# X-Ray Diagnosis Techniques for Warm Dense Matter

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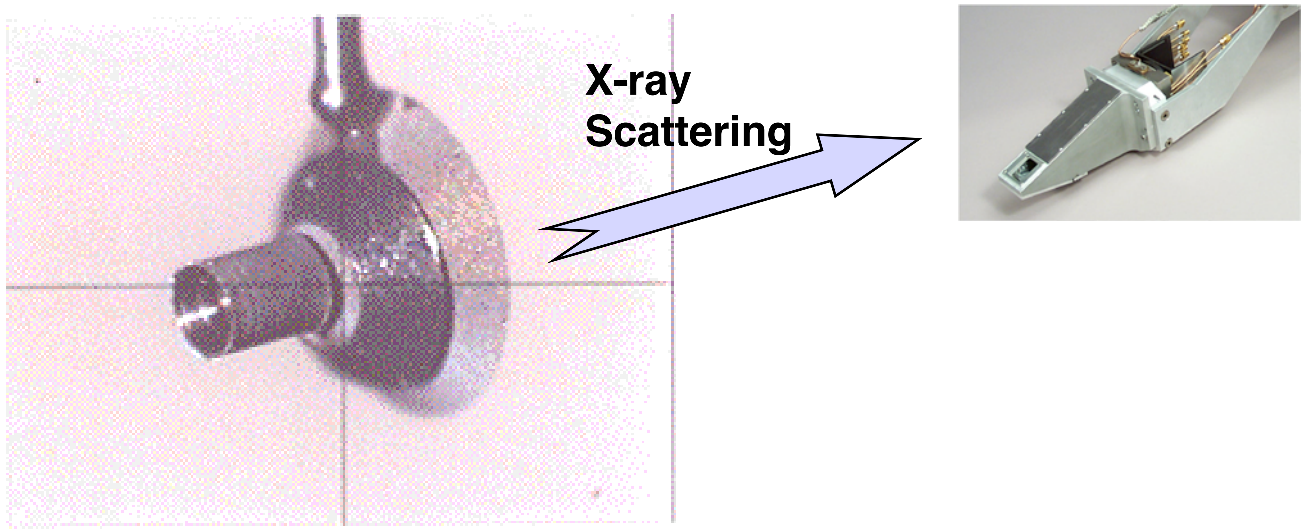


**Otto L. Landen, P.T. Springer, G.W. Collins, W.W. Hsing, S.H. Glenzer, G. Gregori, B.A. Remington, D.H. Kalantar, K.T. Lorenz, J. Edwards, R. Heeter, R. Shepherd, B. Yaakobi, D.D. Meyerhofer, J. Wark, D. Riley, E. Wolfrum, R.W. Lee**

**Workshop on Accelerator Driven Warm Dense Matter Physics**

**Pleasanton, CA**

**Feb 23, 2006**

# Warm dense matter spans bound and conduction electron to quantum and classical free electron physics

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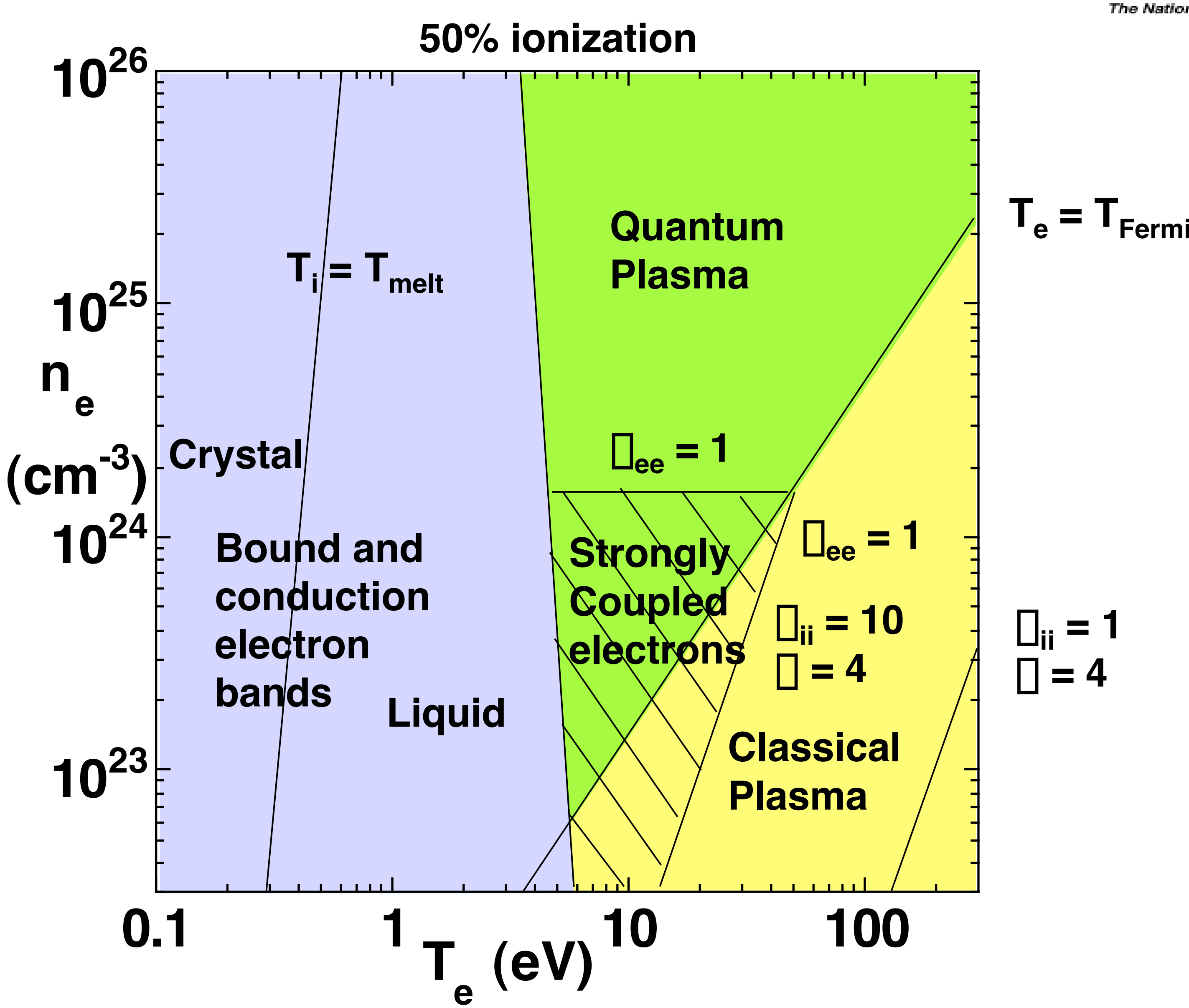

# Physics issues amenable to laser-based experiments abound in warm dense matter regime

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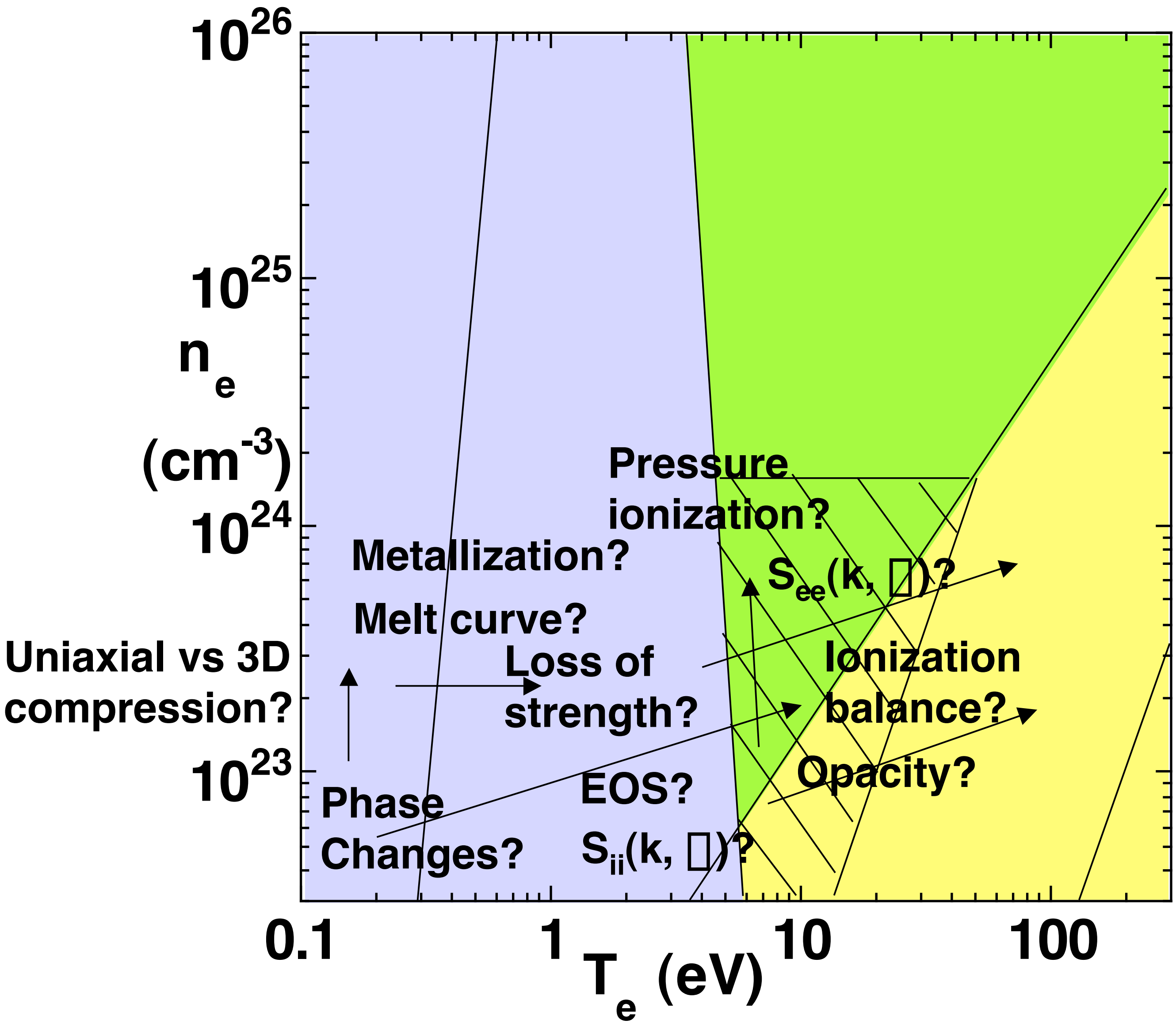

# Several operating regimes for preparing warm dense matter using high energy lasers

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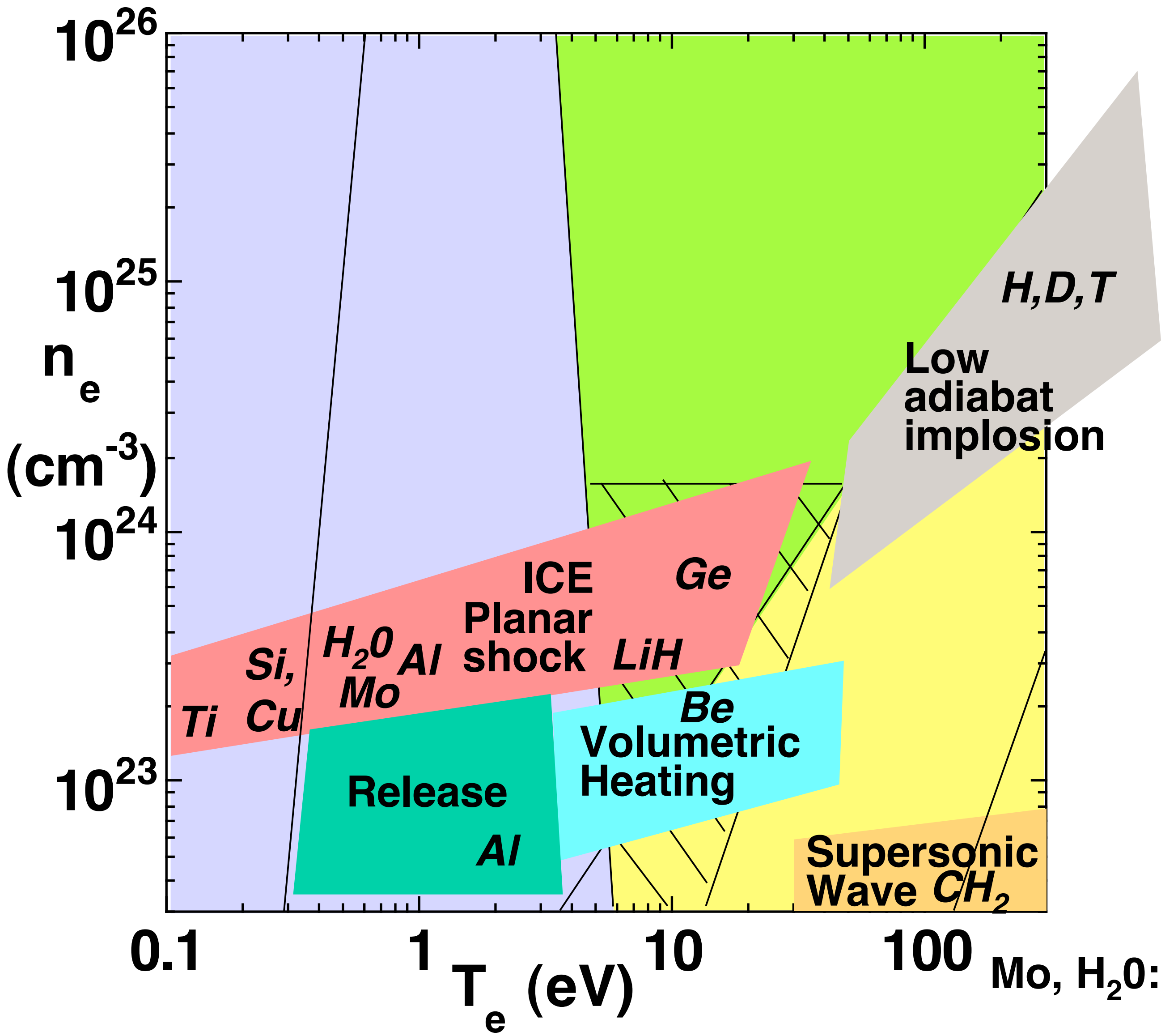



Laser experiments

H,D,T: Lindl/Haan

Ge: Springer/Heeter

LiH: Collins/Glenzer

Be: Landen/Glenzer

$CH_2$: Edwards

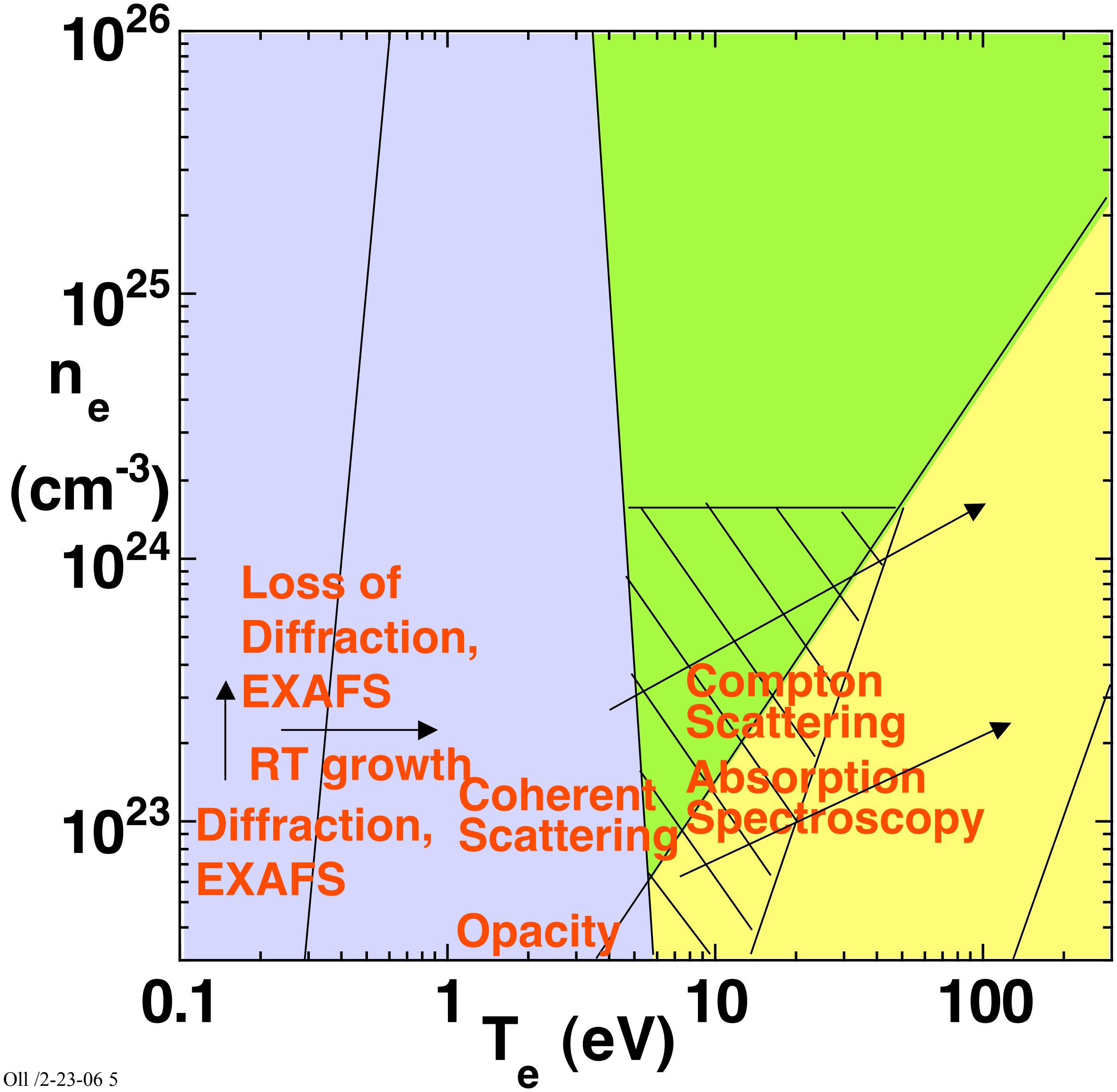
Si, Cu: Kalantar

Ti: Yaakobi

Al: Riley, Wolfrum

Mo, $H_20$: Collins/Celliers/Bradley

# A variety of transient x-ray techniques have already been deployed




- Radiography
- EXAFS
- Diffraction
- Scattering
- Transmission / Opacity
- Absorption Spectroscopy

# Material strength inferred from radiographing hydroinstability growth upon sample acceleration

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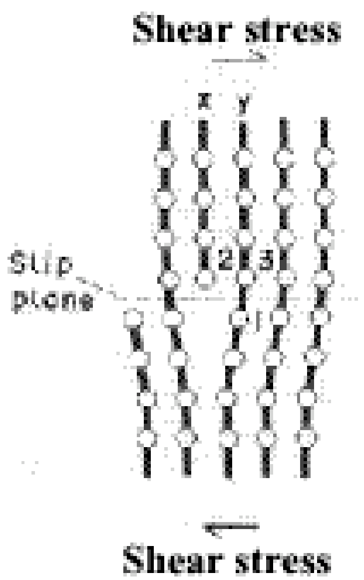
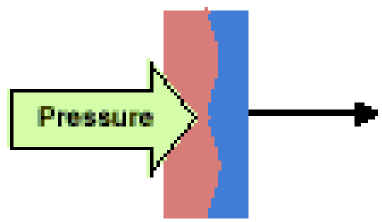
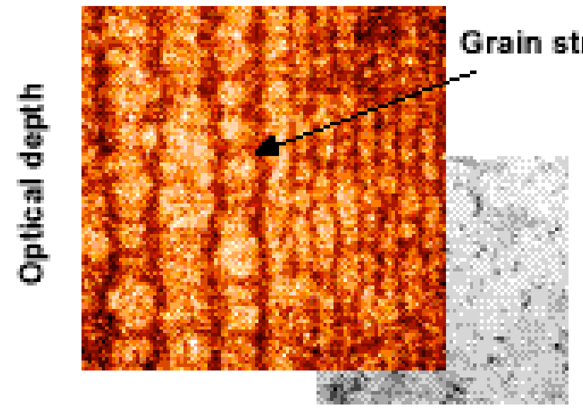
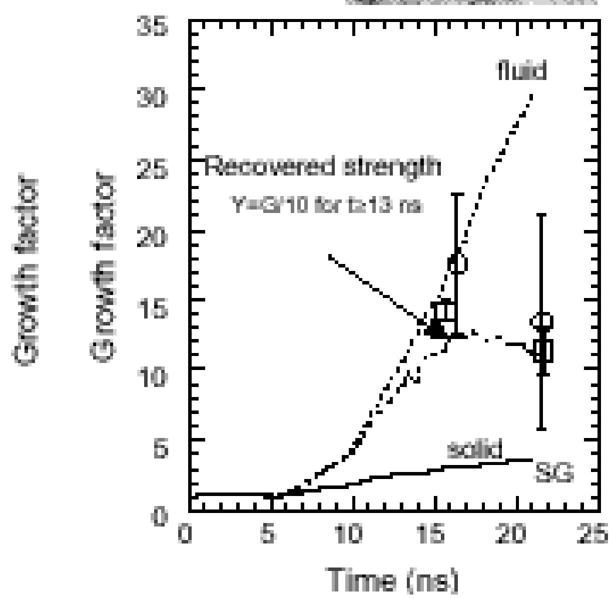
Kalantar, Remington




Laser generated X-rays isentropically compress




- The resistance to dislocation transport is called material strength
- Growth rates with strength are expected to be reduced from classical (fluid)

Kalantar, D. H., et al. (2000). Physics of Plasmas 7(5 PT2): 1999-2006.
Kalantar, D. H, et al. (2000). ApJS 127(2): 357-363.

**High energy Radiography measures Δx changes (expansion, shock compression, hydroinstability growth)**

# Both point projection and area backlighting envisaged for high energy x-ray radiography

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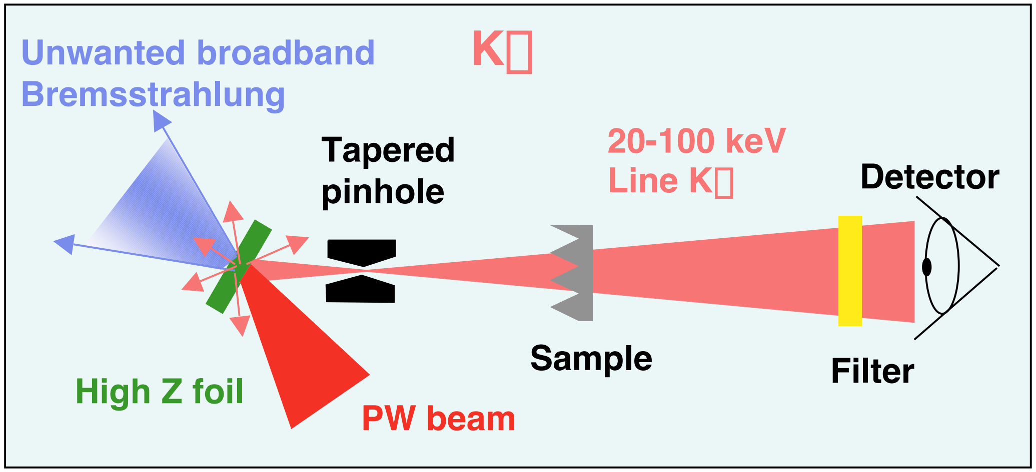
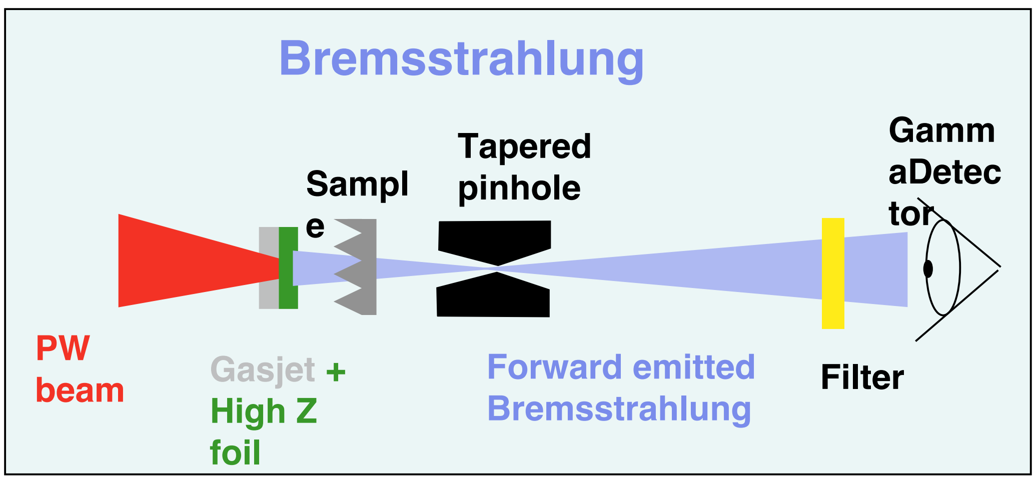
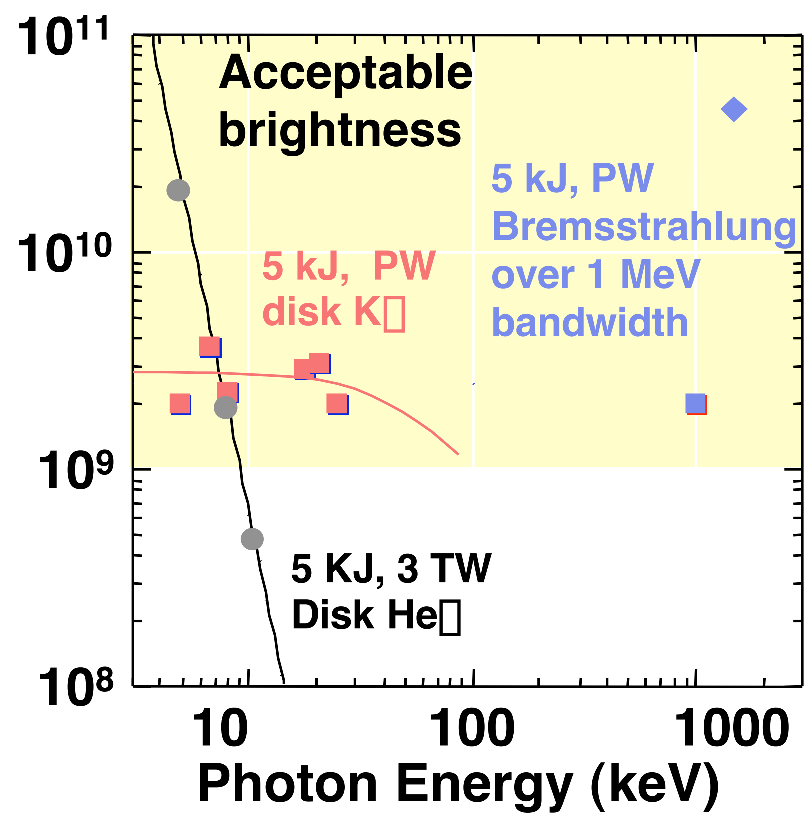


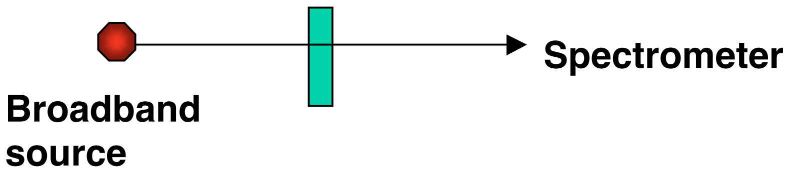

**NIF HEPW Brightness in photons/μm²/sr/100 ps gate scaled from existing data**



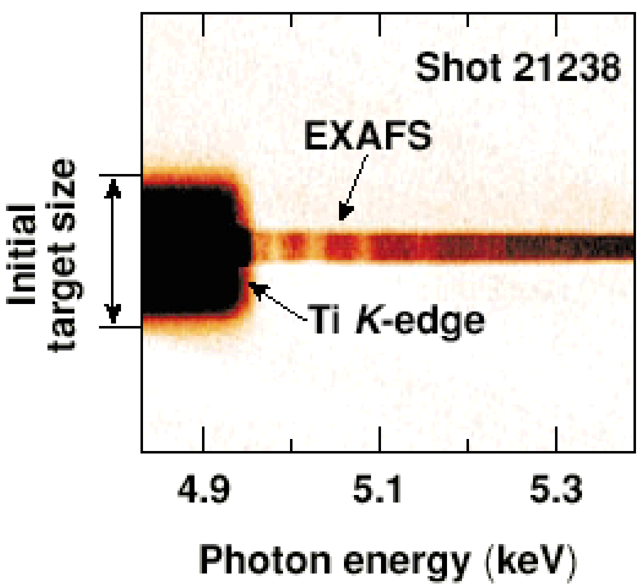

**Acceptable brightness criterium:**
**SNR ≥ 20 at 10 μm resolution, with transmission and detector efficiency at 10% each**

0.1-1 eV

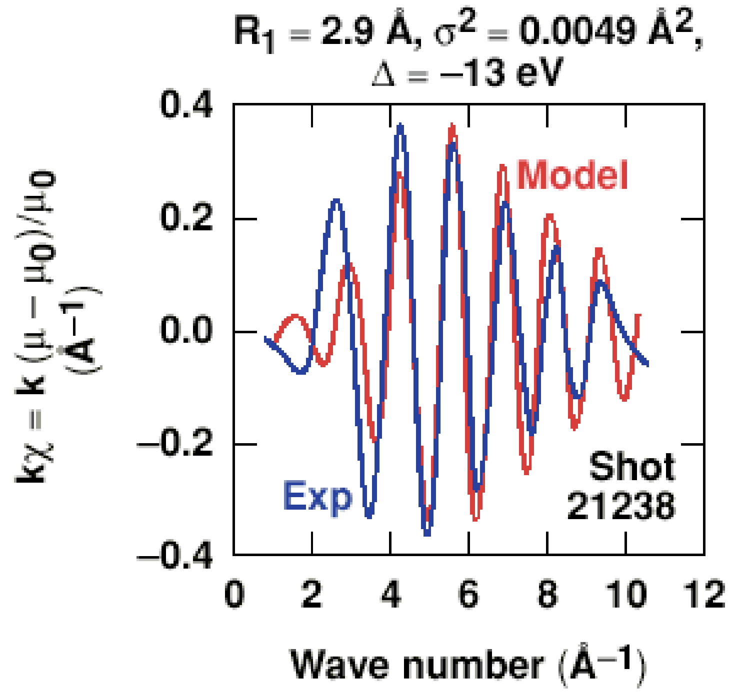
# Extended x-ray absorption fine structure (EXAFS) is being used to characterize metals shocked to ~Mbar pressures




Yaakobi, Meyerhofer




High-contrast modulations from a Ti-foil absorber were obtained using a laser-imploded spherical target as a backlighter.




Shock compression (density and temperature) is measured by fitting the EXAFS spectrum to the model.

**Spectral modulation frequency measures lattice d spacing**

**Envelope and broadening measures disorder = f ( $T_i/T_{Debye}$(□) )**

0.1-1 eV

# X-ray diffraction used to measure dynamic response of crystal lattice to compression

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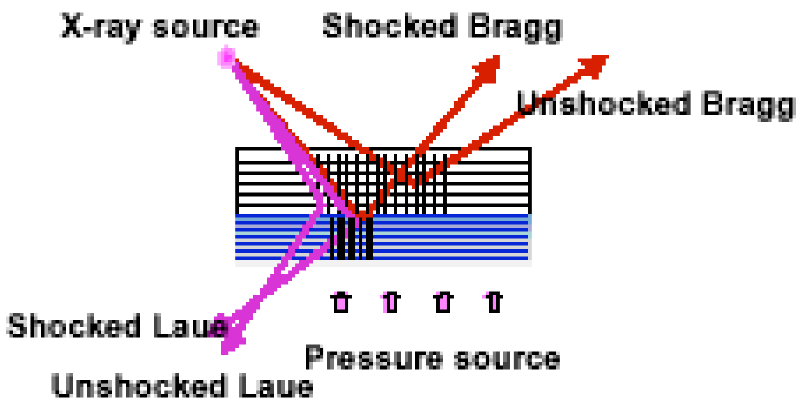
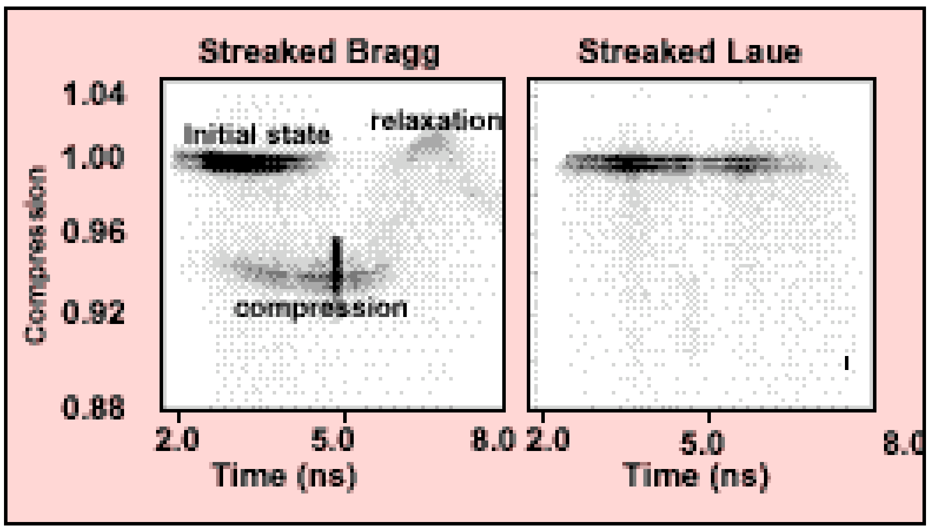
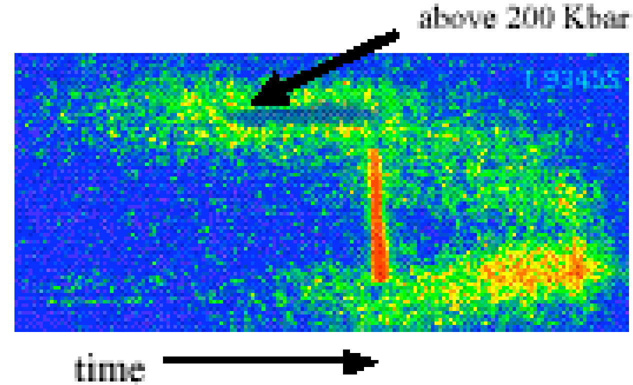
Kalantar, Wark




- Si responds uniaxially on a ns time scale to compression 2x over elastic limit
- Trident experiments have observed signals suggestive of a diamond - BCT solid phase change




"splitting" of shocked diffracted signal above 200 Kbar




Samples are recovered after the experiment and analyzed

Loveridge-

Kalantar, D

**Spectral shift measures lattice d spacing, phase changes**

# X-ray coherent scattering experiments are sensitive to ion-ion structure factor and ion temperature

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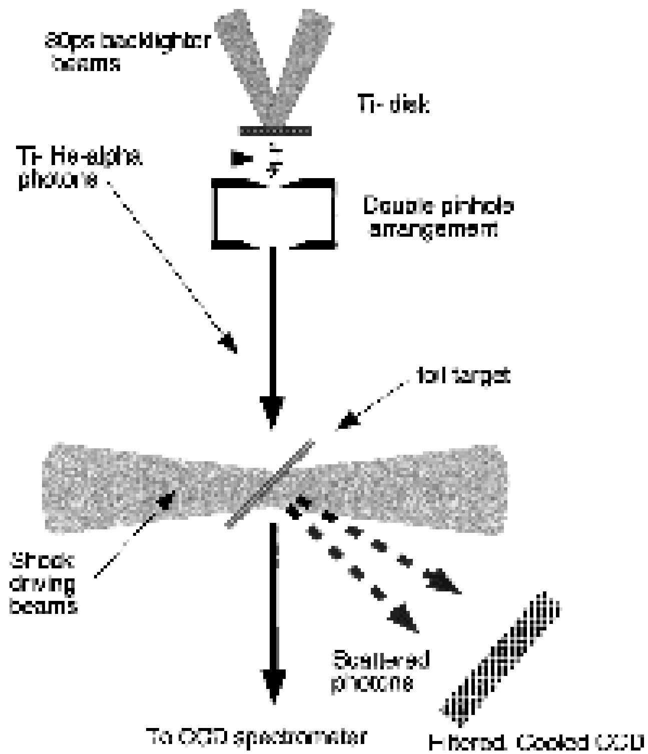
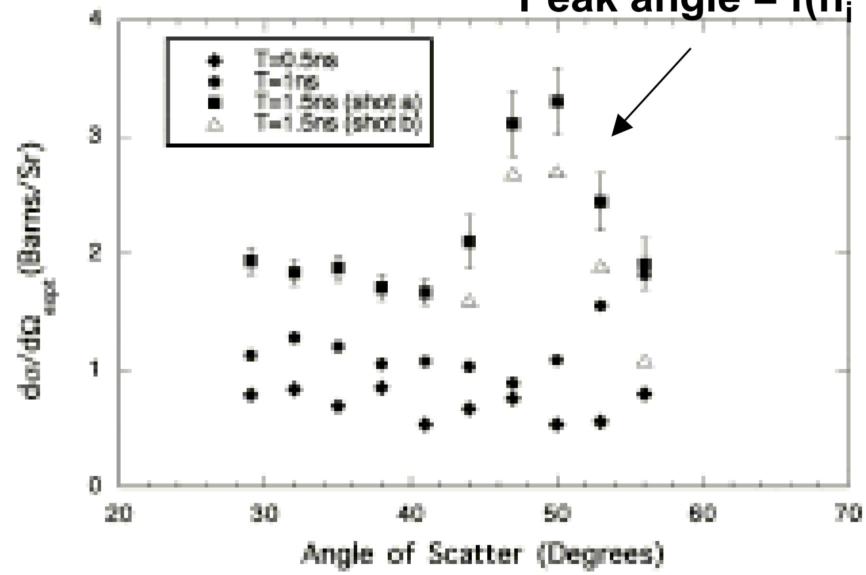
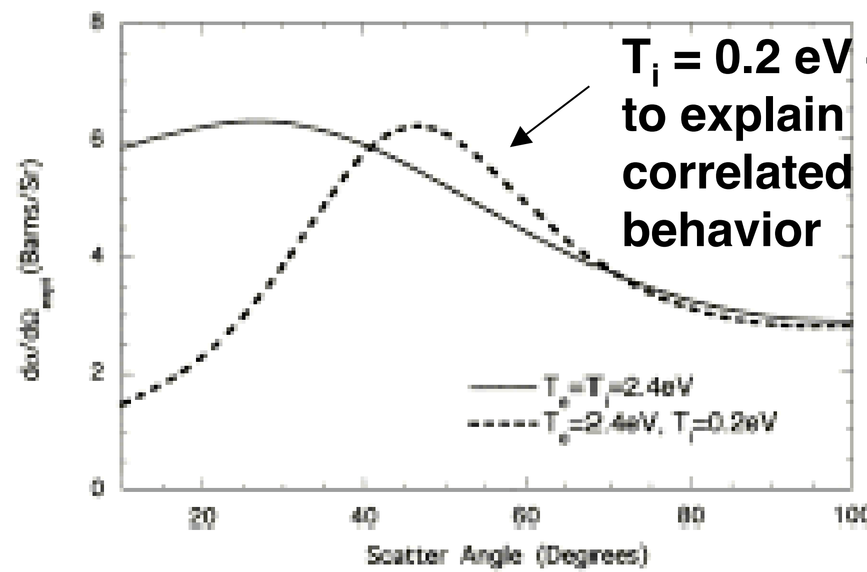
D. Riley *et. al.*, PRL (2000)

**Al, 1g/cc, 2.4 eV**




Peak angle = f($n_i^{1/3}$)



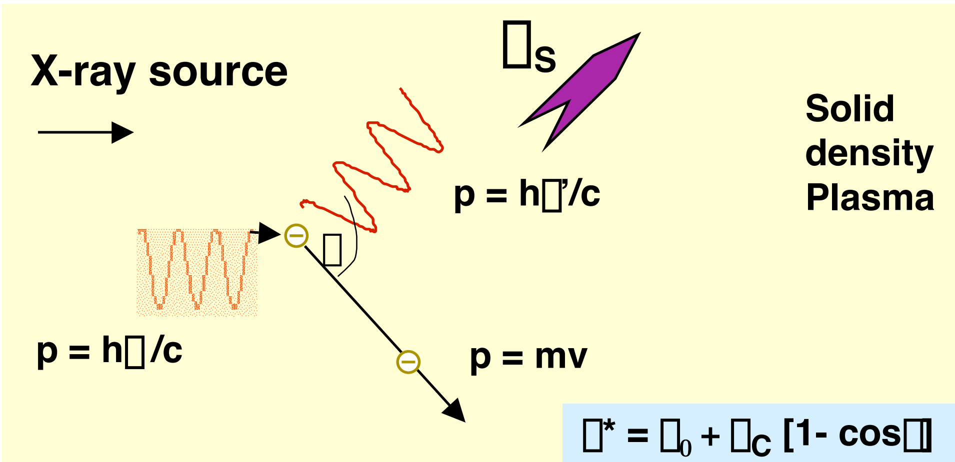




**$T_i$ = 0.2 eV << $T_e$ to explain correlated ion behavior**

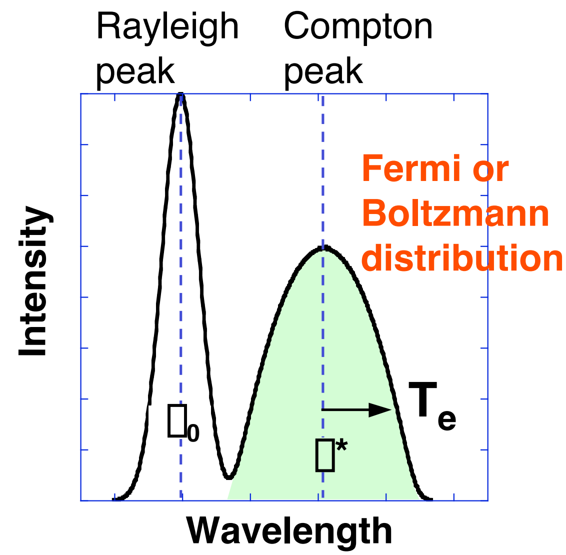
**K-resolved Scattering measures ion structure factor = f ($T_i$, □)**

1-100 eV

# X-ray scattering from free electrons (Thomson) for measuring velocity distribution




Scattering on free and weakly bound electrons

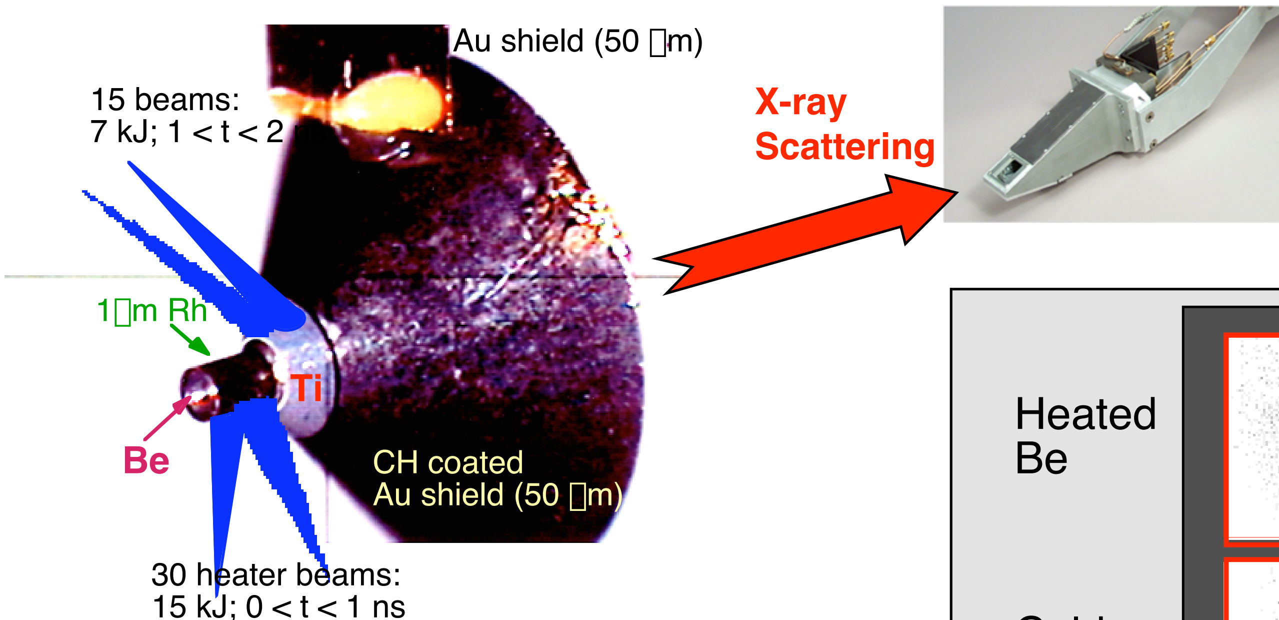



**Spectrally-resolved Incoherent Scattering measures :**

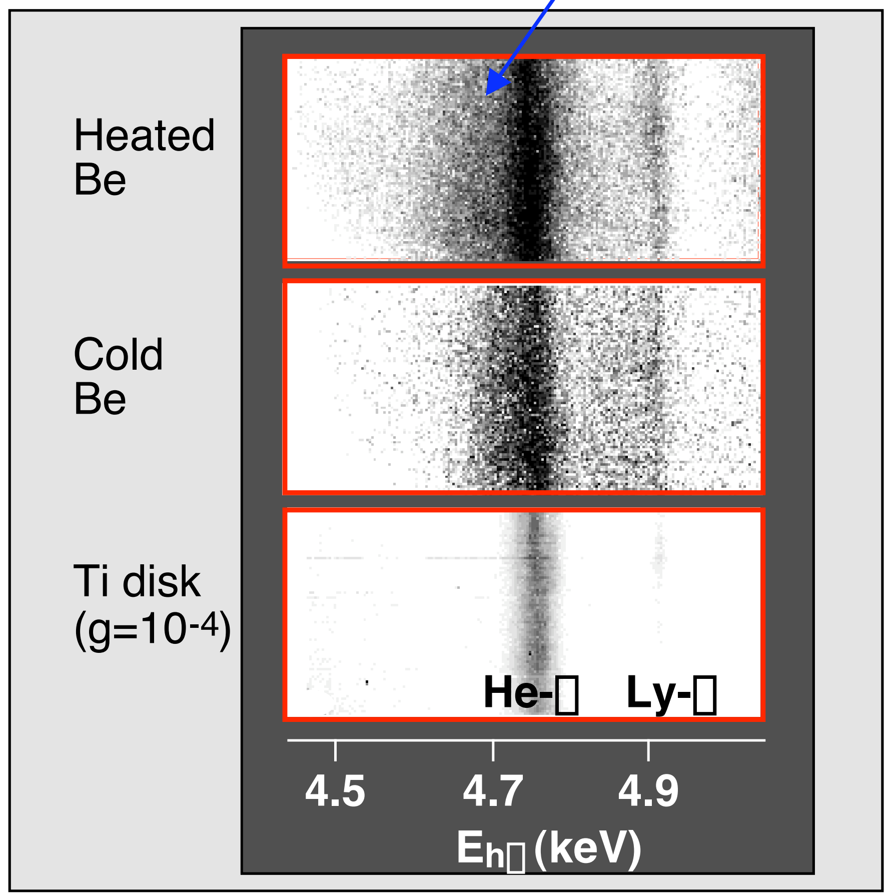
**Free and weakly bound electron momentum distribution = f ($T_e$. $T_{Fermi}$, I.P.)**
**Ratio of free/weakly bound / tightly bound electrons**

# X-ray “Thomson’ scattering in warm solid density matter

**Gated HOPG spectrometer**




**Compton downshifted and Doppler broadened Thomson spectrum observed as expected**




- **$T_e$ broadening was predicted in 1928: Chandrasekhar: “scattering will not be influenced by ranges of temperatures available in the laboratory” Proc R.S. A 125, 37 (1929)**

**S. H. Glenzer et al., Phys. Rev. Lett. 90, 175002 (2003).**

# X-ray scattering provides accurate temperature measurements in solid-density Be plasmas

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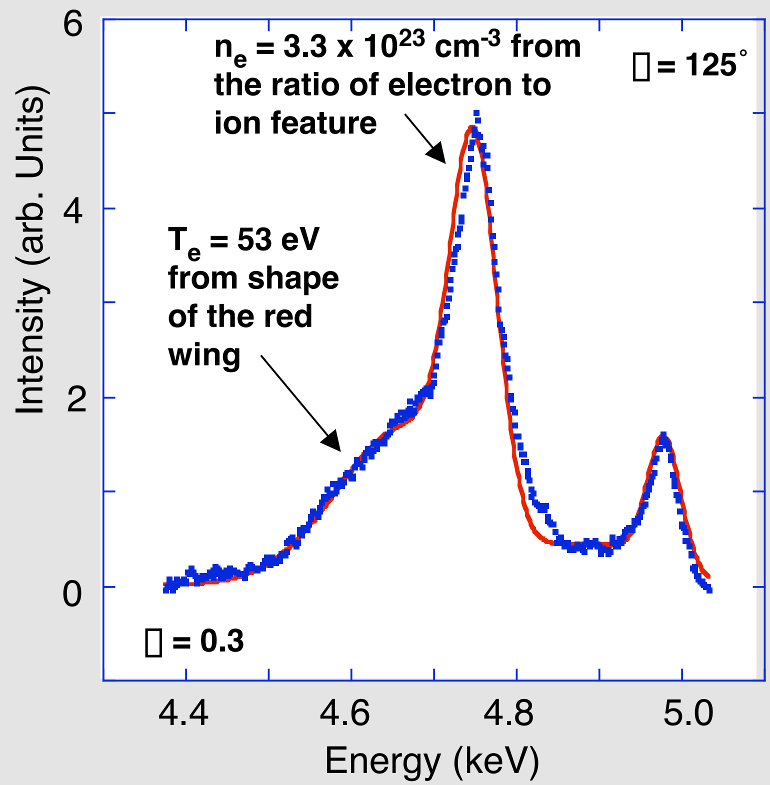
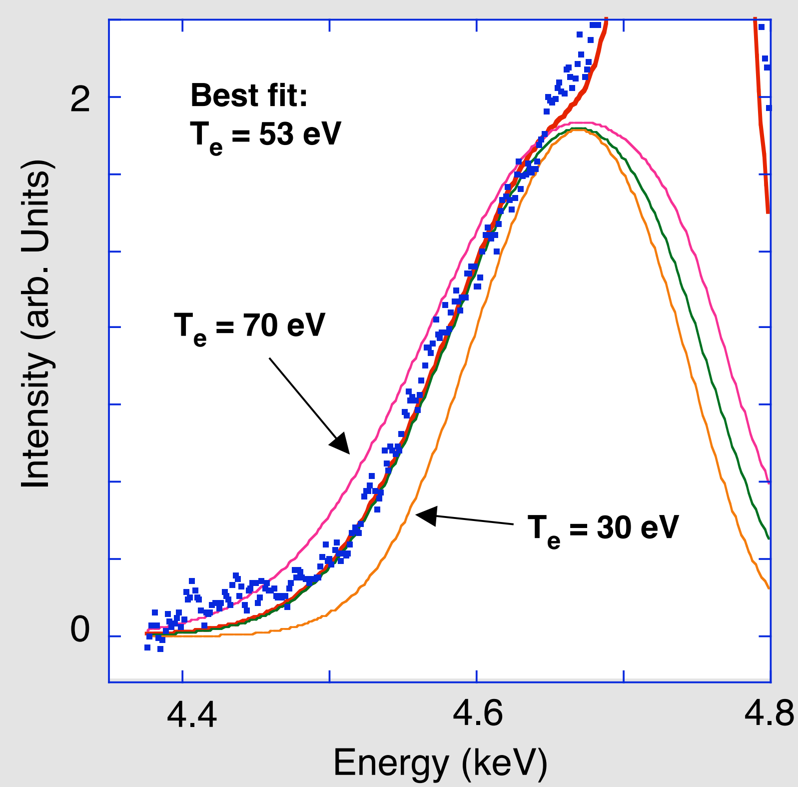
## X-ray scattering spectra provide accurate data on $T_e$ and $n_e$




**From the theoretical fit to the data: $T_e$ = 53 eV and $Z_{free}$ = 3.1 hence $n_e = 3.8 \times 10^{23}$ cm$^{-3}$**

## Comparison of experimental data and fits for various $T_e$




**A sensitivity analysis shows that we can measure $T_e$ within ~15%**

10-300 eV

# Collisionally broadened plasma resonance for cold plasmas is model sensitive

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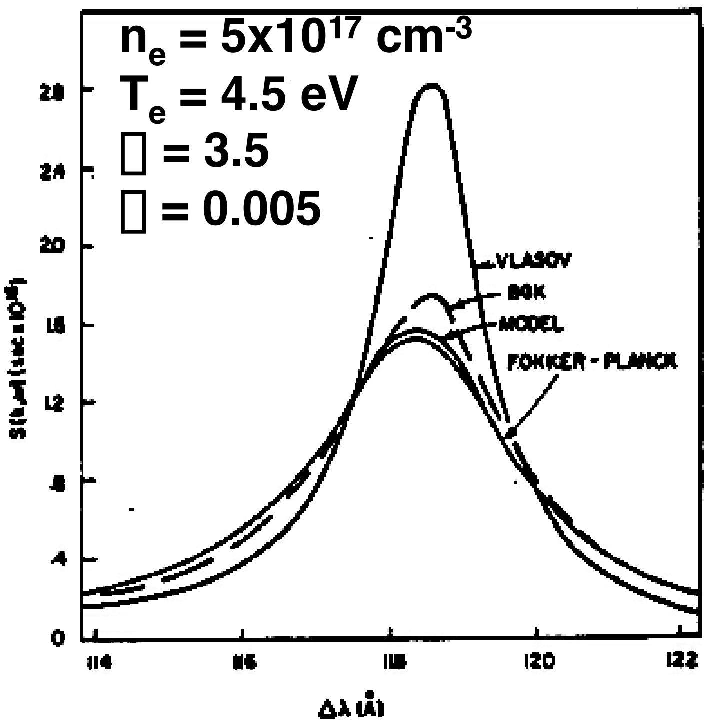
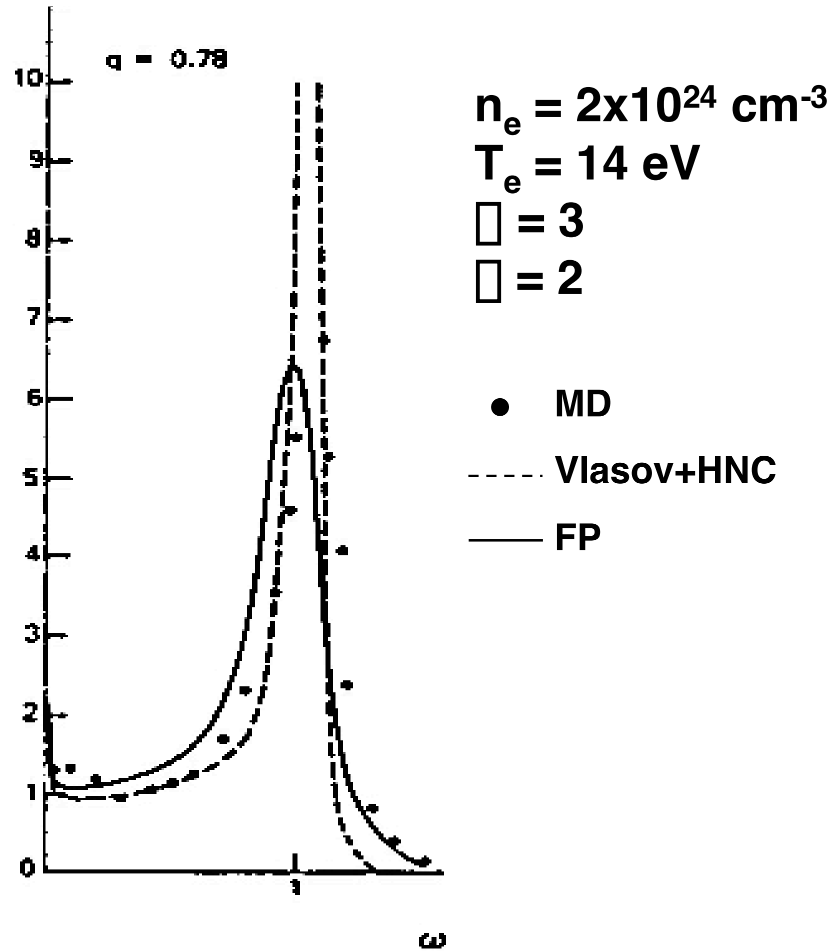
Linnebur and Duderstadt (1973) Theory Cauble and Boercker (1983)



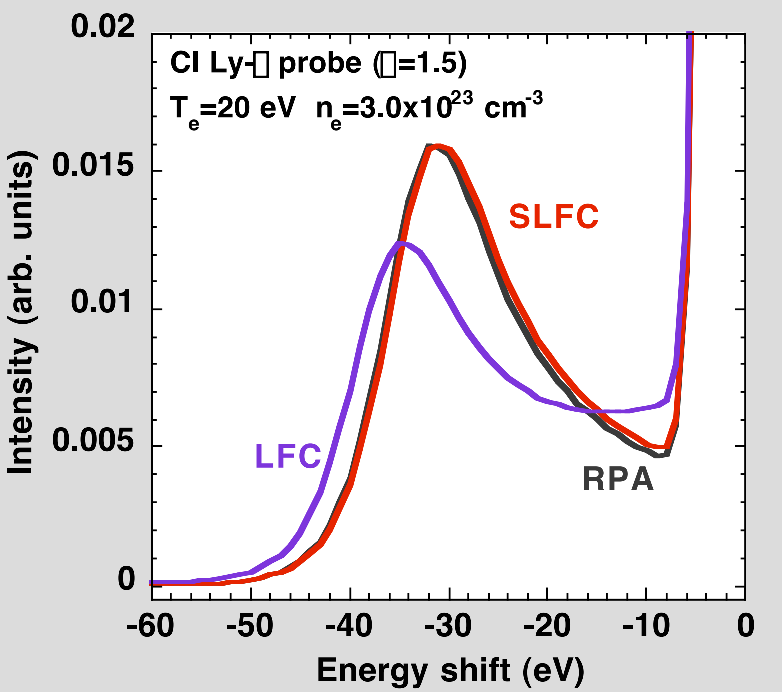




•XRTS experiment could validate collisionality model at high $n_e$, variable □

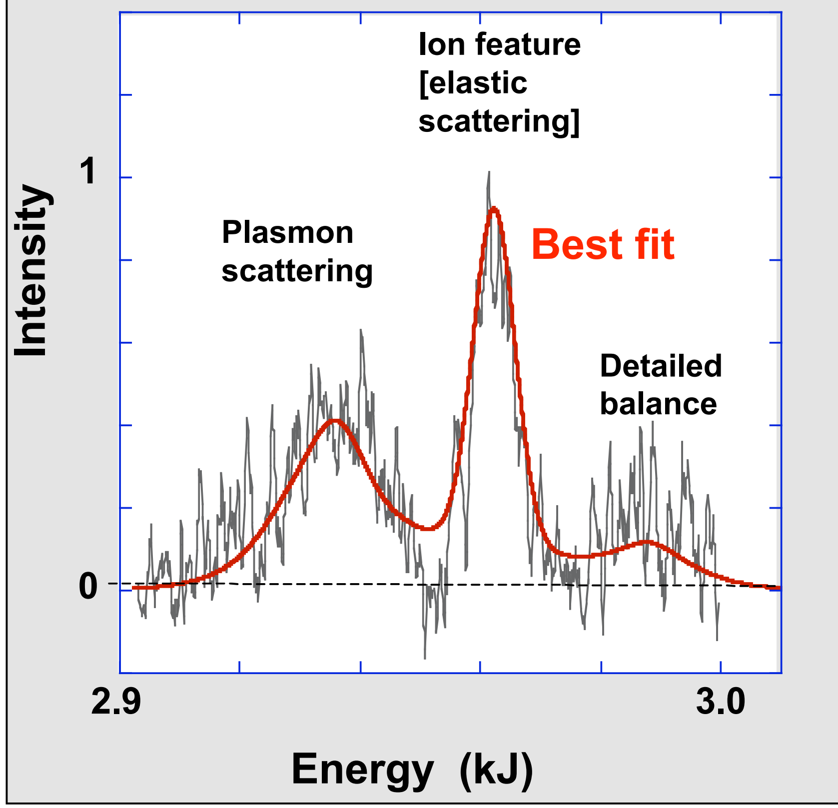
Collisionality, plasma wave behavior in Fermi degenerate and strongly coupled plasmas

# Spectrally-resolved forward x-ray scatter can test dense matter energy transport models

## Theory




## First data

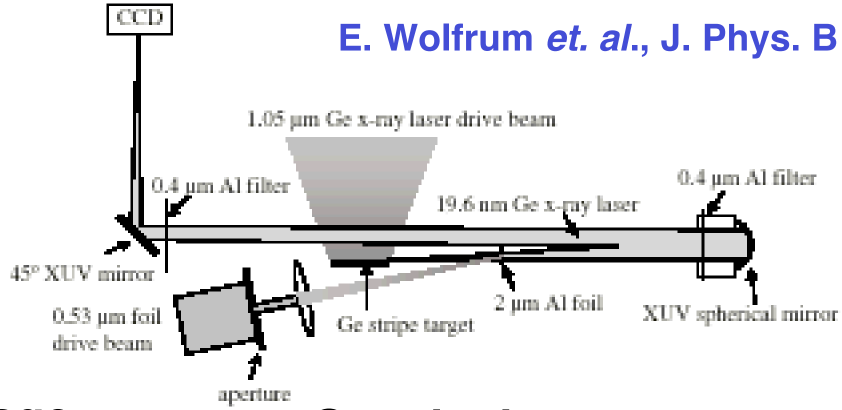



**Spectrally-resolved Collective Scattering measures:**
**Free electron density from plasmon shift**
**Ratio of $T_e/T_i$ from ratio of ion feature to plasmon**
**May distinguish between $\nu_{ei}$ collisionality models**

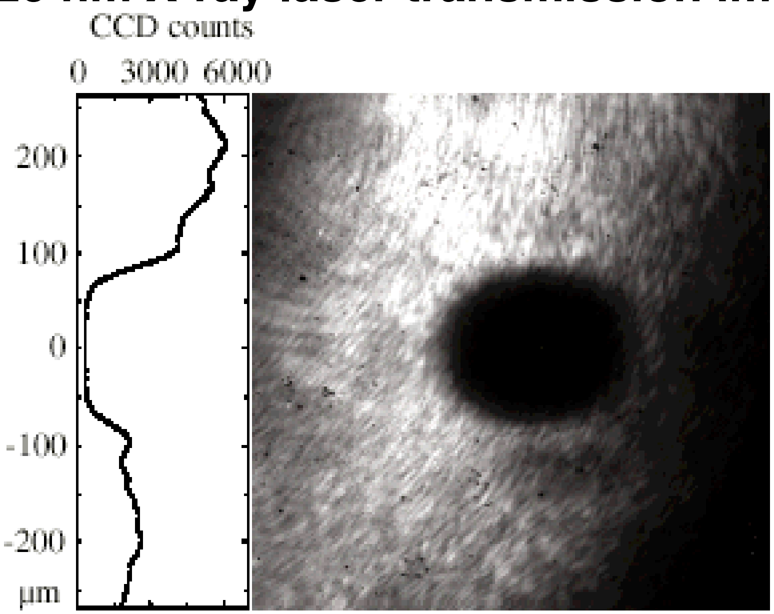
# Soft x-ray laser used to demonstrate increased opacity at increased density

**Al, 4 g/cc, $n_e = 3\times10^{23}$ $cc^{-1}$,**
**$T_e = 1$ eV**

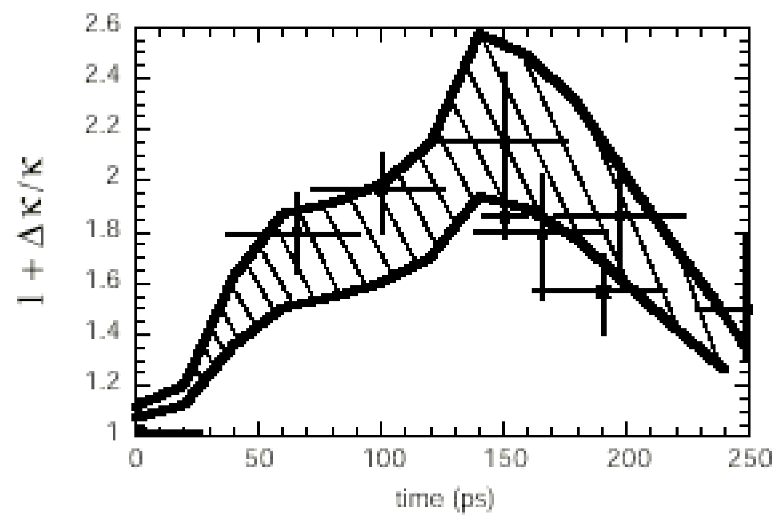
E. Wolfrum *et. al.*, J. Phys. B (2000)




## 20 nm X-ray laser transmission image



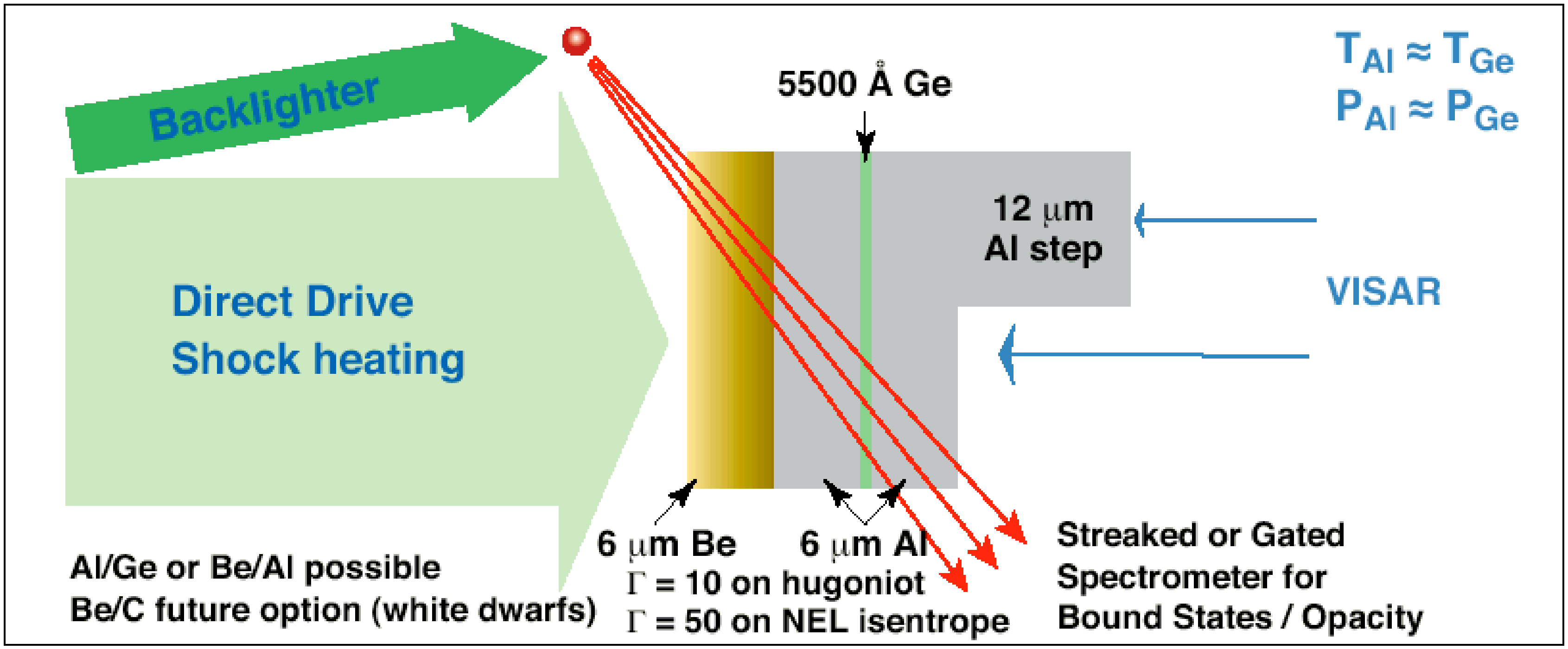

## Opacity increase




**Stimulated or spontaneous X-ray line transmission measures opacity**

# Characterization of Warm Dense Matter: EOS and Opacity of shocked material at Omega/NIF

- Objective: Elucidate atomic properties in strongly-coupled matter
  — EOS, ionization and opacity are all uncertain in this regime
- Build upon ongoing successful shock EOS/VISAR experiments
- Possible candidate for NEL experiment; PRL$^{+}$ if it works
- Initial exploration/validation study on Omega, late FY02 or early FY03




Shepherd, Ng, Heeter, Foord, Iglesias, Rogers, Springer

**Absorption spectroscopy measures ionization state, opacity**

# Spectral measurement of ionization state will help differentiate between plasma EOS models

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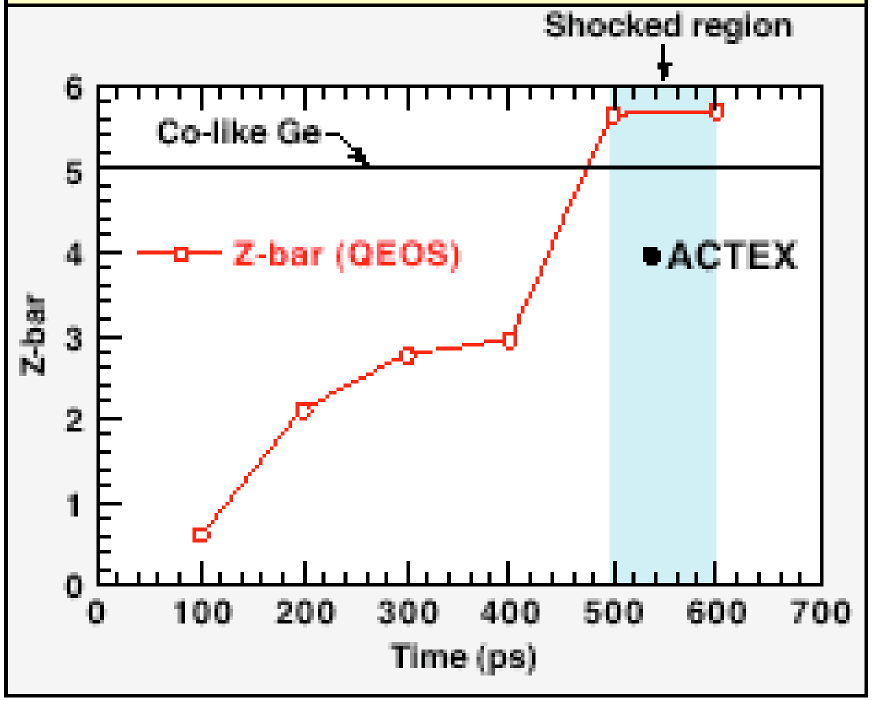
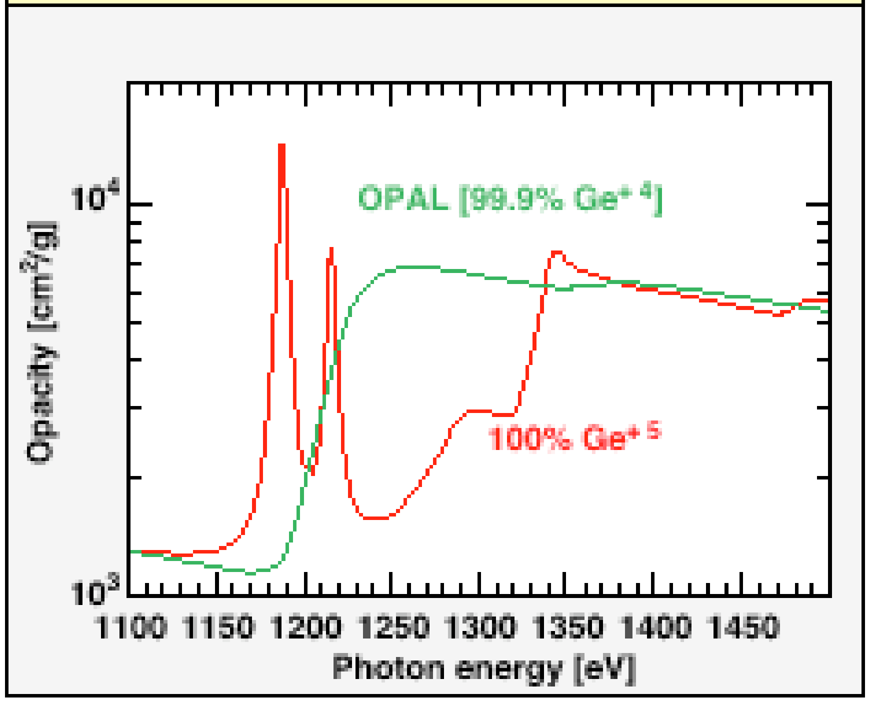
**EOS Calculations for "Armageddon" Target**




**OPAL Calculations for Ge at T = 10eV, ρ = 15g/cc**




**We will use these experiments to benchmark codes for states in correlated plasmas**

Shepherd, Ng, Heeter, Foord, Iglesias, Rogers, Springer

# A variety of transient x-ray techniques have already been deployed

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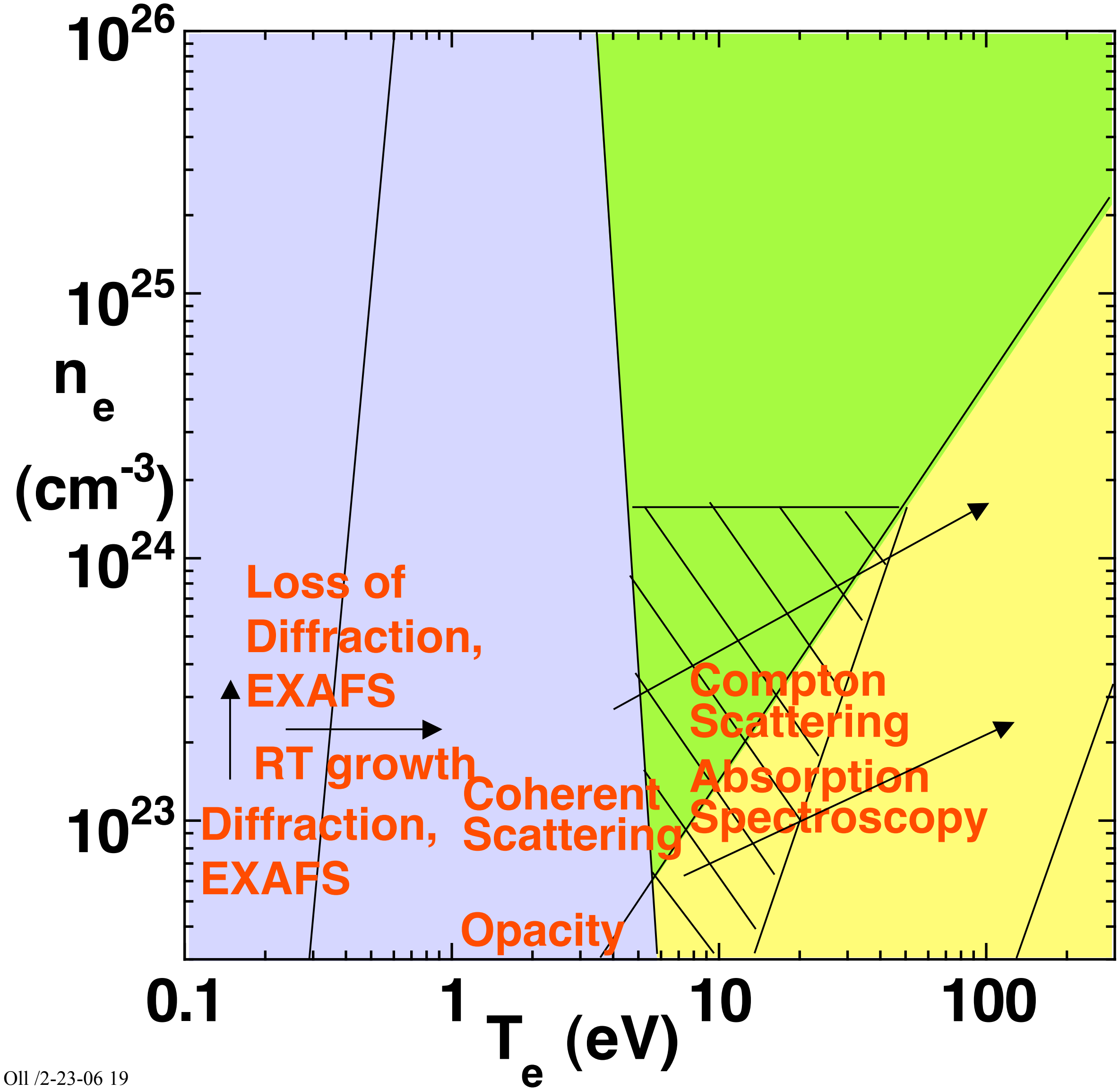


- Radiography
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