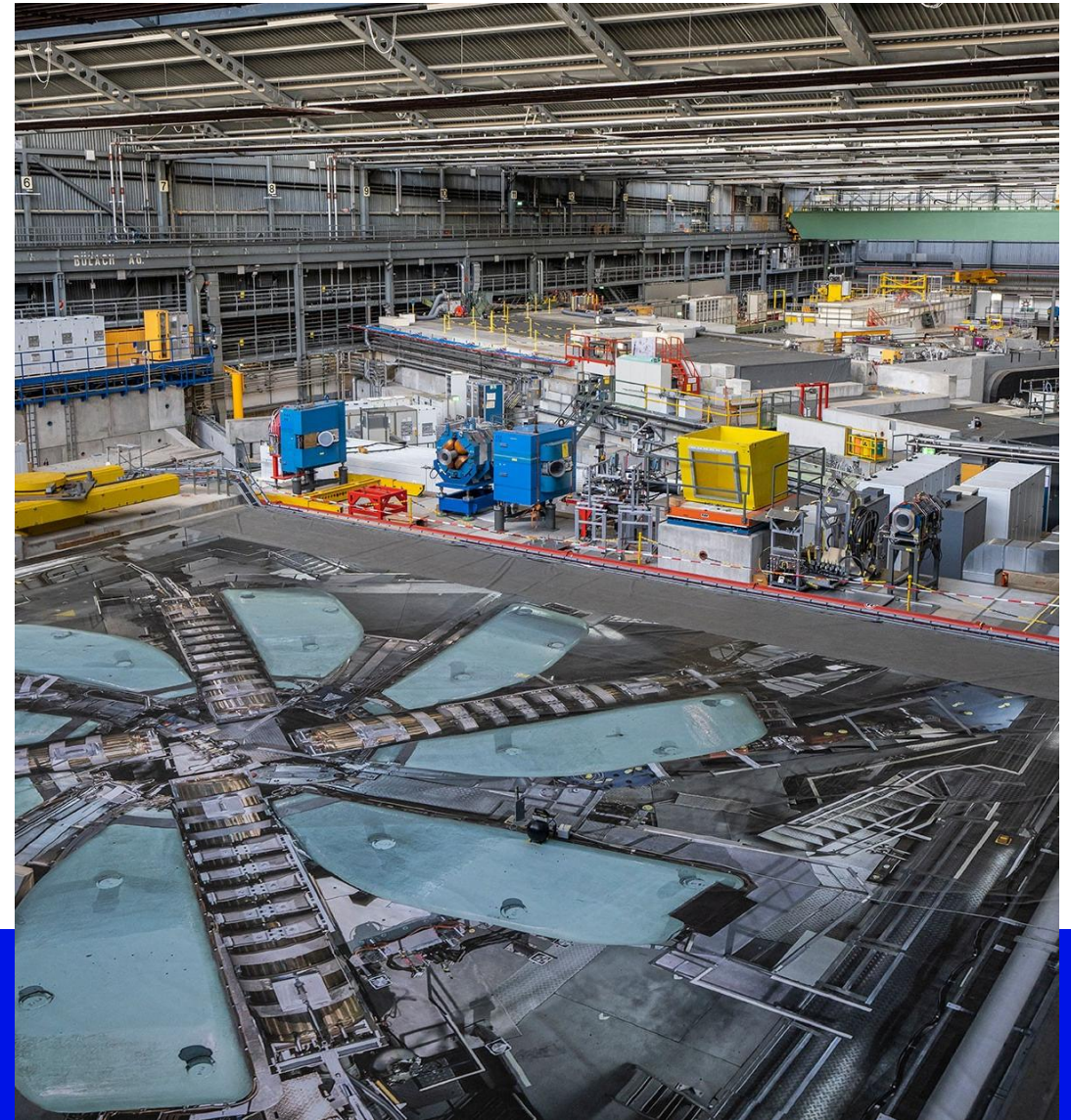


PSI Center for Neutron and
Muon Sciences

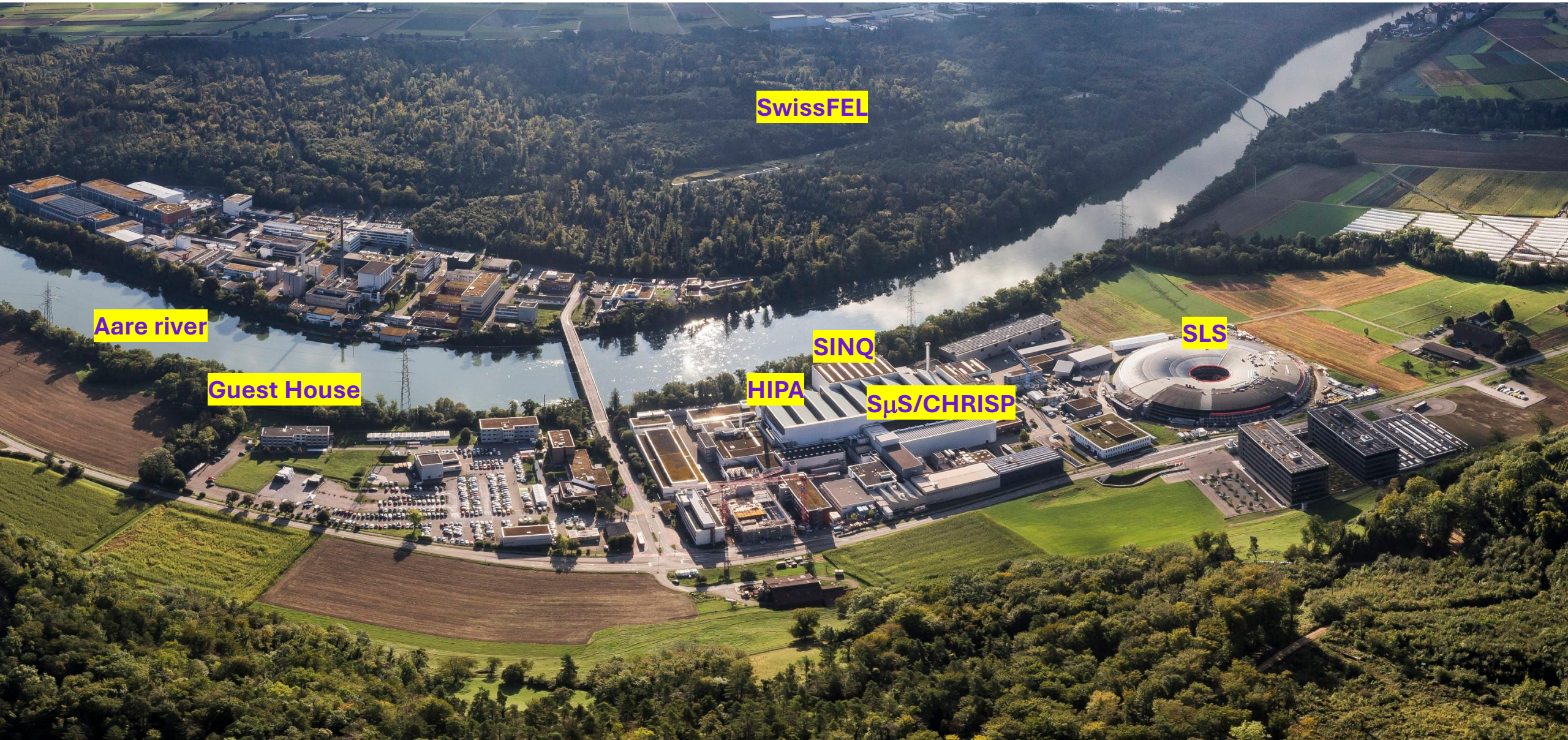
Muon Instruments and Science at the S μ S



Thomas Prokscha

New Science and Applications at the SNS Workshop, 11 June 2026

The Paul Scherrer Institute



SwissFEL

Aare river

Guest House

HIPA

SINQ

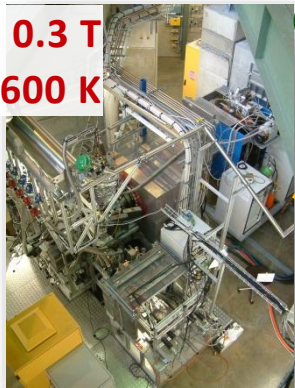
S μ S/CHRISP

SLS

Instruments at the S μ S (Swiss Muon Source)



LEM Thin films, devices
 Low Energy Muon Facility
 Muon Energy: 1-30 keV (μ^+)



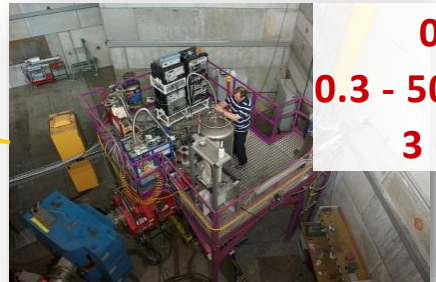
0.3 T
 2.5 - 600 K



DOLLY/VMS Uniaxial pressure, 1 GPa
 Muon Energy: 4 MeV (μ^+)
 π E1 beam line shared with LTP, in operation 50% of the year

0.8 T
 0.25 - 300 K
 1 GPa uniaxial

GPD Hydrostatic pressure, 3 GPa
 General Purpose Decay Channel Instrument (for Pressure Studies)
 Muon Energy: 5-60 MeV (μ^+ / μ^-)



0.6 T
 0.3 - 500 K
 3 GPa

HAL-9500 9.5 T, 10 mK
 High Field and Low Temperature
 Muon Energy: 4 MeV (μ^+)



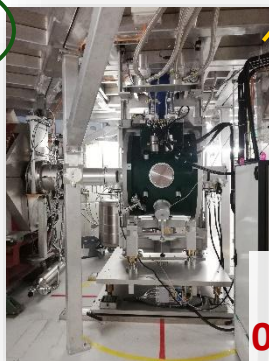
9.5 T
 0.01 - 300 K
 $\Delta t \sim 60$ ps

GPS Very fast MORE
 General Purpose Surface Muon Instrument
 Shared Surface Muon Beam
 Muon on Request (MORE)
 Muon Energy: 4 MeV (μ^+)



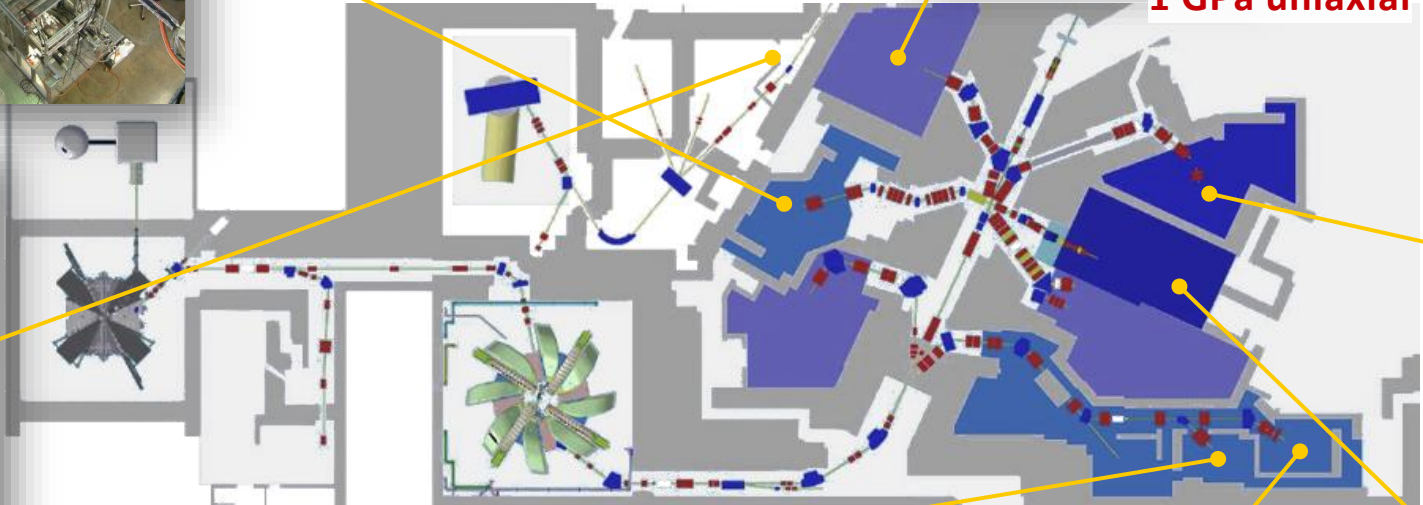
0.8 T
 1.6 - 1000 K

FLAME Veto at mK multi-sample MORE
 Flexible Advanced MuSR Environment



3.5 T
 0.02 - 310 K

GIANT
 MIXE, 1 - 15 MeV (μ^-)
 elemental analysis
 3 weeks per year



SμS User Facility Statistics



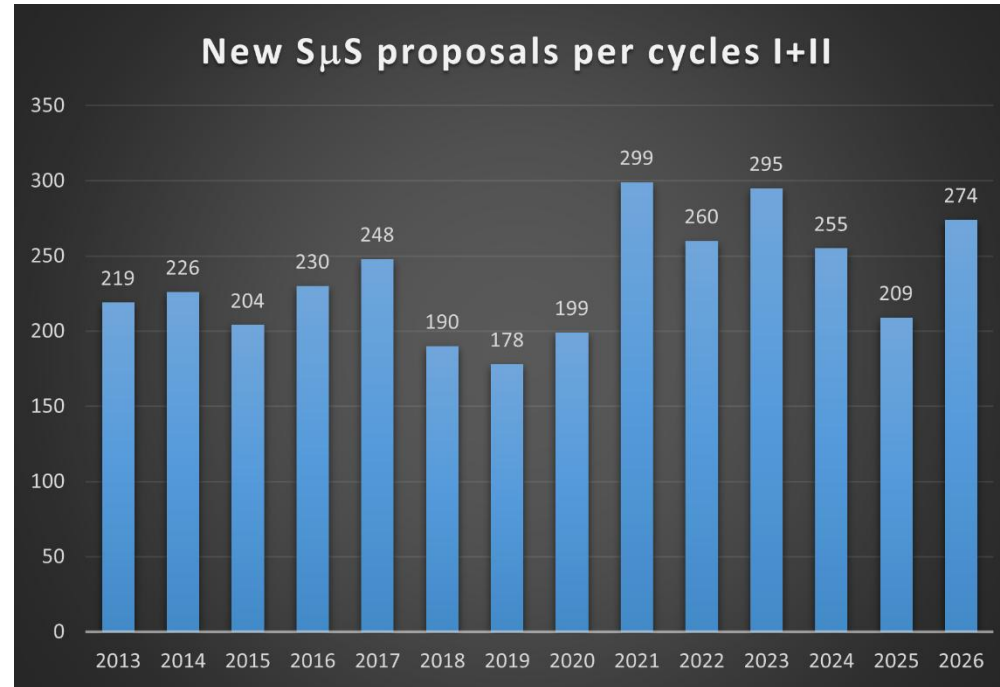
Number of instruments: 6 (7 in 2026)

New proposals: ~ 260 / y

Experimental days: ~ 750 / y

Overbooking : 1.7 – 4.5

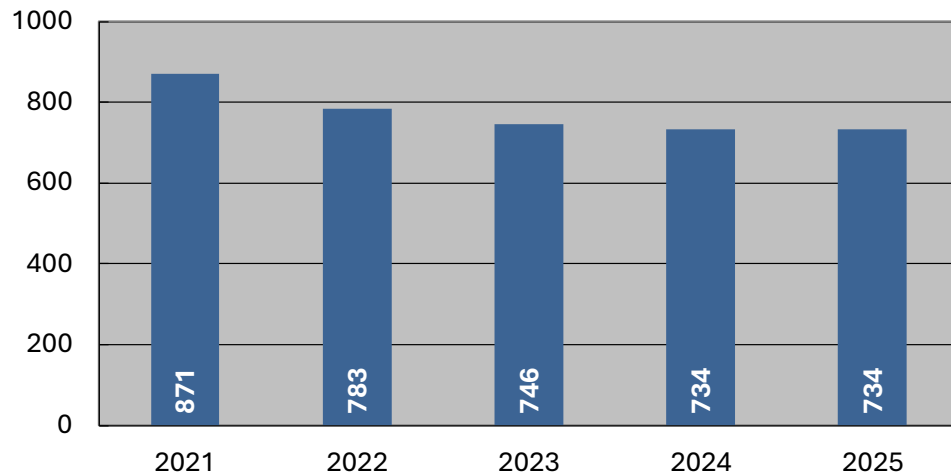
User visits: ~220 / y



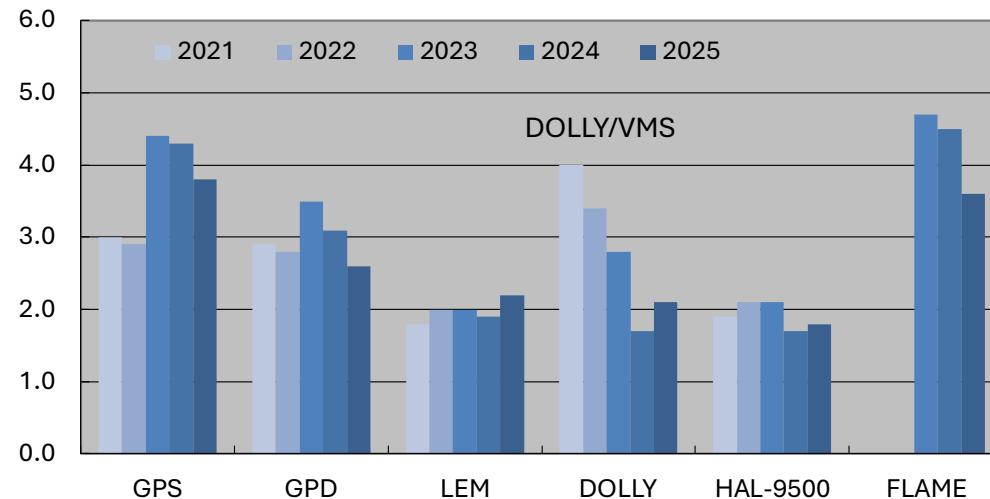
2013 – 2017: 2 cycles, 8 mth, 6 instr.
 2018 – 2020: 1 cycle, 6 mth, 5 instr.
 2021 – 2022: 2 cycles, 8 mth, 5 instr.
 2023 – 2025: 2 cycles, 7 mth, 6 instr.
 2026 – 2027: 2 cycles, 7 mth, 7 instr.
 2028 – 9/2029: long shutdown (**HIMB**)

HIMB: High-Intensity-Muon-Beams project, sub-project of the **IMPACT** project

experimental days SμS - 5y history



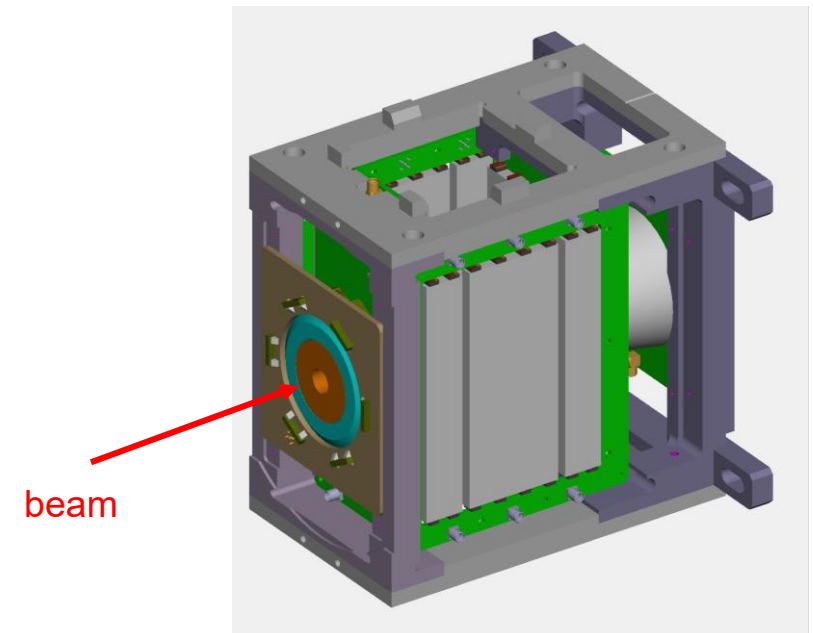
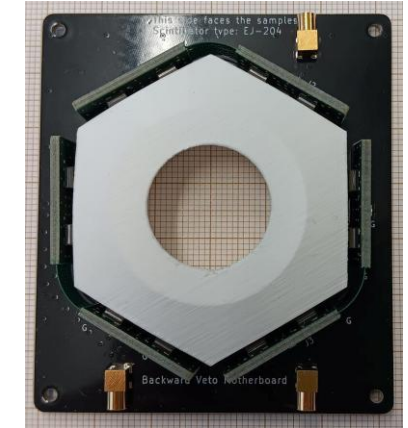
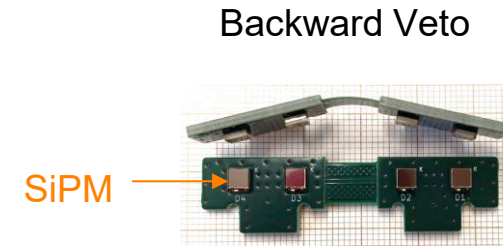
Overbookings SμS, 5y history



S μ S Upgrades and Projects

Upgrade of Dolly to SiPM Technology in 2025

- Detector geometry optimized by Geant4 simulations
- Plastic scintillators with **SiPM readout**
- Time resolution: **160 ps**
- Passive (Pb) and active scintillating collimators
- Active F / B vetos: **small samples / low background**
 - Minimal sample size: 2x2 mm² (better 4x4 mm²)
 - Minimal sample mass: >12 mg (better 50 mg)
- Temperature range: 250 mK – 300 K
 - Heliox ³He insert (T = 250 mK – 80 K)
 - Variox ⁴He cryostat (T = 1.5 – 300 K)
- Field range: 0 – 0.8 T
 - Main field up to 0.8 T
 - ZF, <20 mG with active zero field compensation
- Sample rotation
- In-situ piezoelectric uniaxial pressure device (1 GPa)
- Project: In-situ cold press 500 kg

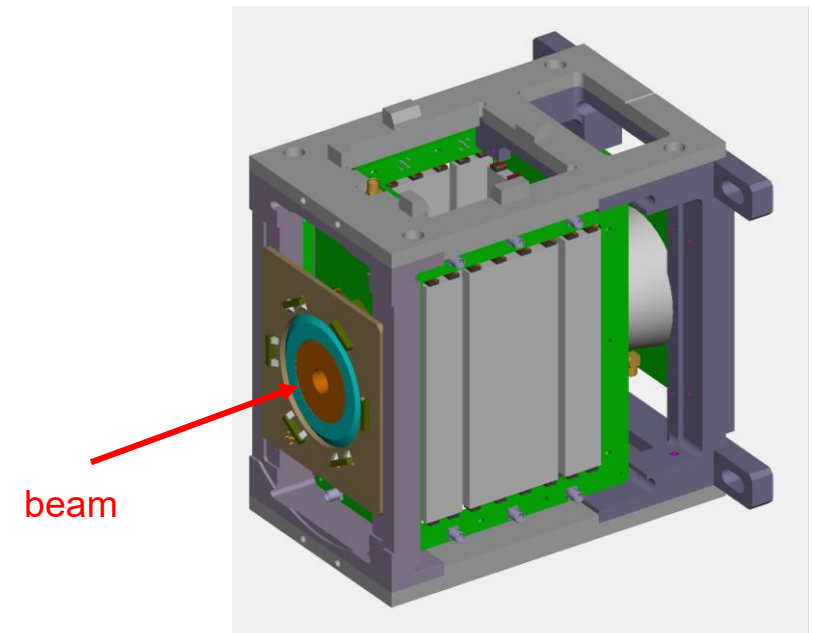
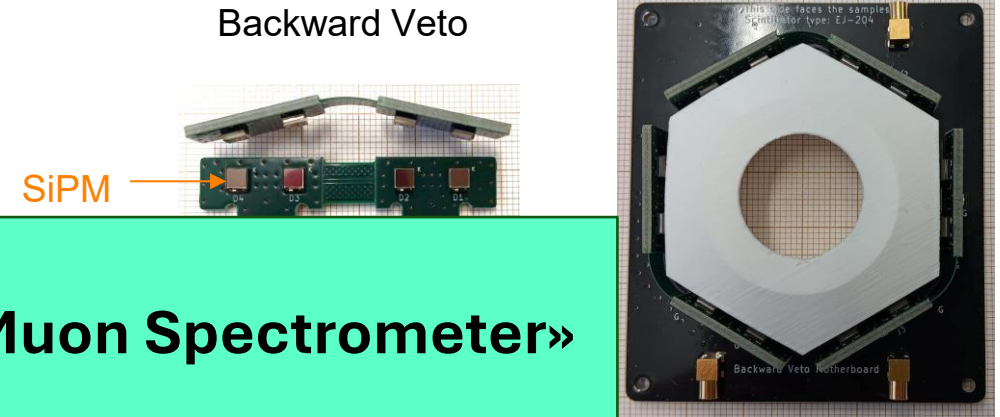


Upgrade of Dolly to SiPM Technology in 2025

- Detector geometry optimized by Geant4 simulations
- Plastic scintillators with **SiPM readout**
- Time resolution: **160 ps**

In 2025 Dolly became VMS: the «Versatile Muon Spectrometer»

- Minimum sample mass: > 12 mg (better 50 mg)
- Temperature range: 250 mK – 300 K
 - Heliox ^3He insert ($T = 250$ mK – 80 K)
 - Variox ^4He cryostat ($T = 1.5$ – 300 K)
- Field range: 0 – 0.8 T
 - Main field up to 0.8 T
 - ZF, < 20 mG with active zero field compensation
- Sample rotation
- In-situ piezoelectric uniaxial pressure device (1 GPa)
- Project: In-situ cold press 500 kg



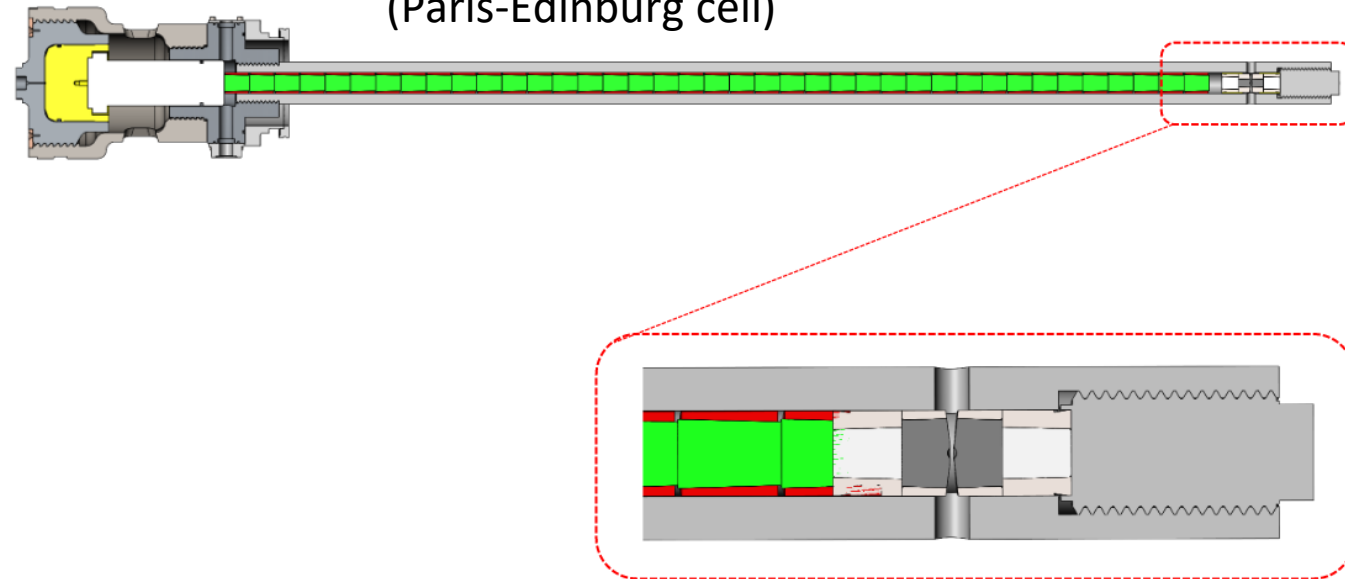
Pressure Development Project (SNSF R'EQUIP ExtremeP) with SINQ and S μ S



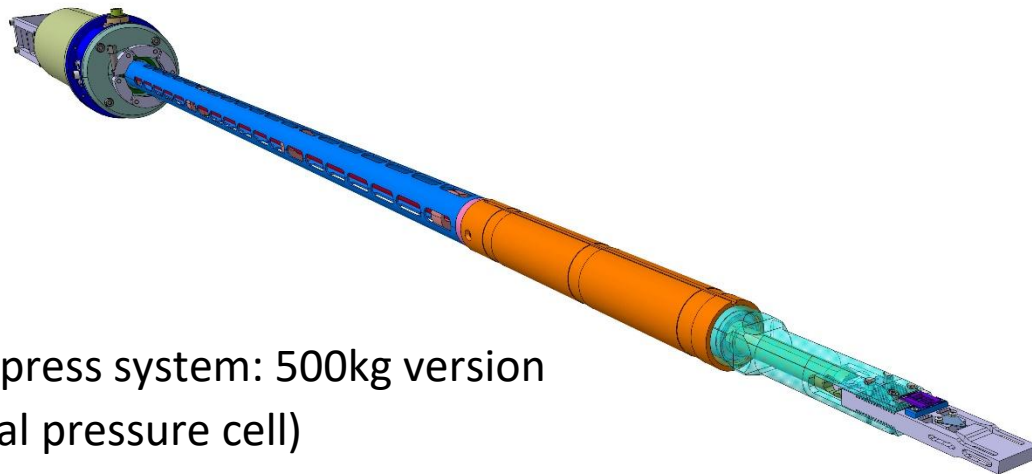
In-situ press system: 20t version
(piston cylinder cell)



In-situ press system: 80t version
(Paris-Edinburg cell)

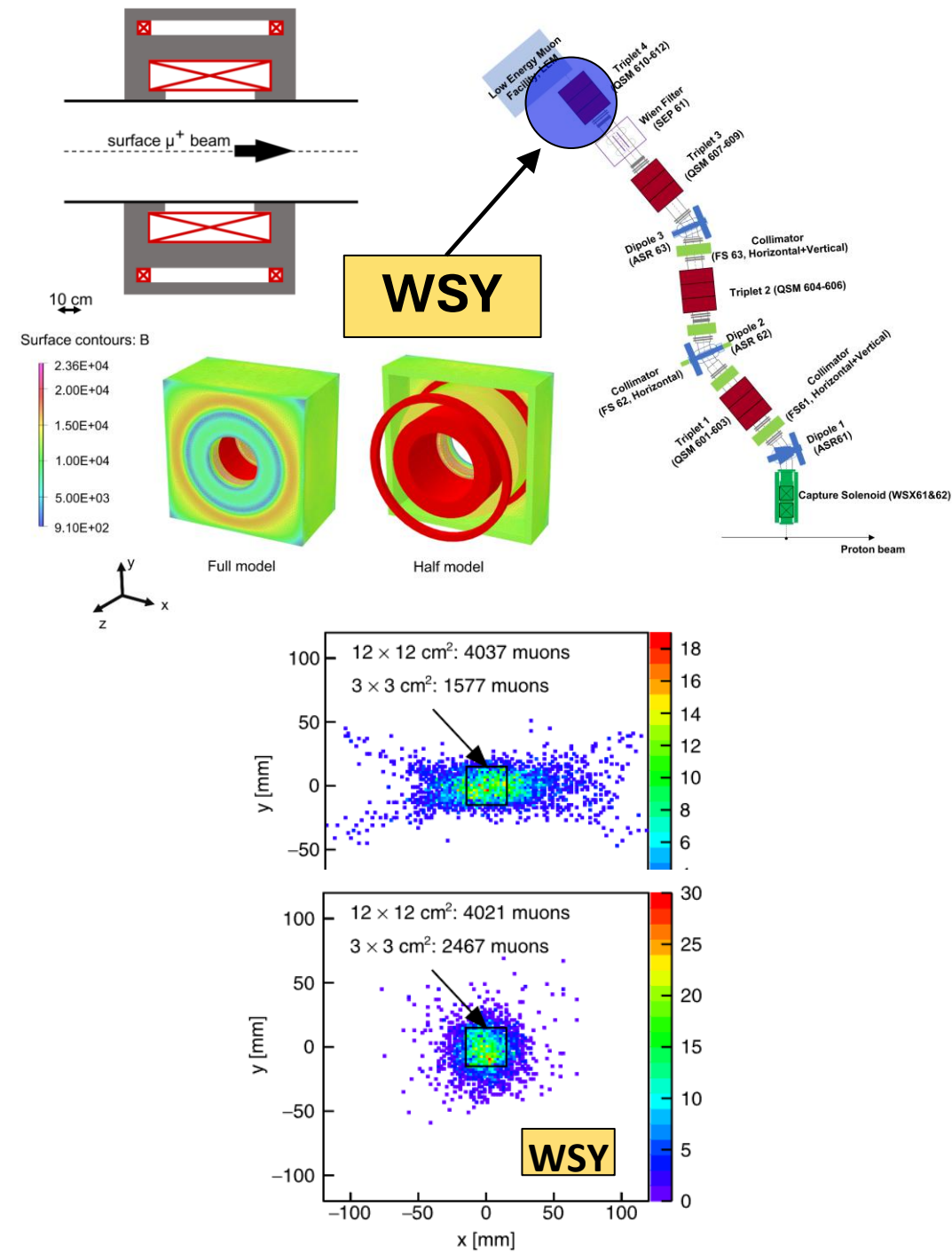


In-situ press system: 500kg version
(uniaxial pressure cell)



LEM μ E4 Upgrade in 2026

- **Increase LEM rate by 40-50%** by better beam focusing with solenoid WSY on LEM moderator target
- Smaller samples, higher external stimuli, $T_{\min} = 100$ mK, faster measurements
- L.-P. Zhou et al., Physical Review AB 25, 051601 (2022), **minimum fringe fields in LEM**
- Total costs: 300 kCHF
- **In operation in μ E4 beam since May 2026:** rate increase confirmed, up to 3'700 LEM events/sec at 2.2 mA proton current (corresponding to 1.3 MW beam power)



Low-energy μ^+ facility at the μ E4 surface μ^+ beamline

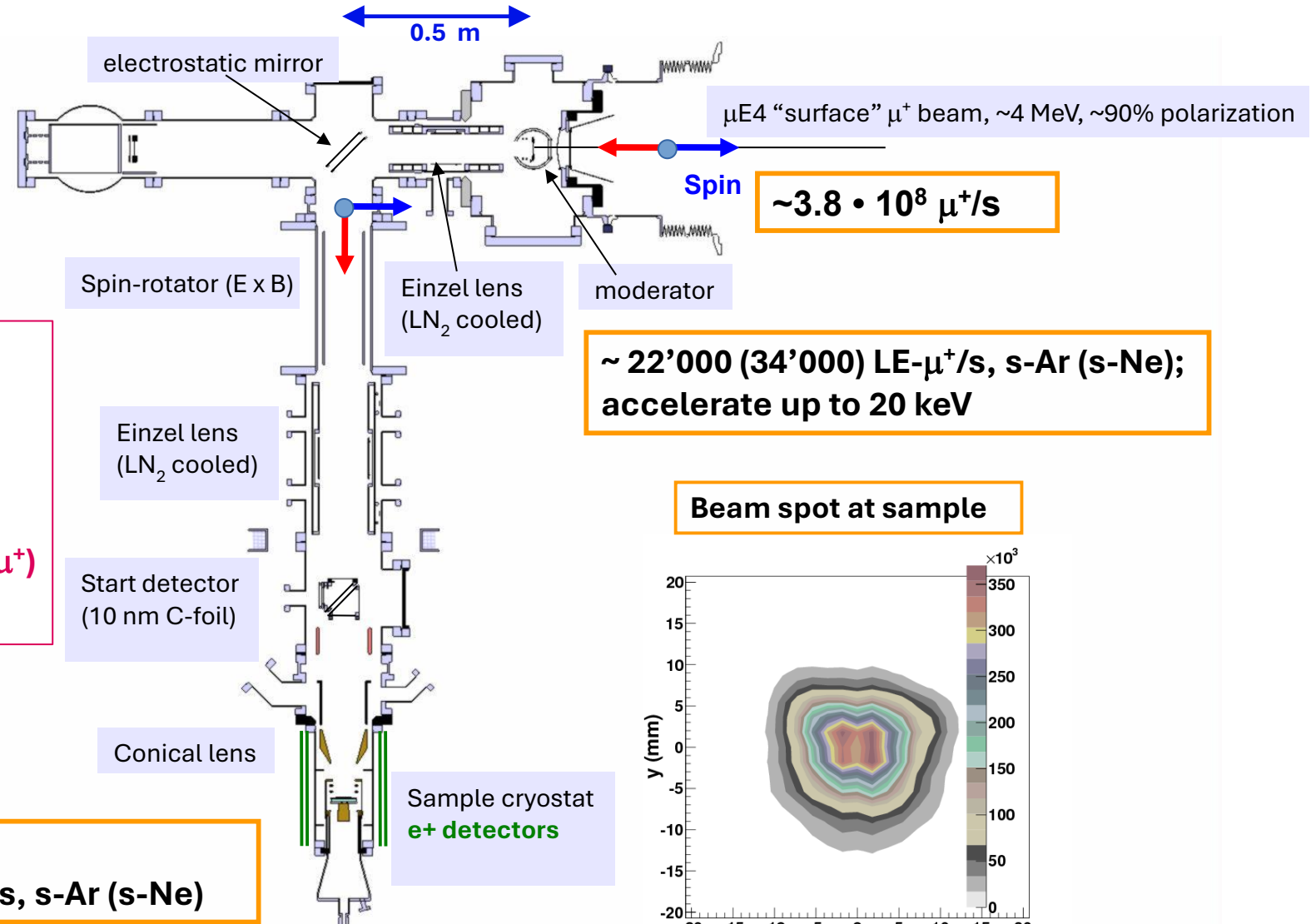
Rates at 2.2 mA proton beam current (2026), with WSY solenoid

- UHV system, 10^{-10} mbar
- some parts LN₂ cooled

Polarized low-energy μ^+ Beam

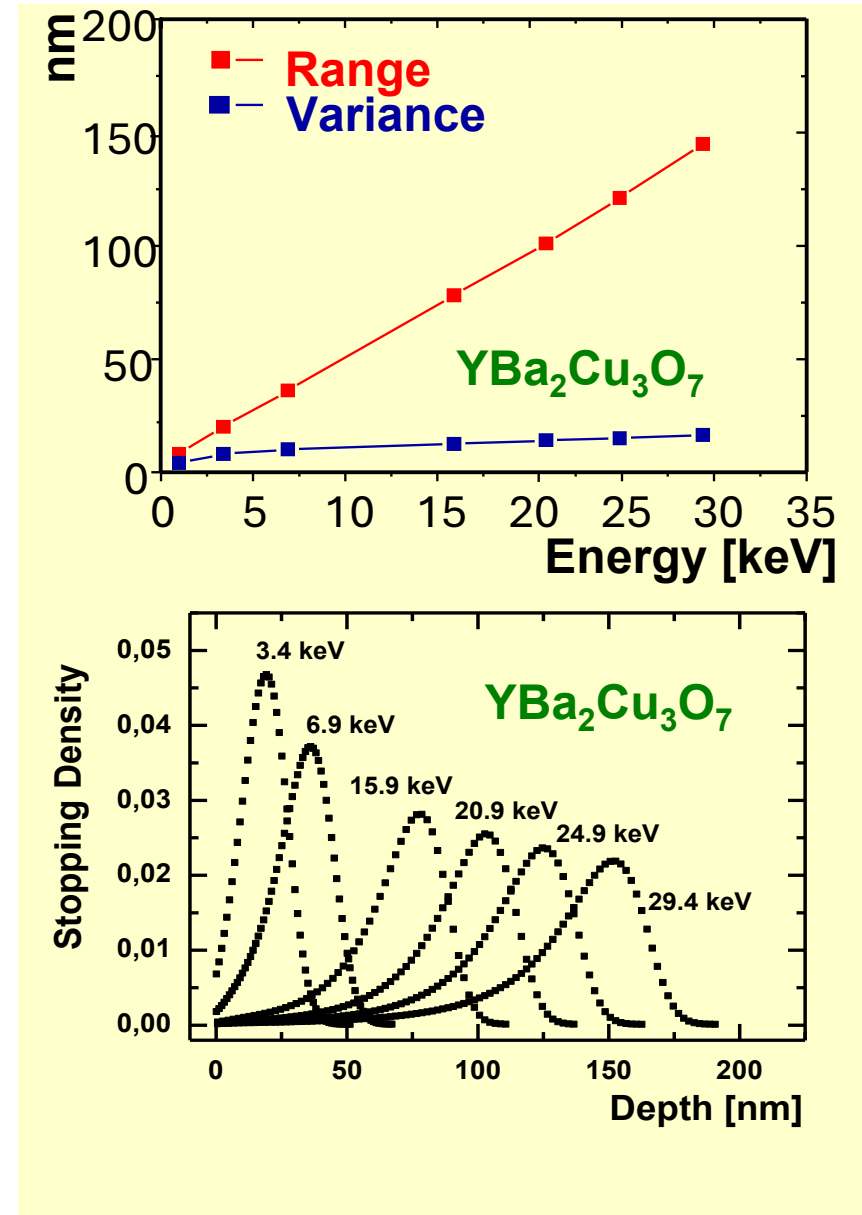
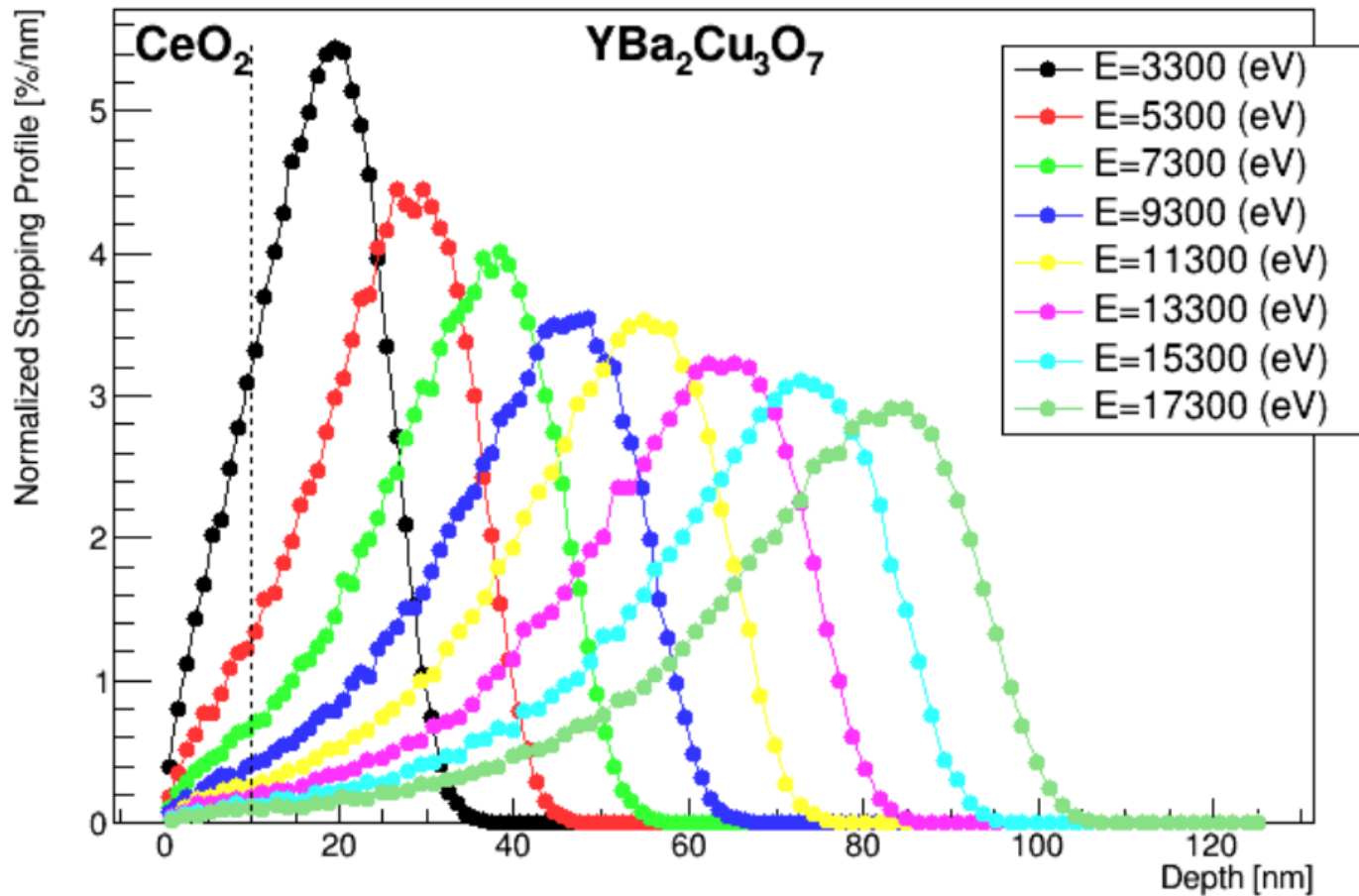
- Energy: 1 - 30 keV
- $\Delta E, \Delta t$: 400 eV, 5 ns
- Mean Depth: 5 - 200 nm
- Polarization: ~90 % (surface μ^+)
- Beam Spot: 12 mm (FWHM)

at sample:
up to ~ 9'000 (14'000) μ^+ /s, s-Ar (s-Ne)



Low-energy μ^+ stopping profiles

Calculated by the Monte Carlo code TRIM.SP

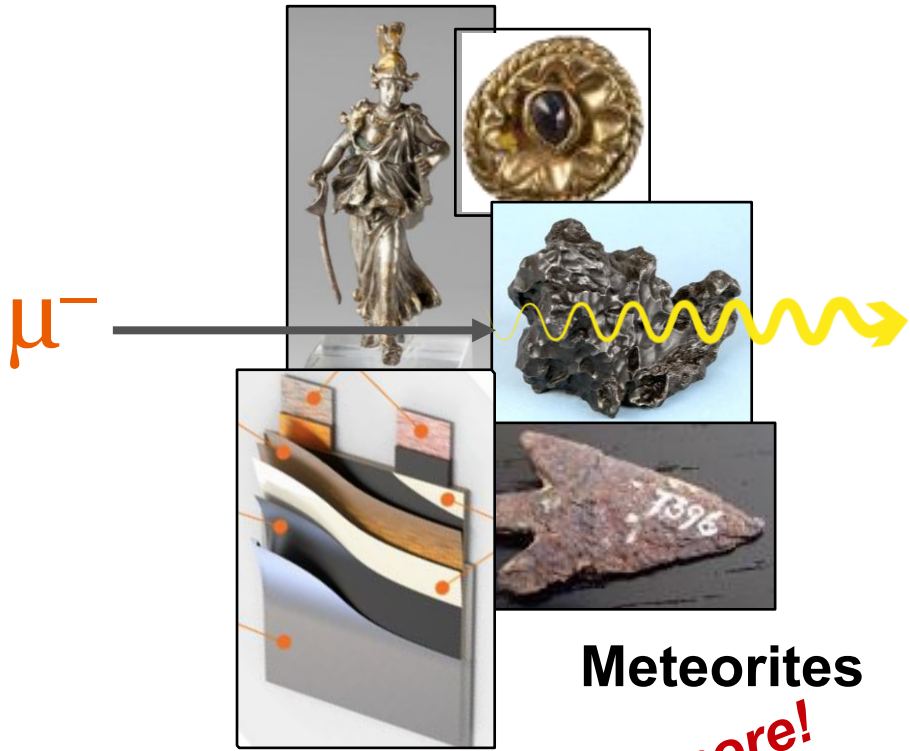


TRIM.SP: W. Eckstein "Computer Simulation of Ion-Solid Interactions", Springer (1991)

MIXE (Muon Induced X-ray Emission) with instrument GIANT



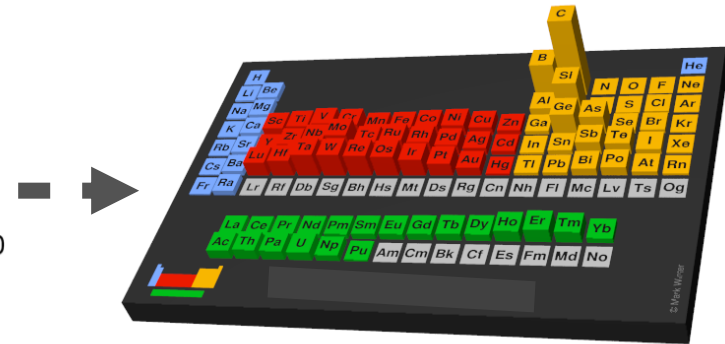
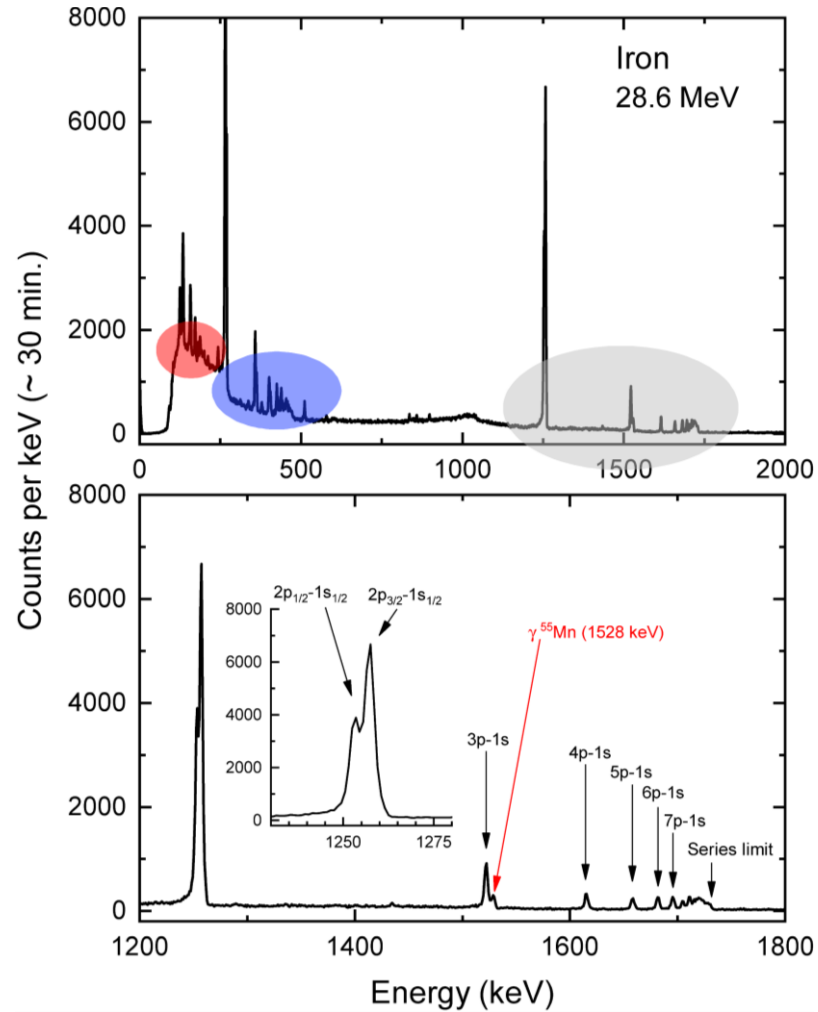
Archeological artifacts



Meteorites

Batteries

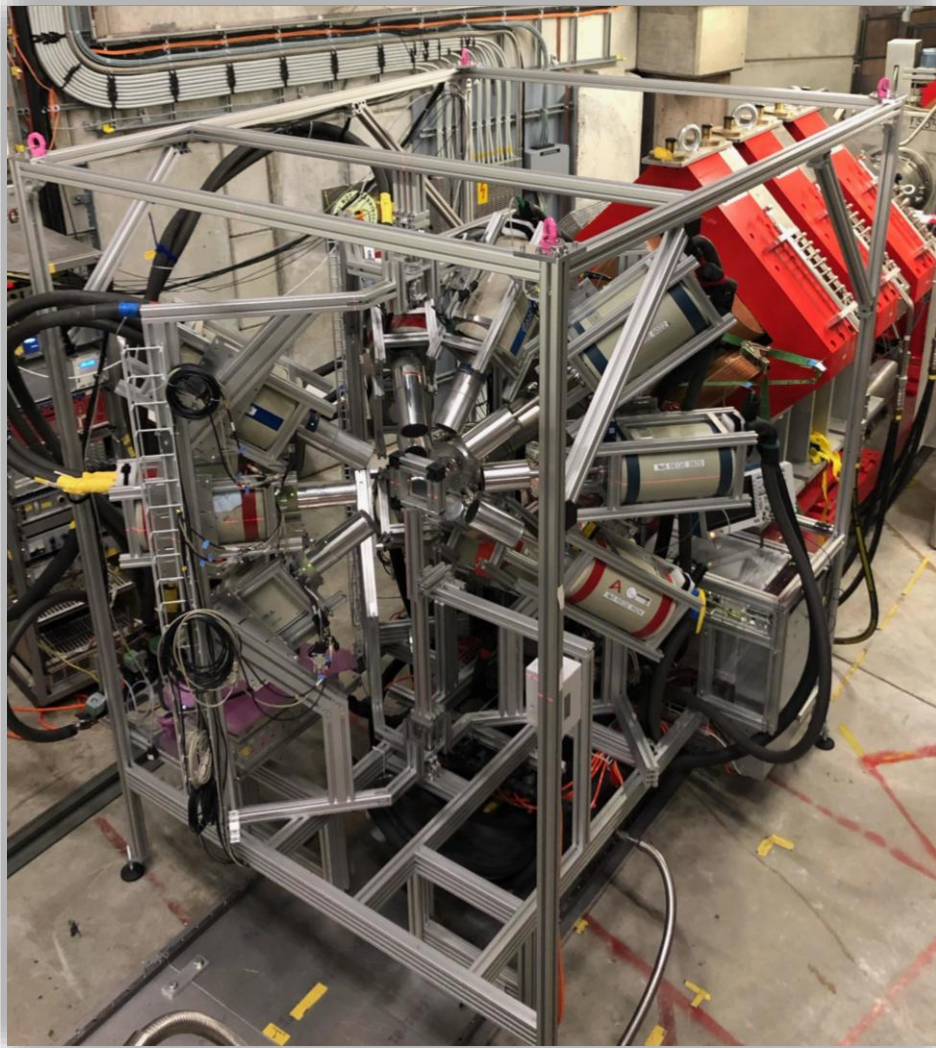
and many more!



- [1] S. Biswas et al., *Characterization of a Continuous Muon Source for the Non-Destructive and Depth-Selective Elemental Composition Analysis by Muon Induced X- and Gamma-rays*, Applied Sciences 12(5), 2022.
- [2] S. Biswas et al., *The non-destructive investigation of a late antique knob bow fibula (Bügelknopffibel) from Kaiseraugst/CH using Muon Induced X-ray Emission (MIXE)*, Herit. Sci. 11(1):43, Mar 2023.
- [3] L. Gerchow et al., *Germanium Array for Nondestructive Testing (GIANT) setup for Muon Induced X-ray Emission (MIXE) at the Paul Scherrer Institute*, Rev. Sci. Instrum. 94(4):045106, 04 2023.
- [4] B. A. Hofmann et al., *An arrowhead made of meteoritic iron from the late Bronze Age settlement of Mörigen, Switzerland and its possible source*, J. Archaeol. Sci. 157:105827, 2023.
- [5] E. Quérel et al., *Overcoming the probing-depth dilemma in spectroscopic analyses of batteries with muon-induced X-ray emission (MIXE)*, J. Mater. Chem. A 2025.

Courtesy of Michael Heiss

GIANT: Germanium Array for Non-destructive Testing – Overview

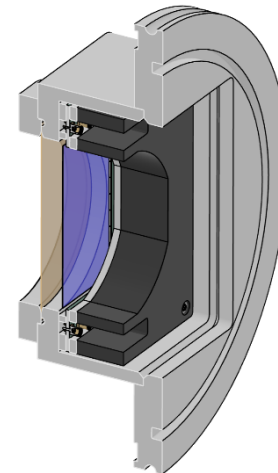


Large solid angle detector array

- currently **~12 HPGe detectors** (up to 30) pooled with PP exp. (muX, Ref.Radii, MONUMENT, ...)
- supports multiple **muon tracking** technologies
- self-contained (rack+frame) and relocatable (~6h setup)

Accessible **sample station in air** (~10cm gap to beam port)

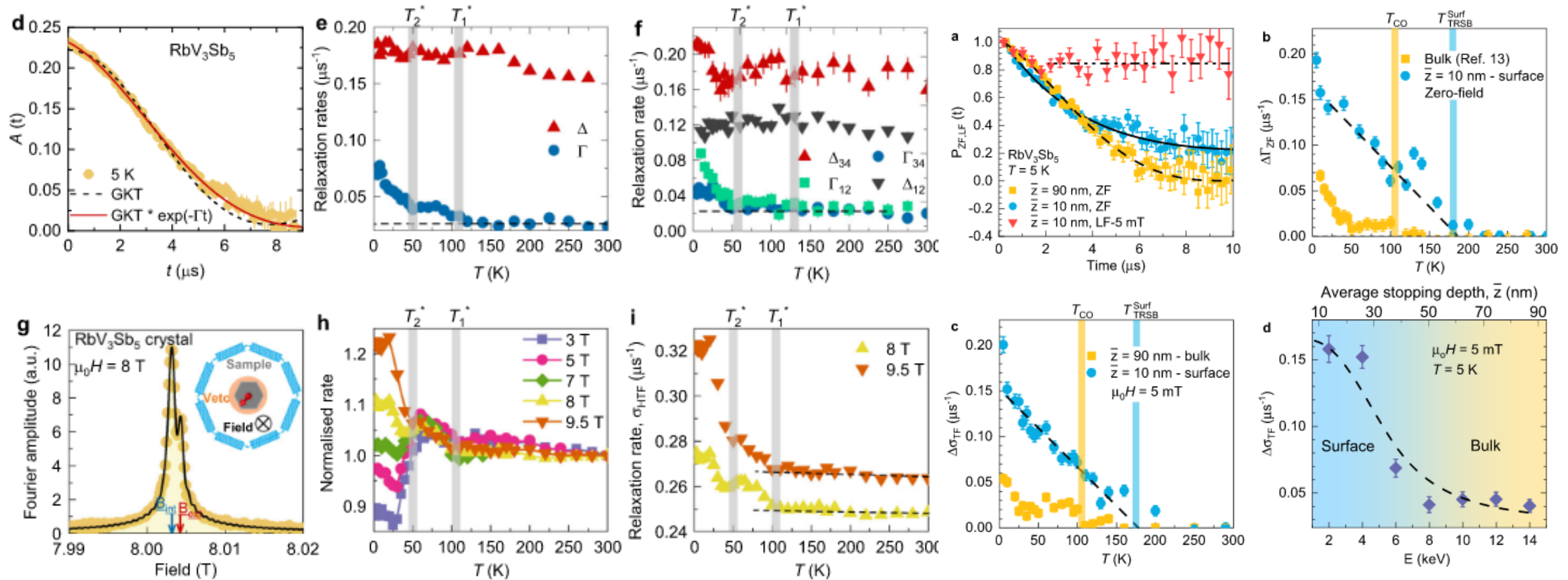
- **low material budget vacuum window** (50 μ m mylar)
- **large area (7x7cm²) muon counter** (adaptable thickness)
- **segmented** design – facilitates higher tracking rates



- Phase diagrams of novel quantum materials as a function of doping and hydrostatic/uniaxial pressure, “topological materials”, quantum phase transitions
- Unconventional superconductors – symmetry of SC gap, superfluid density, coexistence of phases, time-reversal-symmetry-breaking (TRSB)
- Magnetism (FM, AFM, altermagnetism, skyrmions, molecular magnets, 1D/2D)
- Frustrated magnetism and spin dynamics
- Quantum spin liquids
- Role of hydrogen in semiconductors
- Magnetism and superconductivity in thin-film heterostructures, proximity effects
- Semiconductor interfaces (advanced power semiconductors, solar cells), defects and charge carrier distributions
- Battery materials, archaeological artifacts, meteorites, industrial samples
- Muonium spectroscopy (1s-2s transition, Lamb shift), MuMASS collaboration (Paolo Crivelli et al., ETHZ-PSI)

Unique parameter space at S μ S to gain new insights

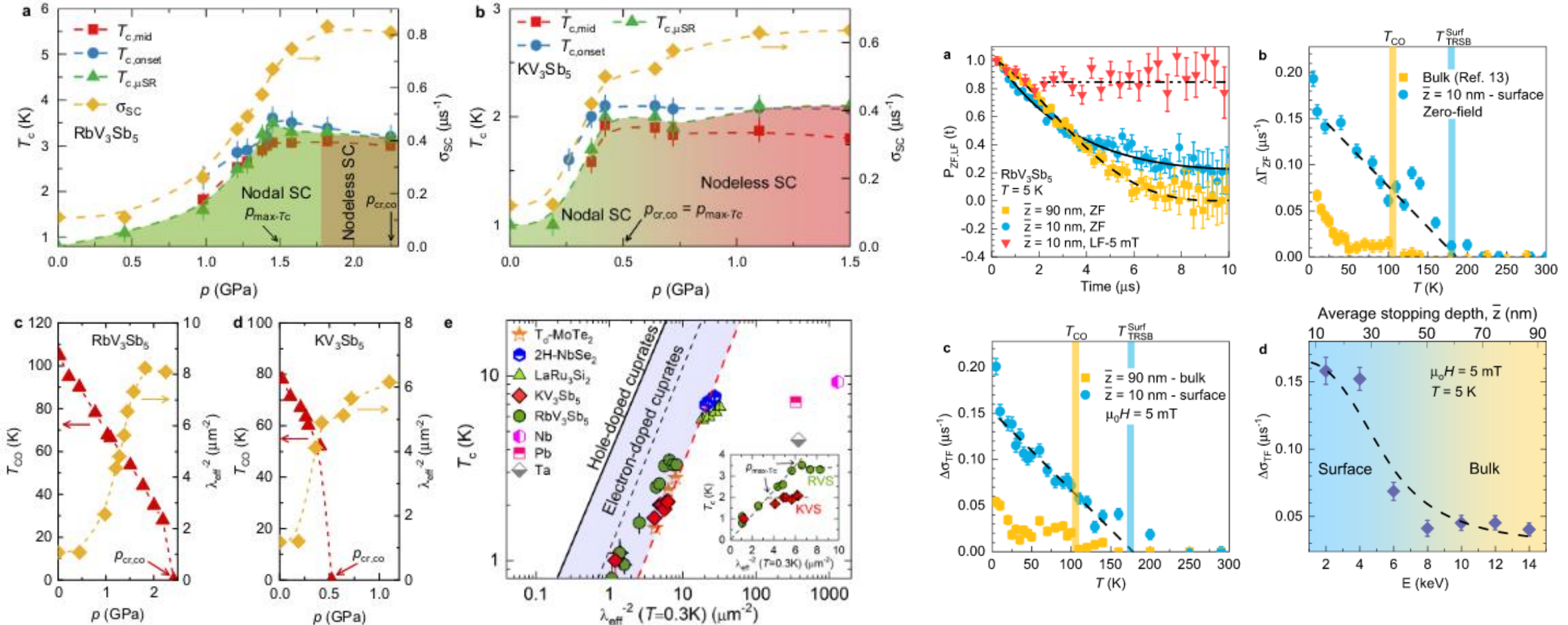
Time-Reversal-Symmetry-Breaking (TRSB) and charge order in kagome superconductors AV_3Sb_5 ($A=K, Rb, Cs$):
combination of standard, high-pressure, high-field, and low-energy μ SR (near-surface)



Unique parameter space at S μ S to gain new insights



Time-Reversal-Symmetry-Breaking (TRSB) and charge order in kagome superconductors AV_3Sb_5 ($A=K, Rb, Cs$):
combination of standard, high-pressure, high-field, and low-energy μ SR (near-surface)



Is RuO₂ Magnetic or Altermagnetic?

Background:

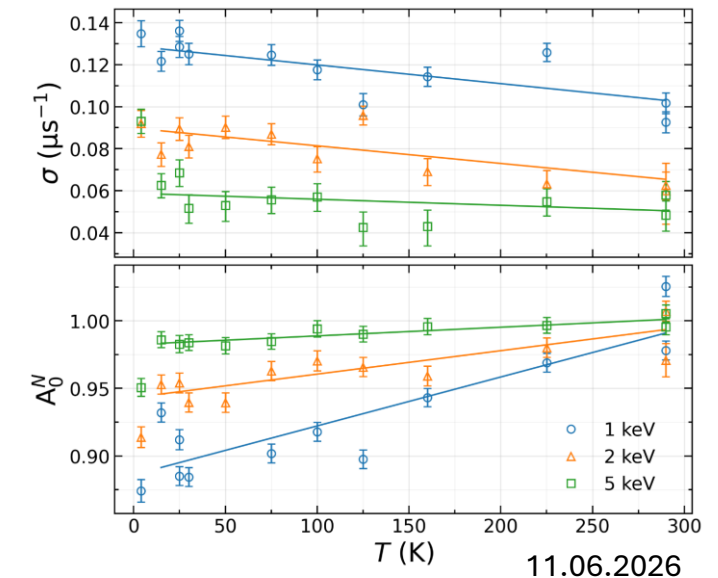
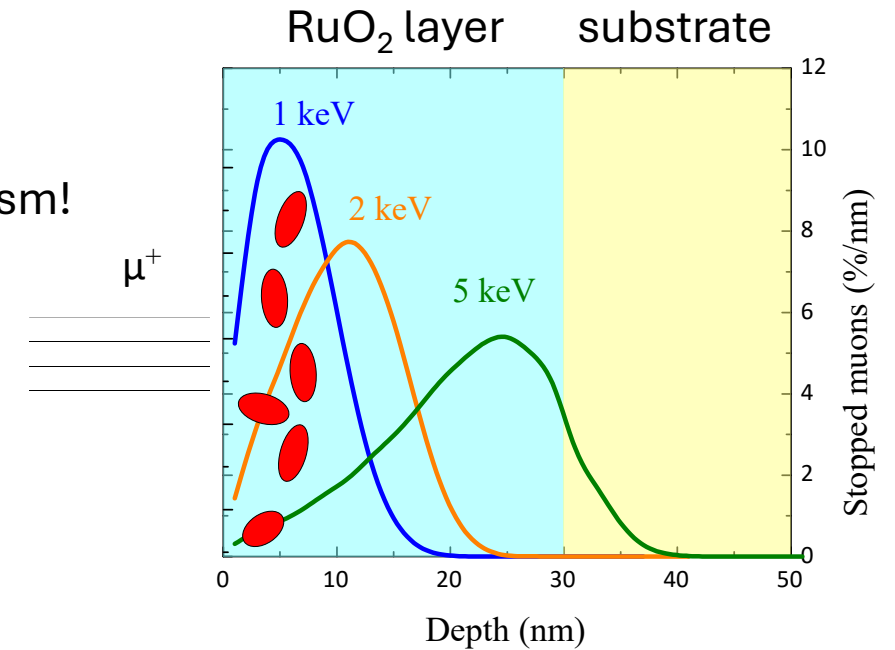
- Bulk μ SR and neutron scattering: no magnetism in crystals/thin films
[KeBler et al, npj Spintronics 2, 50 \(2024\)](#)
- ARPES, magneto-optical effects, and transport: evidence of magnetism!

Strategy: Use depth sensitivity of muons to investigate magnetism

- μ SR damping rate (σ) \rightarrow magnetic field distribution
- Initial μ SR polarization (A_0) \rightarrow paramagnetic volume fraction

Results (consistent across different samples/growth techniques):

- **Increasing σ towards surface** \rightarrow stronger magnetism
- **Decreasing A_0 towards surface** \rightarrow increasing magnetic volume fraction (“magnetic puddles”, 8.5% in the top 10 nm)



This result puts an end to the ongoing debate

- RuO₂ is non-magnetic and there is no long-range magnetic order
- Instead, only a small volume fraction near the surface is magnetic

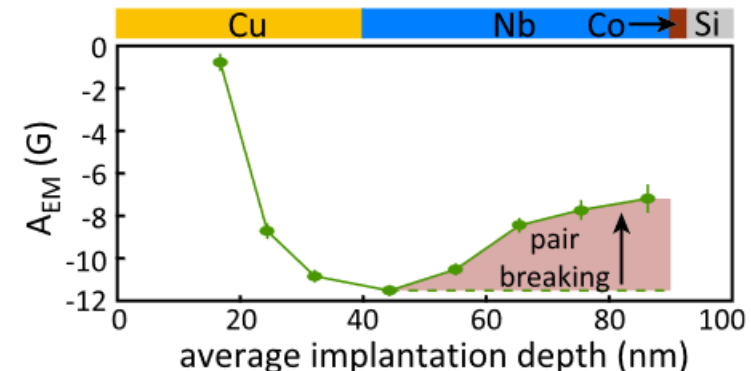
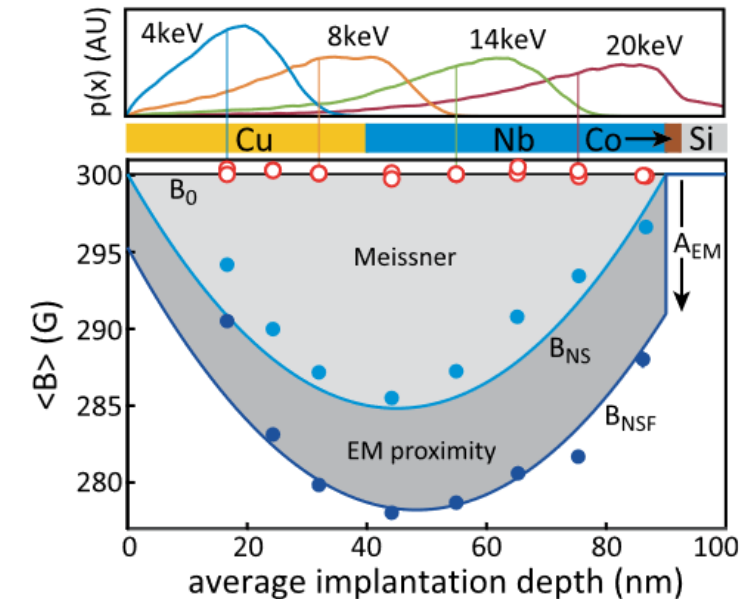
[Akashdeep et al, Appl. Phys. Lett. 128, 022406 \(2026\)](#)

LE- μ SR study of interface/proximity effects

Manifestation of the electromagnetic proximity effect in superconductor-ferromagnet thin film structures

M.G. Flokstra et al., Appl. Phys. Lett. **115**, 072602 (2019)

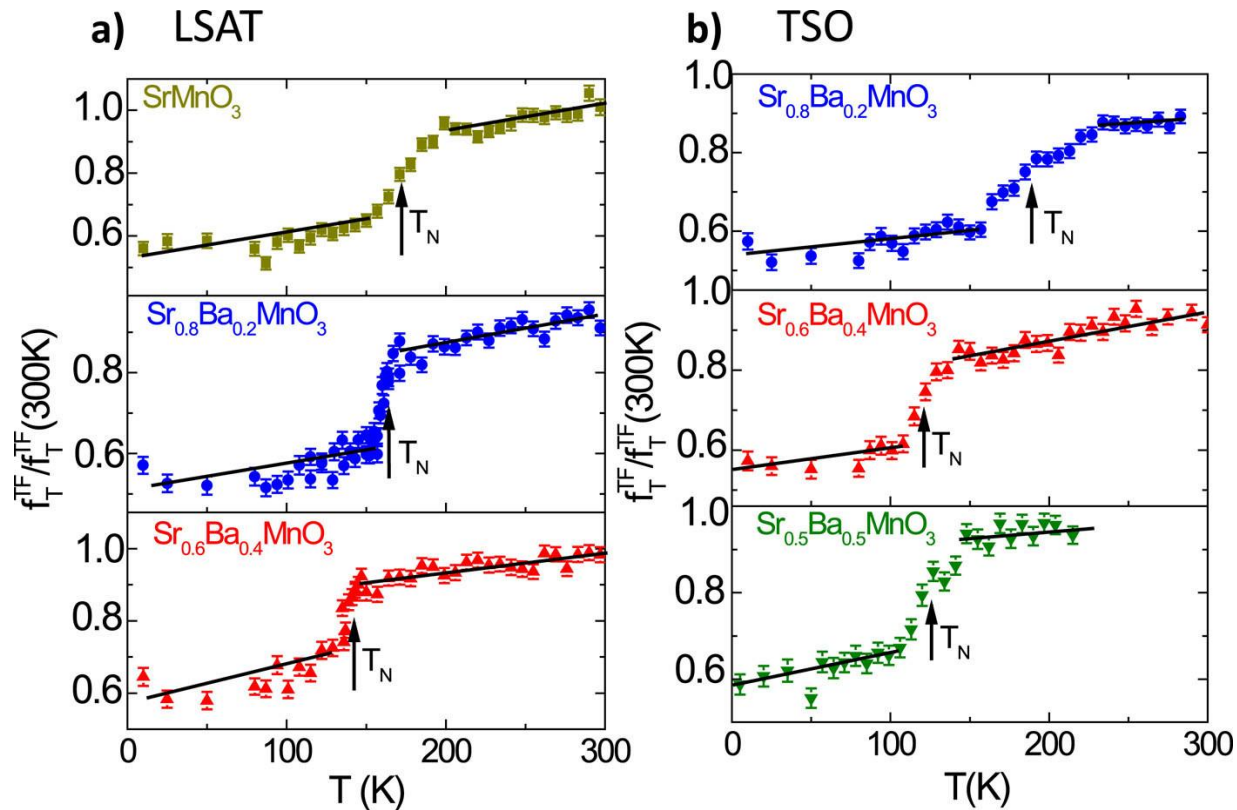
- **Unexpected results: largest flux expulsion observed when a 2.4 nm FM Co layer is added**
- The new, «**electromagnetic proximity effect**» is the origin of the enhanced flux expulsion: screening response of the SC to a vector potential near the SC/FM interface (A.F. Volkov et al., PRB 99, 144506 (2019))
- Observed cooperation of SC and FM could be a key ingredient for superconducting spintronics



LE- μ SR: magnetic transition in multiferroics under strain

Engineering the magnetic order in epitaxially strained $\text{Sr}_{1-x}\text{Ba}_x\text{MnO}_3$ perovskite 10-nm-thin films

L. Maurel et al., APL Materials 7, 041117 (2019)



Substrate	x	V (\AA^3)	c/a	Strain (%)	T_{order} (K)
LSAT	0	56.50(4)	0.976(1)	1.63	171(4)
	0.2	56.81(2)	0.981(2)	1.24	159(1)
	0.4	58.65(1)	1.010(2)	-0.36	140(1)
TSO	0.2	58.97(1)	0.955(1)	3.39	187(5)
	0.4	60.42(1)	0.976(1)	1.82	118(3)
	0.5	60.75(2)	0.983(2)	0.94	124(4)

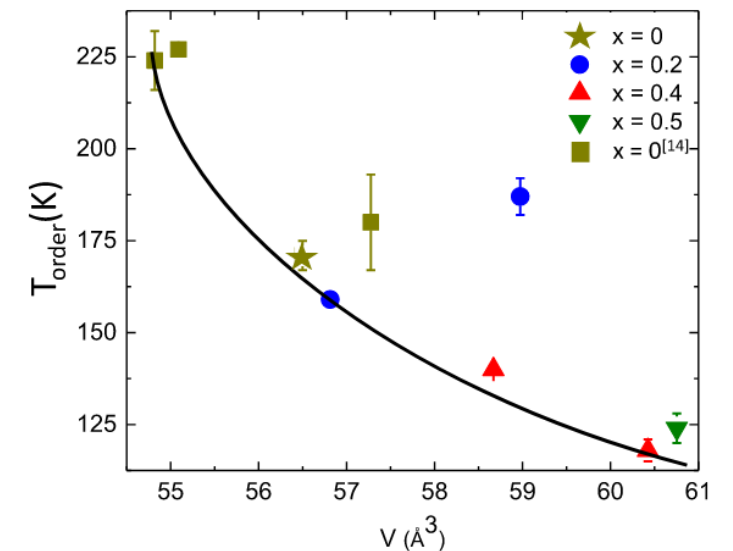


FIG. 2. Temperature dependence of the transverse fraction f_T^{TF} of the muons normalized to the fraction at 300 K, determined from LE- μ SR measurements for 10-nm-thick $\text{Sr}_{1-x}\text{Ba}_x\text{MnO}_3$ films on (a) LSAT and (b) TSO. The arrows indicate the magnetic order temperature.

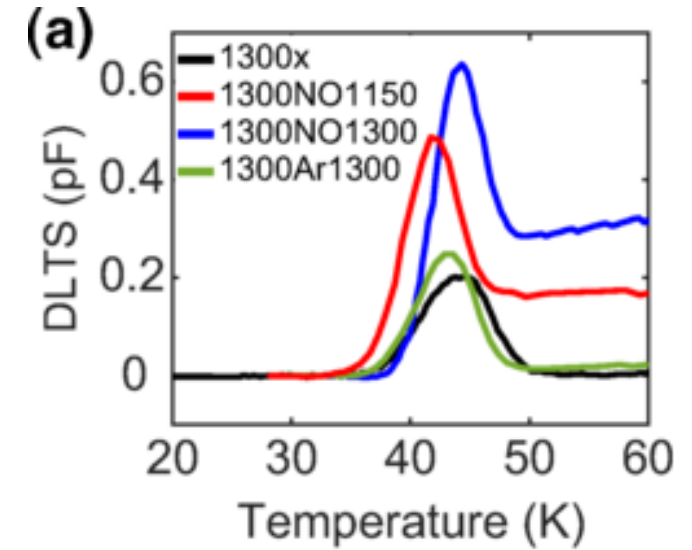
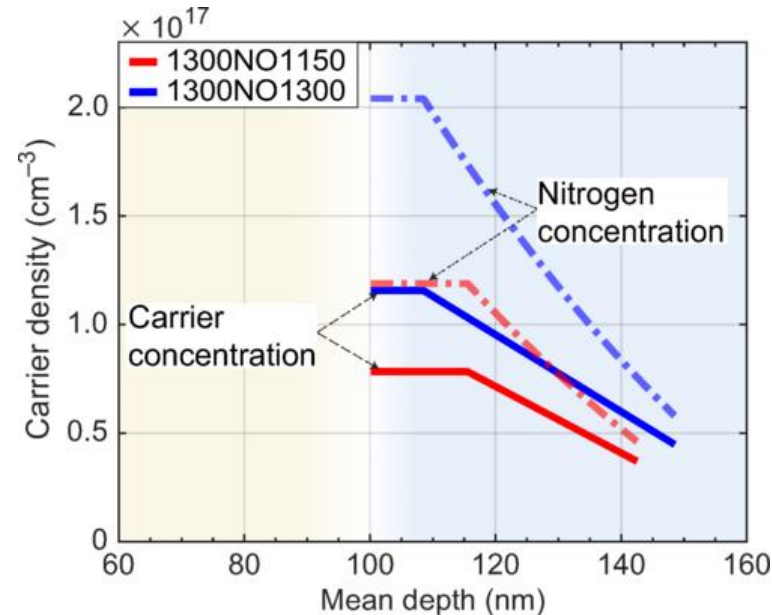
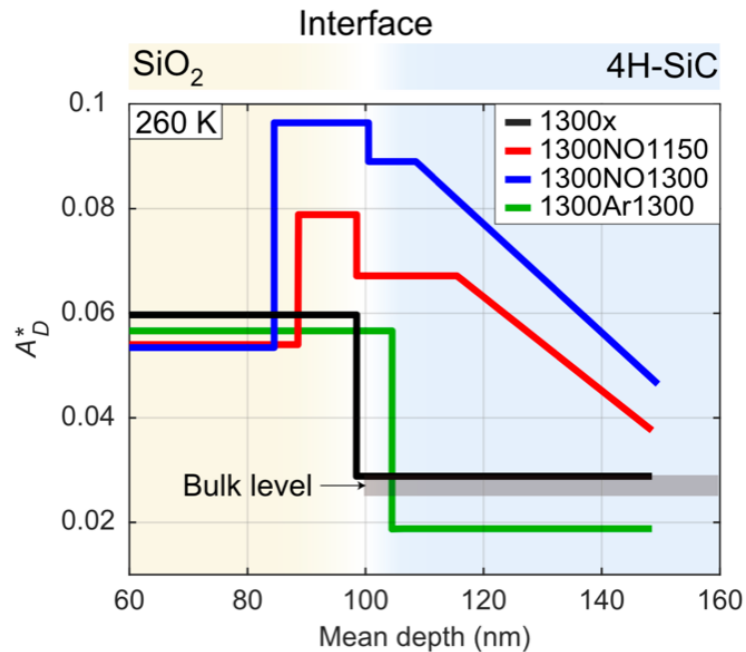
LE- μ SR study of annealing effects at the SiO₂/4H-SiC interface



TABLE I. Description of sample preparation and processing steps. Deposition is performed using PE-CVD for SiO₂ and PVD for Al.

Sample name	Oxidation parameters	Oxide thickness	POA parameters	Deposition
1300x	32 min at 1300 °C	48 nm	...	SiO ₂ , 52 nm
1300NO1150	30 min at 1300 °C	48 nm	70 min at 1150 °C in NO	SiO ₂ , 52 nm
1300NO1300	28 min at 1300 °C	56 nm	70 min at 1300 °C in NO	SiO ₂ , 44 nm
1300Ar1300	32 min at 1300 °C	48 nm	70 min at 1300 °C in Ar	SiO ₂ , 52 nm

4H-SiC $n \sim 3 \times 10^{15} \text{ cm}^{-3}$



Defects created in SiO₂ increase A_D

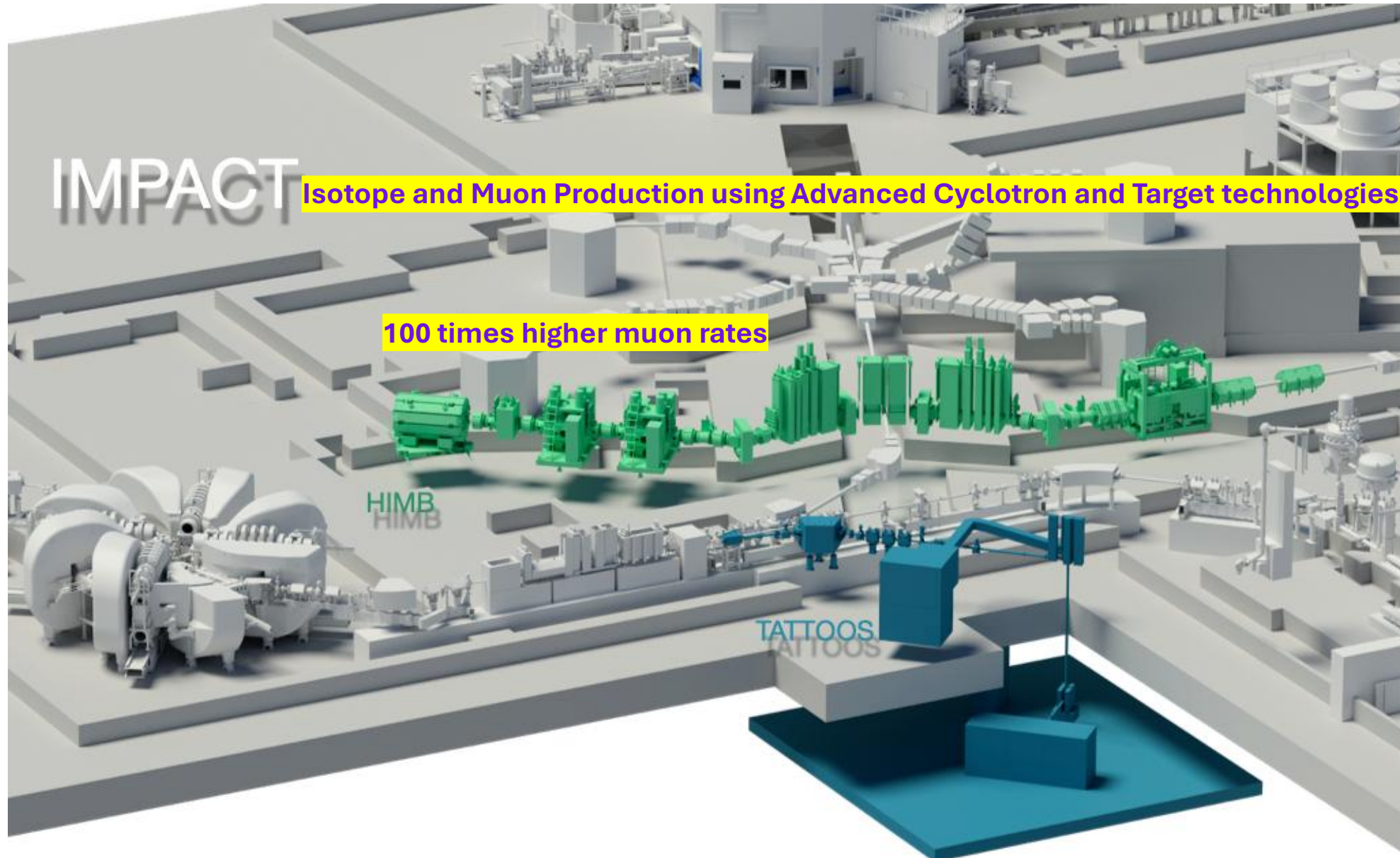
In SiC:

$A_D \uparrow$ due to Mu^- formation, $n \gtrsim 1 \times 10^{16} \text{ cm}^{-3}$ and passivation of V_{Si}

$A_D \downarrow$ due to presence of V_{Si} (Ar1300)

Annealing in NO at 1300 °C introduces N which acts as donor, and which passivates V_{Si} : $A_D \uparrow$

IMPACT – a Major Upgrade for HIPA in 2028 & 2029



IMPACT – a Major Upgrade for HIPA

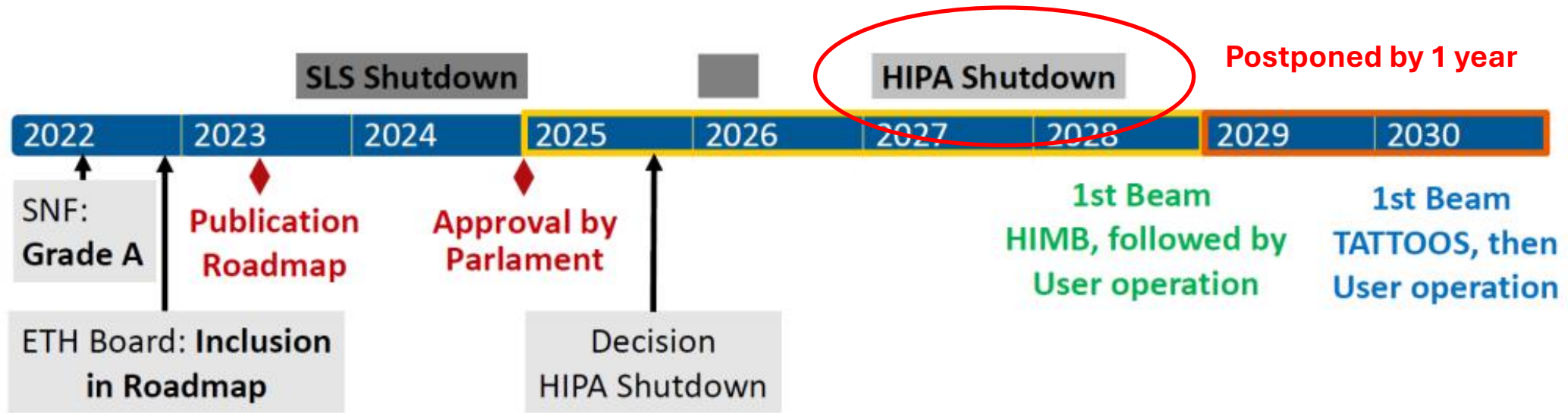


IMPACT: Isotope and Muon Production using Advanced Cyclotron and Target technologies

Major upgrade of HIPA within the Swiss Roadmap for Research Infrastructures 2025 – 2028

- 12/2024 final approval by Swiss Parliament
- TATTOOS (**T**argeted **A**lpha **T**umor **T**herapy and **O**ther **O**ncological **S**olutions)
- HIMB (**H**igh-Intensity **M**uon **B**eams)
 - Particle physics beamline **MuH2** → **100x higher muon rate than the π E5 particle physics beam line**
 - μ S material science beamline **MuH3** (GPS and FLAME) → **10 – 100x higher muon rate**
- 1.5 y shutdown of HIPA in 2028/2029
- Requires the development of a new positron tracking spectrometer based on monolithic Si-pixel detector technology 2025 -2028 (LMU, LTP, μ 3e experiment, U Heidelberg, U Mainz, U Zurich, LIN)
- Requires redesign of GPS cryogenics 2026-2028
- → **AMS (Advanced Muon Spectroscopy) Project**

IMPACT – a Major Upgrade for HIPA



BFI-Periode/Funding:



IMPACT Project team PSI:



D. Kiselev
CAS



R. Eichler
NES



A. Knecht
CNM



N. v.d.Meulen
CLS

Scientific Lead (PSI)



K. Kirch
CNM



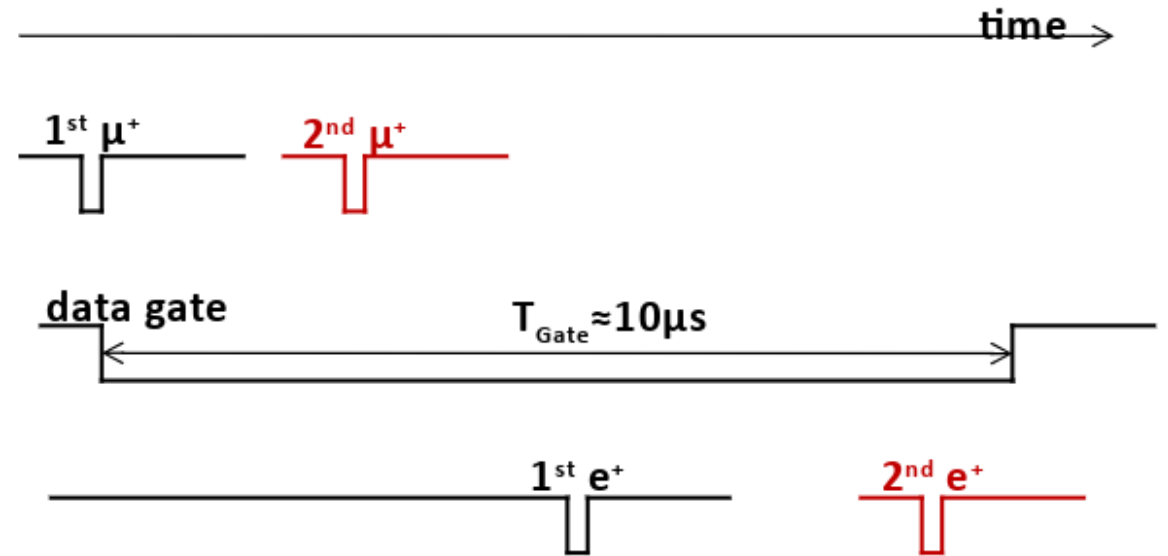
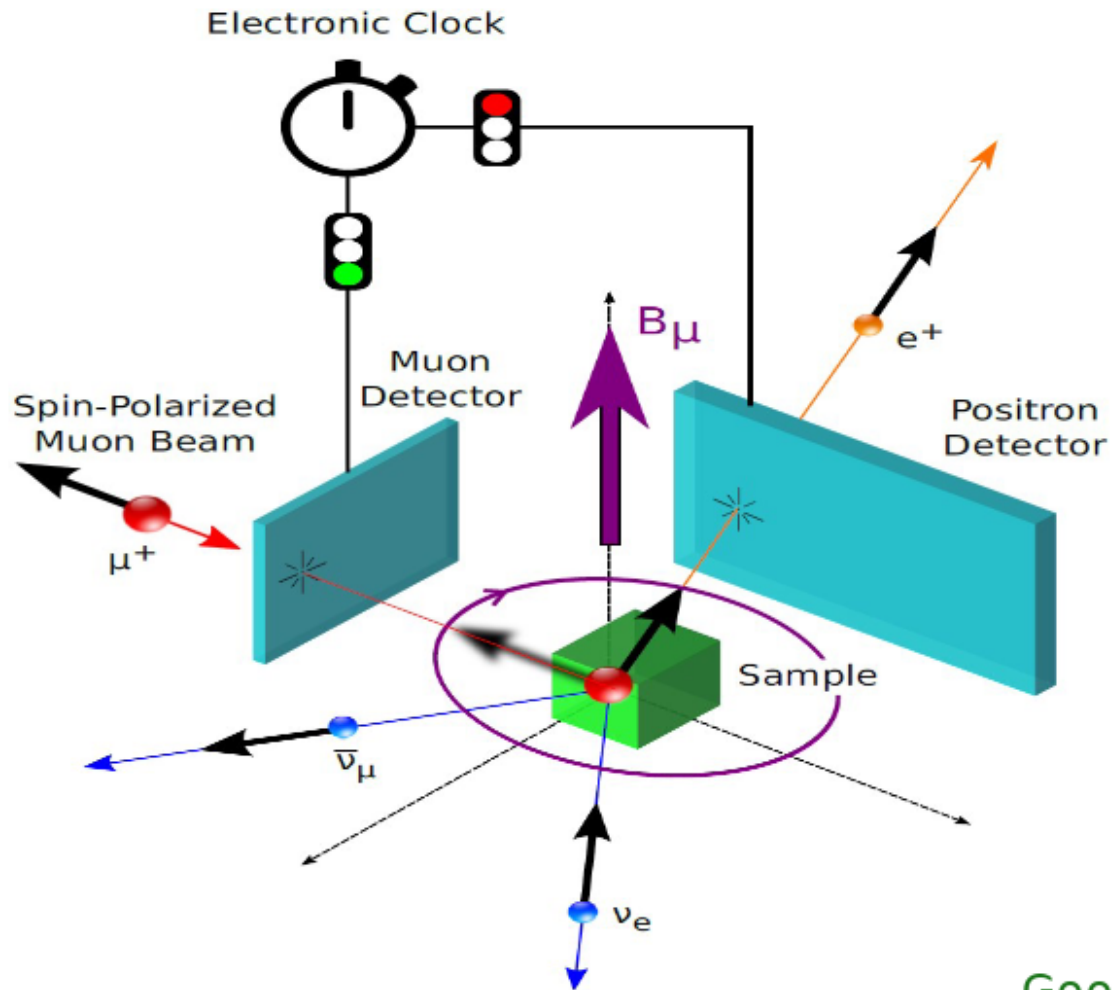
R. Schibli
CLS

Project Office



A. Koschik
CAS

μ SR at a continuous muon source and its limitations



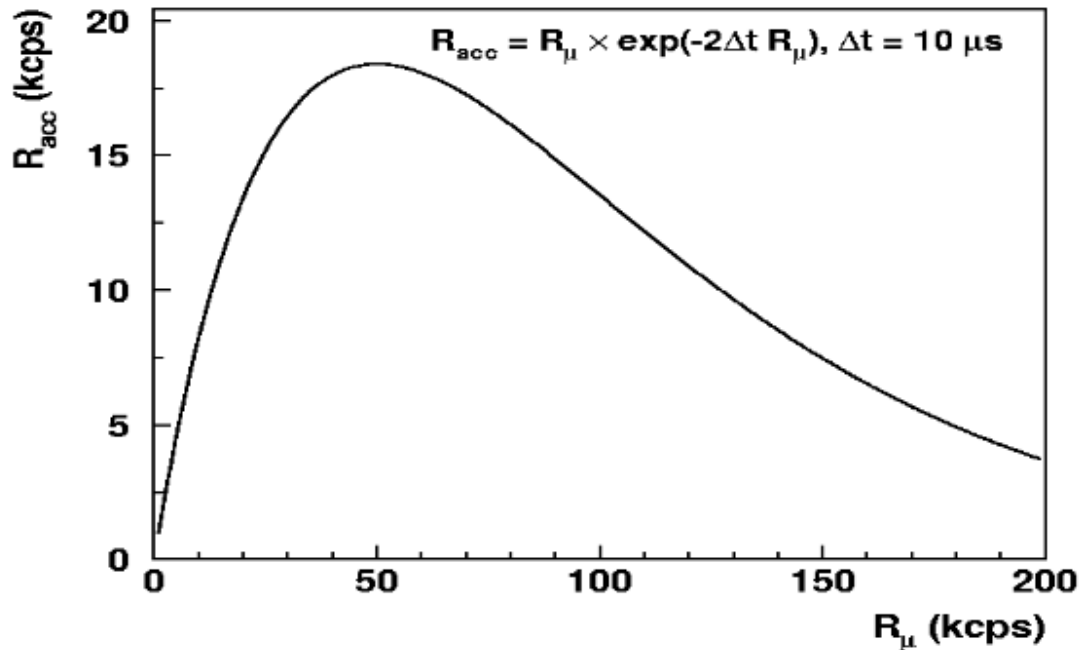
- 1st μ^+ : there was **no** other μ^+ for at least T_{Gate} in the past
- Single muon detection: only **one** μ^+ and **one** e^+ in observation window ($T_{\text{Gate}} \approx 10\mu\text{s}$)
- Second μ^+ / e^+ rejection electronically and by rate limitation

Good Event = (data gate) \wedge (1st e^+) \wedge (**no** 2nd μ^+) \wedge (**no** 2nd e^+)

μ SR at a continuous muon source and its limitations

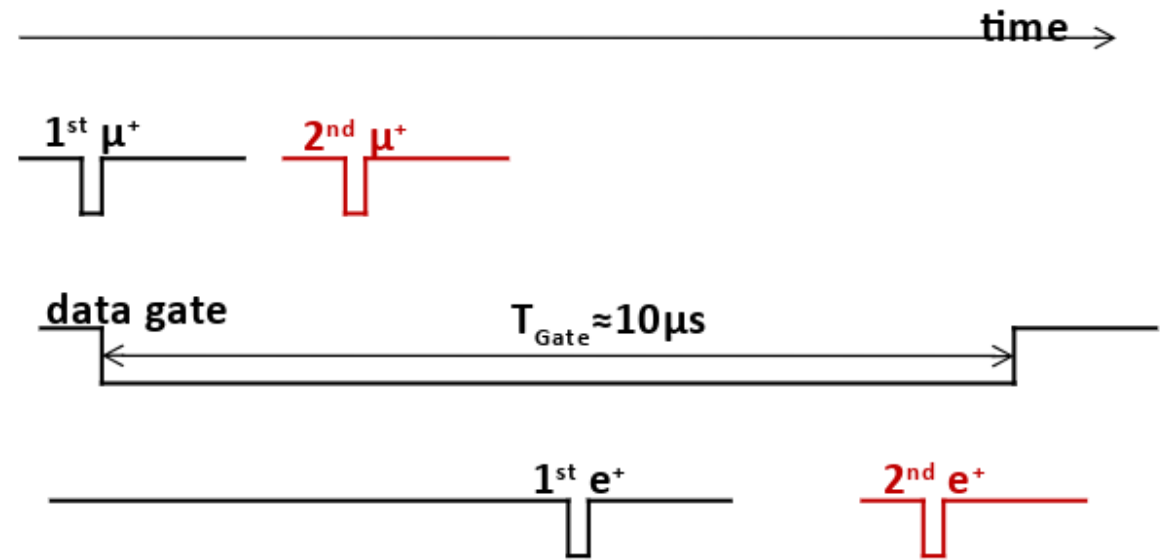


Accepted rate (R_{acc}) versus incoming rate (R_{μ})



Current rate limit for $T_{Gate} = 10 \mu s$ is **~40k μ^+/s**

100x more rate with HIMB



- 1st μ^+ : there was **no** other μ^+ for at least T_{Gate} in the past
- Single muon detection: only **one** μ^+ and **one** e^+ in observation window ($T_{Gate} \approx 10 \mu s$)
- Second μ^+ / e^+ rejection electronically and by rate limitation

$$\text{Good Event} = (\text{data gate}) \wedge (1^{\text{st}} e^+) \wedge (\text{no } 2^{\text{nd}} \mu^+) \wedge (\text{no } 2^{\text{nd}} e^+)$$

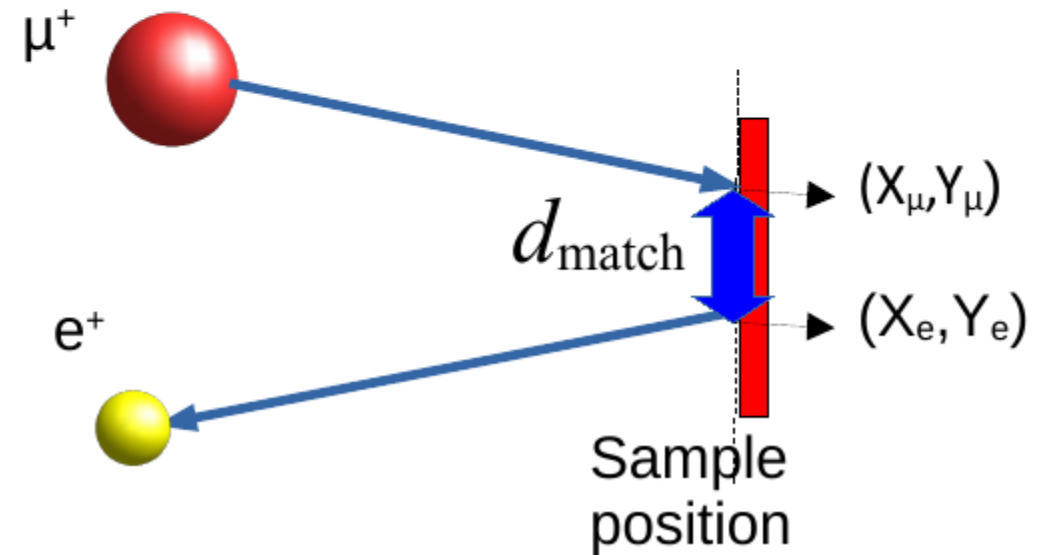
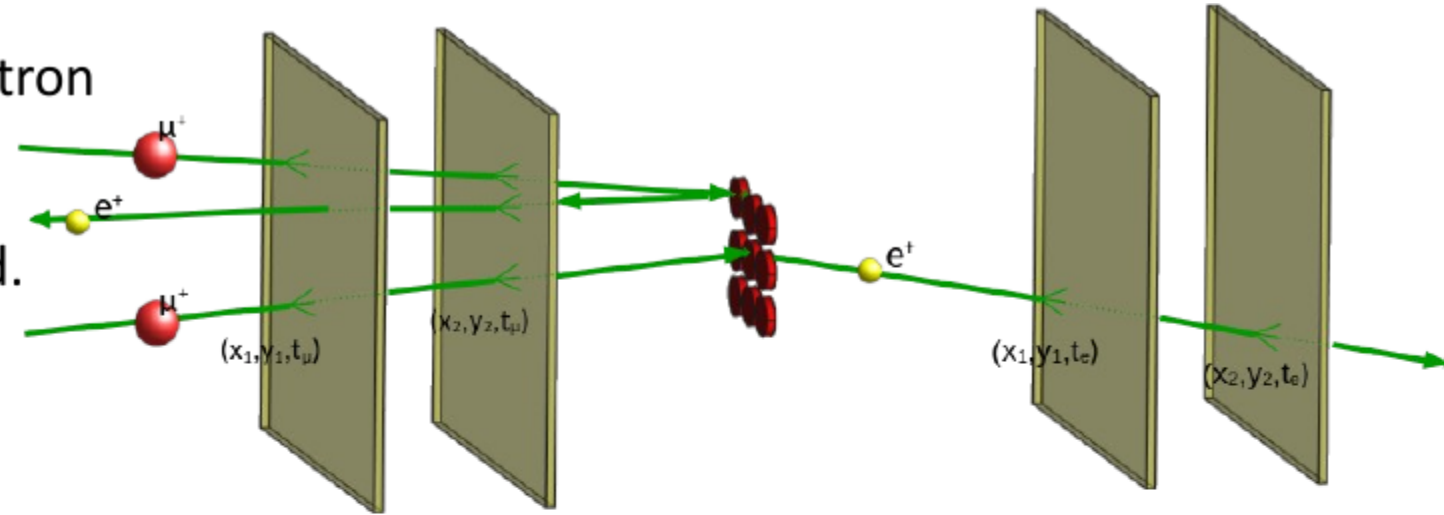
What are the limitations we want to overcome?



	Current limit	Aim
Incoming muon rate	< 40kHz @ 10 μ s	> 400 kHz @ 20 μ s
Sample size	> 4x4 mm ²	< 1x1 mm ²
Number of samples	One at a time	> 1
Veto detectors	necessary	obsolete
Data gate length	10 μ s or 20 μ s with MORE (muons on request)	20-30 μ s

Vertex Reconstruction Scheme

- For each muon, look for a matching positron within a t_{gate} time ($\sim 12\mu\text{s}$).
- Matching within d_{match} ($\sim 1\text{mm}$) is allowed.
- If found, record: (X_{μ}, Y_{μ}) , (X_e, Y_e) and $(t_e - t_{\mu})$
- Construct time histograms: upstream/downstream depending on the positron trajectory.
- The time histograms can be added for specific regions in the sample.



Vertex reconstructed μ SR (vx- μ SR) – A Game Changer for μ SR

Current limitations of μ SR at PSI:

- Maximum rate 40k muons/s
- Sample area > 4x4 mm²
- Thickness > ~200 μ m, < 200 nm

Vertex Reconstruction

- Novel small samples
- Multi samples in parallel
- >10x faster measurements
- 3x higher pressure/strain

Pulsed beam

- Pump-probe measurements
- Multiple stations in parallel
- Semi-integral measurements

High Rate

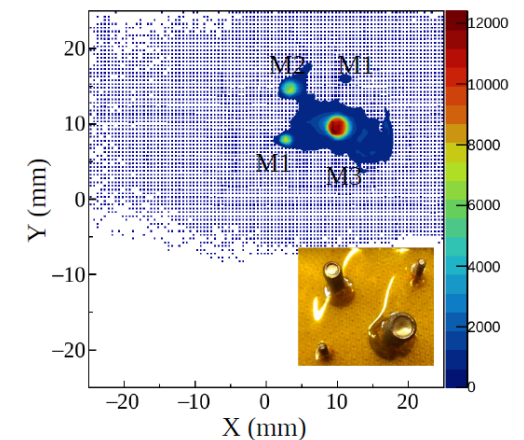
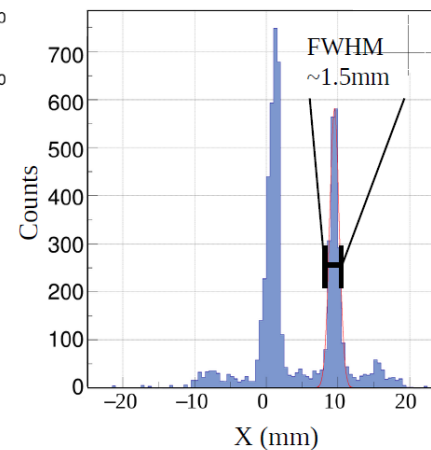
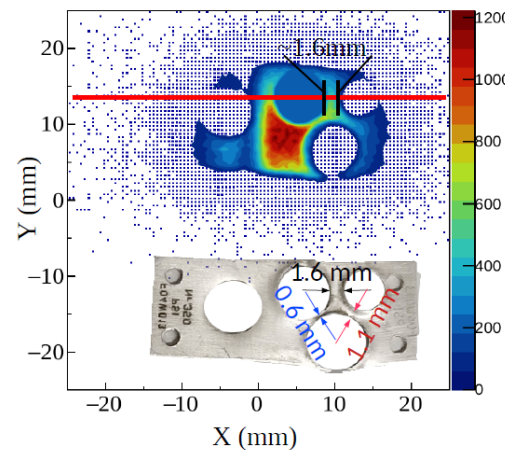
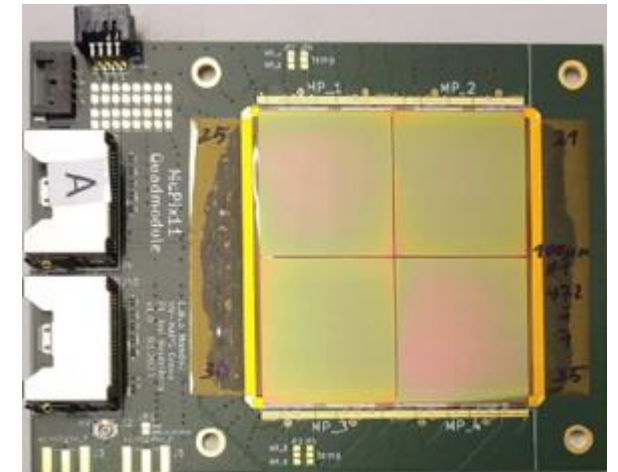
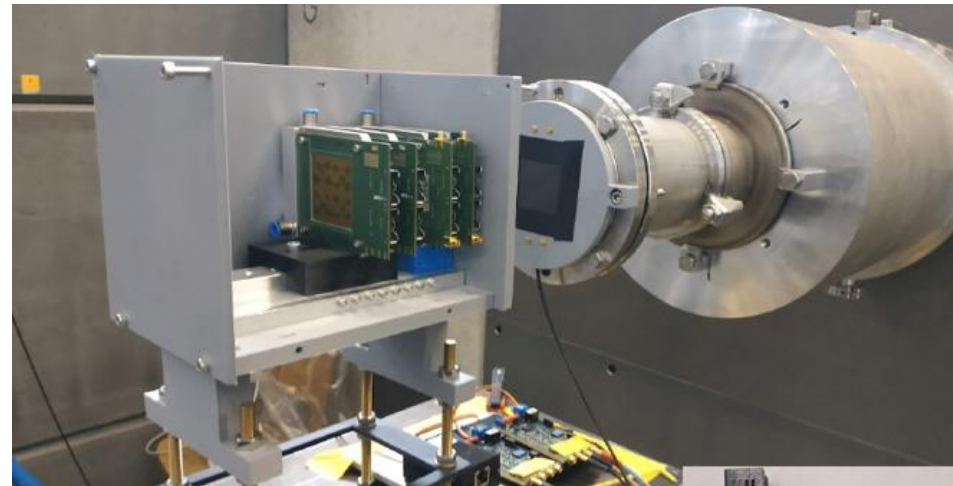
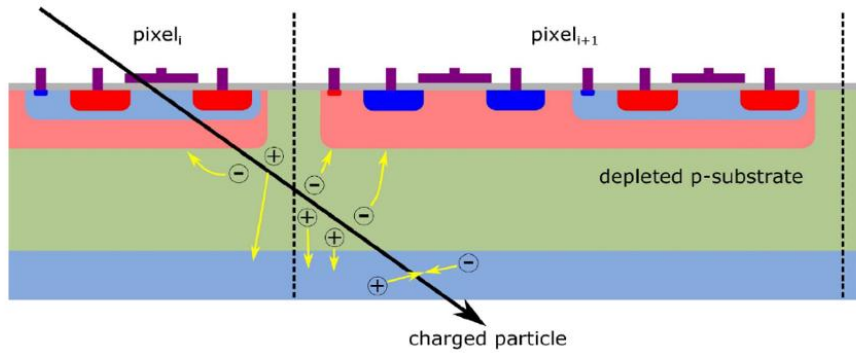
- Extend muon range to 200 nm – 200 μ m (“sub-surface muons”)
- 10x more low energy muons for thin-film and device applications (< 200 nm)
- Elemental analysis tomography (mm sized objects)

Vertex reconstructed μ SR (ν x- μ SR) using Si-Pixel Detectors



AMS (Advanced Muon Spectroscopy) Project lead by Zaher Salman: ν x- μ SR and upgrade of GPS

Using MuPix11 chip from μ 3e collaboration

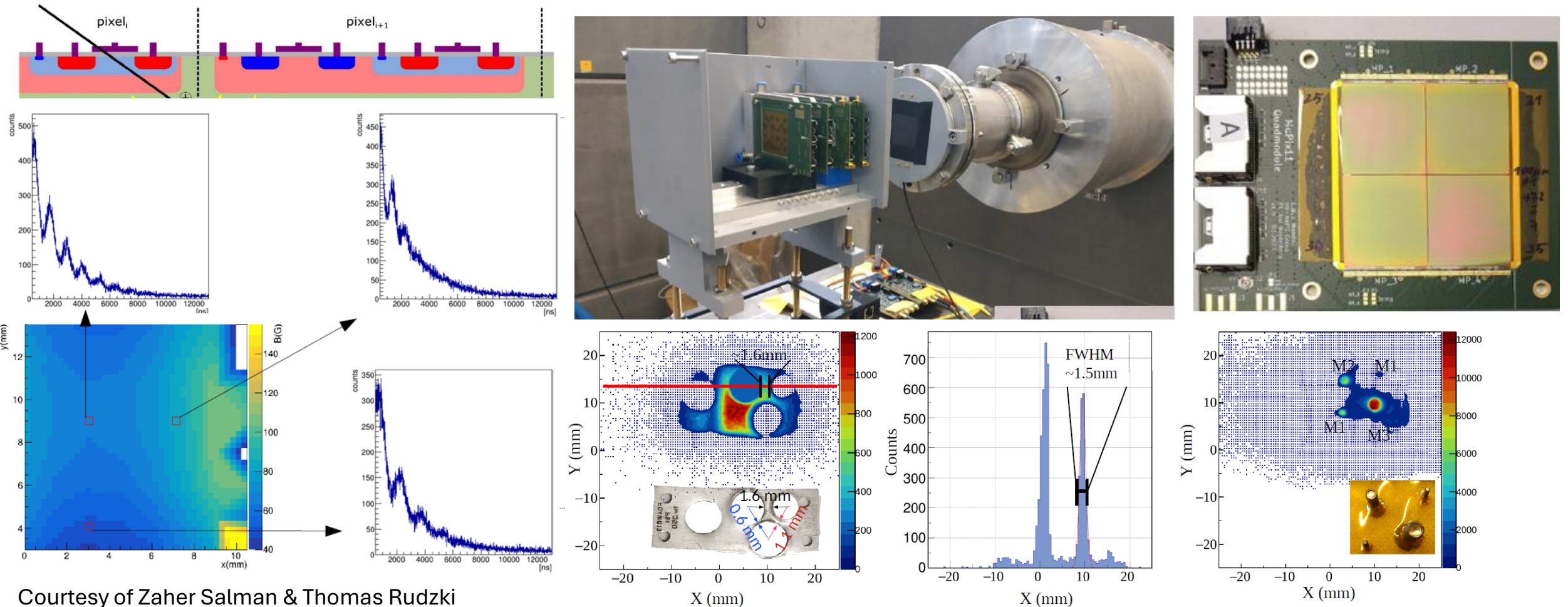


Vertex reconstructed μ SR (νx - μ SR) using Si-Pixel Detectors



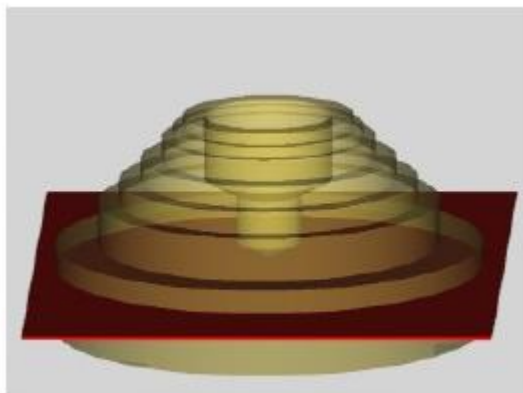
AMS (Advanced Muon Spectroscopy) Project lead by Zaher Salman: νx - μ SR and upgrade of GPS

Using MuPix11 chip from $\mu 3e$ collaboration

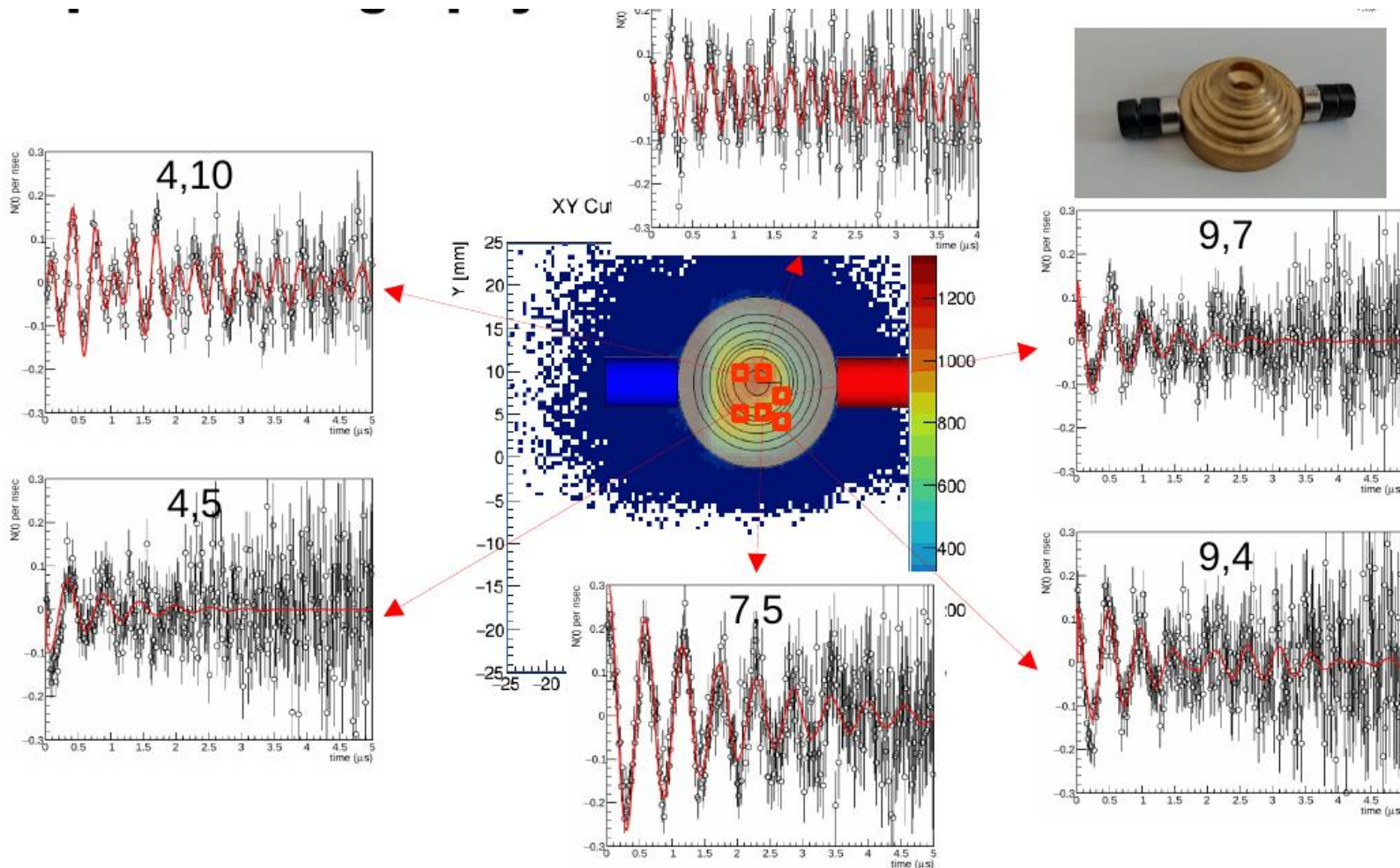
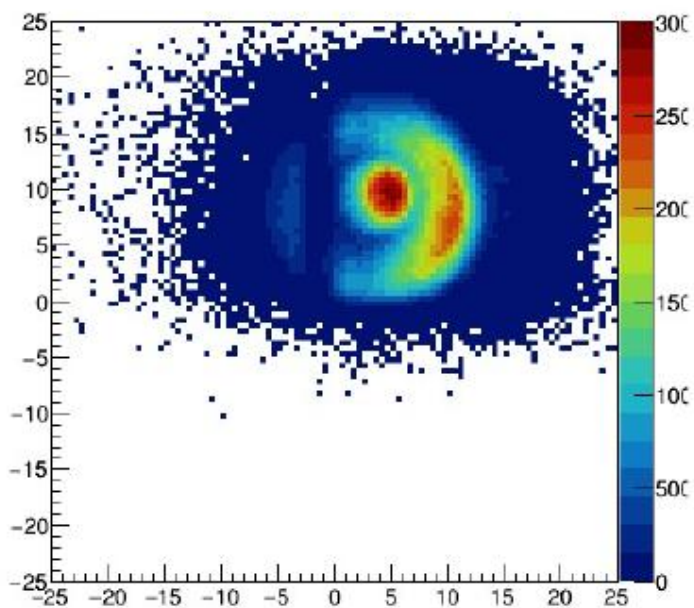


Courtesy of Zaher Salman & Thomas Rudzki

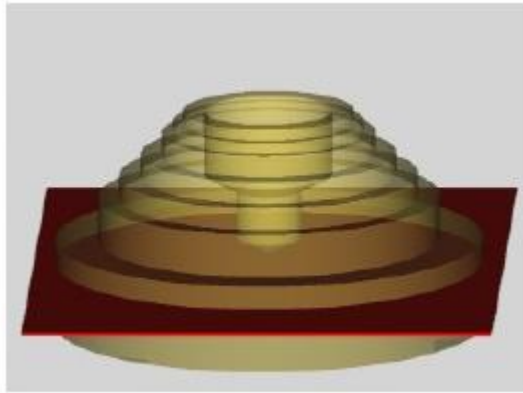
vx- μ SR: 3D «tomography»



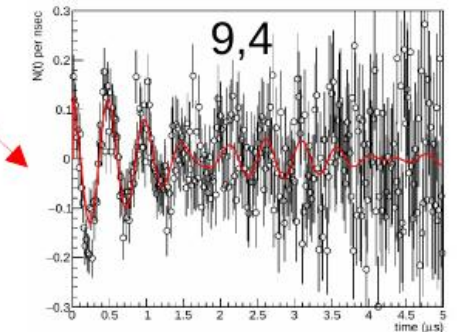
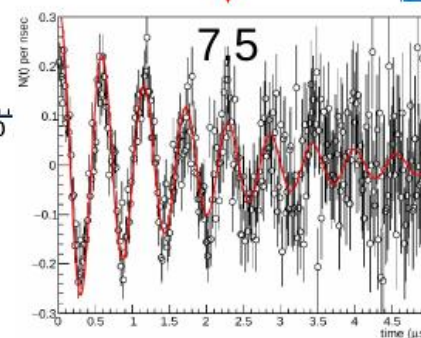
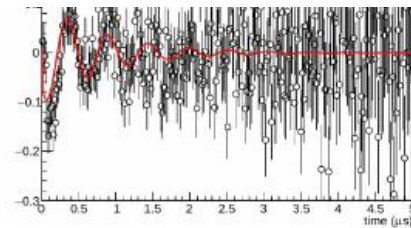
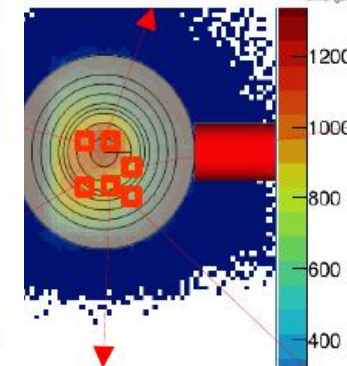
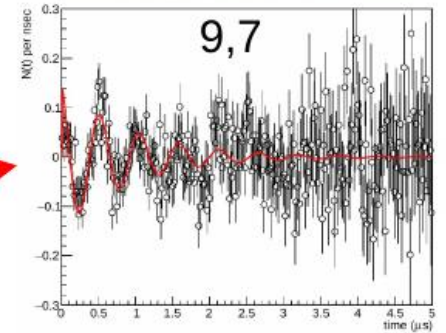
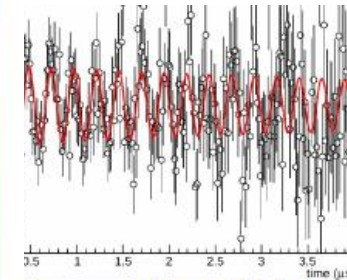
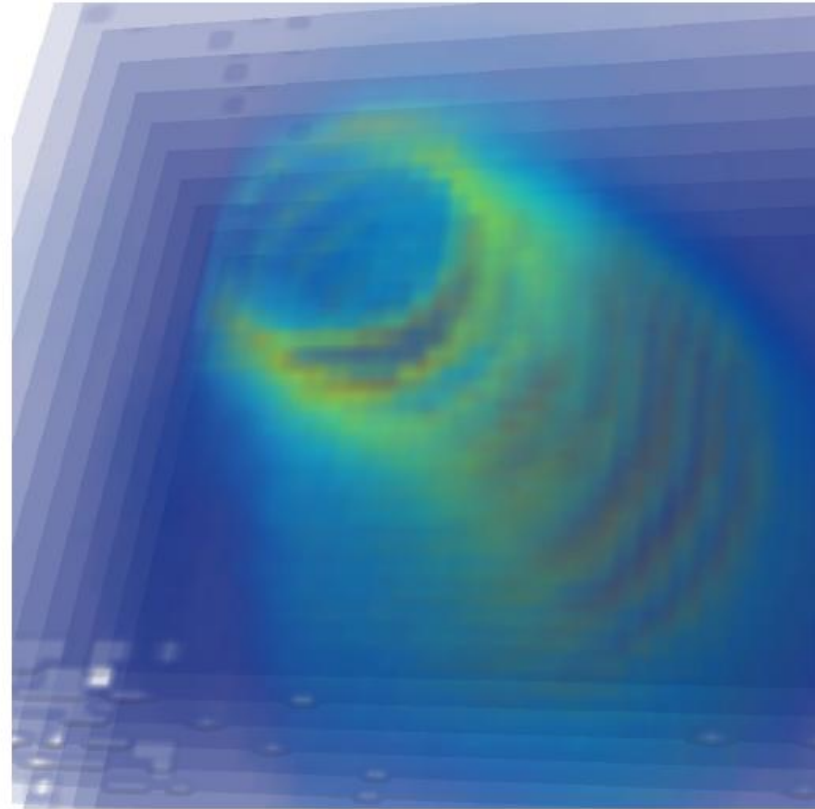
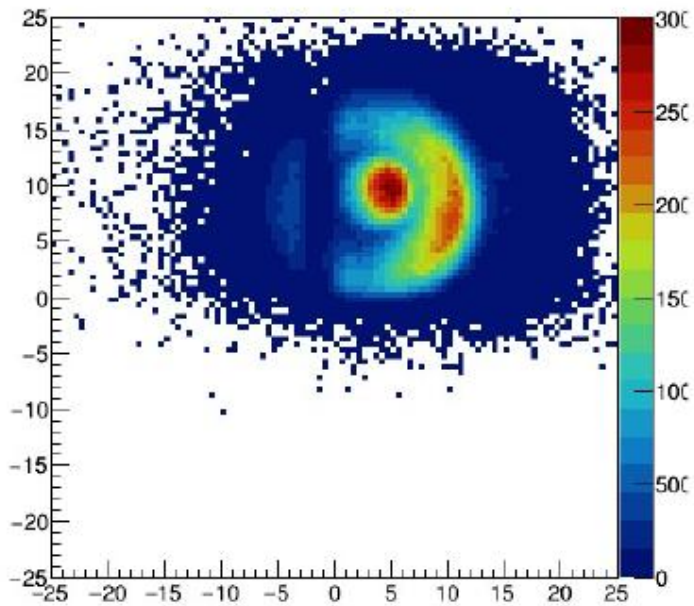
XY Cut of matching (Muon Position)



vx- μ SR: 3D «tomography»



XY Cut of matching (Muon Position)



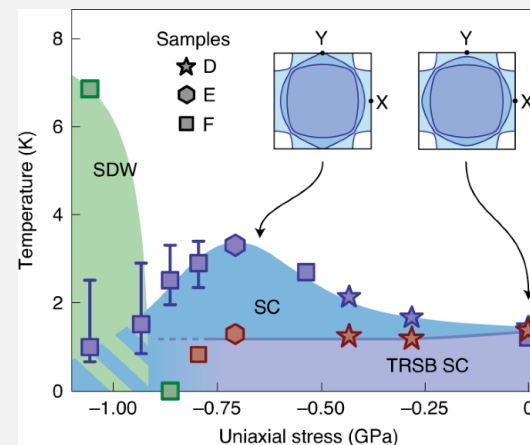
Next-Generation Pressure Cells for Quantum-Materials Research

New opportunities with HIMB + vertex reconstruction

- Spatial resolution $< 1\text{mm}^2$ (virtual beam spot size)
- Faster measurements (avoiding pile-up)
- Virtual scanning
 - Strain homogeneity / gradients
- Smaller samples and better stability
 - 3x higher strain: 3 GPa
 - 3x higher pressure: 10 GPa (anvil cells)

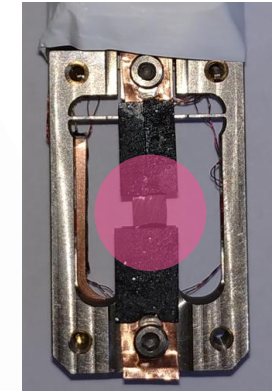
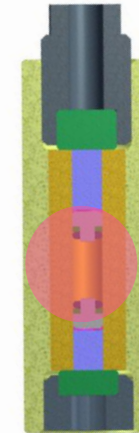
Enabling new science for μSR

- Quantum phase transitions
- TRSB in exotic superconductors
- Tuning nematicity in Fe-based SC
- Tuning of competition of orders (AFM, CDW, SC, topological order)
- ...

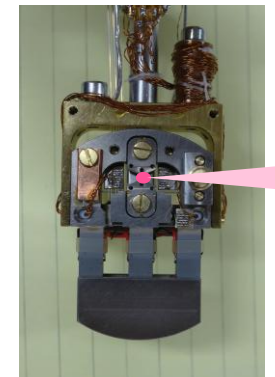
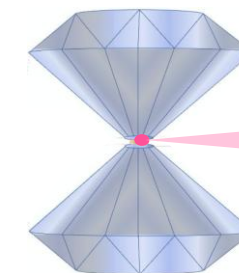


V. Grinenko *et al.*, Nature Physics (2021)

Muon beam today: $\varnothing 1\text{cm}$



Virtual beam spot: $\varnothing 1\text{mm}$



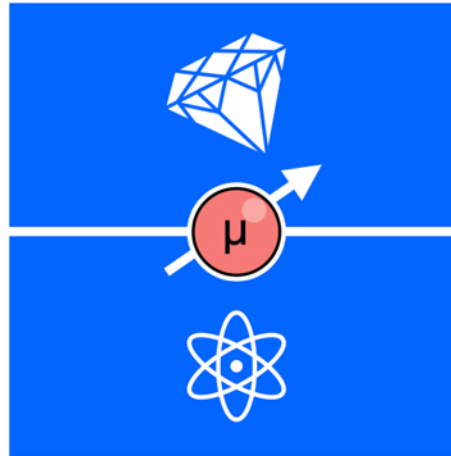
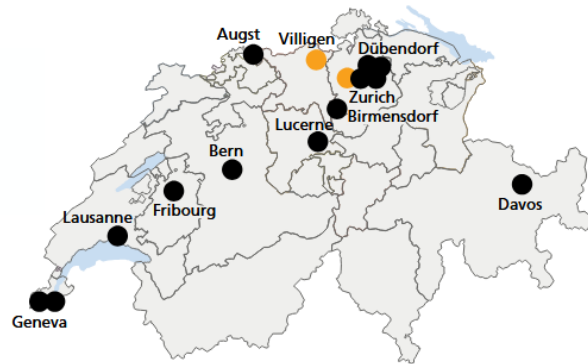
Muons for science and society — bridging discovery and application

National Centre of Competence in Research (NCCR)

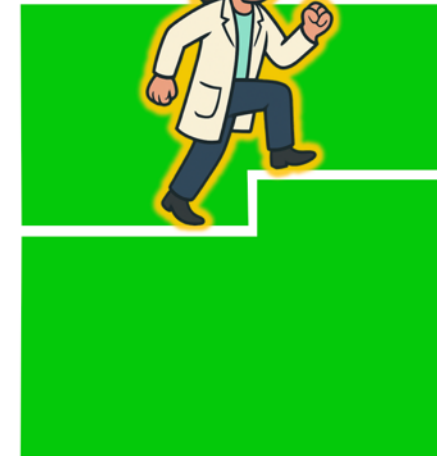


Courtesy of Marc Janoschek

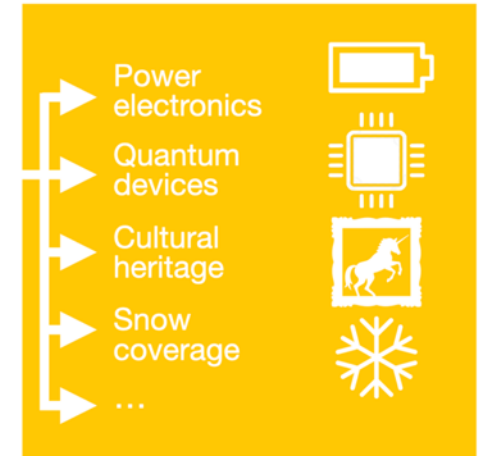
muoniverse



Muons are powerful and established probes of advanced materials and for high-precision particle physics



Technological developments within Muoniverse will drive a step-change in muon science

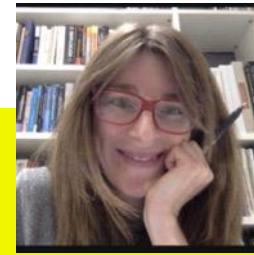


This step-change will open up the power of muons to new scientific domains and applications

- SNF funding ~14 MCHF (2026-29) plus cash and in-kind contributions from PSI and UZH
Total volume 33 MCHF/4 years
- Three new professorships (2 joint PSI/UZH 80/20, 1 UZH)
- **12++ year perspective boosting leading muon science at PSI HIPA**
- www.muoniverse.ch



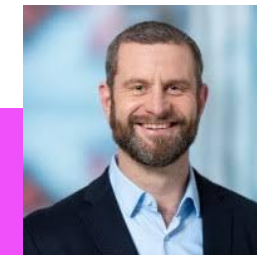
Klaus Kirch
Director



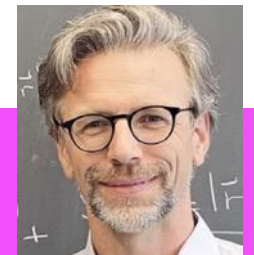
Angela Papa
Deputy Director



Leading House



Marc Janoschek
Co-Director



Titus Neupert
Deputy Co-Director



Universität Zürich
UZH

Co-Leading House

- **The S μ S operates and develops 6 state-of-the-art μ SR instruments** for the international user community
- **Several S μ S instruments offer unique sample environments** (nanometer depth range, hydrostatic and uniaxial pressure up to 3 GPa, high magnetic field (9.5 T) combined with mK temperatures), allowing to gain new and more detailed insights, particularly into novel quantum materials
- **The 7th muon spectroscopy instrument GIANT for Muon-Induced-Xray-Emission (MIXE) for elemental analysis** starts user operation in 2026: new muon spectroscopy applications in cultural heritage, energy research
- **The development of vertex-reconstructed μ SR (vx- μ SR) based on Si-Pixel detectors will boost the μ SR technique to new research directions** (small samples $\leq 1\text{mm}^2$, 10 – 100 times faster measurements, 3D scanning, >3 times higher pressures, multiple samples, new pump-probe capabilities etc)
- **«The future for muon research at PSI is bright»:** IMPACT/HIMB and the NCCR Muoniverse will advance muon research into new areas of applications and push the boundaries