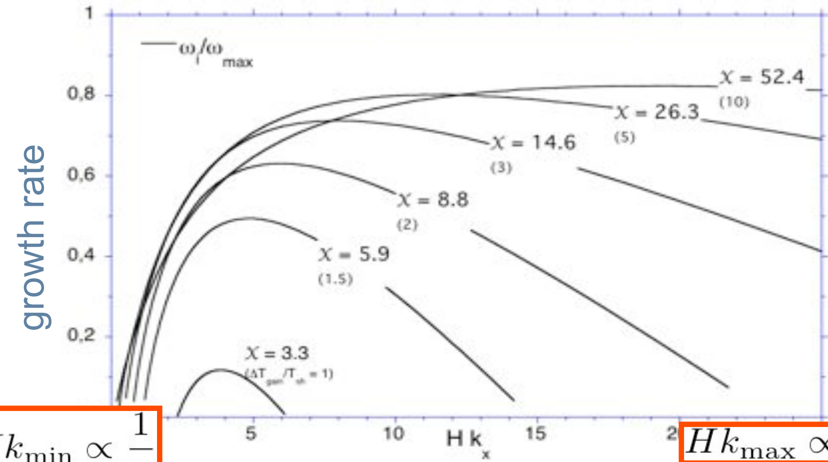


Foglizzo, Scheck & Janka 06

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

$$\sim 3.1\left(\frac{v_1}{7v_2}\right)\left(\frac{H}{0.4r_{\rm sh}}\right)^{\frac{1}{2}}$$

!



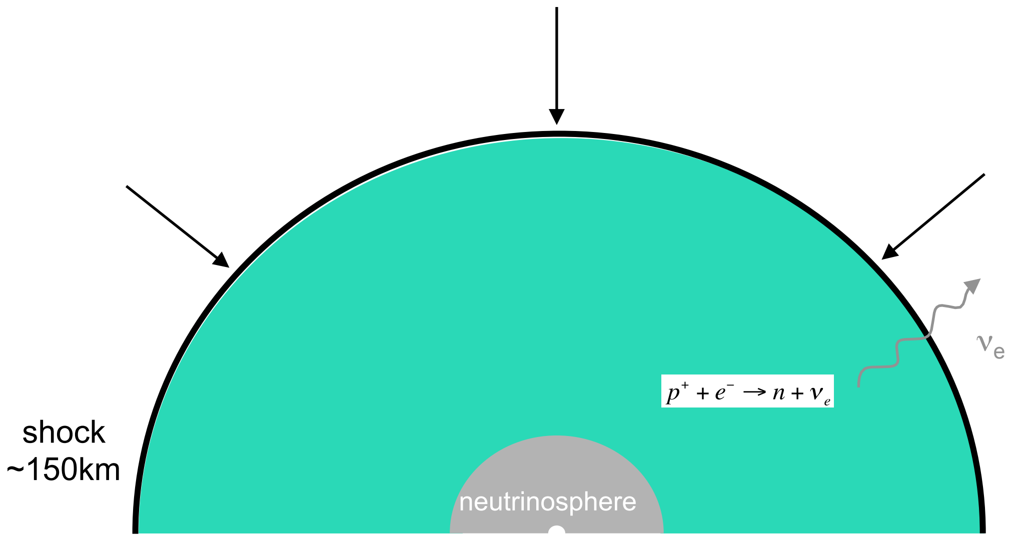
$Hk_{\rm min} \propto \frac{1}{\chi}$ horizontal wavenumber $Hk_{\rm max} \propto \chi$

threshold $\chi \sim 3$

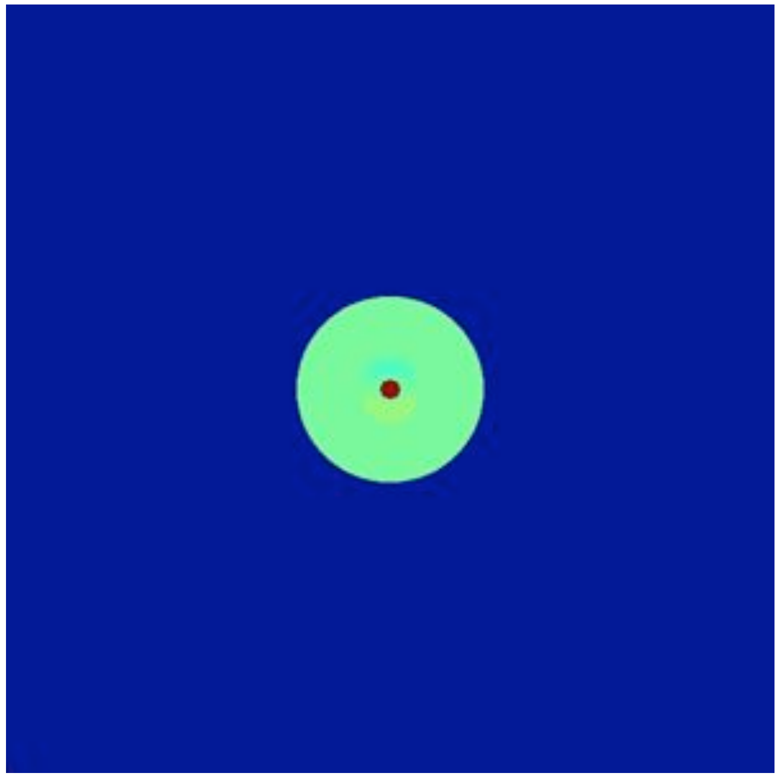
->the convective instability cannot be responsible for large scale oscillations (also Yamasaki & Yamada 07)

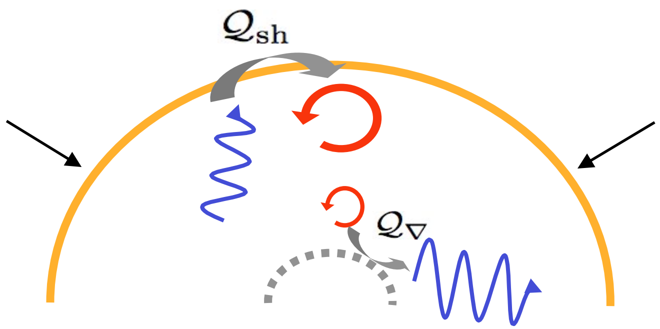
but non linear buoyancy may drive turbulence
(Scheck et al. 08, Fernandez & Thompson 09)

Stationary Accretion Shock Instability : SASI



Blondin et al. 03



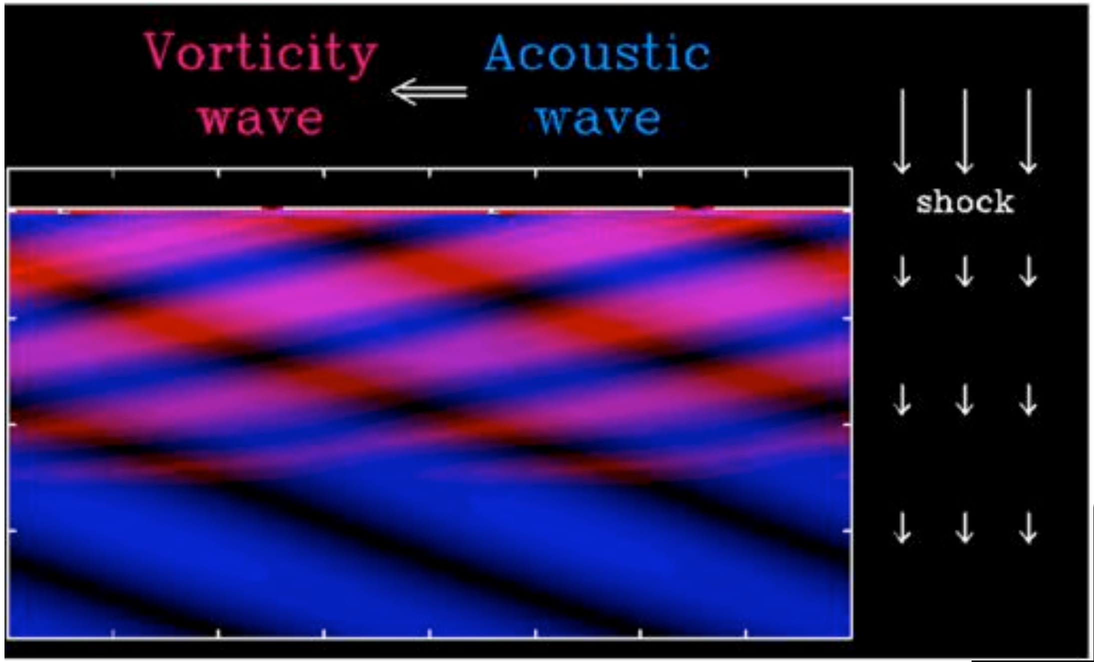


Mechanism of SASI: advective-acoustic cycle

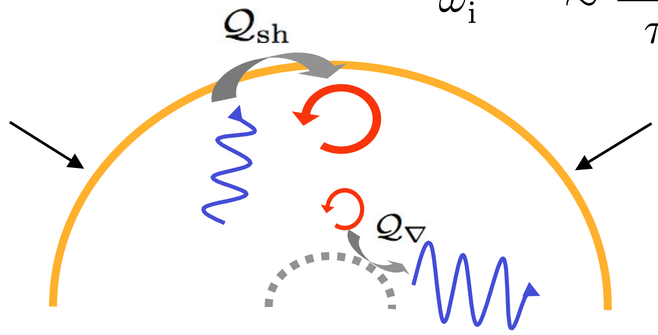
(Foglizzo 02, Ohnishi et al. 06, Foglizzo et al. 07, Scheck et al. 08,
Fernandez & Thompson 09, Guilet & Foglizzo 12)

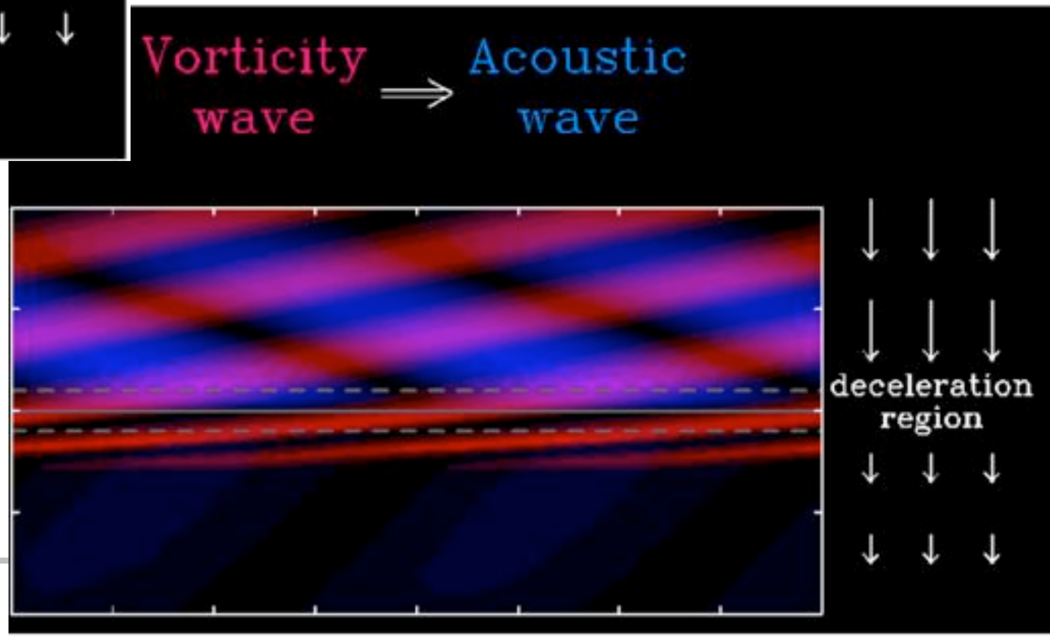
Linear coupling between the acoustic wave and the entropy/vorticity wave

(Sato, Foglizzo & Fromang 09)



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





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

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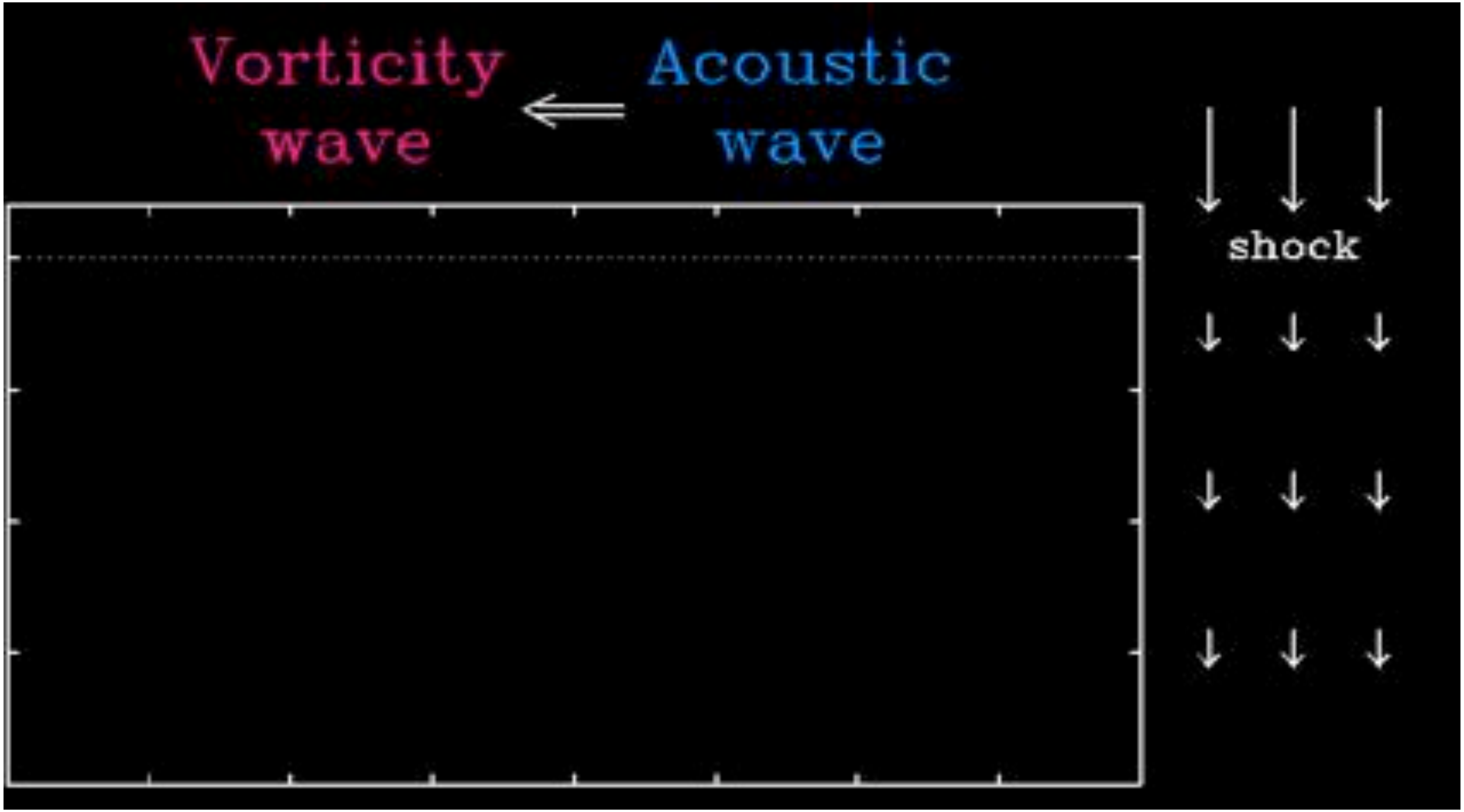
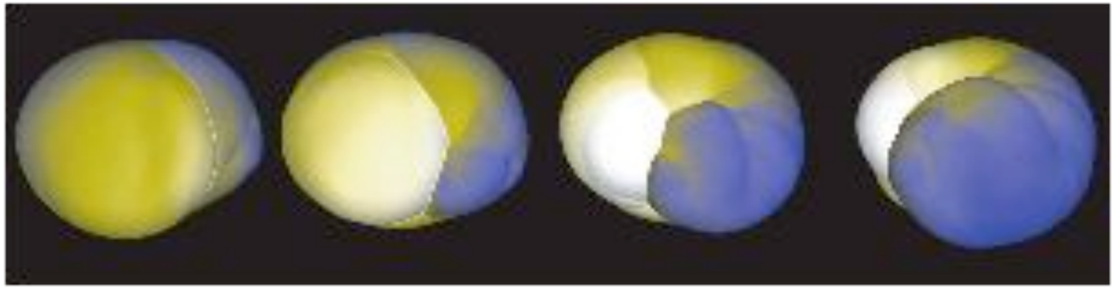
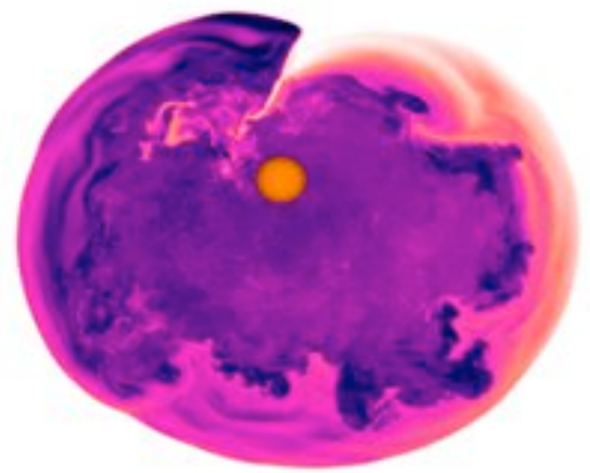


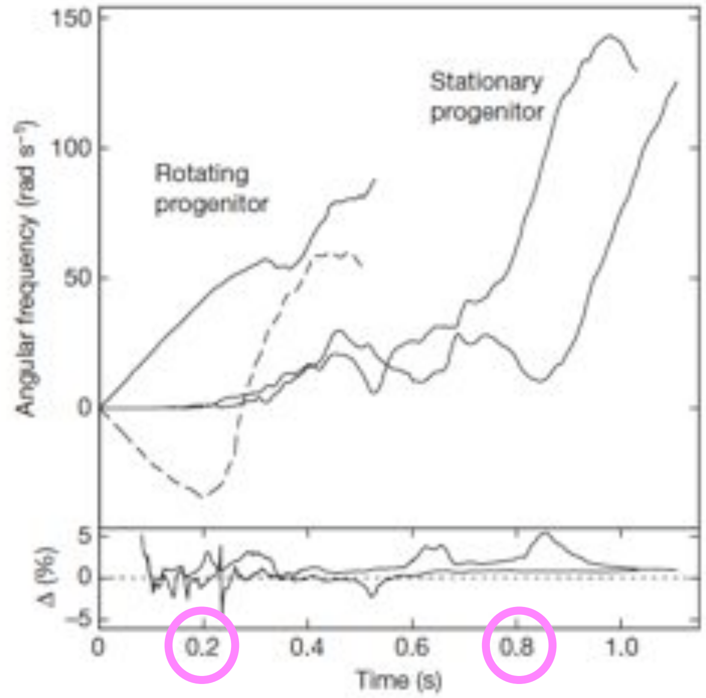
Surprising spiral mode of SASI in 3D

Blondin & Mezzacappa 07
Fernandez 10



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





Timescale for symmetry breaking ?

-too slow for slow rotators ?
(Iwakami et al. 08, Wongwathanarat et al. 10, Rantsiou et al. 11)

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

From SN explosions to a shallow water experiment

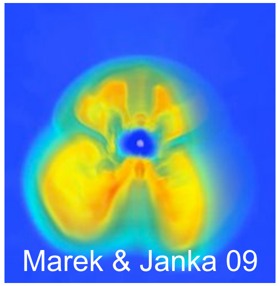
realism & complexity

simplicity & understanding

Observations of SN and pulsars

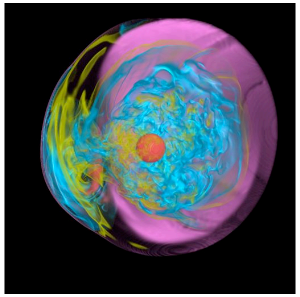
- SN light curve, polarimetry, neutrinos, grav. waves, nucleosynthesis,
- Pulsar kick and spin

Complex comprehensive simulations
(Marek & Janka 09, Burrows et al. 06, Wongwathanarat 10, Suwa et al. 10, Müller et al. 12, Kuroda et al. 12, Sumiyoshi & Yamada 12)



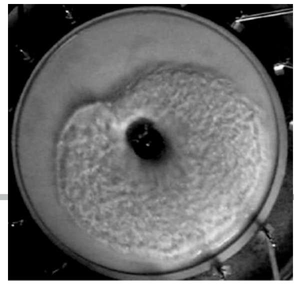
progenitor structure + nuclear EOS
+ neutrino "transport" & interactions
+ "GR" + "multi-D" hydro
(no magnetic field)

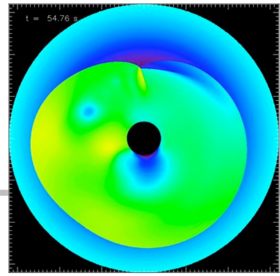
Multi-D hydro processes only
Blondin & Mezzacappa 07



stationary accretion,
ideal gas,
3D adiabatic

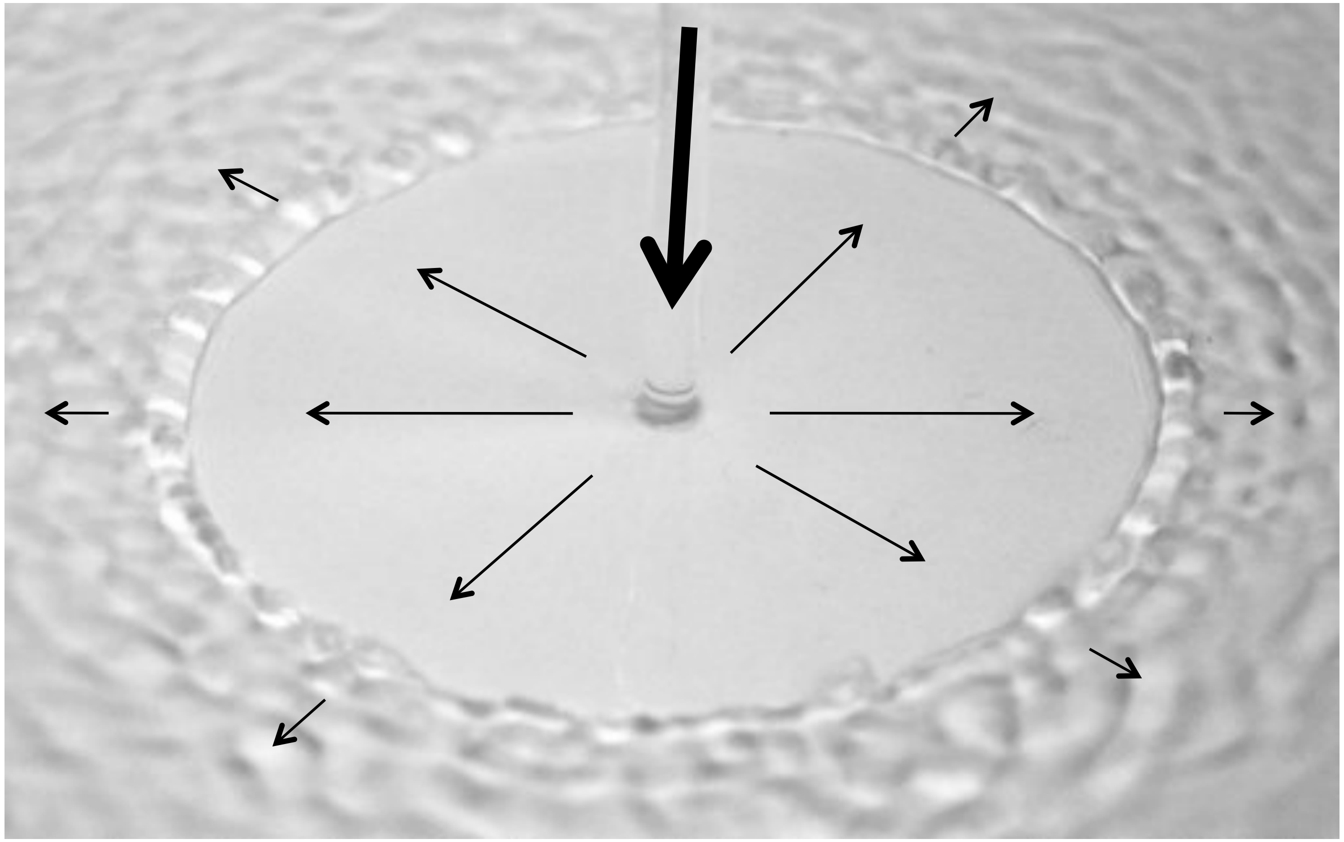
SWASI experiment
Foglizzo et al. 12



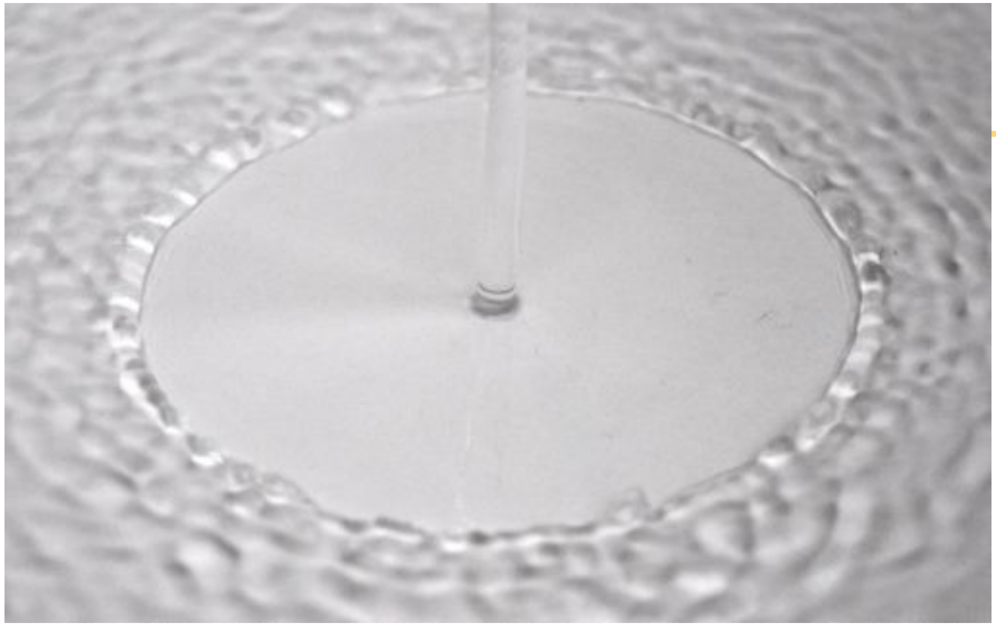


- 2D shallow water inviscid

Hydraulic jumps = analog to shock waves

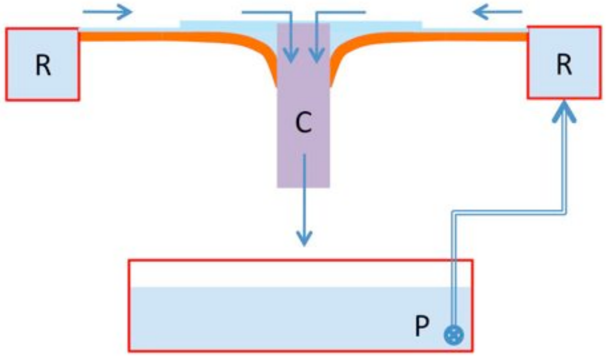


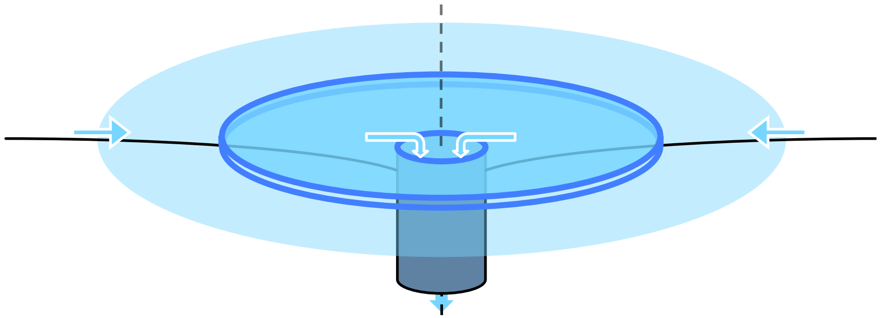
acoustic waves shock wave pressure	↔	surface waves hydraulic jump depth



SWASI

Shallow Water Analogue of a Shock Instability



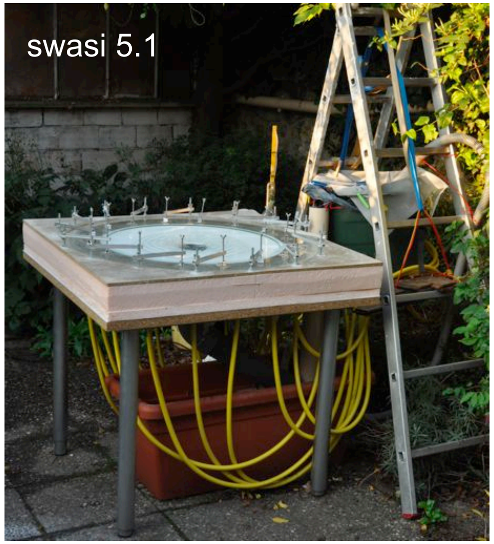


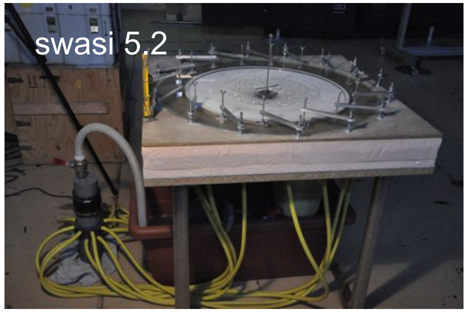
Analogues of Bondi accretion on a black hole

Bell-mouth spillway
of Monticello dam, lake Berryessa, CA

William Pye's water sculptures

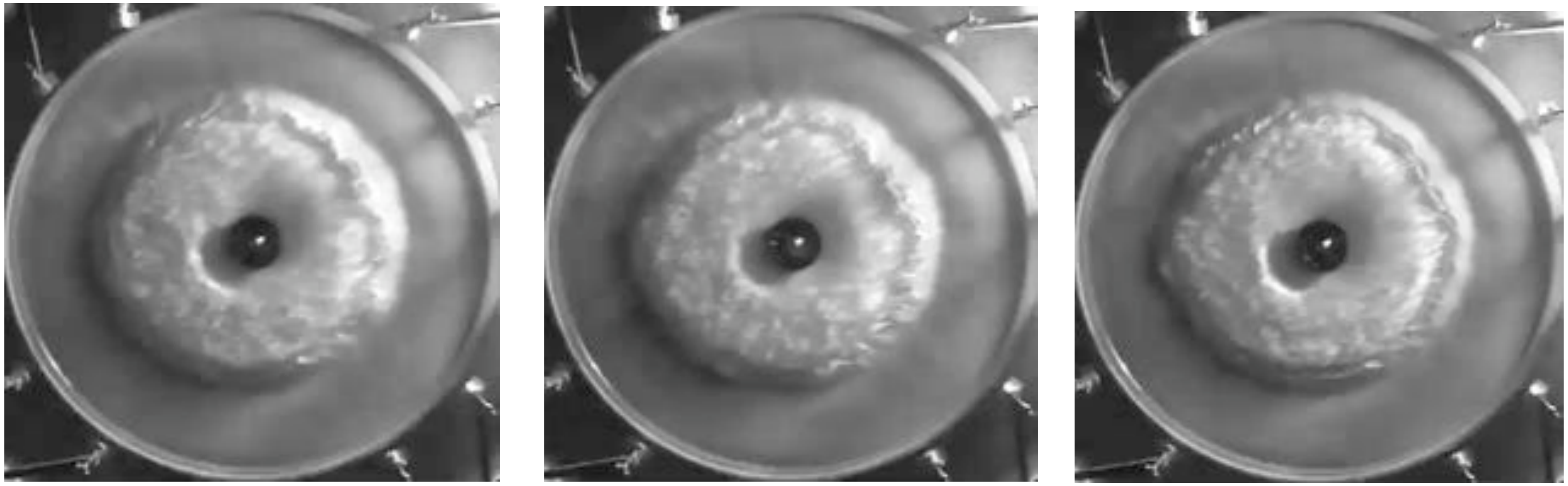
SWASI: simple as a garden experiment

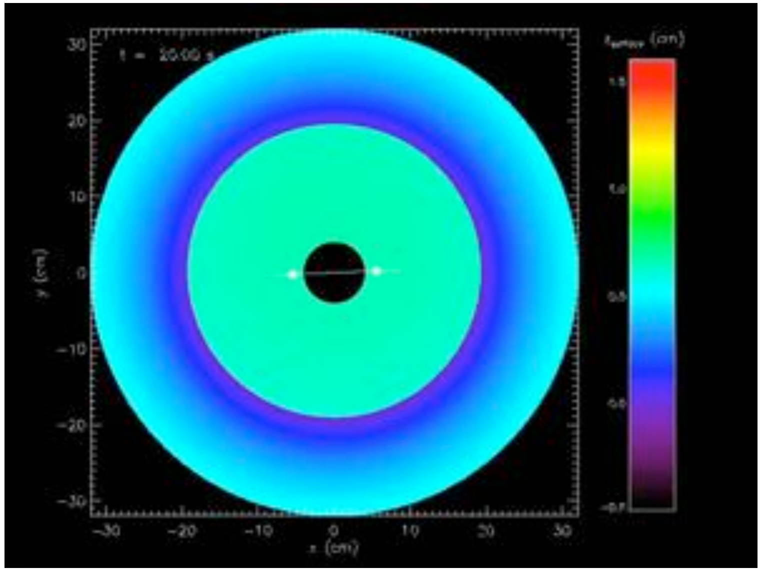




from May to Oct. 2010:
5 versions, 2k€

unstable oscillation and nonlinear symmetry breaking





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

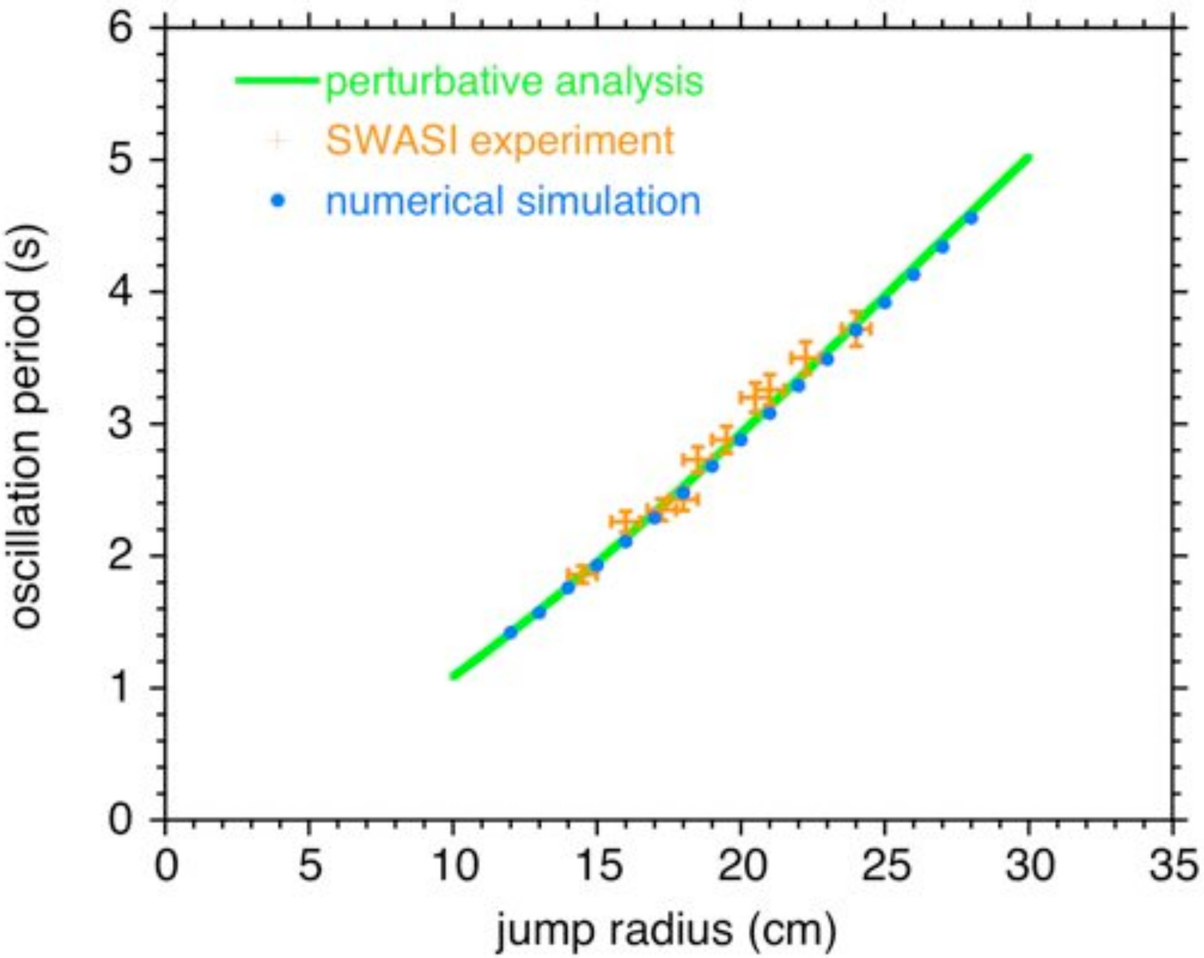
(intermediate between "isothermal" and "γ=2 without entropy")

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

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

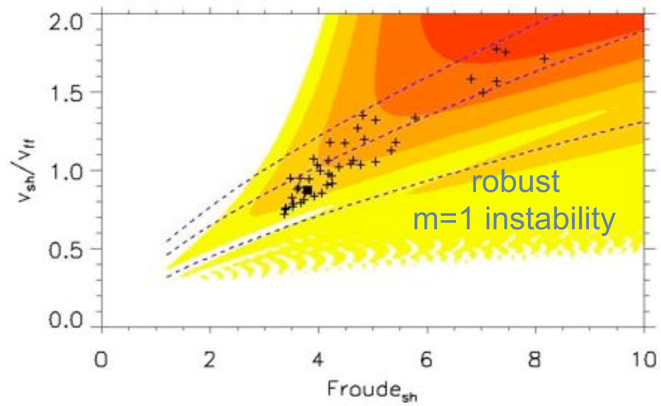
oscillation period $\times 10^{2}$ 30 ms $\rightarrow$ 3 s

Comparison to a 2D shallow water model



No free parameter:

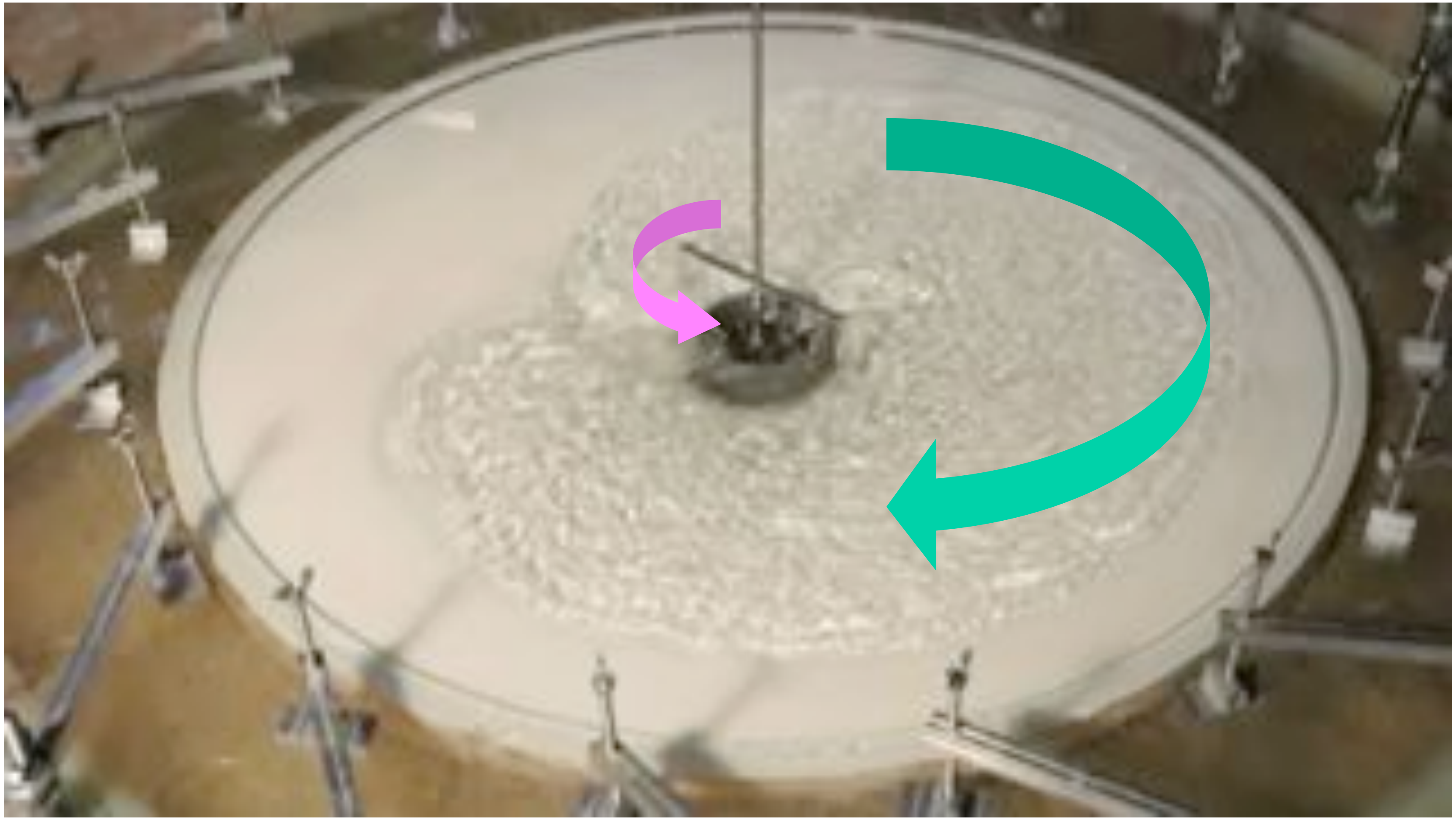
- laminar viscous drag measured in the stationary flow
- inner boundary: free spillover



Foglizzo, Masset, Guilet, Durand
PRL (2012)

Angular momentum budget

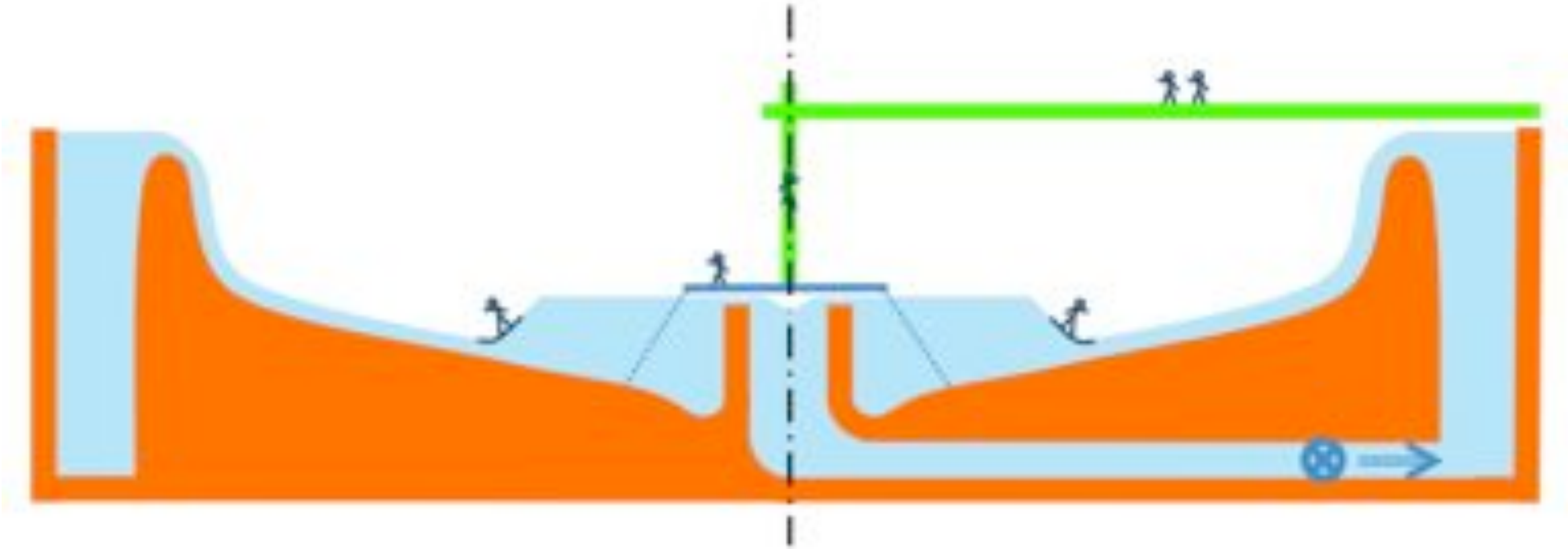
rotating wave + advected vorticity = 0



Angular momentum budget

rotating wave + advected vorticity = 0

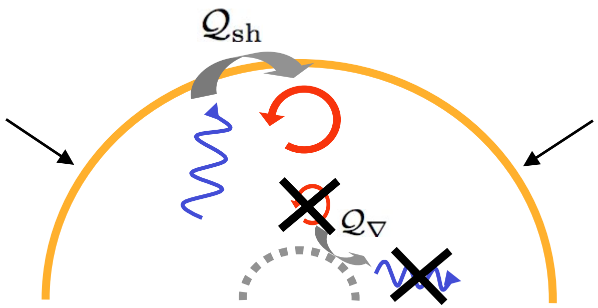
Surfing SWASI ?

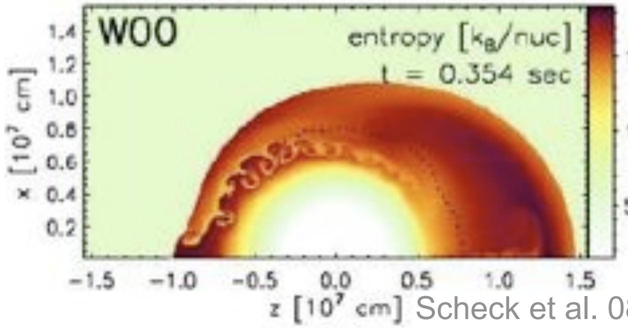


SWASI experiment, beside public outreach

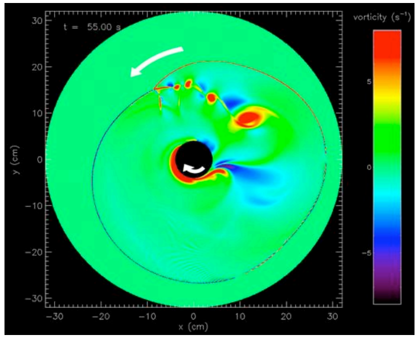
- test the saturation mechanism of SASI

  growth of parasitic instabilities ? (Guilet et al. 10)





Scheck et al. 08

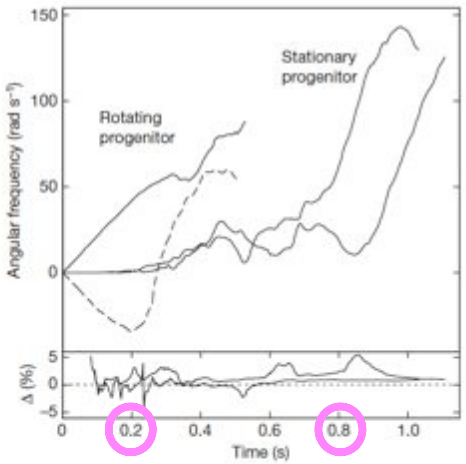


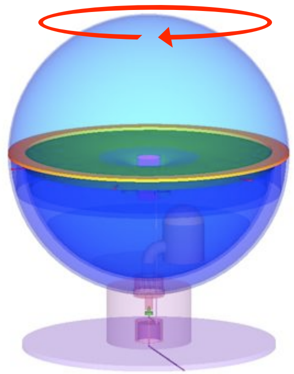
parasitic Kelvin-Helmholtz ?

- timescale for spiral domination ?

  Blondin & Mezzacappa 07, Fernandez 10, Foglizzo et al. 12

  Iwakami et al. 08, Wongwathanarat et al. 10, Rantsiou et al. 11



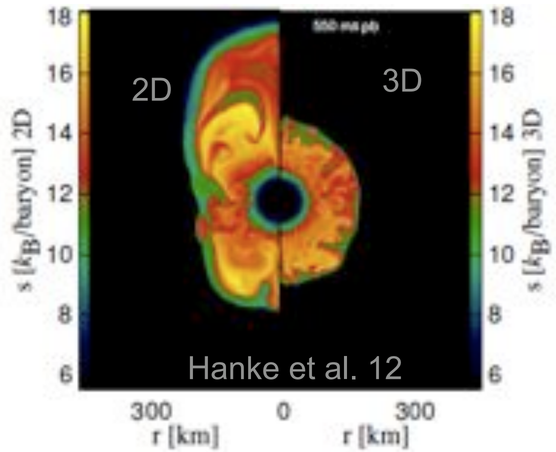


- how is SASI destabilized by rotation ?

  Blondin & Mezzacappa 07, Yamasaki & Foglizzo 08

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

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



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

> stabilisation of the advective-acoustic mode by turbulent damping of vorticity waves (turbulent viscosity) and entropy waves (turbulent diffusion of heat)

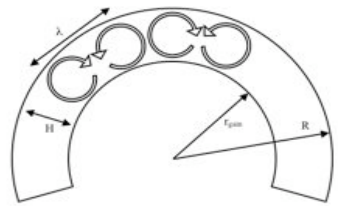
$$\nu_{\rm turb} \equiv \alpha \frac{\omega_{\rm BV}}{k^2_{\rm gain}}$$

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

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

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

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

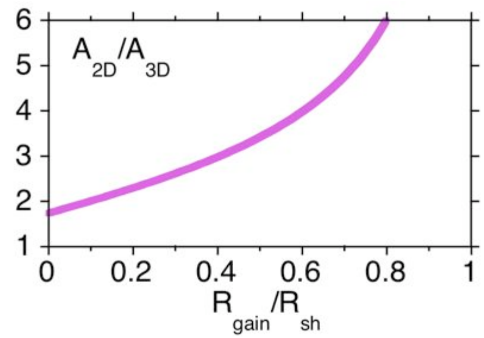


> stochastic excitation of the stable advective-acoustic mode: random walk (e.g. solar p-modes)

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

(e.g. Foglizzo 98)

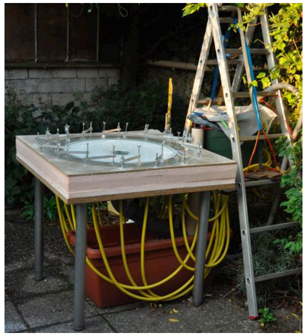
$$\frac{A_{\rm 2D}}{A_{\rm 3D}} \sim \frac{N^{\frac{1}{2}}_{\rm 2D} < a_{\rm 2D} >}{N^{\frac{1}{2}}_{\rm 3D} < a_{\rm 3D} >} \propto \left(1 - \frac{R_{\rm gain}}{R_{\rm sh}}\right)^{-\frac{1}{2}}$$



consequences
- stochastic direction of oscillation (Kotake et al. 10)
- larger SASI amplitude in 2D vs 3D (Iwakami et al. 09, Hanke et al. 12)
- the interplay of SASI and buoyancy depends on the core structure (Müller et al. 12)

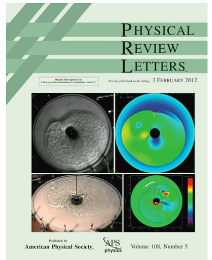
-> Need to characterize the linear strengths of buoyancy (χ) and SASI (Q) in the collapsing core (~1D)

Conclusions



SWASI: first experimental view on SASI

- complementary to analytical and numerical approaches
- makes asymmetric explosions more intuitive



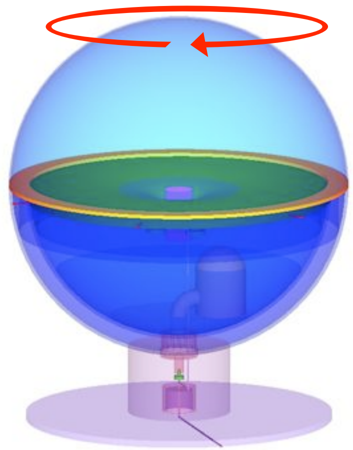
PRL (2012)

Several hydro questions:

- saturation mechanism ?
- spiral domination ?
- destabilized by rotation ?

} SWASI relevant

- interplay of SASI and convection ?
- 2D/3D properties of SASI ?



Two new prototypes built at CEA Saclay (end 2012)

- improved accuracy + global rotation for research
- simplified model for public outreach