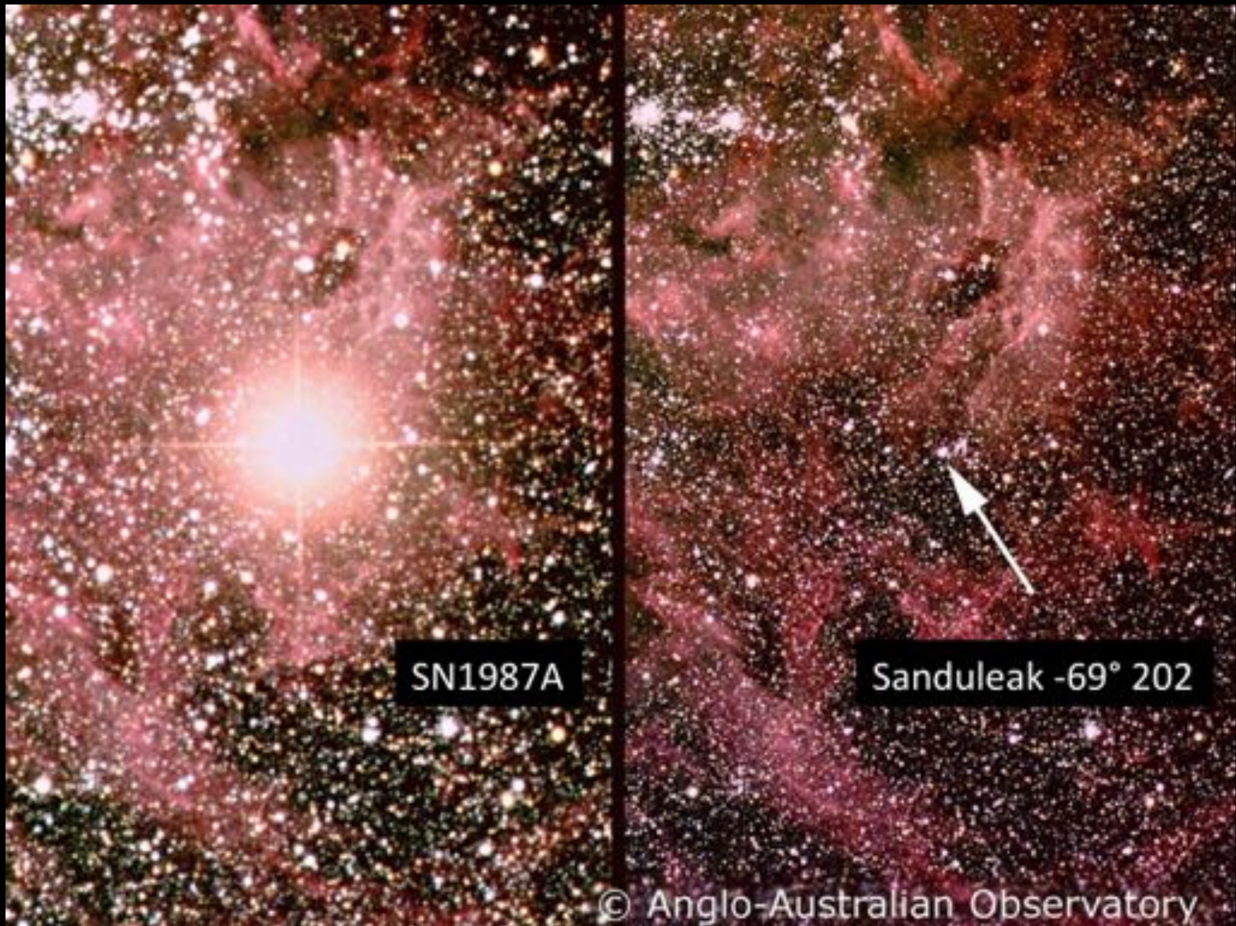
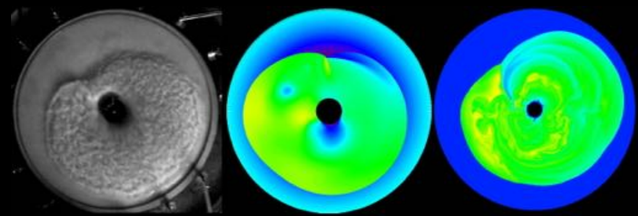


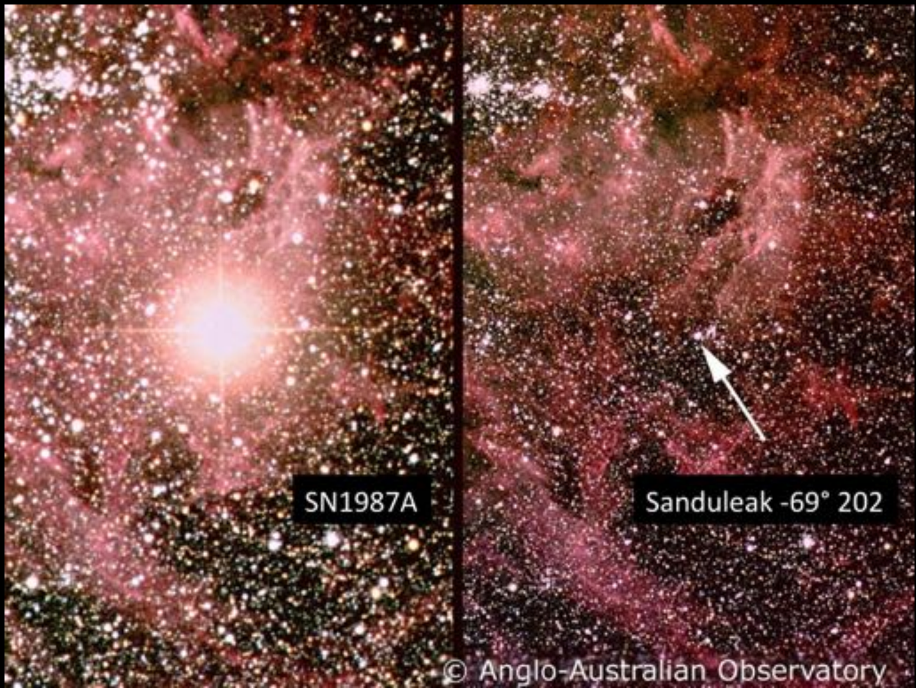


Stellar explosions
as sources of
gravitational waves
illustrated by
the dynamics of a fountain

Thierry Foglizzo

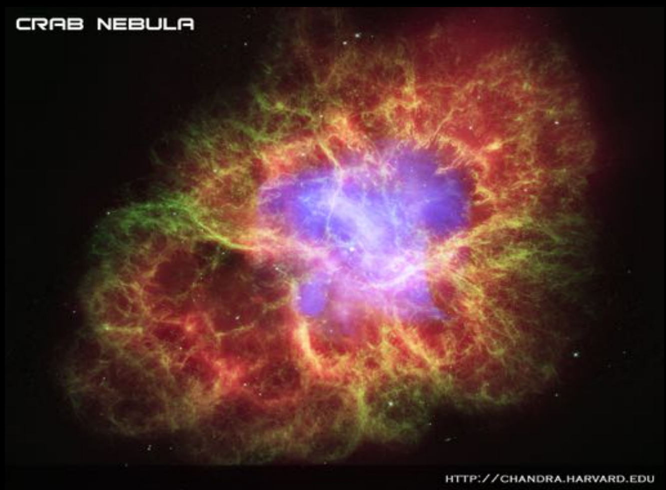
CEA Saclay

A supernova fountain for public outreach



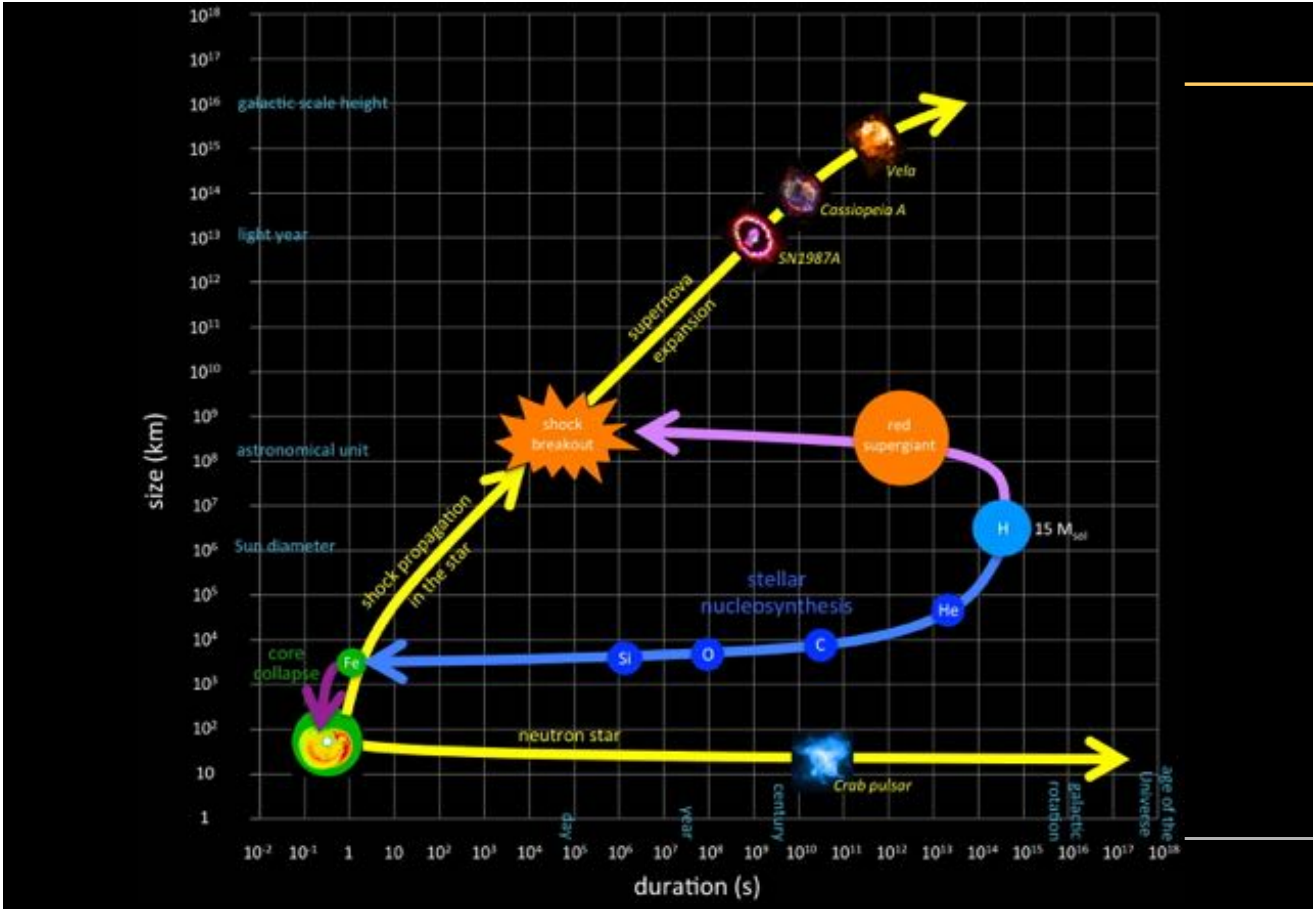
Astrophysical questions

-why should a spherical star explode sideways?
-why are neutron stars so fast at birth?
-can a neutron star spin be opposite to its parent star?



Physical concepts

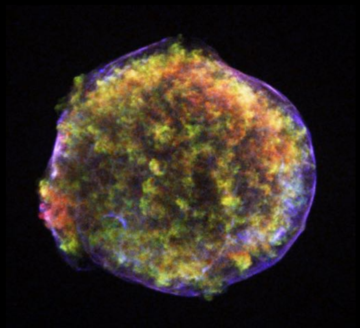
-fluid mechanics and scales
-shock waves and hydraulic jumps
-energy conversion: potential, kinetic
-conservation of momentum: linear, angular
-instabilities



galactic scale height
light year
astronomical unit
Sun diameter
size (km)
duration (s)
day
year
century
galactic rotation
age of the Universe
supernova expansion
Vela
Cassiopeia A
SN1987A
shock breakout
red supergiant
shock propagation in the star
H
15 M_sol
stellar nucleosynthesis
He
C
O
Si
Fe
core collapse
neutron star
Crab pulsar

Supernovae remnants

SN 1006



Tycho (1572)

Kepler (1604)

thermonuclear
supernovae
(24%)

thermonuclear fusion of
a $1.4M_{sol}$ white dwarf

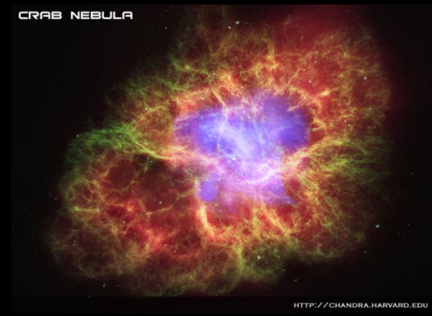
C,O→ejected elements
from C to Fe

core-collapse
supernovae
(76%)

collapse of
a $1.4M_{sol}$ core
of a massive star $8\text{-}40M_{sol}$

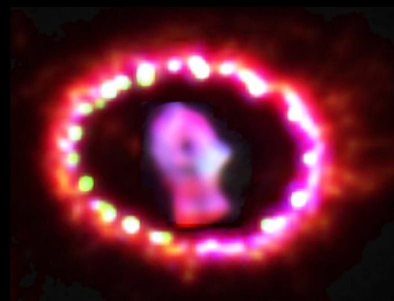
Fe core→neutron star

stellar enveloppe→ejected
elements from H to Ag



Crab (1054)

Cassiopeia A (~1680)



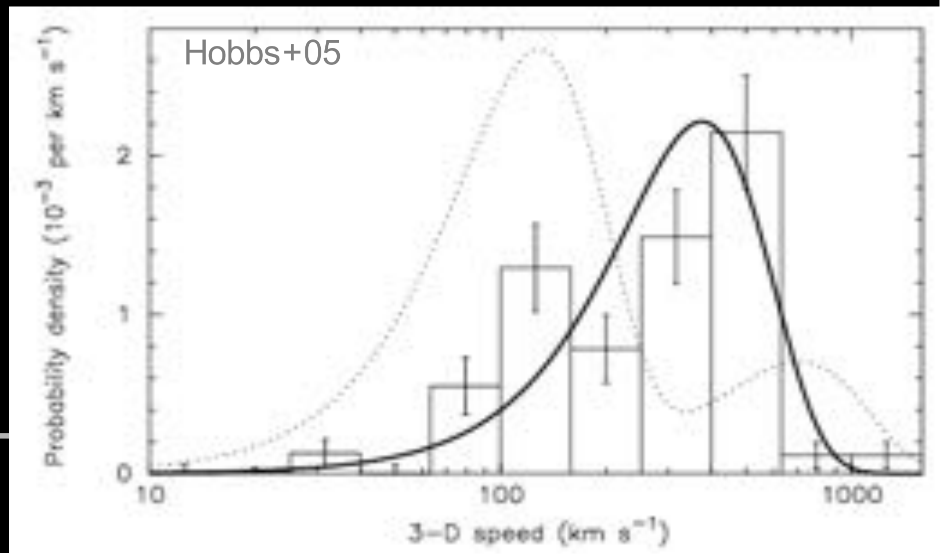
SN1987A

The high velocities of neutron stars suggest an asymetric supernova explosion

Chatterjee & Cordes 03

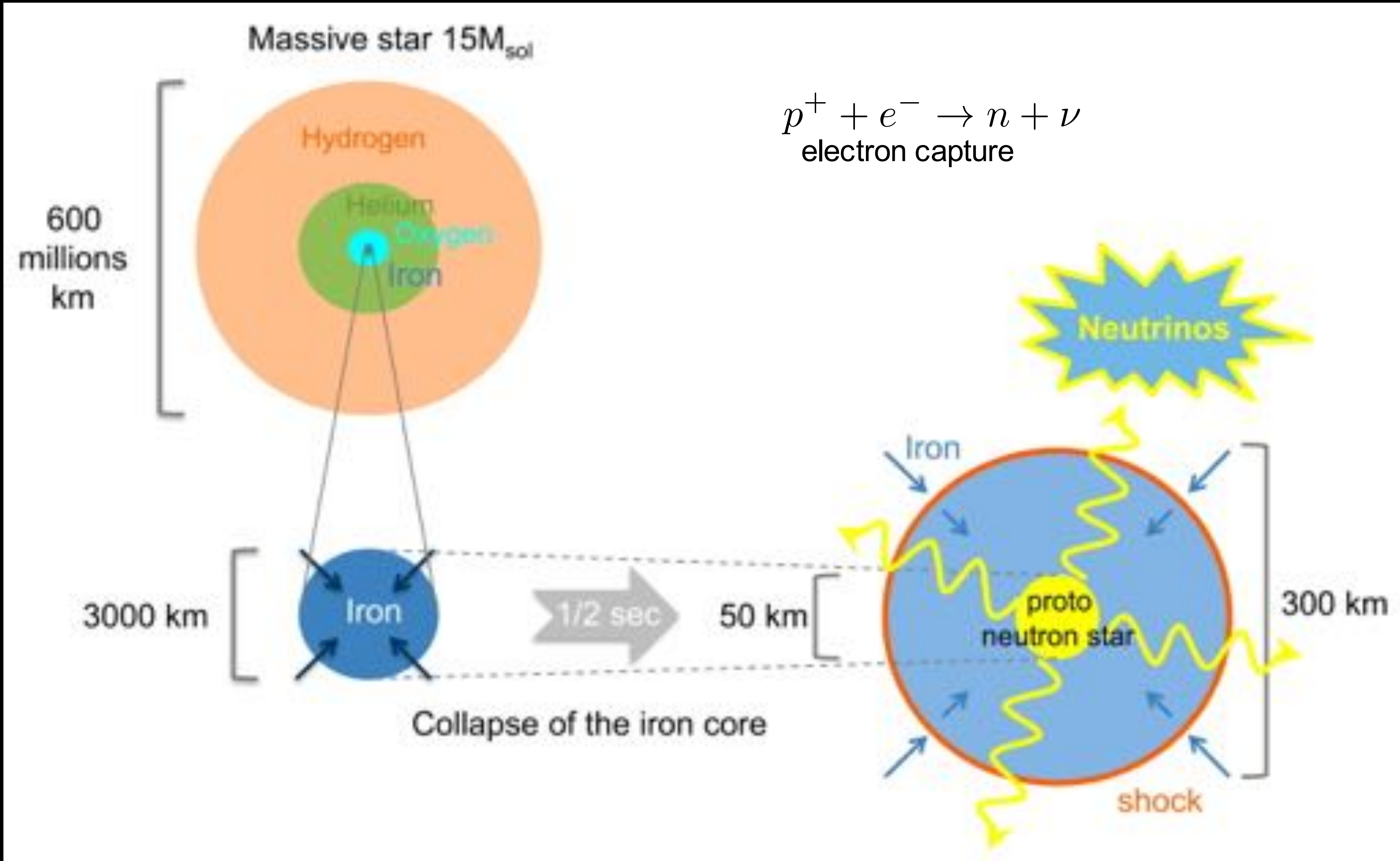
pulsar in the guitar nebula > 1000km/s

typical stellar velocities: 20-30km/s
typical pulsar velocities: 200-300km/s



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

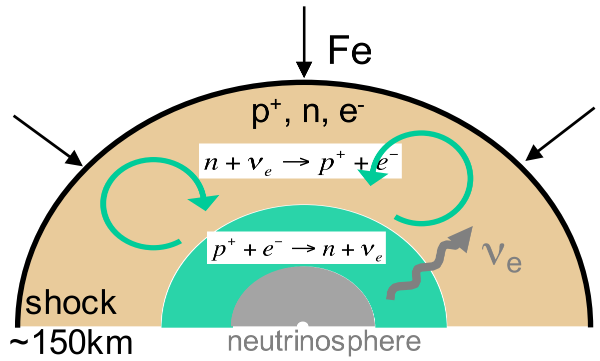
electron capture

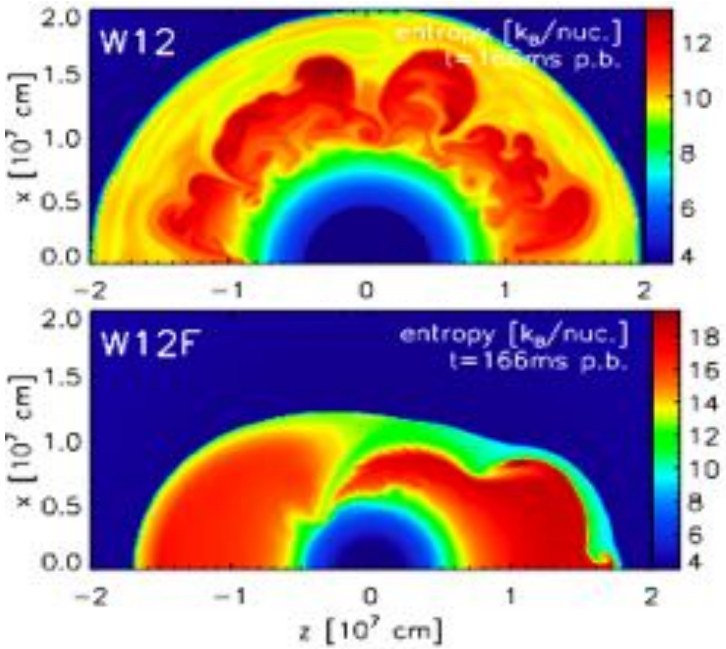


$27M_{sol}$ stellar core collapse in 3D

Hanke et al. 13

2 instabilities during the phase of stalled accretion shock



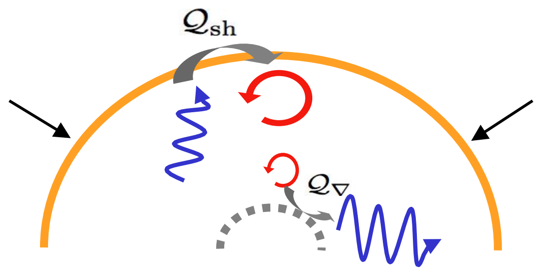


Neutrino-driven convection:

rising bubbles heated up by neutrino absorption

Standing Accretion Shock Instability (SASI):

interaction of acoustic waves and vortices

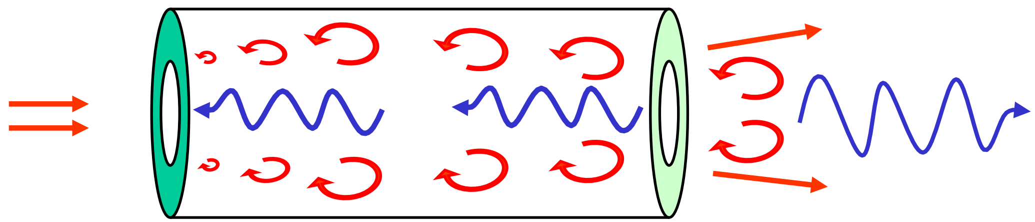


aeroacoustic instabilities

- advected perturbations
- acoustic feedback

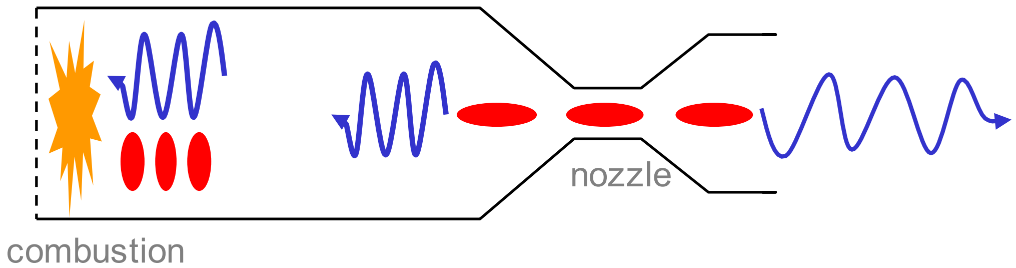
wistling kettle
Chanaud & Powell 65

- vortical-acoustic cycle



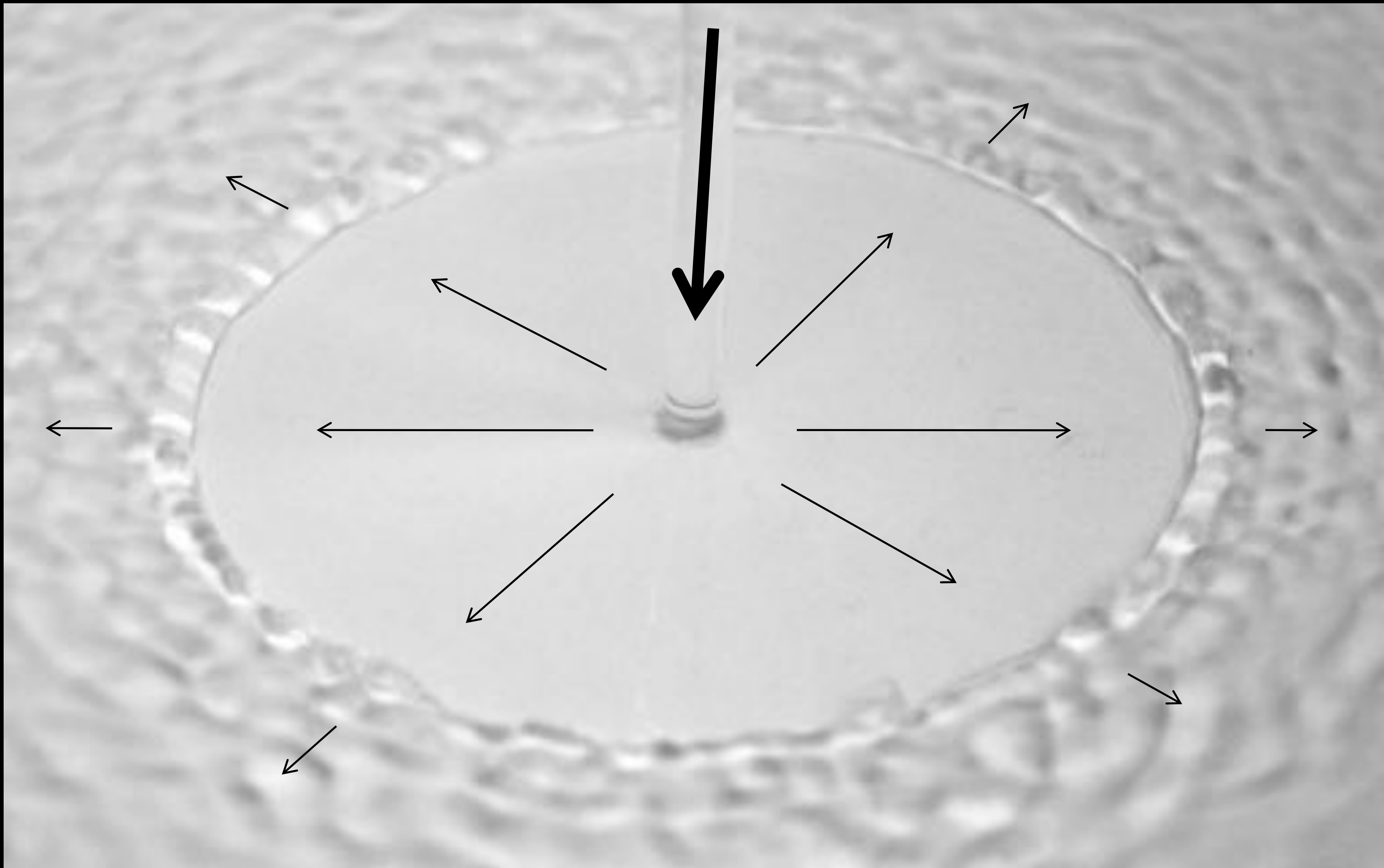
Ariane 5 vibrations
Mettenleiter, Haile & Candel 00

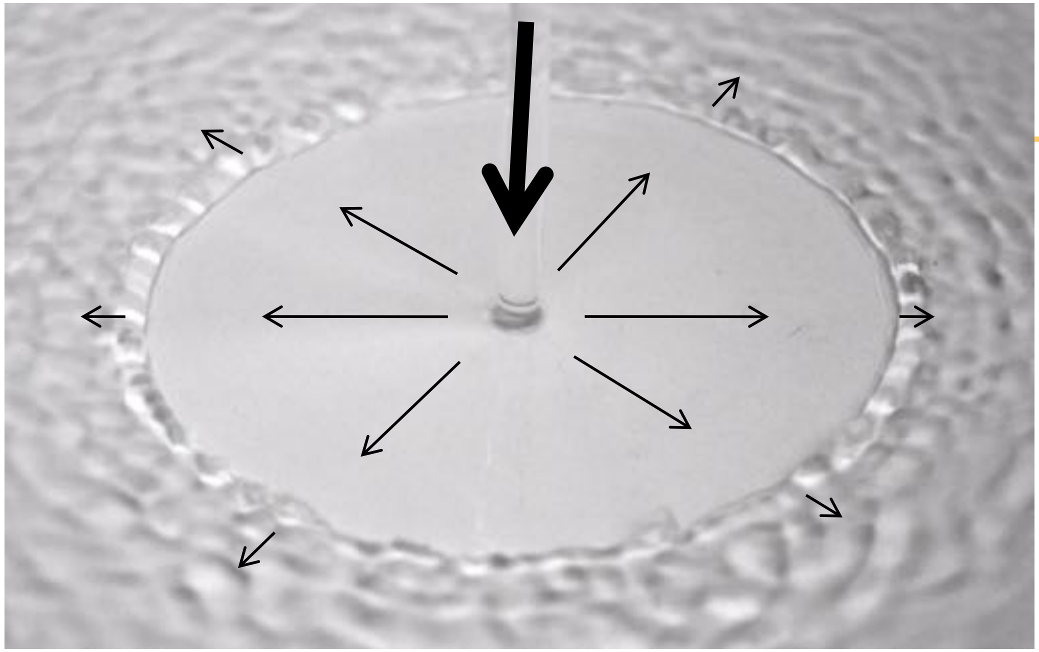
- entropic-acoustic cycle



ramjet rumble instability
Abouseif, Keklak & Toong 84

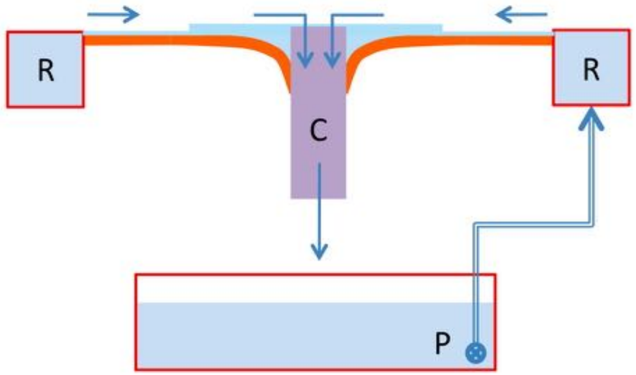
Hydraulic jumps and shock waves

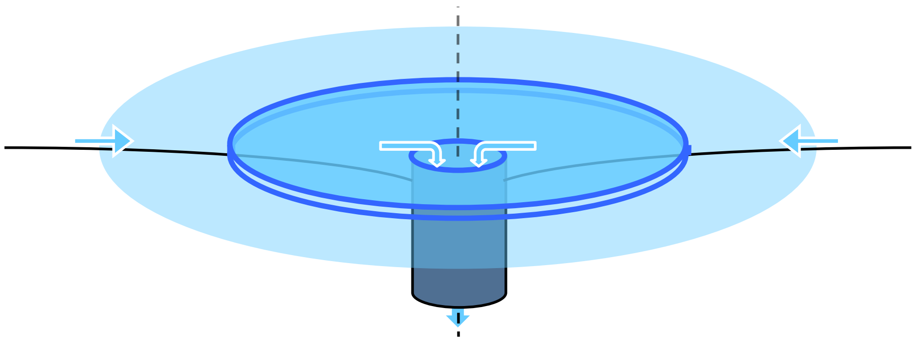


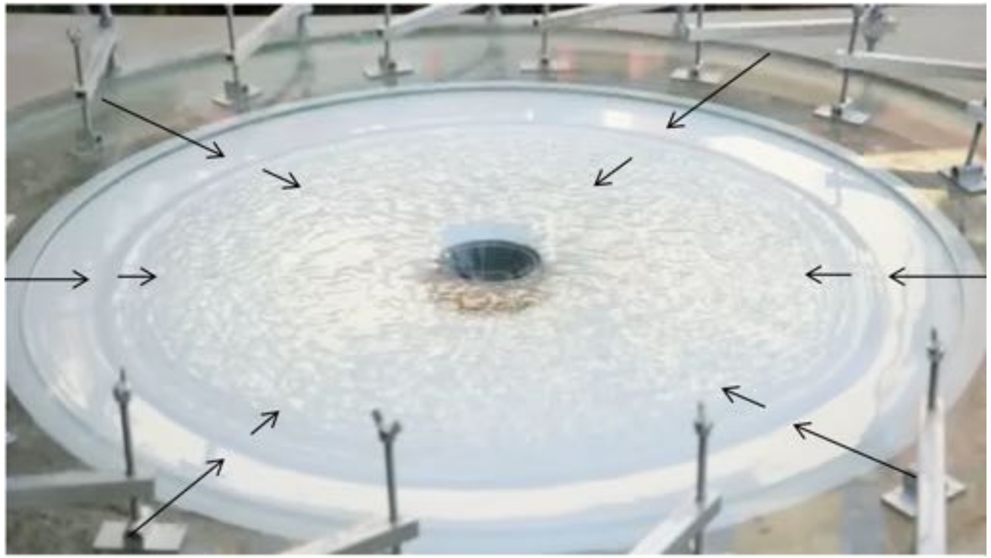


SWASI: an experimental analogue of SASI

Shallow Water Analogue of a Shock Instability







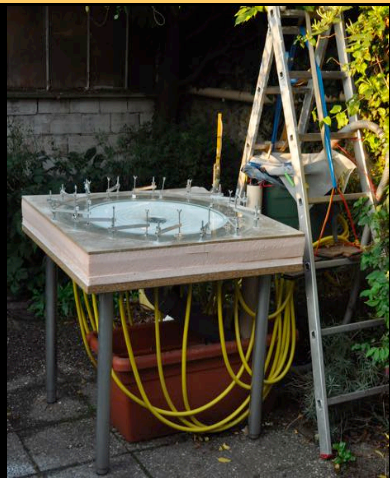
acoustic waves
shock wave
pressure

↔

surface waves
hydraulic jump
depth

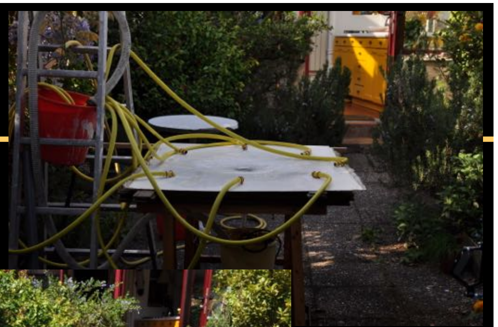
SWASI: simple as a garden experiment

November 2010



October 2010

June 2010



May 2010

February 2012

PRIX 2014
LE GOÛT DES SCIENCES

November 2013

June 2014

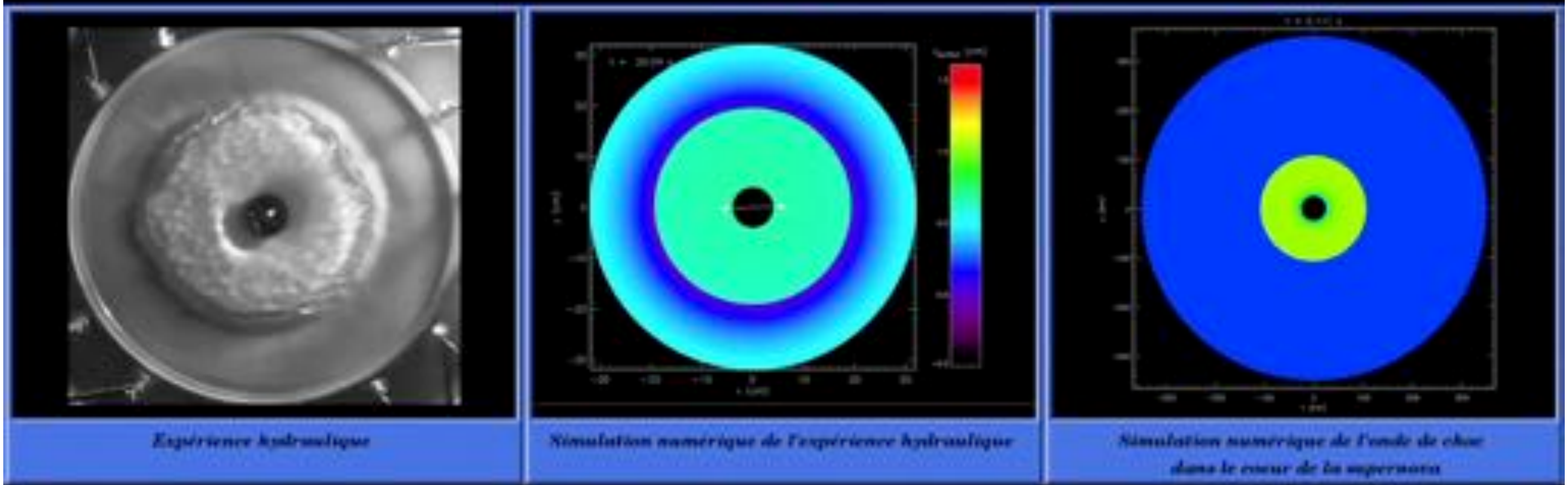
February 2017

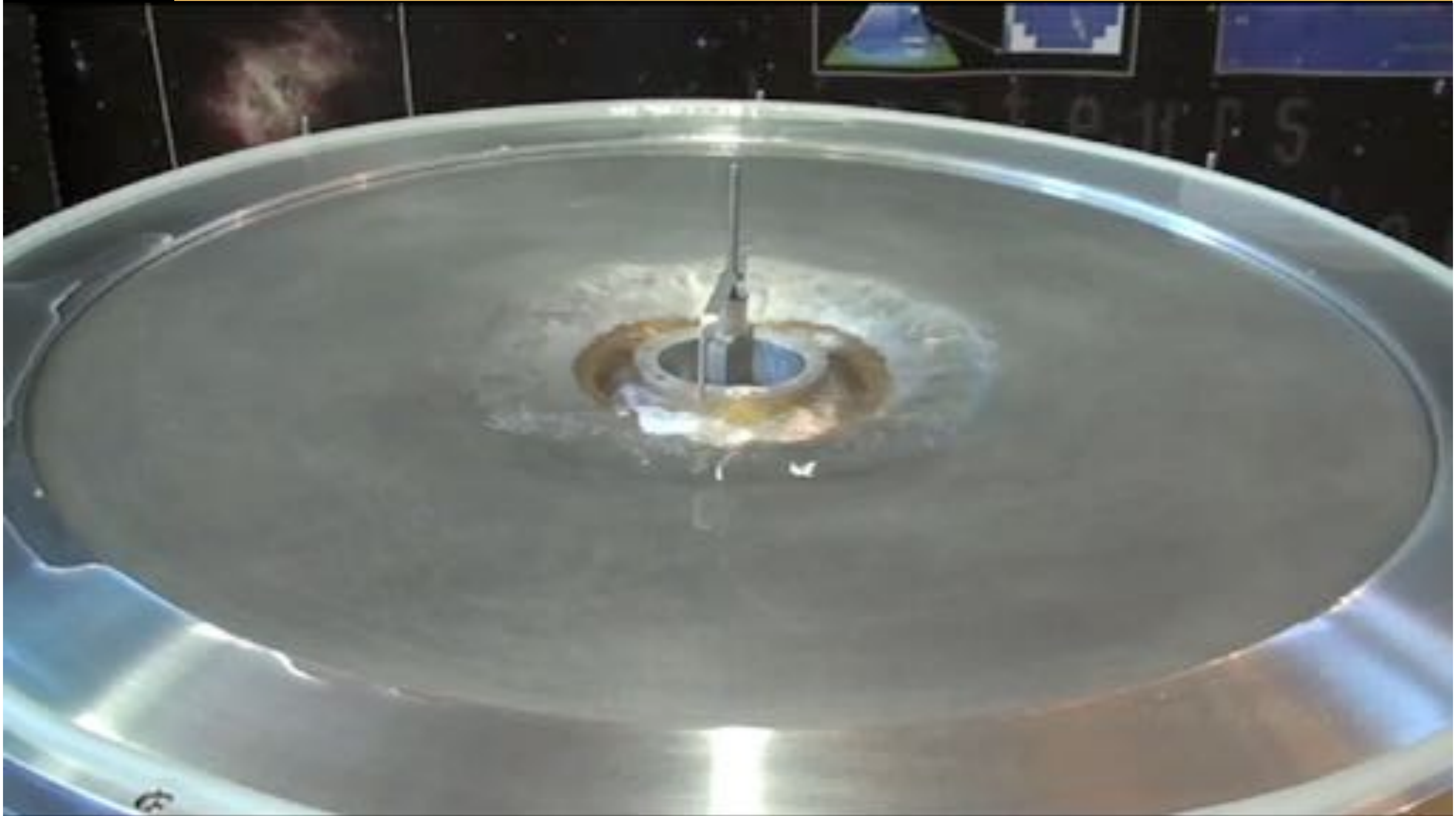
Dynamics of water
in the fountain

Dynamics of the gas
in the supernova core

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

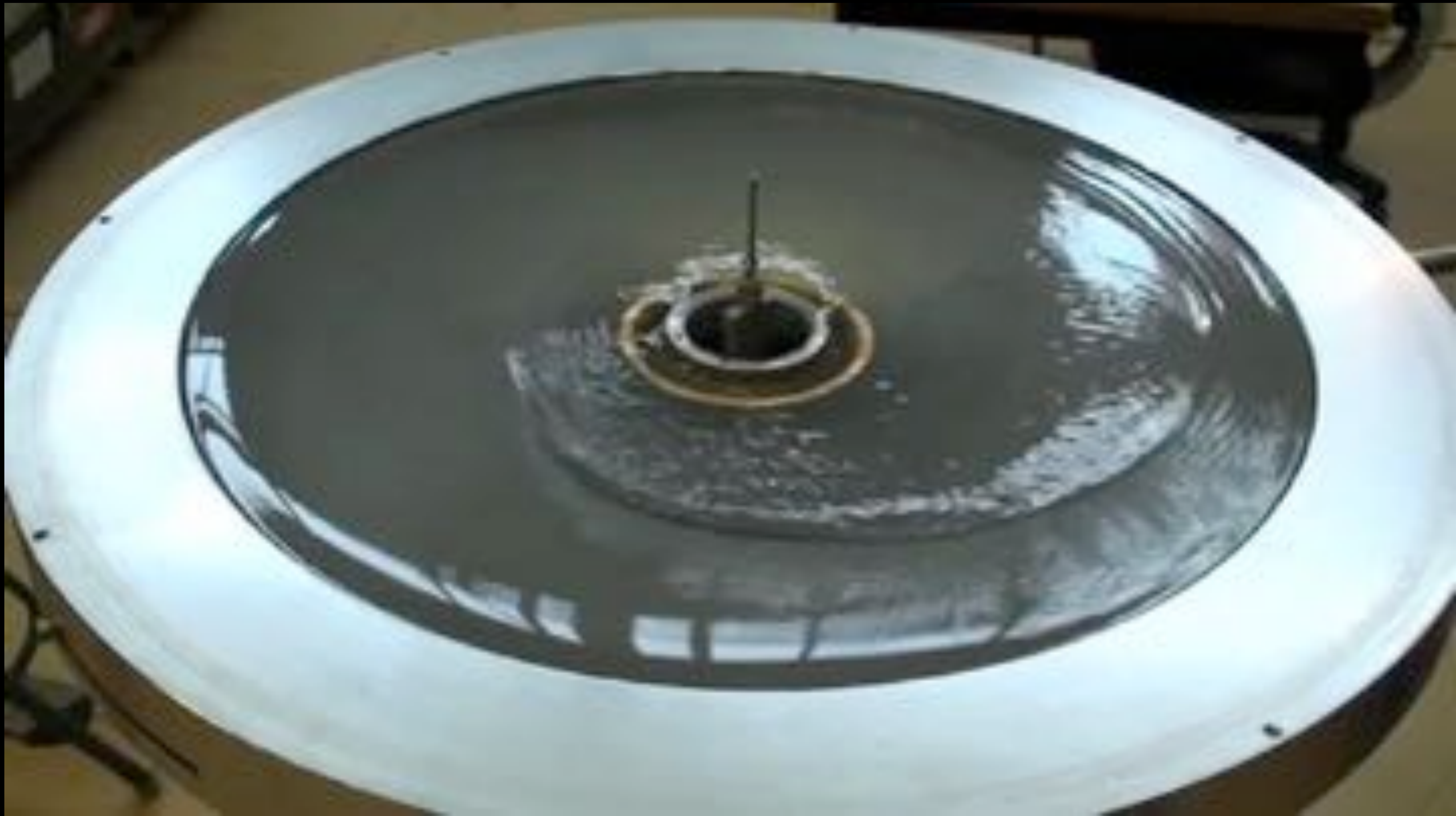
3s/oscillation ← 100 x faster → 0.03s/oscillation





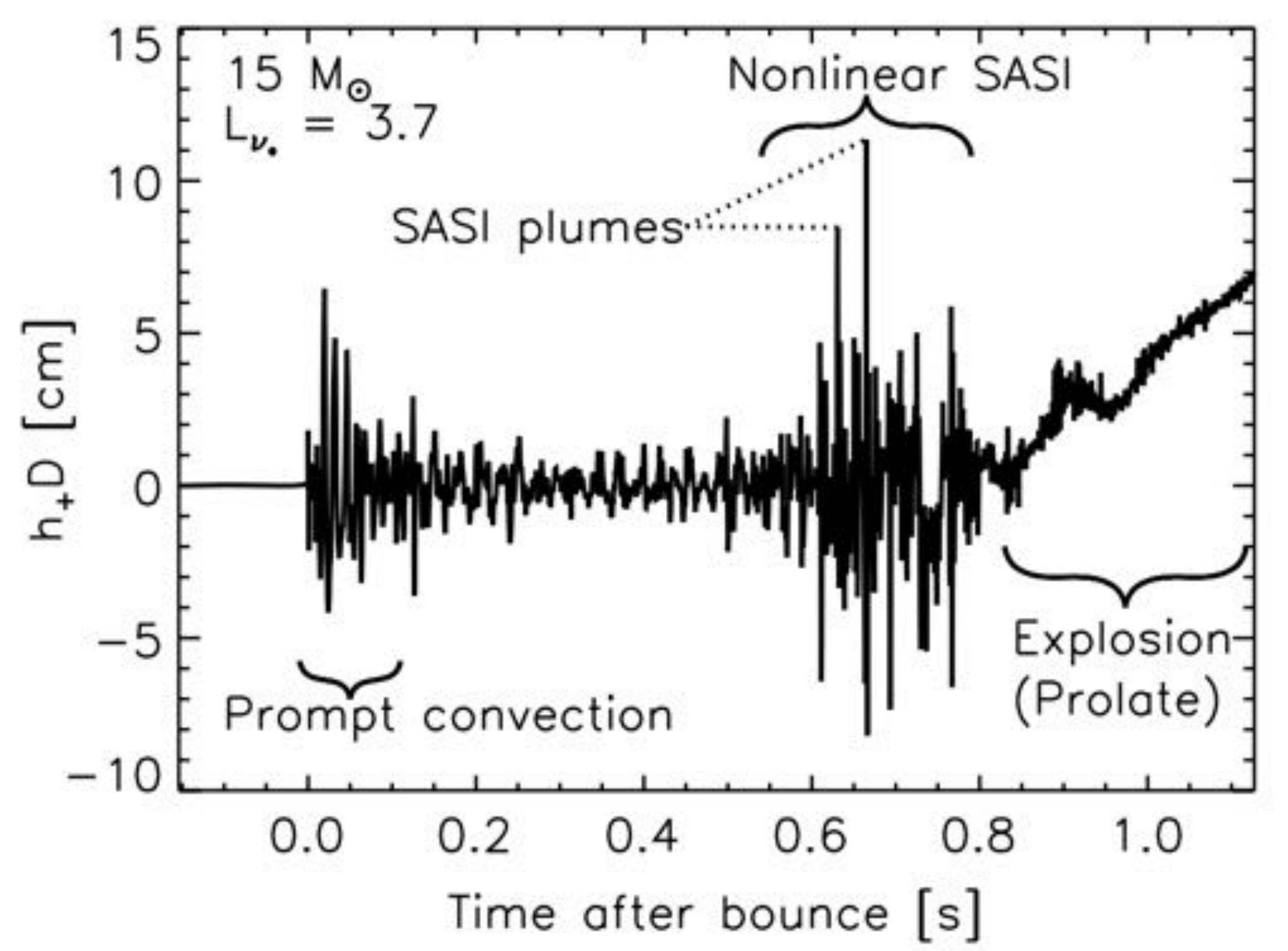
Rotating progenitor: the accreted angular momentum changes its sign as SASI grows

faster rotation : another instability associated to differential rotation



even faster rotation: centrifugal limit, also unstable

Gravitational wave signatures from supernovae



Murphy+09

Gravitational waves signatures from non axisymmetric features

Low T/W spiral modes of fast spinning cores produce strong gravitational waves (e.g. Hayama+15)

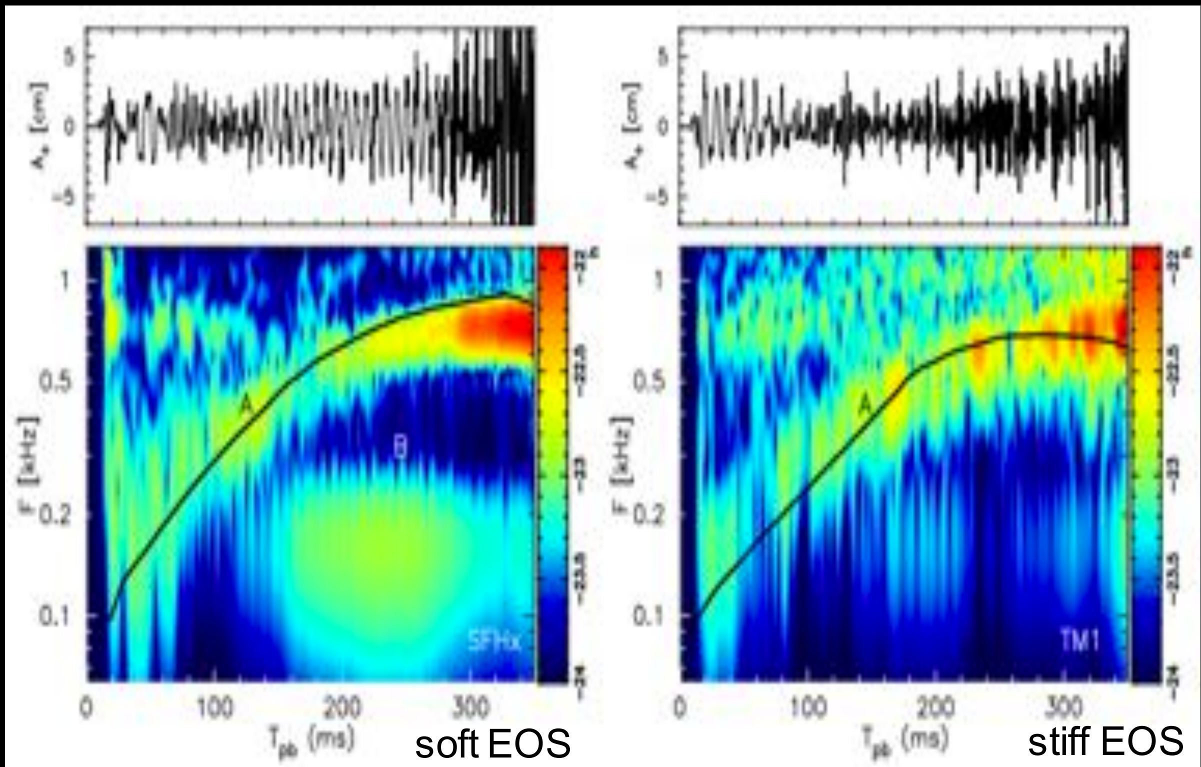
The SASI induced GW signal is sensitive to
- -the compactness of the core,
- -the equation of state,
- -the rotation rate.

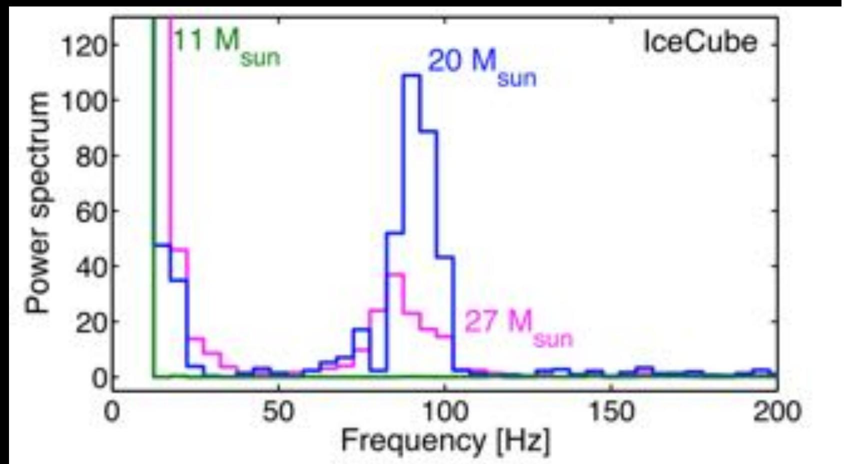
detection by LIGO, KAGRA for a non rotating galactic supernova at 10kpc:

g-mode activity with S/N=10
SASI activity with S/N~50

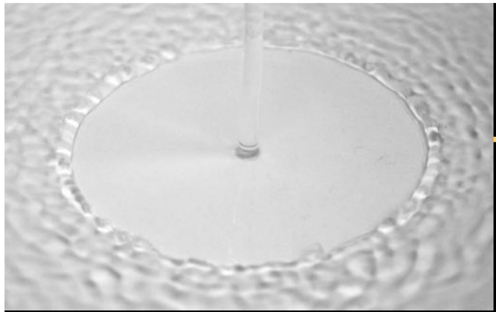
combination with neutrino detection

Kuroda+16





A: NS g-mode oscillations (600-700Hz)
B: SASI activity (100-200Hz)



Conclusion

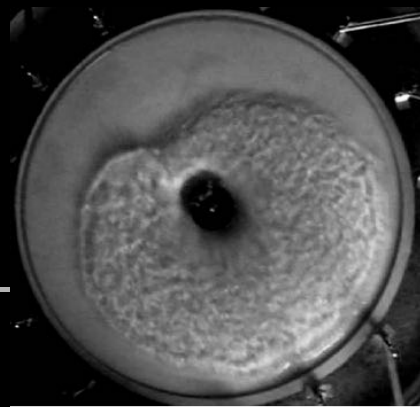
Massive stars end their life when their iron core is too massive. Its collapse leads to the birth of a neutron star or a black hole, and the ejection of their envelope visible as a supernova

Numerical models indicate that hydrodynamical instabilities break the spherical symmetry: these motions generate gravitational waves and neutrinos which detection can be direct signatures of the explosion mechanism

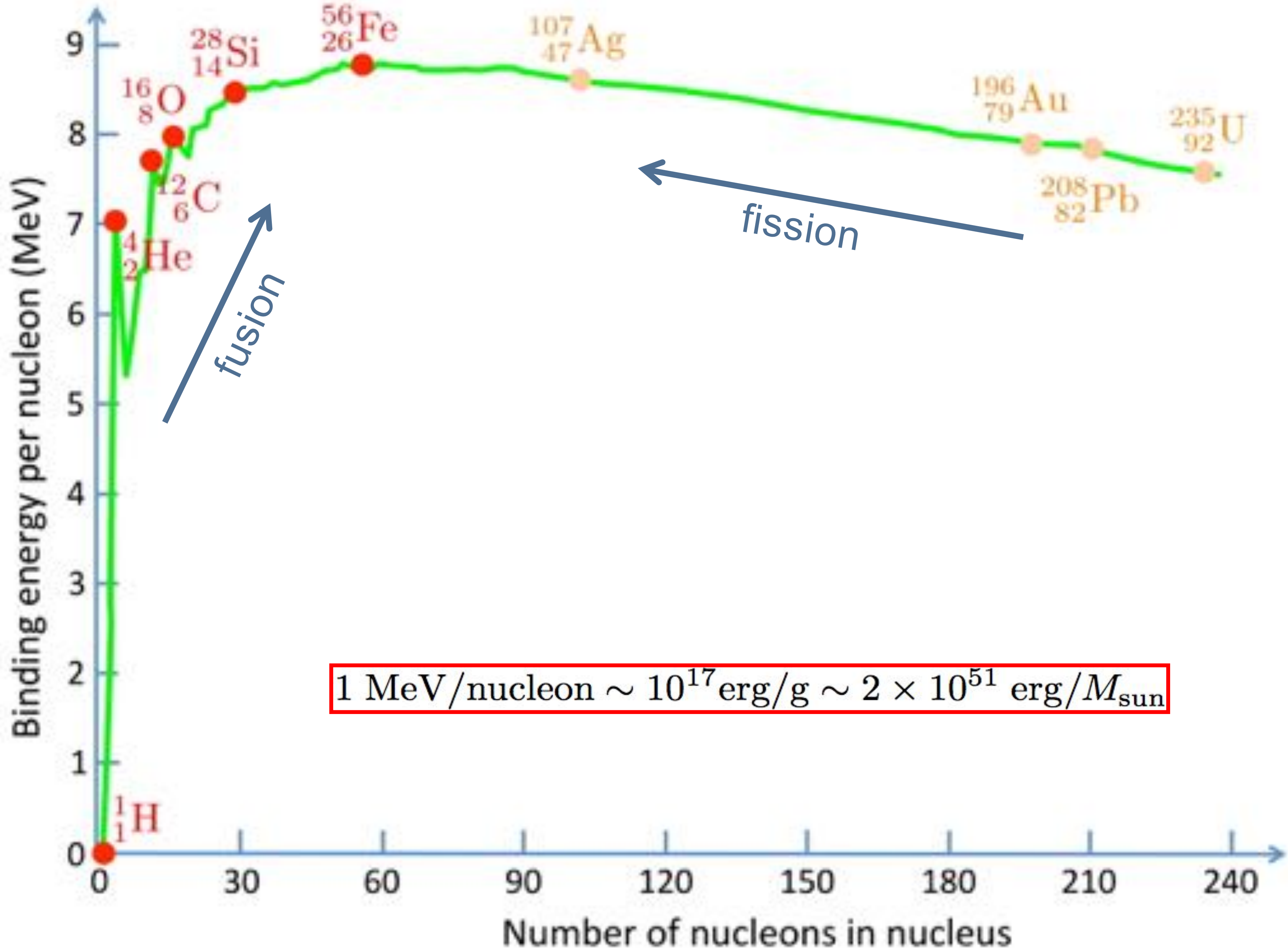
The supernova fountain uses accessible timescales and lengthscales to illustrate extreme astrophysical processes

The dynamics of the fountain suggests that

1/ neutron stars can be kicked at birth
2/ neutron stars can be spun up at birth
3/ transverse motions are favorable to neutrino capture and explosion



Nuclear binding energy



$1\ \mathrm{MeV/nucleon} \sim 10^{17}\mathrm{erg/g} \sim 2\times10^{51}\ \mathrm{erg}/M_{\mathrm{sun}}$

(protons+neutrons)