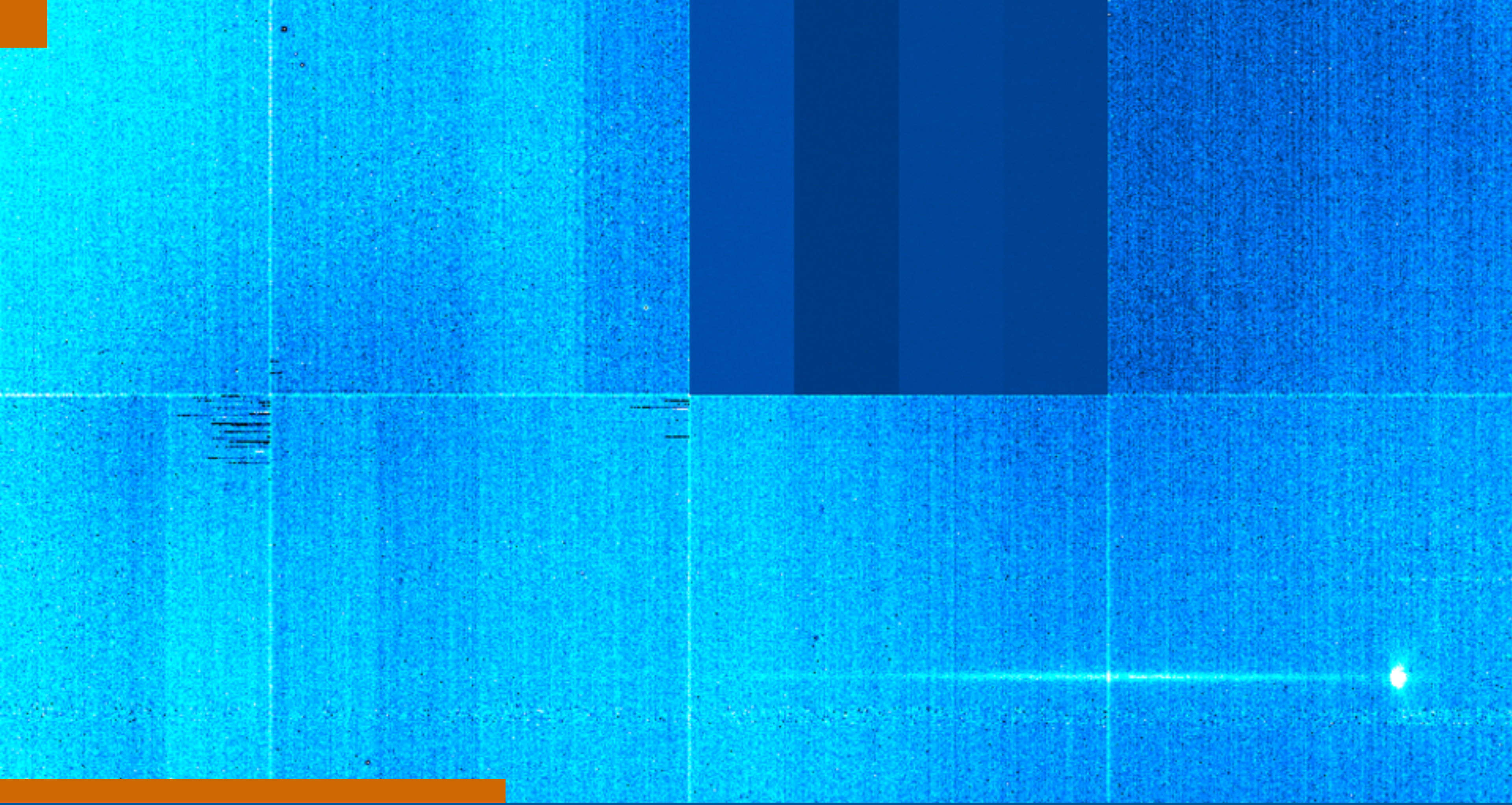


Elastic and inelastic X-ray scattering from isochorically heated carbon

Dominik Kraus

HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF

Experiment 2180 at European XFEL (HED instrument)

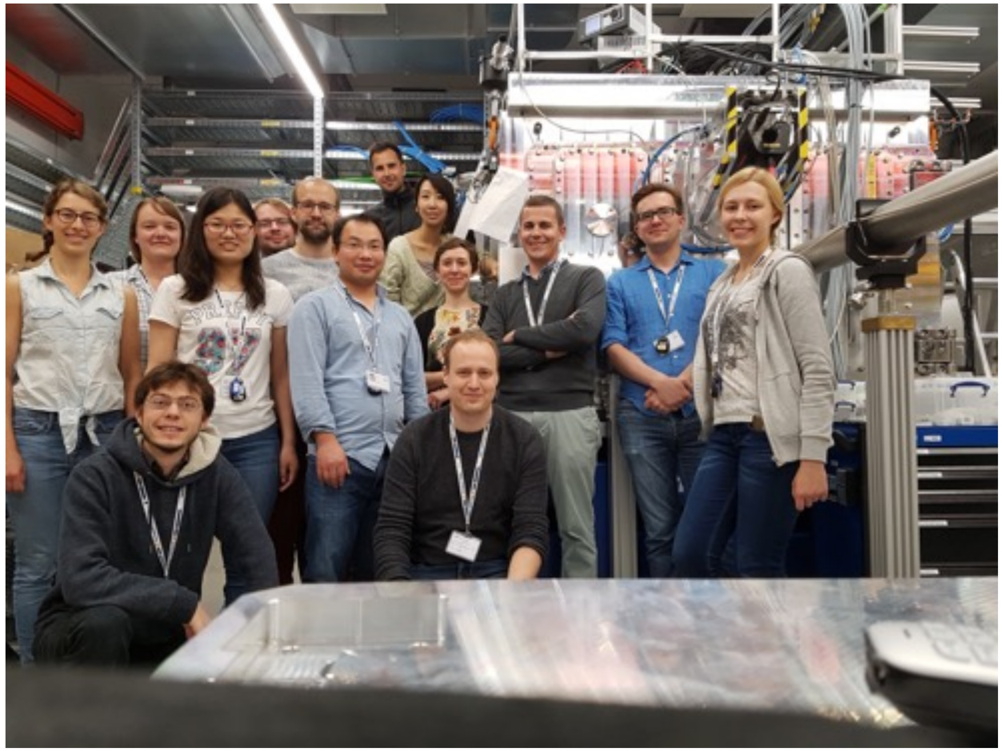












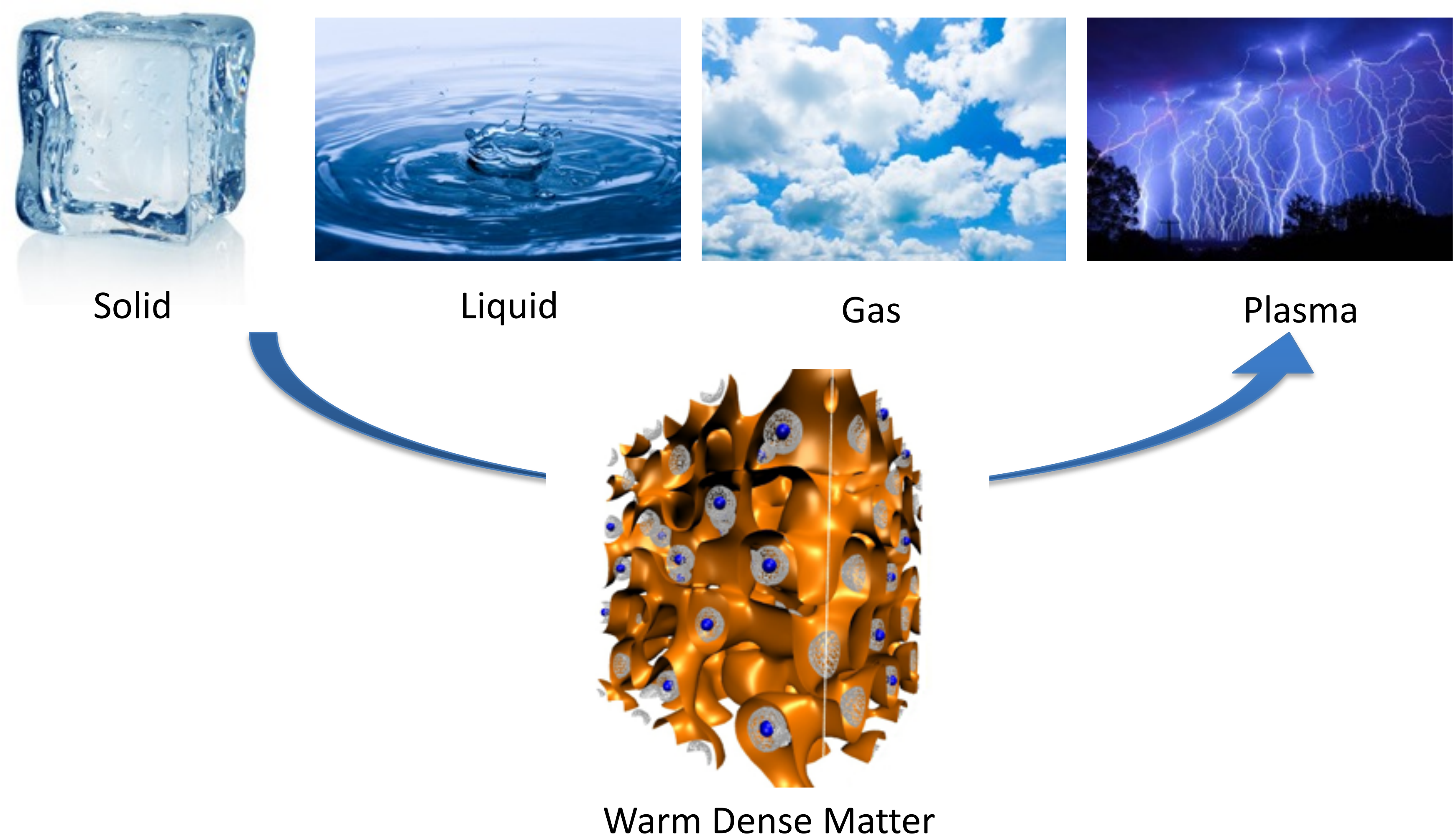




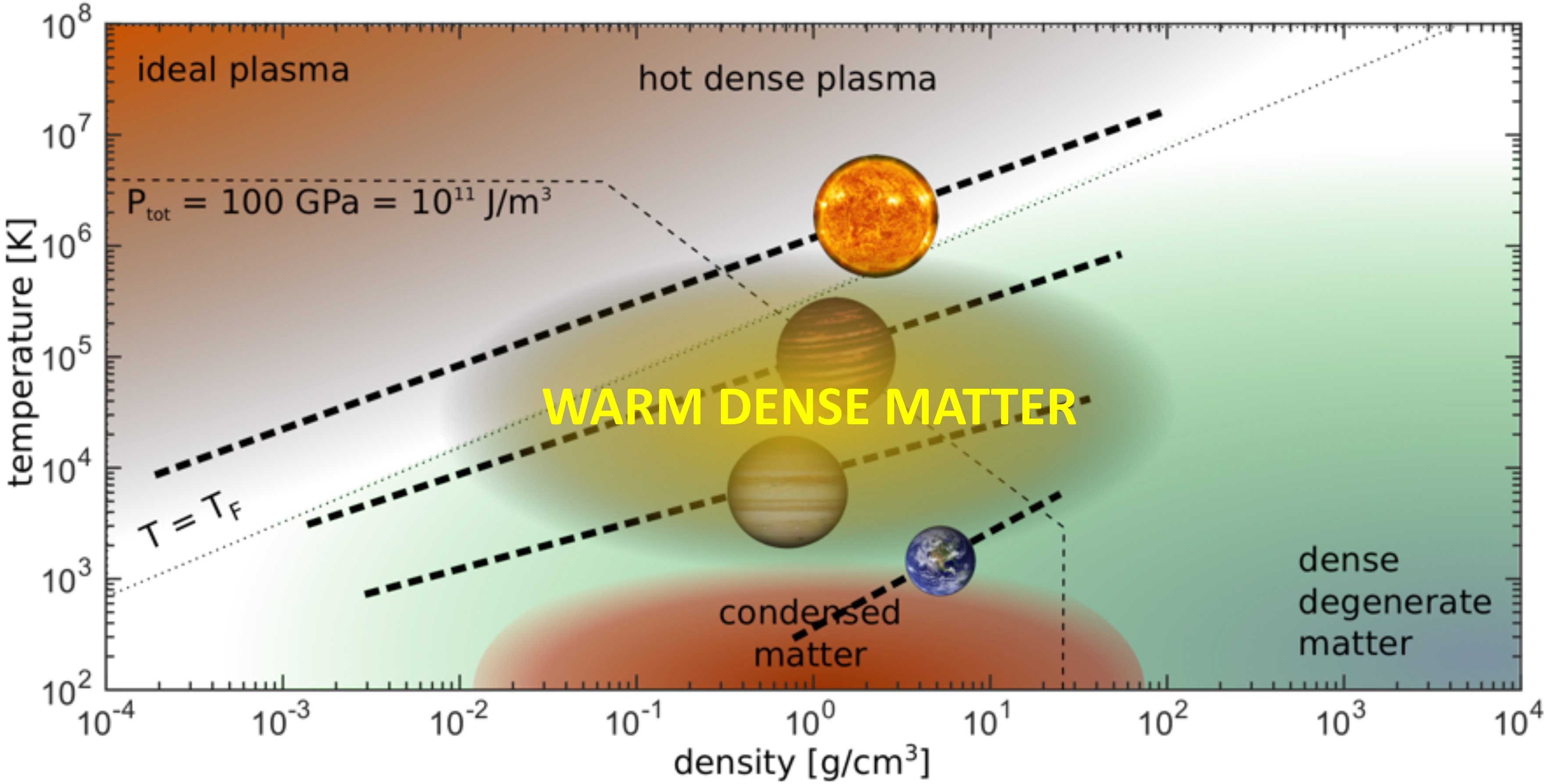


HZDR
European XFEL
SLAC
Lawrence Livermore National Laboratory
The University of Warwick
Berkeley University of California
GSI
大阪大学 Osaka University
UPMC Sorbonne Universités
Universität Rostock

Warm Dense Matter

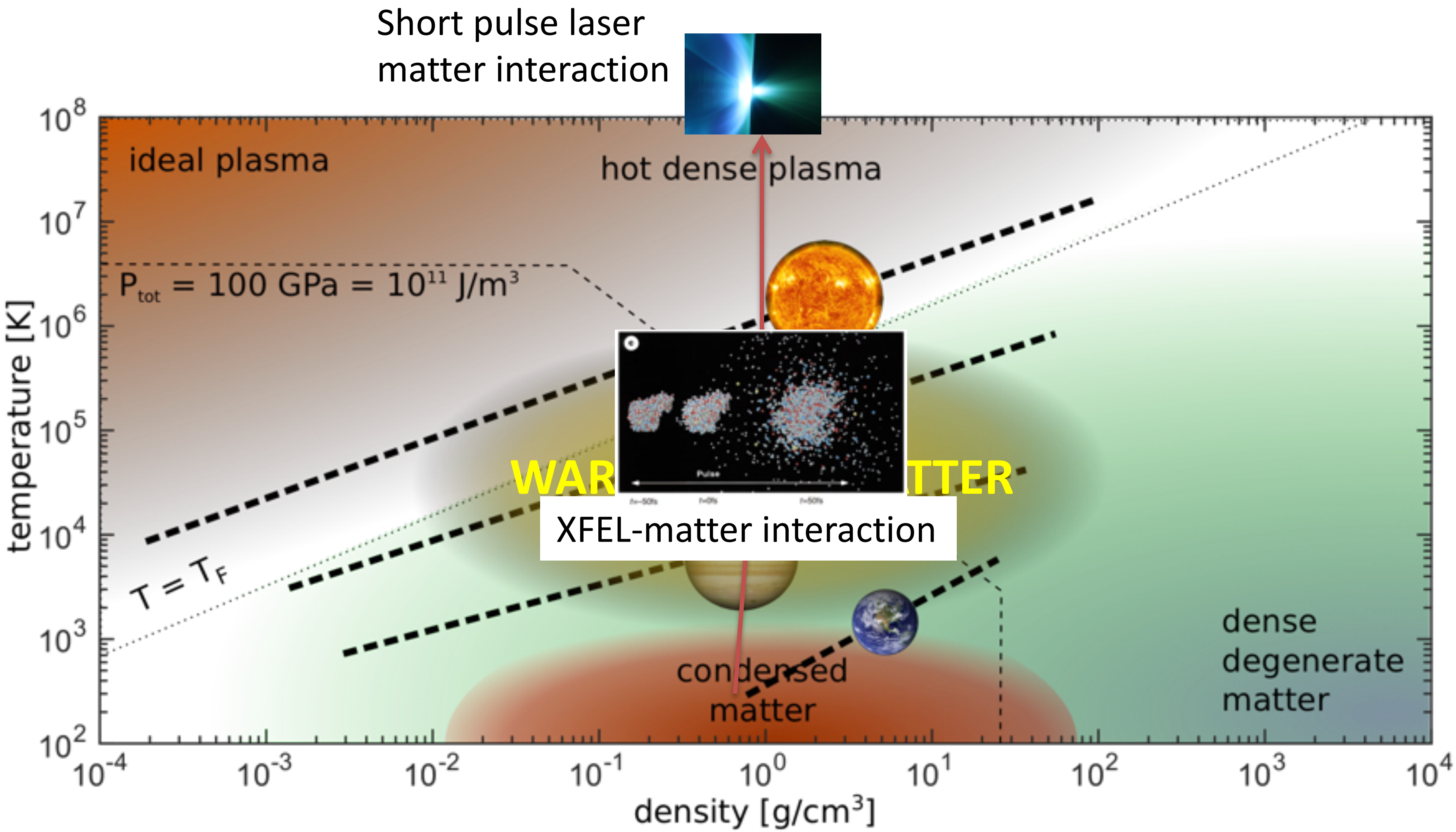


High energy density matter



*R. Neutze et al., Nature (2000)

High energy density matter



*R. Neutze et al., Nature (2000)

Warm Dense Matter

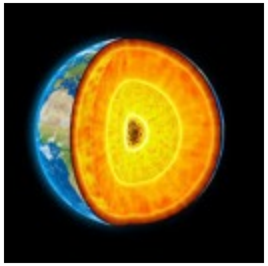
transition regime

solid state ⟺ hot dense plasma

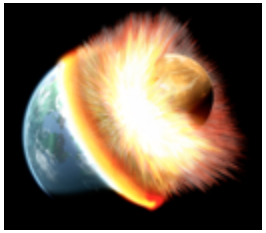
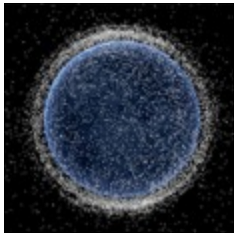
properties:

- 0.1 – 10 times solid state density
- temperature: ~5000 K up to ~10^6 K
- pressure: ~1 GPa up to ~10 TPa
- partially ionized
- partially degenerate $n_e \lambda_{th}^3 \approx 1$
- strongly coupled ions
- $k_B T \sim \frac{e^2}{4\pi\varepsilon_0} \frac{1}{\langle d \rangle} \sim E_F \sim E_{bond} \sim \text{eV}$

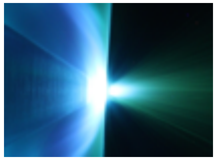
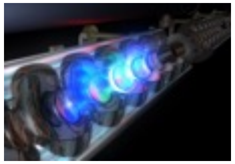
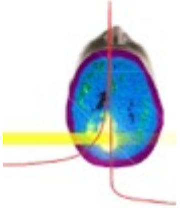
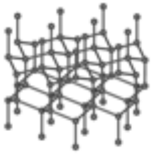
Planets / Brown Dwarfs / Stars



Impacts

Technology applications

Warm Dense Matter

transition regime

solid state ⟺ hot dense plasma

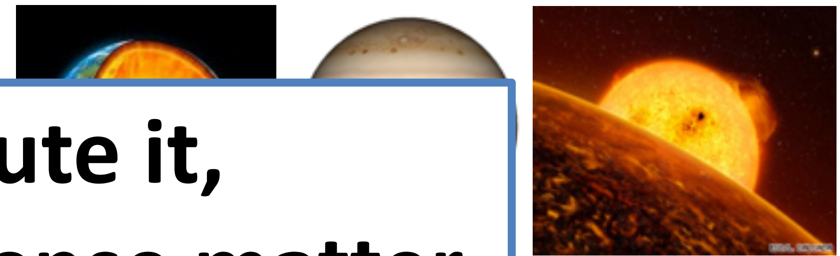
properties:

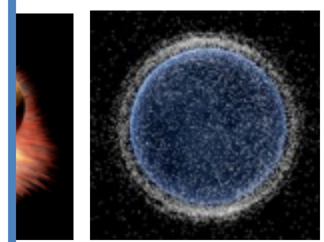
- 0.1 – 10 time
- temperature
- pressure: ~1
- partially ioni
- partially deg
- strongly coupled ions
- $k_B T \sim \frac{e^2}{4\pi\varepsilon_0}\frac{1}{\langle d\rangle} \sim E_F \sim E_{bond} \sim$ eV

If you can compute it,
it is not warm dense matter.

If you can measure it,
it is not warm dense matter.

Planets / Brown Dwarfs / Stars



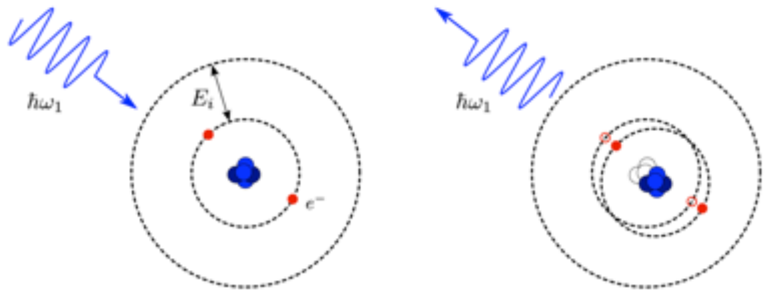


Technology applications

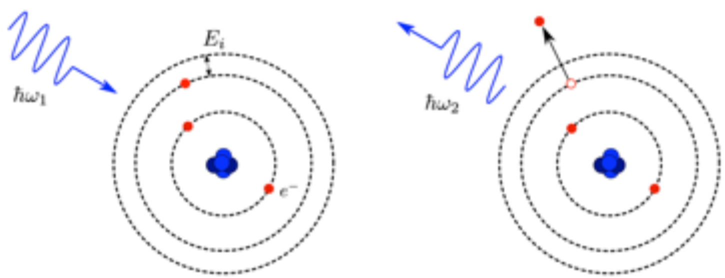
Dominik Kraus | Institute of Radiation Physics | www.hzdr.de

Using X-ray scattering to study partially ionized plasmas

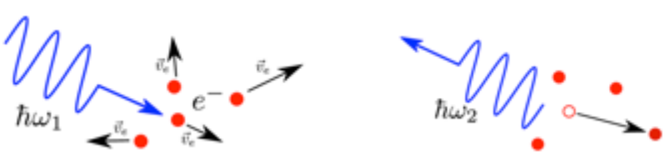
Elastic scattering:



Bound-free scattering:



Free-free scattering:

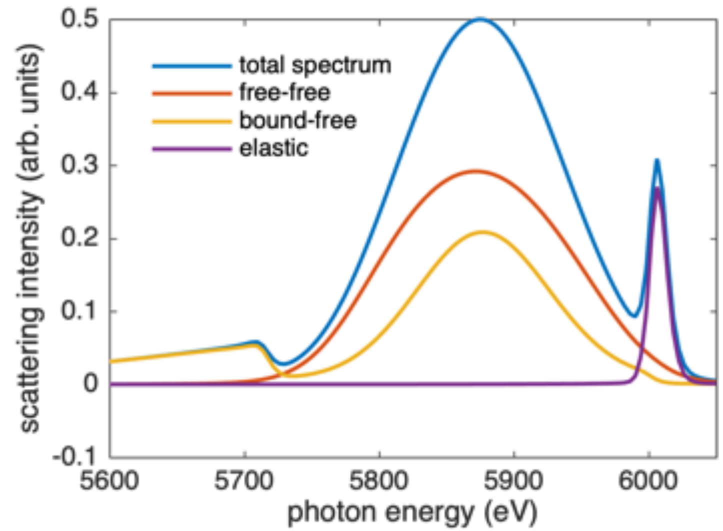


Scattered Power:

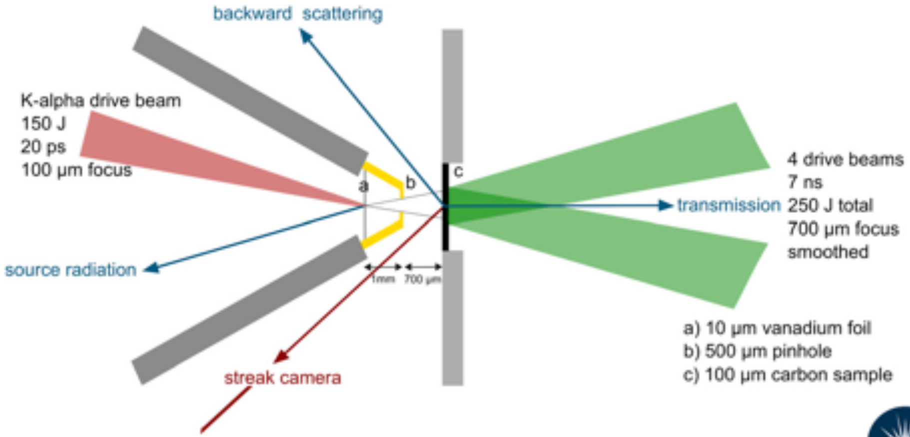
$$\frac{dP}{d\Omega d\omega} = r_0^2 \, \frac{1}{2} \, (1+\cos^2\theta) \left(\frac{\omega_s}{\omega_i}\right)^2 \; N \, I_0 \, S(k,\omega)$$

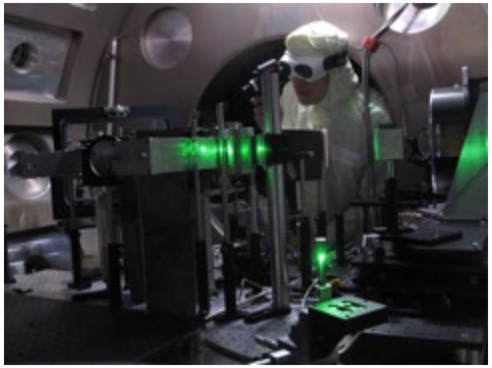
Structure factor:

$$S(k,\omega) = |\ f(k) + q(k)\ |^2 \ S_{ii}(k,\omega) + Z_f S_{ee}(k,\omega) + Z_b \int S_{be}(k,\omega-\omega')S_s(k,\omega')d\omega'$$



X-ray scattering at high energy laser systems (examples)

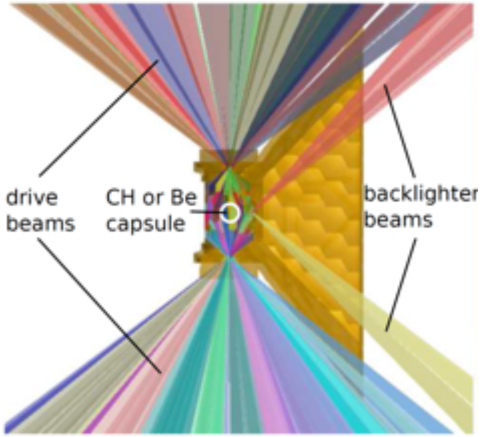


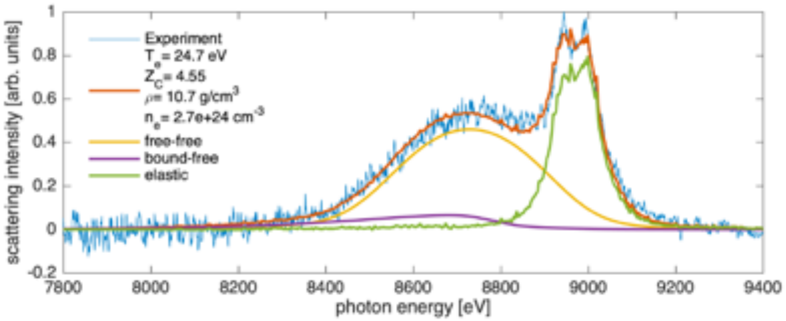


D. Kraus et al., Phys. Rev. Lett. 111, 255501 (2013)
D. Kraus et al., Phys. Plasmas. 22, 056307 (2015)
J. Helfrich et al., HEDP 14, 38-43 (2015)

Science & Technology Facilities Council
Central Laser Facility

PHELIX

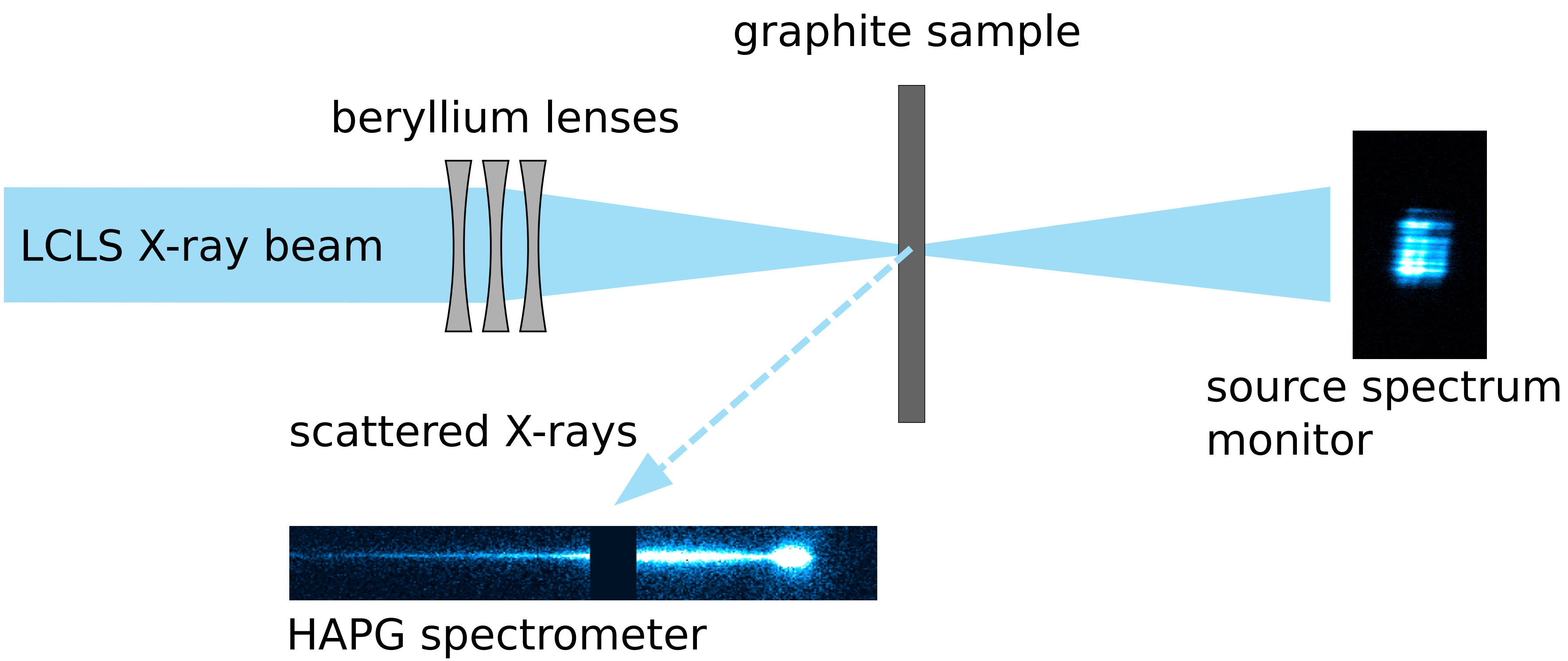




NIF

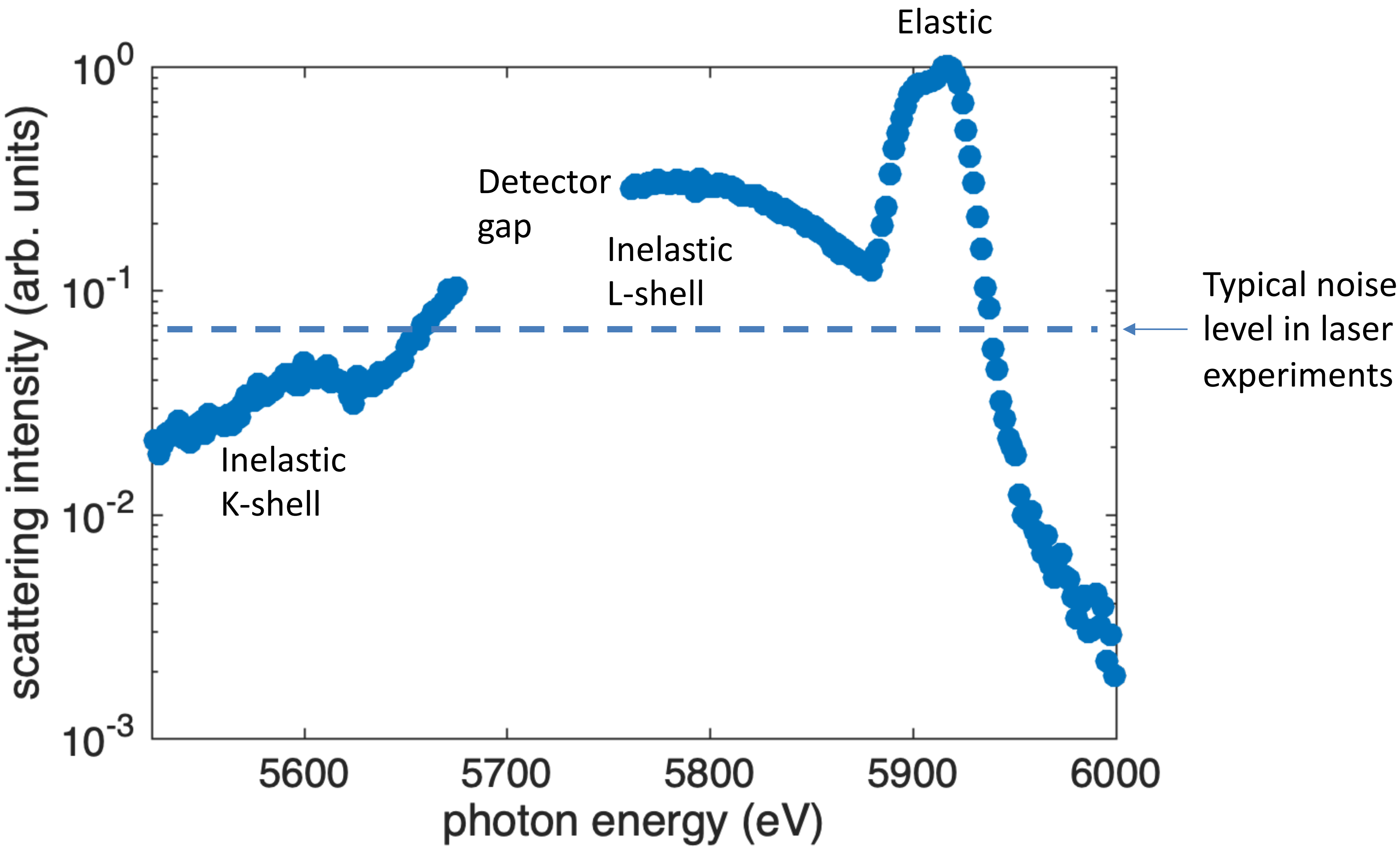
D. Kraus et al., Phys. Rev. E 94, 011202(R) (2016)
D. Kraus et al., JPCS 717, 012067 (2016)
K.-J. Boehm et al., Fusion Sci. Technol. 70, 324-331 (2016)

How can XFELs help
-> isochoric heating and precise scattering measurements



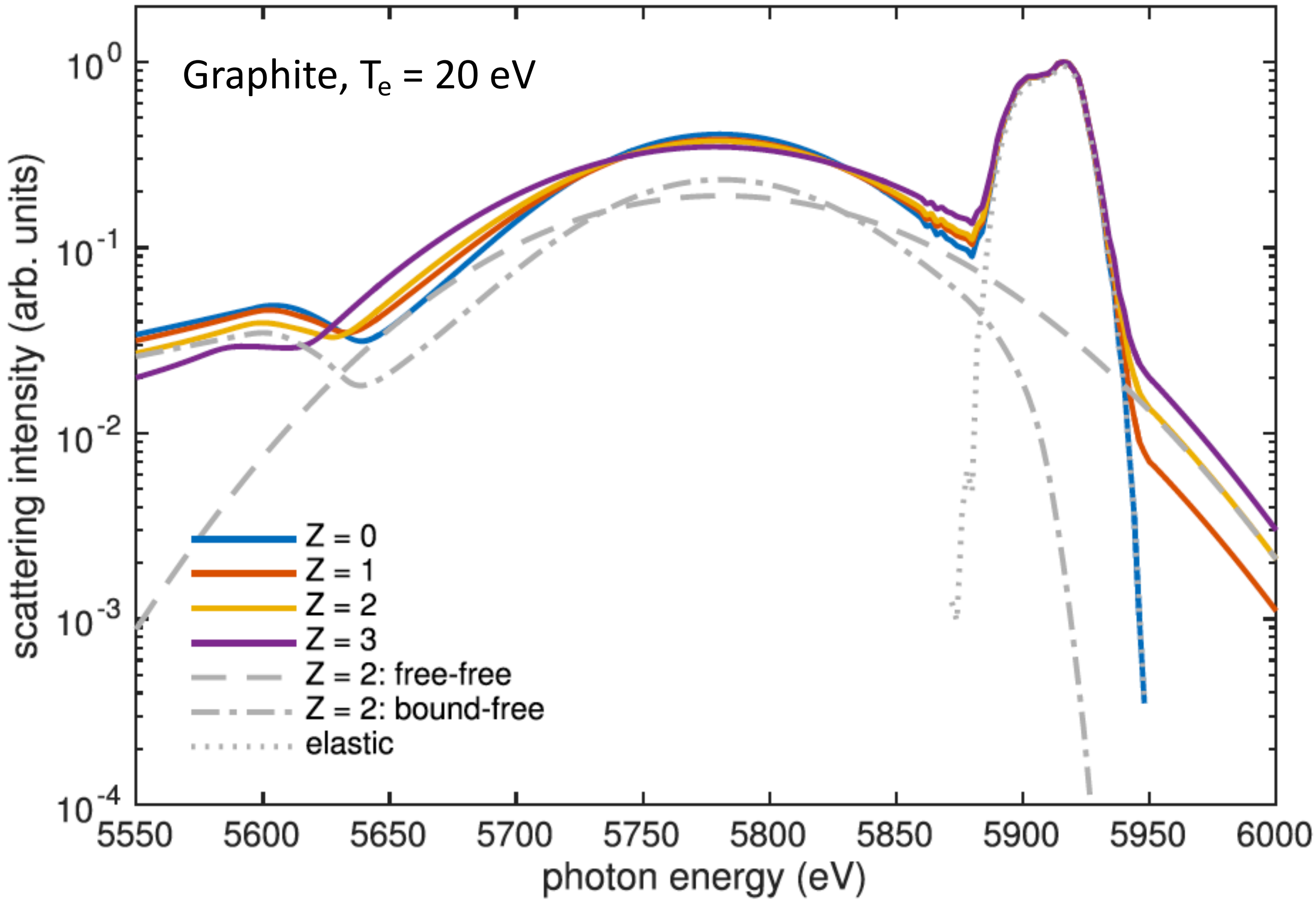
D. Kraus et al., PPCF **61**, 014015 (2019)

High-quality spectra from graphite obtained at LCLS



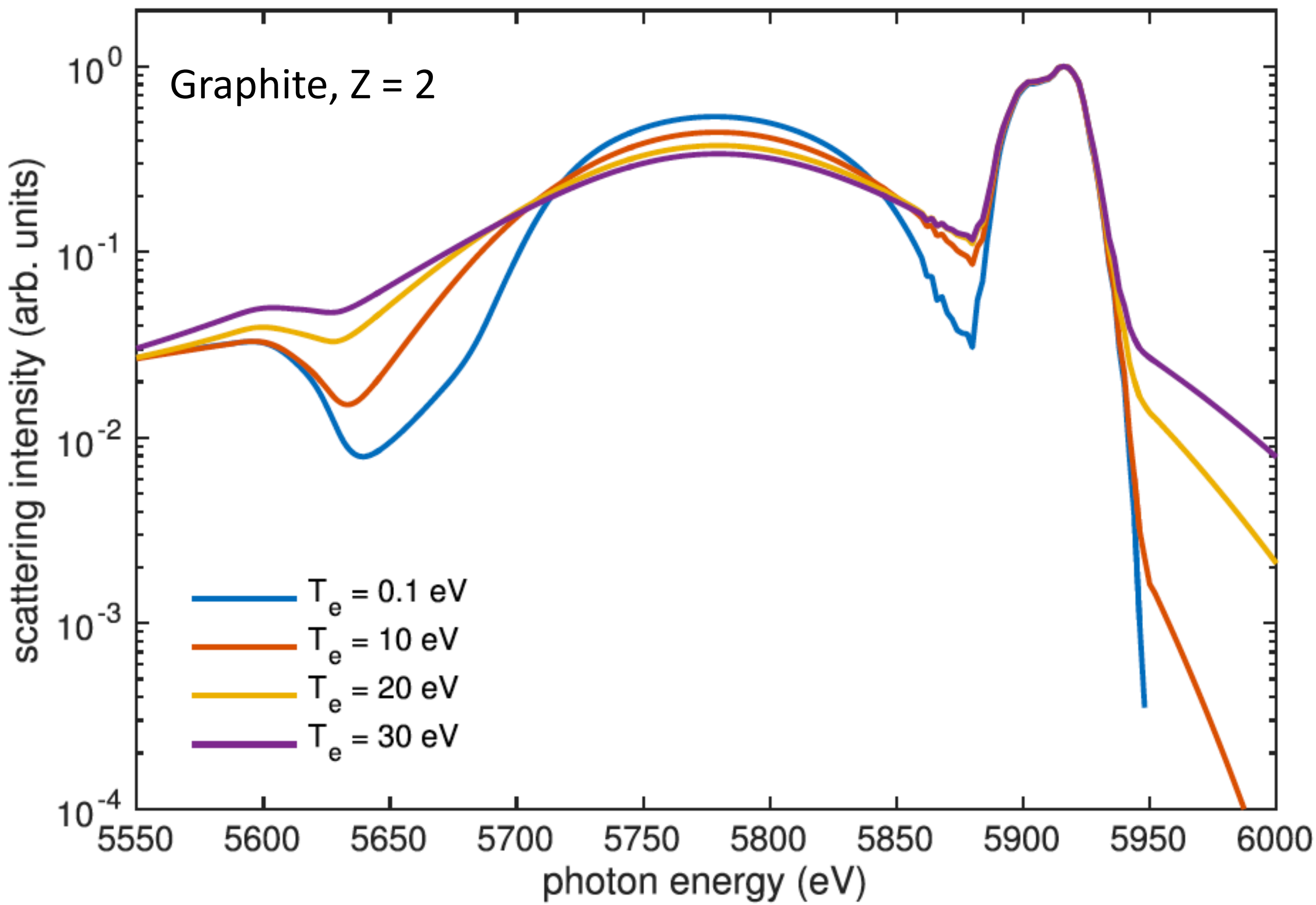
D. Kraus et al., PPCF **61**, 014015 (2019)

Opportunities with high-quality spectra



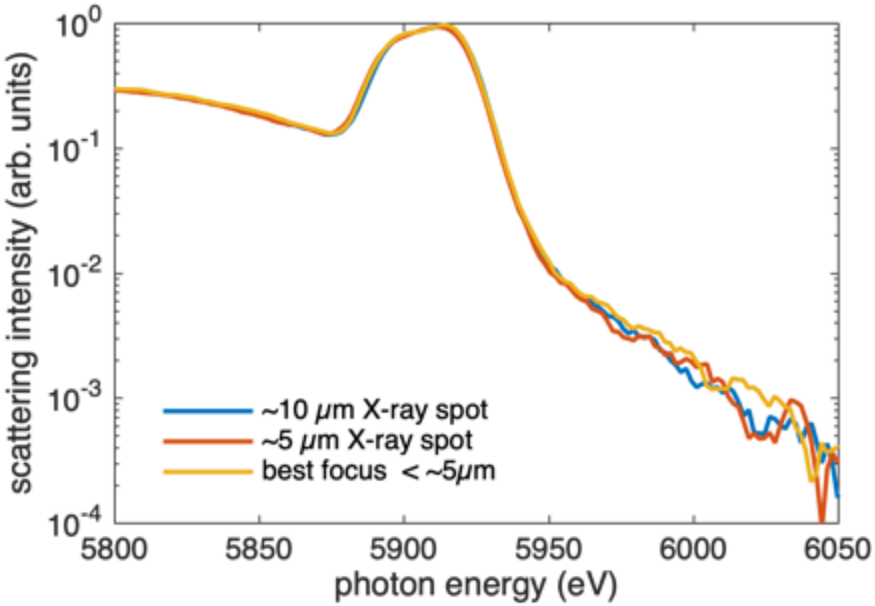
D. Kraus et al., PPCF **61**, 014015 (2019)

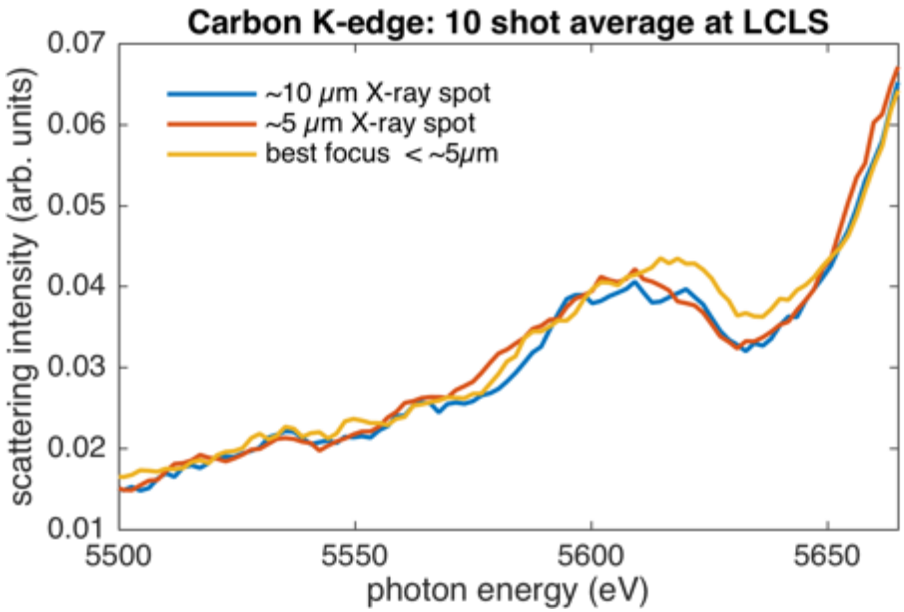
Opportunities with high-quality spectra



D. Kraus et al., PPCF **61**, 014015 (2019)

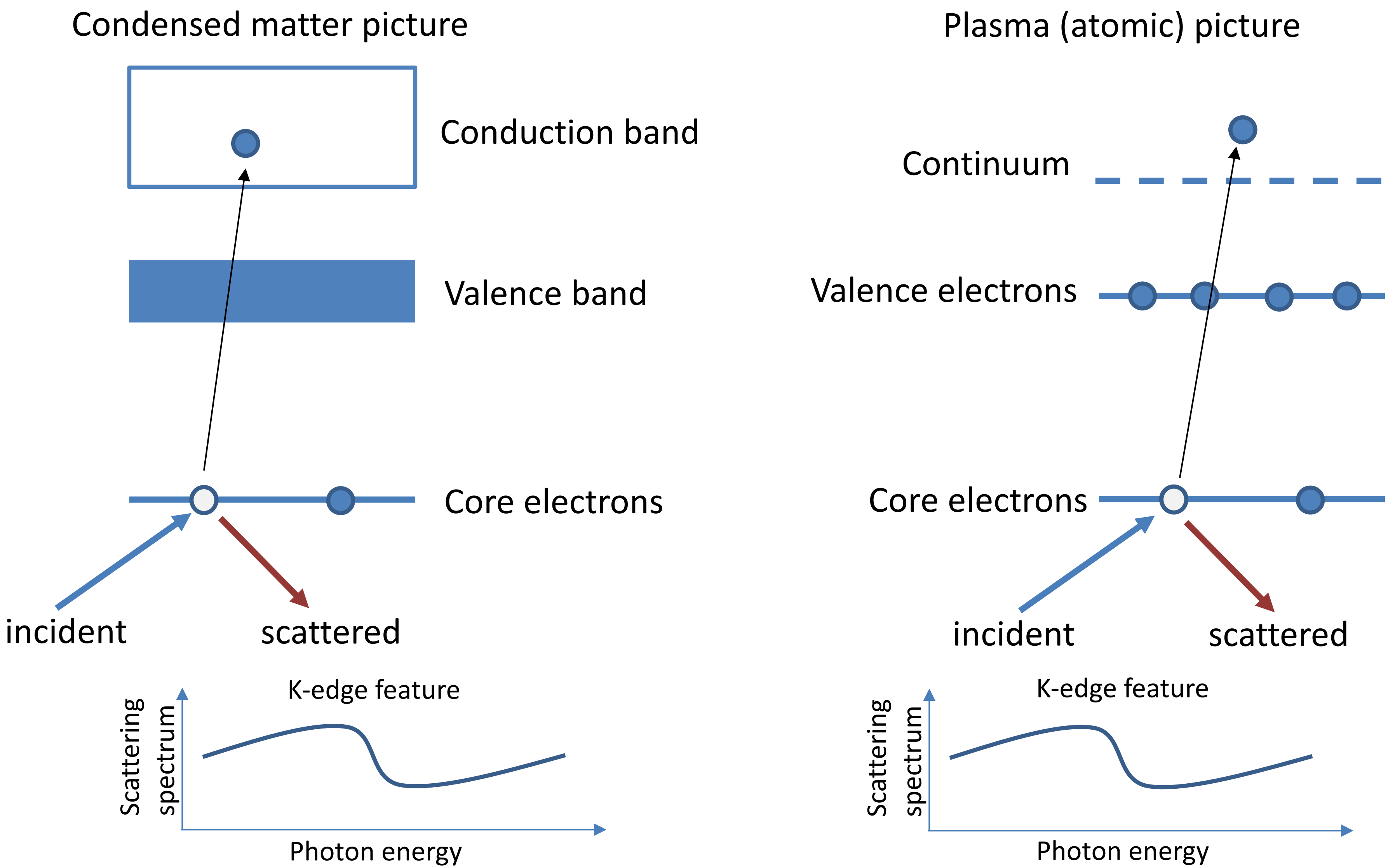
Isochoric heating effects on scattering spectra at LCLS





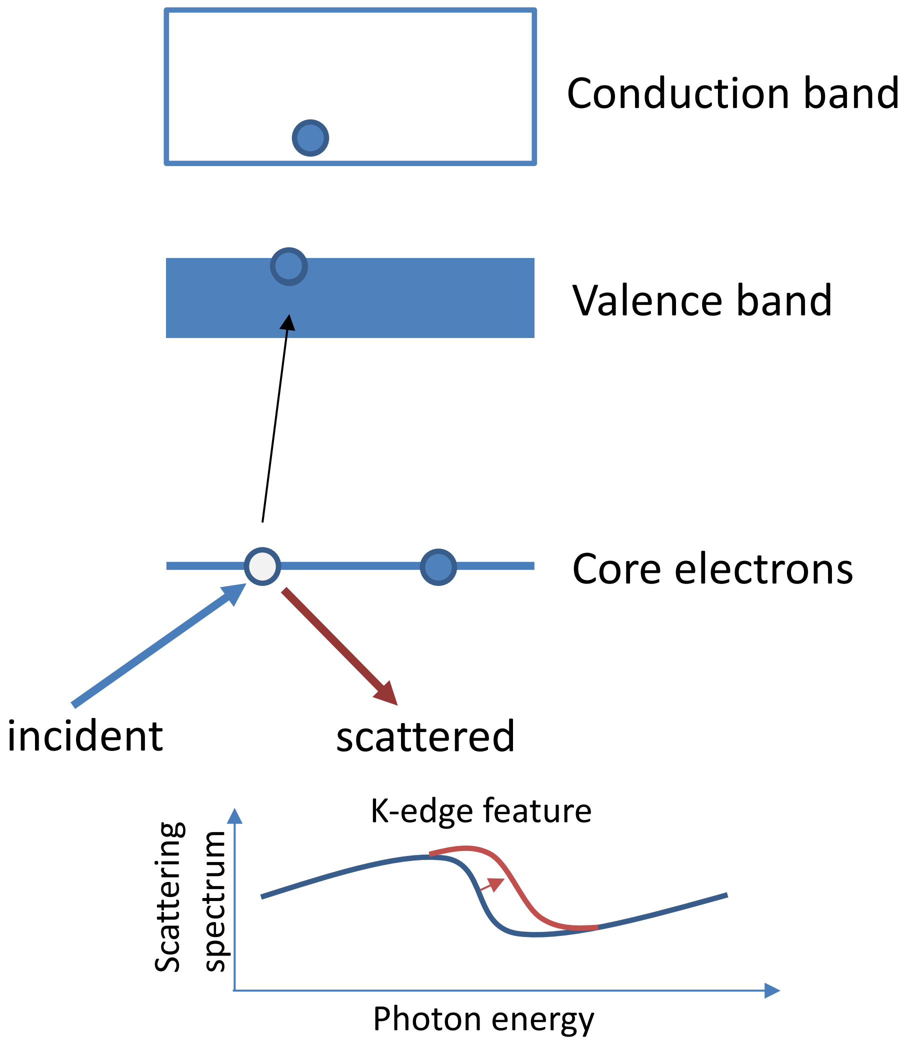
D. Kraus et al., PPCF **61**, 014015 (2019)

Electronic structure of dense plasmas

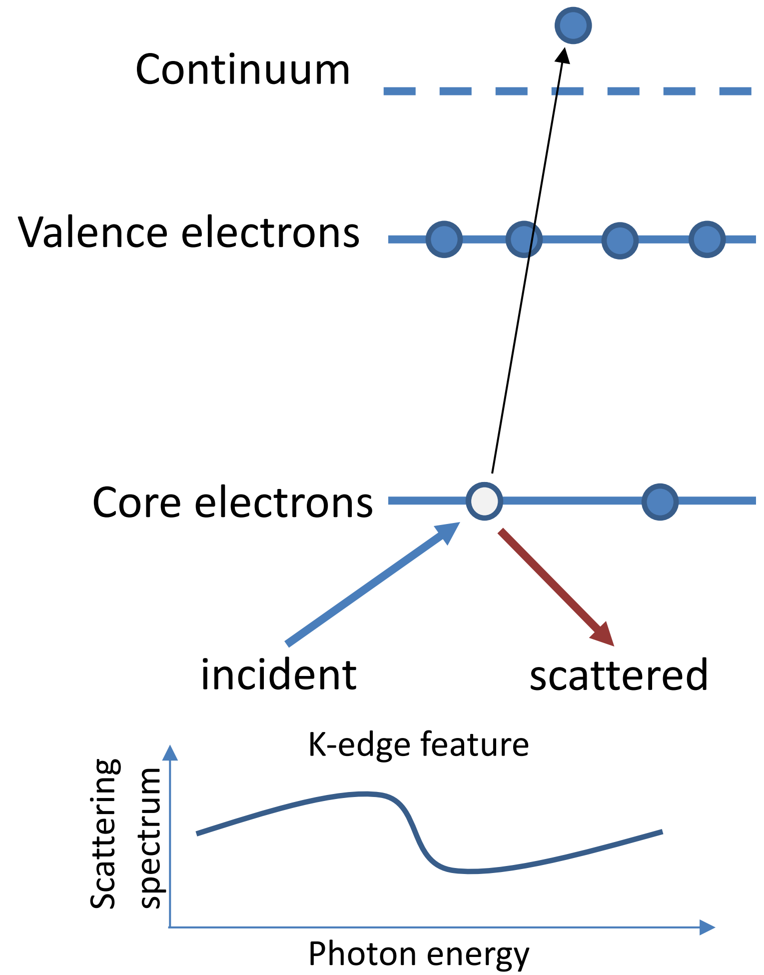


Electronic structure of dense plasmas

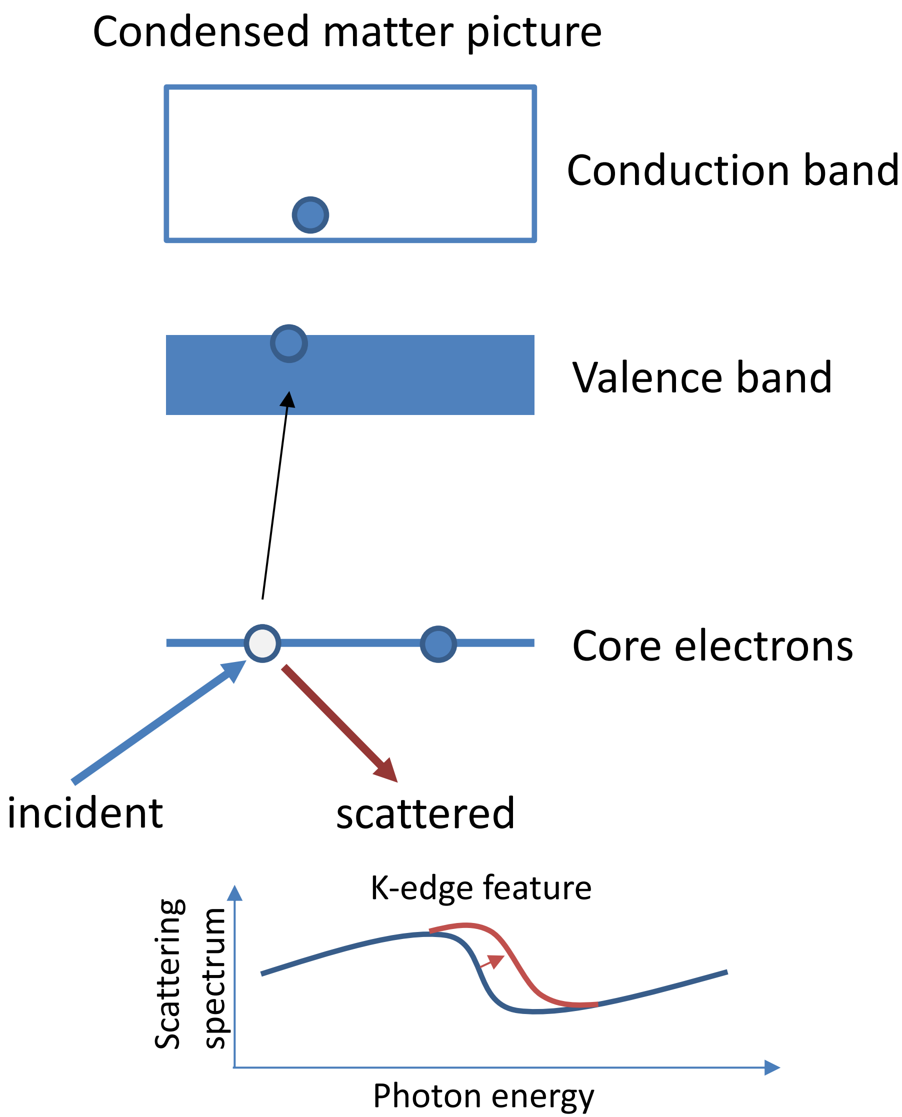
Condensed matter picture

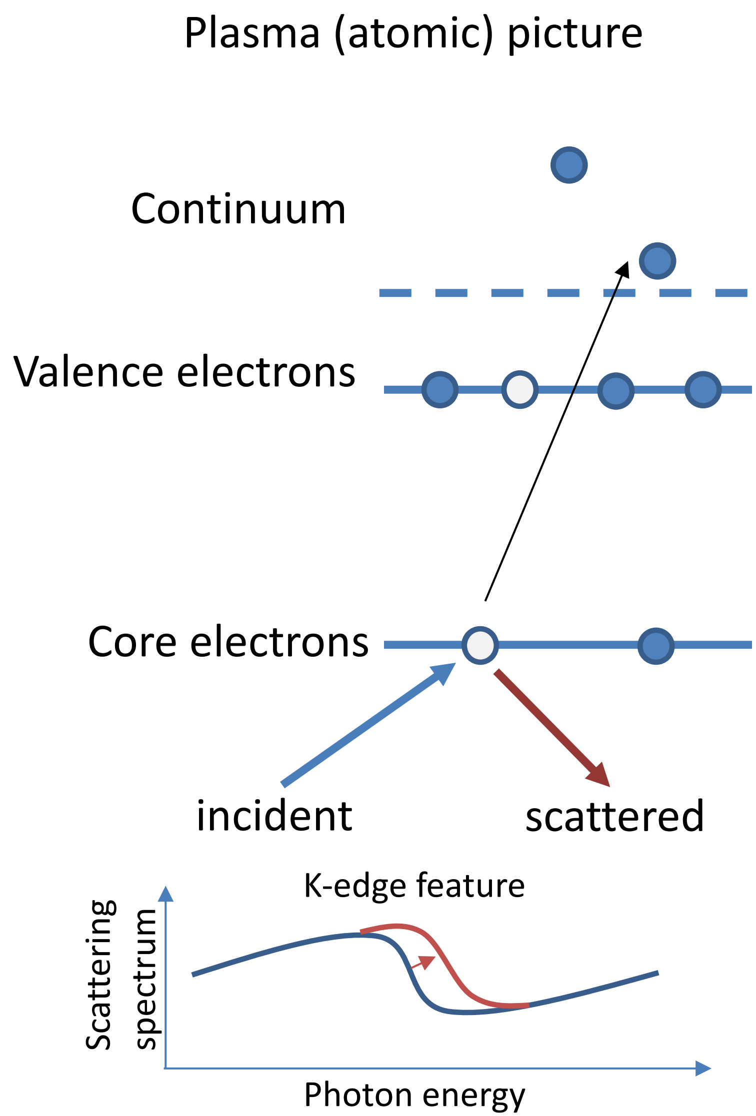


Plasma (atomic) picture



Electronic structure of dense plasmas





Effects of free electrons in dense plasma

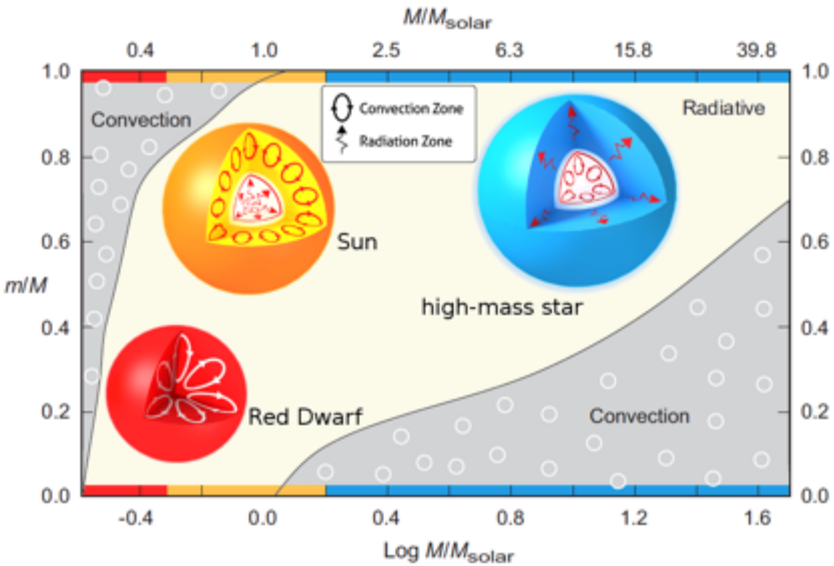
"ionization potential depression"

"pressure ionization"

"continuum lowering"

free electrons in dense plasma for given T, ρ

e.g. Stellar interiors
Radiative transport vs. convection

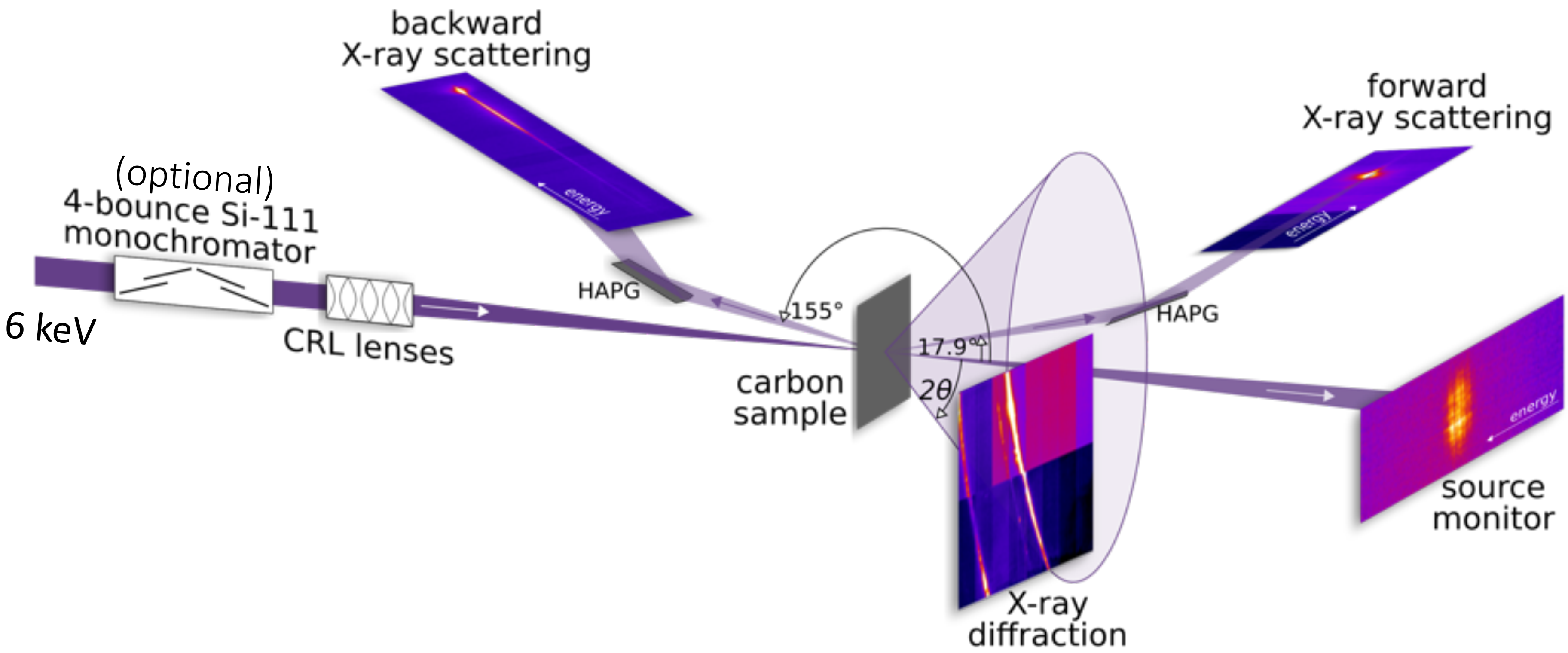


Numerous experiments and calculations in recent years

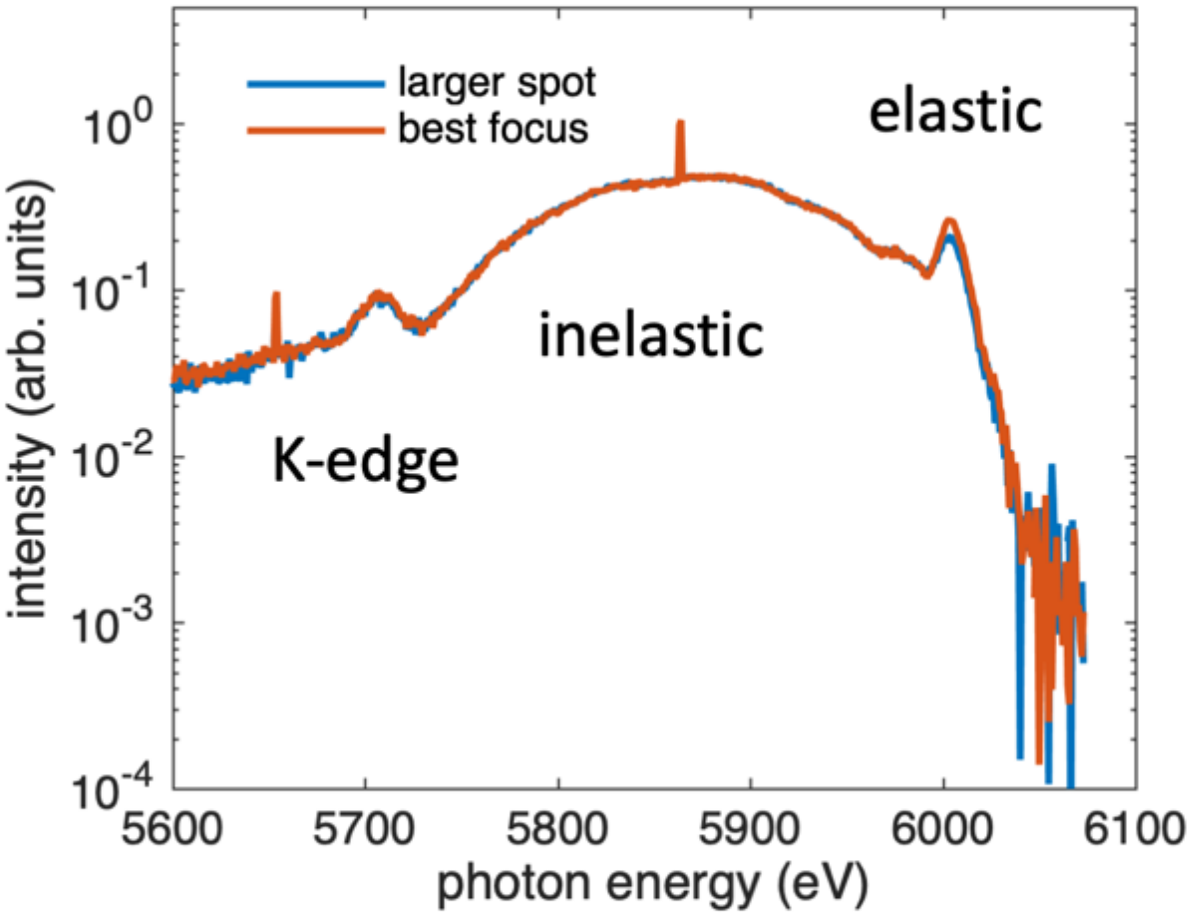
Problem in experiments:
Determine T, ρ, Z + IPD at the same time

-> presented X-ray scattering method is very promising!

Experiment at HED instrument of European XFEL

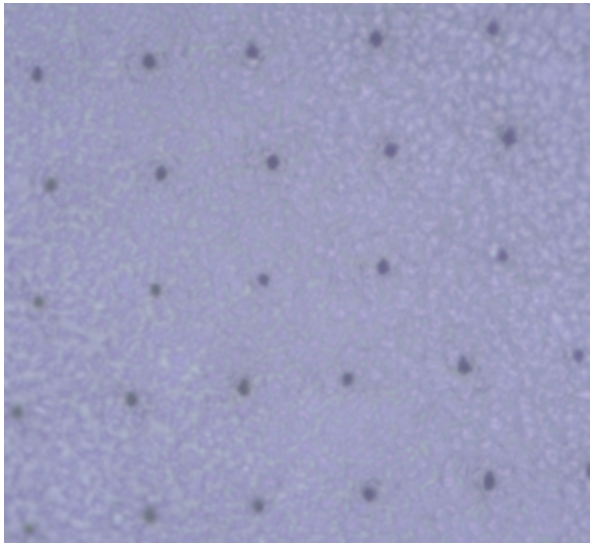


X-ray scattering spectra from diamond at the HED instrument 155°

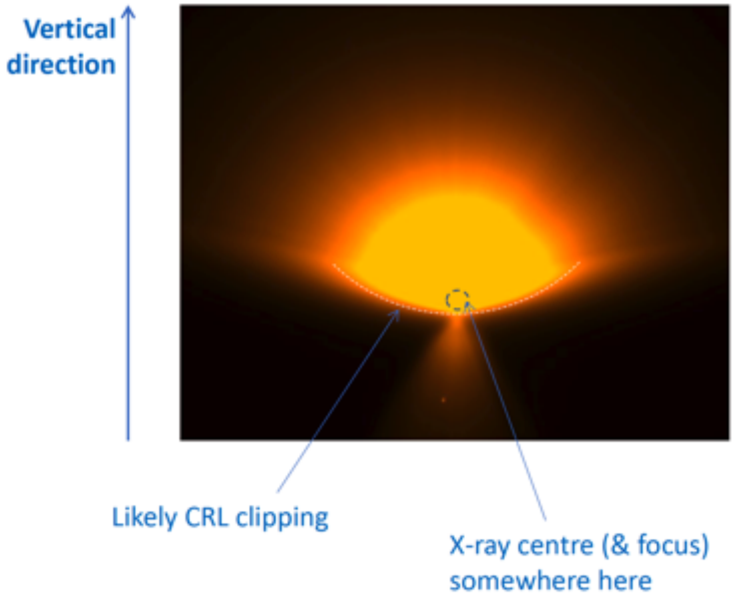


X-ray focus

Graphitization imprints

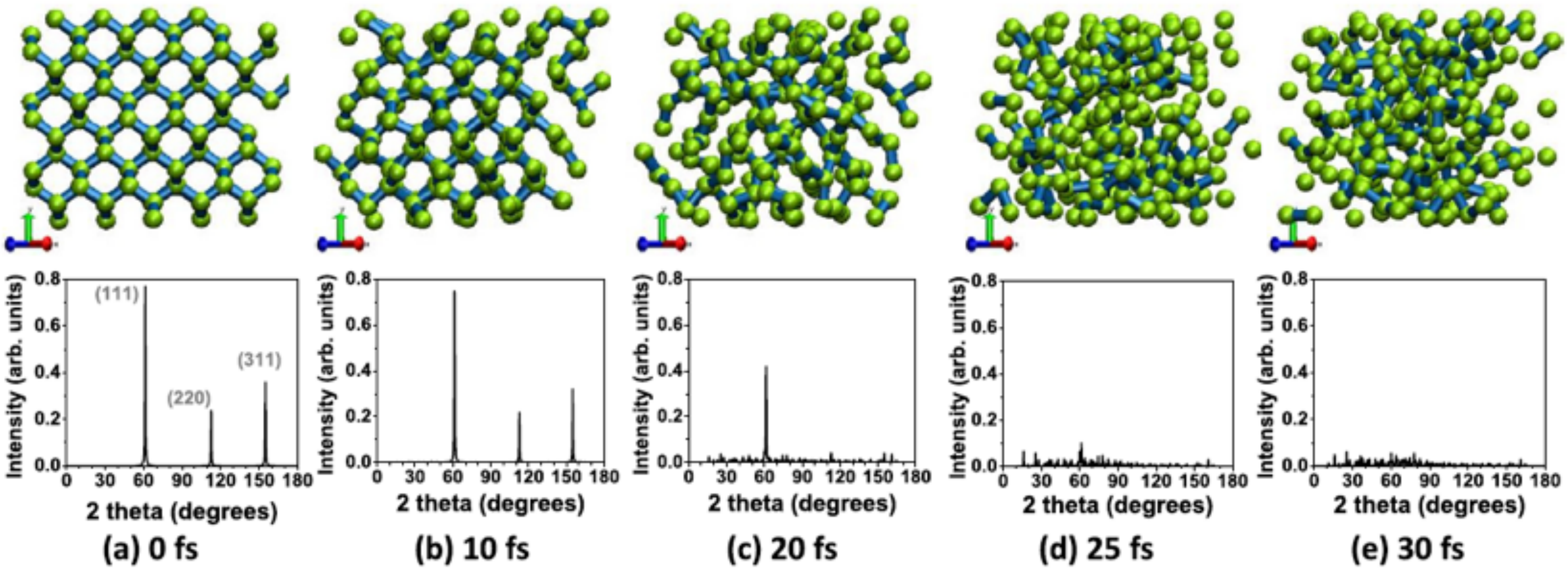


LiF imprints -> halo around central spot



Total pulse energy: ~ 2 mJ
Central spot: ~ 1.5 µm diameter, ~ 2.5 eV/atom absorbed dose, ~ 5% of total pulse energy
Halo: ~ 20 µm diameter, ~ 0.5 eV/atom absorbed dose

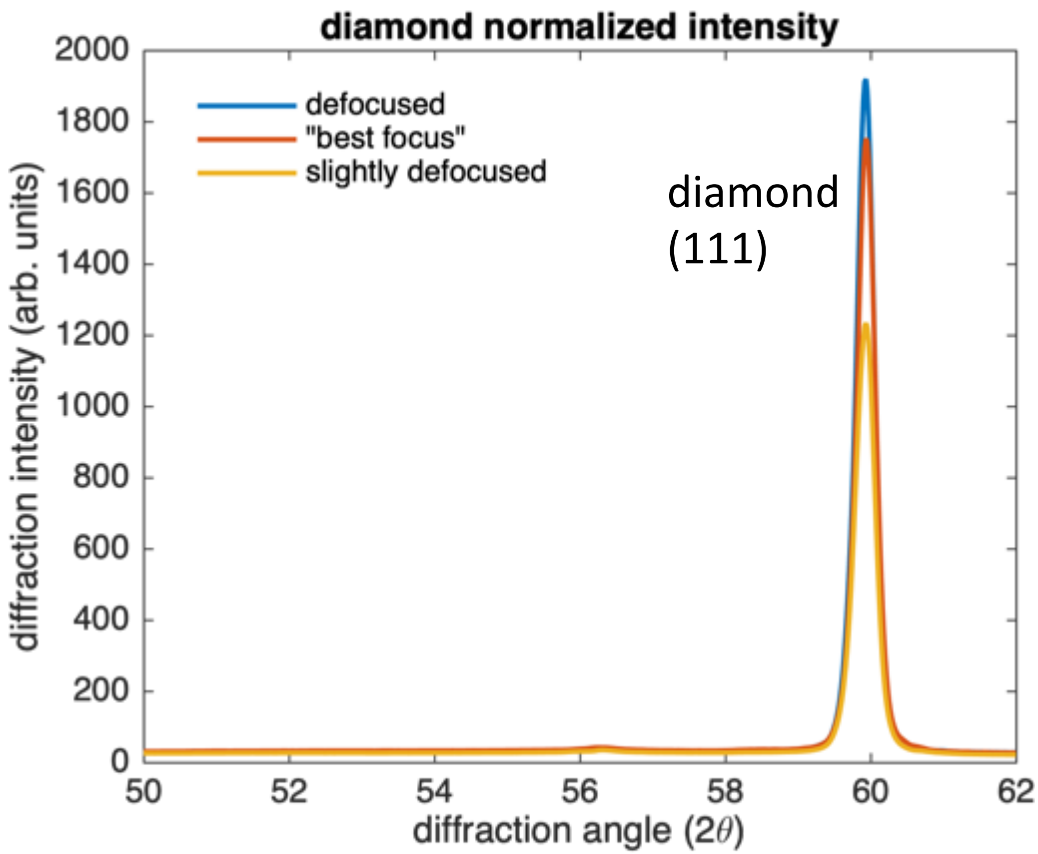
Ultrafast disintegration / graphitization of diamond



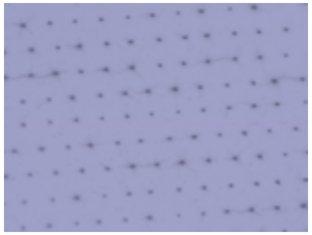
N. Medvedev et al., 4open (2018) https://doi.org/10.1051/fopen/2018003
N. Medvedev et al., Sci. Rep 8, 5284 (2018)

Graphitization threshold ~0.7 eV/atom
-> ~1.5% of valence electrons excited to conduction band (condensed matter picture)
-> ionization of ~0.06 (plasma physics picture)

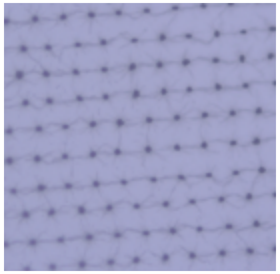
Heating effect in diamond



defocused

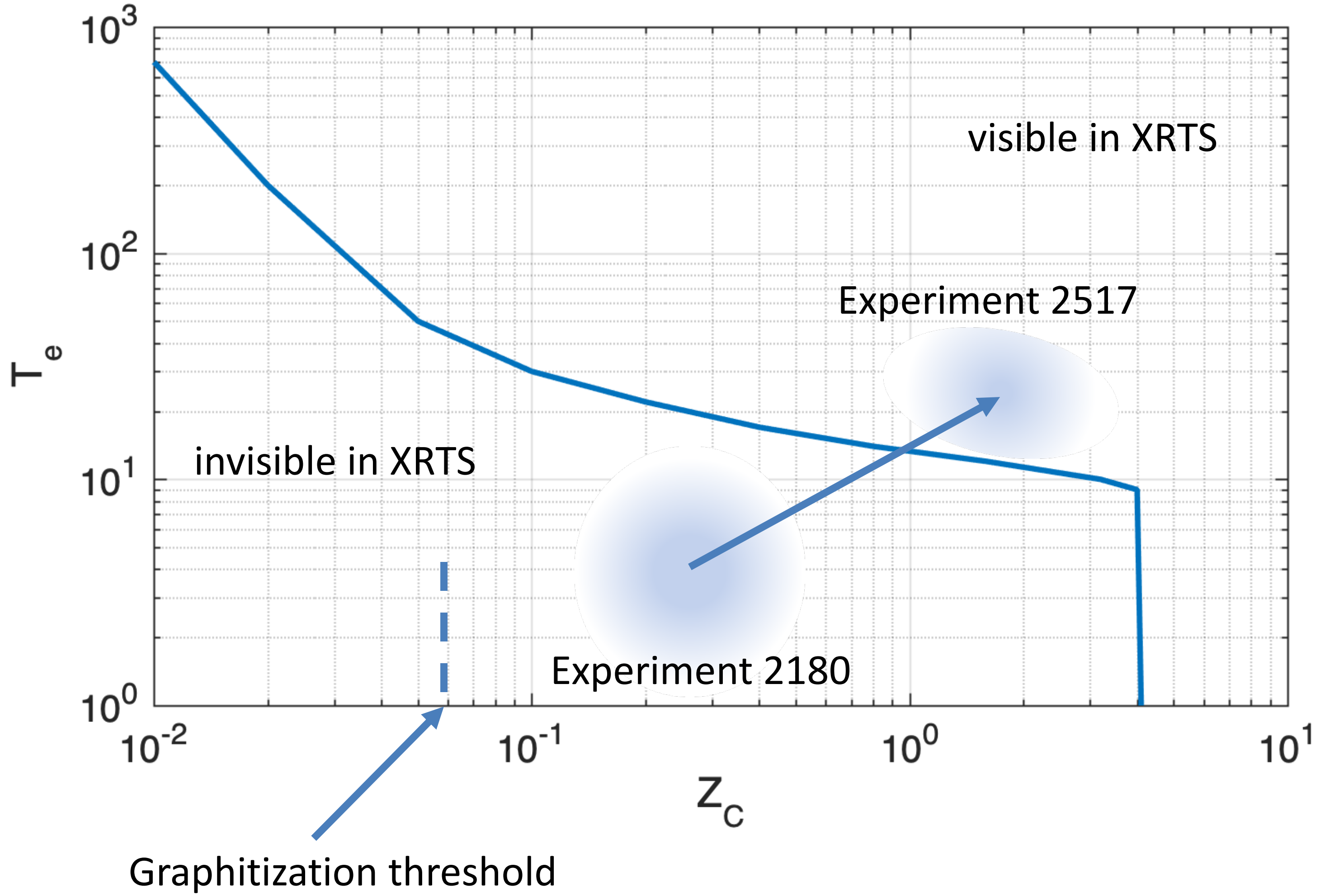


“best focus”

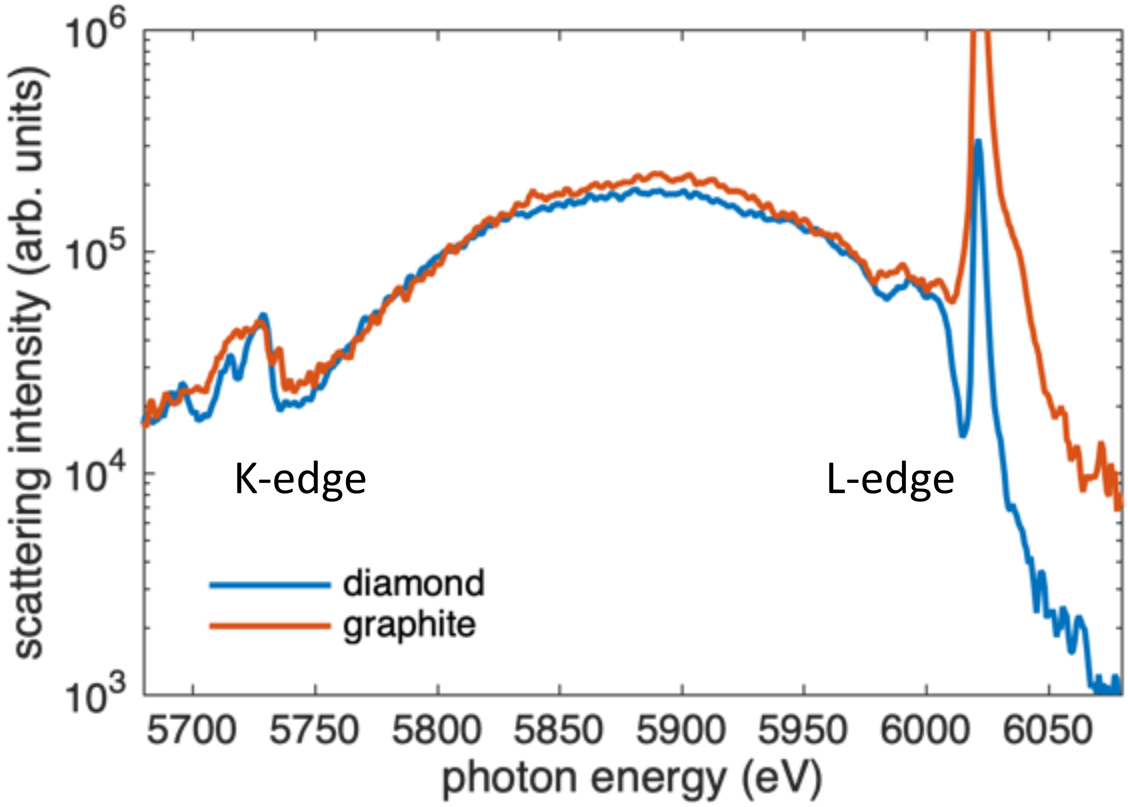


Slightly defocused

Exclusion plot plasma conditions in isochoric heating experiment (diamond sample)



Using the 4-bounce monochromator: X-ray Raman Spectroscopy

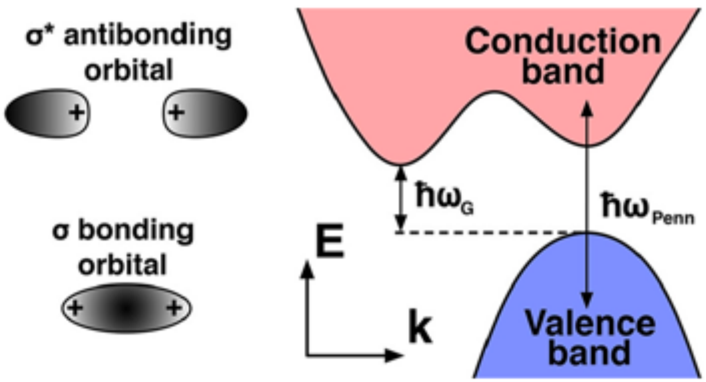


Seeding:

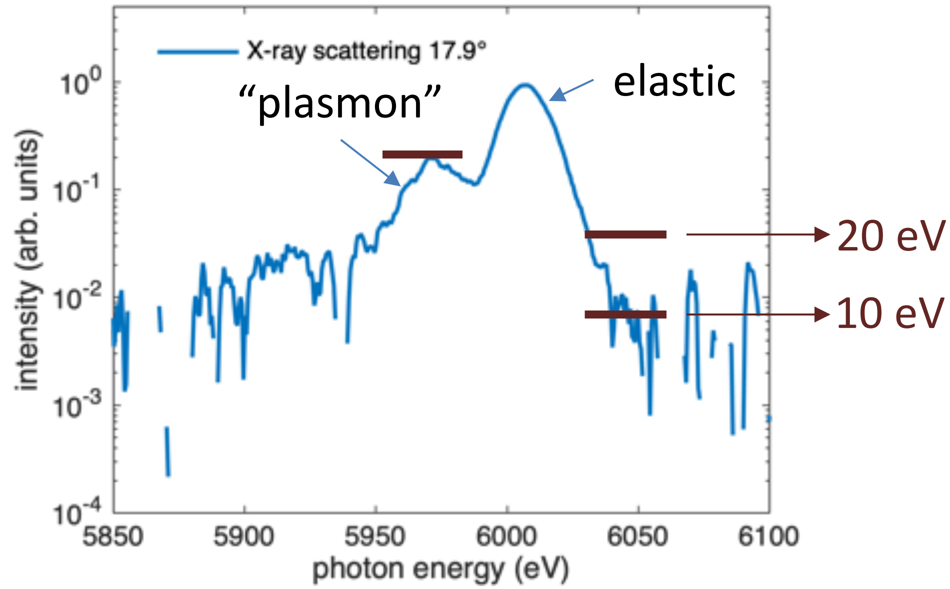
- comparable bandwidth as with monochromator similar heating intensity as with SASE
- Also interesting as in situ probe for upcoming rep-rated drive lasers at HED instrument

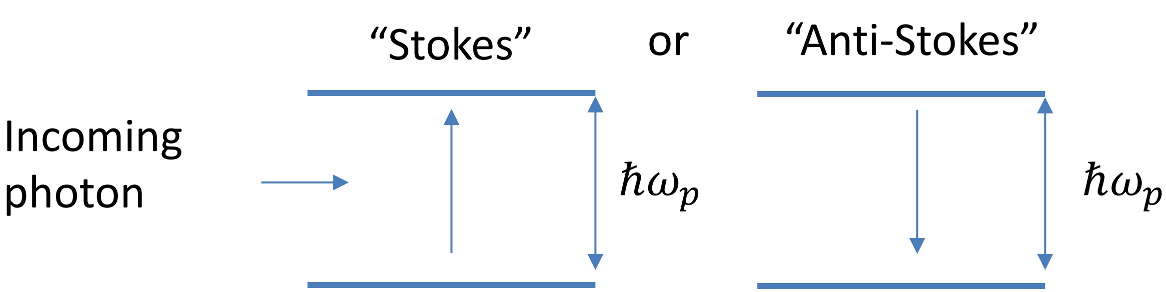
Comparable to XANES method, most useful for bulk low-Z materials

Collective oscillations by crossing into available states in the conduction band -> “Plasmons”



E. J. Gamboa et al., Phys. Plasmas 22, 056319 (2015)





$$\frac{N_{Anti-Stokes}}{N_{Stokes}} = \exp\left(-\frac{\hbar\omega_p}{k_B T}\right)$$

“detailed balance”

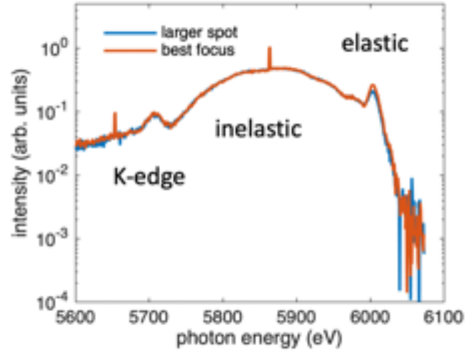
Summary

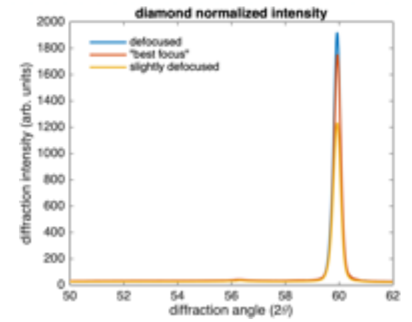
- Demonstrated high-quality X-ray scattering setup at HED to characterize plasma dynamics in Warm Dense Matter

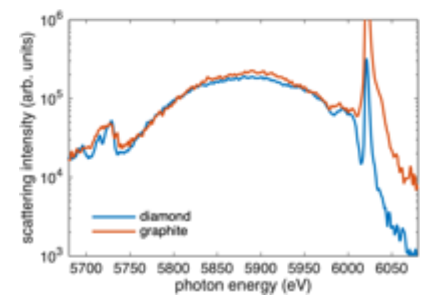
- Saw effects of heating: ultrafast disintegration of diamond lattice, but not the expected significant ionization and electron temperature -> most probably due to focusing problems

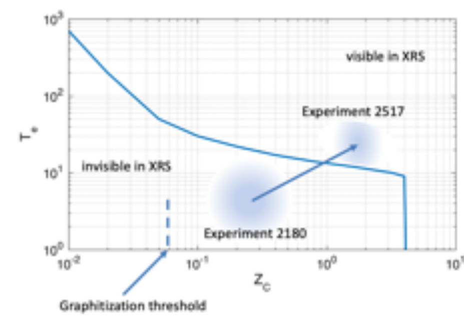
- Demonstrated that X-ray Raman Spectroscopy is a highly promising HED diagnostics, in particular towards rep-rated drive lasers

- Outlook: Experiment 2517 in April 2020 will improve focusing and sensitivity!









Thanks!