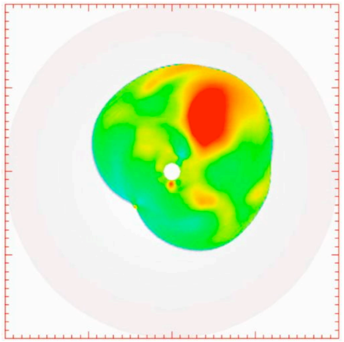
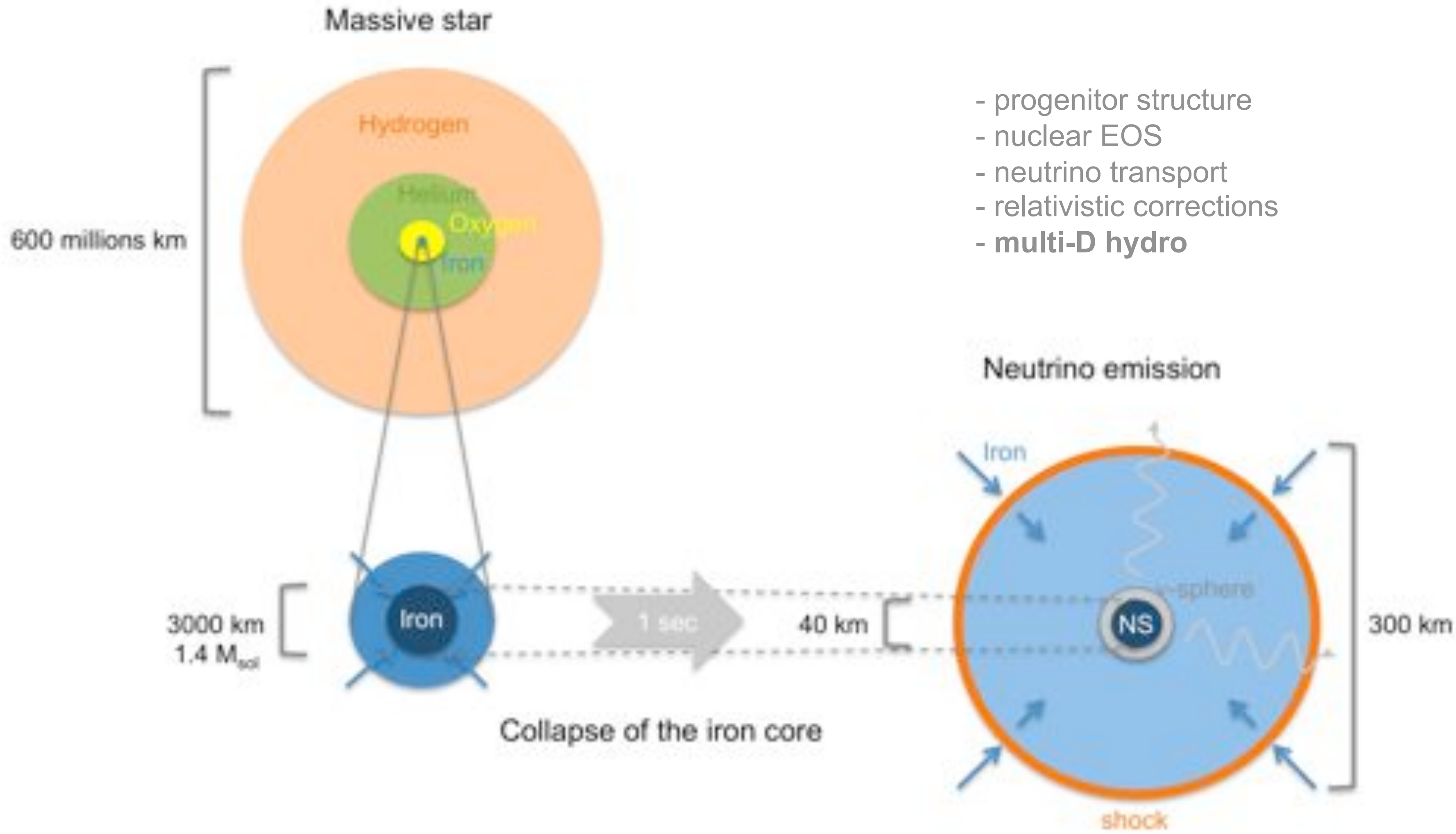
A shallow water analog for asymmetric core-collapse, neutron star kick and spin



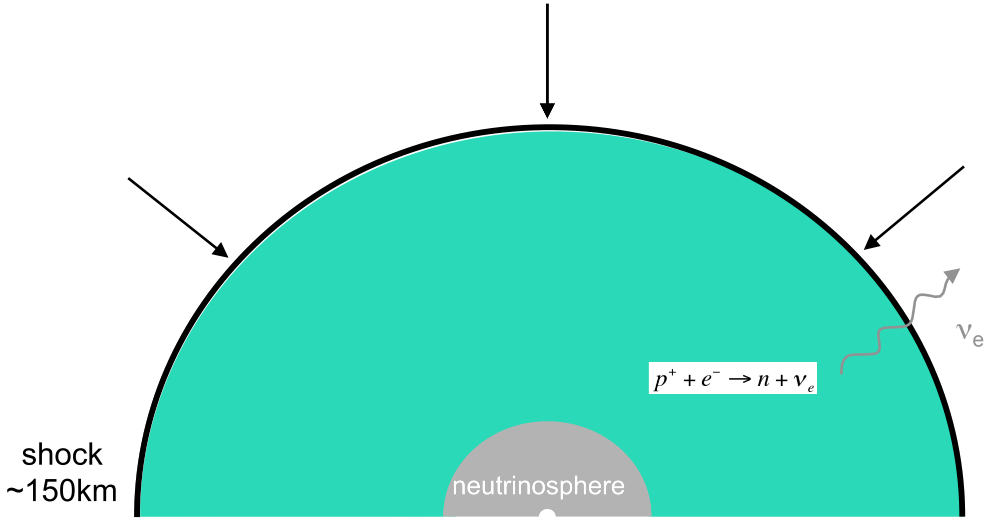
T. Foglizzo, CEA Saclay
J. Guilet, J. Sato, S. Fromang, F. Masset, G. Durand

Theoretical framework: stellar core-collapse, neutrino-driven delayed explosion (Bethe & Wilson 1985)

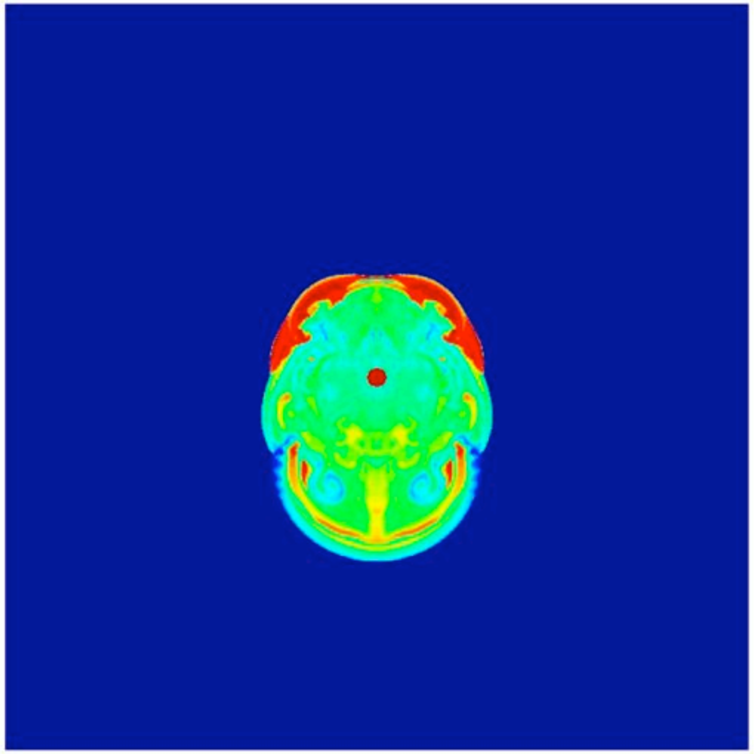


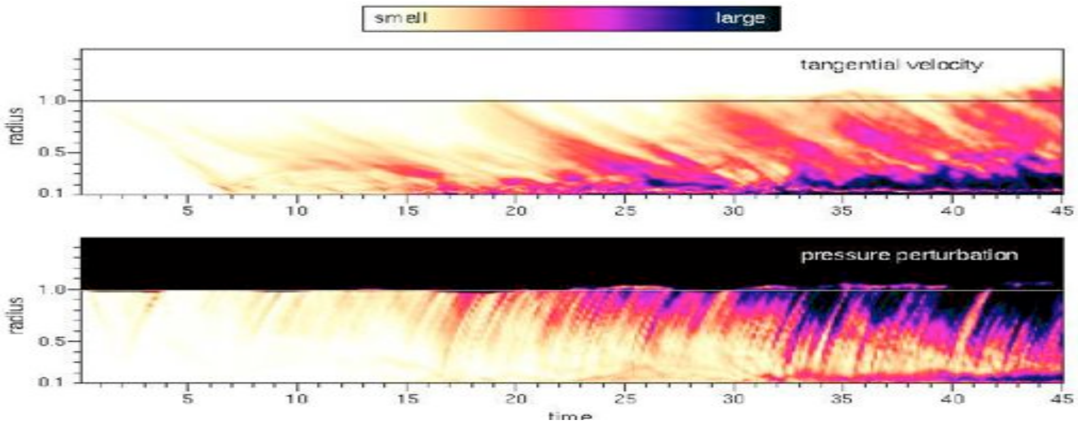
- progenitor structure
- nuclear EOS
- neutrino transport
- relativistic corrections
- **multi-D hydro**

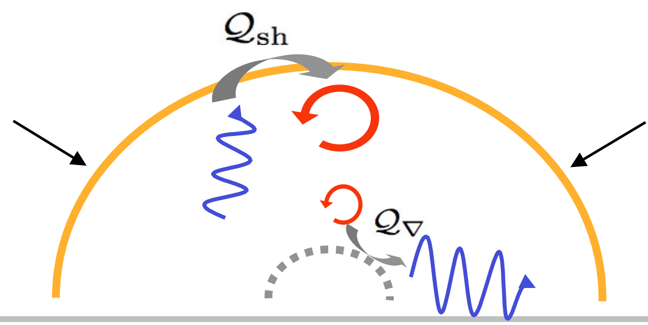
Stationary Accretion Shock Instability : SASI



Blondin et al. 03





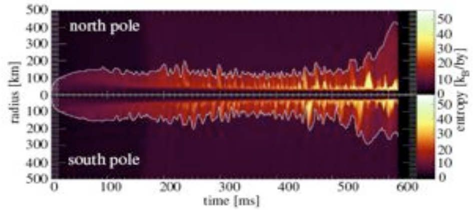


Mechanism of SASI: advective-acoustic cycle

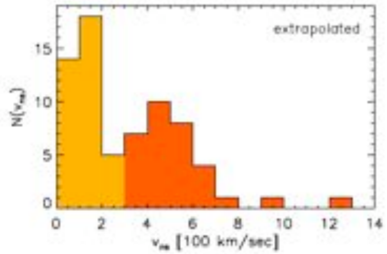
(Foglizzo 2002, Foglizzo et al. 07, Scheck et al. 08, Fernandez & Thompson 09)

The unexpected possible consequences of SASI

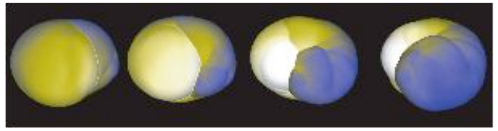
- successful explosion of $15M_{sol}$ driven by neutrino energy
  (Marek & Janka 09, Nordhaus et al. 10a, Suwa et al. 10)



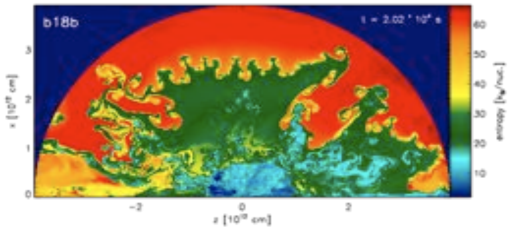
- pulsar kick
  (Scheck et al. 04, 06, Nordhaus et al. 10b, Wongwathanarat et al. 10)



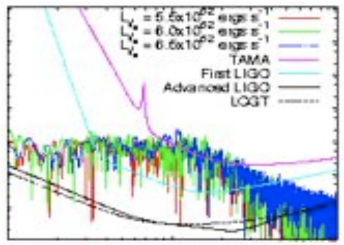
- pulsar spin ?
  (Blondin & Mezzacappa 07, Yamasaki & Foglizzo 08, Iwakami et al. 09, Rantsiou et al. 11)



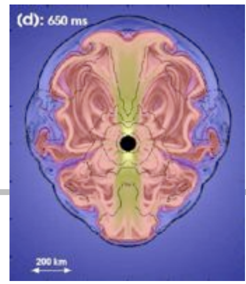
- H/He mixing in SN1987A
  (Kifonidis et al. 06, Hammer et al. 09)



- gravitational waves
  (Ott et al. 06, Kotake et al. 07, Marek et al. 09, Ott 08, Murphy et al. 09, Kotake et al. 11)

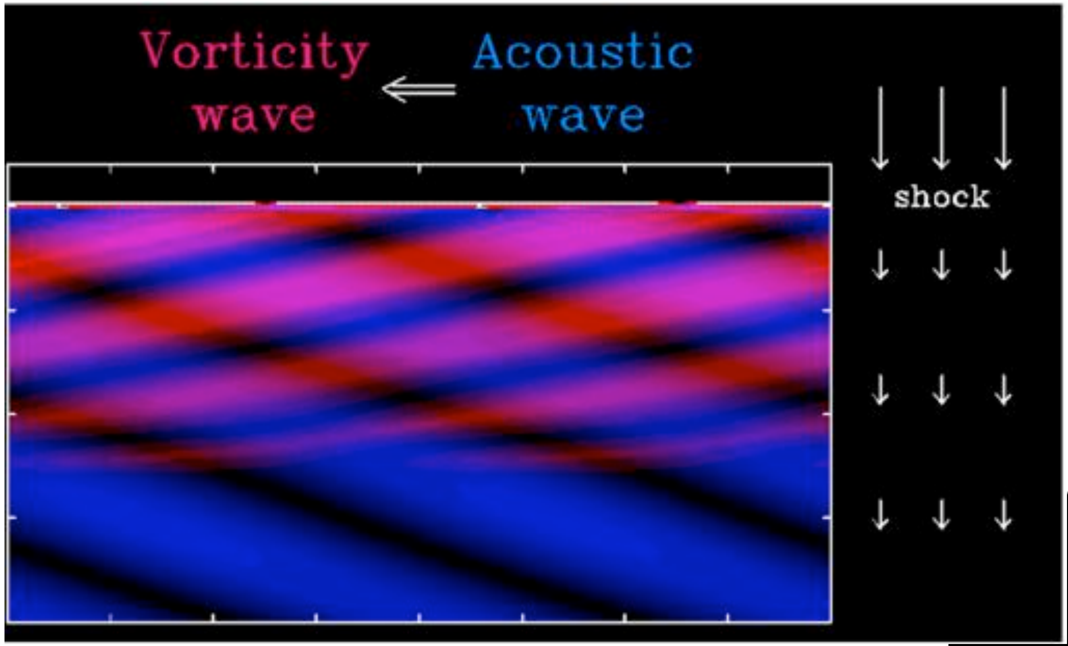


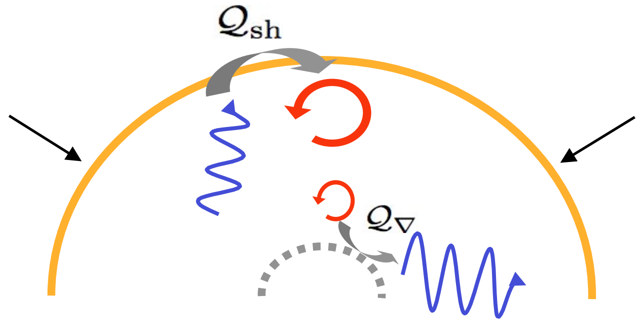
- magnetic field amplification ?
  (Endeve et al. 10, Guilet et al. 11, Obergaulinger & Janka 11)

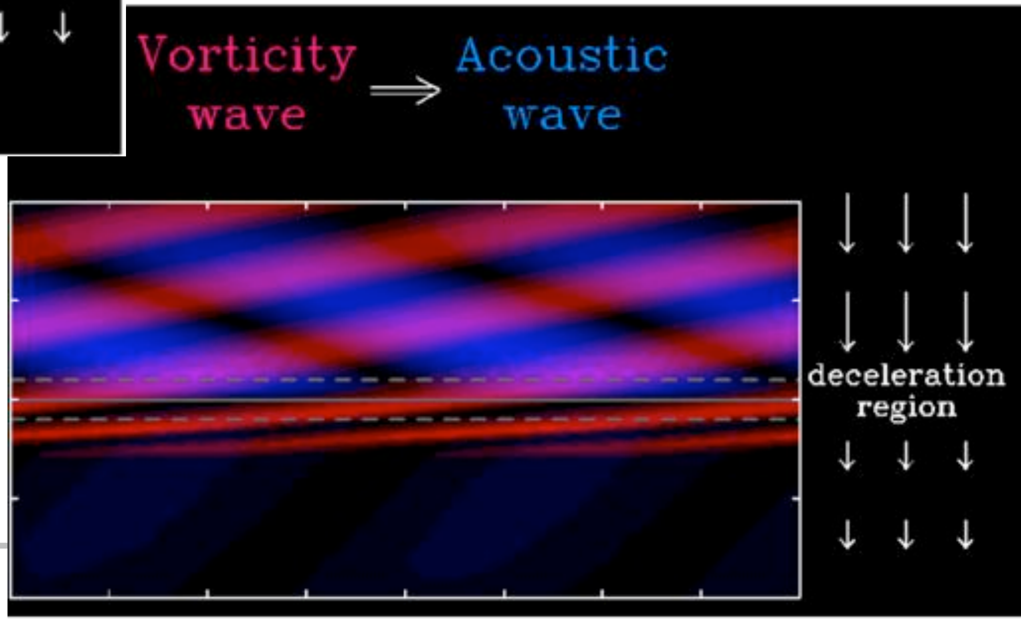


Linear coupling between the acoustic wave and the entropy/vorticity wave

(Sato, Foglizzo & Fromang 09)

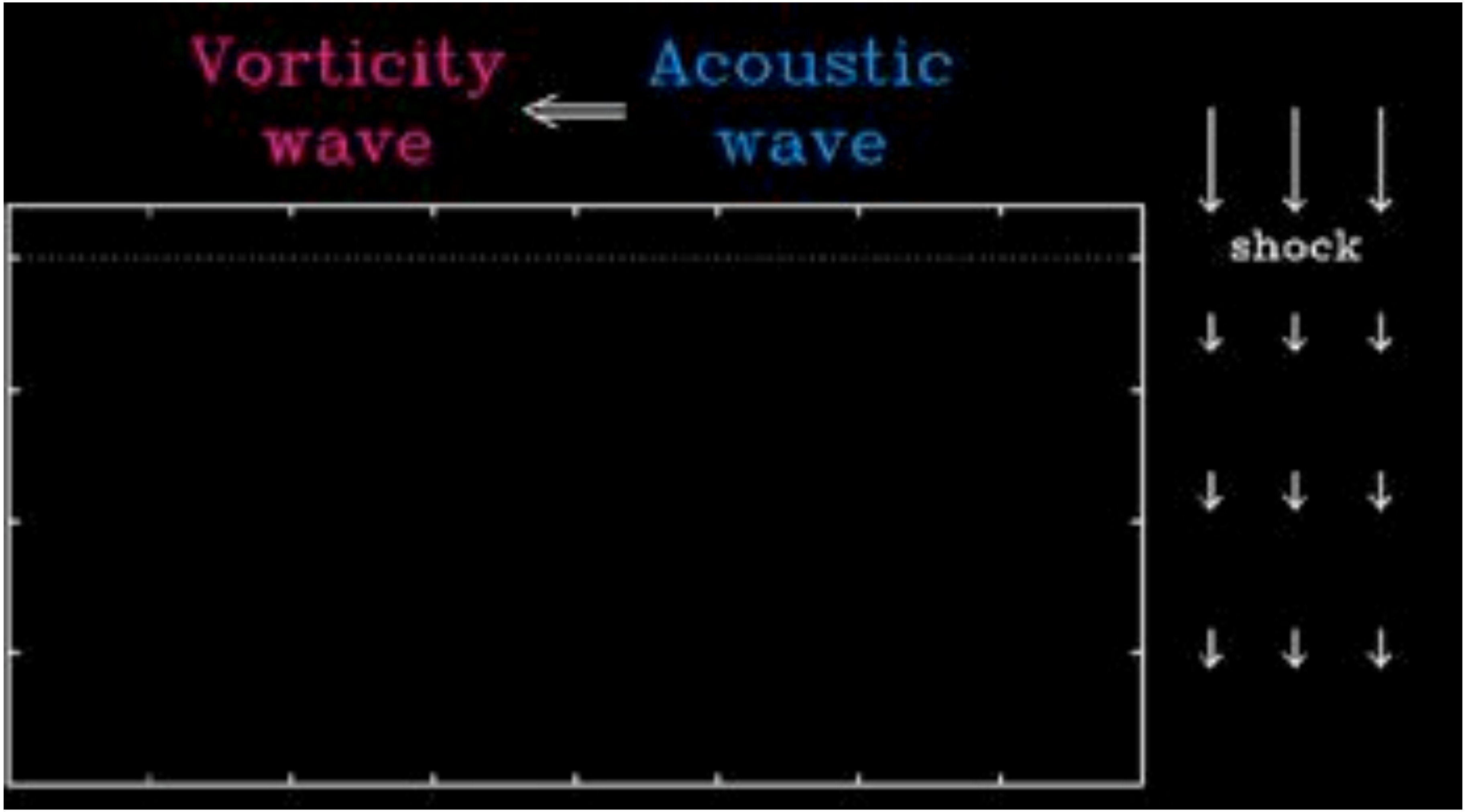






Linear coupling between the acoustic wave and the entropy/vorticity wave

(Sato, Foglizzo & Fromang 09)

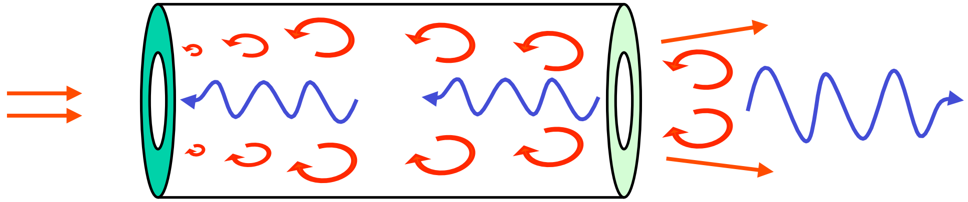


Aero-acoustic instabilities

- advected perturbations
- acoustic feedback

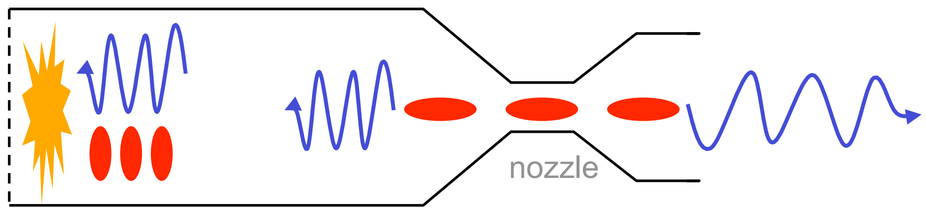
whistling kettle
Chanaud & Powell 65

- vortical-acoustic cycle



vibrations in Ariane 5
Mettenleiter, Haile & Candel 00

- entropic-acoustic cycle



rumble instability of ramjets
Abouseif, Keklak & Toong 84

From SN explosions to a shallow water experiment

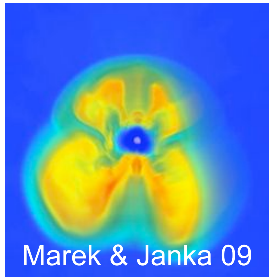
realism & complexity

simplicity & understanding

Observations of SN and pulsars

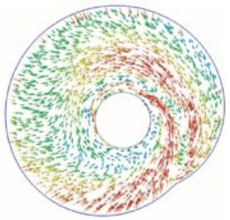
- SN light curve, polarimetry, neutrinos, grav. waves, nucleosynthesis,
- Pulsar kick and spin

Complex comprehensive simulations
(Marek & Janka 09, Burrows et al. 06)



progenitor structure + nuclear EOS
+ neutrino transport & interactions
+ relativistic corrections + multi-D hydro
(no magnetic effects, moderate rotation)

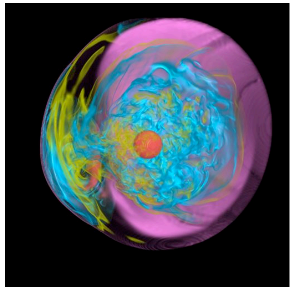
Multi-D hydro processes:
ideal gas, stationary accretion



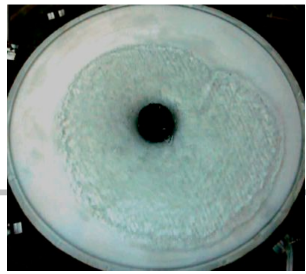
- equatorial approx. with cooling
(Blondin & Shaw 07)

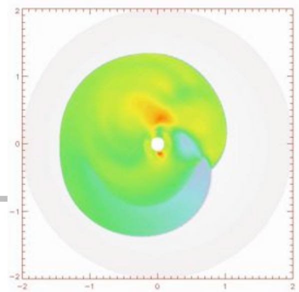
- cylindrical approx. with cooling & rotation
(Yamasaki & Foglizzo 08)

- adiabatic approx. 3D
(Blondin & Mezzacappa 07)



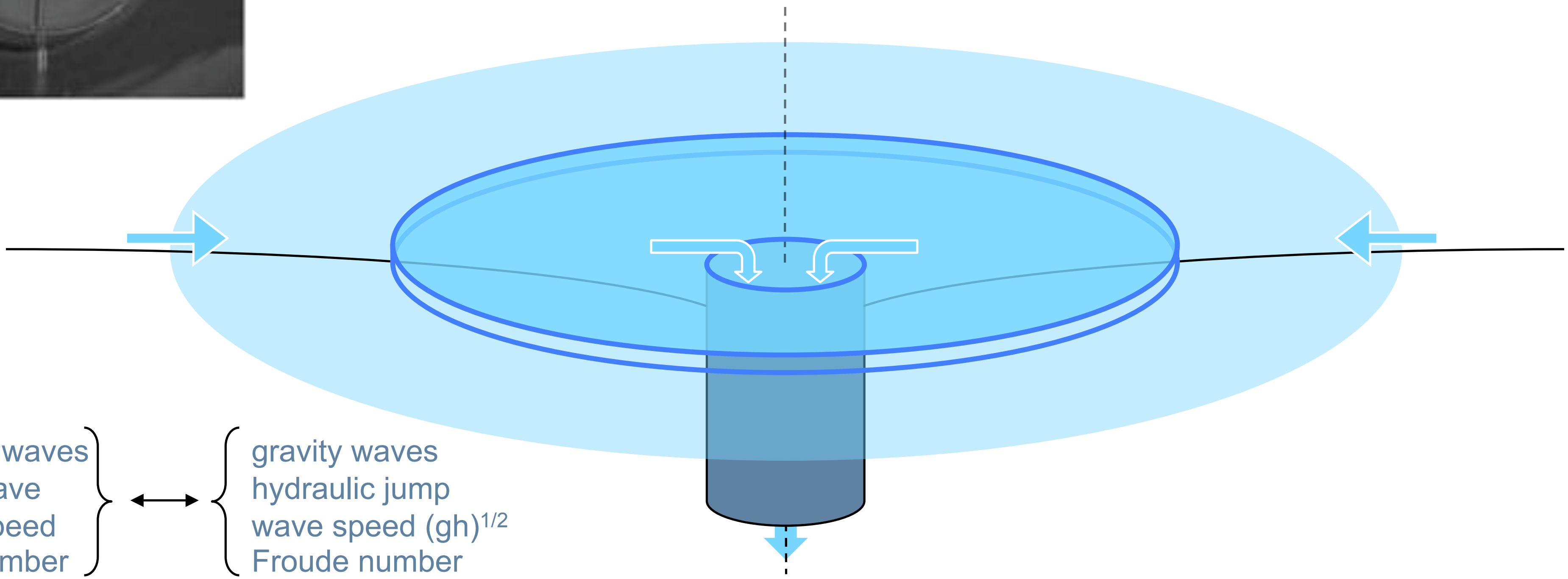
SWASI experiment





- shallow water
inviscid approx.

SWASI: a shallow water SASI experiment
(Low Cost Laboratory Astrophysics)



acoustic waves, shock wave, sound speed, Mach number ⟷ gravity waves, hydraulic jump, wave speed $(gh)^{1/2}$, Froude number

acoustic waves	⟷	gravity waves
shock wave		hydraulic jump
sound speed		wave speed $(gh)^{1/2}$
Mach number		Froude number

St Venant approximation

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

$$c^2 = gH \qquad \frac{\partial H}{\partial t} + \nabla \cdot (Hv) = 0$$

Vorticity-driven advective-acoustic instability ?

+ energy and angular momentum budgets ?
+ spiral/sloshing mode ?
+ non linear saturation ?
+ destabilizing effect of rotation ?

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 $c = (gH)^{\frac{1}{2}}$

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

$$c^2 = gH$$

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

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

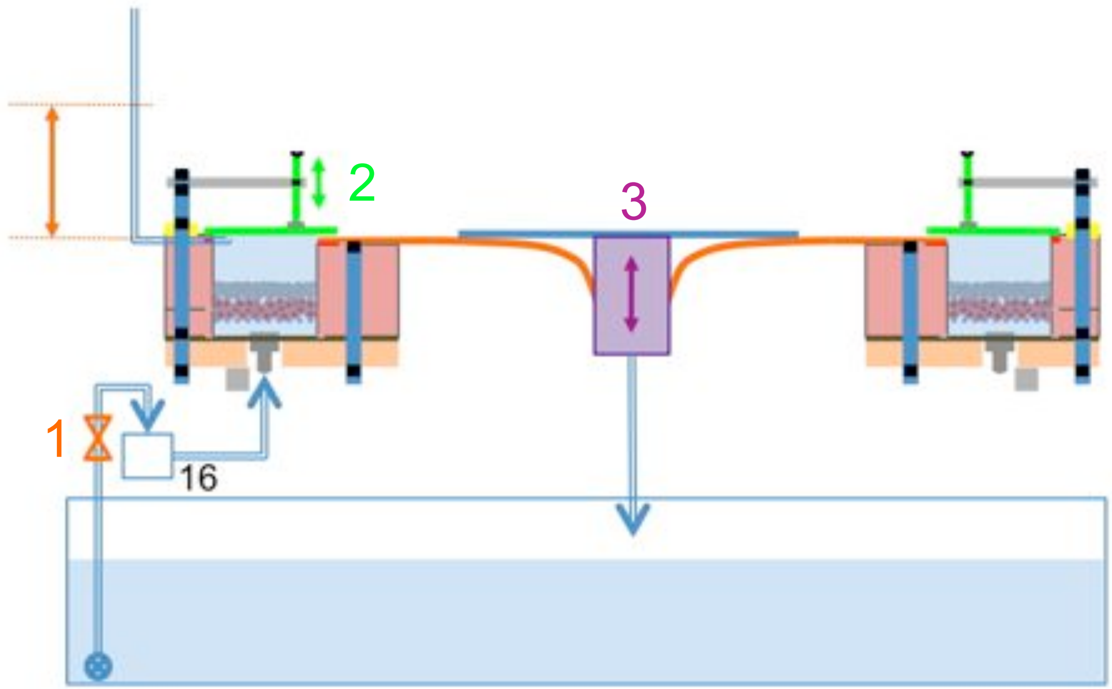
(intermediate between "isothermal" and "γ=2 without entropy")

isothermal shock $\mathcal{M}_2 = \frac{1}{\mathcal{M}_1}$

hydraulic jump $\mathcal{M}_2 = \frac{2^{\frac{3}{2}} \mathcal{M}_1}{\left[(1 + 8\mathcal{M}_1^2)^{\frac{1}{2}} - 1 \right]^{\frac{3}{2}}}$

jump conditions: conservation of mass flux and momentum flux (energy is dissipated)

SWASI: experimental setup



three parameters:

1: flow rate Q

2: size of the injection slit H

3: height of the exit cylinder (hydraulic jump radius)

} Froude number $\mathrm{Fr} \equiv \frac{v}{(gH)^{\frac{1}{2}}} = \frac{Q}{2\pi r g^{\frac{1}{2}} H^{\frac{3}{2}}}$

SWASI: simple as a garden experiment

SWASI: simple as a garden experiment

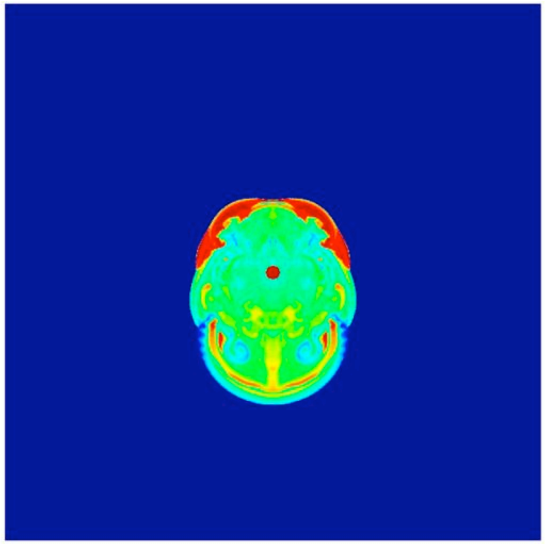
1. Check the stationary, axisymmetric injection in a stable configuration

Fr=13.8, H=0.5mm, Q=1.0L/s, stable

Axisymmetric, stationary injection

Fr=13.8, H=0.5mm, Q=1.0L/s, stable

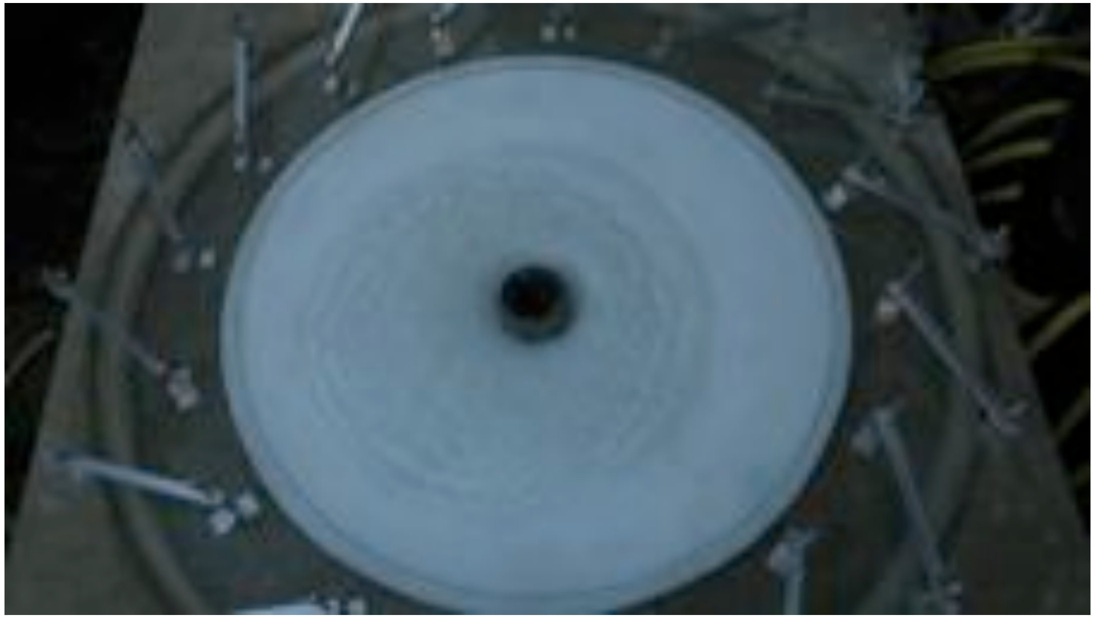
2. Unstable sloshing oscillations in supernova simulations and in the SWASI experiment



Blondin et al. 03

SWASI experiment
Fr=7.0, H=1mm, Q=1.4L/s, T=2.9s

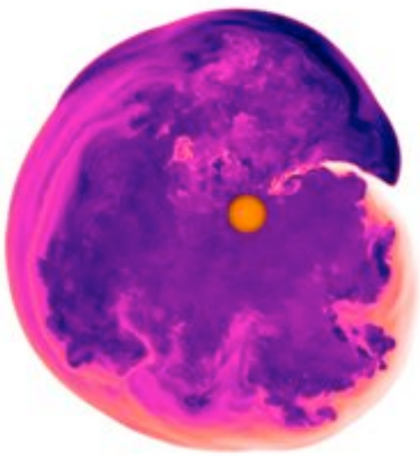
sloshing m=1 mode



Fr=7.0, H=1mm, Q=1.4L/s, T=2.9s

inviscid, 2D

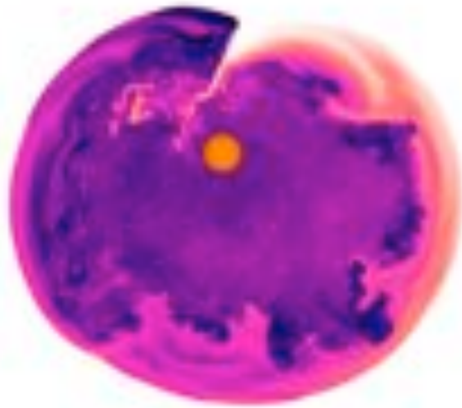
3. unstable spiral oscillations in supernova simulations and in the SWASI experiment



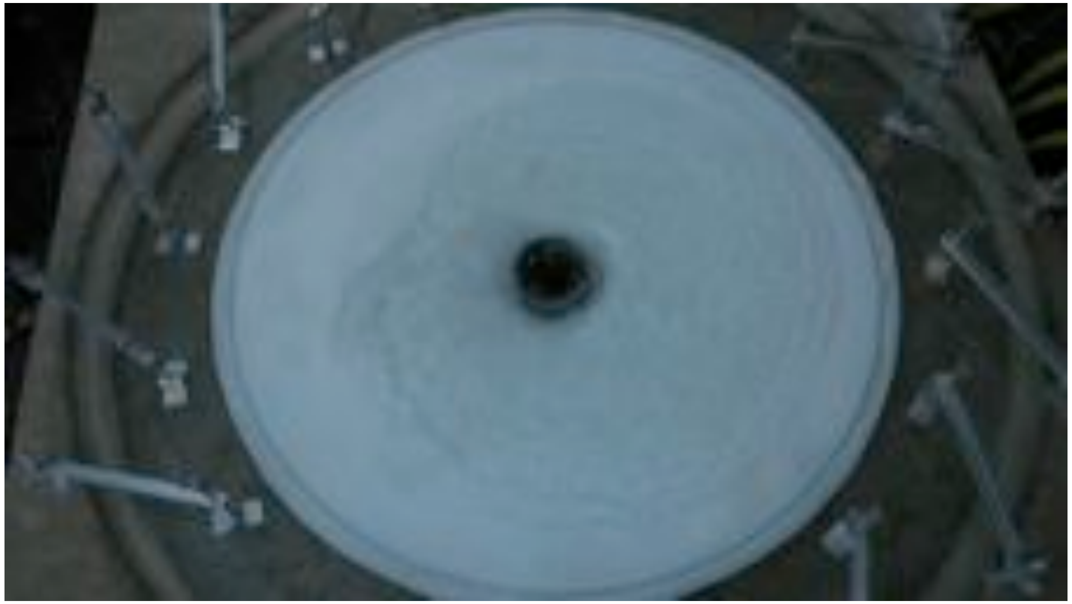
Blondin & Mezzacappa 07

SWASI experiment
Fr=17.1, H=0.5mm, Q=1.2L/s, T=2.4 to 3.2

growing m=1 spiral



Blondin & Mezzacappa 07



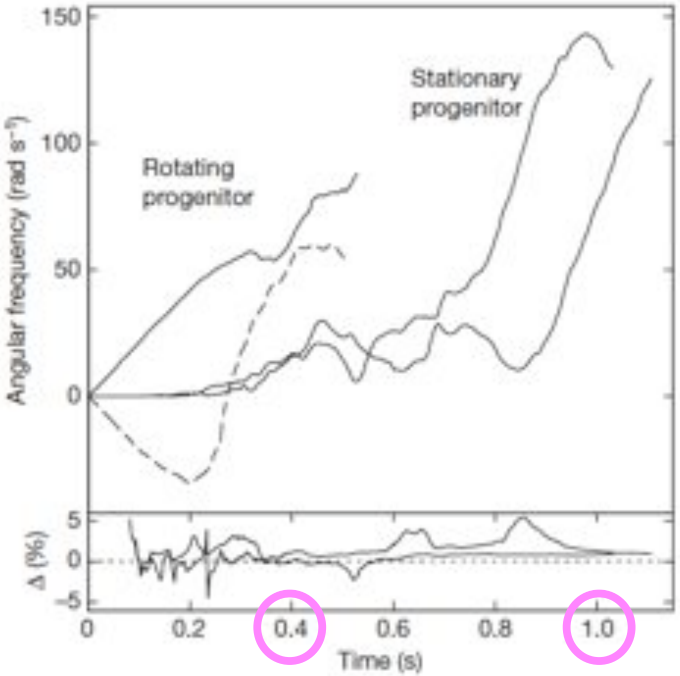
Fr=17.1, H=0.5mm, Q=1.2L/s, T=2.4 to 3.2

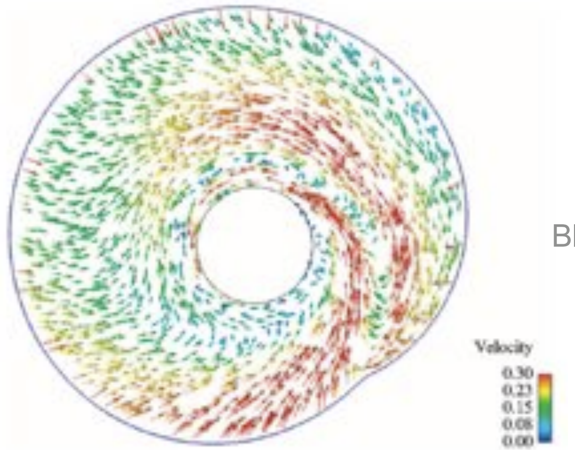
inviscid, 2D

F. Masset

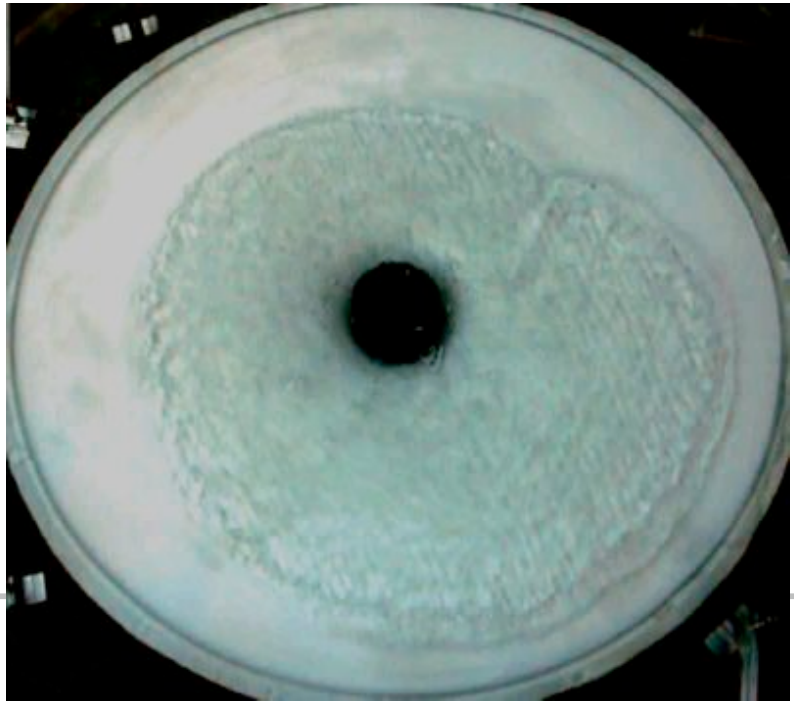
Spiral SASI mode and the angular momentum budget

Blondin & Mezzacappa 07





Blondin & Shaw 07



Timescale for symmetry breaking ?

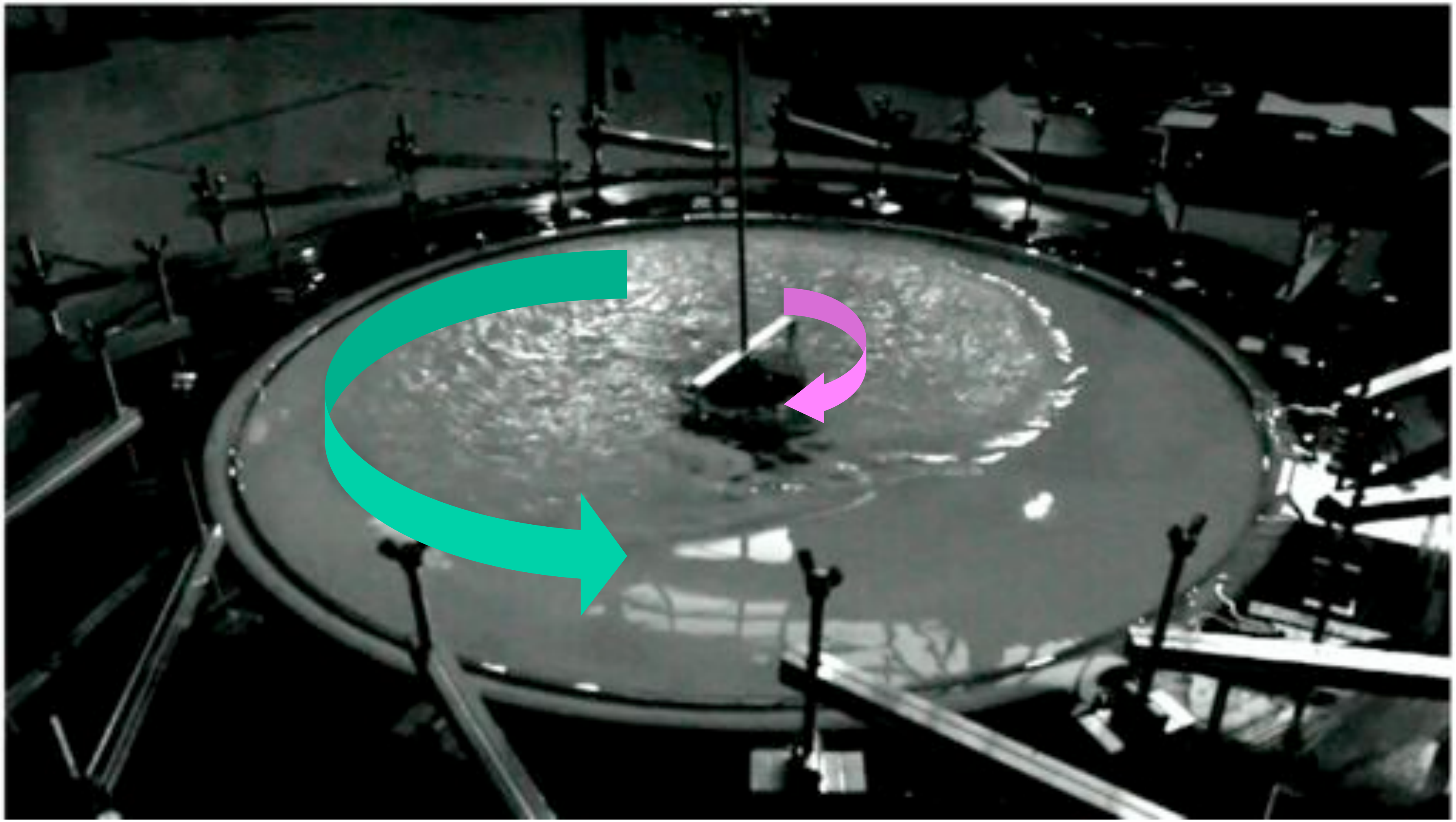
-too slow for slow rotators ?
(Iwakami et al. 08, Wongwathanarat et al. 10, Rantsiou et al. 11)

-angular momentum ~ $0.6 \times \dot{M} r_{\rm sh}^2$
(Fernandez 10)

→ Need for 3D simulations of a rotating progenitor
(Iwakami et al. 09)

Spiral SASI mode and the angular momentum budget:

propagating wave + advected vorticity = 0



Spiral SASI mode and the angular momentum budget:

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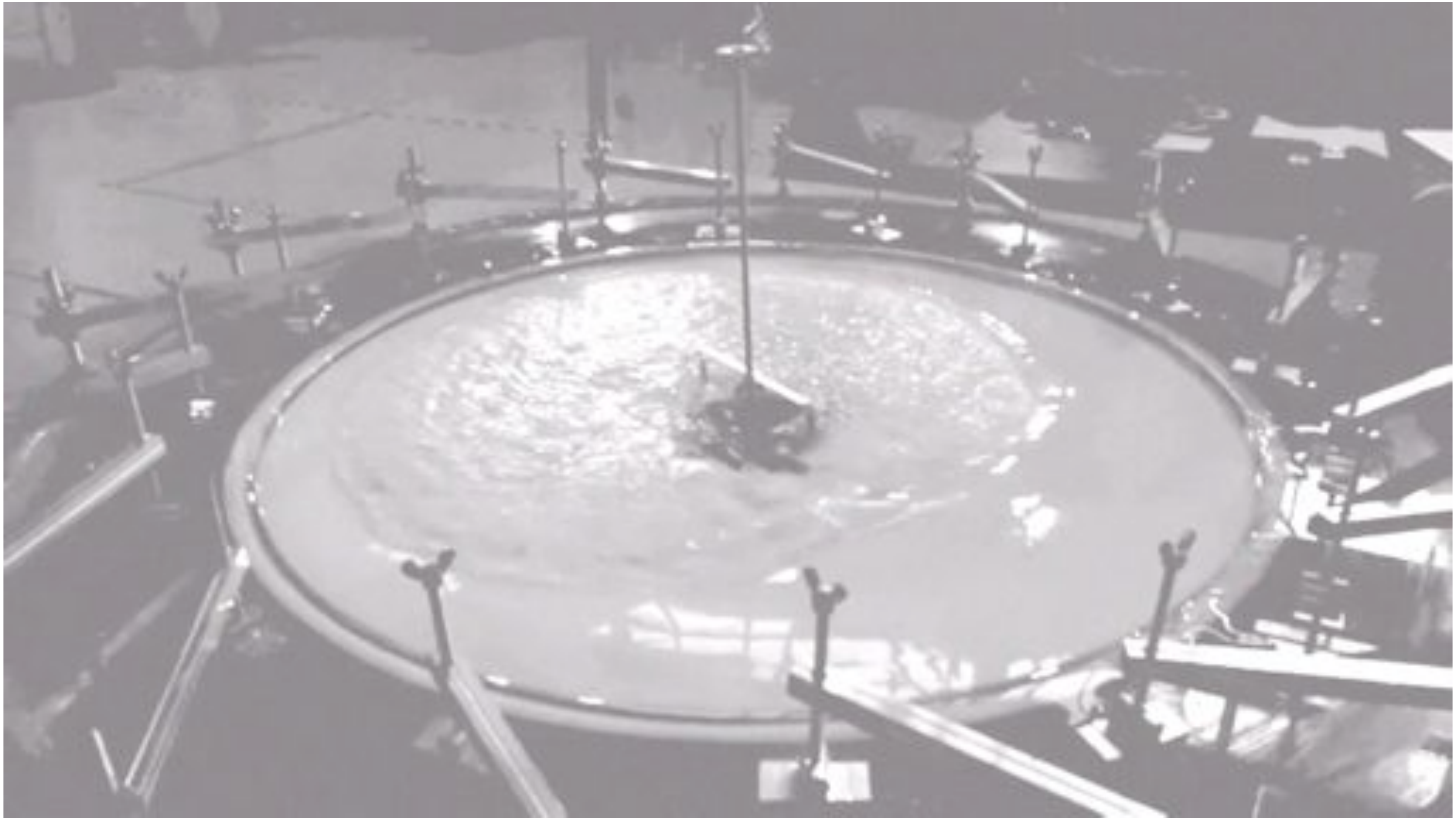


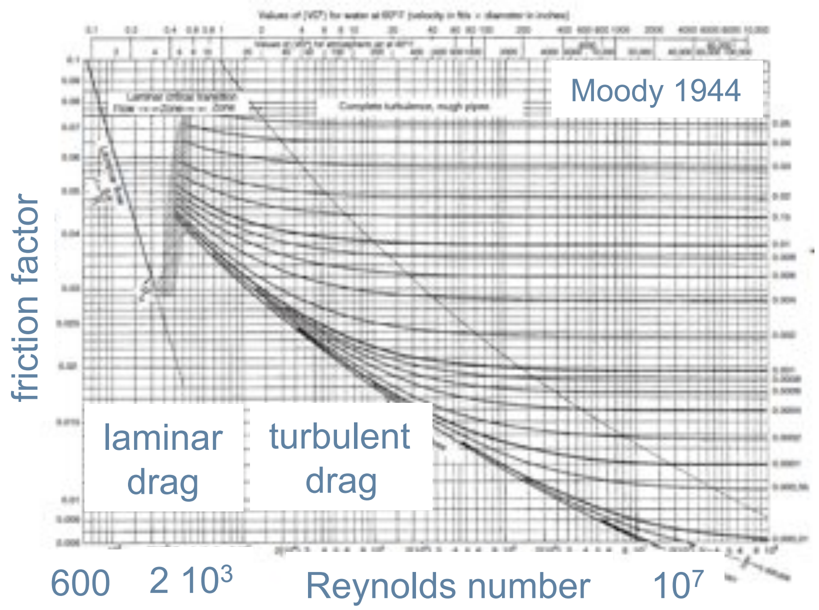
Quantitative analysis

Input parameters: Flow rate Q (0-3L/s), injection slit H (0.5-1mm), "shock" radius R_{sh} (10-30cm)

- Measure of H(r): estimate the viscous drag

- Measure of the stability threshold (Fr, R_{sh}/R_*, Q)

- Measure of the oscillation frequency (1-3 sec)
  and shape of the dominant mode (m=1)

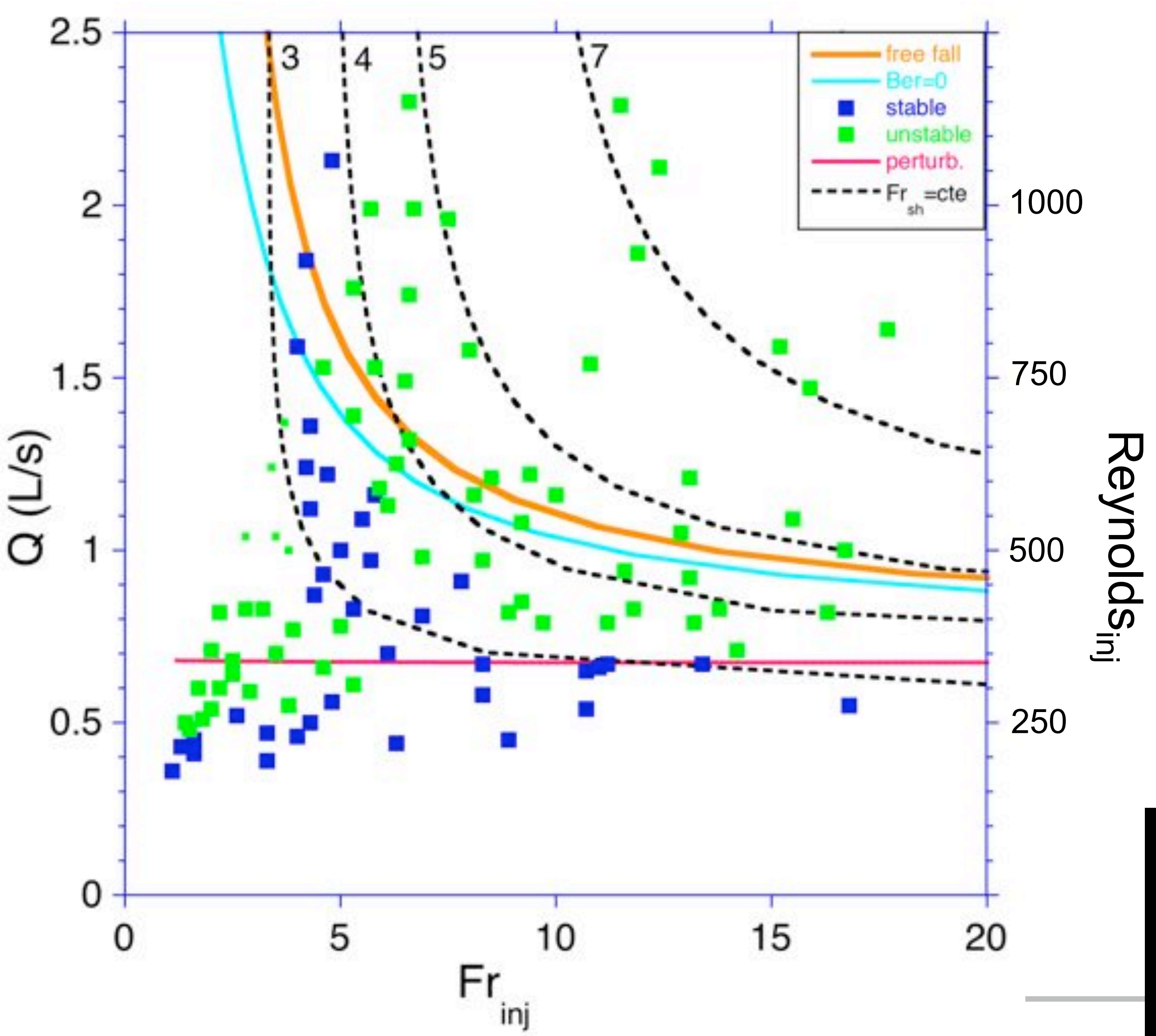


Comparaison with a perturbative analysis
and numerical simulations of a shallow water 2D model

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

laminar
drag

Instability parameter space



2D shallow water model:

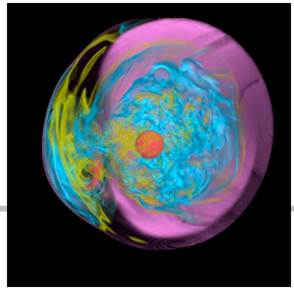
- laminar viscous drag
- inner boundary: free spillover

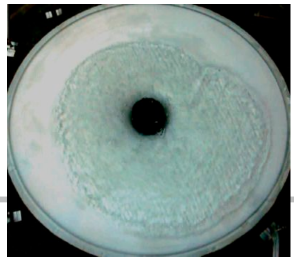
Eigenfrequencies confirmed with numerical simulations (F. Masset)

Robust m=1 instability

astrophysical scaling:

30 ms	time x 100	3 sec
200 km	distances / 10^6	20 cm



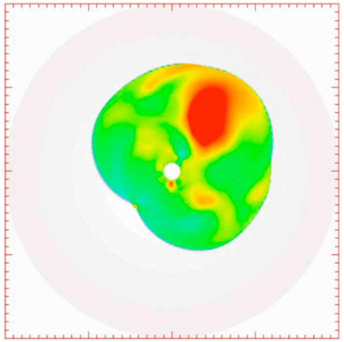


Conclusions

Potential consequences of SASI are numerous:

neutrino driven explosion, NS kick & spin

mixing, grav. waves, magnetic field

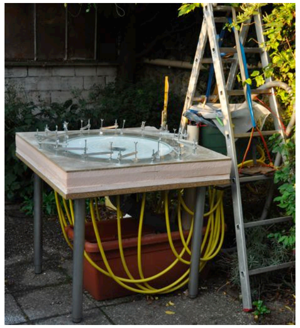


Uncertainties are also numerous

3D validity of 2D results ? SASI vs convection ?

effect of EOS ? GR ?

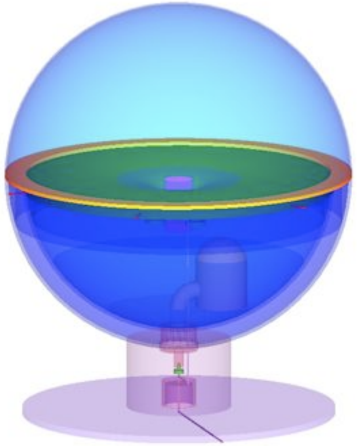
SWASI: an experimental view on SASI



complementary to the perturbative and numerical approaches

makes SASI more intuitive + public outreach

- inner boundary effect ?
- saturation mechanism ?
- symmetry breaking ?
- destabilized by rotation ?



A new SWASI prototype built at CEA Saclay:

- improved accuracy
- global rotation