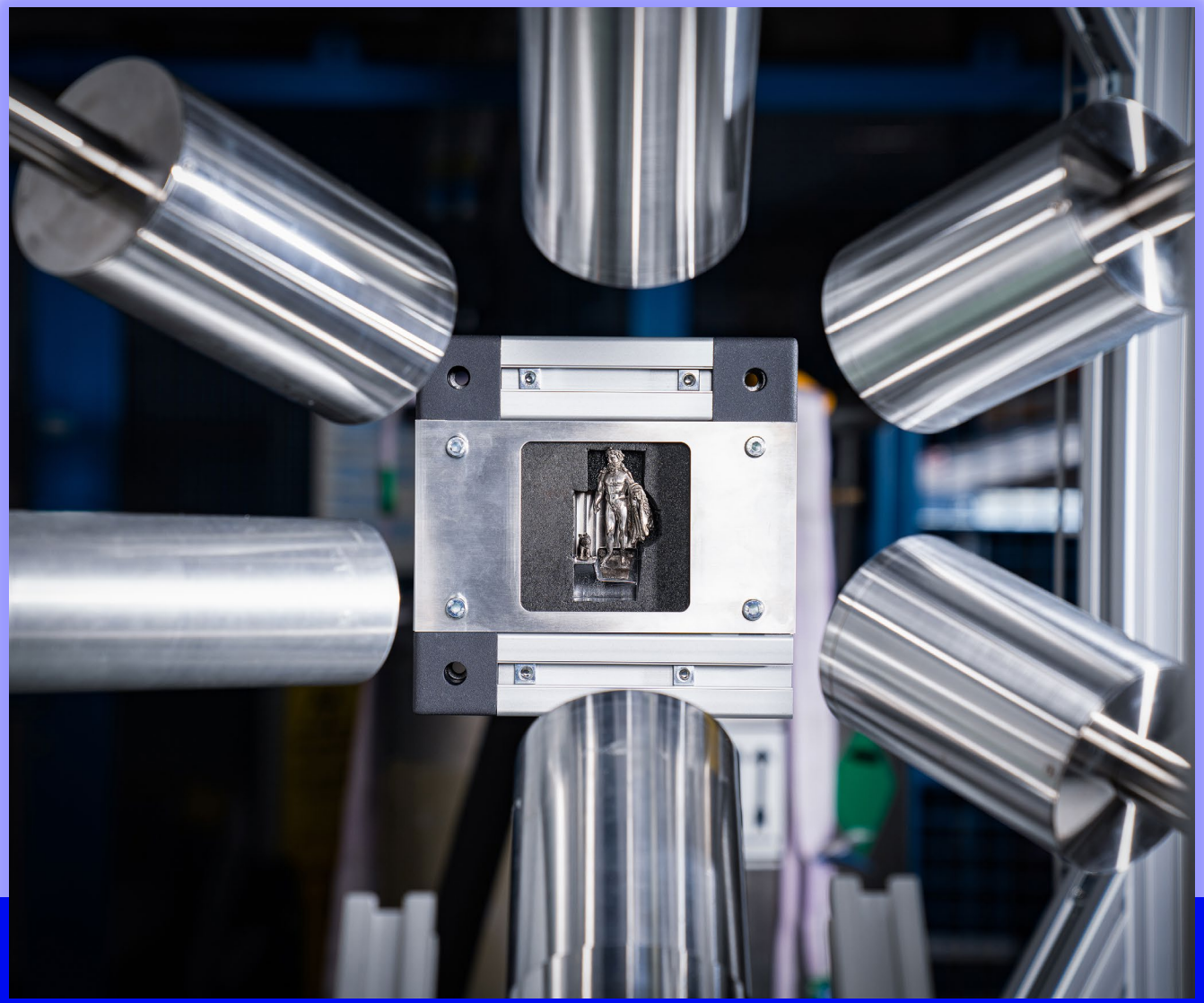
PSI Center for Neutron and Muon Sciences

Muon-Induced X-ray Emission

Activities at PSI



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

BRIDGE2025 Workshop, Tokyo, 22 October 2025

Part I

Muon Induced X-ray Emission

Technique & Instrument

MIXE: Muon Induced X-ray Emission – Overview

PSI

Archeological artifacts

Meteorites

Batteries

and many more!

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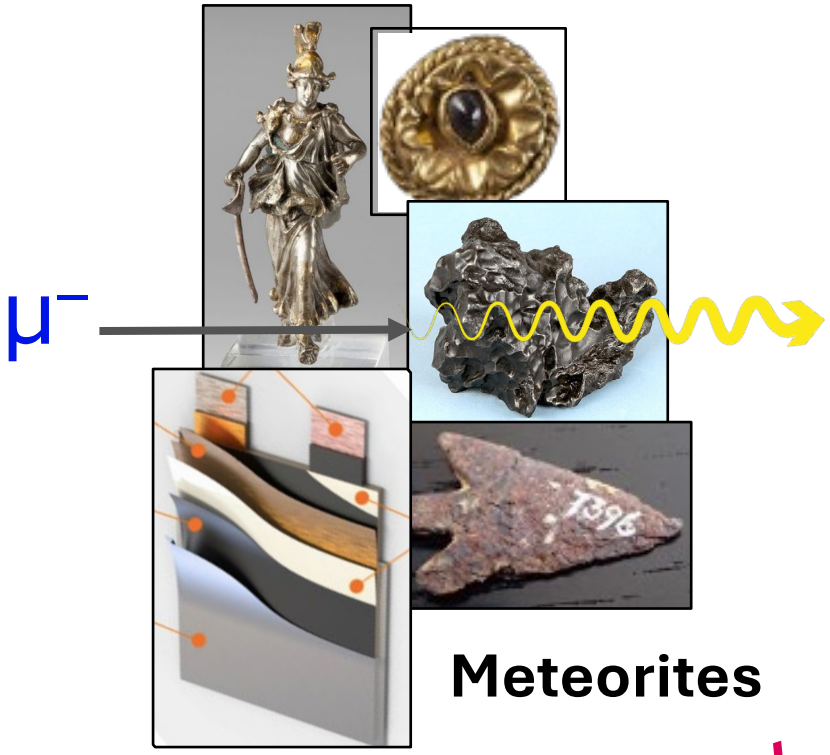

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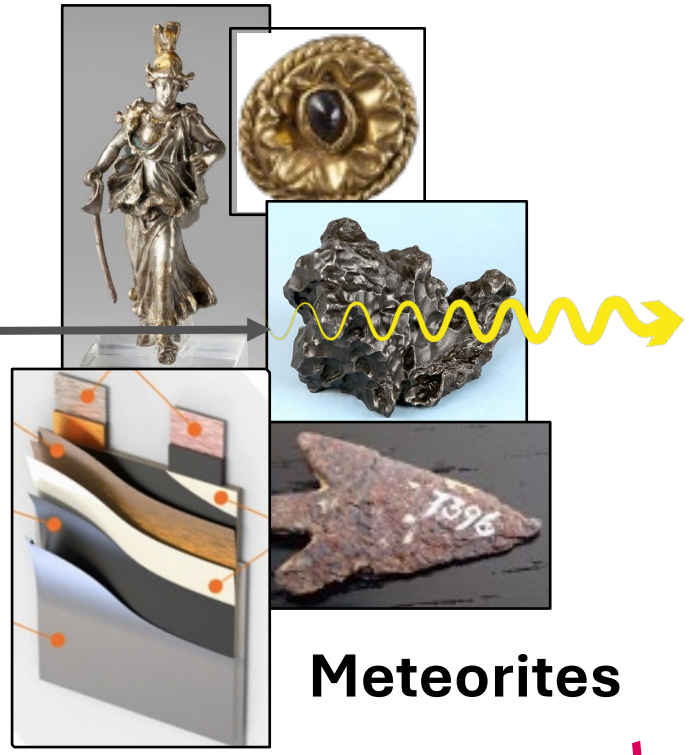

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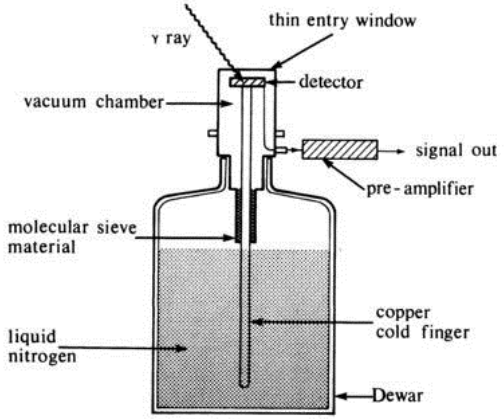
High Purity Germanium Detectors



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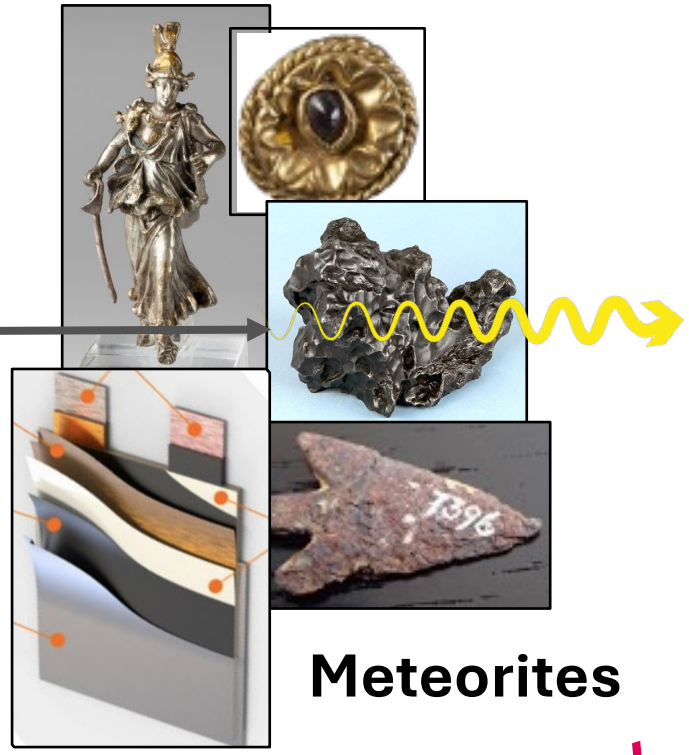

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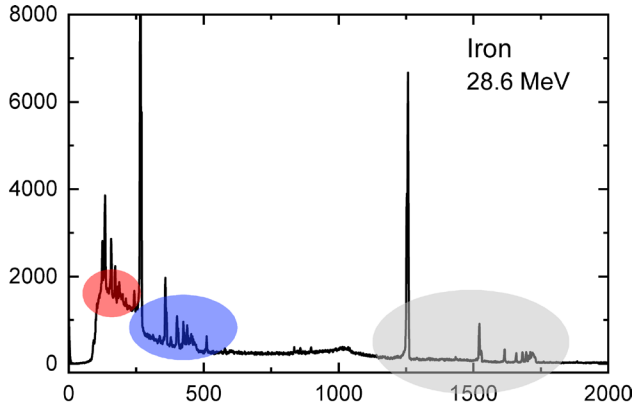

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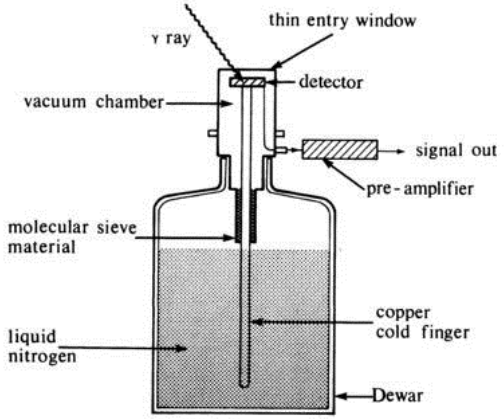

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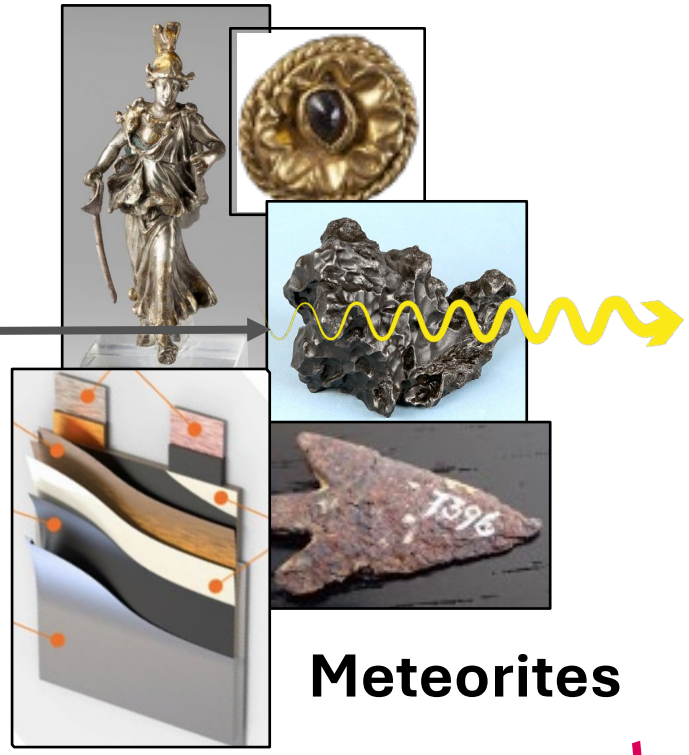

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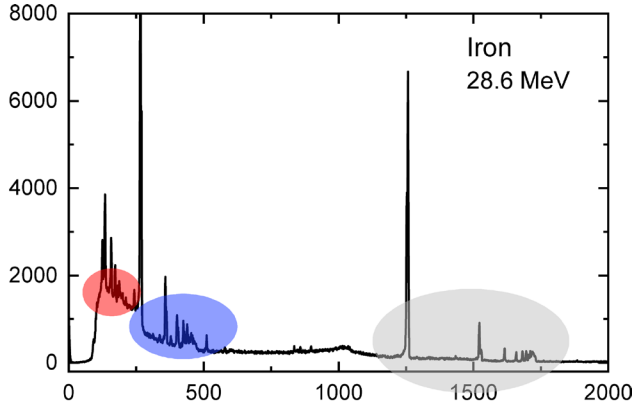

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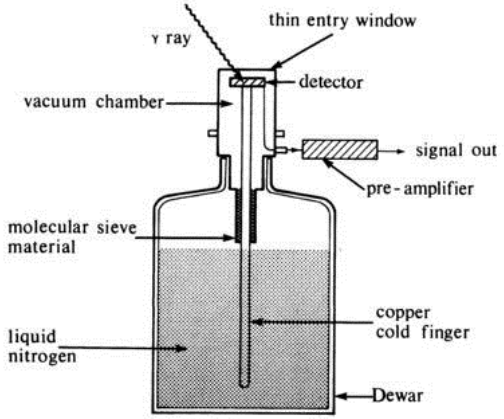

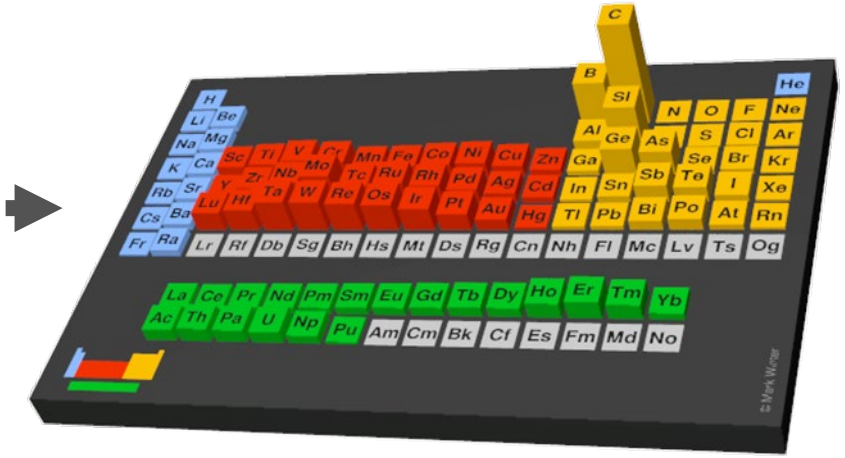

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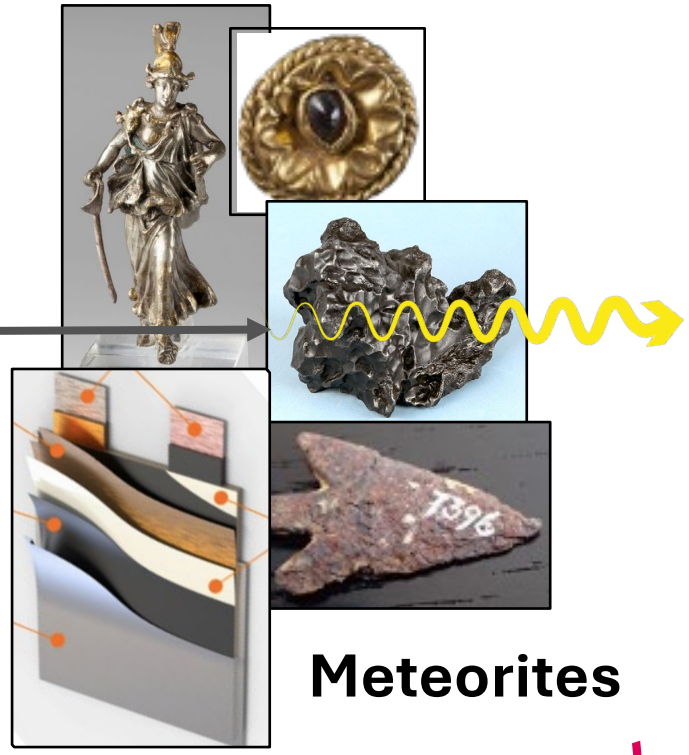

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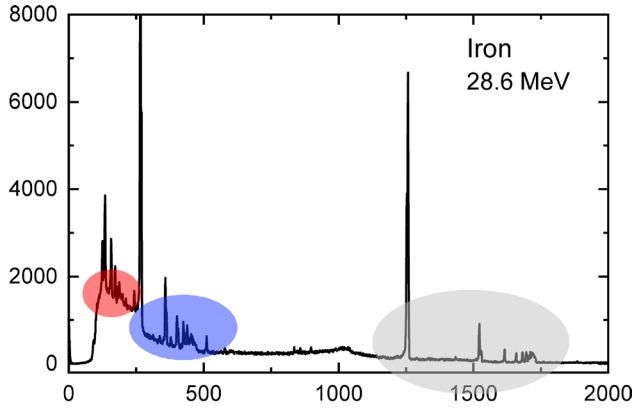

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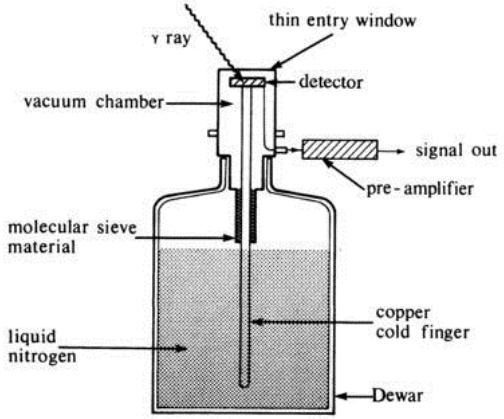

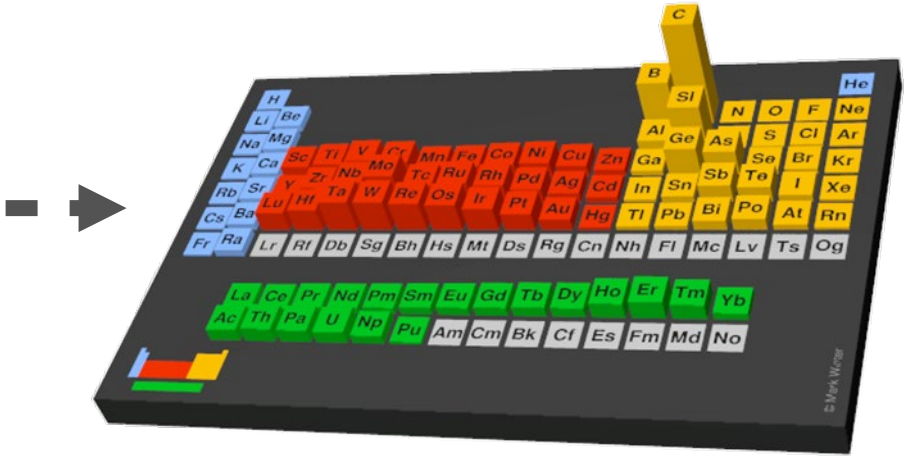

Highlights:

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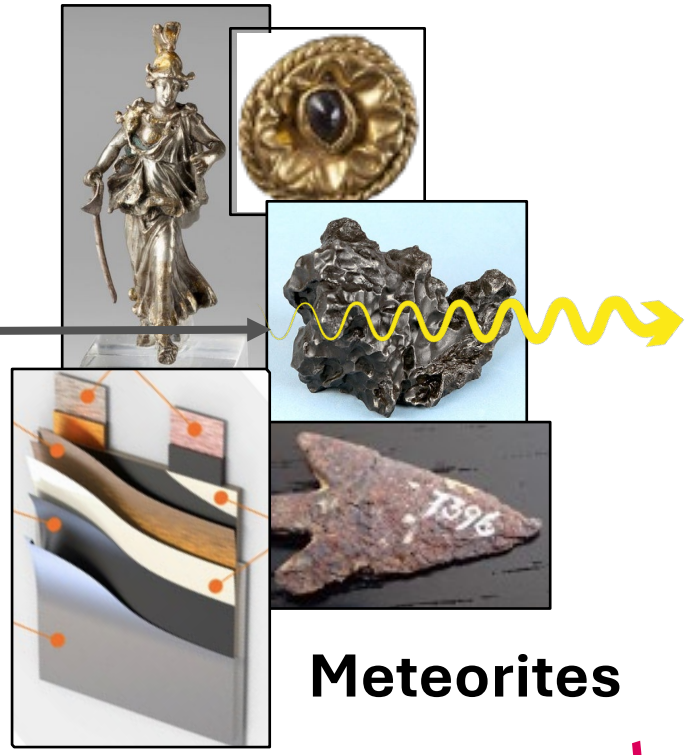

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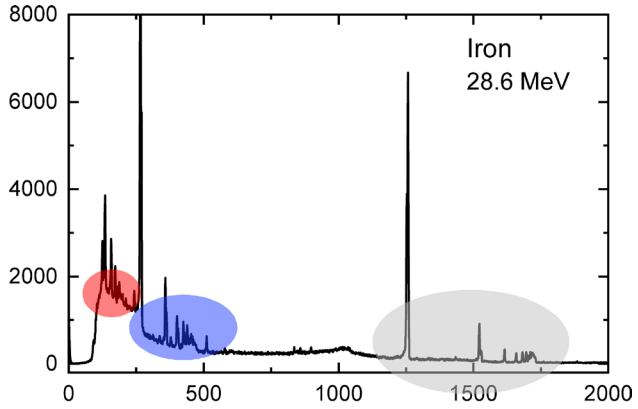

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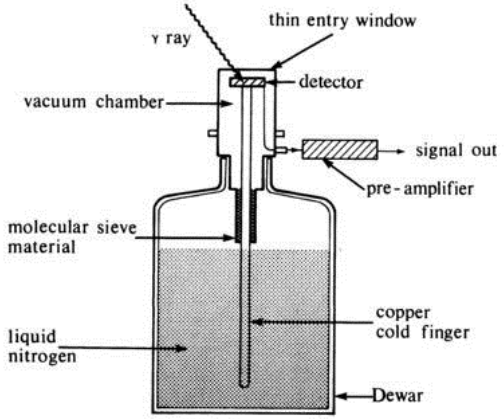

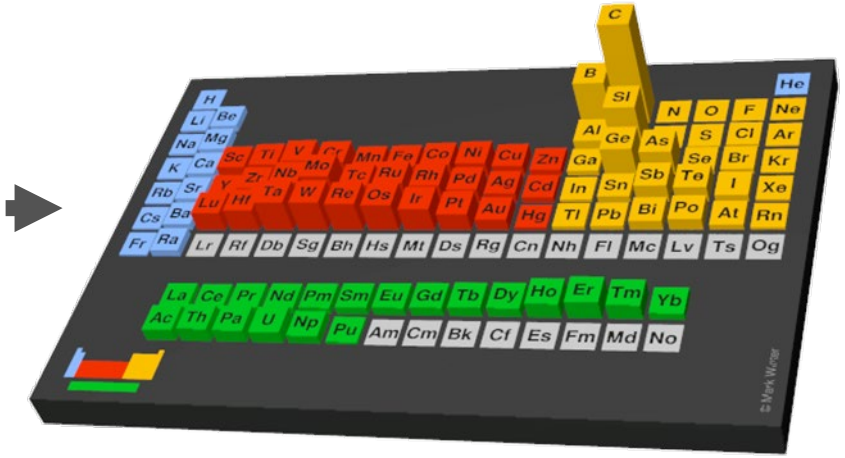

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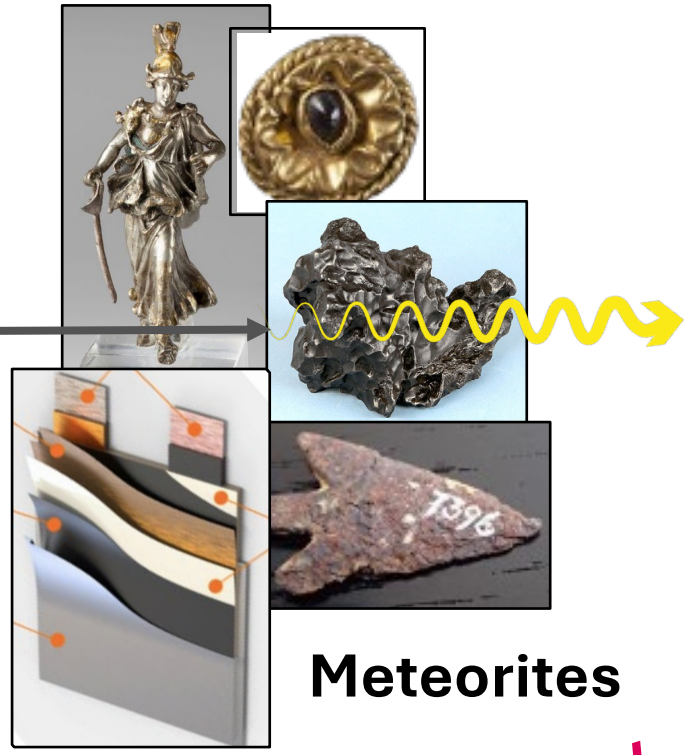

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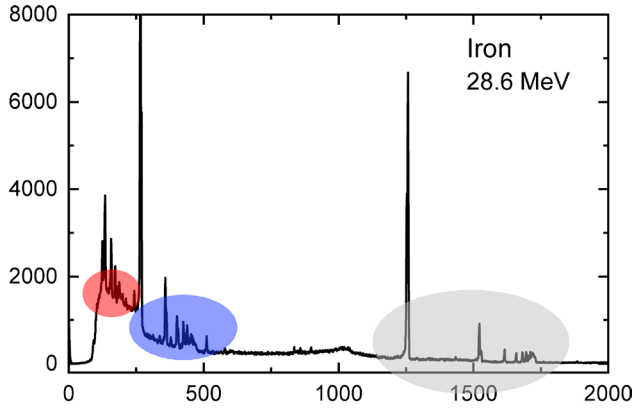

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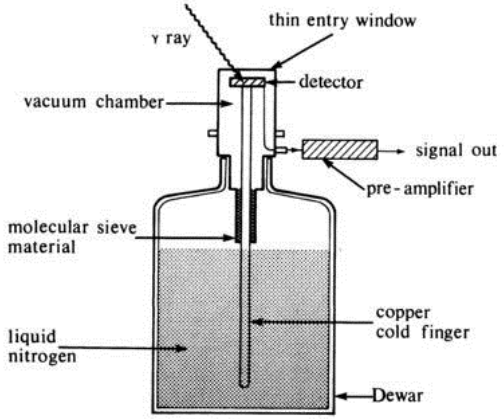

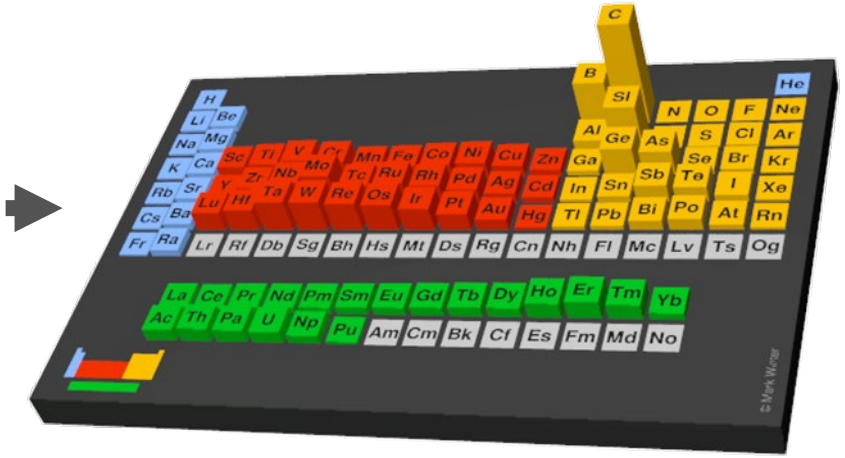

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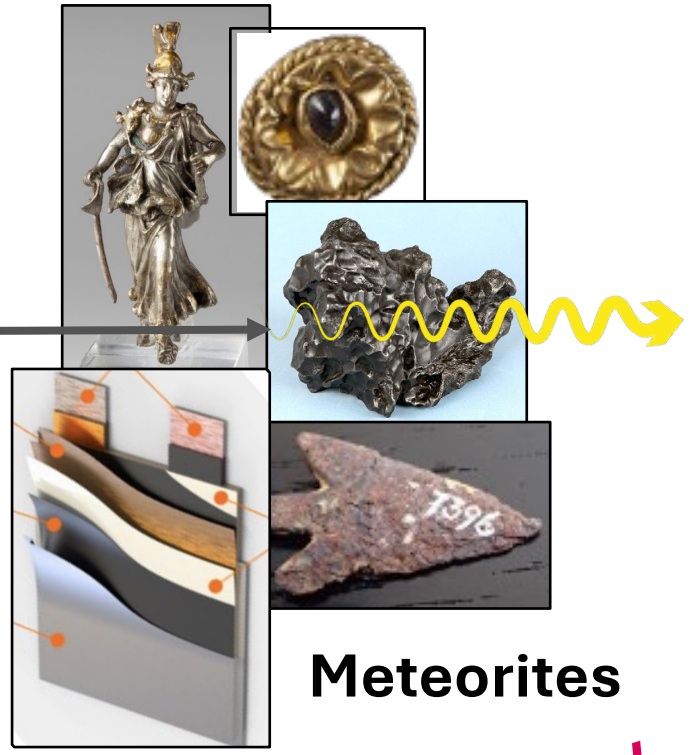

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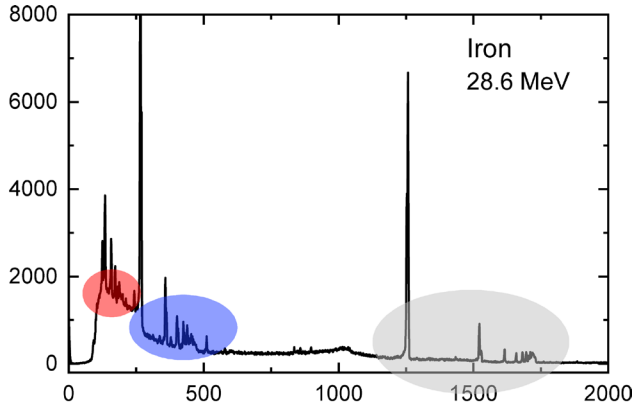

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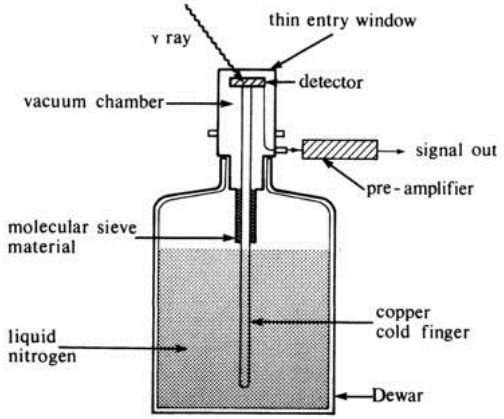

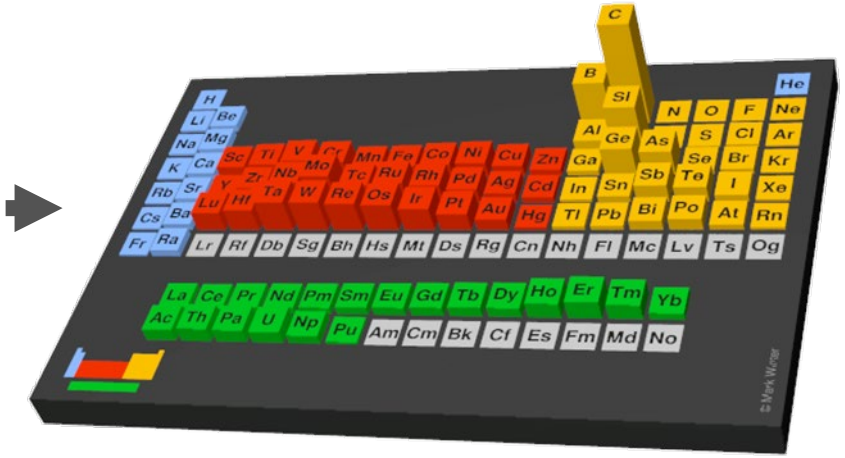

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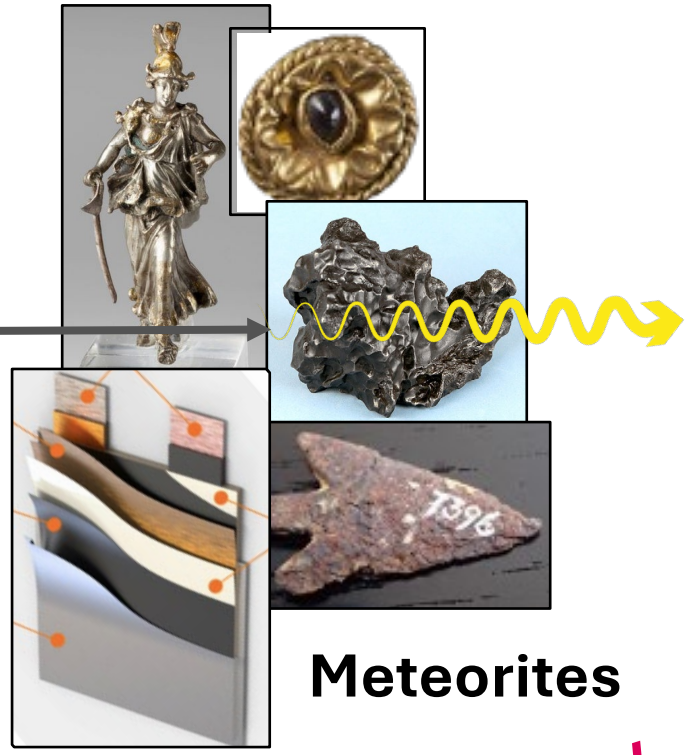

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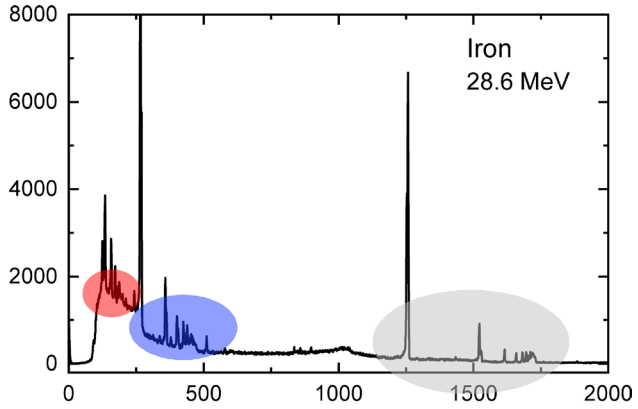

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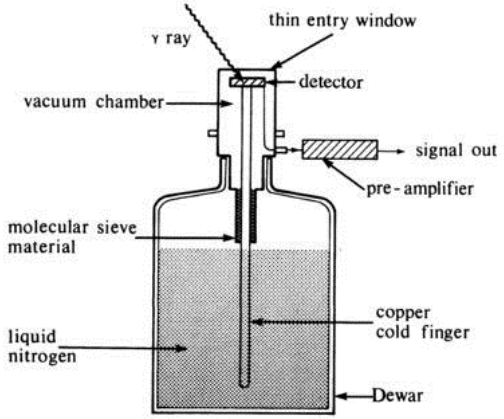

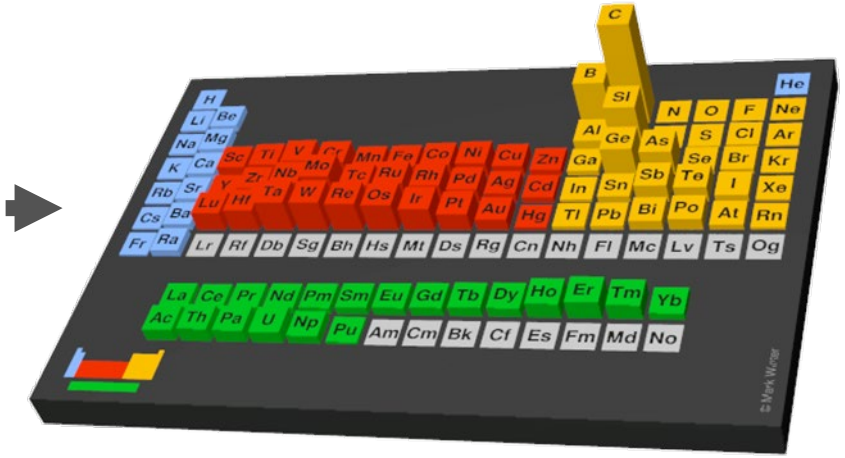

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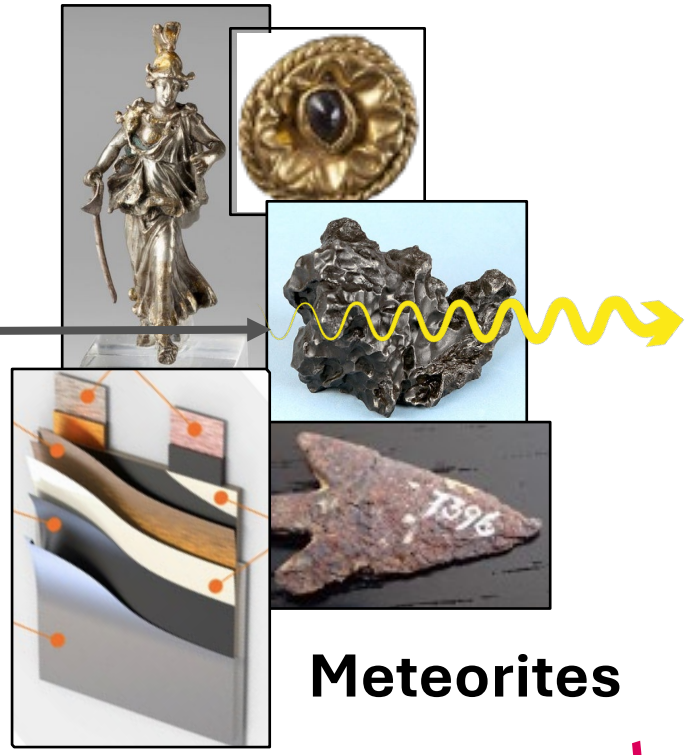

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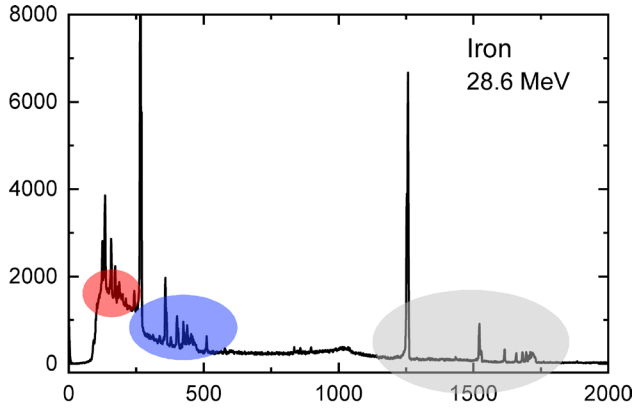

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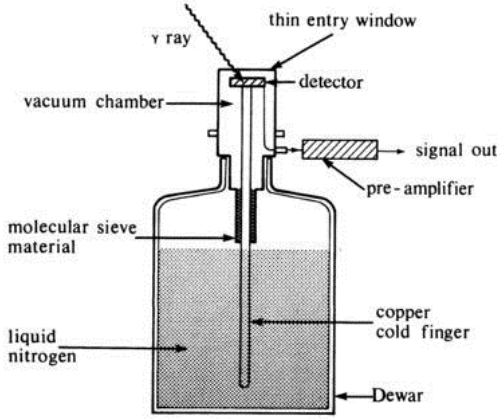

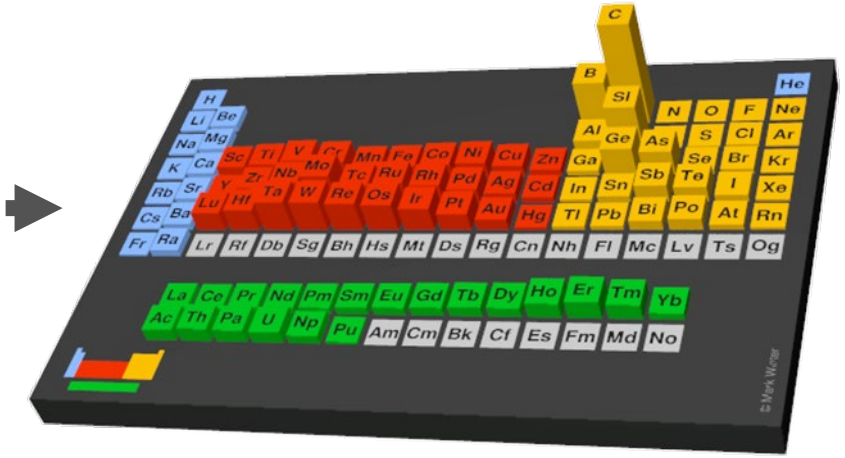

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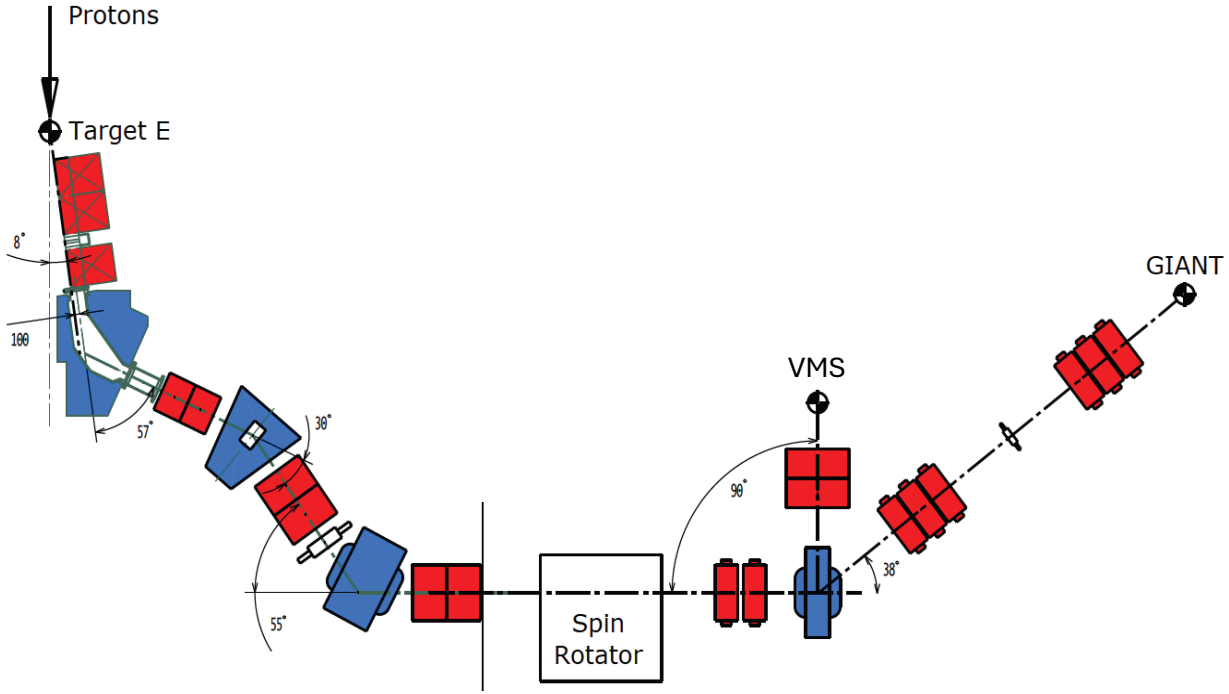
- **Tomography** possible (see Part III)

MIXE: Muon Induced X-ray Emission – Beamlines: πE1

High intensity π beamline at target E

- production of “cloud” π^- and decay to μ^-



MIXE: Muon Induced X-ray Emission – Beamlines: πE1

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High intensity π beamline at target E

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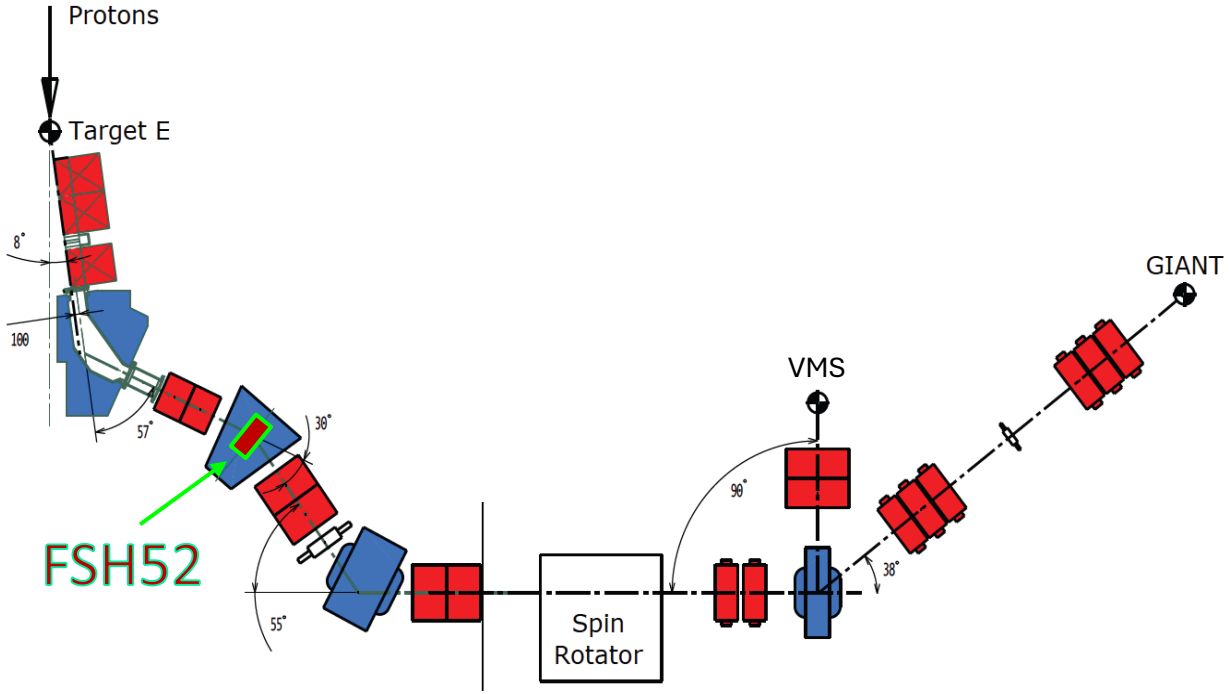
- typical μ^- momenta: **15-60 MeV/c**

  implantation depths: **~10um to ~cm**



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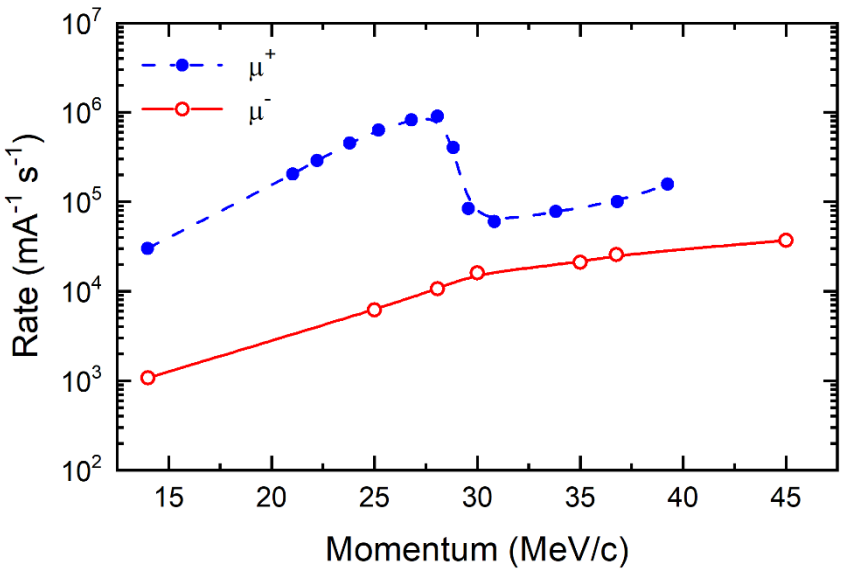

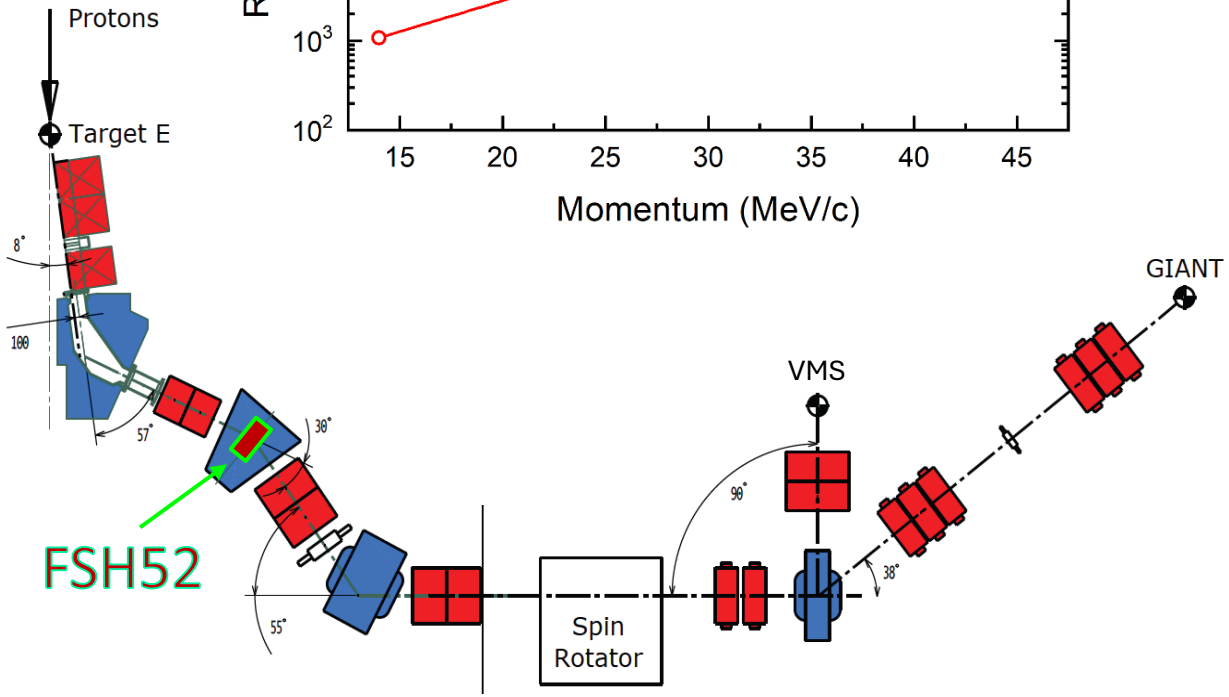

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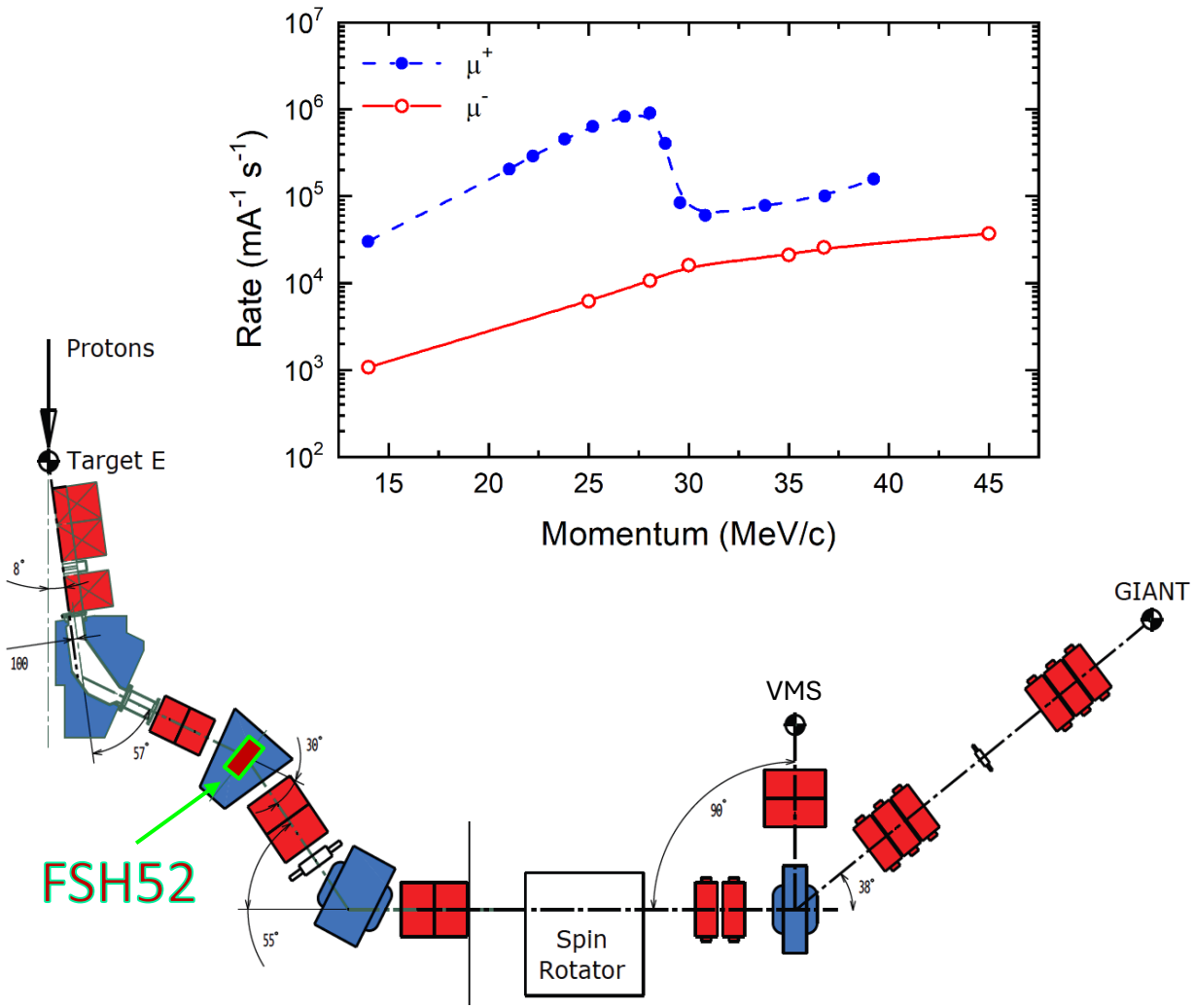

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- *For the "average" sample, we collect enough statistics within ~1 hour*

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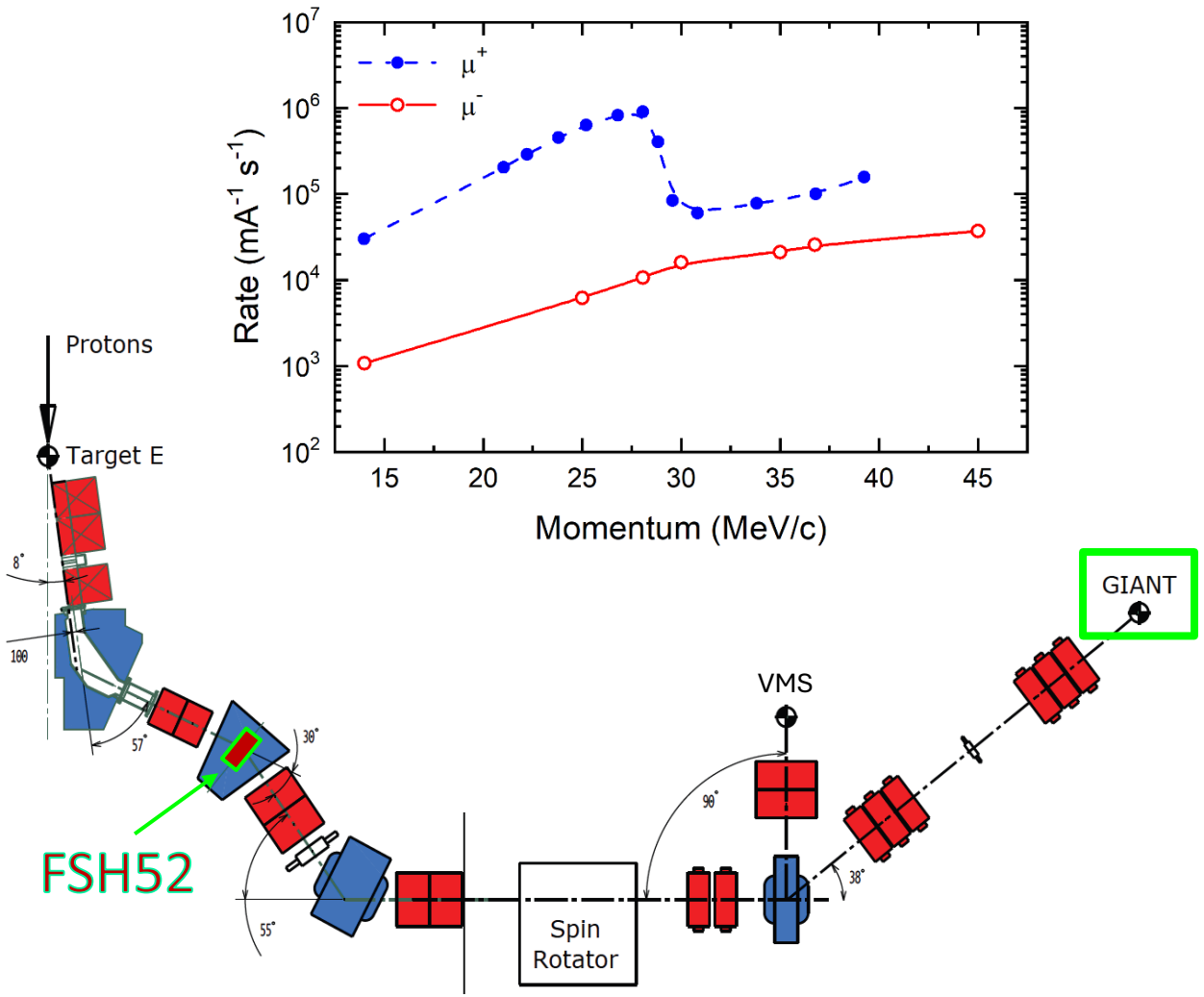

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All past MIXE campaigns hosted at πE1.2

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

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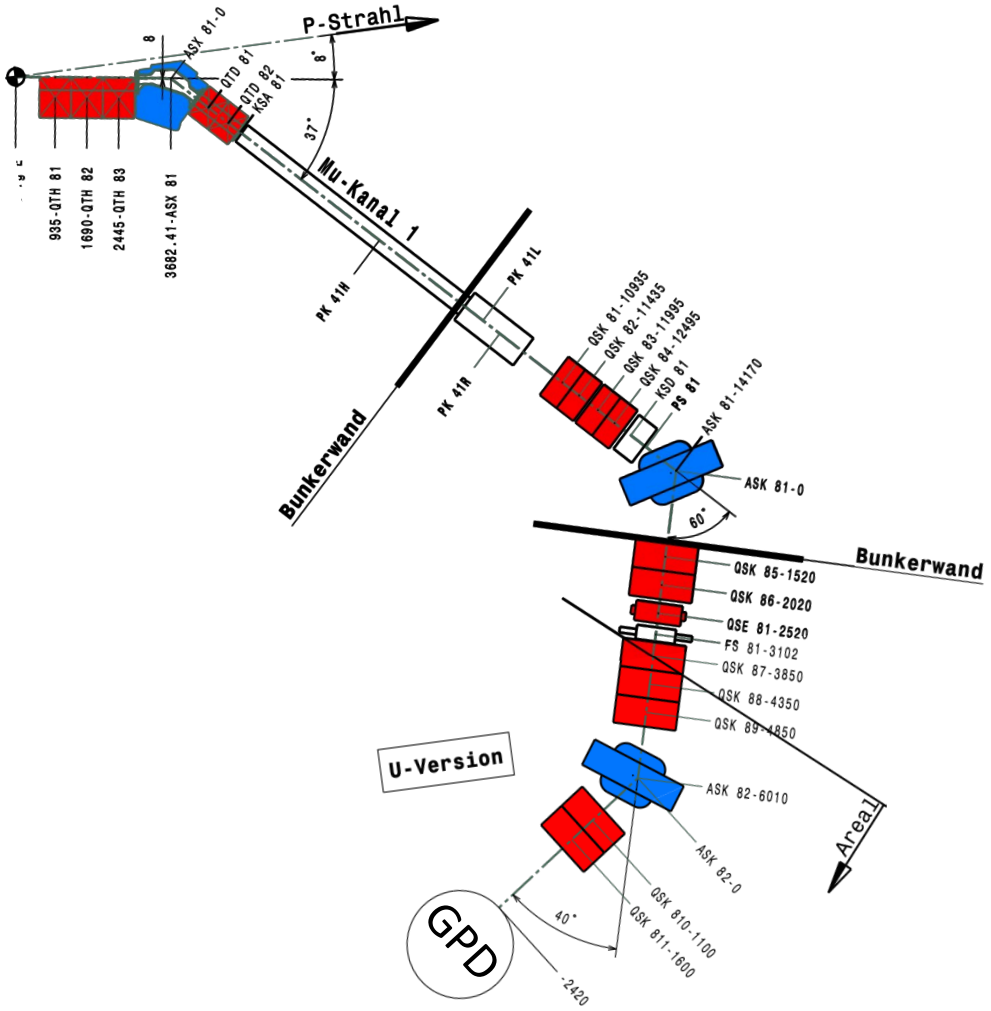

High intensity μ beamline at target E

- (cold-bore) superconducting decay solenoid

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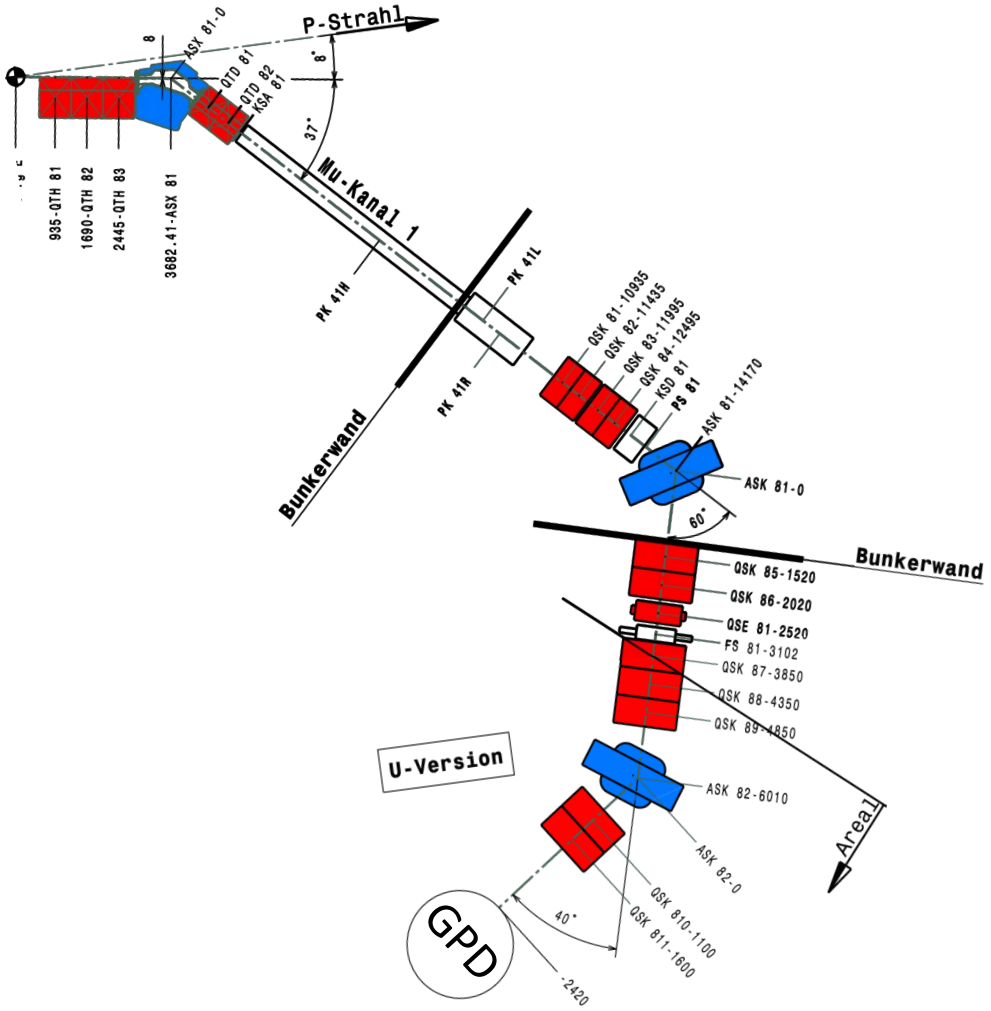

High intensity μ beamline at target E

- (cold-bore) superconducting decay solenoid
- typical μ^- momenta: **60-120 MeV/c**

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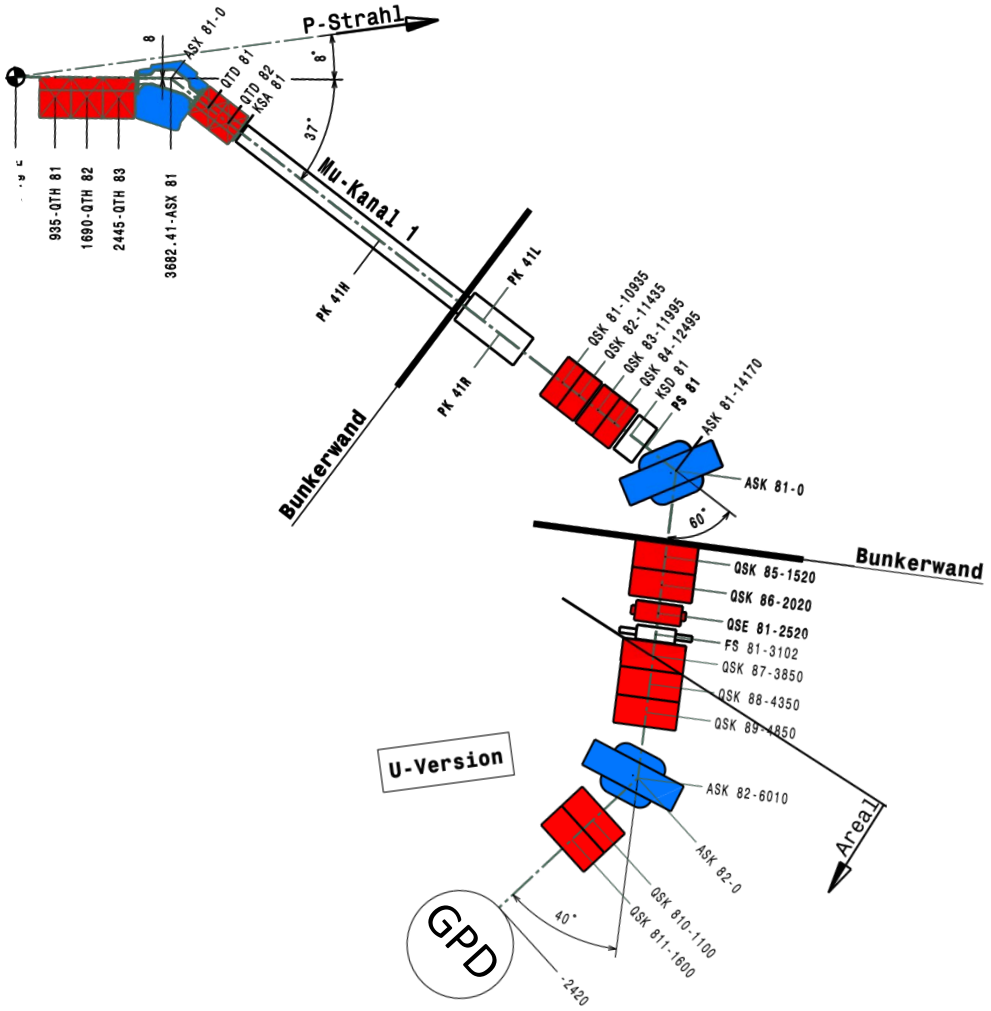

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Rates from 10^7 up to 10^8 μ^-/s on target

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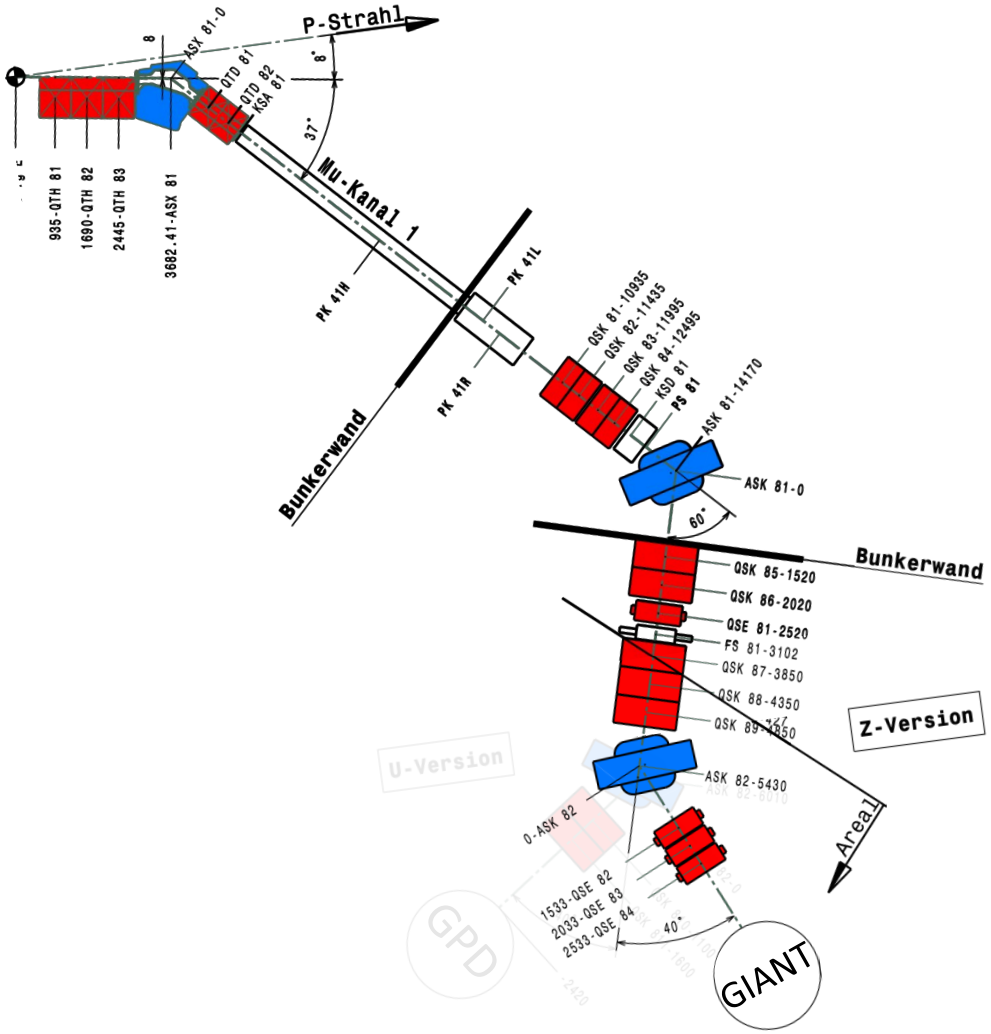

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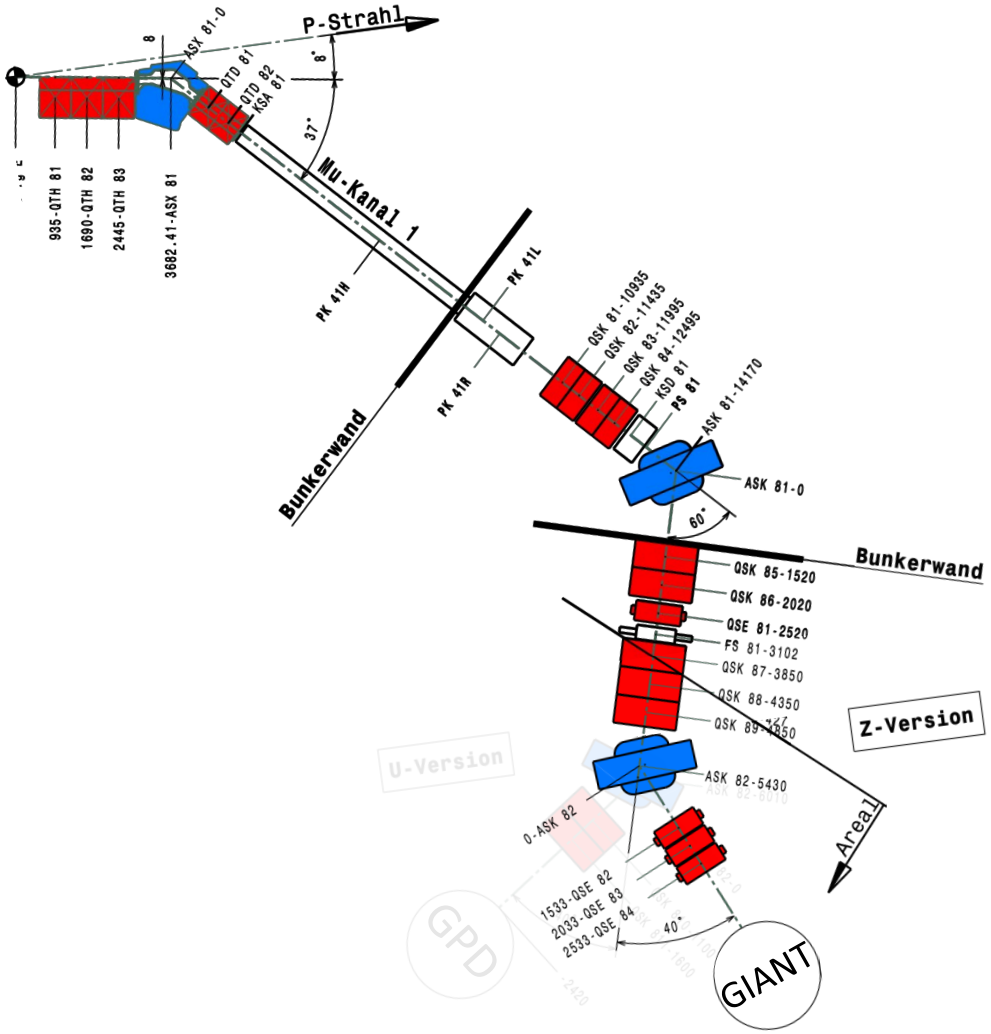

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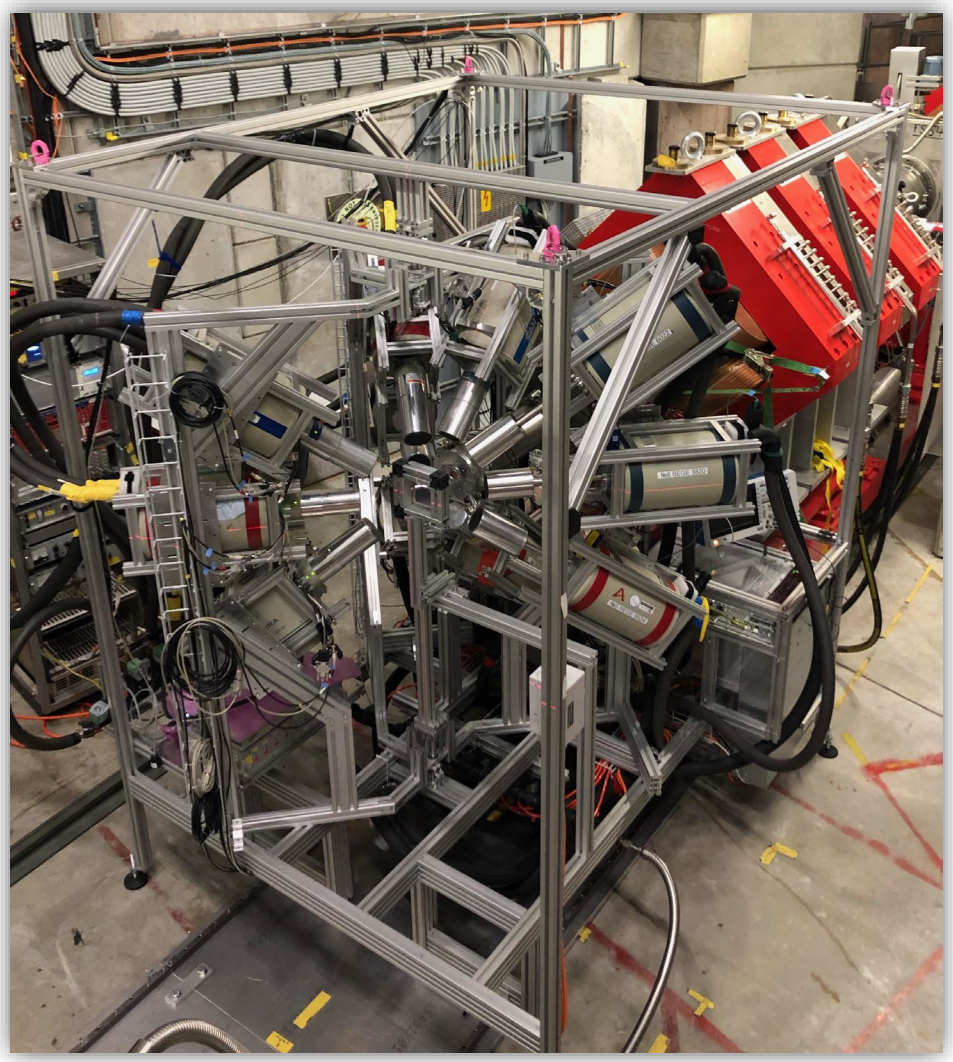
Dual configuration: U (GPD) and Z (GIANT)

Future beam-line for MIXE

- installation during 2027/2028 shutdown (HIMB)
- high momentum / high rate studies (degrader)
- shorter πE1 campaign for low mom. / high res.

GIANT: GermanIum Array for Non-destructive Testing – Overview

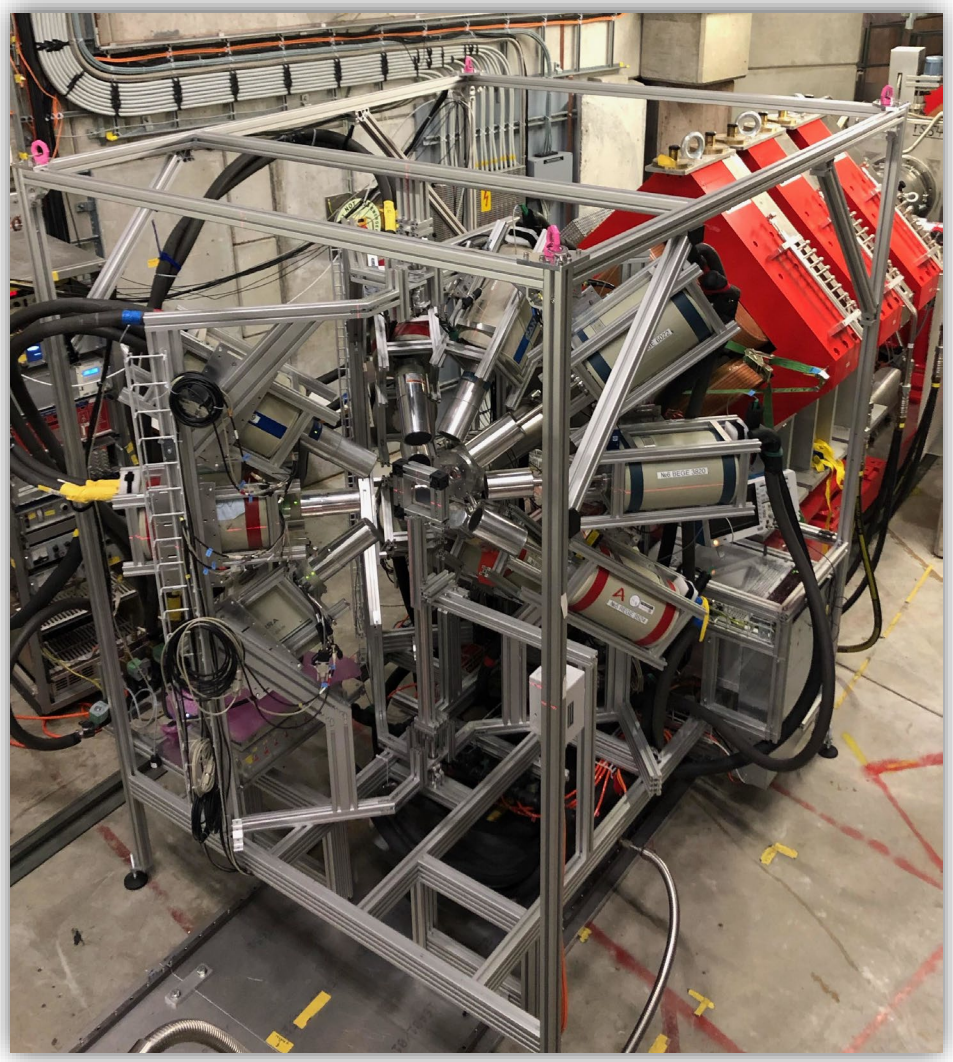
PSI



Large solid angle detector array

- currently ~**12 HPGe detectors** (up to 30)
  pooled with PP exp. (muX, Ref.Radii, MONUMENT, …)

GIANT: GermanIum Array for Non-destructive Testing – Overview



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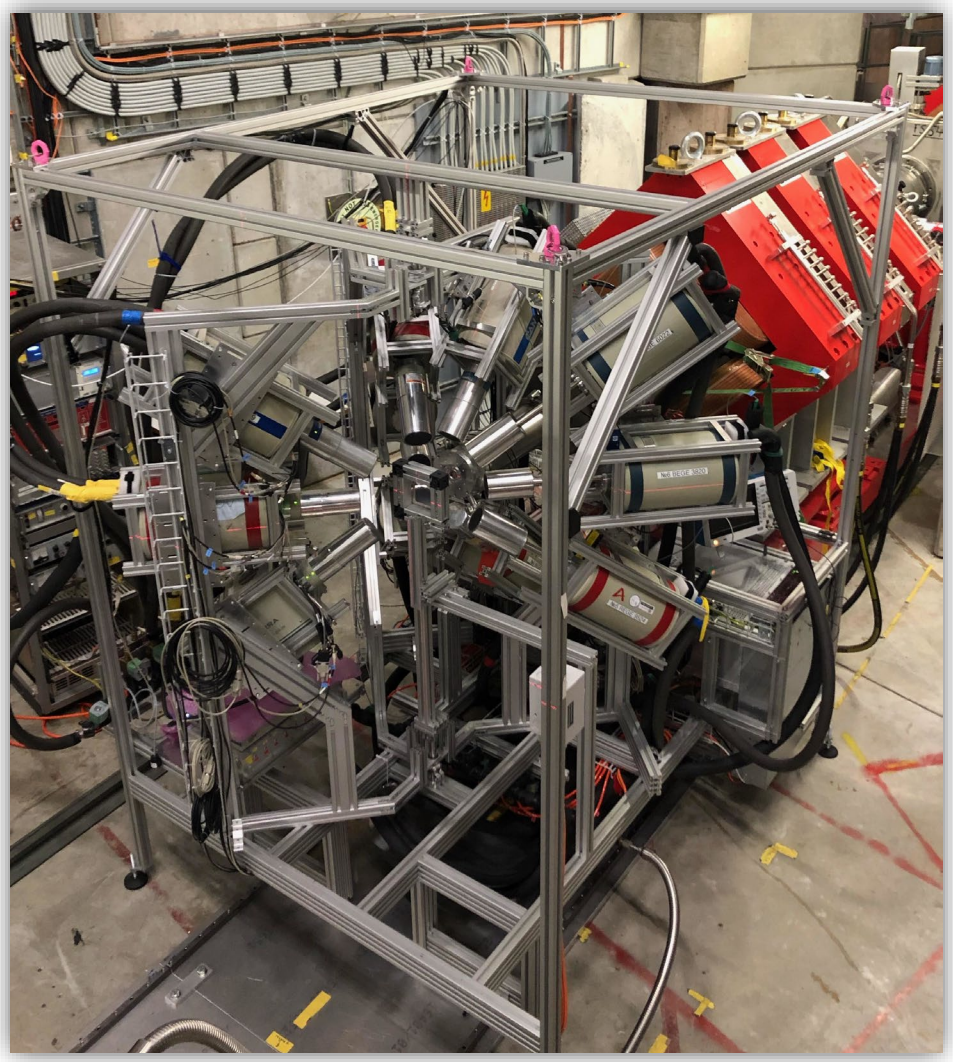

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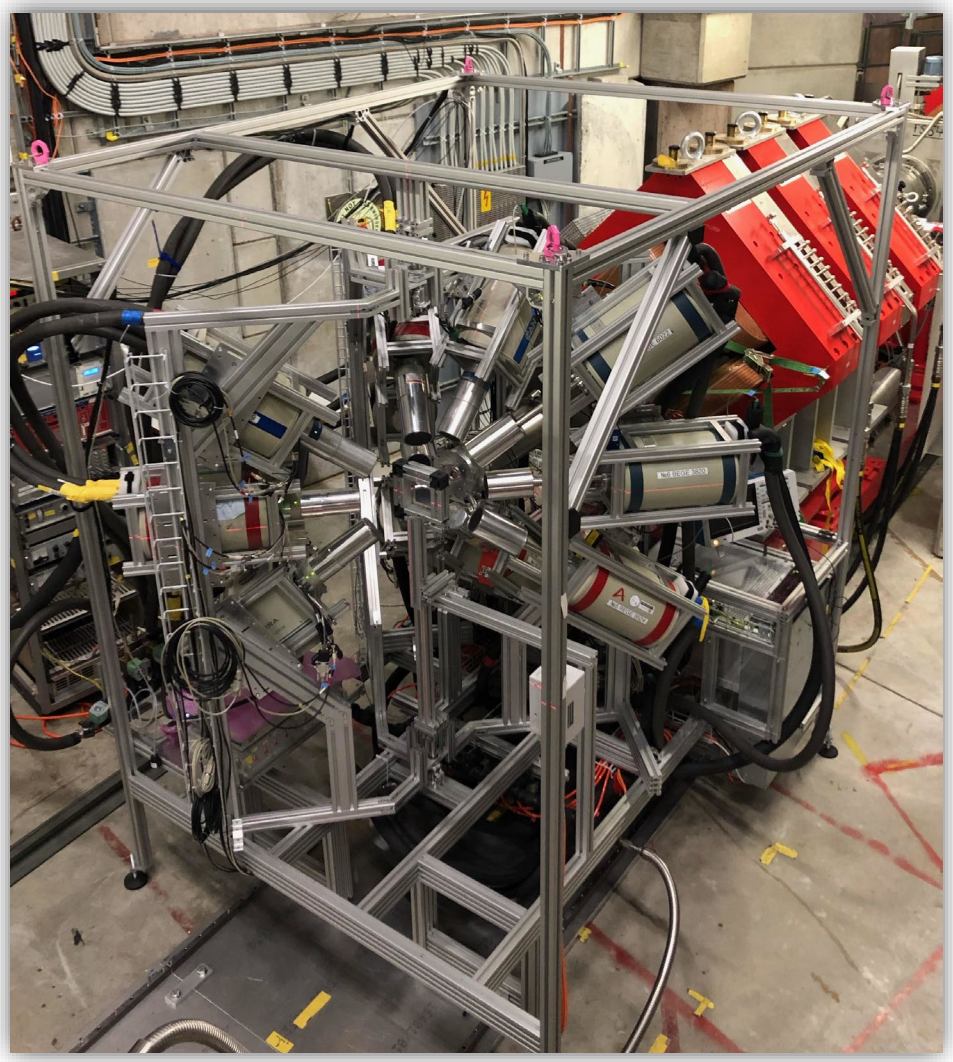

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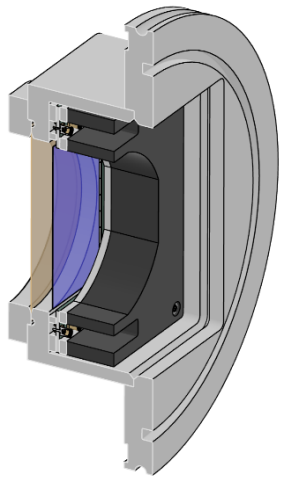

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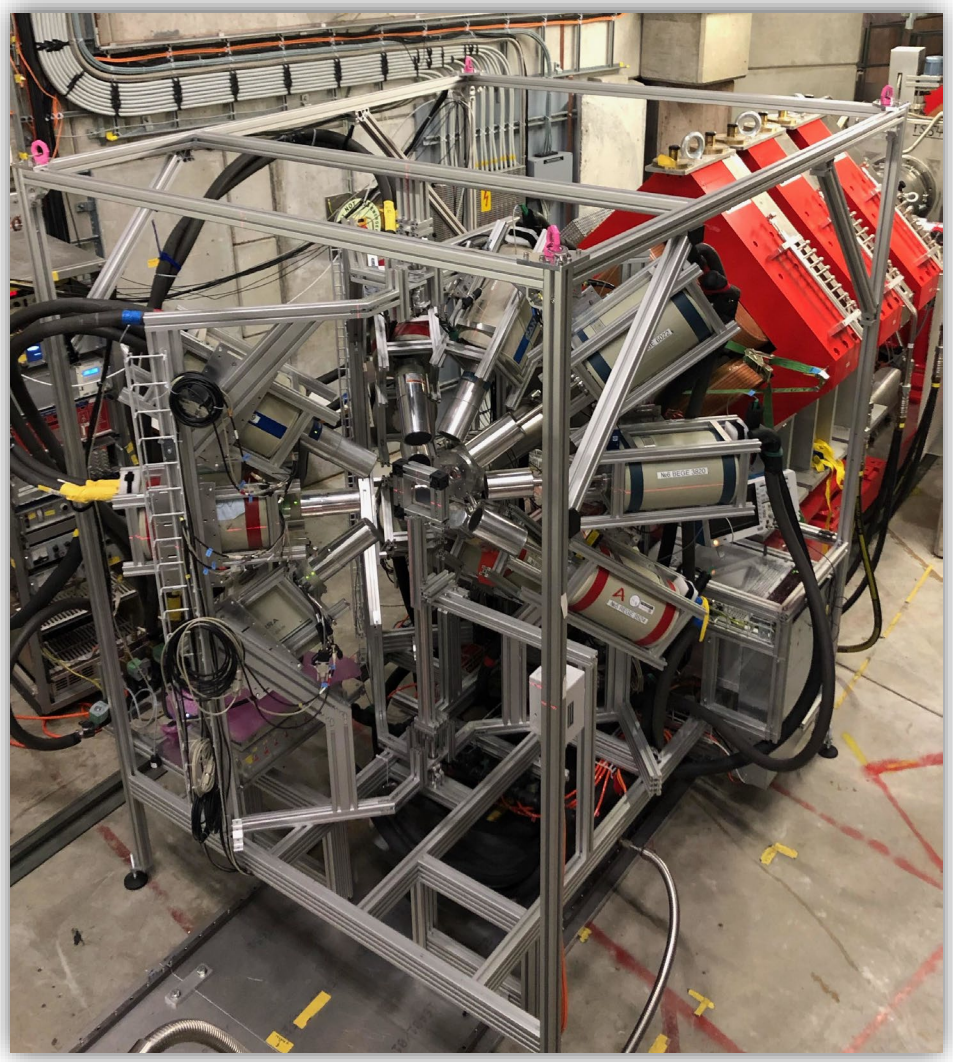

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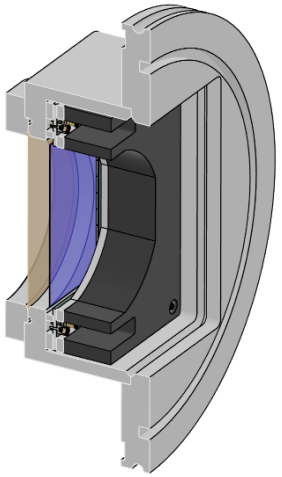
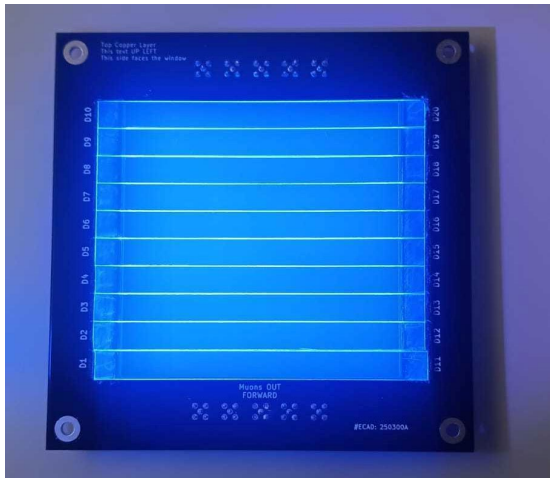
- **low material budget** vacuum **window** (50µm mylar)
- **large area** (7x7cm^2) **muon counter** (adaptable thickness)
- **segmented** design – facilitates higher tracking rates





Part II

Muon Induced X-ray Emission

Showcase Studies

Arrowhead: Sample and Reception

PSI

Bernisches Historisches Museum
Musée d'Histoire de Berne

UNI FREIBURG

NATUR HISTORISCHES MUSEUM BERN

UNIVERSITÄT BERN

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ELSEVIER

Journal of Archaeological Science
Volume 157, September 2023, 105827

An arrowhead made of meteoritic iron from the late Bronze Age settlement of Mörigen, Switzerland and its possible source

Beda A. Hofmann [a b], Sabine Bolliger Schreyer [c], Sayani Biswas [d], Lars Gerchow [d], Daniel Wiebe [e], Marc Schumann [e], Sebastian Lindemann [e], Diego Ramírez García [e], Pierre Lanari [b], Frank Gfeller [a b], Carlos Vigo [d], Debarchan Das [d], Fabian Hotz [d], Katharina von Schoeler [f d], Kazuhiko Ninomiya [g], Megumi Niikura [h], Narongrit Ritjoho [i], Alex Amato [d]

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Archäologische Sensation

Pfeilspitze vom Bielersee ist aus Eisen aus dem All

Rätsel um eiserne Pfeilspitze aus Bronzezeit gelöst: Das Material lieferte ein in Estland abgestürzter Meteorit.

SRF

Diese Pfeilspitze ist nicht von dieser Welt

Forschende haben herausgefunden, dass eine bronzezeitliche Pfeilspitze aus dem Bernischen Historischen Museum aus meteoritischem Eisen hergestellt wurde. Laut Museum ein «extrem seltener» Nachweis.

20 minuten

Prähistorische Pfeilspitze vom Bielersee soll aus Meteorit sein

Nau.ch

Am Bielersee ist im 19. Jahrhundert eine prähistorische Pfeilspitze gefunden worden. Nun steht fest, dass sie aus Meteorit besteht.

Forschende weisen Herkunft nach

Prähistorische Pfeilspitze vom Bielersee aus Meteorit hergestellt

BZ

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Eisen aus dem Weltall Bronzezeitliche Pfeilspitze aus Meteorit entdeckt

TAGESSPIEGEL

Schweizer Forscher haben bei Ausgrabung einer fast 3000 Jahre alten Siedlung eine Pfeilspitze entdeckt, deren Material offenbar aus dem Weltall stammt. Der Fund ist überaus selten.

Archäologische Sens

Pfeilspitze

dem All

Rätsel um eiserne Pfeilspitze aus Bro

DERSTANDARD

Pfeilspitze aus dem Bernischen Historischen Museum aus meteoritischem Eisen hergestellt wurde. Laut Museum ein «extrem seltener» Nachweis.

SELTENE KOSTBARKEIT

Bronzezeitliche Pfeilspitze aus Meteoriteneisen kam von weit her

Eine 2.900 Jahre alte Eisenpfeilspitze aus der Schweiz wurde erstmals genauer untersucht. Sie kann nicht aus der Umgebung stammen, sondern kam vermutlich aus Estland

SPIEGEL

Fund aus der Schweiz

Bronzezeitliche Pfeilspitze wurde aus Meteorit gefertigt

Im 19. Jahrhundert fanden Fachleute bei Mörigen eine Pfeilspitze aus der Bronzezeit. Nun steht fest: Das Material dafür ist kosmischen Ursprungs. Eine Spur führt zu einem Meteoriteneinschlag in Estland.

Nau.ch

Prähistorische Pfeilspitze vom Bielersee soll aus Meteorit sein

GESCHICHTE UND KULTUR

NATIONAL GEOGRAPHIC

Bronzezeitliche Pfeilspitze aus Meteorit-Eisen

Vor etwa 2.900 Jahren fertigten Menschen in der heutigen Schweiz eine Pfeilspitze aus Eisen – und nutzten dabei laut aktuellen Untersuchungen kosmisches Material. Nun suchen Forschende nach dem Ursprung des Metalls aus einer anderen Welt.

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Arrowhead made from meteorite 3,000 years ago found near lake in Europe

CNN

SPIEGEL

Archeologists Discover Bronze Age Arrowhead Made Of 'Alien Metal'

Forbes

THE TIMES

Bronze Age arrowhead is sole meteorite iron work from western Europe

Researchers have discovered the extraterrestrial secret behind an artefact that had been kept in a Swiss museum for decades, Rhys Blakely writes

3000-year-old arrowhead revealed to be made of meteorite

A new study has revealed a bronze-age arrowhead dug up in Switzerland was made from a meteorite.

1news

THE JERUSALEM POST

Archaeologists Find 'Alien Metal' In A Bronze Age Arrowhead

indiatimes

This Bronze Age arrowhead was made from materials out of this world

An arrowhead from 900-800 BCE was found to be made of materials not naturally found on Earth.

Arrowhead: The search for “Heavenly Iron”

Bronze age

- **Metalworking** was known
- **Iron extraction** from ore *not yet discovered*

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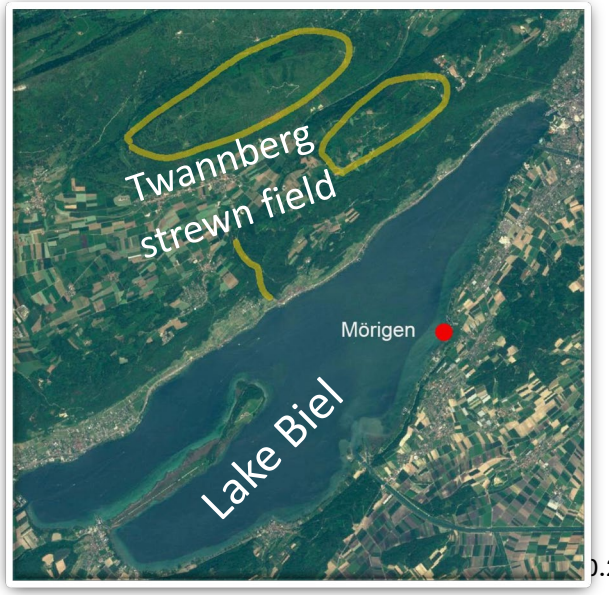
Search in **archaeological collections** (area of *Lake Biel*)

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



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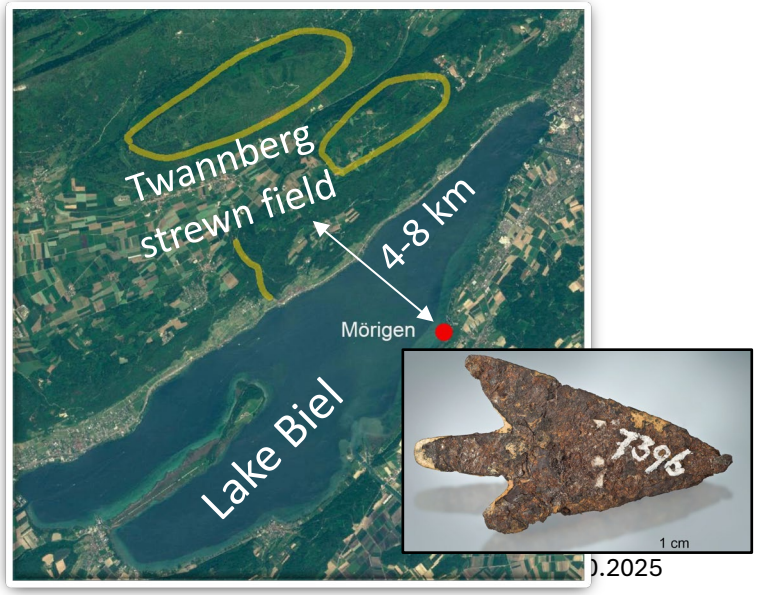
- *Twannberg*: largest **meteorite find** in Switzerland

Such an artifact identified: An **arrowhead**

- Find site: *Pile-dwelling settlement* in **Mörigen**
- Era: **Bronze Age** (900-800 BCE)
- Made from a large **iron meteorite** (*>2 tons*)



Arrowhead: The surprise!

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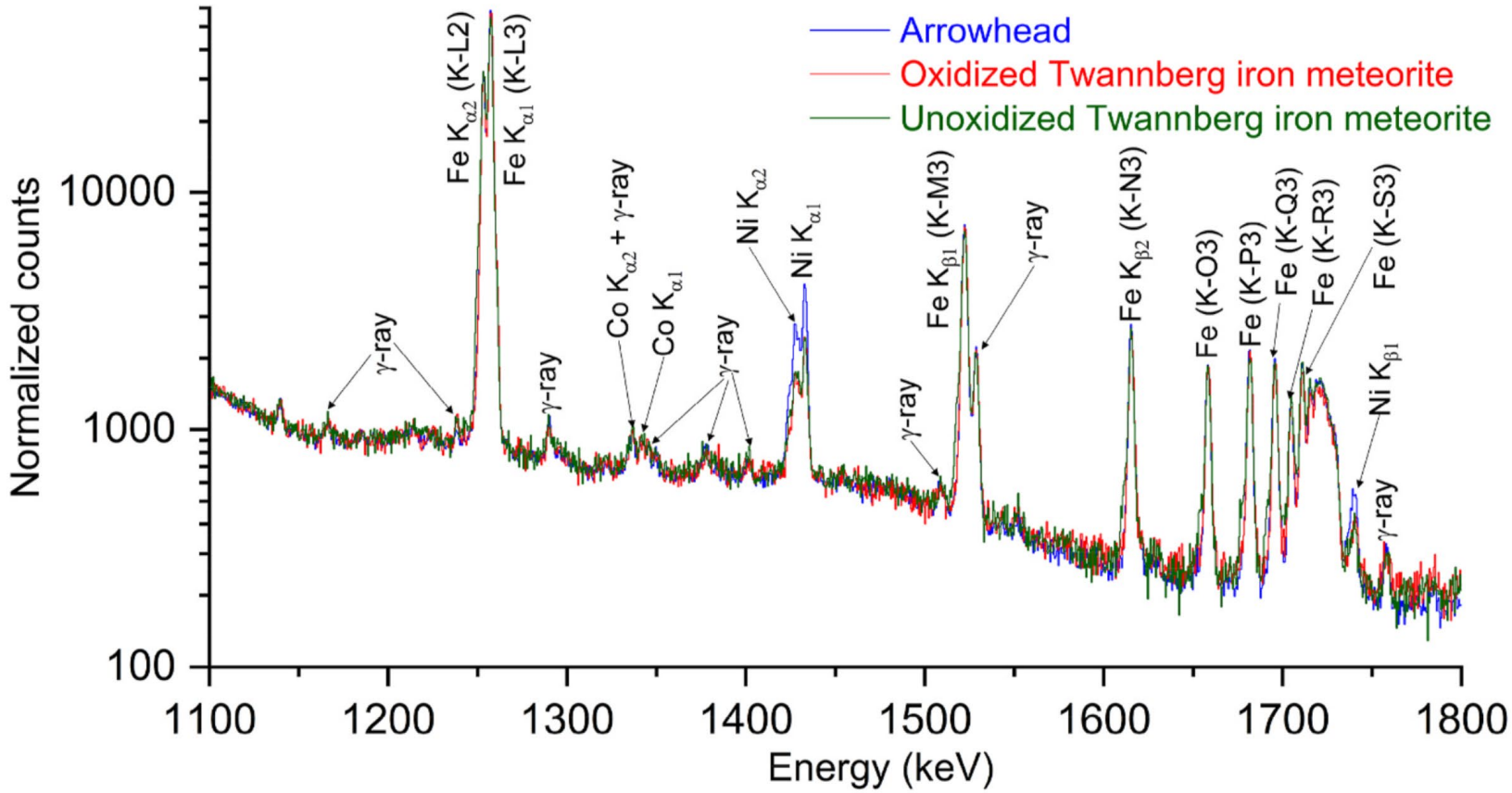

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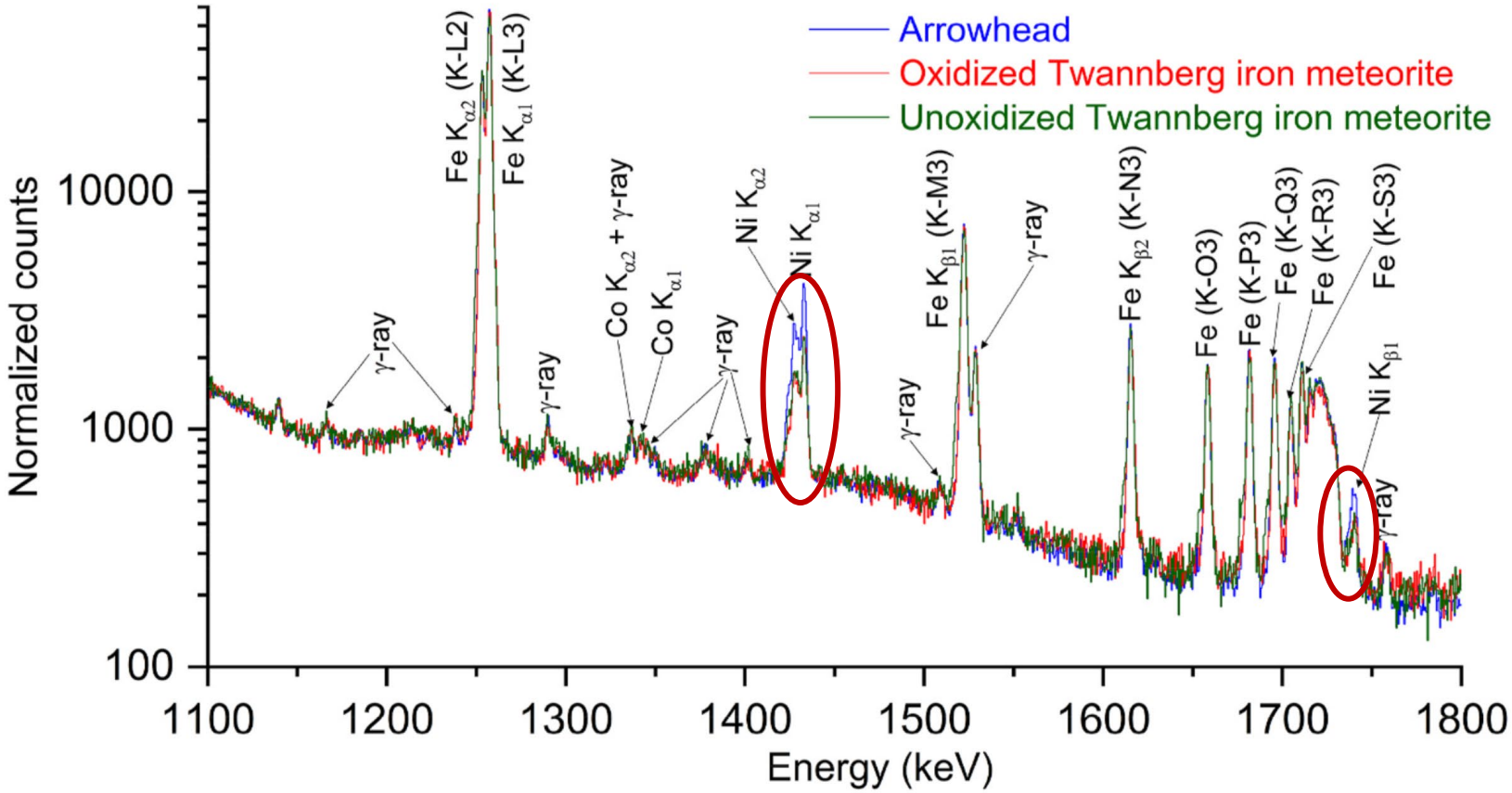

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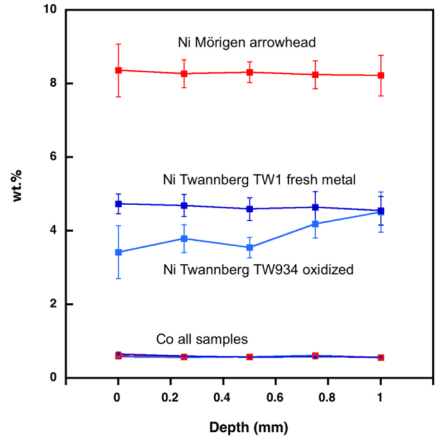

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Only 3 possible meteorite candidates in Europe

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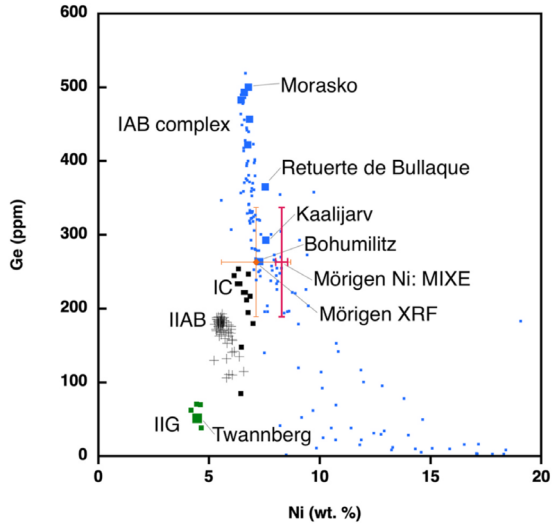

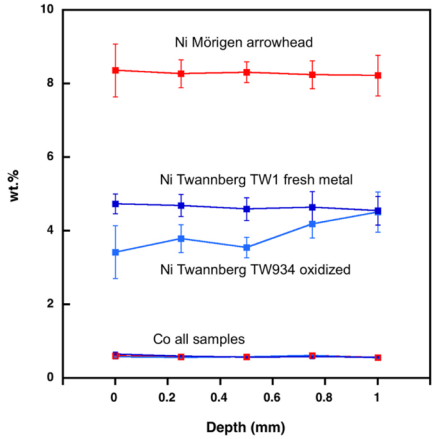

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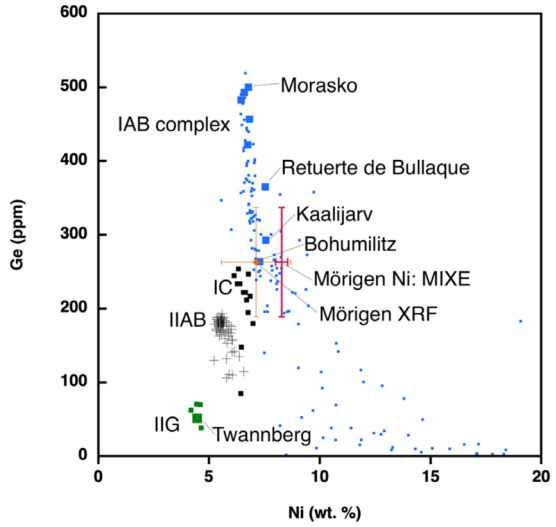

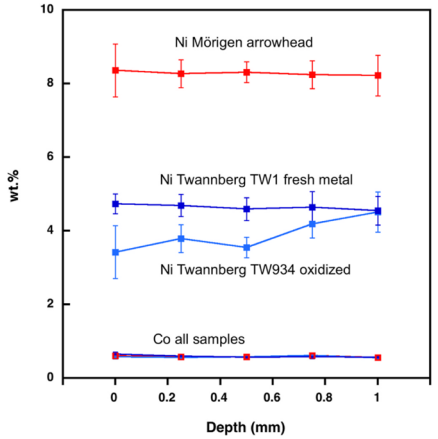

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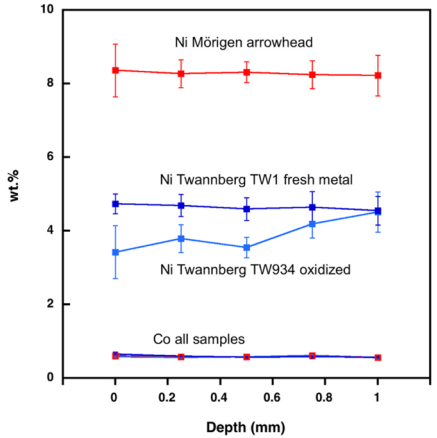

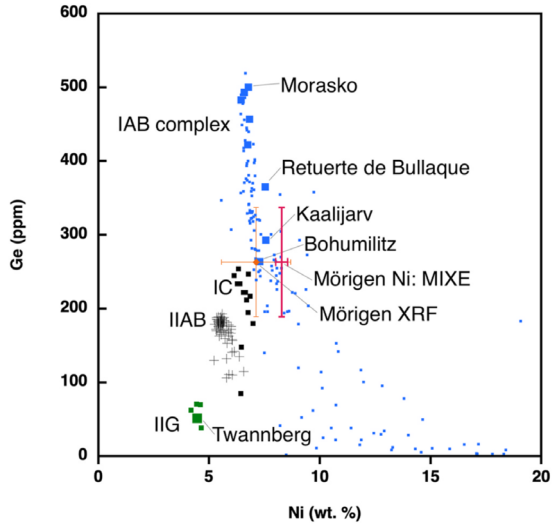

- **Use and trade** of **iron meteorites** in Europe as early as the *Bronze Age* – 800 BCE (or earlier)
- **Transport and trade** over **1.600 kilometers**
- Probably brought to Switzerland via **amber trade routes** from the Baltic region
- *High likelihood of additional similar discoveries!*

Fibula: Sample and Study

AUGUSTA RAURICA PSI

Late-antique knob-bow fibula

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

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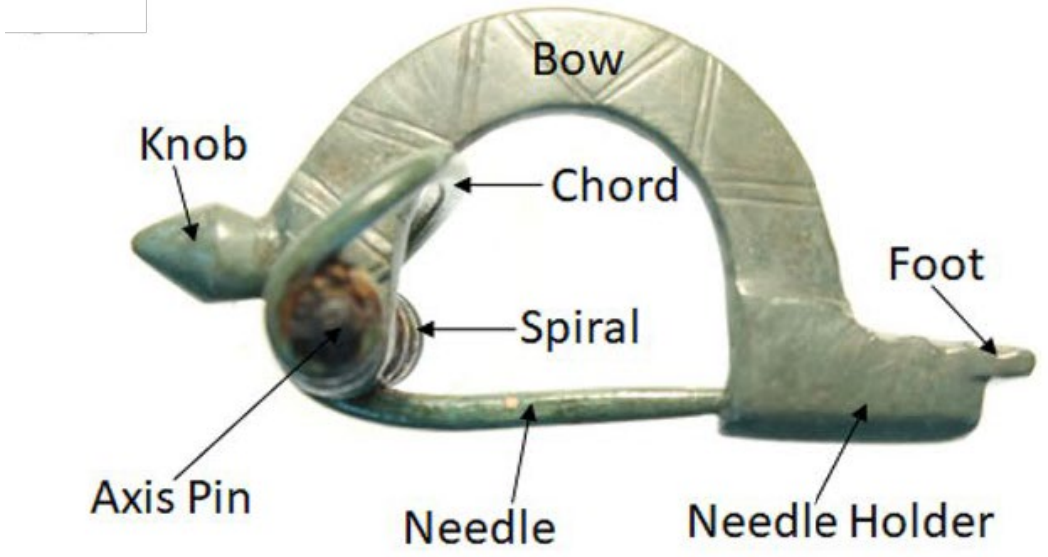

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Sample **not suitable for XRF**

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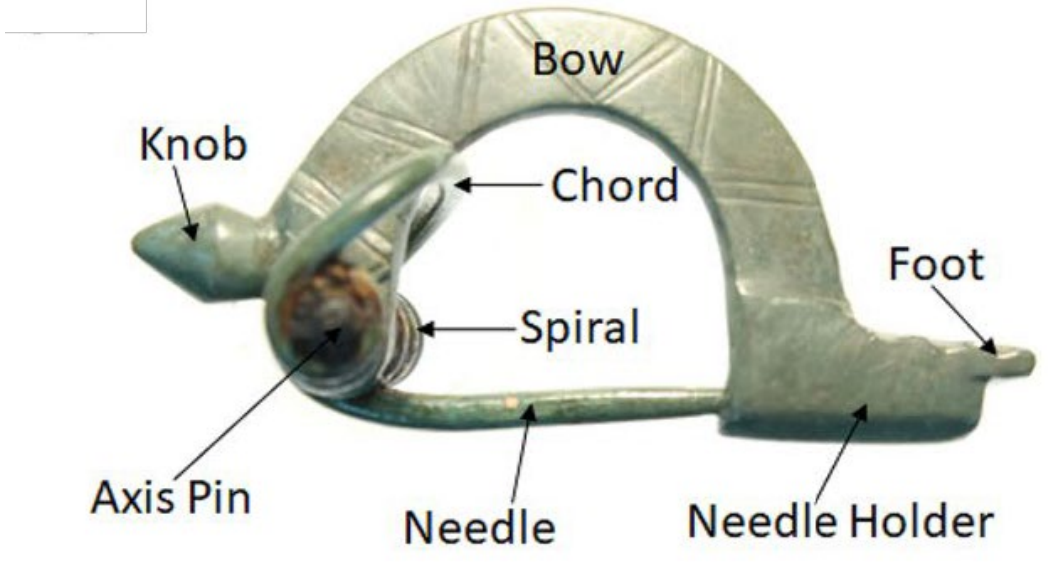

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Six measurements (**~1.5 hours** each):

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

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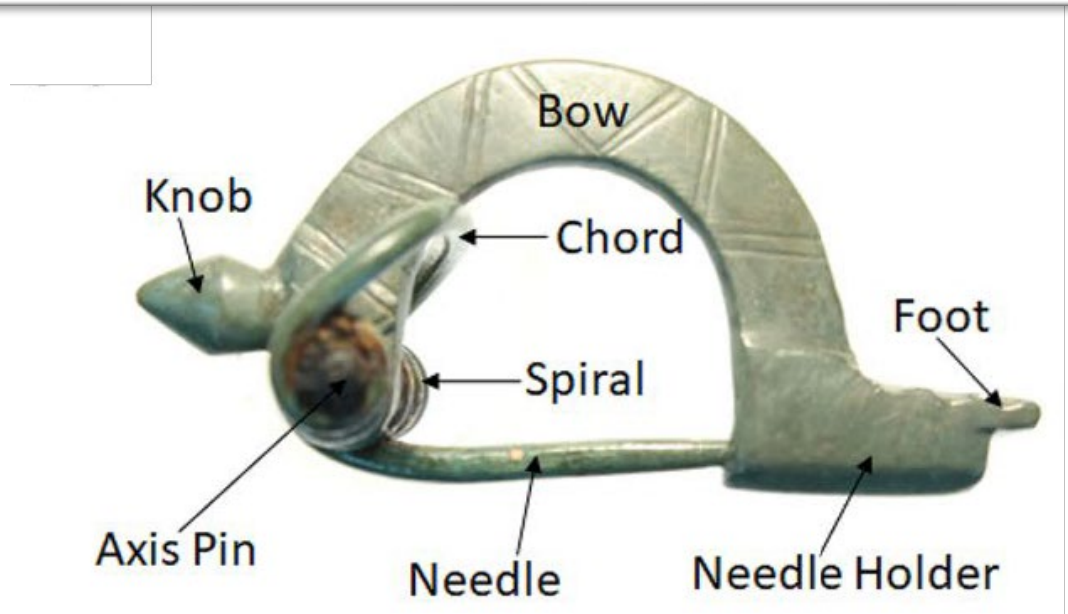

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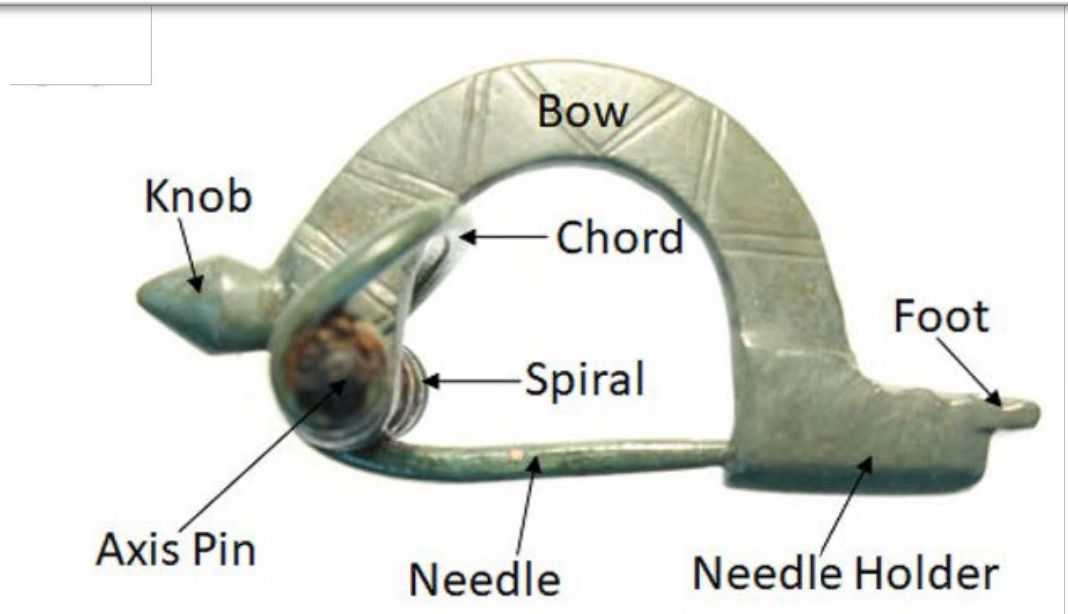
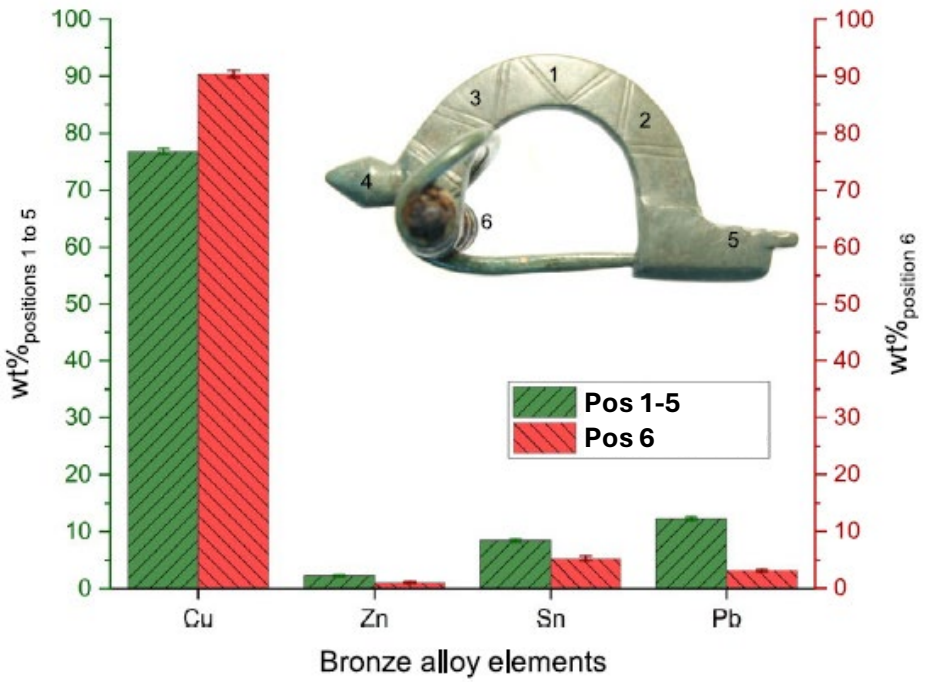


Fibula: Results and Relevance

Elemental Composition

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



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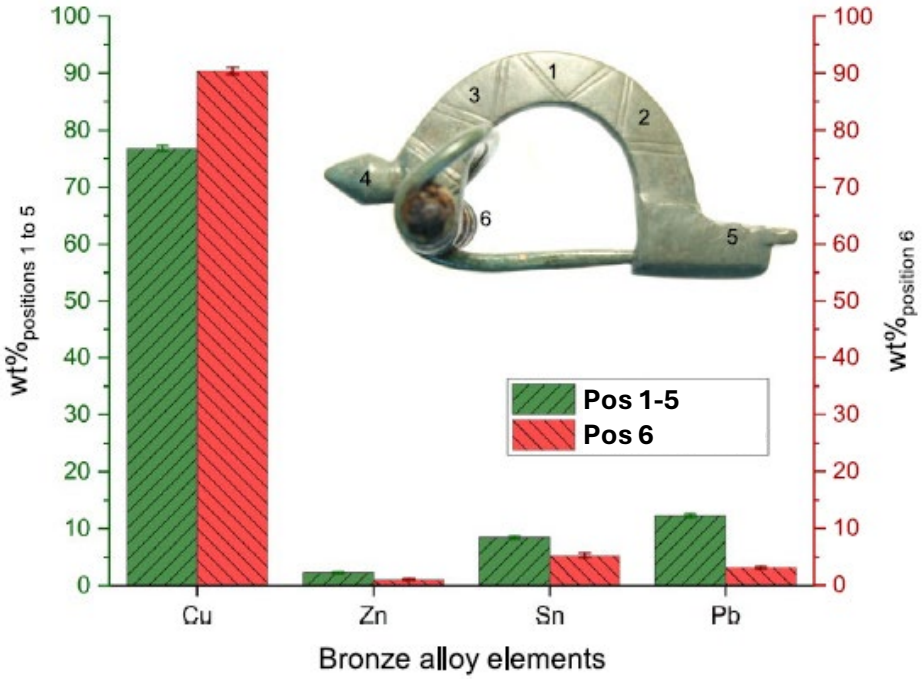

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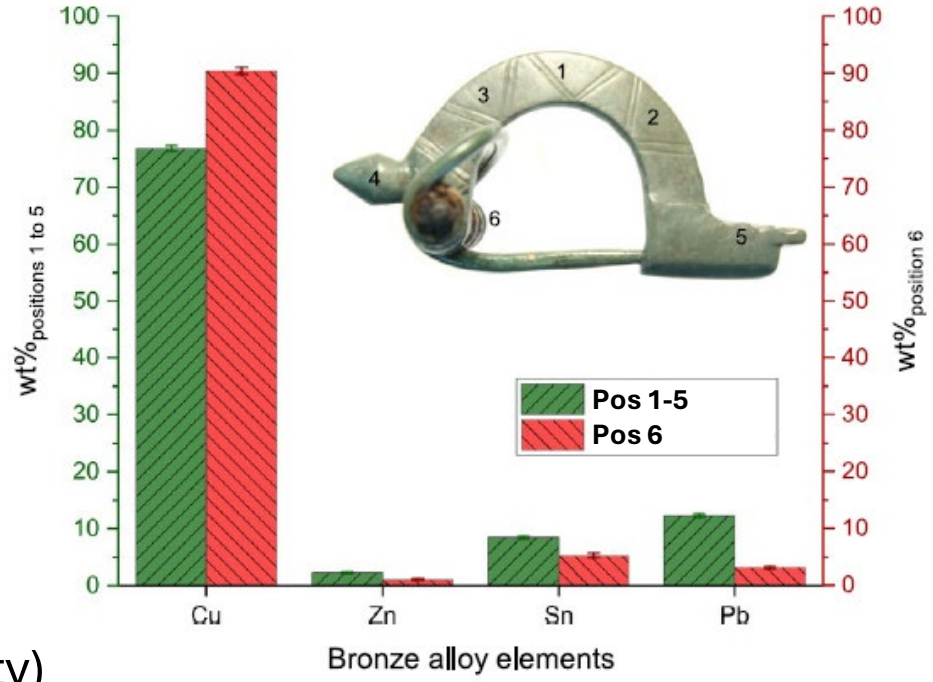
- **Main body** (knob, bow, foot) **alloy** indicative of **casting** (low-melting point and bubble-free flow)
- **Spiral alloy** indicative for **forging** (high strength and ductility)



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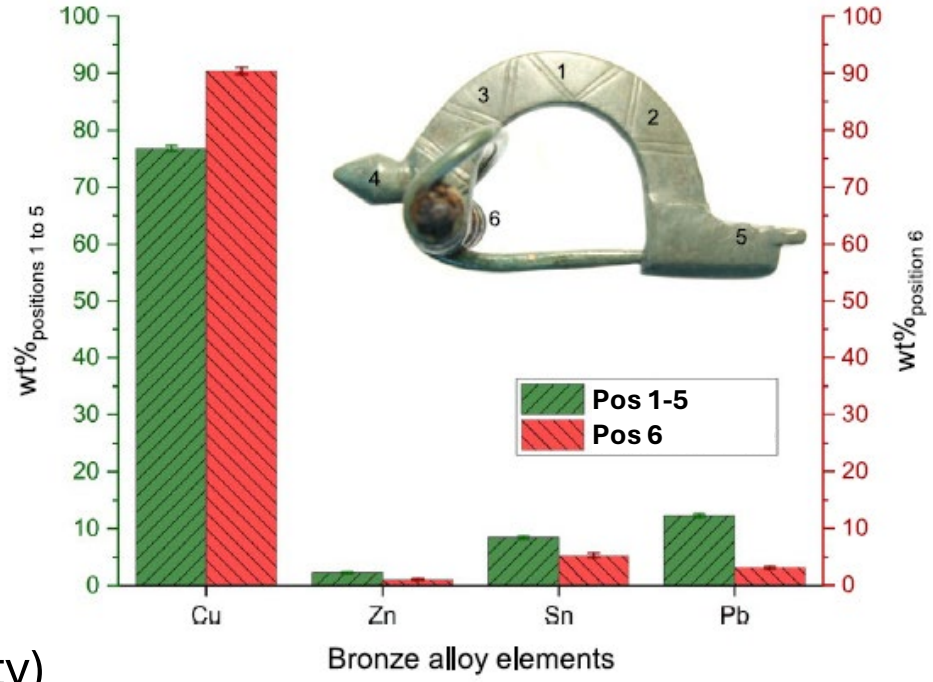

Conclusions

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

MIXE 4 Batteries:
Charge Carrier Ion Transport

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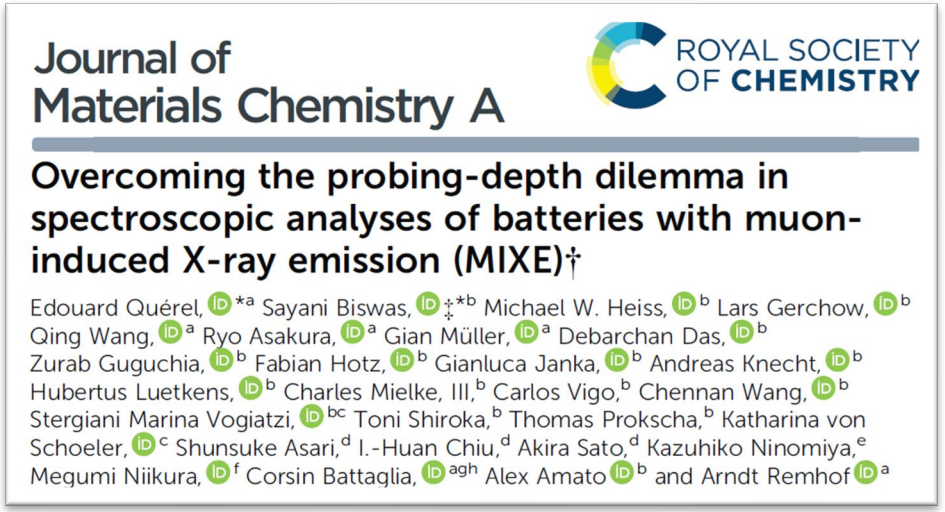

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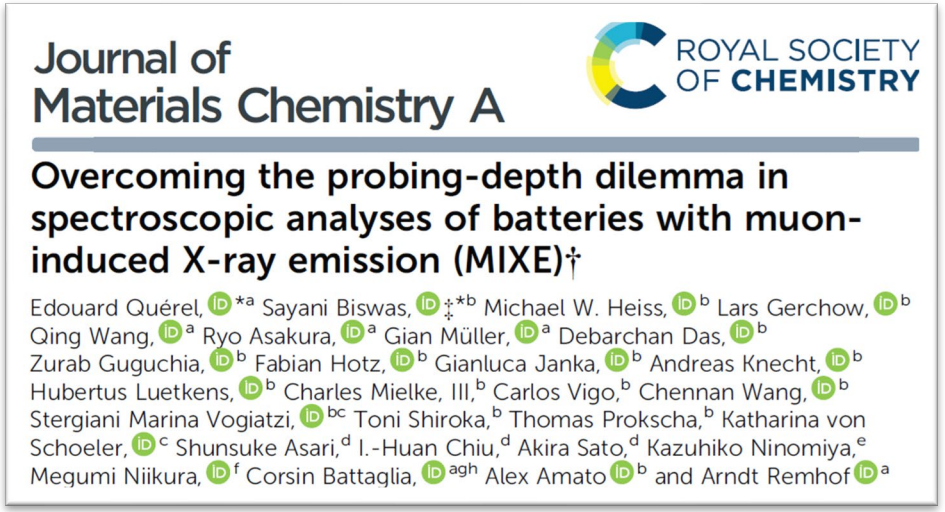

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Li: 54 eV (electronic) Na: 1 keV (electronic)

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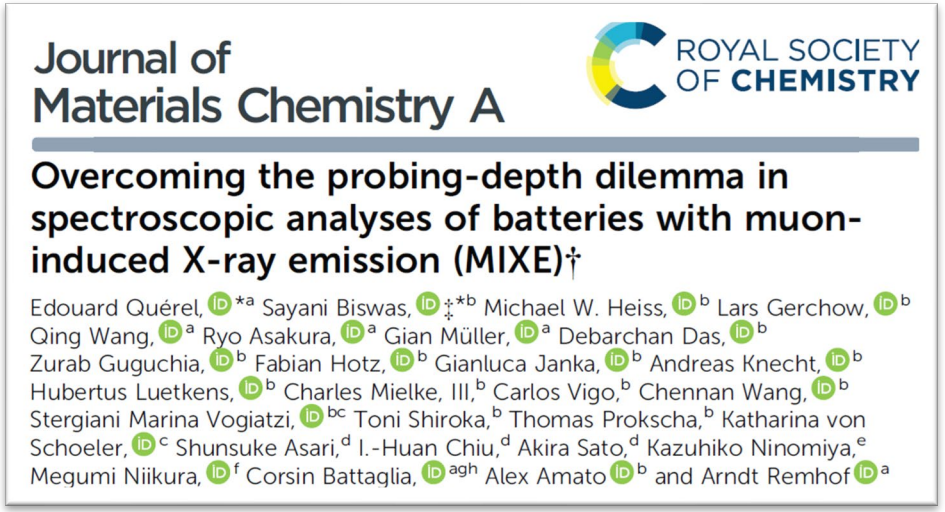

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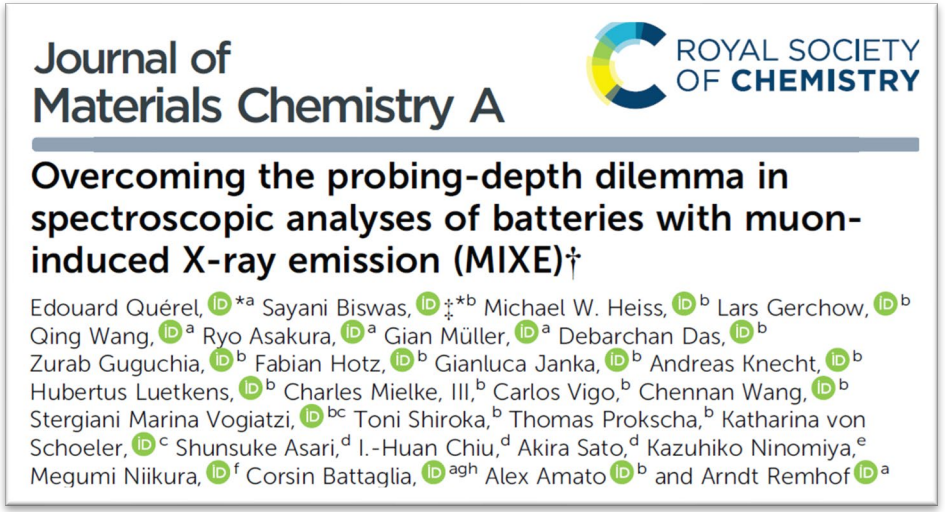

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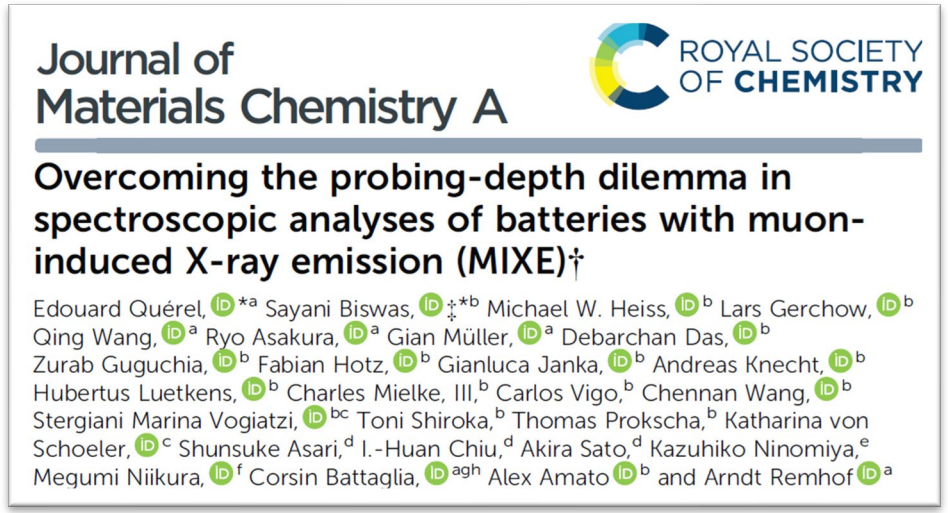

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Journal of Materials Chemistry A
ROYAL SOCIETY OF CHEMISTRY

Overcoming the probing-depth dilemma in spectroscopic analyses of batteries with muon-induced X-ray emission (MIXE)†

Edouard Quérel,[*a] Sayani Biswas,[‡*b] Michael W. Heiss,[b] Lars Gerchow,[b] Qing Wang,[a] Ryo Asakura,[a] Gian Müller,[a] Debarchan Das,[b] Zurab Guguchia,[b] Fabian Hotz,[b] Gianluca Janka,[b] Andreas Knecht,[b] Hubertus Luetkens,[b] Charles Mielke, III,[b] Carlos Vigo,[b] Chennan Wang,[b] Stergiani Marina Vogiatzi,[bc] Toni Shiroka,[b] Thomas Prokscha,[b] Katharina von Schoeler,[c] Shunsuke Asari,[d] I.-Huan Chiu,[d] Akira Sato,[d] Kazuhiko Ninomiya,[e] Megumi Niikura,[f] Corsin Battaglia,[agh] Alex Amato[b] and Arndt Remhof[a]

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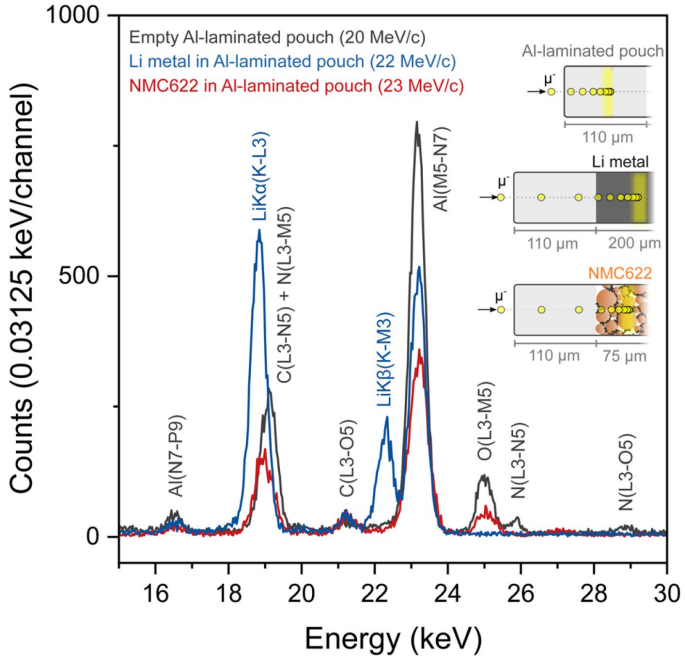
- **Clear Li signal** observed in Li metal
- Li **tracking in electrode** material **very challenging**
  - **Low efficiency** and **capture probability** (e.g. ~16 in Ni vs. Li)
  - **Masked** by **C-L_β** and **N-L_α**
  - *Very **promising** first results for **Na cells** (see also Part III)*



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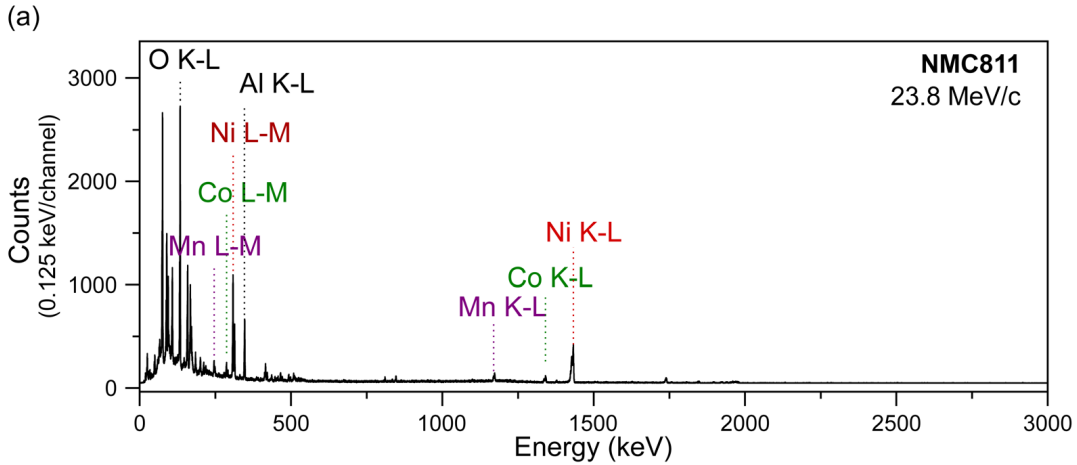

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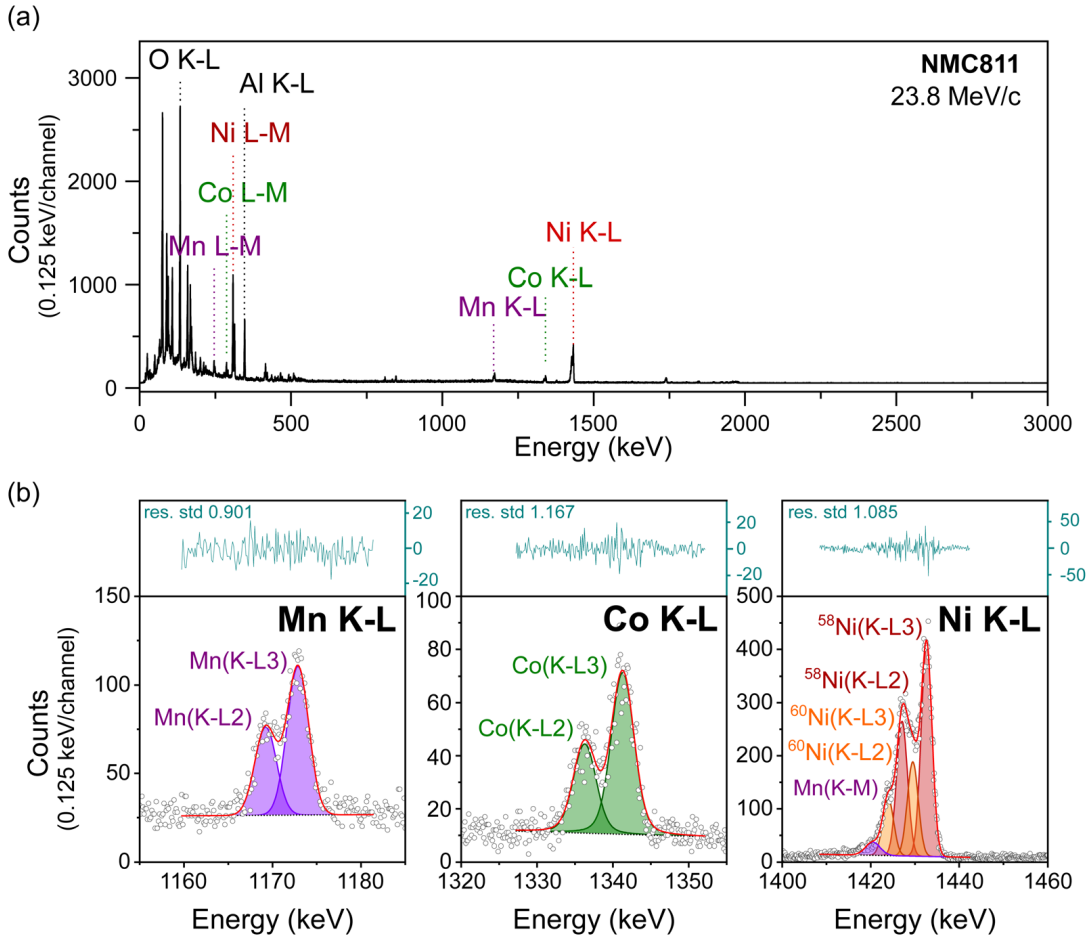

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*Result **reproduces** known elemental **composition** with **high accuracy**!*

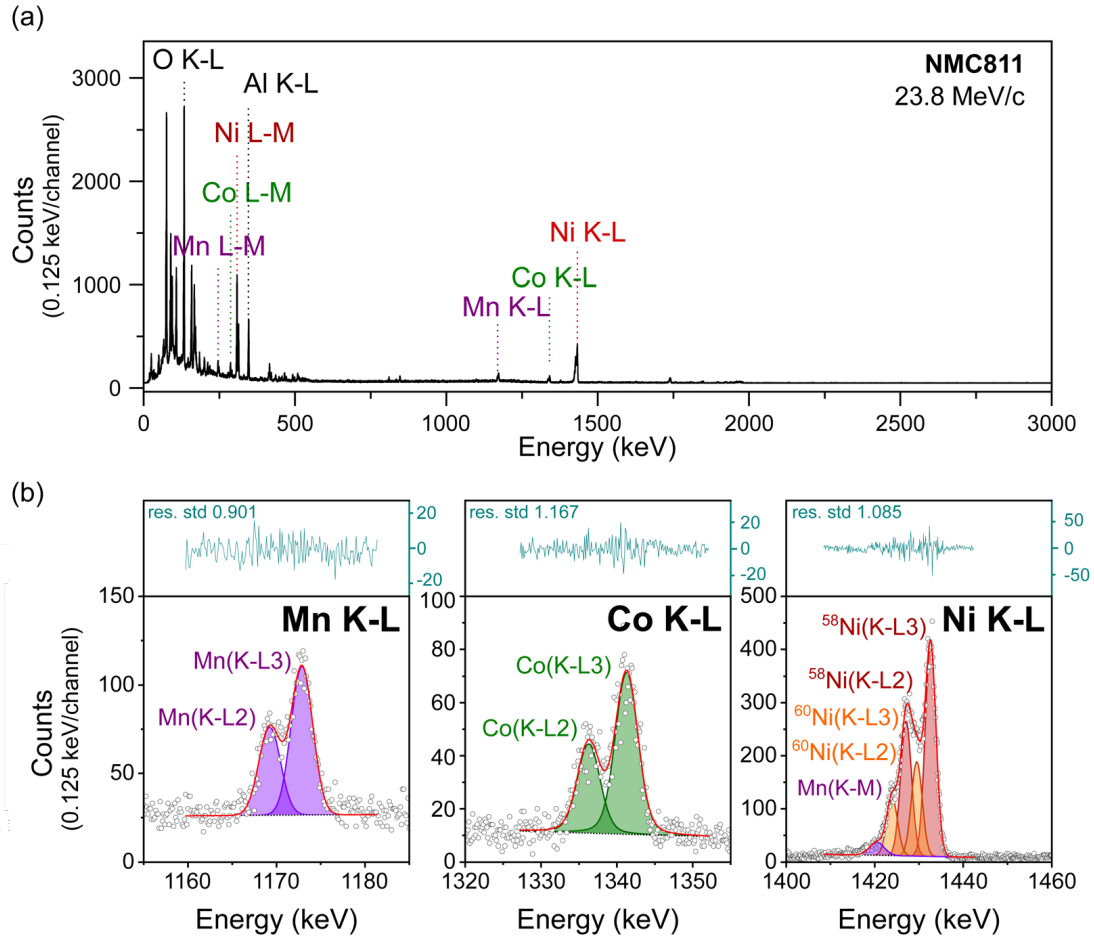

Table 1 Experimentally measured ratios for three different NMC electrodes

NMC type	Nominal composition	Ni/(Ni + Mn + Co)	Mn/(Ni + Mn + Co)	Co/(Ni + Mn + Co)
NMC111	$Li_{1-x}Ni_{0.33}Mn_{0.33}Co_{0.33}O_2$	0.32 ± 0.02	0.35 ± 0.02	0.32 ± 0.01
NMC622	$Li_{1-x}Ni_{0.6}Mn_{0.2}Co_{0.2}O_2$	0.58 ± 0.05	0.21 ± 0.02	0.21 ± 0.02
NMC811	$Li_{1-x}Ni_{0.8}Mn_{0.1}Co_{0.1}O_2$	0.80 ± 0.03	0.103 ± 0.005	0.10 ± 0.02

Part III

Muon Induced X-ray Emission

Future Outlook: Tomography

MIXE-T(omography): Introduction

PSI

μ^-

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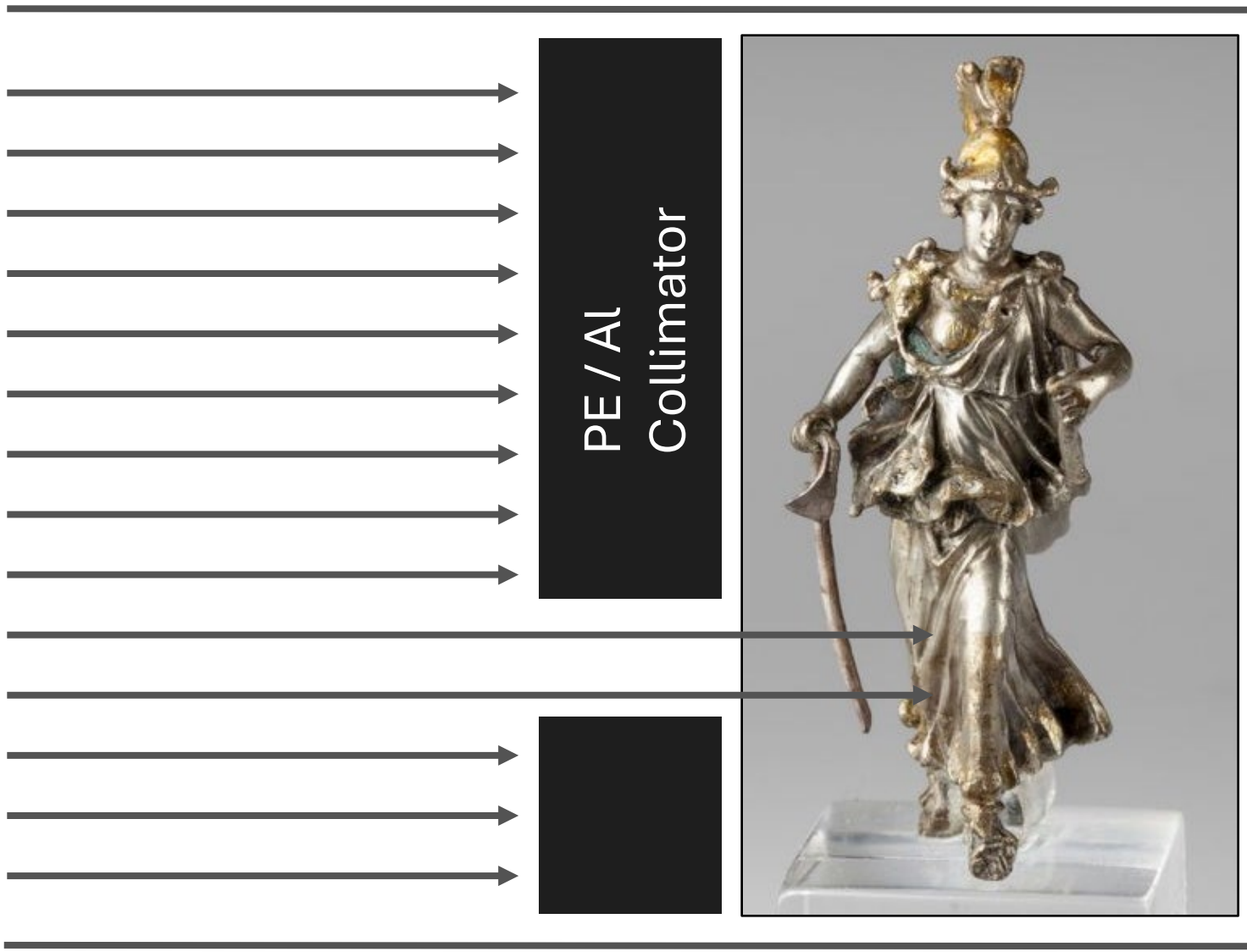
PSI

μ^-



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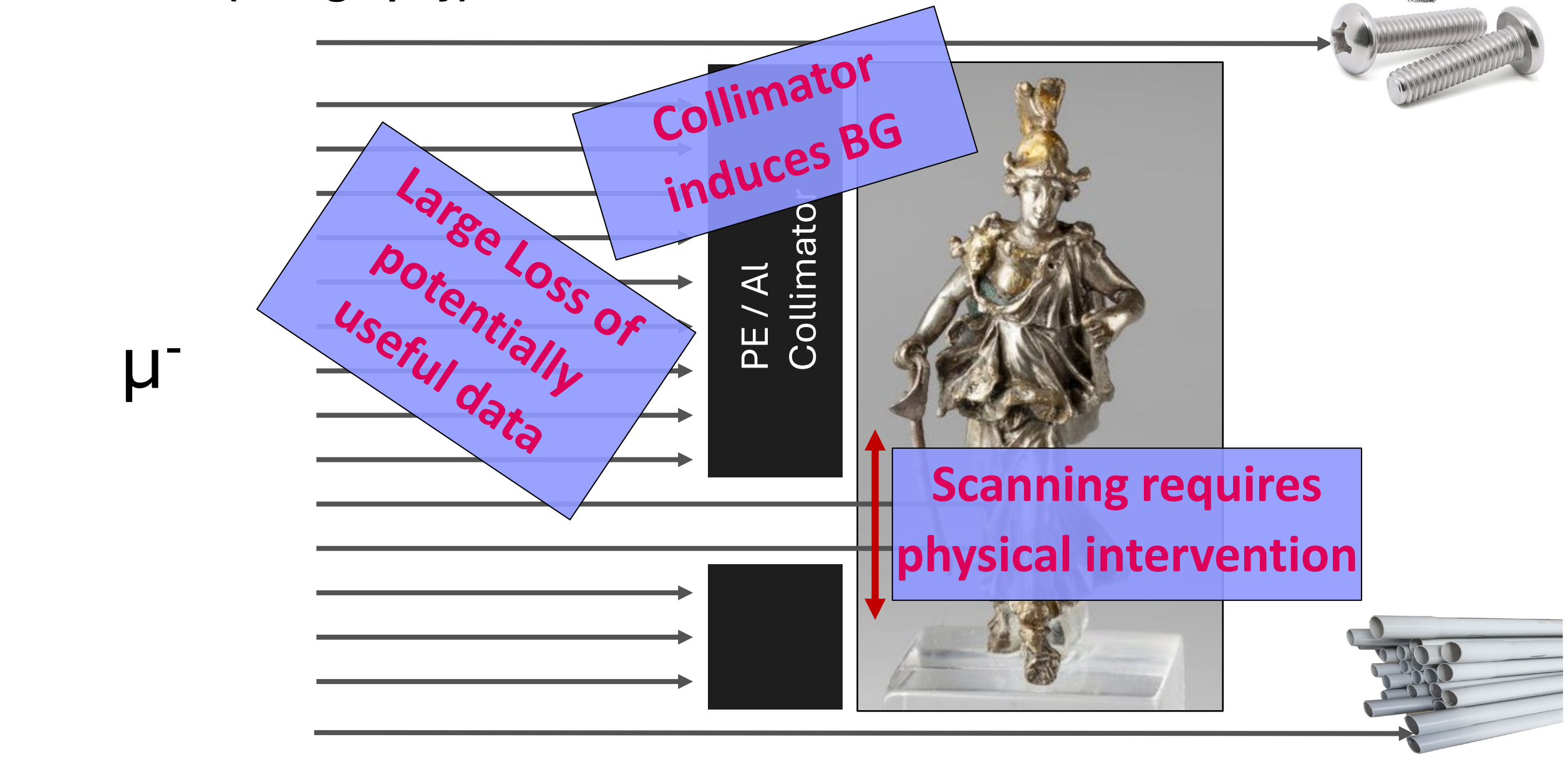

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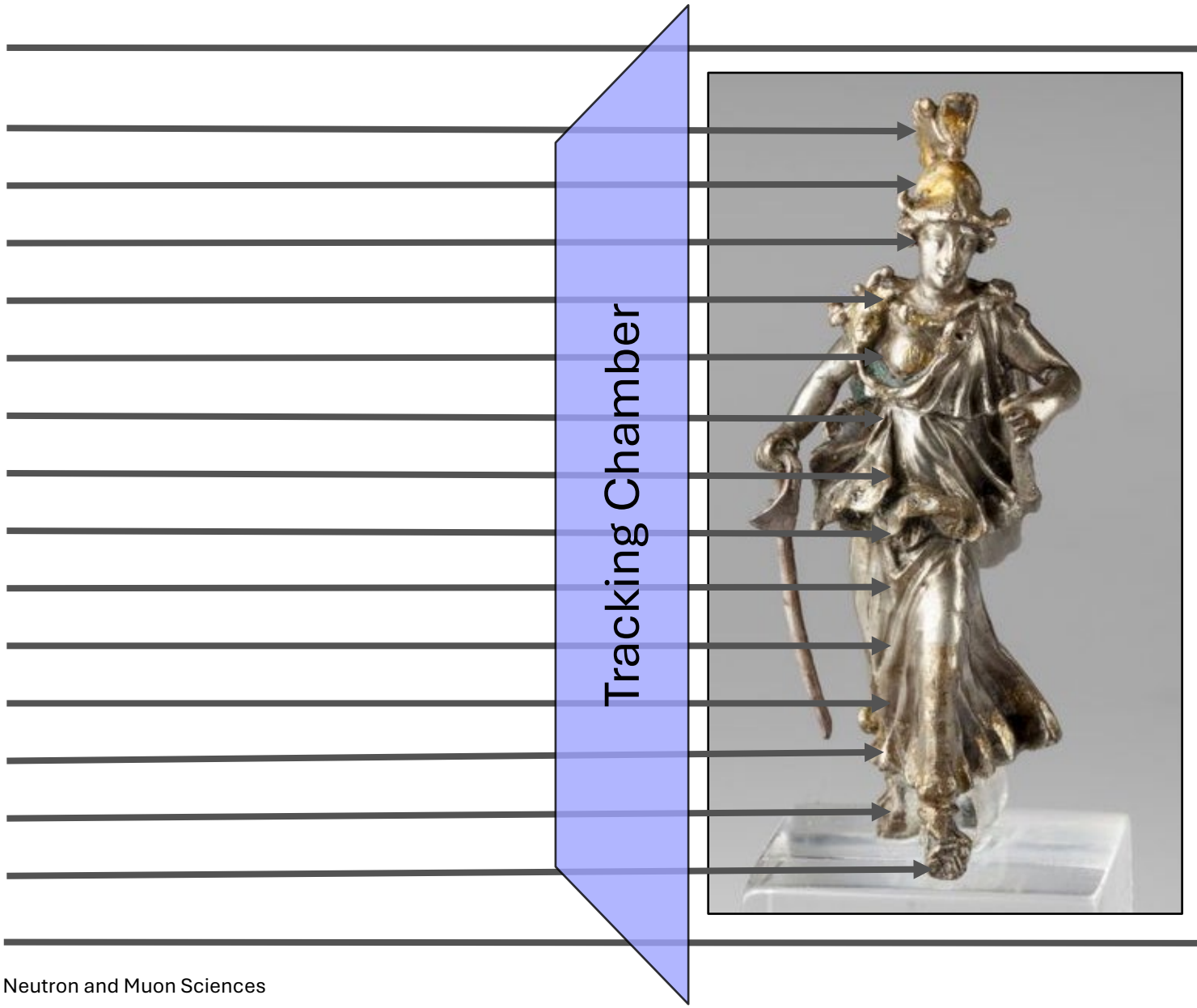

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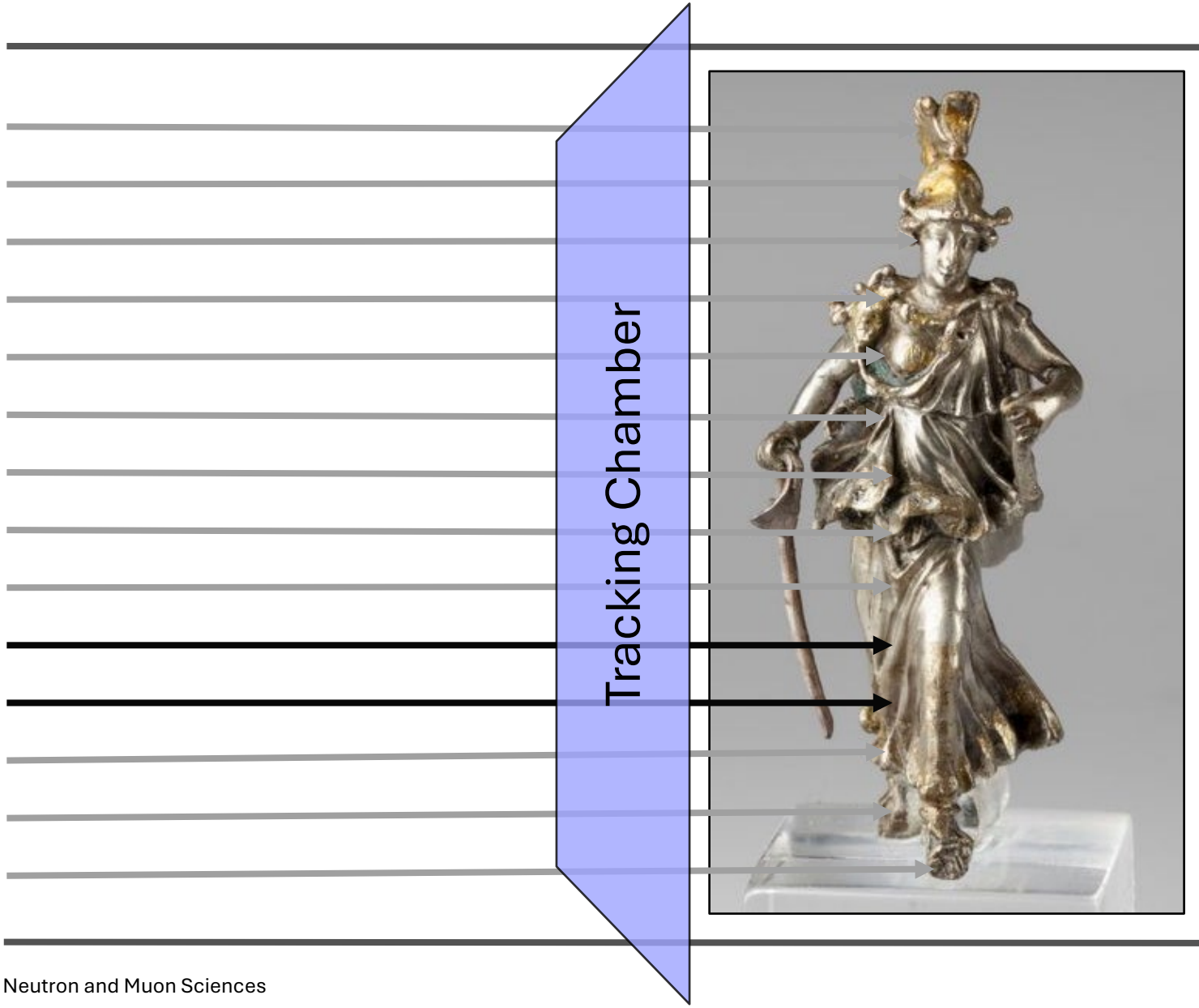

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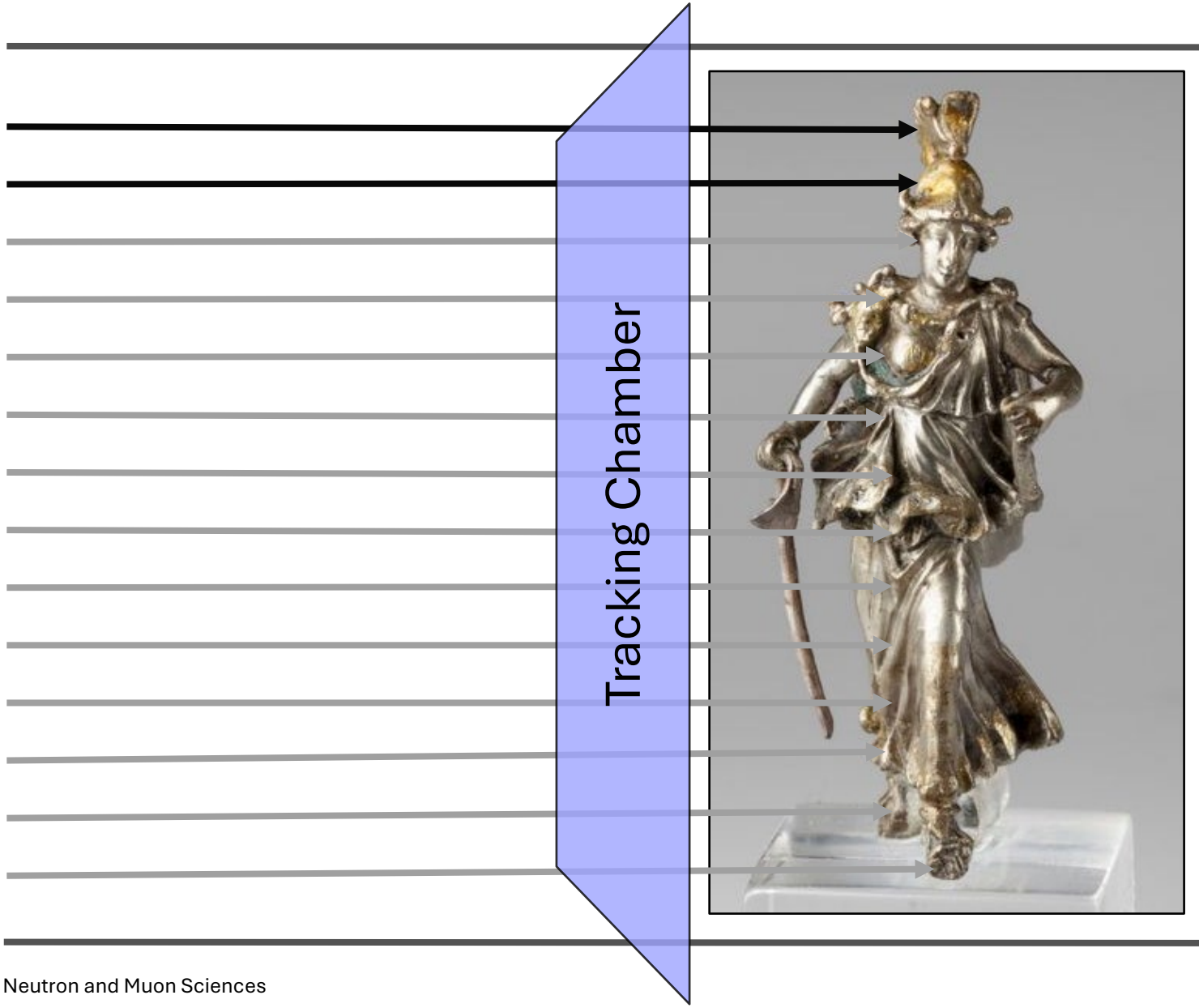

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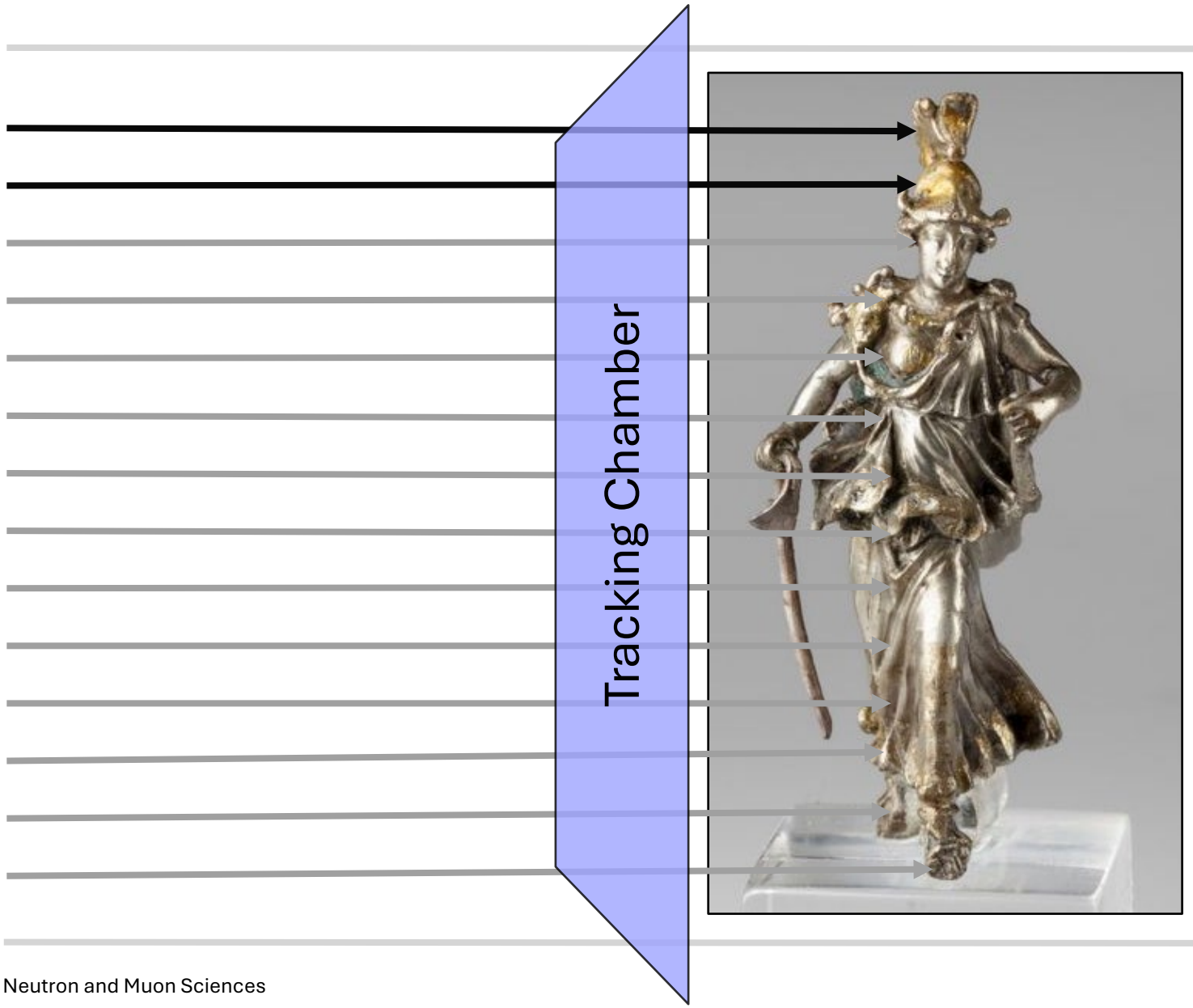

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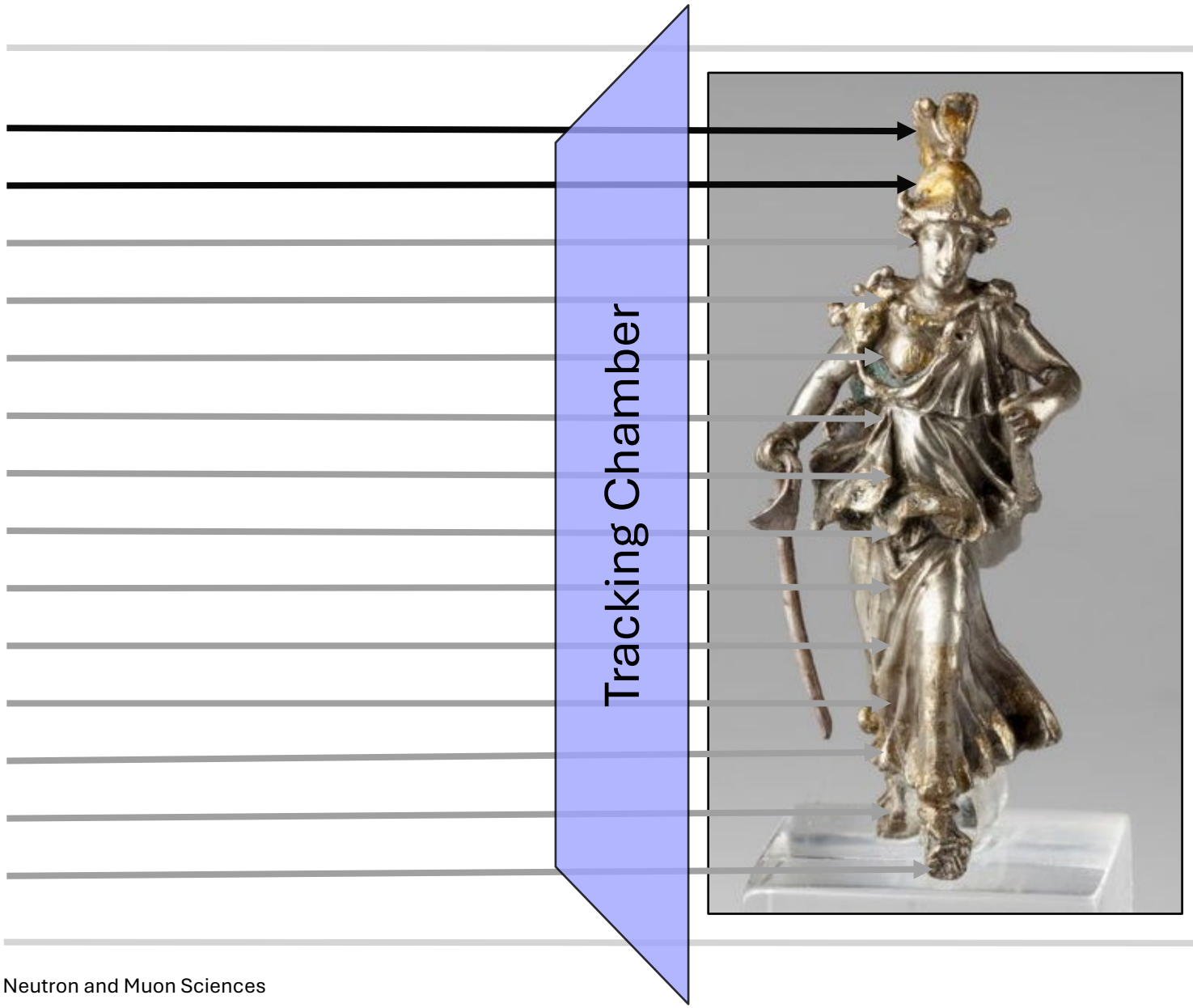

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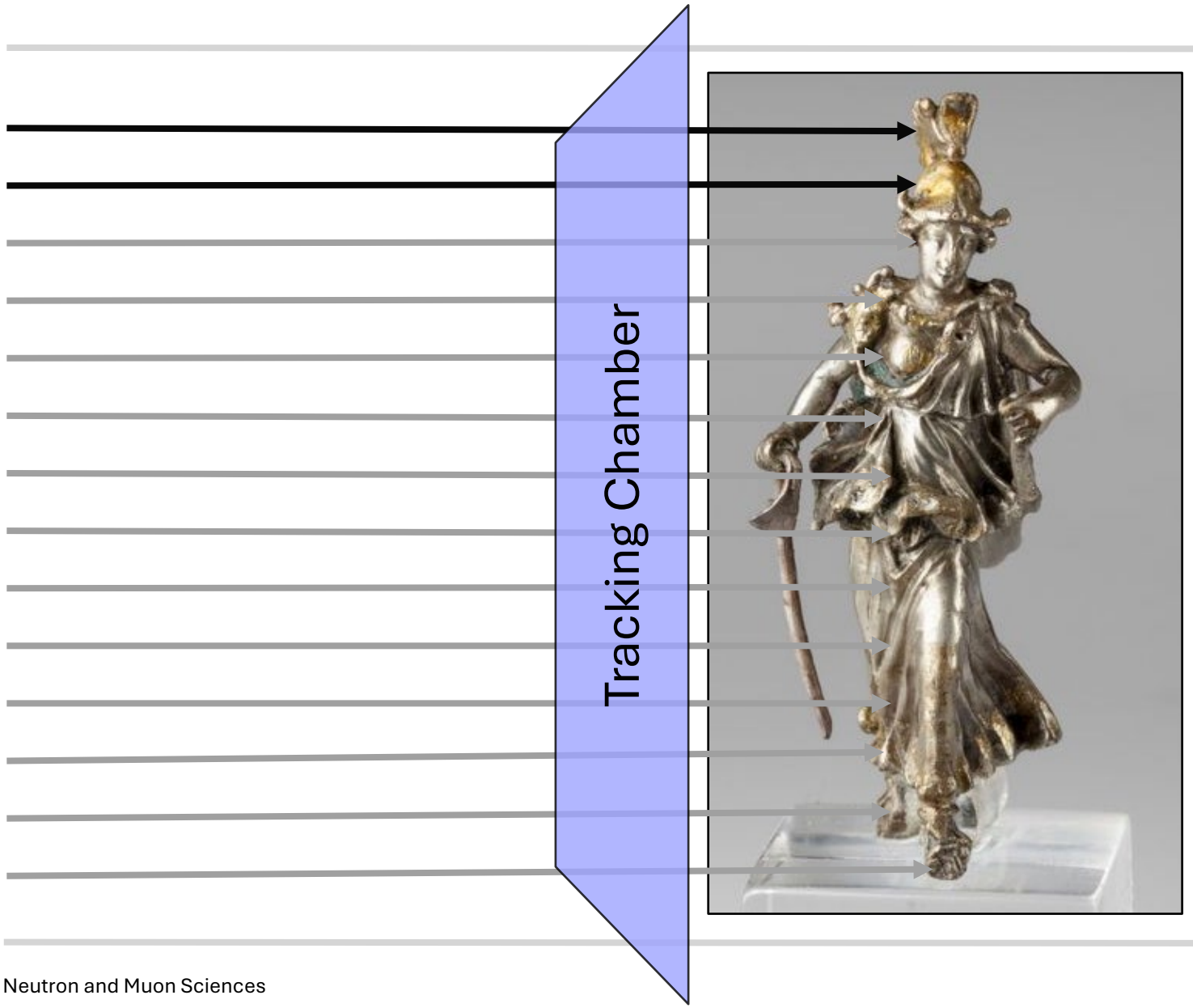

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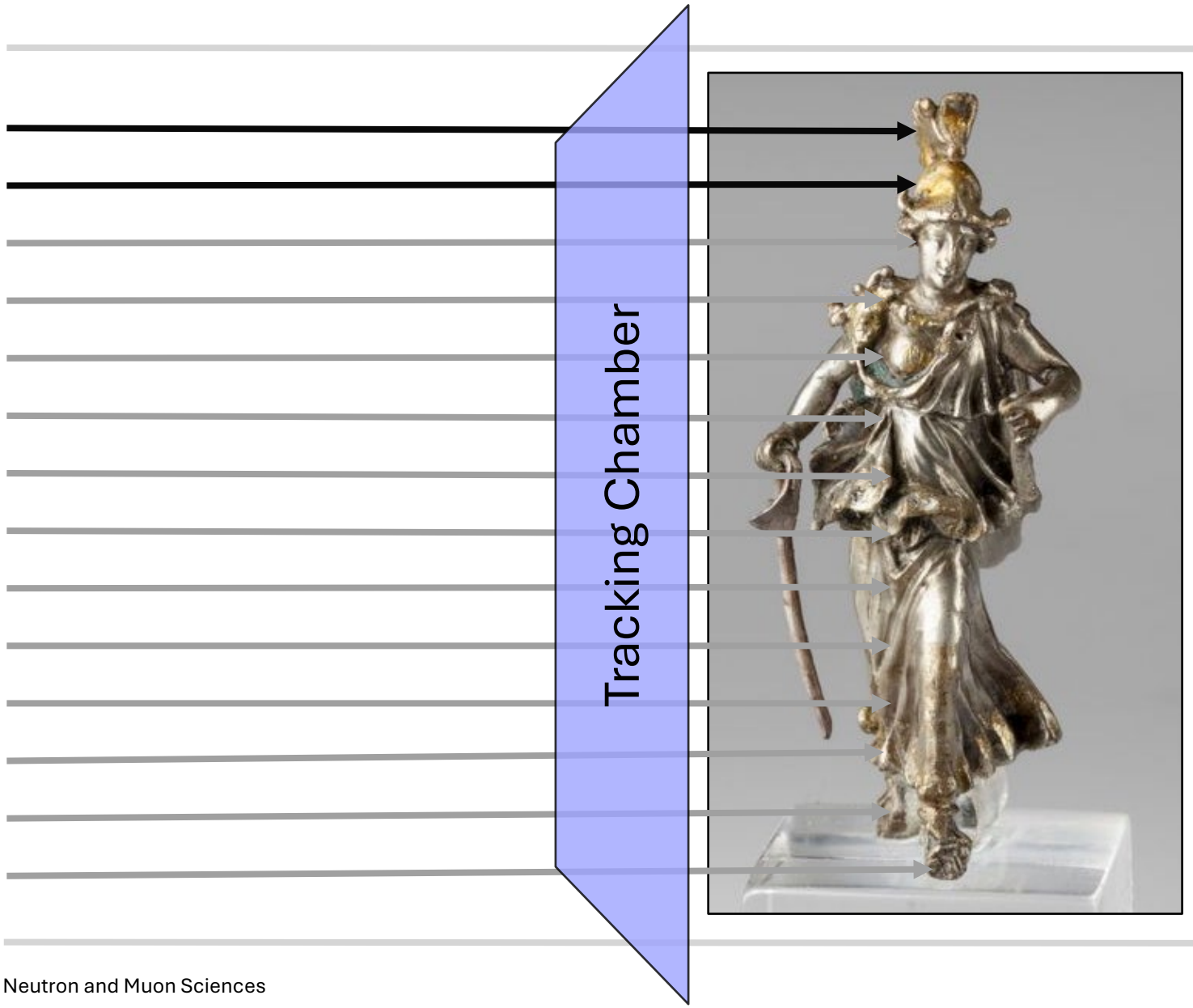

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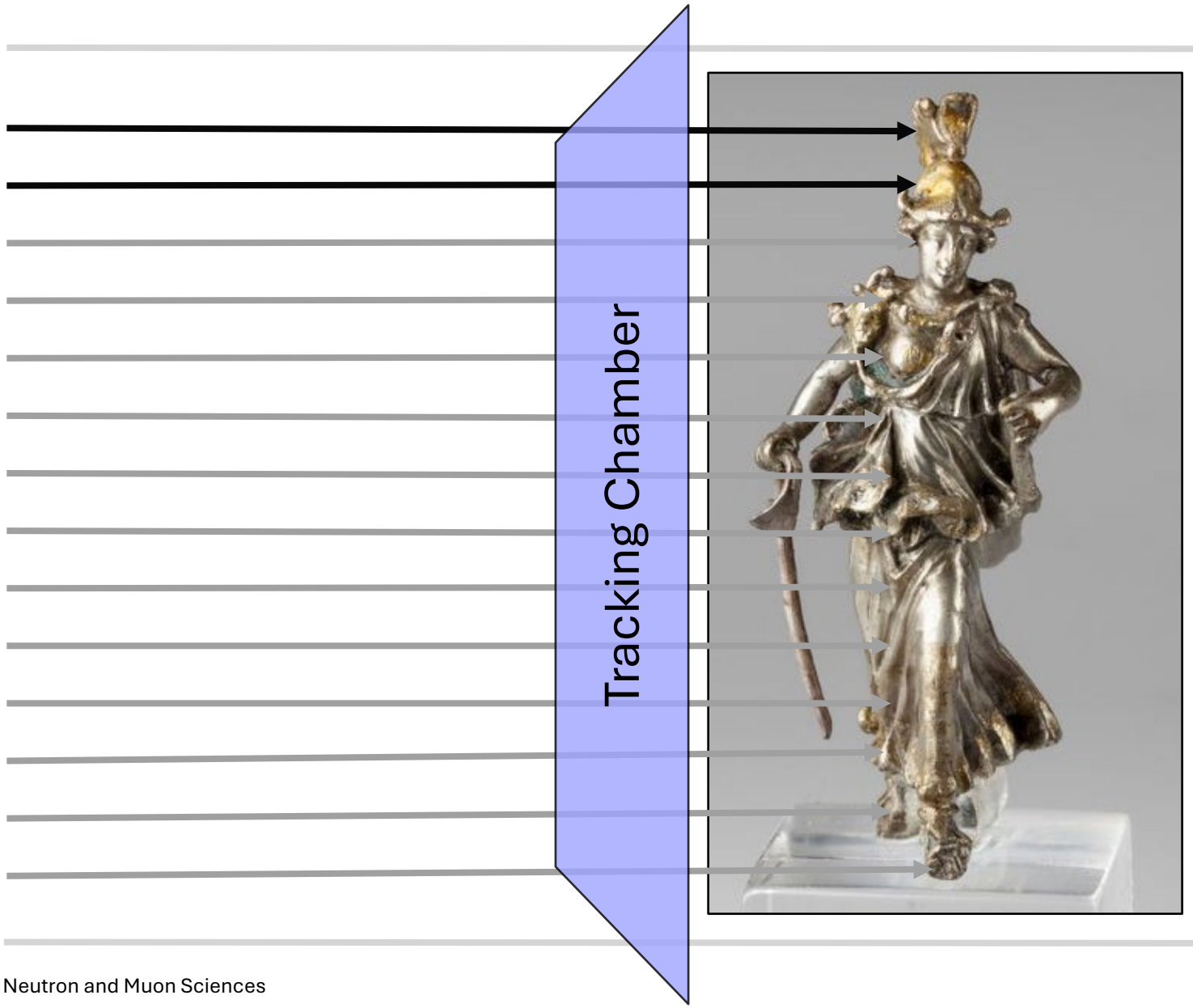
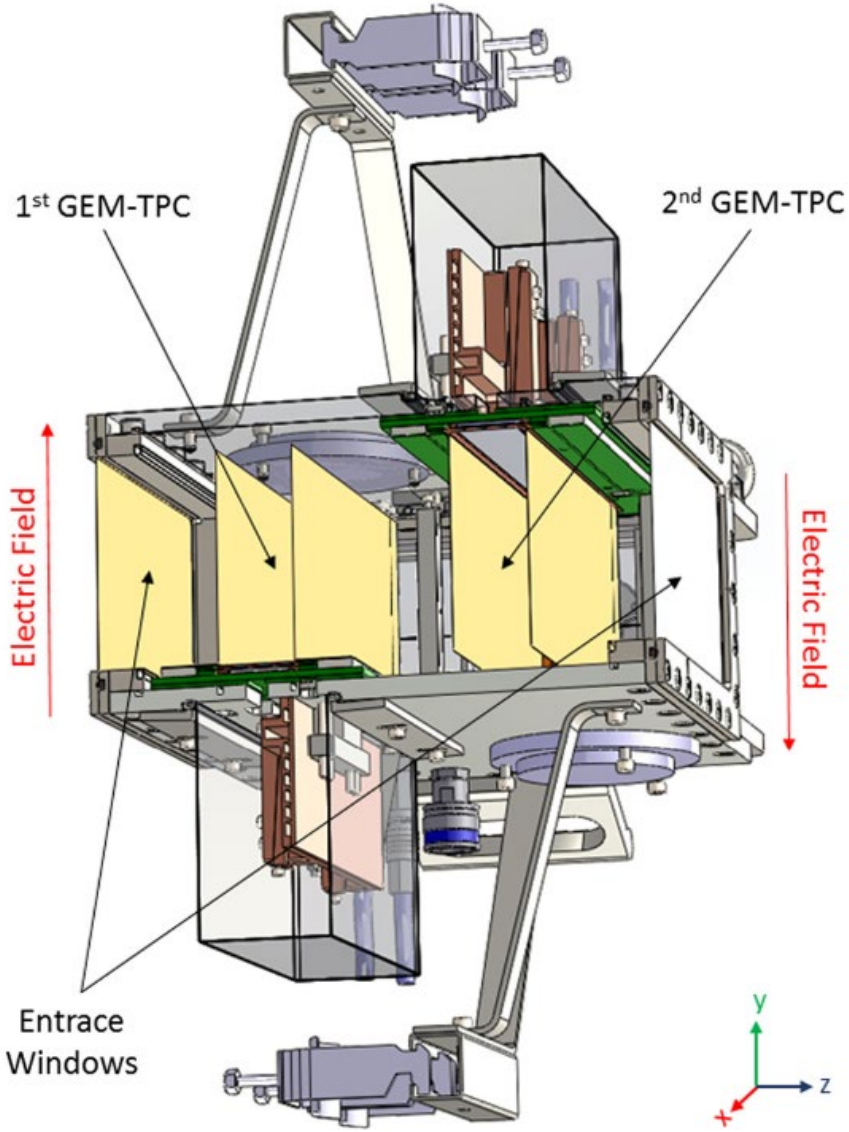


Tomography! of the sample

MIXE-T(omography): Muon Tracking

Adaptation of existing tracking **detector prototype**

- Twin **TPC** (Time-Projection-Chamber) (active area: **20x10cm^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)



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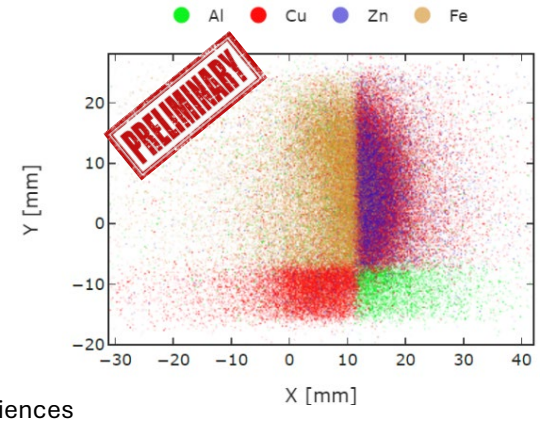
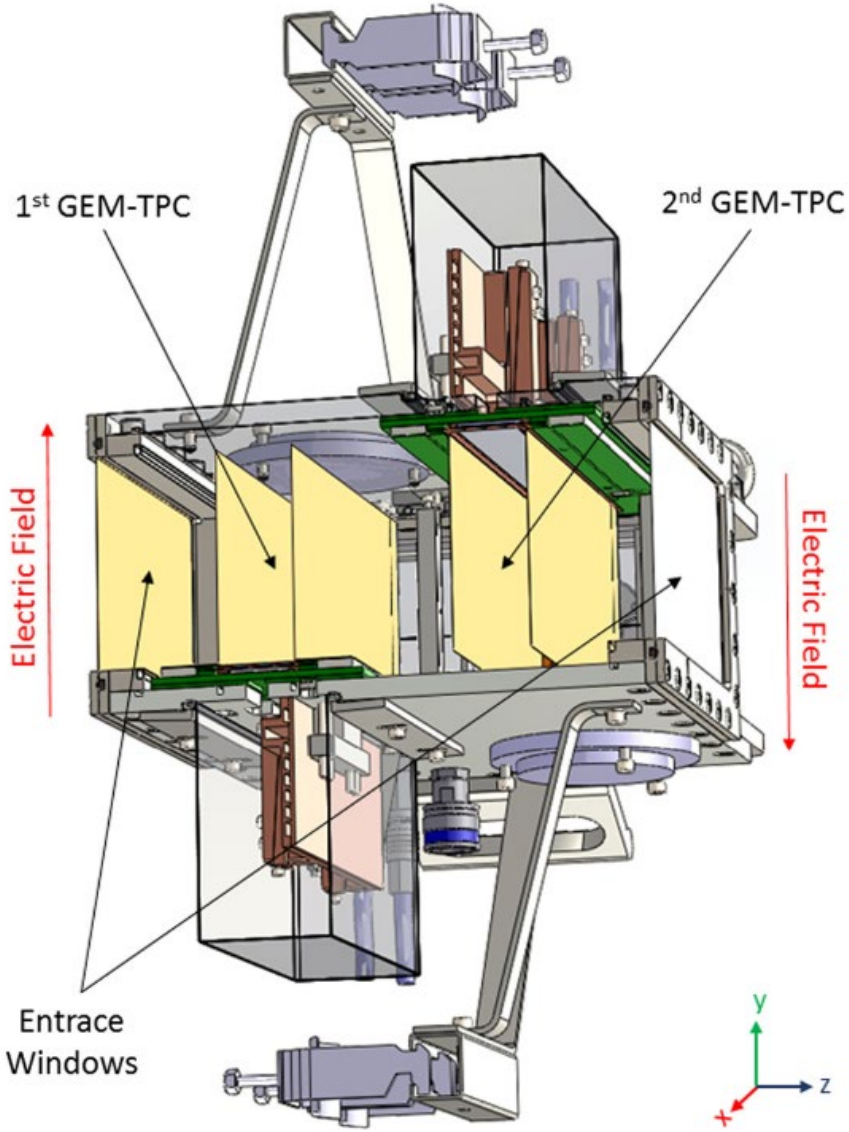
Very encouraging **results**:

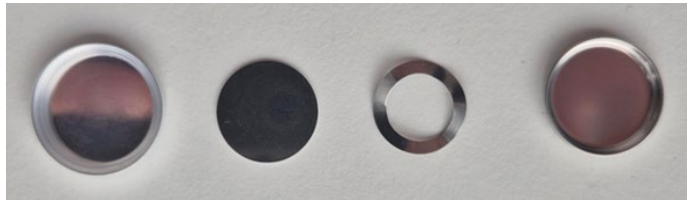
- Spatial Resolution >50MeV/c – X/Y: ~1 mm ; Z: ~0.1 mm
- Limited by large gas volume
  Specialized prototype detector in development!





MIXE-T(omography): Battery tomography PoC

coin cell battery analogue



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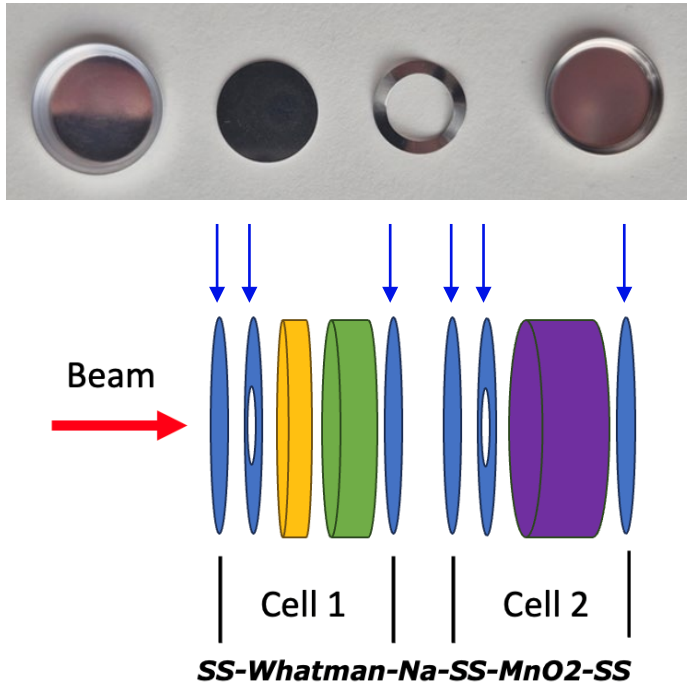

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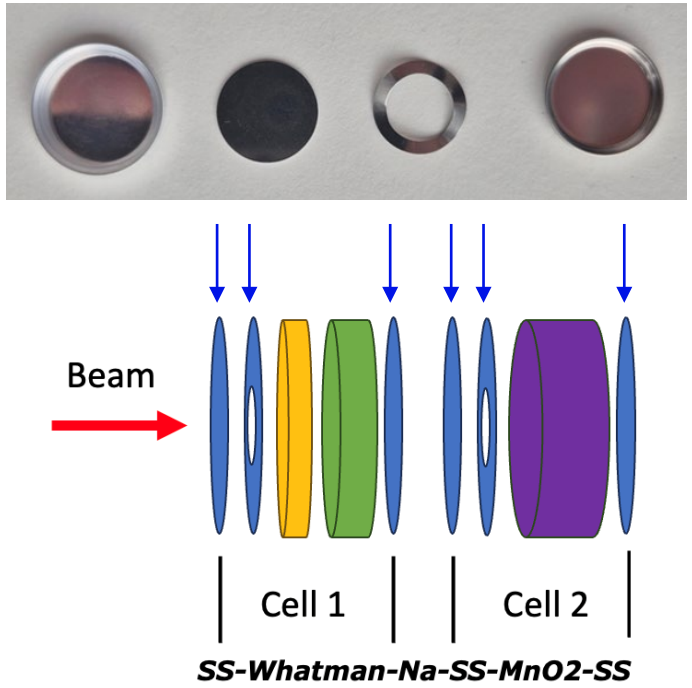

30/32/34/39/46/49/51/55/60
MeV/c

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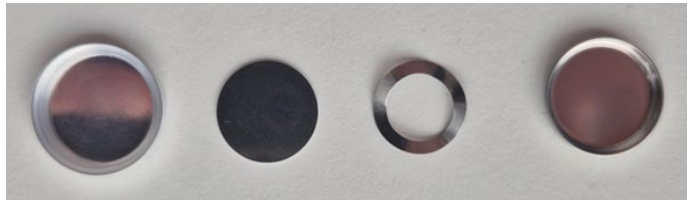

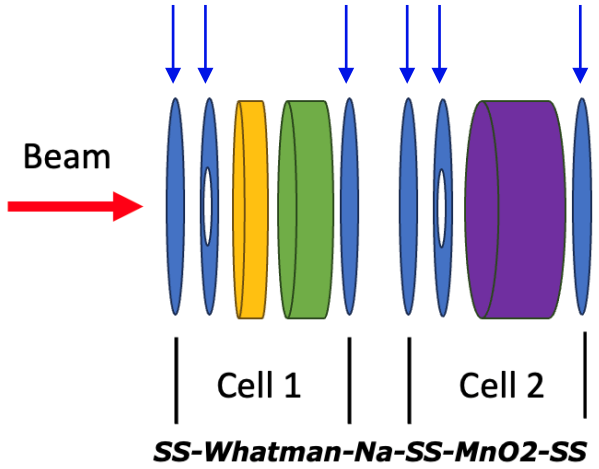

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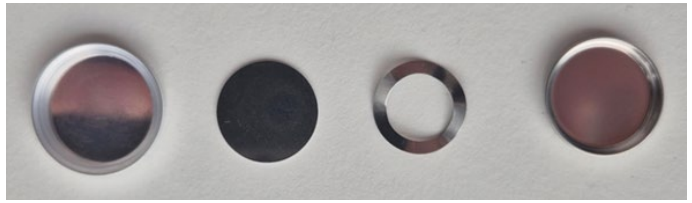
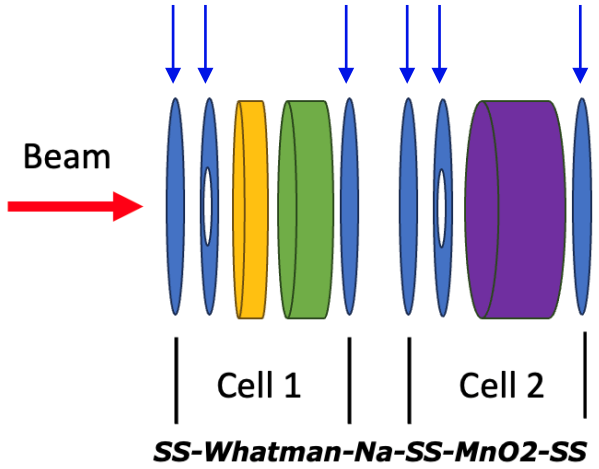




30/32/34/39/46/49/51/55/60
MeV/c
+interpolation

Thank you for your attention!

GIANT/MIXE is transitioning to user instrument!

Open call for user **proposals** for (September) 2026 measurement campaign will open **Nov 1**!

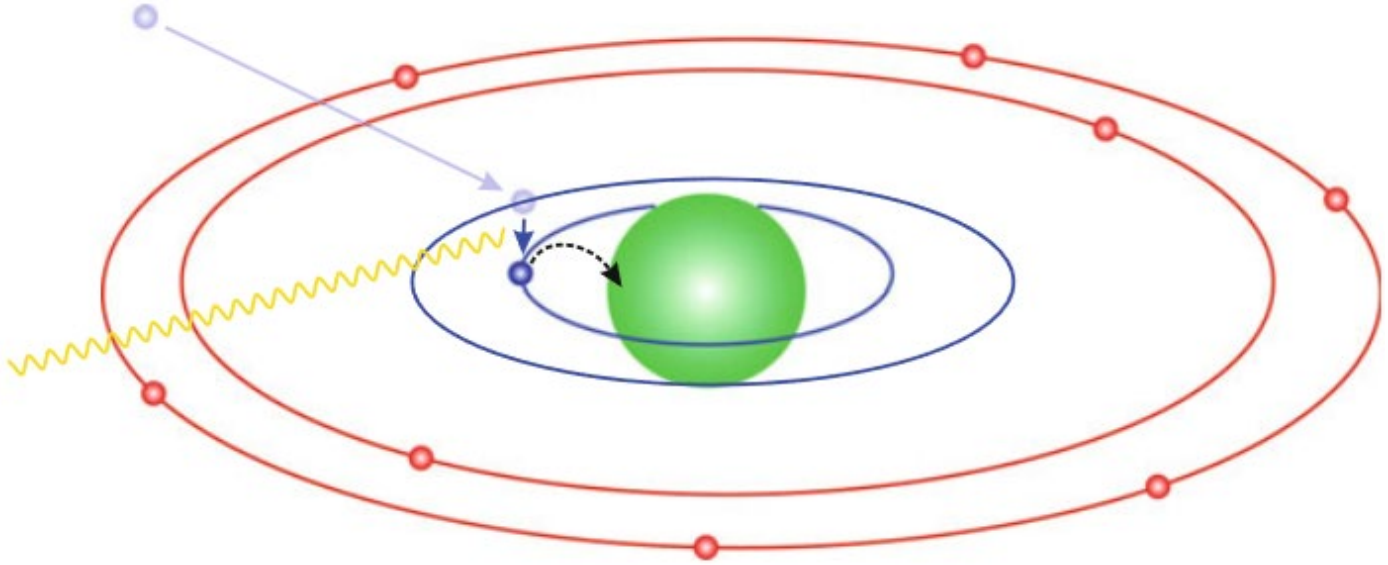
Please don't hesitate to contact us if you are interested!

michael.heiss@psi.ch

https://www.psi.ch/en/smus/calls

Backup

MIXE: Muon Induced X-ray Emission – Physics



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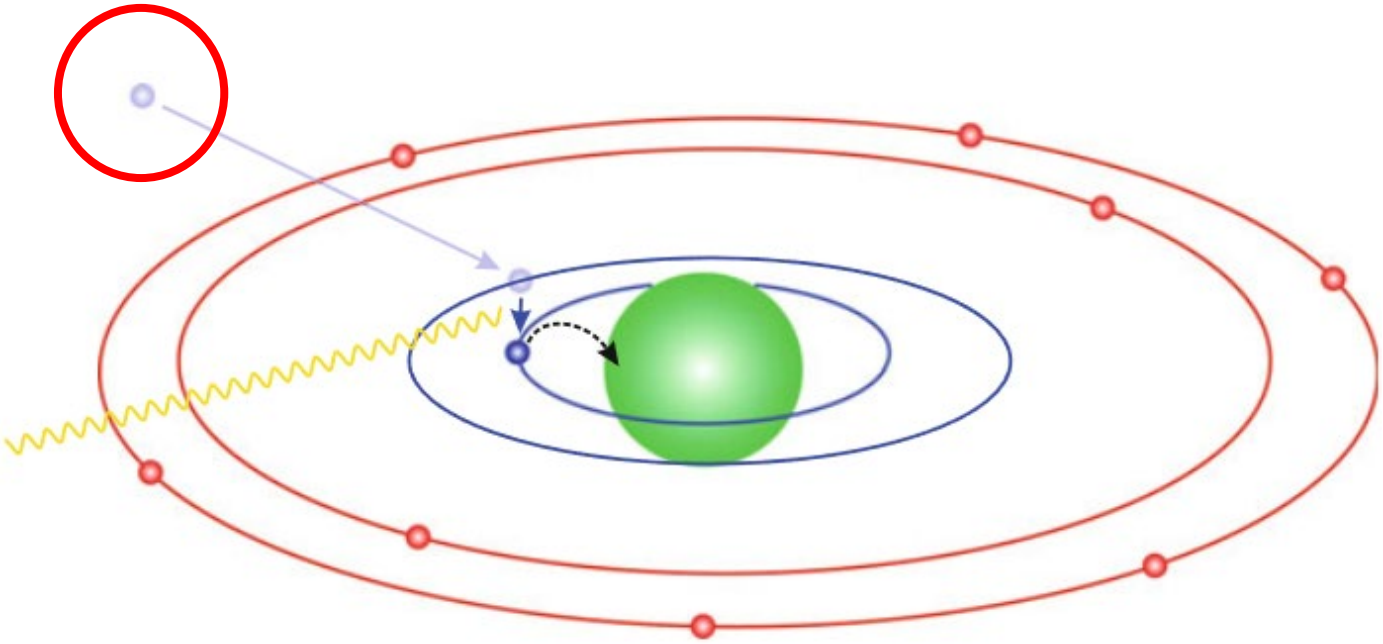
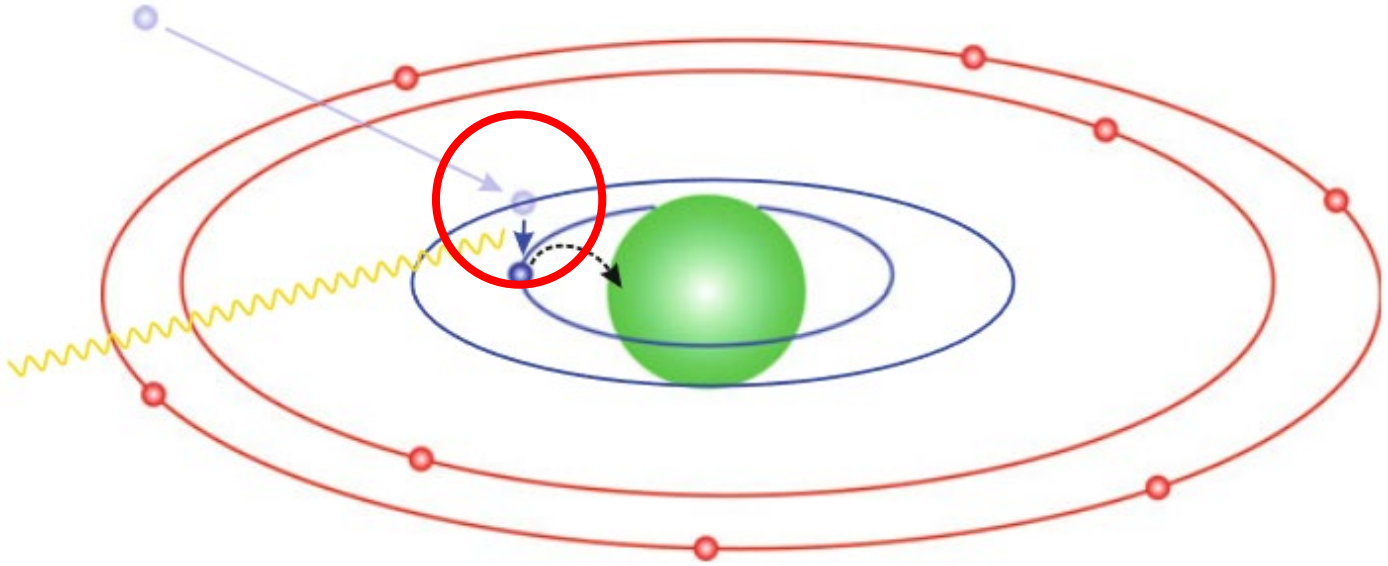
- Muon is implanted (Bragg peak; depth given by momentum and density of material)



MIXE: Muon Induced X-ray Emission – Physics

- Muon is implanted (Bragg peak; depth given by momentum and density of material)
- Muon is captured by the atom in higher excited states around:

$$n_\mu \approx \sqrt{\frac{m_\mu}{m_e}} \approx 14$$



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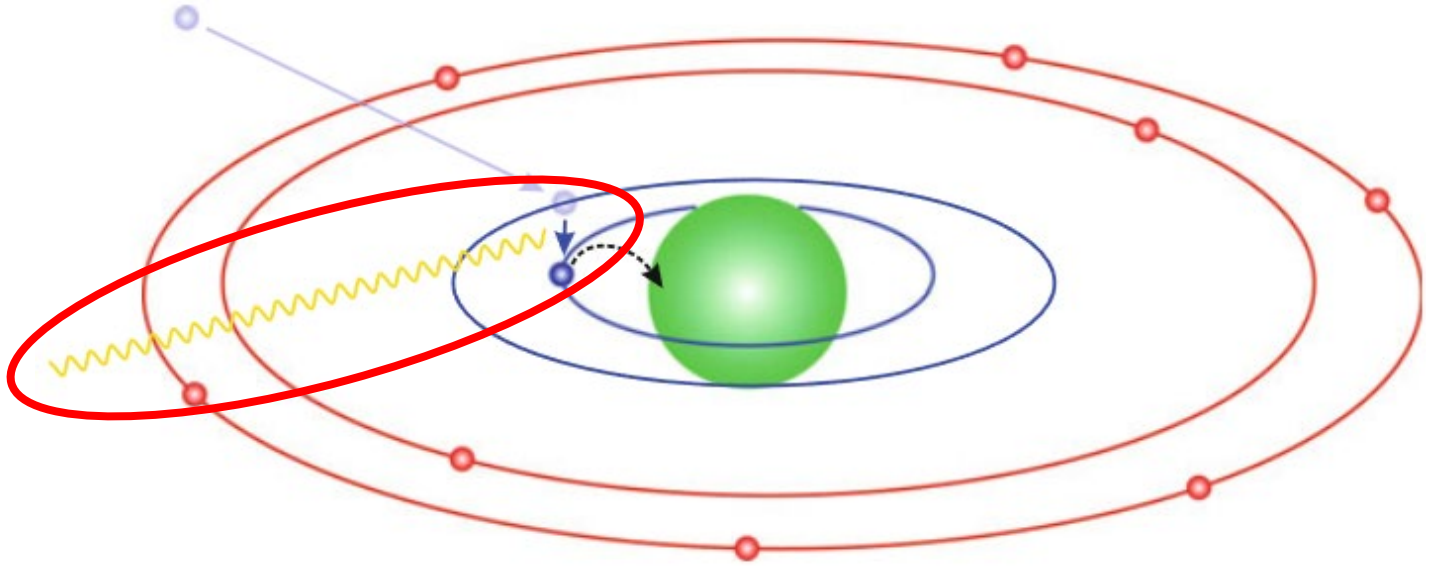
- Muon is implanted (Bragg peak; depth given by momentum and density of material)
- Muon is captured by the atom in higher excited states around:

$$n_\mu \approx \sqrt{\frac{m_\mu}{m_e}} \approx 14$$

- Cascades down to $n_\mu = 1$ while emitting X-rays characteristic to the element / isotope



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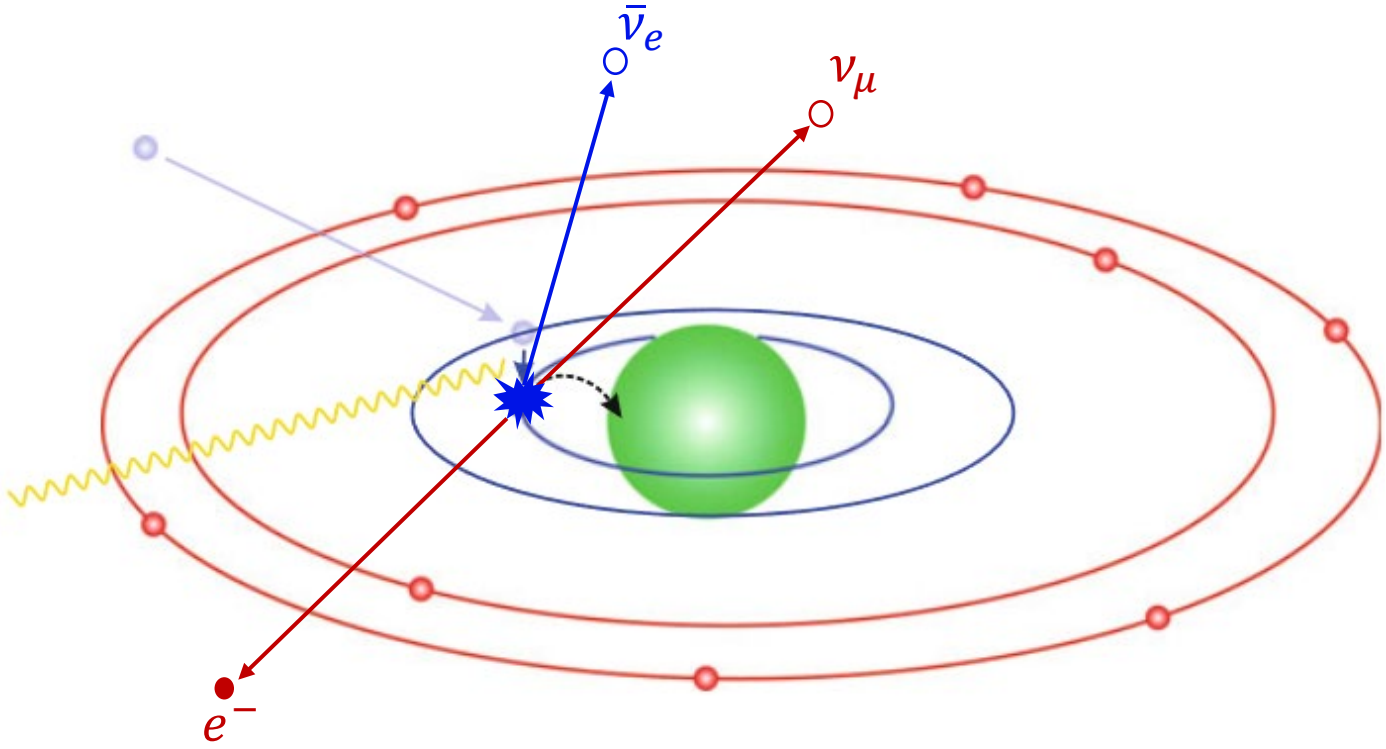

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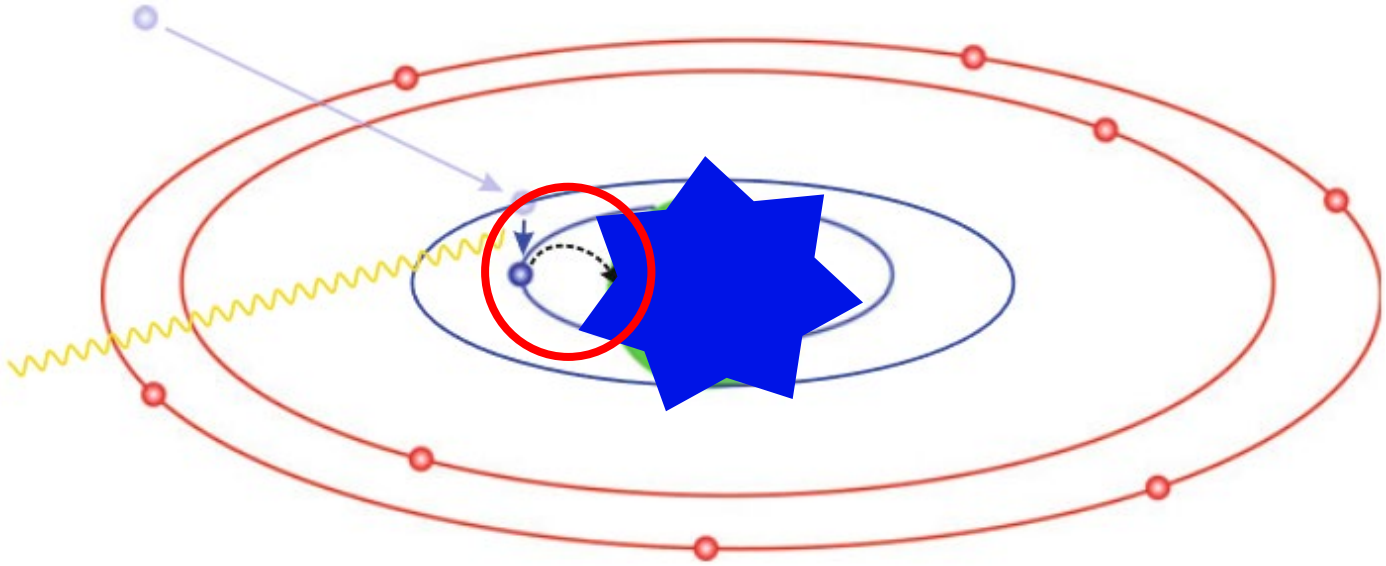
$$\mu^- + p \rightarrow \nu_\mu + n \quad (+ \sim 10\text{-}20\ \text{MeV})$$



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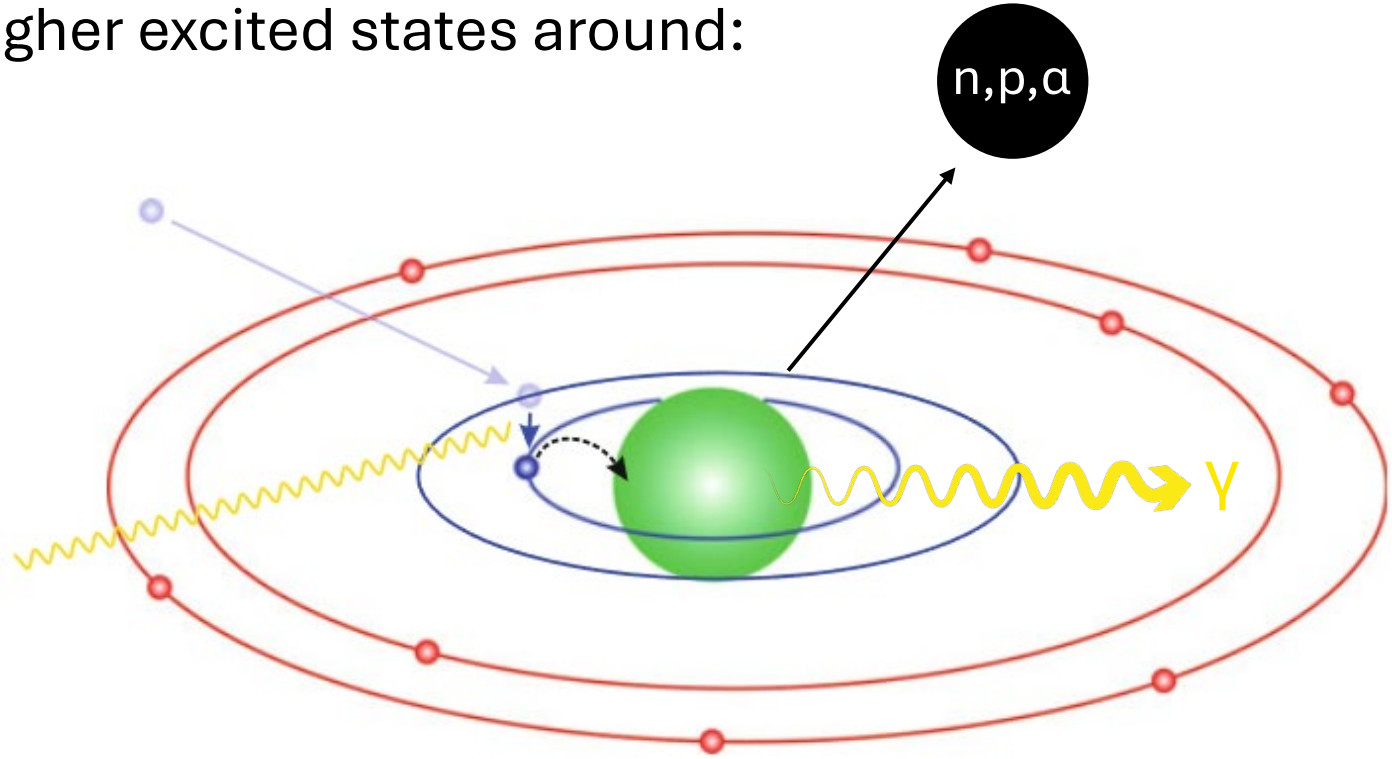
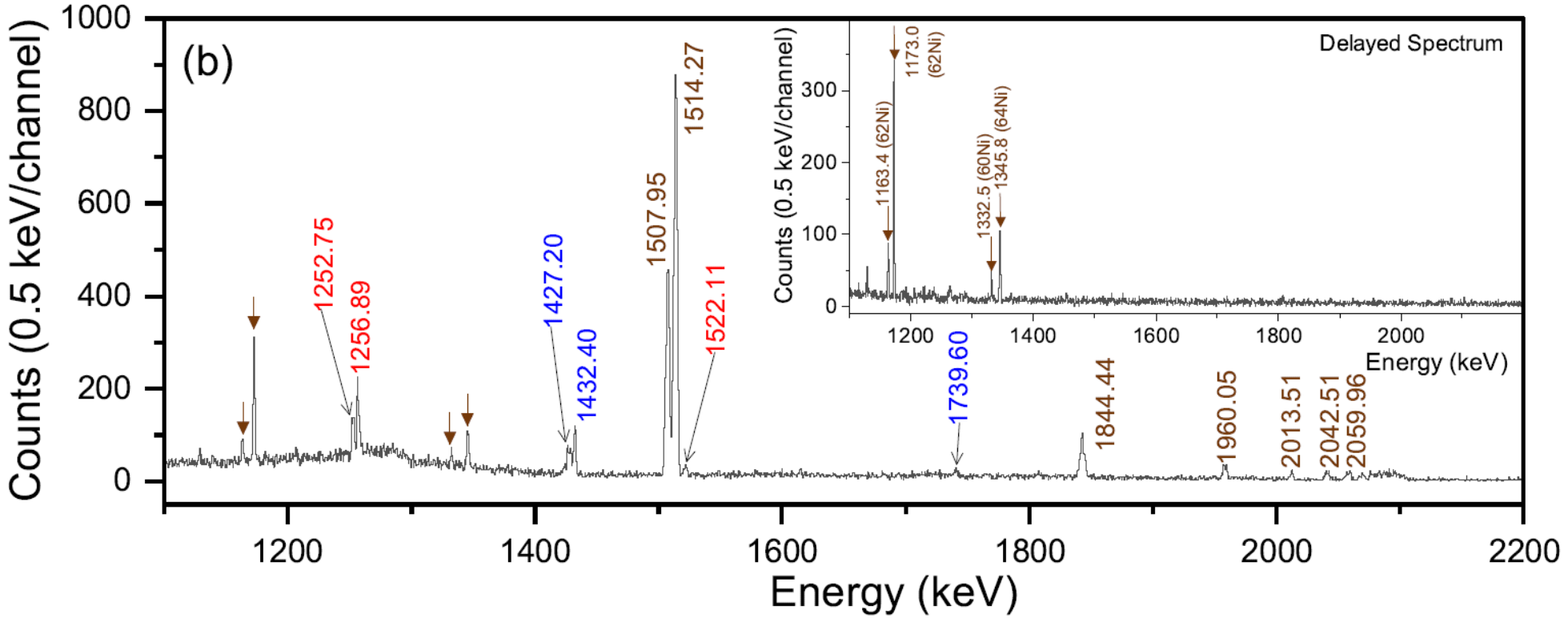


- Nucleus loses excess energy by emitting (some combination of) n, p, α, γ

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



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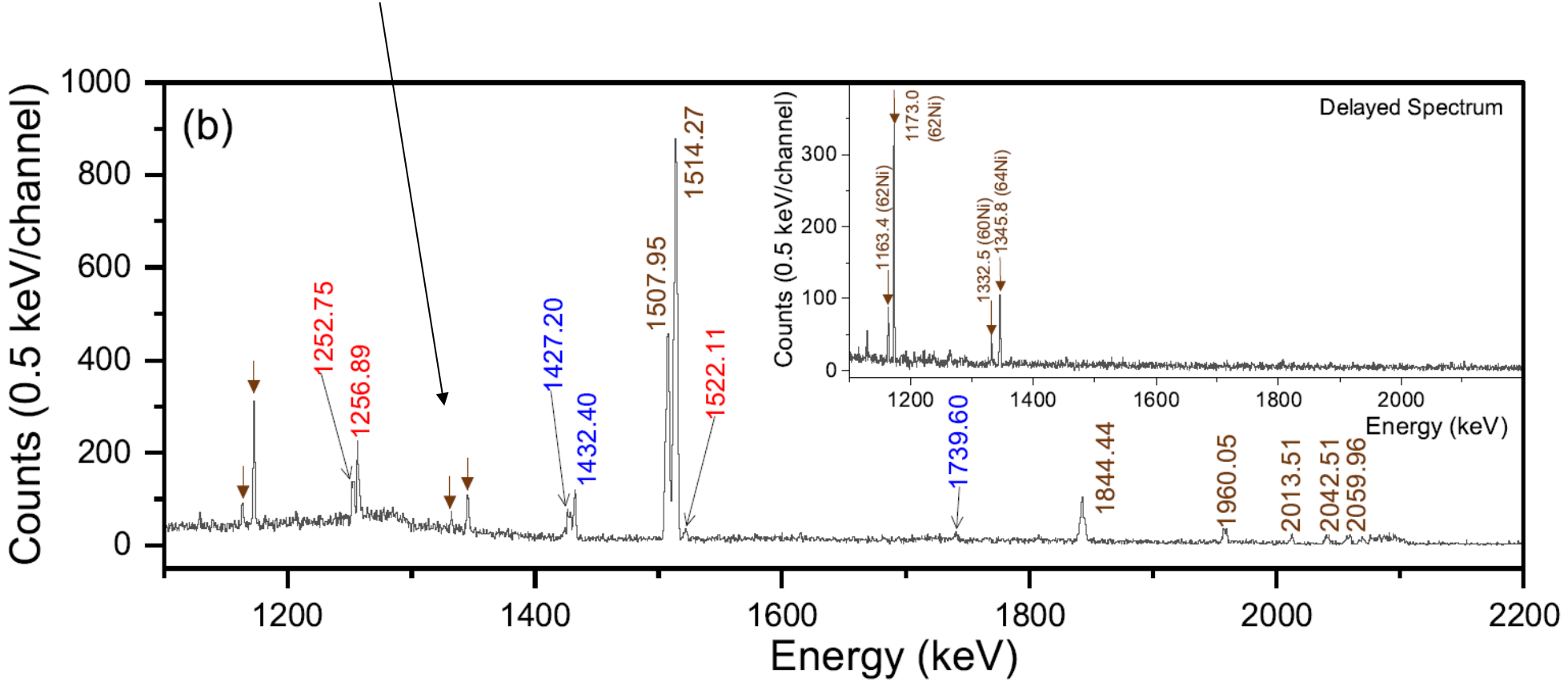
X-ray cascade:

prompt, ROI: <100ns



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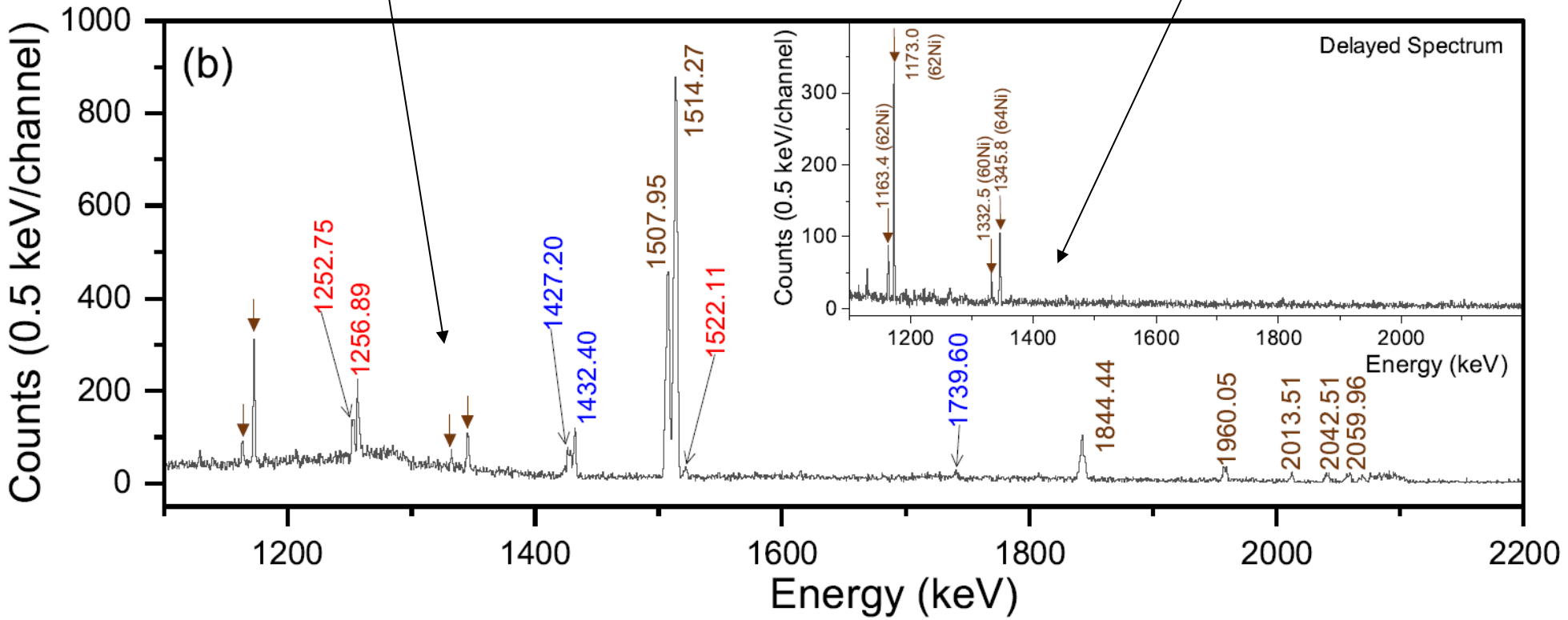

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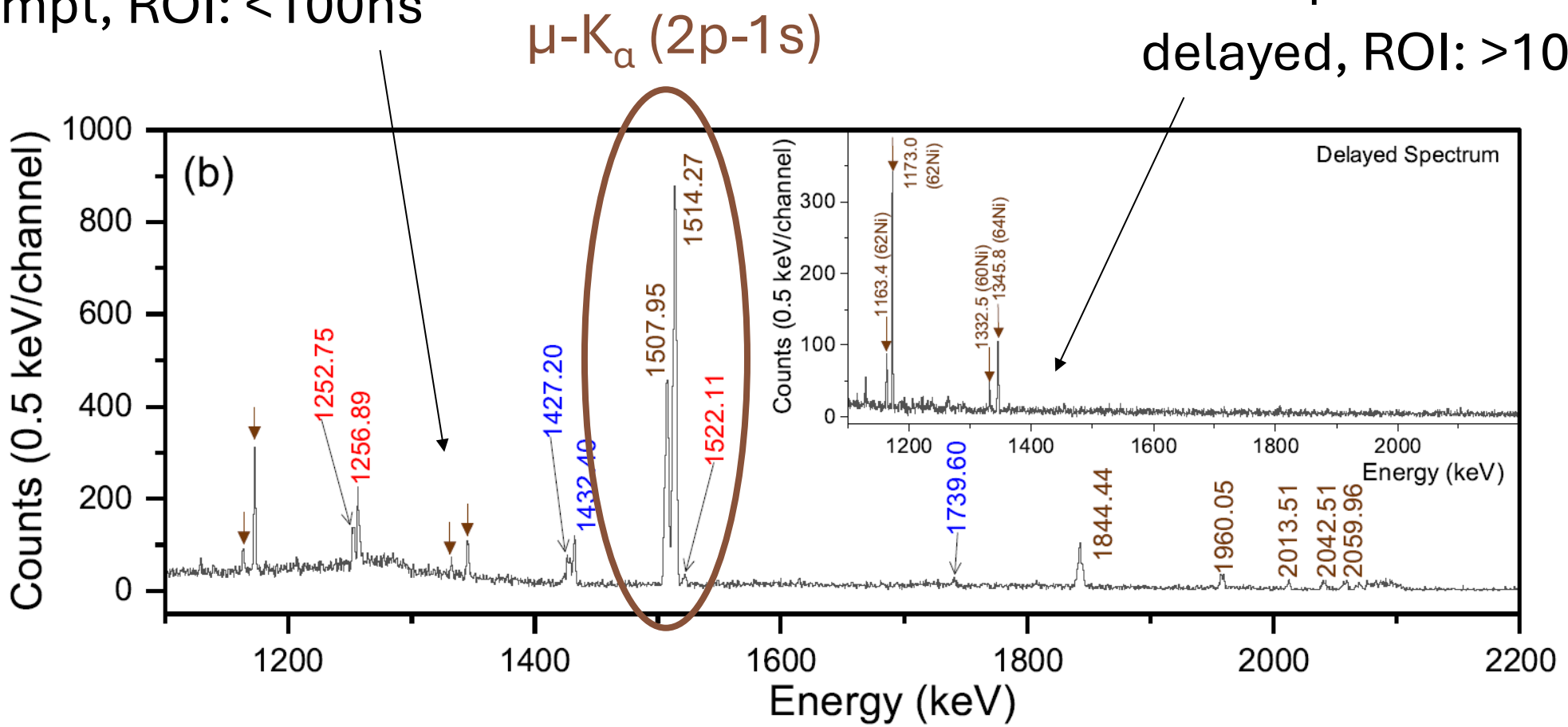

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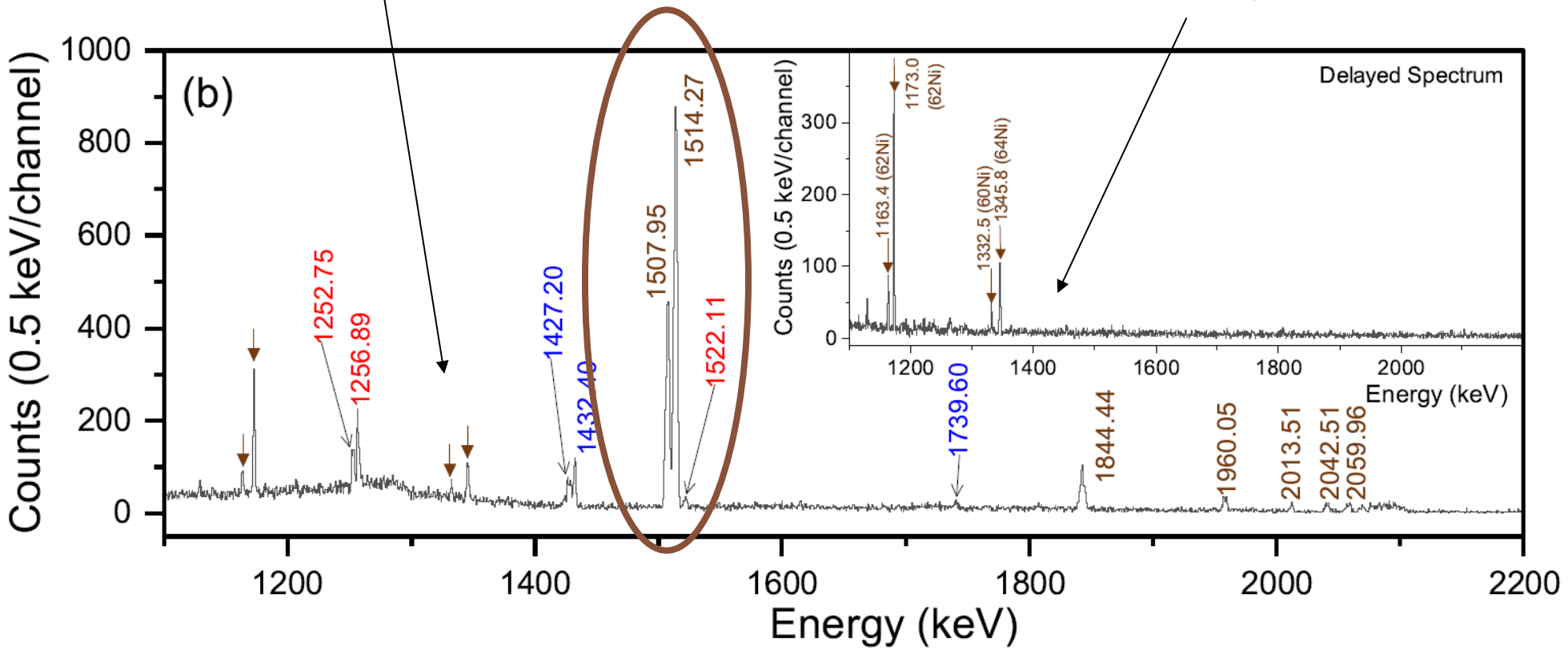

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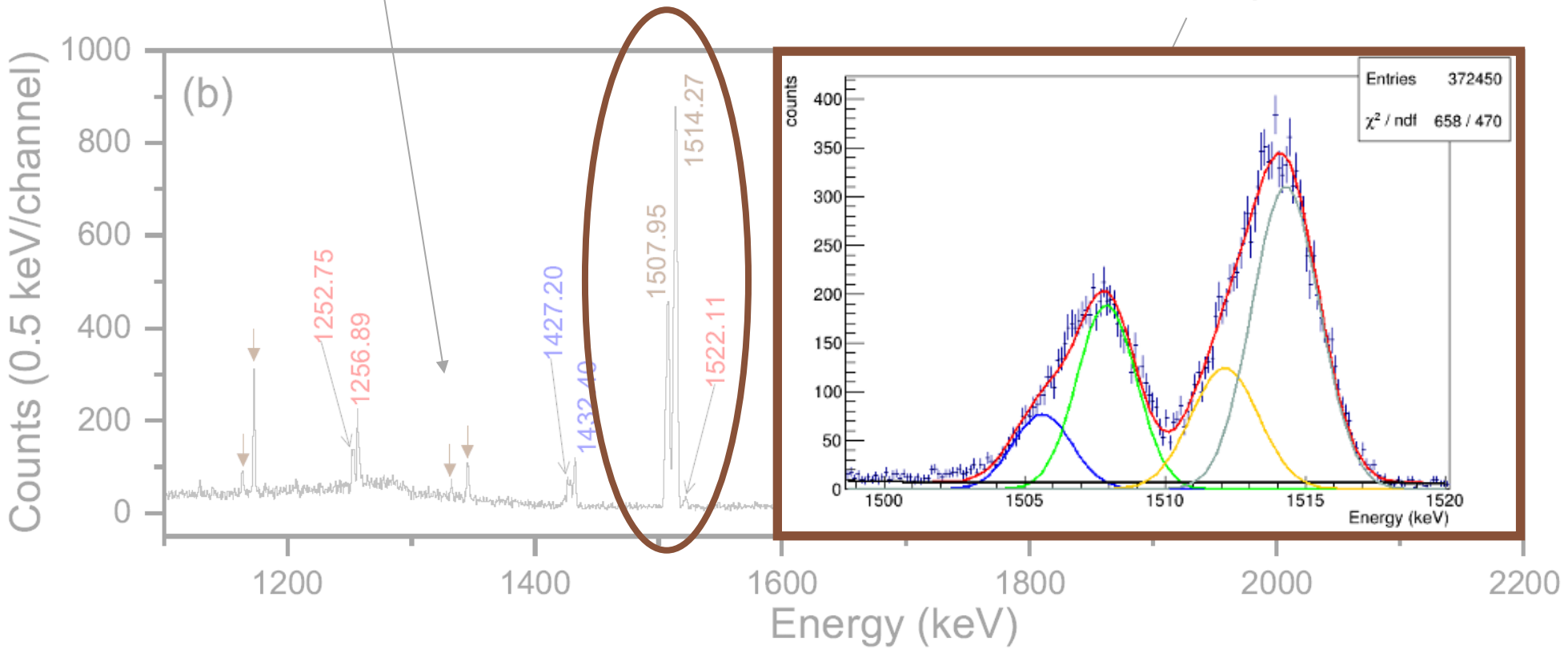

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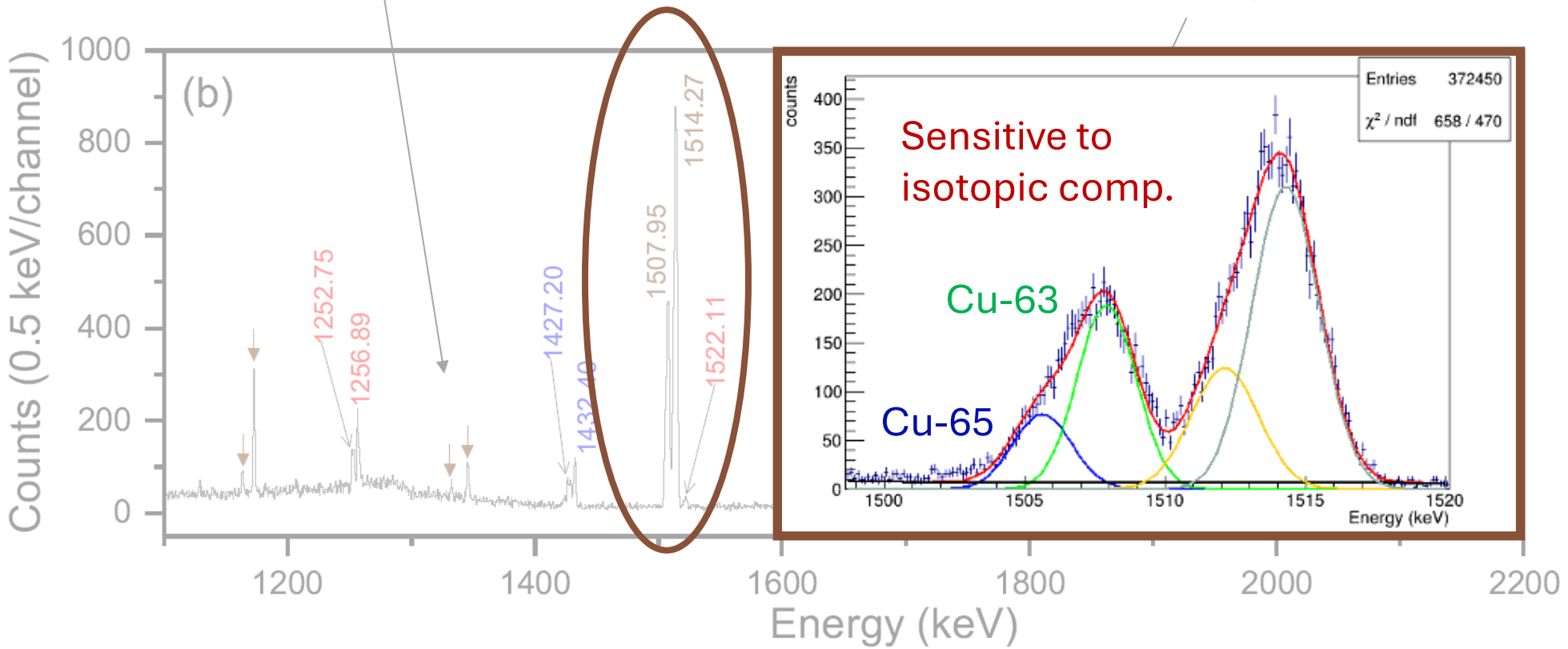
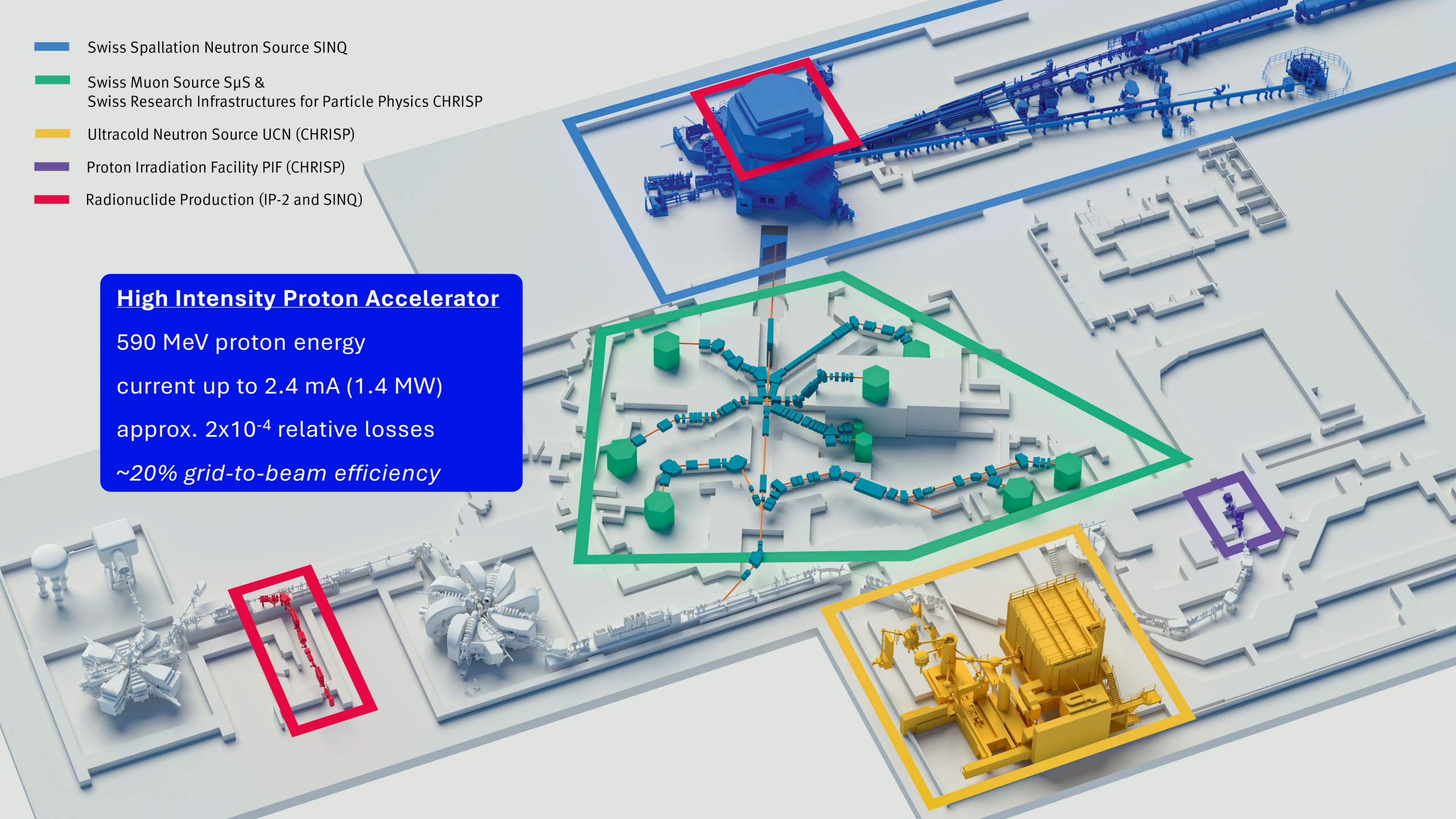
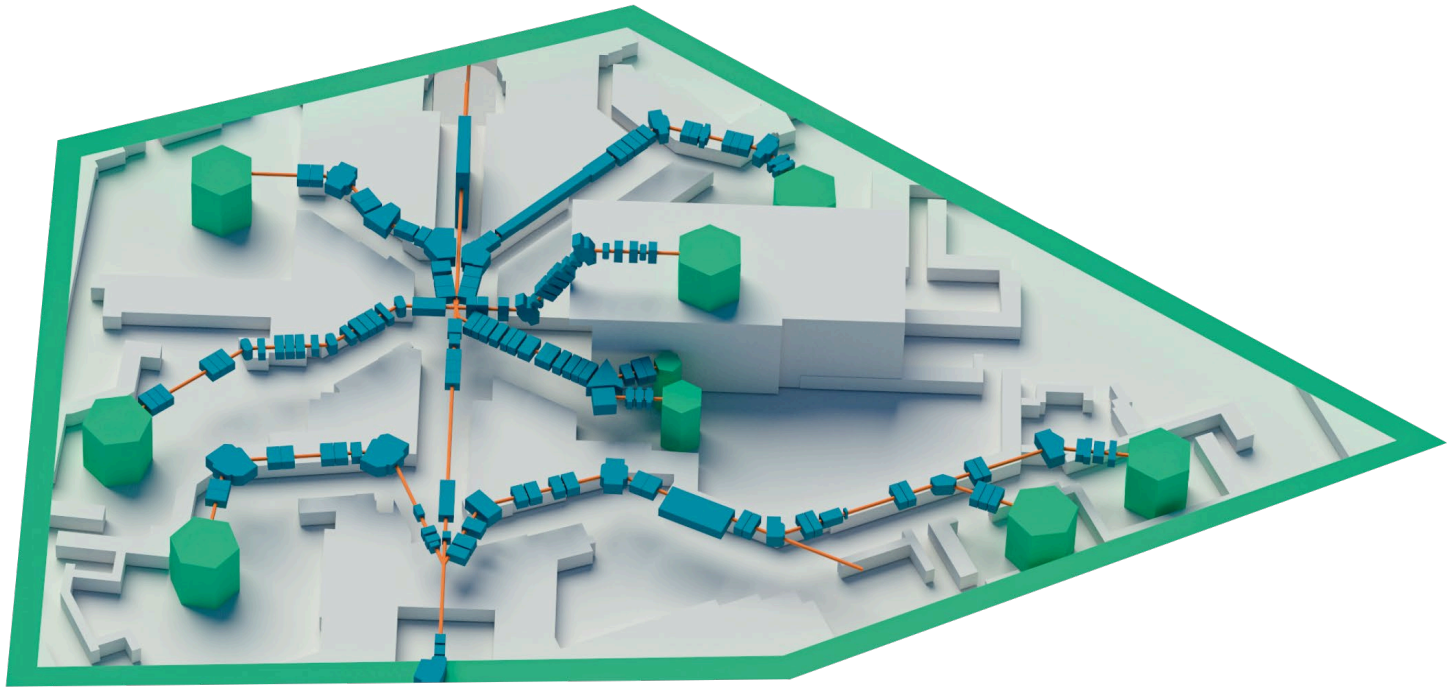



Swiss Spallation Neutron Source SINQ
Swiss Muon Source SμS &
Swiss Research Infrastructures for Particle Physics CHRISP
Ultracold Neutron Source UCN (CHRISP)
Proton Irradiation Facility PIF (CHRISP)
Radionuclide Production (IP-2 and SINQ)
High Intensity Proton Accelerator
590 MeV proton energy
current up to 2.4 mA (1.4 MW)
approx. 2x10-4 relative losses
~20% grid-to-beam efficiency

SμS: Swiss Muon Source



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Target M (mince) – 5mm graphite

designed for π production (low rate)

πM3: 10-40 MeV/c (surface) μ^+ for μSR

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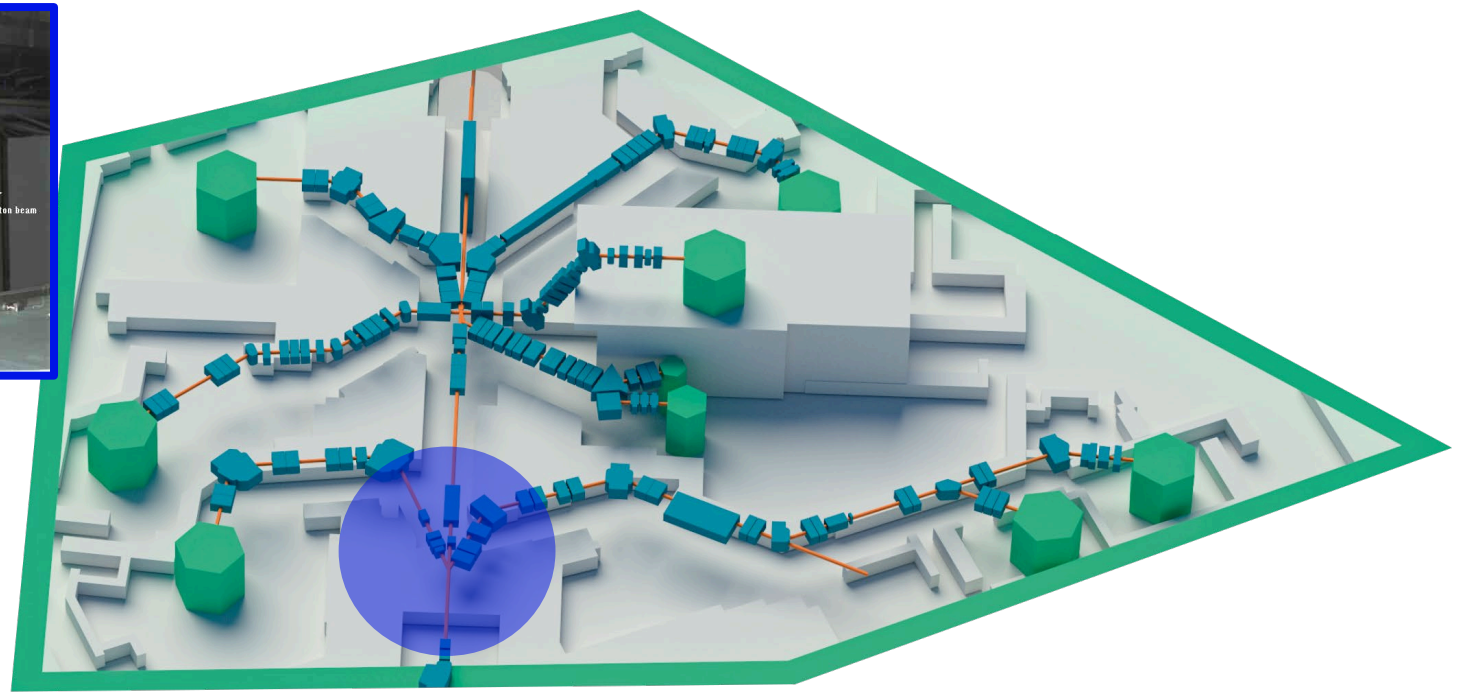

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Target E (epaisse) – 40mm graphite

designed for π/μ production (high rate)

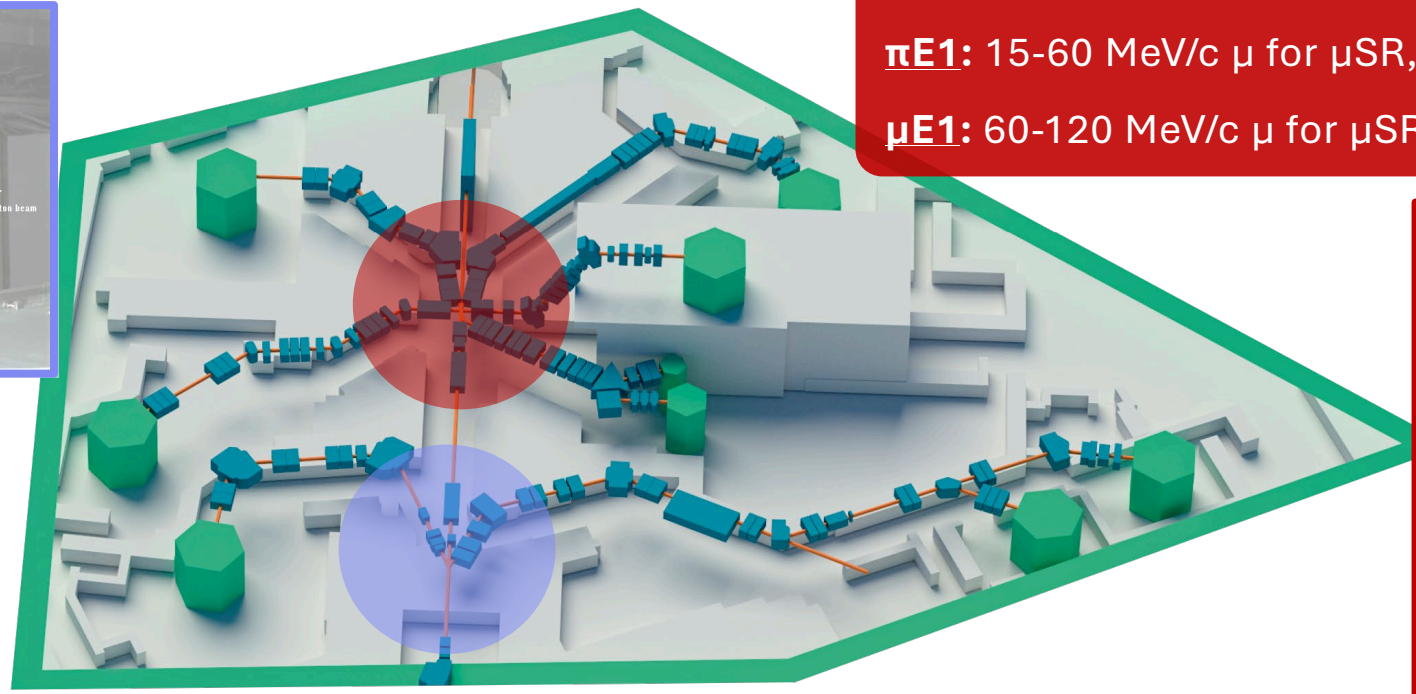
πE5: 20-120 MeV/c high rate μ for PP

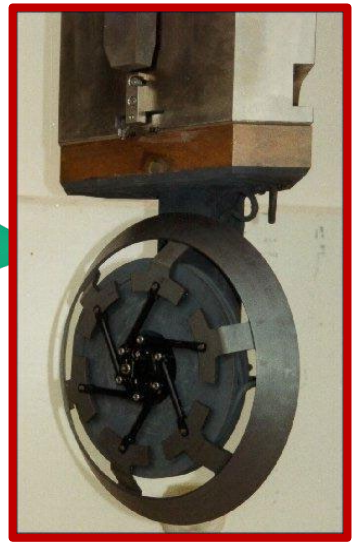
μE4: 10-40 MeV/c μ^+ for LEM – μSR and PP

πE3: 10-40 MeV/c (surface) μ^+ for bulk μSR

πE1: 15-60 MeV/c μ for μSR, PP & **MIXE**

μE1: 60-120 MeV/c μ for μSR & **MIXE** (2028)

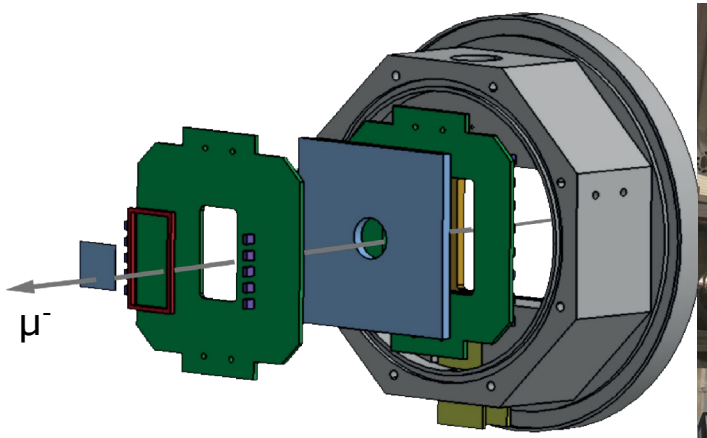


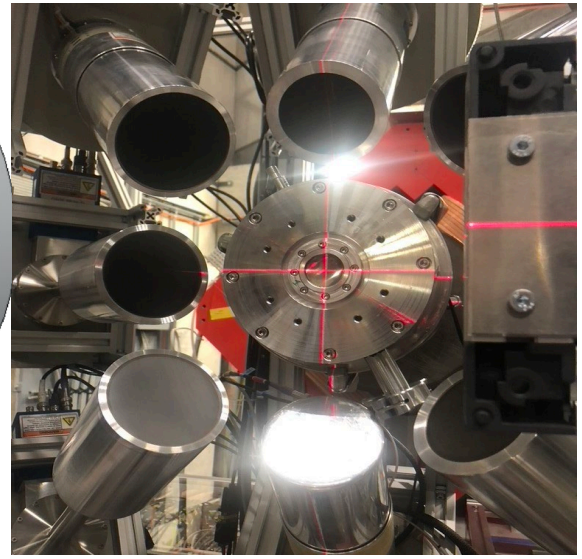


GIANT: GermanIum Array for Non-destructive Testing – Tagging

Tagger & Beamport (developed for muX experiment)

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





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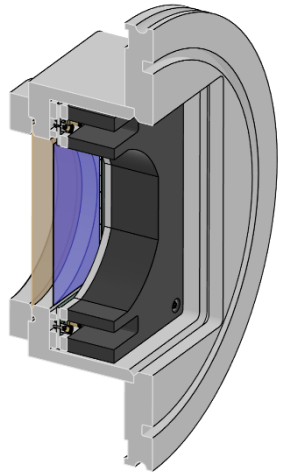
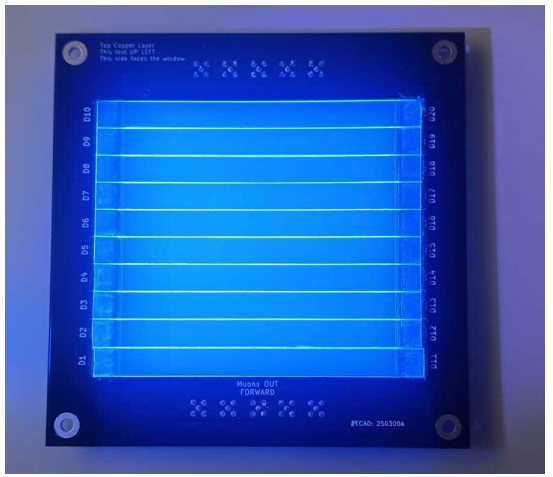
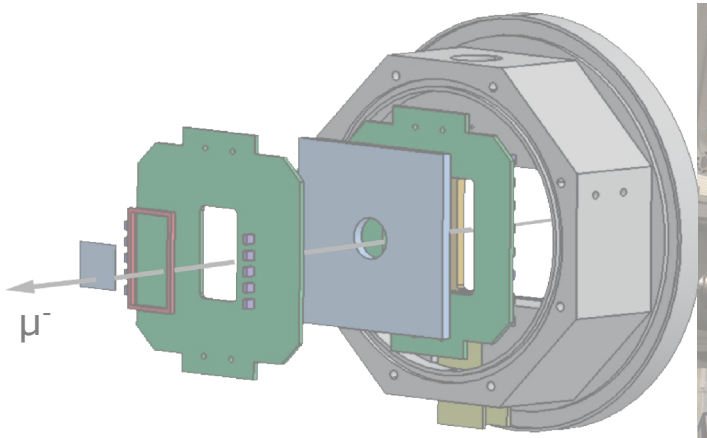
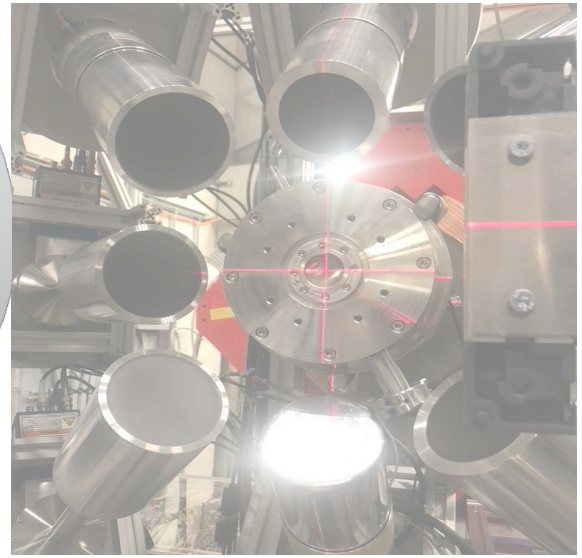






200 µm µ-counter

Ø 18mm active Veto



Upgraded version (2025)

- Much larger active area (~7x7cm^2)
- Matching Window (Ø7cm) – 50µm Mylar
  - Same overall material budget!
- Optimized shielding to reduce BG
- Striped design (10 individual channels)
  - Allows higher tracker rate (see Part IV)

MIXE 4 Batteries: Full depth profiling

Goal:

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

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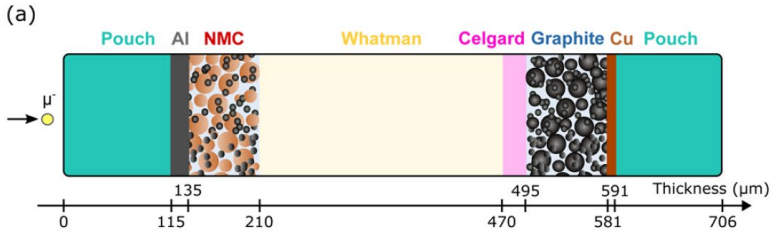

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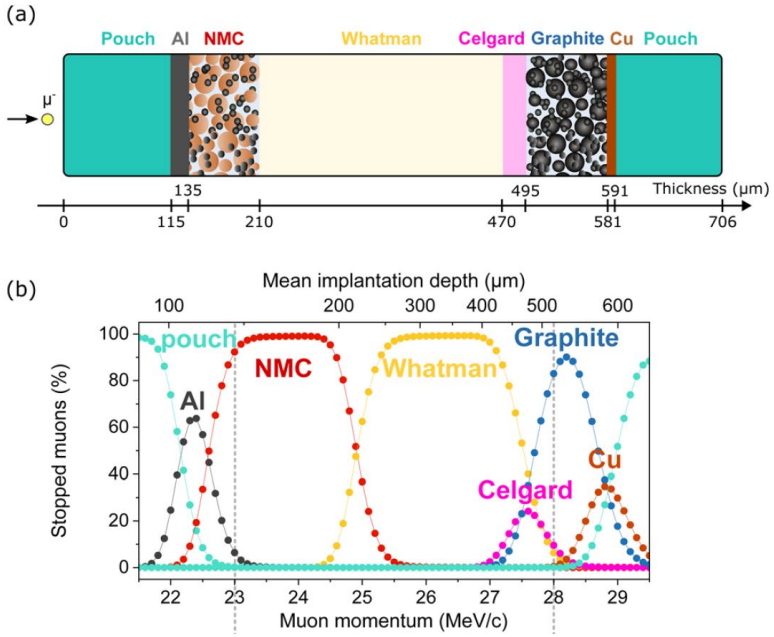

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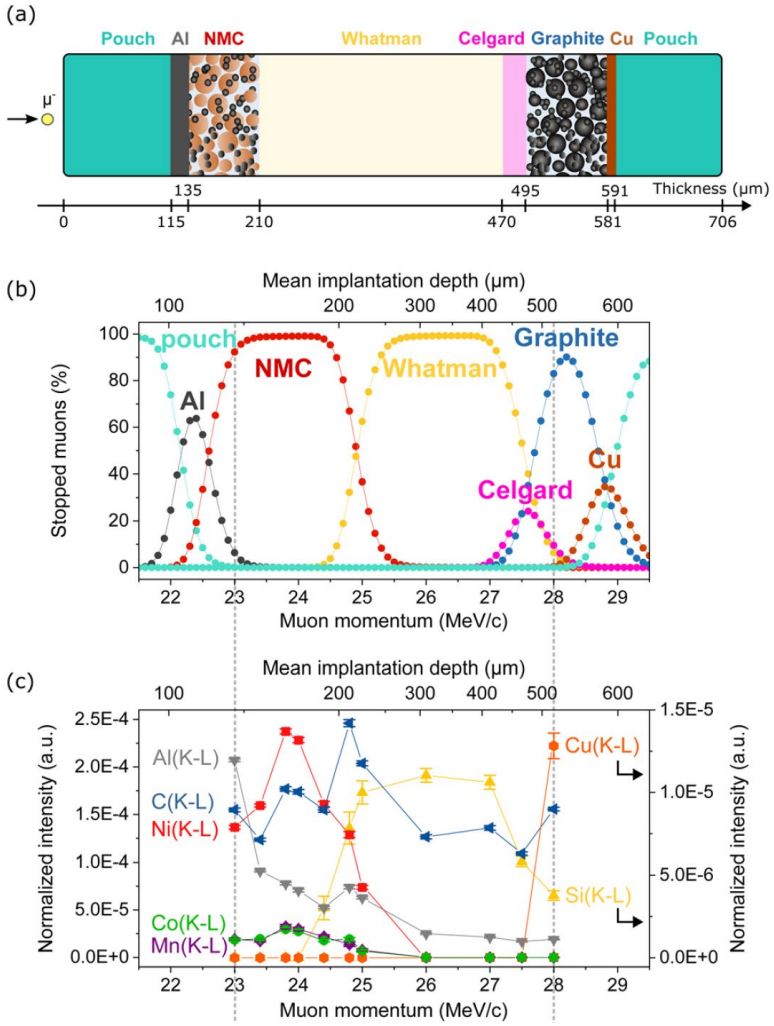

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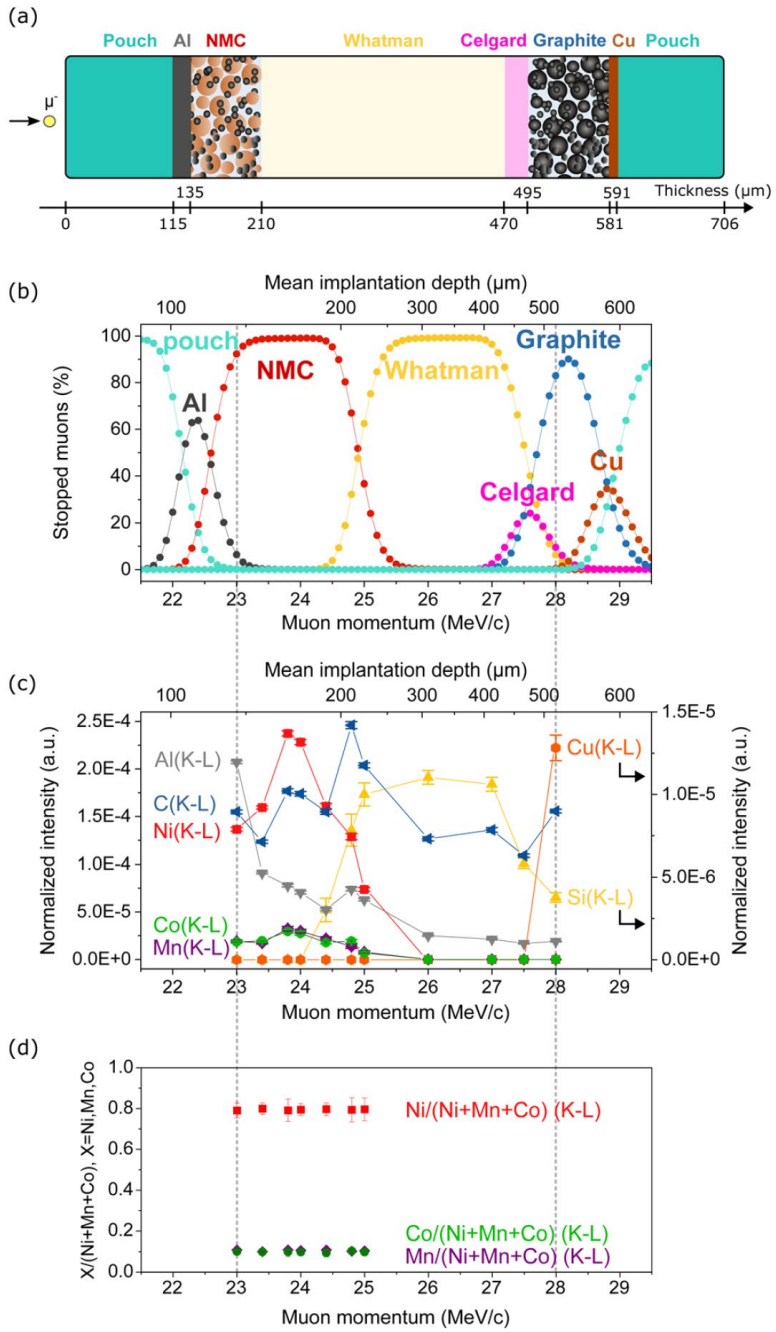
- **Cross-check** of quantitative results: **NMC Stoichiometry**
  Reproduces 8:1:1 ratio very well **over full thickness**



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.

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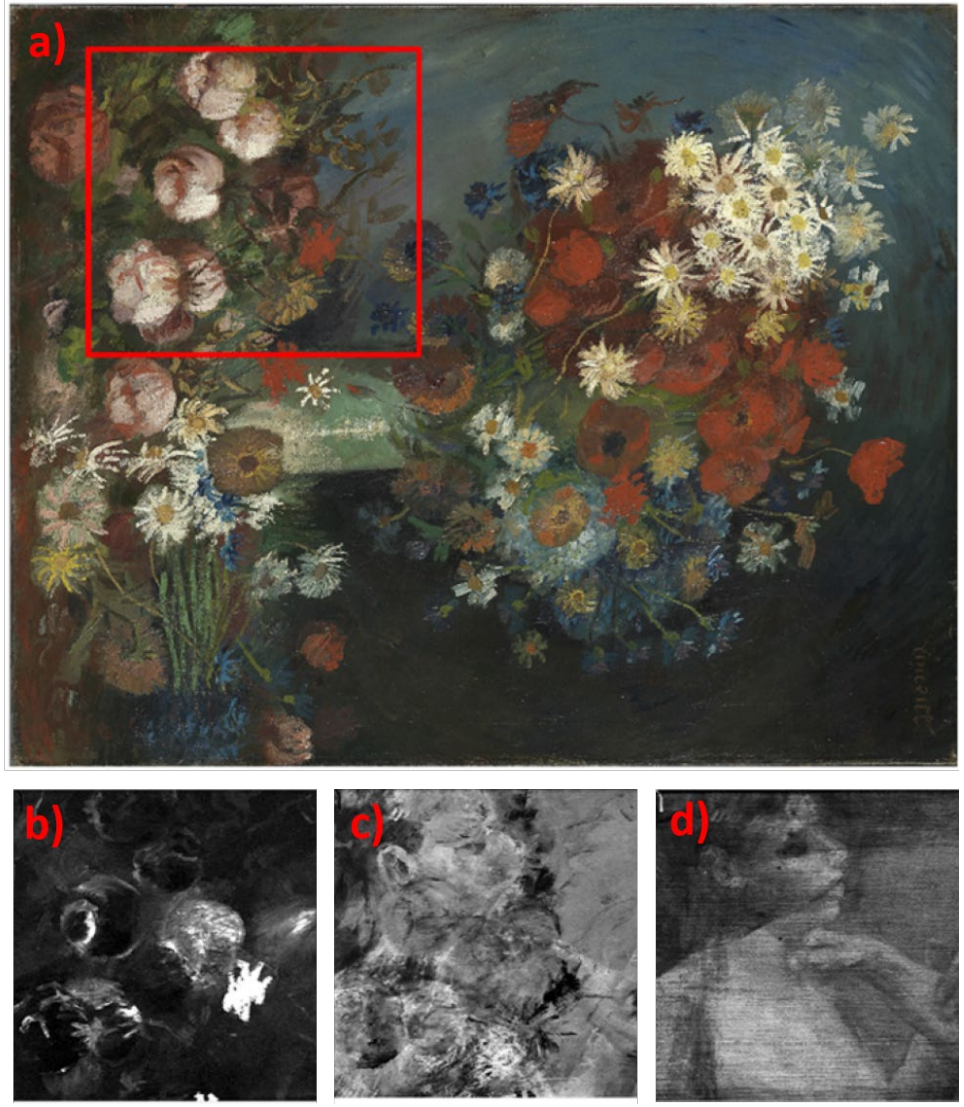
Study using **XRF**



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c) Zn fluorescence signal of the same area, hints of a human face visible.

d) Zn fluorescence measured from the back of the painting with less absorption, revealing the human face as part of an overpainted wrestling scene..

M. Alfeld and J. A. C. Broekaert, Spectrochimica Acta Part B 88, 211-230 (2013)

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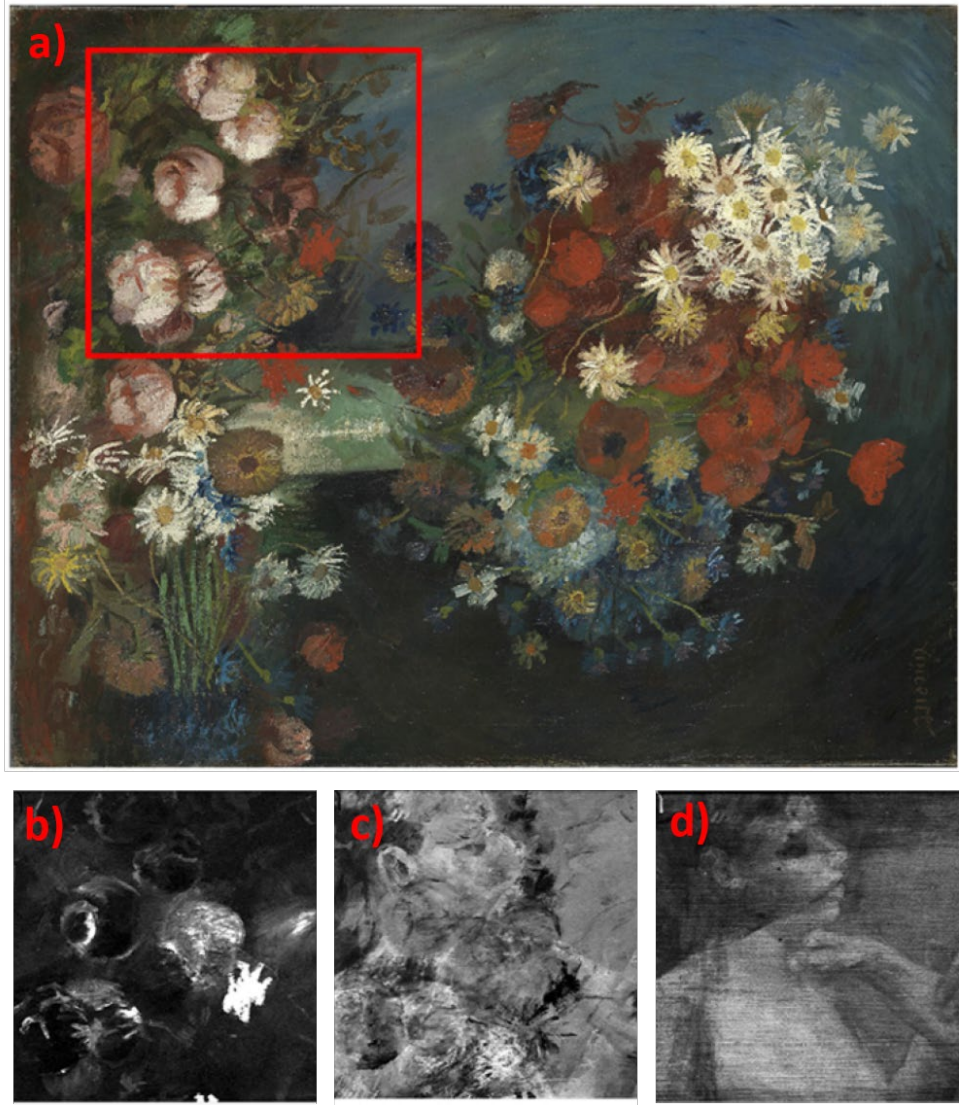

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MIXE-T could image all elements over full canvas with much higher depth-resolution!

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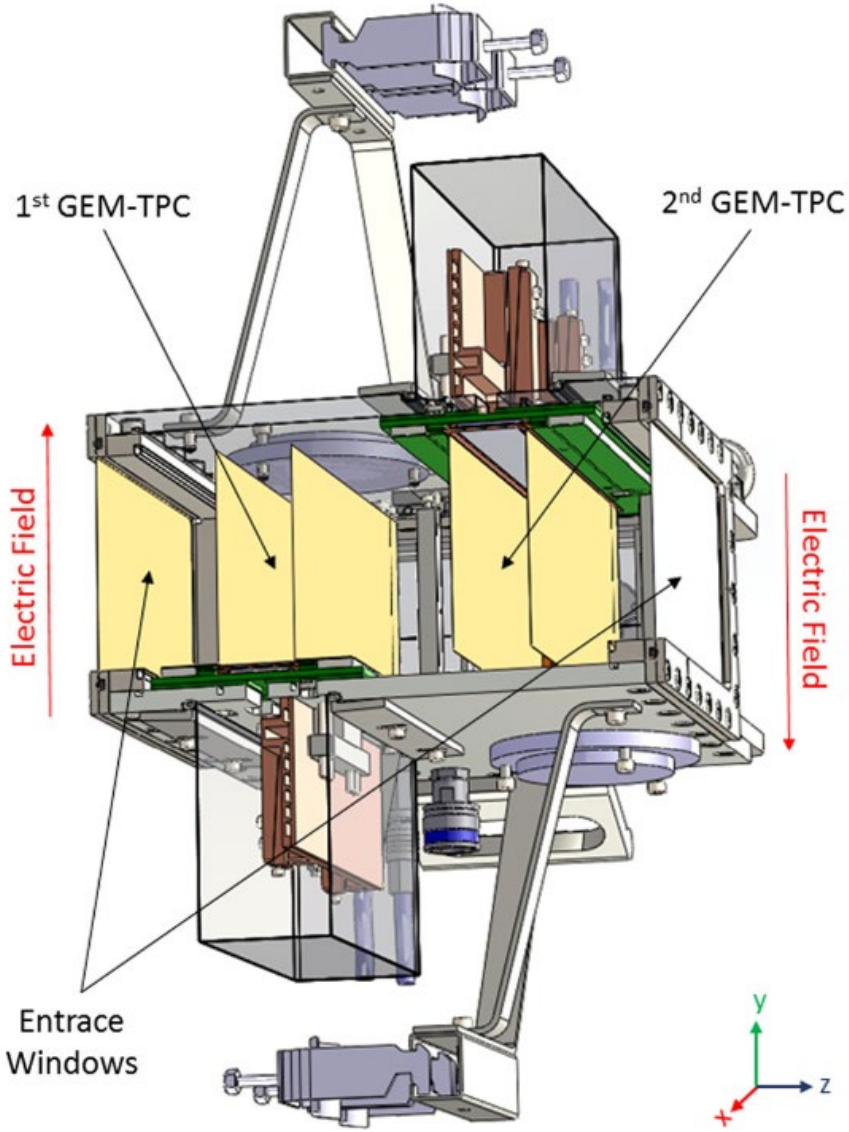

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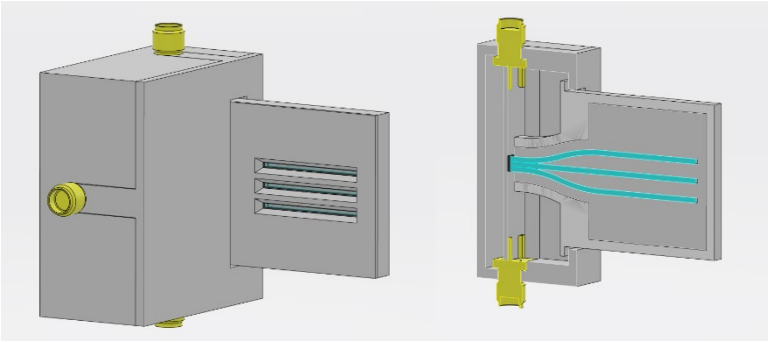

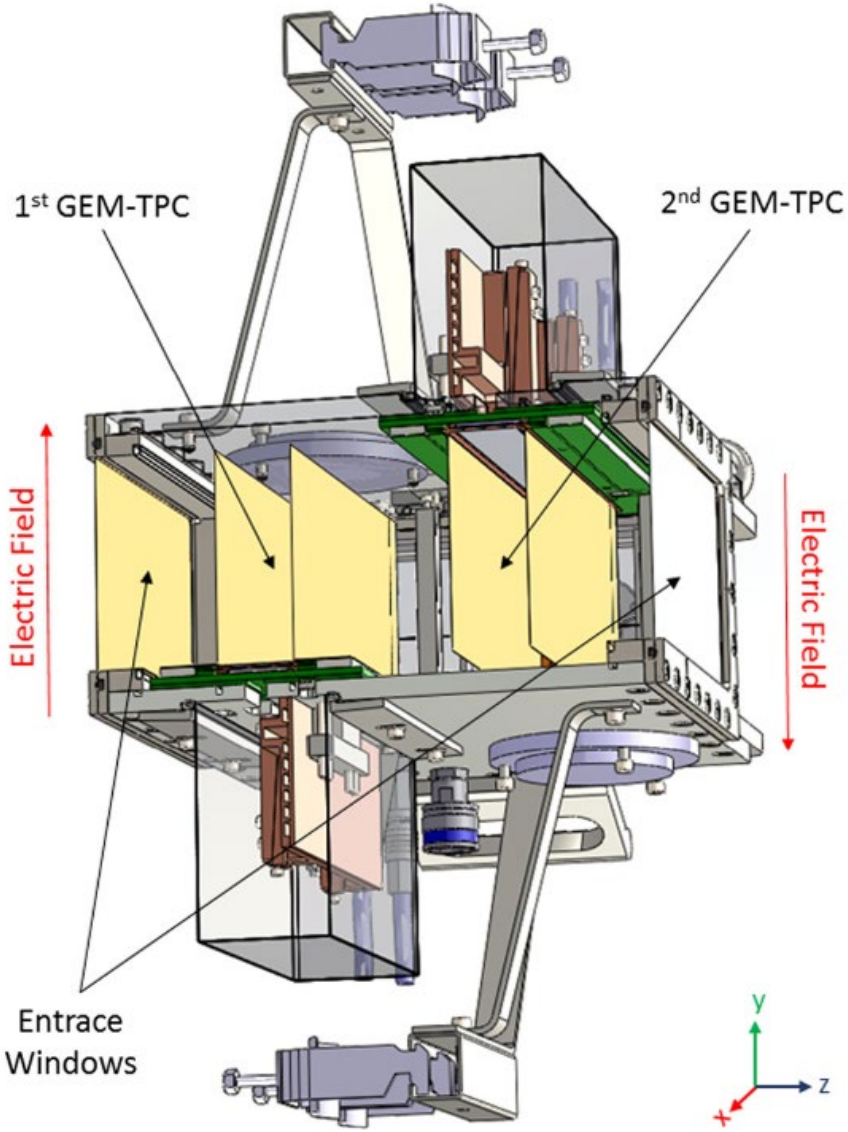

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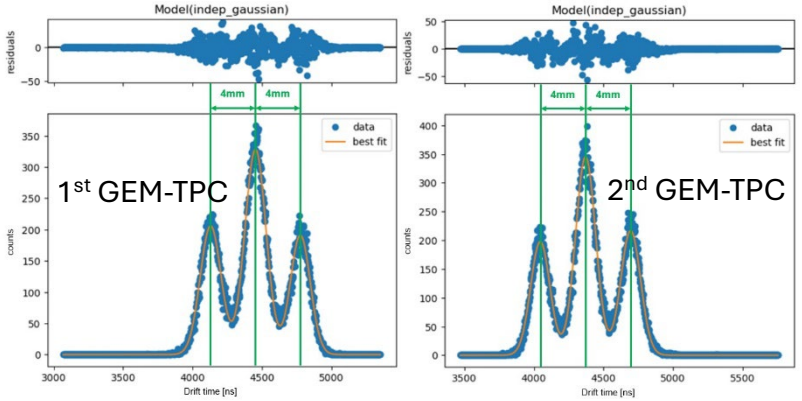

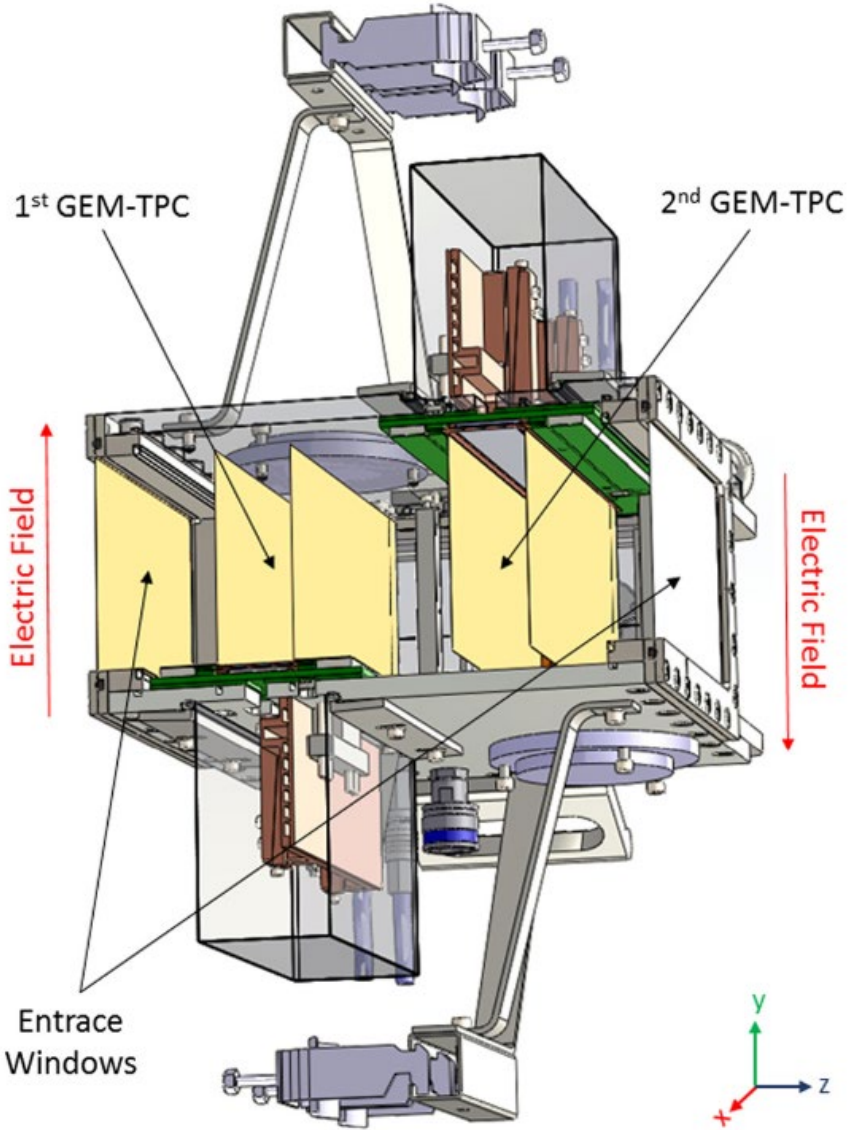

MIXE-T(omography): First Elemental Imaging (Jun 23)

PRELIMINARY

Experimental setup

- Tracker mounted after beam port (roughly aligned)
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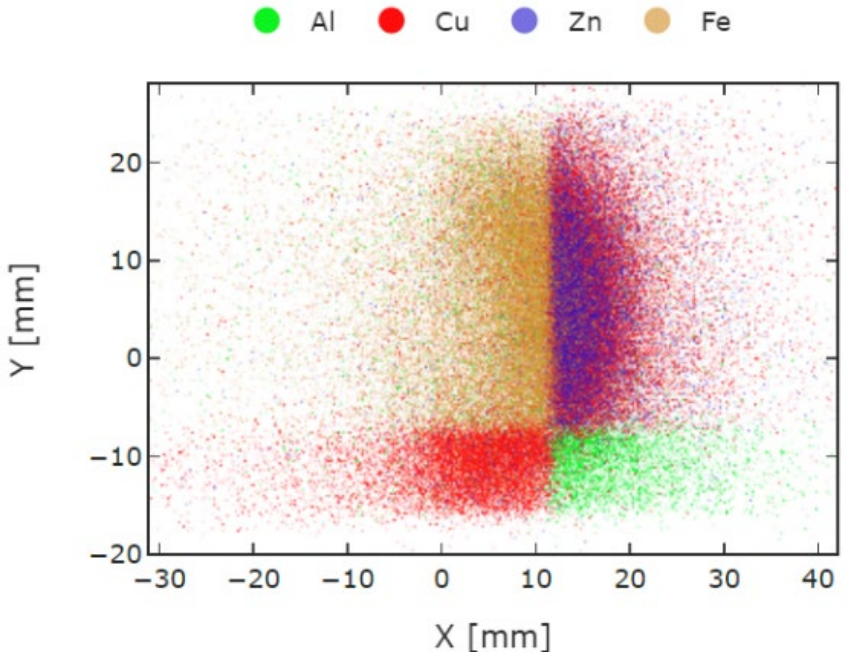
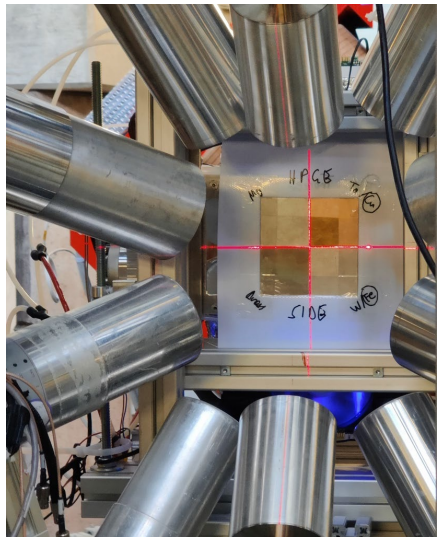


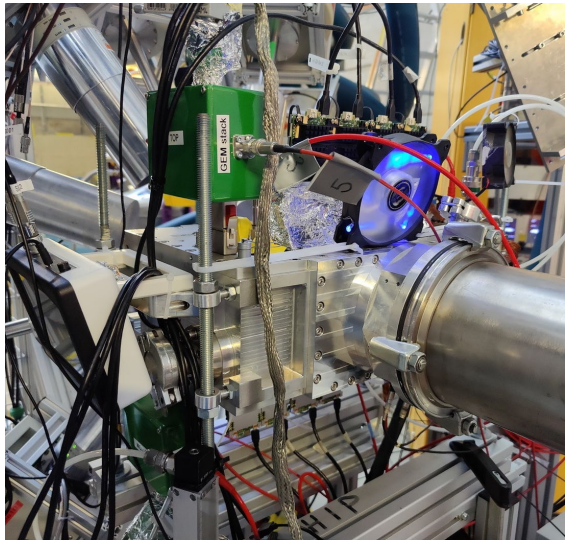
MIXE-T(omography): Spatial Resolution for Tomography

PRELIMINARY

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) in 2025





MIXE-T(omography): Spatial Resolution for Tomography

PRELIMINARY

Upgrades

- Layered targets & Momentum Scans
- Detector flanged directly to beamport
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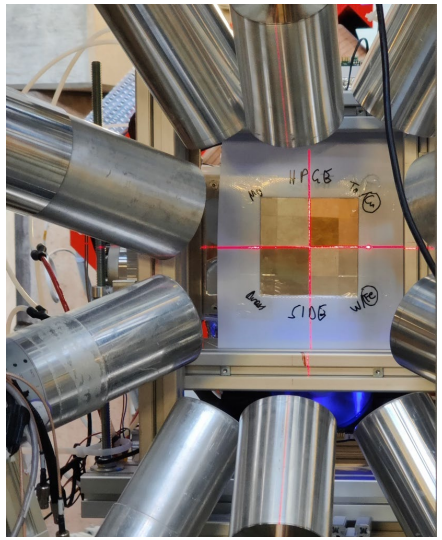
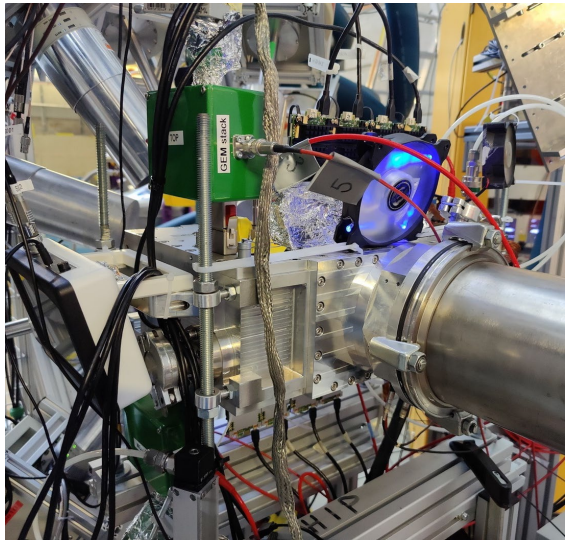
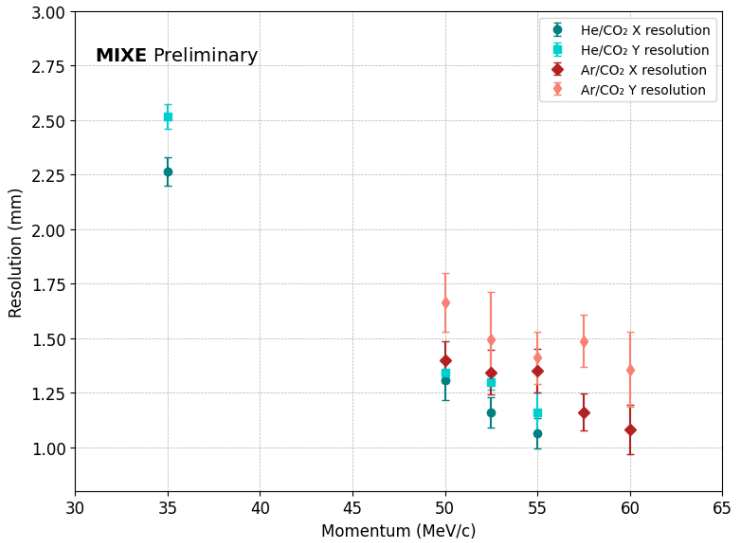




Results

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



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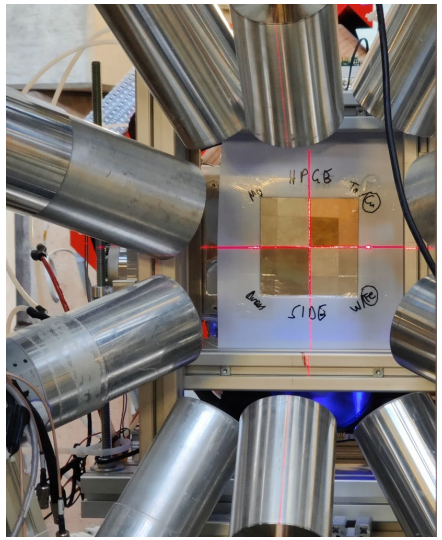
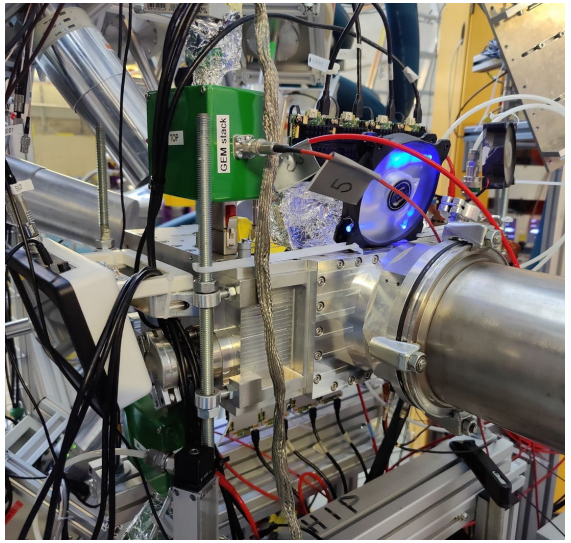
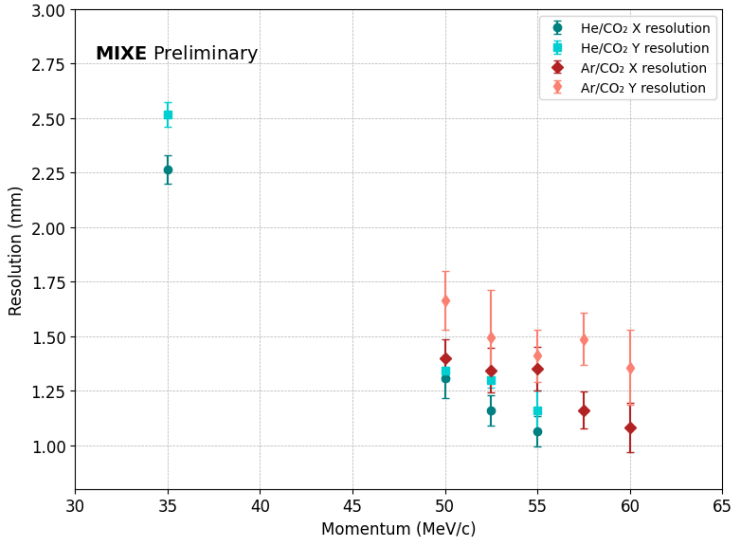
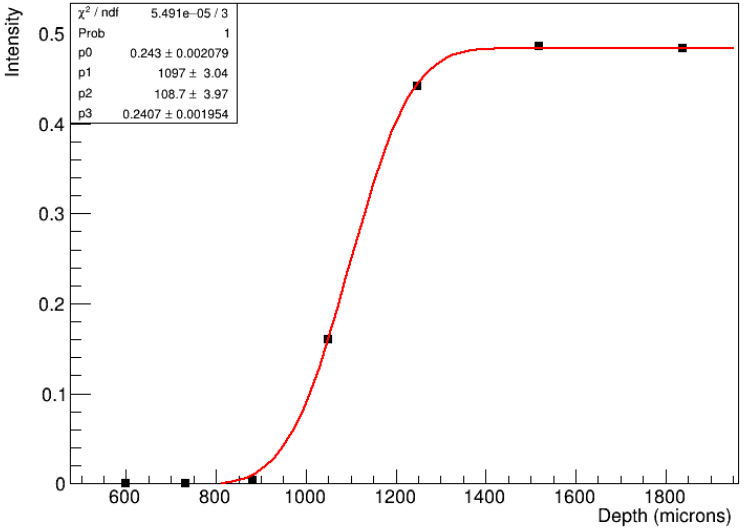




Results

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





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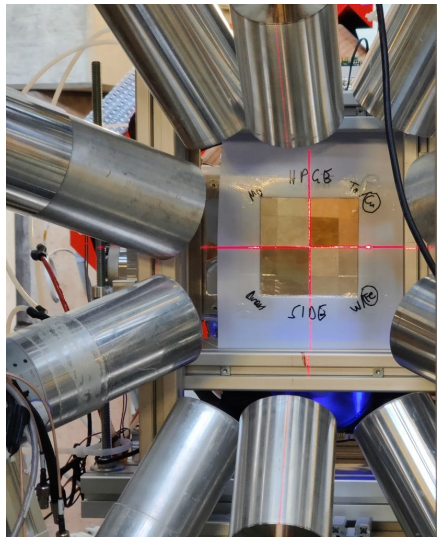

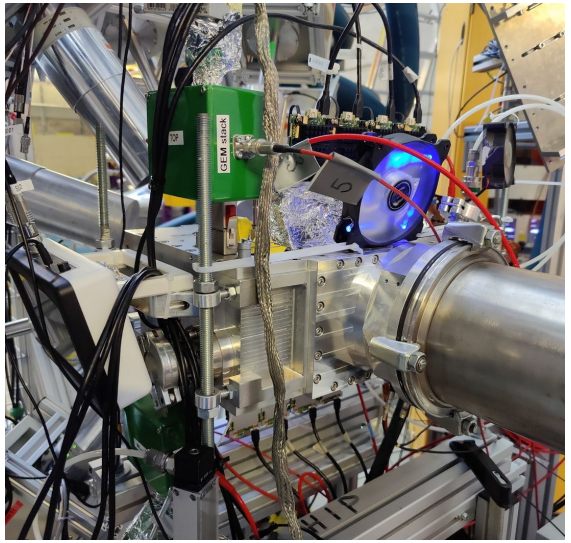

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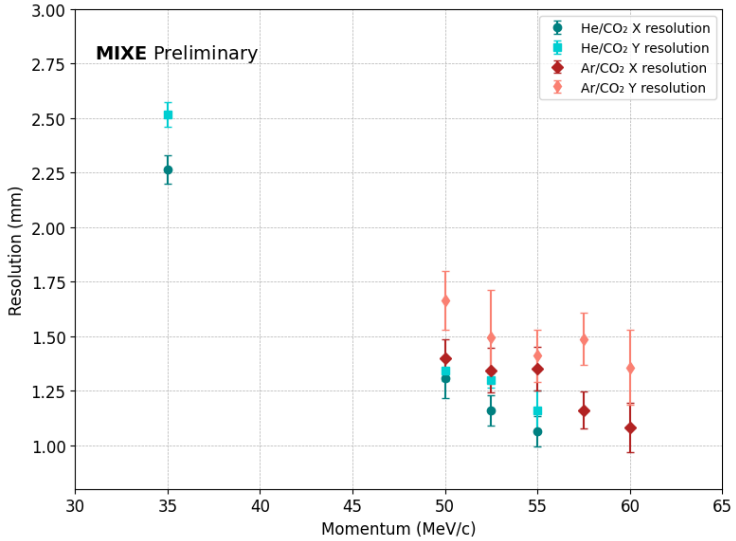
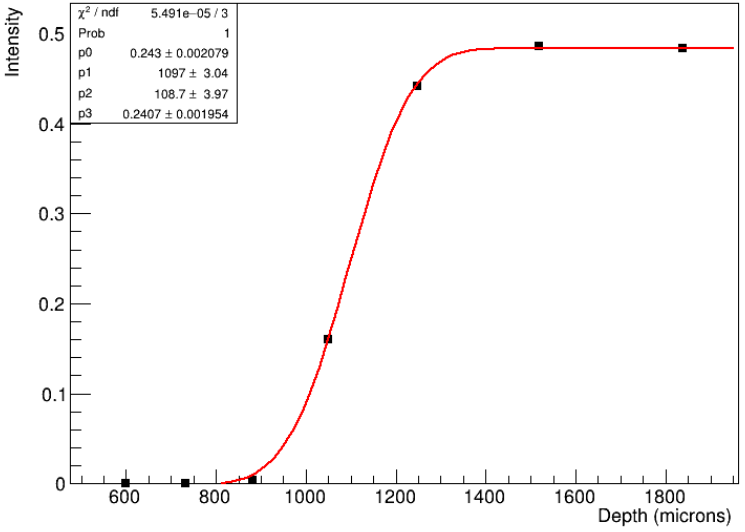
Limited by large gas volume

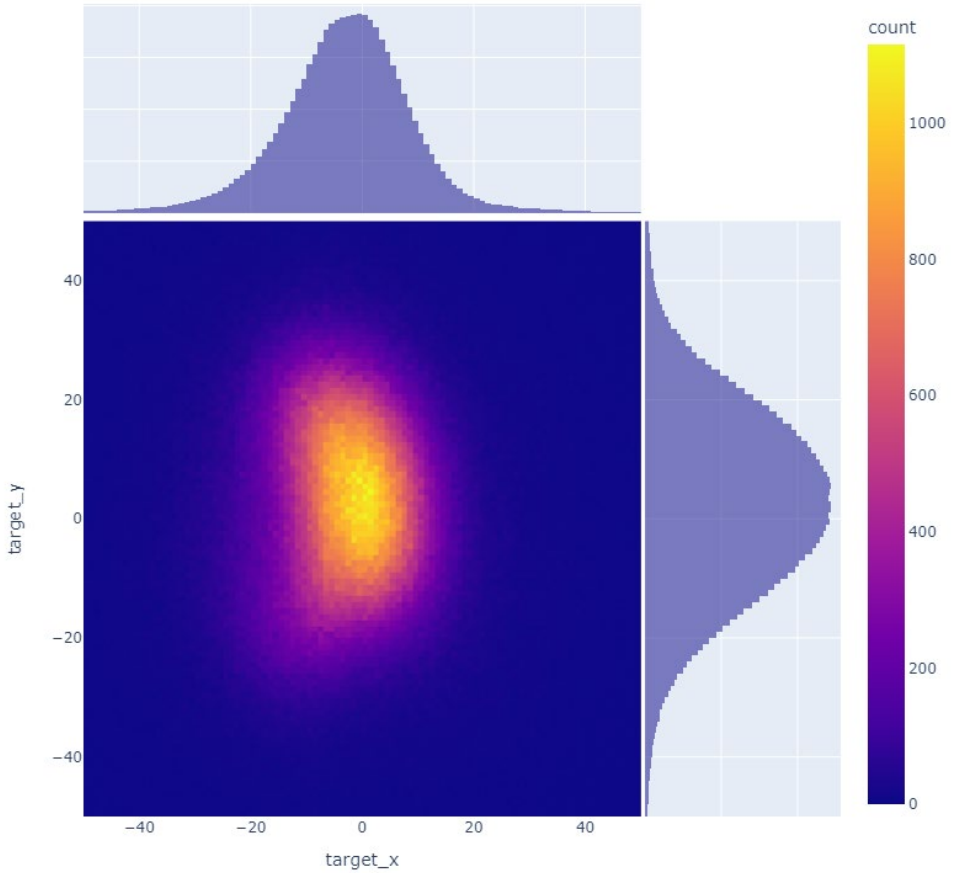
Specialized prototype detector in development!





MIXE-T(omography): Determining the Resolution

PRELIMINARY



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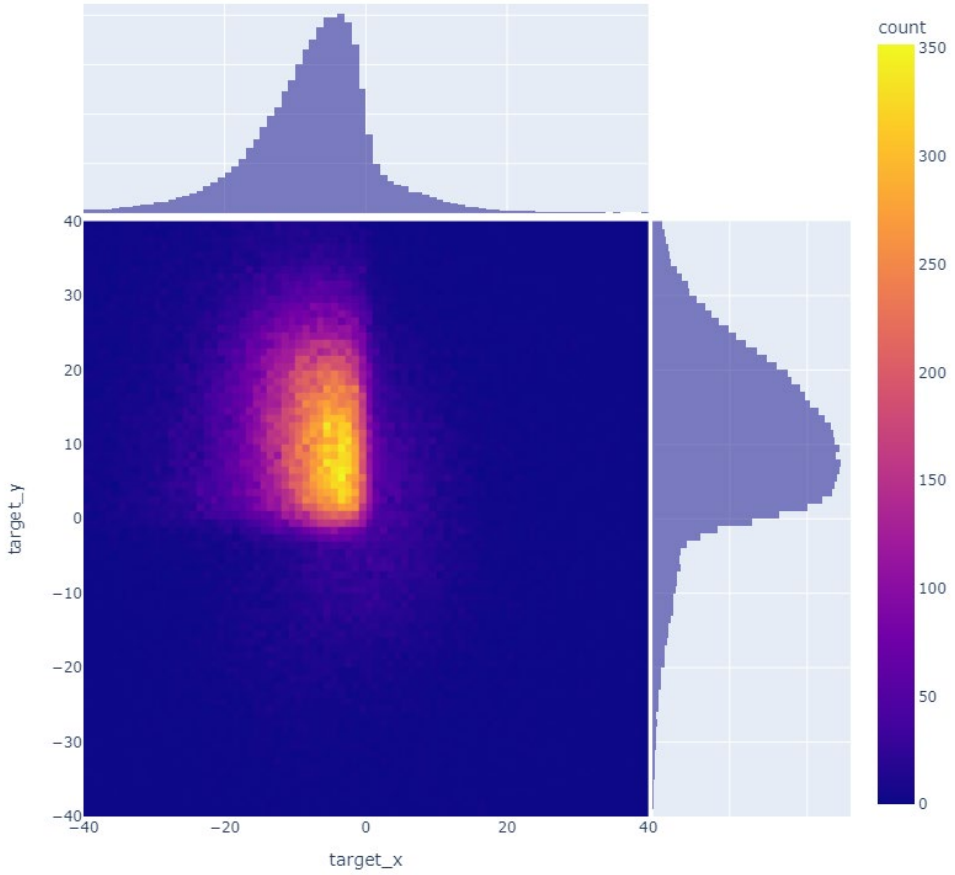

Step 1: Select the desired element (Mo)

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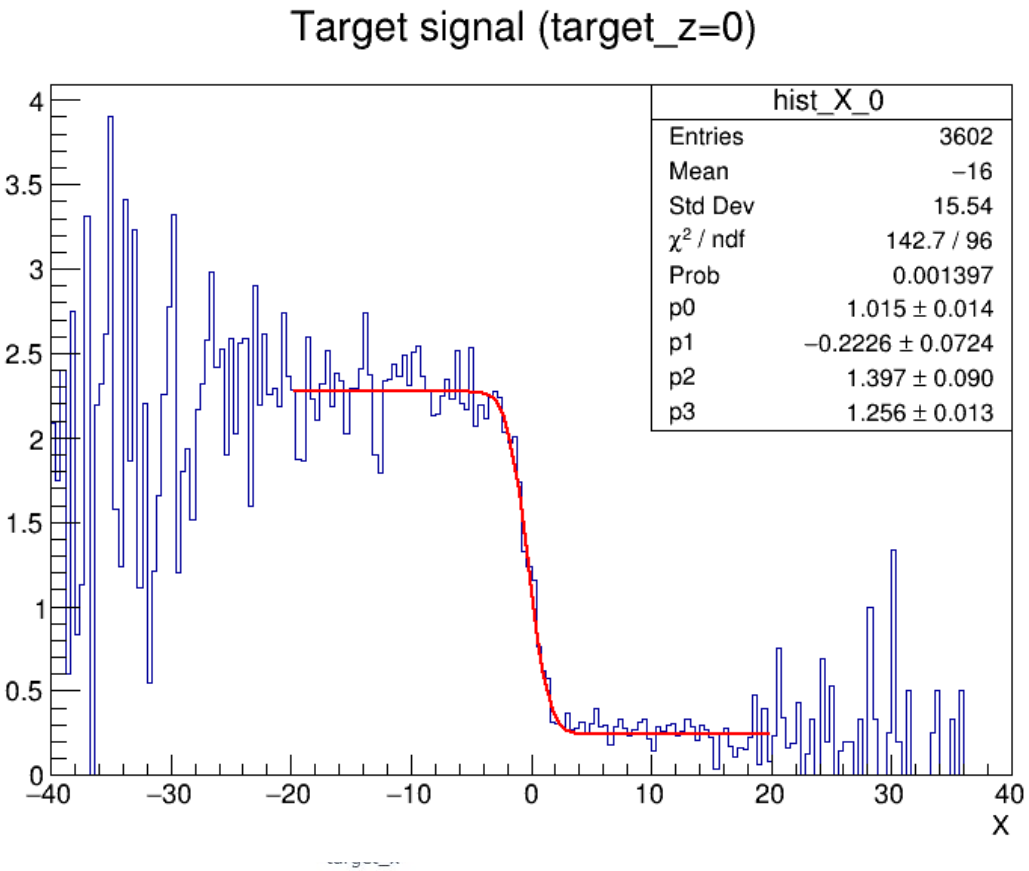

Step 1: Select the desired element (Mo)

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

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

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

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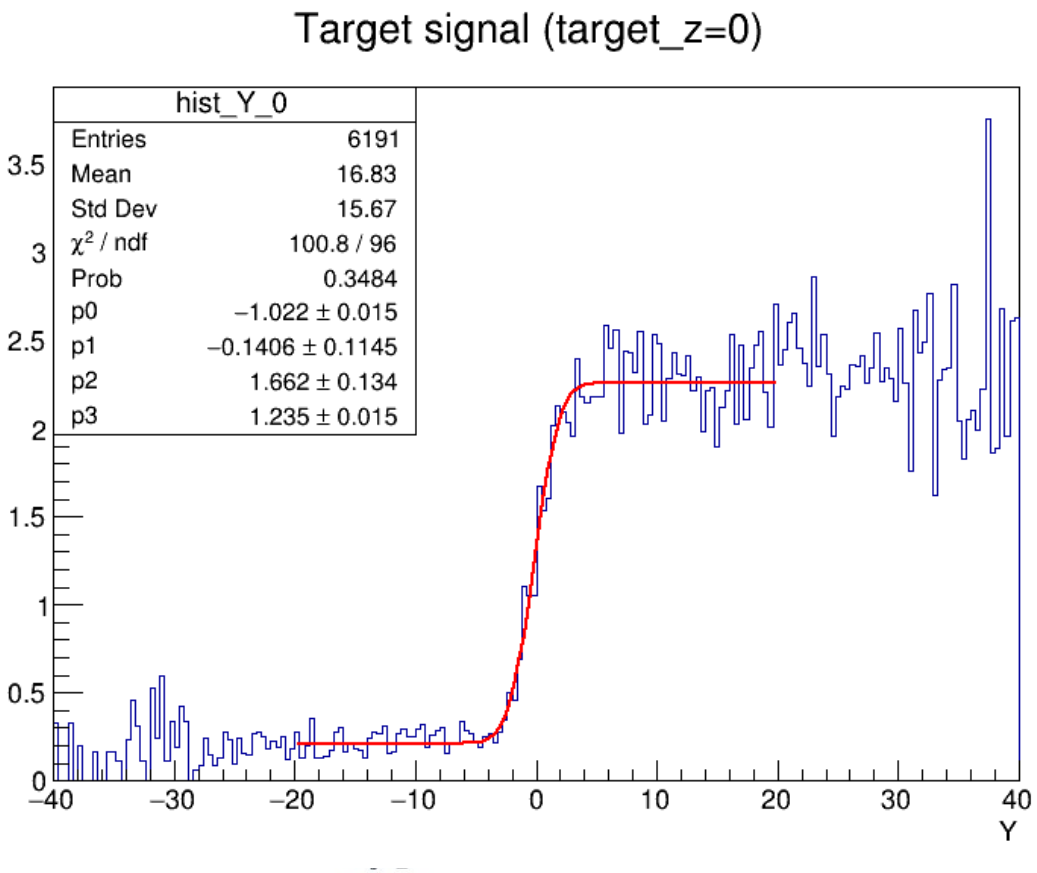
PRELIMINARY



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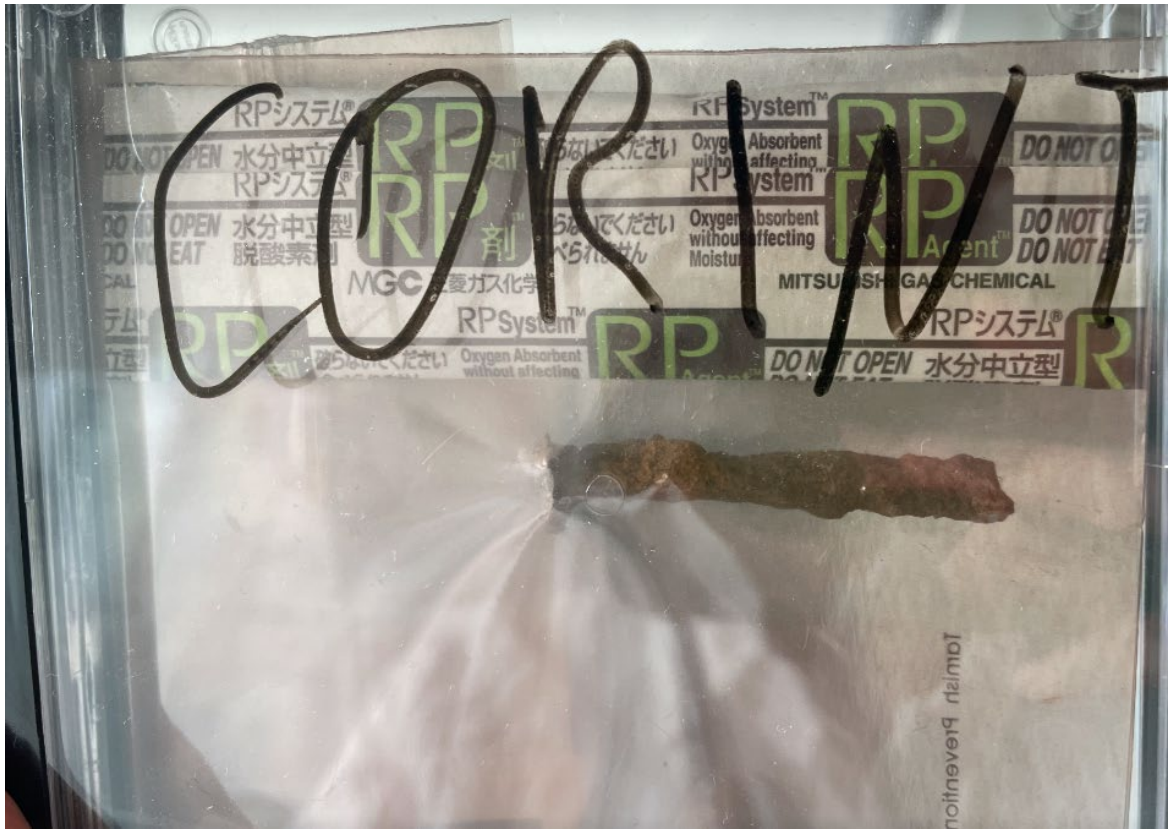
MIXE-T(omography): “Real” Sample

PRELIMINARY

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



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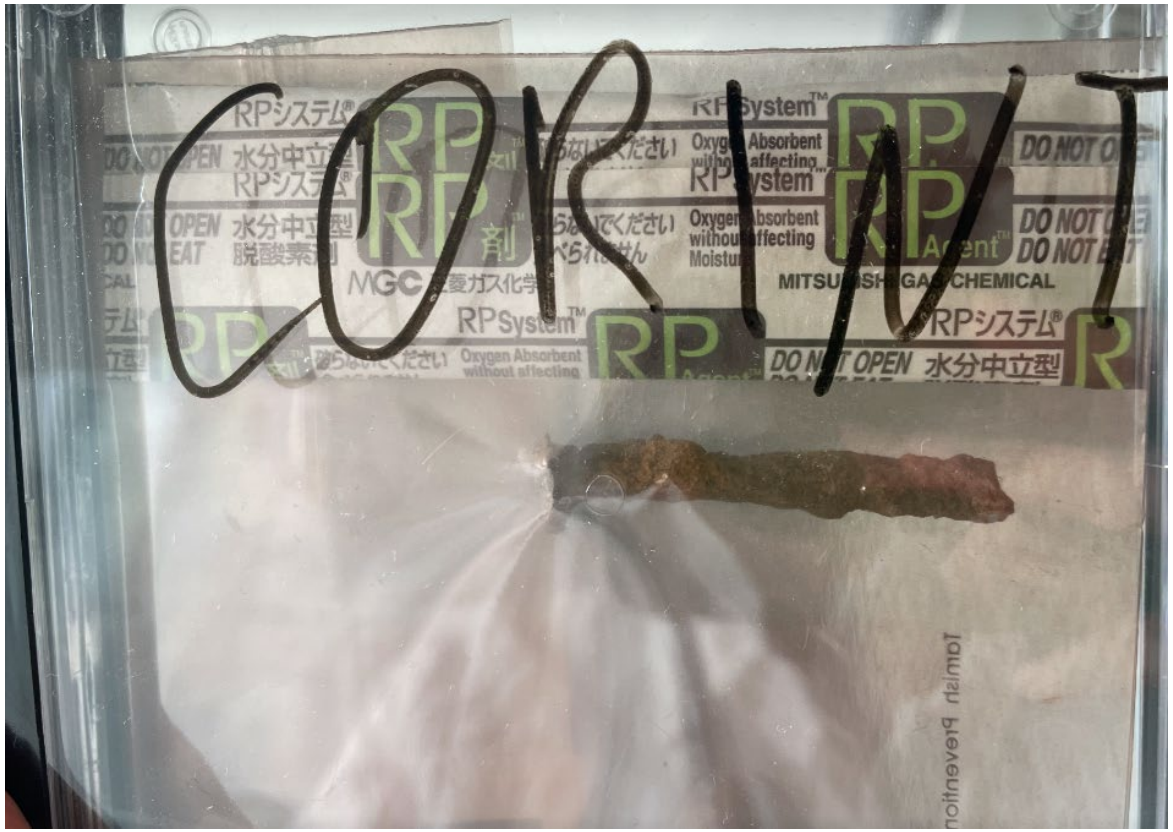
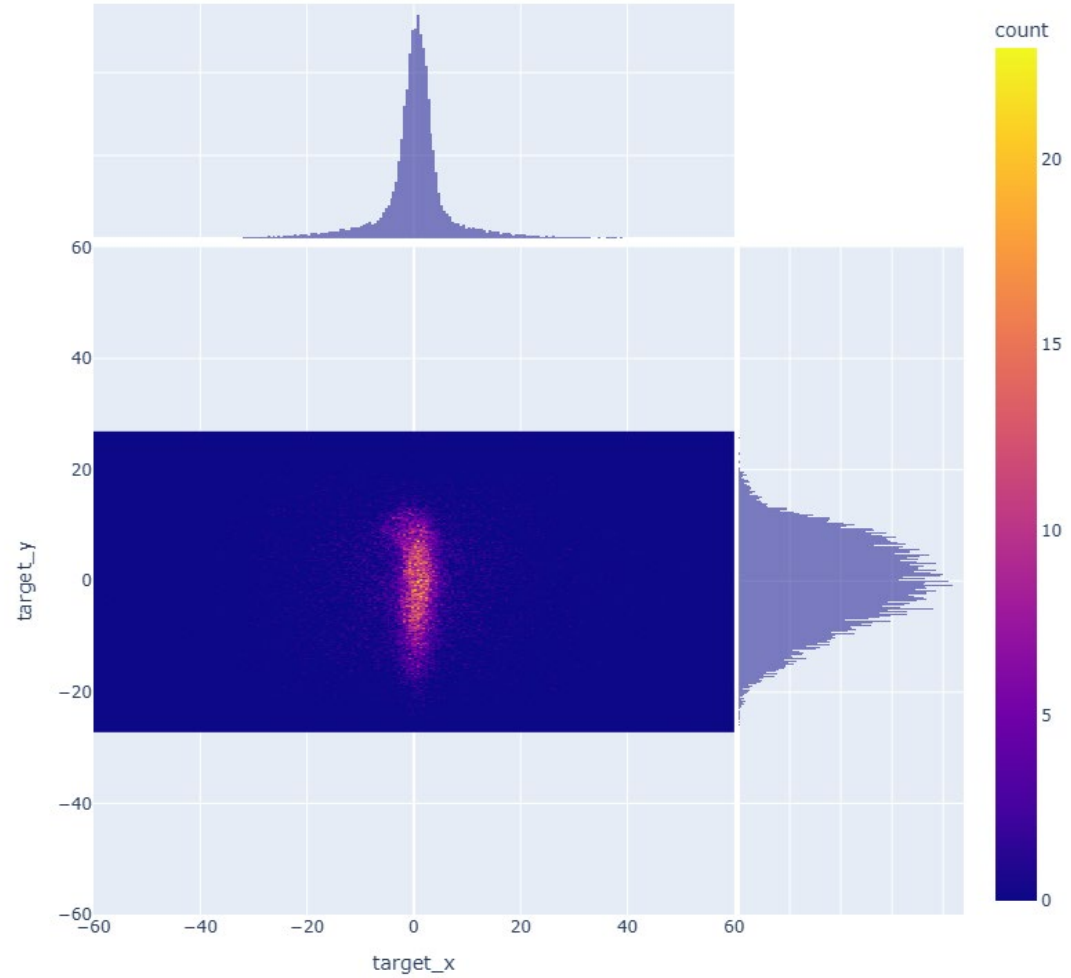


- Tracks filtered for Fe K_α and K_β peaks



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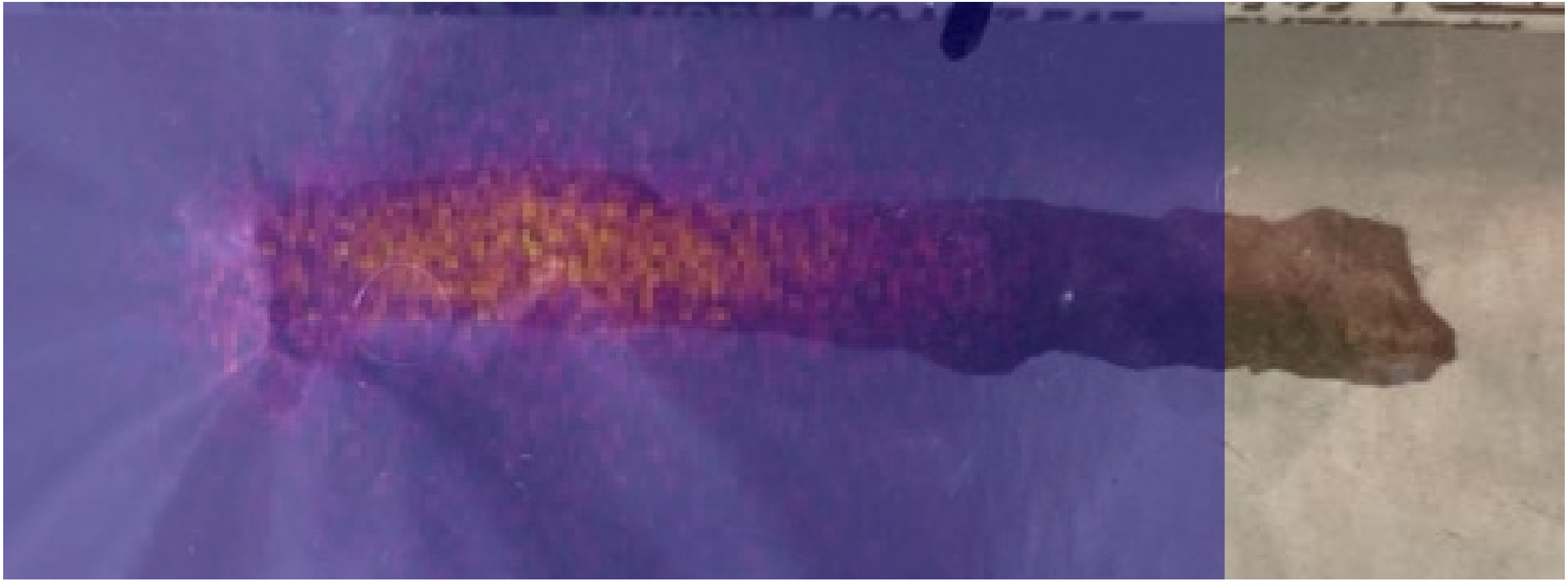


Backup

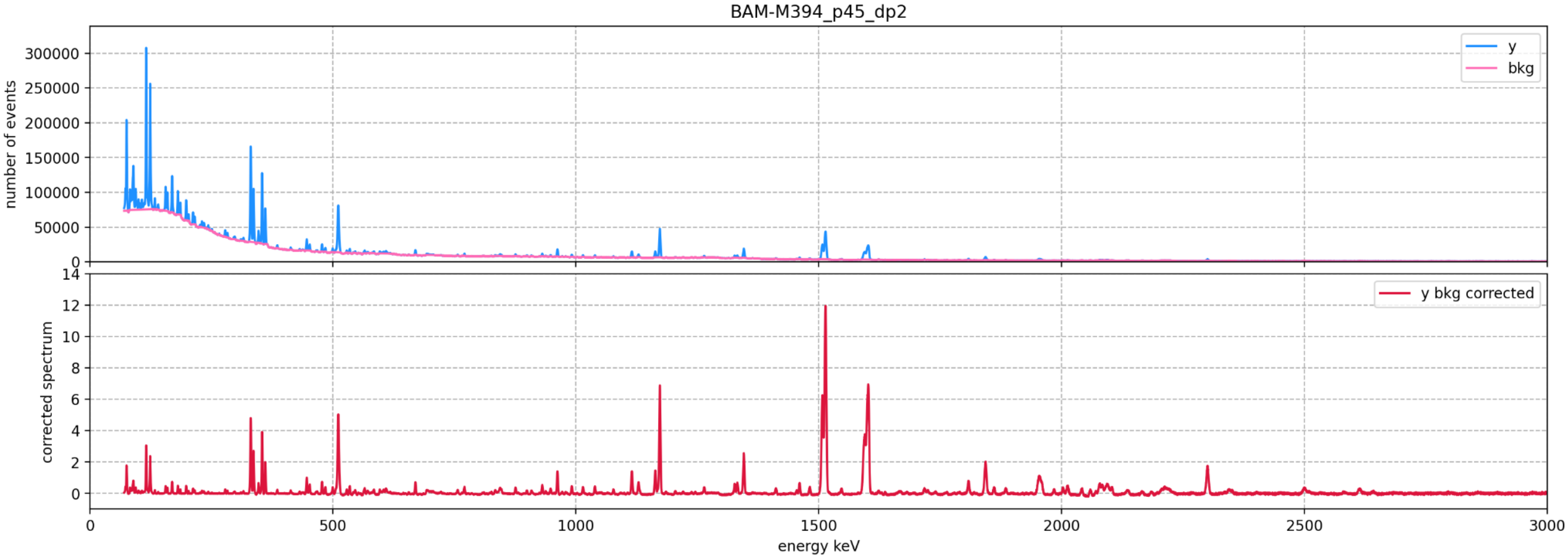
Smart Analysis of MUonic x-Rays with AI

SAMURAI: Smart Analysis of MUonic x-Rays with AI – Basics

- **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

SAMURAI: Demo I

- 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 Kα 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

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

Secondary template

Main penalty

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

Measured spectrum

Main amplitudes

Kα template

Secondary amplitudes

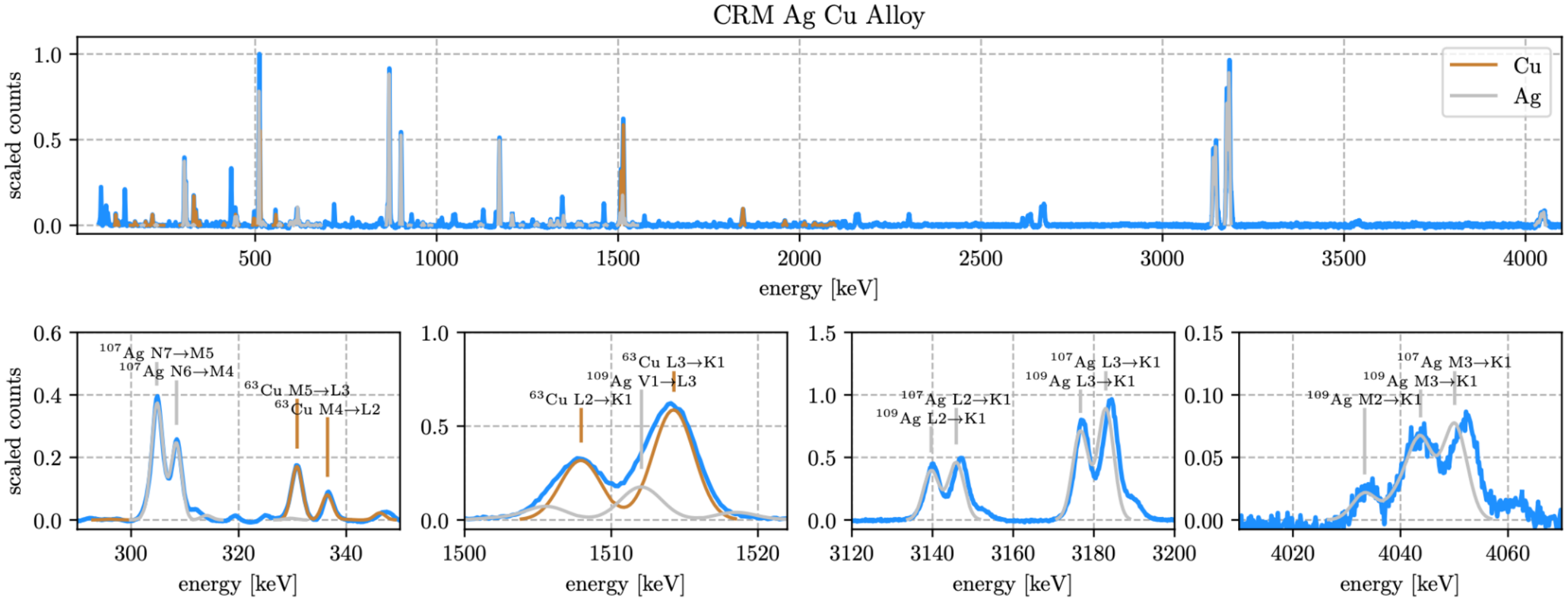
Secondary penalty

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

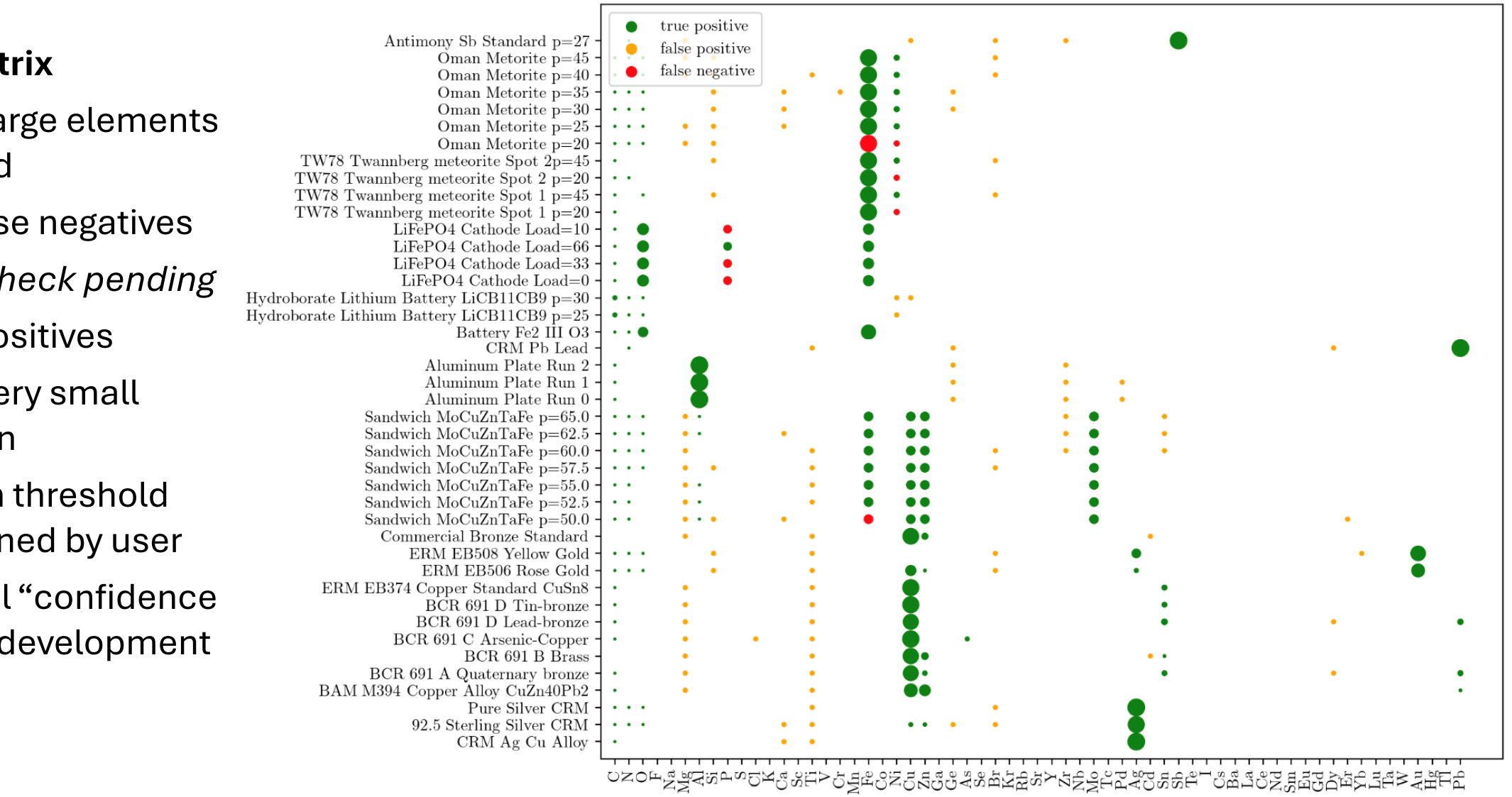


SAMURAI: Qualitative Results

PRELIMINARY

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