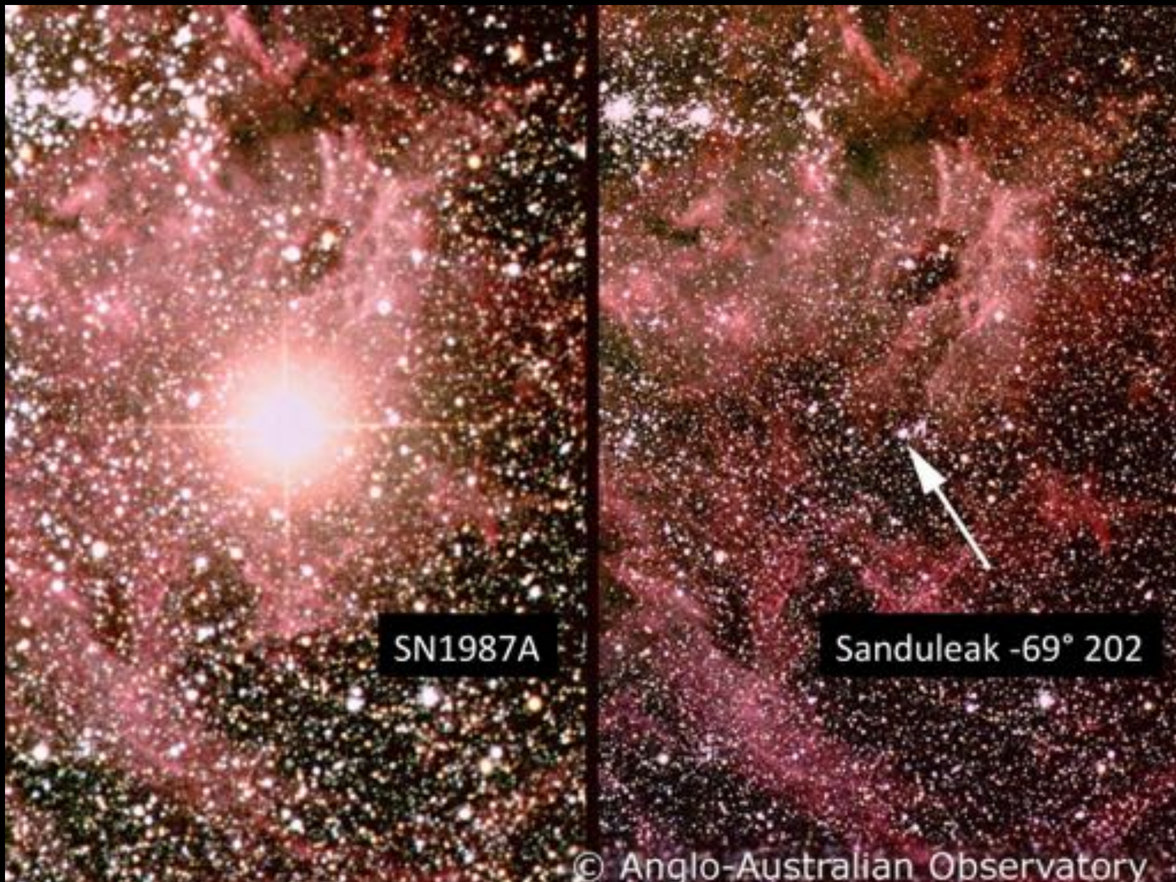
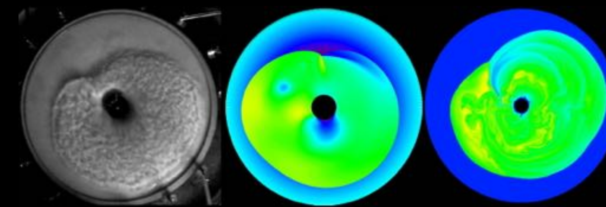




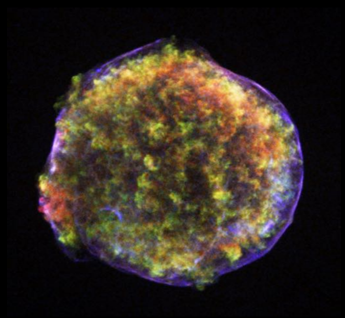
From simple fluid dynamics to the asymmetric character of supernova explosions

Thierry Foglizzo

CEA Saclay

Supernovae types

SN 1006

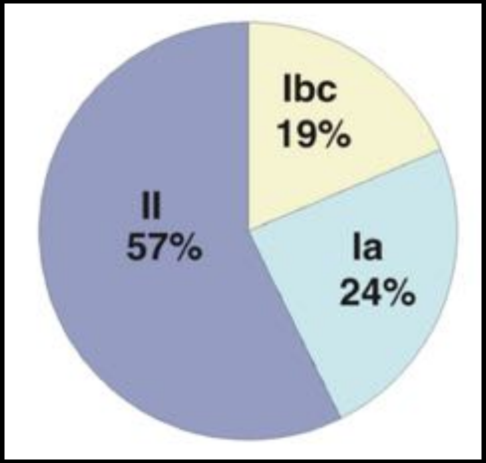


Tycho (1572)

Kepler (1604)

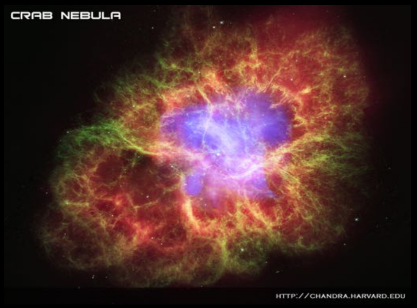
thermonuclear
supernovae
Ia

gravitational
supernovae
II, Ibc



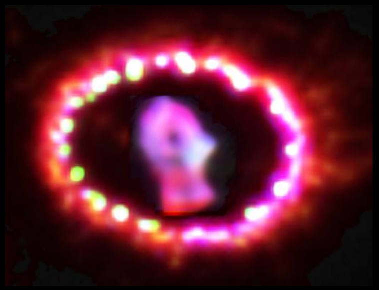
Volume distribution

(Li+11)



Crab (1054)

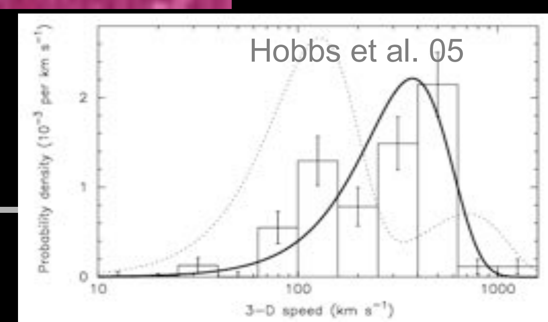
Cassiopeia A (~1680)



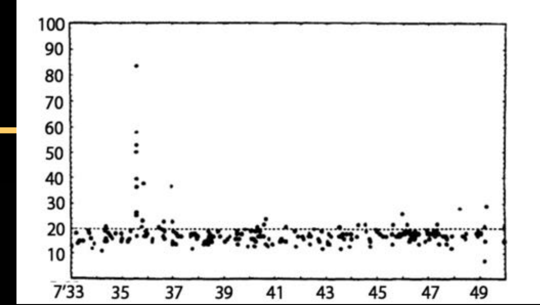
SN1987A

The high velocities of neutron stars suggest an asymetric supernova explosion

pulsar in the guitar nebula: 1600km/s

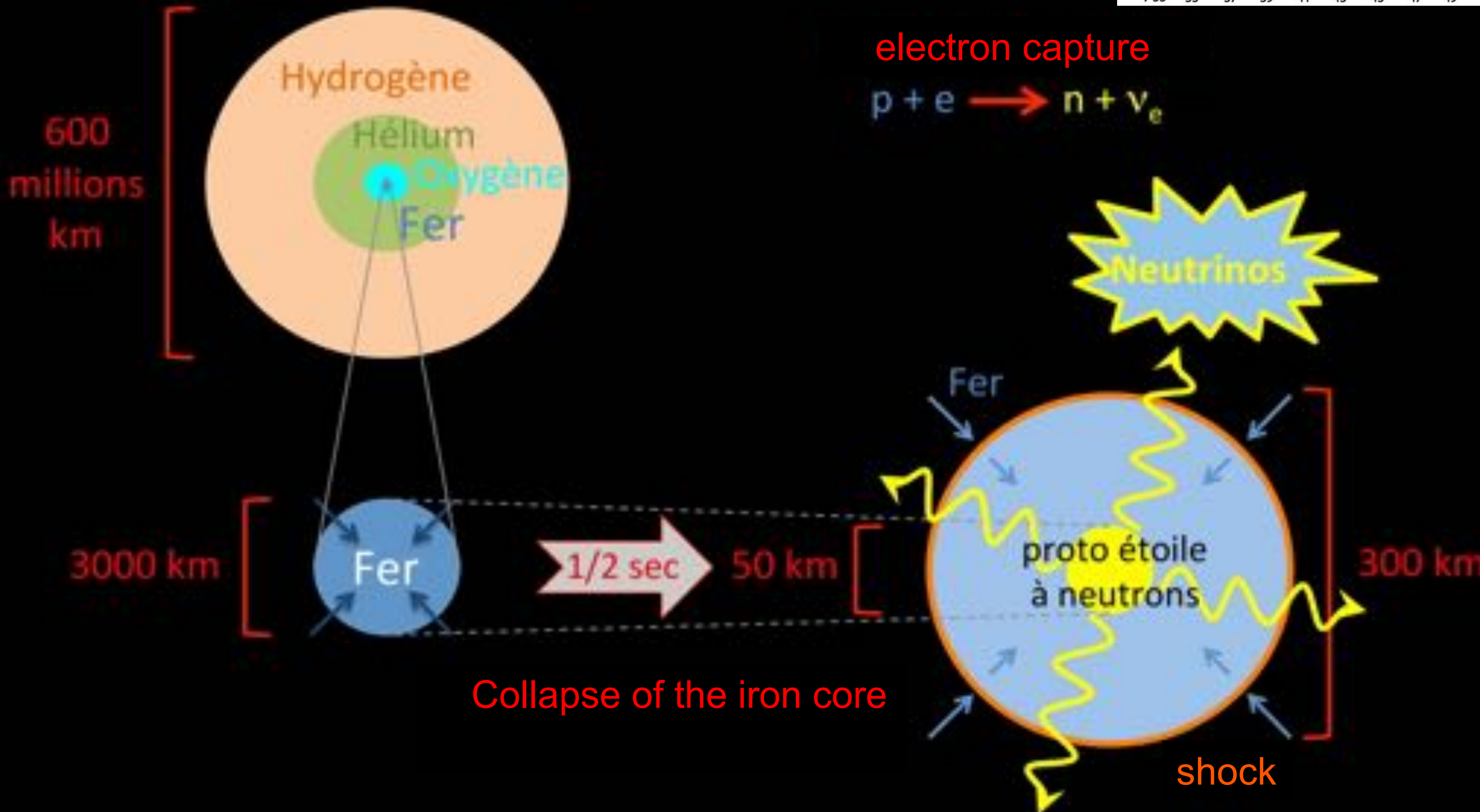


Massive star $15M_{sol}$



electron capture

$p + e \rightarrow n + \nu_e$



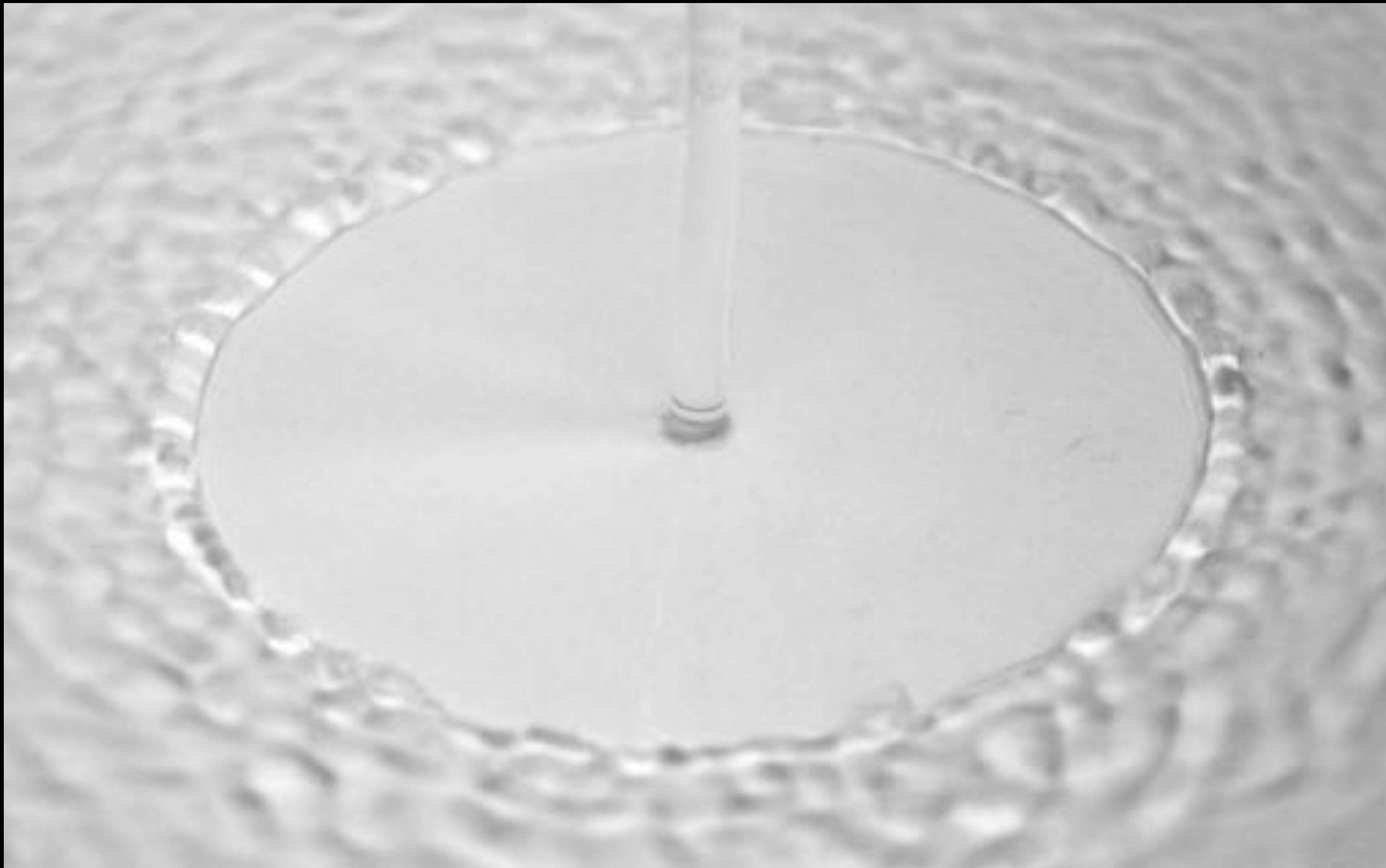
Collapse of the iron core

shock

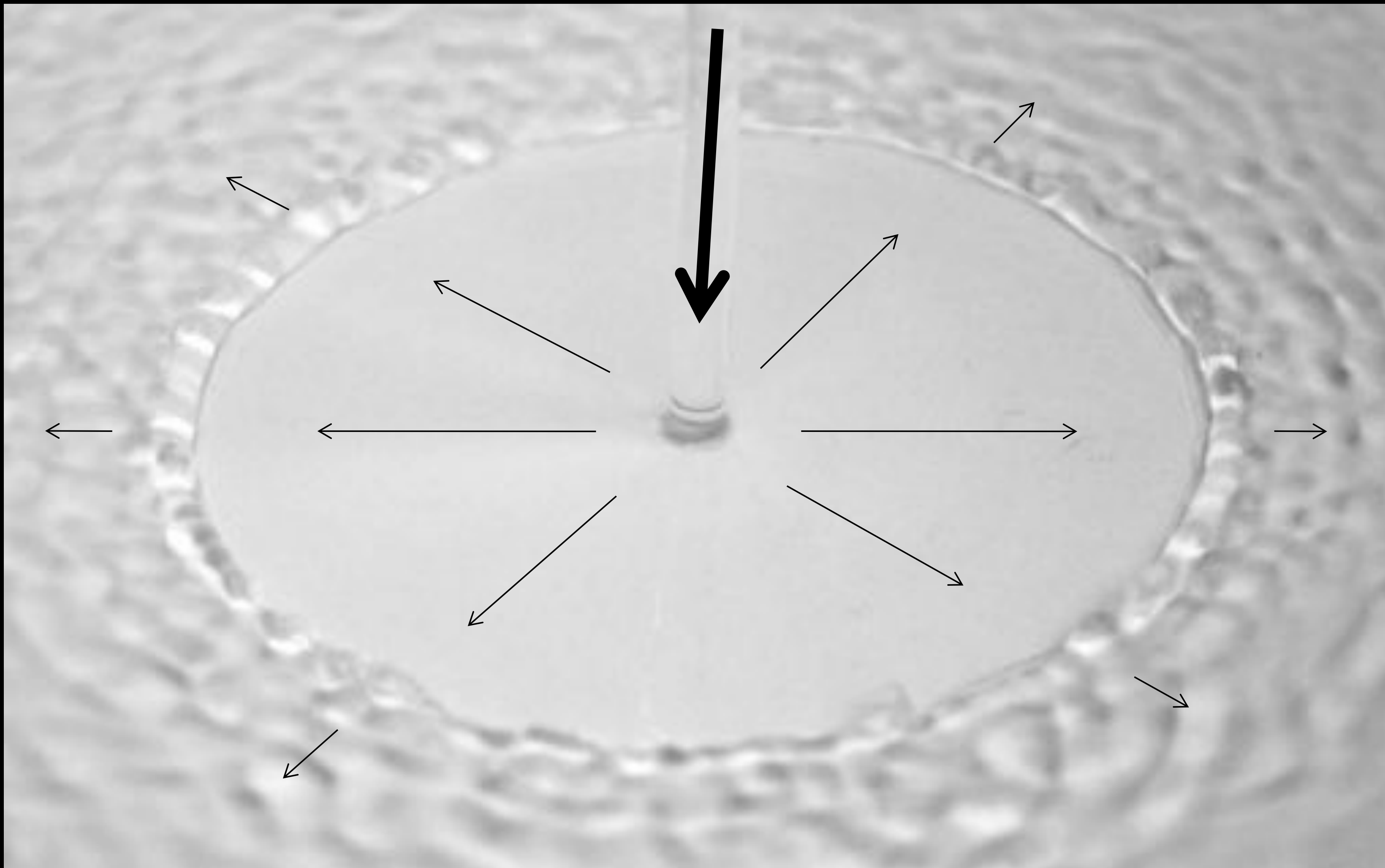
27M_{sol} stellar core collapse in 3D

Hanke et al. 13

Hydraulic jumps and shock waves

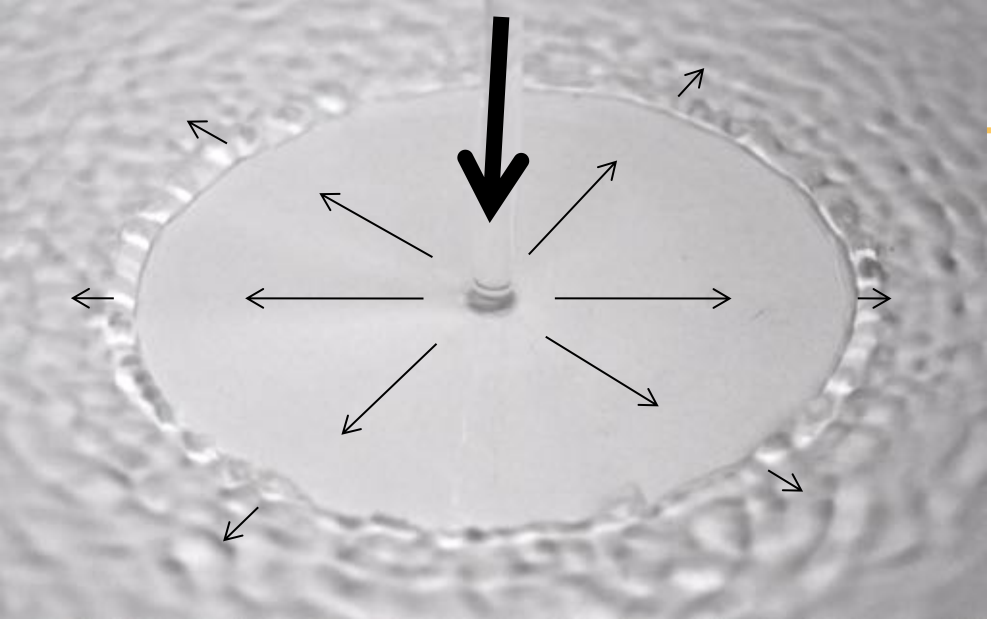


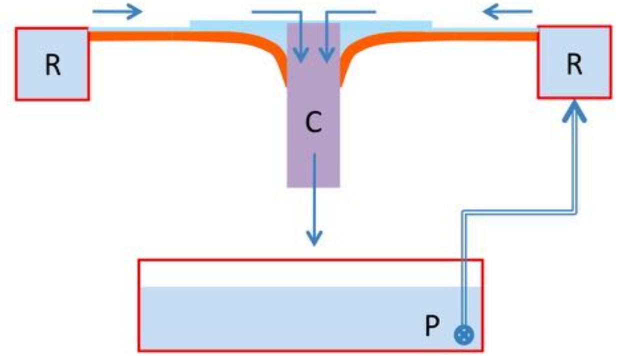
Hydraulic jumps and shock waves

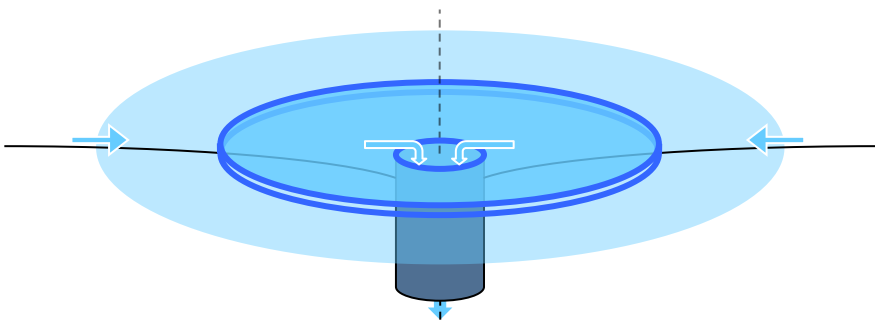


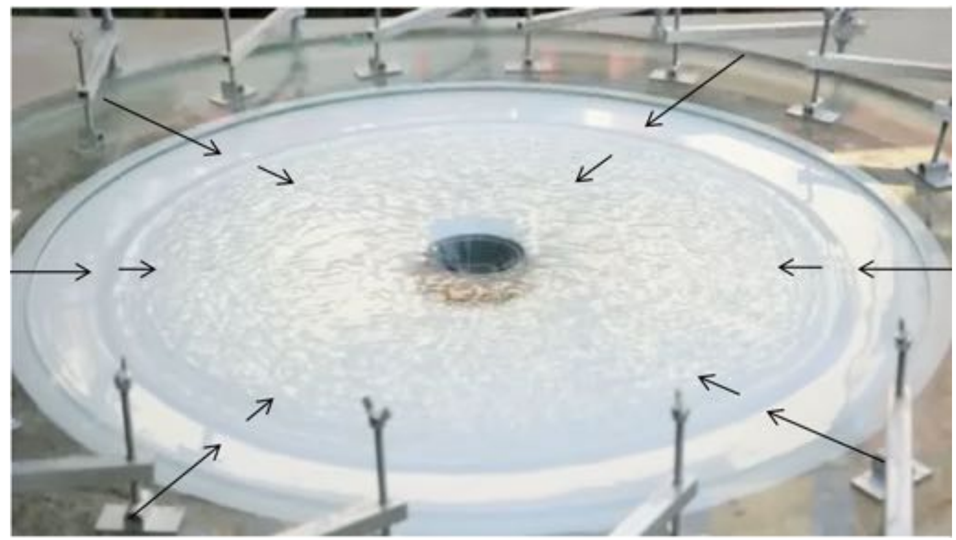
SWASI: an experimental analogue of SASI

Shallow Water Analogue of a Shock Instability

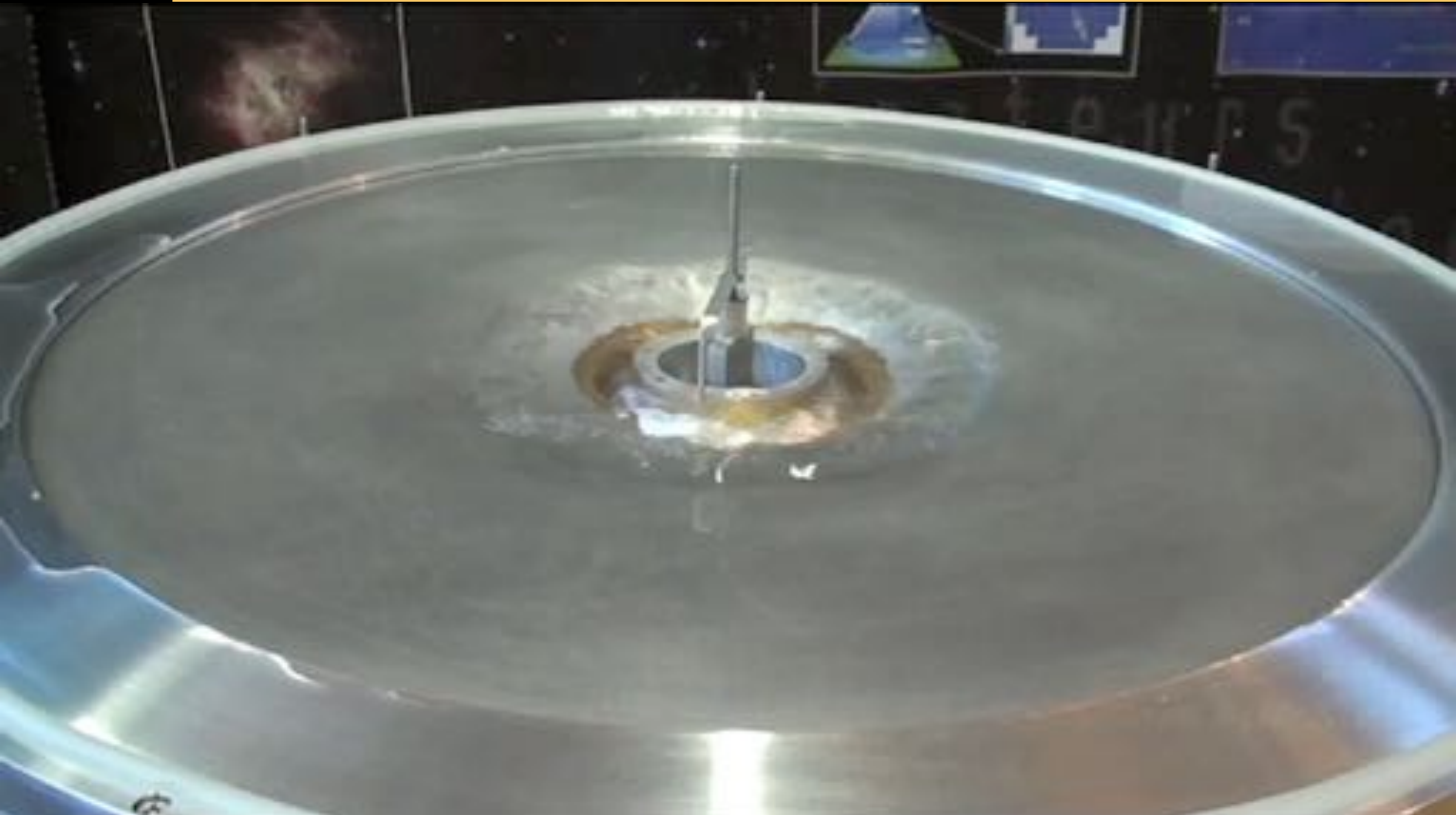




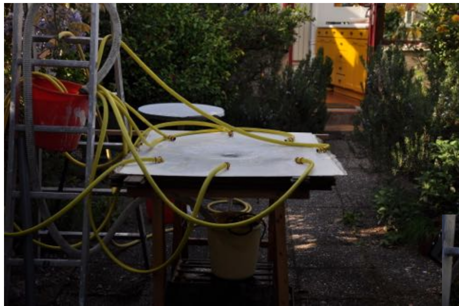




acoustic waves shock wave pressure	↔	surface waves hydraulic jump depth



SWASI: simple as a garden experiment

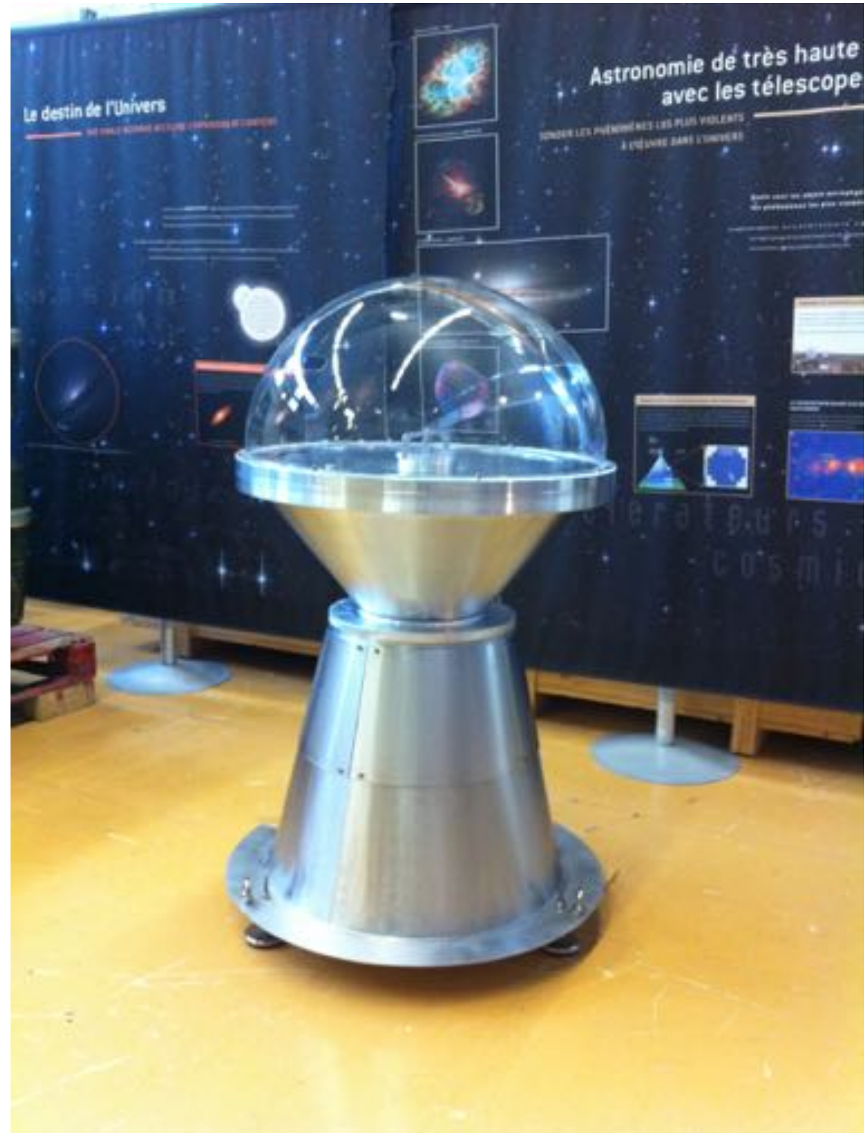


May 2010

June 2010

October 2010

November 2010

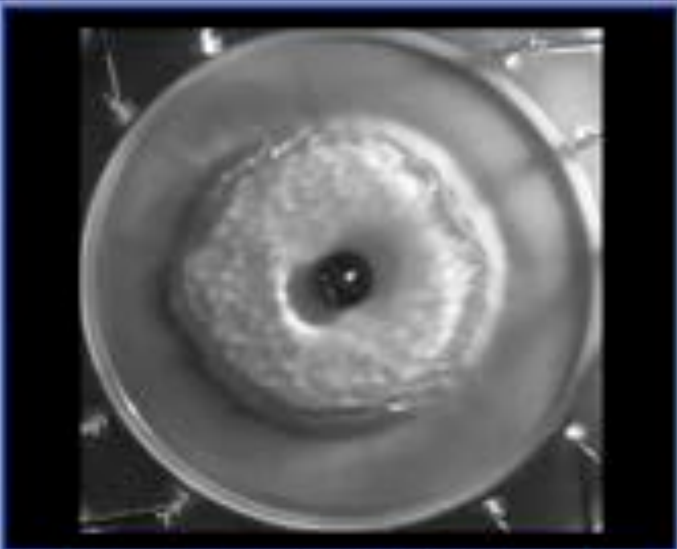


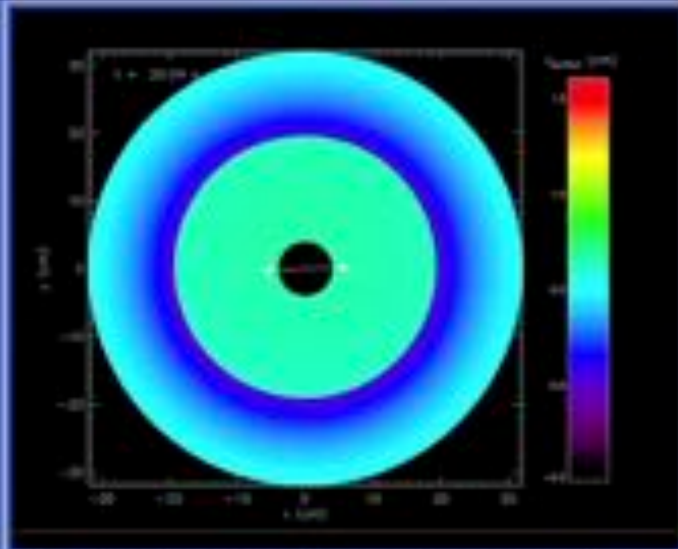
CEA Saclay November 2013

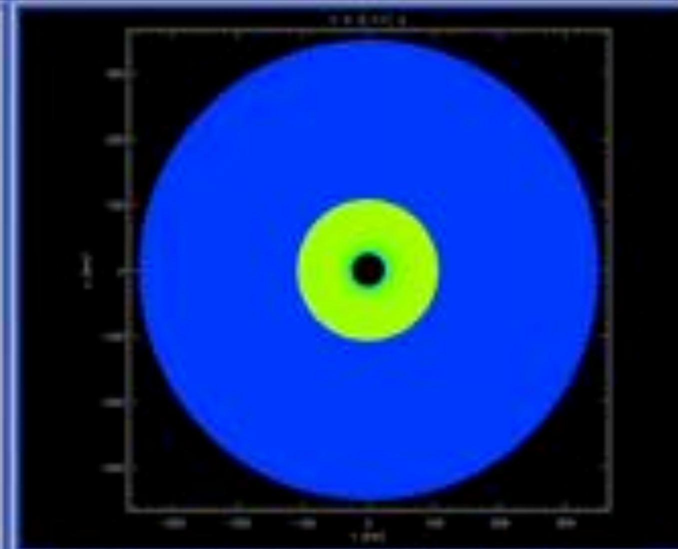
Dynamics of water
in the fountain

Dynamics of the gas
in the supernova core

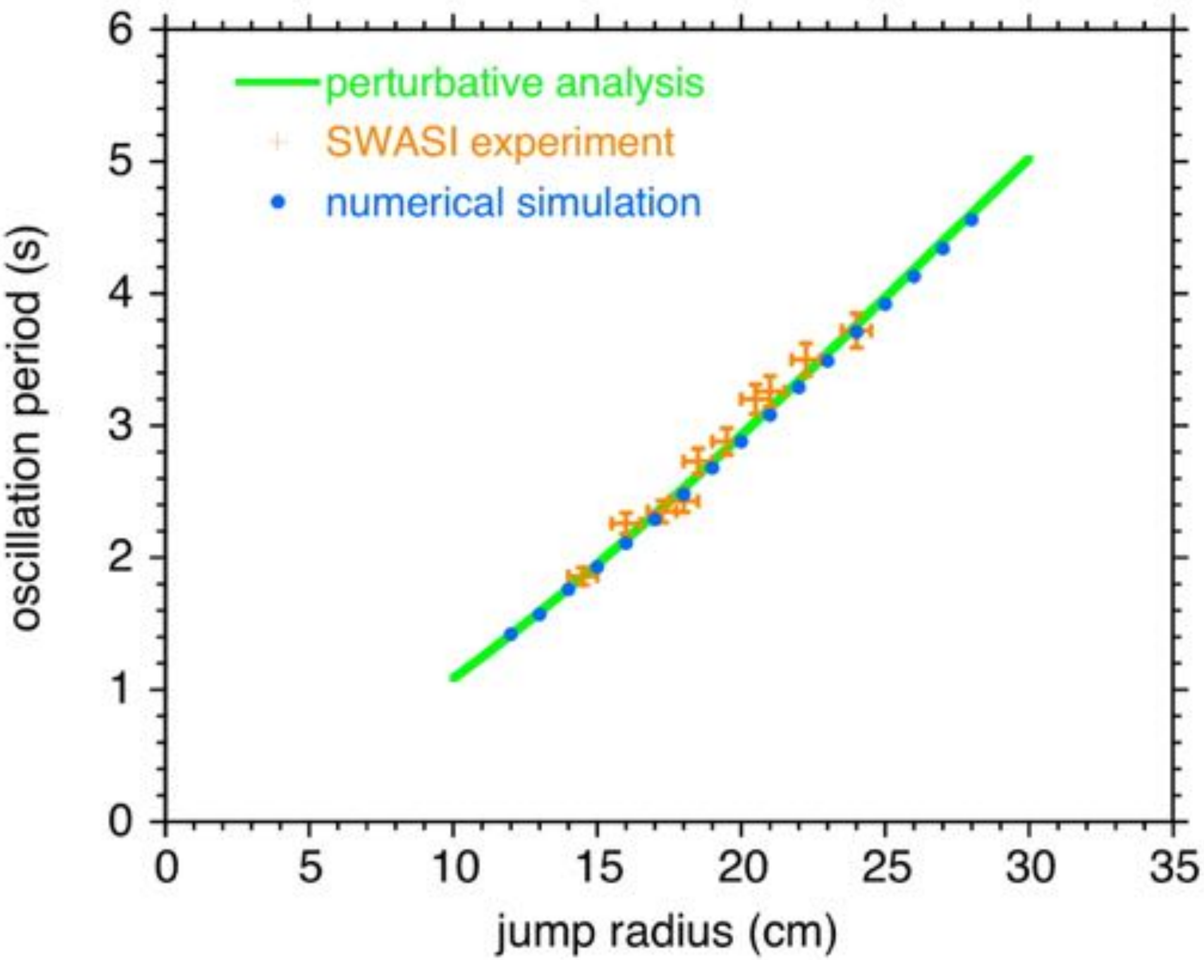
diameter 40cm ← 1 000 000 x bigger → diameter 400km
3s/oscillation ← 100 x faster → 0.03s/oscillation


Expérience hydraulique


Simulation numérique de l'expérience hydraulique


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

Comparaison to a 2D shallow water model



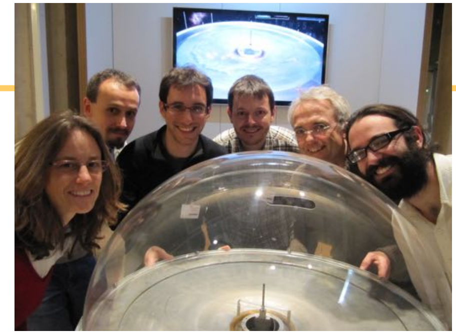
Foglizzo, Masset, Guilet, Durand
PRL (2012)

The “supernova fountain” in Paris science museum “Palais de la Découverte”

17 December 2013-16 February 2014

PRIX 2014
LE GOÛT DES SCIENCES

12 astrophysicists
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

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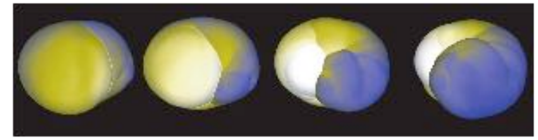
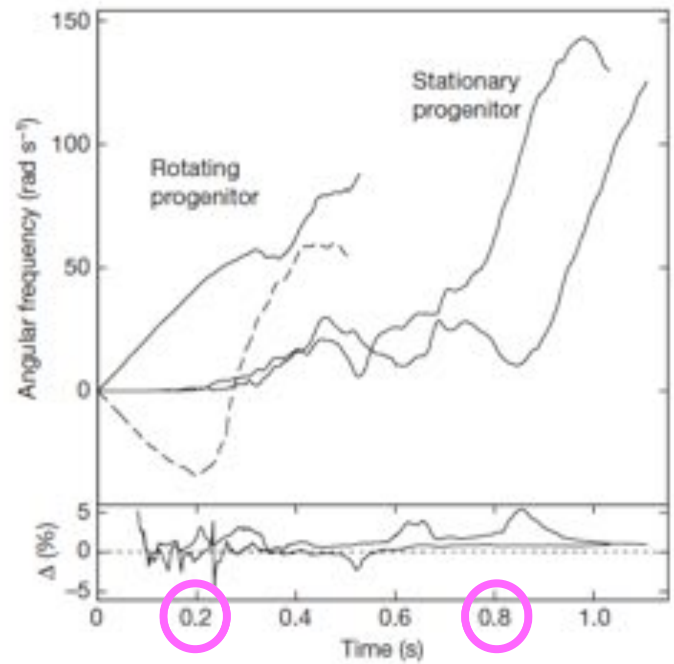
l'Observatoire de Paris – LUTH
Laboratoire Univers et Théories
MAX-PLANCK-GESELLSCHAFT

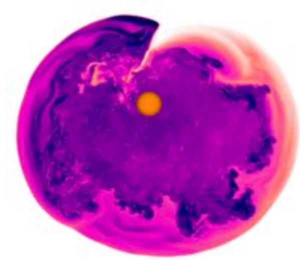
Rotating progenitor: redistribution of angular momentum by SASI





Blondin & Mezzacappa 07

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



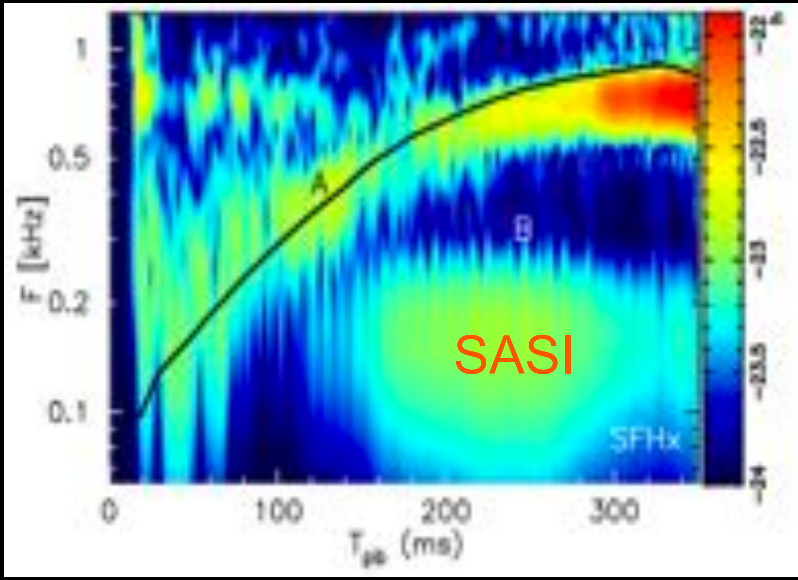
faster rotation : another instability

Towards higher Reynolds numbers

-diameter 3m50: Reynolds x 15
-overspilling injection
-angular momentum

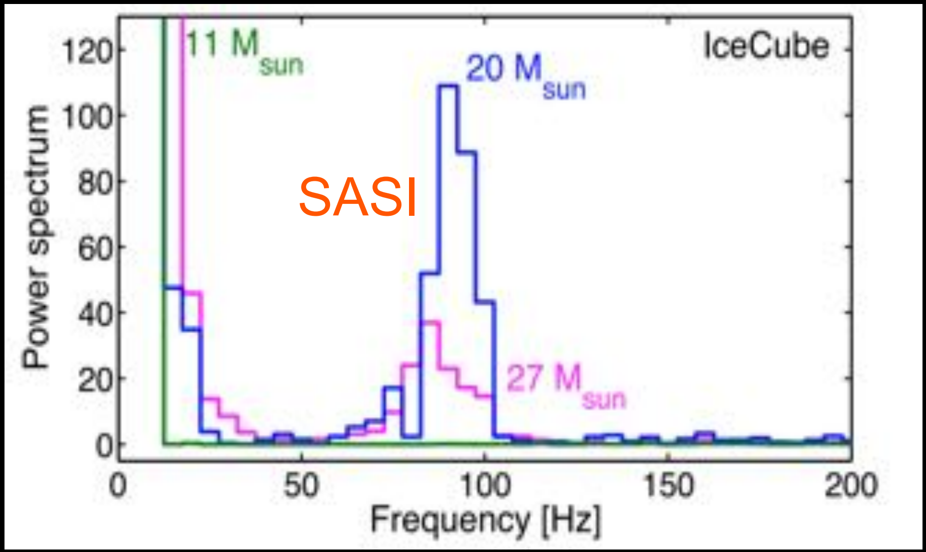
SASI oscillations can leave a direct imprint on the gravitational wave and neutrino signals

Gravitational Waves



Kuroda+16

Oscillations of the neutrino flux

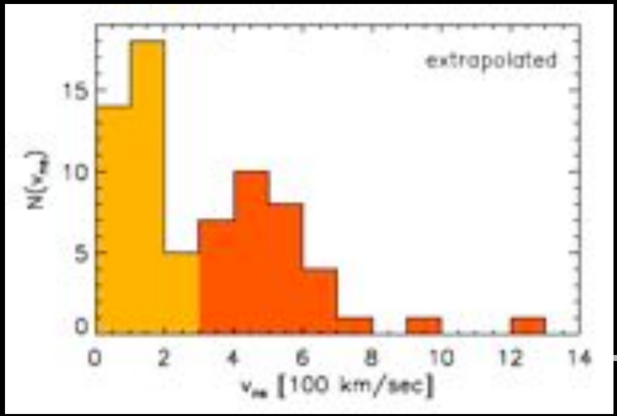


Tamborra+13

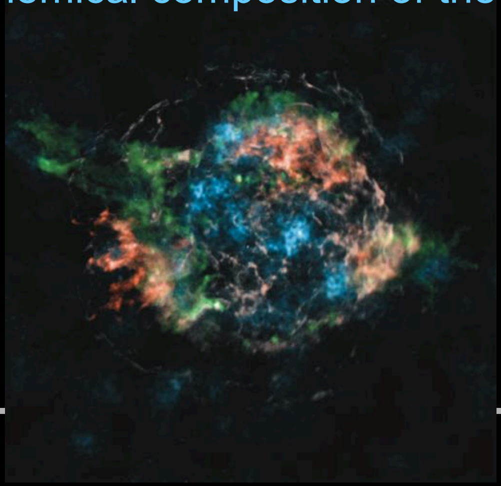
Indirect information can be learnt from

-the kick, spin of the compact object

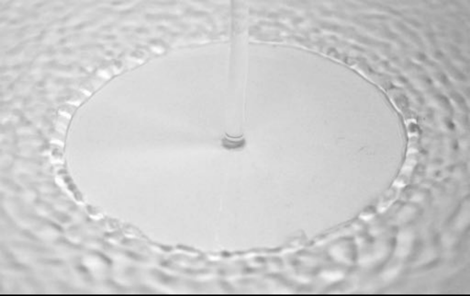
-the chemical composition of the remnant



Scheck+06



Grefenstette+14



Conclusion

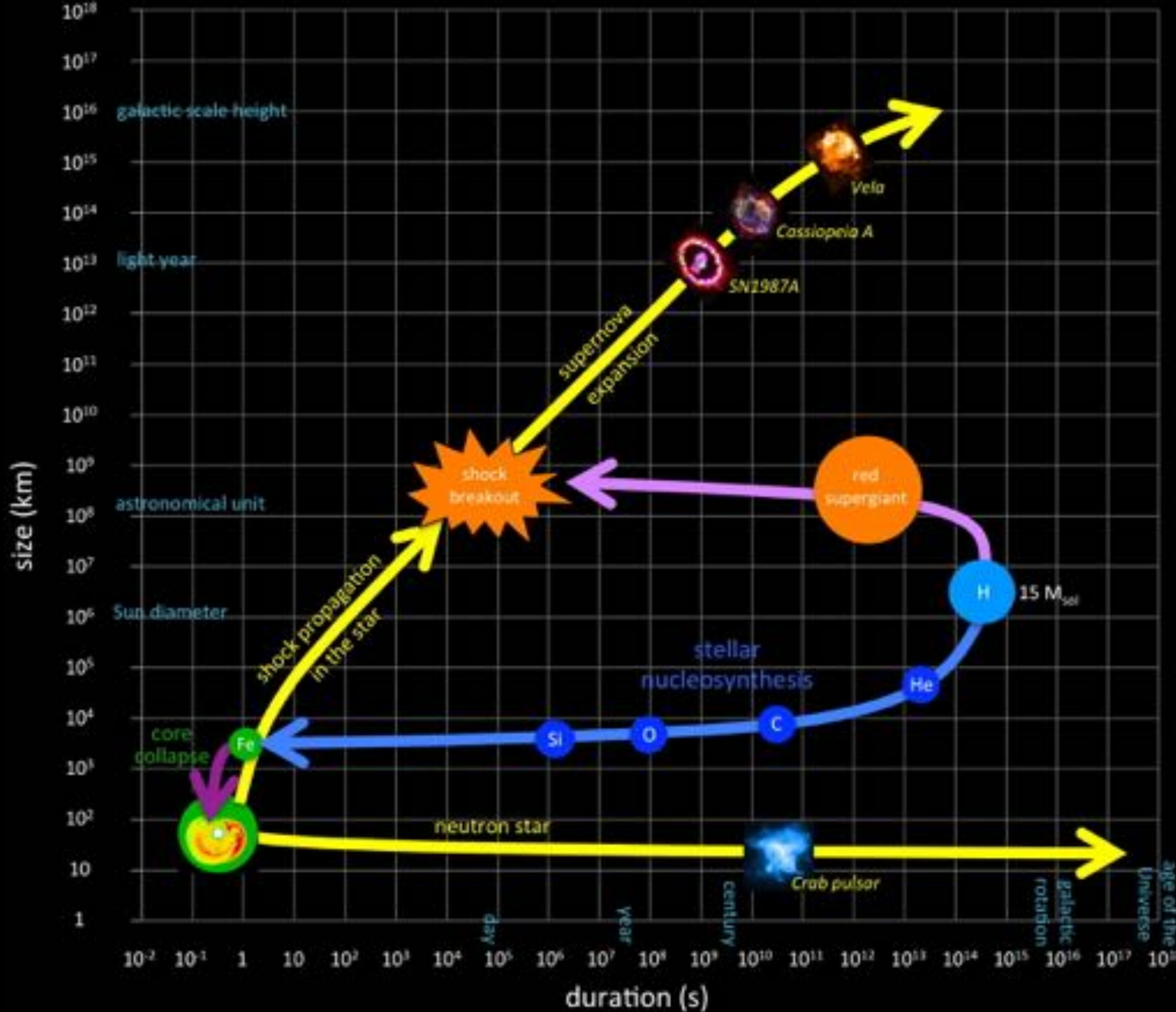
Massive stars end their life when their iron core is too massive. Its collapse leads to the birth of a neutron star or a black hole, and the ejection of their envelope visible as a supernova

Numerical models indicate that hydrodynamical instabilities break the spherical symmetry

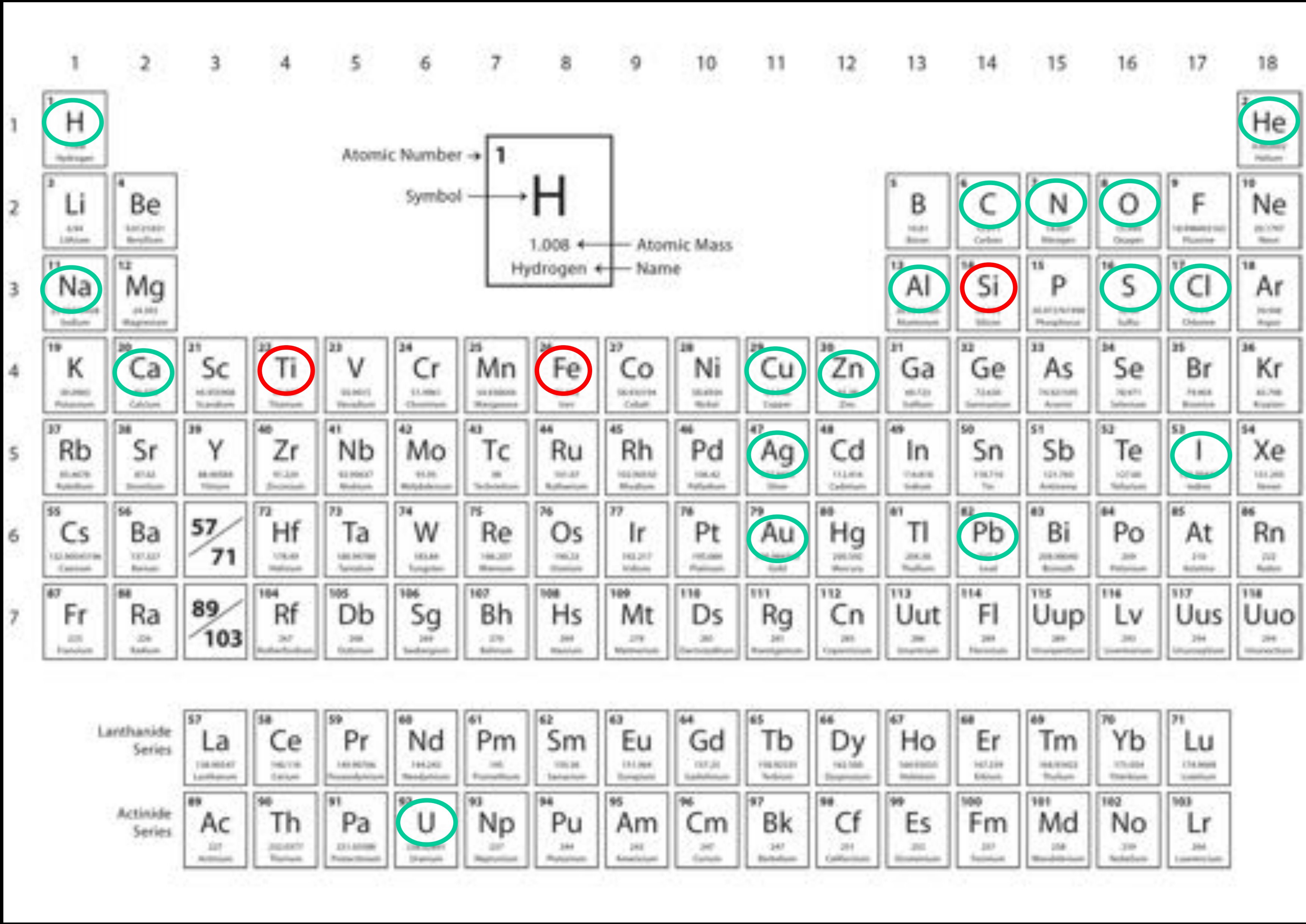
The supernova fountain uses accessible timescales and lengthscales to illustrate extreme astrophysical processes

The dynamics of the fountain suggests that

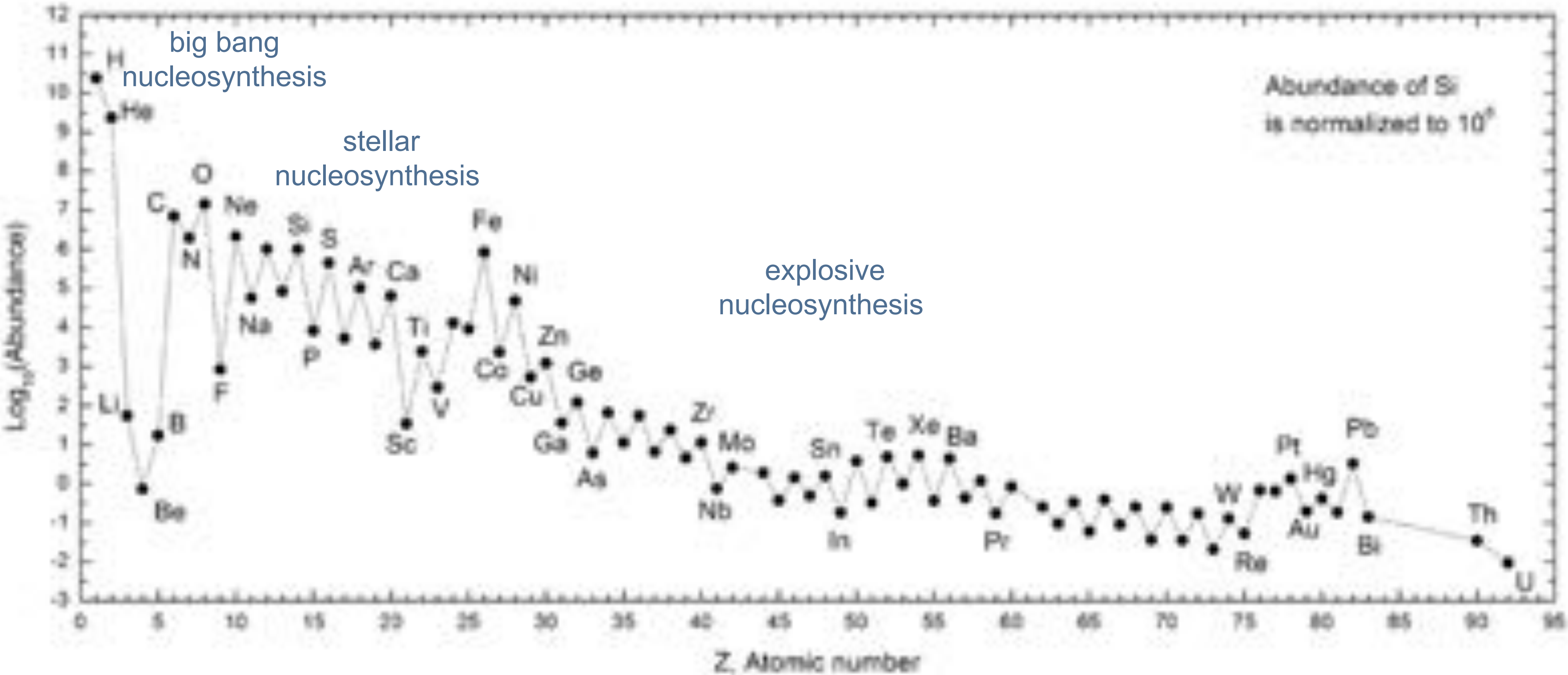
1/ neutron stars can be kicked at birth
2/ neutron stars can be spun up at birth
3/ transverse motions are favorable to neutrino capture and explosion
4/ direct information expected from gravitational waves and neutrinos
LIGO, VIRGO & KAGRA, Super Kamiokande & IceCube


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

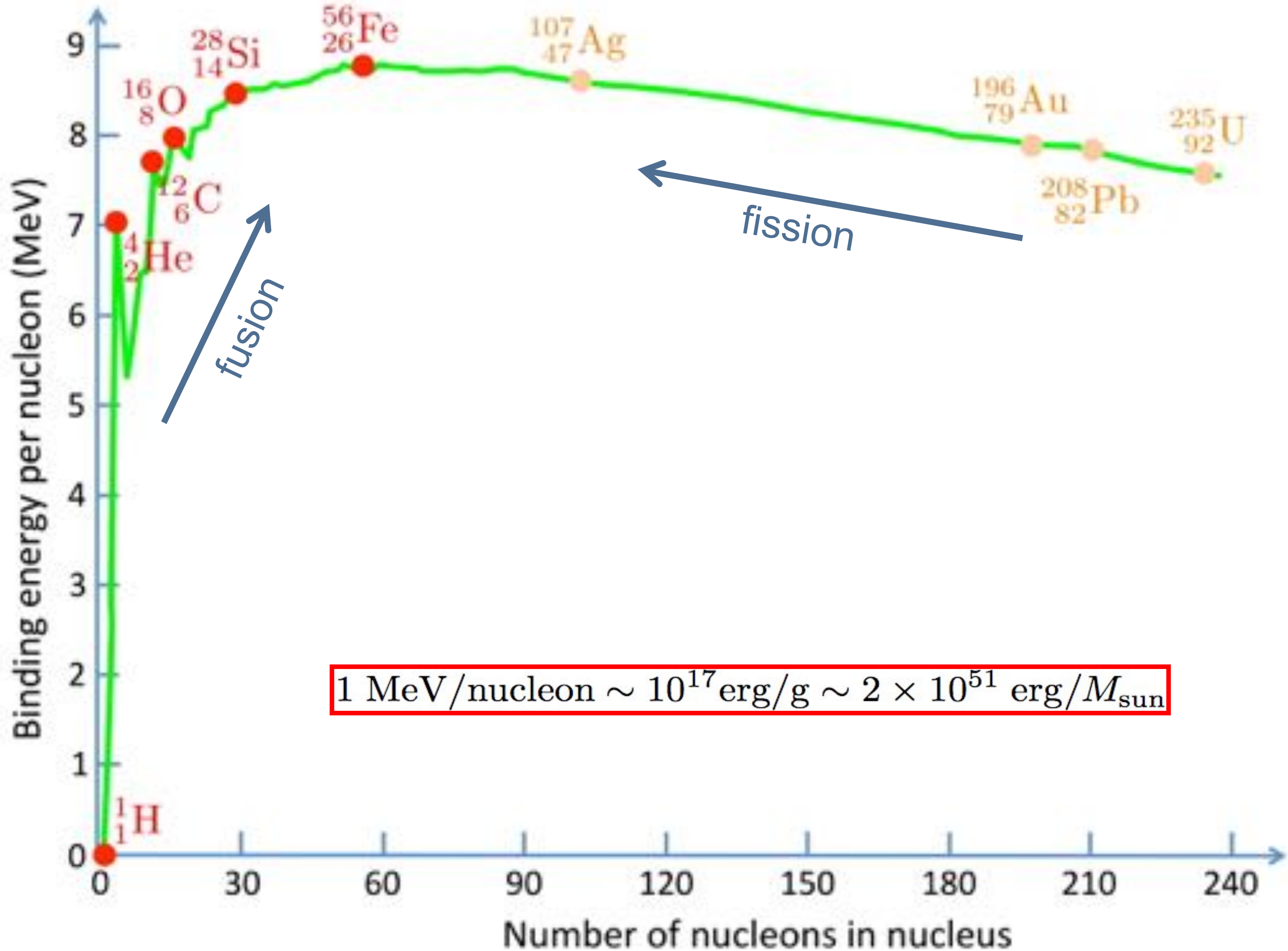
Classification of the elements



Abundances of elements
In the solar system



Nuclear binding energy



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

(protons+neutrons)