Investigating warm, dense matter with x-ray scattering

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OUTLINE

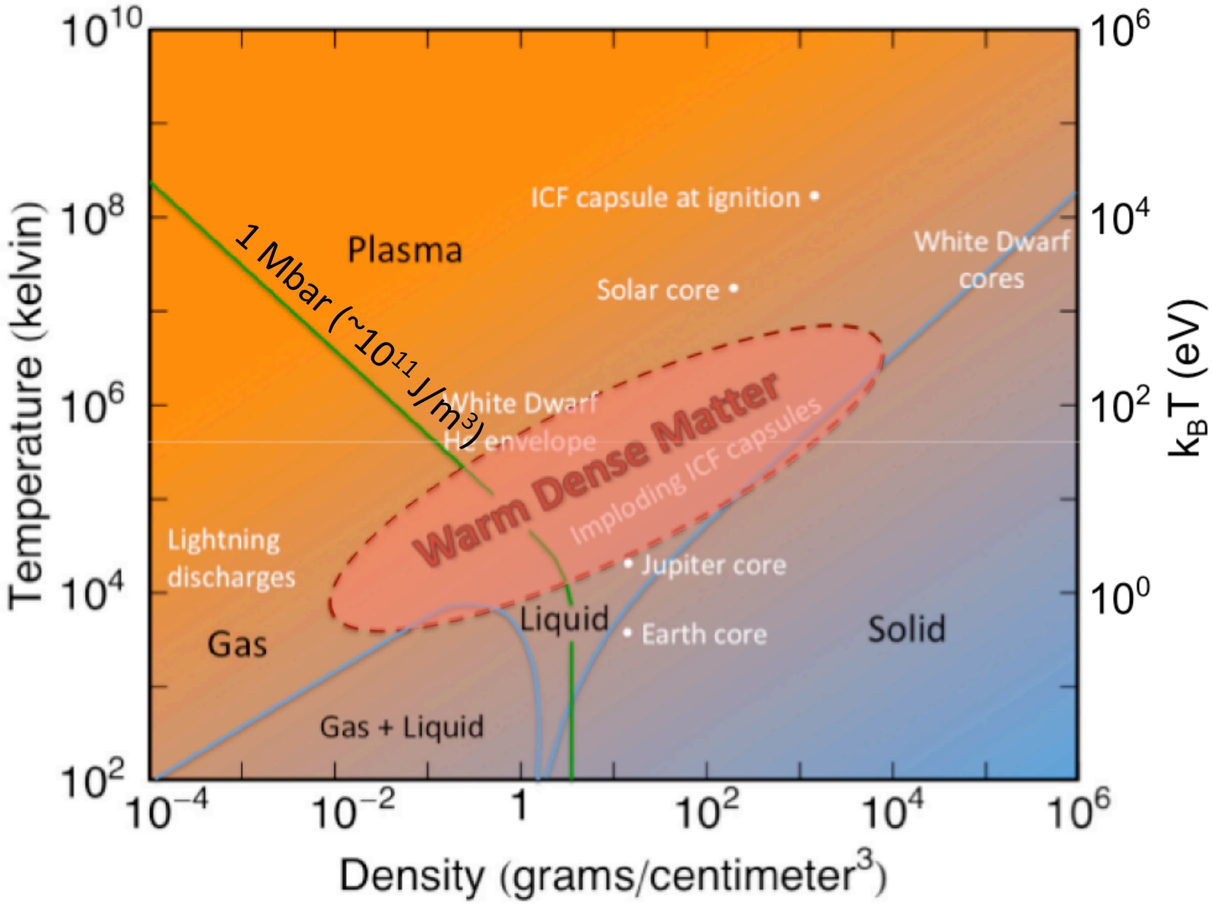
What is warm dense matter?

X-ray scattering as a dense plasma diagnostic

Ionization in shock-compressed cryogenic D_2

Band structure in proton-heated systems

The warm, dense regime presents major experimental and theoretical challenges



Experiment:

Short lived (dynamic) experiments

Opaque in the optical regime

Small targets in noisy environments

Theory:

Strongly coupled ions

Partially degenerate electrons

No small expansion parameter

From "Basic Research Needs for High Energy Density Laboratory Physics," DOE 2009

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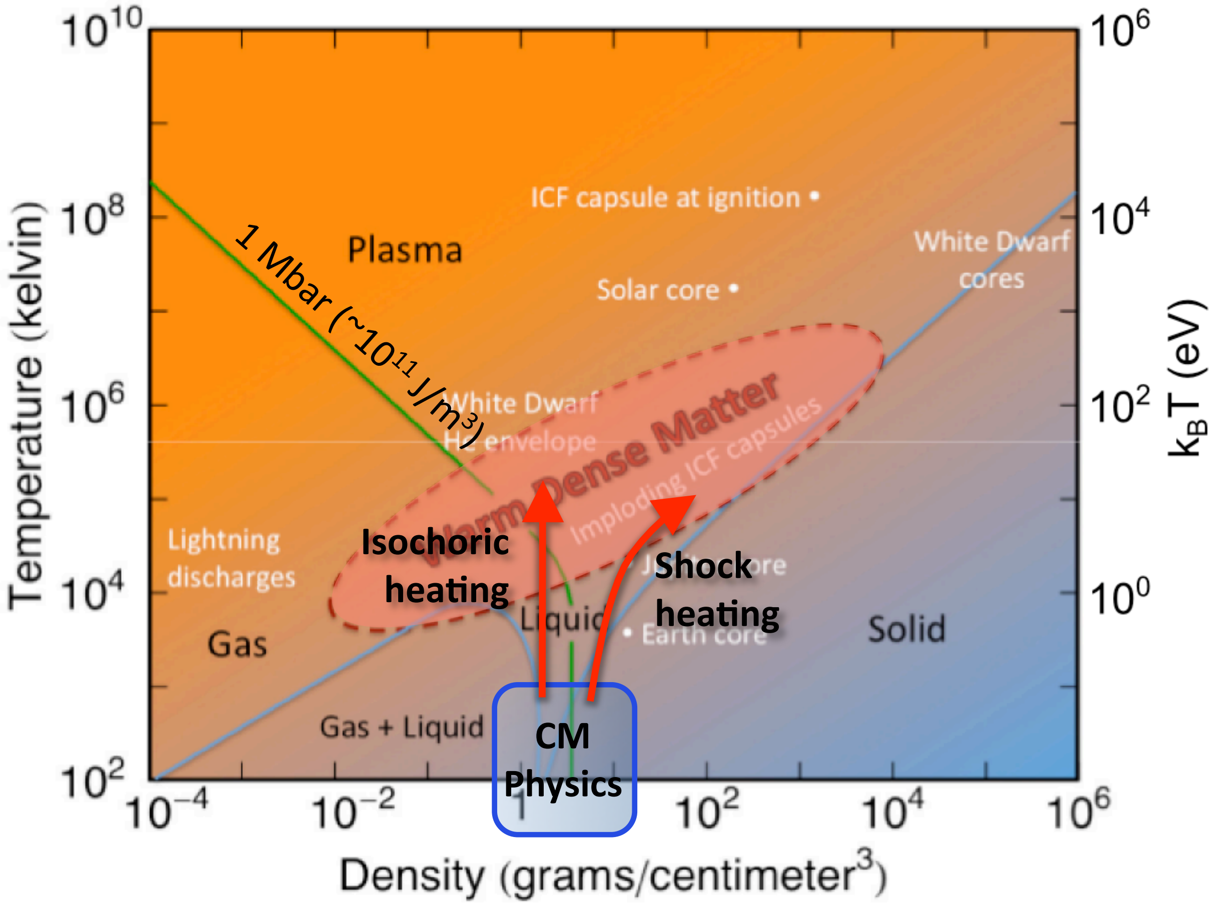

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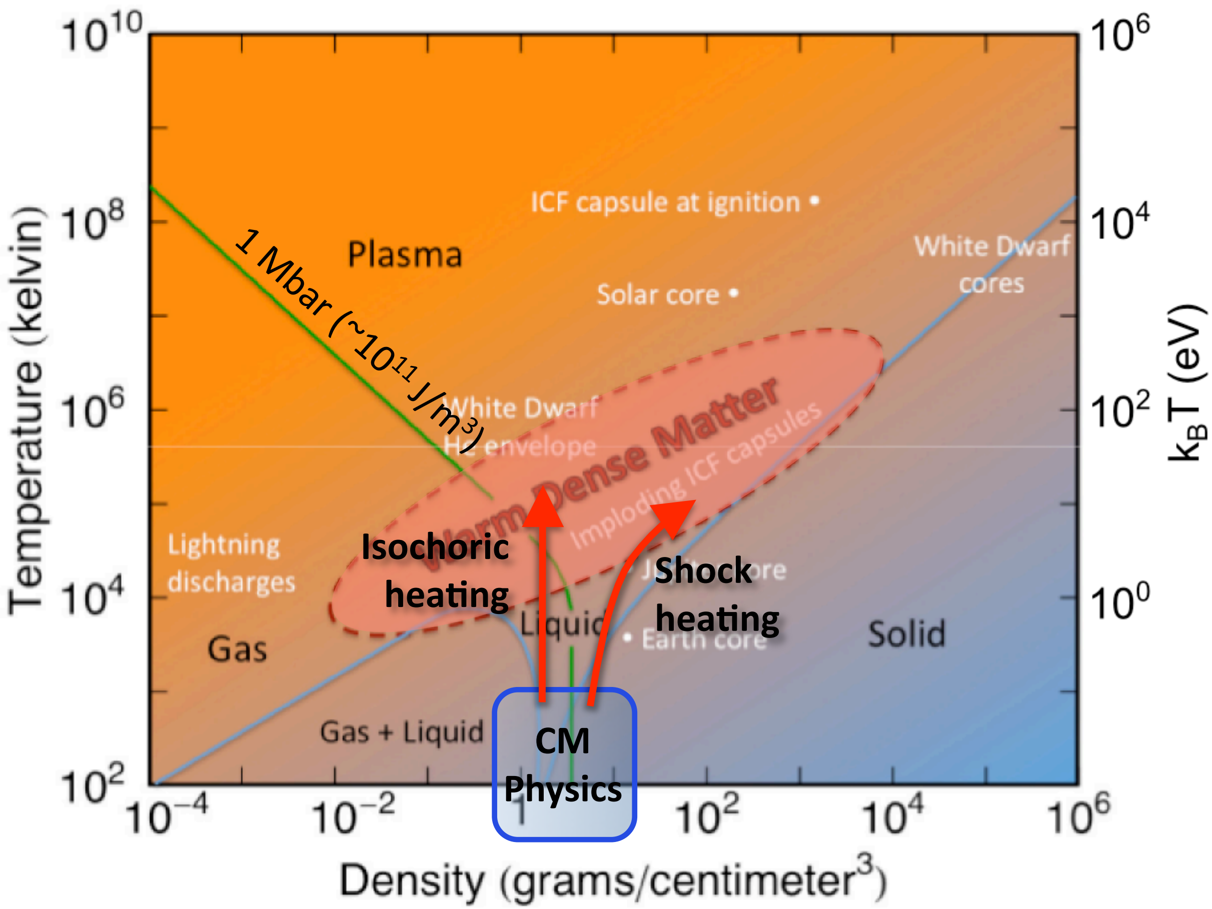

Experiment:

Short lived (dynamic) experiments
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Theory:

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X-ray scattering offers a sophisticated way of measuring material properties and testing theoretical models in dynamic experiments

From "Basic Research Needs for High Energy Density Laboratory Physics," DOE 2009

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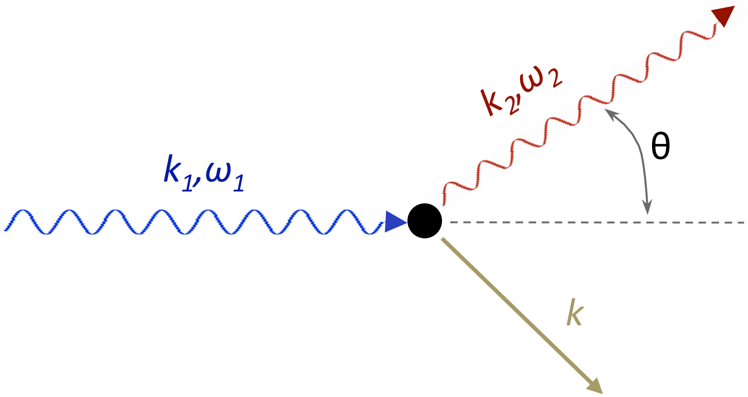
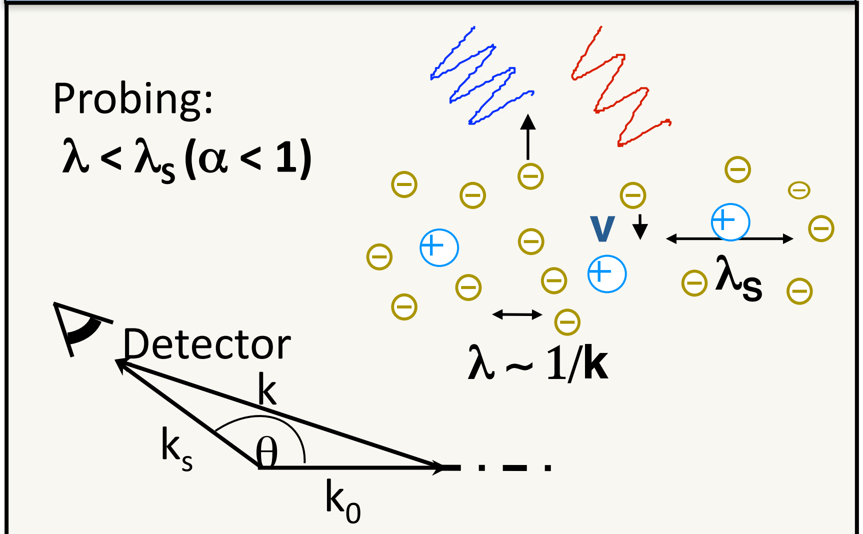
Scattering of x-rays from electrons



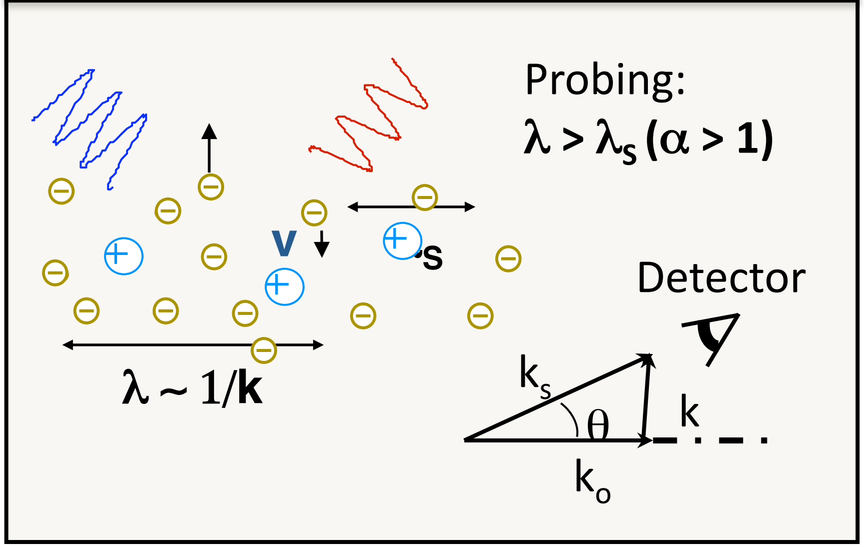
Momentum transfer $k = \frac{4\pi}{\lambda_o}\sin(\theta/2)$

Scattering is characterized by the scattering parameter α $\alpha = \frac{1}{k\lambda_s} \propto \frac{\lambda}{\lambda_s}$

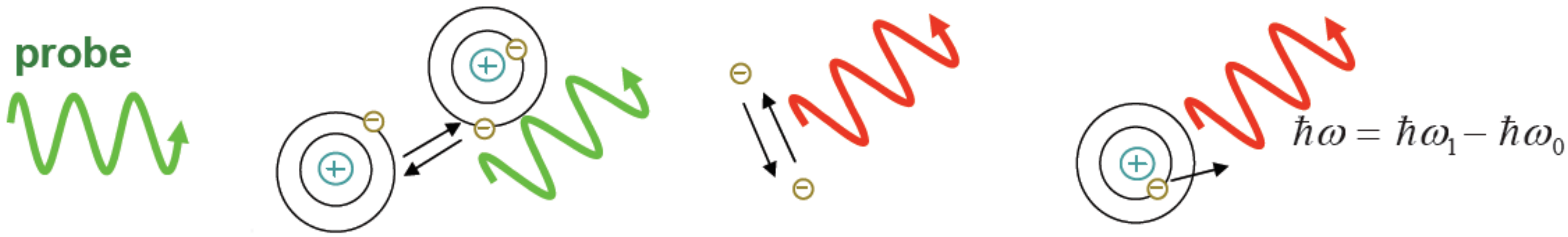
Backscatter: large θ probes non-collective (single particle) effects



Forward scatter: small θ probes collective (plasmon) effects



Scattered x-ray signal contains information about ions, free and bound electrons

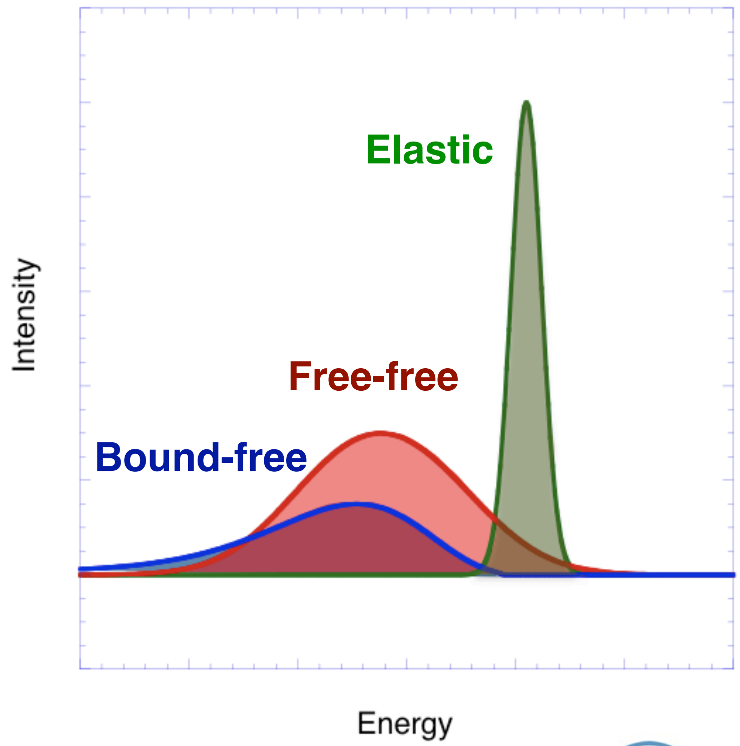


$$S_{ee}(k,\omega) = \left|f_I(k) + q(k)\right|^2 S_{ii}(k,\omega) + Z_f S_{ee}^0(k,\omega) + Z_b \int \tilde{S}_{ce}(k,w-w')S_s(k,w')dw'$$

Quasi-Elastic:
Scatter from tightly bound and screening e^-
-sensitive to T_e

Free-free:
Scatter from free (delocalized) e^-
-sensitive to n_e

Bound-free:
Compton scatter into continuum
-sensitive to bound e^- wavefunction



Gregori *et al*, Phys. Rev. E., **67**, 026412, (2003)

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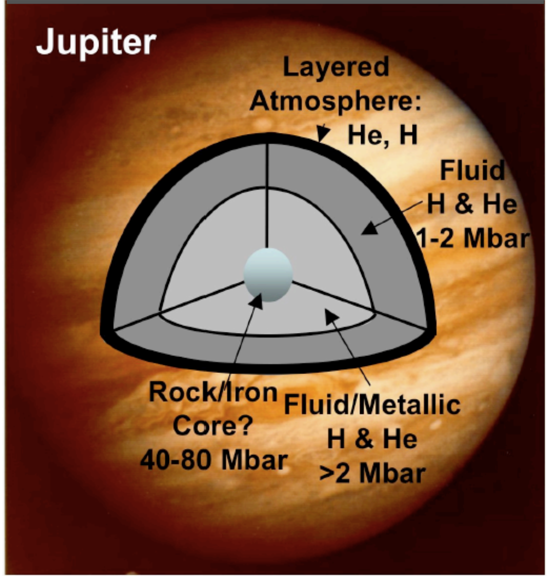
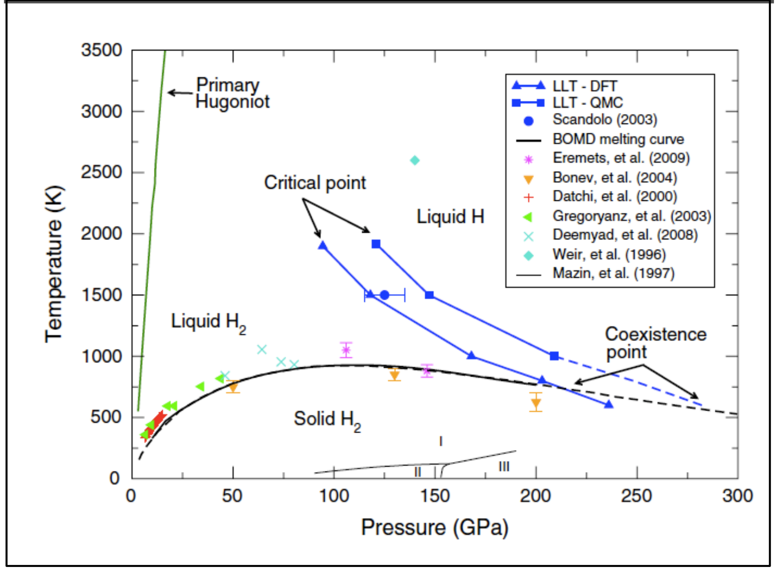
Band structure in proton-heated systems

The properties of hydrogen under extreme conditions are important to several fields of physical science

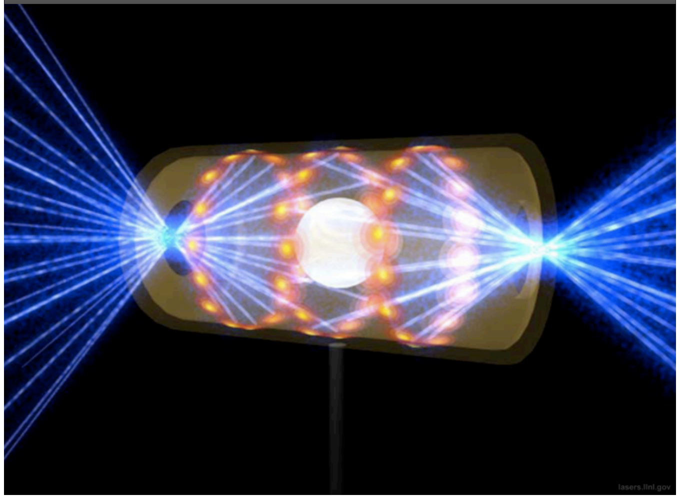
Planetary Science



Basic Science



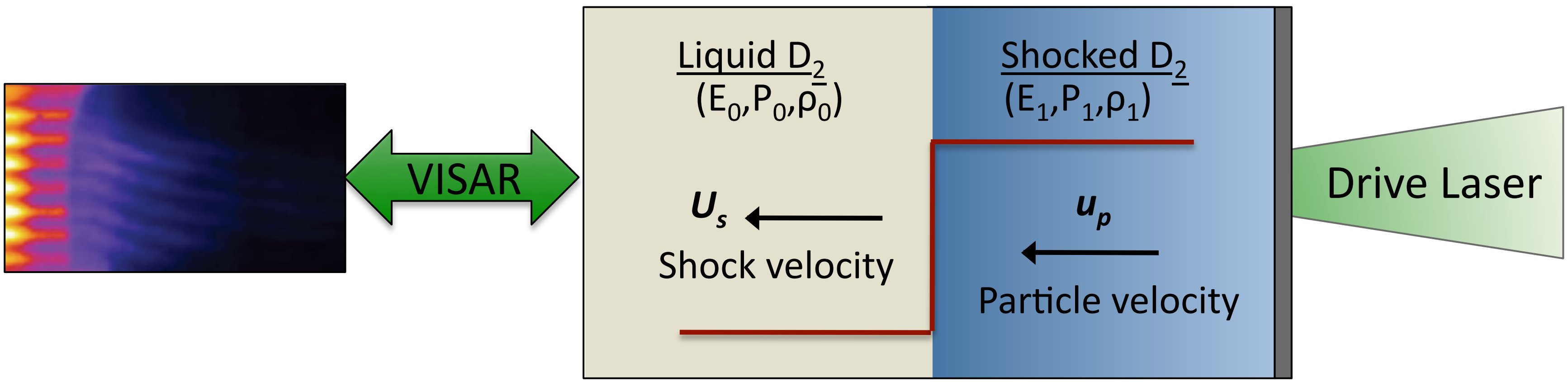
Inertial confinement fusion



H.B. Neimann, Science **272**, 846 (1996), M. Morales et al, PNAS **107**, 12799 (2010)

Laser-driven shocks can be used to study the high-pressure behavior of hydrogen

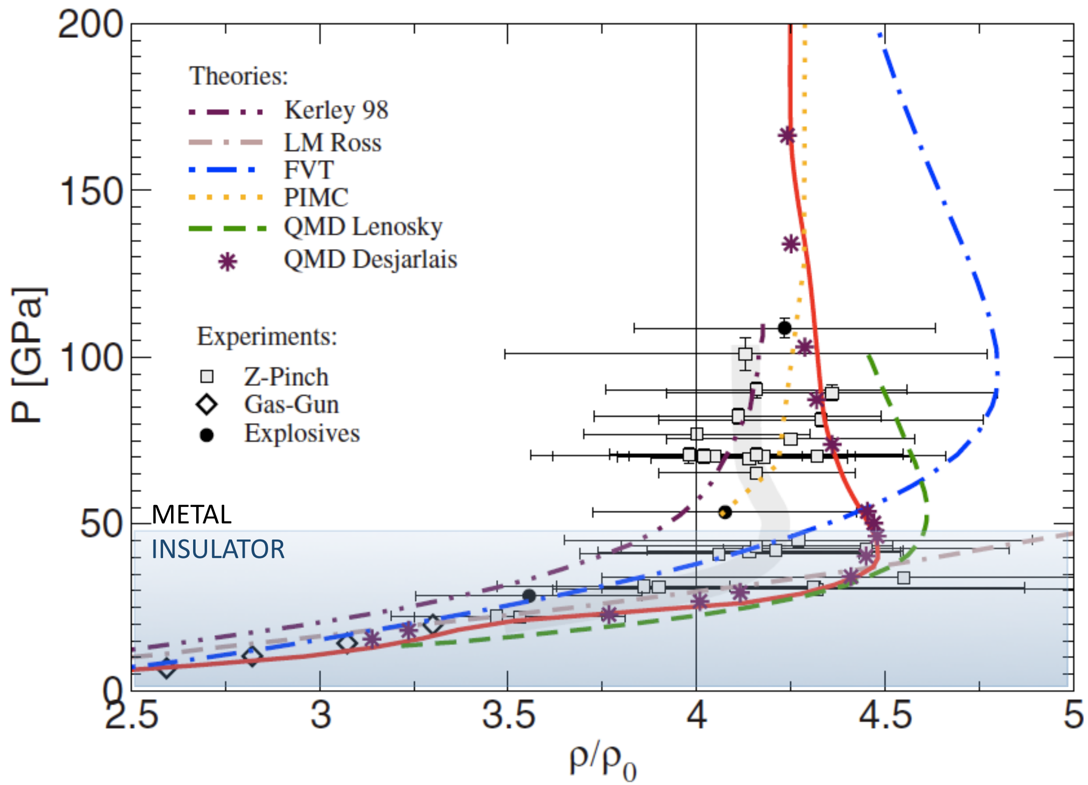
High intensity laser irradiation creates an ablation pressure that drives a shock into a hydrogen target.



Since hydrogen is reflective at high pressure, velocity interferometry (VISAR) can be used to measure the shock velocity and infer material properties.

Liquid hydrogen becomes metal-like under shock compression

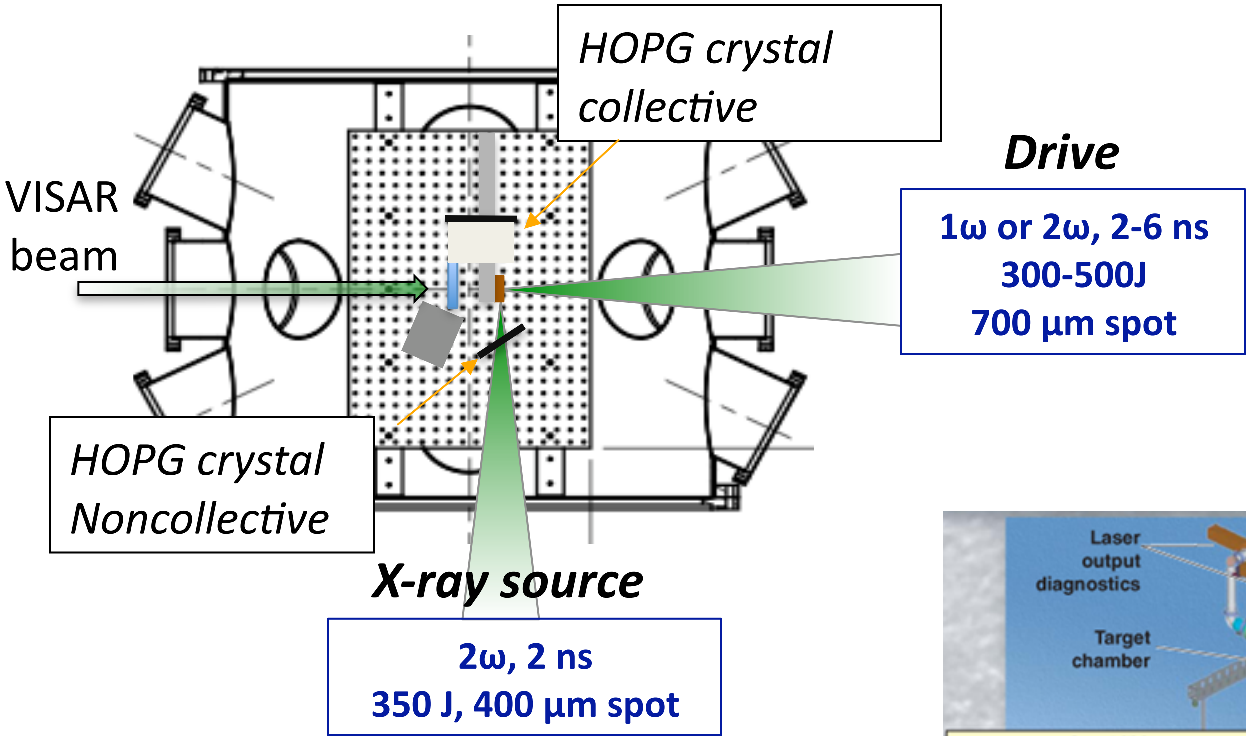
Previous experiments have measured the hydrogen Hugoniot, observing a transition to metallic behavior

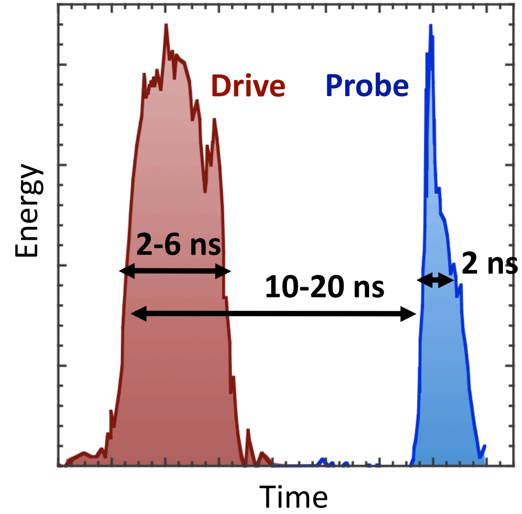


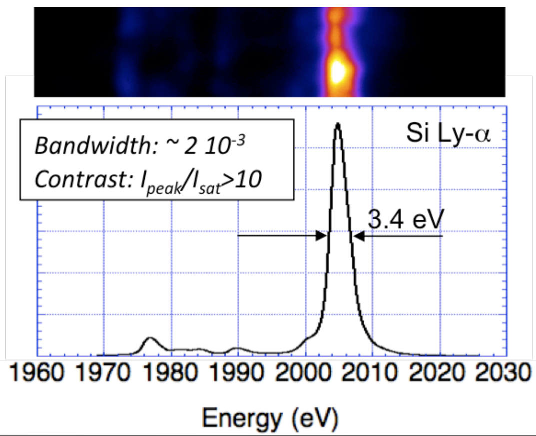
We use x-ray scattering to directly observe the free electron oscillations produced by shock-induced ionization along the Hugoniot

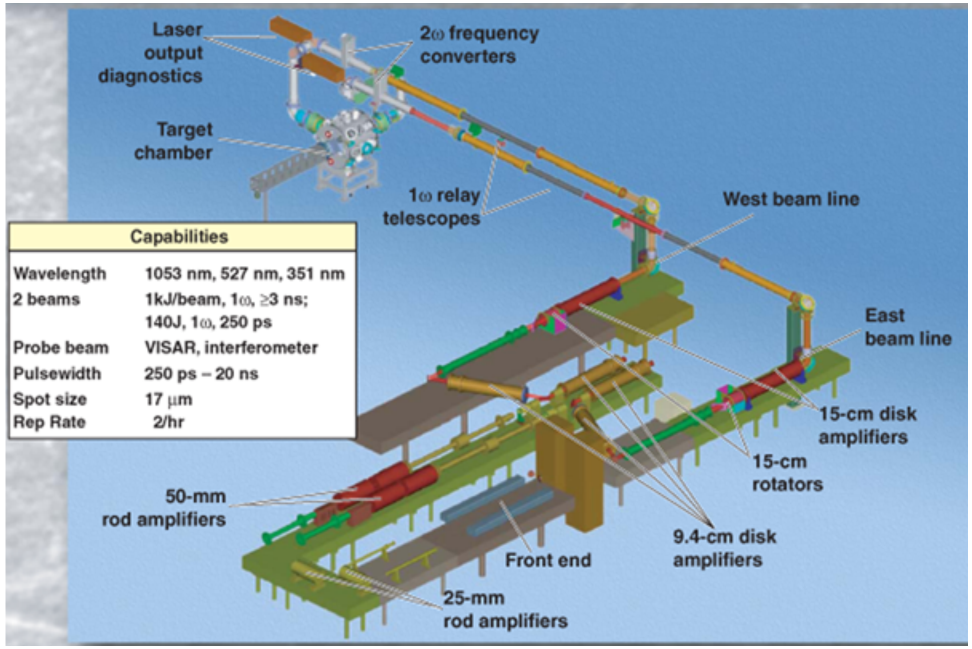
B. Holst *et al*, Phys. Rev. B **77**, 184201 (2008)

Experiments on cryogenic deuterium were performed at the 2 beam, long pulse Janus facility

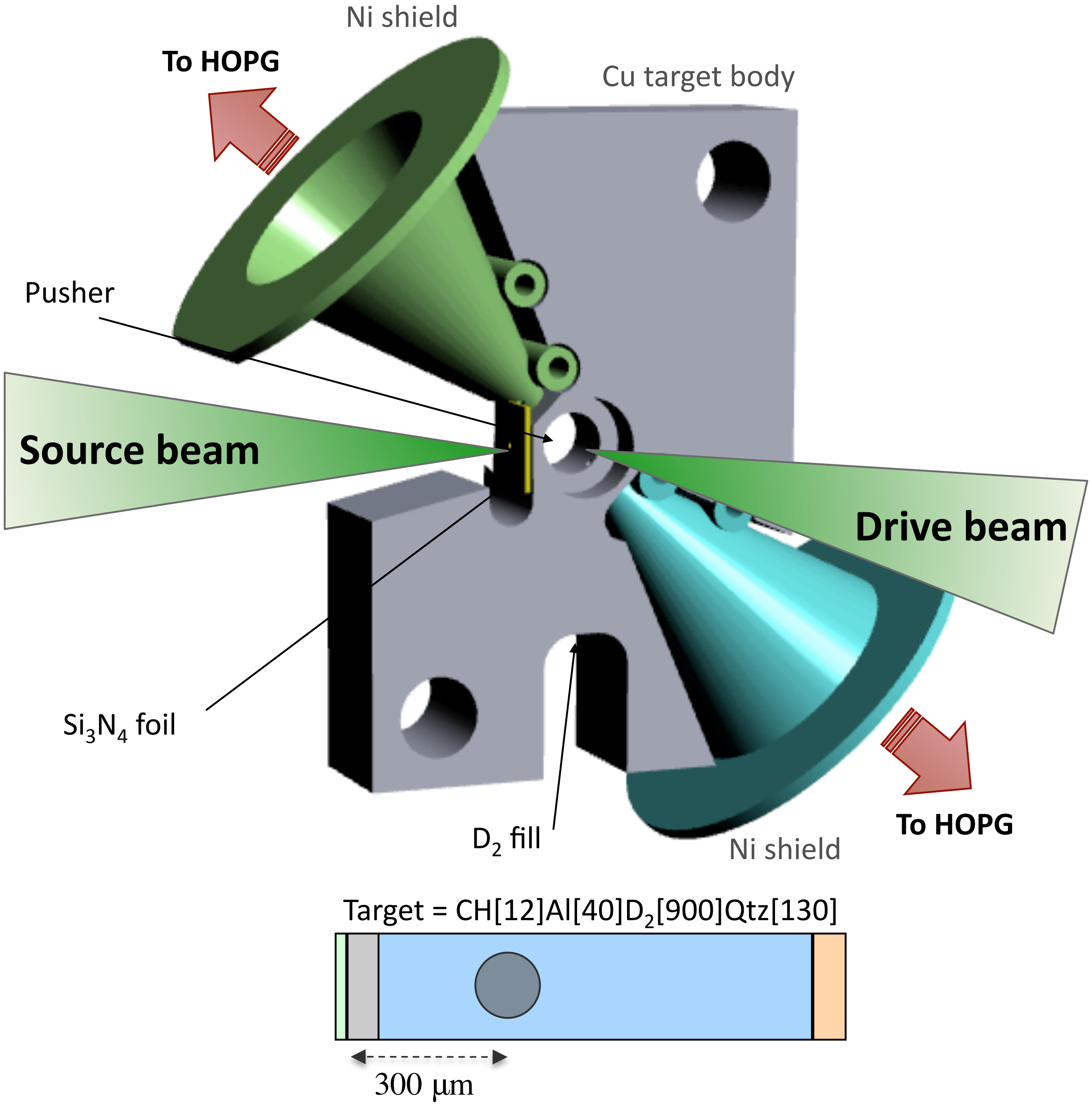


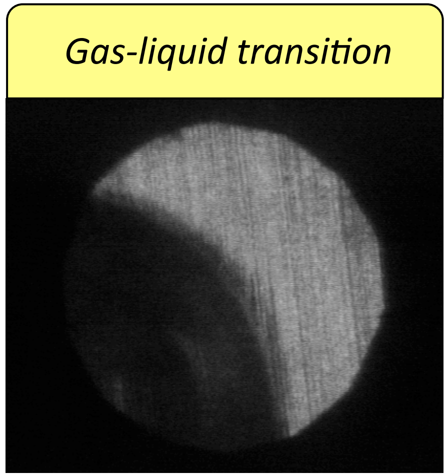


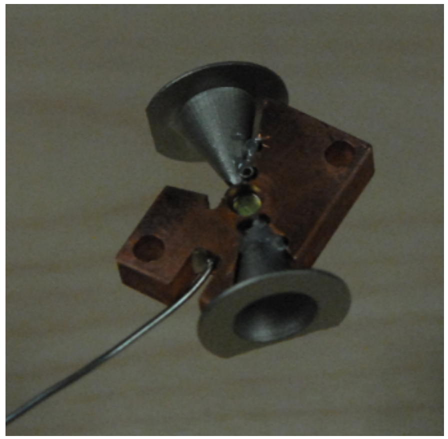




Cryogenically cooled copper target cell integrates x-ray source, scattering geometry and x-ray shielding

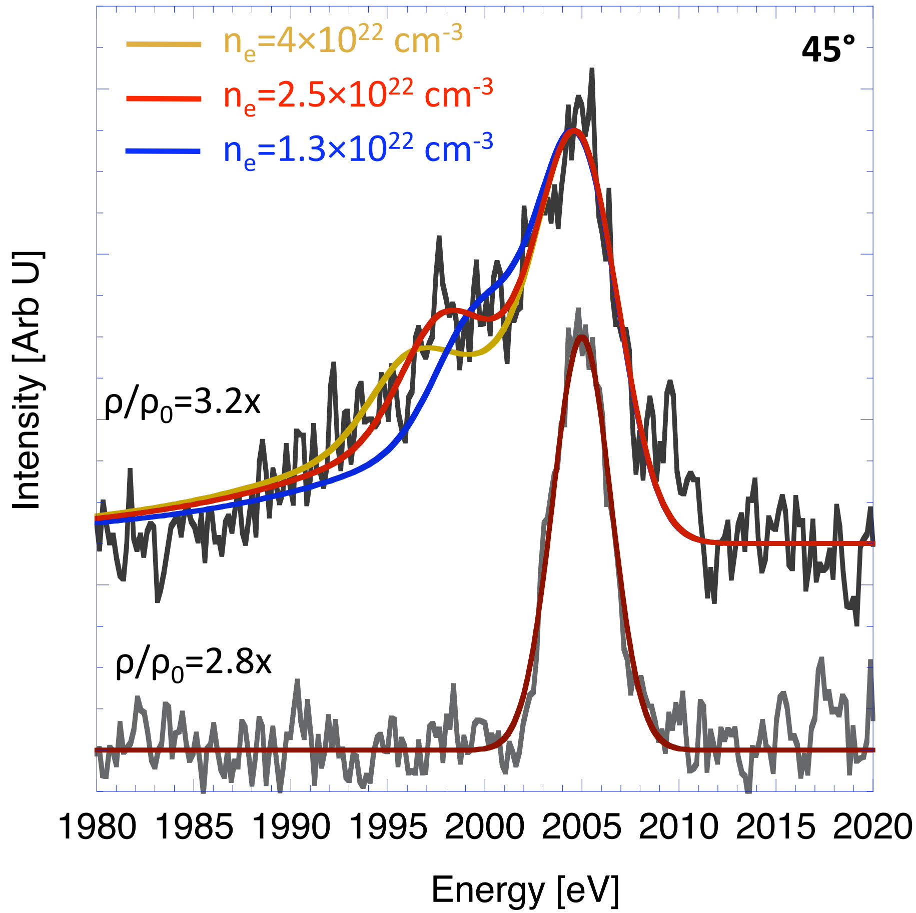




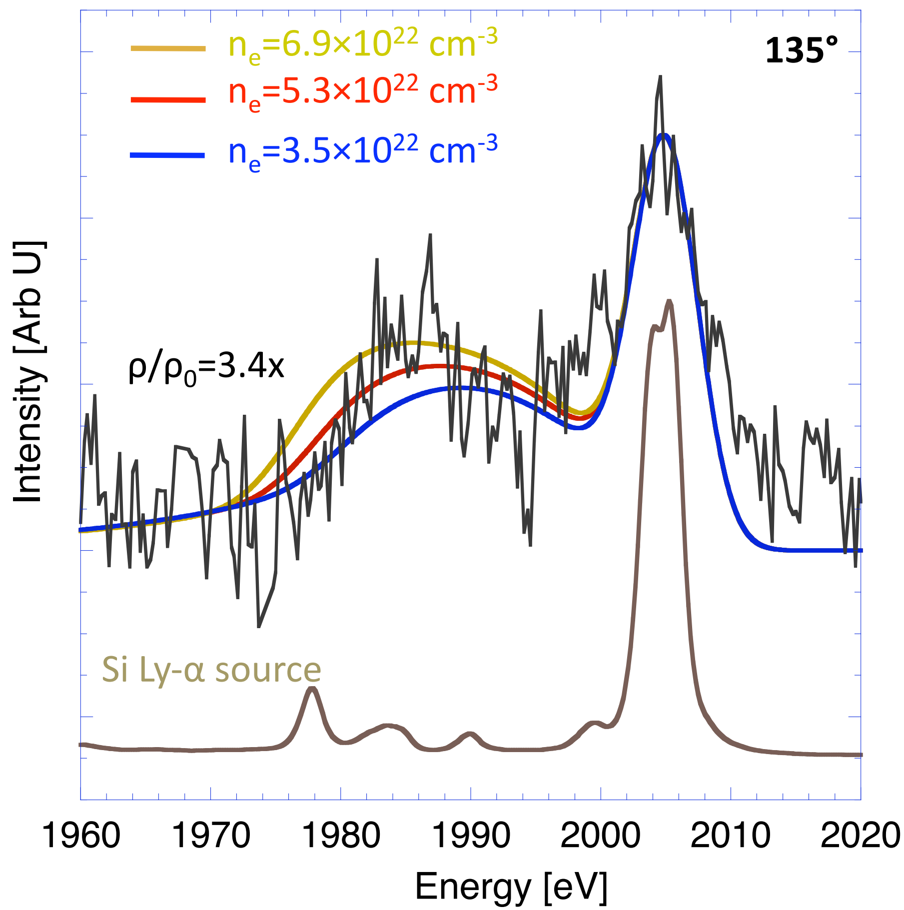


Free electrons are observed at compressions > 3x

Forward scattering spectrum shows the emergence of plasmons at ρ/ρ_0=3.2x

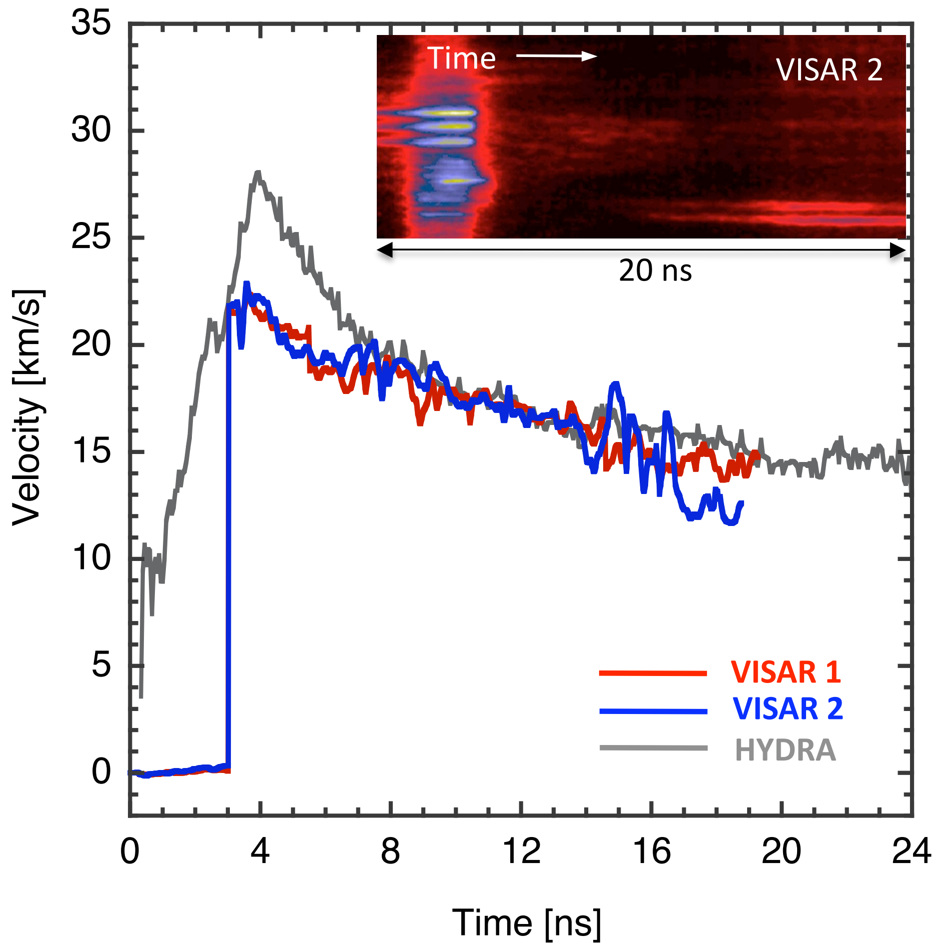


Backscattering spectrum corroborates onset of ionization

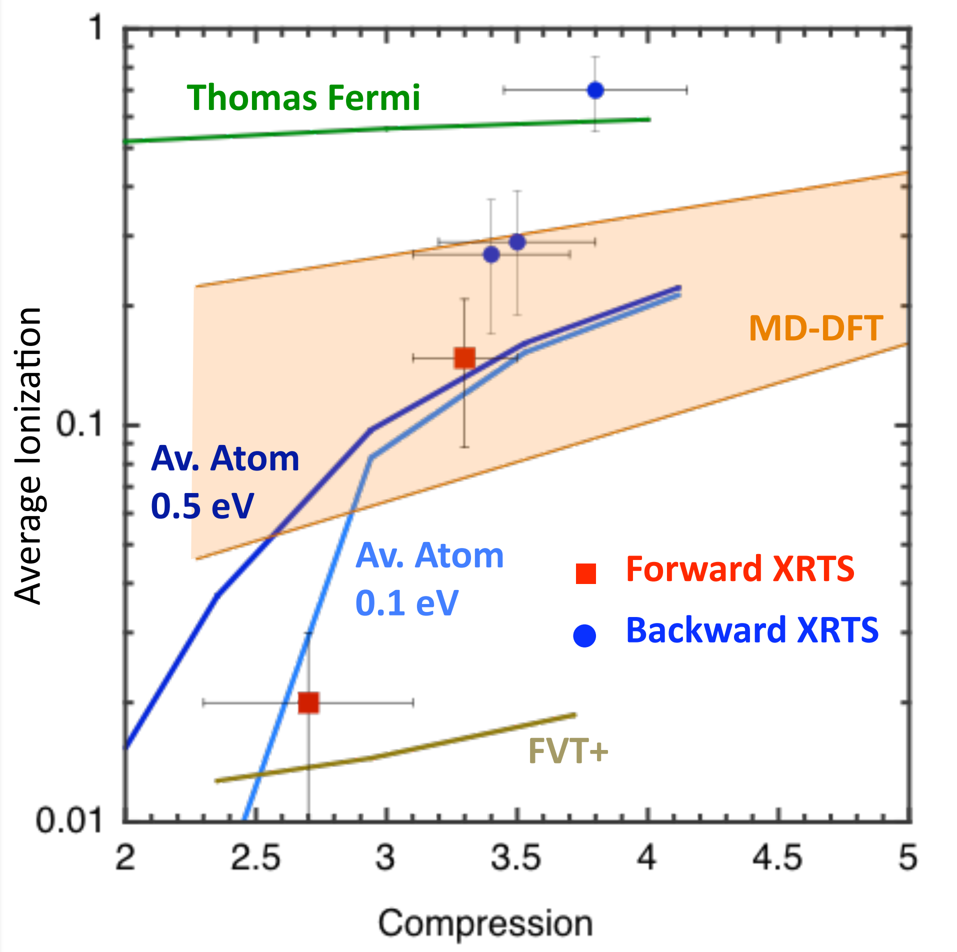


With VISAR and HYDRA simulations, we infer a sharp onset in ionization of compressed Deuterium

Shock velocity measurements and simulations allow us to extract mass density



Ionization occurs very quickly past compressions of 3x



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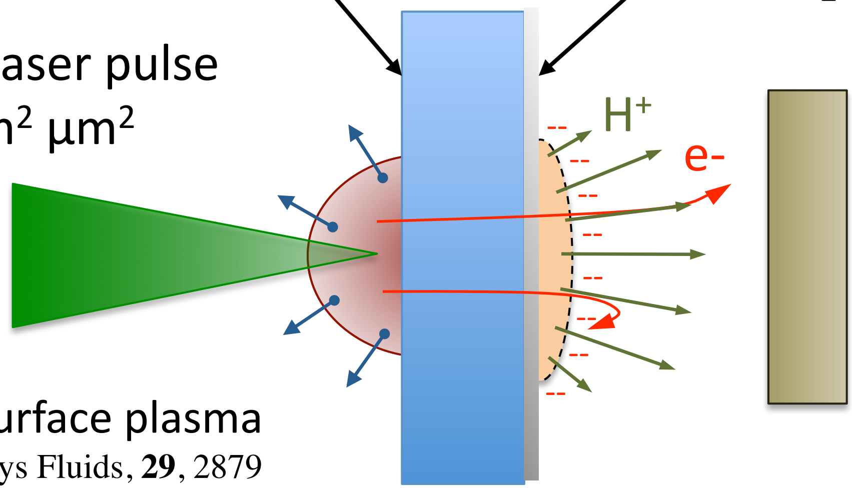
Band structure in proton-heated systems

We use TNSA protons to volumetrically heat solids to 10s of eV

High intensity laser pulse
$I\lambda^2 \geq 10^{18}$ W/cm^2 μm^2

Bulk target

Surface contaminant (CH, H_20)



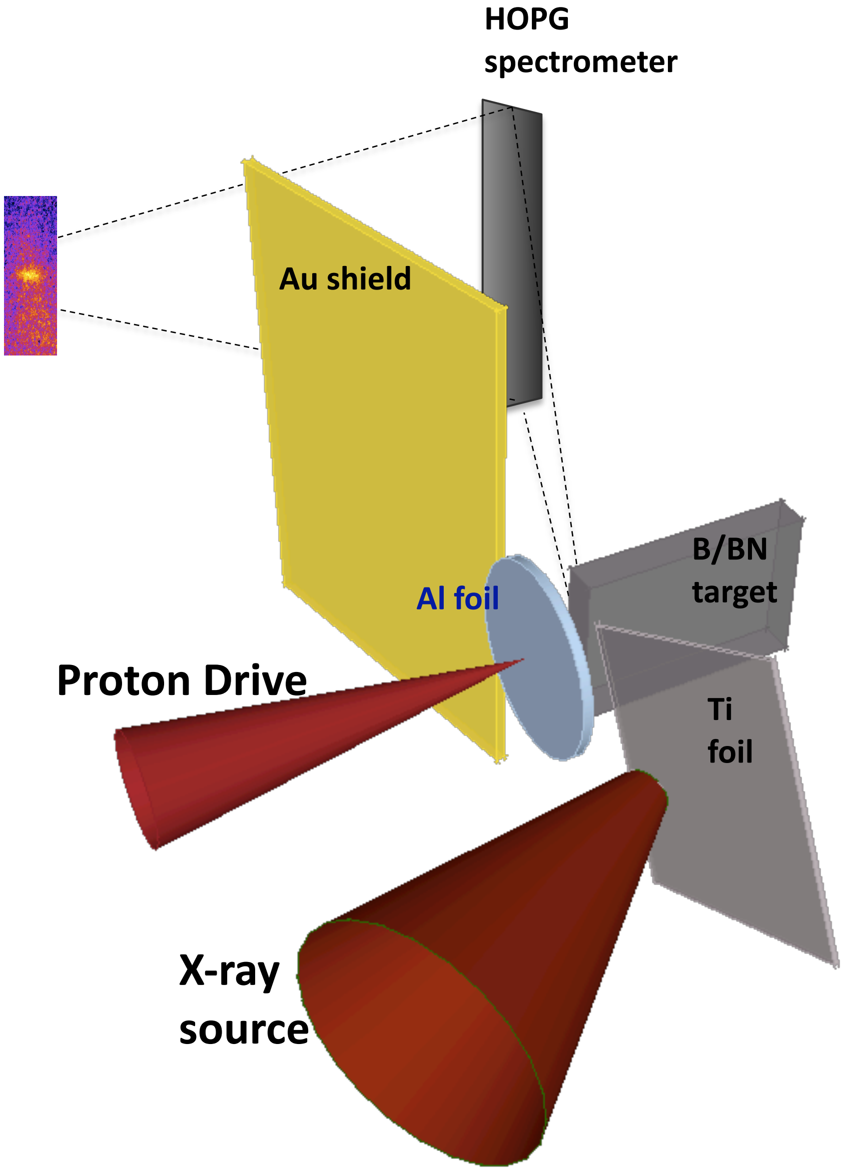
Target material is heated isochorically on ps time scale
Patel *et al*, Phys. Rev. Lett., **91**, 125004 (2003)

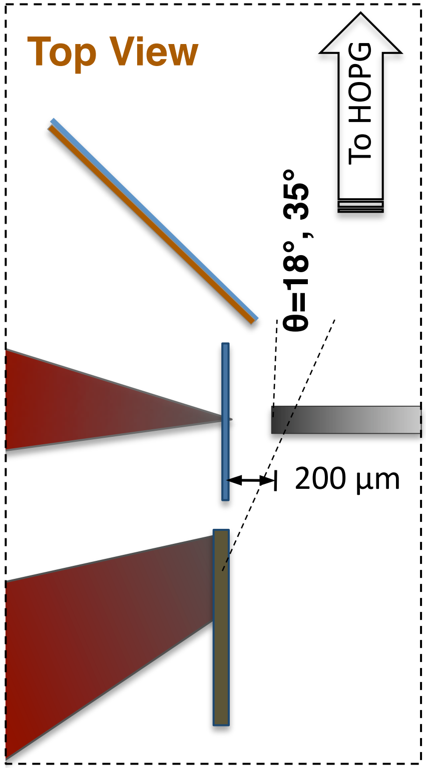
Expanding surface plasma
Gitomer *et al*, Phys Fluids, **29**, 2879 (1986)

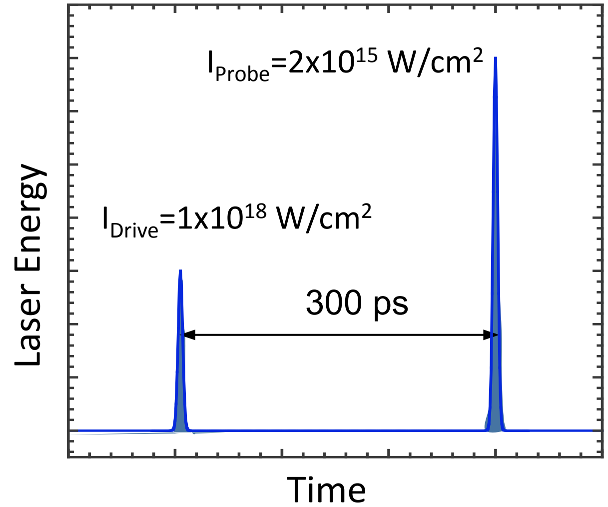
Rear surface ion acceleration
Snavely *et al*, Phys. Rev. Lett., **85**, 2945 (2000)

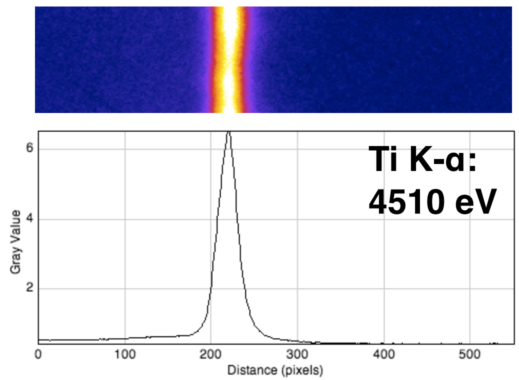
Volumetric isochoric heating preserves mass density until hydrodynamic expansion occurs.

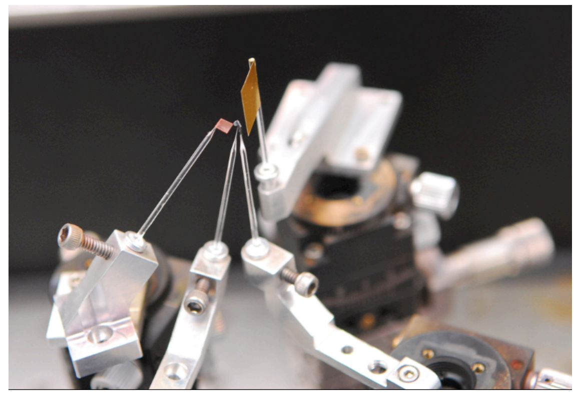
At LLNL's Titan laser, we split the ultra-high-intensity pulse into two arms to study high-T solids





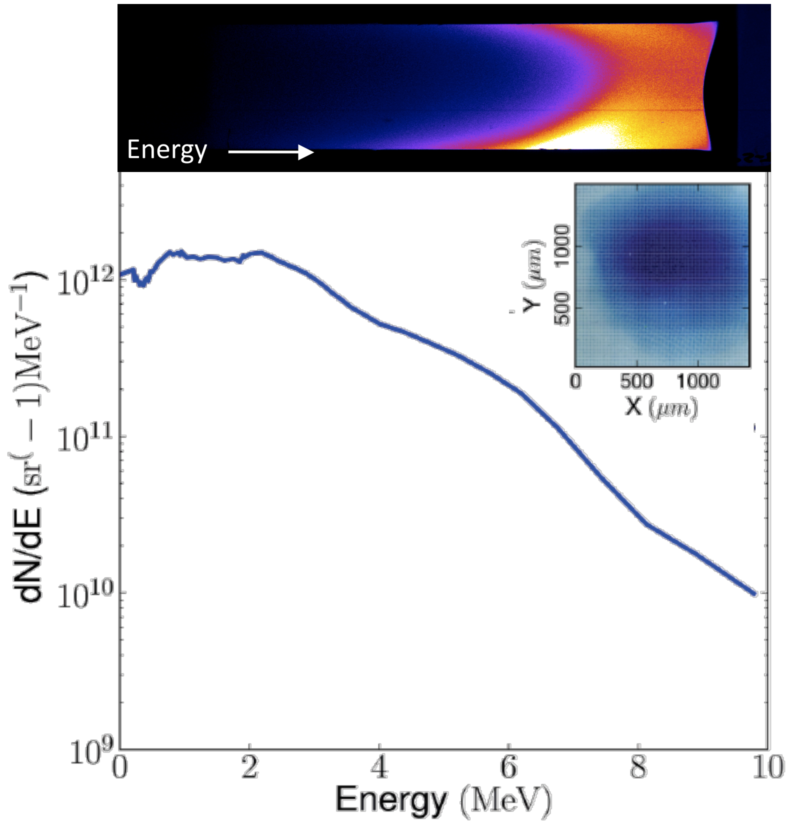






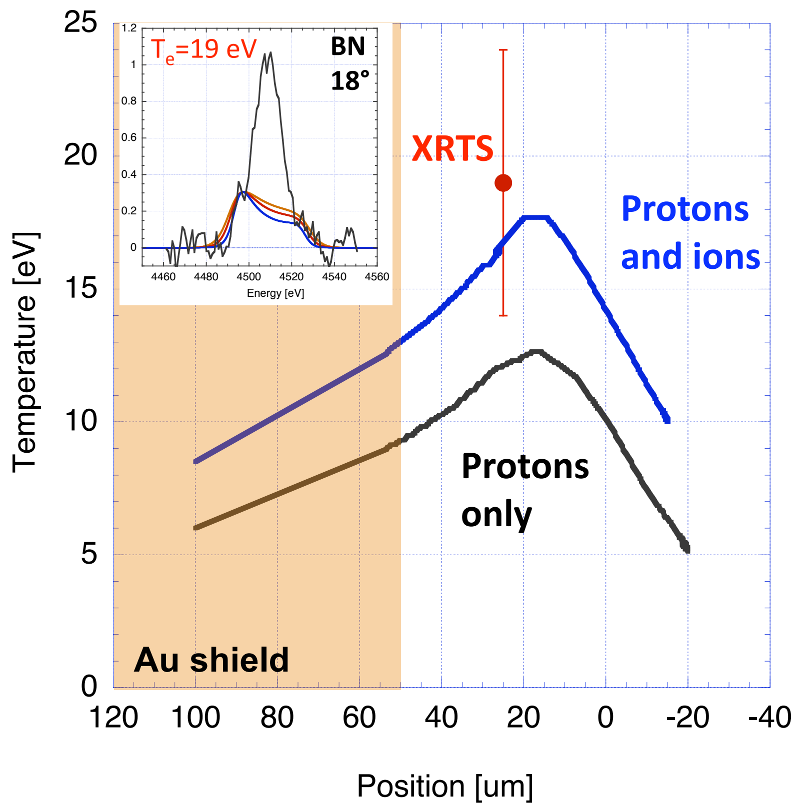
TNSA proton beam heats targets to nearly 20 eV

Proton beam is characterized with RCF stacks and proton spectrometer



Average proton range in target ≤ 50 μm

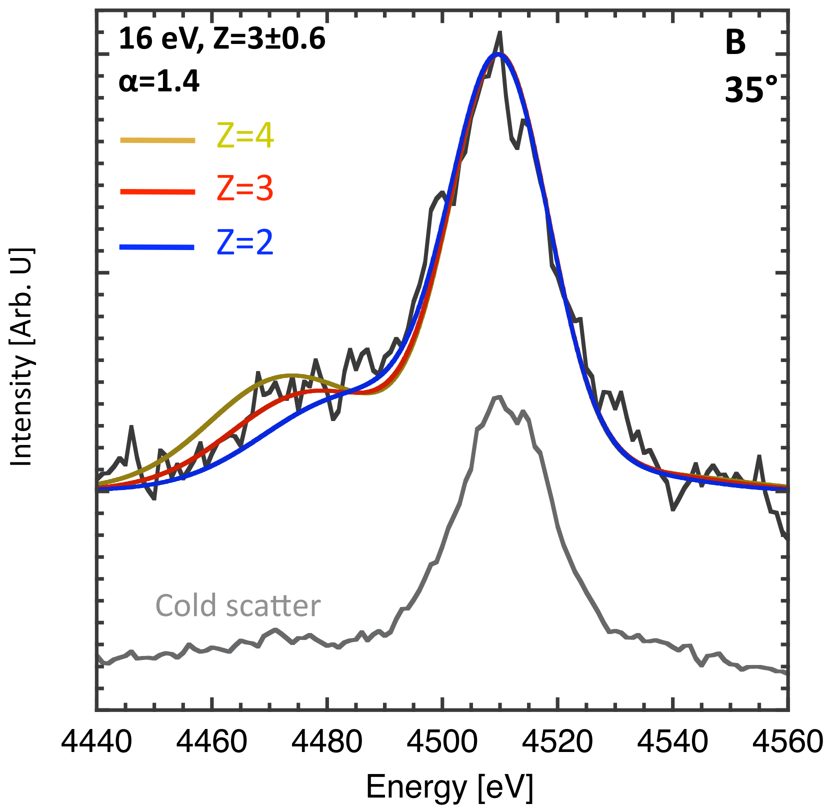
LASNEX T_e calculations



Detailed balance temperature measurement is consistent with hydrodynamic simulations

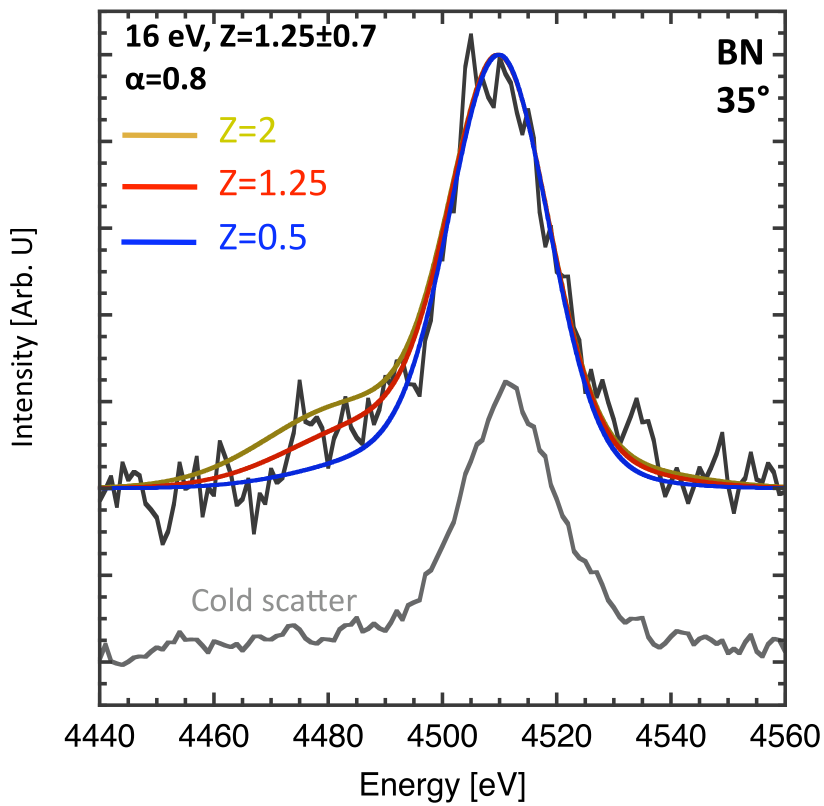
Plasmon measurements indicate BN ionization < 50% B at similar temperatures

Boron



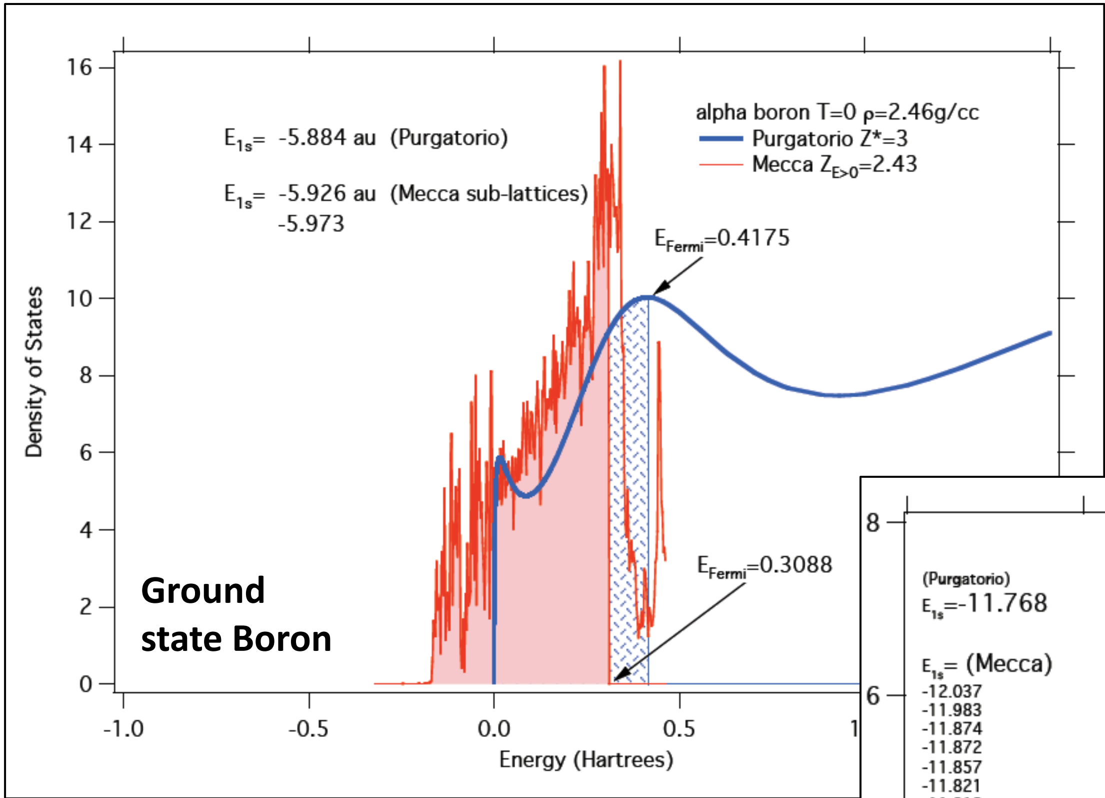
B shows strong plasmon signal corresponding to predicted levels of ionization

Boron Nitride

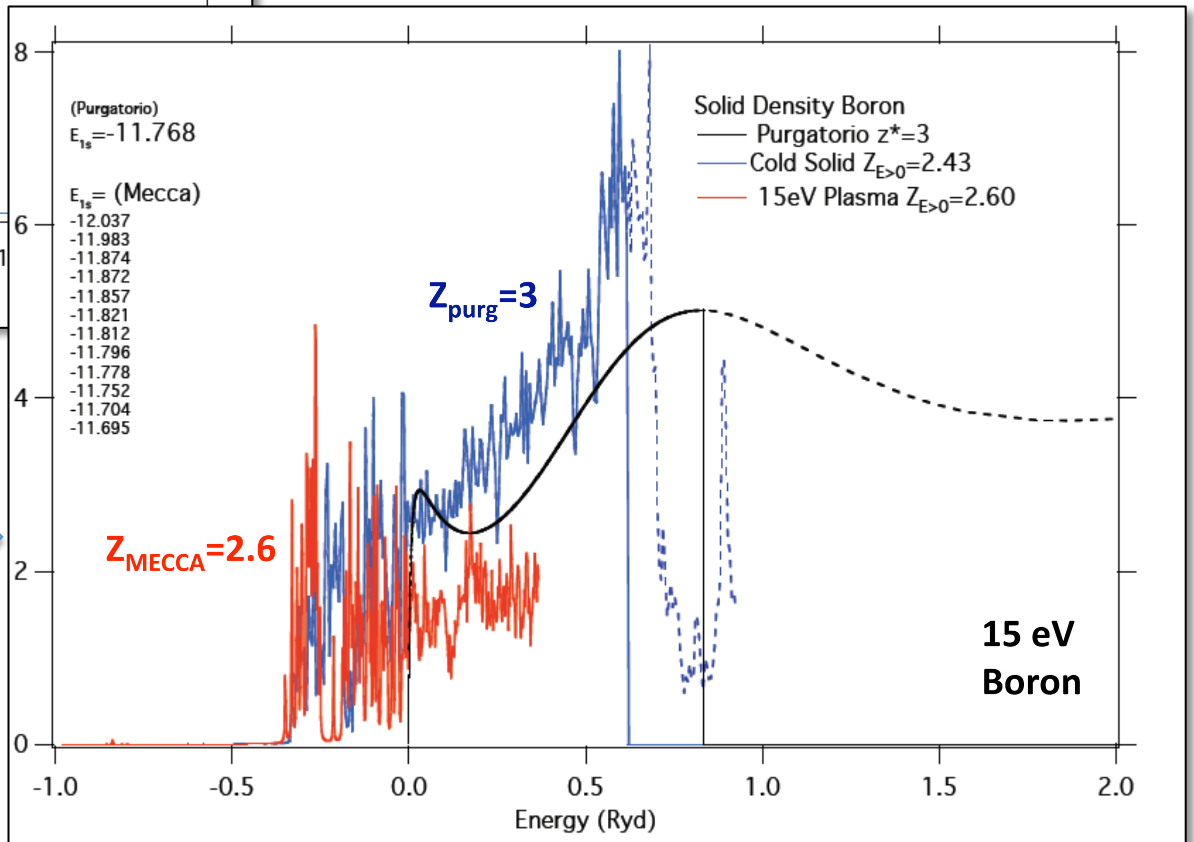


BN has a small inelastic feature – scattering has become non-collective due to very low ionization

Simulations show Boron becomes plasma-like under proton heating

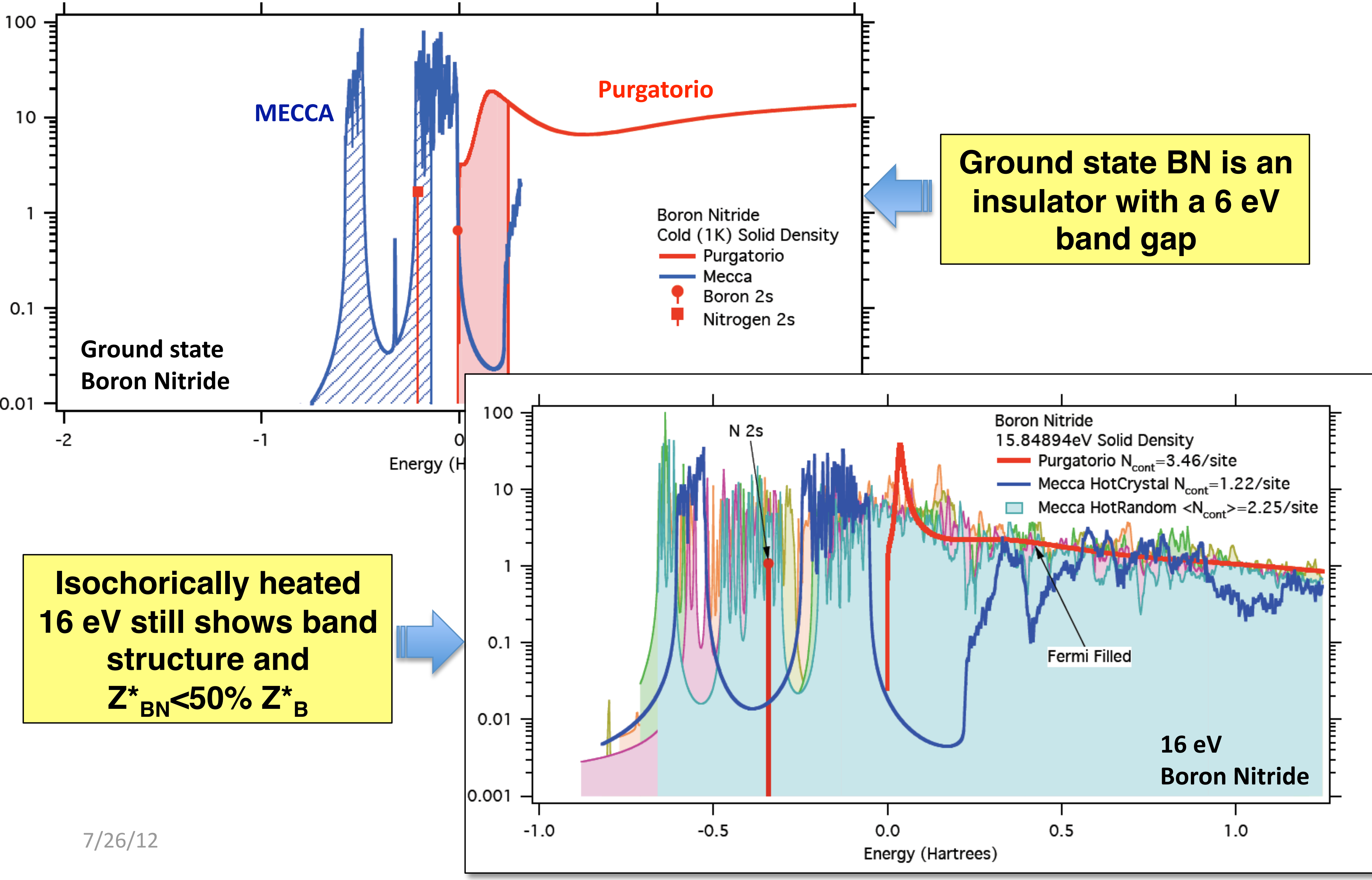


Ground state B is a semi-metal



Isochorically heated 15 eV B is metallic

Persistent band gaps in high temperature Boron Nitride reduces presence of free electrons



Ground state BN is an insulator with a 6 eV band gap

Isochorically heated 16 eV still shows band structure and $Z^*_{BN} < 50\% \, Z^*_B$

Conclusion

X-ray scattering is a powerful probe of dense plasma conditions

First observations of x-ray scattering in cryogenic D_2

- **-onset of pressure ionization at compressions ~ 3**
- **-platform can be scaled to study D_2 structural phase transitions on LCLS and extreme pressure behavior at NIF**

First observations of x-ray scattering in proton-heated matter

- **-evidence for high temperature band structure**
- **-continued development of theory capability for electron structure at 10s of eV**
- **-ongoing Titan experiments in proton-heated systems**

Conclusion

THANK YOU