PAUL SCHERRER INSTITUT
PSI

Polarized muons as microscopic probes of materials, thin films and heterostructures

Elvezio Morenzoni

Laboratory for Muon Spin Spectroscopy
Paul Scherrer Institut, Villigen PSI, Switzerland
and University of Zurich, Zurich, Switzerland

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Outline

- PSI μSR facility (SμS, Swiss Muon Source) and instruments

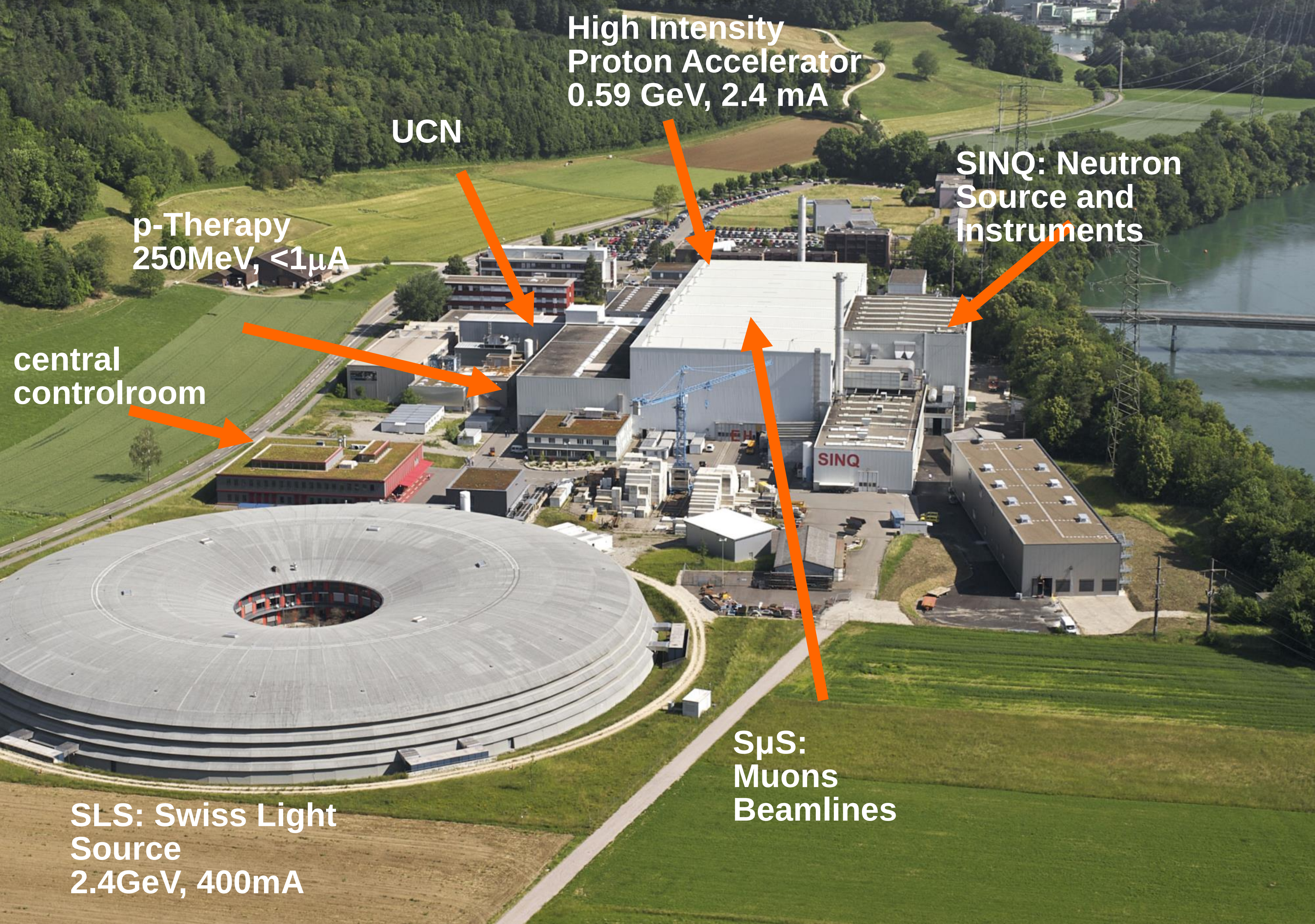
- Selected scientific examples:

  magnetism, superconductivity and spin transport

  in bulk materials, thin films and heterostructures

- Summary and outlook

Accelerator Facilities PSI West



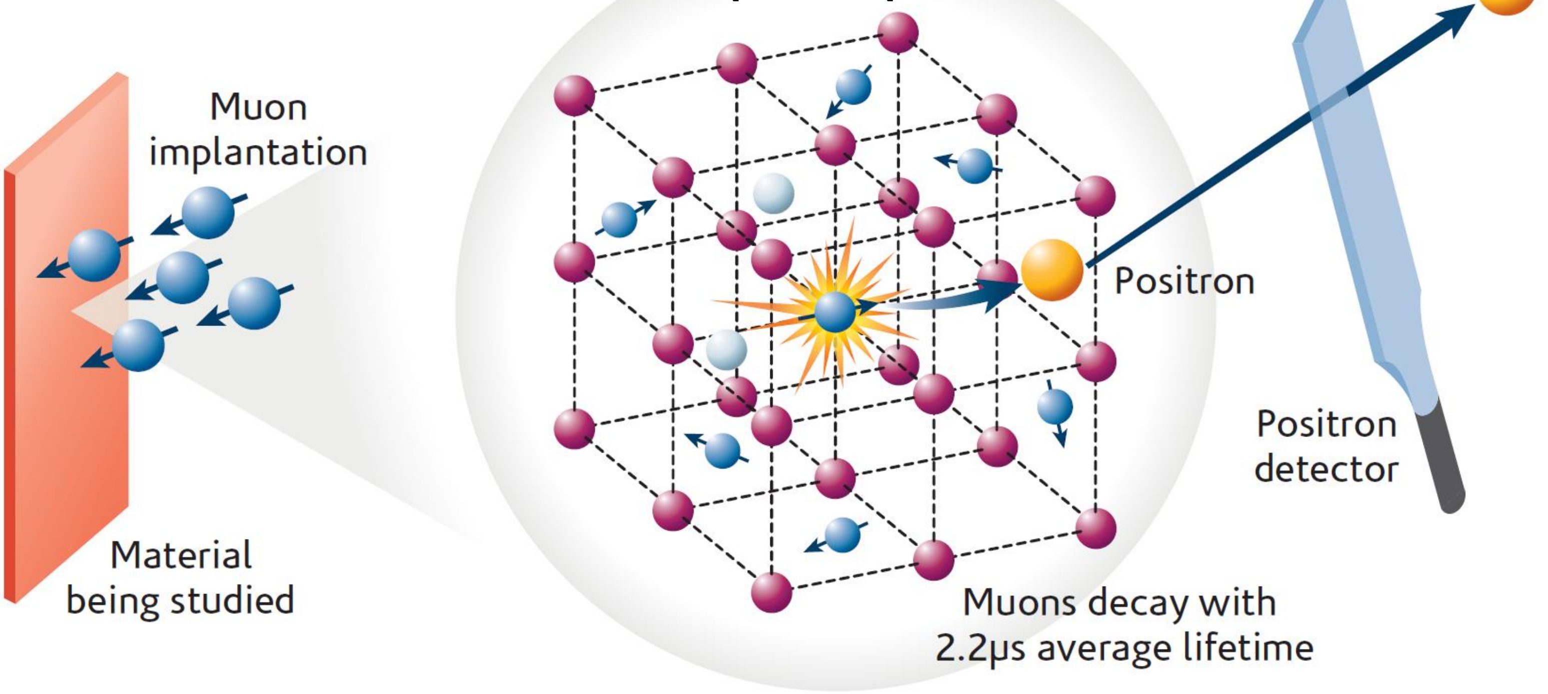
Polarized positive muons: magnetic microprobes of matter

Implant and thermalize (~ ps) ensemble of 100% polarized μ^+ **P(0)**

Muon spin interacts with local environment → **P(t)**

Measure **P(t)** via asymmetric muon decay

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



μSR is sensitive to everything (static and dynamic) that changes the polarization of the muon: local magnetic fields, currents, spins, magnetic moments, fluctuations, chemical reactions (via muonium formation), electronic states

Muon Instruments at PSI : SμS (Swiss Muon Source)

590MeV
2.4 mA

HAL9500

High Field and Low Temperature

Muon energy: **4.2 MeV** (μ^+)

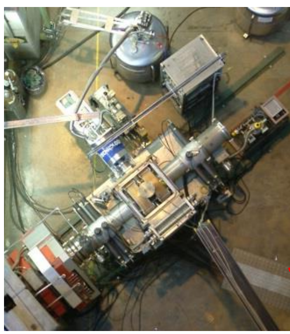
9.5 T, < 20 mK

GPS

General Purpose Surface Muon Instrument

Muon energy: **4.2 MeV** (μ^+)

0.6 T,
1.6 K 1200 K



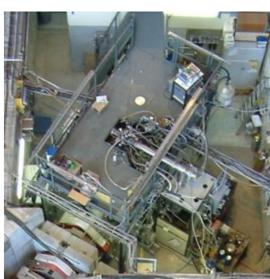
Shared Beam Surface Muon Facility (Muon On REquest)

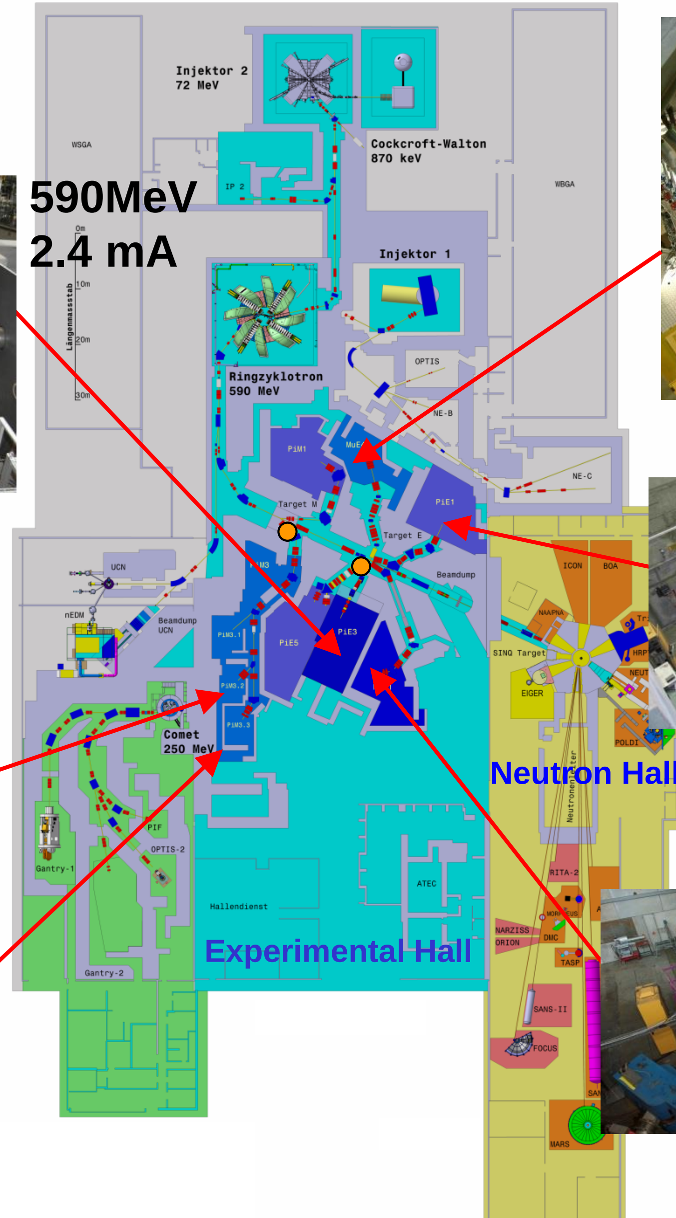
FLAME

Low Temperature Facility

Muon energy: **4.2 MeV** (μ^+)

3.5 T,
30 mK- 300 K
TF, LF

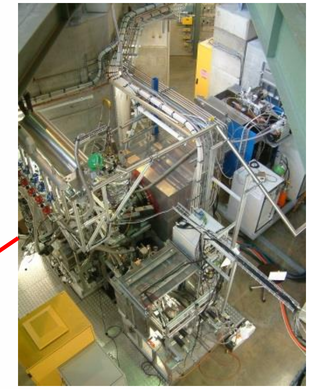




LEM

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
2.2 – 300 K



DOLLY

General Purpose Surface Muon Instrument

μ^+ energy: **4.2 MeV**

0.5 T
250 mK

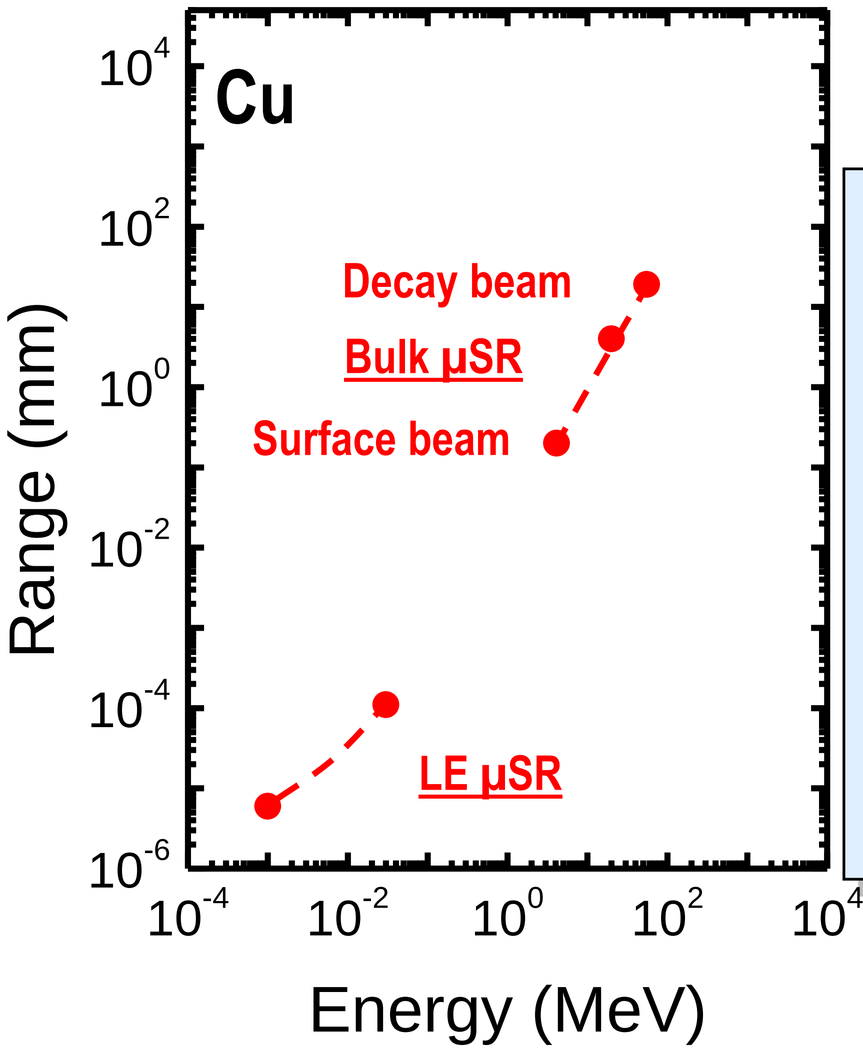
GPD

General Purpose Decay Channel Instrument Pressure studies

Muon energy: **5 - 60 MeV** (μ^+ or μ^-)

0.5 T,
250 mK
2.8 GPa

Different muon energies for different studies



Bulk μSR:

- “Surface” Muon Beams (4 MeV): “Normal” samples (sub-mm thick)
- Decay Muons beam (10-60 MeV): Bulky samples in pressure cells or in containers

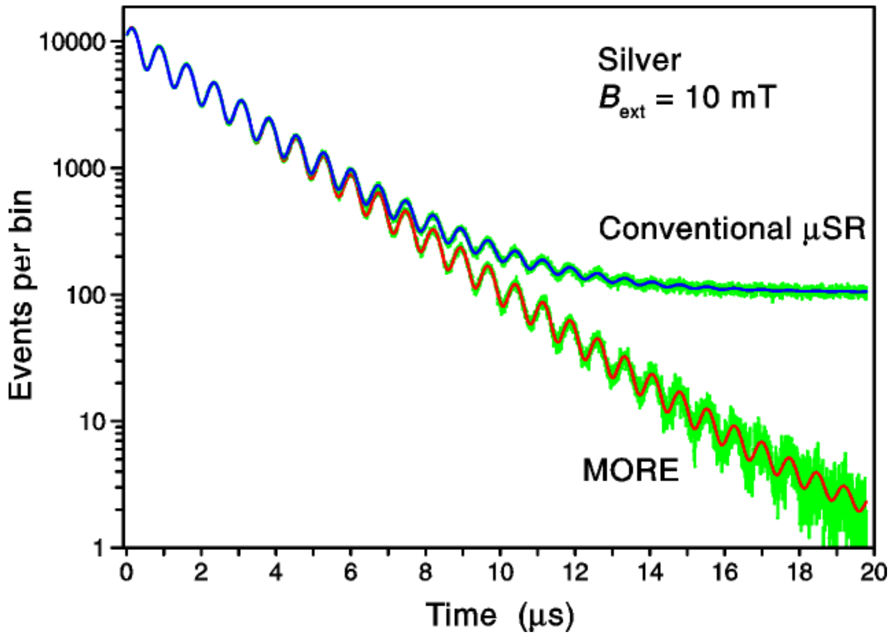
LE μSR:

- Low energy muon beam (0.5-30 keV) for depth-dependent investigations (~ 2–300 nm), thin films and heterostructures

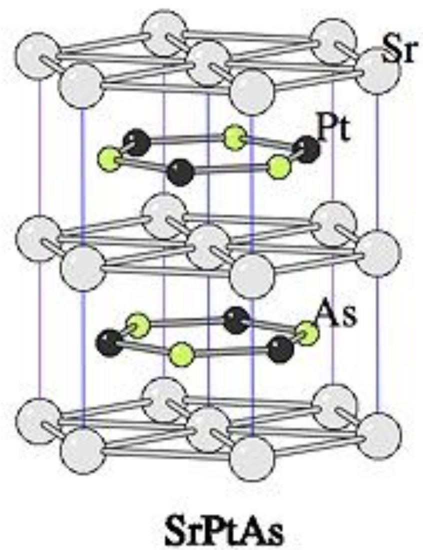
Muon On REquest: MORE on GPS/Flame

Extract one muon at a time out of a continuous beam using fast-switching kicker

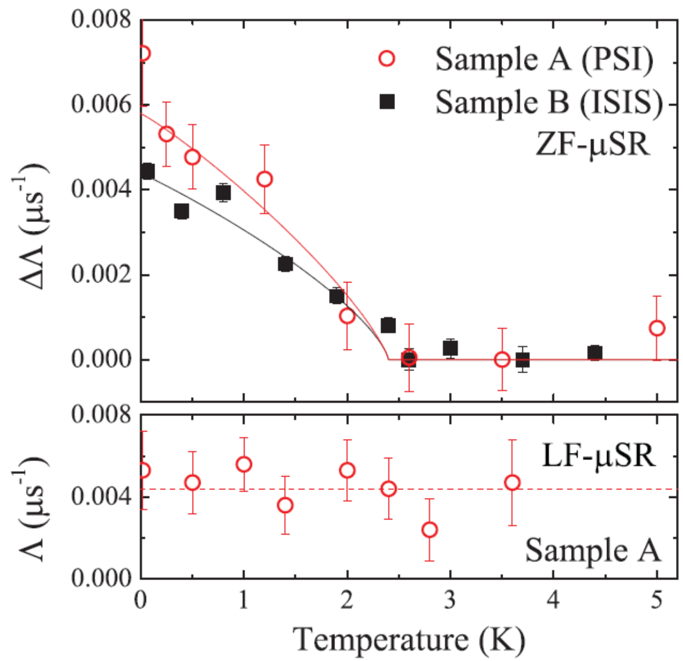
Combines advantages of **continuous beam** (very fast timing → magnetism, superconductivity, high muon spin relaxation rate) and **pulsed beam** (very low background, → very weak magnetism, low muon spin relaxation rate)

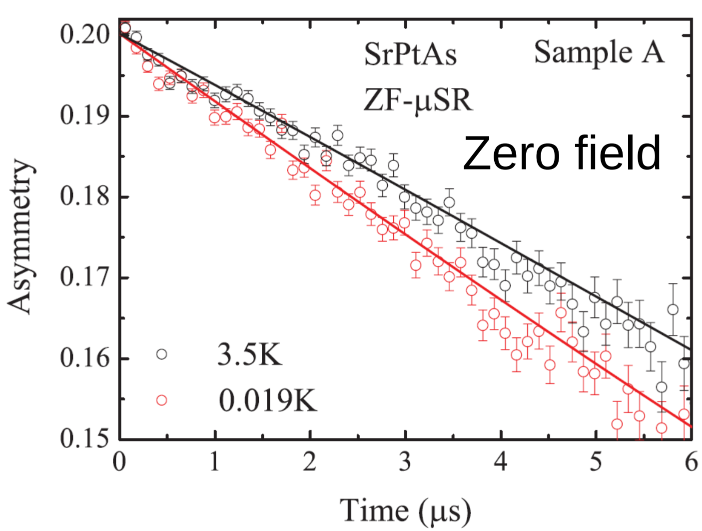


Time reversal symmetry breaking in SrPtAs



T_c=2.4 K
locally non-centrosymmetric
→ non trivial sc state, f, d+id, TRSB





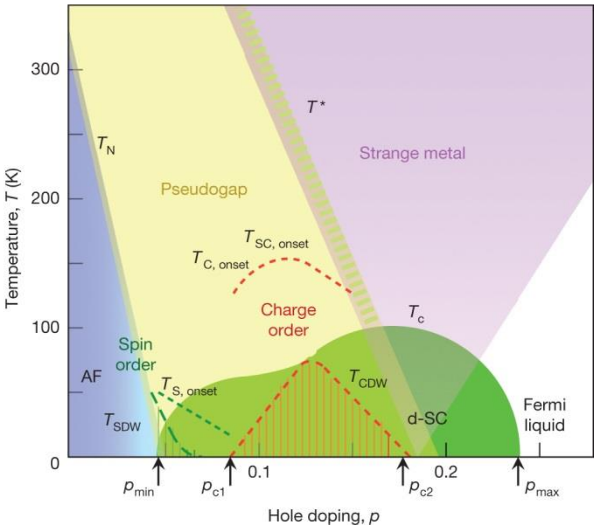
Spontaneous very small magnetic field below T_c → ΔB ≈ 0.007 mT → TRSB

Detecting very small fields

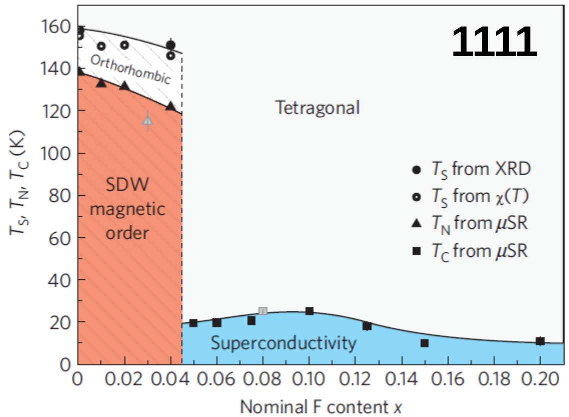
*P.K. Biswas et al., Phys. Rev. B **87**, 180503(R) (2013)*

Phase diagrams of superconductors

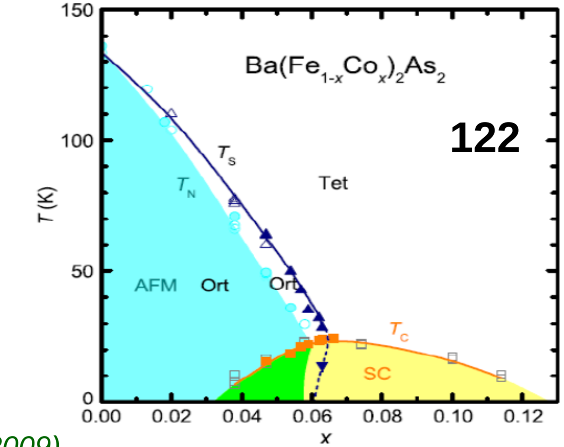
Electronic order/SC, magn., Phase competition/coexistence, QCP, interactions



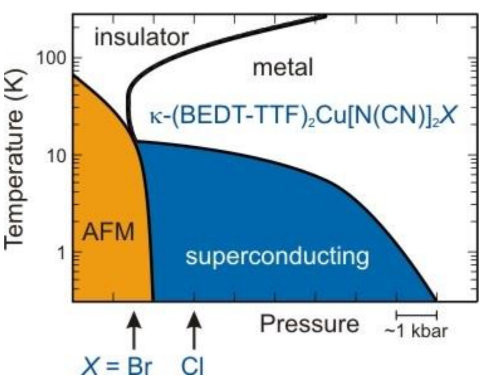
B Keimer et al. Nature **518**, 179-186 (2015)



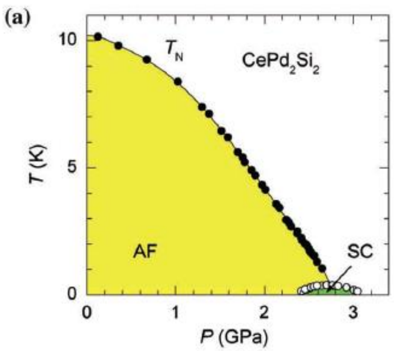
H. Luetkens et al., Nat. Mat. 8, 305 (2009)



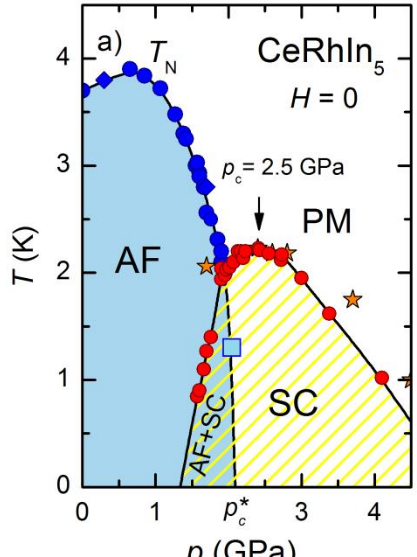
S. Nandi et al., PRL 104, 057006 (2009)



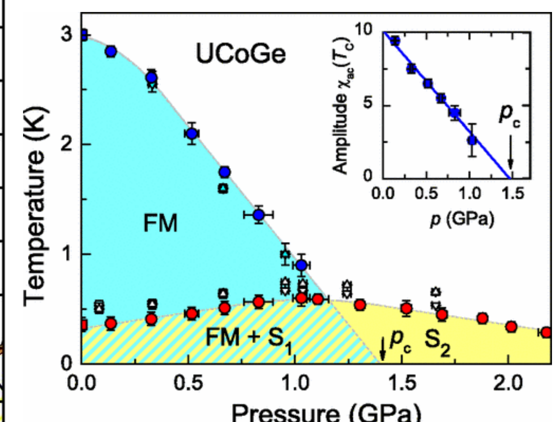
D. Faltermeier et al.,
Phys. Rev. B76 , 165113 (2007)



N.D. Mathur et al., Nature 1998



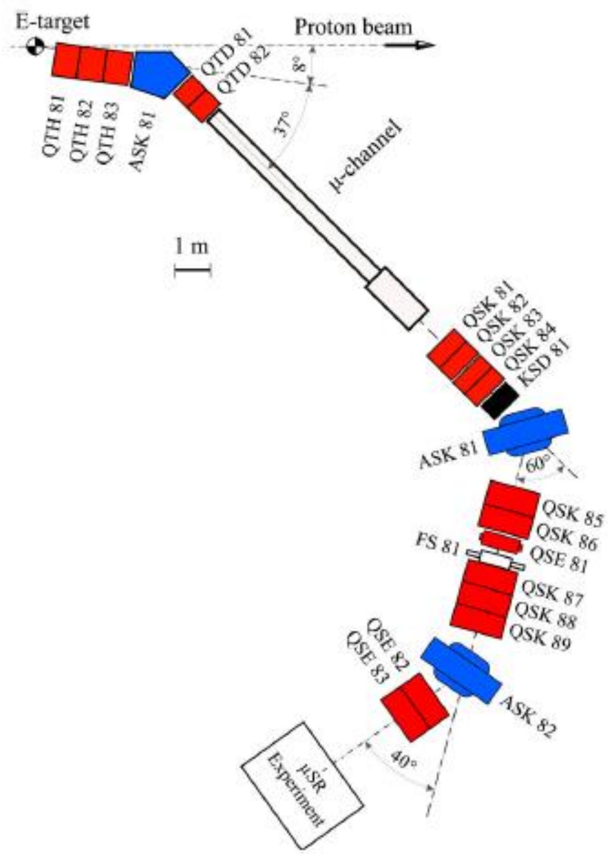
G. Knebel et al., Phys. Rev. B 74, 020501(R) – (2006)



E. Slooten et al, PRL 2009

μSR studies under pressure

μE1: Superconducting Decay Channel Beamline

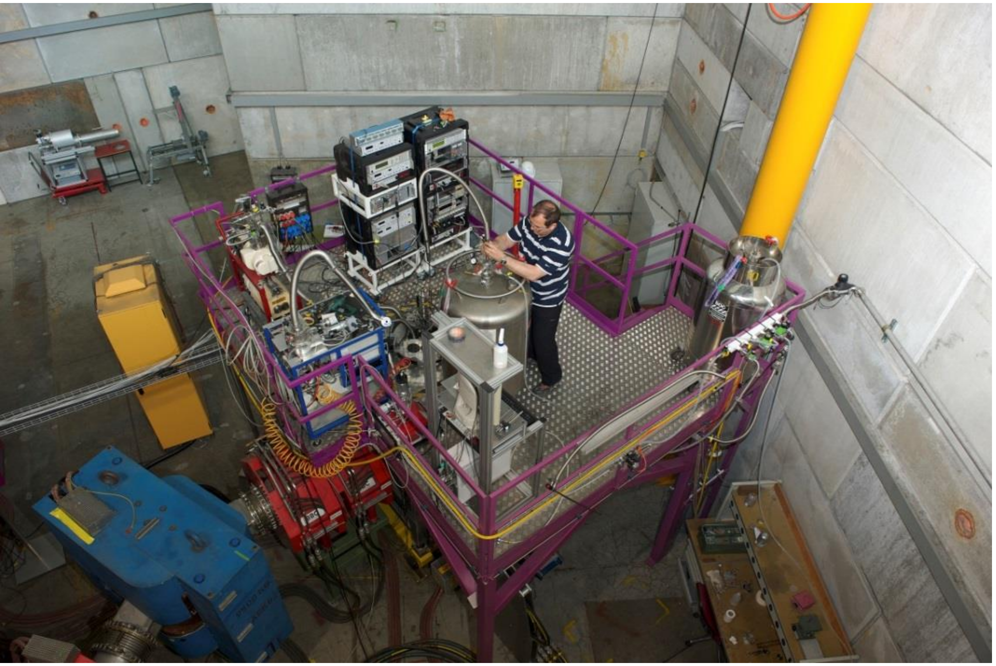


- 10 - 60 MeV μ^+ or μ^- , 80% Polarization
- $\mathbf{B_{ext}}$ 0 - 0.6 T
- **T** 0.25 - 475 K
- Large sample chamber for **pressure cells** (diameter up to 40 mm)

μSR studies under pressure

μE1 Superconducting Decay Channel Beamline

High Energy Muon Instrument GPD



- 10 - 60 MeV μ^+ or μ^- , 80% Polarization
- **B_{ext}** 0 - 0.6 T
- **T** 0.25 - 475 K
- Large sample chamber for **pressure cells** (diameter up to 40 mm)

Pressure up to **2.8 GPa** (@4K)

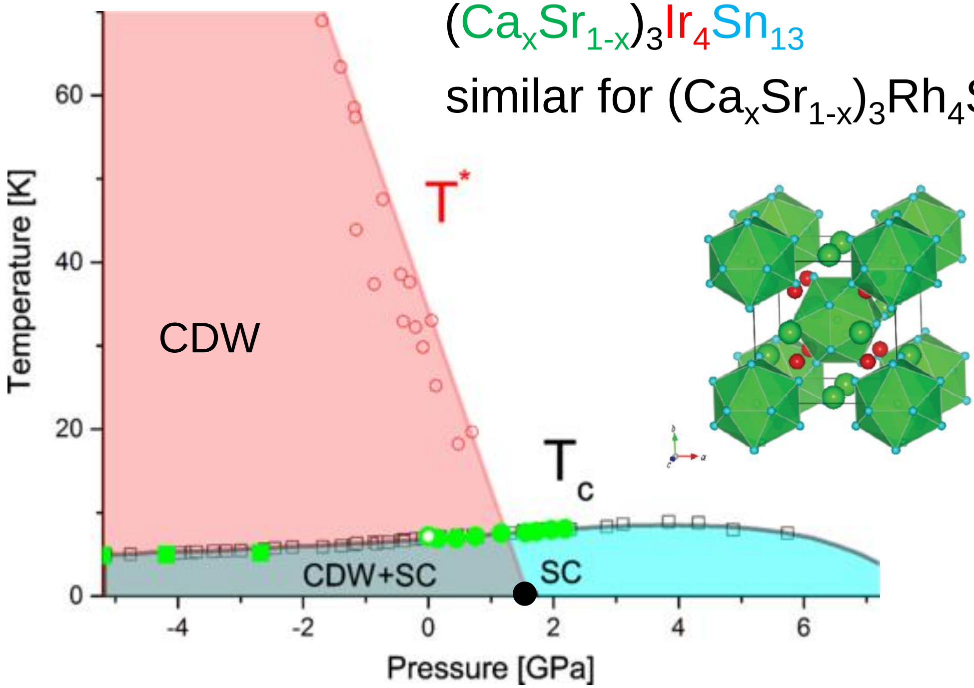
R. Khasanov et al.
High Pressure Research, **36,** 140 (2016)

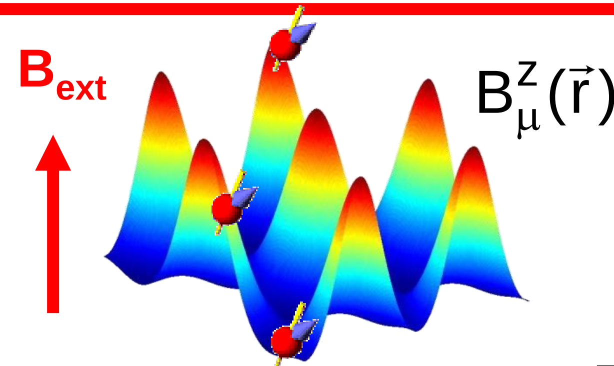
Double and single wall cells
Material: CuBe or MP35 alloy.
Diameter of the sample channel: 5.2 mm (7.2 mm).
Maximum sample height: 18mm
Pressure media: Daphne 7373 oil.

QCP in the superconducting state of quasiskutteridites $R_3T_4X_{13}$

$(Ca_xSr_{1-x})_3Ir_4Sn_{13}$

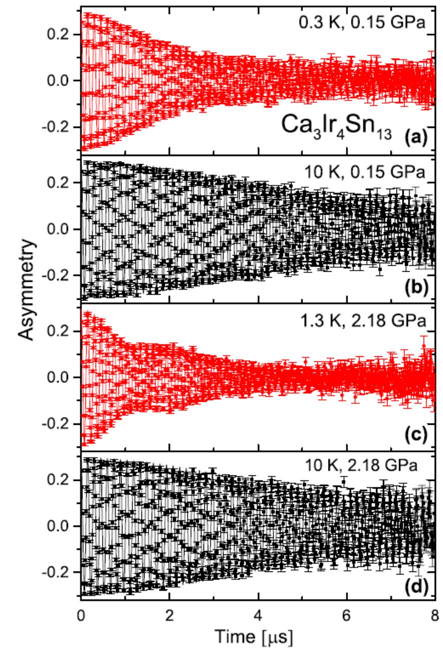
similar for $(Ca_xSr_{1-x})_3Rh_4Sn_{13}$





Muon spin relaxation $\sigma = \gamma_\mu \sqrt{<\Delta B_z^2>}$

$\propto$ *superfluid density* $\propto \frac{1}{\lambda^2} \propto \frac{n_s}{m^*}$



T* : structural transition and FS reconstruction/CDW

T*(p) decreases with pressure suggesting **quantum critical point** (QCP) at $p_c \approx 1.8$ GPa for $Ca_3Ir_4Sn_{13}$ and -0.6 GPa for $Ca_3Rh_4Sn_{13}$ (corresponds to $(Ca_{0.9}Sr_{0.1})_3Rh_4Sn_{13}$)

P. Biswas, J. Krieger, E. M. et al., PRB ***92****, 195122 (2015), PRB* ***90,*** *144505 (2014) and in preparation (2019)*

QCP in the superconducting state of quasiskutteridites $R_3T_4X_{13}$

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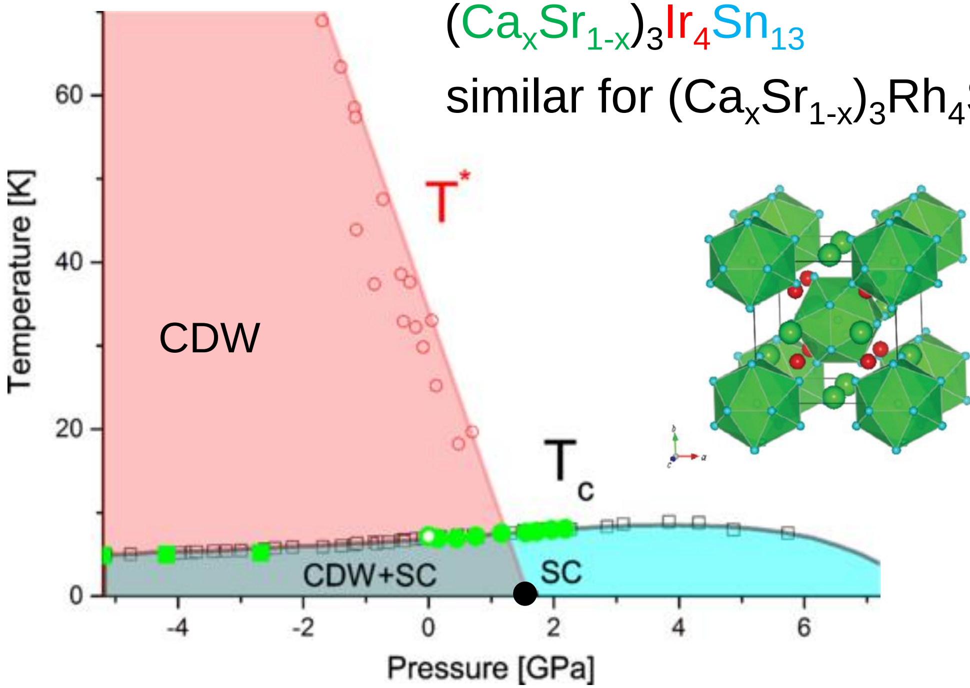

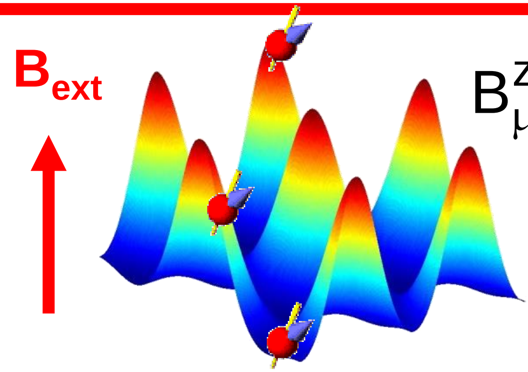

$B^z_\mu(\vec{r})$

Muon spin relaxation $\sigma = \gamma_\mu \sqrt{<\Delta B_z^2>}$

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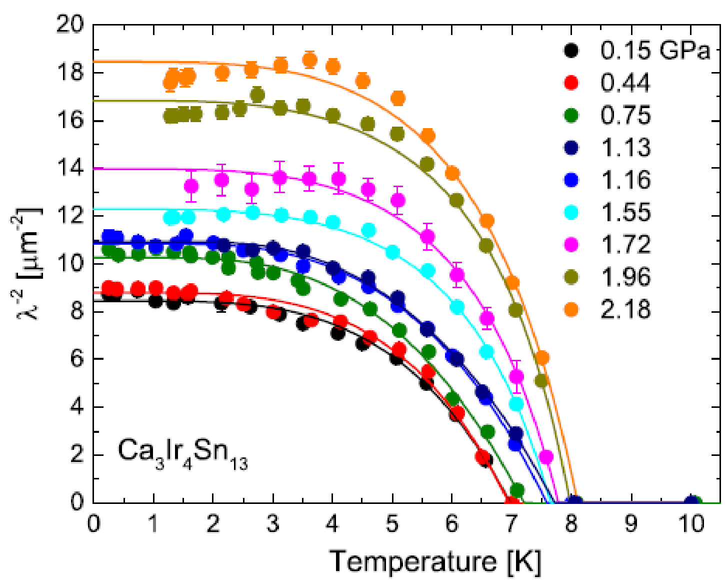
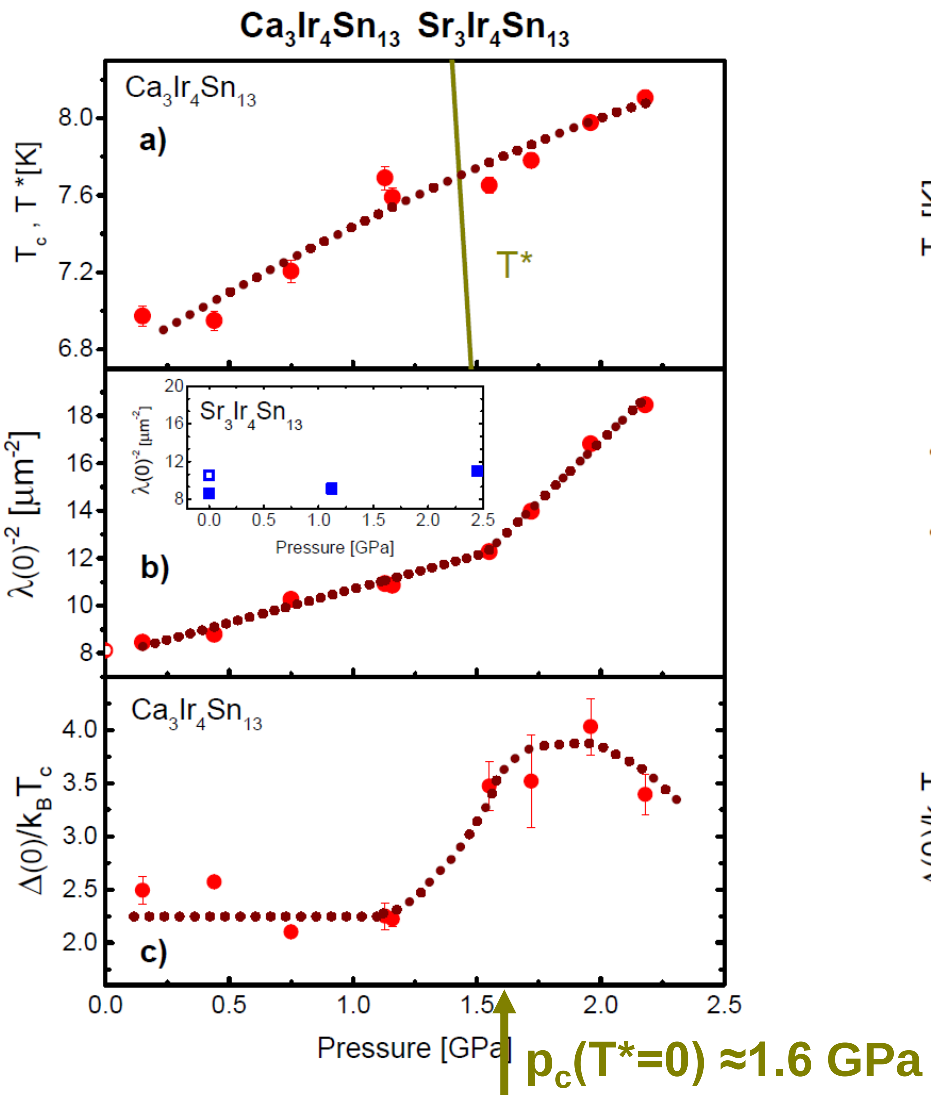
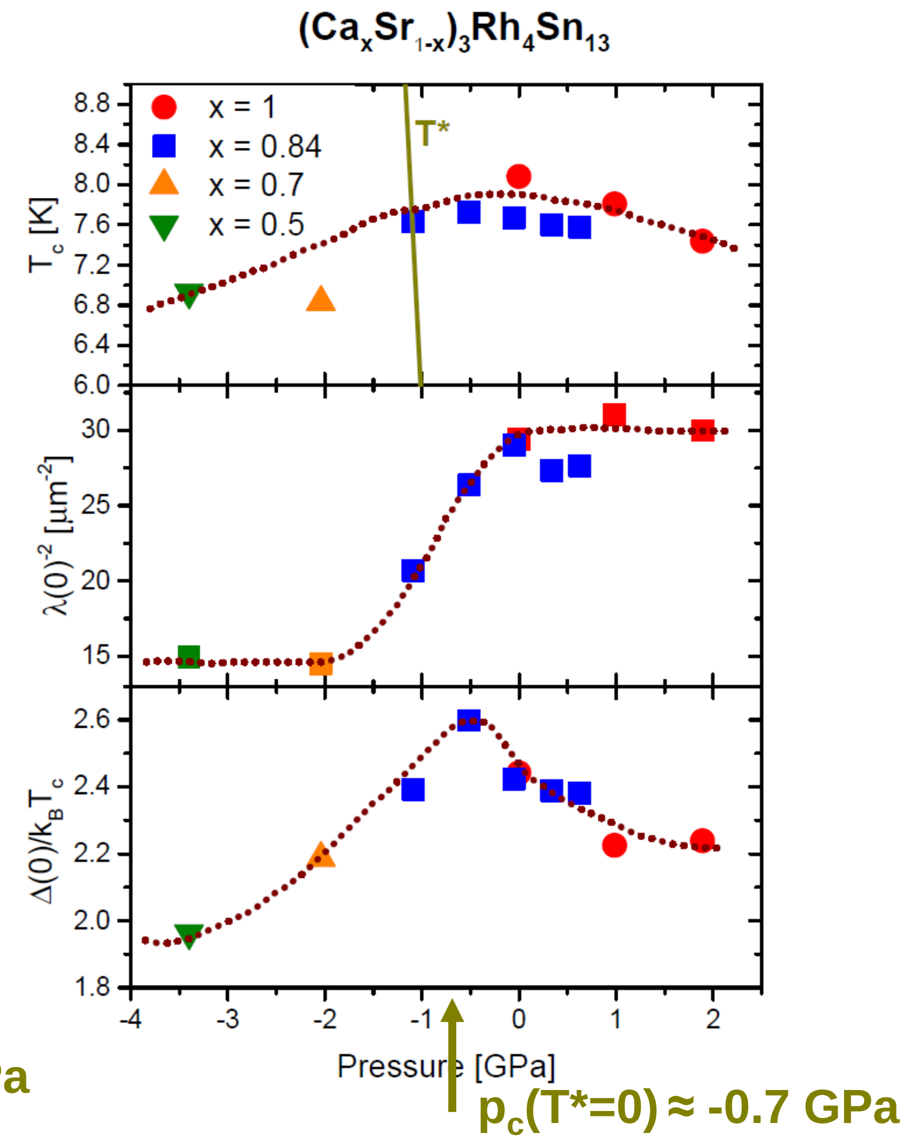


*P. Biswas, J. Krieger, E. M. et al., PRB **92**, 195122 (2015), PRB **90**, 144505 (201*
and in preparation (2019)

Strong enhancement of SC at QCP



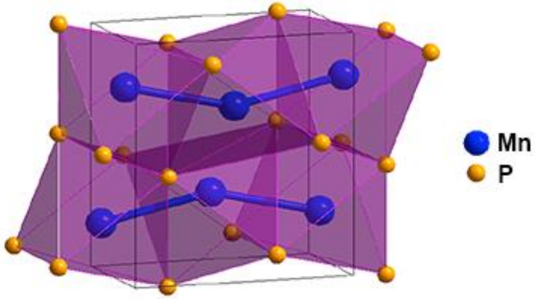


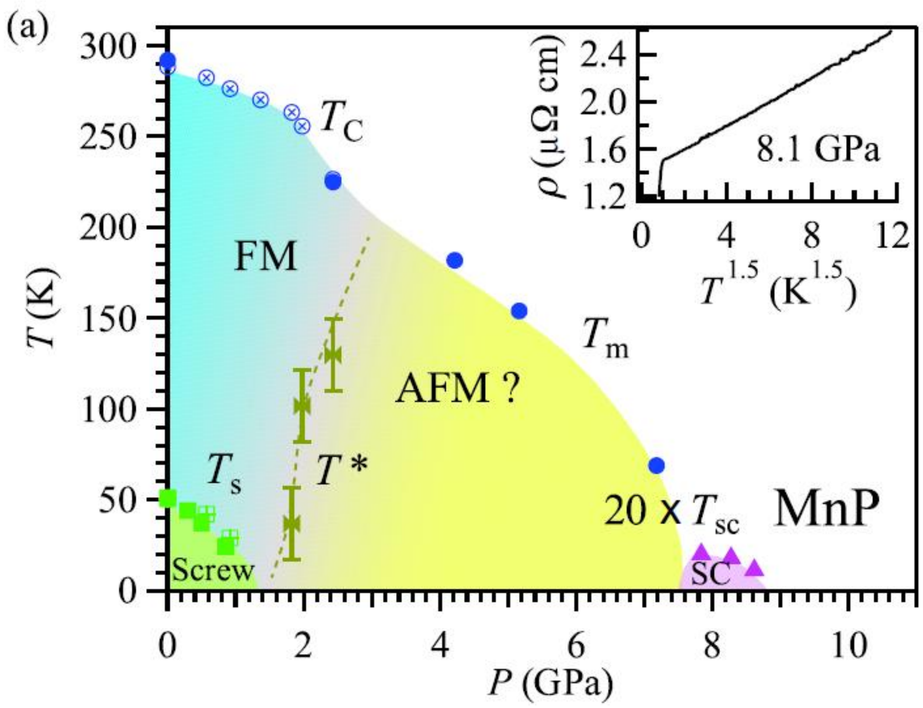
$\frac{\Delta(0)}{k_B T_c} = 2.04(8)$ @ p=-5.2 GPa ($Sr_3Ir_4Sn_{13}$)

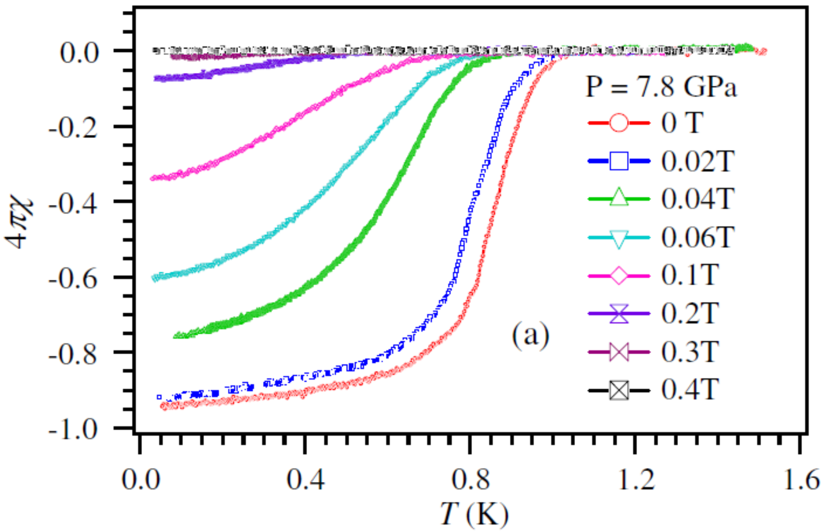
$\frac{\Delta(0)}{k_B T_c} = 1.93(8)$ @p=-6.8 GPa ($Sr_3Rh_4Sn_{13}$)

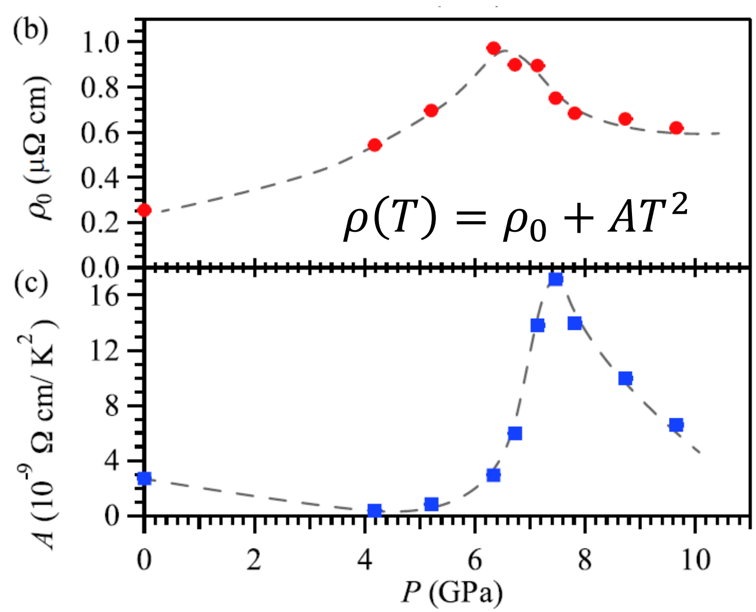
Pressure Induced Superconductivity in Mn based "helical" magnet

MnP: First Mn based SC $T_c \approx 1$ K





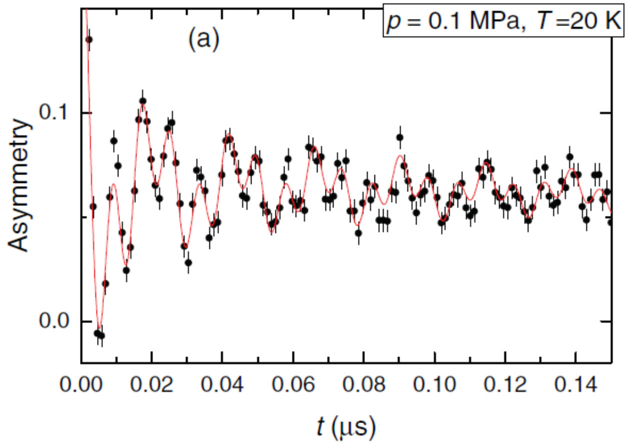




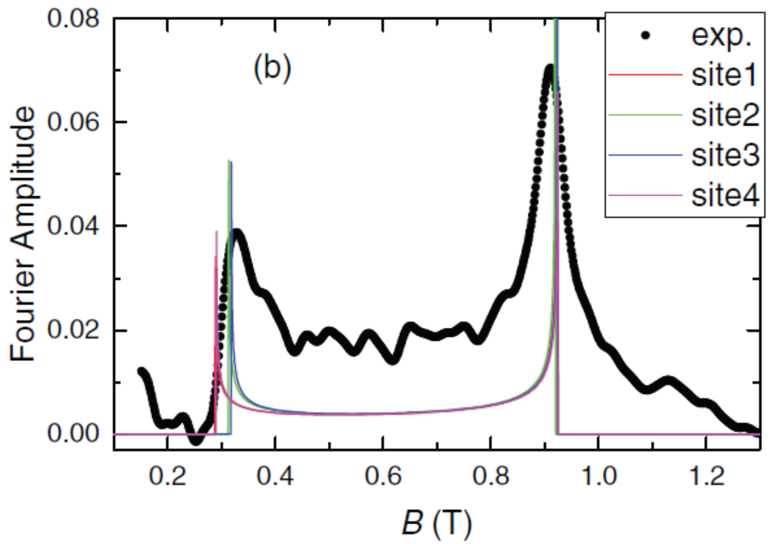
J. G. Cheng et al, PRL 114, 117001 (2015)

Magnetic structure of MnP under pressure

μSR spectrum (ZF)



Fourier transform



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

DFT calculation → muon sites

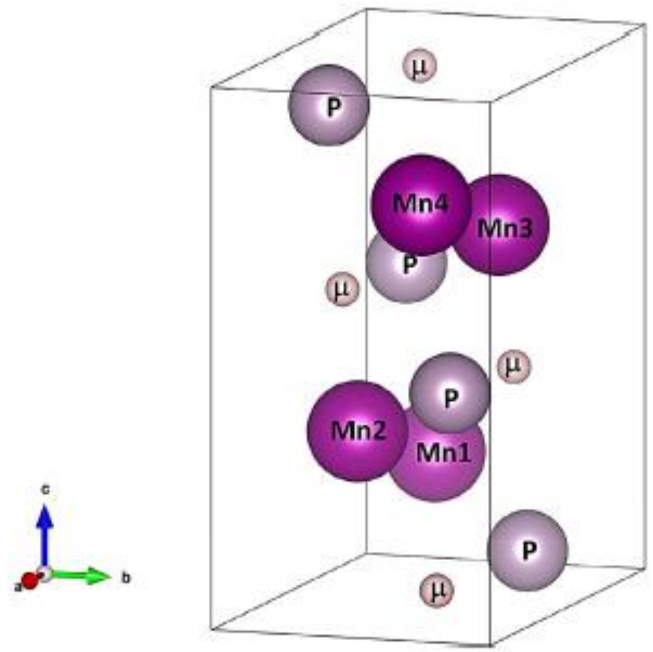
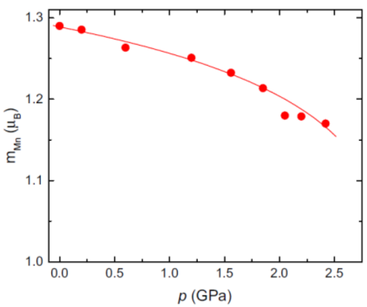
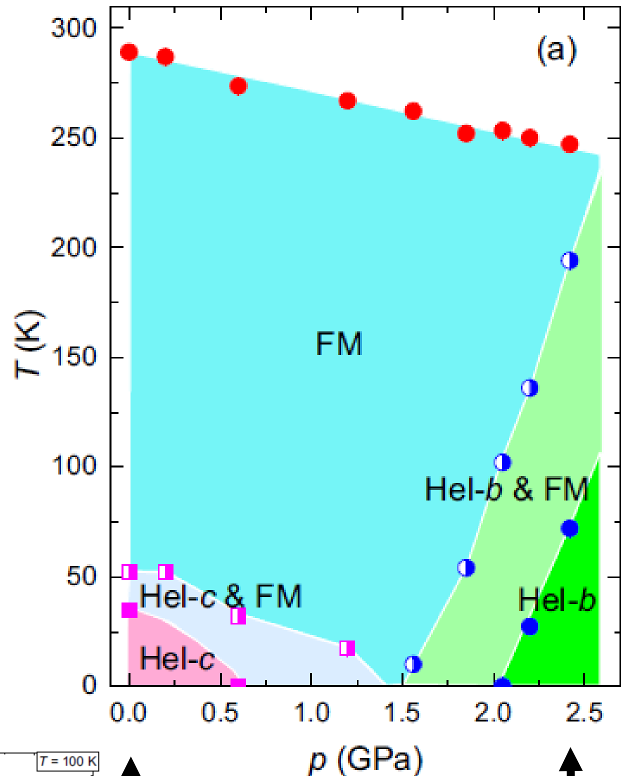


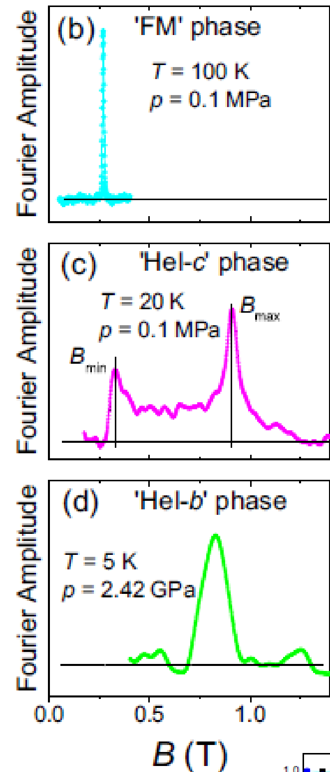
Figure 2. The orthorhombic crystal structure of MnP (*Pnma*, 62). The muon stopping positions (sites #1) were obtained by *ab initio* calculations (see section 3.2 and table 1). The structure was visualized by using VESTA [19].

Comparison local fields (determined by magnetic structure) with experiment → magnetic structure

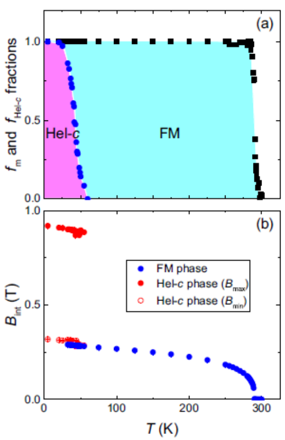
Magnetic structure of MnP under pressure

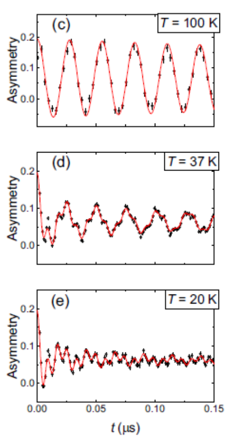


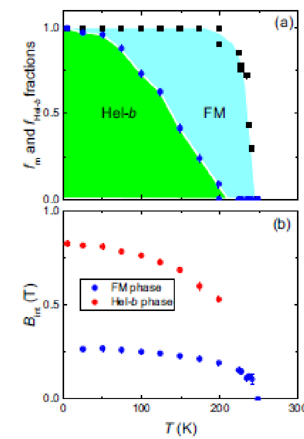


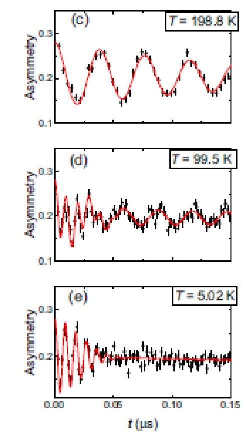


μSR resolves discrepancy between neutron and X-ray structure data



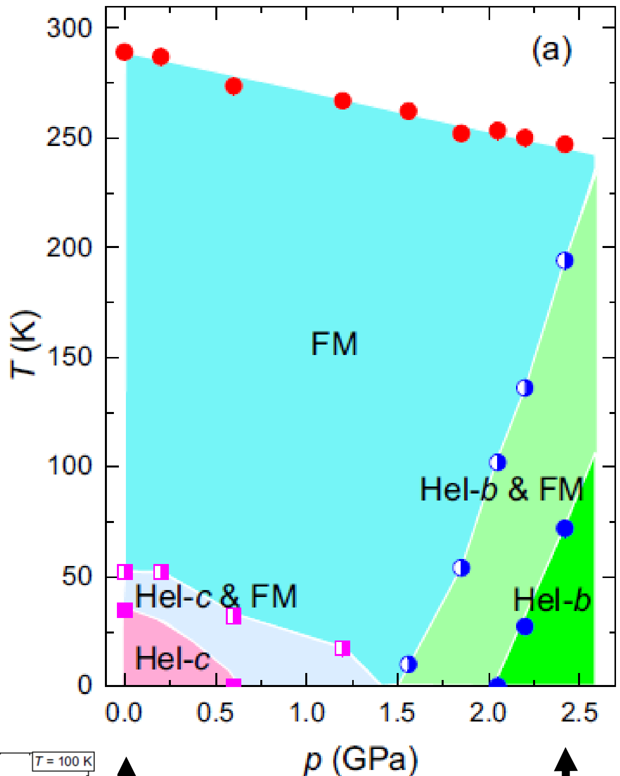


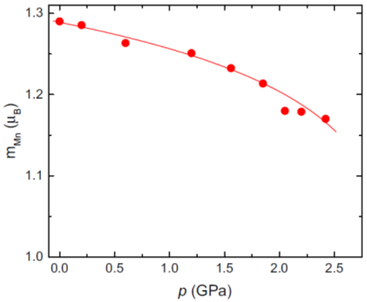


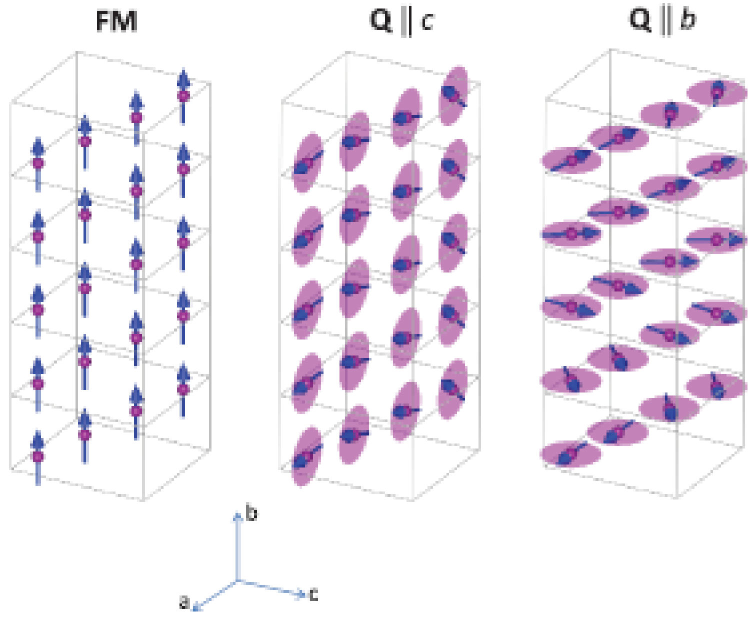


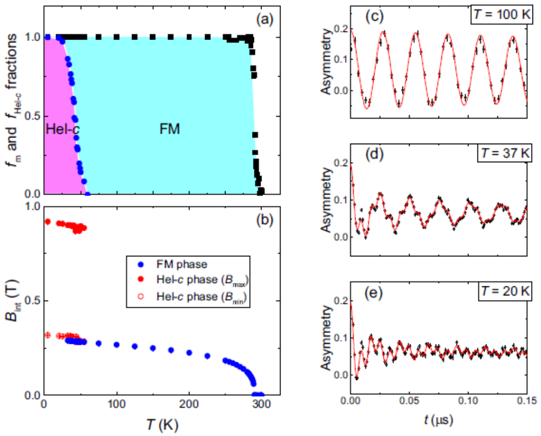
R. Khasanov et al, PRB 93, 180509(R) (2016)
and J. Phys.: Condens. Matter 29, 164003 (2017)

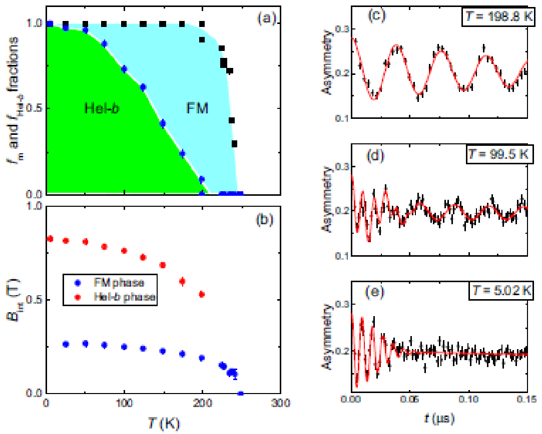
Magnetic structure of MnP under pressure







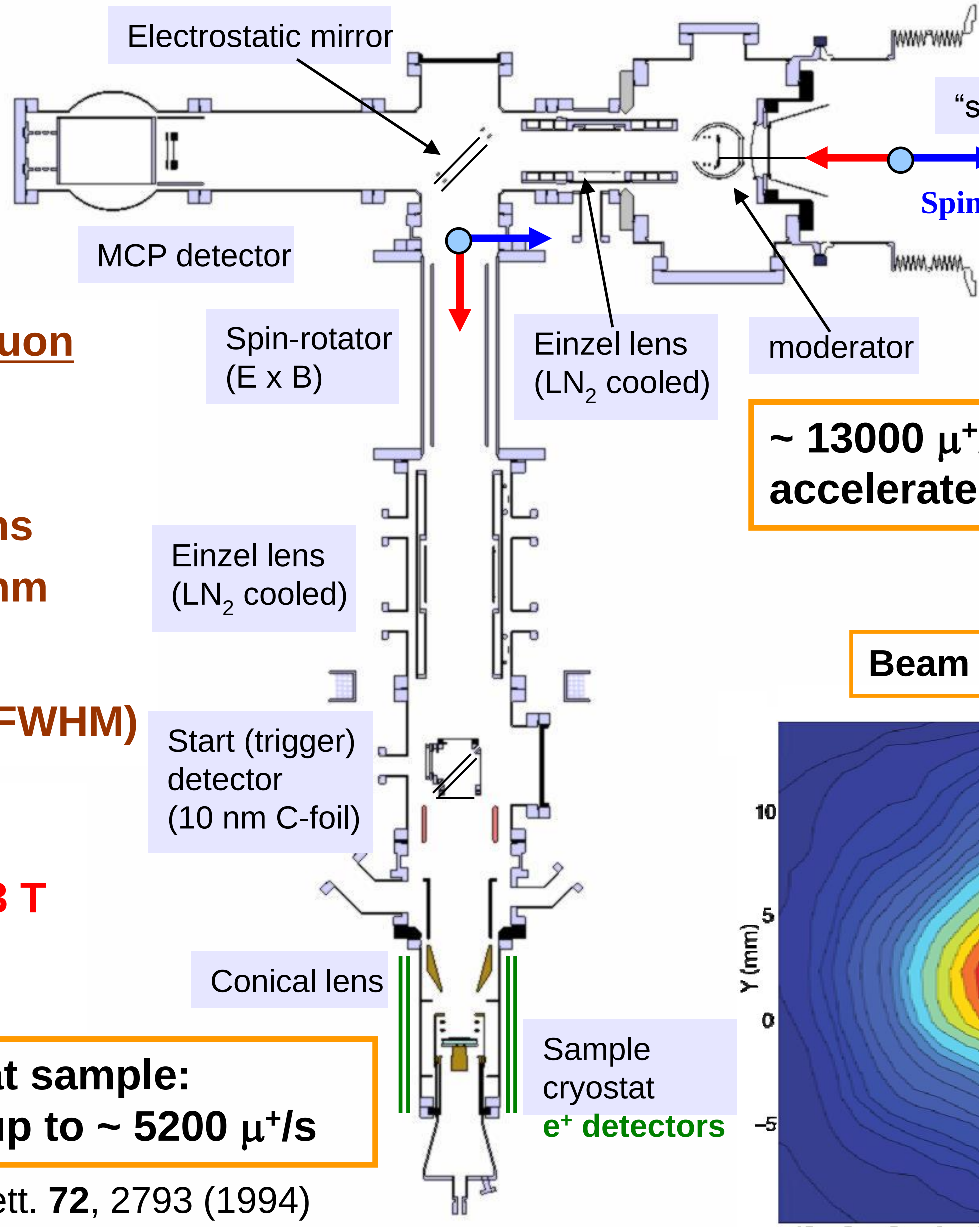




R. Khasanov et al, PRB 93, 180509(R) (2016)
and J. Phys.: Condens. Matter 29, 164003 (2017)

Low energy μ^+ beam and instrument for LE-μSR

- UHV system, 10^{-10} mbar
- some parts LN_2 cooled



~2.2 • 10^8 μ^+/s

~ 13000 μ^+/s @ ~ 15 eV; accelerate up to 20 keV

<u>Polarized Low Energy Muon Beam</u>

Energy: 0.5-30 keV

ΔE, Δt: 400 eV, 5 ns

Depth: ~ 2 – 300 nm

Polarization: ~ 100 %

Beam Spot: ~ 12 mm (FWHM)

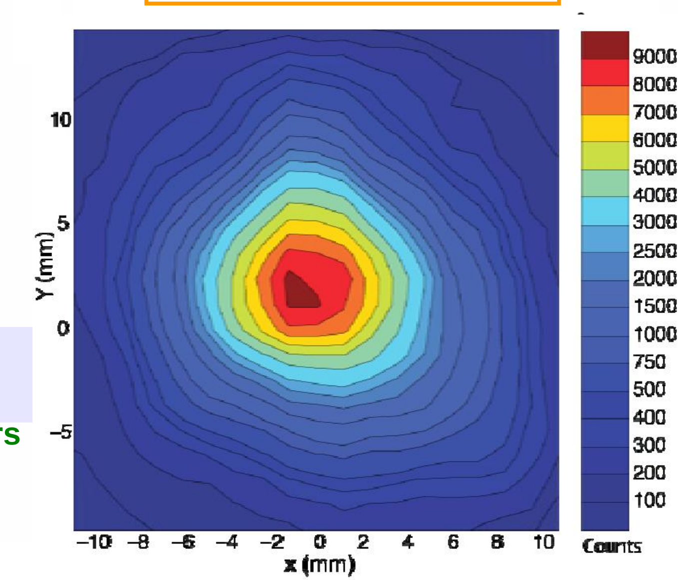
Sample environment:

$B_\perp$ = 0 – 0.3 T, $B_\parallel$ 0 – 0.03 T (to sample surface)

T = 2.5 – 320 K

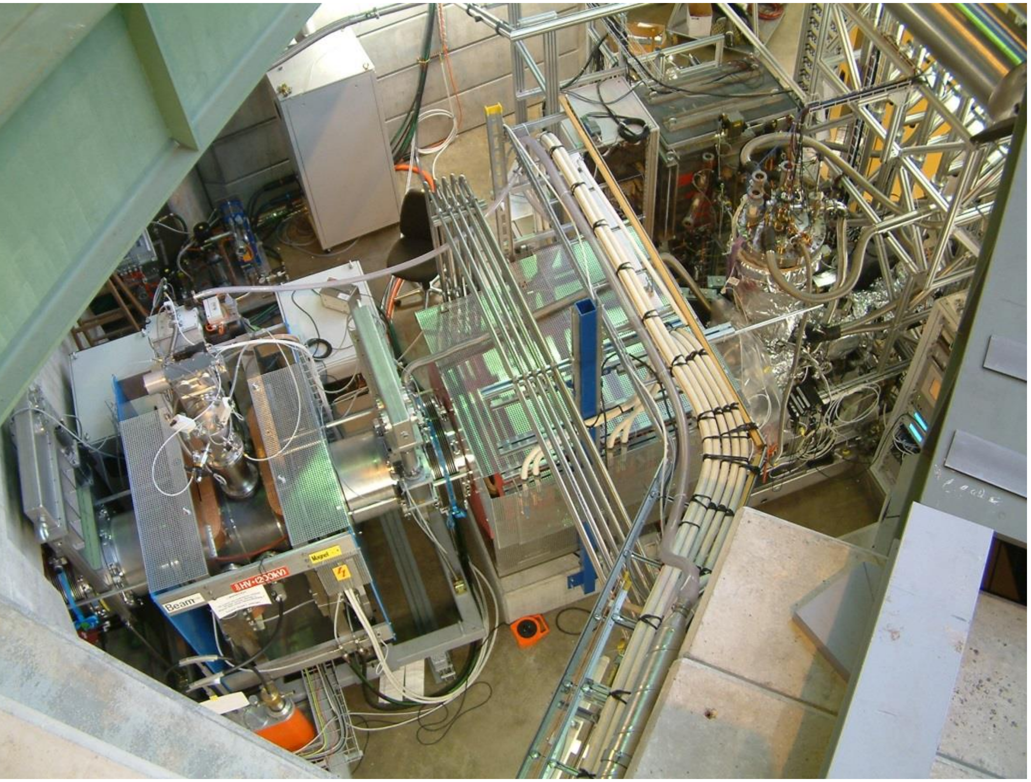
at sample: up to ~ 5200 μ^+/s

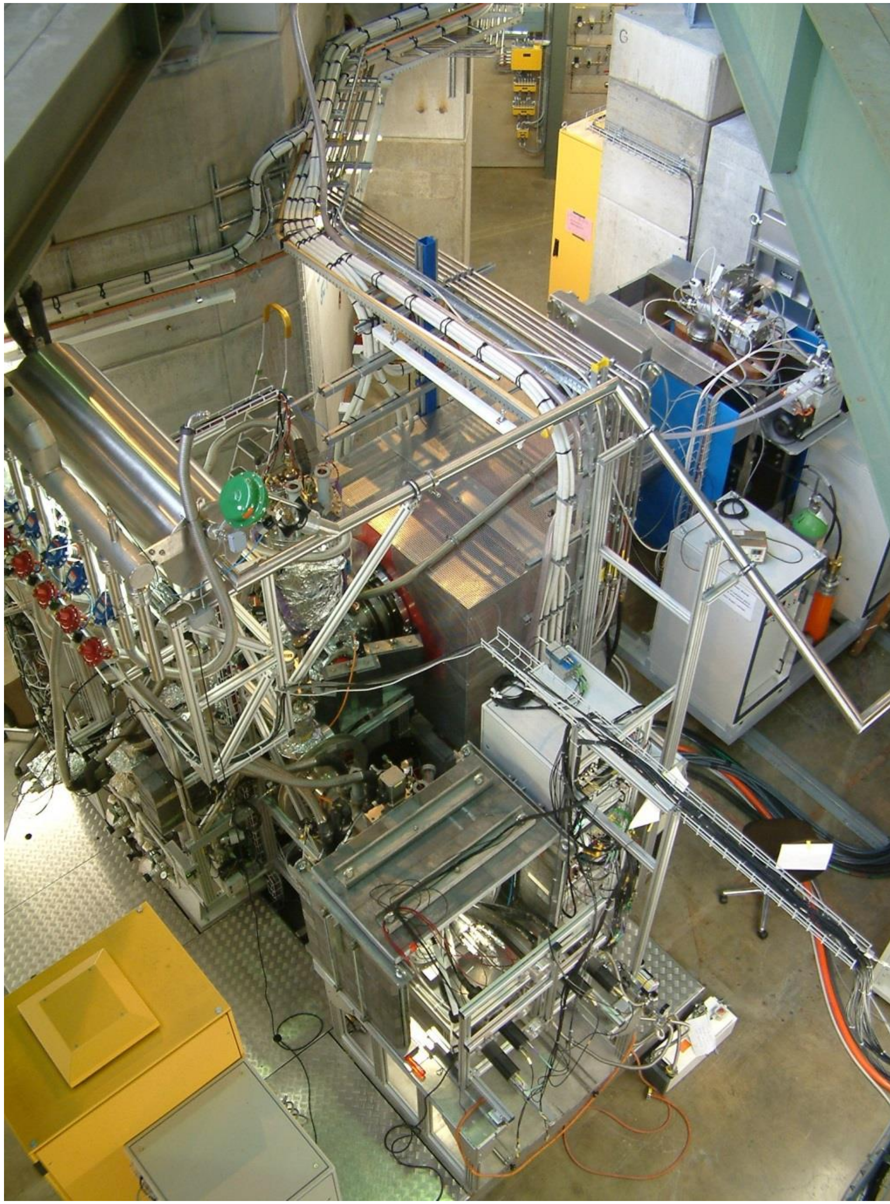
Beam spot at sample



E. Morenzoni et al., Phys.Rev.Lett. **72**, 2793 (1994) and J. Phys.: Cond. Matt. **16**, S4583 (2004)

Low Energy-μ⁺ Apparatus @ μE4





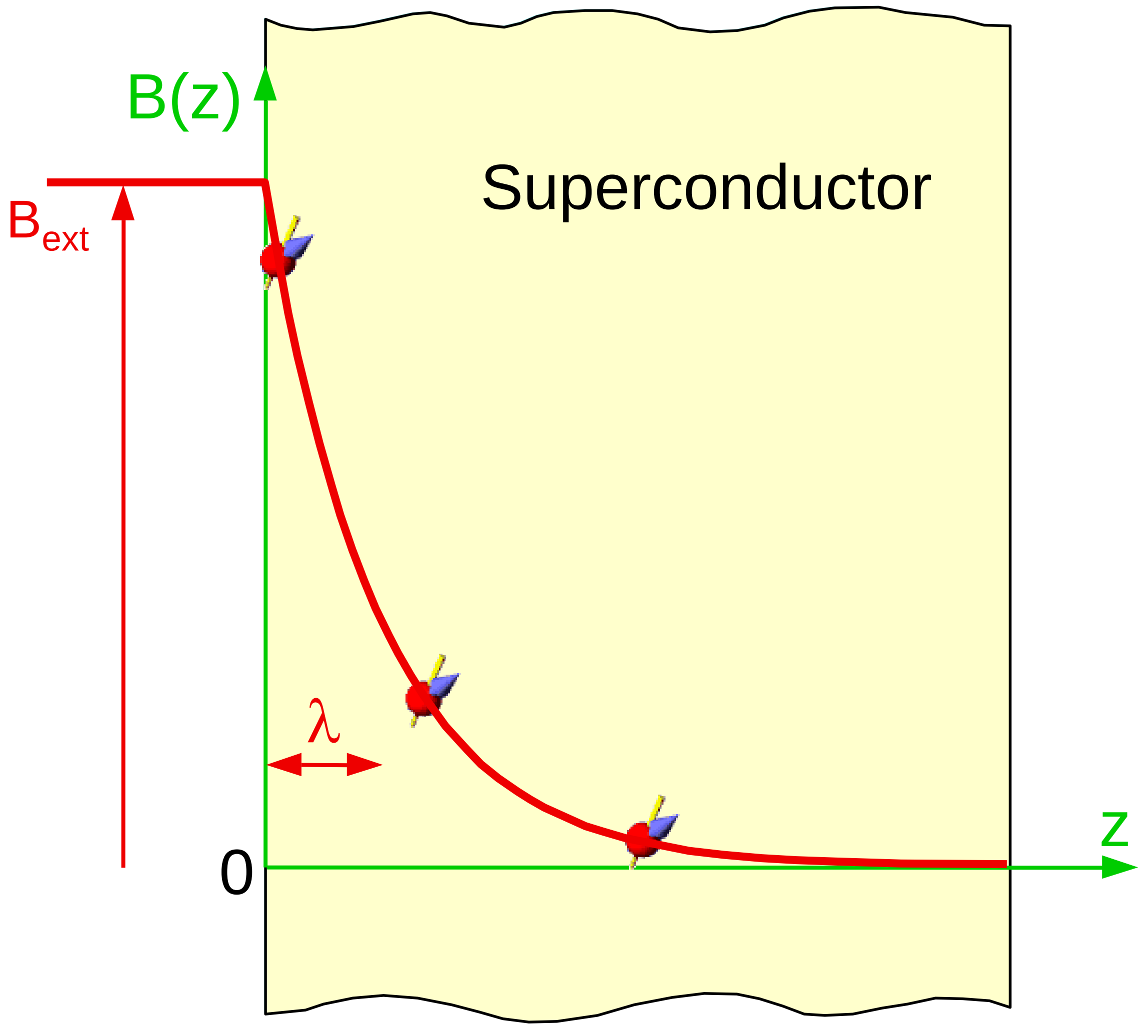
~6.6 •10⁸ μ⁺/s total

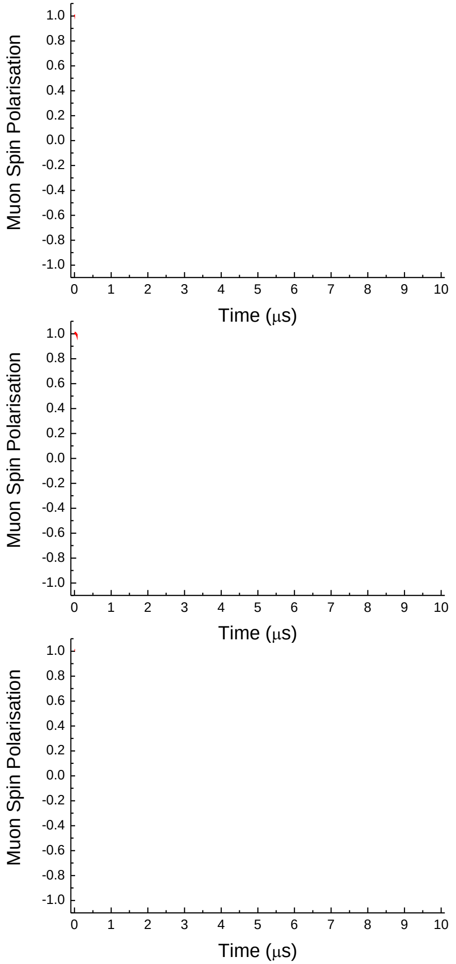
~2.2 •10⁸ μ⁺/s on LEM source

High flux "surface" muon beam → Worldwide most intense surface muon beam

Th. Prokscha, E. Morenzoni, K. Deiters, F. Foroughi, D. George, R. Kobler, A. Suter and V. Vrankovic
Physica B 374-375, 460-464 (2006)
and Nucl. Instr. Meth. A 595, 317-331 (2008)

Depth dependent μSR measurement

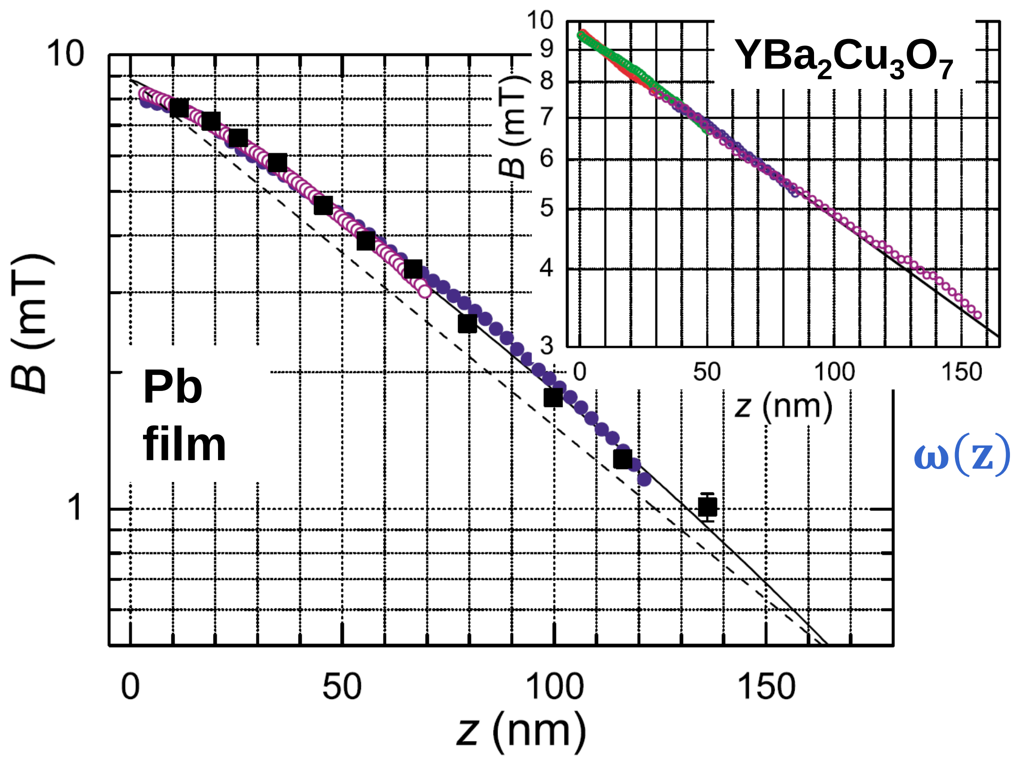




$$\omega_\mu(z) = \gamma_\mu B_{loc}(z)$$

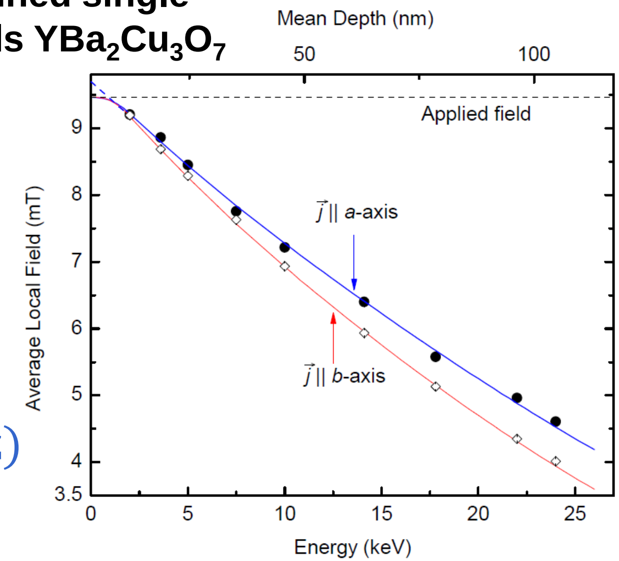
→ Magnetic field profile B(z) over nm scale,
Direct measurements of SC length scales, λ, ξ

Magnetic field profiling at surfaces and in thin films

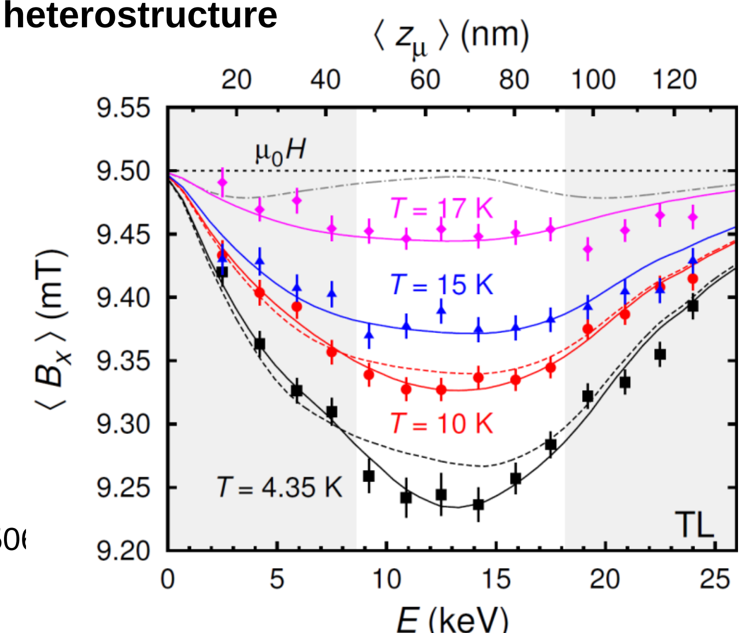


$$\omega(z) = \gamma_\mu B_{loc}(z)$$

Detwinned single crystals YBa$_2$Cu$_3$O$_7$



LSCO OP/UD/OP heterostructure



Magnetic field profiling on nm scale
Characteristics length scales λ, ξ
Anisotropies
Proximity effects

T.J. Jackson et al., Phys. Rev. Lett. **84**, 4958 (2000)
A. Suter, E. M. et al Phys. Rev. Lett. **92**, 087001 (2004) and Phys. Rev. B**72**, 02450(
R. F. Kiefl et al., Phys. Rev. B **81**, 180502(R) (2010)
E. Morenzoni et al., Nat. Commun. 2:272 (2011).

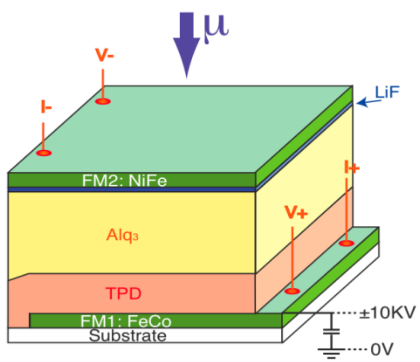
Direct measurement of the electronic spin diffusion length in a fully functional organic spin valve by low-energy muon spin rotation

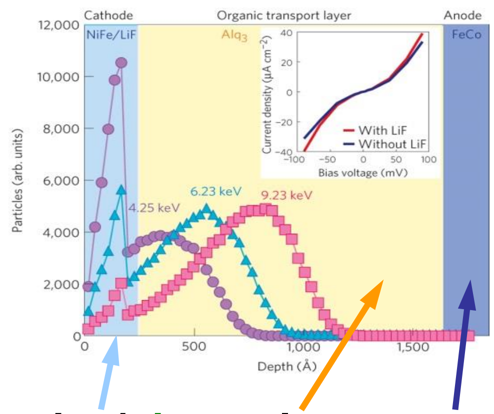
nature materials

Probing spins in heterostructures

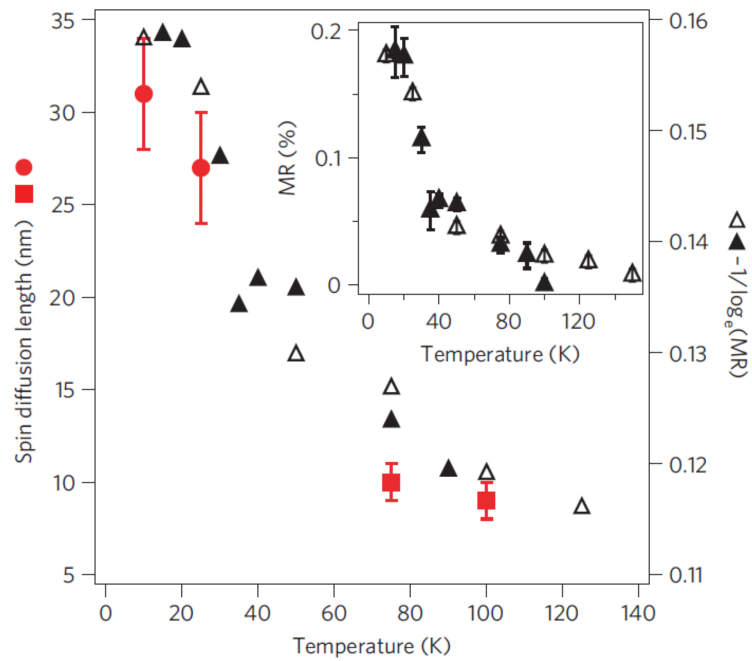
A. J. Drew[1,2]*, J. Hoppler[1,3], L. Schulz[1], F. L. Pratt[4], P. Desai[2], P. Shakya[2], T. Kreouzis[2], W. P. Gillin[2], A. Suter[5], N. A. Morley[6], V. K. Malik[1], A. Dubroka[1], K. W. Kim[1], H. Bouyanfif[1], F. Bourqui[1], C. Bernhard[1], R. Scheuermann[5], G. J. Nieuwenhuys[5], T. Prokscha[5] and E. Morenzoni[5]

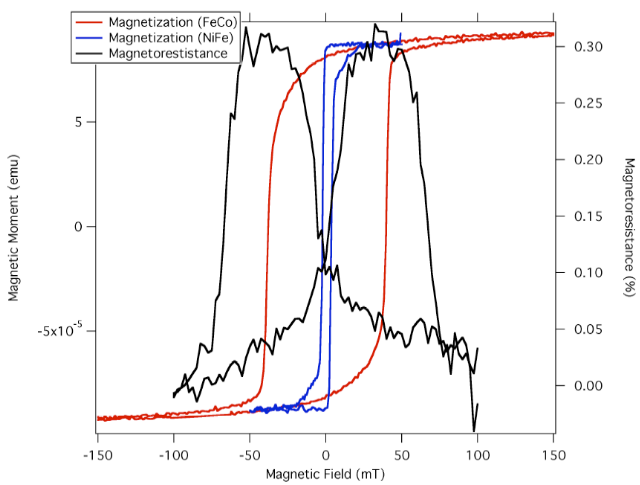
FM/sm/FM

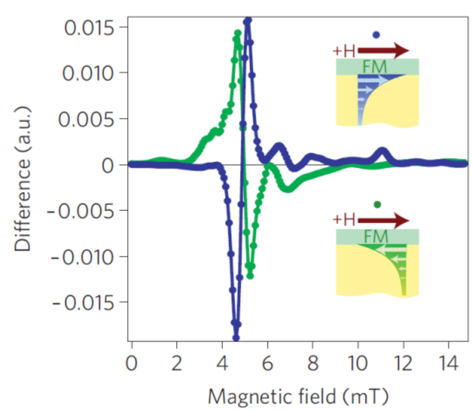




NiFe/LiF Alq3 FeCo







Spin diffusion (decoherence) length ←→ Magnetoresistance

A. Drew et al. Nature Materials (2009)
L. Schultz et al. Nature Materials (2011)

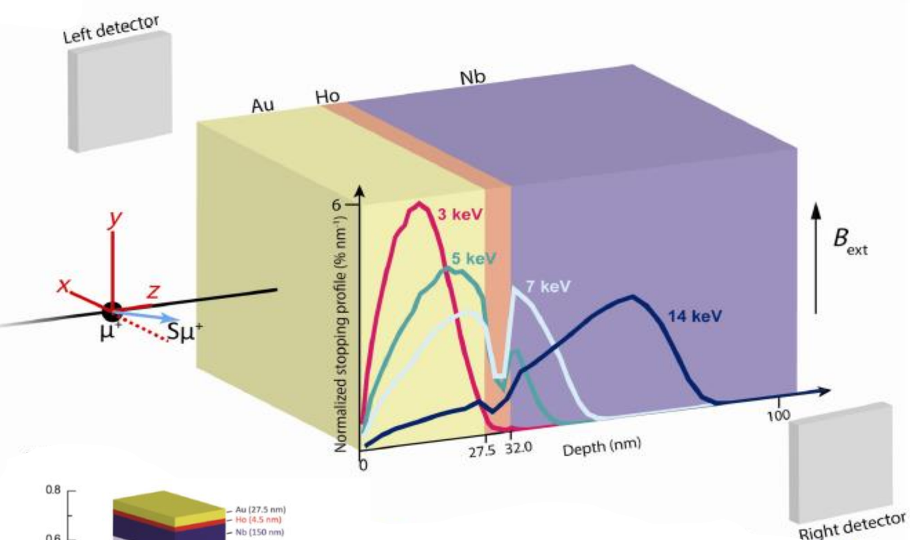
PHYSICAL REVIEW X 5, 041021 (2015)

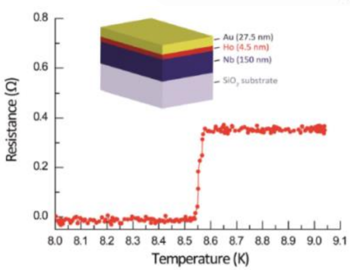
Intrinsic Paramagnetic Meissner Effect Due to s-Wave Odd-Frequency Superconductivity

A. Di Bernardo,[1] Z. Salman,[2] X. L. Wang,[3] M. Amado,[1] M. Egilmez,[4] M. G. Flokstra,[5] A. Suter,[2] S. L. Lee,[5] J. H. Zhao,[3] T. Prokscha,[2] E. Morenzoni,[2] M. G. Blamire,[1] J. Linder,[6] and J. W. A. Robinson[1,*]

Cambridge-PSI-CAS-Sharjah-St.Andrews-NTNU

NM/FM/SC





Pauli principle: F(1,2) = - F(2,1)		
Spin	Time	Parity
Triplett		s-wave
Even	Odd	Even

Spin singlet n_s: Meissner effect (diamagnetic)

$$\vec{J} = -\frac{e^2}{mc}\, n_s\, \vec{A}$$

Spin triplet component n_t:
paramagnetic Meissner effect
(increase of magn. flux instead of decrease)

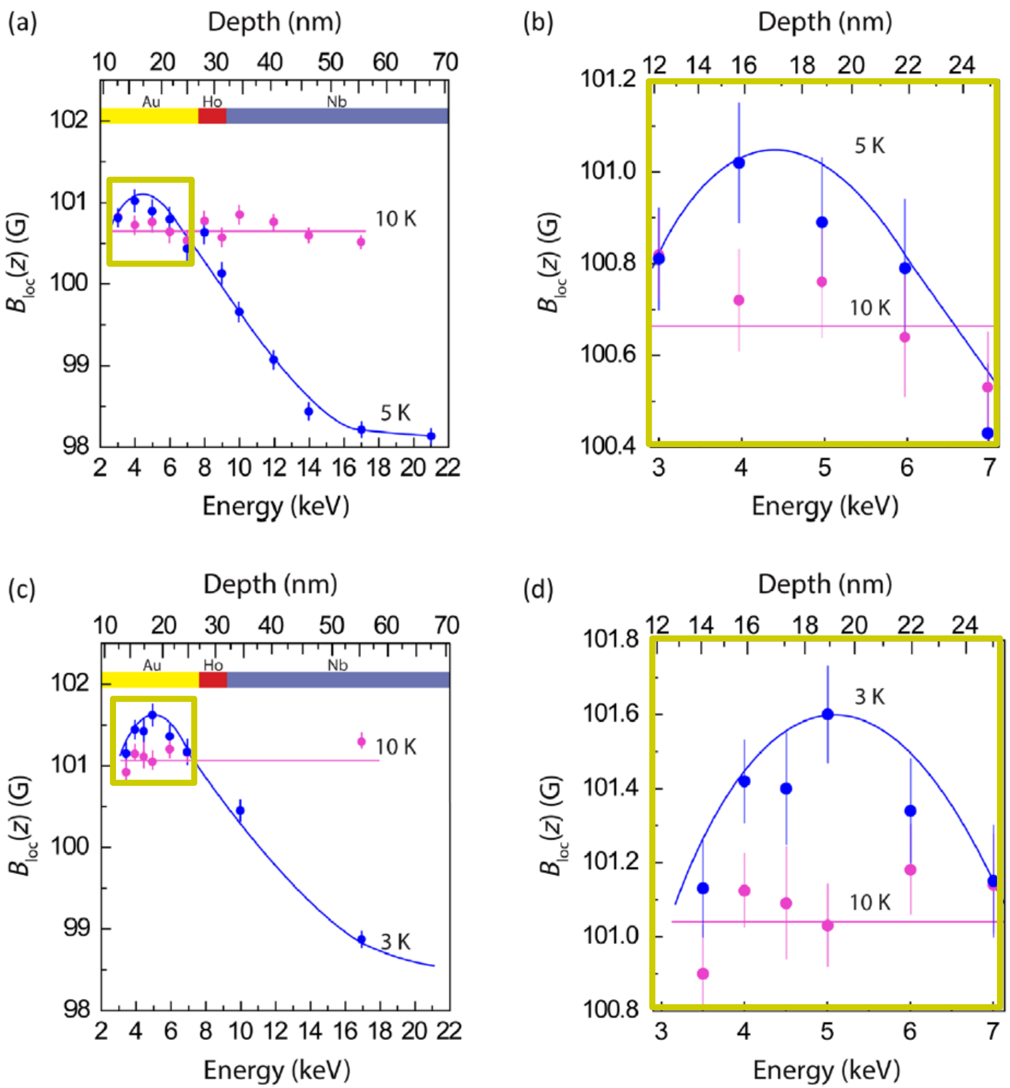
$$\vec{J} = -\frac{e^2}{mc}\,(n_s - n_t)\,\vec{A}$$

Singlet and triplet components have different decay lengths

S. Mironov, A. Mel'nikov, and A. Buzdin, Phys. Rev. Lett. ***109****, 23700 (2012)*
V. L. Berezinskii JETP 20, 287 (1974)
J. Linder, A. Balatsky, Rev. Mod. Phys. (2019)

Magnetic field profiles

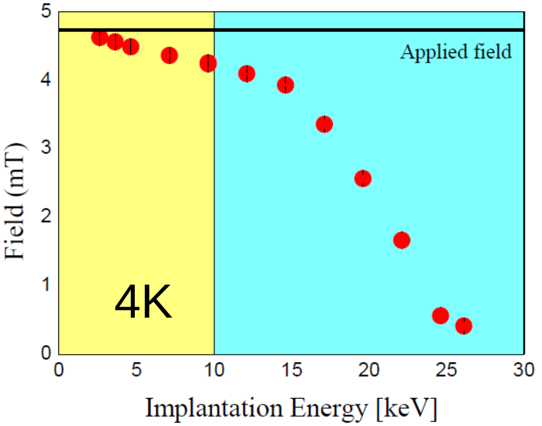
N/FM/SC



A. di Bernardo et al., Phys. Rev. X. ***5****, 041021 (2015)*

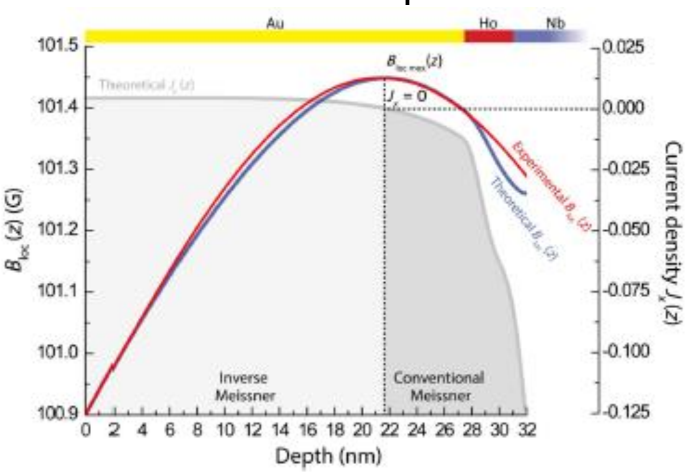
N/SC Al/Nb

Al(90nm)/Nb(270nm)



E. M et al., unpublished

Calculated field profile



Summary and outlook

- **Some selected examples of use of μSR in the study of magnetic and superconducting properties of bulk materials and thin films and heterostructures**

- **Not shown: many things**
    - Applications in chemistry, soft matter, semiconductors (muonium spectroscopy), defect and diffusion studies, (quantum) impurities…
    - Resonance experiments or experiments with external stimulus, decoupling…

- **μSR now a standard technique making increasing significant contribution in Condensed Matter, Material Science research and other fields**

- **Synergy and complementary with other probes and facilities: neutrons, photons, β-NMR … and with macroscopic techniques: transport, magnetization, thermodynamic measurements,…**

- **Increasing interest (> 200 proposals/year at PSI, overbooking factor > 2.5)**

- **New techniques, such as low energy μSR are extending the already broad range of applications, new tools: high pressure, high field and low temperature instruments, external stimuli**

- **The new μSR facility at RAON has great potential to address a new user community and enlarge the worldwide existing community (complementary to pulsed source at J-PARC)**

Thank you

Acknowledgements

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R. Khasanov, J. Krieger, M. Chinotti, P. Biswas, Z. Guguchia, A. Amato, H. Luetkens, T. Prokscha, Z. Salman, A. Suter