



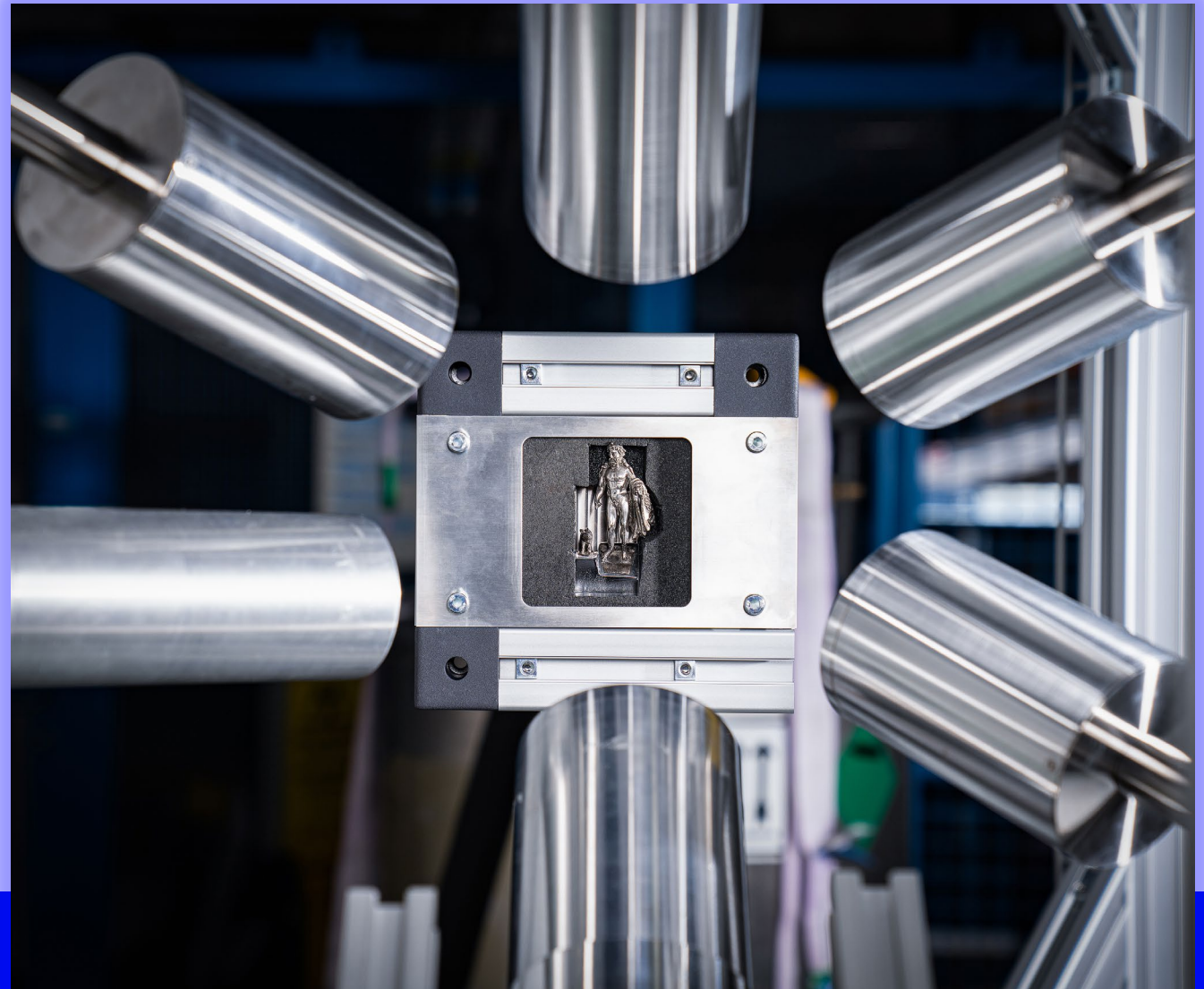
PSI Center for Neutron and
Muon Sciences

Muon-Induced X-ray Emission at PSI

From Elemental Analysis towards Tomography

Michael W. Heiss (on behalf of the **MIXE** team)
Laboratory for Muon Spin Spectroscopy

MELODY2026, Dongguan, 25 October 2026



Contents

- I. Facility Overview & News
- II. MIXE Technique & Instrument
- III. Recent Studies
- IV. Elemental Tomography

Part I

Swiss Muon Source

Facility Overview & News

- Swiss Spallation Neutron Source SINQ
- Swiss Muon Source SμS & Swiss Research Infrastructures for Particle Physics CHRISP
- Ultracold Neutron Source UCN (CHRISP)
- Proton Irradiation Facility PIF (CHRISP)
- Radionuclide Production (IP-2 and SINQ)

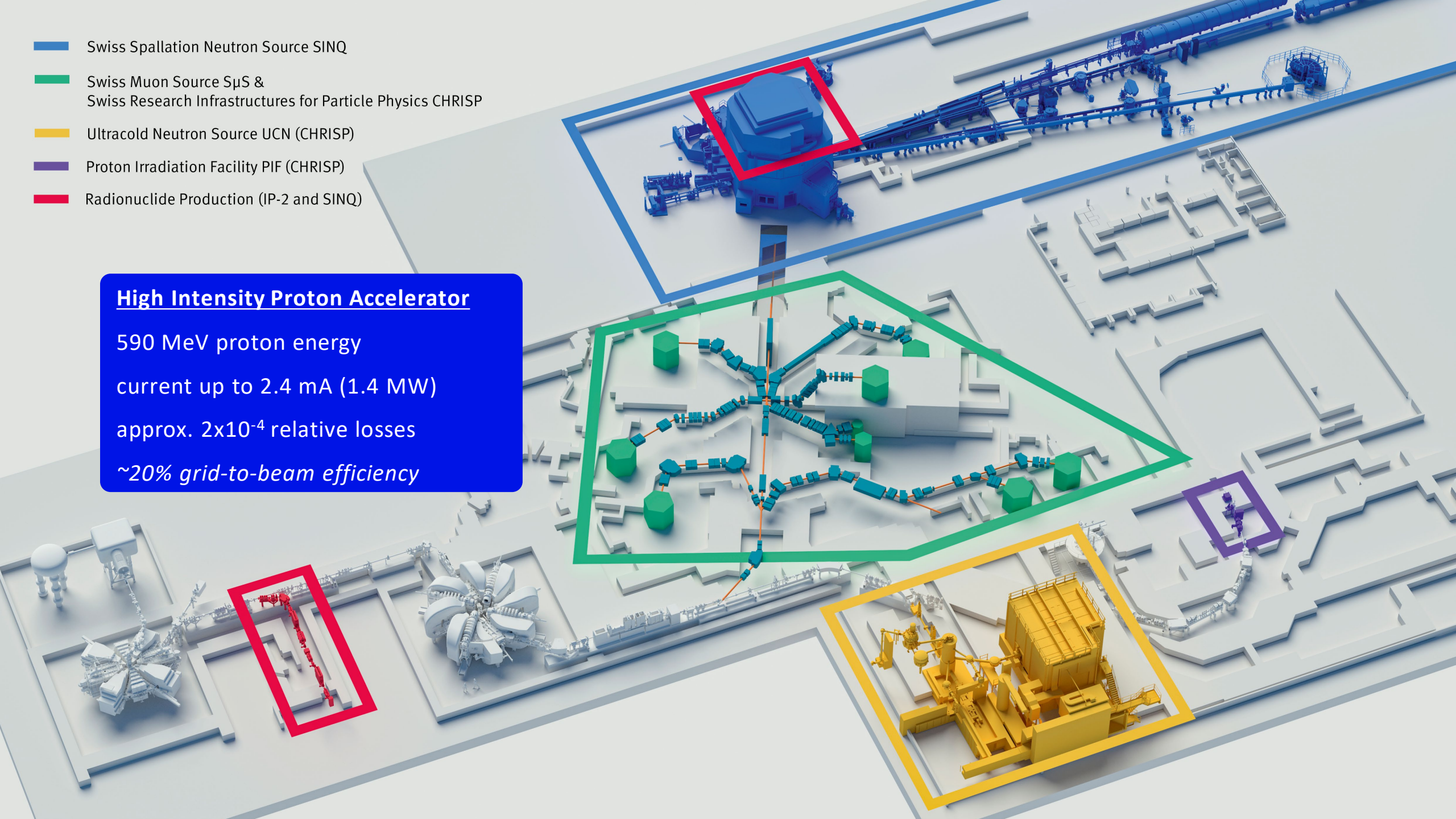
High Intensity Proton Accelerator

590 MeV proton energy

current up to 2.4 mA (1.4 MW)

approx. 2×10^{-4} relative losses

~20% grid-to-beam efficiency



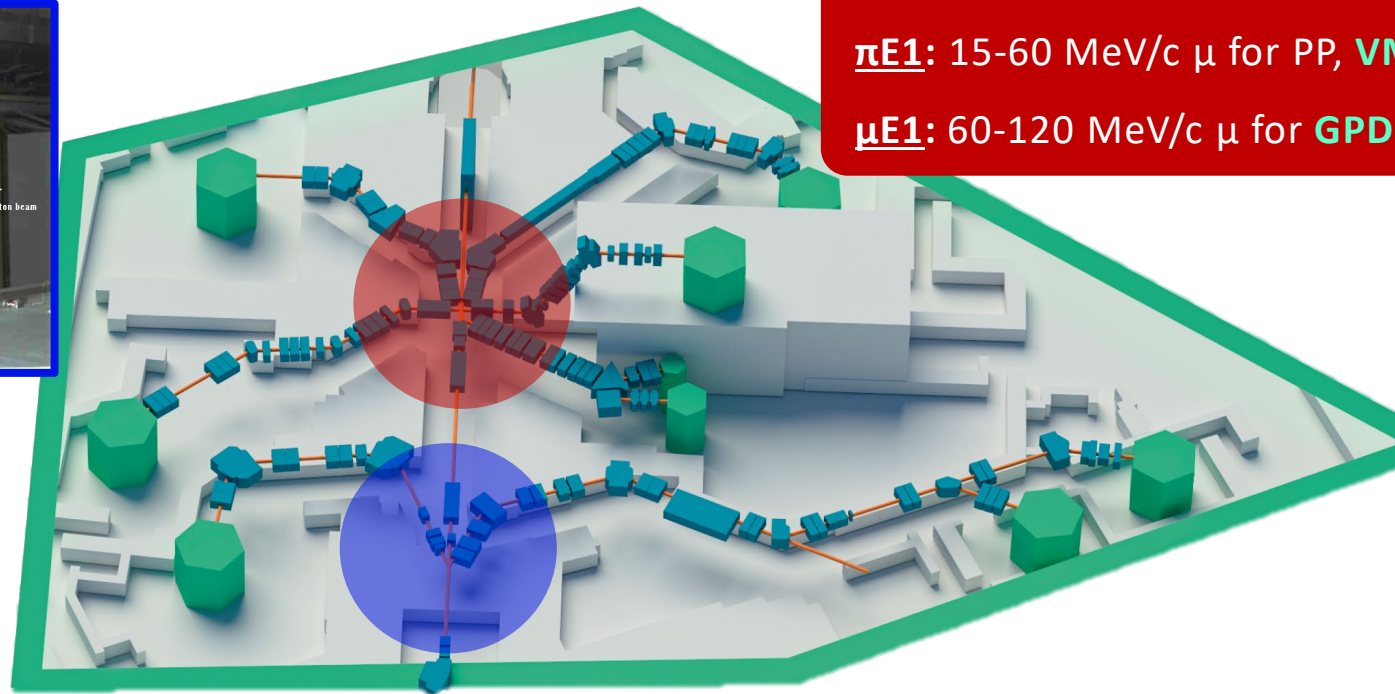
S μ S: Swiss Muon Source (+CHRISP for PP)

Target M (mince) – 5mm graphite

designed for π production (low rate)

π M3: 10-40 MeV/c (surface) μ^+ for μ SR (**GPS** & **FLAME**)

π M1: 10-300 MeV/c $\pi \rightarrow \mu/e$ for tests/PP



Target E (epaisse) – 40mm graphite

designed for π/μ production (high rate)

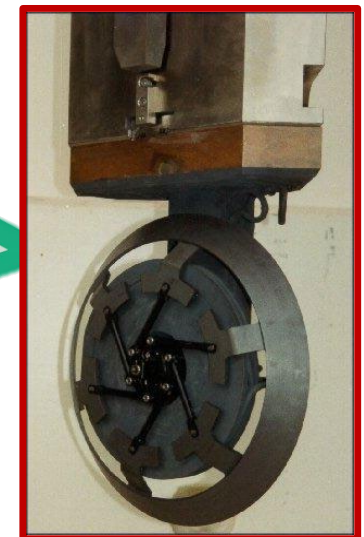
π E5: 20-120 MeV/c high rate μ for PP

μ E4: 10-40 MeV/c μ^+ for PP and **LEM**

π E3: 10-40 MeV/c (surface) μ^+ for **HAL**

π E1: 15-60 MeV/c μ for PP, **VMS** & **GIANT/MIXE**

μ E1: 60-120 MeV/c μ for **GPD** & **GIANT/MIXE** (2027+)



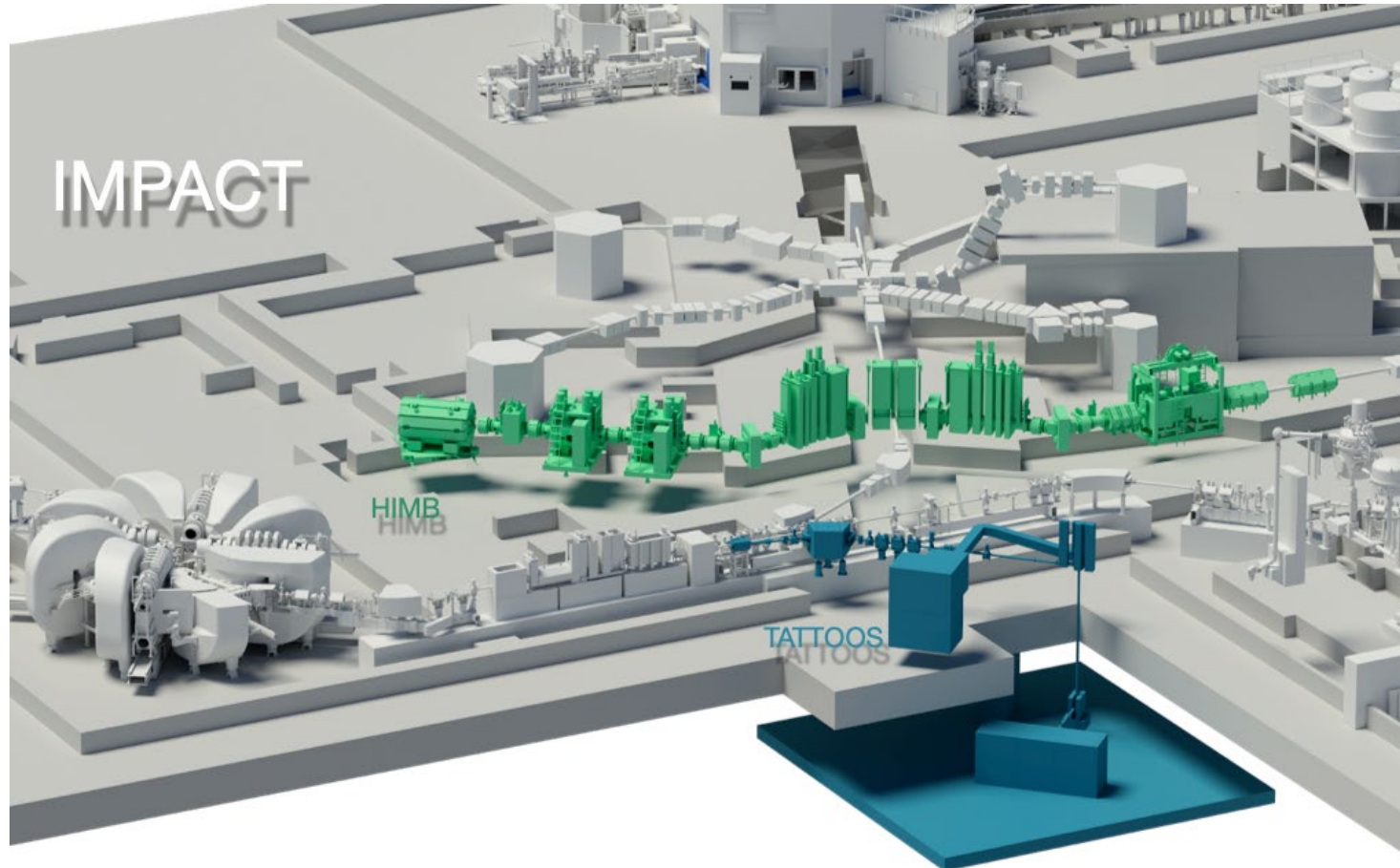
S μ S: Swiss Muon Source (+CHRISP for PP) : Isotope and Muon Production using Advanced Cyclotron and Target technologies



High
Intensity
Muon
Beamline

μ SR $\rightarrow$ MuH3:
10-100x of PiM3
GPS and FLAME

PP $\rightarrow$ MuH2:
100x of PiE5



Targeted
Alpha
Tumor
Therapy
and
Other
Oncological
Solutions

*following
HIMB*

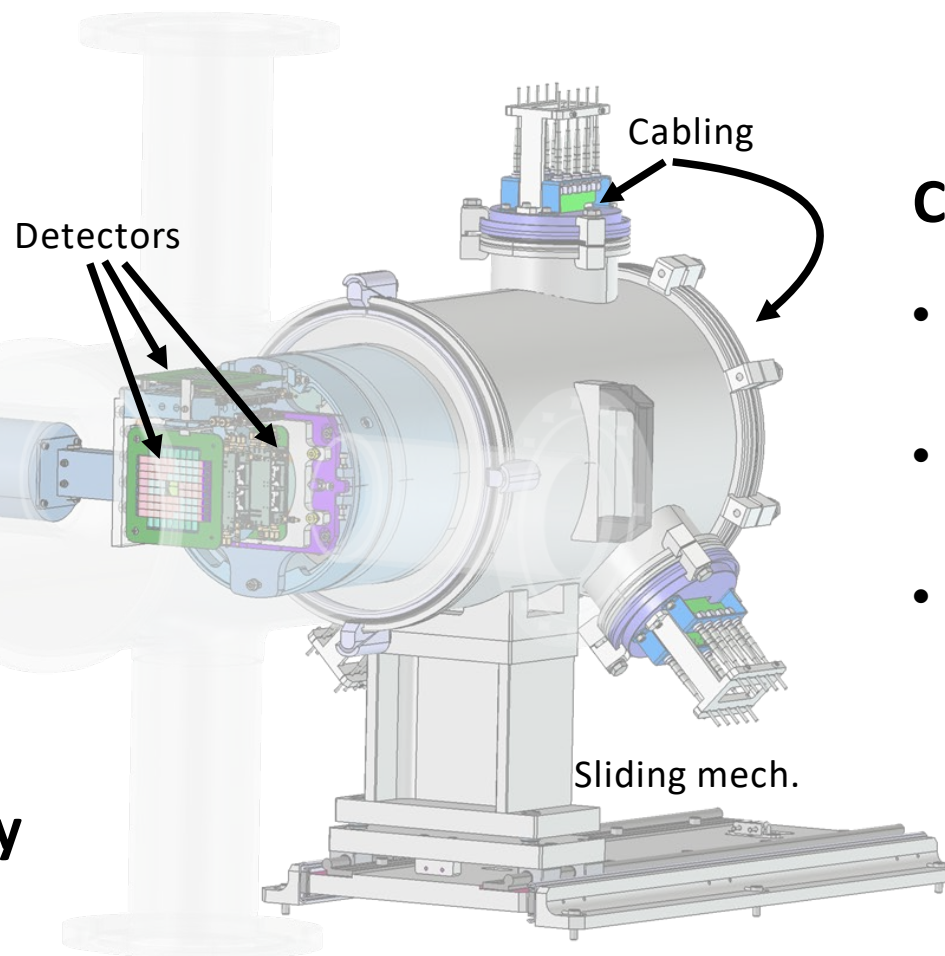
Postponed by 1 year $\rightarrow$ Shutdown 2028 (first beam fall 2029)

S μ S: Swiss Muon Source (+CHRISP for PP) : Isotope and Muon Production using Advanced Cyclotron and Target technologies

High
Intensity
Muon
Beamline

μ SR $\rightarrow$ MuH3:
10-100x of PiM3
GPS and FLAME

Advanced Muon Spectroscopy
vx- μ SR based on Si pixel



Current status

- Close-to-final detector insert concept defined
- Insert geometry compatible with GPS vacuum vessel
- Main interfaces identified: detectors, cryostat, cabling, sliding mechanism

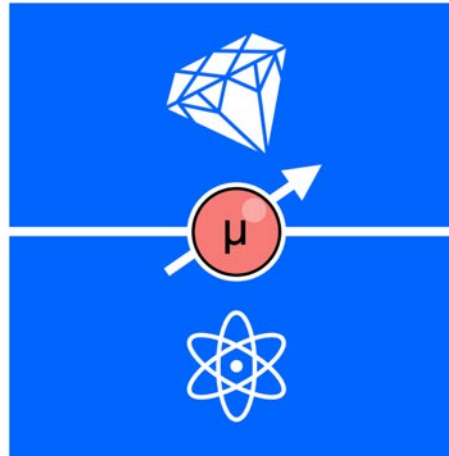
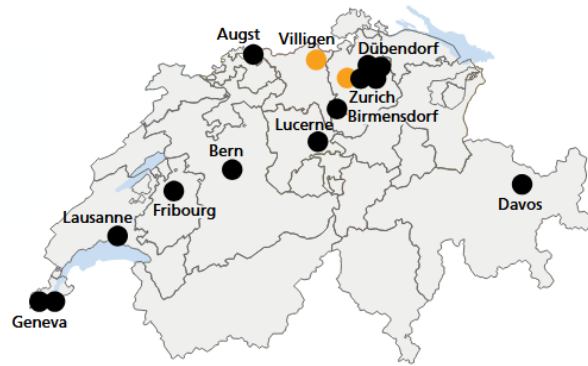
Muons for science and society — bridging discovery and application

National Centre of Competence in Research (NCCR)

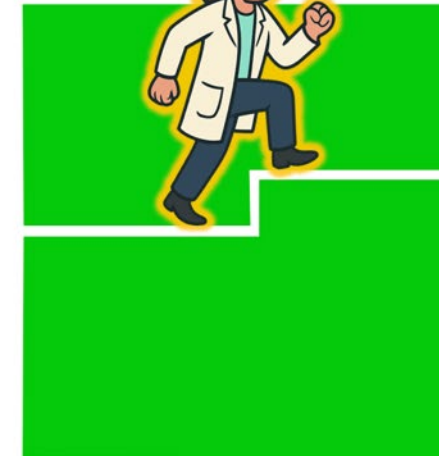


Courtesy of Marc Janoschek

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

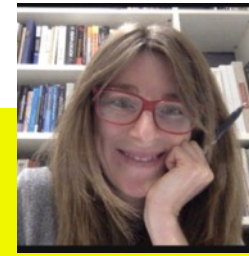


This step-change will open up the power of muons to new scientific domains and applications

- 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



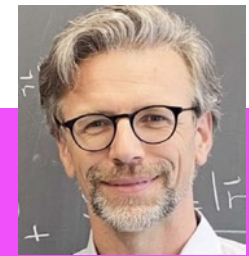
Angela Papa
Deputy Director



Leading House



Marc Janoschek
Co-Director



Titus Neupert
Deputy Co-Director



**Universität
Zürich**

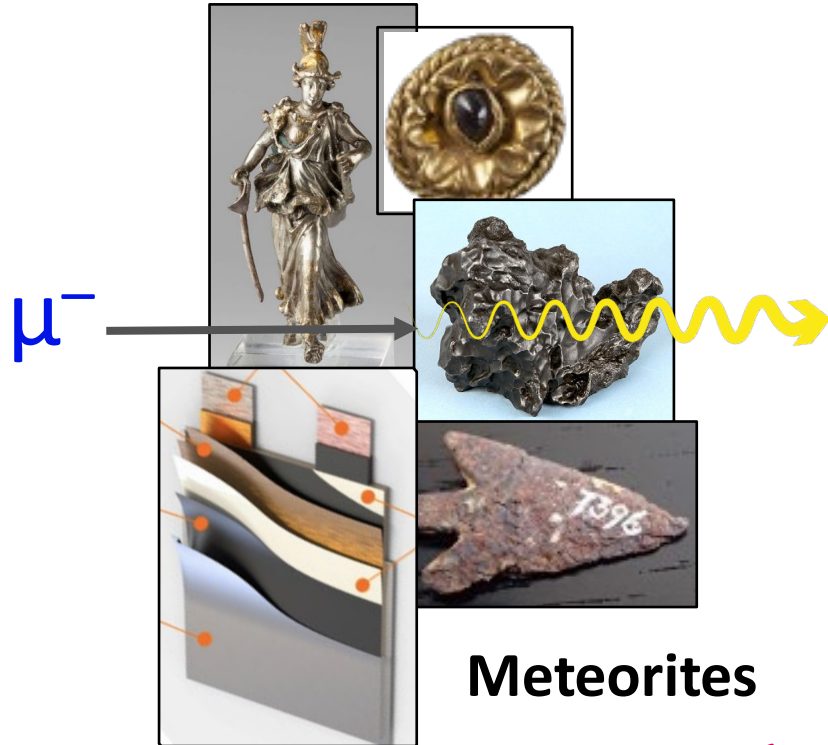
Co-Leading House

Part II

Muon **I**nduced **X**-ray **E**mission *Technique & Instrument*

MIXE: Muon Induced X-ray Emission – Overview

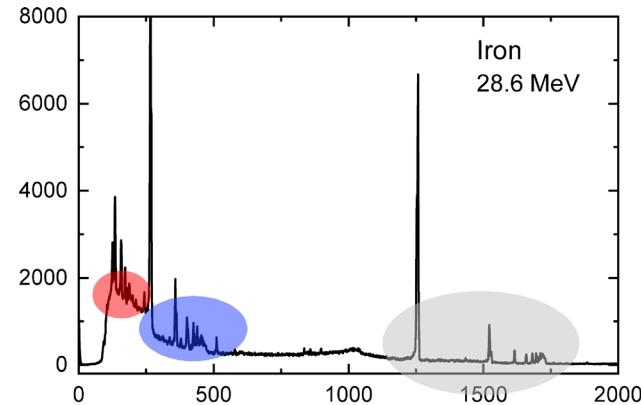
Archeological artifacts



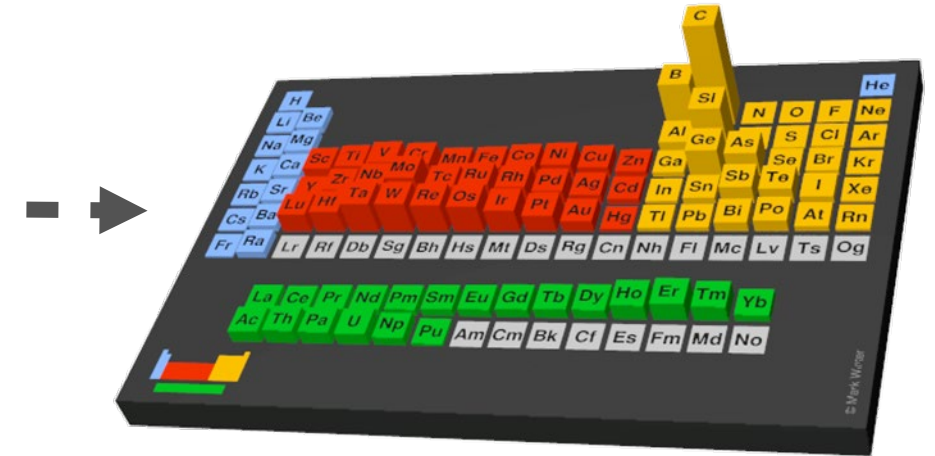
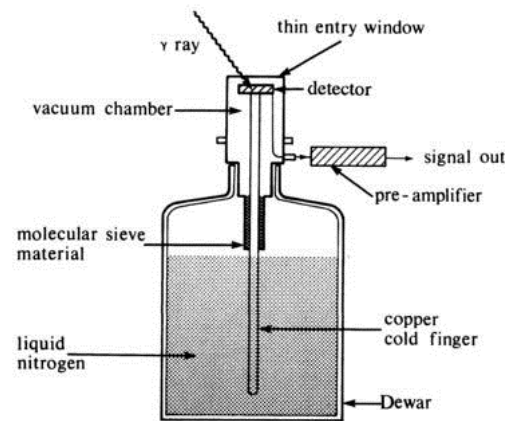
Batteries

Meteorites

and many more!



High Purity Germanium Detectors

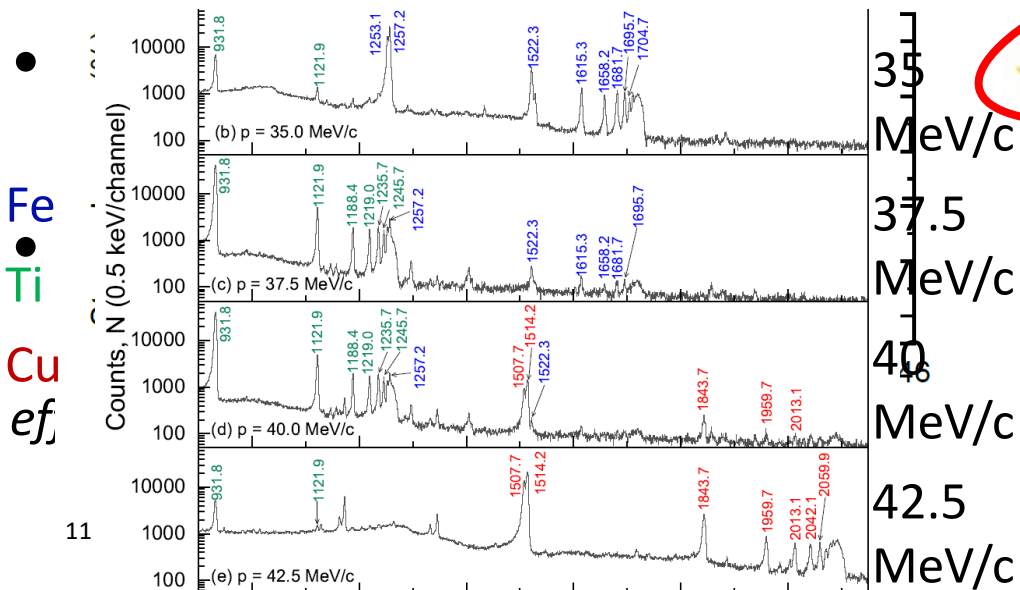
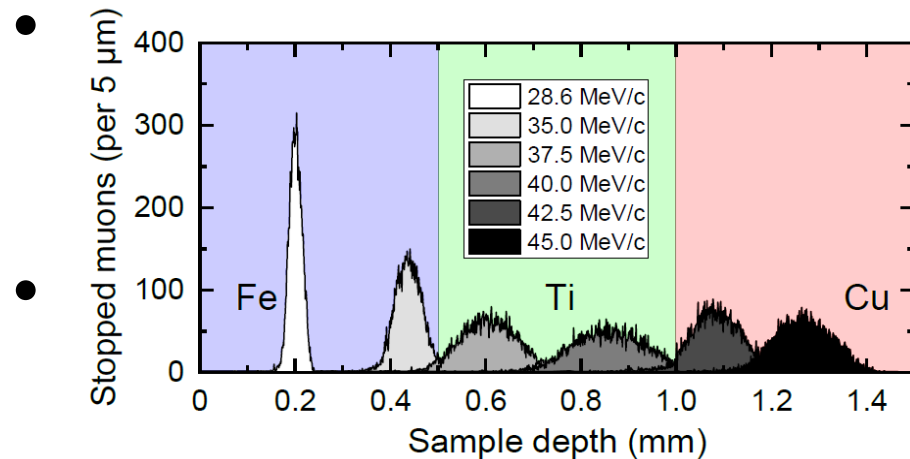


Highlights:

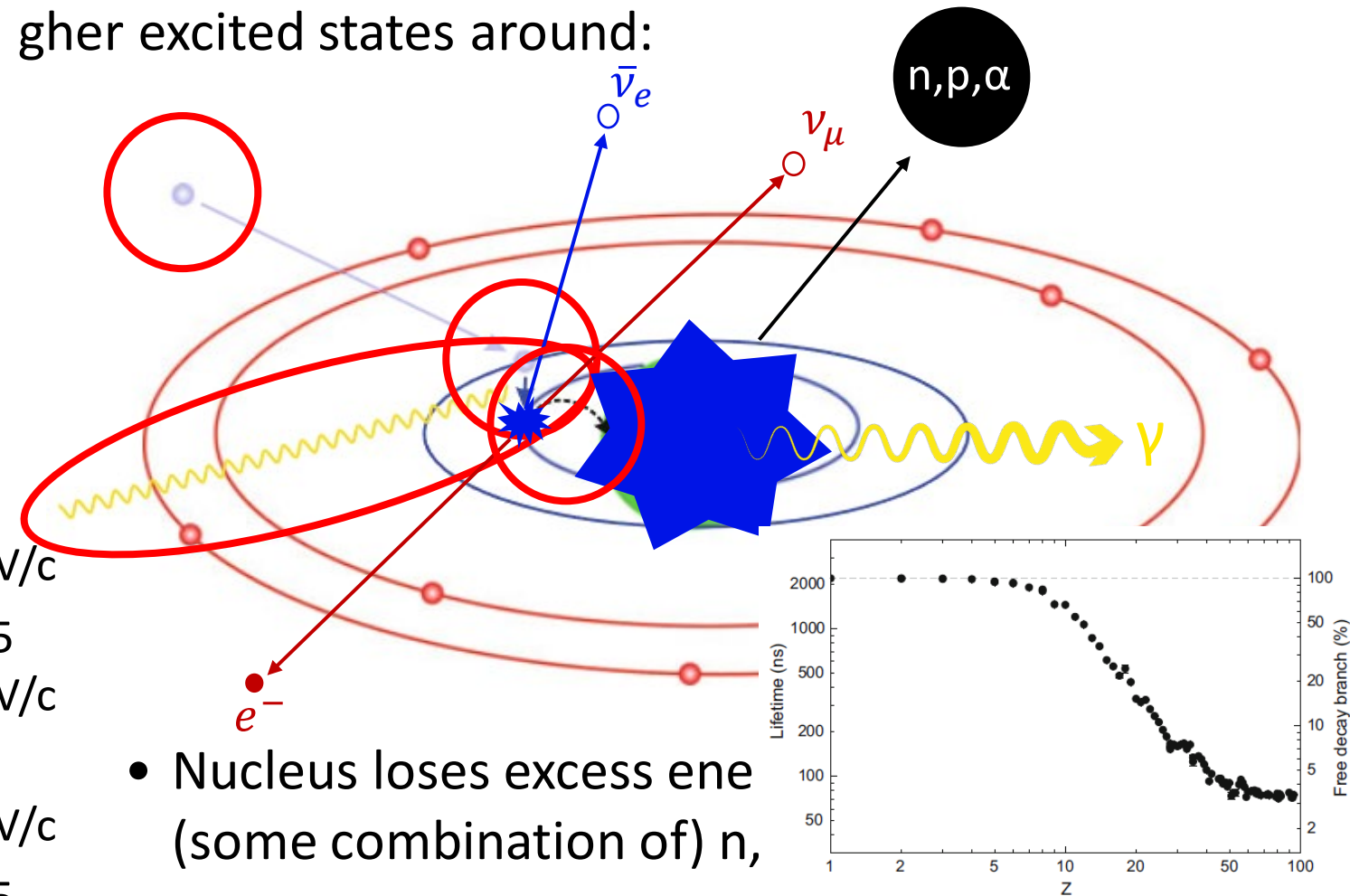
- Sensitive to all elements
- Isotopic composition (high Z)
- Indications of chemical states
- Depth-resolved ($\sim \mu\text{m}$ to $\sim \text{cm}$)
 - Completely non-destructive
- Element-sensitive Tomography

MIXE: Muon Induced X-ray Emission – Physics

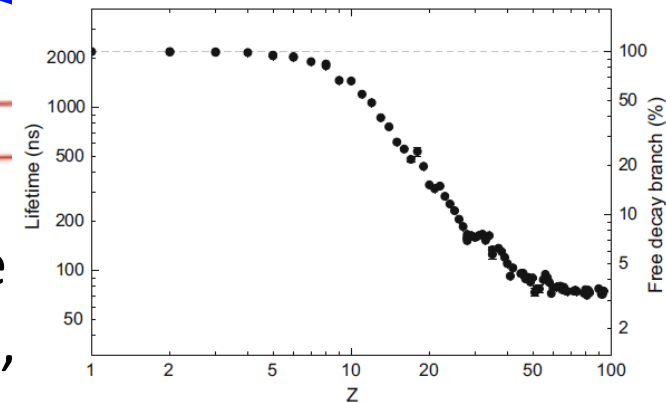
- Muon is implanted (Bragg peak; depth given by momentum and density of material)

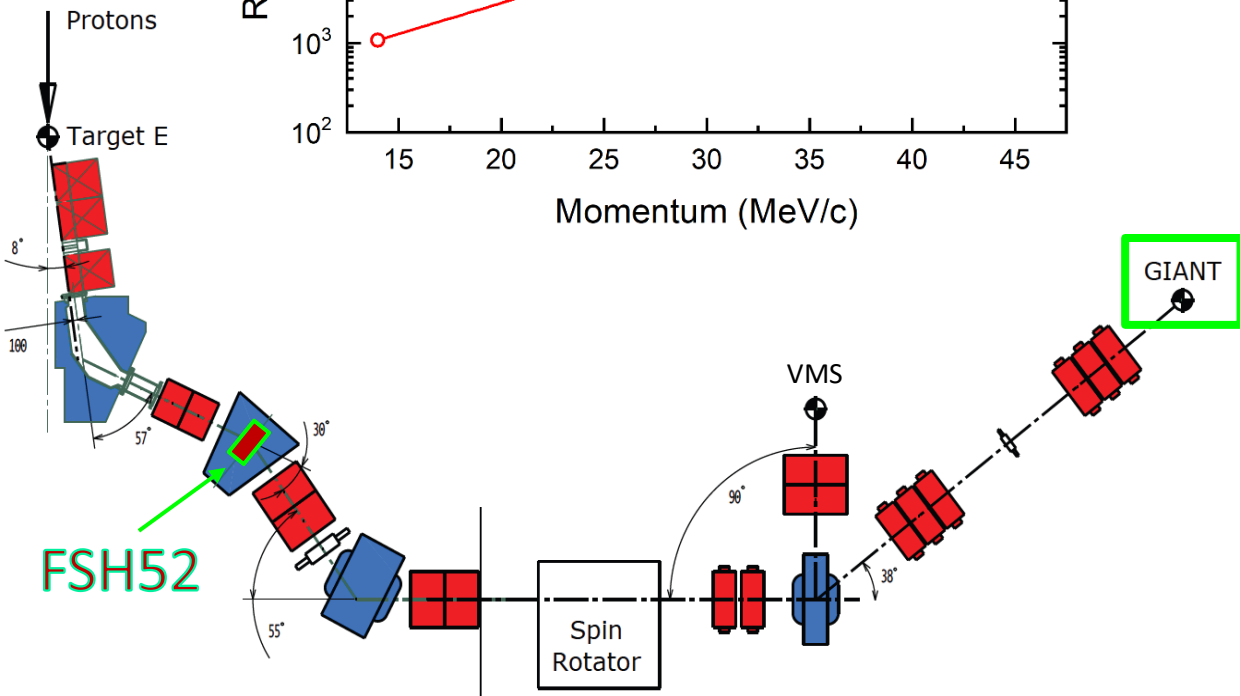
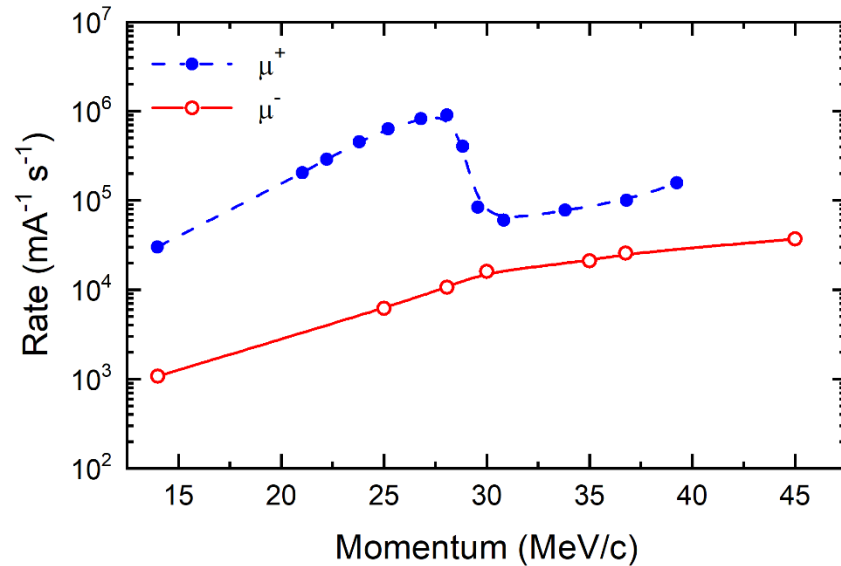


gher excited states around:



- Nucleus loses excess ene (some combination of) n ,





High intensity π beamline at target E

- production of “cloud” π^- and decay to μ^-
- typical μ^- momenta: **15-60 MeV/c**
*momentum bite: **$\sim 0.2\%$ to 3% (FWHM)***

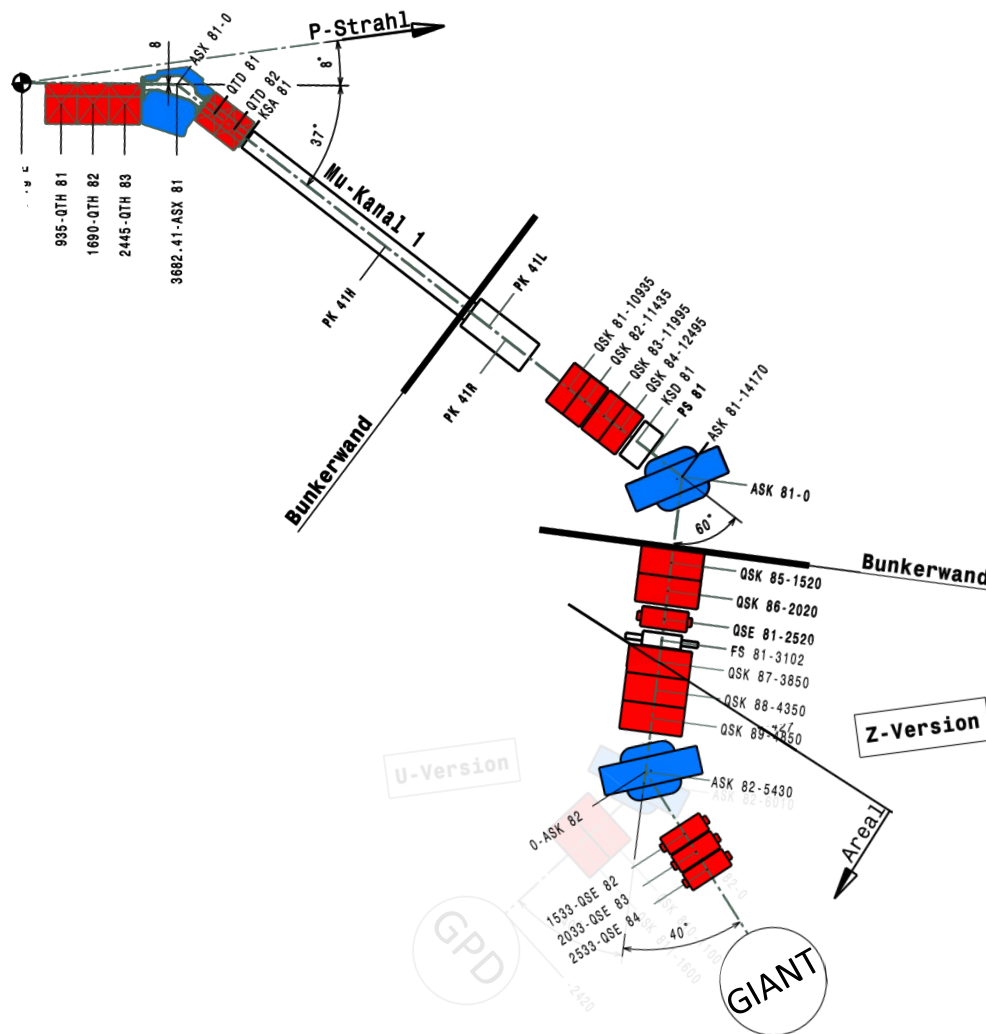
*implantation depths: **$\sim 10\mu\text{m}$ to $\sim \text{cm}$***

Rates from 10^3 up to $10^5 \mu^-/\text{s}$ on target

- close to **ideal sampling rate** (cont.!)
• *For a “typical” measurement, we collect enough statistics within **~ 1 hour***

All past MIXE campaigns hosted at π E1.2

- non-permanent installation
- so far ~ 3 weeks beam time per year



High intensity μ beamline at target E

- (cold-bore) superconducting decay solenoid
- typical μ^- momenta: **60-120 MeV/c**
momentum bite: 1% to 3% (FWHM)

implantation depths: ~mm to ~10cm

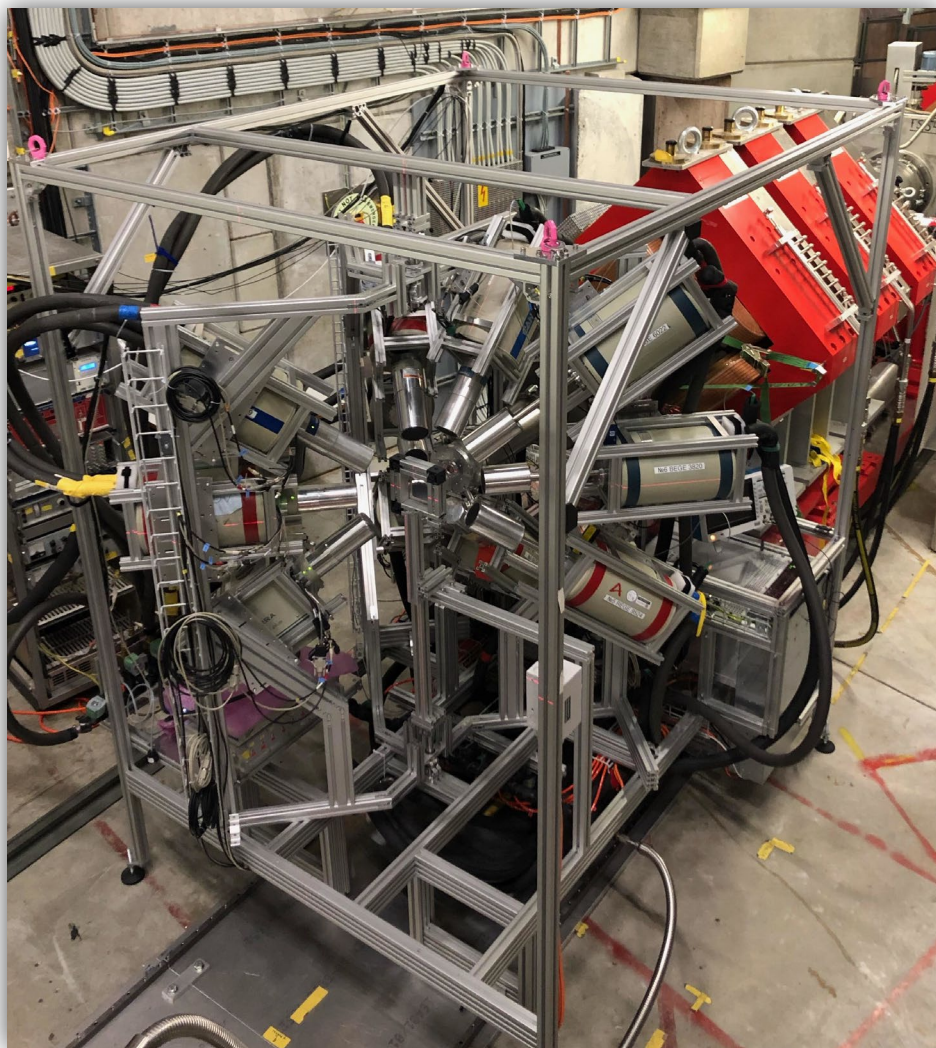
Rates from 10^7 up to $10^8 \mu^-/s$ on target

Dual configuration: U (GPD) and Z (GIANT)

Future beam-line for MIXE

- parts produced / installation planned SD 2027
 - high momentum / high rate studies (degrader)
 - shorter π E1 campaign for low mom. / high res.
- If funding permits: *Warm-bore upgrade!*

GIANT: Germanium Array for Non-destructive Testing – Overview

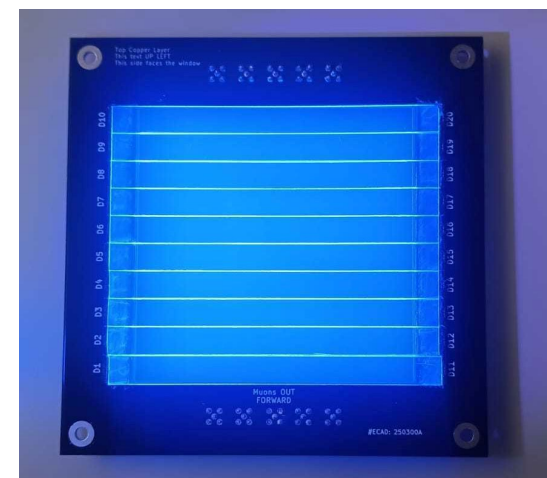
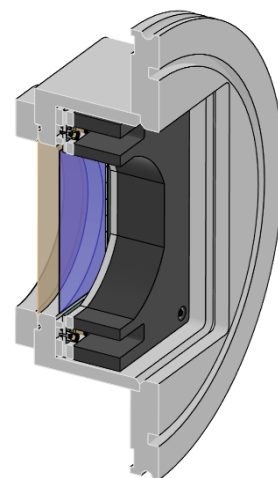


Large solid angle detector array

- 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 (~10cm Air / He 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



Part III

Muon **I**nduced **X**-ray **E**mission *Recent Studies*

Why isotopic analysis of lead?

Provides **geological fingerprints** to help **trace the origin** of archaeological metals

Conventional methods (MC-ICP-MS, TIMS)

- Highly precise (<0.1% relative)

requires removing material!

Expected differences

Ores can differ by ~5% in relative isotope abundances (e.g. Milos, GR / Bushmanland, ZA)

Geologically similar sources: often only per-mille-level differences or overlapping signatures

Non-destructive state of the art (no reliable ^{204}Pb !)

- Nuclear Resonance Fluorescence (Ohgaki et al., 2024): ~10% (^{208}Pb only)
- Neutron Resonance Transmission Analysis (Noguère et al., 2007): ~7% (*it's complicated*)
- **MIXE** @ MuSIC (Terada et al., 2024): ~3–10%

Reference Set (3x MC-ICP-MS)



(very)
PRELIMINARY

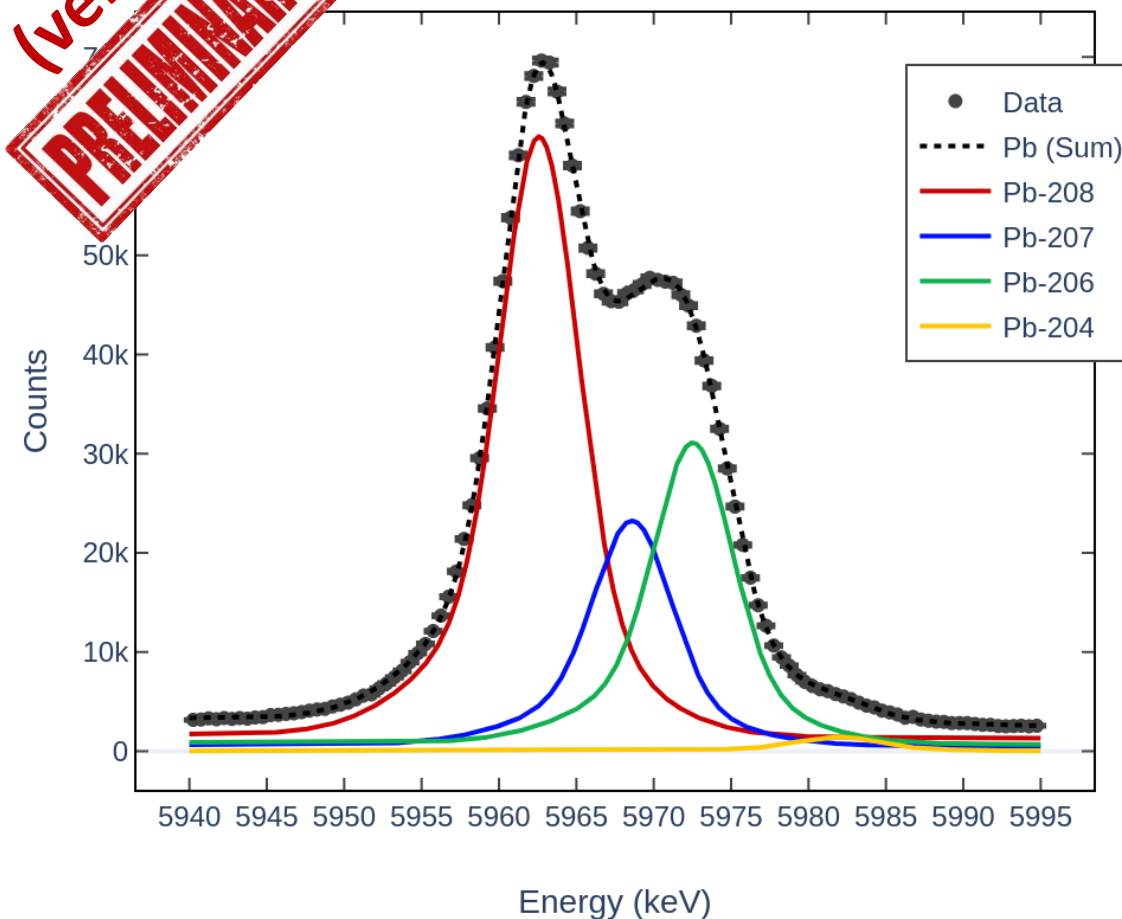
Isotope	Relative abundance error (fit 1σ)
^{208}Pb	0.3%
^{207}Pb	0.6%
^{206}Pb	0.4%
^{204}Pb	5.4%

Best so far: ~3–10%

Inv. No.	Date	208Pb/204Pb	207Pb/204Pb	206Pb/204Pb	208Pb/206Pb	207Pb/206Pb
1990.054.C05454.19	1st c. AD	38.333	15.614	18.384	2.08514	0.84933
1993.003.C09865.5	4th c. AD	38.406	15.635	18.425	2.08456	0.84858
1972.6776	3rd c. AD	38.587	15.621	18.656	2.06853	0.83744

Lead Isotopic Analysis

(very)
PRELIMINARY

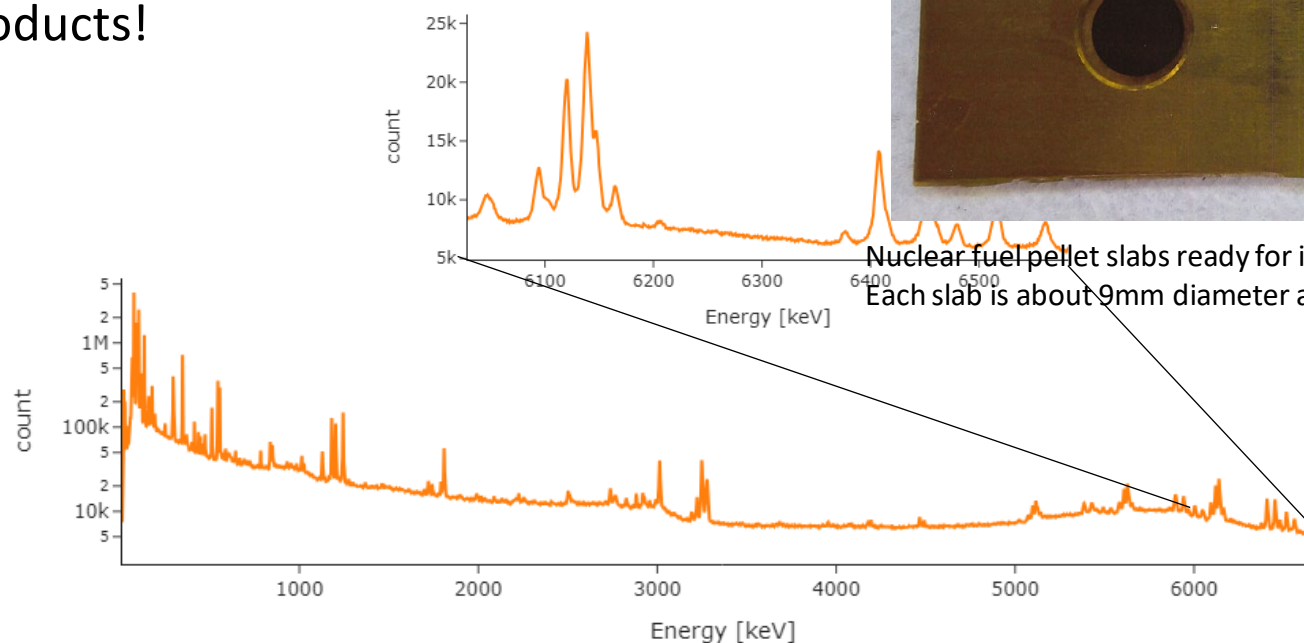
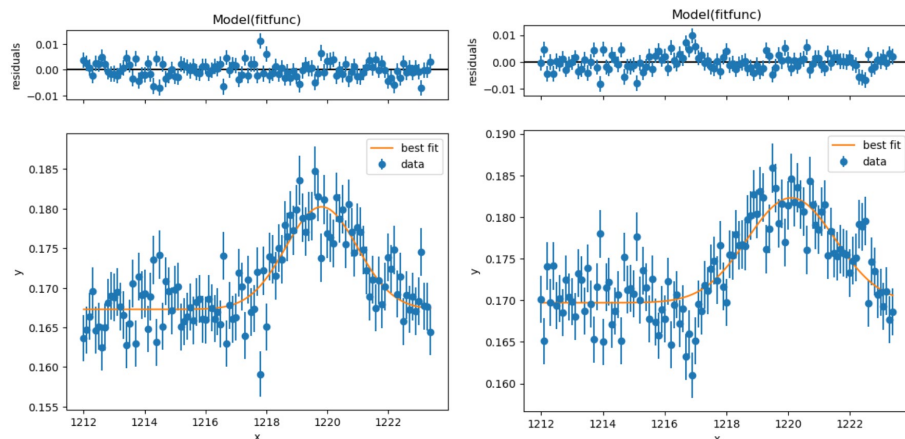


MIXE 4 Nuclear: Analysis of commercial nuclear fuel

- Proof-of-principle measurement of commercial nuclear fuel
 - Clear separation of hyperfine lines in U-235 & U-238 (highly deformed)
 - Determination of the enrichment (specs: 3.95 % and 4.8 %)
 - Simple fit of isolated U-235 line with constant BG in both samples
 - **Ratio of intensity (from specs: 0.83): 0.85 ± 0.11**
- Long-term goals: QC of fresh & analysis of irradiated fuel samples
 - *Direct* determination of fission products!



Nuclear fuel pellet slabs ready for irradiation at MIXE.
Each slab is about 9mm diameter and weighs 0.5g.



Part IV

Muon **I**nduced **X**-ray **E**mission *Elemental **T**omography*

MIXE-T(omography): Introduction

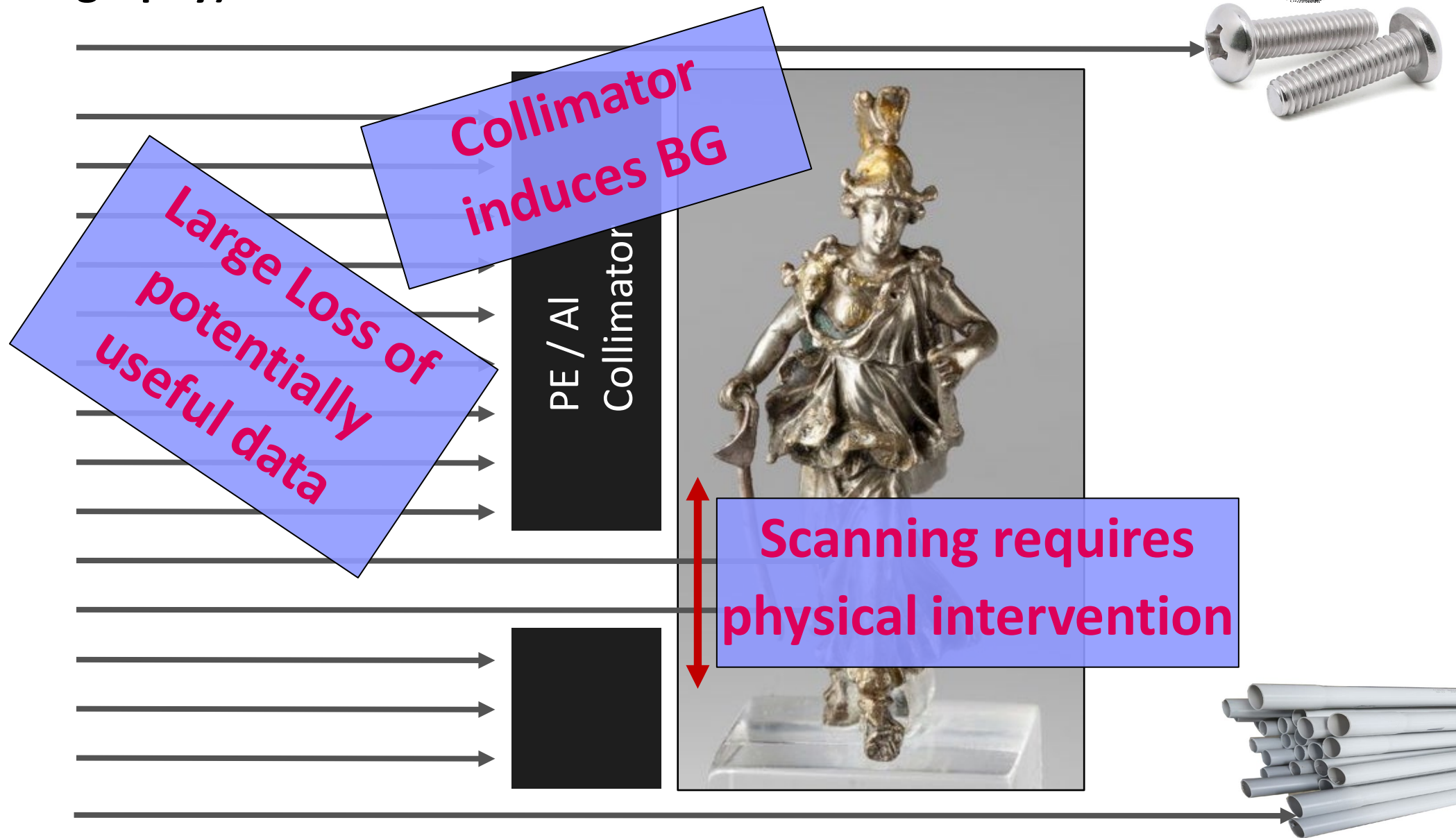
PSI

μ^-



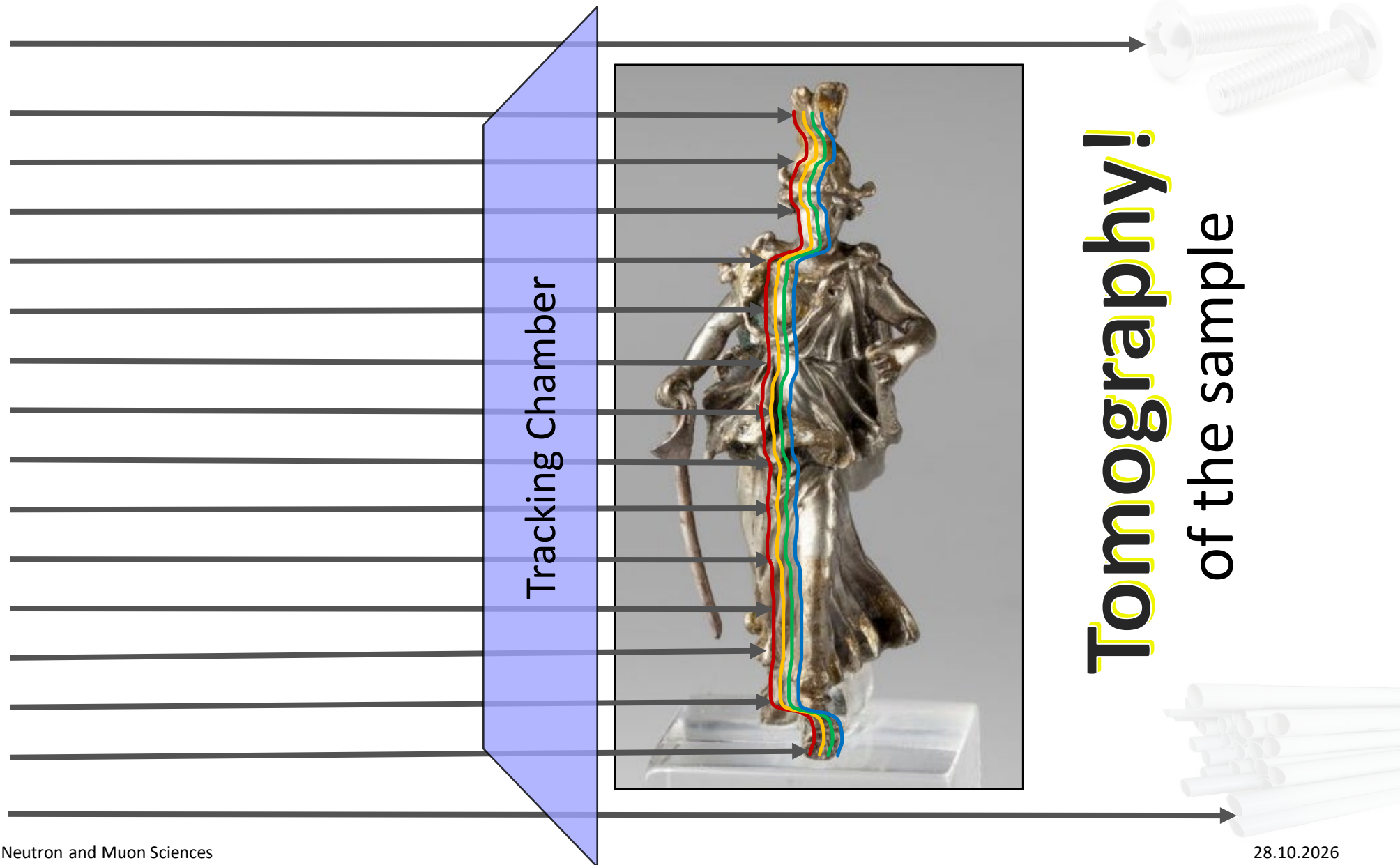
MIXE-T(omography): Introduction

μ^-



MIXE-T(omography): Introduction

μ^-



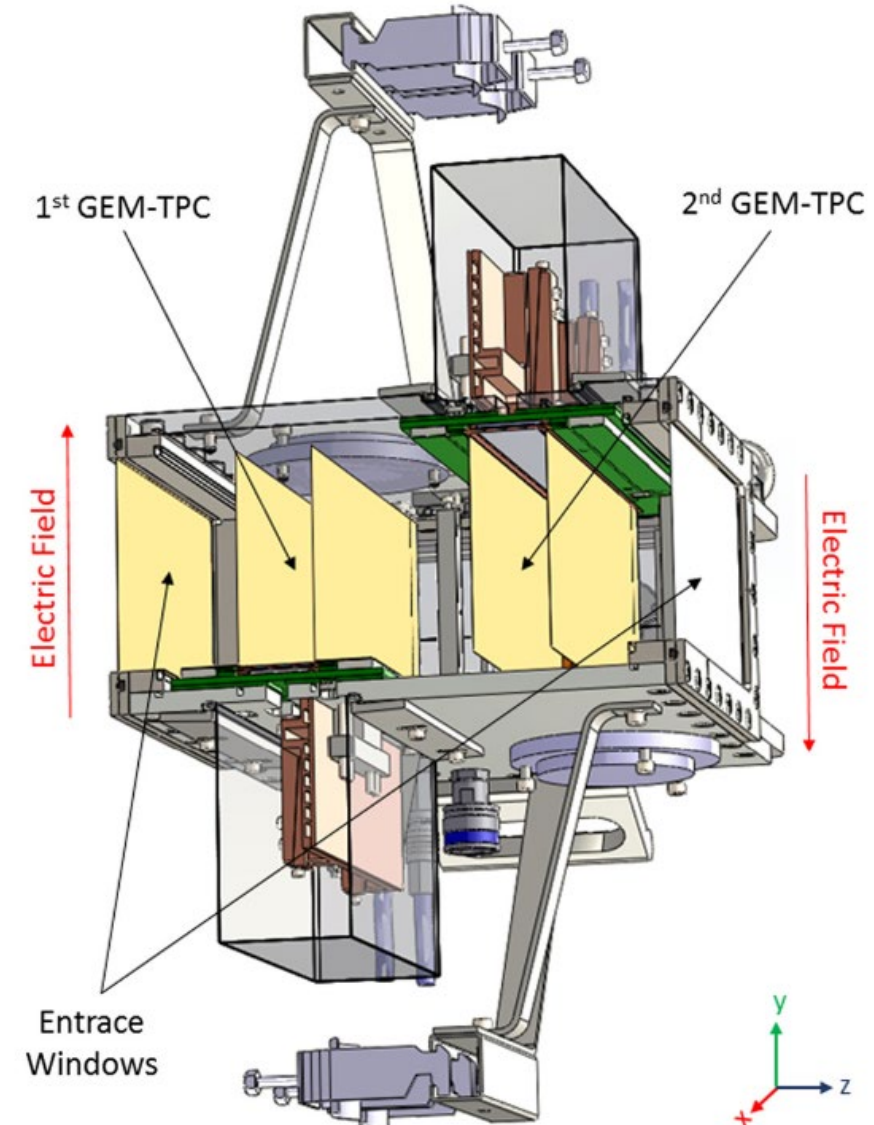
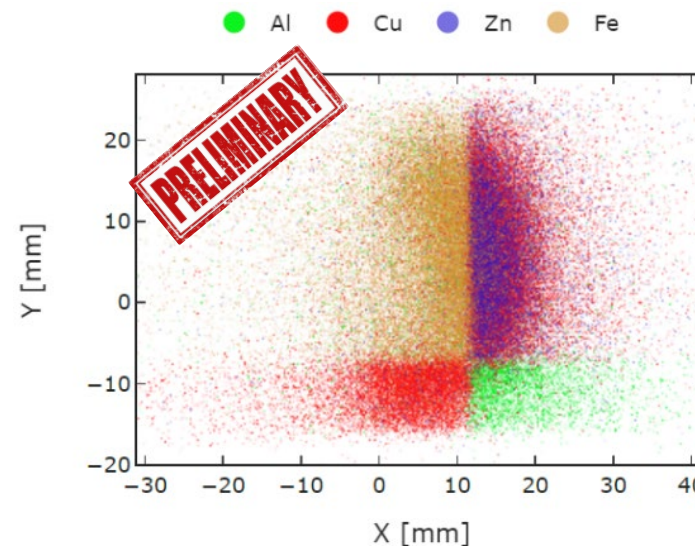
MIXE-T(omography): Muon Tracking

Adaptation of existing tracking detector prototype

- Twin TPC (Time-Projection-Chamber) (active area: $20 \times 10 \text{ cm}^2$)
- Triple GEM stack amplification stage
- 1D strip readout – 0.4 mm pitch (1024 ch total)
- Ultra-low material budget gas (He/CO₂, up to 97:3)

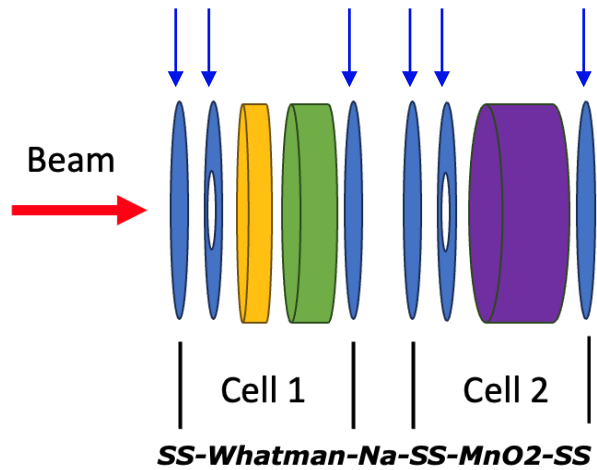
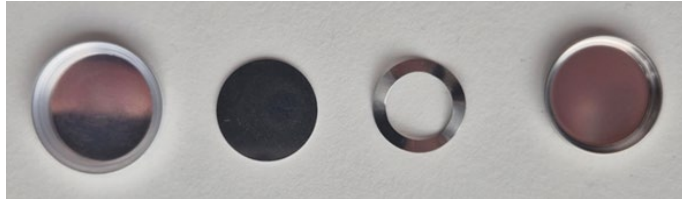
Very encouraging early results:

- Spatial Resolution $> 50 \text{ MeV/c}$ – X/Y: $\sim 1 \text{ mm}$; Z: $\sim 0.1 \text{ mm}$
- Limited by large gas volume



MIXE-T(omography): Battery tomography PoC

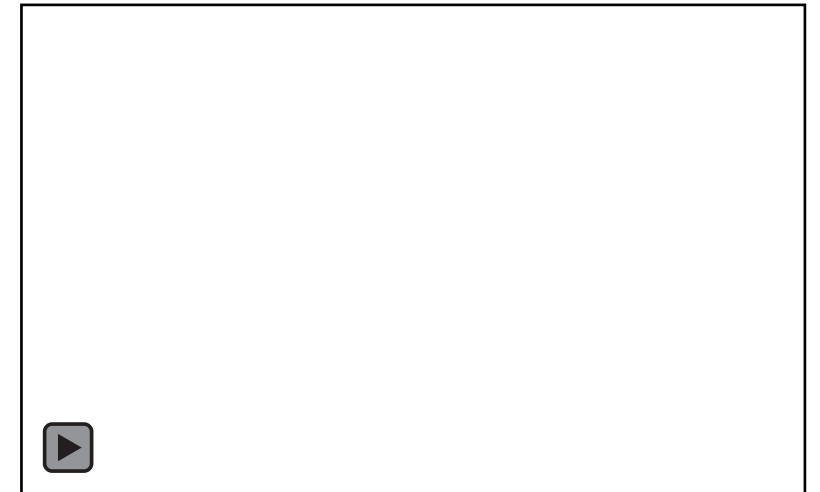
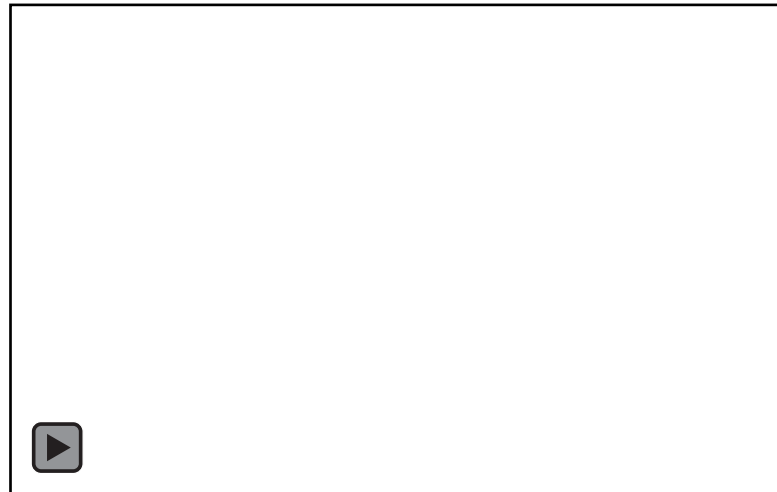
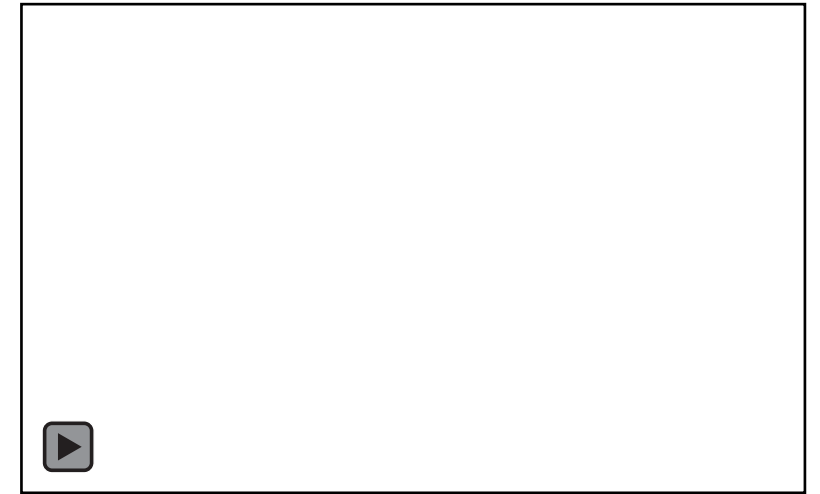
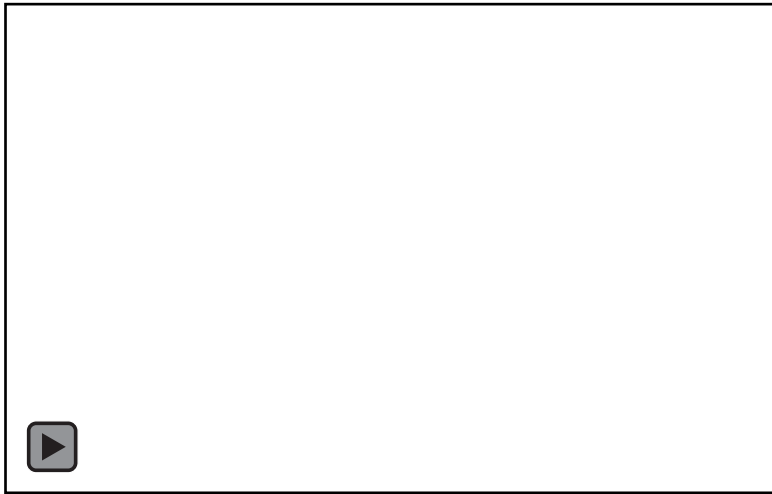
coin cell battery analogue



30/32/34/39/46/49/51

MeV/c

+interpolation



Towards the future: Truly universal elemental **MIXE-T**

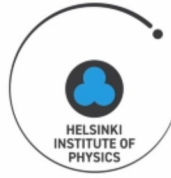
Current **MIXE-T** setup is limited by several factors

- Large detector volume → significant scattering
- resolution significantly worse than intrinsic detector resolution ($\sim 150 \mu\text{m}$)
- Depth-resolution depends on knowledge of shape and density of sample
 - can require complementary measurements, e.g. 3D-scan, X-ray CT, etc.

The solution: A custom TPC detector for **MIXE-T**!

- Miniaturized **single TPC** detector with **pixelated readout** plane
 - *reduces impact of scattering by an order of magnitude*
- Striped muon tagger
 - *reduces effective pileup significantly*
- **Multiple detectors around sample → decay electron tracking!**

**Construction of two
prototypes in progress!**



Thank you for your attention!

PSI MIXE Team: X. Zhao, L. de Sousa Borges, M. Lamotte, G. Janka, T. Prokscha, A. Amato, ...

HIP GEM-TPC: F. Garcia

DRD1/GDD Team: K. Flöthner, L. Scharenberg, E. Oliveri, ...

SDSC SAMURAI Team: T. Kacprzak, B. Béjar, ...

PP Partners: muX, ReferenceRadii, and MONUMENT collaborations

Michael W. Heiss (on behalf of the **MIXE** team)
Laboratory for Muon Spin Spectroscopy

MELODY2026, Dongguan, 25 October 2026

Backup

Muon **I**nduced **X**-ray **E**mission **T**omography

MIXE-T(omography): Completely New Possibilities!

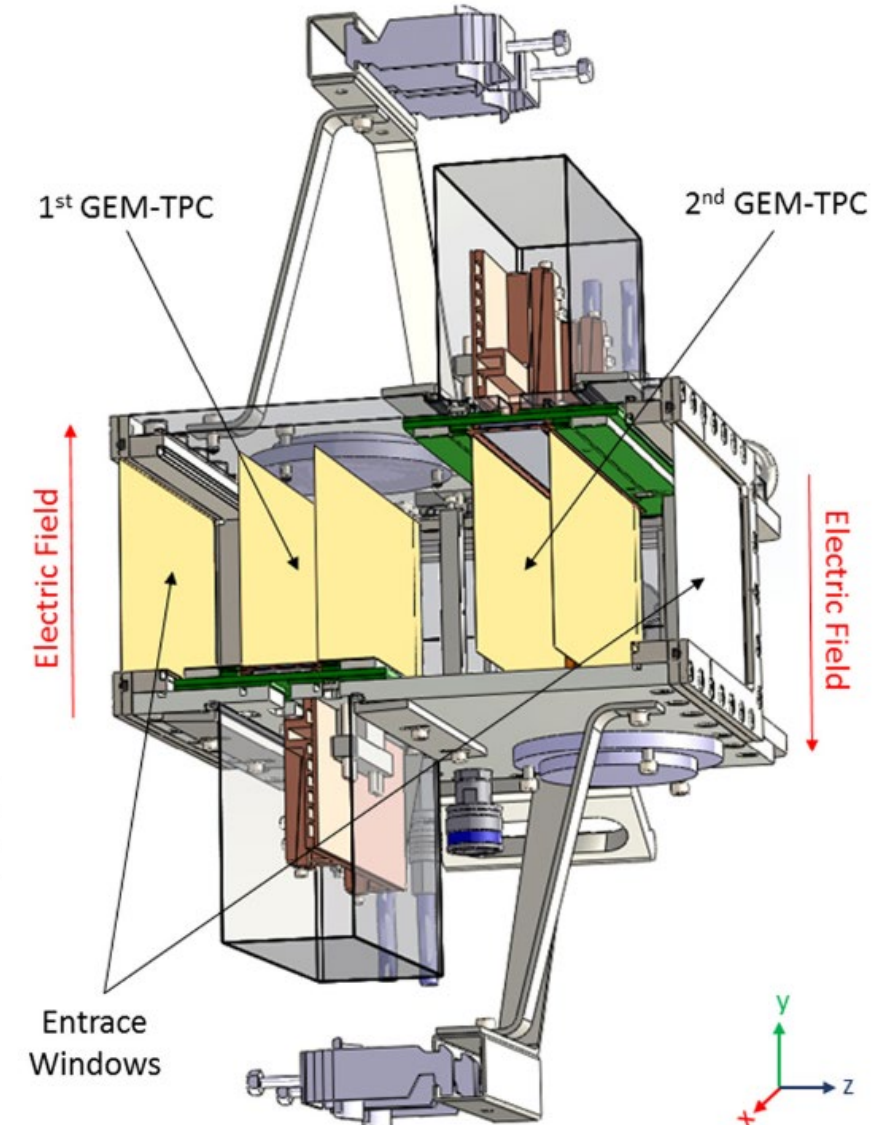
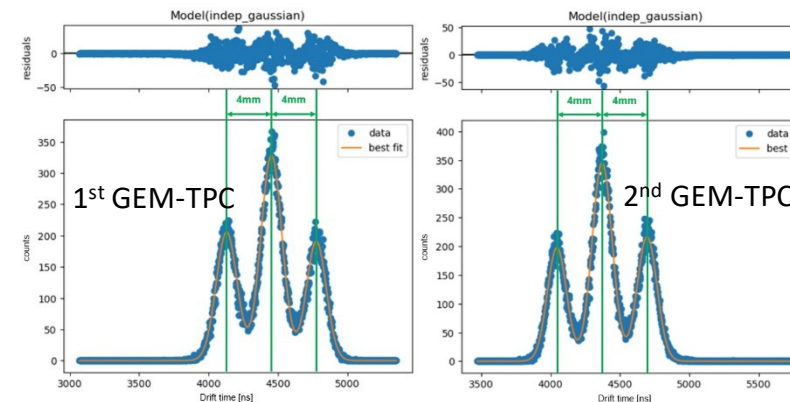


a) Vincent van Gogh's Flower Still Life with Meadow Flowers and Roses, summer 1886 (Kröller-Müller Museum, Otterlo, the Netherlands), rotated for illustration purposes.

MIXE-T could image all elements over full canvas with much higher depth-resolution!

MIXE-T(omography): Muon Tracking

- Adaptation of existing tracking detector prototype
 - Collaboration with HIP & DRD1, CERN
 - Designed for heavy ion tracking @ GSI/FAIR
- Twin Time-Projection-Chamber (Active Area $\sim 20 \times 10 \text{ cm}^2$)
 - Triple GEM stack amplification stage
 - 1D strip readout – 1024 ch in total – 0.4 mm pitch
 - X position given by cluster on strips
 - Y position by drift time(s) – *requires calibration*
- Home-made, 3D-printed drift time calibration detector
 - 3 scintillating fibers in exactly 4mm distance
 - High speed SiPM
 - In-situ calibration!



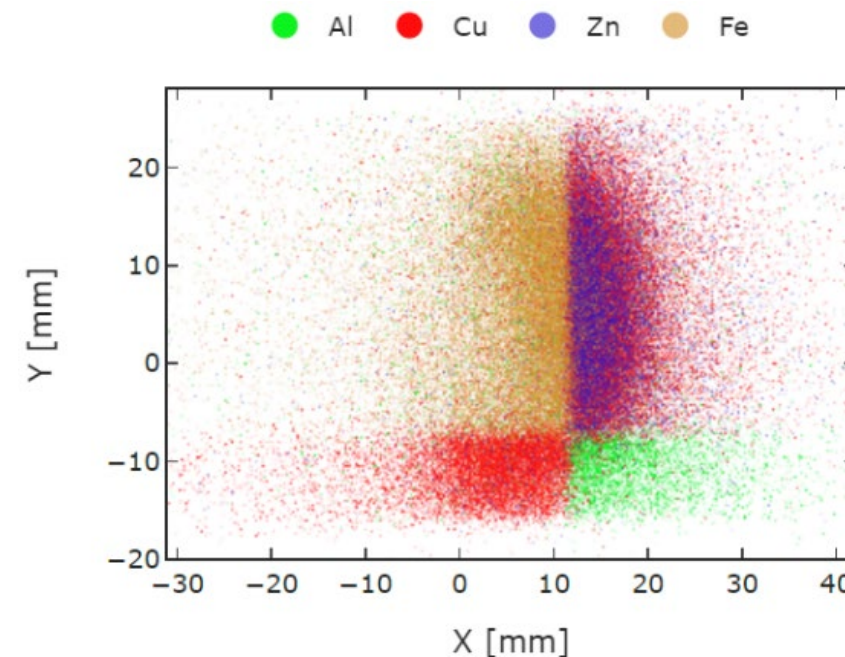
MIXE-T(omography): First Elemental Imaging (Jun 23)

Experimental setup

- Tracker mounted after beam port (roughly aligned)
- Standard Ar/CO₂ (75:25) gas mixture
- Single HPGe detector
- 60 MeV/c muon beam

Reference targets

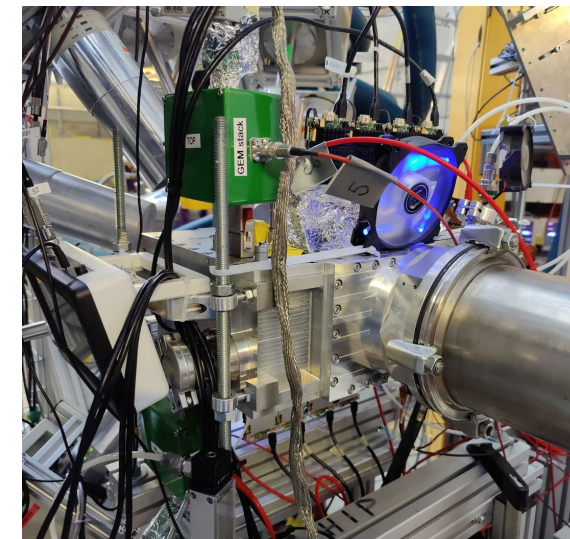
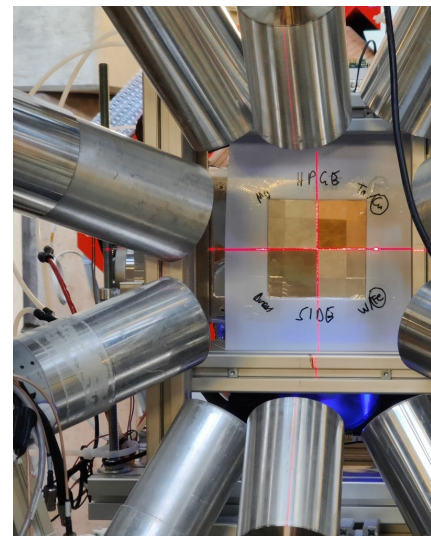
- Four metals:
 - Brass (37% Zn)
 - Aluminium
 - Copper
 - Stainless Steel: Fe, Cr, Ni, Mo, Mn, Si + traces
- Thicknesses optimized to stop downstream



MIXE-T(omography): Spatial Resolution for Tomography

Upgrades

- Layered targets & Momentum Scans
- Detector flanged directly to beamport
- Low density gas mixtures to reduce scattering
 - He/CO₂ (90:10) in 2024
 - He/CO₂ (97:3) planned for 2025

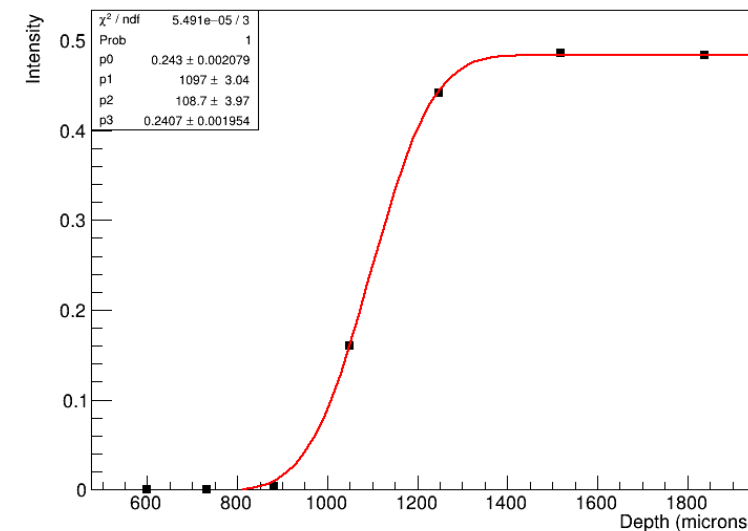
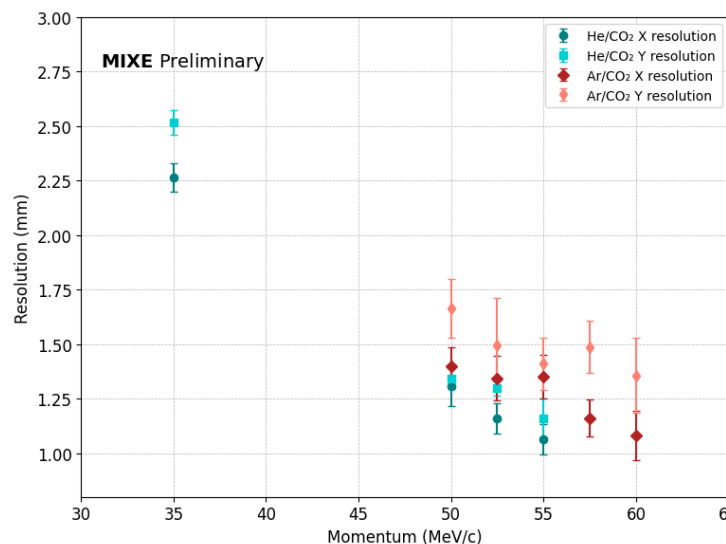


Results

- Spatial Resolution >50MeV/c:
 - X/Y: **~1 mm**
 - Z: **~0.1 mm**

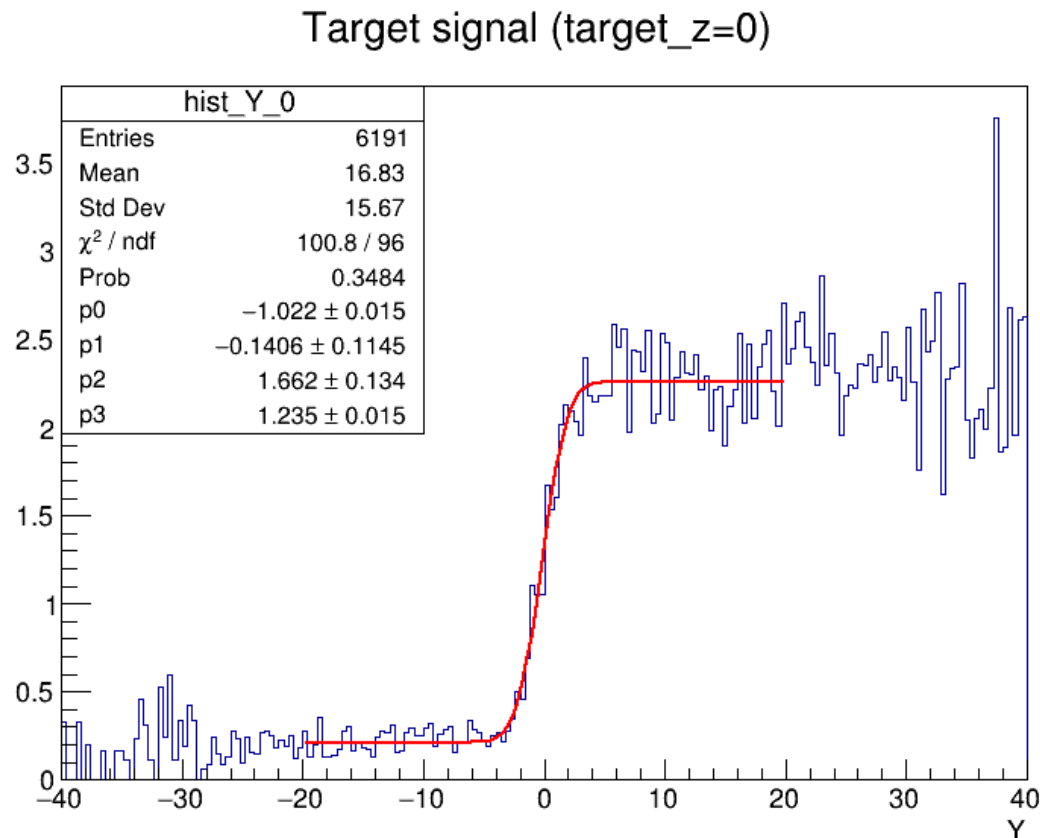
Limited by large gas volume

*Specialized prototype detector
in construction!*



MIXE-T(omography): Determining the Resolution

PRELIMINARY



Step 1: Select the desired element (Mo)

Step 2: Normalize the data by the beamspot

Step 3: Select a X/Y range to remove background

Step 4: Sum the data along the X/Y axis

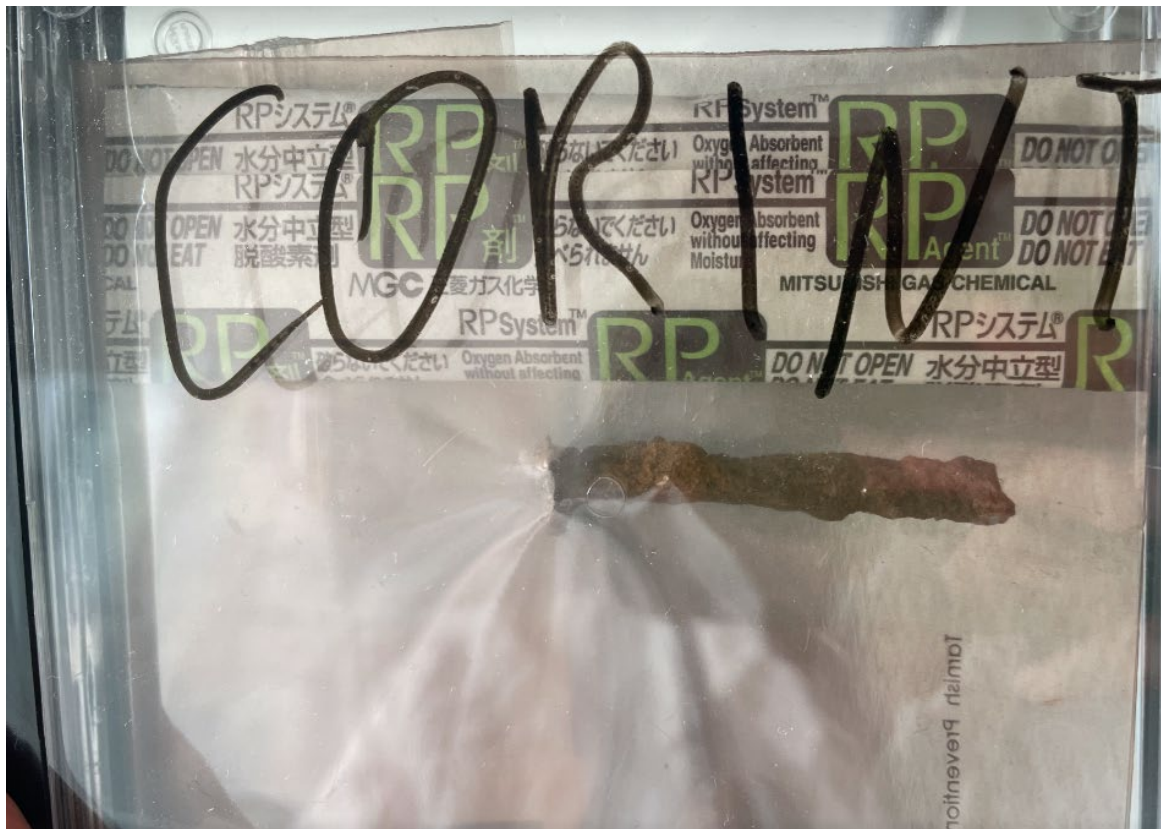
Step 5: Fit result using a Gauss error function

$$F(x) = P[3] + P[0]e^{\left(\frac{x-P[1]}{P[2]}\right)^2}$$

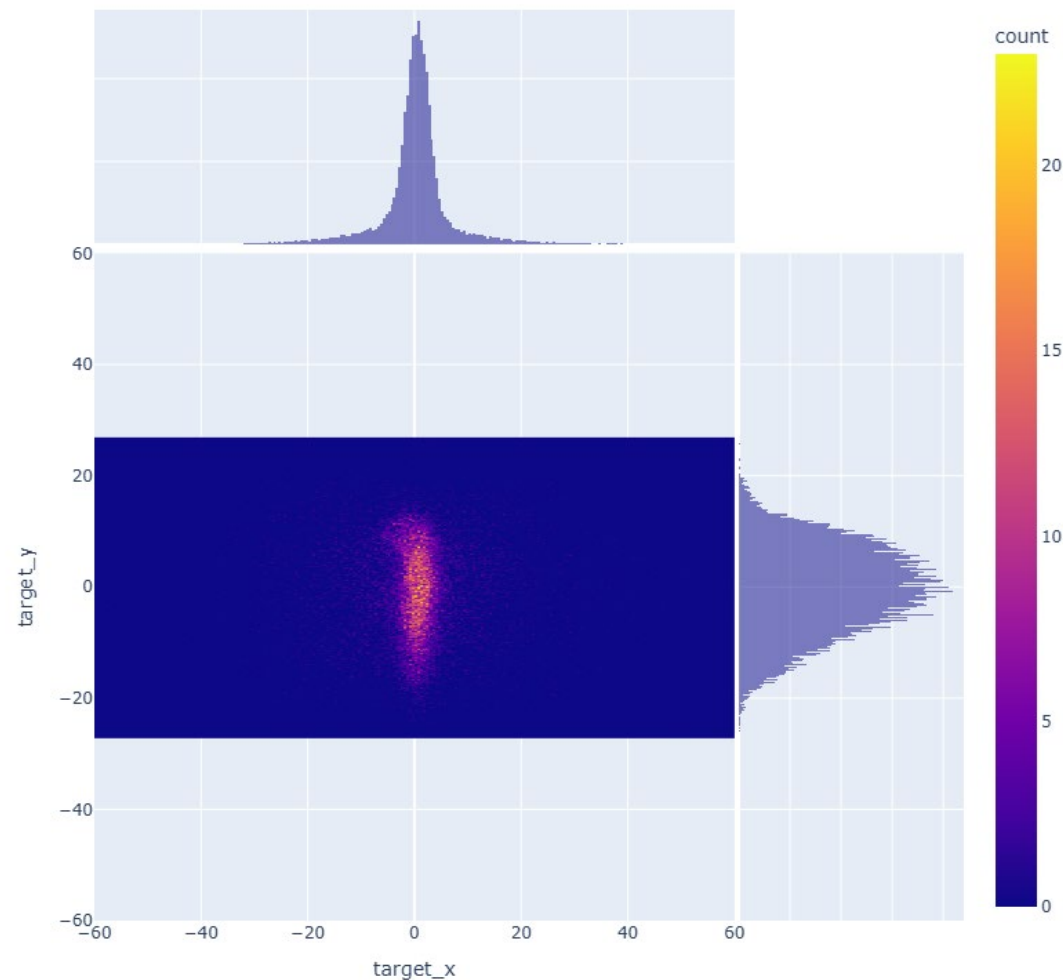
P[1]: mean P[2]: sigma

MIXE-T(omography): “Real” Sample

- Roman iron nail (fresh find – conservation study)
- ~1.5 hours data collection with 46MeV/c muons
- Spot size covering only ~50% of the nail



- Tracks filtered for Fe K_α and K_β peaks



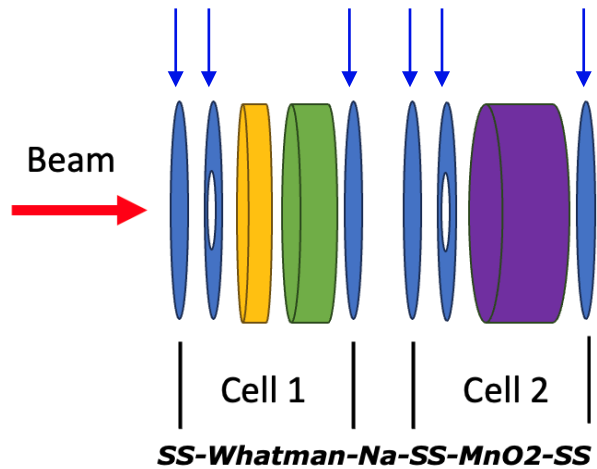
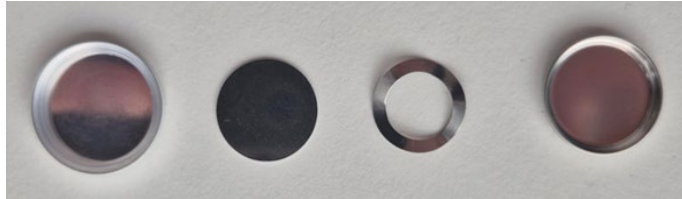
MIXE-T(omography): “Real” Sample

PRELIMINARY



MIXE-T(omography): Battery tomography PoC

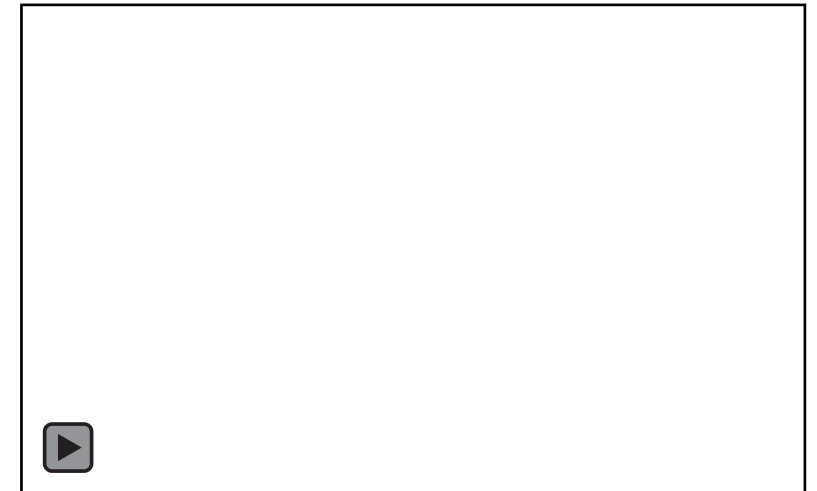
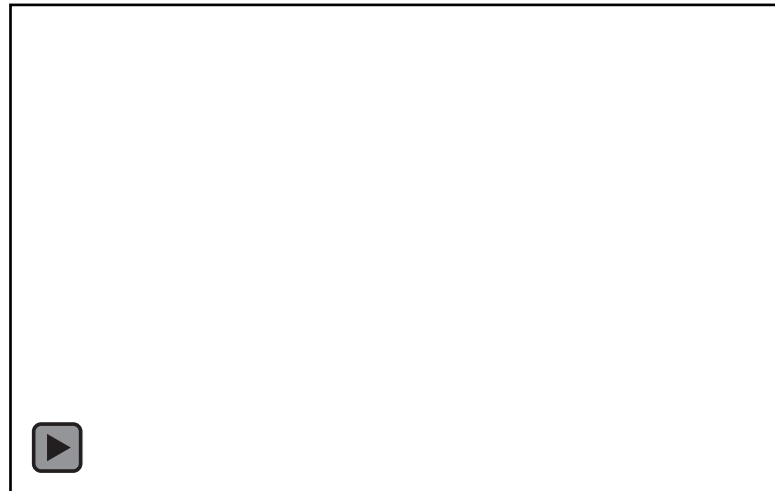
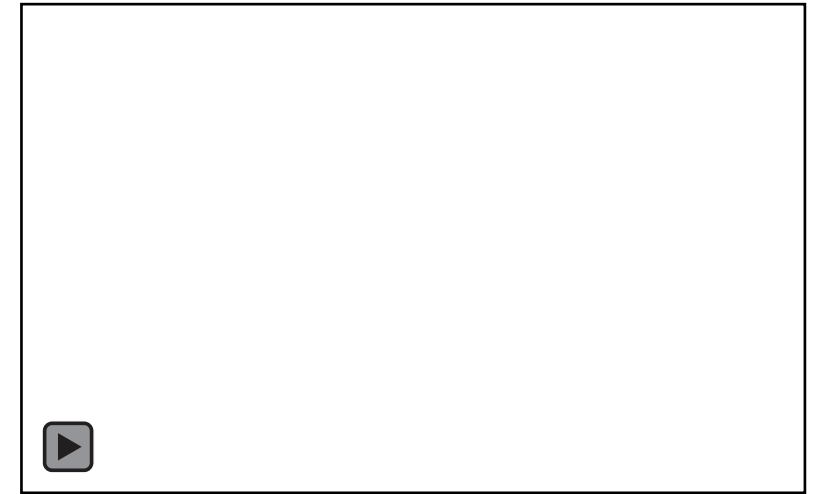
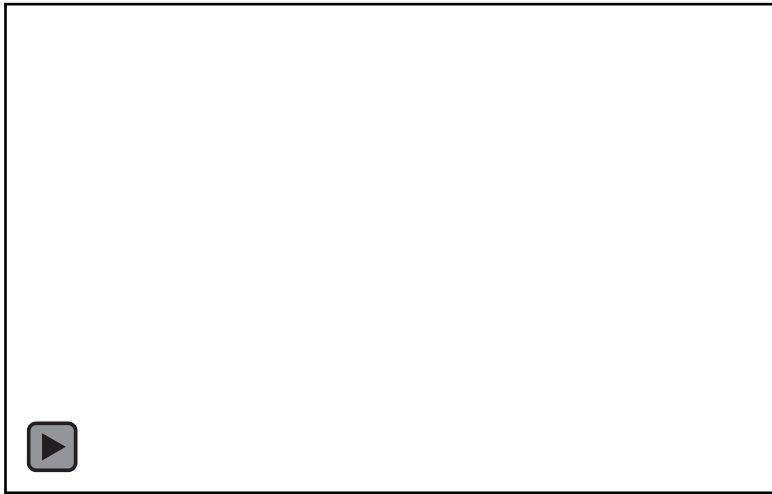
coin cell battery analogue



30/32/34/39/46/49/51

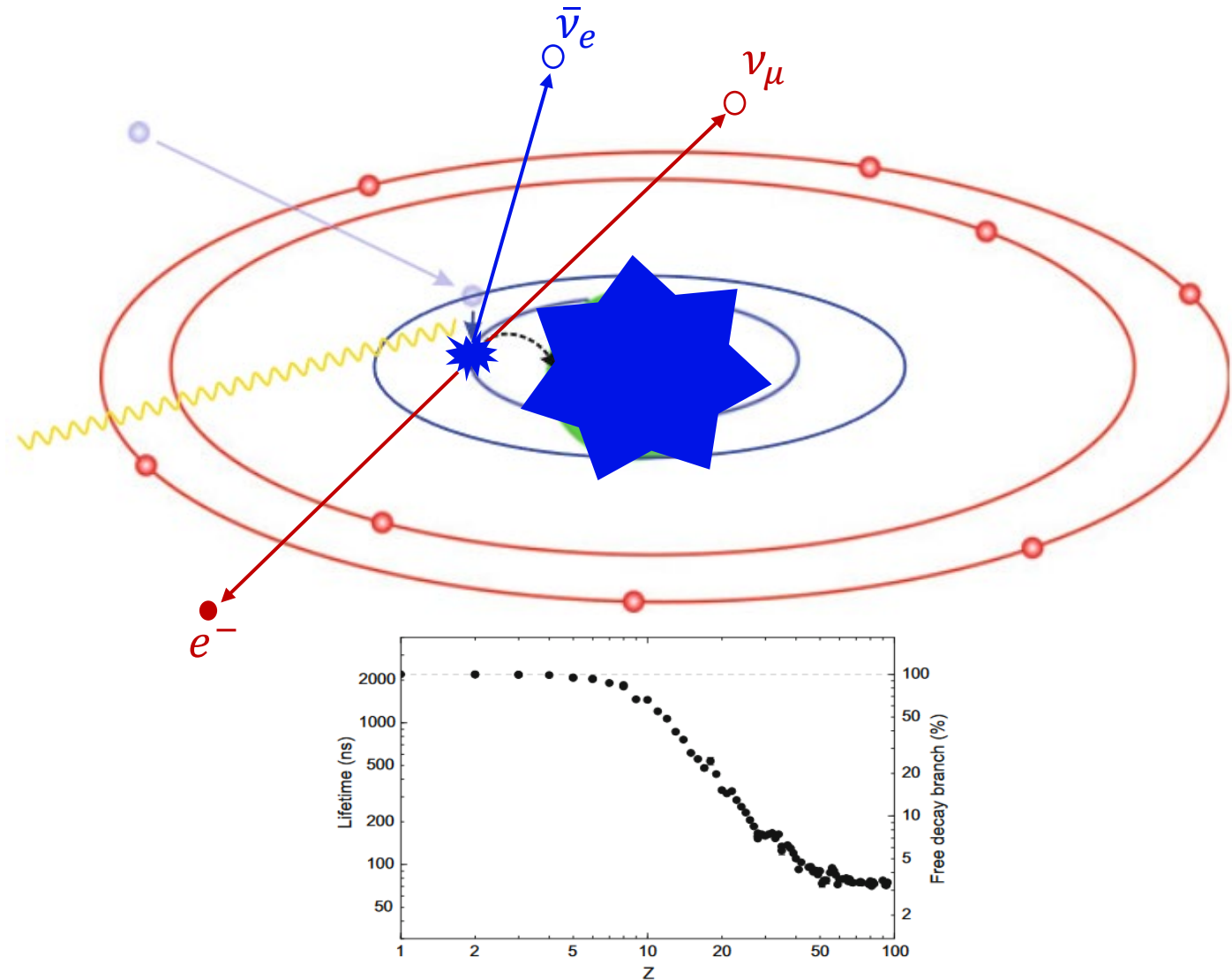
MeV/c

+interpolation



Towards the future: Decay electron tracking and measurement of muon lifetimes

- Tracking of decay electron allows direct determination of stopping position
 - *No a-priori knowledge of sample required!*
- Muon lifetime effectively suppressed by nuclear capture
 - depends on Z of capturing nucleus
 - lifetime spectrum can be measured with tracker and fitted according to sample composition
- Allows to significantly enhance the sensitivity on isolated light elements
 - e.g. Li, Na in batteries; C, O content in metals (carbon steel, copper)



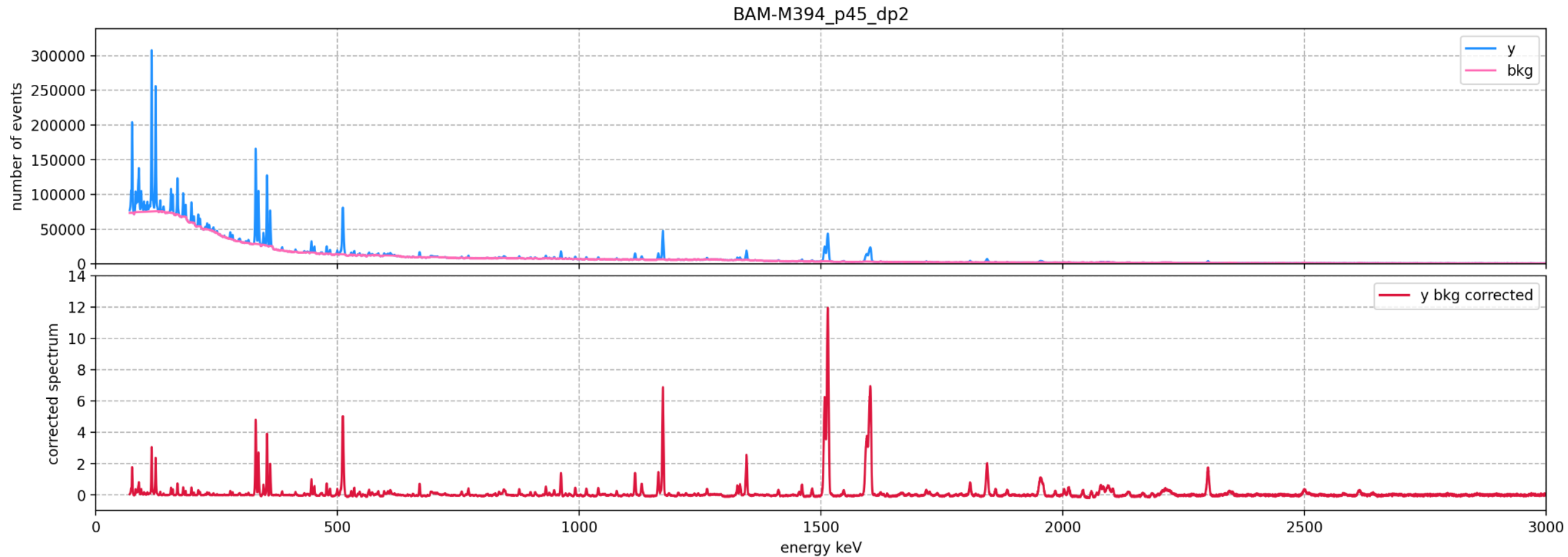
Amato, A., & Morenzoni, E. (2023). *Introduction to Muon Spin Spectroscopy*. Springer.

Backup

Smart Analysis of MUonic x-Rays with AI

- **Challenge:** *“Data analysis involves extensive domain knowledge and labor”*
 - Usually >100 (complex!) spectra taken each biannual measurement campaign
 - High degree of involvement of MIXE scientists in preparation, data-taking, and analysis
 - This leads to increasing backlog of sample analyses
- **SAMURAI:** Software development in collaboration with Swiss Data Science Center
 - Software package for fully automated analyses of MIXE spectra
 - User-friendly, no need for specialized domain knowledge or computational skills
 - Provides online analyses as immediate feedback to users
 - Allows for live changes in the experimental parameters (implantation depth, position, etc.)
 - Based on cutting-edge, efficient AI methods for rapid results (~1 minute on standard CPU)
 - Leveraging customized, problem-specific machine learning algorithm

- Step 1: Heuristic Background and Efficiency correction of raw spectra



SAMURAI: Regression Problem

- **Datafit:** Use distance between event counts (as opposed to squared residuals): Huber distance for small δ allows for this and for efficient optimization
- **Penalty:** use Hierarchical Sparsity, where main weight controls the K α lines, secondary lines are dependent on it
- **Optimization:** coordinate descent, alternating LASSO problems for w and v , fast and stable, using sparse representation of the feature (30k, 30k) matrix which saves memory and time

$$\mathbf{Huber}_\delta[a] = \begin{cases} \frac{1}{2}a^2 & \text{for } |a| \leq \delta, \\ \delta \cdot \left(|a| - \frac{1}{2}\delta\right), & \text{otherwise.} \end{cases}$$

$$\mathbf{Huber}_\delta \left[\mathbf{y} - \sum_{z=1}^Z w_z \left(\mathbf{x}_0 + \sum_{t=2}^{T_z} v_t \mathbf{x}_t \right) \right]$$

Diagram illustrating the regression model structure with labels:

- Measured spectrum**: points to $\mathbf{y}$
- Main amplitudes**: points to w_z
- K α template**: points to $\mathbf{x}_0$
- Secondary amplitudes**: points to v_t
- Secondary template**: points to $\mathbf{x}_t$
- Main penalty**: points to the $\mathbf{Huber}_\delta$ term
- Secondary penalty**: points to the v_t term

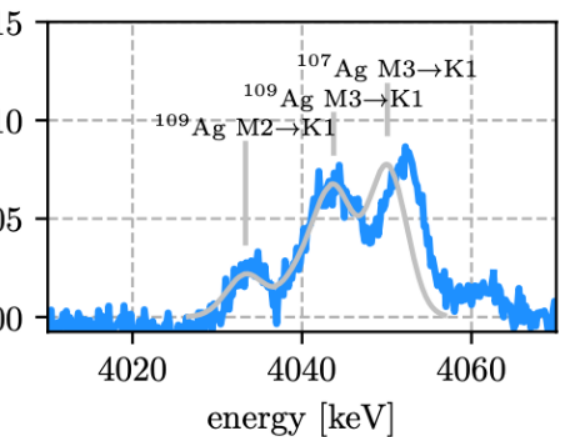
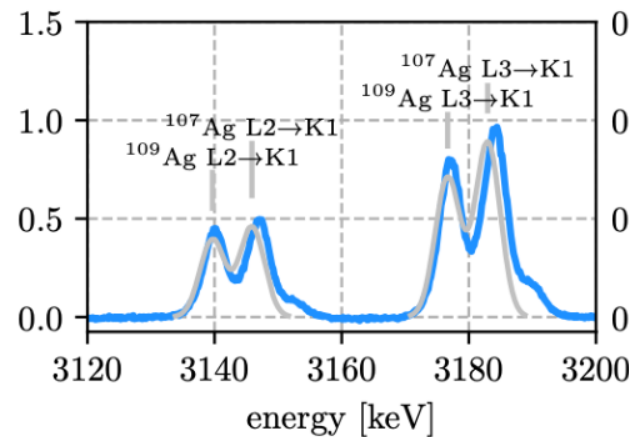
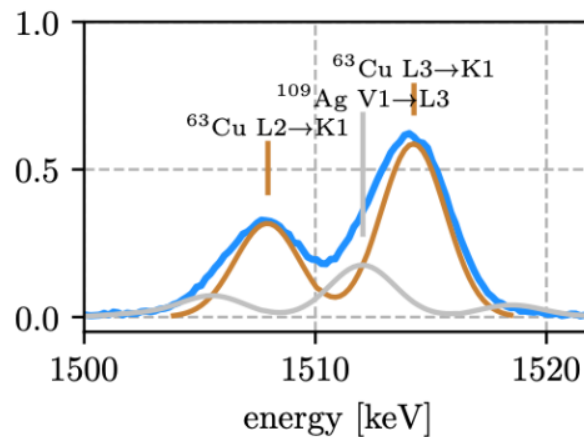
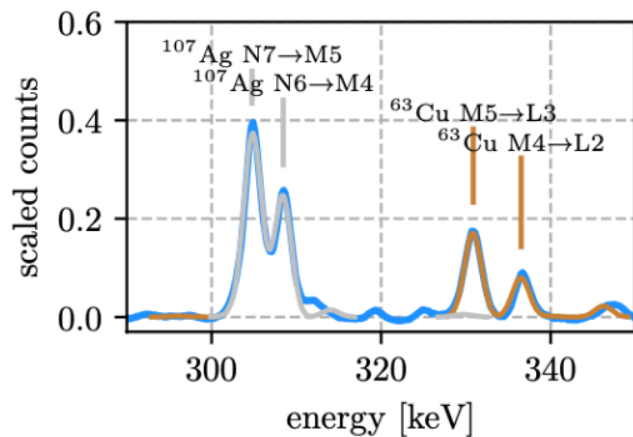
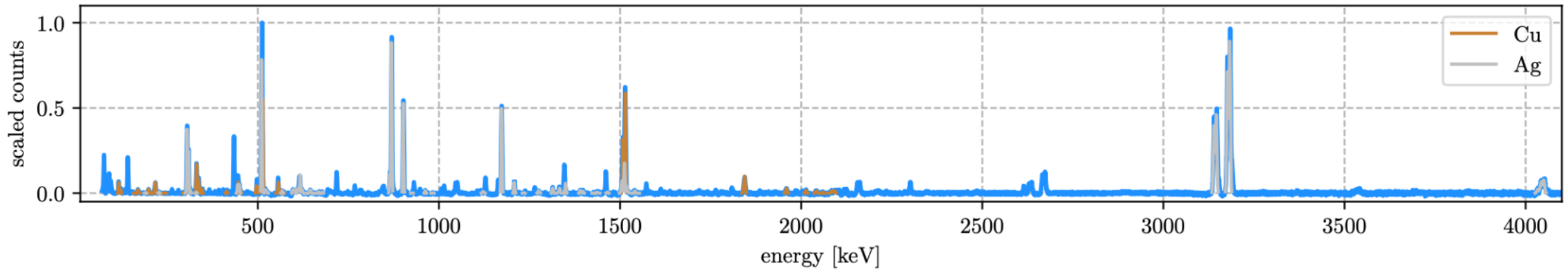
SAMURAI: Demo II

PRELIMINARY

Sturniolo, S, Hillier, A. Mudirac: A Dirac equation solver for elemental analysis with muonic X-rays. *X-Ray Spectrom.* **2020**

- Step 2: Simultaneous fitting of all theory (MuDirac 1.0) peaks, using hierarchical sparsity

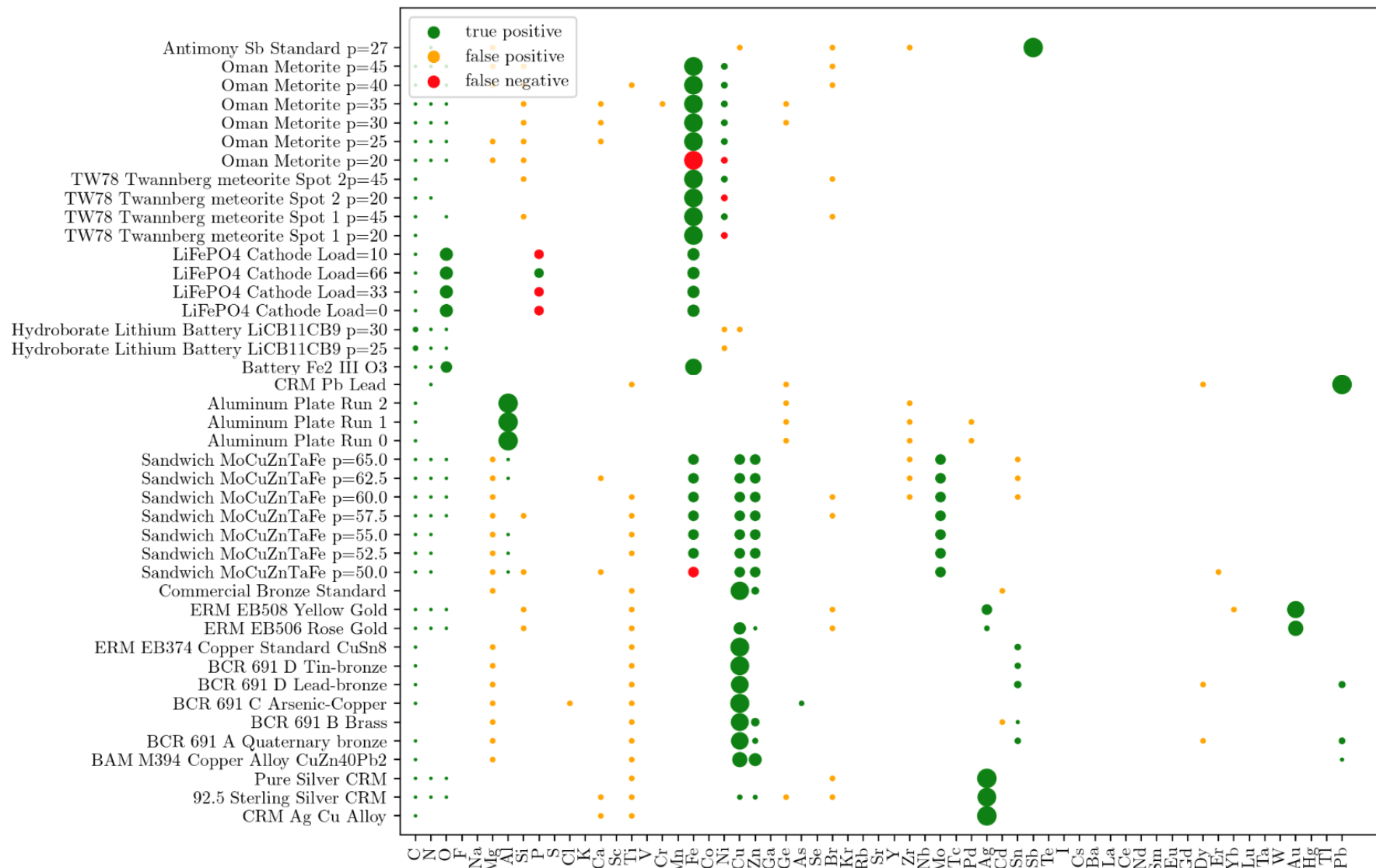
CRM Ag Cu Alloy



SAMURAI: Qualitative Results

Confusion matrix

- Almost all large elements are detected
- Very few false negatives
 - *manual check pending*
- Few false positives
 - Usually very small proportion
- Detection threshold can be tuned by user
- Additional “confidence score” in development



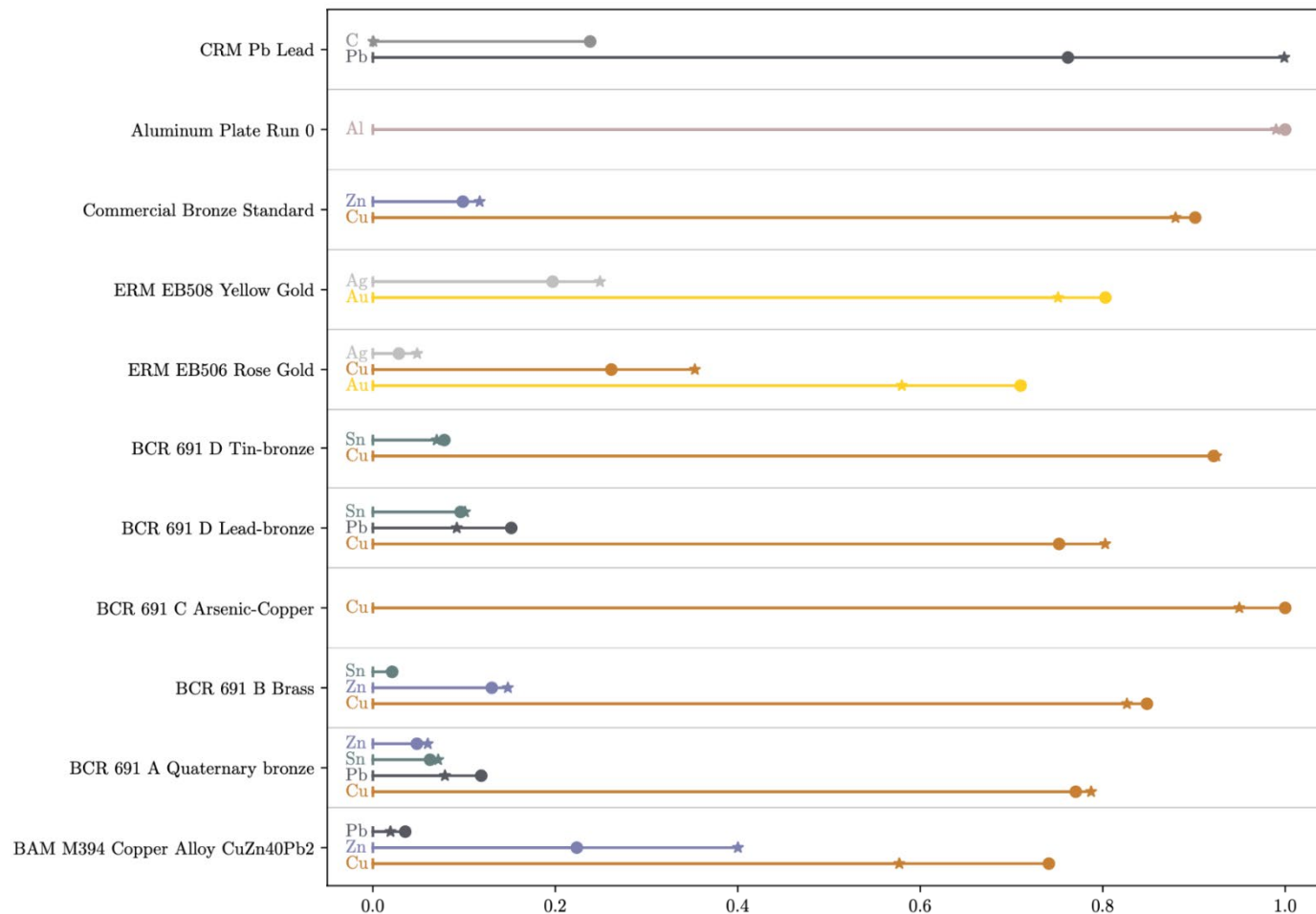
SAMURAI: Quantitative Results

PRELIMINARY

Composition table

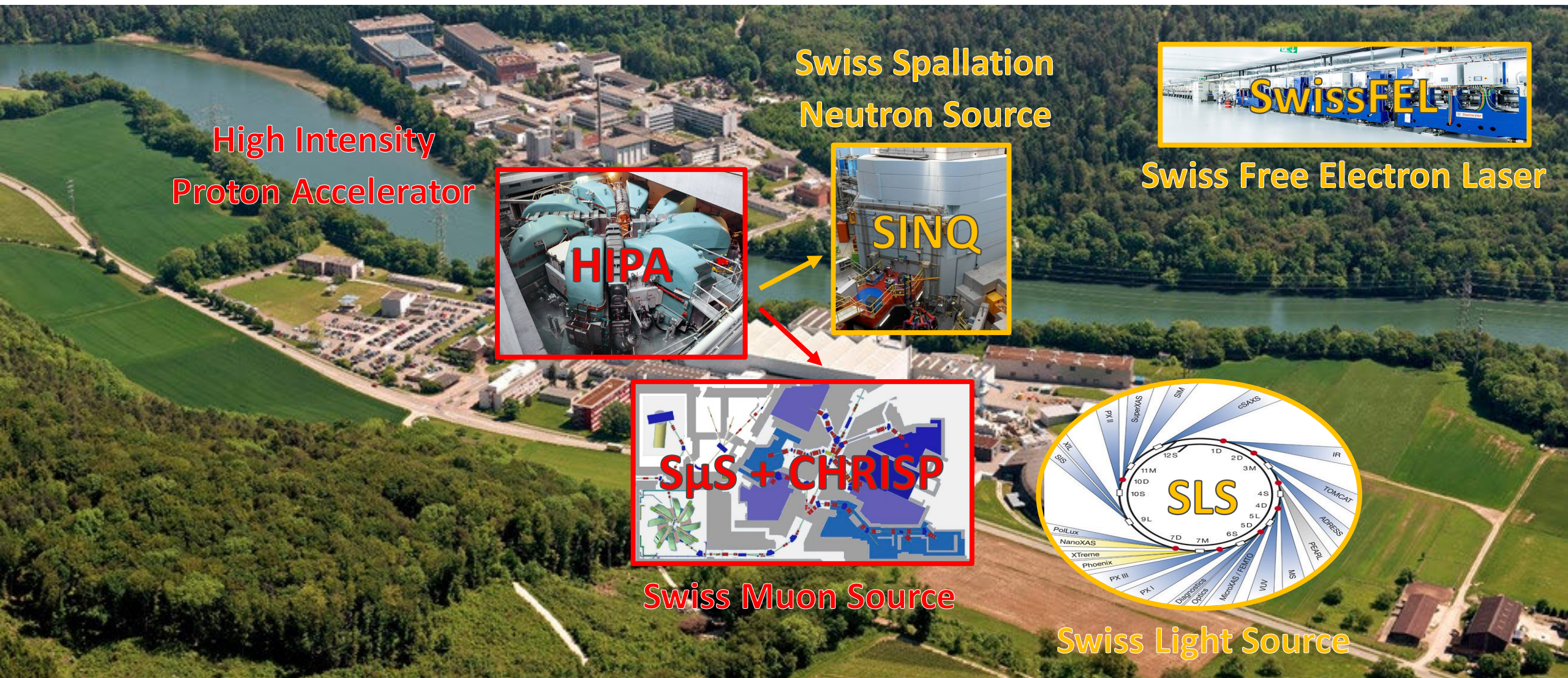
- Benchmarked on CRMs
- Composition calculated (no references)
 - generally fair agreement
 - *manual check pending*
- overall precision ~ 5-20 %
 - main limitation: knowledge of muon capture probabilities
 - to a lesser degree: self-absorption in sample, efficiency estimate

***open-source software
release in preparation***



Backup High Intensity Proton Accelerator

Large Research Facilities at PSI



HIPA: High Intensity Proton Accelerator Facility

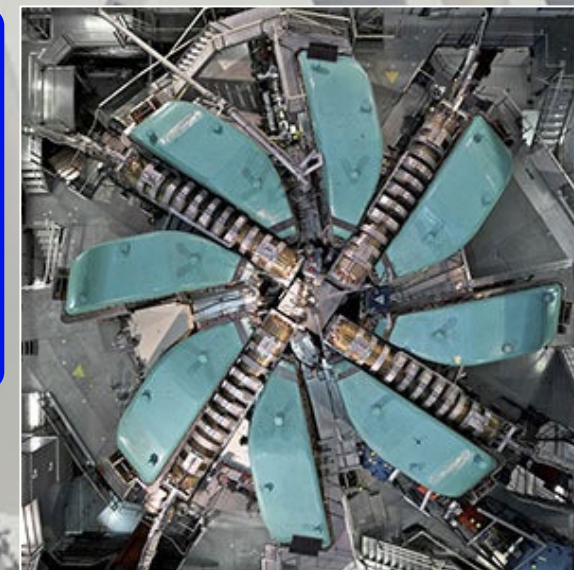
Cockcroft-Walton

60 kV extraction from ion source
810 kV DC acceleration
870 keV proton energy



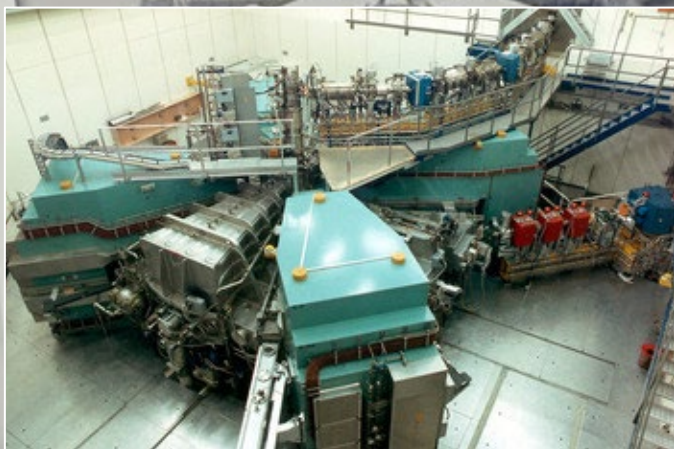
Main Cyclotron

590 MeV proton energy
current up to 2.4 mA (1.4 MW)
approx. 2×10^{-4} relative losses
~20% grid-to-beam efficiency



Injektor 2 (1st cyclotron)

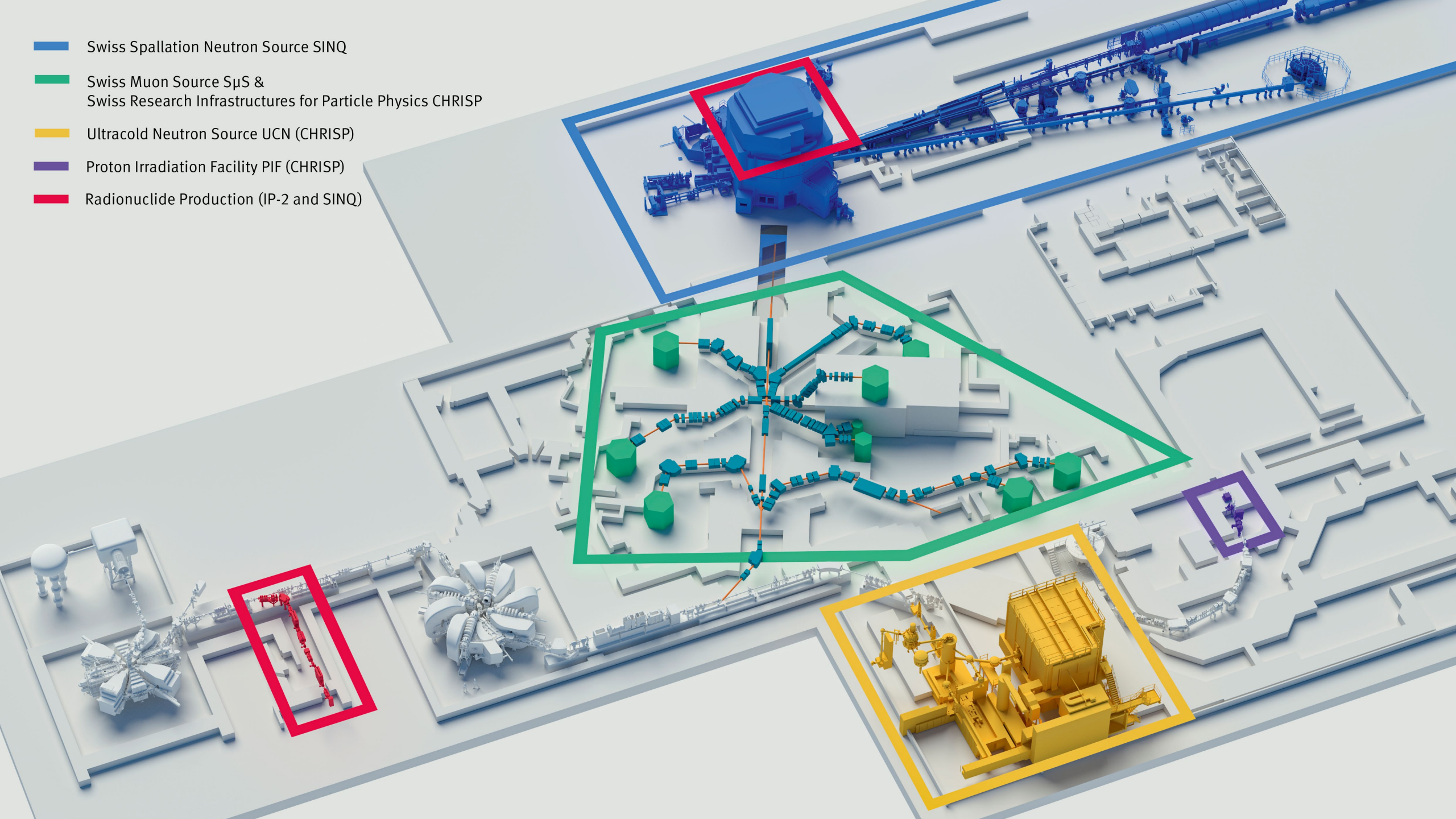
72 MeV proton energy
~50 MHz accelerator frequency
current up to 2.5 mA



Cyclotron World Record
Holder for
Beam Power


**HAPPY
BIRTHDAY
50**

- Swiss Spallation Neutron Source SINQ
- Swiss Muon Source SμS &
Swiss Research Infrastructures for Particle Physics CHRISP
- Ultracold Neutron Source UCN (CHRISP)
- Proton Irradiation Facility PIF (CHRISP)
- Radionuclide Production (IP-2 and SINQ)

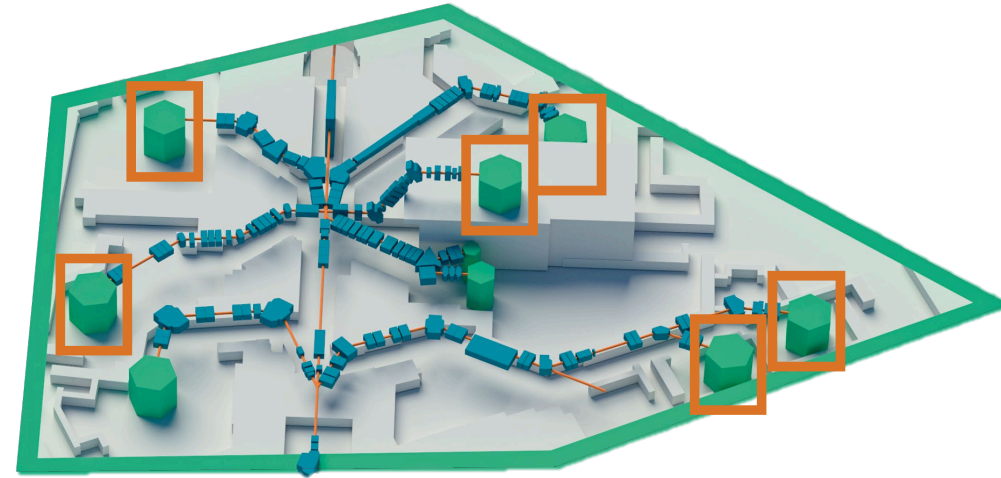


Laboratory for Muon Spin Spectroscopy (LMU)

- Provision and development of **instruments & methods** for the **international, interdisciplinary user community** at 5 muon beamlines

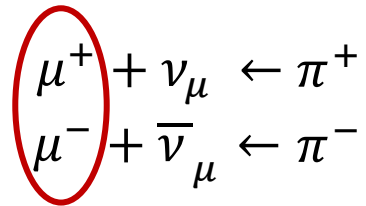
Main fields of research

- **Muon Spin Rotation Spectroscopy (μ SR):**
Measurement of **magnetic, electronic, and structural properties** of **novel and functional materials** at the atomic level
- **Muon Induced X-ray Emission (MIXE):**
Non-destructive, depth-resolved material analysis of the **elemental and isotopic composition**

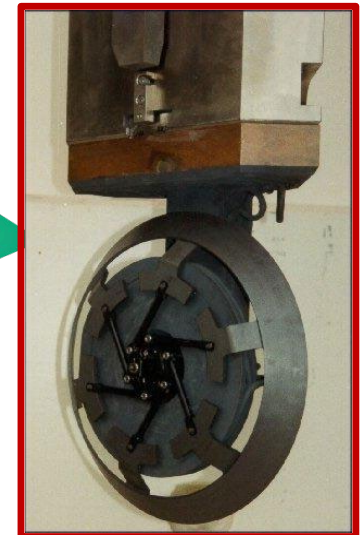
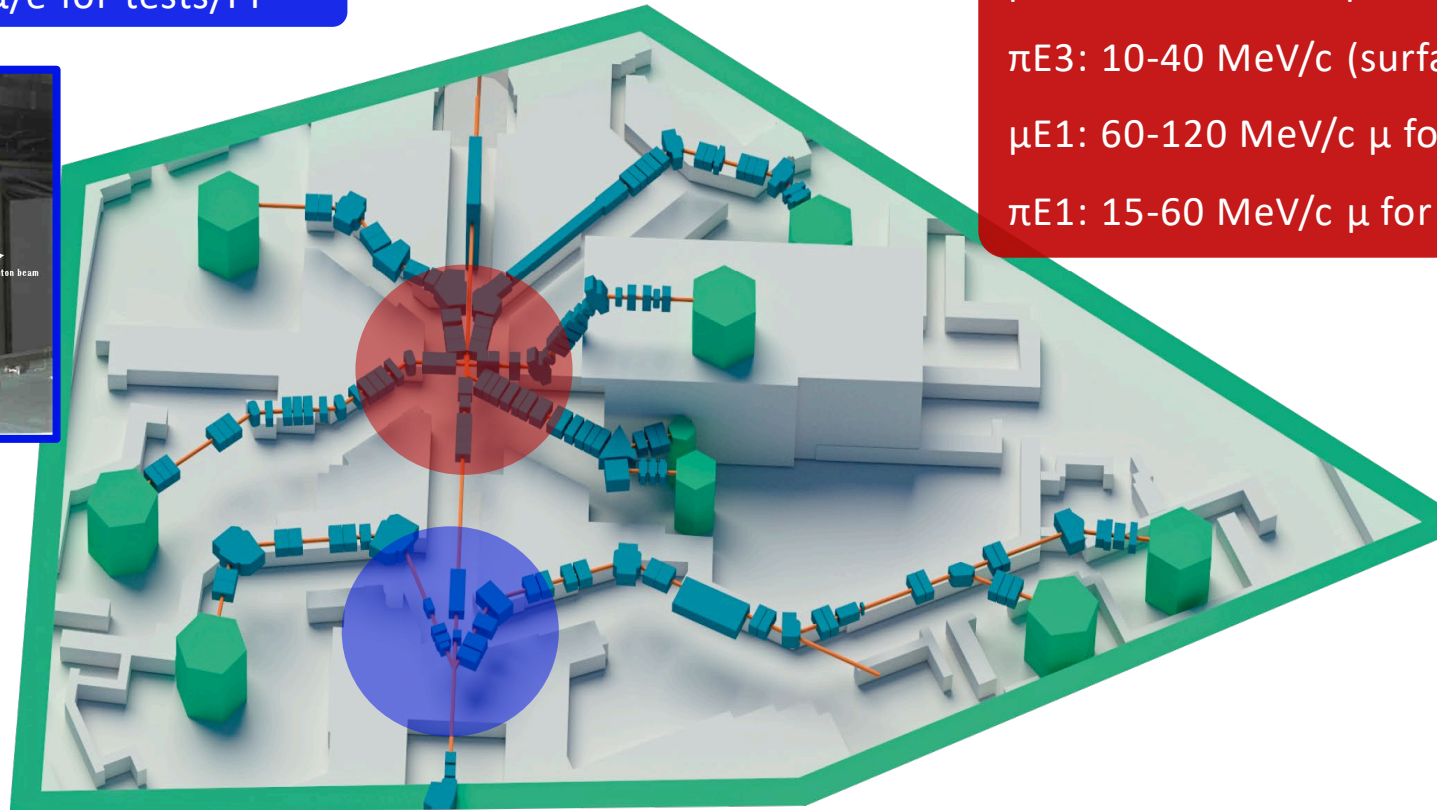


SμS: Swiss Muon Source

Target M (mince) – 5mm graphite
designed for π production (low rate)
 π M3: 10-40 MeV/c (surface) μ^+ for μ SR
 π M1: 10-300 MeV/c $\pi \rightarrow \mu/e$ for tests/PP



Target E (epaisse) – 40mm graphite
designed for π/μ production (high rate)
 π E5: 20-120 MeV/c high rate μ for PP
 μ E4: 10-40 MeV/c μ^+ for LEM – μ SR and PP
 π E3: 10-40 MeV/c (surface) μ^+ for bulk μ SR
 μ E1: 60-120 MeV/c μ for μ SR (*and future MIXE*)
 π E1: 15-60 MeV/c μ for μ SR, MIXE, PP



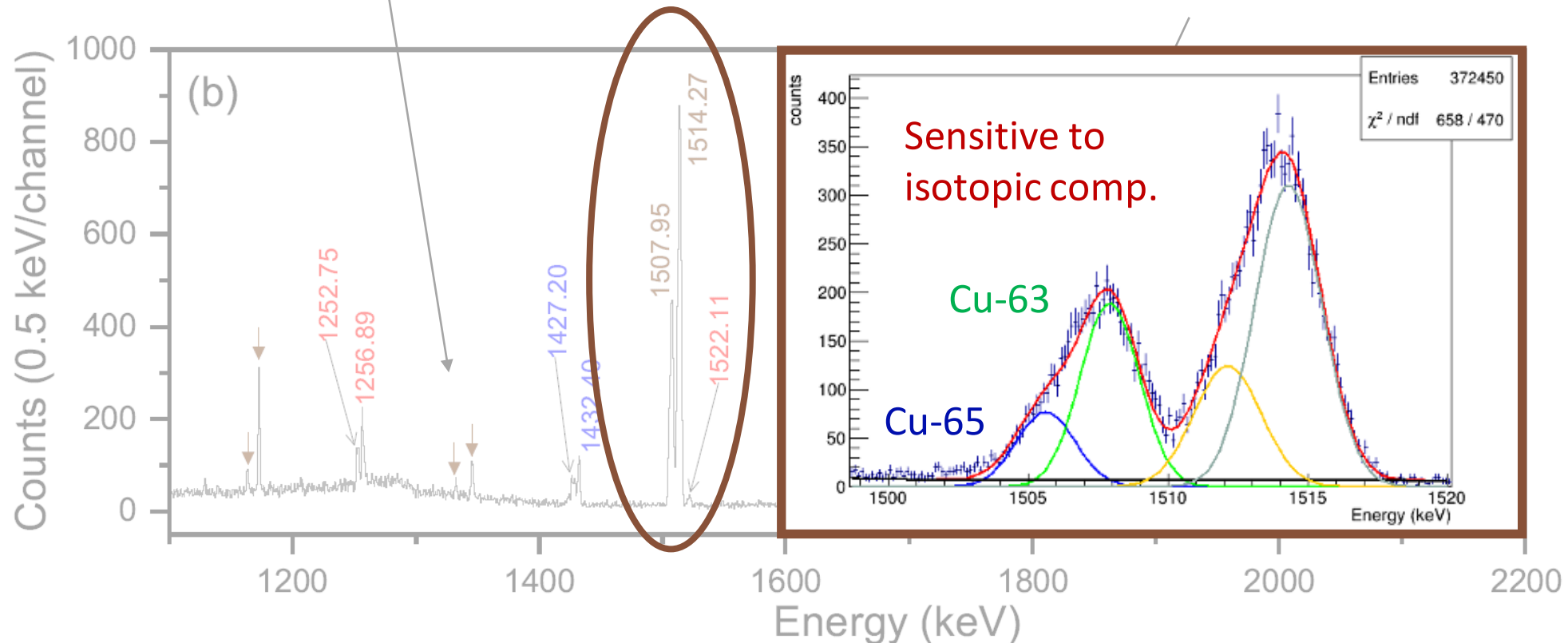
MIXE: Muon Induced X-ray Emission – Example: Copper

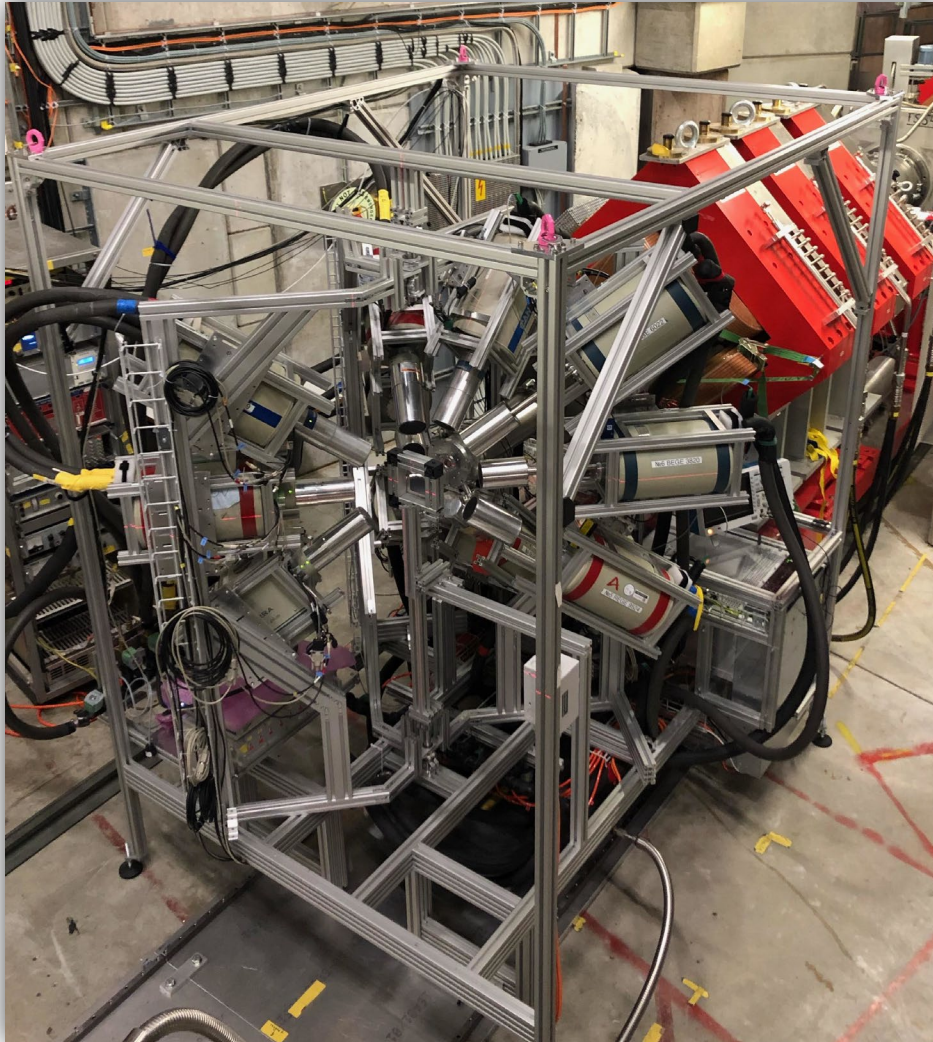
X-ray cascade:
prompt, ROI: <100ns

compare:
 $e\text{-}K_{\alpha} = 8.04 \text{ keV}$

$\mu\text{-}K_{\alpha} (2p\text{-}1s)$

Nuclear Capture and
subsequent decay:
delayed, ROI: >100ns





Modular Setup

- up to 8 freely rotating arms (curr. 5)
- up to 4 BigMac HPGe per arm
- up to 30 HPGe detectors (curr. ~12)
- shared with PP (muX, ReferenceRadii, MONUMENT, ...)

Reproducible positions and angles

Fully movable as a unit

- final setup time ~6 hours

Fully automatic LN2 cooling system

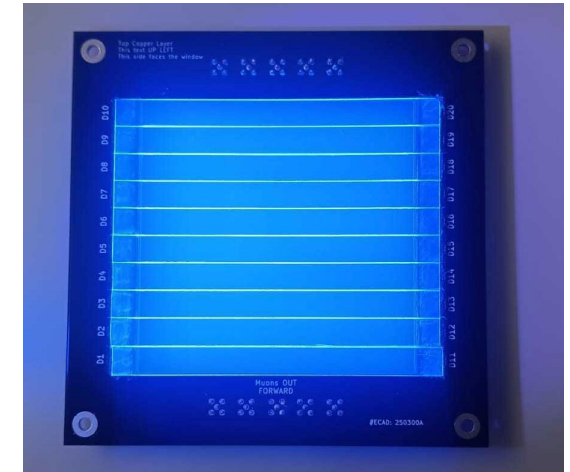
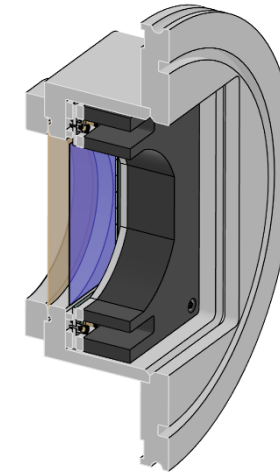
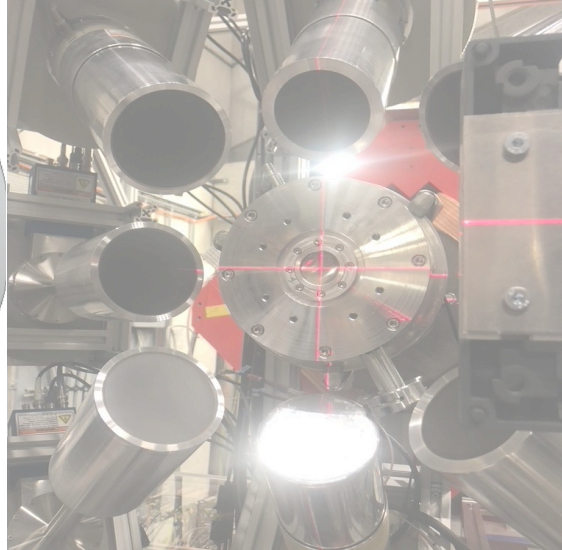
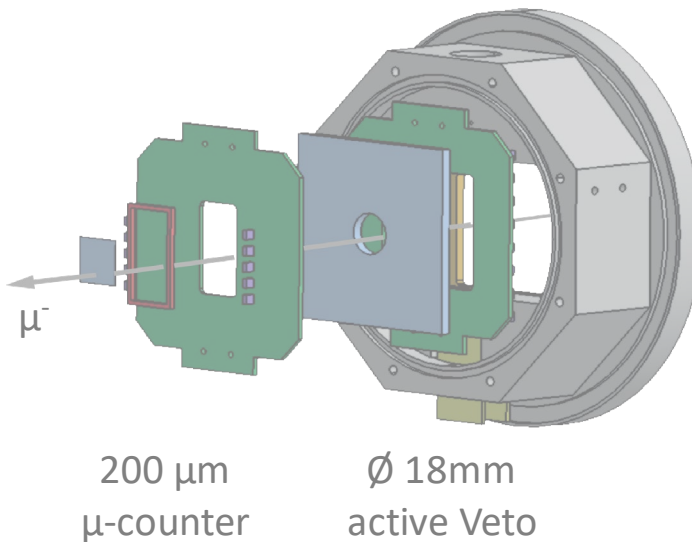
Twin sample station in control room

- roughly 5 min sample change

GIANT: Germanium Array for Non-destructive Testing – Tagging

Tagger & Beamport (developed for muX experiment)

- BC-400 plastic scintillators (Counter and Veto)
- reduces uncorrelated background
- allows for discrimination of nuclear capture events
- 10 μ m titanium foil window to sample (~10cm air gap)



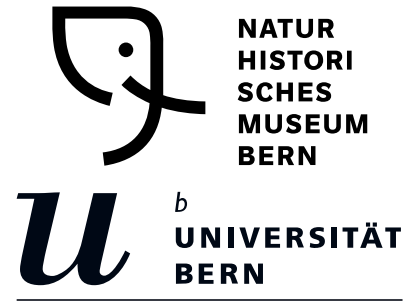
Upgraded version (2025)

- Much larger active area (~7x7cm²)
- Matching Window (Ø7cm) – 50 μ m Mylar
 - Same overall material budget!
- Optimized shielding to reduce BG
- Striped design (10 - 14 individual channels)
 - Allows higher tracker rate (see Part IV)

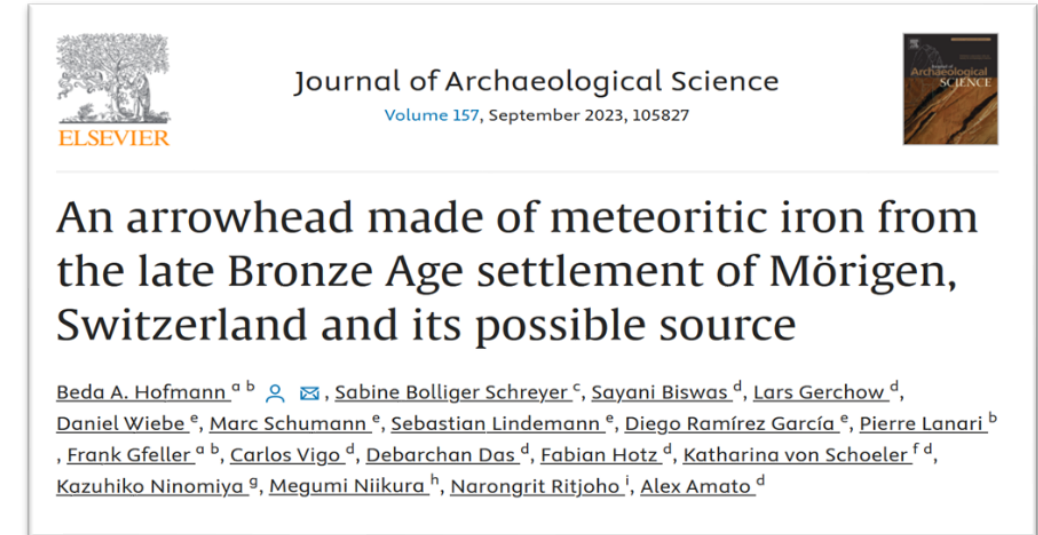
Backup

Muon **I**nduced **X**-ray **E**mission *Showcases*

Arrowhead: Sample and Reception



1 cm



Arrowhead: The search for “Heavenly Iron”

Bronze age

- **Metalworking** was known
 - **Iron extraction** from ore *not yet discovered*
- „Heavenly Iron”
- Iron from **meteorite** fragments
 - **Production** of *jewelry, weapons, tools, ...*
 - Very *rare* and *valuable* **trade goods**

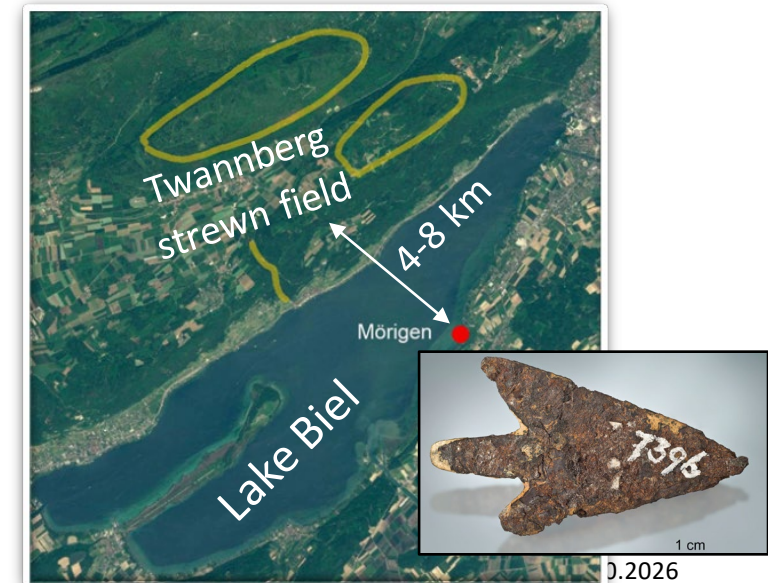
Search in **archaeological collections** (area of *Lake Biel*)

- *Twannberg*: largest **meteorite find** in Switzerland

Such an artifact identified: An **arrowhead**

- Find site: *Pile-dwelling settlement* in **Mörigen**
- Era: **Bronze Age** (900-800 BCE)

XRF & gamma spectroscopy: **Large iron meteorite (>2t)**



Arrowhead: The surprise!

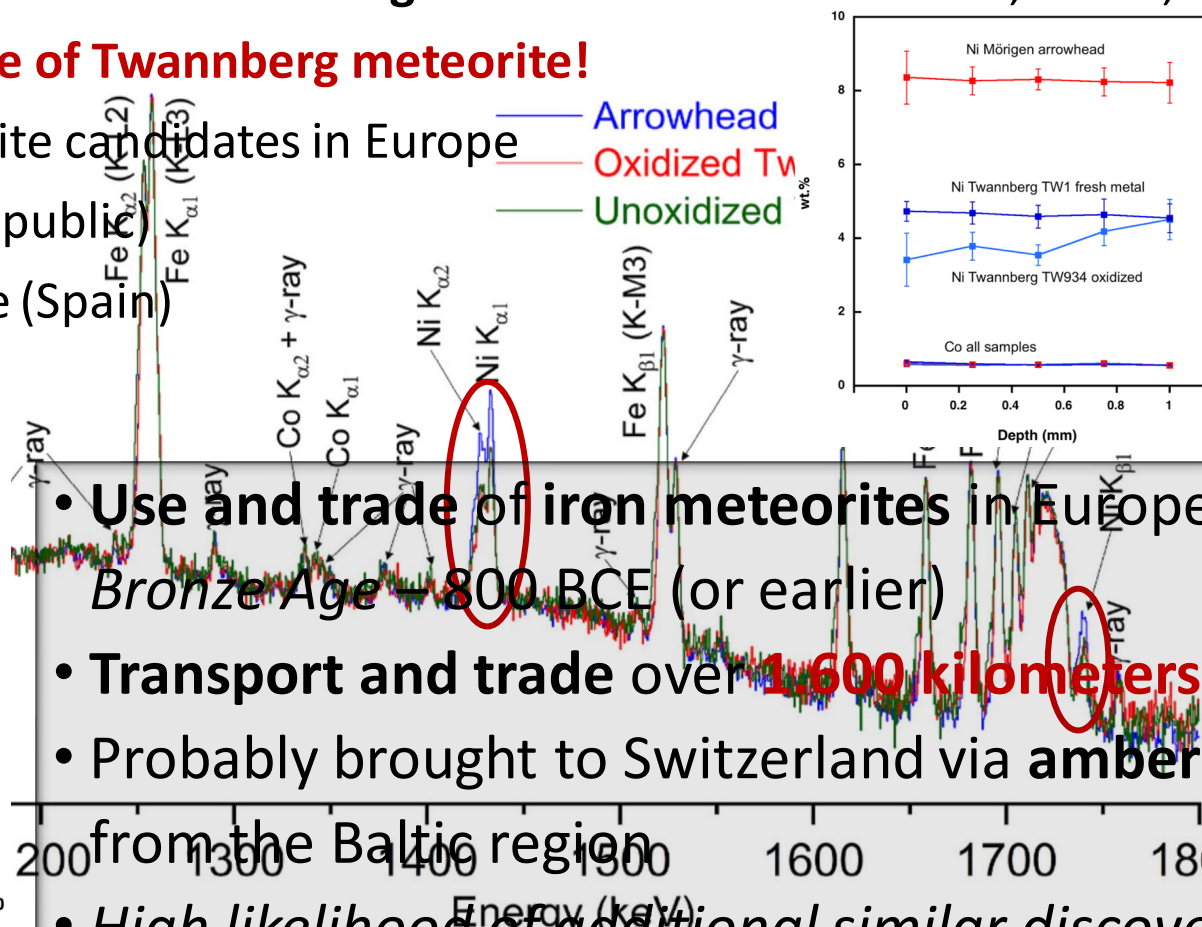
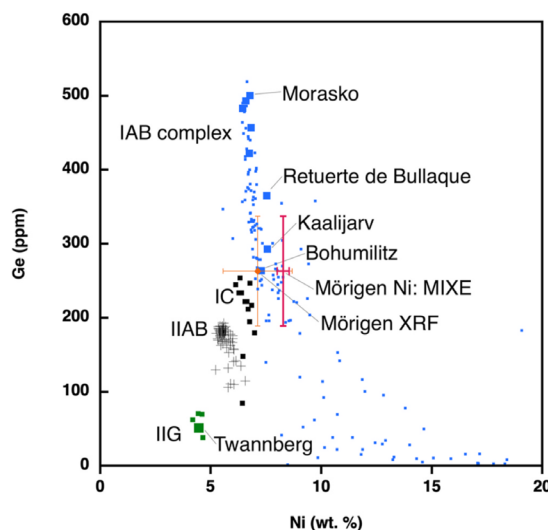
XRF is great but can't probe below thick corrosion layer and/or fusion crust!

→ **MIXE** Study: Comparison to **Twannberg** reference meteorite for *Iron, Nickel, and Cobalt*

- **Arrowhead not made of Twannberg meteorite!**

Only 3 possible meteorite candidates in Europe

- Bohumilitz (Czech Republic)
- Retuerte de Bullaque (Spain)
- Kaaliyarv (Estonia)



- Use and trade of iron meteorites in Europe as early as the Bronze Age — 800 BCE (or earlier)
- Transport and trade over **1,600 kilometers**
- Probably brought to Switzerland via **amber trade routes** from the Baltic region
- *High likelihood of additional similar discoveries!*

Fibula: Sample and Study



AUGUSTA RAURICA



Late-antique knob-bow fibula

- excavated **2018** at Augusta Raurica (CH)
- **Leutkirch-type** fibula, **400-500 CE**

Sample not suitable for XRF

- surface completely **covered** with **patina**
- **corrosion layer** on parts of **spiral**
- **coated** in **acrylic resin** for conservation

Six measurements (~1.5 hours each):

- **positions:** bow (3x), knob, foot, and spiral
- 1 cm **PE collimator** with **3 mm aperture**
- momentum: **33 MeV/c** – depth: **~320 μm**

3 Brass and **2 Bronze CRMs** for calibration

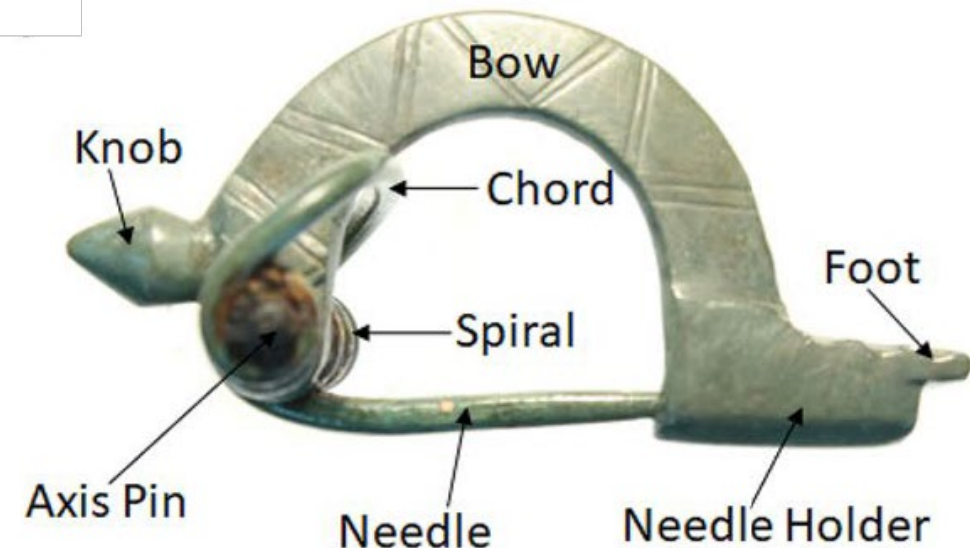
Biswas et al. *Heritage Science* (2023) 11:43
<https://doi.org/10.1186/s40494-023-00880-0>

Heritage Science

The non-destructive investigation of a late antique knob bow fibula (Bügelknopffibel) from Kaiseraugst/CH using Muon Induced X-ray Emission (MIXE)



Sayani Biswas^{1*}, Isabel Megatli-Niebel^{2,3*}, Lilian Raselli³, Ronald Simke³, Thomas Elias Cocolios⁴, Nilesh Deokar⁹, Matthias Elender¹, Lars Gerchow¹, Herbert Hess⁵, Rustem Khasanov¹, Andreas Knecht¹, Hubertus Luetkens¹, Kazuhiko Ninomiya⁶, Angela Papa^{1,7}, Thomas Prokscha¹, Peter Reiter⁵, Akira Sato⁶, Nathal Severijns⁴, Toni Shiroka¹, Michael Seidlitz⁵, Stergiani Marina Vogiatzi^{1,8}, Chennan Wang¹, Frederik Wauters⁹, Nigel Warr⁵ and Alex Amato¹



Fibula: Results and Relevance



Elemental Composition

- Positions 1-5: **High ratio of alloyants** (esp. Pb)
- Position 6: **Low ratio of alloyants**

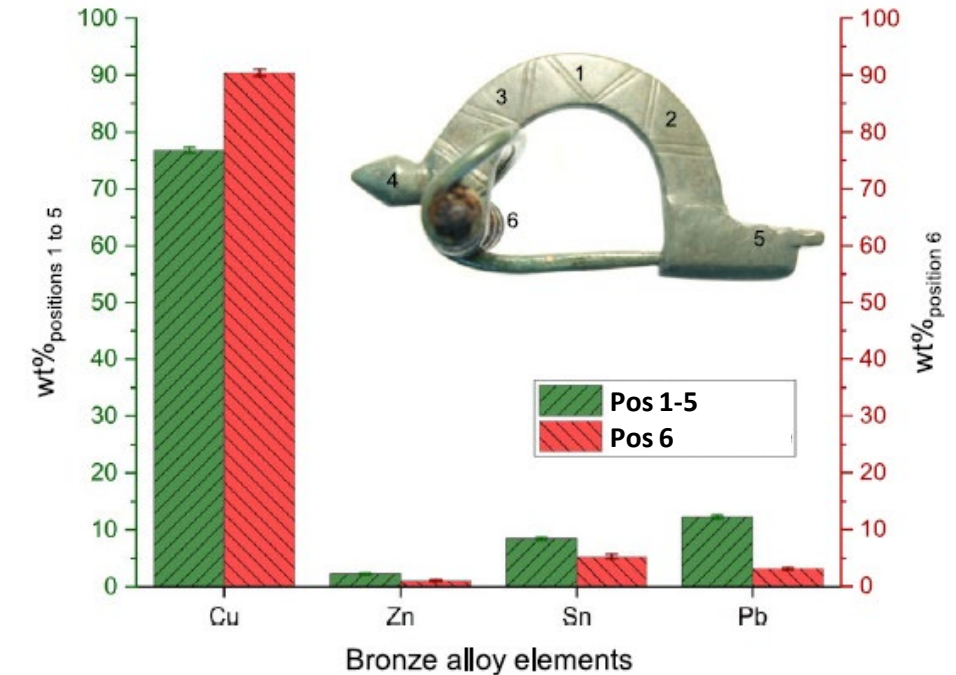
Detection limit: **0.4 wt%** in **~1.5h**

Manufacturing Insights

- **Main body** (knob, bow, foot) **alloy** indicative of **casting** (low-melting point and bubble-free flow)
- **Spiral alloy** indicative for **forging** (high strength and ductility)

Conclusions

- **two-workpiece construction** reflecting **conscious alloy selection**
- **decentralized workshop** practice with **recycling** and **local mixing** of source metals



Charge Carrier Ion Transport

Goals:

- Tracking **charge carrier ion distributions** (especially relevant for thick electrodes)
- Mapping **parasitic ion** depositions (e.g. dendrite formation – common failure mode)

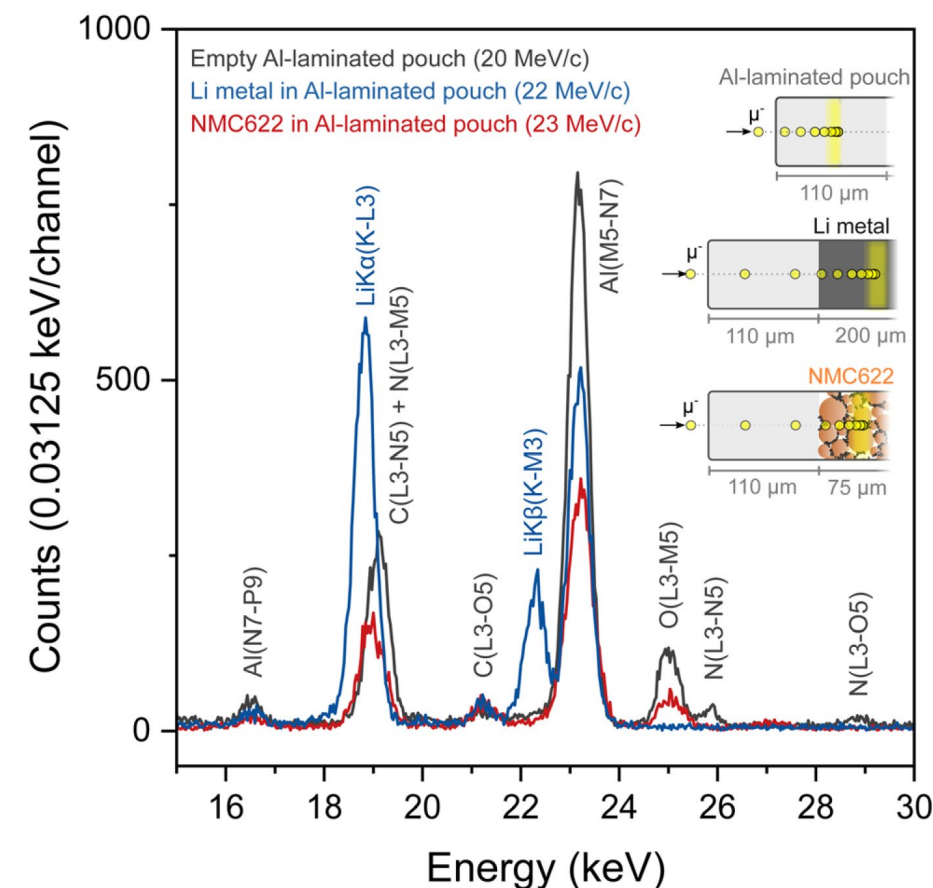
K_{α} X-ray energies and attenuation lengths (here in PP)

Li: 54 eV (electronic) **~100 nm** Na: 1 keV (electronic) **~5 μ m**
 18.8 keV (muonic) **~10 mm** 250 keV (muonic) **~40 mm**

Measurement: empty pouch, Li metal and NMC622 (in pouch)

- **Clear Li signal** observed in Li metal
- Li tracking in electrode material **very challenging**
 - **Low efficiency** for HPGe
 - **Low muon capture probability** (~16 in Ni vs. Li)
 - **Masked** by $C-L_{\beta}$ and $N-L_{\alpha}$

*Very **promising** first results for **Na cells** (early analysis ongoing)*



MIXE 4 Batteries:

Stoichiometry of Electrodes

Goal:

- Accurate **in-situ elemental quantification** of electrode layers

Measurement:

- 3x **NMC** (1h each) with **different Ni:Mn:Co ratios**
- Fitting** of Mn, Co, and Ni K_{α} peaks

could even recover Ni isotopic abundance

Result reproduces known elemental composition with high accuracy!

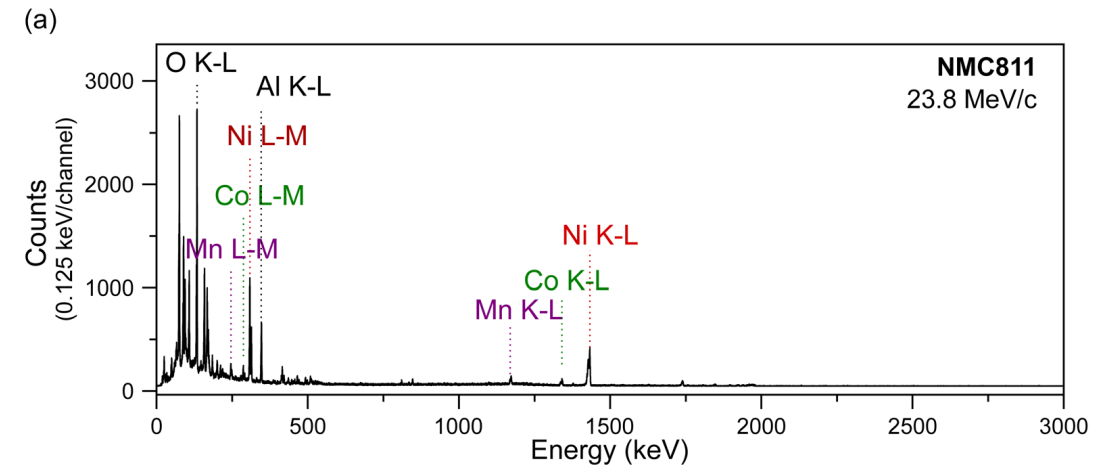


Table 1 Experimentally measured ratios for three different NMC electrodes

NMC type	Nominal composition	Ni/(Ni + Mn + Co)	Mn/(Ni + Mn + Co)	Co/(Ni + Mn + Co)
NMC111	$\text{Li}_{1-x}\text{Ni}_{0.33}\text{Mn}_{0.33}\text{Co}_{0.33}\text{O}_2$	0.32 ± 0.02	0.35 ± 0.02	0.32 ± 0.01
NMC622	$\text{Li}_{1-x}\text{Ni}_{0.6}\text{Mn}_{0.2}\text{Co}_{0.2}\text{O}_2$	0.58 ± 0.05	0.21 ± 0.02	0.21 ± 0.02
NMC811	$\text{Li}_{1-x}\text{Ni}_{0.8}\text{Mn}_{0.1}\text{Co}_{0.1}\text{O}_2$	0.80 ± 0.03	0.103 ± 0.005	0.10 ± 0.02

MIXE 4 Batteries: Full depth profiling

Goal:

- In-situ elemental **depth-profiling** of functional cells

Measurement:

- Custom **NMC811 / graphite pouch cell**
commercial materials – 0.7mm total thickness
- **Full GEANT4 / PHITS simulation of sample and instrument**
accurate **modelling of energy loss** → **implantation profile**
- **Spectra** acquired for **eleven momenta** (30min each)
- **Fingerprint** signals for each layer (**Al, Ni/Mn/Co, Si, Cu**) & C
Good agreement of simulation and data
- **Cross-check** of quantitative results: **NMC Stoichiometry**
Reproduces 8:1:1 ratio very well over full thickness

