X-Rays and Magnetism
From Fundamentals to Nanoscale Dynamics

Joachim Stöhr
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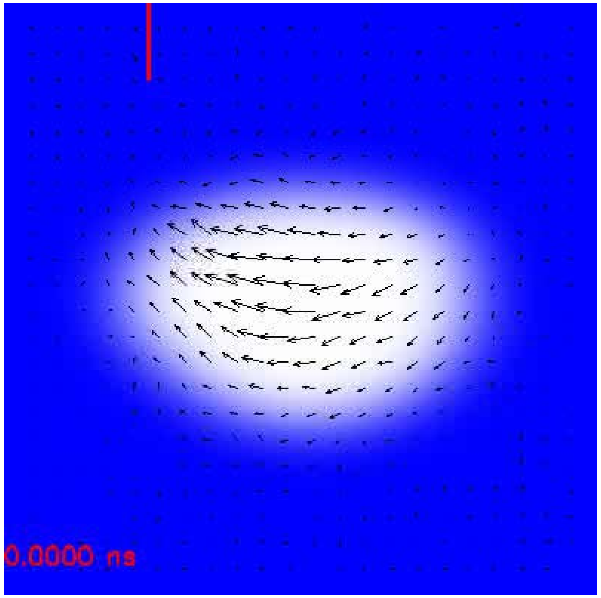
X-rays have come a long way……

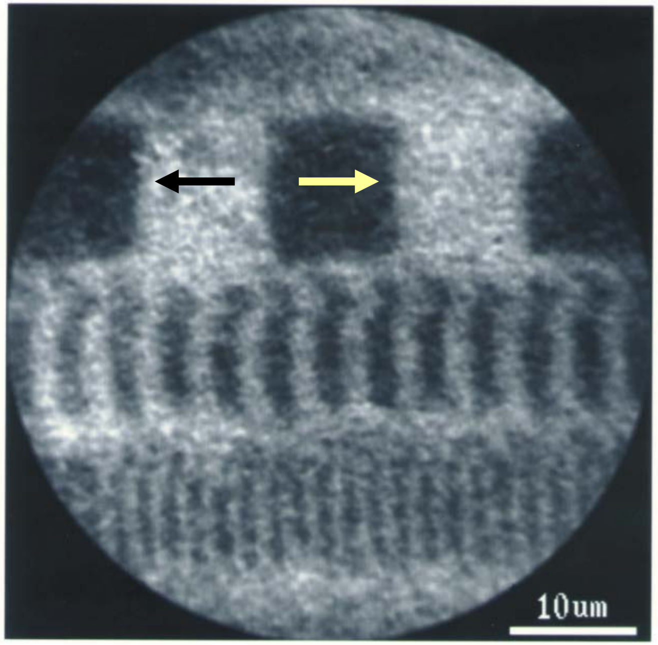
1895

10 cm



100 nm

1993



10 μm

Collaborators:

SSRL – Stanford:

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J. Katine
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M. Carey

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S. Eisebitt
M. Lörgen
W. Eberhardt

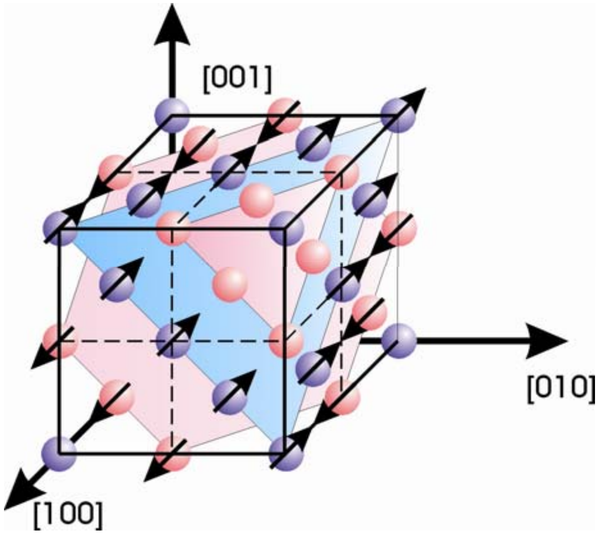
Understanding magnetism: from neutrons to x-rays

The past: **1994** Nobel Prize in Physics: B. N. Brockhouse and C. G. Shull

Press release by the Royal Swedish Academy of Sciences:

``**Neutrons** are small magnets…… (that) can be used to study the relative orientations of the small atomic magnets. ….. the **X-ray method** has been powerless and in this field of application neutron diffraction has since assumed an entirely dominant position."

Bulk atomic and magnetic structure
e.g. NiO



But: The new magnetic materials are not the bulk materials of old !

The paradigm shift in magnetism

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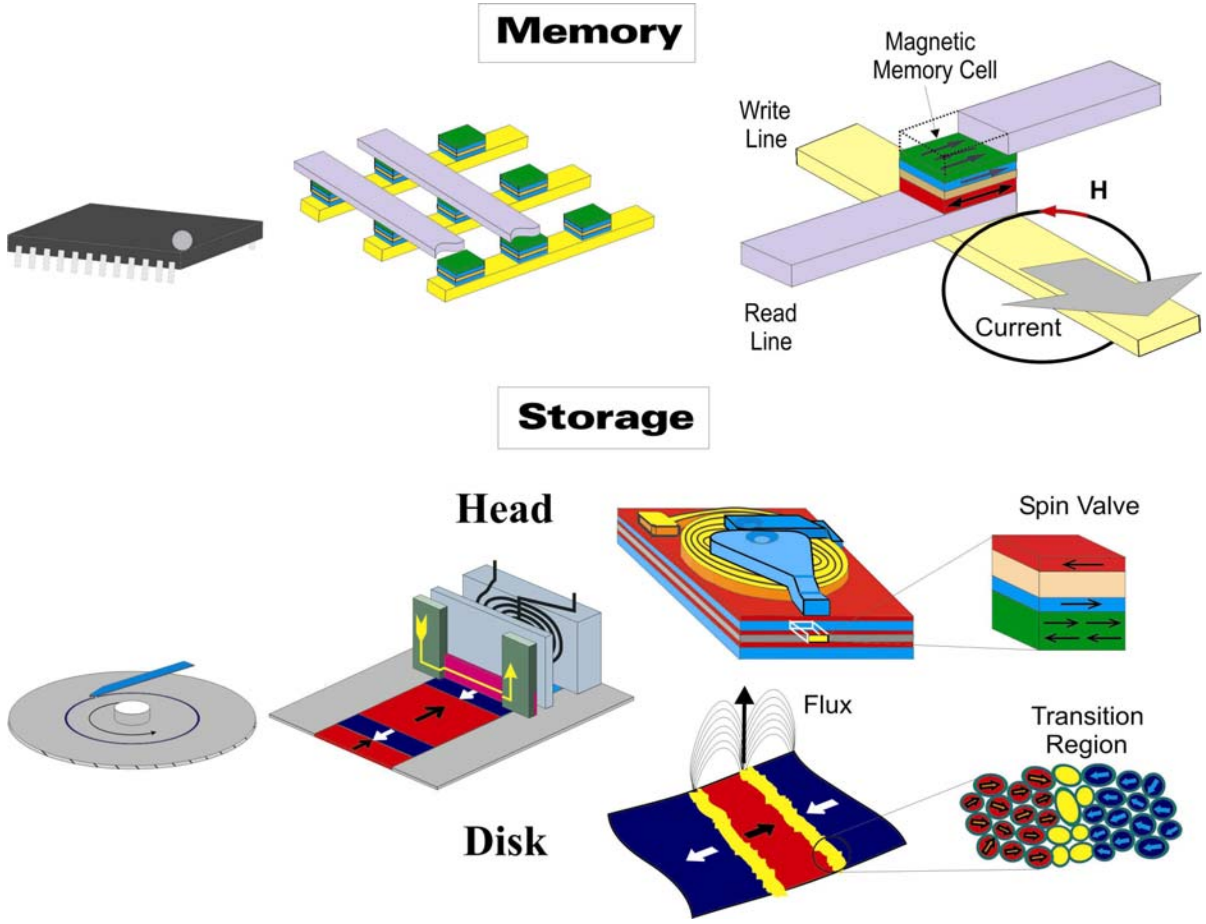
from bulk to thin films and nanostructures

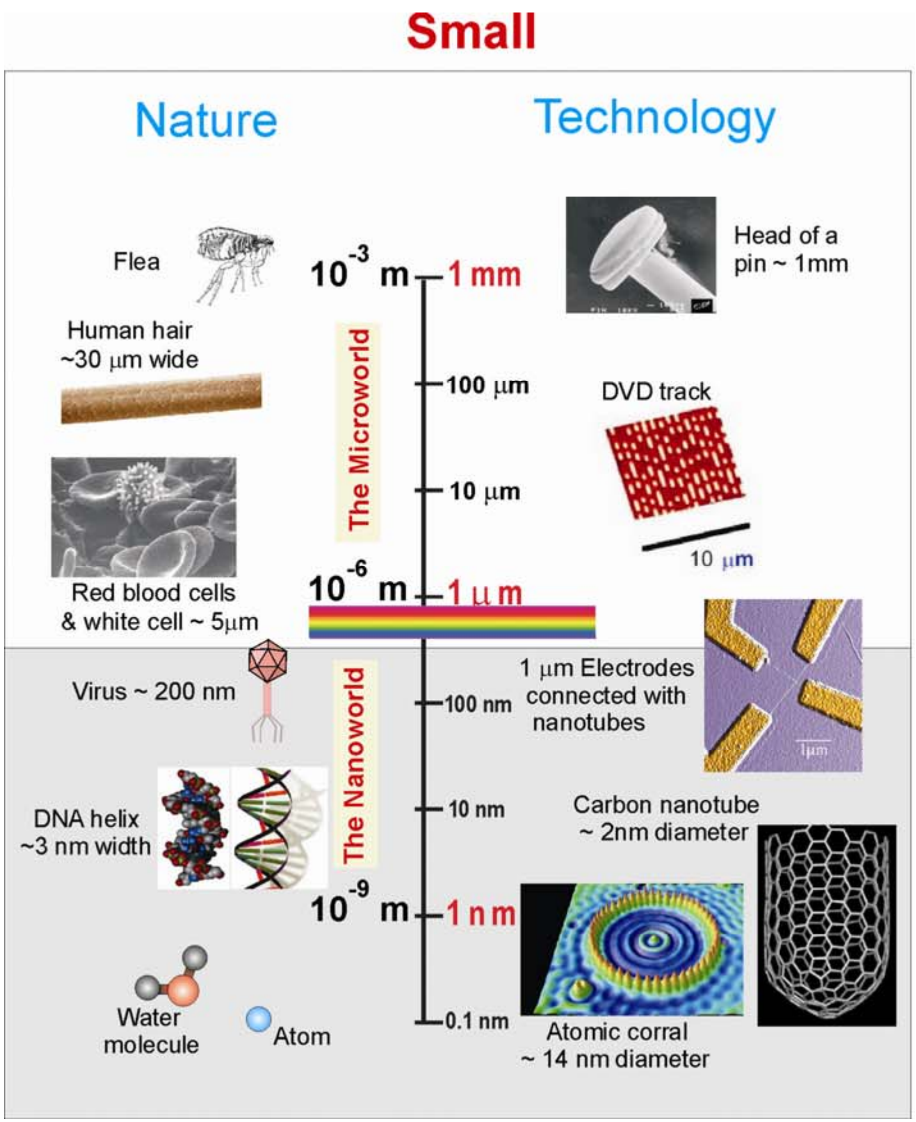
The New Paradigm: Smaller and Faster

Examples: Magnetic Devices in Computers



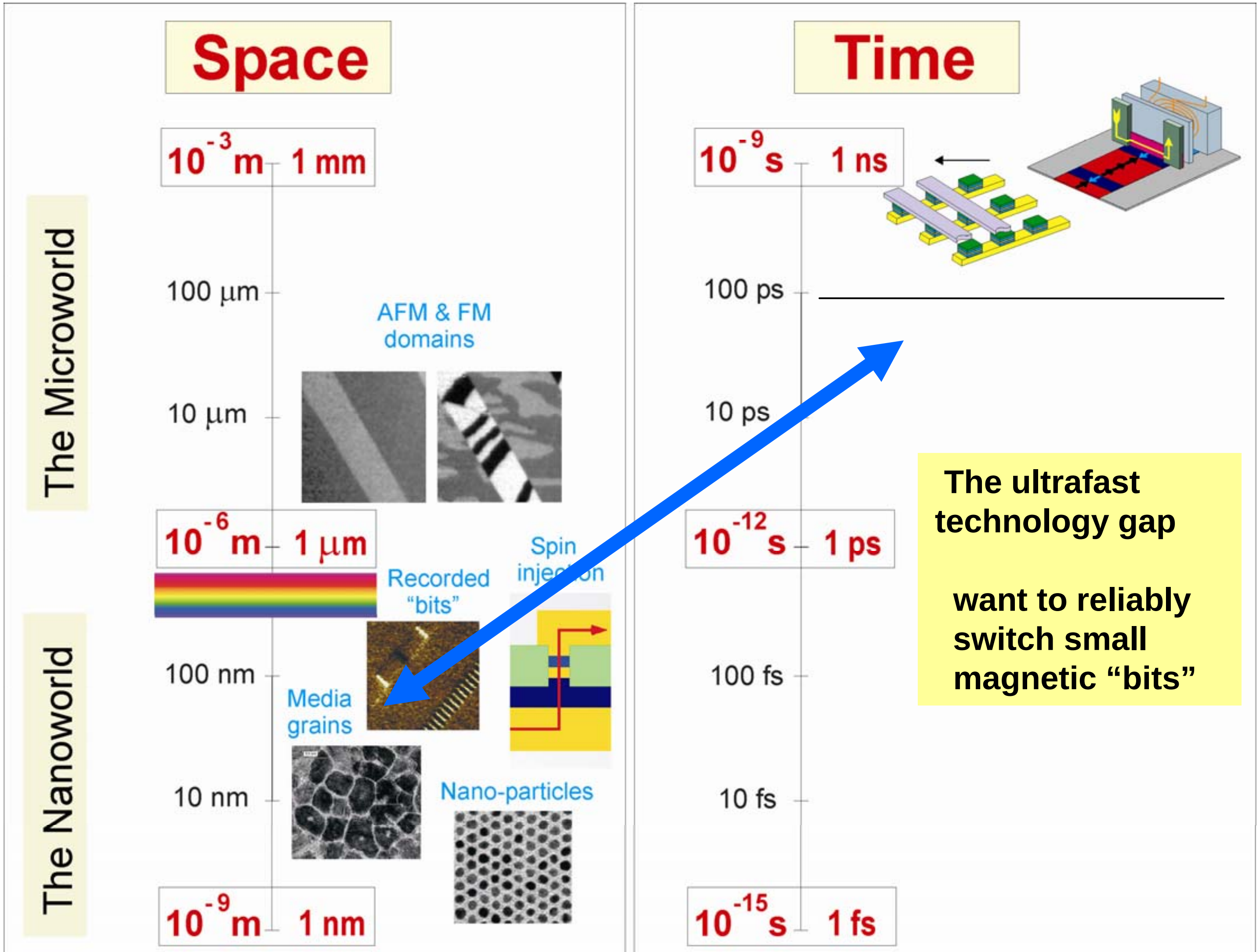
Future: < 100 nm, < 1 nsec ⟶ **Ultrafast Nanoscale Dynamics**

Space and Time: What is ultra-small and what is ultra-fas



Rule of thumb: the smaller the faster!

The Technology Problem in Magnetism: Smaller and Faster



X-rays combine nanometer spatial with picosecond time resolution

"seeing the ultrafast magnetic nanoworld"

What does it take to explore advanced magnetic materials and phenomena ?

General requirements:	*Technique requirements:*
see the invisible	**nanoscale spatial resolution**
separate spin and orbital contributions	**sensitive to s-o coupling**
study thin films and interfaces	**large cross section for "signal"**
look below the surface	**depth sensitivity**
distinguish components	**elemental (chemical) specificity**
resolve dynamic motions	**time resolution < 1 nanosecond**

…. x-rays

The 5 keys to magnetic information

- x-ray cross section and flux
- x-ray tunability: resonances and sum rules
- x-ray polarization
- x-ray spatial resolution
- x-ray temporal resolution

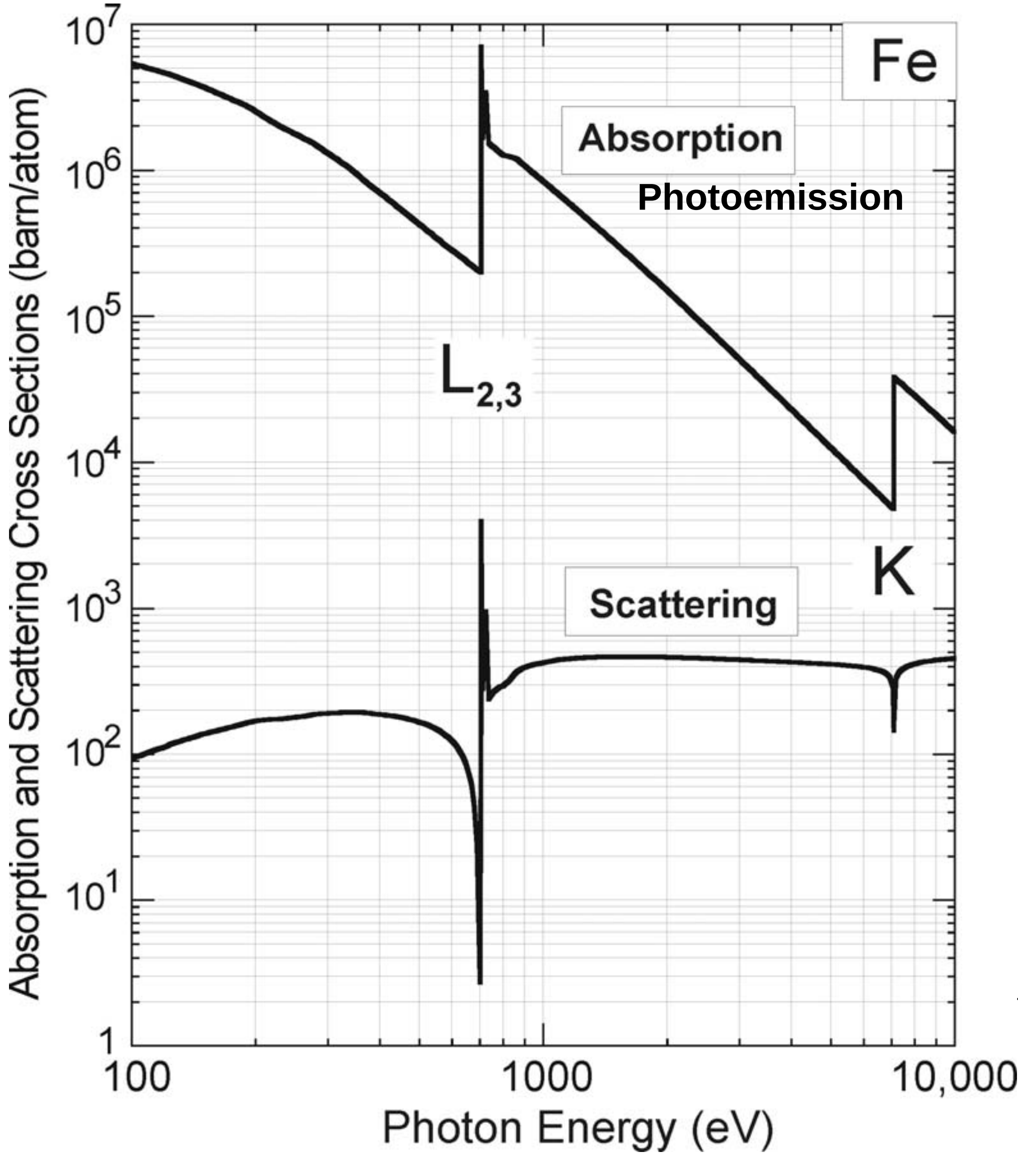
X-rays and Magnetism

Fundamentals

Tunable x- rays offer variable interaction cross sections

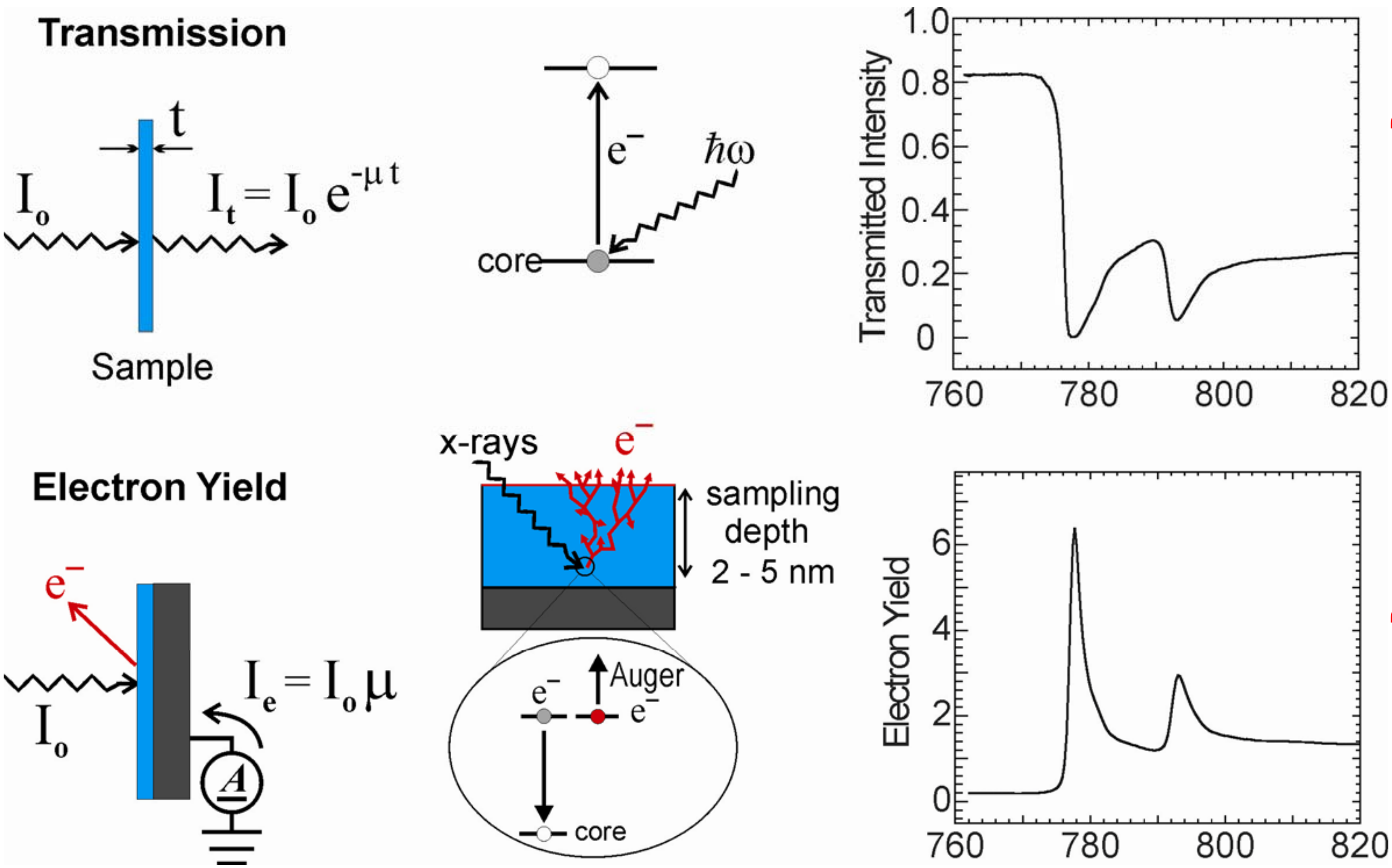
optical light

electrons



neutrons

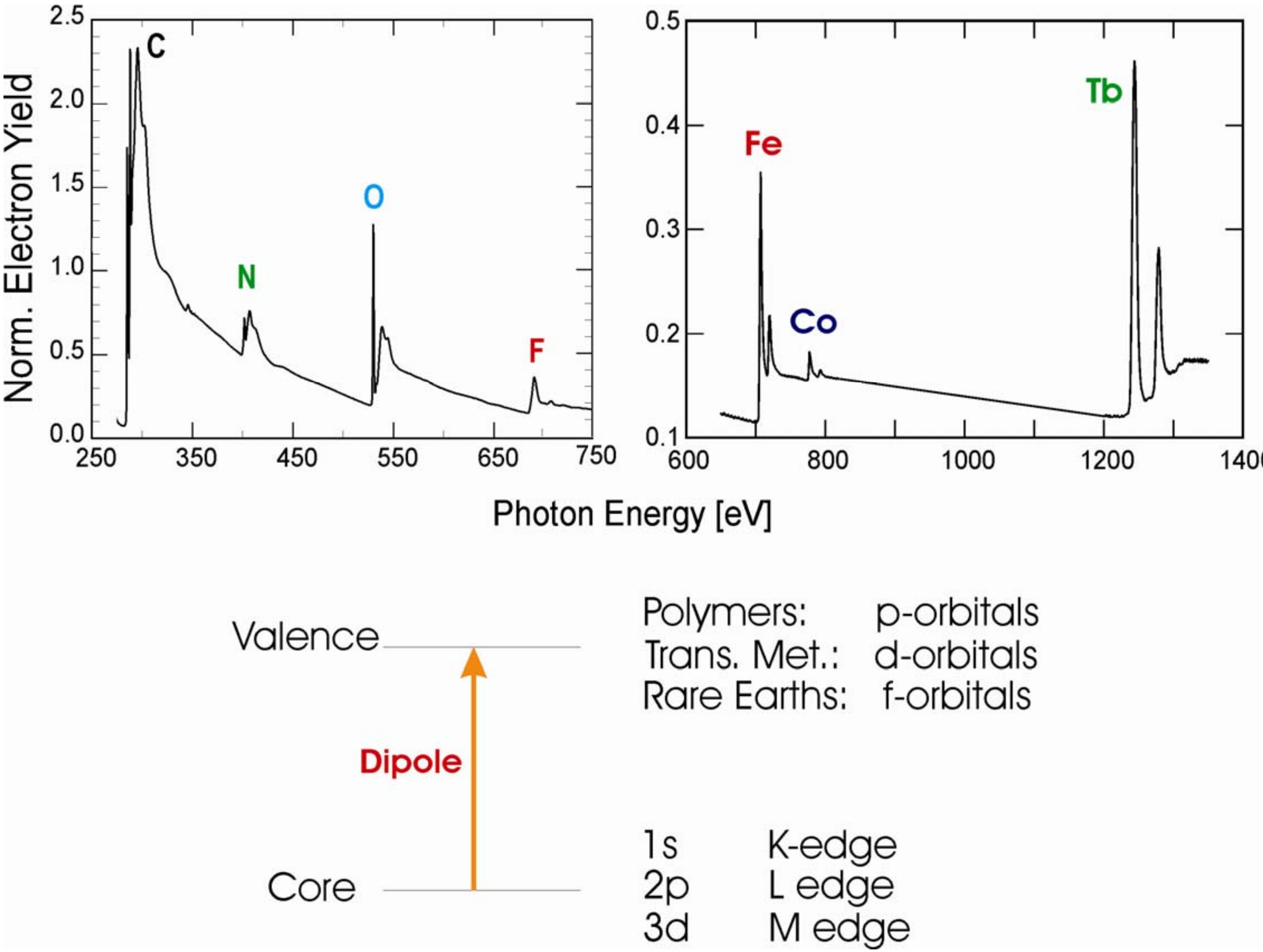
X-Ray Absorption
The simplest x-ray technique



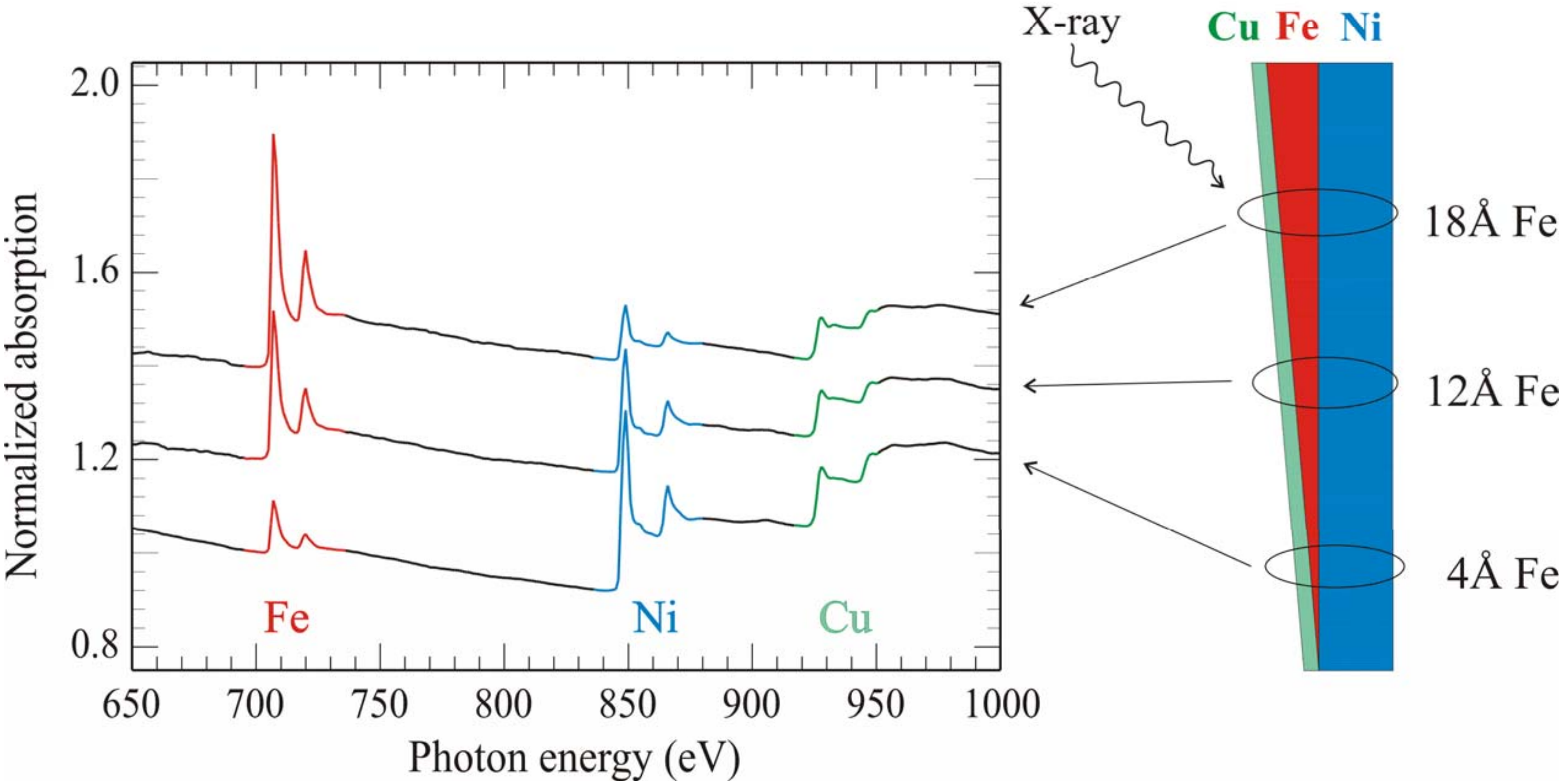
“Photons lost”

“Electrons generated”

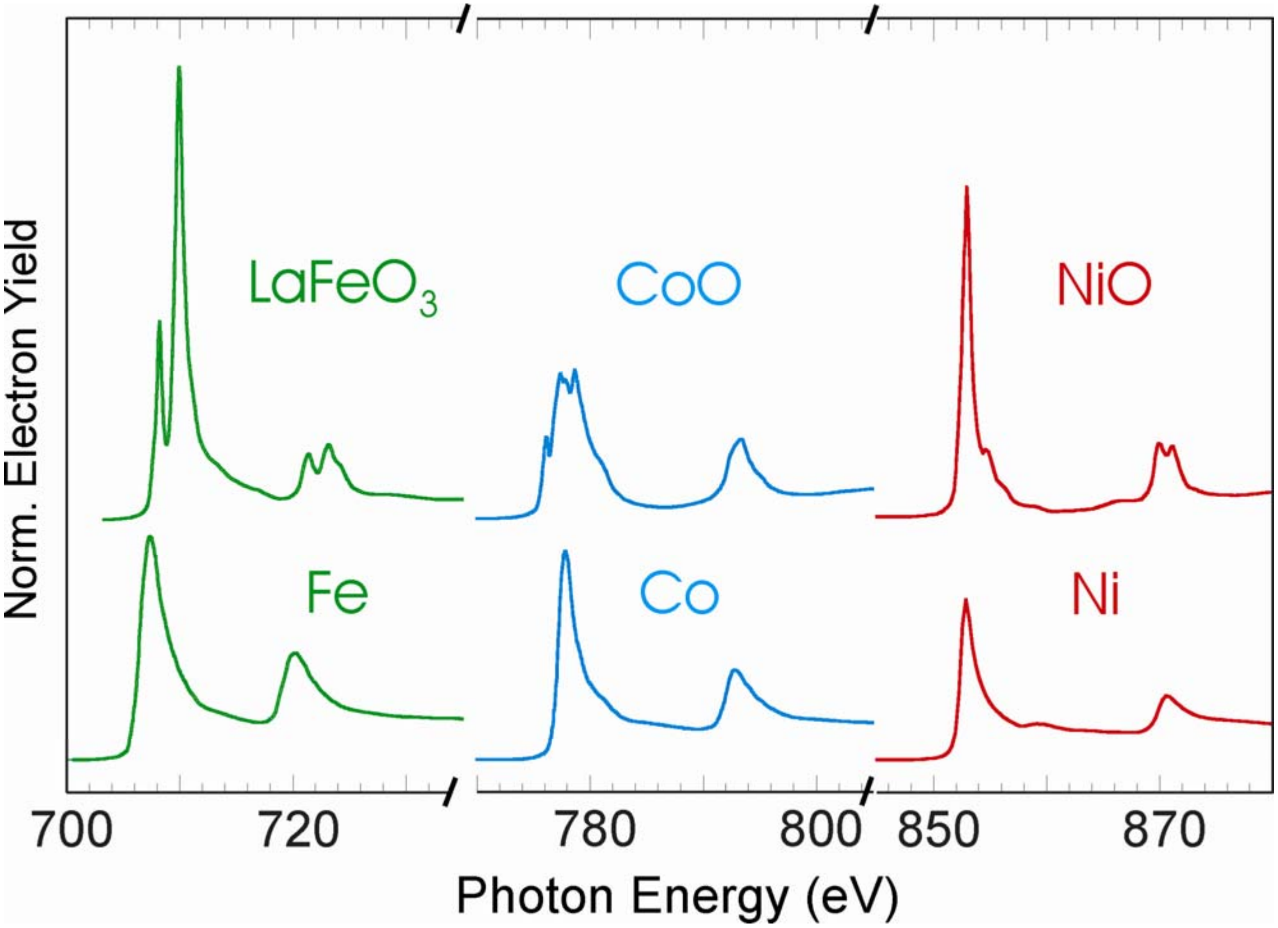
Tunable x-rays offer elemental specificity



X-rays can pick materials apart: layer-by-layer



Rich “multiplet structure” reveals local bonding

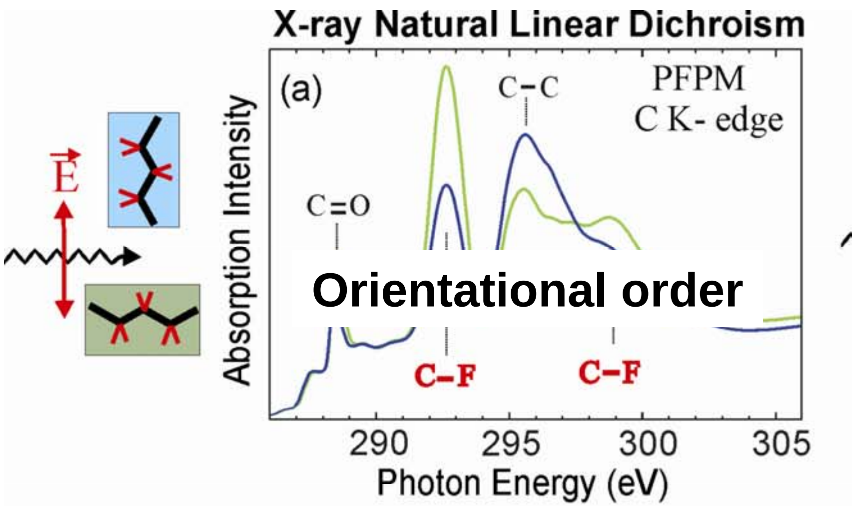


The power of polarization

-

Magnetic dichroism

Polarized x-rays offer orientation sensitivity

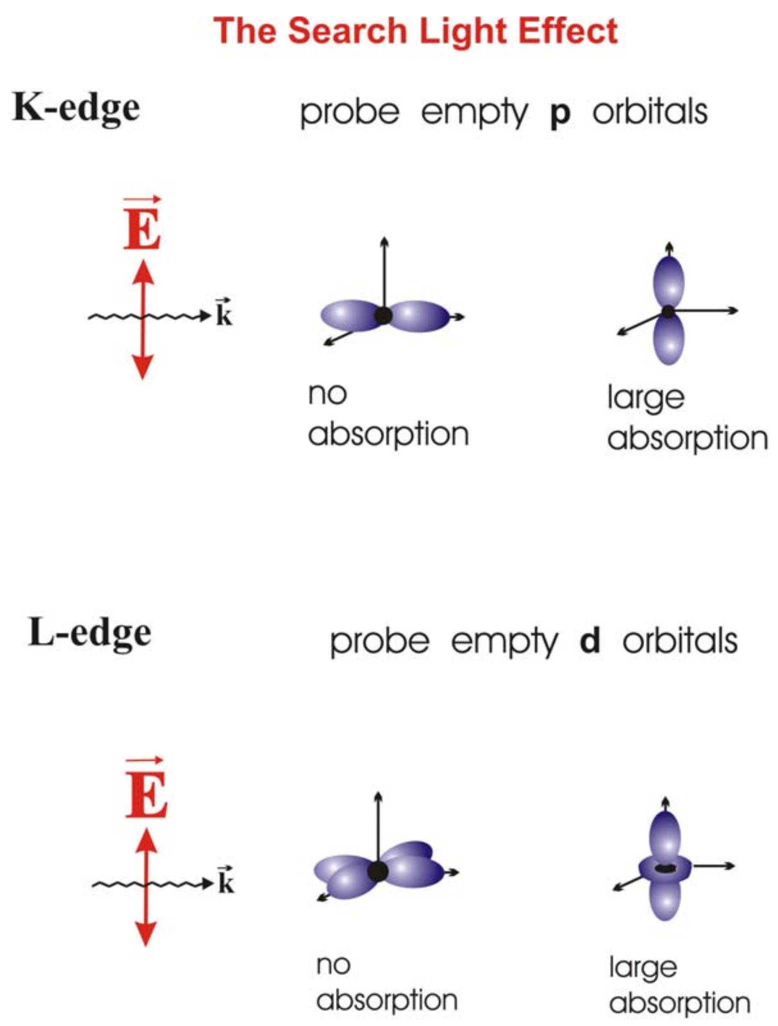


Stöhr *et al.*, Phys. Rev. Lett. **47**, 381 (1981)

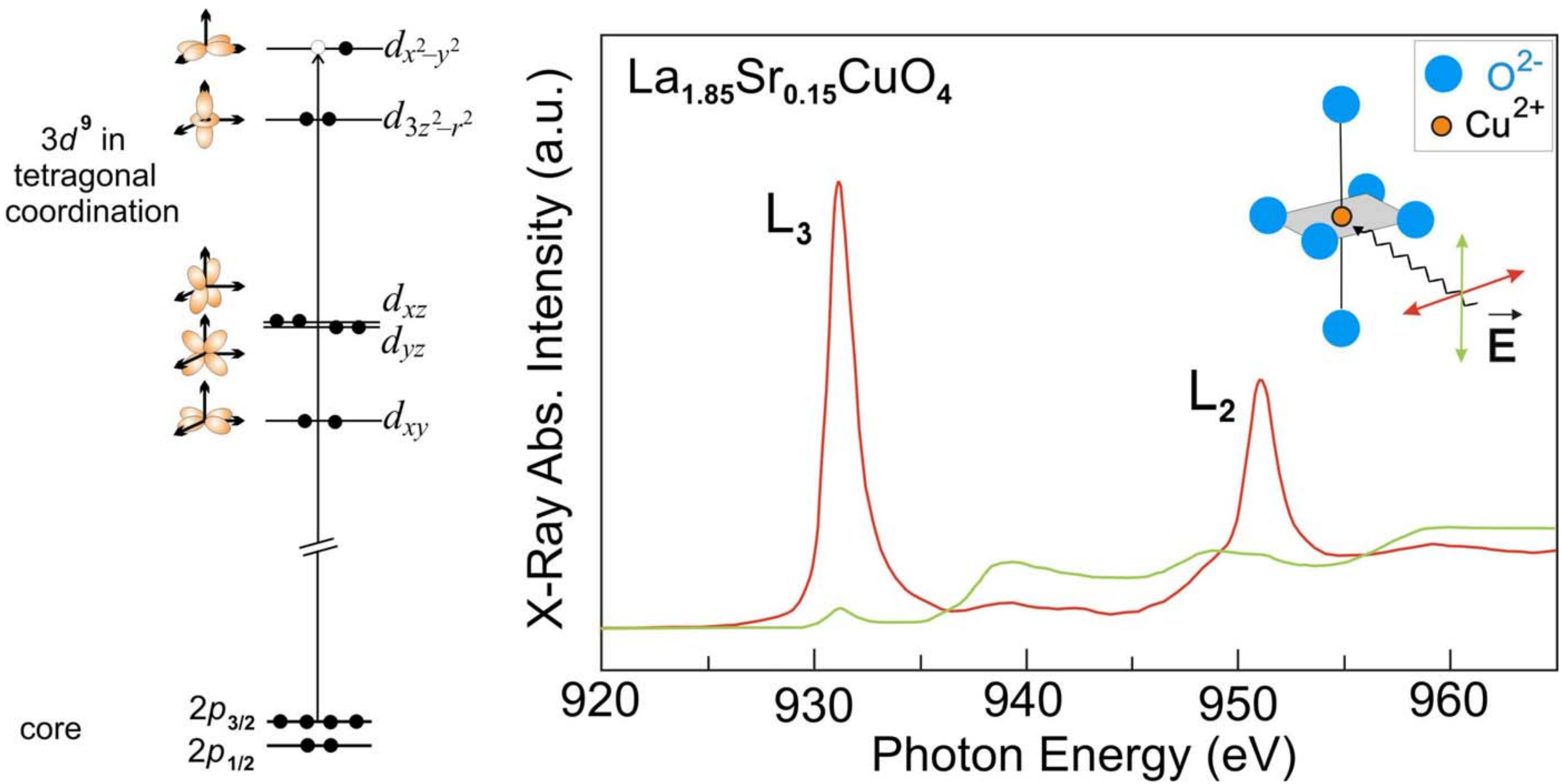
X-ray Natural Linear Dichroism

XNLD

X-ray Natural Linear Dichroism



Linear Natural Dichroism in a d-electron system



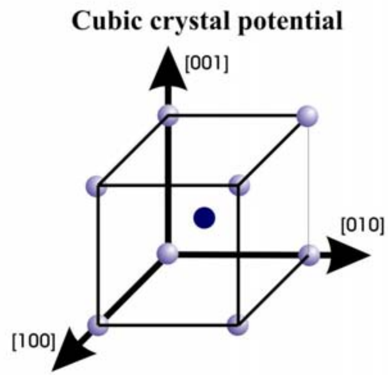
C. T. Chen *et al.* PRL **68**, 2543 (1992)

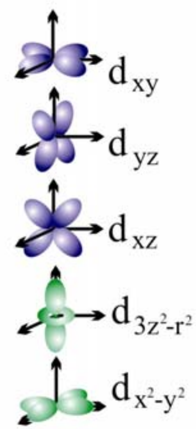
X-ray Magnetic Linear Dichroism

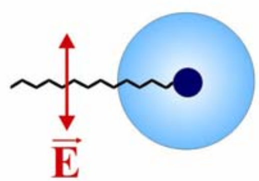
XMLD

Polarization, Charge and Spin: X-Ray Magnetic **Linear** Dichroism

Non-magnetic state

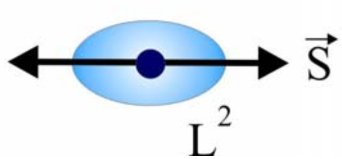






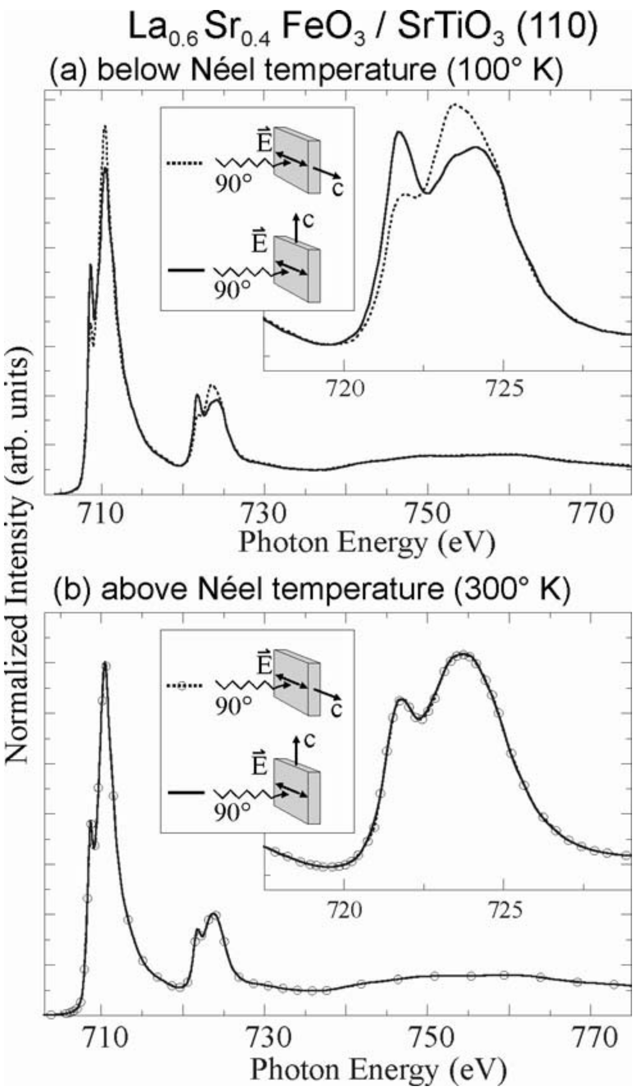
d electron charge density is isotropic
no polarization dependence

Magnetic state - preferred spin axis



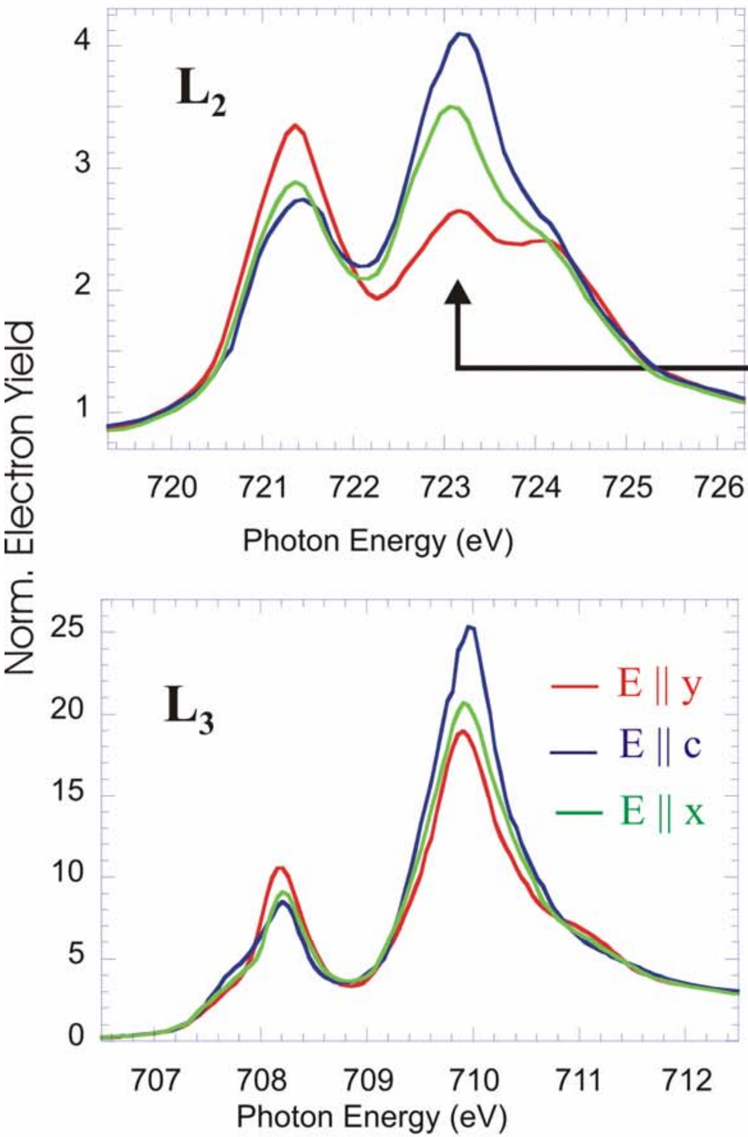
spin-orbit coupling distorts charge
creates polarization dependence

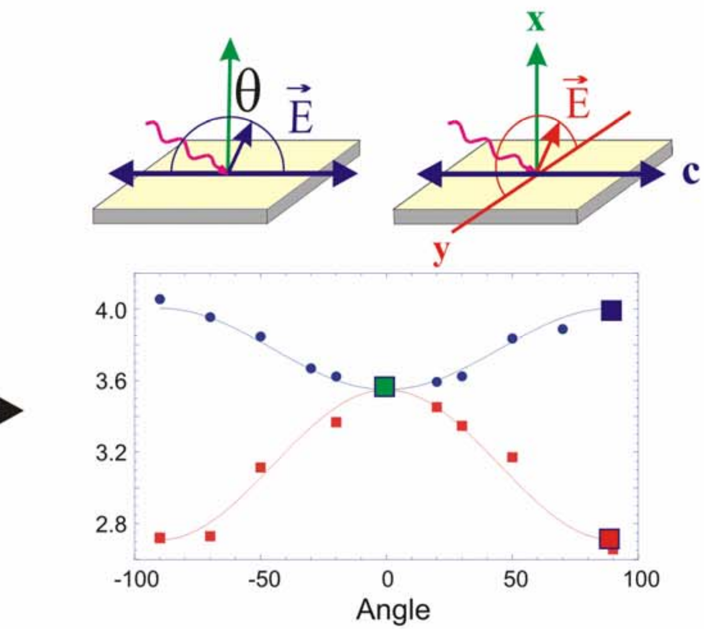
XMLD – spectra below and above T_N



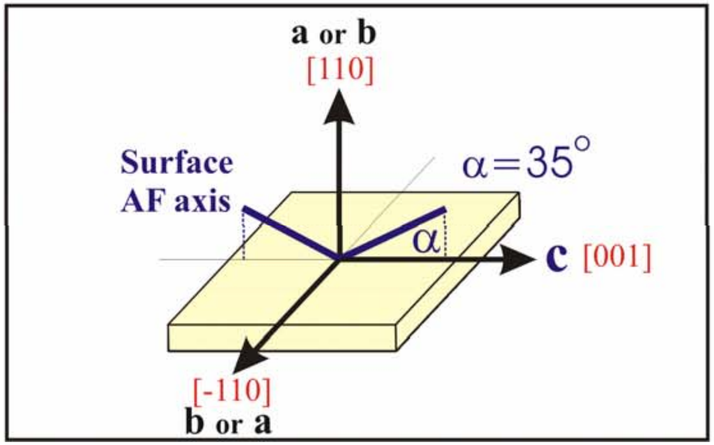
Lüning et al. Phys. Rev. B 67, 214433 (2003)

XAFS Spectra and Orientation of AF Axis in $LaFeO_3$ on $SrTiO_3$(110)





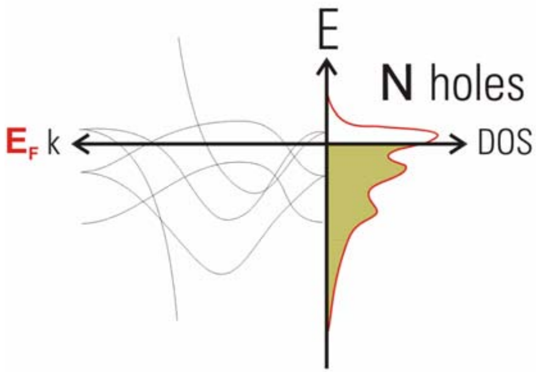
AF axis is rotated from bulk



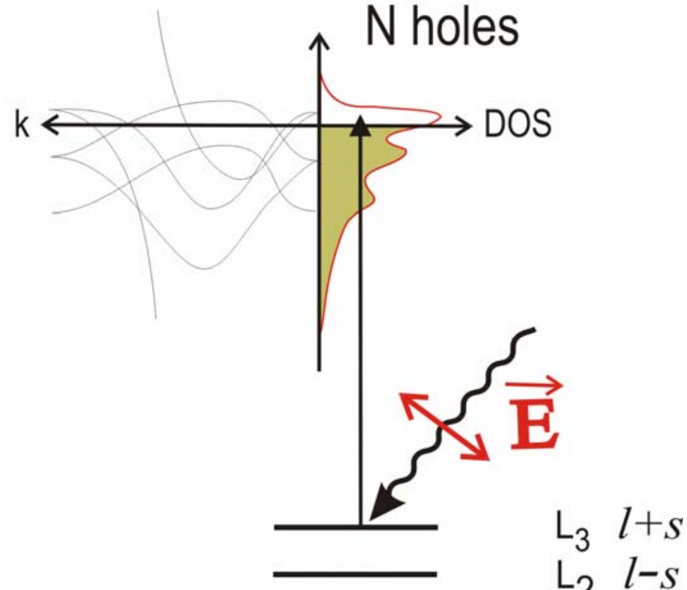
X-ray Magnetic Circular Dichroism

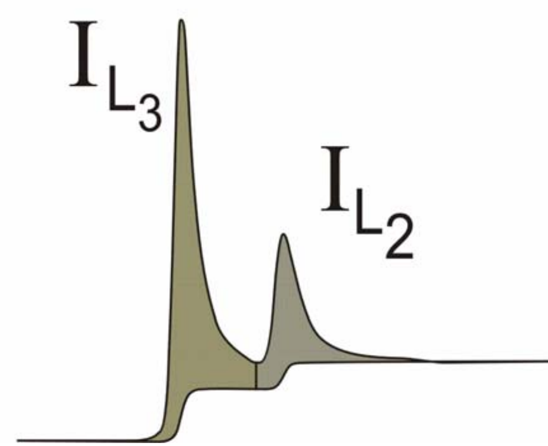
XMCD

Properties of 3d Transition Metals

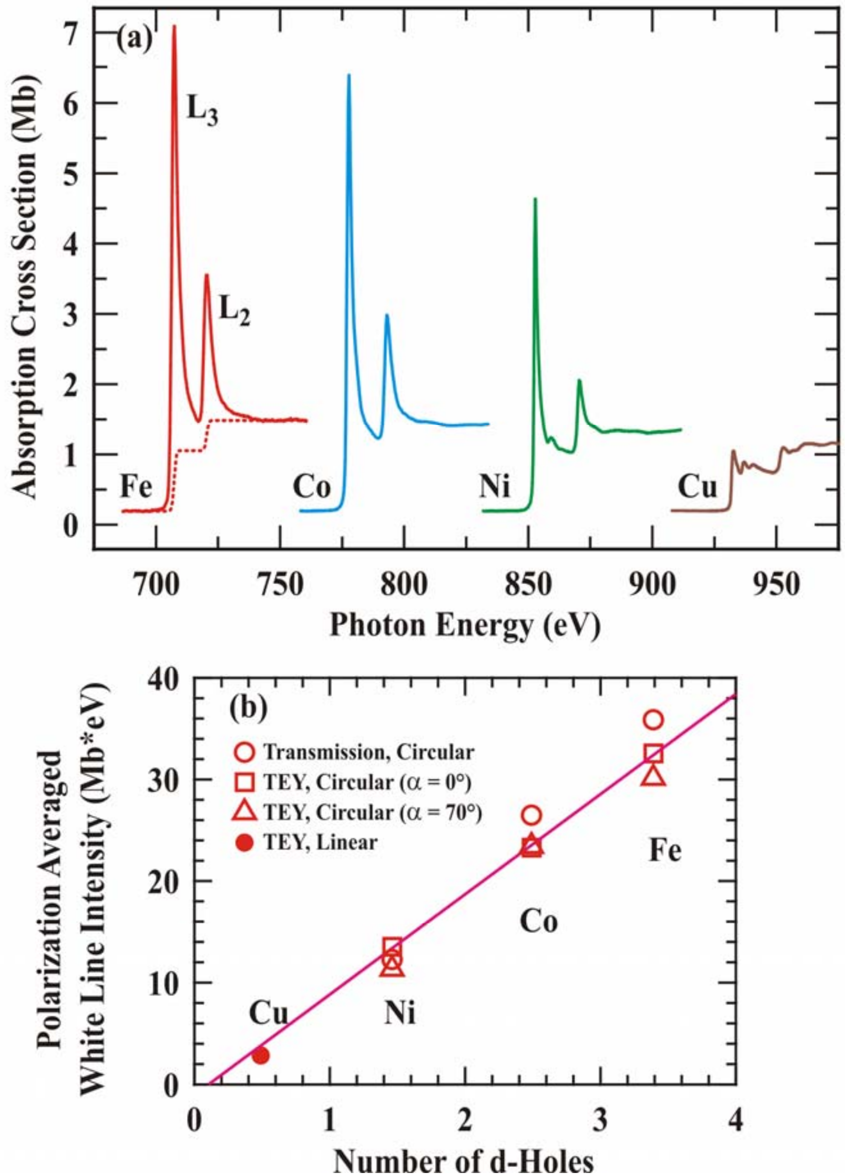


	holes
Fe	3.4
Co	2.5
Ni	1.5

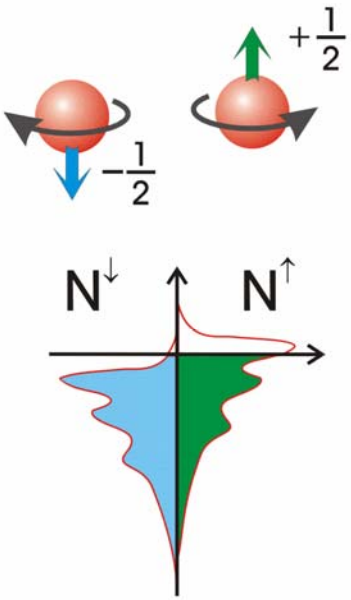




White Line Intensity in 3d Metals

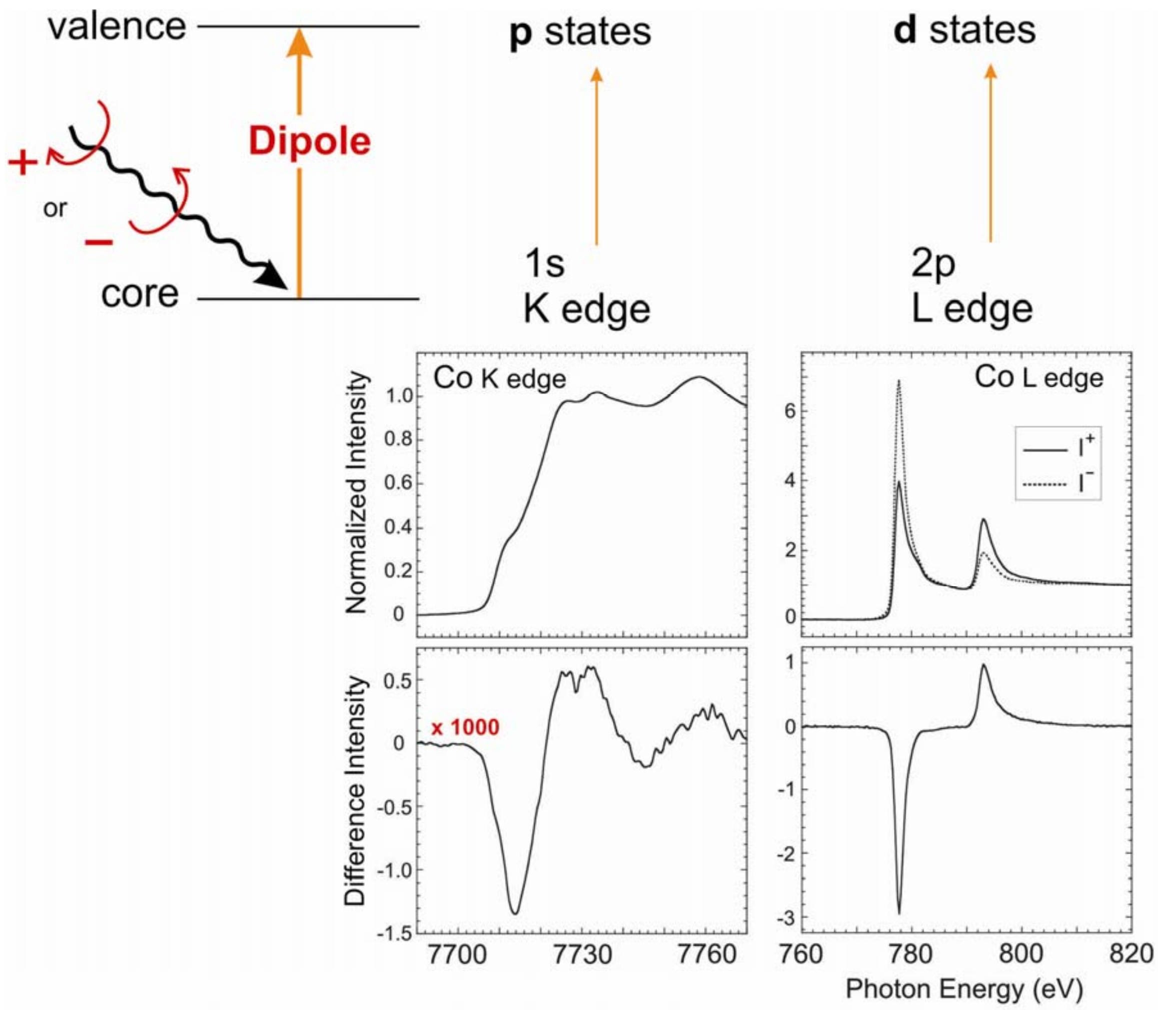


X-ray Magnetic Circular Dichroism

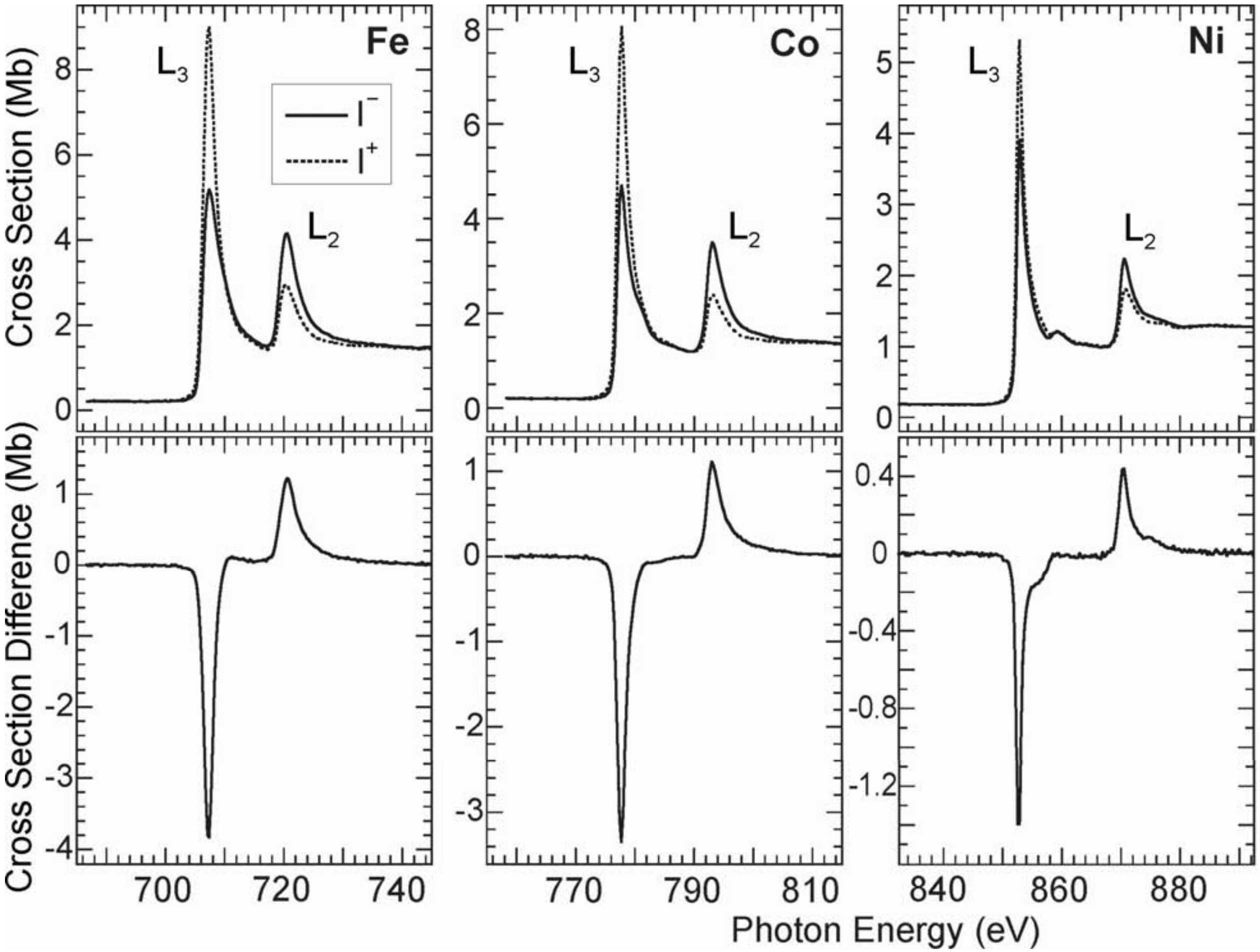


m_{spin}^{tot}	m_{spin}^{d}	m_{spin}^{sp}
2.19	2.26	−0.07
1.57	1.64	−0.07
0.62	0.64	−0.02

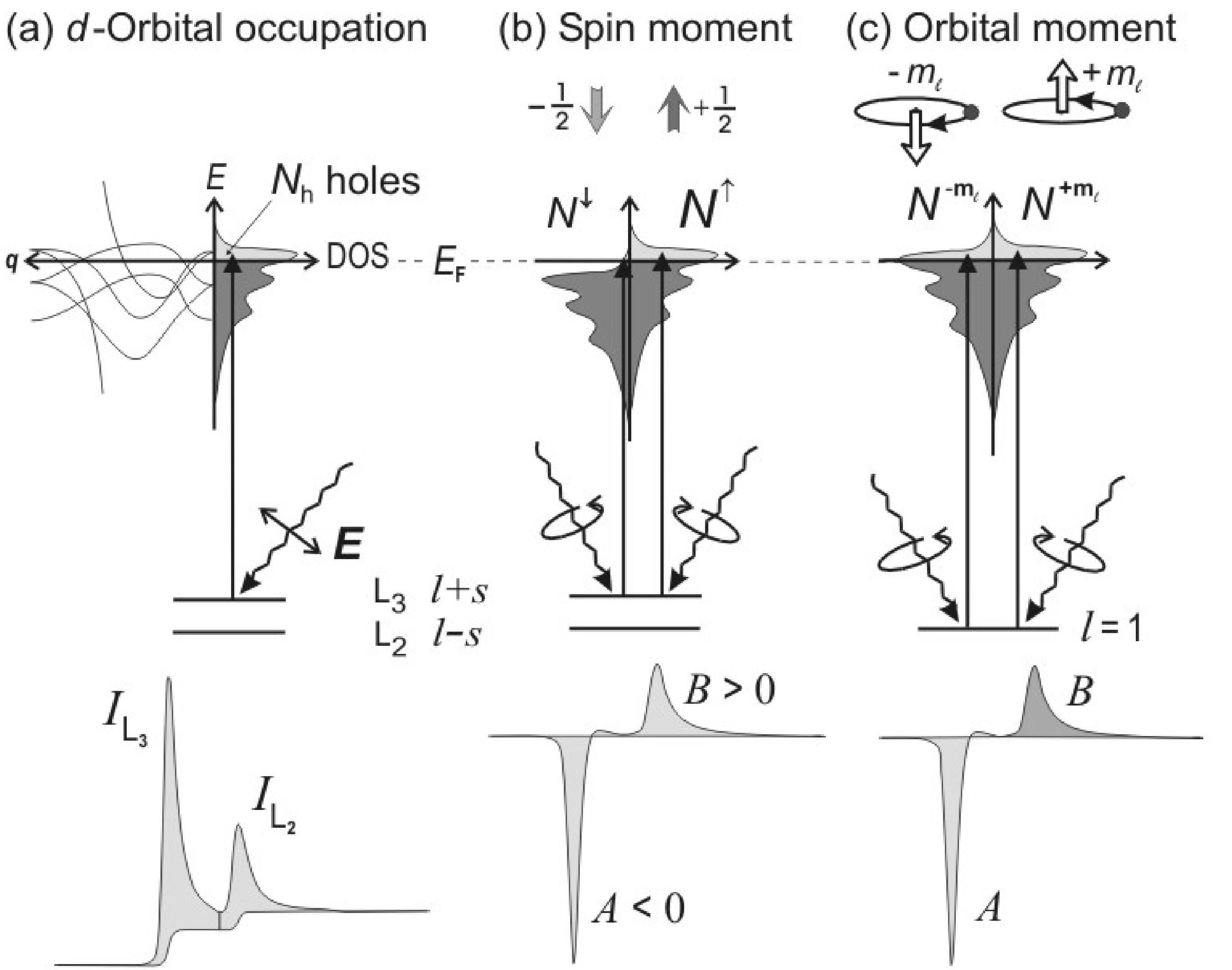
Soft x-rays are best for magnetism



XMCD spectra of the pure ferromagnetic 3d metals



The sum rules



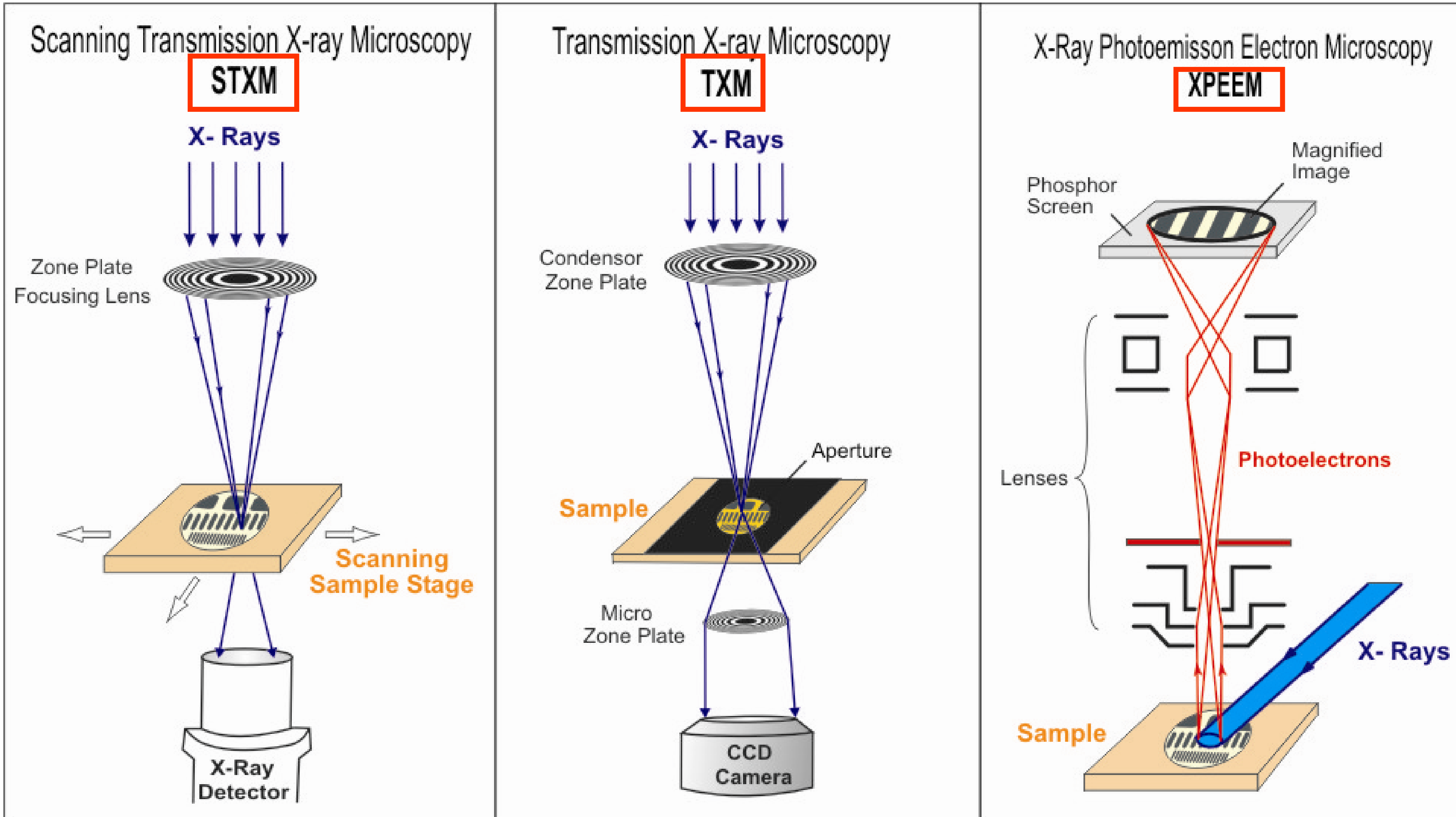
$N_h = \langle I_{L_3} + I_{L_2} \rangle / C$

$m_s = \mu_B \langle -A + 2B \rangle / C$

$m_o = -2\mu_B \langle A + B \rangle / 3C$

X-ray Magnetic Microscopy

Focusing of x-rays offers nanoscale resolution



Present resolution in the 20 - 40 nm range

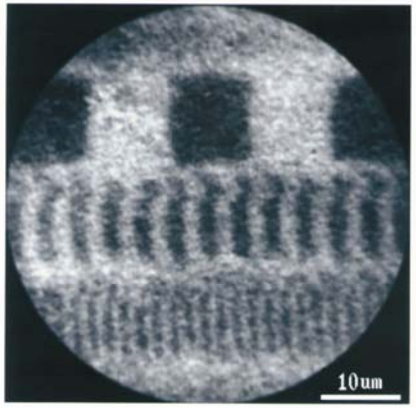
x-rays in / x-rays out – bulk like sensitivity

x-rays in / electrons out – near-surface sensitivity

Polarization Dependent Imaging with X-Rays

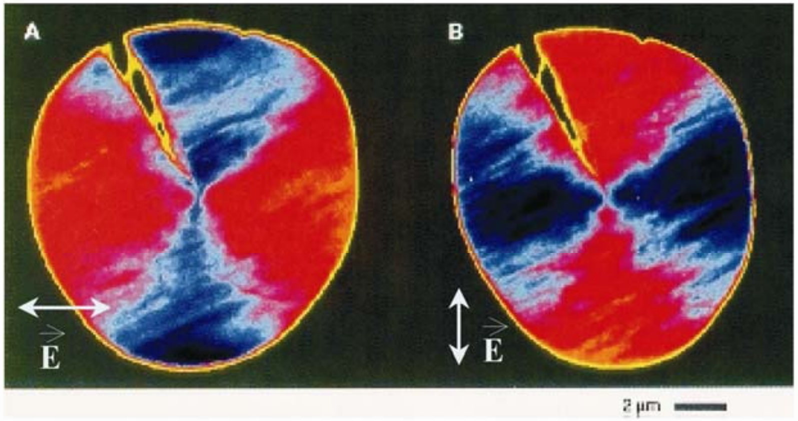
X-Ray Magnetic Circular Dichroism

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



X-Ray Natural Linear Dichroism

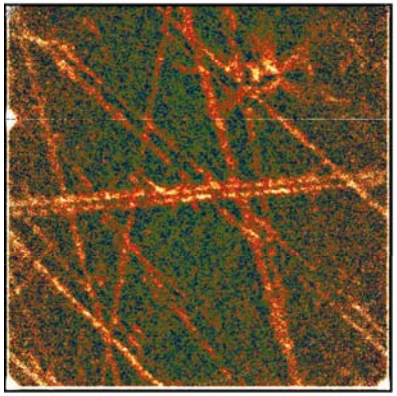
Ade and Hsiao., Science **262**, 1427 (1993)

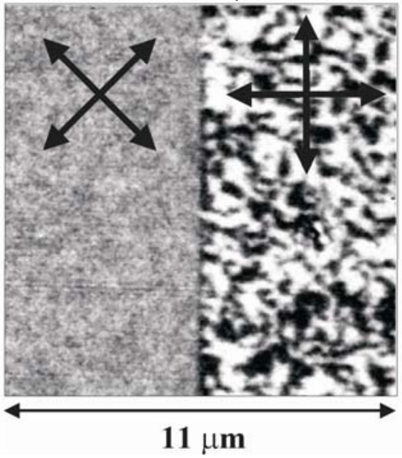


X-Ray Magnetic Linear Dichroism

Stöhr *et al.*, Phys. Rev. Lett. **83**, 1862 (1999)

Scholl *et al.*, Science **287**, 1014 (2000)



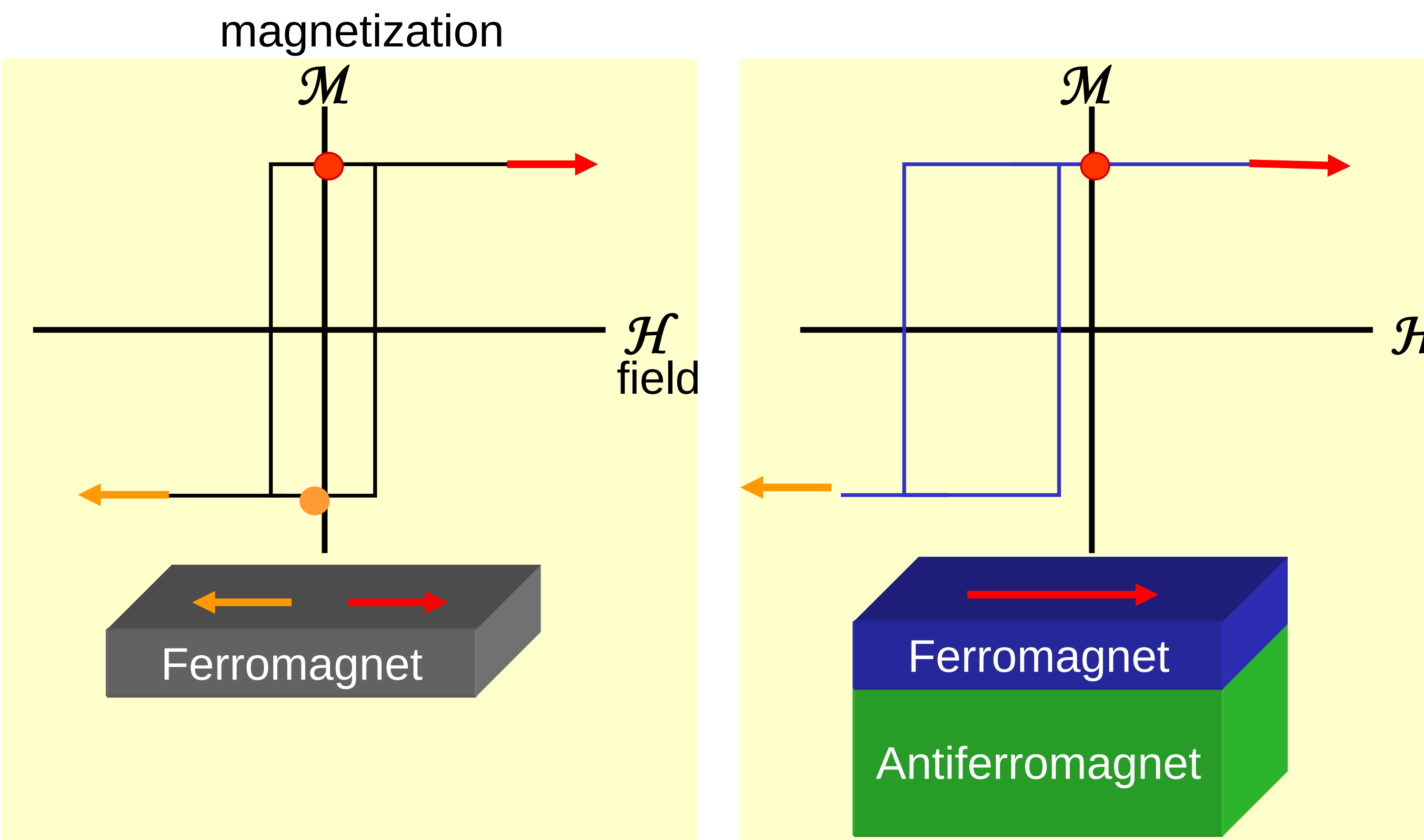


Applications of X-Rays

in Modern Magnetism

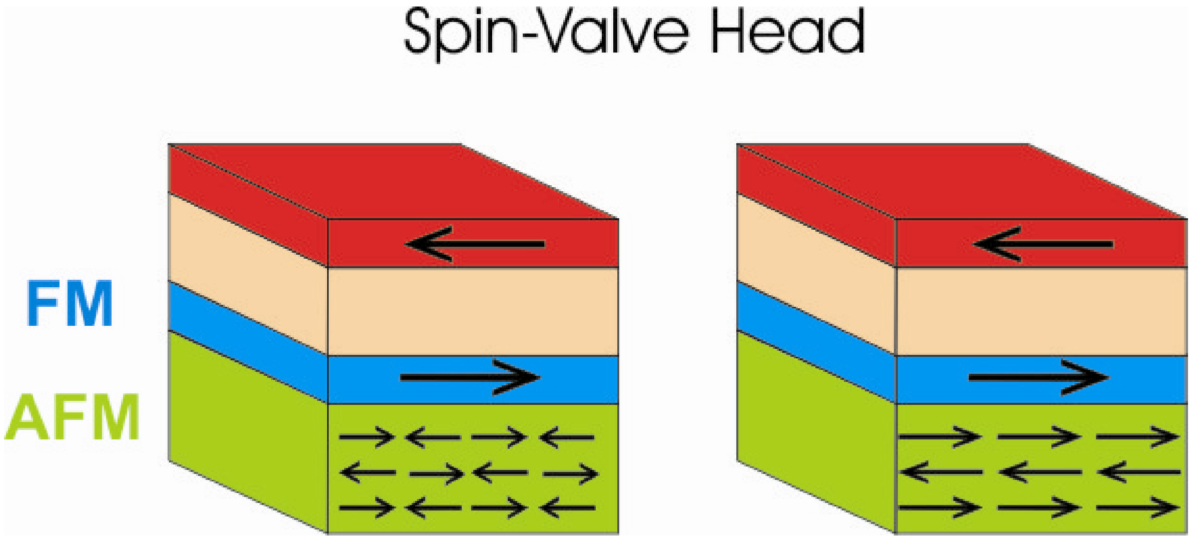
An important problem: Exchange Bias

discovered in 1956, technologically used for many years, ill understood



$\mathcal{M}$ of blue layer is "pinned"
or "exchange biased"

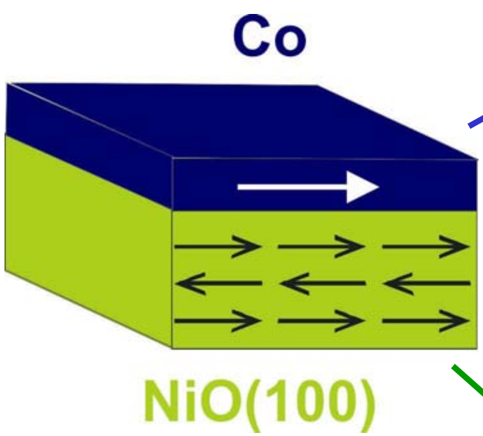
Example : The Spin Valve Sensor



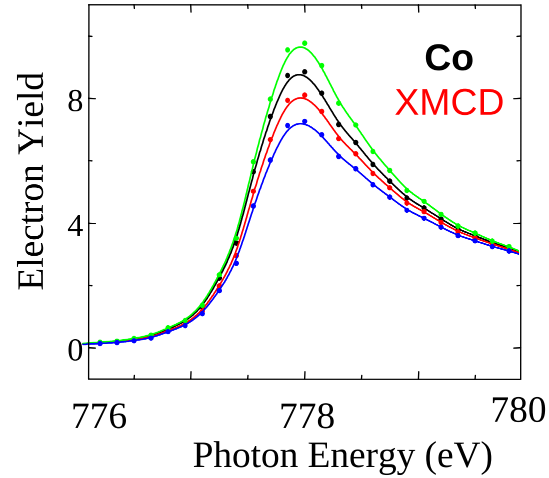
AFM is “neutral”

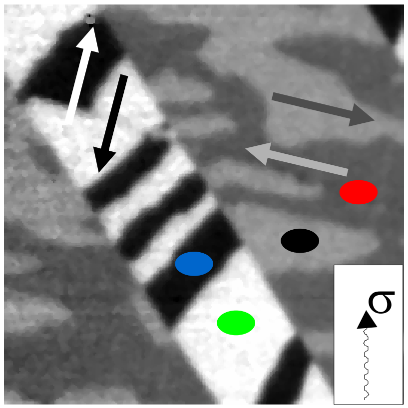
AFM is “magnetic” at surface

Coupling of ferromagnetic and antiferromagnetic domains

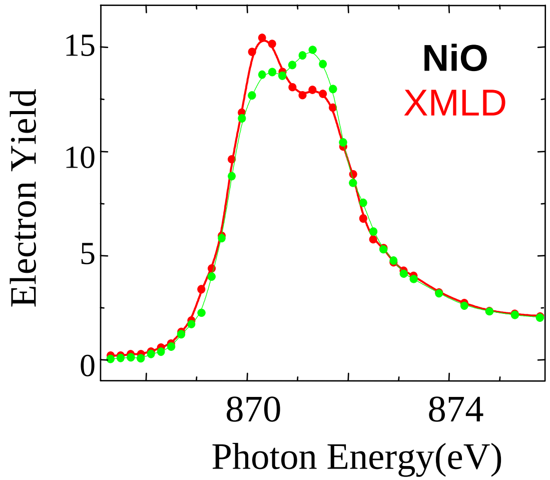


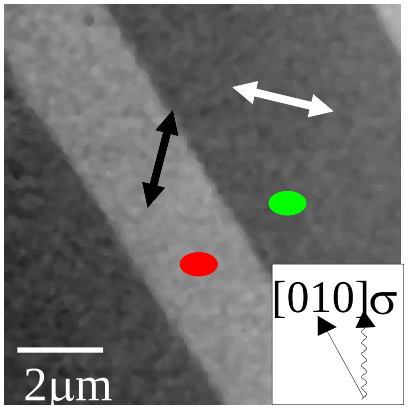
Co edge – use **circular** polarization – **ferromagnetic** domains





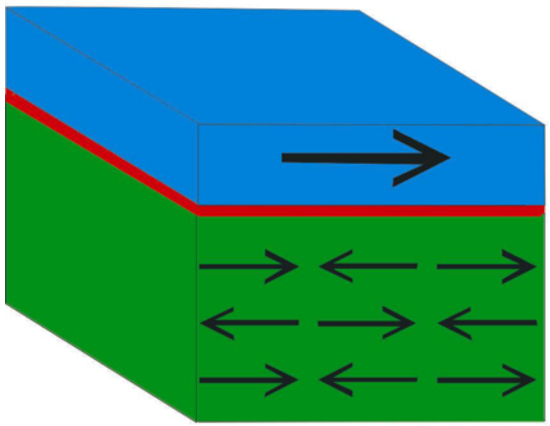
Ni edge – use **linear** polarization – **antiferromagnetic** domains

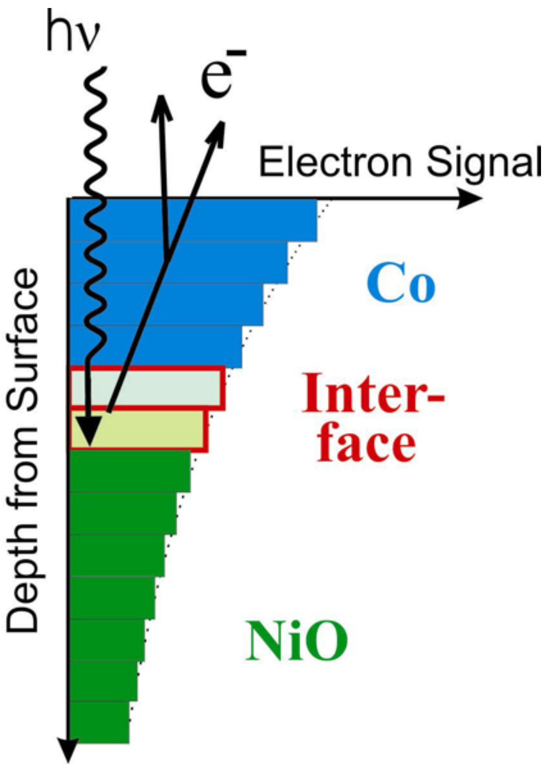




H. Ohldag *et al.*, PRL **86**, 2878 (2001)

X-Rays-in / Electrons-out - A way to study Interfaces



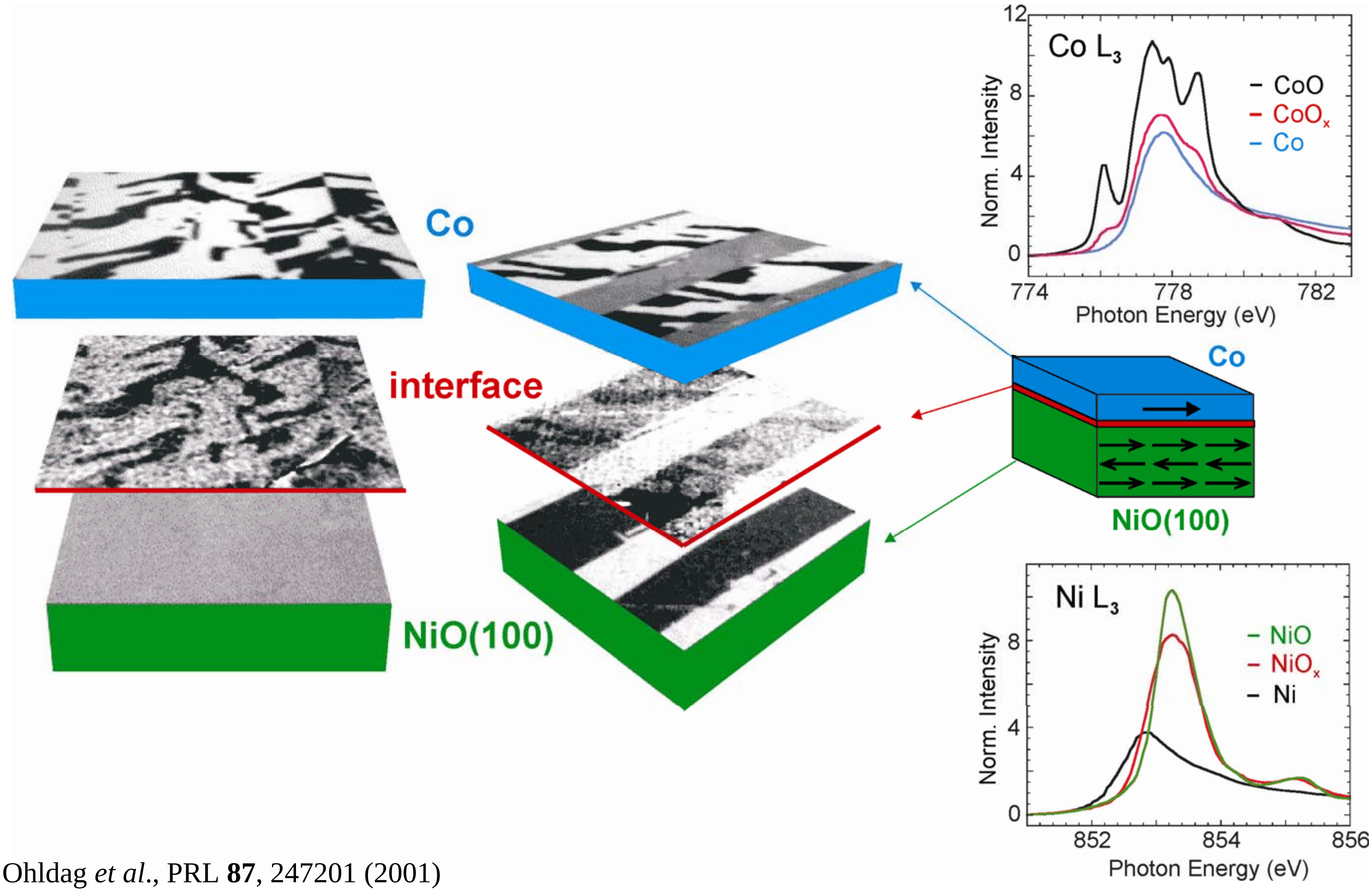


FM Co – tune to Co edge – circular polarization

AFM NiO – tune to Ni edge – linear polarization

FM Ni(O) – tune to Ni edge – circular polarization

Images of the Ferromagnet-Antiferromagnet Interface



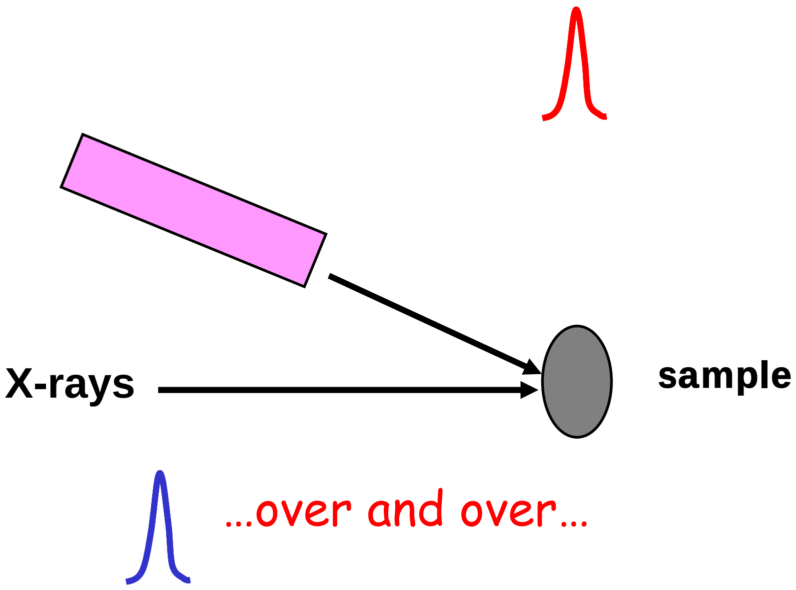
Ohldag *et al.*, PRL **87**, 247201 (2001)

From Static Pictures

to

Movies

Principle of Pump/Probe Dynamics

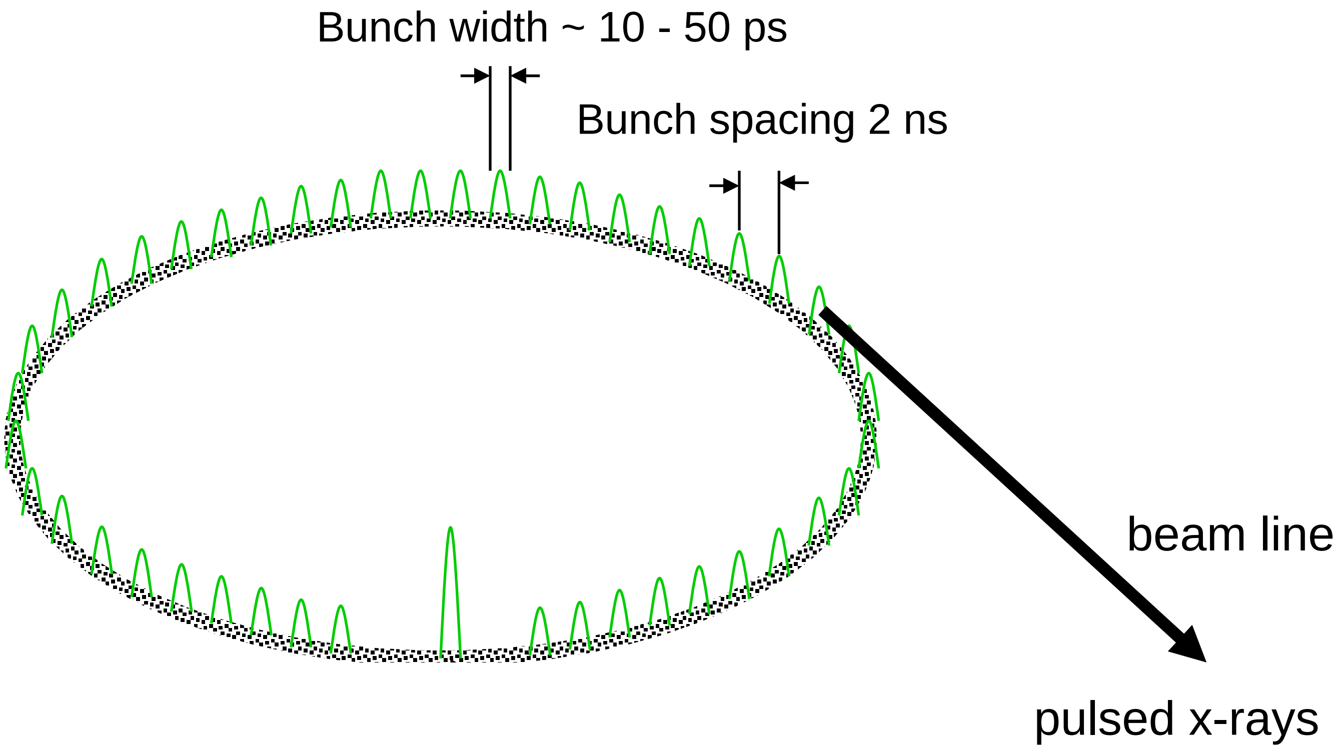


Process has to be repeatable:

Not enough intensity for
Single-shot x-ray experiments

Pulsed X-Rays from Electron Storage Rings offer picosecond temporal resolution

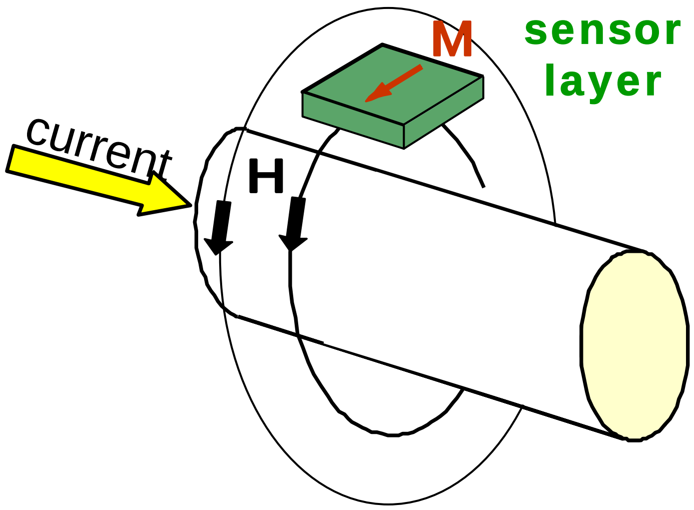
Electron bunches radiate pulsed x-rays



Spin currents: a new way of magnetic switching:

traditional switching

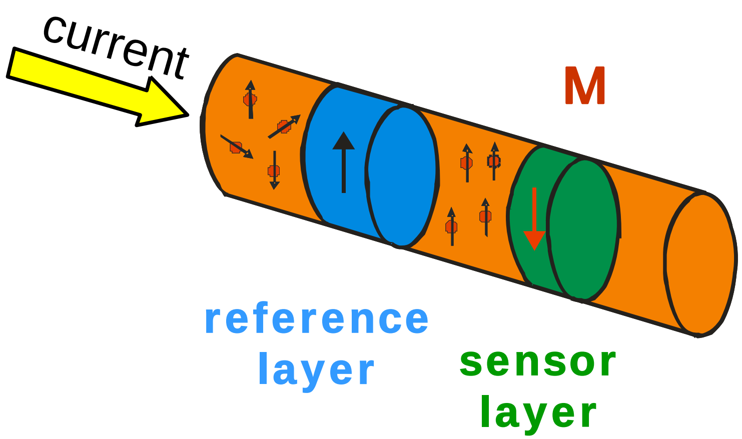
torque on M by "Oersted field"



Weak, long range

new idea

torque on M by "spin current"



Strong, short range

Spin currents: a new way of magnetic switching:

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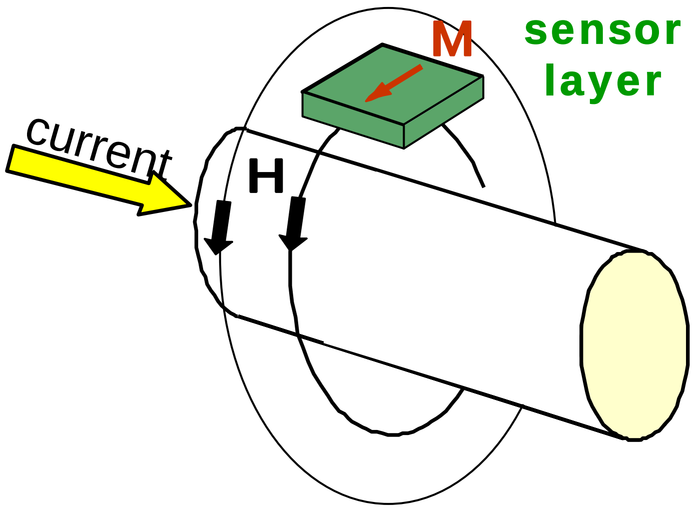

Weak, long range

new idea

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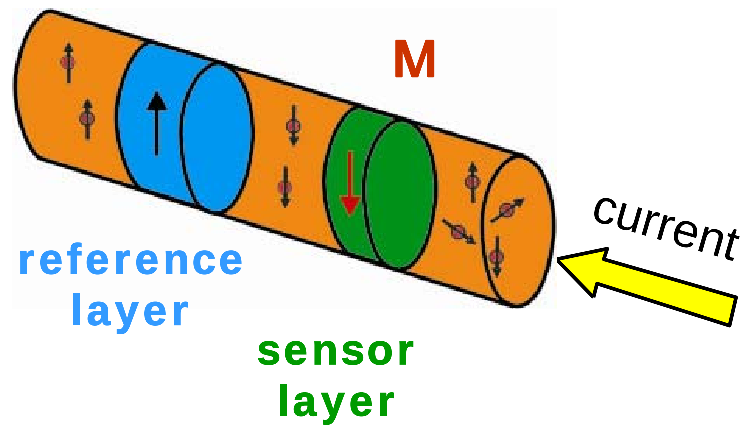
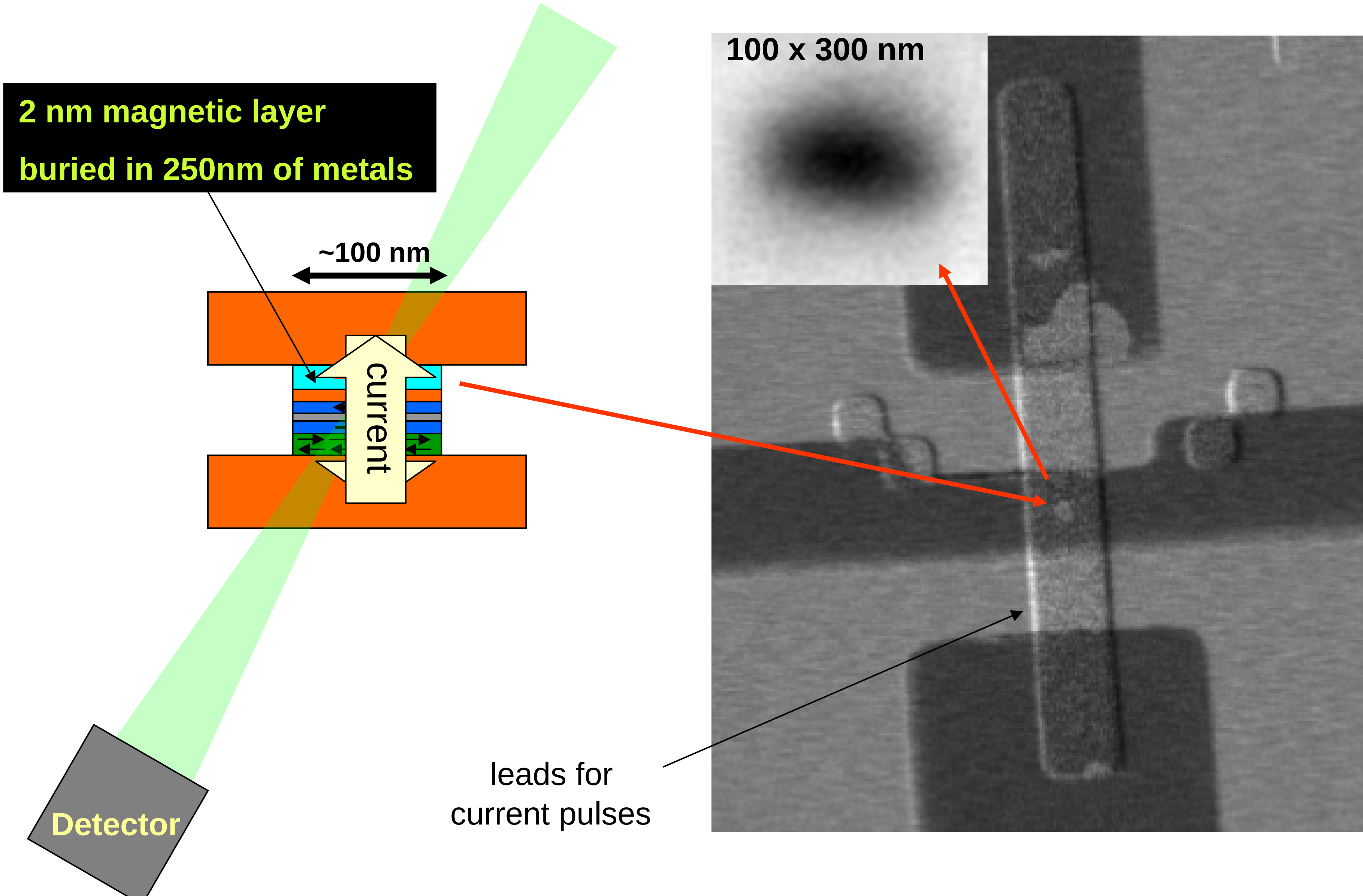


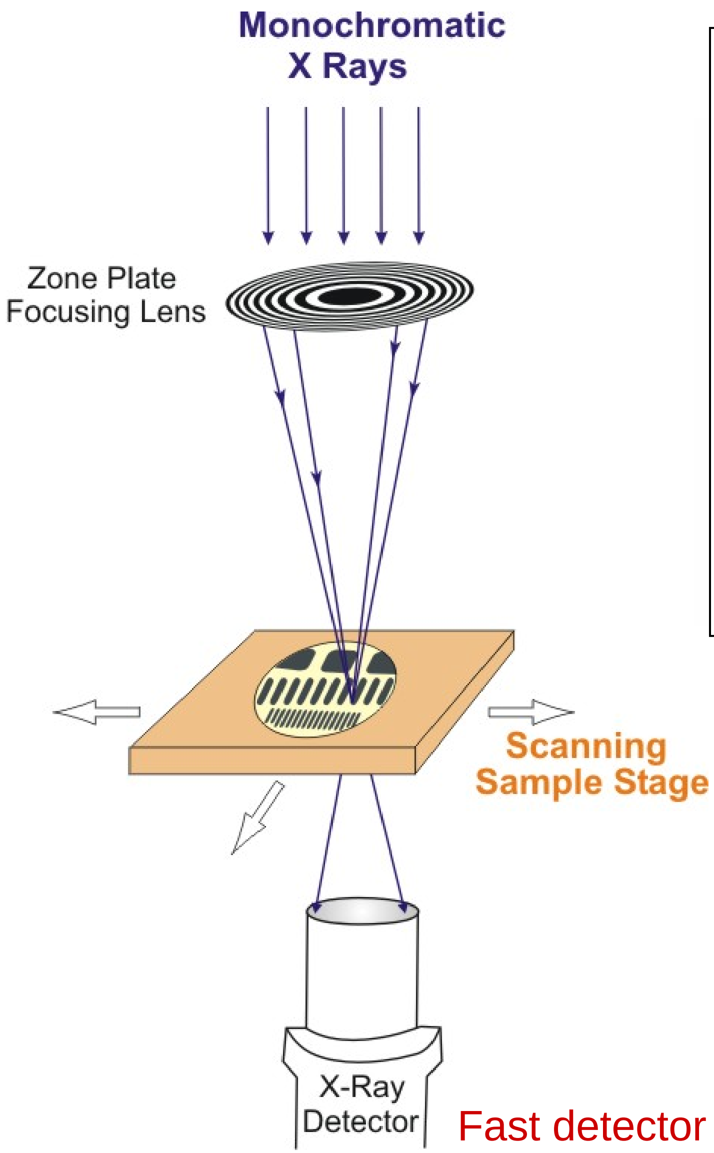
Strong, short range

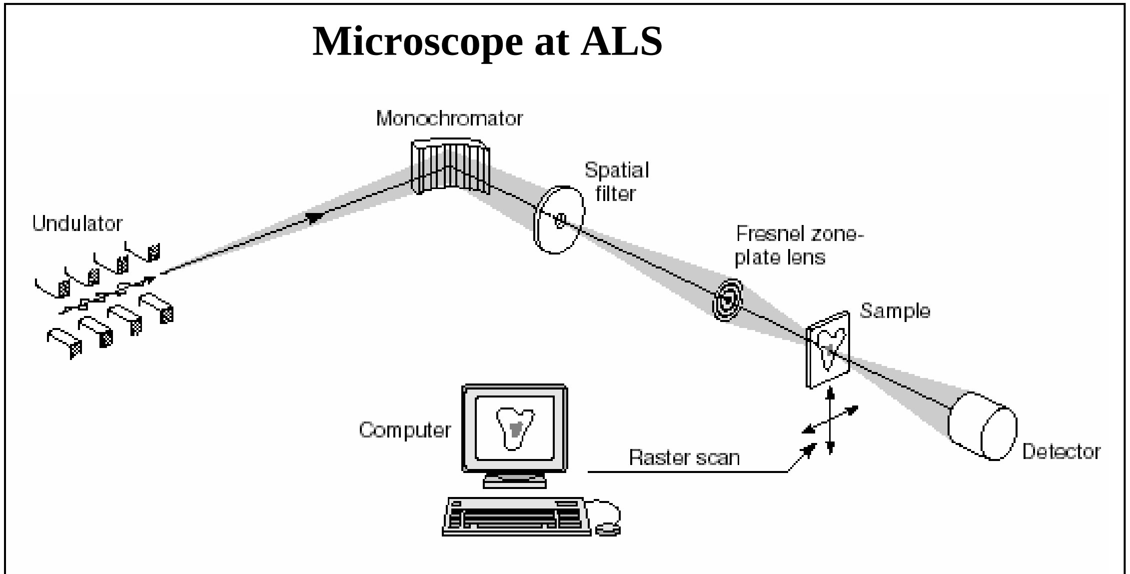
Scanning Transmission X-Ray Microscopy image of spin injection structure



Y. Acremann et al., Phys. Rev. Lett. **96**, 217202 (2006)

Scanning Transmission X- Ray Microscopy





Schematic layout of the STXM endstation.

Fast detector for dynamics

Soft x-rays at their best…..

- **Sensitivity to buried thin layer (2nm)**

  Cross section just right - can see signal from thin layer

  X-rays can distinguish layers, tune energy to Fe, Co, Ni, Cu

- **Resolving nanoscale details (< 100 nm)**

  Spatial resolution, x-ray spot size ~ 30 nm

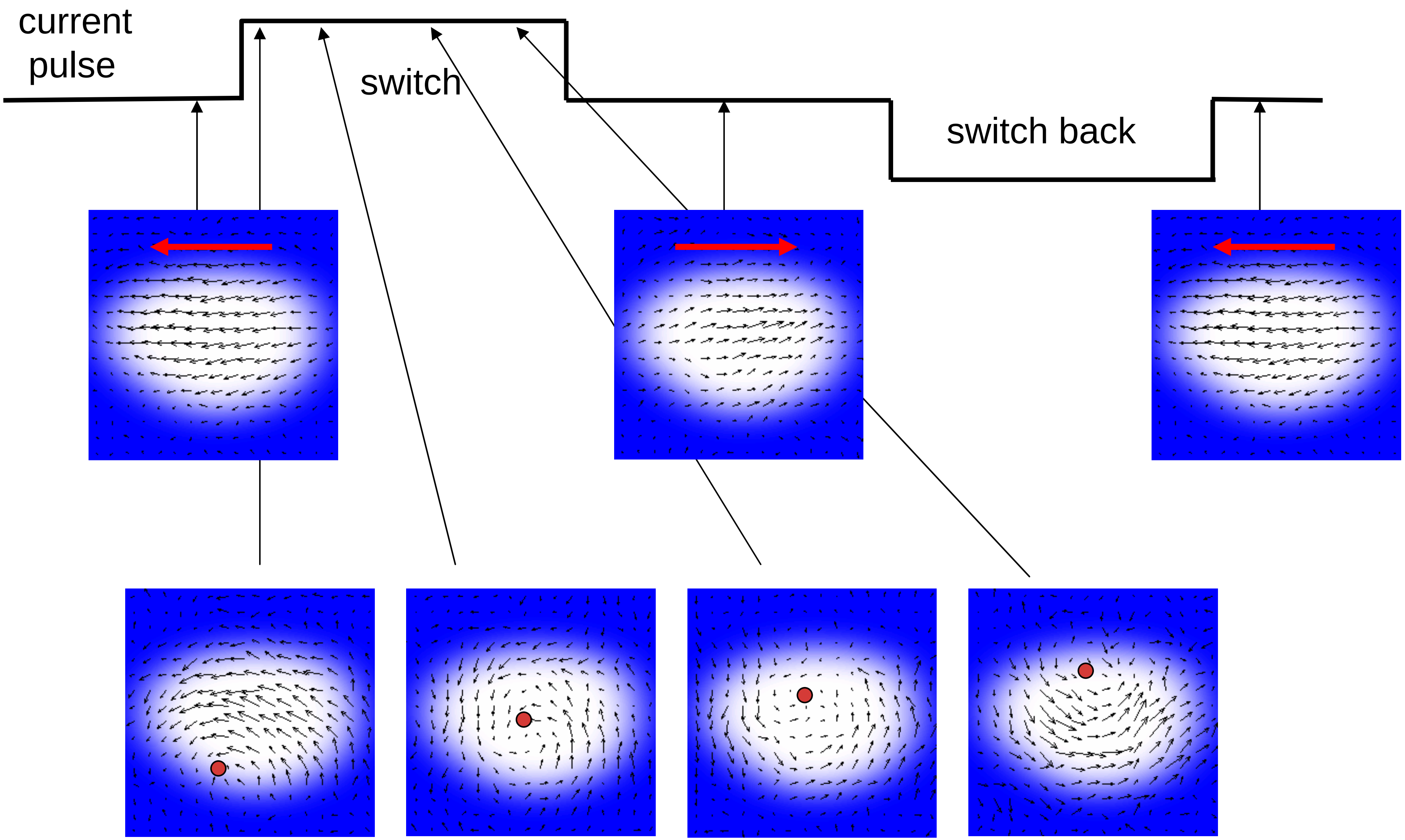
- **Magnetic contrast**

  Polarized x-rays provide magnetic contrast (XMCD)

- **Sub-nanosecond timing**

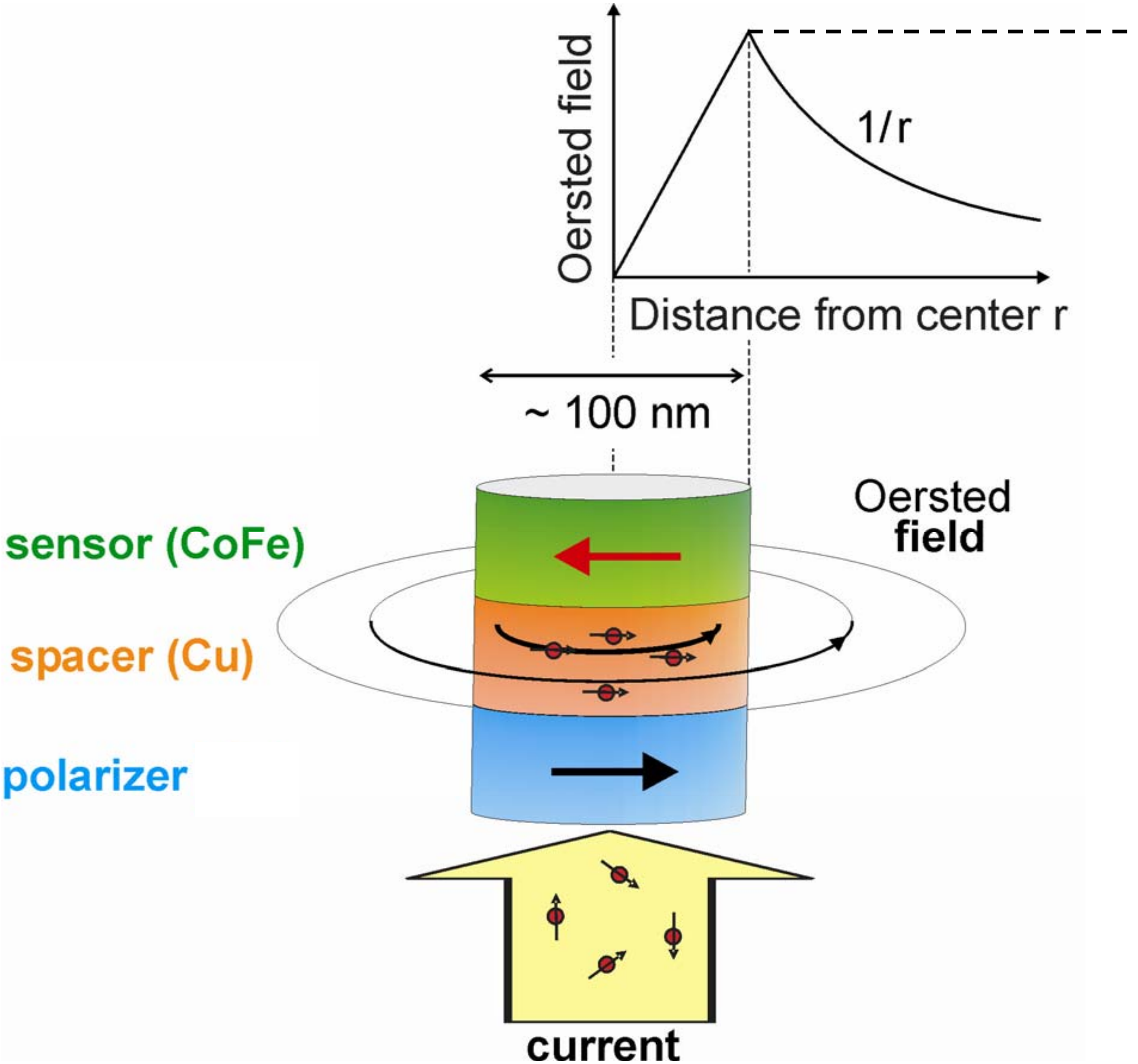
  Synchronize spin current pulses with 100 ps x-ray pulses

Sample 100nm x 200nm, 2nm CoFe free layer



Switching best described by movement of vortex across the sample!

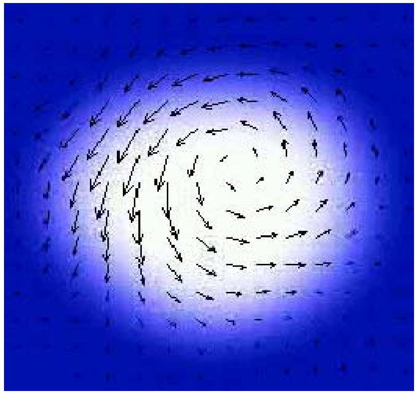
Charge current – creates vortex state
Spin current – drives vortex across sample



= 950 Oersted

for 150x100nm

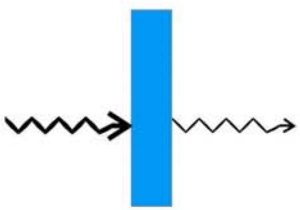
$j = 2x10^8$ A/cm^2



Lensless X-ray Magnetic Microscopy

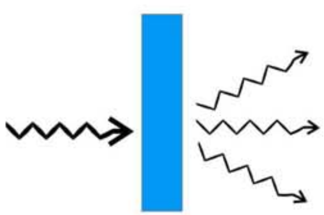
X-Ray Dichroism in Absorption and Scattering

Absorption



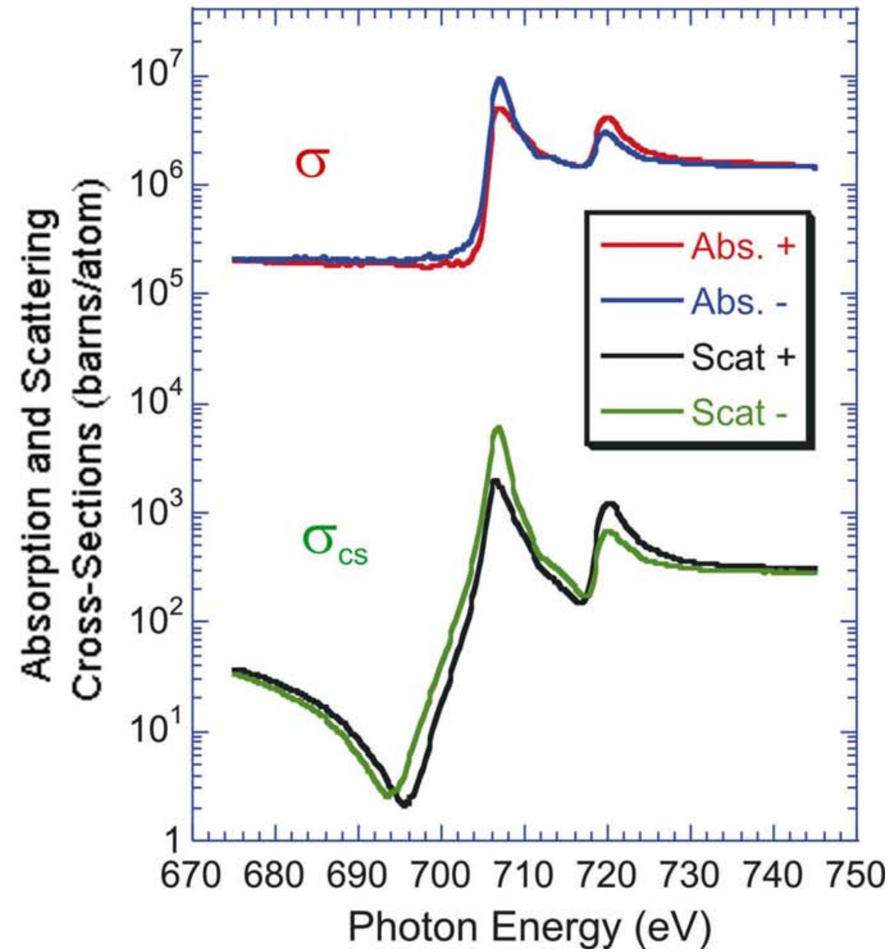
$$\sigma_{abs} \propto f_2$$

Resonant Elastic Scattering



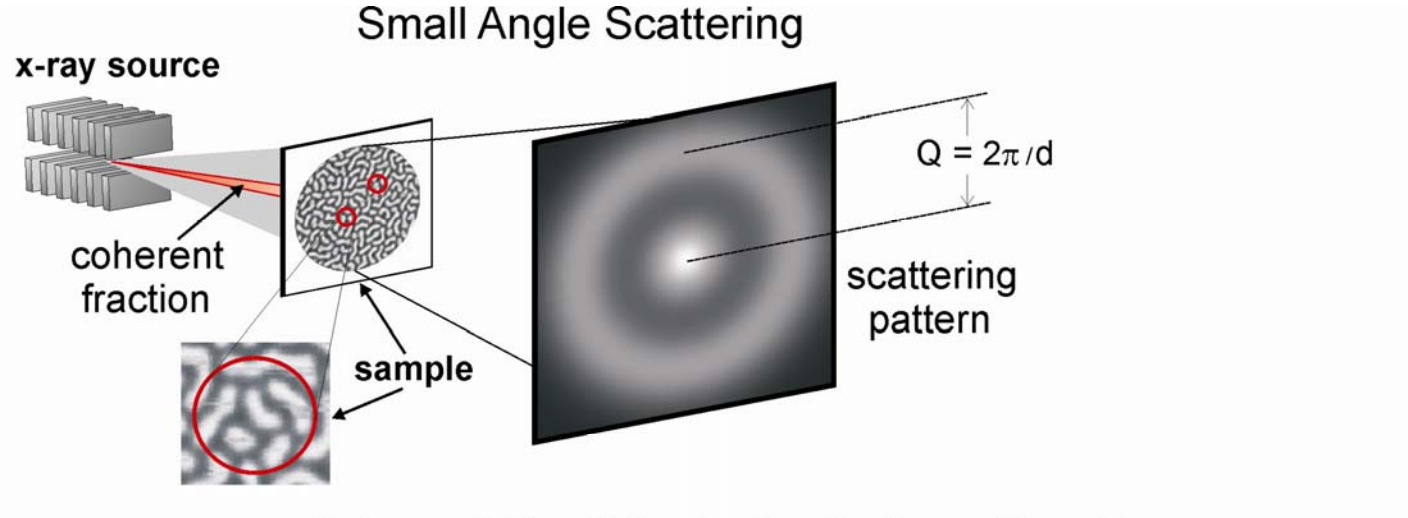
$$\sigma_{scat} \propto |\, f_1 + i\, f_2 \,|^2$$

Fe metal – L edge



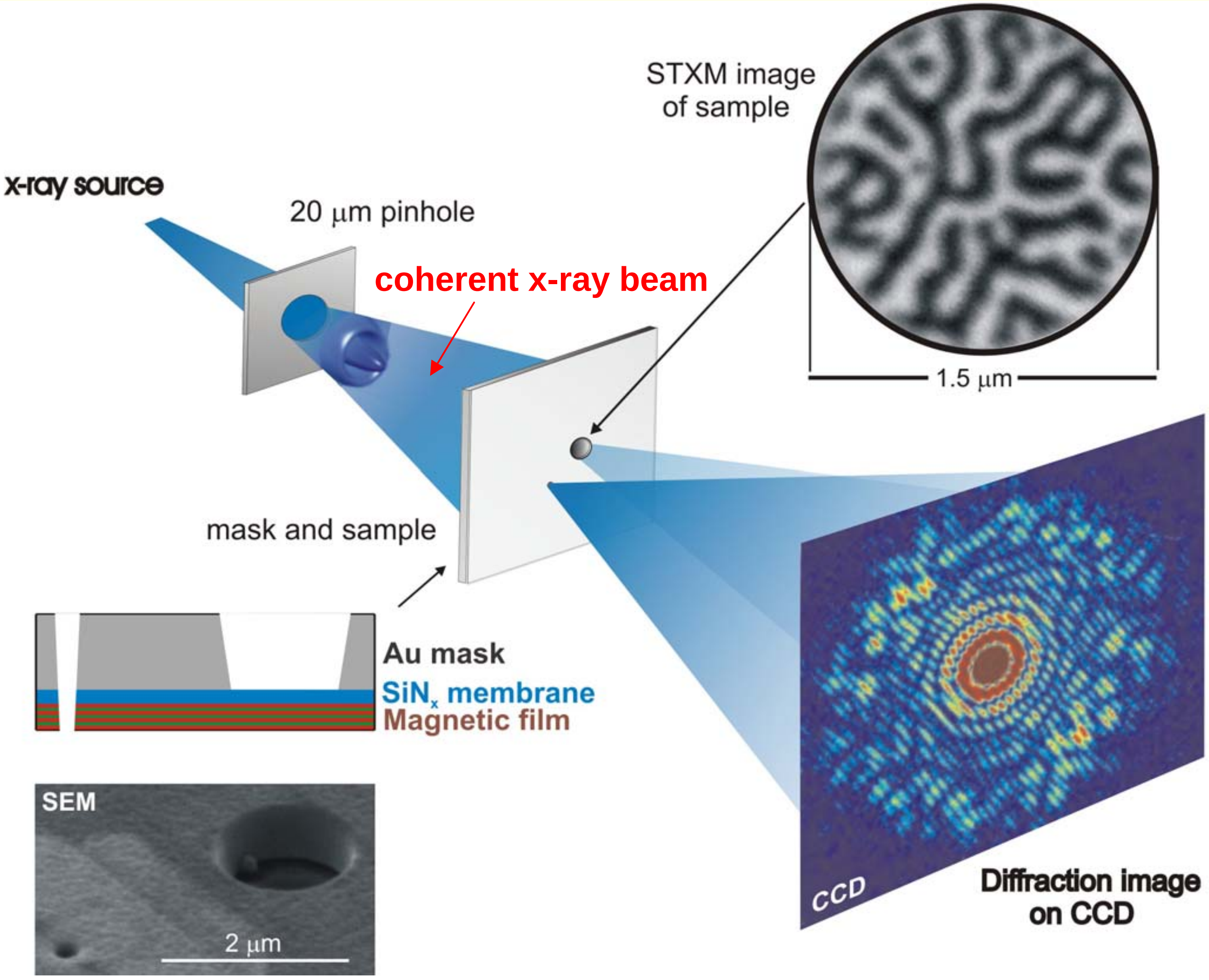
Kortright and Kim, Phys. Rev. B **62**, 12216 (2000)

Lensless magnetic imaging by scattering



But can one solve the phase problem and invert the image?

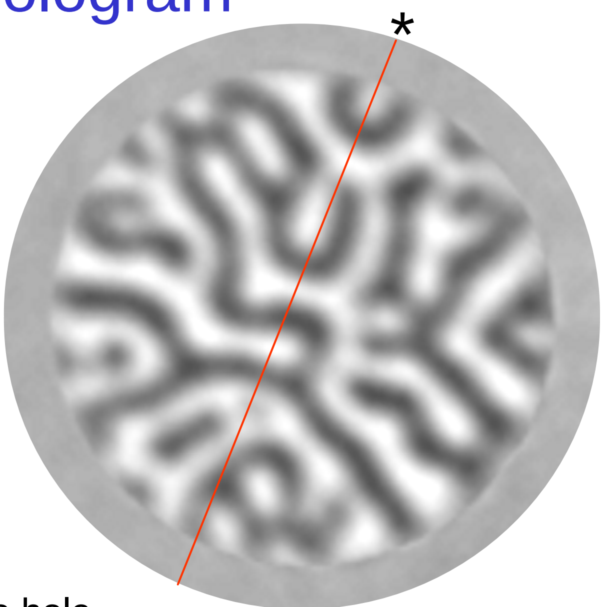
Development of coherent imaging with low intensity synchrotron radiation
"soft x-ray spectro –holography"



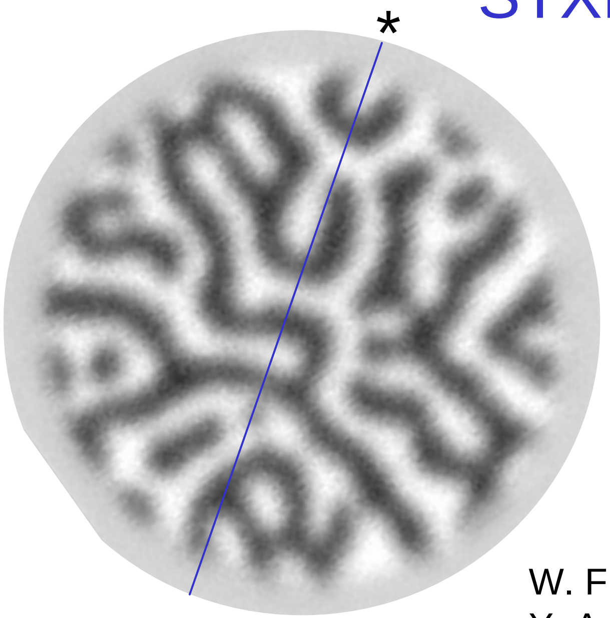
Eisebitt, Lüning, Schlotter, Lörgen, Hellwig, Eberhardt and Stöhr, *Nature* ***432**, 885 (2004)*

Is it real?

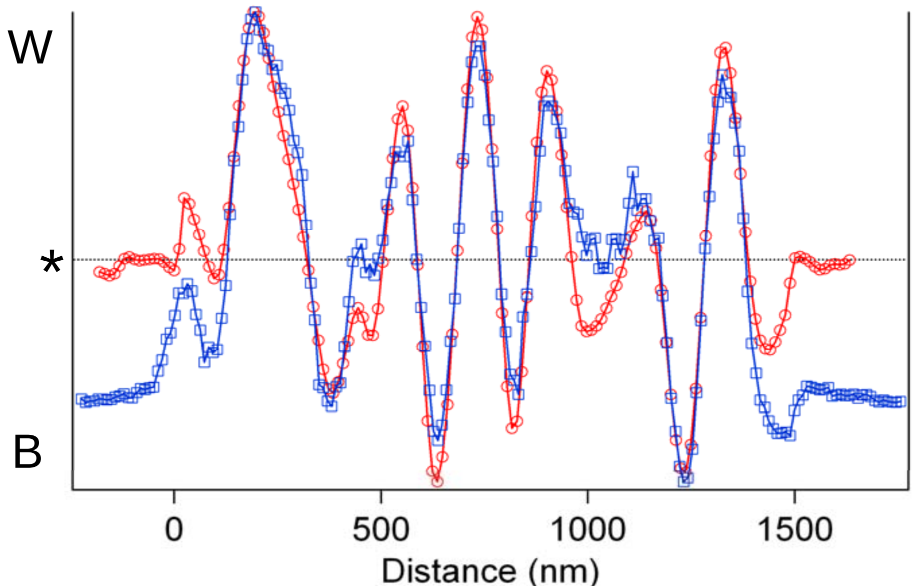
FT Hologram



STXM



Reference hole
∅ 100 nm

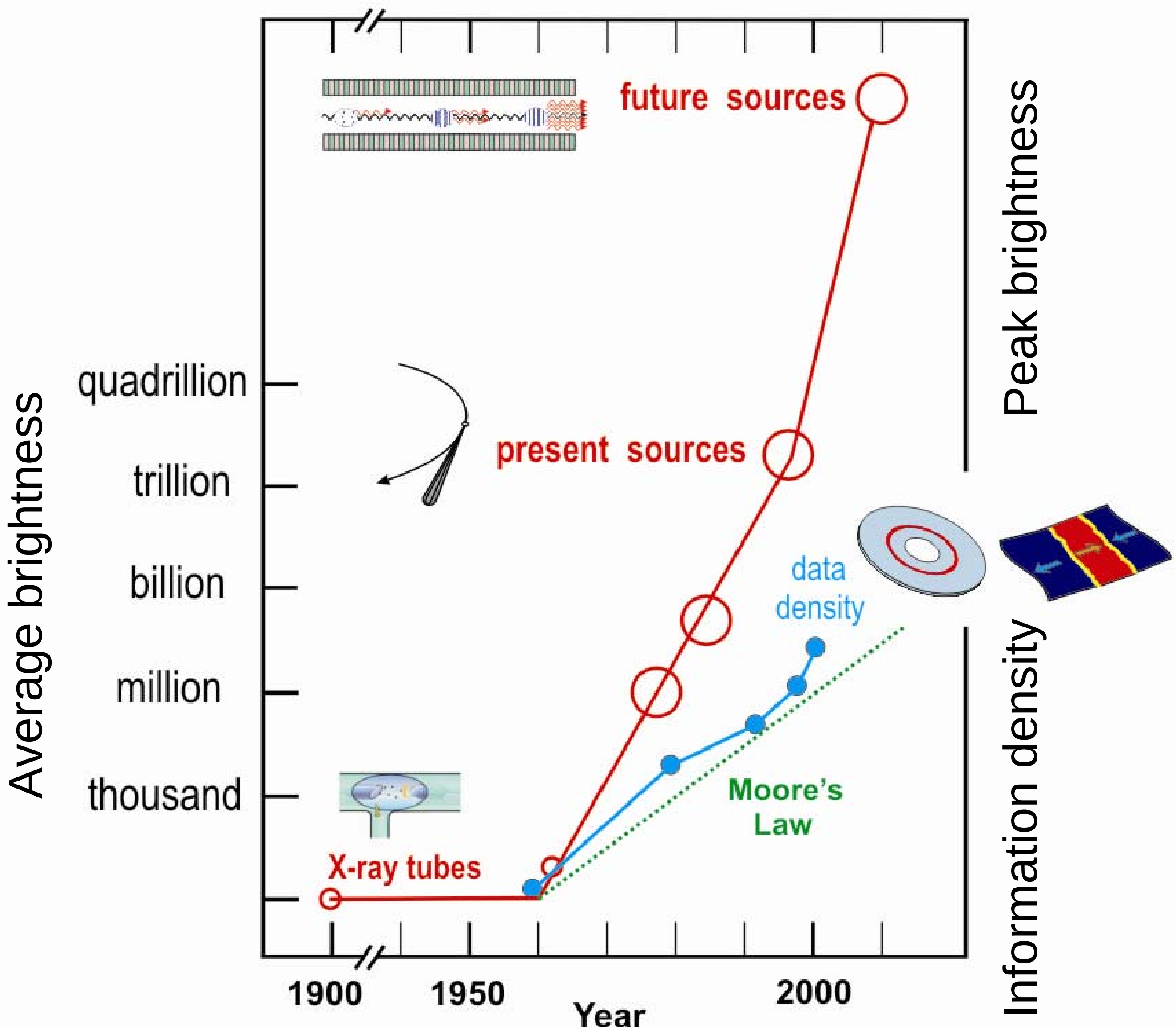


W. F. Schlotter
Y. Acremann

Resolution
30 - 40 nm

A Glimpse of the Future

Evolution of Magnetic Storage and X-Ray Sources

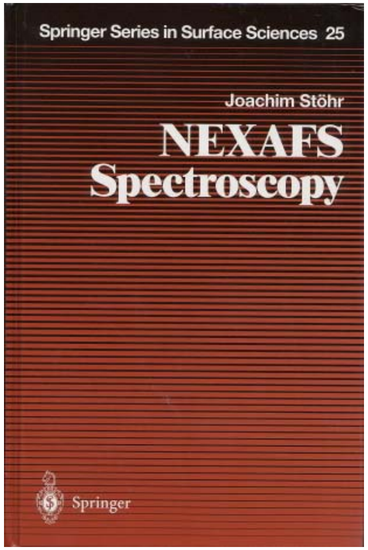


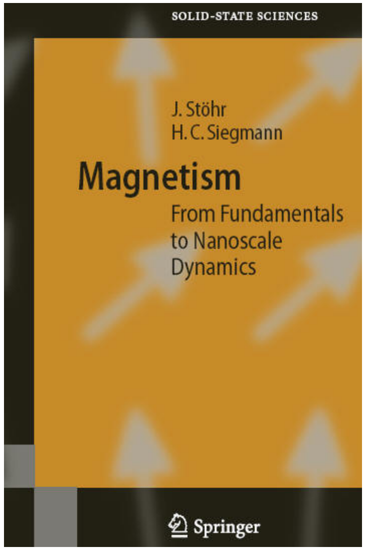
For more, see:

www-ssrl.slac.stanford.edu/stohr

J. Stöhr,
NEXAFS SPECTROSCOPY,
Springer Series in Surface Sciences 25, (Springer, Heidelberg, 1992).

J. Stöhr and H. C. Siegmann
MAGNETISM: FROM FUNDAMENTALS TO NANOSCALE DYNAMICS,
Springer Series in Solid State Sciences 152, (Springer, Heidelberg, 2006)





What has been accomplished by x-rays ?

- Determination of **element specific** magnetic moments in thin films & at surfaces
  enhanced and quenched moments
  induced moments (e.g. C, O, Cu, Pd, Pt)

- Distinction of **spin and orbital** contributions

- Link of **orbital moment anisotropy** to magneto-crystalline anisotropy

- Improved understanding of **interfacial magnetic coupling**
  FM-FM: modification of Curie temperature
  AFM-FM: origin of exchange bias

- Improved understanding of **nanoscale magnetization dynamics < 100 ps**
  motion and switching of magnetic vortices by external field pulses
  switching of nano-elements by spin currents