ELISS2023

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Dolní Břežany, Czech Republic

Laboratory astrophysics:

Studying planetary interior conditions by laser-driven shock compression

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IMPULSE

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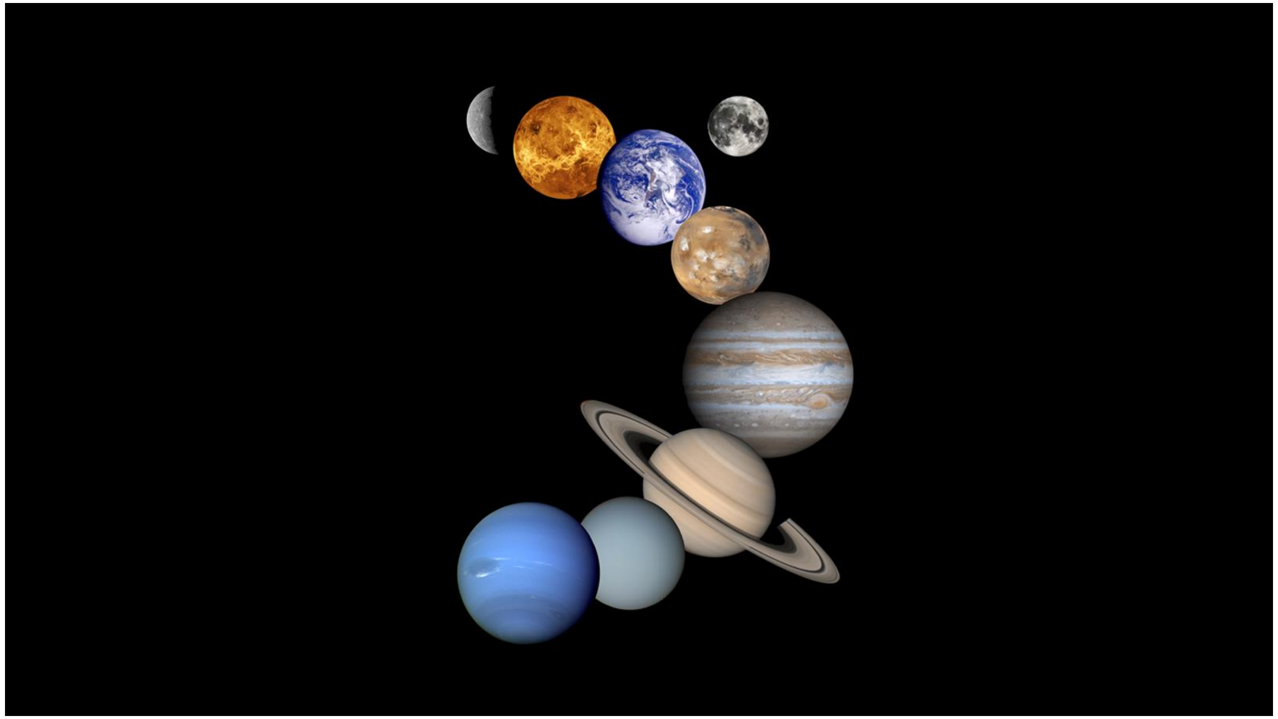
NASA

Structure

- Why we do Laboratory Astrophysics
- How we do Laboratory Astrophysics
  - Theoretical Framework
  - Experimental Setup
  - Targets
  - Diagnostics
- Our Research
- Summary



Why we do Laboratory Astrophysics

Exoplanets

Over 5000 exoplanets confirmed so far by telescope missions (Hubble, Spitzer, Kepler, JWST, …)

Very limited data experimentally available (size, mass, transit time, some information on upper atmosphere)

Strong need for modeling of exoplanets!

Types of planets

Gas Giants (# 1733)

e.g. Jupiter, Saturn

H / He rich

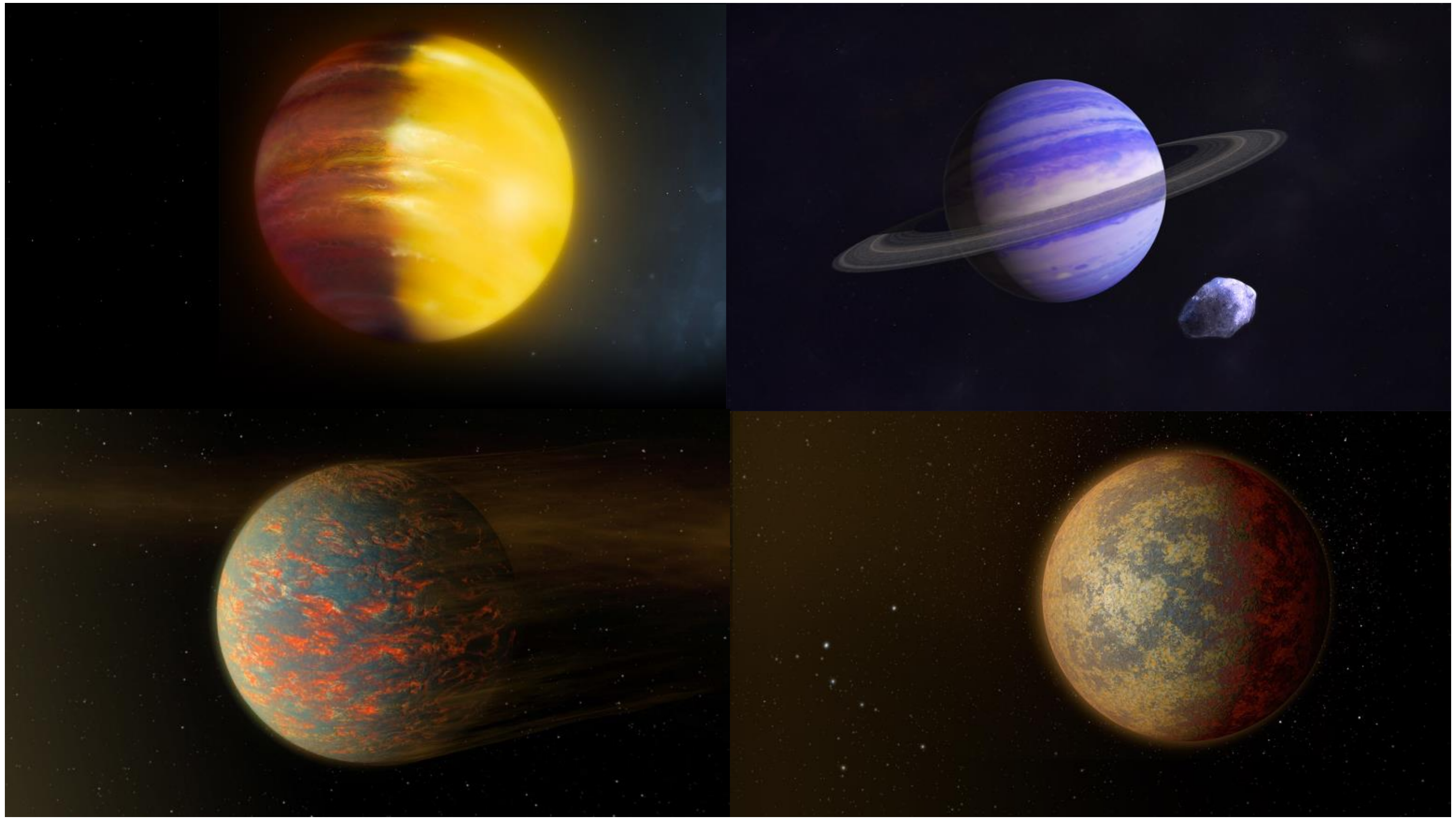
gas planets

$T_{core} < 20{,}000K$

Super Earth (# 1668)

rocky planets

$m < 10\ m_E$



Icy Giants (# 1891)

Uranus, Neptune

H / He rich

solid core

$T_{core} \sim 5{,}000K$

Terrestrial (# 198)

$0.5\ r_E < r < 2\ r_E$

rock / iron

solid / liquid surface

Planet Models

Planetary model

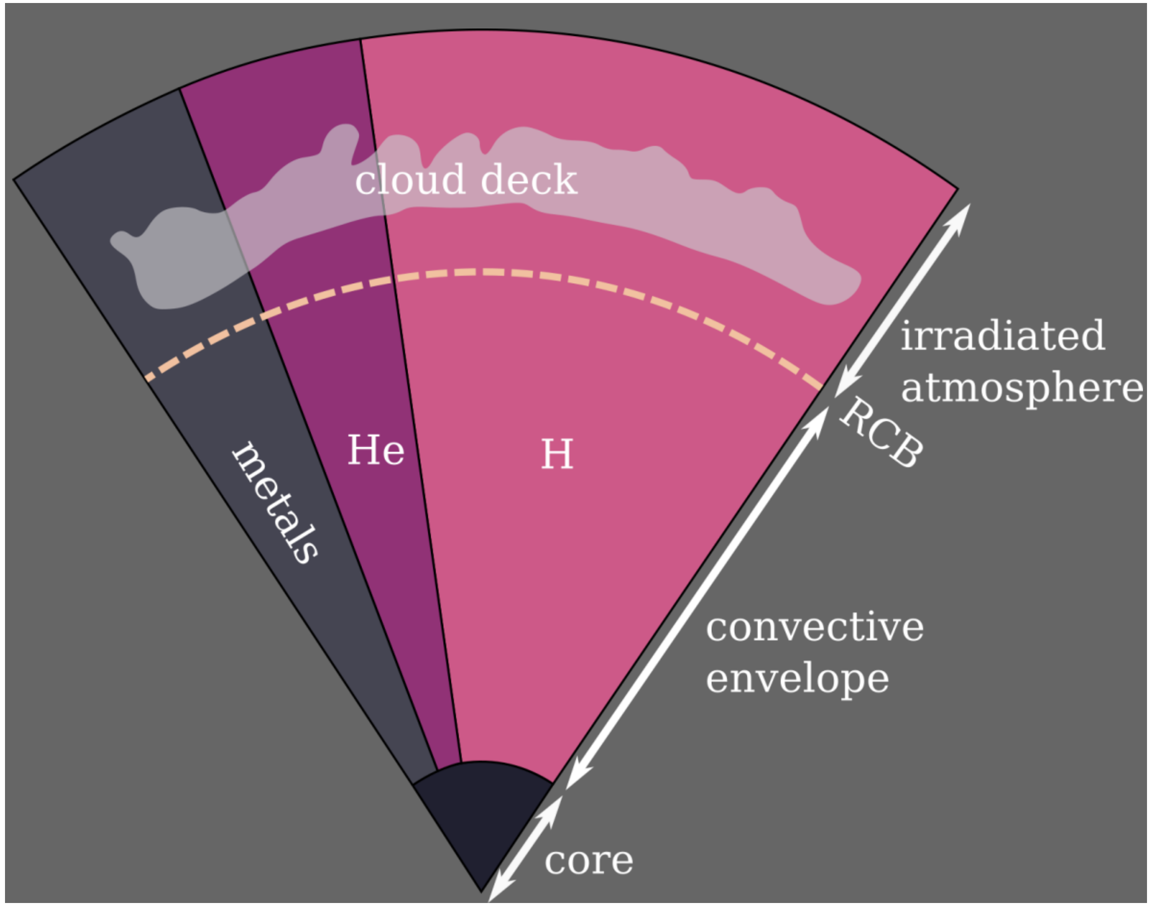


Fig.: Simple 3-layer model of a gas giant with a coupled atmosphere and interior model

Input

???

Output:

Radial profiles: m(r), P(r), T(r), ρ(r)

Input for Models

Assumptions:

Element distribution and composition

Heat transport (internal heat flux, convection, heat sources, ...)

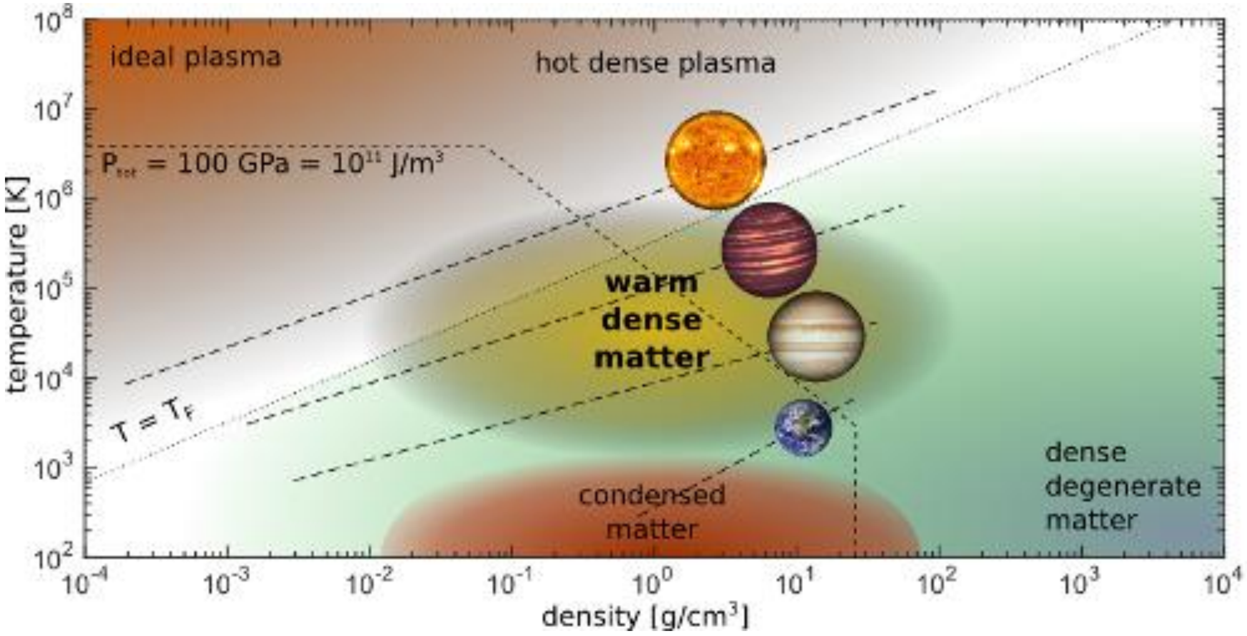
Core properties

Data:

Phase diagrams

Equation of States (EOS)

Transport properties (el. Conductivity, ...)



Measurements!

Example: Evolution of Uranus and Neptune

Temperatures ~ several 1000 K

Pressures ~ several 100 GPa (1Mbar)

We want to know chemistry, EOS, phase diagram, transport properties of these conditions!

→ very difficult to study these pressures!

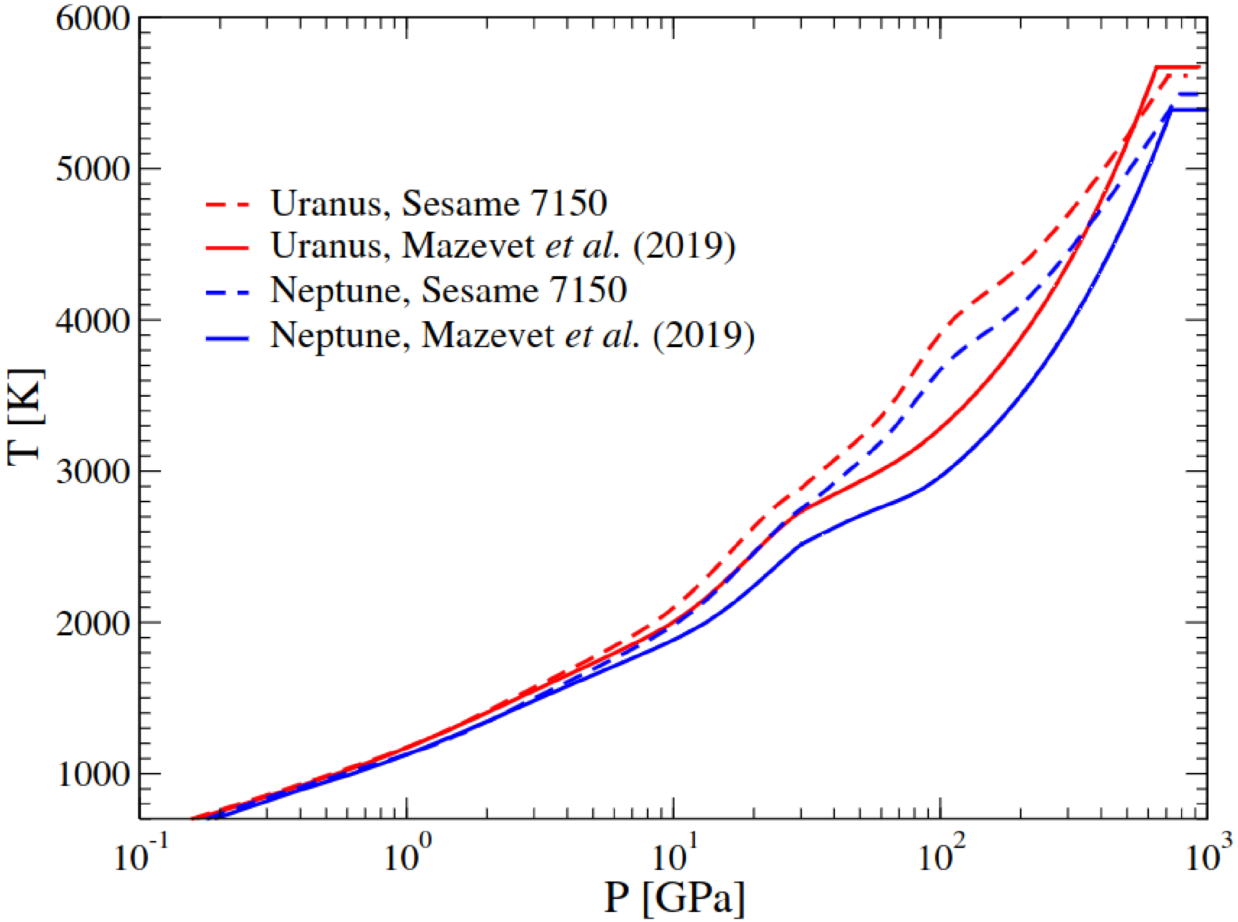


Fig.: Pressure-temperature profiles of Uranus and Neptune
Scheibe et al., A&A **632**, A70 (2019)

Types of measurements we can do

Direct Measurements:

Solar System:

direct observation possible (flight by, satellite probes, …)

available:

mass/radius (bulk density), orbital distance, luminosity, gravitational field, magnetic field, detailed atmospheric composition, central star properties

Exoplanets:

telescope observation

transit information (light curves, transmission spectra), radial velocity

available:

mass/radius (bulk density), orbital distance, limited atmospheric composition, clouds

How we do Laboratory Astrophysics

What do we need for a planet in the lab?

We need:

Elementary composition of planets

Thermodynamic properties of planetary interiors

(high T, very high P)

Sensitive diagnostics for probing these conditions

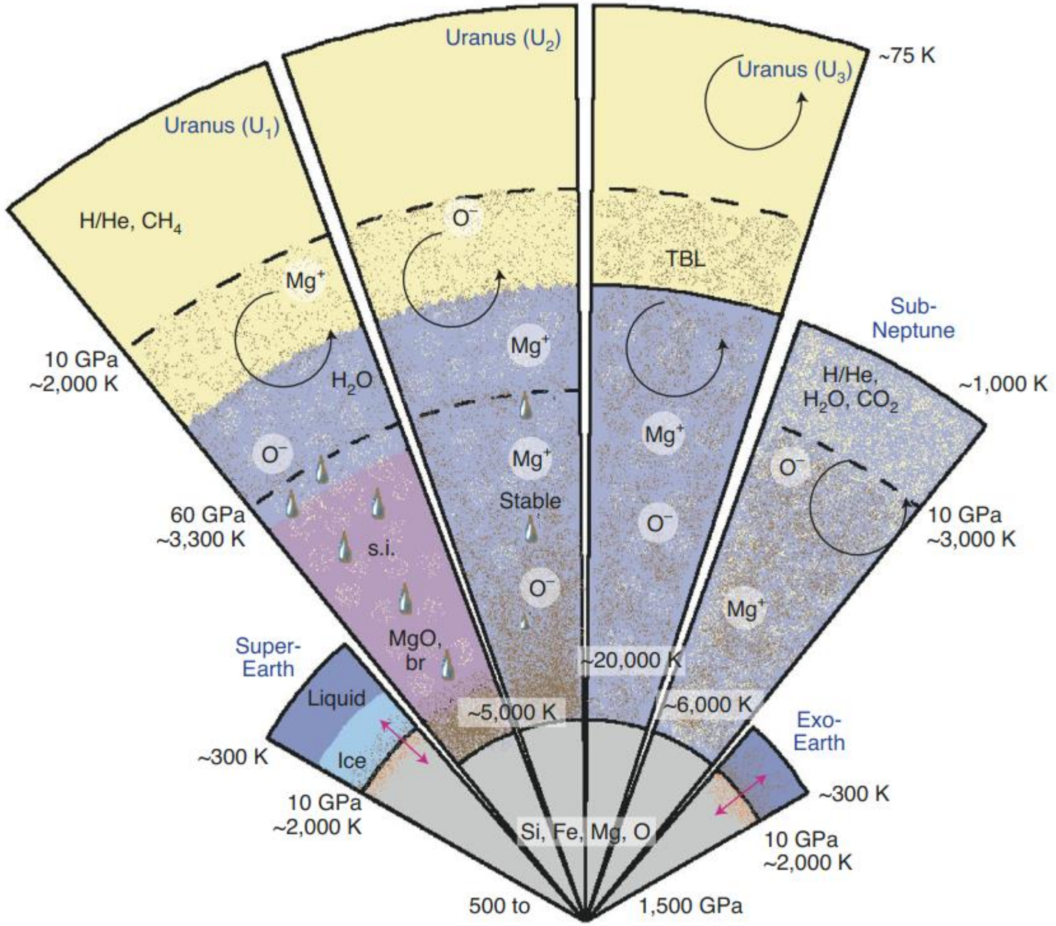
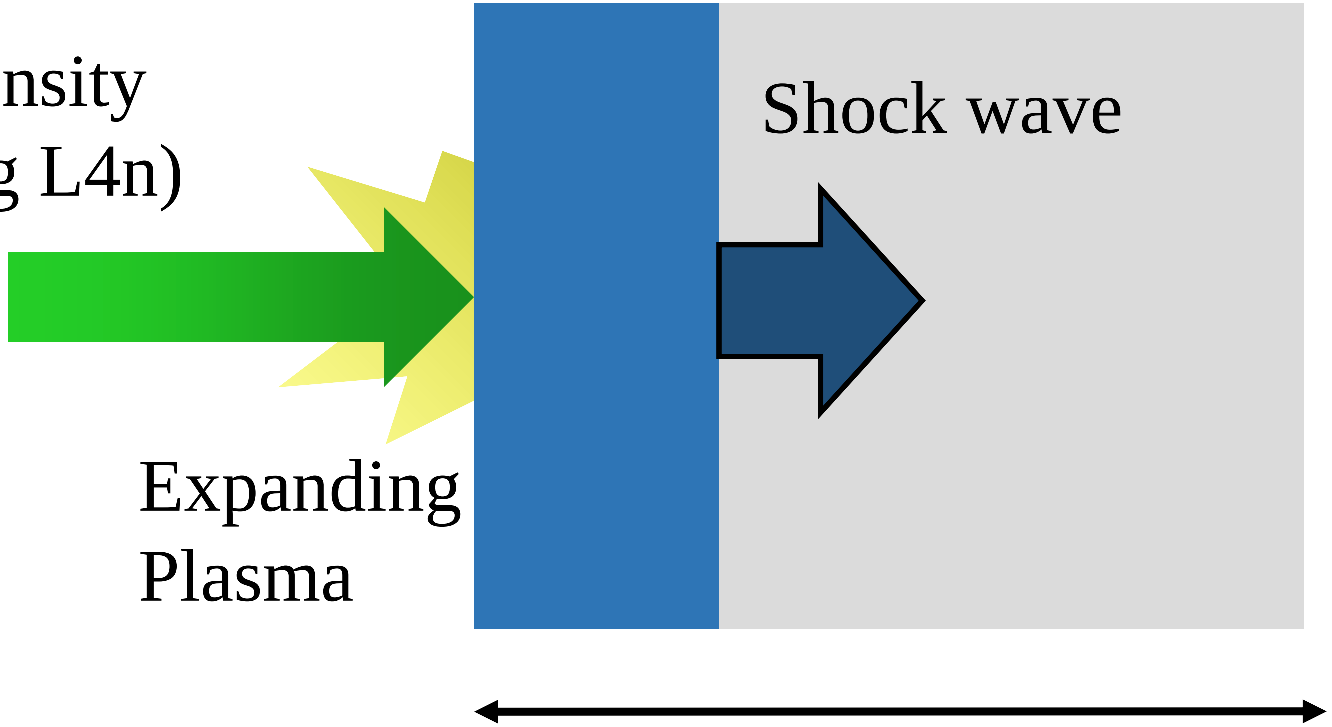


Fig.: Low-mass planet water-rock miscibility
Nettelmann, Nat Astron **5(8)**, 744 (2021)

Way to high pressures

Laser-driven shock-compression



High intensity
Laser (e.g L4n)

Shock wave

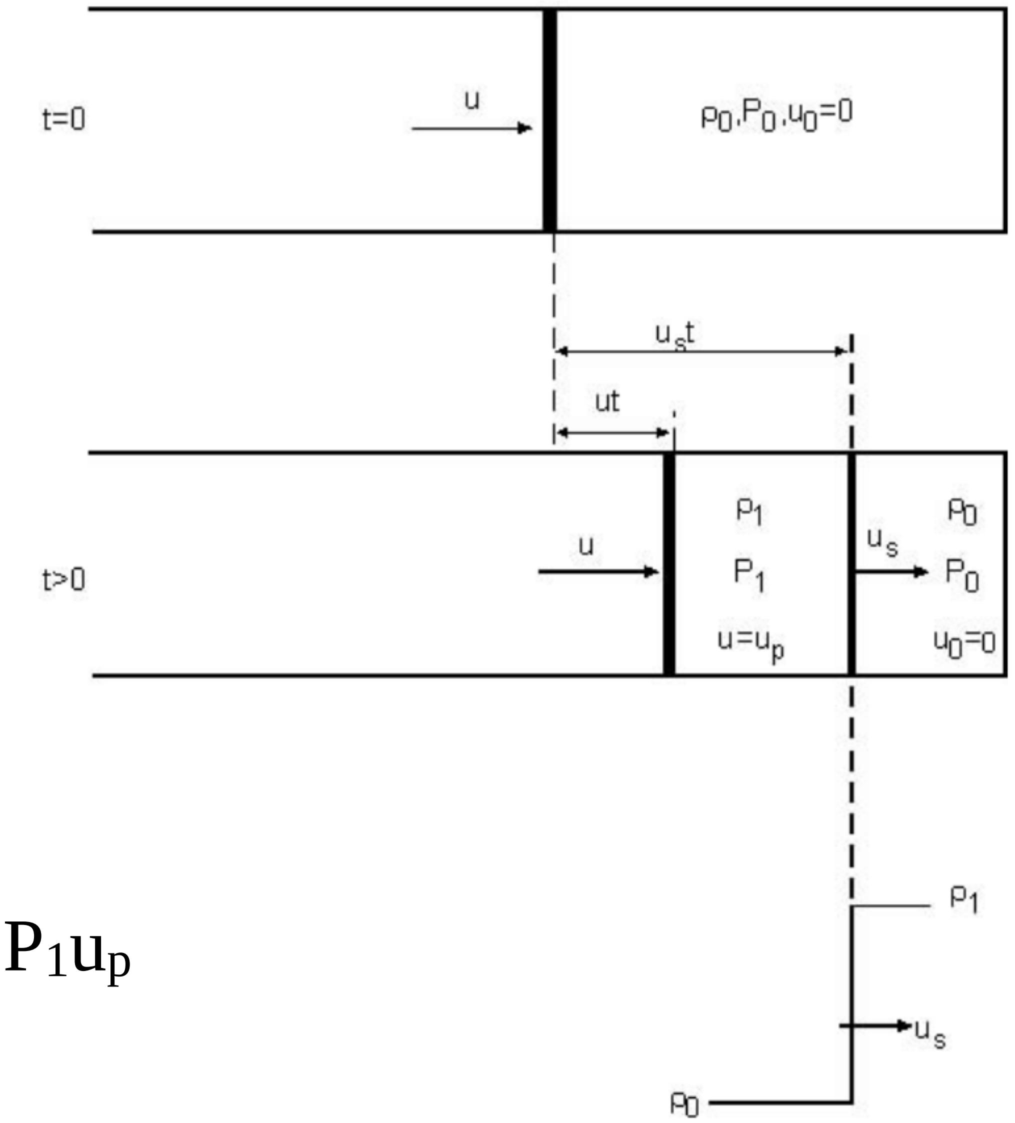
Expanding
Plasma

Typical thickness ~ 100µm

Ablated plasma and conservation of momentum lead to shock wave

Jump in P, T, ρ

Theoretical framework of shocks:



Eliezer, IoP, 2002

Conservation of mass:

$$\rho_0 u_s = \rho_1 (u_s - u_p)$$

Conservation of momentum:

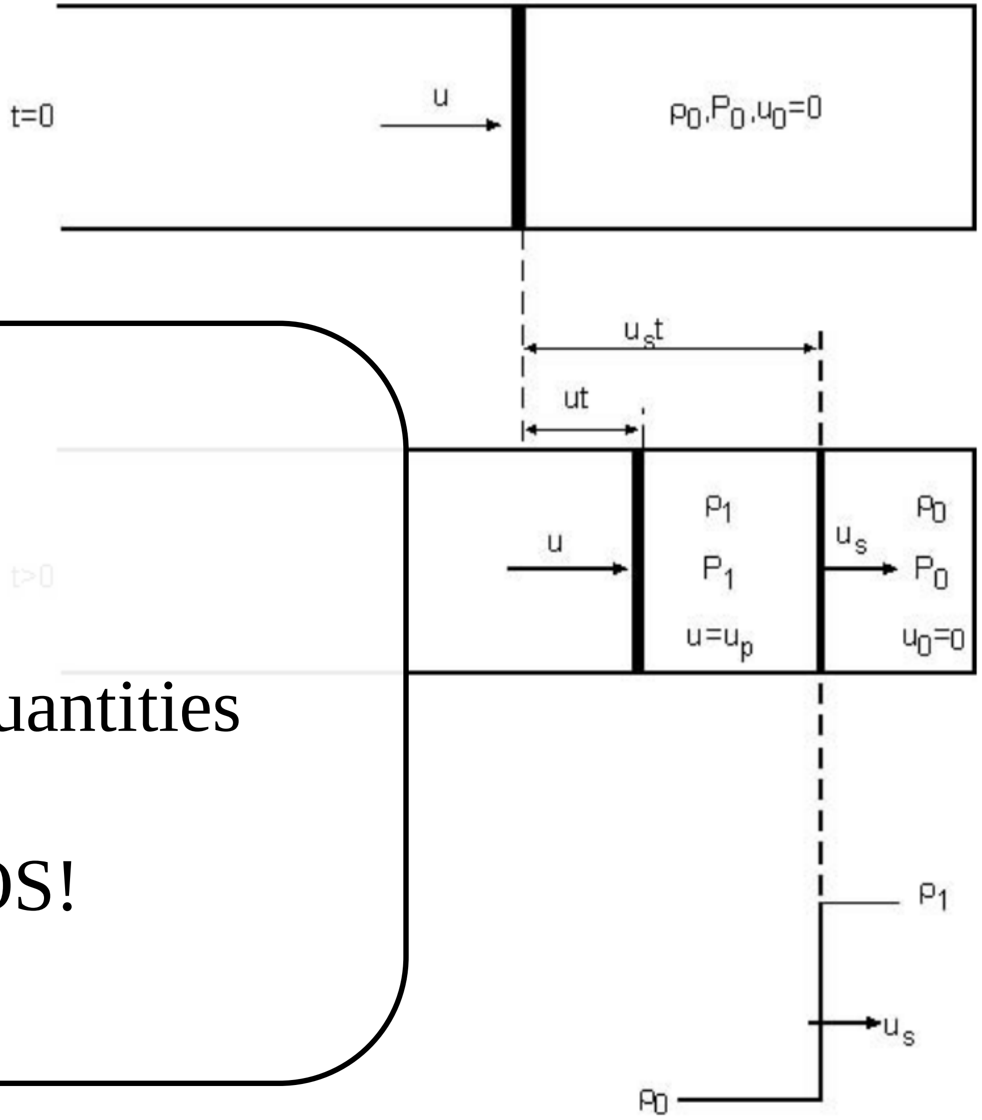
$$\rho_0 u_s u_p = P_1 - P_0$$

Conservation of Energy:

$$\rho_0 u_s (E_1 - E_0) + \tfrac{1}{2} u_p^2 = P_1 u_p$$

… across the shock-front

Theoretical framework of shocks:



Eliezer, IoP, 2002

Conservation of mass:

Conservation of momentum:

Conservation of Energy:

… across the shock-front

- 5 unknowns
- 3 equation

We need to measure 2 quantities

or

1 and know the EOS!

Theoretical framework of shocks:

Theoretical framework of shocks:

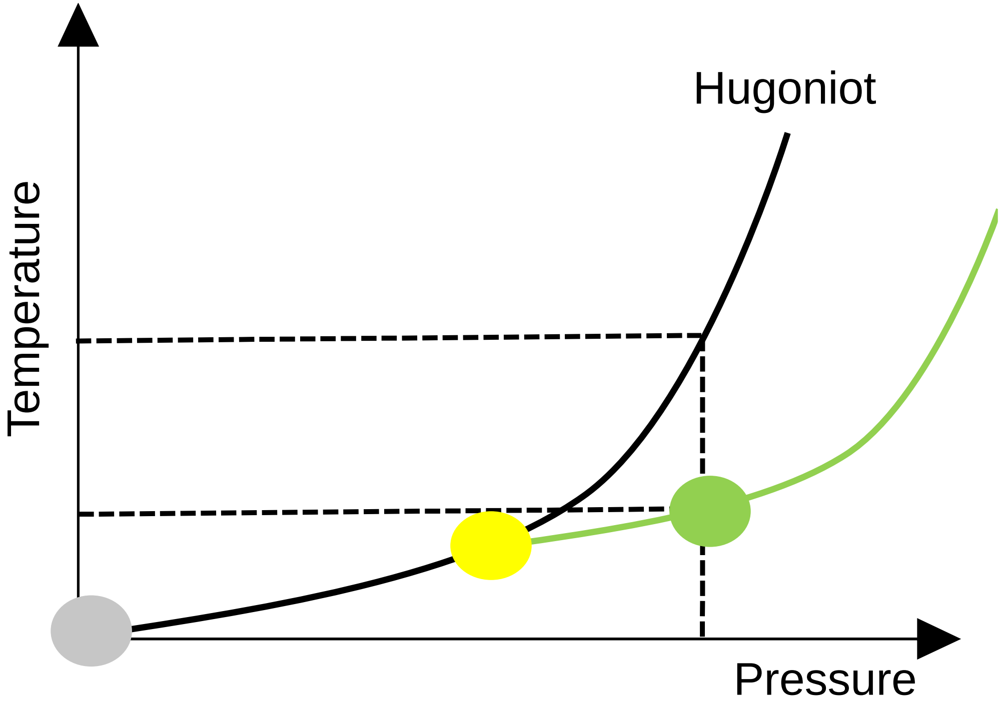
Conservation of mass:

Conservation of momentum:

Conservation of Energy:

… across the shock-front

A single shock can only reach one point on a material specific P-T curve!
Hugoniot - curve



Principle and secondary Hugoniot

Experimental Setup:

Pump probe fashion

Optical pump laser

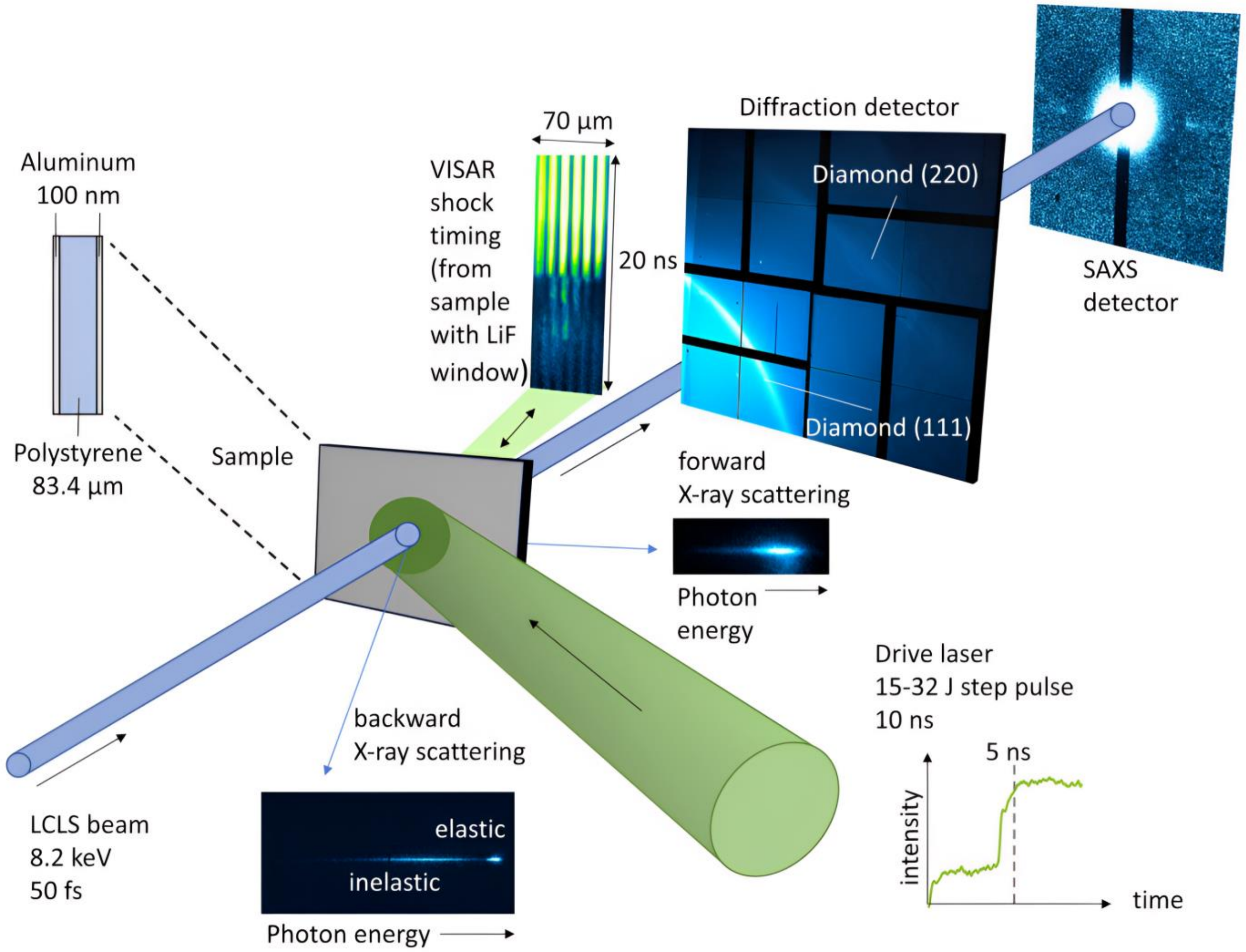
VISAR System → shock state

Xray probe → XFEL (Xray Free Electron Laser)

Xray-Diffraction (XRD) → structure

Small-angel Xray Scattering (SAXS) → structure

Forward/backward scattering → plasma state, chemsitry, ...



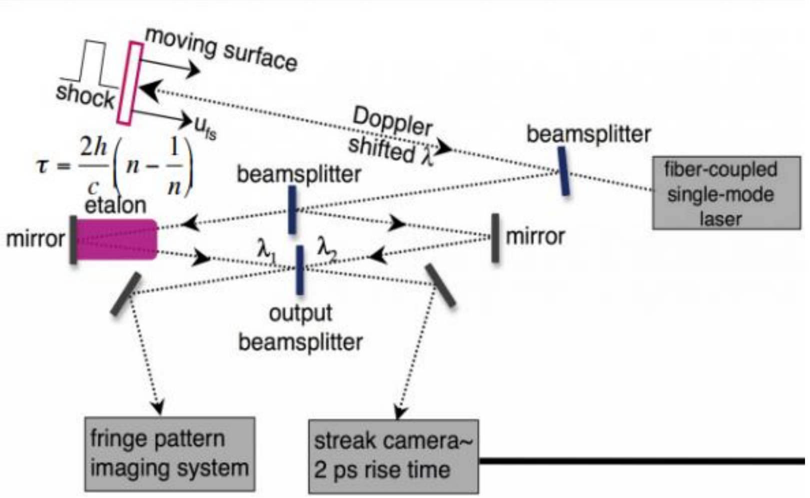
Kraus et al. , Nat Astr, 1, 606-611 (2017)

Velocity Interferometer System for Any Reflector (VISAR)

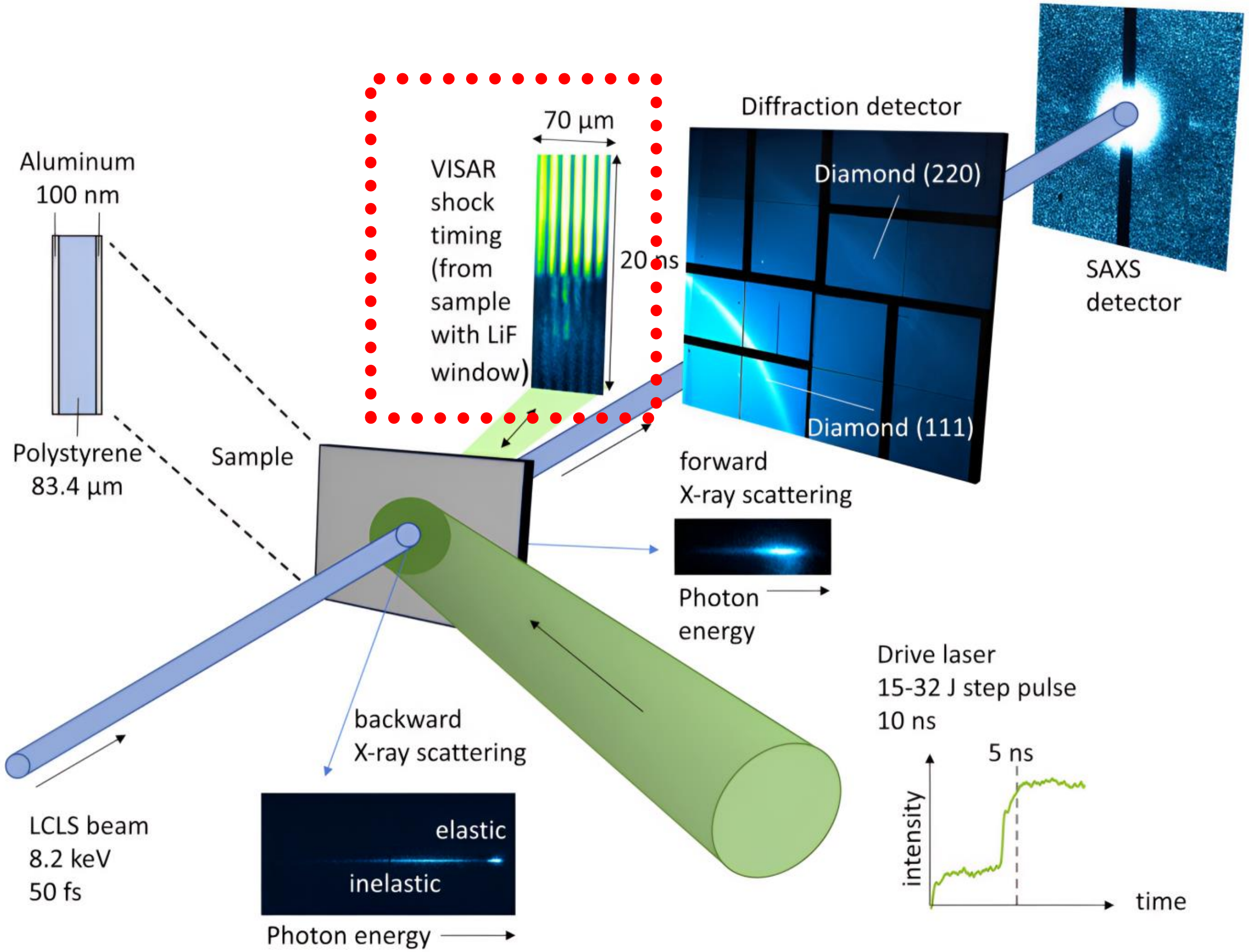
measure shock (particle) velocity

interference pattern from rear surface gets Doppler shifted

Streaked for temporal resolution



LCLS



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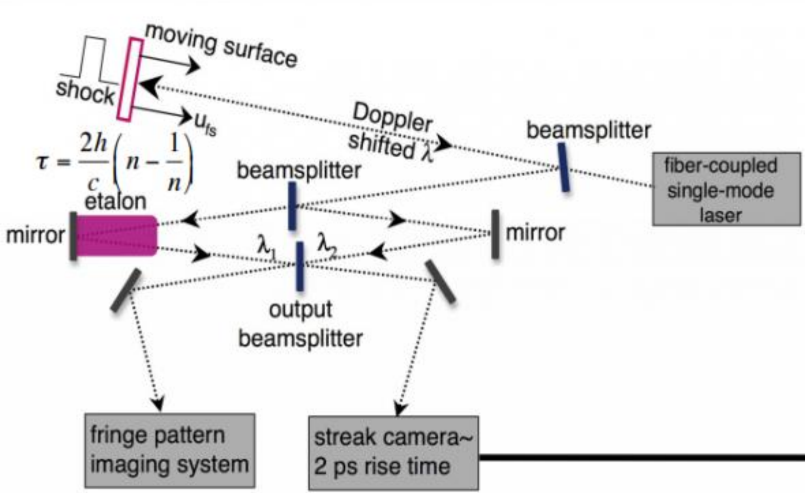

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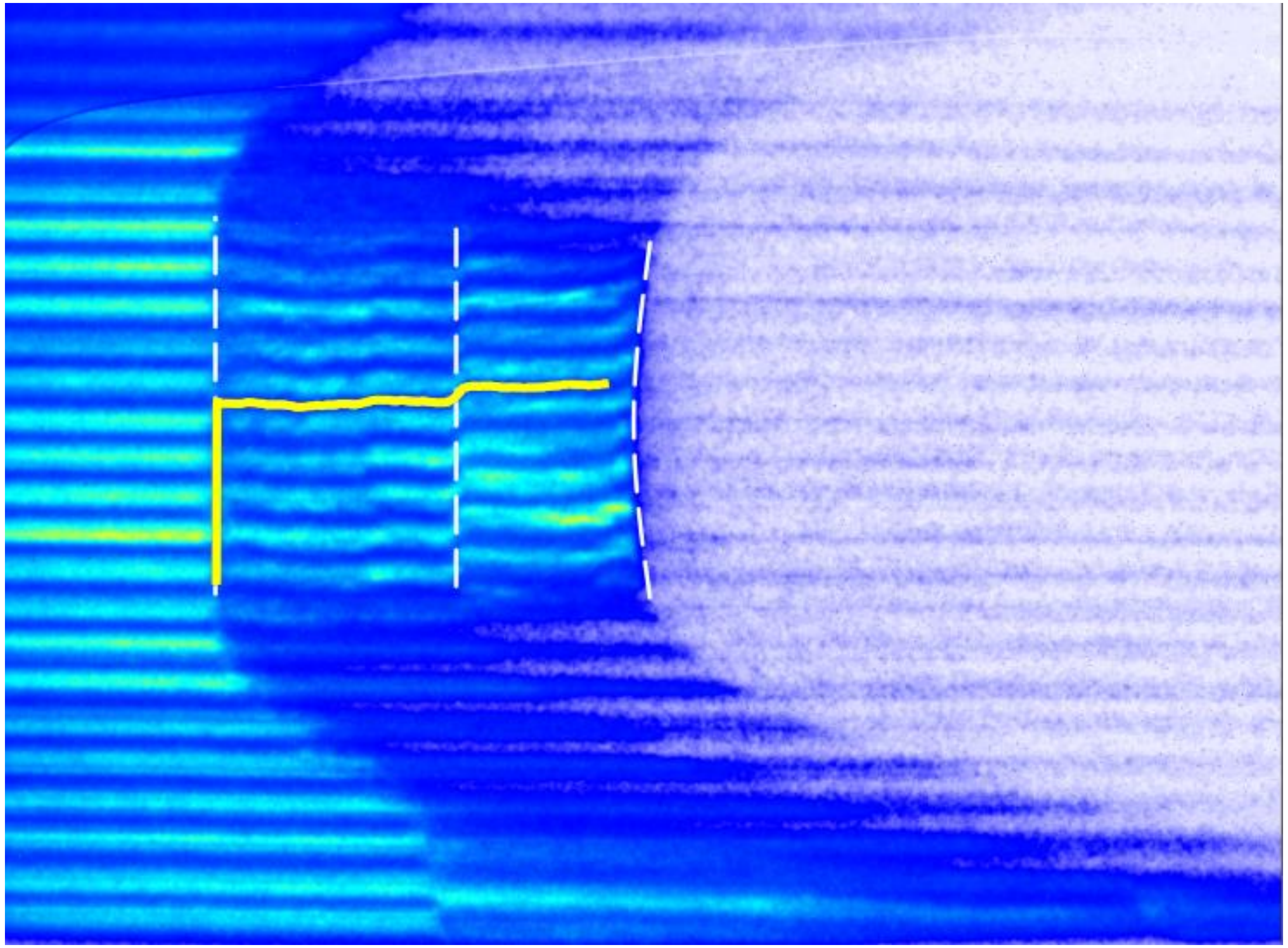


Example of a VISAR image of a two layered taget

Target design

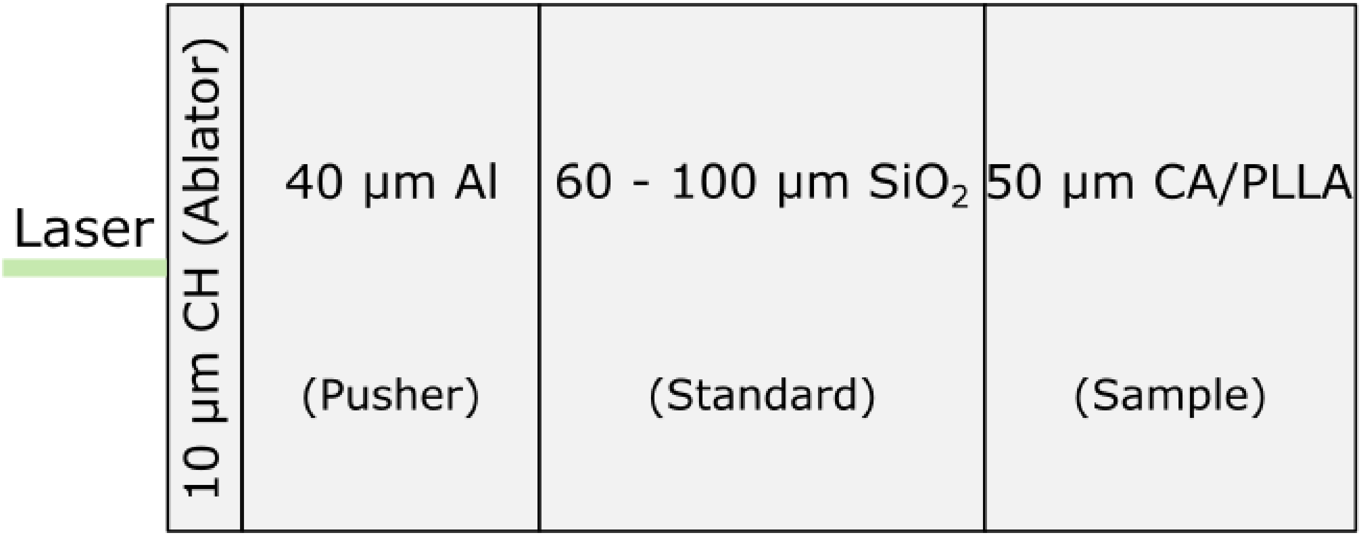
Easy to handle, cheap, elemental composition of planets (C-H-O-N)

→ Plastics

First analyze Hugoniot curve

Characterize P-T state with standard (SiO2)

Afterwards pump and probe

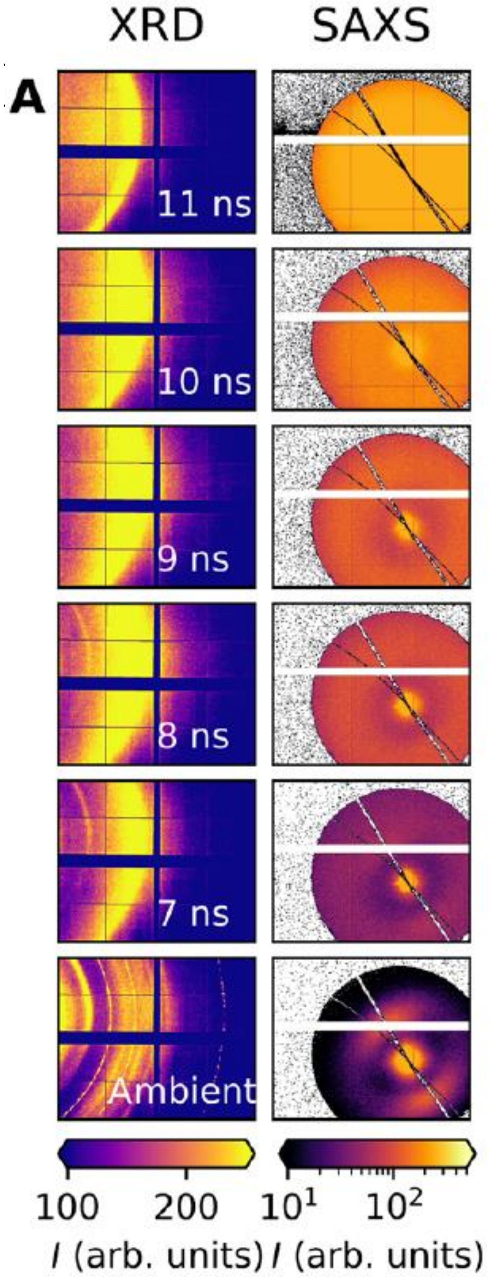


Typical target design for Hugoniot measurements – May, Master Thesis (2022)

Our Research

He, Sci. Adv.,
8 (35), 2375-2548(2022

Nanodiamonds



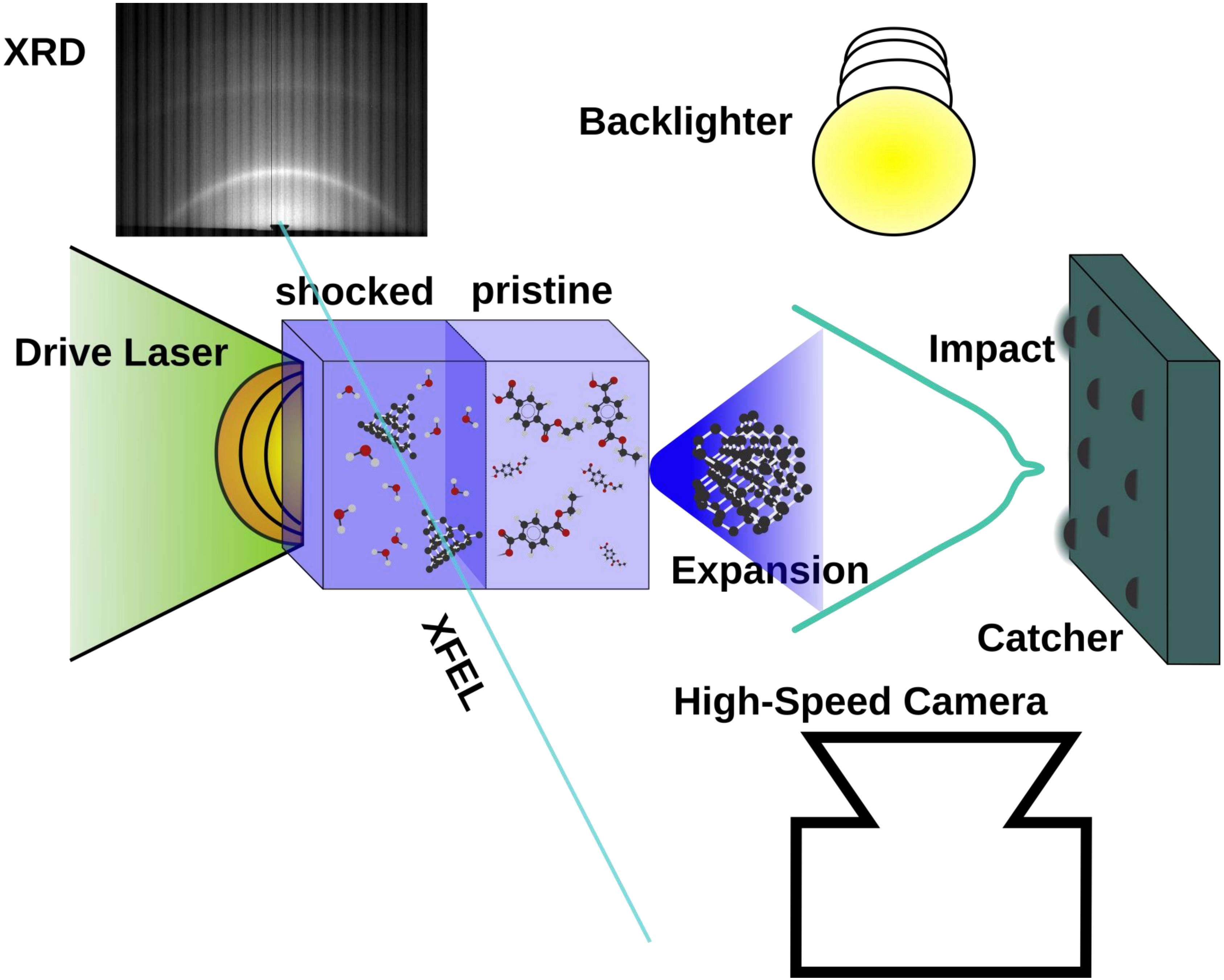
Diamond formation in shock compressed plastics (C-H, C-H-O)

Several nm

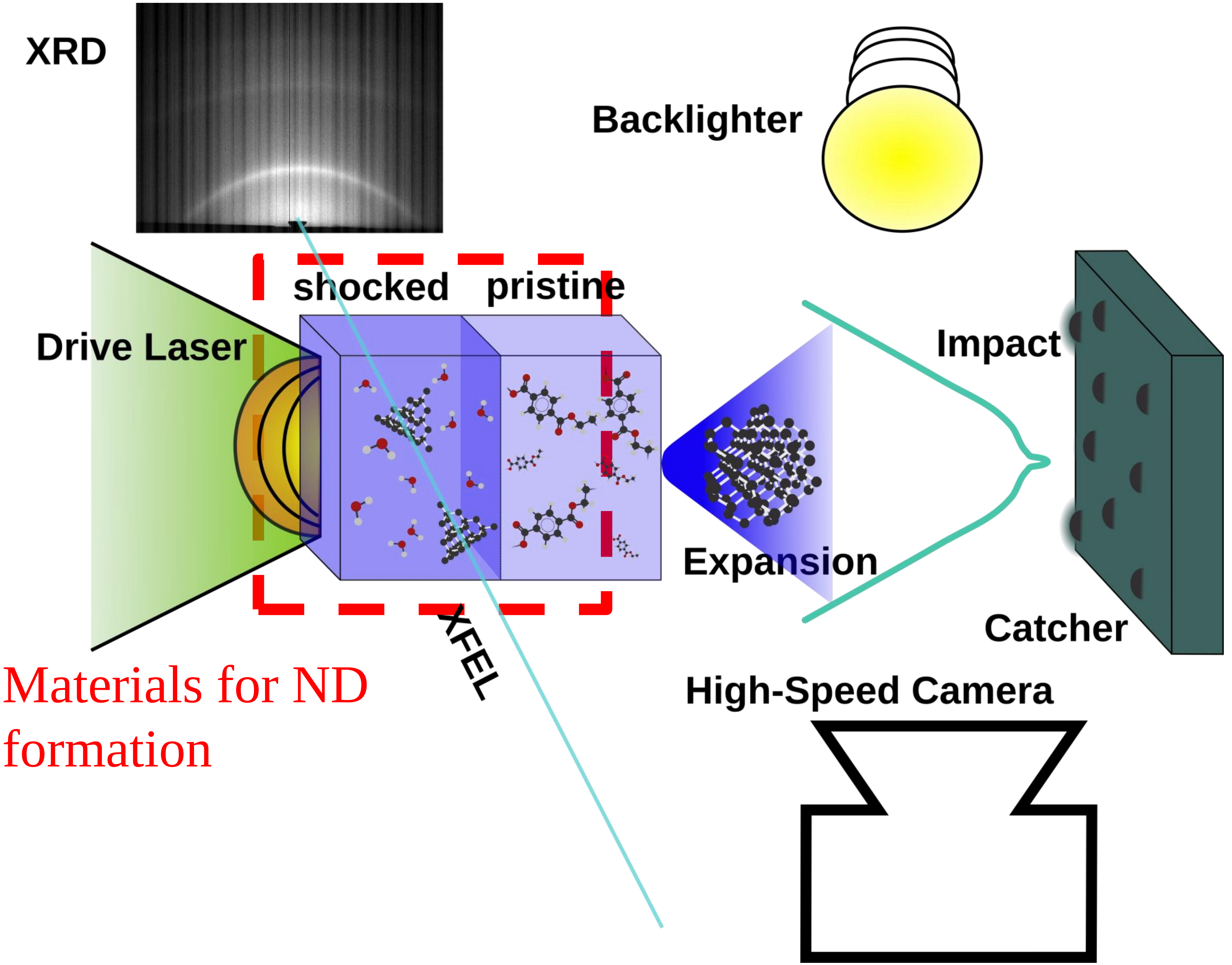
Nanodiamonds (ND) have many applications (quantum sensors, catalysts, drug delivery, …)

Theoretically possible to recover ND from laser-compressed plastics

We need to know:

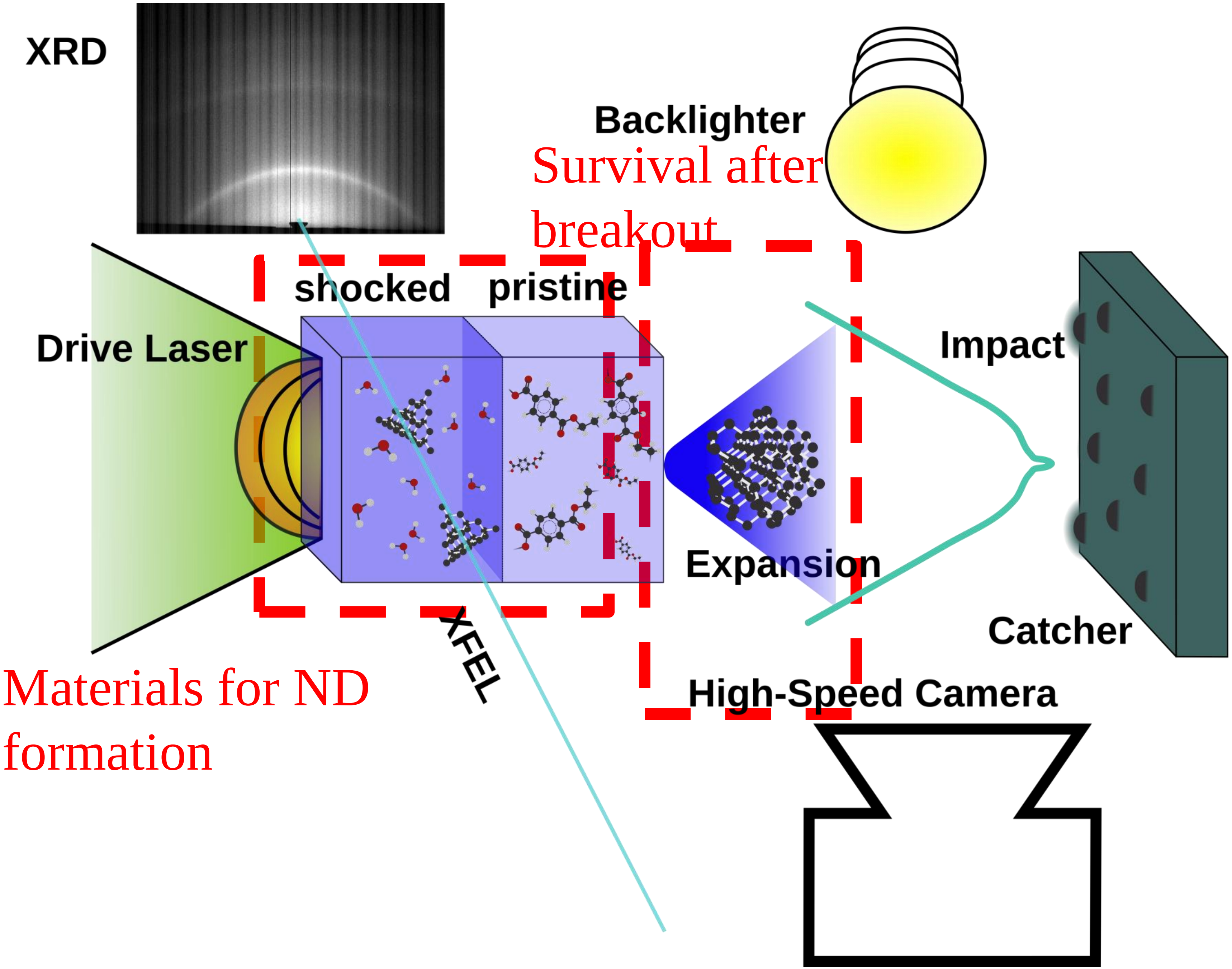


We need to know:



Materials for ND formation

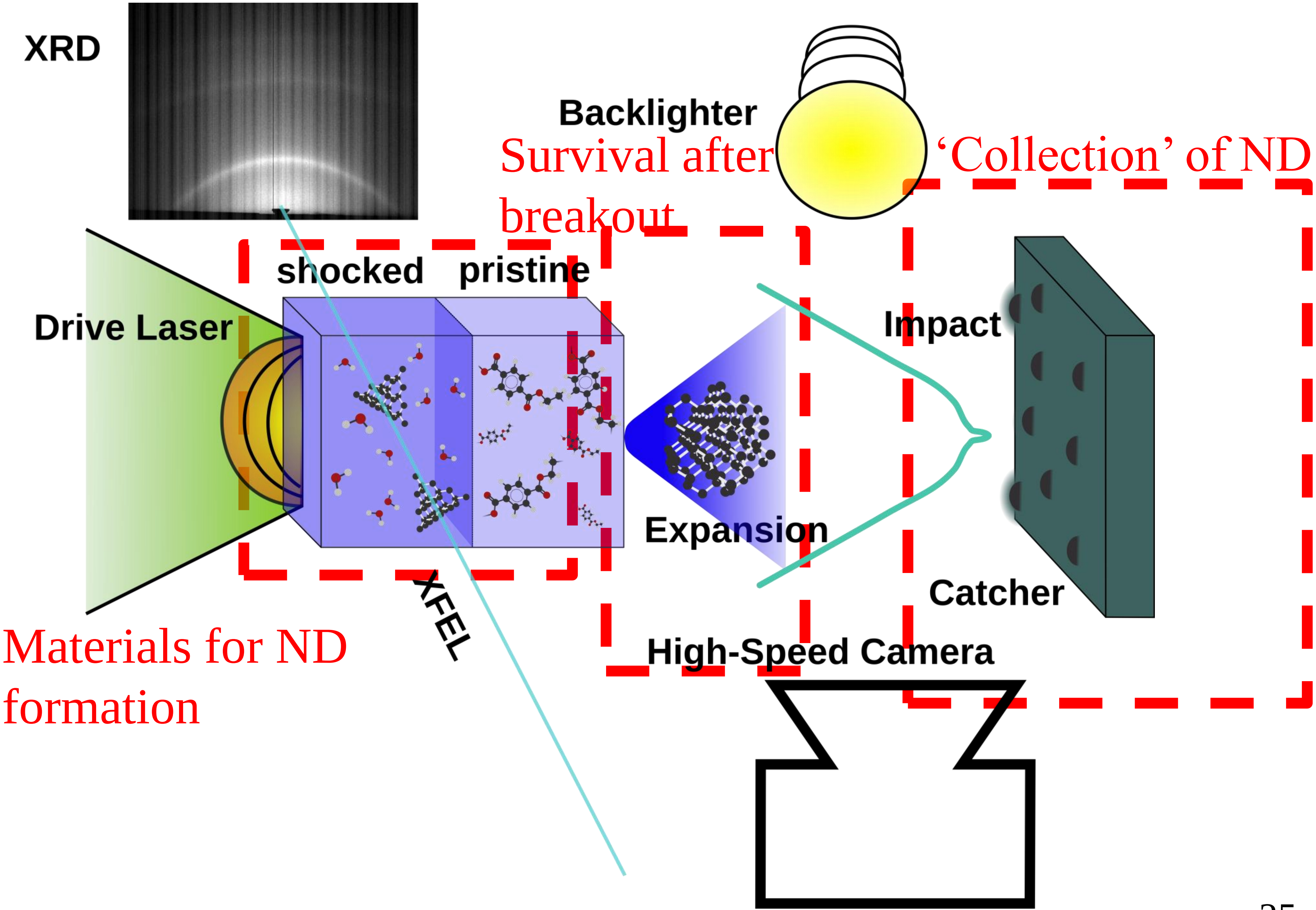
We need to know:



Survival after breakout

Materials for ND formation

We need to know:



Survival after breakout

'Collection' of ND

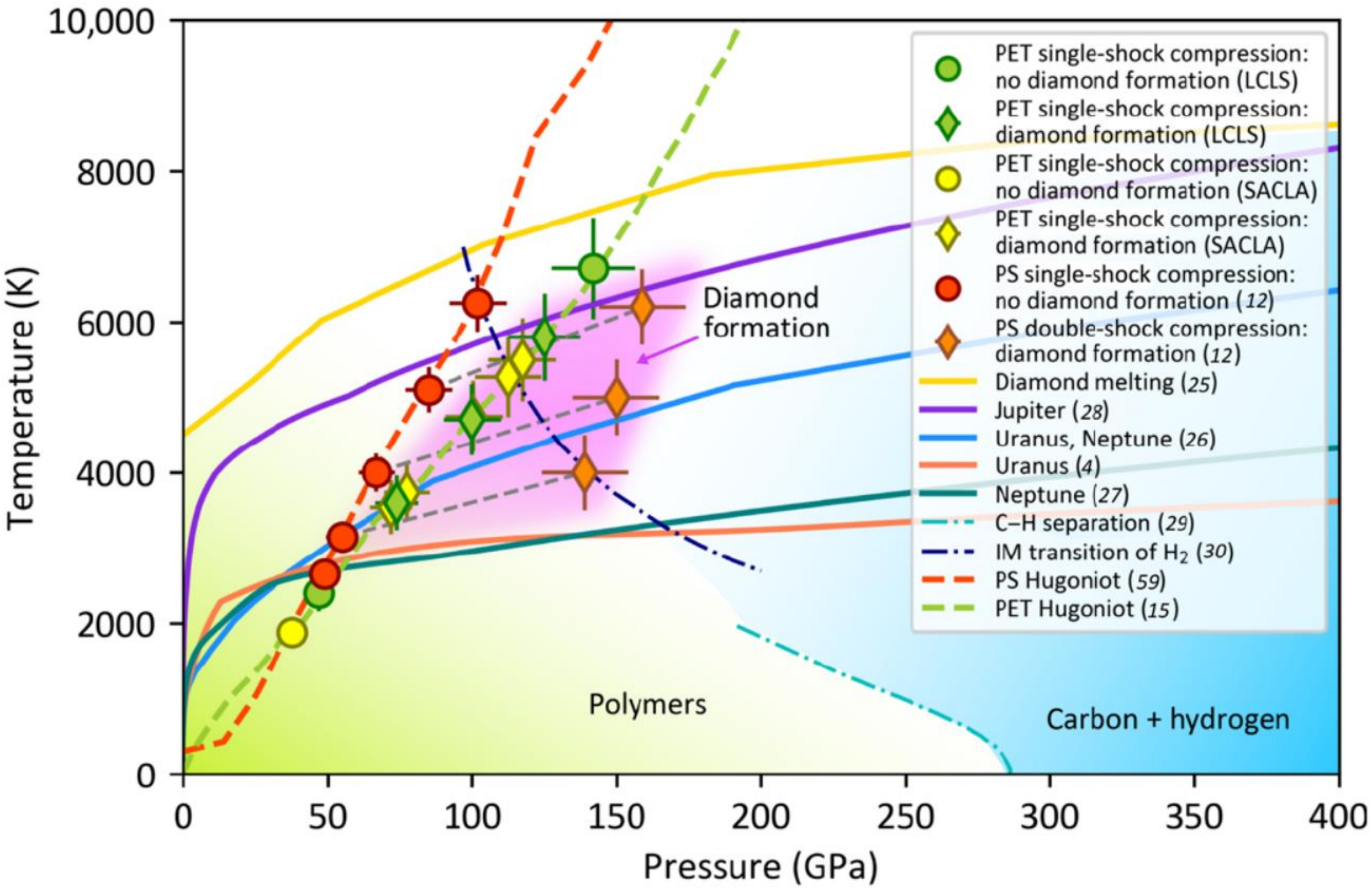
Materials for ND formation

Materials for ND formation

Formation in Polystyrene (double shock)

PET (single shock)

→ more diamond fraction in PET, O helps diamond formation



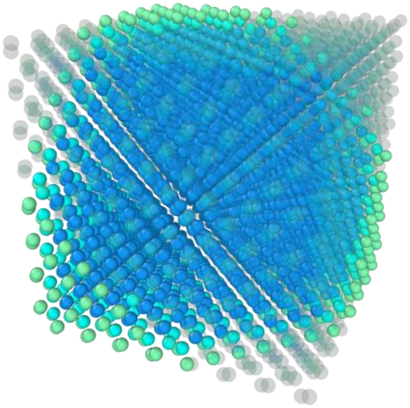
He, Sci. Adv.,8 (35), 2375-2548 (2022)

Stability after breakout

Extremely fast – ps timescale

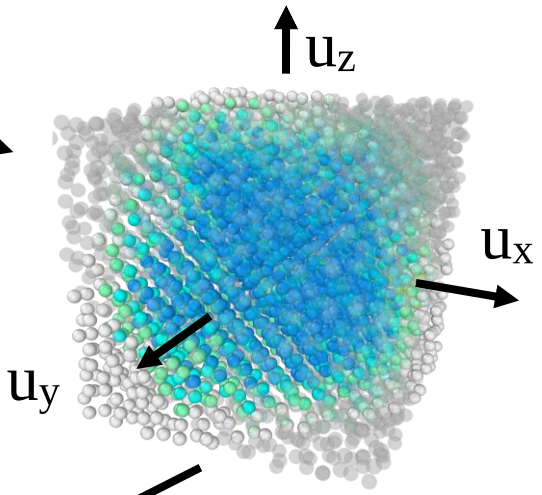
→ MD simulation

Four states on the PET-Hugoniot



1. Equilibration ND cube at Hugoniot P, T state – equilibration in N,V,T ensemble

2. Expansion
Expand simulation box consistent with adiabatic expansion



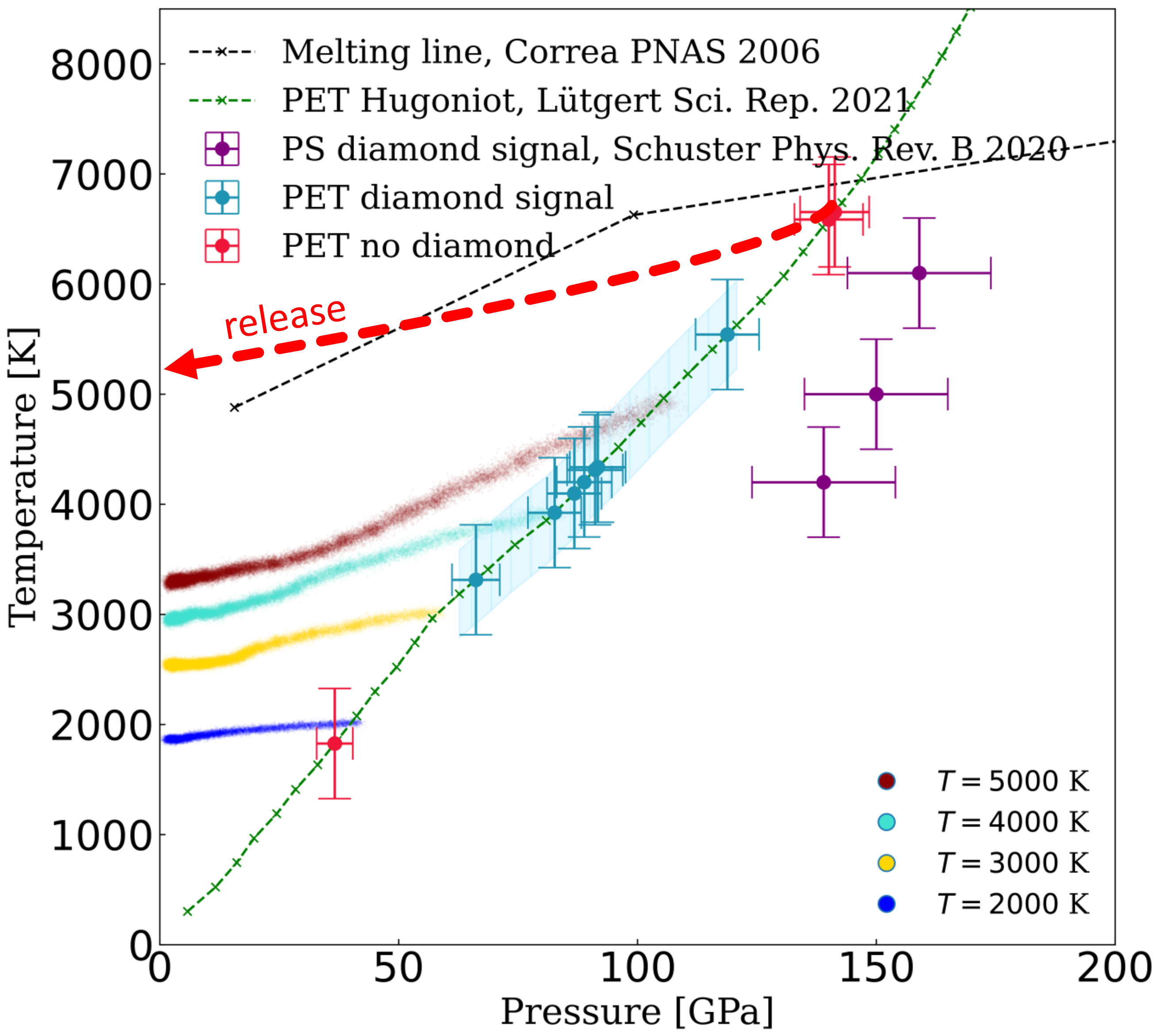
3. Cooling
After expansion cooling to ambient temperature (different cooling rates)

Stability after single shock

Sudden drop of temperature after release

ΔT is proportional to P_{init}

Expansion does volume work against the pressure



Stability after single shock

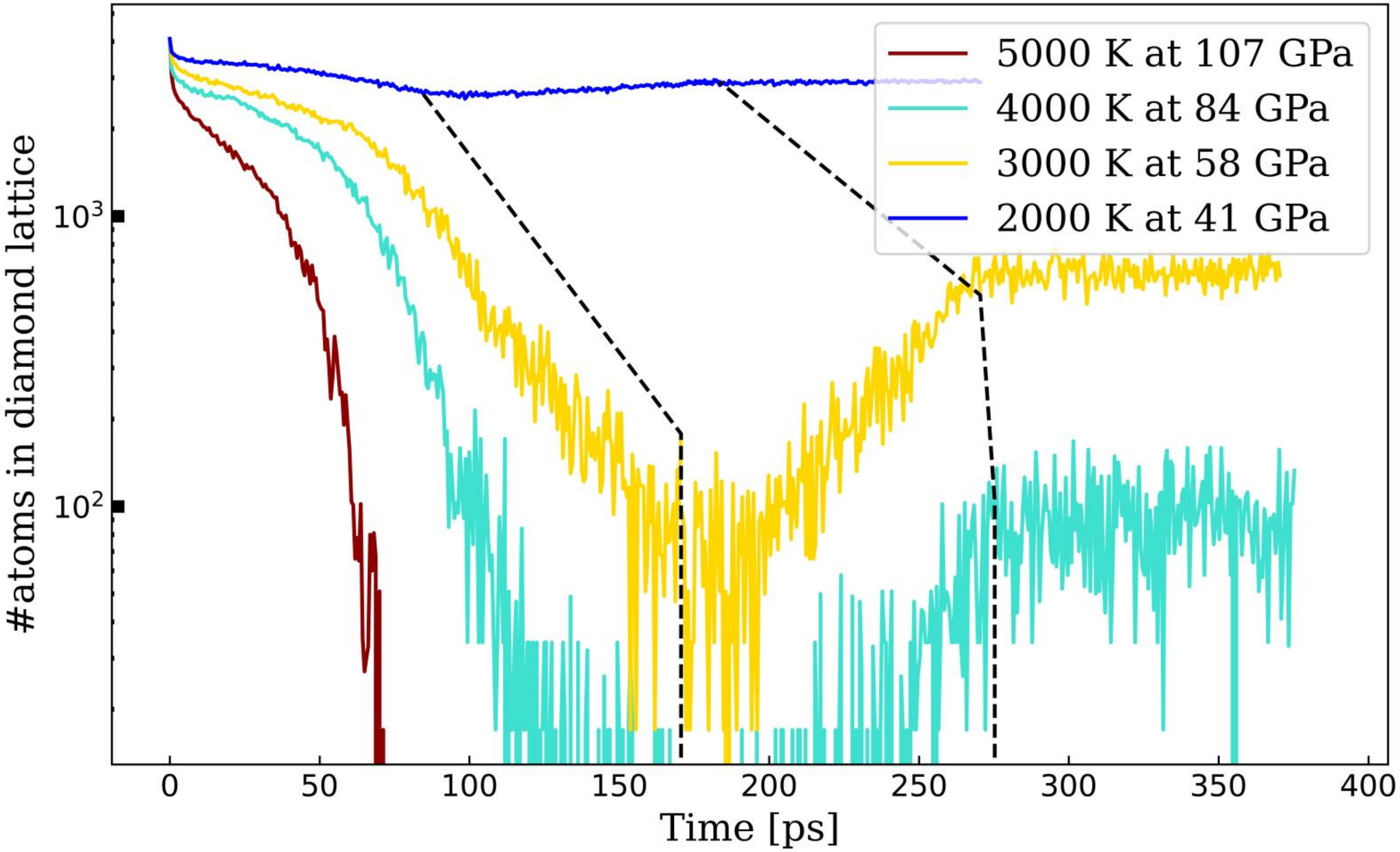
Significant disintegration of diamond lattice upon release

Recovered diamond phase proportional to initial Hugoniot state

→ higher state, less diamond

Recrystallization in the cooling phase

Stable after cooling

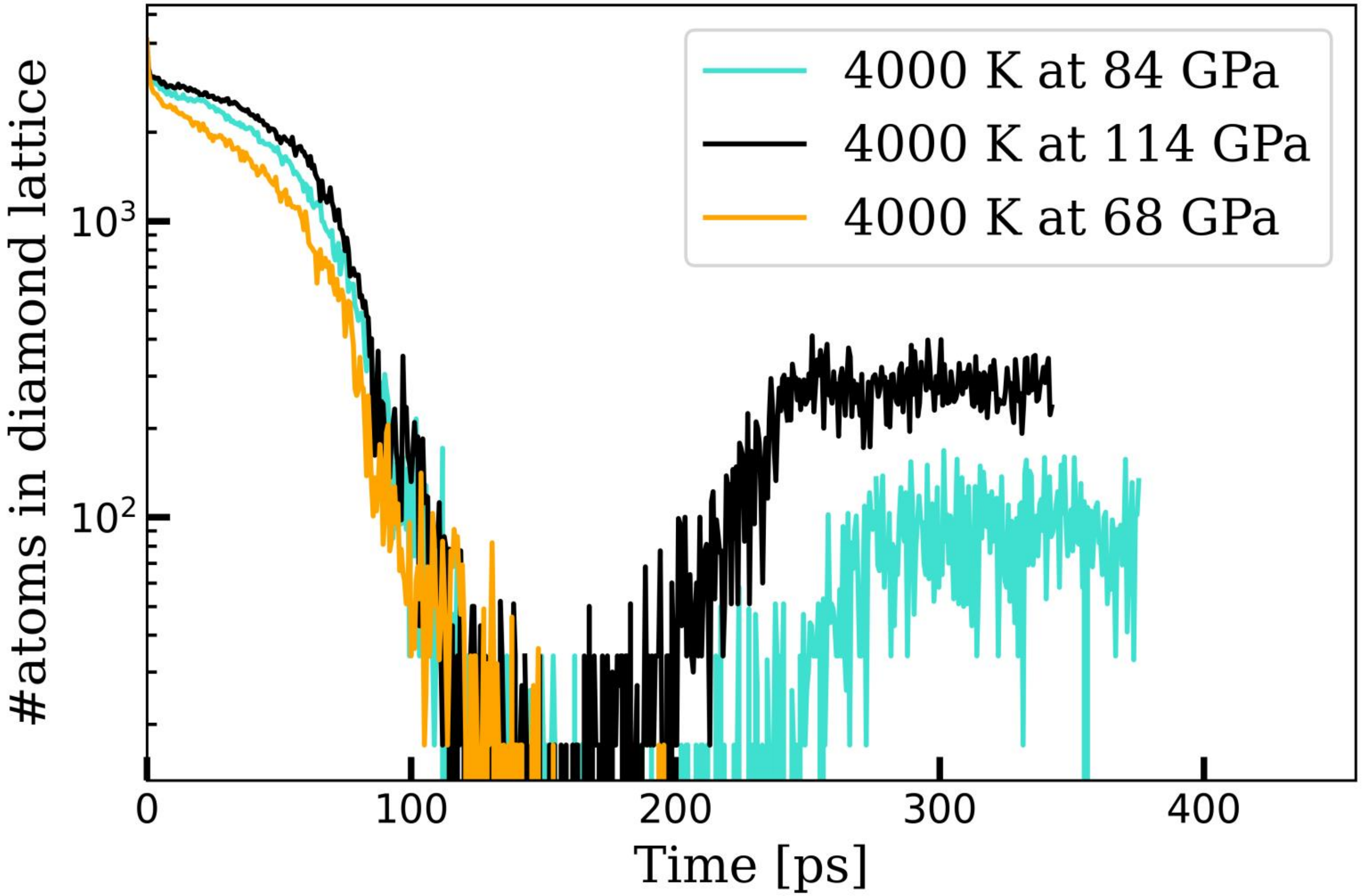


Stability after double shock

Less melting at **higher** pressures

More recrystallization at higher pressures

Most diamond at the highest pressure state

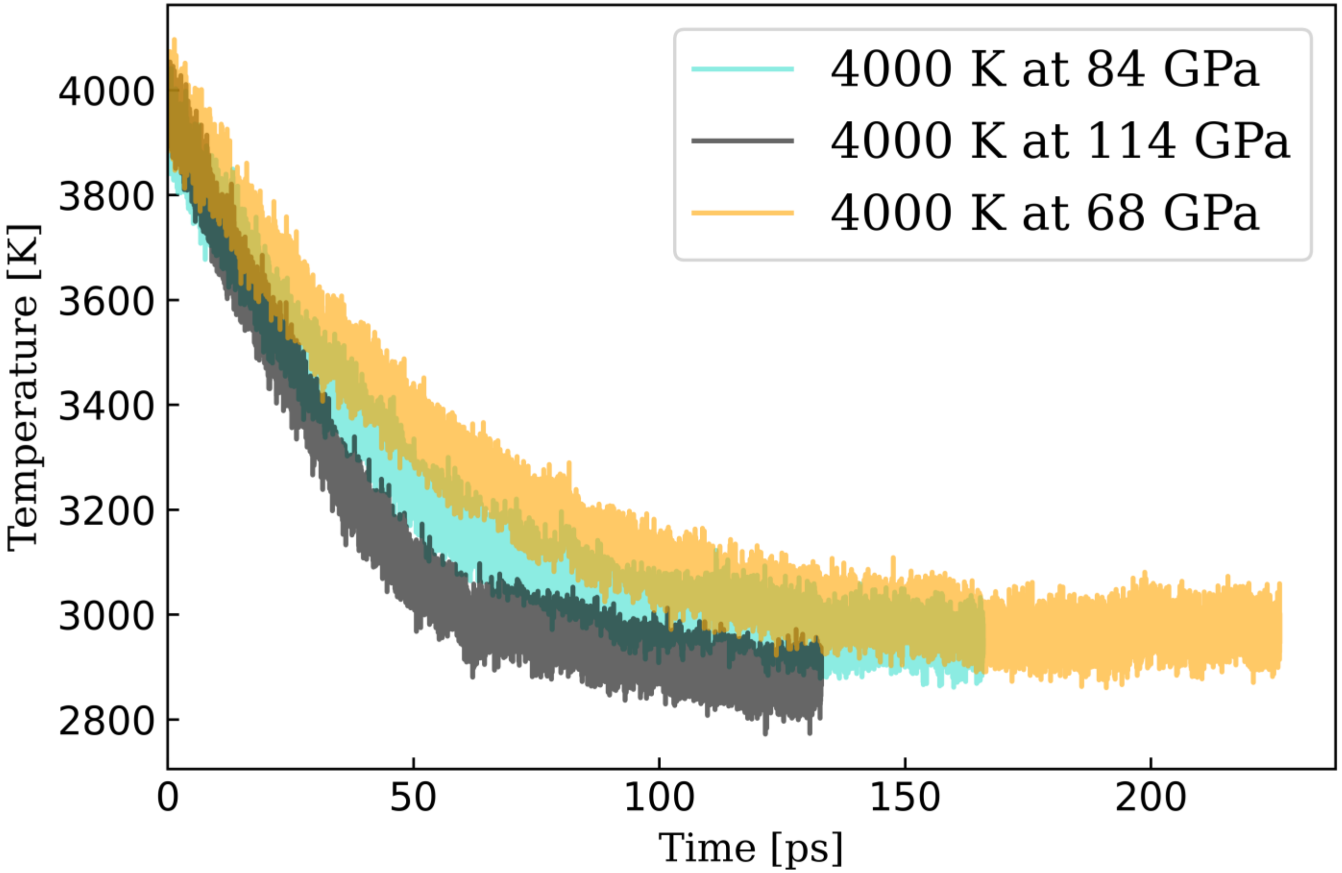


More diamond after double shock

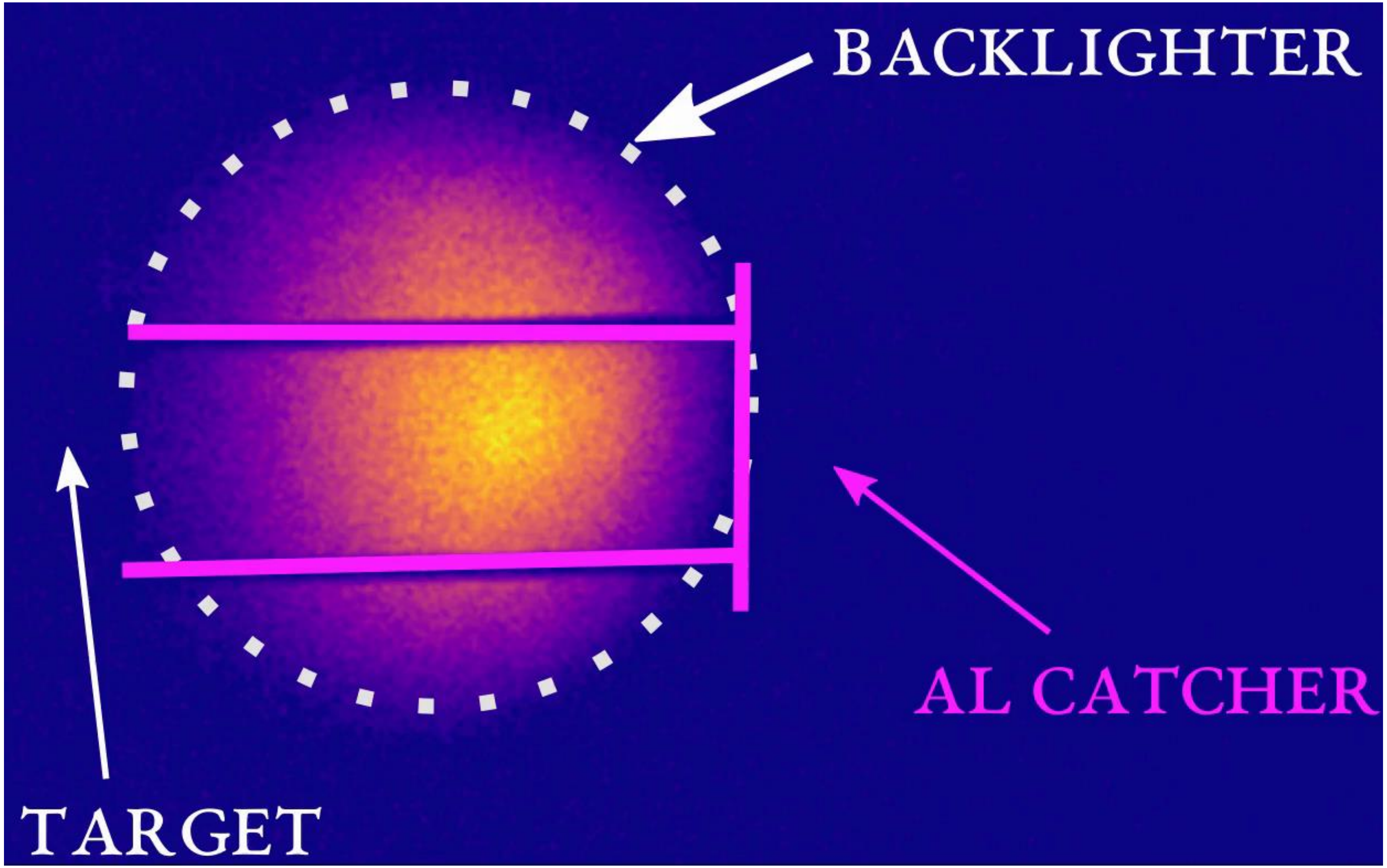
Faster cooling

→ less disordering of carbon atoms

→ higher recrystallization rates upon cooling



What does the release look like?

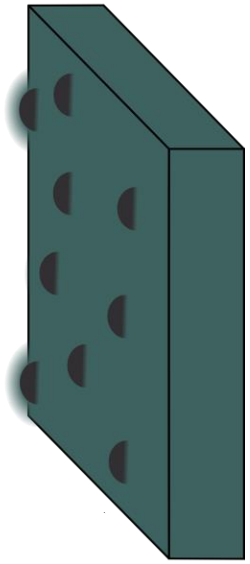


“Collecting” Diamonds - Catchers

Defined impact from nanometer sized impactor visible

No Diamond signal in previous catchers

Experiments with liquid catcher materials

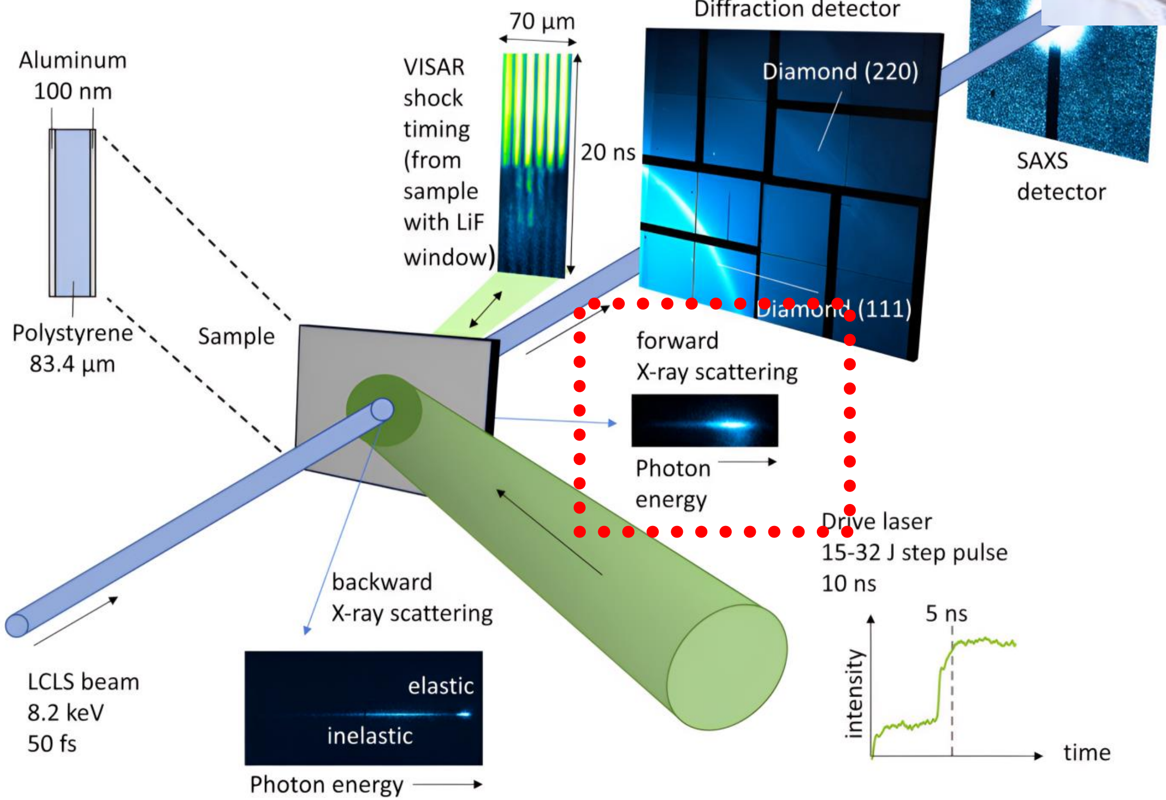


Detecting Metallic Hydrogen

Measure de-mixing of H – C at planetary interior conditions (hydrogen metallization)

Xray probing of cold diamond

Xray-Thompson Scattering (XRTS) measurents → plasmon feature



Kraus et al. , Nat Astr , 1, 606-611 (2017)

Plasmon feature

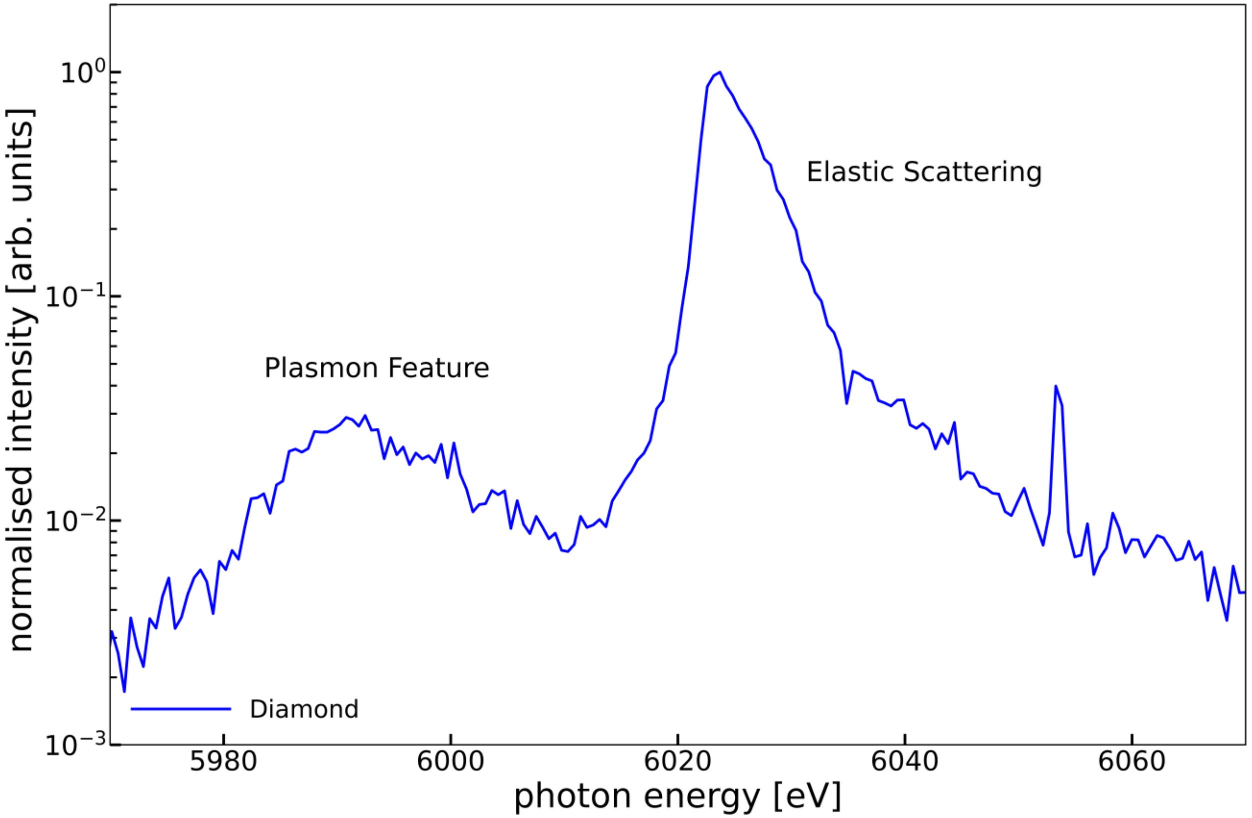
Resolve contributions to plasmon feature

Signal is convoluted with instrument function

Low signal

Requires extremely narrow instrument function

Combined thousands of shots



Ranjan et al. Physics of Plasmas 30, 052702 (2023)

Simulated data (TDDFT)

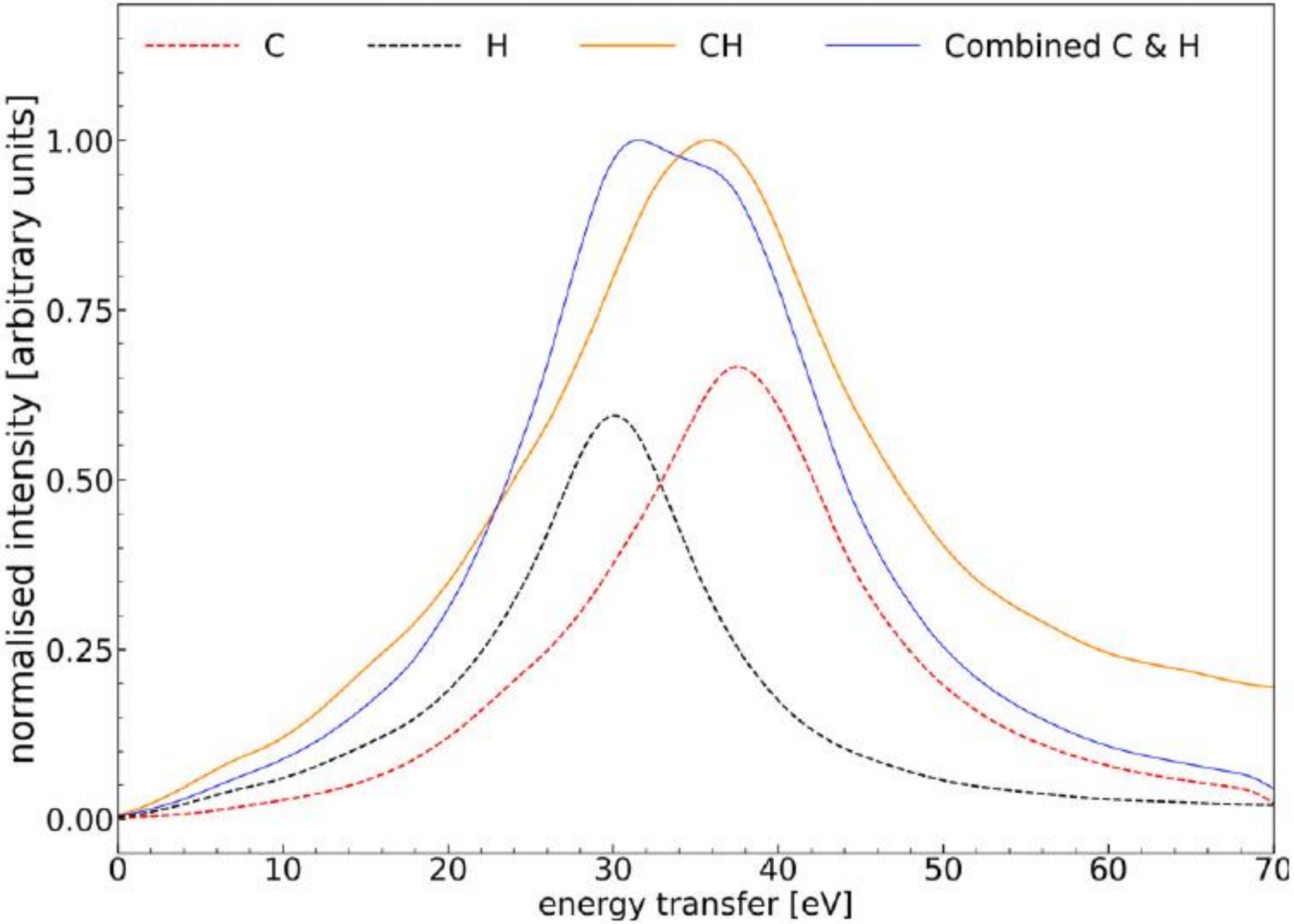
Based on experimental measurements of instrument function

Clear separation of mixed state and de-mixed contributions when driven

Spectral resolution of ~3eV

Probing bulk not only surface (reflectivity)

Sufficient for detecting de-mixing



Ranjan et al. Physics of Plasmas 30, 052702 (2023)

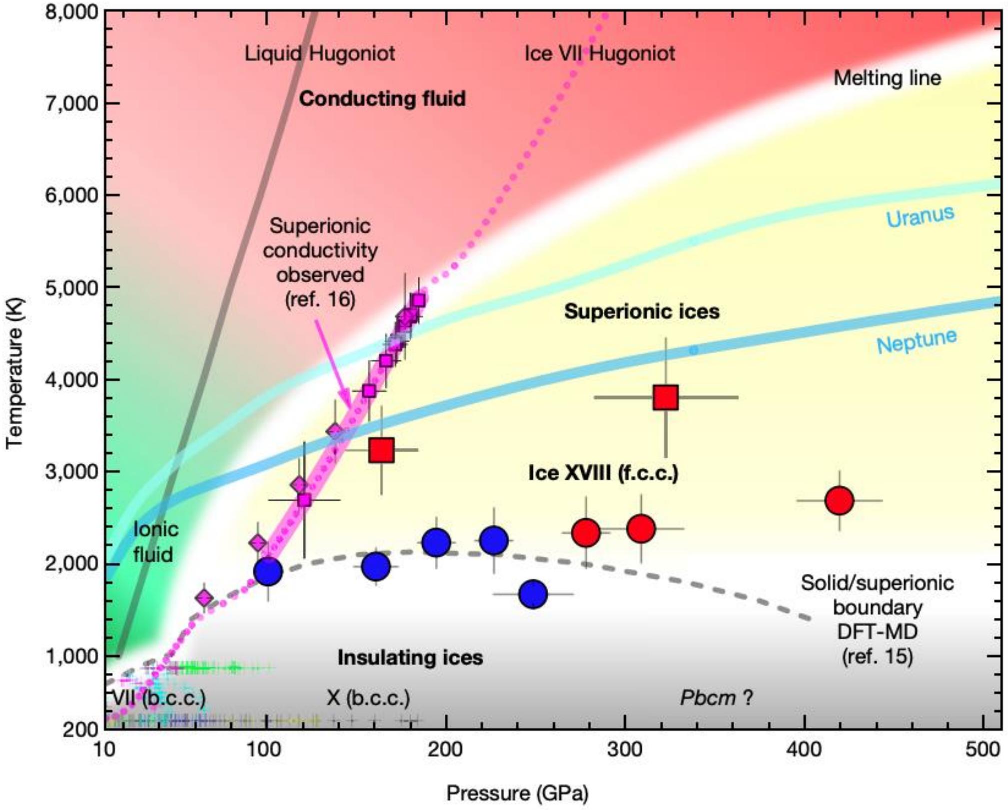
Superionic Water in Planets

Superionic Water is O in crystal lattice and free H ions

Exists at high P -T states

Two reported phases of SW fcc/bcc

Study phase transitions and possible additional phases



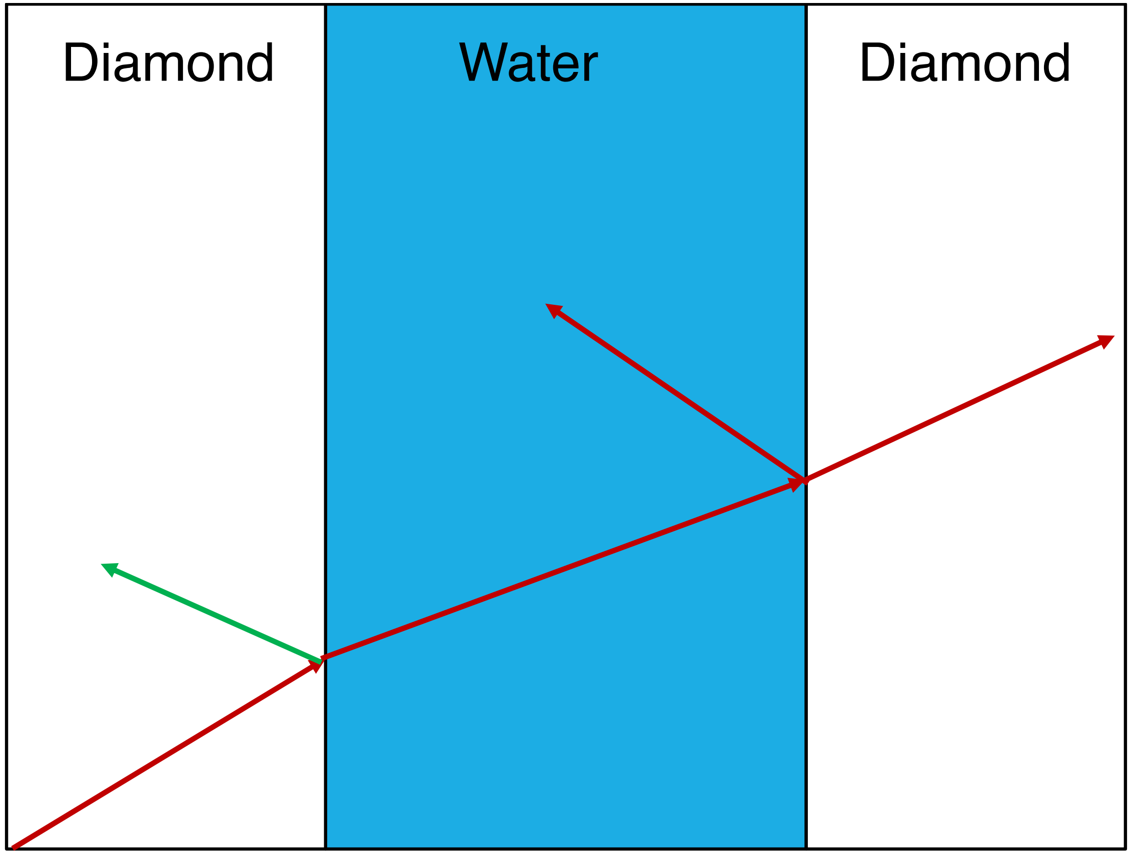
Salzmann, J. Chem. Phys., 150, 06091 (2017)
Milot, Nature, 569, 251-255 (2019)
French, Phys. Rev. E., 93, 022140 (2016)

Target design

Reverbaration shock in sandwich targets → off-Hugoniot stated

Multiple reflections in the sandwich

Study structure of water with XRD → remove single crystal diamond peaks

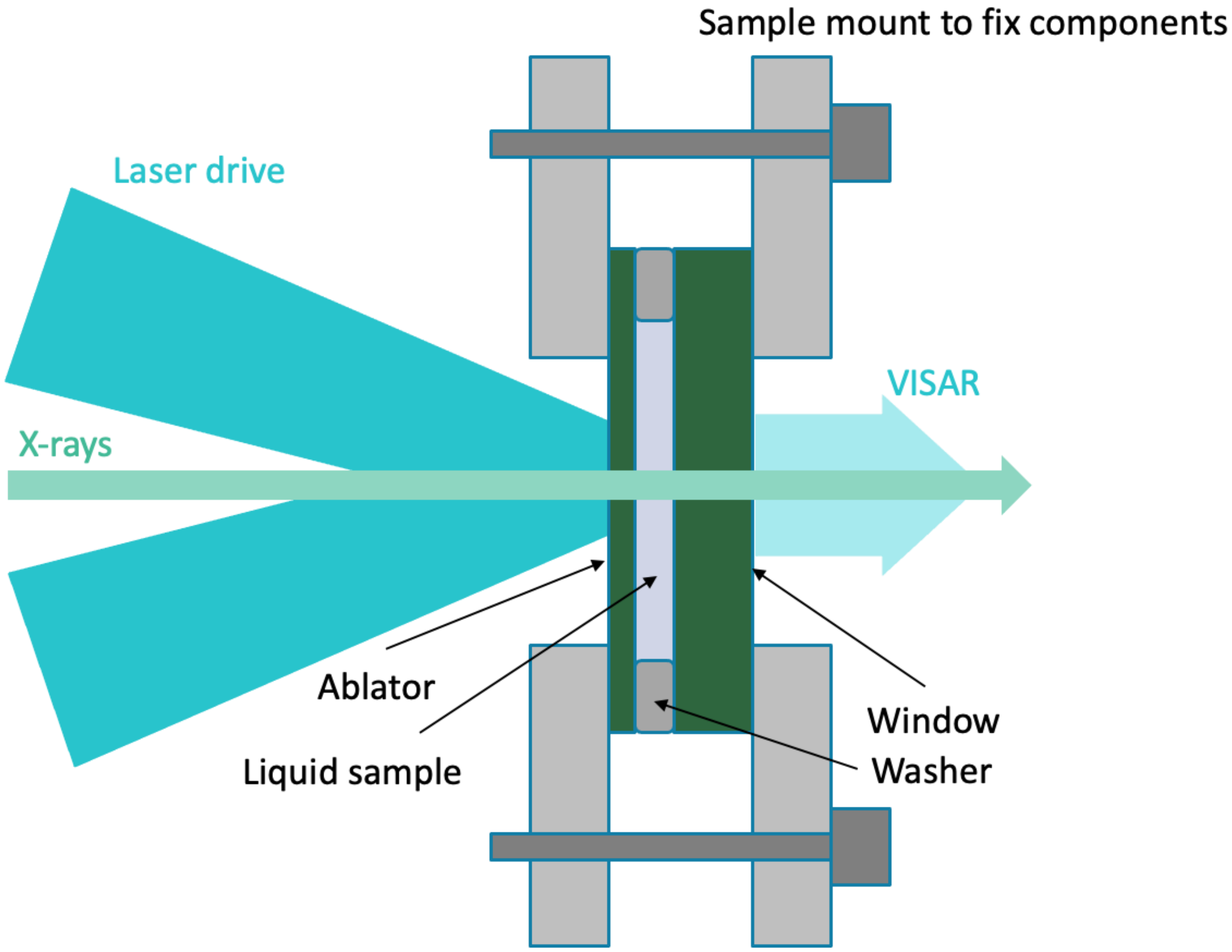


Target mounting

Diamond Ablator with AR coating

Washer window (e.g silicone)

Diamond coated with Al



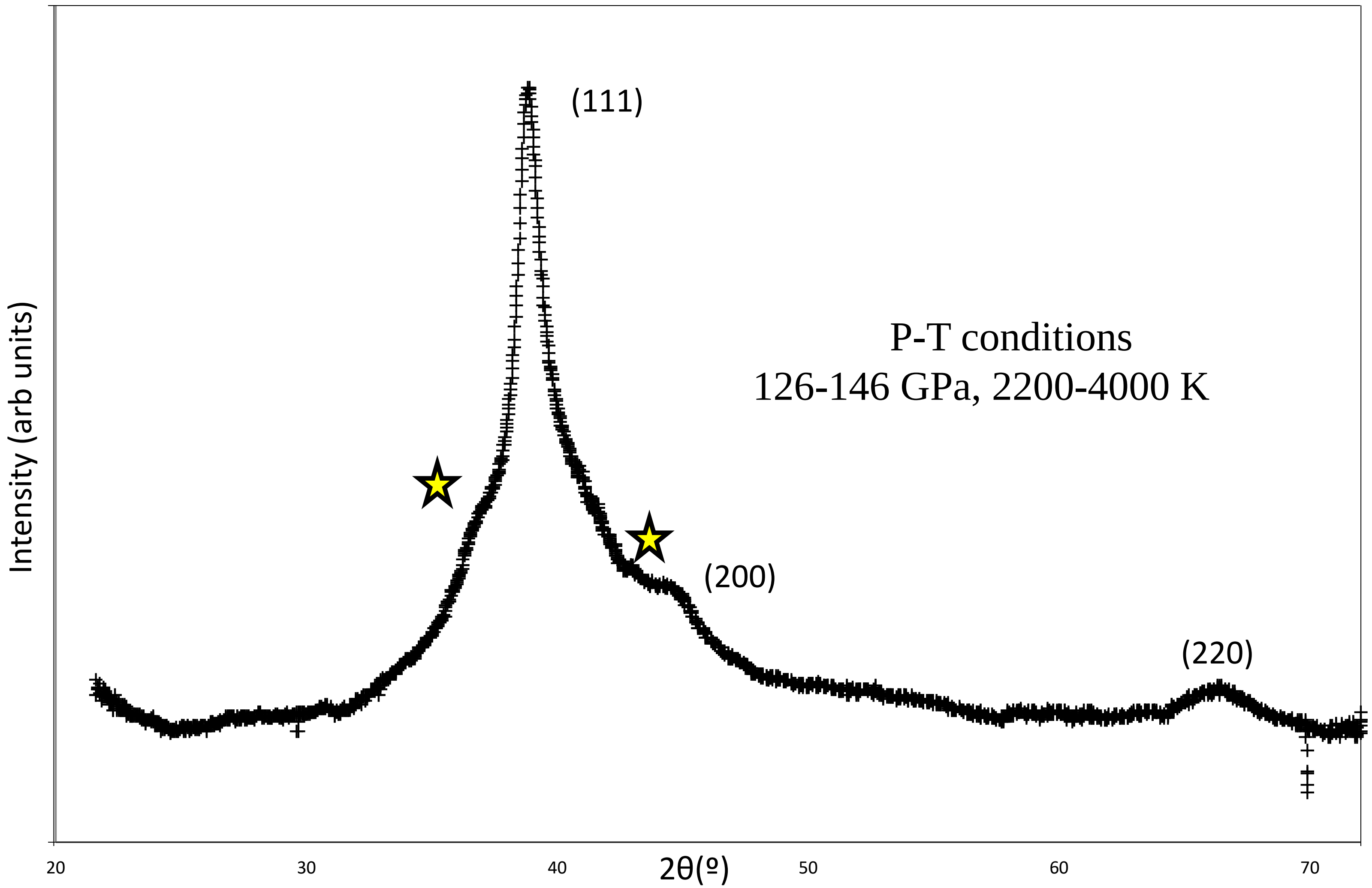
Rietveld refinements XRD

fcc phase evident with densities: 3-3.4 g/ccm

Another phase in the data

Broad structure neither fcc/bcc nor liquid

Several possible candidates ($P4_22_12$, Pbcm, Pbca)



P-T conditions
126-146 GPa, 2200-4000 K

Probing Red Dwarf conditions

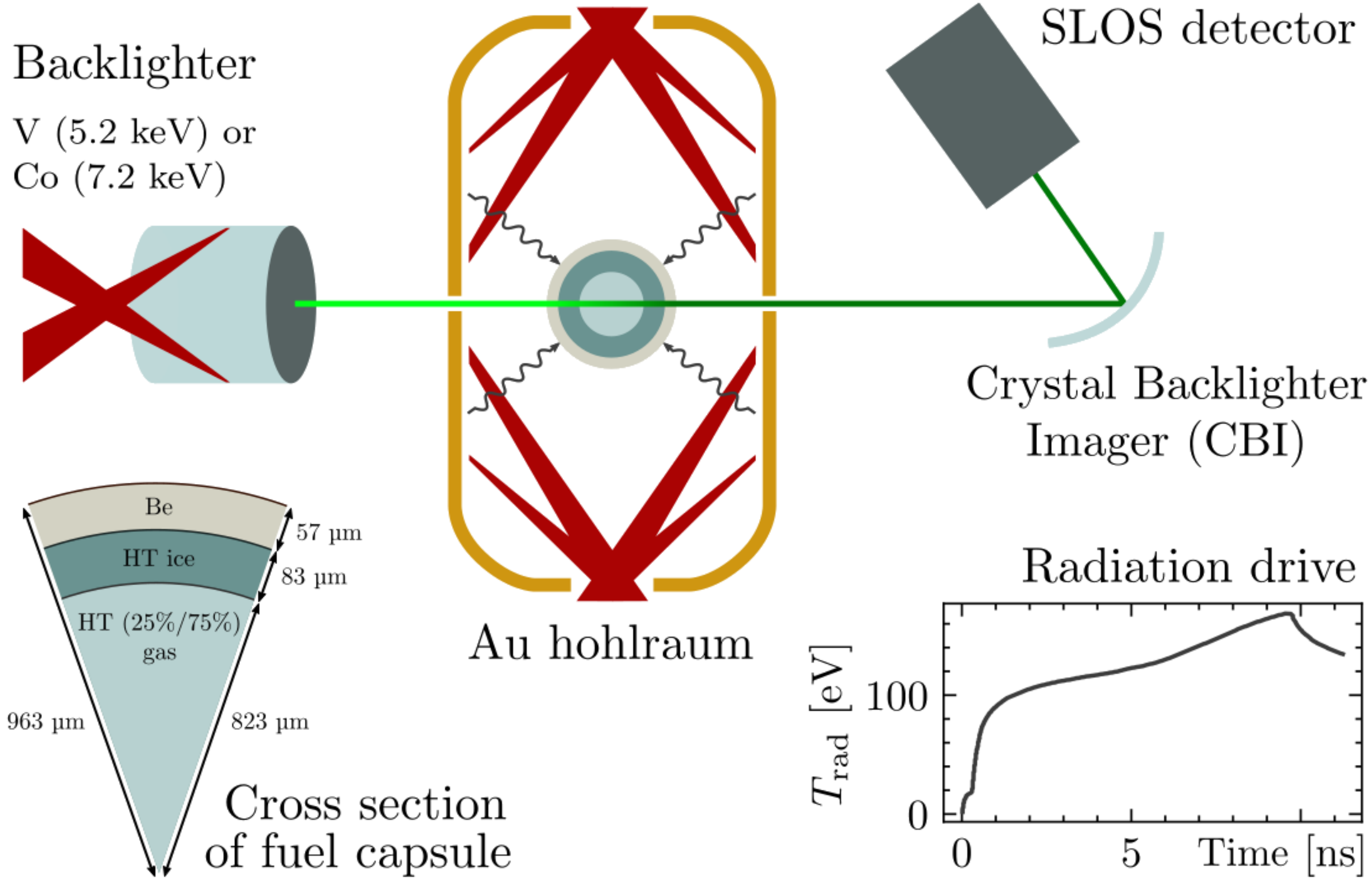
Red Dwarfs (70% of stars)

Coolest stars

Convection dominates radiation transport

Opacity dominated by Inverse Bremsstrahlung

Measurement of free-free absorption (IB) by opacity at the National Ignition Facility

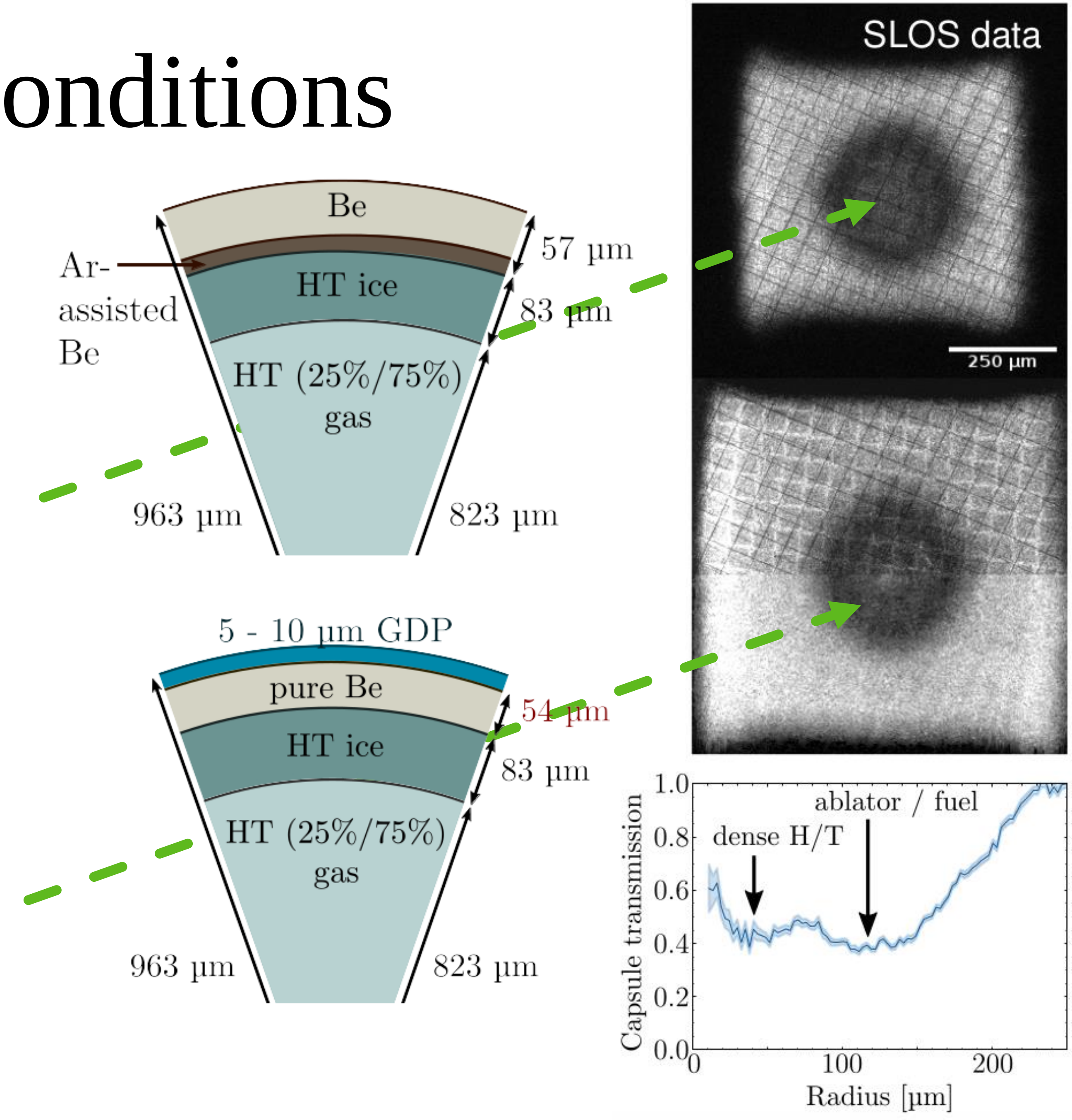


Probing Red Dwarf conditions

Probing shocked capsule with backlighter laser to obtain opacity

Single-Line-Of-Sight (SLOS) detector – ultrafast imaging

Opacity data of warm-dense useful for benchmarking models



Summary

- We need to recreate planets on earth for benchmarking and modeling!
- We can use high-power laser facilities to recreate these conditions!
- We have the experimental tools at hand!
- Dynamic material synthesis might produce novel materials – promising first results.
- We can even bring stars to earth!

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Thank you for your attention!

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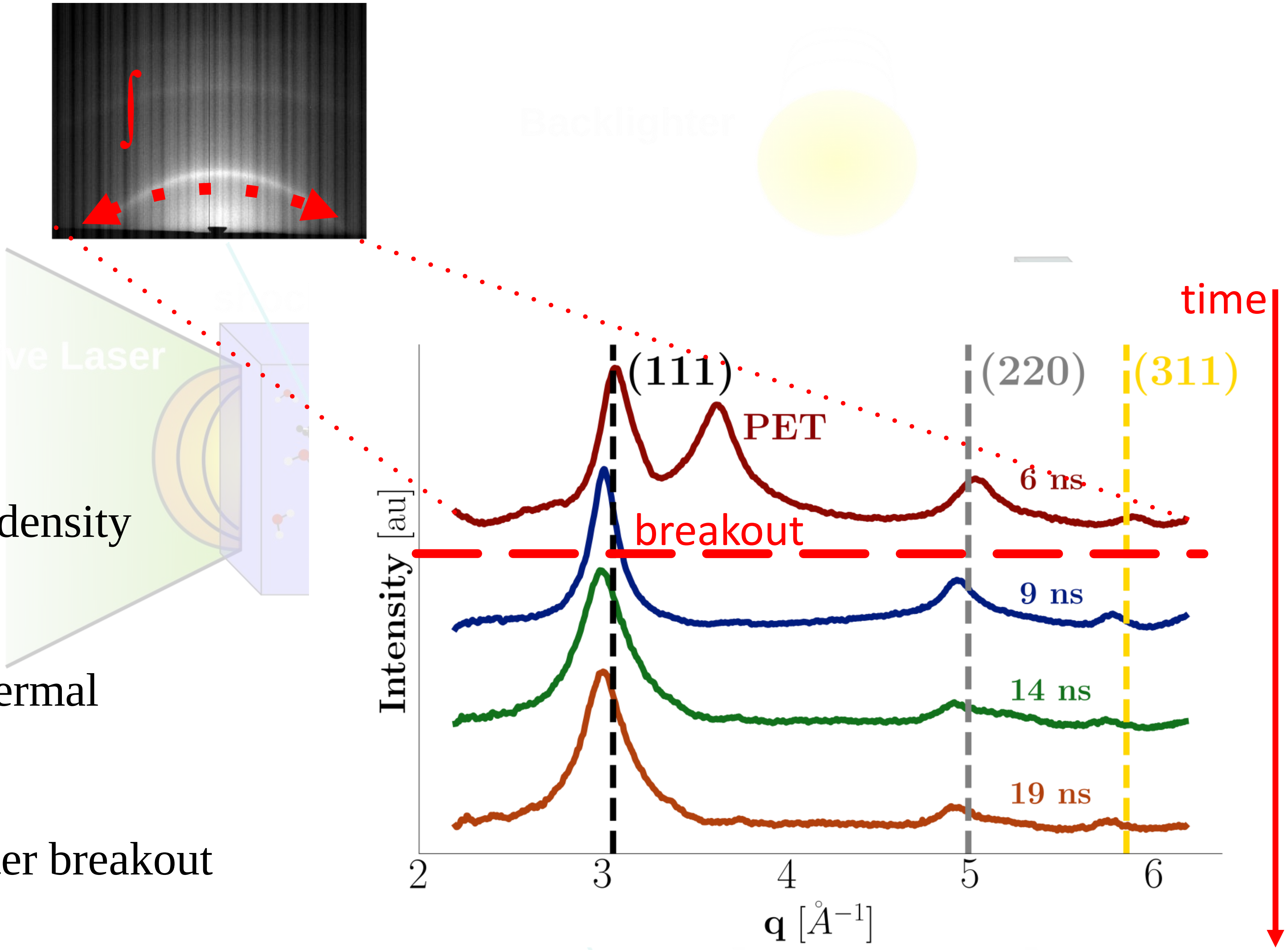
Experimental evidence of stability



ND release to ambient density after breakout

Pressure release and thermal expansion

Stability up to 11 ns after breakout