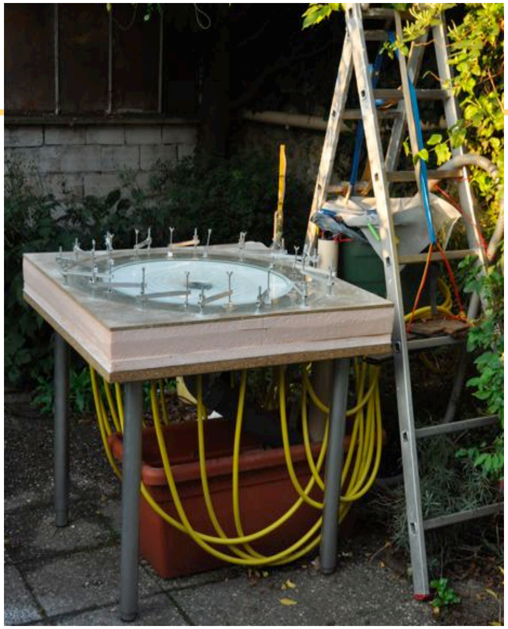
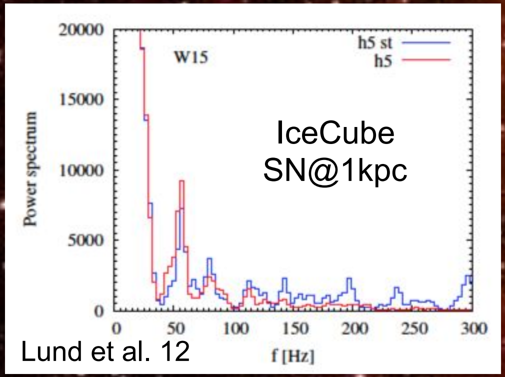
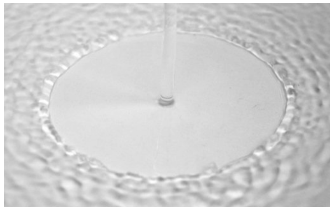
Asymmetric core collapse supernovae induced by hydrodynamical instabilities





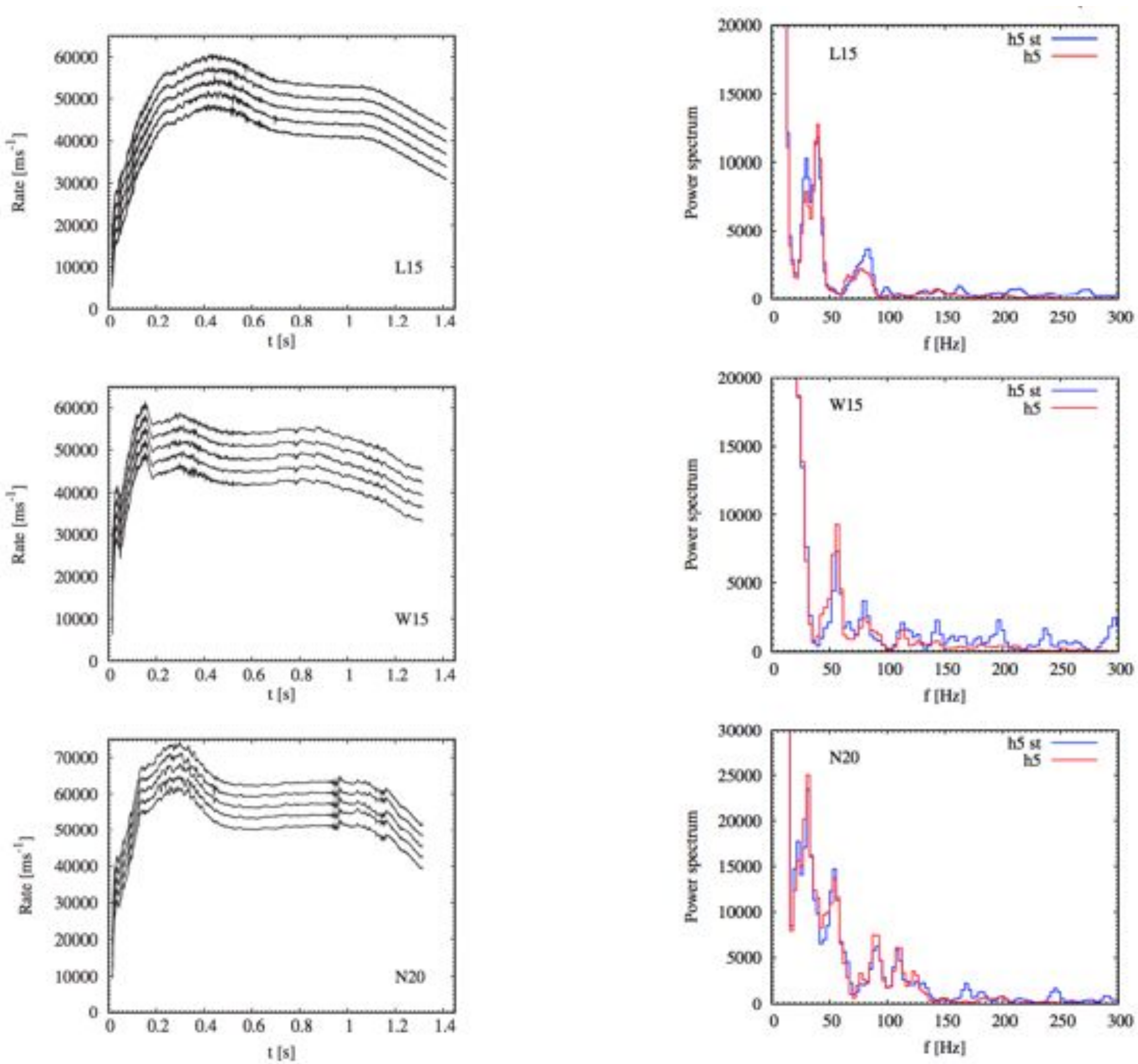
Lund et al. 12



Thierry Foglizzo

CEA Saclay

Examples of neutrino signature from the explosion of 3 progenitor models @ 1kpc (Lund+12)

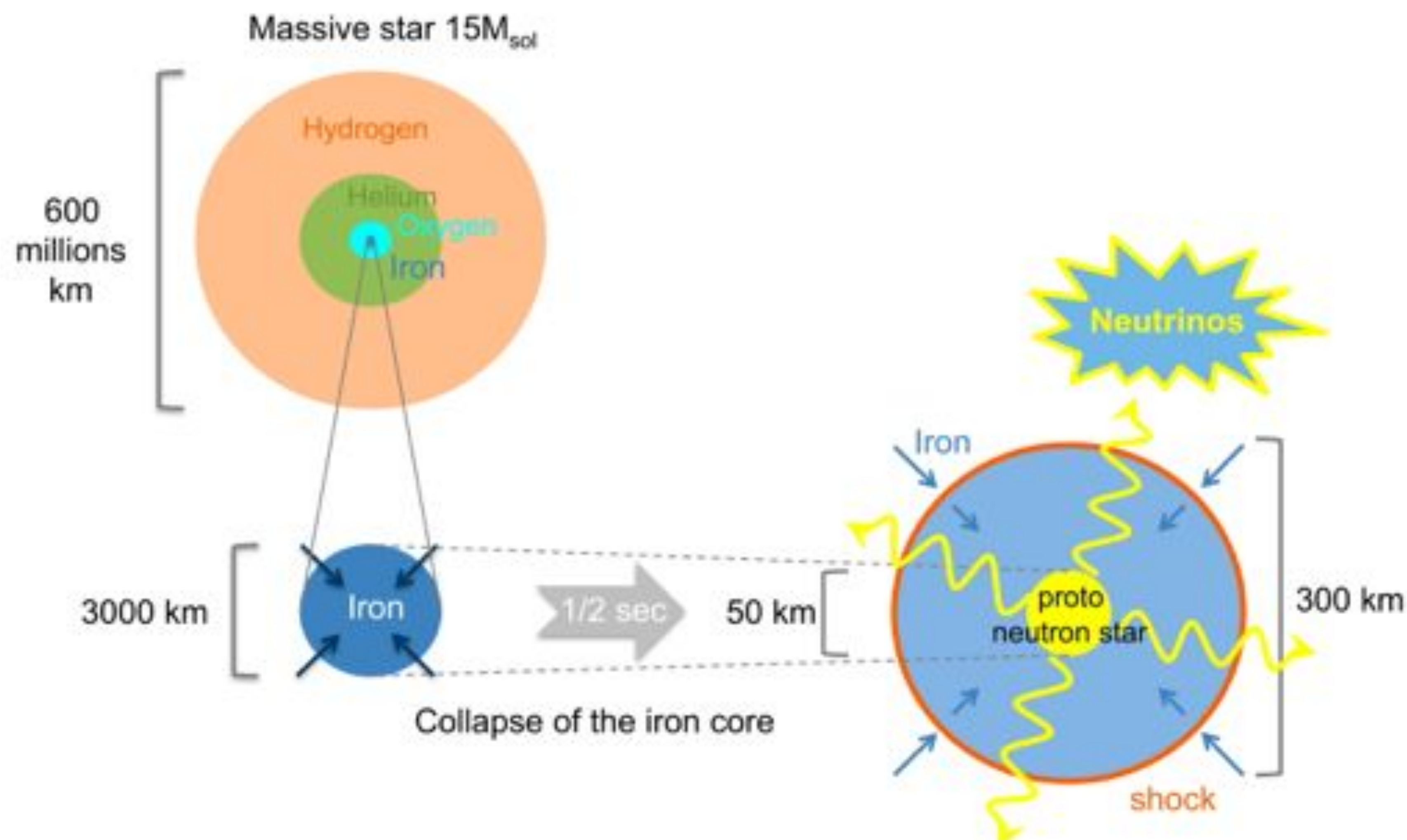


$15M_{sol}$ (Woosley & Weaver 95)

$15M_{sol}$ (Limongi 00)

$20M_{sol}$ (Shigeyama & Nomoto 90)

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

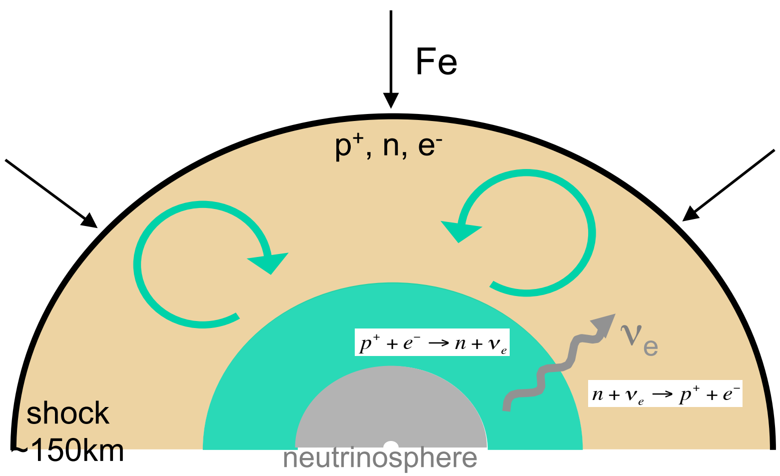


Why does the star explode ?
How does the collapse turn into an explosion ?

VOLUME 90, NUMBER 24 PHYSICAL REVIEW LETTERS week ending 20 JUNE 2003

Improved Models of Stellar Core Collapse and Still No Explosions: What Is Missing?

R. Buras, M. Rampp, H.-Th. Janka, and K. Kifonidis

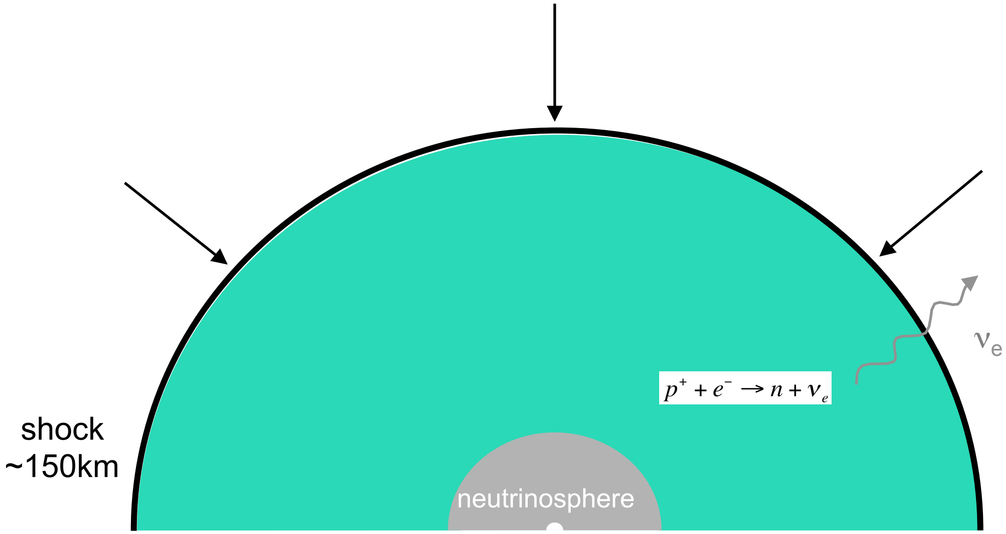


A challenging numerical modeling:

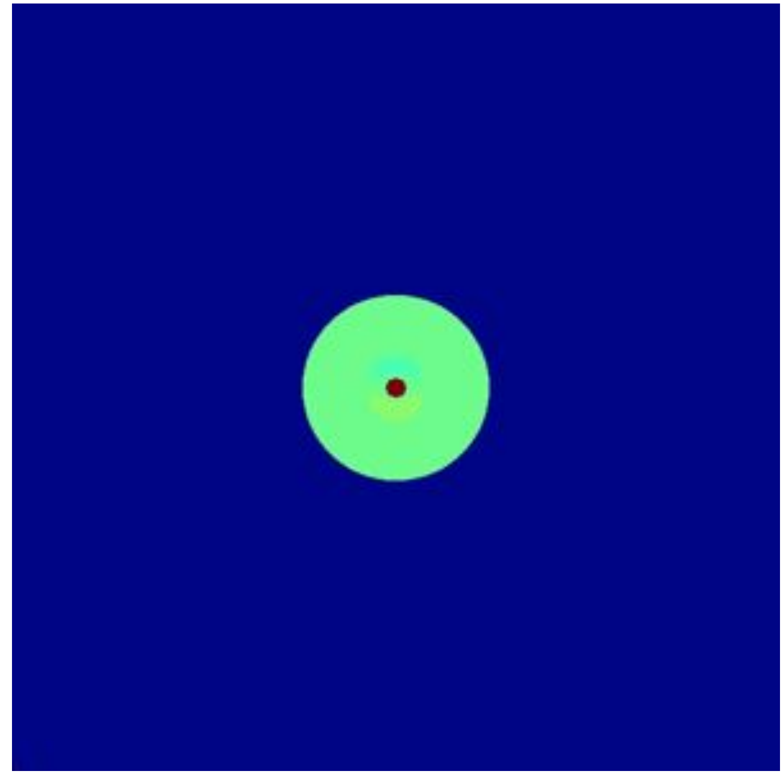
Garching, Oak Ridge, Princeton, Tokyo
Los alamos, Basel, Chicago, CalTech
SN2NS ?

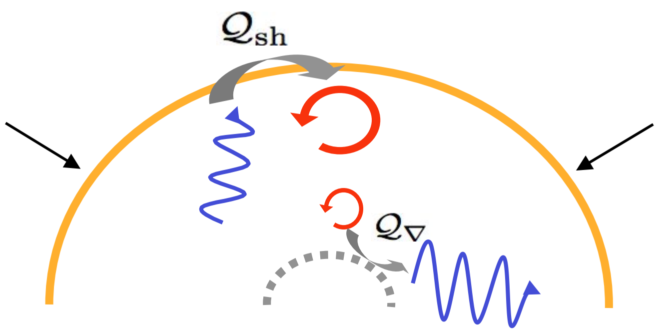
- neutrino transport
- 3D hydrodynamics
- nuclear density
- general relativity

Stationary Accretion Shock Instability : SASI



Blondin et al. 03



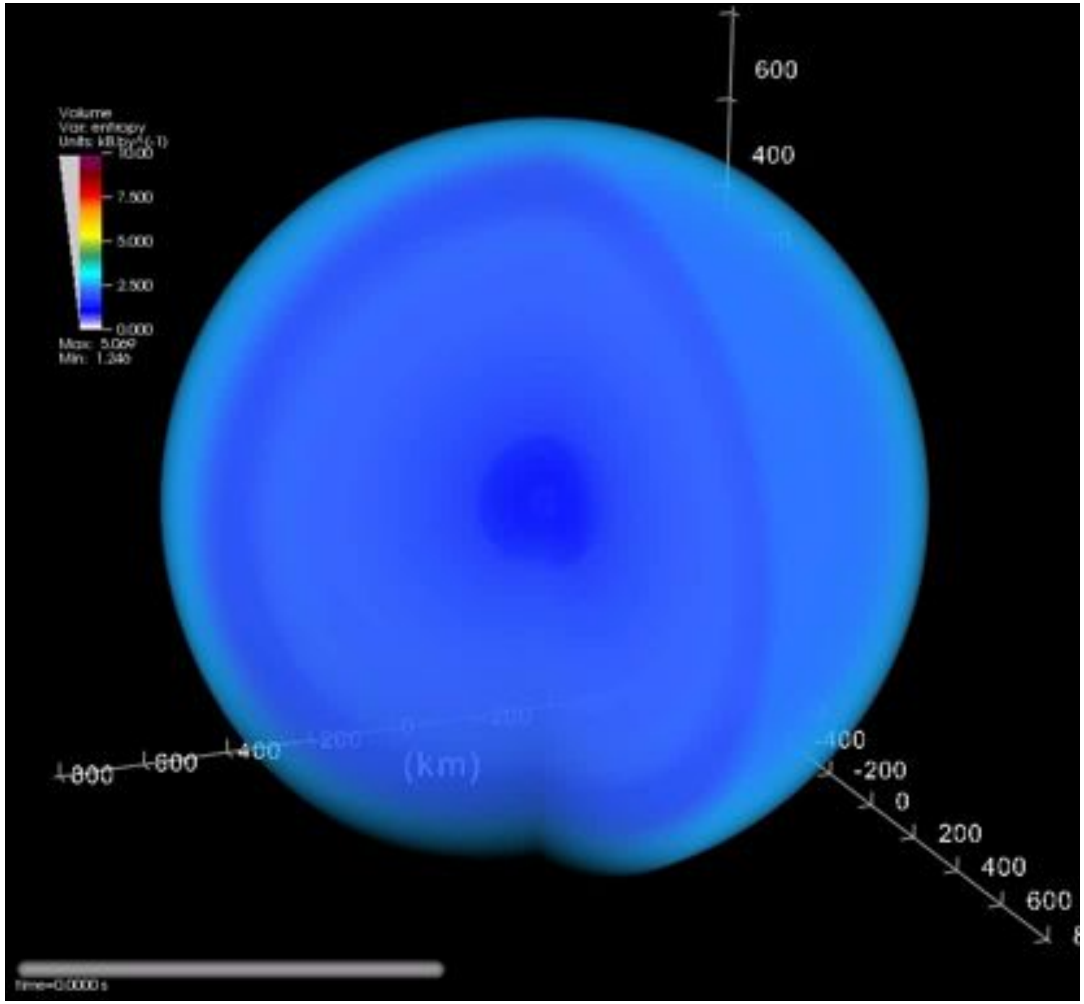


Mechanism of SASI: advective-acoustic cycle

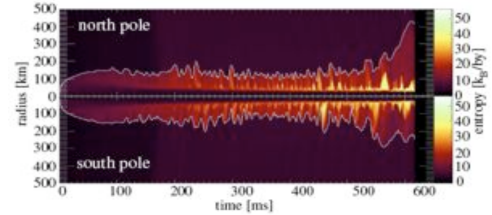
(Foglizzo 02, Ohnishi et al. 06, Foglizzo et al. 07, Scheck et al. 08, Fernandez & Thompson 09, Guilet & Foglizzo 12)

Asymmetric explosion of a $15M_{sol}$ star aided by SASI

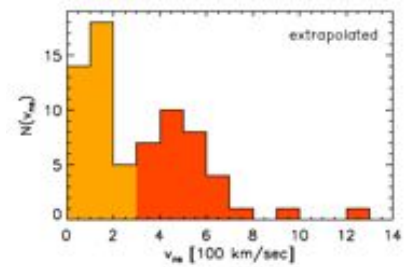
Marek & Janka 09



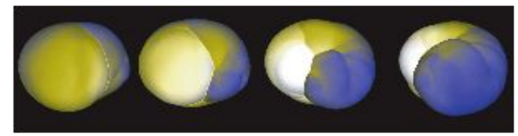
The possible consequences of SASI



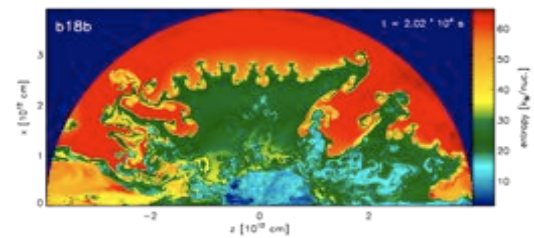
- successful explosion of $15M_{sol}$ driven by neutrino energy
(Marek & Janka 09, Suwa et al. 10, Müller et al. 12)



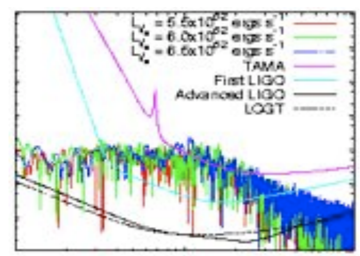
- pulsar kick
(Scheck et al. 04, 06, Nordhaus et al. 10, 11, Wongwathanarat et al. 10)



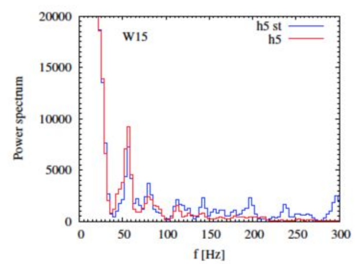
- pulsar spin ?
(Blondin & Mezzacappa 07, Yamasaki & Foglizzo 08, Iwakami et al. 09, Rantsiou et al. 11)



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

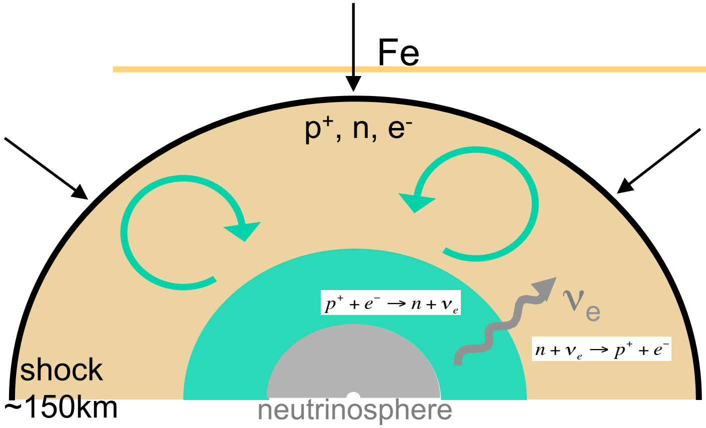


- gravitational waves
(Ott et al. 06, Kotake et al. 07, Marek et al. 09, Ott 08, Murphy et al. 09, Kotake et al. 11)

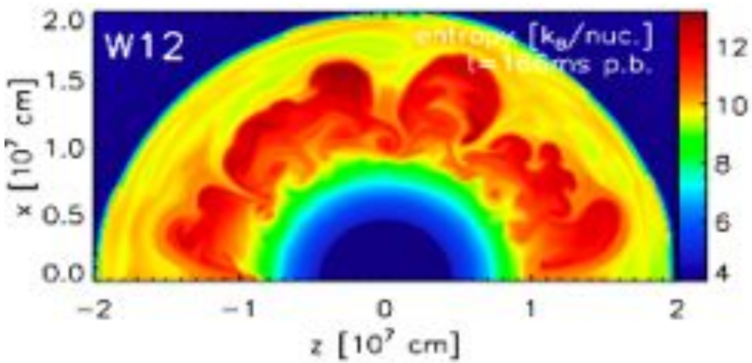


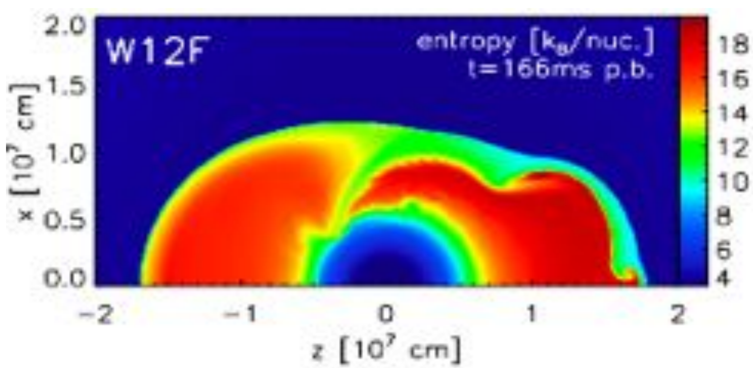
- neutrino signature
(Marek et al. 09, Müller et al. 12, Lund et al. 10, 12)

Instabilities during the phase of stalled accretion shock



Foglizzo et al. 06, Müller et al. 12





neutrino-driven convection
&
SASI

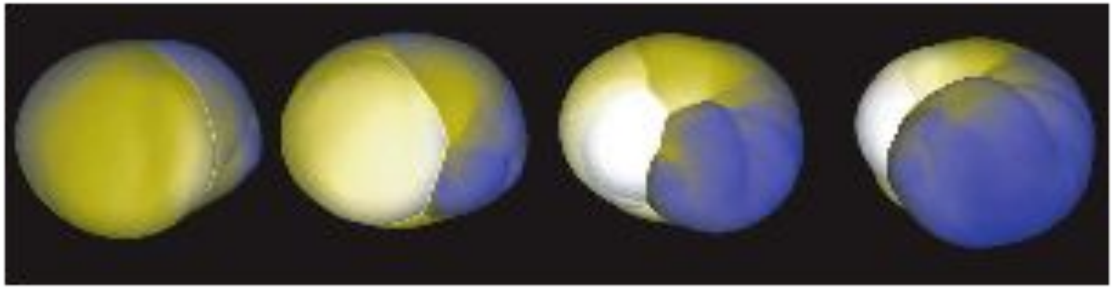
- Neutrino-driven convection (Herant, Benz & Colgate 92, ...)
  - entropy gradient
  - purely growing
  - typical size of the gain region, l>5

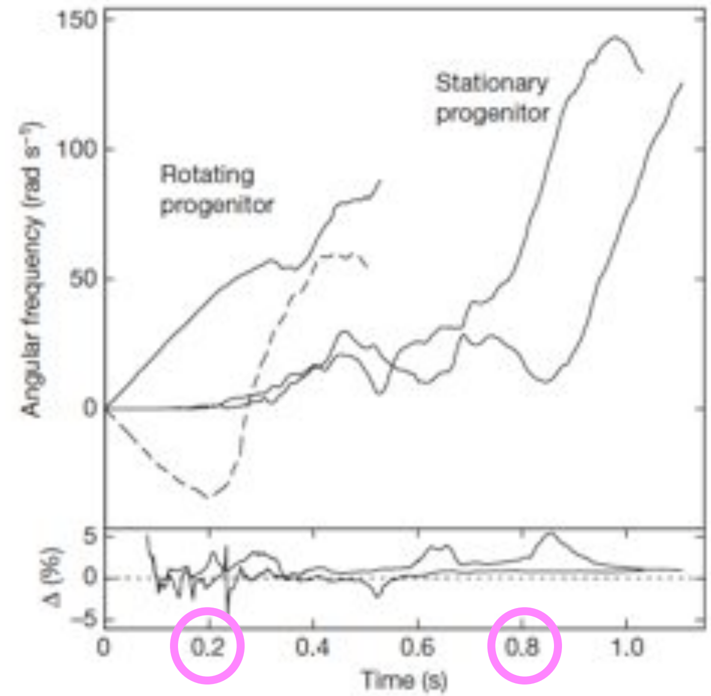
- SASI exists even in an adiabatic flow (Blondin et al. 03 ...)
  - advective-acoustic cycle
  - oscillatory
  - large angular scale l=1,2

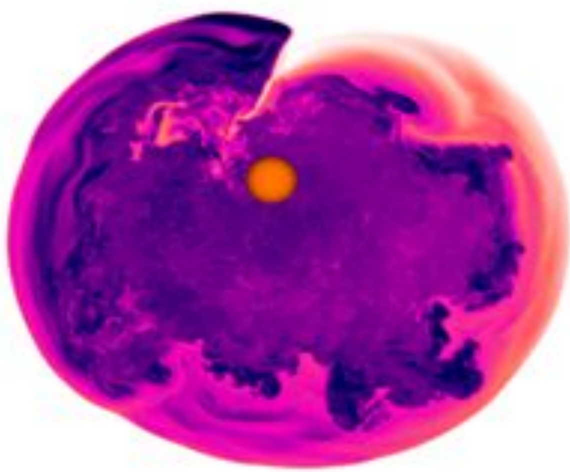
Current debate about the **nonlinear** consequences of these 2 instabilities in 2D/3D

Surprising spiral mode of SASI in 3D

Blondin & Mezzacappa 07
Fernandez 10





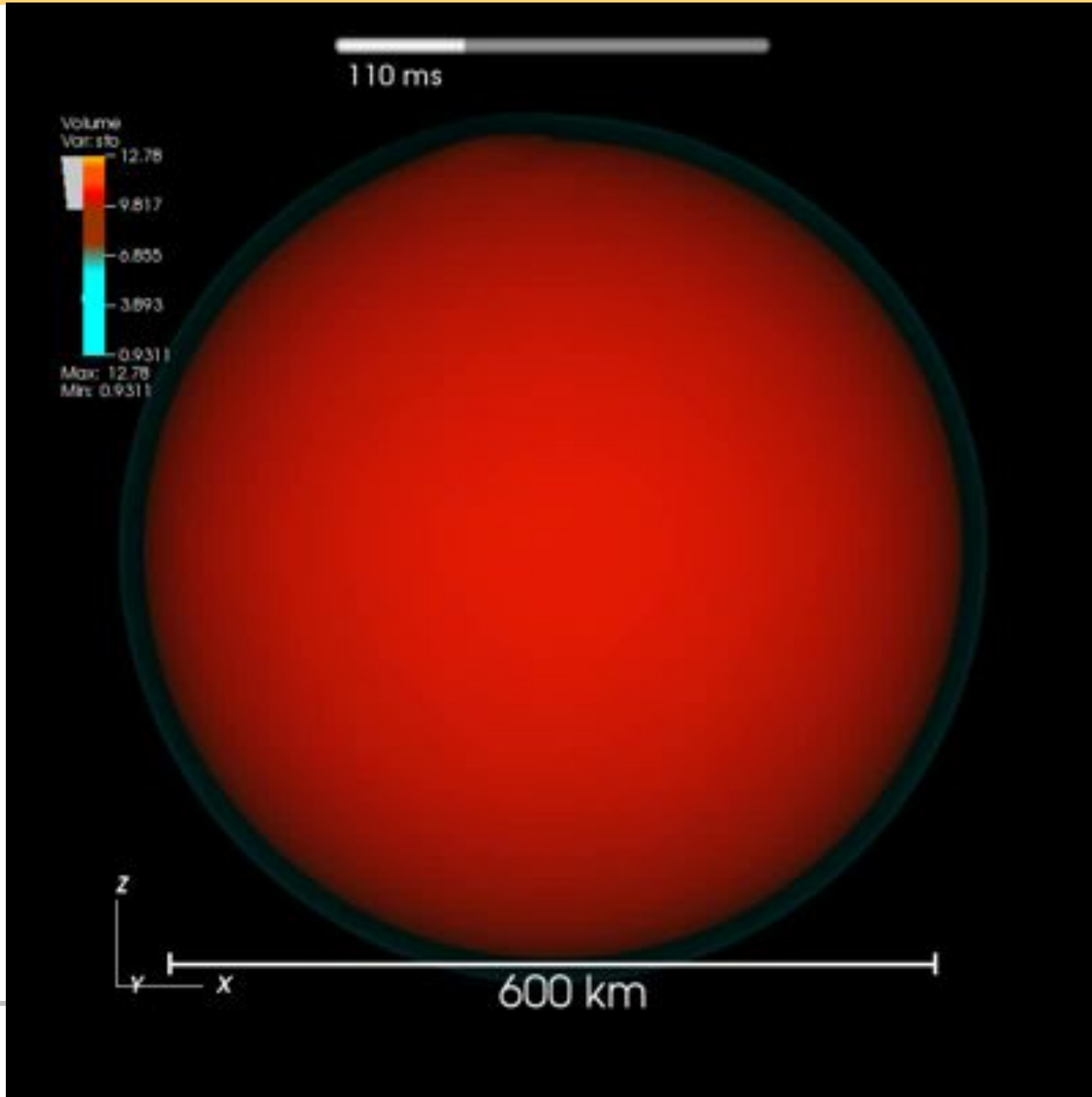


Timescale for symmetry breaking ?

-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
- better understanding (Yamasaki & Foglizzo 08)

3D spiral mode, $27M_{sol}$, Hanke+13

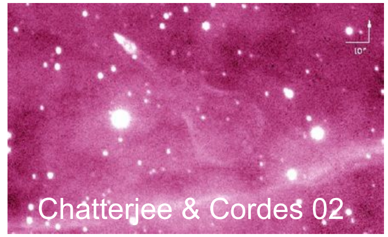


From SN explosions to a shallow water experiment

realism & complexity

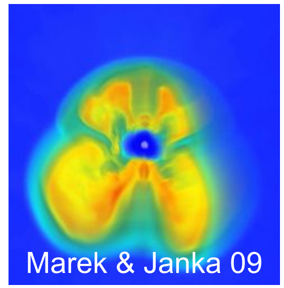
simplicity & understanding

Observations of SN and pulsars



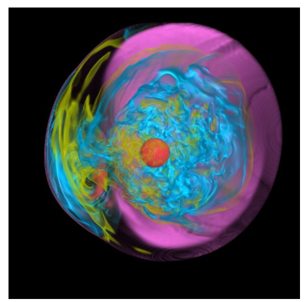
- SN light curve, polarimetry, neutrinos, grav. waves, nucleosynthesis,
- Pulsar kick and spin

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)



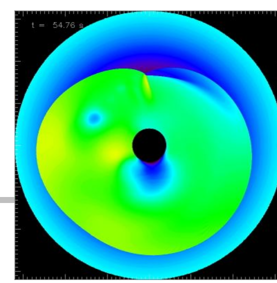
progenitor structure + nuclear EOS
+ neutrino "transport" & interactions
+ "GR" + "multi-D" hydro
(no magnetic field)

Multi-D hydro processes only
Blondin & Mezzacappa 07



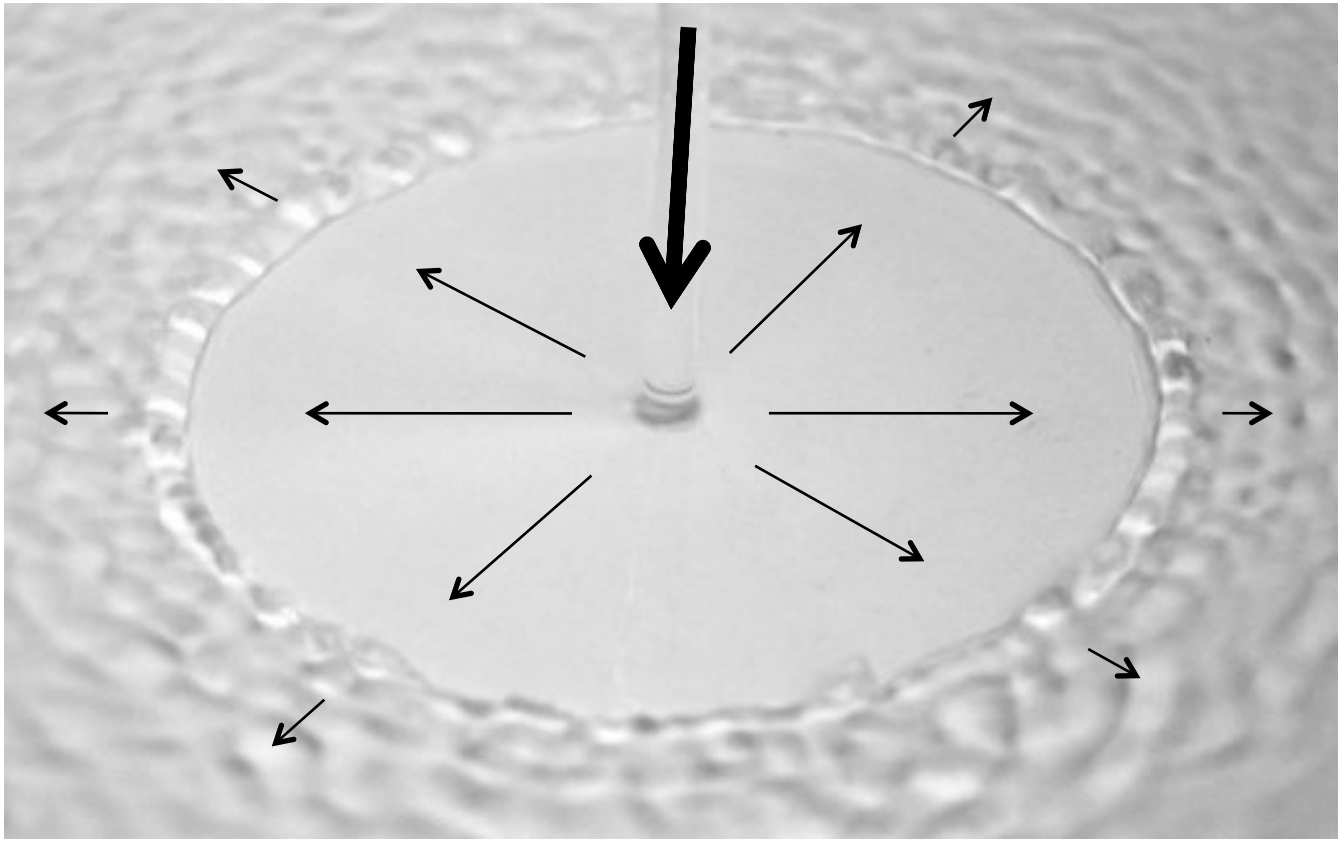
stationary accretion,
ideal gas,
3D adiabatic

SWASI experiment
Foglizzo et al. 12

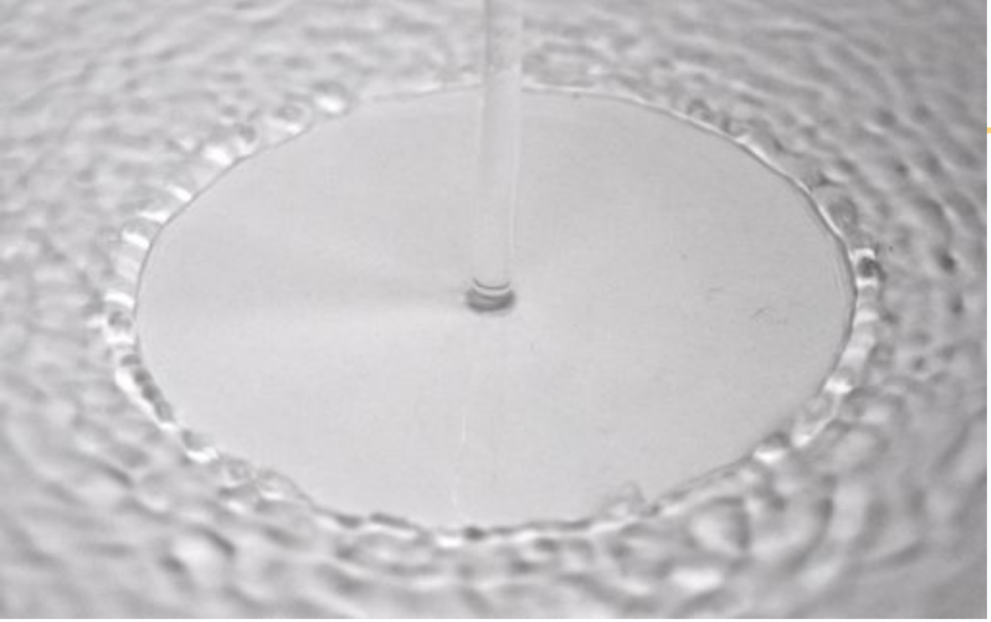


- 2D shallow water
  inviscid

Hydraulic jumps = analog to shock waves

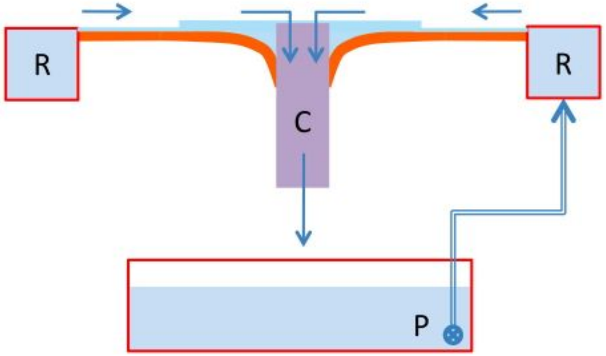


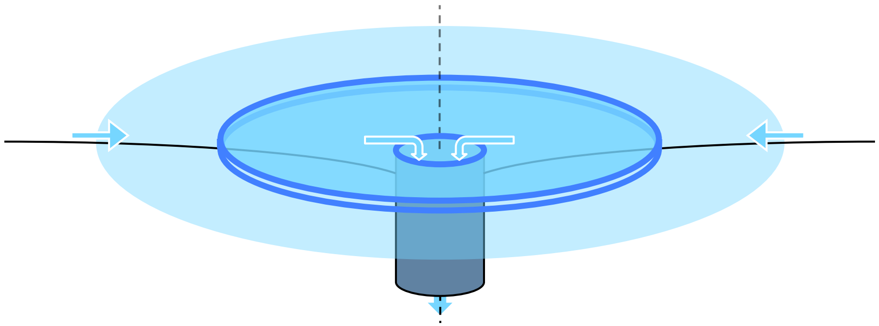
acoustic waves shock wave pressure	↔	surface waves hydraulic jump depth

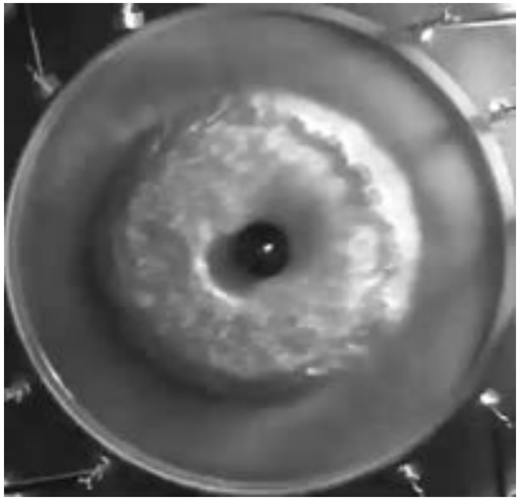


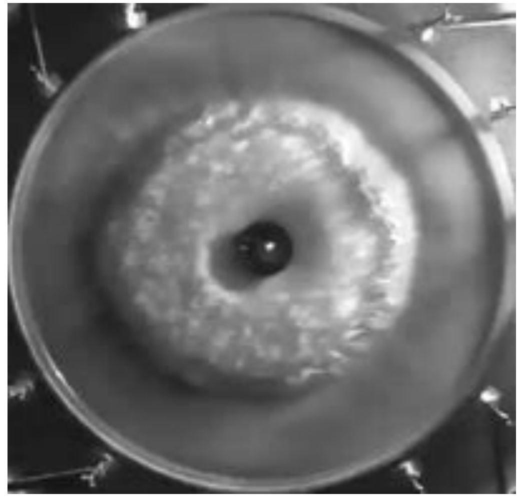
SWASI

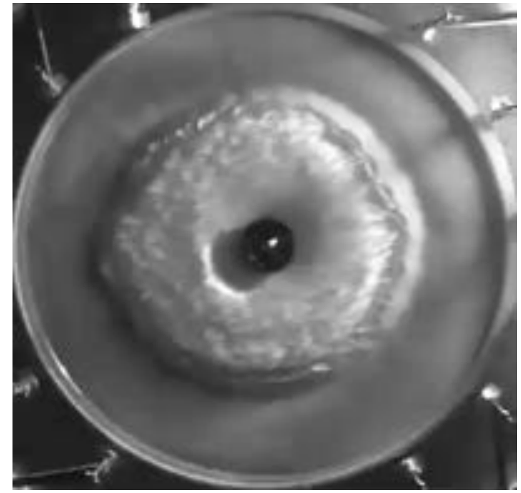
Shallow Water Analogue of a Shock Instability





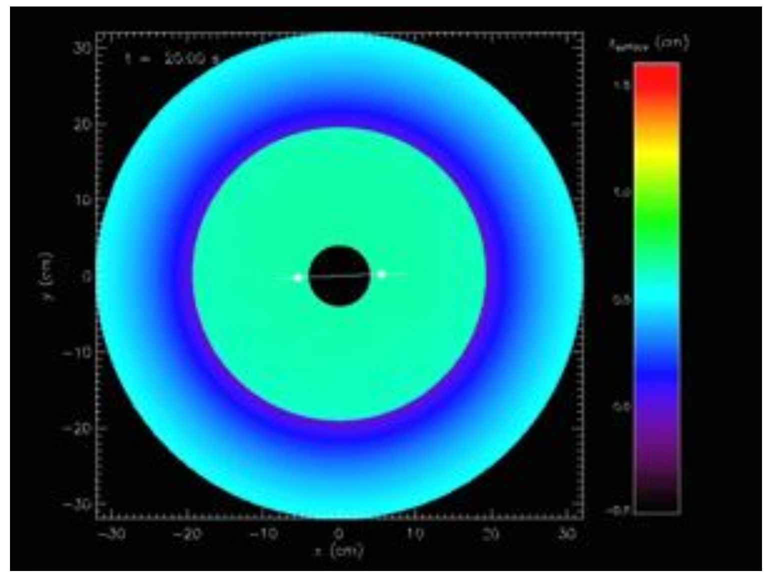




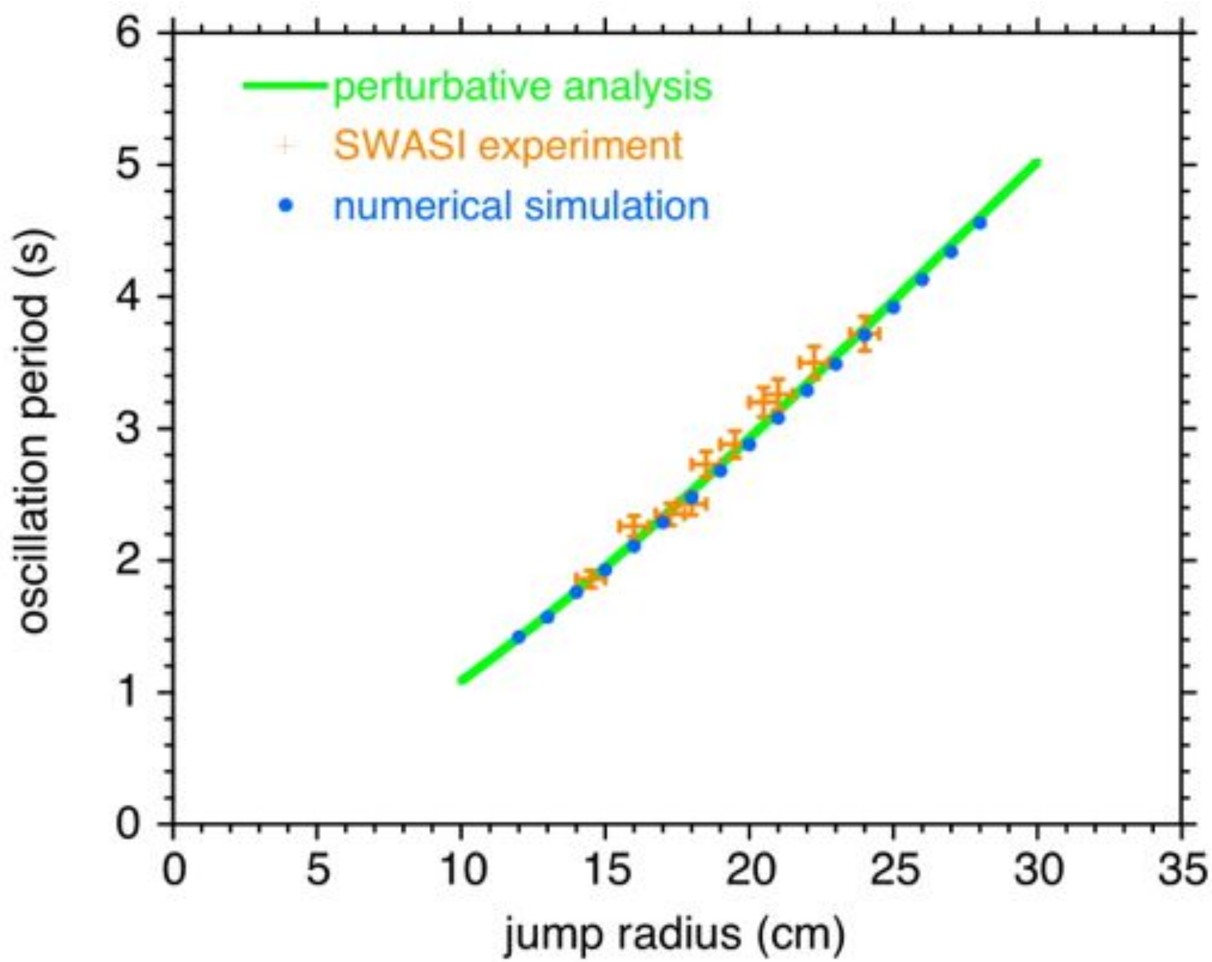


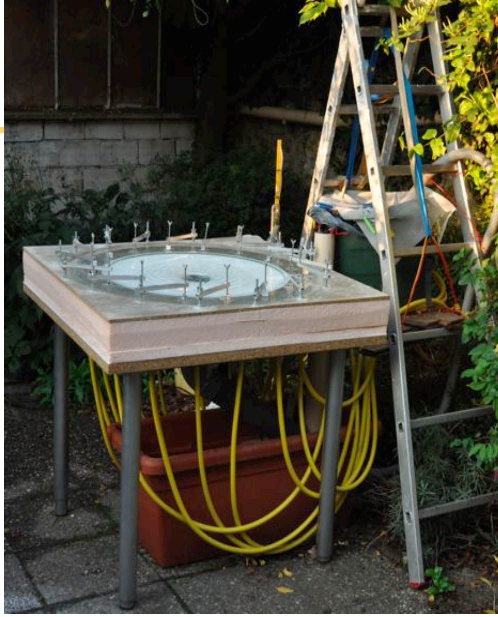
shock radius $\times 10^{-6}$ 200 km $\rightarrow$ 20 cm

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



Comparison to a 2D shallow water model

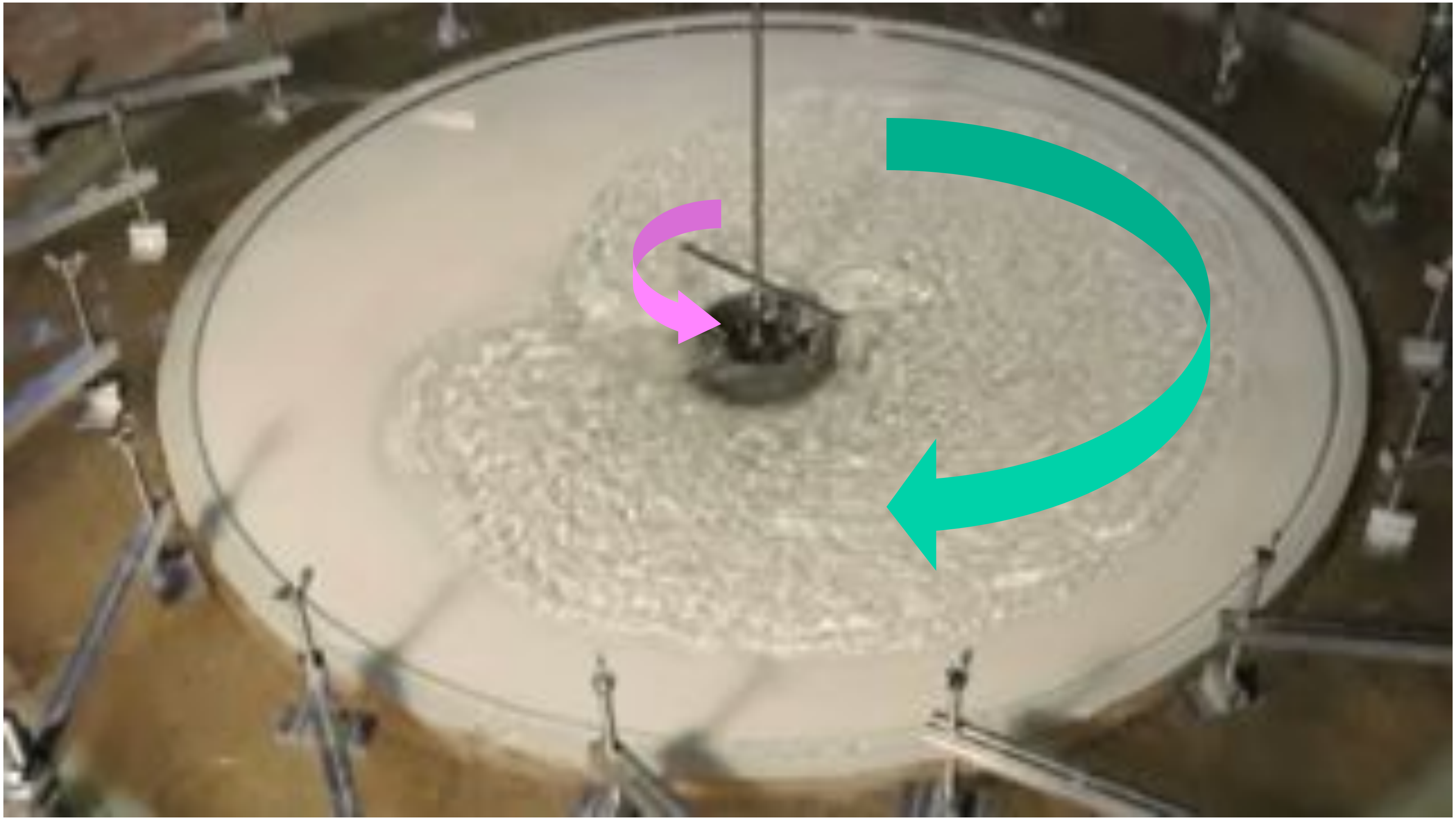




Foglizzo, Masset, Guilet, Durand
PRL (2012)

Angular momentum budget

rotating wave + advected vorticity = 0



Angular momentum budget

rotating wave + advected vorticity = 0

From 2D axisymmetric to 3D

Is SASI more dominant in 2D than in 3D ? no consensus among 3D simulations in 2013

-Inverse turbulent cascade in 2D favours the build up of large scale motions

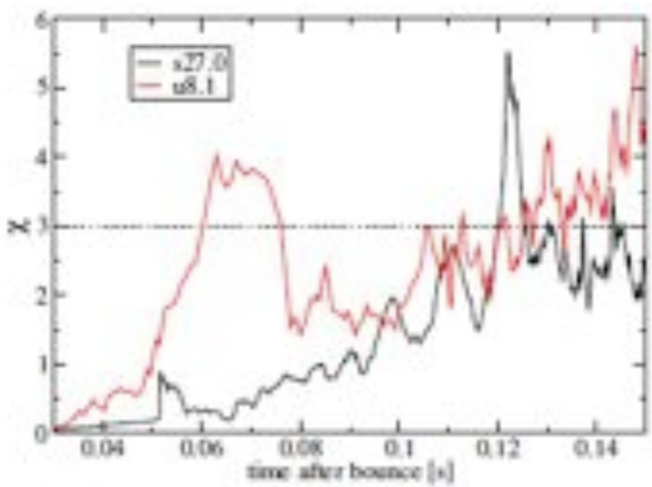
-3D spiral SASI ($27M_{sol}$, Hanke+13) is strengthened by rotation (Yamasaki & Foglizzo 08)

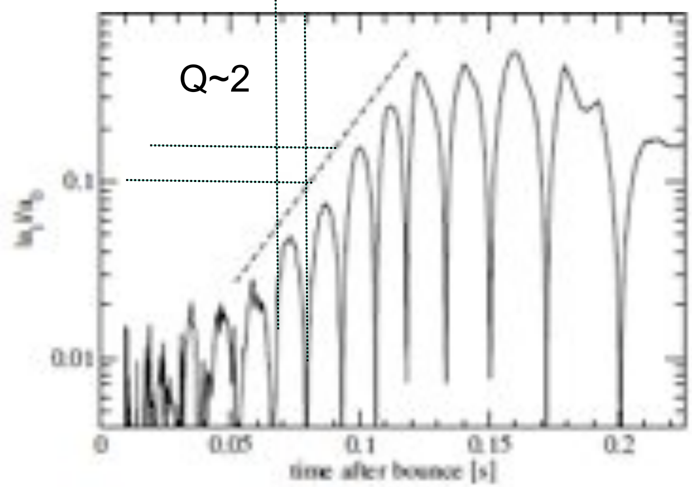
Even in 2D, instabilities depend on the progenitor structure: 8.1, 11.2, 15, 27 M_{sol} (Müller+12)

-strength of ν-driven buoyancy: parameter $\chi \sim \tau_{adv}/\tau_{buoy}$

-strength of SASI: amplification parameter Q

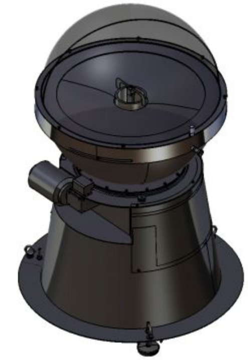
$$\omega_i^{SASI} \equiv \frac{\log Q}{\tau_Q}$$





$27M_{sol}$ in 2D

Conclusions



SWASI: first experimental view on SASI

- complementary to analytical and numerical approaches
- two new prototypes built at CEA Saclay in 2013

More 3D simulations are needed:

- numerical convergence ?
- neutrino transport in 3D ?
- uncertain EOS ?
- progenitor diversity ?
- rotation ?

ANR

SN2NS

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

Irfu cea saclay — LYTh — IPN Orsay

Huge parameter space & prohibitive computational cost

-> a better theoretical understanding is needed

Direct detection of neutrinos and gravitational waves are needed !