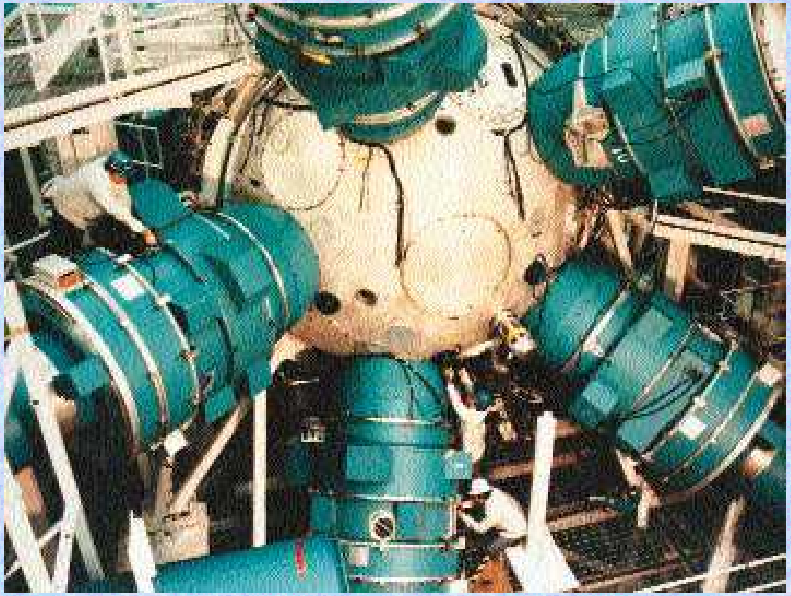
FROM PARSEC TO MICRON: THE LABORATORY OF ASTROPHYSICS



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I Jornada de Recerca del Dpt. De Física i Enginyeria Nuclear, 02/2006

Astronomy & Astrophysics has traditionally been a very special Science because it **was not possible** to dessign controlled laboratory Experiments to validate models.

The ultimate goal of Astronomers is to solve the cosmic puzzle by decodying the information arriving from outer space.

OBSERVATIONS ARE CRUCIAL !!

But also are

GOOD PHYSICS !!

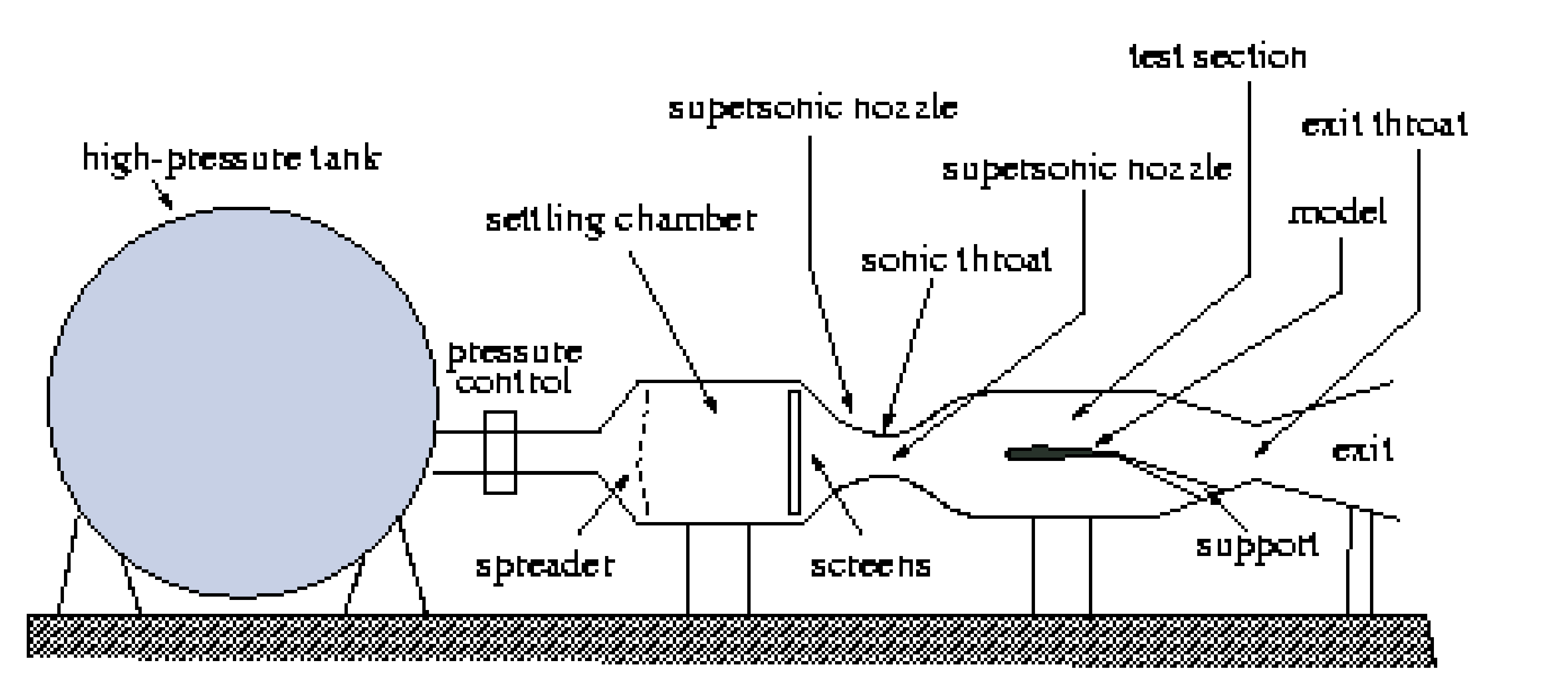
Laboratory experiments on Earth would be extremely useful in many areas of Astrophysics:

- To improve the Equation of State in extreme physical conditions
- Simulate gas-dynamical processes in terrestrial laboratories
- To study radiative transport in stellar plasmas
- To measure nuclear cross-sections of nuclear reactions.

However:

Fluid-dynamical studies are routinely conducted in wind tunnels to study aerodynamics.

Would it be possible to reach astrophysical conditions ?


test section
supersonic nozzle
exit throat
high-pressure tank
supersonic nozzle
model
settling chamber
sonic throat
pressure
control
exit
spreader
screens
support

SCALING LAWS:

•Geometrical similarity:

$$\frac{L_m}{L_p} = L_r \Rightarrow \frac{A_m}{A_p} = L_r^2 ; \frac{V_m}{V_p} = L_r^3$$

•Kinematical similarity:

$$\frac{v_m}{v_p} = \frac{L_r}{t_r} \Rightarrow \frac{Q_m}{Q_p} = \frac{L_r^3}{t_r}$$

$$\frac{a_m}{a_p} = \frac{L_r}{t_r^2}$$

•Dynamical similarity:

$$F_r = \rho_r A_r v_r^2$$

Adimensional numbers:

$$E_u = \frac{ma}{pA} = \frac{\rho v^2}{p}$$ Euler number

$$R_e = \frac{ma}{\tau A} = \frac{\rho v L}{\mu}$$ Reynolds number

$$F_r^2 = \frac{ma}{mg} = \frac{v^2}{Lg}$$ Froude number

Very often it is sufficient: Eu (m)=Eu (p),
Re (m)= Re (p), Fr (m)=Fr (p), etc ....to have dynamical similarity

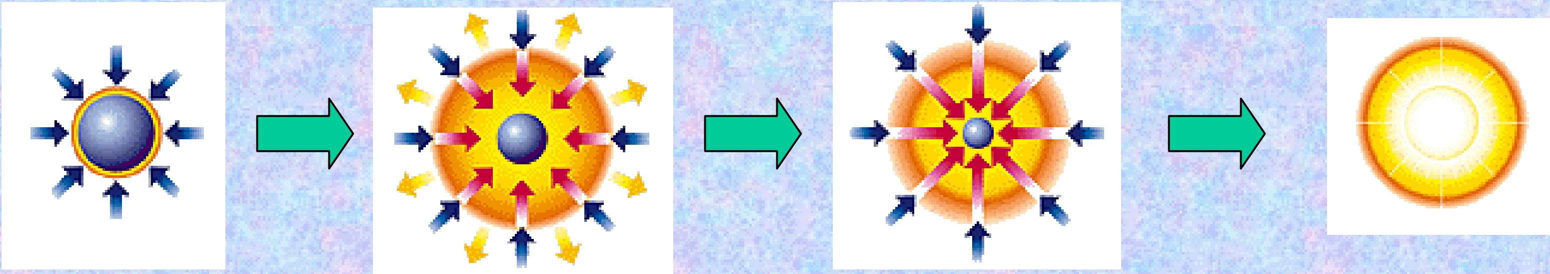
As soon as LASER was invented in 1964 people realized that it could be used to reproduce Astrophysical situations:

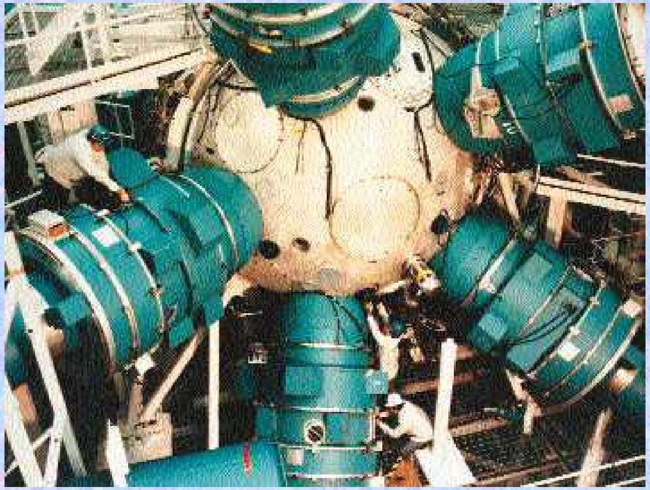
- Even moderate LASERs can deposite an enormous energy density.

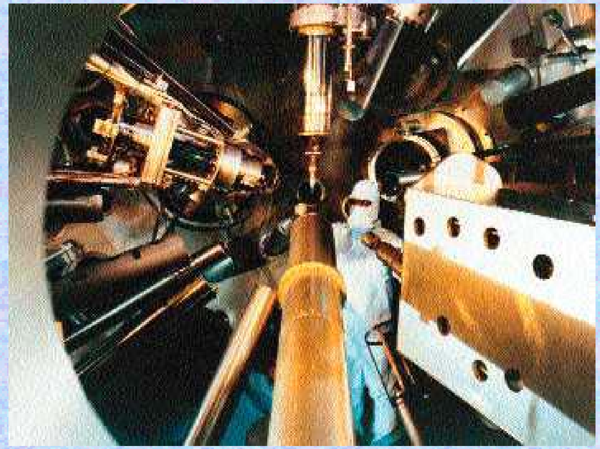
- Experiments in Inertial Confinement Fusion showed that it is possible to reproduce extreme thermodynamical conditions on Earth.

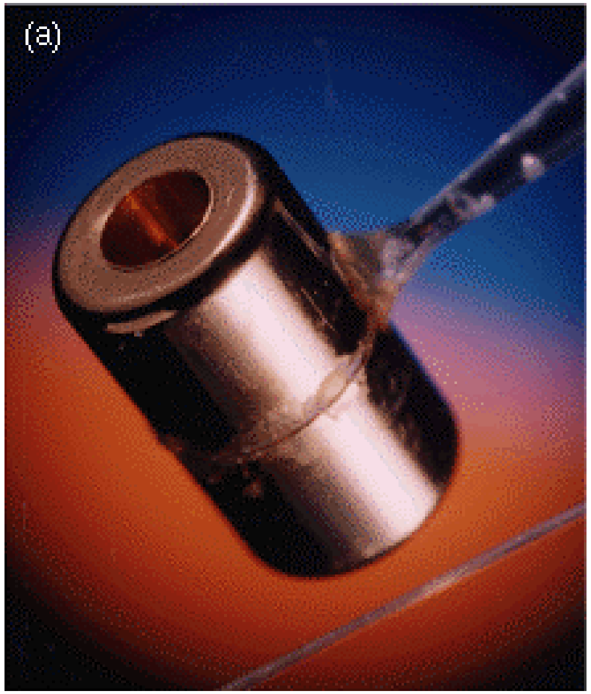
- Experiments in ICF also showed that it was easy to get plasma acceleration/deccelerations compatible with very large gravity values.

ICF BASIC SCHEME









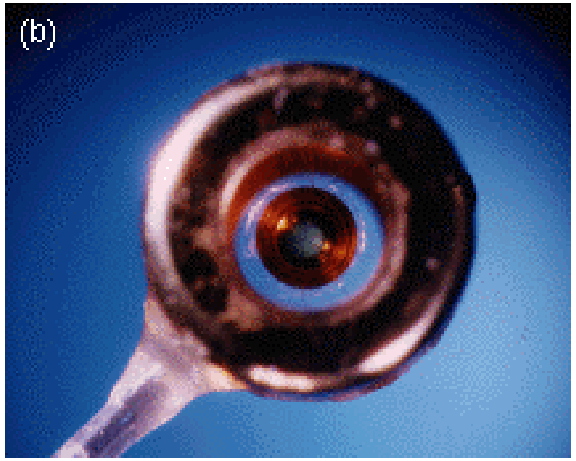
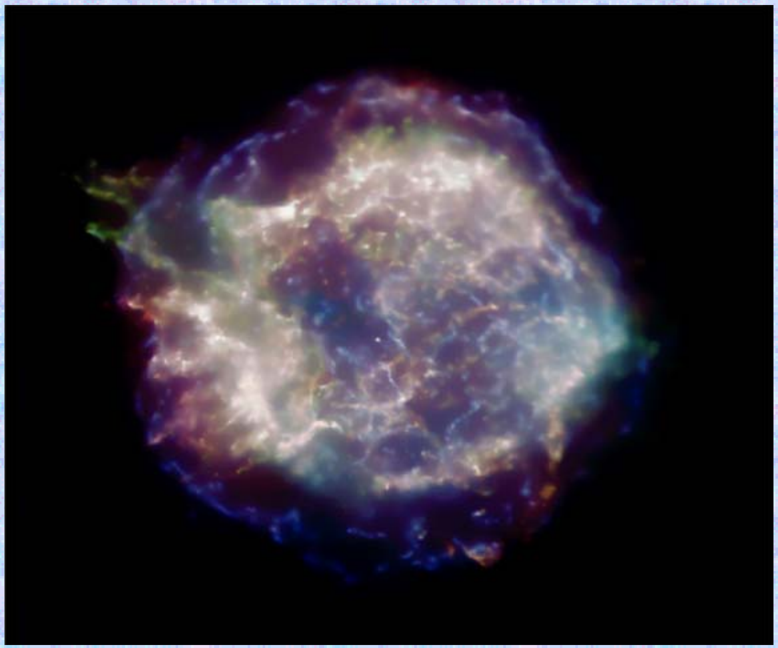


Figure 3. (a) Side view of a typical Nova hohlraum shown nect to a human hair. (b) The end-on view shows a target within the hohlraum. Hohlraums for the National Ignition Facility will have linear dimensions about five times greater than those for Nova.

Target size: 1mm diameter
Neodymium glass laser dumping 1 ns pulse of 10^5 Joules

1.- An specific experiment: Simulation of a Supernova Remnant in the laboratory.

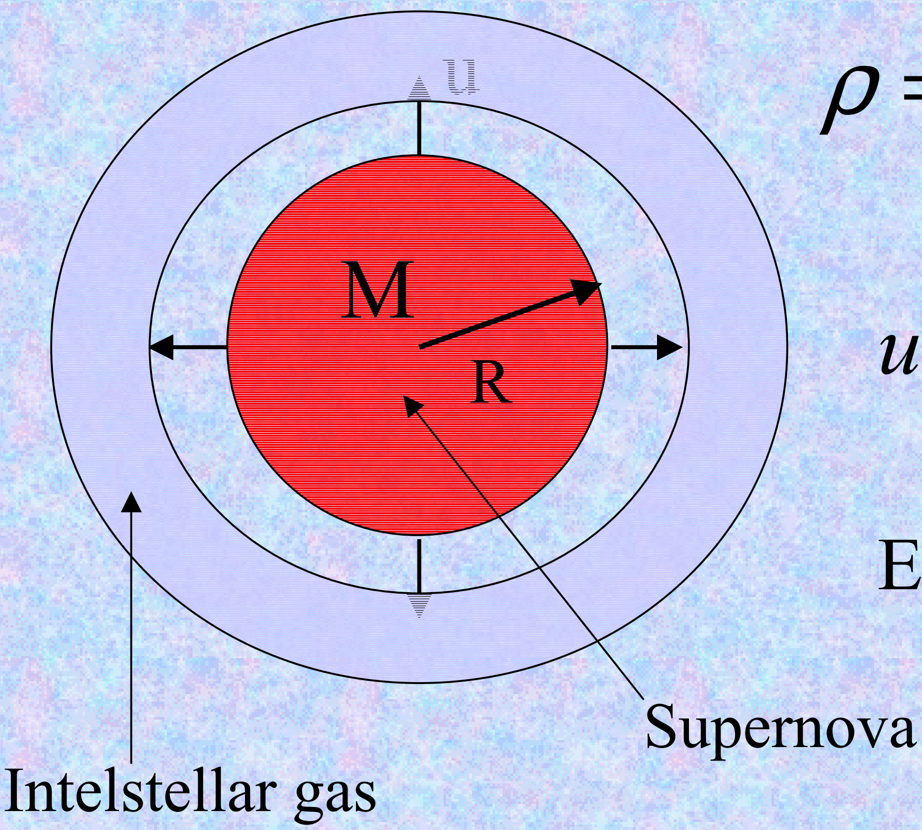


Cassiopea SNR
In X-rays.

Main goals:

* Validate the output of Hidrodydamical Codes
* Reproduce the main trends of SNR observed in nature

Model: Interaction of SNII ejected gas (15 Mε) with the interstellar medium ($\rho 0=10^{-24}$ g/cm3)



$$\rho = \rho_0 (\frac{r}{r_0})^n$$

n=-12

$$u = u_0 \frac{r}{r_0}$$

$E_T=E_K= 10^{51}$ erg

Adiabatic evolution during 10.000 years

Hydrodynamic Equations:

$$\rho\left(\frac{\partial\vec{v}}{\partial t}+\vec{v}\cdot\vec{\nabla}\vec{v}\right)=-\vec{\nabla}p$$

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

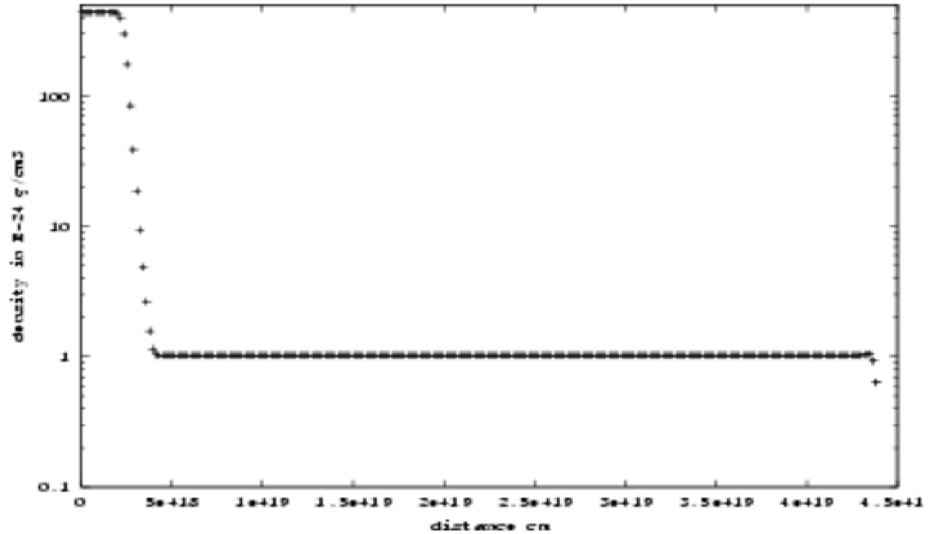
Euler equations

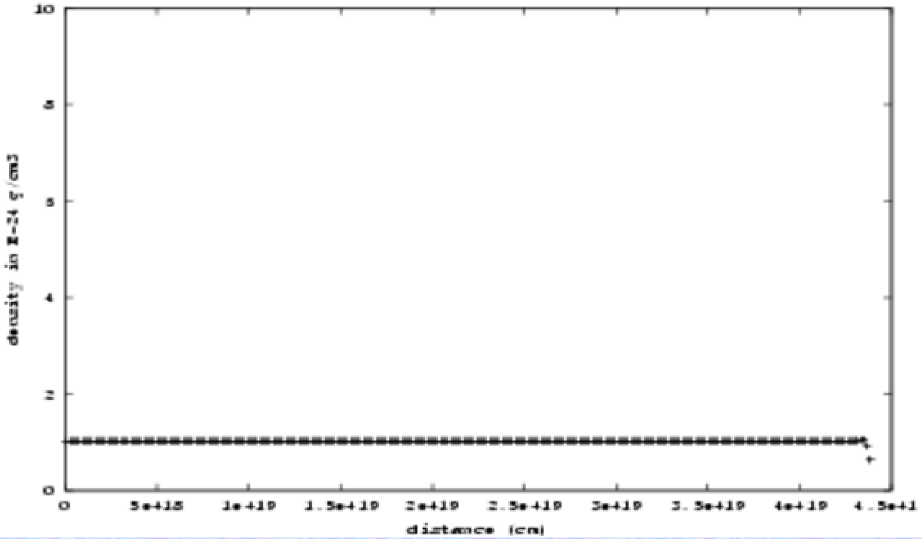
$$\frac{\partial p}{\partial t}-\gamma\frac{p}{\rho}\frac{\partial p}{\partial t}+\vec{v}\cdot\vec{\nabla}p-\gamma\frac{p}{\rho}\vec{v}\cdot\vec{\nabla}\rho=0$$

$$\vec{r}=a\vec{r}_1;\quad \rho=\mathrm{b}\rho_1;\quad \mathrm{p=cp_1}$$

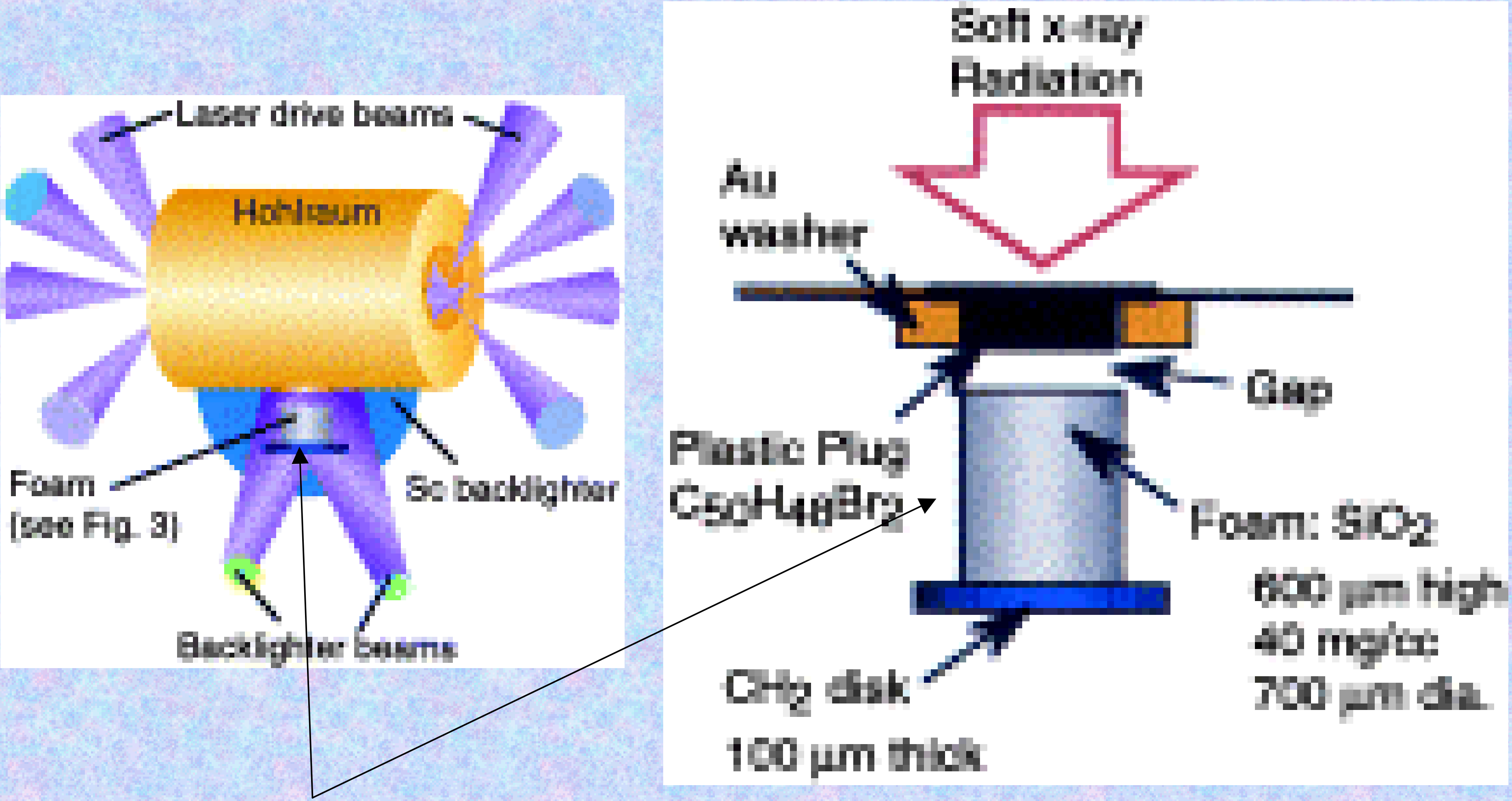
Invariant under scale transformation:

$$then:\quad \mathrm{t=a}\sqrt{\frac{\mathrm{b}}{\mathrm{c}}}t_1;\quad \vec{\mathrm{v}}=\vec{\mathrm{v}}_1\sqrt{\frac{\mathrm{c}}{\mathrm{b}}}$$


100
10
1
0.1
0
5e+18
1e+19
1.5e+19
2e+19
2.5e+19
3e+19
3.5e+19
4e+19
density in E-24 g/cm3
distance cm


10
8
6
4
2
0
5e+18
1e+19
1.5e+19
2e+19
2.5e+19
3e+19
3.5e+19
4e+19
density in E-24 g/cm3
distance (cm)

Experimental Device:



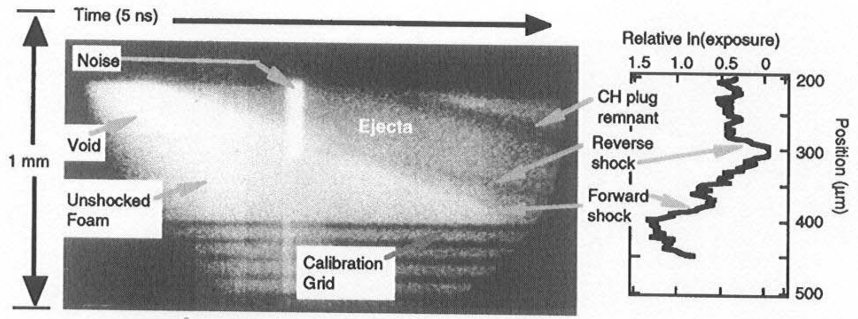


FIG. 5.—Transmitted backlighter intensity in space and time, as recorded by an X-ray streak camera. The darker regions are those of larger optical depth, such as the region of stagnated ejecta.

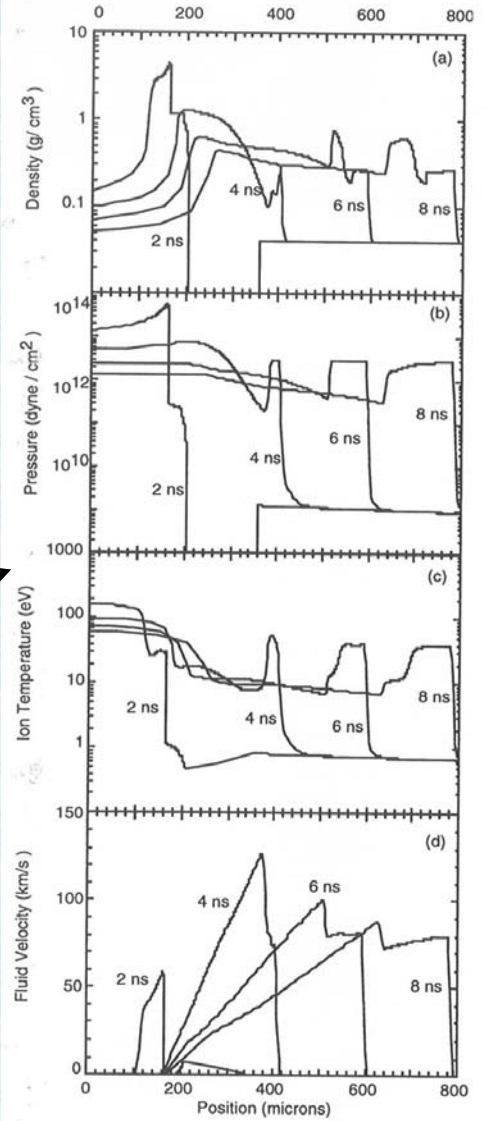


FIG. 2.—One-dimensional simulations of the laser experiments. Profiles of (a) density, (b) pressure, (c) ion temperature, and (d) velocity are shown at four times during the evolution of the system.

Scale equivalence:

1 ns ---------→ 1 year

100 km/s ---→ 10,000 km/s

100 μm ------→ 0.1 parsec

simulation

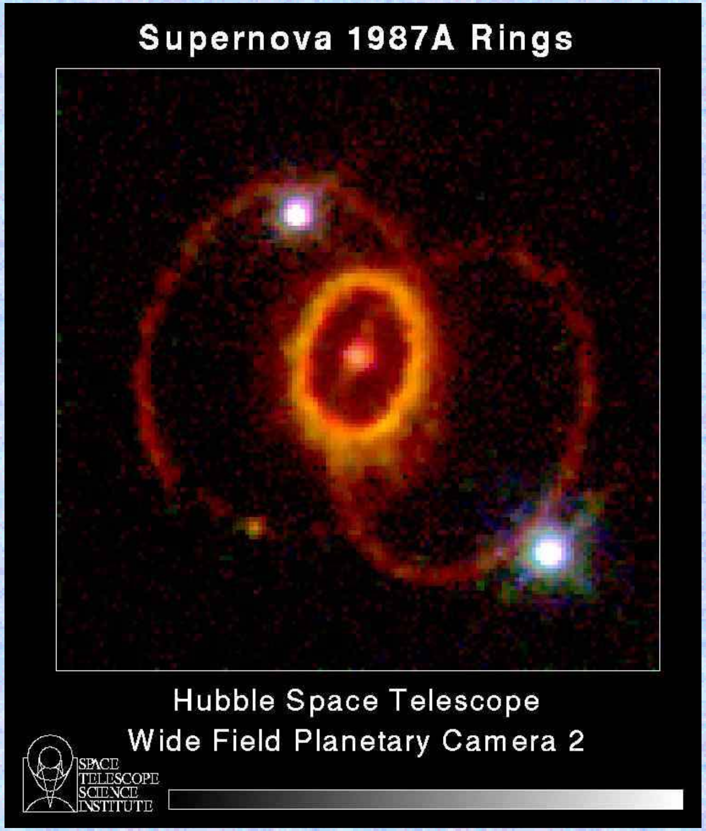
Total elapsed time ~ 8ns

spatial range ~600 μm ---→ 0.6 pc

V(fs)=108 km/s (exp); V(fs)=96 km/s (simulation)

V(rs)=76 km/s (exp); V(rs)=61 km/s (simulation)

2.- Role of Hydrodynamic instabilities in Supernovae



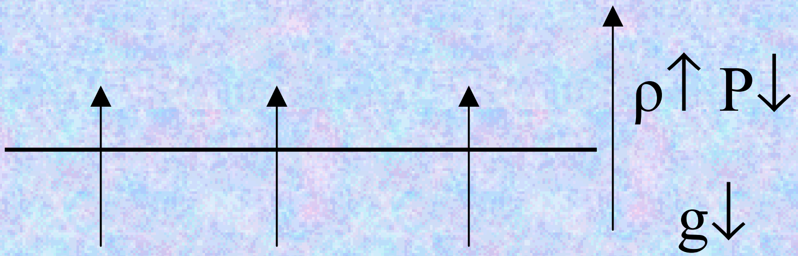
SN1987 which exploded in the Magellan Cloud (52 Kpc distance) ls one of the best natural laboratories to study stellar evolution.

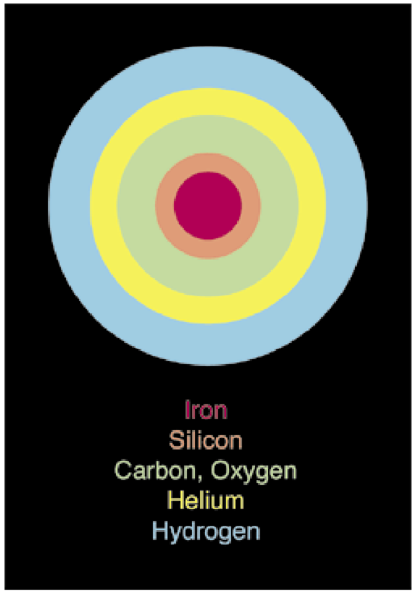
SN comes from the explosion of a 15 solar-masses progenitor star. It has been predicted that gamma rays from radioactive nuclei will show up 1 yr after explosion.

BUT

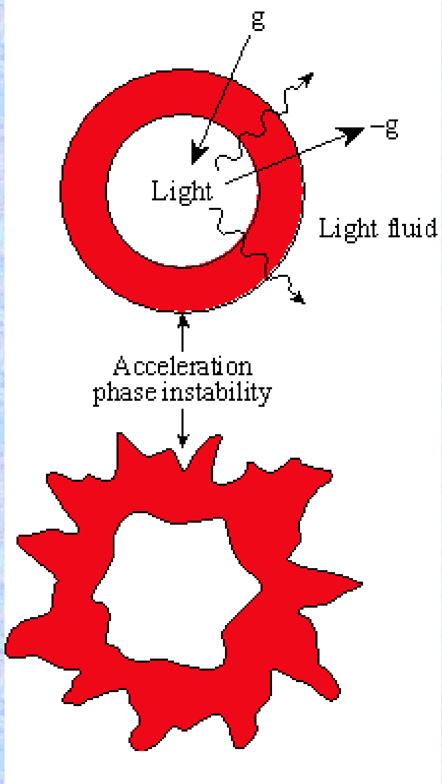
X-ray japanese satelite GINGA detected them only 3 months after.

Existence of hydrodynamic instabilities which transport radioactive nuclei to the surface of the star.

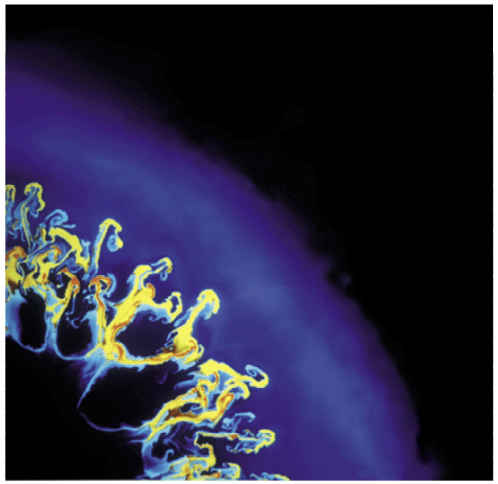




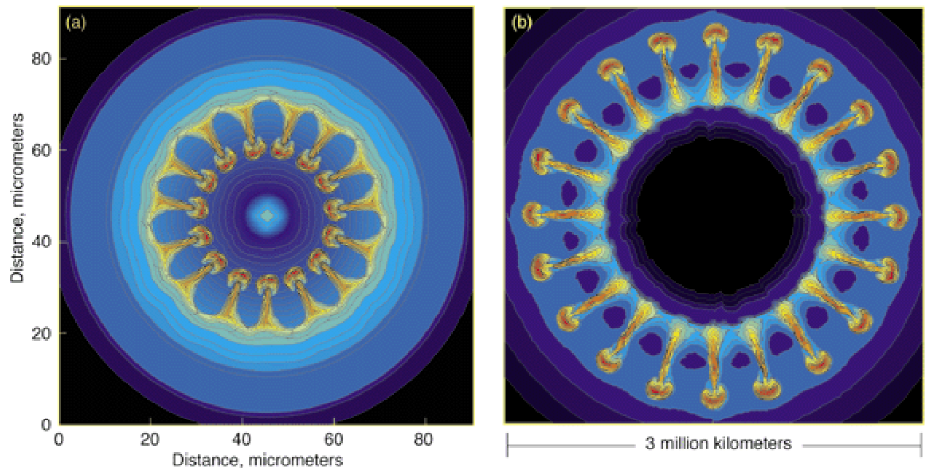
In its death throes, Supernova 1987A resembled an enormous, many-layered onion as successively heavier layers of fuel ignited and burned.



Rayleigh-Taylor instability

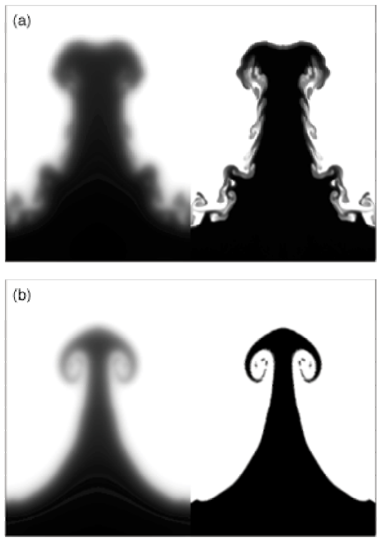


Supernova 1987A provided strong evidence of turbulence emanating from the core of the exploded star because core materials were observed well before they were predicted. The turbulence caused mixing among the layers and greatly complicated the tidy "onion" model of dying stars. [Image reproduced from Muller, Fryxell, and Arnett, Astronomy & Astrophysics 251, 505 (1991).]



Striking similarities exist between hydrodynamic instabilities in (a) inertial confinement fusion capsule implosions and (b) core-collapse supernova explosions. [Image (a) is from Sakagami and Nishihara, *Physics of Fluids B* **2**, 2715 (1990); image (b) is from Hachisu et al., *Astrophysical Journal* **368**, L27 (1991).]

Rayleigh-Taylor instability



The hydrodynamic mixing of the most unstable region (the hydrogen and helium layers) of Supernova 1987A has been modeled using (a) the multidimensional PROMETHEUS code and (b) the two-dimensional CALE code.

Scheme of the experimental device.

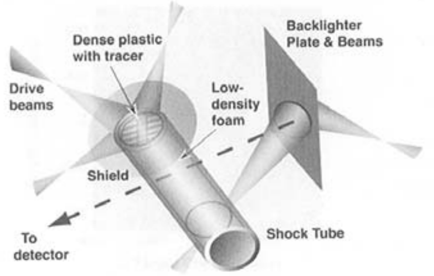


Figure 10. Schematic drawing of the target and the experiment producing a blast wave using an intense laser, from [33].

Comparison with hidrodynamical models.

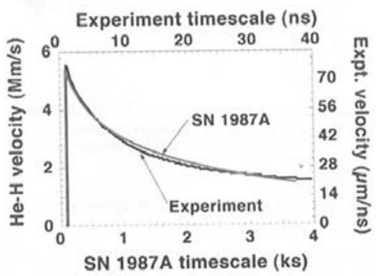
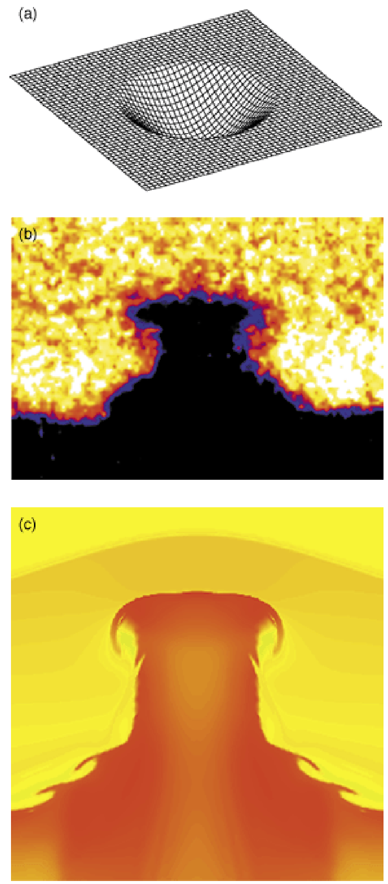
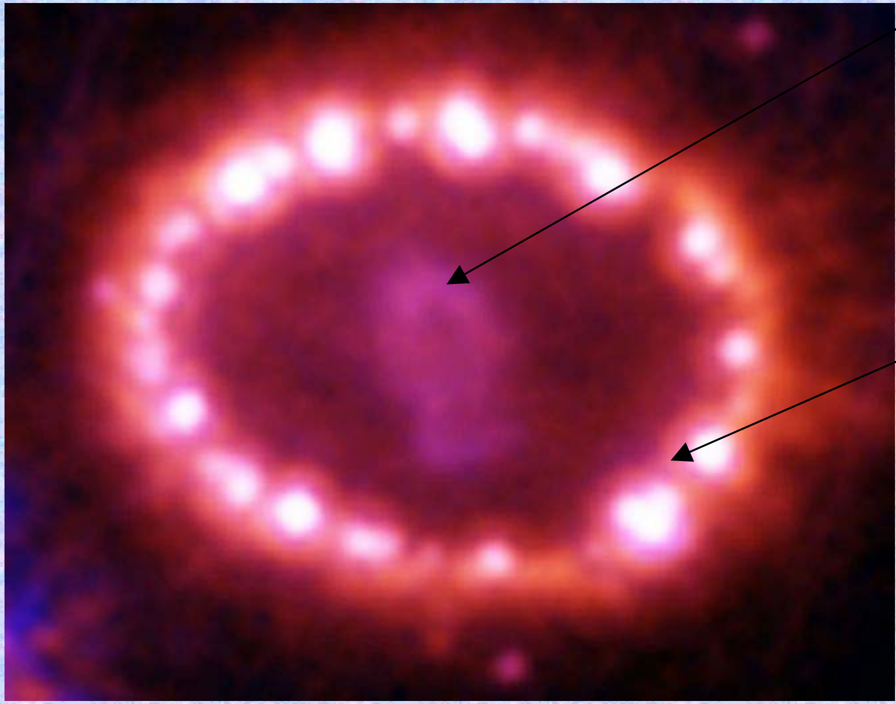


Figure 11. Interface velocity in SN1987A and an experiment, from computer simulations (adapted from [28]).



Using (a) "dimpled" targets, Nova experiments yielded (b) three-dimensional radiograph data of a laser implosion's hydrodynamics that show strong similarities to (c) a two-dimensional model of supernova hydrodynamics.

Inner Ring (1.3 ly diameter)



0rigin of the explosion

Origin of the
"Hot-spots" spreaded
around the ring ??

Can the ring be simulated
in the laboratory?

Explanation: Collision of expanding blast-wave of SN1987A with inner of circumstellar ring structure

LABORATORY SIMULATION

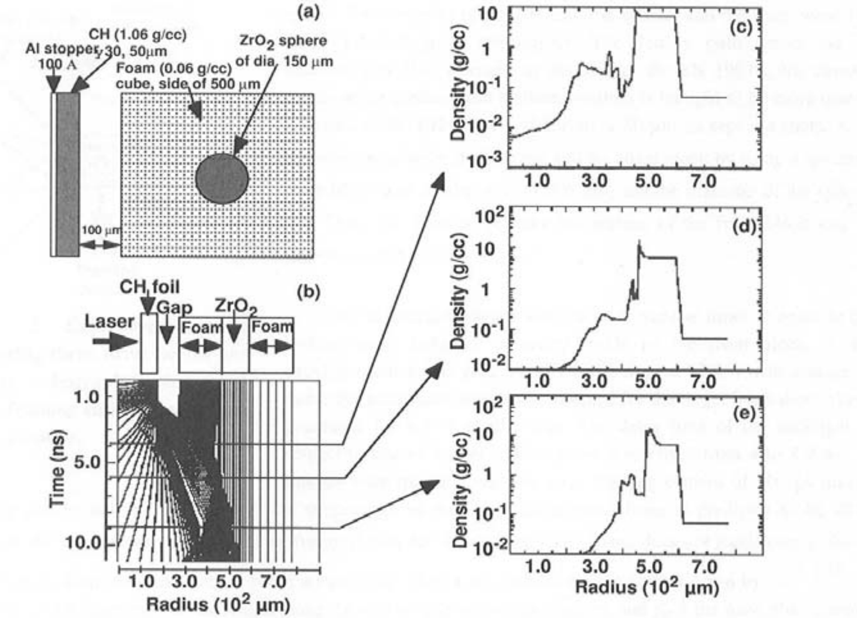


Fig. 2 Target and results of the hydrodynamic simulation with ILESTA-1D. Density profiles of collision of the ejecta with the low density foam and high density ZrO_2 are shown. (a) Schematic diagram of designed target, (b) Radius-time diagram, (c) t = 4.0 ns, (d) t = 6.0 ns, (e) t = 8.9 ns

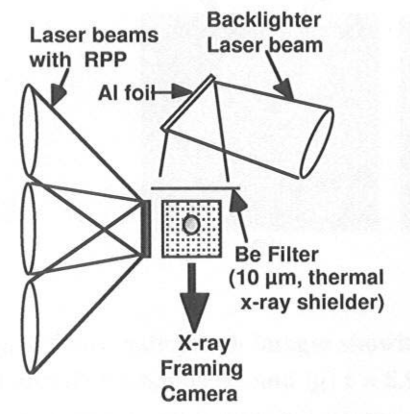


Fig. 3 Experimental setup showing three drive beams and x-ray radiography using an x-ray framing camera and a flash x-ray source.

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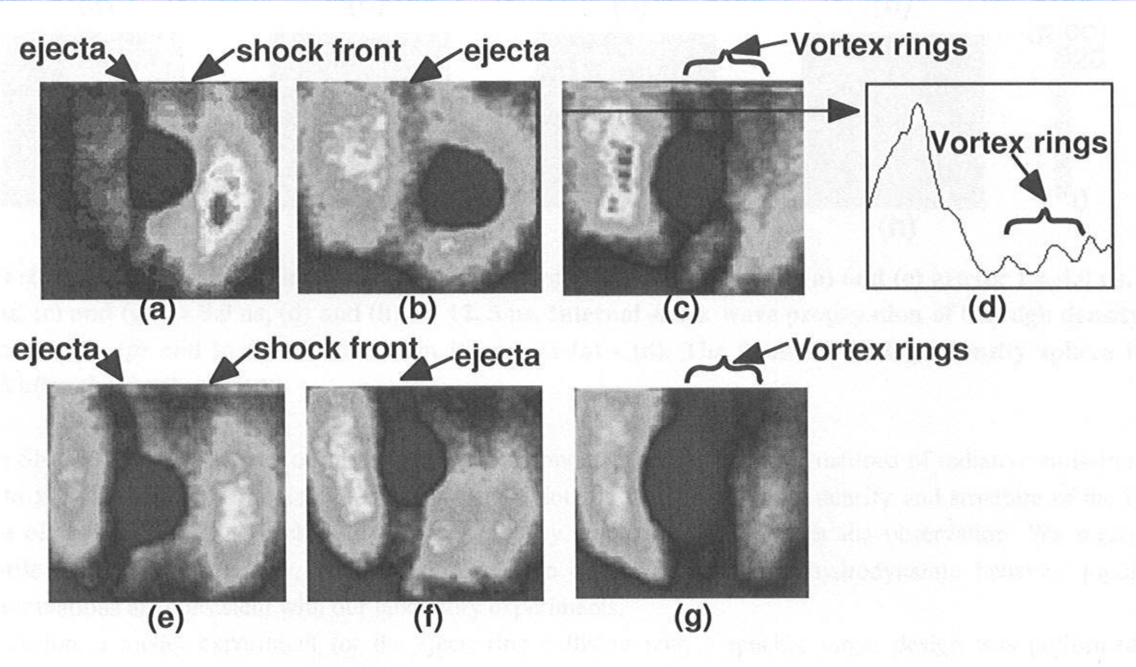
Experiment →



Numerical Simulation →

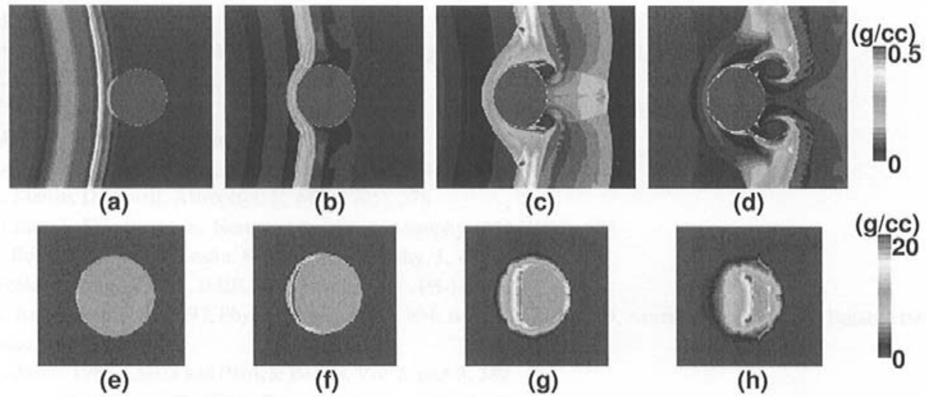


Fig. 5 2D simulation results obtained with the second-order Godunov scheme. (a) and (e) are for t = 4.0 ns, (b) and (f) t = 6.0 ns, (c) and (g) t = 8.9 ns, (d) and (h) t = 12. 5 ns. Internal shock wave propagation of the high density sphere is shown in (e), (f), (g) and in (h) as zoom - in figures of (a) - (d). The front of the high density sphere is highly compressed after the shock passage

Other areas suitable for Laboratory Astrophysics studies.

1) Jet formation, structure and interaction with the environment

2) Magnetohydrodynamics. Because extended Euler-equations to MHD are also scalable.

3) Other sort of hydrodynamical instabilities (Kelvin-Helmholtz, Ritchmyer-Meskov).

4) Study of the EOS at high density (important to study the Interior of planets for example)

VERY EXCITING EMERGING FIELD