PAUL SCHERRER INSTITUT


WIR SCHAFFEN WISSEN – HEUTE FÜR MORGEN

Muons for solid state research at PSI

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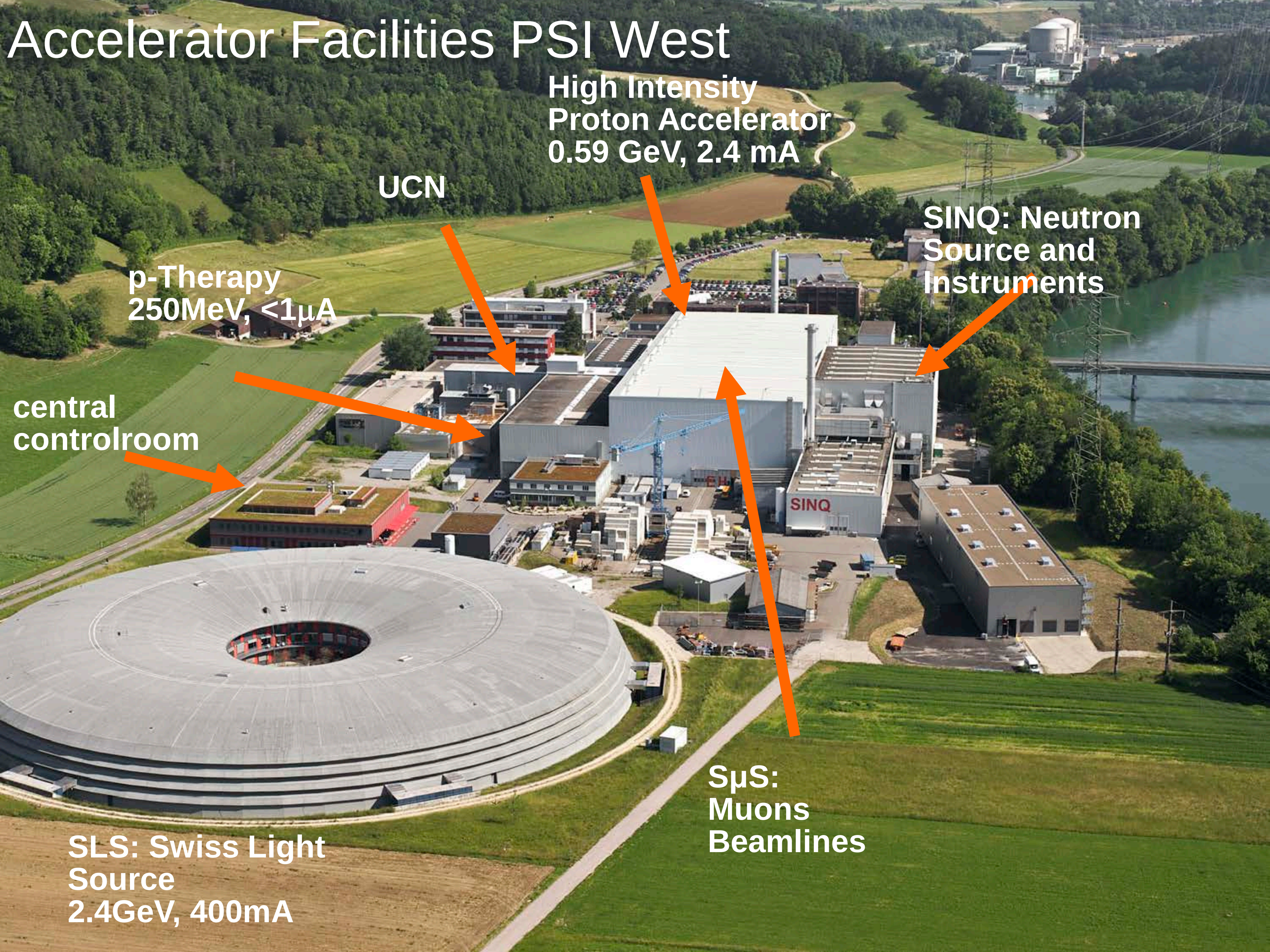
Future Muon Source Possibilities at SNS Workshop,
1-2 September 2016, Oak Ridge National Laboratory

Outline

- PSI facility (SµS, Swiss Muon Source)
  - instruments
  - statistics usage and scientific output
- Selected scientific examples:
  - magnetism, superconductivity, spin transport
  - in bulk materials, thin films/heterostructures

Accelerator Facilities PSI West



High Intensity
Proton Accelerator
0.59 GeV, 2.4 mA

UCN

SINQ: Neutron
Source and
Instruments

p-Therapy
250MeV, <1μA

central
controlroom

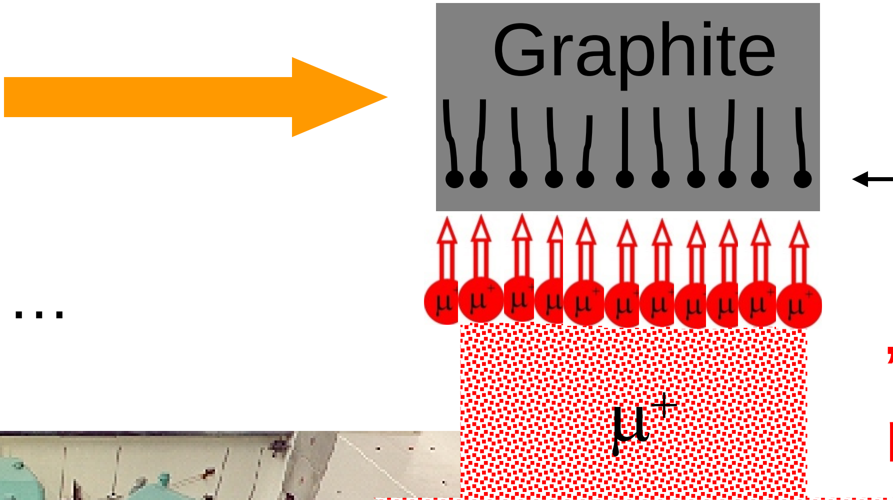
SμS:
Muons
Beamlines

SLS: Swiss Light
Source
2.4GeV, 400mA

Generation of polarized muons (μ^+)

2.4 mA $\cong$ 1.5 10^{16} Protons/sec

with 590 MeV



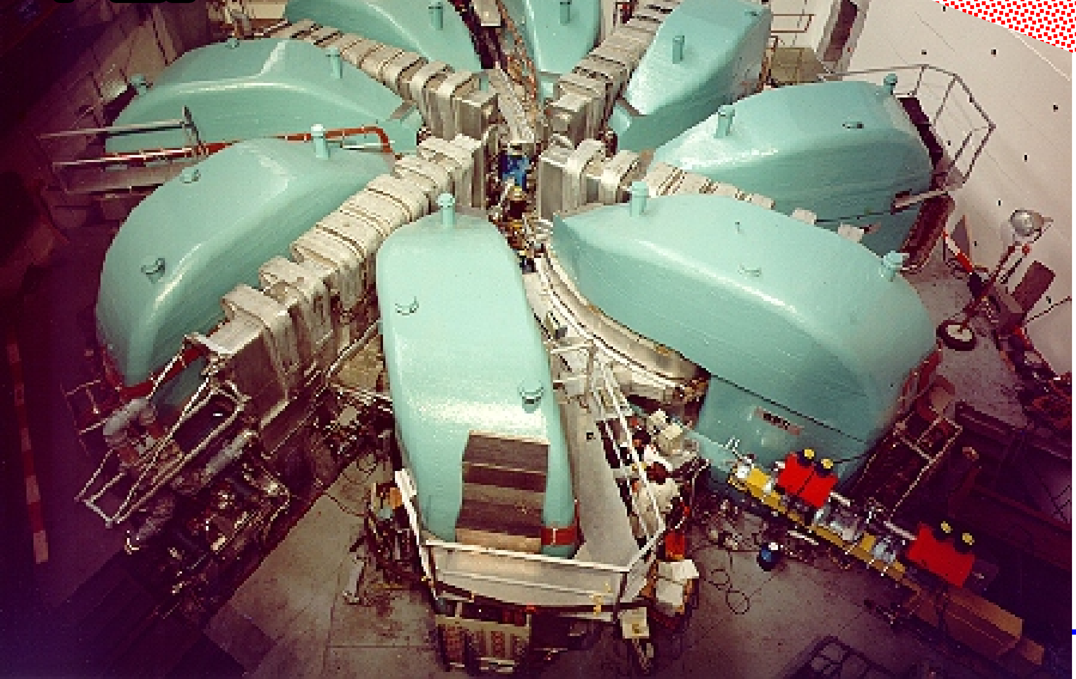
Production Targets
(5.2 mm, 40 mm)

$\longleftarrow \pi^+ \longrightarrow \mu^+ + \nu_\mu$

p + C → $\pi^+ \pi^-$ p n …

„Surface“

muons

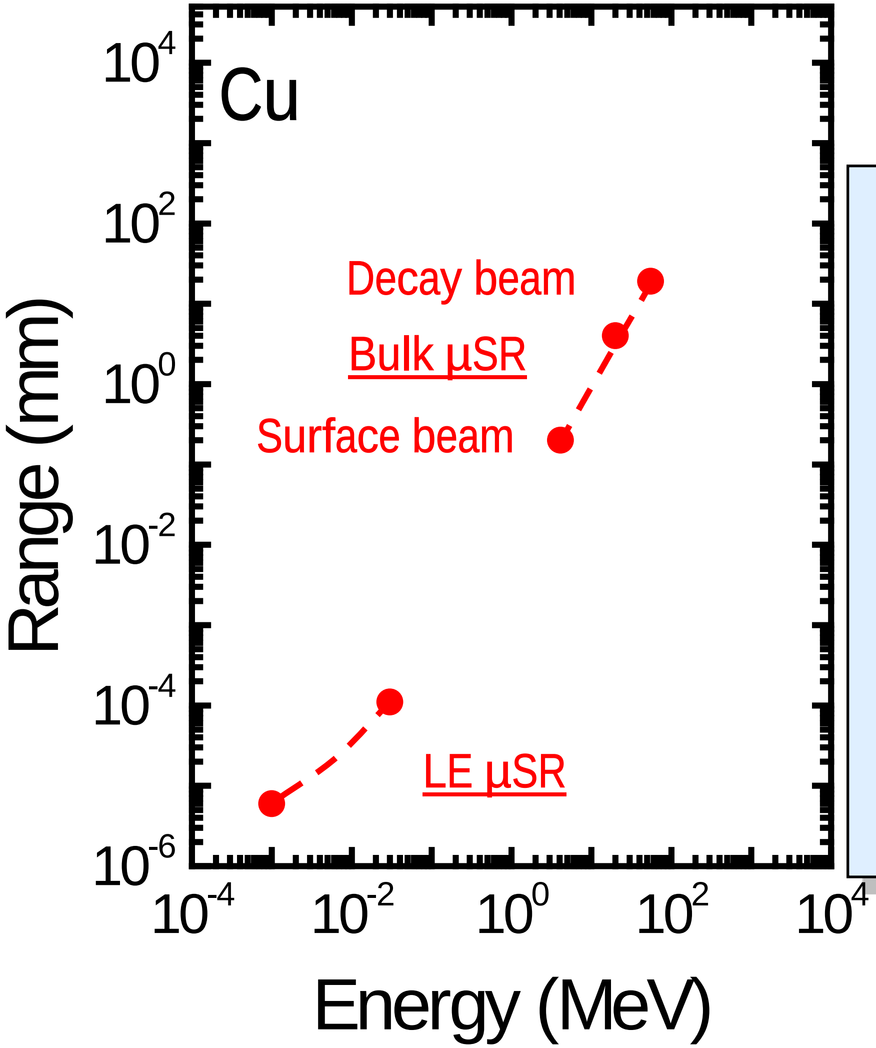


~10^7- 10^9 μ^+/sec, 100 % pol., ~ 4 MeV
generally used for “bulk”
condensed matter studies

For higher energies: „decay muons”
from π^+ decay in flight, ~ 80 % pol.

For thin film studies: low energy muons
(eV-30 keV) 100 % pol.

Different muon energies for different studies



Bulk μSR:

- “Normal” samples (sub-mm)
- Bulky samples in pressure cells or in containers

LE μSR:

- Depth-dependent investigations (~ 2–300 nm)

Muon Instruments at PSI : SμS (Swiss Muon Source)

HAL9500

High Field and Low Temperature

9.5 T, < 20 mK

GPS

General Purpose Surface Muon Instrument

Muon energy: **4.2 MeV** (μ⁺)

0.6 T, 1.6 K

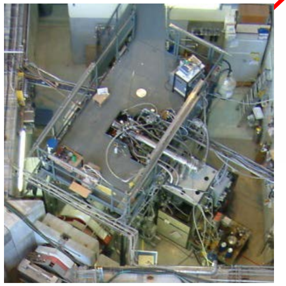
Shared Beam Surface Muon Facility (Muon On REquest)

LTF

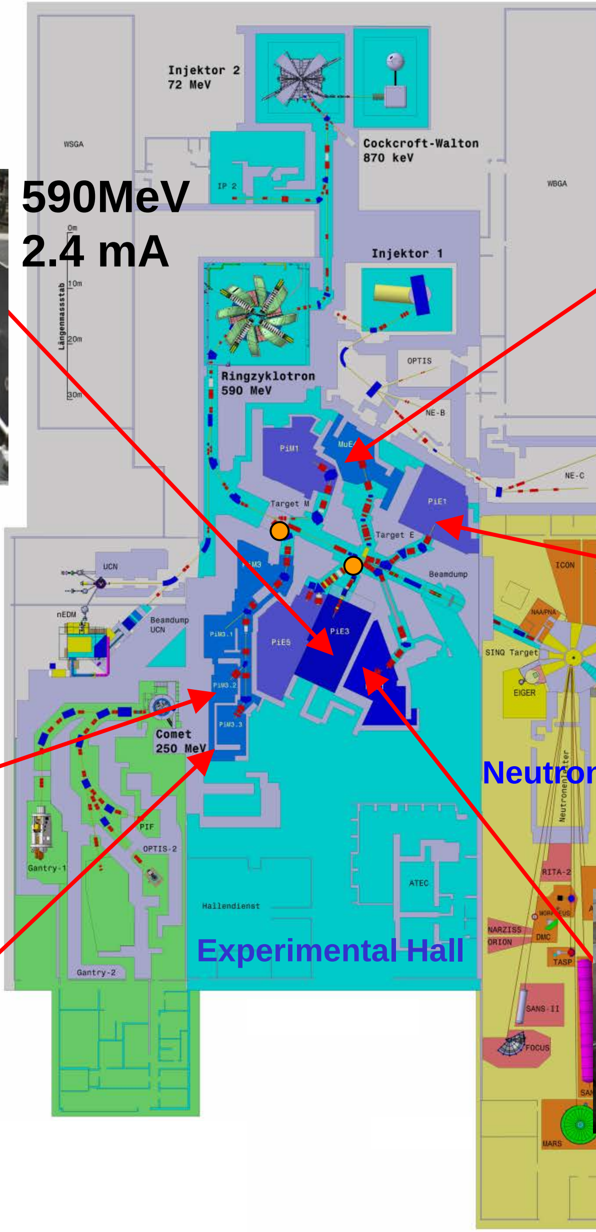
Low Temperature Facility

Muon energy: **4.2 MeV** (μ⁺)

3 T,
20 mK- 4 K

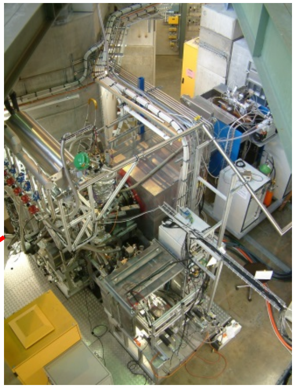


590MeV
2.4 mA



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

DOLLY

General Purpose Surface Muon Instrument

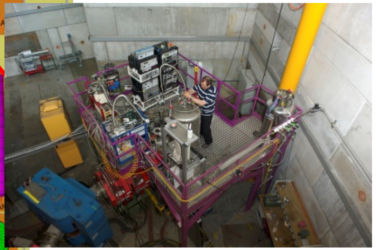
μ⁺ energy: **4.2 MeV**

0.5 T
250 mK

GPD

General Purpose Decay Channel Instrument
Pressure studies

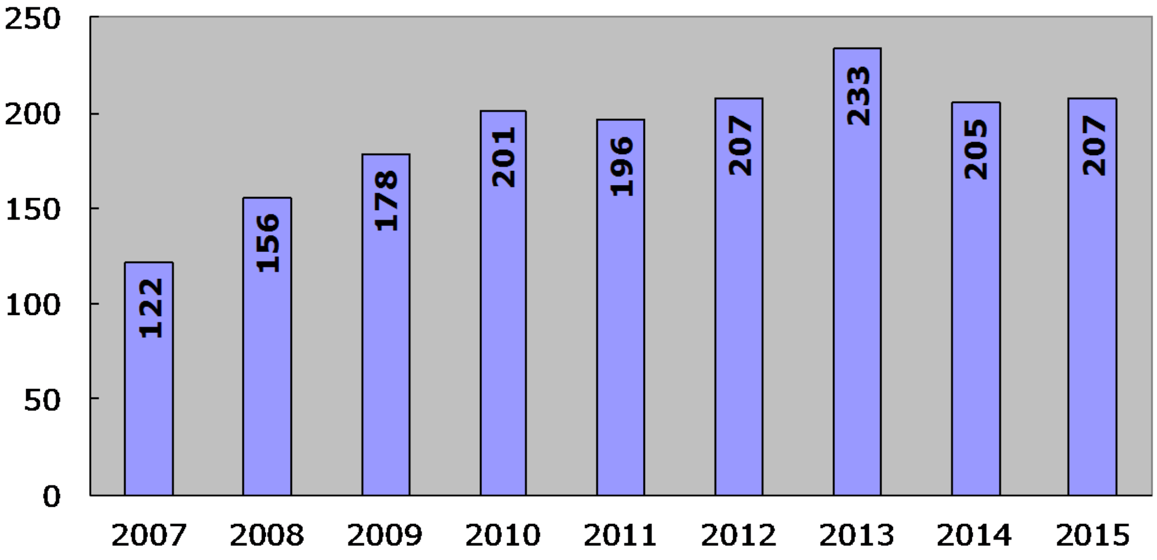
Muon energy: **5 - 60 MeV** (μ⁺ or μ⁻)



0.5 T,
300 mK
2.8 GPa

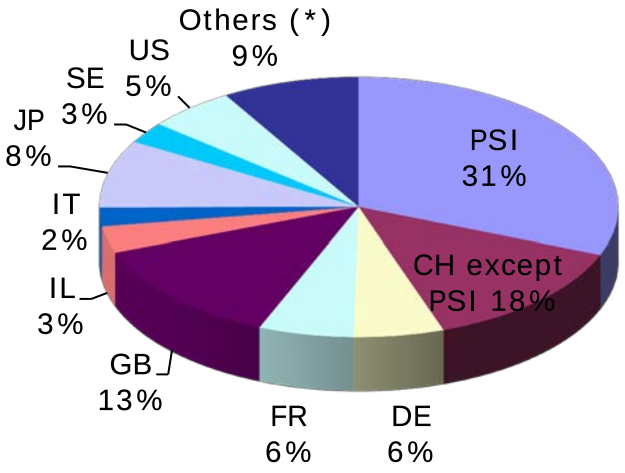
SμS Statistics

Submission of new proposals



2015: Submitted Proposals : 207
User Visits : 211
Experiments : 230
Experimental days * : 763
*without instrument setup and development
Instrument <u>overbooking factor</u> : 2-3.5

Geographic distribution of users 2014



(*) others: 9 countries with less than 1.5%

US: 2013 3%
2014 5%
2015 6%

Publications:~ 60 papers/year
~ 10 PRL, Science, Nature Journals, Nanoletters, ACS
~ 20 PRB

Research at the SμS

Magnetic materials
Molecular magnets
Iridates
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

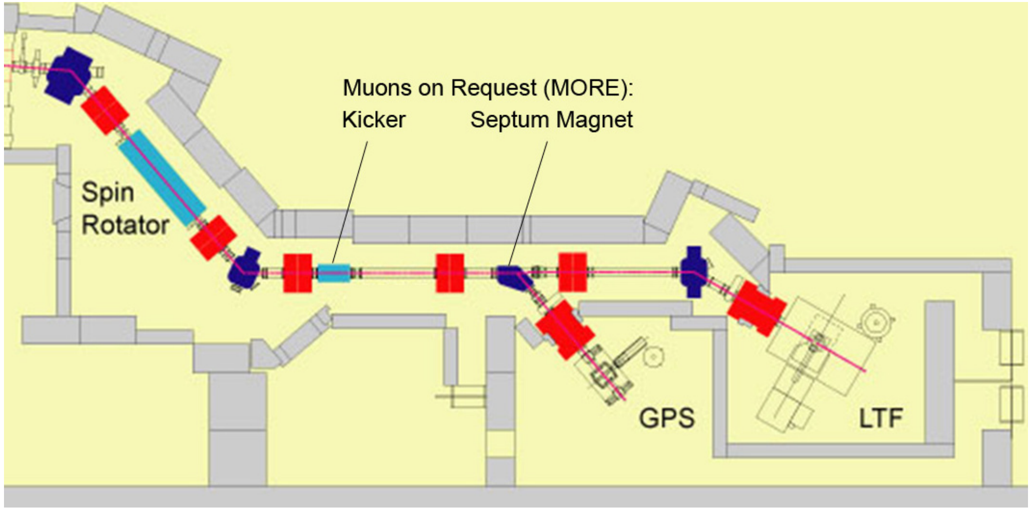
Superconductors
Cuprates
FeSC
Layered SC
Low T_c

Chemistry, Soft matter
Free radicals
Liquid crystals

Material Science
Multiferroics
Battery materials
H storage materials

Surface Muon Instruments – GPS/LTF/Dolly

πM3: Shared by: General Purpose Spectrometer and Low Temperature Facility



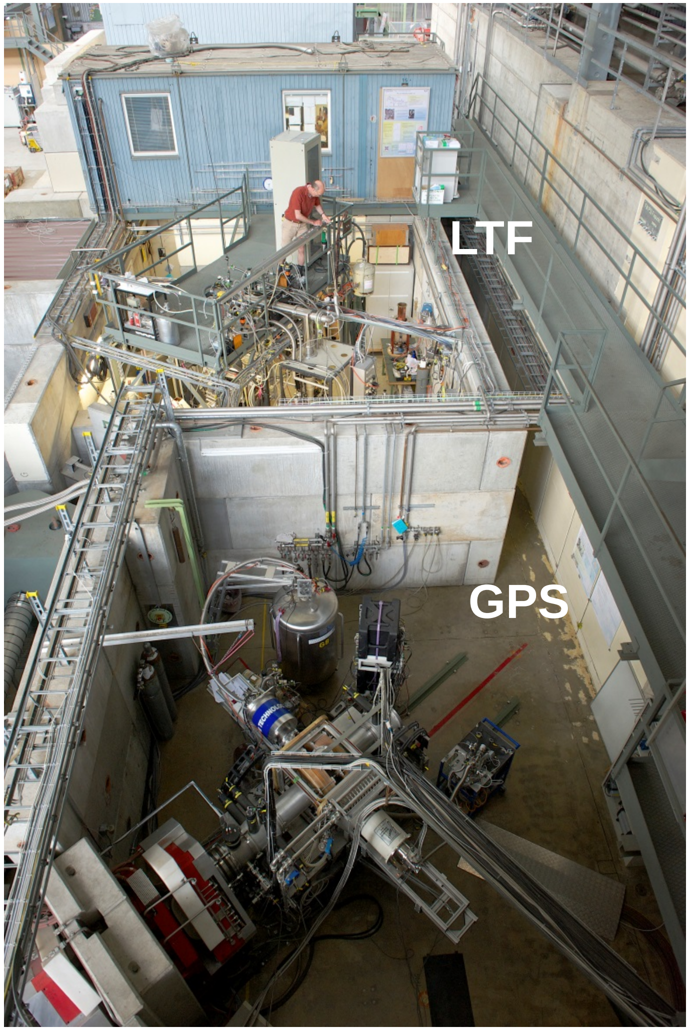
- 4 MeV μ^+, 100% polarized
- B_{ext} GPS: 0 - 0.6 T
  Dolly: 0 - 0.5 T
  LTF: 0 - 3 T
- T GPS: 1.8 - 1200 K
  Dolly: 0.25 – 300 K
  LTF(DR): 0.02 - 4.2 K

Veto system for low background and small samples:

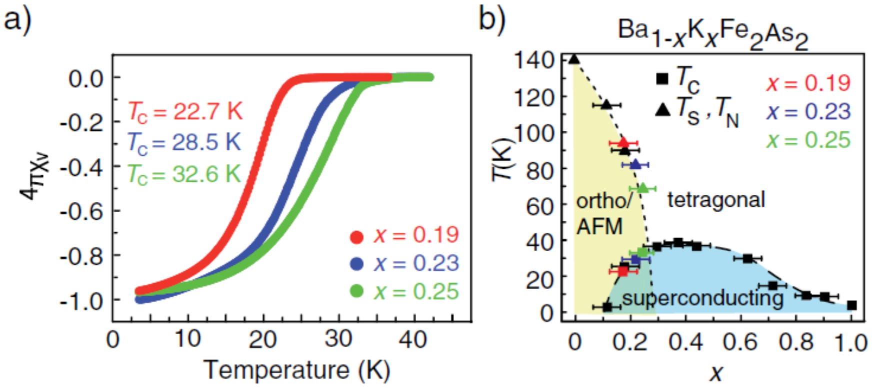
Sample size:

~ 2 mm DIA

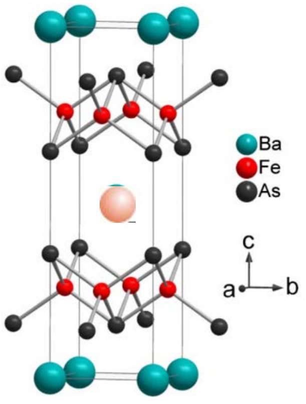
or ~ **30 mg**

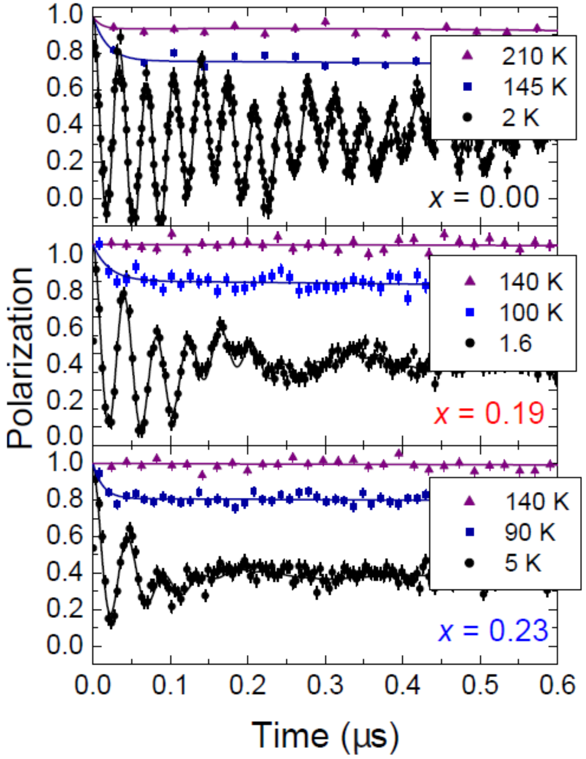


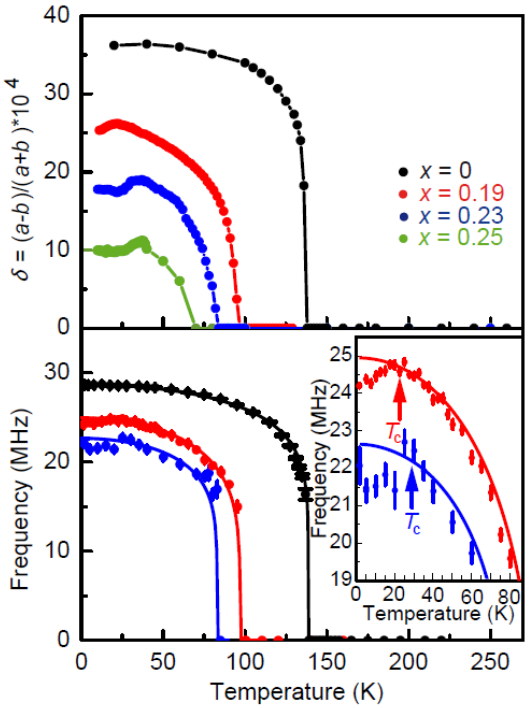
Interplay SC/magnetism

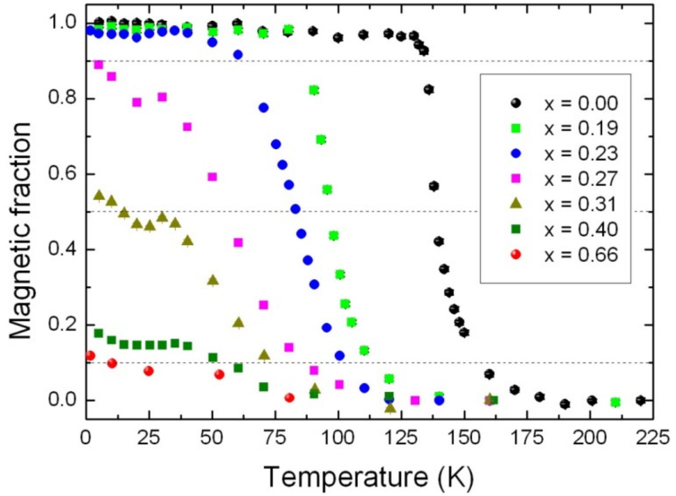


$Ba_{1-x}K_xFe_2As_2$ (122)



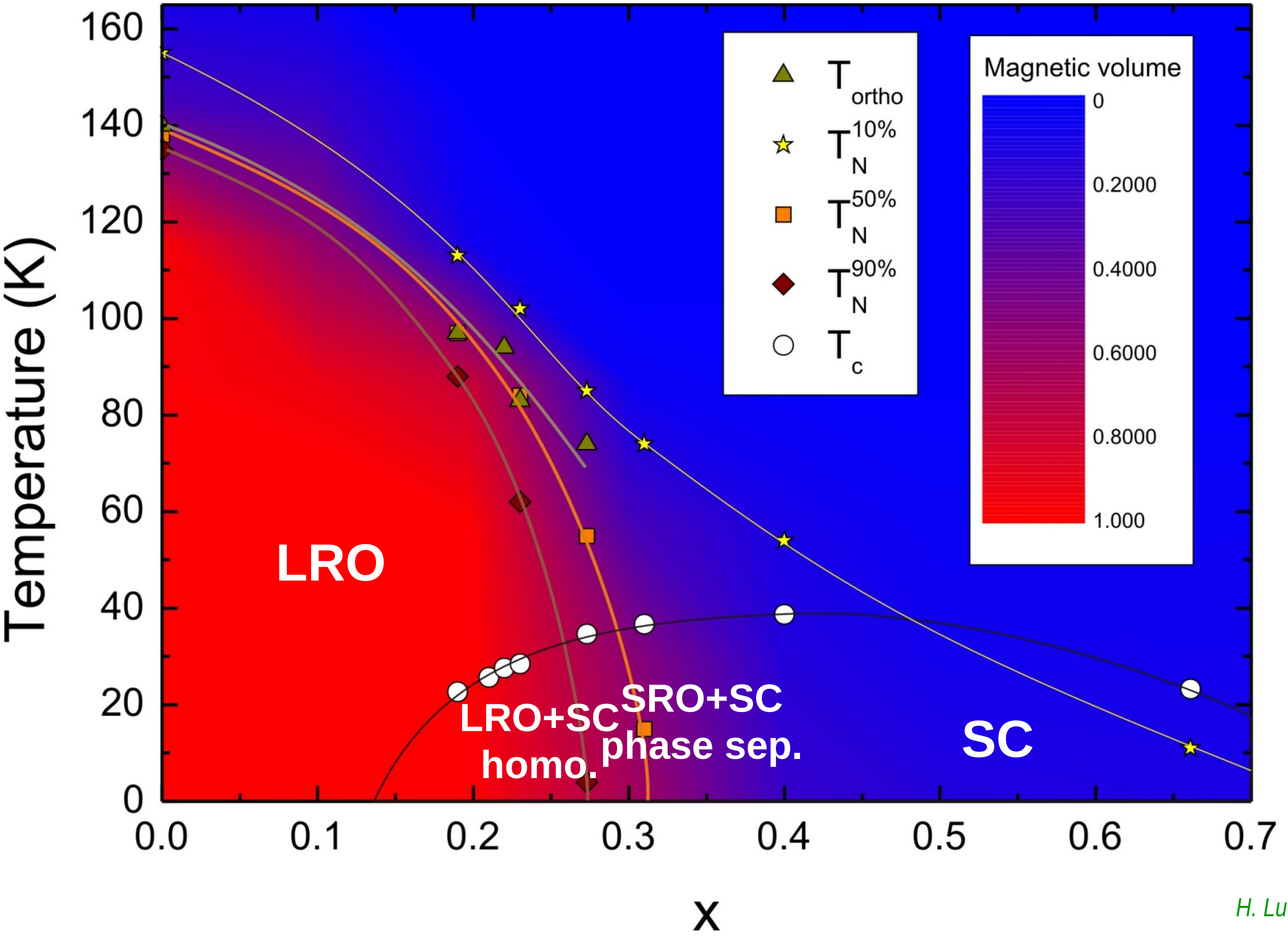






E. Wiesenmayer, H. Luetkens et al., Phys. Rev. Lett. 107, 237001 (2011).

Phase Diagram of $Ba_{1-x}K_xFe_2As_2$ (122)

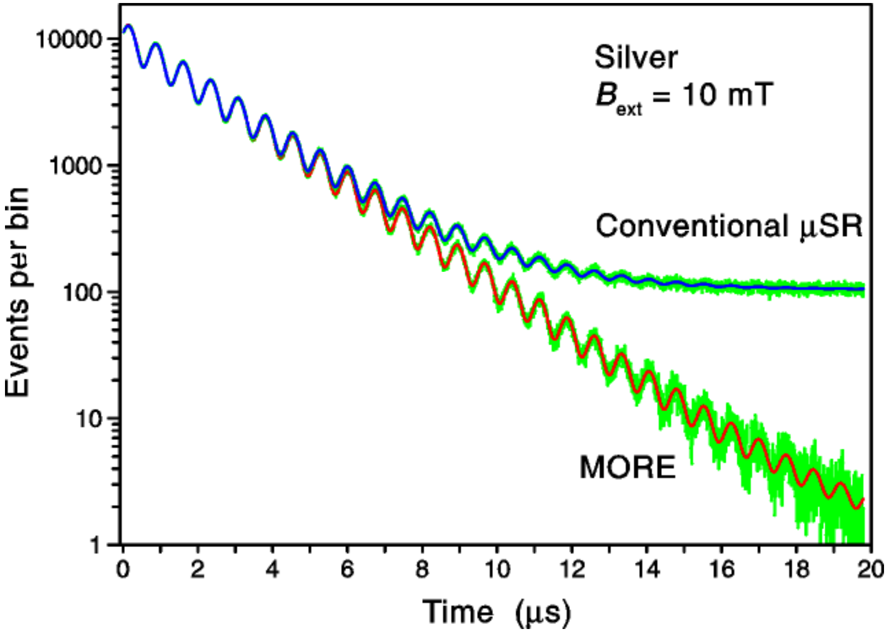


H. Luetkens et al.

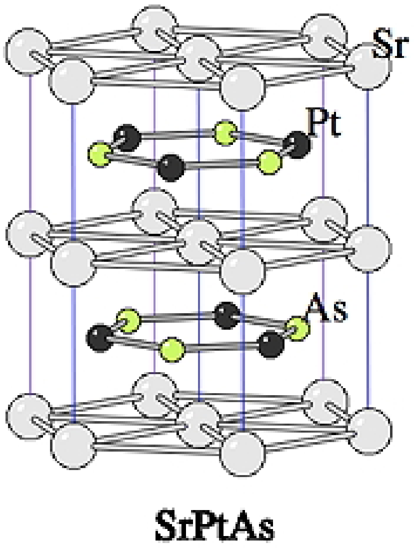
Muon On REquest: MORE on GPS/LTF

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

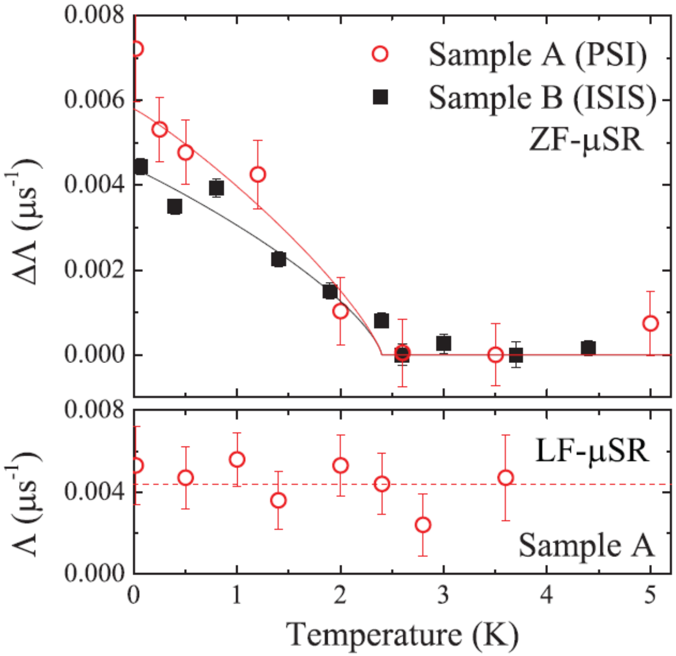
Worldwide Unique:
Combines advantages of continuous beam (very fast timing → magnetism, superconductivity, high muon spin relaxation rate) and pulsed beam (very low background, → very weak magnetism, low muon spin relaxation rate)

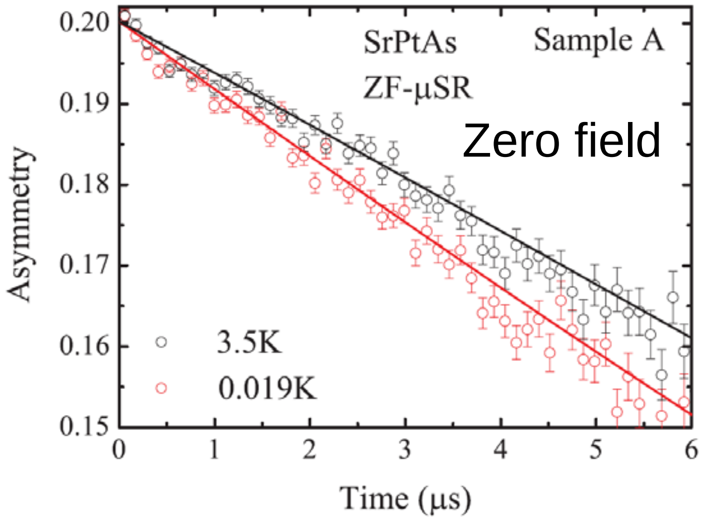


Time reversal symmetry breaking in SrPtAs



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





- ZF: Spontaneous very small magnetic field below T_c → ΔB ≈ 0.007 mT → TRSB
- TF: no line nodes in the gap
- Data consistent with d+id SC state

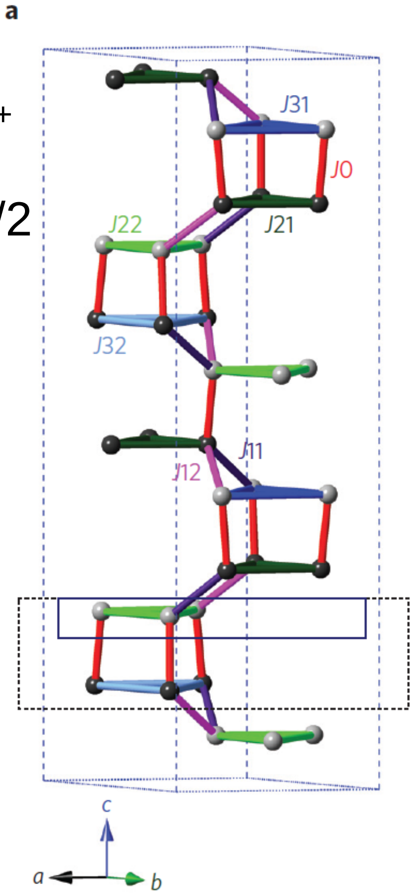
*P.K. Biswas et al., Phys. Rev. B **87**, 180503(R) (2013)*

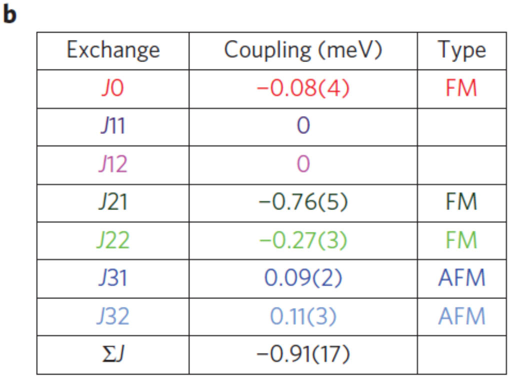
Complex frustration mechanism of a Quantum Spin Liquid

$Ca_{10}Cr_7O_{28}$: Quantum Spin Liquid with dominant isotropic FM interaction

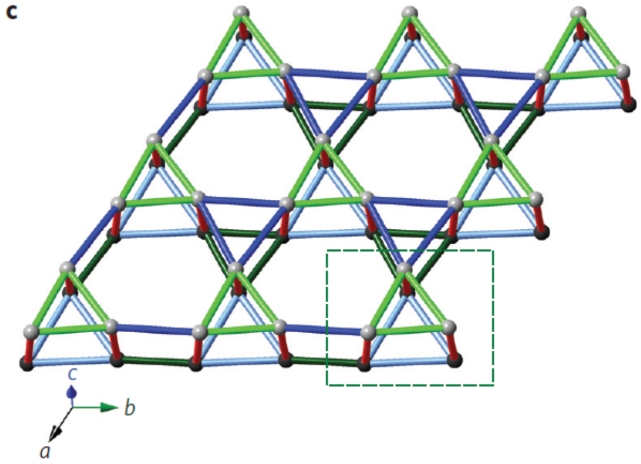
Cr^{5+}

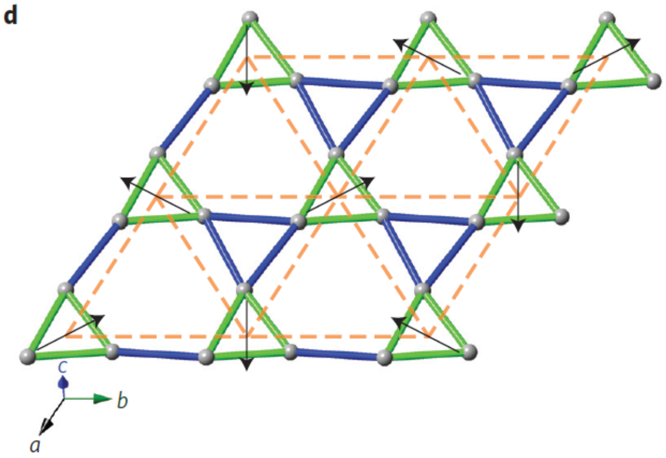
S=1/2

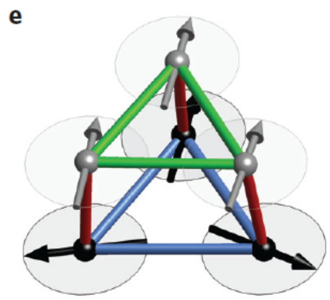




Exchange	Coupling (meV)	Type
*J*0	−0.08(4)	FM
*J*11	0	
*J*12	0	
*J*21	−0.76(5)	FM
*J*22	−0.27(3)	FM
*J*31	0.09(2)	AFM
*J*32	0.11(3)	AFM
Σ*J*	−0.91(17)	

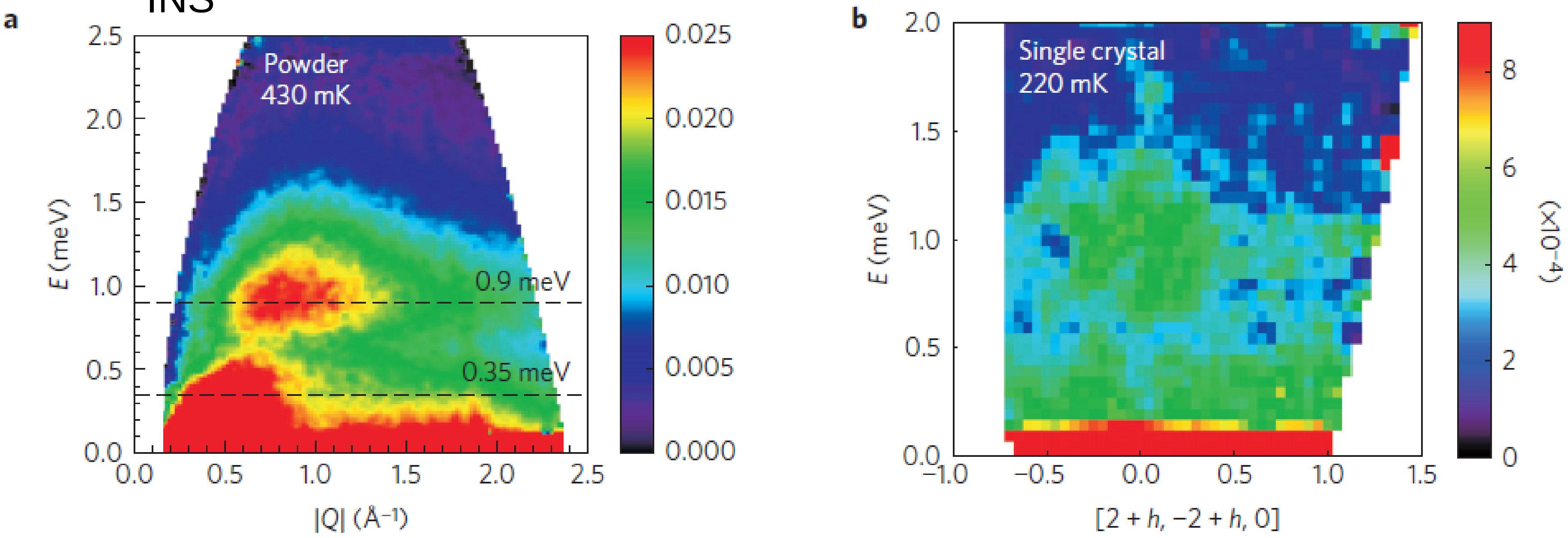




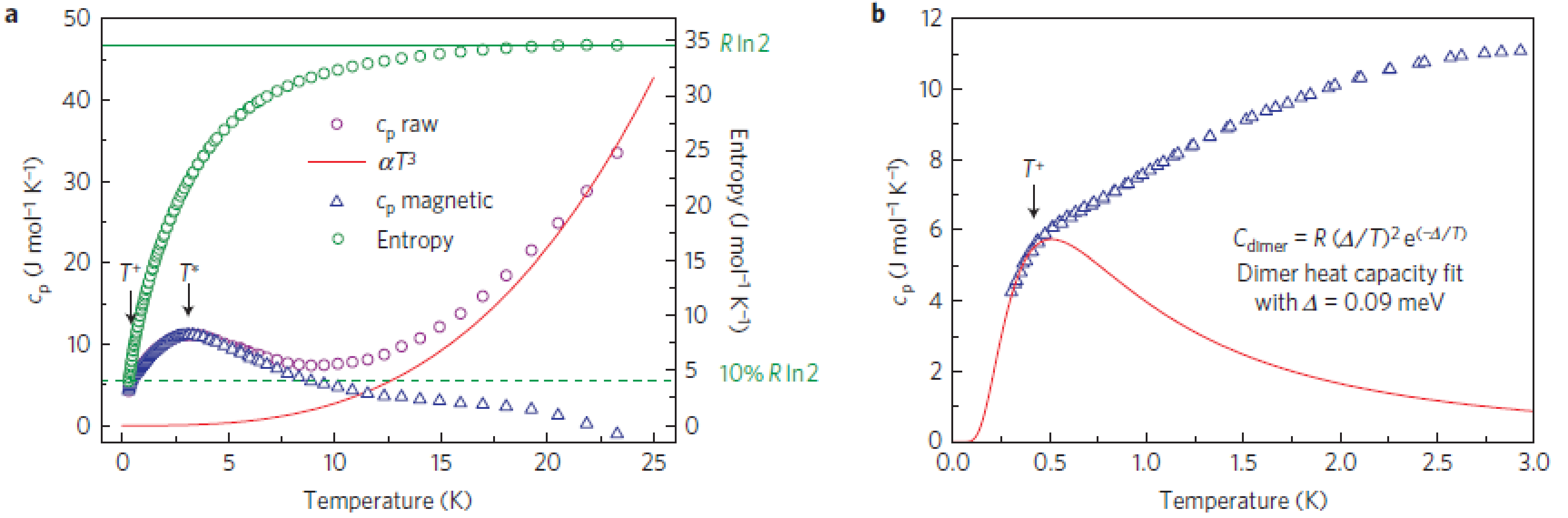


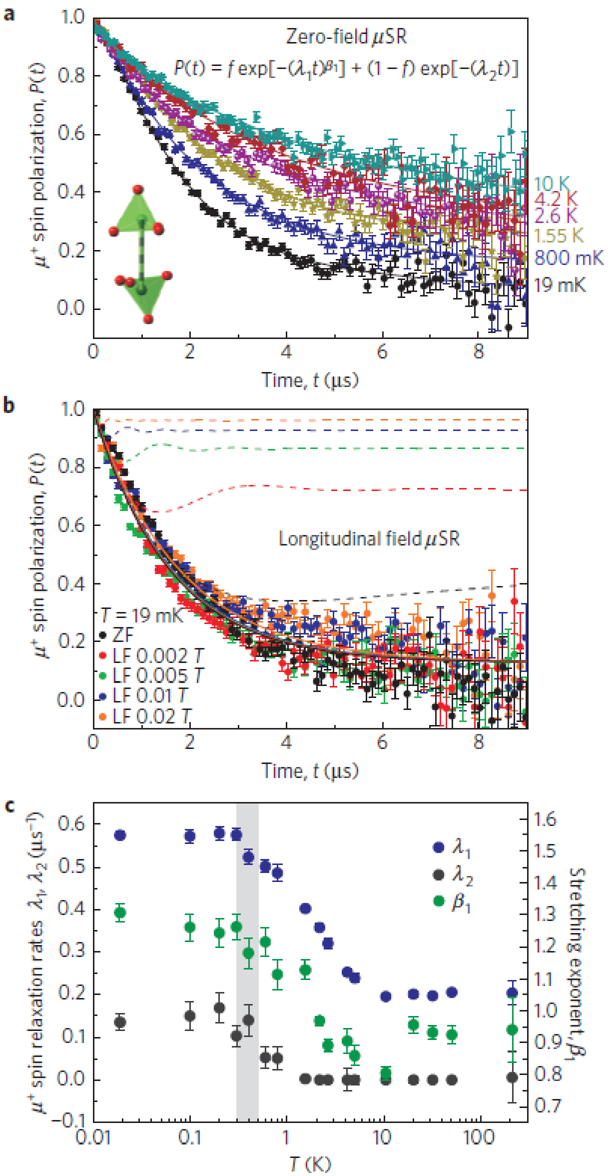
C. Balz, B. Lake et al., Nat. Phys., online 25 July 2016

INS



Specific heat





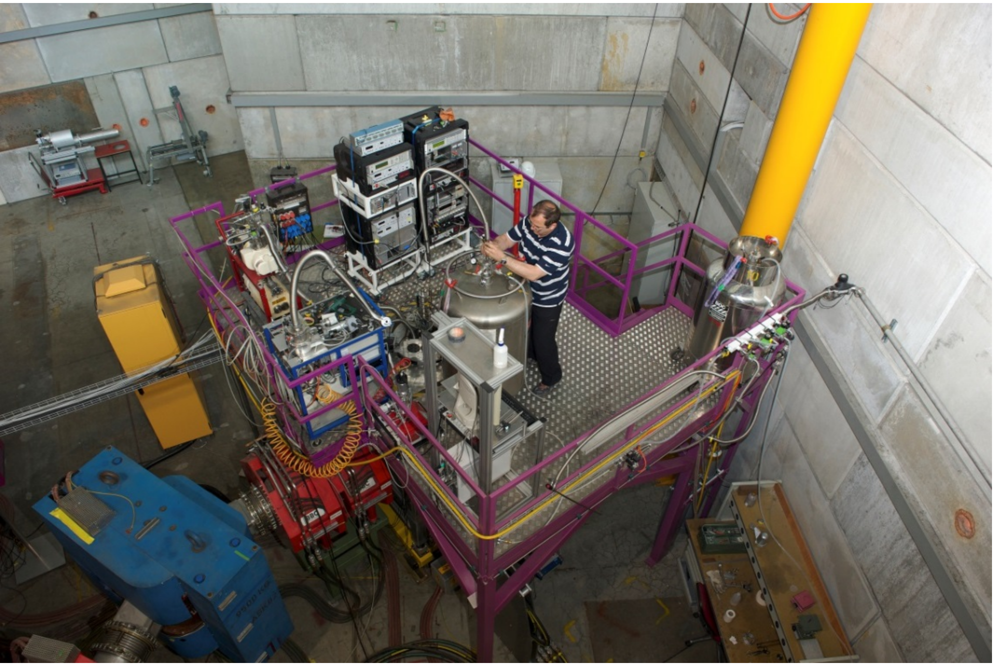
μSR: absence of static magnetism, dynamical ground state down to the lowest temperature (19 mK)

Persistent, temperature independent dynamic at low temperatures

μSR studies under pressure

High Energy Muon Instrument GPD

μE1 Superconducting Decay Channel Beamline



- 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)

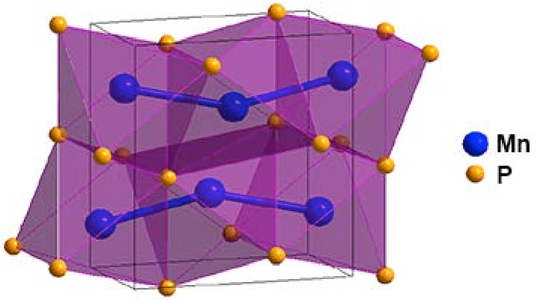
Pressure up to **2.8 GPa** (@4K)

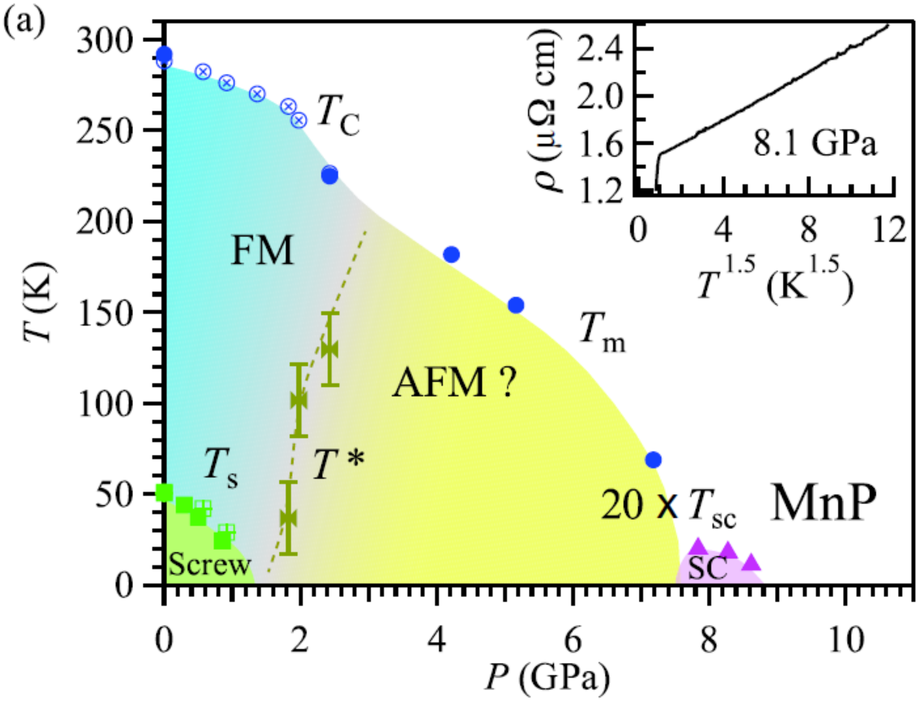
R. Khasanov et al.
High Pressure Research, **36,** 140 (2016)

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.

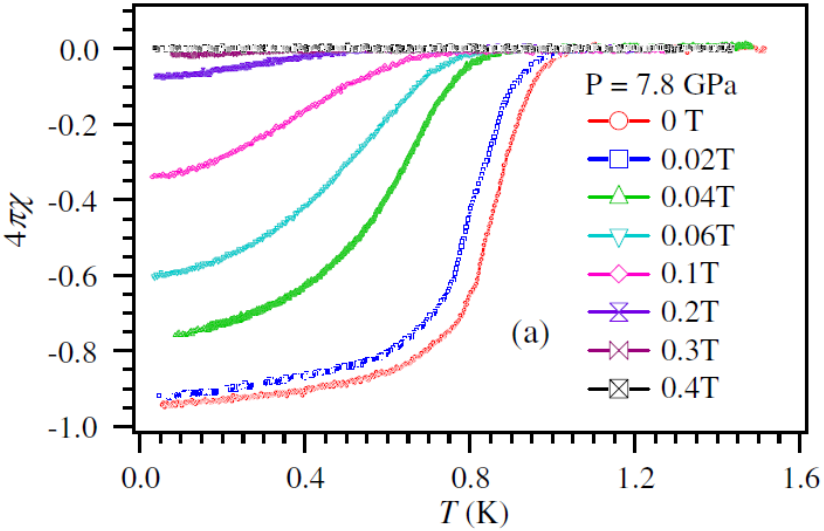
Pressure Induced Superconductivity in Mn based “helical” magnet

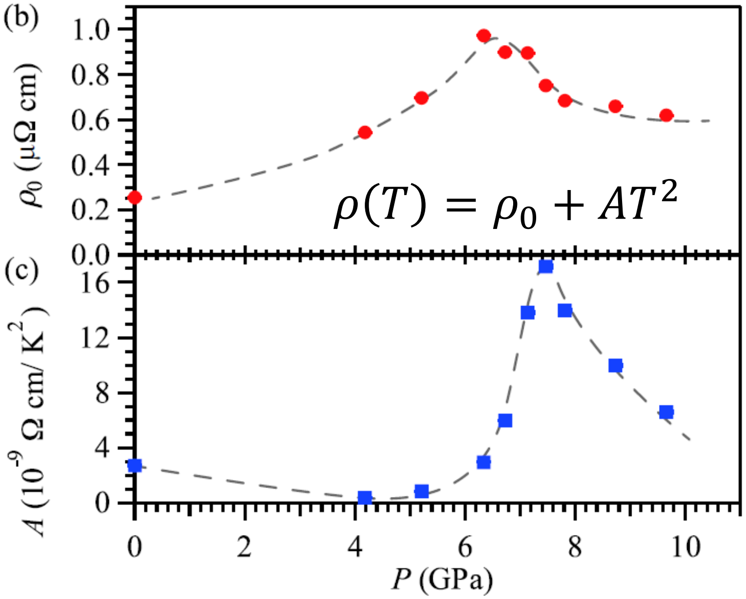
MnP: First Mn based SC $T_c \approx 1$ K



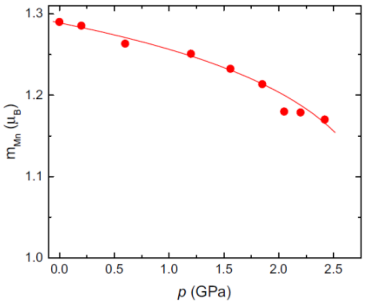


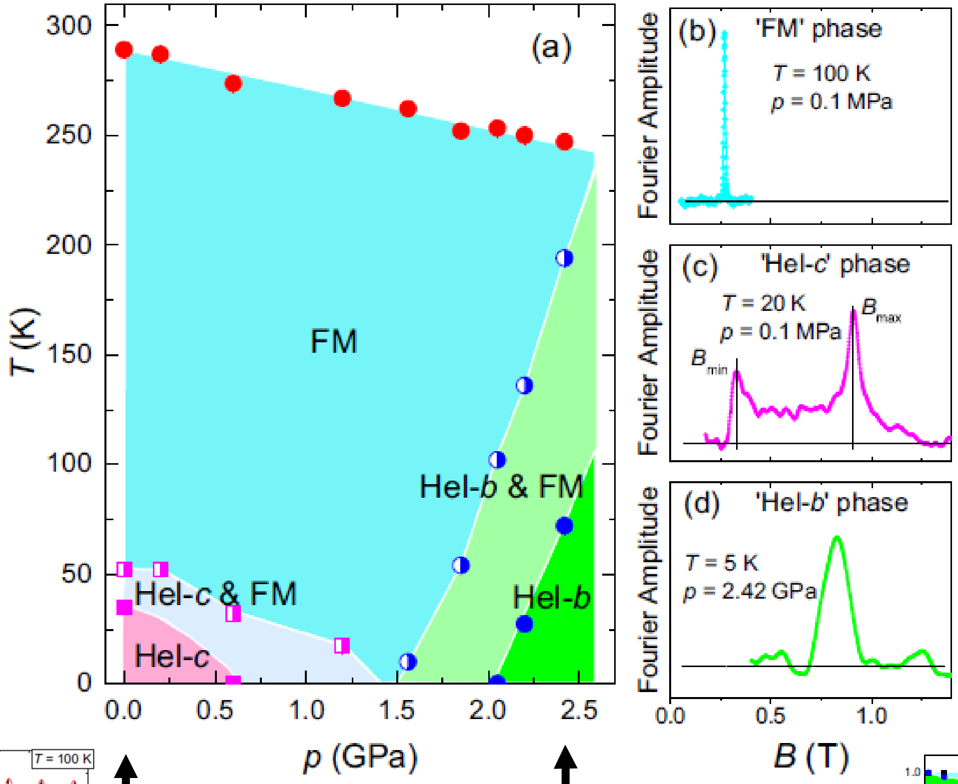
J. G. Cheng et al, PRL 114, 117001 (2015)



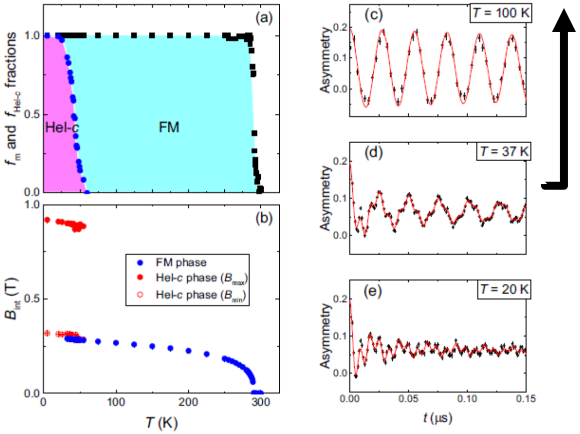


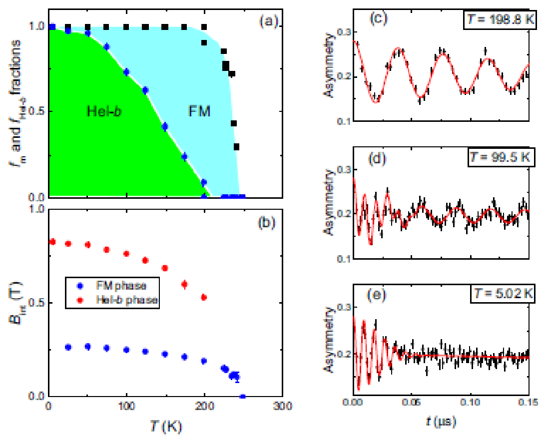
Magnetic structure of MnP under pressure





μSR resolves discrepancy between neutron and X-ray data



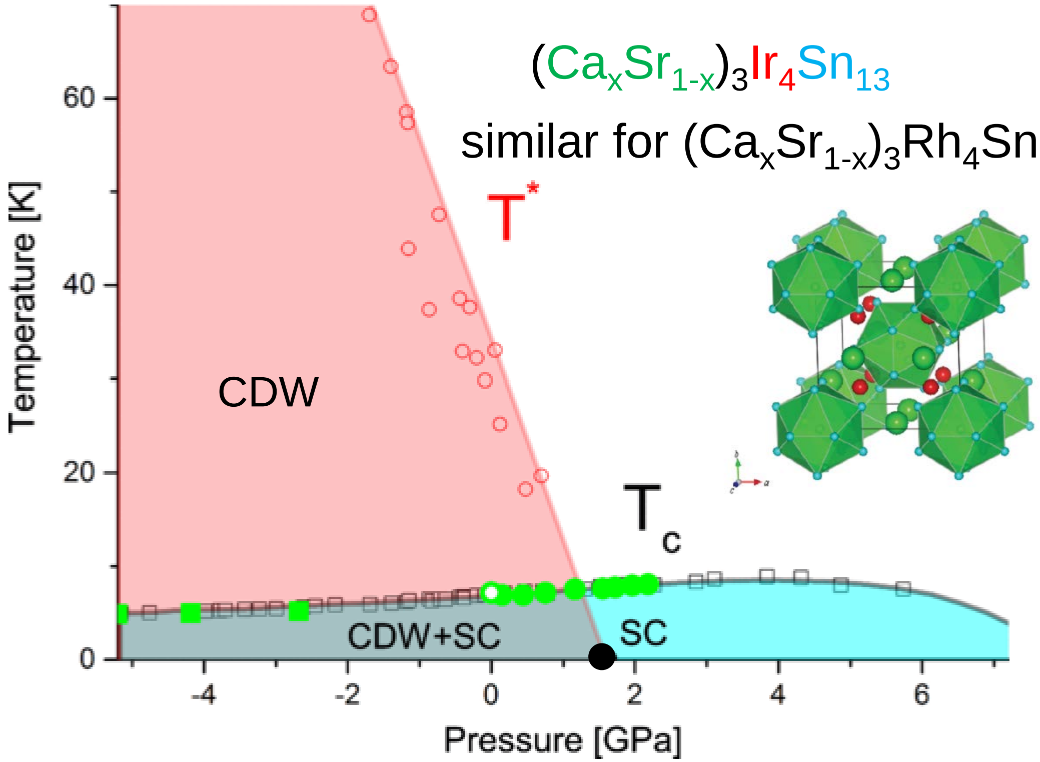


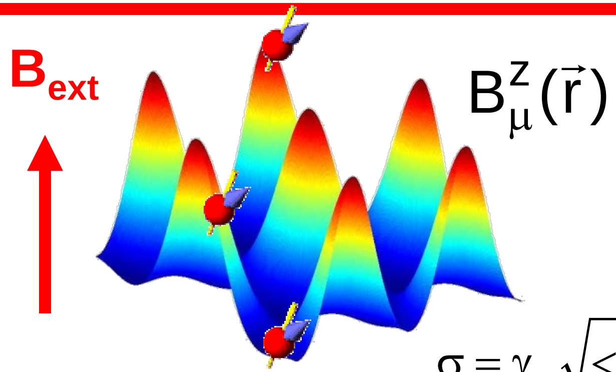
R. Khasanov et al, PRB 93, 180509(R) (2016)

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

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

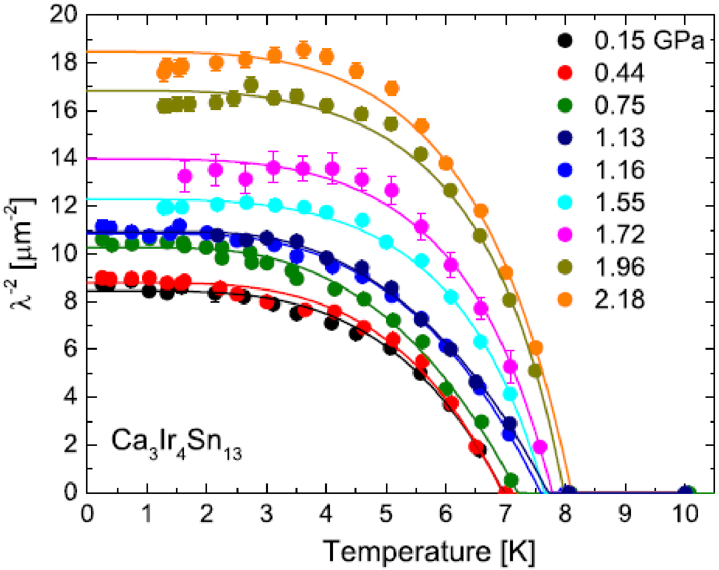
similar for $(Ca_xSr_{1-x})_3Rh_4Sn_{13}$





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

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

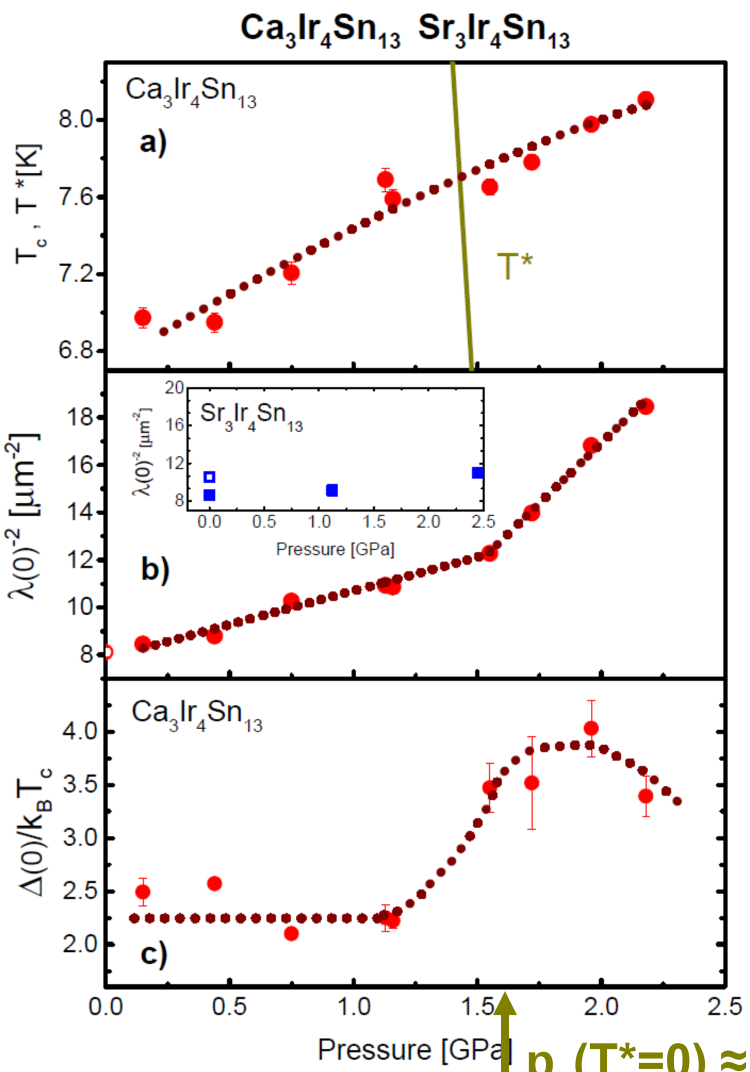


T* : structural transition and FS reconstruction/CDW

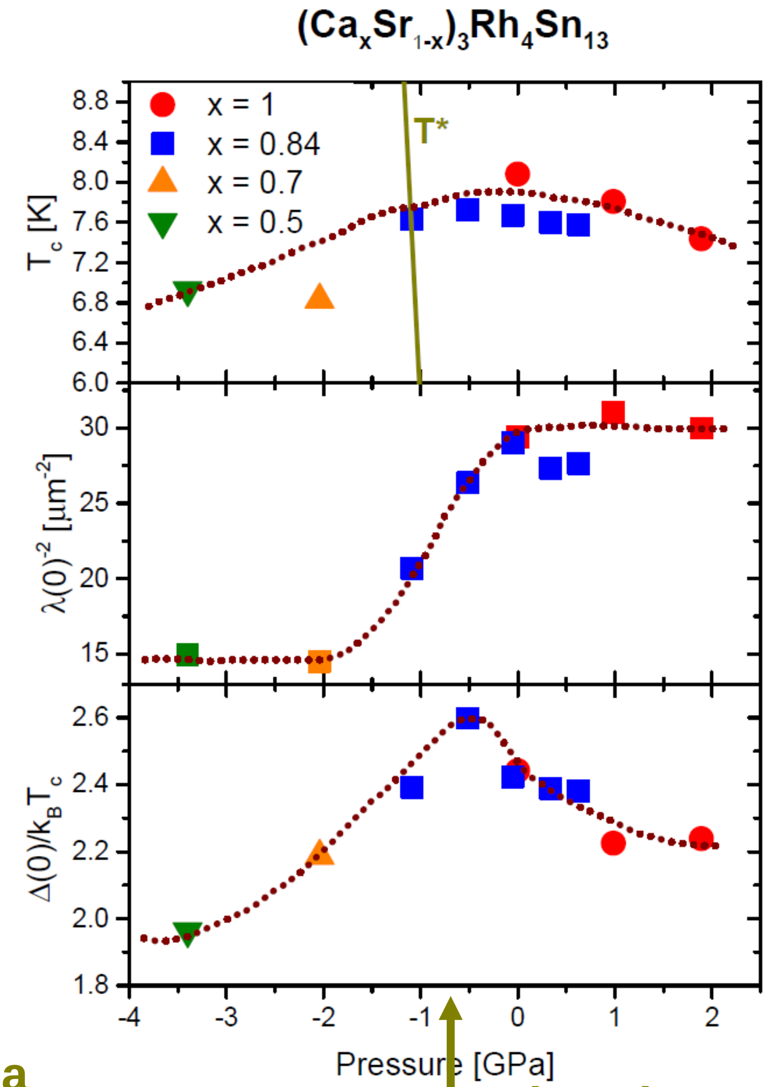
T*(p) decreases with pressure suggesting **quantum critical point** (QCP) at $p_c \approx 1.8$ GPa for $Ca_3Ir_4Sn_{13}$ and -0.6 GPa for $Ca_3Rh_4Sn_{13}$ (corresponds to $(Ca_{0.9}Sr_{0.1})_3Rh_4Sn_{13}$)

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

Strong enhancement of SC at QCP



$p_c(T^*=0)$ ≈1.6 GPa

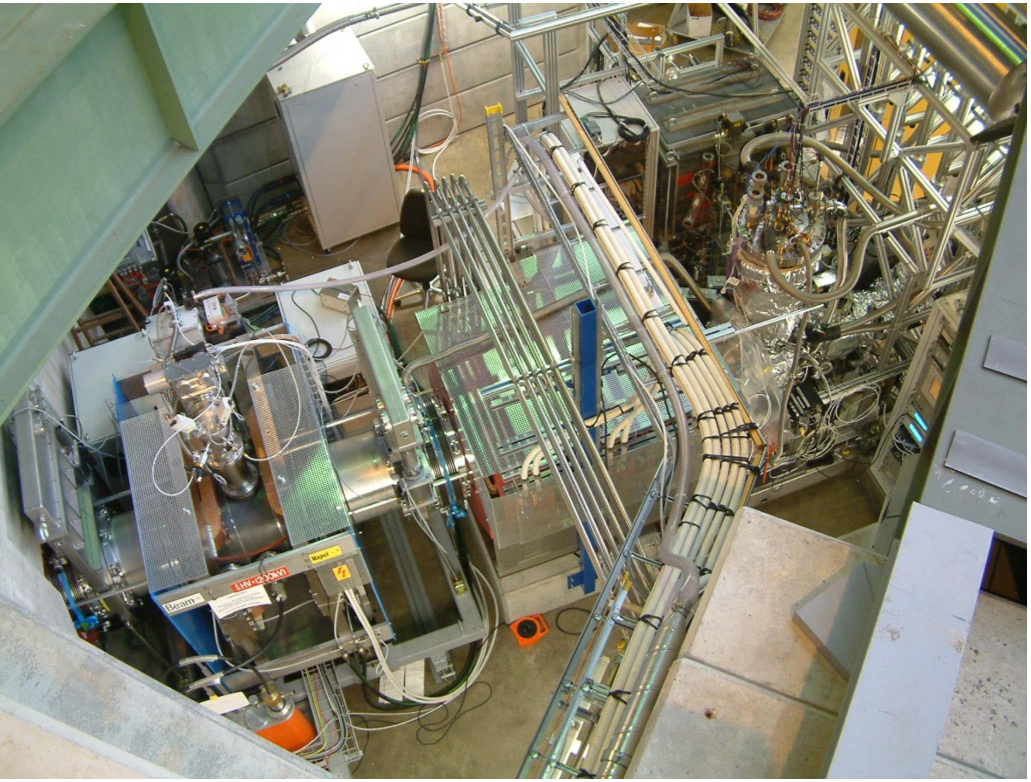


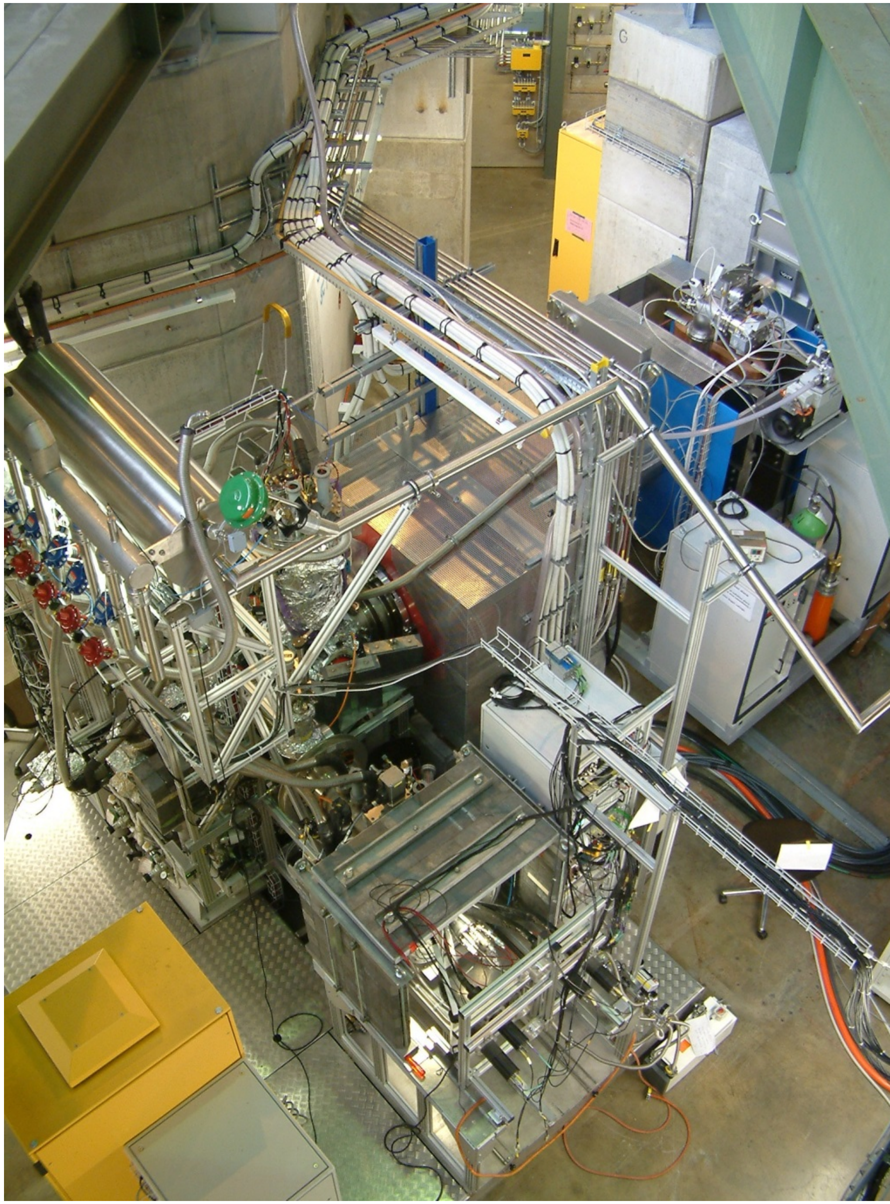
$p_c(T^*=0)$ ≈ -0.7 GPa

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

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

LE-μ^+ Apparatus @ μE4





~6 •10^8 μ^+/s total

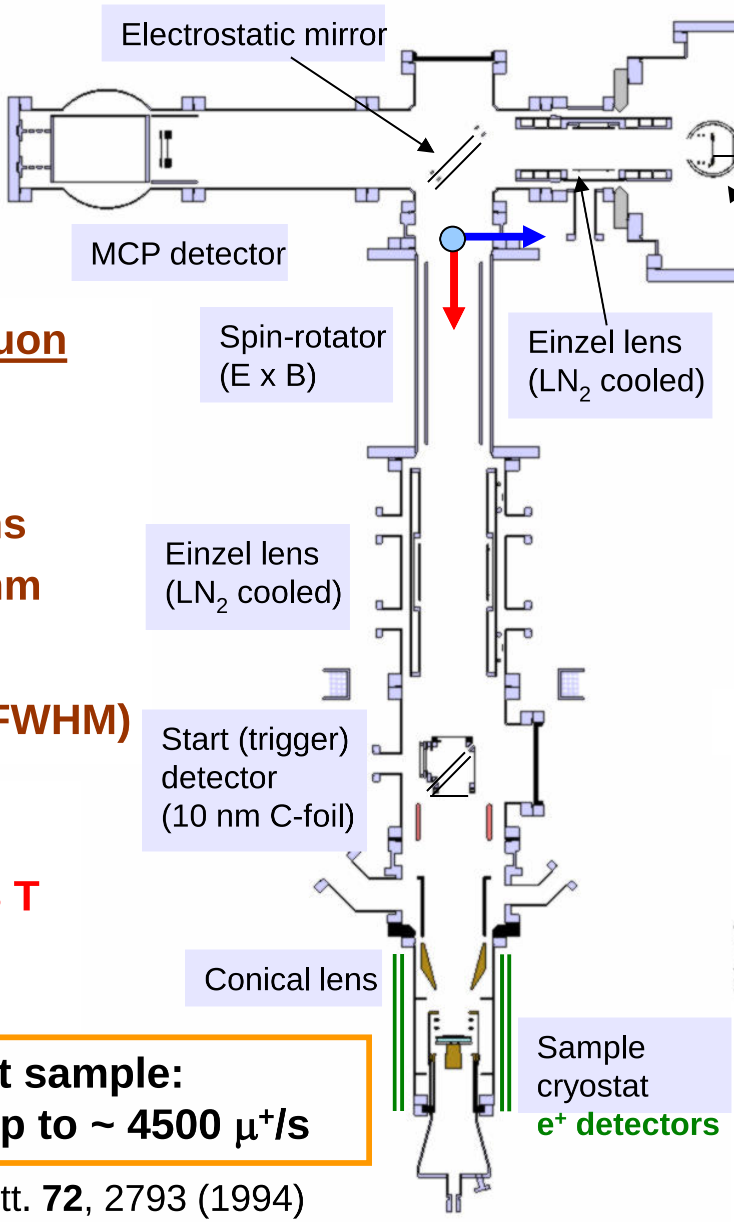
~1.9 •10^8 μ^+/s on LEM source

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)

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

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



Electrostatic mirror

"surface" μ^+ beam, ~ 4 MeV

Spin

~1.9 • 10^8 μ^+/s

MCP detector

Spin-rotator (E x B)

Einzel lens (LN_2 cooled)

moderator

~ 11000 μ^+/s @ ~ 15 eV; accelerate up to 20 keV

Einzel lens (LN_2 cooled)

Start (trigger) detector (10 nm C-foil)

Conical lens

Sample cryostat

e^+ detectors

at sample: up to ~ 4500 μ^+/s

Polarized Low Energy Muon Beam

Energy: 0.5-30 keV

ΔE, Δt: 400 eV, 5 ns

Depth: ~ 2 – 300 nm

Polarization: ~ 100 %

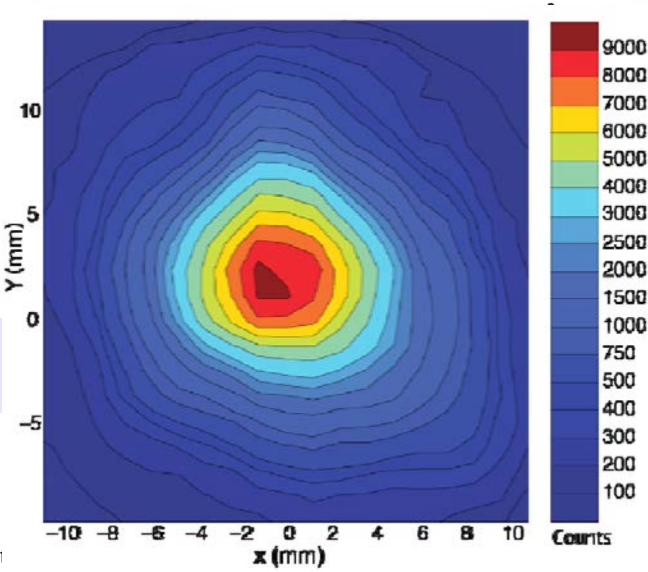
Beam Spot: ~ 12 mm (FWHM)

Sample environment:

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

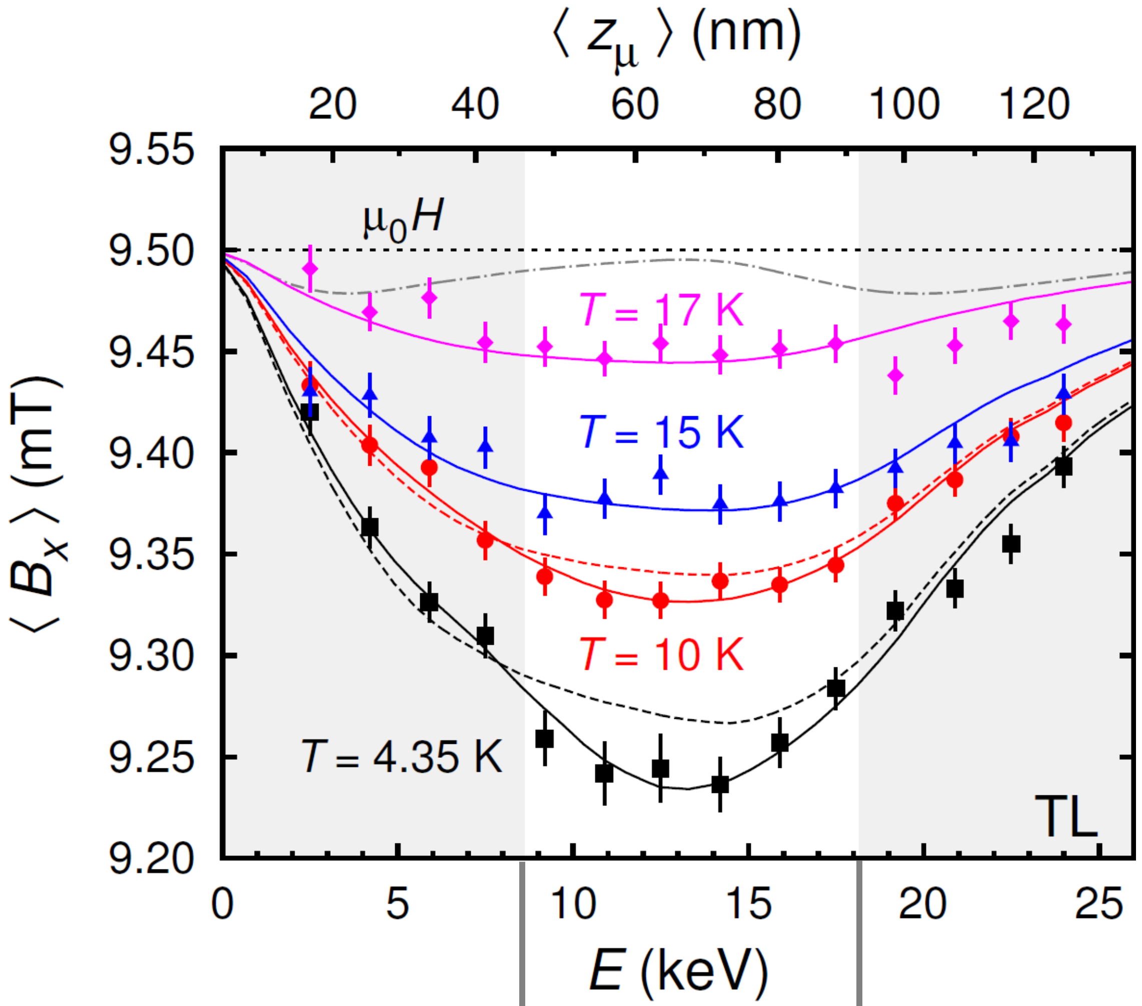
T = 2.5 – 320 K

Beam spot at sample



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

Heterostructure: $La_{1.84}Sr_{0.16}CuO_4$ / $La_{1.94}Sr_{0.06}CuO_4$ / $La_{1.84}Sr_{0.16}CuO_4$



$La_{1.84}Sr_{0.16}CuO_4$
46nm **$T_c \cong 32$ K**

$La_{1.94}Sr_{0.06}CuO_4$
46nm **$T_c' < 5$K**

$La_{1.84}Sr_{0.16}CuO_4$
46nm **$T_c \cong 32$ K**

Giant proximity effect:

Field exclusion in a “non-superconducting” thick layer embedded in two superconductors

$$d >> \xi_c \approx 0.3\ \text{nm},$$

$$d >> \xi_N = \sqrt{\frac{\hbar v_c \ell}{2\pi k_B (T - T_c')}} \ \leq\ 3\ \text{nm}$$

(for T $\geq$10K)

Magnetic field profiling on nm scale proximity, length scales, spin

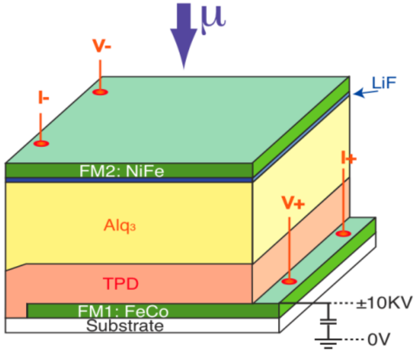
E.Morenzoni., B. Wojek, A. Suter, T. Prokscha, G. Logvenov, I. Božovic, Nat. Commun. 2:272 (2011).

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

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]

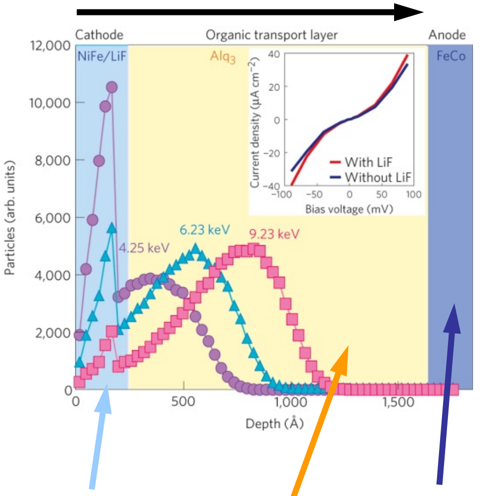
nature materials 8, 109 (2009)

Probing spins in heterostructures

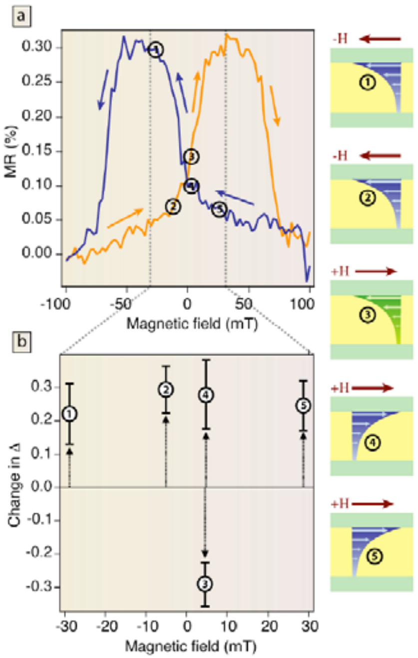


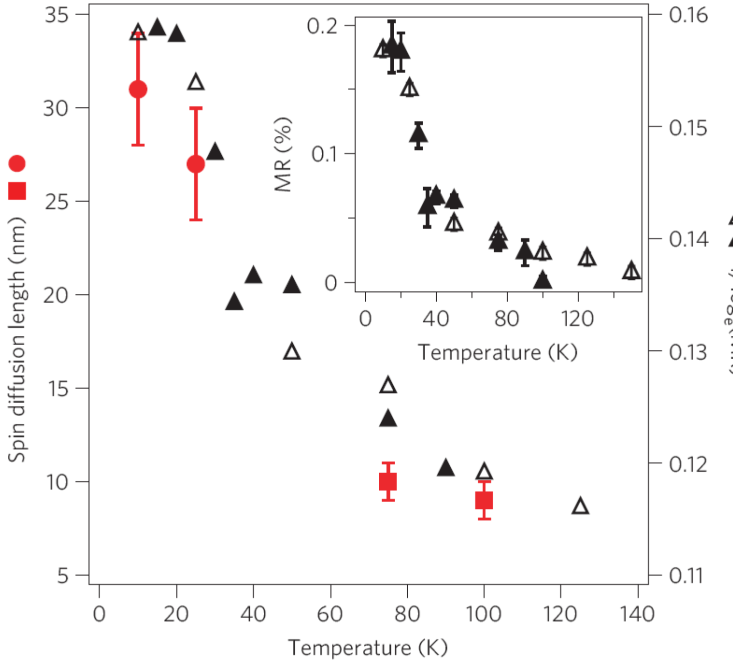
FM/sm/FM

current I



NiFe/LiF (1nm) **Alq3** **FeCo**





Spin Diffusion Length
<-> Magnetoresistance

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

PHYSICAL REVIEW X **5,** 041021 (2015)

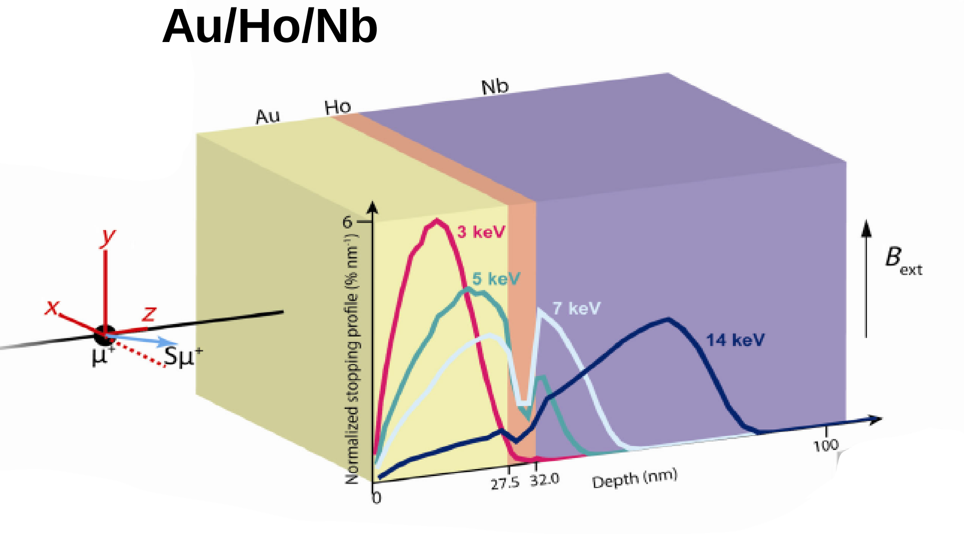
Intrinsic Paramagnetic Meissner Effect Due to *s*-Wave Odd-Frequency Superconductivity

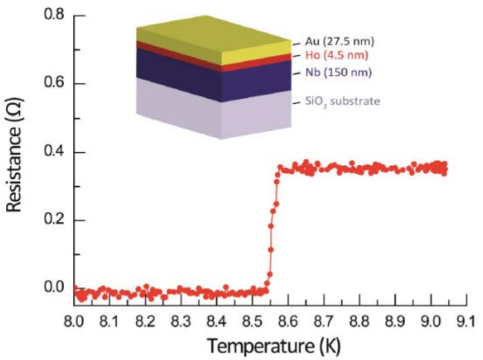
A. Di Bernardo,[1] Z. Salman,[2] X. L. Wang,[3] M. Amado,[1] M. Egilmez,[4] M. G. Flokstra,[5] A. Suter,[2] S. L. Lee,[5] J. H. Zhao,[3] T. Prokscha,[2] E. Morenzoni,[2] M. G. Blamire,[1] J. Linder,[6] and J. W. A. Robinson[1,*]

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

N/FM/SC

Au/Ho/Nb





Spin singlet: Meissner effect (diamagnetic)

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

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

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

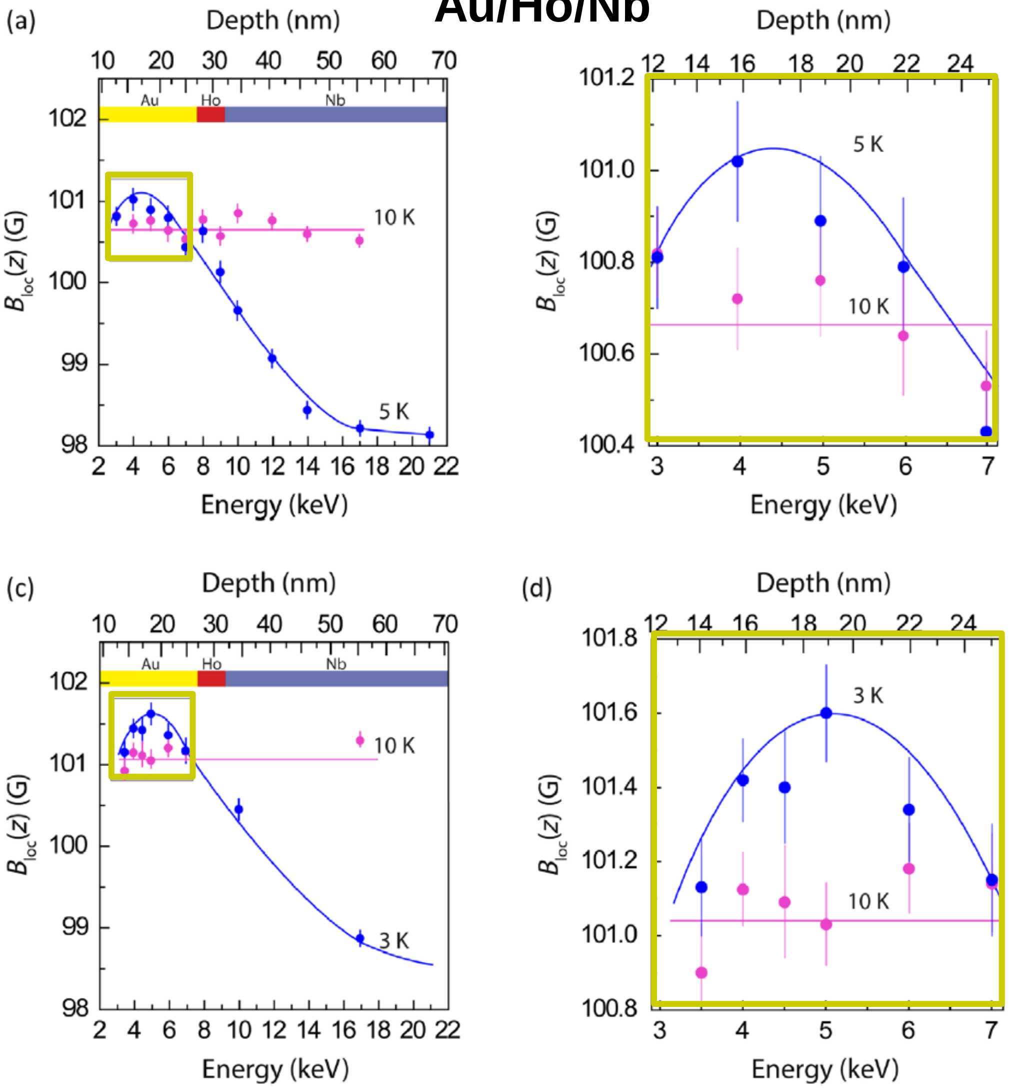
Singlet and triplet components have different decay lengths

S. Mironov, A. Mel’nikov, and A. Buzdin
Phys. Rev. Lett. ***109****, 23700 (2012)*

Magnetic field profiles

N/FM/SC

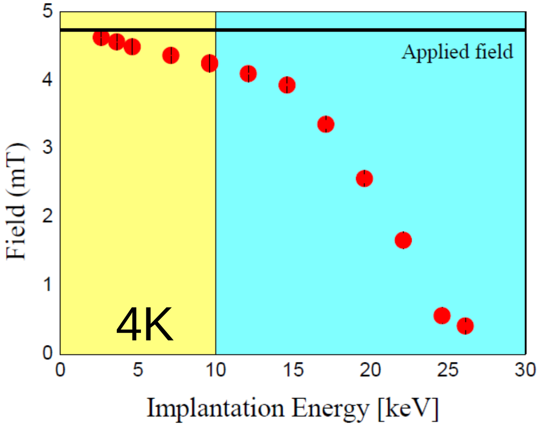
Au/Ho/Nb



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

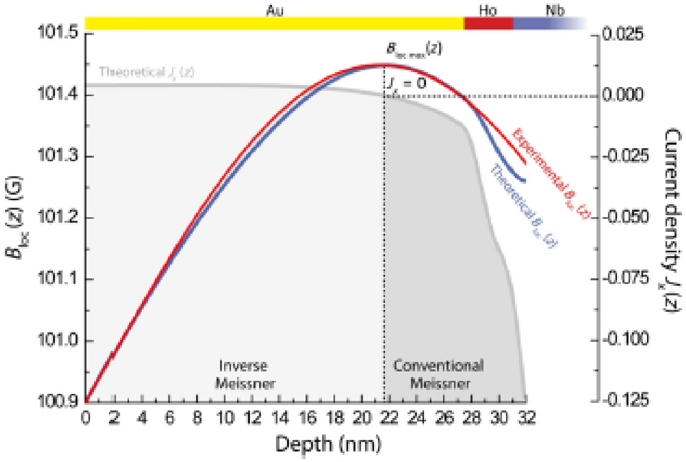
N/SC **Al/Nb**

Al(90nm)/Nb(270nm)

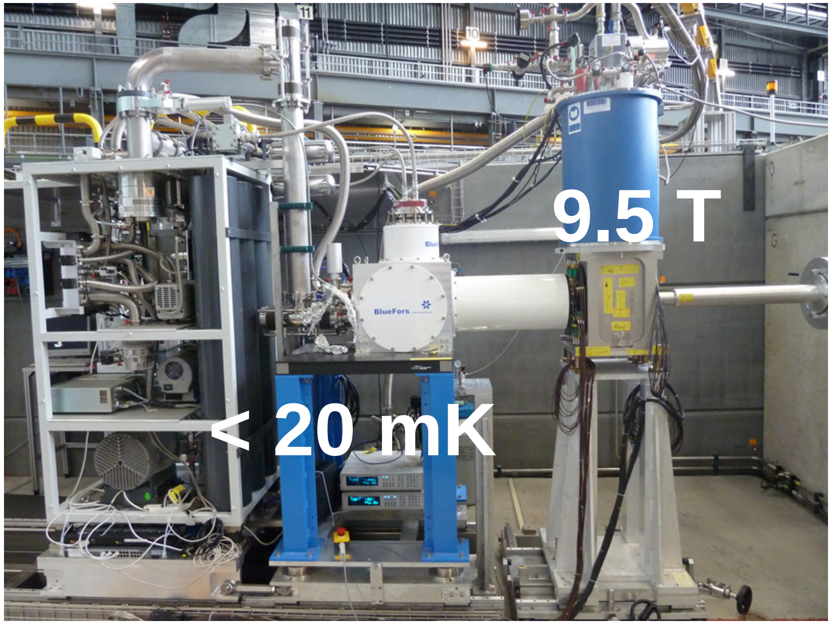


E. M et al., unpublished

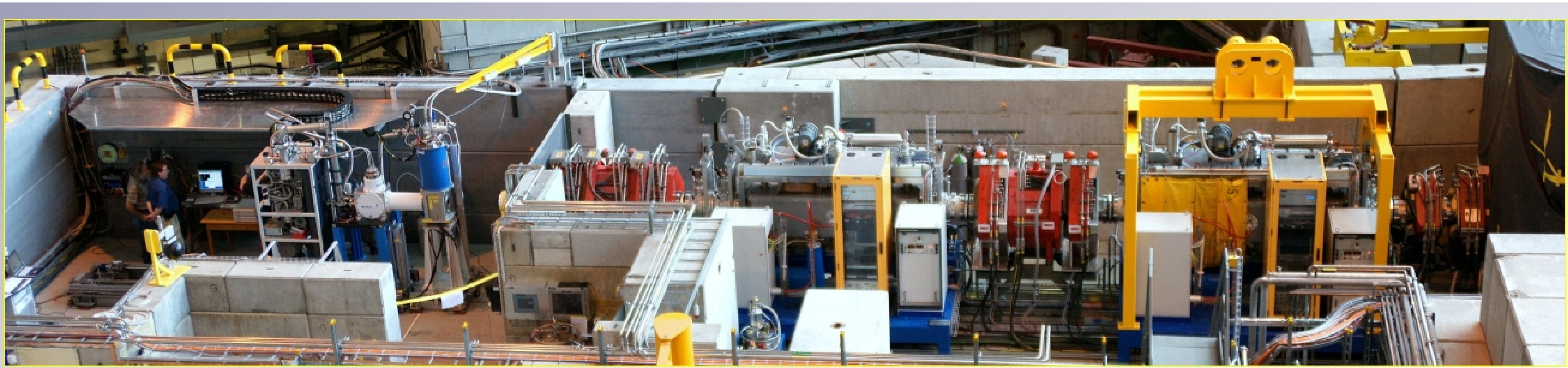
Calculated field profile



HAL-9500: High field And Low temperature μSR (9.5 T, < 20 mK)



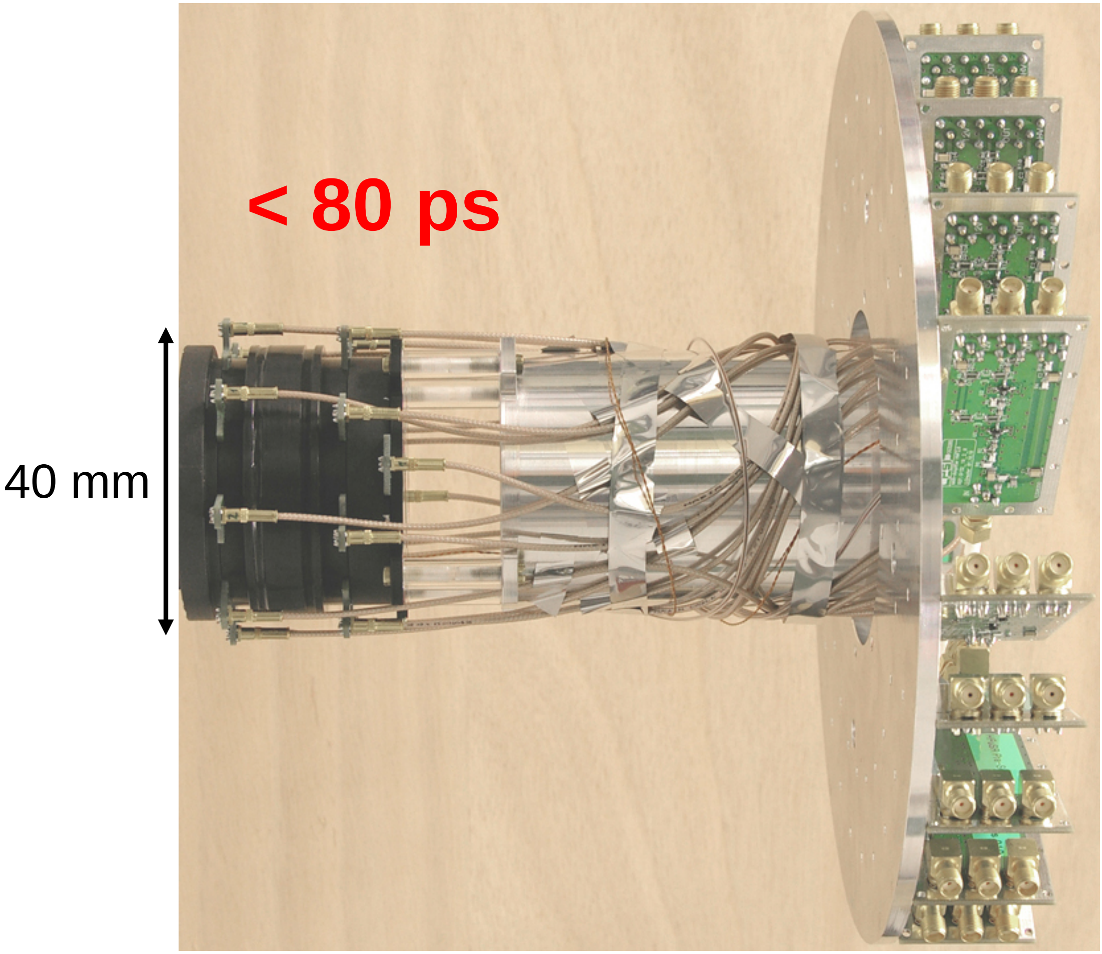
Optimized for TF measurements
LF also possible



Instrument

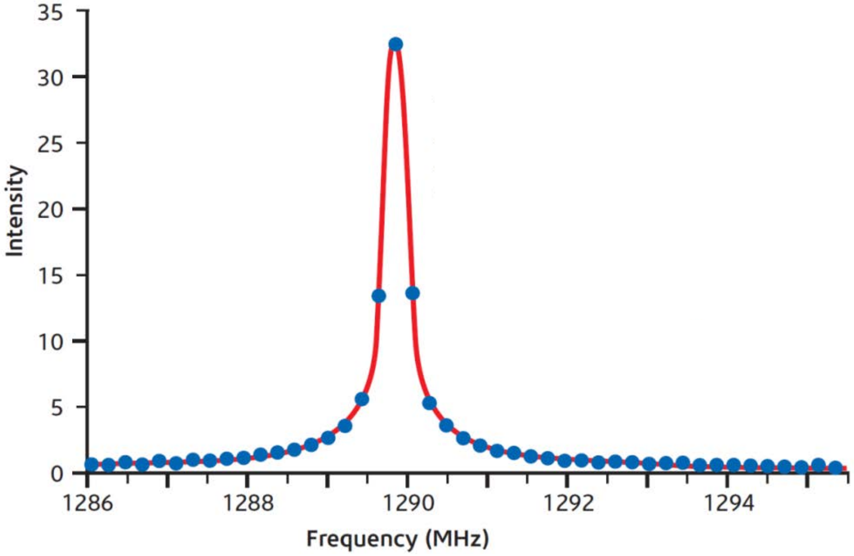
Beam line with 90º spin rotator

A very compact and ultra fast spectrometer



Detector system based on Avalanche Photo Detectors (APD)

A. Stoykov, R. Scheuermann et al.

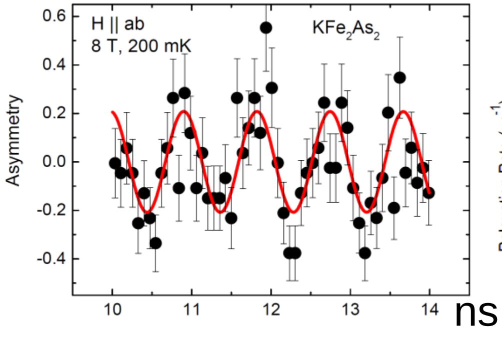


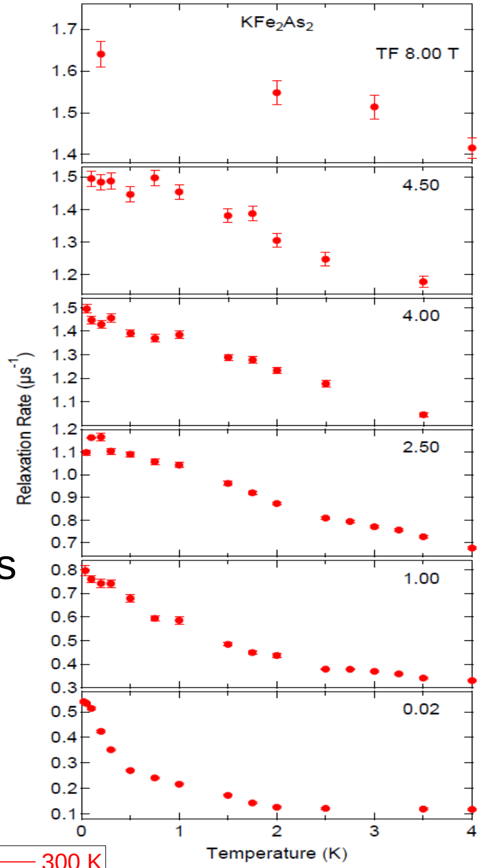
ν = (1287.9222 ± 0.0002) MHz

σ = (0.069 ± 0.002) μs^{-1}

Field homogeneity: Δ*B*=0.08 mT (8.4ppm)

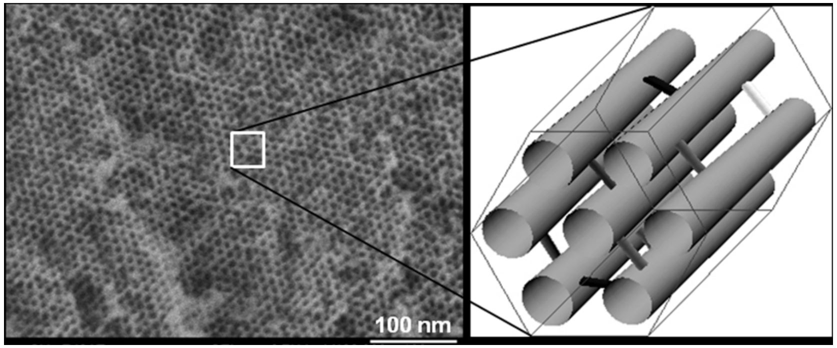
Vortex state in Pauli limited KFe_2As_2

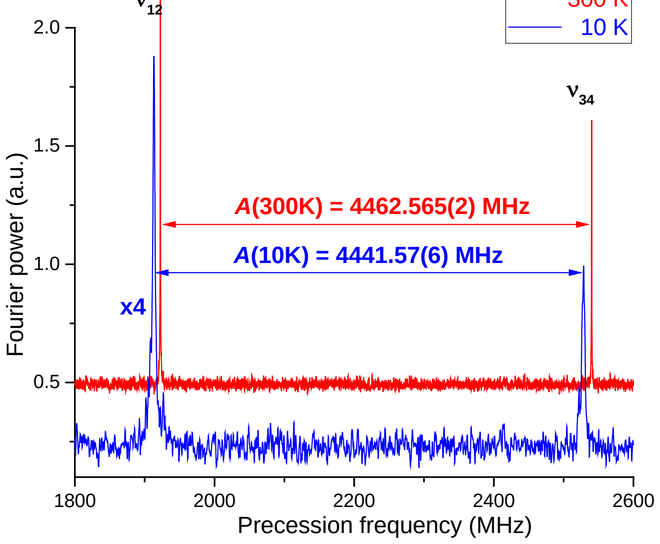




E.M.,T. Goko et al.

Muonium in mesoporous Silica





R. Kiefl, R. Scheuermann et al.

Summary and outlook

- **SμS @ PSI has 6 different instruments covering a wide range of T, B, p and depth**

- **Some examples of use of μSR in the study of magnetism, superconductivity, spin transport**

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

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

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

- **Future possibilities: Introducing lateral resolution: microbeams or spectrometers for μ-e vertex determination**

- **Synergy and complementarity with other probes and facilities: neutrons, photons…**

- **Synergy and complementarity with macroscopic techniques: transport, magnetization, thermodynamic measurements,…**

- **A new μSR facility in the US @ SNS has great potential to address a new user community and enlarge the existing one and is complementary to existing facilities**