

From simple
fluid dynamics
to the asymmetric character of
supernova explosions



Thierry Foglizzo

CEA Saclay





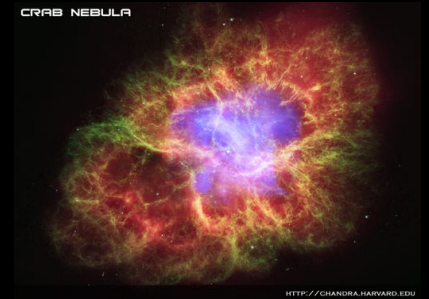
Supernovae types



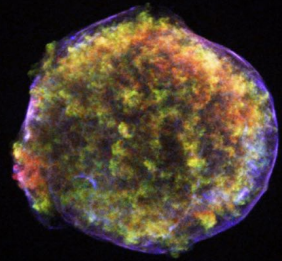
SN 1006

thermonuclear
supernovae
Ia

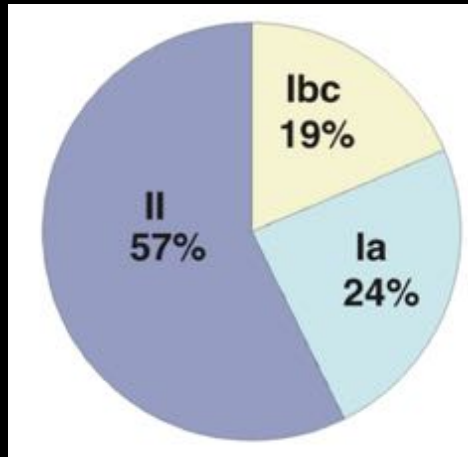
gravitational
supernovae
II, Ibc



Crab (1054)



Tycho (1572)



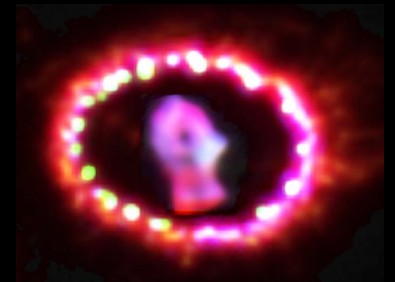
Volume distribution
(Li+11)



Cassiopeia A (~1680)



Kepler (1604)

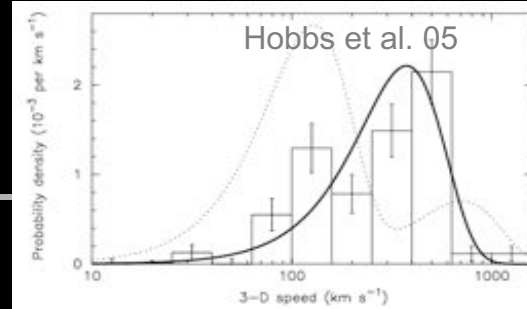


SN1987A

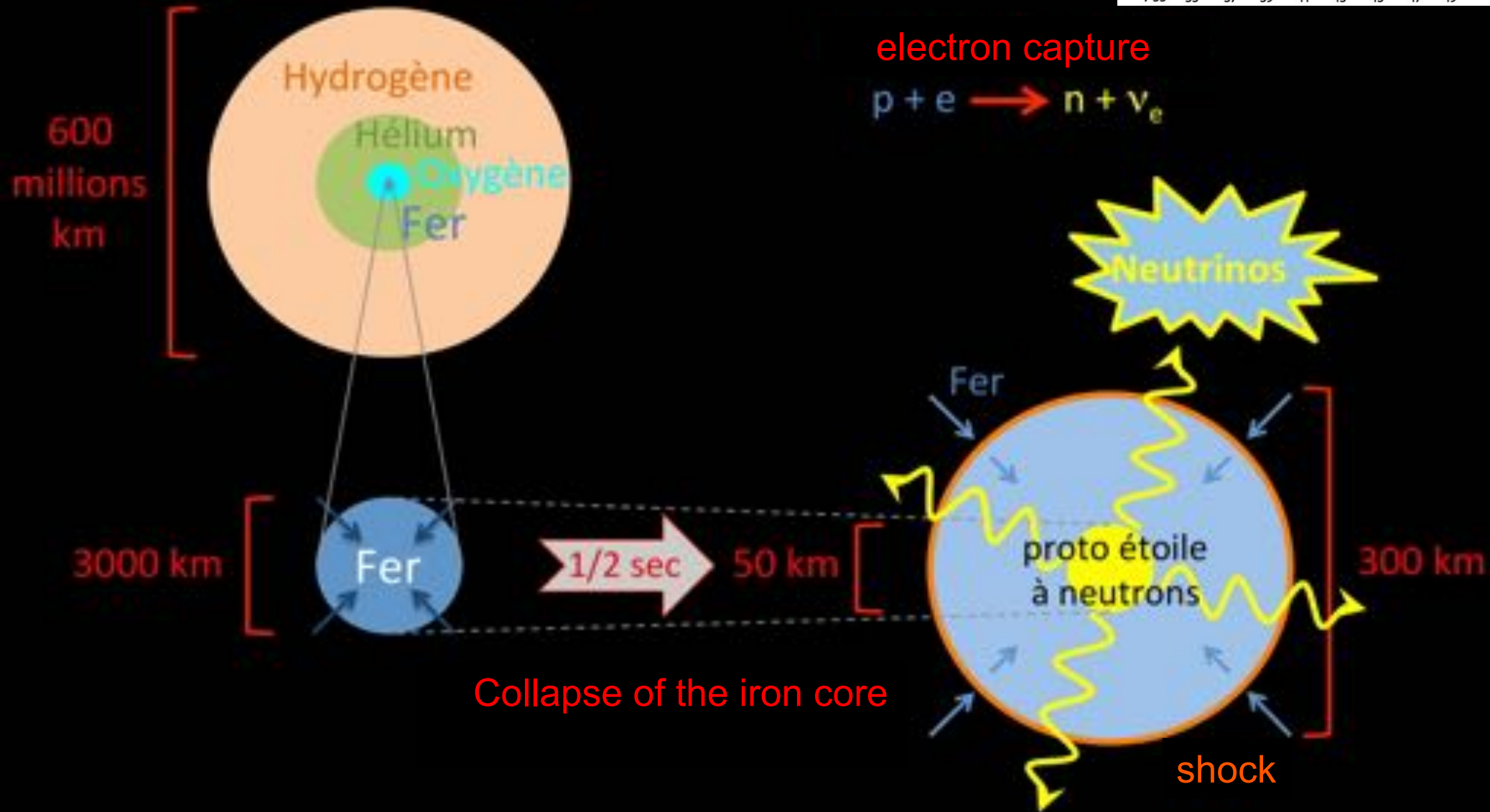
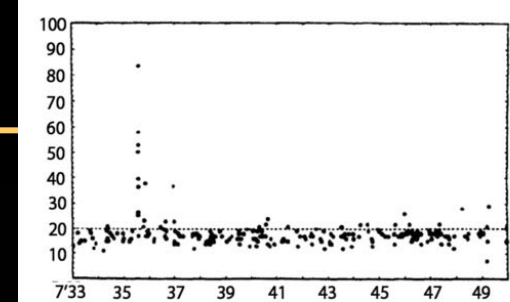
The high velocities of neutron stars suggest an asymmetric supernova explosion



pulsar in the guitar nebula: 1600km/s

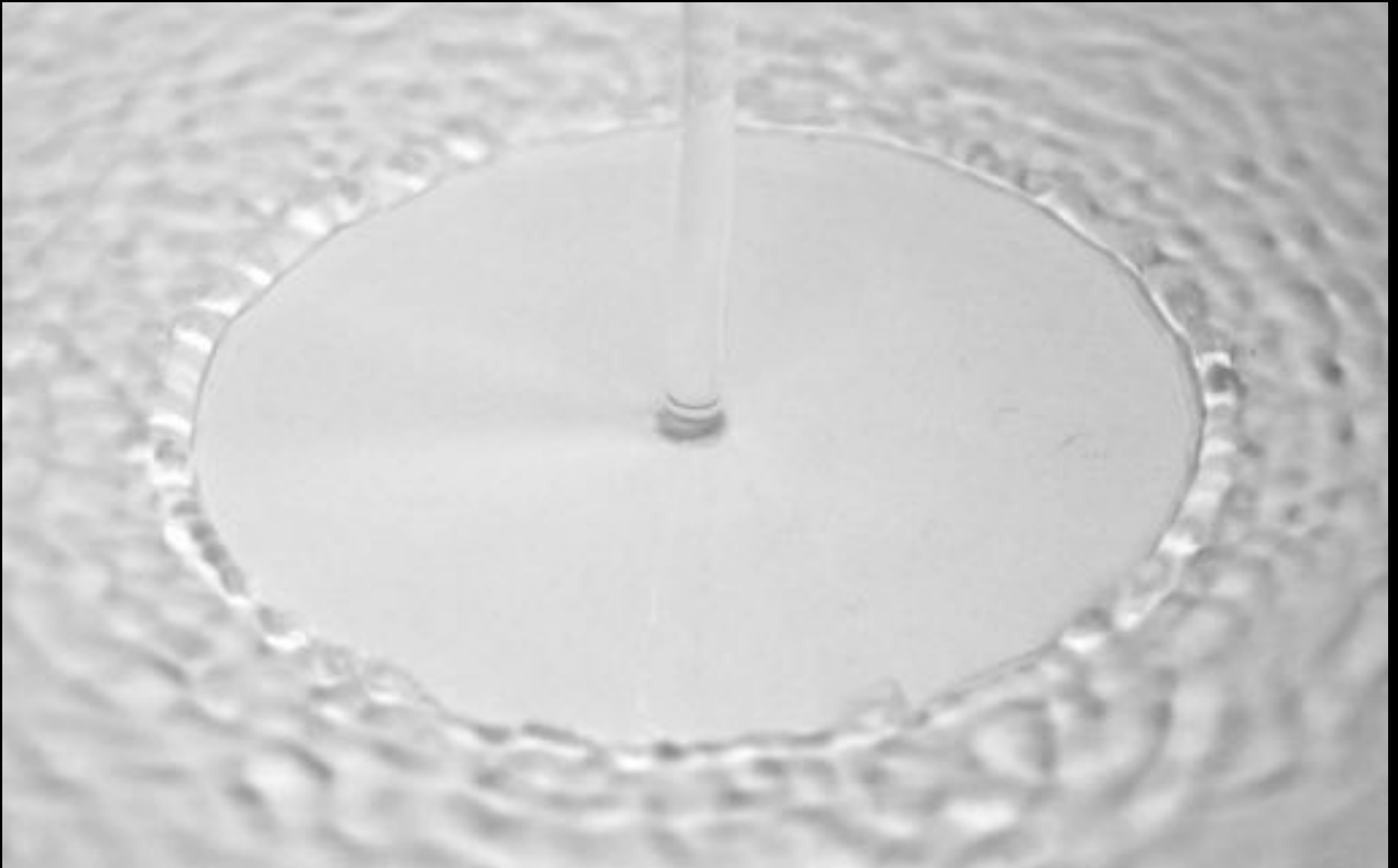


Massive star $15M_{\text{sol}}$

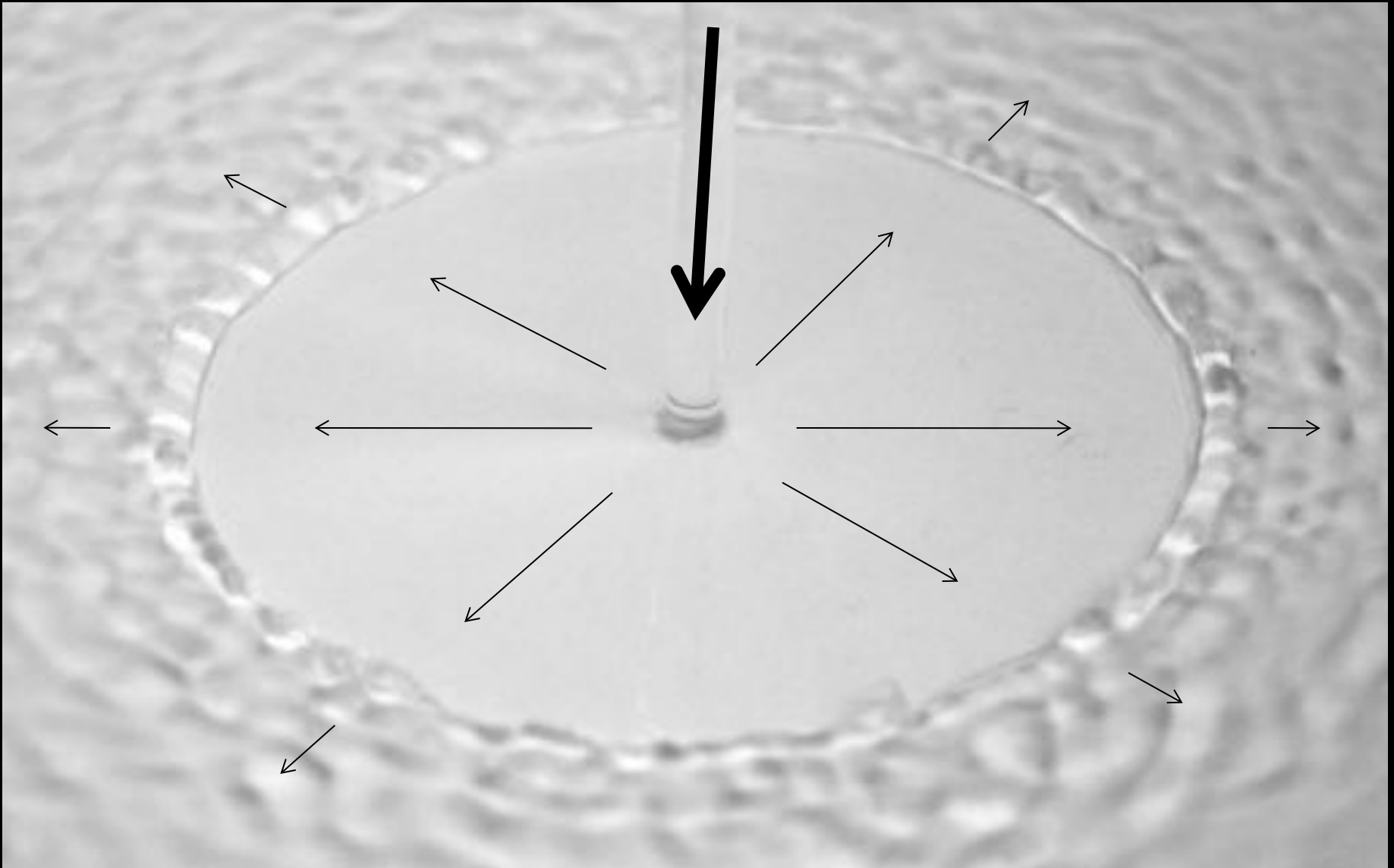


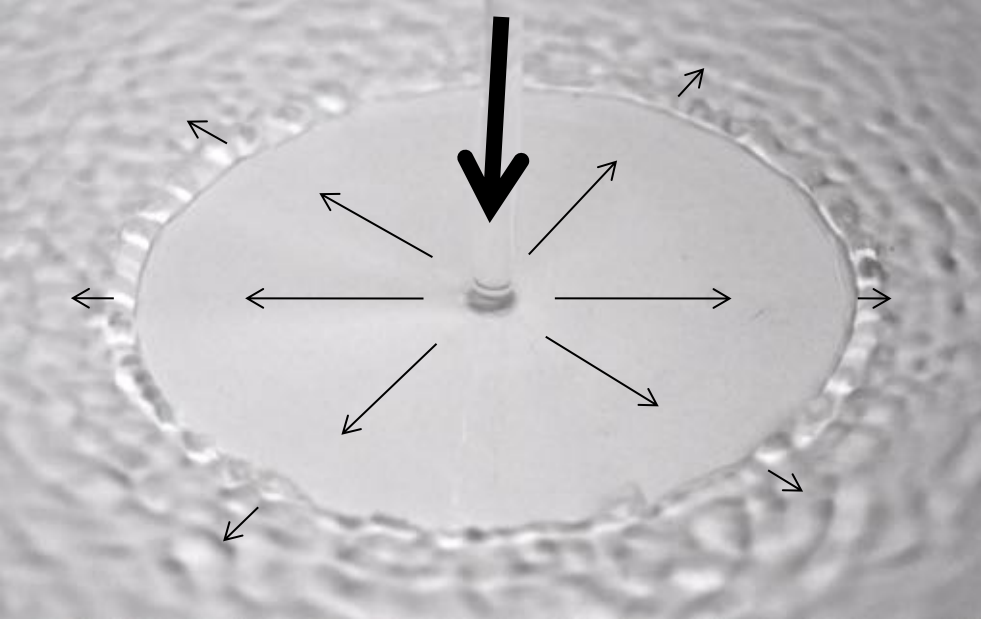


Hydraulic jumps and shock waves



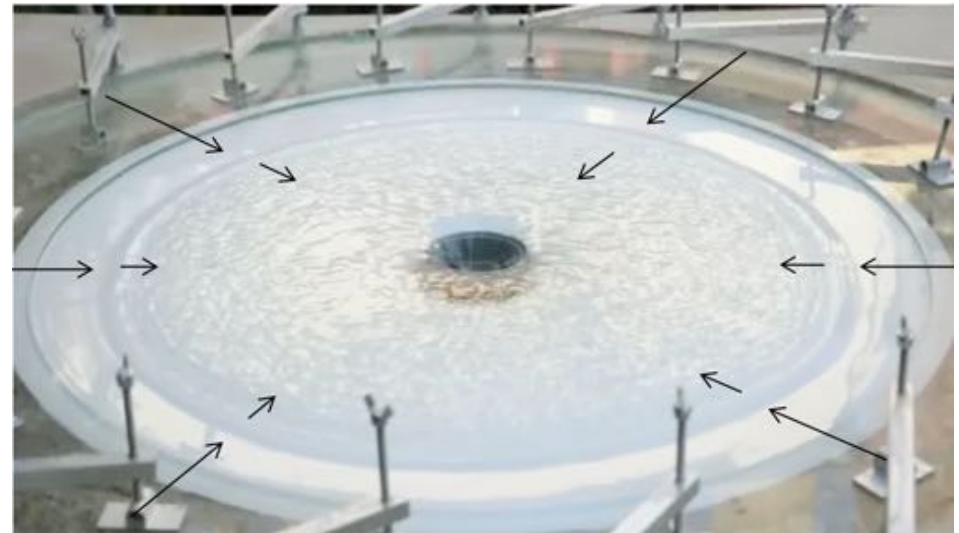
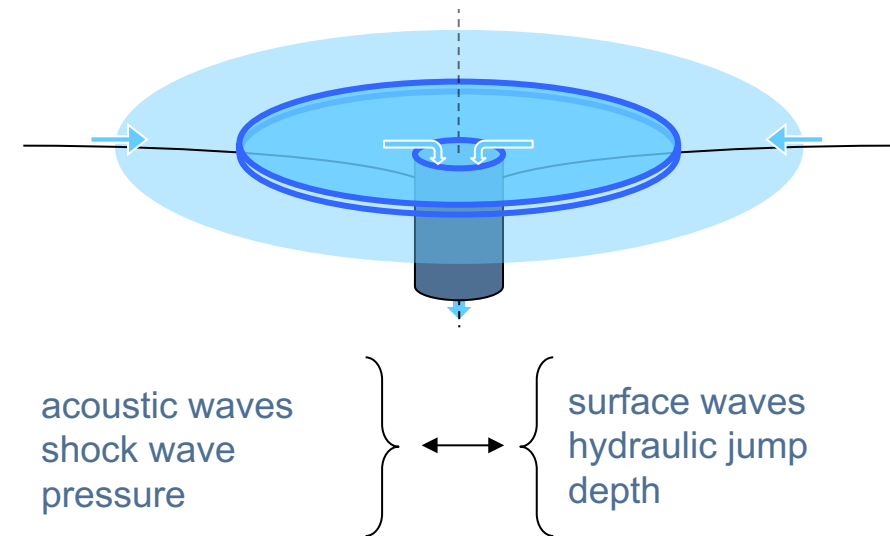
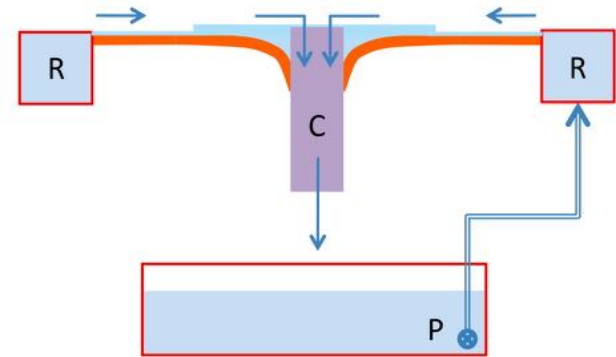
Hydraulic jumps and shock waves

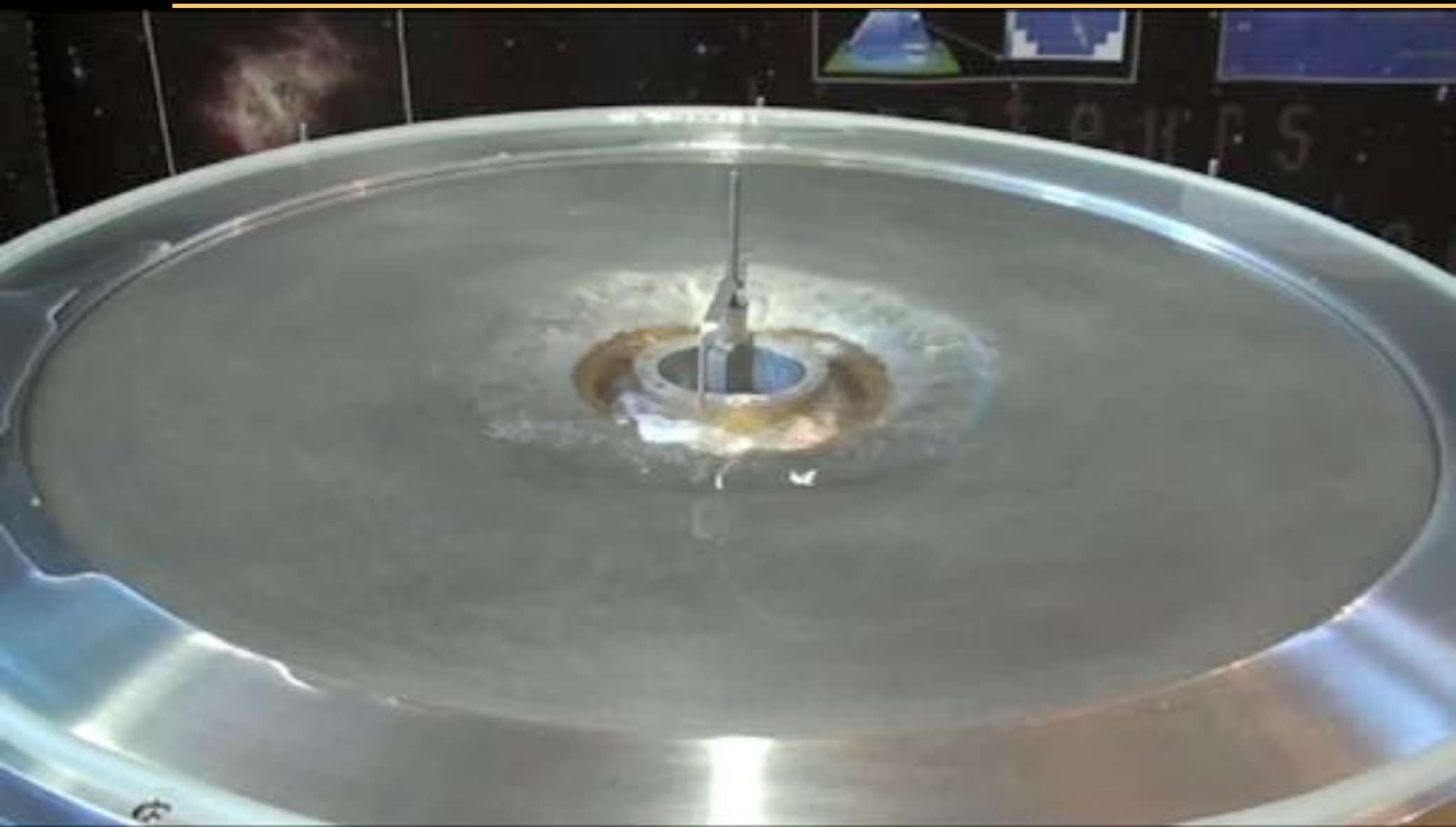




SWASI: an experimental analogue of SASI

Shallow Water Analogue of a Shock Instability





SWASI: simple as a garden experiment



May 2010



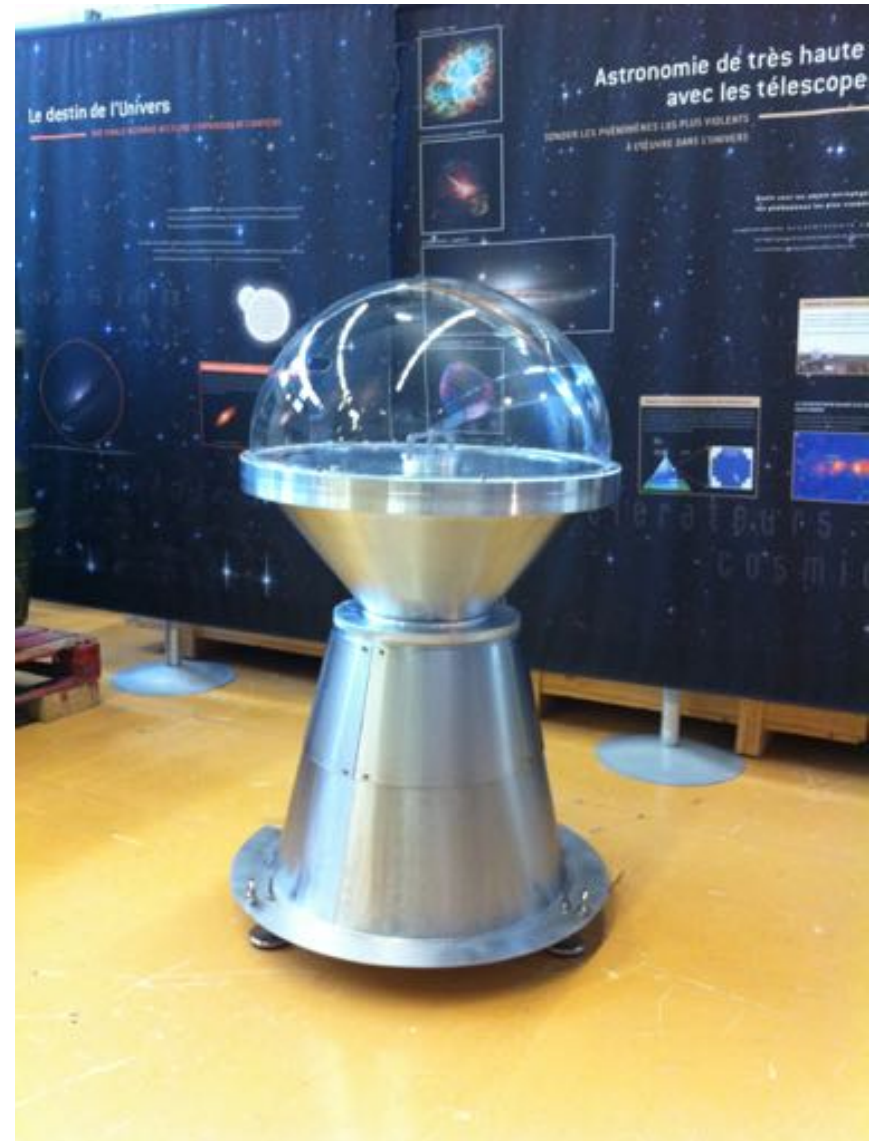
June 2010



October 2010



November 2010

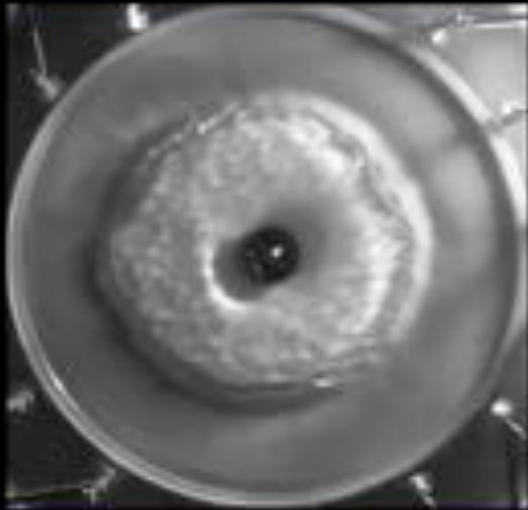


CEA Saclay November 2013

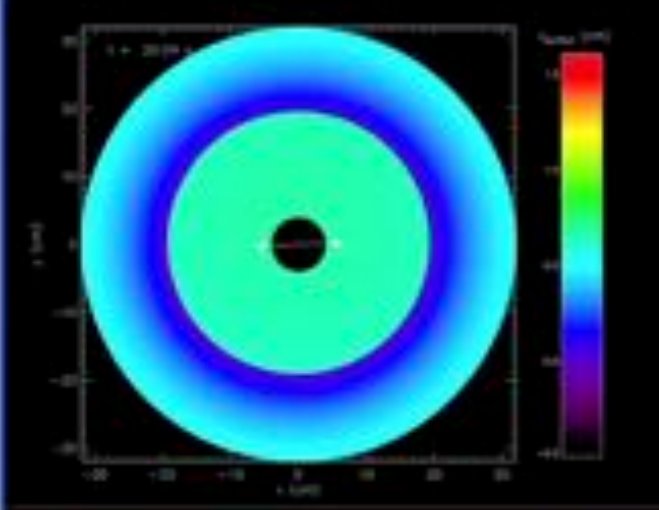
Dynamics of water in the fountain

Dynamics of the gas in the supernova core

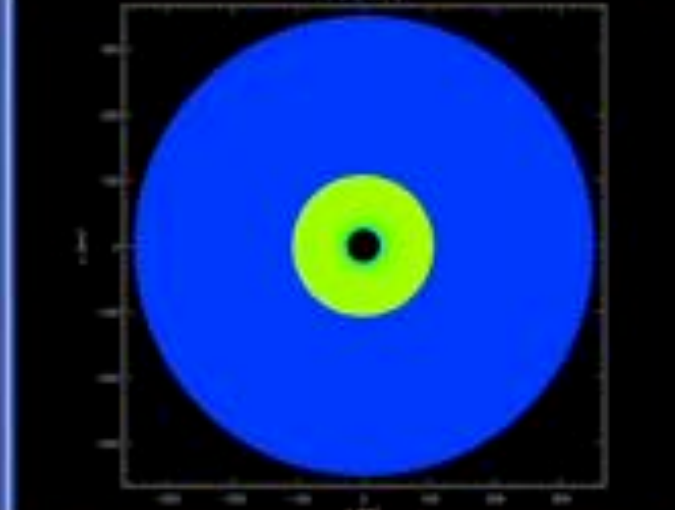
diameter 40cm ← 1 000 000 x bigger → diameter 400km
3s/oscillation ← 100 x faster → 0.03s/oscillation



Expérience hydraulique

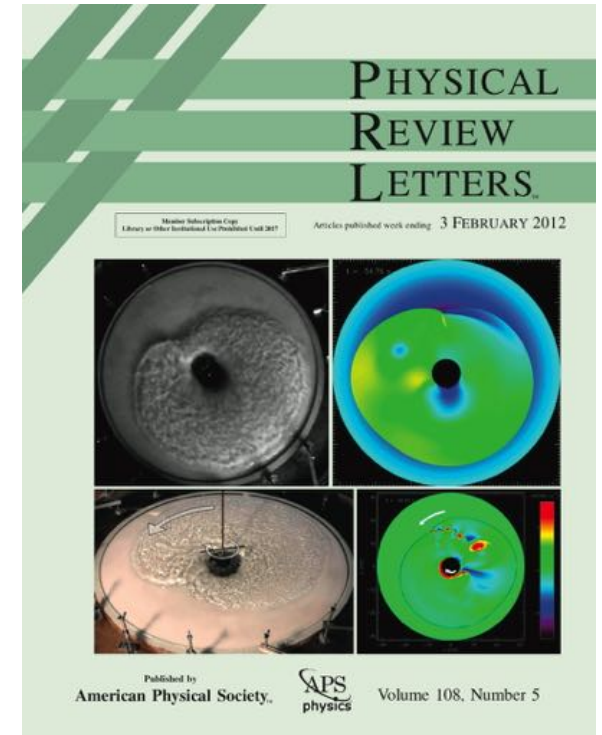
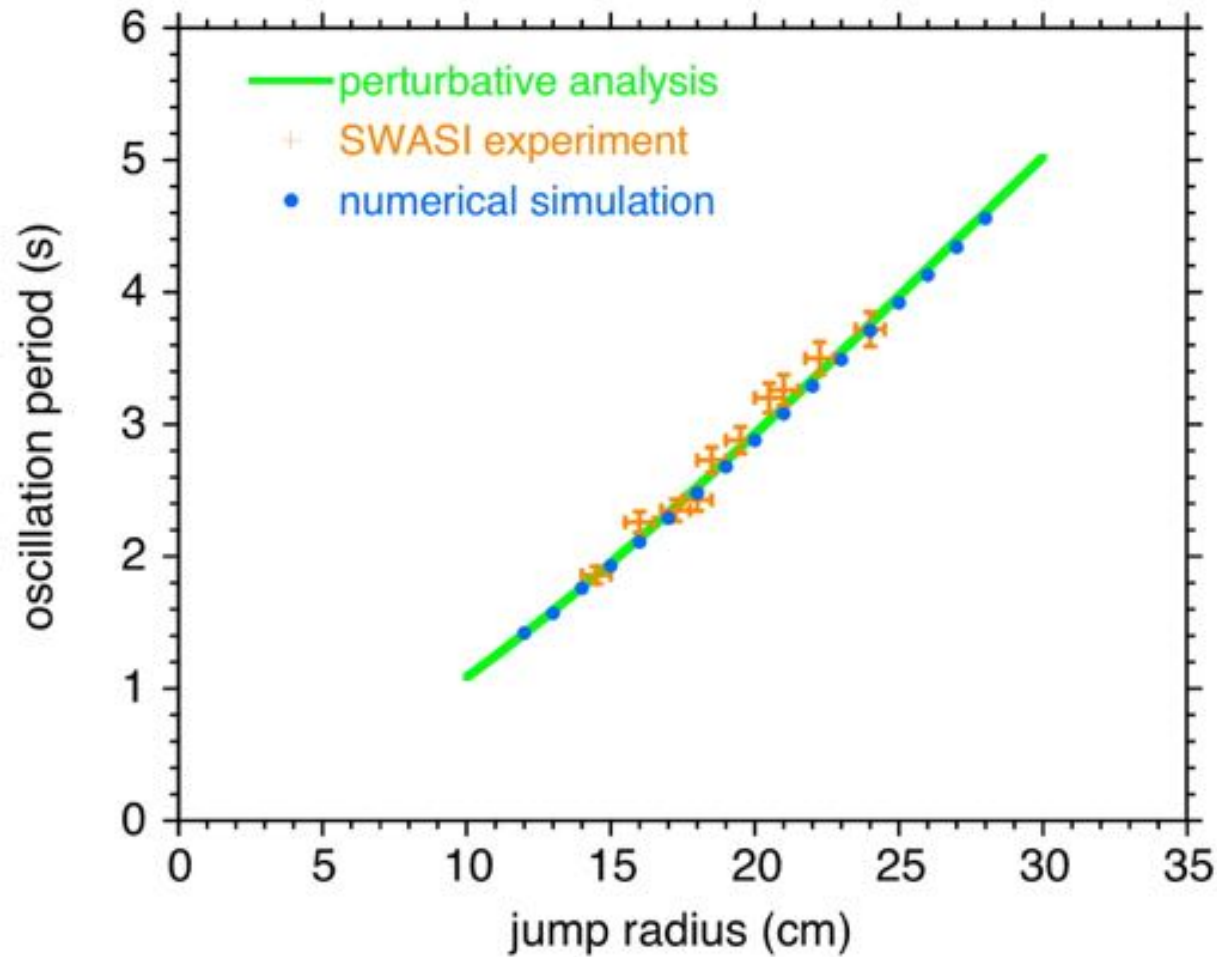


Simulation numérique de l'expérience hydraulique



*Simulation numérique de l'état de choc
dans le cœur de la supernova*

Comparison to a 2D shallow water model



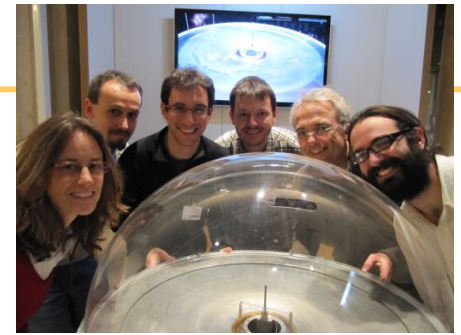
Foglizzo, Masset, Guilet, Durand
PRL (2012)

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

17 December 2013-16 February 2014



12 astrophysicists
138 presentations
2059 visitors



SN_2NS

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



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

Agence Nationale de la Recherche
ANR



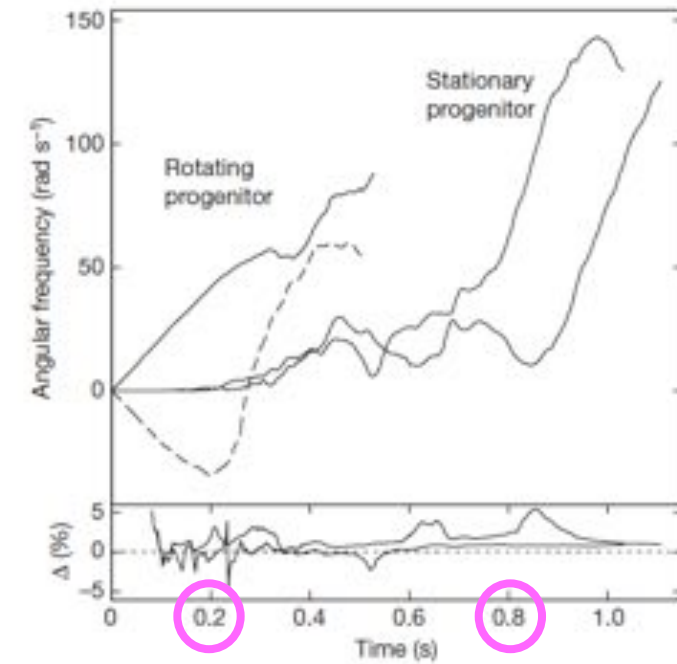
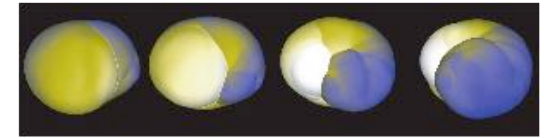
permanent collection since May 2015



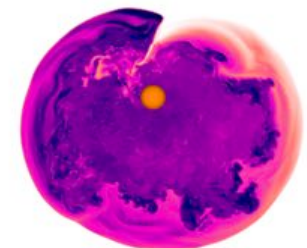
Rotating progenitor: redistribution of angular momentum by SASI



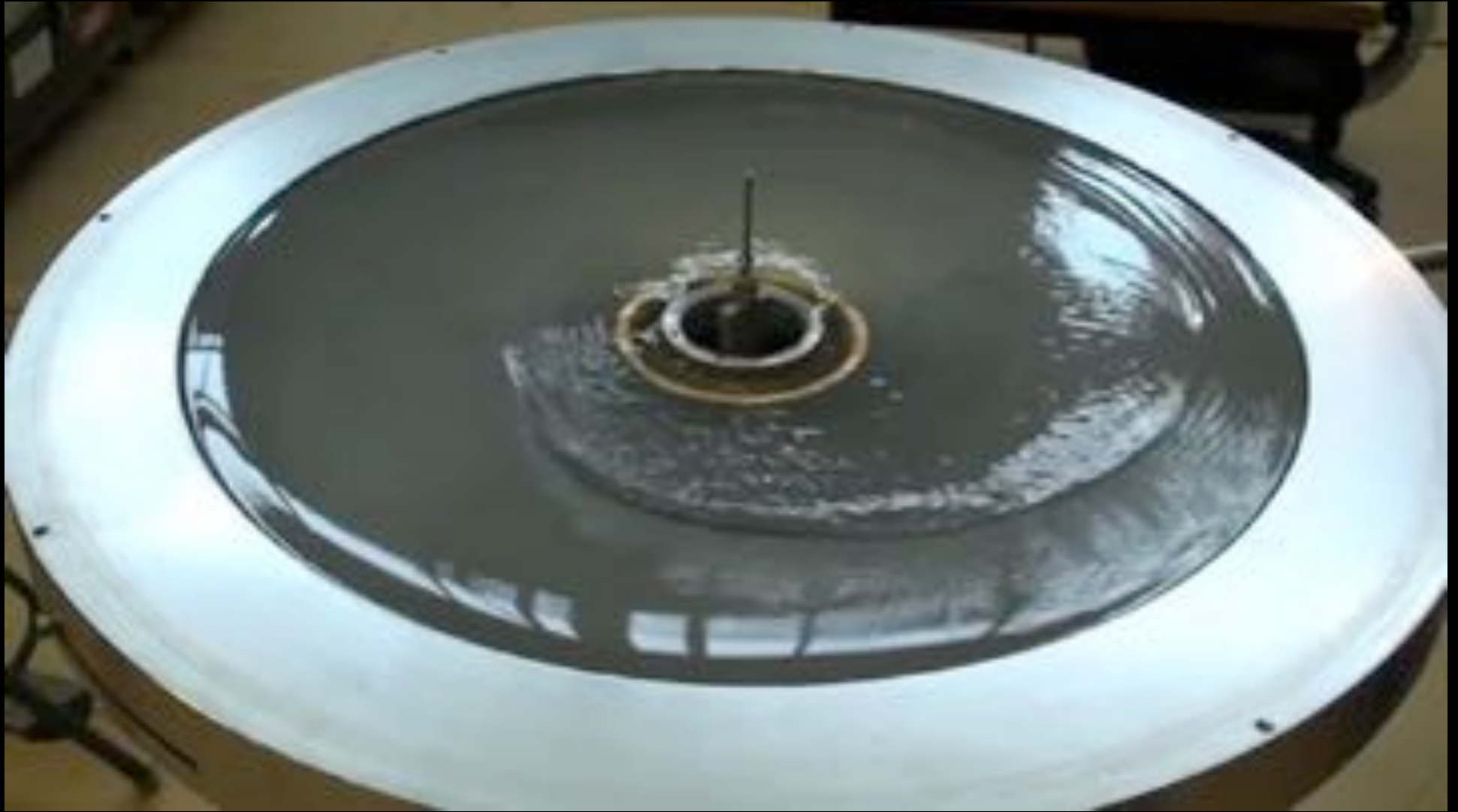
rotation period: 246s
injection slit: 0.55mm
flow rate: 1.17L/s



Blondin & Mezzacappa 07



faster rotation : another instability



Towards higher Reynolds numbers

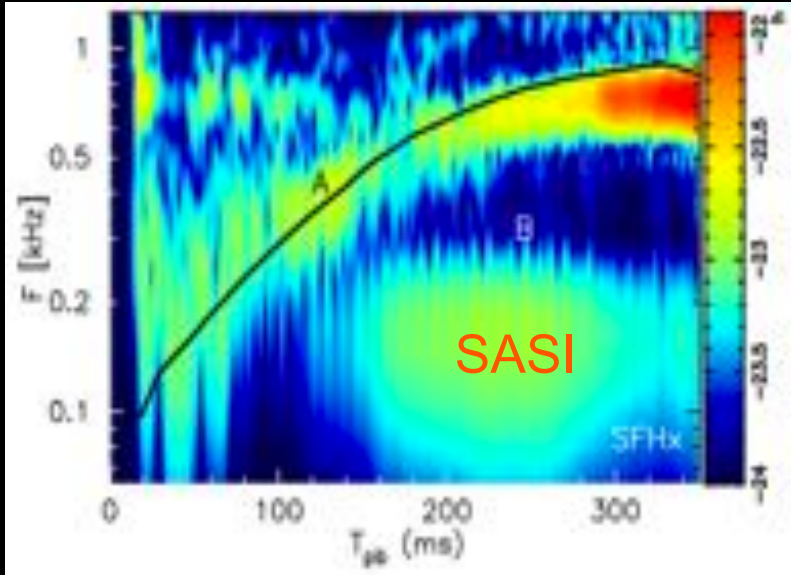


- diameter 3m50: Reynolds x 15
- overspilling injection
- angular momentum



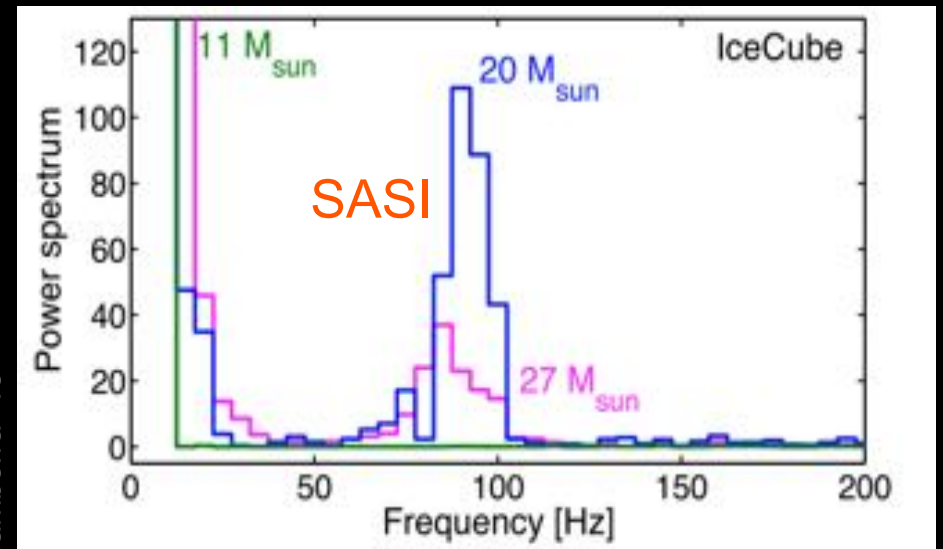
SASI oscillations can leave a **direct** imprint on the gravitational wave and neutrino signals

Gravitational Waves



Kuroda+16

Oscillations of the neutrino flux

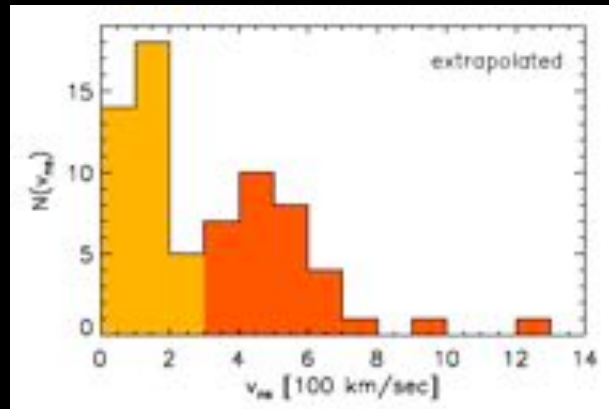


Tamborra+13

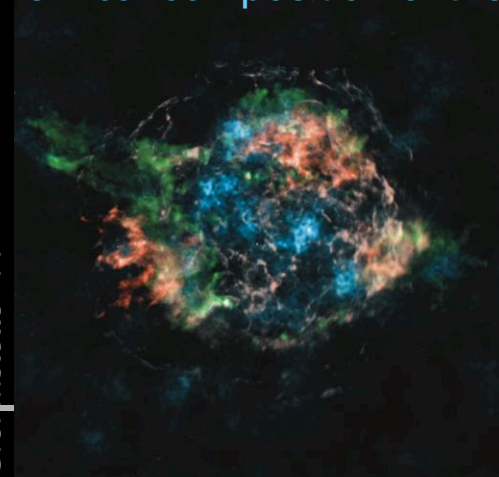
Indirect information can be learnt from

-the kick, spin of the compact object

-the chemical composition of the remnant

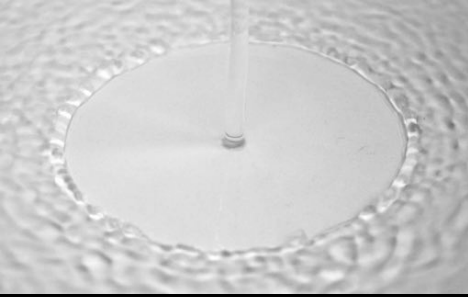


Scheck+06



Grefenstette+14

Conclusion



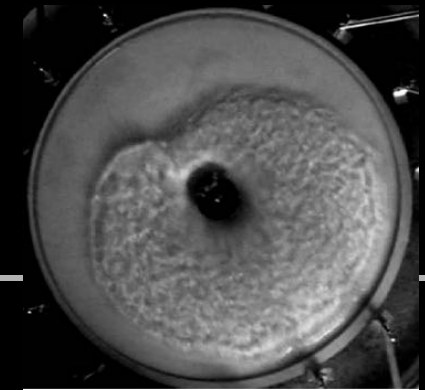
Massive stars end their life when their iron core is too massive. Its collapse leads to the birth of a **neutron star** or a **black hole**, and the ejection of their envelope visible as a **supernova**

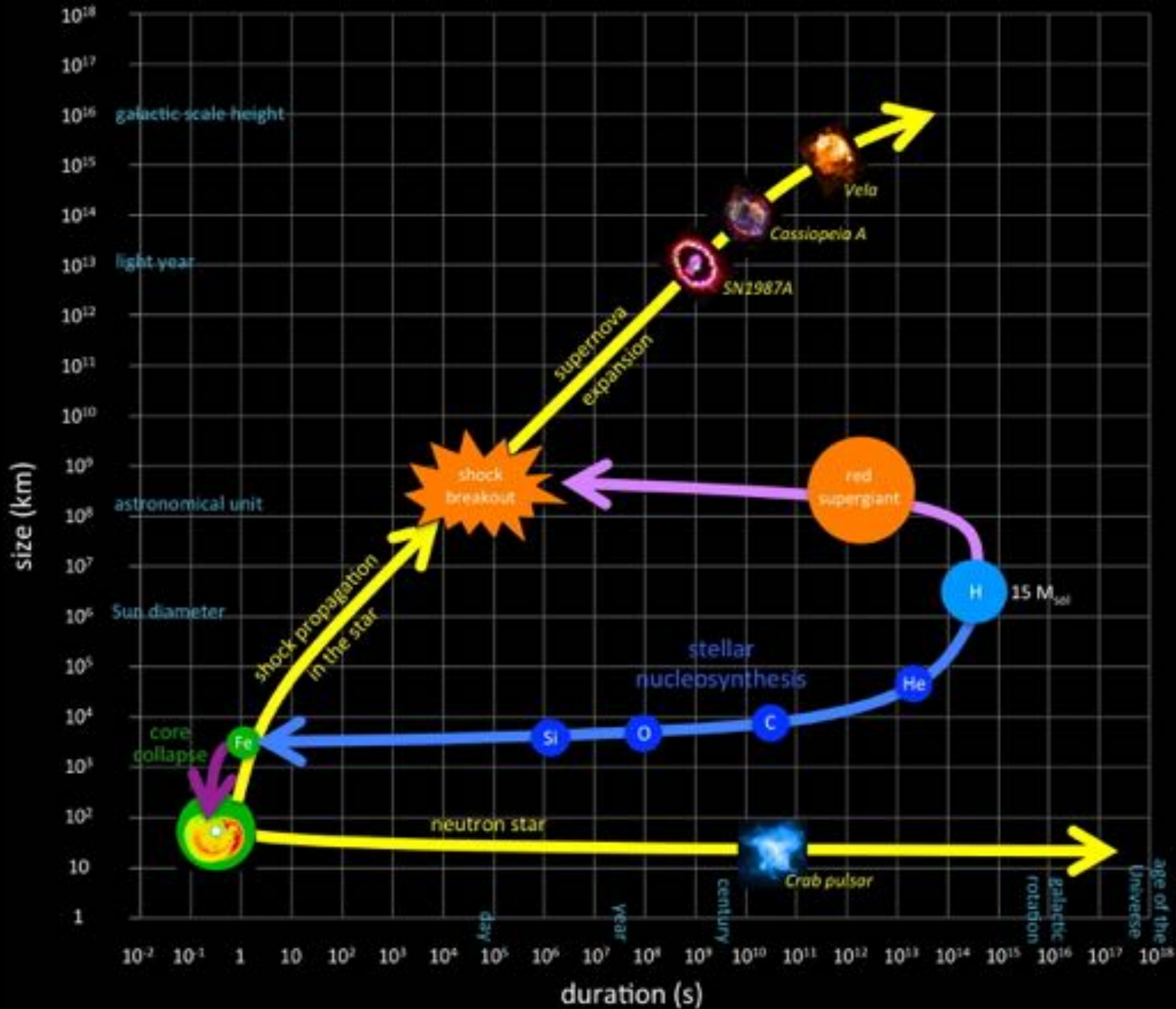
Numerical models indicate that **hydrodynamical instabilities** break the spherical symmetry

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

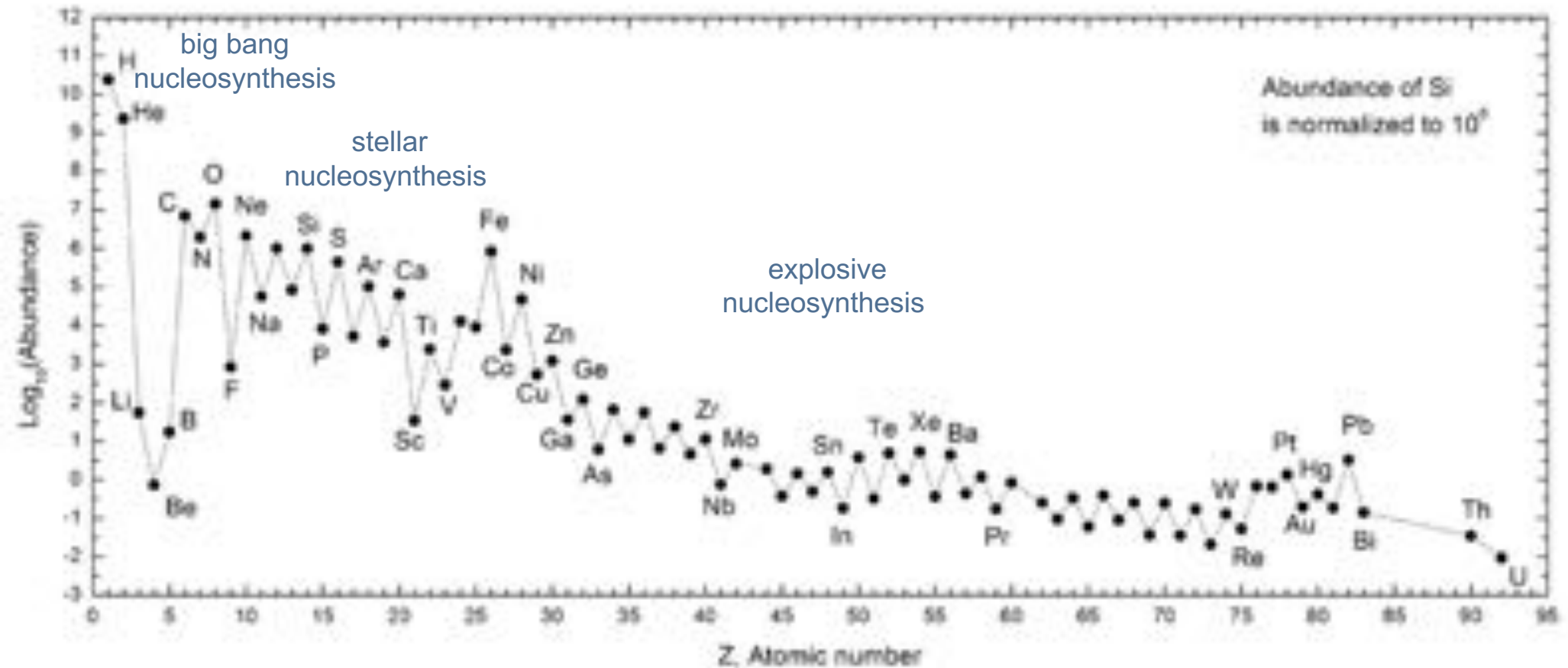




Classification of the elements

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	<div>1 H Hydrogen</div>																	<div>2 He Helium</div>
2	<div>3 Li Lithium</div>	<div>4 Be Beryllium</div>											<div>5 B Boron</div>	<div>6 C Carbon</div>	<div>7 N Nitrogen</div>	<div>8 O Oxygen</div>	<div>9 F Fluorine</div>	<div>10 Ne Neon</div>
3	<div>11 Na Sodium</div>	<div>12 Mg Magnesium</div>											<div>13 Al Aluminum</div>	<div>14 Si Silicon</div>	<div>15 P Phosphorus</div>	<div>16 S Sulfur</div>	<div>17 Cl Chlorine</div>	<div>18 Ar Argon</div>
4	<div>19 K Potassium</div>	<div>20 Ca Calcium</div>	<div>21 Sc Scandium</div>	<div>22 Ti Titanium</div>	<div>23 V Vanadium</div>	<div>24 Cr Chromium</div>	<div>25 Mn Manganese</div>	<div>26 Fe Iron</div>	<div>27 Co Cobalt</div>	<div>28 Ni Nickel</div>	<div>29 Cu Copper</div>	<div>30 Zn Zinc</div>	<div>31 Ga Gallium</div>	<div>32 Ge Germanium</div>	<div>33 As Arsenic</div>	<div>34 Se Selenium</div>	<div>35 Br Bromine</div>	<div>36 Kr Krypton</div>
5	<div>37 Rb Rubidium</div>	<div>38 Sr Strontium</div>	<div>39 Y Yttrium</div>	<div>40 Zr Zirconium</div>	<div>41 Nb Niobium</div>	<div>42 Mo Molybdenum</div>	<div>43 Tc Technetium</div>	<div>44 Ru Ruthenium</div>	<div>45 Rh Rhodium</div>	<div>46 Pd Palladium</div>	<div>47 Ag Silver</div>	<div>48 Cd Cadmium</div>	<div>49 In Indium</div>	<div>50 Sn Tin</div>	<div>51 Sb Antimony</div>	<div>52 Te Tellurium</div>	<div>53 I Iodine</div>	<div>54 Xe Xenon</div>
6	<div>55 Cs Cesium</div>	<div>56 Ba Barium</div>	<div>57 La Lanthanum</div>	<div>72 Hf Hafnium</div>	<div>73 Ta Tantalum</div>	<div>74 W Tungsten</div>	<div>75 Re Rhenium</div>	<div>76 Os Osmium</div>	<div>77 Ir Iridium</div>	<div>78 Pt Platinum</div>	<div>79 Au Gold</div>	<div>80 Hg Mercury</div>	<div>81 Tl Thallium</div>	<div>82 Pb Lead</div>	<div>83 Bi Bismuth</div>	<div>84 Po Polonium</div>	<div>85 At Astatine</div>	<div>86 Rn Radon</div>
7	<div>87 Fr Francium</div>	<div>88 Ra Radium</div>	<div>89 Ac Actinium</div>	<div>104 Rf Rutherfordium</div>	<div>105 Db Dubnium</div>	<div>106 Sg Seaborgium</div>	<div>107 Bh Bohrium</div>	<div>108 Hs Hassium</div>	<div>109 Mt Meitnerium</div>	<div>110 Ds Darmstadtium</div>	<div>111 Rg Roentgenium</div>	<div>112 Cn Copernicium</div>	<div>113 Uut Ununtrium</div>	<div>114 Fl Flerovium</div>	<div>115 Uup Ununpentium</div>	<div>116 Lv Livermorium</div>	<div>117 Uus Ununseptium</div>	<div>118 Uuo Ununoctium</div>
Lanthanide Series			<div>57 La Lanthanum</div>	<div>58 Ce Cerium</div>	<div>59 Pr Praseodymium</div>	<div>60 Nd Neodymium</div>	<div>61 Pm Promethium</div>	<div>62 Sm Samarium</div>	<div>63 Eu Europium</div>	<div>64 Gd Gadolinium</div>	<div>65 Tb Terbium</div>	<div>66 Dy Dysprosium</div>	<div>67 Ho Holmium</div>	<div>68 Er Erbium</div>	<div>69 Tm Thulium</div>	<div>70 Yb Ytterbium</div>	<div>71 Lu Lutetium</div>	
Actinide Series			<div>89 Ac Actinium</div>	<div>90 Th Thorium</div>	<div>91 Pa Protactinium</div>	<div>92 U Uranium</div>	<div>93 Np Neptunium</div>	<div>94 Pu Plutonium</div>	<div>95 Am Americium</div>	<div>96 Cm Curium</div>	<div>97 Bk Berkelium</div>	<div>98 Cf Californium</div>	<div>99 Es Einsteinium</div>	<div>100 Fm Fermium</div>	<div>101 Md Mendelevium</div>	<div>102 No Nobelium</div>	<div>103 Lr Lawrencium</div>	

Abundances of elements In the solar system



Nuclear binding energy

