energie atomique • energies alternatives

Laboratoire de l’Accélateur Linéaire (LAL)
Orsay, mardi 18 janvier 2011

LABORATORY ASTROPHYSICS with HIGH-ENERGY-DENSITY FACILITIES

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

CEA/DAM/DIF
Centre de Bruyères-le-Châtel
F - 91297 Arpajon, France

Emeric FALIZE and Bérénice LOUPIAS
- Claire MICHAUT and LUTH group (CNRS, Observatoire de Paris),
- Michel KOENIG and LULI group (CNRS, Ecole polytechnique),
- Xavier RIBEYRE (CEA-CESTA/CELIA, Université of Bordeaux),

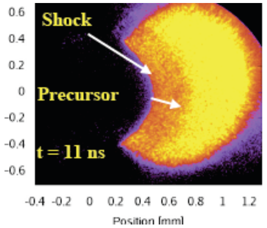
- Nigel WOOLSEY and RAL group (University of York, UK),

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

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

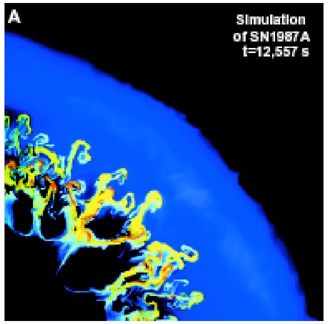
energie atomique • energies alternatives

PHILOSOPHY of LABORATORY ASTROPHYSICS

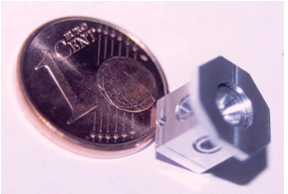


USING HIGH ENERGY/POWER TOOLS

Lasers (USA, Japan, UK, France …)



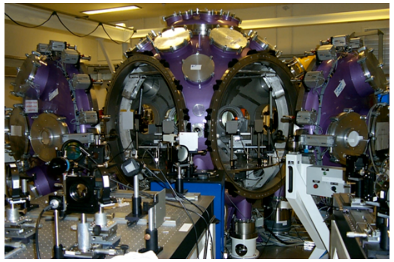
Z-pinches (Sandia, Imp. Coll.- UK …)

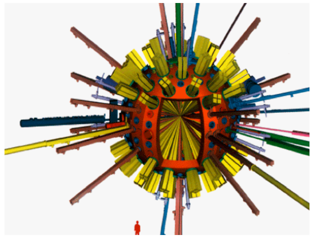


Spheromacks (Caltech’, LLNL …)

TO REPRODUCE OR TO SIMULATE

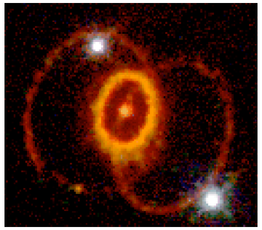
in the LABORATORY





ASTROPHYSICAL PHENOMENA

and/or



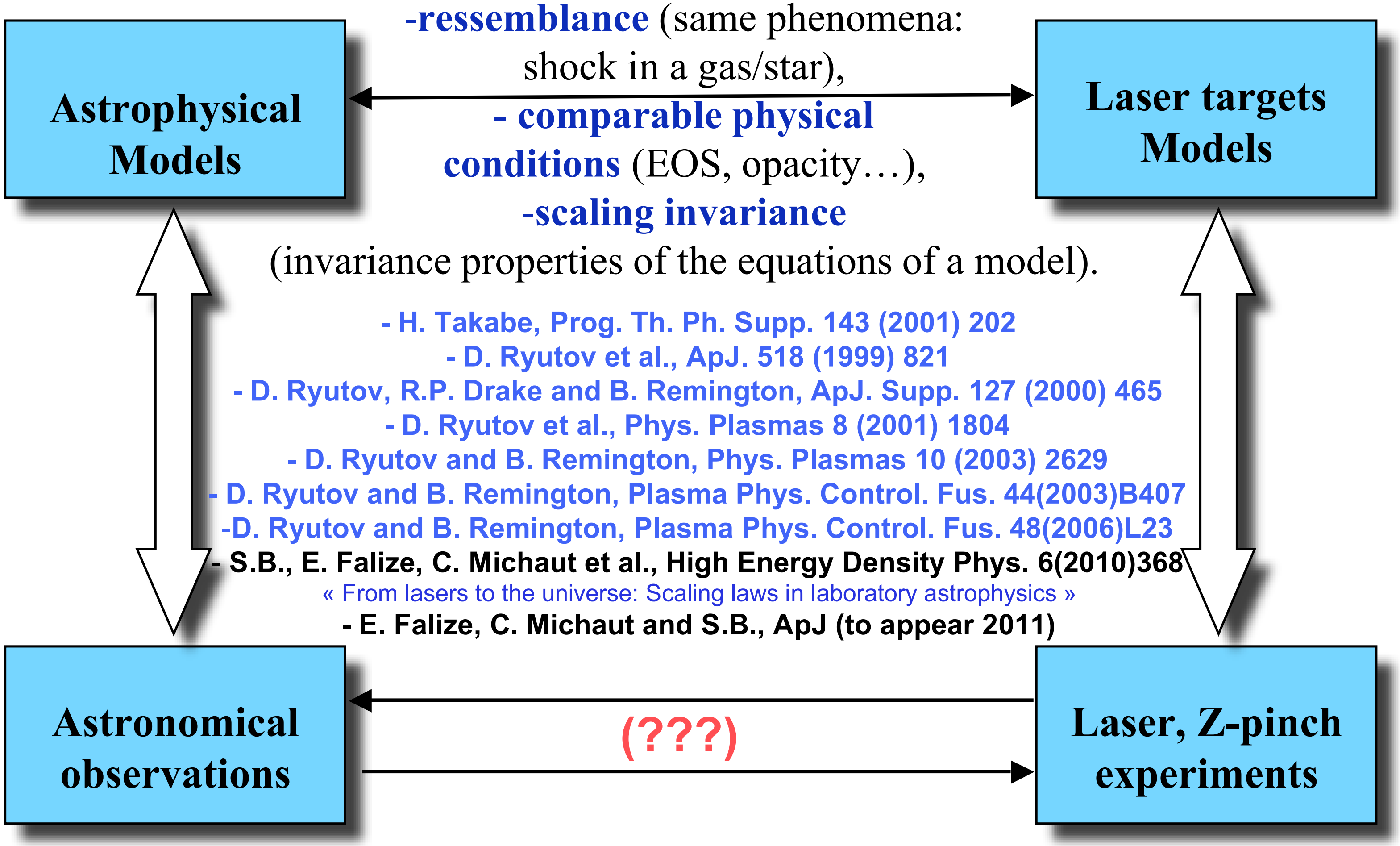
PIECES OF ASTRONOMICAL OBJECTS

OUTLINE

1) - LABORATORY ASTROPHYSICS
2) - LASER FACILITIES
3) - ASTROPHYSICAL RADIATIVE SHOCKS (RS) and LASER EXPERIMENTS
4) - ASTROPHYSICAL JETS and LASER EXPERIMENTS
5) - CONCLUSION

1) - LABORATORY ASTROPHYSICS
2) - LASER FACILITIES
3) - ASTROPHYSICAL RADIATIVE SHOCKS (RS) and LASER EXPERIMENTS
4) - ASTROPHYSICAL JETS and LASER EXPERIMENTS
5) - CONCLUSION

LASER EXPERIMENTS versus ASTRONONOMICAL OBSERVATIONS



Astrophysical Models

-ressemblance (same phenomena: shock in a gas/star),
- comparable physical conditions (EOS, opacity…),
-scaling invariance (invariance properties of the equations of a model).

Laser targets Models

- H. Takabe, Prog. Th. Ph. Supp. 143 (2001) 202
- D. Ryutov et al., ApJ. 518 (1999) 821
- D. Ryutov, R.P. Drake and B. Remington, ApJ. Supp. 127 (2000) 465
- D. Ryutov et al., Phys. Plasmas 8 (2001) 1804
- D. Ryutov and B. Remington, Phys. Plasmas 10 (2003) 2629
- D. Ryutov and B. Remington, Plasma Phys. Control. Fus. 44(2003)B407
-D. Ryutov and B. Remington, Plasma Phys. Control. Fus. 48(2006)L23
- S.B., E. Falize, C. Michaut et al., High Energy Density Phys. 6(2010)368
« From lasers to the universe: Scaling laws in laboratory astrophysics »
- E. Falize, C. Michaut and S.B., ApJ (to appear 2011)

Astronomical observations

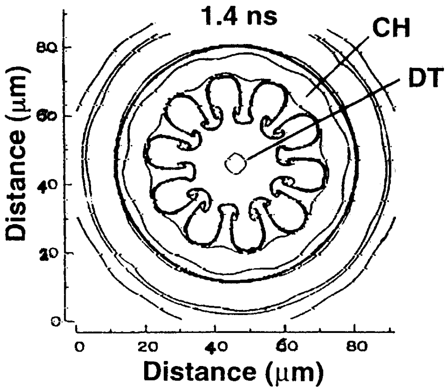
(???)

Laser, Z-pinch experiments

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

AN EXAMPLE:
LASER TARGET versus SUPERNOVA

RAYLEIGH-TAYLOR INSTABILITY



Imploding laser target

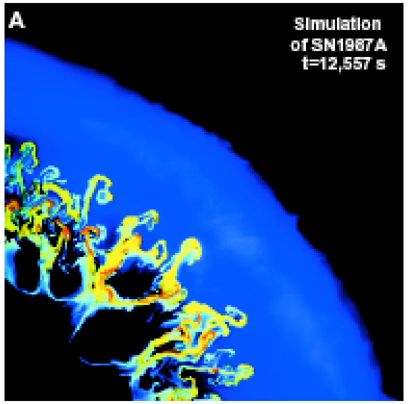
Typical quantities for laser target (S1) and supernovae (S2)

Physical quantities	Laser target (S1)	Supernova (S2)
Characteristic length	$\ell_1 \approx 100$ μm $\approx 10^{-2}$ 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 the supernovae is very weak !!!

Characteristics of the Rayleigh-Taylor Instability (RTI)

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}	$N_{IRT,1} \approx 1$	$N_{IRT,2} \approx 1$



Exploding star : supernova

Among the most violent phenomena
In the universe !!!

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

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

N_{IRT}(target) = N_{IRT}(supernova) = 1 !!!

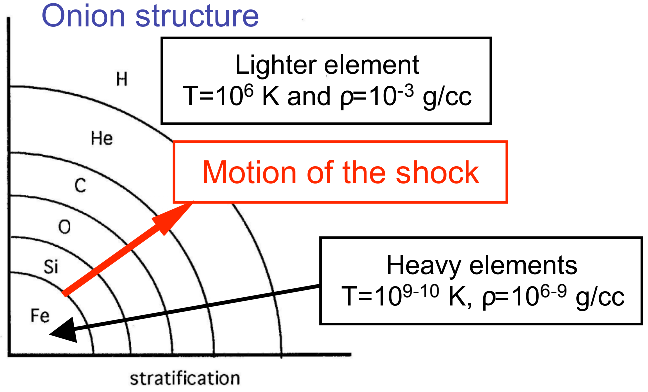
energie atomique • energies alternatives

SUPERNOVA SN87A (type II): SIMULATION versus EXPERIMENT

Scaling laws : Rayleigh - Taylor instabilities in SNe

EXPERIMENTS from DRAKE's GROUP :

Onion structure

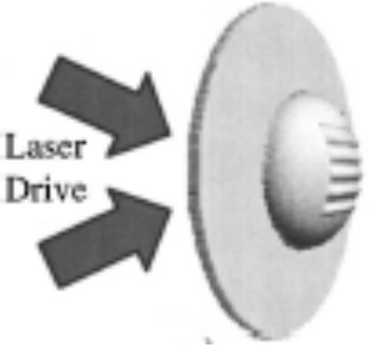


Lighter element
$T=10^6$ K and $\rho=10^{-3}$ g/cc

Motion of the shock

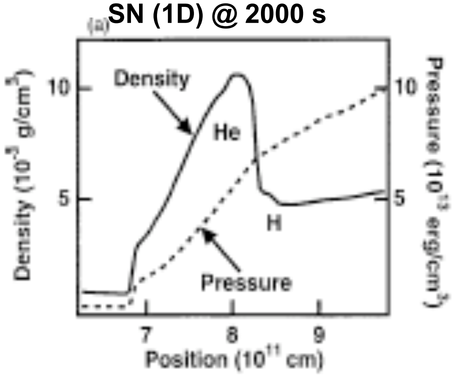
Heavy elements
$T=10^{9-10}$ K, $\rho=10^{6-9}$ g/cc

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



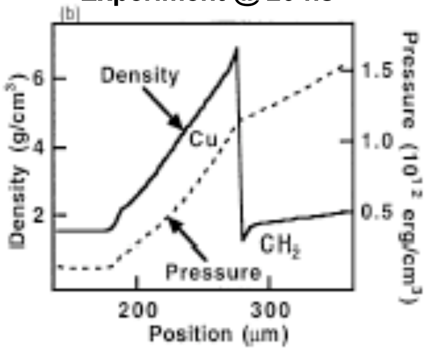
Ryutov et al., Phys. Plasmas 8 (2001) 1804

SN (1D) @ 2000 s

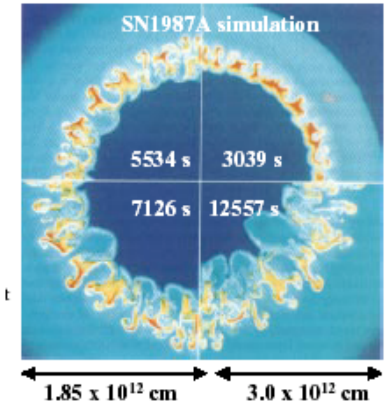


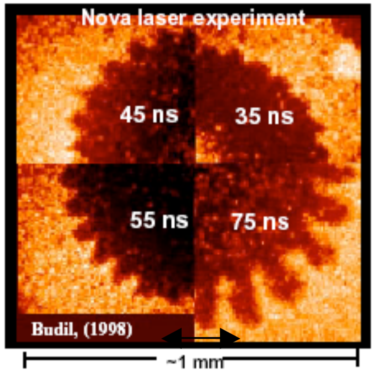
Ryutov et al., ApJ 518 (1999) 821

Experiment @ 20 ns



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





Length: 100 μm ↔ 10^{11} cm **and** Time: 20 ns ↔ 2000 s

Therefore: Velocity: 100 km/s ↔ 10 000 km/s

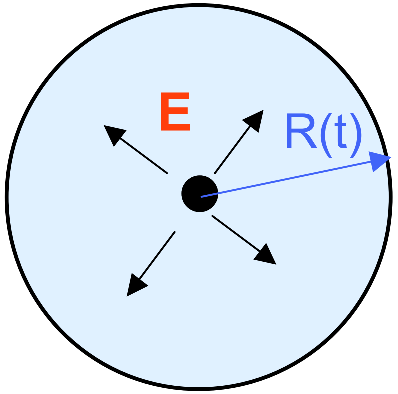
10 000 km/s is relevant for SN remnants
100 km/s is relevant for laser targets

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



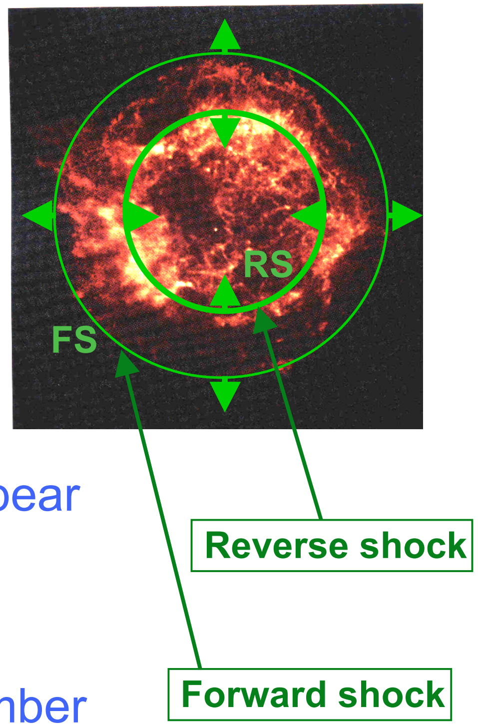
density ρ_0

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

Use of Dimensional analysis

- Unit of mass: M $[E] = M.L^2.T^{-2}$
- Unit of length: L $[\rho_0] = M.L^{-3}$
- Unit of time: T $[R] = L$

Cassiopée A (1680)
Type Ia SN



- 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 !!!

CONCLUSION : $(E/\rho_0).t^2/[R(t)]^5 \sim \xi$: 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

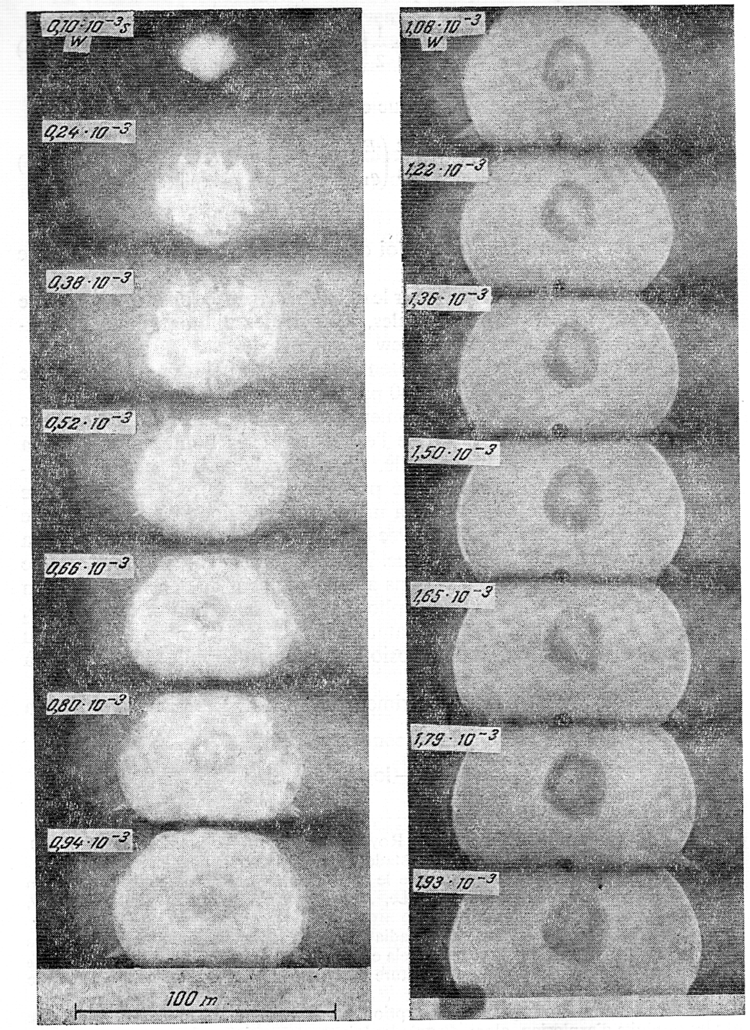


Fig. 67. Photographies d'une boule de feu prise dans l'intervalle de $t=0{,}1\cdot10^{-3}$ à $t=1{,}93\cdot10^{-3}$ s lors de l'explosion de la bombe atomique à New Mexico

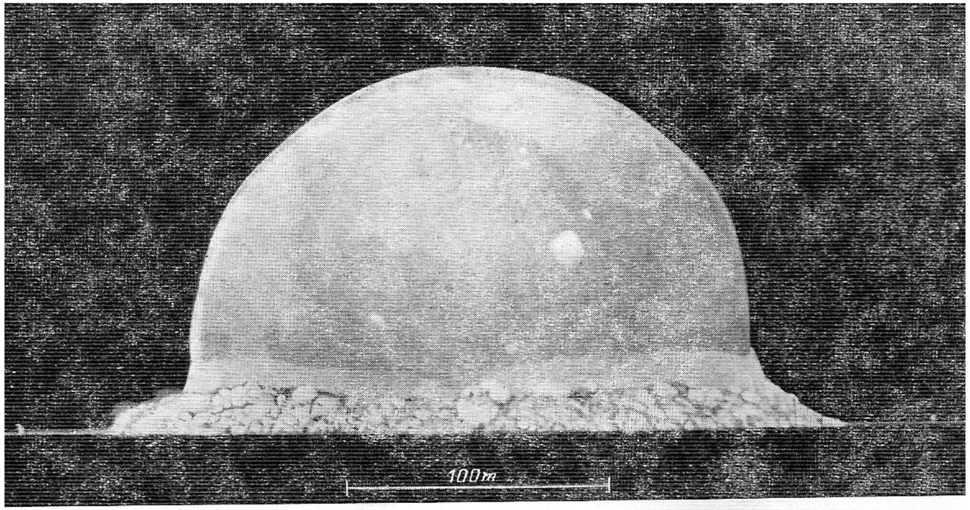
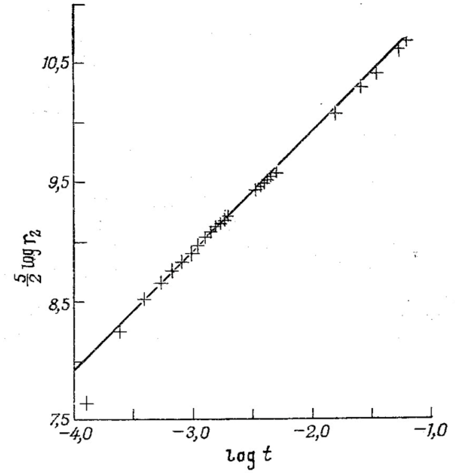


Fig. 68. Boule de feu à l'instant $t=15\cdot10^{-3}$ s

Measurements Vs. Theory



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

Self-Similar Solution (SSS)

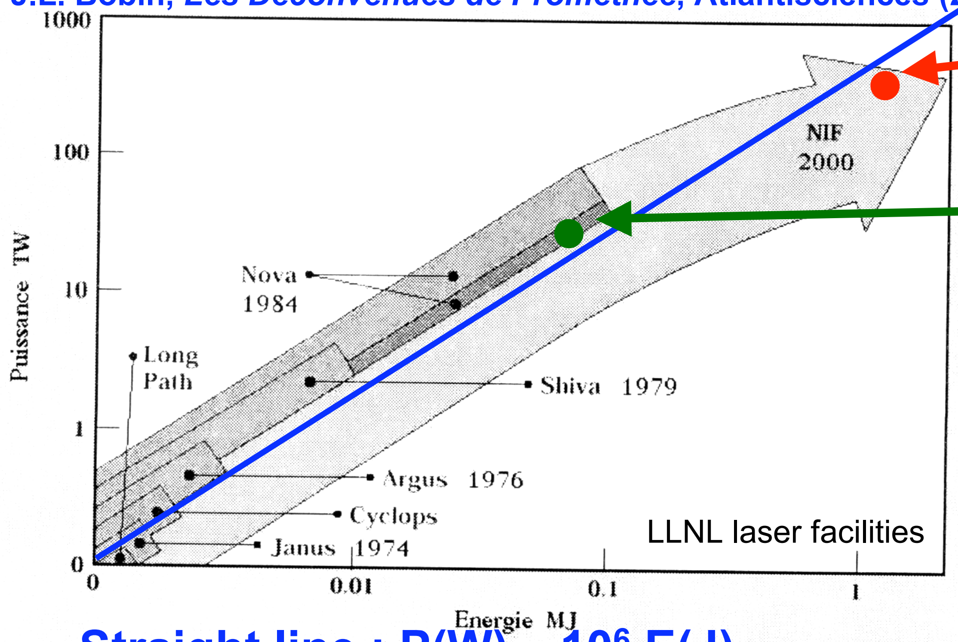
- **Fireball:** **$R \sim 100$ m $\sim 10^4$ cm**
- **Supernova remnant:** **$R \sim 1$pc $\sim 3.10^{18}$ cm**

SAME BEHAVIOUR

1) - LABORATORY ASTROPHYSICS
2) - LASER FACILITIES
3) - ASTROPHYSICAL RADIATIVE SHOCKS (RS) and LASER EXPERIMENTS
4) - ASTROPHYSICAL JETS and LASER EXPERIMENTS
5) - CONCLUSION

EVOLUTION OF THE LASER FACILITIES

J.L. Bobin, *Les Déconvenues de Prométhée*, Atlantisciences (2001)



Laser MégaJoule
LMJ (1.8 MJ, ns)
240 beams

Laser Integration Line
LIL (60 kJ, ns)

- China : ShenGuang II (10 kJ, 1 ns)
  ShenGuang III (100 kJ, 60 beams)
- Japan : Gekko XII (10 kJ, 1 ns), LFEX (PW)
- European array:
  UK: Helen (TW), Vulcan (PW); G: Phelix (TW)
  Prague: PALS (TW), I: TW/PW, F: Luli2000, etc ...

Straight line : $P(W) \propto 10^6.E(J)$

- Early 70 's : intense development of laser facilities,
- 1984 : second big step with NOVA (10 beams, 45 kJ),
- End 90 's : third step OMEGA (Rochester-USA, 60 beams, 60kJ)
- Begin. 2000 : new progress NIF (National ignition facility, LLNL-USA, 192 beams, 1.8 MJ), working now,
- Since 2004: LIL (Laser integration line, CEA/CESTA, 4 beams, 30 kJ)
- In 2014: LMJ (Laser MégaJoule, CEA/CESTA, 240 beams, 1.8 MJ)

energie atomique • energies alternatives

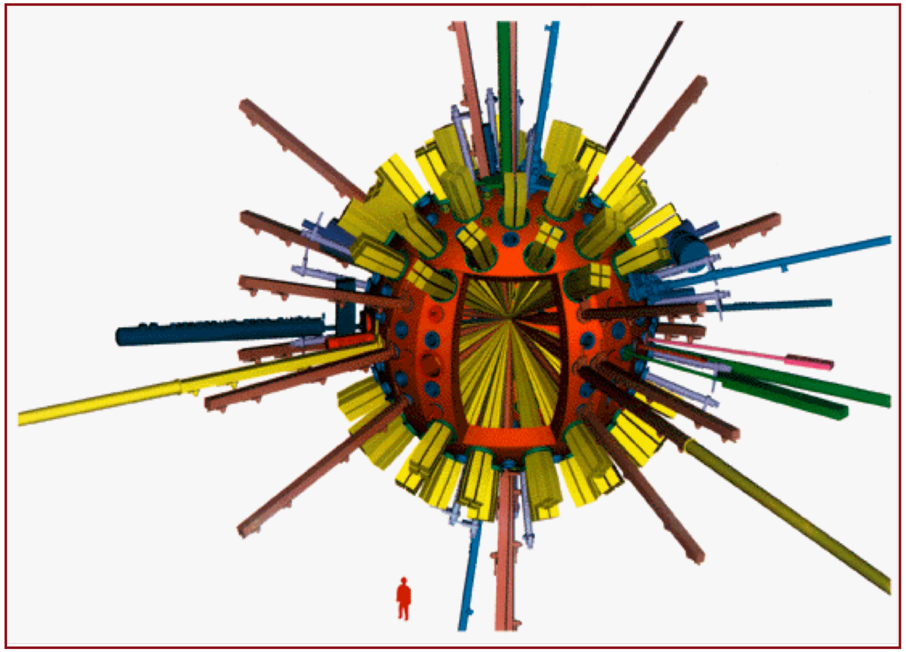
LASER MEGAJOULE (CEA/CESTA)

- The **Laser MégaJoule (LMJ)** is a venture undertaken by the French **Atomic Energy Commission** (CEA) for the study of **Inertial Confinment Fusion** (ICF),

- The **LMJ** will be operating on **2014** (first target shots) and **ignition** is planned for **2016,**

-The construction takes place in **Bordeaux** at **CEA-CESTA** (Centre d 'Etudes Scientifiques et Techniques d'Aquitaine).

Target Chamber

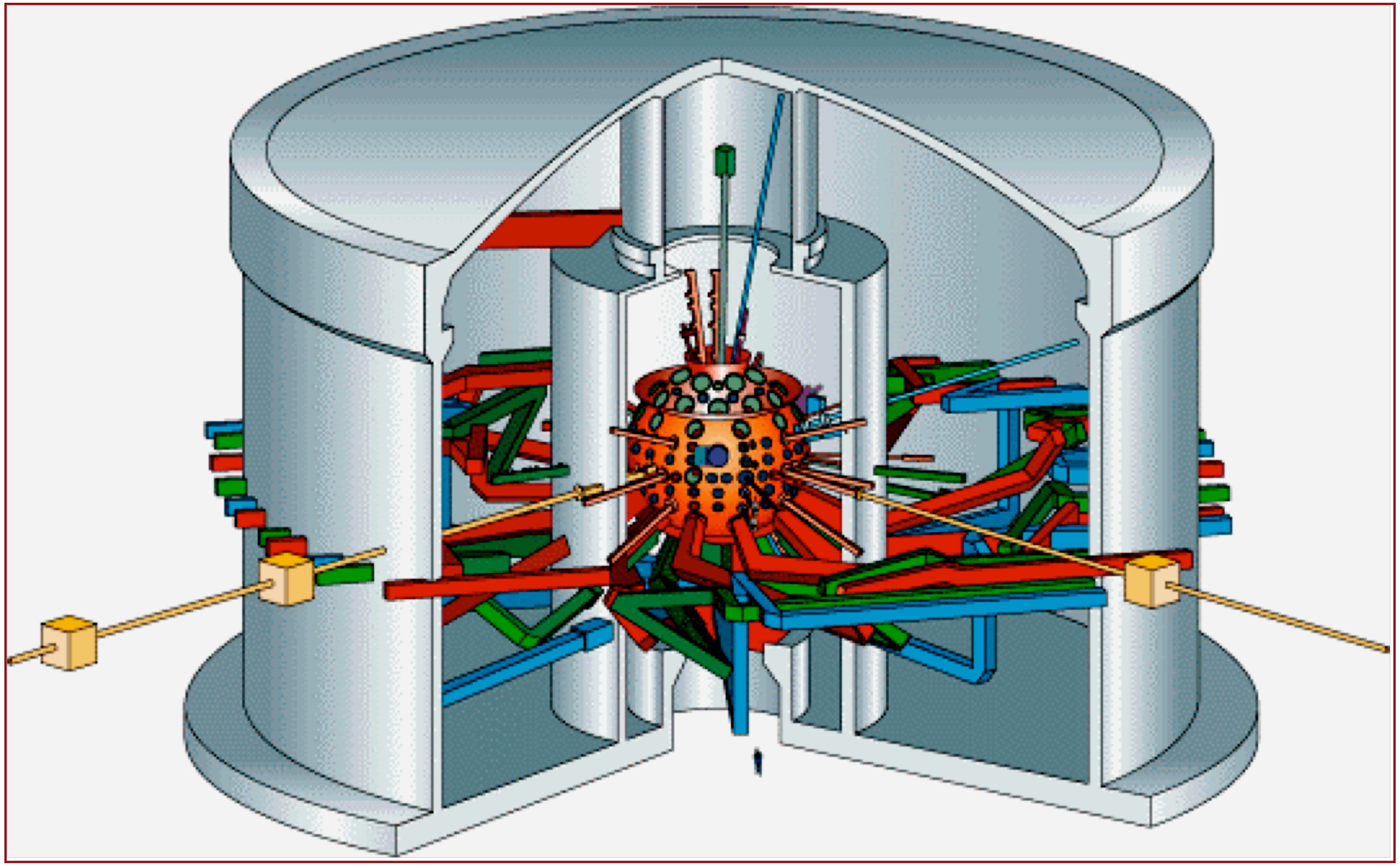


10 meter diameter target chamber

(chamber inserted in the target bay in Dec.06)

Makes the energy contained in ten 0% fat yogourts !!!
But over 1 s duration, that is 10^{10} yogourts = 2 yogourts per human being/s

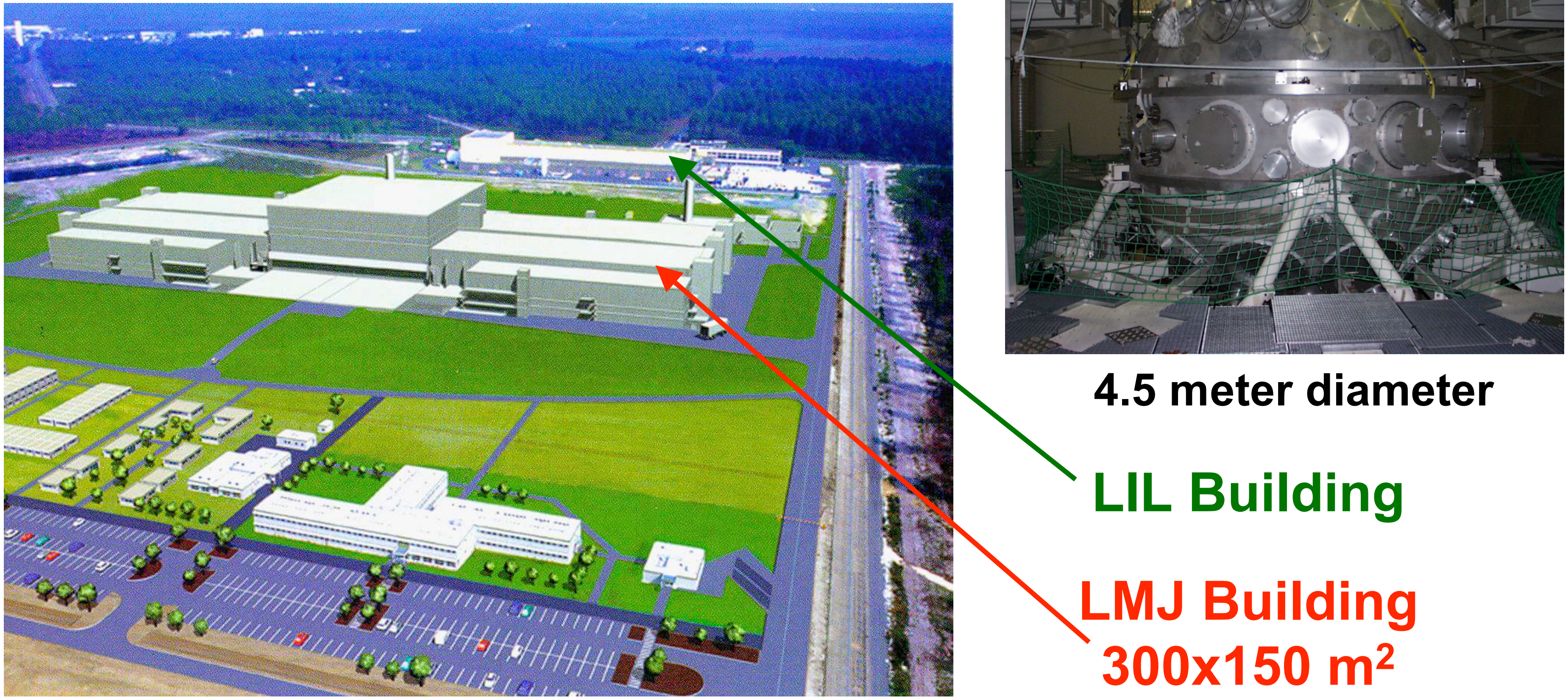
VIEW OF THE TARGET HALL



40 meters high with a 60 meter diameter

Dwarf physicist

LMJ and LIL BUILDINGS



LIL: target chamber from Nova

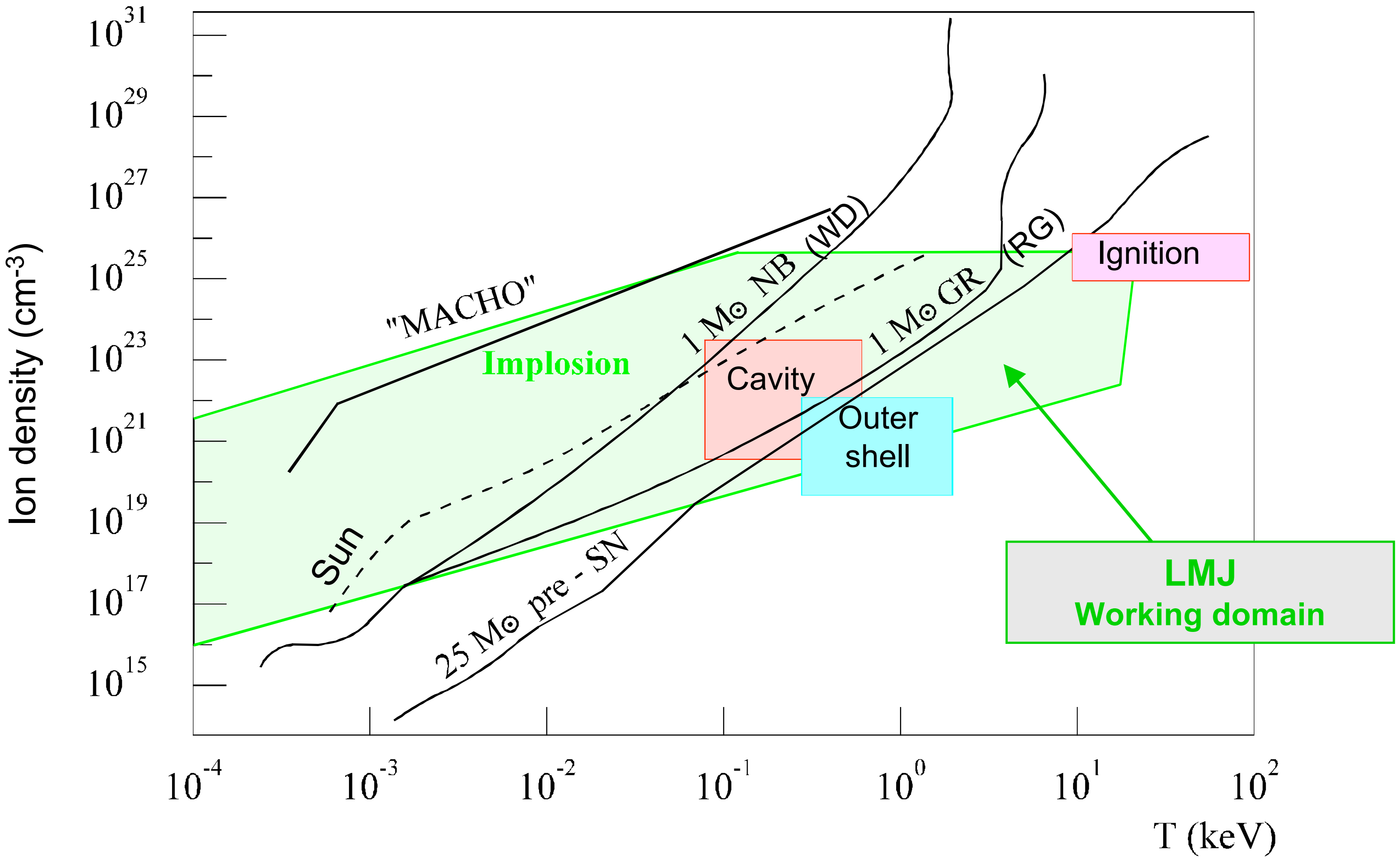
4.5 meter diameter

LIL Building

LMJ Building
300x150 m^2

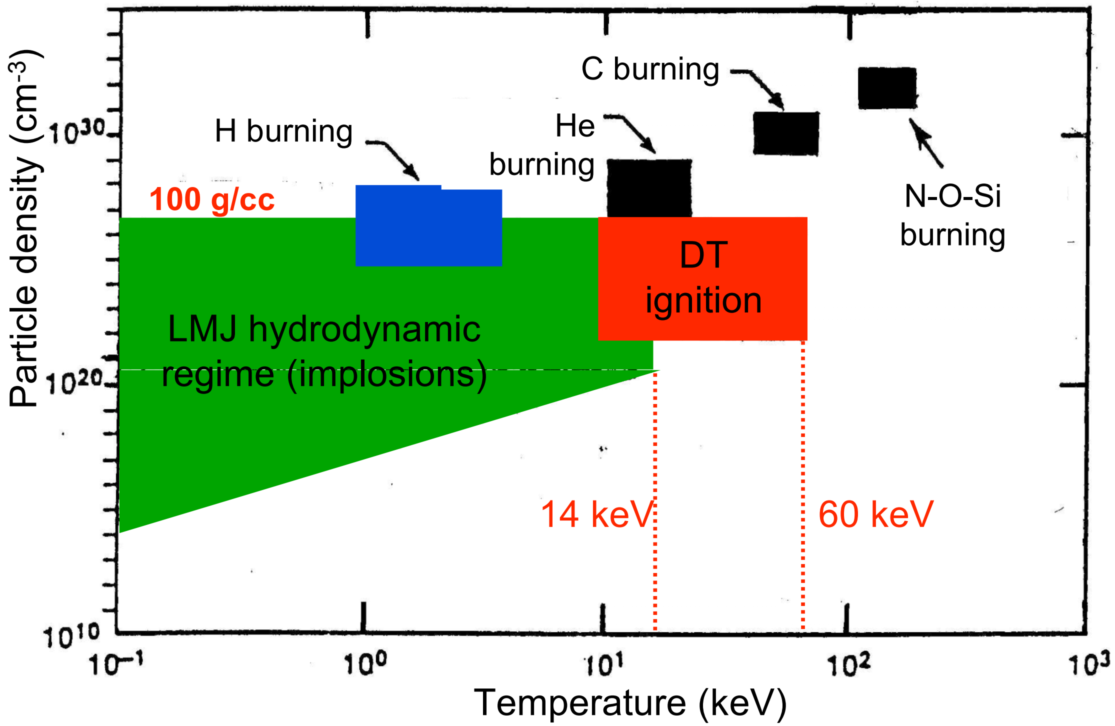
Nice case for the **Eiffel Tower** which could lay down in this building !!!

ASTRONOMICAL OBJECTS and LASER PLASMAS



STELLAR NUCLEAR BURNING

🟩 + 🟥 = **LMJ working domain (or NIF)**

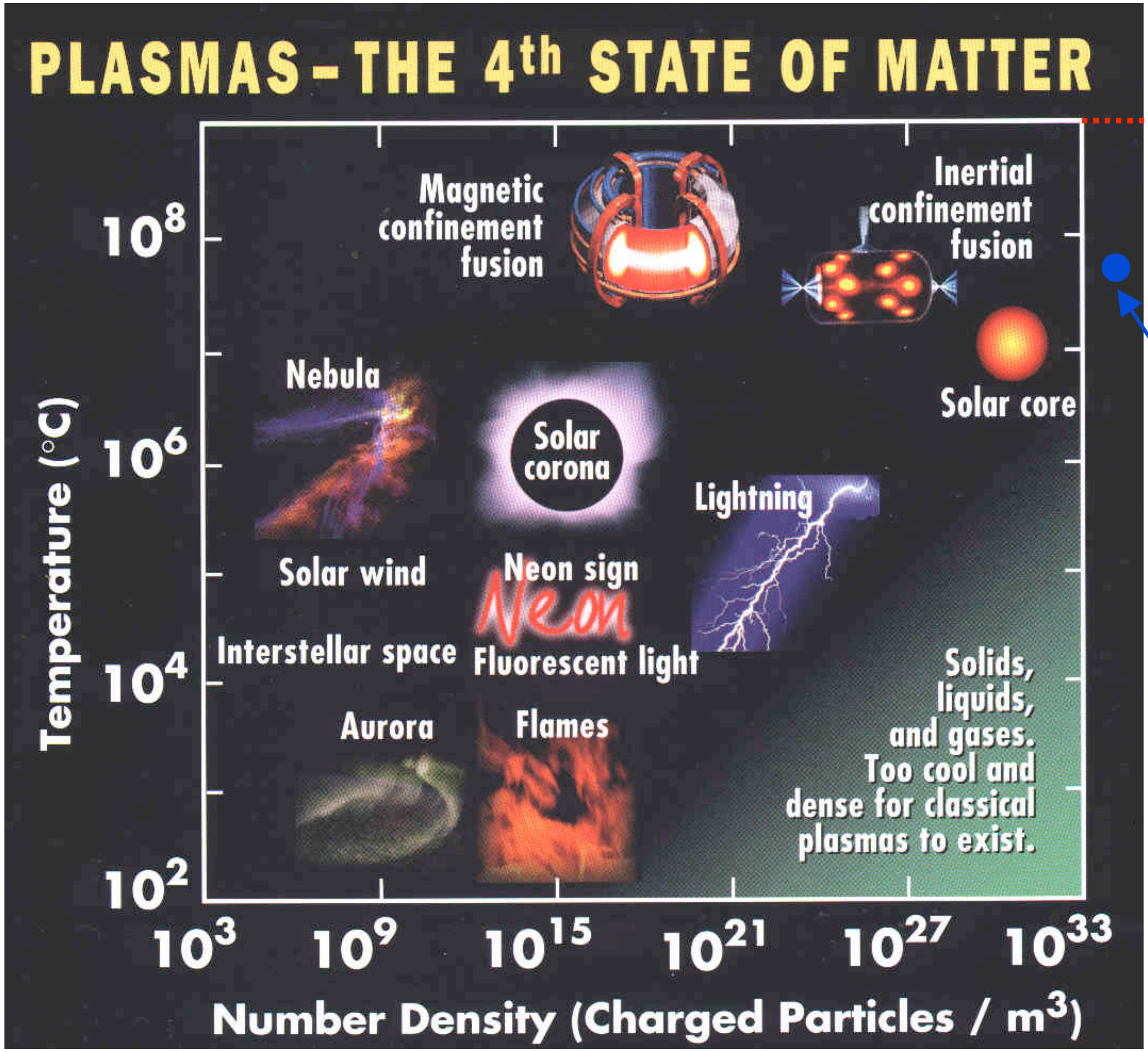


- <u>PURE HYDRODYNAMIC REGIME</u> :
  Condition similar to **Solar type star** with **H-burning**

- <u>IGNITION REGIME</u> :
  Later stage of stellar evolution
  He-burning
  Temperature similar **(60 keV)** to **C-burning** evolved stars
  (density is too low)

Sun : $\rho \approx 150$ g/cc ; T ≈ 15 MK ≈ 1.5 keV

RANGE OF ASTRONOMICAL DATA



Neutron star

$T_c \approx 10^{8\text{-}9}$ K, $\rho_c \approx 10^{12}\ \rho_\odot$

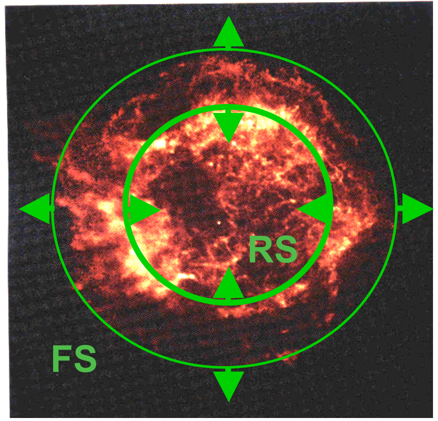
White dwarf

$T_c \approx 10^{7\text{-}8}$ K, $\rho_c \approx 10^{4\text{-}5}\ \rho_\odot$

1) - LABORATORY ASTROPHYSICS
2) - LASER FACILITIES
3) - ASTROPHYSICAL RADIATIVE SHOCKS (RS) and LASER EXPERIMENTS
4) - ASTROPHYSICAL JETS and LASER EXPERIMENTS
5) - CONCLUSION

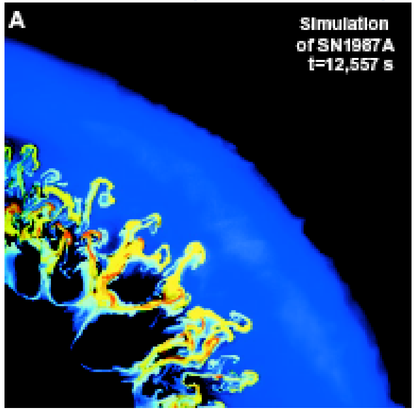
RADIATIVE SHOCKS in SUPERNOVAE and in SUPERNOVA REMNANTS

Cassiopeia A (1685)



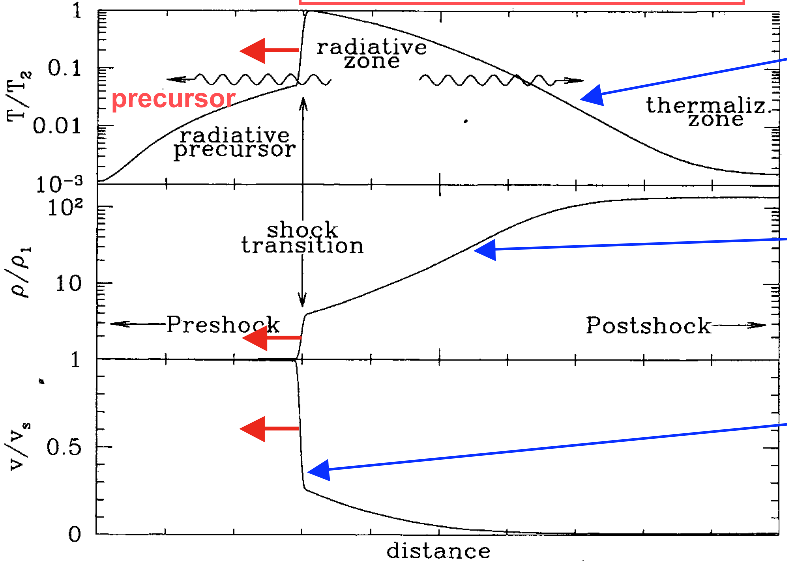
Crab Nebula (1054)

SN1987a (Feb. 23, 1987)



Muller et al. Astron. Astrophys. (1991)

Motion of the Forward Radiative Shock



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

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

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

H. Bethe, Astrophys. J. (1997)

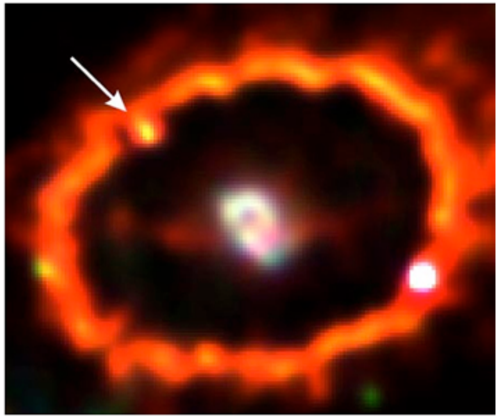
Radiative precursor: the energy goes through the discontinuity and heats the medium ahead of the shock

OTHER RADIATIVE SHOCKS

Radiative Shocks are very common in astrophysical processes & objects

Jets in Protostars

Bow shock in Orion

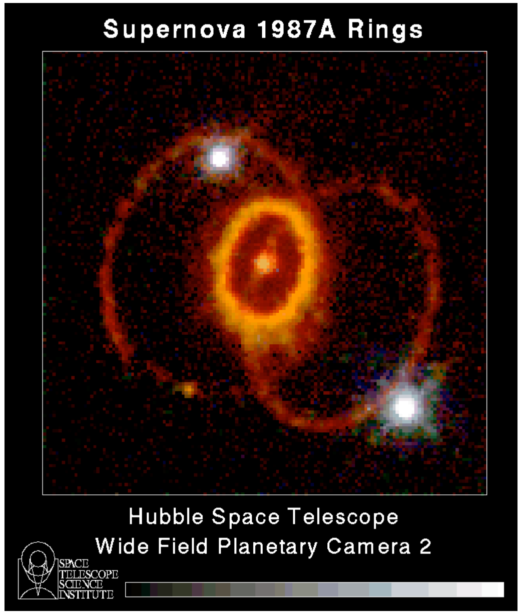


Supernova SN87A

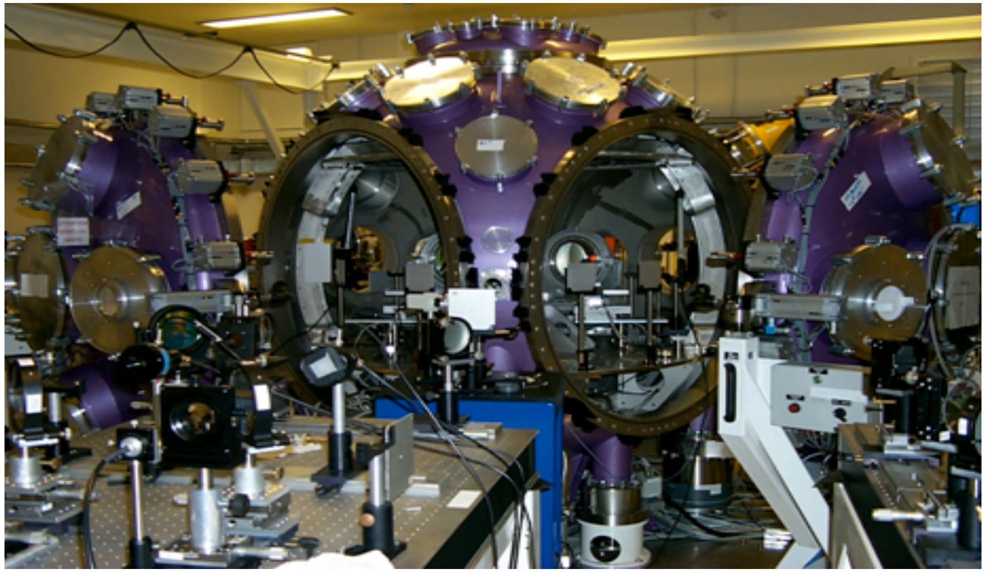
Crab nebula

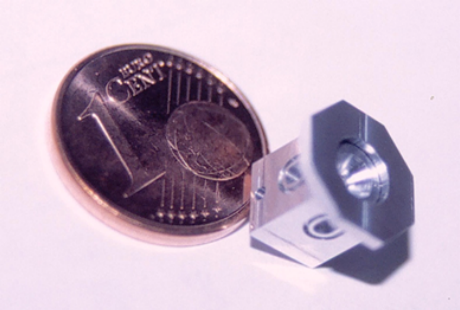
To understand RS's, analytical modeling and numerical simulations bring key answers
BUT, we need also to perform laboratory experiments : vary initial conditions …

LULI LASER FACILITY: LULI2000



LULI2000, ≤ 1 kJ, 1 ns **Michel KOENIG group**

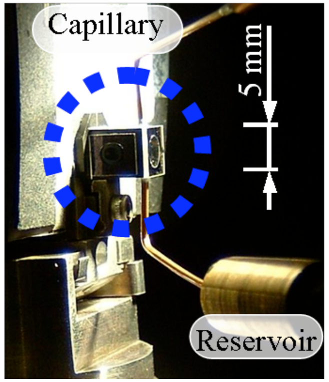




LULI2000 targets

(Paris observatory and LULI)

Claire MICHAUT group
Patrice BARROSO



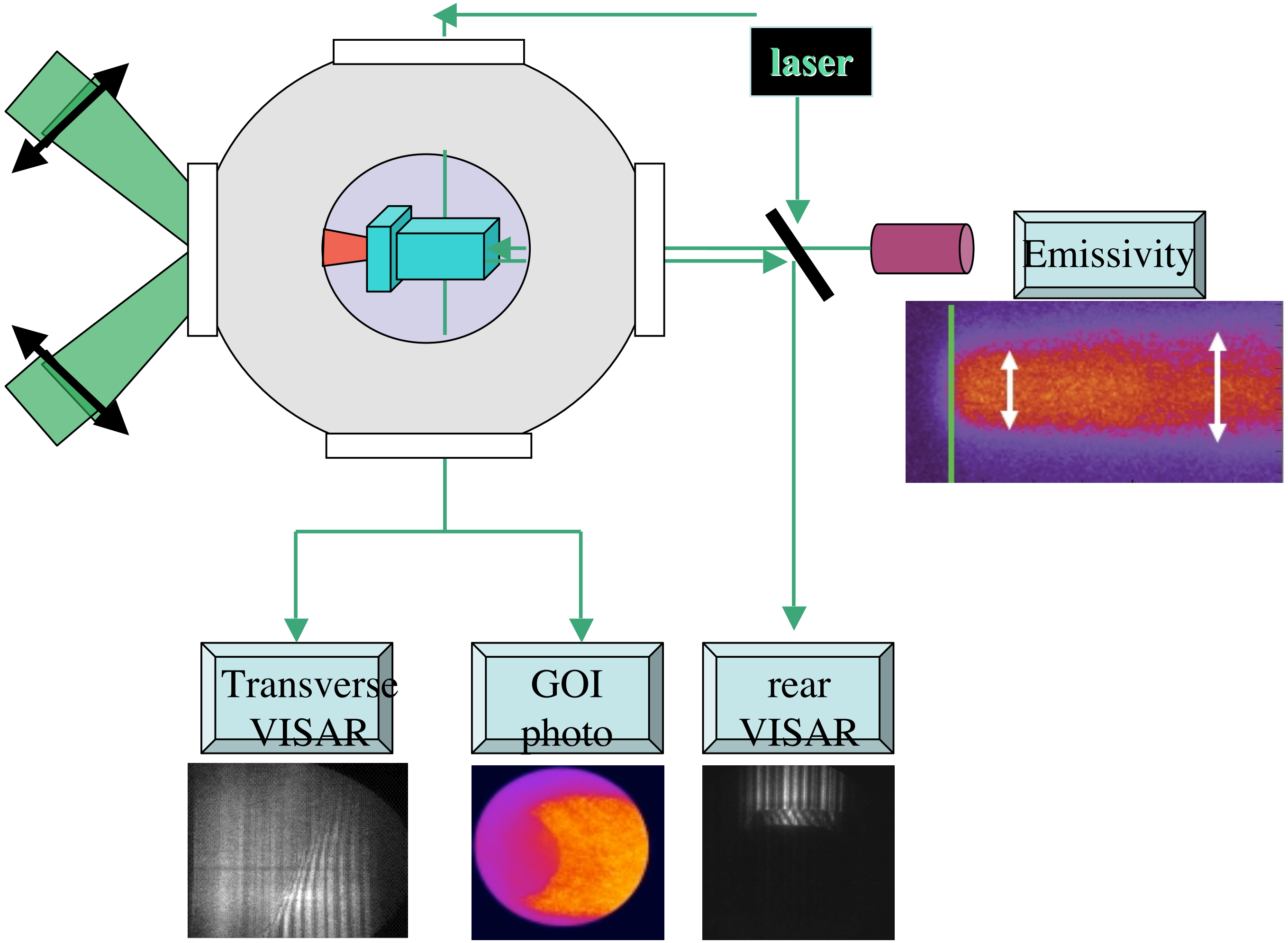
LULI 2000 EXPERIMENTAL SET UP

2 laser beams

$E = 1$ kJ
$\lambda = 0{,}53$ μm
$\Delta t = 1{,}4$ ns

$I = 10^{14}$ W/cm^2

Ø=500 μm FWMH



laser

Emissivity

Transverse VISAR

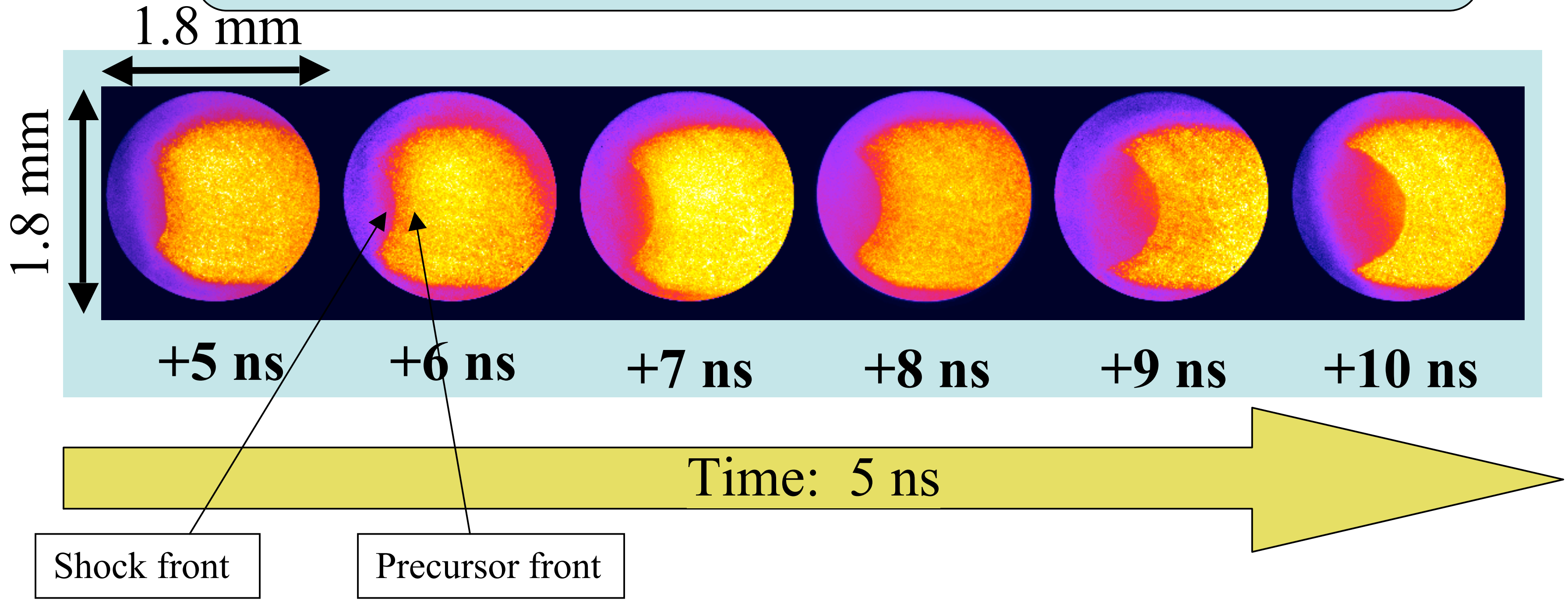
GOI photo

rear VISAR

2D-IMAGING OF THE SHOCK FRONT

GOI (Gated Optical Imager) Exposure time: 100ps

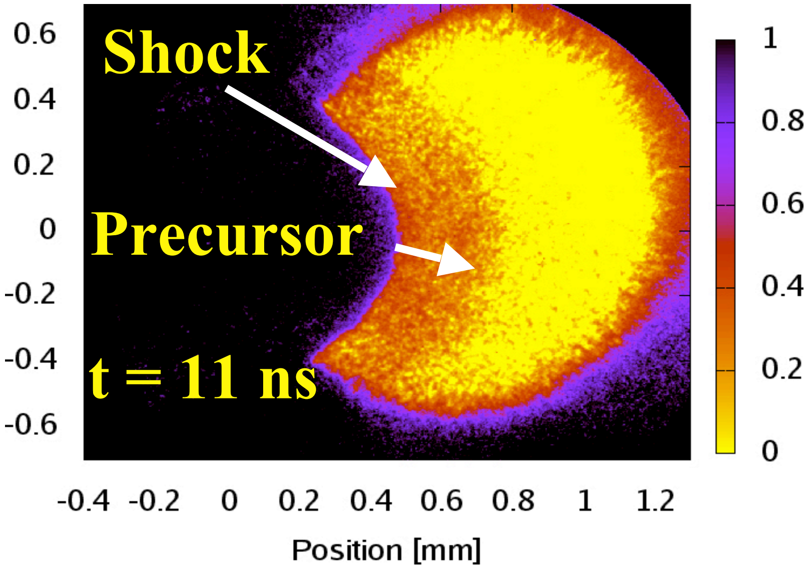
Series of Snapshots for initial pressure P_{Xe}=0.1 bar

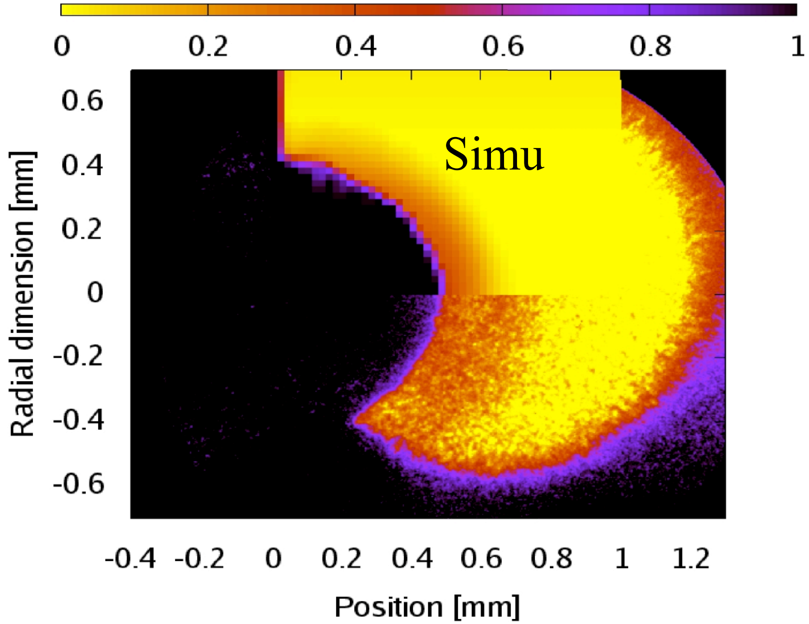


Paul DRAKE experiments (OMEGA): Xe is denser (atmospheric pressure) - Keiter et al. PRL (2002)
- no precursor, BUT
- collapsed dense layer behind the shock front:
radiative losses ∝(density)^{power} are important and compression rate ~ 50-100

C. MICHAUT et al., Astrophys. Space Science 307(2007)159

GOI versus DUED SIMULATIONS

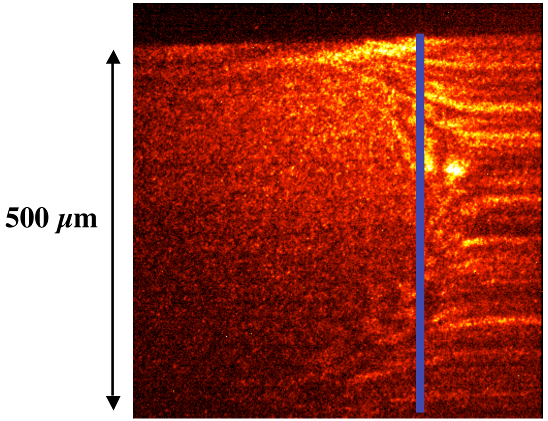




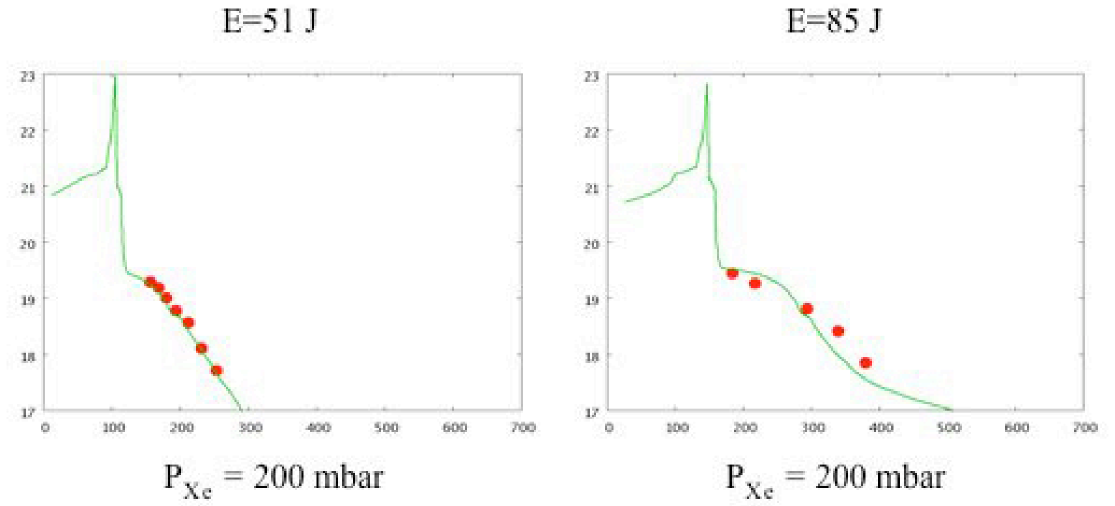
Tommaso Vinci (LULI) + Stefano Atzeni (ROMA)

- Diagnostic reproduction
- Temperature : 15 eV
- Good curvature
- Precursor length too short

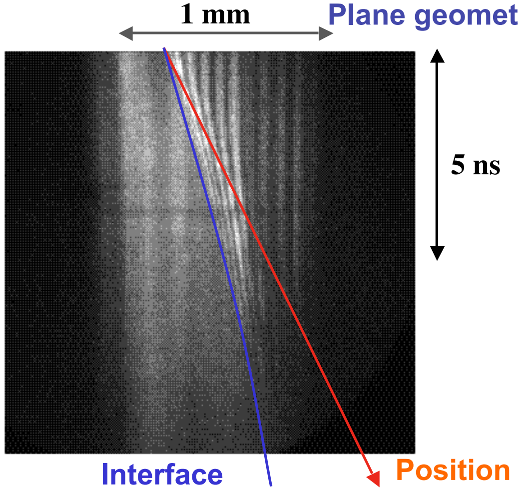
6 BEAM-FACILITY (≤ 100 J) AT LULI



2D effects Deviation to Plane geometry

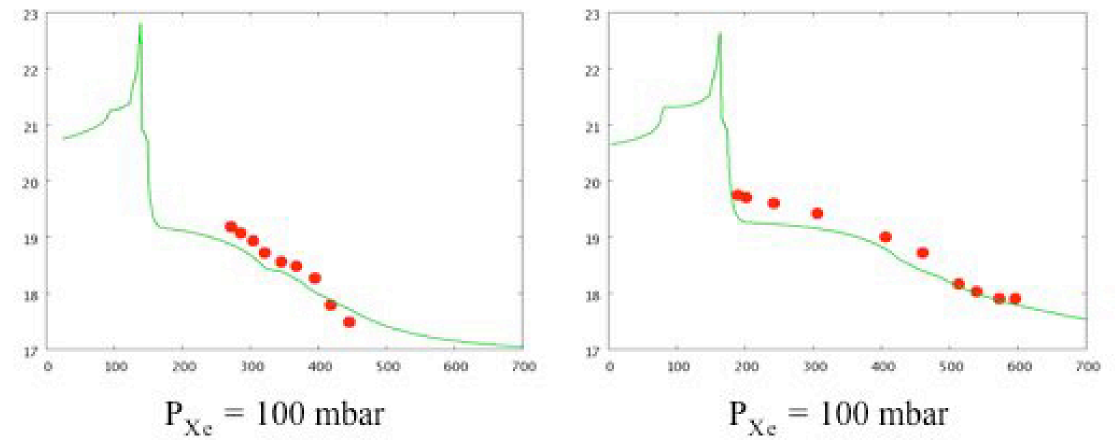


1D-simulations (MULTI) by T. VINCI, T. VINCI et al., Phys. Plasmas 13(2006)010702



Interface piston (foam) / Xénon ~ 60 km/s

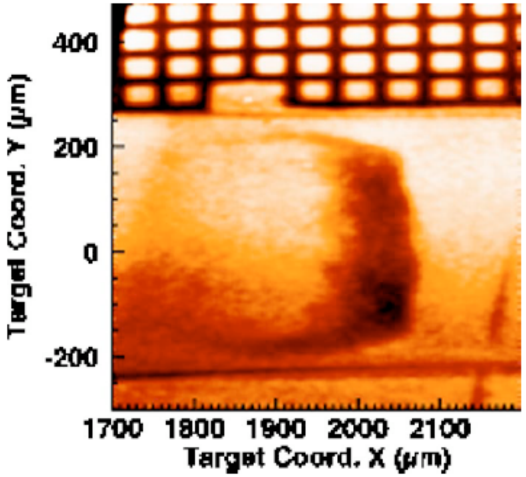
Position of the Radiative precursor V ≈120 km/s

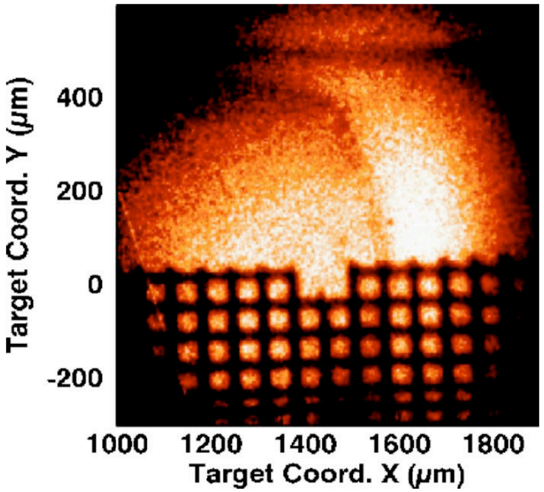


Bouquet et al., PRL (2004), Koenig et al., APIP-AIP, CP926 (2007) 110 , Michaut et al., Astrophys. Space Science 322(2009)77

OMEGA EXPERIMENTS (ROCHESTER-USA)

Amy Reighard-Cooper (LLNL), R.Paul Drake (U. of Michigan @ Ann Arbor)
Laurent Boireau, Paul students …





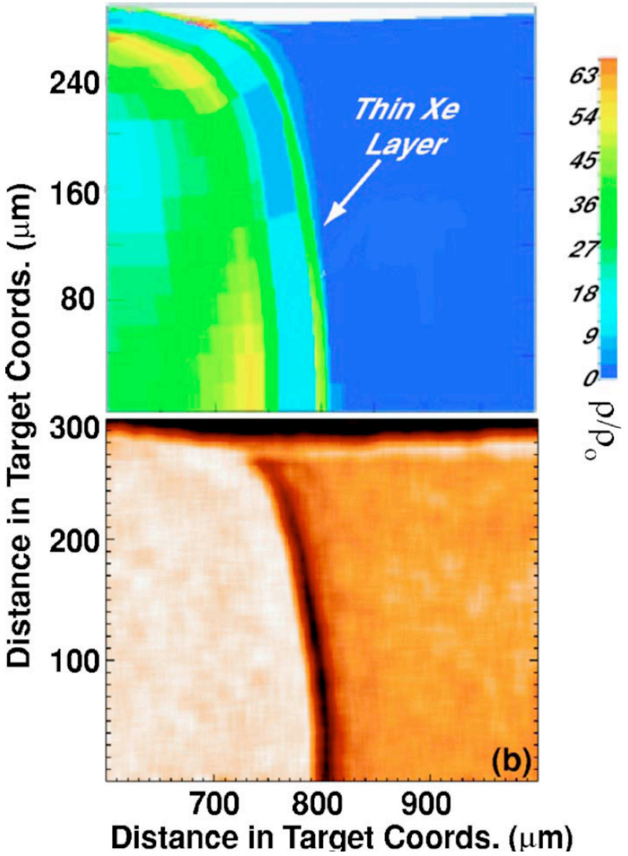


FIG. 5. (Color online) (a) Density profile at 7 ns, from a 2D simulation of the experiment, using the FCI code. The shock is moving to the right. The color bar calibrates the density as a ratio to the initial gas density. (b) Simulated radiograph, using density data from (a). Poisson noise and a point-spread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

High
compression
rate in
the shocked
material

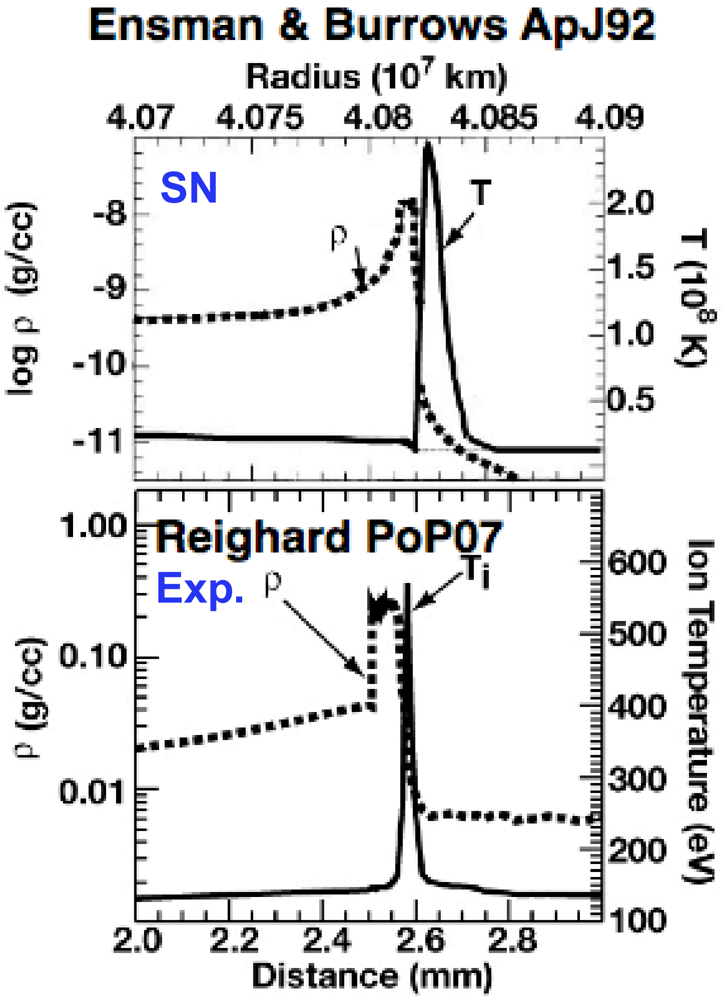
Reighard et al., Physics Plasmas 13 (2006) 032901

Our work is motivated by both high-energy-density physics and astrophysics

- Radiative shocks have strong radiative energy transport that determines the shock structure

- Our experiments
  - have behavior and dimensionless parameters relevant to shocks emerging from supernovae
  - We should see any important unanticipated physics
  - Good code test in any event

- There are ongoing active observations of supernova breakout shocks



GEKKO XII LASER FACILITY

$I = 10^{15}\ W/cm^2 = 10 \times LULI2000$

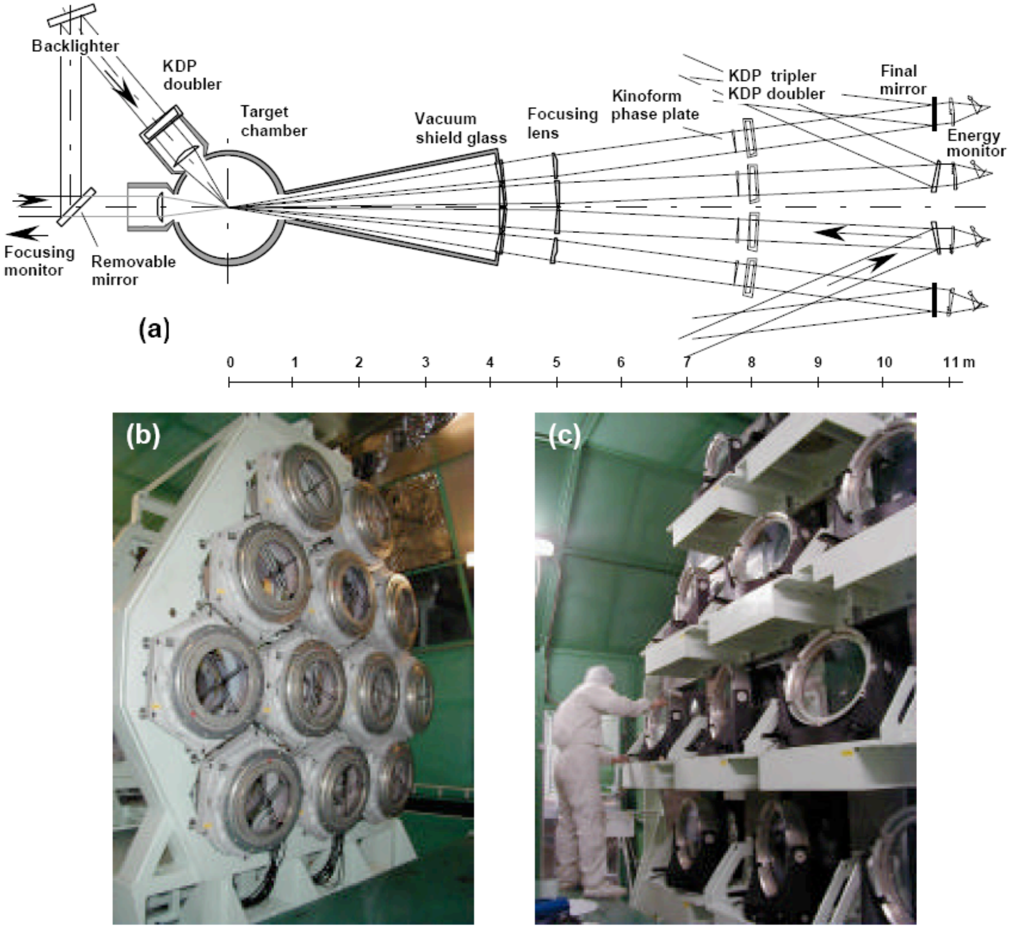
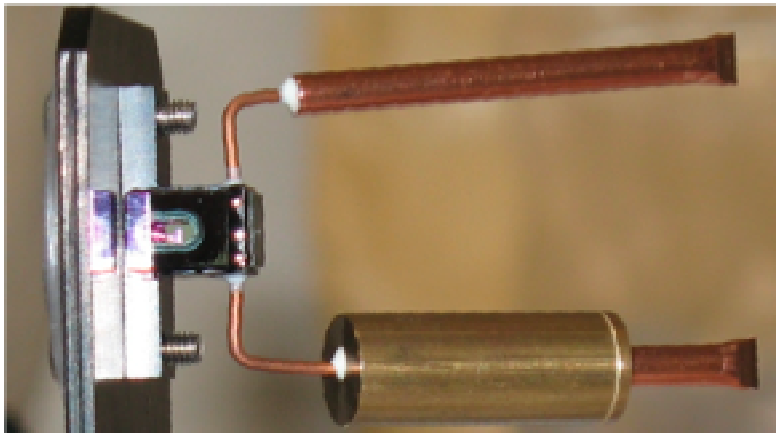


FIG. 1 HIPER focusing system. (a): schematic optical arrangement, (b): arrayed KDP cells, and (c): final mirror bundle.

HIPER:

High Intensity Plasma Intense Research

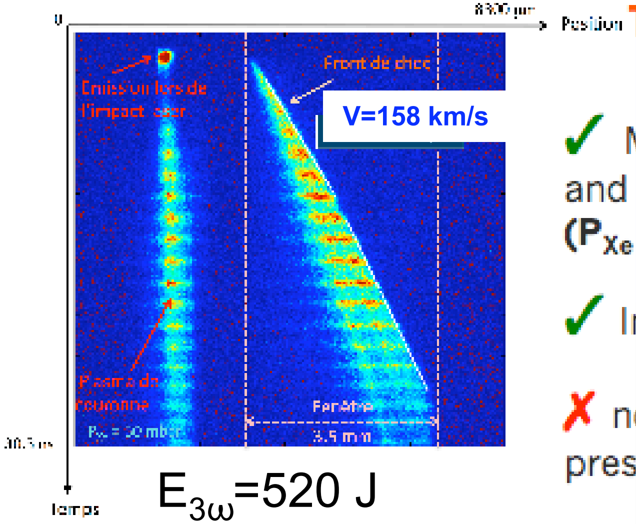
12 faisceaux du même côté



Michaut group, LUTH
Koenig group, LULI
Sakawa group and Kodama group (OSAKA)

RADIATIVE SHOCKS ON GEKKO XII

From C. Michaut , Radiative shock experiments on GEKKO XII, Workshop France/Japon, Les Houches, 9 au 14 janvier 2011



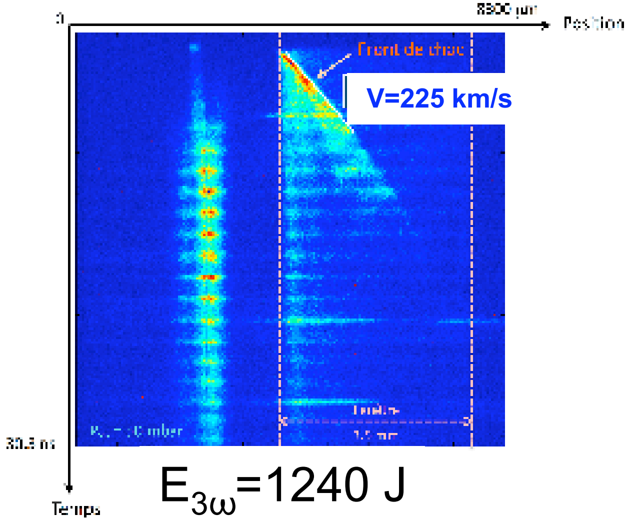
$E_{3\omega}$=520 J

Transverse streaked self-emission optical pyrometry

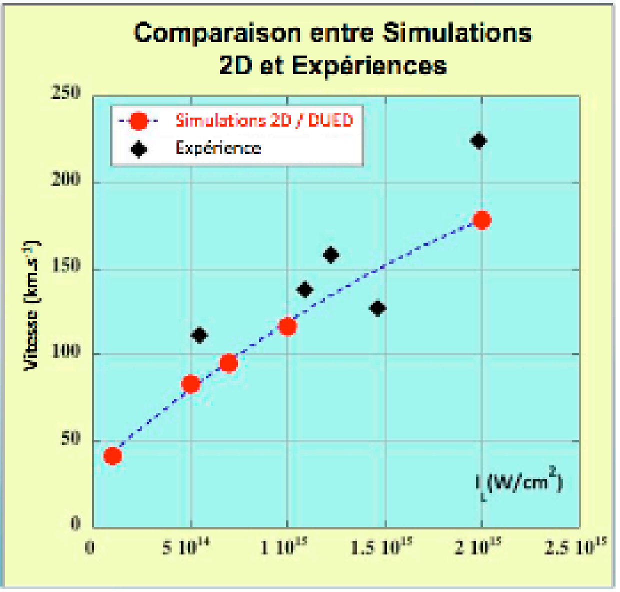
✓ Mean velocities around **150 km/s** with $E_{3\omega}$ ≈ 520 J and **225 km/s** with $E_{3\omega}$ ≈ 1240 J at **same pressure (P_{Xe} = 50 mbar)**

✓ In adequation with 2D simulations

✗ non observed precursor with SOP → too small gas pressure (density and temperature)?



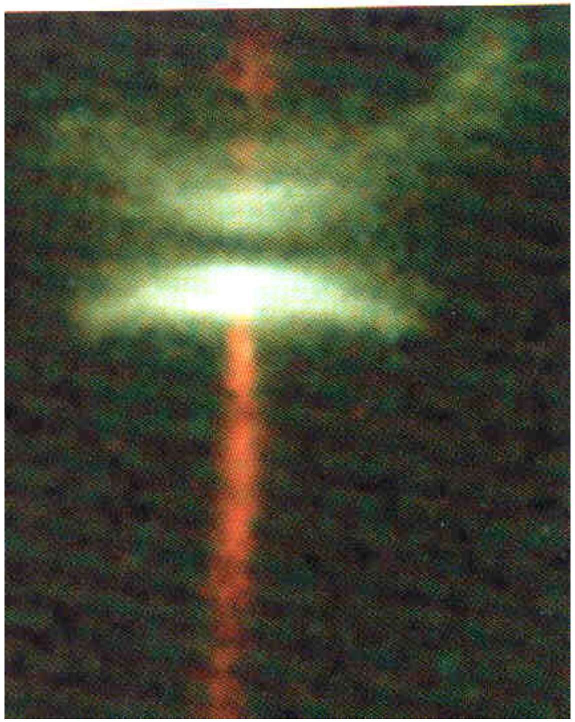
$E_{3\omega}$=1240 J



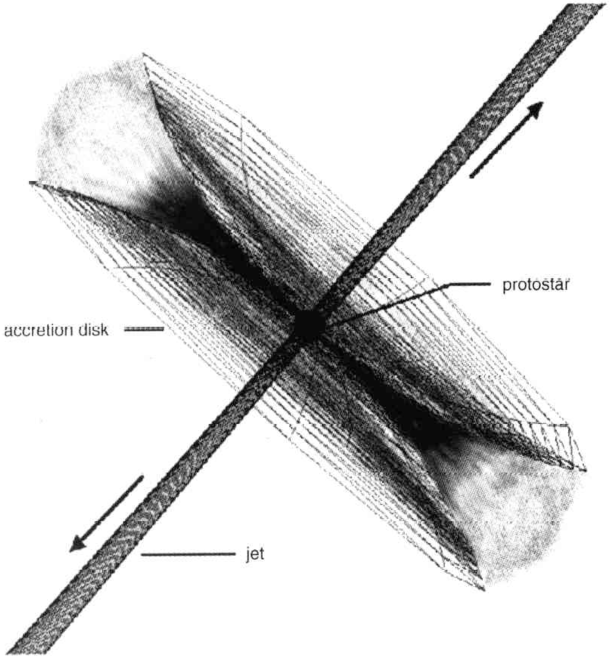
1) - LABORATORY ASTROPHYSICS
2) - LASER FACILITIES
3) - ASTROPHYSICAL RADIATIVE SHOCKS (RS) and LASER EXPERIMENTS
4) - ASTROPHYSICAL JETS and LASER EXPERIMENTS
5) - CONCLUSION

ACCRETION DISK AND JETS

Protostellar disks always produce protostellar jets via B : D. Lynden-Bell, astro-ph/0203480 (2002)



Protostar HH30 and its surrounding dusty disk + jets. The direction of the jets is perpendicular to the disk.



The magnetic field B « transforms » the strong kinetic momentum energy into high axial velocity jets (ideal Frozen MHD).

Jet Properties :

- hypersonic (Mach=20) v = 50 to 250 km/s,
- length/diameter = 20,
- T = 1 to a few eV,
- $\eta=\rho_{jet}/\rho_{ambiant}$ between 0.1 and 10.

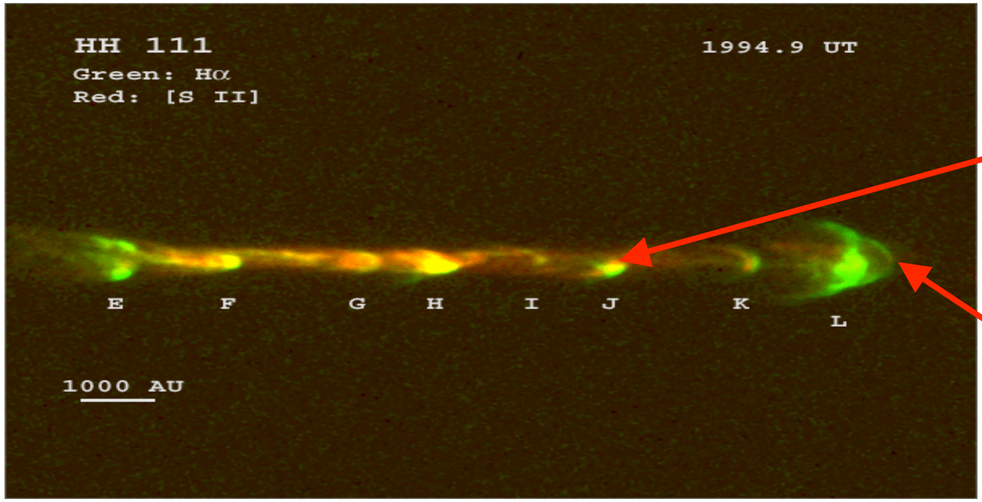
Use of lasers and Z-pinches:

Twisted magnetic field lines

Lebedev et al., Ciardi et al., etc…

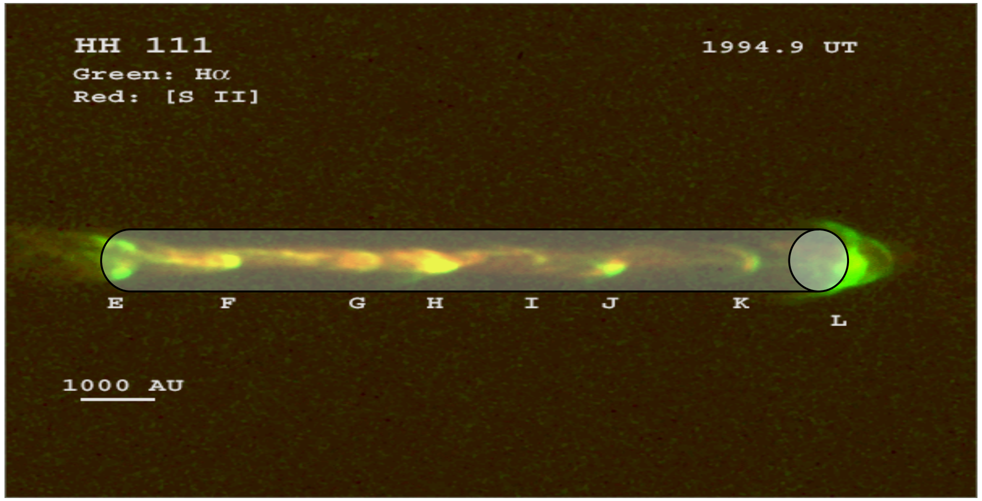
energie atomique • energies alternatives

HERBIG-HARO OBJECTS



Knots:
- Kelvin-Helmholtz instability (interface : shear with the ambiant medium)
- Pulsating source

Bow shock:
- Structure
- Stability

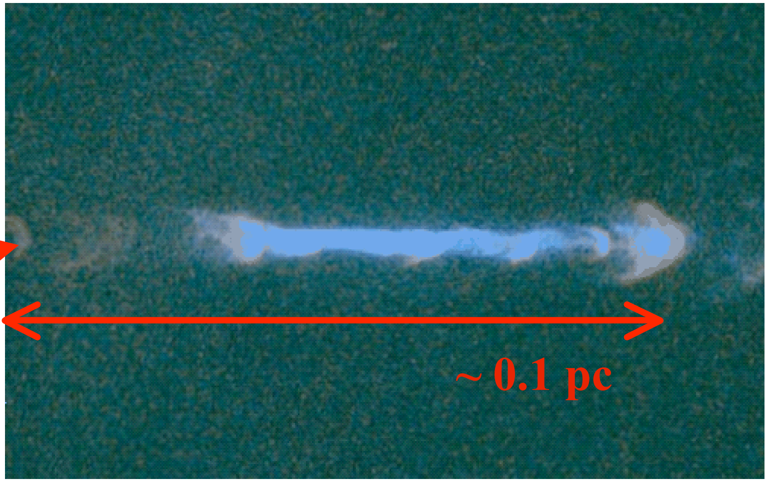


COLLIMATION

- Radiative cooling ?
- Magnetic field ?
- Both ?

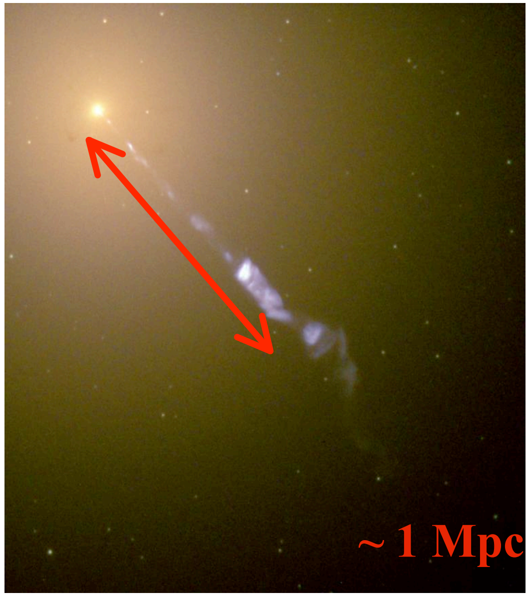
WHERE ELSE DO WE FIND JETS ?

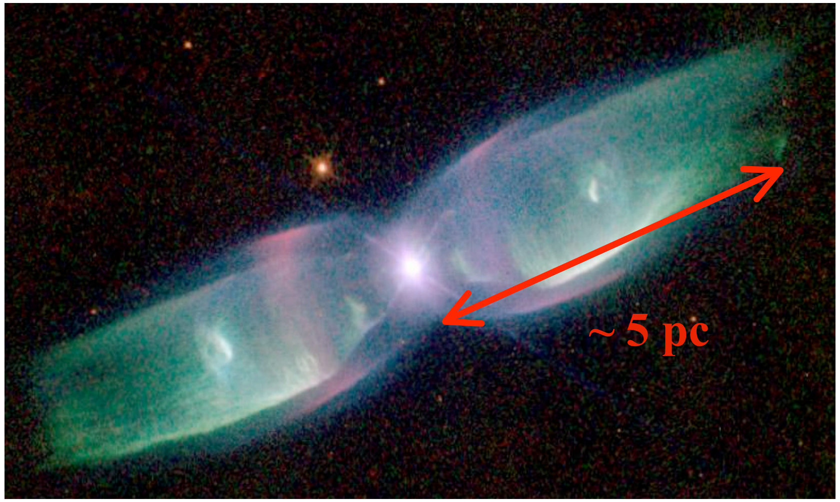
1 a.u = $1.5\ 10^{12}$ cm , 1 pc = 3.10^{18} cm



Young stars

From a black hole



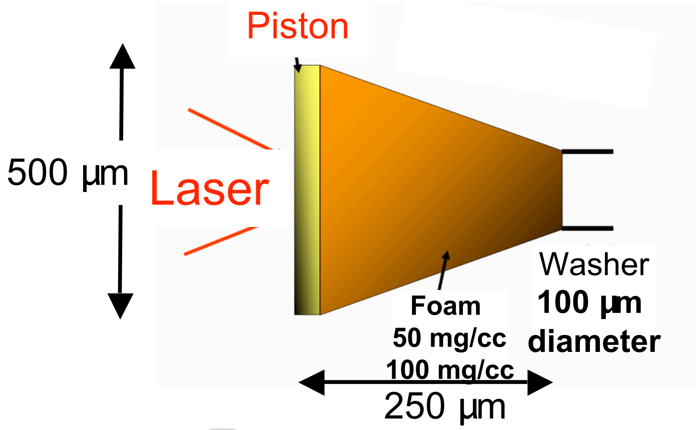


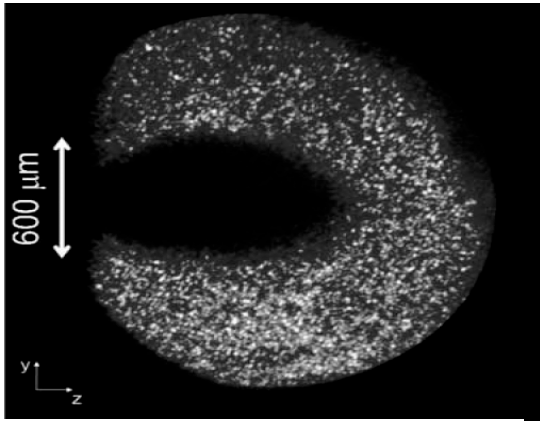
Planetary nebulae

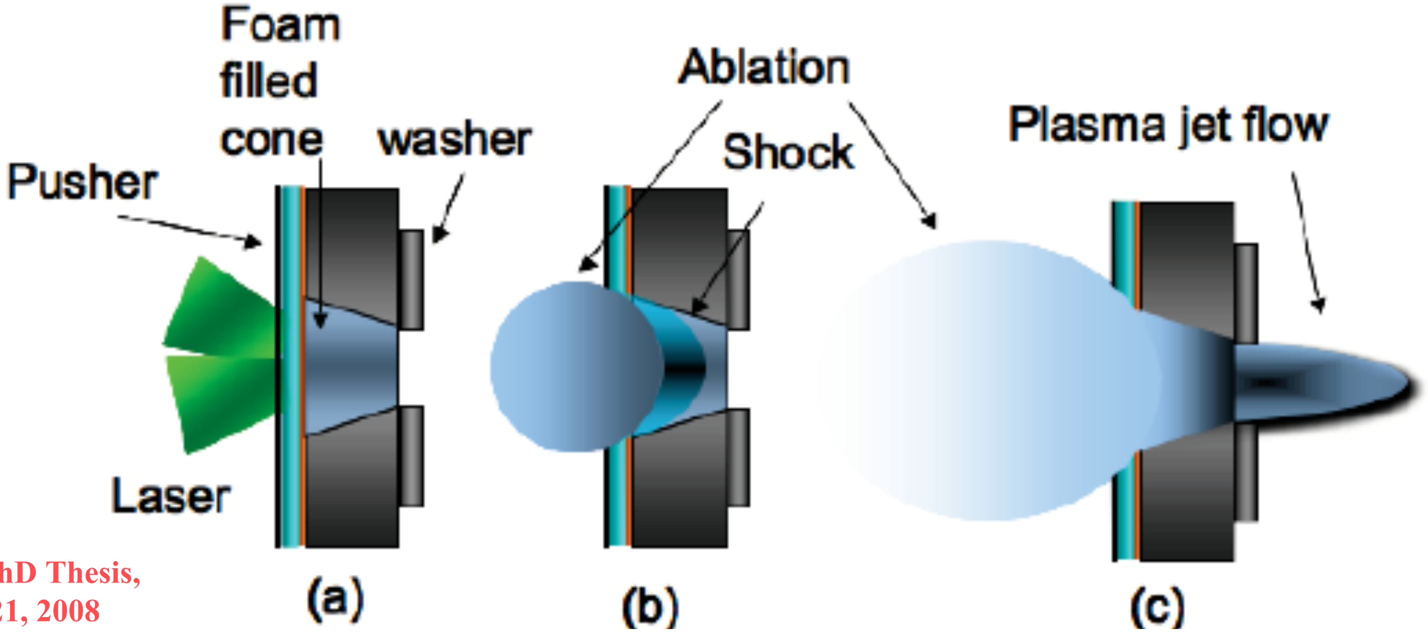
X-binaries (SS433)
QUASARS
(Radio-emission of galaxy core)
QSO
(galaxy core, no emission)

CH-FOAM FILLED CONES

Shadowgraphy 10 ns after the shock break-out (LULI)







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

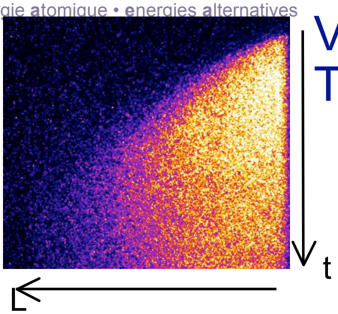
B. Loupias et al., Phys. Rev. Lett. 99 (2007) 265001

B. Loupias et al., Plasma Phys. Controlled Fus. 51 (2009) 124027

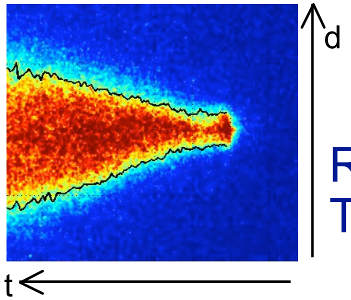
C.D. Gregory et al., PPCF 50(2008)124039

C.D. Gregory et al., PoP 17(2010)052708

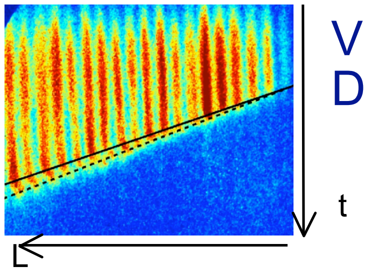
SEVERAL DIAGNOSTICS



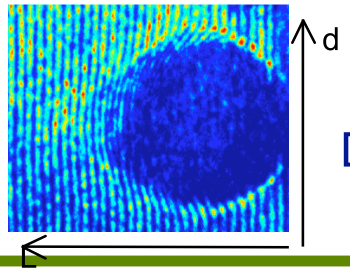
Vitesse: **V(t)**
Température: **T(t)**



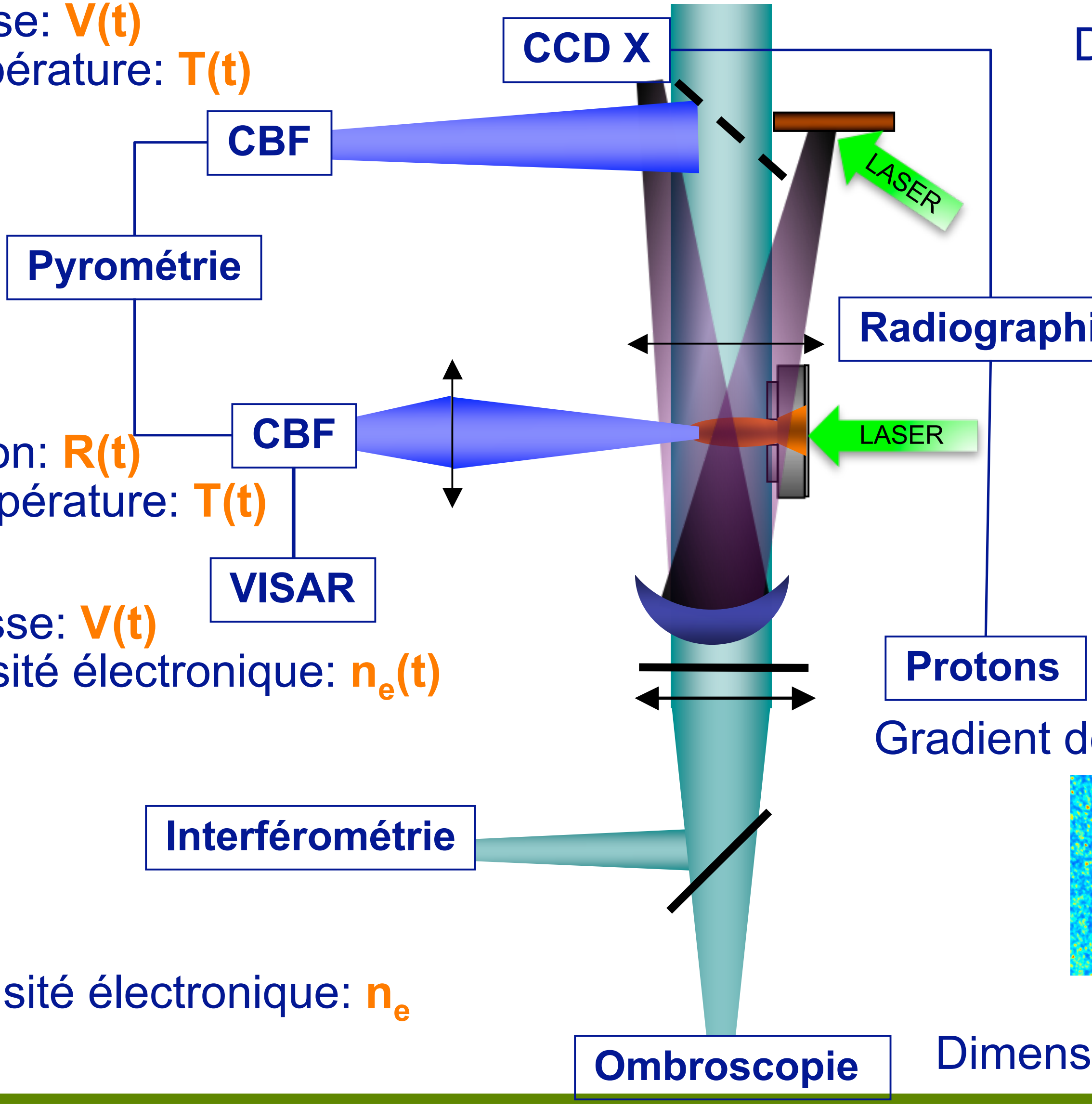
Rayon: **R(t)**
Température: **T(t)**



Vitesse: **V(t)**
Densité électronique: **n_e(t)**



Densité électronique: **n_e**



CCD X

CBF

Pyrométrie

CBF

VISAR

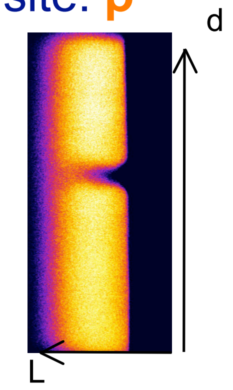
Radiographie

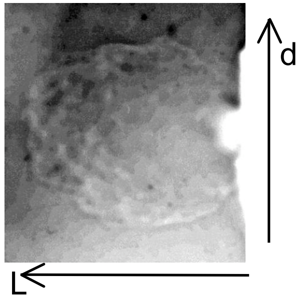
Protons

Interférométrie

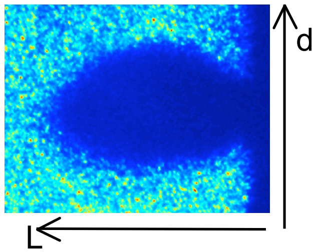
Ombroscopie

Densité: **ρ**



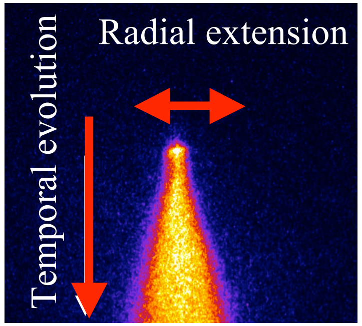


Gradient de densité

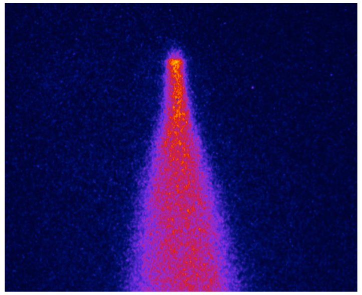


Dimensions: **d, L**

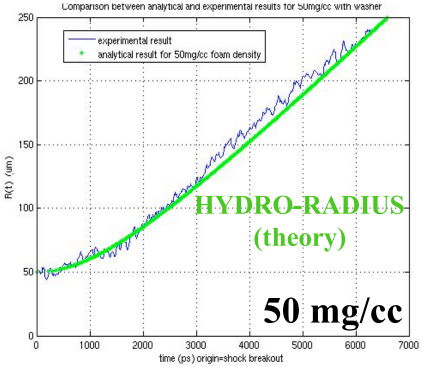
COMPARISON BETWEEN THEORY and JET EXPERIMENTS

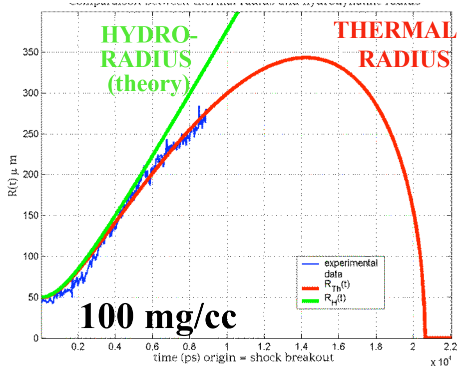


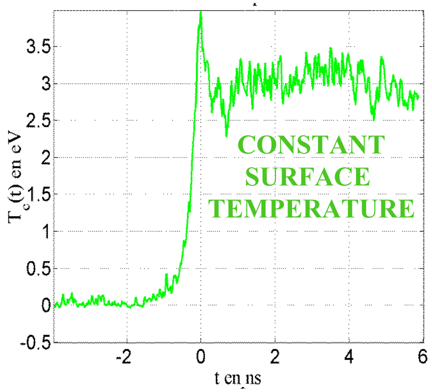
Into vacuum

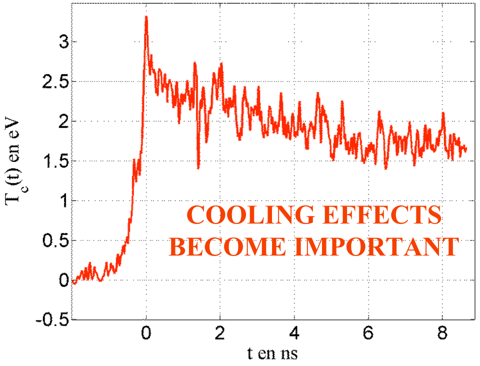


Into vacuum









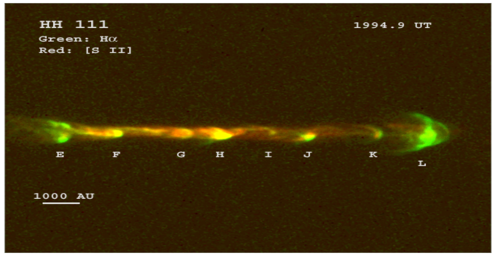
	Re	Pe = F_{conv}/F_{cond}	$\chi = t_{cool}/t_{dyn}$	Mach	$\zeta = \lambda_{mfp}/L_{hydro}$
YSO jet	10^7	10^6	0.1 - 10	10 - 30	10^{-7}
Exp. 5 ns	10^6	10^3	100	2	10^{-7}
Exp. 25 ns	10^5	10^2	10	20	10^{-7}

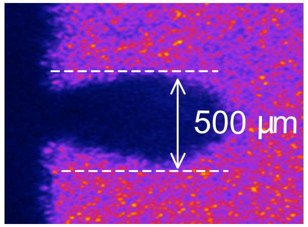
E. FALIZE, PhD Thesis, Paris, October 23, 2008

E. Falize et al., Journal Physics: Conf. Series 112 (2008) 042015; Astrophys. Space Science (2009)

INFLUENCE of an AMBIANT MEDIUM

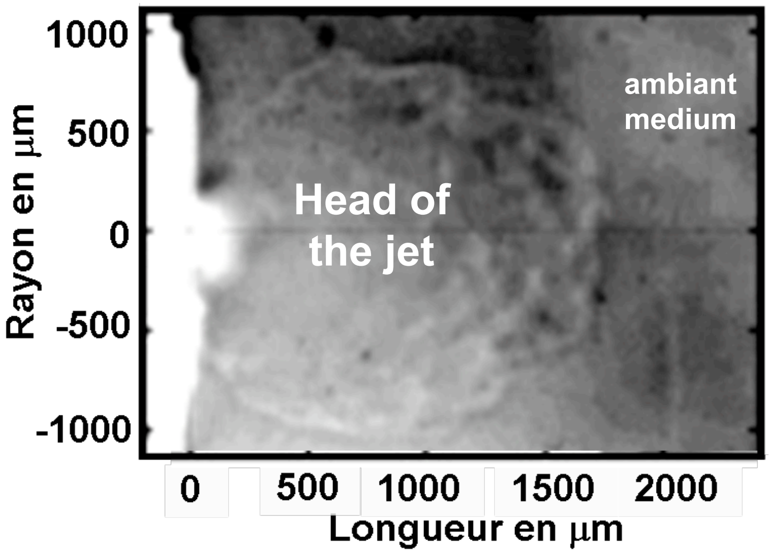
C.D. Gregory et al., PPCF 50(2008)124039





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

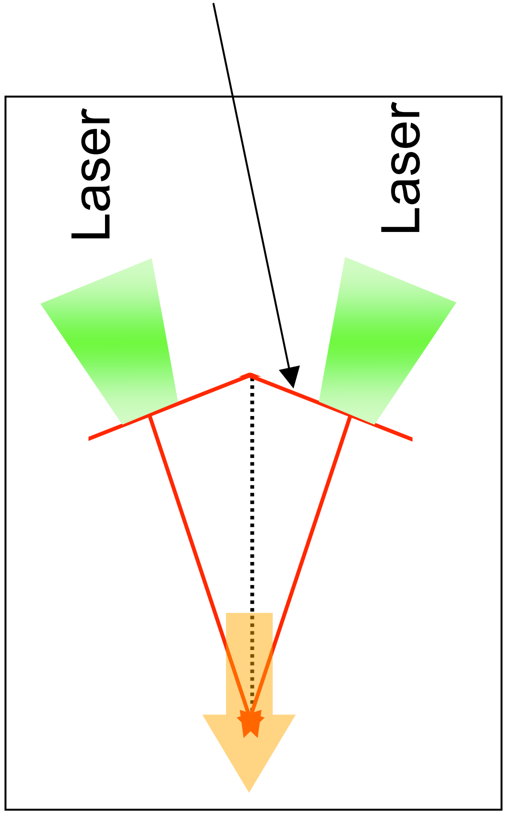
$$\boxed{\tau_{RTI} = 1/\omega \approx 3\,ns}$$

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

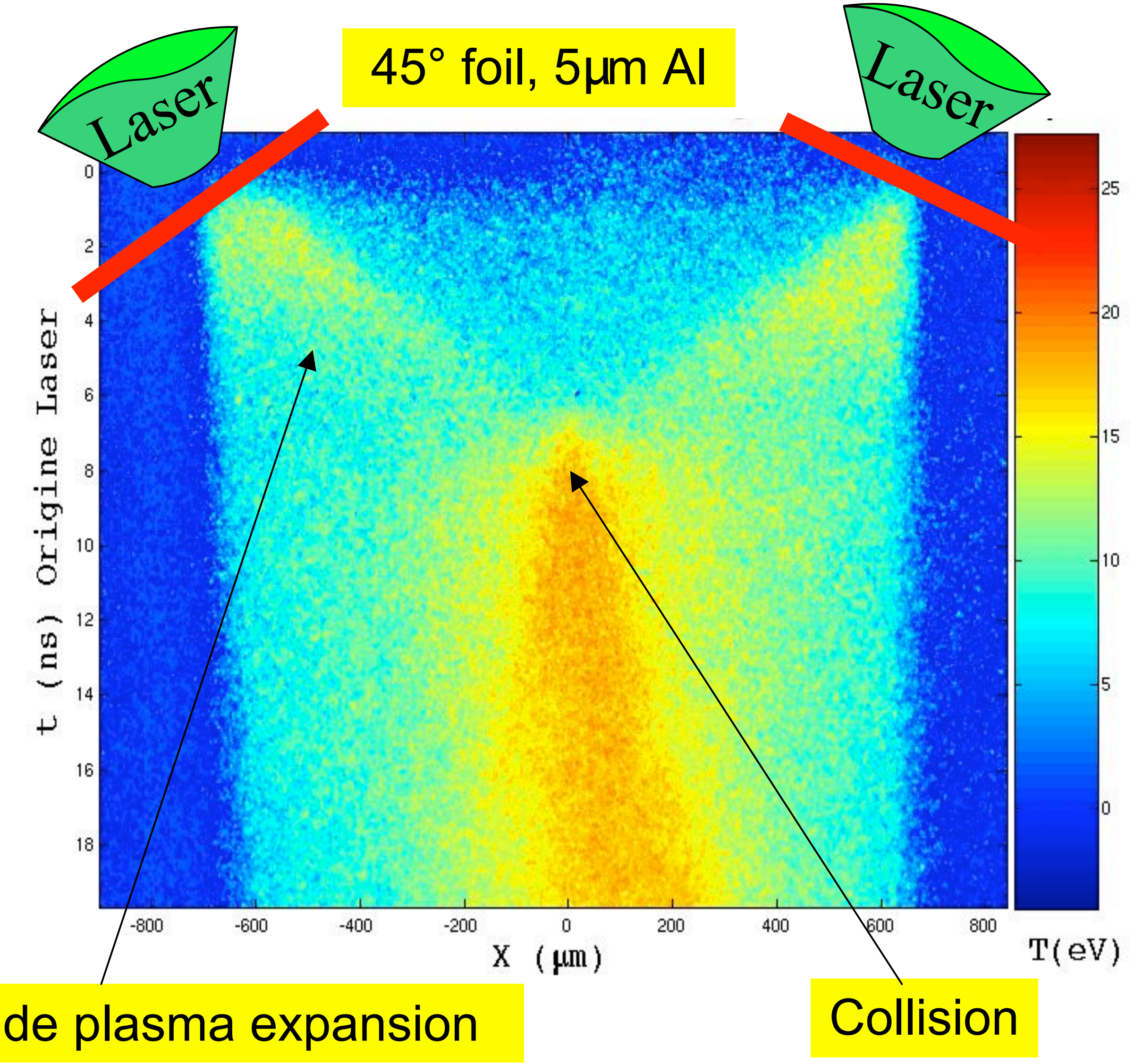
HIGHER RESOLUTION REQUIRED IN OBSERVATIONS + Compressible effects …

ANOTHER TYPE of TARGET

V-FOIL TARGET



COLLIDING PLASMAS

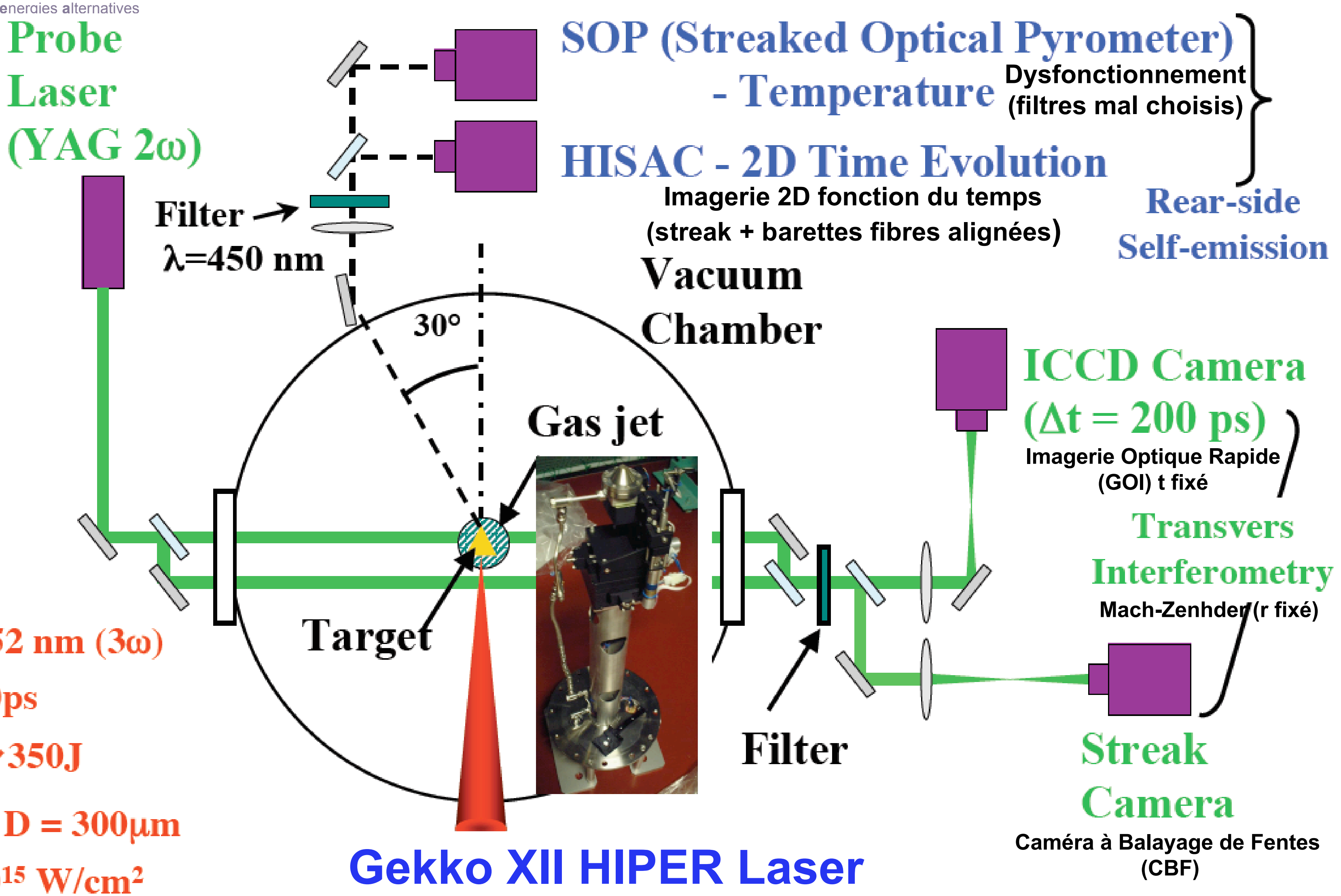


45° foil, 5µm Al

Rear side plasma expansion

Collision

GEKKO EXPERIMENTAL SET-UP



Probe Laser (YAG 2ω)

Filter → λ=450 nm

SOP (Streaked Optical Pyrometer) - Temperature

Dysfonctionnement (filtres mal choisis)

HISAC - 2D Time Evolution

Imagerie 2D fonction du temps (streak + barettes fibres alignées)

Rear-side Self-emission

Vacuum Chamber

30°

Gas jet

Target

Filter

ICCD Camera ($\Delta t = 200$ ps)

Imagerie Optique Rapide (GOI) t fixé

Transvers Interferometry

Mach-Zenhder (r fixé)

Streak Camera

Caméra à Balayage de Fentes (CBF)

λ_L : 352 nm (3ω)

τ : 500ps

E_L : ~350J

Spot : D = 300µm

I_L : 10^{15} W/cm²

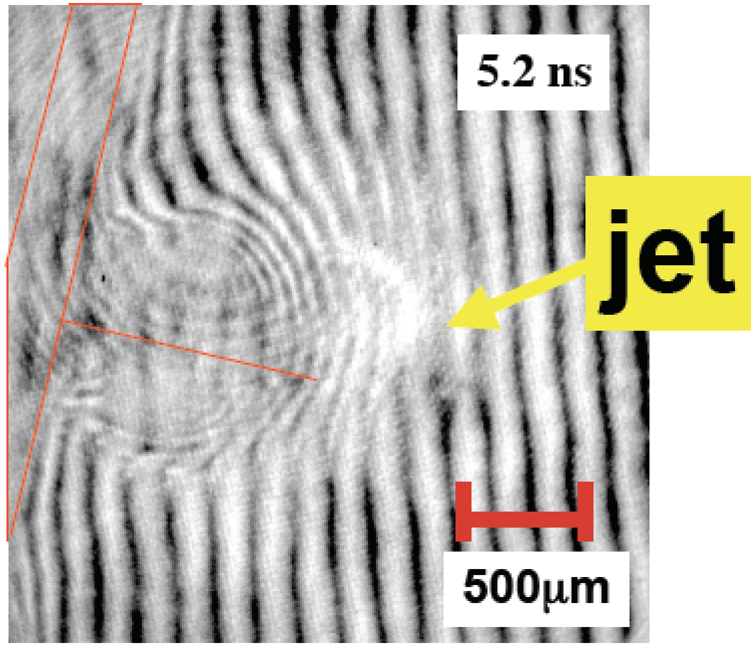
Gekko XII HIPER Laser

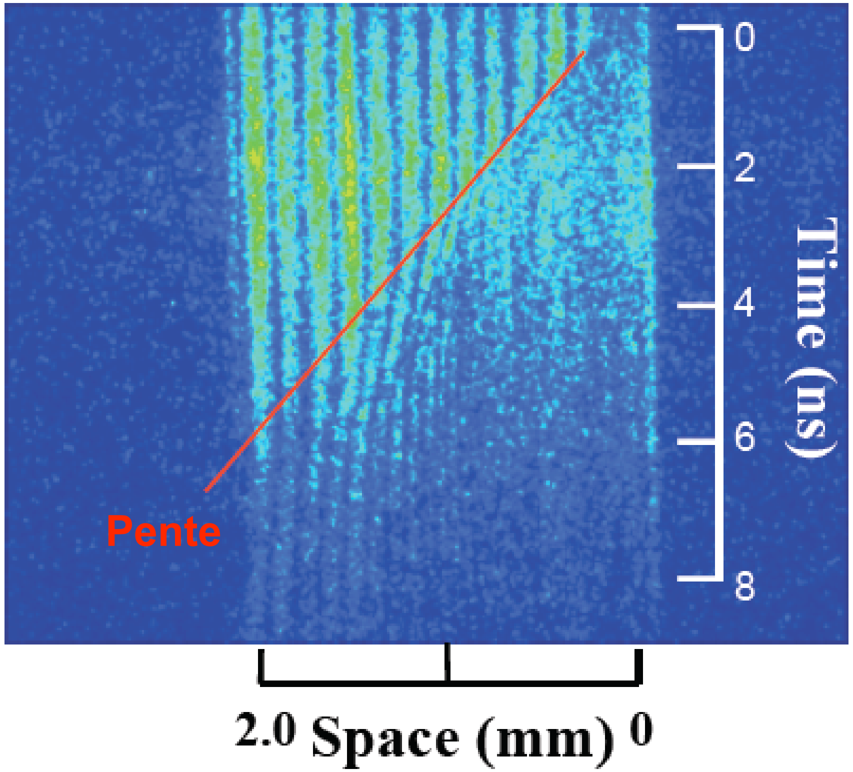
9 faisceaux utilisés

energie atomique • energies alternatives

TRANSVERSE INTERFEROMETRY

Vitesse de propagation + densité électronique n_e(r fixé, z, t)





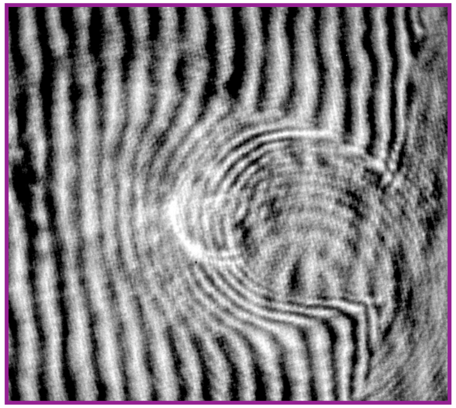
Jet velocity = 2/6 mm/ns : environ **330 km/s**

WITH NO AMBIENT GAS

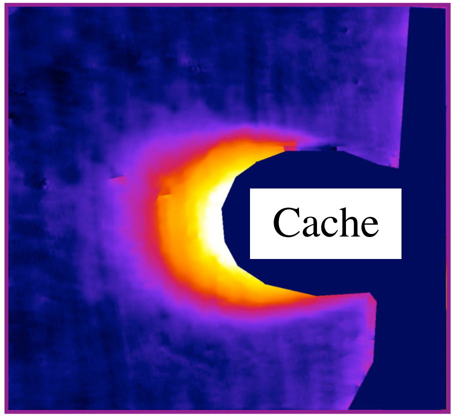
To generate higher temperature, the beams were focused directly into the foam to propagate radiative shock through the foam.

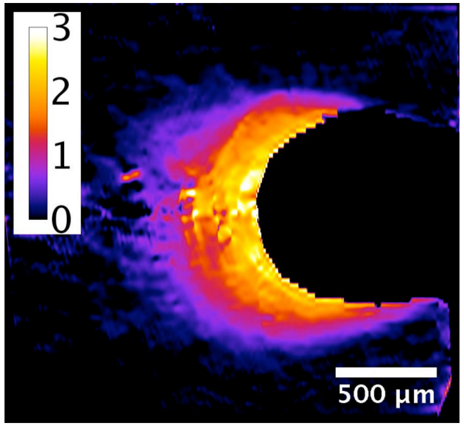
Interferometry result without ambient gas

7ns



Phase map result





The scale is $n_e \times 10^{19}$ per cc

$$\delta\phi = \int \frac{\omega n_e}{2 n_c c} dl \quad \rightarrow \quad n_e(r, z, t \text{ fixé})$$

$\delta\varphi$= phase shift

ω= frequency

n_c = critical density

c = speed of light

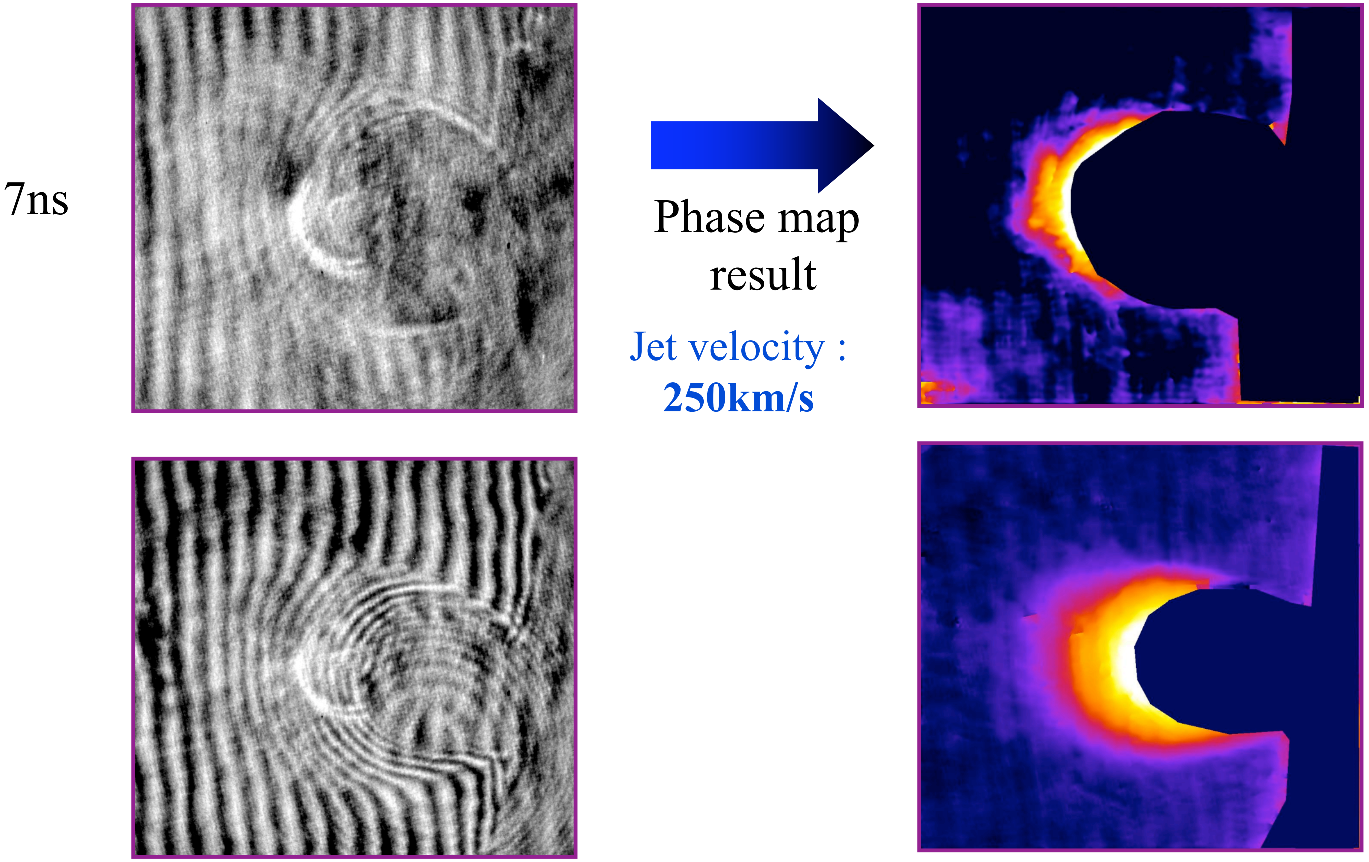
l = length of plasma traversed by probe beam

Jet velocity : **285km/s**

WITH AMBIENT GAS

Interferometry result with ambient gas

Helium gas: Pressure 1 atm, atom density = 3.10^{19} cm^{-3}



Phase map result

Jet velocity : **250km/s**

The ambient medium seems to confine and slow down the plasma propagation ahead of jet.

ET AUSSI LES LOIS D’ECHELLE …

INVARIANCE and 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.)

Solution: **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

$x = A_x . \bar{x}$, $t = A_t . \bar{t}$

Dependent variable: T(x,t)

$T = A_T . \bar{T}$

A_x , A_t and A_T : Scaling parameters

$$\frac{A_T}{A_t} . \frac{\partial \bar{T}}{\partial \bar{t}} = \frac{(A_T)^n}{(A_x)^2} . D.\frac{\partial^2 \bar{T}^n}{\partial \bar{x}^2}$$

$$\frac{\partial \bar{T}}{\partial \bar{t}} = \frac{A_t.(A_T)^{n-1}}{(A_x)^2} . D.\frac{\partial^2 \bar{T}^n}{\partial \bar{x}^2}$$

$$\boxed{\frac{\partial \bar{T}}{\partial \bar{t}} = D.\frac{\partial^2 \bar{T}^n}{\partial \bar{x}^2}} \quad \boxed{\frac{A_t.(A_T)^{n-1}}{(A_x)^2} = 1}$$

A_x and A_t are arbitrary !

$A_T = [(A_x)^2 / (A_t)]^{1/(n-1)}$

The equation is **invariant** under the transformation

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

The solution is **invariant**

The solution is **the same** at **both scales**

INVARIANCE OF RADIATION HYDRODYNAMICS ?

E. Falize et al., Astrophys. Sp. Sc. (2009)

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
- $\left[\frac{\partial}{\partial t}+(\vec{v}.\vec{\nabla})\right].\vec{v}=-\frac{1}{\rho}\vec{\nabla}P$ and $\left[\frac{\partial}{\partial t}+(\vec{v}.\vec{\nabla})\right].P-\gamma\frac{P}{\rho}.\left[\frac{\partial}{\partial t}+(\vec{v}.\vec{\nabla})\right].\rho=-(\gamma-1).\Lambda(\rho,P)$

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

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

Λ_0= constant
power law form
exponents ε and ζ

$\boxed{\Lambda(\rho,P)\ \rightarrow\ \Lambda(\rho,T)}$

$P=C_{EOS}(Z).\rho^{\mu}.T^{\nu}$
C_{EOS} = constant
exponents μ and ν and $\gamma=(\nu-\mu)/(\nu-1)$, I.G.: $\mu=\nu=1$

- **Invariance ? Scaling parameters:** A_q (q: any physical quantity)

$t_{astro} = A_t . t_{lab}$ $v_{astro} = A_v . v_{lab}$ $T_{astro} = A_T . T_{lab}$ $C_{EOS,astro} = A_{C_{EOS}}.C_{EOS,lab}$

$x_{astro} = A_x . x_{lab}$ $p_{astro} = A_p . p_{lab}$ $\Lambda_{astro} = A_\Lambda . \Lambda_{lab}$ $\Lambda_{0,astro} = A_{\Lambda_0} . \Lambda_{0,lab}$

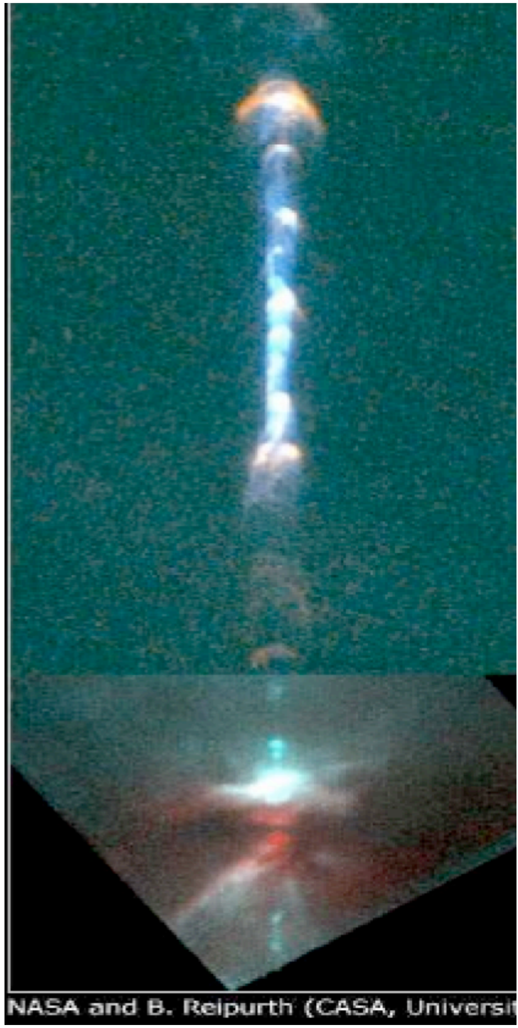
$\rho_{astro} = A_\rho . \rho_{lab}$

Yes !

energie atomique • energies alternatives

ASTROPHYSICS and LABORATORY EXPERIMENTS

$A_\rho \equiv \rho_{astro}/\rho_{lab}$, $A_P \equiv P_{astro}/P_{lab}$, $A_\rho \approx 3\ A_P \approx 2.10^{-19}$


NASA and B. Reipurth (CASA, Universit

HH 111

TWO CONDITIONS TO FIND A_ρ and A_P:

Velocities about 100 km/s in both cases and YSO time scale = 1000 years (length: 0.1 pc) and laser jet time scale = 10 ns

Physical quantities	Cold protostellar jet (HH111)	Experimental values	Scaling factor
Length (cm)	3.10^{17}	0.1 (1 mm)	3.10^{18}
Time (s)	3.10^{10} (1000 y)	10^{-8} (10 ns)	3.10^{18}
Velocity (km/s)	100	100	1
Density (g/cm^3)	10^{-22}	10^{-3} (1 mg/cc)	10^{-19} ($\approx A_\rho$)
Density (part/cm^3)	100	5.10^{20}	2.10^{-19}
Temperature (K)	10 000	10 000	1

1) - LABORATORY ASTROPHYSICS

2) - LASER FACILITIES

3) - ASTROPHYSICAL RADIATIVE SHOCKS (RS) and LASER EXPERIMENTS

4) - ASTROPHYSICAL JETS and LASER EXPERIMENTS

5) - CONCLUSION

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, consistence and redundance of the models

3) – Laboratory astrophysics is a relevant approach in spite of some
difficulties: Rad. Shocks, for instance.

BUT:
- I have neglected Erad and Prad in the rescaling
- Although we know radiation produces significant Erad and Prad in SNe,
- And this is not yet achieved in laboratory experiments.

4) – EoS (H2, H2+He), opacities of heavy elements (N, C, O, Fe)

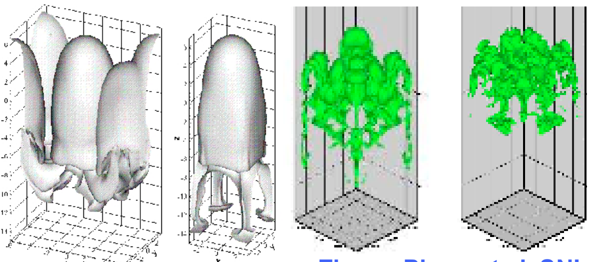
P. LOUBEYRE (CEA), GUYOT (Jussieu), MAZEVET (LUTH), KOENIG (LULI), TURCK-CHIEZE (CEA), CHIEZE (CEA) …

CONCLUSION (following)

Lois d'Echelle : Assise et justification de l'approche « Astrophysique de Laboratoire »

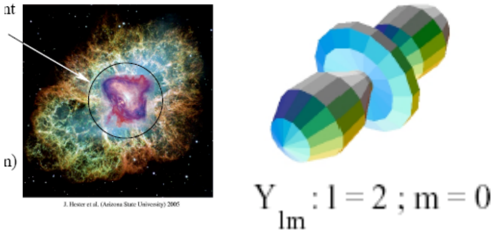
Astrophysi-
-que de
Laboratoire

Jets
B. Loupias et al., E. Falize et al.,
LULI et CEA/DIF

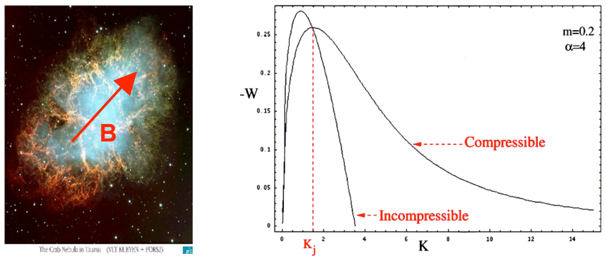


Zhang, Plewa et al. SNIa, ApJ2007

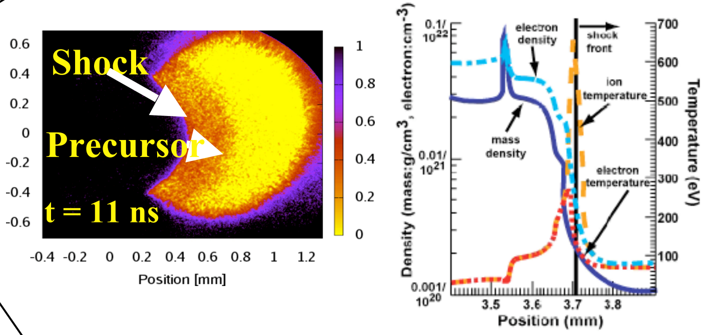
Rayleigh-Taylor Non Linéaire
Incomp. M. Tricottet, CEA/DIF



Rayleigh-Taylor Instabilities
X. Ribeyre et al., CESTA/CELIA



RTI Magnétique
S. Liberatore, CEA/DIF



P. Drake, 1D-Hyades, 2008

Radiative Shocks; C. Michaut, L. Boireau, E. Falize et al., Meudon et CEA/DIF

Scaling Laws, Self Similar Solution
E. Falize et al., CEA/DIF

Thank you !