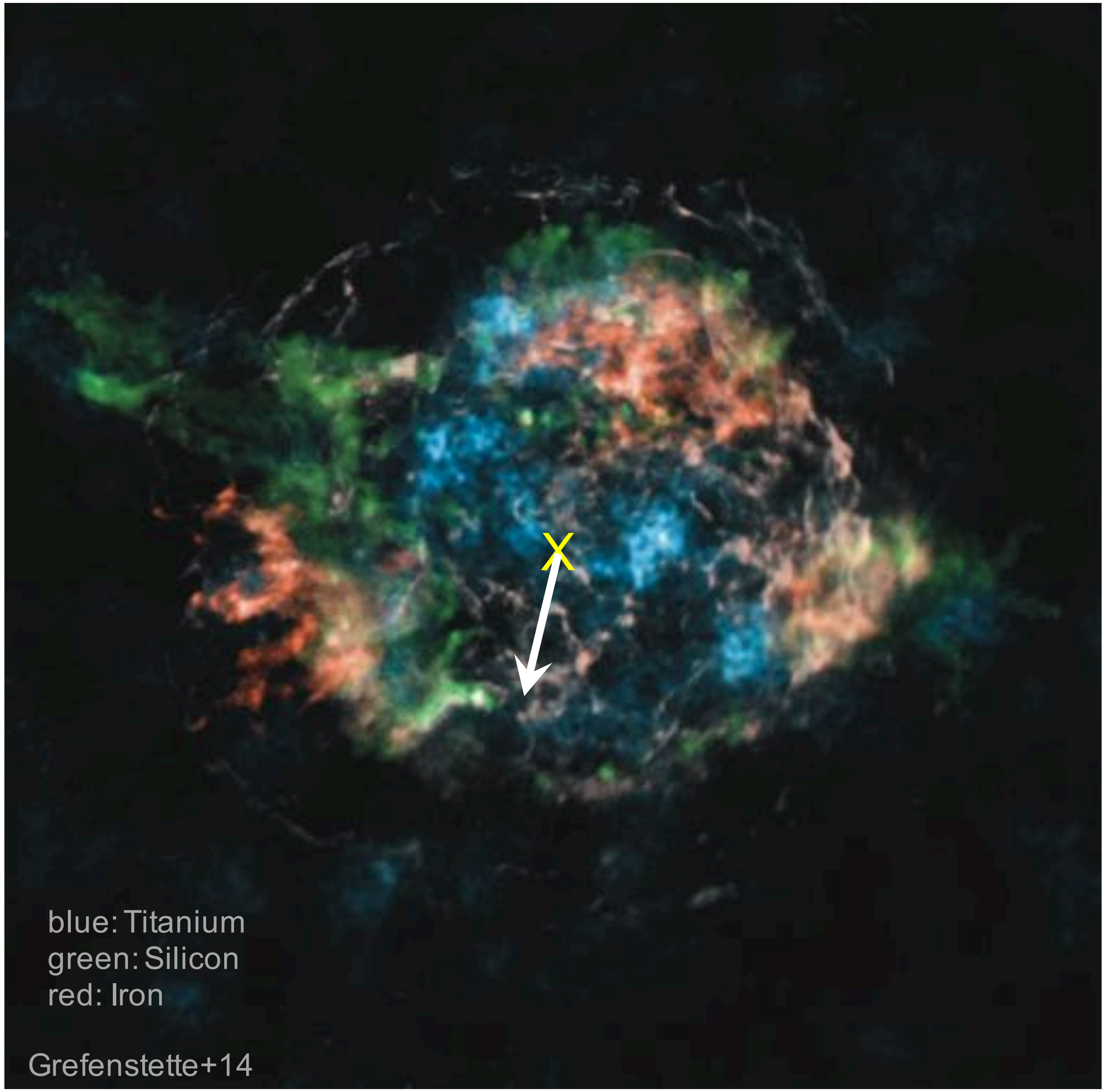
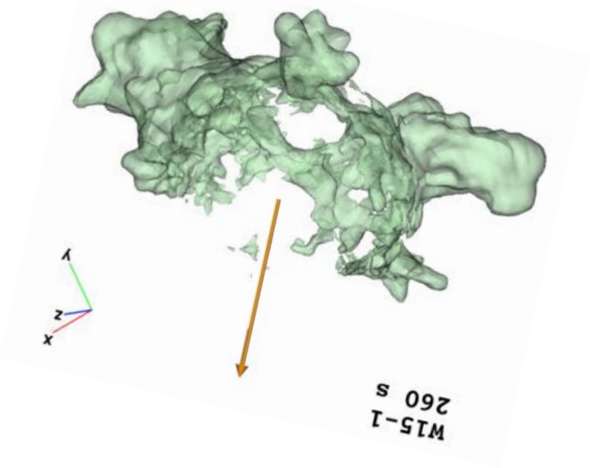
The supernova fountain



Grefenstette+14

Wongwathanarat+13



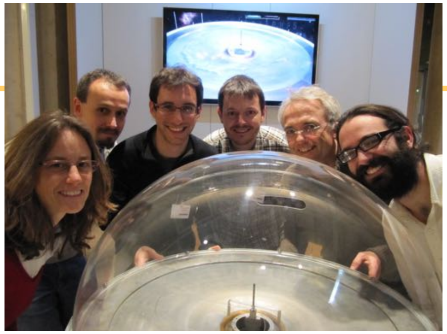
Thierry Foglizzo
CEA Saclay

R. Kazeroni, M. Gonzalez, J. Guilet, G. Durand

The “supernova fountain” at the Palais de la Découverte, Paris

17 December 2013-16 February 2014

138 presentations
2059 visitors



SN2NS

Supernovae explosions, from stellar core-collapse
to neutron stars and black holes

Thierry Foglizzo
Julien Faure
Rémi Hosseini-Kazeroni
Noël Martin
Jérôme Novak
Micaela Oertel
Patrick Blottiau
Elias Khan
Jérôme Guilet
Bruno Peres
Michael Urban
Jérôme Margueron

PRIX 2014
LE GOÛT
DES SCIENCES

Agence Nationale de la Recherche ANR

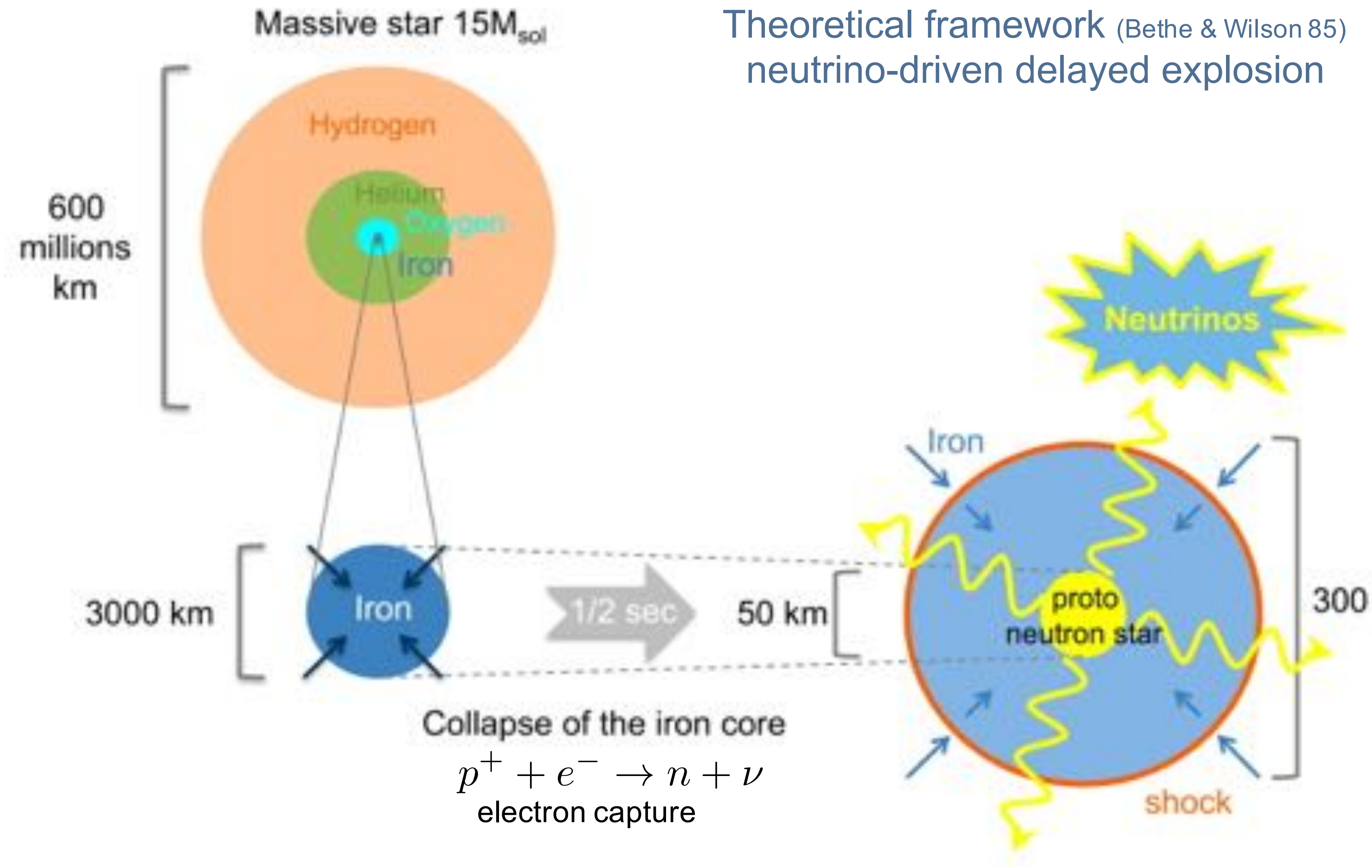
De la recherche à l'industrie cea

IPN Institut de Physique Nucléaire Orsay

l'Observatoire de Paris | LUTH
Laboratoire Univers et Théories

Max-Planck-Gesellschaft

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



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

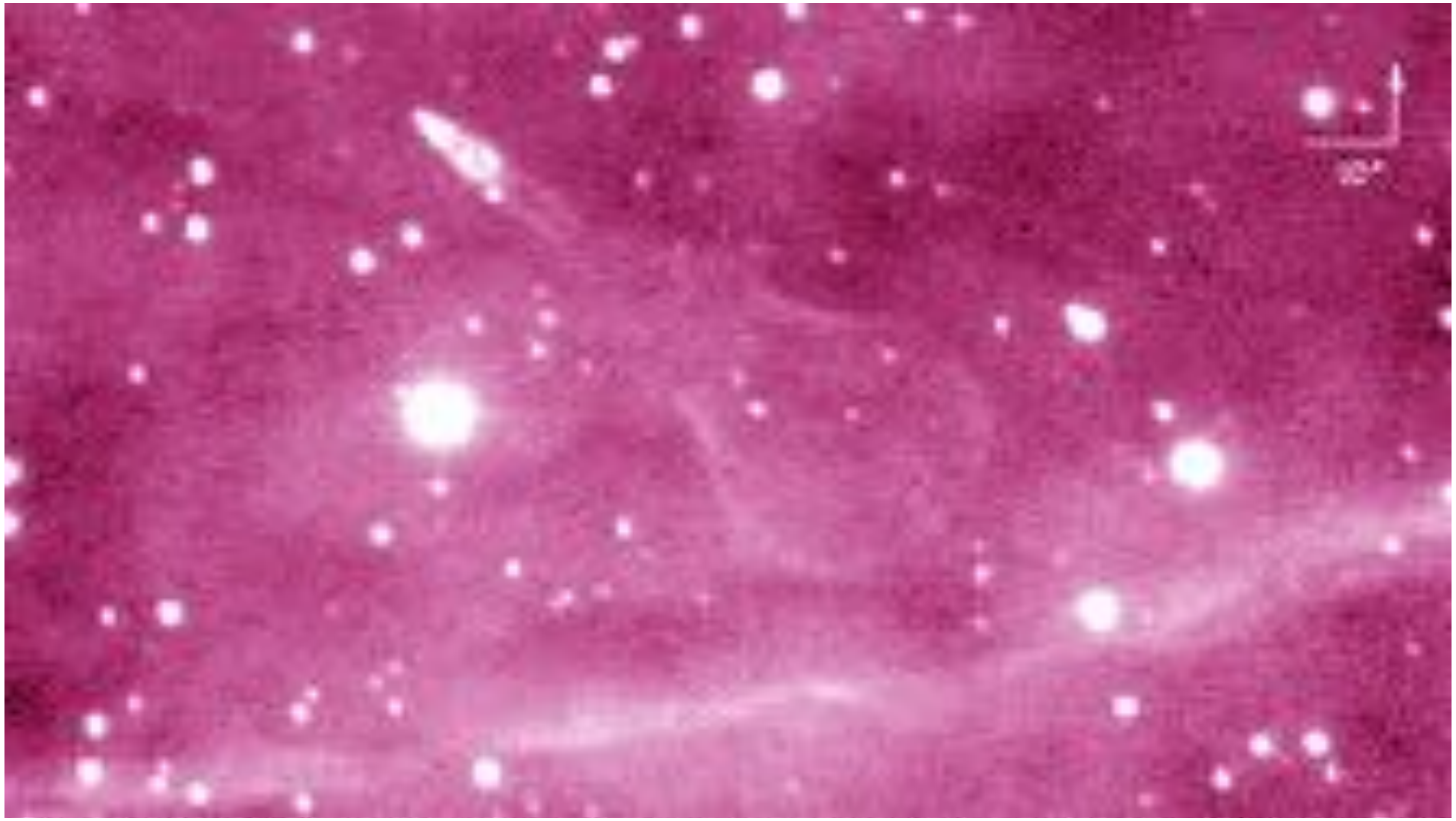
electron capture

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

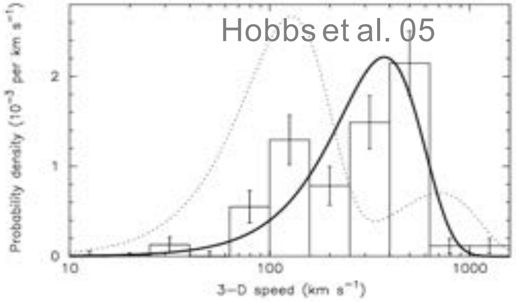
---

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

The high velocities of neutron stars suggest an asymmetric supernova explosion



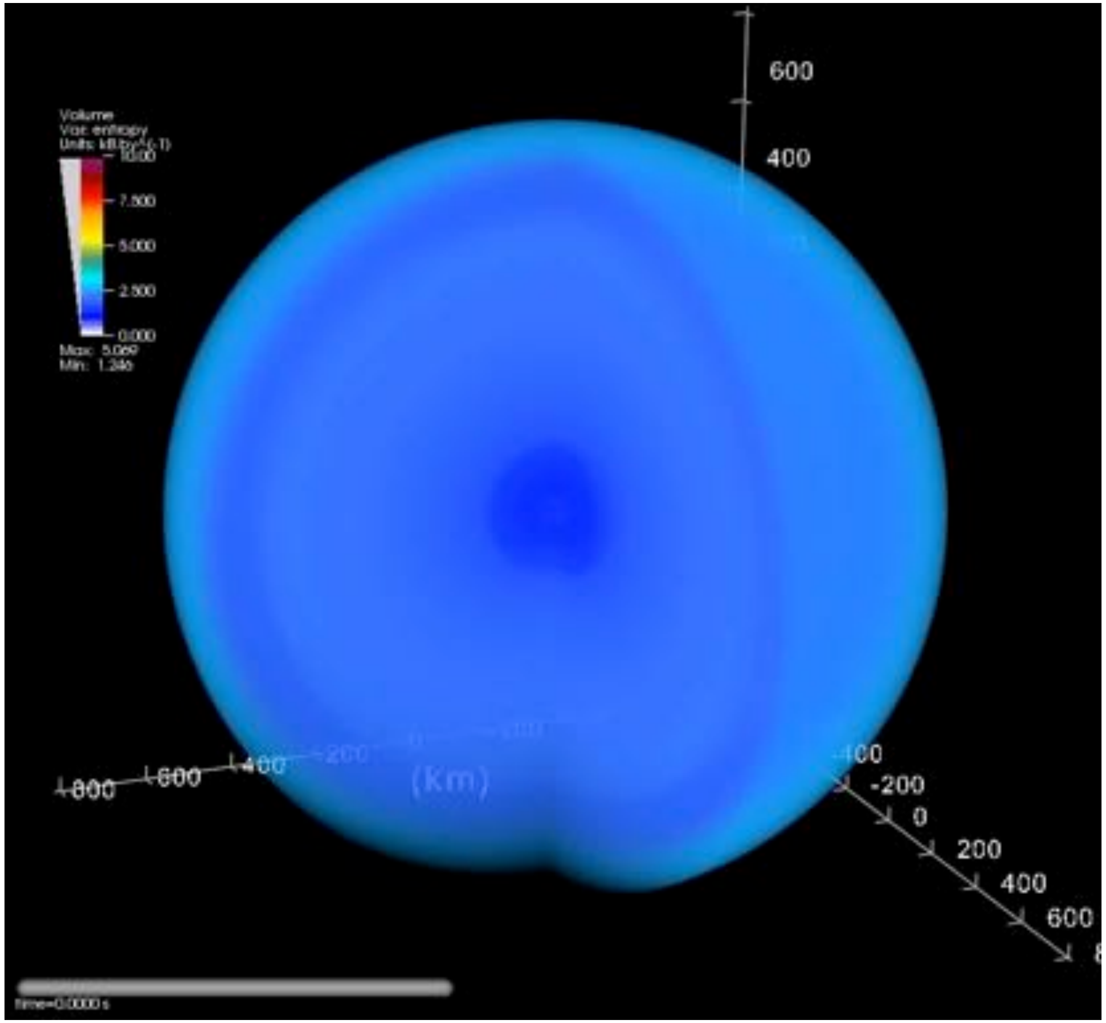
pulsar in the guitar nebula: 1600km/s



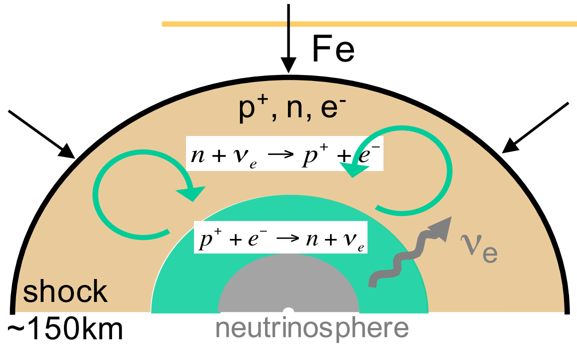
Hobbs et al. 05

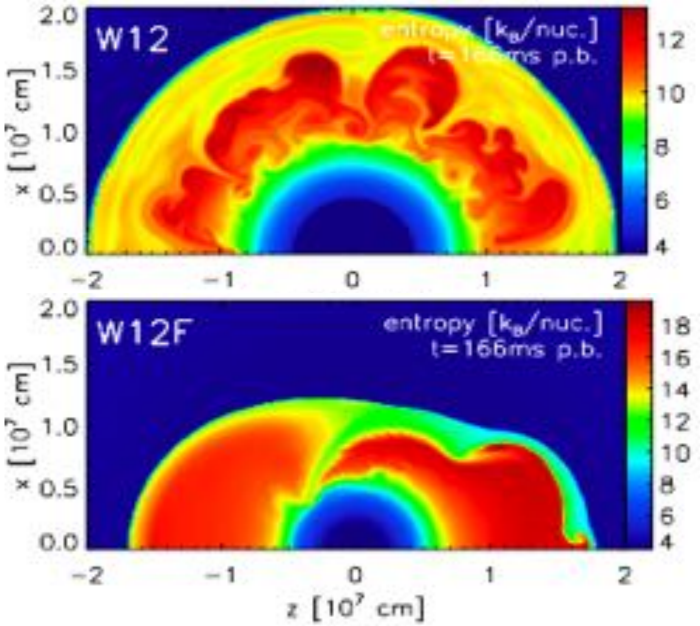
Numerical simulation of an asymmetric explosion

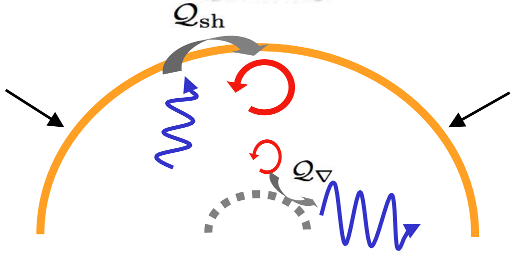
Marek & Janka 09



2 instabilities during the phase of stalled accretion shock







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

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

(Foglizzo et al. ’06)

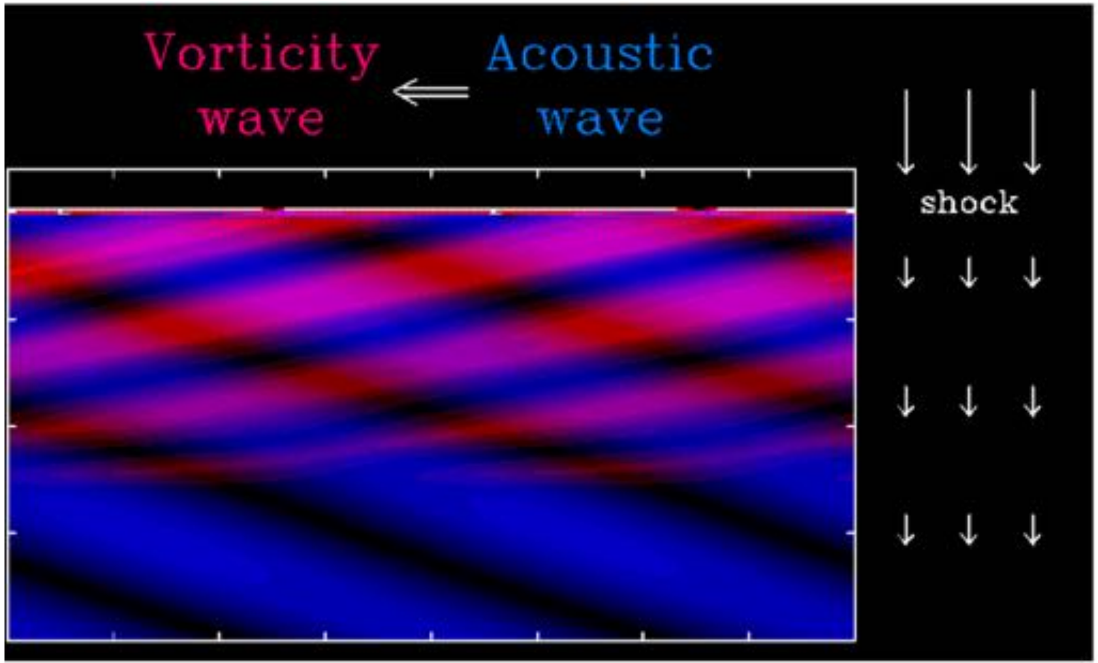
$$\chi \equiv \int_{\rm sh}^{\rm gain} \omega_{\rm BV} \frac{{\rm d}r}{v_r} < 3$$

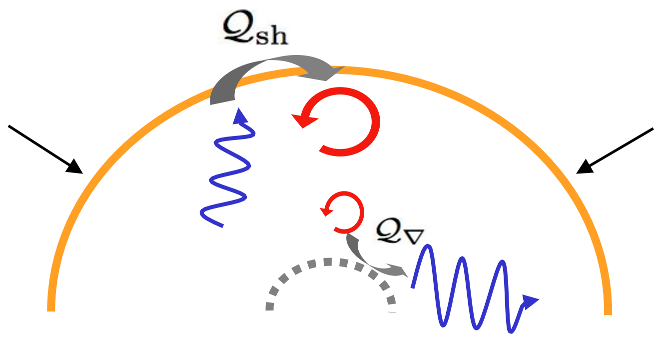
SASI: Standing Accretion Shock Instability

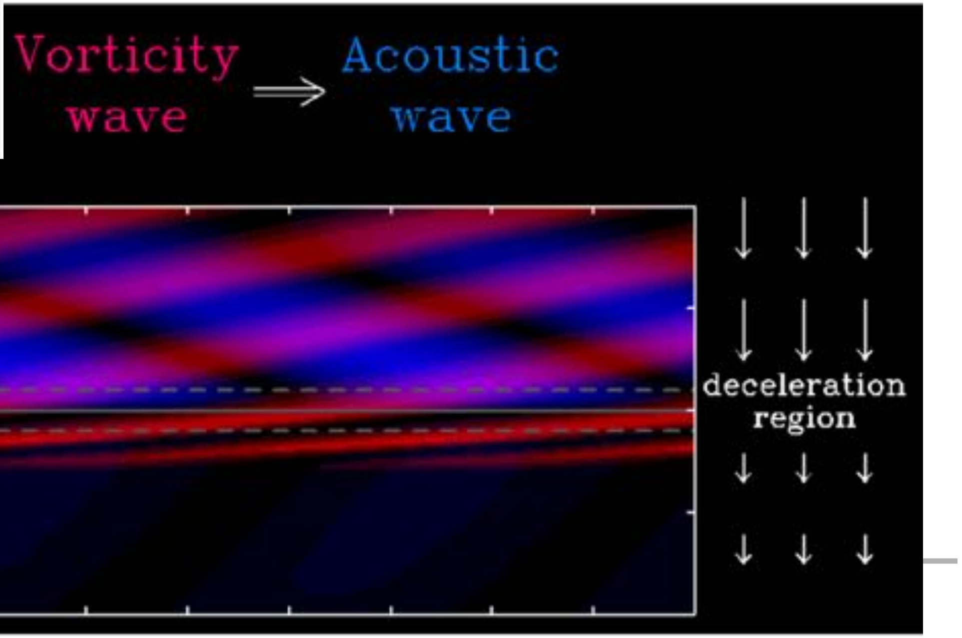
(Blondin et al. 03 ...)

- advective-acoustic cycle
- oscillatory, large angular scale l=1,2:
  pulsar kick, nucleosynthesis,
  gravitational waves & neutrino signatures

Interaction between acoustic waves and vorticity







Sato, Foglizzo & Fromang 09

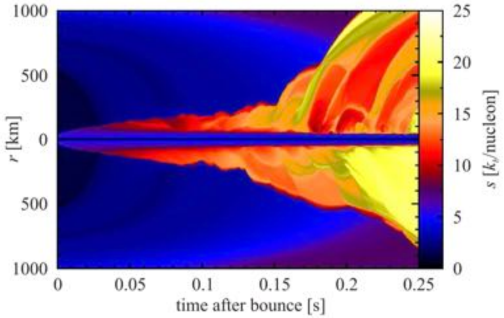
Progress of ab initio simulations: understandable diversity

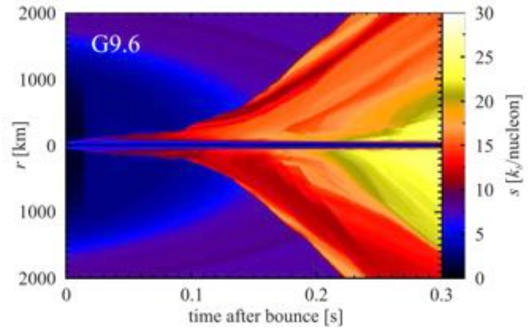
-axisymmetric explosions from first principles

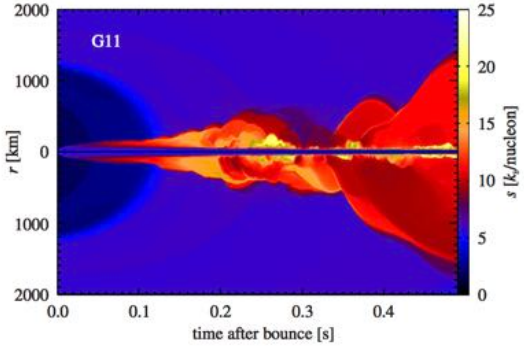
8.1, 9.6 ,11.2, 15, 27M_{sol} (MPA)

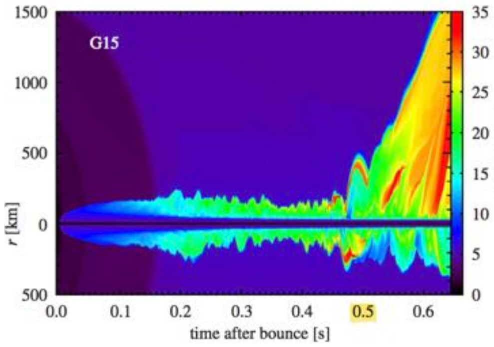
12, 15, 20, 25 M_{sol} (ORNL)

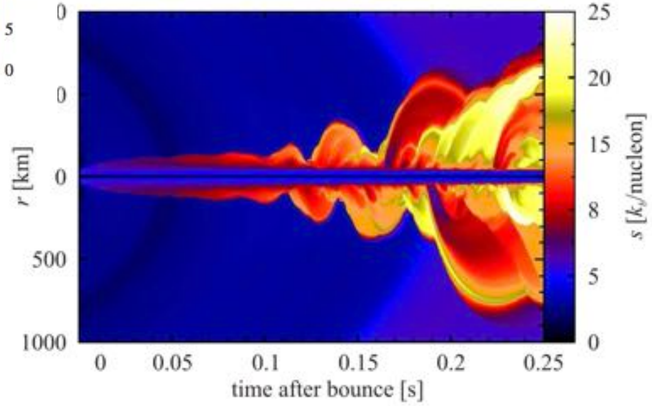
(Müller+12a,b,+13, Bruenn+13)











-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)

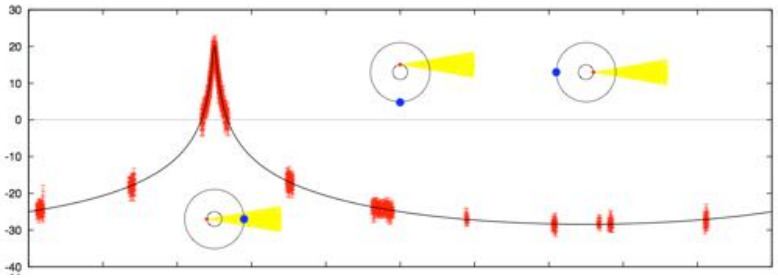
-neutrino transport questioned by Dolence+14

The parameter space shrinked in nuclear physics, but inflated in stellar structure

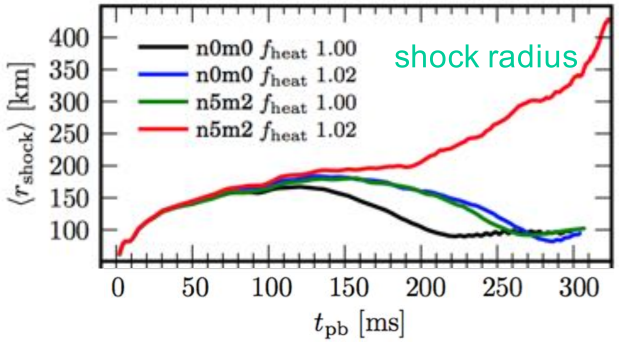
-EOS is better constrained

PSR J1614−2230: M=1.97M_{sol}±0.04 (Demorest+10)

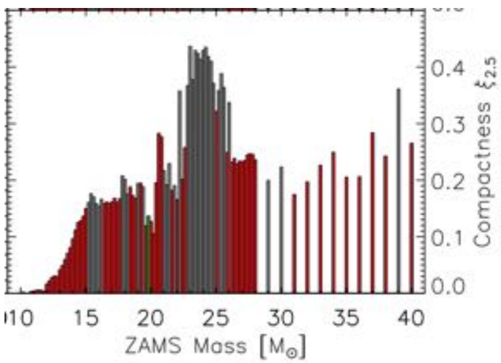
J0348+0432: M=2.01M_{sol}±0.04 (Antoniadis+13)



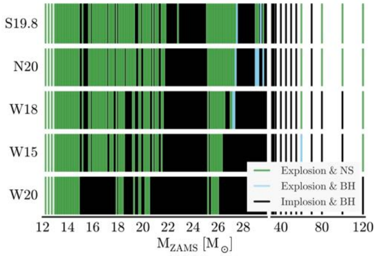
-the explosion is sensitive to precollapse asymmetries (Couch & Ott+15, Müller & Janka+15, Abdikamalov+16)



-the dependence on the progenitor mass is non-monotonous (Ugliano+12, Ertl+16, Sukhbold+16)



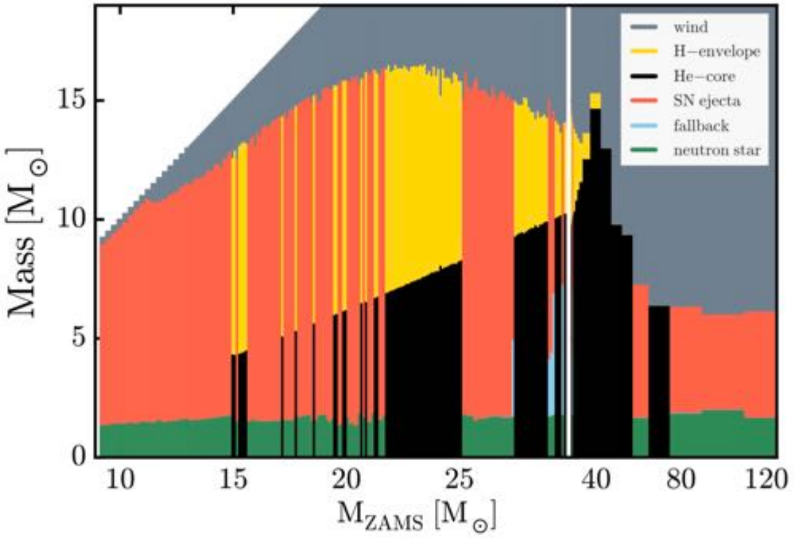
(O'Connor & Ott 11)



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

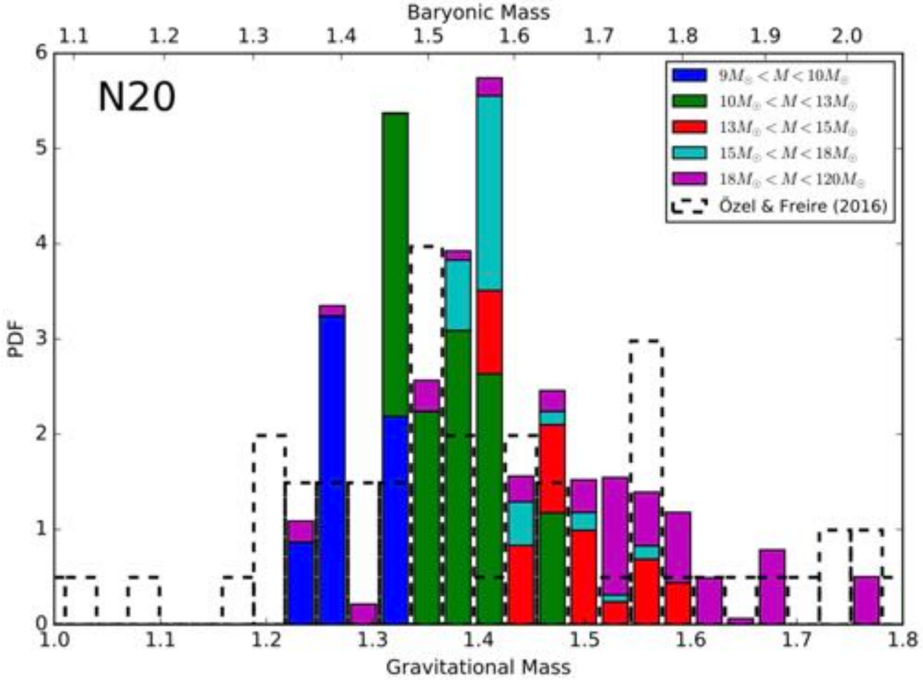
Sukhbold+16

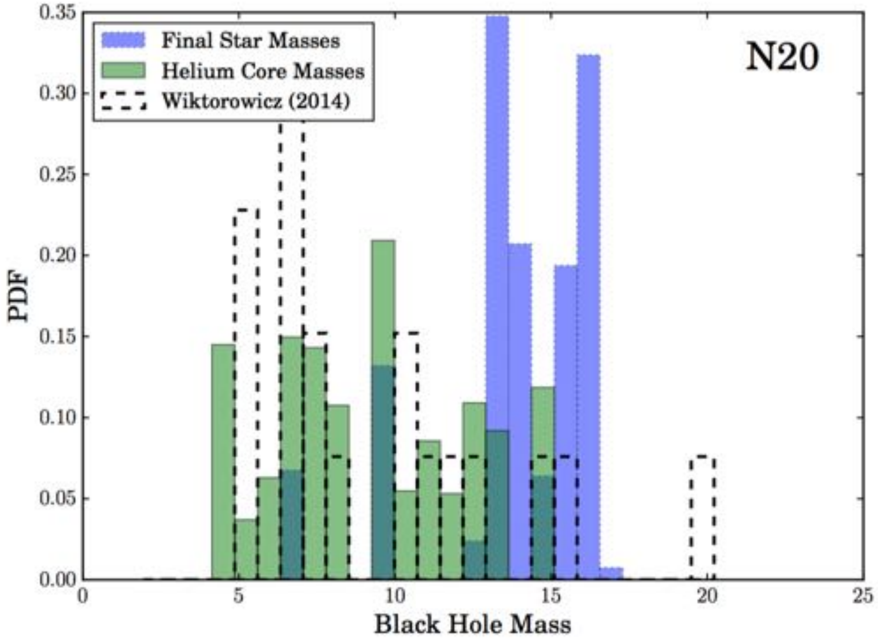
1-D models calibrated with SN1987A (~18M_{sol}) and the Crab (~10M_{sol})



-single star evolution: binarity is ignored
-rotation largely neglected
-SN1987A was peculiar
-the SASI/convective multi-D diversity is ignored

distribution of masses
of neutron stars and black holes



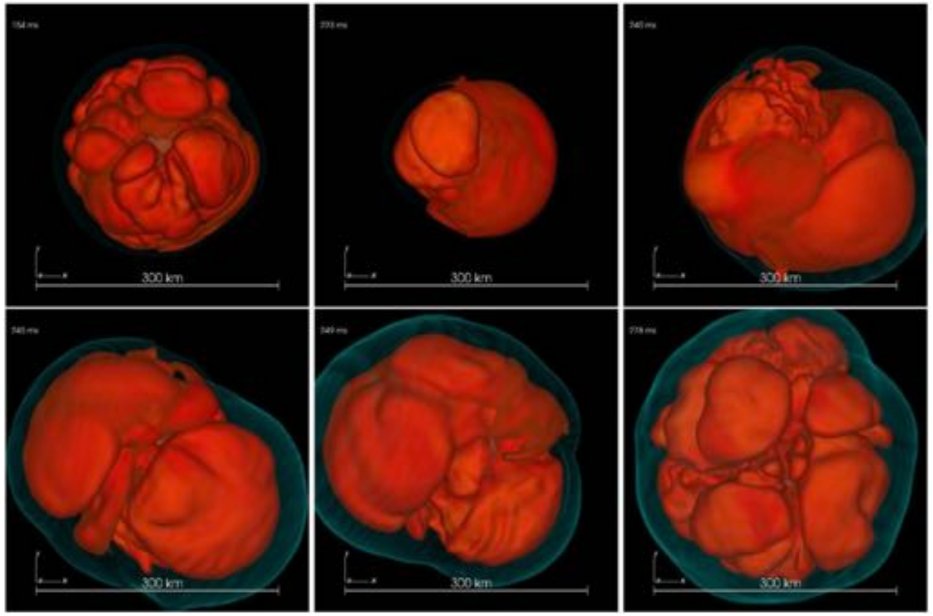


Towards ab initio simulations in 3D (MPA Garching)

-Explosion is not easier in 3D than in 2D (Hanke+12, Couch & O'Connor 13) but Müller+16

-The first 3D ab initio simulation did not explode after380ms (Hanke+13)

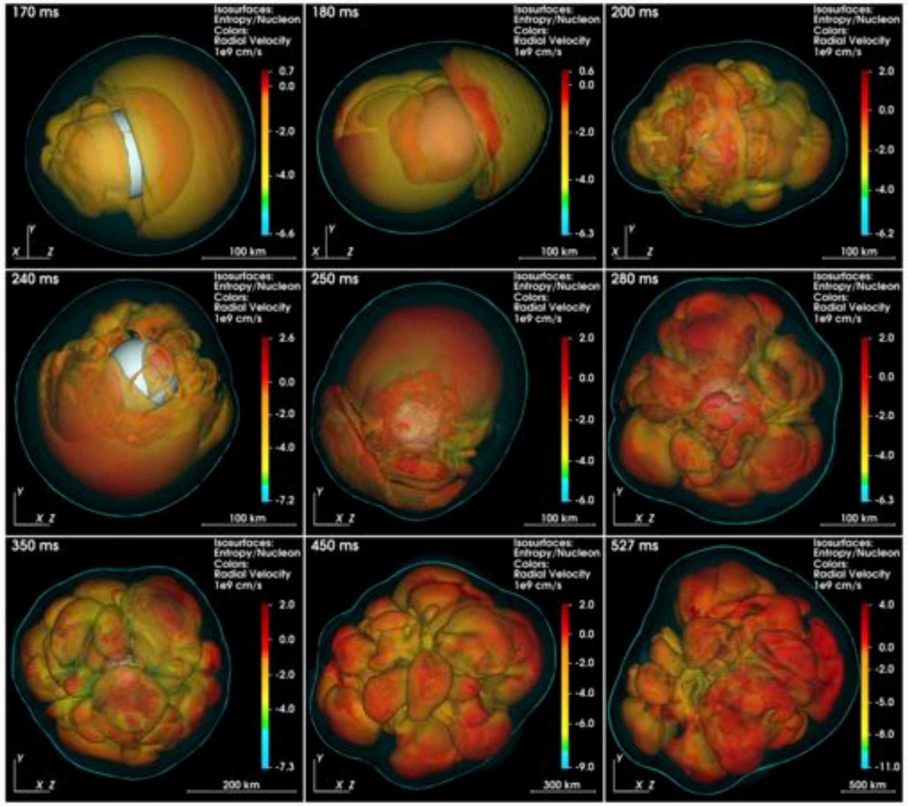
… but a minor change in the nucleon strangeness was enough to produce an explosion (Melson+15)



Hanke+13

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

evolution time : 500ms
diameter: 300km



Melson+15

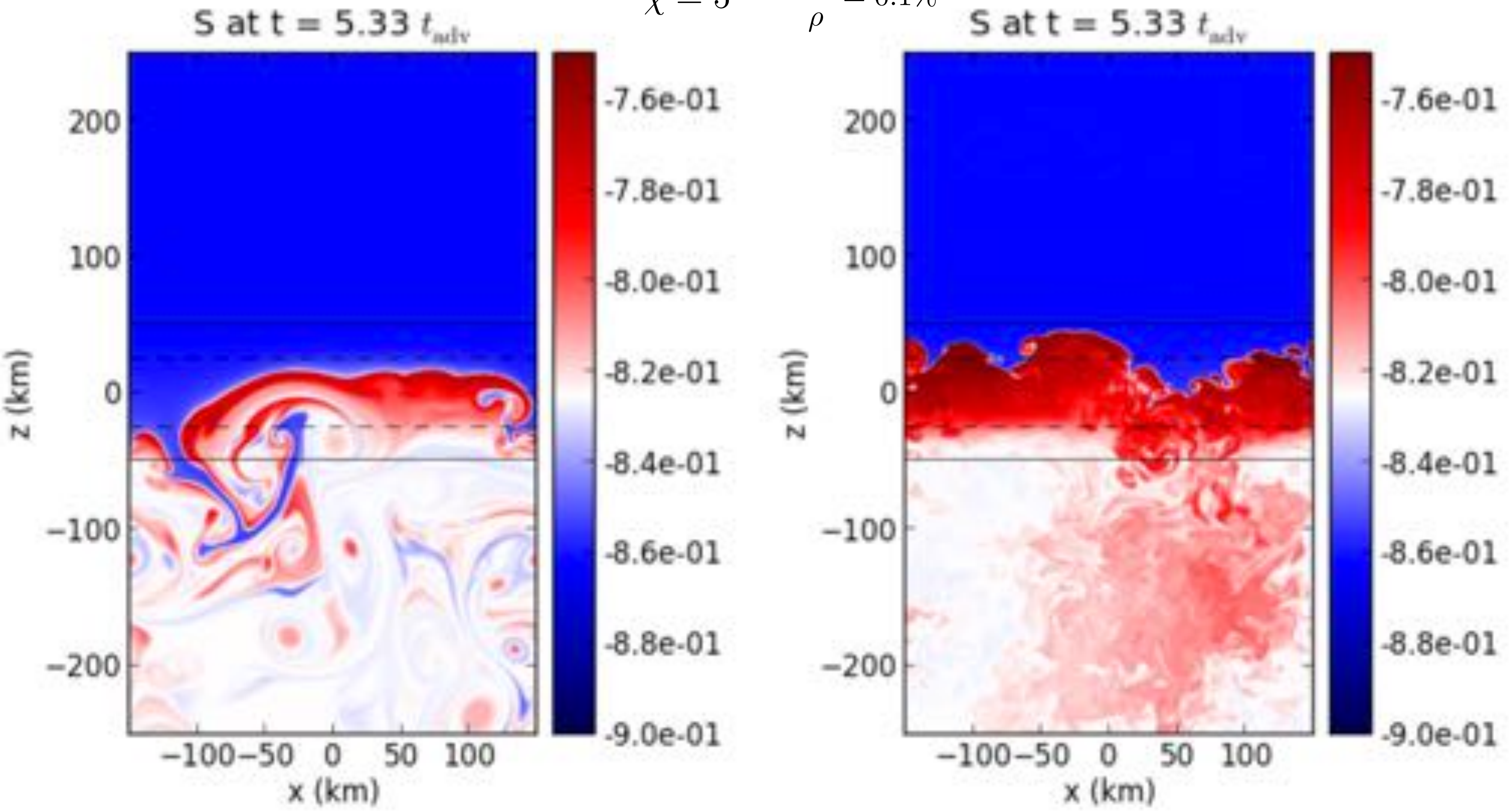
$27M_{sol}$ stellar core collapse in 3D

Hanke et al. 13

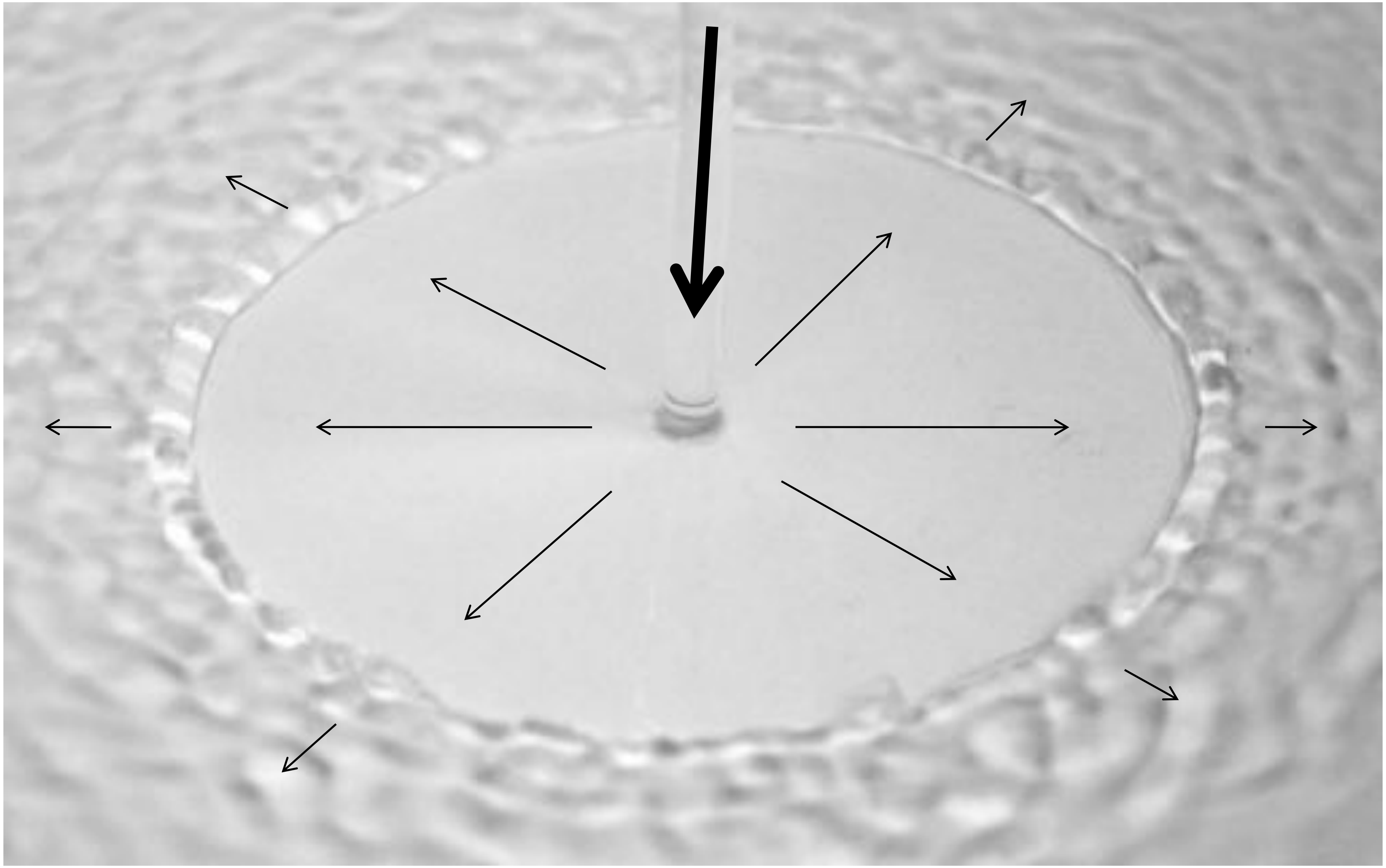
Convection vs advection, 3D vs 2D

Kazeroni PhD 2016

$\chi = 5$ $\frac{\delta\rho}{\rho} = 0.1\%$

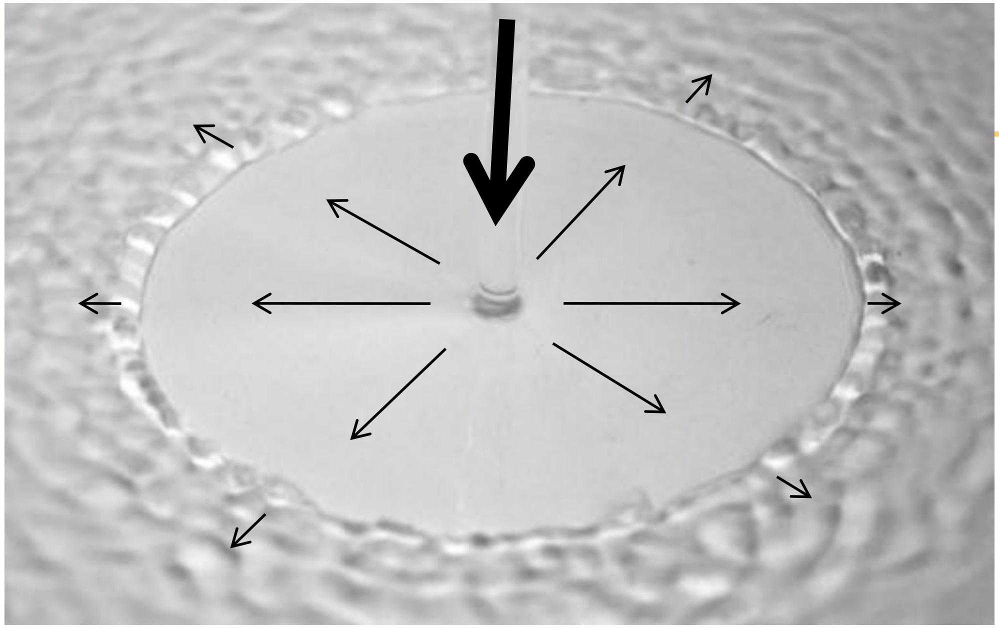


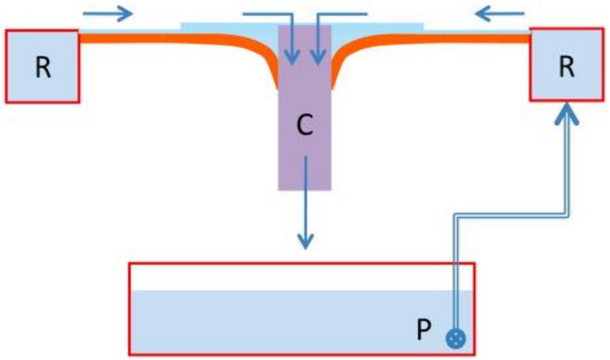
Hydraulic jumps and shock waves

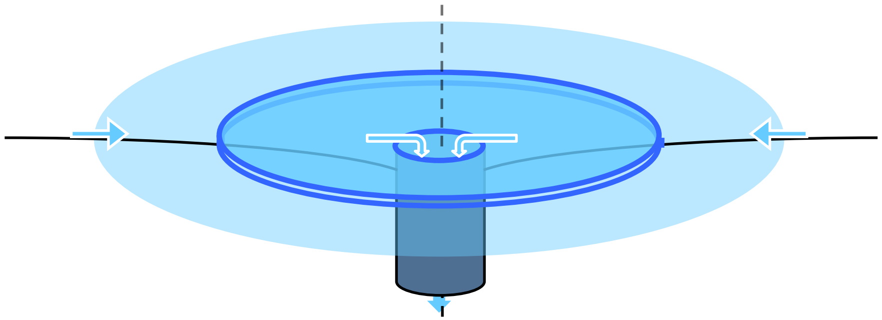


SWASI: an experimental analogue of SASI

Shallow Water Analogue of a Shock Instability



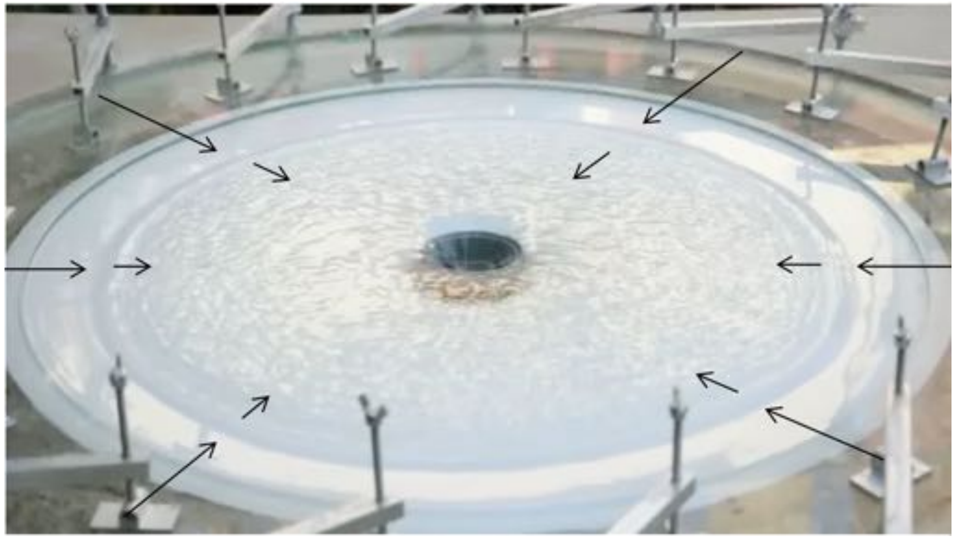




acoustic waves
shock wave
pressure

↔

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

$$\Phi = gz$$

$$c^2 = gH$$

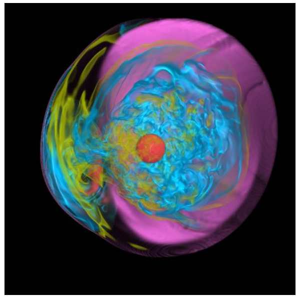
$$\frac{\partial H}{\partial t} + \nabla \cdot (H v) = 0$$

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

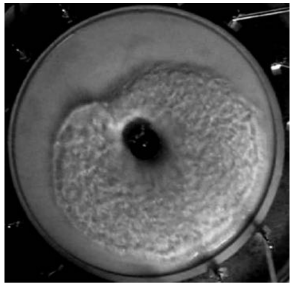
- Inviscid shallow water: analogue to an isentropic gas γ=2

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

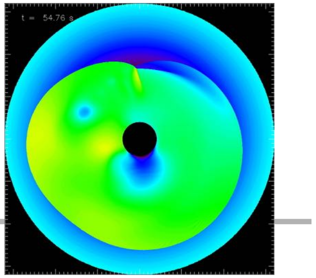
3D spherical
γ=4/3



Blondin & Mezzacappa 07



2D cylindrical
γ=2 isentropic

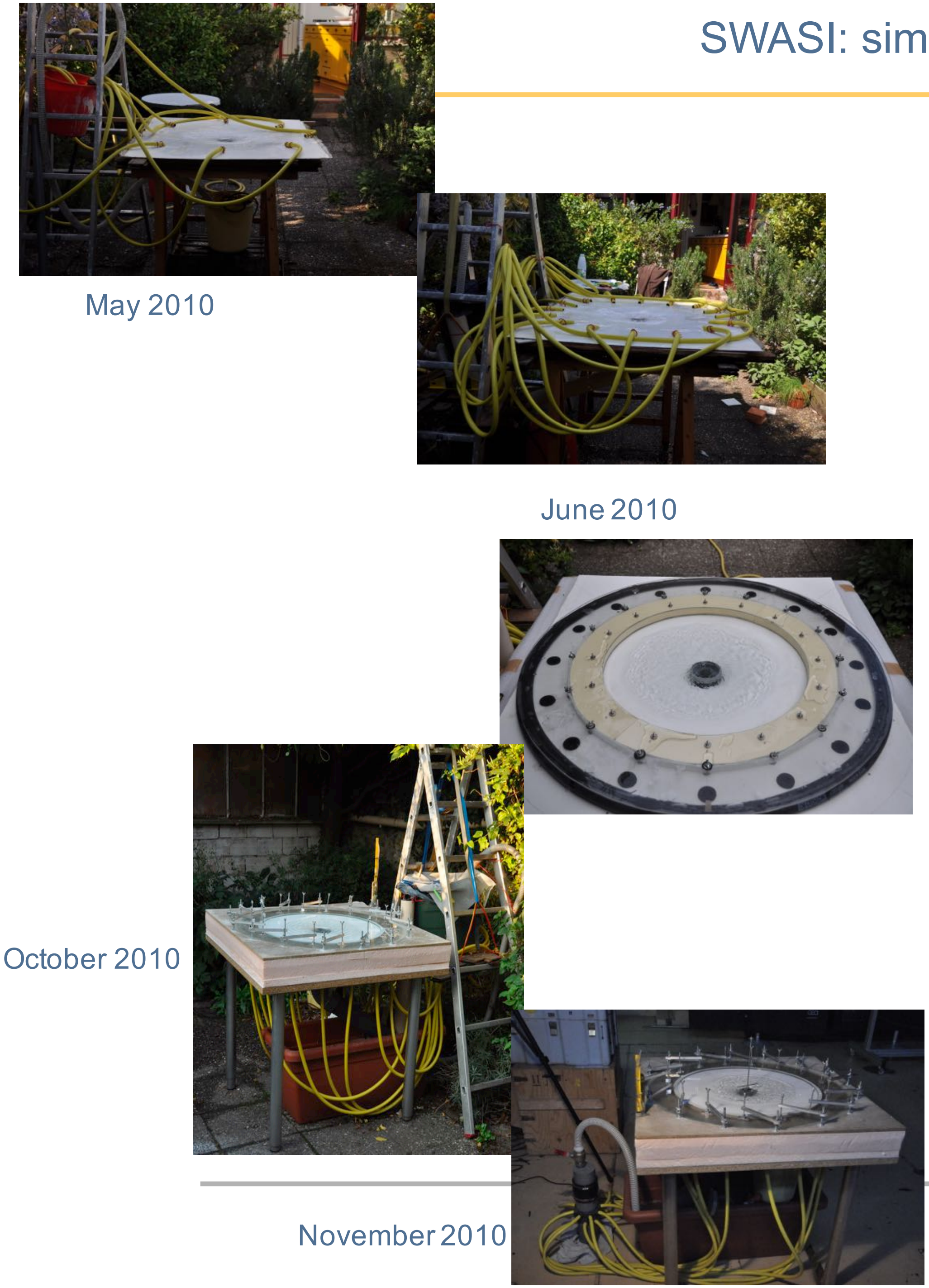


expected scaling $\frac{t_{\rm ff}^{\rm sh}}{t_{\rm ff}^{\rm jp}} \equiv \left(\frac{r_{\rm sh}}{r_{\rm jp}} \right) \left(\frac{r_{\rm sh} g H_{\rm jp}}{G M_{\rm NS}} \right)^{\frac{1}{2}} \sim 10^{-2}$

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

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

SWASI: simple as a garden experiment

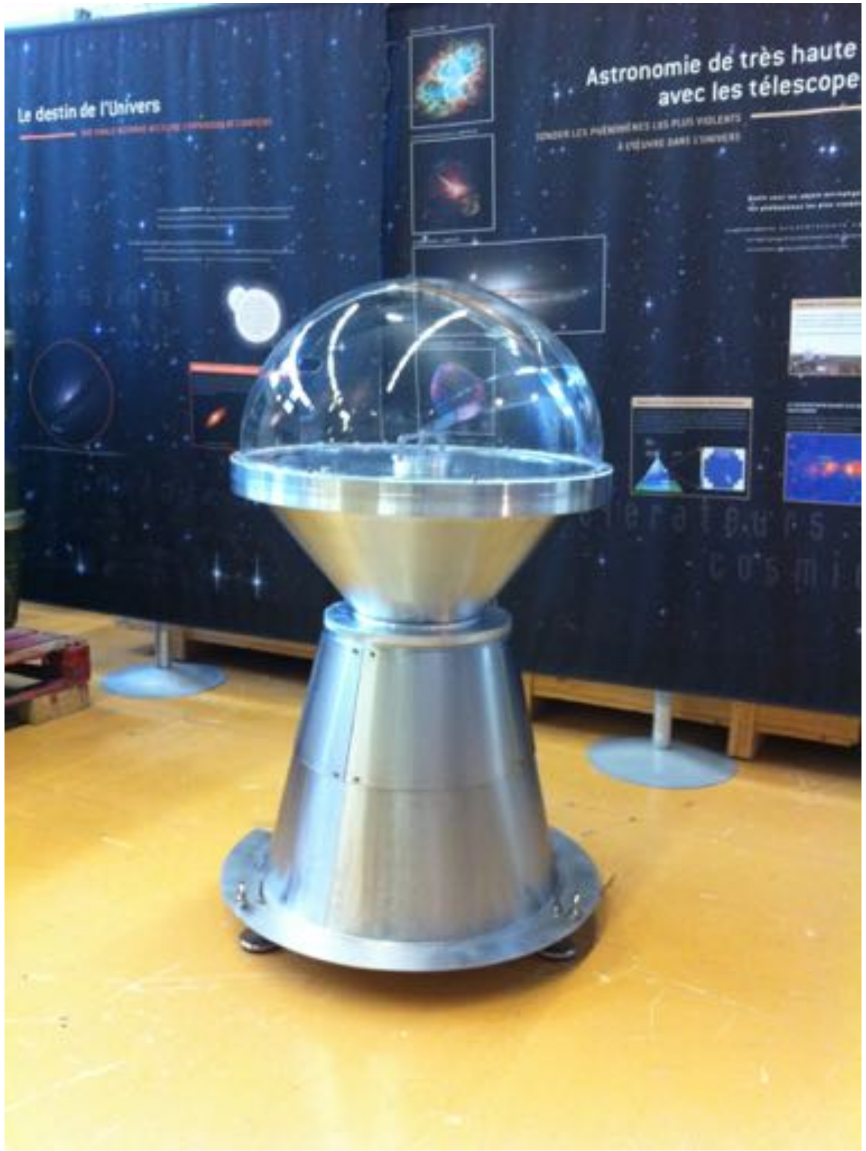


May 2010

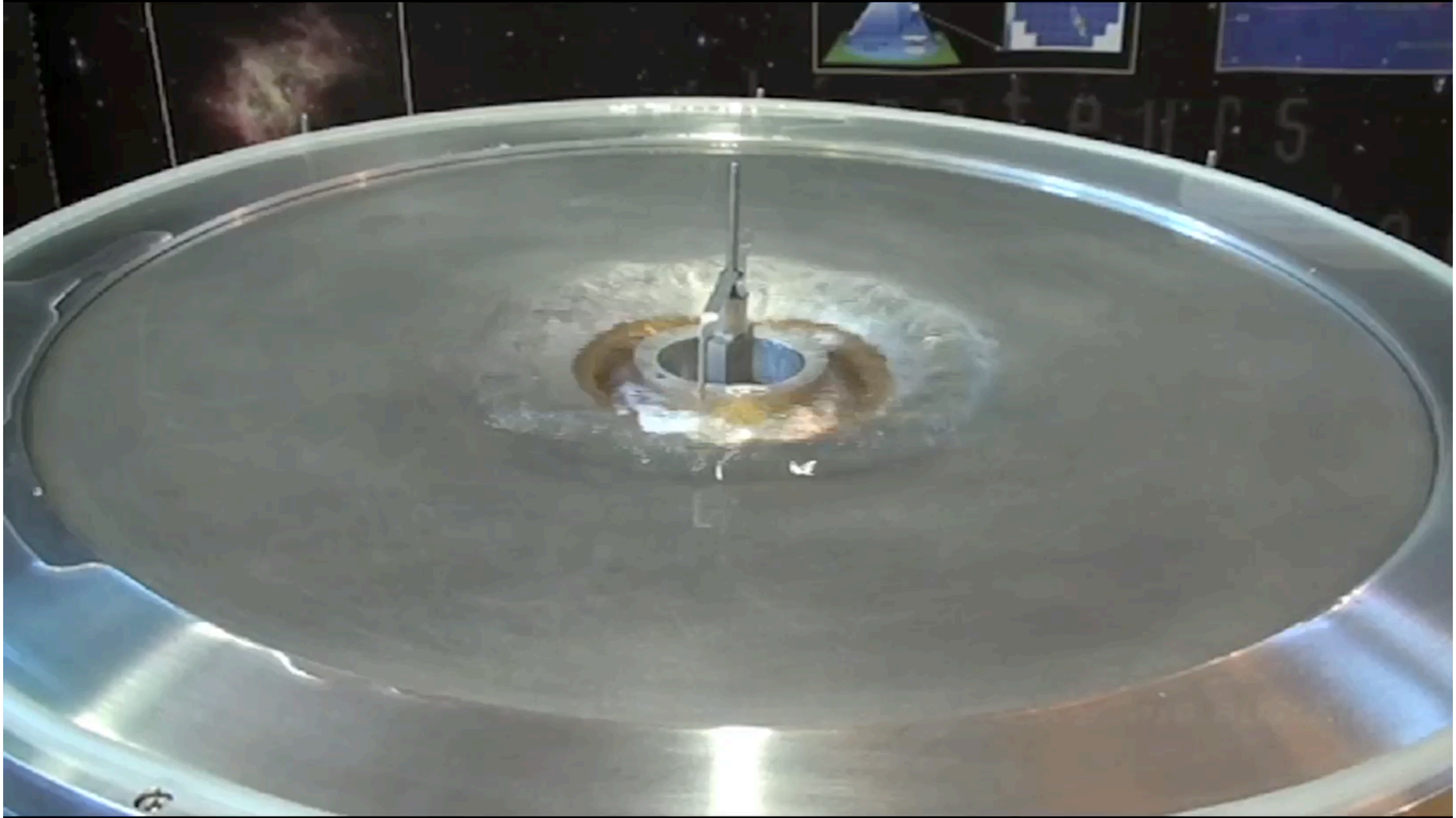
June 2010

October 2010

November 2010



CEA Saclay November 2013



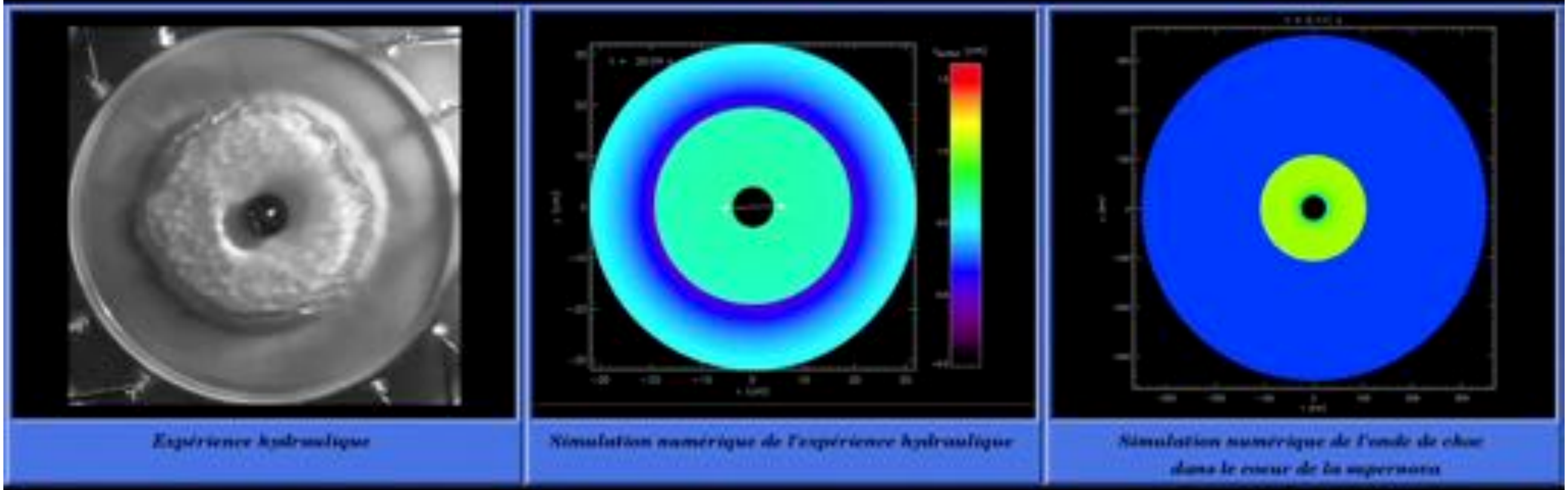
Dynamics of water
in the fountain

Dynamics of the gas
in the supernova core

diameter 40cm
3s/oscillation

1 000 000 x bigger
100 x faster

diameter 400km
0.03s/oscillation

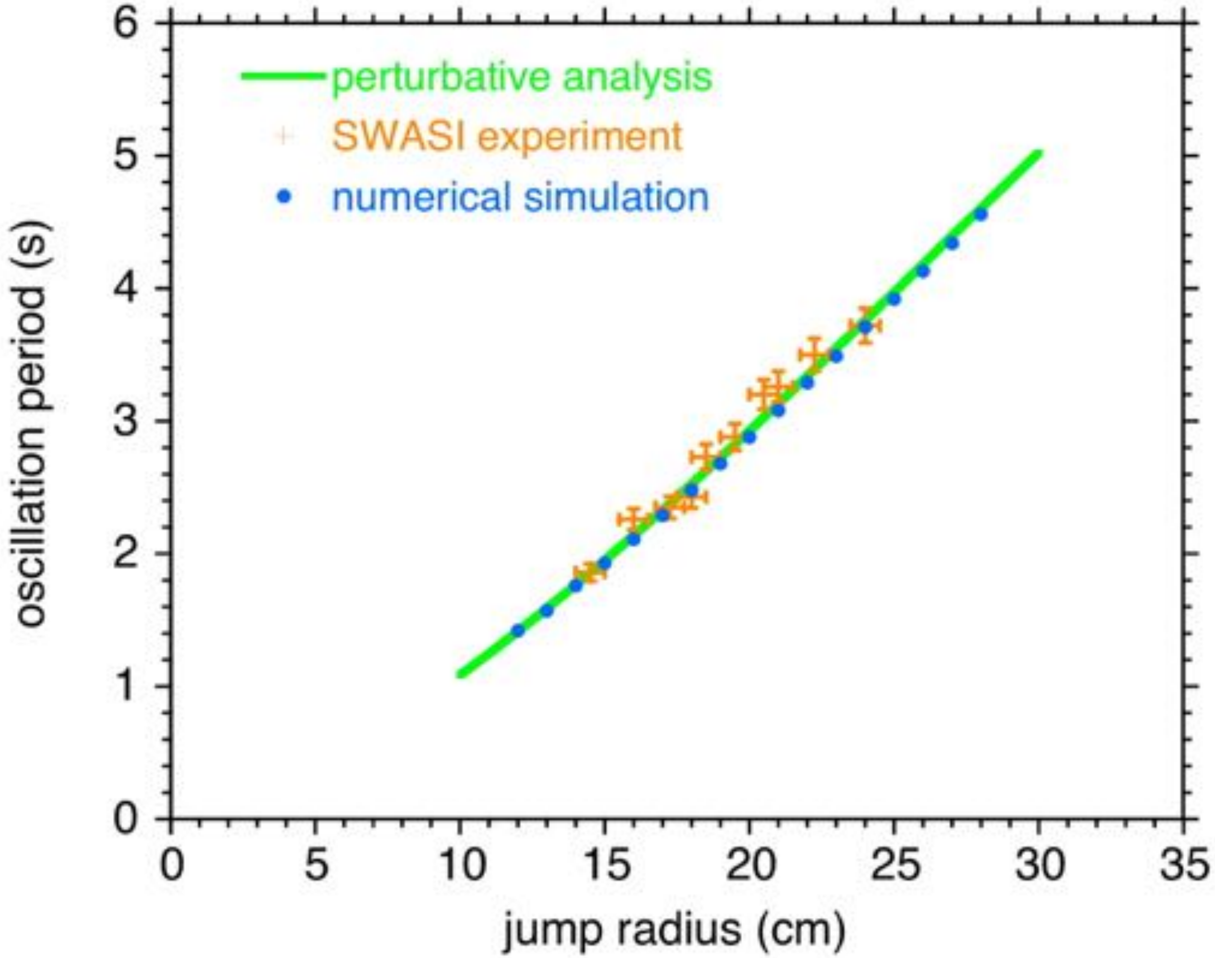


Expérience hydraulique

Simulation numérique de l'expérience hydraulique

Simulation numérique de l'onde de choc
dans le coeur de la supernova

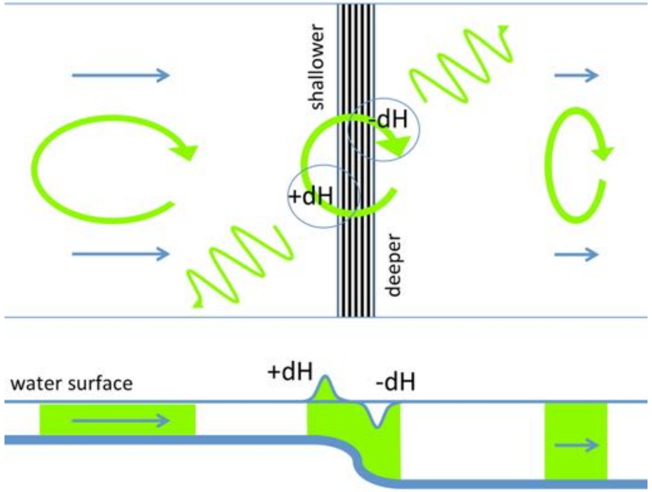
Comparaison to a 2D shallow water model



Foglizzo, Masset, Guilet, Durand
PRL (2012)

Advantages and limitations of the analogy

- simple & intuitive
- explore with an experimental tool
- inexpensive



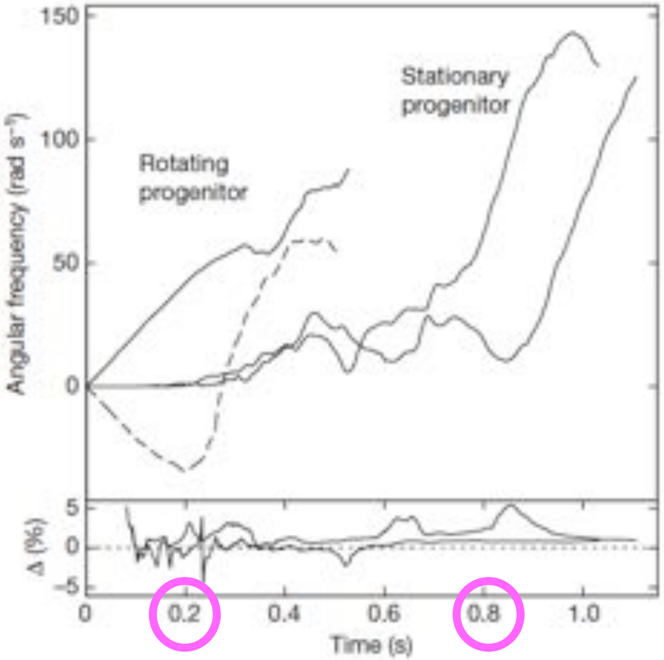
Theoretical framework:

- 2D slice of a 3D flow
- no buoyancy effects
- gamma=2
- accreting inner boundary

Experimental constraints:

- viscous drag
- turbulent viscosity
- approximately shallow water
- hydraulic jump dissipation 3<Fr<8

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

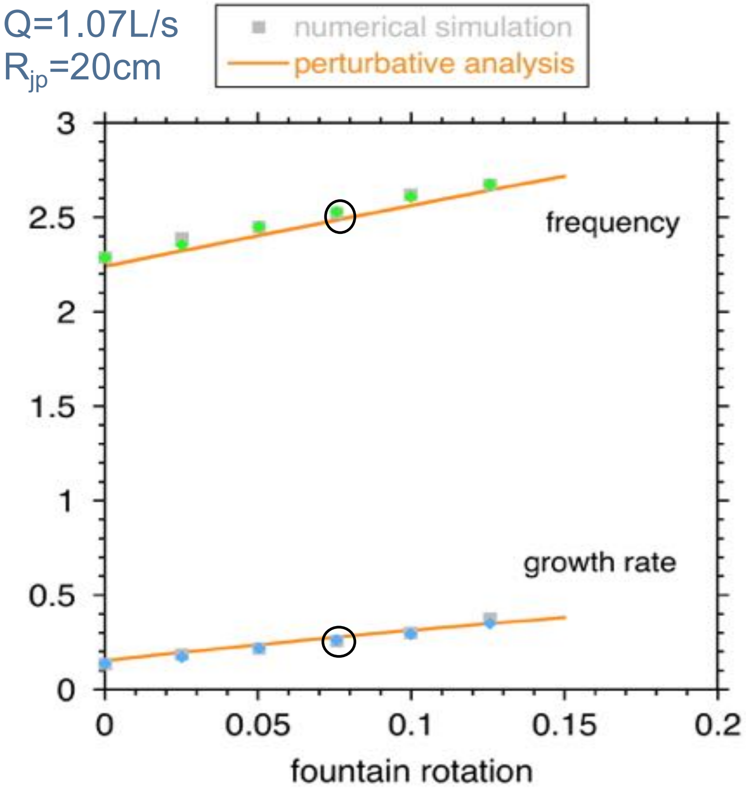


Blondin & Mezzacappa 07

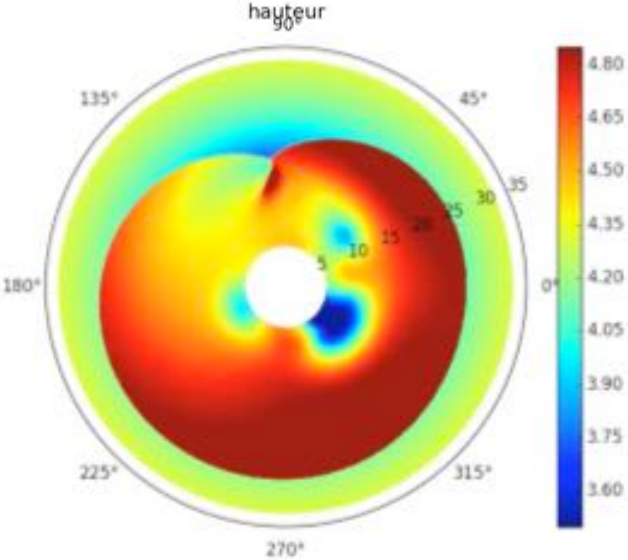
fountain rotation period: 246s
injection slit: 0.55mm
flow rate: 1.17L/s

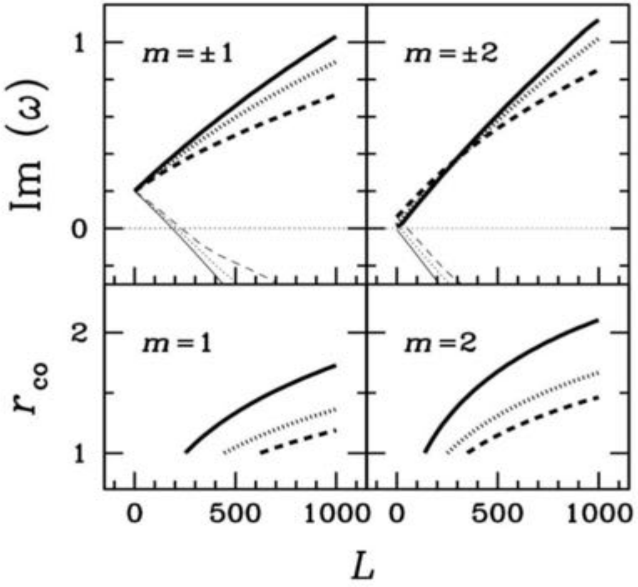
Comparison of rotation effects on shallow water equations and gas dynamics

Q=1.07L/s
R_{jp}=20cm



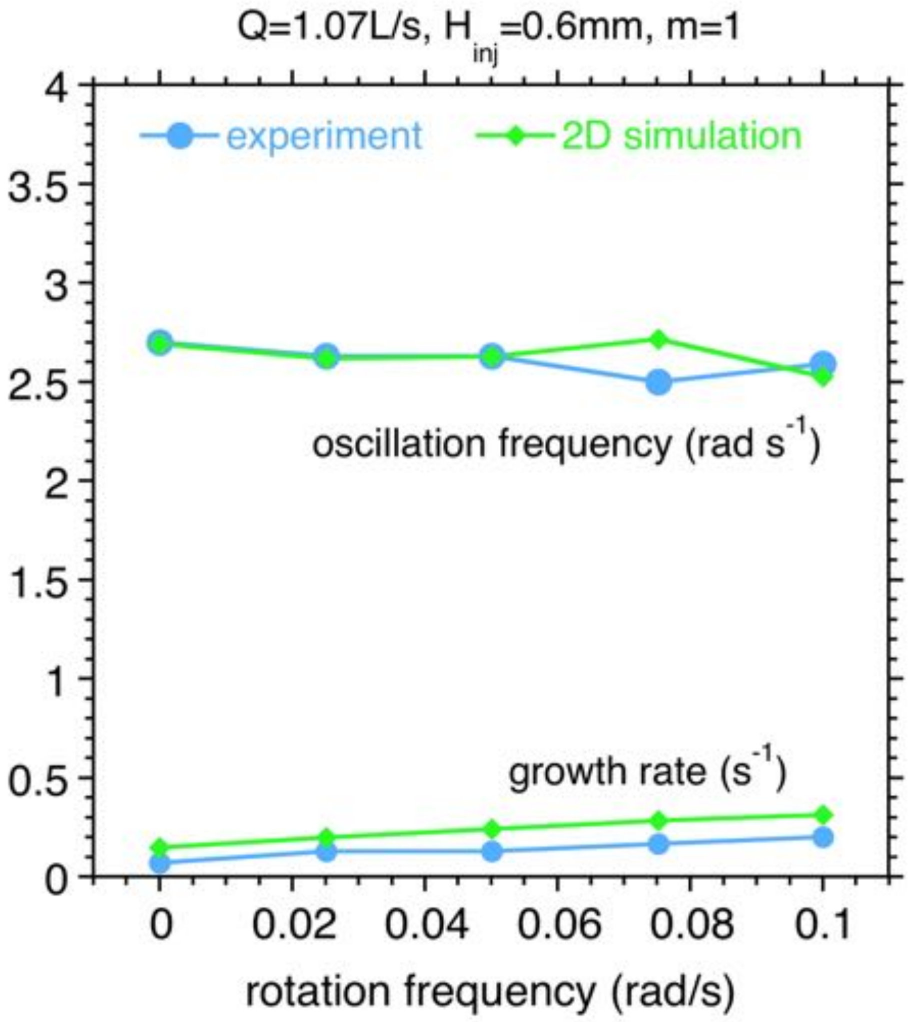
same linear increase of the growth rate as in YF08, despite
- the absence of buoyancy effects
- γ=2 instead of γ=4/3
- accreting inner boundary





Yamazaki & Foglizzo 2008

Comparison of the experiment with the shallow water equations

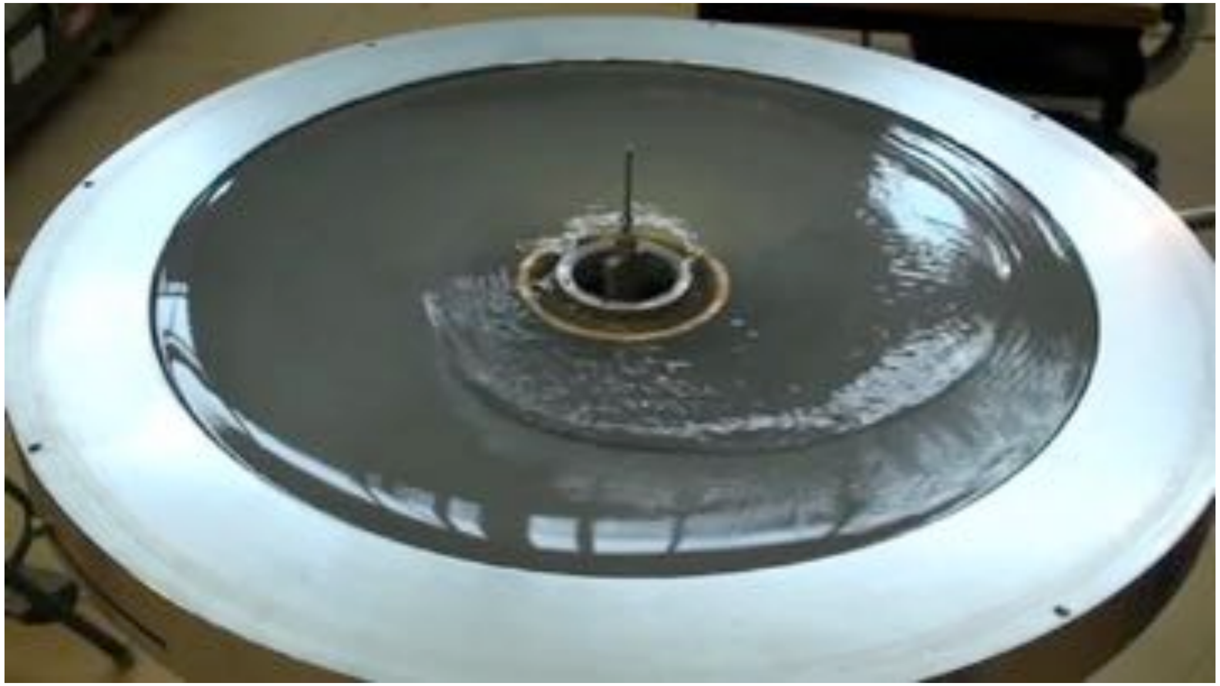


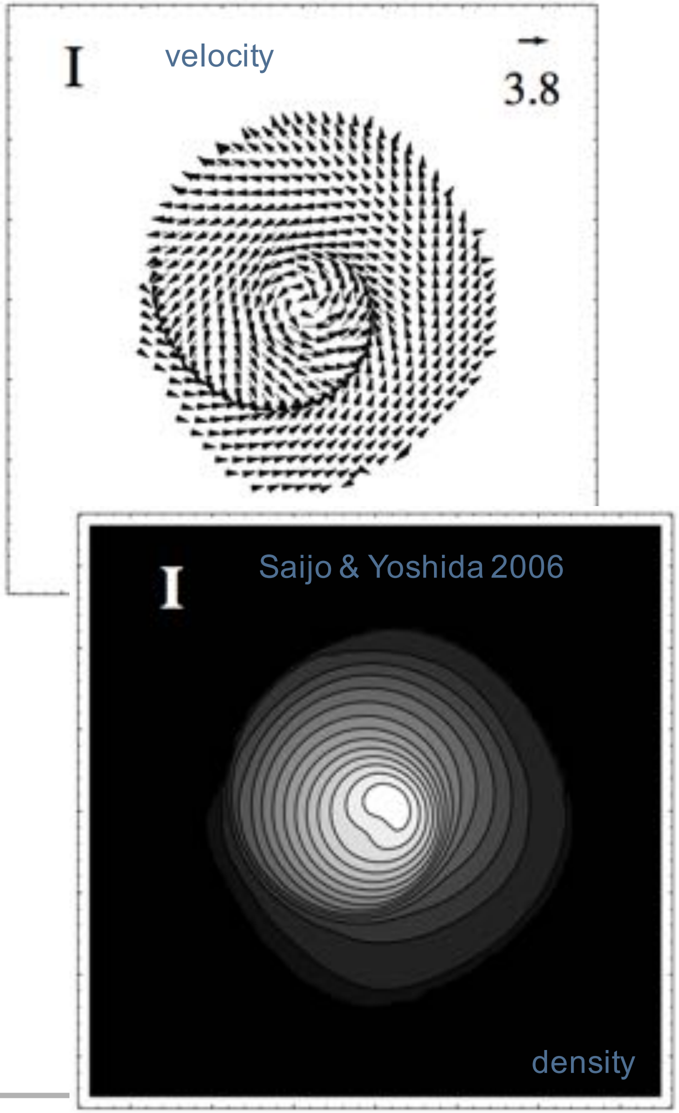
-surprisingly good agreement, despite
  - -2D shallow water modeling,
  - -laminar drag without any free parameter,
  - -ignoring turbulence,
  - -ignoring surface tension,
  - -ignoring the radial extension of the jump

-m=2 dominates m=1 for fast rotation

-experimental growth rates are systematically lower by $\Delta\omega_i \sim 0.2\ s^{-1}$

Unexpected robust spiral shock driven at the corotation radius when the inner rotation rate reaches 20% Kepler





Saijo & Yoshida 2006

analogue to the instability of a neutron star rotating differentially
(Shibata+02,03, Saijo+03,06, Watts+05, Corvino+10)

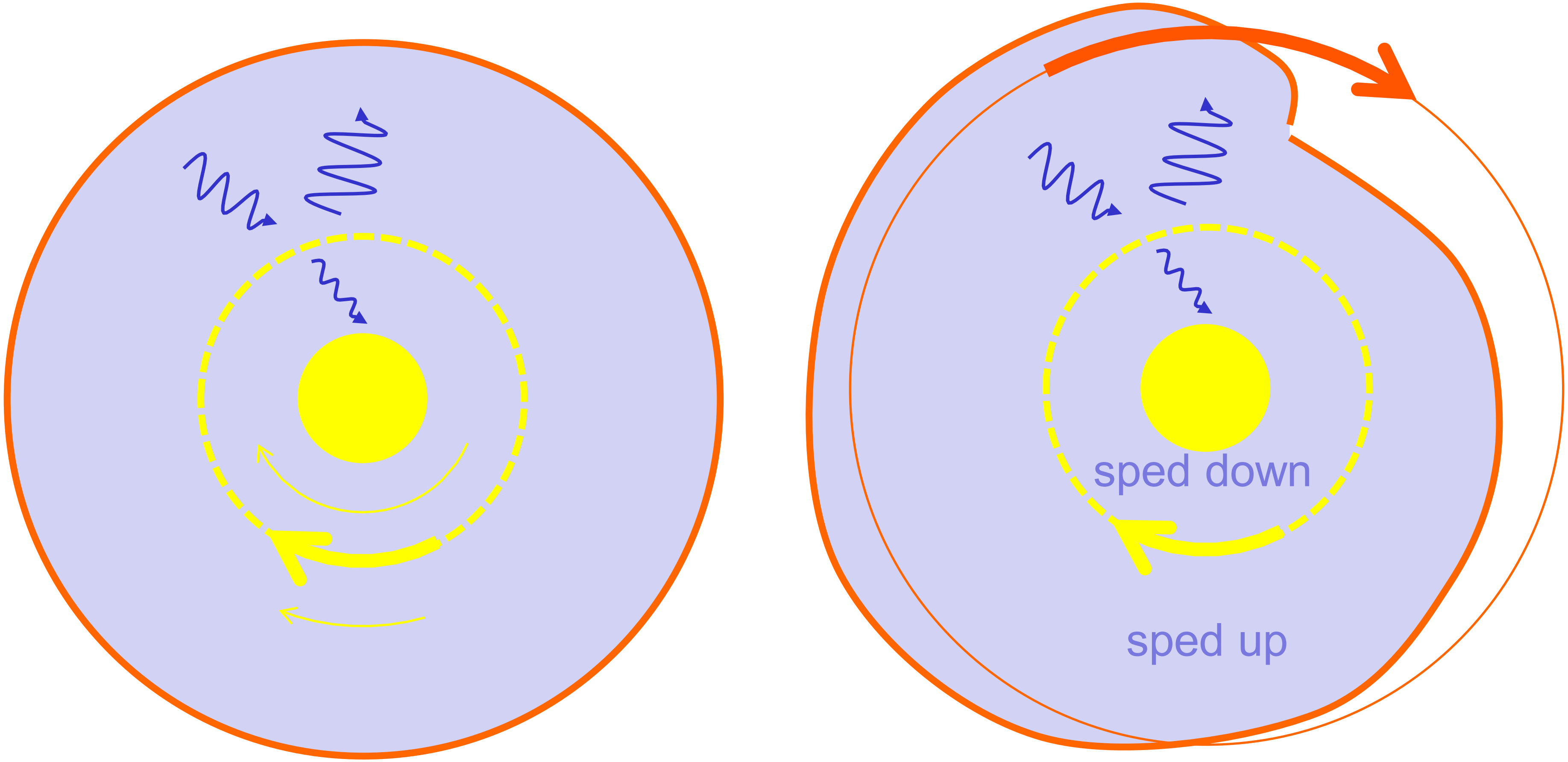
instability mechanism dominated by the corotation trapping of acoustic waves
(Papaloizou & Pringle 84, Goldreich & Narayan 85)

flow rate: 0.3L/s,
slit size: 1.6mm

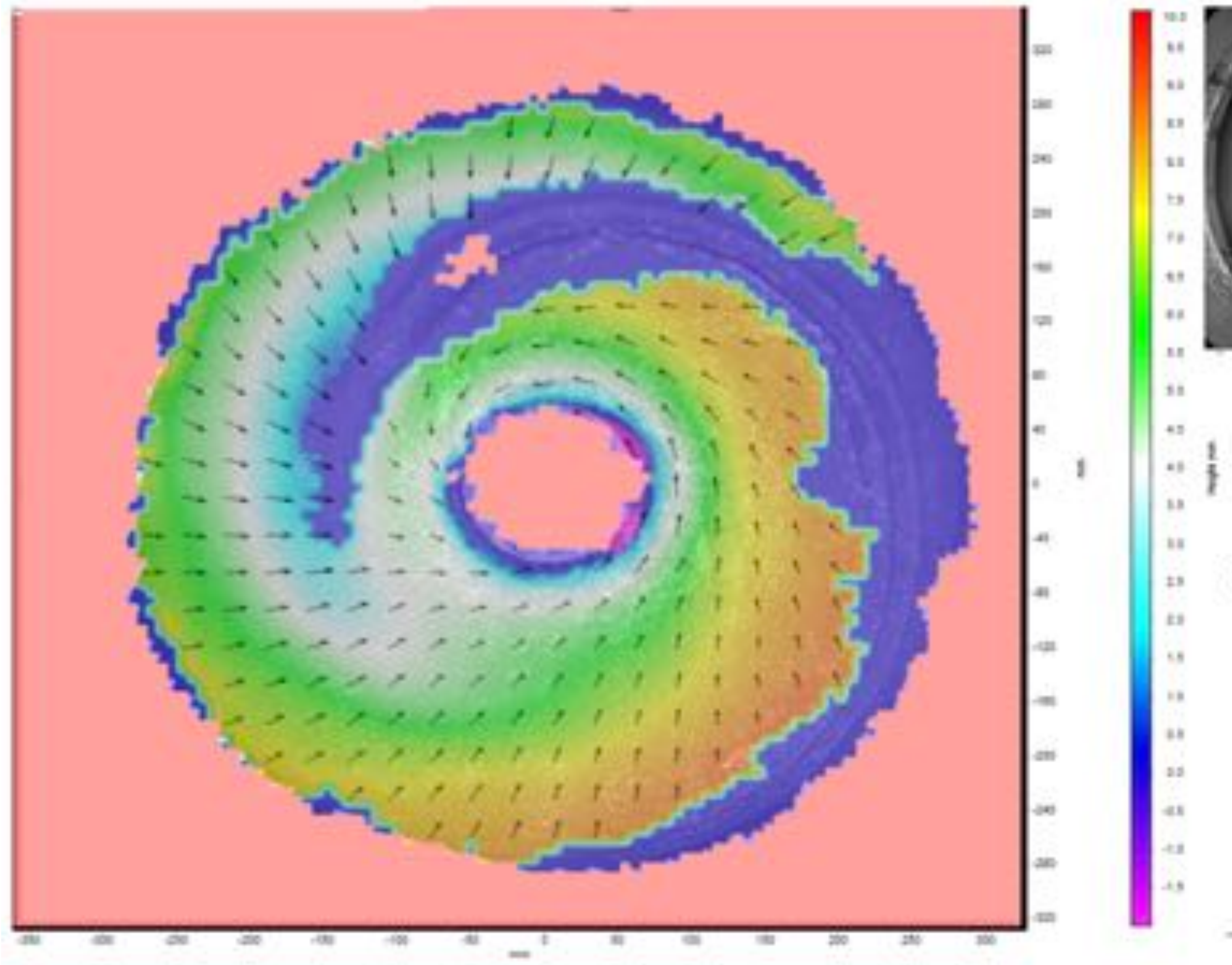
A small scale view at the low T/W instability mechanism:

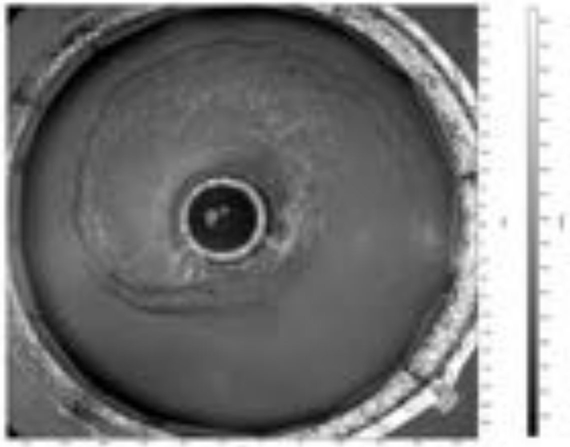
Angular momentum exchange across the corotation radius

(Papaloizou & Pringle 84, Goldreich & Narayan 85)



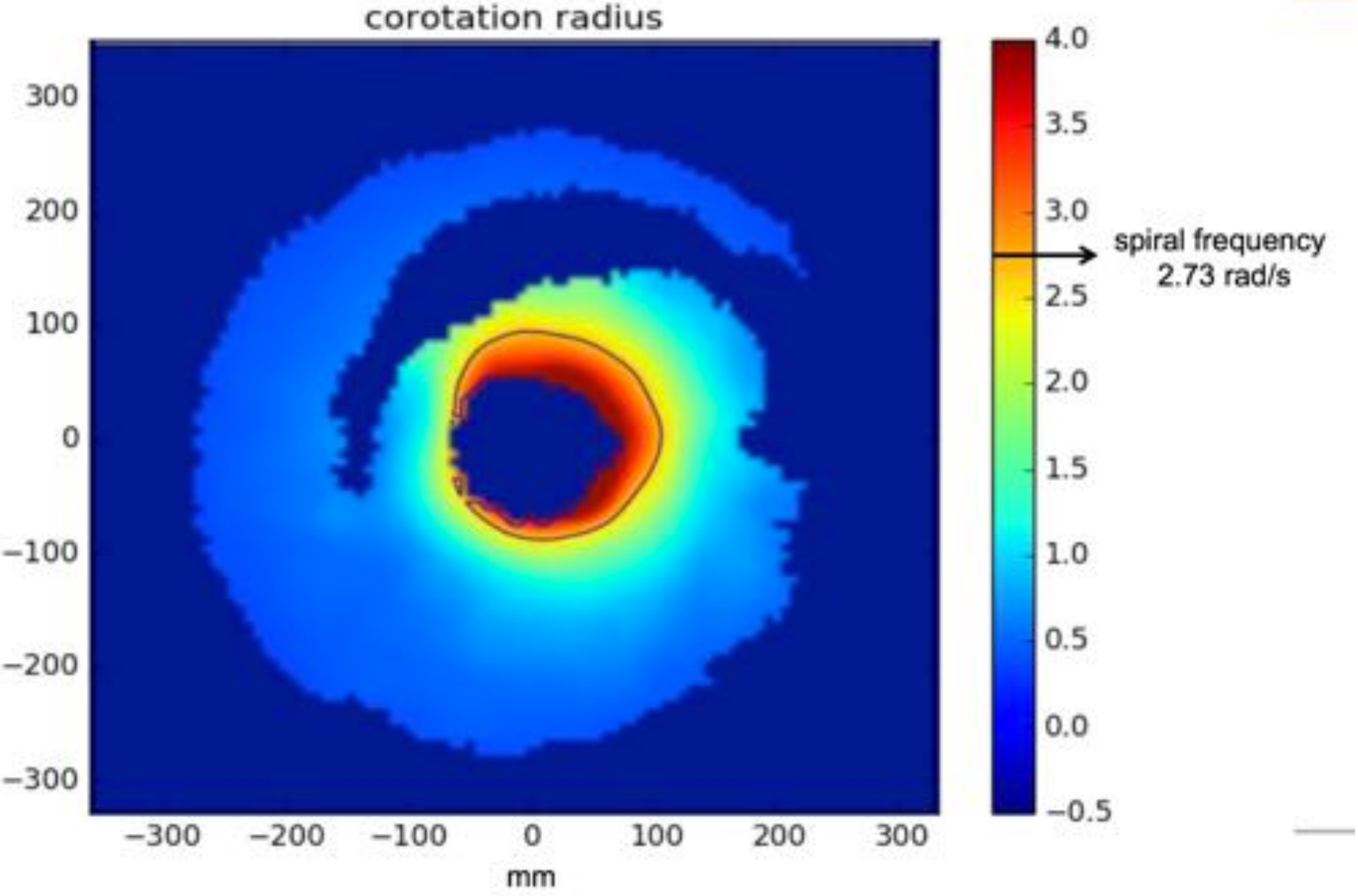
Evidence for a corotation radius using a PIV analysis





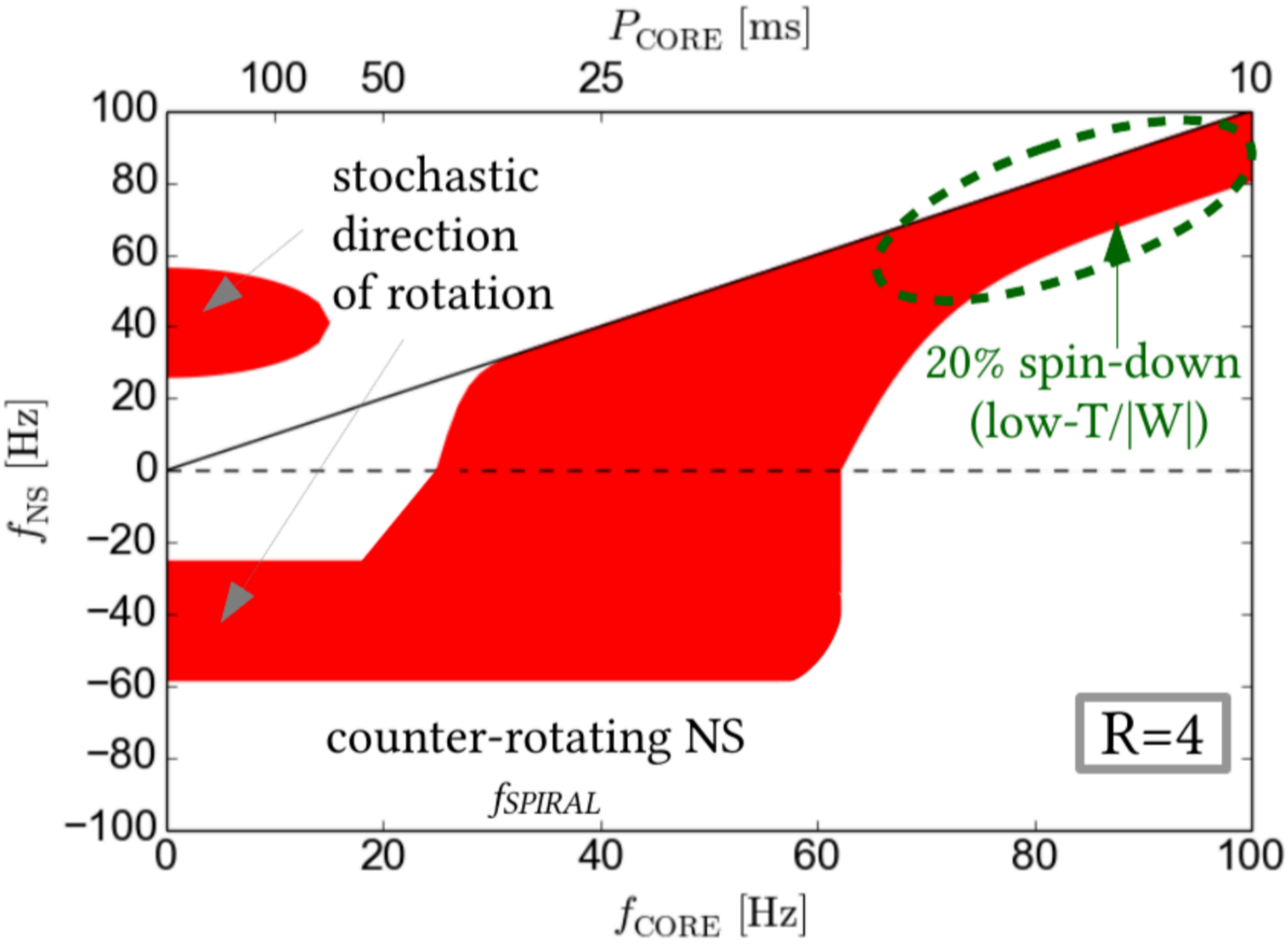
stereo measurement
of the free surface
height and velocity

Evidence for a corotation radius using a PIV analysis

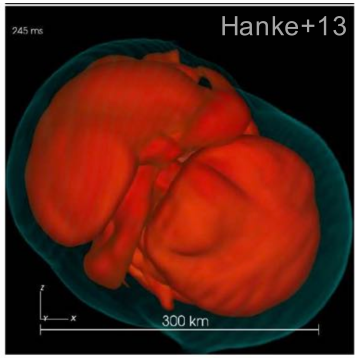


Spin up or spin down of the neutron star ?

Kazeroni PhD 2016

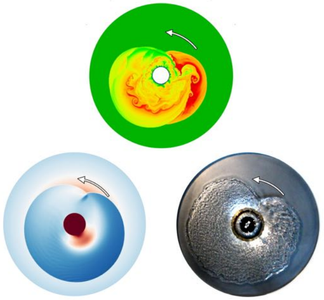


Conclusions

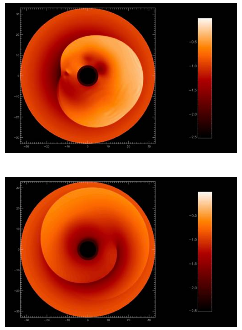


Hydrodynamical instabilities are a key ingredient to supernova theory

- enable the explosion by locally increasing neutrino capture
- pulsar kick up to ~1000km/s
- pulsar spin up to ~10 Hz



The large parameter space precludes a systematic numerical study in 3D: a better understanding of the physical processes is needed to assess the robustness of the numerical results: SASI, ν-driven convection, low T/W, MRI?



Two instabilities captured in the shallow water approximation including rotation

T>150s: spiral SASI with a counter-spinning neutron star

T~30-60s: corotation instability 'low T/W'