LABORATORY ASTROPHYSICS WITH HIGH POWER LASERS

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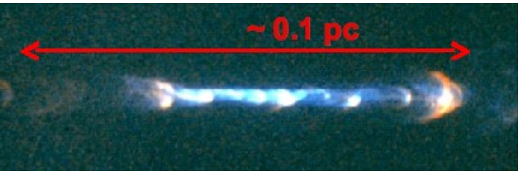
Laboratoire LULI

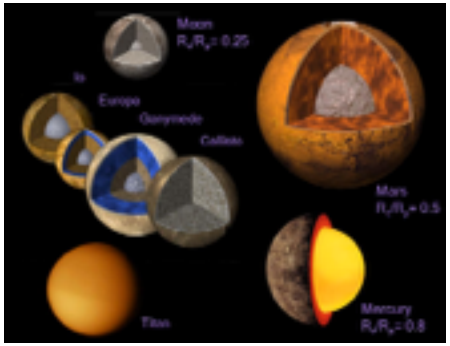
MOTIVATIONS

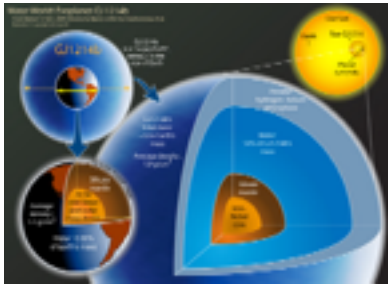
- Astronomical observations bring us many interesting objets...



jets

planètes solaires
et leur lunes





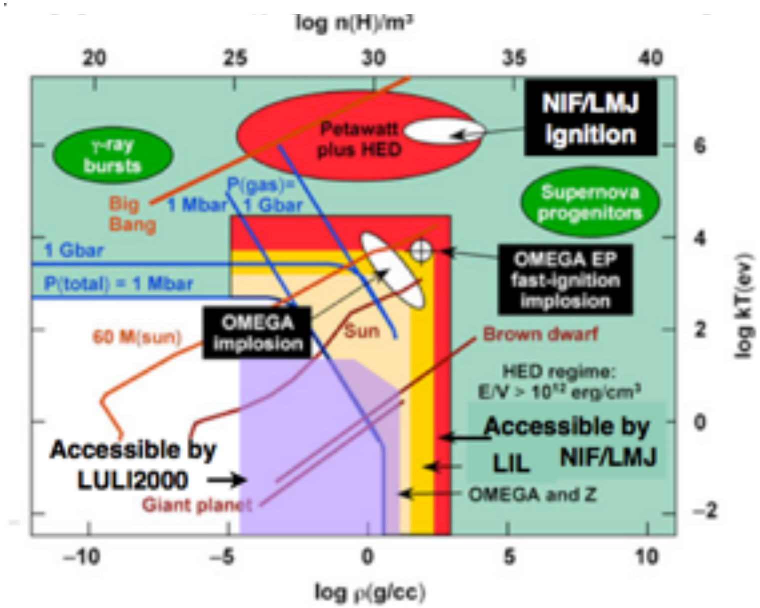
exoplanets

champs
magnétiques
cosmiques

- ...but their study is really challenging:
  - Mostly no evolution in the life time of a scientist
  - No possibility to change conditions in a controlled way
  - Many measurements are indirect
  - Measurements limited to electromagnetic emission

HIGH POWER LASERS CAN HELP

- Accessing the density/temperature regimes of some astrophysical objects



- This gave rise to laboratory astrophysics. Experiments allow to:
  - Deliver material properties useful for astronomical objects

    Precise data not directly measurable in the universe

  - Study phenomena relevant to astrophysical objects on small temporal and spatial scales

    Study temporal evolution and modify boundary conditions

OUTLINE

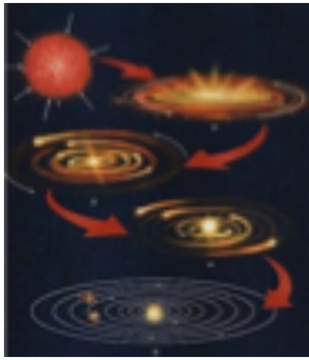
PLANETARY SCIENCE

- What do we need to measure
- How do we produce planetary conditions
- How do we probe them
- Application to super earths and giant planets

ASTROPHYSICS

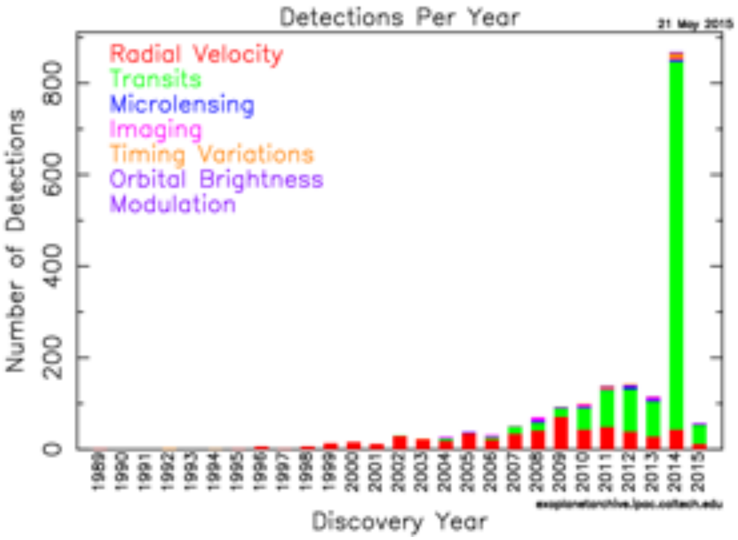
- Examples of experiments
  - Magnetic field
  - Accretion shocks
  - Nested outflows

PLANETARY SCIENCE



- Study the formation and evolution of planets
- Fast growing science due to exoplanets discovery

1523 planets discovered since 1989



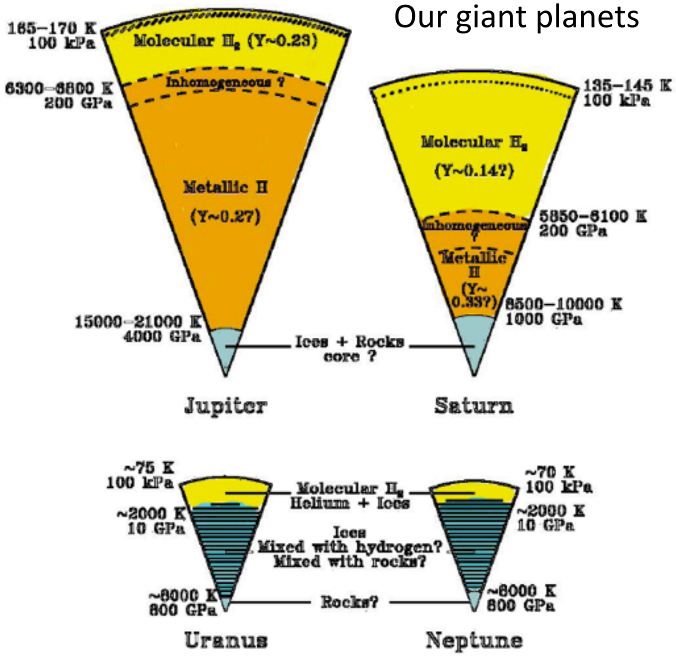
- Key questions
  - What is the nature of the iron core at the center of Earth and other terrestrial planets?
  - What is the interior of Jupiter and the other giant planets?
  - Why Saturn's luminosity is not comparable with its age?
  - Which kinds of planets exist outside our solar system?

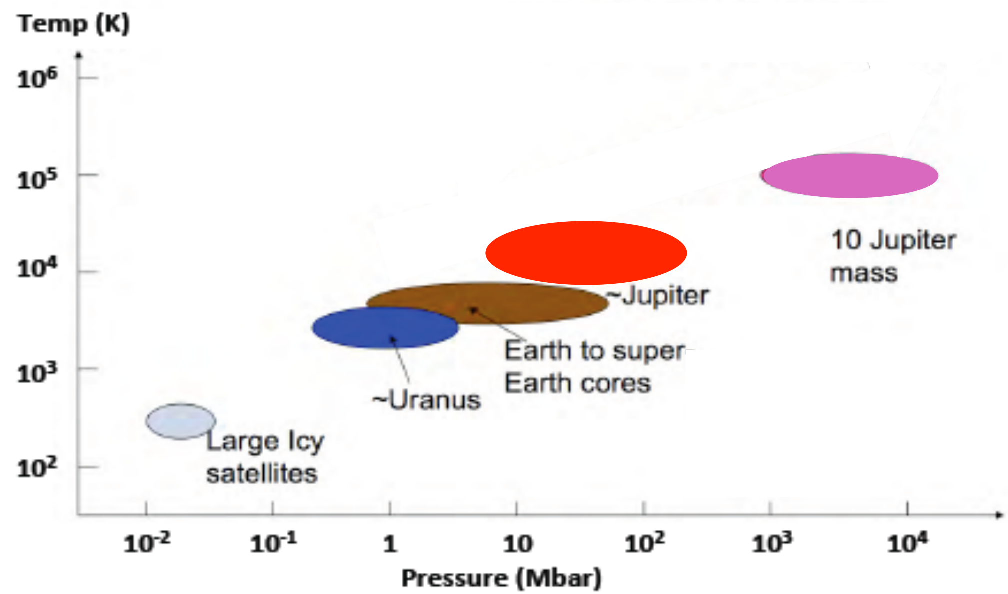
PLANETARY SCIENCE

- Layered structure and chemical composition defines properties

- At which conditions?

Our giant planets





- Main materials are hydrogen, helium, **water**, ammonia, CH_4, **iron** and silicates with pressures up to 15 Mbar

EOS ROLE IN PLANETARY STRUCTURE MODELS

Material properties are crucial to relate planetary models with the astronomical observations

$$\begin{cases} \nabla P = \rho \nabla (V + Q) \\ \nabla T = \nabla P \left(\frac{T}{P} \nabla_T \right) \\ \nabla M = 4\pi r^2 \rho \end{cases}$$

$$V(\vec{r}) = G \int \frac{\rho(\vec{r})}{|\vec{r} - \vec{r}'|} d^3\vec{r}$$

$$Q(\vec{r}) = \frac{1}{2} \omega^2 r^2 \sin^2 \theta$$

gravitational & centrifugal potentials

Few observational constrains

P is pressure, ρ the density, T the temperature and V & Q gravitational & centrifugal potentials. For giant planets $Q \approx 0.1$ V.

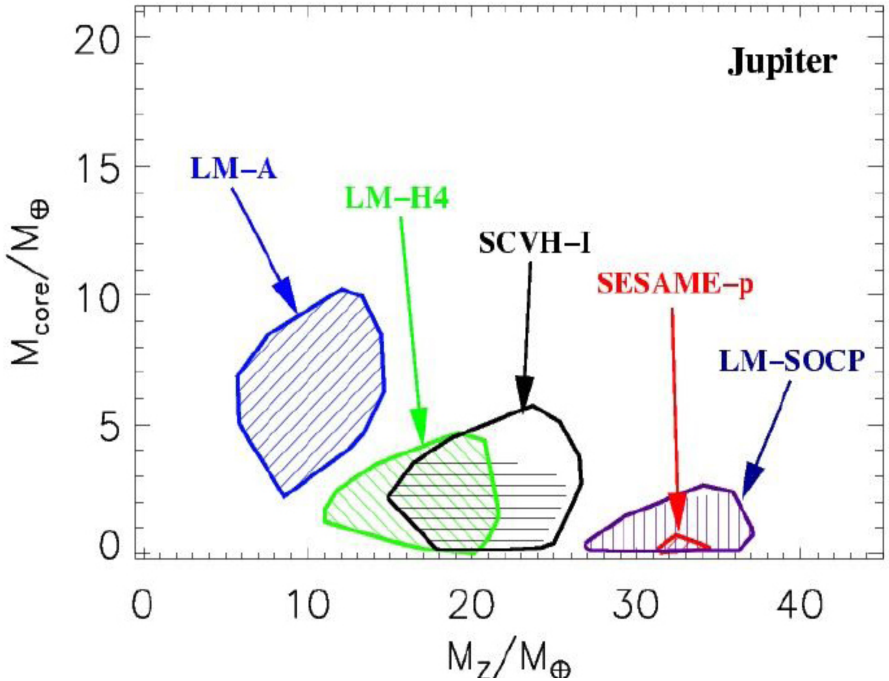
r is the radius with origin at the centre of the planet, θ the angle with respect to the rotation axis, & ω the rotation frequency at point r.

To close the system we need EOS; i.e. f(ρ,T,P) = 0

INFLUENCE OF EOS: an example

- **Equations of state in these regimes are very difficult to model**
  - at the frontier between plasma physics and condensed matter: non ideal plasmas
    - perfect gas does not apply
    - perturbation theory is invalid

- **Results for JUPITER**



- $M_\oplus$ is the earth mass, Mz envelop mass with heavy elements
- Sophisticated EOS models ≠answers

  ≠ formation scenarios

- Core

  ⇒ accretion around solid mass

- No core or very small one

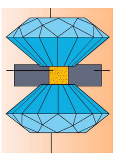
  ⇒ collapse due to condensation

HOW TO CREATE EXTREME STATES OF MATTER

Static way

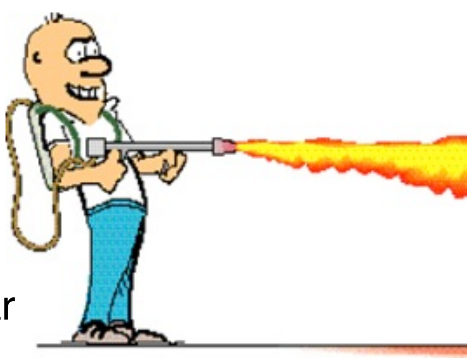
Diamond cell → **Isothermal Compression**

P ≈ 0 - a few Mbar



Dynamic way

Chemical explosions, gas guns



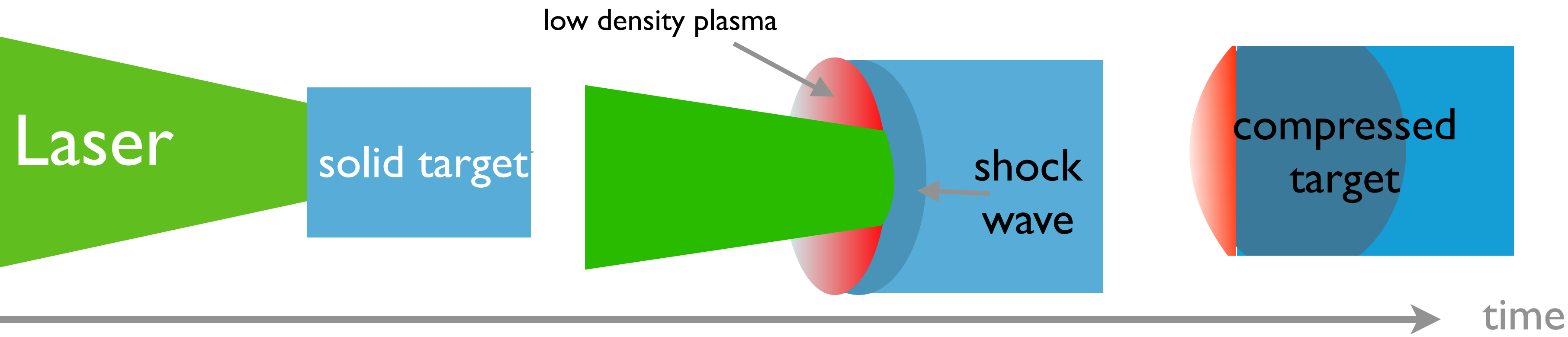
High power lasers

→ **Shock Compression**

P ≈ 0 - hundreds of Mbar

LASER GENERATED SHOCK WAVE

- A shock wave is a discontinuity in pressure, density and energy that propagates in a medium
- We can generate a shock wave with lasers



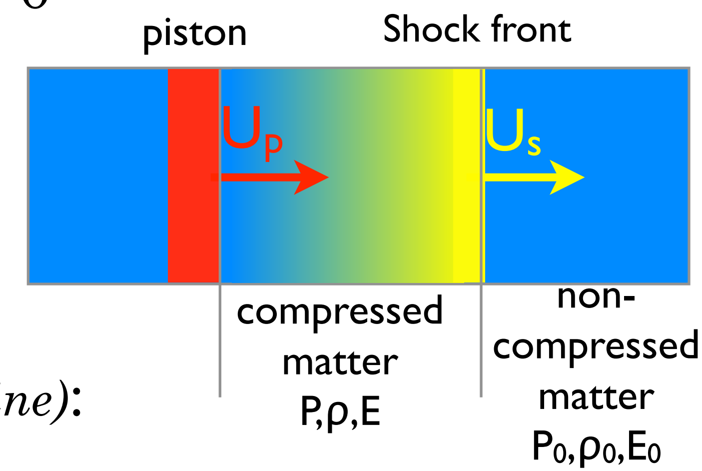
- As the laser impact the solid target a hot low density plasma is created and releases into vacuum. As a reaction to this expansion a shock wave is launched in the target
- The shock compresses and heat the sample
- The pressure attaint depends on the laser characteristics

$$P \approx 12(I_L/\lambda)^{2/3}$$

Today severals tens of Mbar

SHOCK WAVE AND Equation Of State

- Equation Of State *(EOS)* is the relation between the thermodynamics quantities : $f(P,E,\rho)=0$



- Conservation relations *(Hugoniot-Rankine)*:

mass	$\rho_0 U_S = \rho(U_S - U_P)$
momentum	$\rho_0 U_S U_P = P - P_0$
energy	$\rho_0 U_S (E - E_0 + U_P^2/2) = P U_P$

$\Rightarrow$ 3 equations et 5 parameters

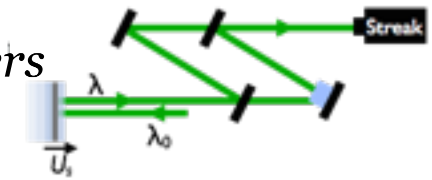
$\Rightarrow$ <u>We need to measure 2 quantities to close the system</u>

2 parameters in the same material $\Rightarrow$ absolute measurement

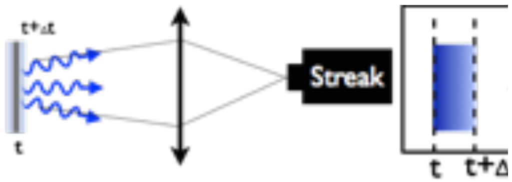
1 parameter in 2 material one of which in well known (Al) $\Rightarrow$ relative measurement

WHAT DO WE MEASURE

- Classical approach: **VISIBLE DIAGNOSTICS**
  - *Velocity interferometers (doppler effect)*



  - *Self emission*



Shock velocity
Particle velocity — **EOS**

Reflectivity/ **conductivity**

Grey body **Temperature**

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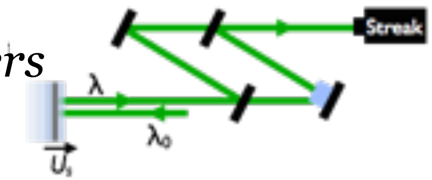
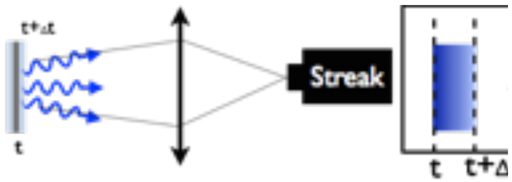


Shock velocity
Particle velocity — **EOS**

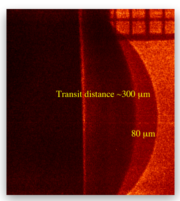
Reflectivity/ — **conductivity**

  - *Self emission*



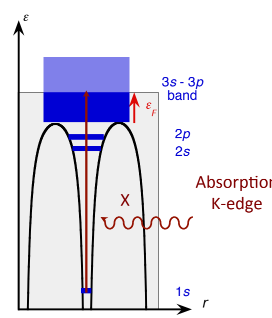
Grey body — **Temperature**

- More recent: **X-RAY & Particle DIAGNOSTICS** *(microscopic probe)*
  - *X-ray radiography*



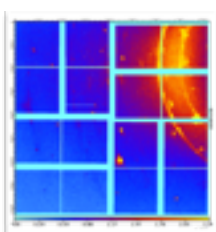
Mass density

  - ***X**-ray **A**bsorption **N**ear **E**dge **S**pectroscopy*



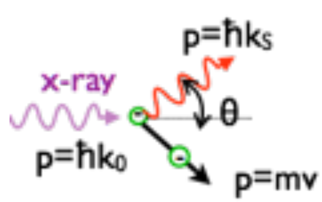
Electronic structure

  - *X-ray diffraction*



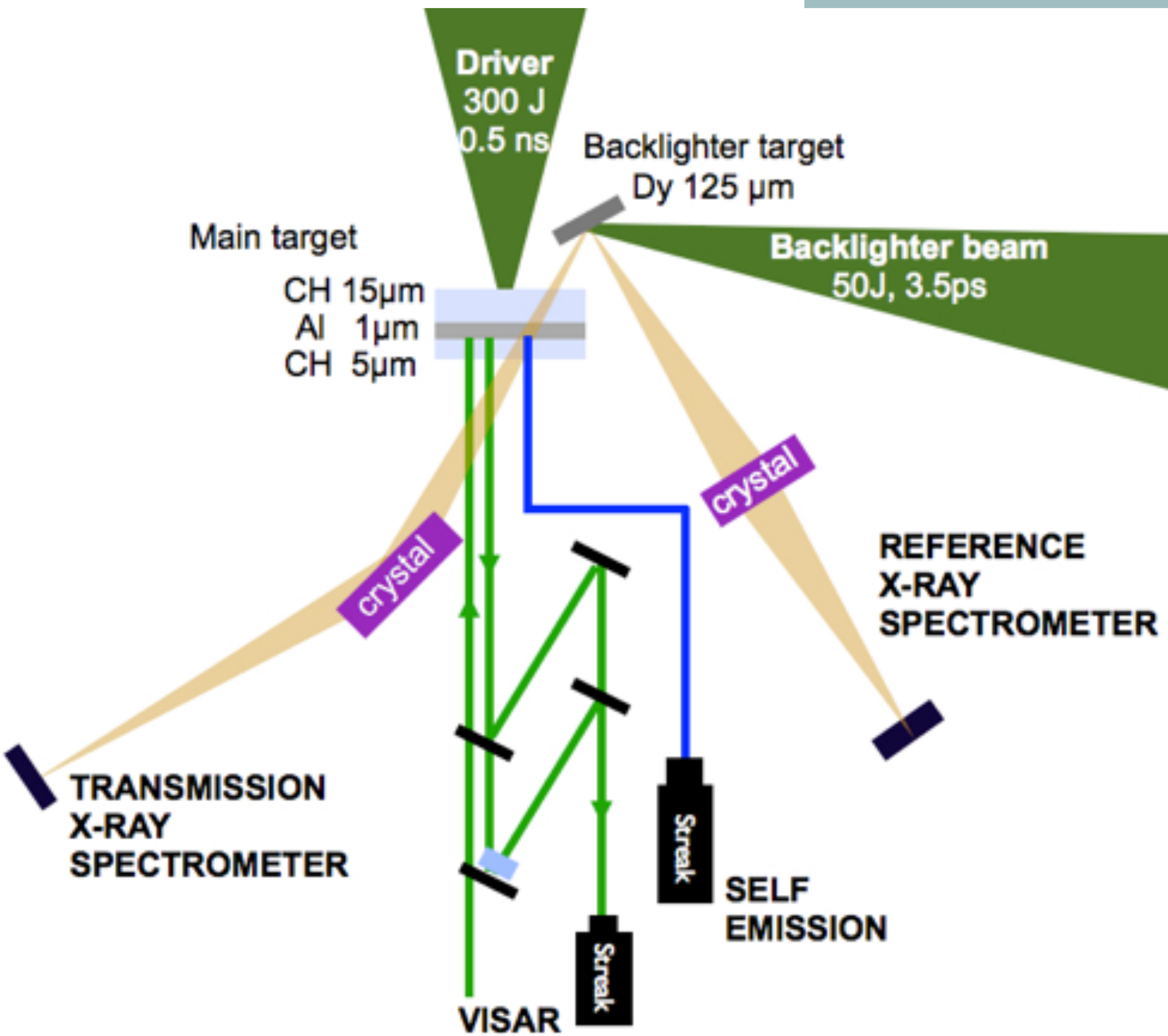
Ionic structure
phase transitions

  - ***X**-**R**ay **T**homson **S**cattering*



Temperature
Electronic density

TYPICAL EXPERIMENTAL SET-UP



LULI 2000 LASER

- 2x 1kJ@1054nm (IR) 0.5-10ns
- **1kJ@1054nm (IR), 0.5-3ns + 100J@1054nm, 1-5ps**

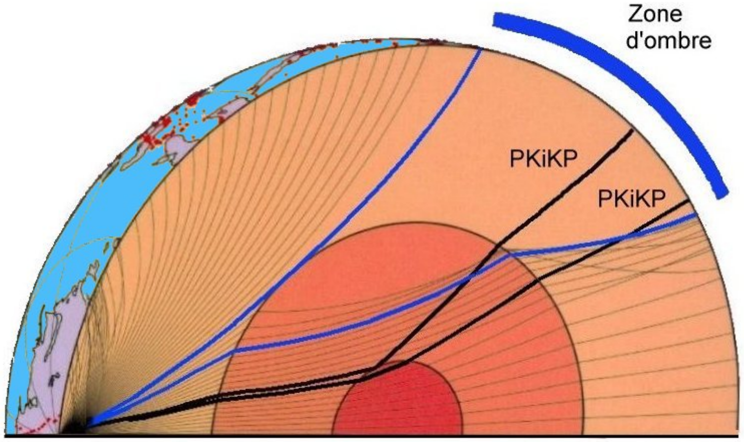
THE EXPERIMENTAL HALL

THE EXPERIMENTAL CHAMBER

Ex. IRON : OUR EARTH but also FURTHER EARTHS

- Iron is the main component of Earth's core
- Magnetic field +seismic wakes trajectories give us informations on internal structure:

  Earth's core is made of a solid core surrounded by liquid iron



- Which is the iron melting temperature at the solid/liquid boundary? (P=3,3 Mbar)

  Puissance émise par le noyau
  ⇒**Geodynamo + évolution**

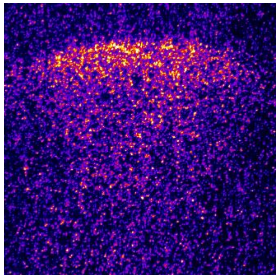
Necessity to explore Iron melting curve P(T)

- Life on super earths? B field (liquid iron) sustaining a magnetosphere
  - The presence of molten metallic cores is less likely for as the size of terrestrial planets increases.

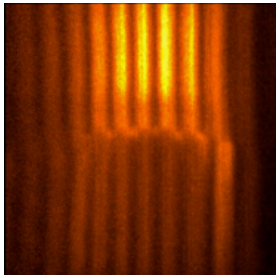
SHOCKED IRON

- The simultaneous measurement of the velocity and self emission allows to fill the temperature-pressure diagram

•SOP

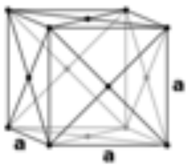


•VISAR



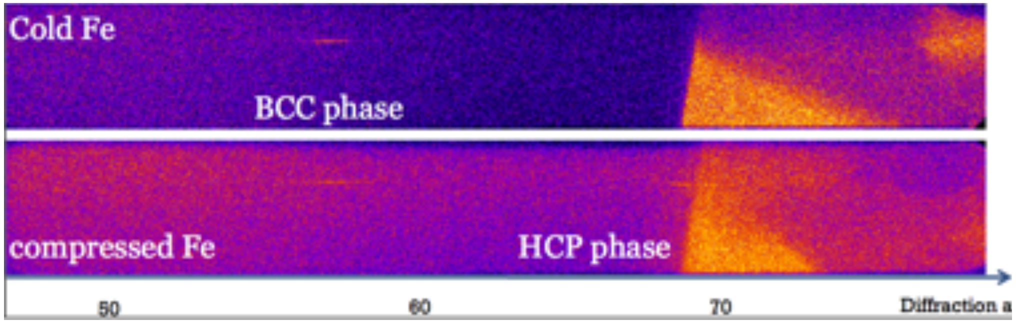
- Change in structure with pressure:

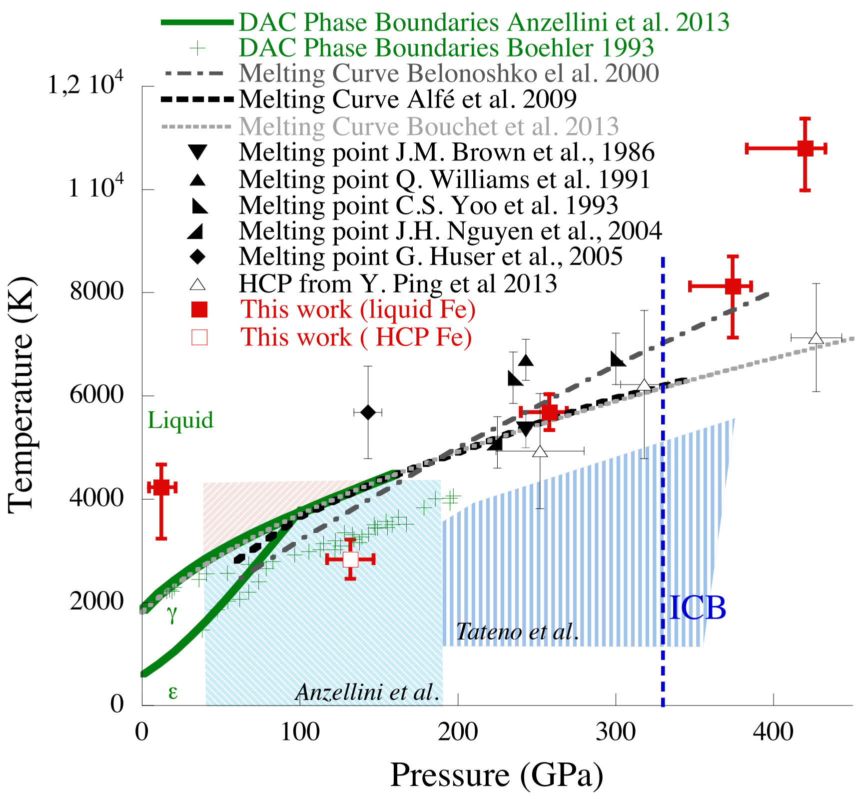
Diffraction measurements. Phase transitions+melting



cold iron: bcc phase

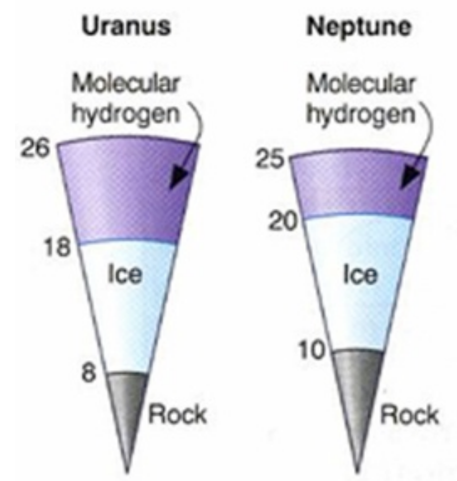
compressed iron: hcc phase



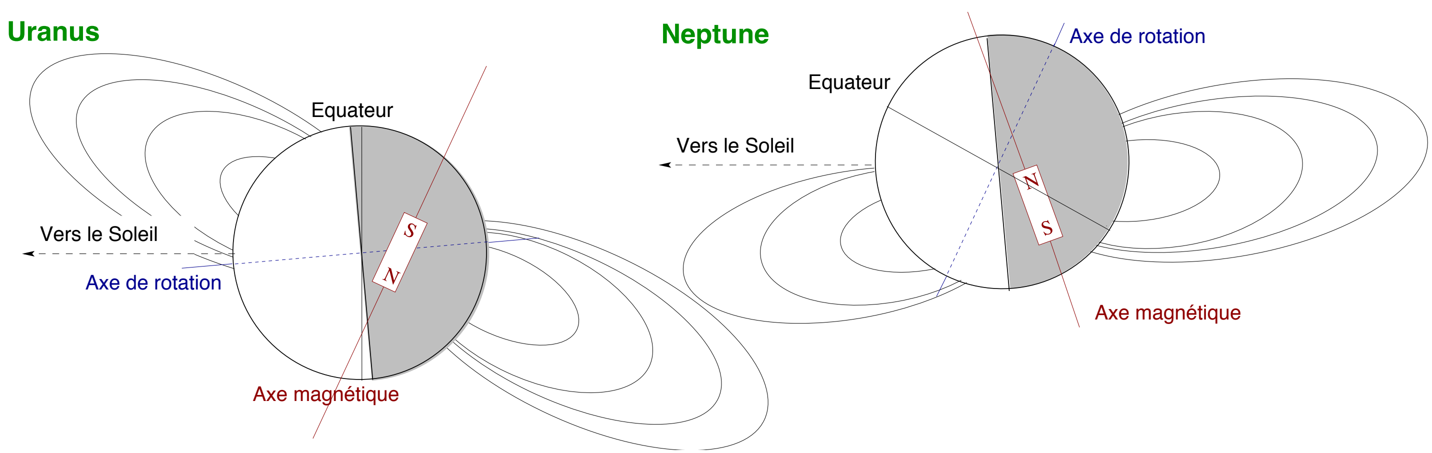


EX. WATER : OUR GIANT PLANETS

- Water (ices) at pressure of ~7Mbar



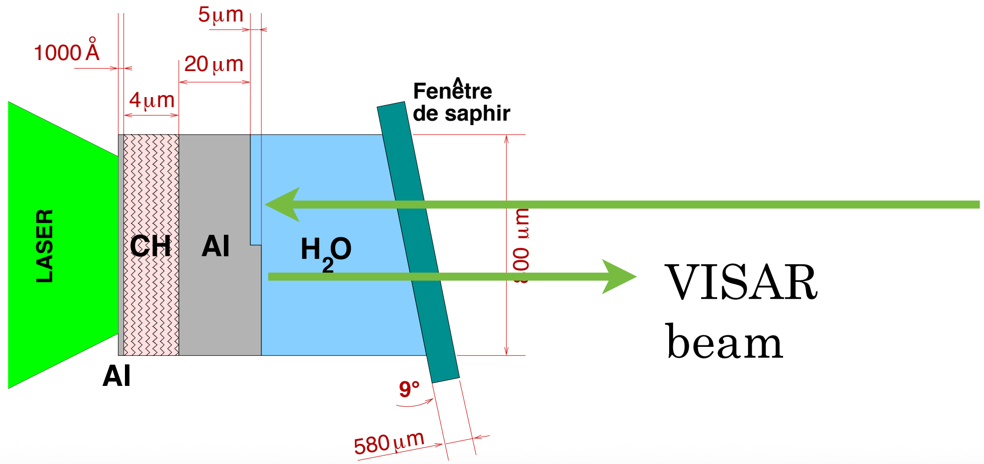
- The magnetic field of these two planets is more intense than expected and it is **asymmetric** (Voyager 2).

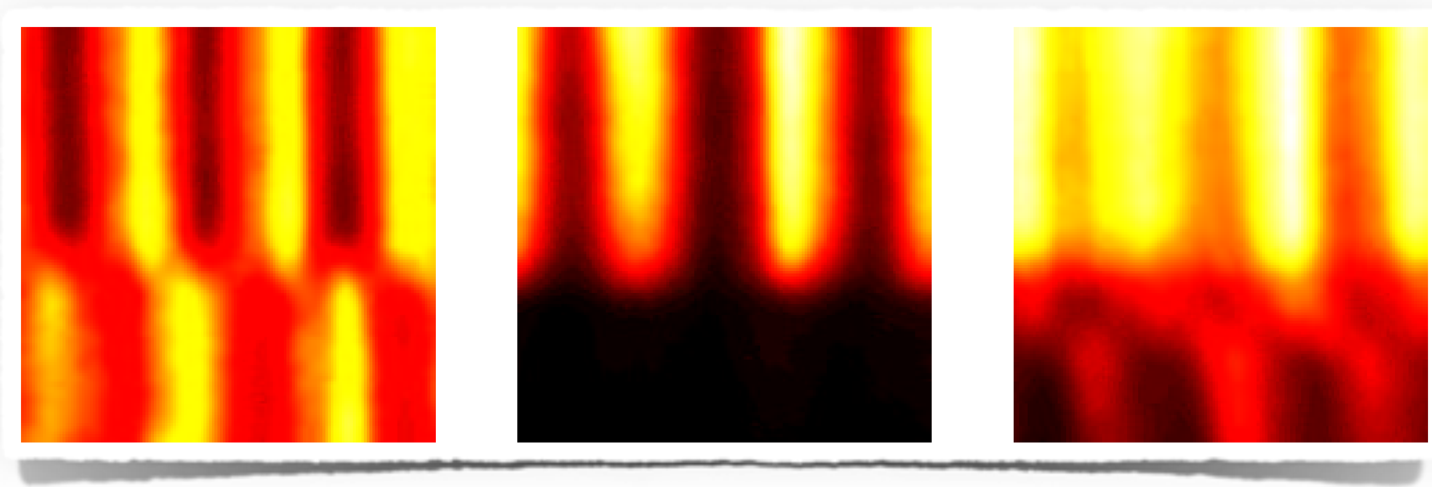


- Is there a fluid **conducting region**, able to explain this B field by dynamo effect?

SHOCKED WATER

- Different properties as pressure is risen





- Transparent

P≤ 0.5Mbar

- Opaque

0.5≤ P≤ 1 Mbar

- Reflecting

P≥ 1 Mbar

OUTLINE

PLANETARY SCIENCE

- What do we need to measure
- How do we produce planetary conditions
- How do we probe them
- Application to super earths and giant planets

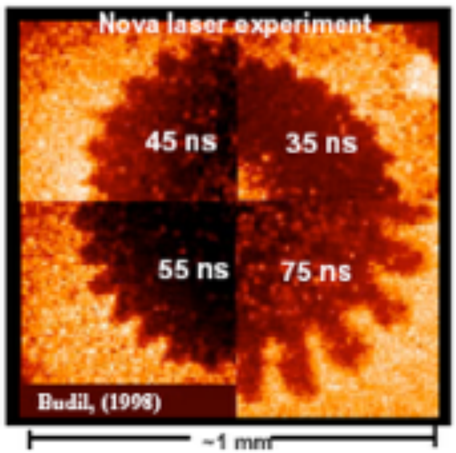
ASTROPHYSICS

- Scaling laws
- Example of experiments
    - Magnetic field
    - Accretion shocks
    - Nested outflows

SCALING LAWS

Well designed experiments to simulate in

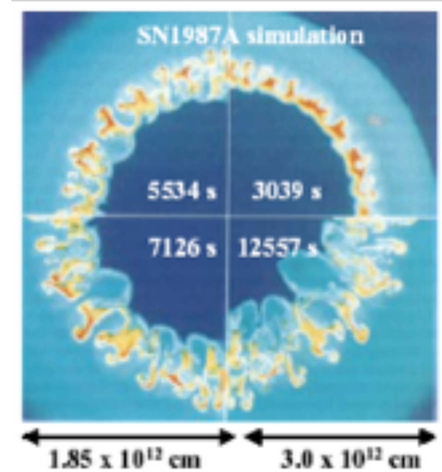
laboratory some ***astrophysical phenomena***



10^{-3} m
ns-10 ns

← 15-20 orders of magnitude →

10^{16} m
1000 ys



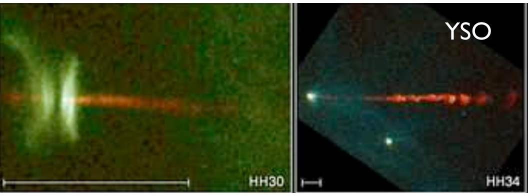
•same equations (same physics) and boundary conditions
•scaling laws (dimensionless numbers)

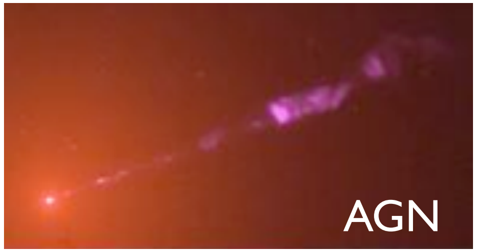
⇒ ***the two systems will show the same scaled evolution***

- direct characterisation (a part) of the phenomenon
- test astrophysical models/codes

ASTROPHYSICAL JETS

Astrophysical jets are extremely collimated matter flows common to very different objects





How do they stay collimated on such large distances?

- radiative losses
- interaction with IGM
- magnetic fields but
  - no direct observational evidence for the dynamical role of B
  - how far from the star B remains dynamically important?
  - an outer boundary pressure to the magnetic coil to maintain the jet collimated?

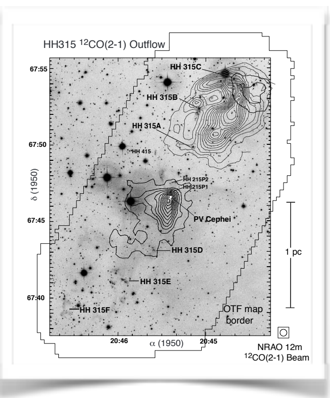
NESTED OUTFLOWS

- Often **jets** are **associated** with **accretion disk + Jets propagate** in **winds**

YSO

- Connection between outflow and environment well established

Arce et al. 1998



AGN:

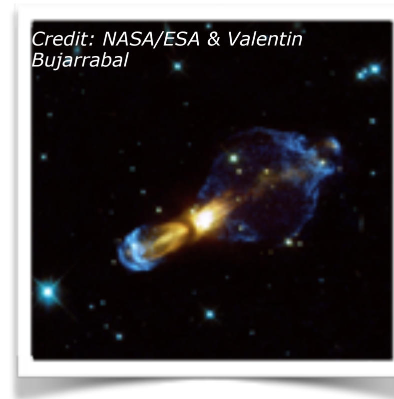
- Evidence of accretion disk in the form of Ultra Fast Outflows (UFO) helping collimating the inner jet.

Tombesi et al. 2012

- Observational evidence of structured jet: simultaneous presence of an inner highly relativistic jet, and an outer, more massive, mildly relativistic plasma.

Asada&Nakamura 2012,
Ghisellini et al 2005,
Xie et al 2012

PNe- PPNe:



- Binary is emerging as the preferred method for shaping PNe

Soker 1998, 2006

- Very high accretion rate disks needed to account for the observed jets properties

Blackman&Lucchini 2014

- Fast collimated winds sweep into a slower denser wind ejected most strongly during the PPN phase

Bujarrabal et al. 2001,
Rizzo et al. 2013

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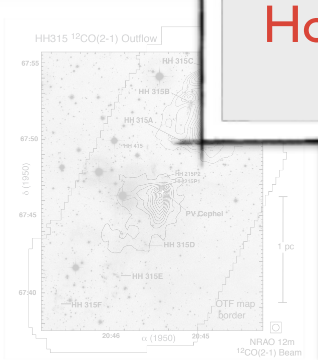

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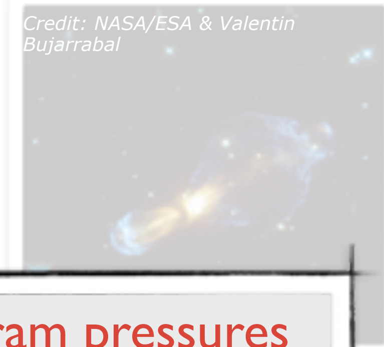
Tombesi et al. 2012

How different time-dependent ambient thermal and ram pressures affect jet collimation?

more massive, highly relativistic plasma.

Asada&Nakamura 2012, Ghisellini et al 2005, Xie et al 2012

PNe- PPNe:



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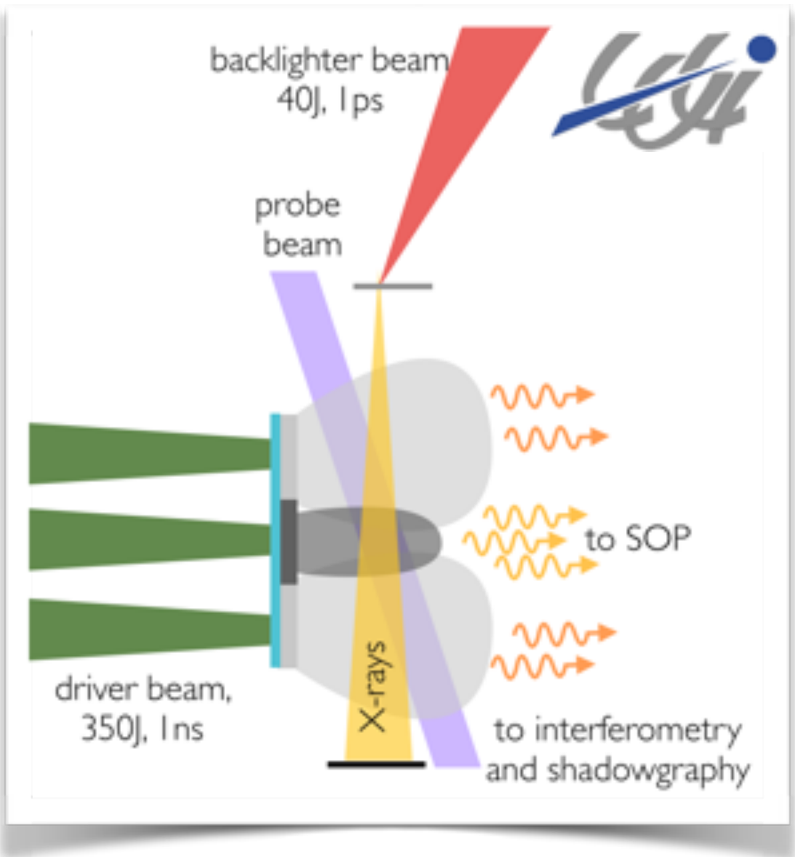
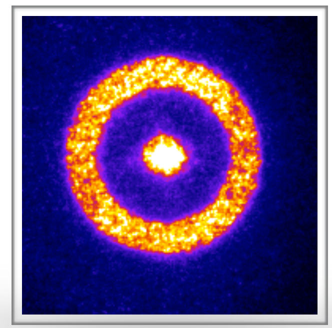
OUR EXPERIMENTAL APPROACH

- Create **nested** *(surrounding)* **outflows** *(dynamic "wind")* from laser plasma interaction
  - Spatially shaping the laser focal spot
  - Specific target

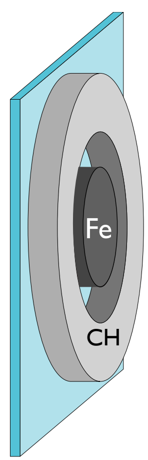


- Focal Spot (Phase Plates)
  - inner dot (100μm)
  - outer ring (75μm)



Data from rear-side Gated Optical Imager
Snapshot of 2D emission

- Targets
  - inner Fe dot
  - outer CH ring
  - common CH-Al pusher

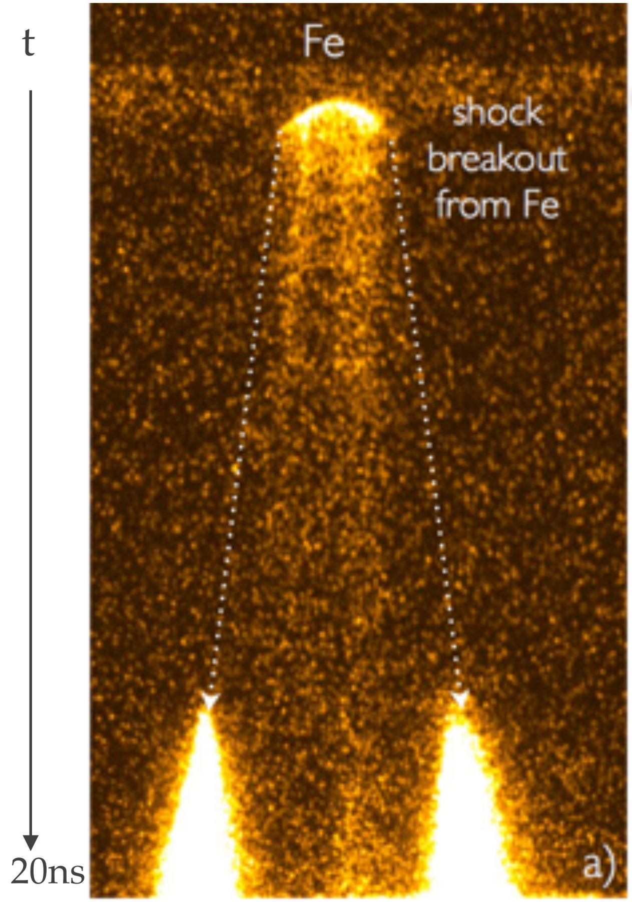


REAR SIDE TIME RESOLVED OPTICAL EMISSION

- Light emitted from rear side @ 450nm

Fe dot only, NO CH ring

Fe dot + 15 μm CH ring

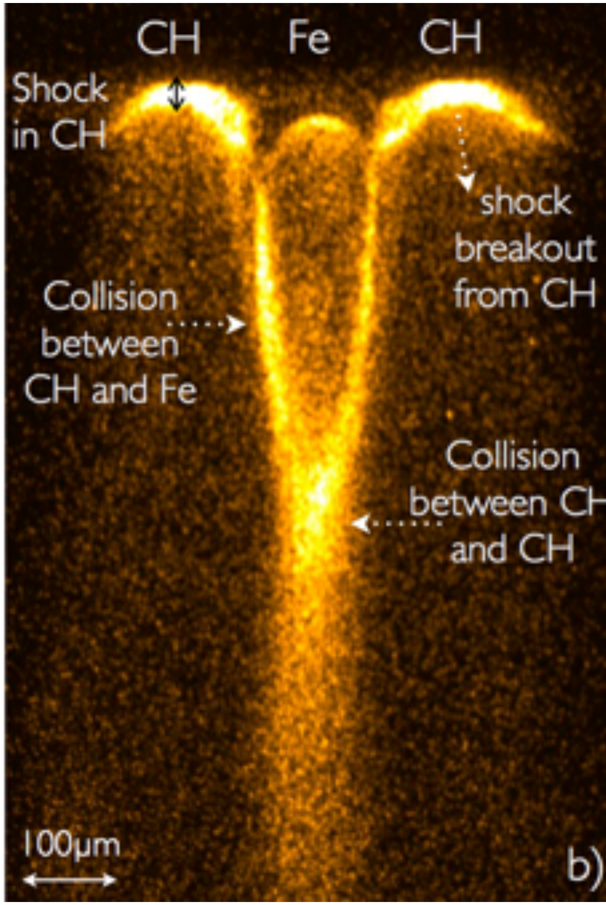


- Emission from the expanding plasma after shock breaks out.
- Lateral expansion

- Shock transit in CH (transparent)
- Collision between CHFe:

-high emission
-iron seems constrained

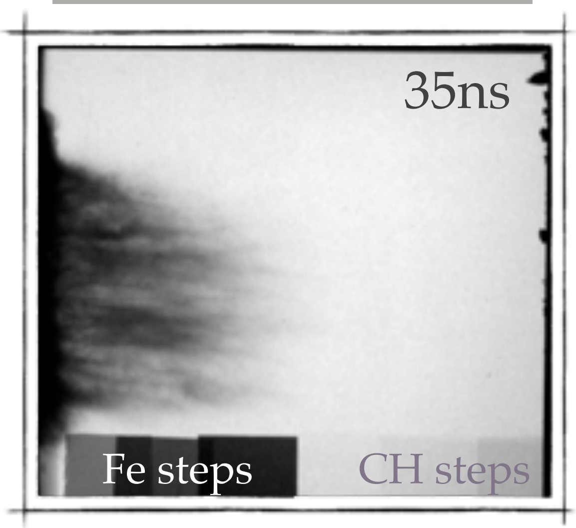
- Collision between CH-CH at later times



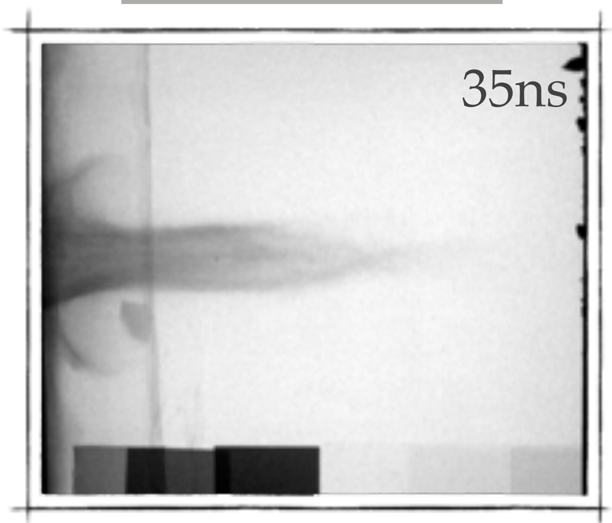
XRAY RADIOGRAPHY

- Hard X-rays (Cu Kα @~8 keV) ⇒ CH is transparent, Fe morphology

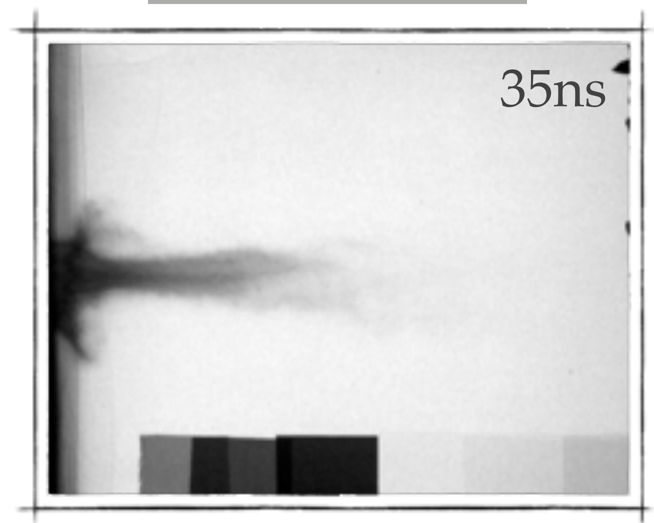
Fe dot only, NO CH ring



Fe + 15μm CH ring



Fe + 50μm CH ring



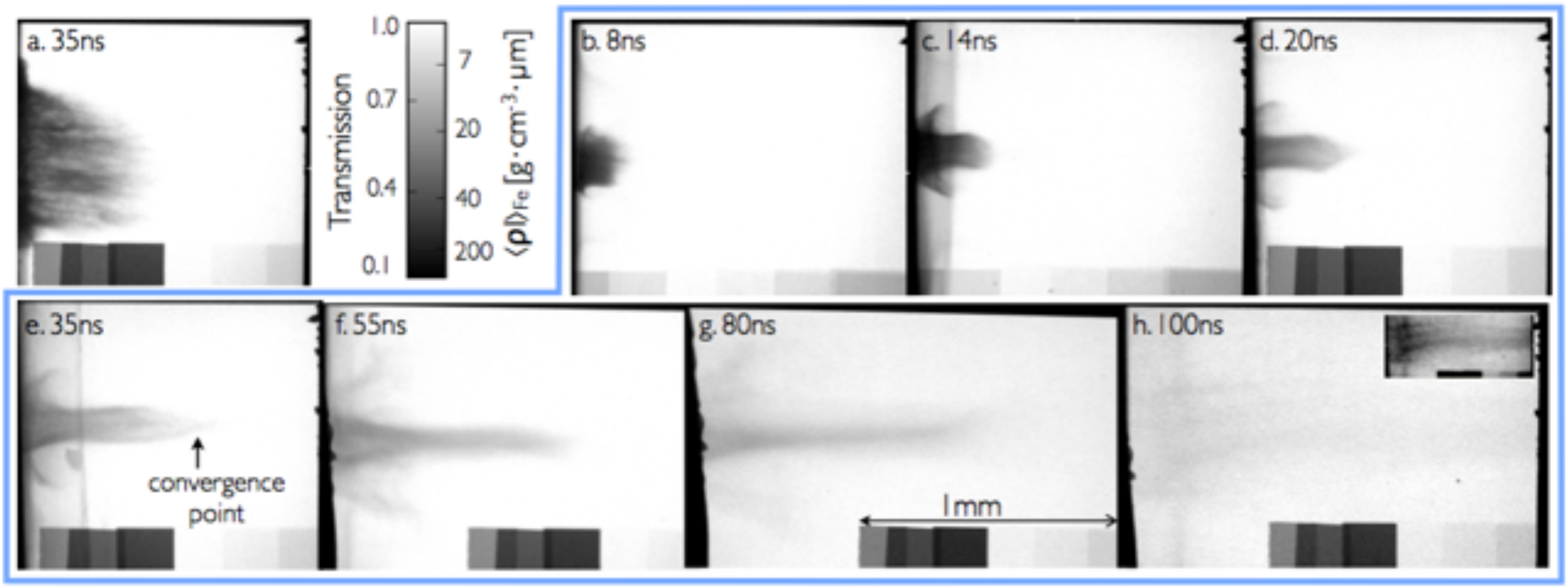
Quasi spherical expansion

Lateral expansion highly suppressed

XRAY RADIOGRAPHY TIME EVOLUTION

Fe + 15μm CH ring

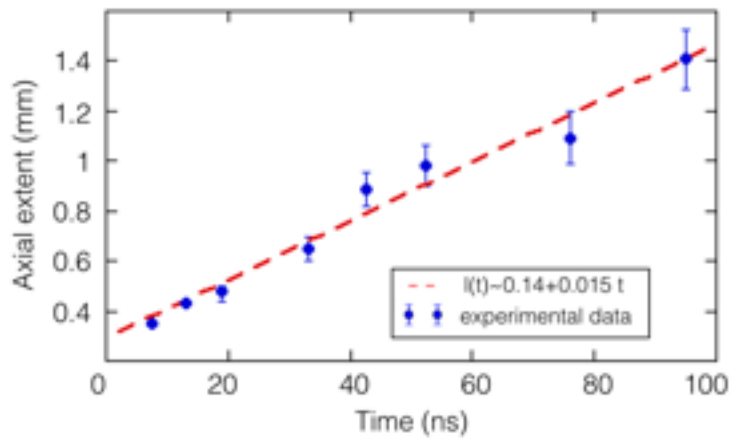
Yurchak et al. PRL 2014



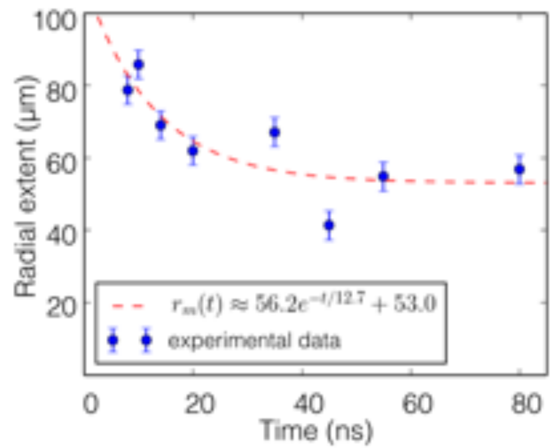
- Different phases :
  - expansion
  - collision with CH - ***high absorption*** *layers at the iron edge (in d. nicely visible)*
  - focusing on axis - *convergence point (d.- e.)*
  - collimate propagation up to 80 ns *(f.-g.)*

DYNAMICS OF THE IRON FLOW

Axial extent



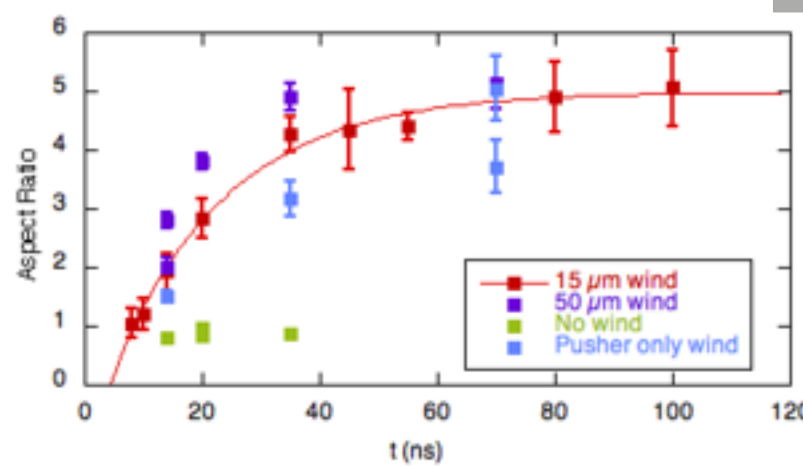
Radial extent



- The iron expands linerly along the propagation axis: from few 100μm at early times to **mm size**
- Iron shrinks in the radial direction *(focusing)*

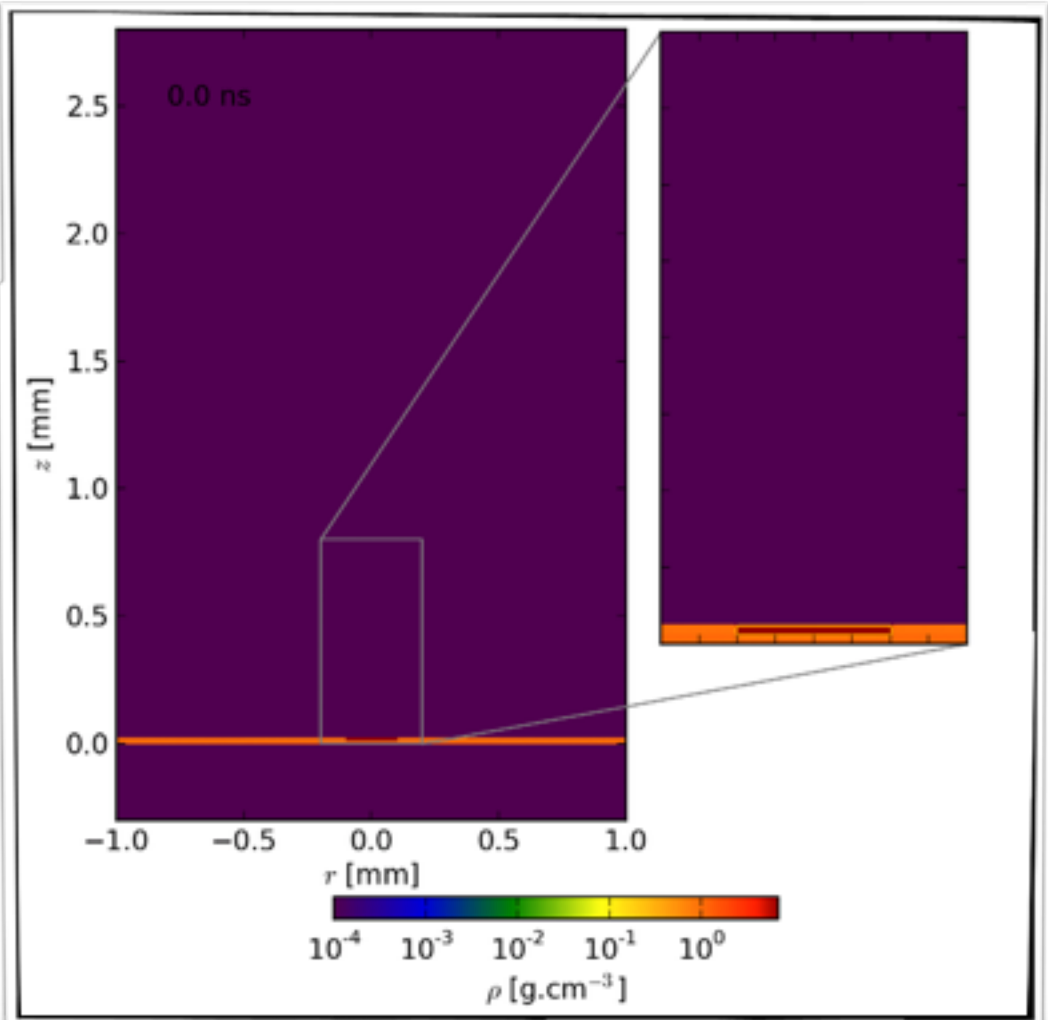
- Aspect ratio (**AR=l/d**)
  - Quasi spherical expansion without wind
  - Rapid increase in the AR with time when wind is added (more rapid for denser wind)
  - Saturation to a constant regime which is kept for long delays

AR



HYDRODYNAMIC SIMULATIONS

- **FLASH** code



- Multi-physics AMR code developed by the FLASH center at the University of Chicago
- Extensively used in astrophysics
- Recently extended to include high-energy density physics capabilities
- I_L calibrated with experimental optical data: shock velocities and breakout timings *(transverse and rear side SOPs)*, electron density *(interferometry)* and morphology *(shadowgraphy)*

HYDRODYNAMIC SIMULATIONS

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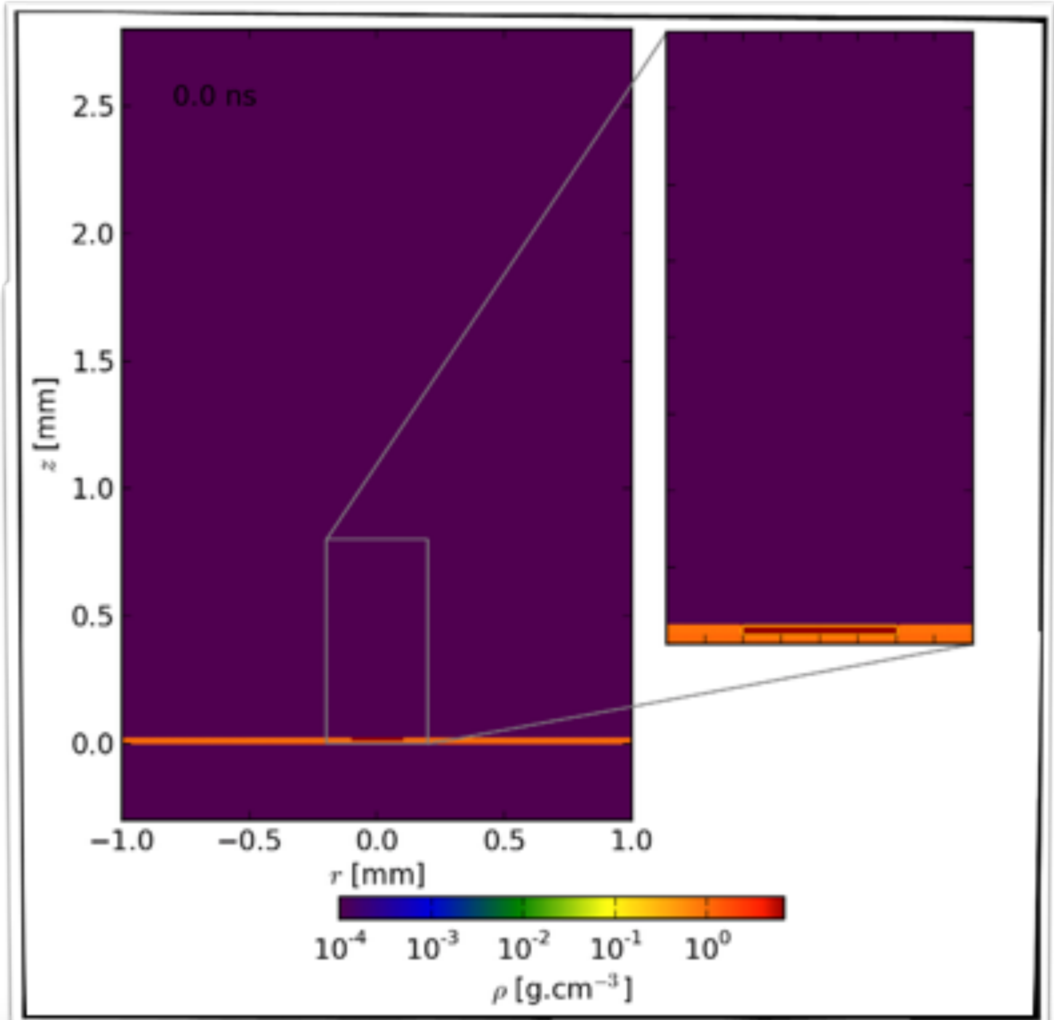

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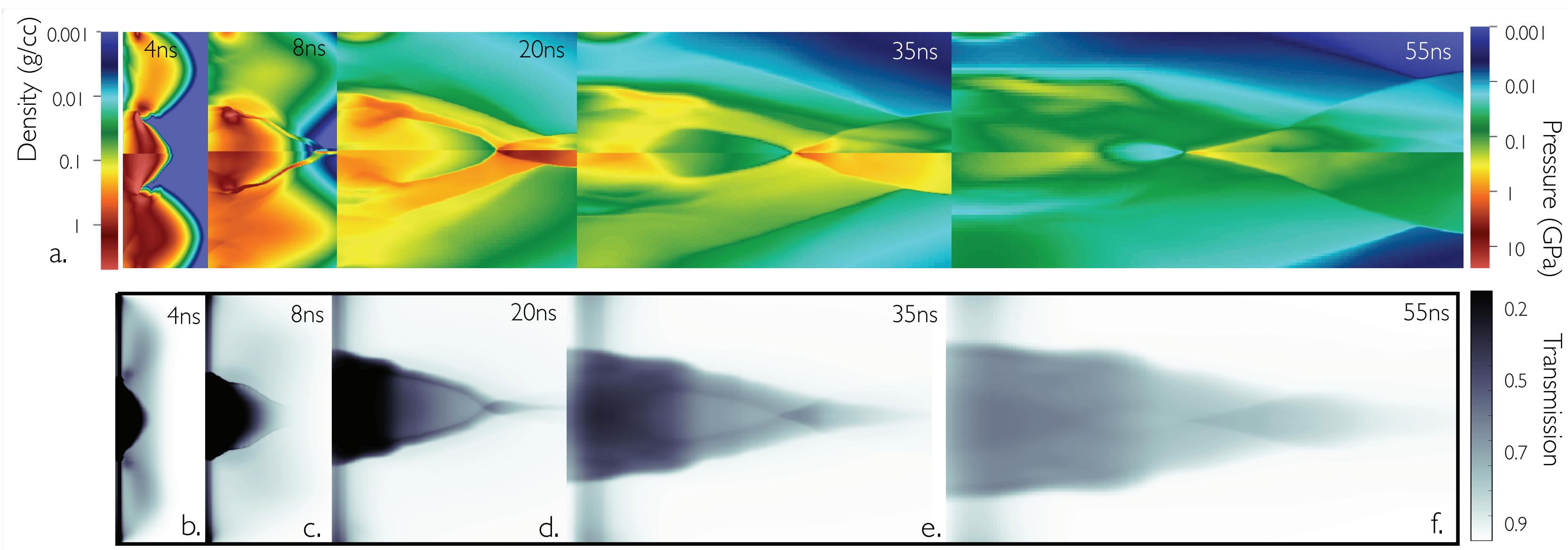
- I_L calibrated with experimental optical data: shock velocities and breakout timings *(transverse and rear side SOPs)*, electron density *(interferometry)* and morphology *(shadowgraphy)*

SYNTHETIC X-RAY RADIOGRAPHY

- Evidence of the **formation of a shock** in the collision:
  2 pressure jumps, 3 density discontinuities

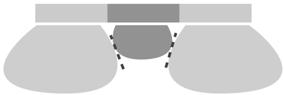


- Synthetic X-ray radiographies in really good agreement with the experiment :
  - -presence of the iron jet
  - -its time evolution: *expansion+collision+focusing*
  - -convergence point
  - -higher absorption layer at iron edge

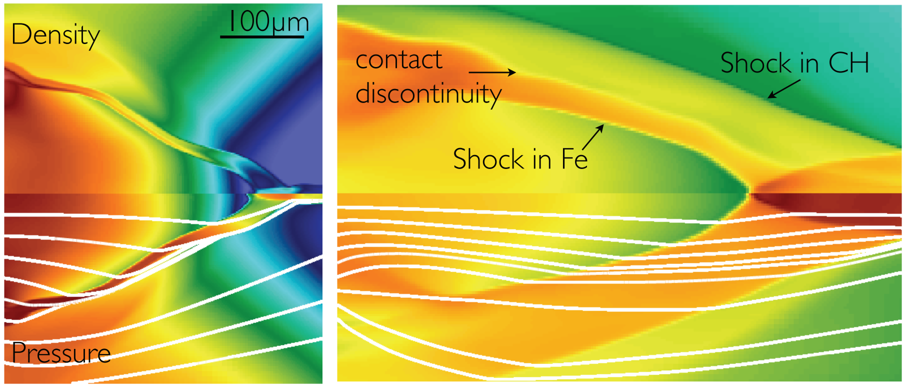
SHOCK FOCUSING INERTIAL CONFINEMENT (SFIC)

- The expanding Iron strikes the Shock surface at an **oblique angle**
  Hugoniot-Rankine relations for obliques shocks: **only the normal component of the velocity is affected**

- The **shape of the shock** determines how the iron is deviated at the shock front
  CH breaks out before Fe forming a ***converging conical shock*** *in the collision*



STREAMLINES



8 ns 20 ns

- **Iron flow is strongly deflected at the front shock**
  - **Focusing effect**

PRL **112,** 155001 (2014) PHYSICAL REVIEW LETTERS week ending 18 APRIL 2014

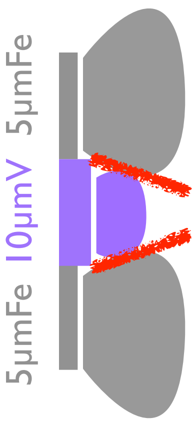
Experimental Demonstration of an Inertial Collimation Mechanism in Nested Outflows

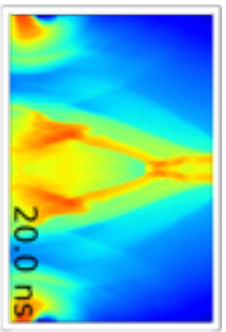
R. Yurchak,[1] A. Ravasio,[1,*] A. Pelka,[1] S. Pikuz, Jr.,[2] E. Falize,[3] T. Vinci,[1] M. Koenig,[1] B. Loupias,[3] A. Benuzzi-Mounaix,[1] M. Fatenejad,[4] P. Tzeferacos,[4] D. Q. Lamb,[4] and E. G. Blackman[5]

FOCUSING vs NON FOCUSING

- By changing the dynamics we change the shock shape
- Done with Fe-V targets: varying thickness to vary the mutual timing *(CH too fast!!)*

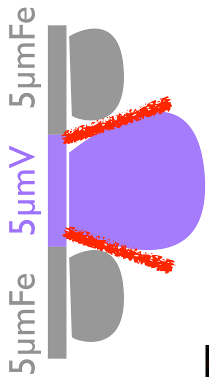
◉ Wind (Fe!) breaks out~jet (V) *same as CH*
"converging shock" **FOCUSING**

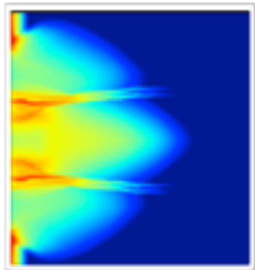


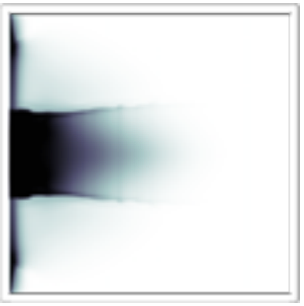


SOP data

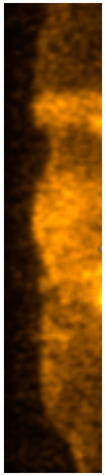
◉ Wind (Fe!) breaks out later than jet (V)
"diverging shock" **NON FOCUSING**







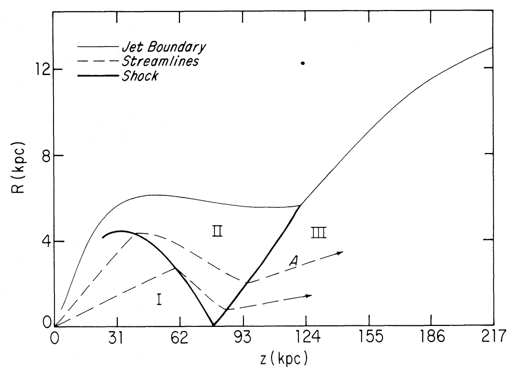
SOP data



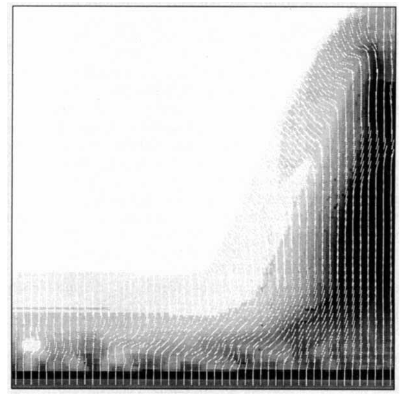
SFIC IN ASTROPHYSICS

- Many theoretical works ans simulations from the 80's-'90s…

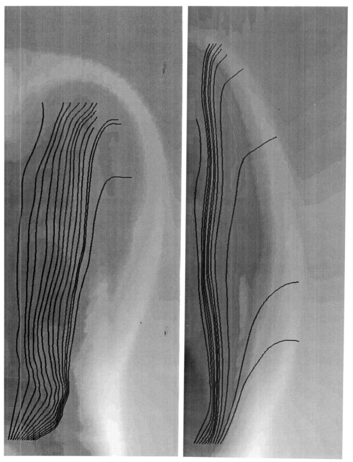
Sanders, ApJ 1983



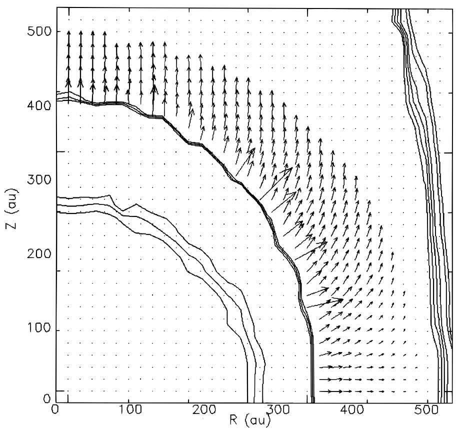
Icke et al. Nature 1992



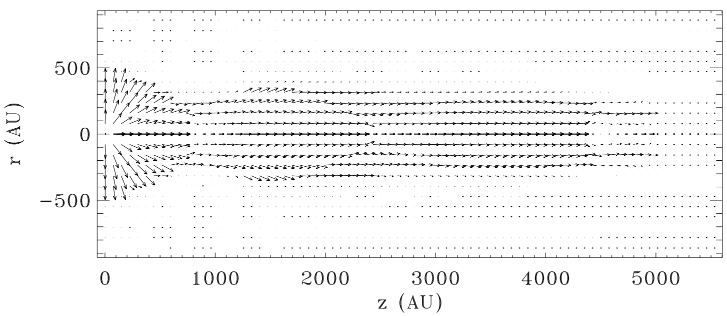
Frank&Noriega-Crespo A&A 1994

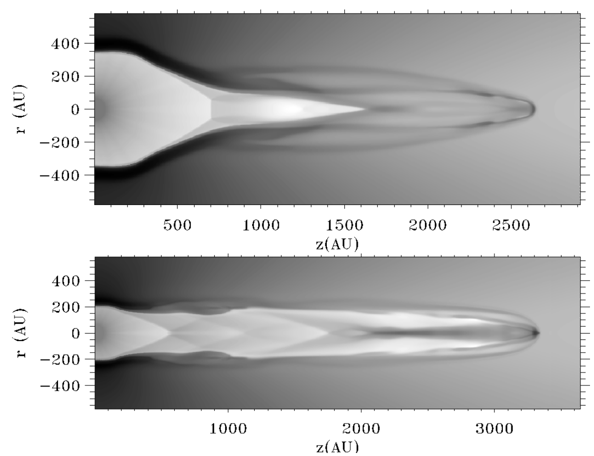


Frank&Mellema 1996



Mellema&Frank 1997





- …but never be verified: occurring in the innermost regions where the high opacity makes direct observations difficult. **Our work gives an experimental confirmation.**

SIMILARITY PROPERTIES

- Dimensionless analysis: highly collimated *(AR ~ 5)* supersonic flow *(M ~ 10)* in a pure HD regime where radiative *(χ ≫ 1)* and microphysical conductive *(Pe ≫ 1)* effects are negligible

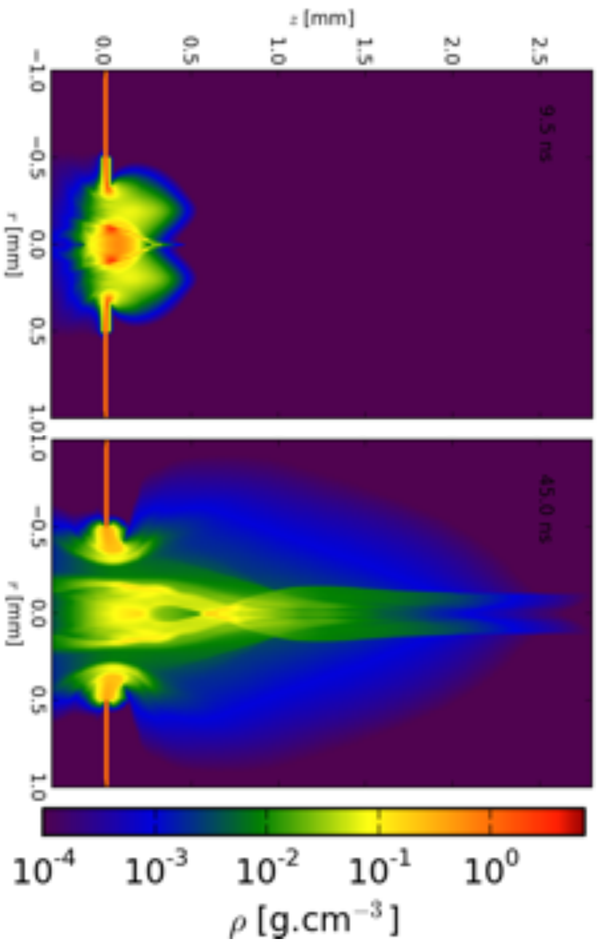
Parameter	Laboratory	YSO	PPN	AGN
Collimation scale	1 mm	10^{-3} pc	< 0.01 pc	0.1 pc
Int. Mach, $M_{\rm int} = V_j/c_{s,j}$	5–10	> 10	> 10	> 10
Ext. Mach, $M_{\rm ext} = V_j/c_{s,a}$	5–10	> 10	> 10	> 10
Aspect ratio, $\mathrm{AR} = l_j/r_j$	5	10	10	> 10
Density ratio, $\eta = \rho_j/\rho_a$	5–10	10	< 1	≪ 1
Cooling, $\chi = t_{\rm rad}/t_{\rm hydro}$	100	< 1	< 1	≫ 1
Peclet, $\mathrm{Pe} = \rho r V_j/\chi$	10^4	≫ 1	≫ 1	≫ 1
$\beta = V_j/c$	10^{-4}	10^{-3}	10^{-3}	0.9–0.99

- YSO jets are the most similar to the experiment, except for cooling
- In PPN young jets of low density seem to interact with the denser wind of the post-AGB star $\eta>1$
- AGN also have $\eta>1$ and more important they are relativistic $\beta\approx1$

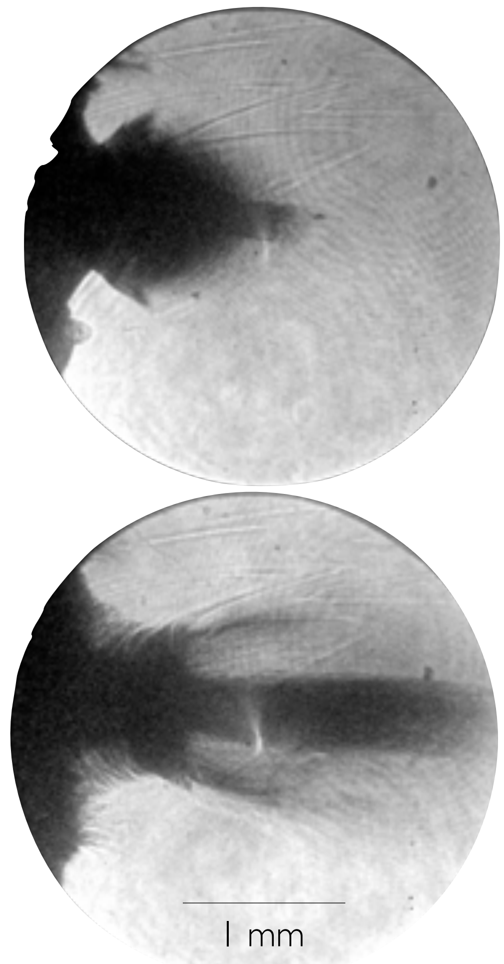
COLLAPSING OF CH PLASMA

- As the CH overcomes the Iron, it collapses on axes
- A very collimated mm-size CH jet is observed in both optical diagnostic and simulations

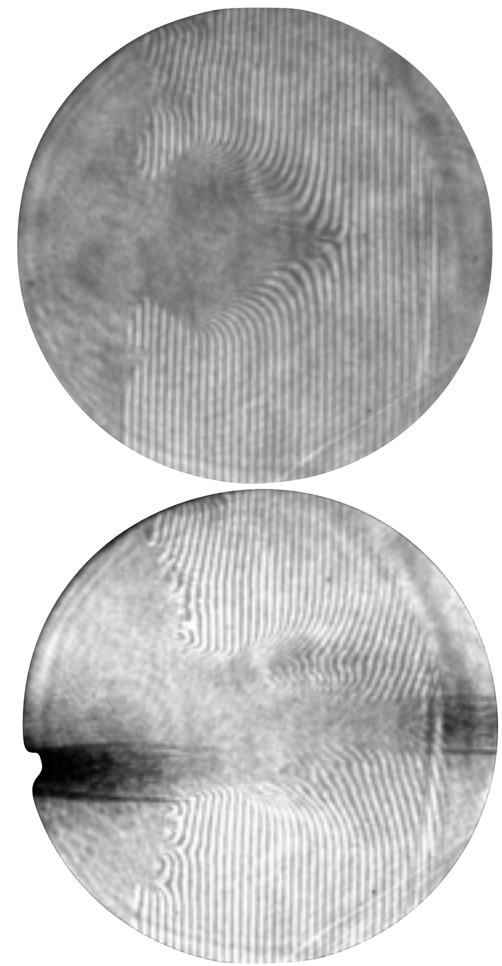
- **FLASH**



- **SHADOWGRAPHY**



- **INTERFEROMETRY**



COSMIC MAGNETIC FIELD

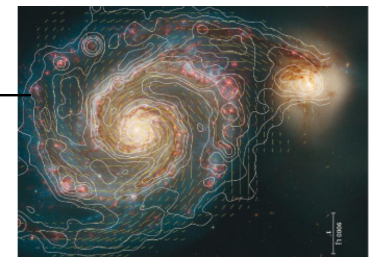
The B fields play a role in numerous physical processes in the universe:

- "Fluid" like properties and behavior of cosmic plasma affecting transport properties (thermal conduction, viscosity, resistivity, etc..)
- Star formation and possibly determine the typical star mass
- Accretion and ejection flows
- Origin of energetic cosmic rays

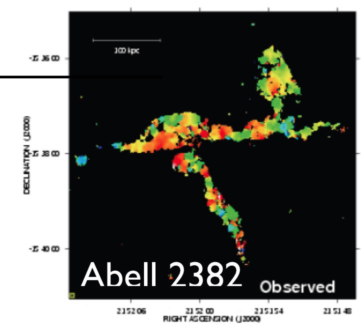
AN INTRIGUING PHENOMENON

- Astronomical observations *(Zeeman splitting, Synchrotron radiation, Faraday Rotation)* indicate B fields in **all observed objects, correlated on scales of the order of the object size and probably also present in voids** outside galaxies and galaxy clusters

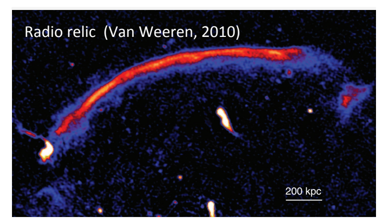
  - Galaxies: B~ μG, l_{corr}~kpc
    Zweibel 1997, Han 2007, ...



  - Galaxy clusters: B~ μG, l_{corr}~100 kpc
    Carilli and Taylor 2002, Guidetti et al. 2007,...
  - Quasars: B~few μG, l_{corr}~kpc
    Athreya et al. 1998, Pentericci et al. 2002, Kronberg et al. 2007



  - IGM: B~fG
    Neronov and Vovk 2010, ...



WHAT ARE THEIR ORIGINS?

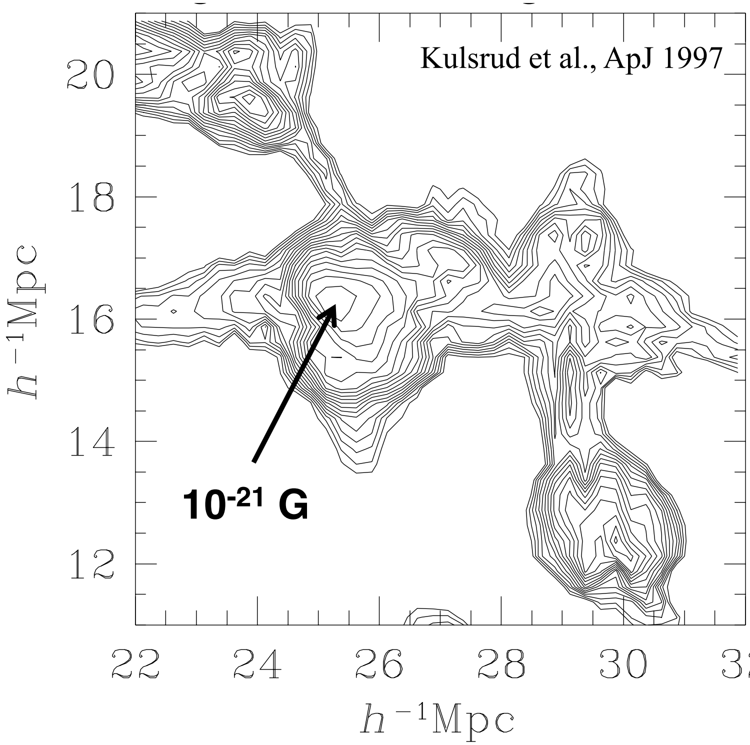
- How do such ordered large-scale fields arise in galaxies and clusters?
- An initial primordial magnetic field seed then amplified?
- If so, what is the primordial seed?
- And what are the amplification mechanisms?

MAGNETIC FIELDS AT PROTOGALACTIC SHOCK WAVES

Today, as a result of **gravitational instability, matter forms a web-like structure made of filaments and clusters**.

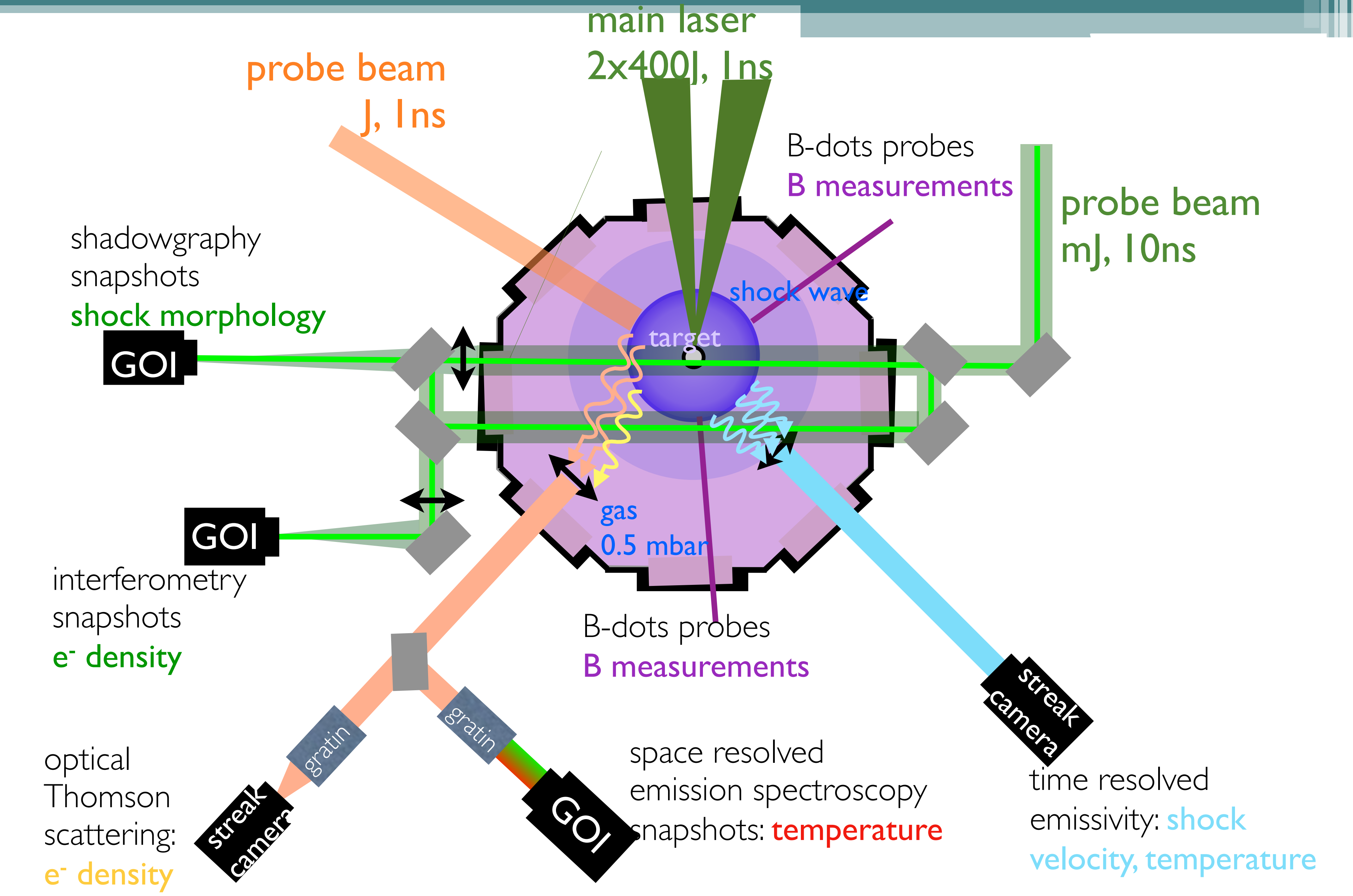
Gas accretion onto clusters generates **shock waves**

MHD simulations indicates that **cosmological shocks generate B fields**



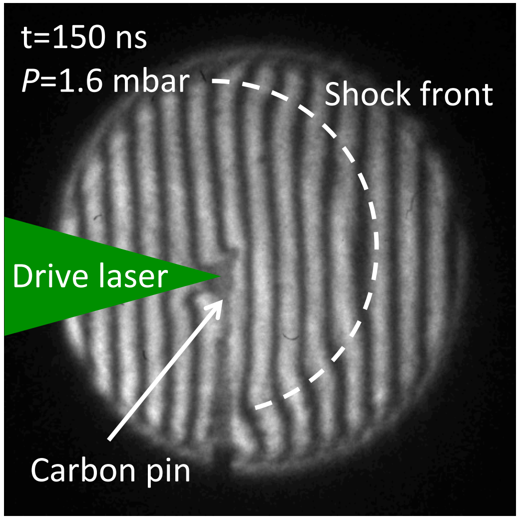
Cosmological simulations show curved intergalactic shocks with B field of 10^{-21} G

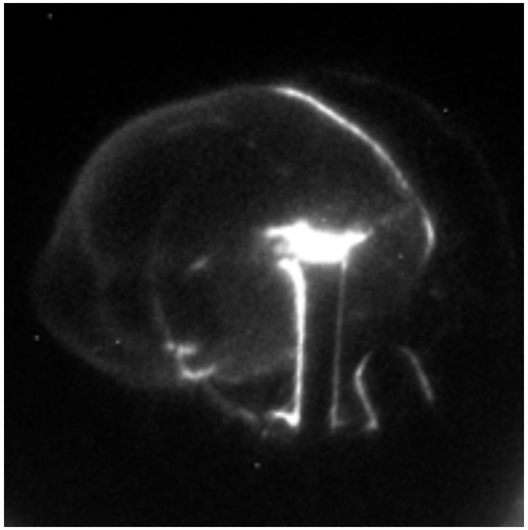
EXPERIMENTAL SET-UP



TRANSVERSE DIAGNOSTICS

From fringe shift we can get the radial electron density profile





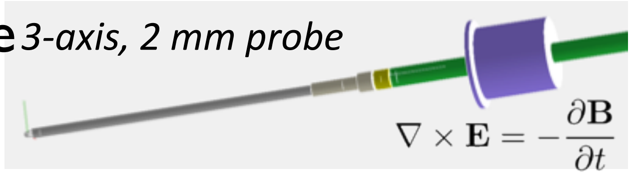
From shadowgraphy we can get the shock morphology

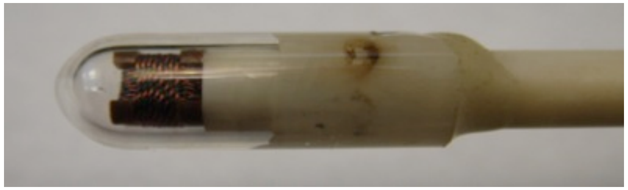
MAGNETIC INDUCTION COILS

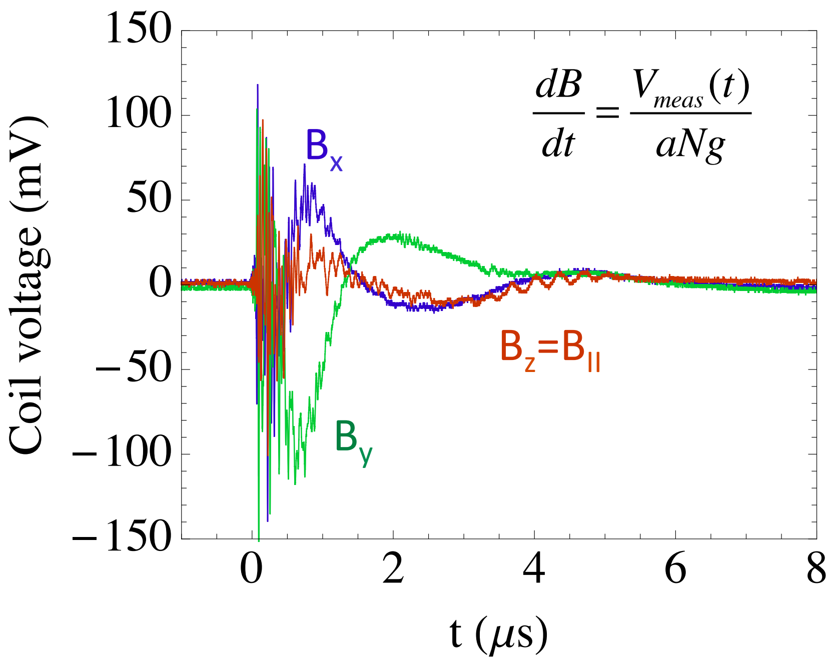
➔ Induction coils are placed at ~30 mm from ample position and measure B-field as shock reaches their position

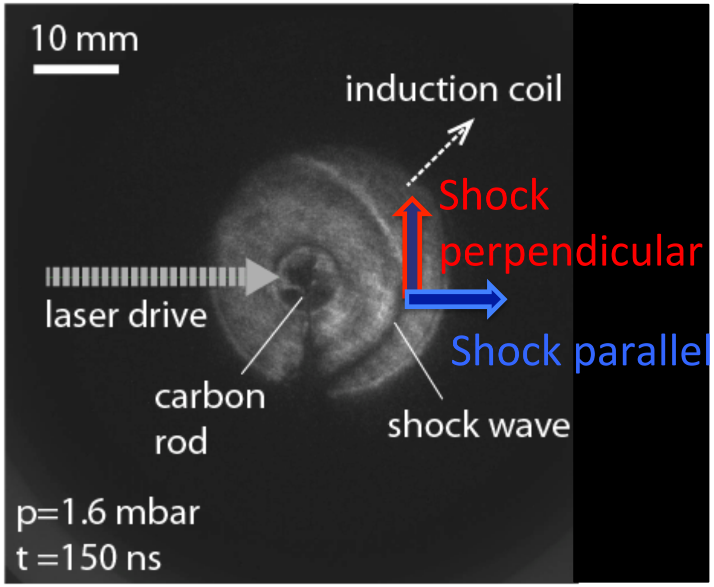
➔ Twisted pairs used to avoid EM pickup

➔ Coil voltage proportional to first derivative of B field

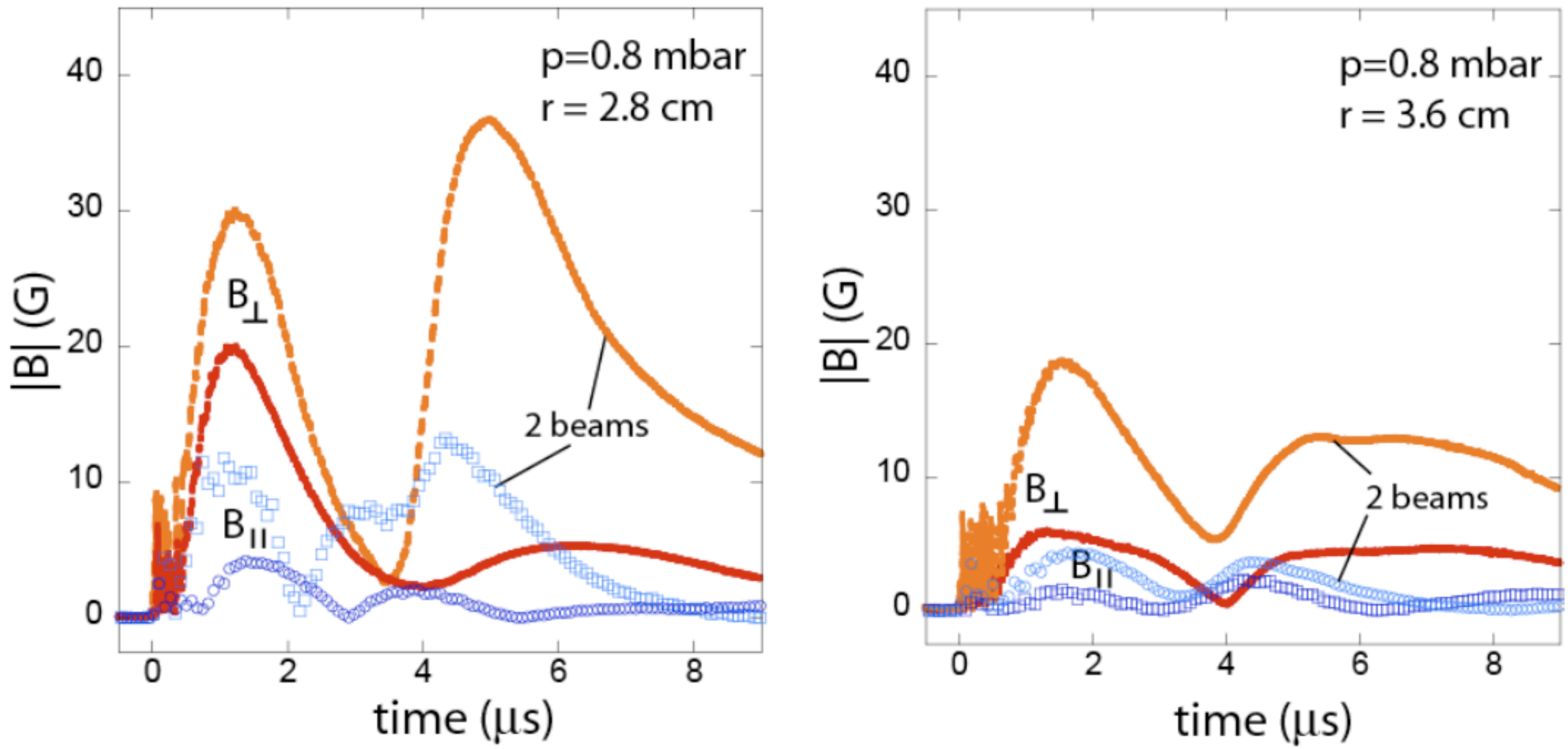








MAGNETIC FIELD MEASUREMENTS



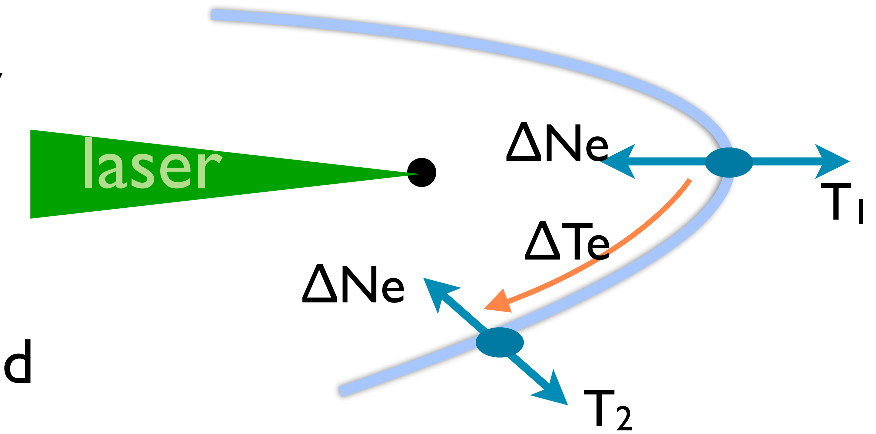
Field is larger at earlier times

➔ Field is predominantly in the perpendicular direction

➔Second bump in 2-beam case likely due to ejected material from target

BIERMANN BATTERY AT CURVED SHOCK FRONT

Non spherical shock generates vorticity



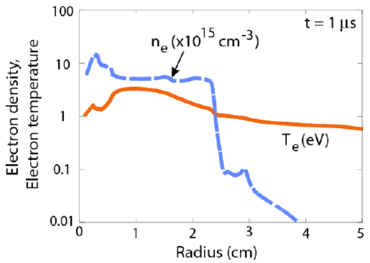
- Vorticity can generate magnetic field

Biermann battery via shock vorticity associated to a shock asymmetry

$$B_{vort} = \frac{m_i \omega}{e} \approx \frac{(\rho - 1)^2}{\rho} \frac{m_i}{e} \left| \frac{\partial \mathbf{v}_{sh}}{\partial S} \right| \sim \kappa v_{sh}/\mathrm{r}$$

hydro sim ~3

experimentally ~0.1-0.3



Gives field in the range 10-30 G

SCALING TO PROTOGALACTIC SHOCKS

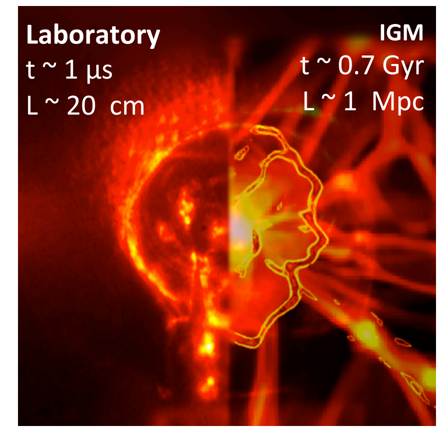
Experimental parameters	Laboratory (LULI)	IGM
Length scale ($\sim 2r/\kappa$)	18.8 cm	1 Mpc
Time scale	1 μs	0.7 Gyr
T_e (eV)	2	100
n (cm^{-3})	5×10^{15}	10^{-4}
$\Omega_B = \frac{eB}{m_i}$ (s^{-1})	4.8×10^4	8.7×10^{-18}
Re	7.9×10^3	3.0×10^{13}
Pe	69.0	7.0×10^{11}
Re_M	16.5	3.9×10^{27}

Because of viscous dissipation, similarity is achieved at scales L>5 µm (L>25pc)


nature

LETTER

Generation of scaled protogalactic seed magnetic fields in laser-produced shock waves



Our results scaled to protogalactic structures indicate that B fields of $B \sim 10^{-21}$G can be generated at shock fronts changing curvature of few tens of per cent on scaled of around one megaparsec

First experimental confirmation of theoretical estimation

R.M.Kulsrud et al. Astrophys. J. 480, 481 (1997)

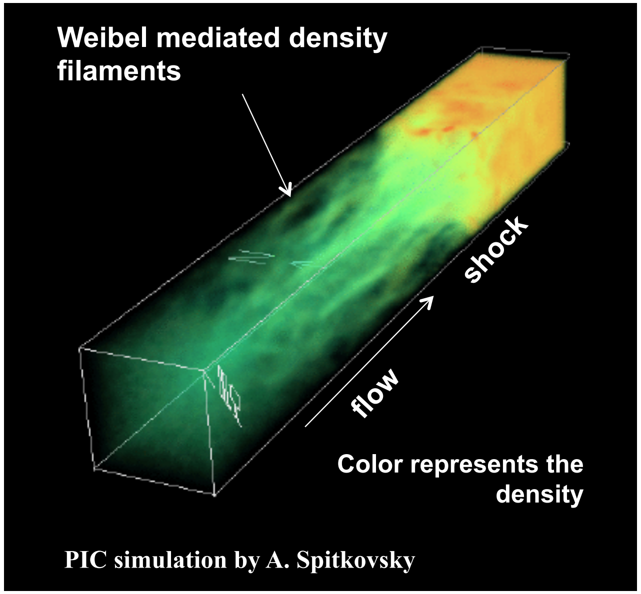
WHAT'S NEXT

Comsological seed fields (10^{-21} G) from Biermann battery are considerably smaller than present day astronomical observations (~1 μG)

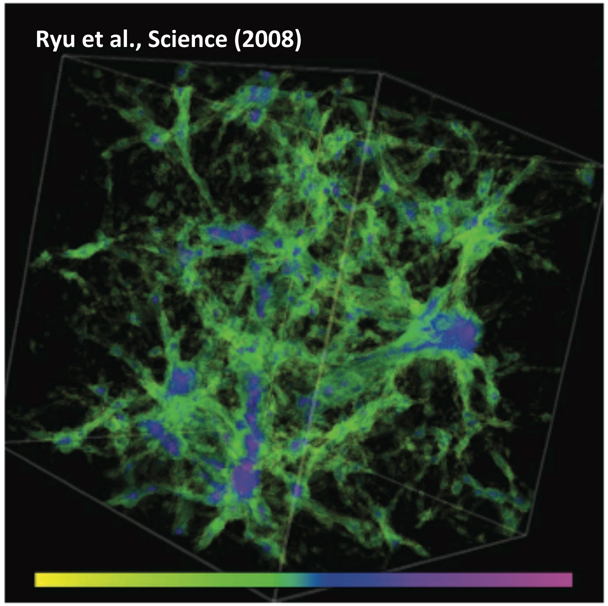
Two possible research axis:

- different generation mechanism
- amplification

Plasma instabilities can drive stronger fields *(Weibel)*



The initial seed is amplified by dynamo or turbulence



CONCLUSIONS

- High power laser can help in reproducing pressure and temperature conditions typical of astrophysical objects

- Laboratory astrophysics can help in getting interesting hints on :
    - materials behaviour for planetology studies
    - the dynamics of (a part of) an astrophysical phenomenon through scaled experiments

COLLABORATIONS

UNIVERSITY OF OXFORD

Flash Center for computational science

SLAC NATIONAL ACCELERATOR LABORATORY

UNIVERSITY of ROCHESTER

MELIORA

HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF

ОБЪЕДИНЕННЫЙ ИВТАН

l'Observatoire de Paris

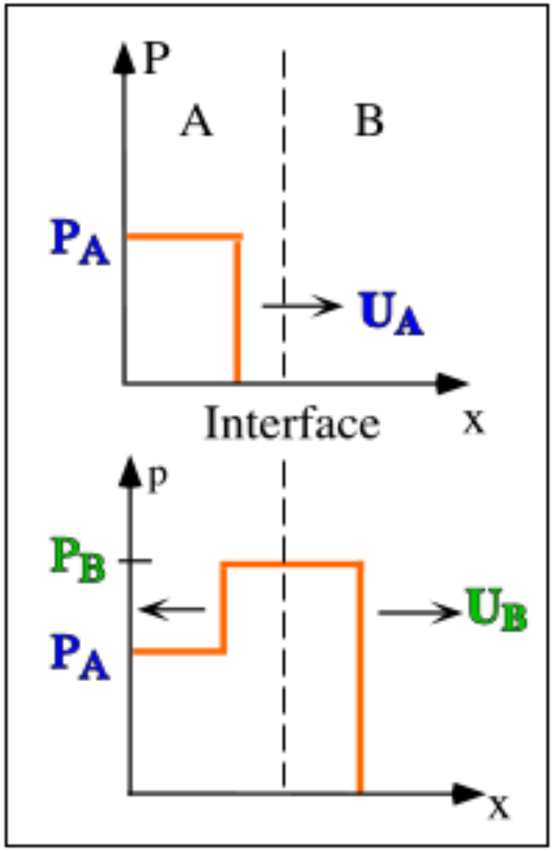
UPMC SORBONNE UNIVERSITÉS

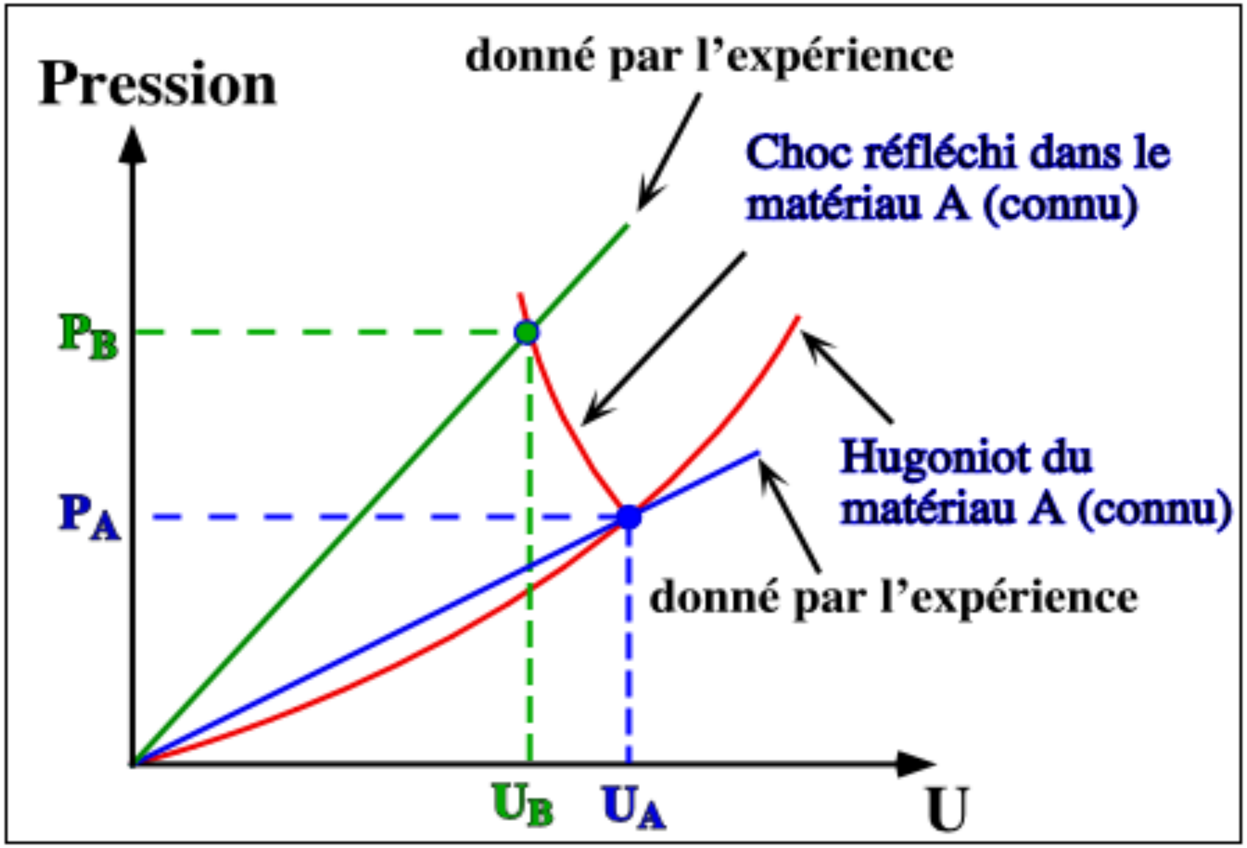
ETH Zürich

DE LA RECHERCHE À L'INDUSTRIE cea

CELIA

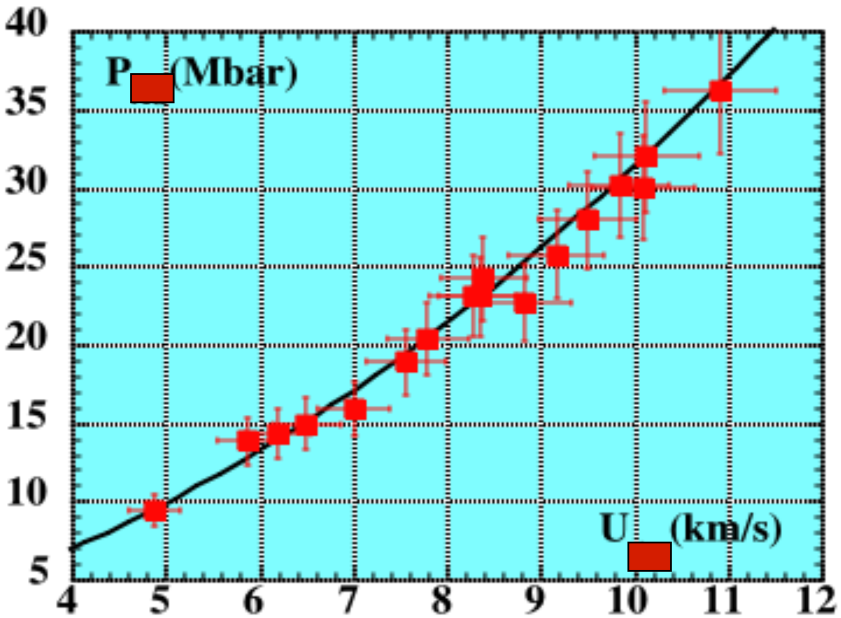
HOW TO OBTAIN AN EOS POINT





Deuxième relation de Rankine-Hugoniot ➡ $P = \rho_0 D U$

RELATIVE MEASUREMENTS

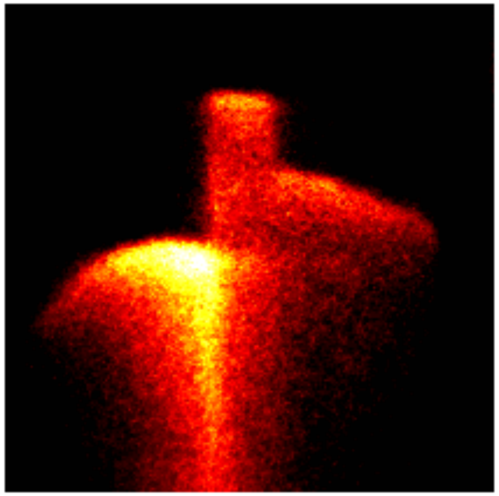


Experiment

Theory

4.5 Mbar< P_{Al} < 16 Mbar

10 Mbar < P < 37 Mbar



Demonstration of precise EOS data with "small" laser E ≈ 100 J

M. Koenig et al., PRL, 1995