Results on laser compression experiments for warm dense matter study in the domain 1-10 Mbar

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Workshop ESRF: studies of Dynamically COmpressed MAtter with X-rays 29-30 March 2017

Goal of the talk

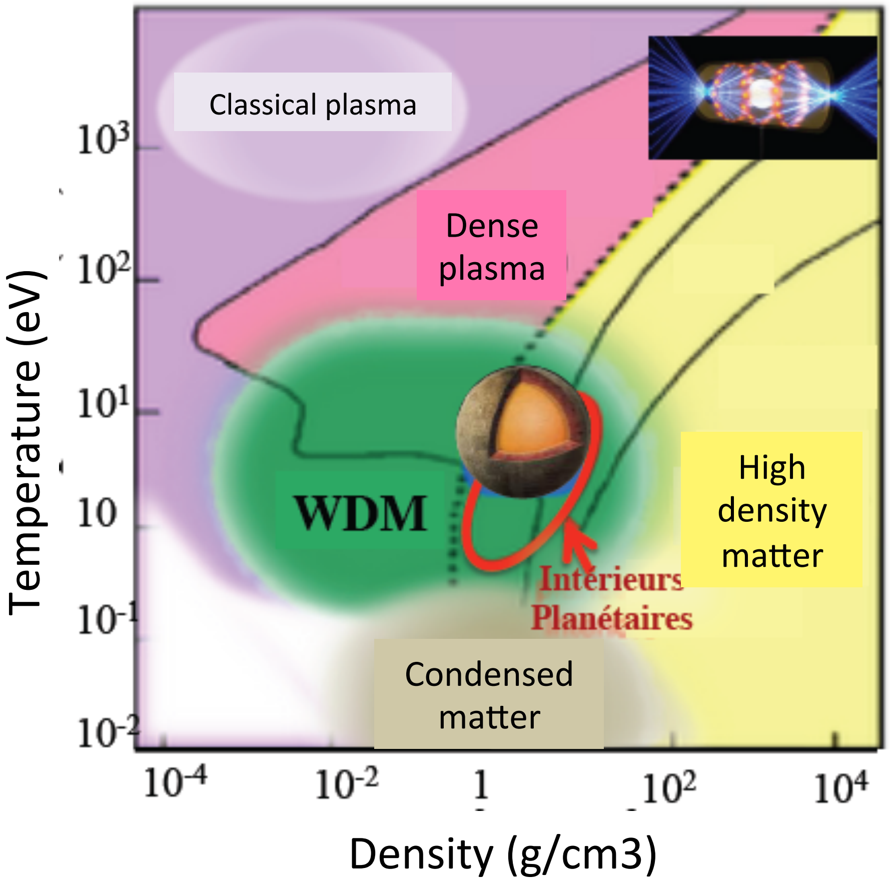
- ✓ To give a short overview of results and works in progress of our team using laser compression

- ✓ To give a good basis for discussions to establish future directions in the context of High Power Laser Facility at ESRF

Outline

- ✓ Context (WDM -> planetology).
  Main challenges: microscopic studies and get-off Hugoniot states
- ✓ Electronic and ionic structural changes study : Laser shock coupled to XANES diagnostic
- ✓ Detection of phase transitions : decaying shock using visible diagnostics and laser shock coupled with X-ray diffraction
- ✓ Brief review of different techniques to get-off Hugoniot states
- ✓ Perspectives in the context of HPLF

Warm Dense Matter regime



$0.1\ \rho_{solide} < \rho < 100\ \rho_{solide}$

$0.1\ eV < T < 100\ eV$

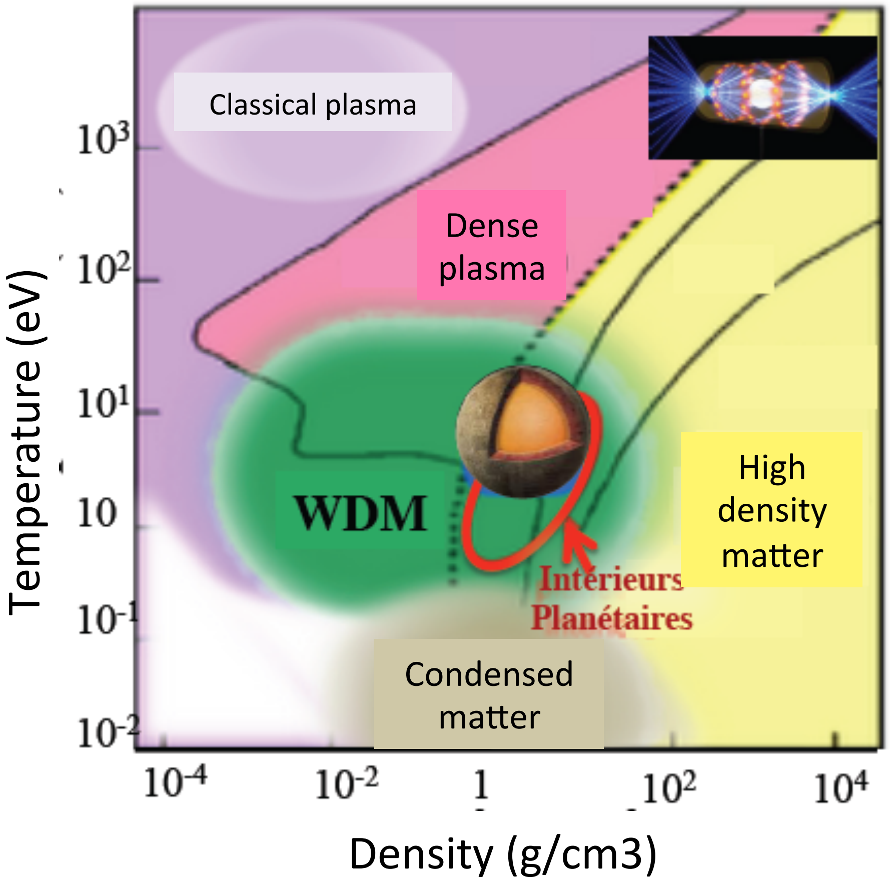
WDM is the state at the intersection between plasma physics and condensed matter physics.

Difficult to simulate -> today ab initio calculations , but they must be validated experimentally

An accurate study of WDM matter has important repercussions in high pressure physics and planetology

The challenges ……

In the last 20 years, a lot of Hugoniot data



-> **Microscopic studies** (i.e. phase transitions, structural information etc..) are today necessary

Test calculations approximations

High pressure physics and planetary models

-> Develop compression techniques to **reach extreme states of matter off the principal Hugoniot to span a large region of the phase diagram** is today necessary

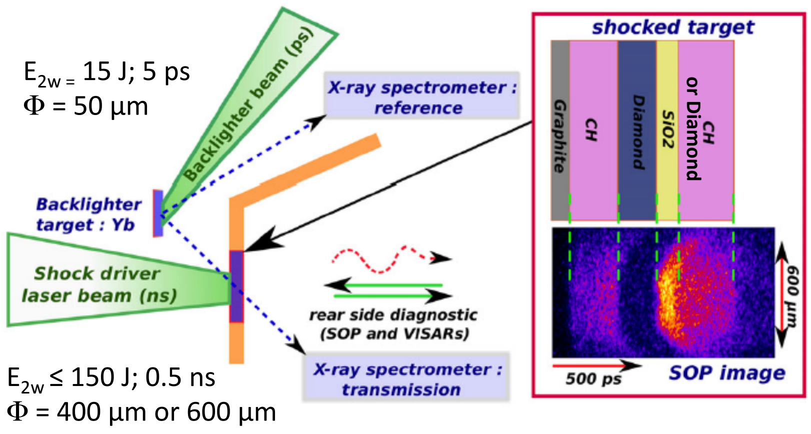
Electronic and ionic structural changes study

(laser shock coupled to XANES diagnostic experiment)

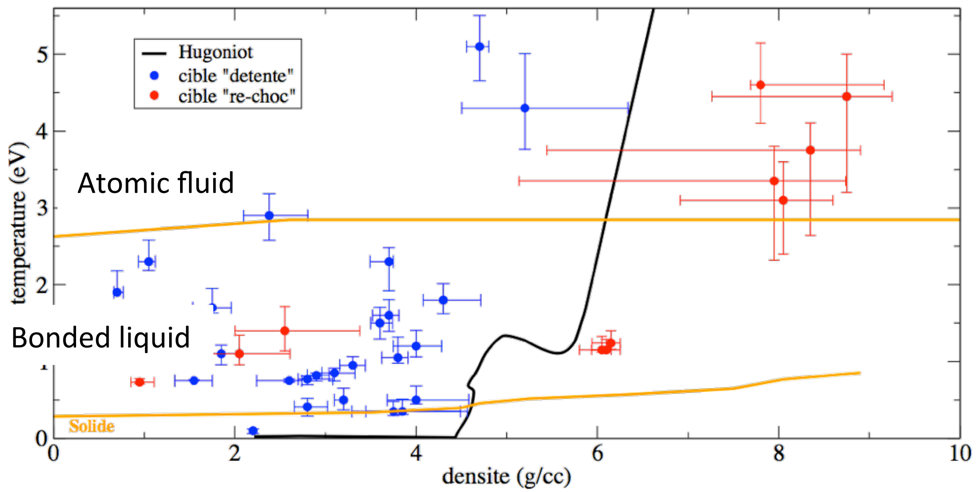
Work on shocked SiO_2 with XANES diagnostic

LULI and LLNL experiments

X-rays Absorption Near Edge Spectroscopy



Many probed conditions in WDM range



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PLANETLAB

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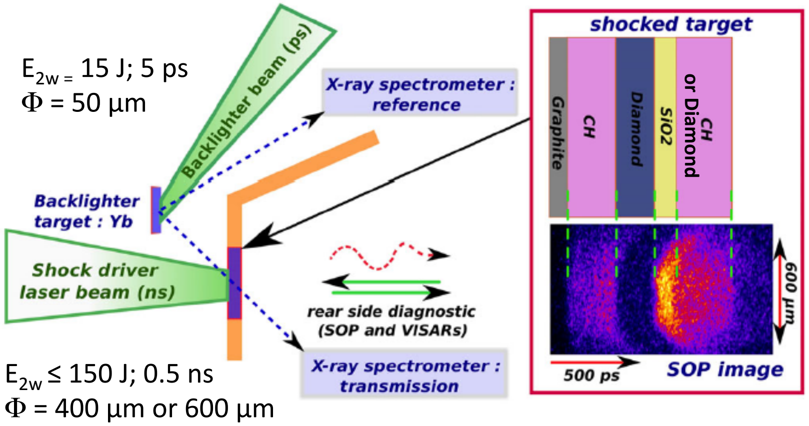

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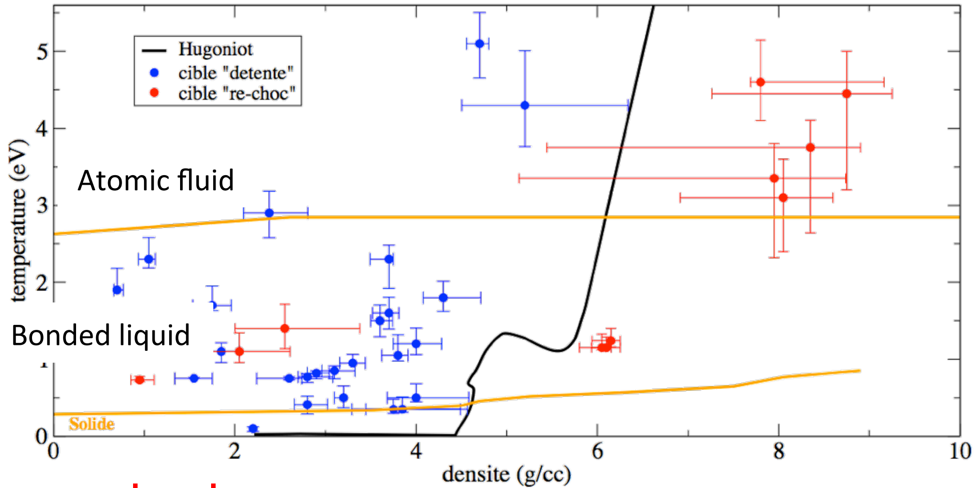
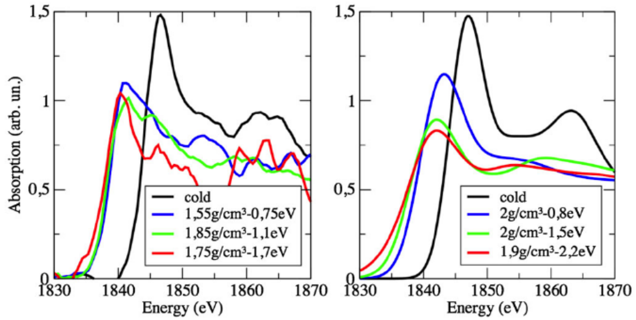


Metallization mechanism : allowed energy levels become available in the gap → pseudo-gap is formed

Denoeud et al PRL 2014

In the liquid phase the coordination number increases with density

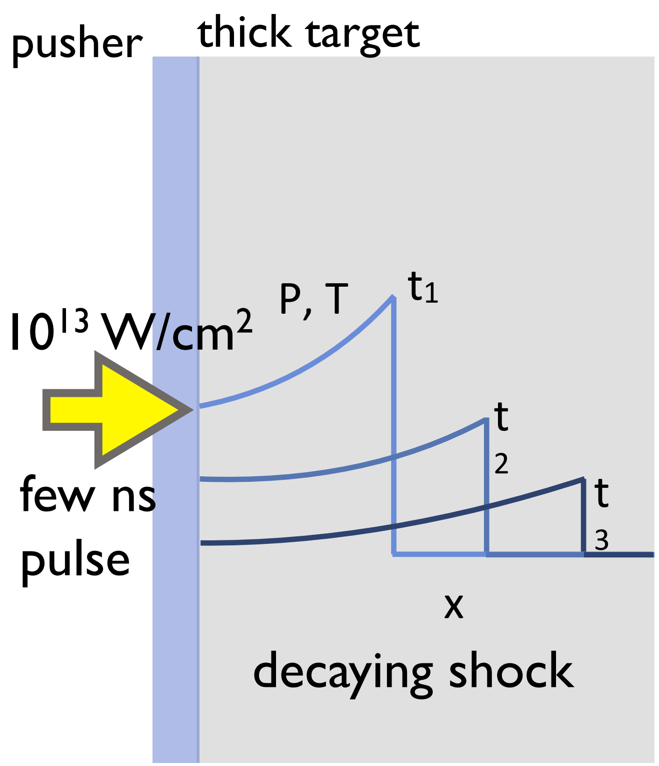
Denoeud et al PRE Rapid Com. 2016



Detection of phase transitions

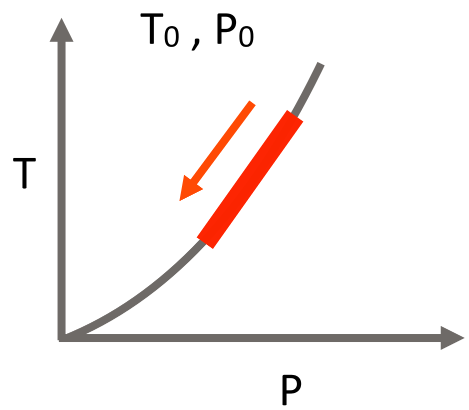
(decaying shock using visible diagnostics and laser shocks coupled with X-ray diffraction)

Decaying shocks to detect phase transitions

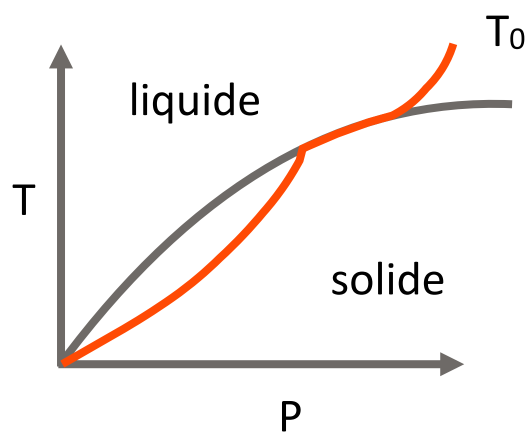


(e.g. Hicks et al PRL 2006; Millot et al. Science 2015; Spaulding et al etc..)

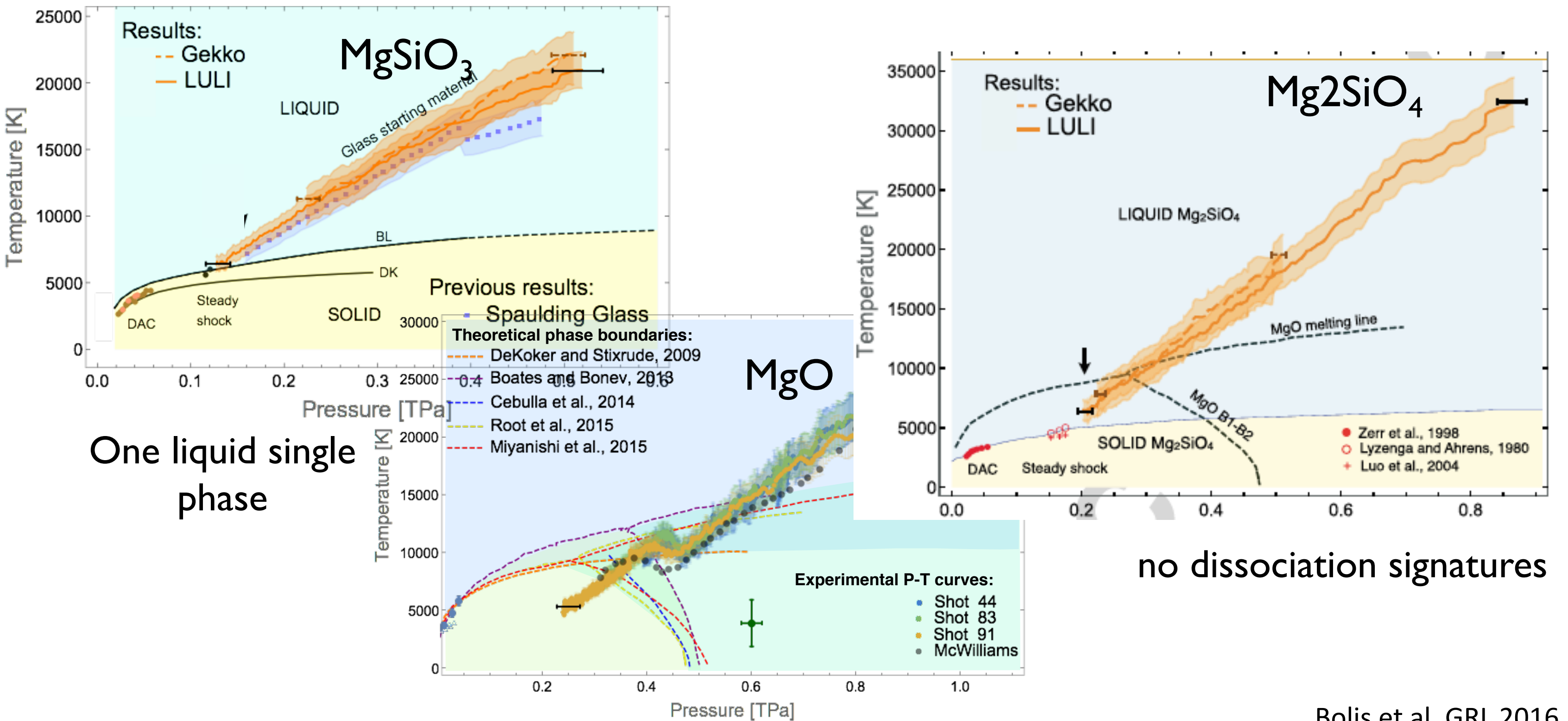
With one shot you explore a segment of the Hugoniot



If the shock crosses a phase boundary:



Recent results on $MgSiO_3$, MgO, Mg_2SiO_4



One liquid single phase

Melting at 4.7 Mbar

no dissociation signatures

Bolis et al. GRL 2016

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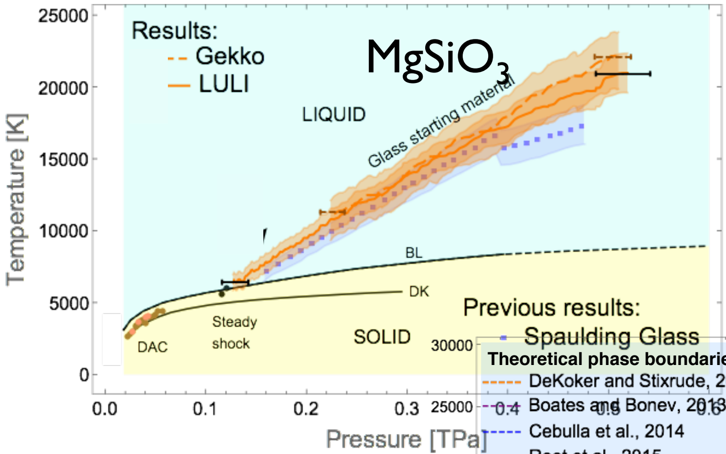

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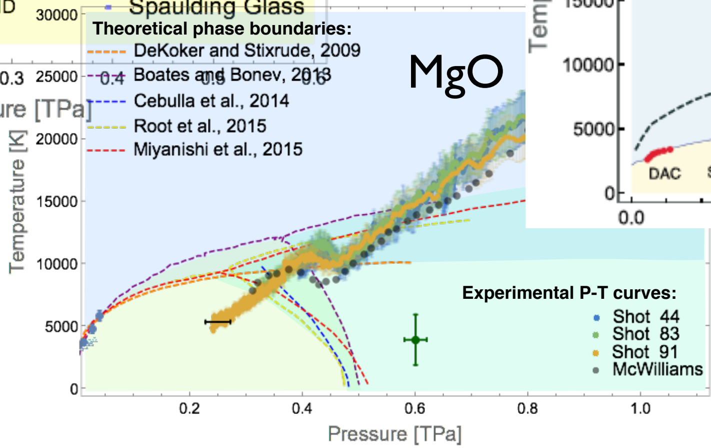

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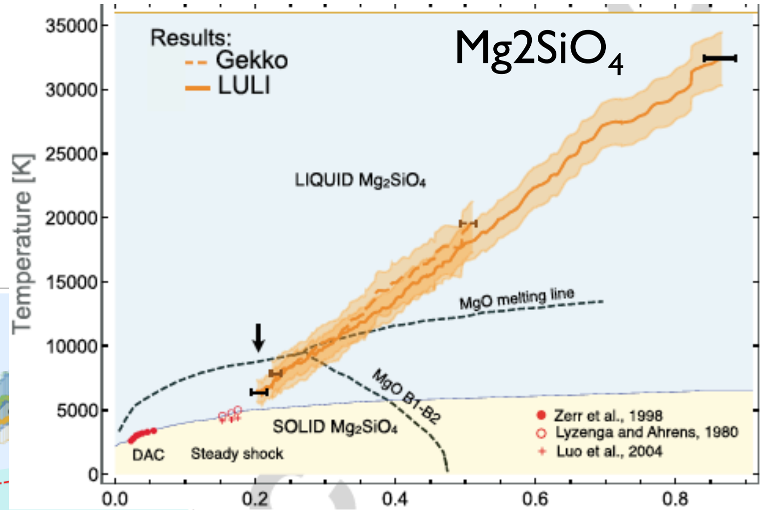

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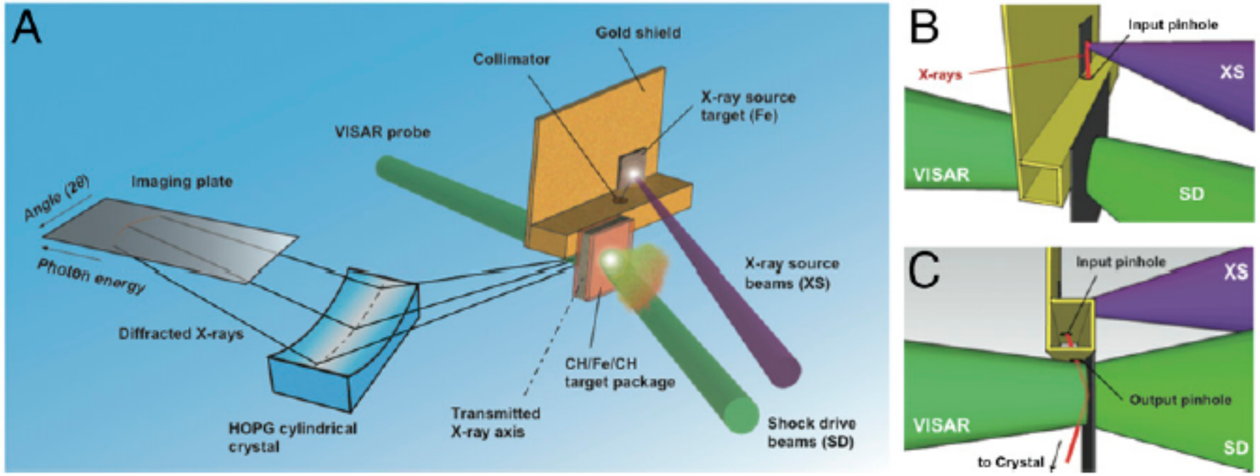
Good results, but
- phase transitions with small volumes changes could be missed
- it is necessary to be very careful to hydrodynamics effects

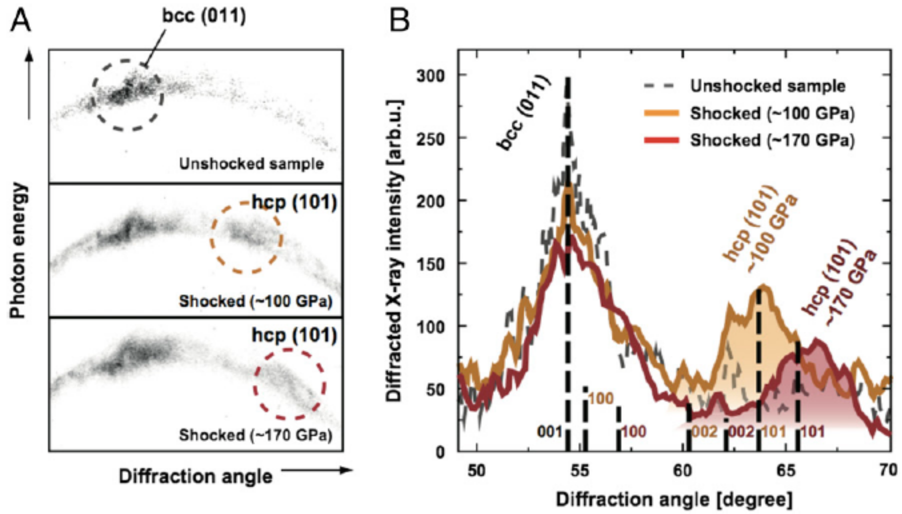
-> <u>X-ray diffraction is essential to have a direct information on phase</u>

X-ray diffraction experiment using X-ray laser sources



Previous works on iron:
Kalantar et al PRL 2005

Backlighter : 9 beams (2.5 ns) E_{tot} = 1.1 kJ (3ω)
Drive beams : 3 beams (2.5 ns) E_{tot} = 400 J (3ω), 1 mm focal spot, 10^{12}-10^{13} W/cm2



The results show the presence of hcp iron up to 1.7 Mbar along the Hugoniot.

A. Denoeud et al. PNAS (2016)

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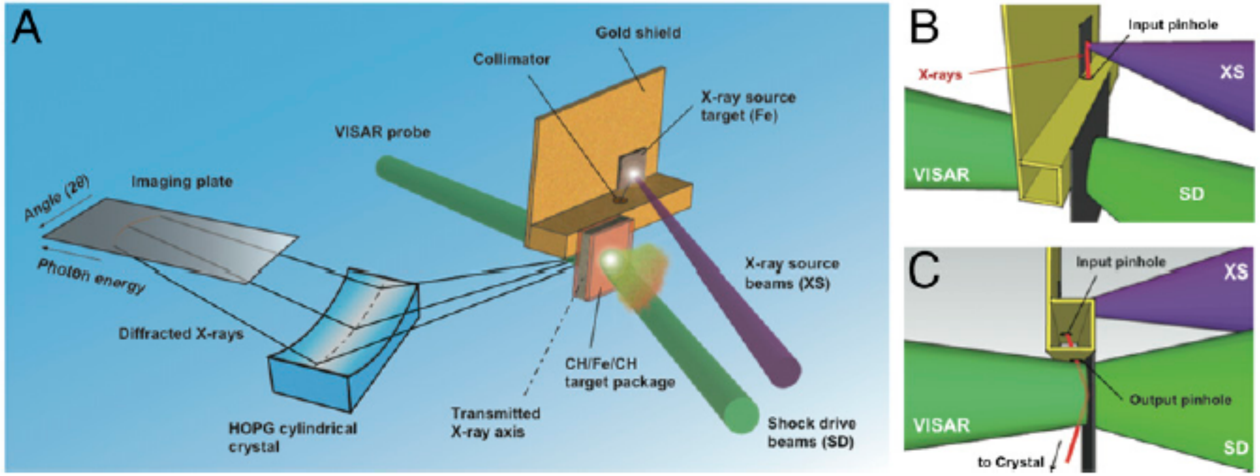

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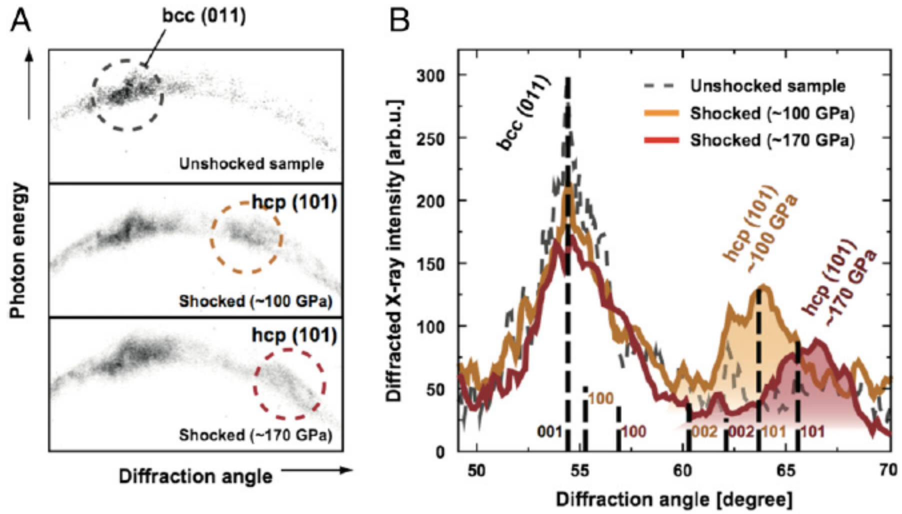

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X-ray laser sources

Main constraint for X-ray laser source:
to have enough photons -> high energy laser

Some examples : X-ray diffraction at Omega 4-10 beams (≈ 400 J each), 1ns
(Rygg et al. RSI 2012)
: EXAFS at Omega on iron -> 50 laser beams (≈ 400 J each)
in implosion configuration (Ping et al PRL 2013)

Critical points : divergence, max energies limited to 10keV

-> **Today Synchroton radiation or XFEL are a great opportunity to have very clean X-ray data on Warm Dense Matter**

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↓

How to span a large part of the phase diagram ?

Getting off Hugoniot states

(different techniques and constraints)

Techniques to reach off the principal Hugoniot states

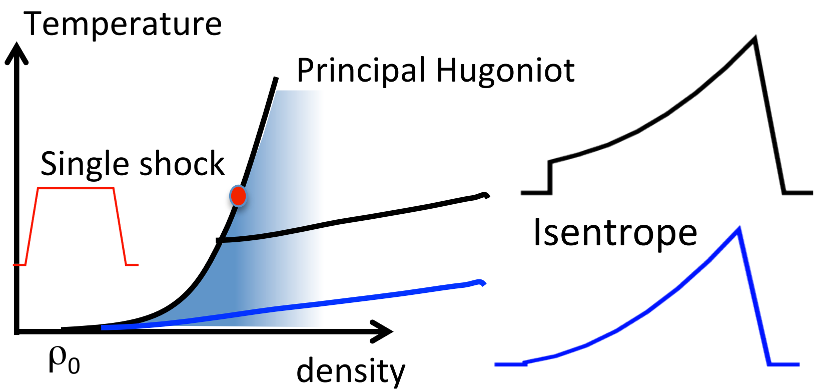
Techniques to reach high pressure states colder than Hugoniot

- ✓ Quasi-isentropic compression

- ✓ Laser shock on Diamond Anvil Cell (DAC) precompressed target

- ✓ Double shock, reverberation, reshock, ramp on confined targets

Quasi-isentropic compression



long pulses and high laser energy (>KJ) are necessary

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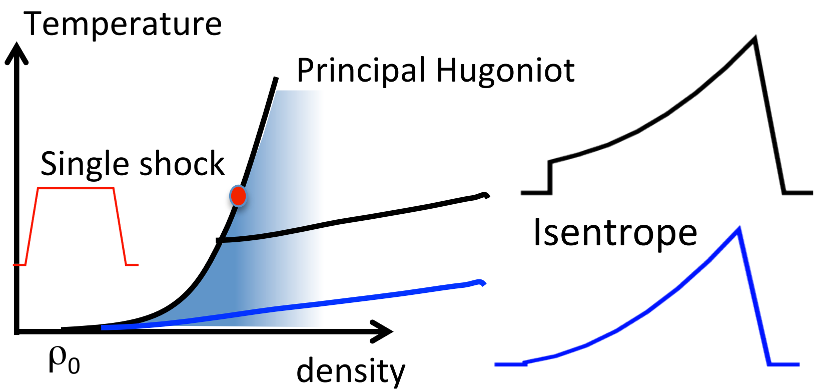

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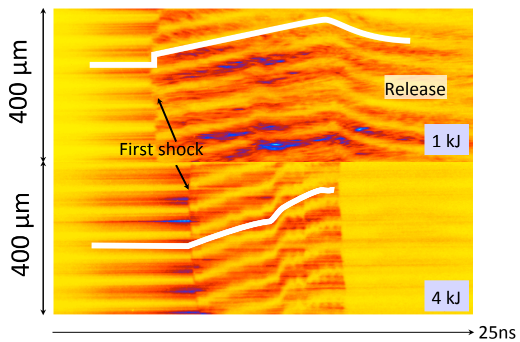
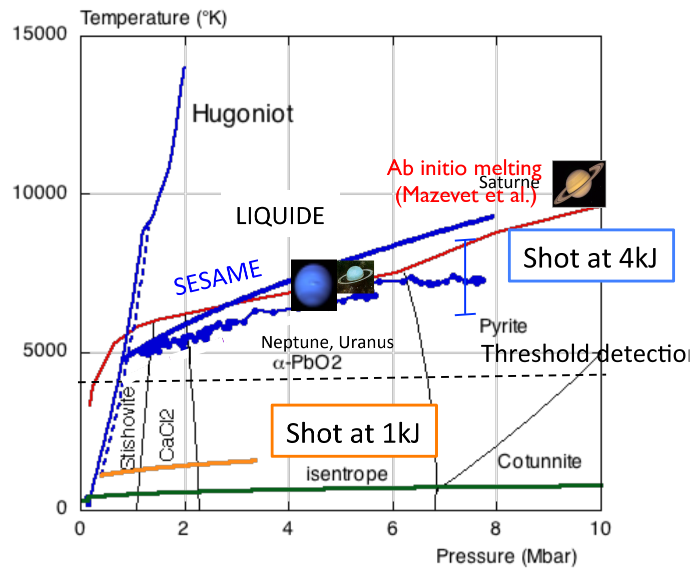
EXPERIMENT at LIL on iron and SiO_2



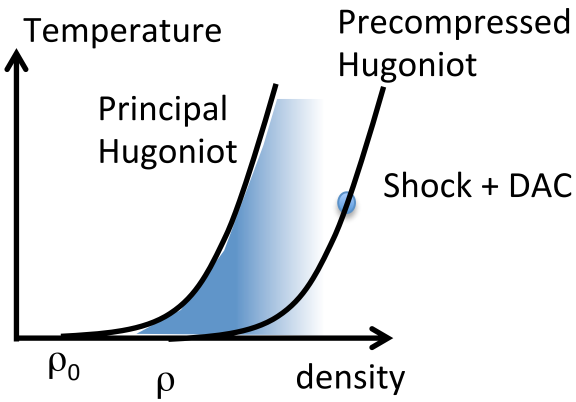


LIL -> 6-8 Mbar iron and SiO_2

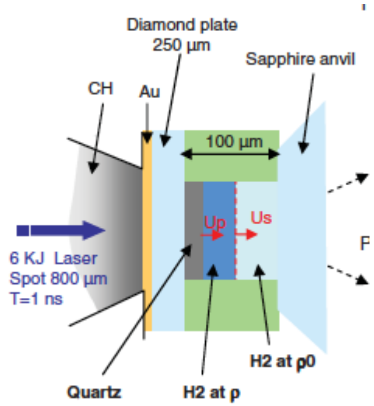
(N. Amadou PoP 2015;
A. Benuzzi et al Phys Scripta 2014)

Other works : NIF -> 50 Mbar in the diamond (Smith et al. 2014)
OMEGA -> 8 Mbar in the diamond (Bradley et al.PRL 2009)

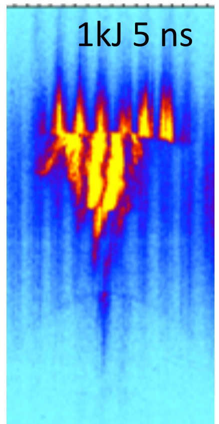
Laser shock on DAC precompressed target



OMEGA laser-> precompression up to several tens of kbar (Loubeyre et al. 2014)



LULI, recently tested with NH_3 precompression up a few kbar

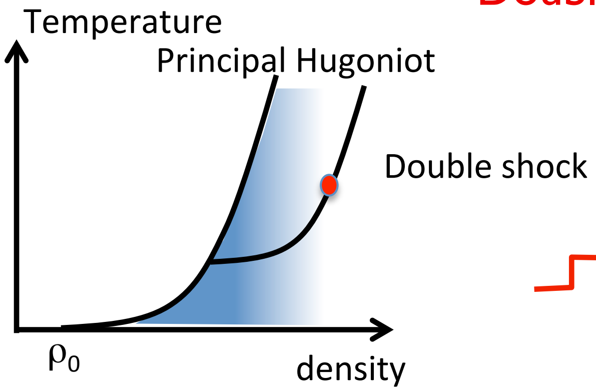


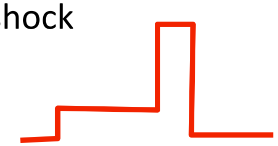
ANR Pompei
In collaboration
with CEA and IMPMC

Constraint: **high laser energy (≥ 1 kJ)**

Double shock, reverberation technique or reshock ....

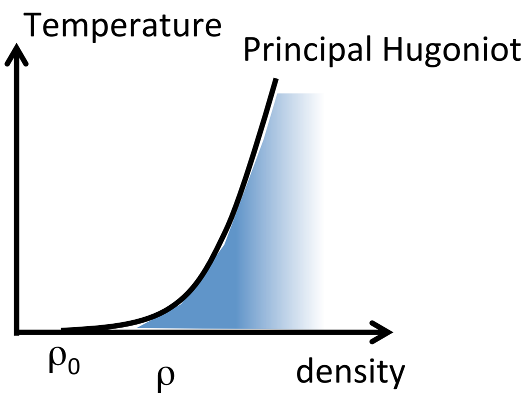
Double shock

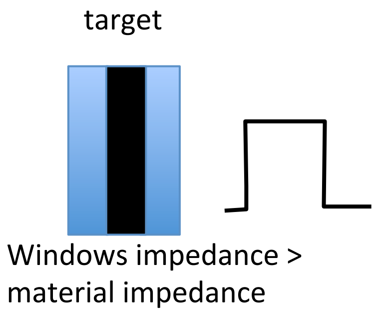




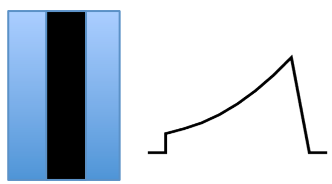
« Dynamic precompression »:
Constraints : an excellent control of timing and of precompressed matter

Reverberation or reshock





Ramp compression on confined target



Complex thermodynamical path. Thermodynamics conditions can be obtained using rear side diagnostics coupled to hydrodynamical simulations.

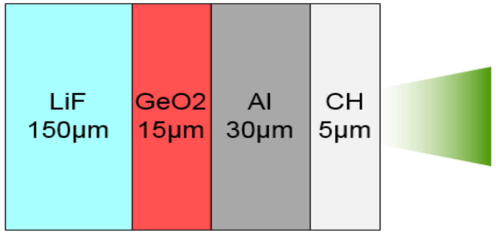
these techniques can be used with a laser of moderate energy (100 J)

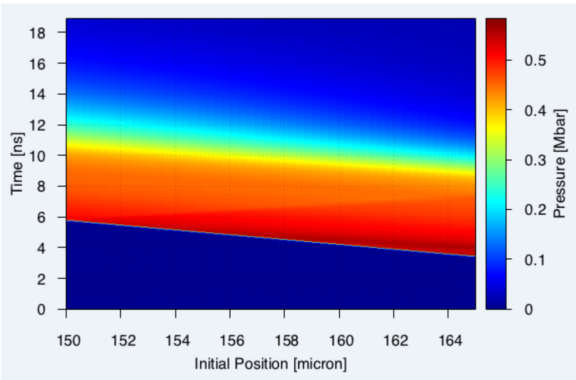
Some perspectives for HLPF

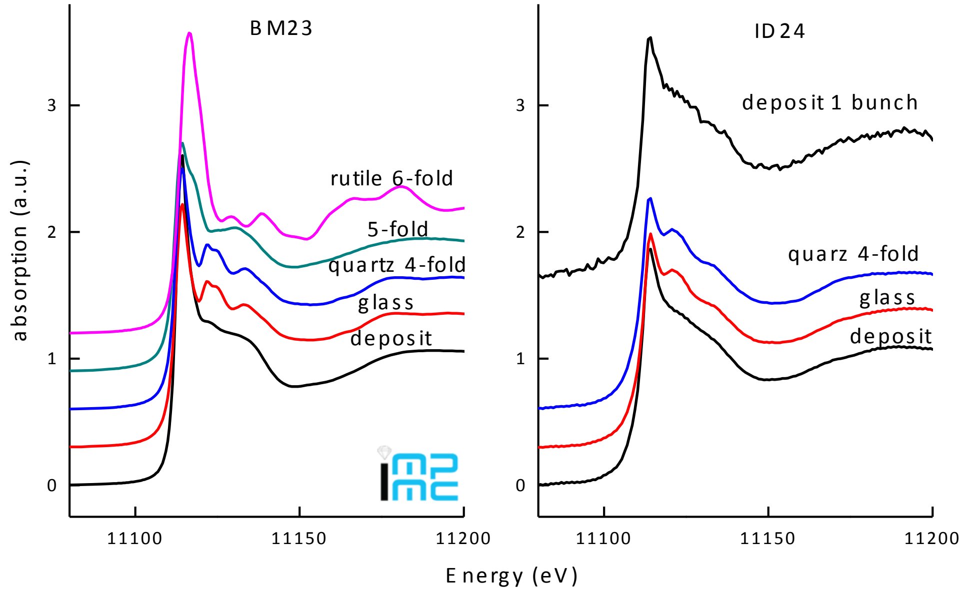
Perspectives at short term: EXAFS experiment on shocked GeO_2

GeO_2 is chemical and structural analogue of SiO_2, a major component of earth's interior

R. Torchio, S. Pascarelli, O. Mathon
LULI and CELIA







- phase transitions
- metallization
- Re-crystallation

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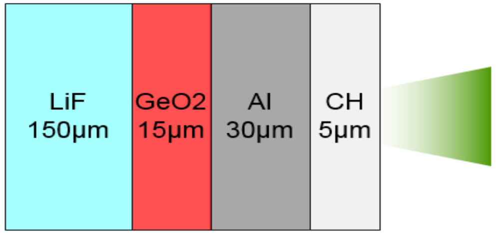

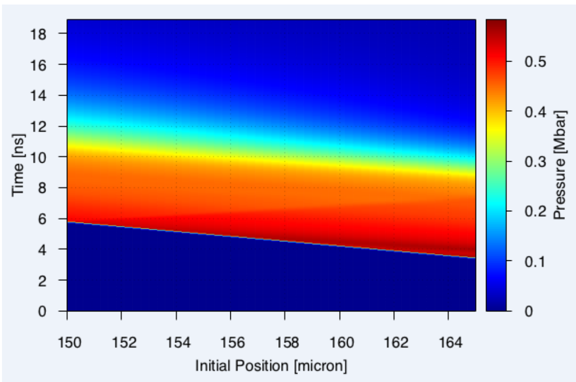

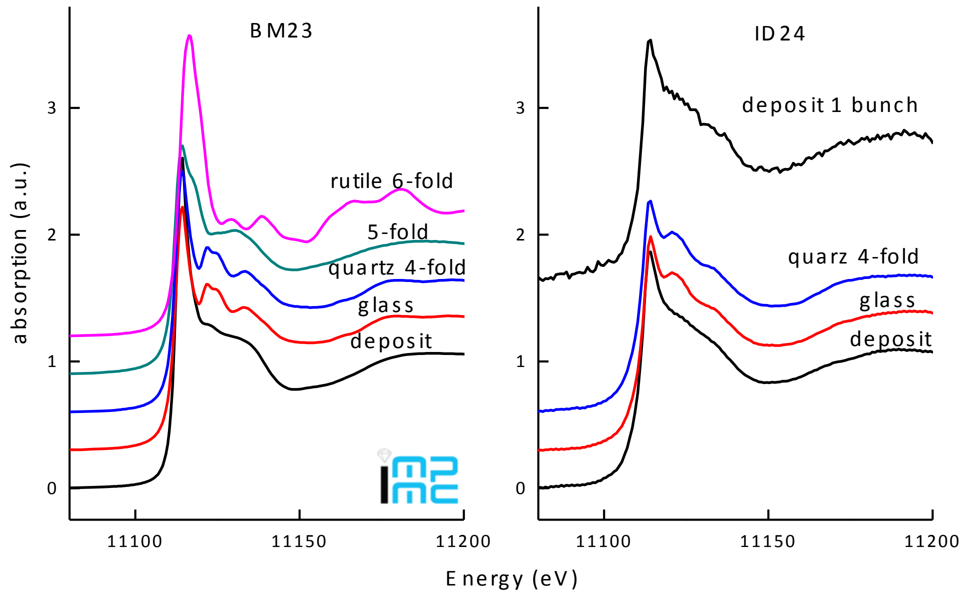

- phase transitions
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- Re-crystallation

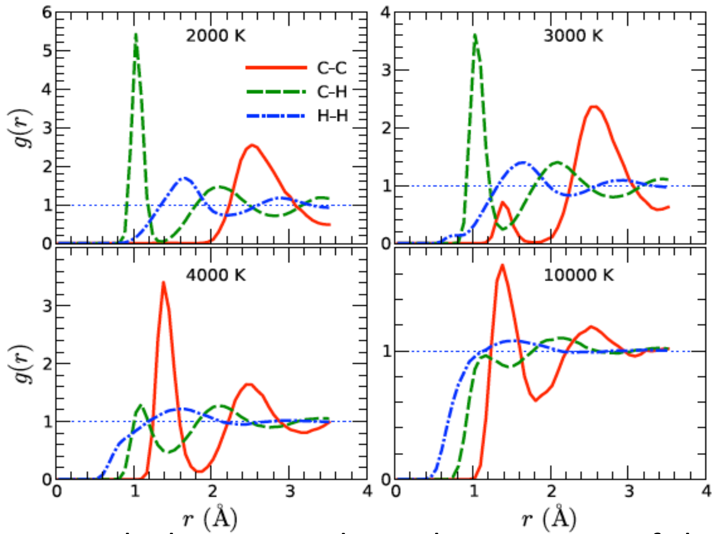
Other materials interesting to investigate : olivine (Mg_2FeSiO_4) or MgFeO

Perspectives at long term: study of H_2O/NH_3/ CH_4

ANR POMPEI

The context -> icy giant planets, Uranus and Neptune (2/3 of their mass)

The states of matter, equations of state, transport, chemical and structural properties of the $H_2O/CH_4/NH_3$ system are basically unknown at extreme conditions.



Sherman et al. 2012

Ab initio calculations predict polymerization of shocked CH_4

Targets are the challenge

-> shock + X-ray diffraction/scattering

Some points for discussion

HLPF opens a great oppurtunity for Warm Dense Matter microscopic characterization

Beside X-ray diagnostics, laser compression must be caracterized by indipendent diagnostic (SOP and VISAR)

Interesting data along the Hugoniot states up to ≈ 10 Mbar will be « easily » obtained with 100 J laser.

Concerning off Hugoniot states, some constraints exist. To keep low temperatures and high pressures is not trivial, but possible with reverberation, multiple shocks etc... The range of pressures is specific to each design of target

It is important to have different X-ray diagnostics simultaneously

Thank you for your attention and thank you to collaborators

R. Bolis, A. Ravasio, T. Vinci, A. Denoeud, E. Brambrink, M. Guarguaglini, M. Koenig
LULI

F. Dorchies, J. Gaudin, P.M. Leguay *CELIA*

G. Morard, F. Guyot, F. Datchi, S. Ninet, M. Harmand, G. Fiquet *IMPMC, UMPC*

S. Brygoo, F. Occelli, P. Loubeyre *CEA*

N. Ozaki, R. Kodama, *Un of Osaka*

T. Sekine *Un of Hiroshima*

S. Mazevet, R. Musella *LUTH*

J. Bouchet, F. Remus, V. Recoules *CEA*

S. Le Pape, R. Smith *LLNL*

S. Pascarelli, R. Torchio, O. Maton *ESRF*

Thank you to the laser and technical staff of laser facilities

ANR SECHEL, PLANETLAB and POMPEI