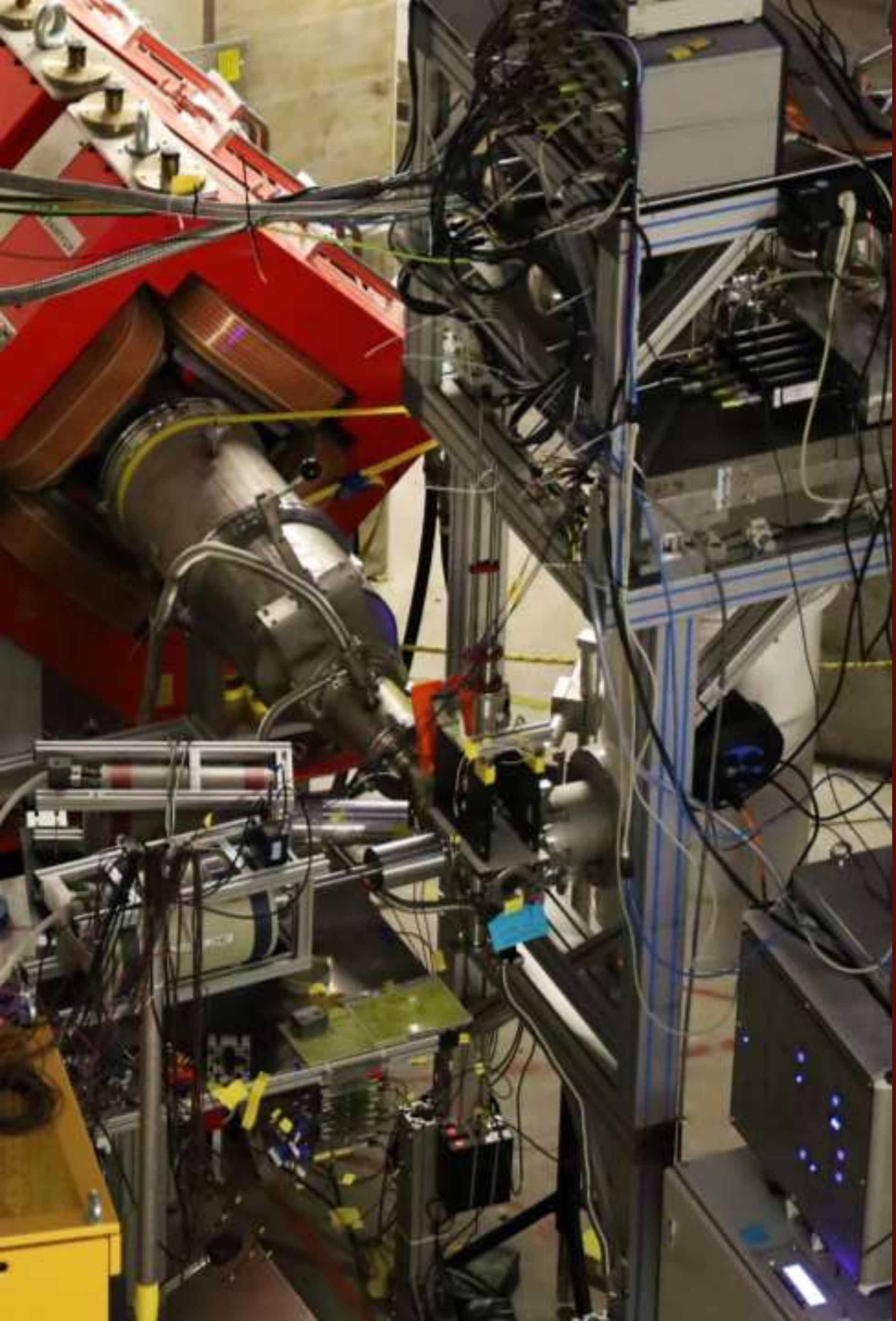


MMC Arrays to Study X-ray Transitions in Muonic Atoms

New Perspectives in the Charge Radii Determination for Light Nuclei, Trento 2025

Andreas Abeln, Christian Enss, Andreas Fleischmann, Loredana Gastaldo, Daniel Hengstler, Daniel Kreuzberger, Andreas Reifenberger, Daniel Unger, and Peter Wiedemann

— for the QUARTET Collaboration

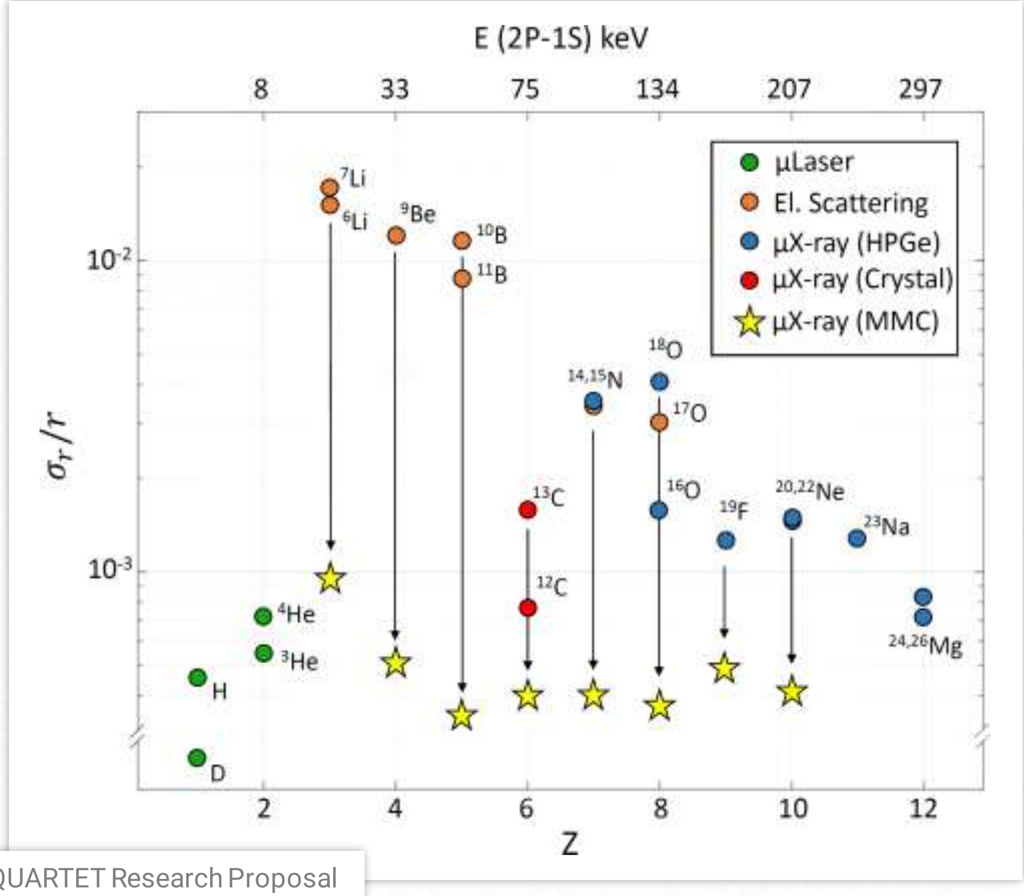
Our Goal

Precise measurement of absolute nuclear charge radii

- test of nuclear theory
- essential input parameter for QED tests
- search for physics beyond the Standard Model

Large accuracy gap for $2 < Z < 11$

→ Improve knowledge on stable nuclei from ^{6}Li to ^{22}Ne



QUARTET Research Proposal

The QUARTET Collaboration

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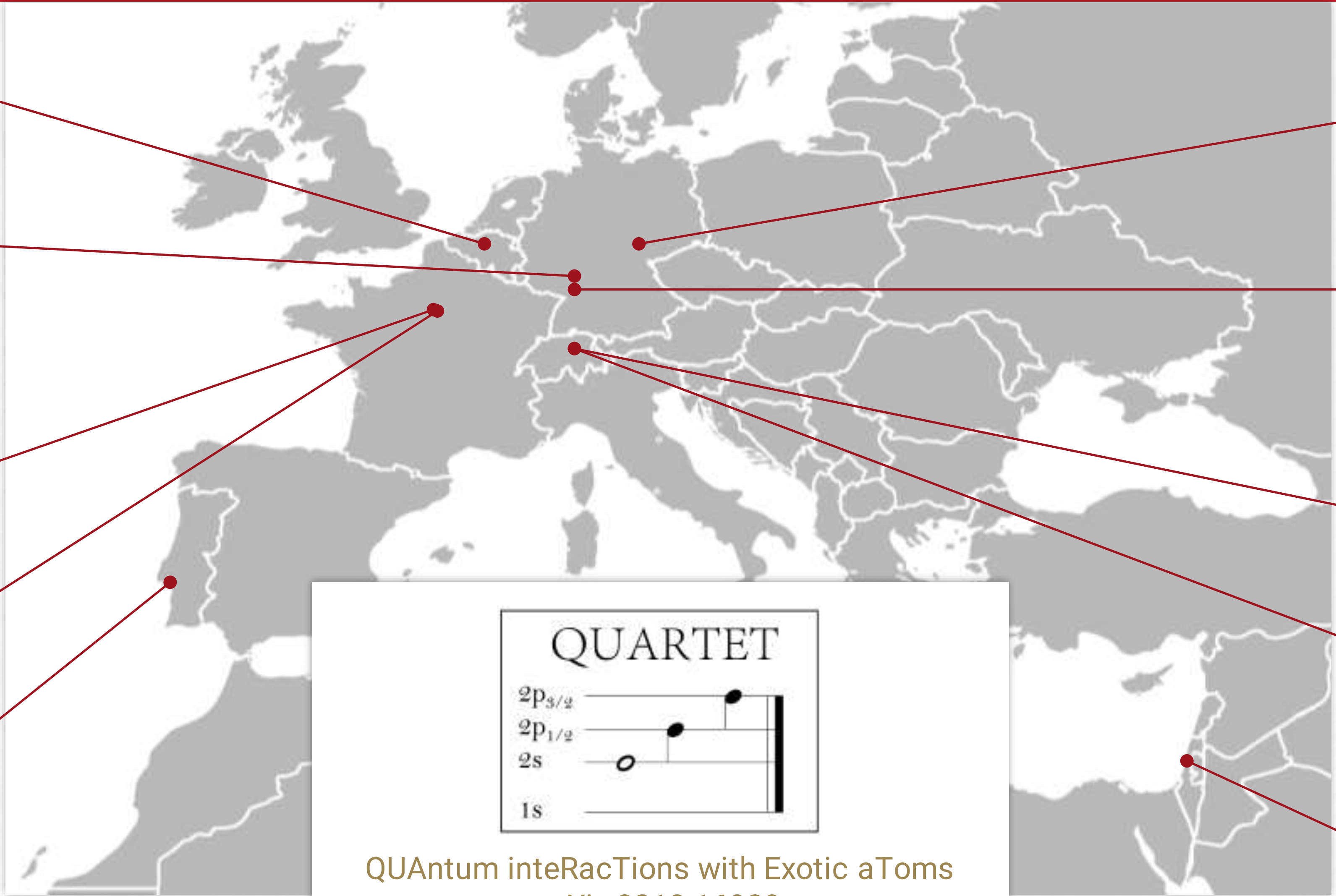
Physique quantique et applications

université PARIS-SACLAY

NOVA UNIVERSIDADE NOVA DE LISBOA



HELMHOLTZ
Helmholtz-Institut Jena

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PAUL SCHERRER INSTITUT PSI

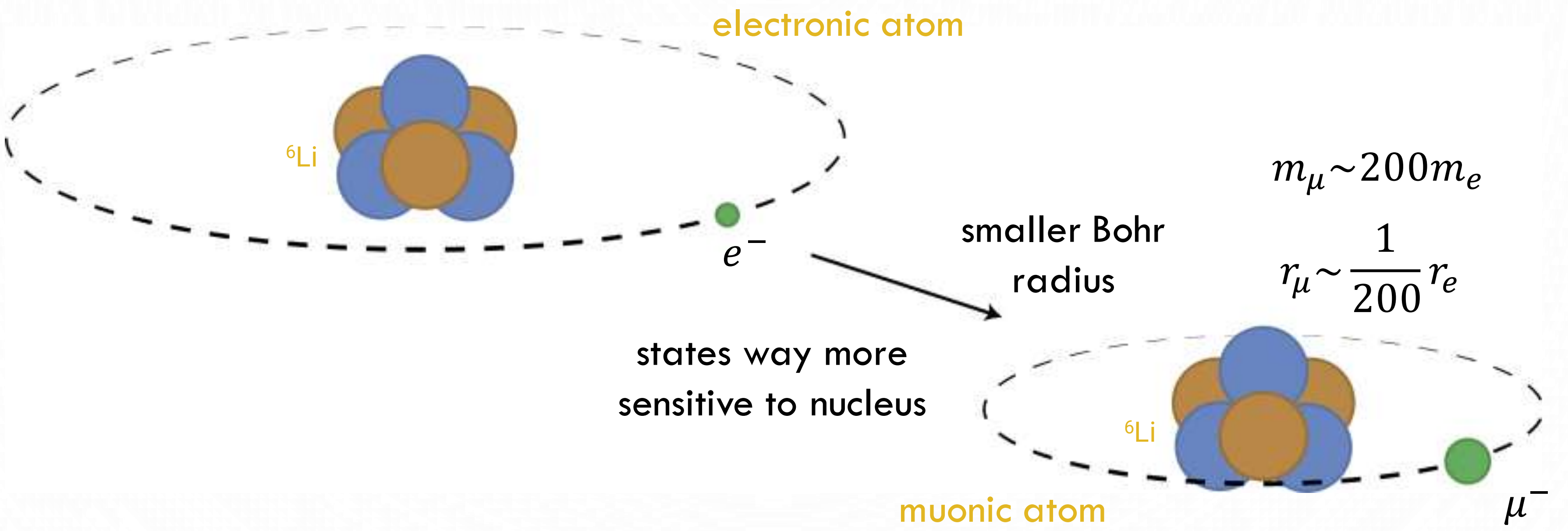
ETH zürich

TECHNION Israel Institute of Technology

QUARTET

QUAntum inteRacTions with Exotic aToms
arXiv:2210.16929
Physics 2024, 6(1), 206-215
arXiv:2311.12014

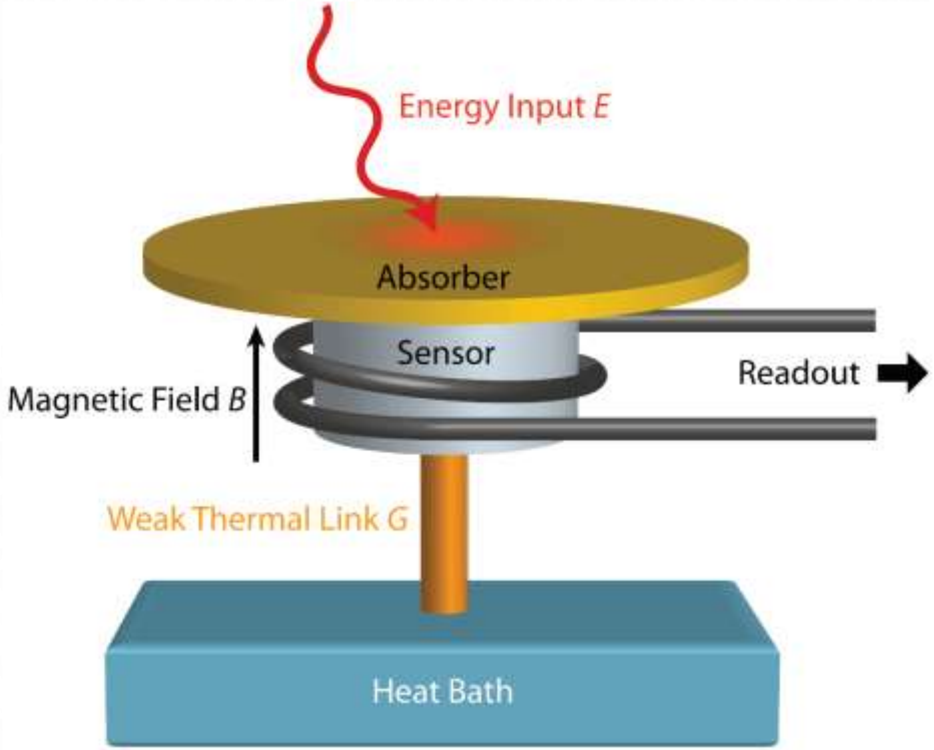
Transitions in Muonic Atoms



- Muonic atoms: low-*n* states very sensitive to nuclear charge radius
- Transition energies $E \propto mZ^2$ shifted to range of 10keV – 200keV

→ broadband X-ray detectors with very high resolving power and precise energy calibration

Working Principle of MMCs



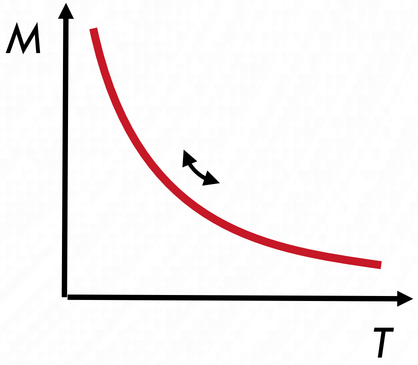
Operated at ≈20 mK

Metallic magnetic calorimeters (MMCs)

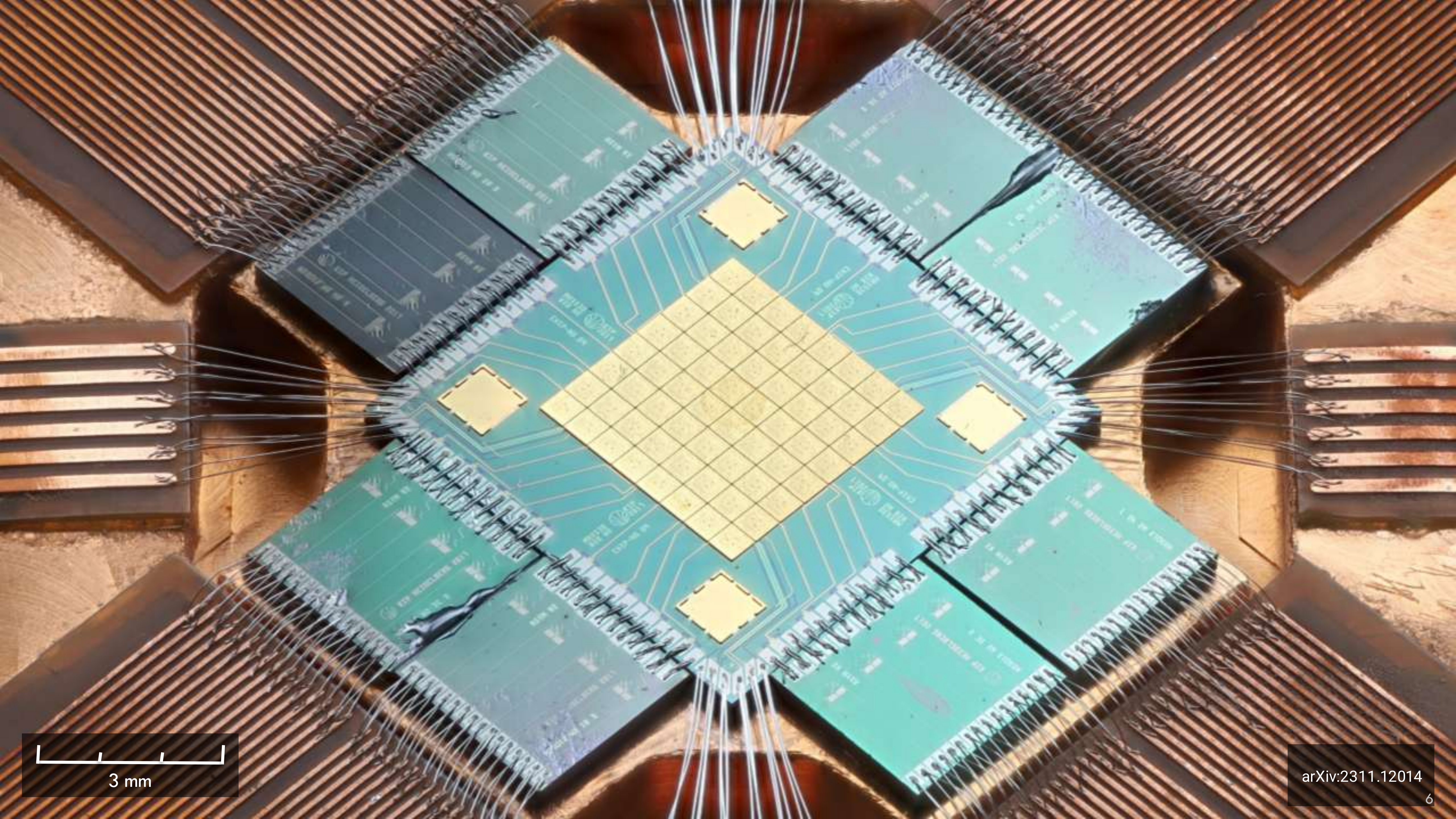
- Paramagnetic temperature sensor Au:Er or Ag:Er
- Simple thermodyamic system
- No dissipation in the sensor

Fundamental energy resolution

$$\Delta E_{\mathrm{FWHM}} \simeq 2{,}36\sqrt{4k_{\mathrm{B}}C_{\mathrm{Abs}}T^2}\sqrt{2}\left(\frac{\tau_0}{\tau_1}\right)^{1/4}$$

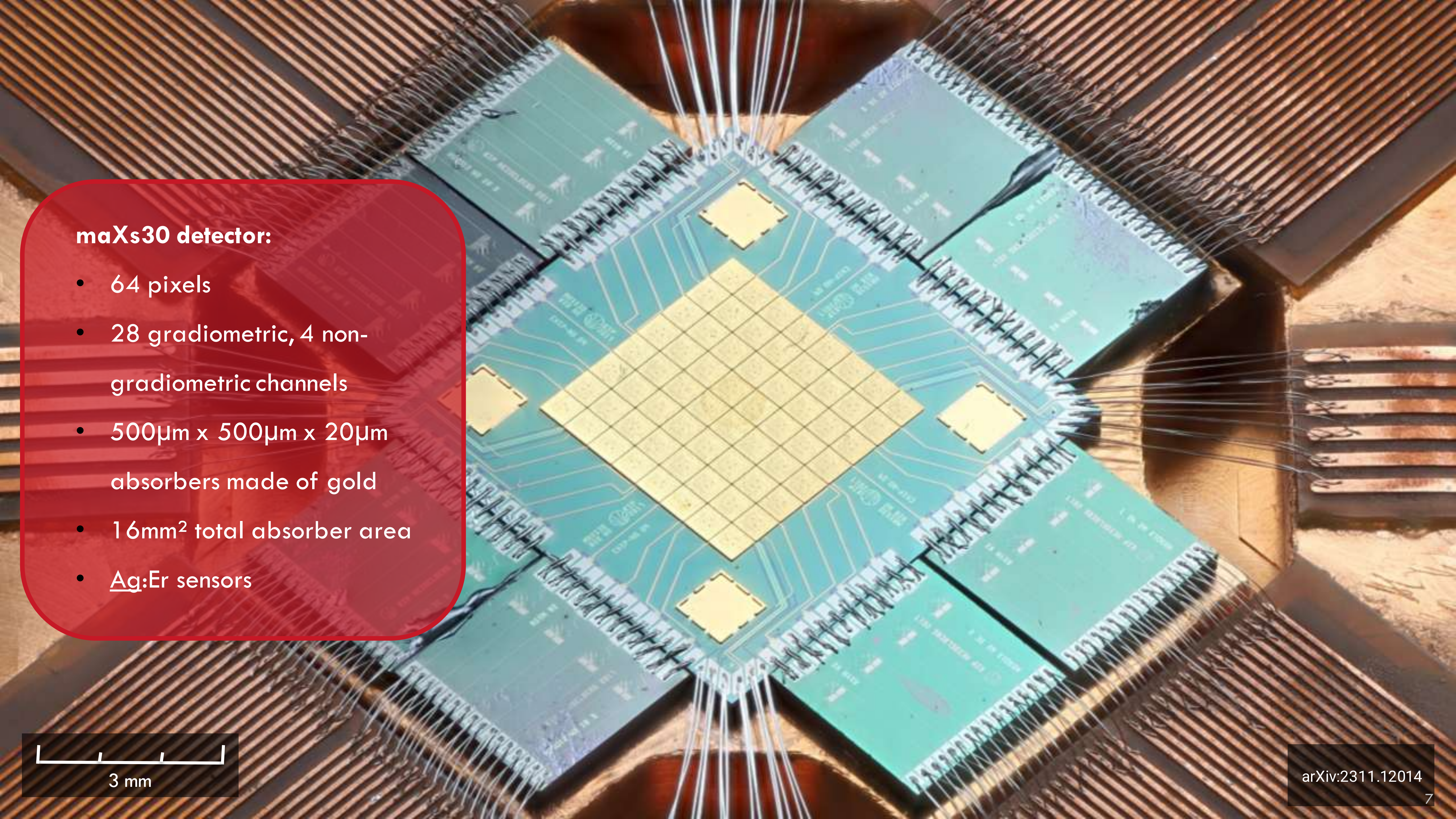


Ideal for broadband high-resolution X-ray spectroscopy


3 mm
arXiv:2311.12014

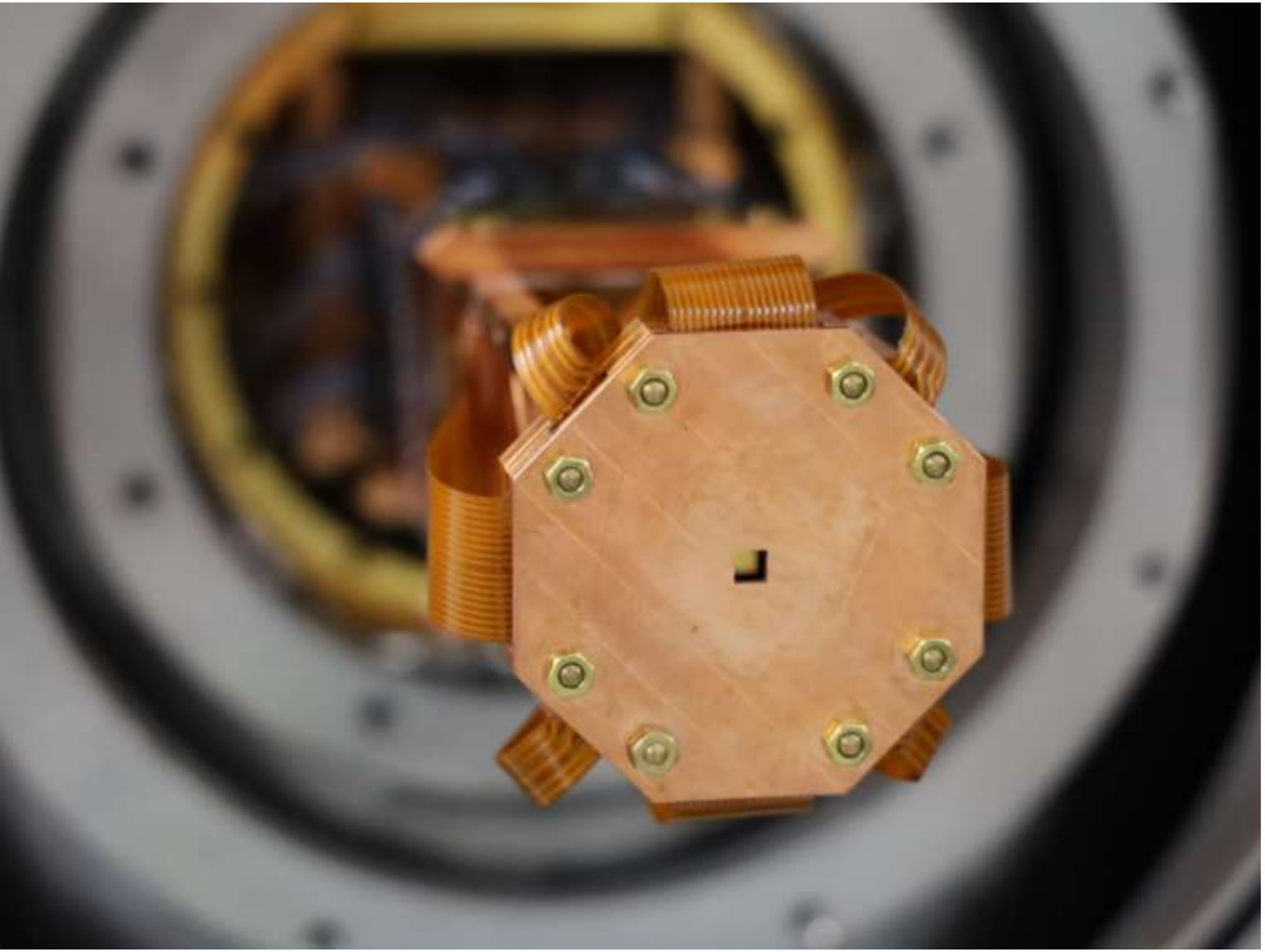
maXs30 detector:

- 64 pixels
- 28 gradiometric, 4 non-gradiometric channels
- 500µm x 500µm x 20µm absorbers made of gold
- 16mm² total absorber area
- Ag:Er sensors

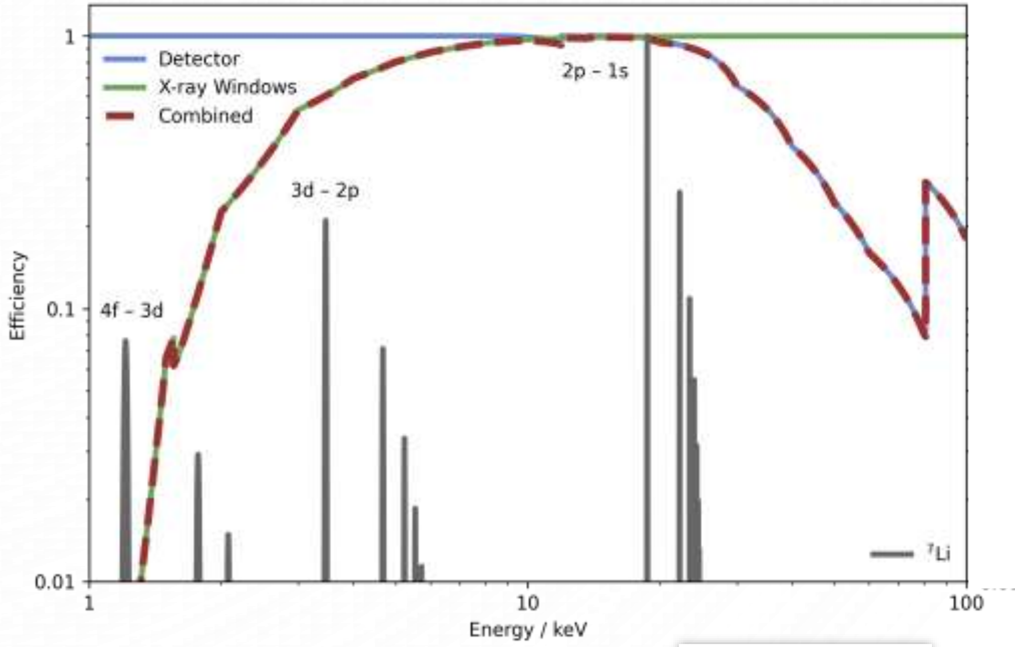


arXiv:2311.12014

Detector Setup

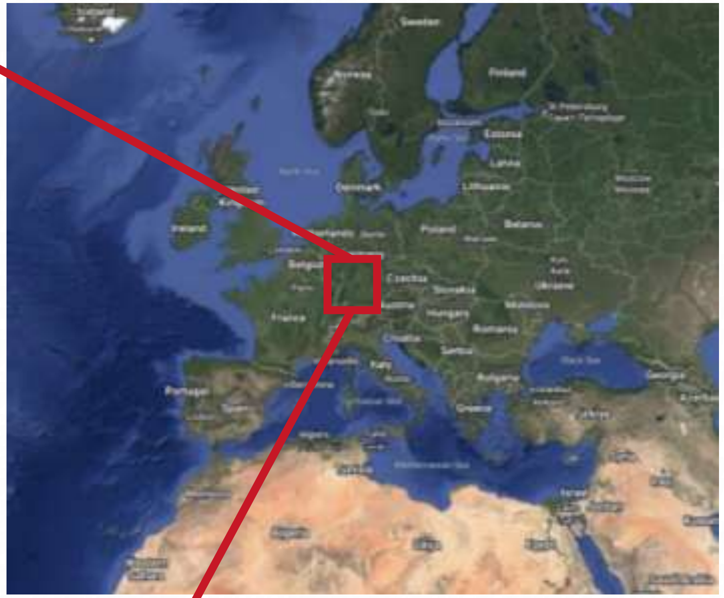


- operated in a dry dilution refrigerator
- sidearm with X-ray windows
- maXs30 detector suited for 2p-1s transition of light muonic atoms



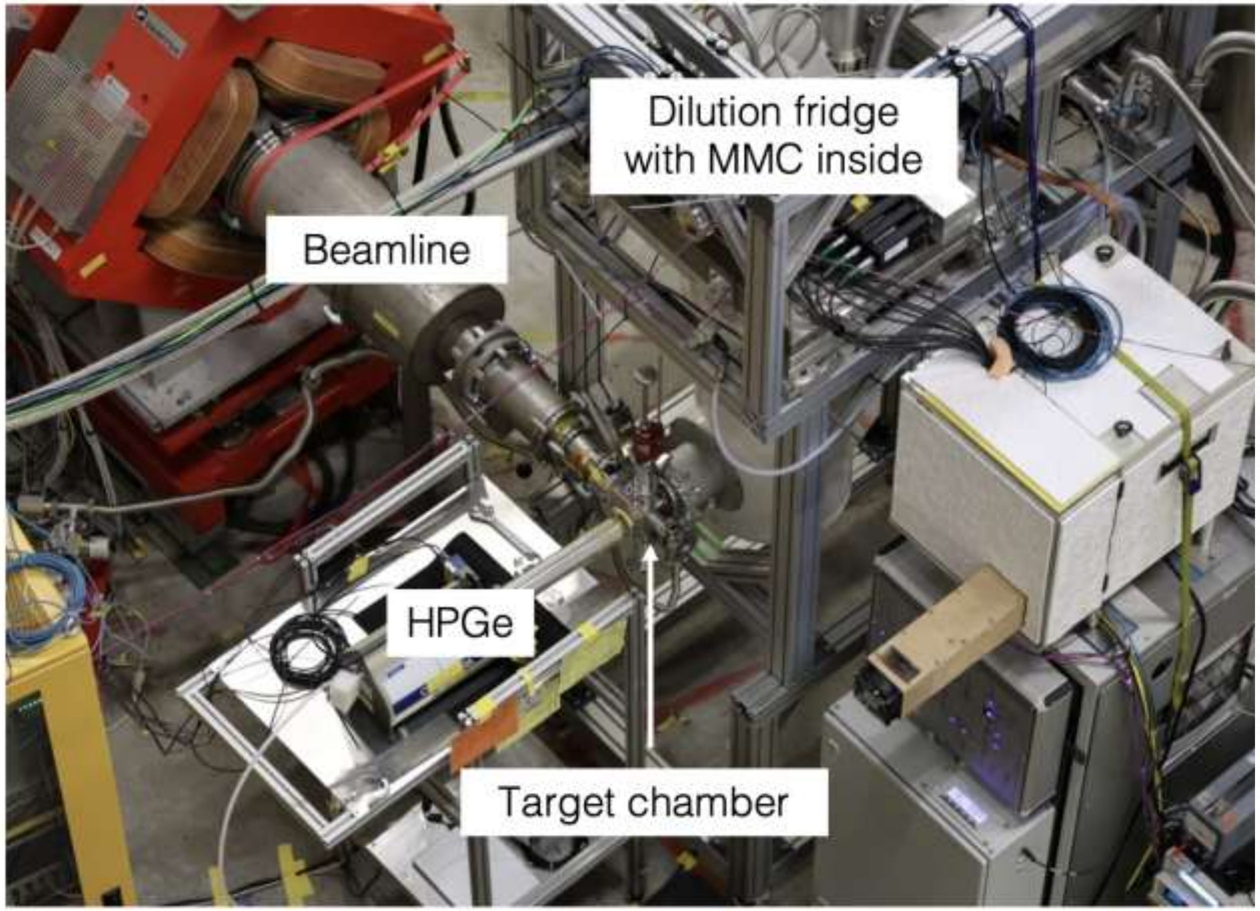
arXiv:2311.12014

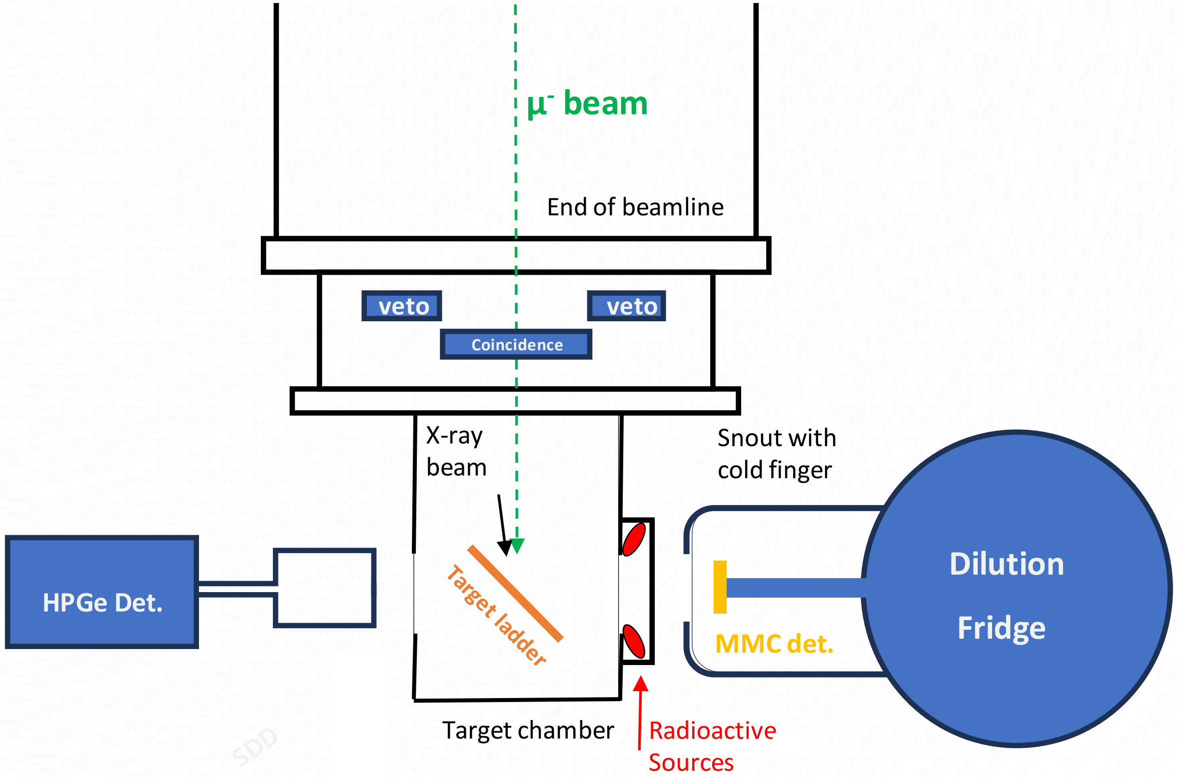
Beamtime at Paul-Scherrer Institute



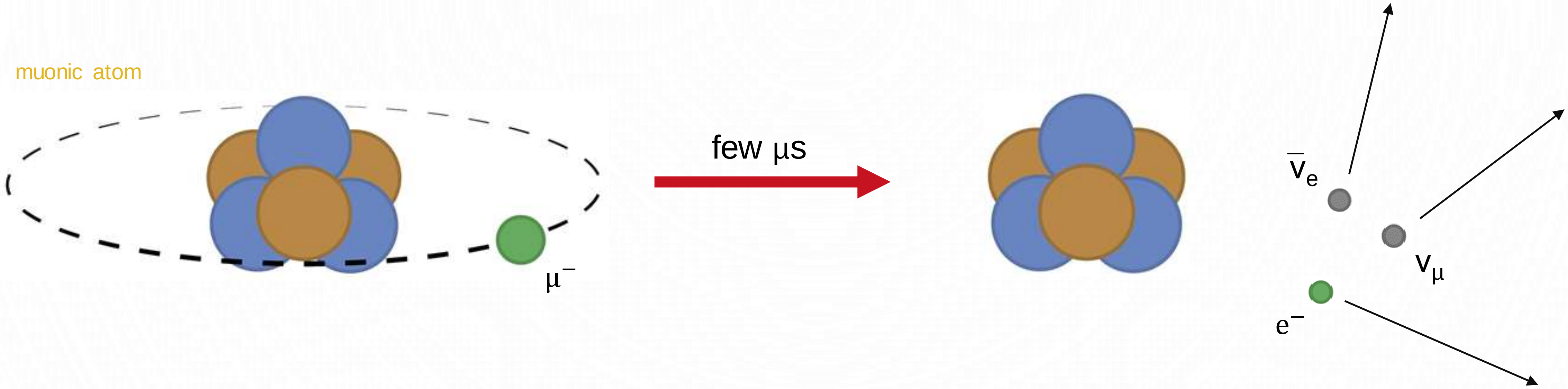
- Experiment takes place at muon beam line of High-Intensity Proton Accelerator at PSI
- Typical beamtime 10 days
- Assembly to mK ~ 36 h
- Assembly to “first light” ~ 48 h

Setup at Paul-Scherrer Institute



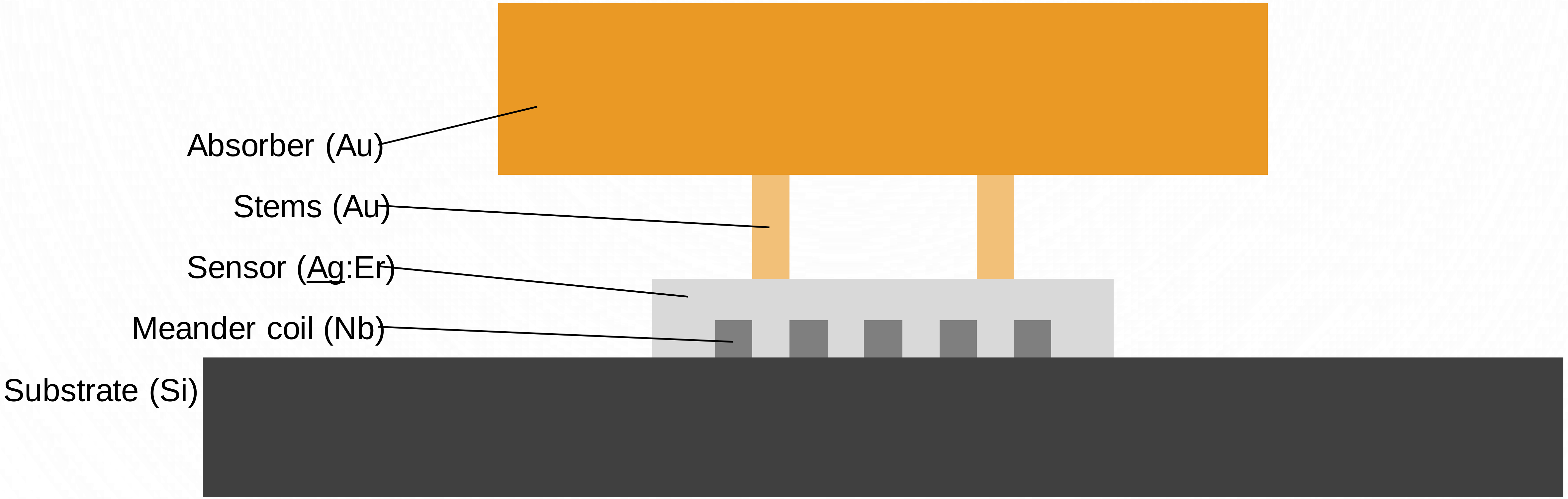


Michel electrons



- Muons decay with $\tau_{1/2}$=1.5μs
- Energy of daugther electron (Michel electron) up to ~50MeV
- Michel electrons will penetrate detector system and deposit ~150keV in detector chip

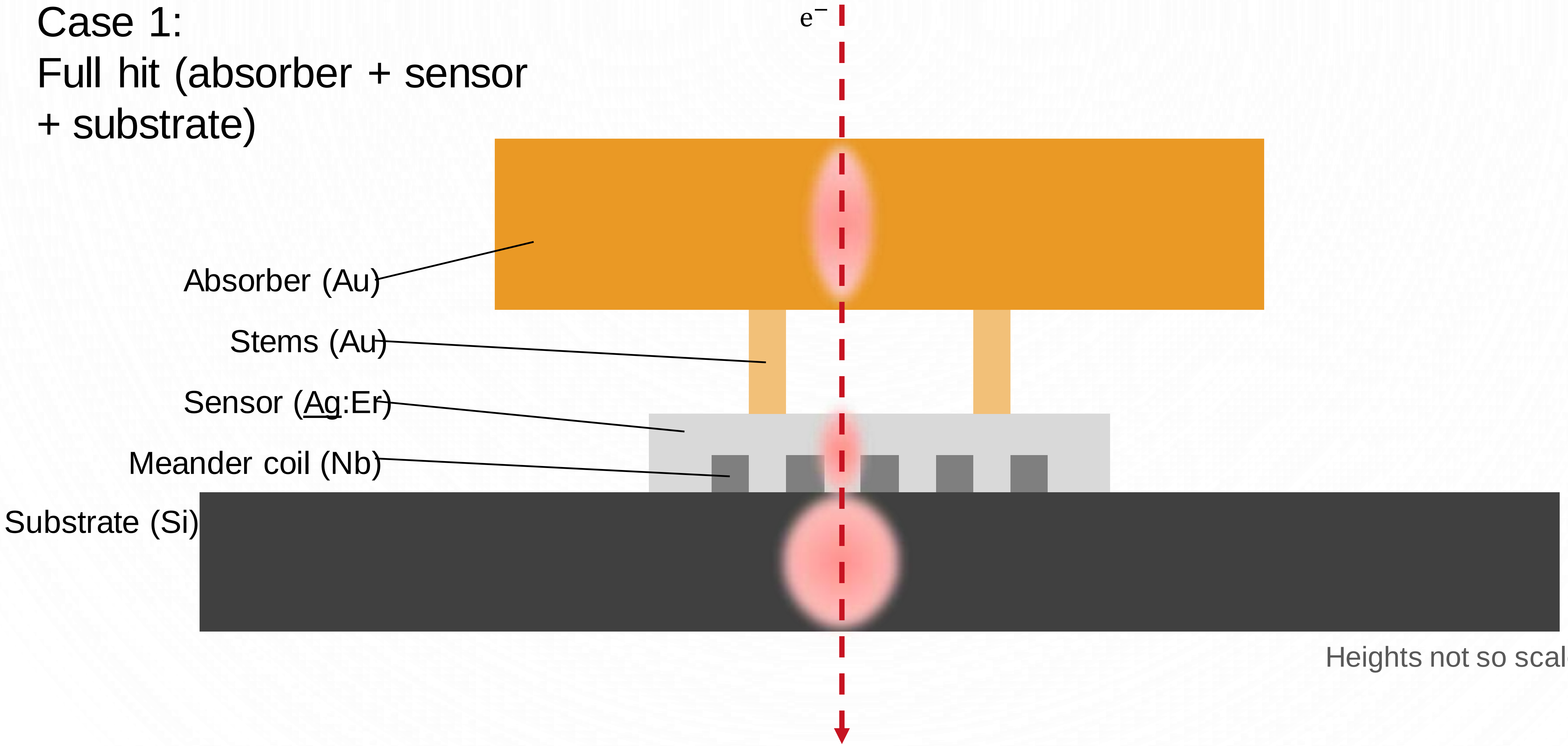
Michel electrons: event types



Heights not so scale

Michel electrons: event types

Case 1:
Full hit (absorber + sensor + substrate)



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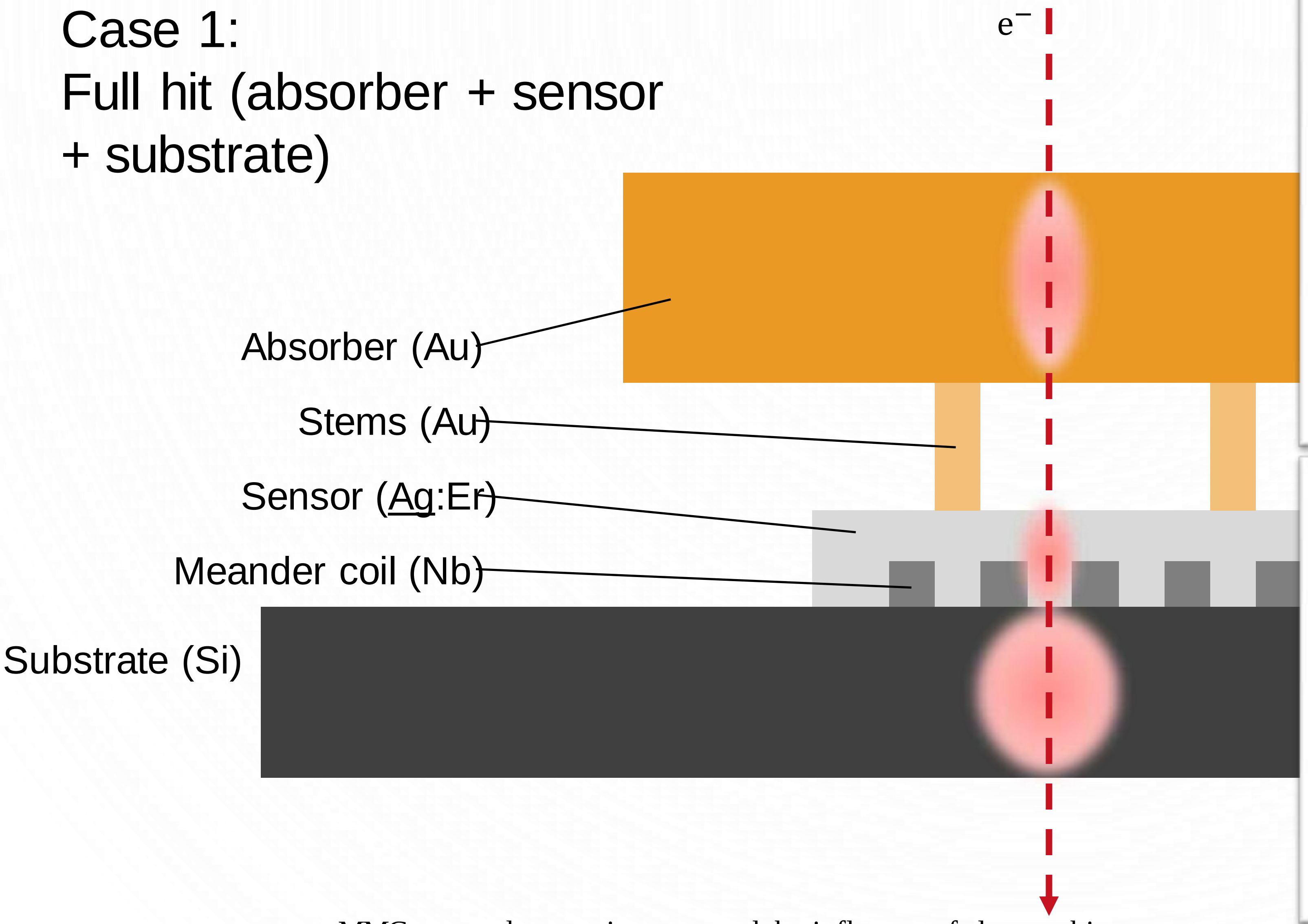
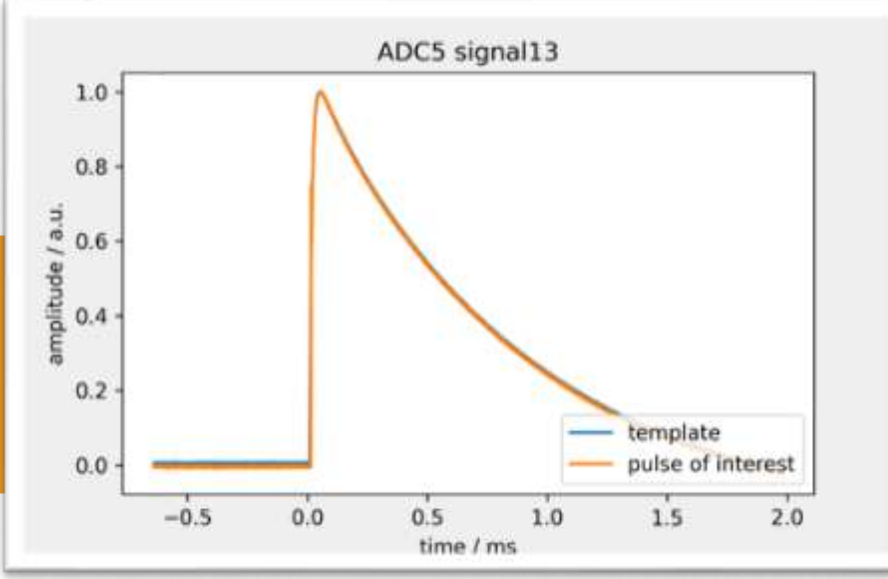
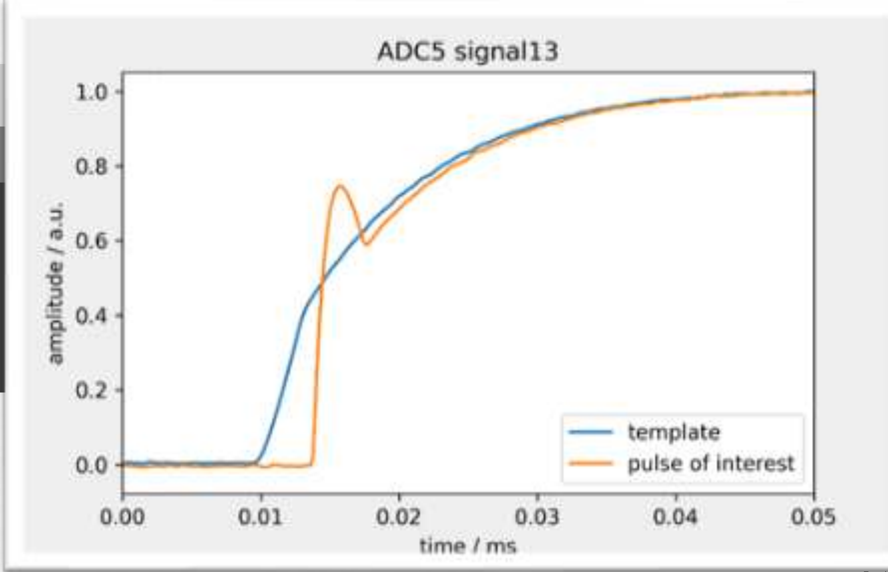
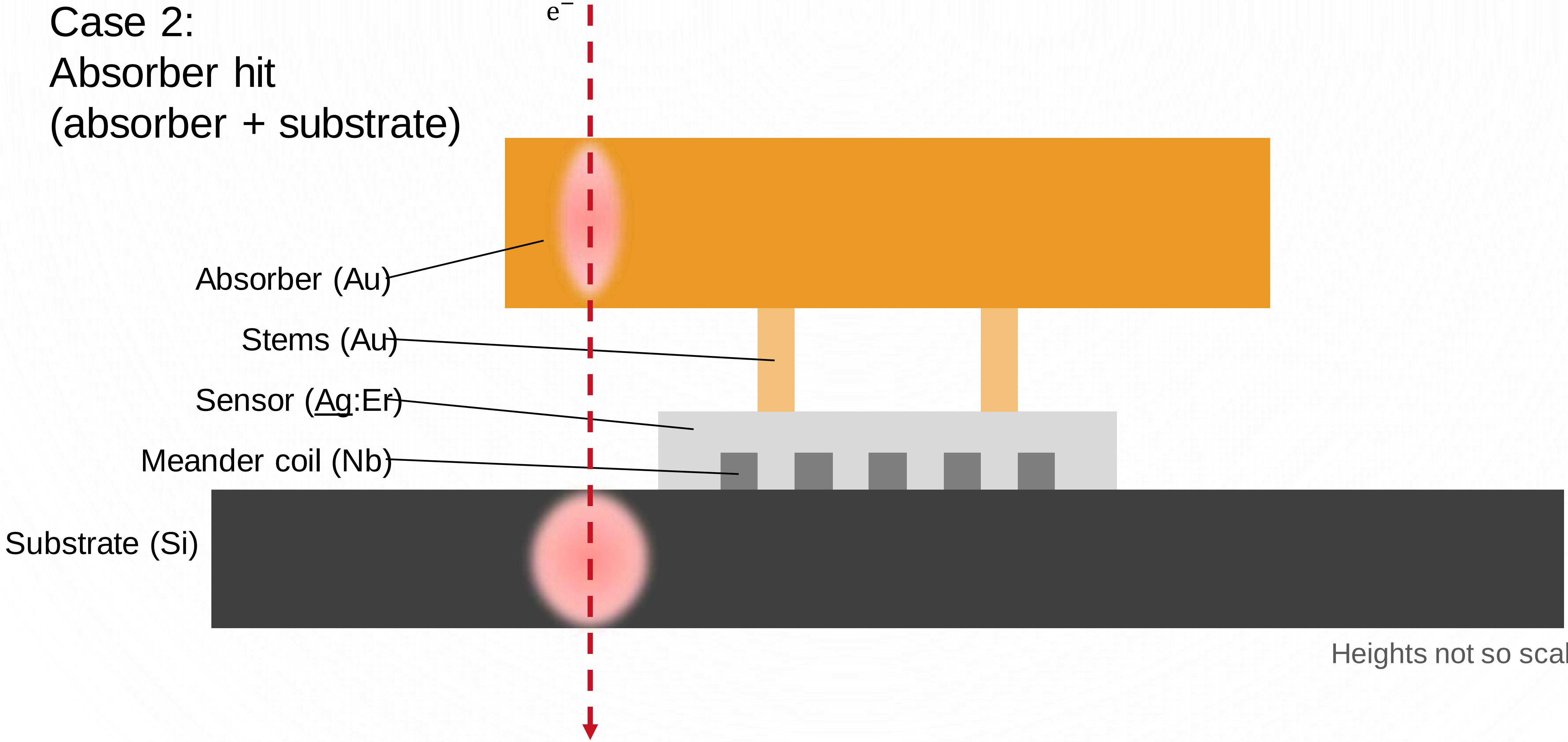






Michel electrons: event types

Case 2:
Absorber hit
(absorber + substrate)



Heights not so scale

Michel electrons: event types

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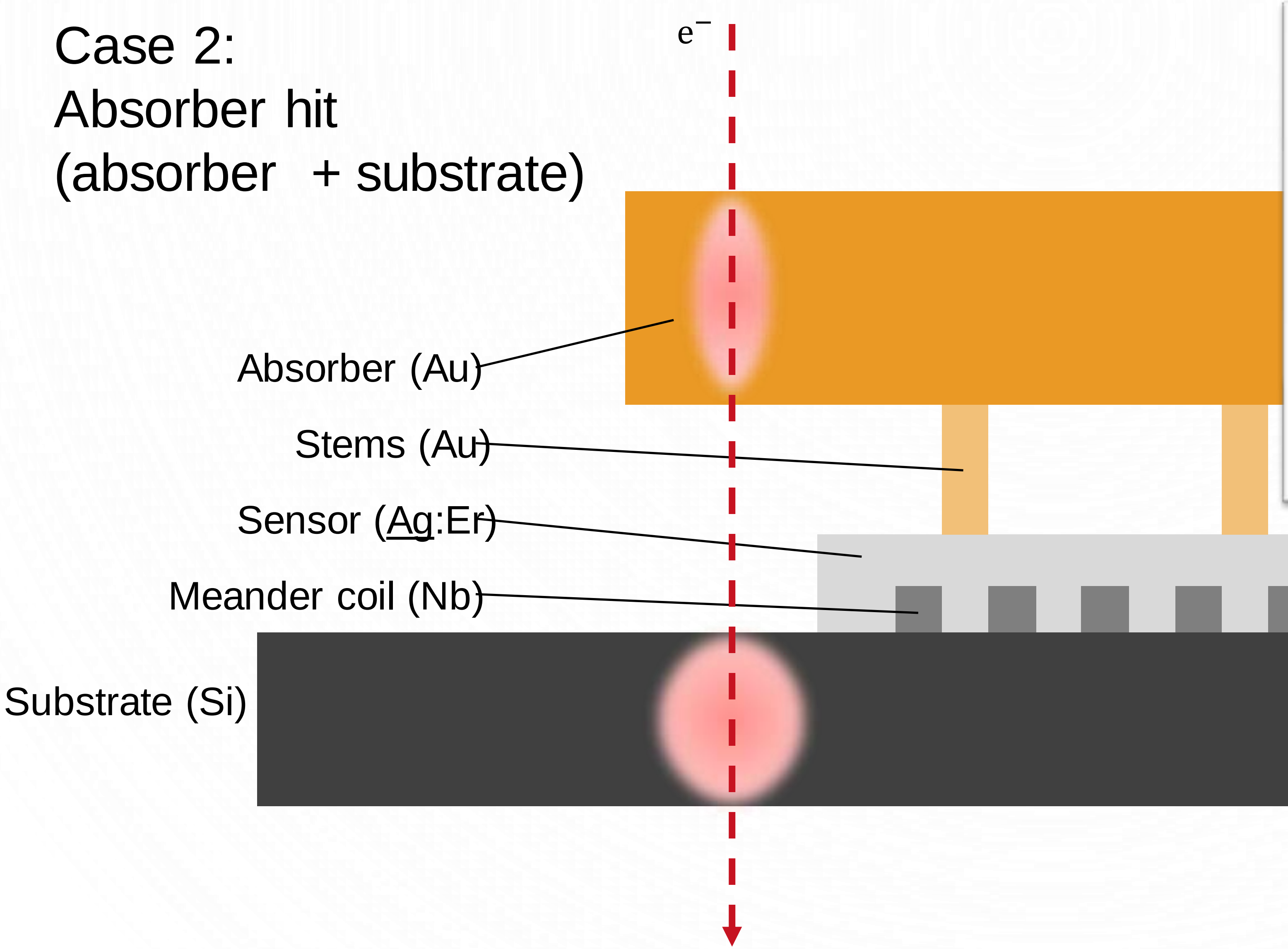
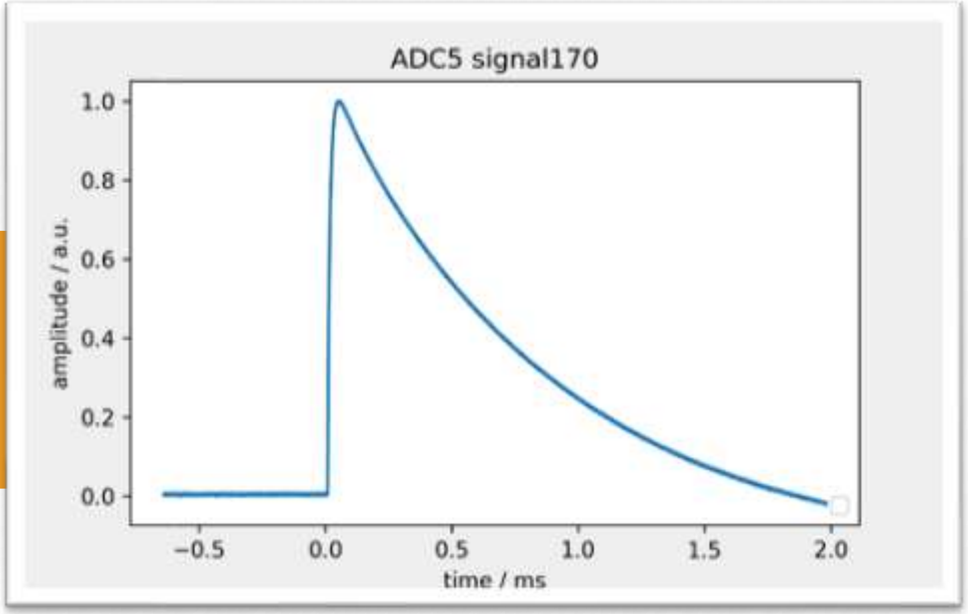
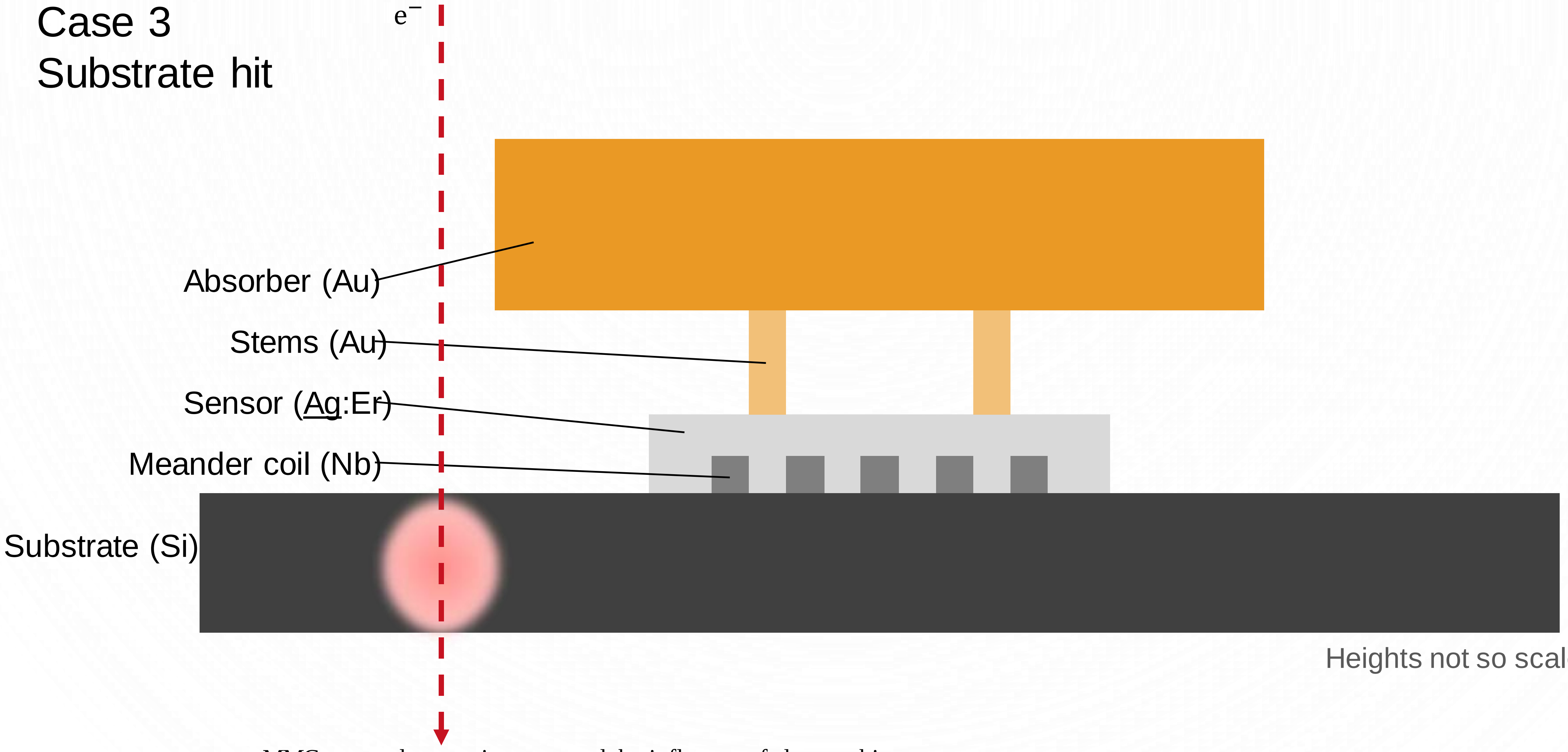




Heights not so scale

Michel electrons: event types

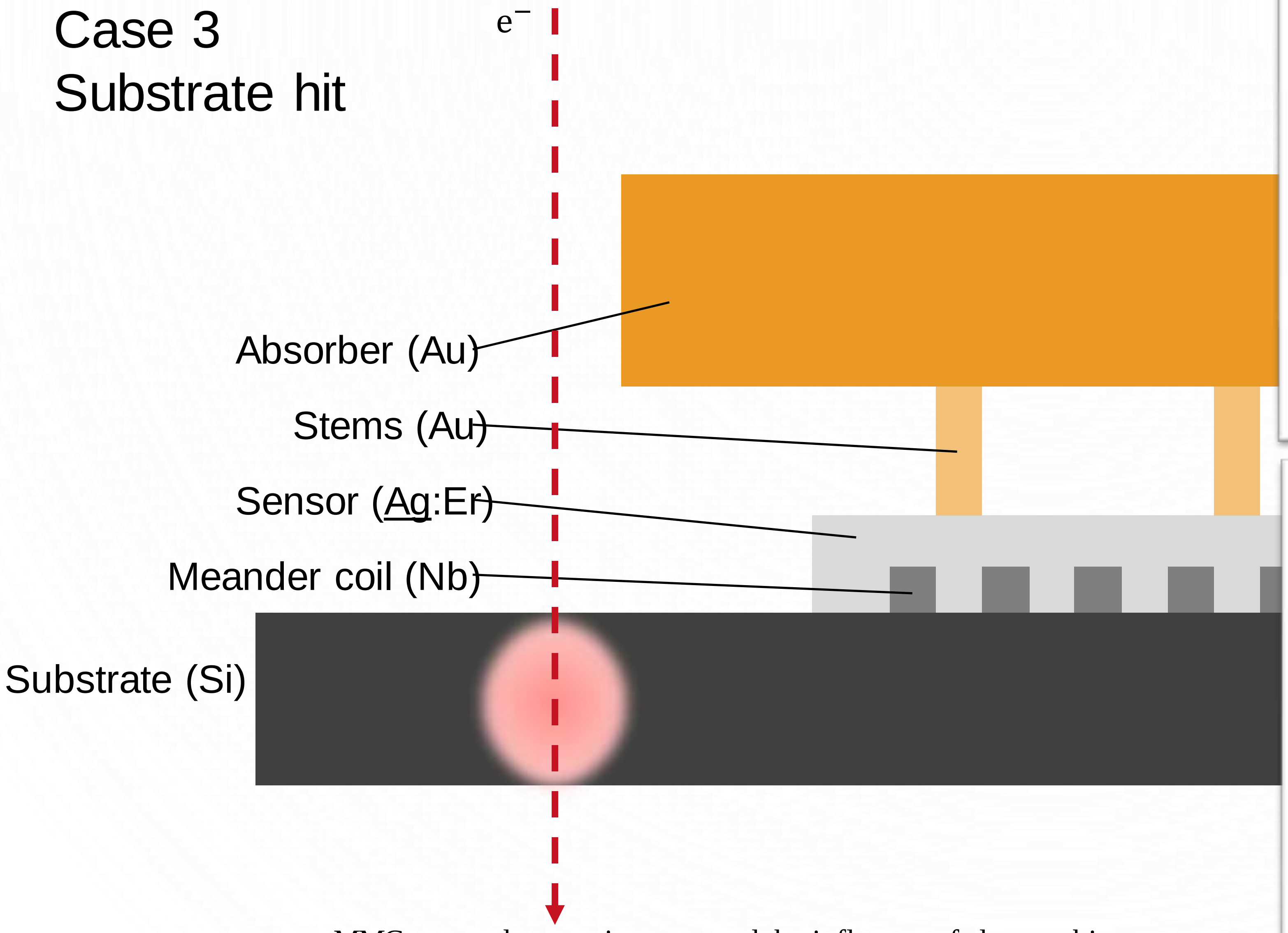
Case 3
Substrate hit

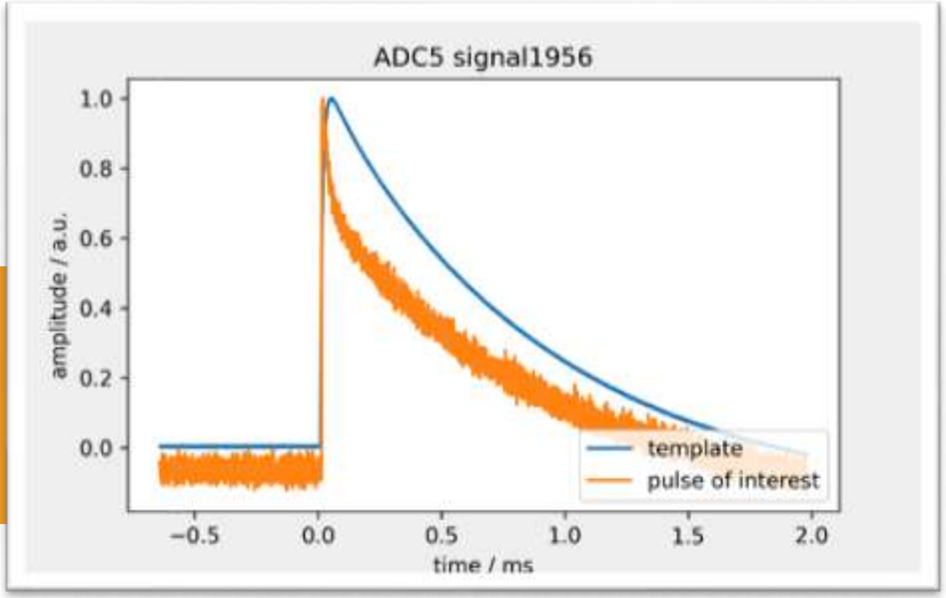


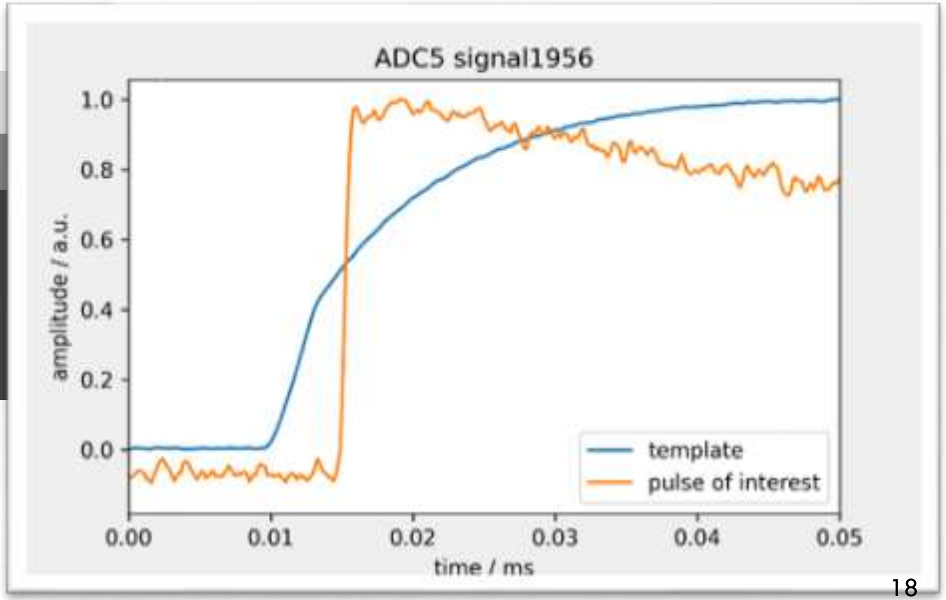
Heights not so scale

Michel electrons: event types

Case 3
Substrate hit







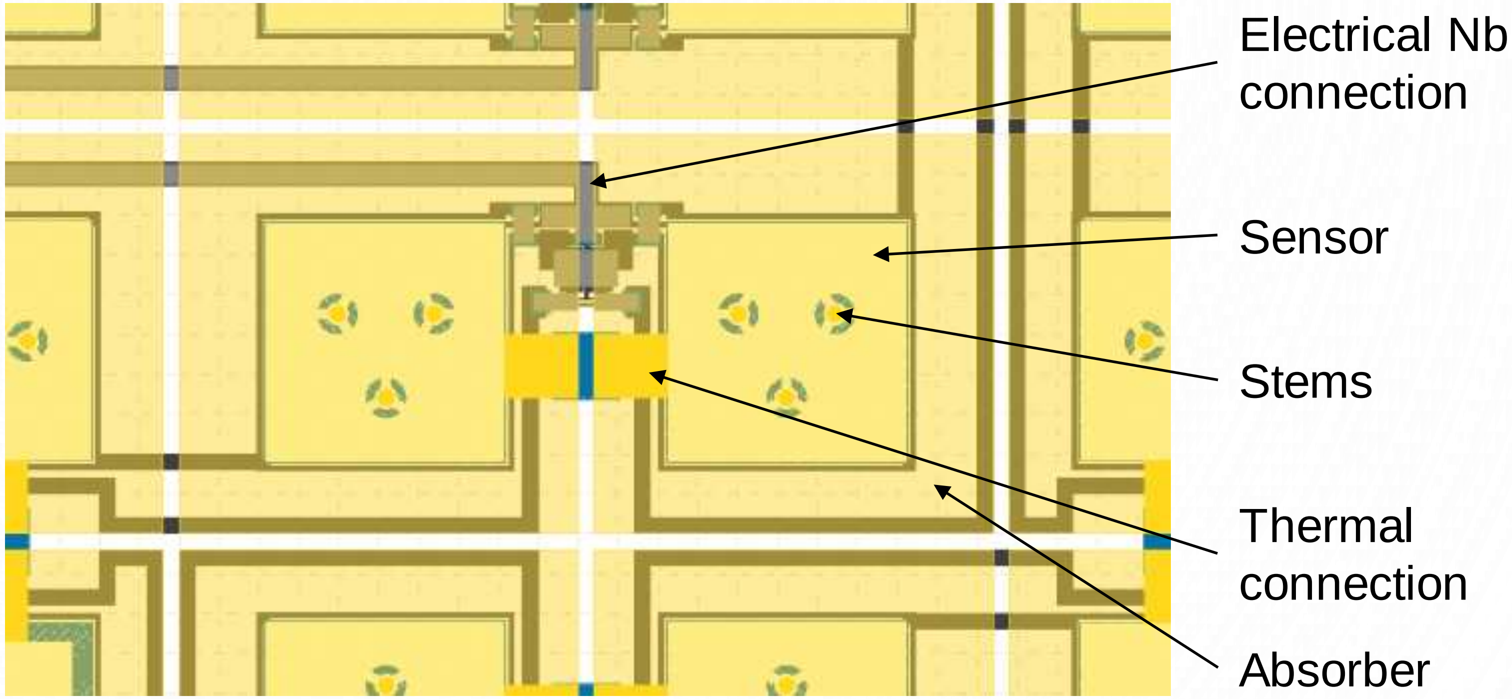
Michel electrons

- Implication of Michel electrons:
  - Significant heat load on many pixels

  → Systematic temperature deviation of affected pixel from temperature of on-chip thermometers

  → Need to discriminate electron induced events

maXs30 v2b detector design: gradiometric channels



Thermal coupling of maXs30 v2b detector:

- Pixel-to-pixel coupling 3ms
- Pixel-to-bath coupling ~20ms

Michel electrons

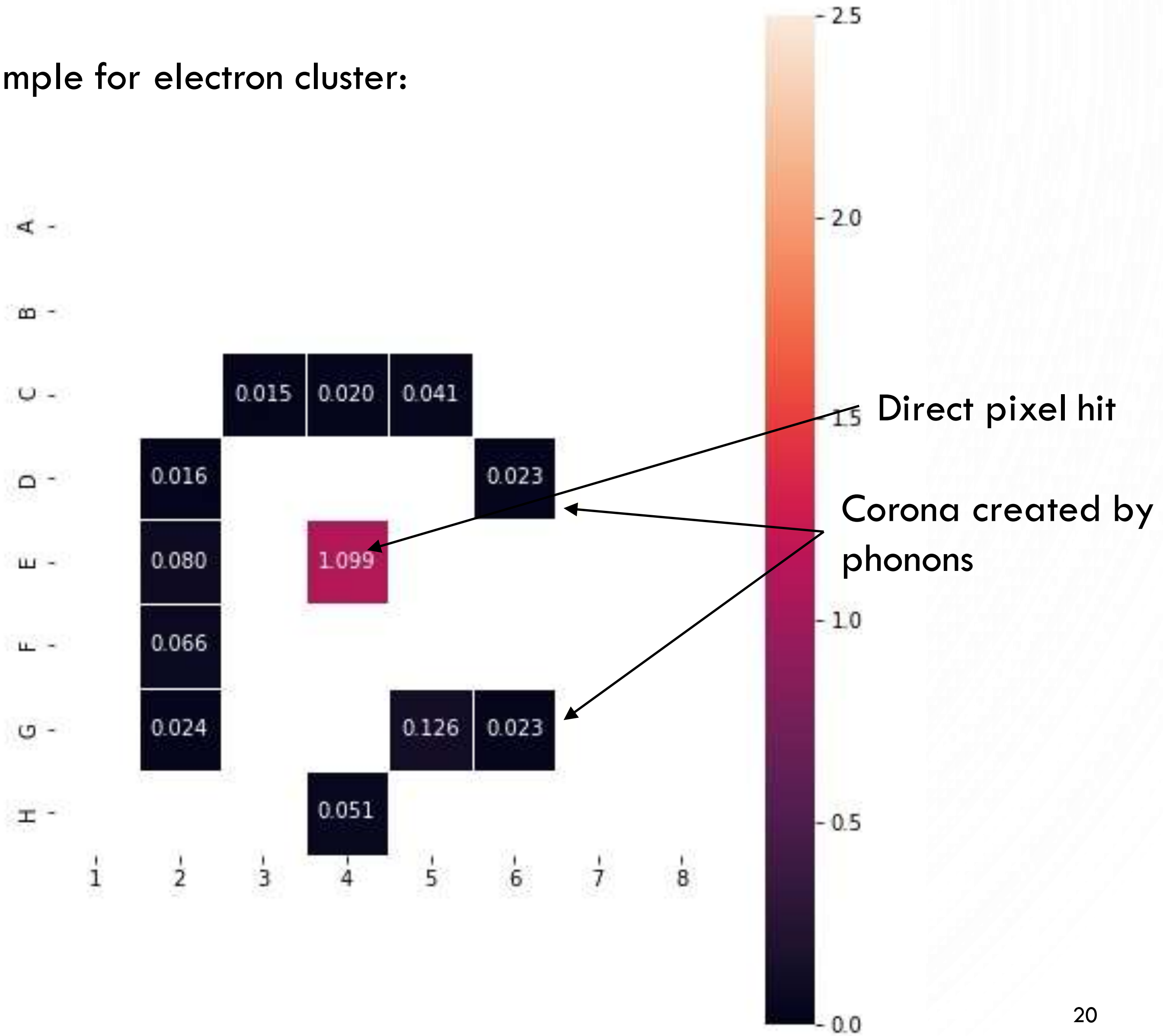
- Implication of Michel electrons:
  - Significant heat load on many pixels

    → Systematic temperature deviation of affected pixel from temperature of on-chip thermometers

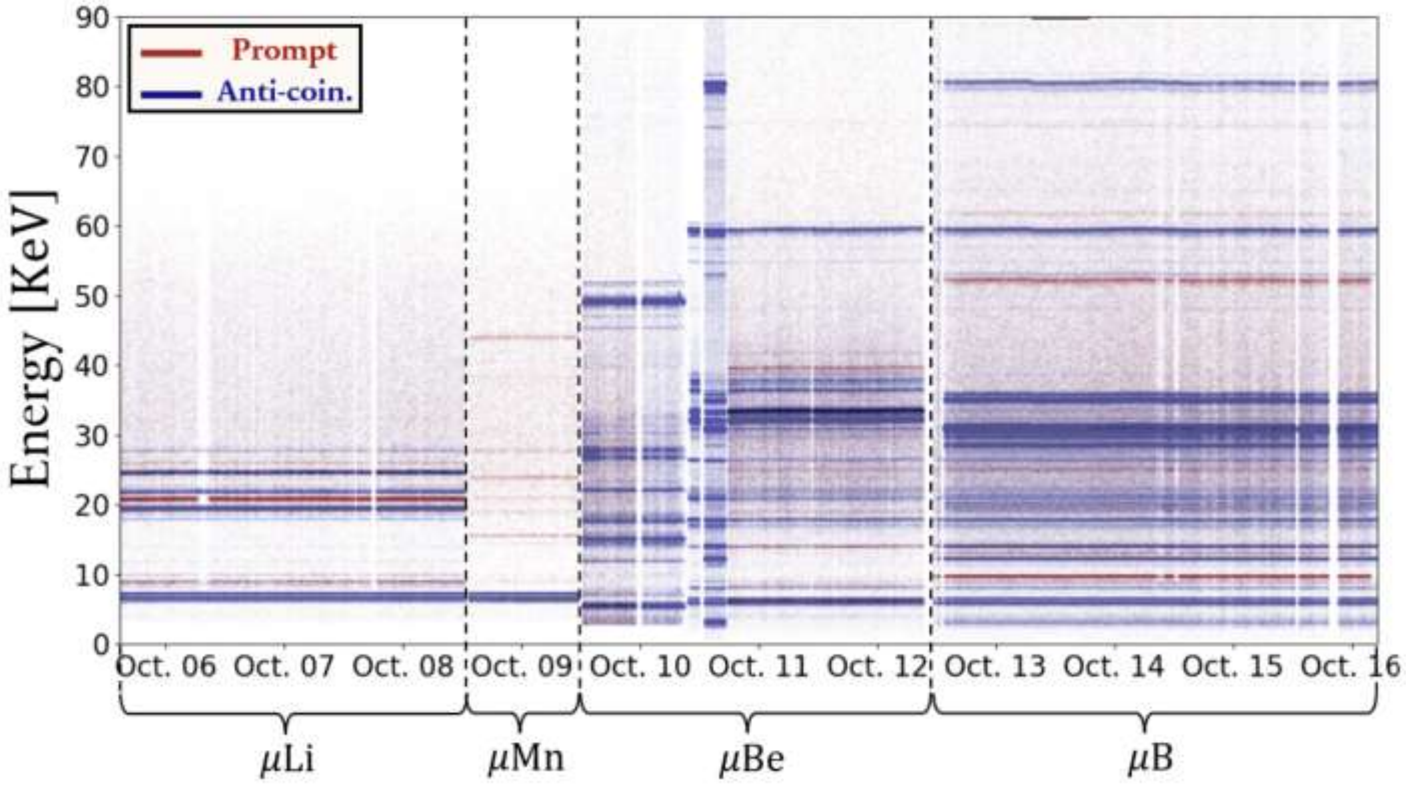
    → Need to discriminate electron induced events
- Discrimination of Michel electron induced events:
  - Clusters of coincident events

    → Detector global hold off for ~100ms

Example for electron cluster:



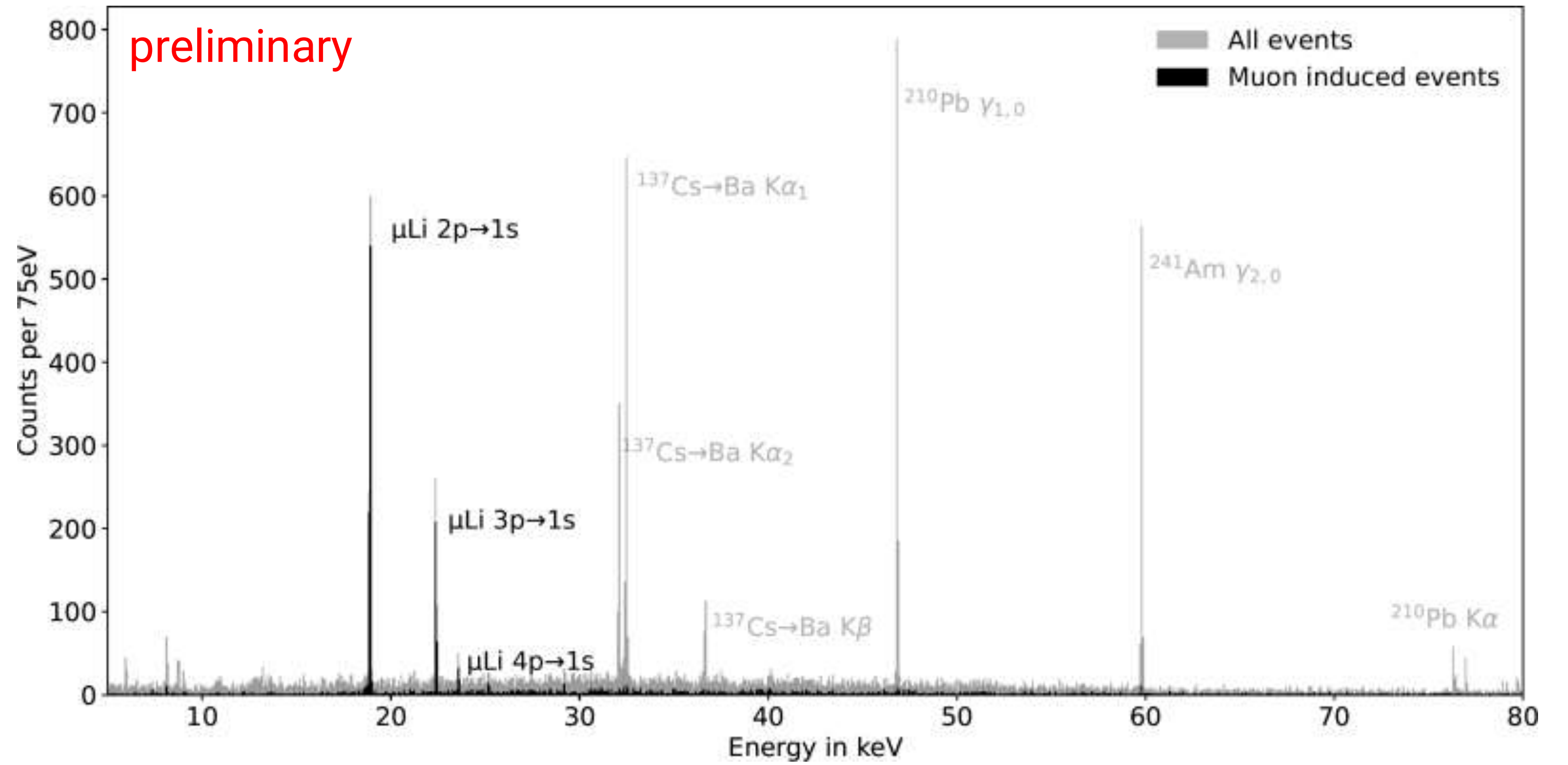
2024 Beamtime



Target	Production	Calibration	Conclusion
$^{6,7}Li$	70 h	^{55}Fe Mo/Ag XRF	✓
Mn	20 h	^{55}Fe	Proof-of-principle
^{9}Be	40 h	^{55}Fe Ba/La XRF ^{241}Am	✓
$^{10,11}B$	80 h	^{55}Fe ^{241}Am ^{133}Ba	✓

High statistics data suitable for physics analysis obtained for all main channels of interest

Preliminary Results



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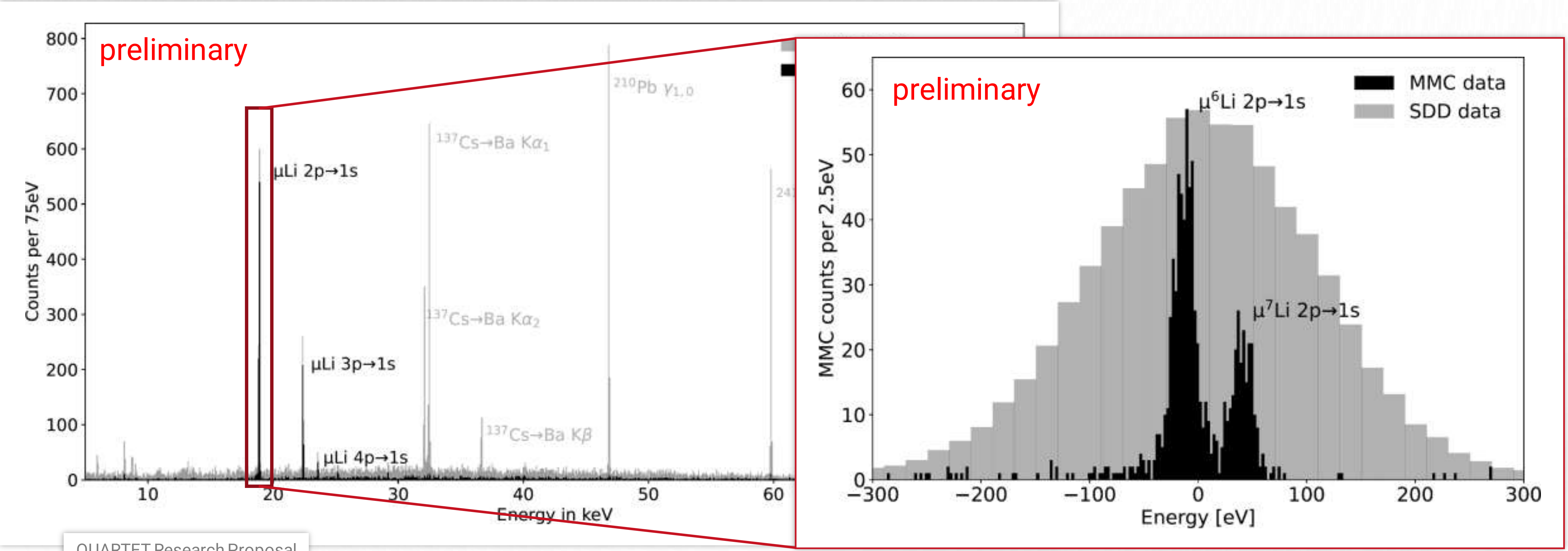
- Muon coincidence allows for effective background suppression + separation of muonic lines from calibration lines
- μLi Lyman np → 1s transitions detected
- Statistics allow <1 eV centroid determination

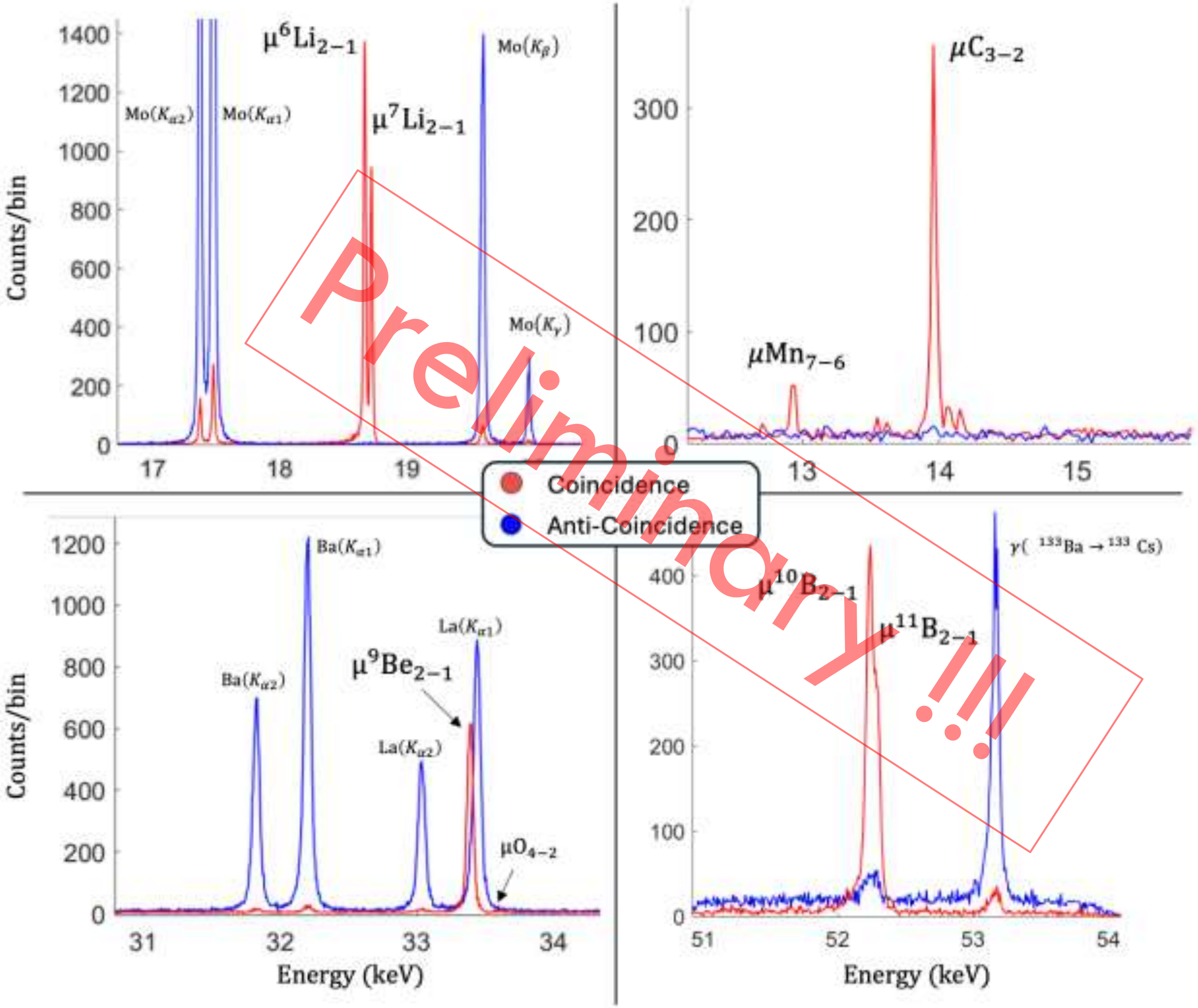
Preliminary Results



QUARTET Research Proposal

Isotope shift of muonic ^{6}Li and ^{7}Li resolved !

Preliminary Results



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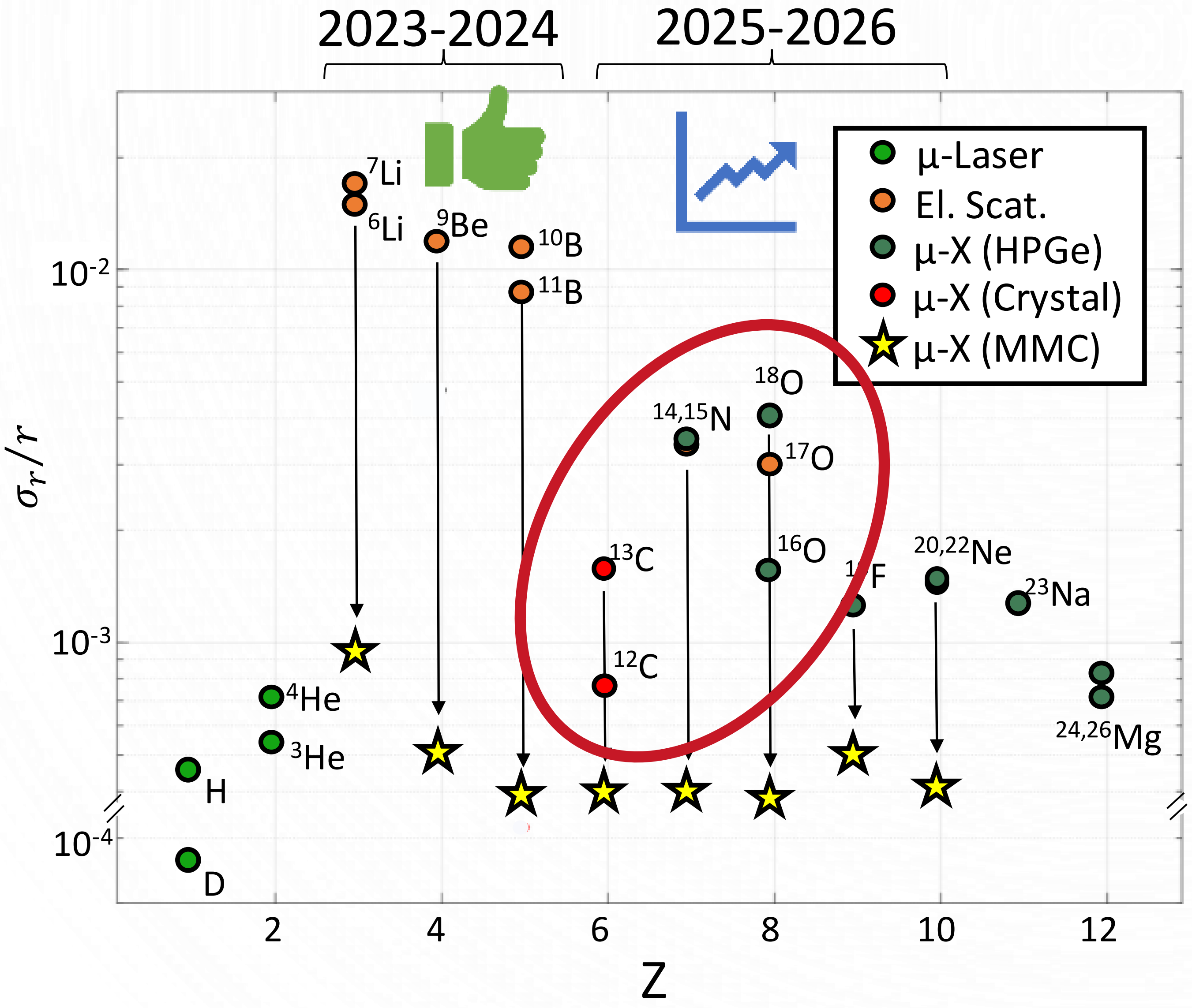
2025 Beamtime – New targets

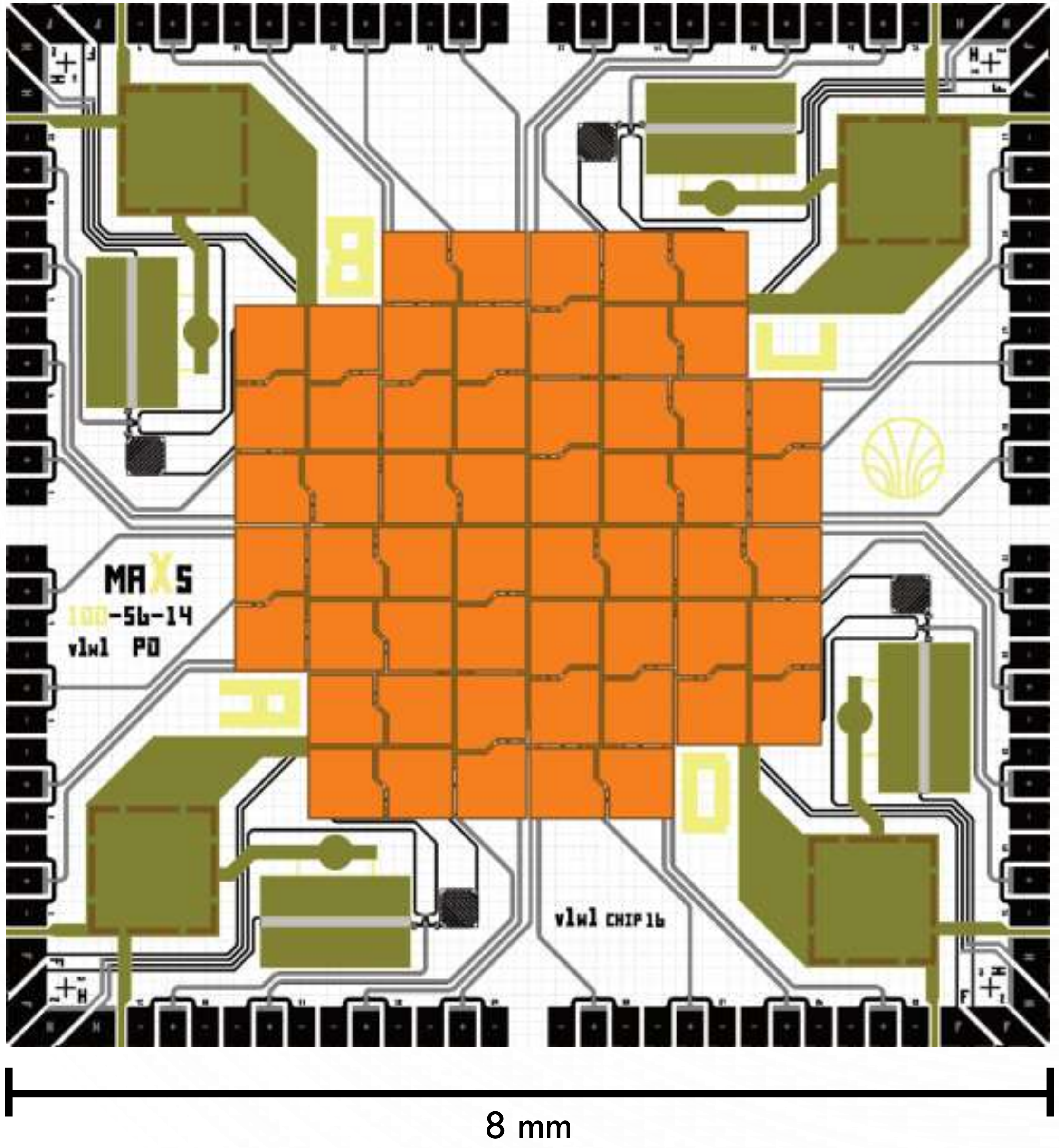


2025 goals :

- ^{12,13}C (tests already done in 2023)
- ^{14}N
- ^{16,18}O
- Adapted and improved detector design

Energy range: ~ 50 - 150 keV

2025 Beamtime – New detector



Features:

- 56 pixels in 28 gradiometric channels

  → total active area of 14mm²

- Specialized temperature channels with phonon collector panels

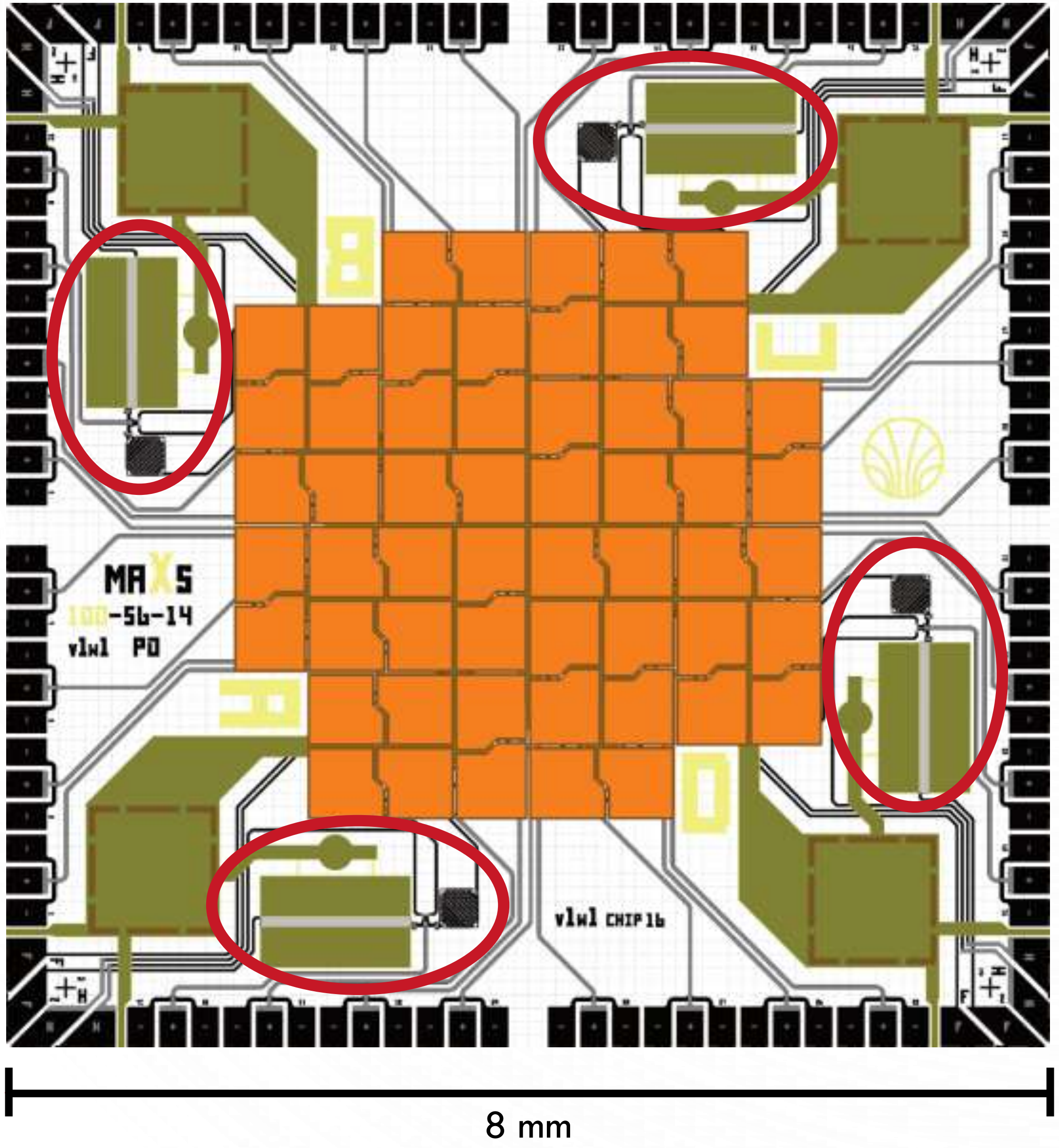
  → Improved discrimination of Michel electron hits

- Improved thermalization structures with Through-Silicon-Vias (TSVs) filled with copper

- 100µm thick absorbers

Fabricated in cleanroom @KIP !

2025 Beamtime – New detector



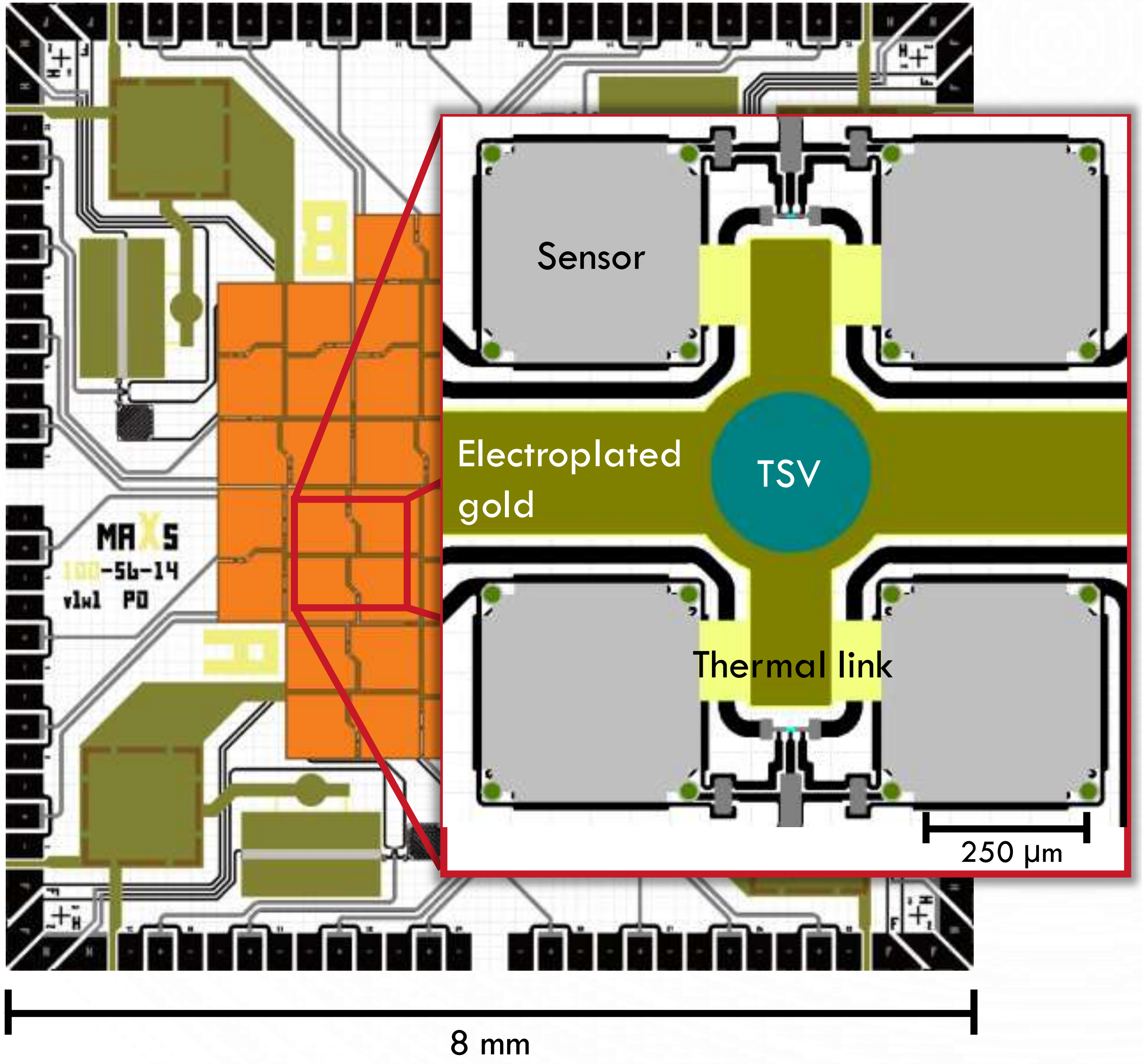
Specialized temperature chanels:

- Fully asymetric for maximal sensitivity
- Large phonon collector pads
- No classic absorbers

→ Improved sensitivity for electron impacts

→ Better detection and handling of electron events

2025 Beamtime – New detector



Improved Heatbath:

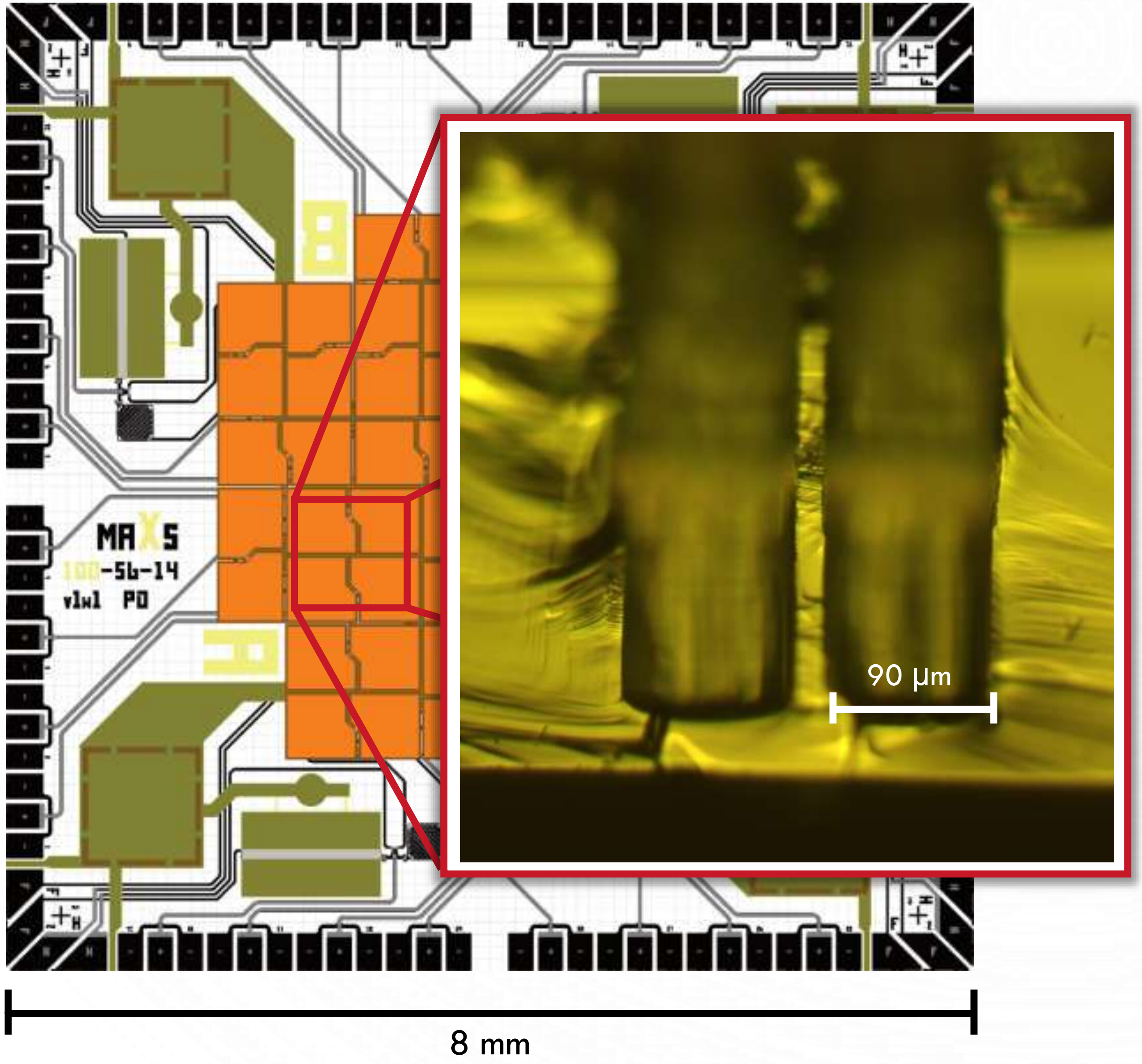
- Large thermalization pads connected to copper clamp
- Through Silicon Vias:
  - Etched through wafer
  - Filled with copper

→ Fast and efficient thermalization

→ Excellent coupling to cryostat

→ Detector can handle more rate

2025 Beamtime – New detector



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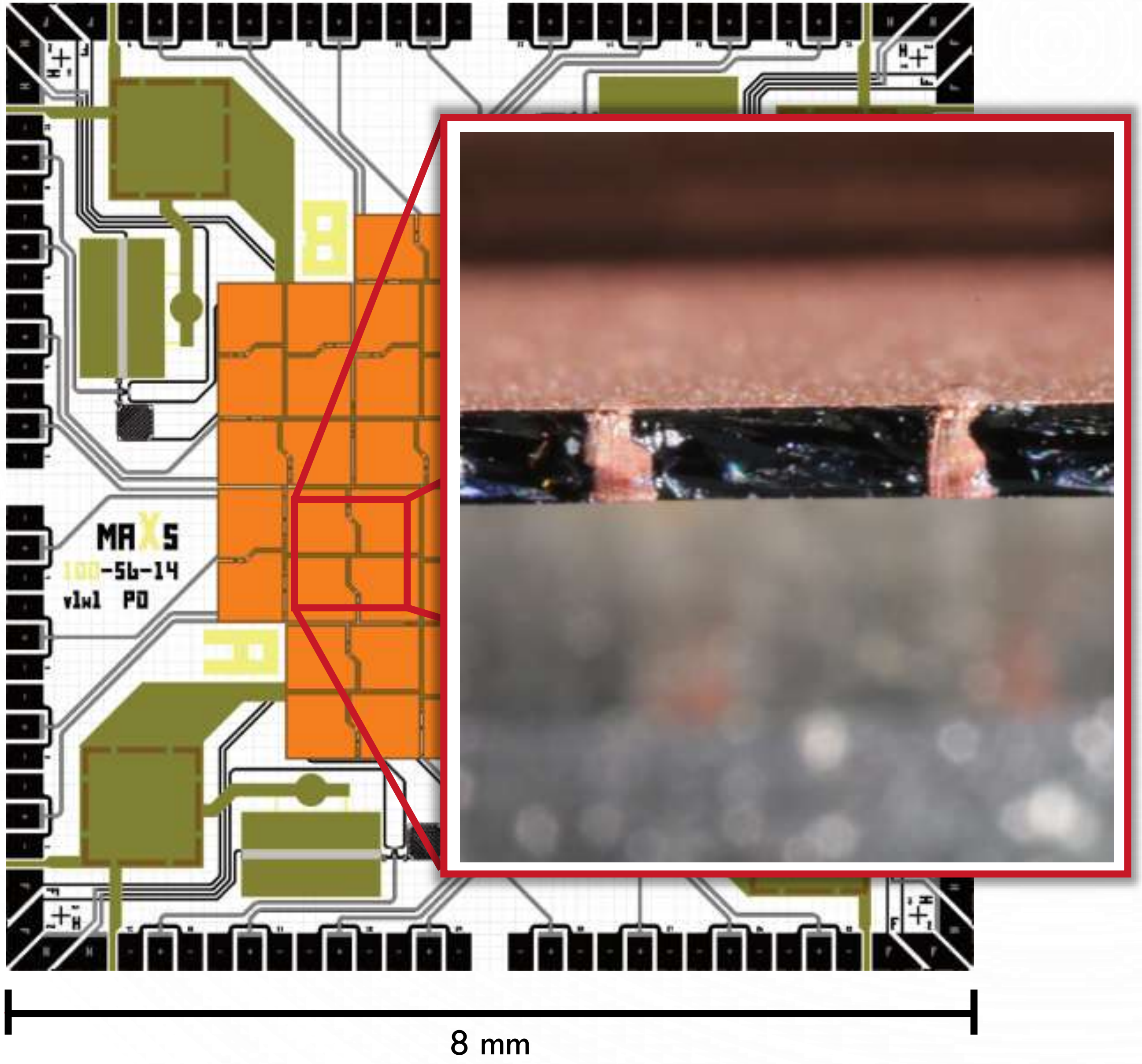

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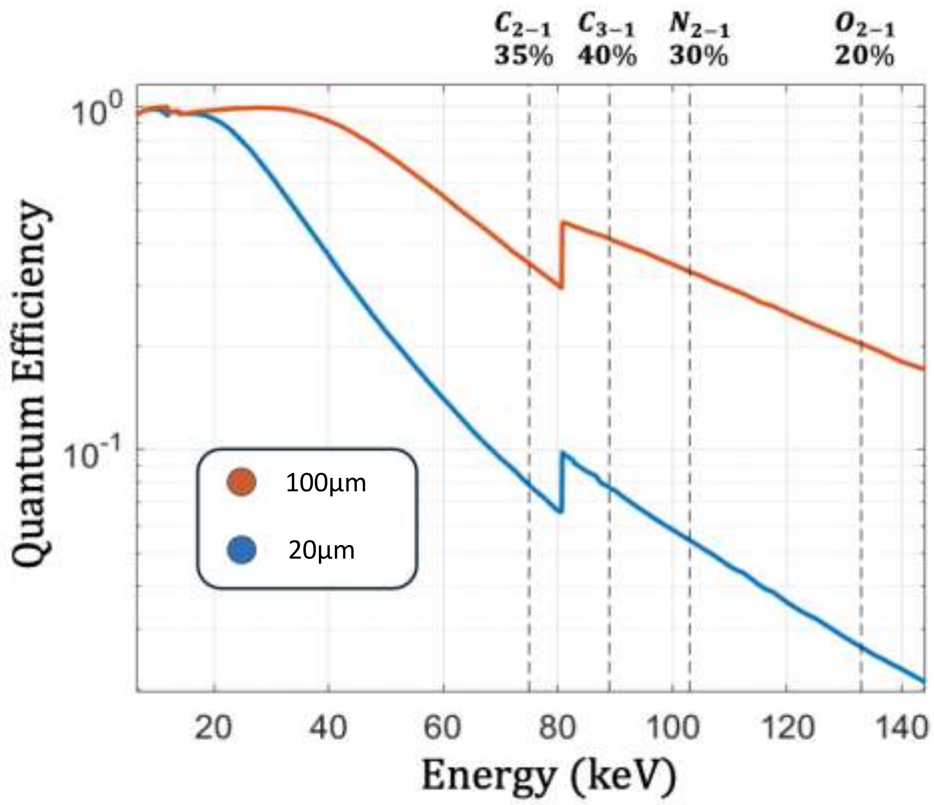
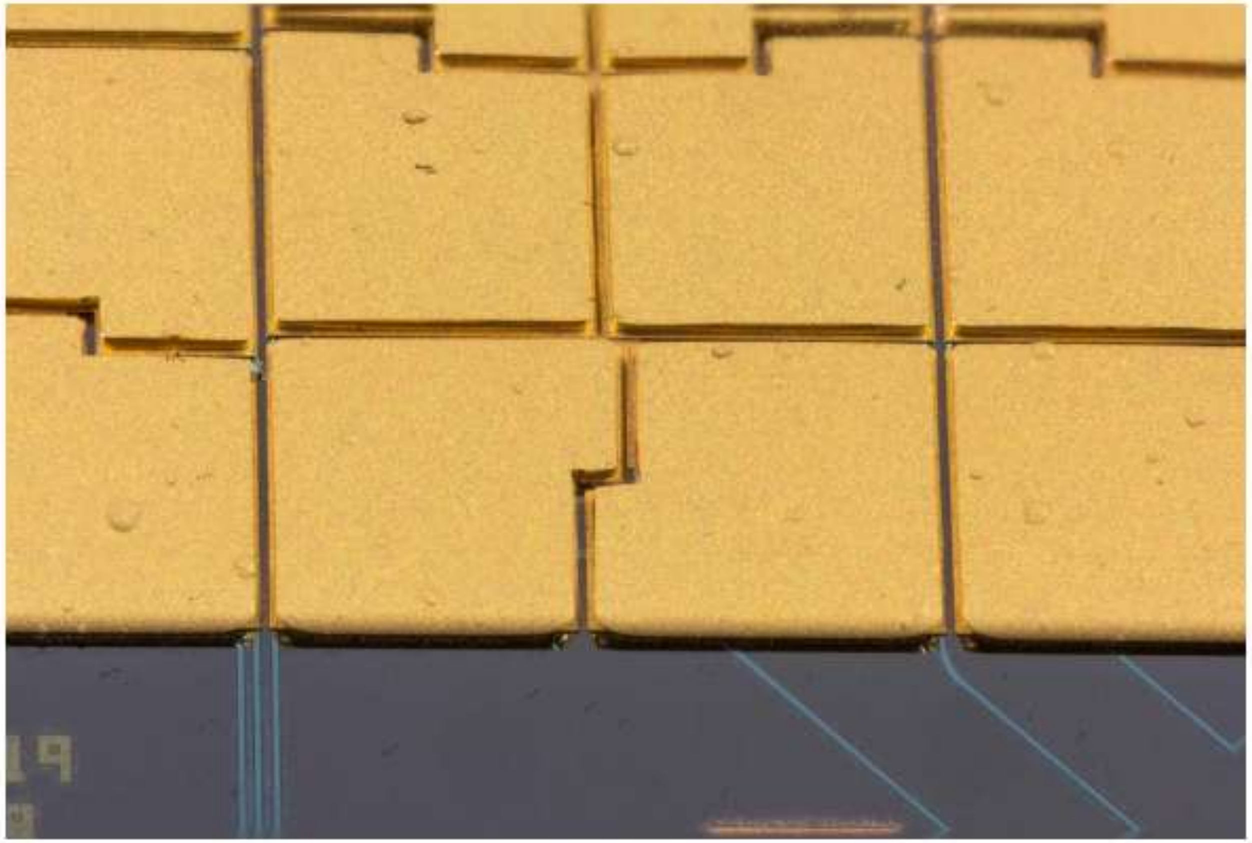
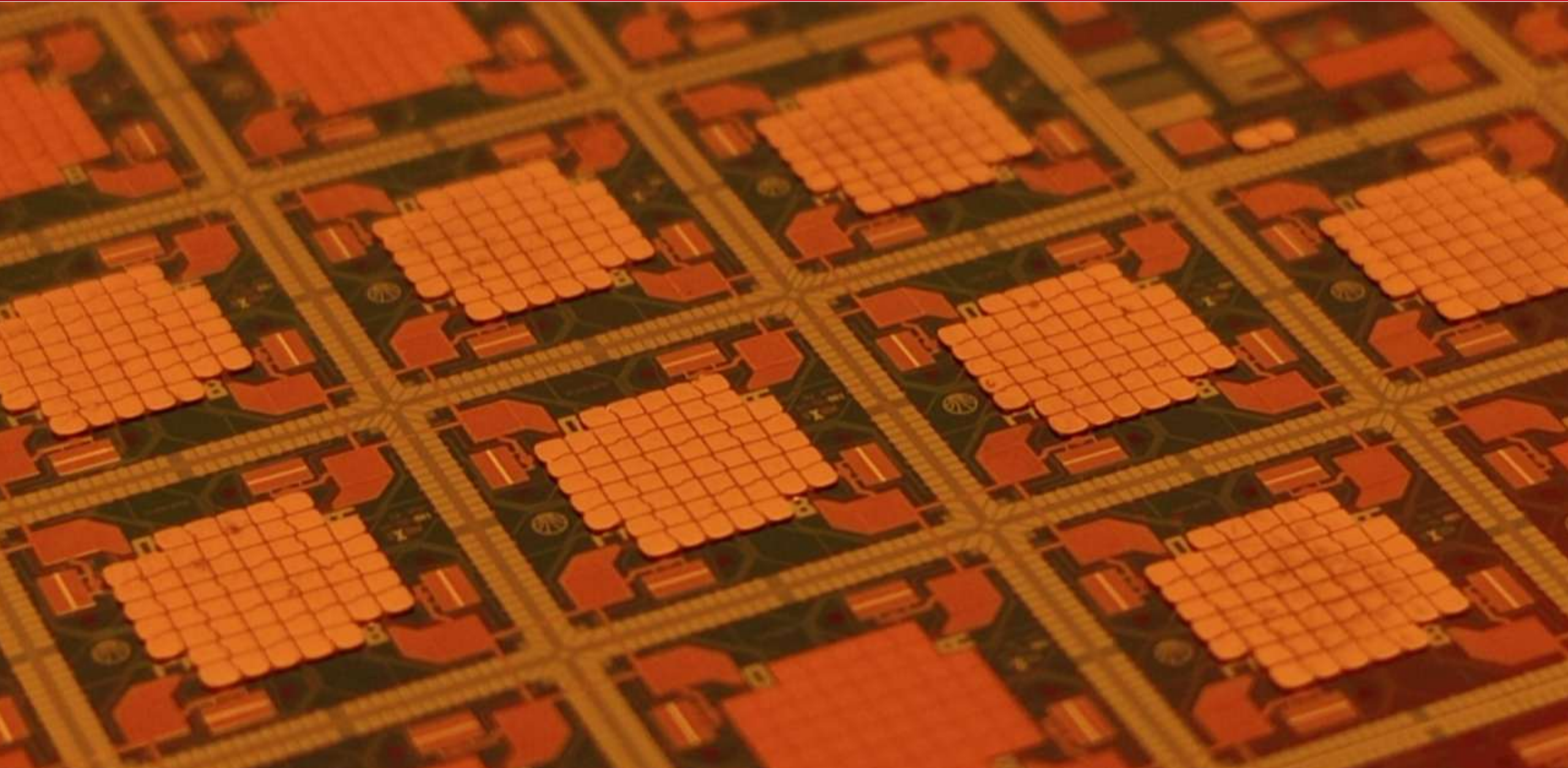




- 100 micrometer thick x-ray absorbers made of electroplated gold
- High quantum efficiency for 100 keV x-rays
- New fabrication process, used for QUARTET

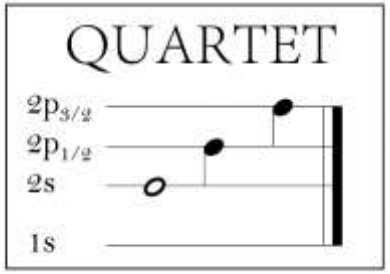
2025 Beamtime – New detector



Conclusion & Outlook

- MMC arrays perfectly suited for spectroscopy of muonic atoms
- Successful proof-of-principle in 2023
- Successful beamtime 2024 with Li, Be, and B
- New beamtime upcoming in 2025 for C, N, O with optimized detector

QUARTET: high-precision measurements of absolute nuclear charge radii from ^{6}Li to ^{22}Ne



Thank you for your attention!