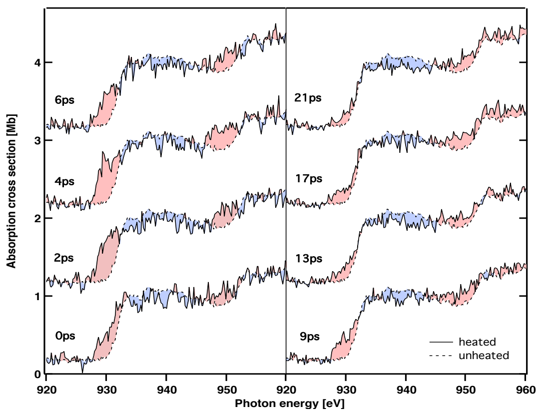
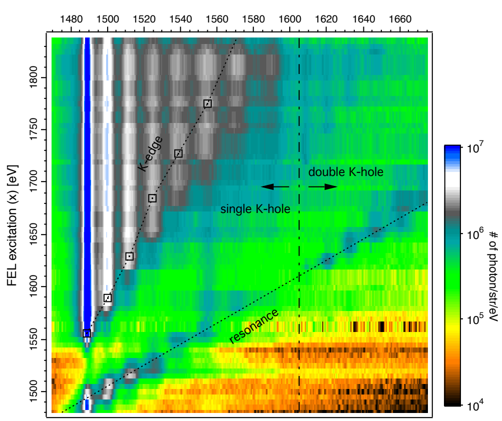
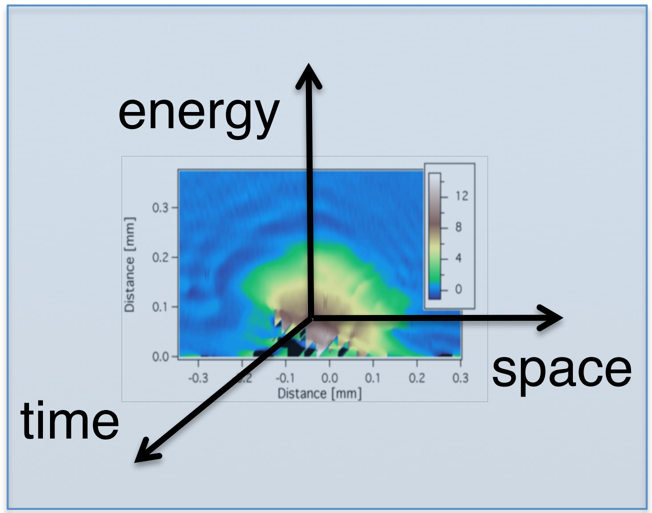
X-ray lasers, laser-plasmas, and high harmonics: what's best for creating and probing high-energy-density matter?

absorption spectroscopy

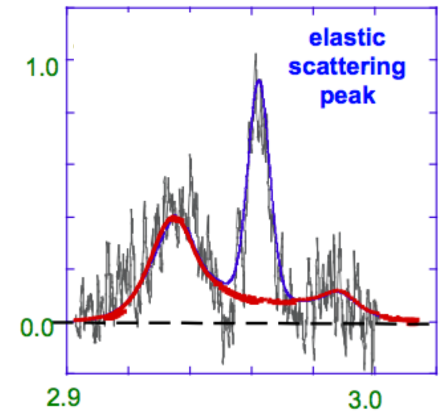


emission spectroscopy

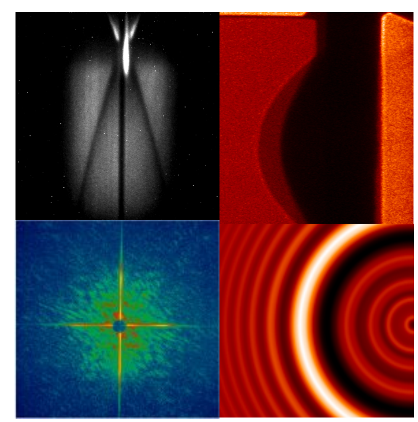




scattering



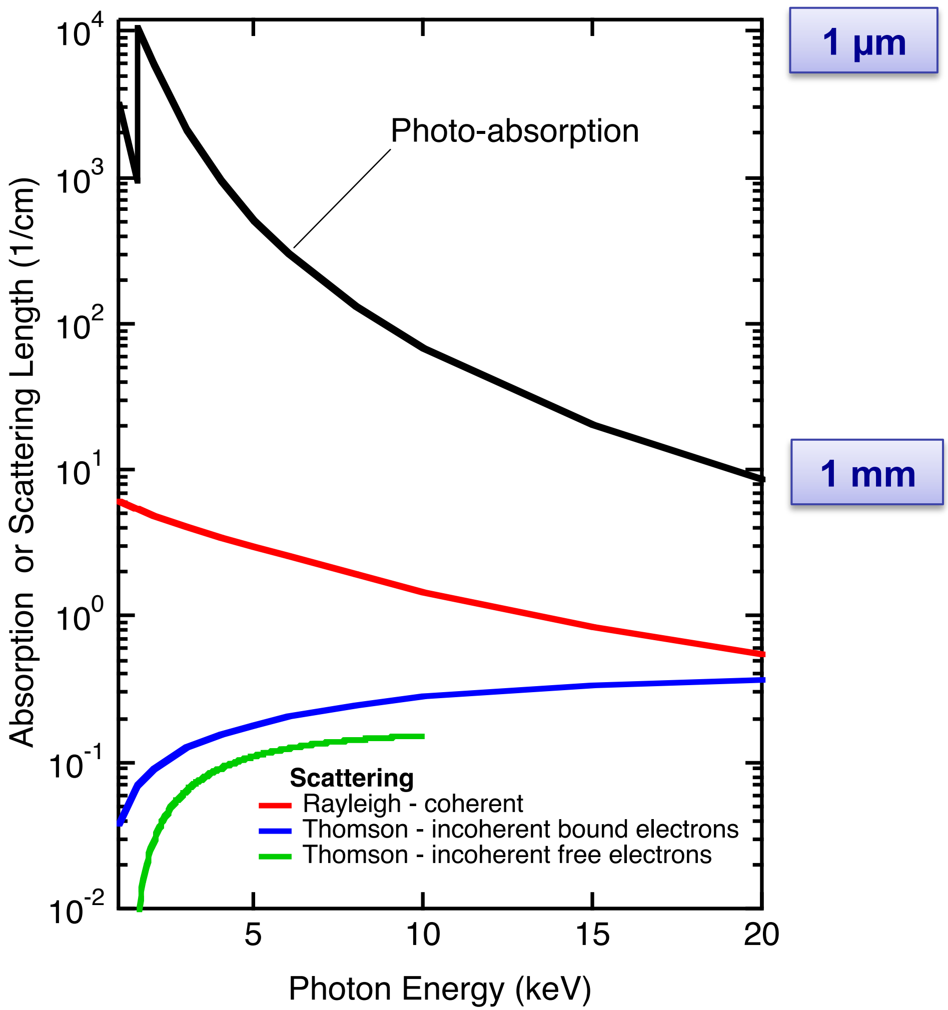
imaging



Roger Falcone
Physics, UC Berkeley
Advanced Light Source, LBNL

CHILI2013 December 2013

X-rays penetrate materials and are differentially absorbed and scattered by atoms



X-ray scattering and absorption in Aluminum

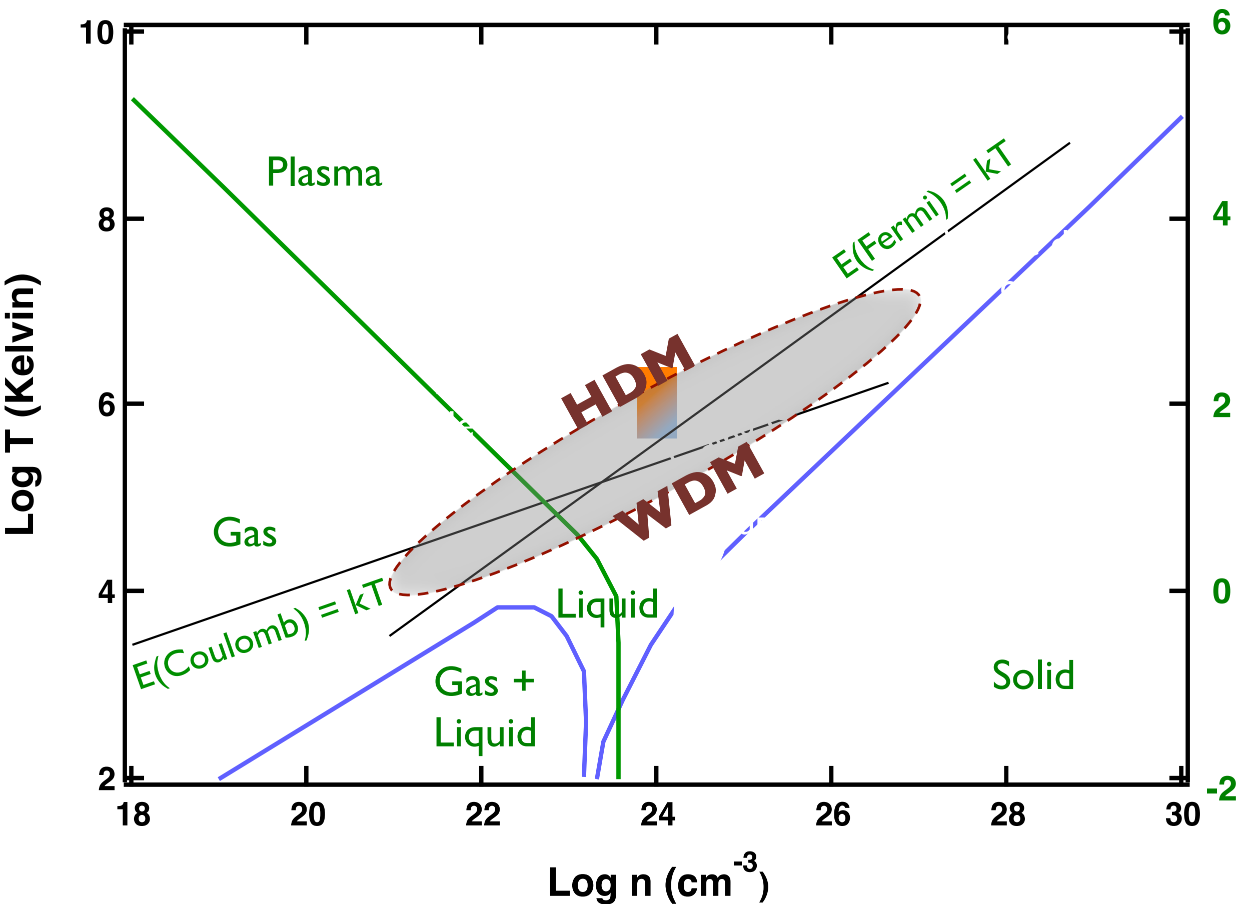
Processes in excited or warm, and dense, materials create a phase space under extreme conditions

Warm & Dense Matter (WDM)

- Excited state materials
- High pressure materials
- Planetary cores
- Inertial confinement fusion (early time)

Hot & Dense Matter (HDM)

- Laser heated plasmas
- Stellar interiors
- Inertial confinement fusion (late time)

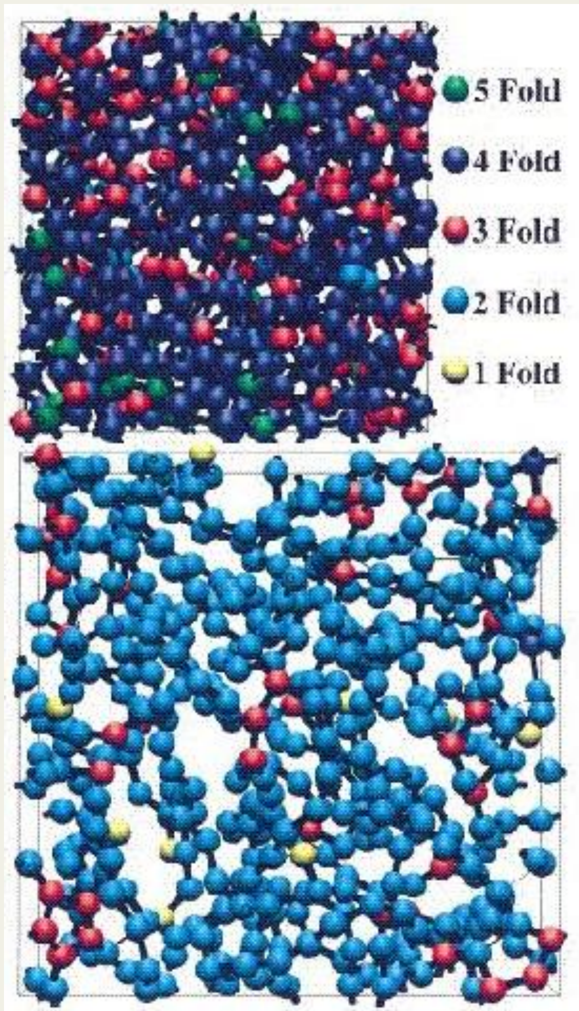


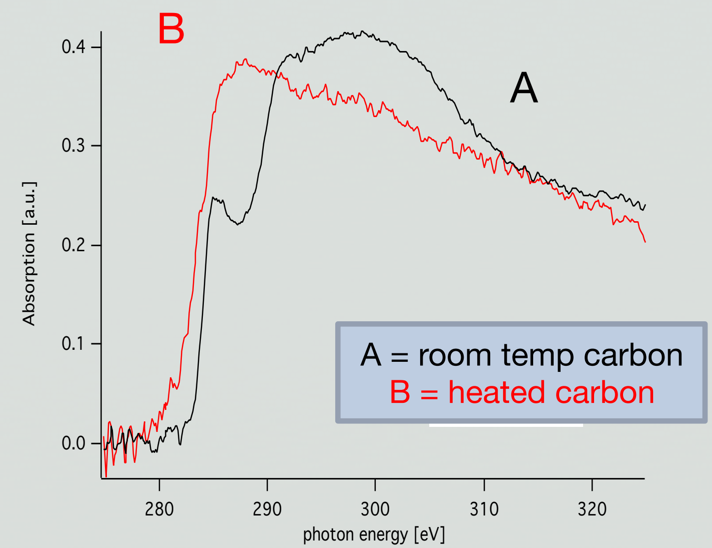
Basic Research Needs for High Energy Density Laboratory Physics, DOE (2010)

Simulations of electronic structure changes of warm and dense matter can be validated using x-ray absorption spectroscopy

A

B





Changes in structure and electronic bonding are observed near x-ray absorption edges

Dynamic x-ray absorption spectroscopy using a synchrotron and ps streak camera detector probes laser-heated matter

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Beamline at ALS x-ray synchrotron

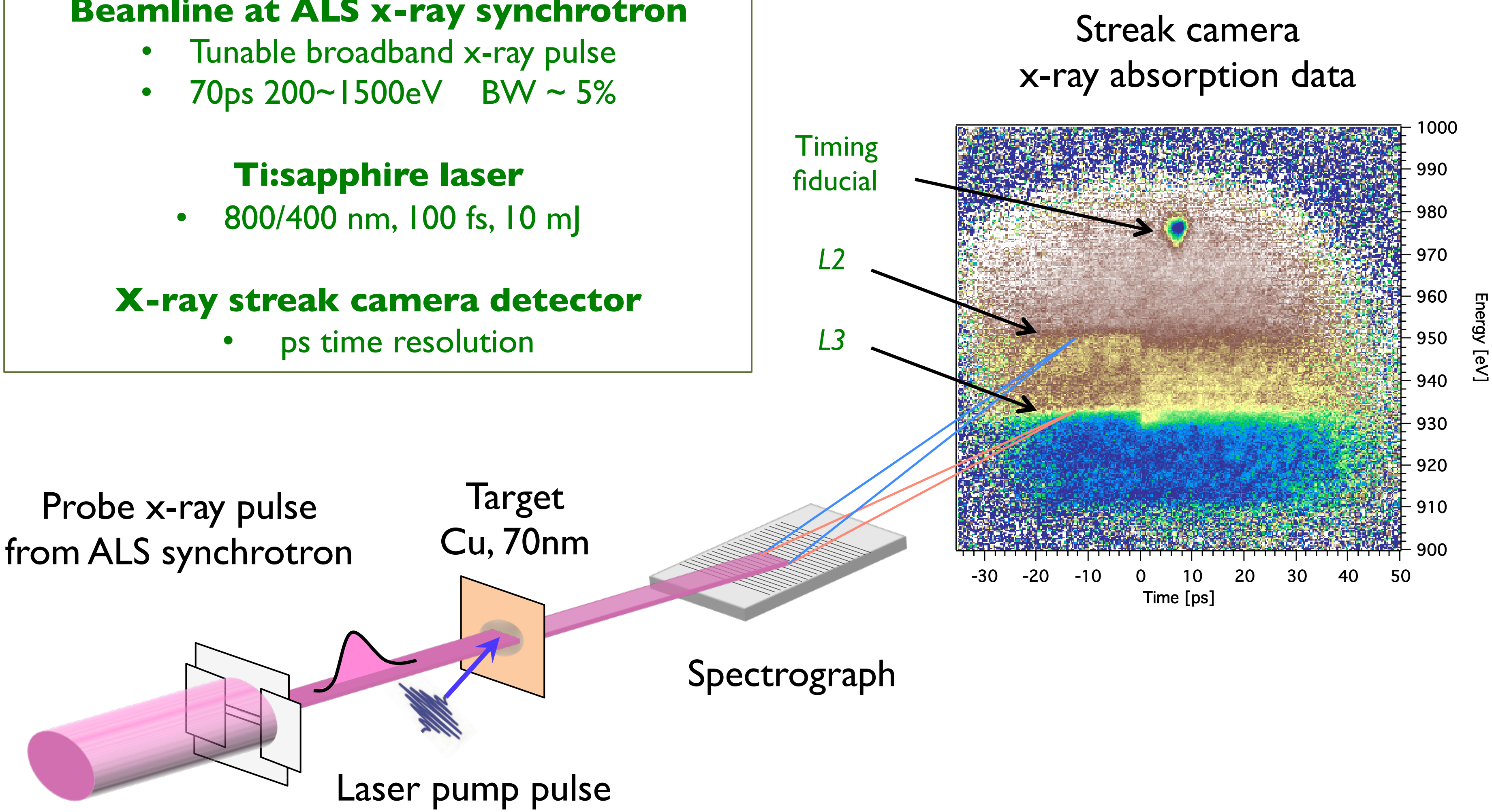
- Tunable broadband x-ray pulse
- 70ps 200~1500eV BW ~ 5%

Ti:sapphire laser

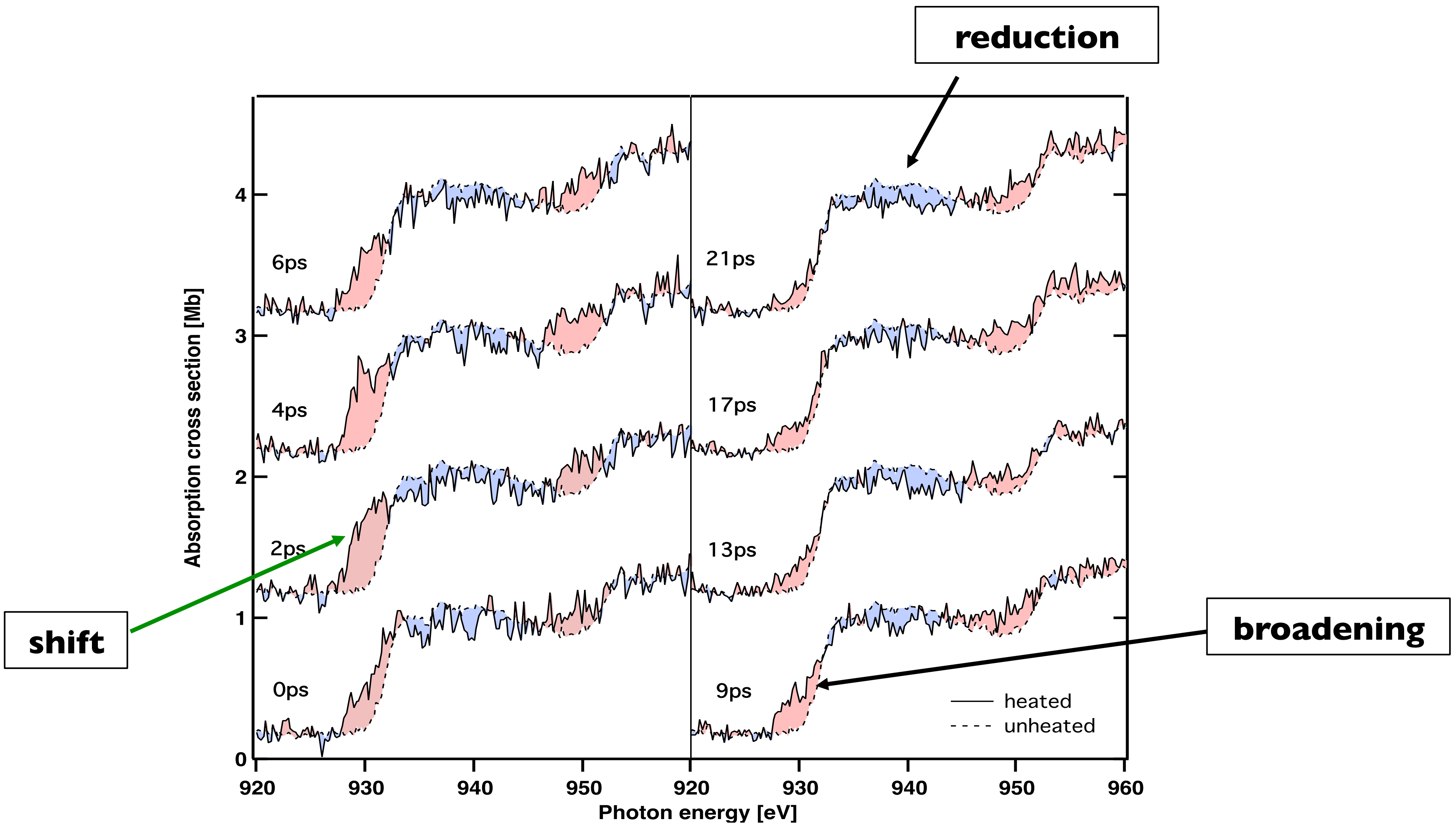
- 800/400 nm, 100 fs, 10 mJ

X-ray streak camera detector

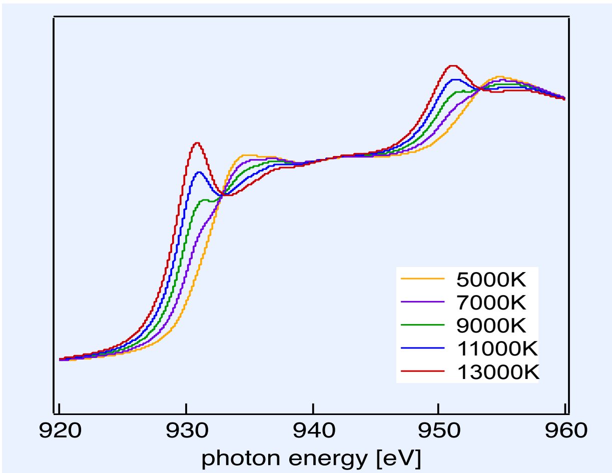
- ps time resolution

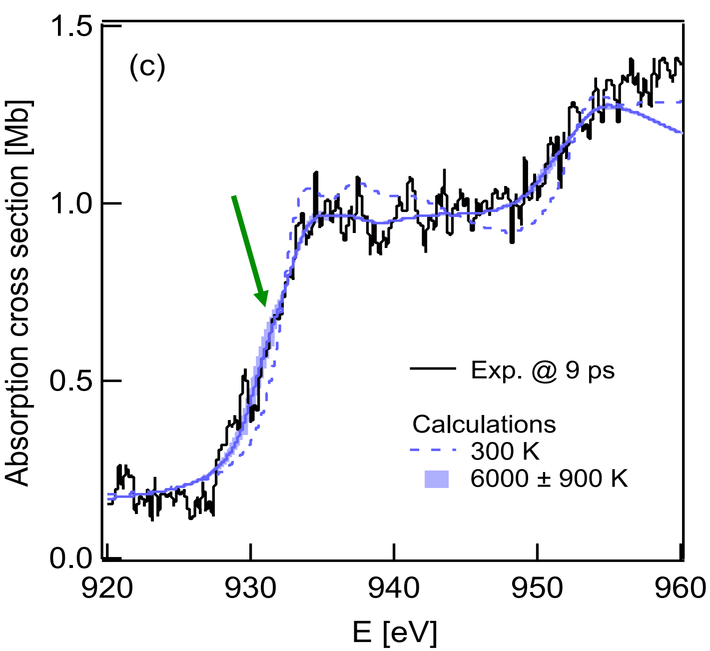


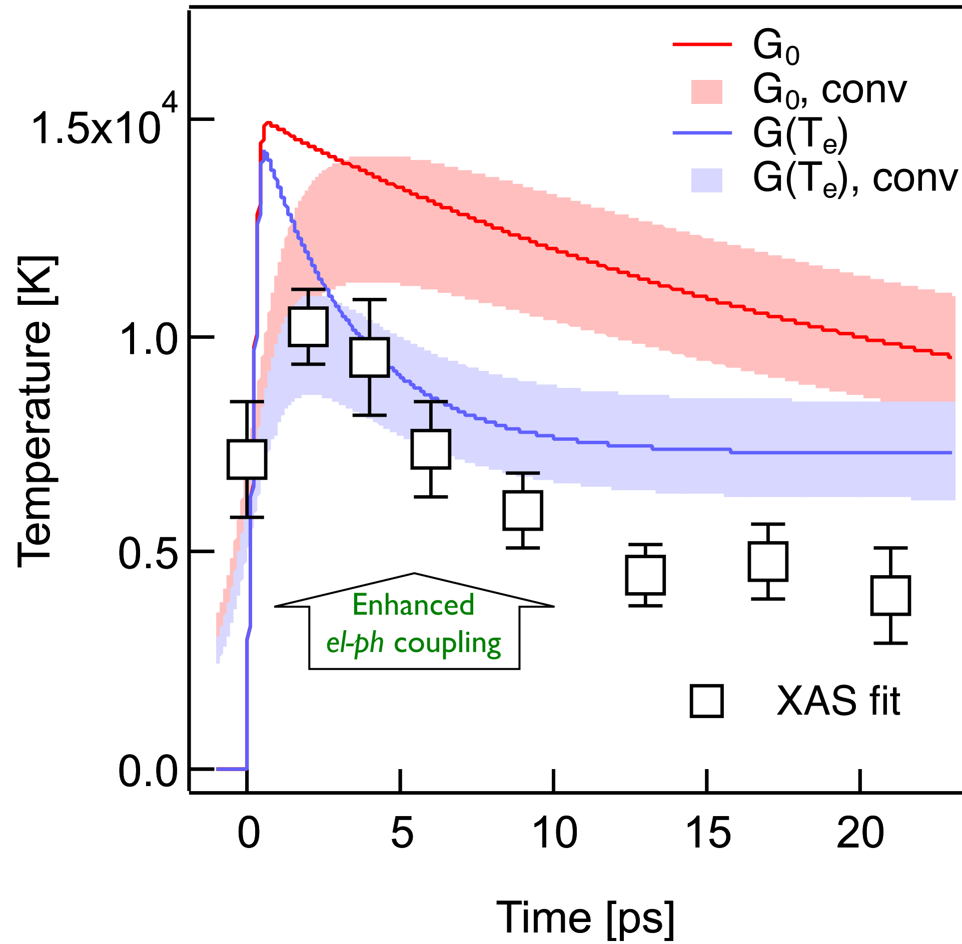
Changes in L-edge x-ray absorption in heated Cu reveal changes in DOS and electron temperatures



Time and temperature dependent electron-phonon coupling accompany electronic structure dynamics



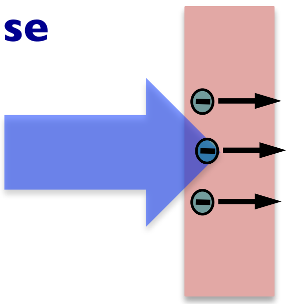




Cho et al, PRL 106. 167601 (2011)

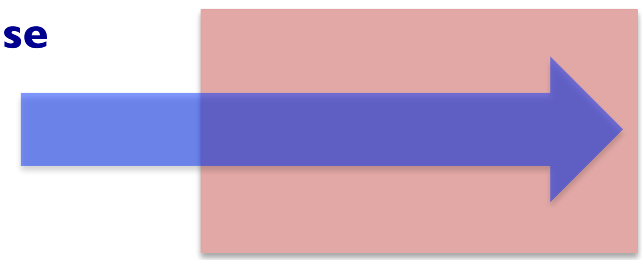
Intense and short x-ray laser pulses can create more uniform hot & dense matter

Optical pulse



- Short penetration depth (10-100 nm)
- Valence electron ionization
- Ionization by hot electrons and collisions
- Heating by electron transport and collisions
- Expands in fs

X-ray pulse

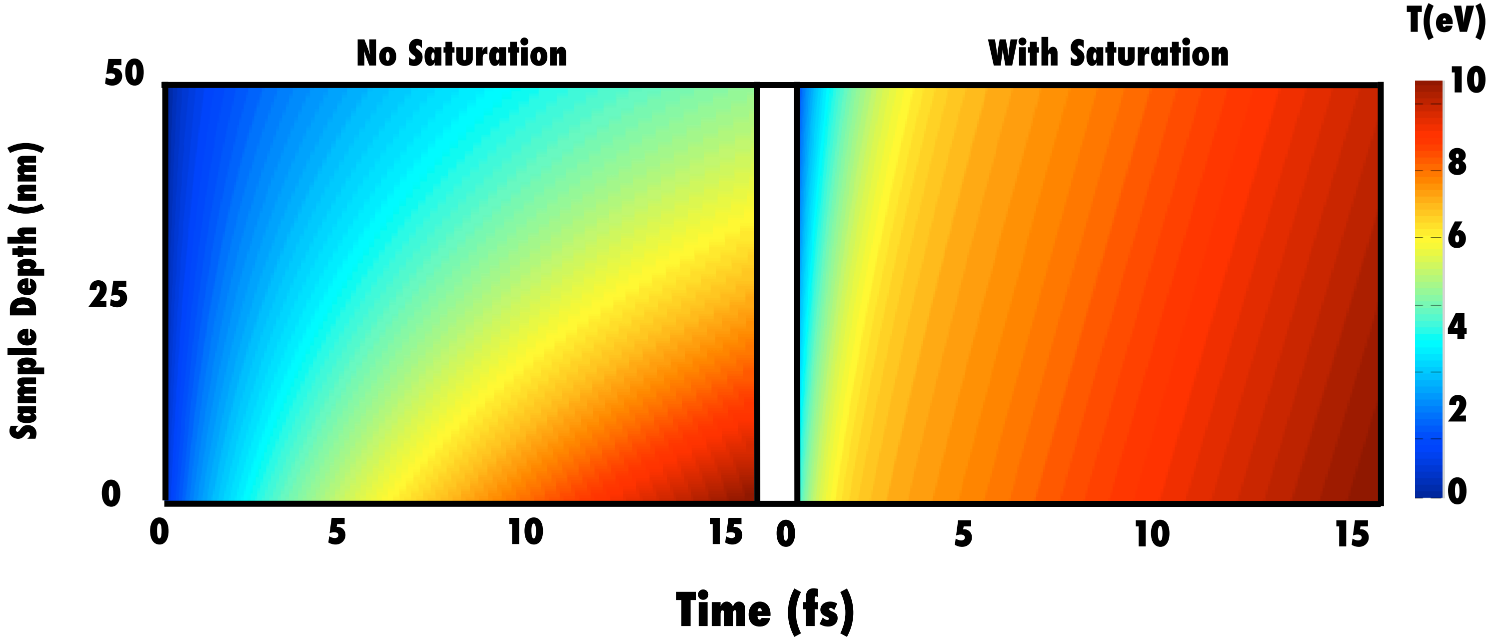


- Long penetration depth (10 -100 μm)
- Core electron ionization
- Ionization by ionizing x-ray flux and collisions
- Heating by large photon energy
- Expands in ps

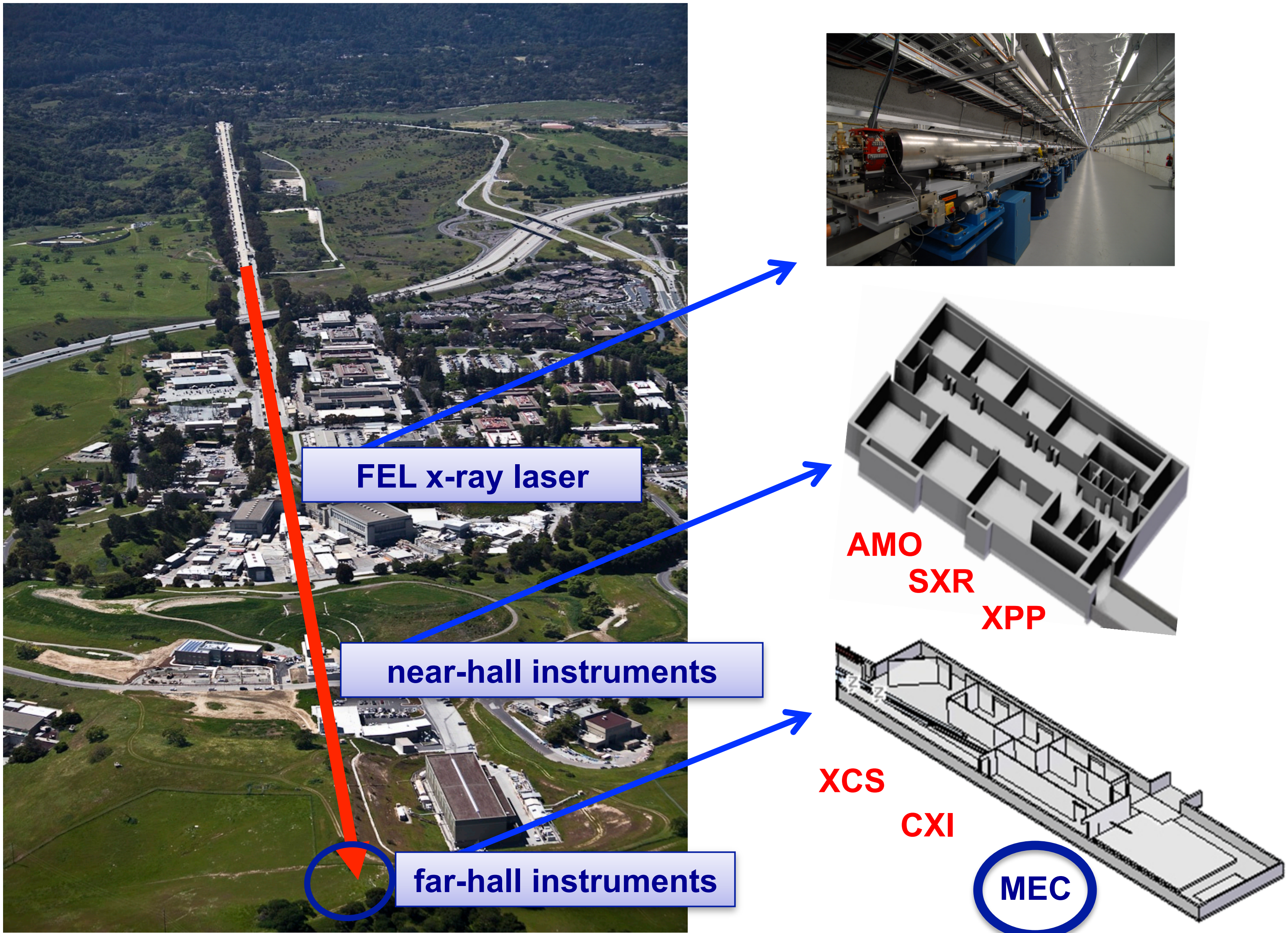
Uniform, single-state physical data are essential for tests of theory (temperature, pressure, conductivity, opacity)

An important consequence of intense x-ray illumination is saturation, creating a homogeneously heated sample

- Essential to create homogeneous WDM in a well-defined state (LTE)



LCLS instrument for Materials in Extreme Conditions (MEC)



X-ray emission spectroscopy at MEC reveals conditions of X-FEL heated aluminum

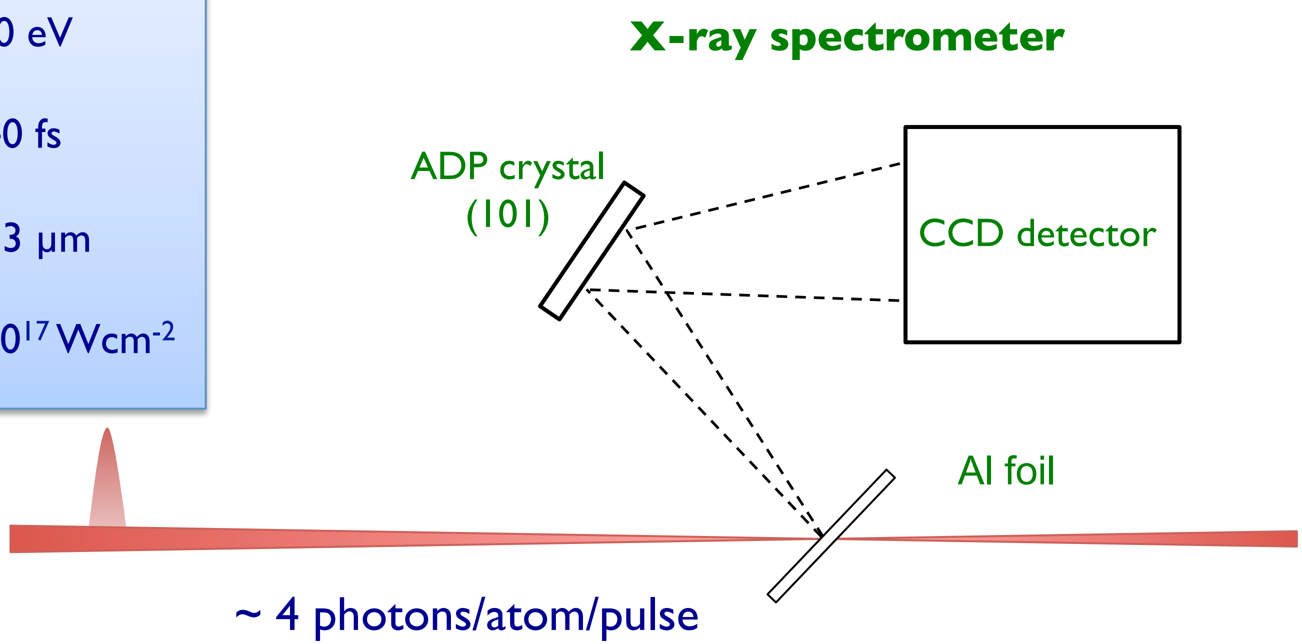
X-ray FEL parameters

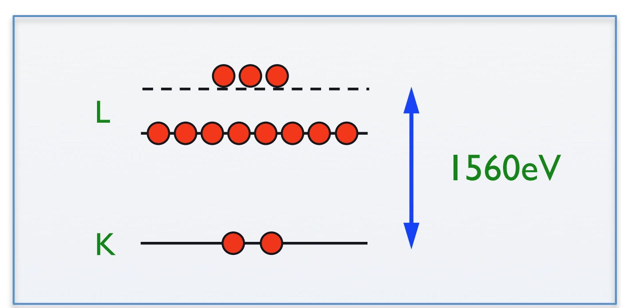
1480 ~ 1800 eV

0.4 mJ @ 40 fs

Focal spot ~ 3 μm

Peak intensity ~ 10^{17} Wcm^{-2}



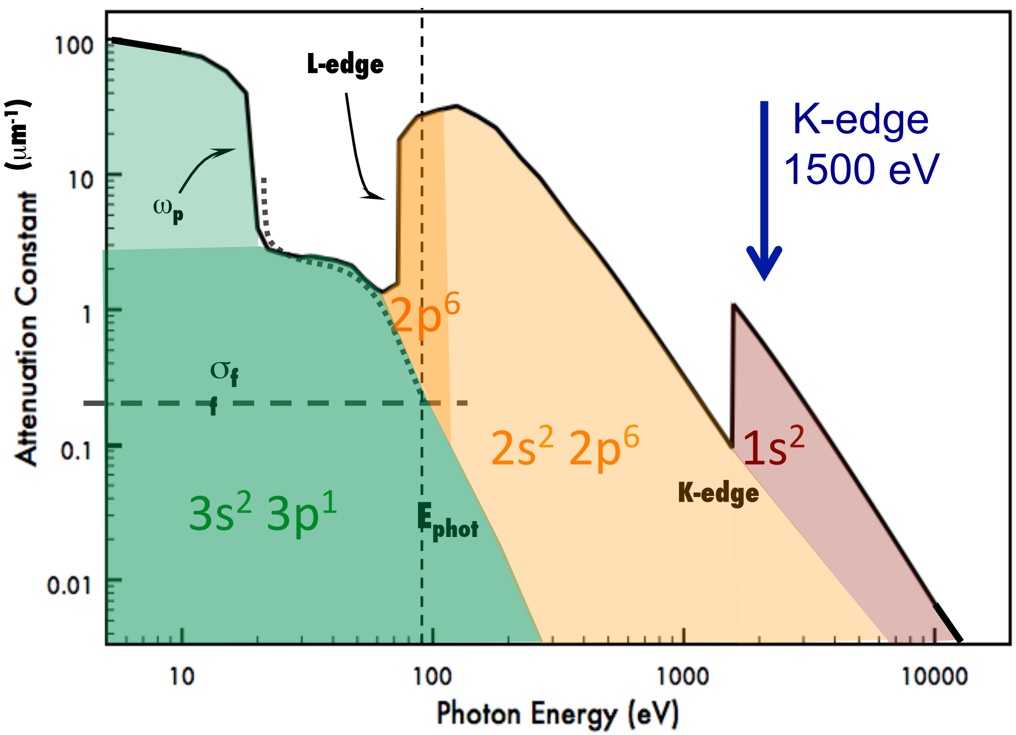


Collaboration: Oxford, LBNL, etc.

Absorption in solid aluminum is wavelength dependent

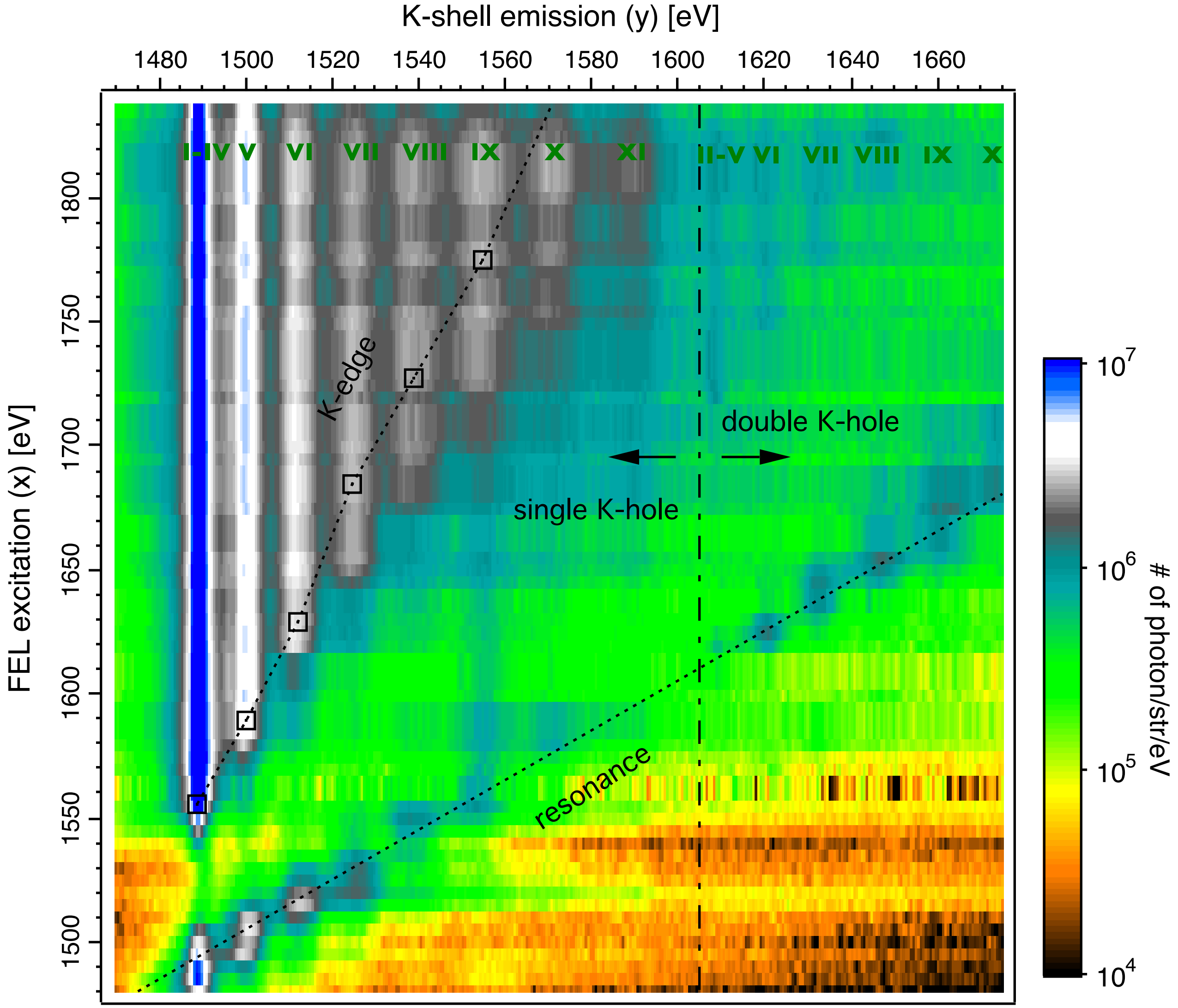
Electron configuration

$1s^2$	$2s^2\ 2p^6$	$3s^2\ 3p^1$
K	L	M

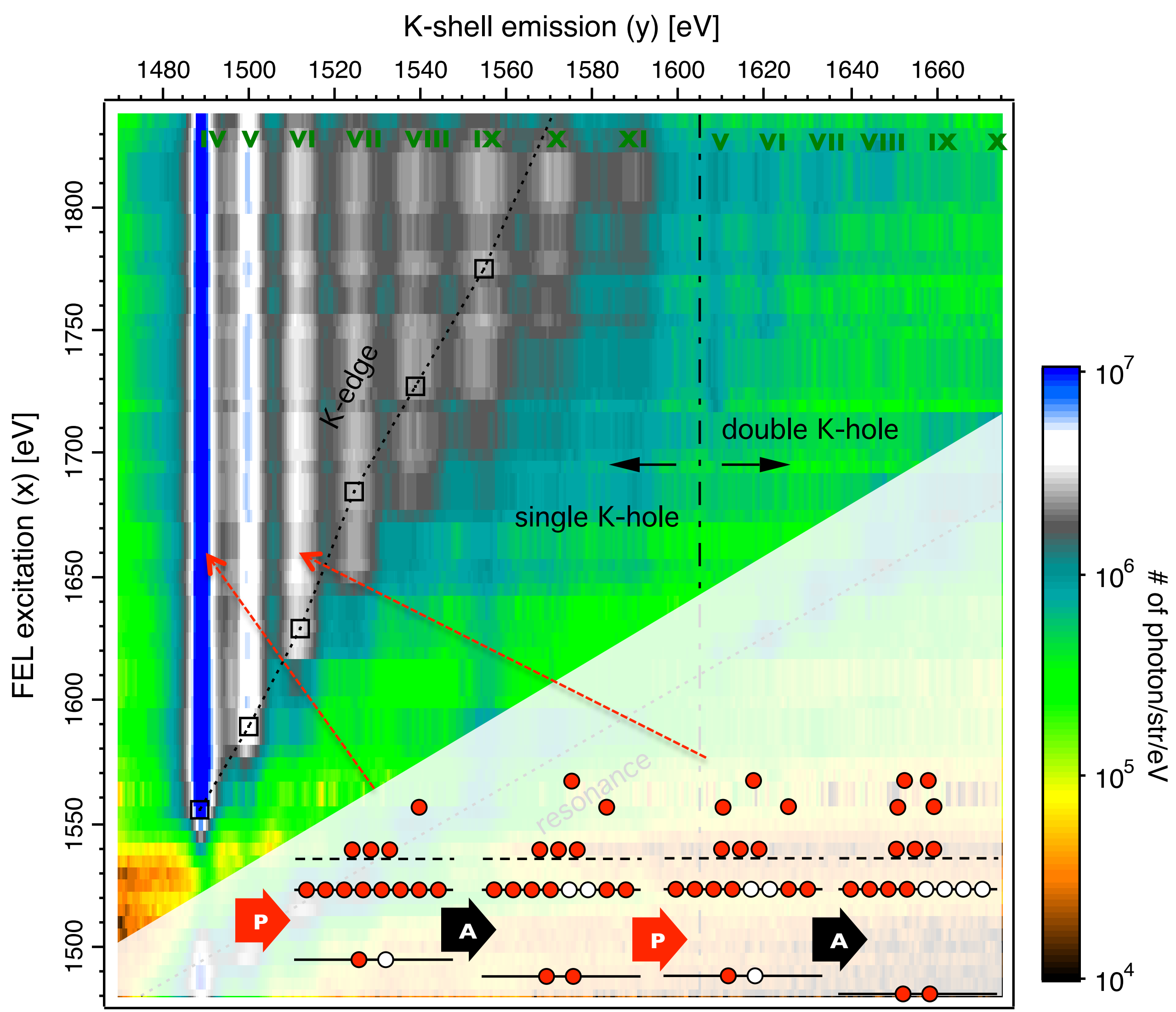


- **Multiple absorption channels at near edge photon energies**

Two types of emission are observed from XFEL-pumped Al: K-alpha from ion stages and resonance scattering



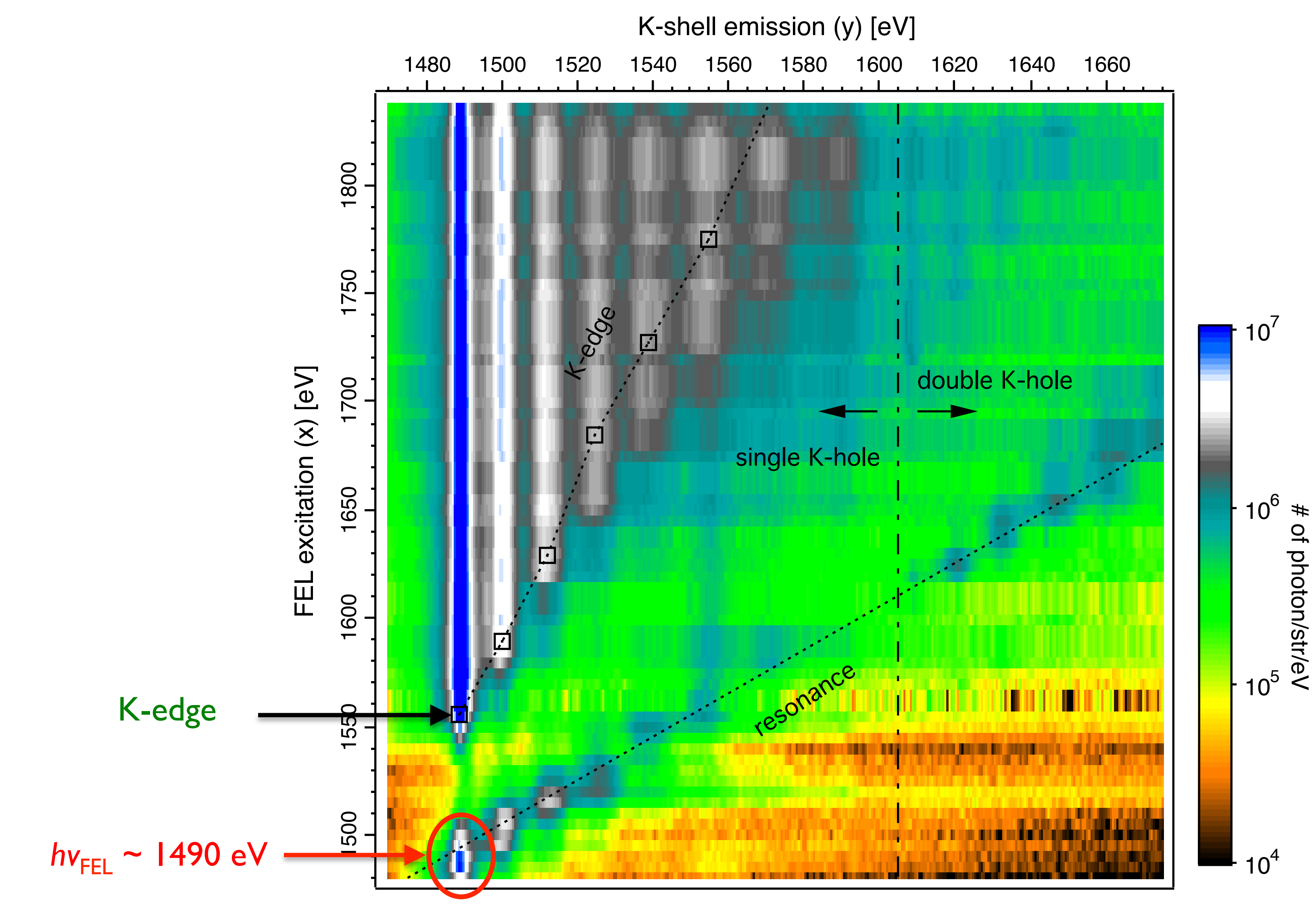
Dynamics include sequential photo-ionization & Auger decay; ionization depression affects dynamics



Vinko et al Nature 482, 59-62 (2011)

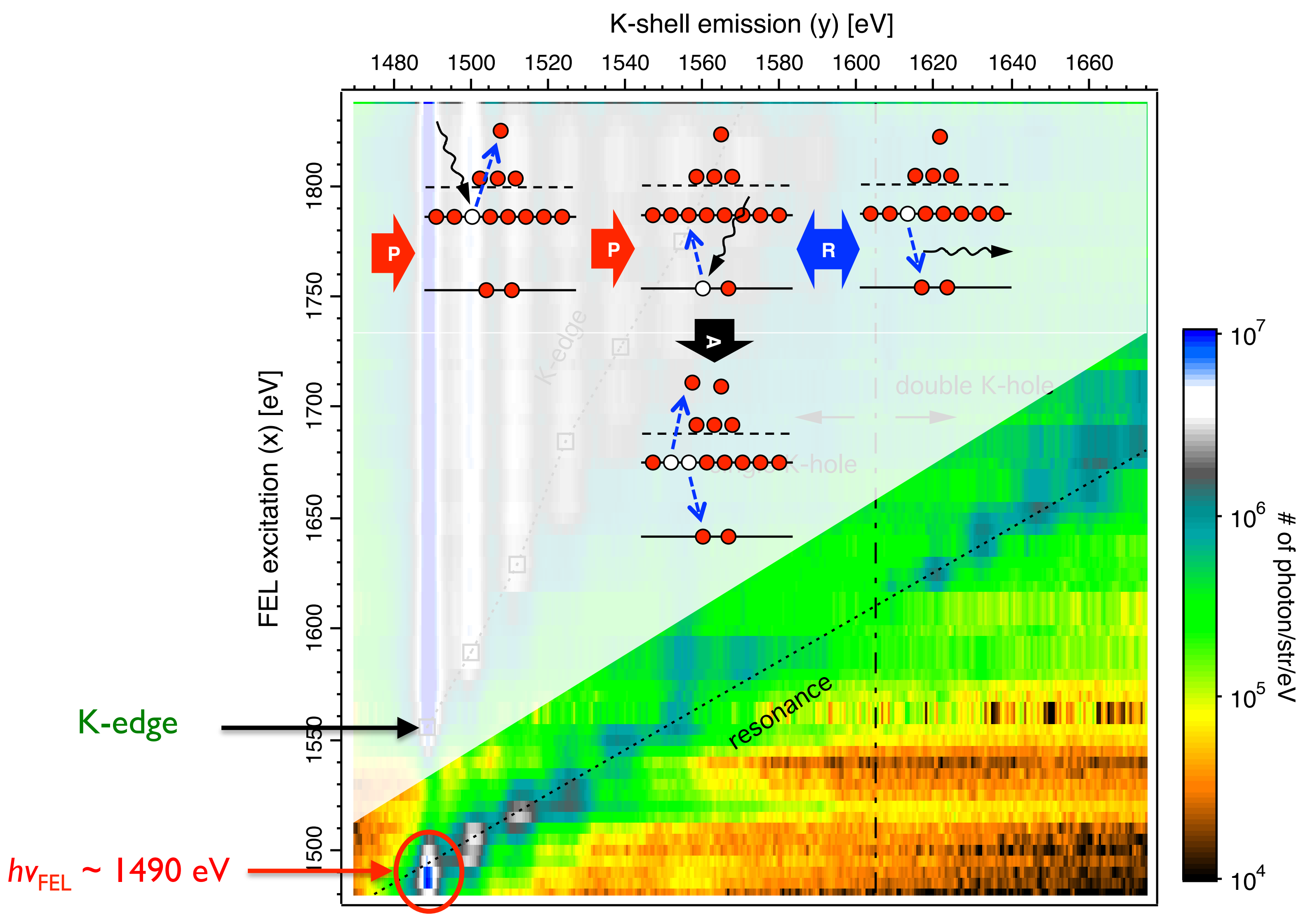
Ciricosta et al PRL 109, 065002 (2012)

High fluence x-ray laser pulse opens inner shell processes that are inaccessible via single photon process



Cho et al. PRL 109, 245003 (2012)

High fluence x-ray laser pulse opens inner shell processes that are inaccessible via single photon process



Spectral line broadening is observed at resonances due to high intensity and opacity effects

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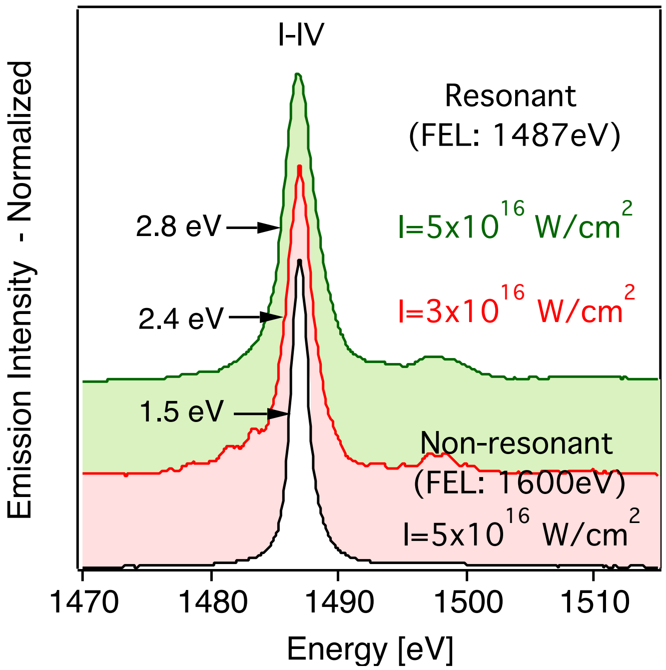
The Ka line widths for different x-ray pulse conditions



Rabi frequency for 1s-2p$_{3/2}$

$$\Omega = \frac{\mu E}{\hbar} = 1.7\times10^{15}\,\mathrm{Hz}$$

$$\left(\Gamma_{K\alpha} \sim 2.3\times10^{13}\,\mathrm{Hz},\ \Gamma_{KLL} \sim 5.7\times10^{14}\,\mathrm{Hz}\right)$$

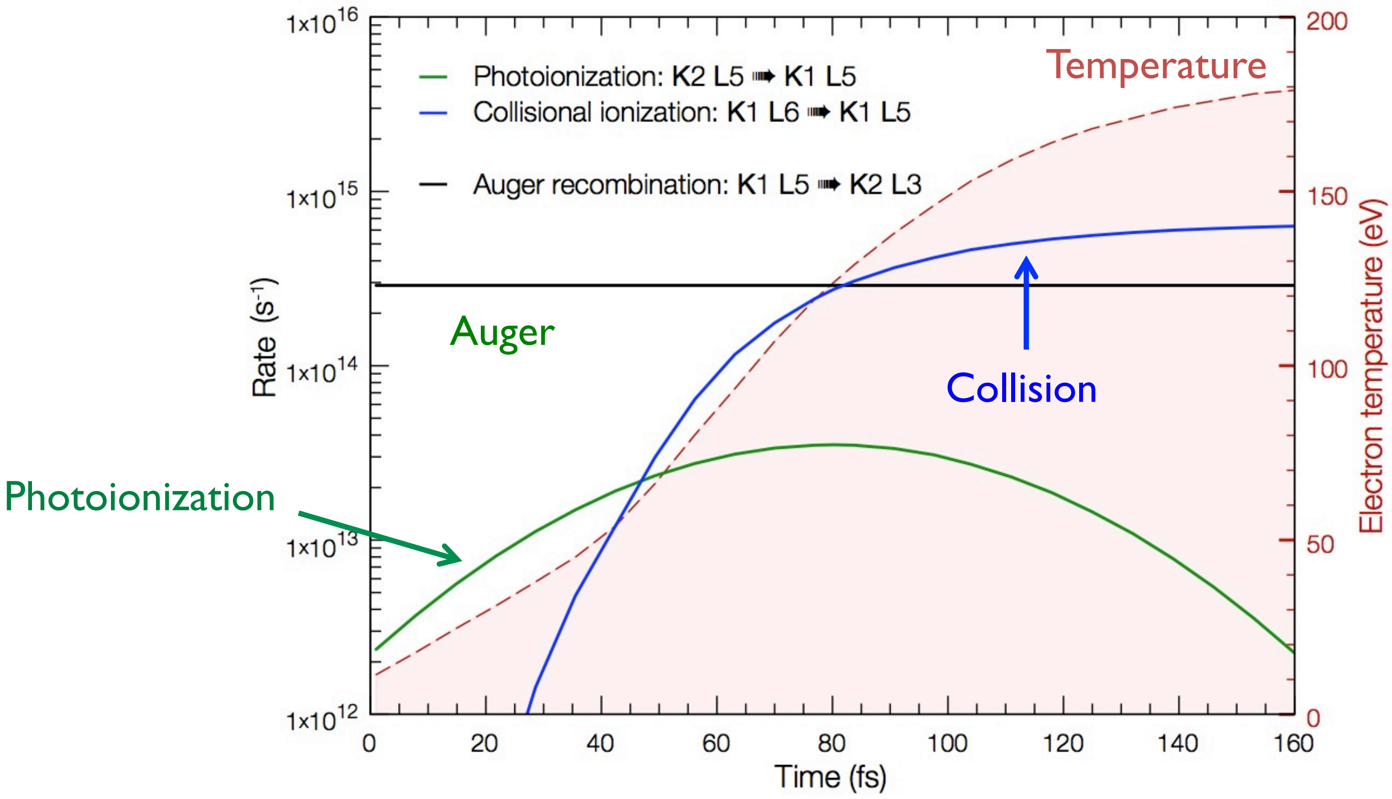
Power broadened spectral line

$$I(\omega) = \frac{\hbar\omega}{2\tau}\,\frac{\Omega^2}{\Omega^2 + 1/(2\tau^2) + (\omega-\omega_0)^2}$$

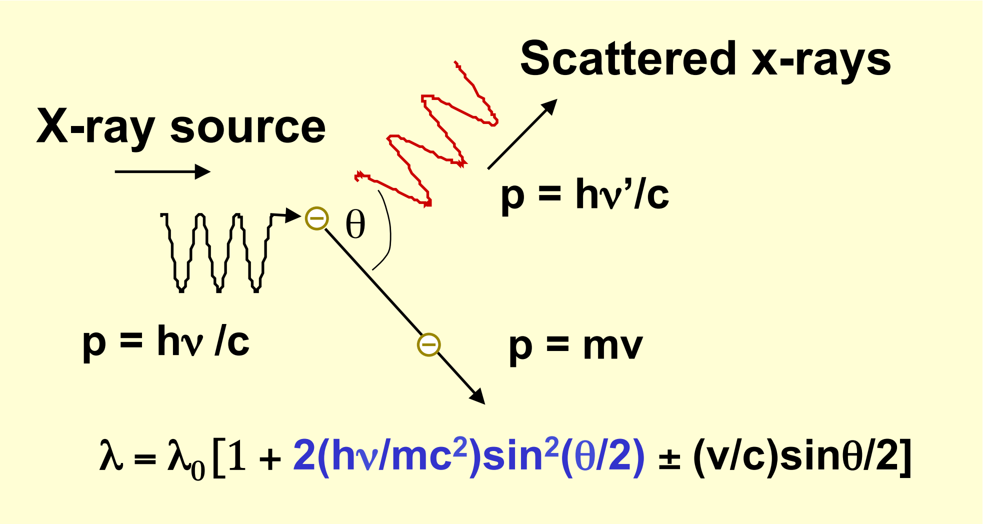
$$\gamma_\omega = (1/\tau)[1 + 2\Omega^2\tau^2]^{1/2}$$

Collisional ionization rates also control population dynamics (utilize collisional radiative code SCFLY)

Rates for Atomic and Collisional processes

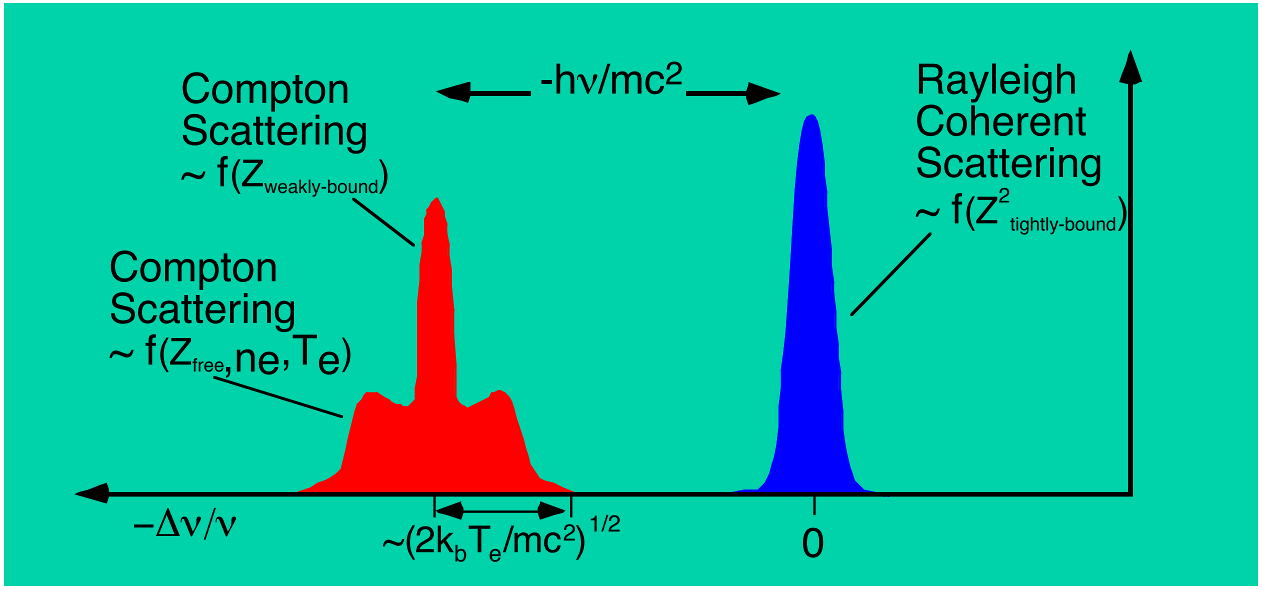


Elastic and inelastic x-ray Thomson scattering reveals plasma properties



Collective modes of dense matter can be probed by varying scattering angle

Reveals
- temperatures
- densities
- ionization
- velocity distribution



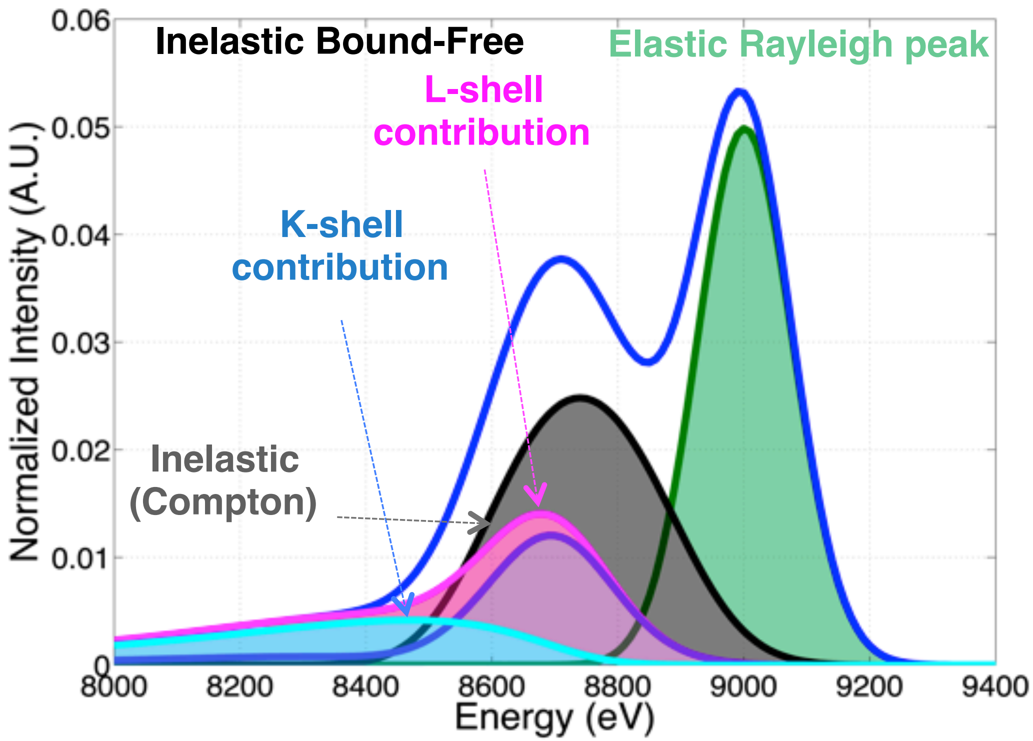
Thomson scattering depends on several factors

Three contributions to the Dynamic Structure Factor:

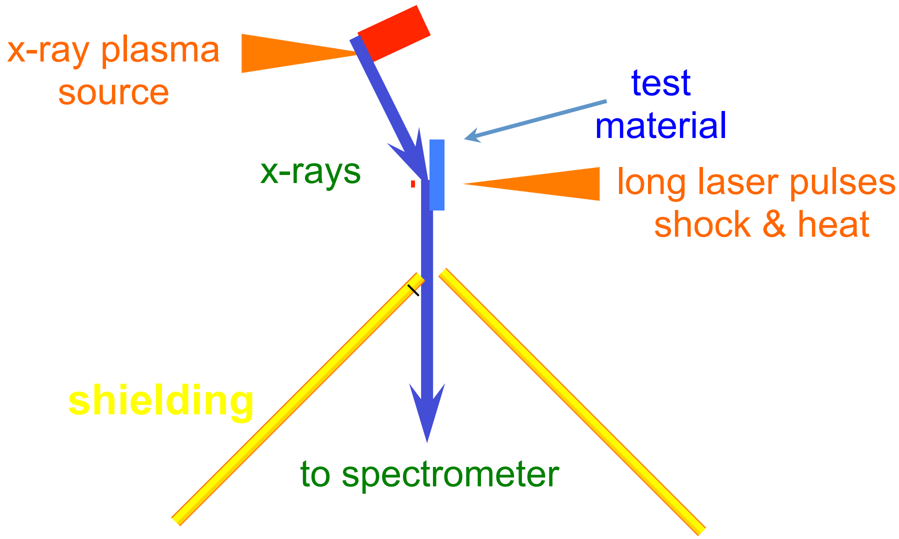
ion feature — electron feature — bound-free feature

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

Z_f =free e^-; Z_c=core e^-; f_i = ion form factor; $q(k)$= free & valence e^- screening cloud



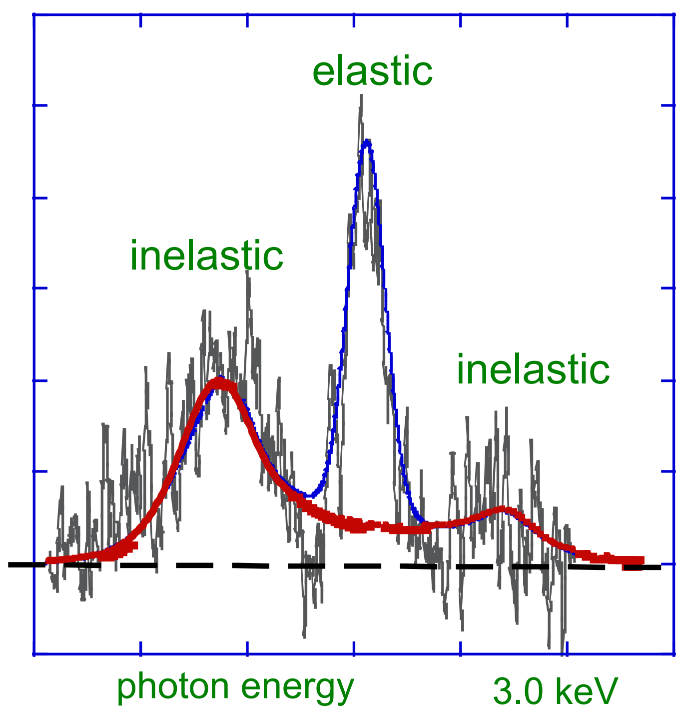
Thomson scattering used to probe compressed Be

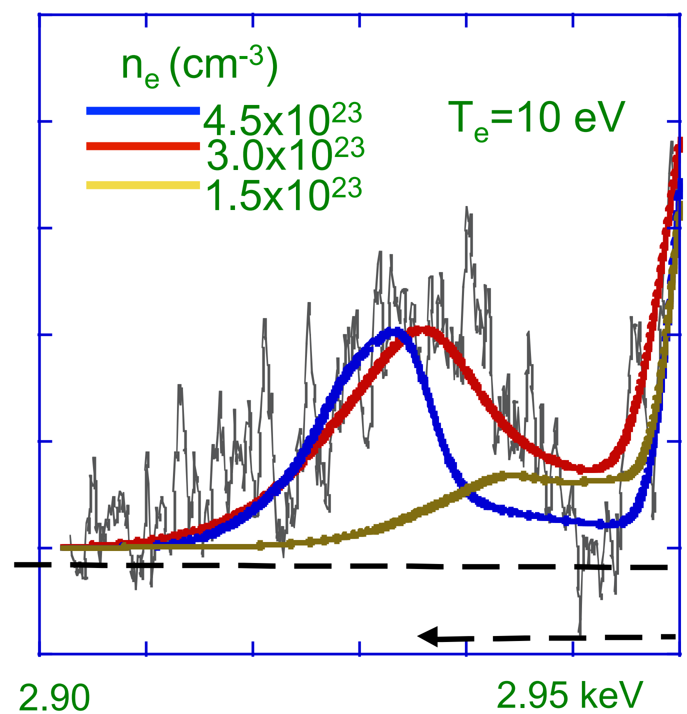


kJ laser pulses create plasma
K-α x-rays radiating into 4π

1 mJ x-rays collected in small solid angle & scatters from shocked & heated material

implies that 1 mJ x-ray XFEL pulses can be used to scatter from excited material





NIF

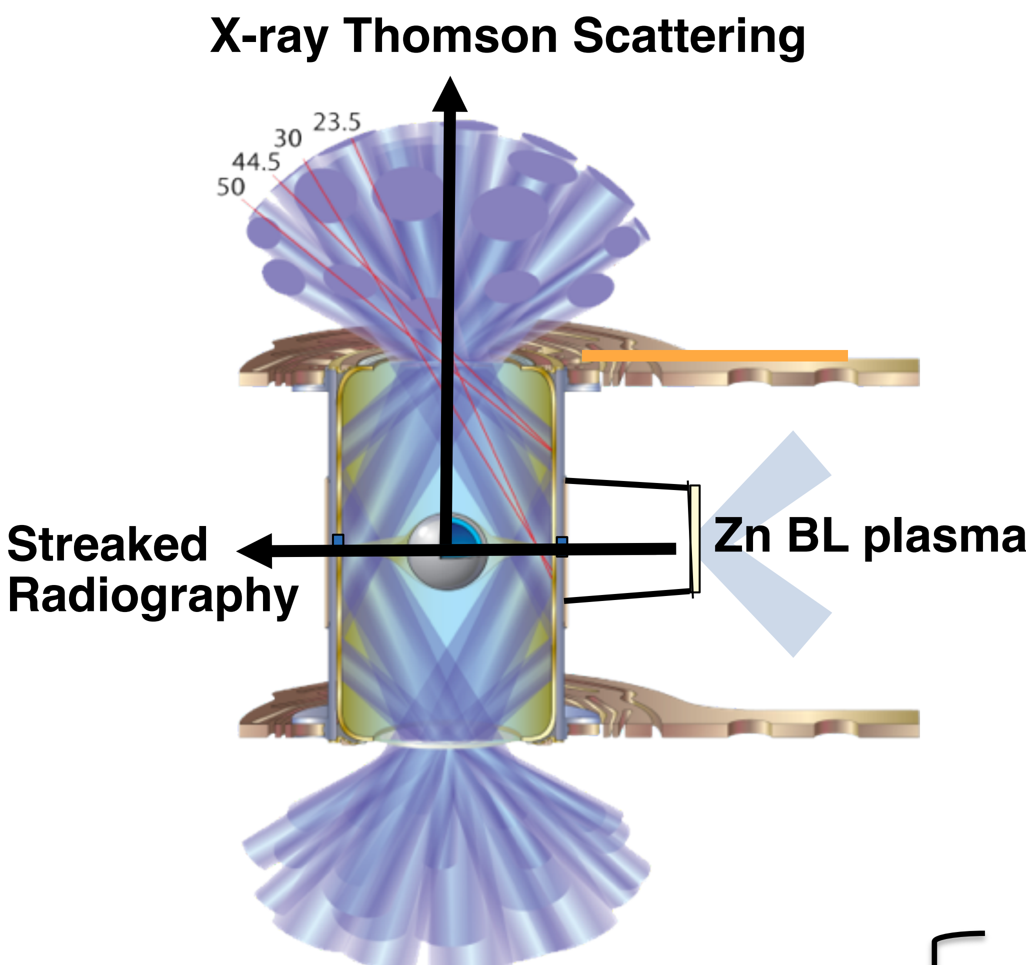
Equation of state measurements of CH plastic at Gbar pressures using the National Ignition Facility

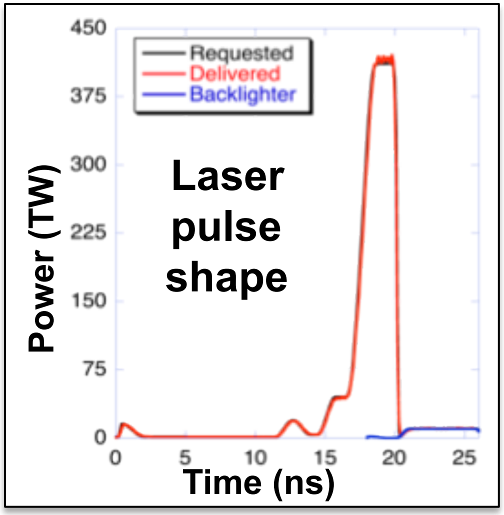
T. Doeppner, A. Kritcher, D. Swift, J. Hawreliak, B. Bachmann, P. Celliers, D. Chapman, G. Collins, J. Eggert, S. Glenzer, D. Kraus, O. Landen, S. Le Pape, H. J. Lee, P. Neumayer, J. Nilsen, R. Redmer, S. Rothman, C. Keane, R. Falcone

This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344

LLNL-PRES-645847

Compressed CH sphere on NIF ICF platform is used to study Gbar-scale pressures using radiography & Thomson scattering





$$D + D \rightarrow n + {}^{3}He \qquad E_n = 2.5\ MeV$$

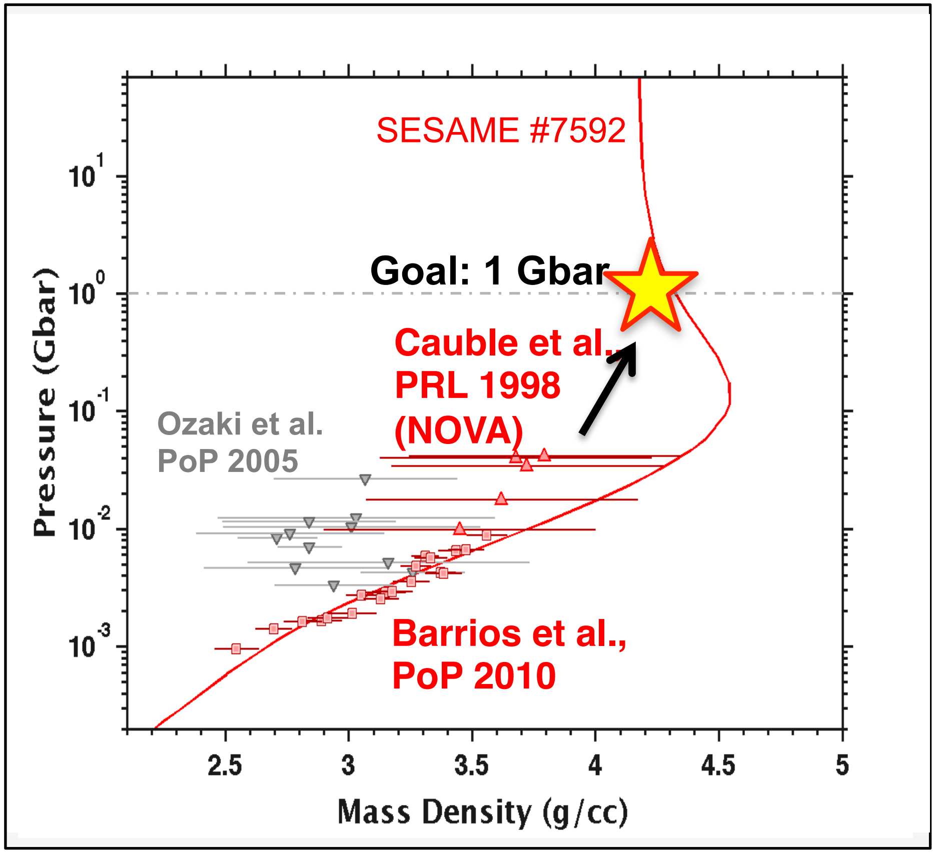
plus neutron time-of-flight detectors

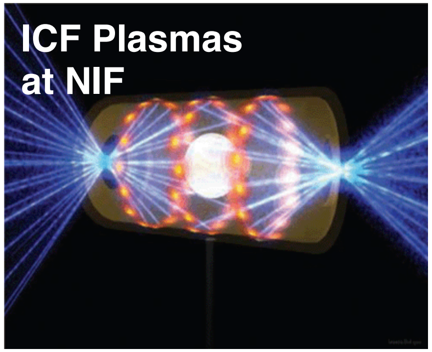
Temperature measurement at shock stagnation from broadening of time-of-flight neutron trace with 10% accuracy at 1keV

Gbar experiments will be important for testing and validating EOS models

- **Gbar pressures occur in ICF and center of brown dwarfs**
- **Pressure & temperature ionization may affect the compressibility (shell effects)**
- **Will benchmark models at 100 Mbar - 1Gbar**

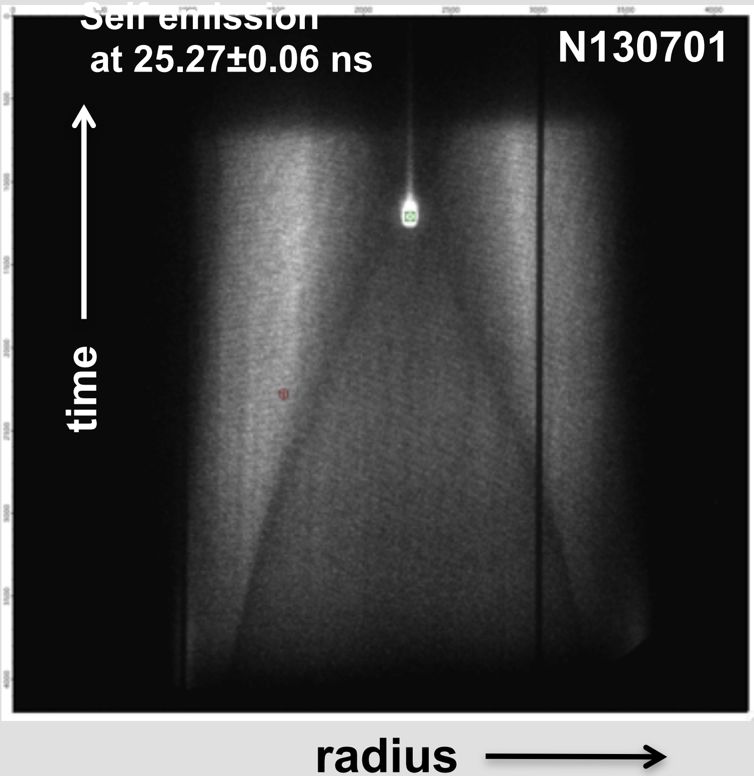
Hugoniot data for Polystyrene



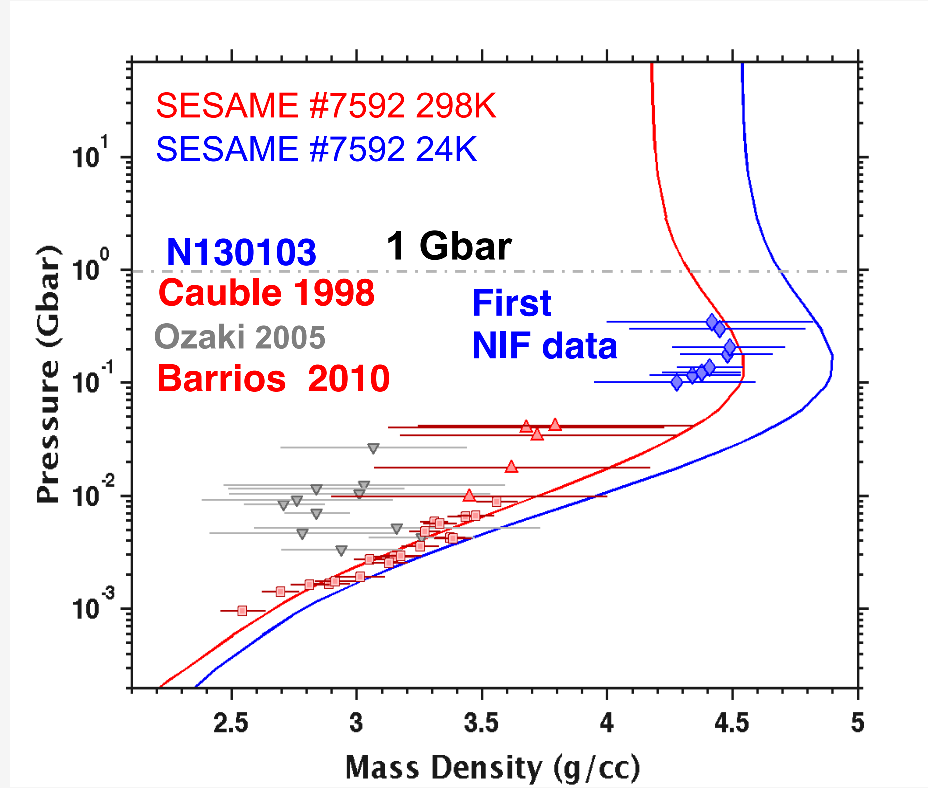


Radiography enables EOS measurements

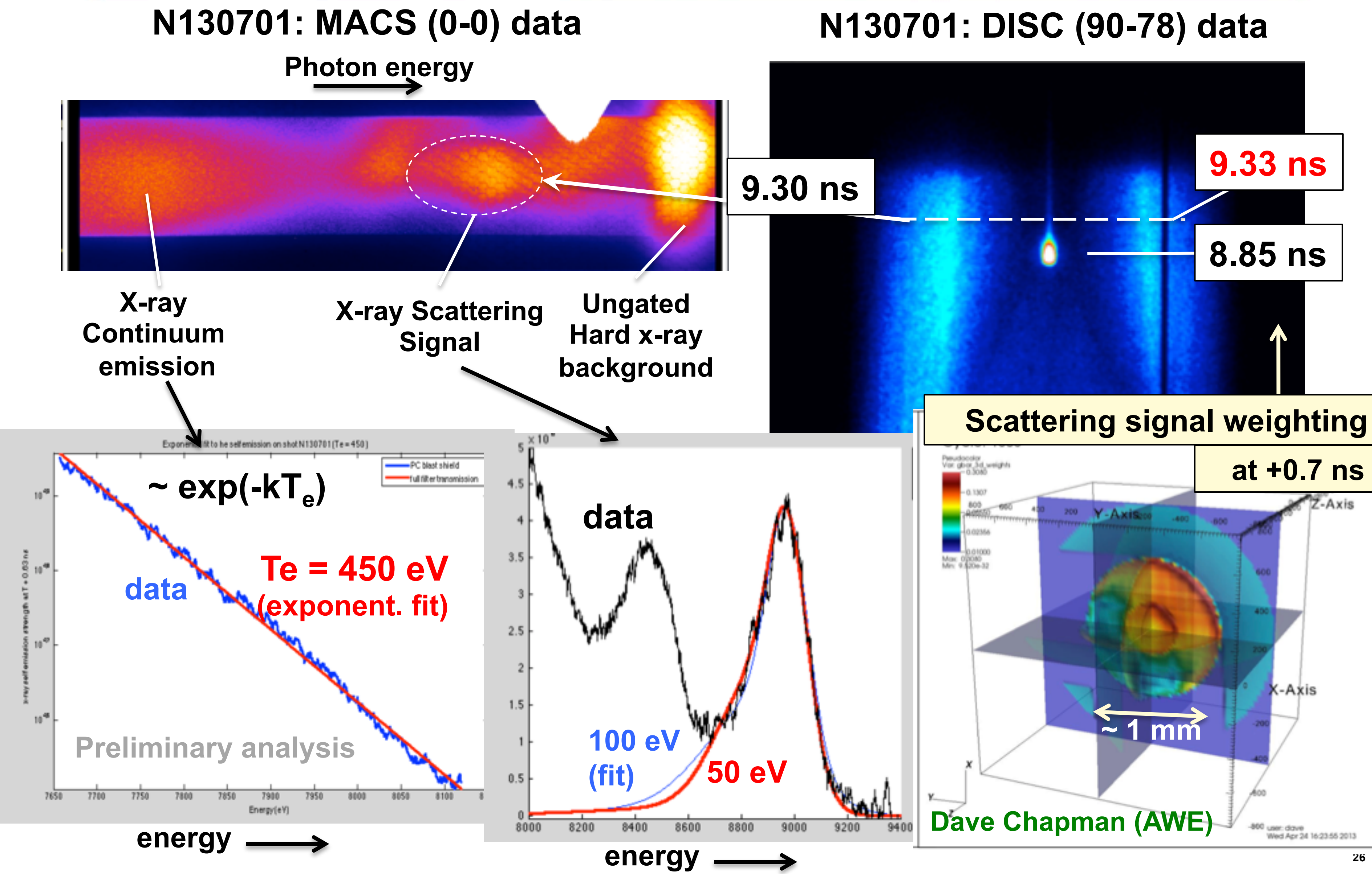
Data: July 01, 2013



Absolute shock Hugoniot measurements of plastic equation of state

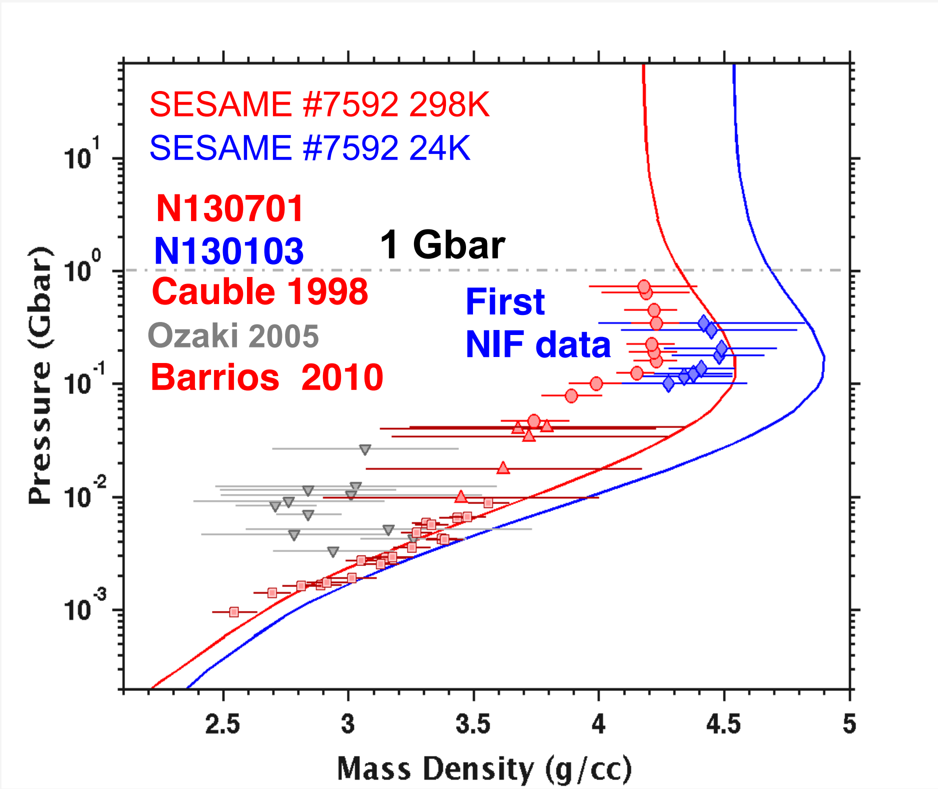


First x-ray scattering data were recorded at 9.33 ns (peak emission + 0.48 ns)



We have reached a pressure of 720 Mbar

Absolute shock Hugoniot measurements of plastic equation of state



- Both NIF data sets (RT & cryo) are stiffer than the Sesame and LEOS Hugoniots
- N130701 data is consistent with Nova data (Cauble et al., PRL 1998)
- Possibly first observation of atomic shell effects
- Future shots will lower drive to rule out adverse impact from preheat

X-ray techniques uniquely probe matter under extreme conditions

1. Absorption spectroscopy
   - reveals electronic structure, bonding, local order
   - utilize synchrotrons, FELs, HHG, Betatron radiation (?)

2. Emission spectroscopy
   - reveals pathways among highly excited states
   - utilize FELs

3. Inelastic scattering
   - reveals temperatures & densities of electrons & ions
   - utilize plasma backlghters, FELs

4. Diffractive scattering and imaging
   - reveals structure
   - utilize FELs

5. Ionization mass spectroscopy
   - reveals mass products of evolving molecular systems
   - utilize HHG sources at high rep rate

Many international collaborators

US: T. Doeppner, J. Belak, R. Bionta, K. Budil, G. Campbell, H.-K. Chung , G. Collins, P. Celliers, J. Dunn, S. Glenzer, G. Gregori. S. Hau-Riege, D. Hicks, J. Kinney, J. Kuba, R. Lee, O. Landen, R. London, H. Lorenzana, J. McNaney, S. Moon, A. Nelson, J. Nguyen, B. Stuart, K. Widmann, C.-S. Yoo, P. Young , J. Zaug (LLNL);
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Thank you