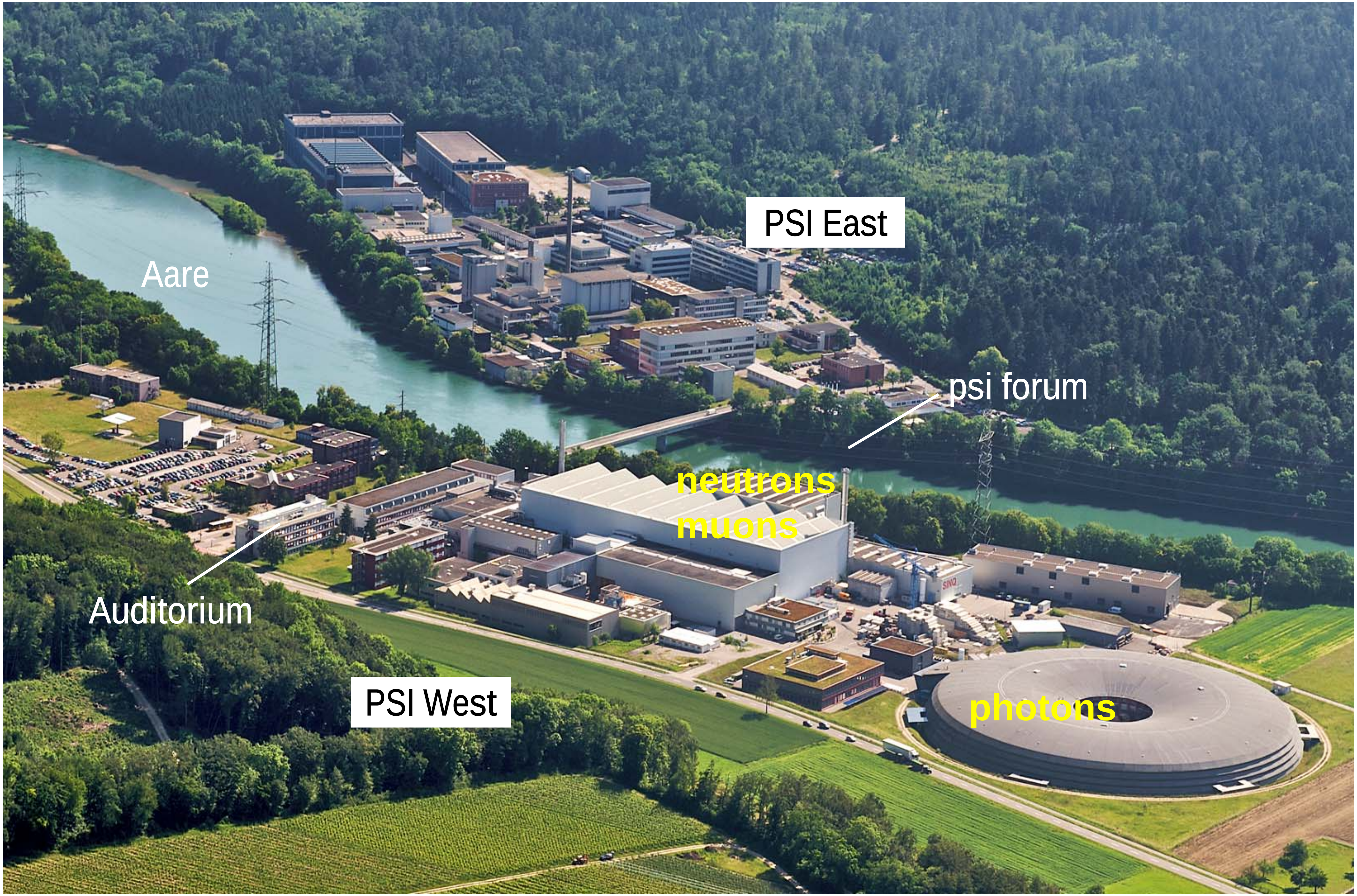
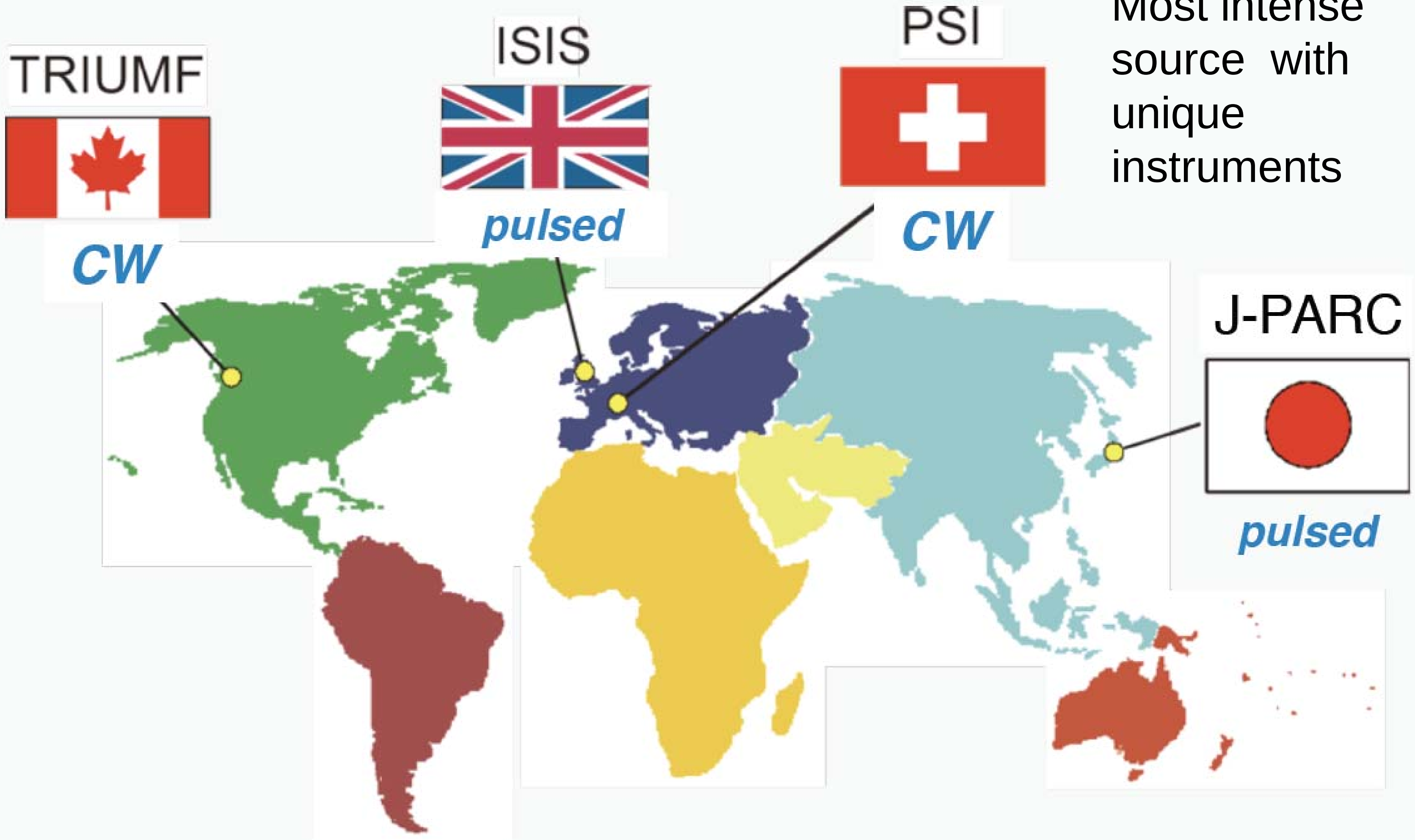
Wir schaffen Wissen – heute für morgen

Muons for study and research in condensed matter
Muon Spin Rotation/Relaxation

Prof. Elvezio Morenzoni
Laboratory for Muon Spin Spectroscopy
Paul Scherrer Institut


PSI East
Aare
psi forum
neutrons
muons
Auditorium
PSI West
photons

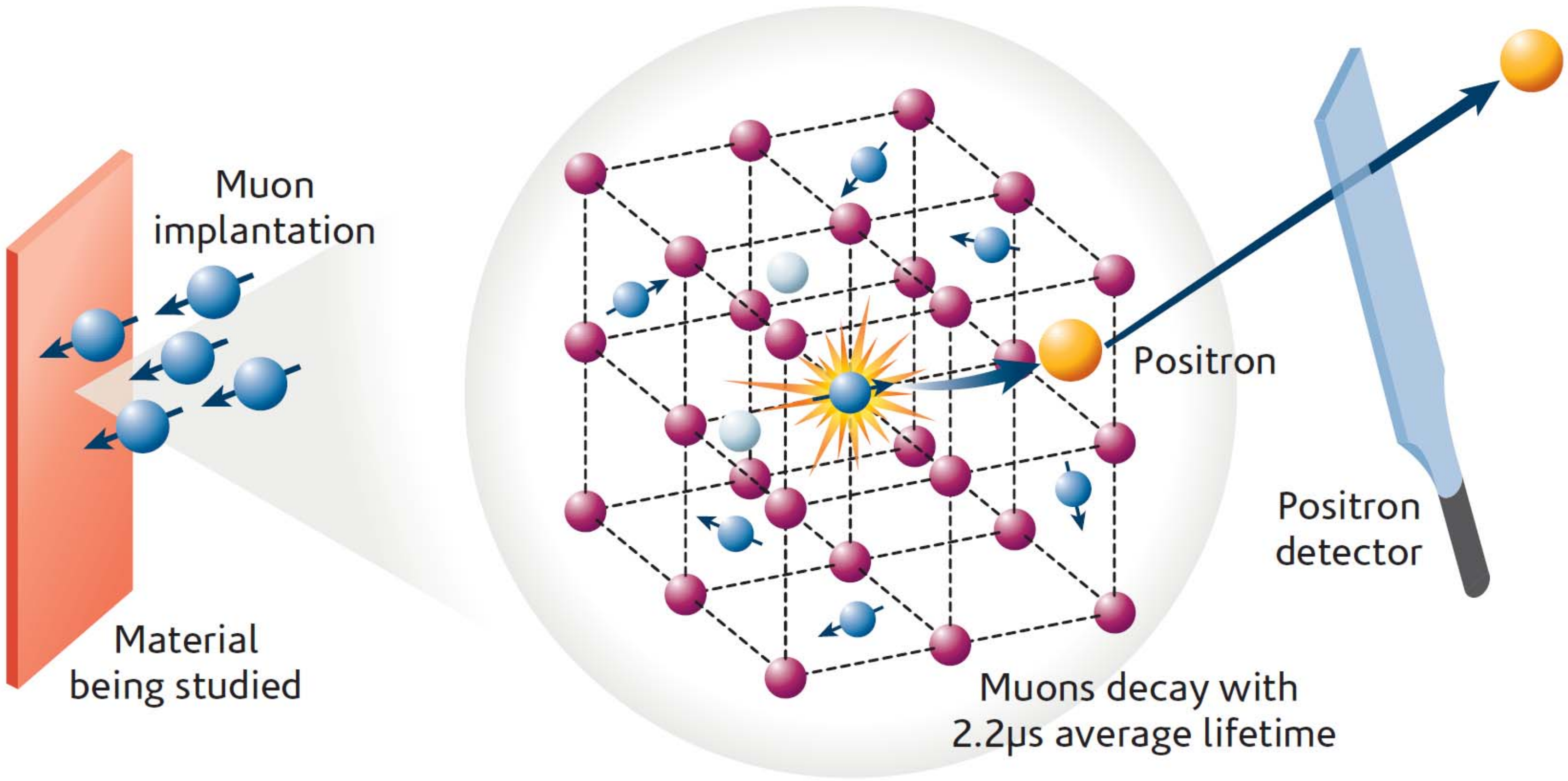
μSR in the world



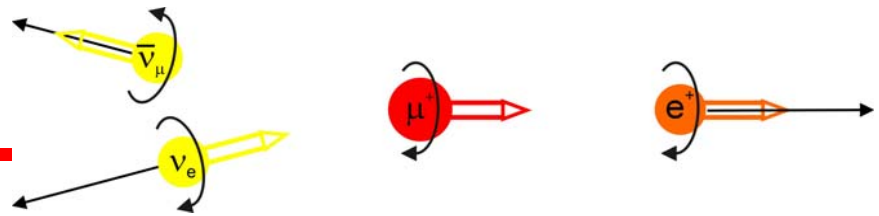
Most intense source with unique instruments

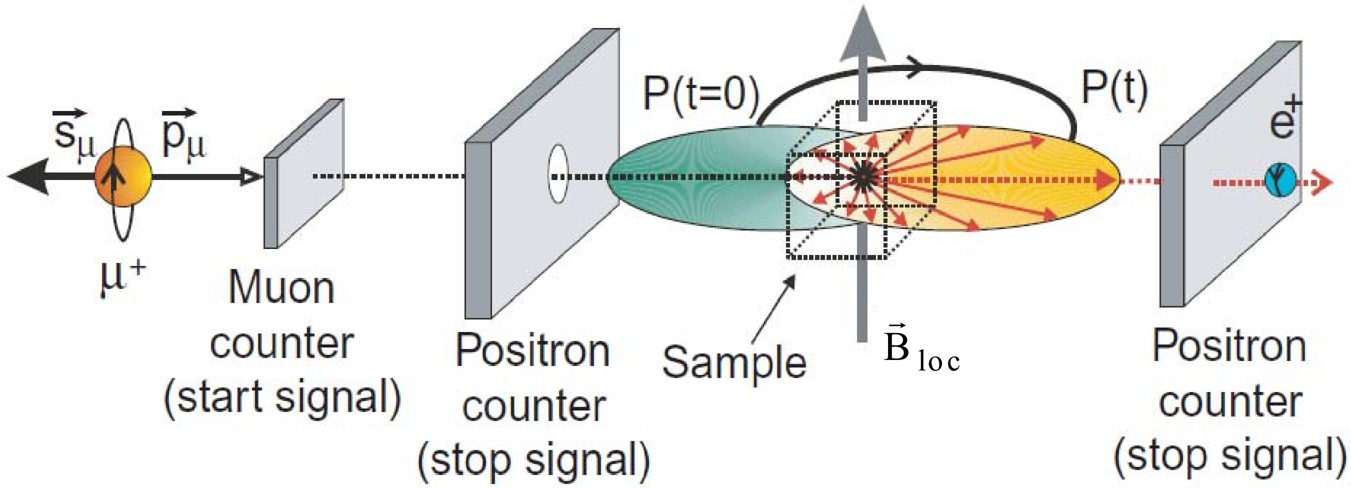
Facilities under study in South Corea, China, US

Polarized positive muons: Magnetic microprobes of matter



μSR: local probe technique





$m_\mu \approx$ 1/9 m_p , τ_μ = 2.19714 μs

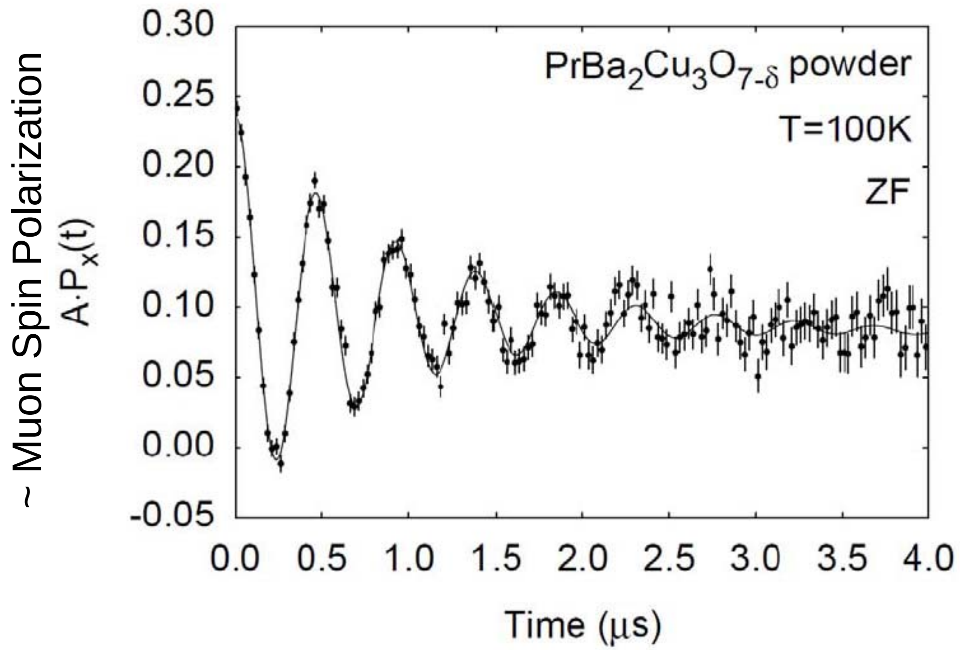
s_μ = ½, μ_μ = 3.18 μ_p

$P(0) \cong 1$

$\vec{P}(t) = 2 < \vec{s}_\mu(t) >$

$P(t) = \vec{P}(t) \cdot \vec{n}$

$$N_{e^+}(t) = B_G + N_0 \exp(-t/\tau_\mu)\,[1 + A_0 P(t)]$$



Precession frequency → Value of local magnetic field at muon site

$\omega = \gamma_\mu B_{loc}$

Damping (Relaxation rate) → Field width, fluctuations

Frequency spectrum → field distributions

Amplitude → magn. /pm/sc fractions

Why muons?

•Study of local magnetic, superconducting, electronic properties (material science but also applications in soft matter, chemistry)

• Simple magnetic probe (spin ½)

• Local and very sensitive probe (large magnetic moment, 100% initial polarization)

Particularly suitable for:
•Very weak effects, small moment magnetism ~ 10^{-3} μ_B /Atom
•Random magnetism (e.g. spin glasses), short range order
•superconductivity

•Phase inhomogeneities, coexistence/competition of order parameters

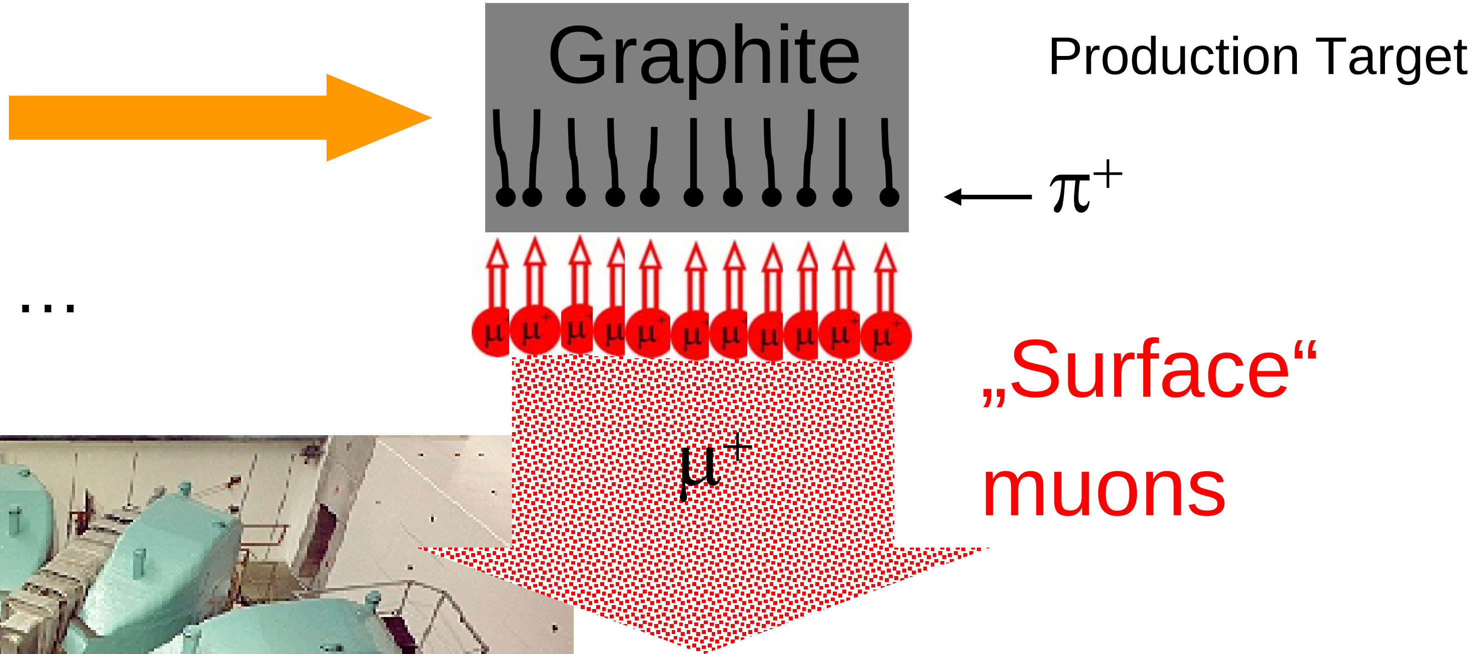
•No restrictions in choice of materials to be studied (solid, liquid, gas,)

•Dynamics: spins, moments, local currents fluctuations:
Fluctuation time window: $10^{-5} < t < 10^{-11}$ s

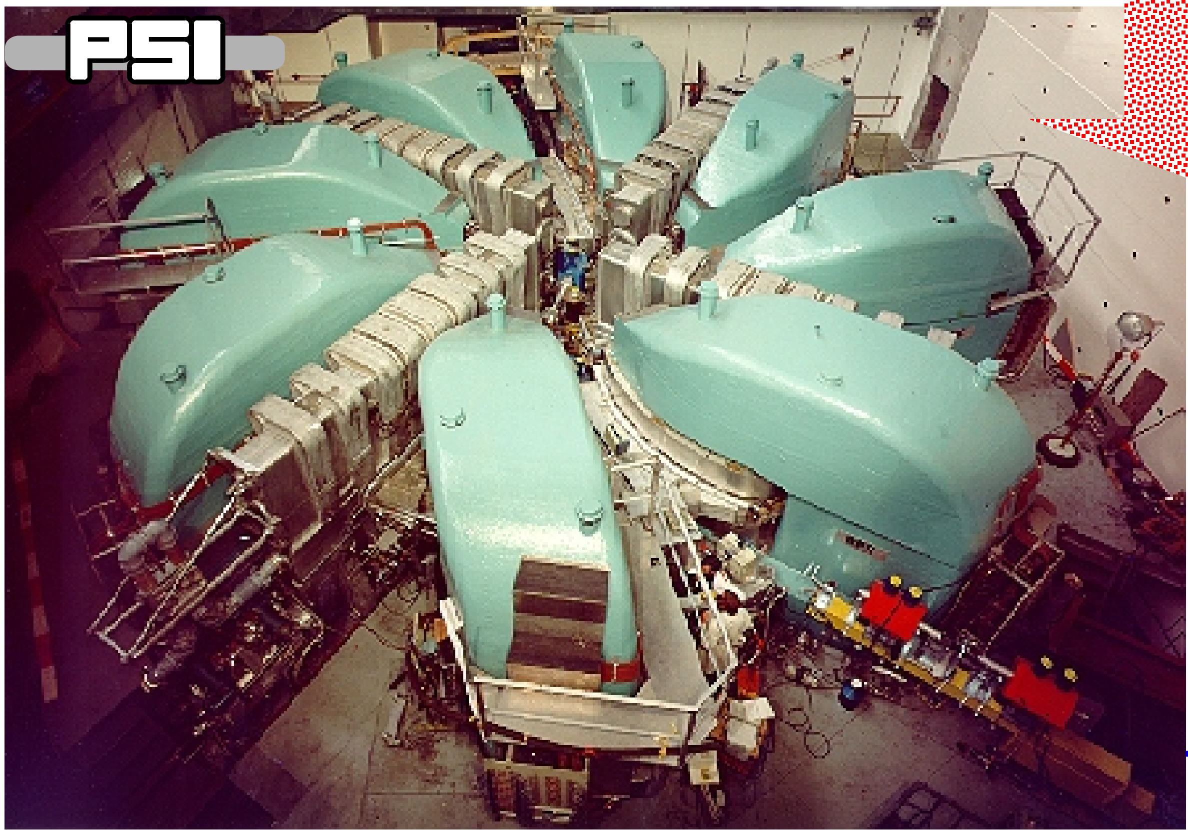
Generation of polarized muons (μ^+)

2.2 mA $\cong$ 1.4 10^{16} Protons/sec

with 600 MeV



p + C → $\pi^+ \pi^-$ p n …



~10^7- 10^8 μ^+/sec

100 % pol.

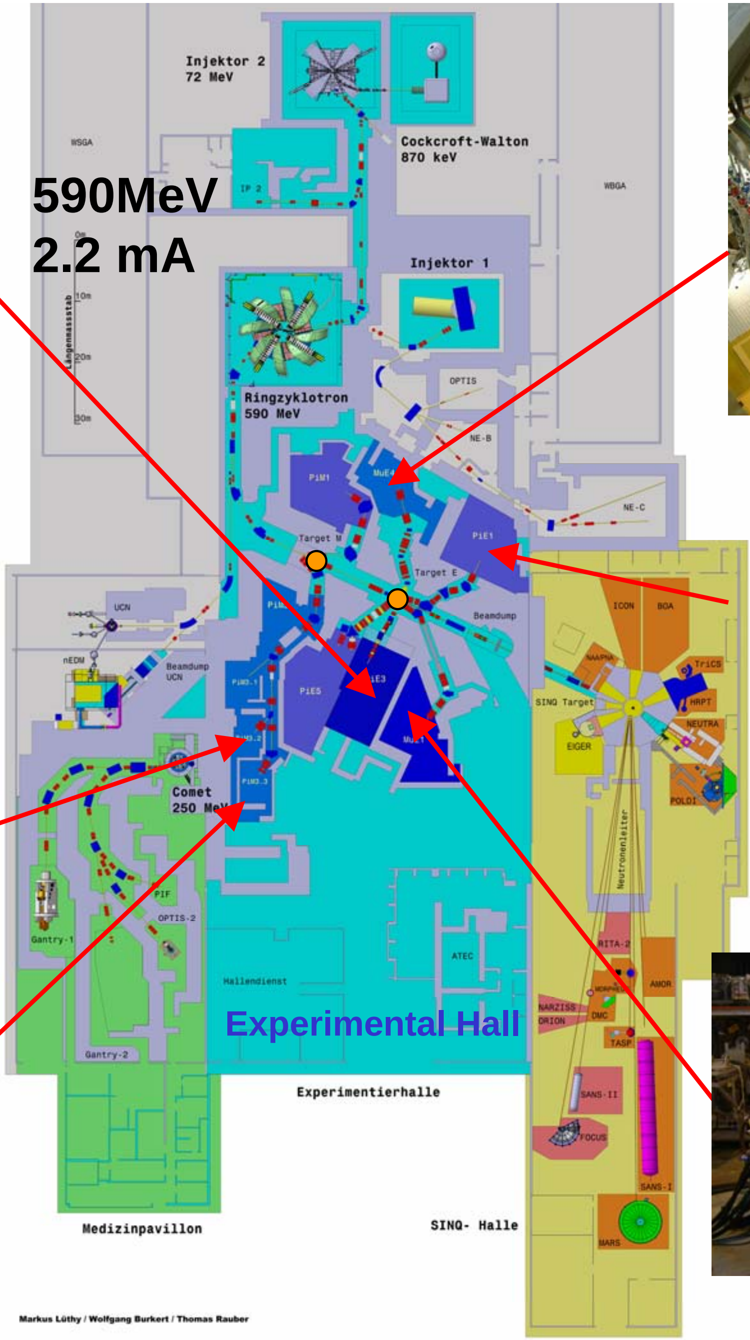
~ 4 MeV

generally used for “bulk” condensed matter studies

For thin film studies: eV-30 keV

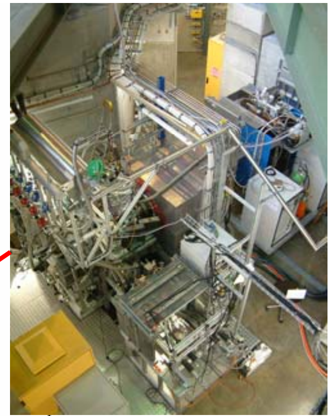
Muon Instruments at PSI : SμS (Swiss Muon Source)

High Field μSR,
9.5 T, 20 mK



LEM
Low-energy muon beam and instrument, tunable energy (**0.5-30 keV**, μ^+), *thin-film, near-surface and multi-layer studies (1-300 nm)*

0.3 T,
2.5 K

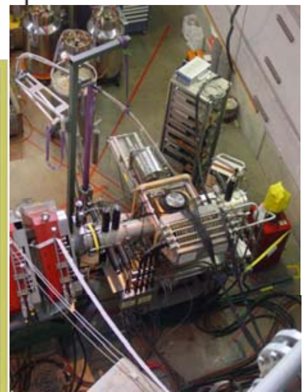


GPS
General Purpose Surface Muon Instrument
Muon energy: **4.2 MeV** (μ^+)

0.6 T, 1.8 K

DOLLY
General Purpose Surface Muon Instrument
Muon energy: **4.2 MeV** (μ^+)

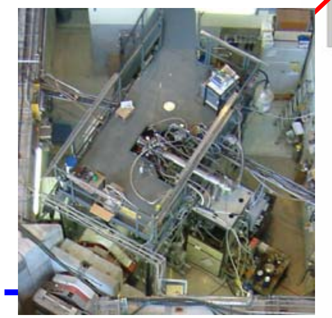
0.5 T
2 K (0.25K)



Shared Beam Surface Muon Facility (Muon On REquest)

LTF
Low Temperature Facility
Muon energy: **4.2 MeV** (μ^+)

3 T,
20 mK- 4 K



GPD
General Purpose Decay Channel Instrument
Muon energy: **5 - 60 MeV**
(μ^+ or μ^-)

0.5 T,
300 mK
2.8 GPa

Research at the SμS

Magnetic materials
Molecular magnets
Cobaltites
Manganites
Heavy Fermions
Intermetallic compounds with
d- and f-elements

Semiconductors
Magnetic sm
Organic sm

Thin films
Multilayers
Oxides
Spin Valves
FM/SC
AF/SC

Low dimensional magnets
Spin liquids, ices, glasses

Superconductors
Cuprates
Iron Based
Low T_c

Chemistry, Soft matter
Free radicals
Liquid crystals

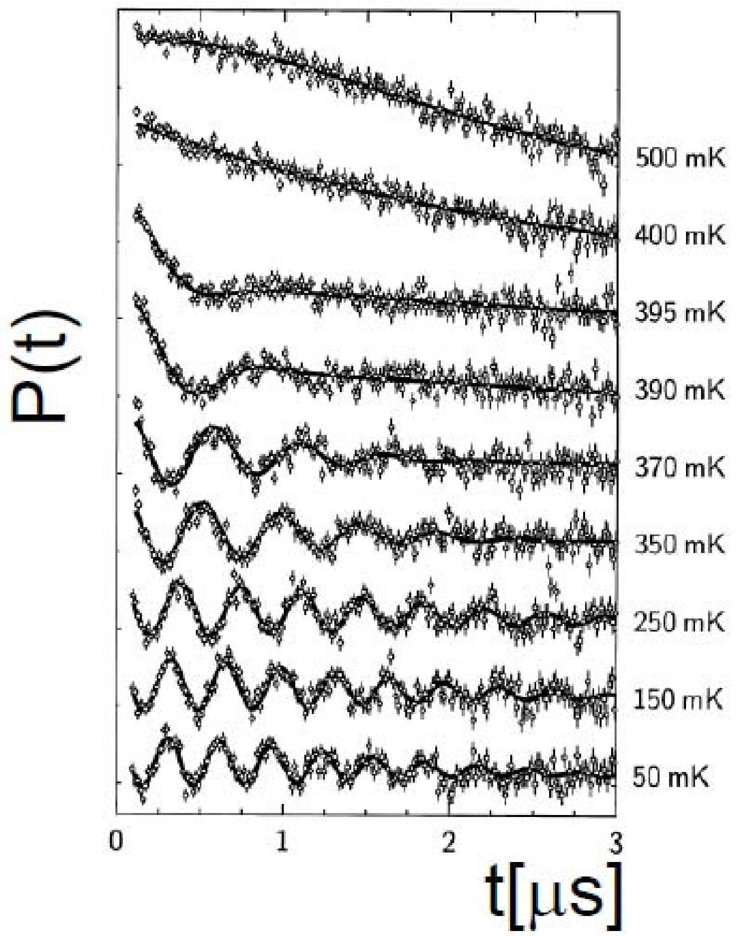
Material Science
Multiferroics
Battery materials

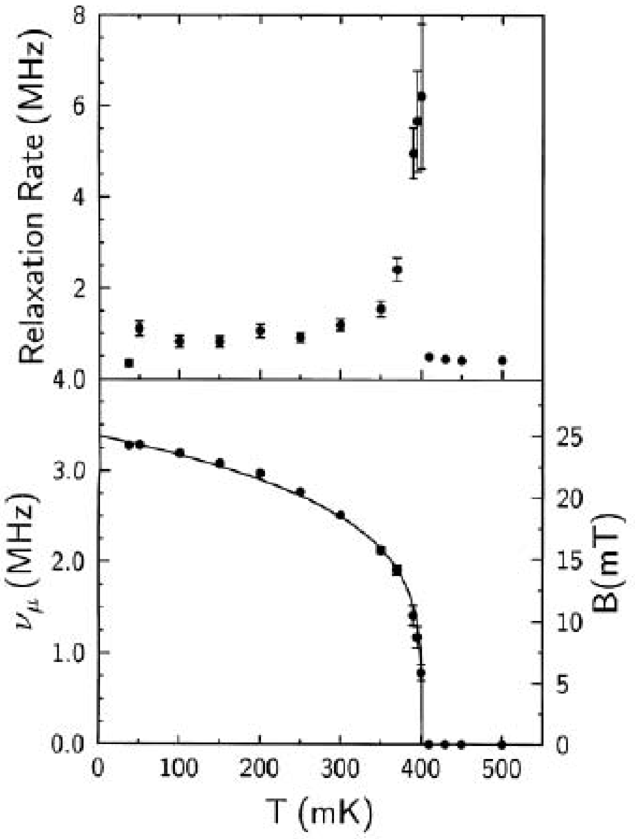
Microscopic magnetometry

$B_{ext}=0$

$(C_{13}H_{23}O_2NO)_2$

Organic antiferromagnet



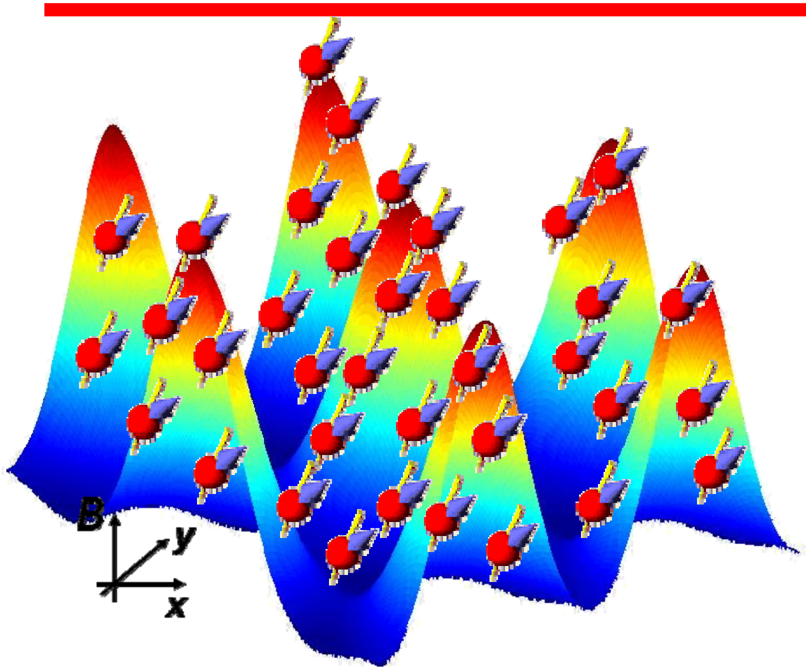


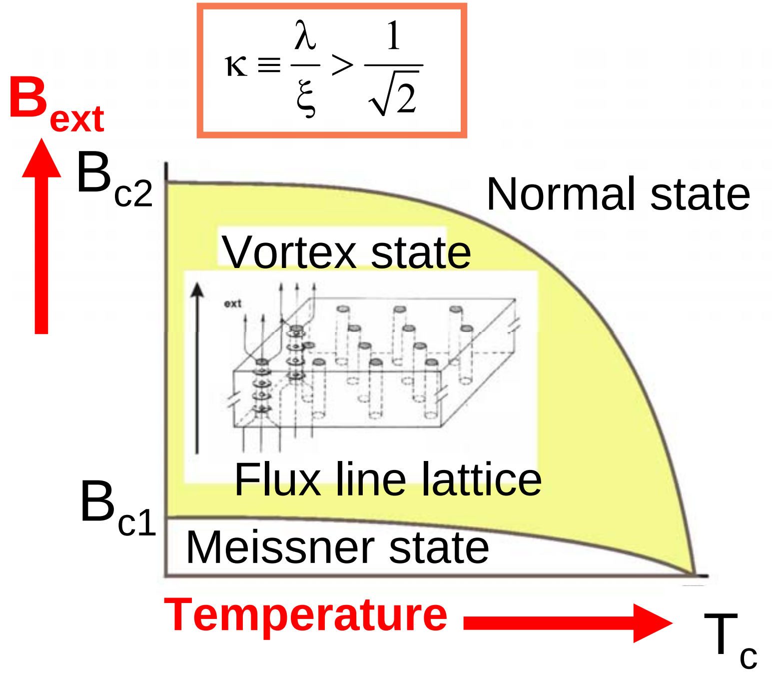
$$P(t) = a_L(t) + a_T e^{-\lambda t}\cos(2\pi\nu_\mu t)$$

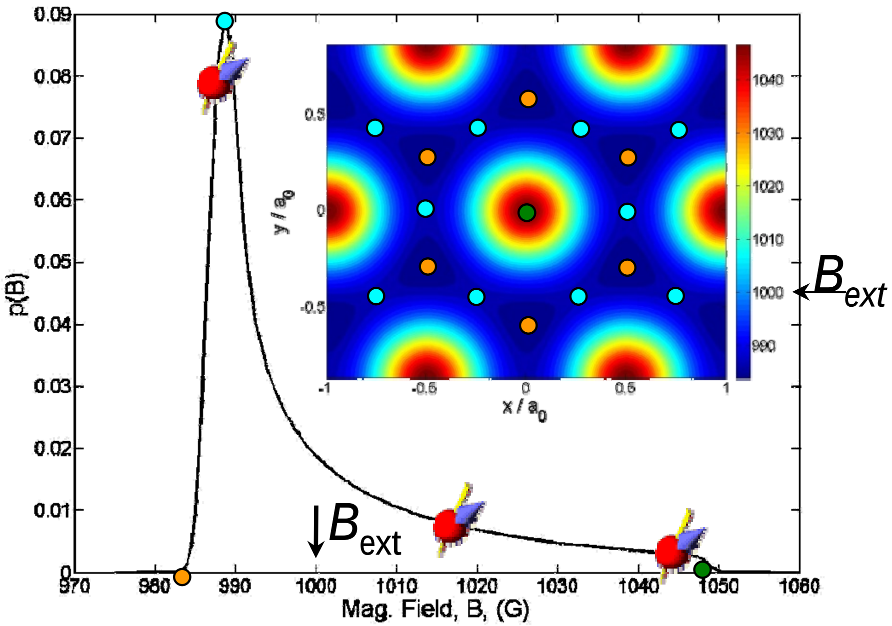
$$\lambda = \frac{1}{T}$$ relaxation rate, $[\mu s^{-1}]$ or [MHz]

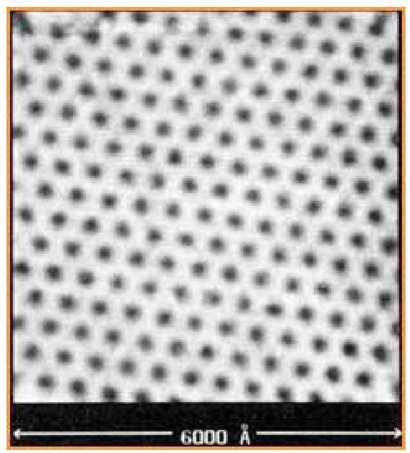
S. Blundell et al., Physica B (2000)

Vortex state: microscopic properties

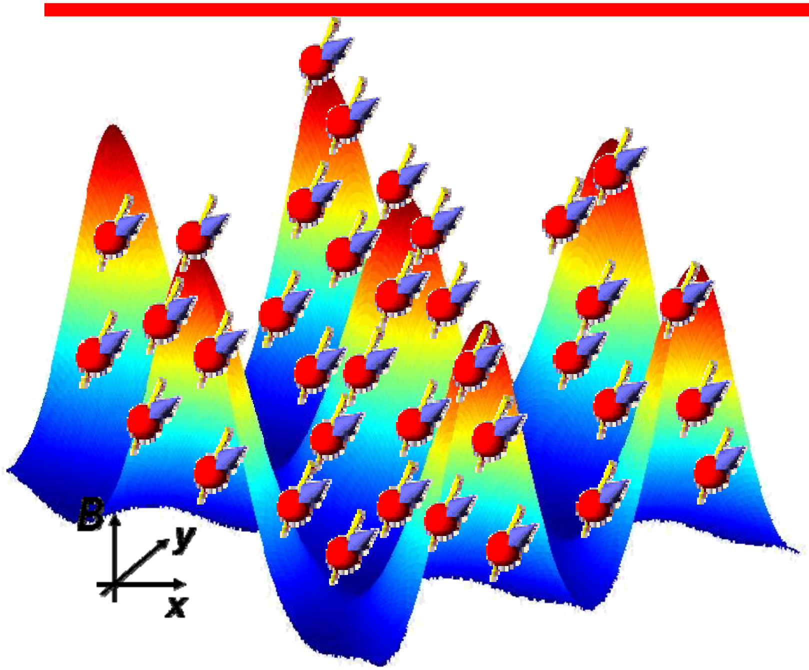


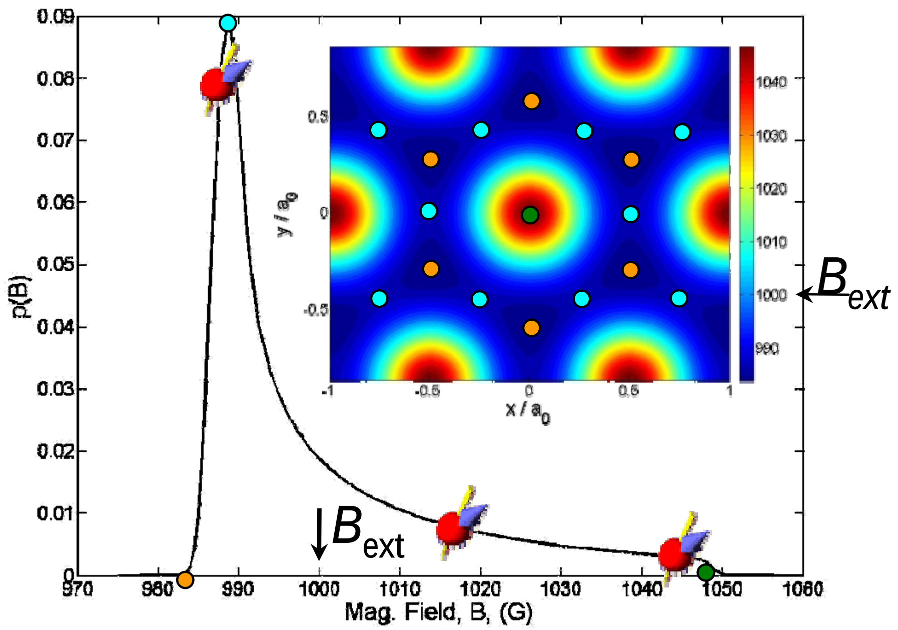






Vortex state: microscopic properties



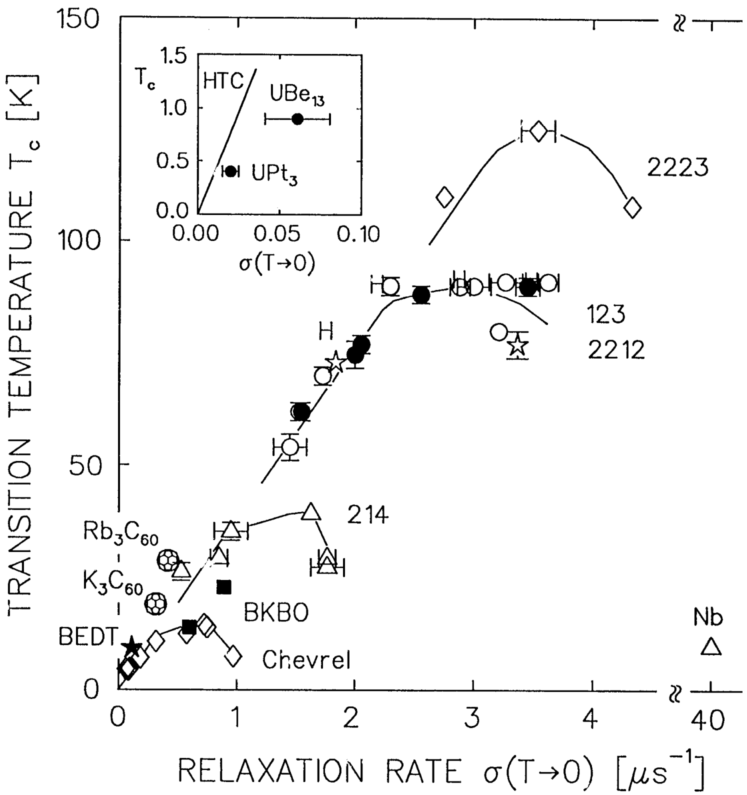


- Characteristic lengths: magnetic penetration depth λ, coherence length
- SC order parameter
- Structure of vortex lattice
- Vortex dynamics
- Classification of superconductors

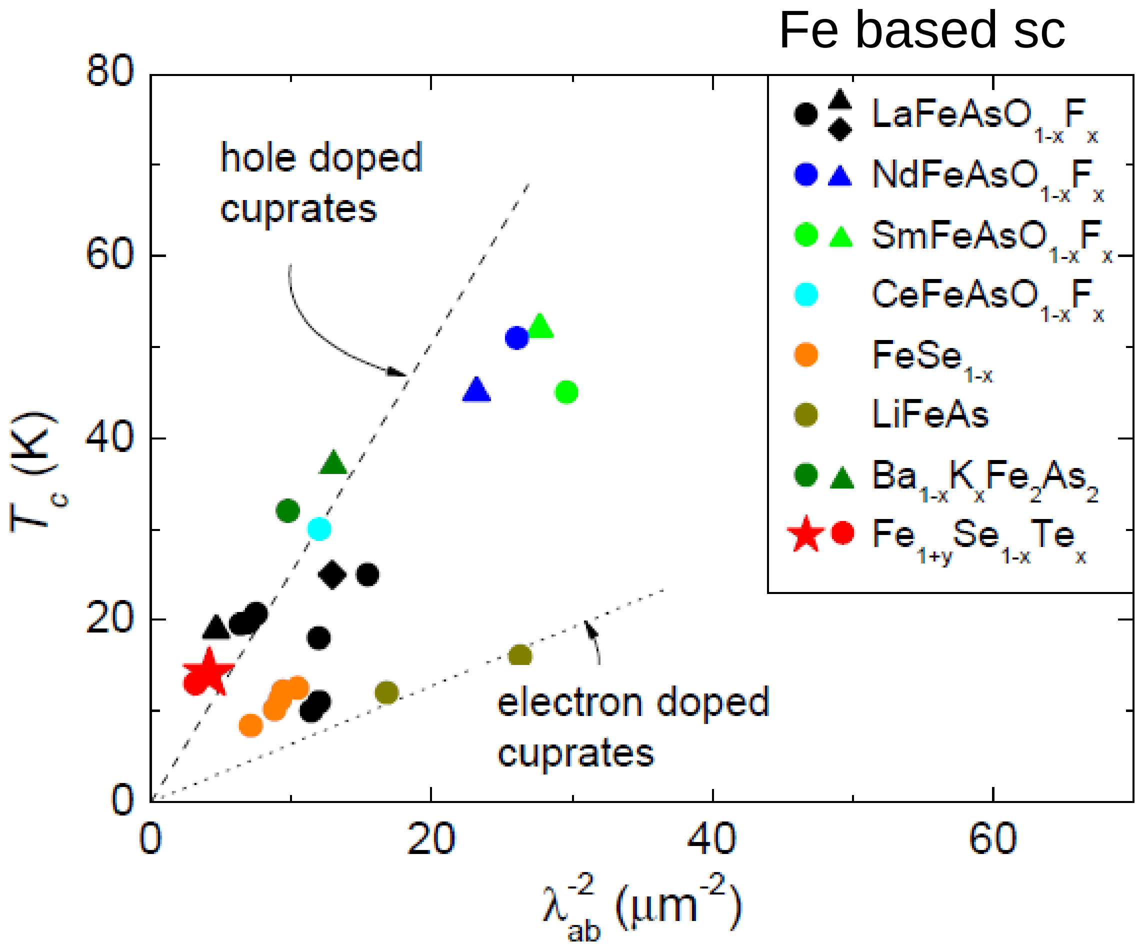
Classification of superconductors

$$T_c \text{ versus } \sigma \propto \frac{1}{\lambda^2} \propto \frac{n_s}{m^*} \text{ , Uemura plot}$$

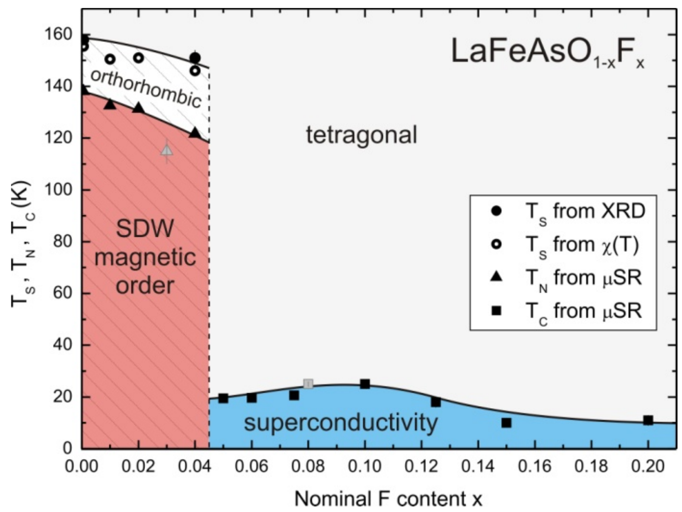
Y.Uemura et al., Phys. Rev. Lett. 66, 2665 (1991)



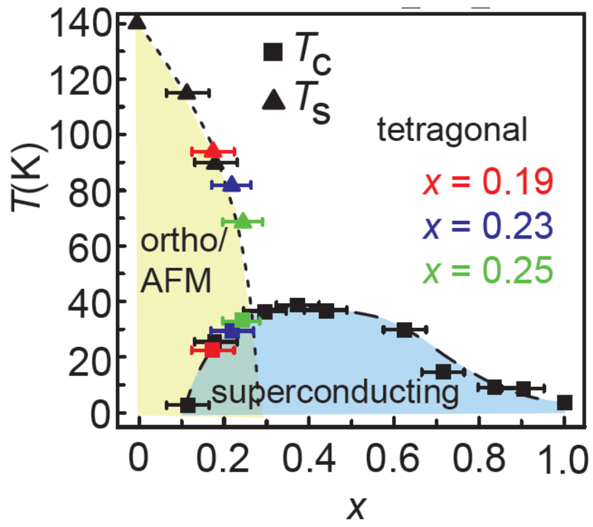
Fe based sc



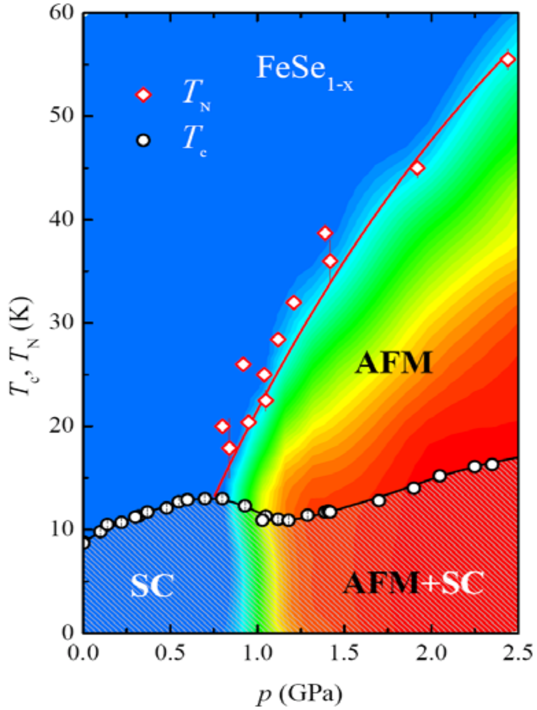
Phase diagrams



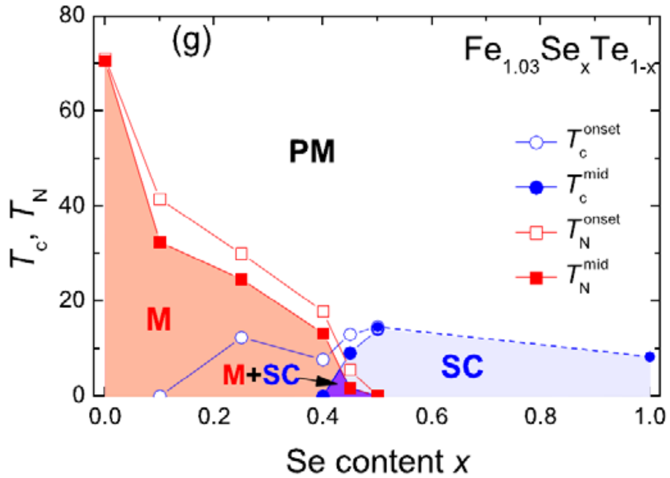
H. Luetkens *et al.*, Nature Materials 8, 305 (2009)



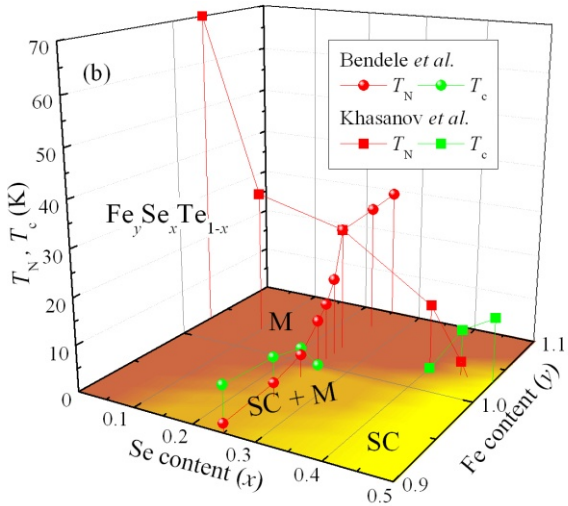
E. Wiesenmayer *et al.*, PRL 107, 237001 (2011)



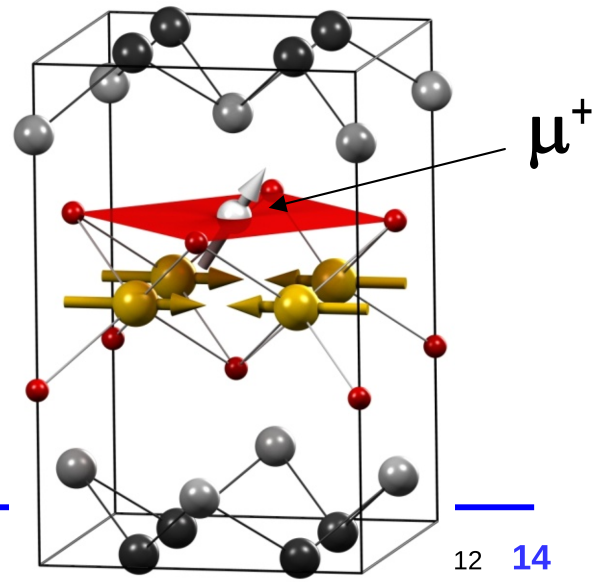
M. Bendele *et al.*, PRL 104, 087003 (2010)



R. Khasanov *et al.*, PRB 80, 14051(R) (2009)

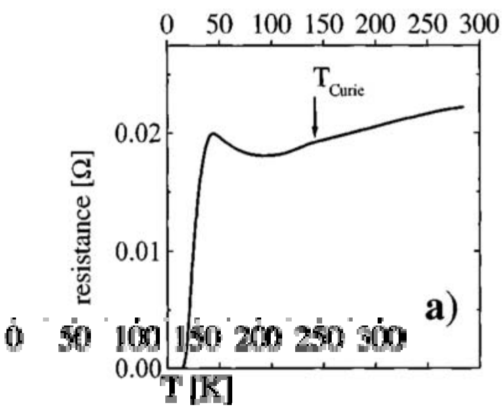


M. Bendele *et al.*, PRB 82, 212504 (2010)

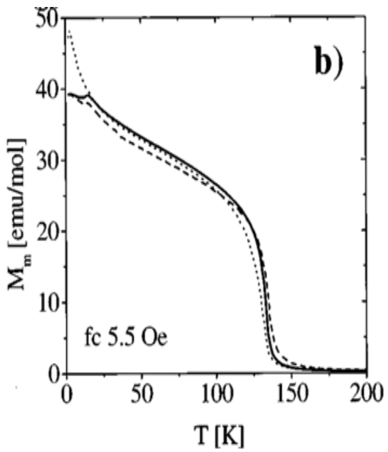


Nanoscale coexistence of superconductivity and magnetism

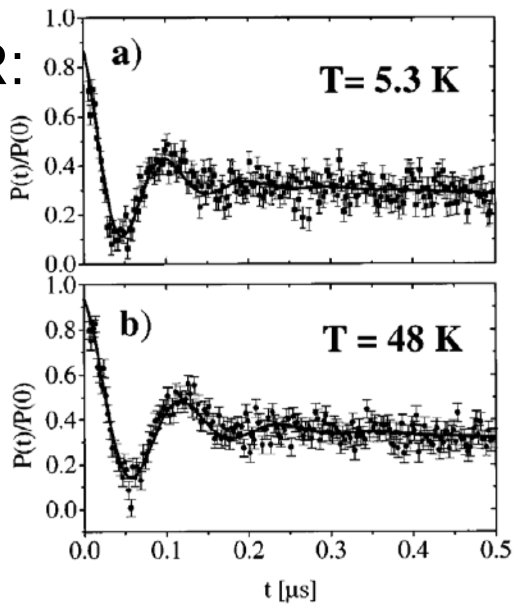
Resistivity:
(**Superconductivity**)

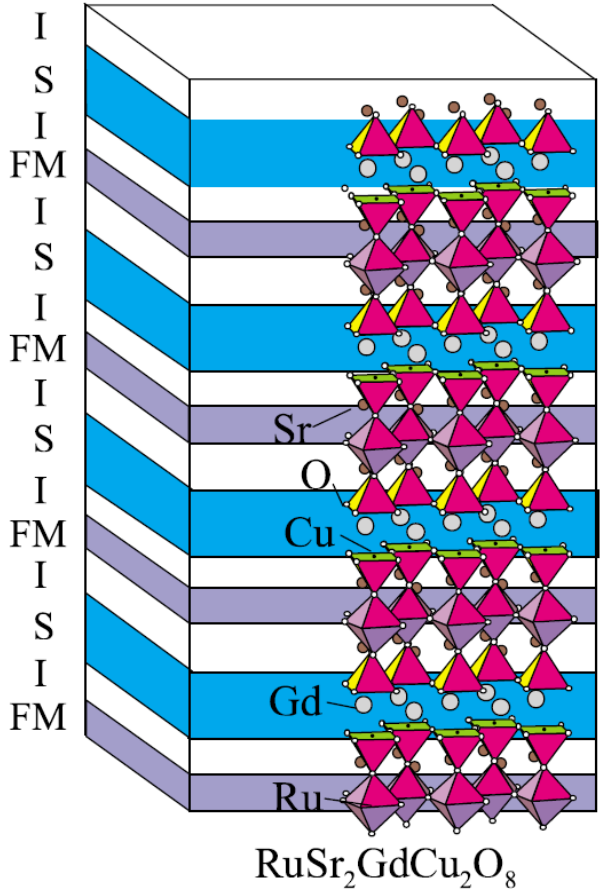


Magnetization:
(**Ferromagnetism**)



μSR:



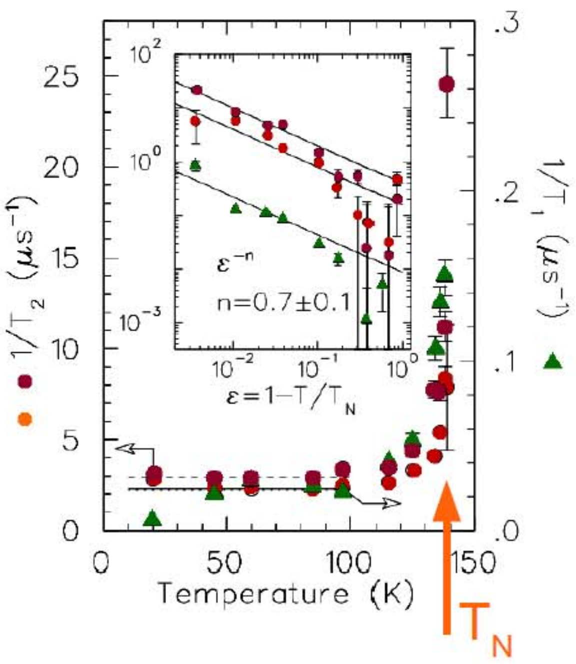


Structure:
T. Nachtrab et al., Phys. Rev. Lett. ***92*** *(2004) 117001*

C. Bernhard et al., Phys. Rev. B 59 (1999) 14099

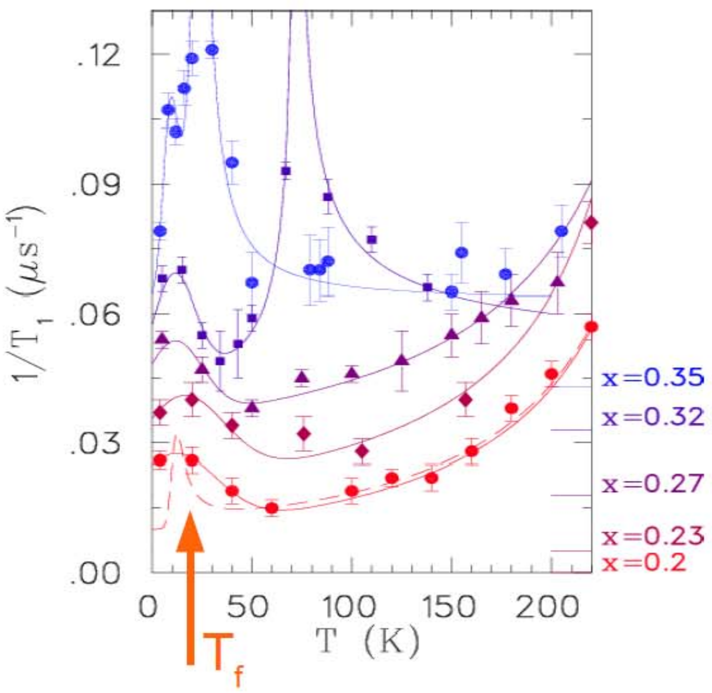
Dynamics: freezing of fluctuations

$LaMnO_3$: $T \rightarrow T_N$



Spin fluctuations slow down approaching the transition

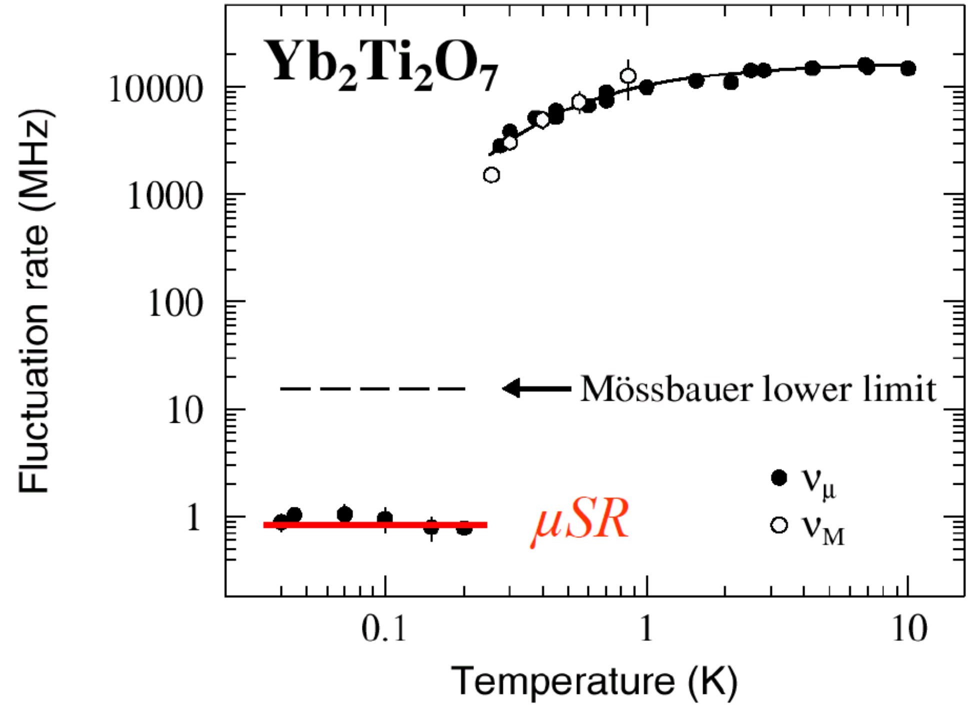
$YBa_2Cu_3O_{6+x}$



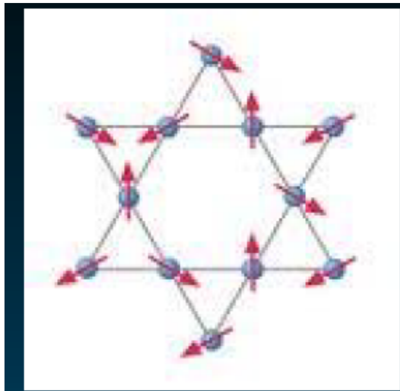
Freezing of hole spins

Other intrinsic spin dynamics ...

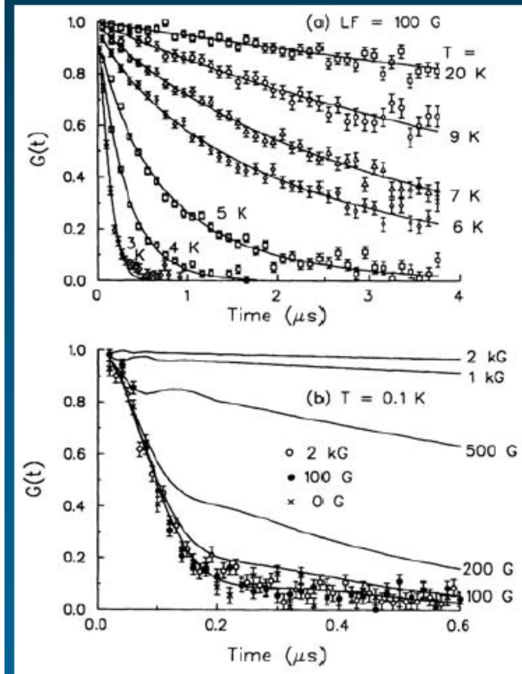
OR persistent spin dynamics



Persistent dynamics at very low temperatures



$SrCr_8Ga_4O_{19}$

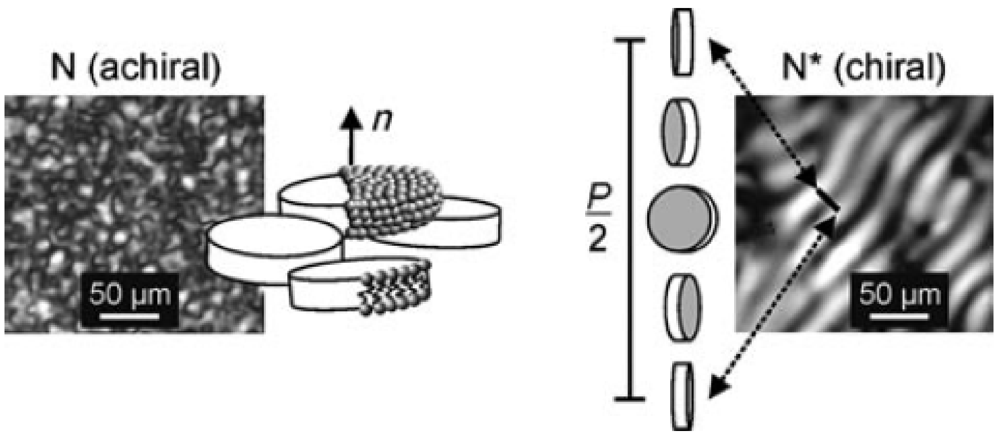


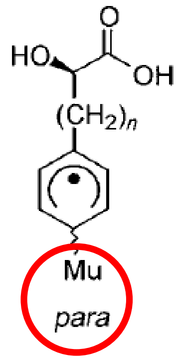
Muon as sensitive tracer in soft matter

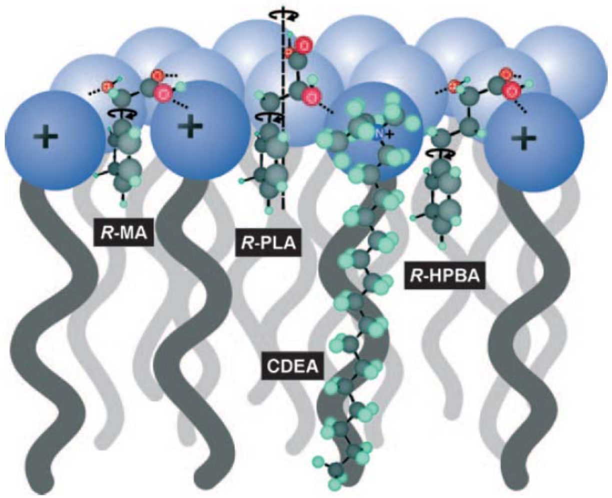
Angewandte Chemie 2001

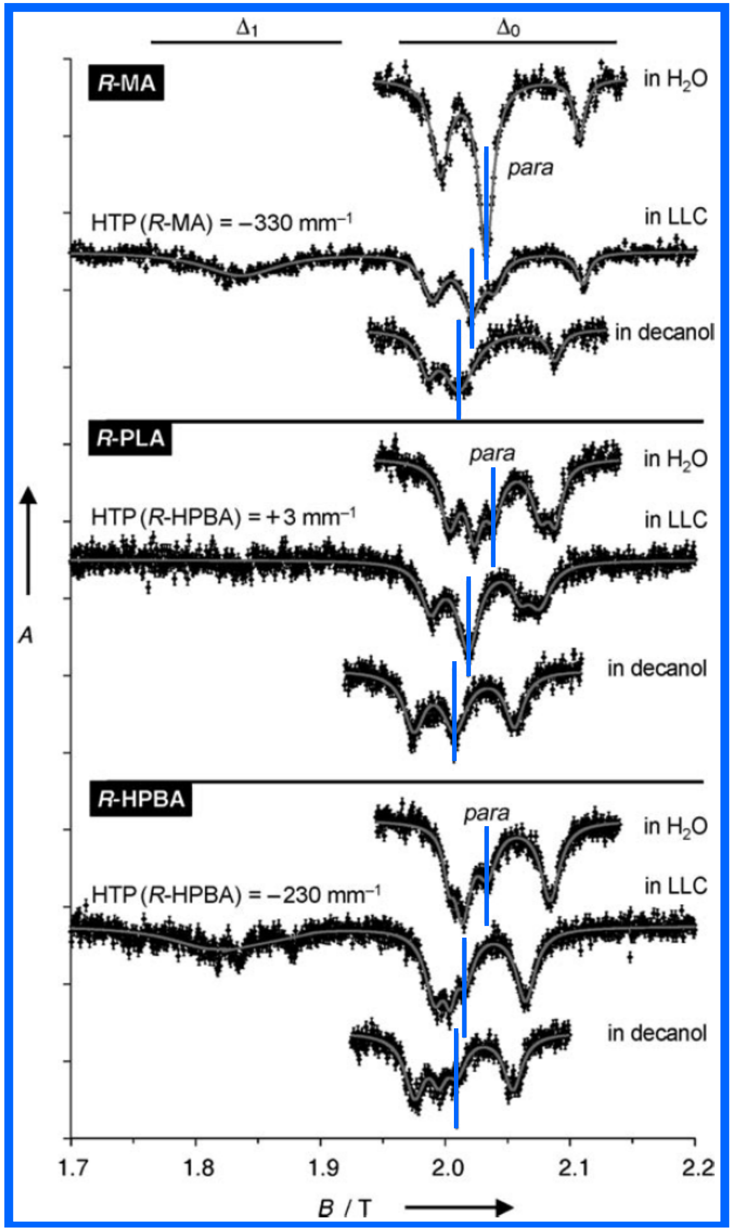
Phase transition in liquid crystals by dopant addition:

resonance lines

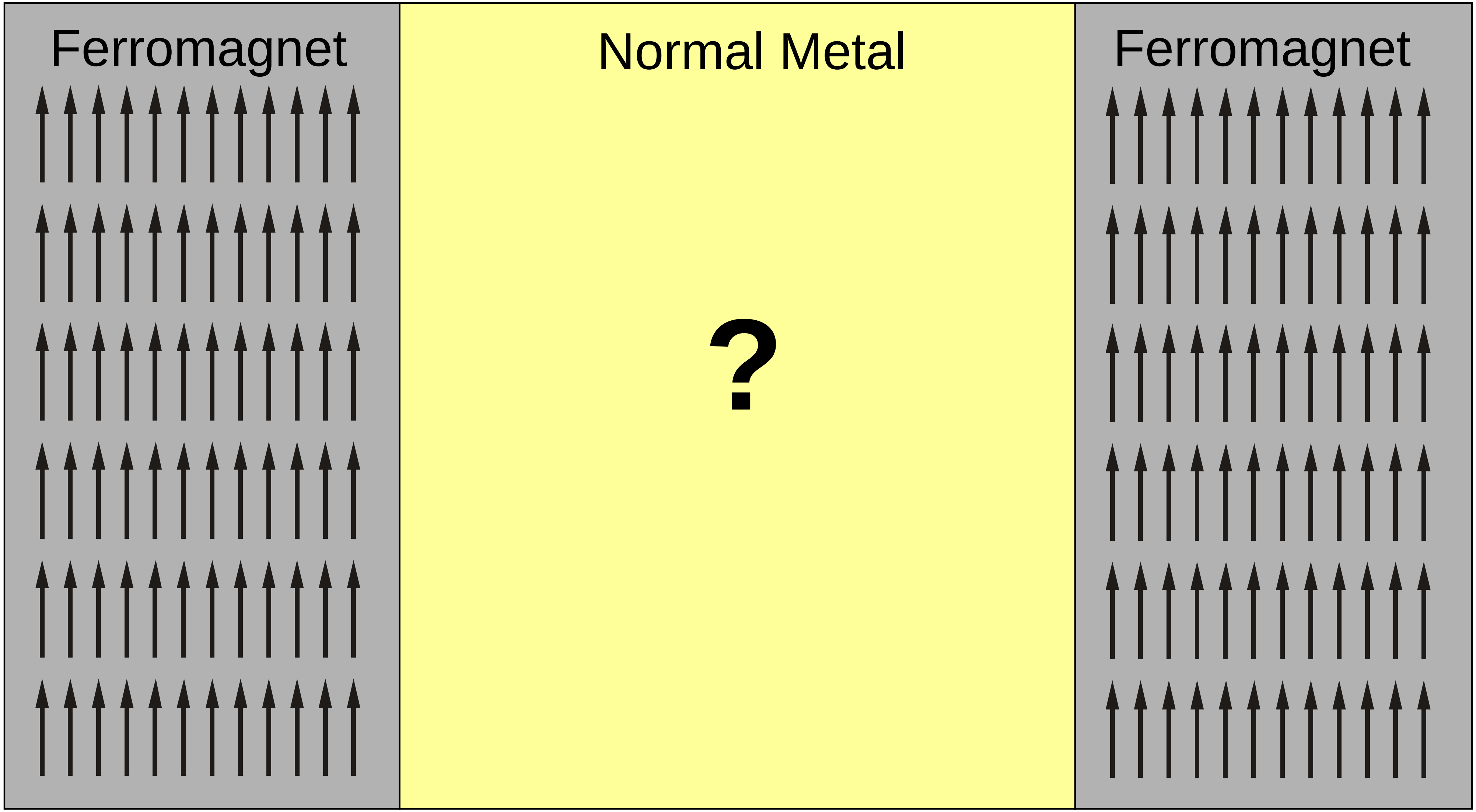






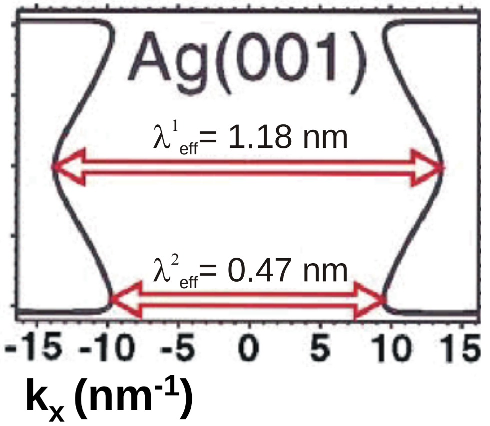


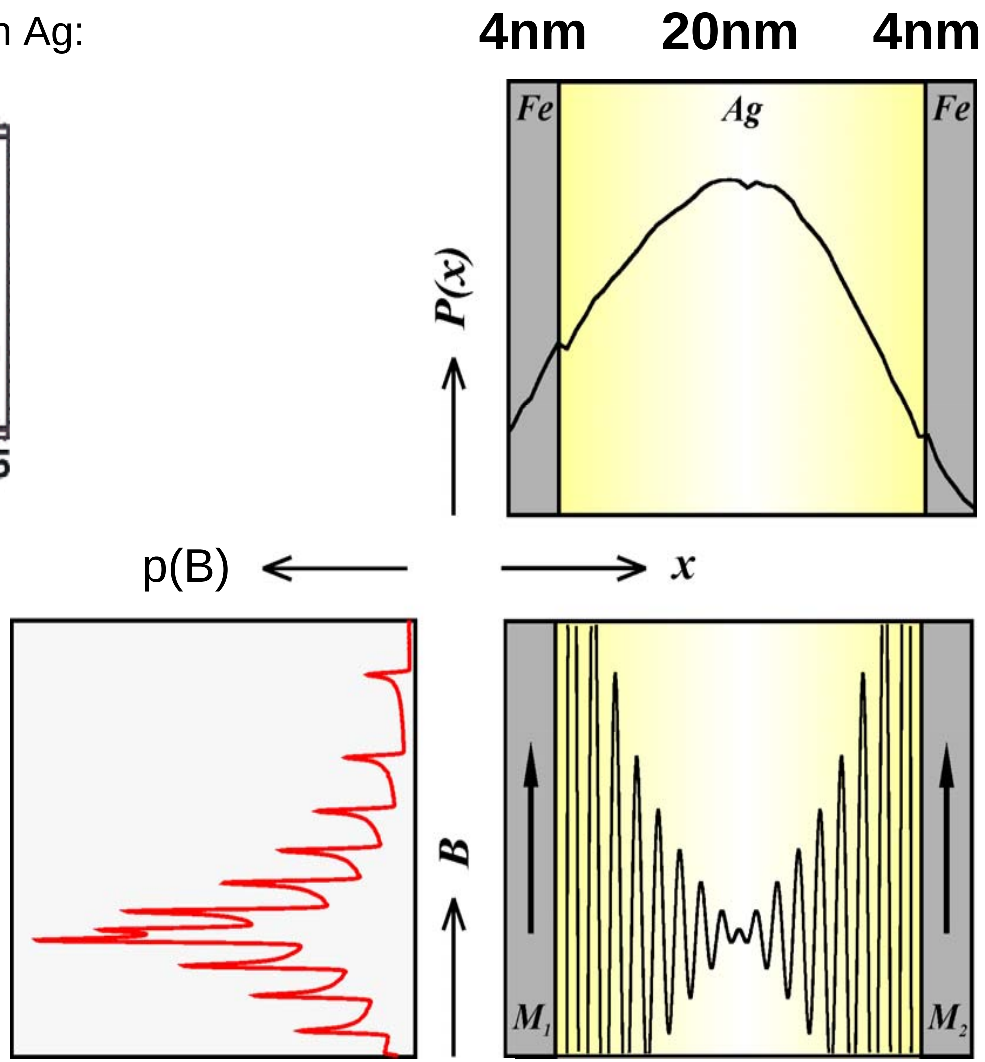
OR in buried layers: Magnetic multilayers (ML)



Oscillating polarization of conduction electrons

Critical spanning vectors in Ag:





Fe/Ag/Fe

Implantation profile of 3 keV muons.

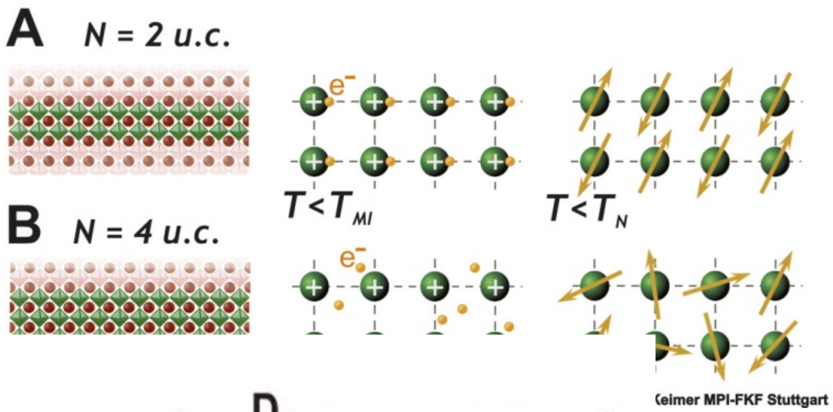
$P(x) \propto B(x)$

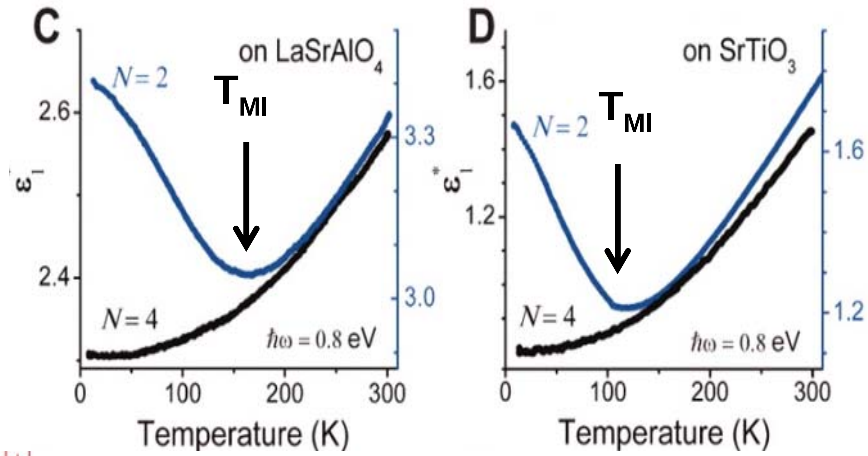
H. Luetkens, J. Korecki, E. Morenzoni, T. Prokscha, M. Birke, H. Glückler, R. Khasanov, H.-H. Klauss, T. Slezak, A. Suter, E. M. Forgan, Ch. Niedermayer, and F. J. Litterst Phys Rev. Lett. **91**, 017204 (2003).

OR probe very thin layers: a few Unit Cells thick

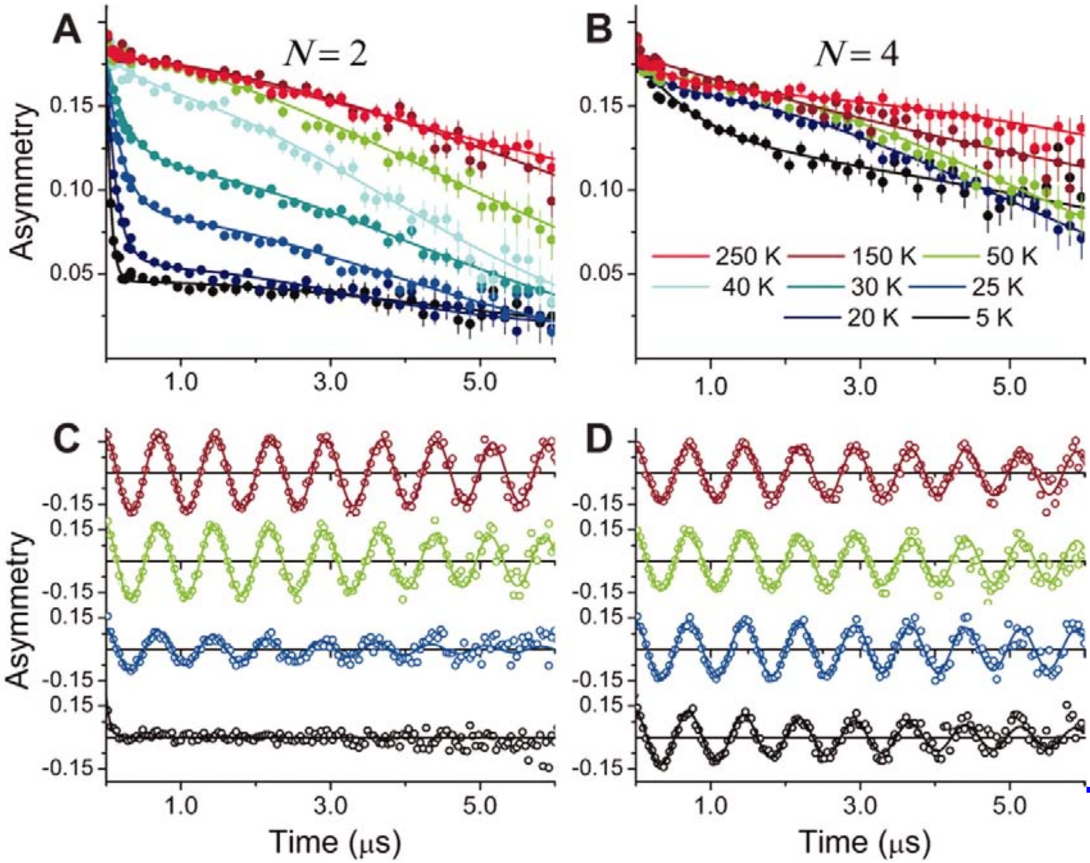
Dimensionality Control of Electronic Phase Transitions in Nickel-Oxide Superlattices

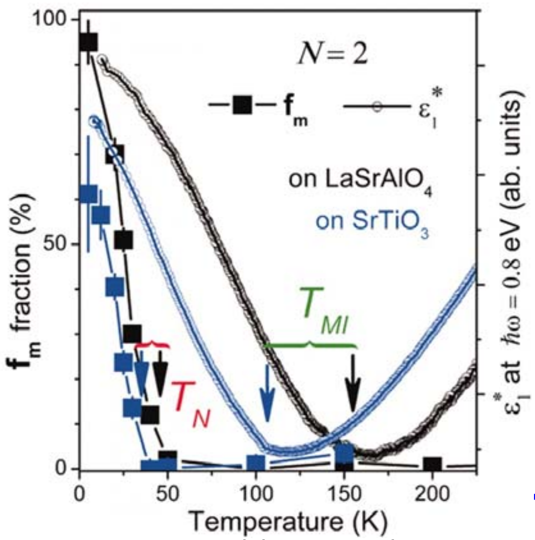
A. Boris et al., Science (2011)



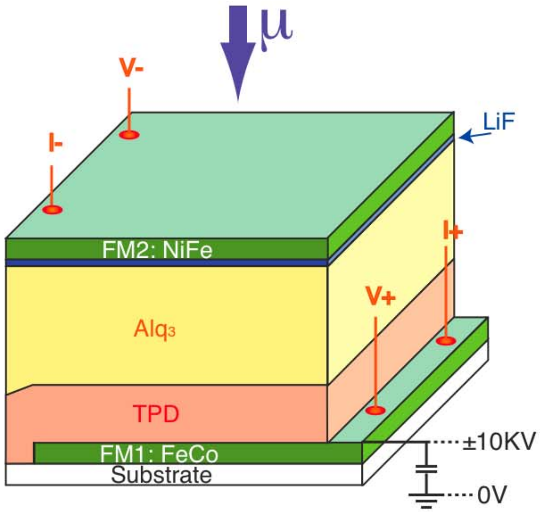


$LaNiO_3/LaAlO_3$ Superlattices

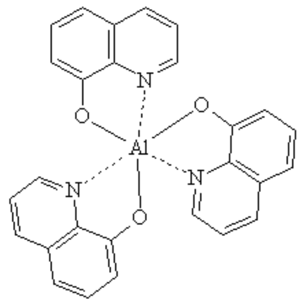




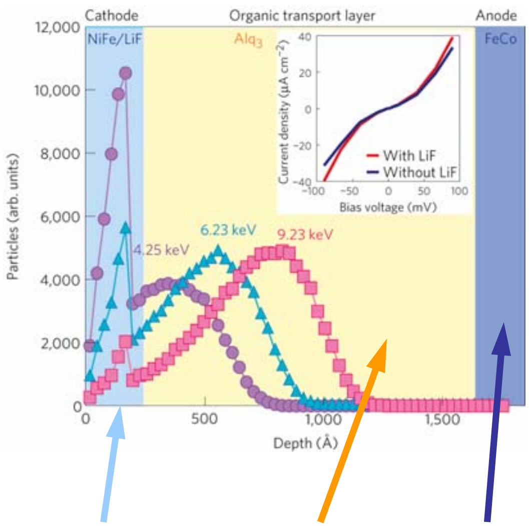
OR study new devices



Operational Spin Valve
With organic organic
Semiconducting spacer
Alq3: C_{27} H_{18} N_3 O_3Al

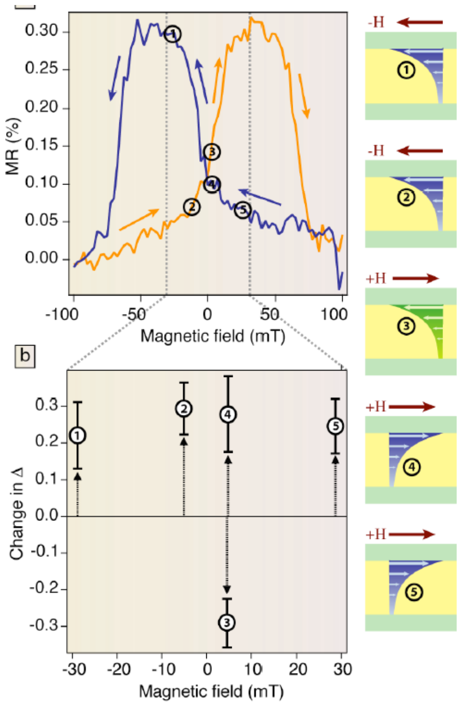


current I

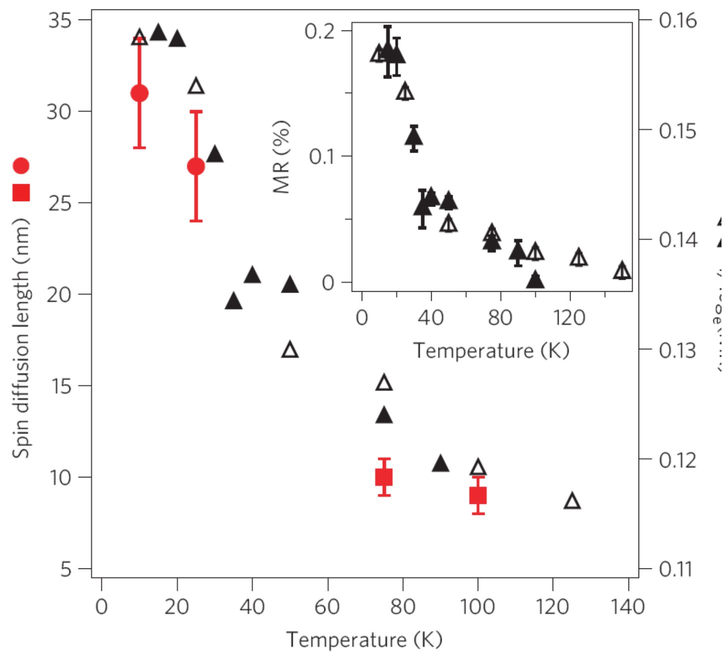


NiFe/LiF Alq3 FeCo

(1nm)



Spin Diffusion length
←→ Magnetoresistance



A. Drew et al Nature Materials (2009)

L. Schultz et al. Nature Materials (2011)

Contact and information

Physics with Muons: from Atomic physics to Condensed Matter physics, 6 CP

Lecture course **402-0770-00L** (ETH-Zürich)

Lecture course **PHY 432** (Univ. Zürich)

Thursday 9-11, starting FHS: Thursday 20.2.2013 (Exercises 11-12)

Lecture script: **http://people.web.psi.ch/morenzoni**

Muon Spin Spectroscopy, 9 CP

Prakticum **402-0549-BSL** and **MSL**

Monday 3.6.2013-Friday 7.6.2013 or by arrangement

Semester/Summer Works

Bachelor/Master/PhD: Muons, neutrons, macroscopic techniques (transport, magnetization..), characterization (XRD, ..)

elvezio.morenzoni@psi.ch or morenzoni@ethz.ch

http://lmu.web.psi.ch/