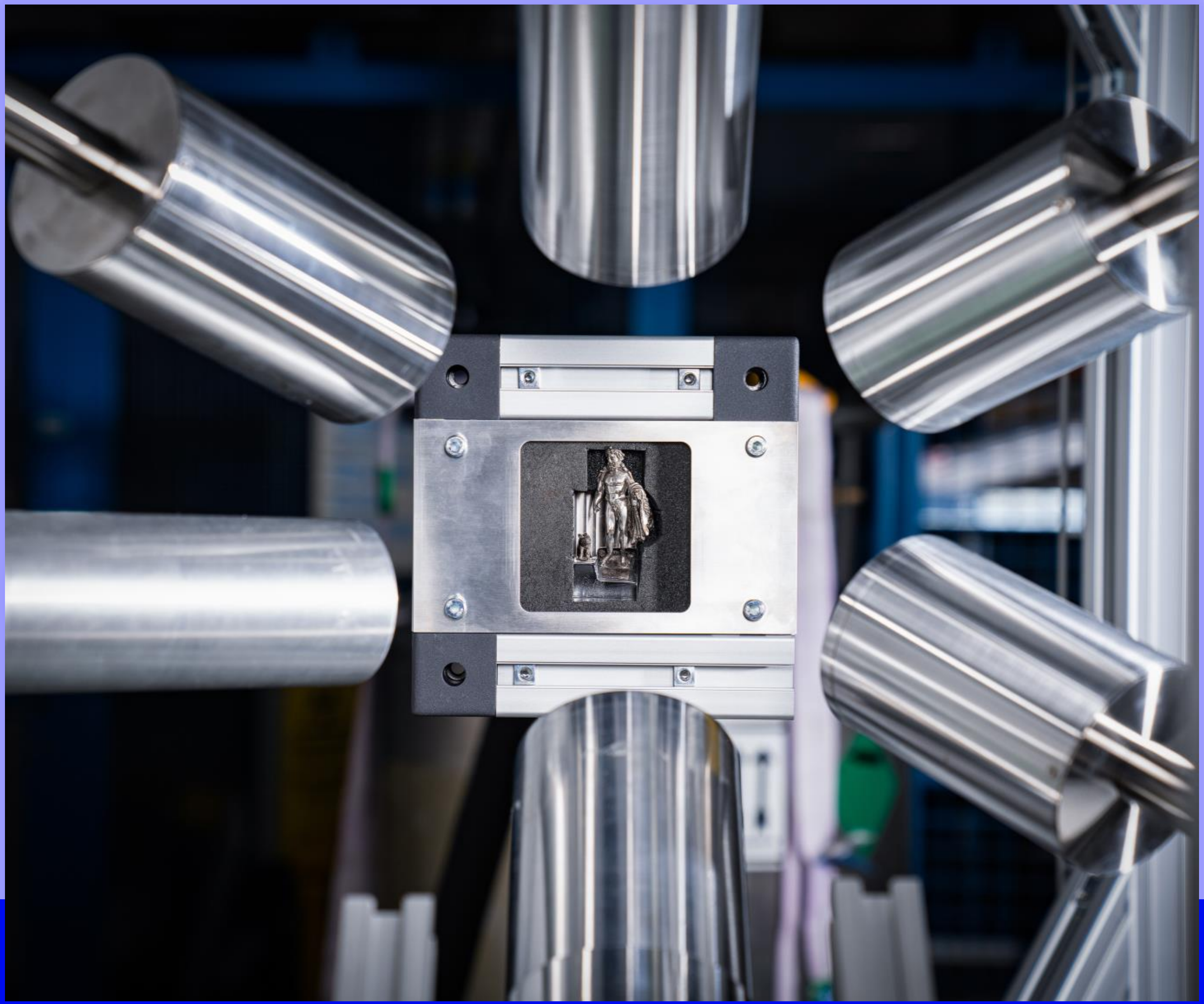
PSI Center for Neutron and Muon Sciences

Rebirth of MIXE

The GIANT Leap in Non-Destructive Elemental Analysis at PSI



Michael W. Heiss
Abschiedskolloquium Alex Amato, 11 December 2024

Content

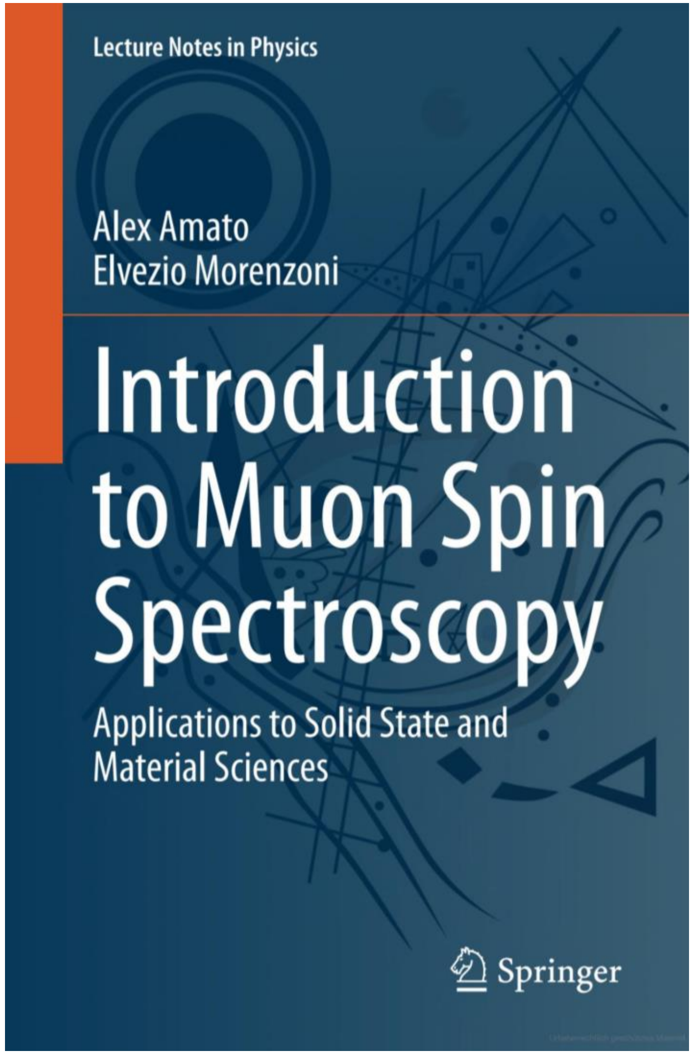
Part I
Introduction:
“Amato Heritage”

MIXE: Alex Amato, the scientist who wrote the ~~book on~~ it!

PSI

~~the chapter~~

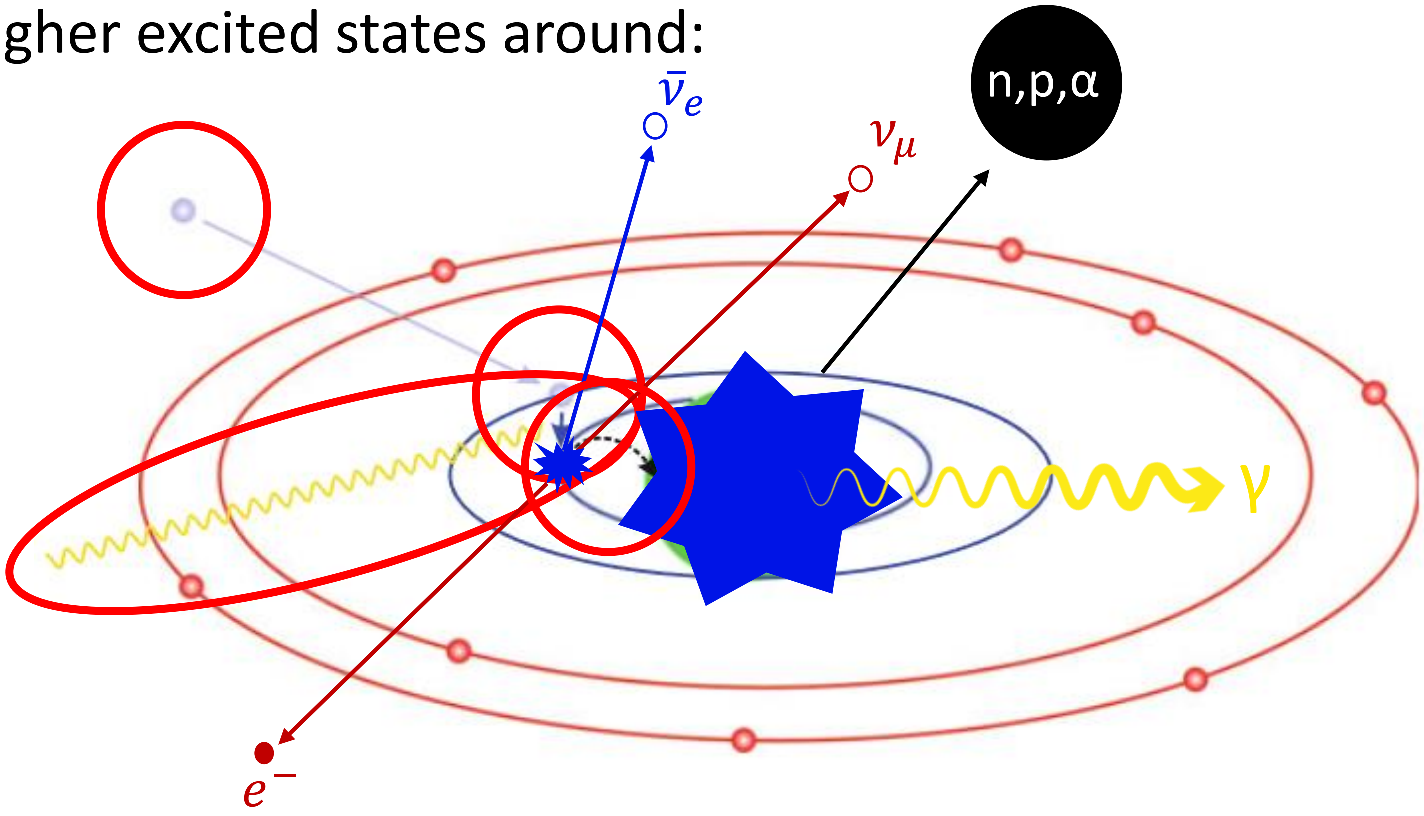
The Book!



MIXE: Muon Induced X-ray Emission – The 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:

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



- Cascades down to $n_\mu = 1$ while emitting X-rays characteristic to the element / isotope
- Muon is unstable and decays

or

- Muon is captured by nucleus

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

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

MIXE: Muon Induced X-ray Emission – The Overview

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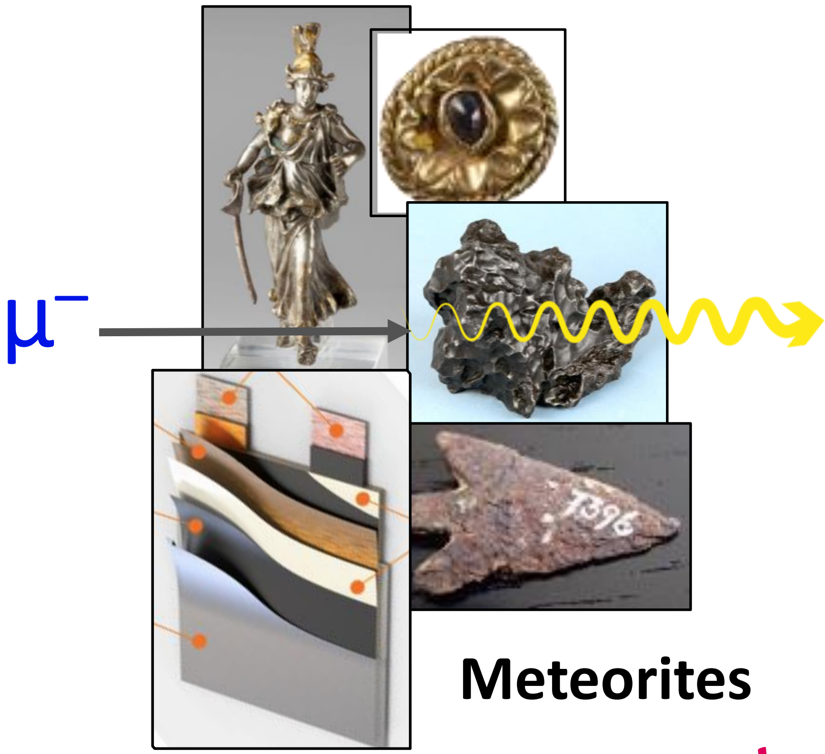
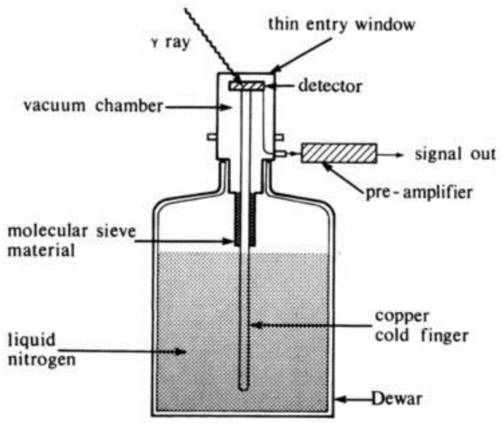
Archeological artifacts



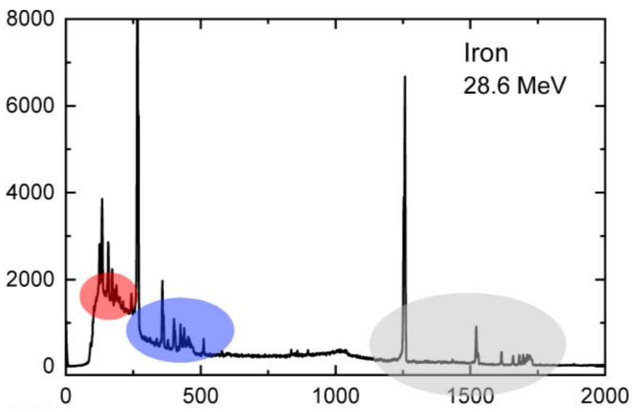
Meteorites

Batteries

and many more!



High Purity Germanium Detectors

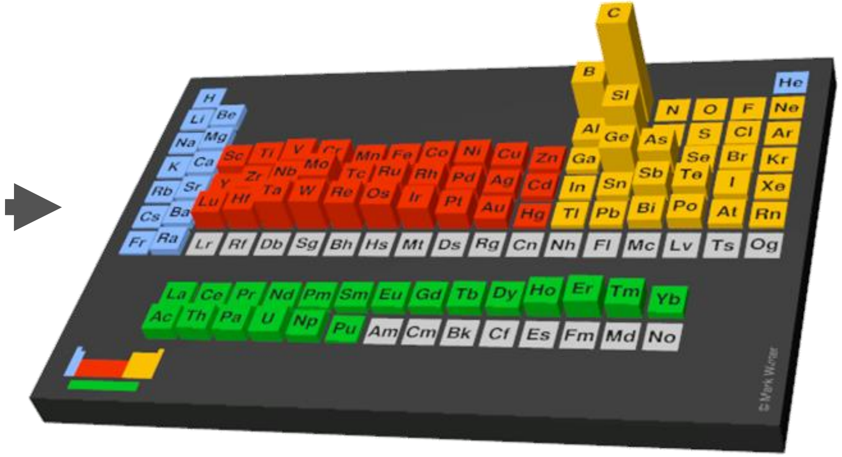


Highlights:

- **Sensitive** to **all elements**
- **Isotopic** composition (high Z)
- Indications of **chemical states**

All in the same measurement!

- **Depth-resolved** (~*μm* to ~*cm*)
- Completely **non-destructive**
- **Tomography** (in development)



MIXE: Muon Induced X-ray Emission – Pioneering studies

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1973

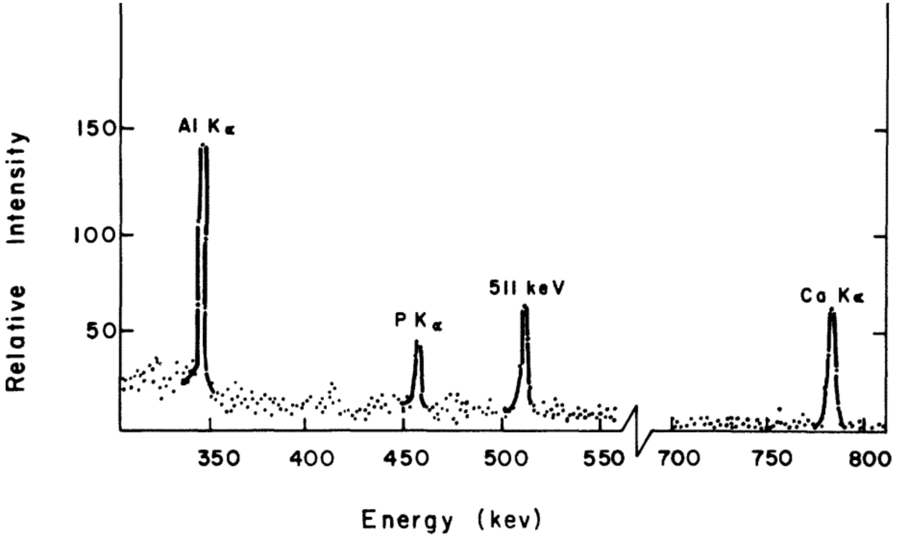
Observation of Muonic X-rays from Bone[1]

M. C. Taylor, L. Coulson and G. C. Phillips

T. W. Bonner Nuclear Laboratories, Rice University, Houston, Texas 77001

Taylor, M. C., Coulson, L., and Phillips, G. C., Observation of Muonic X-rays from Bone. *Radiat. Res.* **54**, 335–342

The muonic x-ray, which results from the capture of a negative muon into orbit around a nucleus to form a "muonic atom," may be a useful diagnostic probe. The x-ray transition energies are about 200 times the energies from electronic transitions—the carbon K_α energy is of the order of 75 keV. Thus, muonic x-rays from light elements have considerable penetrating power and can escape from bulky media. Experimental results for negative muons stopped in bone are presented to demonstrate the potential of the technique for observing elements in the range from carbon to calcium in biological specimens. Advantages and disadvantages of this technique with respect to other methods of elemental analysis are discussed.



1978

40 • ANALYTICAL CHEMISTRY, VOL. 50, NO. 1, JANUARY 1978

Use of Muonic X Rays for Nondestructive Analysis of Bulk Samples for Low Z Constituents

James J. Reidy*

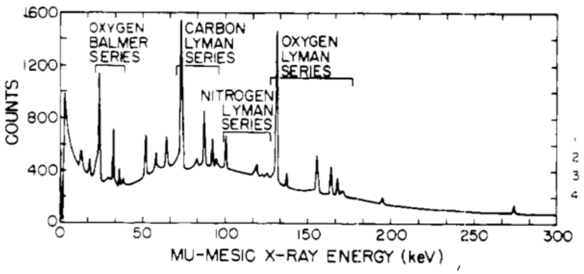
University of Mississippi, University, Mississippi 38677

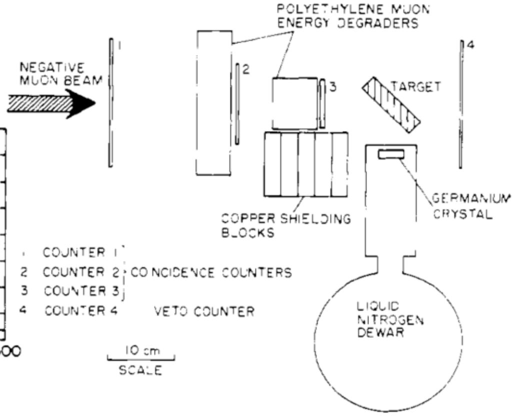
Richard L. Hutson

Los Alamos Scientific Laboratory, Los Alamos, New Mexico 87545

Herbert Daniel[1] and Klaus Springer[1]

Los Alamos Scientific Laboratory, Los Alamos, New Mexico 87545, and Technical University of Munich, D-8046 Garching, West Germany





Tissue Chemical Analysis with Muonic X Rays

Richard L. Hutson, James J. Reidy, Klaus Springer, Herbert Daniel, H. B. Knowles

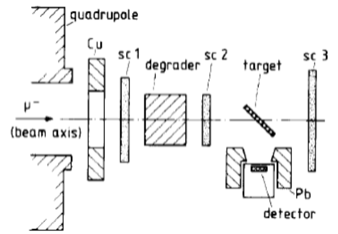
Author Affiliations

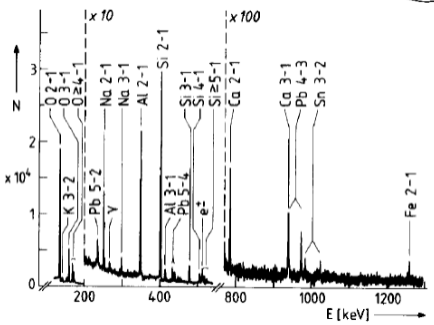
Published Online: Jul 1 1976 |
https://doi.org/10.1148/120.1.193

Abstract

The stopped muon channel at the Clinton P. Anderson Meson Physics Facility was used as a source of muons for studying the elemental composition of tissue *via* muonic x rays. The x-ray spectra from several types of tissue were used to determine the amounts of carbon, nitrogen, and oxygen present. These determinations agree with the results of more conventional chemical analysis. Muonic x rays offer a noninvasive technique for determining the amounts of the more abundant elements in selected regions of the body.

1976





Nuclear Instruments and Methods 187 (1981) 563–568
North-Holland Publishing Company

APPLICATION OF MUONIC X-RAY TECHNIQUES TO THE ELEMENTAL ANALYSIS OF ARCHEOLOGICAL OBJECTS

E. KÖHLER, R. BERGMANN, H. DANIEL, P. EHRHART and F.J. HARTMANN

Physics Department, Technische Universität München, D 8046 Garching, Germany

PSI

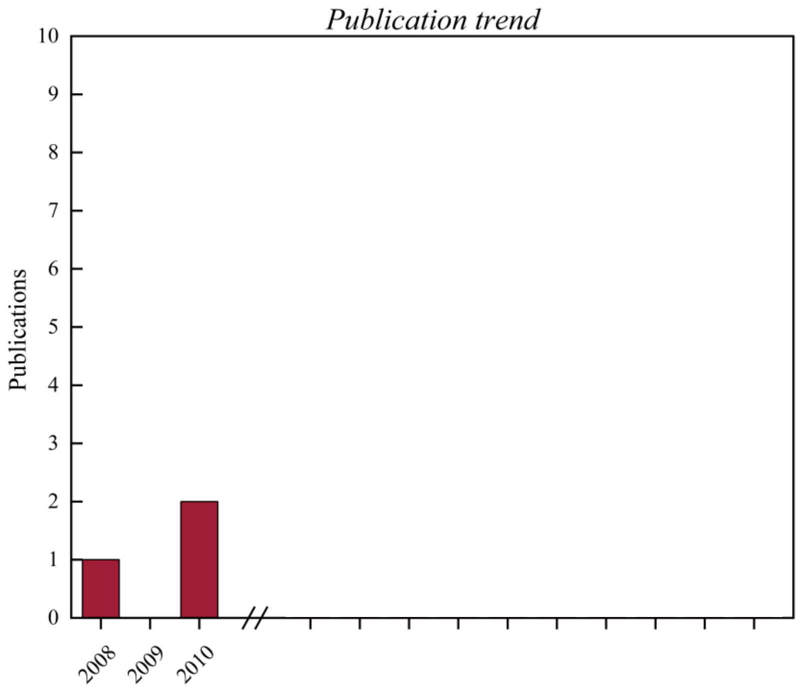
Received 27 February 1981

The use of muonic X-rays as a tool for elemental analysis is described. Bulk analyses of modern and archeological fired clay samples are presented. Comparison with chemical and neutron activation analyses supplies standards for future measurements. Scanning techniques are also described.

1981

MIXE: Muon Induced X-ray Emission – Modern resurgence

- Pioneering measurements in the 1970s and 1980s
  - either *low intensity* or *very large momentum bites*
  - → very long measurements or very limited depth resolution
- Budding resurgence in the late 2000s and early 2010s
  - *high intensity* but *pulsed generation*
  - → low statistics to avoid high pileup
- Thanks to Alex' foresight of the future relevance of MIXE
  - realization that SmuS is uniquely suited for these studies
  - → continous source with *high rate* at *low momentum bites*



MIXE publications in cultural heritage
Source: M. Cataldo, PhD thesis, 2024

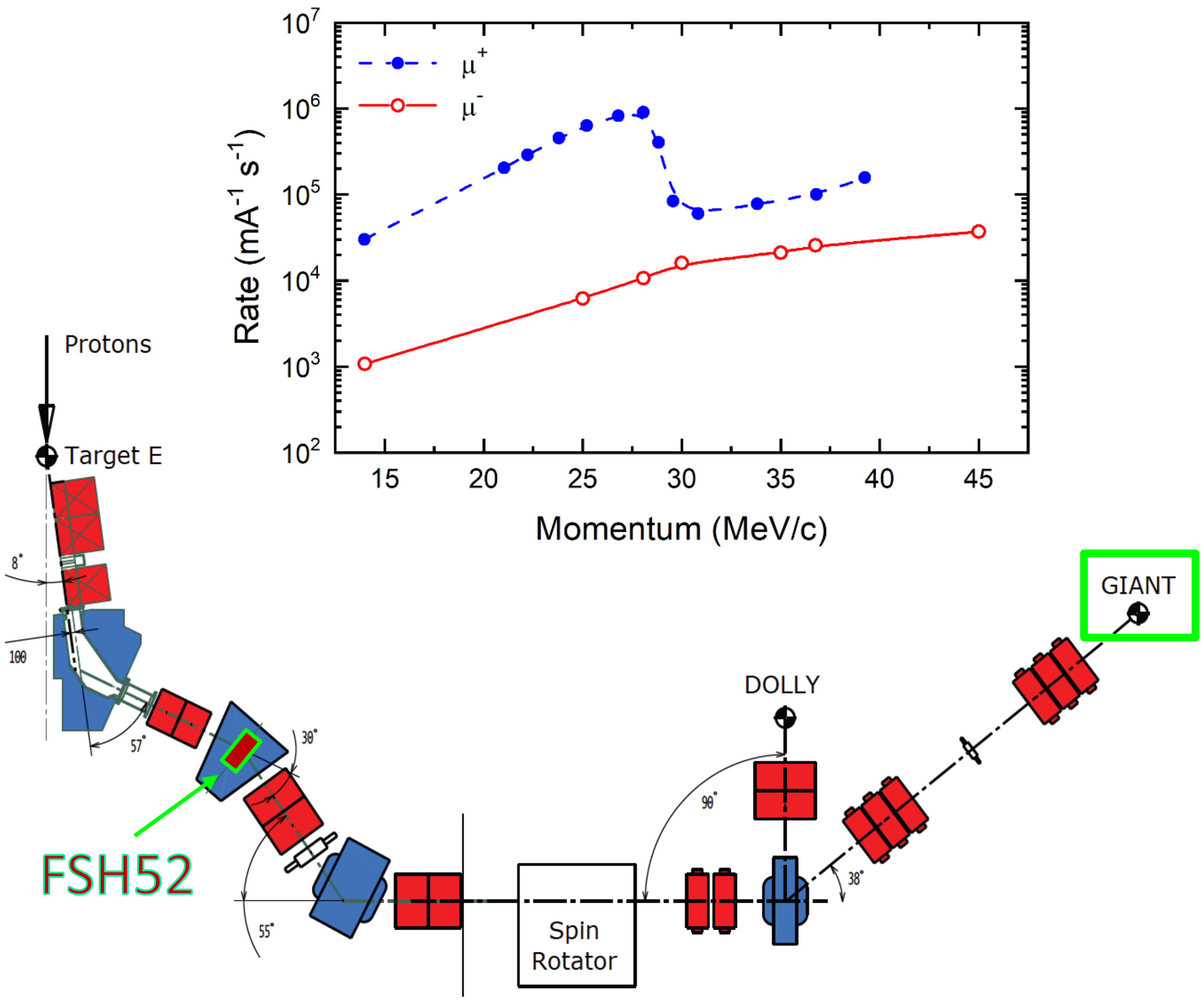
2018 & 2019: First successful pilot studies together with muX collaboration

2020: Interdisciplinary SNF Sinergia (1.5 MCHF): **DEEPμ** ; PIs: AA, MP, AR

2023: SDSC SAMURAI (PI: AA); SNF Bilateral Japan (PI: TP)

Part II
The Instrument:
GIANT

GIANT: GermanIum Array for Non-destructive Testing – πE1



High intensity π beamline at target E

- production of "cloud" π^- and decay to μ^-
- typical μ^- momenta: **15-60 MeV/c**

  implantation depths: ~10um to ~cm

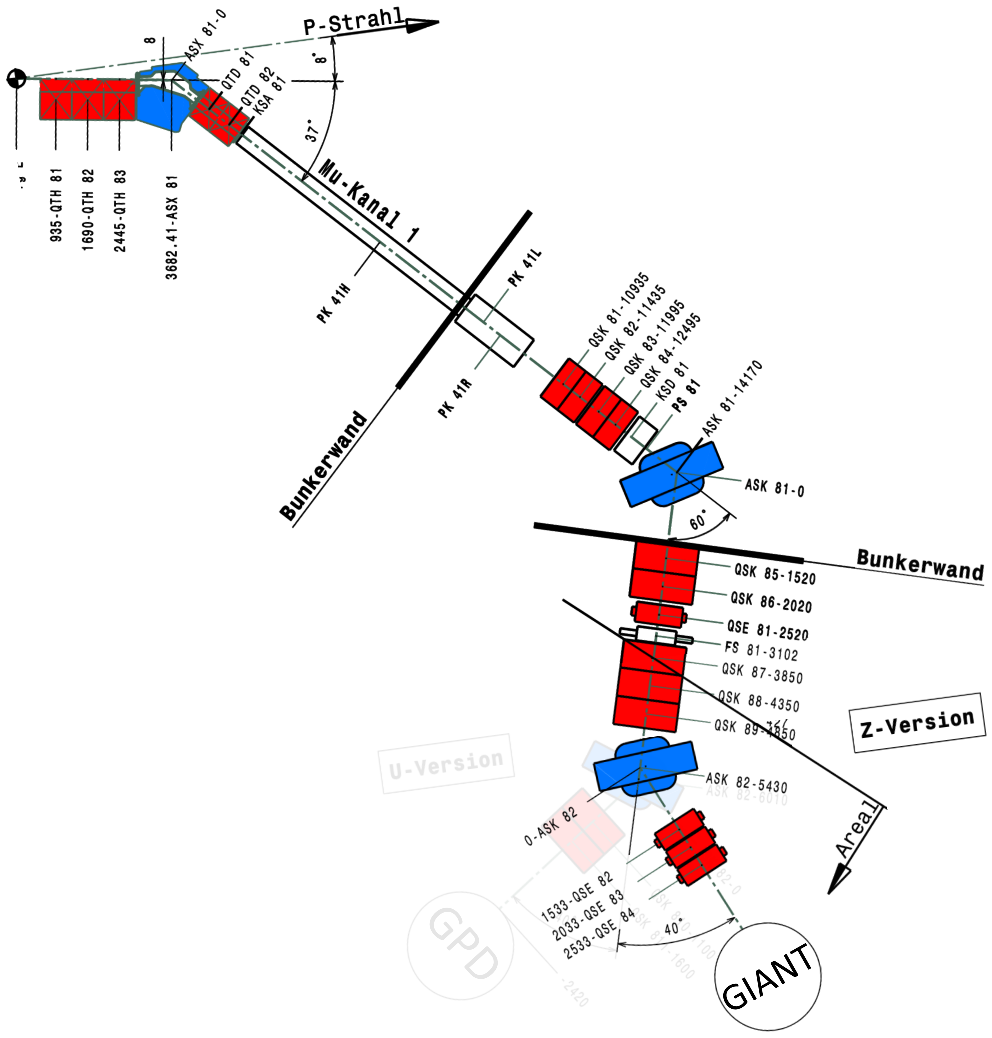
Rates from 10^3 up to 10^5 μ^-/s on target

- close to **ideal sampling rate** (cont.!)
- *For the "average" sample, we collect enough statistics within ~1 hour*

All past MIXE campaigns hosted at πE1.2

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

GIANT: GermanIum Array for Non-destructive Testing – μE1



High intensity μ beamline at target E

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

  implantation depths: ~mm to ~10cm

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

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

Potential future host beam-line for MIXE

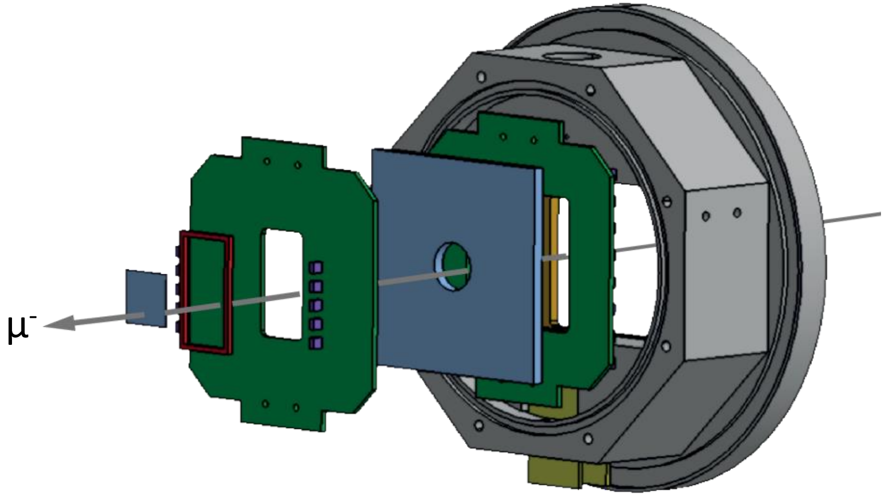
- could be installed during 2027/2028 shutdown
- high momentum / high rate studies (degrader)
- shorter πE1 campaign for low mom. / high res.

Warm-bore solenoid would allow for very wide momentum range → many new possibilities!

GIANT: GermanIum Array for Non-destructive Testing – Tagging

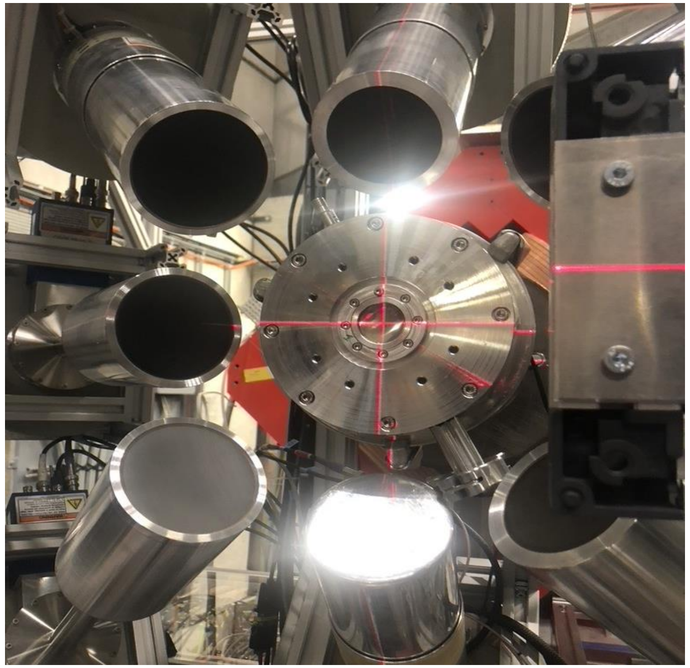
Tagging Detector (developed for muX experiment)

- BC-400 plastic scintillators (Counter and Veto)
- SiPM readout using custom electronics
- reduces uncorrelated background
- allows for discrimination of nuclear capture events



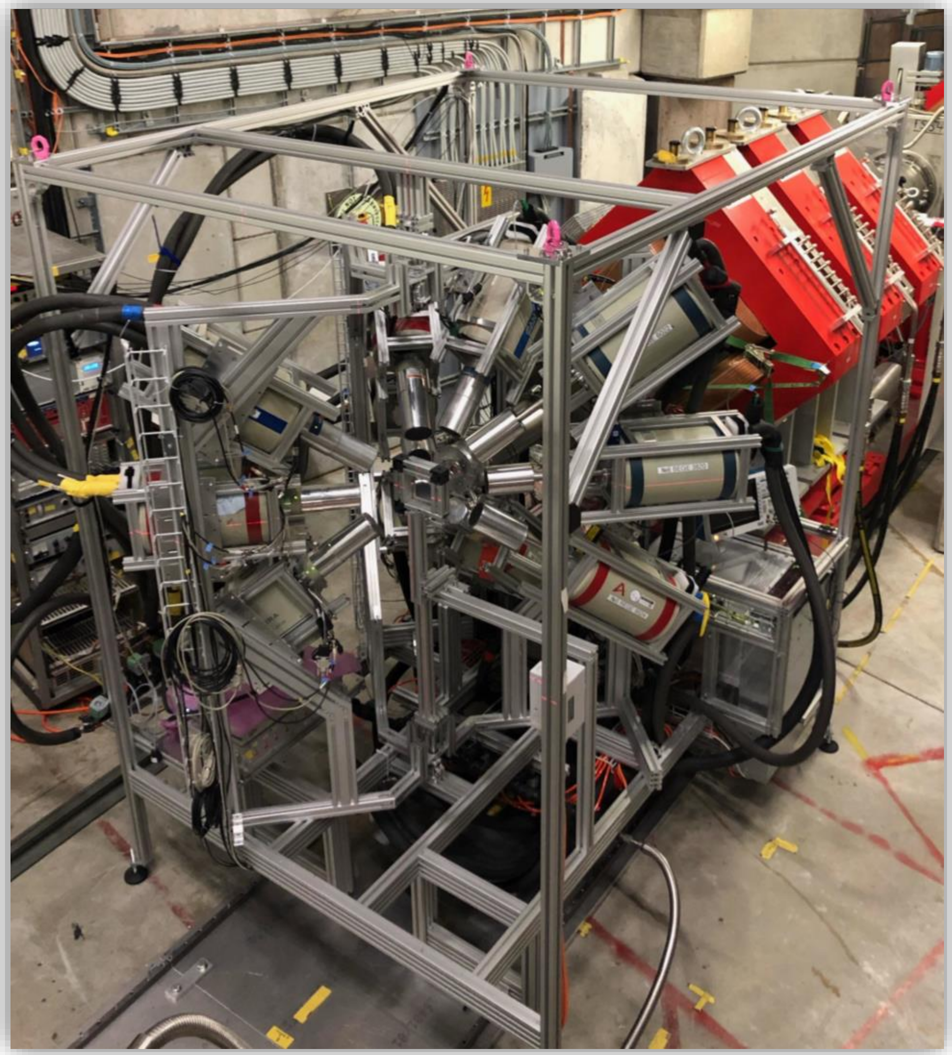
200 µm
µ-counter

Ø 18mm
active Veto



- Beam Port
  - 10µm titanium foil window
  - beam extraction to sample in air
    - approx. 10 cm distance
  - system of collimators available for sample spot measurements

GIANT: GermanIum Array for Non-destructive Testing



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 LTP (muX, ReferenceRadii, …)

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
  (up to ~10% time per sample)

Part III
Research Highlight: The Arrowhead

Arrowhead: Sample and Reception

PSI

Bernisches Historisches Museum
Musée d'Histoire de Berne

UNI FREIBURG

NATUR HISTORI SCHES MUSEUM BERN

u^b UNIVERSITÄT BERN

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]

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

CNN

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

Meteoriteneisen kam vo…

Bielersee soll aus Meteorit sei…

steht fest: Das Material dafür ist kosmischen Ursprungs. Eine Spur führt zu einem Meteoriteneinschlag in Estland.

GESCHICHTE UND KULTUR

Archaeologists Find 'Alien Metal' In A Bronze Age Arrowhead

indiatimes

Vor etwa 2.900 Jahren fertigten Menschen in der heutigen Sch… Untersuchungen kosmisches Material. Nun suchen Forschende…

THE JERUSALEM POST

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*

„Heavenly Iron”

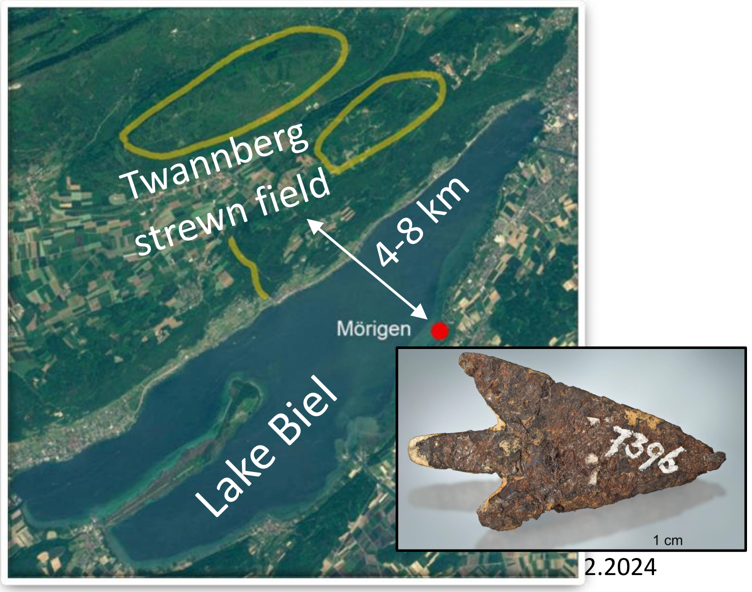
- Iron from **meteorite** fragments
- **Production** of *jewelry, weapons, tools, ...*
- Very *rare* and *valuable* **trade goods**

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)
- Made from a large **iron meteorite** (*>2 tons*)



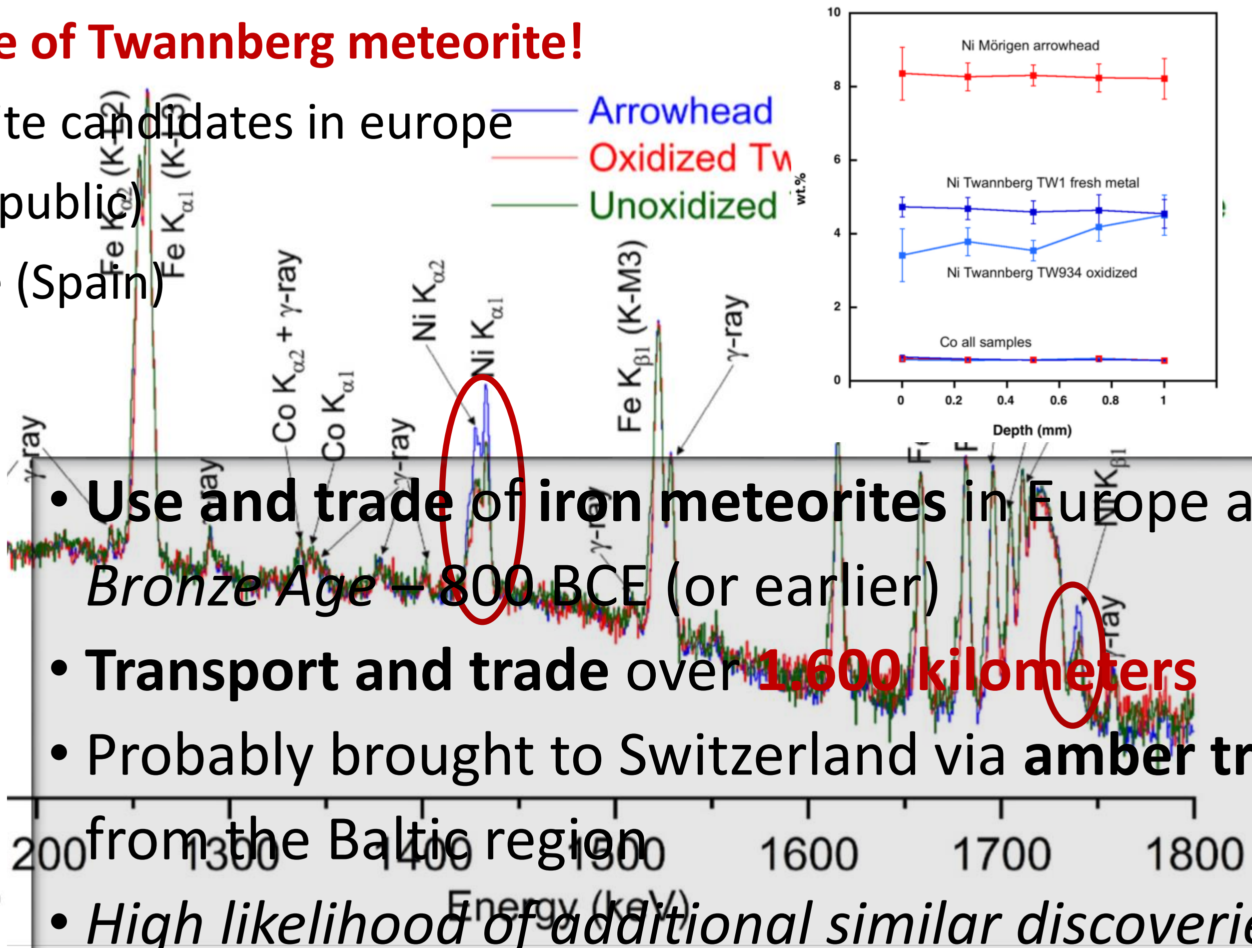
Arrowhead: The surprise!

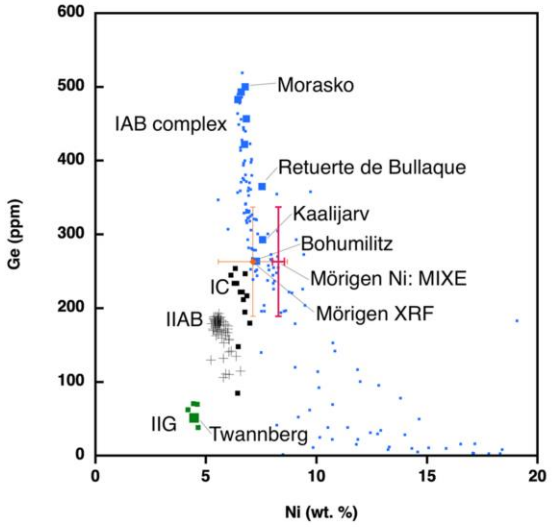
MIXE Study: Comparison to **Twannberg** reference metorite for *Iron*, *Nickel*, and *Cobalt*

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

Only 3 possible meteorite candidates in europe

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





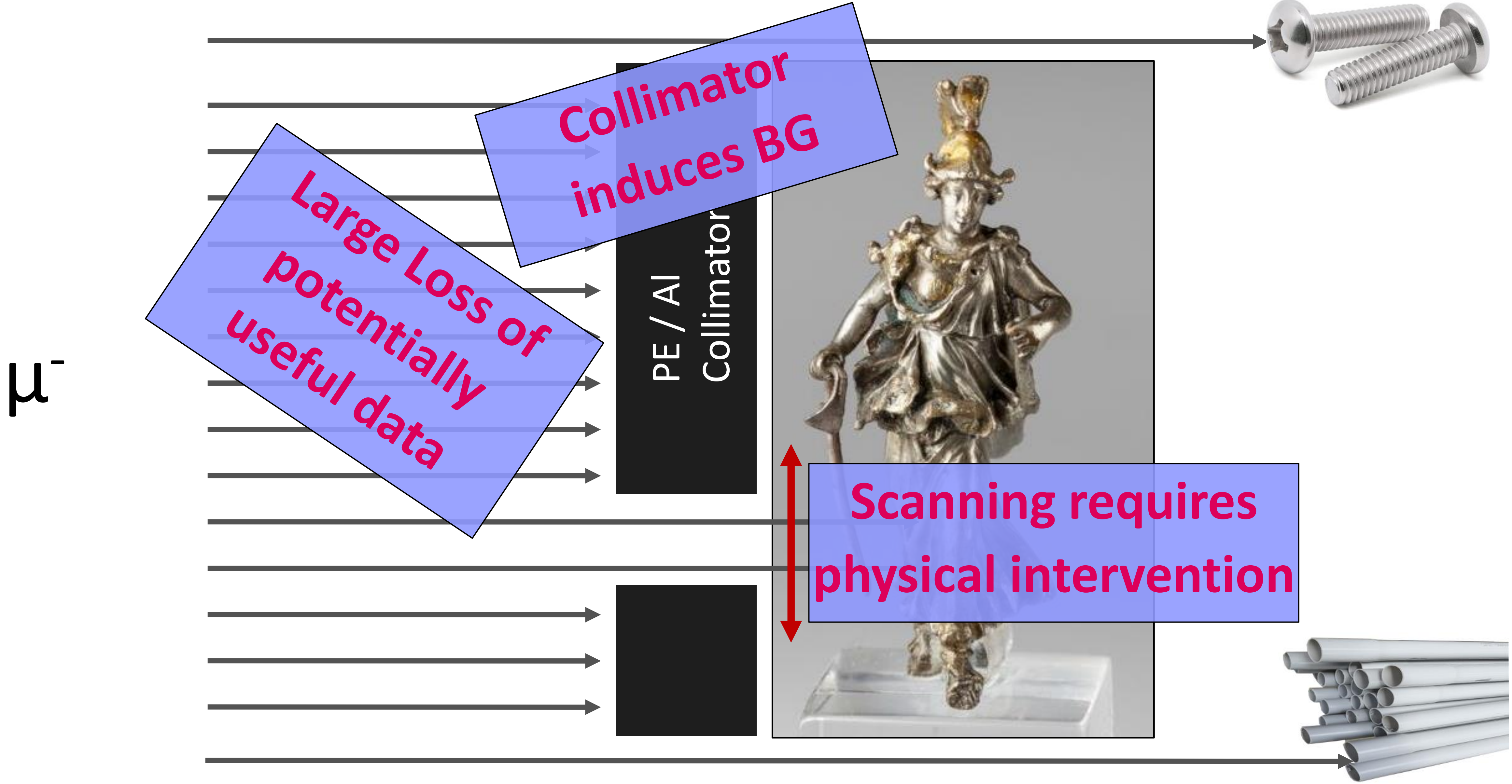
- **Use and trade of iron meteorites** in Europe as early as the *Bronze Age* – 800 BCE (or earlier)
- **Transport and trade** over **1.600 kilometers**
- Probably brought to Switzerland via **amber trade routes** from the Baltic region
- *High likelihood of additional similar discoveries!*

Part IV
The Future:
MIXE-T

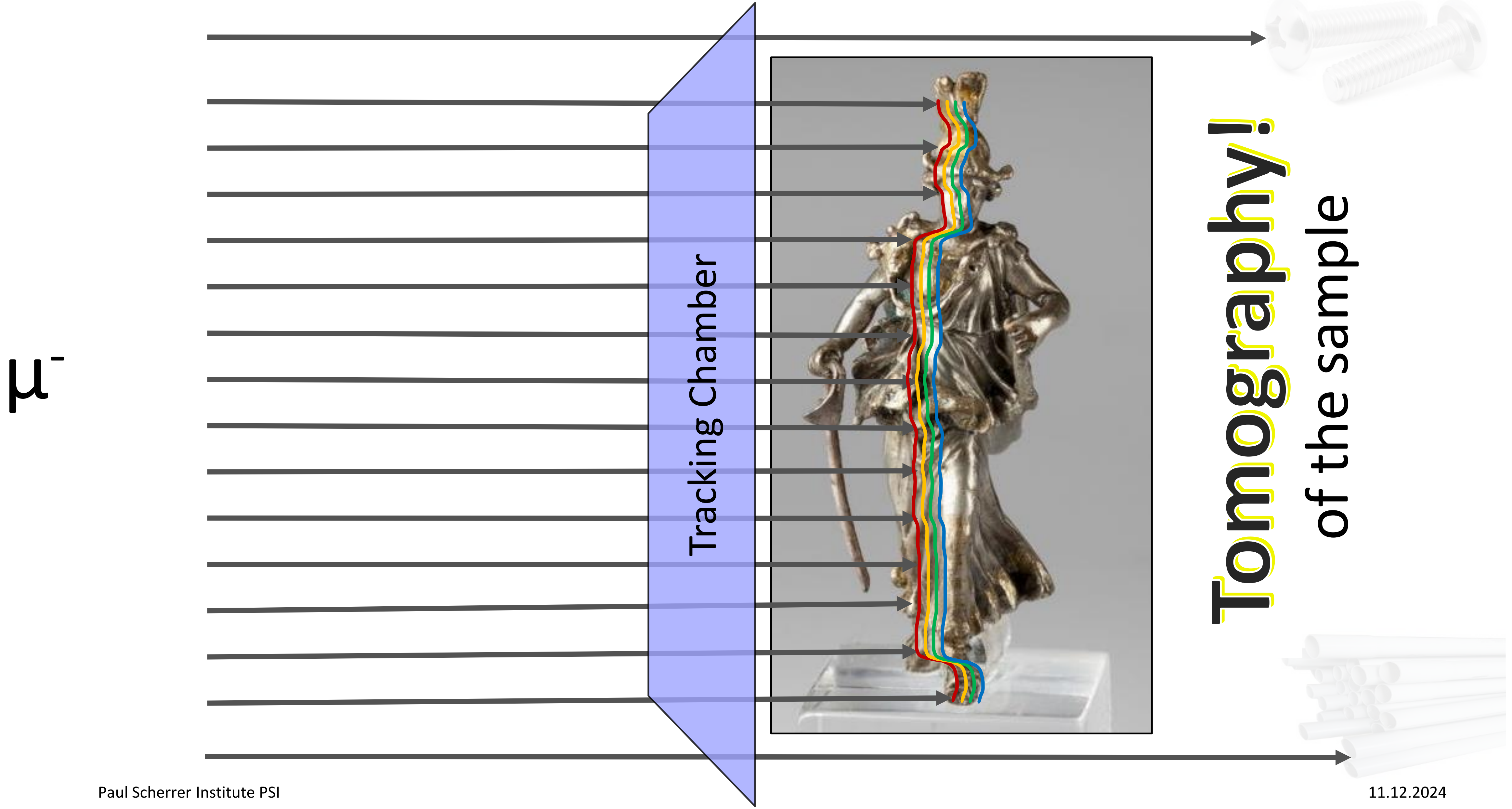
MIXE-T: Motivation

μ^-

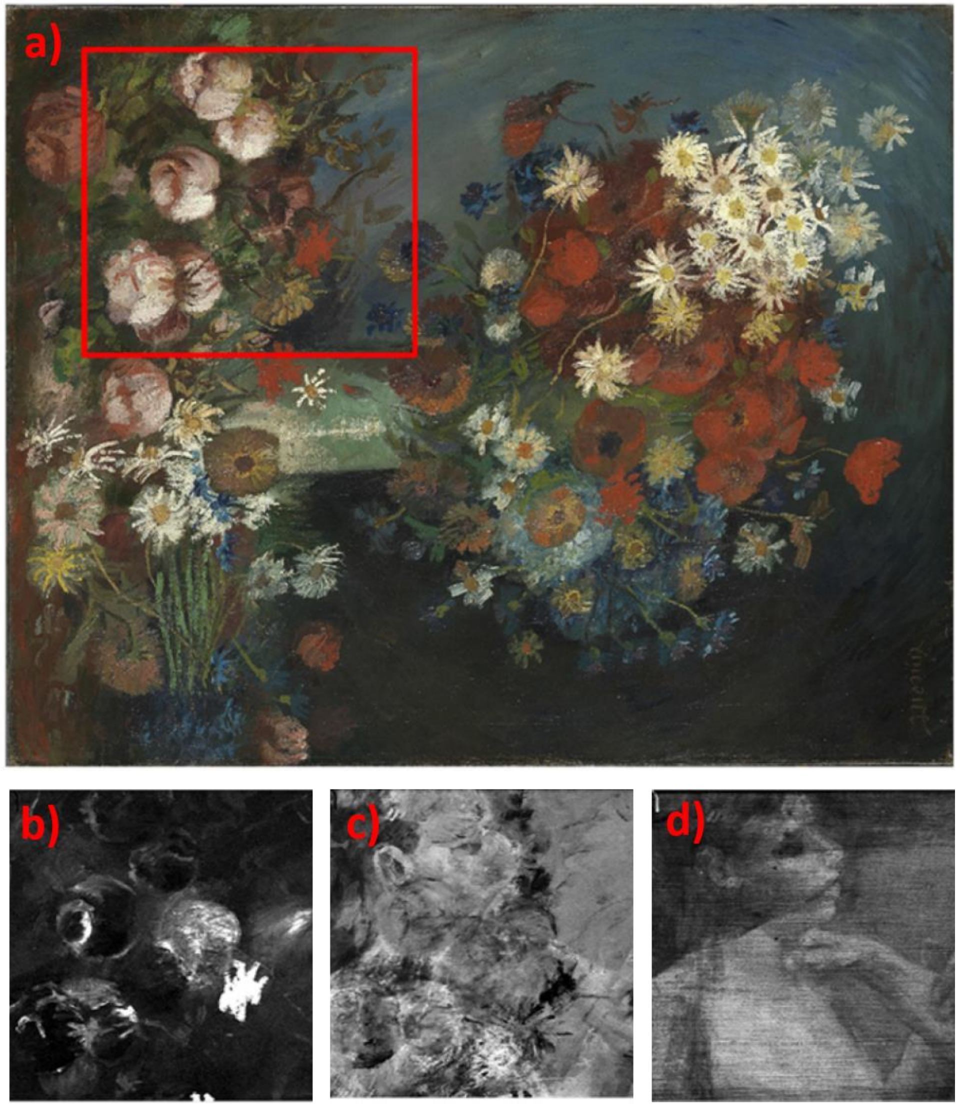
MIXE-T: Motivation



MIXE-T: Motivation



MIXE-T(omography): Completely new capabilties



Study using XRF

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.

b) Hg fluorescence signal of the area in the red box, flowers are visible.

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

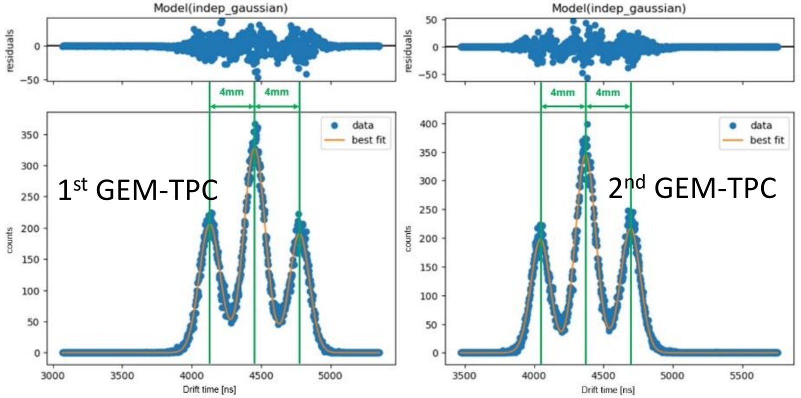
d) Zn fluorescence measured from the back of the painting with less absorption, revealing the human face as part of an overpainted wrestling scene..

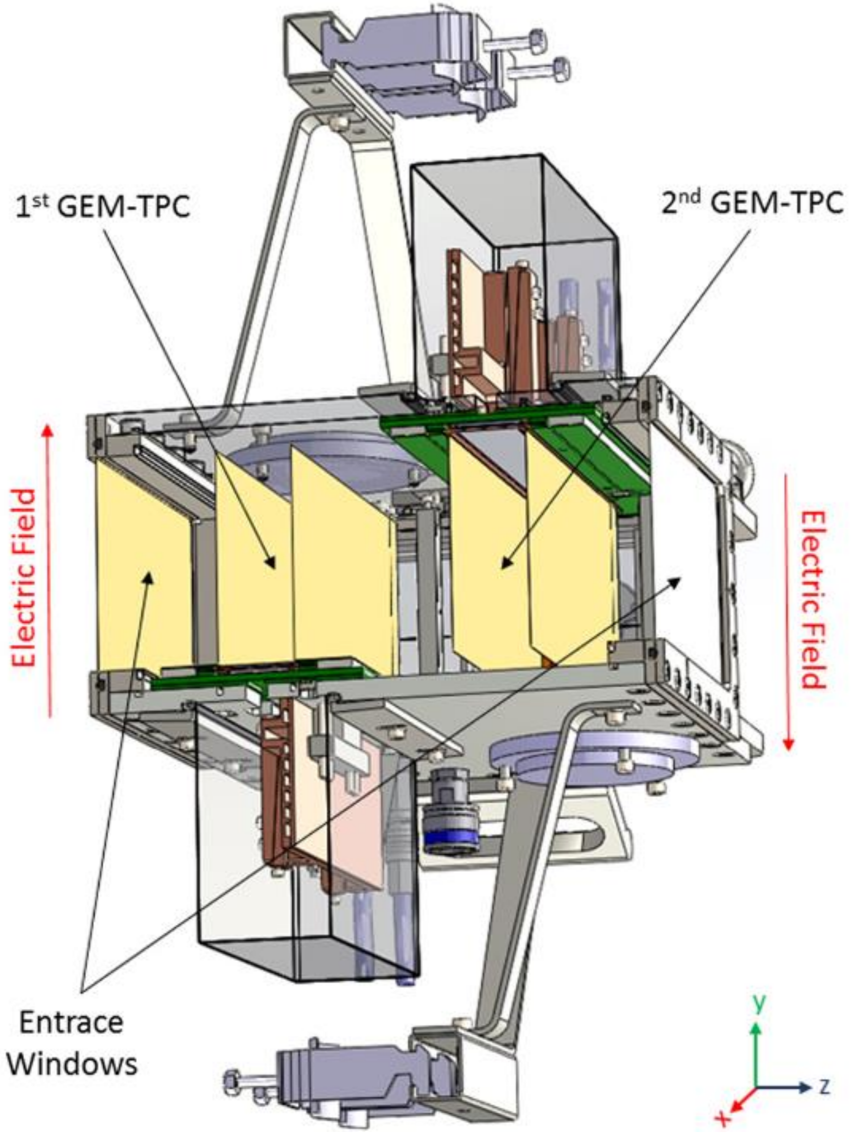
M. Alfeld and J. A. C. Broekaert, Spectrochimica Acta Part B 88, 211- 230 (2013)

MIXE could image whole canvas over full thickness with much higher depth-resolution!

MIXE-T(omography): Tracking the incoming muon

- Adaptation of existing tracking detector prototype
  - Collaboration with HIP & DRD1, CERN
  - Designed for heavy ion tracking @ GSI/FAIR
- Twin Time-Projection-Chamber (Active Area ~20x10 cm²)
  - 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!





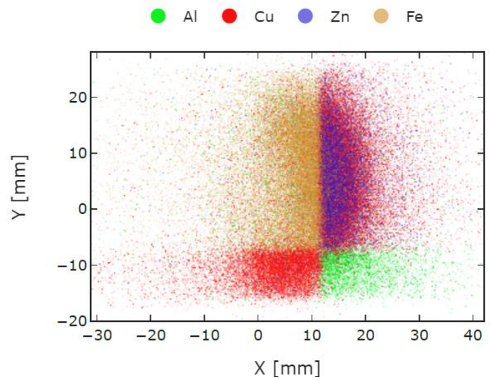
MIXE-T(omography): Milestones

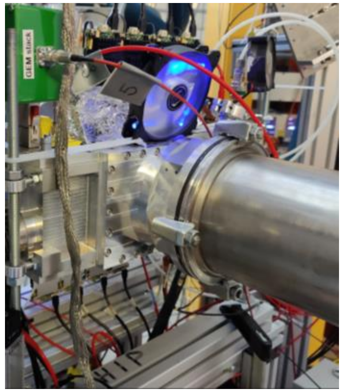
PRELIMINARY

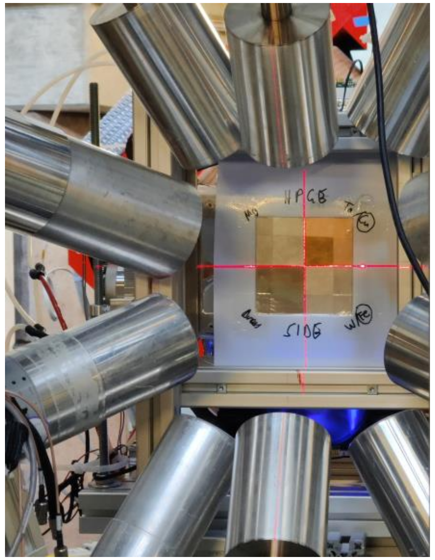
- Successful beam tests of adapted detector using GeV muons at CERN/SPS-H4 in May 2023
- Successful proof-of-concept elemental imaging using 60 MeV/c muons at PieE1 in Jun 2023
- First universal elemental imaging/tomography using 50-65 MeV/c muons at PiE1 in Sep 2023 (~1 mm res)

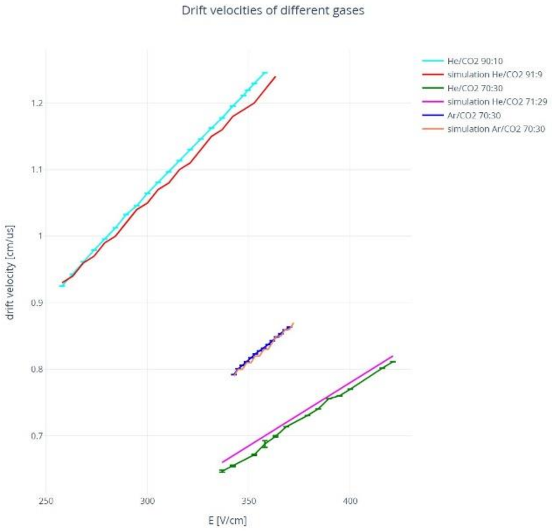
However, resolution/momenta limited due to multiple scattering in high-density gas (Ar/CO2 75:25)

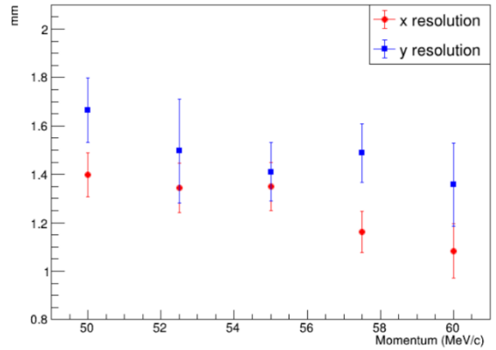
- First operation of a GEM-TPC detector using low density gas mixture (He/CO2 90:10) at CERN/SPS-H4 in Apr 2024 – *found performance to be excellent*
- Tracker with He/CO2 used during full Jun 2024 MIXE campaign – analysis ongoing, so far promising











Thank you for your attention!

一期一会

„Ichi-go ichi-e“

one lifetime,
one meeting