Creating Plasmas and Other Extreme Conditions with FELs and Other Big Lasers

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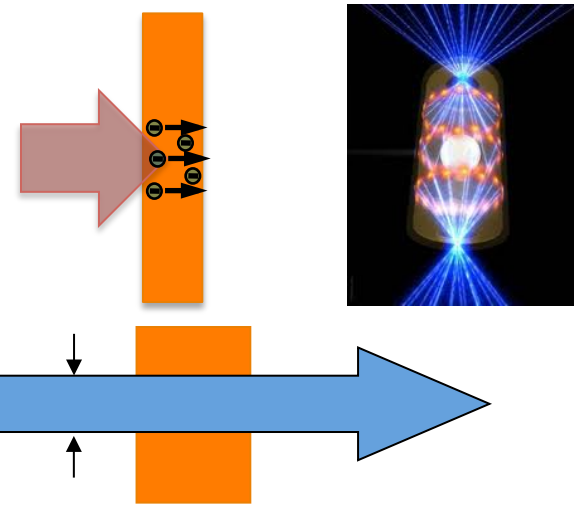
High energy lasers and x-ray FELS can <u>create</u> and <u>probe</u> materials under transient extremes of high temperature, pressure, and density

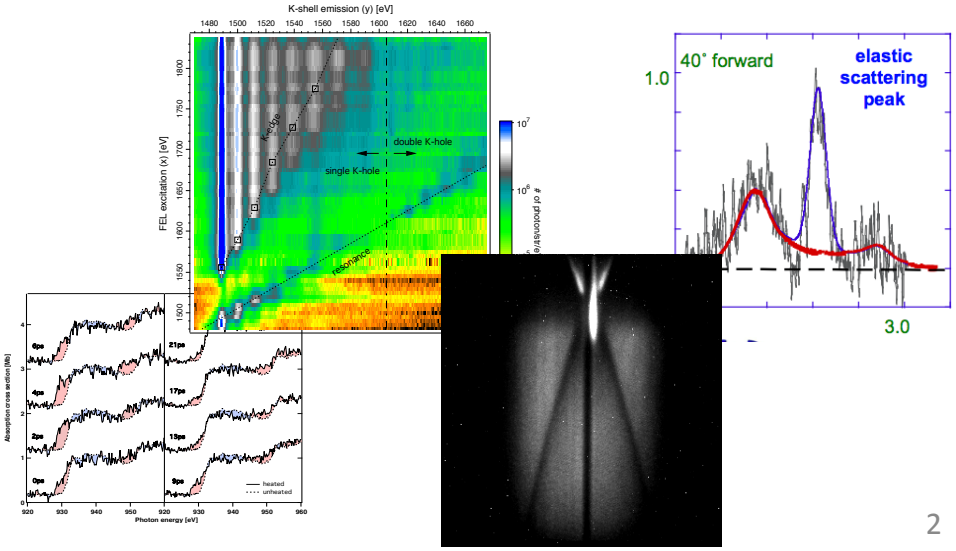
Create by:

- isochoric heating with short pulse optical laser or free-electron x-ray laser
- shock compression with long pulse laser or long pulse x-ray radiation heating/ablation

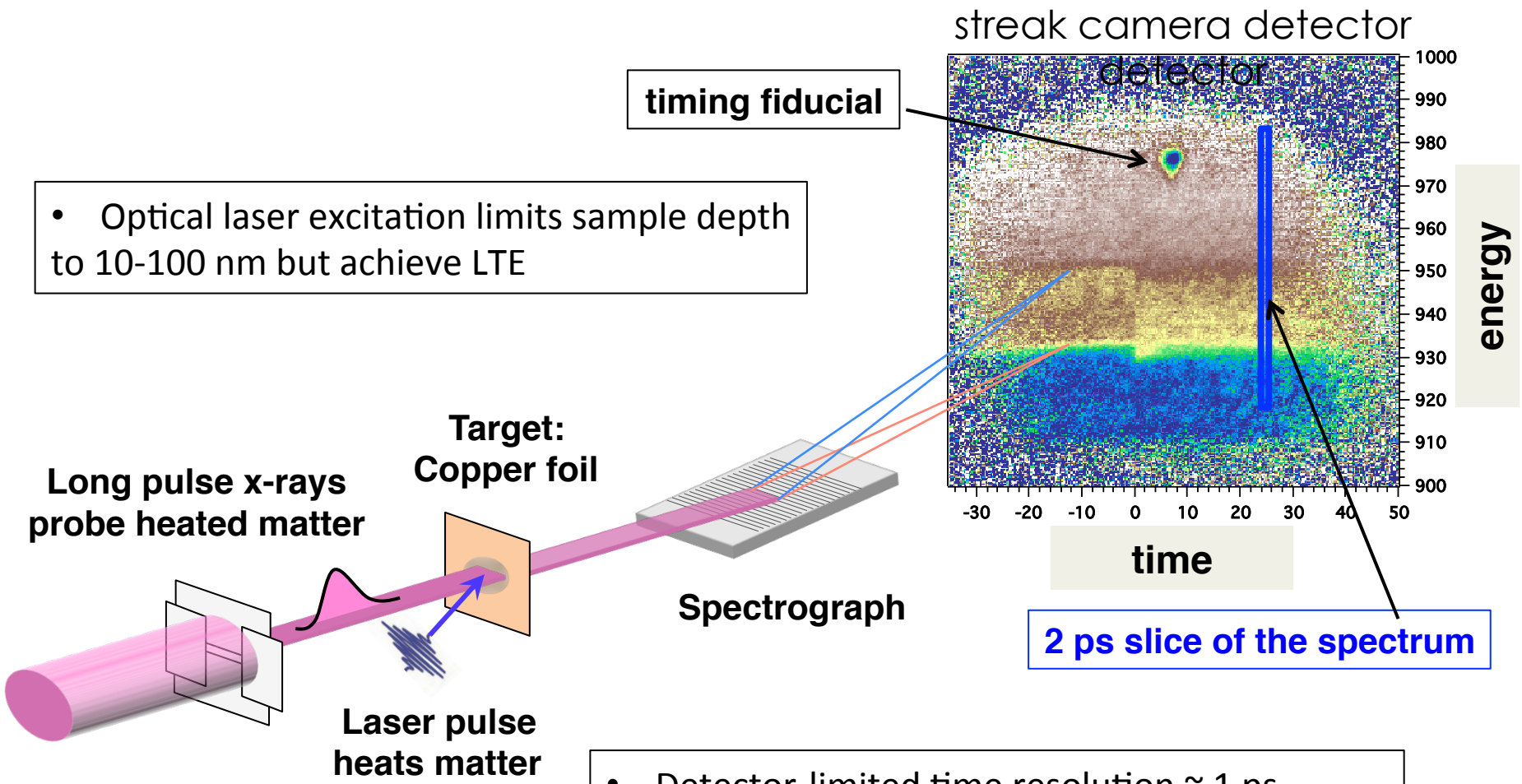


Probe with x-rays:

- near-edge absorption
- emission spectroscopy
- spatial imaging
- inelastic scattering



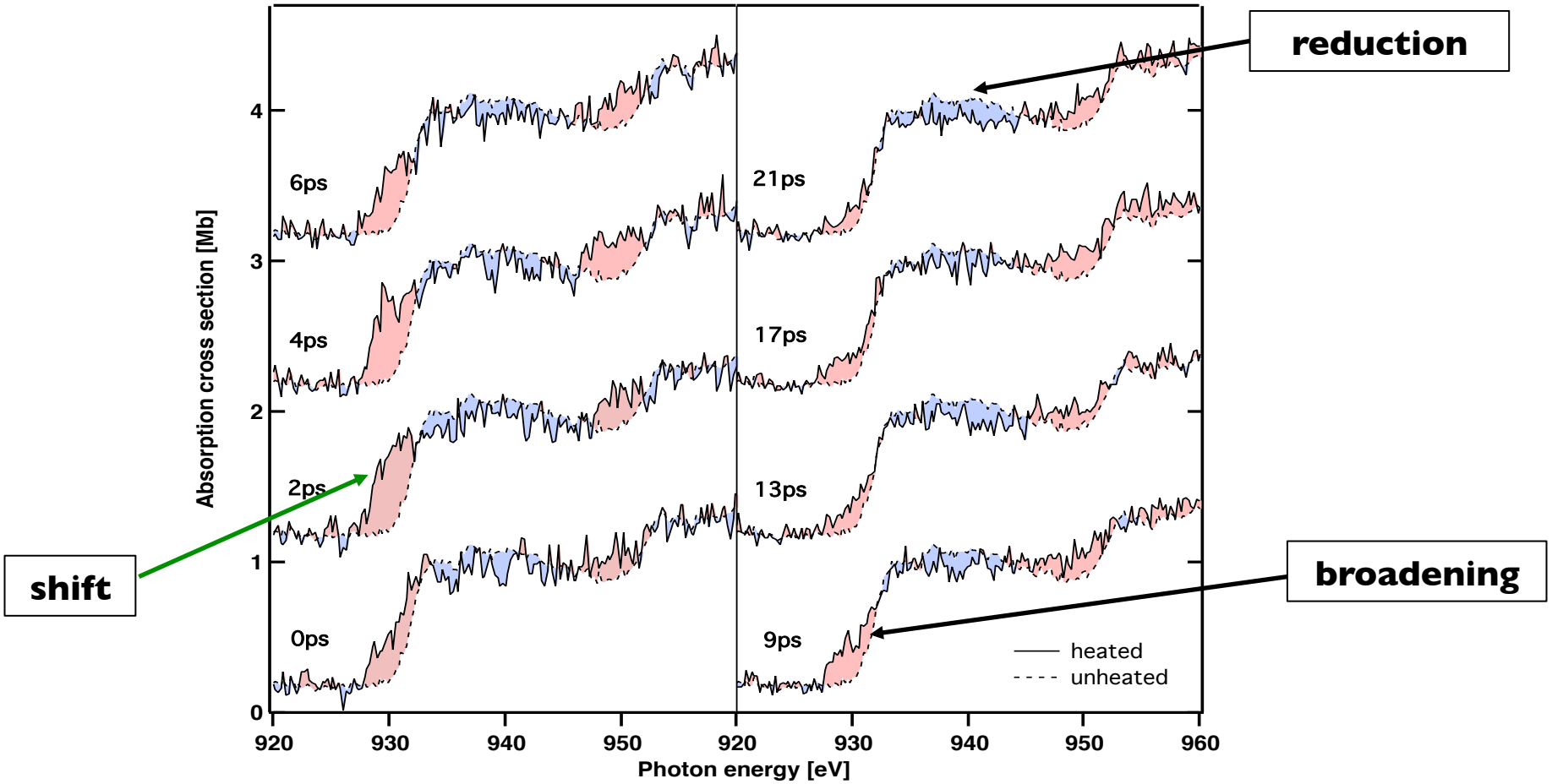
Electronic structure of dense and ionized matter can be studied by near edge absorption spectroscopy



- Optical laser excitation limits sample depth to 10-100 nm but achieve LTE

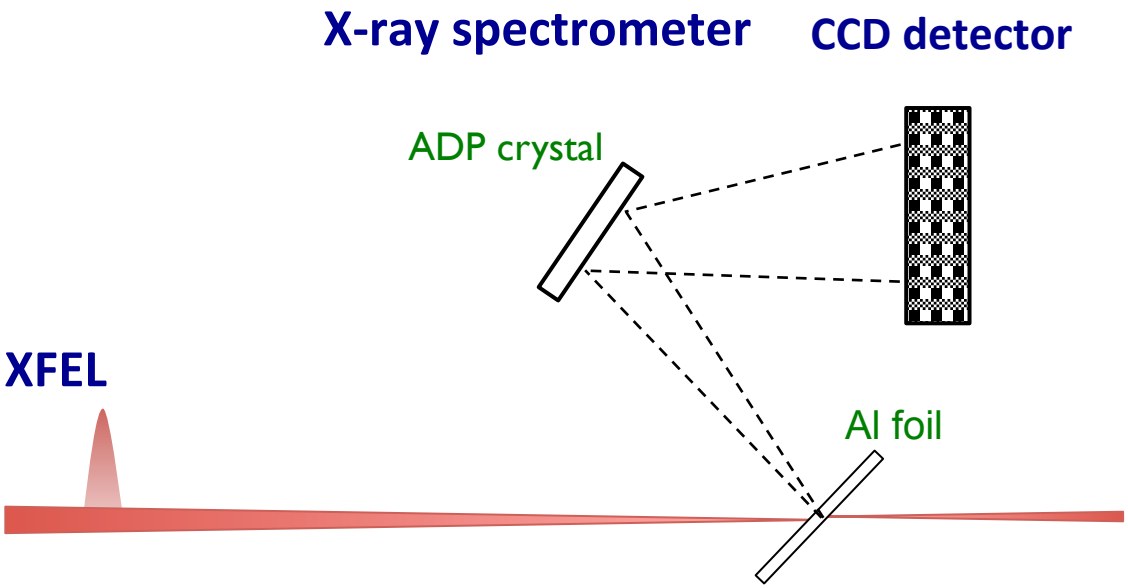
- Detector-limited time resolution ~ 1 ps
- Broad spectral line-width allows for NEXAFS

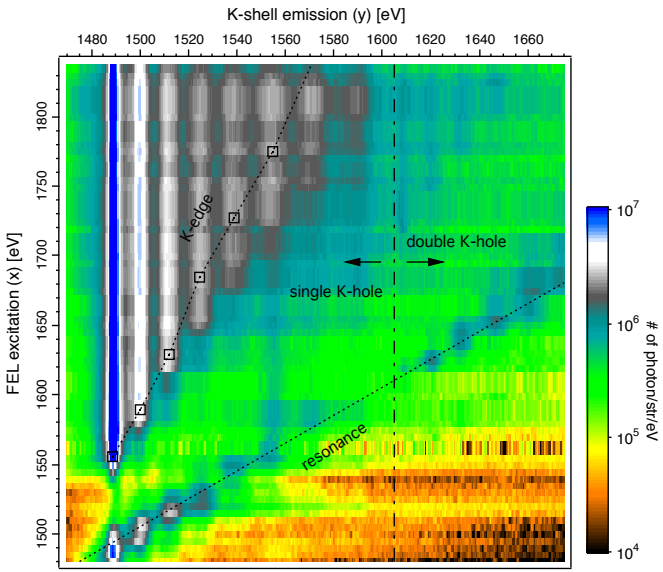
Changes in near edge x-ray absorption in warm/dense matter reveal evolving density of states at solid density with few eV electron and ion temperatures



- observe time/temperature dependent electron-ion coupling and phase transitions

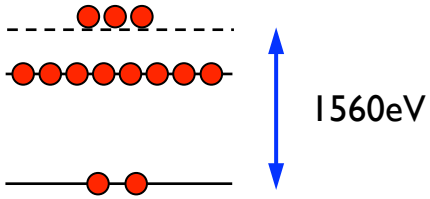
Intense X-ray FEL-illuminated solids reveal K-α emission from ion stages, and resonant x-ray scattering, under plasma conditions





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

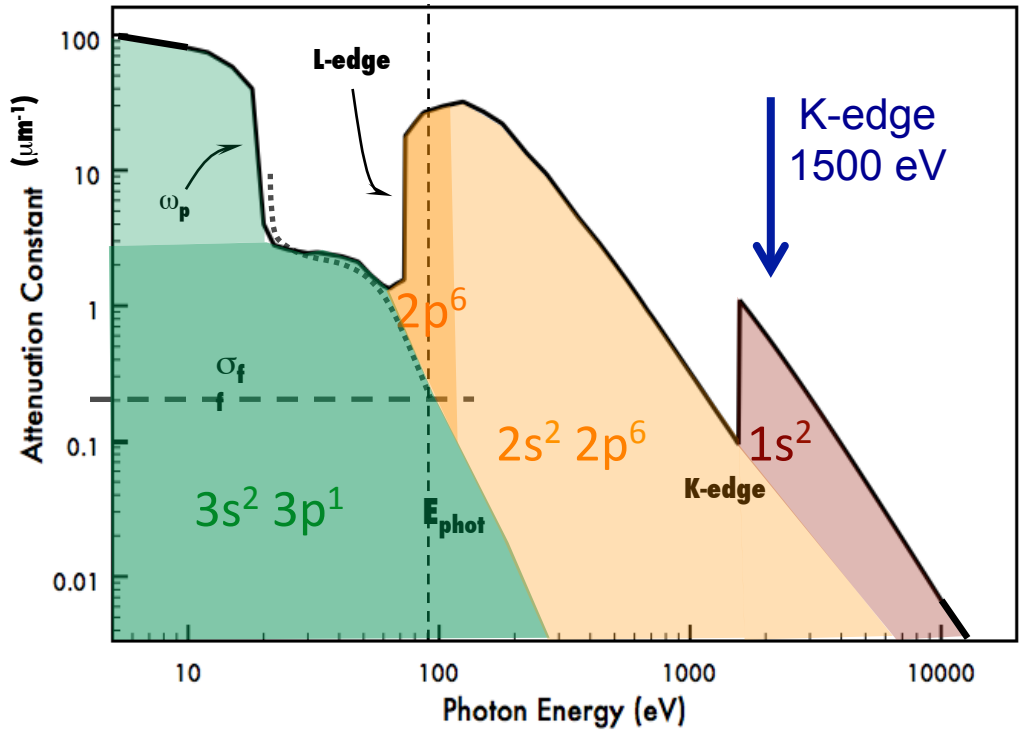
- multiple photons absorbed per atom per pulse
- femtosecond core hole lifetime and the XFEL pulse length gate the emission measurement



Absorption in solid aluminum is wavelength dependent

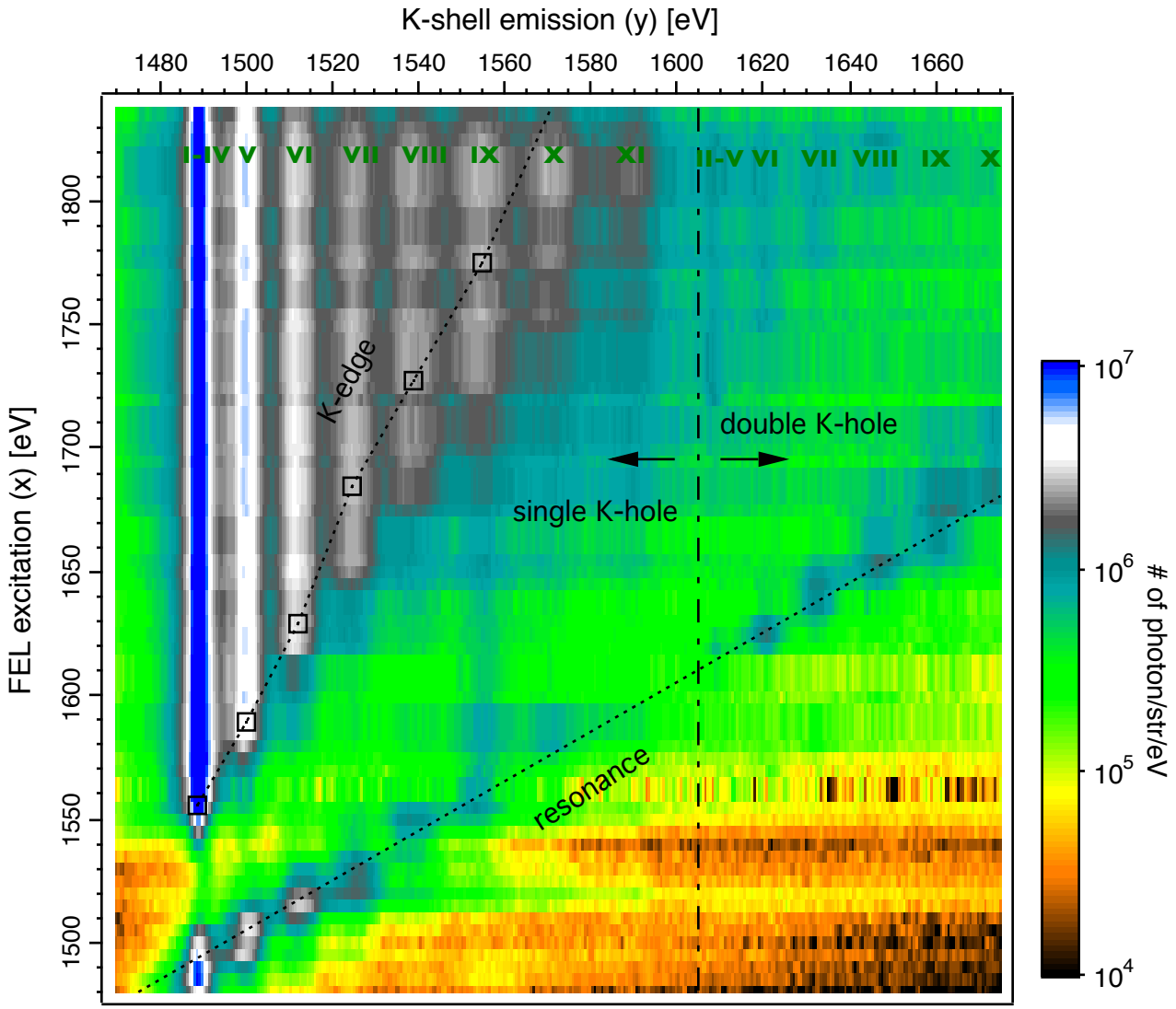
Electron configuration

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

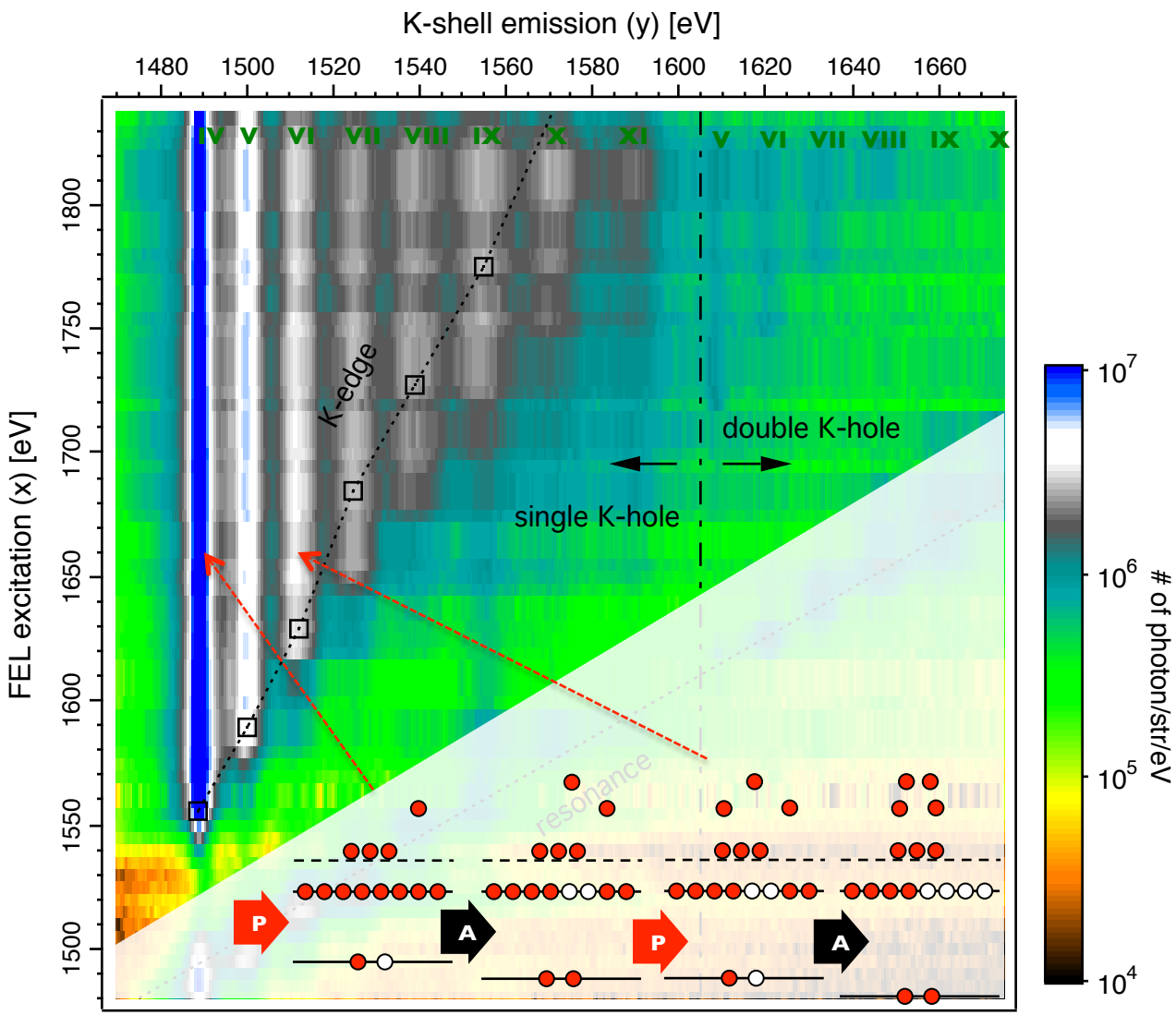


Multiple absorption channels available at near edge photon energies

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



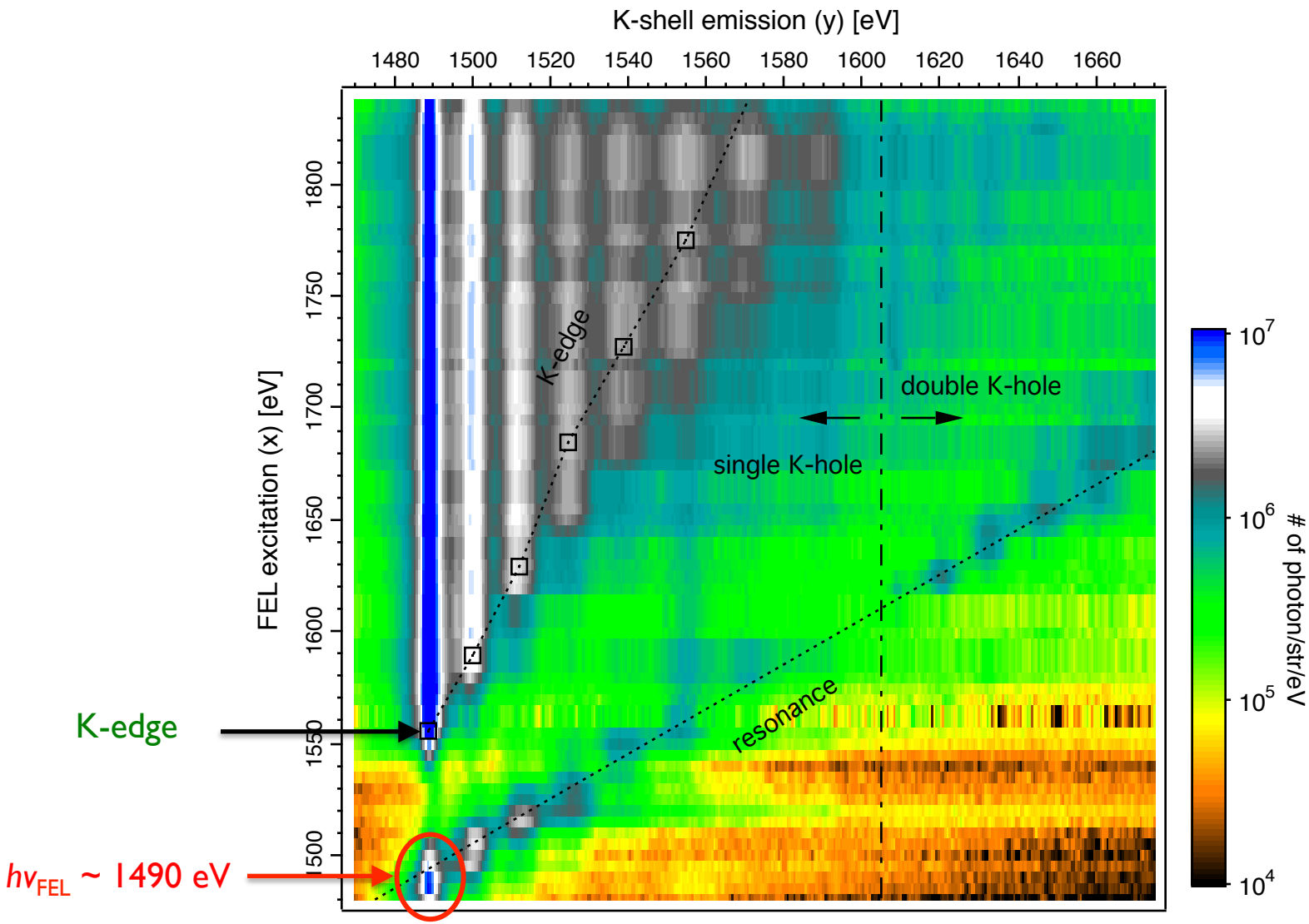
Dynamics include sequential photo-ionization & Auger decay; data tests ionization depression models



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

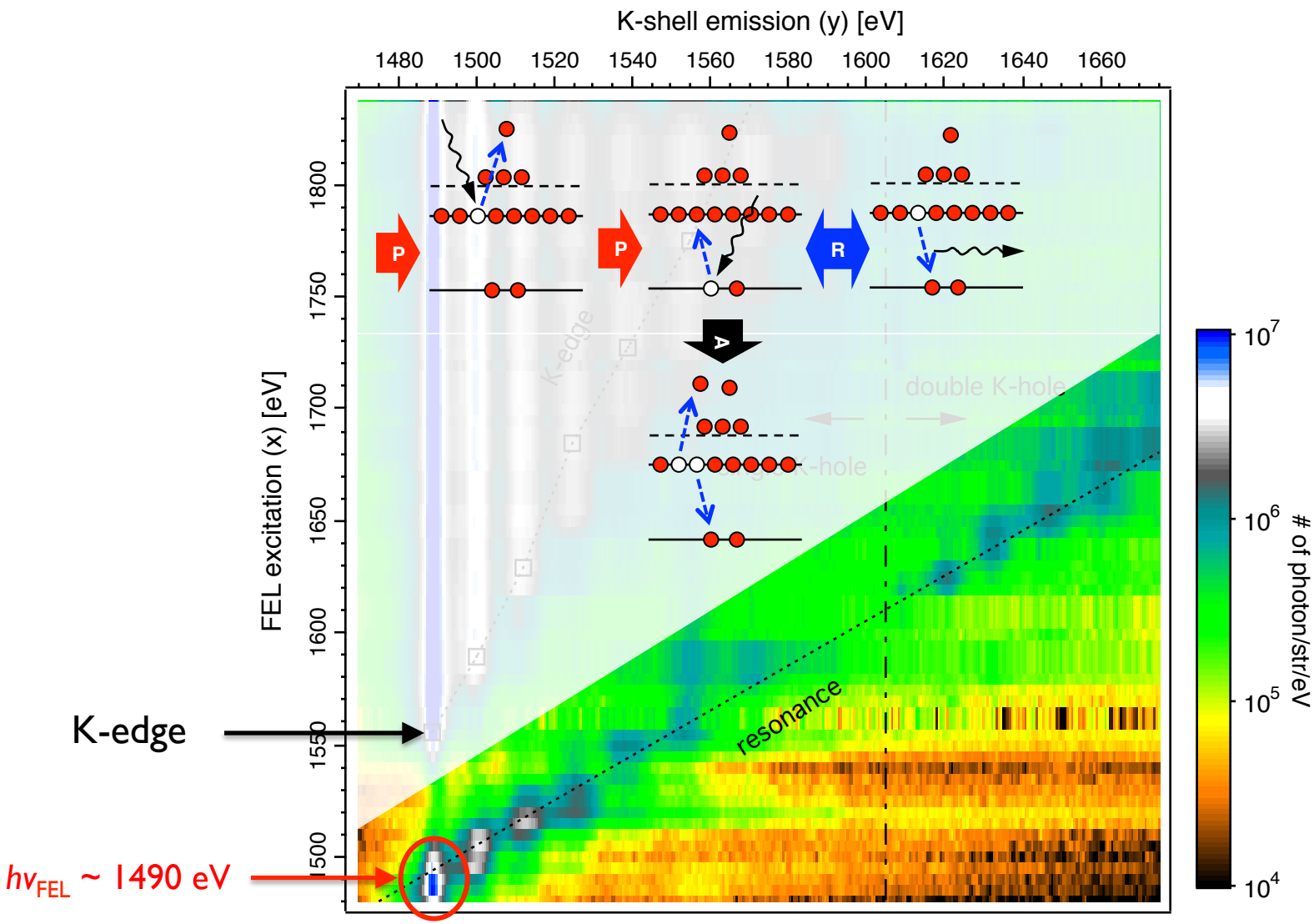
Ciricosta et al PRL 109, 065002 (2012)

Dynamics include resonant scattering following photoionization

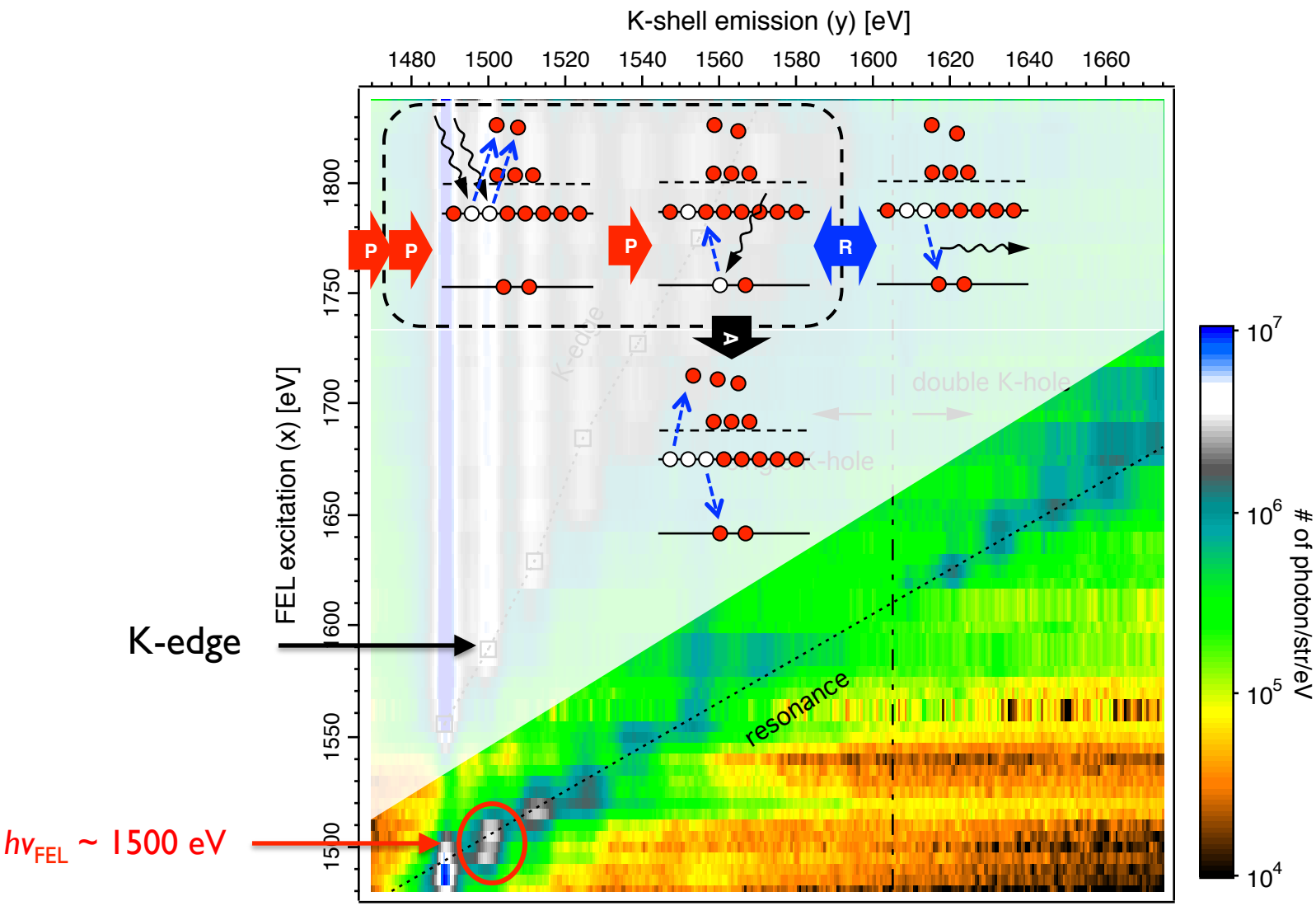


Cho, *et al* PRL

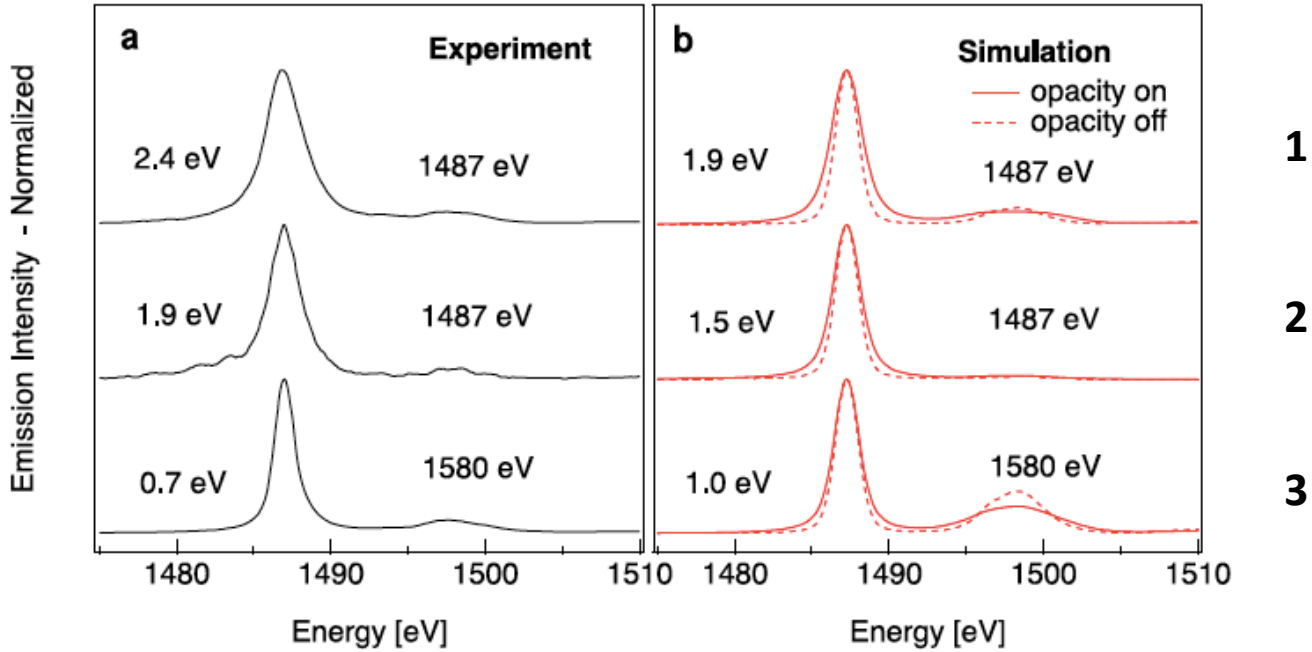
High fluence x-ray pulse opens inner shell transitions



Hidden resonance are revealed through multiphoton processes



Emission spectra reveal sensitivity to opacity effects as L-shell holes reabsorb K-alpha



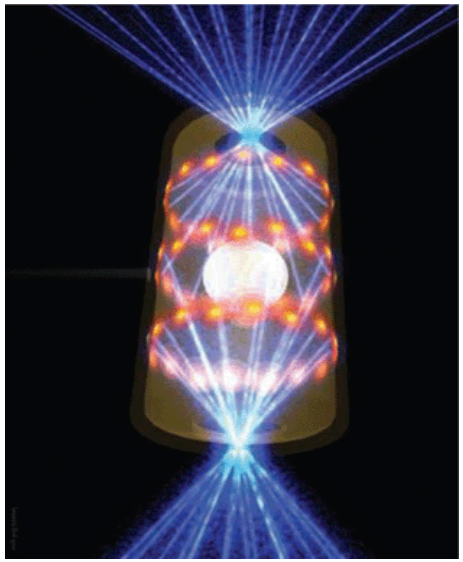
Experimental line shapes of Kα emission

(1a) resonant pumping (1487 eV) with X-ray intensity: 1×10^{17} W/cm^2
(2a) resonant pumping: 0.7×10^{17} W/cm^2
(3a) non-resonant pumping (1580 eV)

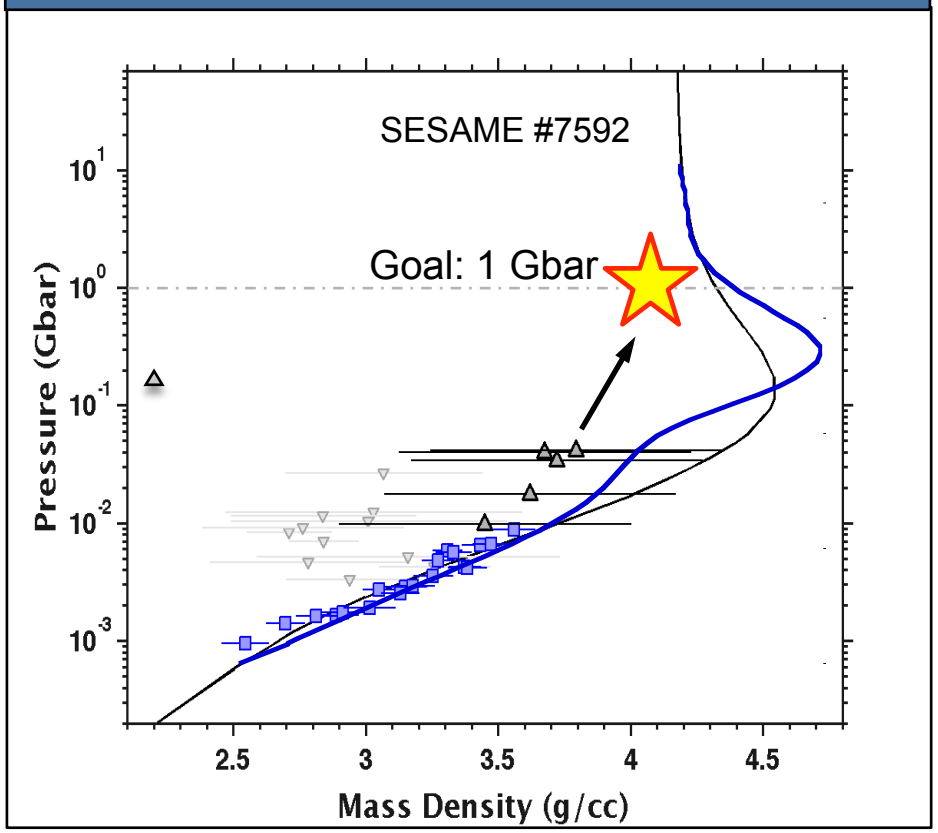
(b) SCFLY simulations with equivalent conditions: with (solid) & without (dashed) opacity

Laser-driven hohlraums create x-ray drives that generate very extreme conditions of high energy density (HED)

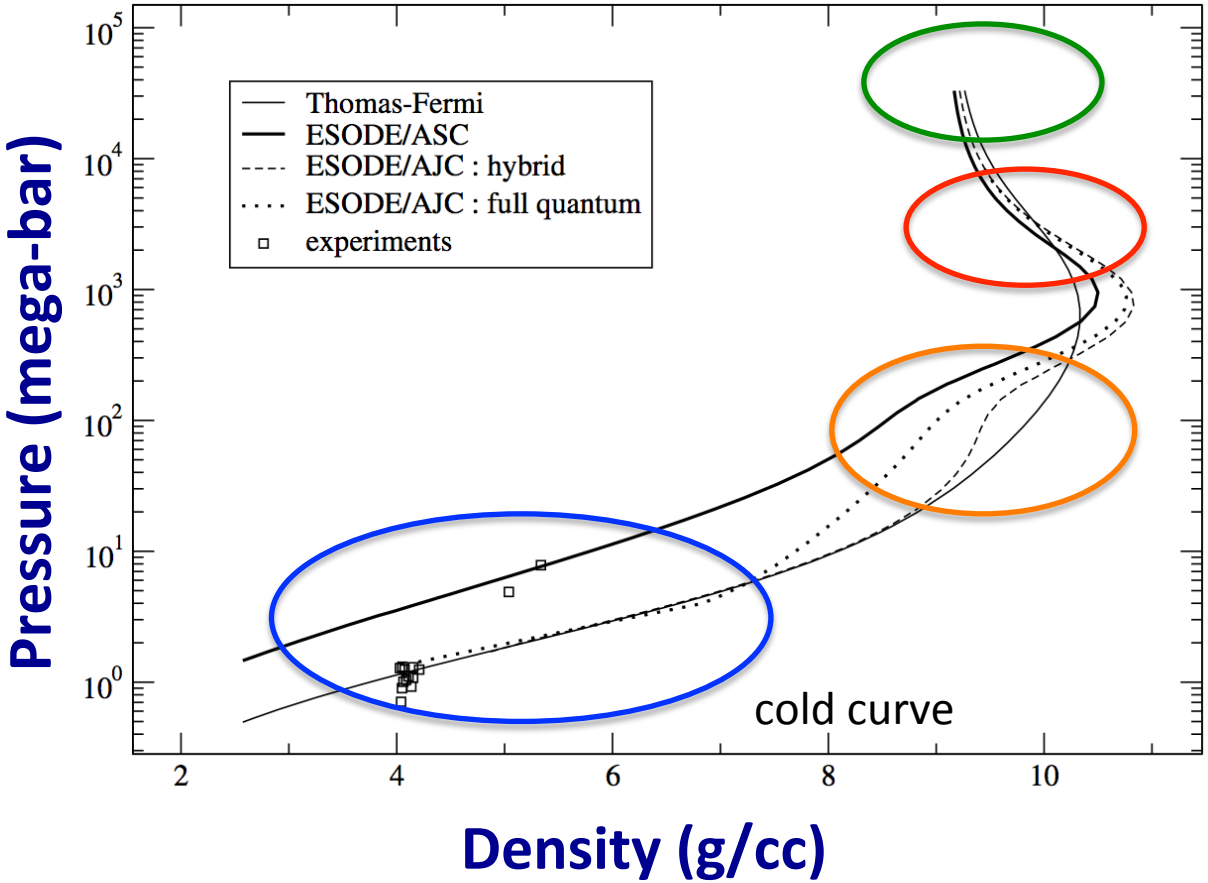
How pressure, temperature, and ionization are interrelated and affect structure



Hugoniot theory and data for CH



Measuring shock speed and density we can determine the equation of state of material in hohlraum, at GBar pressures



relativistic effects

thermal effects

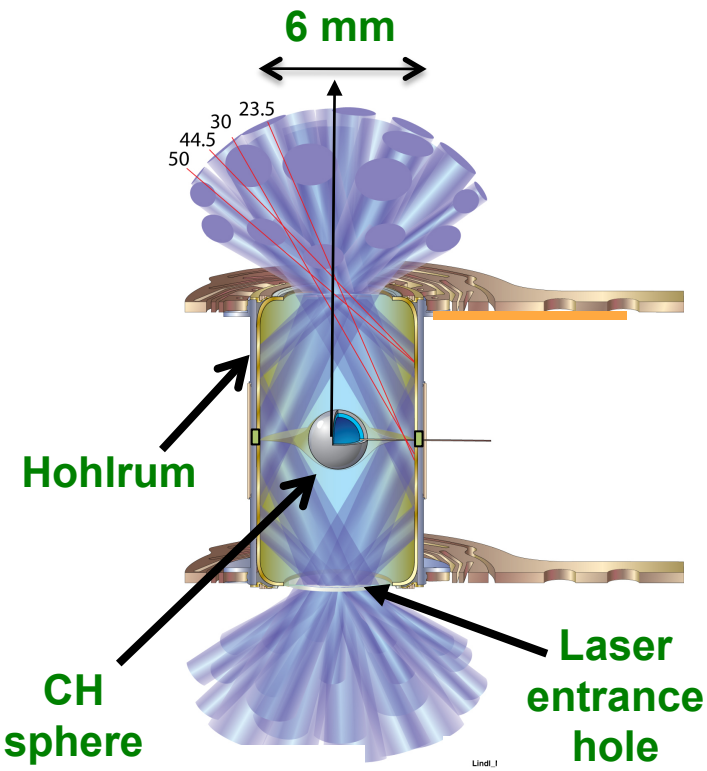
atomic shell structure

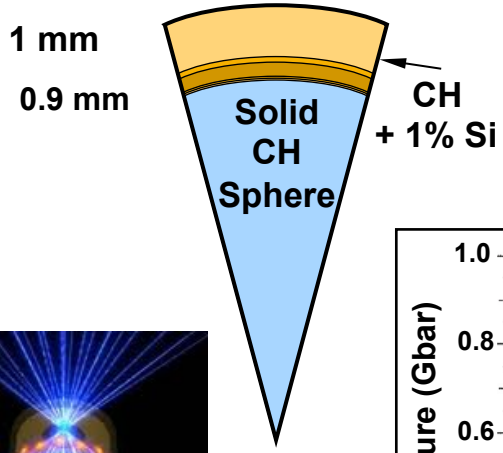
Graphite - *J.C.Pain, Contrib. Plasma Phys.* ***47****, 6 (2007)*

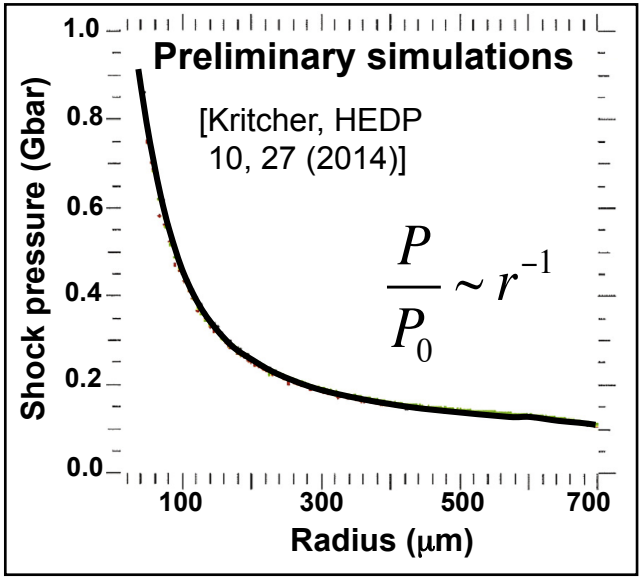
- Important for understanding planetary & stellar physics, inertial confinement fusion
- Little data (not adequate to constrain models; average atom vs detailed configuration)

Highest energy lasers (NIF) produce highest pressure and density with spherical converging shocks

Use hohlraum with spherical material target in center

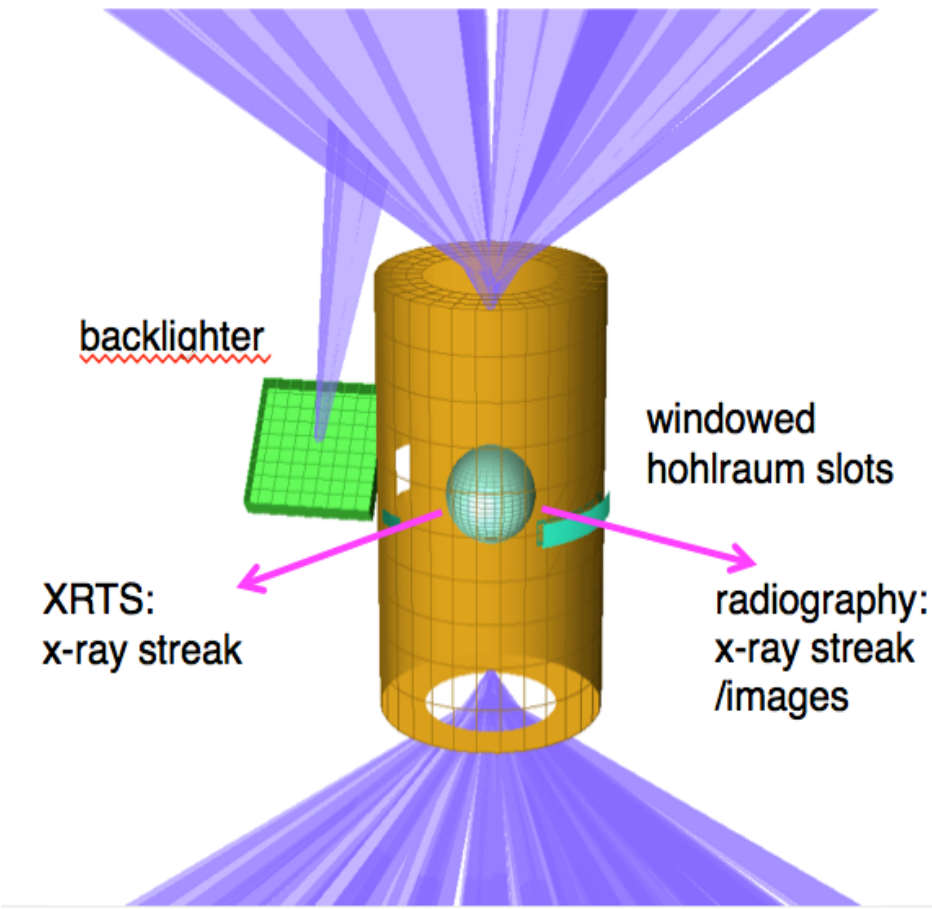


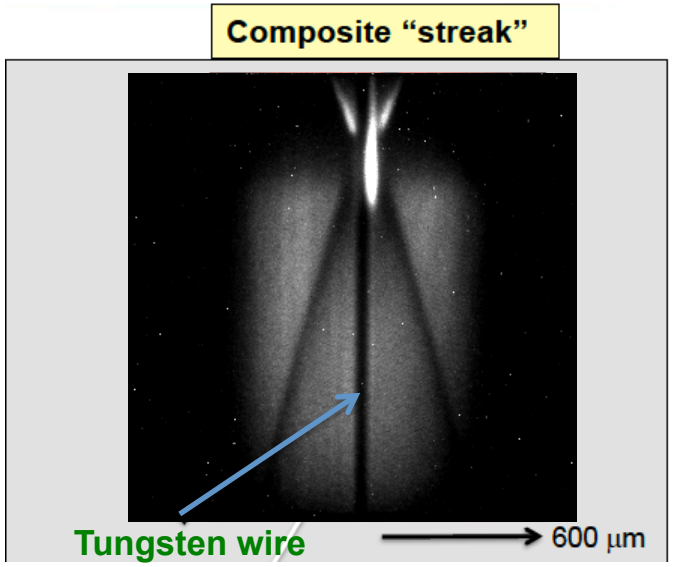


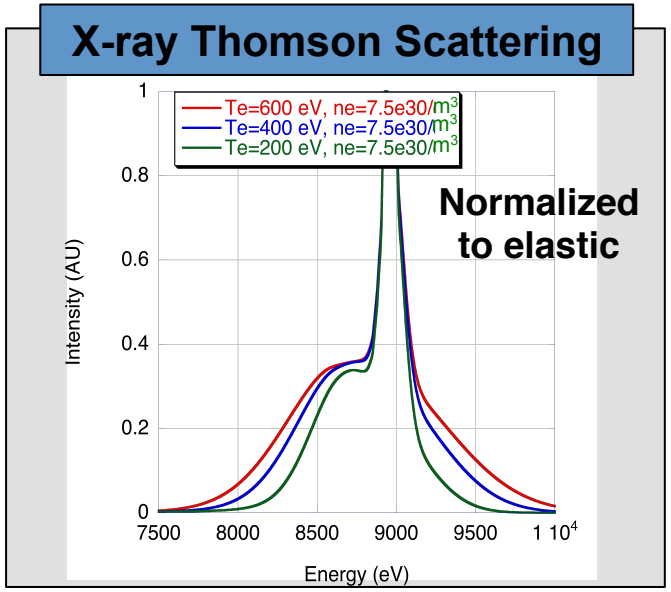


- 192 laser beams focused inside cm-sized hohlraum to > 200 eV BB temperature
- Surface of a mm-sized target in the center vaporizes and ablates
- Converging spherical shock wave compresses target and generates ~ Gbar pressure

Measurements at high pressures include x-ray radiography of shock and inelastic x-ray scattering







Plasma X-Ray Source for Backlighting and Thomson Scattering

Current platform

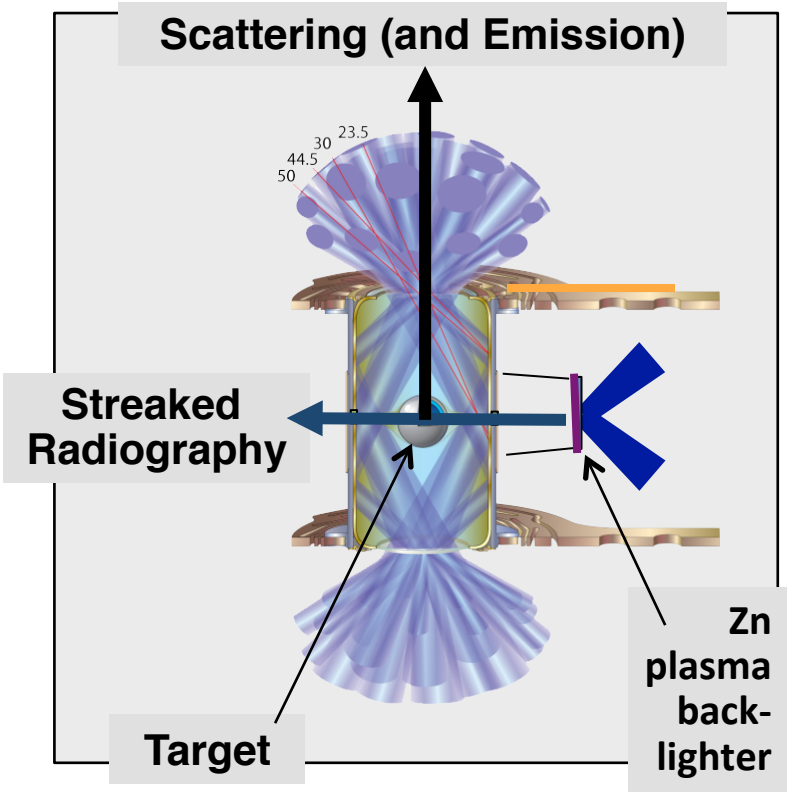
16 x TW beams on Zn foil = 100 kJ
1% conversion to 9 keV x-rays = 1 kJ / 4pi
Source distance from sample = 7.5 mm
Solid angle subtended = 0.006 sr
X-rays on sample = 0.5 J
Gated-imager sets integration time = 100 ps

Improved platform

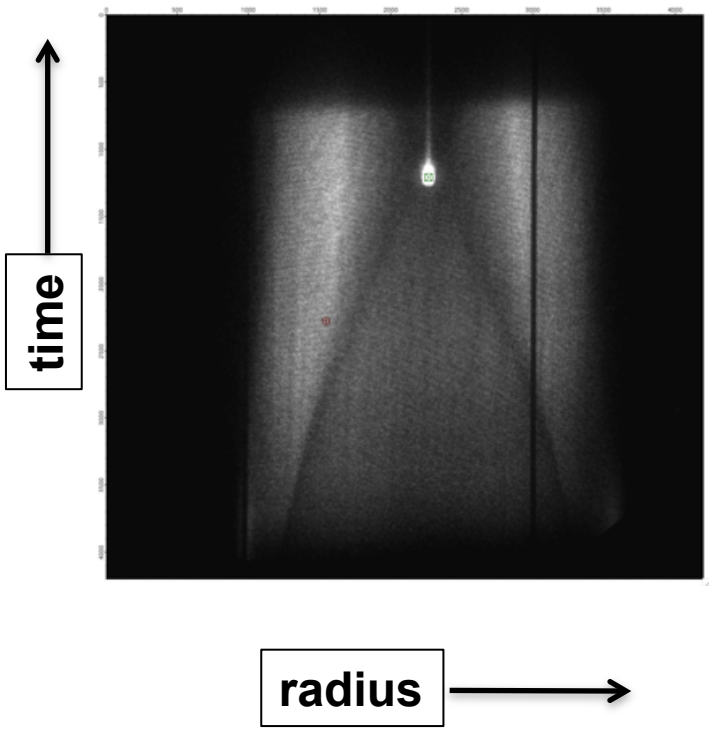
Source 2.5 mm from sample
4x improvement in collected x-ray power

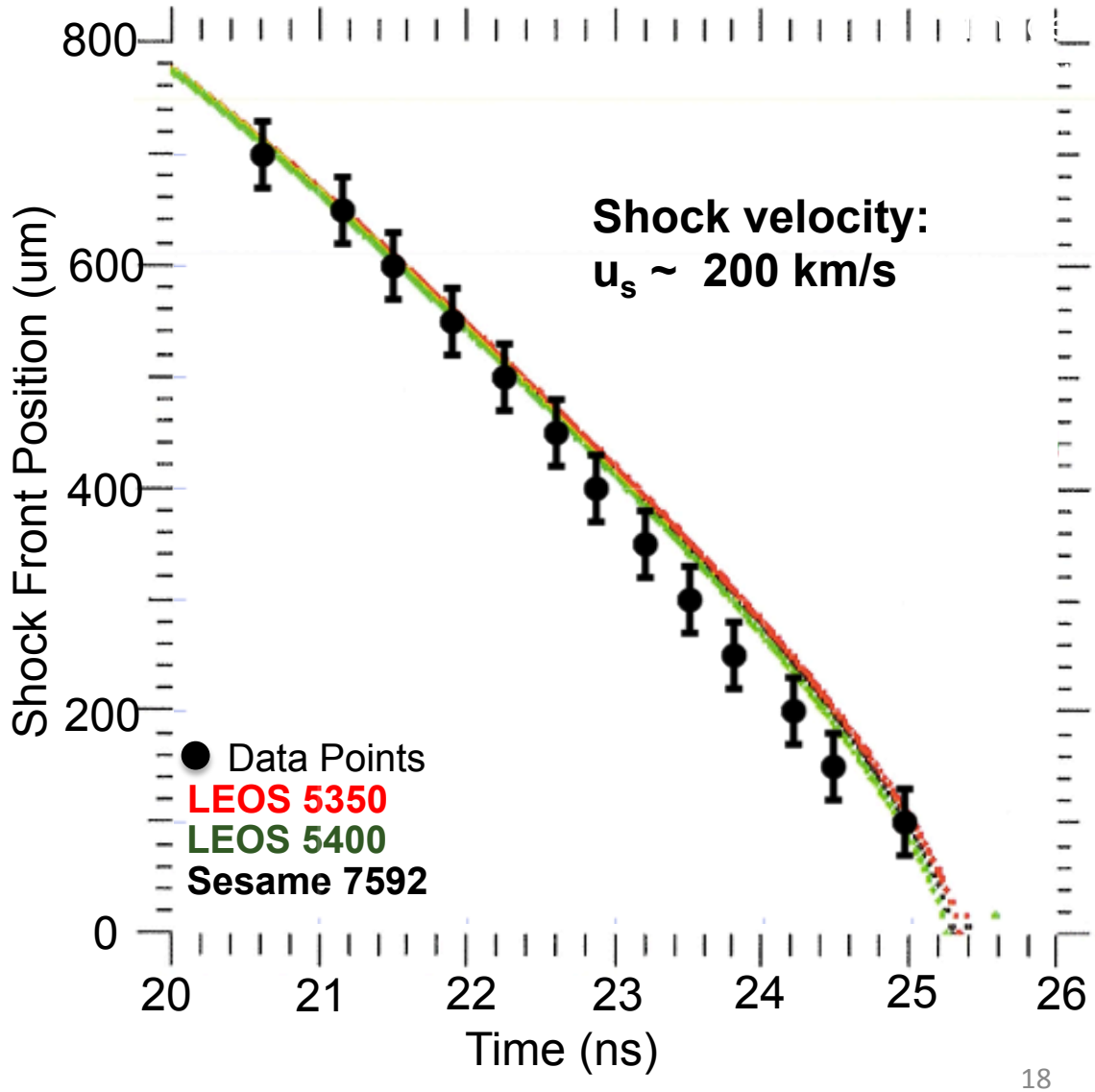
- **0.5 GW x-ray beam**
- **On 200 micron sample at shock coalescence with GBar pressure**
- **50 mJ x-rays in 100 ps gating time**

….but still… 100 ps gating time



Shock speed appears higher than predicted





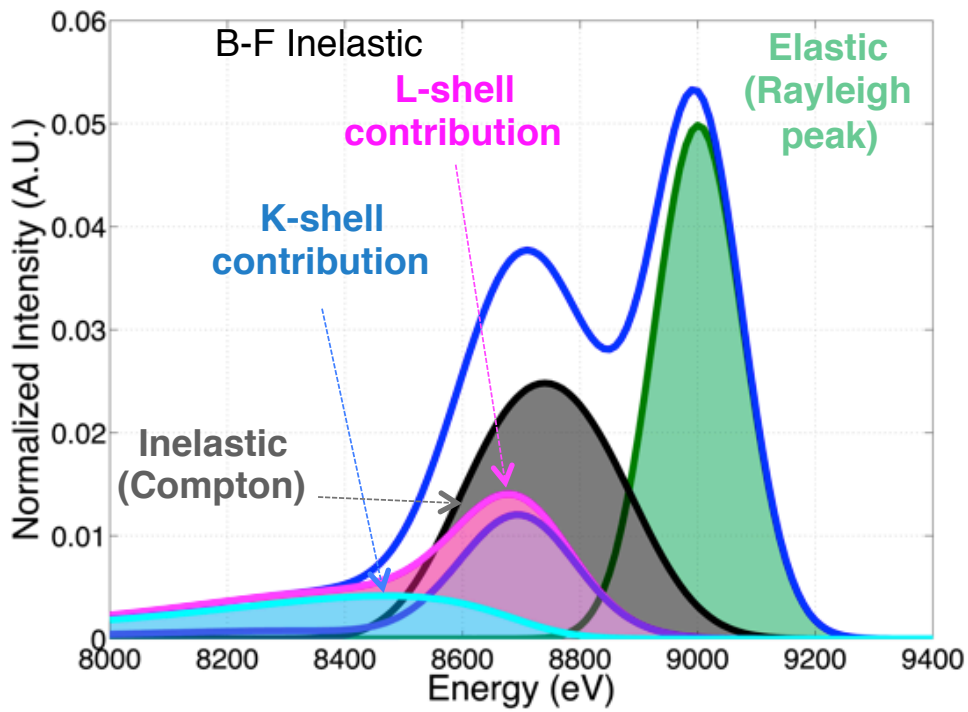
Analyzing x-ray Thomson scattering data

Contributions to the dynamic structure factor:

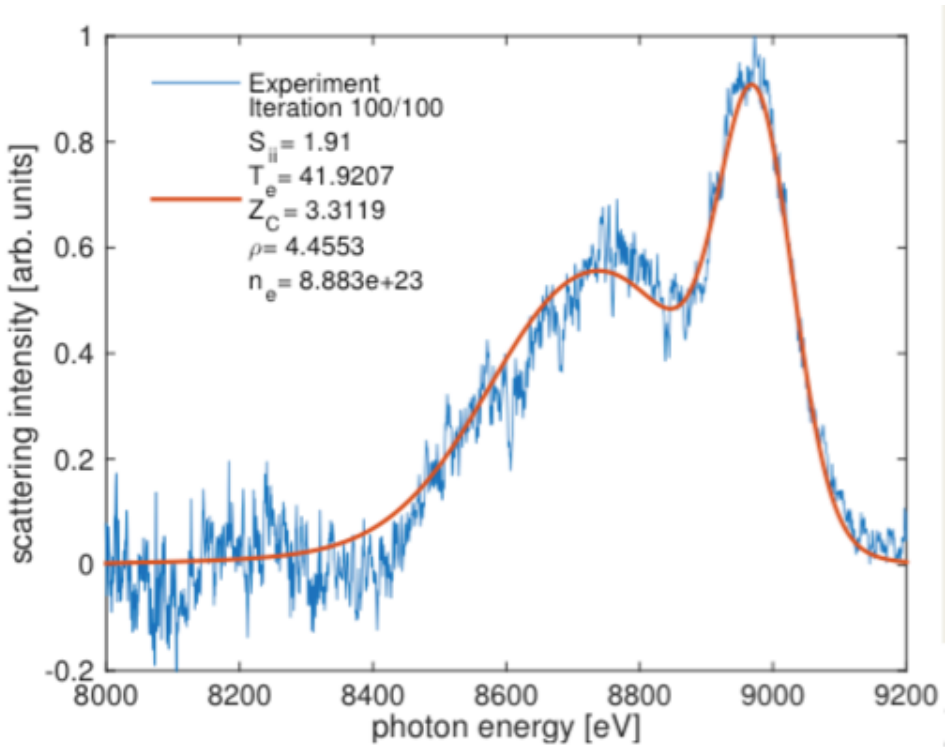
ion feature electron feature bound-free feature

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

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

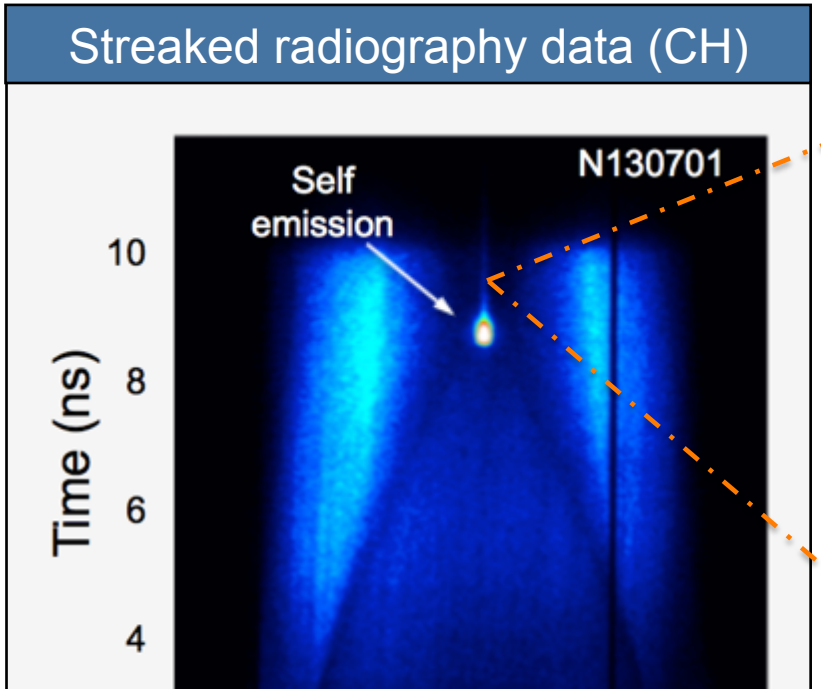


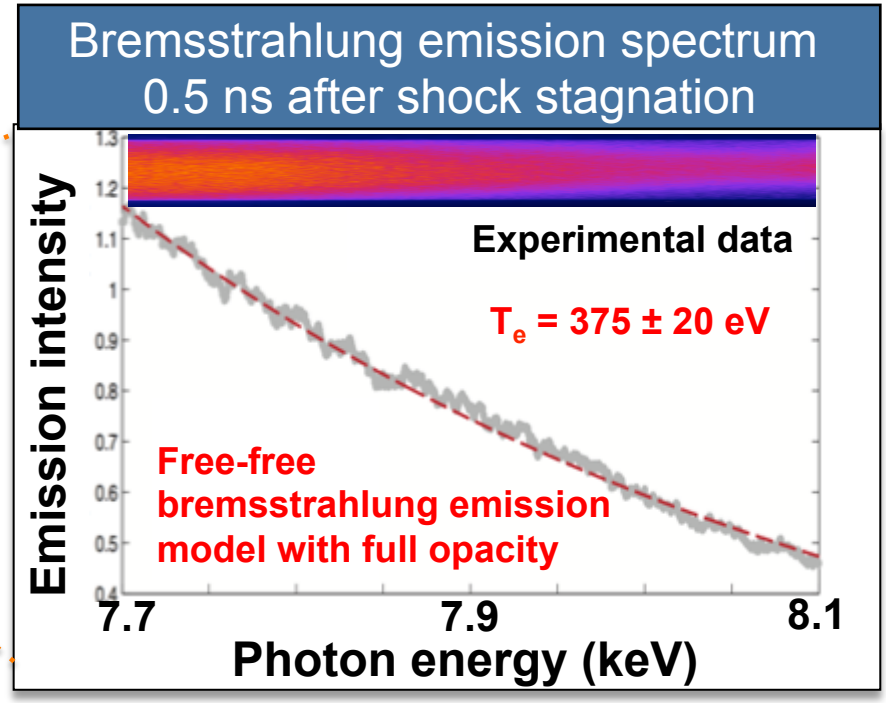
Inelastic scattering results from compressed and ionized CH reveals temperature and density

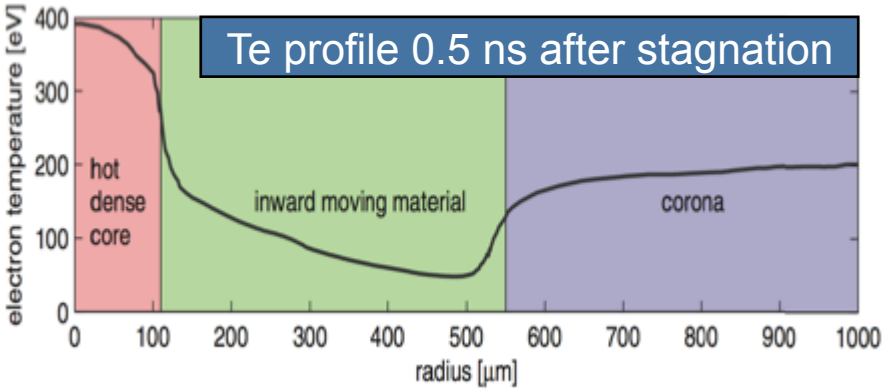


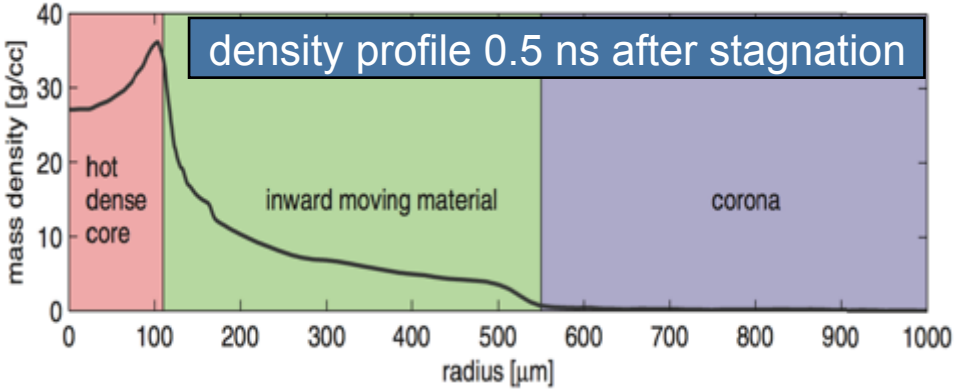
- 4 g/cc,
- Ne = 8 E23
- Te = 40 eV
- Integration to r = 500 um

Temperature measurement at from small compressed core at 30 g/cc CH, ~ 375 eV, from Bremsstrahlung, consistent with modeling



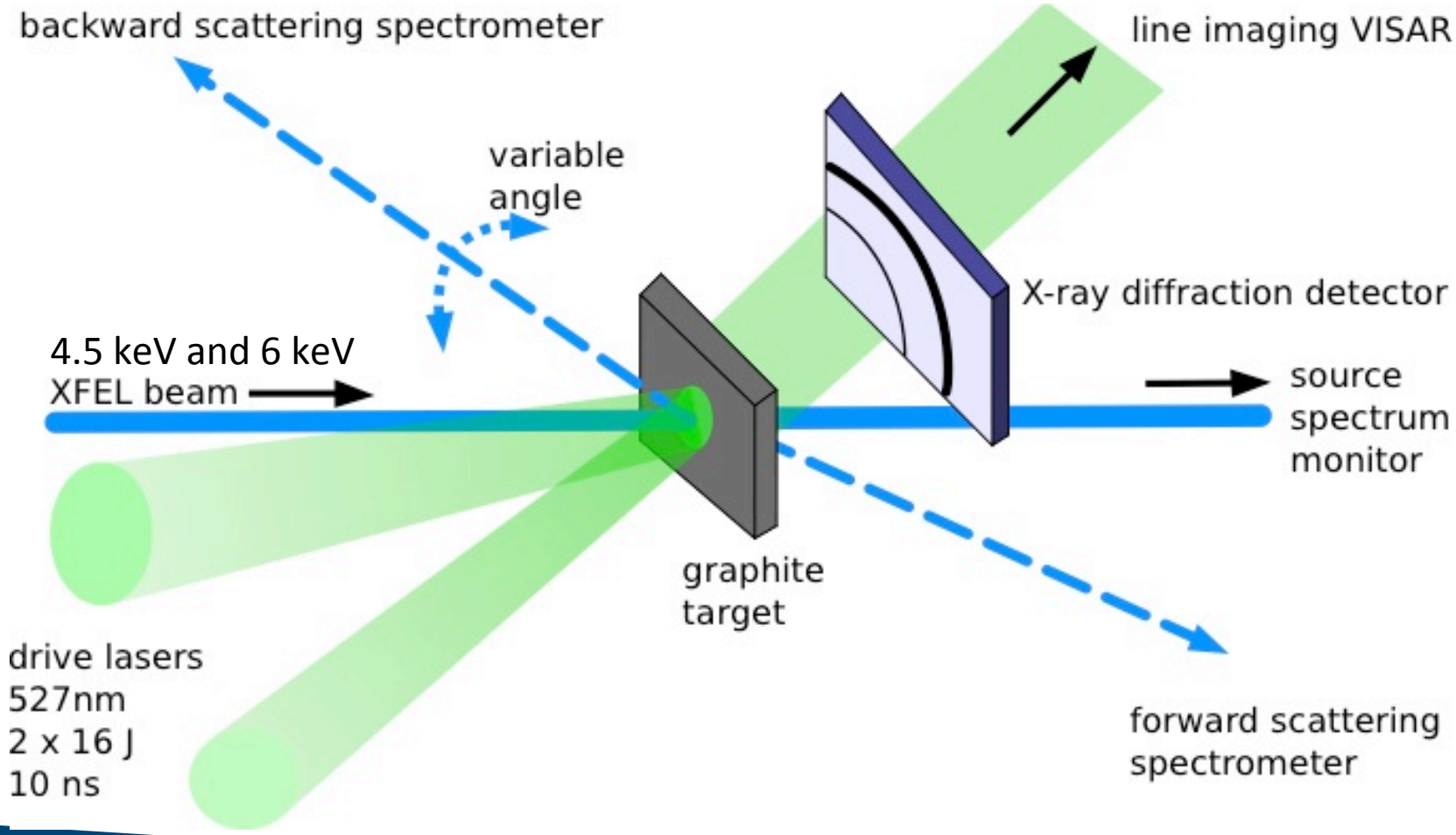




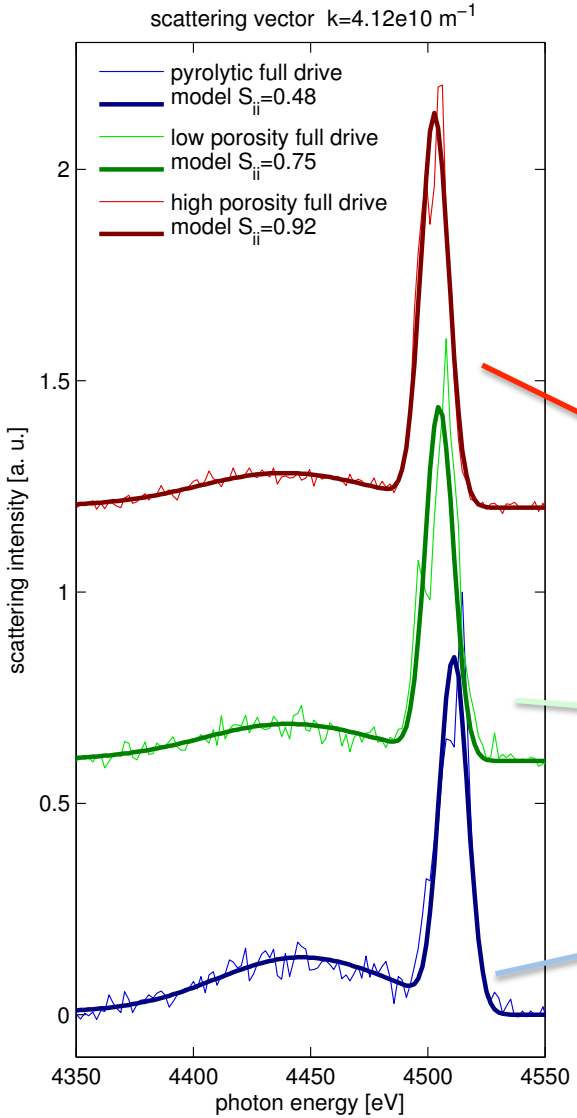


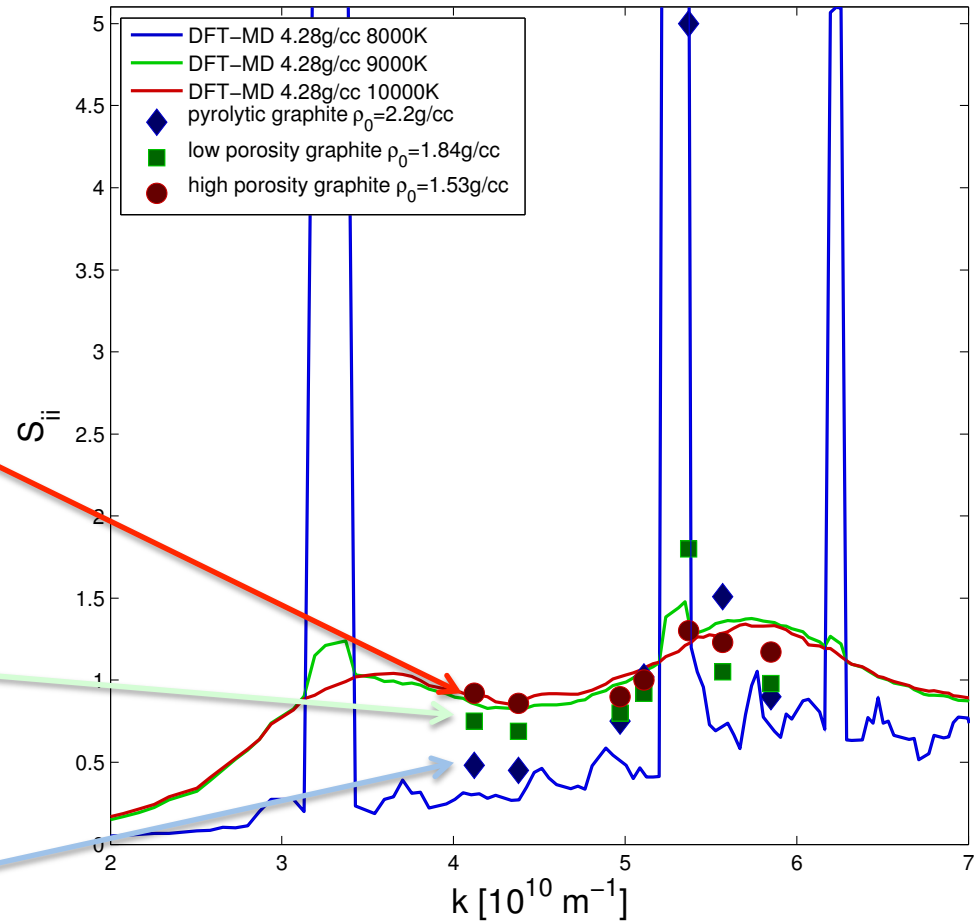
Kraus et al. RSI 85, 11D606 (2014)

At lower pressures, driven by modest long-pulse lasers, we can observe shock-induced transitions, using the LCLS X-FEL, from graphite to hot and dense diamond and liquid carbon



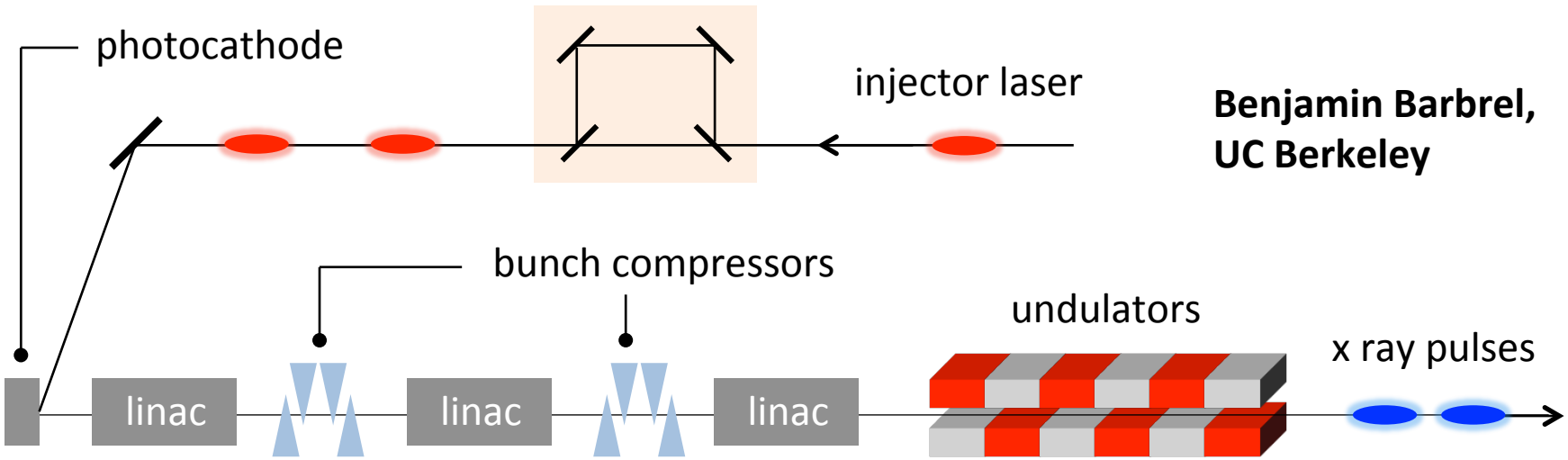
LCLS experiment | Solid and liquid structure at ~180 Gpa = 1.8 Mbar





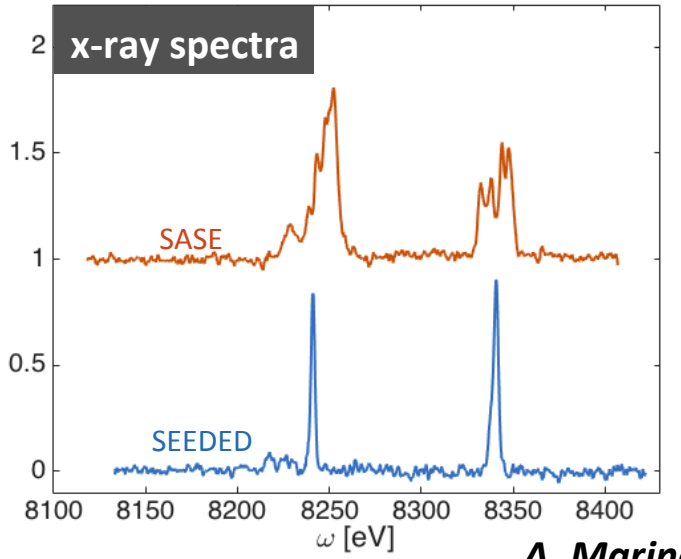
- High porosity samples → liquid
- Low porosity samples → liquid (but cooler)
- Pyrolytic graphite → solid, close to melting

The next step: XFEL heat and probe – 2 pulses – 2 colors



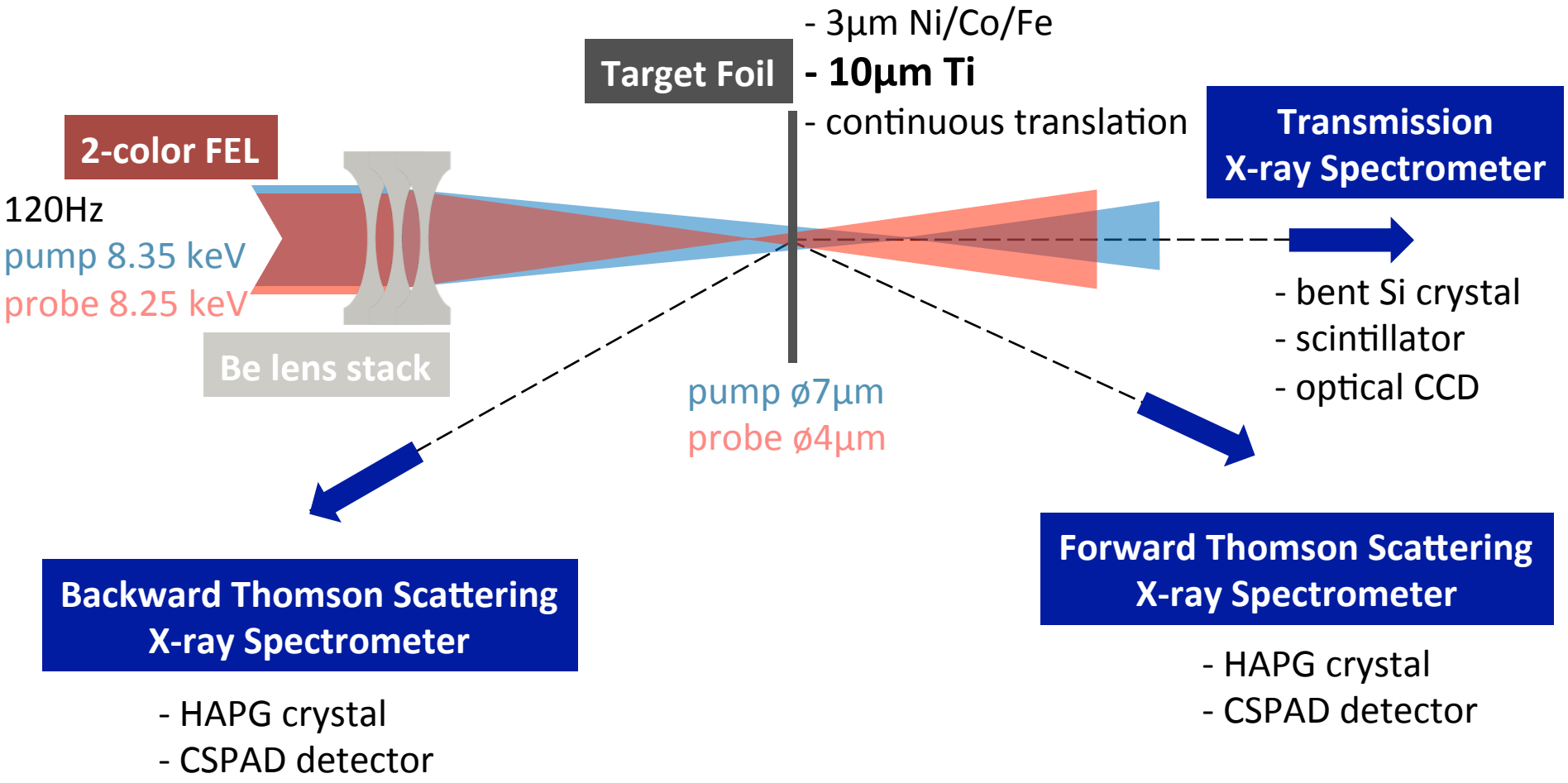
Benjamin Barbrel, UC Berkeley

Beam Parameters (2x75pC, 8keV)	
energy separation	≤ 100eV
time separation	5 – 150fs
energy /color (SASE)	300µJ
pulse duration	12fs
self-seeding avail.	✔

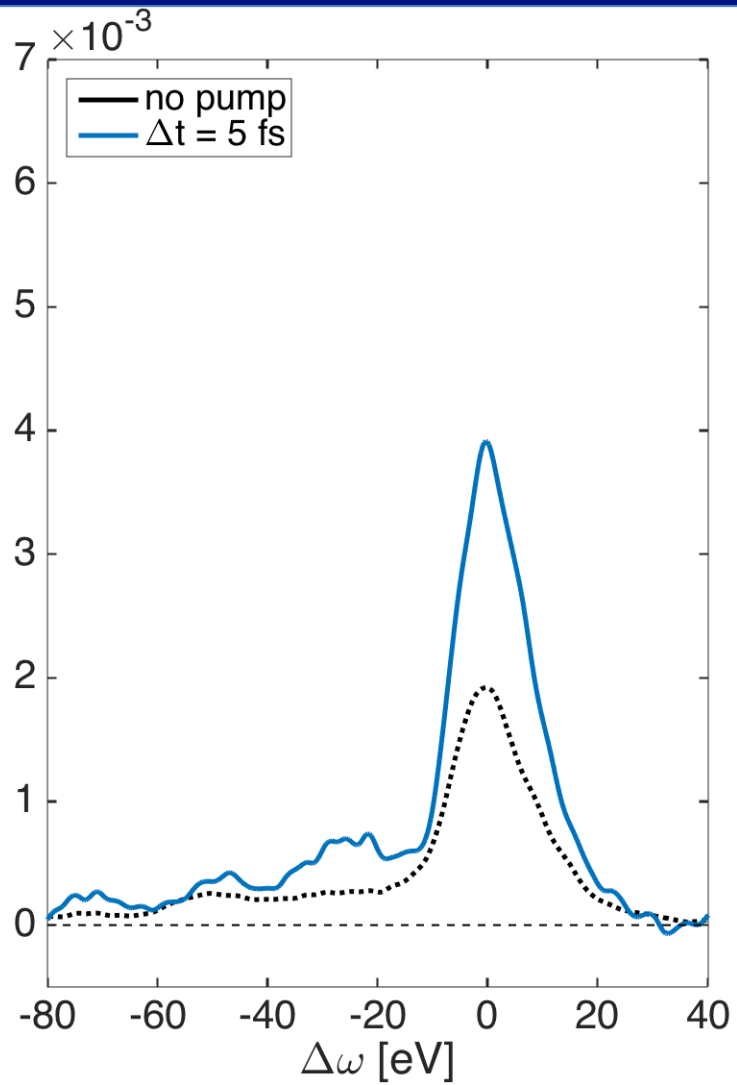


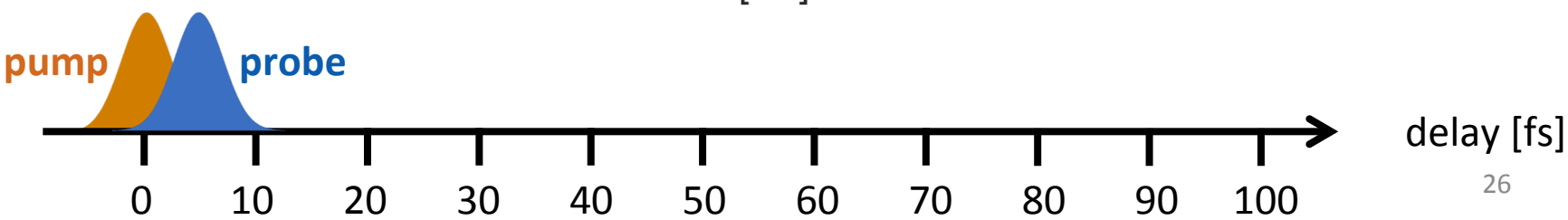
A. Marinelli

Two x-ray FEL pulse experiment setup



Titanium : Time-Resolved Forward Scattering





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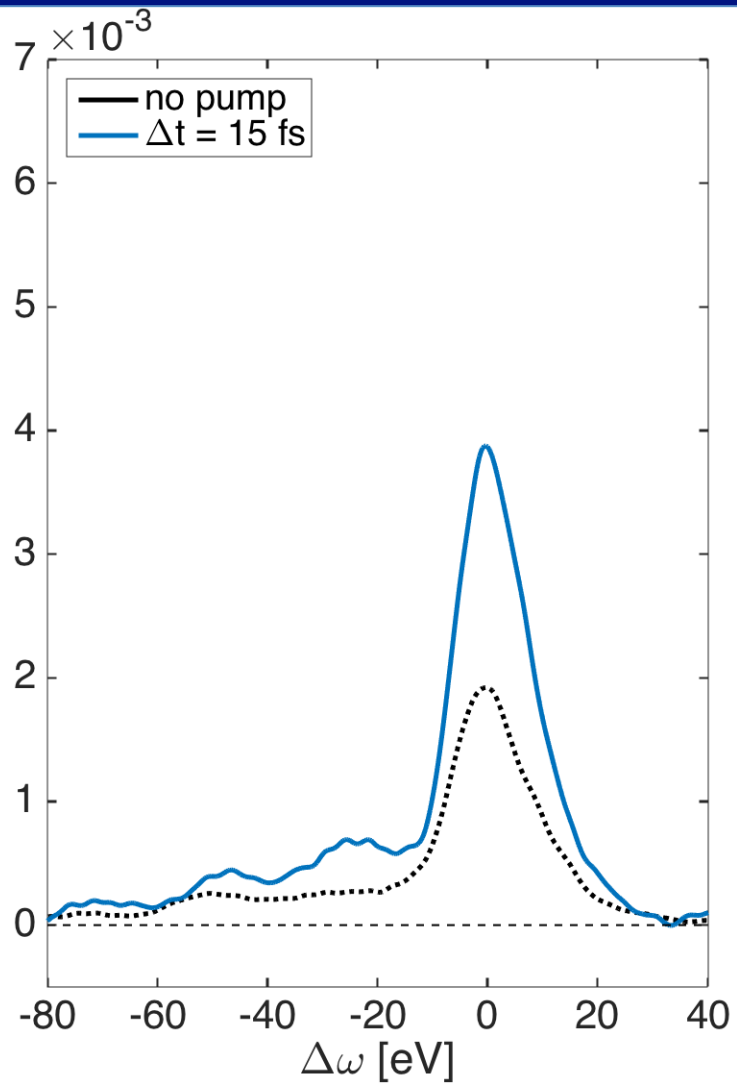

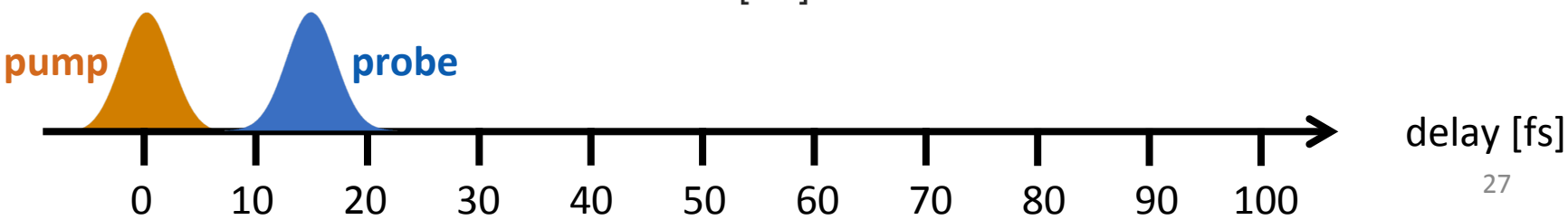

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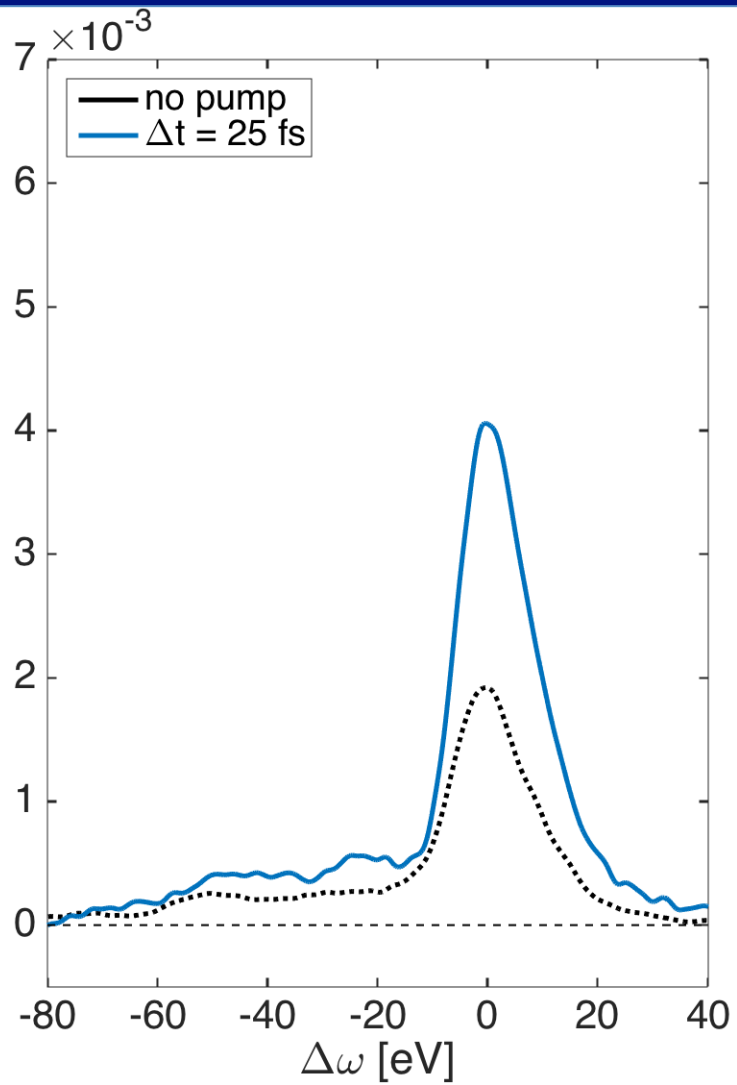

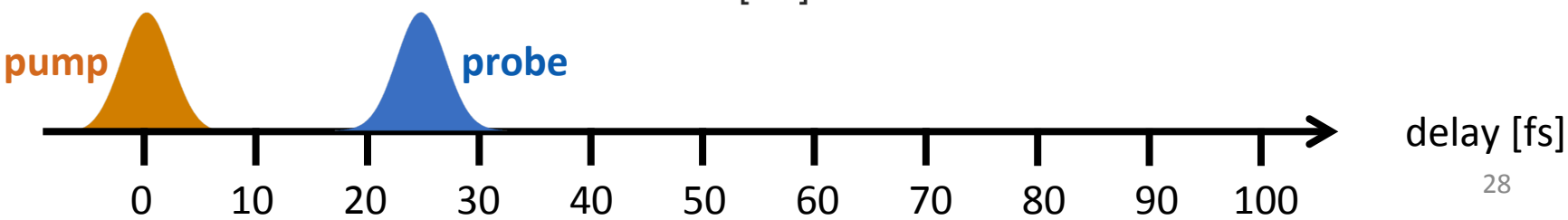

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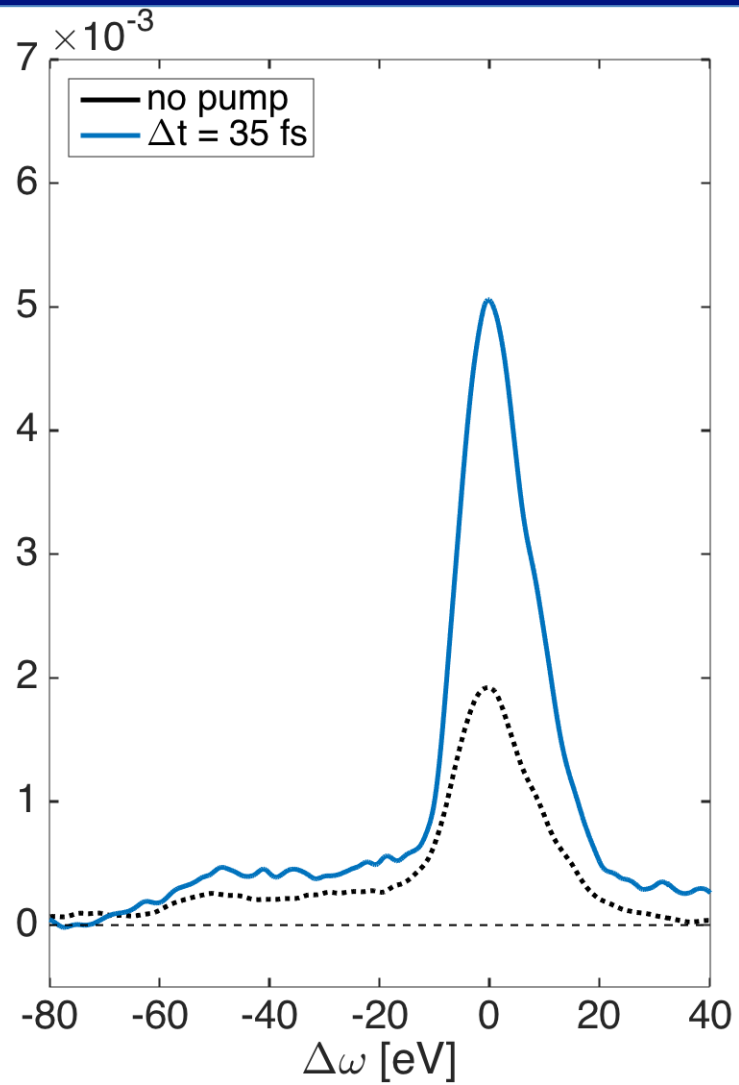

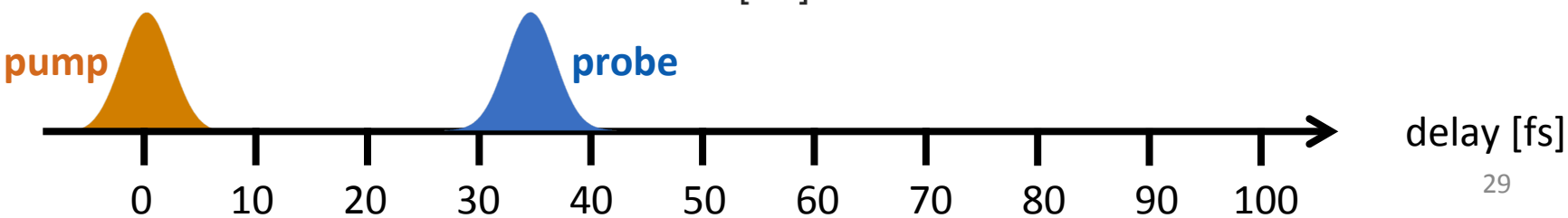

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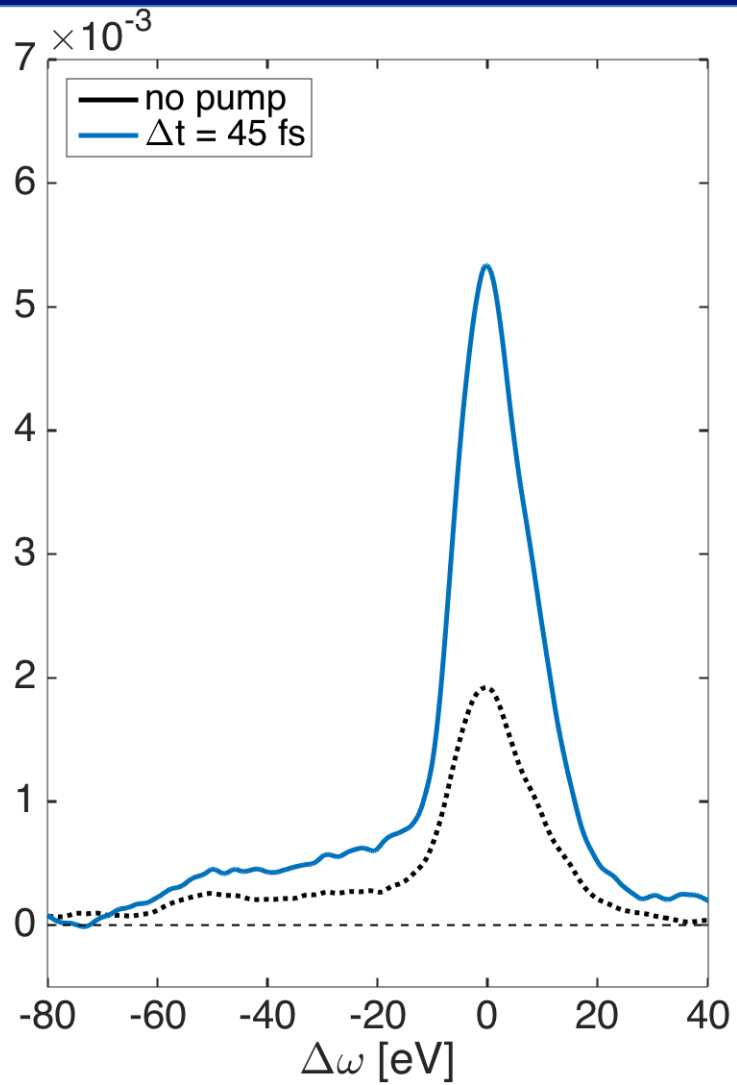

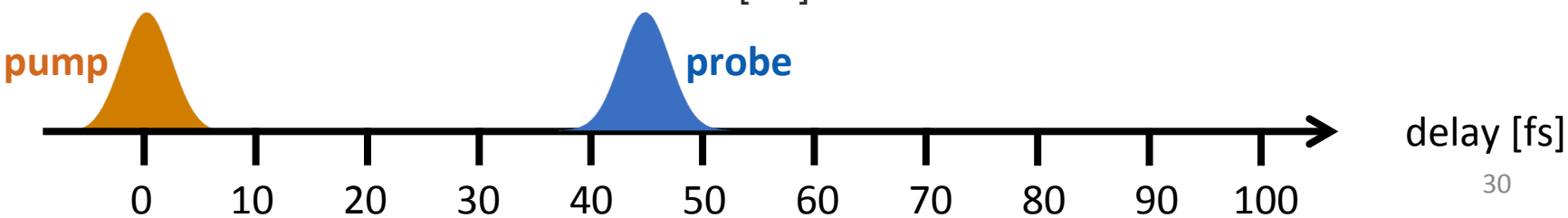

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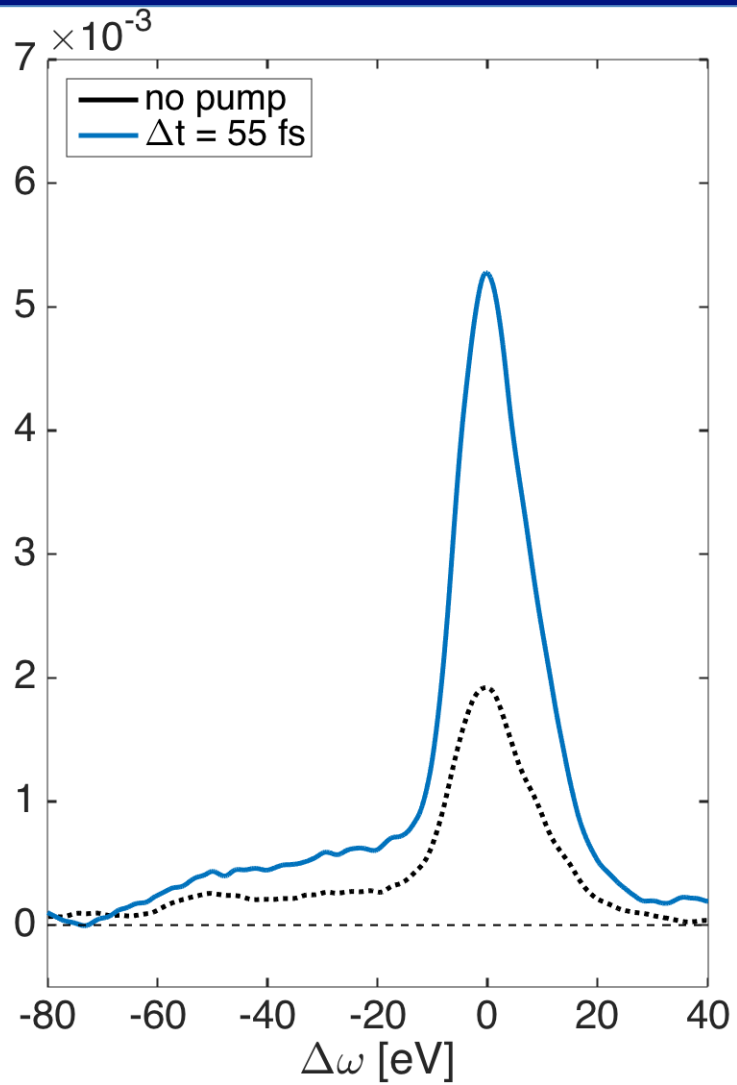
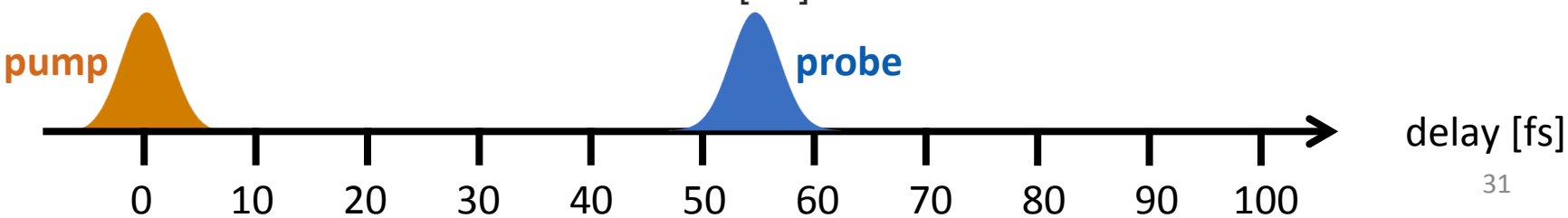
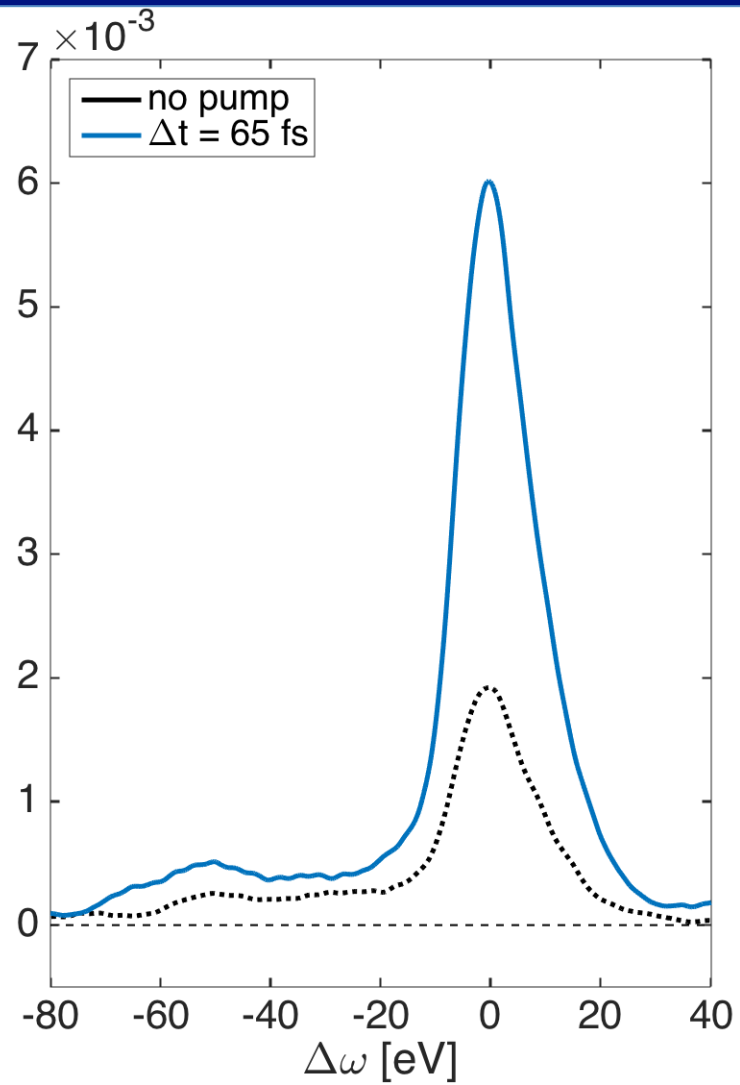
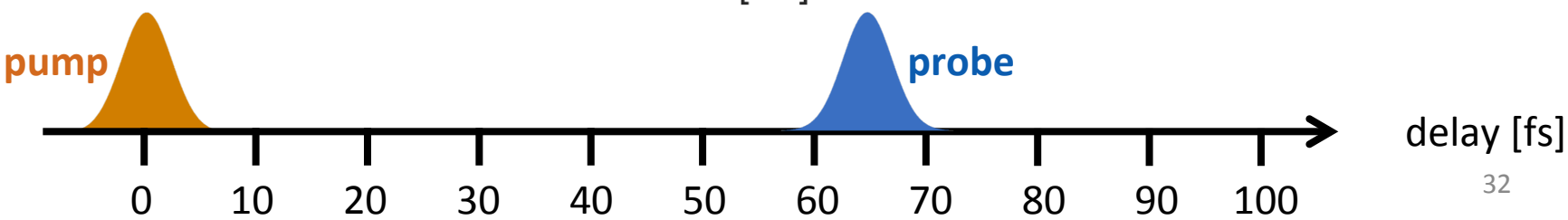




Titanium : Time-Resolved Forward Scattering





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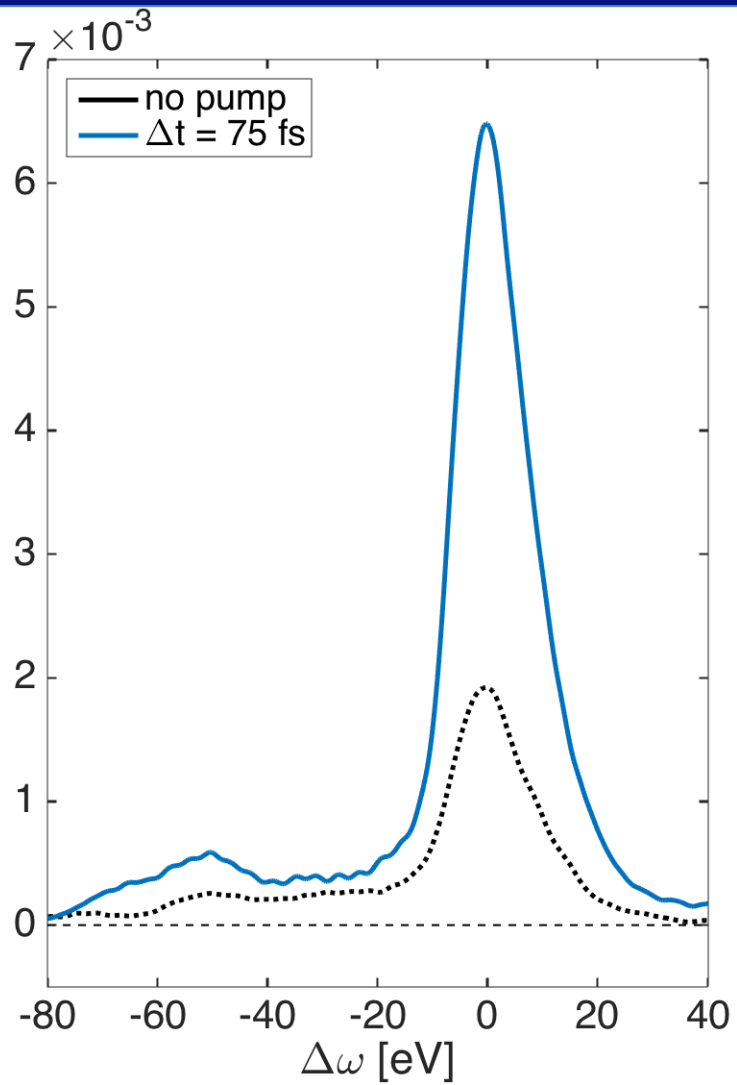

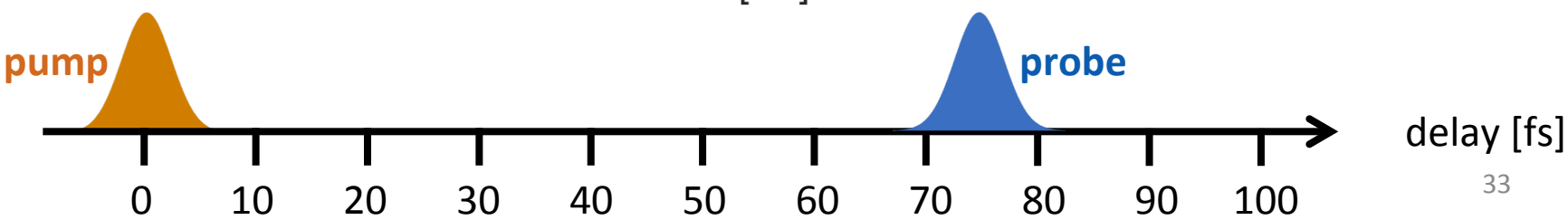

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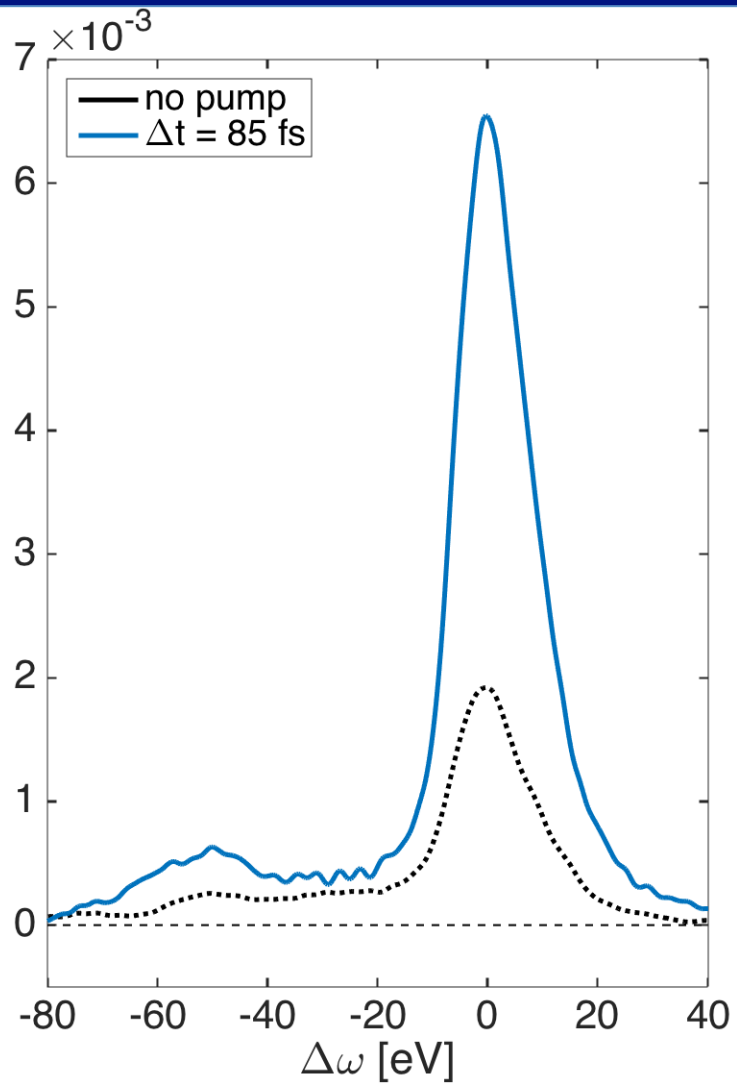
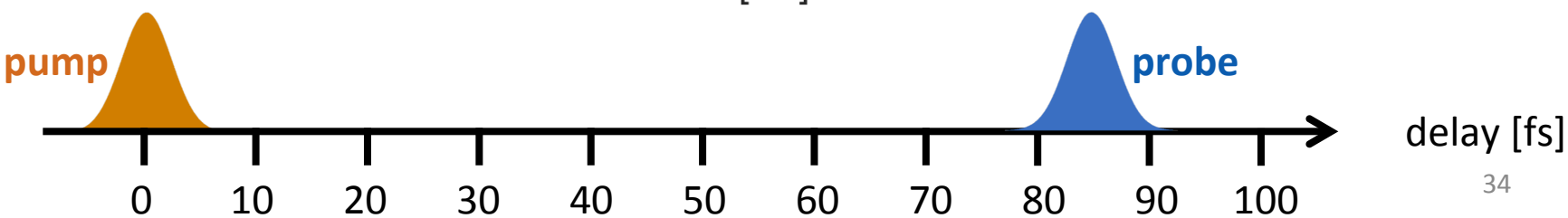
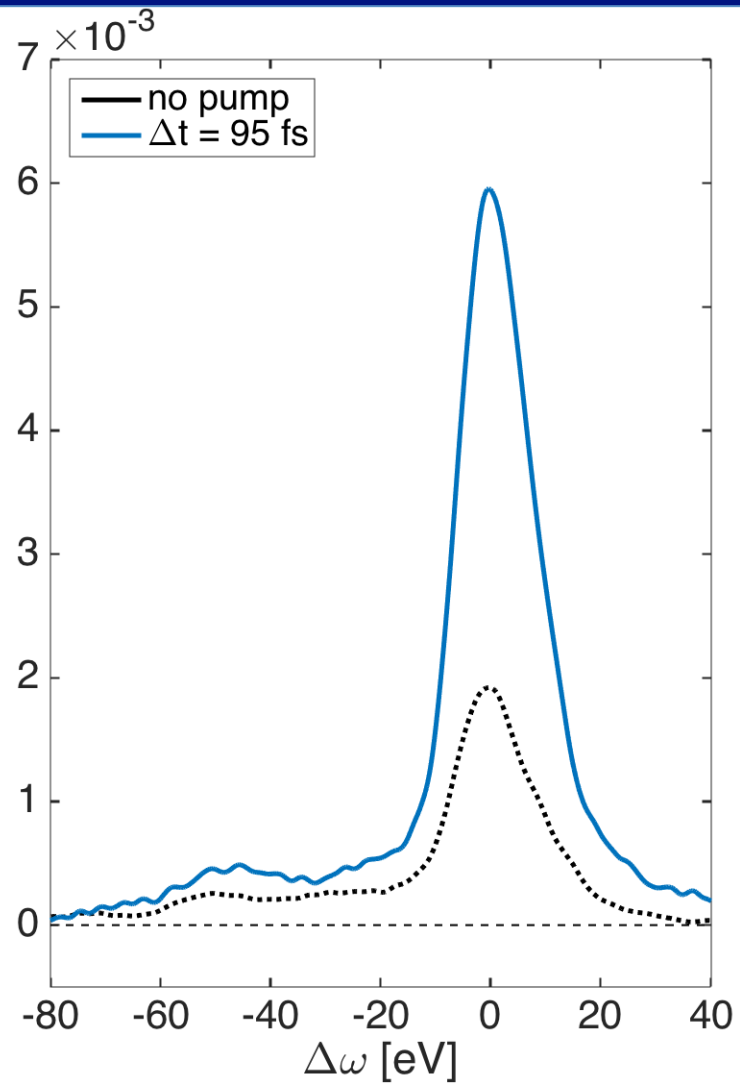
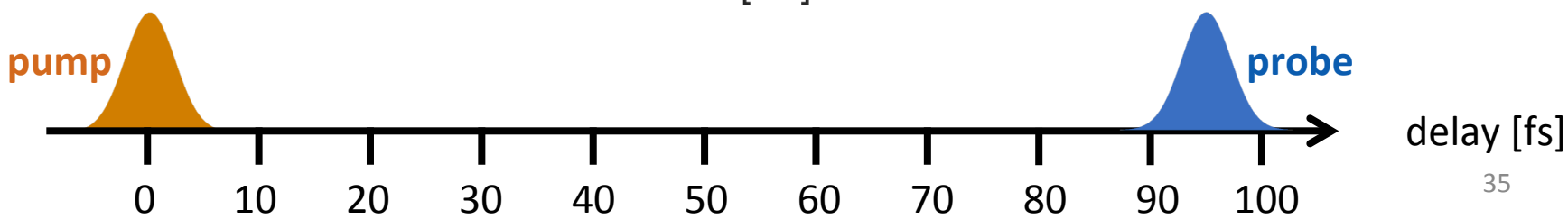




Titanium : Time-Resolved Forward Scattering





Collaboration on warm and dense materials at ALS, LCLS, and NIF

- **UC, Berkeley and LBNL**
  D. Kraus, B. Barbrel, K. Engelhorn, A. Saunders

- **SLAC**
  S. Glenzer, H. J. Lee, L. Fletcher, B. Nagler, E. Galtier, M. Gauthier, P. Heimann, E. Gamboa, M. MacDonald, S. Goede, D. Milathianaki, A. Ravasio, W. Schumaker, J. Hastings, A. Marinelli, T. Maxwell

- **LLNL**
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- **University of Warwick**
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- **Univ. of Rostock, Germany**
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- **LANL**
  J. L. Kline, A. Yi

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- **LULI**
  A. Ravasio

- **University of Trento**
  G. Monaco

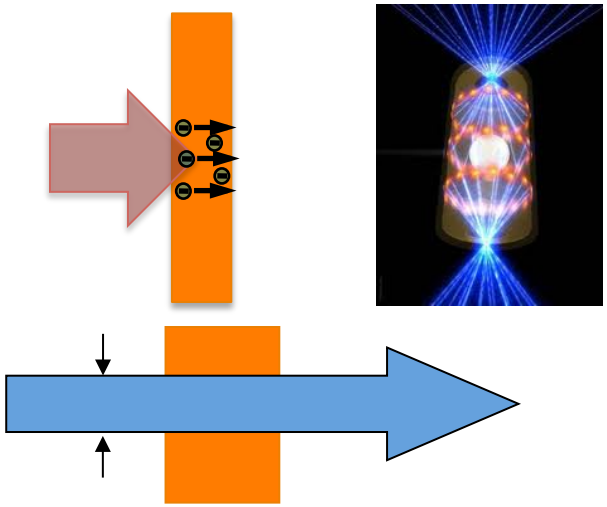
- **University of Jena**
  U. Zastrau

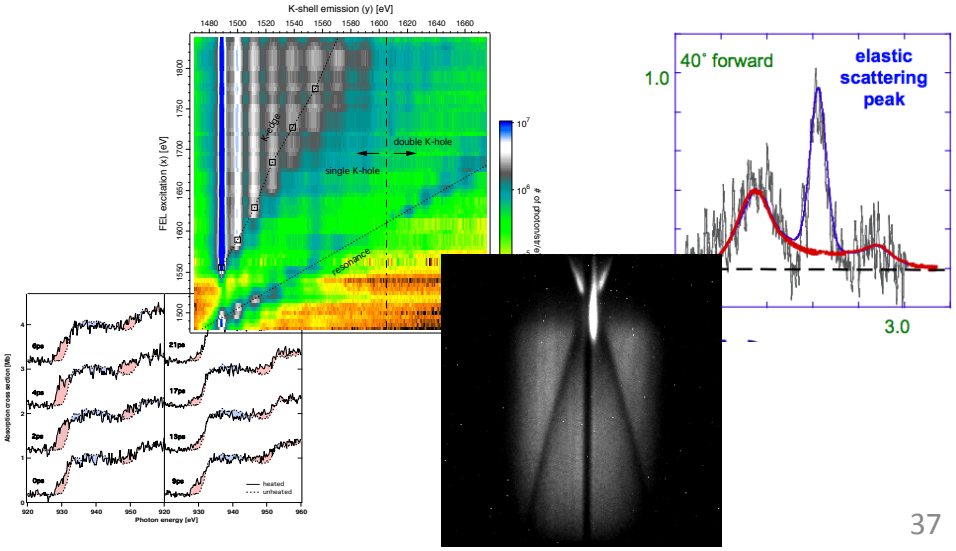
- **GIST**
  B.I. Cho, M. Kim

Both high energy lasers and x-ray FELS can <u>create</u> and <u>probe</u> materials under extremes of high temperature, pressure and density

Create by:

- isochoric heating with short pulse laser or free-electron x-ray laser
- shock compression with long pulse laser or long pulse x-ray heating/ablation



Probe with x-rays:

- near-edge absorption
- emission spectroscopy
- spatial imaging
- inelastic scattering