Time domain experiments in Correlated matter

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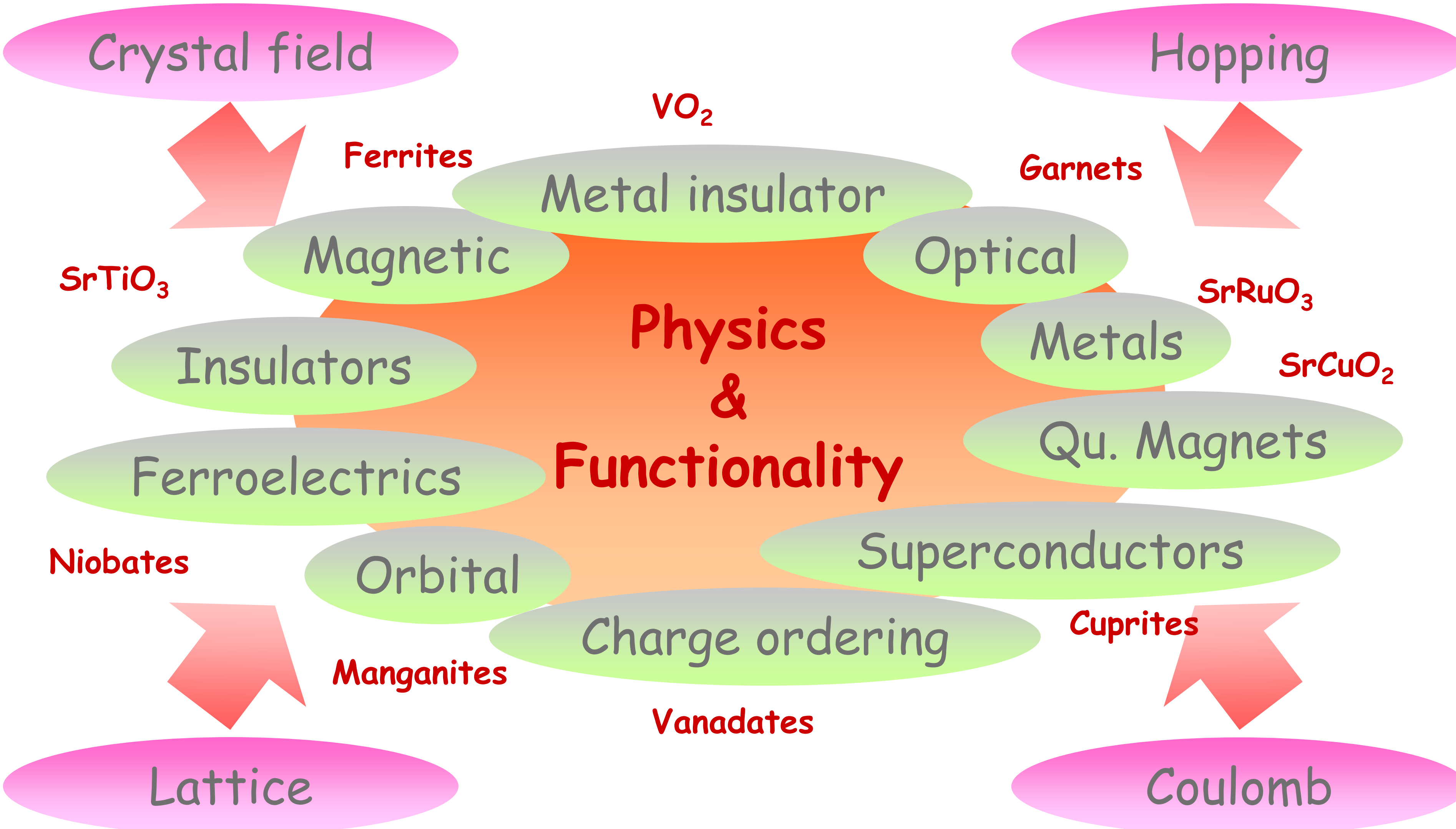
Correlated Matter



Time resolved views on matter

- Induced phase transitions
  - Novel states of matter
  - Ultrafast melting
  - Phase change media
  - Metal-Insulator, Ferro-Paramagnetic/electric, High/low spin, etc.
- Coupling between orbital, lattice, charge and spin
  - Energy transfer
  - Decoupling through timescale
- Inhomogeneities, static, dynamic
  - Stripes
  - Metal/insulator
- Time domain spectroscopies
  - Electronic structure (PES/XAS)
  - Coherent lattice vibrations
  - Mossbauer
- Magnetization reversal processes

Time resolved views on matter

- Challenges
  - Extend accessible physical properties dynamical state
    - How do correlations come about (TR-PES)
    - Lattice structure (TR-diffraction)
    - Spin structure (TR-Mössbauer diffraction)
    - Magnetization (TR-XMCD)
    - Electronic structure (TR-PES, XAS,...)
    - Inhomogeneity (TR-coherent imaging)
  - Selective excitation
    - Excite particular lattice/orbital/charge/magnon modes to drive and control phase transitions
    - Excite non-thermal phases
    - Coherent control

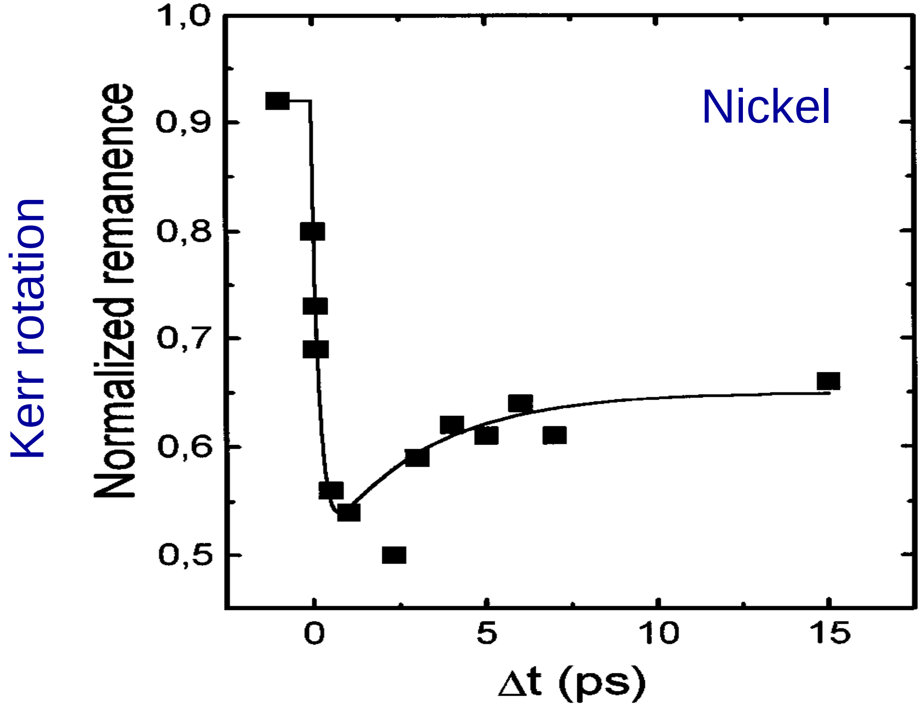
What can XFEL's do: Some dreams

- PES[5]
  Place, Energy, Spin, Momentum & Time resolved
  - Optically induced electronic phase transitions
  - Formation of correlated states
  - Formation of Fermi surface
- Two dimensional spectroscopy
  - Coherent links in the energy landscape
  - Hybridization (e.g. 3d-2p)
- Coherent imaging on nano lengths and femto times
  - Charge inhomogeneity
  - Dynamic stripes
  - nucleation
- Time resolved XMCD
  - Switching bits
- Time resolved diffraction
  - Structural aspects of phase transitions
  - Melting

Some examples

- Magnetization dynamics in EuO
- Metamagnetic staircase in CuFeO2
- Spin and orbital melting in YVO3
- Jones-Peierls physics in the A7 metals

Ultrafast magnetization dynamics



- De-magnetization by laser-heating (not a suprise)
- De-magnetization in 120 fs (faster than expected, ps-ns spin-lattice relaxation)
- Femto-second spin-lattice relaxation mechanism

E. Beaurepaire *et. al.*
Phys. Rev. Lett. 76, 4250 - 4253 (1996)

Magnetization dynamics in EuO

- EuO
  Ferromagnetic (Tc=69 K) semiconductor (1.2 eV bandgap)
- Magnetic interaction mediated by 5d conduction electrons

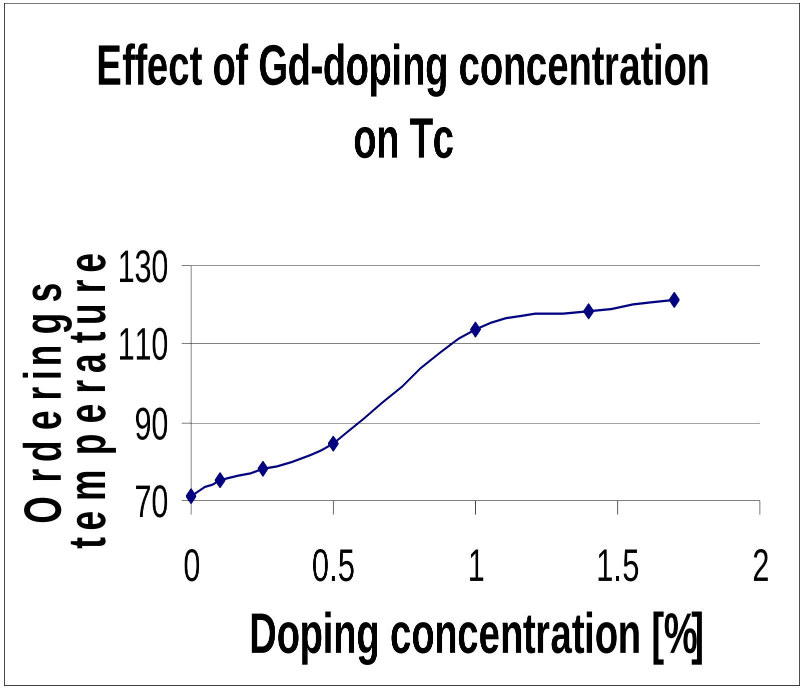
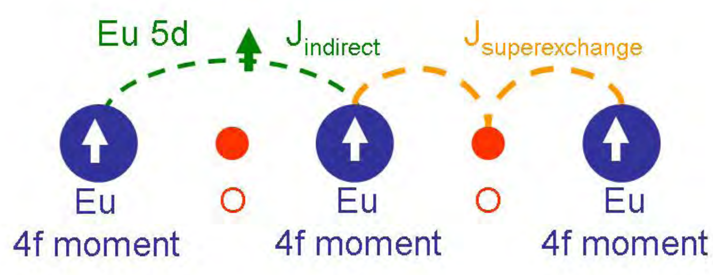
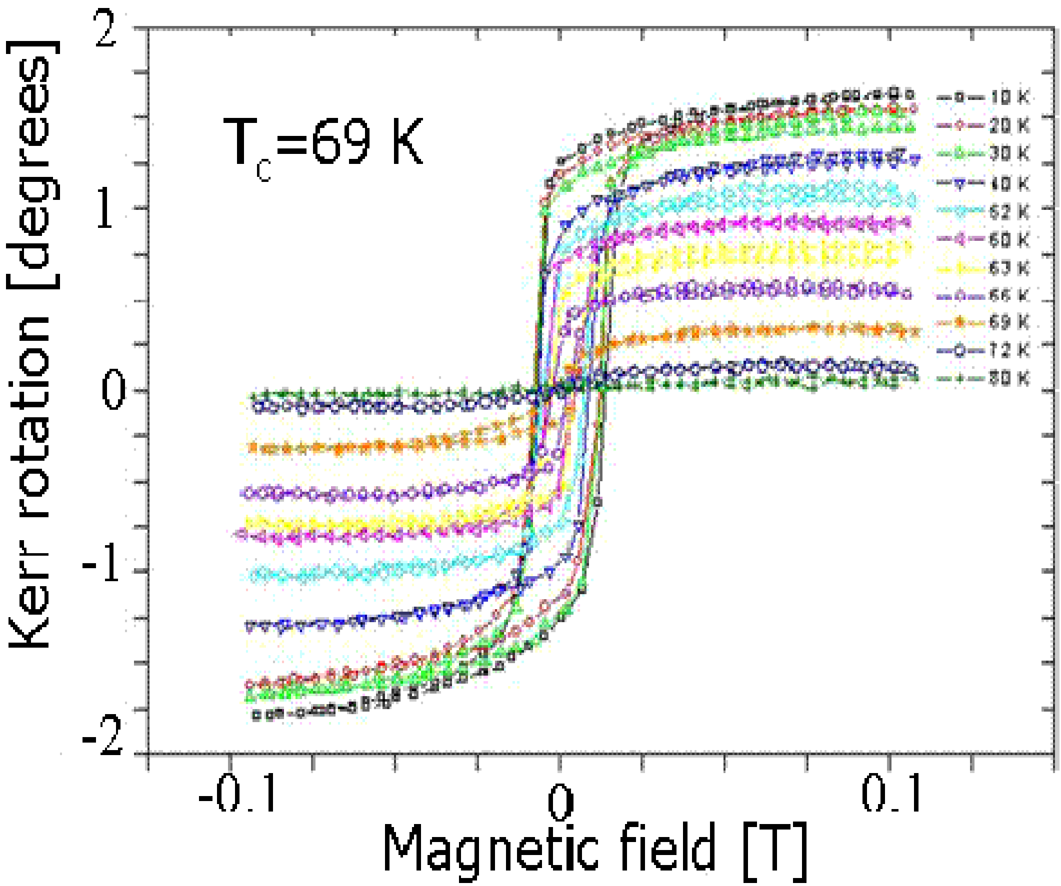


Photo doping → Induce magnetism ?



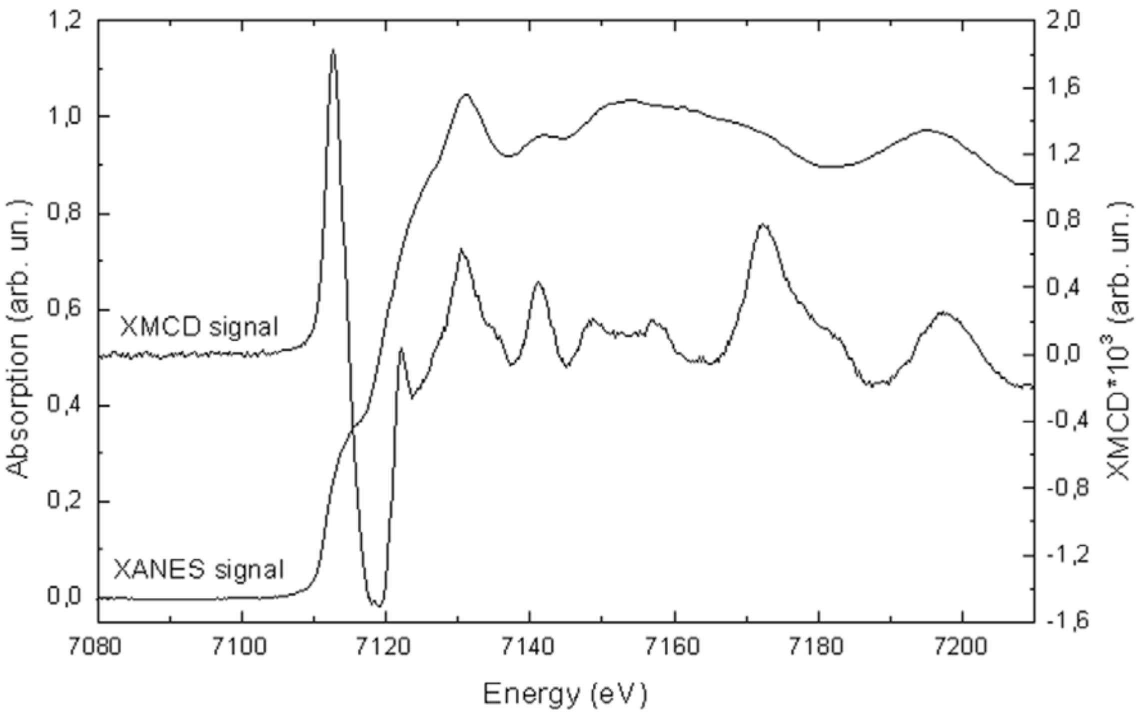
Magnetization dynamics in EuO

- Probing magnetism: MOKE



MOKE

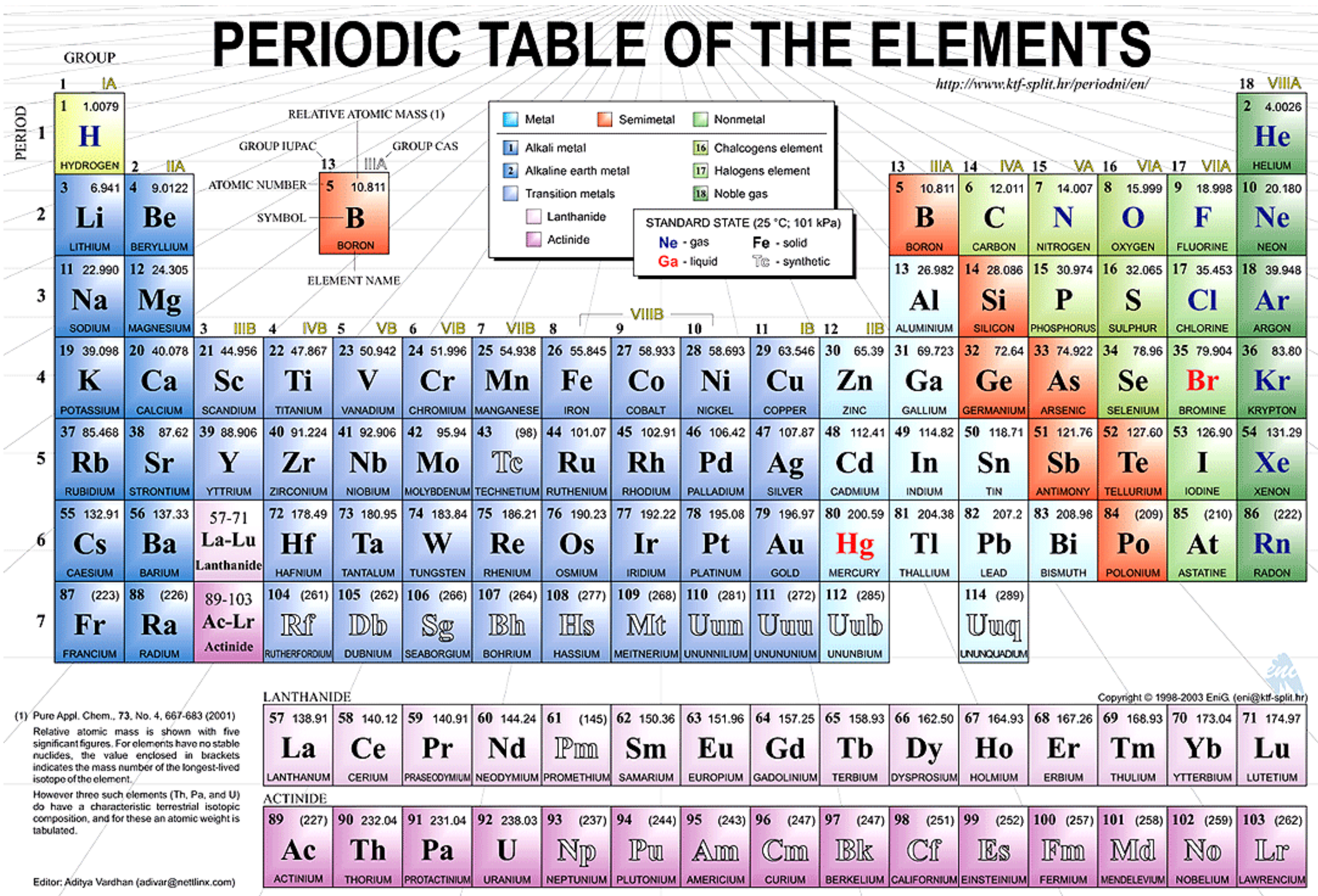
Fe K-edge XMCD



Main disadvantage: Small signal
Main advantage: Large penetration depth

Mathon et al., J. Synchr. Rad. **11**, 423 (2004)

Relevant absorption edges



K-edge 3-15 keV

L-edge 2-5 keV

L,M-edge 2-20 keV

http://www.astro.virginia.edu/class/oconnell/astr121/im/periodic_table.gif

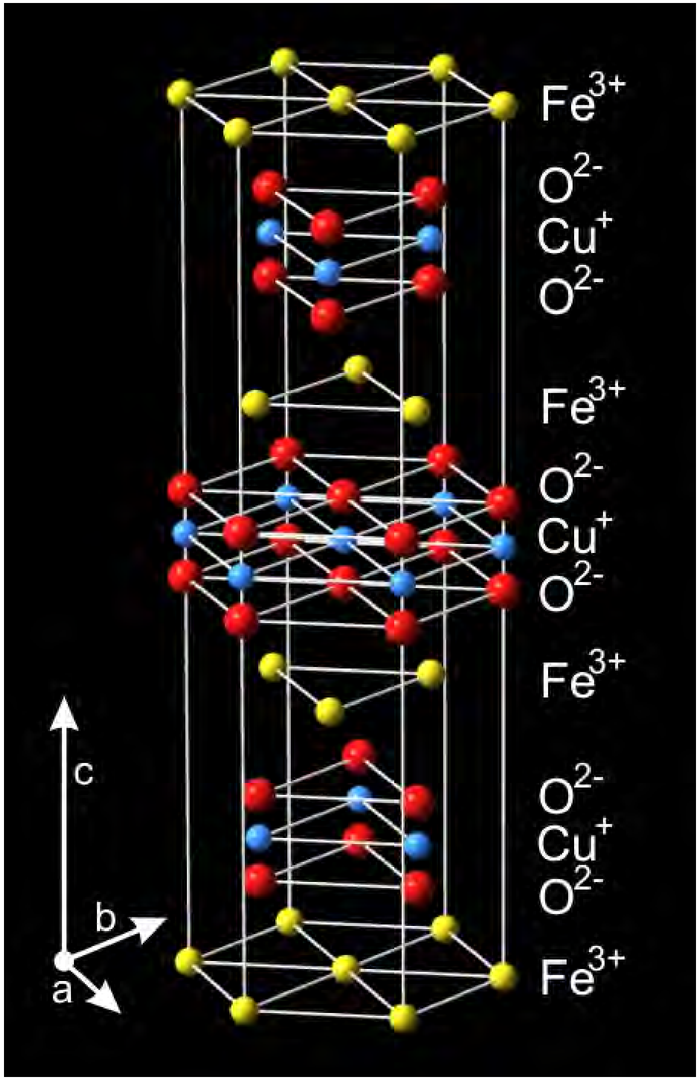
The metamagnetic staircase of $CuFeO_2$

Geometrical spin frustration:

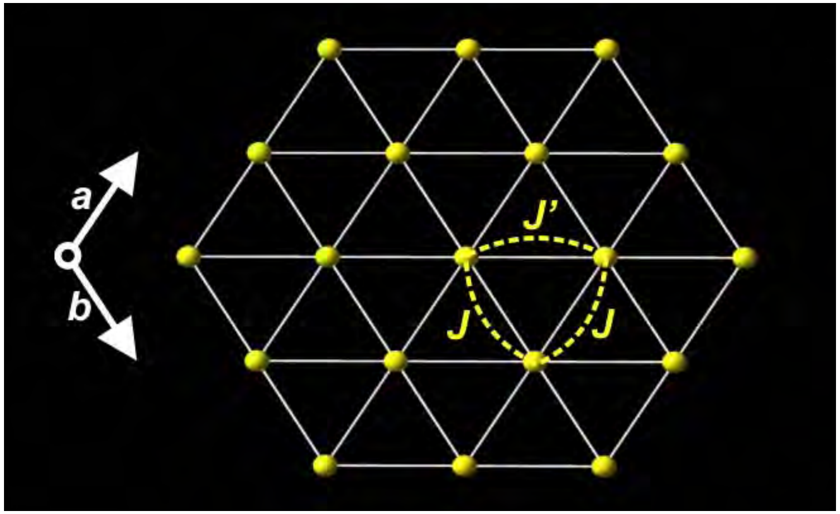
'Personal' goal: satisfy antiferromagnetic exchange interactions
Obstructions: competing exchange interactions with neighboring spins
Emotional response: anomalous magnetic behavior

Frustration is an **emotional response** to **circumstances** where one is **obstructed** from arriving at a **personal goal.**

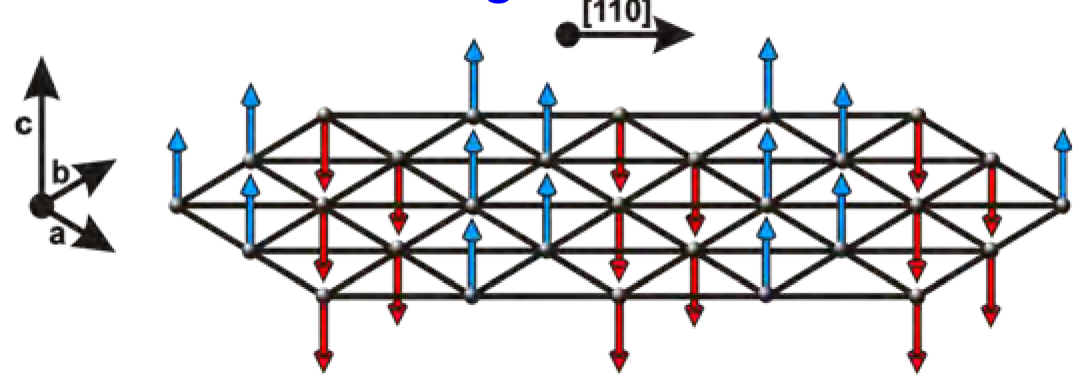
Frustration in metamagnetic compounds



$CuFeO_2$

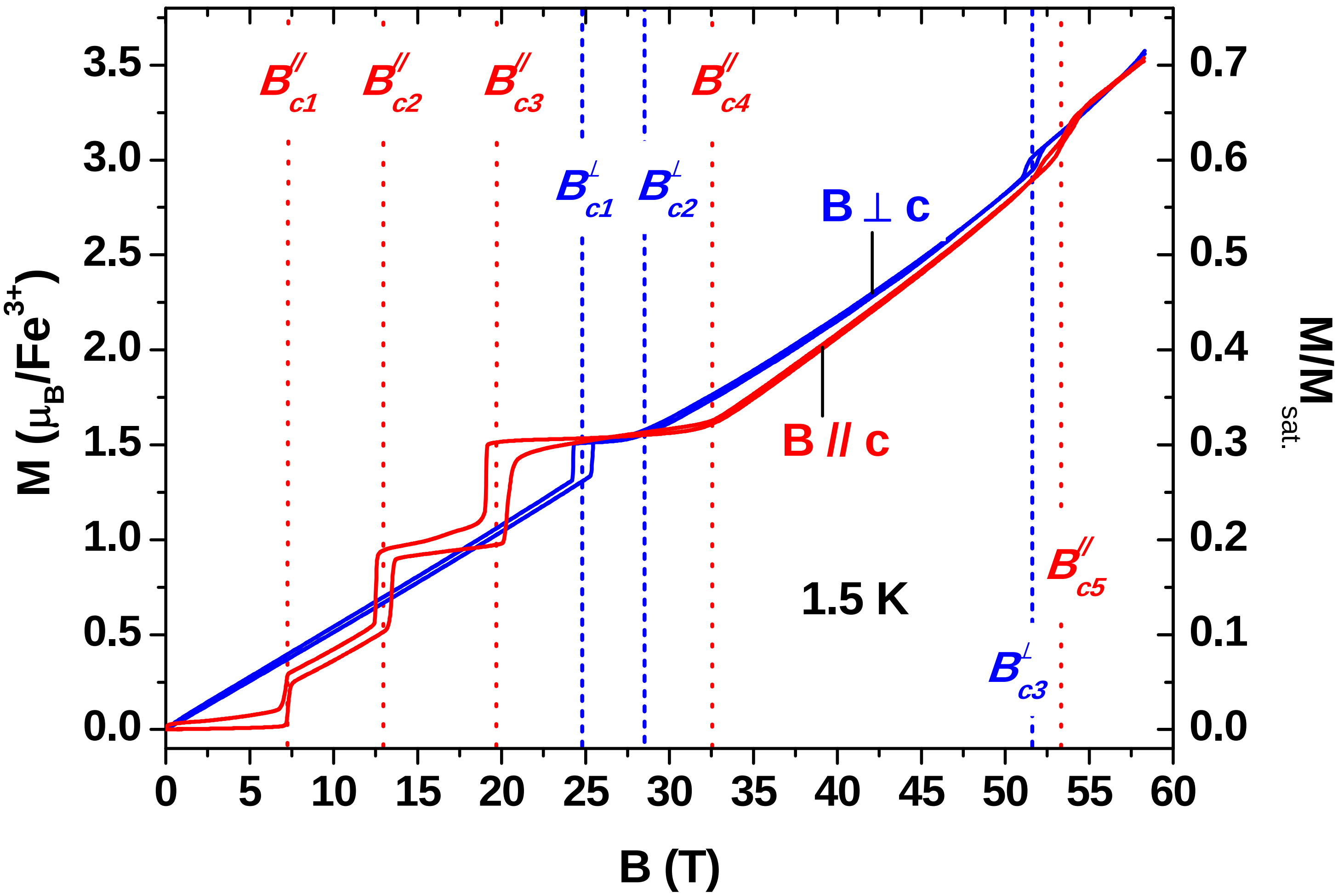


4SL ground state



Frustration in metamagnetic compounds

The metamagnetic staircase of $CuFeO_2$

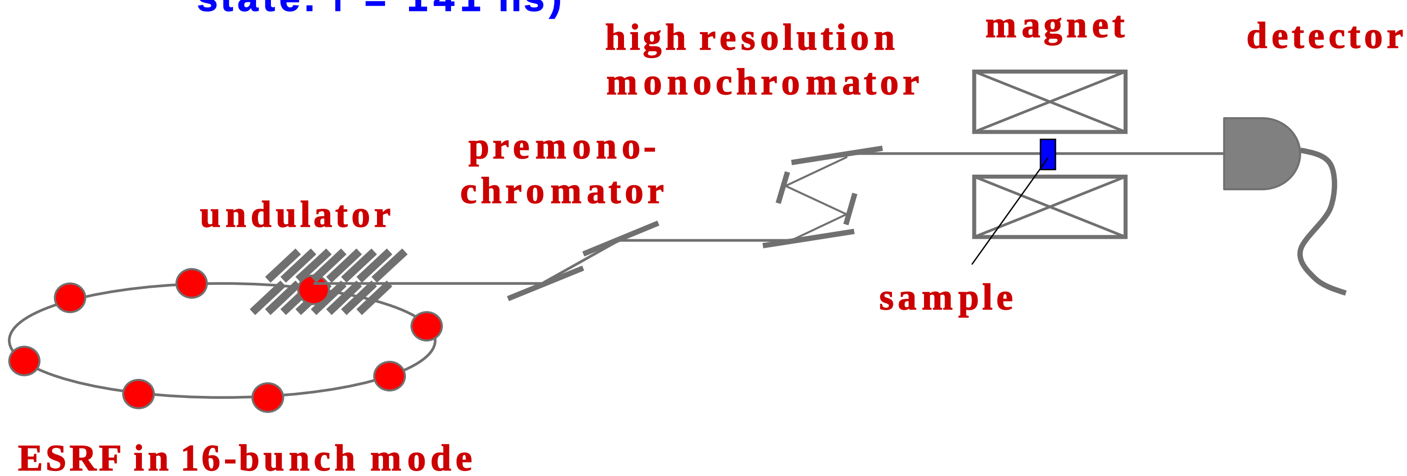


Lummen et al. PRB (2009)

Nuclear Forward Scattering in pulsed fields

➢ Time-based analogue of Mössbauer spectroscopy

- resonantly excite ^{57}Fe nuclei with pulses of synchrotron radiation (~100 ps, 14.4 keV, 56.8 MHz)
- observe real-time γ-decay in the empty 176 ns time window (^{57}Fe excited state: τ = 141 ns)



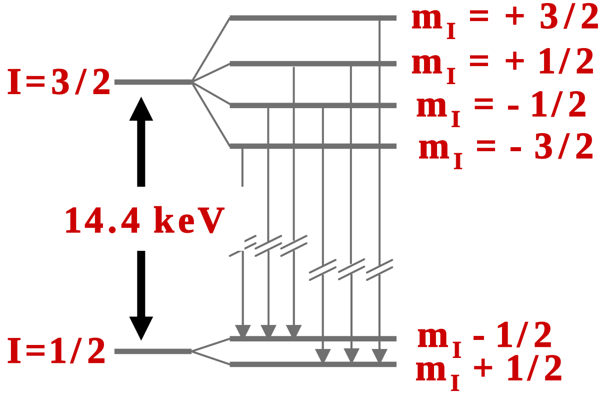
ESRF, Grenoble

- sample environment for extreme conditions possible (due to "laser beam-like" properties):
  - High-pressure measurements, very small samples, high magnetic fields (focusing power, intensity, source level-splitting in conventional Mössbauer)

Nuclear Forward Scattering in pulsed fields

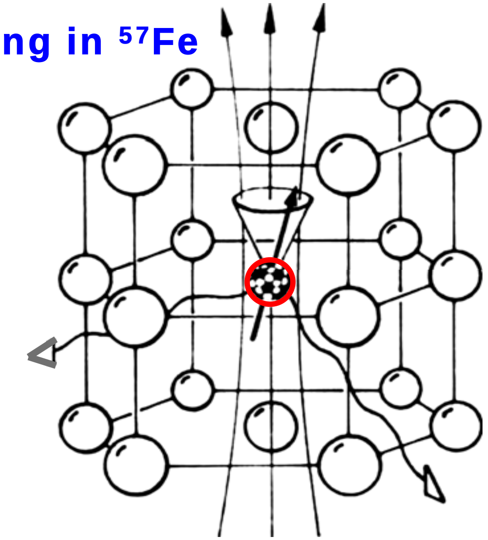
➢ **Time-based analogue of Mössbauer spectroscopy**

- probe the local magnetic field through hyperfine splitting in ^{57}Fe



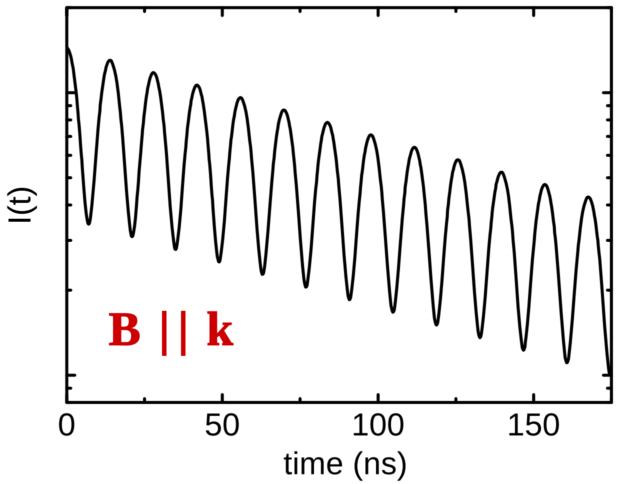
Splitting dependent on:

- local electric field (isomer shift)
- local magnetic field (level splitting)
- local electric field gradient (level splitting)
- local spin-direction

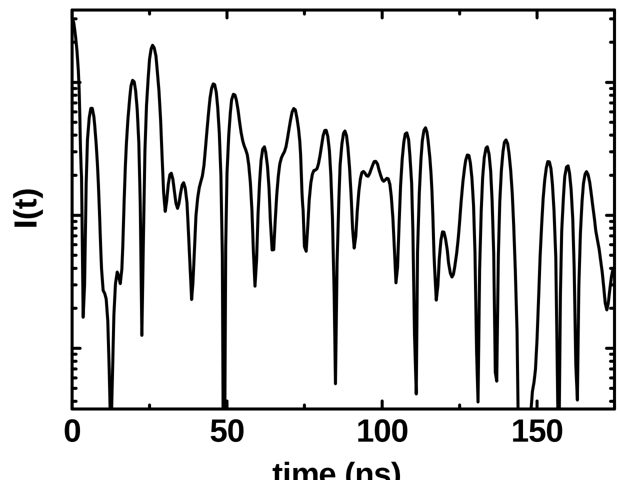


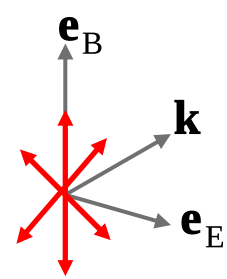
Schatz & Weidinger, ISBN *0-471-95479-9*

exponential decay + beat frequency

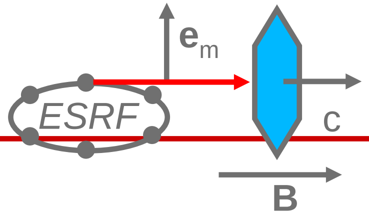


distribution of spins



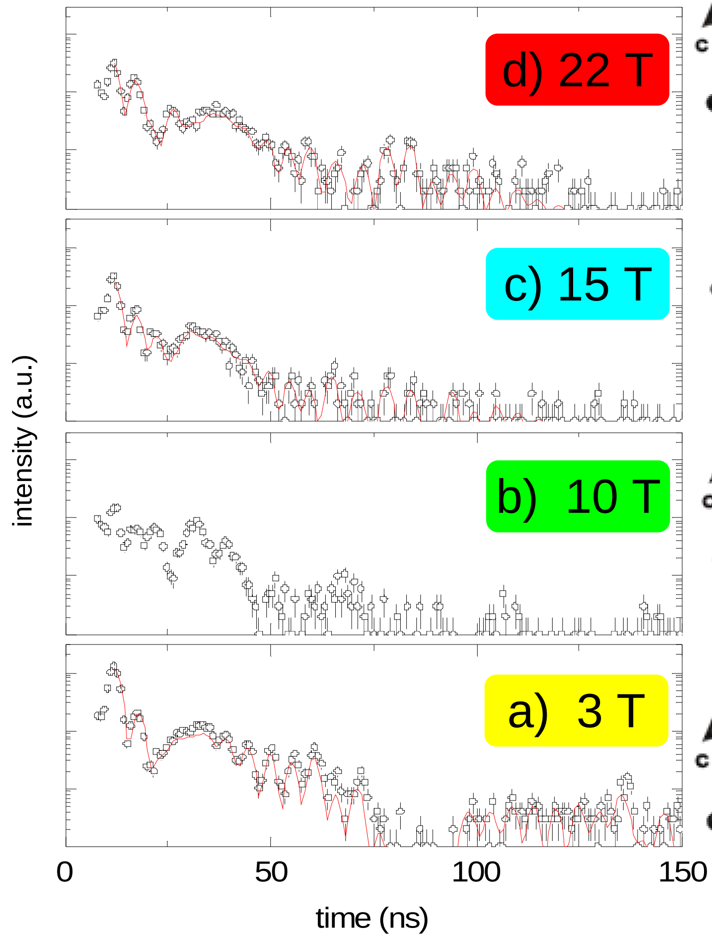


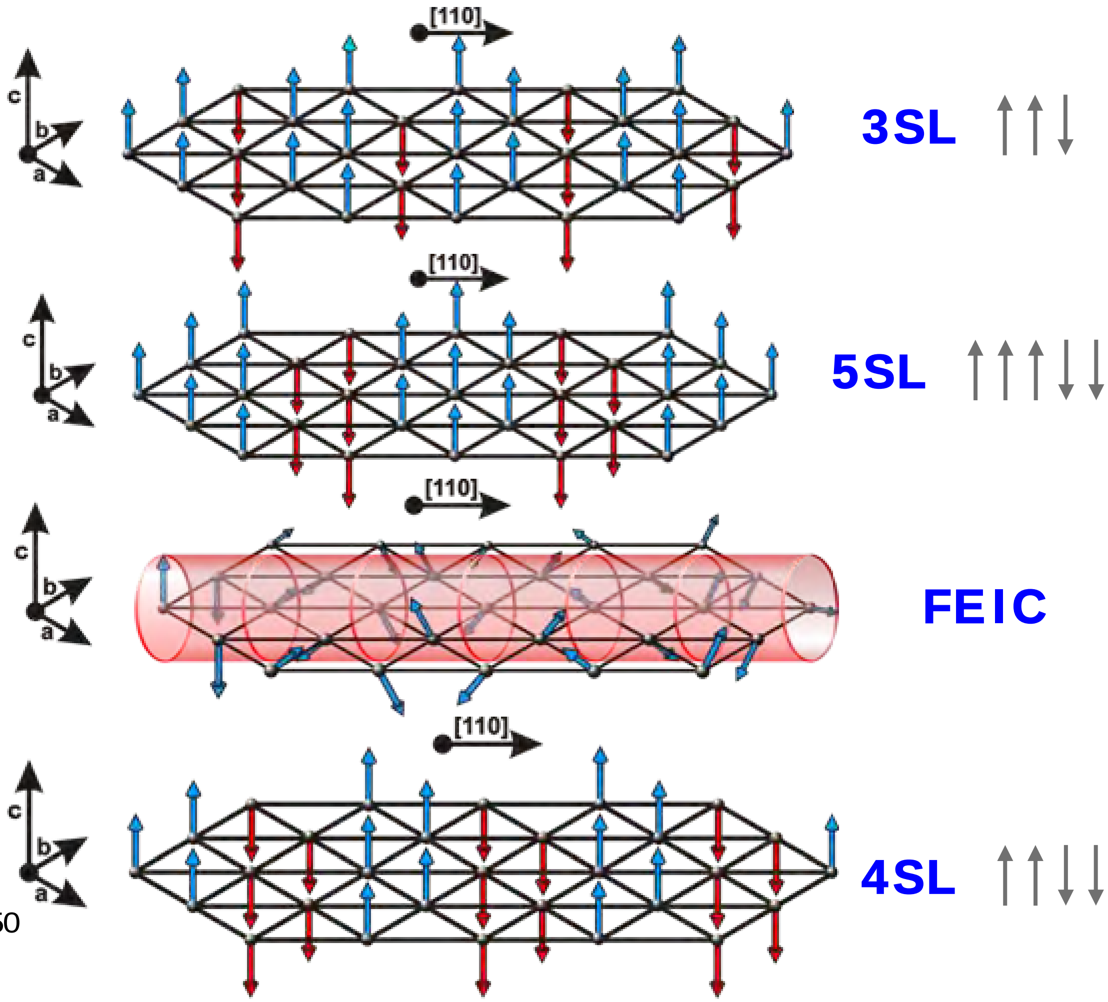
NFS in pulsed fields: B / / c



Lines: fits based on corresponding collinear models, 4SL, 5SL and 3SL

NFS timespectra





Strohm et al. (2009)

Why XFEL

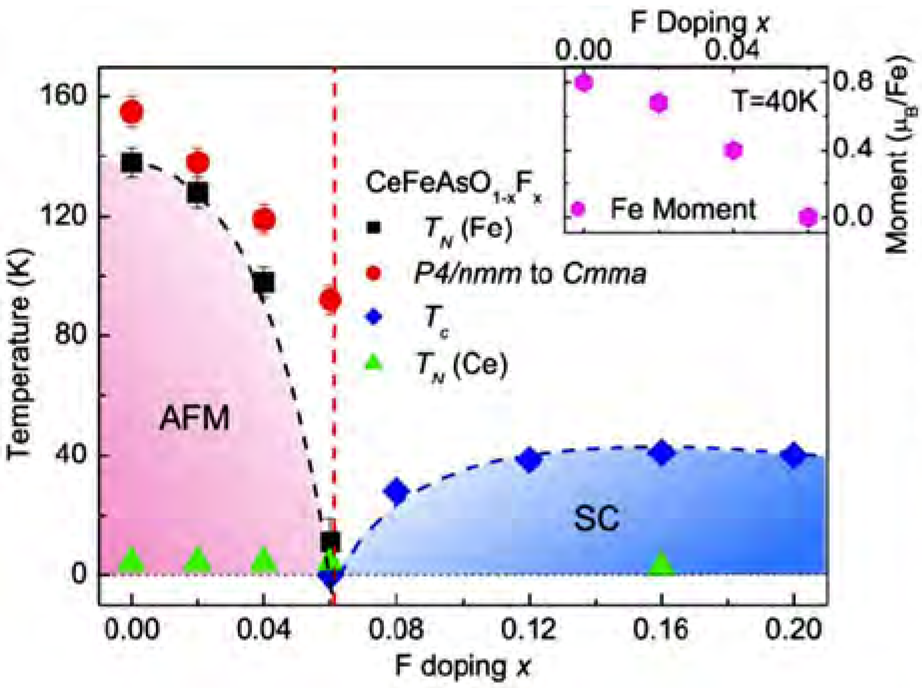
- Counting statistics!
- Interplay between Spin & Lattice order
- Exotic spin structures

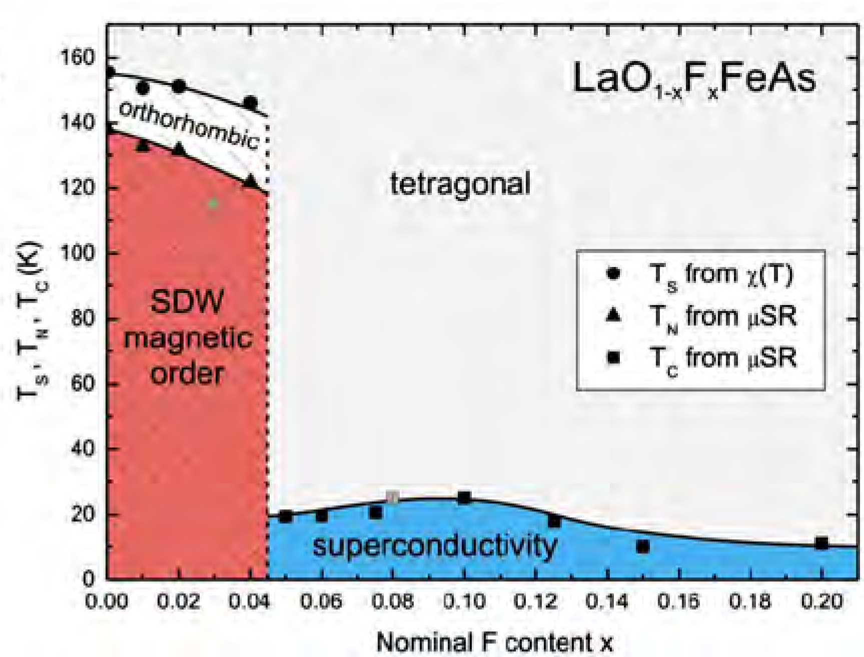
- High field phases
  - TR-Xray in pulsed fields up to 100 T (easy up to 30T)
    - Structure evolution with field → anisotropy
  - Time domain Mössbauer in pulsed fields
    - Magnetic structure (polarized light, resonant diffr.)
    - small samples, extreme conditions (B,P,T)

- LIESST compounds, magnetic switching,...
- Non Iron compounds

Iron Pnictide superconductors

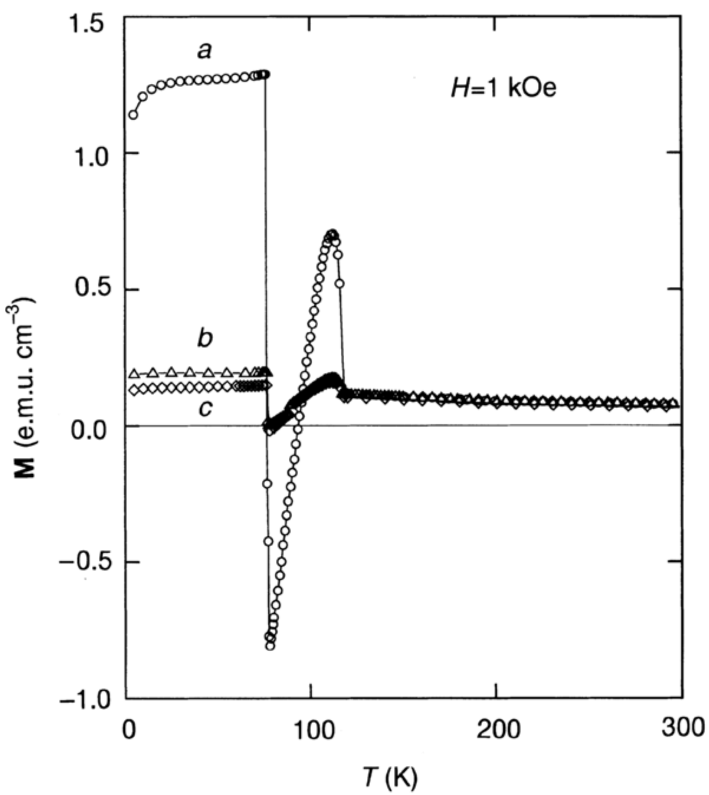
Magnetic ordering at low doping
Interplay between magnetism and superconductivity



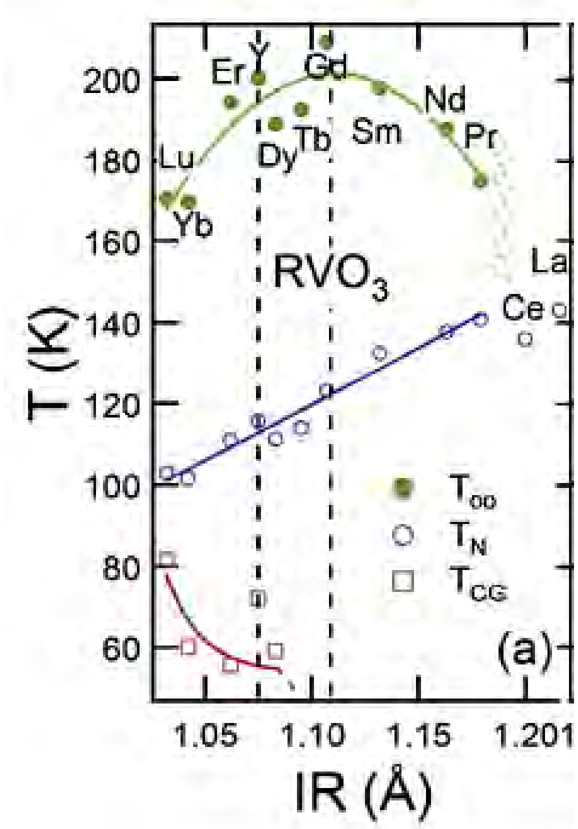


From: Norman, Physics **1,** 21 (2008)

Spin & Orbital melting in YVO3



Ren et al, Nature **396**, 441 (1998)



Yan et al., PRL **99**, 197201 (2007)

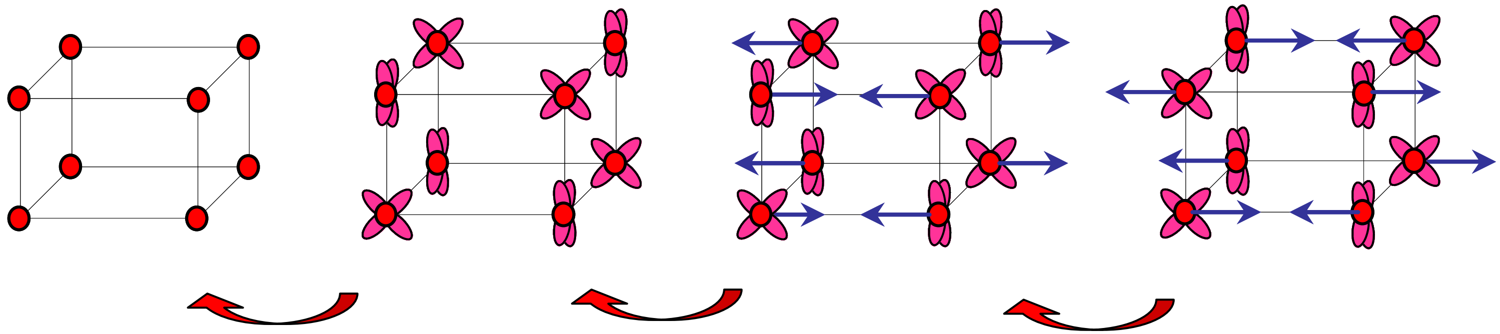
Spin & Orbital melting in YVO3

Spins disordered
Orbitals disordered
T>196 K

Spins disordered
Orbitals G-ordered
196 K>*T*>116 K

Spins C-ordered
Orbitals G-ordered
116 K>*T*>77 K

Spins G-ordered
Orbitals C-ordered
T<77 K



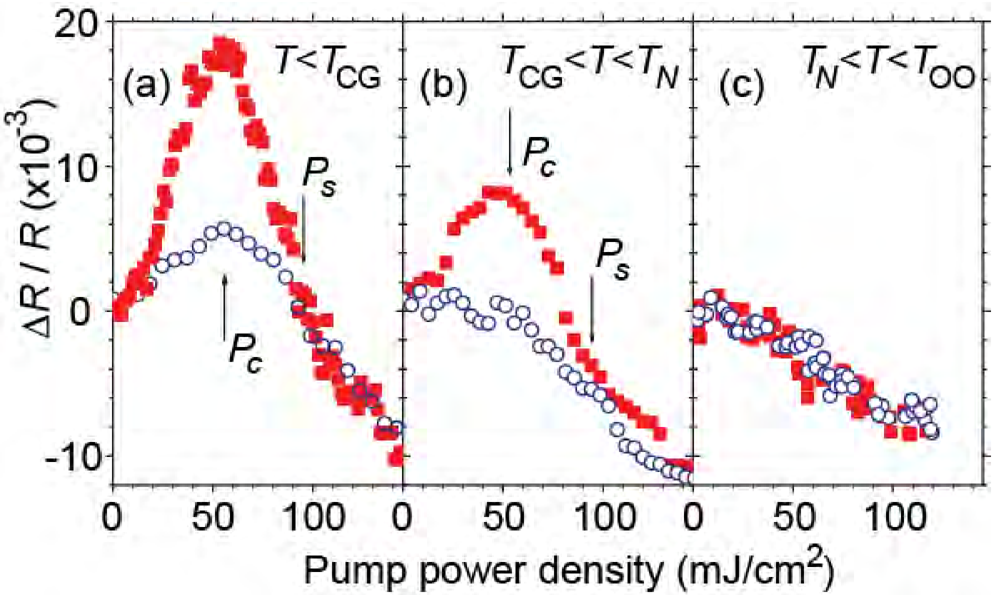
Thermally induced transitions

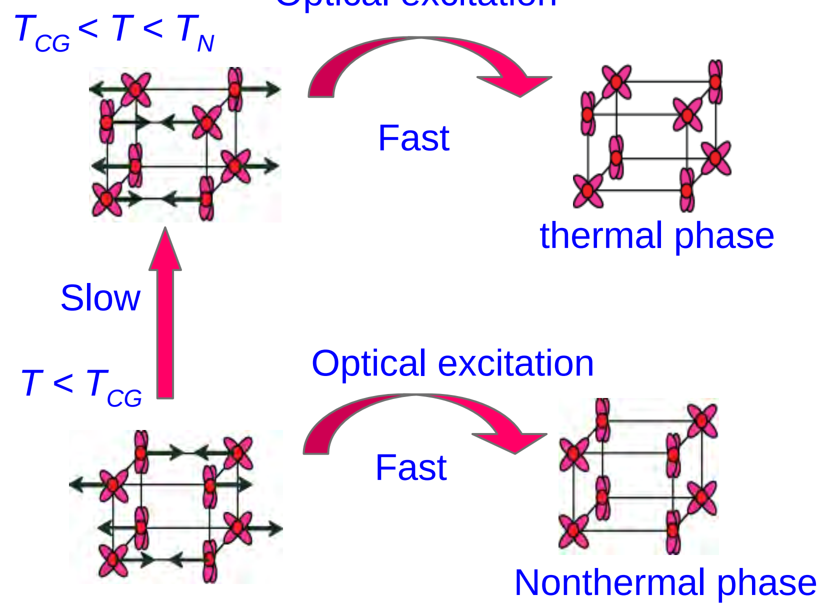
Optically induced transitions ?

- How fast can it be done (current technology > 1 ns)
- What are the restrictions
- Can one induce novel phases

Melting spin order

Time resolved reflectivity

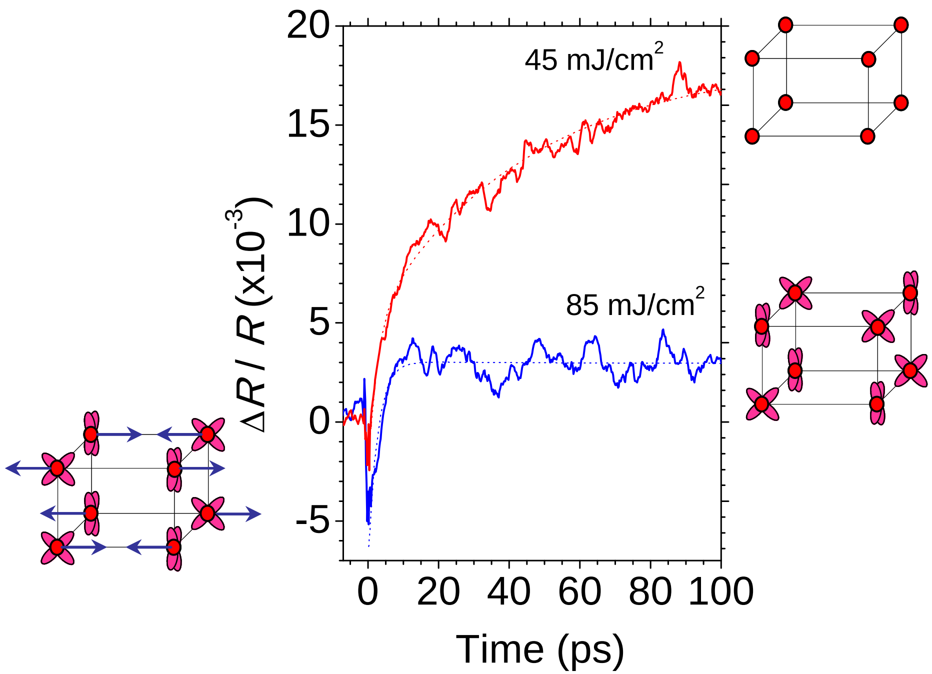




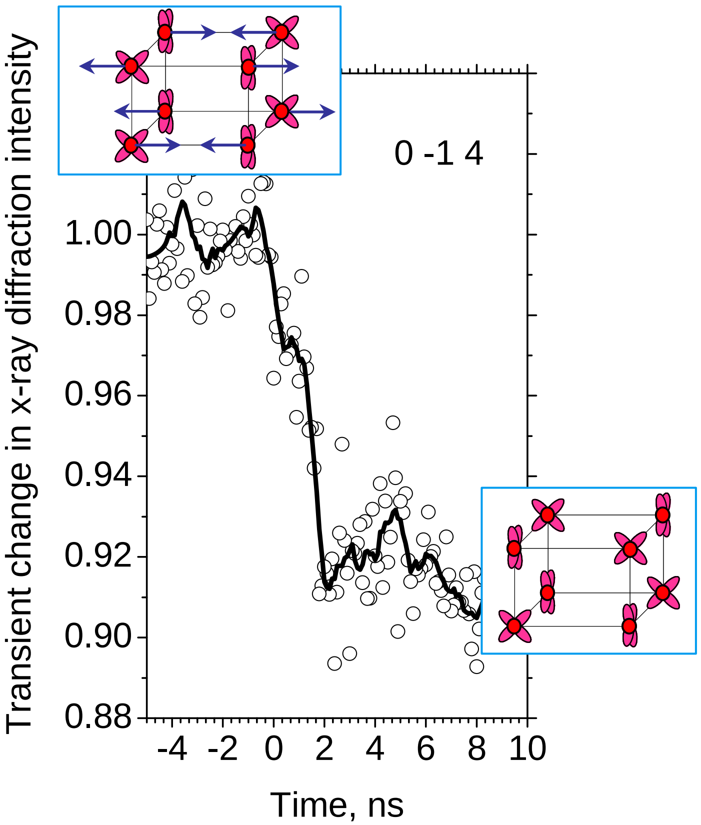
- Melting of spin order within 3 ps
- Phase transition to a non-thermal phase
- Transitions only fast when going to higher symmetry

Melting orbital order

TR-Optics



TR-Xray

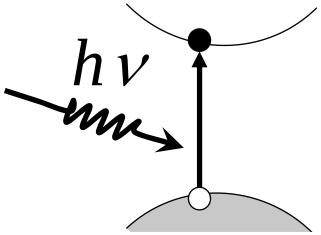


Mazurenko et al., in prep. 2008

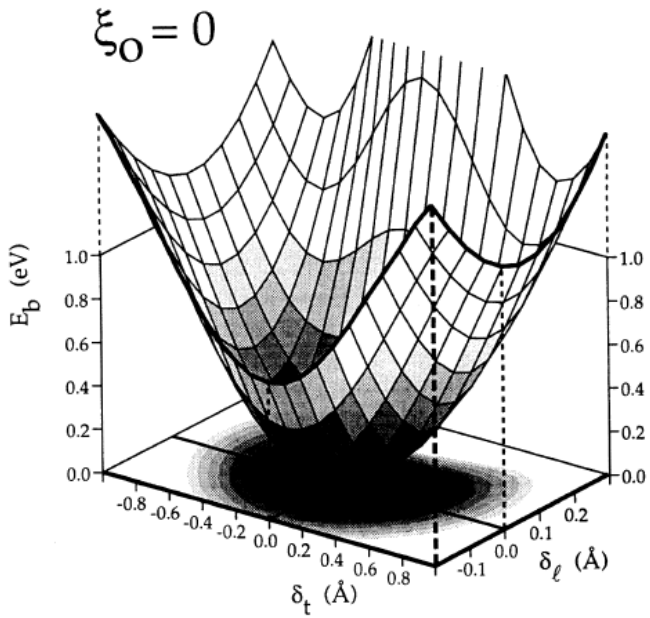
- Spin melting
  - Ultrafast quenching of the magnetic order
    - XMCD is a more direct probe than TR-MOKE, far less problems with data interpretation

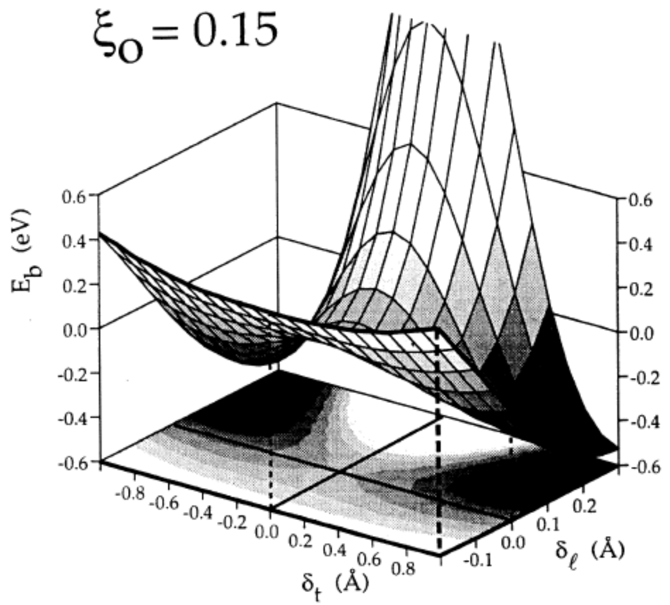
- Orbital melting
  - 'Slow' process (>10-100 ps)
  - TR diffraction: indirect through lattice
  - TR resonant diffraction to more directly probe the orbital order.

Jones-Peierls transition in the A7's



Charge excitation driven instability in GaAs and Si

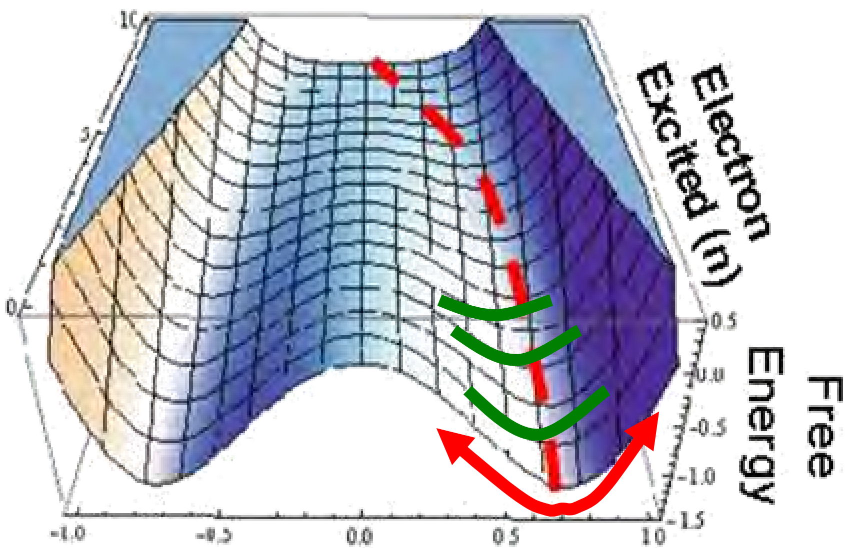


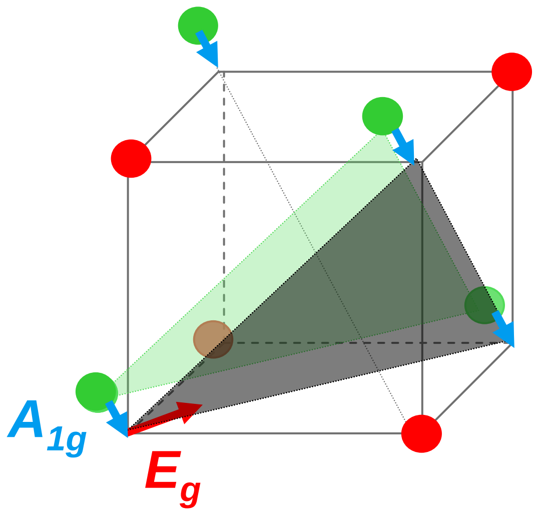


Stampfli & Bennemann, PRB **49**, 7299 (1994)

Jones-Peierls transition in the A7's

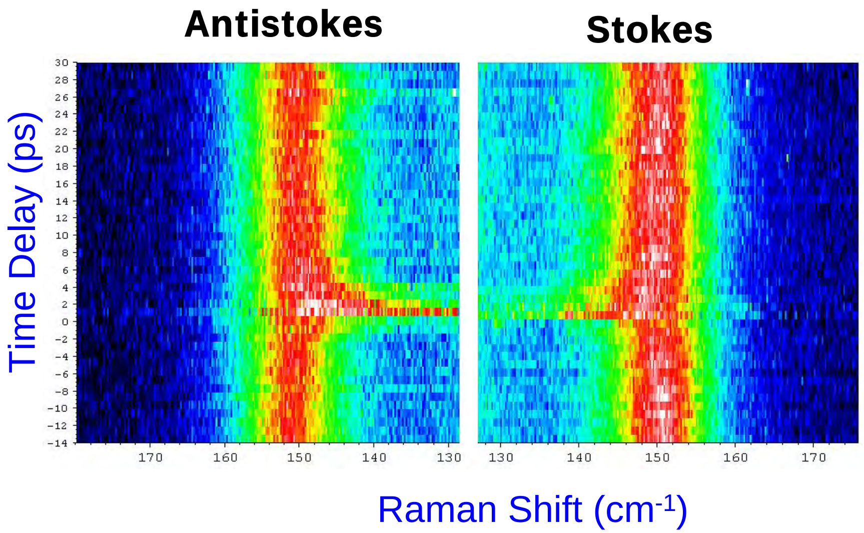
Charge excitation driven instability in the A7 semimetals

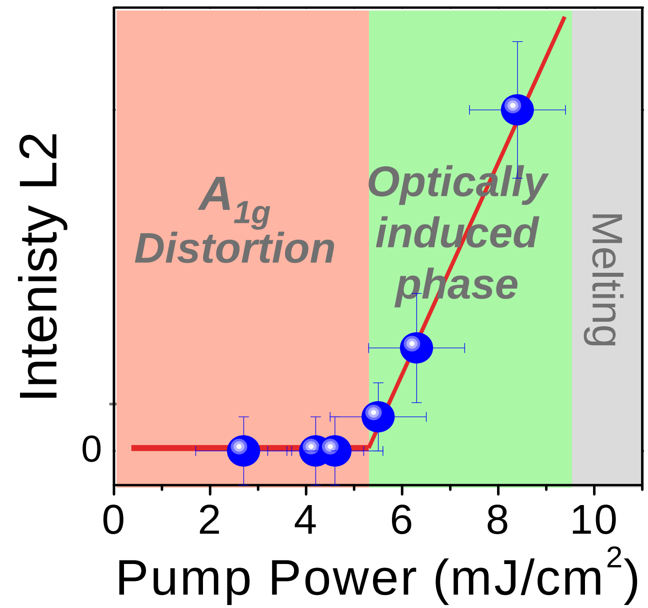


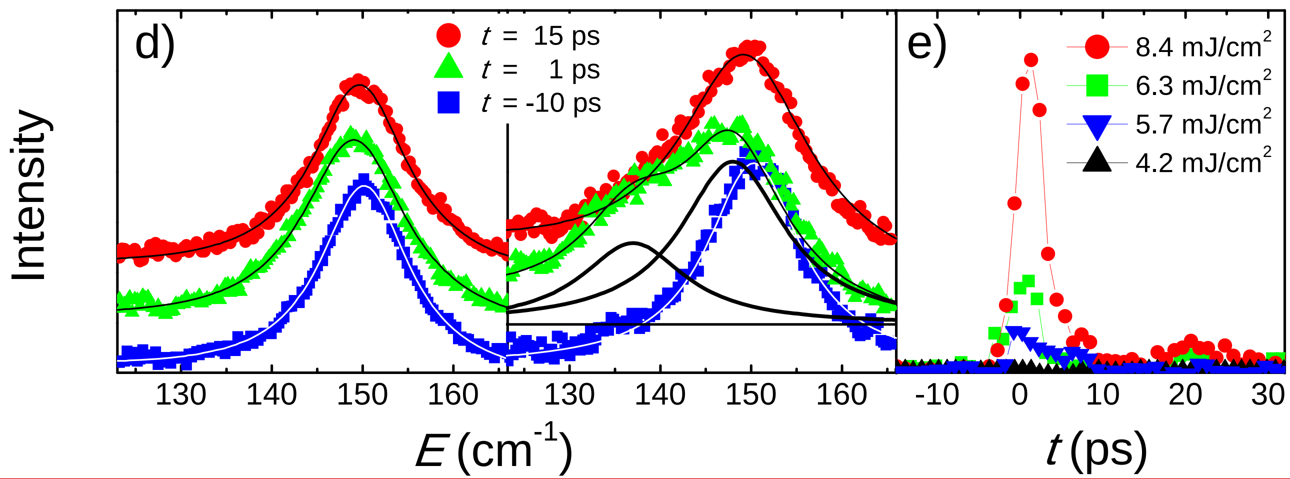


(111) Distorted from cubic

Jones-Peierls transition in the A7's







Why XFEL

› Interplay between charge & lattice order

› Full melting
  - TR-PES → Disappearance of peierls condensed state
  - TR-Xray → Structural dynamics

› Induced structural phase transition
  - TR-PES → Nature of the new state
  - TR-Xray → Nature of the new state

Conclusions

- Selective excitation

- Novel states of matter

- Detailed probing of physical properties of induced phenomena/novel states

- Time scale vs degree of freedom

- New techniques become feasible
  - Polarized time domain Mossbauer
  - Mossbauer diffraction??
  - 2 dimensional spectroscopy??
  - High magnetic fields and other extreme conditions more easy

Acknowledgements

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- Hermann Durr (BESSY)
- Hao Tjeng (Koln)
- Simone Altendorf (Koln)

Thank you

Open Ass. Prof. Position on T-Xray science: contact me