Saturable absorption with high intensity VUV FEL radiation

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Peak Brightness Collaboration:

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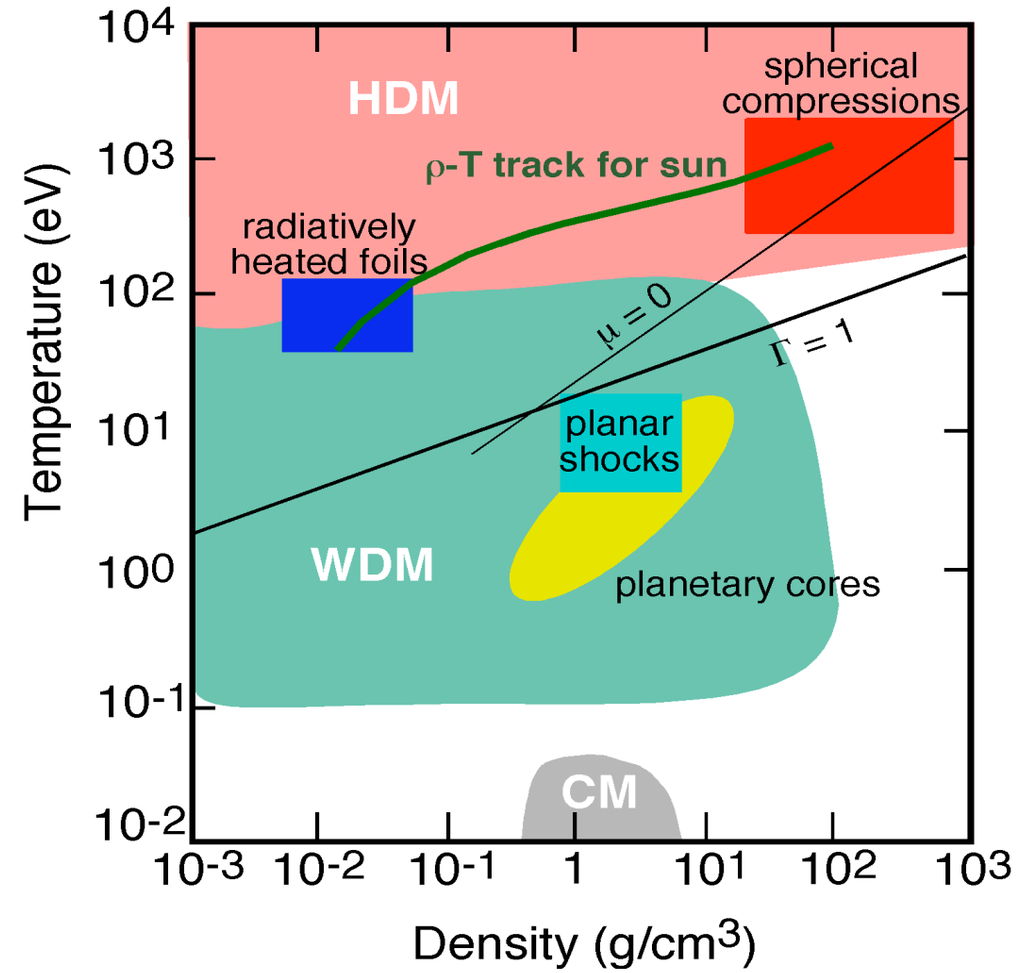
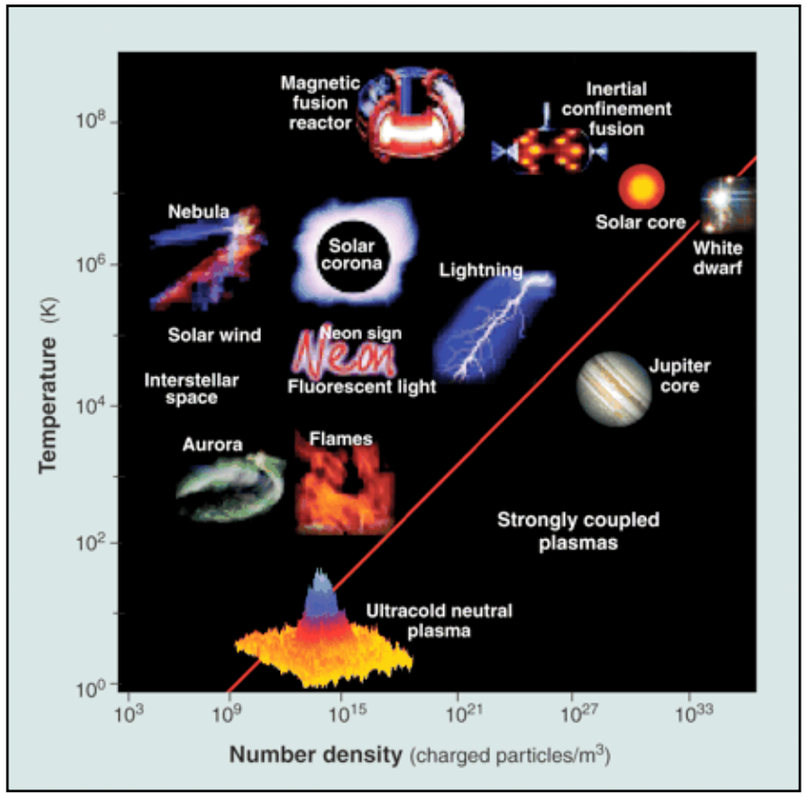
Outline

- Importance of High Energy Density Science (HEDS)
- Unique match of FEL and HEDS
- Experimental results at FLASH (Free-electron LASer Hamburg)
  - transparent aluminium
  - creation of homogeneous warm dense aluminium
- Conclusions & outlook

High Energy Density Matter occurs widely in nature

- **Hot Dense Matter (HDM)**
  - supernova, stellar interiors, accretion disks;
  - plasma devices, laser produced plasmas, Z-pinches;
  - directly and indirectly driven inertial fusion experiments

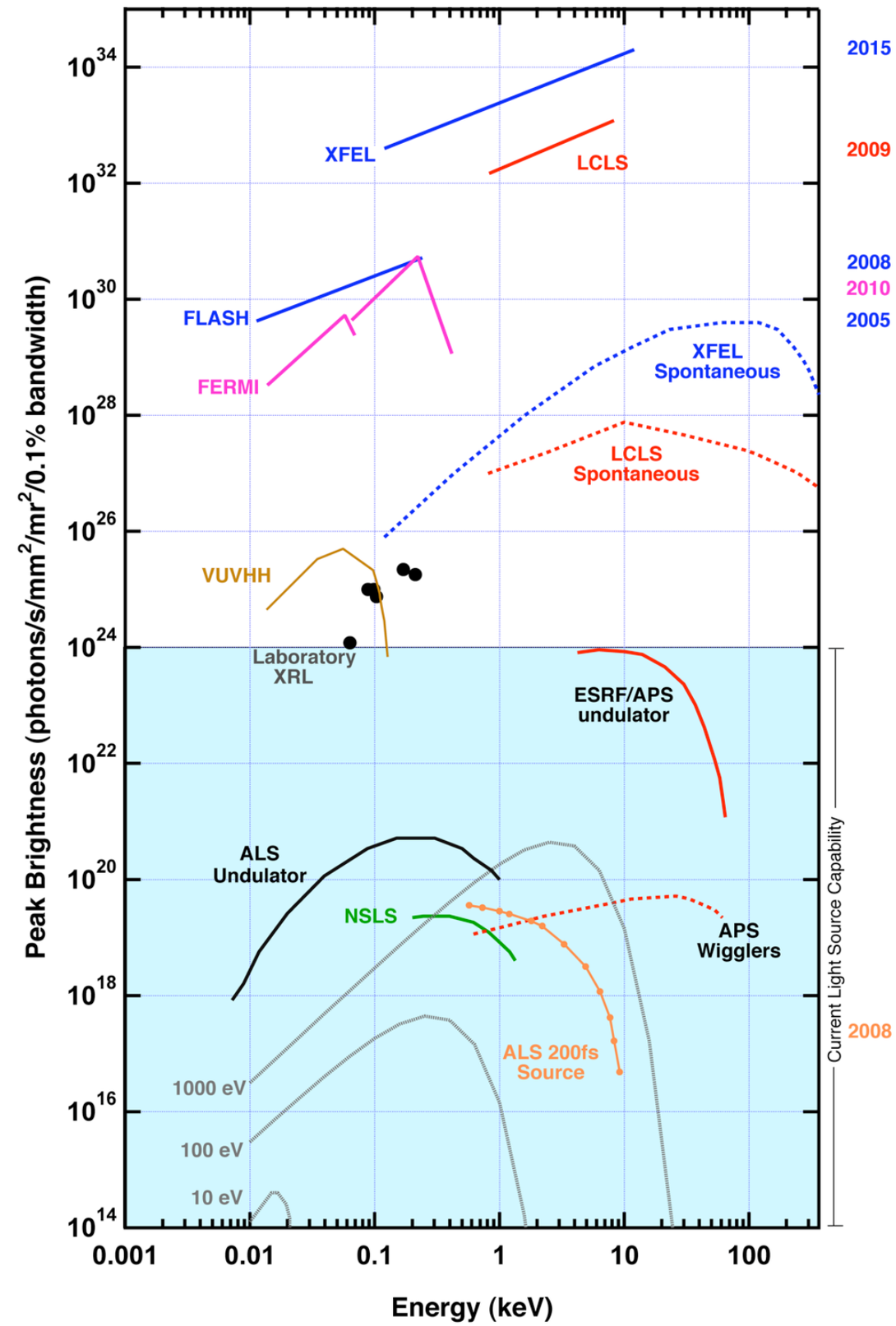




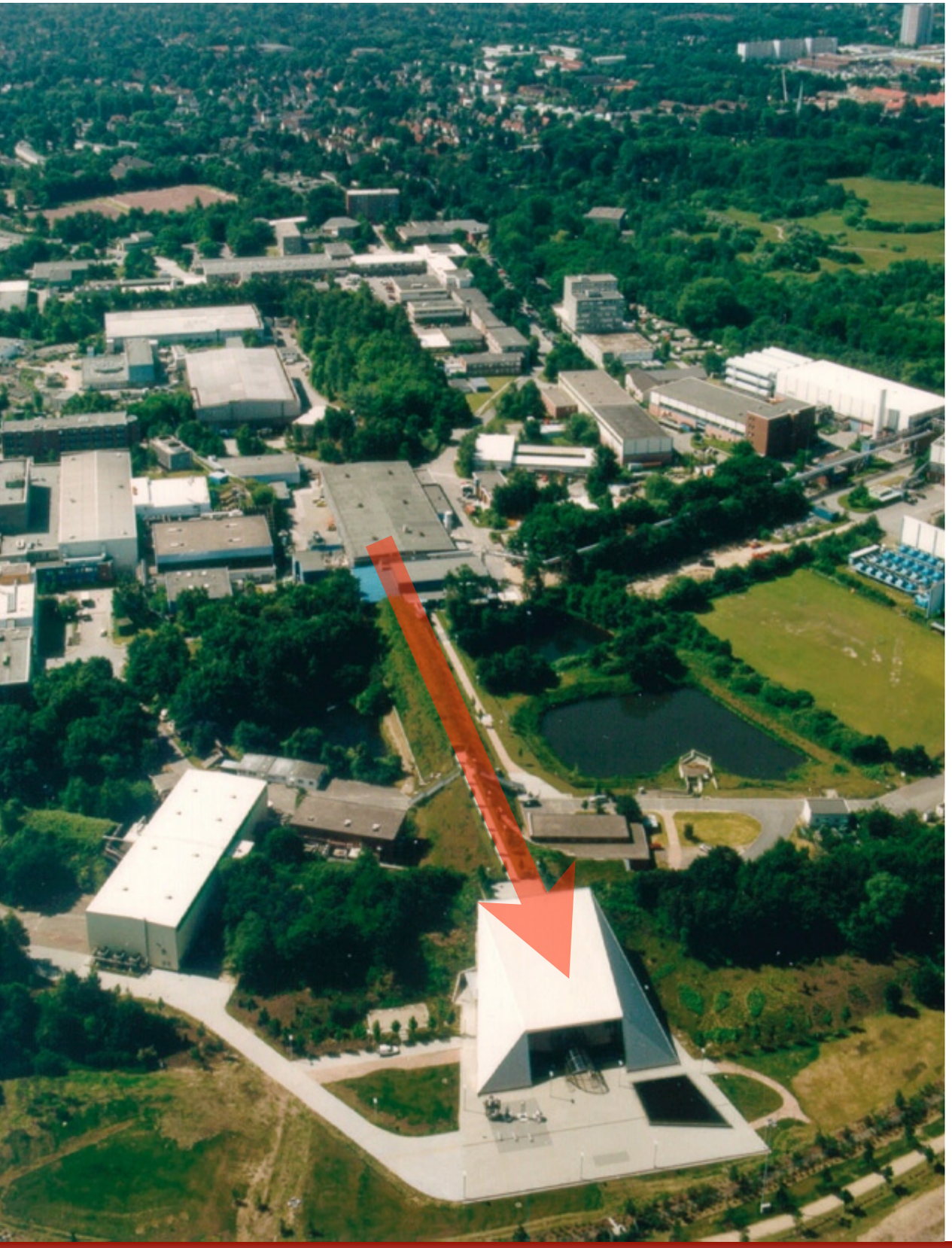
- **Warm Dense Matter (WDM)**
  - cores of large planets;
  - systems that start solid and end as a plasma;
  - X-ray driven inertial confinement fusion

4th generation X-ray sources well matched to HEDM

- **HEDM studies require**
  - intense X-ray sources (produce/probe dense matter at finite temperature);
  - short pulses (study transient behaviour, no hydrodynamic changes)
- **Current PB light sources are synchrotron radiation based:**
  - low # photons per bunch;
  - long bunch duration (≥ 70 ps)
- **Solution: use an FEL source**
  - short bunch duration (≈100 fs);
  - lots of photons per bunch (≥10^{12});
  - tunable wavelength

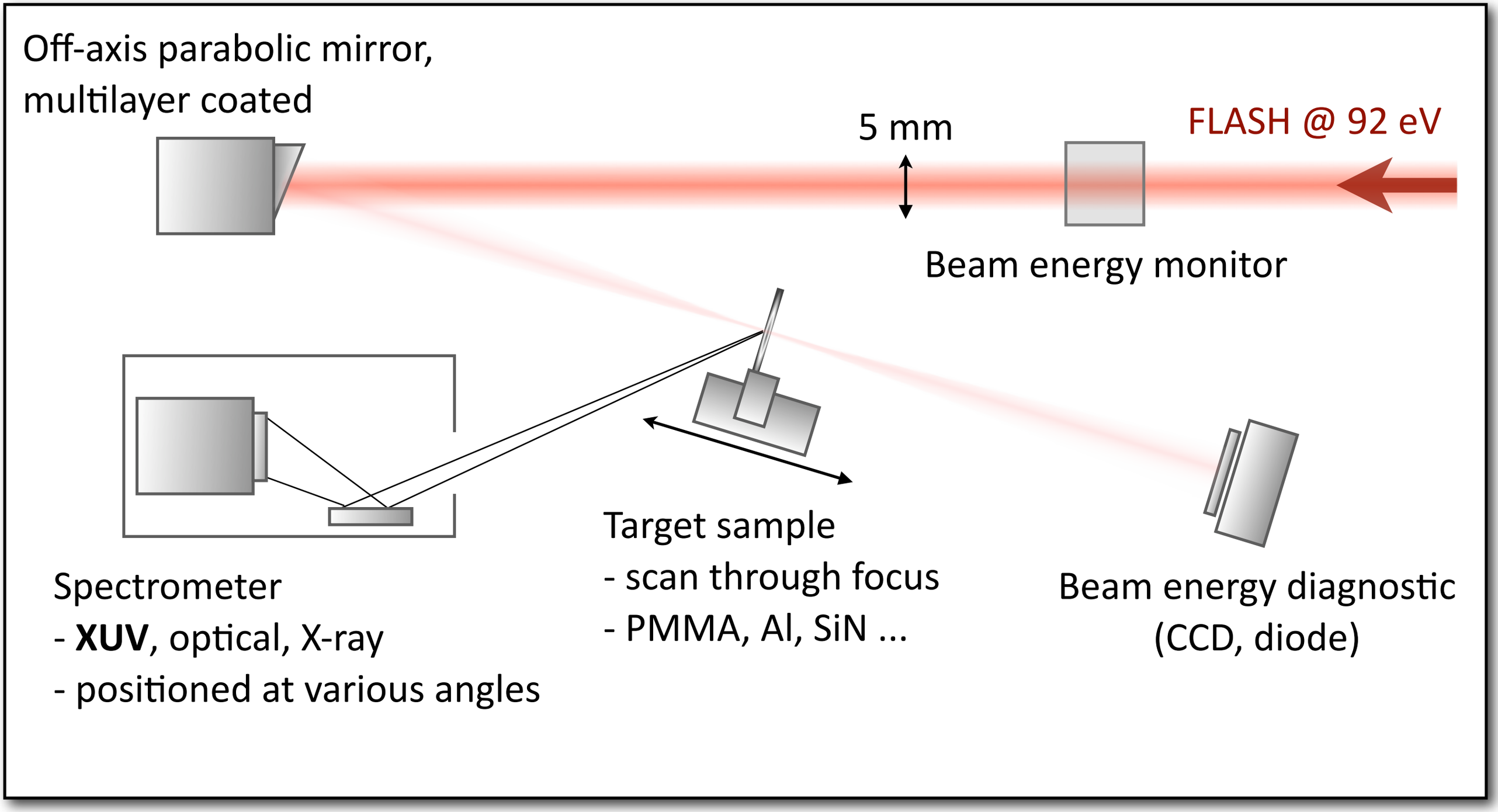


FLASH at DESY - first VUV-FEL

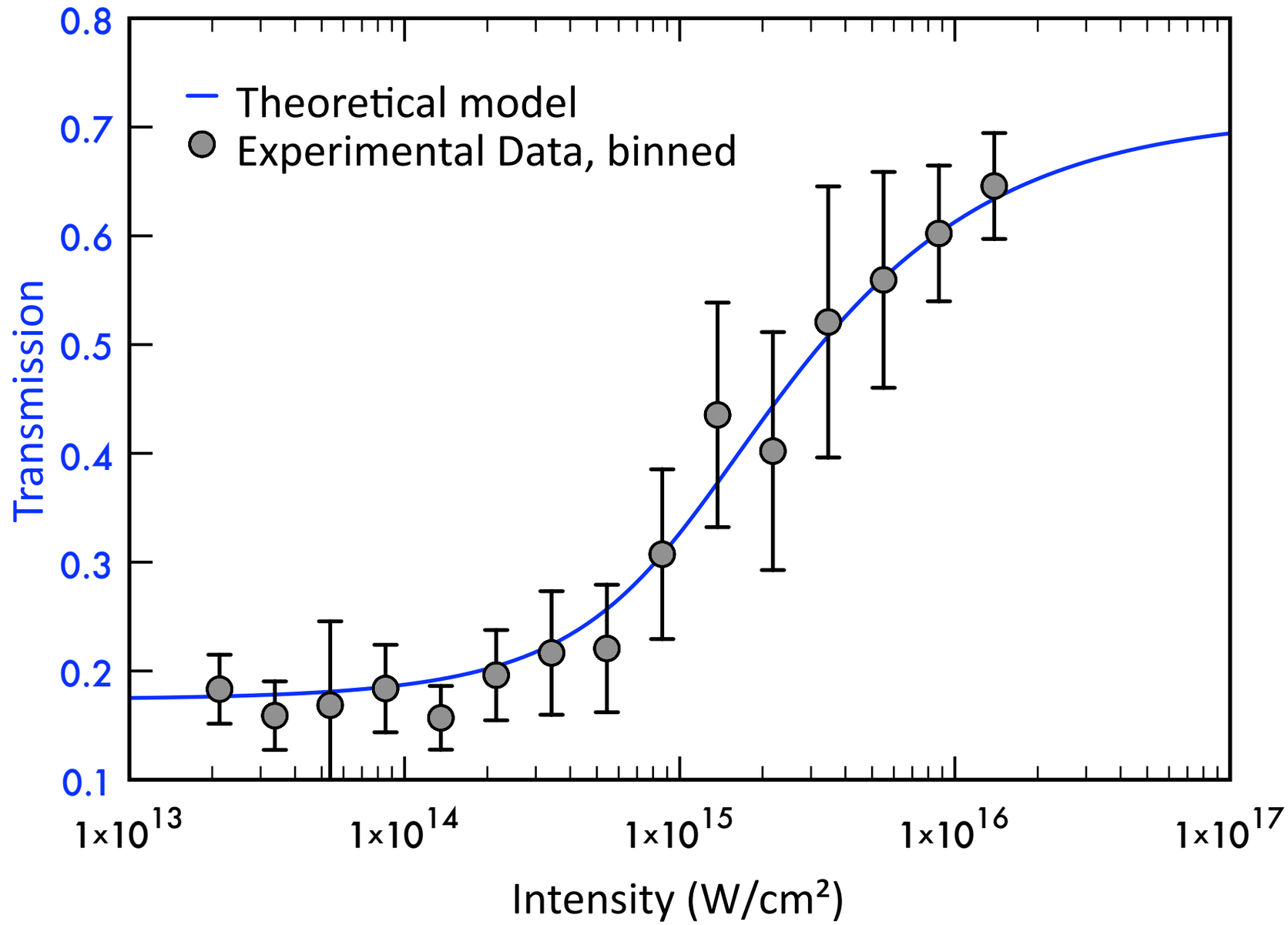


- SASE single-pass FEL;
- tunable photon energy range 40-200 eV (fundamental);
  - 600 eV in 3rd harmonic 1% intensity;
- pulse repetition rate 5 Hz;
- single-bunch / multi-bunch mode;
- 10-50 μJ average pulse energy;
- ~15 fs pulse length;
- recently we managed to achieve intensities > 10^{16} W/cm^2

Experimental setup



Creating transparent aluminium

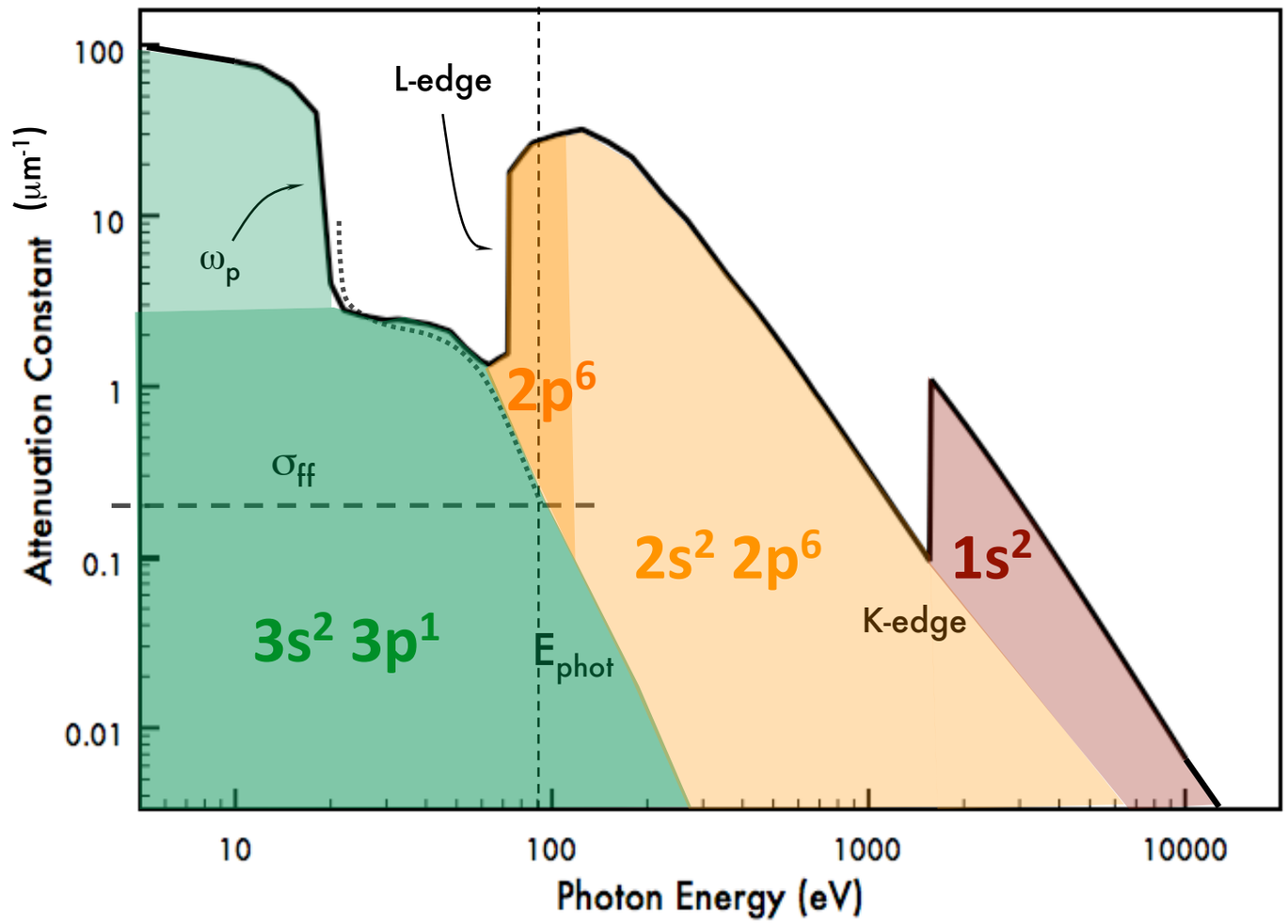


- 52 nm Al foil (+20 nm oxide layer), 92 eV photons
- intensity is peak intensity of Gaussian profile
- effect takes place on 15-25 fs time scale - no ion movement!

Absorption in solid density aluminium

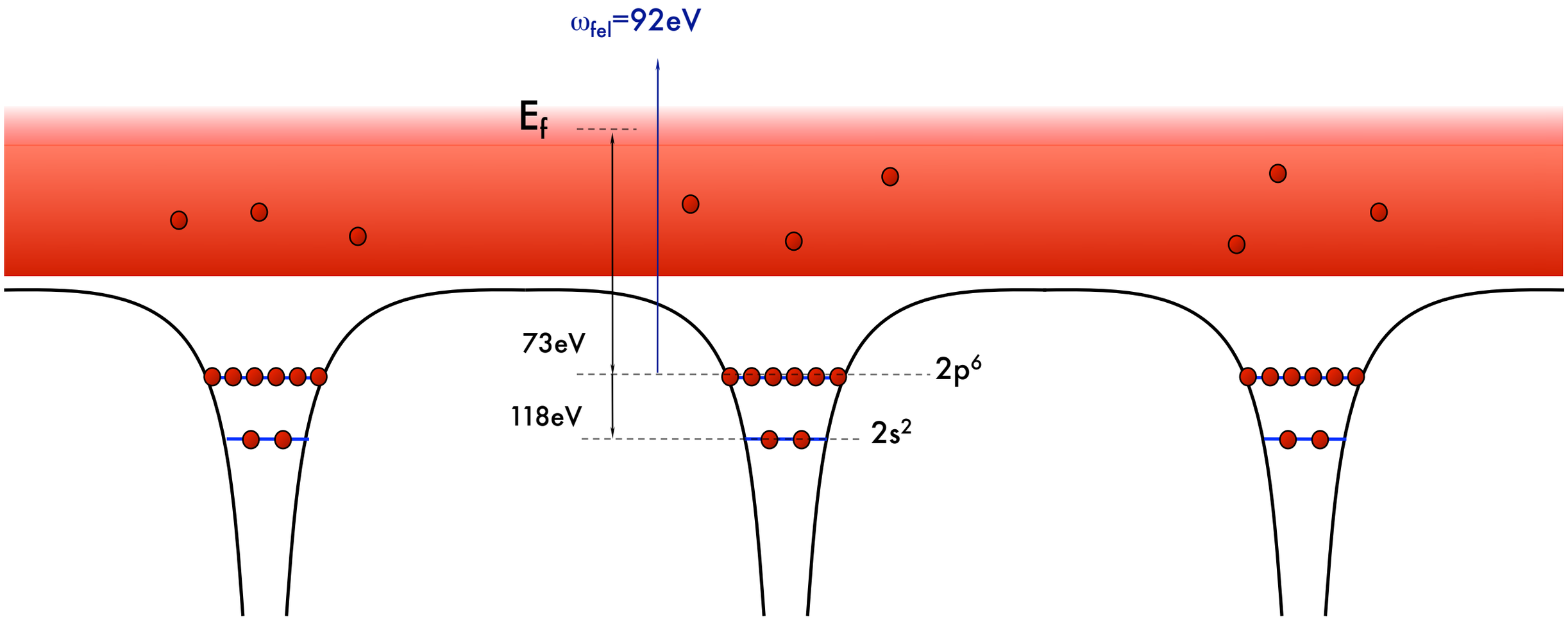
Electron configuration in atomic aluminium:

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

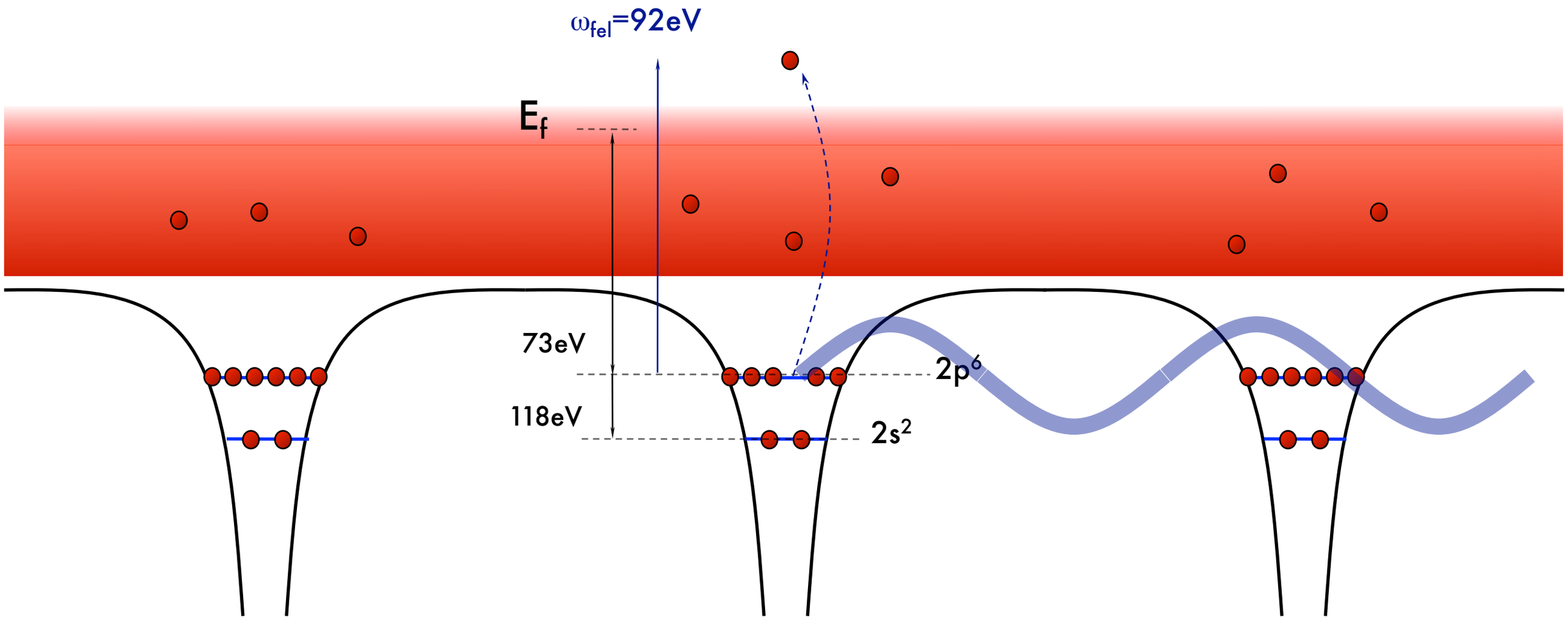


- at 92 eV two absorption channels:
  - bound-free excitation of L-electrons: σ_{bf} = 27 μm^{-1} (CXRO tables online http://www-cxro.lbl.gov/)
  - free-free excitation of the valence band: σ_{ff} = 0.2 μm^{-1} (S.M. Vinko et al., HEDP **5**, 124-131 (2009))

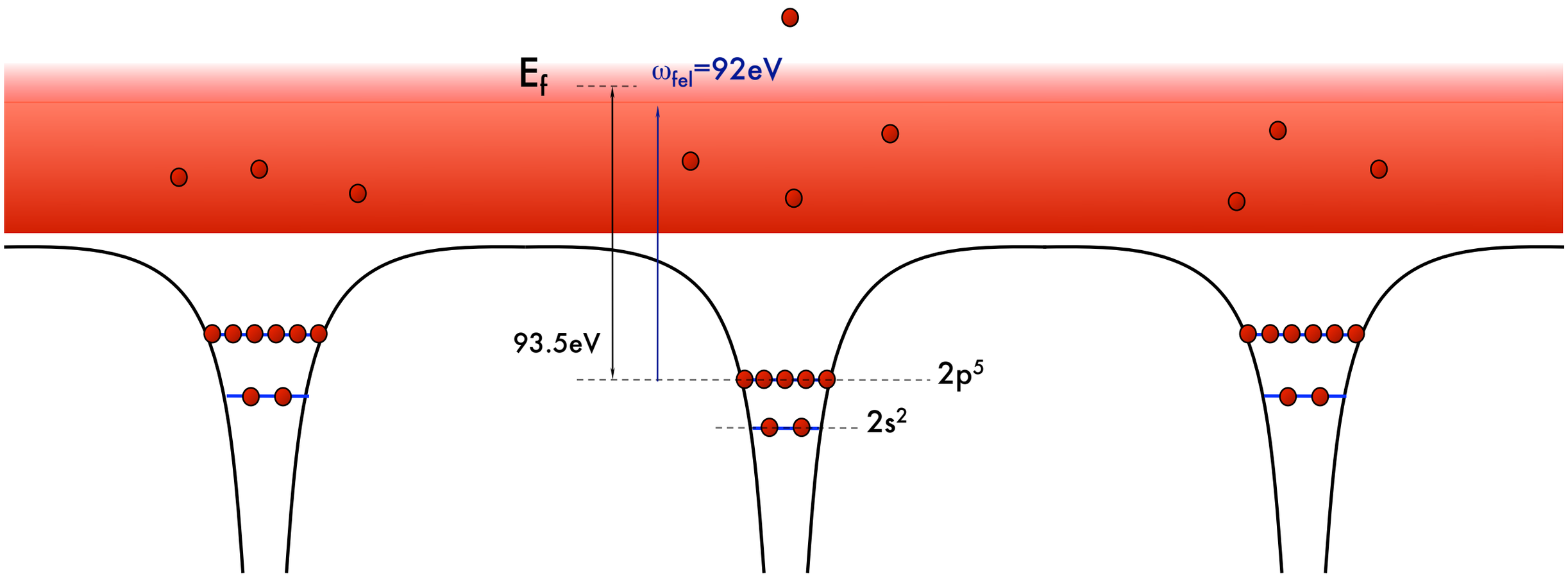
L-shell electron excitation



L-shell electron excitation

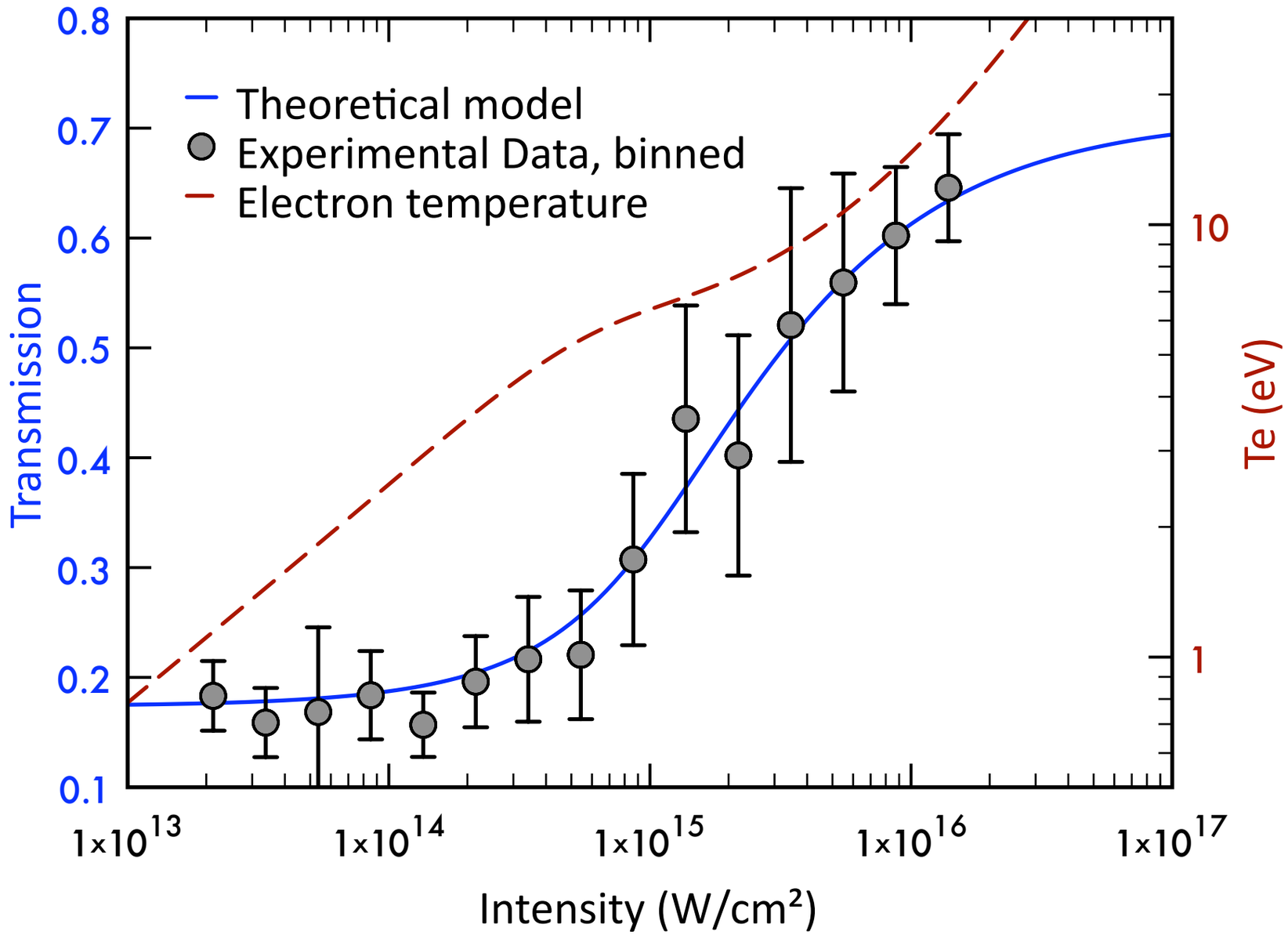


L-shell electron excitation



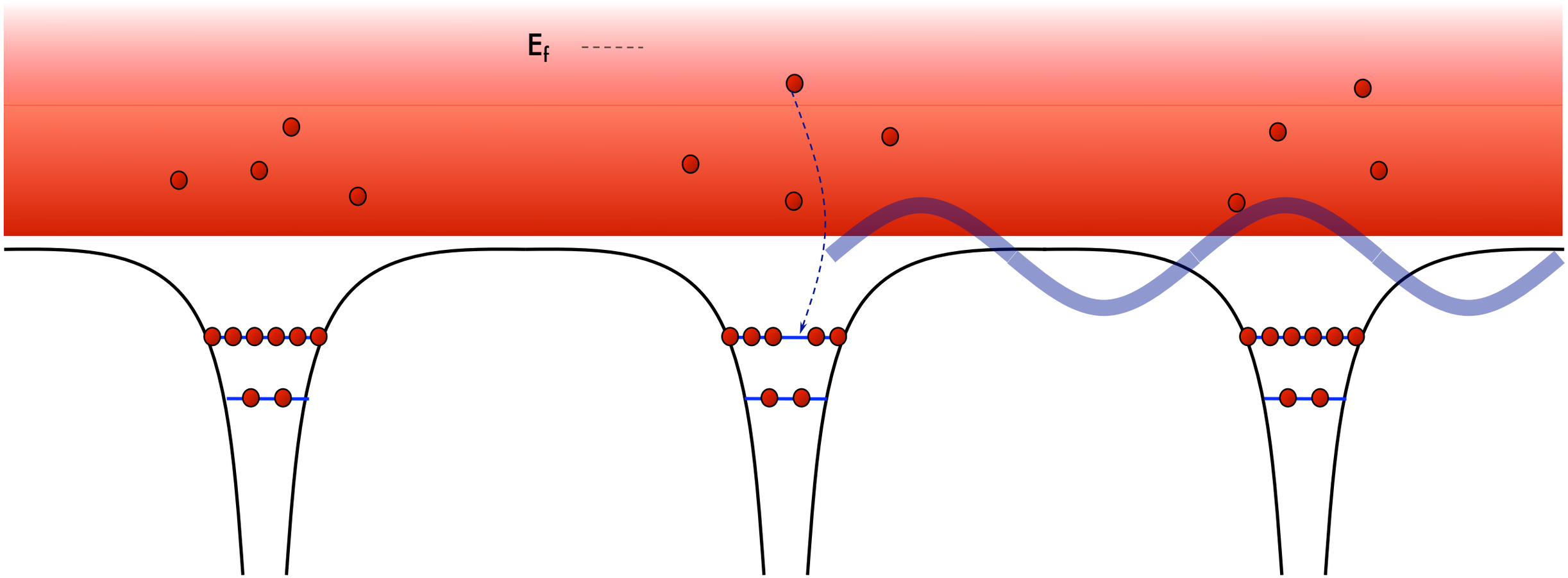
L-shell hole lifetime in Al ~40 fs

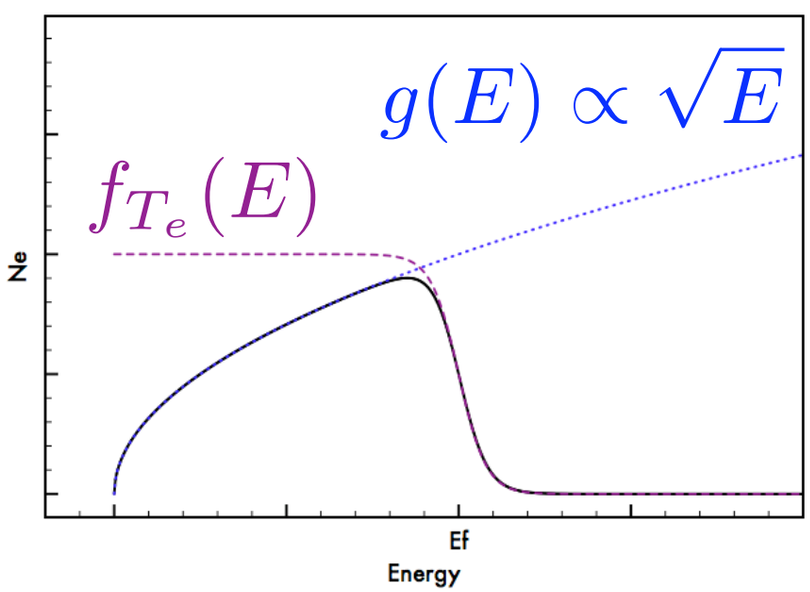
Creating transparent aluminium



- 52 nm Al foil (+20 nm oxide layer), 92 eV photons
- Nagler et al., Nature Physics (doi:10.1038/nphys1341 article)

Core hole recombination - soft x-ray emission

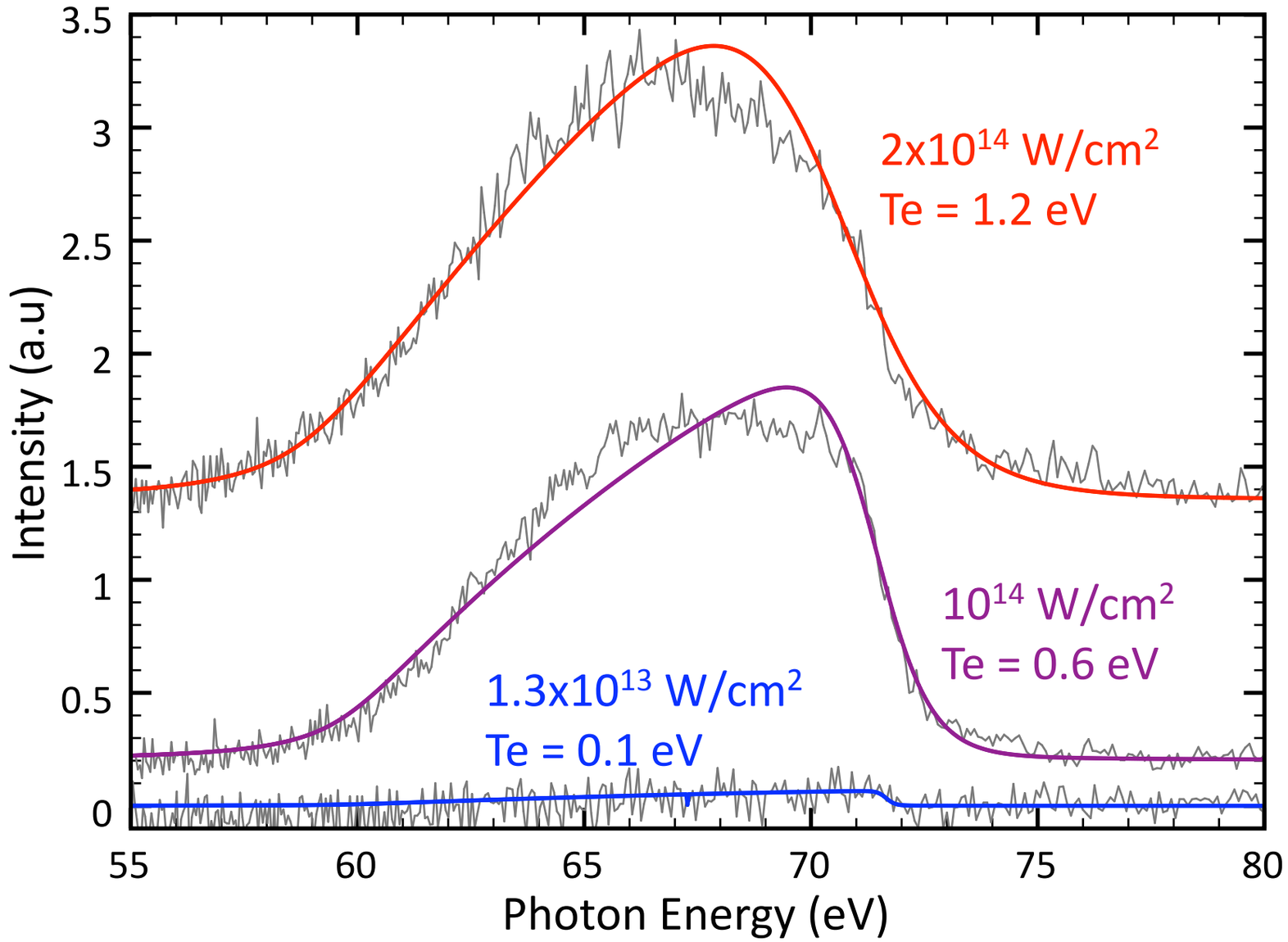




Soft x-ray emission 0.2 % of total recombination, rest is Auger

$$I(E) \sim \omega^3 \, g(E) \, f_{T_e}(E)$$

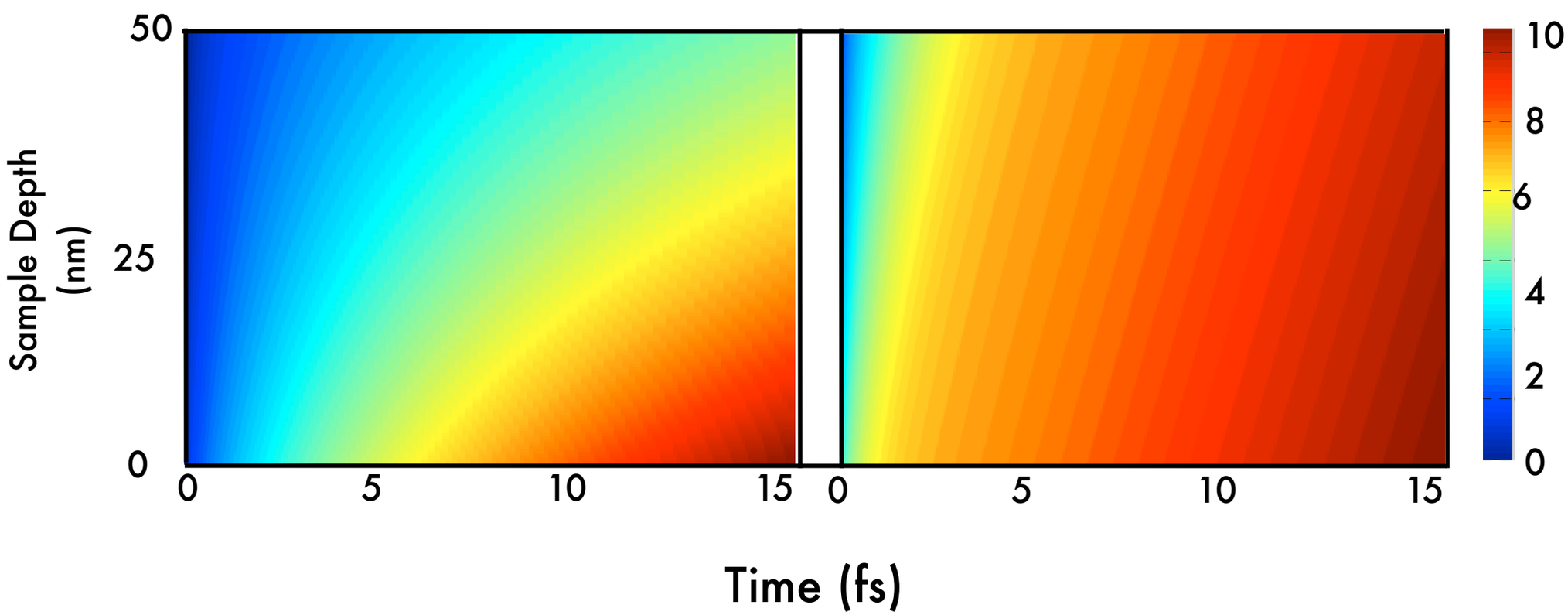
Soft x-ray emission spectroscopy



- Experimental data taken at 20 µm spot (low intensities);
- model represents valence band density of states at a given temperature;
- temperatures in agreement with observations from plasma line spectroscopy

Homogeneously heated WDM

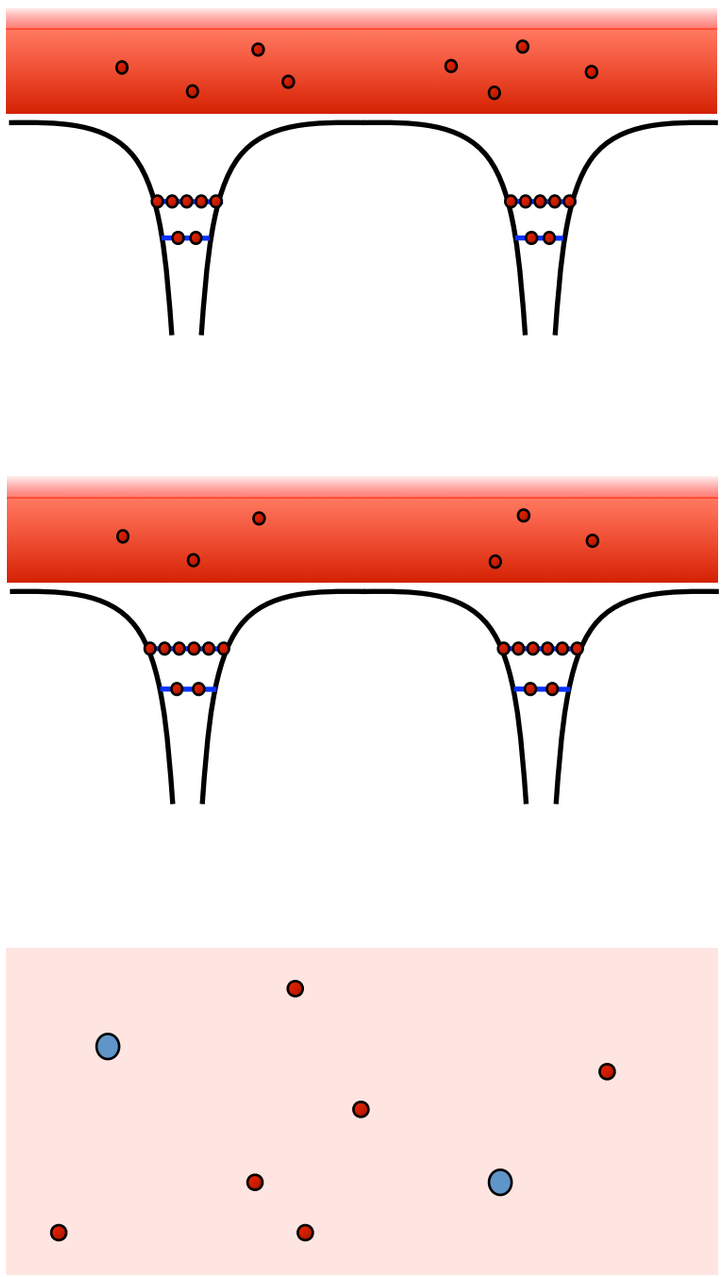
- Essential to create WDM in a well-defined state: very fast & homogeneous heating imperative to obtain near constant (T,ρ)
- Homogeneous heating of a material to Warm Dense Matter an **order of magnitude more** efficient in the saturation regime



Conclusions & outlook

- First experiments at FLASH successful:
  - straightforward;
  - transparent aluminium, homogeneously generated WDM;
  - spectroscopy (on solid density matter and plasmas)
  - list not exhaustive! (Thomson scattering, FEL pump-probe, ...)
- Future plans on FLASH:
  - spectroscopy
  - core-hole lifetime measurements
- TIMEX endstation at FERMI@Electra
- SXR/MEC endstations at LCLS

Evolution of the exotic system to WDM



- 1 L-shell hole/atom
- 4 conduction electrons/atom
- T_e = 10 eV
- T_i = 300 K
- lifetime < 40 fs

↓ recombination

- T_e = 25 eV
- T_i = 300 K
- lifetime > 1 ps

↓ electron-phonon coupling

- Warm Dense Al
- $T_e = T_i$ = 20 eV
- lifetime < 10 ps

↓ hydrodynamic expansion

- Classical plasma