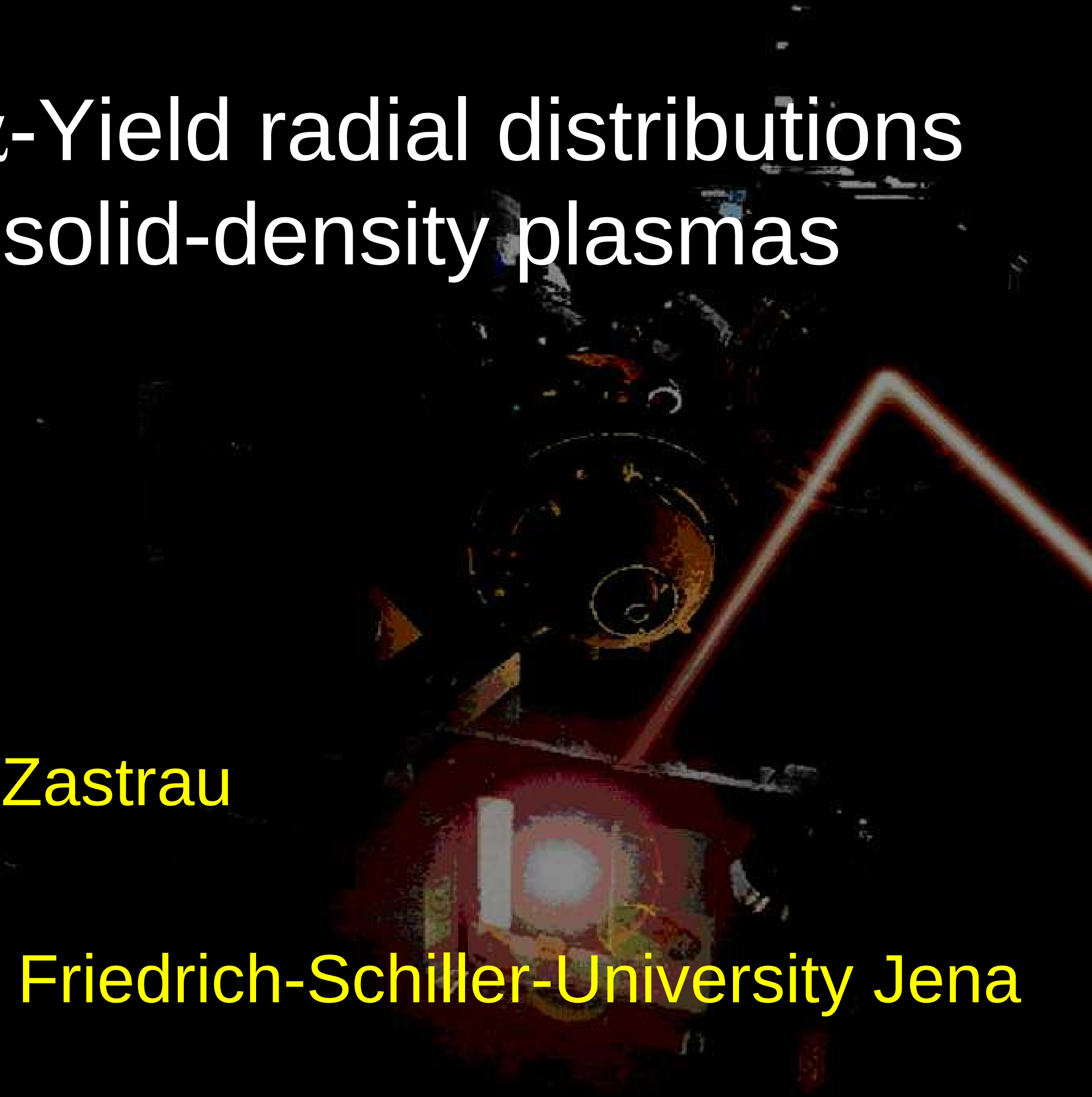
Temperature and Kα-Yield radial distributions of laser-produced solid-density plasmas

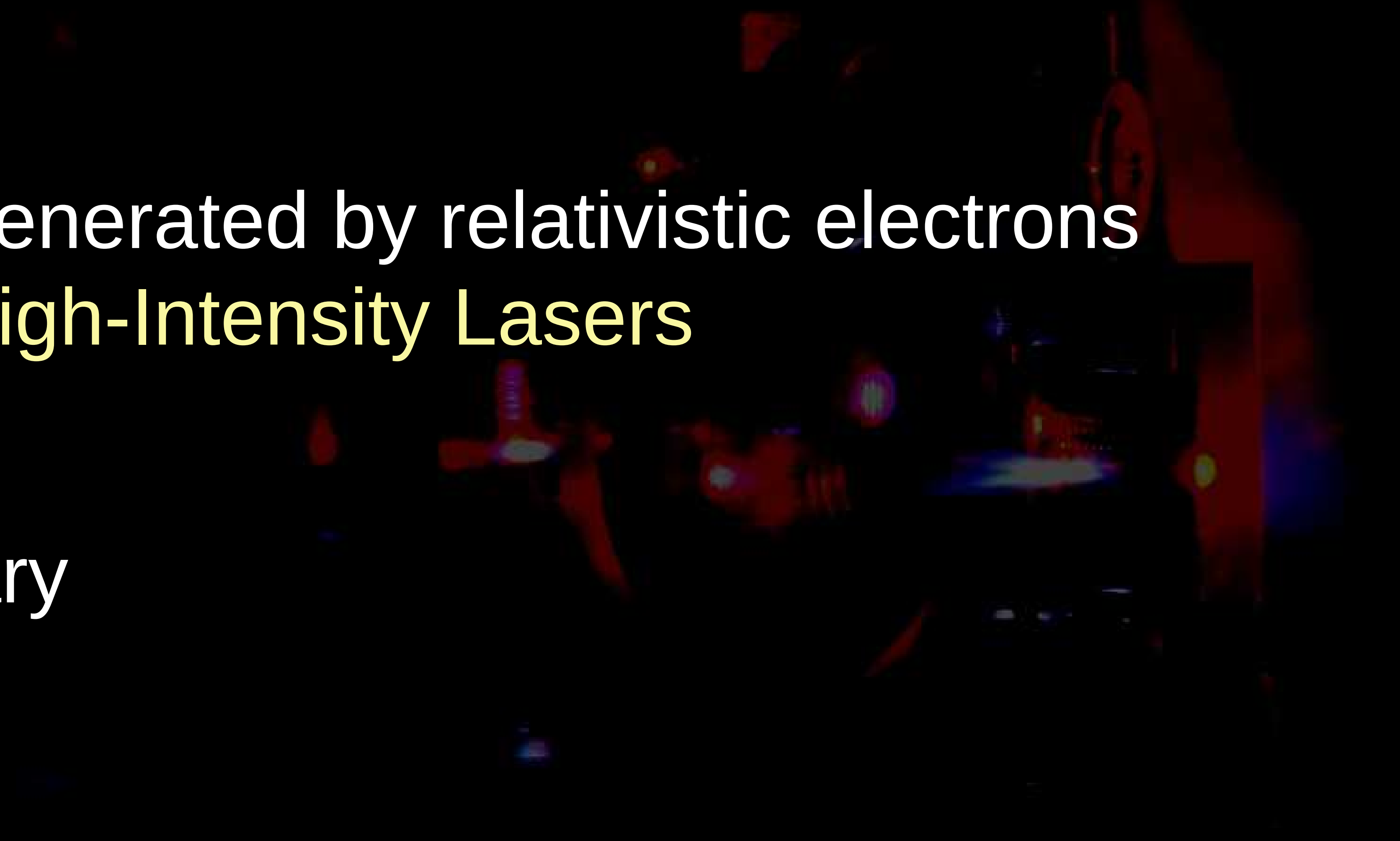


Ulf Zastrau

X-ray Optics Group - IOQ - Friedrich-Schiller-University Jena

Contents

- Physics of “Warm Dense Matter“ (WDM)
- WDM generated by relativistic electrons using High-Intensity Lasers
- Summary



Warm Dense Matter

Condensed Matter <> **Warm Dense Matter** <> Ideal Plasma

$E_{therm} \sim E_{Fermi}$

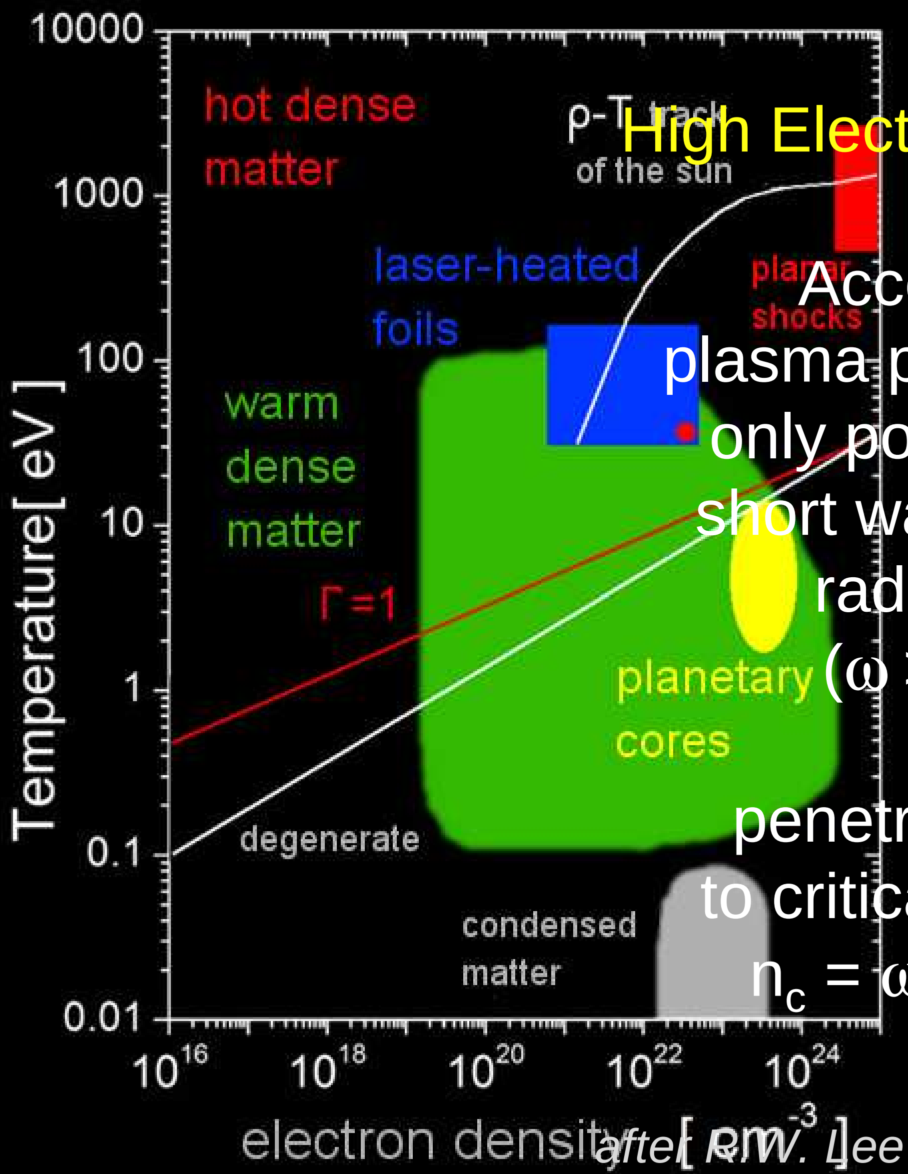
1..100 eV

$\rho_{WDM} \approx \rho_{solid}$

strong coupling

$\Gamma \geq 1$

$E_{coulomb} \sim E_{therm}$



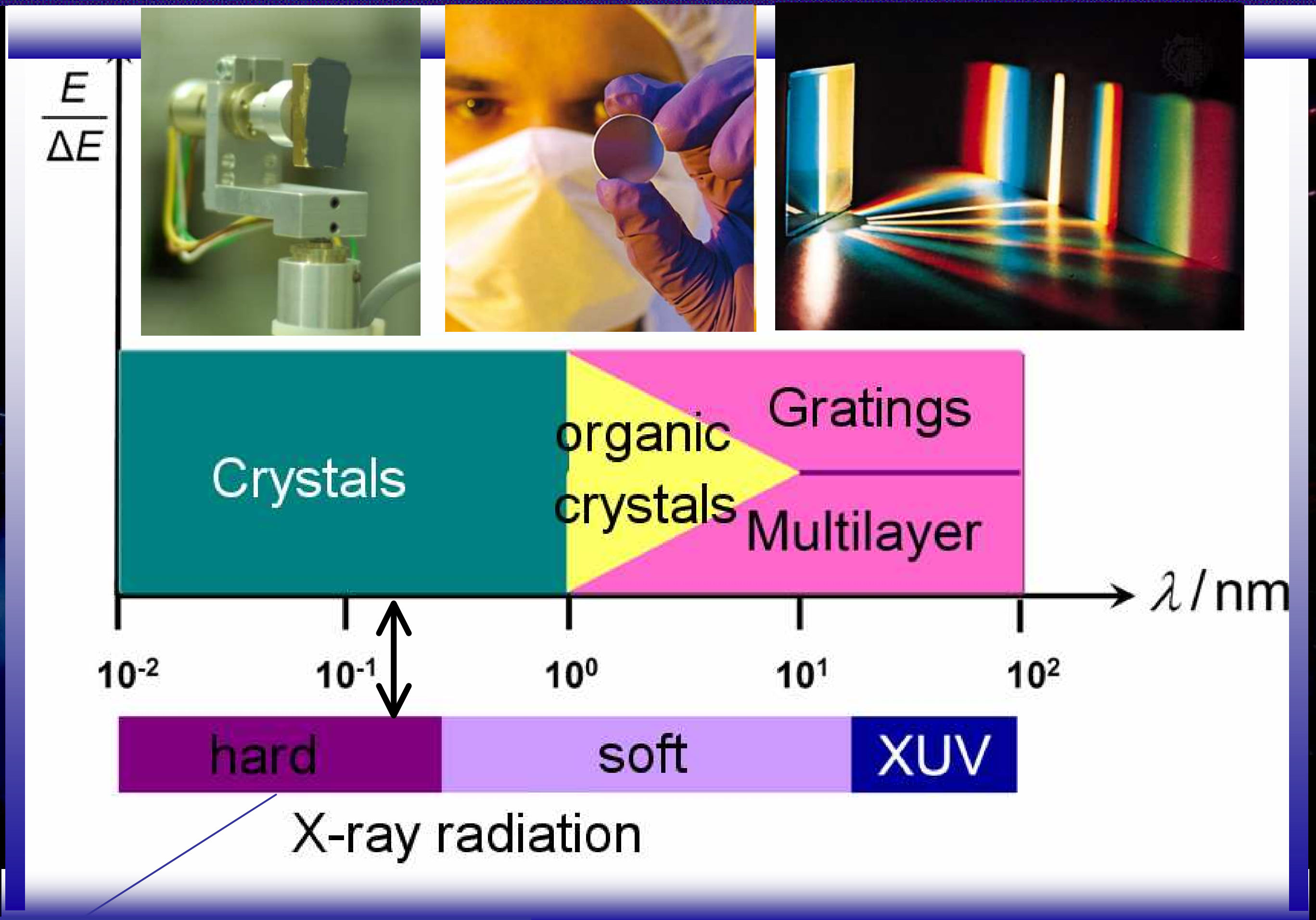
after R.W. Lee

High Electron Density:

Access of plasma parameters only possible by short wavelength radiation ($\omega > \omega_P$)

penetration up to critical density $n_c = \omega^2 \varepsilon_0 m/e^2$

Spectroscopy of Solid Density Plasmas *by X-ray Photons*



Absorption length of λ=0.27 nm in Titanium (Z=22) : ~ 20 µm

in laboratory always transient micro-plasmas with strong gradients
→ spectroscopy with high spatial and temporal resolutions

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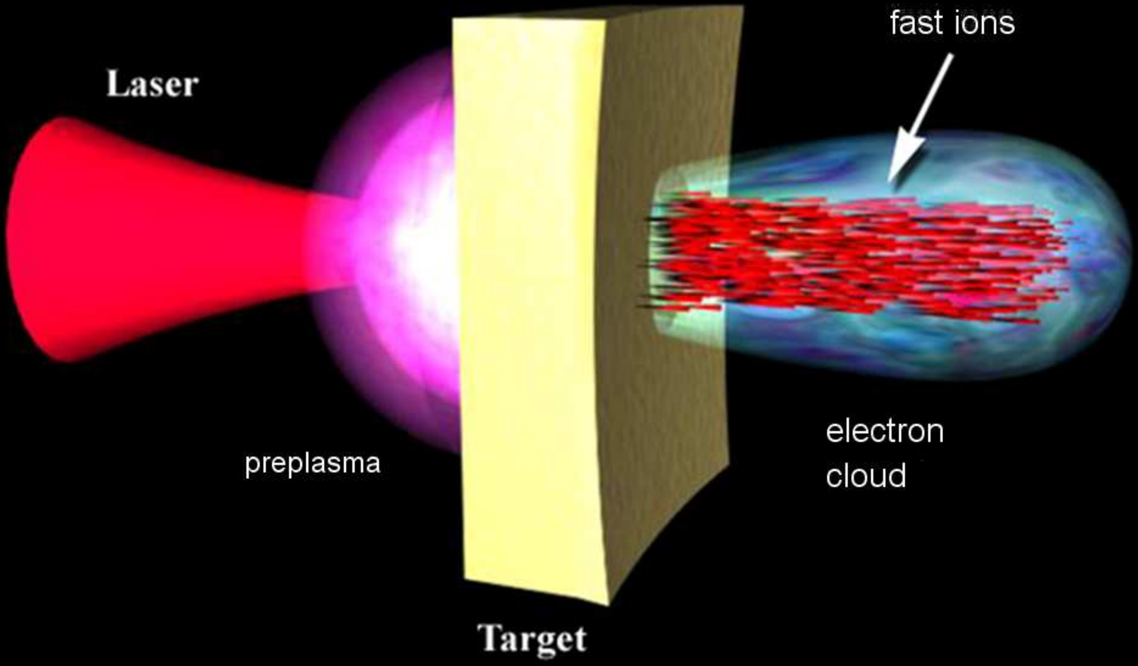
Fundamental Parameter: Brightness

$$\frac{\textbf{number of X-ray photons}}{\textbf{time [s]}\quad\textbf{emitting size [mm}^2\textbf{]}\quad\textbf{divergence [mrad}^2\textbf{]}\quad\textbf{spectral bandwidth [\%]}}$$

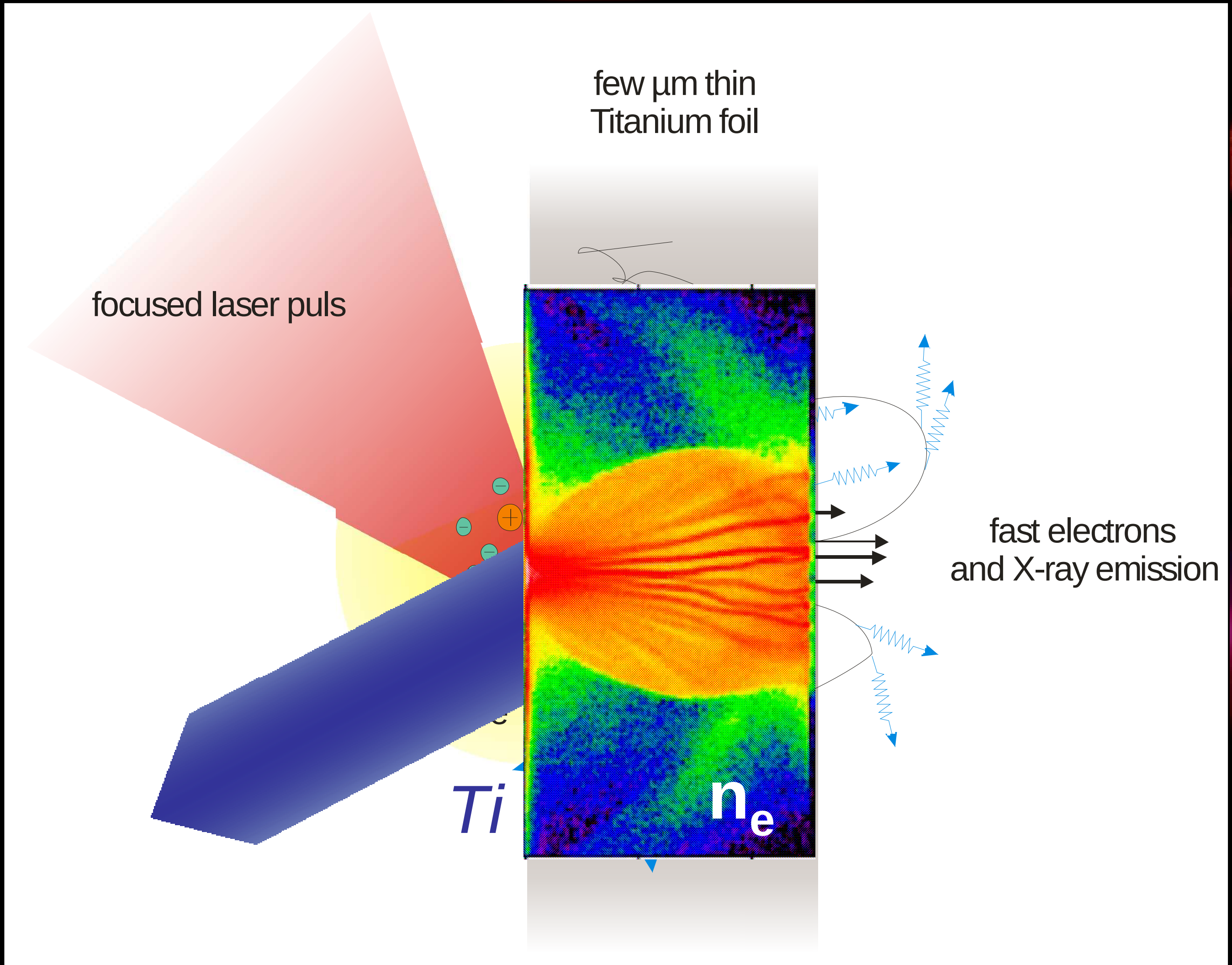
- ✓ time-resolved X-ray diffraction
- ✓ point-source for radiography
- ✓ backlighter for Thomson scattering

- ✓ electron and ion acceleration (TNSA)
- ✓ laser-fusion and the „Fast Ignitor“-scheme



© Wilks

Physics of IR-Laser-Target Interaction



High Density & Fields, refluxing, filamentation,…
Hybrid PIC-fluid model: Evans et al., HEDP 2 (2006)

Ponderomototive Potential
$T_{hot} \sim \phi_{pond} \sim \sqrt{I\lambda^2}$

10^{19} W/cm² IR-laser pulse creates fast electrons

electrons with energies up to MeV heat the cold target by collisions

electrons with E > 5keV in Titanium are capable of K-shell ionization

we observe Kα–emission from the heated target

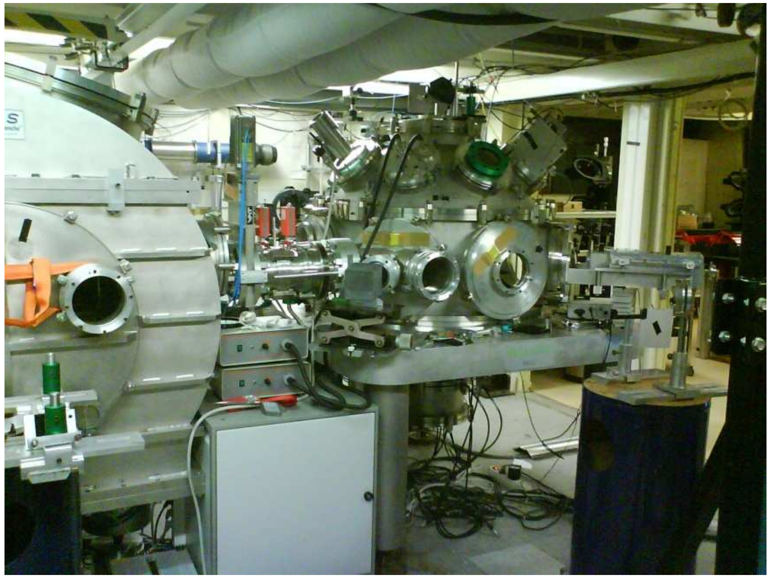
Experiment at 100TW Laser, LULI

LULI 100TW Laser

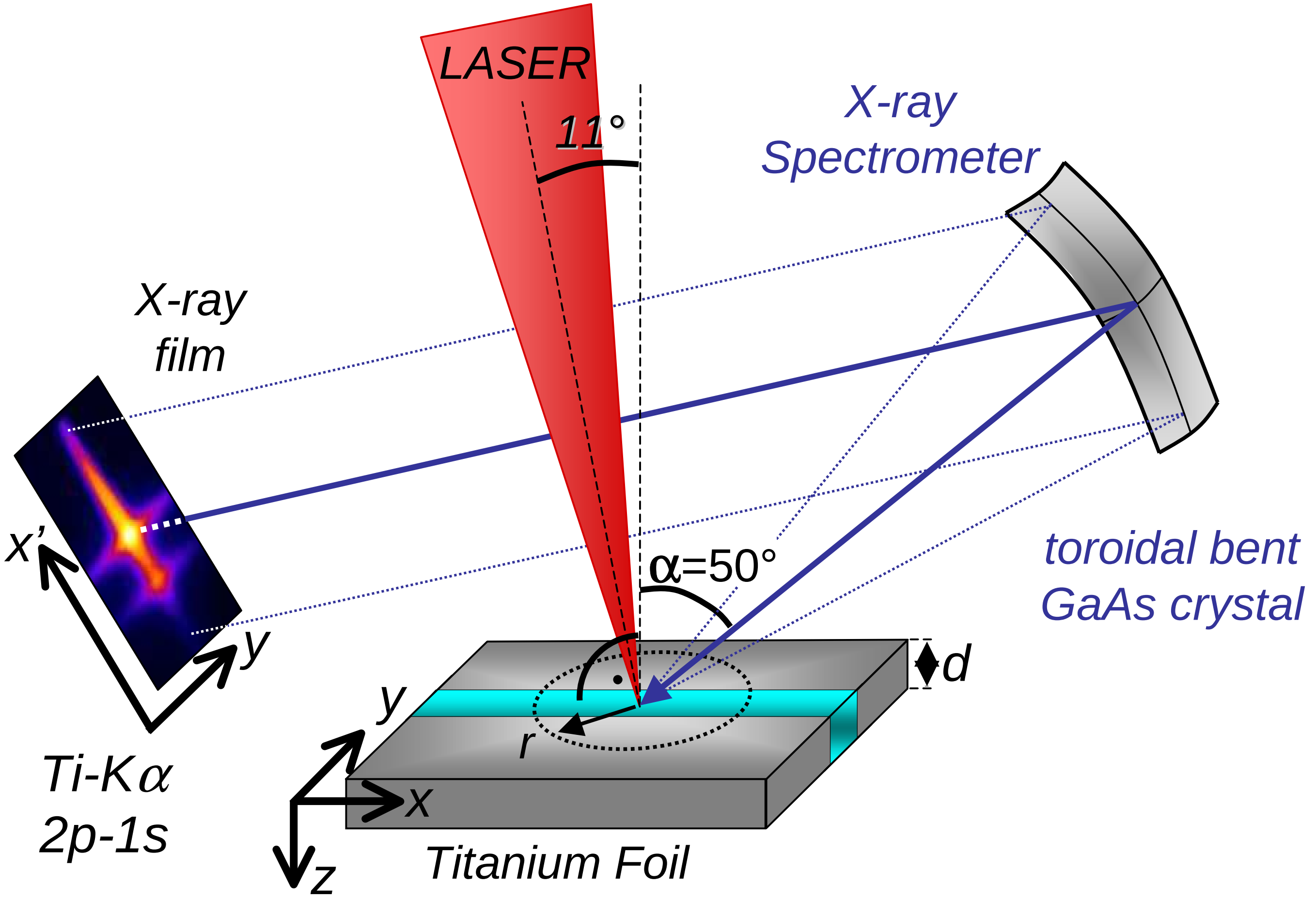
Ti:Sa + Nd:Glas

1057 nm central wavelength
330 fs pulse duration
max. 13 J energy in focus
8 µm focal diameter

→ Intensity ~ $5\cdot10^{19}$ W/cm^2



standard operation (ω) and frequency doubling (2ω)
to obtain higher prepulse contrast

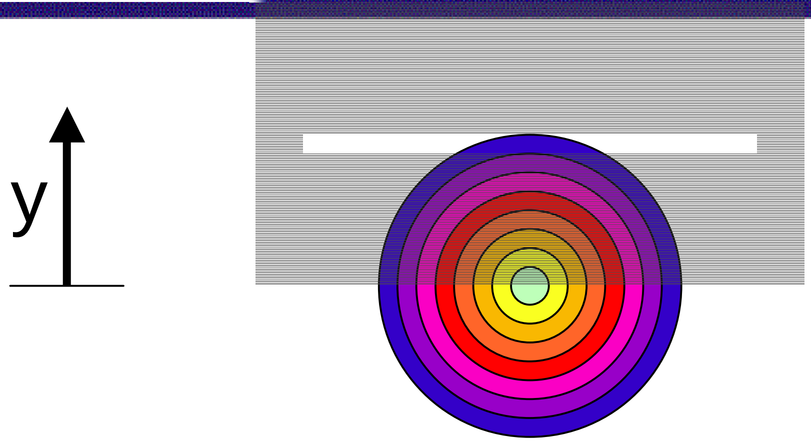


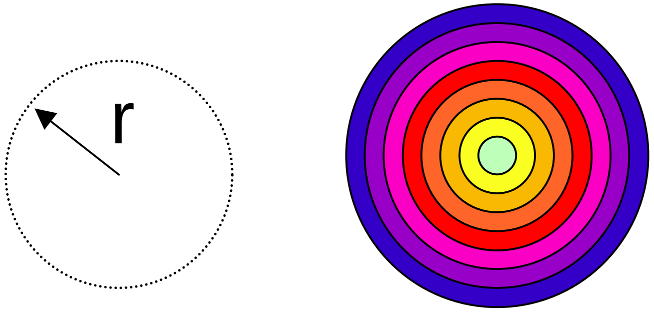
different titanium samples:
massive (bulk) and foils of 25, 10 und 5µm

U. Zastrau et al., PRE **81** (2010), 026406 1-4

2D inverse Abel transformation

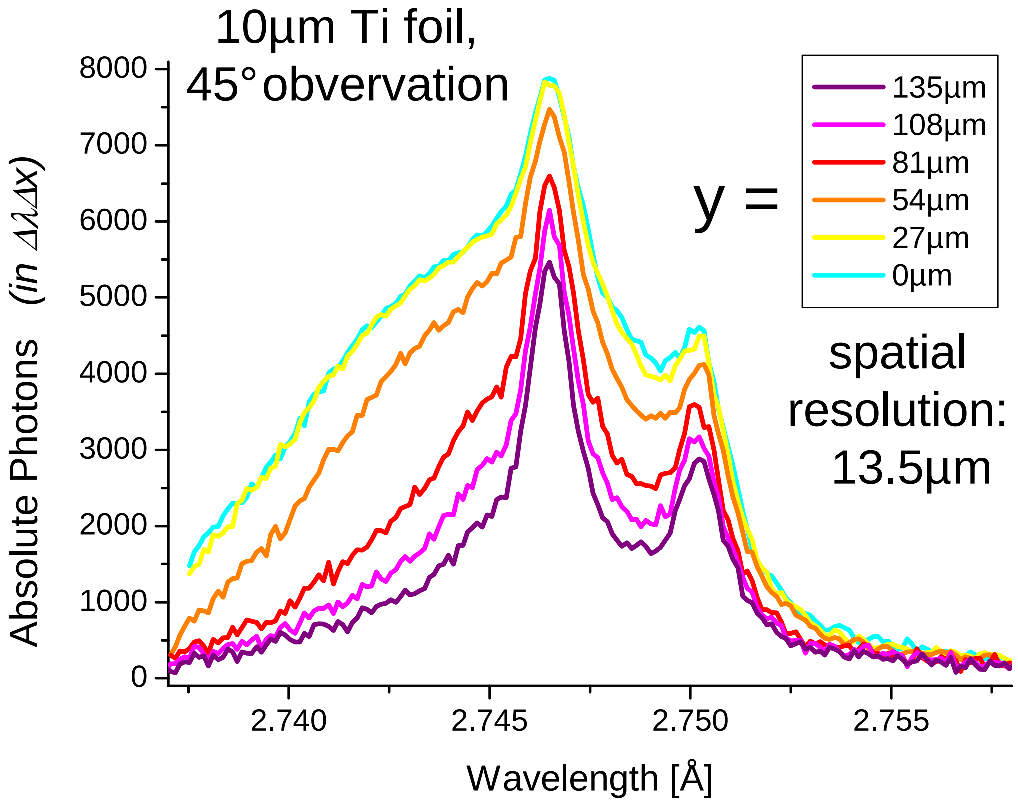
$5 \cdot 10^{19}$ W/cm² - single pulse spectra

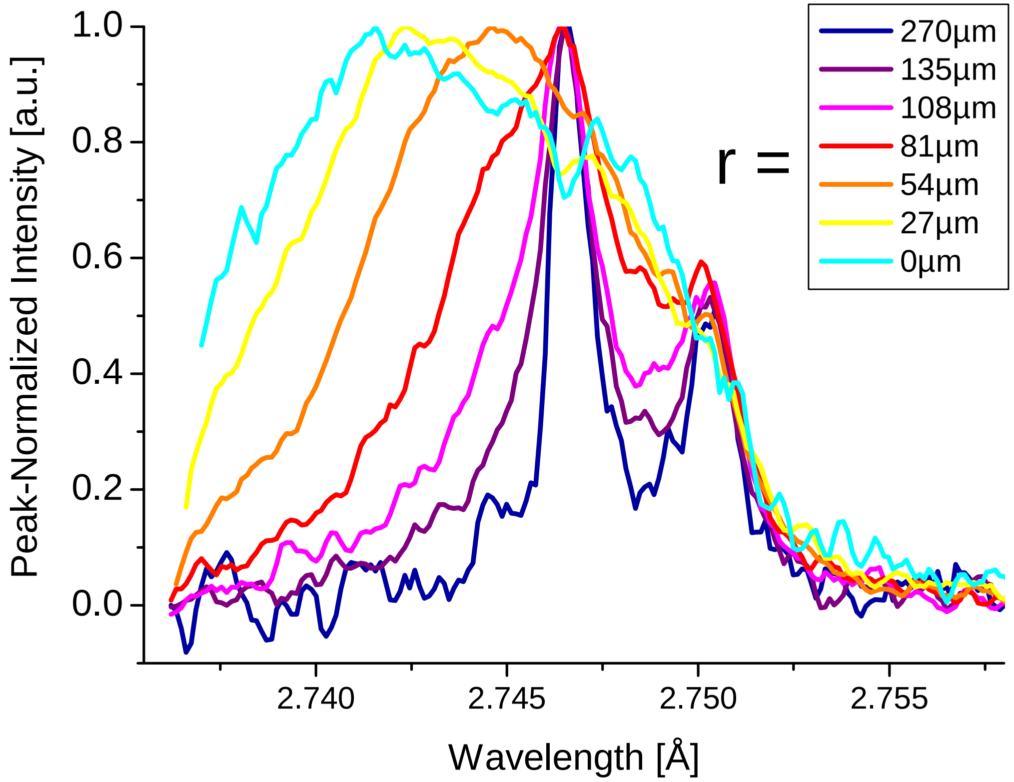




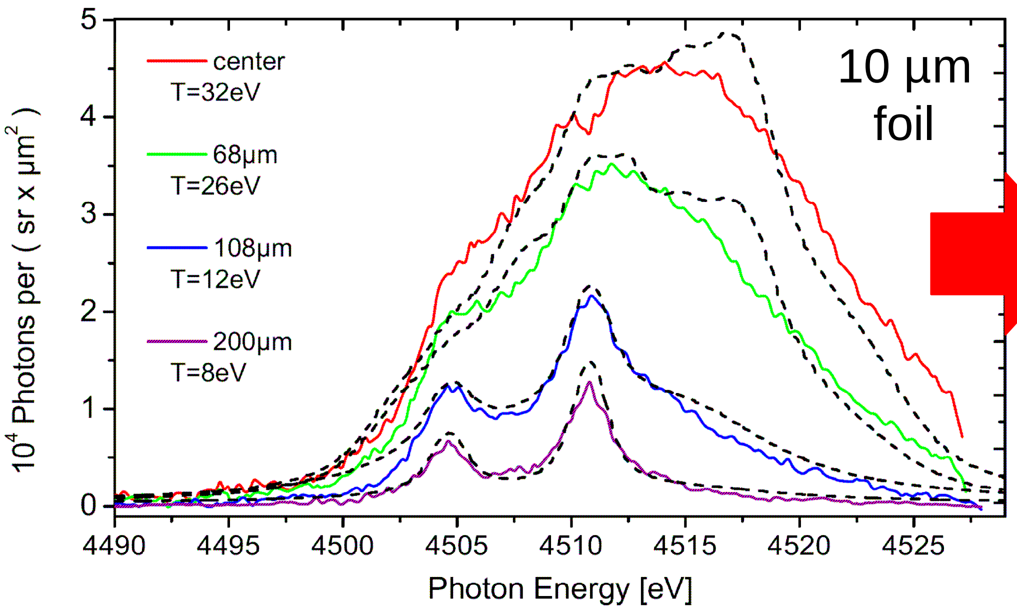
lateral Spectrum (*y*)

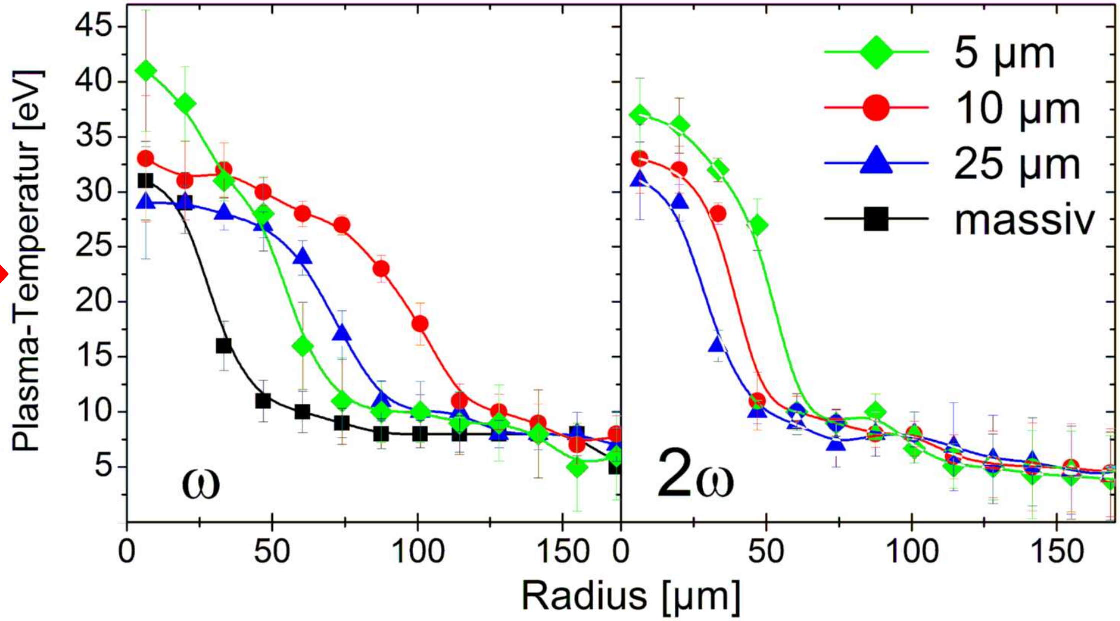
radial Spectrum (*r*)





Radial Temperature Distribution



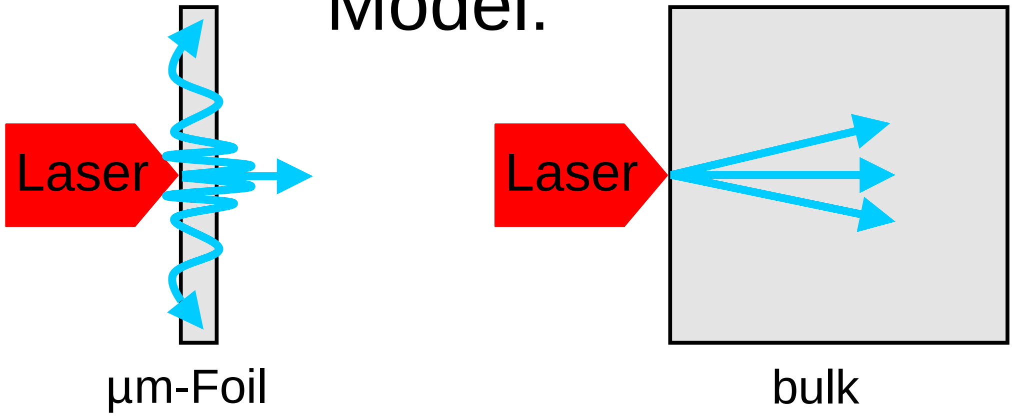


transition from cold
to warm Titanium plasma:

blue-shift due to thermal
M-shell ionization

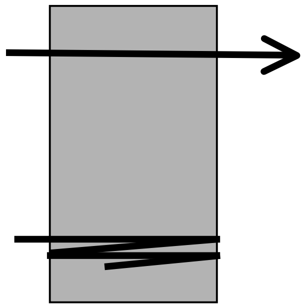
Theoretical line shape models:
Stambulchik,.., Zastrau, et al., J. Phys. A **42** (2009), 214061 1-5
Sengebusch,.., Zastrau, et al., J. Phys. A **42** (2009), 214056 1-10

Model:



U. Zastrau et al., PRE **81** (2010), 026406 1-4

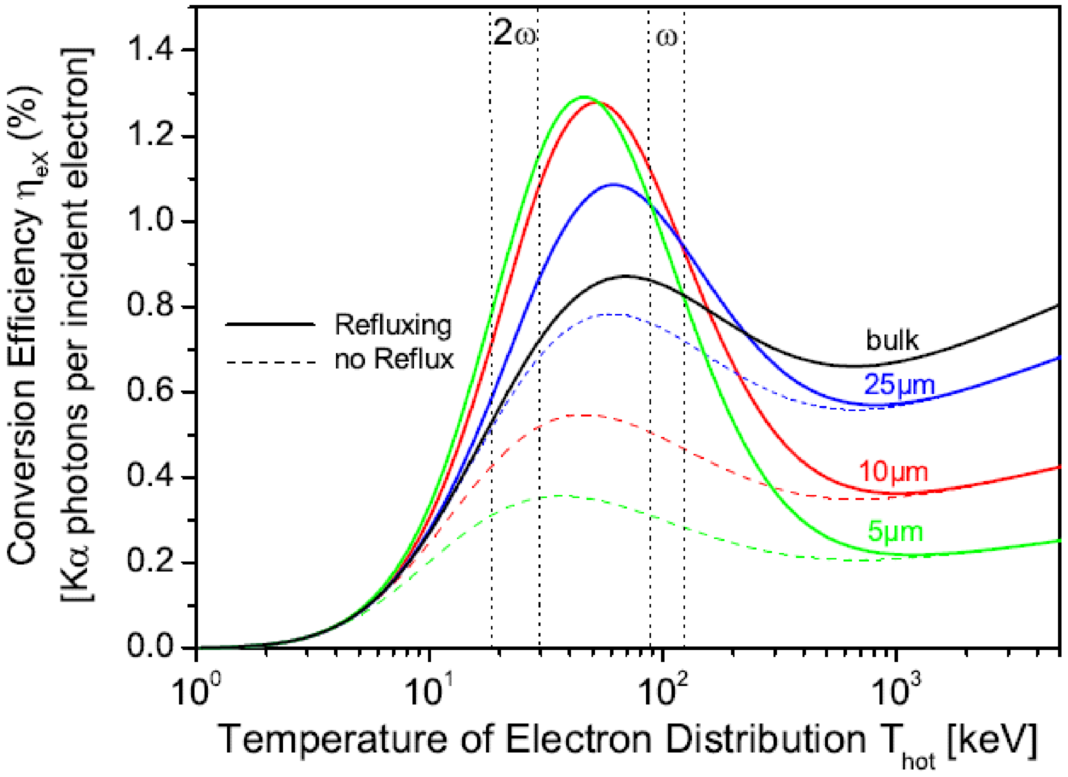
Global Parameter: Kα-Yield and Refluxing

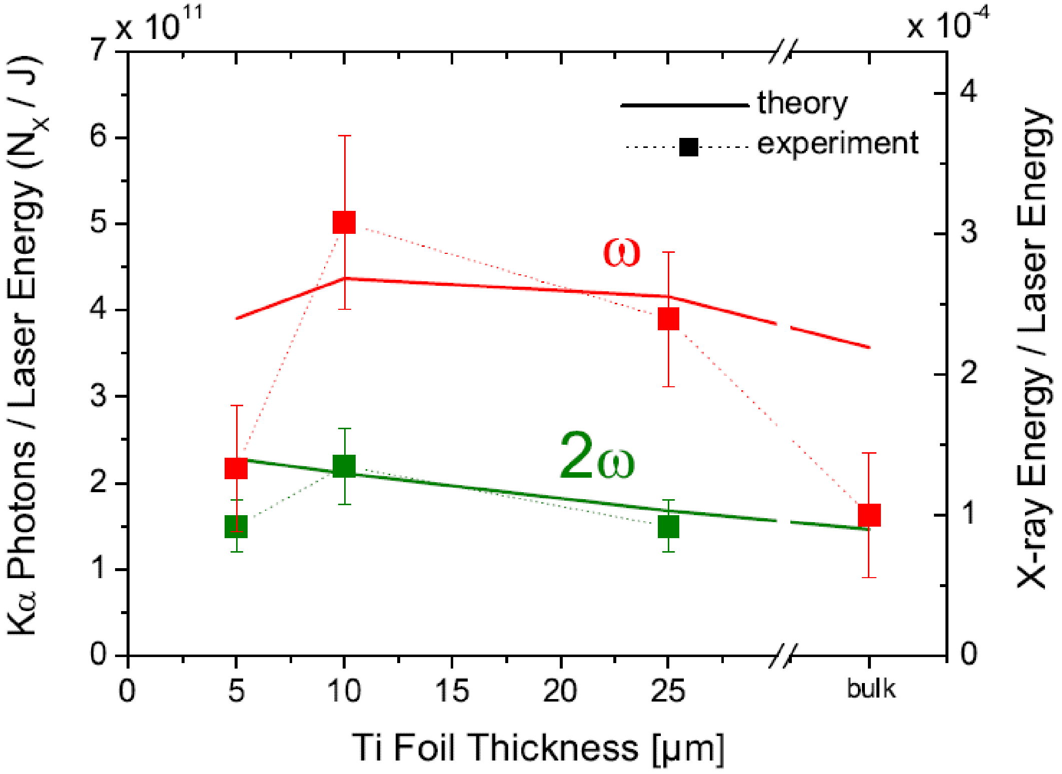


E_e > 100 keV
→ e^- leave the foil

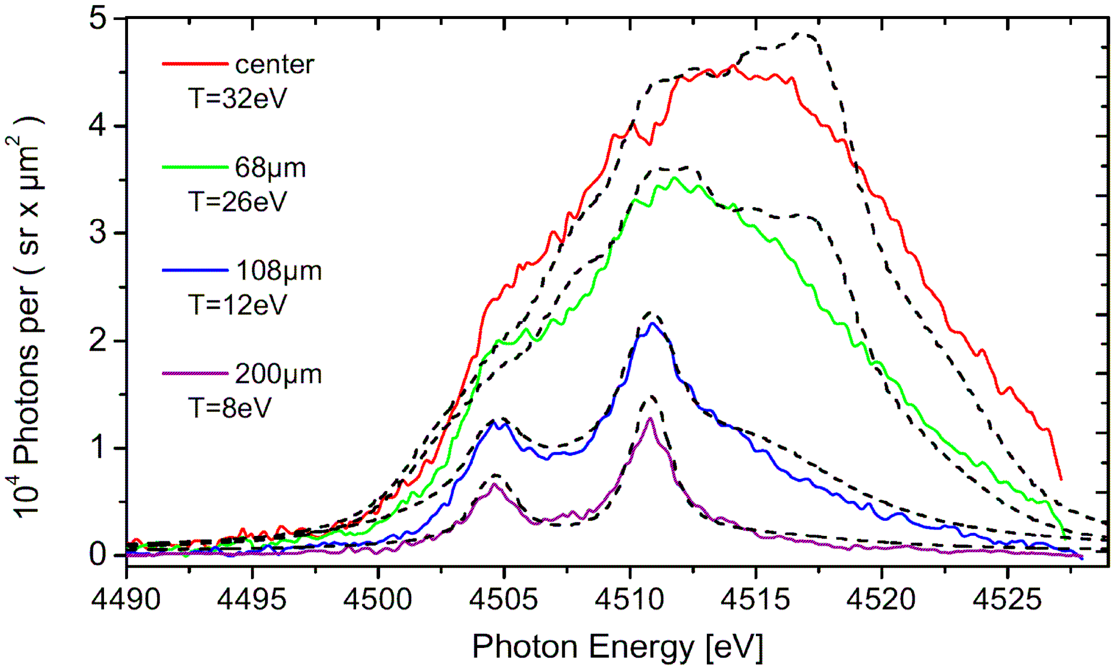
E_e < 100 keV
→e^- stays in foil,
mean free path ~ 20µm

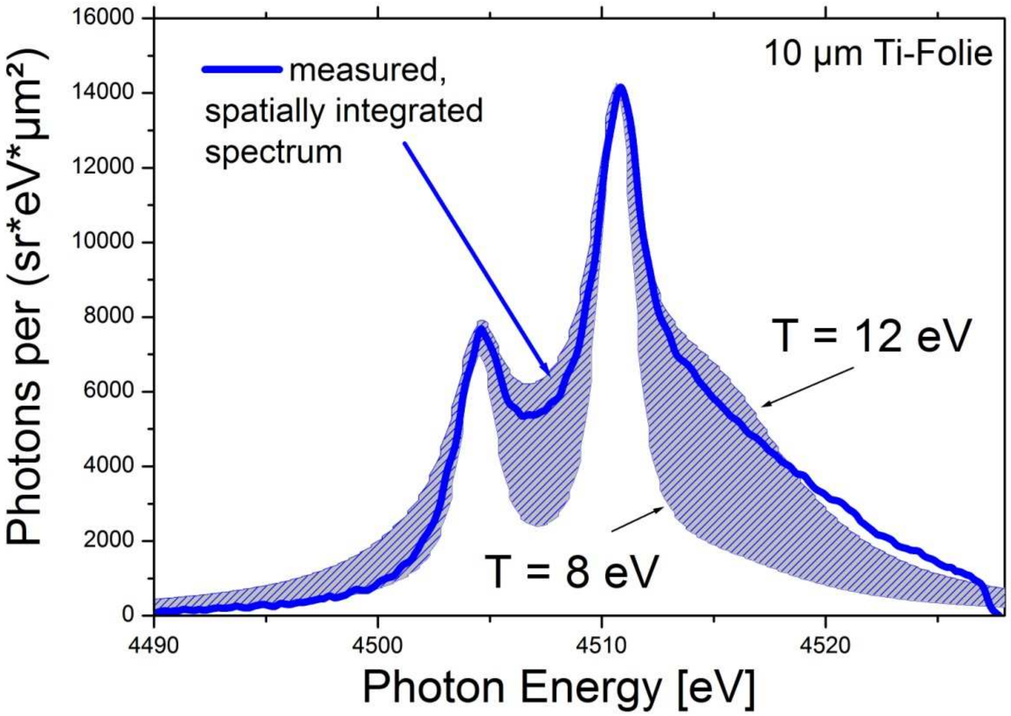
strong electric field ~ MeV/µm
hinders slow electrons
to escape from the foil.
Fit-Parameter: E_e < 100 keV





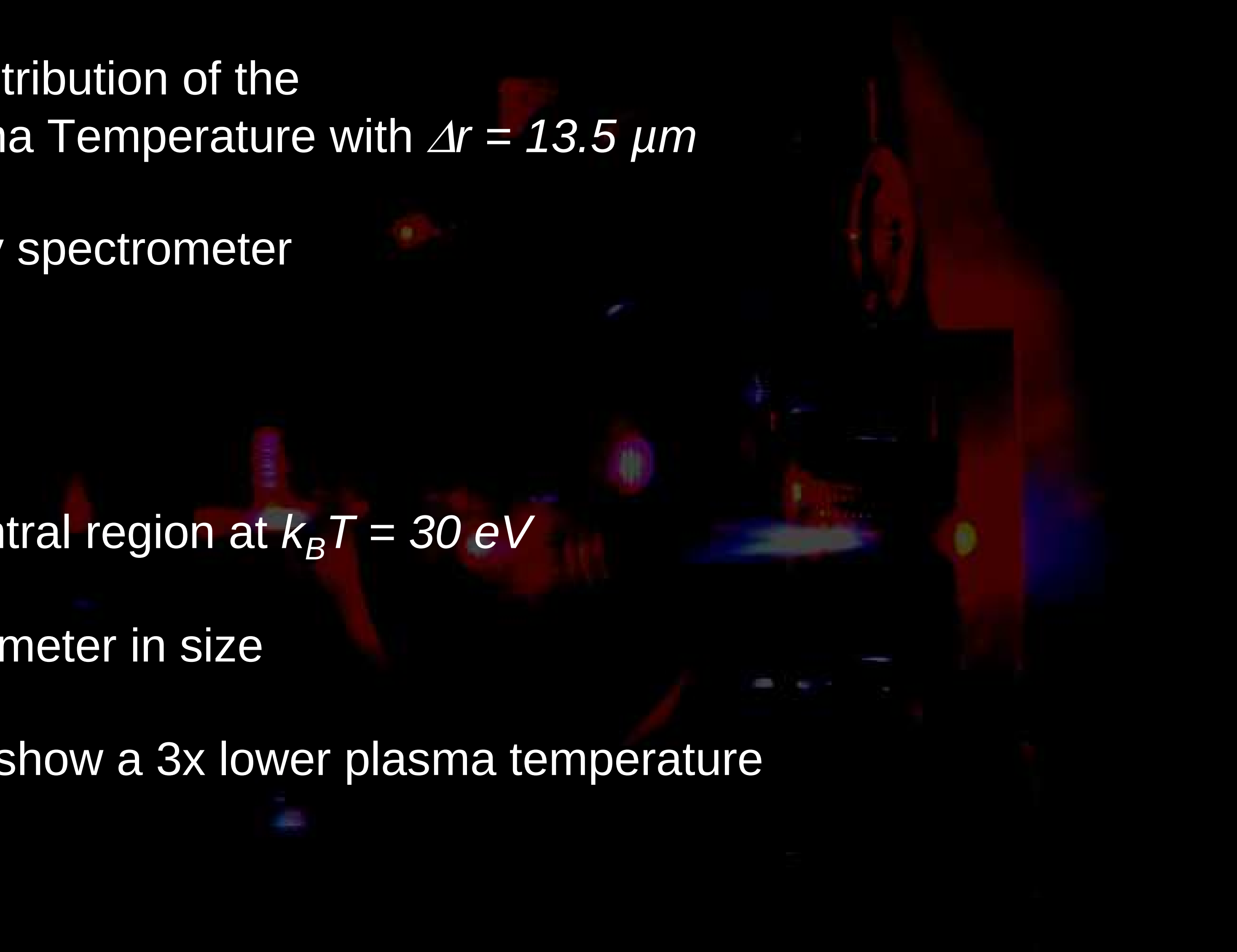
Spatially integrated spectra





Spectrum of a simple, spatially integrating spectrograph yields 3 x lower temperature !

Summary



-LP Titan-Plasmas: radial Distribution of the
Plasma Temperature with $\Delta r = 13.5\ \mu m$

- Toroidally bent crystal X-ray spectrometer
- Single-pulse spectra
- 2D Abel-inversion

- Homogeneously heated central region at $k_B T = 30\ eV$

- up to 10x the laser focal diameter in size

- spatially integrated spectra show a 3x lower plasma temperature

Thanks to International Collaborations

High Energy Density Physics – Peak-Brightness Collaboration

- **AG Röntgenoptik, IOQ, Universität Jena**
  E. Förster, S. Höfer, T. Kämpfer, R. Loetzsch,
  I. Uschmann, O. Wehrhan, colleagues, workshop

- Universität Rostock
  G. Röpke, A. Sengebusch,

- Weizmann Institute of Science, Israel
  I. Maron, E. Kroupp, E. Stambulchik

- LULI, Ecole Polytechnique, Palaiseau, France
  P. Audebert, E. Brambrink

Thanks to DFG

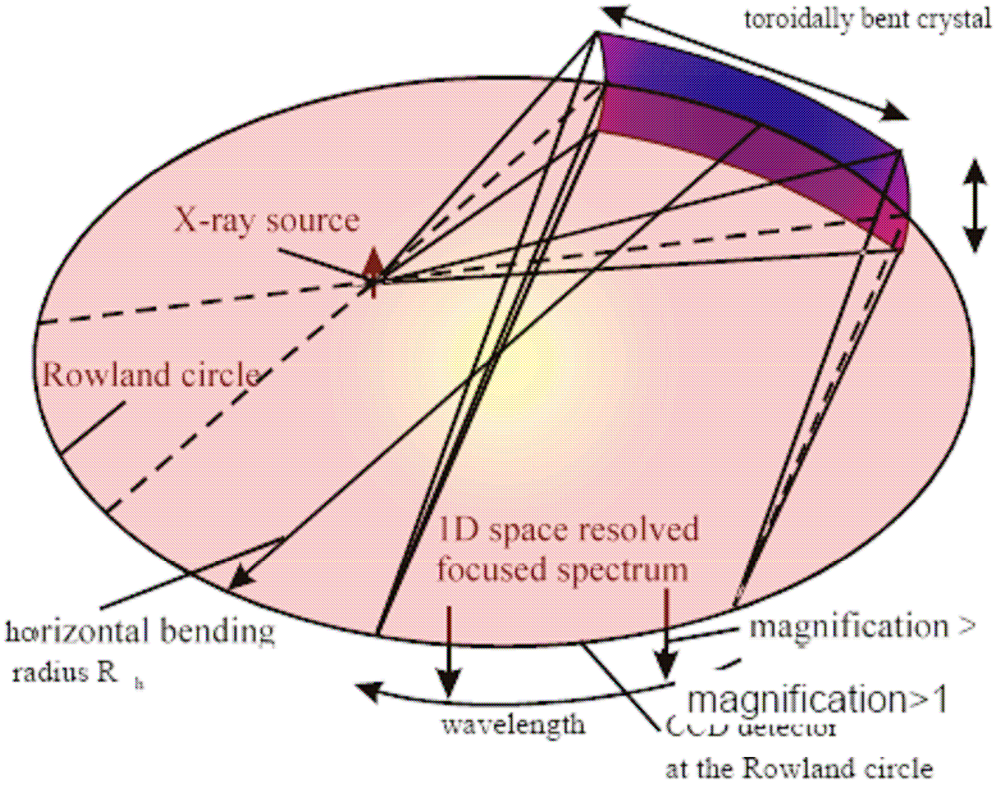
Thank you
for your attention.

High Resolution X-ray Spectroscopy

Basic idea of X-ray optic with toroidally bent crystals

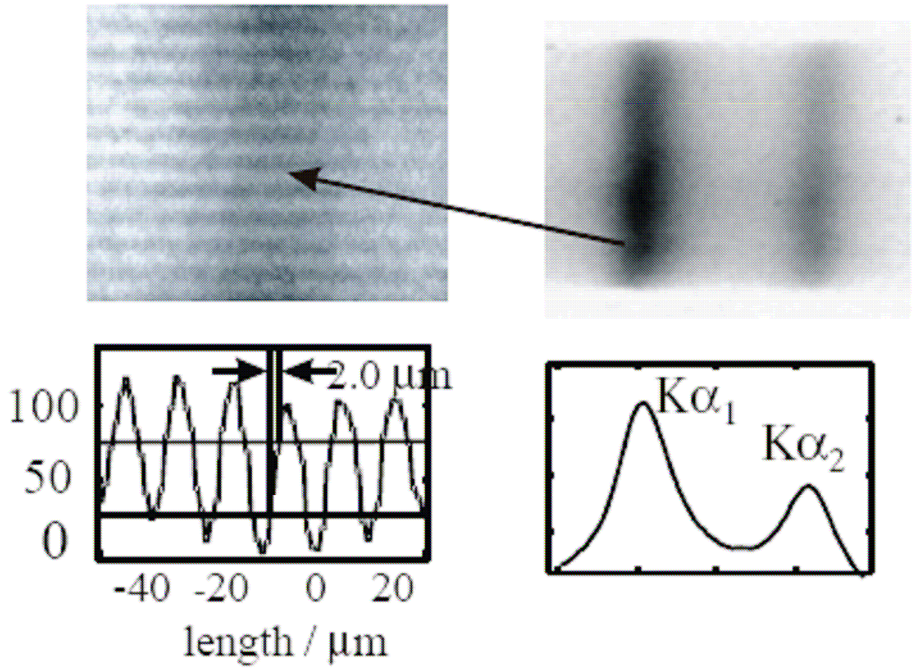
focal lengths: $f_h = (R_h/2)\sin\Theta_B$ $f_v = (R_v/2)\sin\Theta_B$

line focus at Rowland circle - $R_v/R_h < \sin^2 \Theta_B$



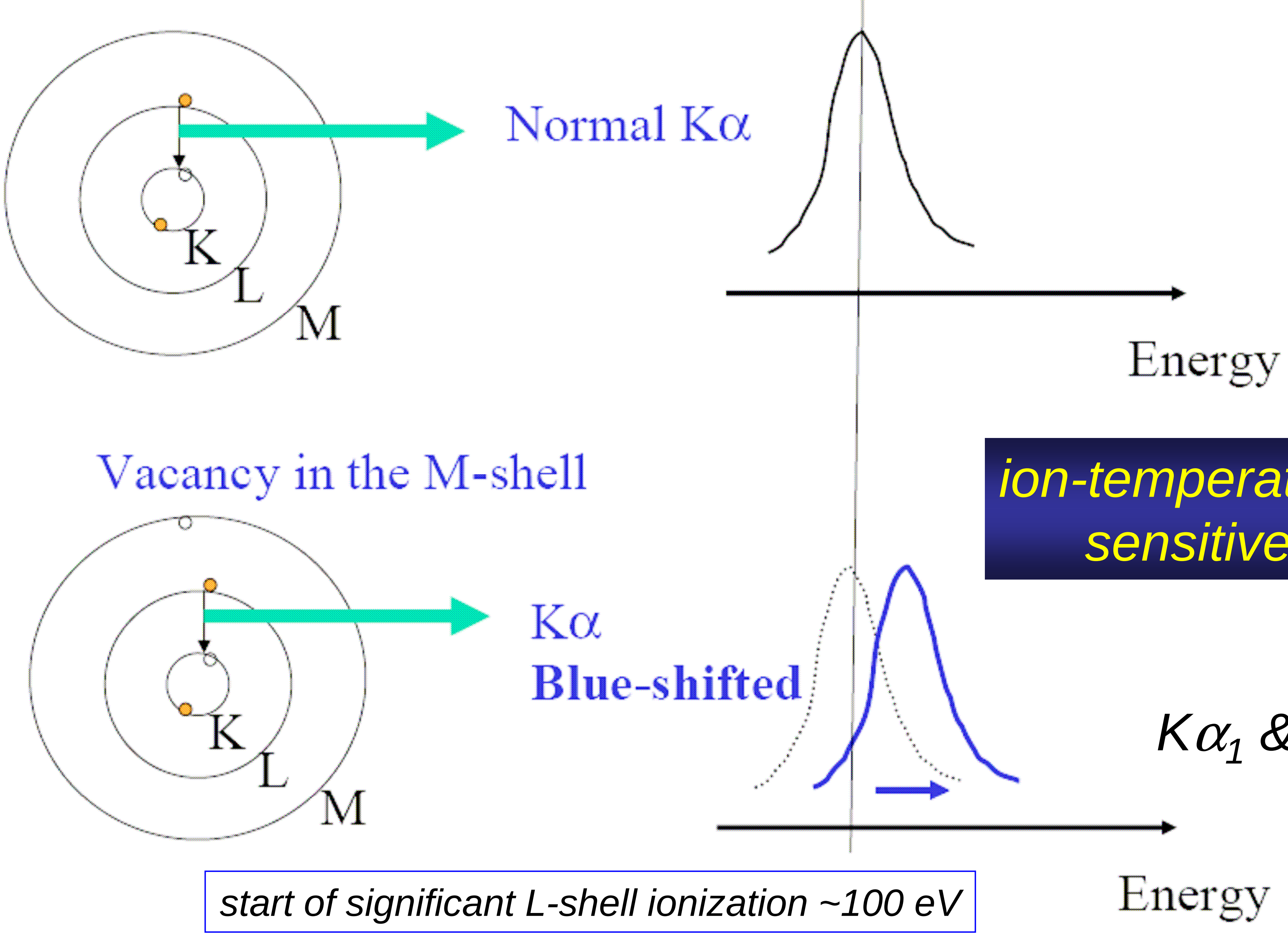
X-ray optical imaging test of bent crystals

1 D imaging and spectroscopy



I. Uschmann et al. 1993, 1997

Blueshift of Kα lines <> M-shell ionization



ion-temperature-sensitive!

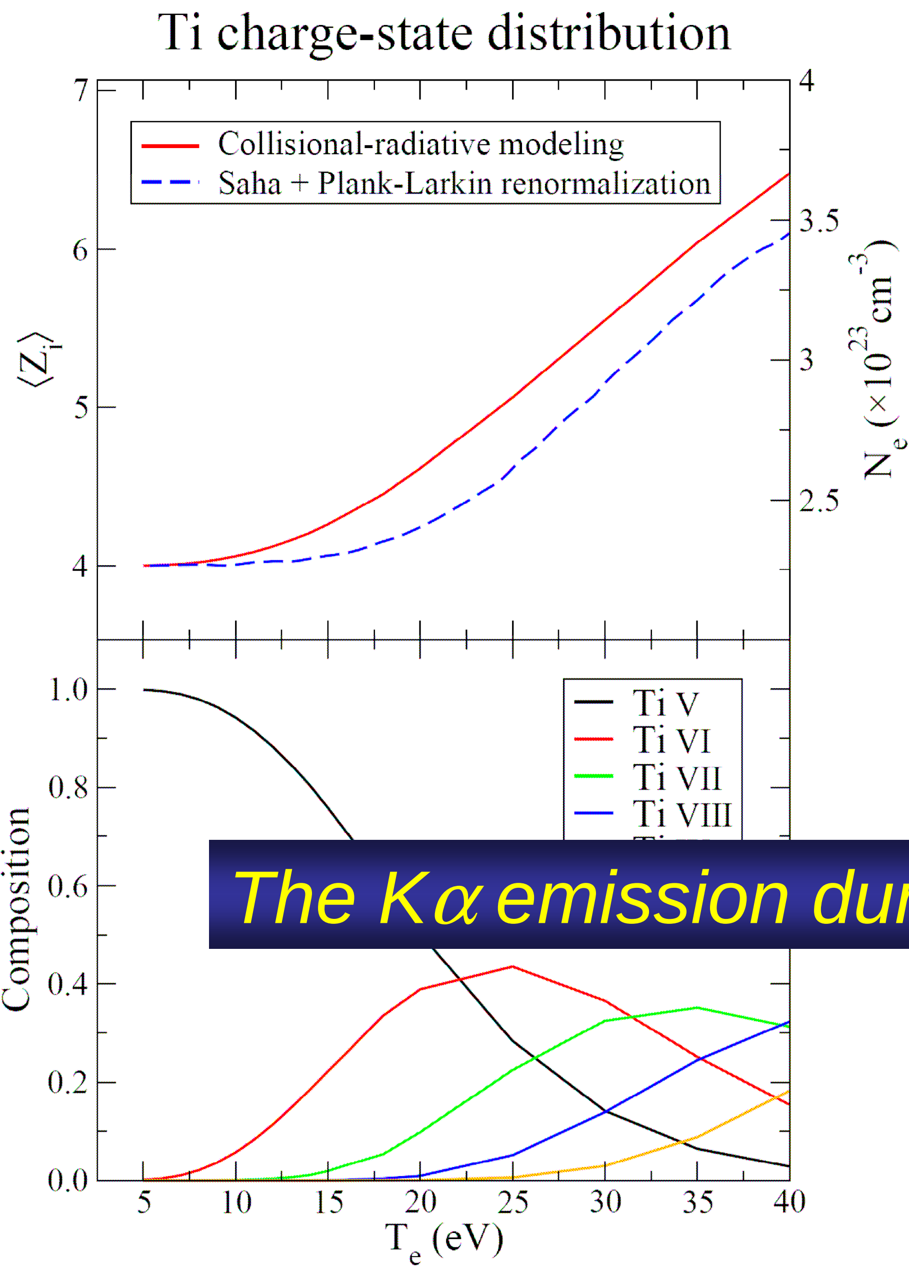
$K\alpha_1$ & $K\alpha_2$

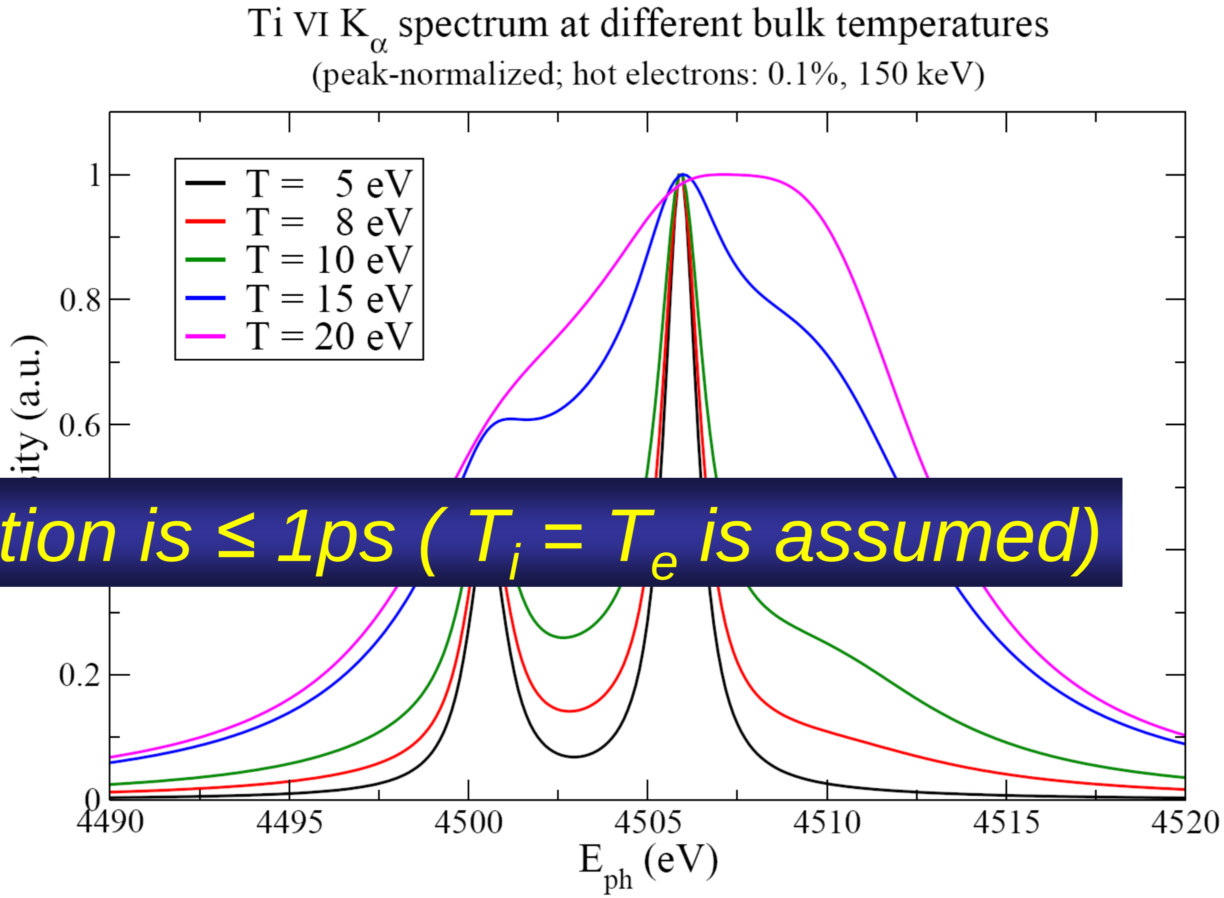
start of significant L-shell ionization ~100 eV

Modeling of Ti Kα radiation

results by E. Stambulchik et al., Weizmann Institute

In bulk titanium, delocalized quasi-free electrons have to be taken into account.
*→ A low-temperature-limit charge-state is **Ti V** (four-times ionised, Ti^{4+}).*

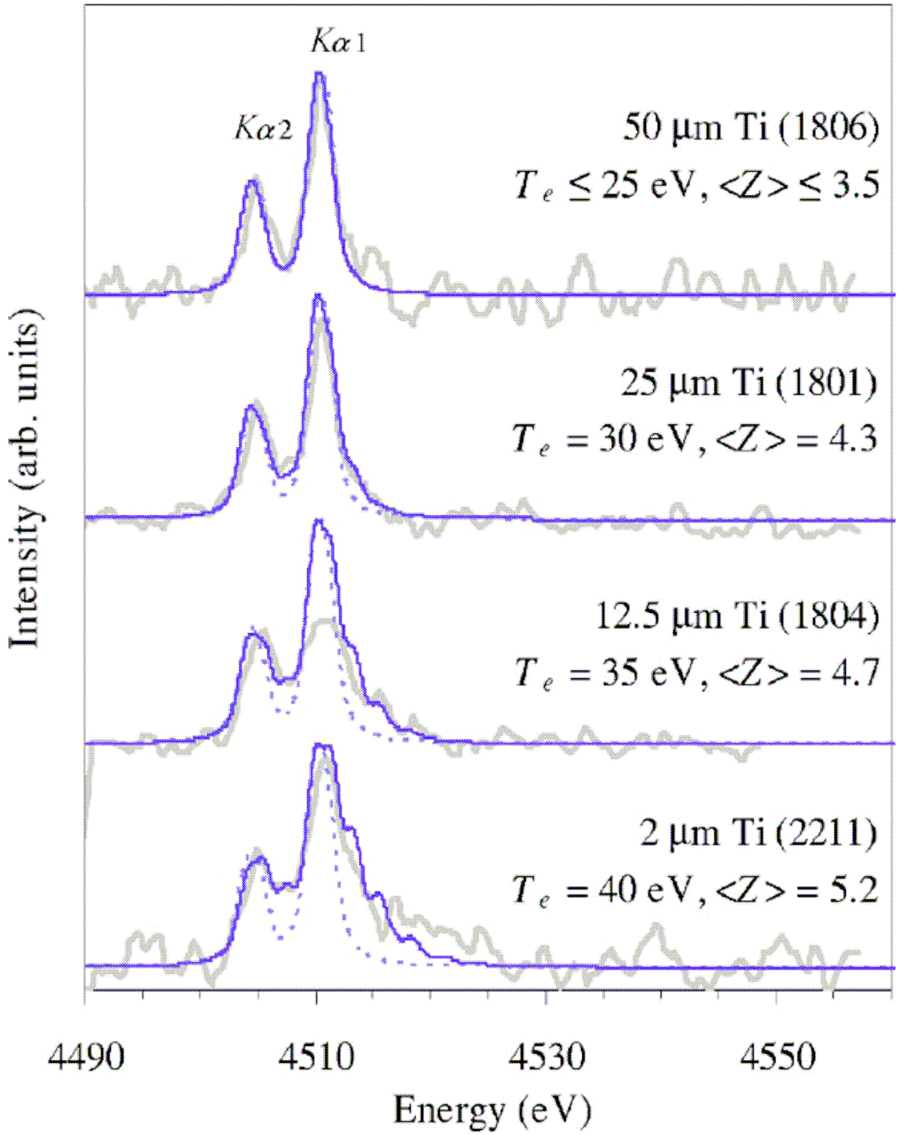




The Kα emission duration is ≤ 1ps ($T_i = T_e$ is assumed)

Hansen et al.

***Accurycy of the method:* COMET laser, LLNL, Kalifornien**
1057nm, 3-6 J, 500fs, 10^{19} W/cm²



Hansen et al.,
PRE ***72****,*
036408
(2005)

Electron Cross Sections

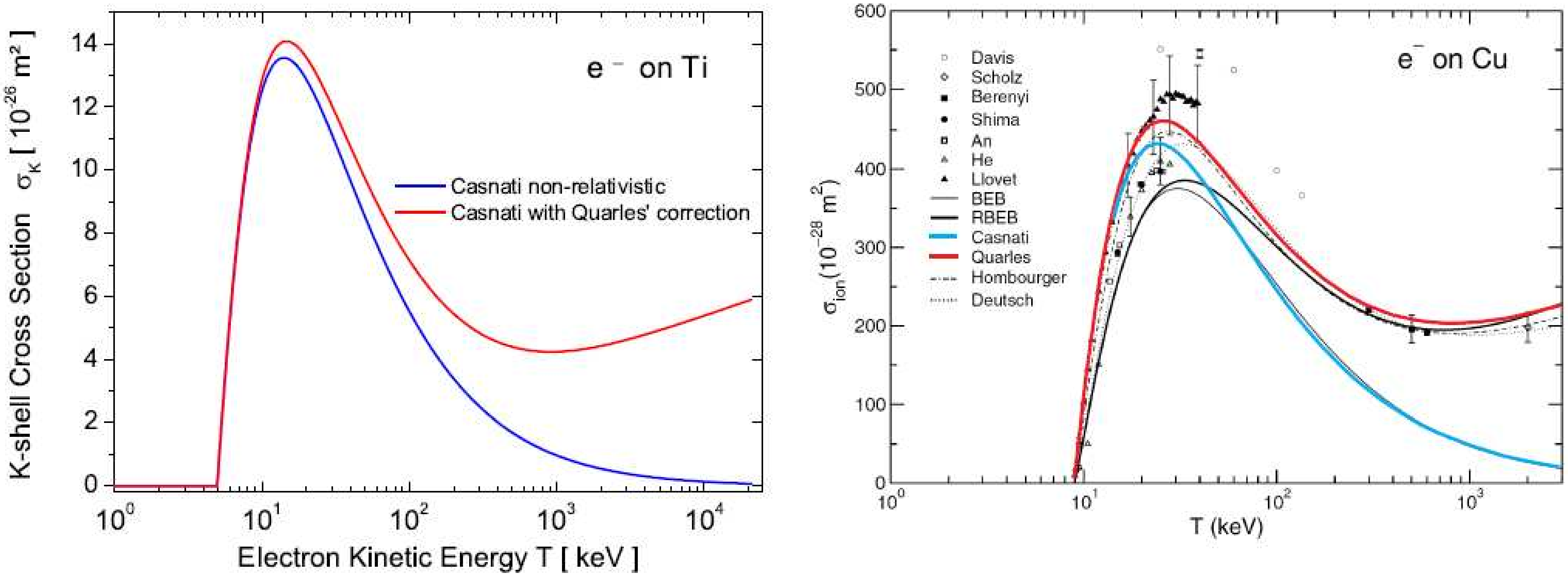


Figure 3.3: Left: K-shell ionization cross section for titanium. Right: Comparison of experimental data (symbols) and several models (lines) for copper. For details, refer to [62]. The non-relativistic model after Casnati *et al.* [60] is indicated by the blue curves, and the relativistic correction [61] was applied by the red curves.