FROM LASERS TO THE UNIVERSE: SCALING LAWS in LABORATORY ASTROPHYSICS

Serge BOUQUET
sbouquet@cea.fr and serge.bouquet@cea.fr

Dept. Applied and Theoretical Physics
CEA, DAM, DIF
F - 91297 Arpajon, France

Emeric FALIZE and Bérénice LOUPIAS

- Claire MICHAUT and LUTH group (CNRS, Observatory of Paris),
- Michel KOENIG and LULI group (CNRS, Ecole polytechnique),
- Xavier RIBEYRE (CEA-CESTA/CELIA, University of Bordeaux),

- Nigel WOOLSEY and RAL group (University of York, UK),

- Paul DRAKE and his group (University of Michigan at Ann-Arbor, USA),

- Aki TAKABE and Ryosuke KODAMA groups (Institute of Laser Engineering, Osaka, Japan).

OUTLINE

1) - CLASSICAL SCALING LAWS

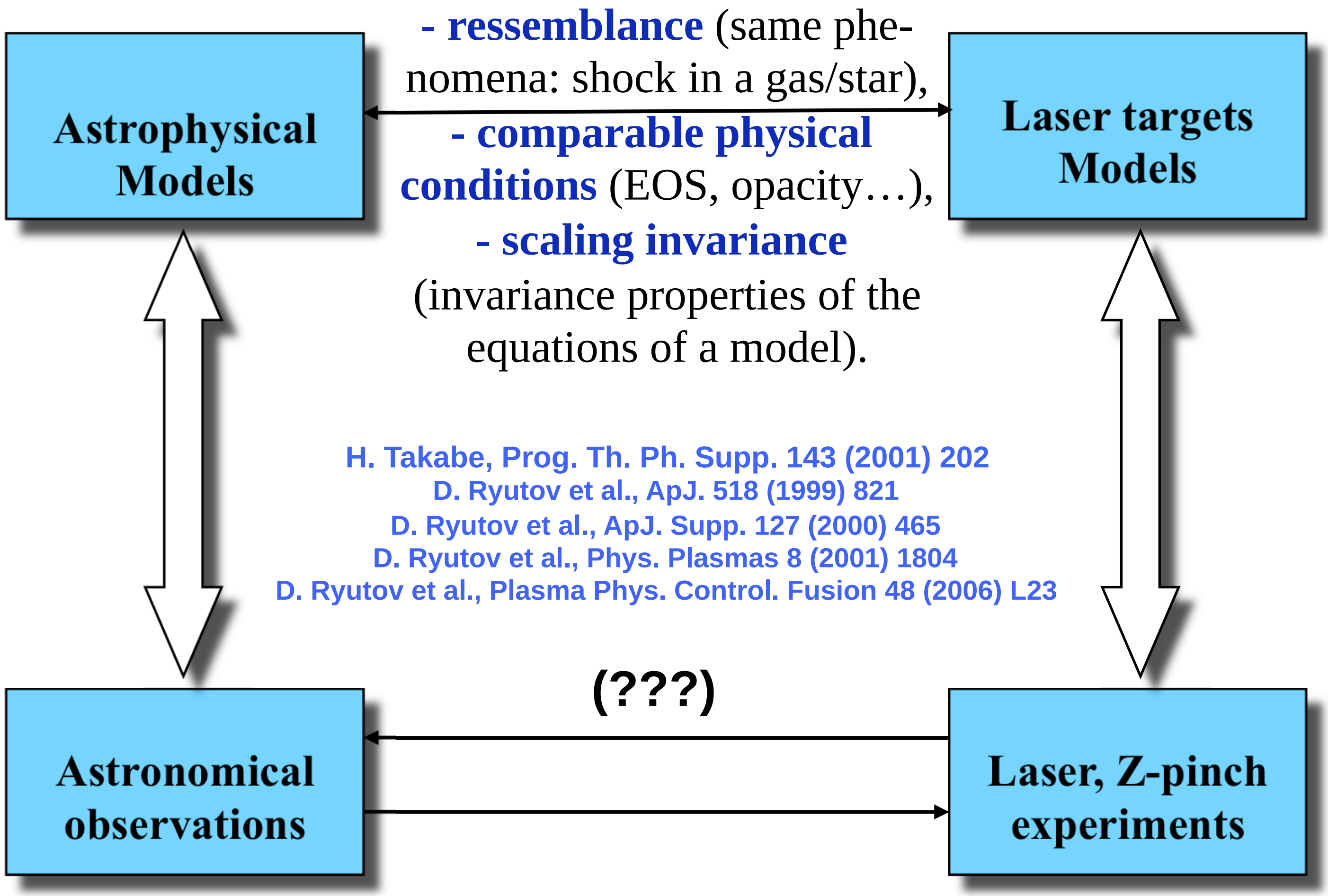
2) - RIGOUROUS FORMALISM

3) - YOUNG STELLAR OBJECT (YSO) JETS

4) - RADIATIVE SHOCKS

5) - CONCLUSION

LASER EXP. vs. ASTRON. OBS.



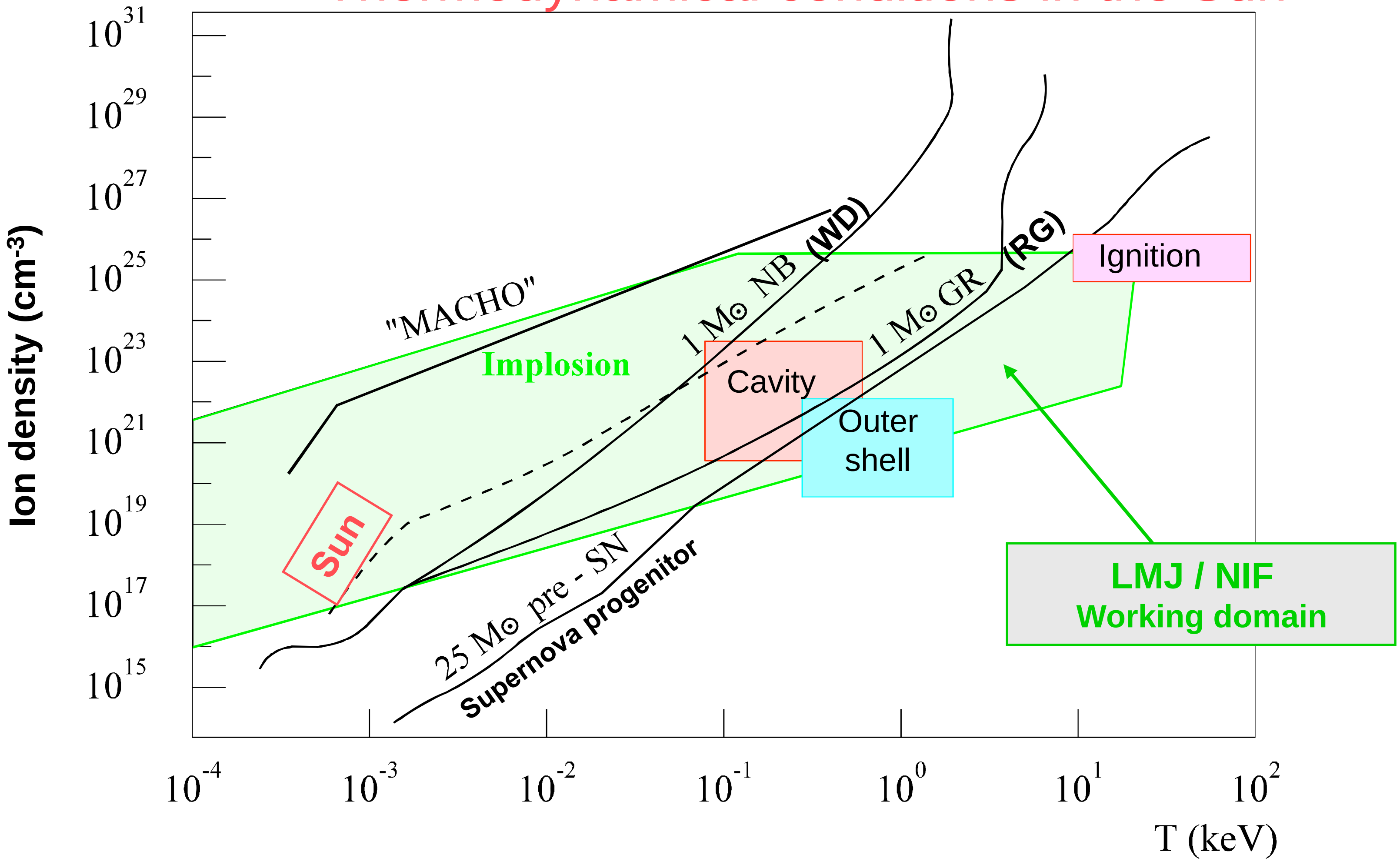
CONNECTION BETWEEN **LASER EXPERIMENTS** AND **ASTRONOMICAL OBSERVATIONS**

ASTRONOMICAL OBJECTS and LASER PLASMAS

Fig. from J.-P. Chièze

Comparable physical conditions:

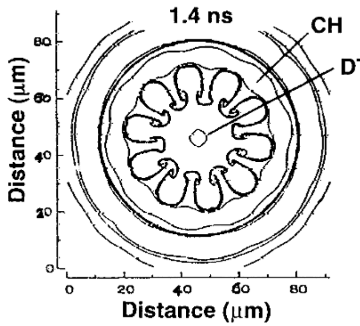
Thermodynamical conditions in the Sun



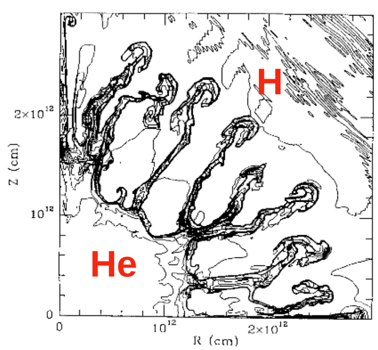
FCI TARGET vs. SUPERNOVA

Dimensionless number : Rayleigh - Taylor instabilities

Imploding laser target (ICF)



Exploding star : supernova



Among the most violent phenomena in the universe !!!

Typical quantities for laser target (S1) and supernovae (S2)

Physical quantities	Laser target (S1)	Supernova (S2)
Characteristic length	$\ell_1 \approx 100\ \mu m \approx 10^{-2}$ cm	$\ell_2 \approx 10^{12}$ cm
Characteristic time	$\tau_1 \approx 10^{-9}$ s	$\tau_2 \approx 1000$ s
Characteristic velocity	$V_1 \approx 10^7$ cm/s	$V_2 \approx c/10 \approx 10^9$ cm/s
Characteristic acceleration	$g_1 \approx 10^{16}$ cm/s^2	$g_2 \approx 10^6$ cm/s^2

The acceleration of supernovae is very weak !!!

Characteristics of the Rayleigh-Taylor Instability (RTI) :

Instability growth rate: $\alpha_{IRT,\,i} \approx \sqrt{g_i / \ell_i}$

We should compare $\alpha_{IRT,\,i}$ to the proper time τ_i of the system S_i

Physical quantities	S1 (target)	S2 (supernova)
Instability rate α_{IRT}	$\alpha_{IRT,1} \approx 10^9$ s^{-1}	$\alpha_{IRT,2} \approx 10^{-3}$ s^{-1}
Dimensionless numb. N_{IRT}	$N_{IRT,1} \approx 1$	$N_{IRT,2} \approx 1$

THE DIMENSIONLESS NUMBER N_{IRT} IS GIVEN BY THE PRODUCT $N_{IRT} = \alpha_{IRT}.\tau$ FOR EACH SYSTEM

N_{IRT}(target) = N_{IRT}(supernova) !!!

and the common value is about 1

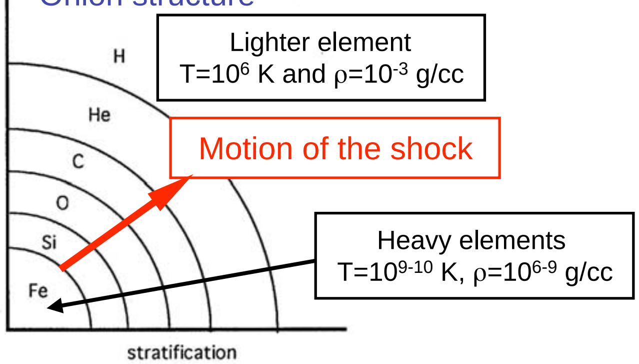
The physics of both objects is similar

SUPERNOVA SN87A: SIMULATION vs EXPERIMENT

Scaling laws : Rayleigh - Taylor instabilities

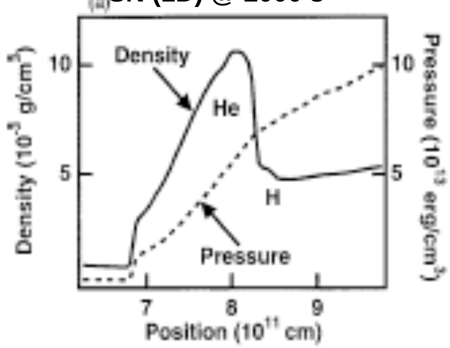
EXPERIMENTS from DRAKE's GROUP :

Onion structure

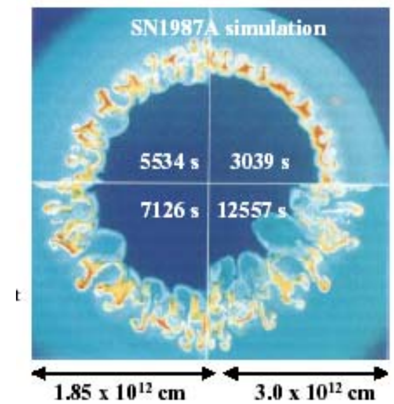


Ryutov et al., Phys. Plasmas 8 (2001) 1804

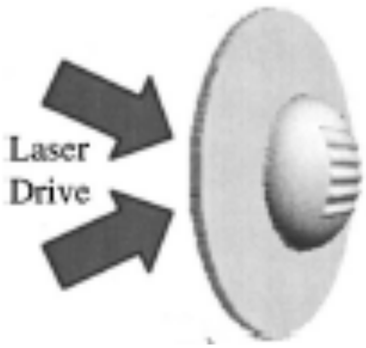
SN (1D) @ 2000 s



Muller et al., Astron. Astrophys. 251 (1991) 505

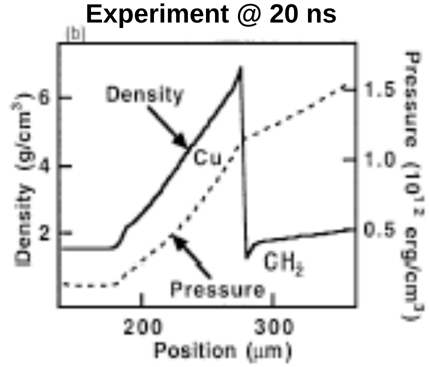


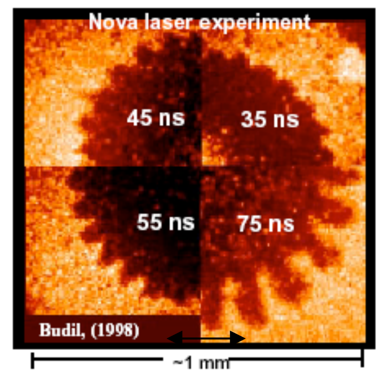
Robey et al., Phys. Plasmas 8 (2001) 2448



Ryutov et al., ApJ 518 (1999) 821

Experiment @ 20 ns





Length: $100\ \mu m \longleftrightarrow 10^{11}\ cm$ and Time: $20\ ns \longleftrightarrow 2000\ s$

Therefore: Velocity: $100\ km/s \longleftrightarrow 10\ 000\ km/s$

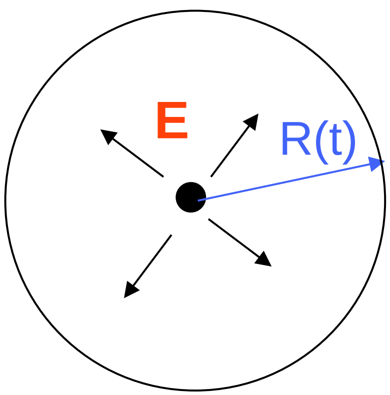
10 000 km/s is relevant for SN remnants
100 km/s is relevant for laser targets

J. Kane et al., Phys. Plasmas 6 (1999) 2065

STRONG EXPLOSION, DIMENSIONLESS NUMBER and SELF-SIMILAR SOLUTION

Strong point explosion with energy E in an ambiant medium of uniform density ρ_0

Fireball



density ρ_0

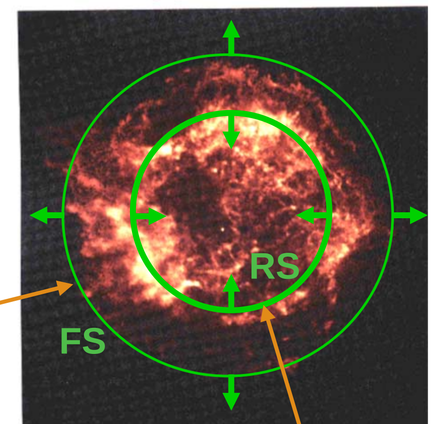
Time position of the shock, R(t)???

Use of Dimensional analysis

Unit of mass: M
Unit of length: L
Unit of time: T

$[E] = M.L^2.T^{-2}$
$[\rho_0] = M.L^{-3}$
$[R] = L$

Cassiopée A (1680)
Type Ia SN



Forward shock

Reverse shock

Ratio $E/\rho_0 \sim L^5.T^{-2}$ → M dissappears

Product $(E/\rho_0).t^2 \sim L^5$ → M and T dissappear

Time t is inserted !!! Nice !!!

<u>CONCLUSION</u> : $(E/\rho_0).t^2 / [R(t)]^5 \sim \xi$: Dimensionless Number

and $\boxed{R(t) \sim (E/\rho_0)^{1/5} .t^{2/5}}$ **Sedov - Taylor law**

$R(t) \sim t^{\alpha}$: SELF-SIMILAR EVOLUTION

SEDOV - TAYLOR SOLUTION

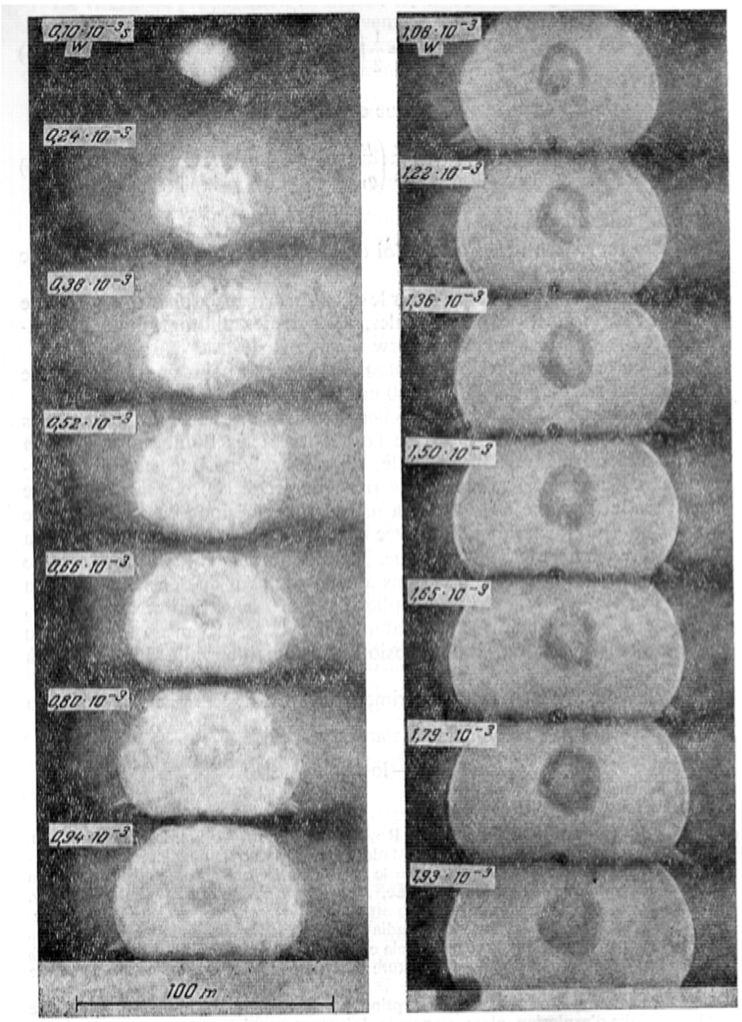


Fig. 67. Photographies d'une boule de feu prise dans l'intervalle de $t=0{,}1\cdot10^{-3}$ à $t=1{,}93\cdot10^{-3}$ s lors de l'explosion de la bombe atomique à New Mexico

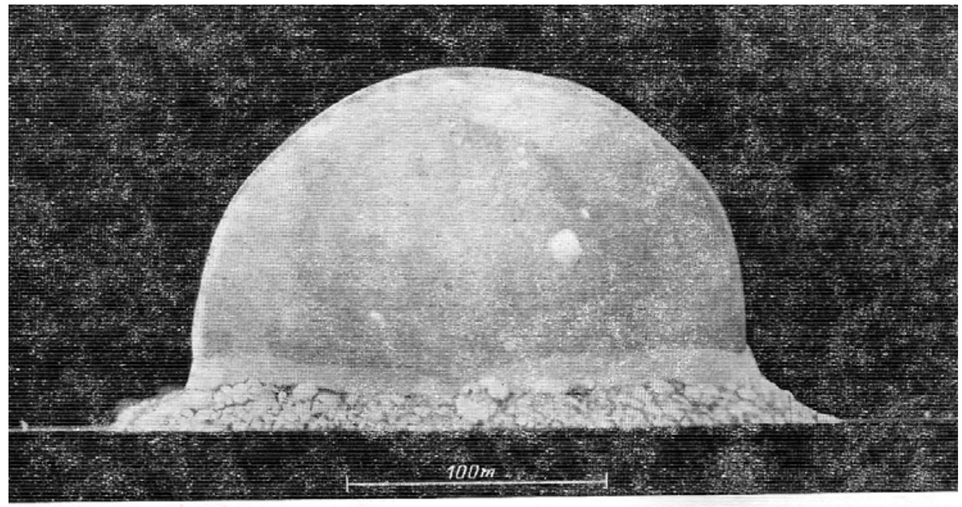
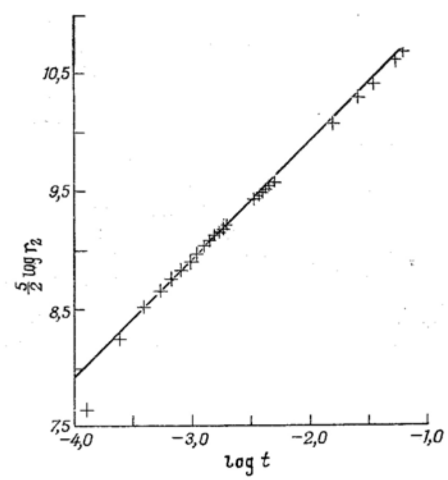


Fig. 68. Boule de feu à l'instant $t=15\cdot10^{-3}$ s

Measurements Vs. Theory



$\boxed{R(t) \sim t^{2/5}}$

Self-Similar Solution (SSS)

- **Fireball:** **R ~ 100 m ~ 10^4 cm**
- **Supernova remnant:** **R ~ 1pc ~ 3.10^{18} cm**

SAME BEHAVIOUR

INVARIANCE - SCALING LAWS

Model equation: Non-linear heat equation

$$\frac{\partial T}{\partial t} = D.\frac{\partial^2 T^n}{\partial x^2}$$

T: temperature (D: diffusion coefficient = cst.)

<u>Solution</u>: **T = S(x,t)** where S is a known function

INVARIANCE under the transformation:

D. Ryutov et al., ApJ 518 (1999) 821

Independent variables: x and t

$x = \lambda_x . \bar{x}$, $t = \lambda_t . \bar{t}$

Dependent variable: T(x,t)

$T = \lambda_T . \bar{T}$

λ_x , λ_t and λ_T : Scaling parameters

$$\frac{\lambda_T}{\lambda_t} . \frac{\partial \bar{T}}{\partial \bar{t}} = \frac{(\lambda_T)^n}{(\lambda_x)^2} . D.\frac{\partial^2 \bar{T}^n}{\partial \bar{x}^2}$$

$$\frac{\partial \bar{T}}{\partial \bar{t}} = \frac{\lambda_t.(\lambda_T)^{n-1}}{(\lambda_x)^2} . D.\frac{\partial^2 \bar{T}^n}{\partial \bar{x}^2}$$

$$\boxed{\frac{\partial \bar{T}}{\partial \bar{t}} = D.\frac{\partial^2 \bar{T}^n}{\partial \bar{x}^2}} \quad \boxed{\frac{\lambda_t.(\lambda_T)^{n-1}}{(\lambda_x)^2} = 1}$$

The equation is **invariant** under the transformation

Solution: $\bar{T} = \bar{S}(\bar{x}, \bar{t})$ but $\bar{S} = S$

λ_x and λ_t are arbitrary !

$\lambda_T = [(\lambda_x)^2 / (\lambda_t)]^{1/(n-1)}$

The solution is **invariant**

The solutions are **the same** at **both scales**

Two free parameters (!!!) to make the 2 systems homothetic

LIE GROUP VIEW POINT

The equation $\dfrac{\partial T}{\partial t} = D.\dfrac{\partial^2 T^n}{\partial x^2}$ is invariant under the transformation:

$x = \lambda_x . \bar{x}$, $t = \lambda_t . \bar{t}$, $T = \lambda_T . \bar{T}$ provided the relation $\lambda_T = [(\lambda_x)^2 / (\lambda_t)]^{1/(n-1)}$ holds.

$$\frac{T \, . \, t^{1/(n-1)}}{(x^2)^{1/(n-1)}} = \frac{\bar{T} \, . \, \bar{t}^{1/(n-1)}}{(\bar{x}^2)^{1/(n-1)}} = \mathrm{I} =$$

INVARIANT of the transformation

It is not a dimensionless number !

Relation between the quantities of the 2 systems

Combine x and t: S.S.S are obtained

$$\boxed{\frac{\lambda_t . (\lambda_T)^{n-1}}{(\lambda_x)^2} = 1}$$

λ_x , λ_t and λ_T : Scaling parameters

$x = a^{\delta_1} \bar{x}$; $t = a^{\delta_2} \bar{t}$ and $T = a^{\delta_3} \bar{T}$ (a: group parameter)

$$\frac{a^{\delta_2} . \left(a^{\delta_3}\right)^{n-1}}{\left(a^{\delta_1}\right)^2} = 1 \Leftrightarrow \delta_2 + (n-1)\delta_3 - 2\delta_1 = 0$$

Two free parameters !

The constraint is a linear equation between the δ_i's

SYSTEMATIC AND RIGOUROUS APPROACH BASED ON LIE GROUP SYMMETRIES

Dimensionless numbers, invarants, S.S.S's, EDP's become EDO's, analytical solutions …

BROKEN SYMMETRY

Add a linear term (still very simple equation !)

$$\frac{\partial T}{\partial t} = D.\frac{\partial^2 T^n}{\partial x^2} + T$$

Independent variables: x and t

$x = \lambda_x . \bar{x}$, $t = \lambda_t . \bar{t}$

Dependent variable: T

$T = \lambda_T . \bar{T}$

$$\frac{\lambda_T}{\lambda_t} . \frac{\partial \bar{T}}{\partial \bar{t}} = \frac{(\lambda_T)^n}{(\lambda_x)^2} . D.\frac{\partial^2 \bar{T}^n}{\partial \bar{x}^2} + \lambda_T . \bar{T}$$

$$\frac{\partial \bar{T}}{\partial \bar{t}} = \frac{\lambda_t.(\lambda_T)^{n-1}}{(\lambda_x)^2} . D.\frac{\partial^2 \bar{T}^n}{\partial \bar{x}^2} + \lambda_t . \bar{T}$$

$\lambda_t = 1$: no scaling for time

One symmetry is lost

$\boxed{\frac{\lambda_t.(\lambda_T)^{n-1}}{(\lambda_x)^2} = 1}$ becomes $\boxed{\lambda_T = (\lambda_x)^{2/(n-1)}}$

$$\frac{\partial \bar{T}}{\partial \bar{t}} = D.\frac{\partial^2 \bar{T}^n}{\partial \bar{x}^2}$$

The equation is **invariant** under the transformation

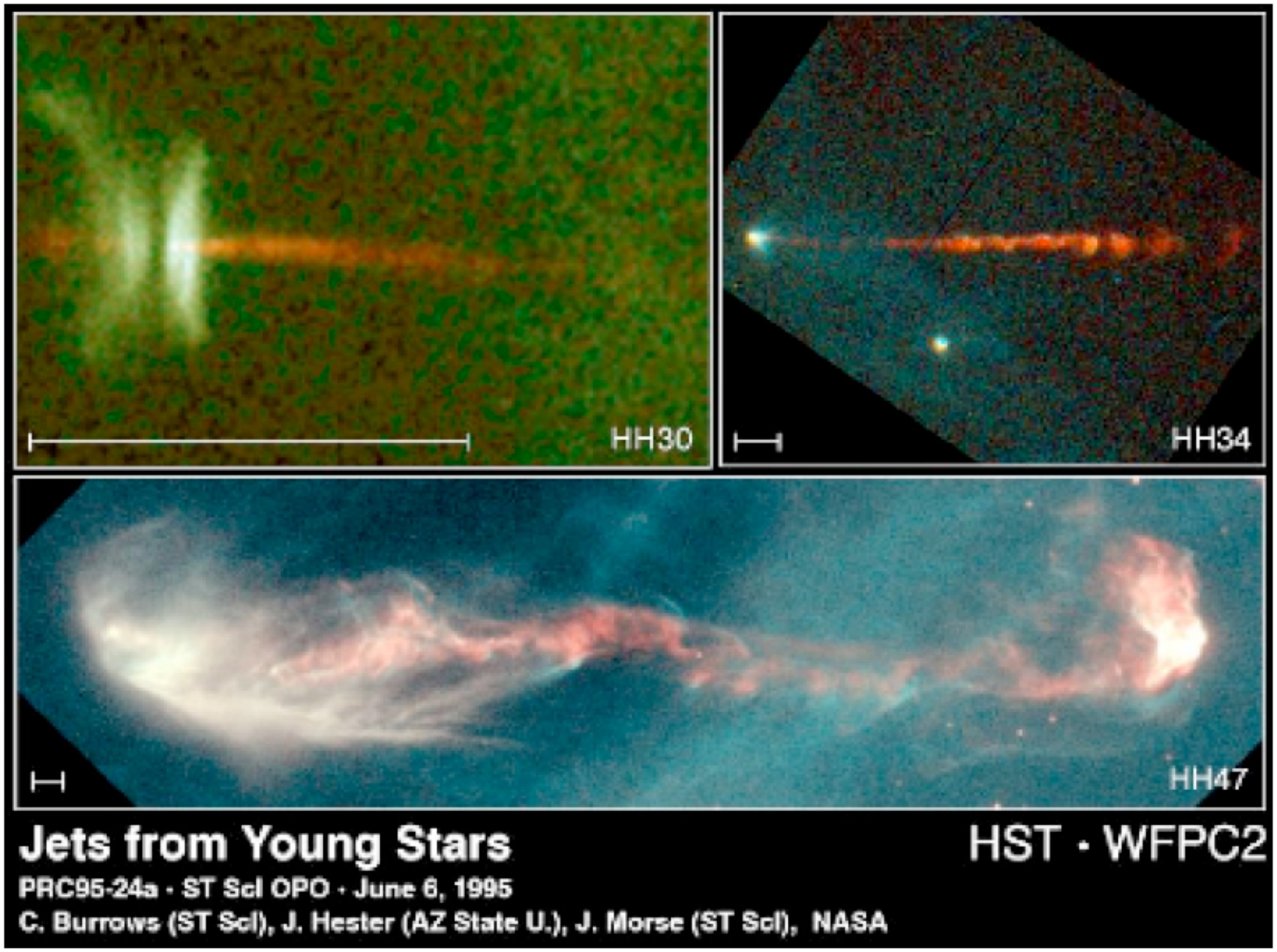
Solution: $\bar{T} = \bar{S}(\bar{x}, t)$ but $\bar{S} = S$ **!**

The solution is **invariant** but with **a single time** ($t = \bar{t}$) **!**

Too much terms or too much equations : **no symmetry at all**

YOUNG STELLAR OBJECTS JETS

Herbig - Haro Objects



Unit : 1 000 au

(1 au = 1.5 10^{13} cm
et 1 pc = 2 10^{5} au)

Length from
1 000 au
to
0.1 pc

Differences
in the structure

INVARIANCE OF RADIATION HYDRODYNAMICS ?

Optically thin radiation hydrodynamics

- $\frac{\partial \rho}{\partial t} + \vec{\nabla}_N.[\rho \vec{v}] = 0$ (N=0: plane, N=1: cylindrical, N=2: spherical geometry)
- $\left[\frac{\partial}{\partial t} + (\vec{v}.\vec{\nabla})\right].\vec{v} = -\frac{1}{\rho}\vec{\nabla}P$
- $\left[\frac{\partial}{\partial t} + (\vec{v}.\vec{\nabla})\right].P - \gamma \frac{P}{\rho}\left[\frac{\partial}{\partial t} + (\vec{v}.\vec{\nabla})\right].\rho = -(\gamma - 1).\Lambda(\rho, P)$

$\Lambda(\rho,P)$ = cooling function

$\boxed{\Lambda(\rho,P) = \Lambda_0 \rho^{\varepsilon} P^{\zeta}}$

Λ_0= constant

Power law form

Exponents ε and ζ

$\boxed{\Lambda(\rho,P) \;\rightarrow\; \Lambda(\rho,T)}$ $P = \varepsilon_0 [Z] \rho^{\mu} T^{\nu}$

Invariance ?

$$x = a^{\delta_1}\tilde{x};\quad t = a^{\delta_2}\tilde{t};\quad \rho = a^{\delta_3}\tilde{\rho};\quad v = a^{\delta_4}v;$$

$$P = a^{\delta_5}\tilde{P};\quad T = a^{\delta_6}\tilde{T};\quad M = a^{\delta_7}\tilde{M};\quad \gamma = a^{\delta_8}\tilde{\gamma};\quad \epsilon_0 = a^{\delta_9}\tilde{\epsilon}_0;\quad \Lambda = a^{\delta_{10}}\tilde{\Lambda}$$

« upper tilde » instead of an « upper bar » ($\tilde{x}$!!!)

Solve a linear system of equations for the δ_i's

Yes !

SCALING LAWS

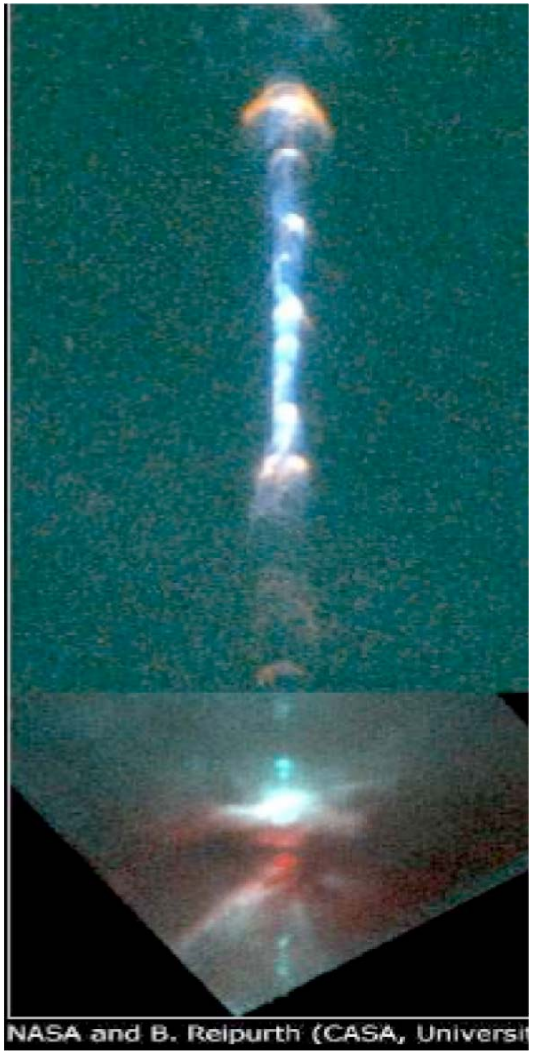
$x = \lambda_x . \bar{x} \longrightarrow q = \lambda_q . \bar{q} \longrightarrow q = \lambda_q . \tilde{q}$ and $\lambda_i \equiv a^{\delta_i}$ i = r, t, v, … = **1, 2, 3, …**

a:Group parameter

Ratios	General laws	A single cooling ε_1 and ζ_1	Bremsstrahlung	
$x/\tilde{x}$	a^{δ_1}	$a^{(3/2-\zeta_1)\delta_5-(\epsilon_1+1/2)\delta_3}$	$a^{\delta_5-2\delta_3}$	B/A^2
$t/\tilde{t}$	$a^{\delta_1+(\delta_3-\delta_5)/2}$	$a^{(1-\zeta_1)\delta_5-\epsilon_1\delta_3}$	$a^{(\delta_5-3\delta_3)/2}$	$(B/A^3)^{1/2}$
$\rho/\tilde{\rho}$	a^{δ_3}	a^{δ_3}	a^{δ_3}	**≡A**
$v/\tilde{v}$	$a^{(\delta_5-\delta_3)/2}$	$a^{(\delta_5-\delta_3)/2}$	$a^{(\delta_5-\delta_3)/2}$	$(B/A)^{1/2}$
$P/\tilde{P}$	a^{δ_5}	a^{δ_5}	a^{δ_5}	**≡B**
$T/\tilde{T}$	$a^{(\delta_5-\delta_9-\mu\delta_3)/\nu}$	$a^{\delta_5-\delta_3}$	$a^{(\delta_5-\delta_3)}$	B/A
$M/\tilde{M}$	$a^{\delta_3+N\delta_1}$	$a^{[1-N(\epsilon_1+1/2)]\delta_3+N(3/2-\zeta_1)\delta_5}$	$a^{[1-2N]\delta_3+N\delta_5}$	$A^{(1-2N)}.B^N$ N: dimensionality
$s/\tilde{s}$	$a^{\delta_5-\gamma\delta_3}$	$a^{\delta_5-\gamma\delta_3}$	$a^{\delta_5-\gamma\delta_3}$	B/A^γ γ: polytropic constant
$\Lambda_{0,1}/\tilde{\Lambda}_{0,1}$	$a^{(3/2-\zeta_1)\delta_5-(\epsilon_1+1/2)\delta_3-(\theta_1+1)\delta_1}$	1	1	
$\Lambda_{0,2}/\tilde{\Lambda}_{0,2}$	$a^{(3/2-\zeta_2)\delta_5-(\epsilon_2+1/2)\delta_3-(\theta_2+1)\delta_1}$	0	0	
	δ_1, δ_3 et δ_5 Three free parameters	δ_3 et δ_5 Two free parameters	δ_3 et δ_5 $(\varepsilon_1 = 3/2; \zeta_1 = 1/2)$	

E. Falize et al., Inertial Fusion Sc. Appl. (IFSA07), Kobe, Japan (2007)
E. Falize et al., Journal Physics: Conf. Series 112 (2008) 042015
E. Falize et al., Astrophys. Sp. Sc., to appear (2009)

ASTROPHYSICS and EXPERIMENTS



HH 111

Velocity (about 100 km/s) and temperature (about 10 000 K) are kept invariants

⟷ δ_3 et δ_5 are calculated:

Wrong, indeed !!!
Use length.

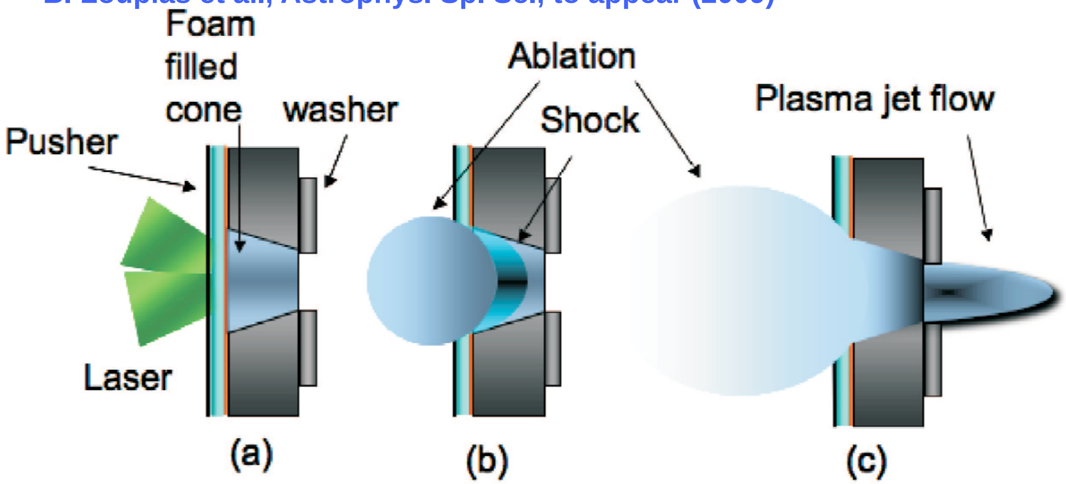
$A \equiv \rho_{astro}/\rho_{lab}$, $B \equiv P_{astro}/P_{lab}$,

$A \approx 3B \approx 2.10^{-19}$

Physical quantities	Cold protostellar jet (HH111)	Experimental values	Scaling factor
Length (cm)	3.10^{17}	0.1	3.10^{18}
Time (s)	3.10^{10}	10^{-8}	3.10^{18}
Velocity (km/s)	100	100	1
Density (g/cm^3)	2.10^{-22}	10^{-3}	2.10^{-19}
Density (part/cm^3)	100	10^{17}	10^{-15}
Temperature (K)	10 000	10 000	1

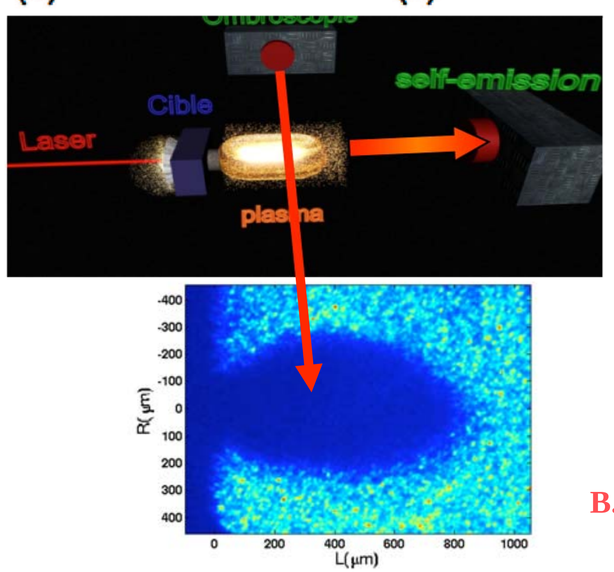
LASER TARGETS

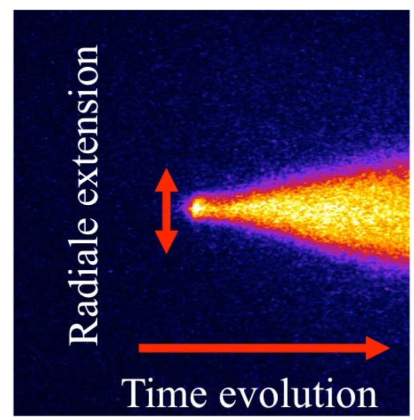
B. Loupias et al., Phys. Rev. Lett. 99 (2007) 265001
B. Loupias et al., Astrophys. Sp. Sc., to appear (2009)



- Différente **densité** : de 20mg/cc à 200mg/cc
- Mousse **dopée** : Br, Cl
- Avec et sans **cible solide**
- Différent **angle de cône** : 38° et 22°
- Différente **intensité laser** : 5.10^{14}W/cm², 7.10^{13}W/cm² ou 3.10^{13}W/cm²
- Différent **profil laser**: Gaussien (RPP) ou supergaussien (PZP)
- Avec ou sans « **washer** »

LULI 2000 laser facility

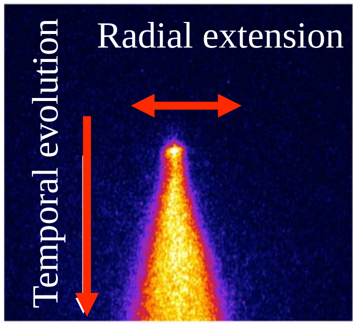




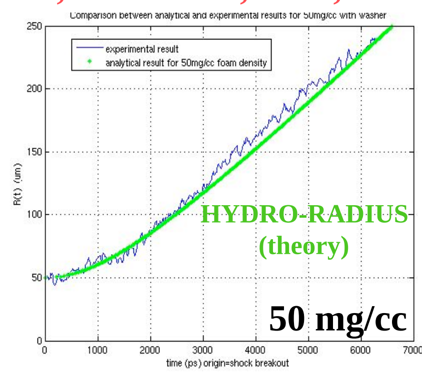
B. LOUPIAS, PhD Thesis, Paris, October 21, 2008

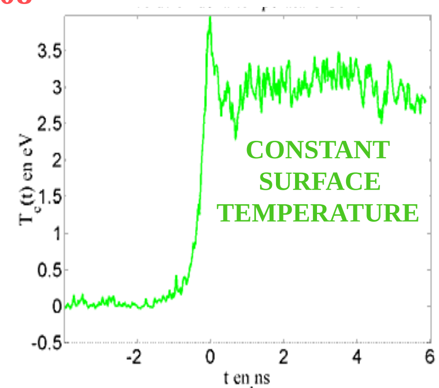
COMPARISON
THEORY / JET EXPERIMENTS

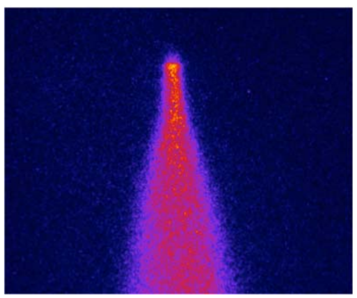
E. FALIZE, PhD Thesis, Paris, October 23, 2008



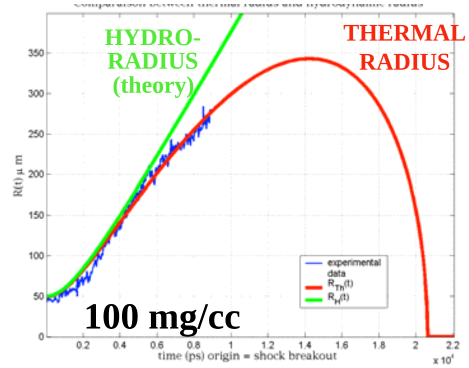
Into vacuum

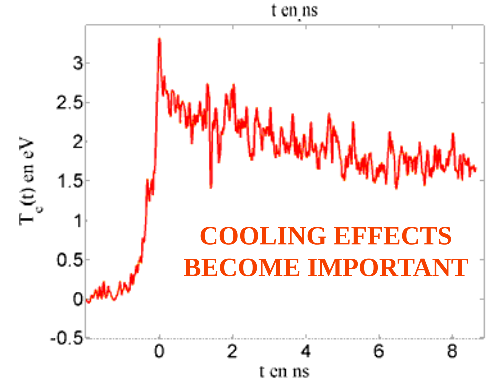






Into vacuum

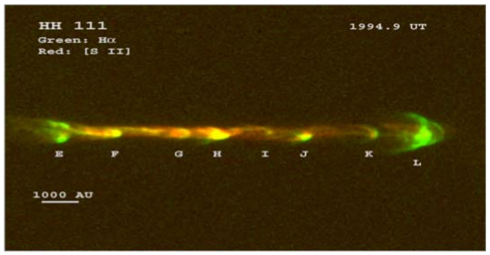


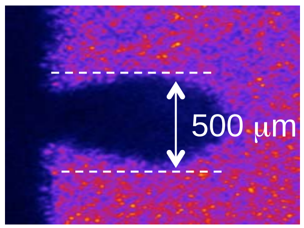


	Re	Pe = F_{conv}/ F_{cond}	$\chi = t_{cool}/t_{dyn}$	Mach	$\zeta = \lambda_{mfp}/ L_{hydro}$
YSO jet	10^7	10^6	0.1 - 10	10 - 30	10^{-7}
Exp. 5 ns	10^6	10^3	100	2	10^{-7}
Exp. 25 ns	10^5	10^2	10	20	10^{-7}

INFLUENCE of an AMBIANT MEDIUM

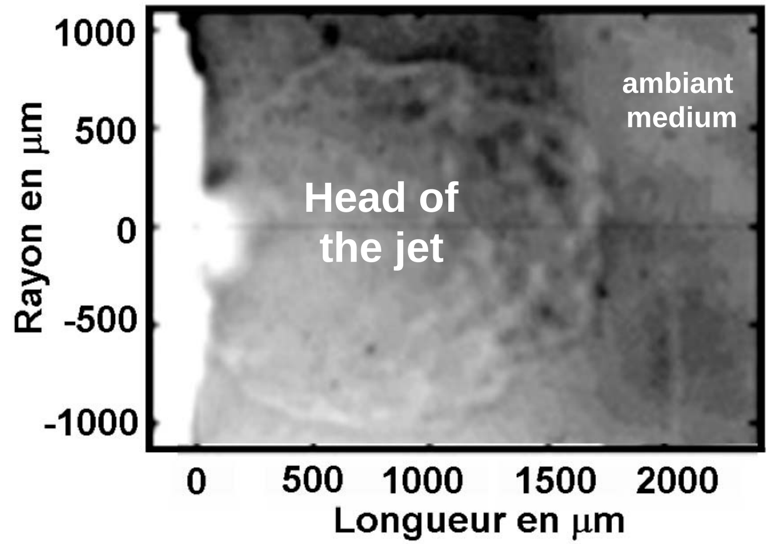
C.D. Gregory et al., PPCF 50(2008)124039





Into vacuum

Into argon gaz (ambiant medium), t = 30 ns



Rayleigh – Taylor instability (RTI):

$$\omega = \sqrt{At.g.k}$$

$At = \dfrac{\rho_2 - \rho_1}{\rho_2 + \rho_1}$: Atwood, ρ_2: heavy, ρ_1: light, g: deceleration, k: wave number

ρ_2 = 1 mg/cc, ρ_1 = 0.04 mg/cc, $\eta = \rho_{jet}/\rho_{ambiant}$ = 25 (= 0.1 – 10), At = 1

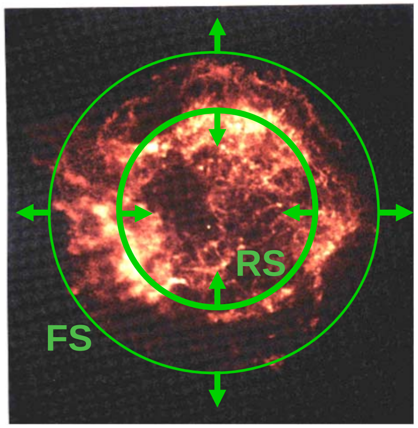
g = 60 (km/s) / 30 (ns) = 2 μm / (ns)^2 , λ = 100 μm

$$\boxed{\tau_{RTI} = 1/\omega \approx 3\,ns}$$

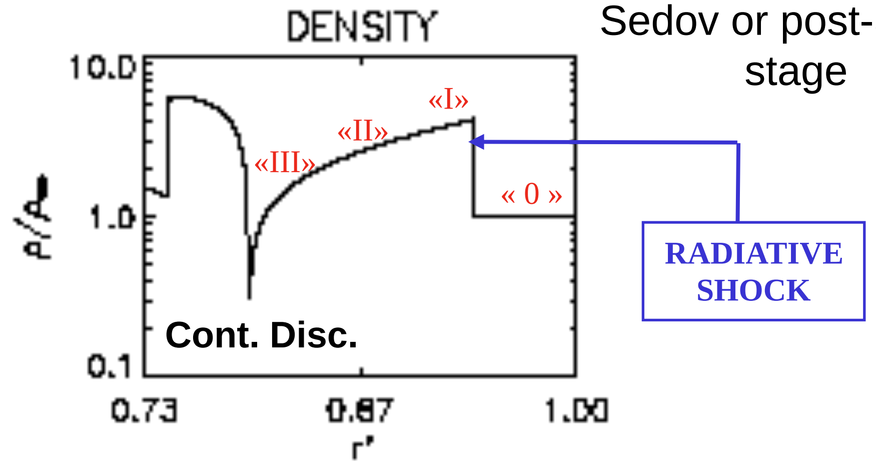
RTI may play a role in the structure of the BOW SHOCK

HIGHER RESOLUTION REQUIRED IN OBSERVATIONS + Compressible effects …

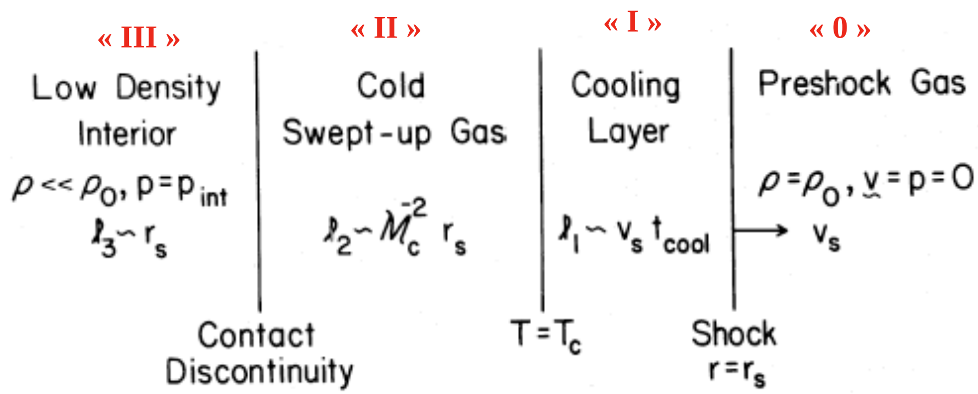
RADIATIVE SHOCK in SNR 's



Sedov or post-Sedov stage



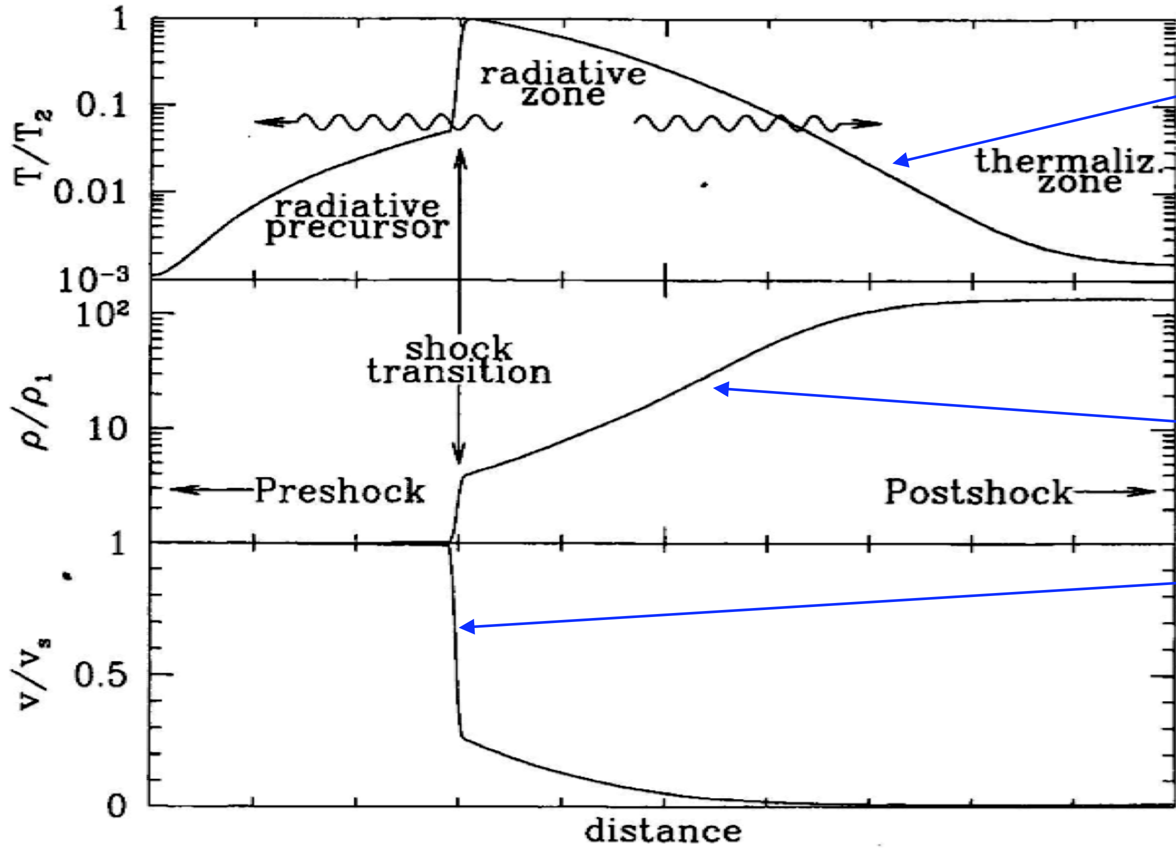
Dwarkadas and Chevalier, ApJ 497 (1998) 497



E. Bertschinger, ApJ 304(1986)154

RADIATIVE SHOCK in SNR 's

Motion of the Forward Radiative Shock



B.T. Draine & C.F. McKee, Annual Rev. Astron. Astrophys. 31, 373 (1993)

T decreases due to the cooling (radiative flux ahead the sock)

therefore

ρ increases (first the compression is 4 and becomes much larger)

The velocity is normalized to the shock velocity

Radiative precursor: the energy goes through the discontinuity and heats the medium ahead of the shock.

Also in supernovae: $\rho_{downstr.} / \rho_{upst.} = 7$ ($\gamma = 4/3$)

OPTICALLY THICK RADIATION HYDRODYNAMICS

- $$\frac{\partial\rho}{\partial t} + \vec{\nabla}.[\rho\vec{v}] = 0$$
- $$\left[\frac{\partial}{\partial t} + (\vec{v}.\vec{\nabla})\right]\vec{v} = -\frac{1}{\rho}\vec{\nabla}(P_{th} + P_{rad}),$$ $$P_{th} = \varepsilon_0[Z]\rho^{\mu}T^{\nu},$$ $$P_{rad} = a_R T^4/3$$
  $\mu = \nu = 1$, Ideal Gas
- $$\frac{d}{dt}\left(\frac{P_{th}}{\gamma-1} + E_{rad}\right) - \gamma\frac{P_{th}/(\gamma-1) + P_{th} + E_{rad} + P_{rad}}{\rho}\frac{d\rho}{dt} = -\vec{\nabla}.\vec{F}_{rad} - Q(\rho,T)$$

$$\frac{d}{dt} = \left[\frac{\partial}{\partial t} + (\vec{v}.\vec{\nabla})\right]$$

$$E_{rad} = a_R T^4$$

$$\vec{F}_{rad} = -\kappa_{rad}\vec{\nabla}T, \quad \kappa_{rad} = \kappa_0\rho^m T^n$$

$Q(\rho, T)$ = heating source/cooling

m = -2, n = 7/2, Kramers opacity
Stellar structure, stellar evolution

Invariance ?

SCALING INVARIANCE … … YES !!!

$P_{rad}/P_{th} << 1$ and $E_{rad}/E_{th} << 1$

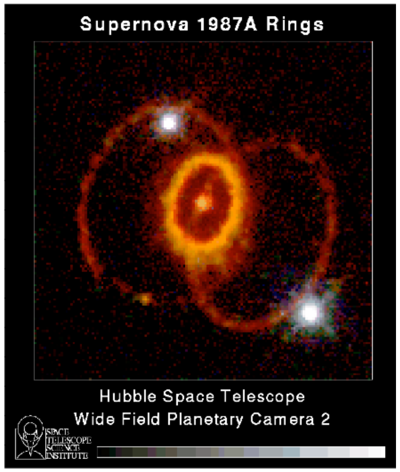
$\mu = \nu = 1$, Ideal Gas and m = -2, n = 7/2, Kramers opacity

quotients	Invariance absolue
$x/\tilde{x}$	$a^{[m+1/2-(n+1)\mu/\nu]\delta_3+[(n+1)/\nu-3/2]\delta_5}$
$t/\tilde{t}$	$a^{[m+1-(n+1)\mu/\nu]\delta_3+[(n+1)/\nu-2]\delta_5}$
$\rho/\tilde{\rho}$	a^{δ_3}
$v/\tilde{v}$	$a^{(\delta_5-\delta_3)/2}$
$P/\tilde{P}$	a^{δ_5}
$T/\tilde{T}$	$a^{(\delta_5-\mu\delta_3)/\nu}$
$\epsilon_0/\tilde{\epsilon}_0$	1
$F_{rad}/\tilde{F}_{rad}$	$a^{3\delta_5/2-\delta_3/2}$
$\kappa_{rad}/\tilde{\kappa}_{rad}$	$a^{n\delta_5/\nu+[m-n\mu/\nu]\delta_3}$
$\kappa_0/\tilde{\kappa}_0$	1

Two free parameters again $A \equiv \rho_{astro}/\rho_{lab}$, $B \equiv P_{astro}/P_{lab}$,

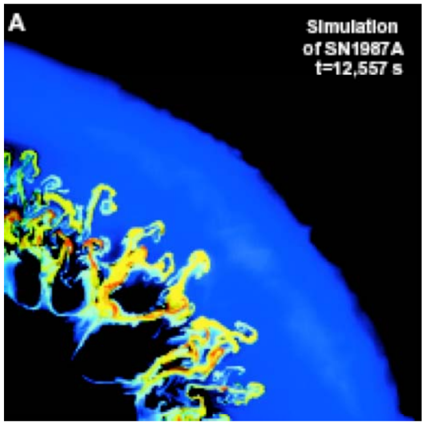
SCALING FACTORS

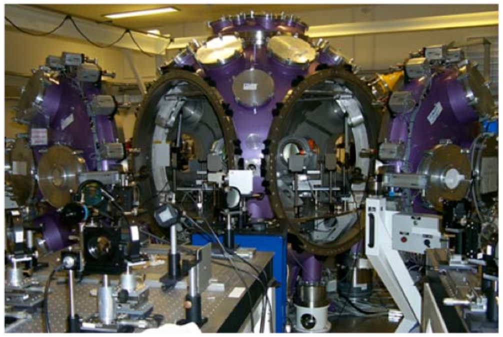
$A \equiv \rho_{astro}/\rho_{lab}$, $B \equiv P_{astro}/P_{lab}$, $A \approx 10^8$; $B \approx 3.10^{-14}$

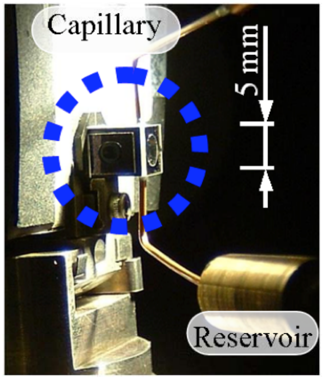


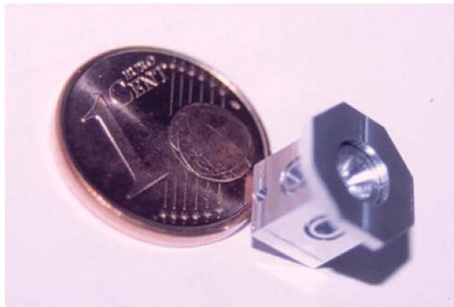
Physical quantities	Supernova	Experiments	Scaling factors
Length (cm)	10^{12}	0.01 (100 microns)	10^{14}
Time (s)	3600	10^{-8}	$3.6\ 10^{11}$
Velocity (km/s)	c/2 !!!	100	10^3
Density (g/cm^3)	10^{-2}	10^{-5}	10^3
Temperature (K)	10^{10}	10 000	10^6

Muller et al. Astron. Astrophys. (1991)

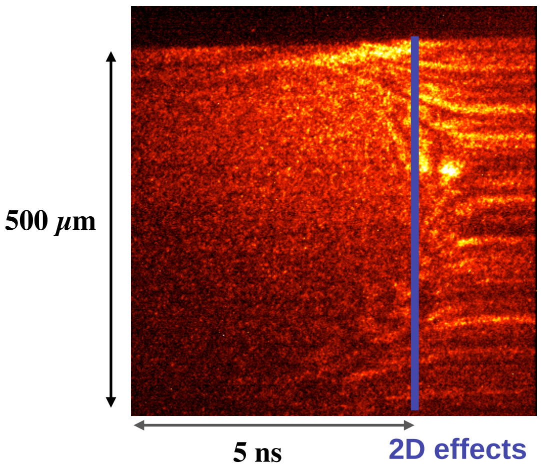




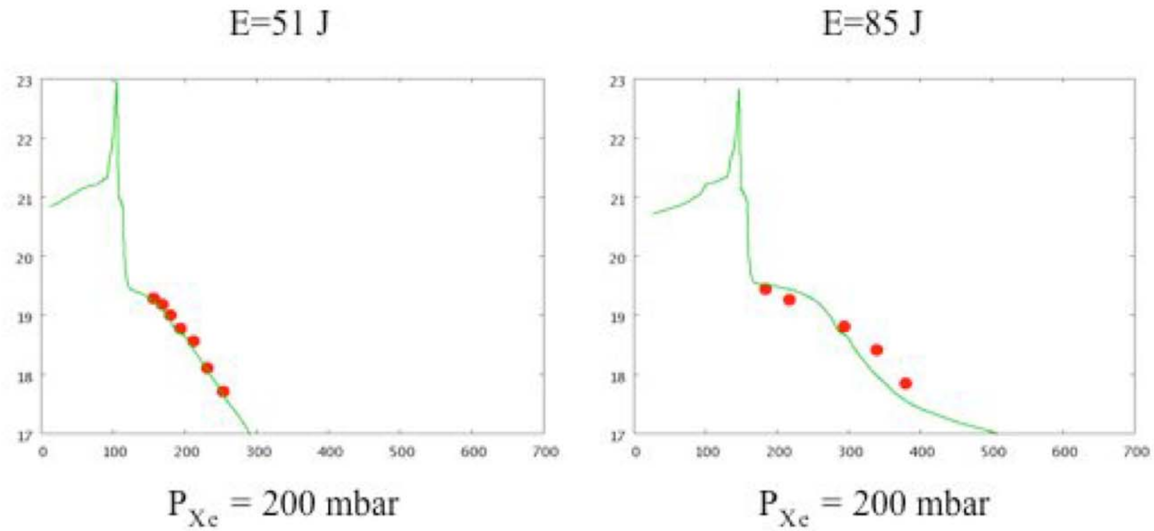


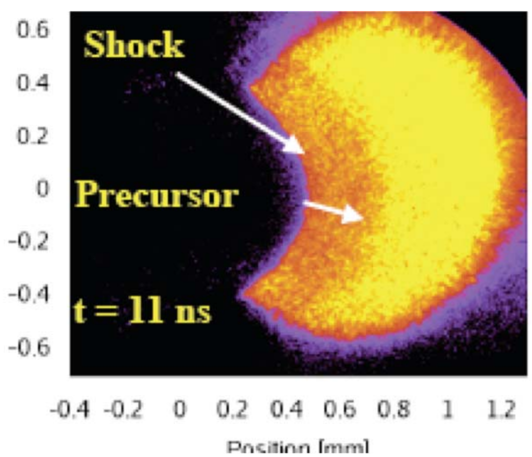


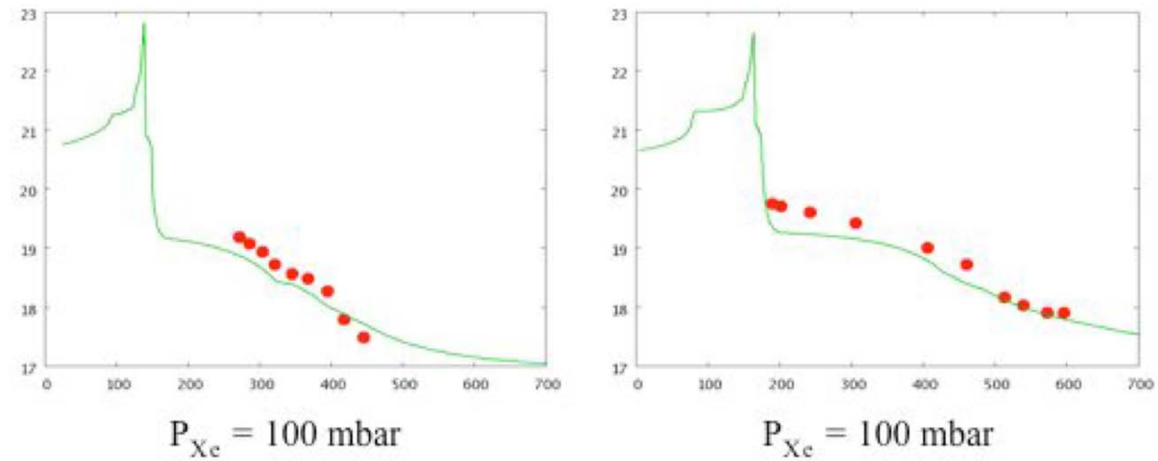
LULI EXPERIMENTS VS. NUMERICAL SIMULATION



2D effects
Deviation to
Plane geometry



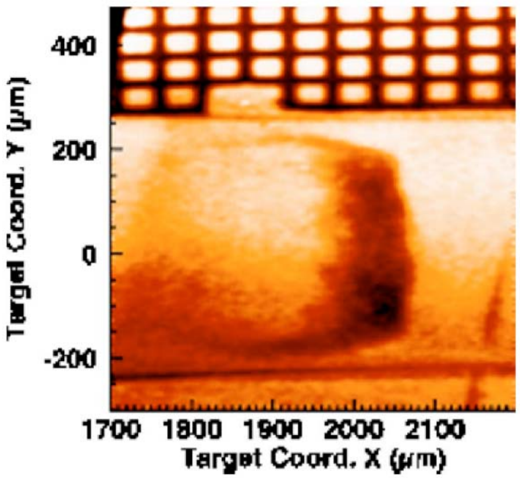


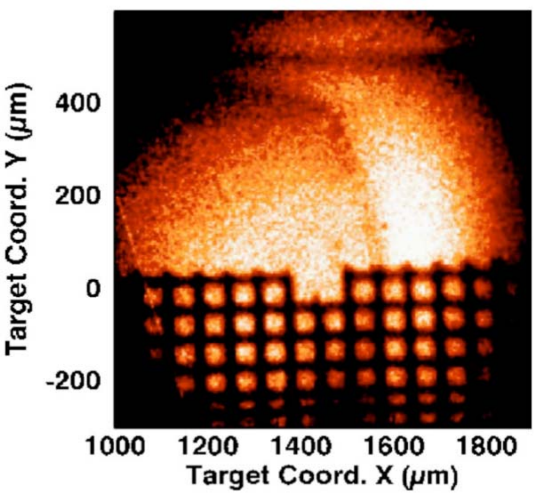


Bouquet et al., PRL (2004), Koenig et al., APIP-AIP, CP926 (2007) 110 , Michaut et al., ApSS, to appear (2009)

OMEGA EXPERIMENTS

Amy Reighard (Cooper), Paul Drake, Laurent Boireau, Paul students …





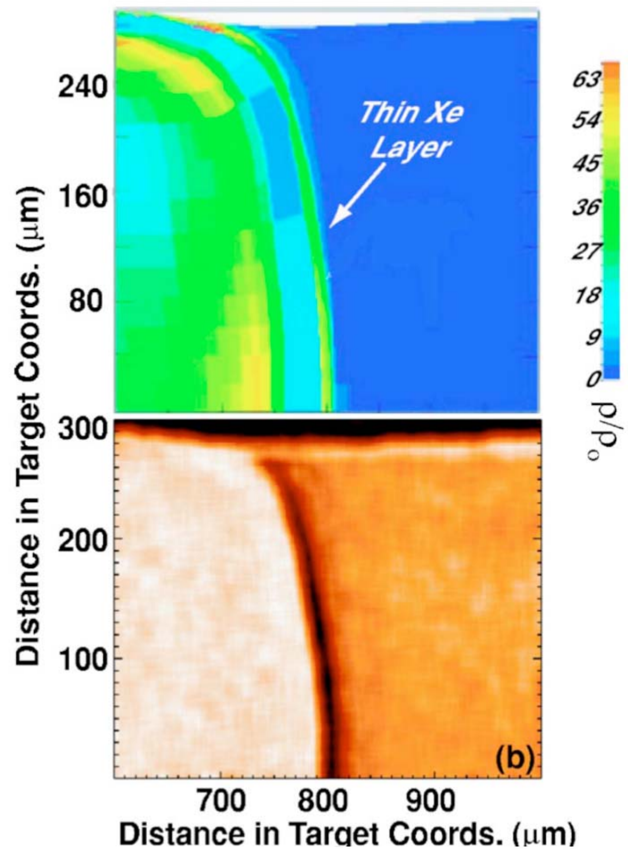


FIG. 5. (Color online) (a) Density profile at 7 ns, from a 2D simulation of the experiment, using the FCI code. The shock is moving to the right. The color bar calibrates the density as a ratio to the initial gas density. (b) Simulated radiograph, using density data from (a). Poisson noise and a point-spread function from data are included.

High compression rate in the shocked material

Reighard et al., PoP 13 (2006) 032901

CONCLUSION

1) – For the first time, rigourous derivation of scaling laws have been made and the connection between experiments and astrophysical objects is 1 to 1

2) – Coherence and redundance of the models

3) – Laboratory astrophysics is a relevant approach