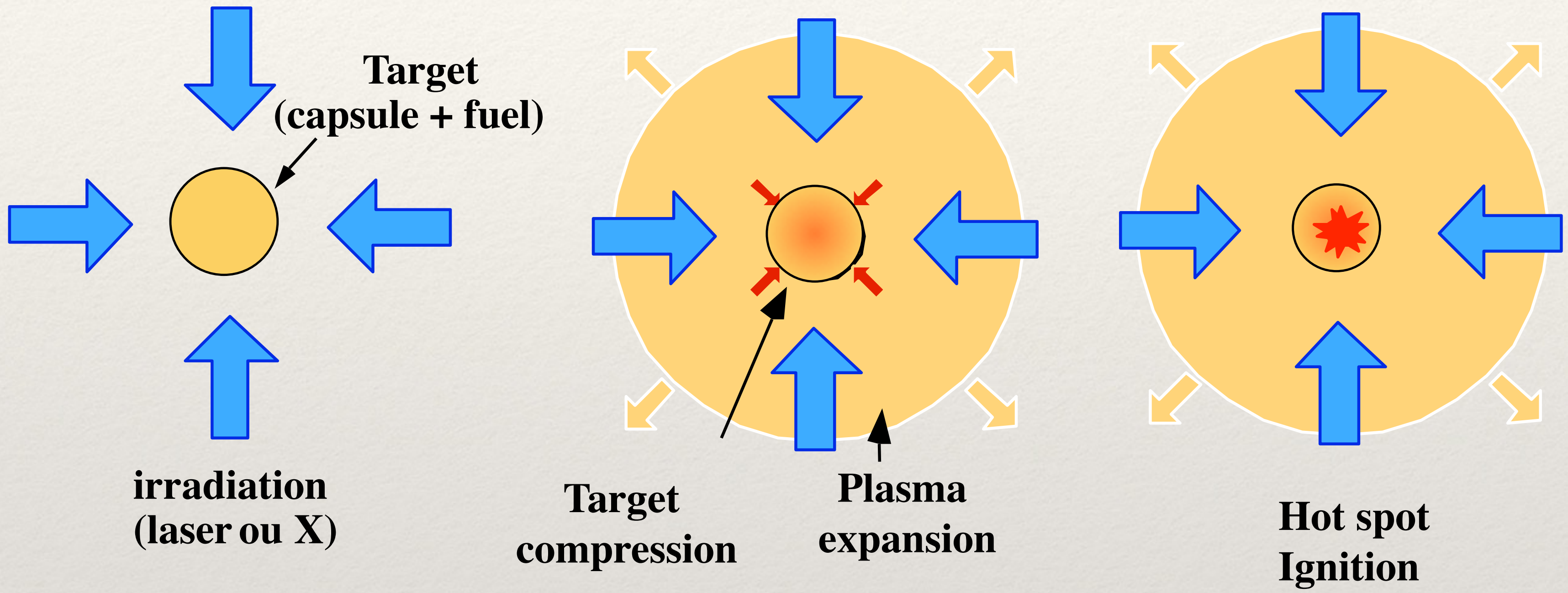
Alessandra RAVASIO

Astrophysique de laboratoire en France

PNPS
Montpellier, 26-28 March 2018

Inertial Confinement Fusion

Very high compressions and temperatures required

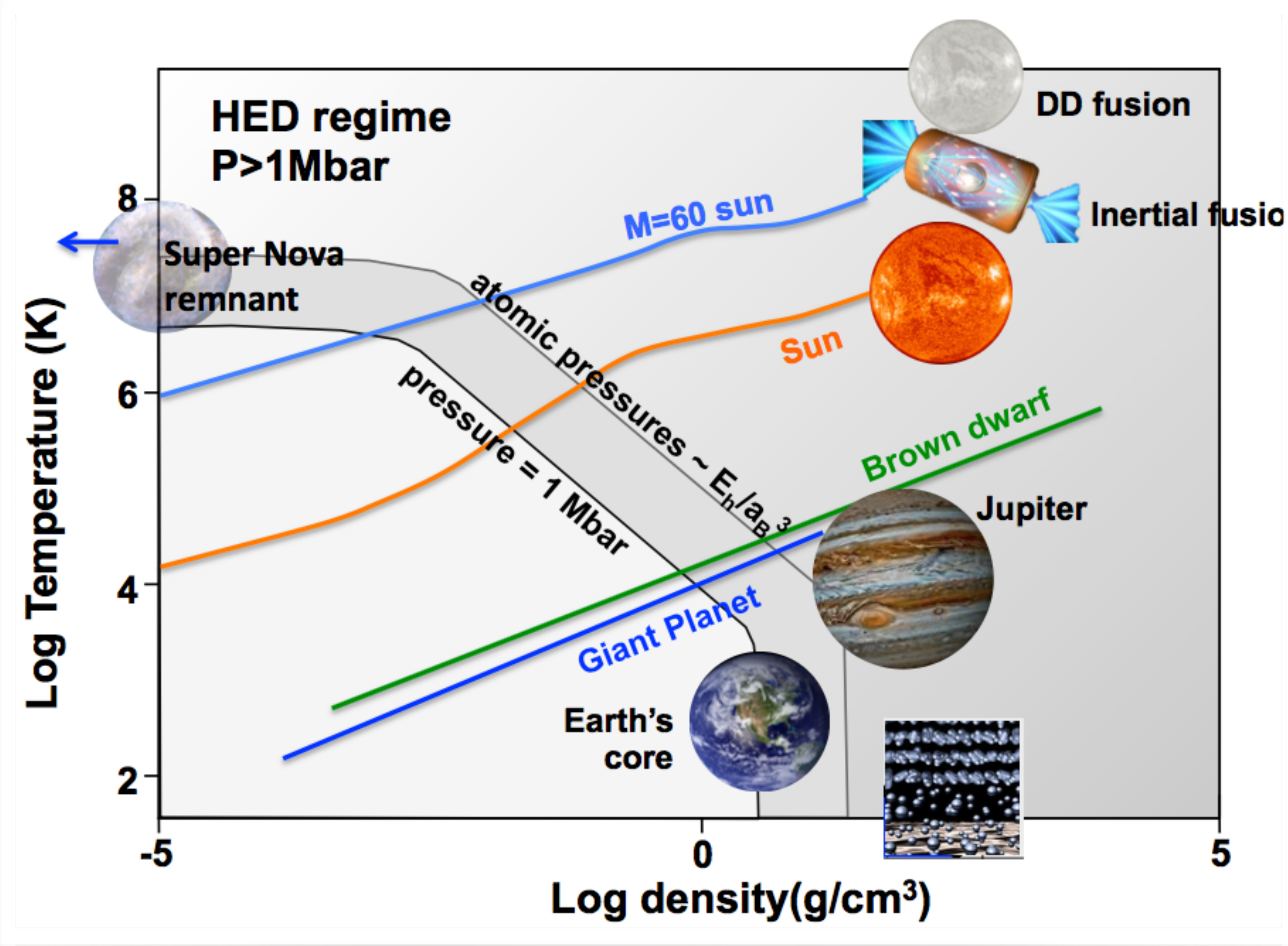


$$D+T \Rightarrow {}^4He\ (3.5\ MeV) + n(14.1\ MeV)$$

Development of HIGH POWER PULSED MACHINES : Z-PINCHES, **HIGH ENERGY LASER**

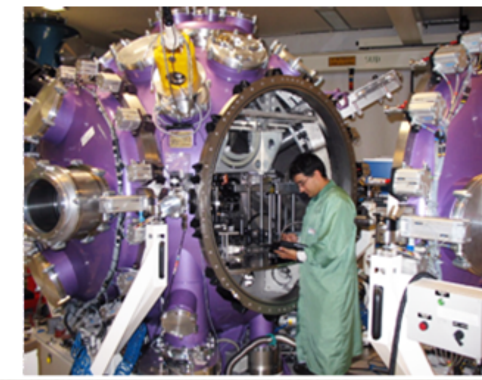
High Energy lasers: an opportunity for astrophysics

Generation of ultra-dense-matter to high temperature plasmas, including a variety of astrophysical objects



Two large facilities in France

- **LULI 2000**: the most powerful academic laser in EUROPE *(Region parisienne)*
  - 2 beams 2KJ, 1.5ns
  - 1KJ beam, 1.5ns + 100J 1 ps (probes)



- **LIL (2002-2014)** : prototype LMJ quad-9kJ

- **APOLLON (2018-2019?)** : 100J, 15fs

- **LMJ**: the most powerful laser in EUROPE *(Aquitaine)*

LMJ: 176 beams, 1.3 MJ, 1.5ns
PETAL: 1KJ 1 ps

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- **LMJ**: the most powerful laser in EUROPE *(Aquitaine)*

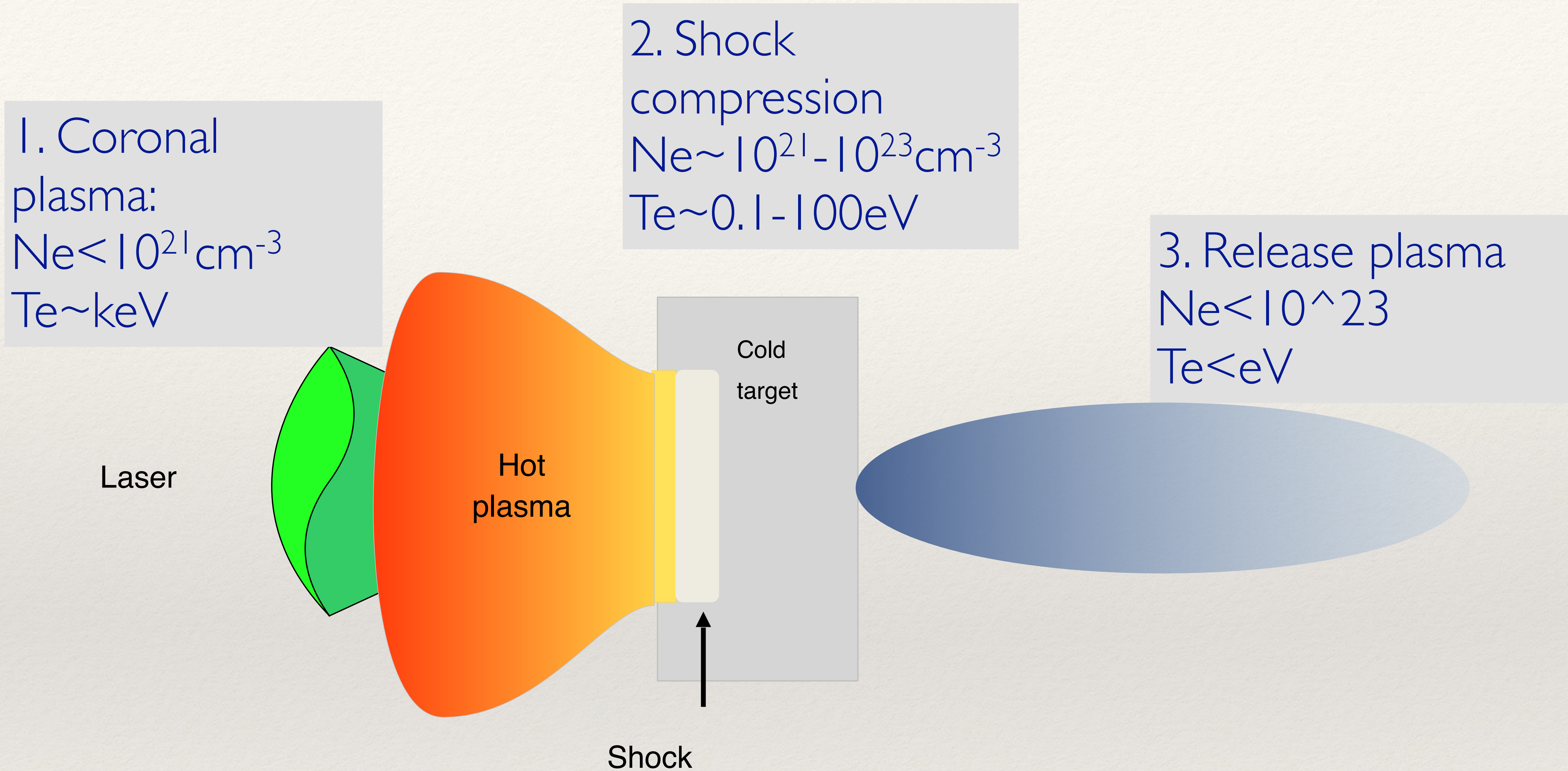
LMJ: 176 beams, 1.3 MJ, 1.5ns

- GEKKO XII (Japan), OMEGA, NIF, MEC (USA), ORION, VULCAN (UK), PALS (Tcheque Reppublic)

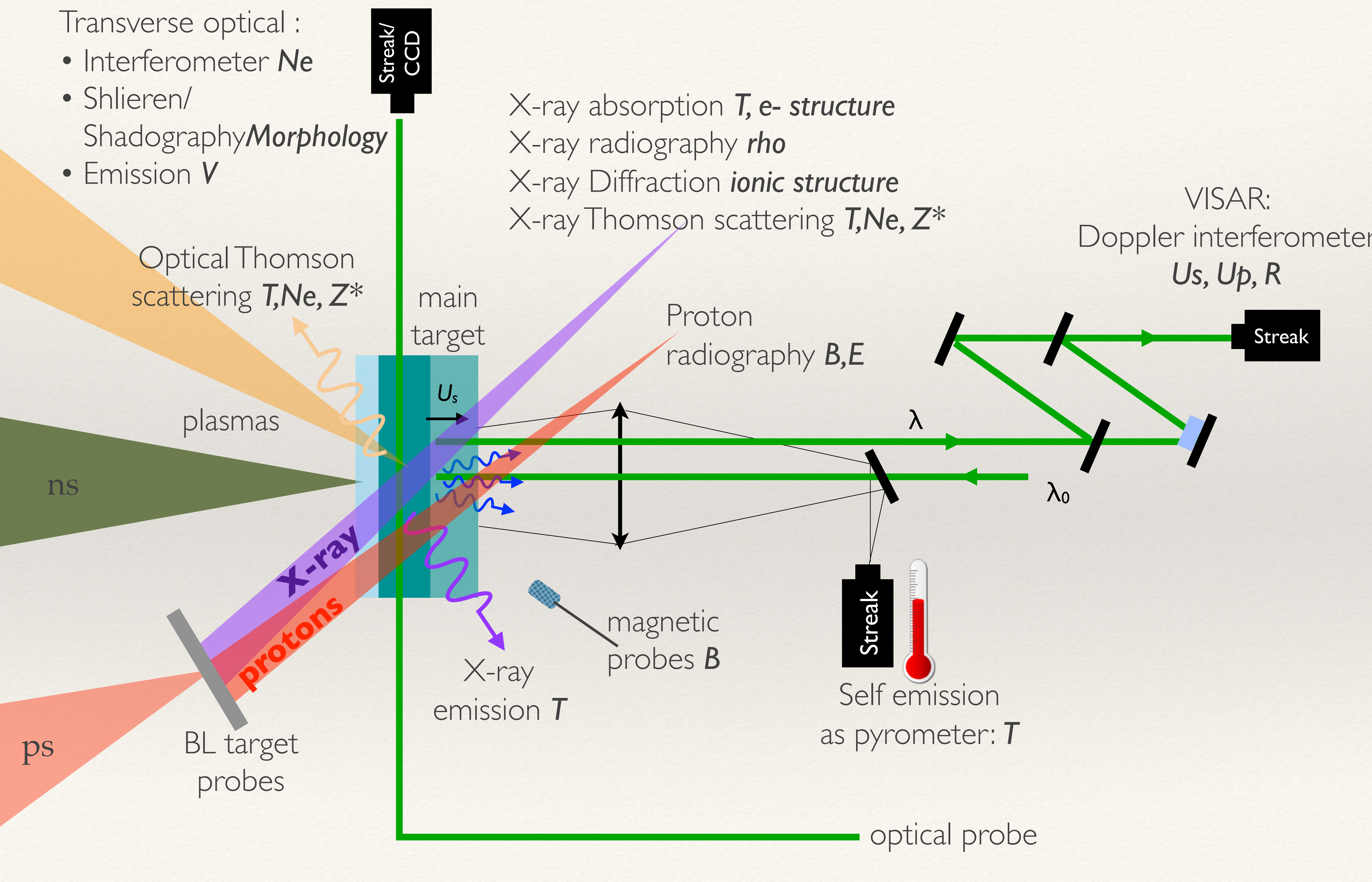
Outline

- Which conditions
- Which diagnostics
- Overview of lab-astro experiments in France
- Examples of experiments:
  - EOS
  - POLAR

Which plasmas we can generate?



Which diagnostics?



Laboratory astrophysics

Three different kind of experiences

- **IDENTICAL** : the physics is exactly the same. They furnish precise data, which are not directly measurable in space. ***EOS***, *Opacities, x*.

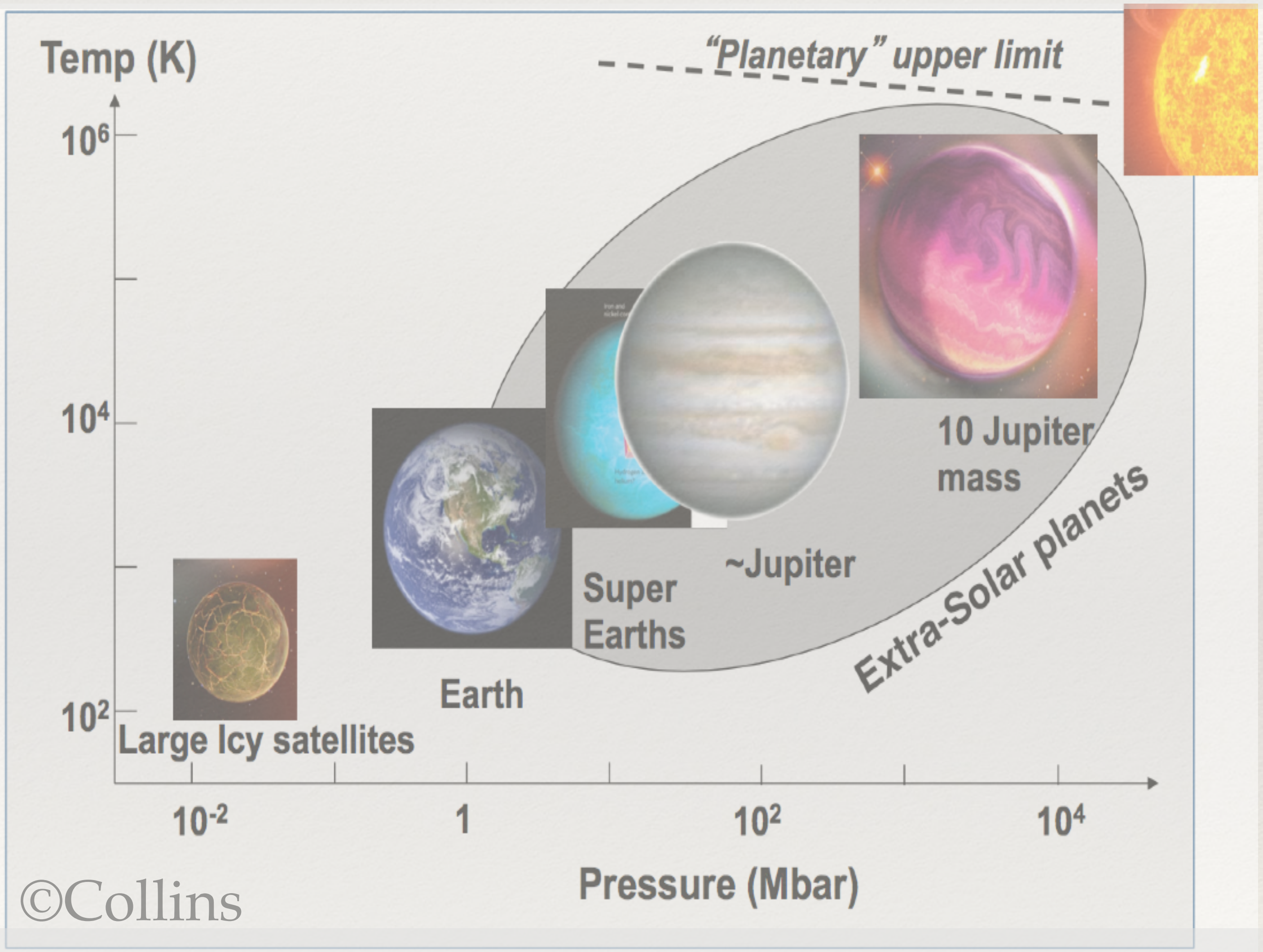
- **SIMILAR** : they are defined by precise scaling laws. Possibility to study temporal evolution and modify initial and boundary conditions. ***POLAR***, *Jets, Shocks and instabilities, accretion in YSO*

- **RESSEMBLANT** : we do not have scaling laws, but we can explore the mechanism and get insight of the major ***Self-generated B fields***, *particle acceleration, relativistic plasmas, Nucleosynthesis in lab, magnetic reconnection*

Identical 1- EOS

Huser, Henry, Denoeud, Bolis, Guarguagini, etc..PhD

Over nearly 2000 known planets, most have internal pressure between 1Mbar to 10 Gbar



$$\nabla P = \rho \nabla (V + Q)$$

$$\nabla T = \nabla P \left(\frac{T}{P} \nabla_T \right)$$

$$\nabla M = 4\pi r^2 \rho$$

gravitational and centrifugal potential

Few observational constraints

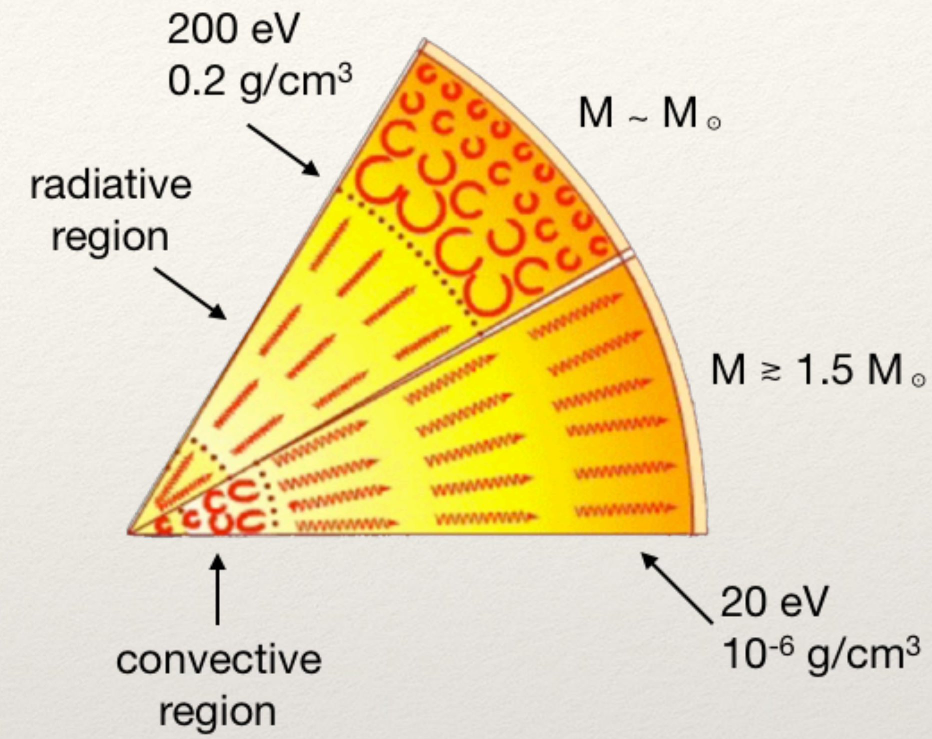
Planetary models need EOS at high P-T conditions

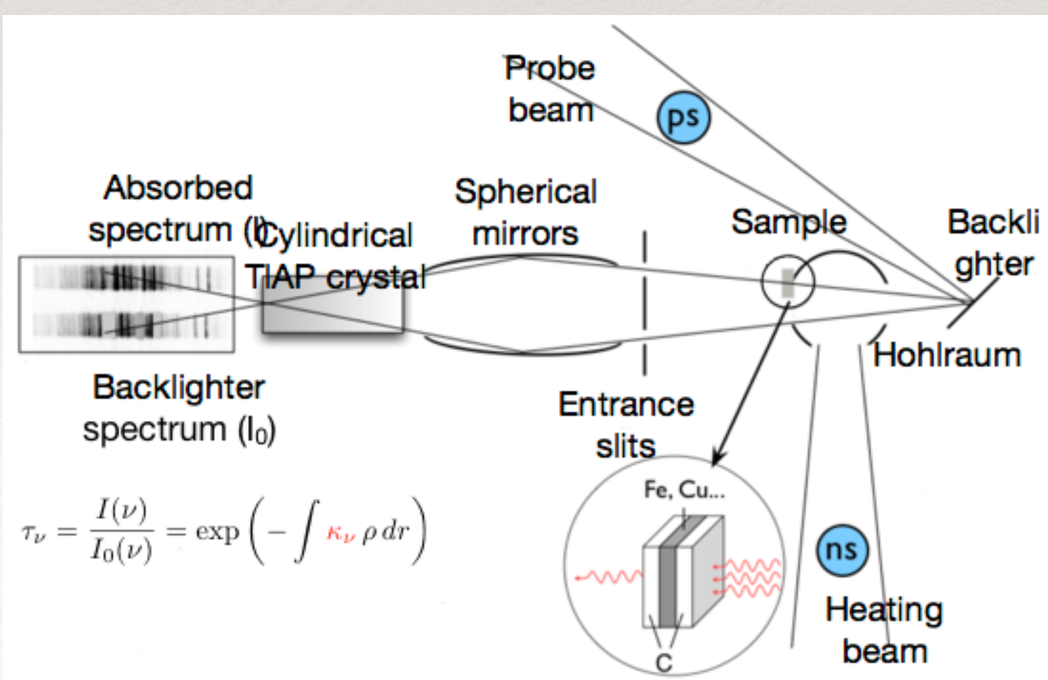
see also F. Subiran talk

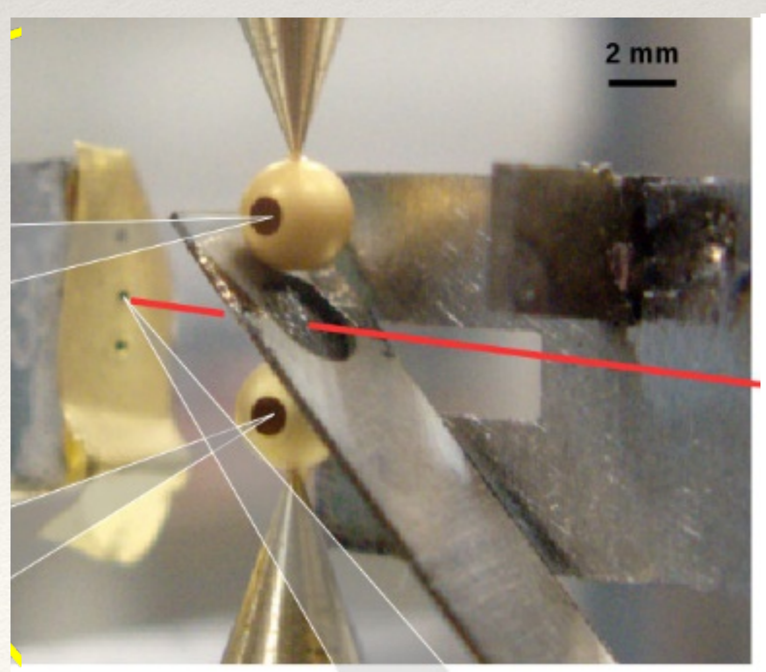
Identical 2-OPACITY

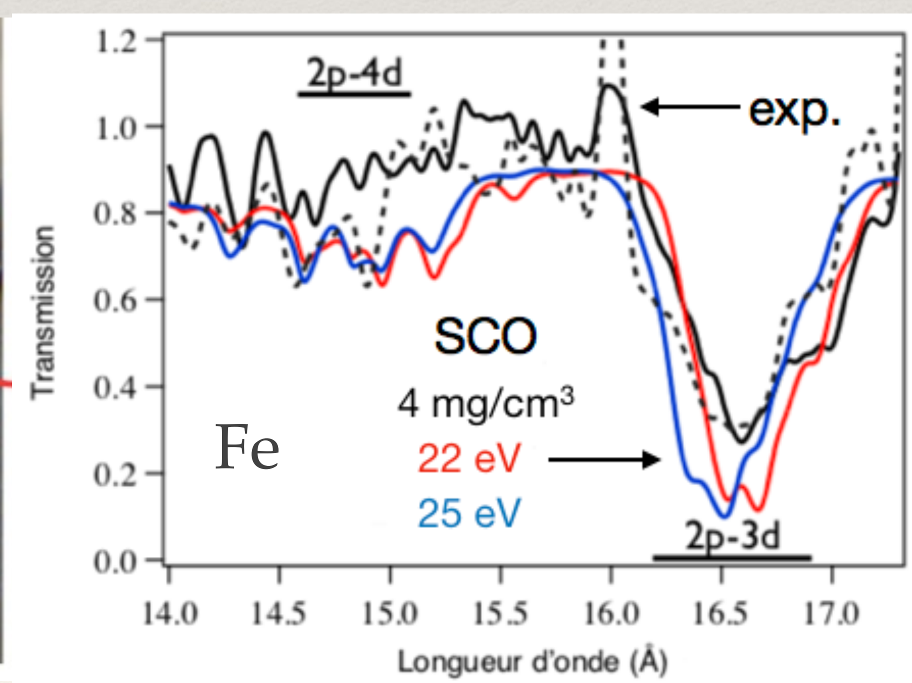
Stars longevity partially determined by stellar opacity

but opacity calculations often disagree
→ experimental measurements in astrophysical relevant conditions are needed.





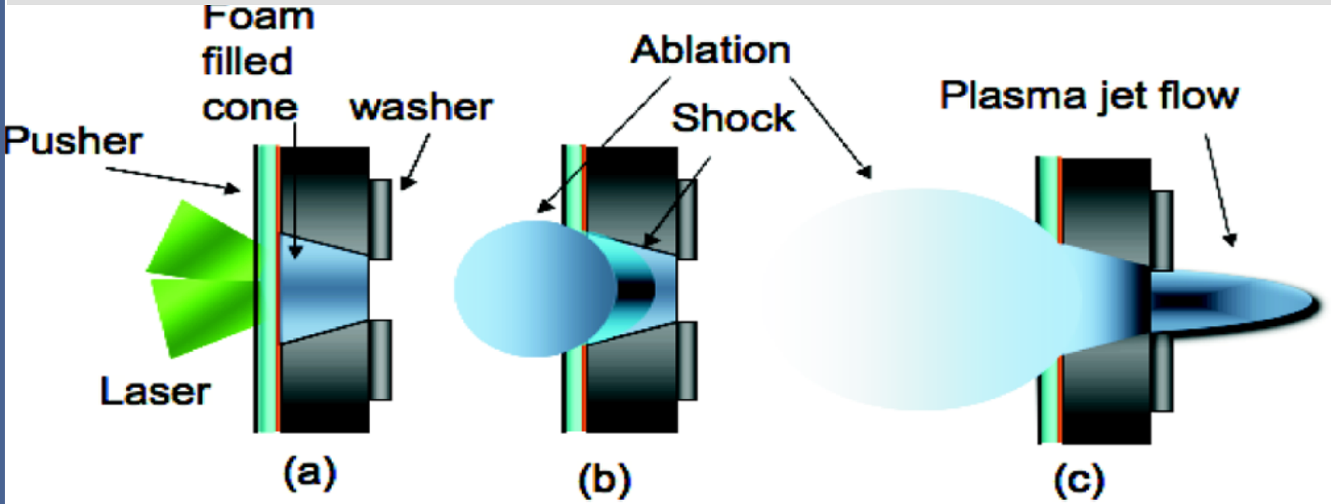




Similar 1- Plasma jets

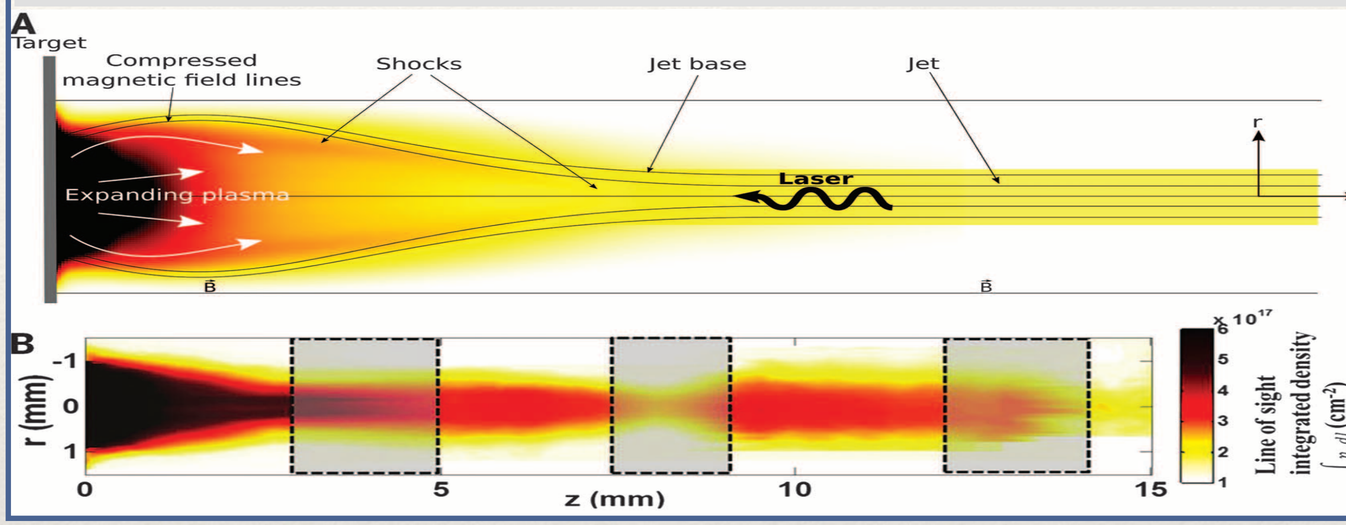
Loupias, Diziere PhD — PRL 2007

Generation of collimated plasma flows



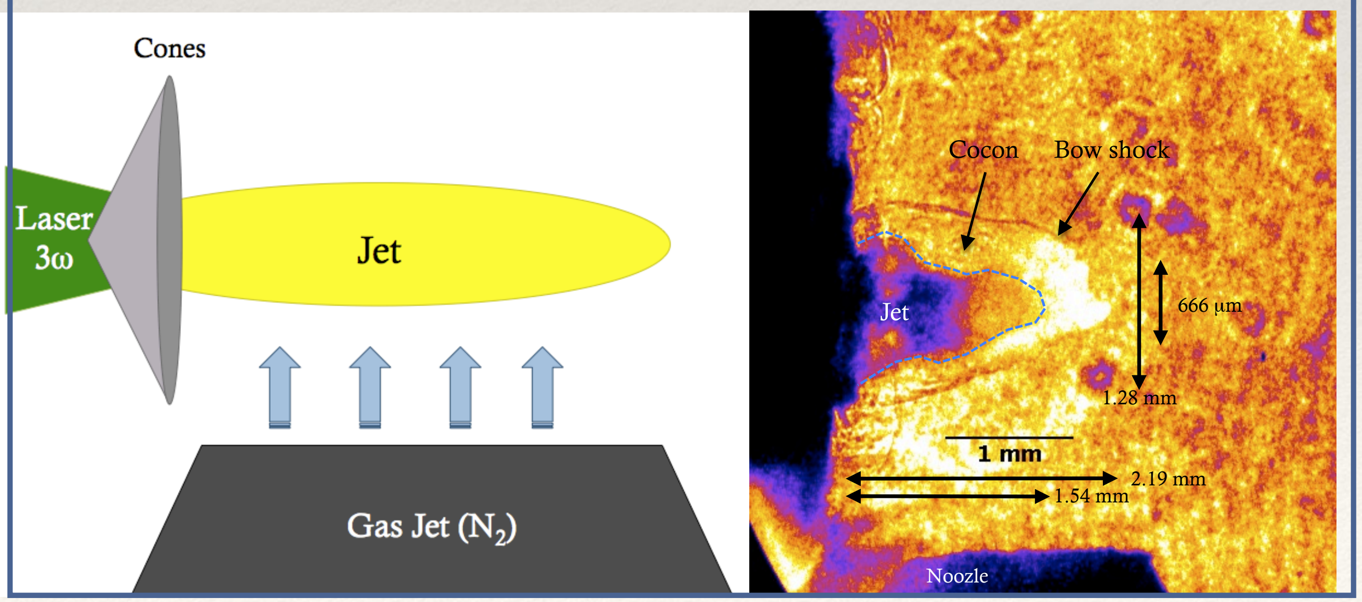
Albertazzi PhD — Science 2014

Collimation by B fields



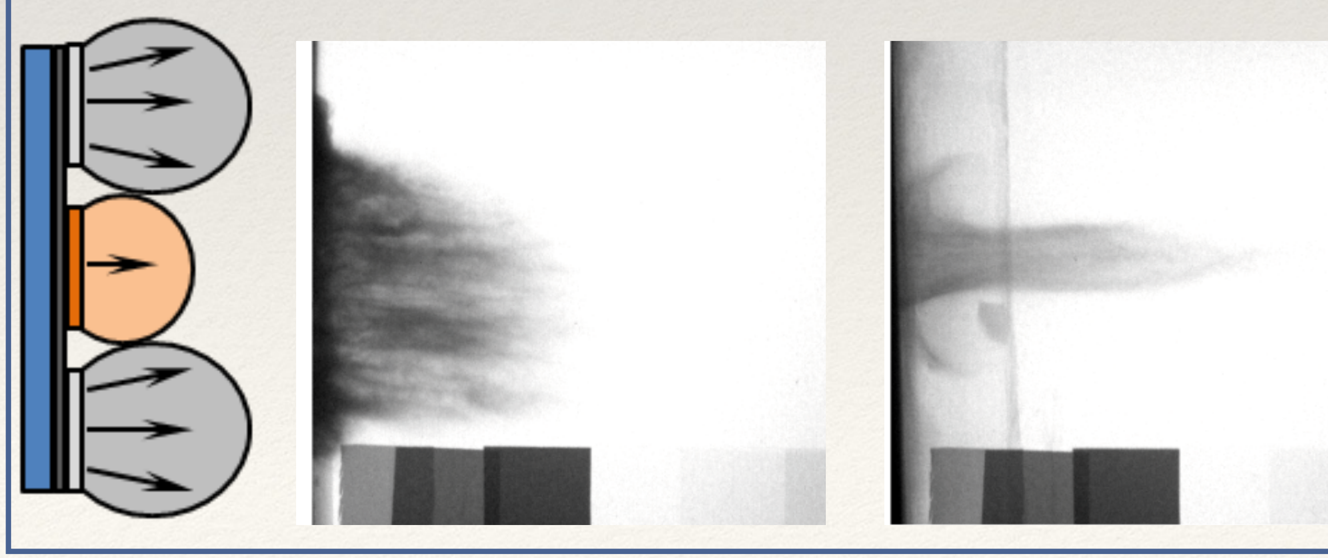
Loupias, Diziere PhD

Interaction with an ambient gas



Yurchak PhD — PRL 2014

Collimation by an ambient wind



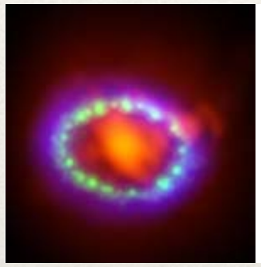
Similar 2- Strong shock & Hydro instabilities

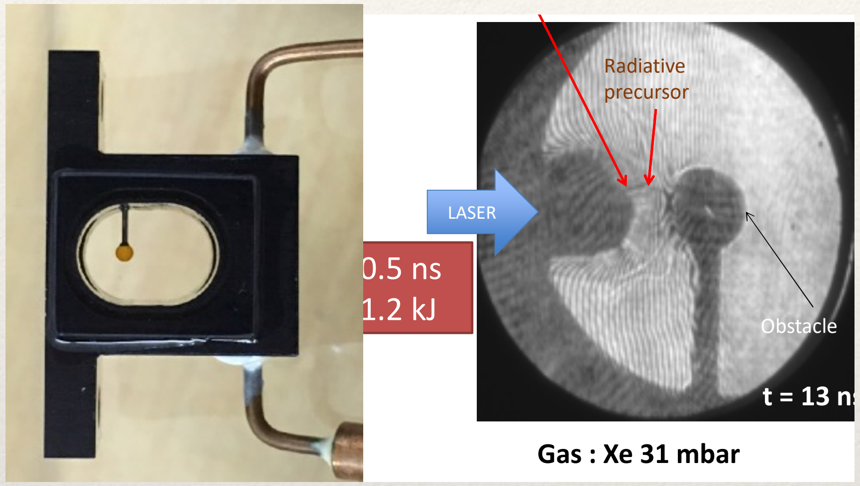
Vinci, Michel, etc.. PhD

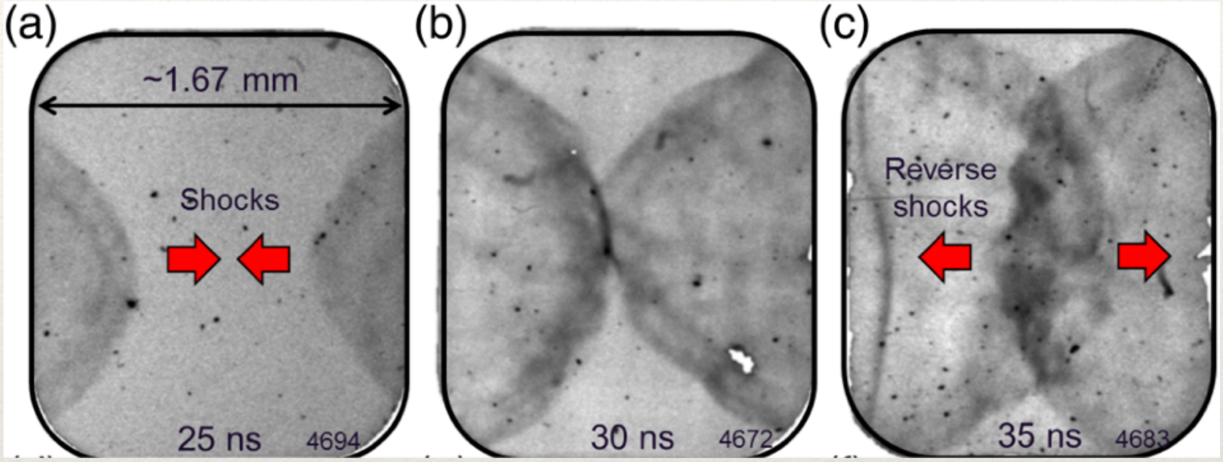
Radiative shocks & with molecular clouds

see also Singh talk

PRL 2017

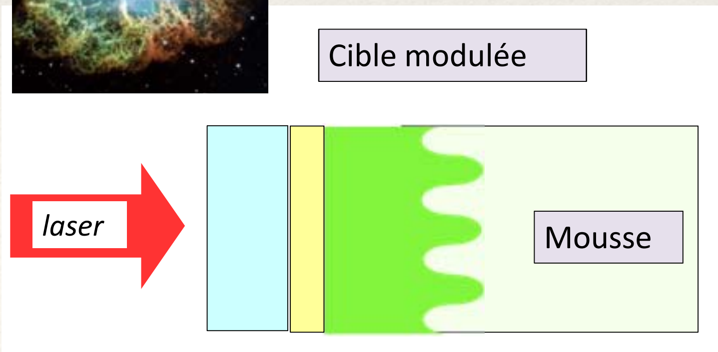




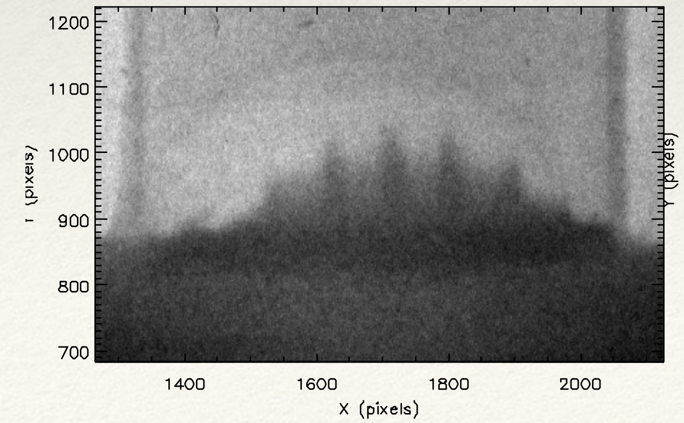


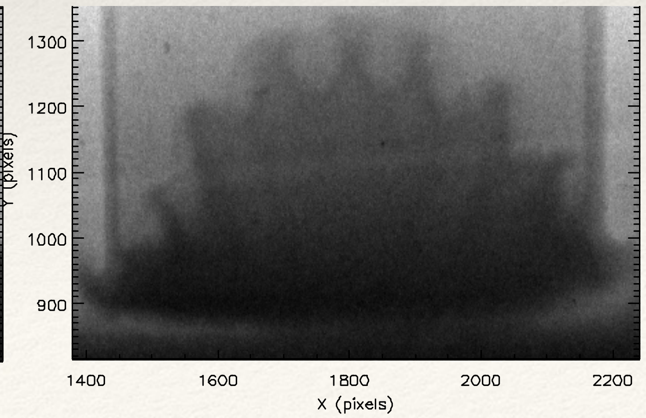
Rigon PhD

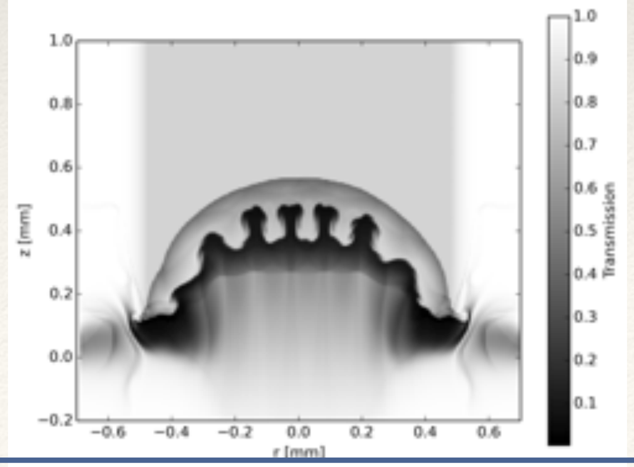
Hydrodynamic instabilities:



non linear regimes



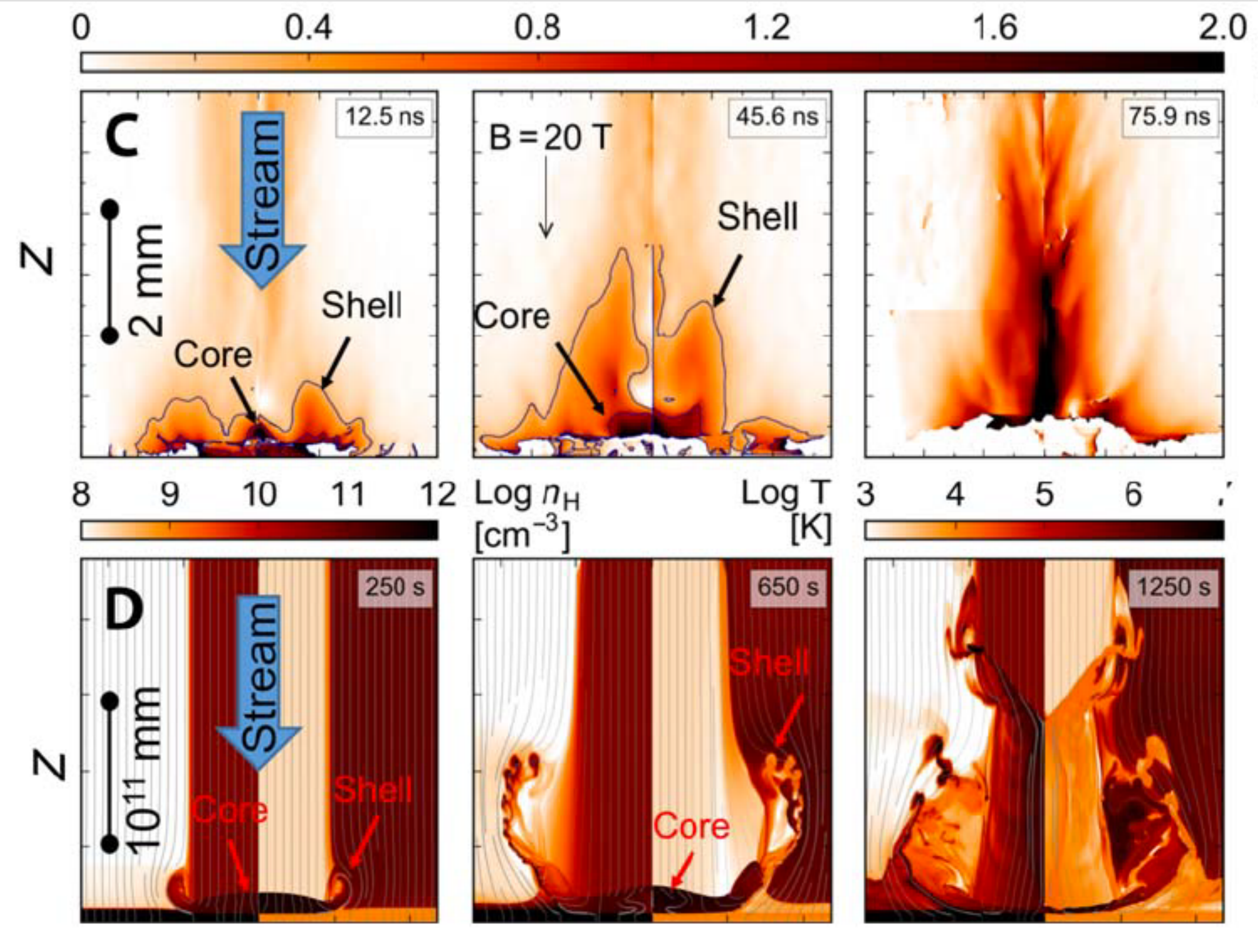




Similar 3- Accretion dynamics

Revet PhD *Sci.Adv. 2017*

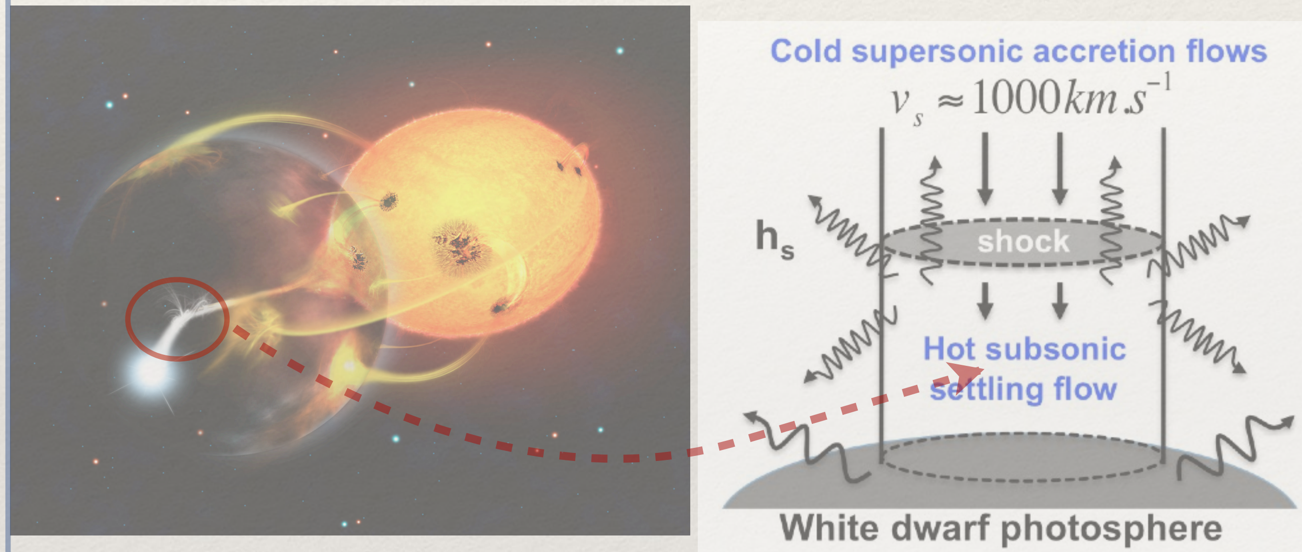
In YSO: magnetised accretion dynamics



Soft x-rays absorbed in the dense shell

Yurchak, BoPhD *HEDP 2012, Nat Com 2016,2018…*

In POLAR: accretion column

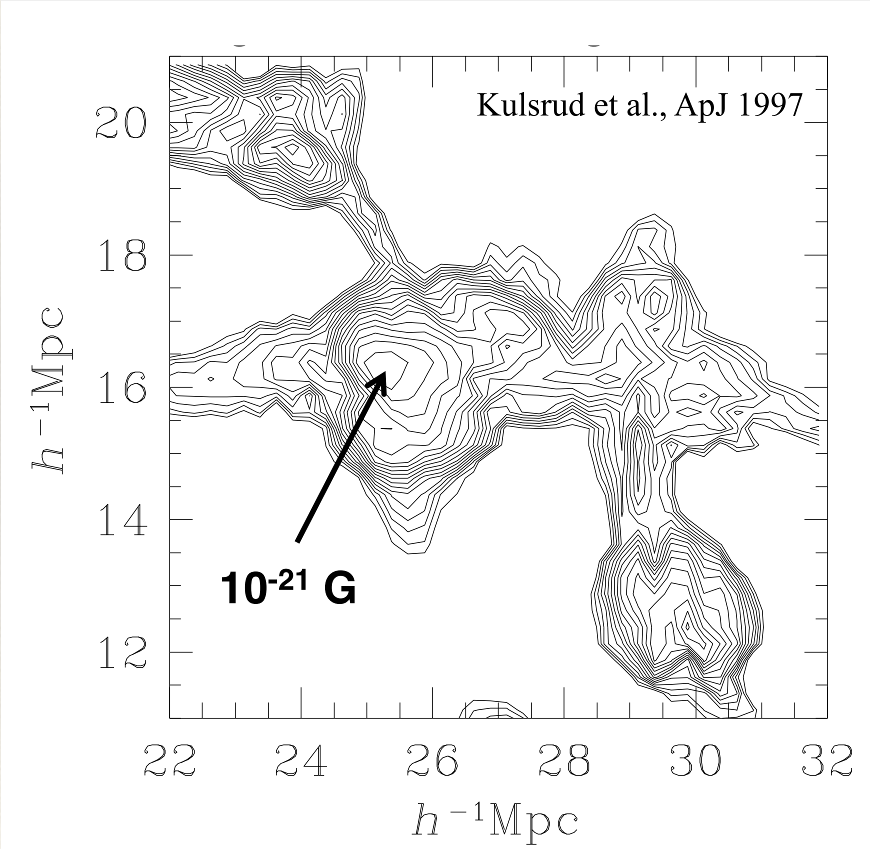


Generation, dynamics and stability of reverse shock

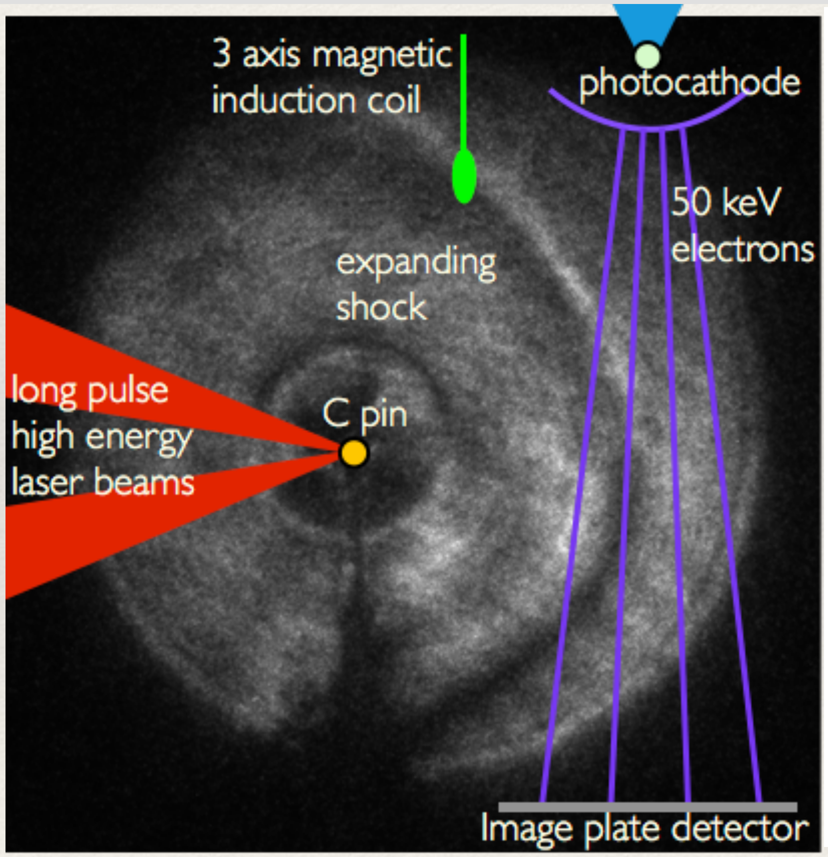
Ressemblant 1 - Self generated B fields

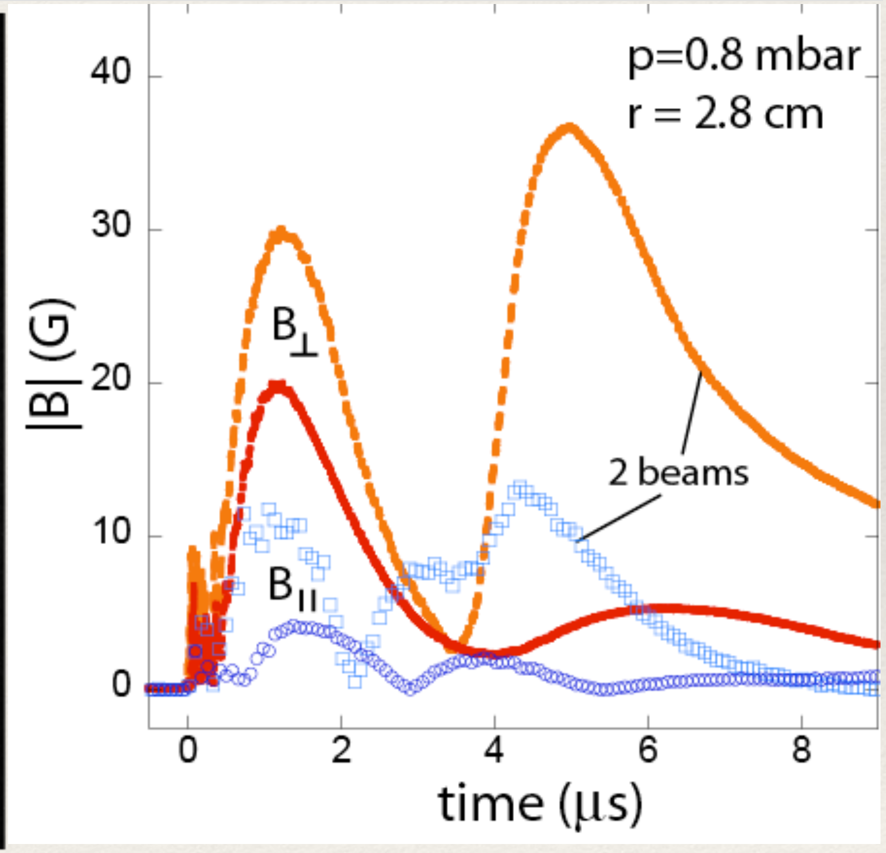
Nature. 2012, Nat Phys 2014

B field generation at cosmological front shocks



Laboratory measurement of self generated B field at shock front

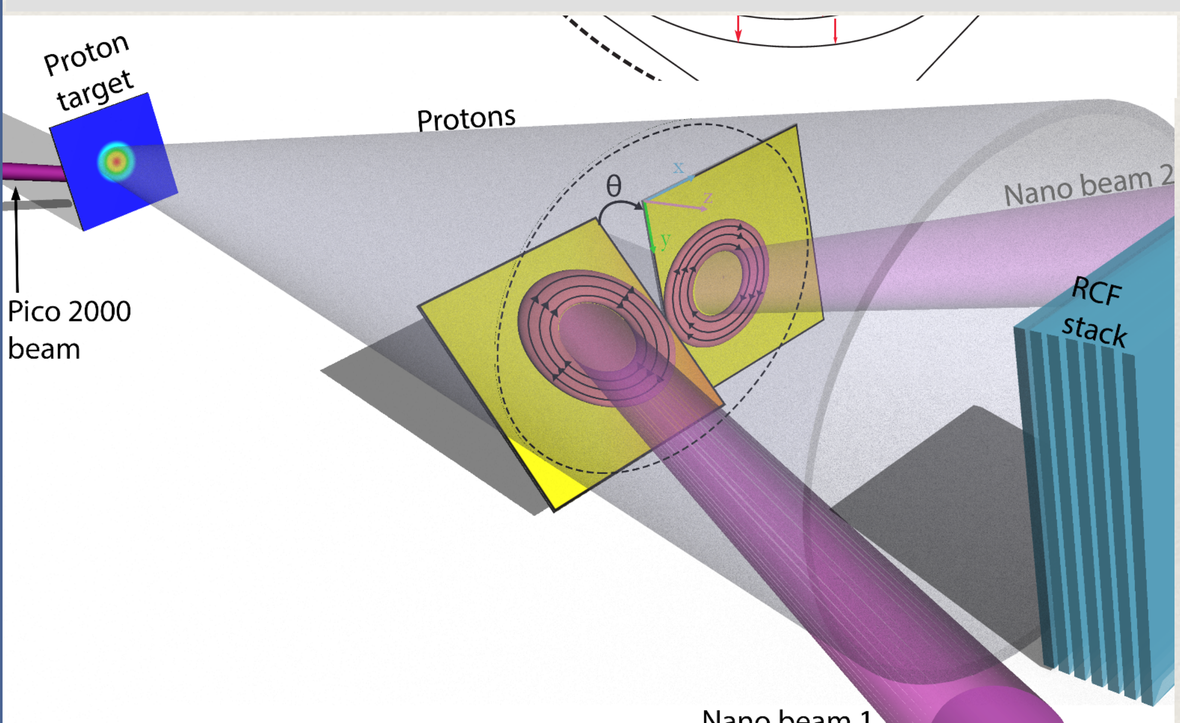




Ressemblant 2- Magnetic Reconnection

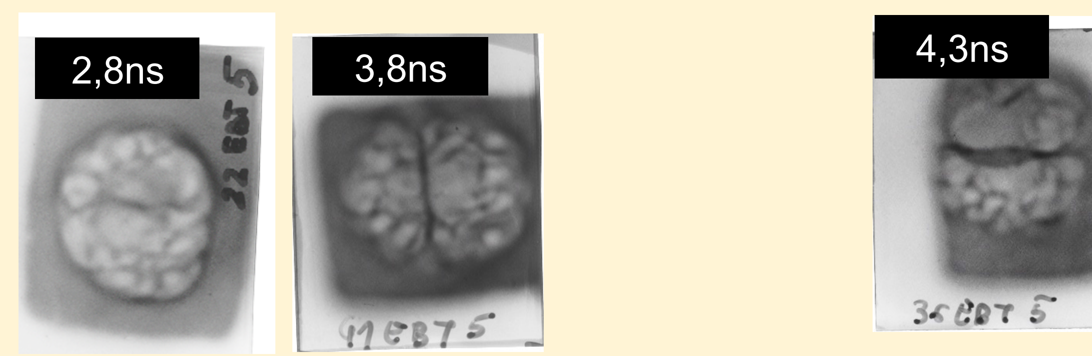
Bolanos PhD

Influence of guided fields in MR

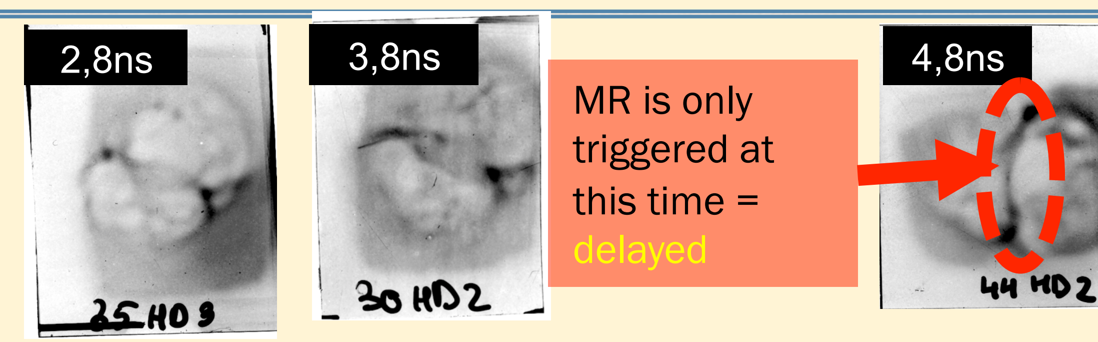


Protons beams to map the B field topology in t

w/o guide field → MR triggered early



with guide field (θ=30°) → MR delayed



Guided fields delay the triggering of MR

Ressemblant 3- Nucleosynthesis

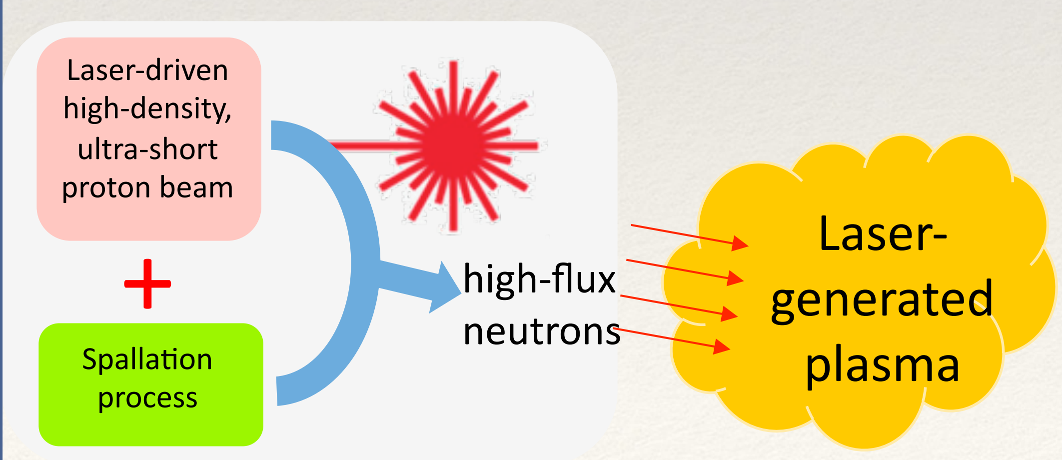
perspectives

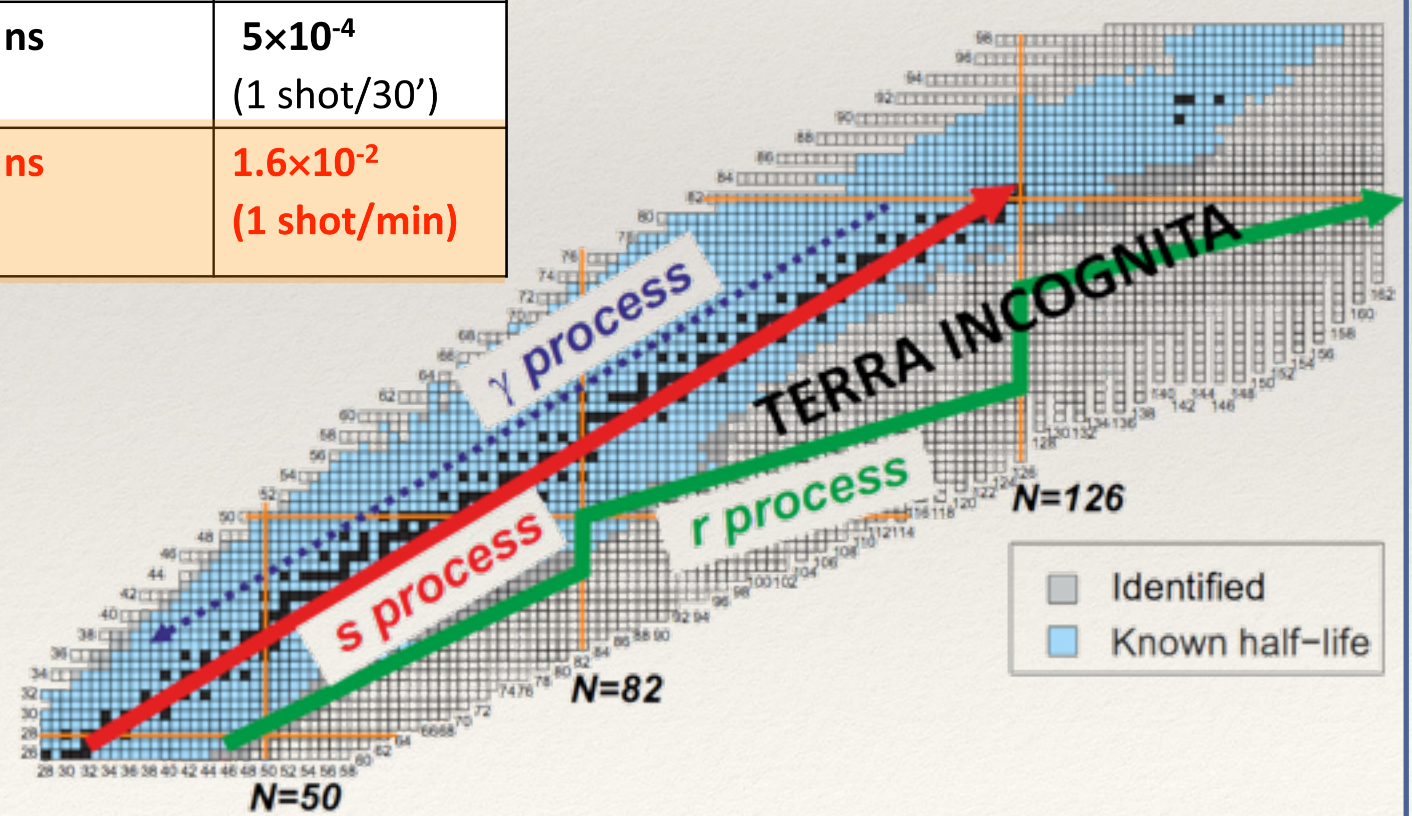
Vassura PhD

Ultra high brightness neutrons to study nucleosynthesis in the lab

Studying of r-processes in lab and plasmas

Facility	Peak neutron flux (neutrons/[cm^2.s])	Average neutron flux (neutrons/[cm^2.s])	Neutron bunch duration (ns)	Repetition rate (Hz)
ILL (reactor)	~10^{15}	~10^{15}	(continuous)	(continuous)
SNS (accelerator)	~10^{16}	~10^{12}	~1 µs	60
Present-day lasers	**10^{18}-10^{19}**	**5×10^{5}-5×10^{6}**	**~1 ns**	**5×10^{-4}** (1 shot/30’)
PetaWatt lasers (“APOLLON”)	**10^{22}-5×10^{24}**	**10^{11}-5×10^{13}**	**~1 ns**	**1.6×10^{-2} (1 shot/min)**



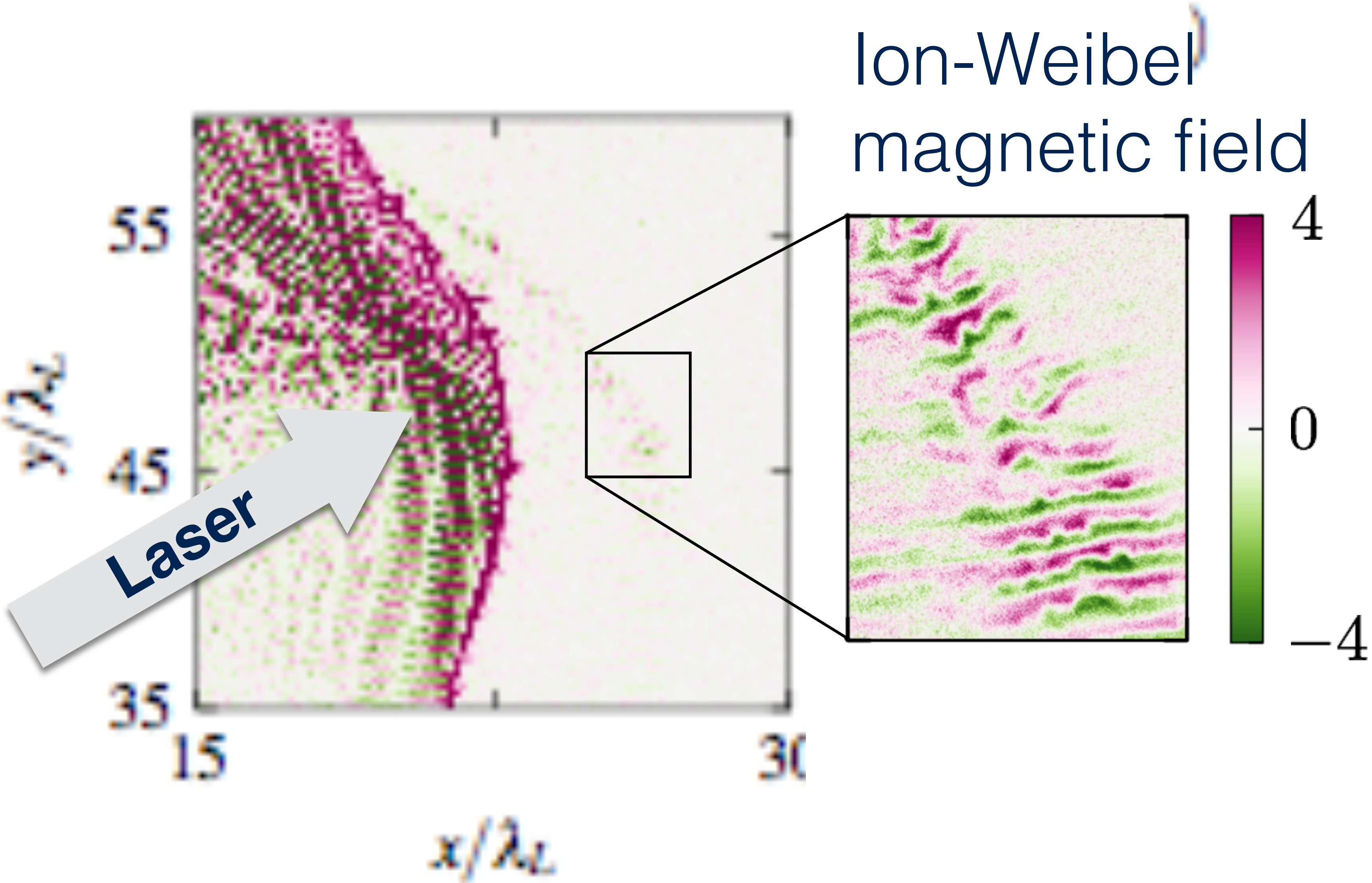


Ressemblant 4- Collisionless shocks & particles acceleration

perspectives

Grassi PhD PRE 2017

PIC **codes**: The ion-Weibel instability can be investigated with soon-available lasers



Laser

$\lambda_L = 1\,\mu\mathrm{m}$

$I \simeq 7 \times 10^{21}\,\mathrm{Wcm}^{-2}$

S-pol $\theta = 45°$

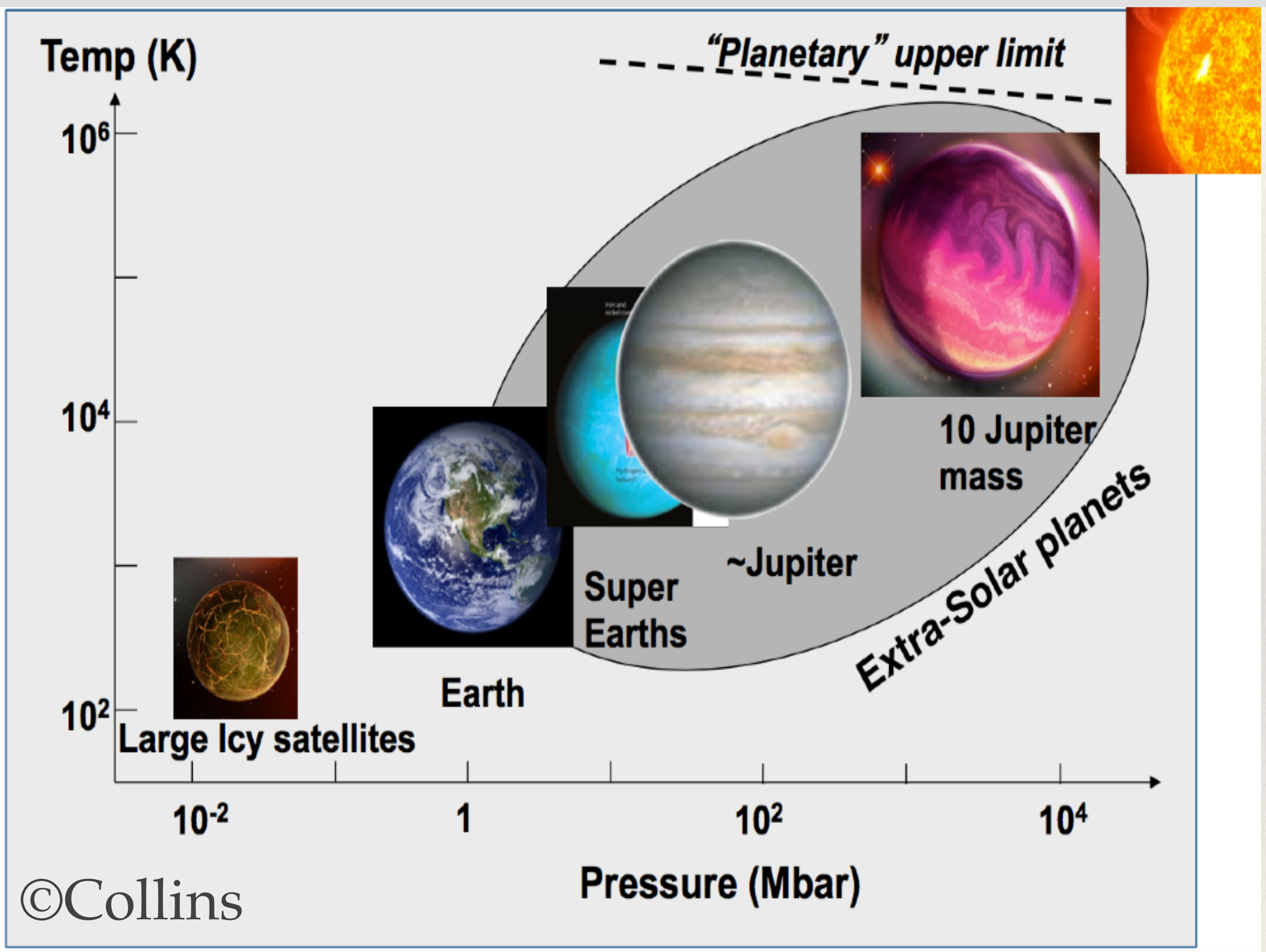
Focal spot $= 10\,\mu\mathrm{m}$

(PETAL, Apollon)

Identical 1- EOS

Huser, Henry, Denoeud, Bolis, Guarguagini, etc..PhD

Over nearly 2000 known planets, most have internal pressure between 1Mbar to 10 Gbar



$$\nabla P = \rho \nabla (V + Q)$$

$$\nabla T = \nabla P \left(\frac{T}{P} \nabla_T \right)$$

$$\nabla M = 4\pi r^2 \rho$$

gravitational and centrifugal potential

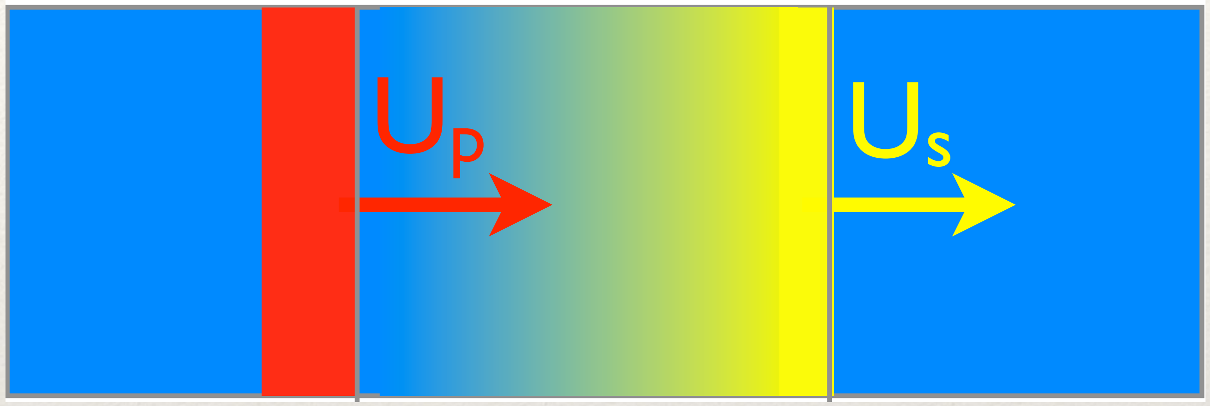
Few observational constraints

Planetary models need EOS at high P-T conditions: Pb in the **EOS** leave lacunae in the understanding of planetary physics

Laser compression and EOS

Rankine-Hugoniot link material properties and shock quantities

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

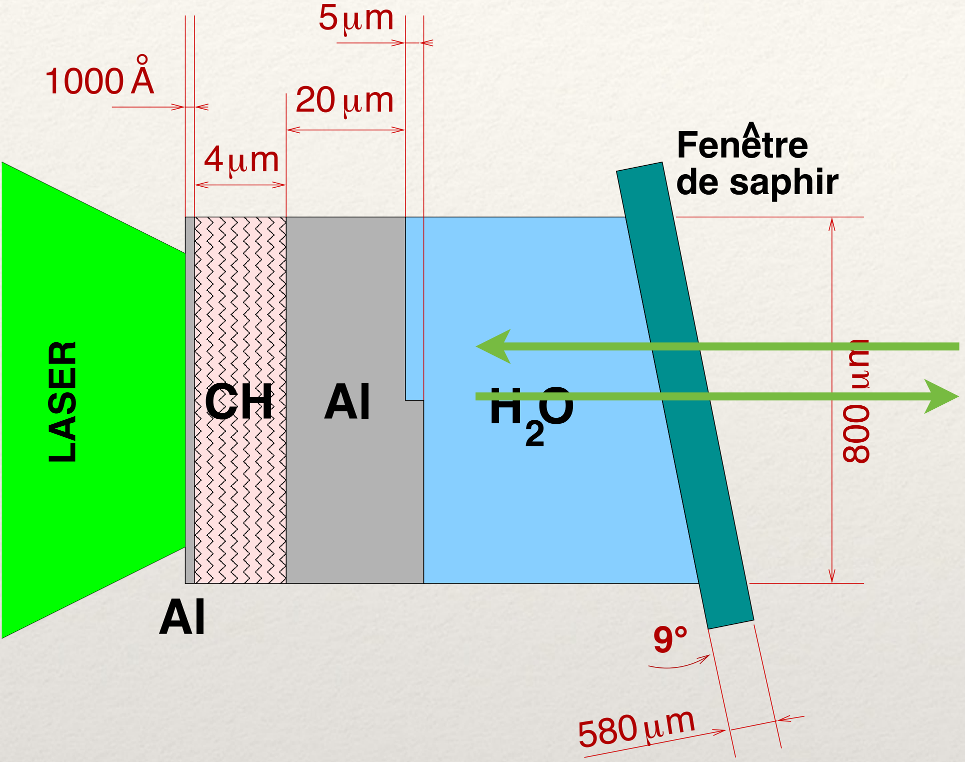


3 equations et 5 parameters ⇒ <u>We need to measure 2 quantities</u>

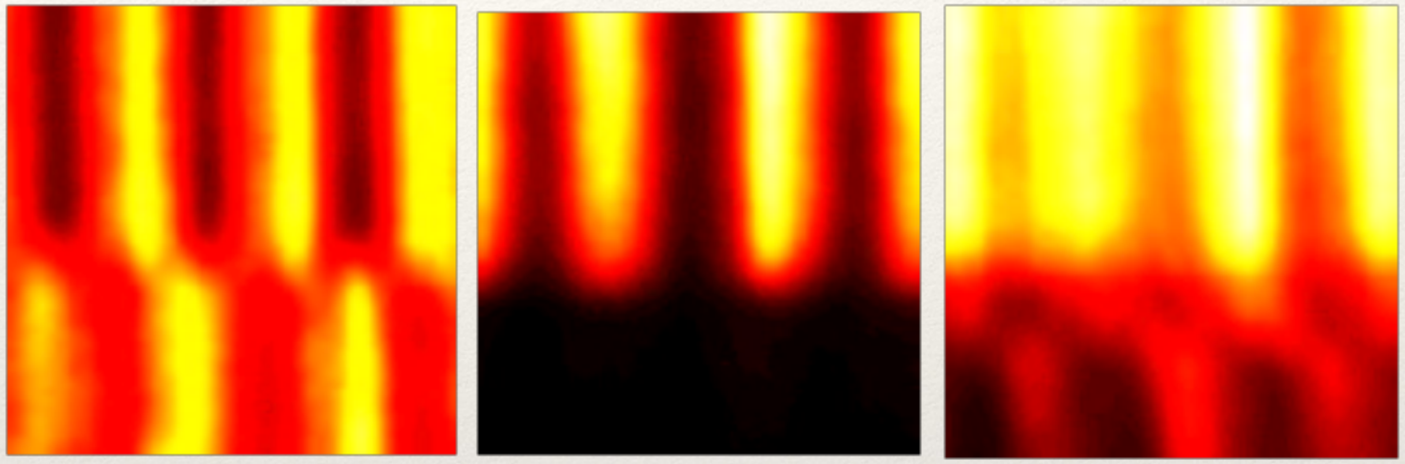
- *2 parameters in the sample* ⇒ absolute EOS measurement U_S (sample), U_p (sample) *VISAR*
  ρ, *X-ray radiography, XRD*

VISAR & EOS

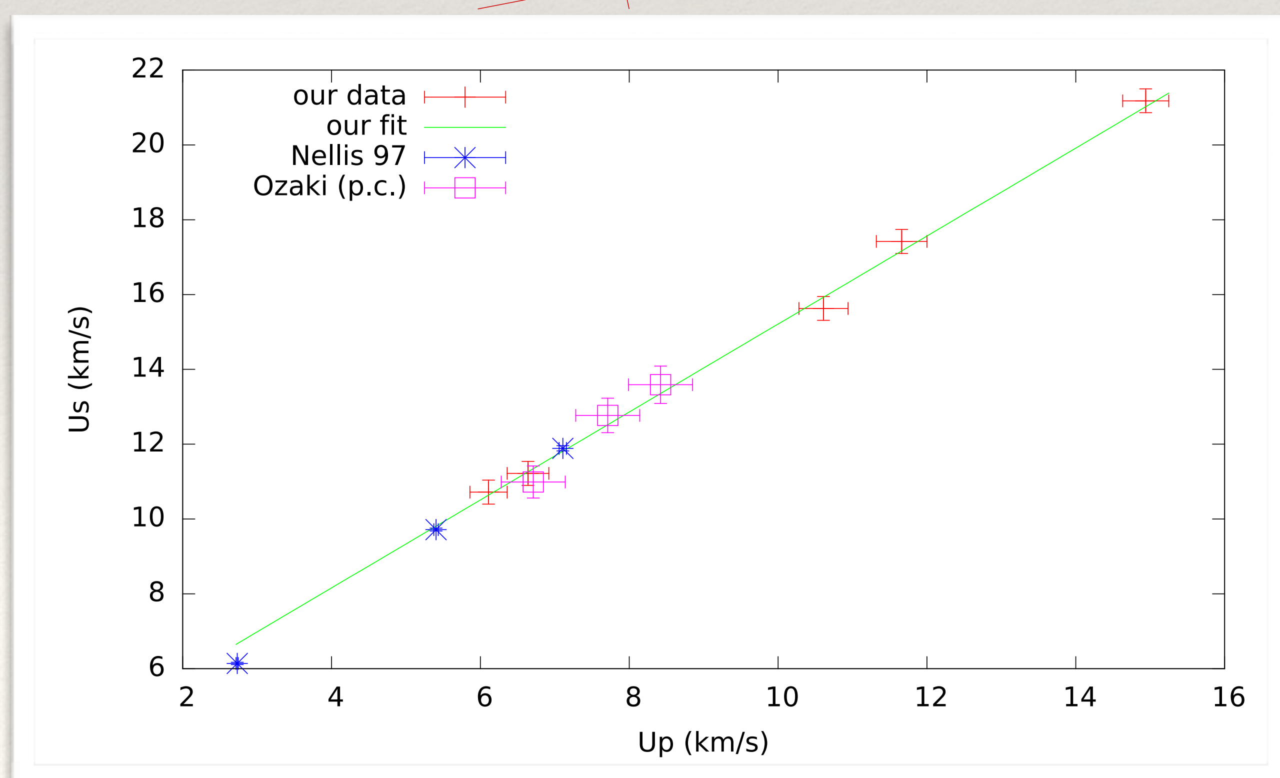
H2O-CHNO mixtures : metallic behaviour at high P

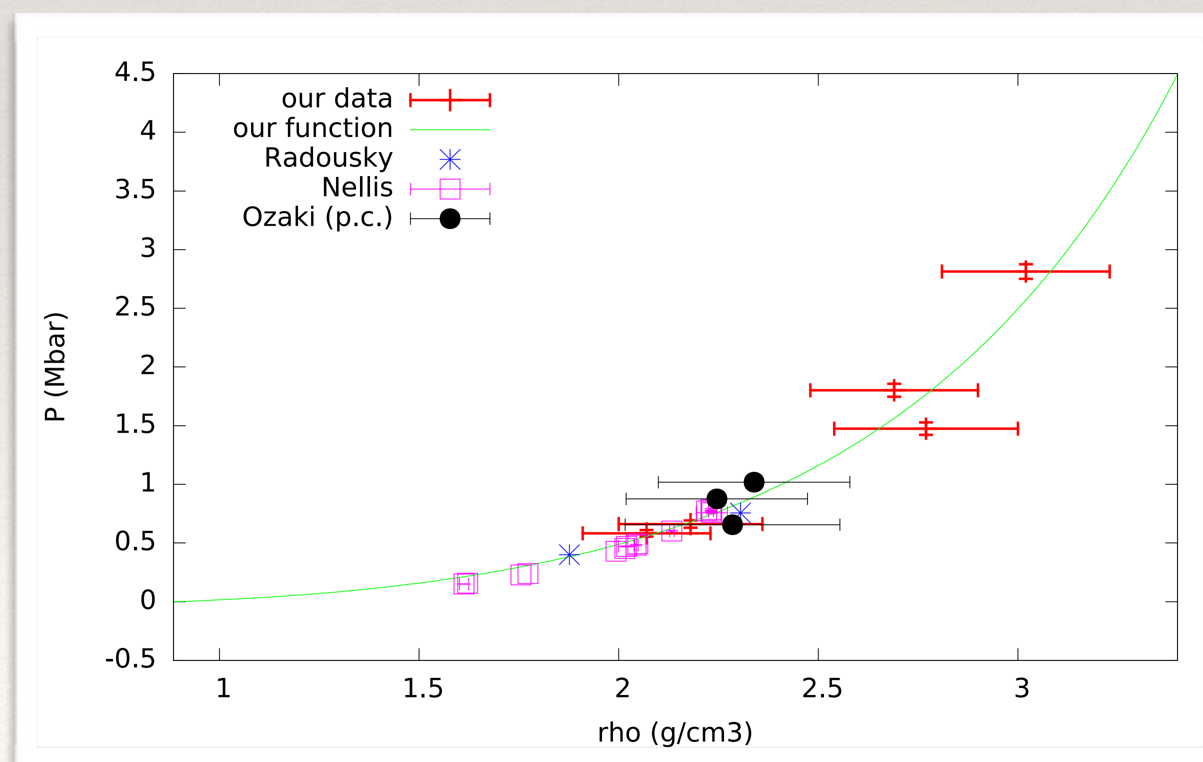


VISAR DATA (Doppler interferometry)



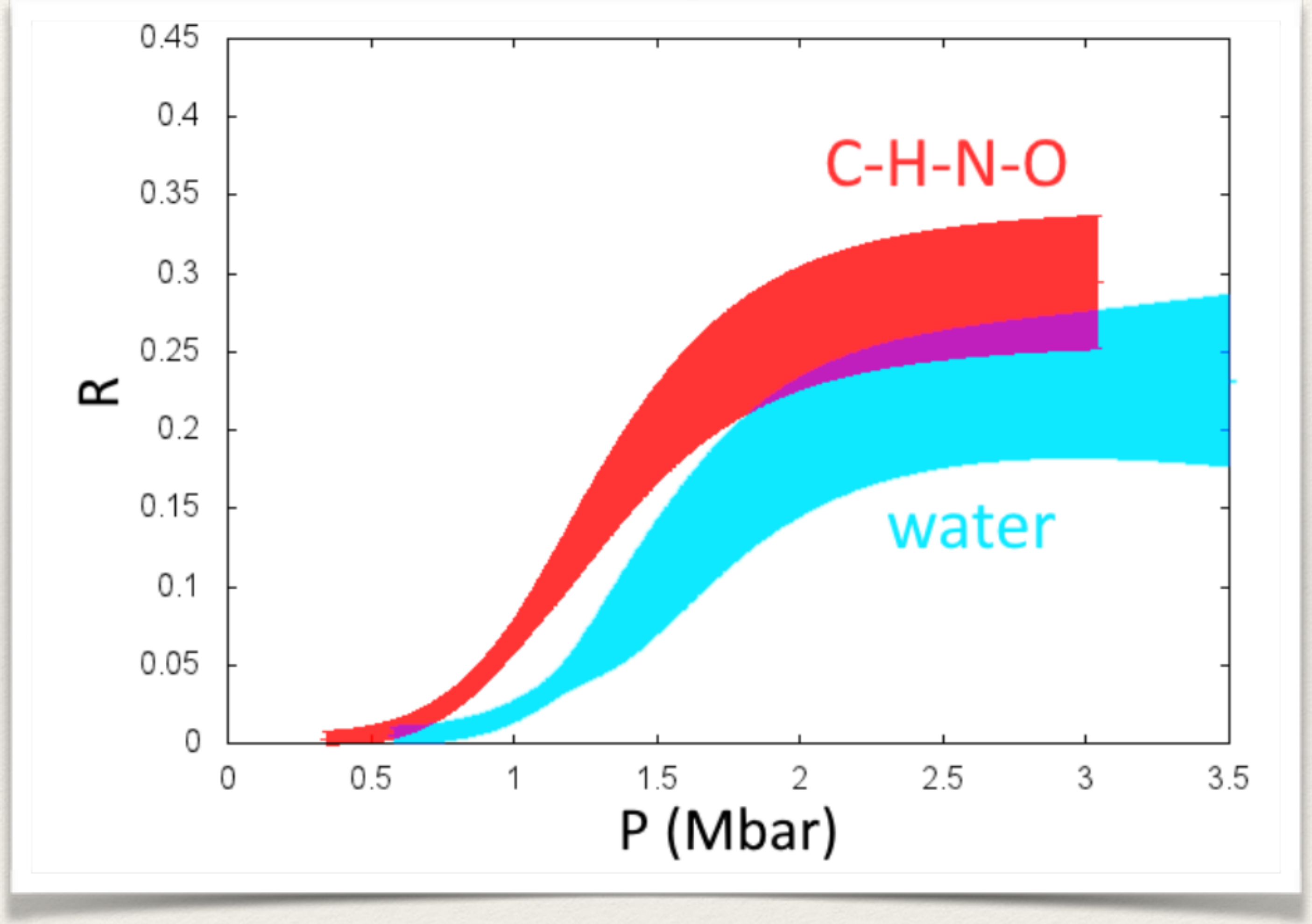
Transparente	Opaque	Réfléchissante
P ≤ 0,5 Mbar	0,5 Mbar ≤ P ≤ 1 Mbar	P ≥ 1 Mbar





VISAR: reflectivity&absorption (e^- conductivity)

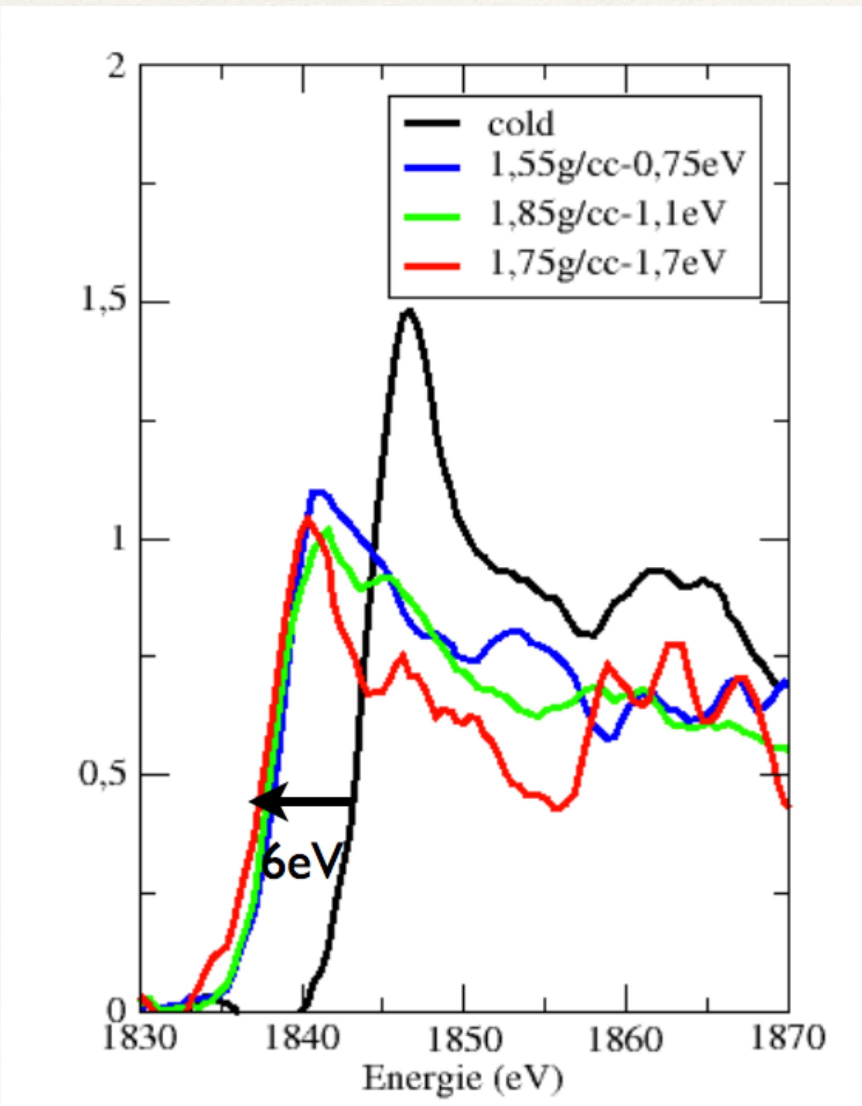
Input for planetary dynamo models



CHNO conductivity is higher than H2O at 1Mbar: implication for Uranus and Neptune dynamos

In situ microscopic measurements

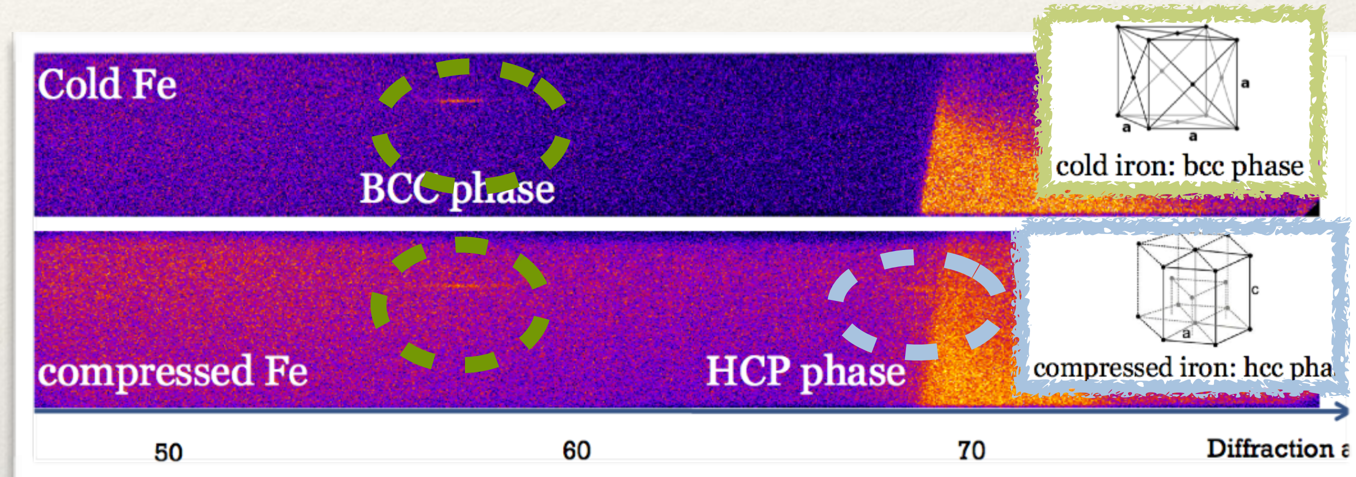
Xray **A**bsorption **N**ear **E**dge **S**pectroscopy: electronic structure



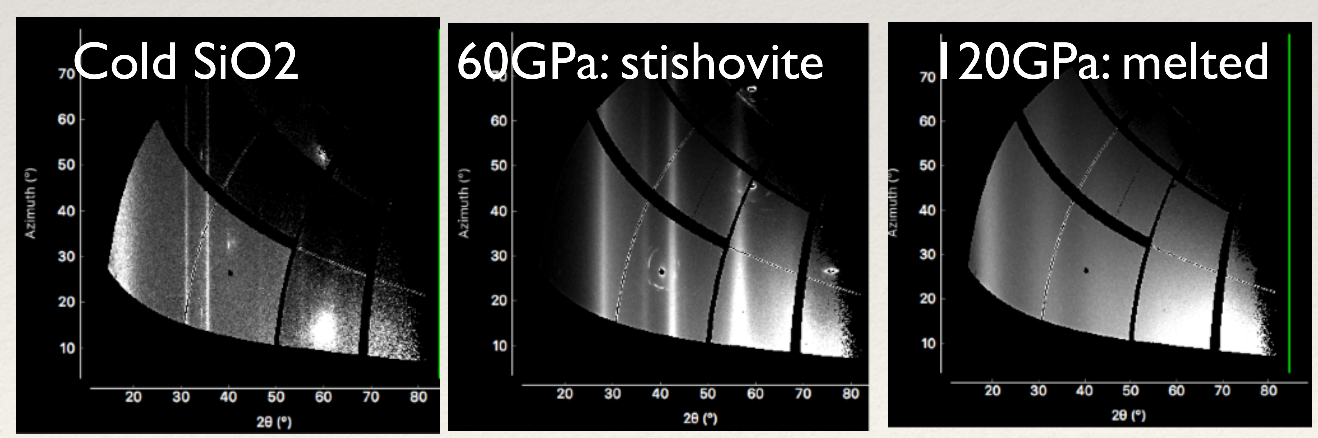
Edge shift: gap closure dynamics at high P/T in Quartz

X-**R**ay **D**iffraction: ionic structure

IRON: BCC-HCP transition



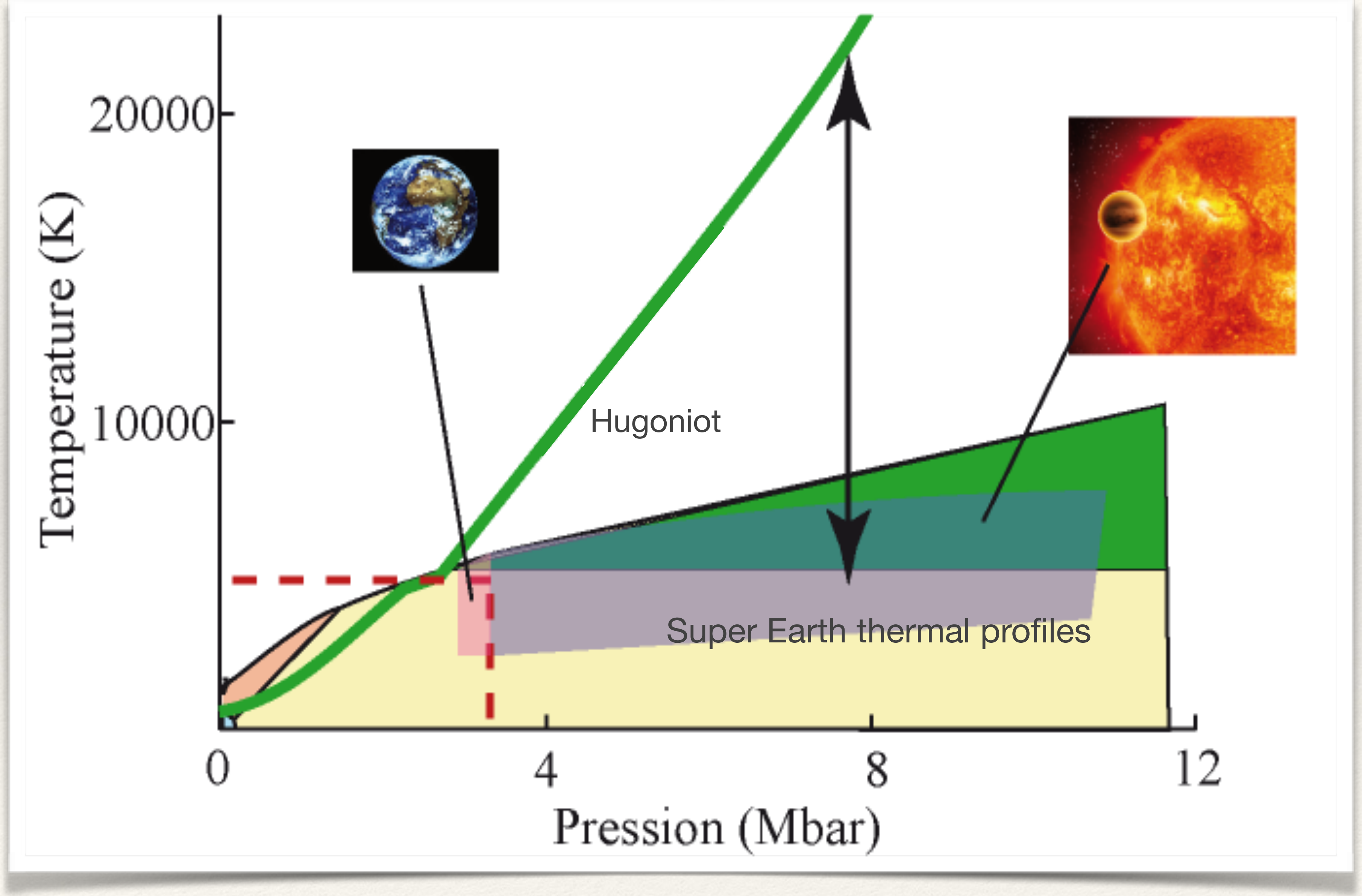
QUARTZ: Transition to high P phase stishovite

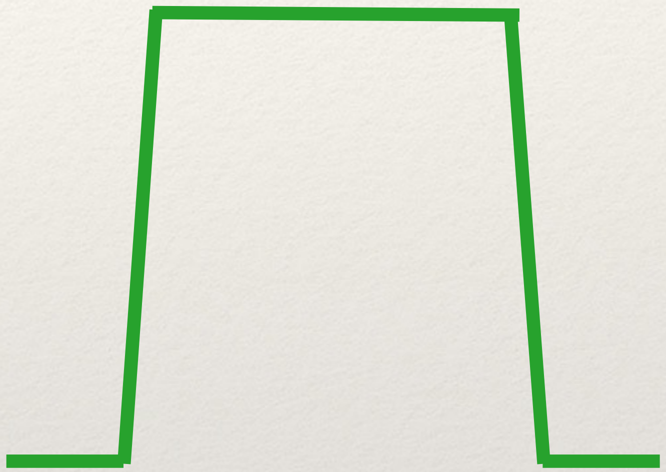


Phase transitions at high P/T conditions and dynamics

Beyond the Hugoniot: lower T

Shock compression leads to too high temperatures: laser pulse shaping to get quasi isentropic compression





High P planetary conditions become accessible

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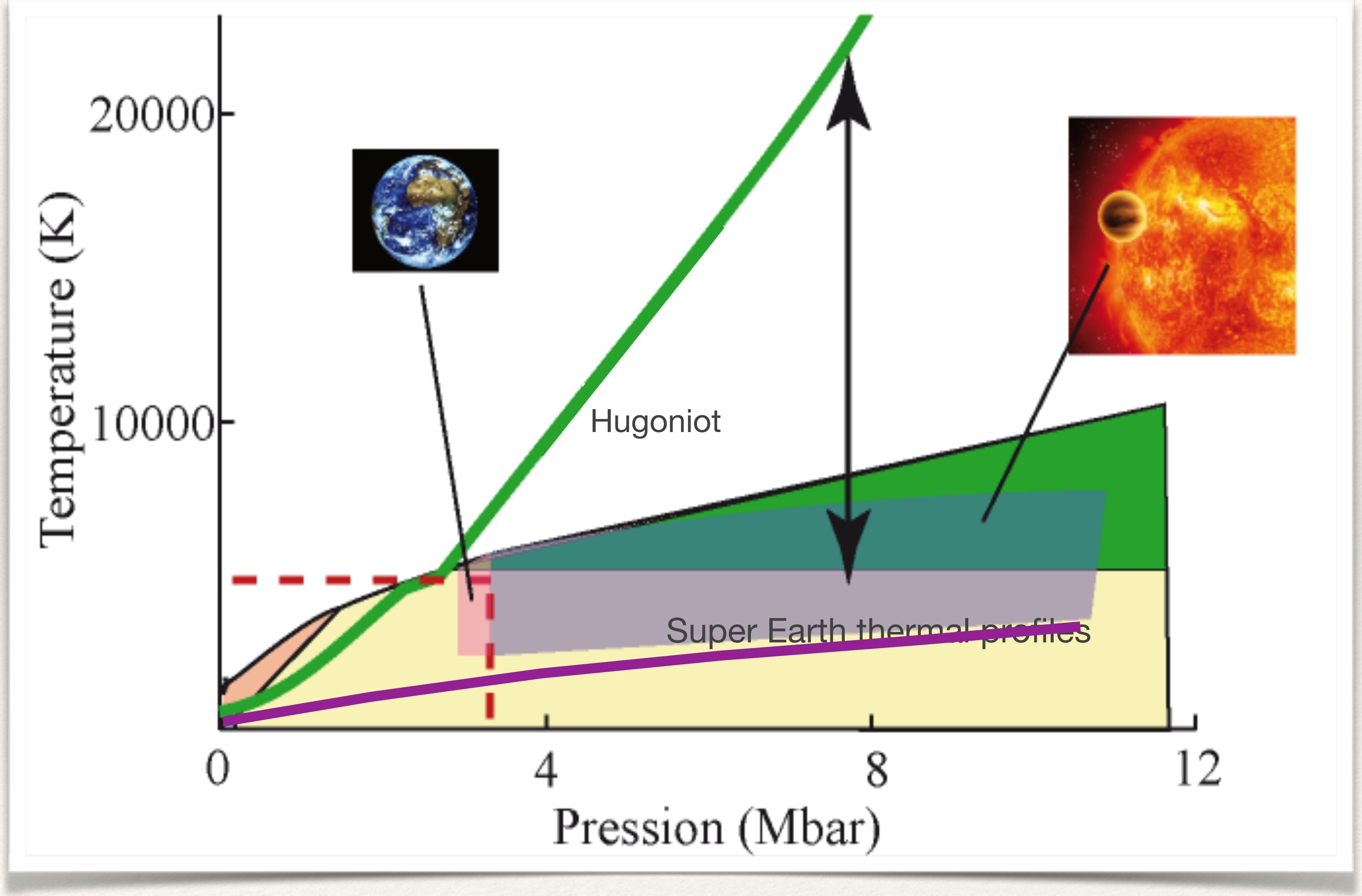

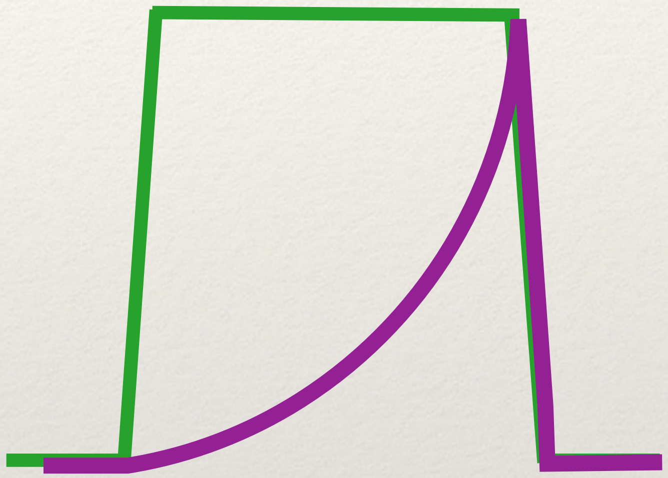

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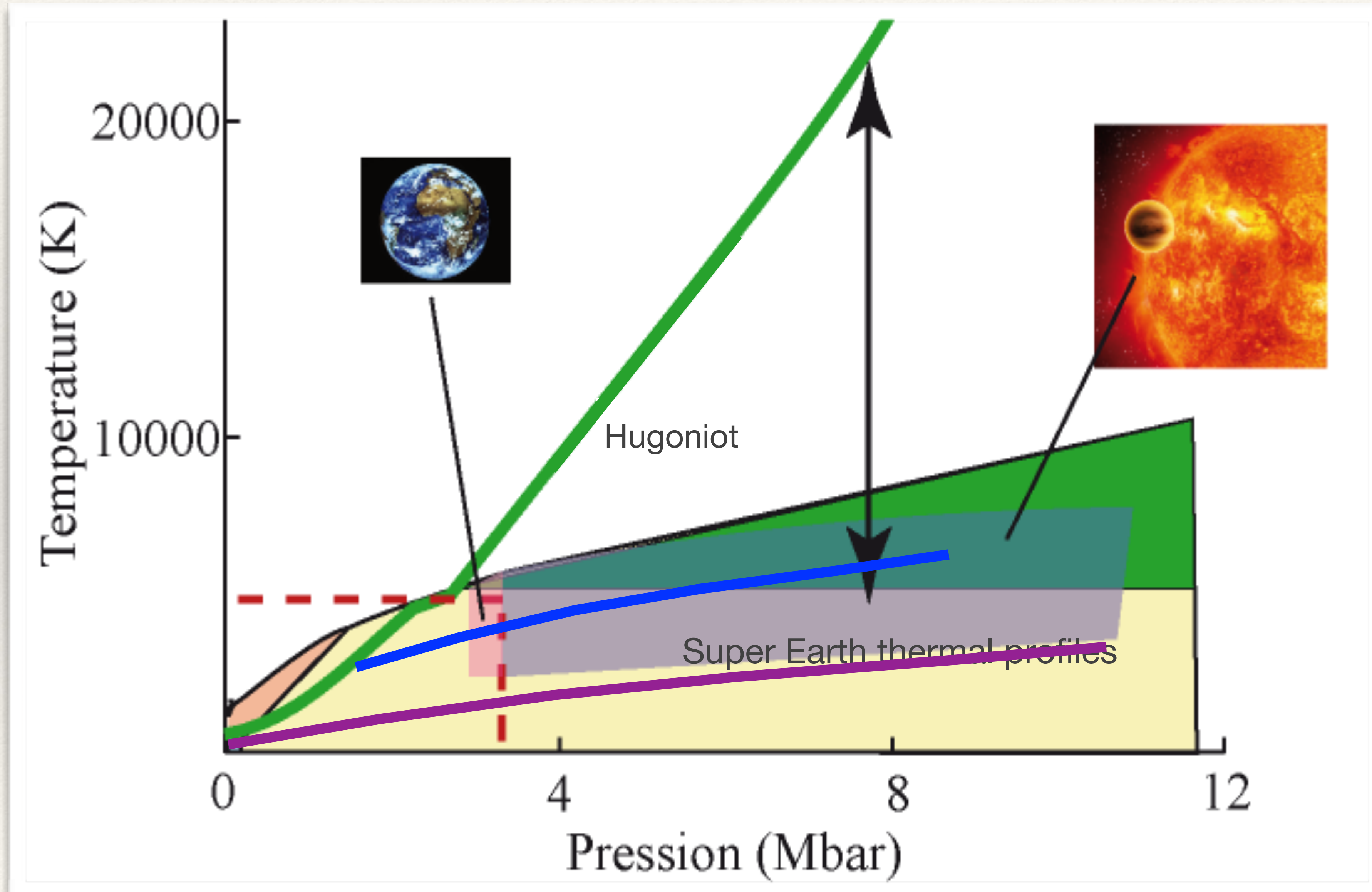

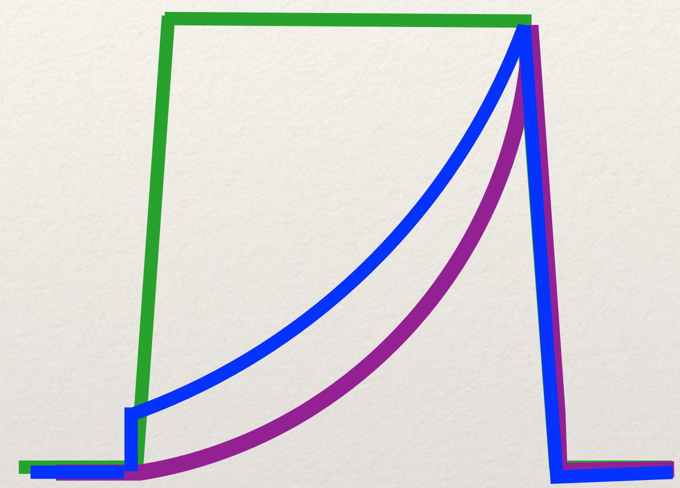

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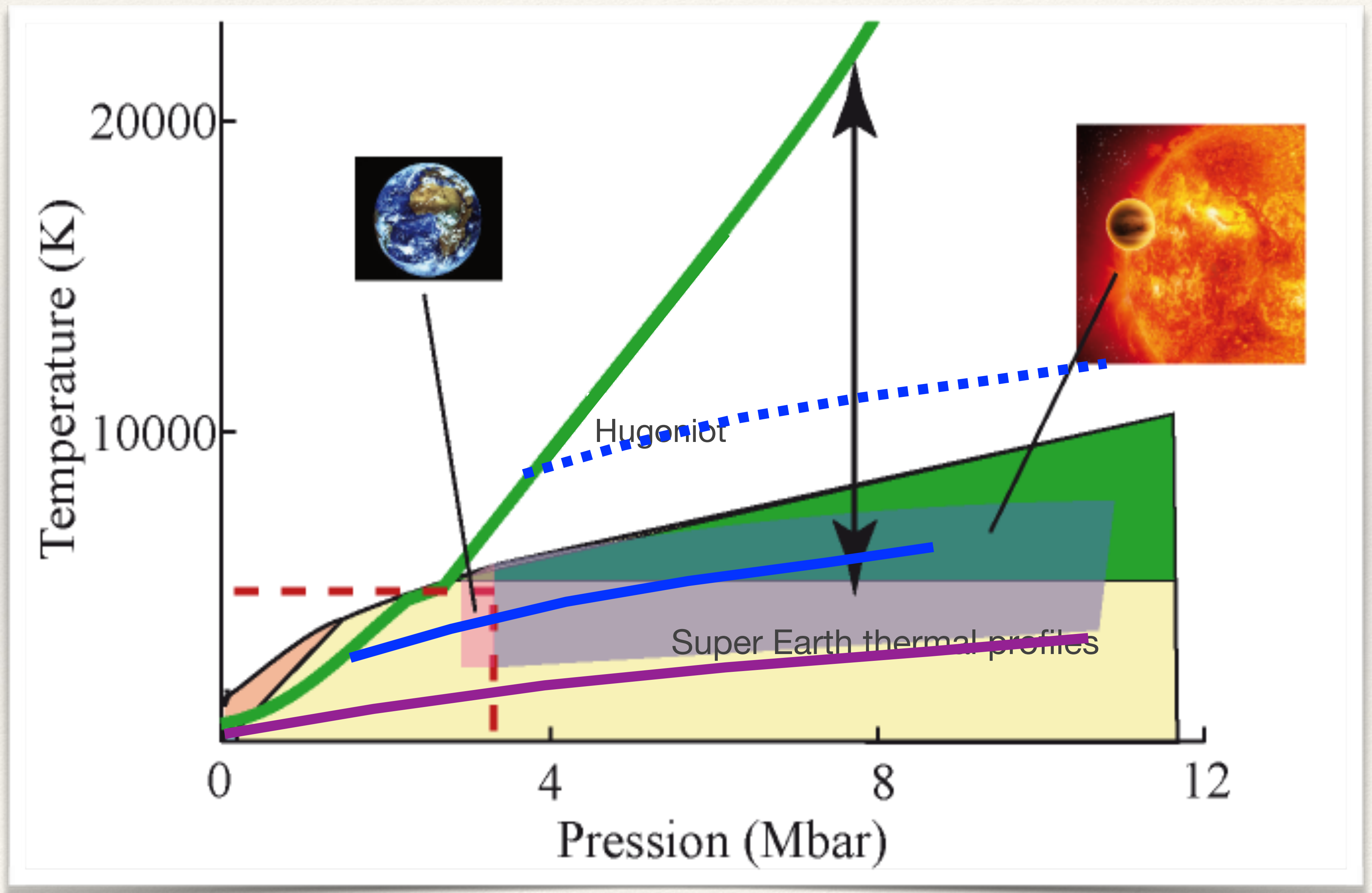
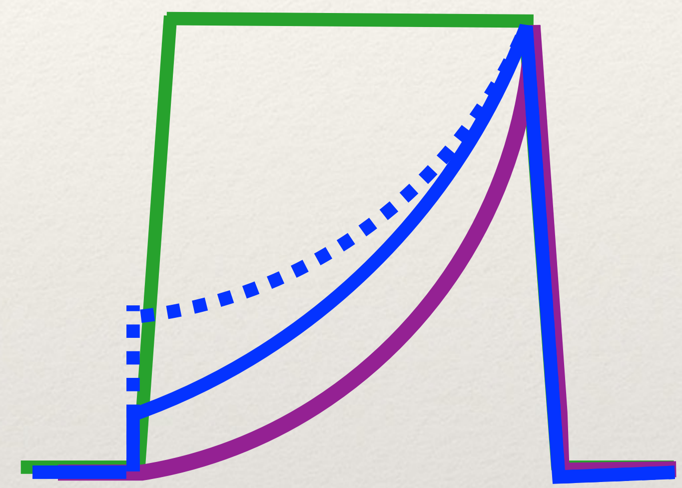
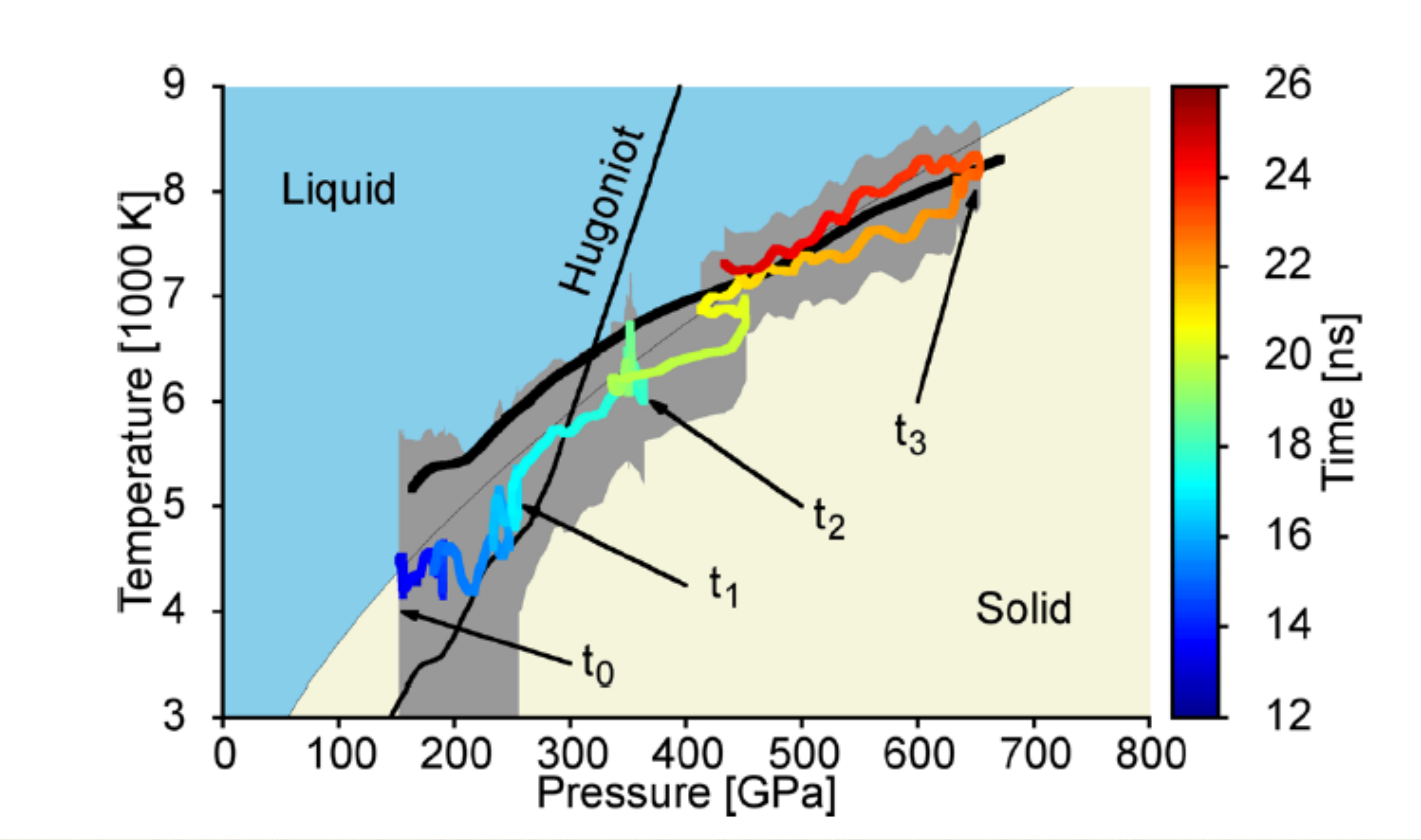




High P planetary conditions become accessible

Quasi isentropic compression

LIL experiment: 7Mbar, 8500K



Quasi isentropic compression

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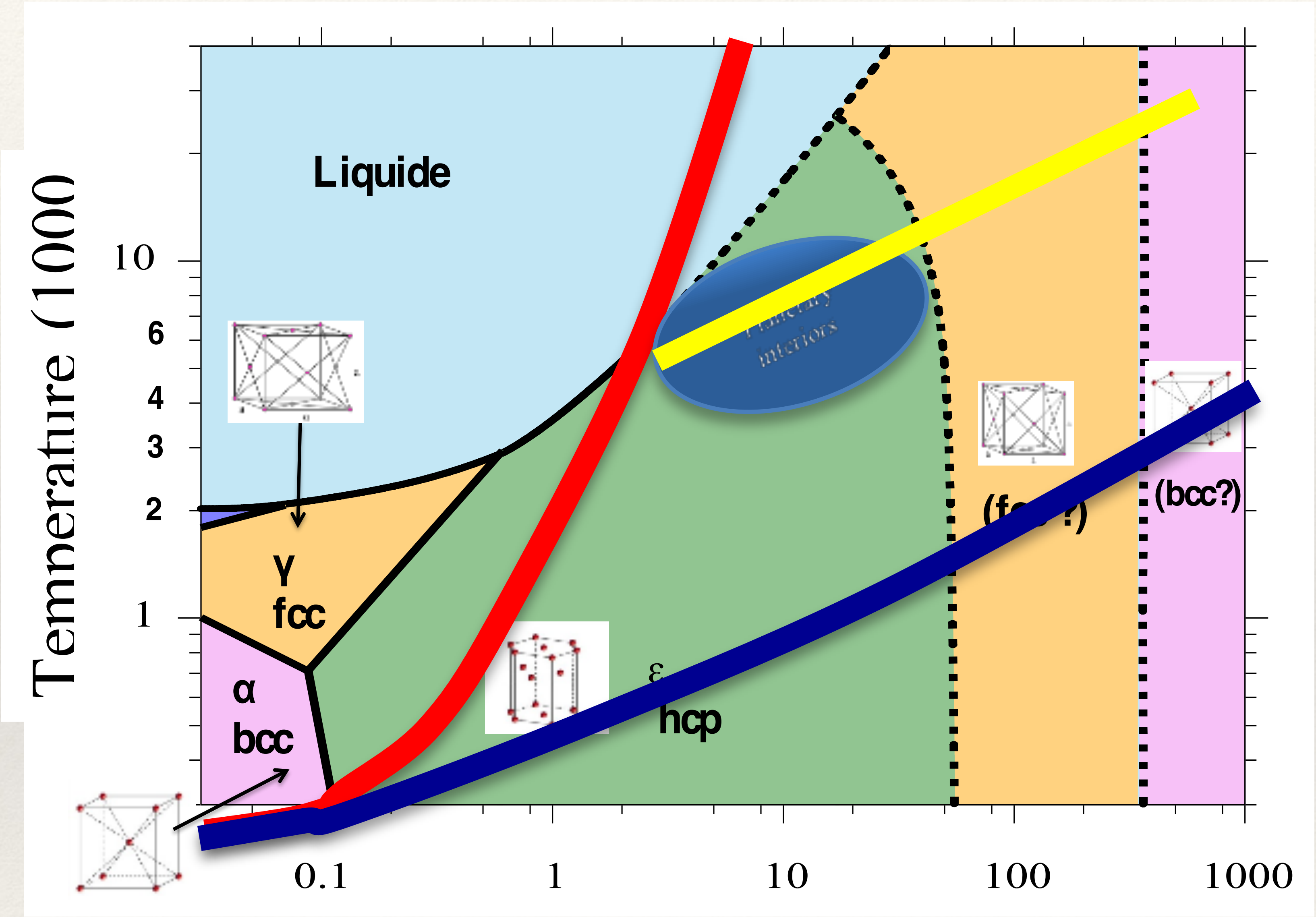
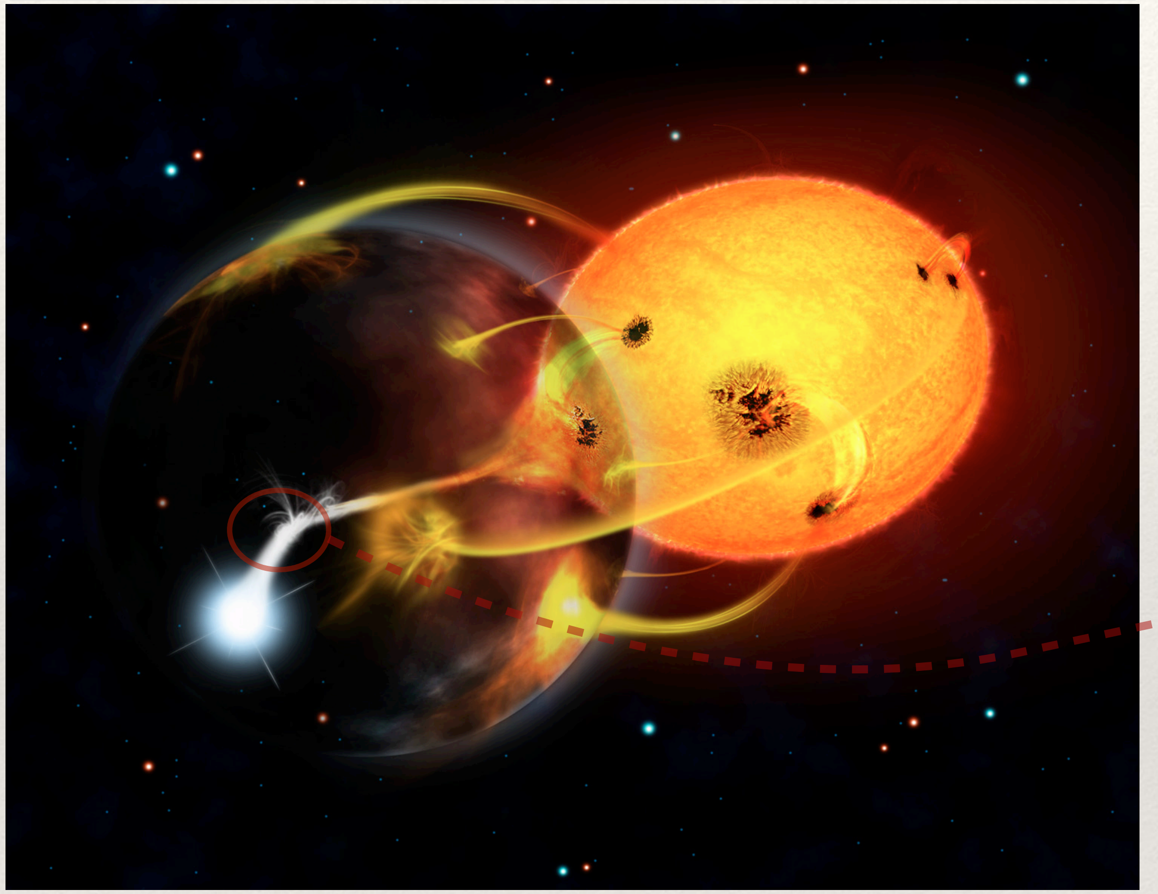


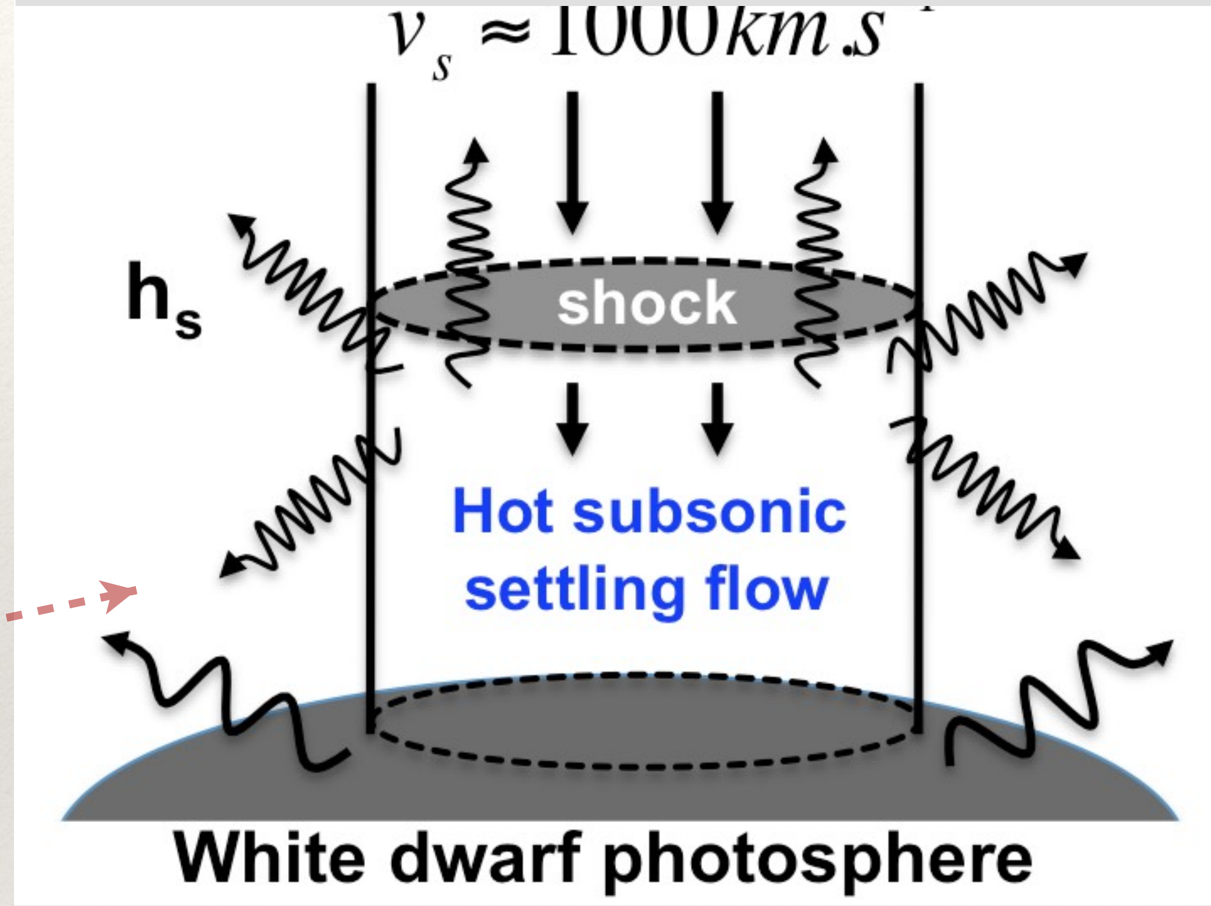
LMJ expriment (accepted for 2019): quasi isentropic compression+XRD
access to both macroscopic and microscopic of high pressures conditions relevant for Super Earth interiors

SIMILARITY: POLAR

In POLAR: cataclysmic variable with B>10MG



Strong B field prevents the accretion disk formation: accretion column



Impact of supersonic flow with the white dwarf photosphere: **reverse radiative shock**

SIMILARITY: POLAR

Exact scaling laws exist for different accretion column regimes

Falize et al. ApSS 2009
Falize et al. ApJ 2011

The stationary position of the reverse shock h_s :

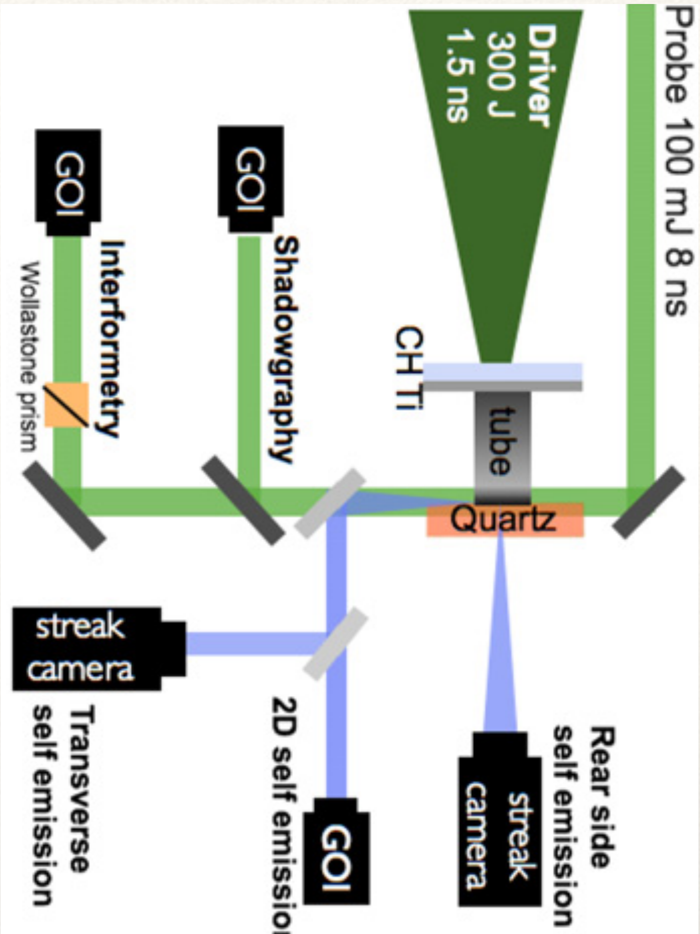
$h_s \approx v_S \times t_{cool}$

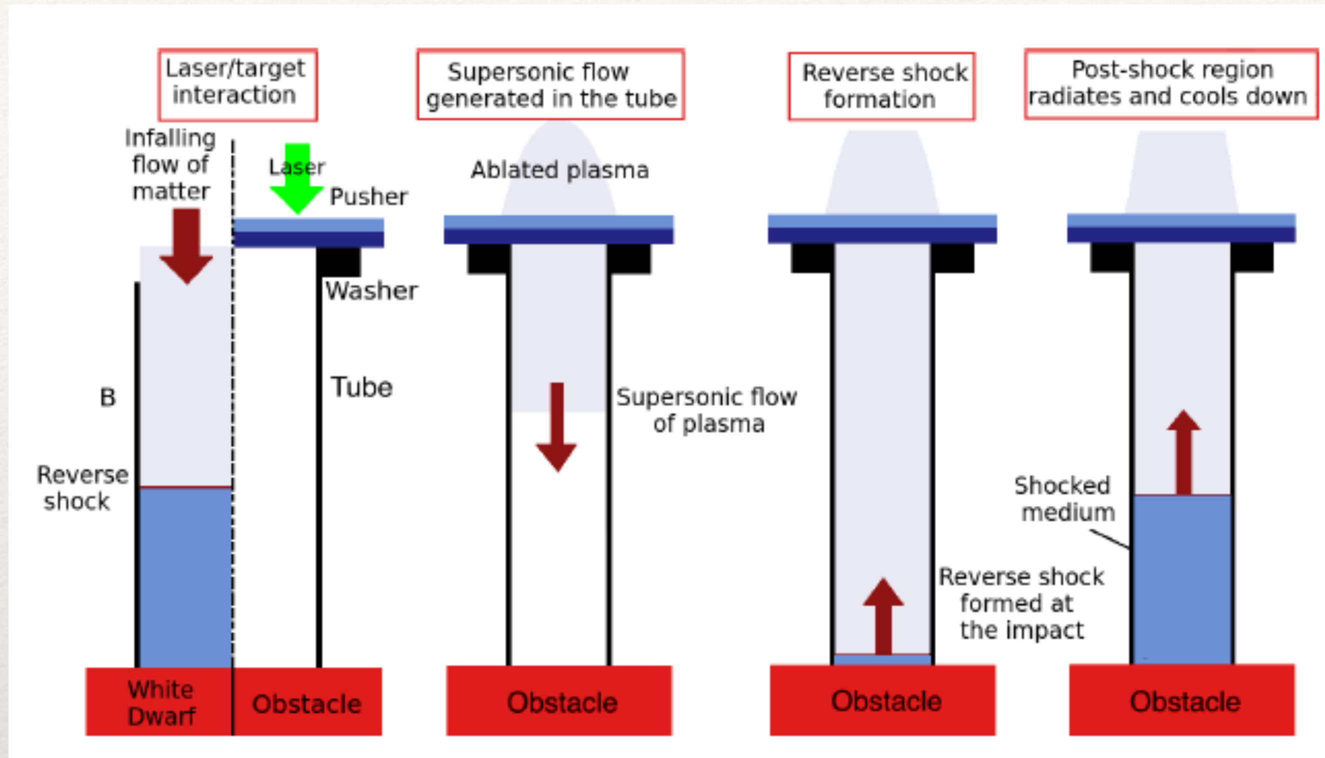
- $v_S \sim 1000$ km/s, $t_{cool} \sim 1$s $\longrightarrow$ $h_S \sim 1000$ km challenging to resolve
- $v_S \sim 100$ km/s, $t_{cool} \sim 1$ns $\longrightarrow$ $h_S \sim 100$ μm easily observable in laboratory

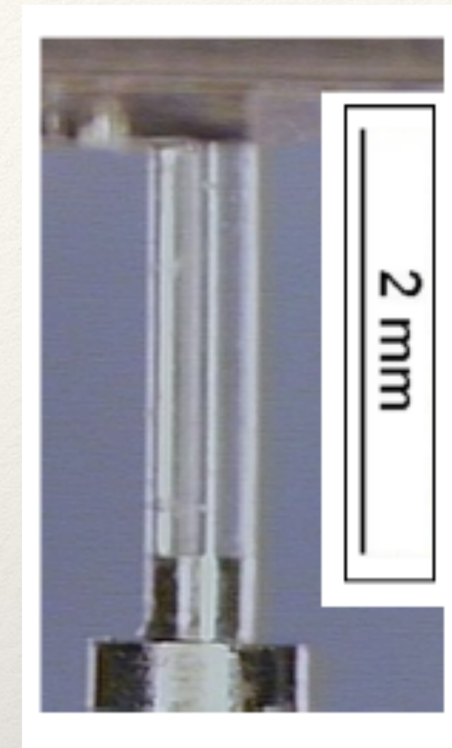
GOAL of the POLAR project: reproduce and study scaled models of accretion process in laboratory.

Falize et al. ApSS 2011

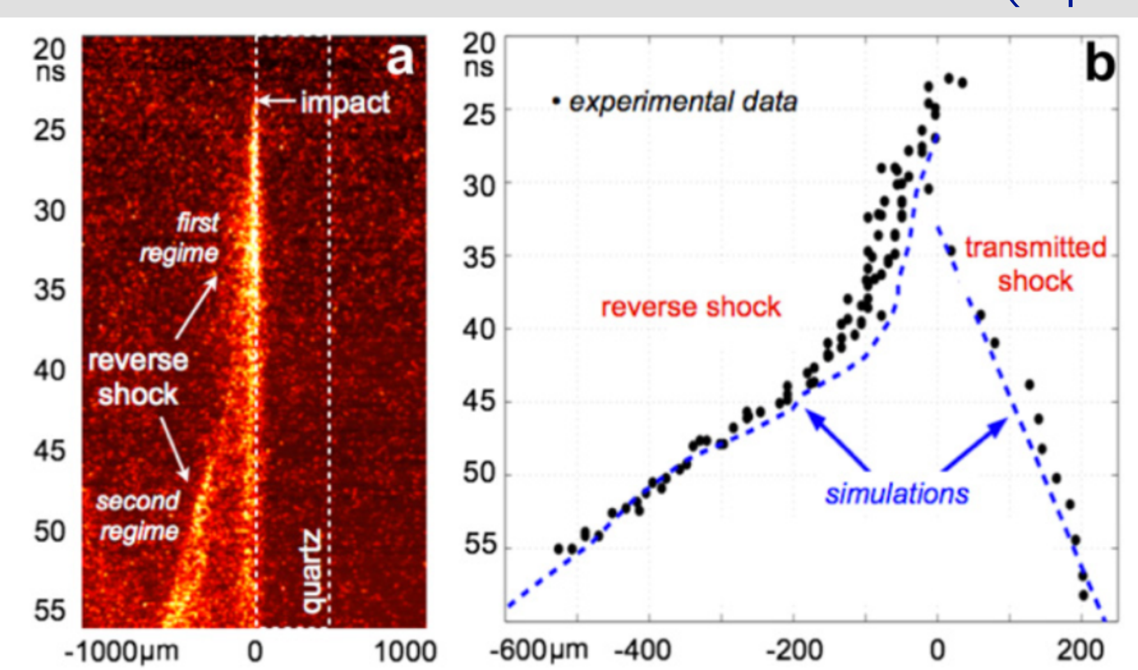
First experiment







First evidence of reverse shock (optical) [E. Falize et al. HEDP, 8 (2012)]



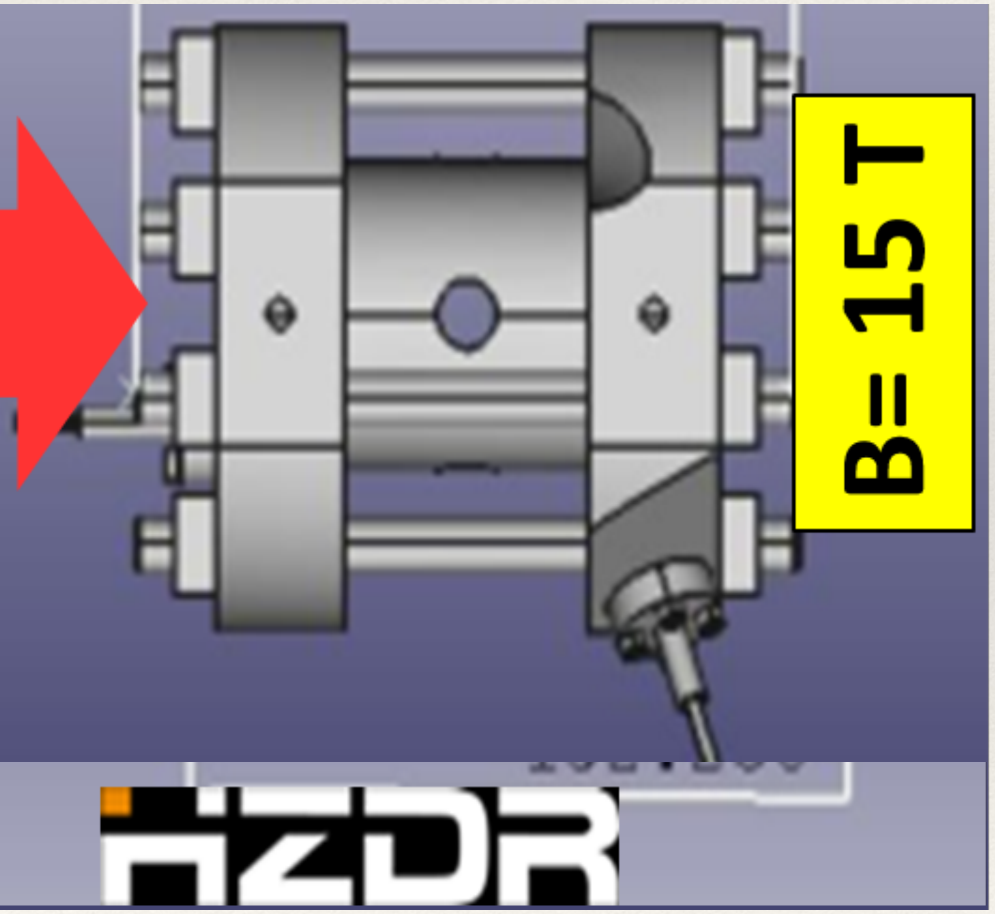
Not fully similar: radiation

Fluid parameter	VCms shock	Laboratory plasma
h_s (cm)	10^7	5×10^{-2}
t (s)	1	5.5×10^{-8}
v_a (km s^{-1})	1000	80
ρ_a (g cm^{-3})	10^{-8}	10^{-2}
T_{ps} (eV)	10^4	15
M	>10	3
χ_{ps}	$\ll 1$	1
Bo_{ps}	$\gg 1$	15
R_{ps}	$\gg 1$	2×10^4

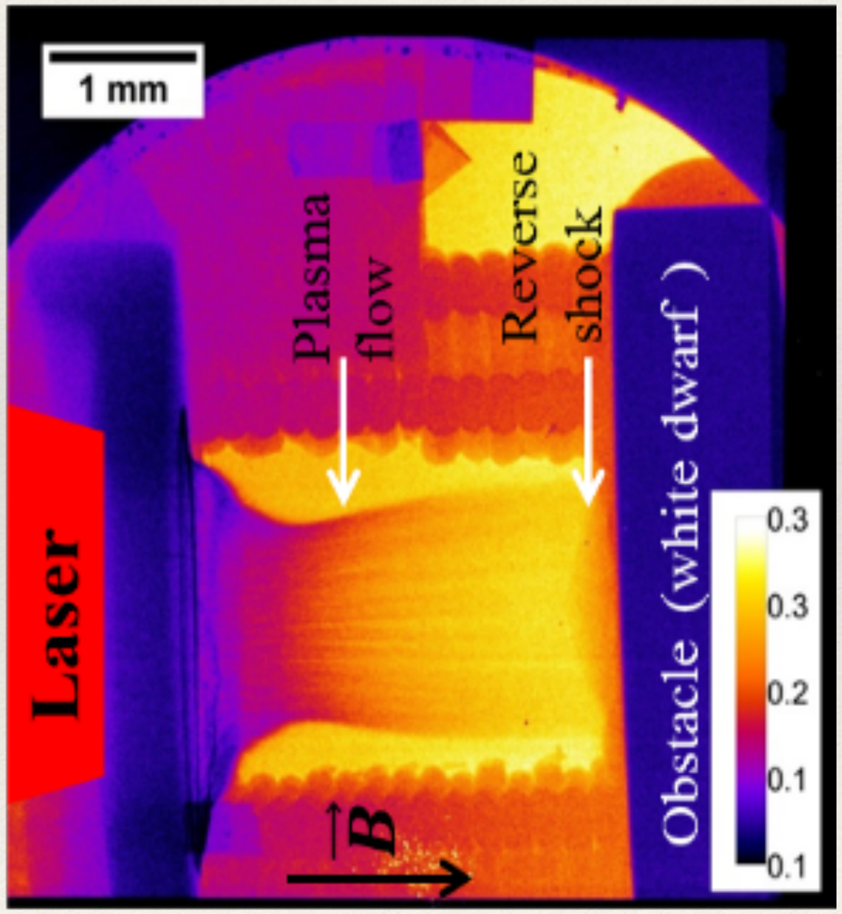
B field collimation

Direct density measurement of the return shock density: B collimation, no tube

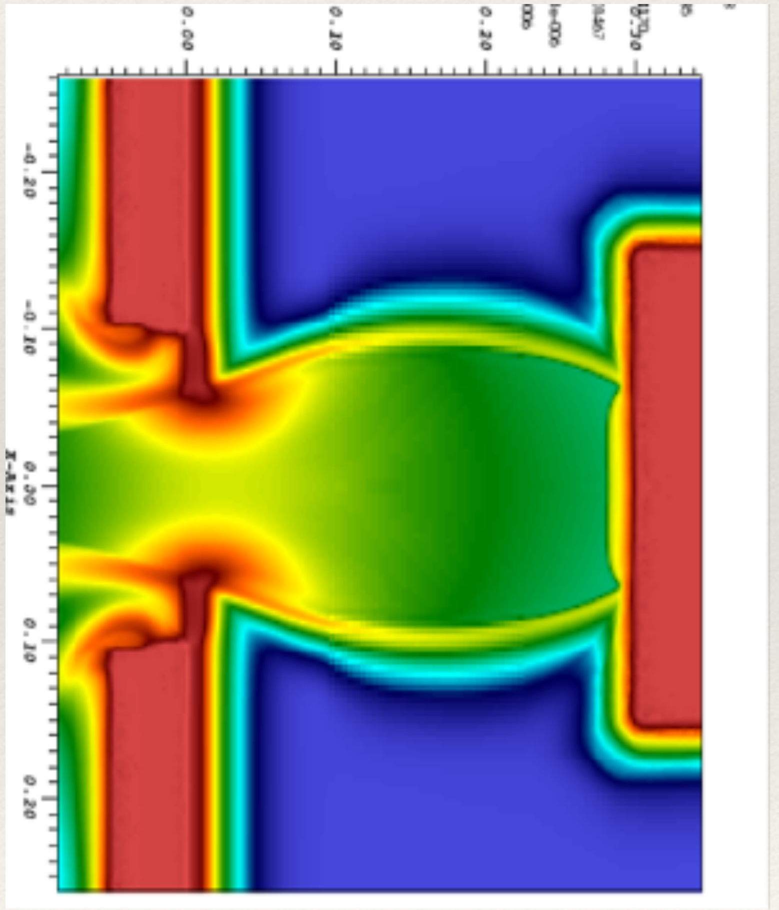
B field ~15 T



X-ray radiography



MHD simulations



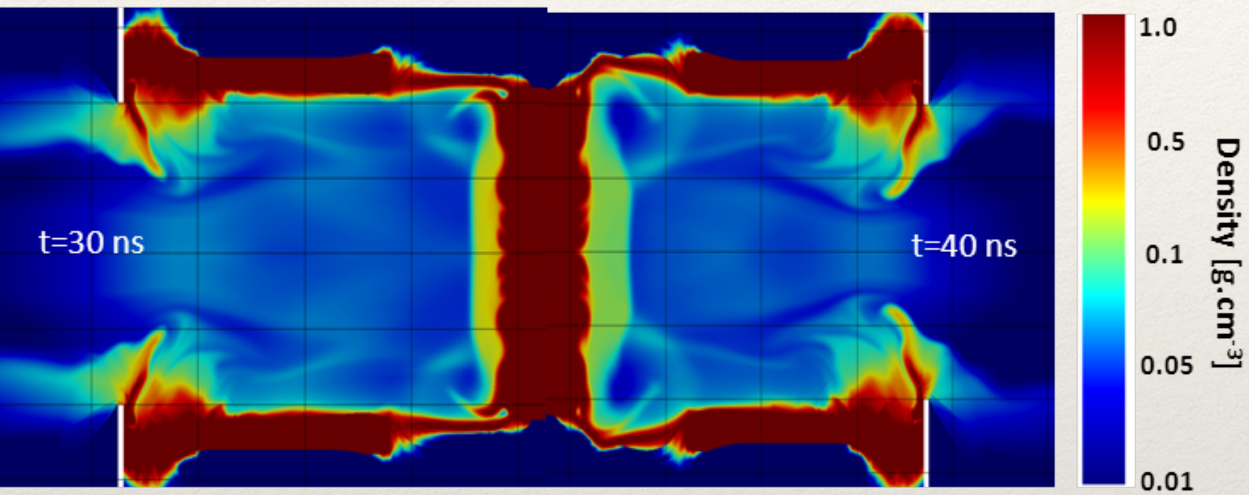
Albertazzi et al. (2018)]

Towards full similarity : LMJ

Emeric.Falize@CEA.fr

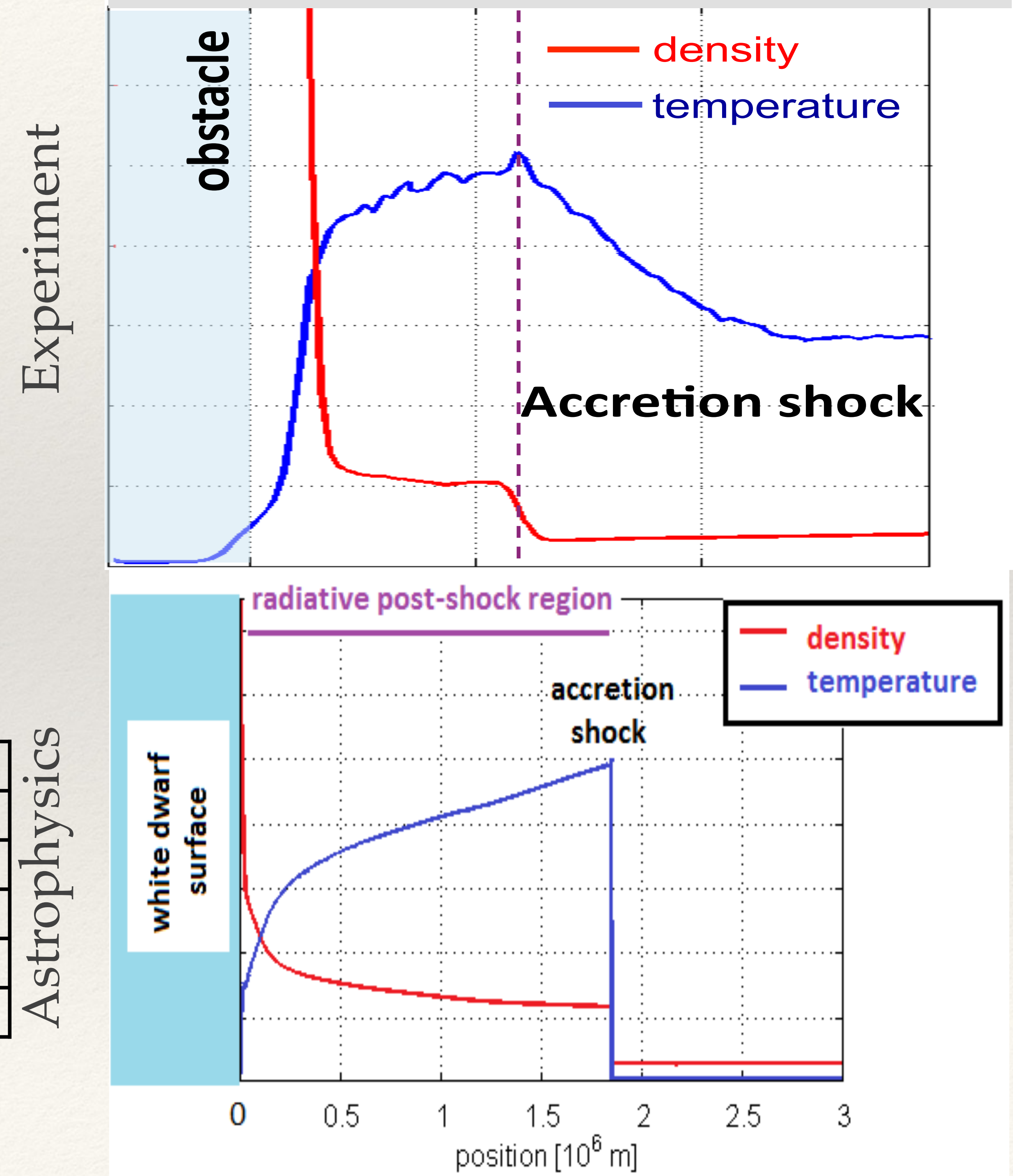
Radiative zone 0.01 $g.cm^{-3}$ - 120 eV

Required regime according to the scaling laws



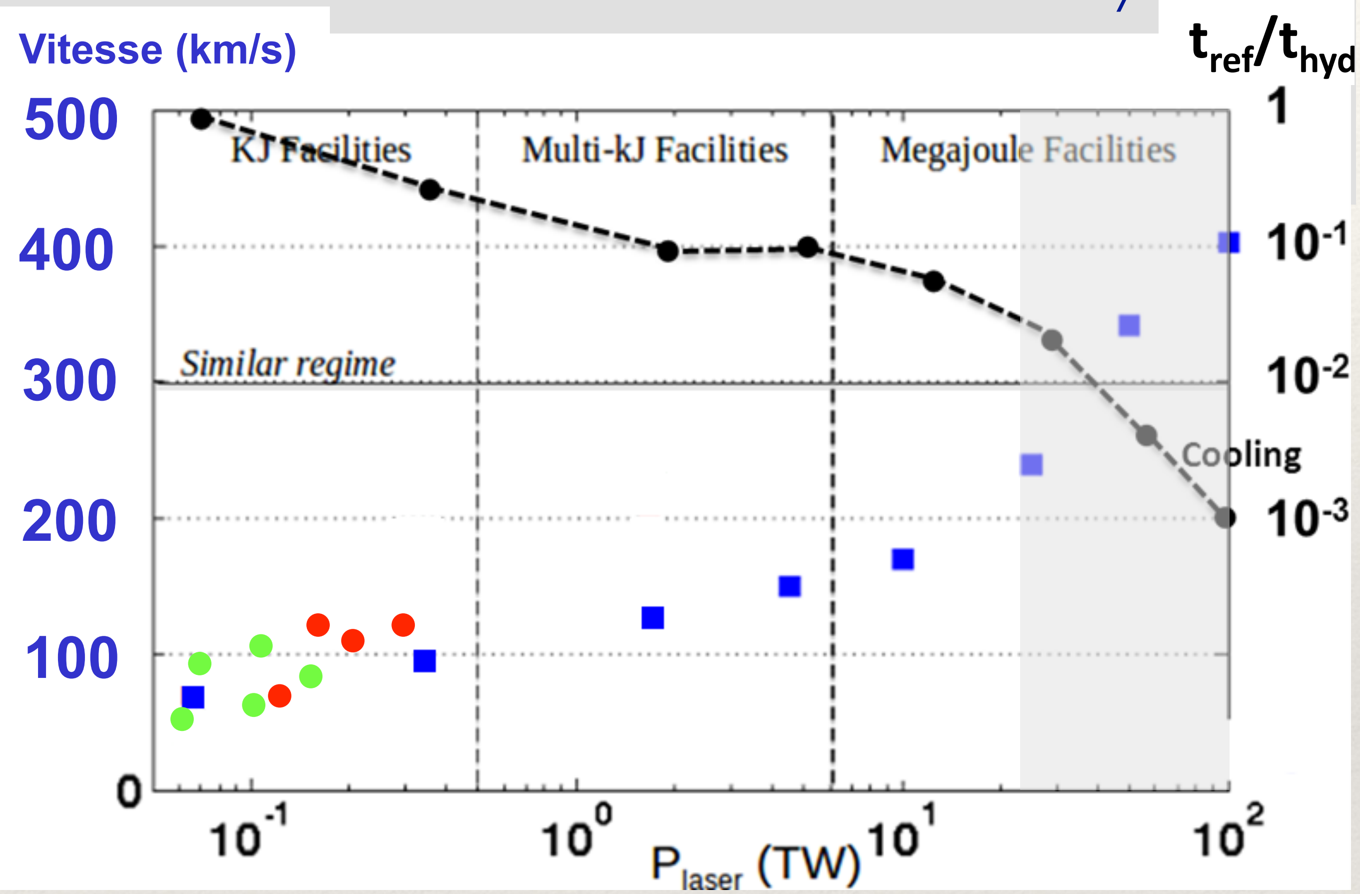
Fluid parameter	Astrophysics	MJ experiment
Velocity ($km.s^{-1}$)	1000	300
Density ($g.cm^{-3}$)	10^{-8}	0.01-0.05
Temperature (eV)	10^4	100-130
Mach number	> 10	**10**
X parameter	10^{-3}-10^{-1}	**10^{-2}**

Density and temperature profiles

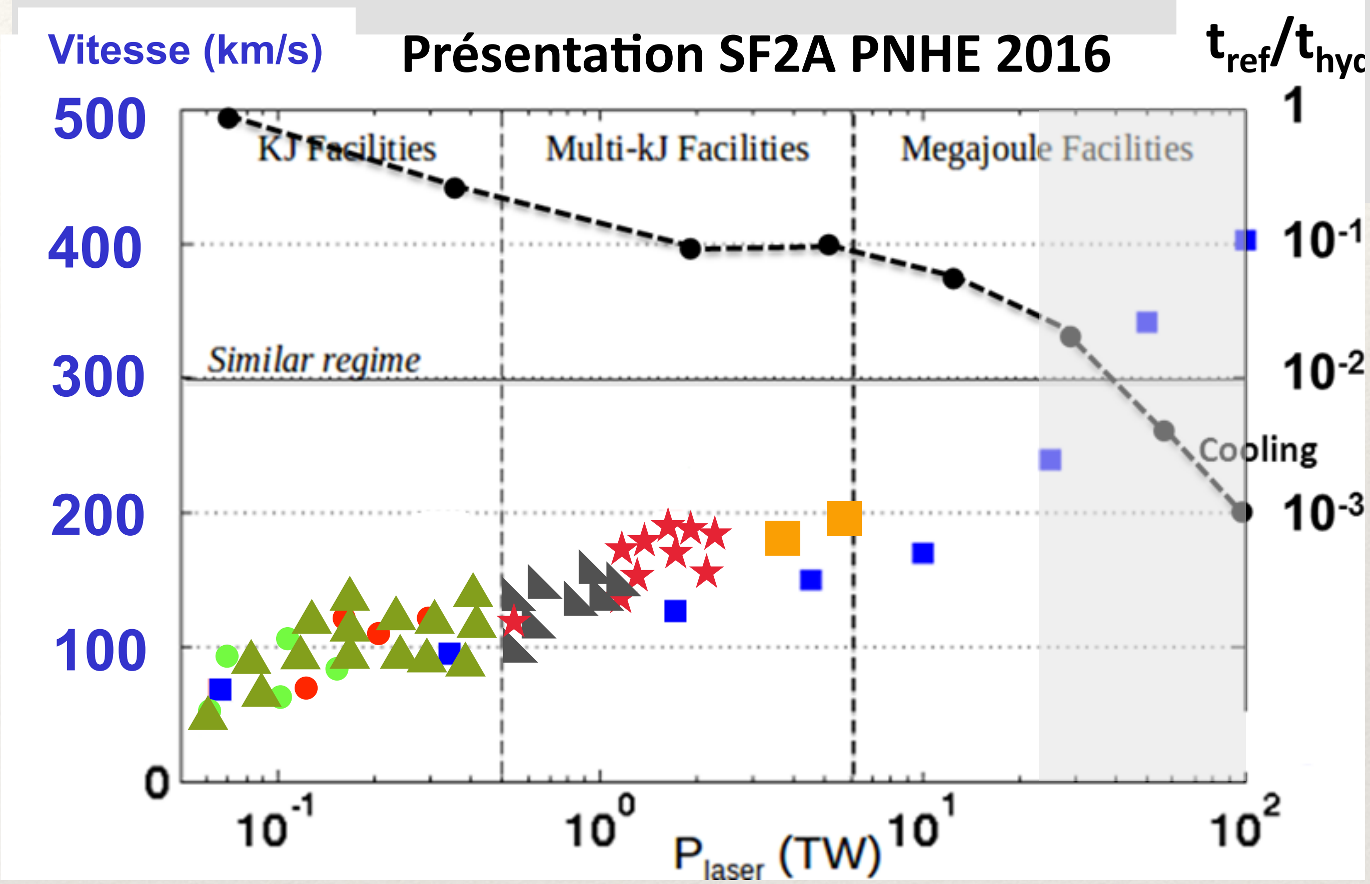


Wide impact on the community

2011: 8 shots on 1 facility



2016: 55 shots on 4 facilities worldwide



Conclusion

- Laboratory astrophysics is a very active field in France (more and more labs involved)

- Started over two decades ago, it evolves very rapidly :
  - New tools (e.x. strong pulsed magnetic fields)
  - New facilities (XFELs, PETAL-LMJ, Apollon)
  - New exciting experiments

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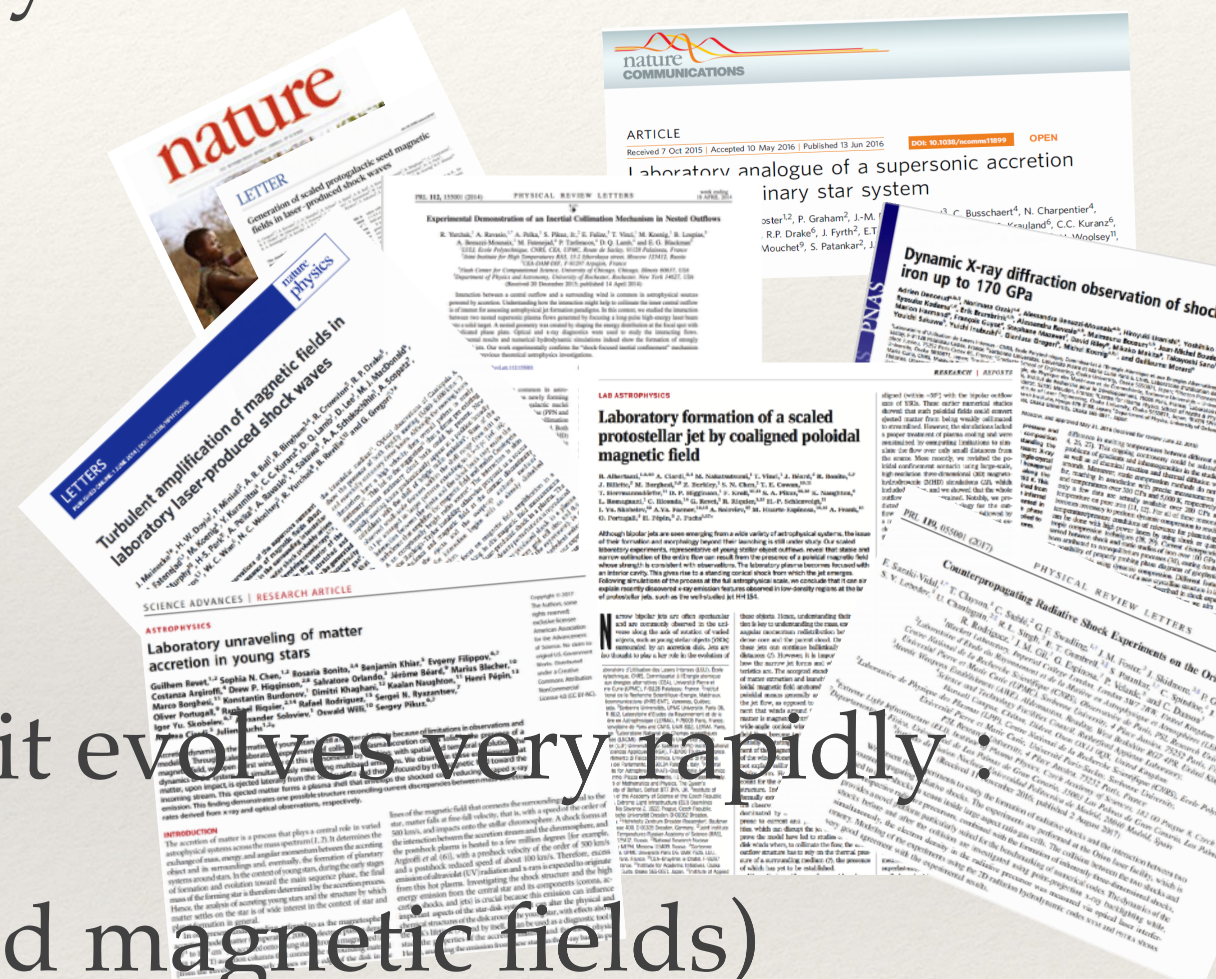

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