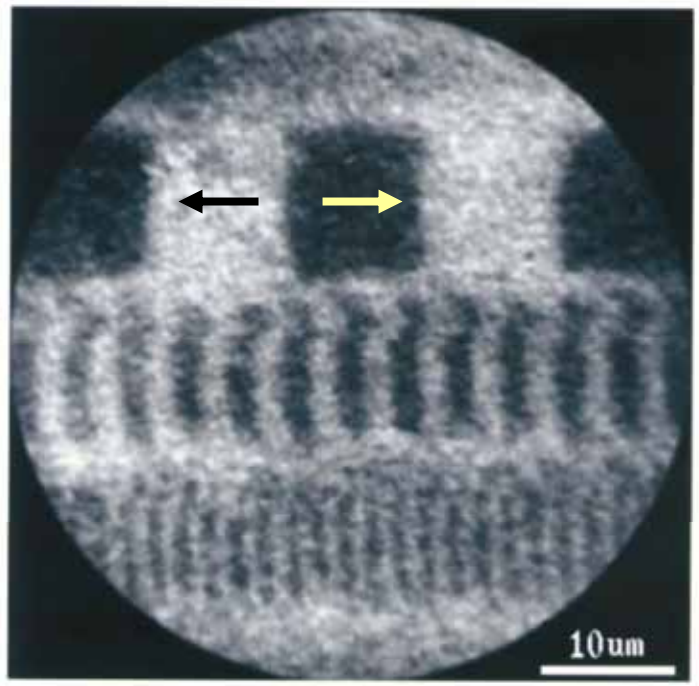
X-Ray Studies of the Nanoworld
Motivation, Concepts and Applications

Joachim Stöhr
Stanford Synchrotron Radiation Laboratory

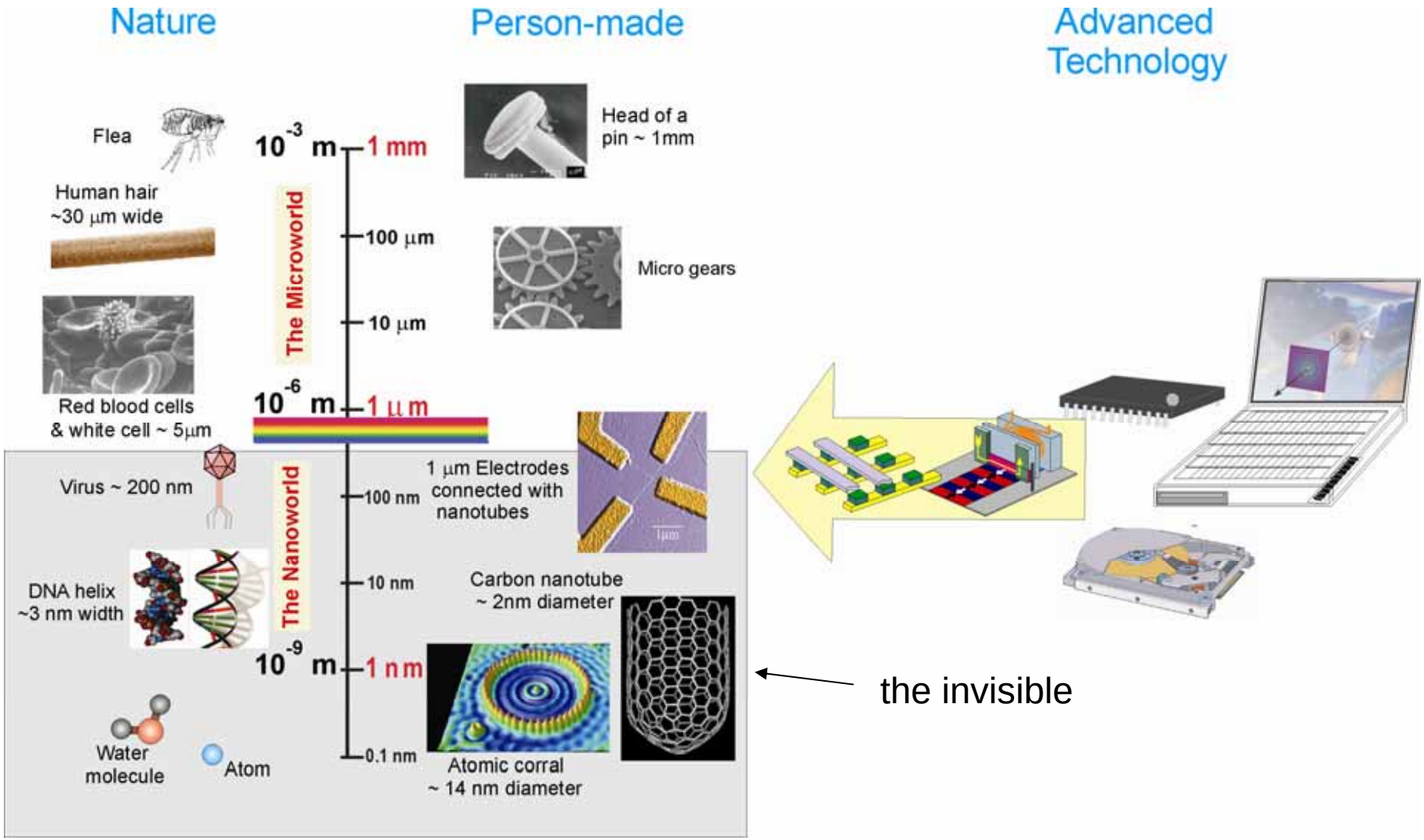
X-rays have come a long way……

1895



1993

The Complex Nanoworld

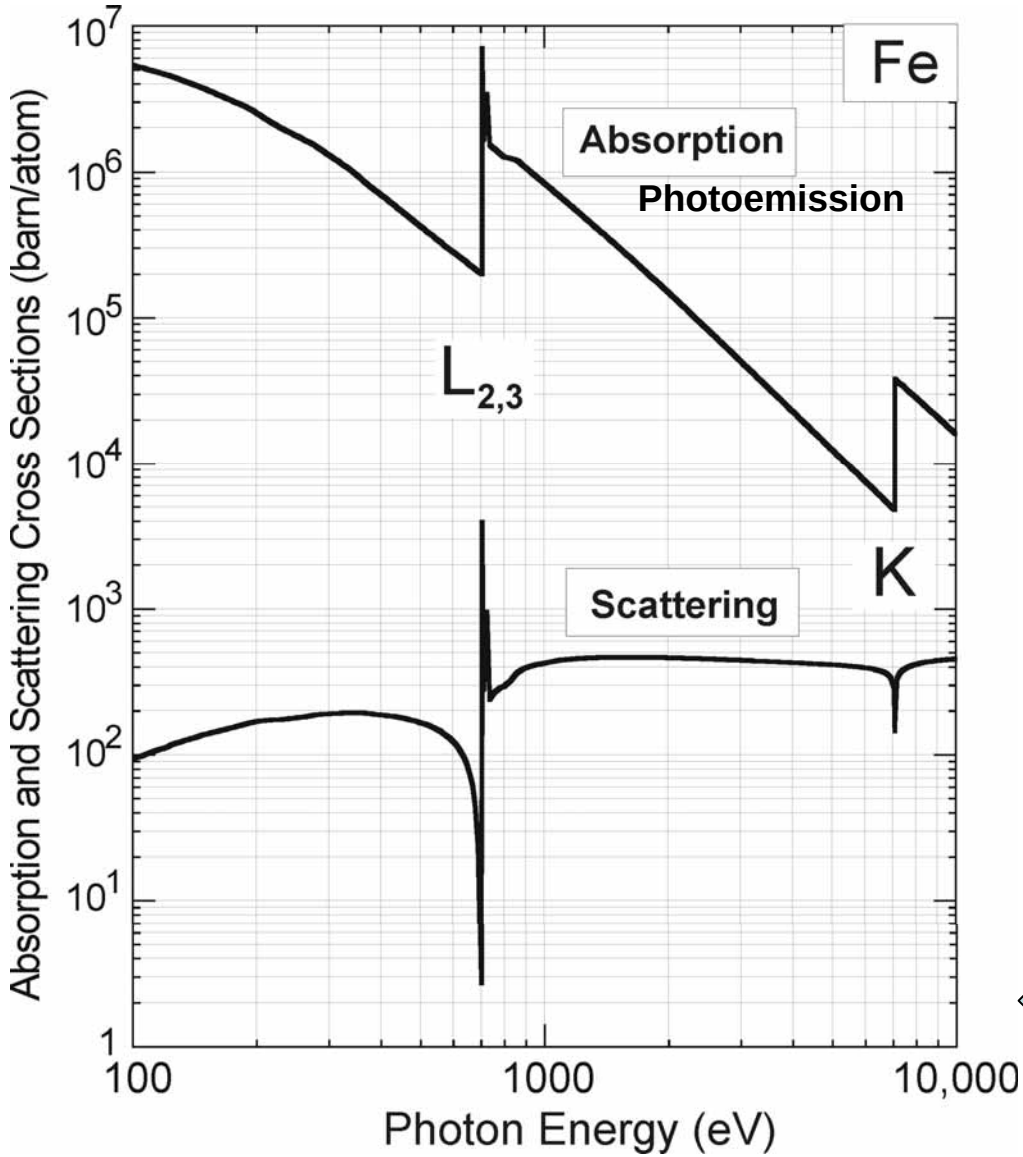


Need techniques that: **see the invisible**, **look below the surface, distinguish components** …. and **resolve dynamic motions**

Tunable x- rays offer variable interaction cross sections

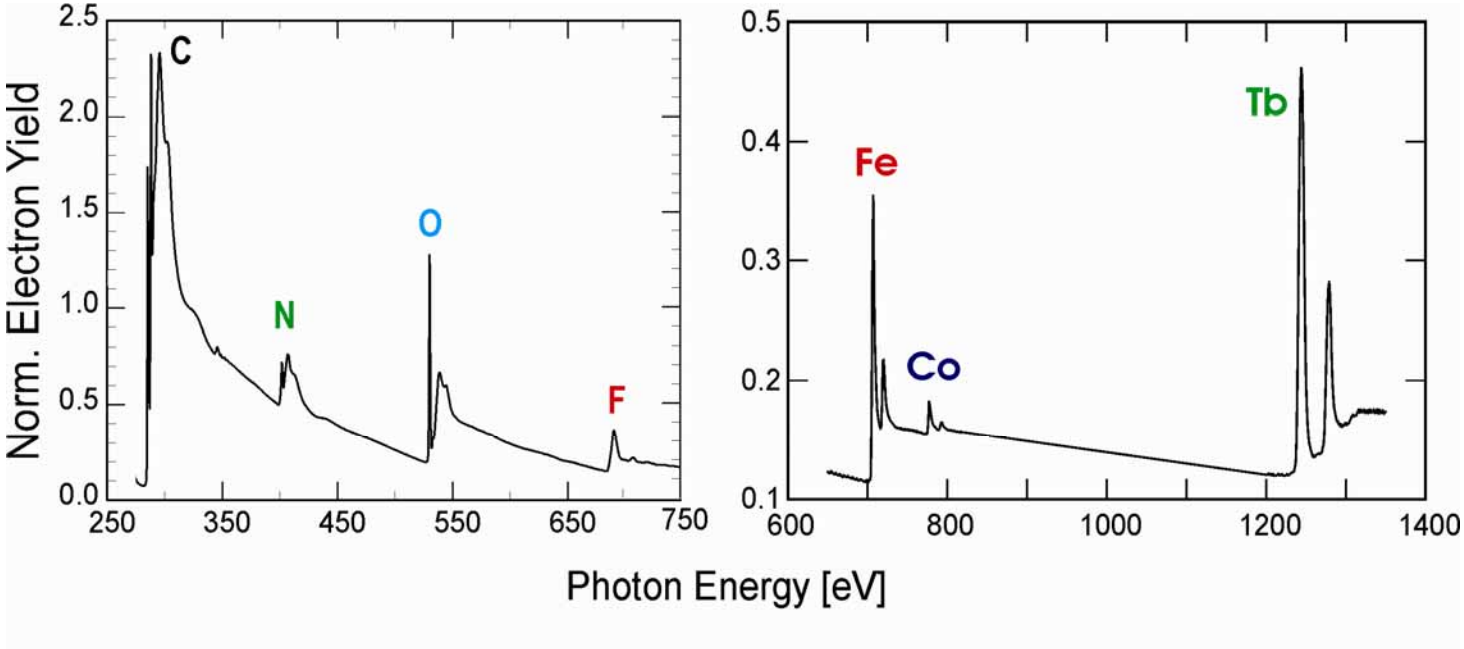
optical light

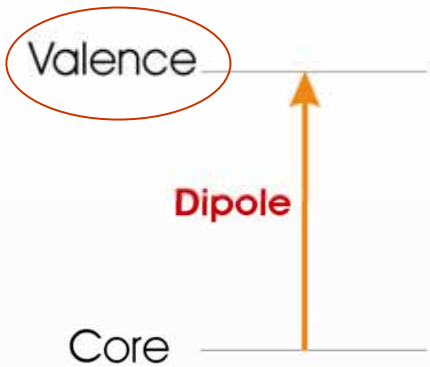
electrons



neutrons

Tunable x-rays offer elemental specificity





Polymers:	p-orbitals
Trans. Met.:	d-orbitals
Rare Earths:	f-orbitals

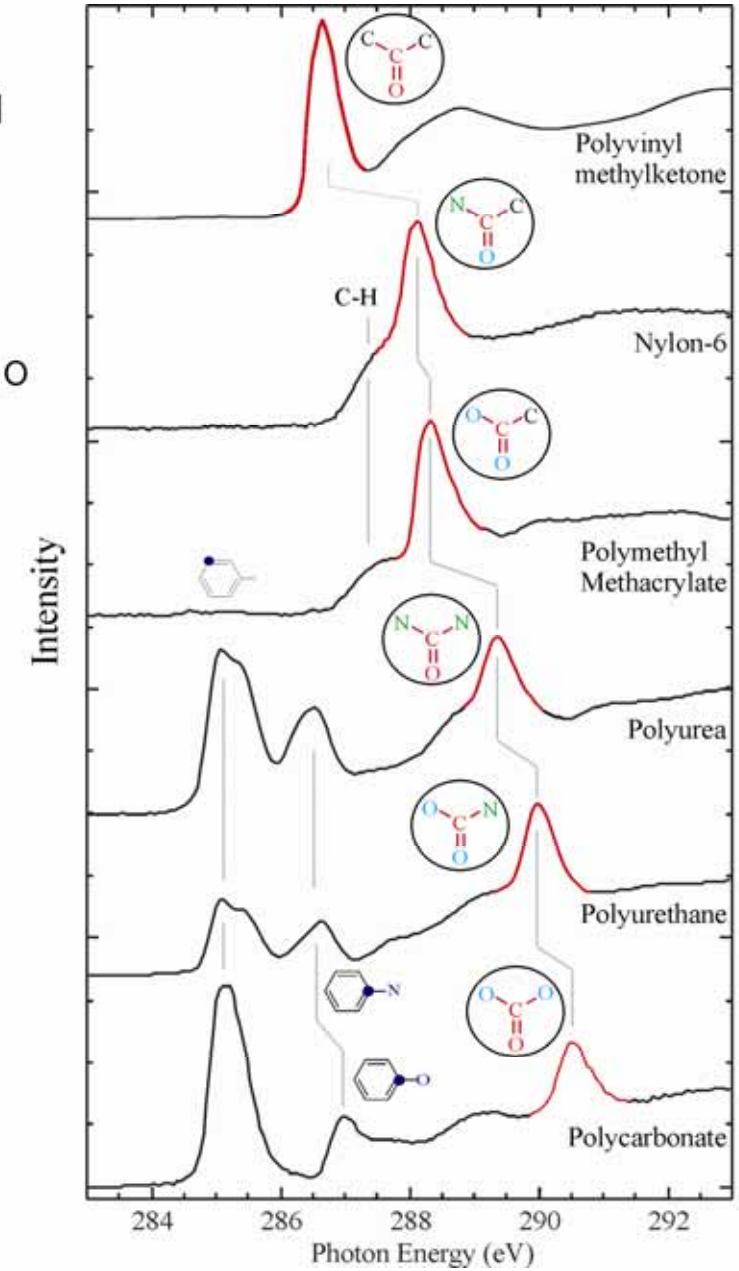
1s	K-edge
2p	L edge
3d	M edge

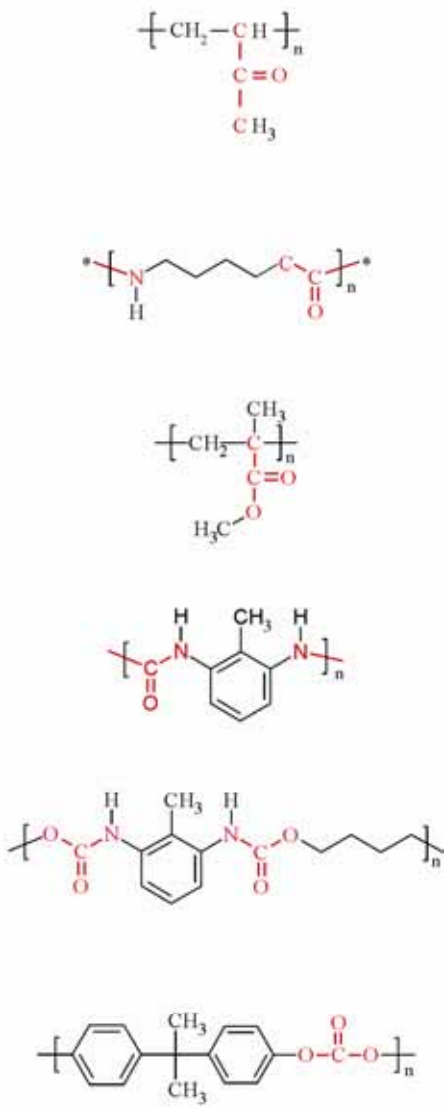
Transitions provide information on valence charge and spin

Tunable x-rays offer chemical specificity

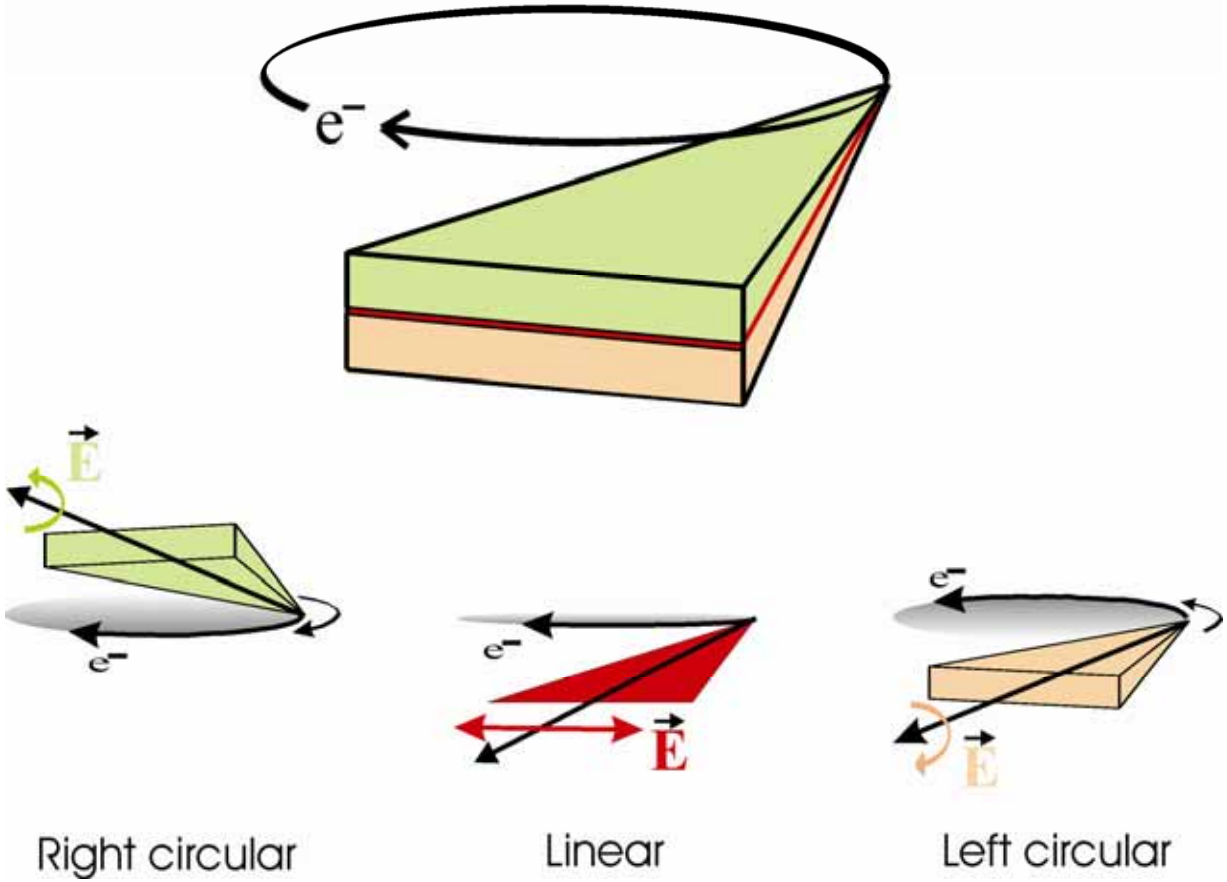
functional group

X, Y = C, N, O



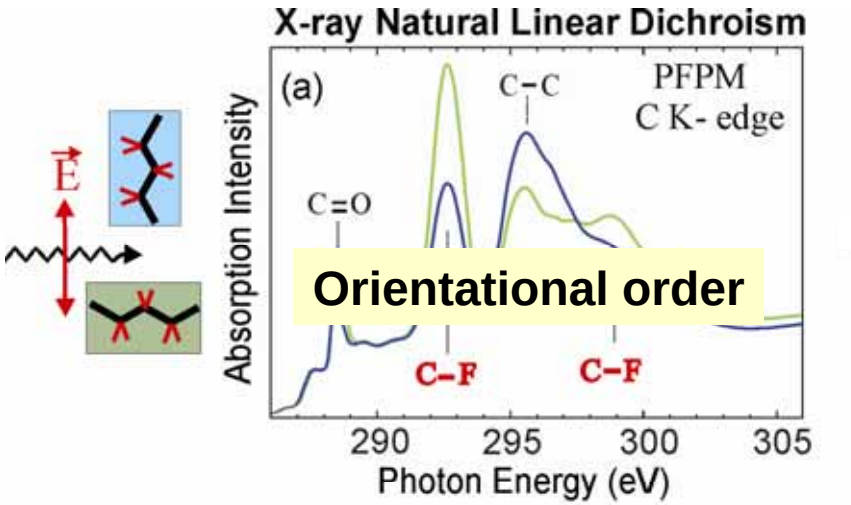


The power of x-ray polarization



Today: variable polarization undulators

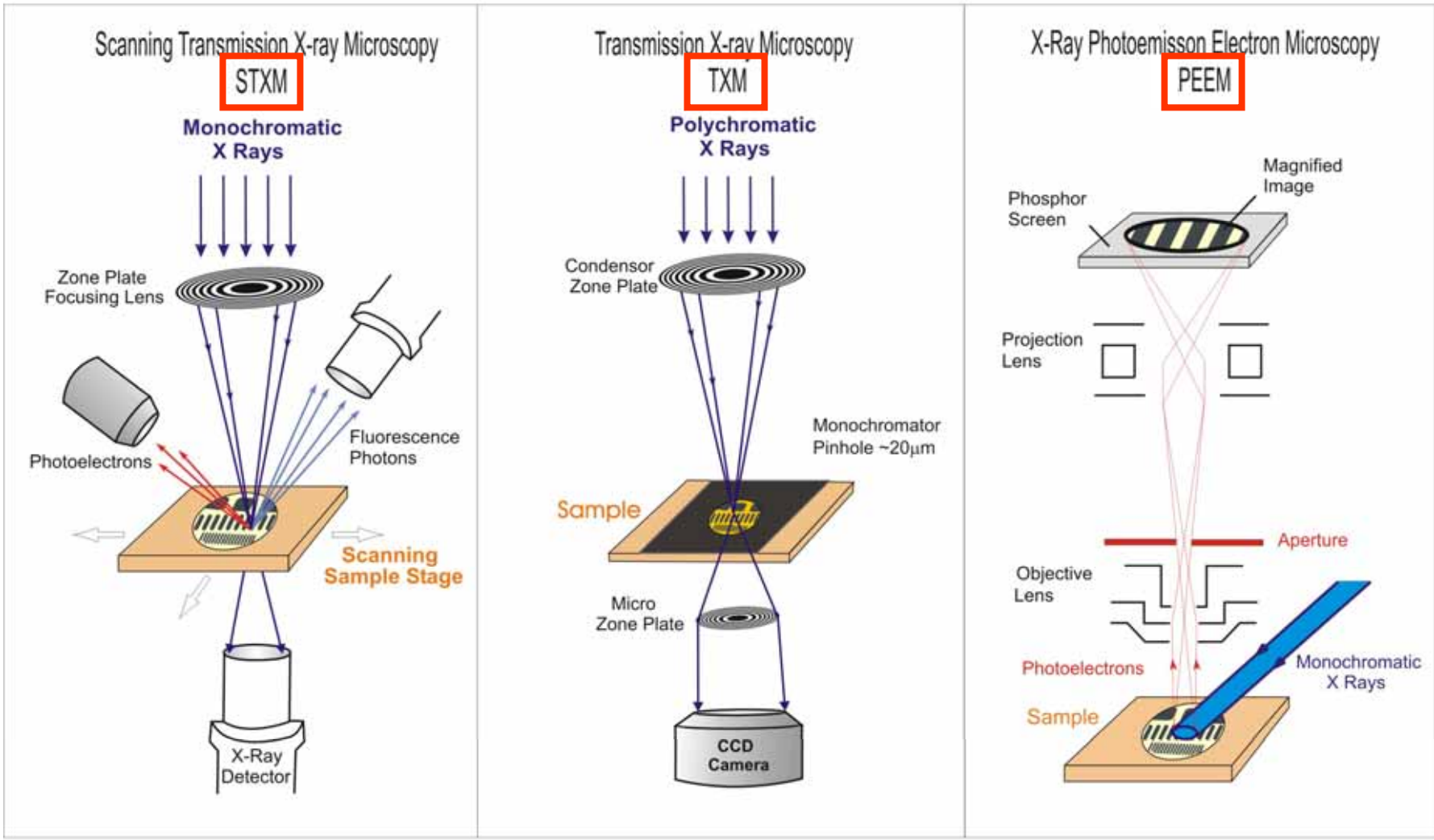
Polarized x-rays offer “orientation” information



Orientational order

Stöhr *et al.*, Phys. Rev. Lett. **47**, 381 (1981)

Focusing of x-rays offers nanoscale resolution

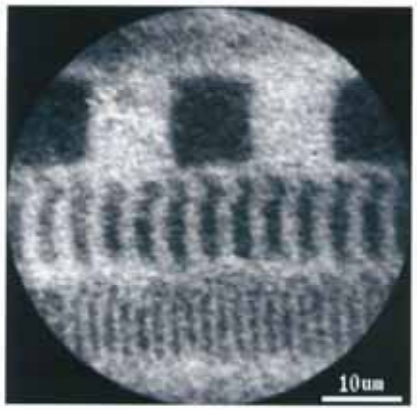


Present resolution in the 20 - 40 nm range

Polarization Dependent Imaging with X-Rays

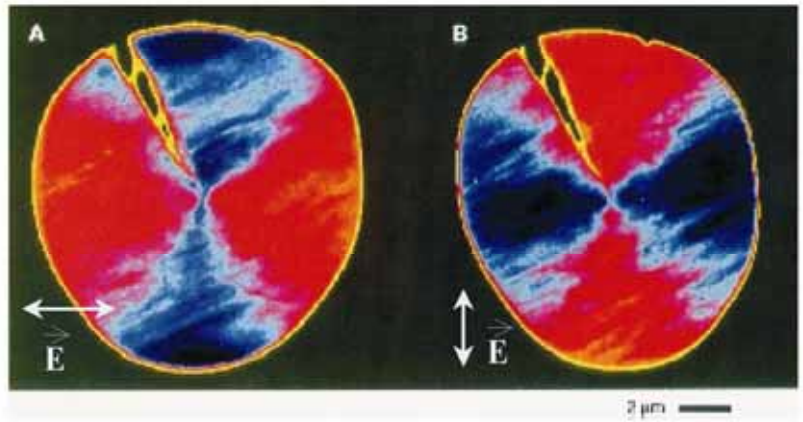
X-Ray Magnetic Circular Dichroism

Stöhr *et al.*, Science **259**, 658 (1993)



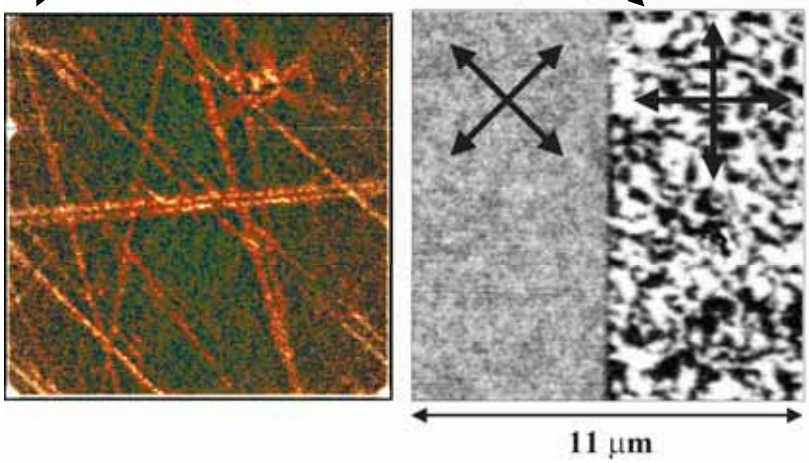
X-Ray Natural Linear Dichroism

Ade and Hsiao., Science **262**, 1427 (1993)



X-Ray Magnetic Linear Dichroism

Stöhr *et al.*, Phys. Rev. Lett. **83**, 1862 (1999)
Scholl *et al.*, Science **287**, 1014 (2000)

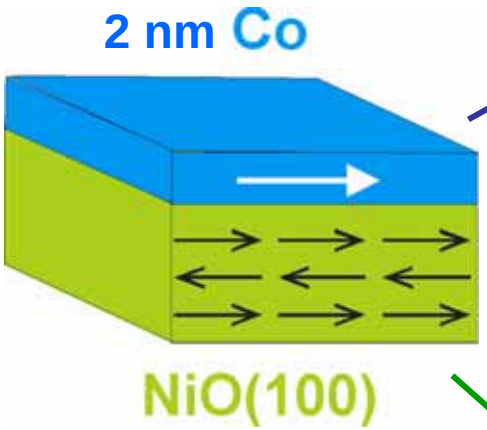


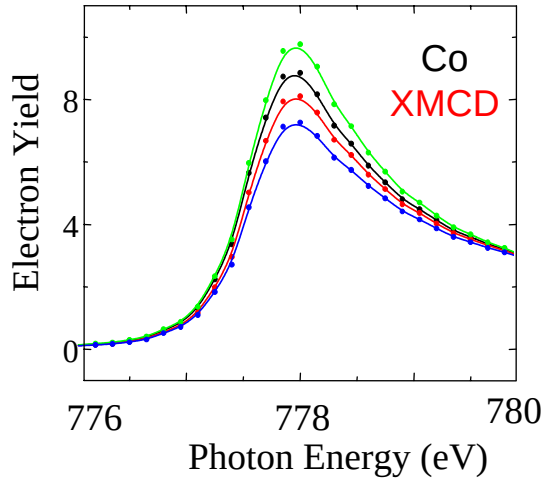
X-Ray Natural Circular Dichroism

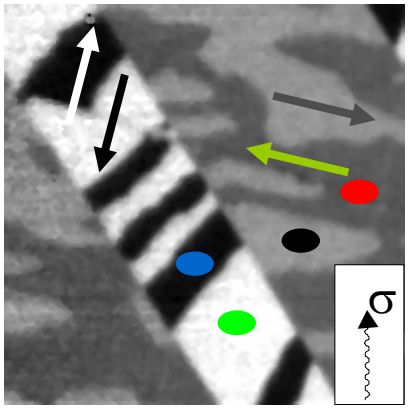
?

Spectro-Microscopy (PEEM) of Ferromagnets on Antiferromagnets

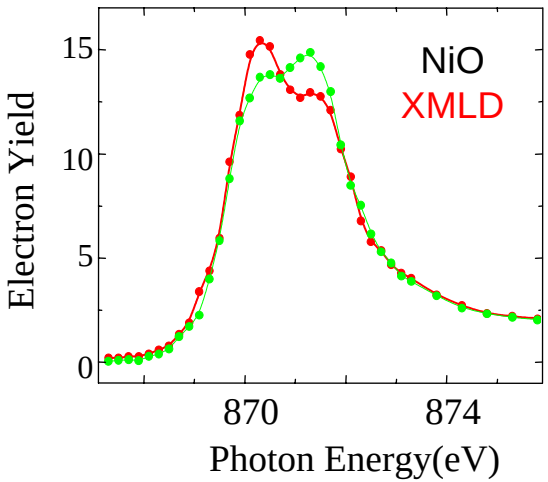
Tune to **Co** edge – use **circular** polarization – **ferromagnetic** domains

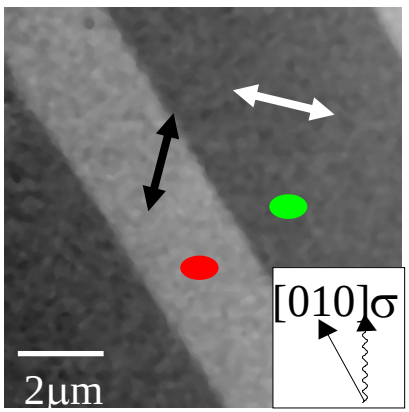






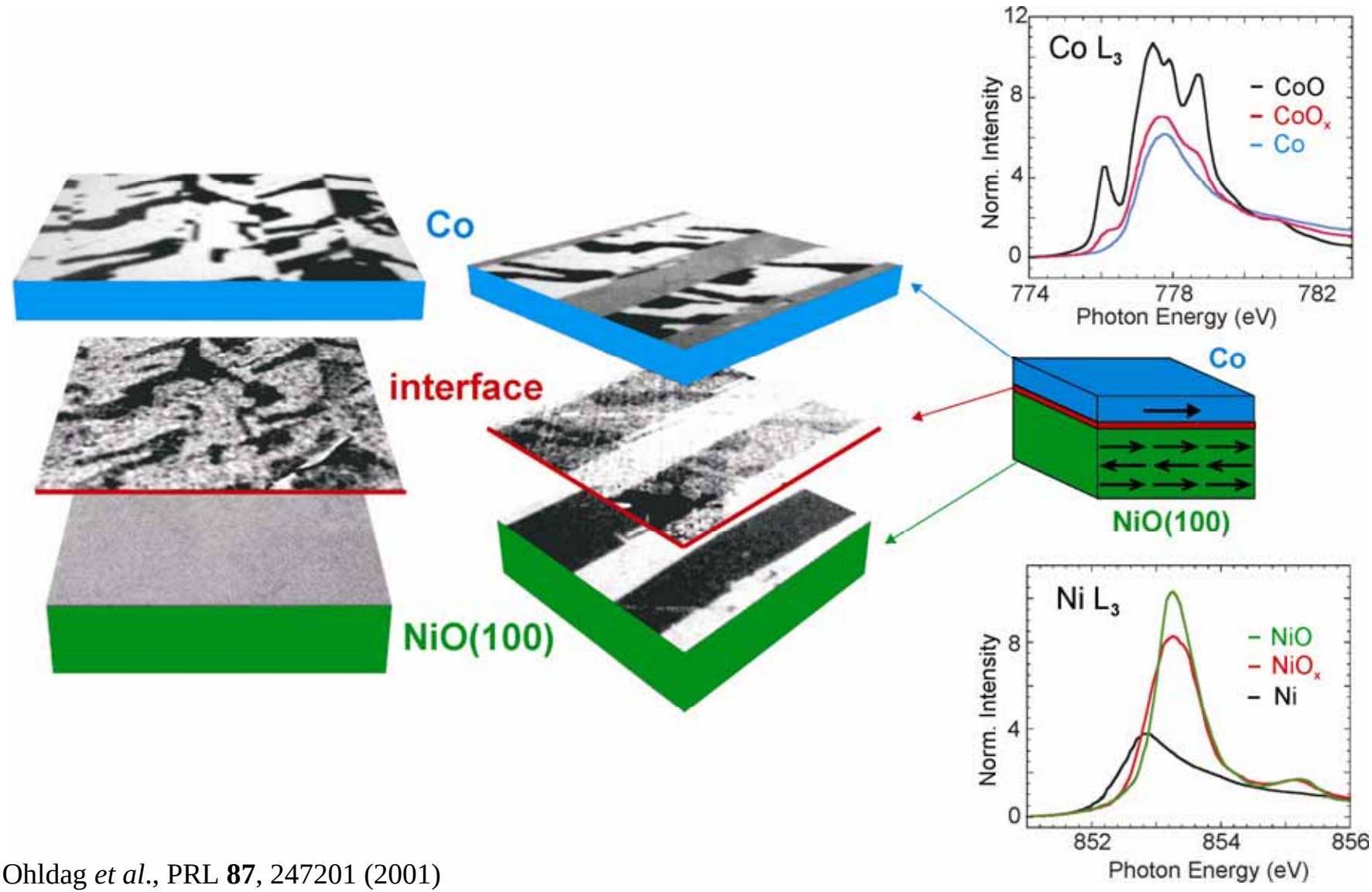
Tune to **Ni** edge – use **linear** polarization – **antiferromagnetic** domains





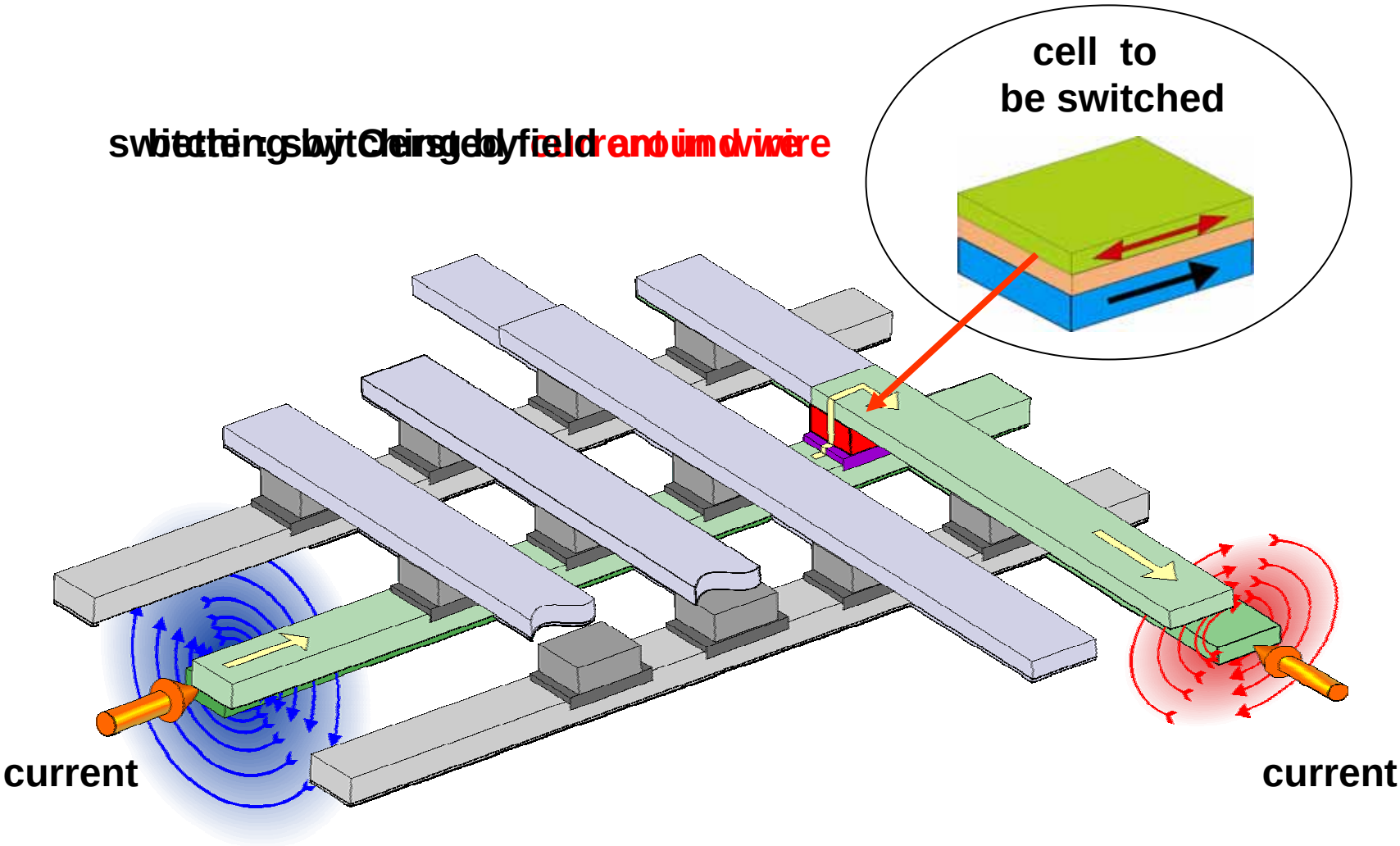
H. Ohldag *et al.*, PRL **86**, 2878 (2001)

Images of the Ferromagnet-Antiferromagnet Interface

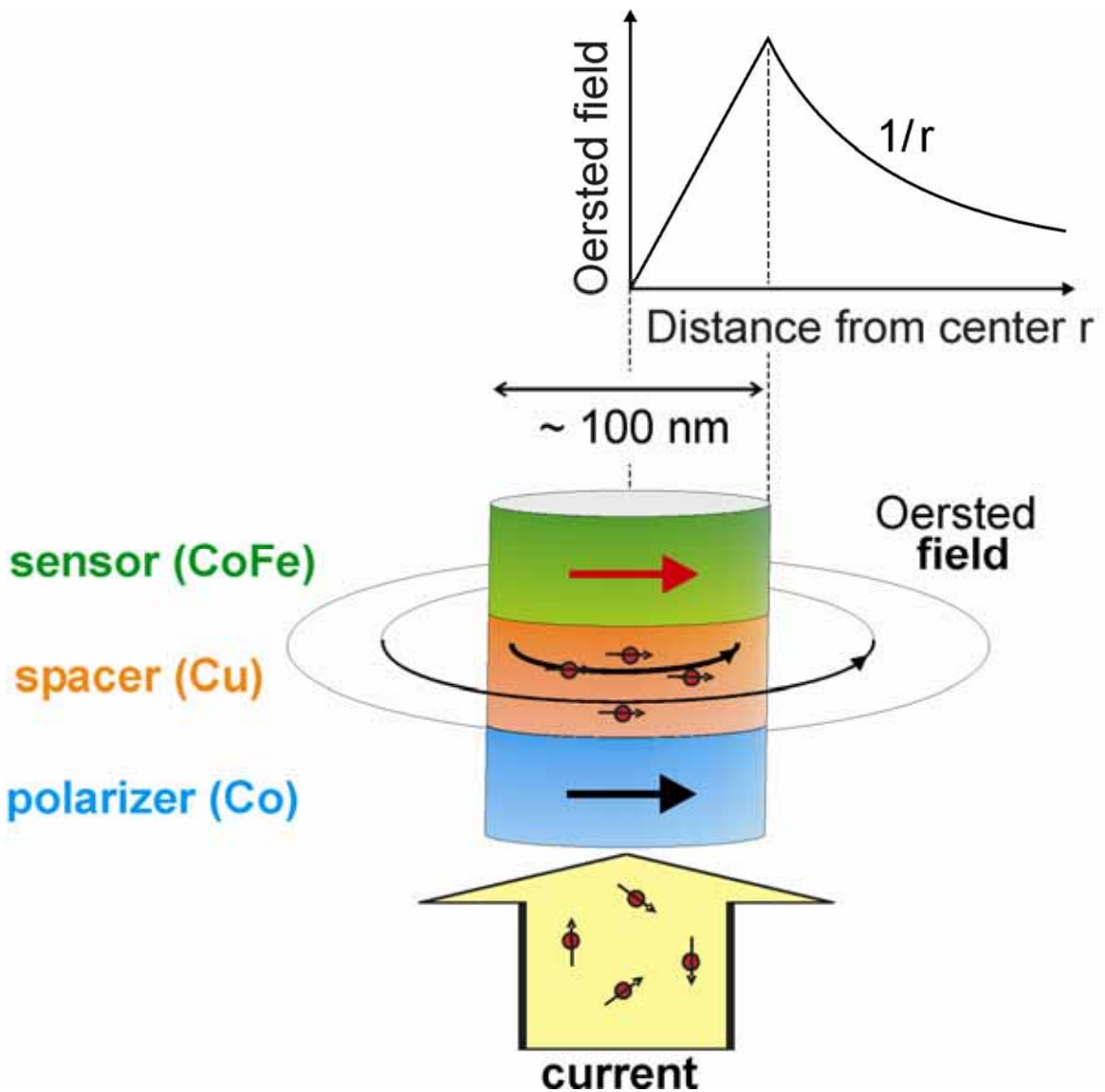


Ohldag *et al*., PRL **87**, 247201 (2001)

Switching of magnetic memory cells (MRAM)

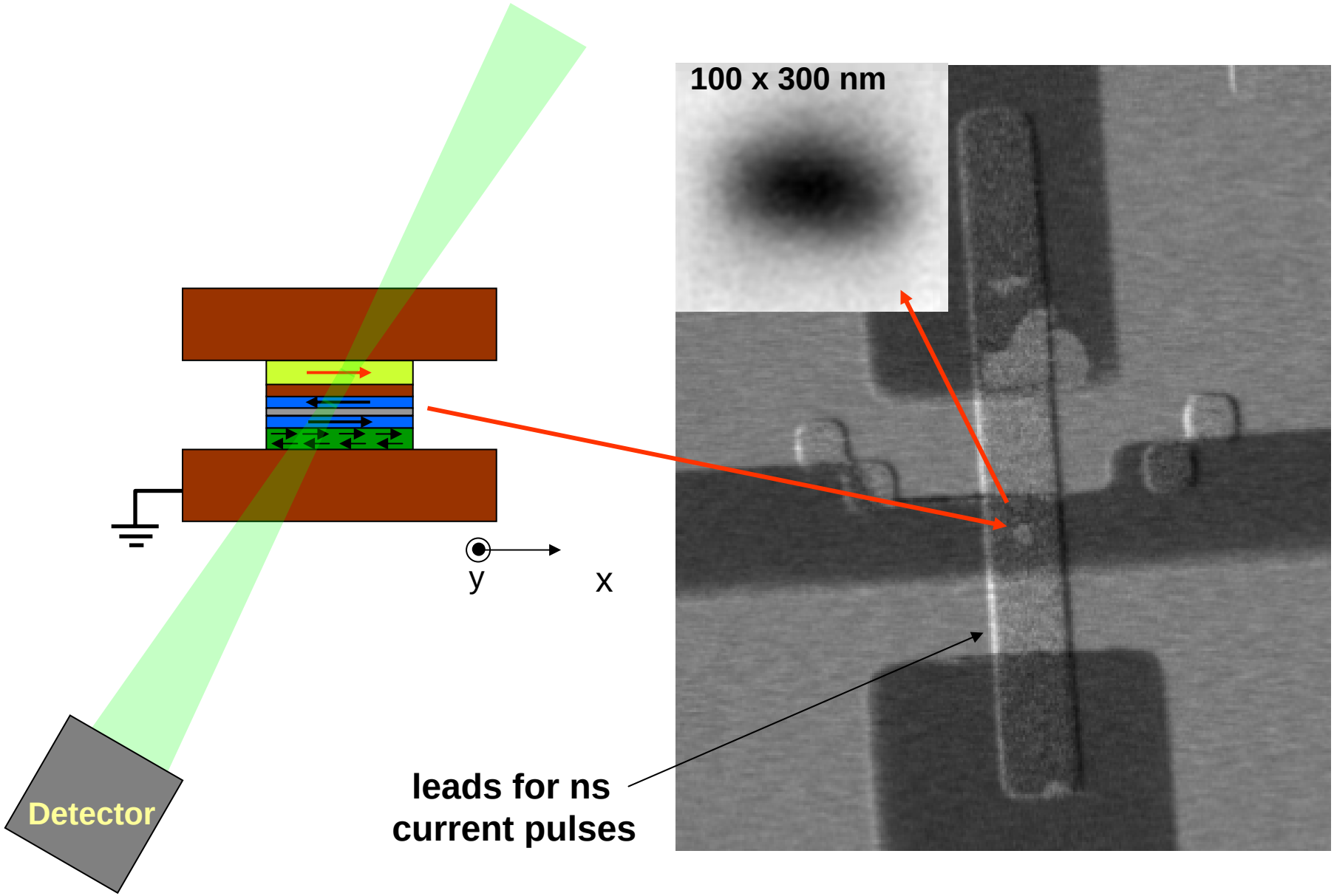


A new way of magnetic switching: spin injection

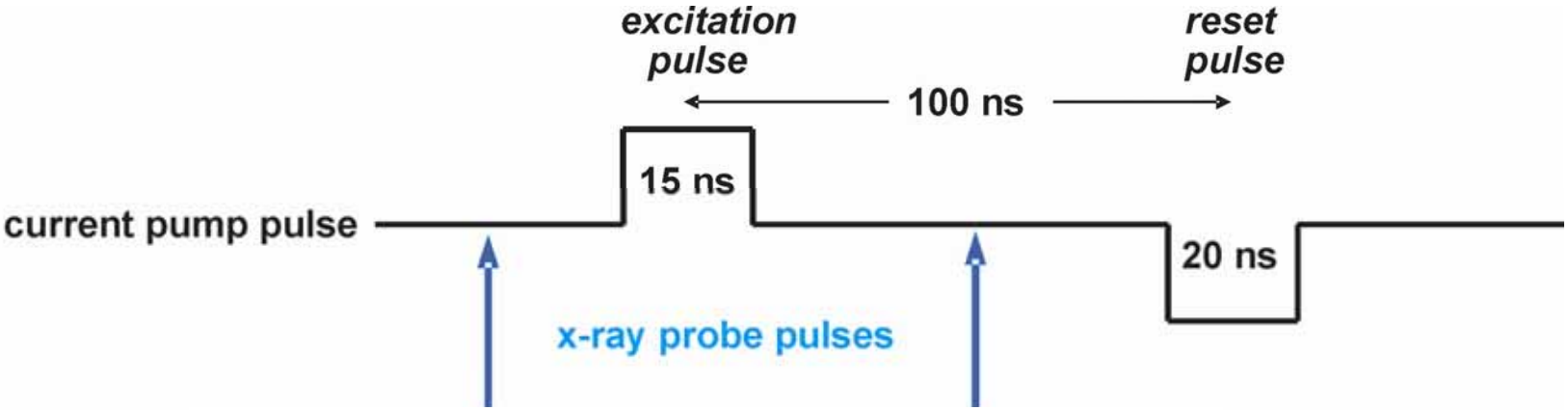


current becomes spin-polarized

STXM image of spin injection structure

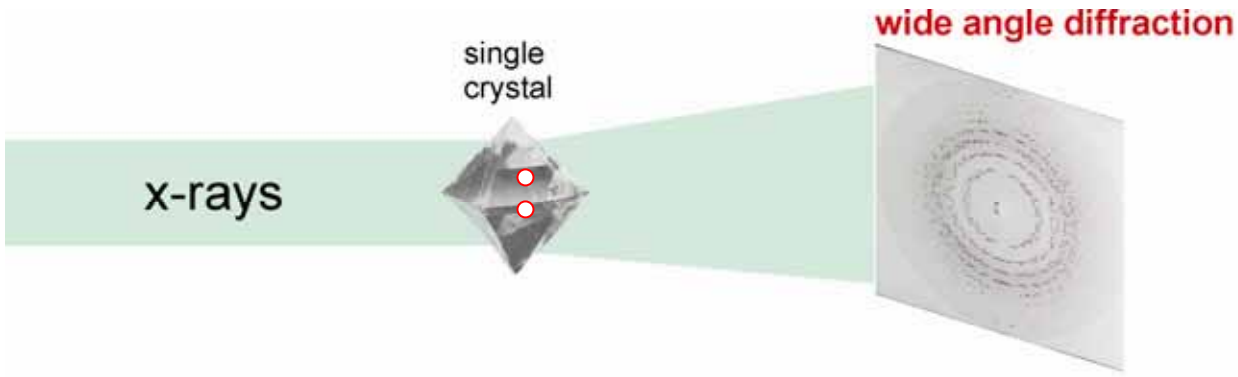


Magnetization changes in sensor layer after spin-injection

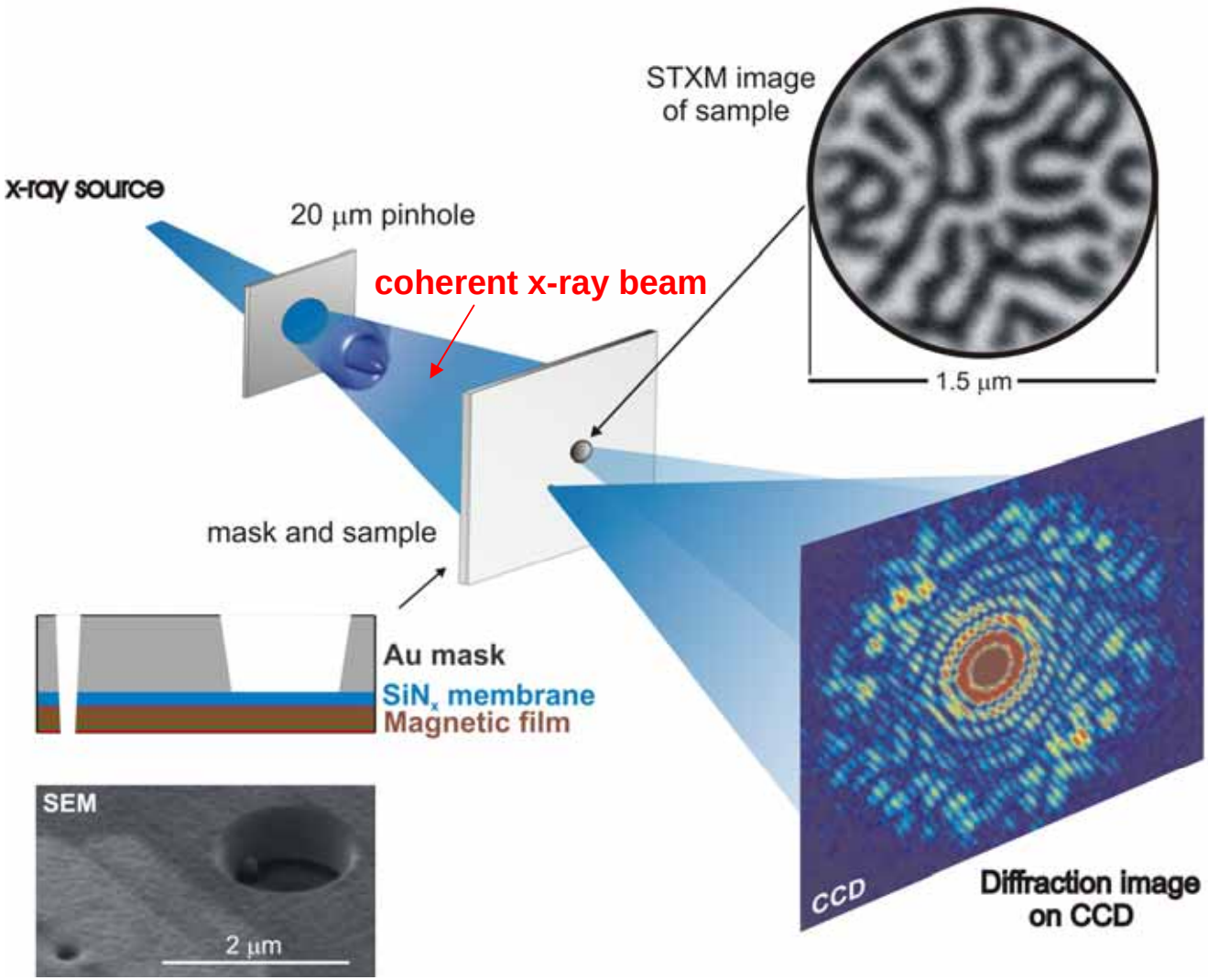


Oersted field of excitation pulse switches layer to curled state
spin current in reset pulse switches it back to homogeneous state

X-ray diffraction and scattering

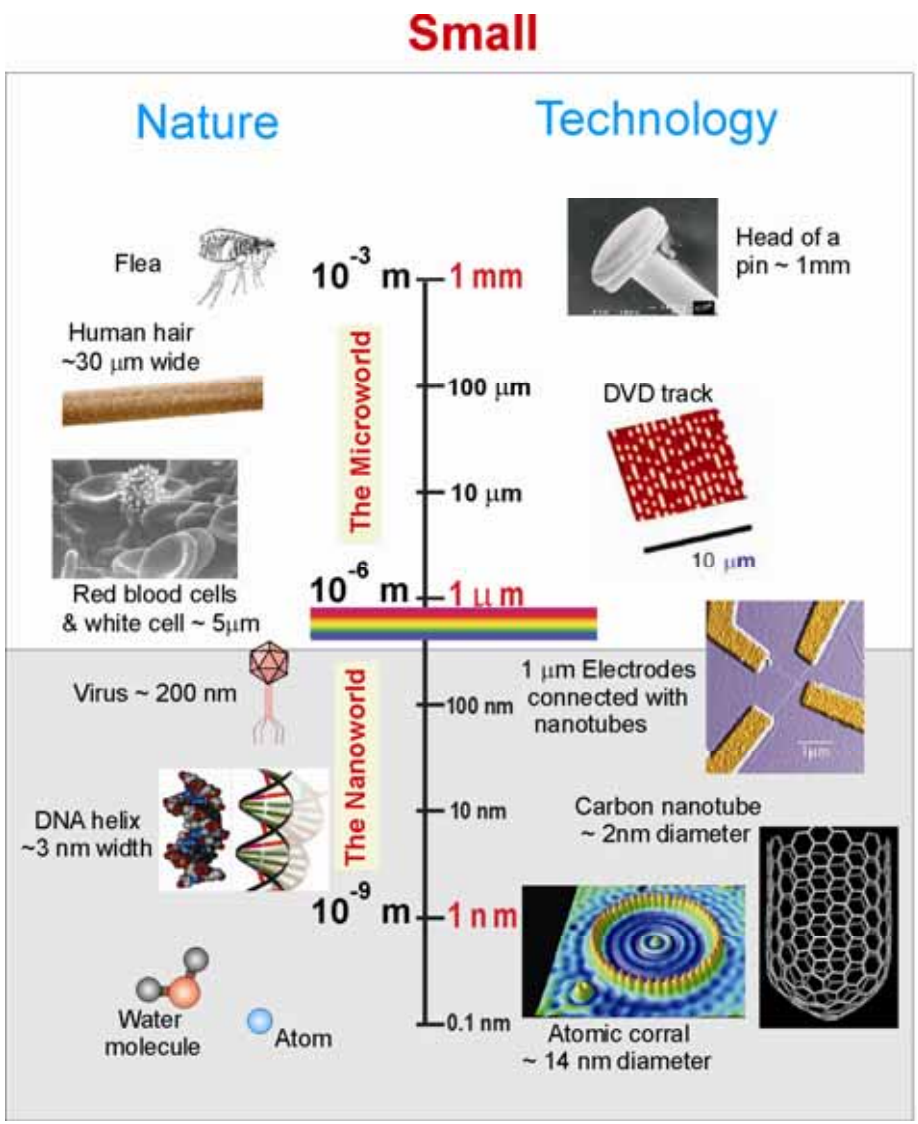


Yes ! - soft x-ray spectro-holography



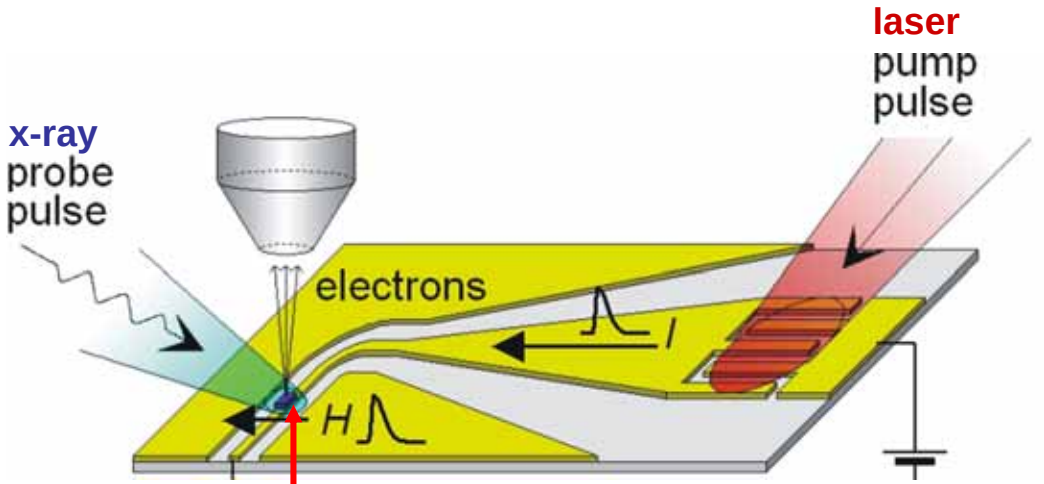
Eisebitt, Lüning, Schlotter, Lörgen, Hellwig, Eberhardt and Stöhr, *Nature* ***432****, 885 (2004)*

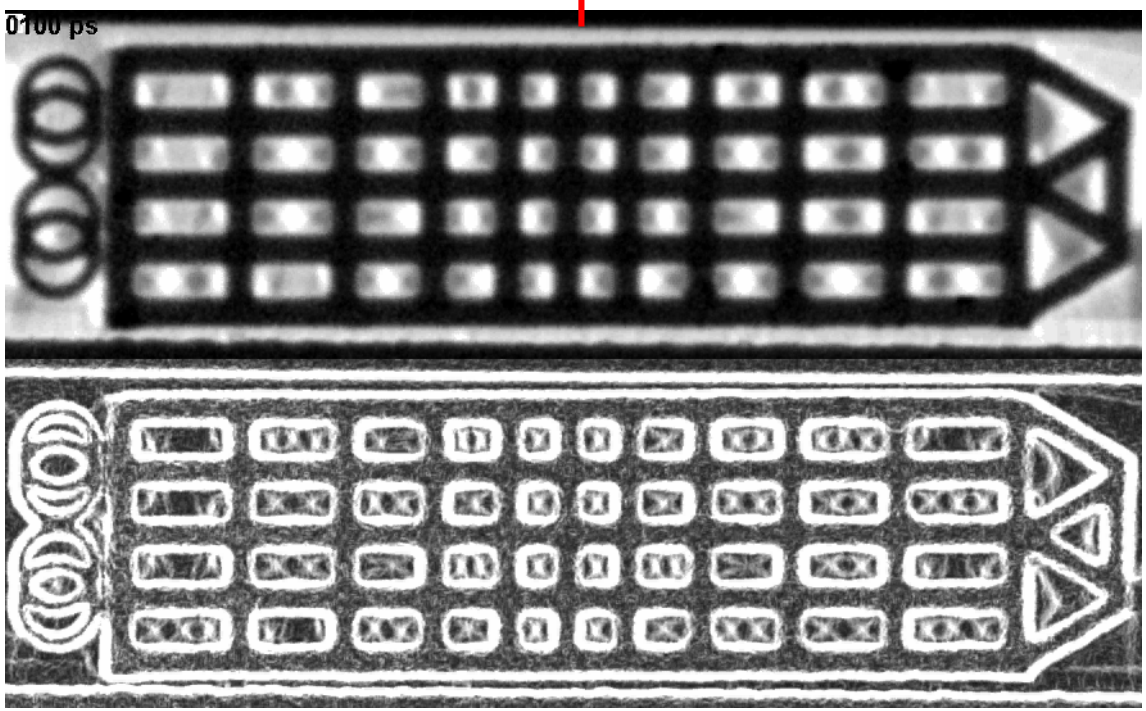
Space and Time: Toward seeing the ultra-fast nanoworld



Rule of thumb: the smaller the faster!

Imaging of Motion of Nanoscale Domains (100 ps)





real image

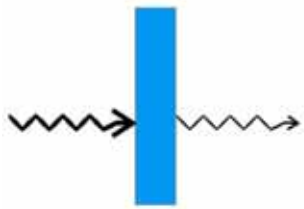
differential image

Conclusions

- Large **resonant cross sections** provide signal from **individual** nanostructures
- X-rays offer **elemental**, **chemical** and **magnetic** specificity with **nanoscale spatial resolution**
- Transmission experiments probe **bulk**, reflection and electron yield experiments probe **surfaces** and **interfaces**
- Pulsed synchrotron sources allow **time-dependent studies**, paving the way for picosecond nanoscale technology
- **Future** x-ray sources, new techniques and instrumentation will allow the complete exploration of the **ultrafast nanoworld** (to femtoseconds)

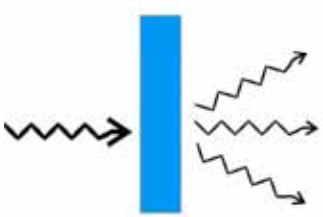
X-Ray Dichroism in Absorption and Scattering

Absorption



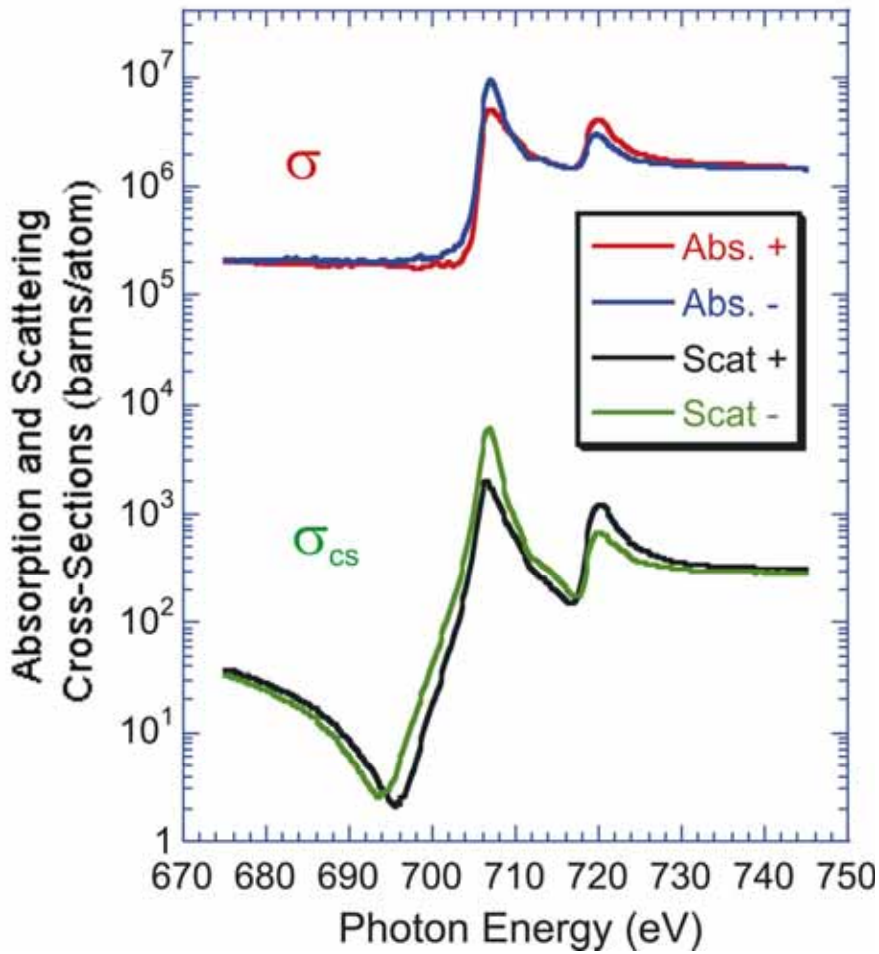
$\sigma_{abs} \propto f_2$

Resonant Elastic Scattering



$\sigma_{scat} \propto |f_1 + i f_2|^2$

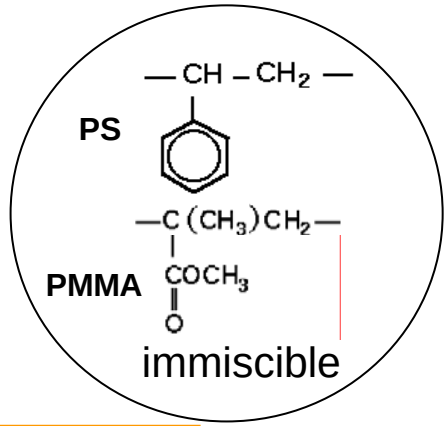
Fe metal – L edge



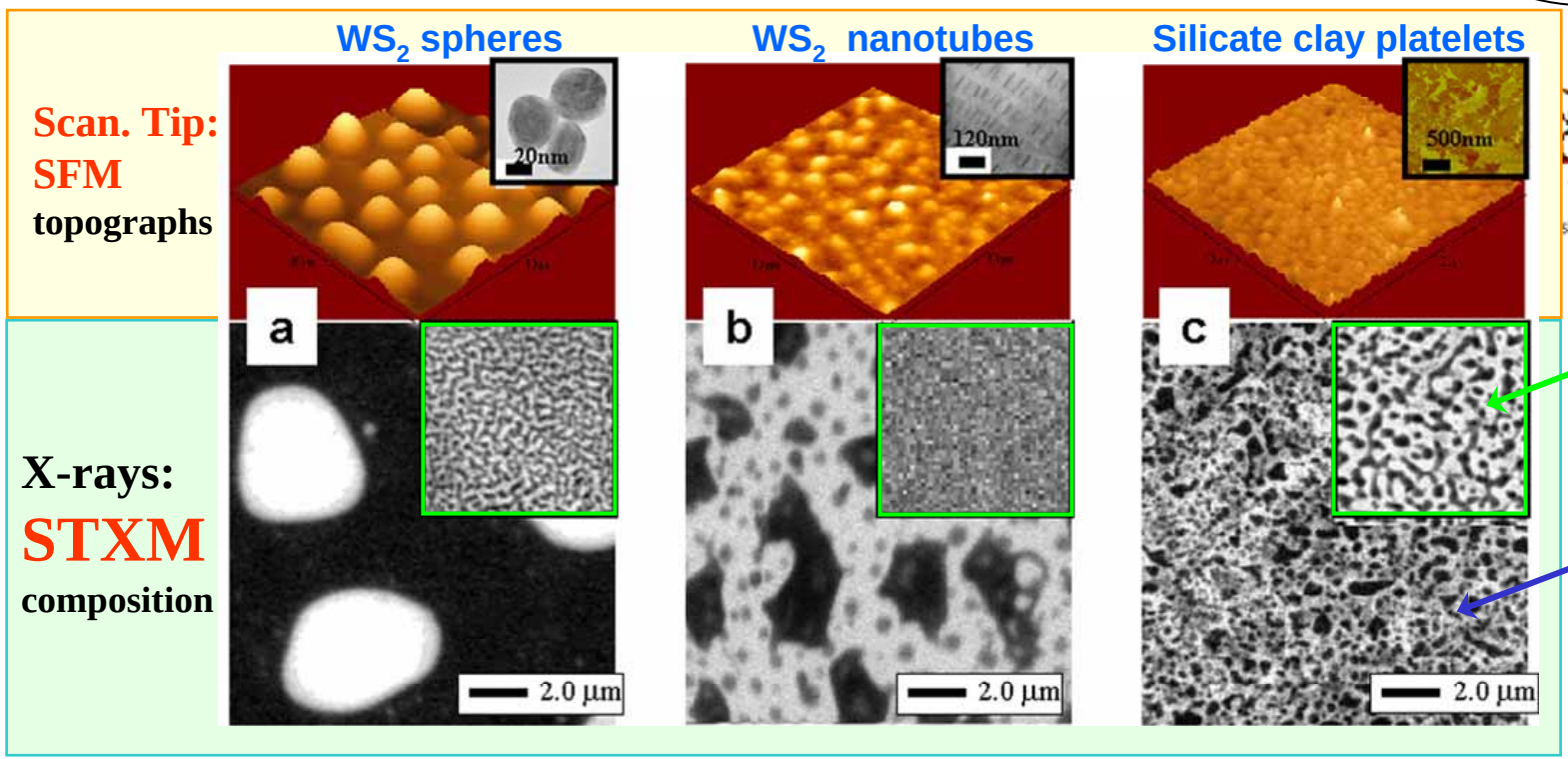
Kortright and Kim, Phys. Rev. B **62**, 12216 (2000)

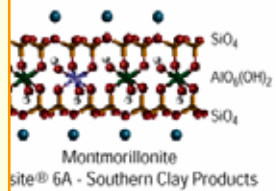
Nanoparticles as Compatibilizers for Polymer Blends

H. Ade, A.L.D. Kilcoyne, T. Araki, W. Zhang, X. Hu, M. Lin,
M. Rubinstein, M. Rafailovich, J. Sokolov



PS /PMMA blends with 5% filler





- **Clay platelets are best for suppressing phase segregation**