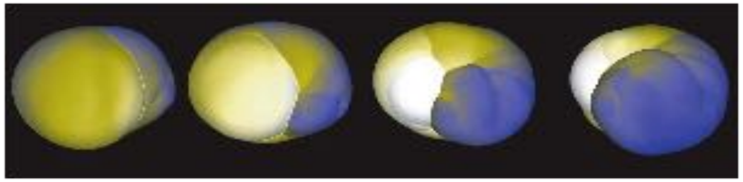
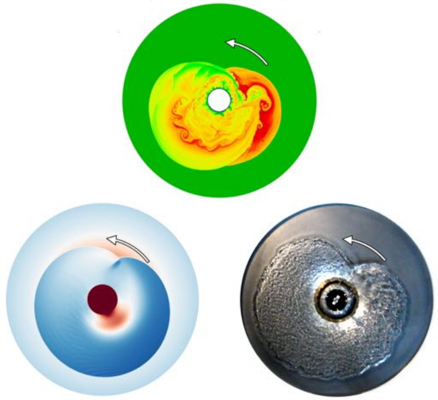
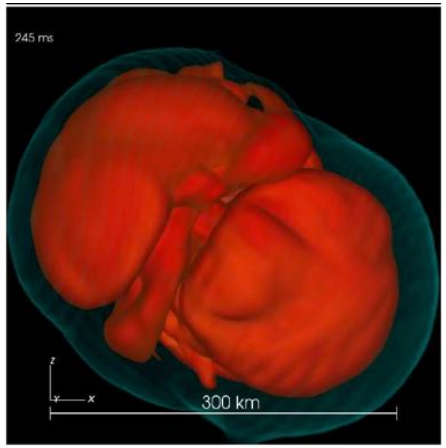
Non axisymmetric instabilities during stellar core collapse illustrated by a shallow-water experiment

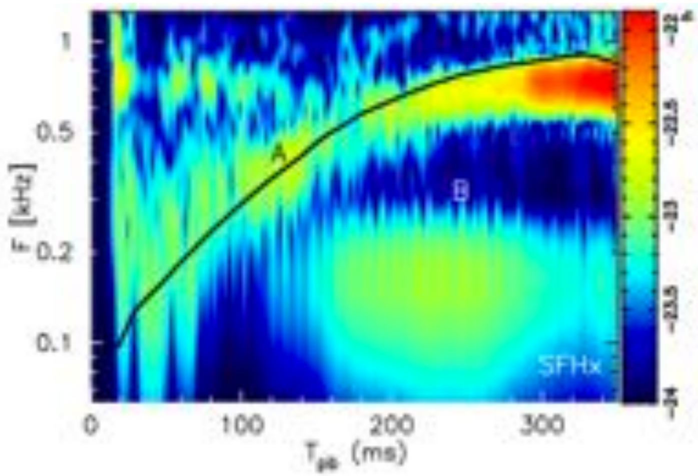


Blondin & Mezzacappa 07

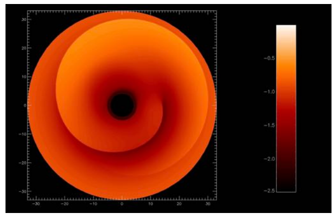


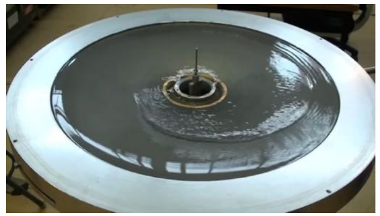


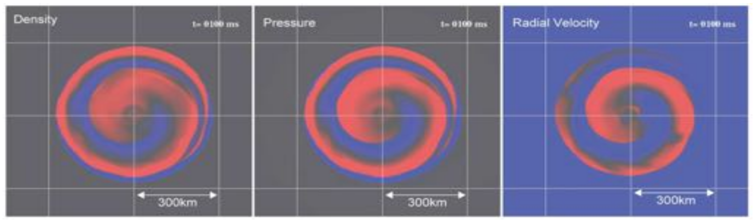
Hanke+13



Kuroda+16







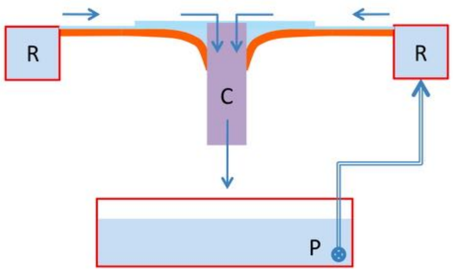
Takiwaki+16

Thierry Foglizzo, Remi Kazeroni, Matthias Gonzalez, Gilles Durand

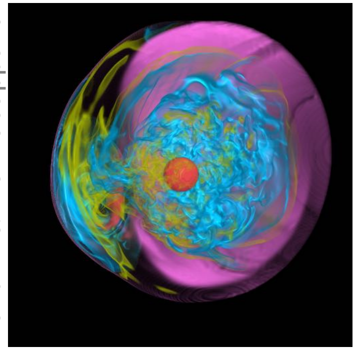
CEA Saclay

SWASI: an experimental analogue of SASI

Shallow Water Analogue of a Shock Instability



Blondin & Mezzacappa 07



adiabatic gas

$$c_s^2 \equiv \frac{\gamma P}{\rho}$$

$$\Phi \equiv -\frac{GM_{ns}}{r}$$

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

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

Inviscid shallow water is analogue to an isentropic gas γ=2

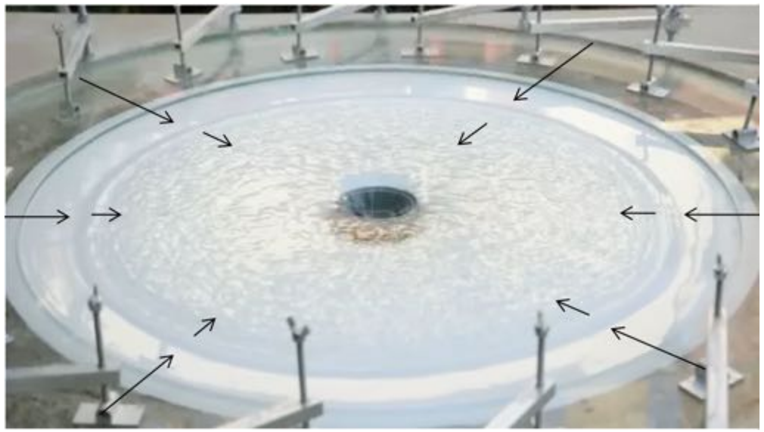
St Venant

$$c_{sw}^2 \equiv gH$$

$$\Phi \equiv gH_\Phi$$

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

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



acoustic waves shock wave pressure	⟷	surface waves hydraulic jump depth

expected scaling

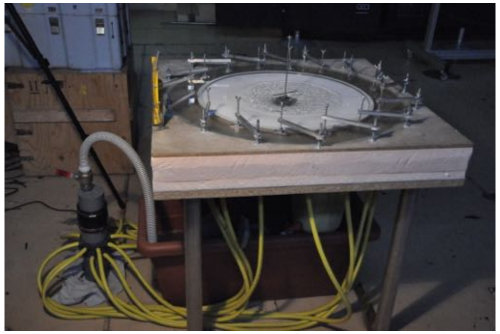
$$\frac{t_{ff}^{sh}}{t_{ff}^{jp}} \equiv \left(\frac{r_{sh}}{r_{jp}} \right) \left(\frac{r_{sh} g H_{jp}}{GM_{NS}} \right)^{\frac{1}{2}} \sim 10^{-2}$$

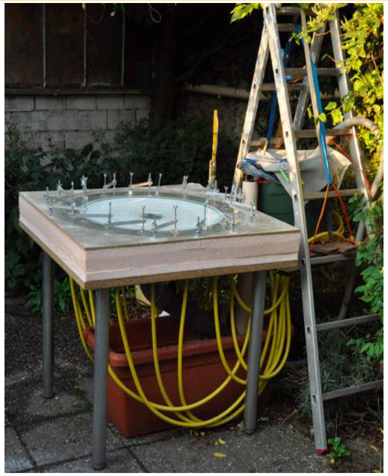
shock radius $\times 10^{-6}$ 200 km → 20 cm

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

SWASI: simple as a garden experiment

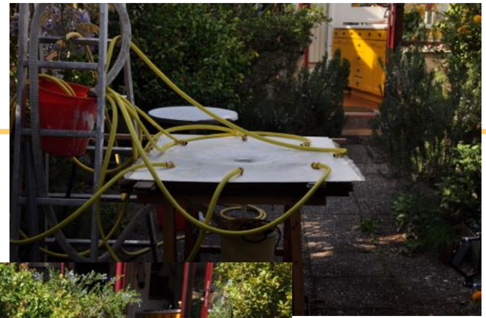
November 2010





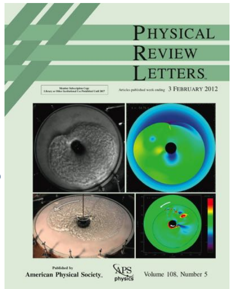
October 2010

June 2010



May 2010

February 2012



PRIX 2014
LE GOÛT DES SCIENCES

November 2013

June 2014

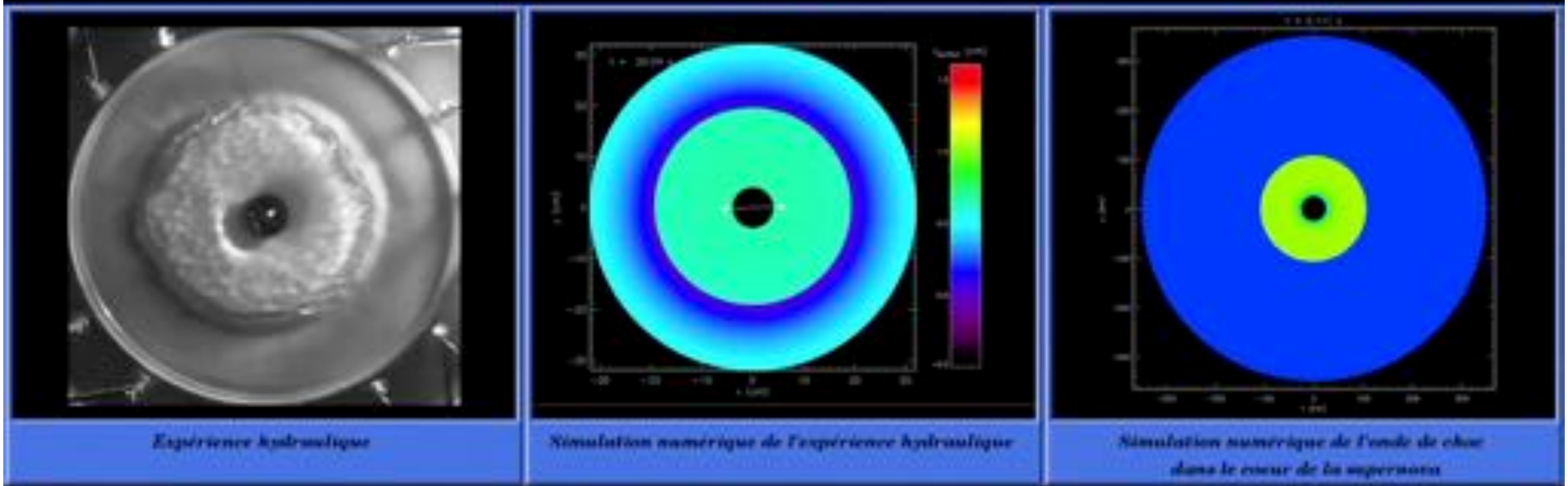
February 2017

Dynamics of water
in the fountain

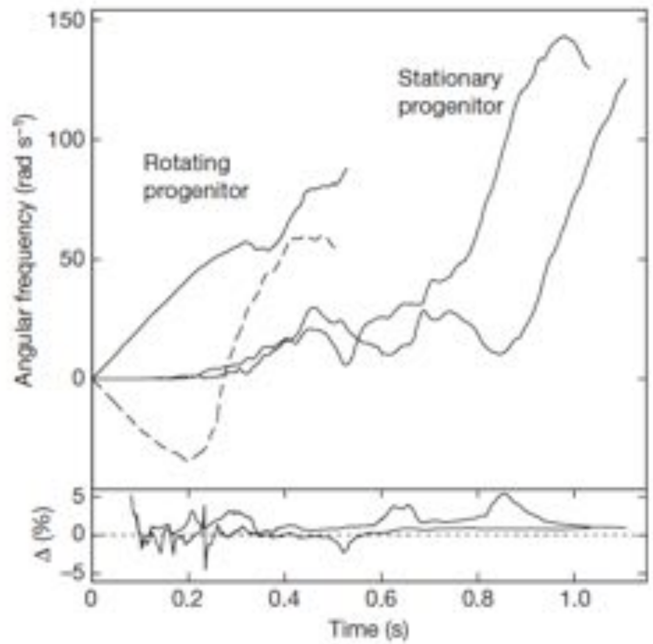
Dynamics of the gas
in the supernova core

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

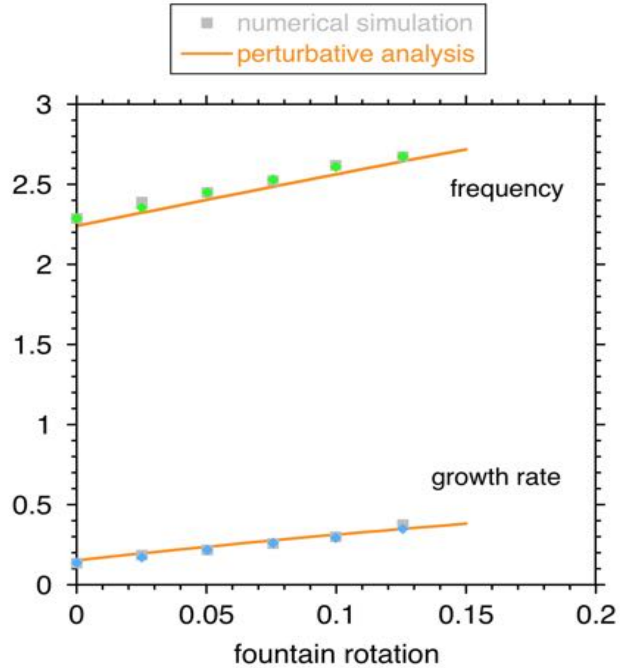
3s/oscillation ← 100 x faster → 0.03s/oscillation



Rotating progenitor: accreted angular momentum changes its sign as SASI grows



Blondin & Mezzacappa 07



similar to Yamasaki & Foglizzo 08

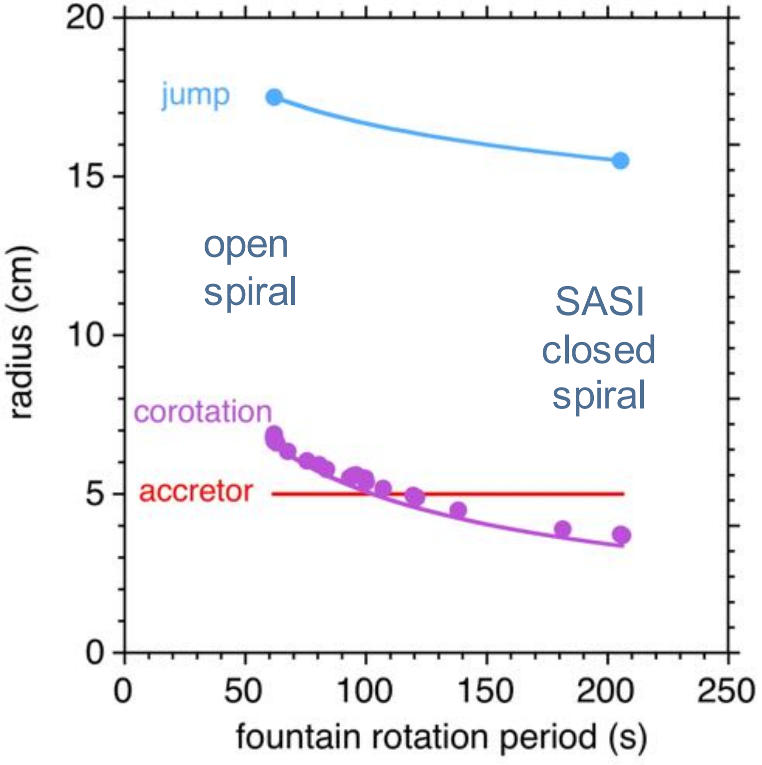
-significant shear even when the centrifugal force $\Omega^2 R$ is weak

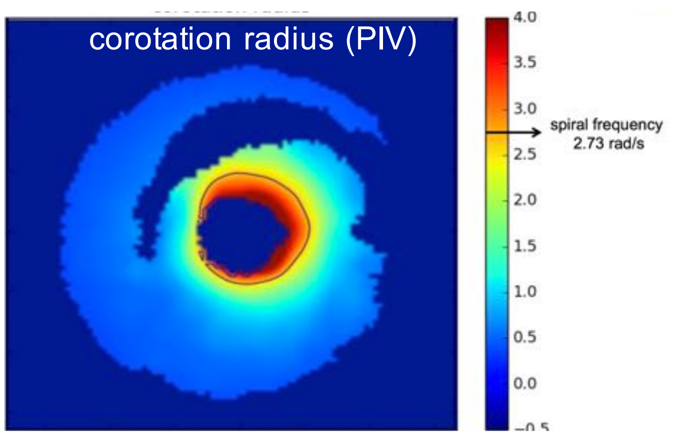
$$\frac{\Omega}{\Omega_{NS}} \propto \left(\frac{R_{NS}}{R}\right)^2$$

-the prograde mode is favoured by differential rotation as in shocked accretion:
can produce counter rotating pulsars up to 30Hz

Blondin & Mezzacappa 07, Yamasaki & Foglizzo 08, Kazeroni+17

Increasing the rotation rate: continuous transition from SASI to the corotation instability





the rotation period is gradually decreased (205s → 62s)

the flow rate is gradually decreased (1.1 L/s → 0.59 L/s)

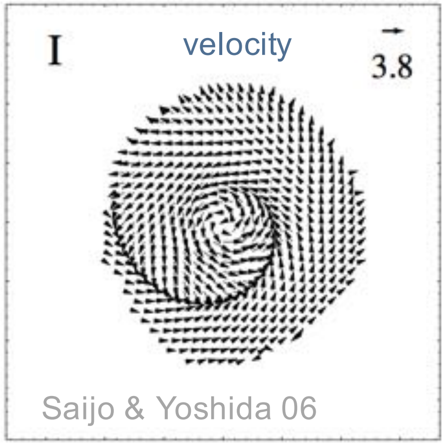
Unexpectedly robust spiral shock driven at the corotation radius when the inner rotation rate reaches 20% Kepler (low T/|W|=0.02)

Spiral instability with a weak shock

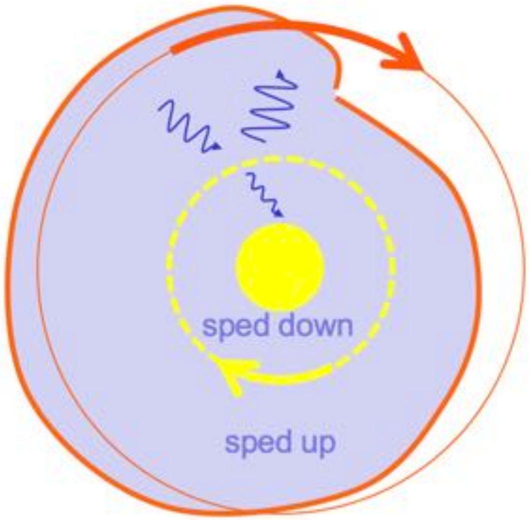
Radial accretion enforces differential rotation

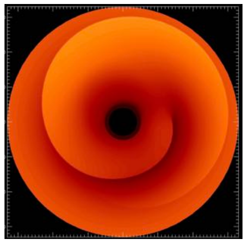
$$\frac{\Omega}{\Omega_{NS}} \propto \left(\frac{R_{NS}}{R}\right)^2$$

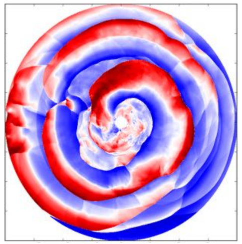
Analogue to the "low T/|W| instability" of a neutron star rotating differentially
(Shibata+02,03, Saijo+03,06, Watts+05, Corvino+10, Passamonti & Andersson 15)



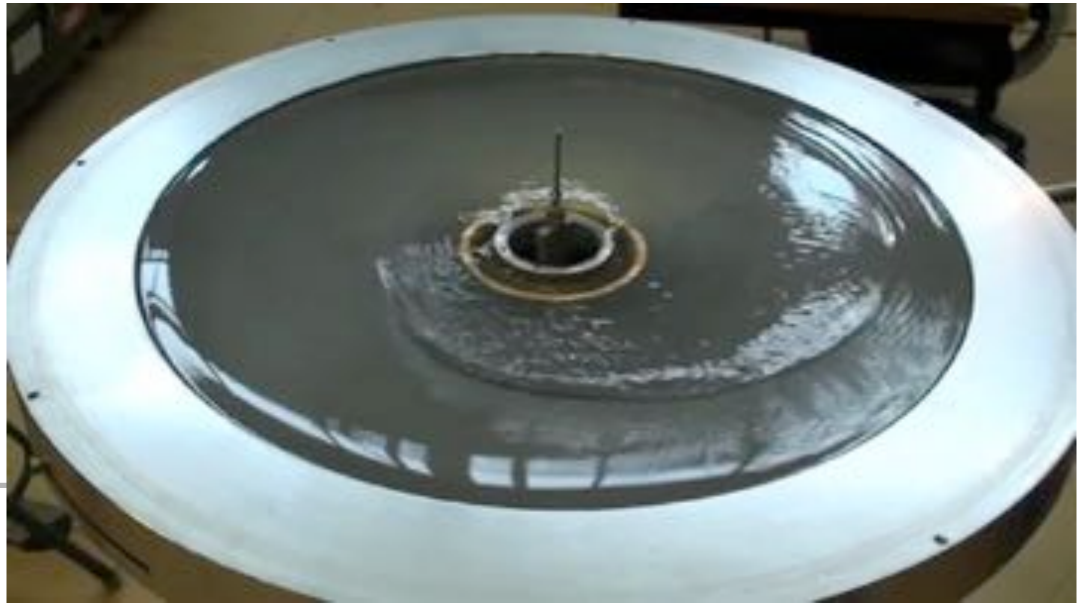
Saijo & Yoshida 06





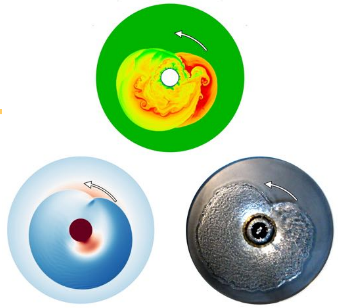


Spiral instability with subsonic accretion

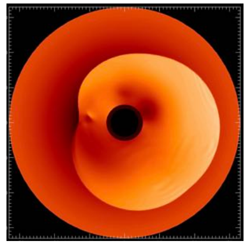


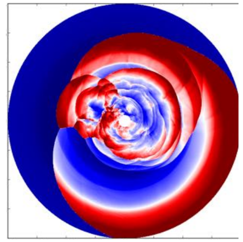
Instability mechanism: interaction of a corotation radius with acoustic waves (Papaloizou & Pringle 84, Goldreich & Narayan 85)

Conclusions



Two core collapse instabilities captured in a hydraulic experiment

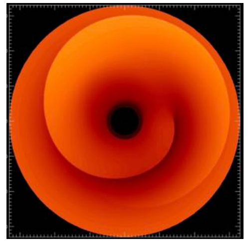


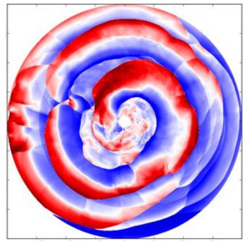


-an intuitive approach to multi-D processes that produce GW

-experimental results confirmed by a shallow water numerical model

-**first** experimental confirmation that spiral SASI can produce a counter-spinning neutron star

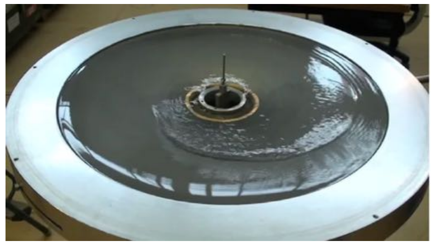




-**first** experimental demonstration of the 'low T/|W|' instability

-the corotation instability ‘low T/|W|’ connects smoothly to SASI

Cylindrical gas dynamics suggests that (Kazeroni+17)



-SASI can account for pulsar rotation rates up to ~30Hz

-for rotation rates >100Hz the corotation instability decreases the pulsar spin by <30%