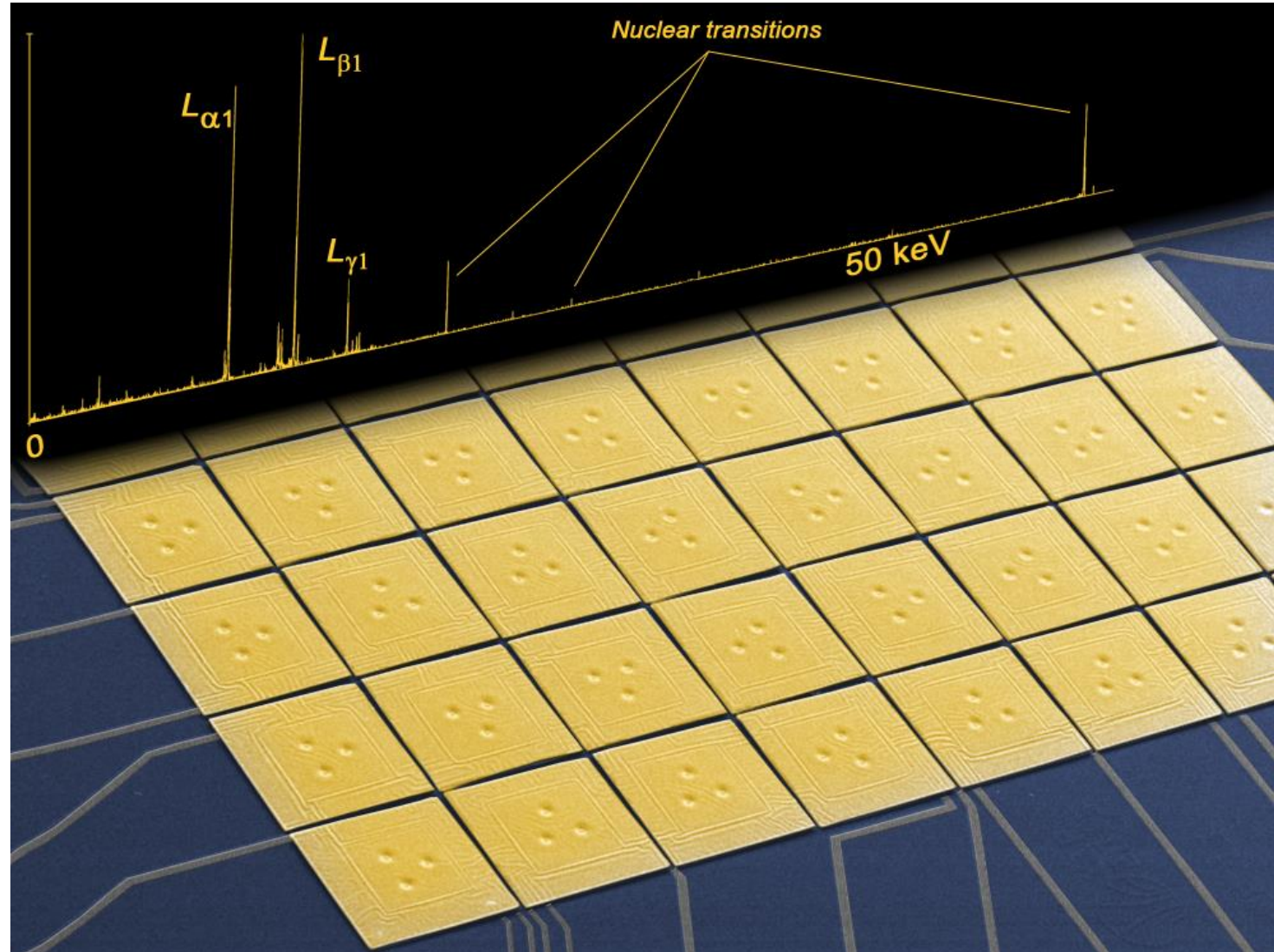


Metallic Magnetic Calorimeters for muonic atoms spectroscopy

A. Abeln, E. Biedert, T. E. Cocolios,
O. Eizenberg, C. Enss, A. Fleischmann,
L. Gastaldo, C. Godinho, M. Heines,
D. Hengstler, P. Indelicato, D. Kreuzberger,
K. Kirch, A. Knecht, J. Machado, B. Ohayon,
N. Paul, R. Pohl, A. Reifenberger,
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S. M. Vogiatzi, F. Wauters, J. Wendel and
P. Wiedemann

— for the QUARTET Collaboration

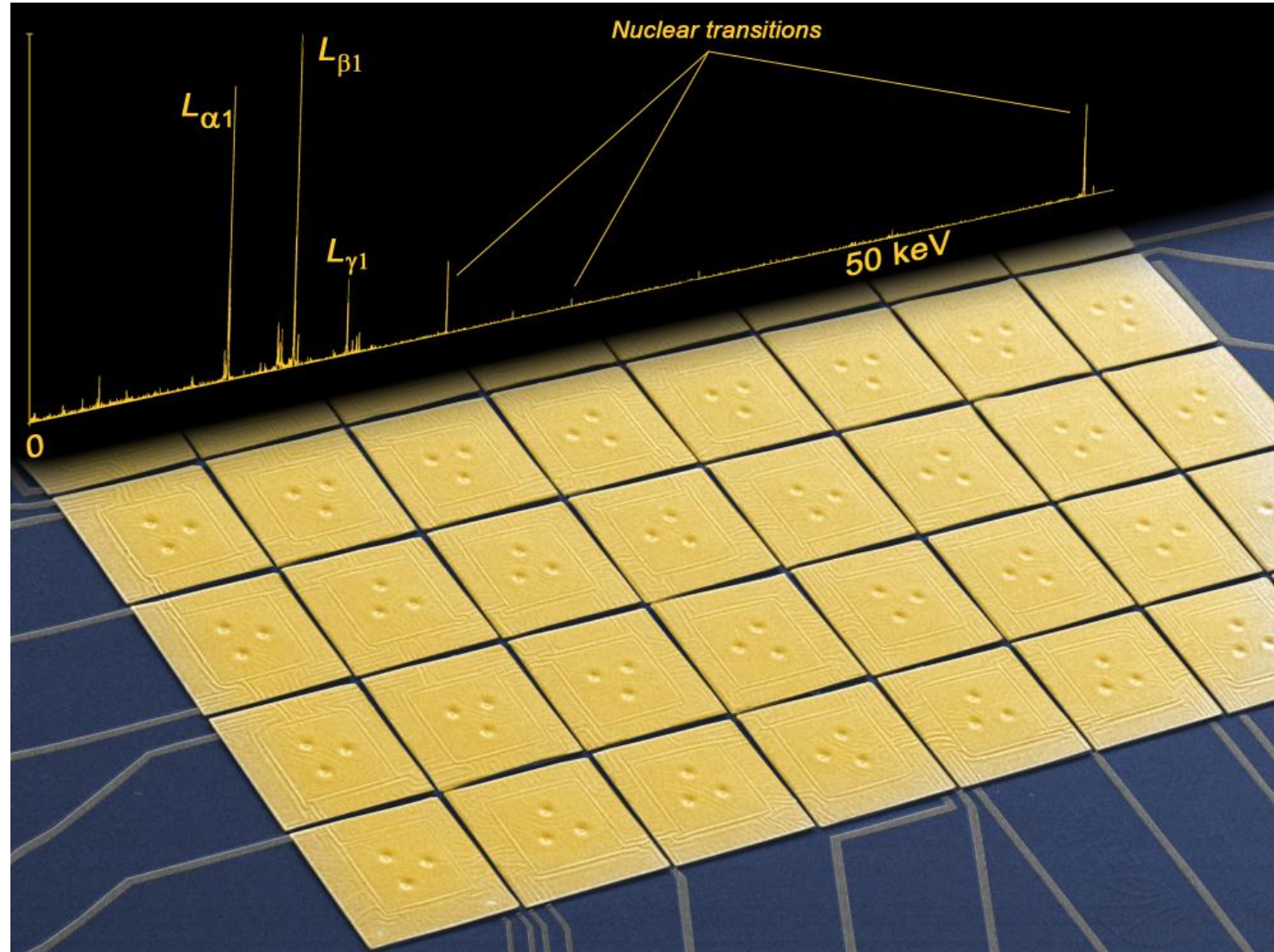


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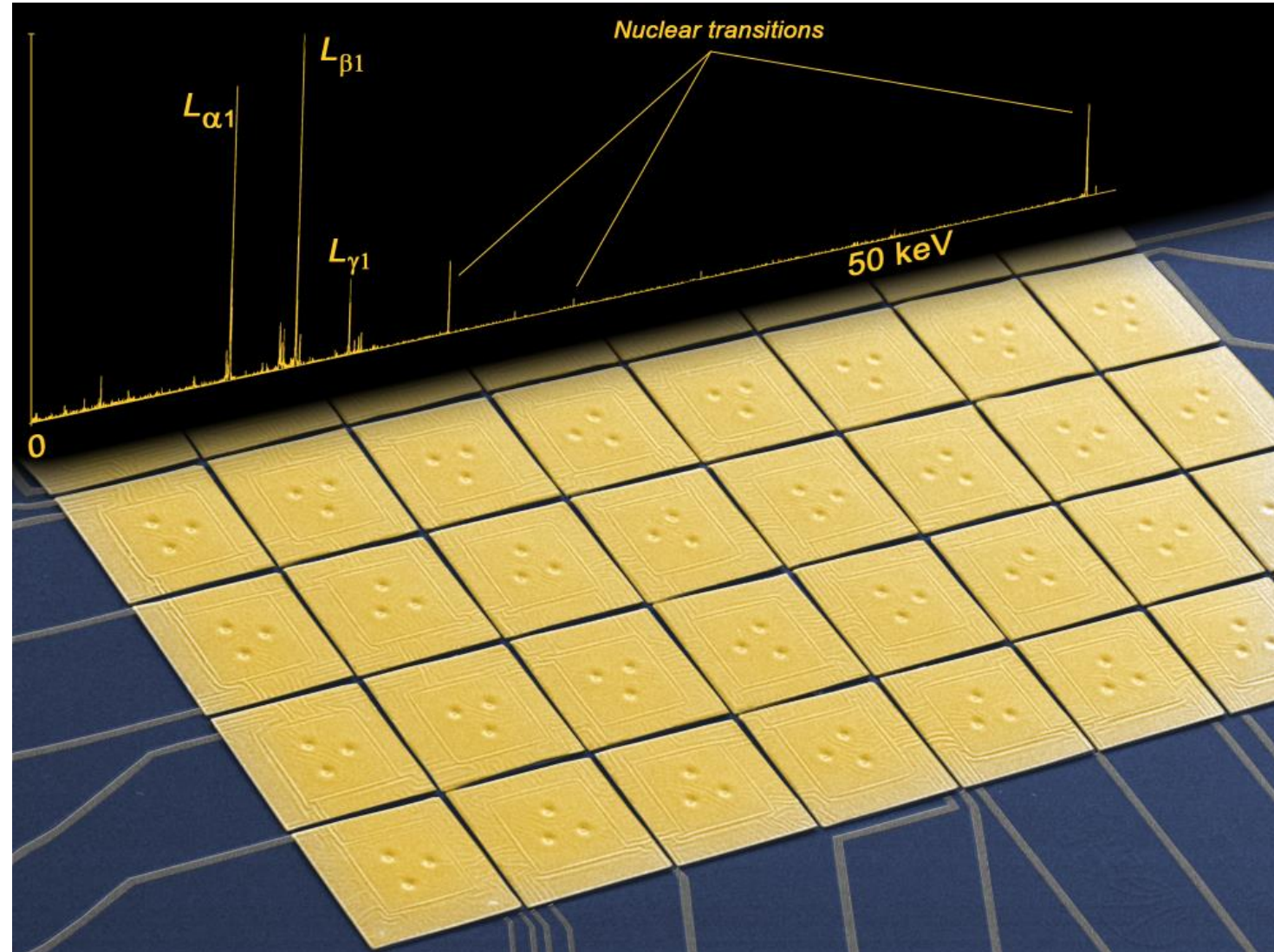
— for the QUARTET Collaboration



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Outlook

- Metallic Magnetic Calorimeters (MMCs)
- MMCs for x-ray spectroscopy
- QUARTET



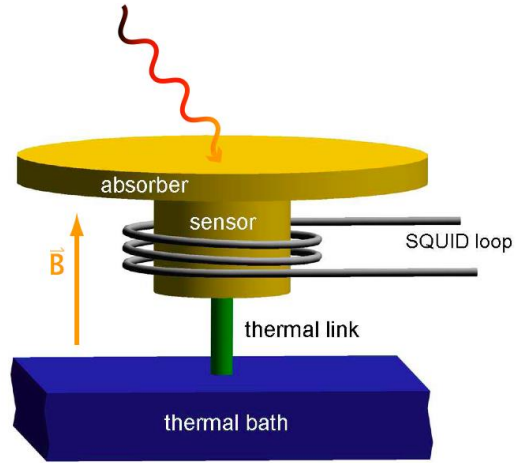
Metallic Magnetic Calorimeters

A.Fleischmann, C. Enss and G. M. Seidel,
Topics in Applied Physics **99** (2005) 63

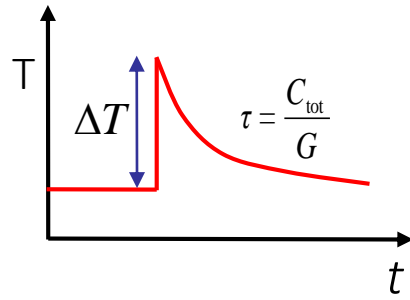
A.Fleischmann et al.,
AIP Conf. Proc. **1185** (2009) 571

Paramagnetic temperature sensor

Dilute alloy Au:Er or Ag:Er (Er concentration: a few hundred ppm)



$$\Delta T \cong \frac{E}{C_{\text{tot}}}$$



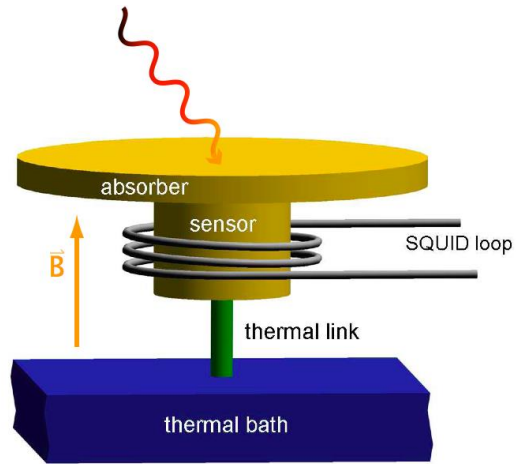
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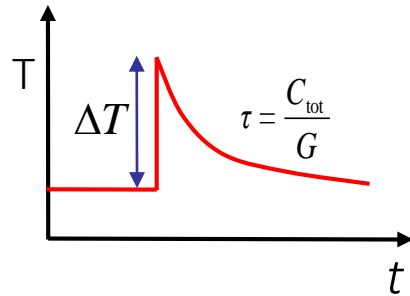
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$$\Delta T \cong \frac{E}{C_{\text{tot}}} \xrightarrow{\text{MMC}} \Delta\Phi_s \propto \frac{\partial M}{\partial T} \Delta T \rightarrow \Delta\Phi_s \propto \frac{\partial M}{\partial T} \frac{E}{C_{\text{tot}}}$$



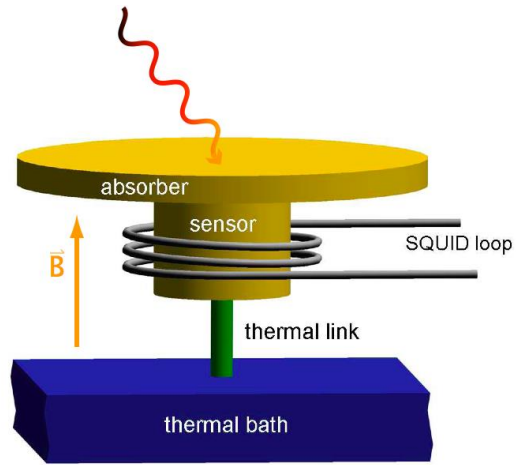
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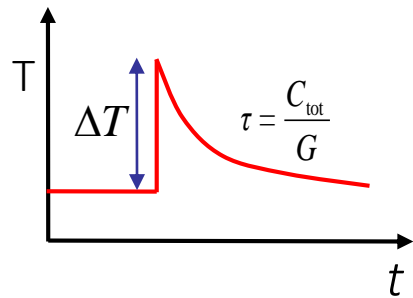
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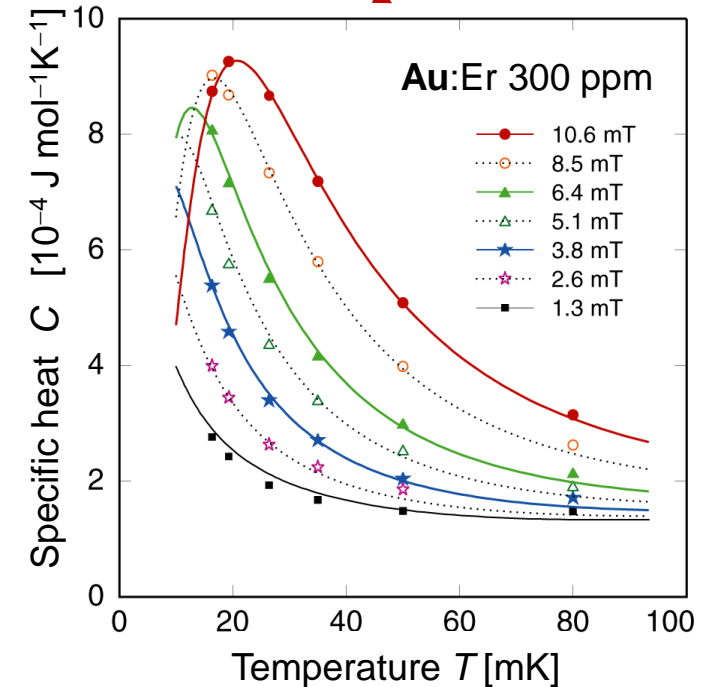
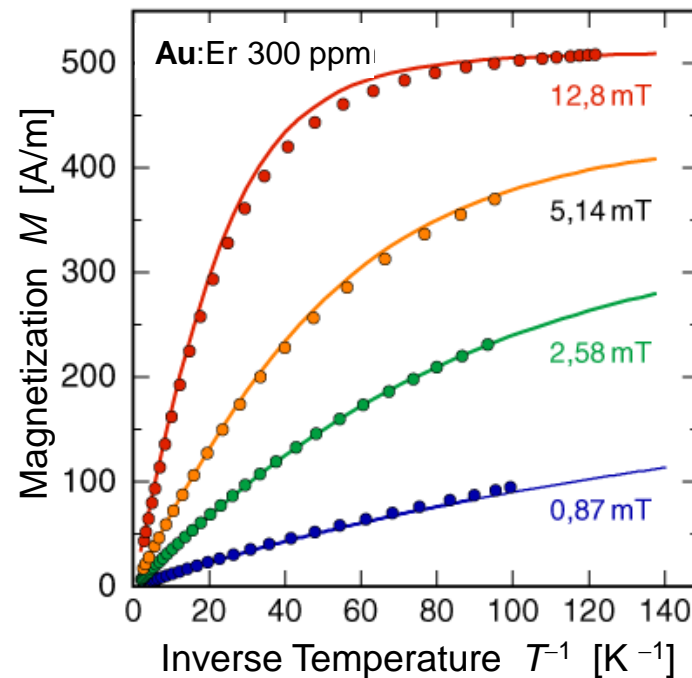


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Very good agreement between data and theoretical expectation for interacting spin system

Optimization of detector geometries for different applications



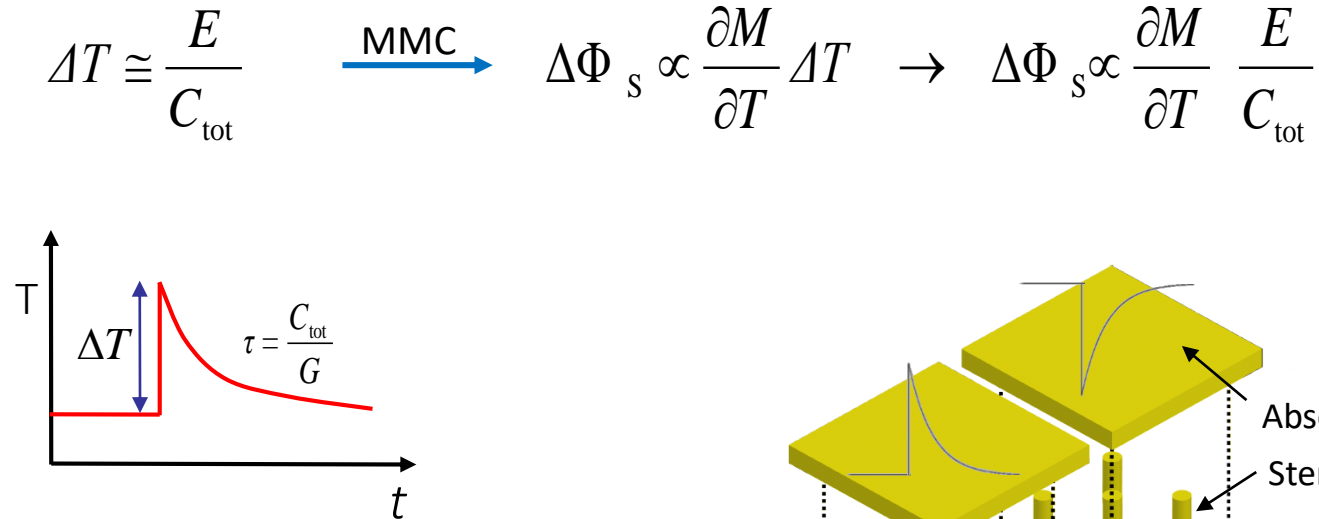
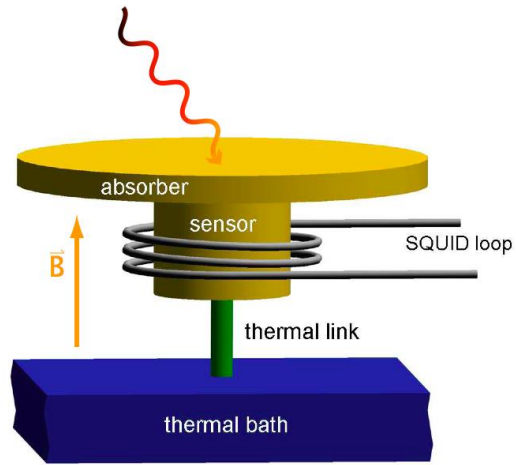
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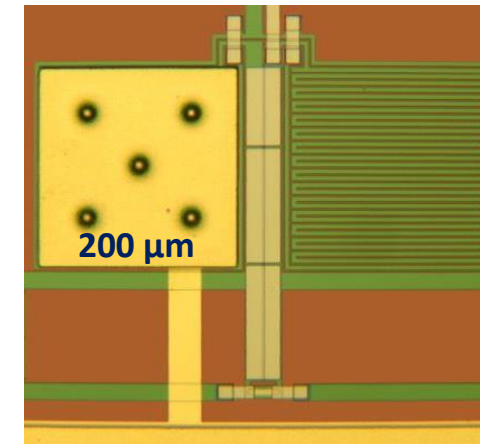
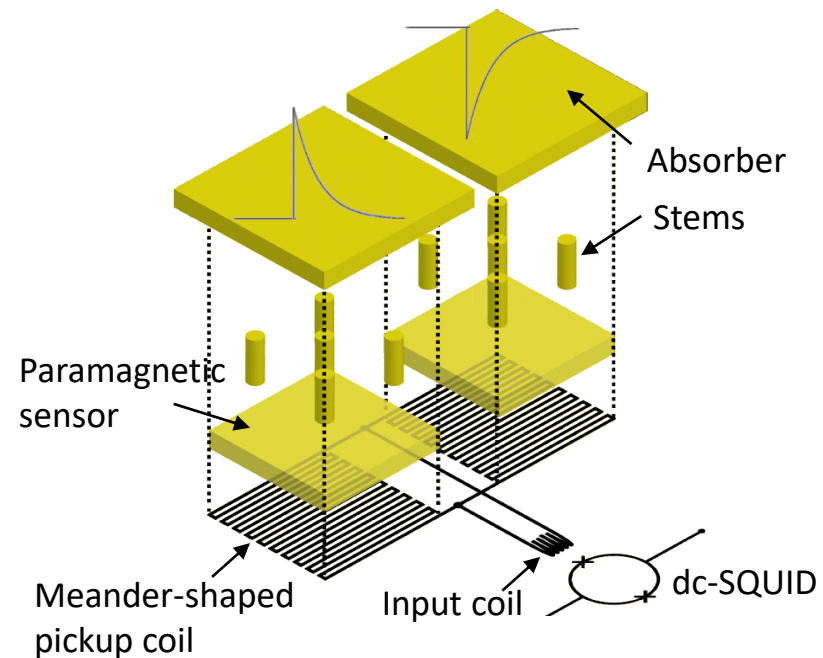
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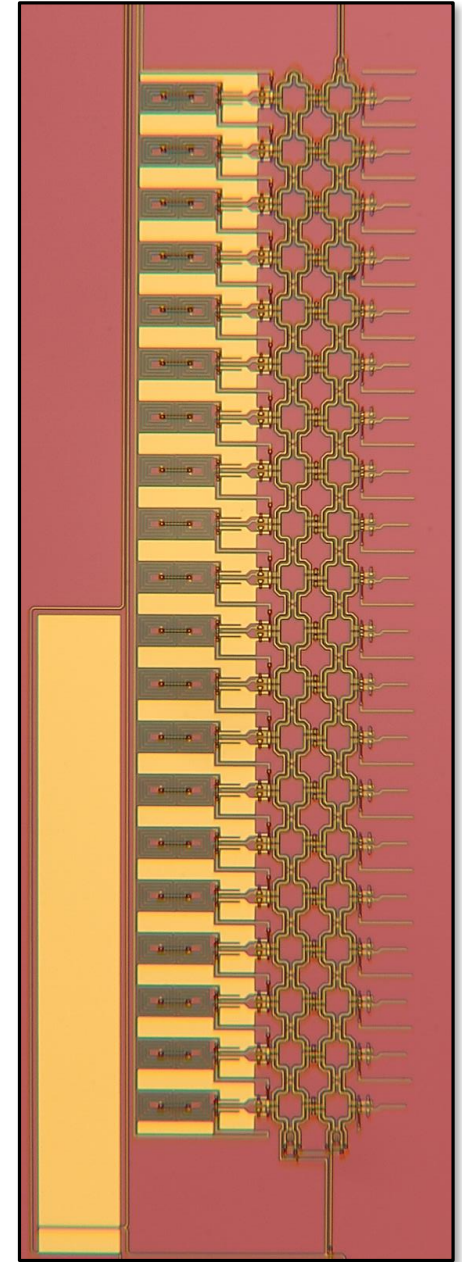
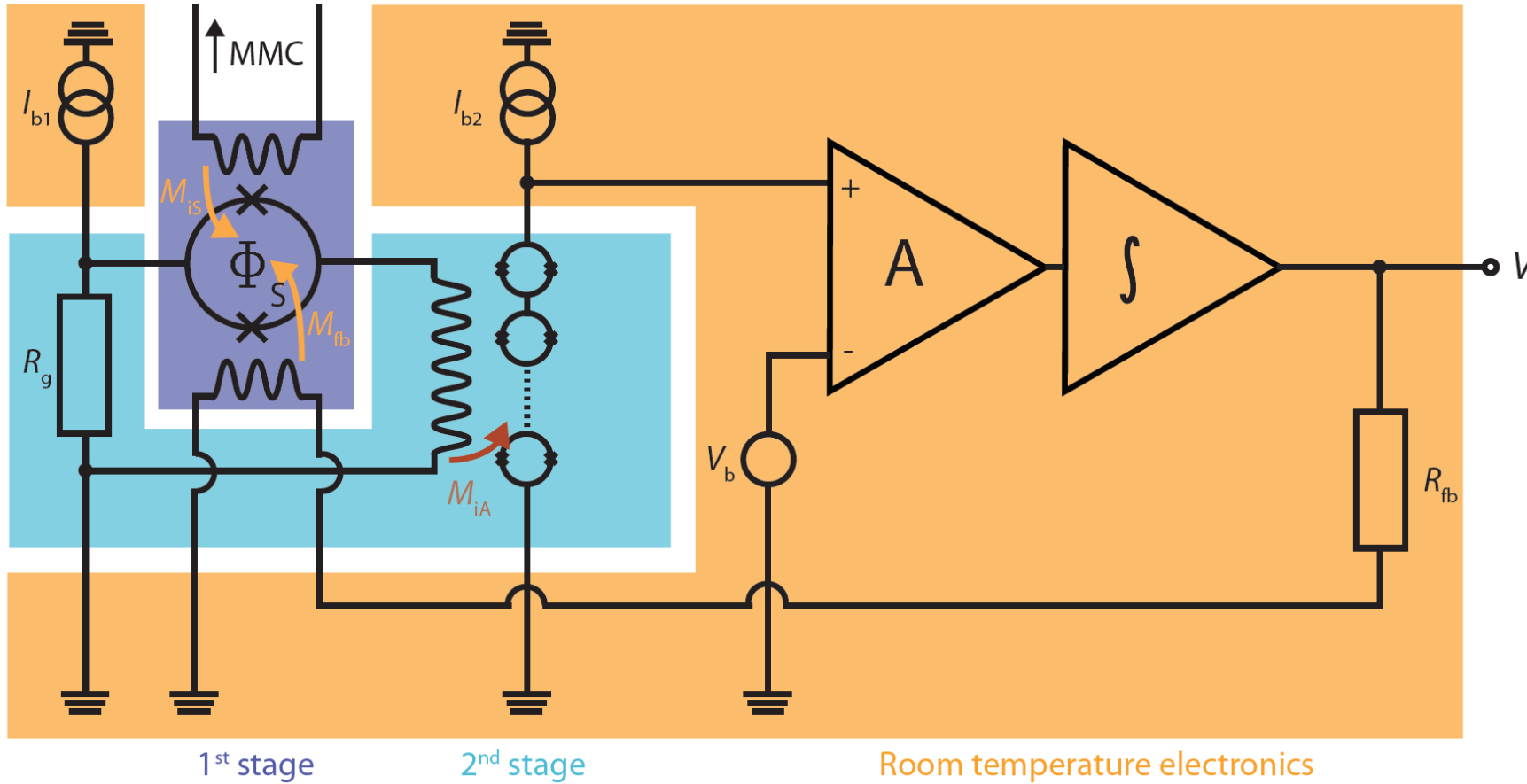


MMC readout

Two-stage dc-SQUID readout with flux-locked loop

low noise

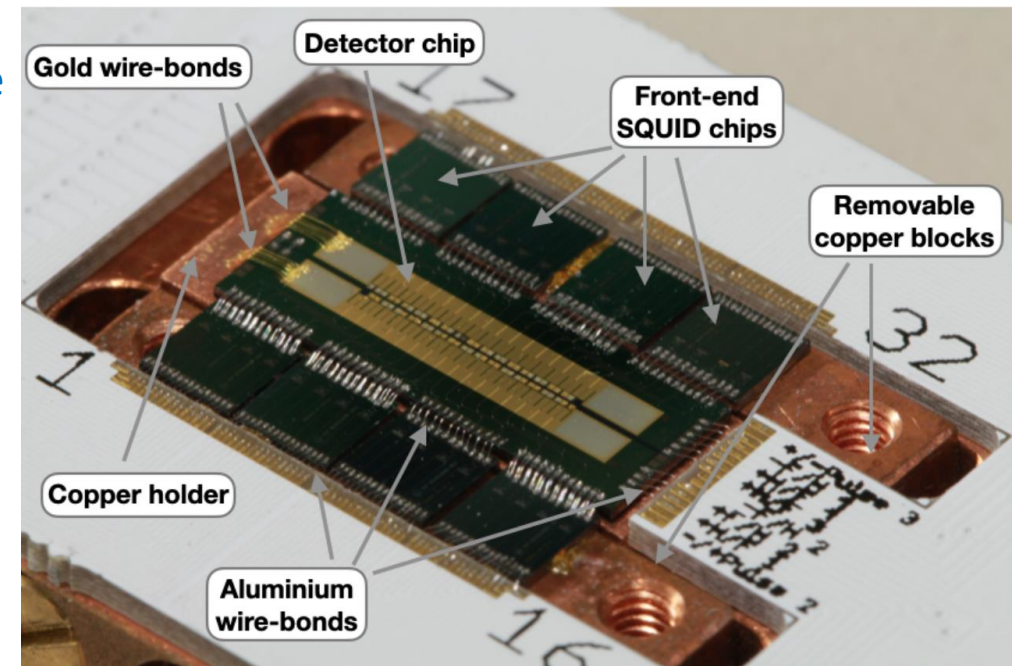
small power dissipation on detector SQUID chip (voltage bias 1st stage)



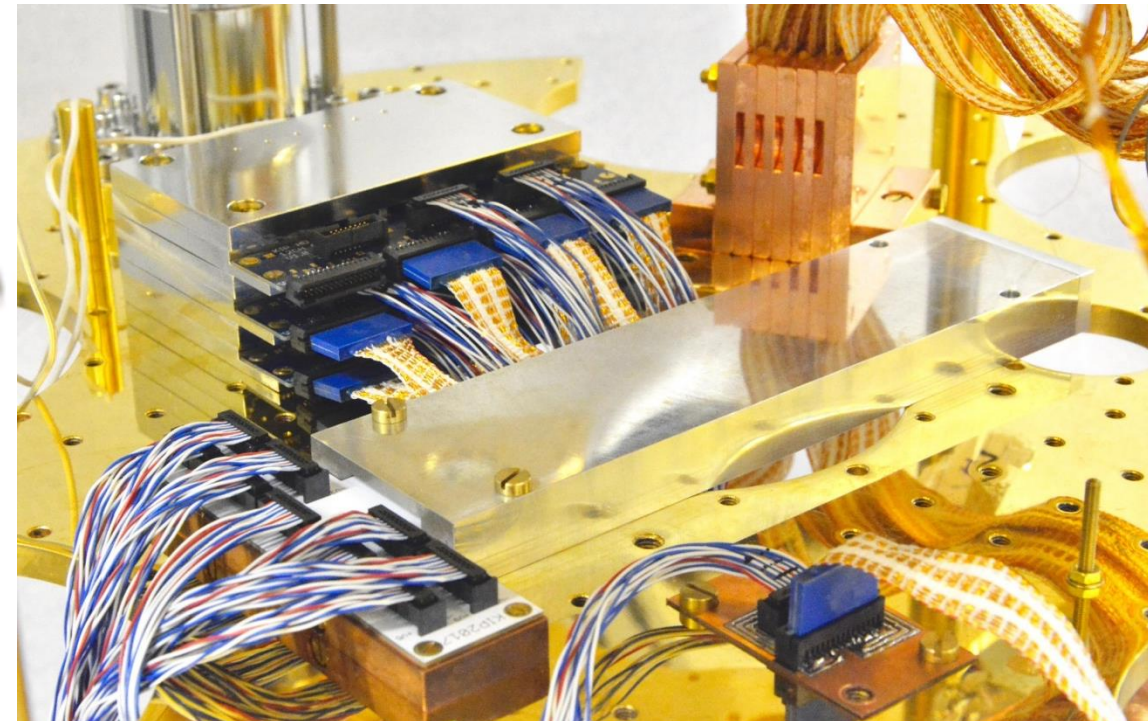
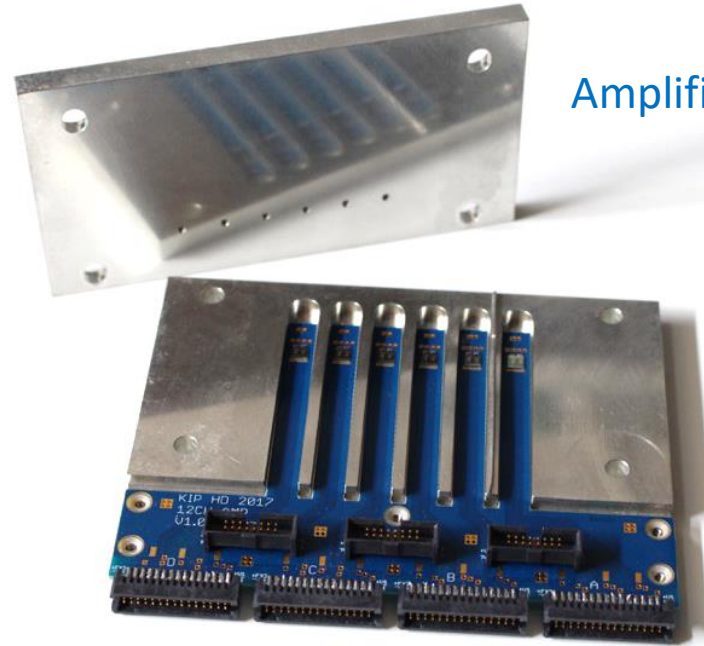
In house produced SQUID array

MMC readout

Detector module

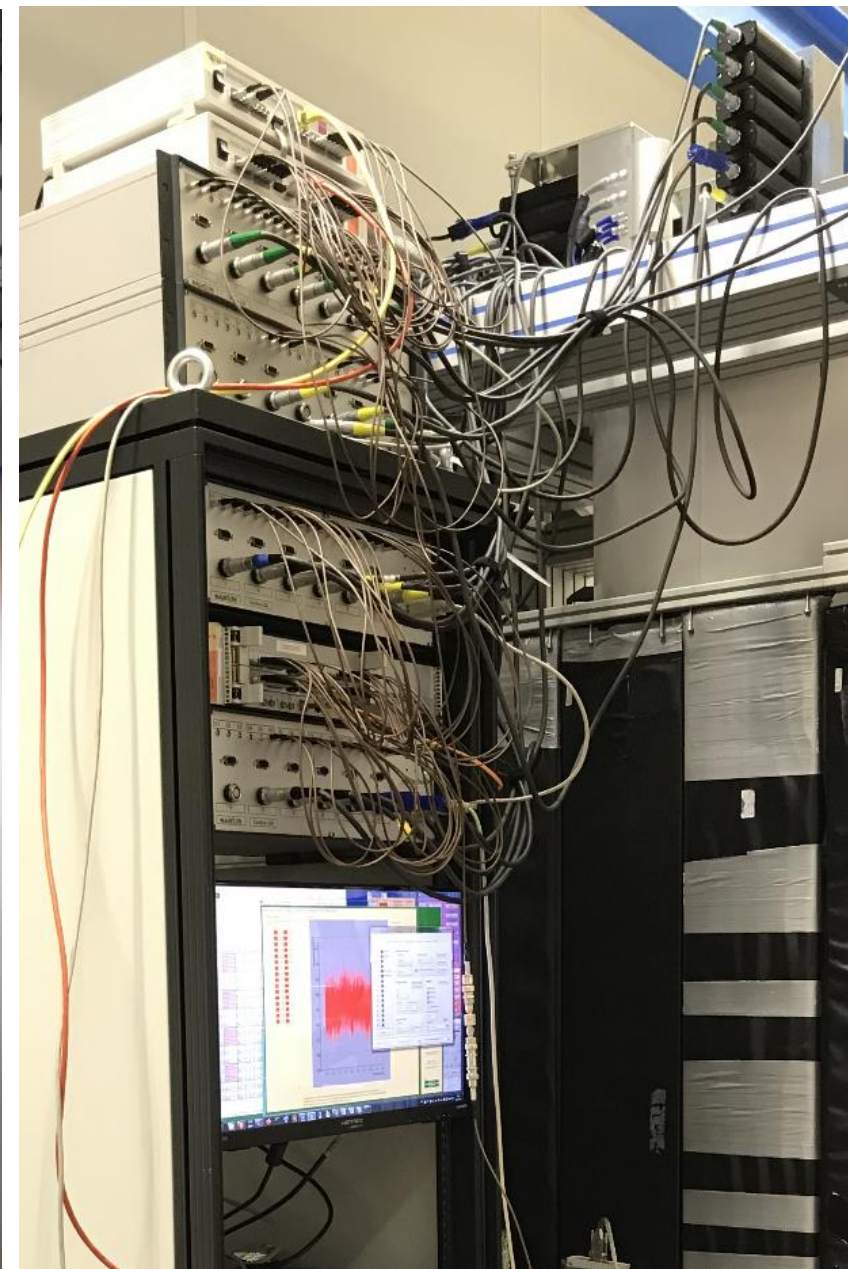
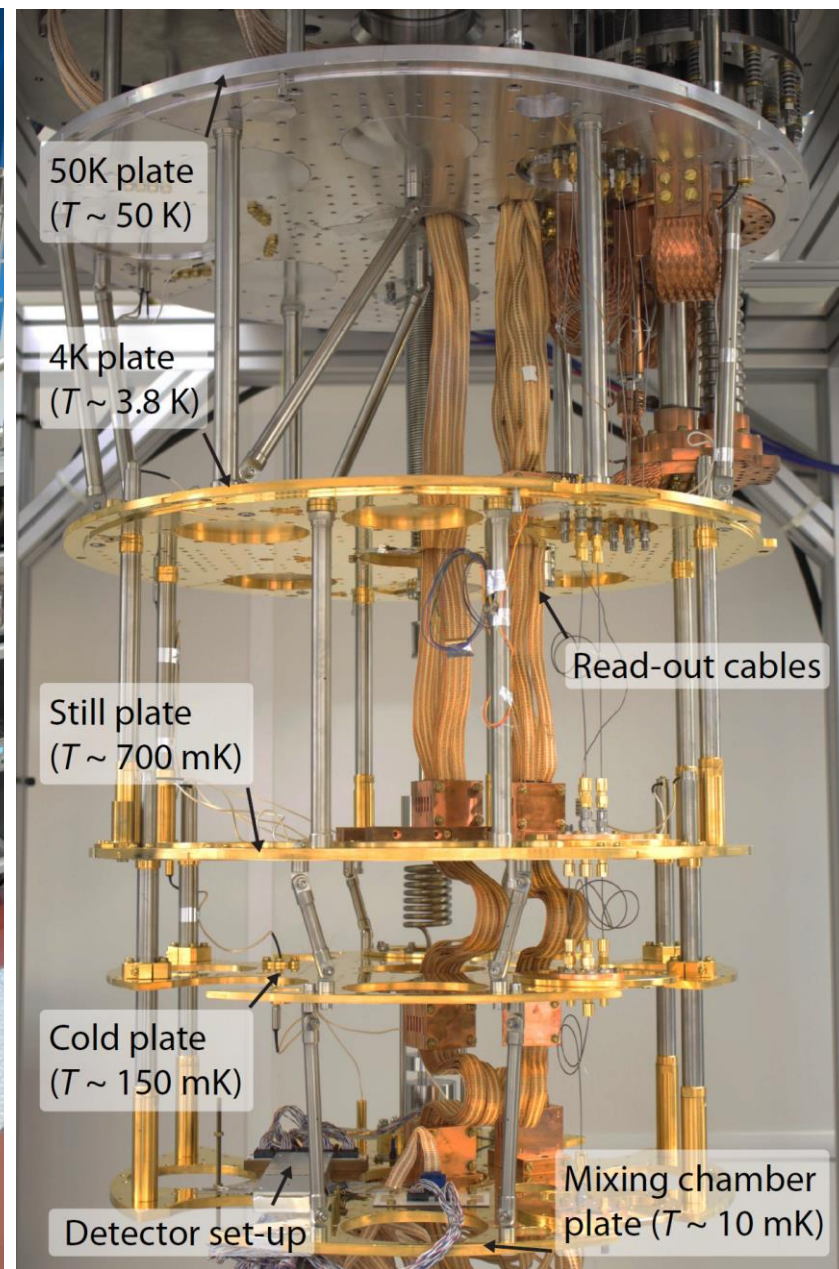
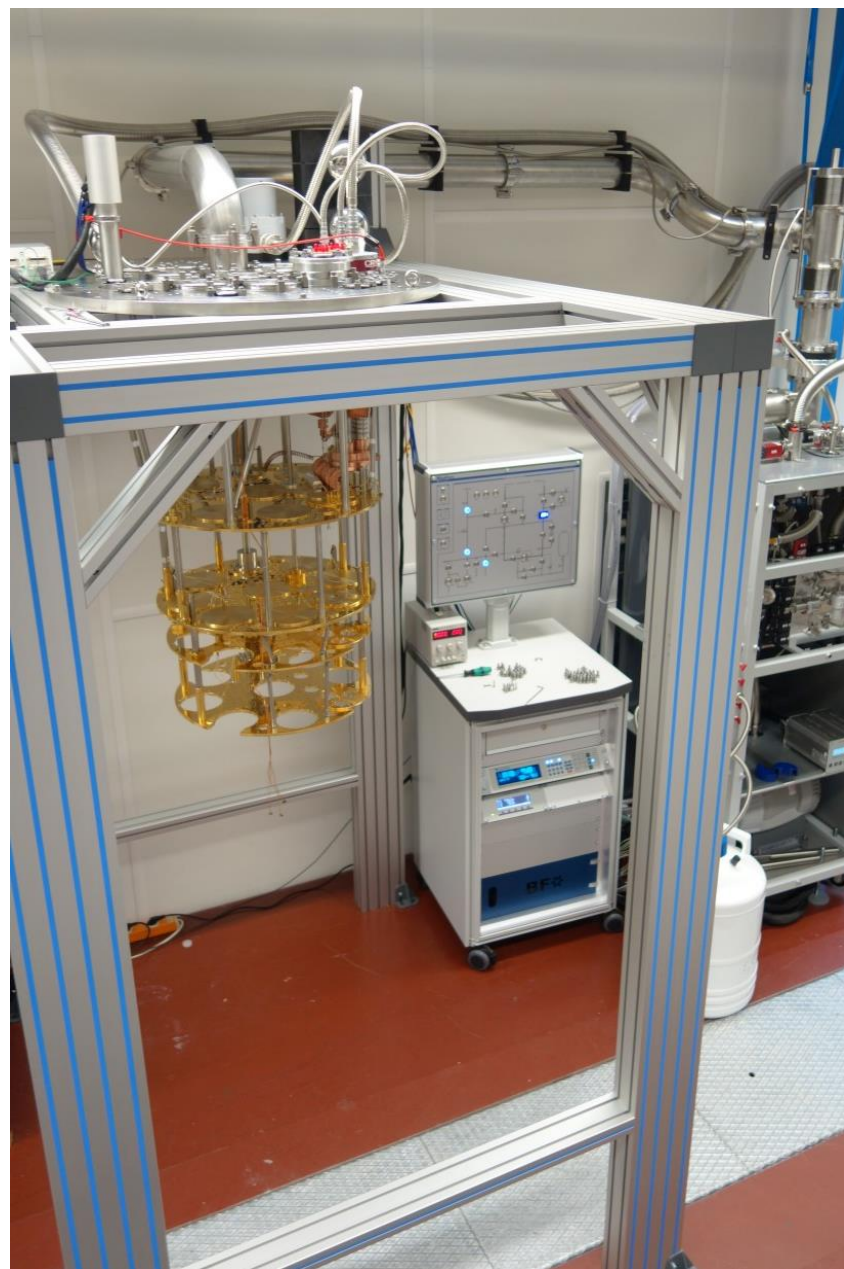


Amplifier module

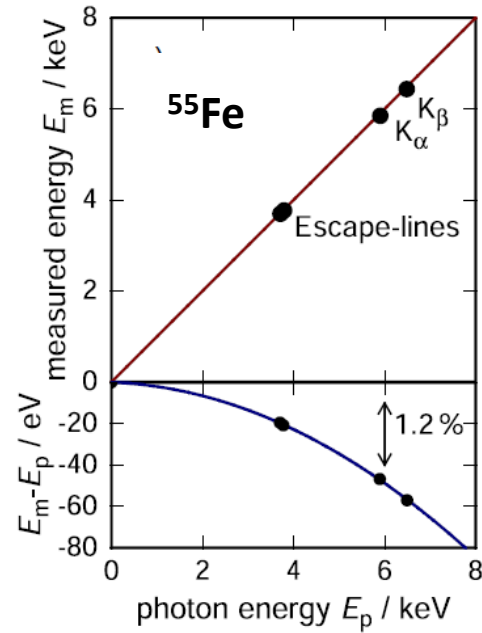
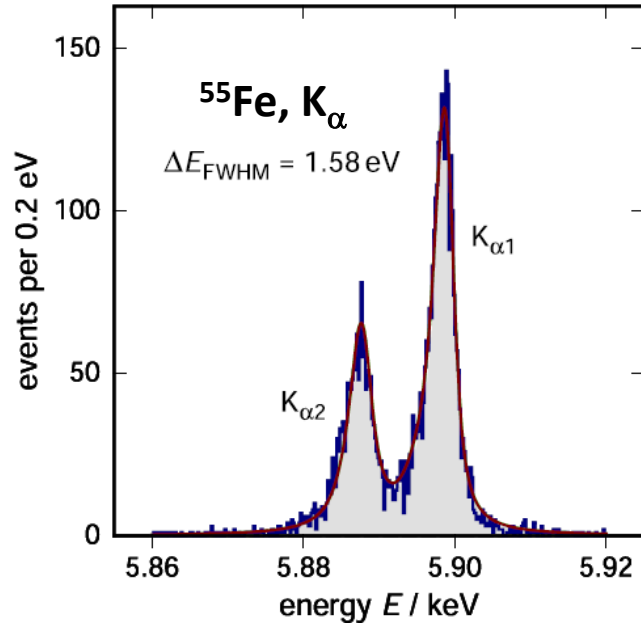
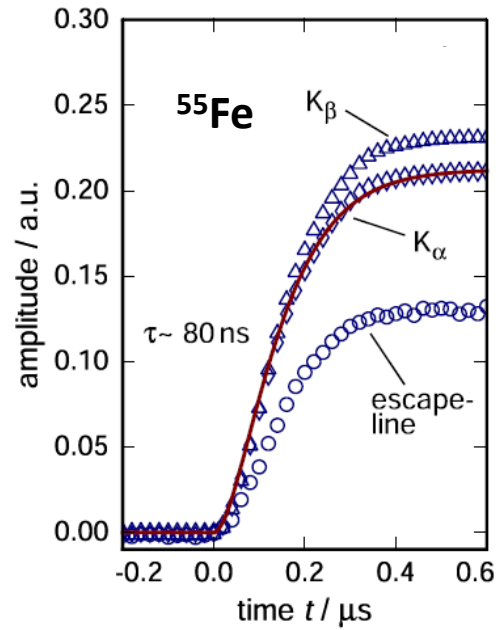


Detector and amplifier module mounted on the mixing chamber plate

MMC readout



Performance



Fast risetime

→ Reduction un-resolved pile-up

Extremely good energy resolution

→ identification of small structures

Excellent linearity

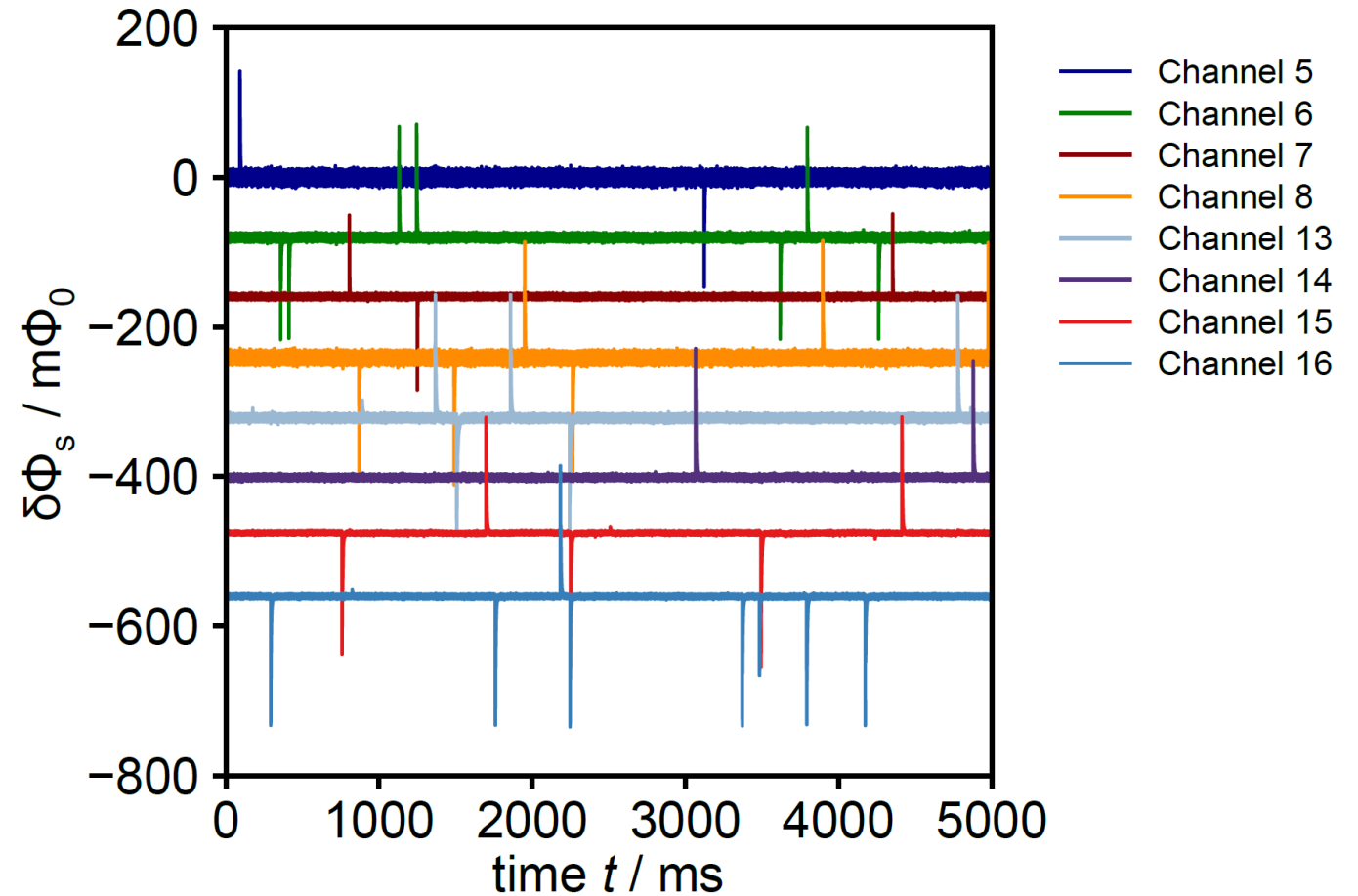
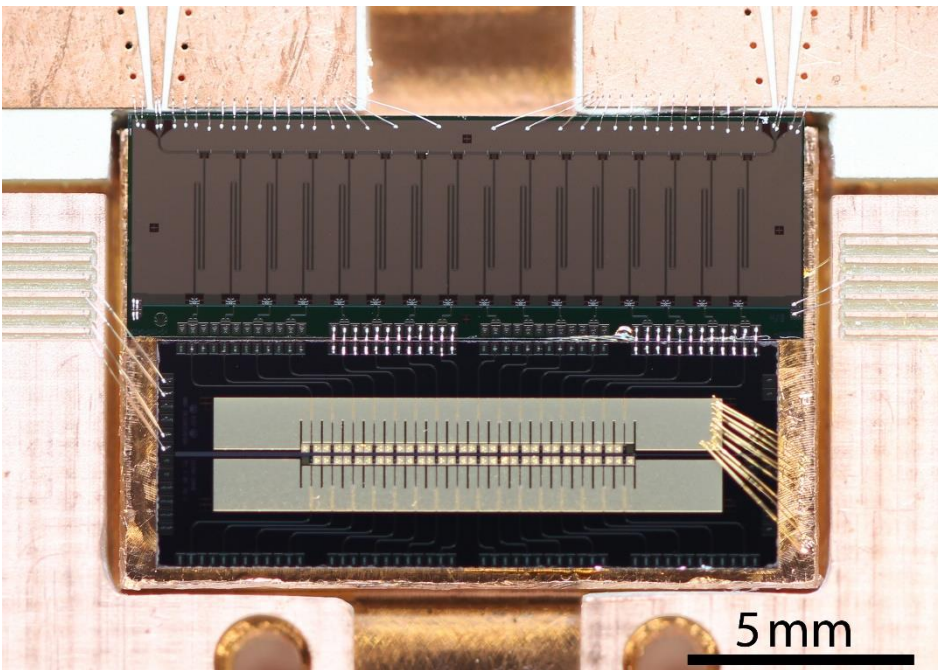
→ precise definition of the energy scale

MMC readout – Multiplexing R&D

Microwave SQUID multiplexing

Single HEMT amplifier and 2 coaxes
to read out **100 - 1000** detectors

- Successful characterization of first prototypes with external ^{55}Fe
→ **Very promising results:**
8 channels (16 pixels)



Energy resolution **below 10 eV FWHM** has been reached

MMC fabrication

40 m² Cleanroom class 100
at Kirchhoff Institute for Physics

Wet bench
Chemistry bench
Maskless aligner
UHV sputtering system
Dry etching system

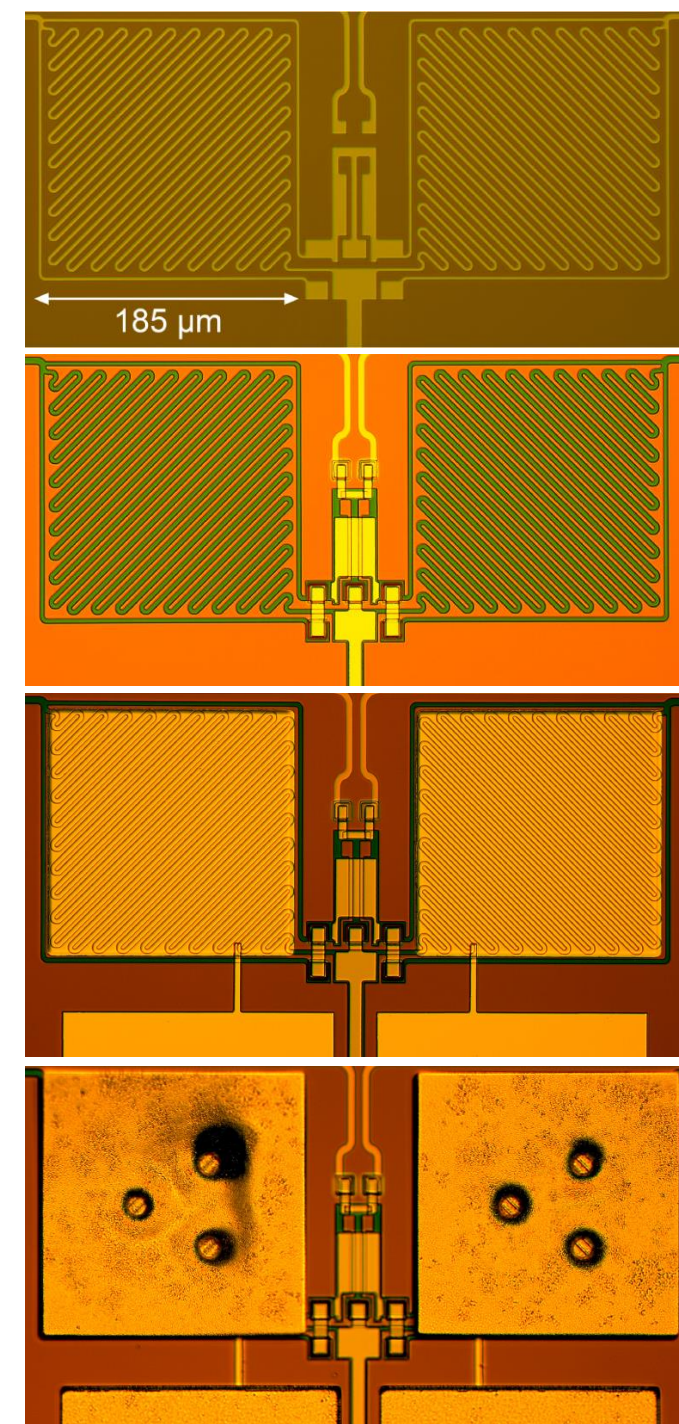
- Flexibility in design and fabrication
- Reliable processes for thin films
- Production of MMC array and superconducting electronics

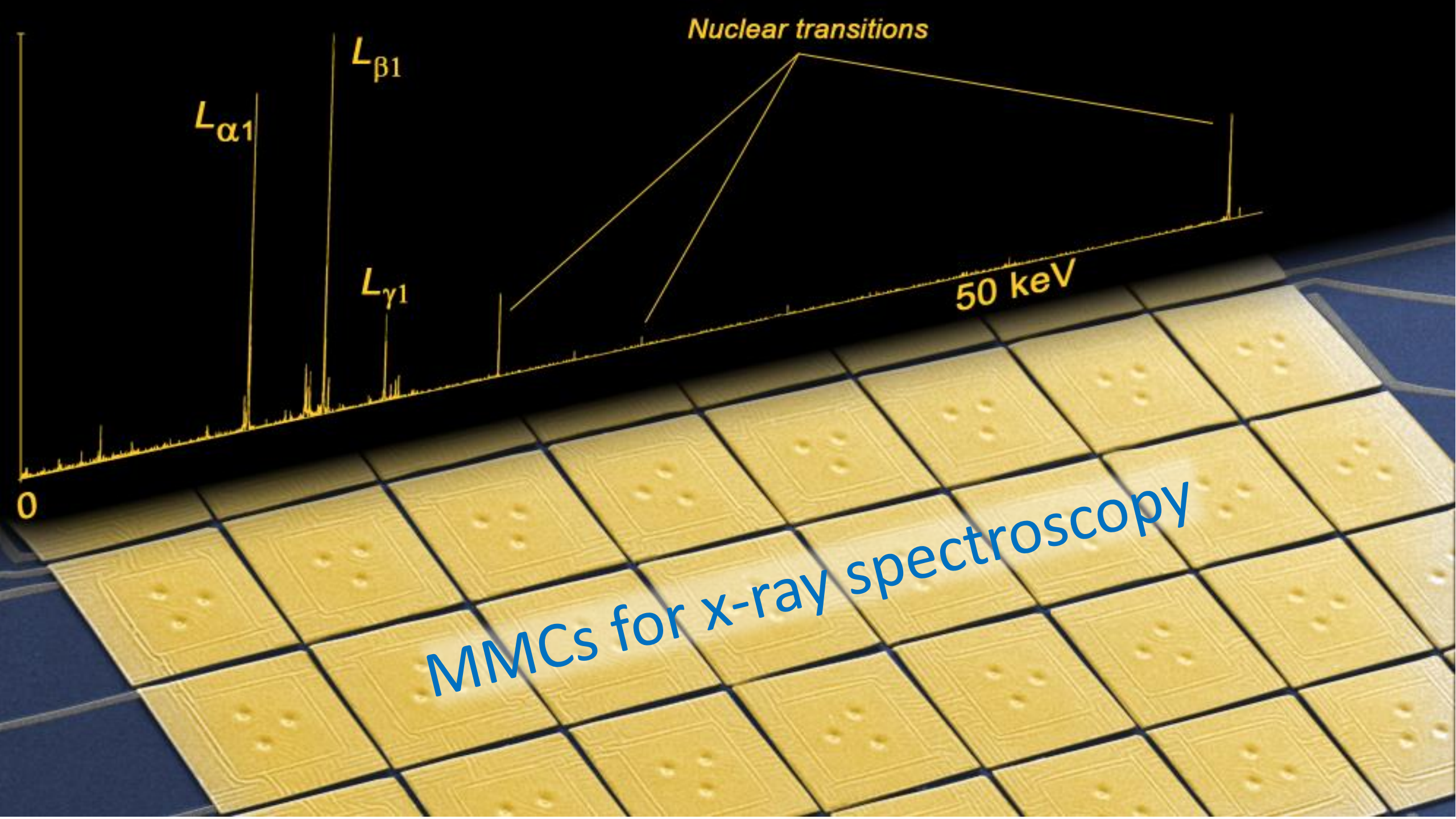


MMC fabrication

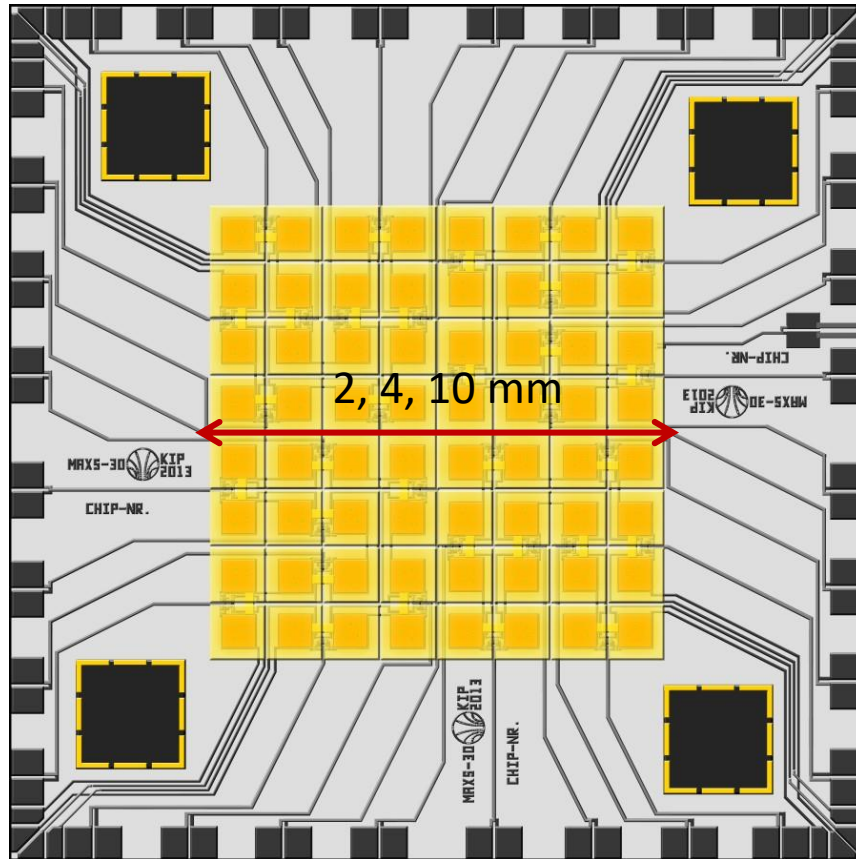
ECHo-100k wafer

Fabrication steps				
#	Layer	Material	Thickness	Deposition technique
1	Pick-up coils, SQUID lines (layer 1)	Nb	250 nm	Sputtering + etching
2	Isolation	Nb ₂ O ₅	-	Anodisation
3	Isolation	SiO ₂	175 nm	Sputtering + lift-off
4	Isolation	SiO ₂	175 nm	Sputtering + lift-off
5	Heaters	AuPd	150 nm	Sputtering + lift-off
6	SQUID lines (layer 2)	Nb	600 nm	Sputtering + lift-off
7	Sensor	AgEr	480 nm	Sputtering + lift-off
8	Thermalisation	Au	300 nm	Sputtering + lift-off
9	Stems	Au	100 nm	Sputtering
10	Absorber - 1st layer	Au	3 μm	Electroplating + lift-off
11	¹⁶³ Ho host material	Ag	100 nm	Sputtering
12	¹⁶³ Ho implantation	¹⁶³ Ho	-	Ion-implantation
13	¹⁶³ Ho host material	Ag	100 nm	Sputtering + lift-off
14	Absorber - 2nd layer	Au	3 μm	Sputtering + lift-off





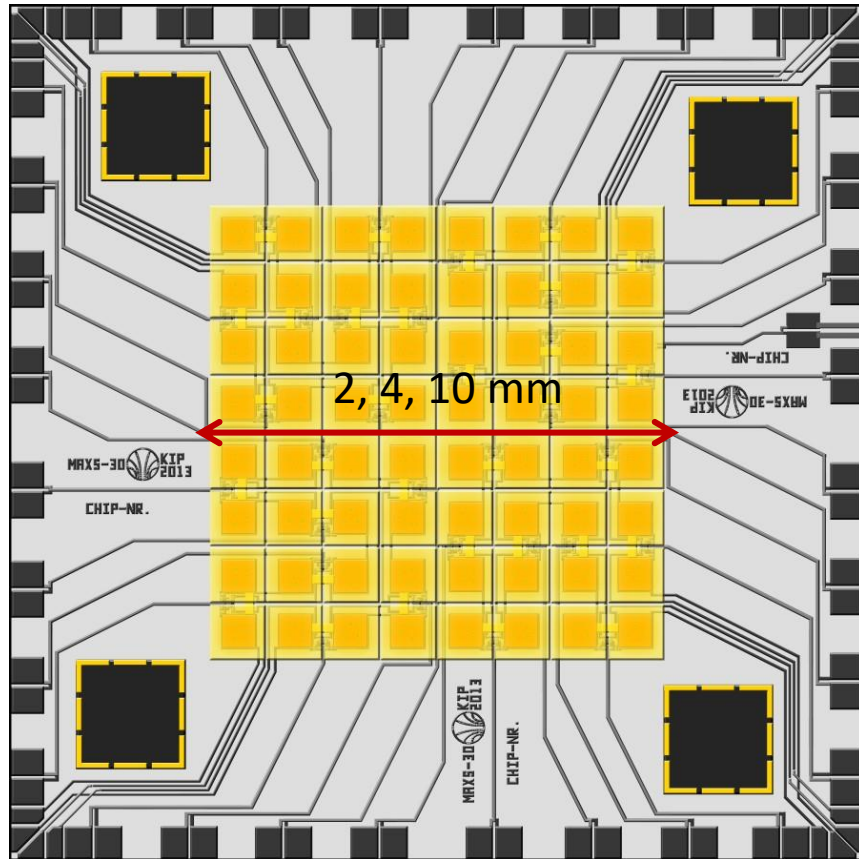
Microcalorimeter arrays for X-rays spectroscopy - maXs



maXs-20/30/100:

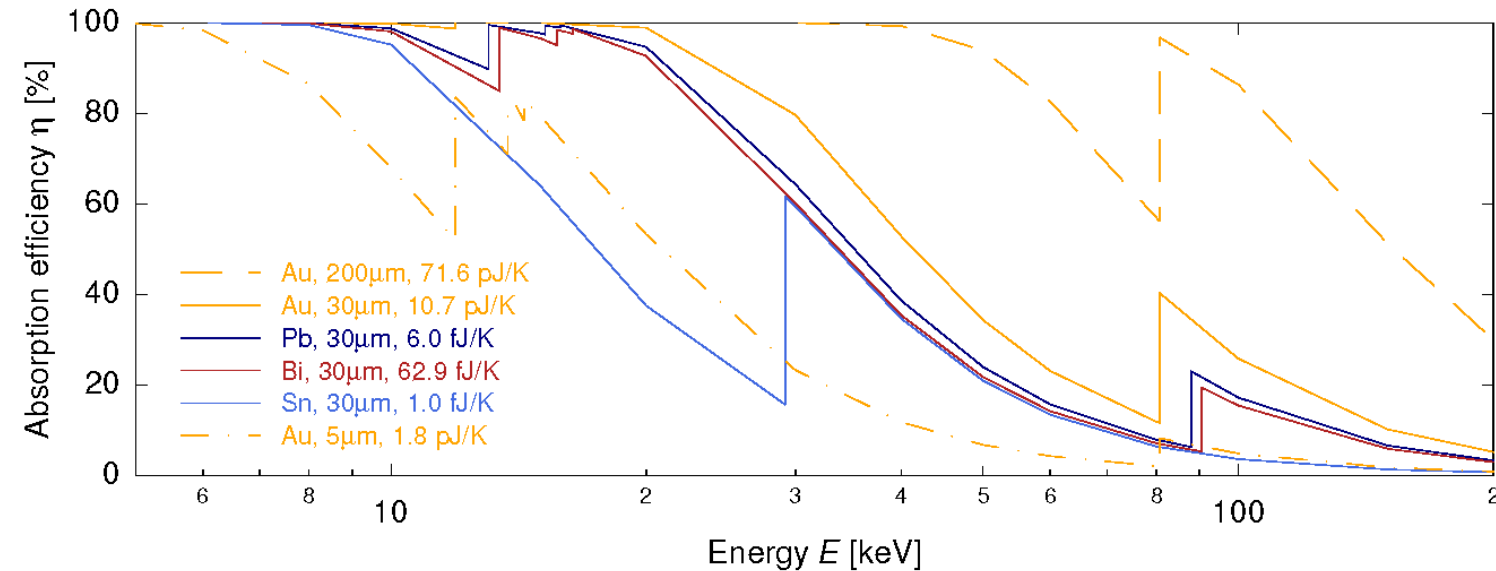
- 8×8 pixels for photons up to 20/30/100 keV
- with $\Delta E_{\text{FWHM}} = 2/5/30$ eV
- 32 two-stage dc-SQUIDs

Microcalorimeter arrays for X-rays spectroscopy - maXs



Absorber material and thickness selected for optimal absorption efficiency

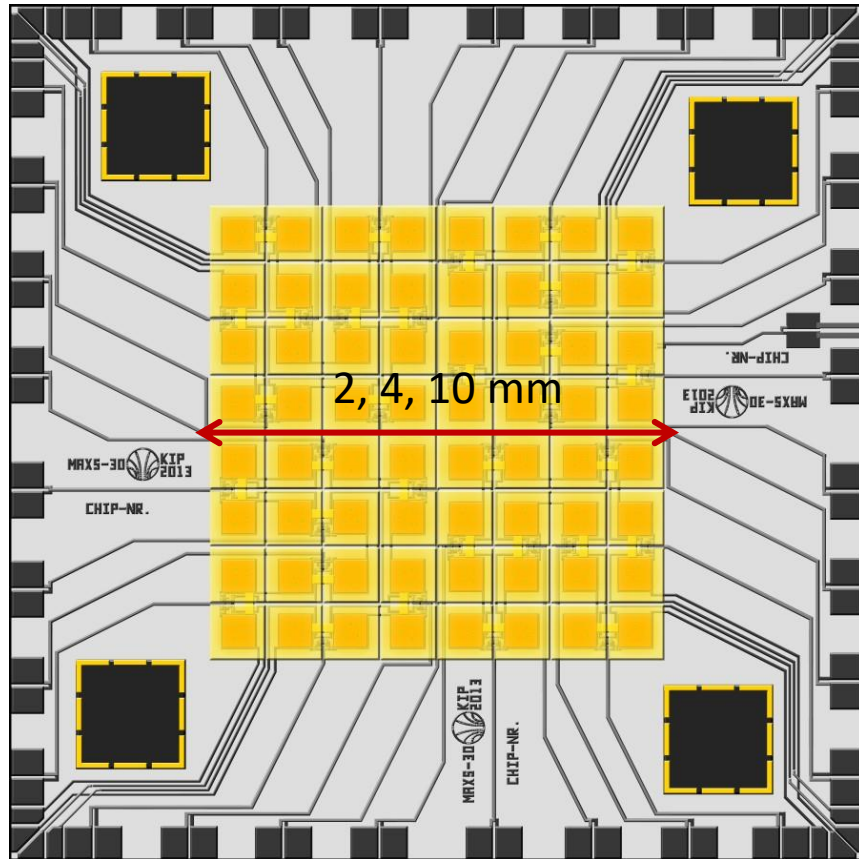
For maXs → electroplated gold



maXs-20/30/100:

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- 32 two-stage dc-SQUIDs

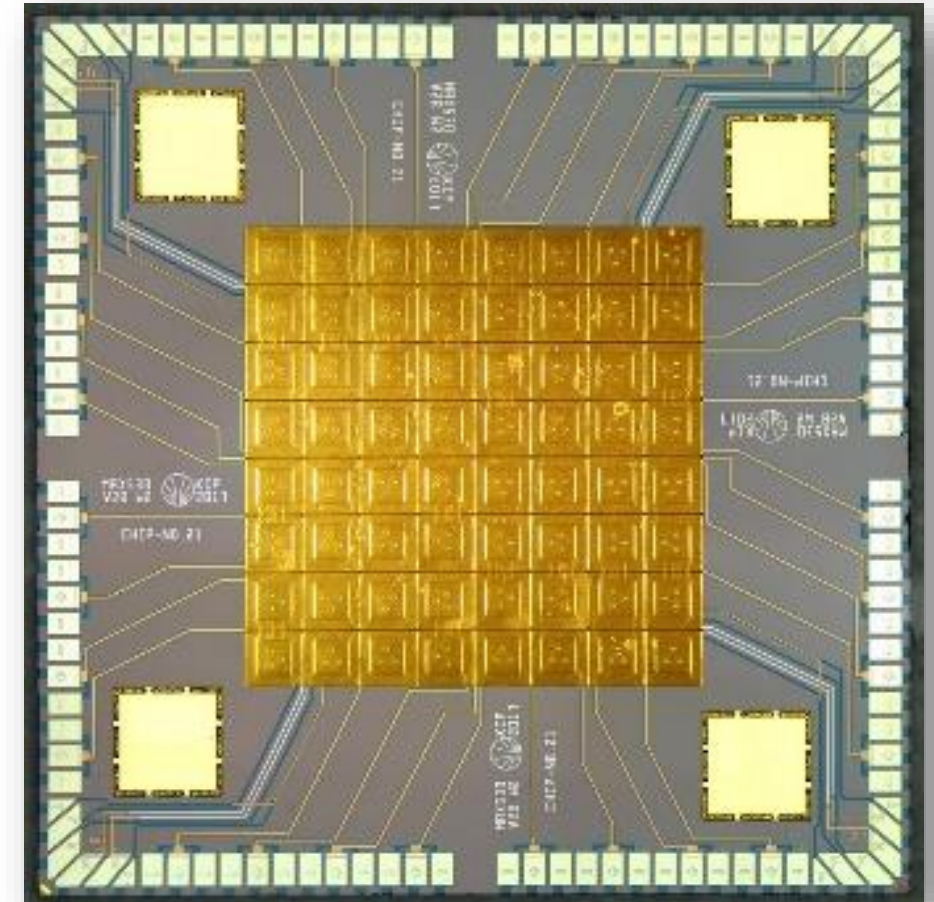
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Hengstler, PhD Thesis, Kirchhoff-Institute for Physics, Heidelberg University (2018)

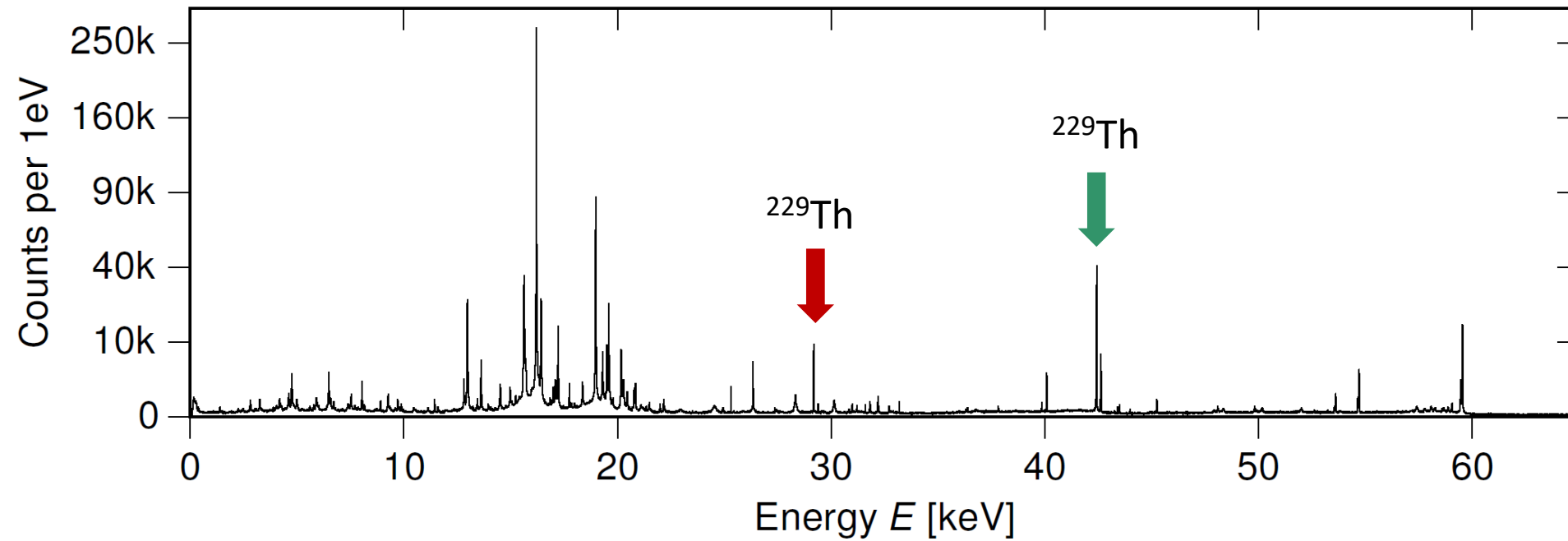


8 mm

maXs-30

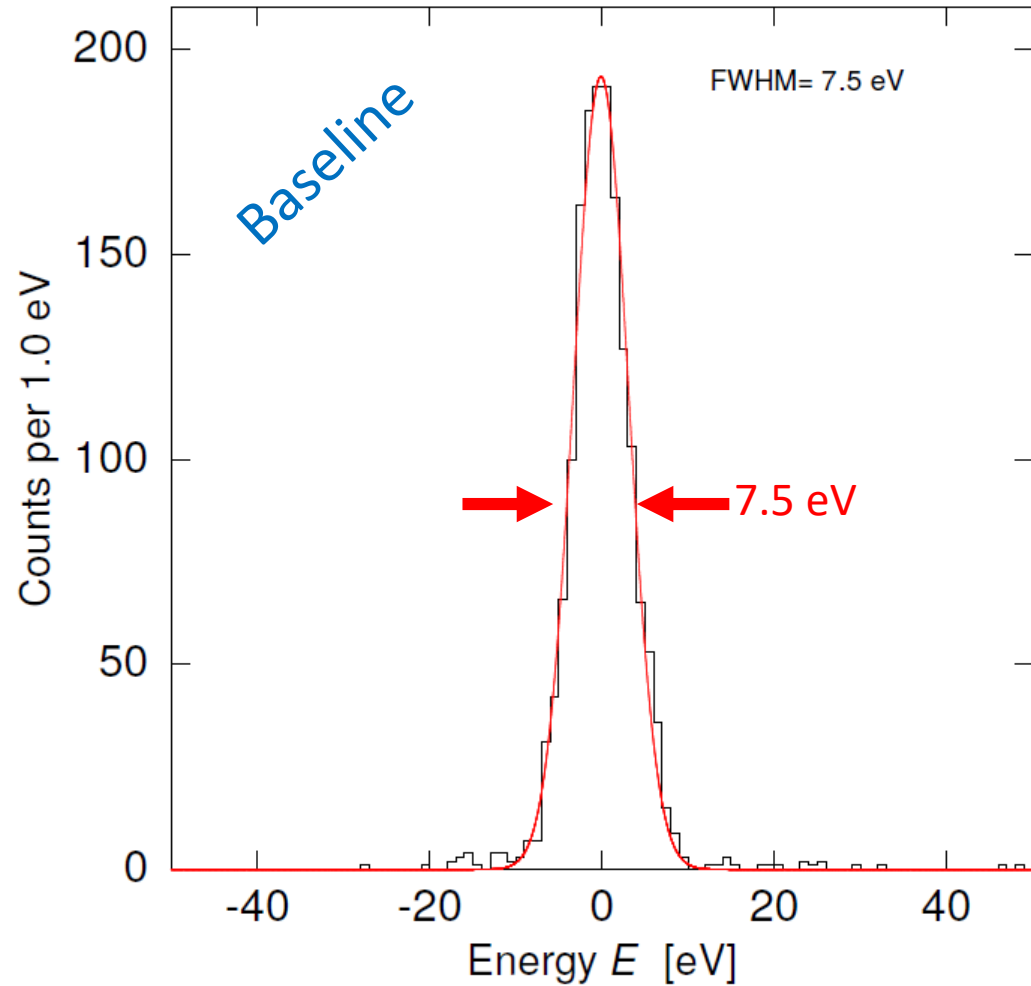
Absorber size: $500 \times 500 \times 30 \mu\text{m}^3$

maXs-30 with ^{241}Am + ^{233}U external sources

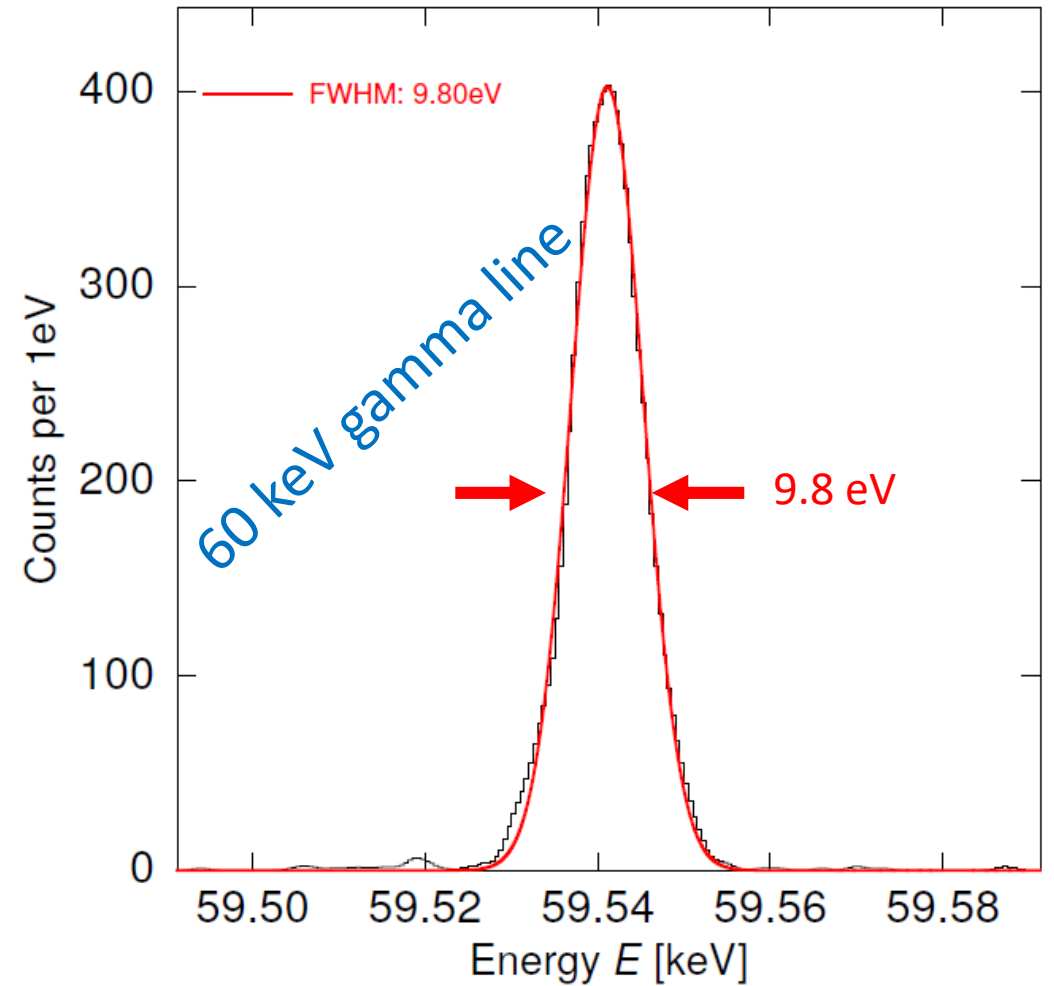


Co-added 20 channels, several weeks

maXs-30 with ^{241}Am + ^{233}U external sources



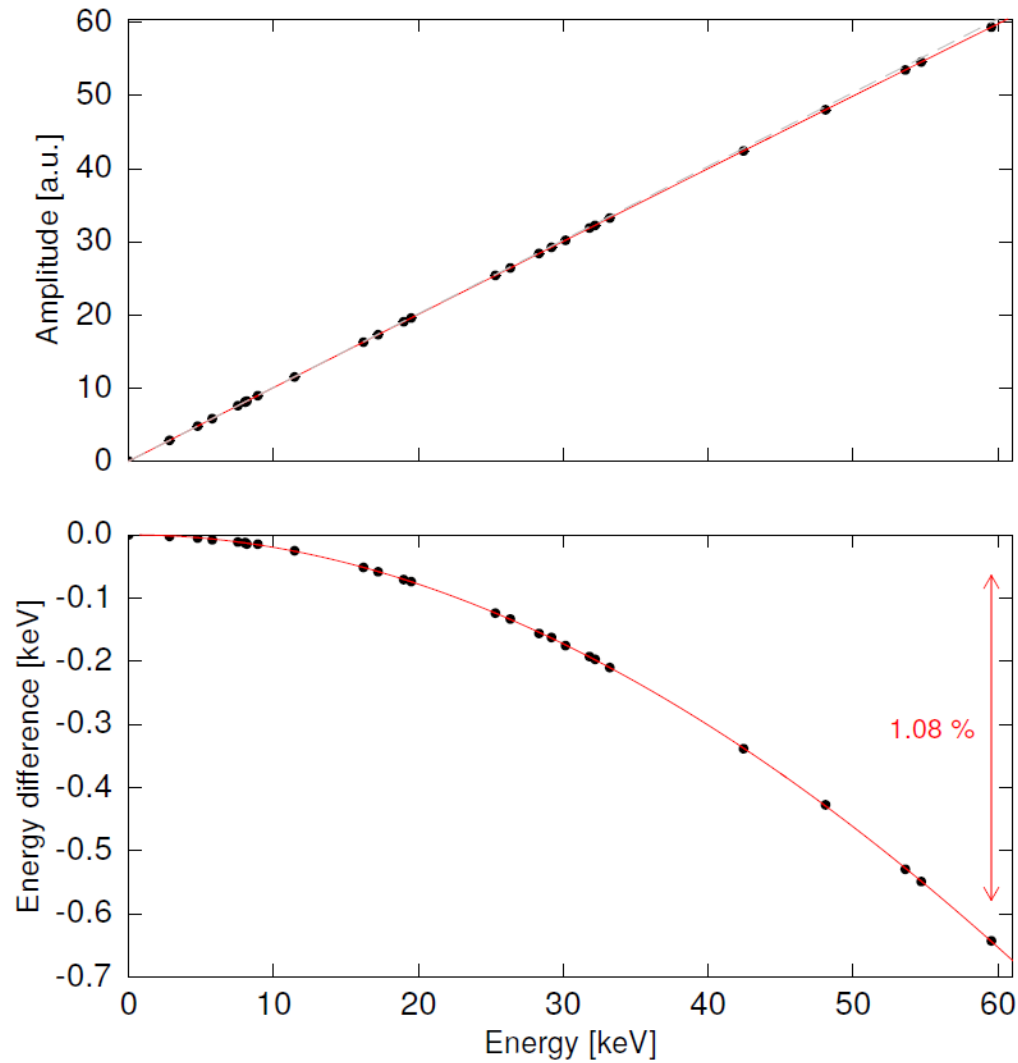
Very close to design value



Energy resolution $\Delta E_{\text{FWHM}} = 9.8 \text{ eV @ } 59 \text{ keV}$

World record resolving power: 6000

maXs-30 set-up - ^{241}Am + ^{233}U external sources

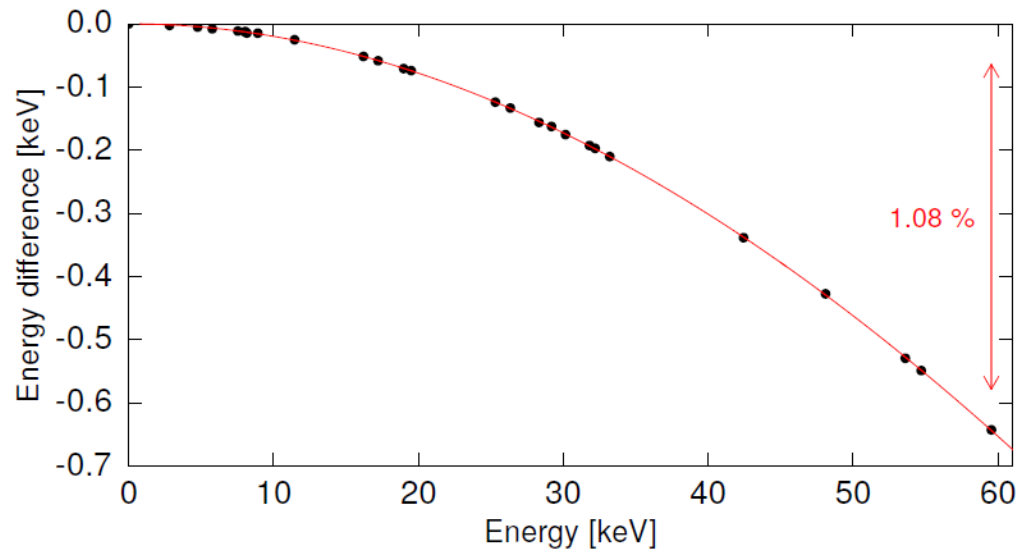
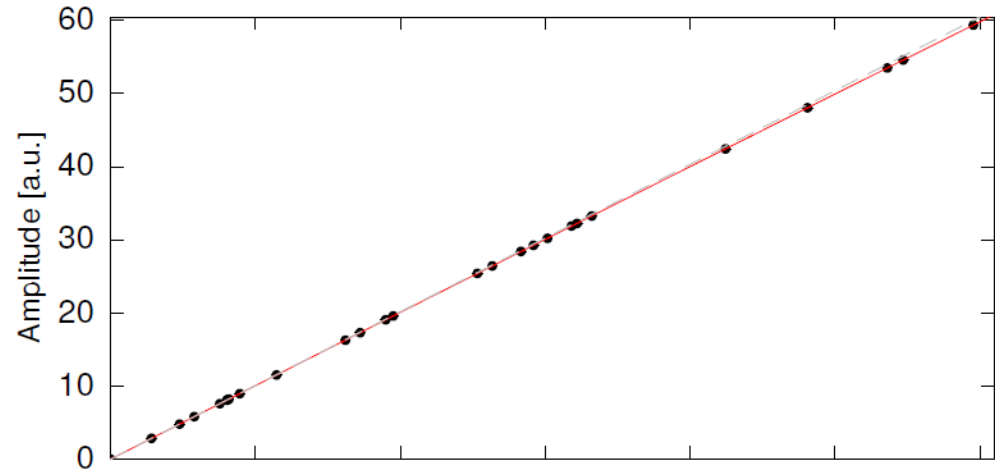


Energy calibration

- Polynomial function 2nd to 4th order
- Stable over long measuring time

non-linearity as expected from thermodynamics!

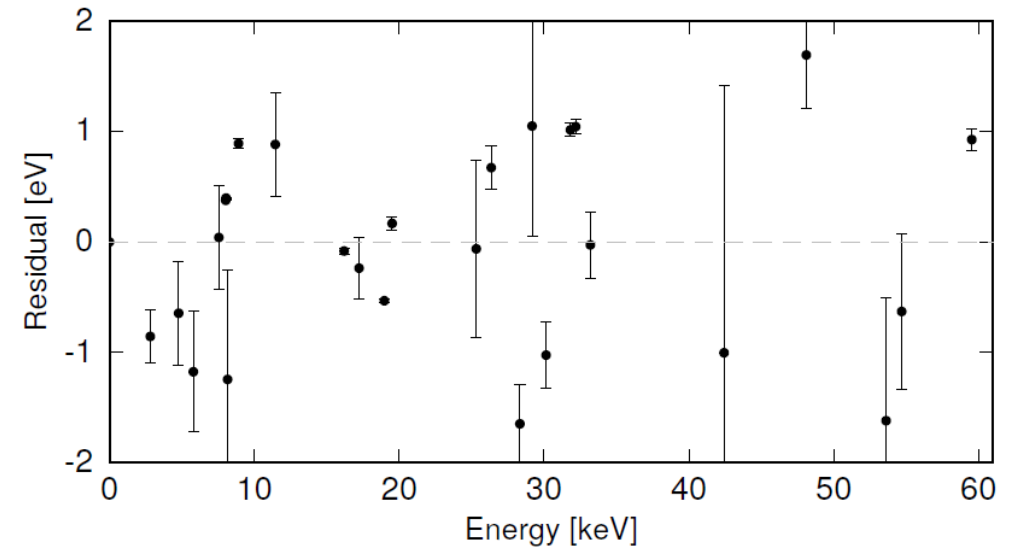
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Energy calibration

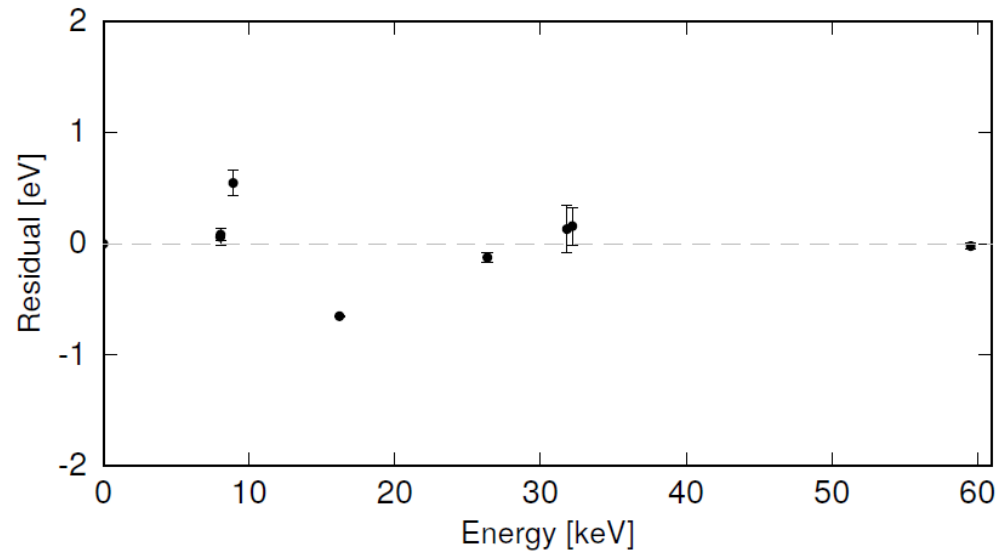
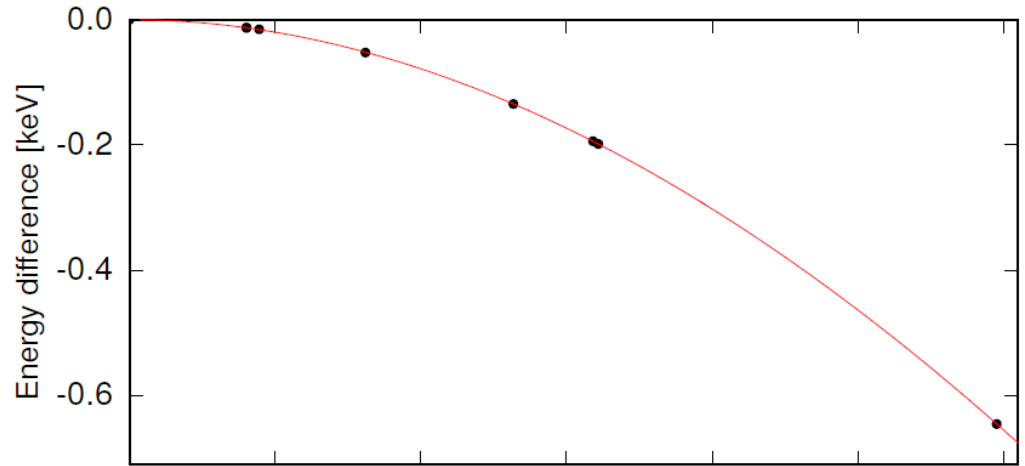
- Polynomial function 2nd to 4th order
- Stable over long measuring time

Most lines from literature have too large uncertainty!



non-linearity as expected from thermodynamics!

maXs-30 set-up - ^{241}Am + ^{233}U external sources

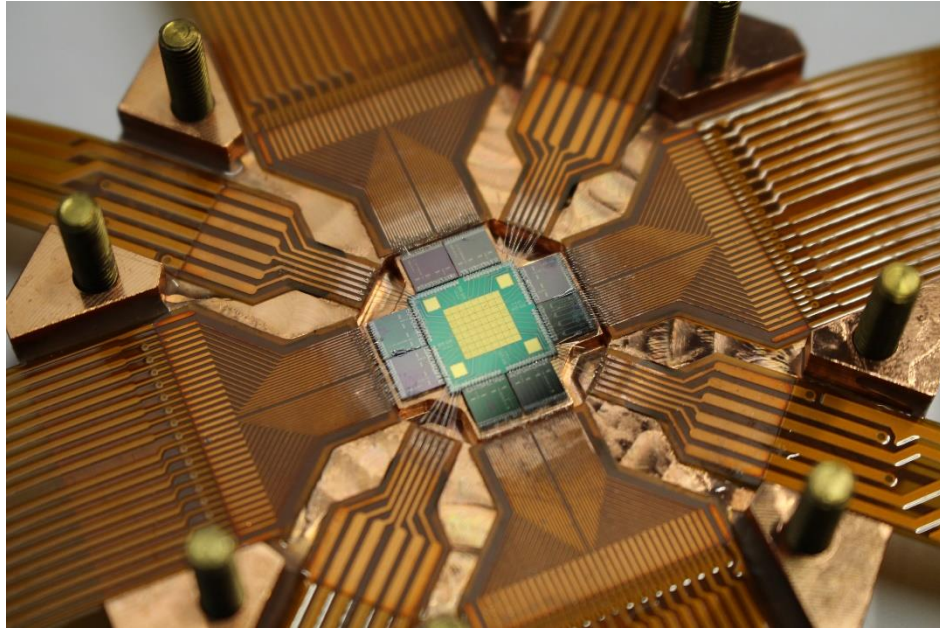


Energy calibration

- Polynomial function 2nd to 4th order
- Stable over long measuring time

Sub-eV agreement for carefully selected calibration lines.

maXs-30 set-up – for IAXO

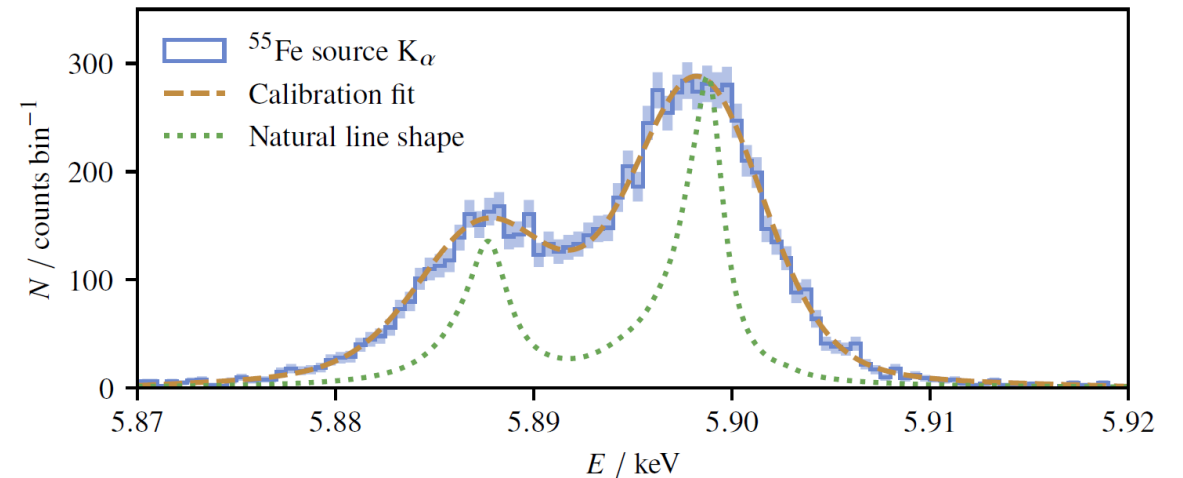
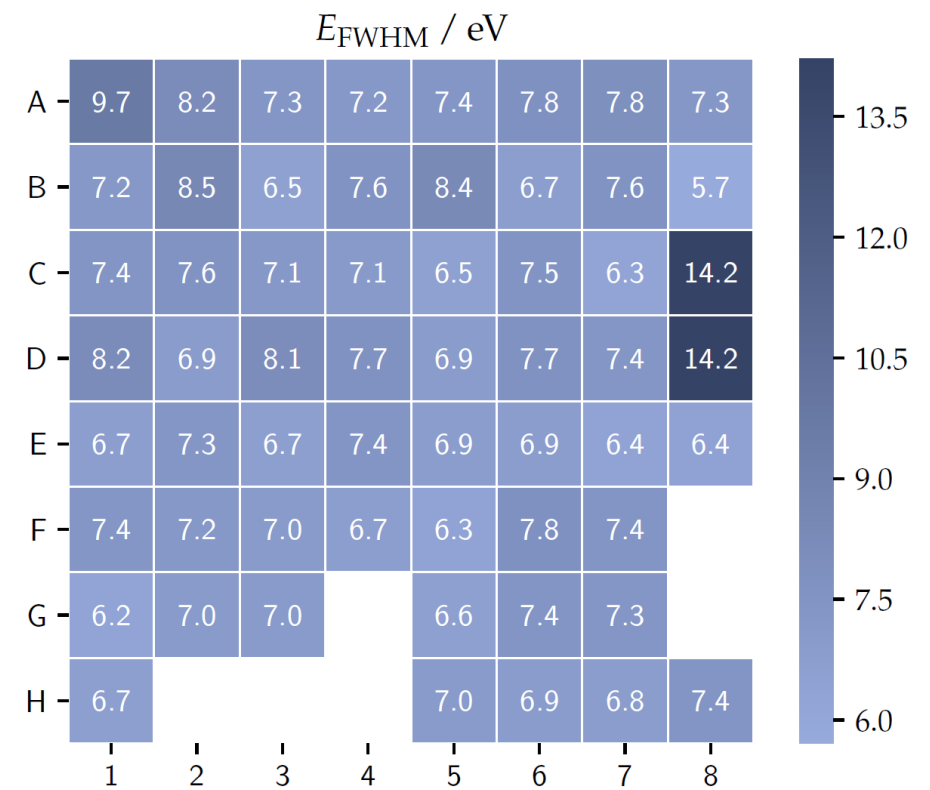


^{55}Fe calibration source

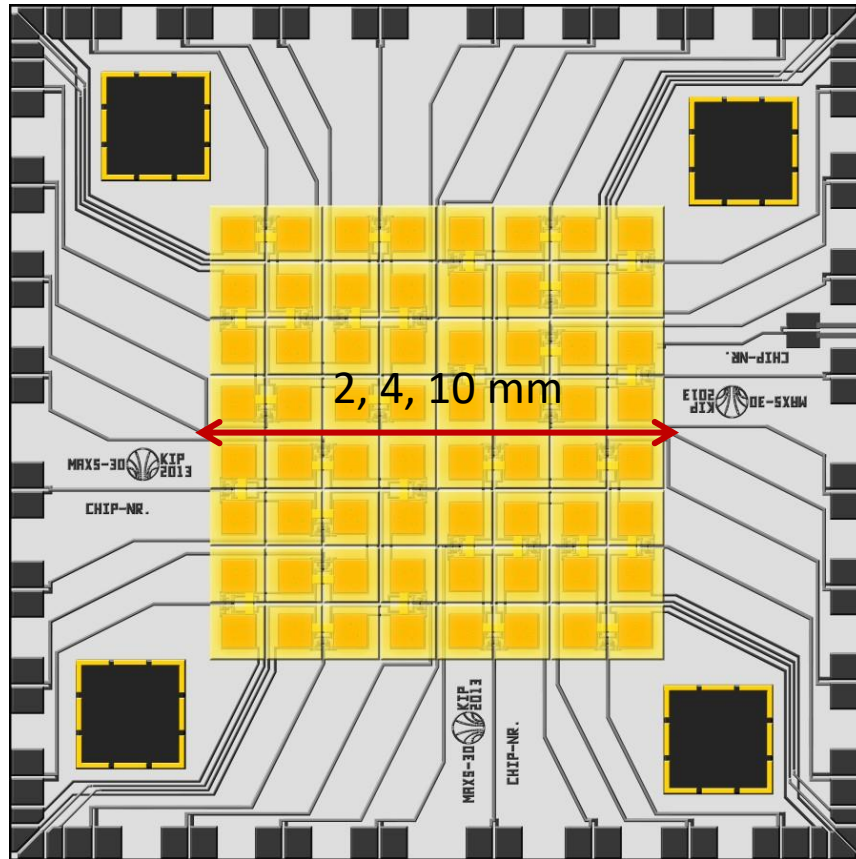
Stopping power @10 keV ~100%

- Homogeneous performance over the array
- Stable operation over 1 month

D. Unger et al., *JINST* **16** (2021) P06006,
[arXiv:2010.15348](https://arxiv.org/abs/2010.15348) [physics.ins-det]



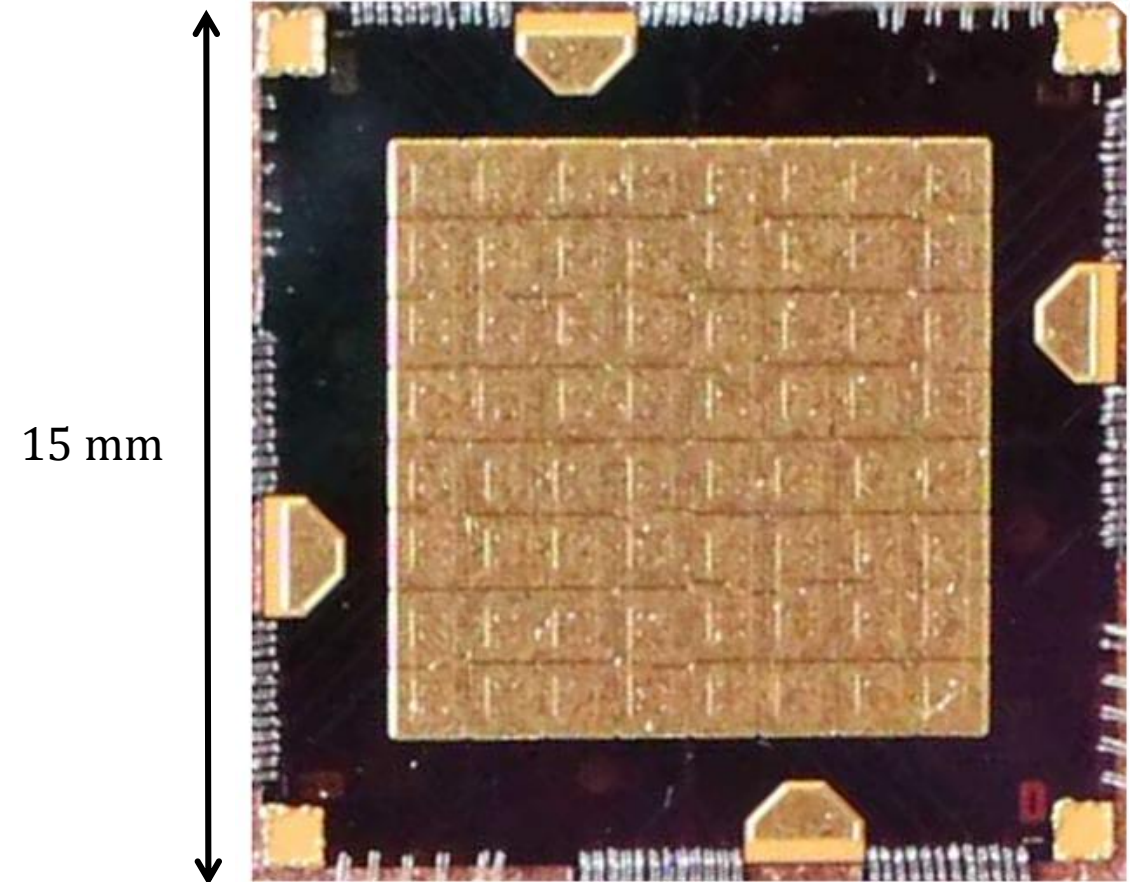
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Hengstler, PhD Thesis, Kirchhoff-Institute for Physics, Heidelberg University (2018)



maXs-100

- Active area 8x8 absorbers
Area 1 cm²
- 50 μm thick electroplated gold
→ 40 % stopping power @ 100 keV

maXs-100 for highly ionized heavy ions

Study of **heavy, highly-charged** ions allows

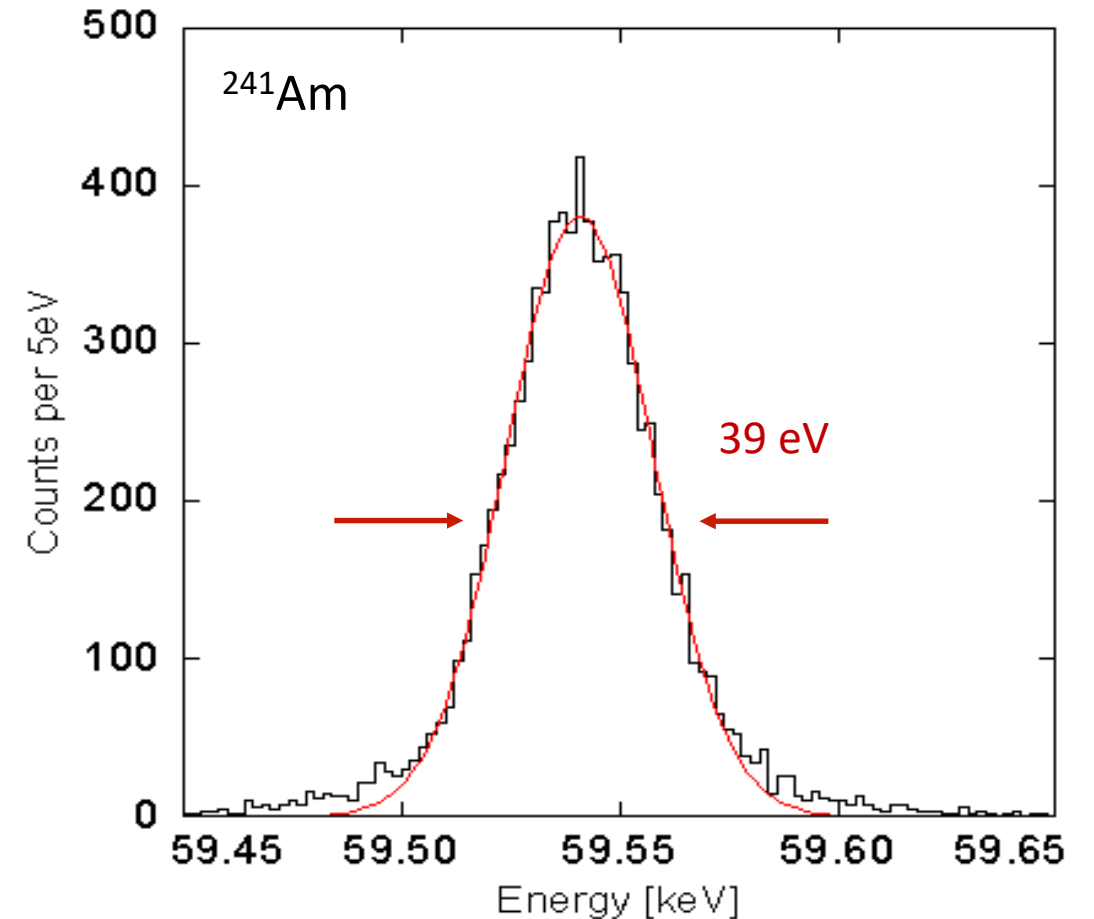
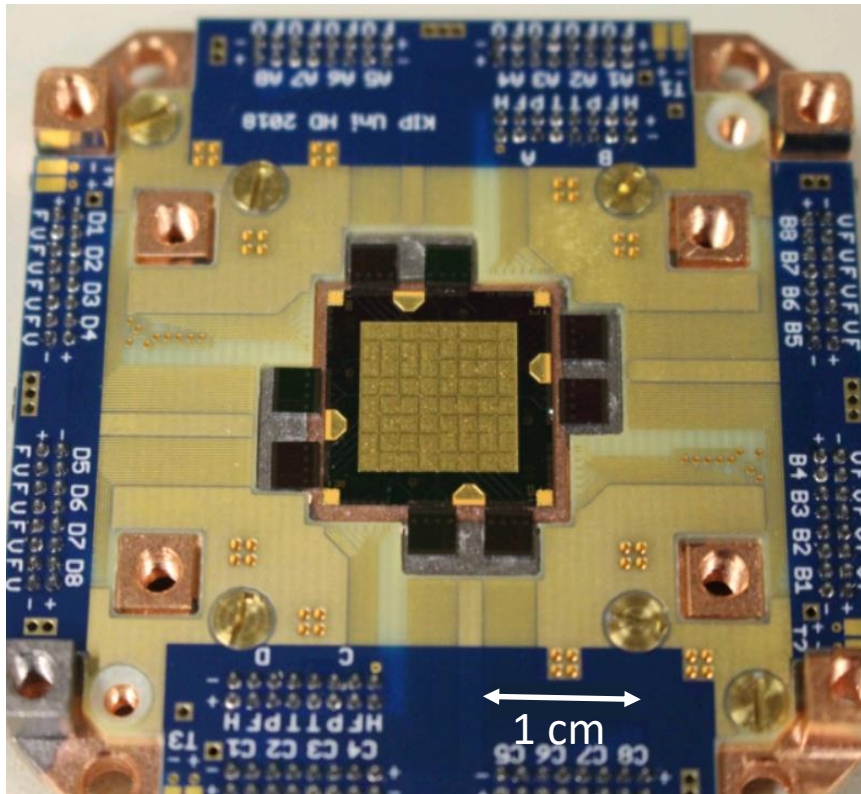
high precision QED measurements in extreme E-fields

→ spectroscopy of **H-like** and **He-like Uranium** ions

Signal rise time limited to $\tau=8 \mu\text{s}$

→ Prevents position-dependent pulse shape

39 eV (FWHM) @ 60 keV (co-added spectrum from 30 pixels)



Experimental configuration @ GSI

Electron cooler

- Superimpose **electron** and **ion beam**
- Reduce momentum spread
- $U^{91+} + e^- \rightarrow U^{90+} + \gamma$

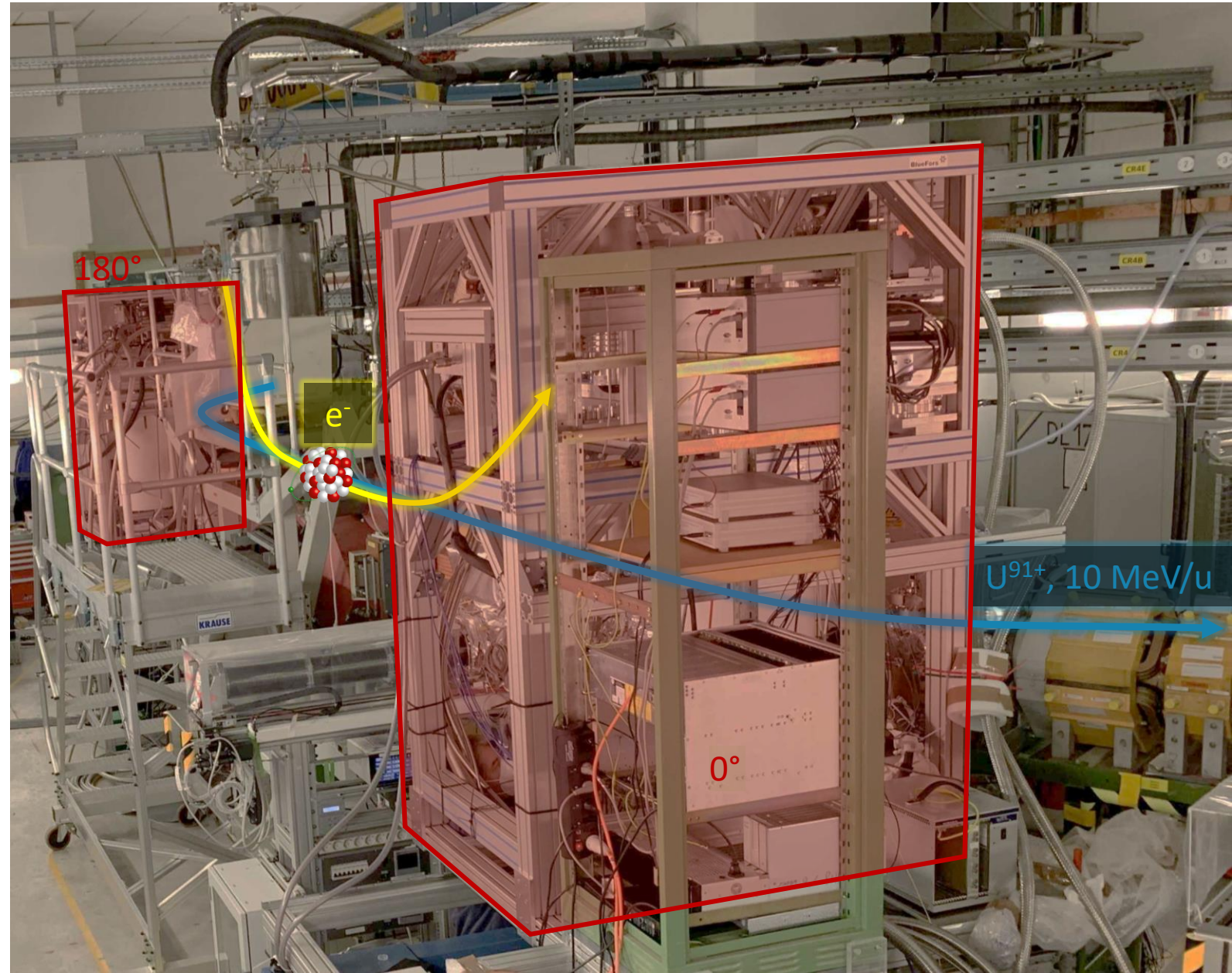
2 detector systems

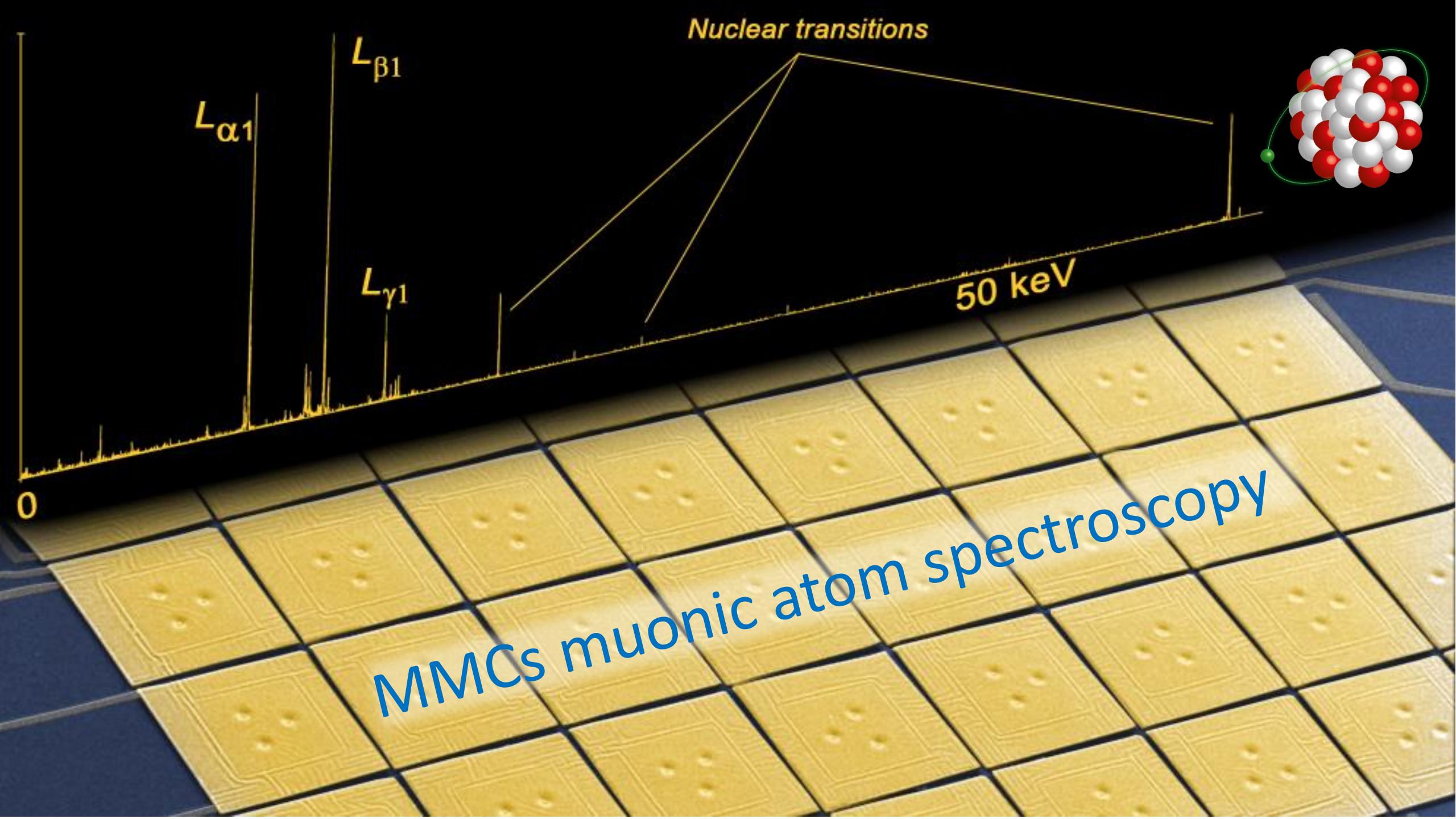
- At 0° and 180° scattering angle
- 13 keV red shift @ 180°
- 15 keV blue shift @ 0°
- intrinsic Doppler shift correction

2x maXs100

- In total 102/128 pixels operated
- Energy resolution
 - 80 eV FWHM @ 122 keV
 - 60 eV FWHM @ 122 keV

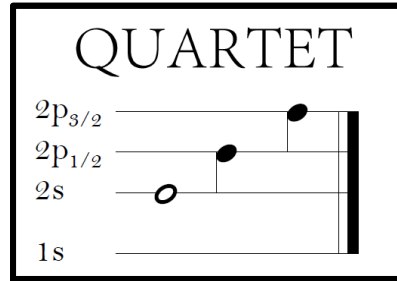
Composite calibration source





MMCs muonic atom spectroscopy

QUARTET*



Precise measurement of absolute **nuclear charge radii**

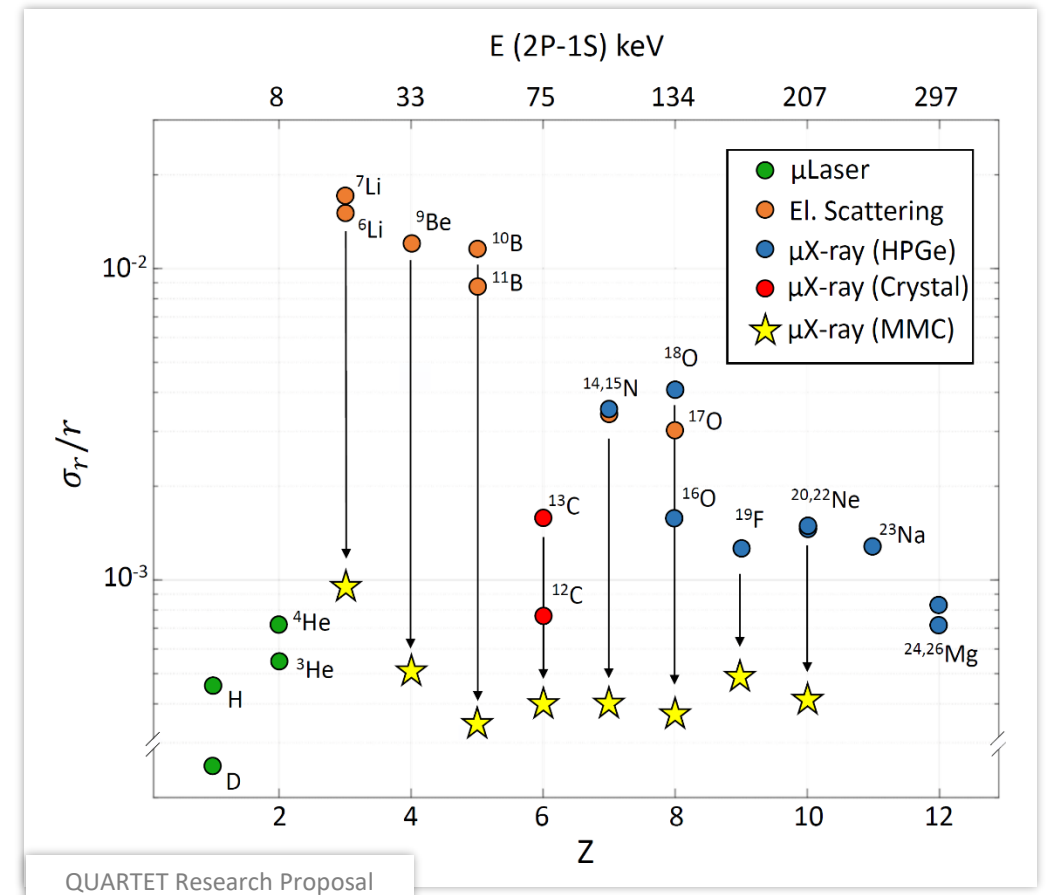
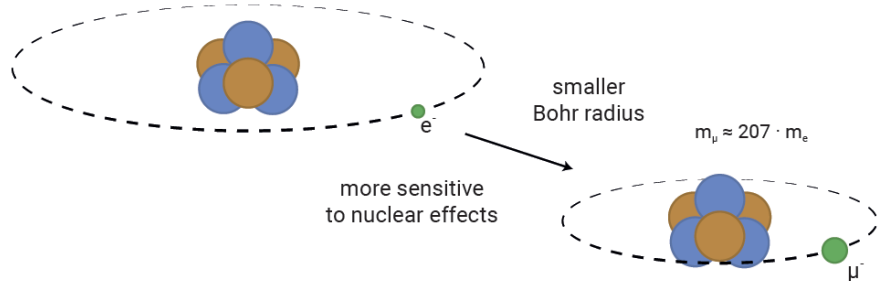
→ test of nuclear theory

→ essential input parameter for QED tests

→ search for physics beyond the Standard Model

Large **accuracy gap** for $2 < Z < 11$

→ Improve precision of stable nuclei from ⁶Li to ²²Ne



QUARTET Research Proposal

* QUANTum inteRactions for Exotic aToms

QUARTET Collaboration

KU LEUVEN

JG|U

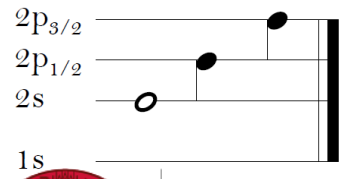
JOHANNES GUTENBERG
UNIVERSITÄT MAINZ

Laboratoire Kastler Brossel
Physique quantique et applications

université
PARIS-SACLAY

NOVA
UNIVERSIDADE NOVA
DE LISBOA

QUARTET



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SEIT 1386

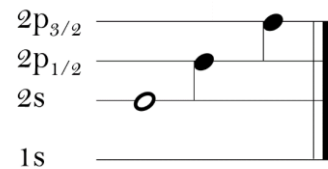
PAUL SCHERRER INSTITUT

PSI

ETH zürich

TECHNION
Israel Institute
of Technology

QUARTET



QUANTum inteRACtions with Exotic aToms

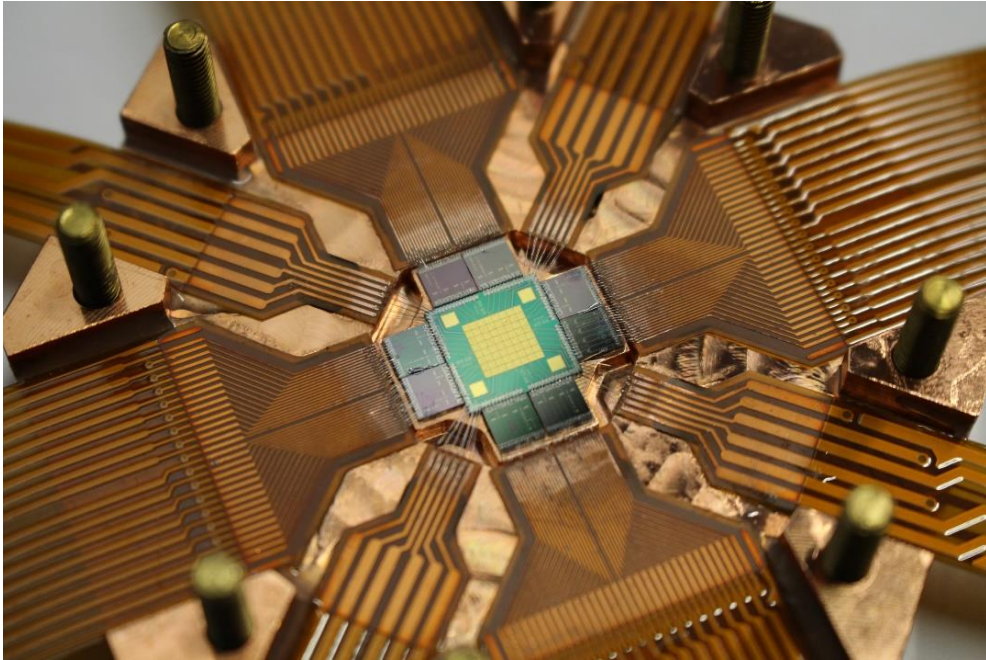
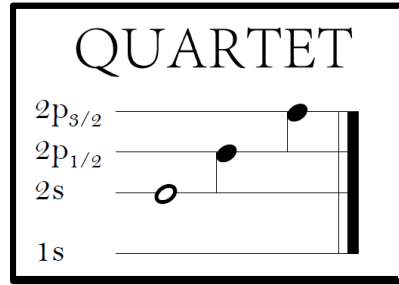
arXiv:2210.16929

Physics 2024, 6(1), 206-215

arXiv:2311.12014

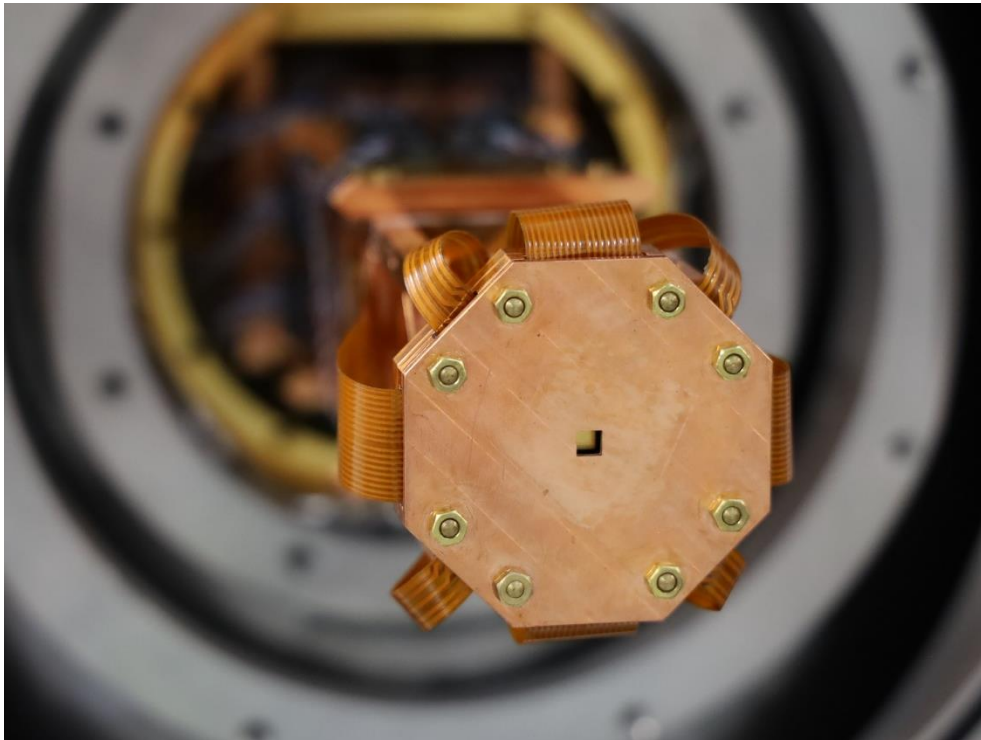
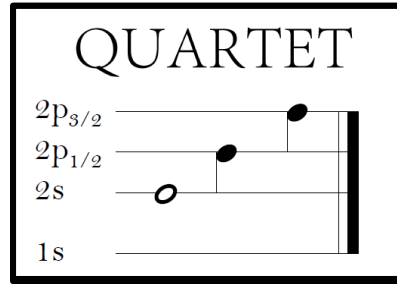
QUARTET – maXs-30

- Proof of concept experiment with muonic atoms
→ PSI measurements in [October 2023](#)
[maXs-30 set-up](#)

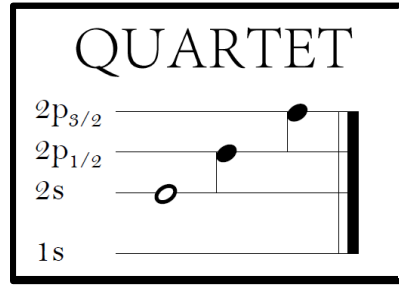


QUARTET – maXs-30

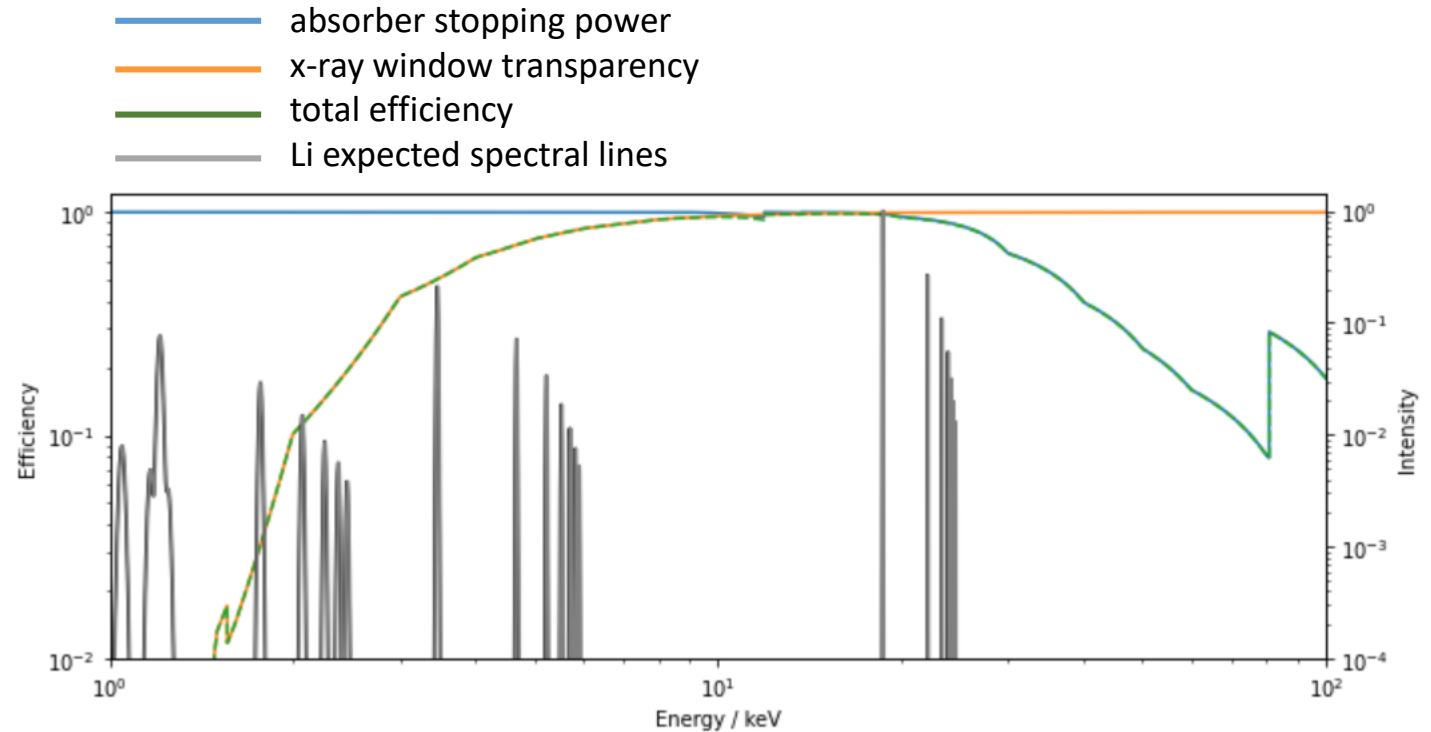
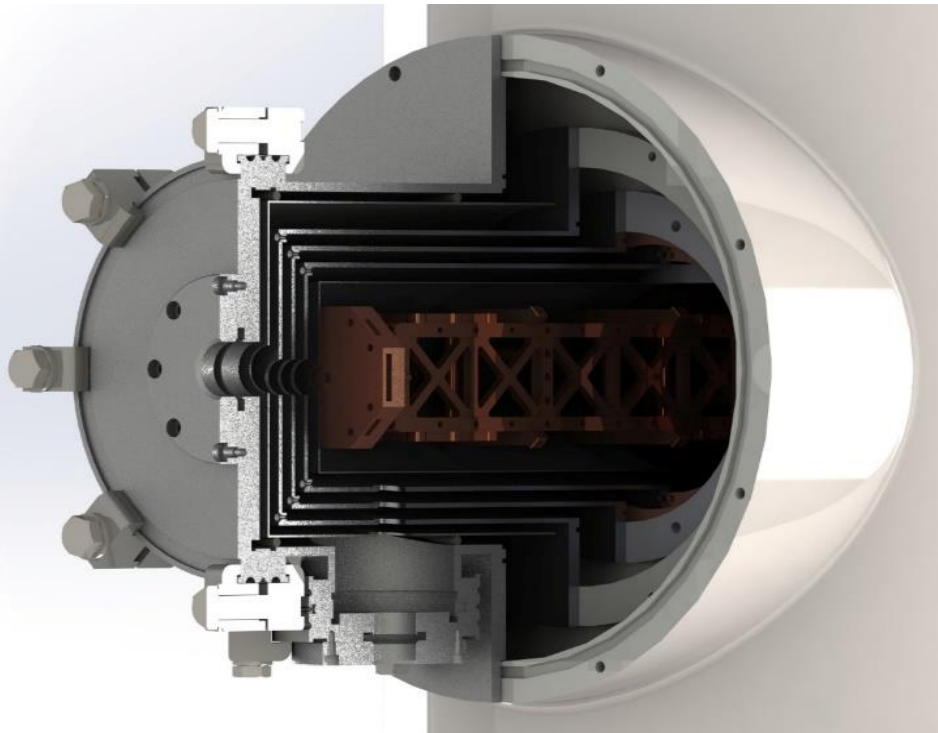
- **Proof of concept** experiment with muonic atoms
→ PSI measurements in **October 2023**
maXs-30 set-up on a side arm



QUARTET – maXs-30

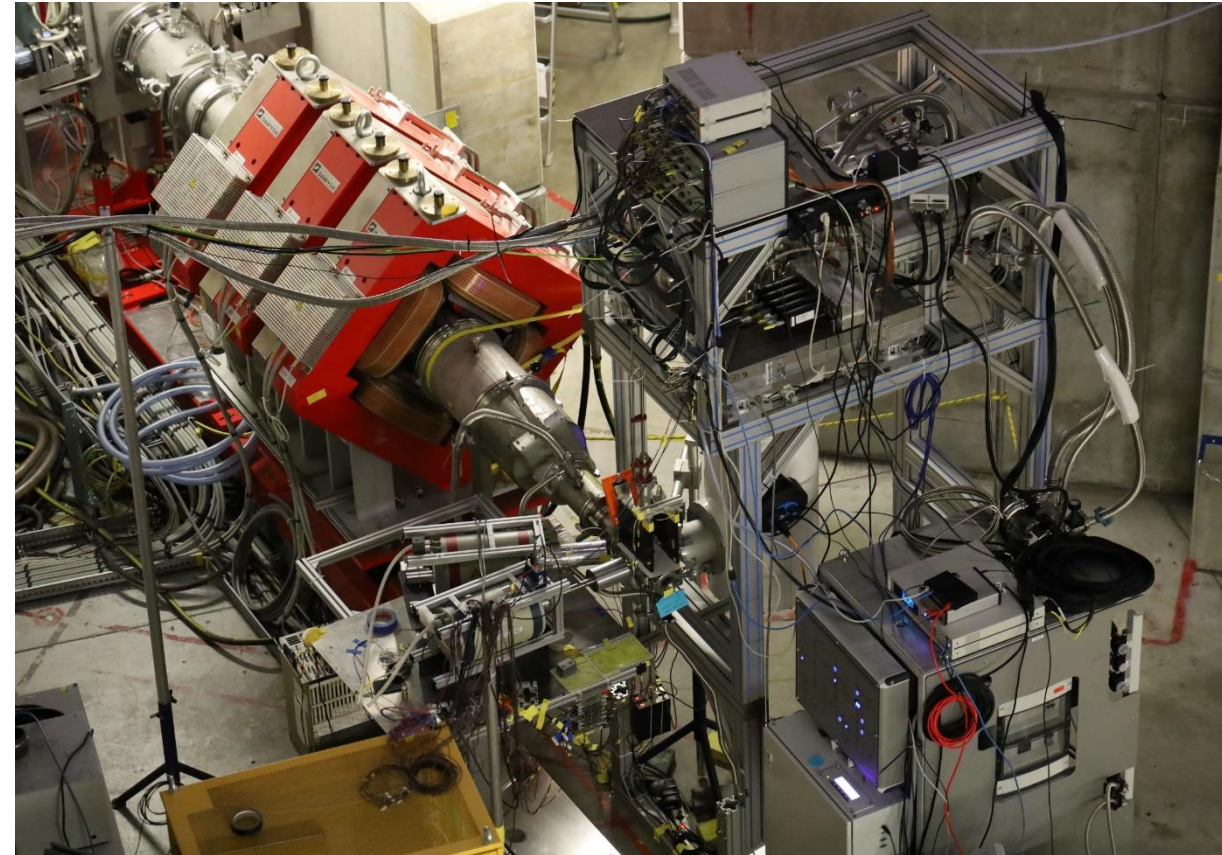
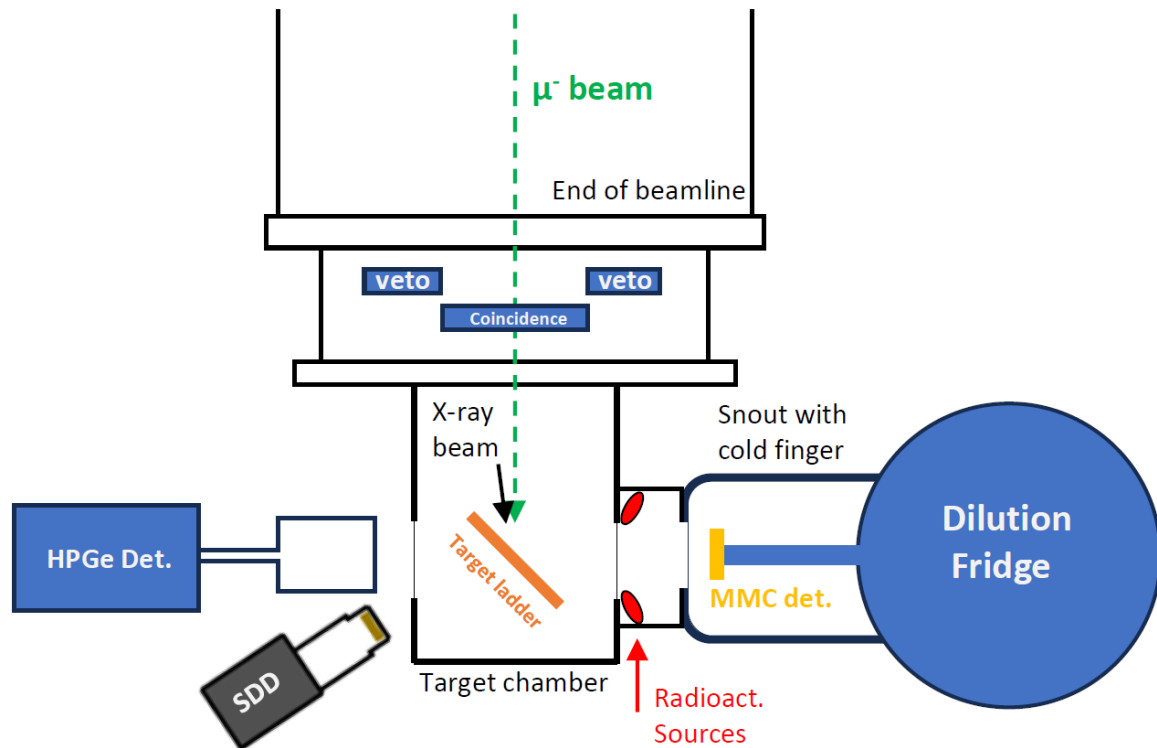
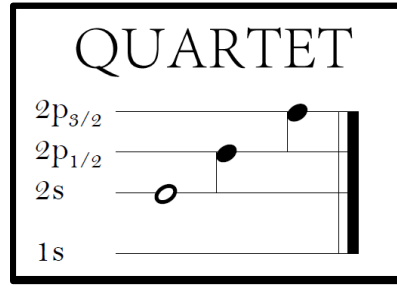


- Proof of concept experiment with muonic atoms
→ PSI measurements in [October 2023](#)
[maXs-30 set-up](#) on a side arm with x-ray windows

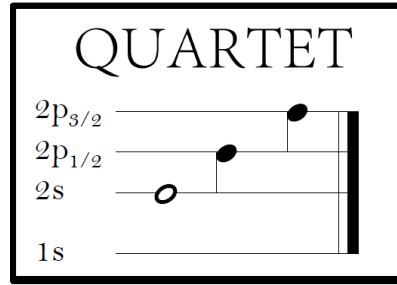


QUARTET – Beamtime 2023

Cryogenic system integrated with existing muon, electron and photon detector

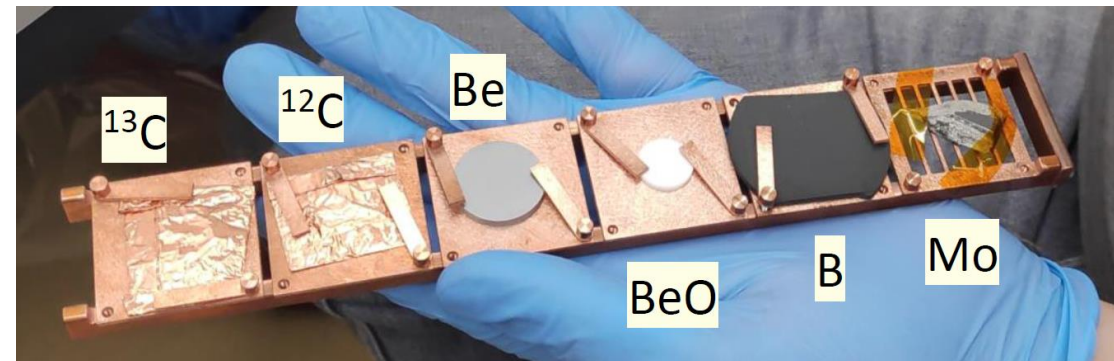
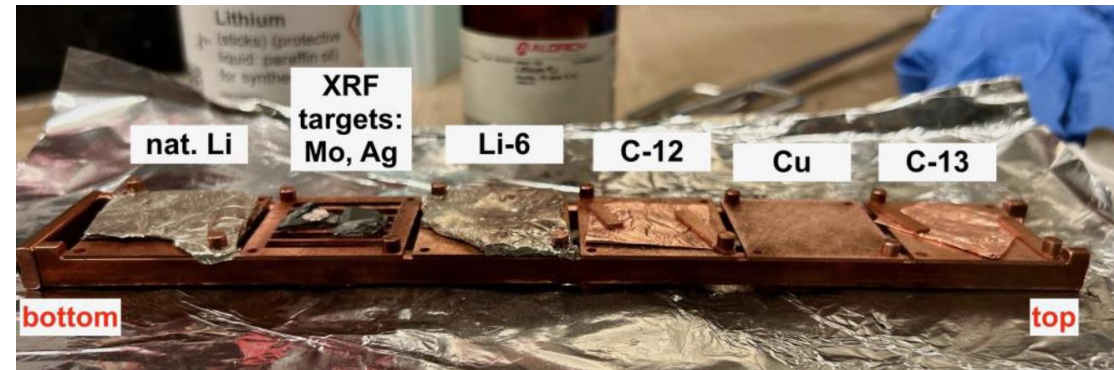
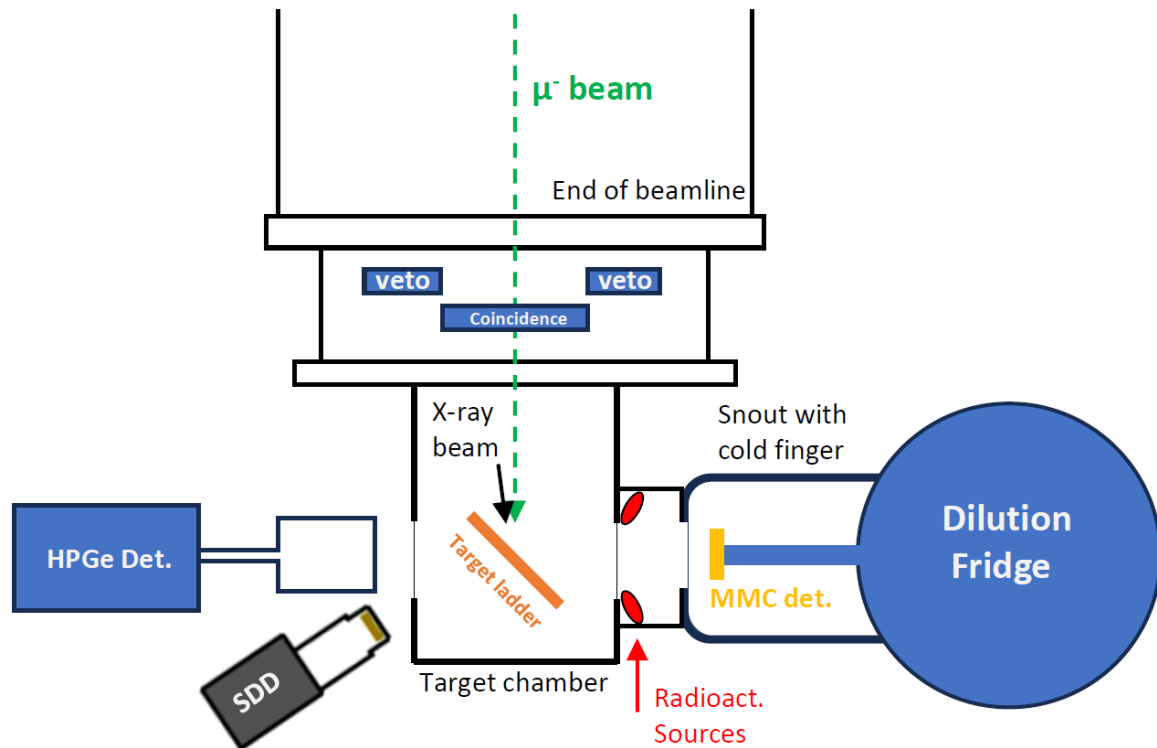


QUARTET – Beamtime 2023

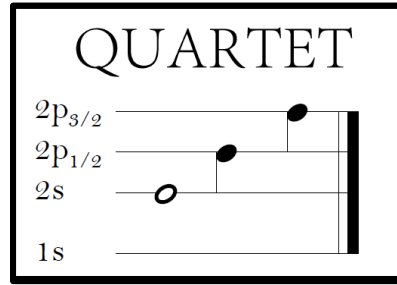


Cryogenic system integrated with existing muon, electron and photon detector

- Target:**
- Natural abundance (95% ^7Li) pure lithium metal foil
 - Enriched 95% ^6Li lithium metal foil
 - ^9Be cylinder and ^9BeO cylinder
 - Natural abundance (80% ^{11}B , 20% ^{10}B) boron foil
 - Enriched ^{12}C powder
 - Enriched ^{13}C D-fructose powder

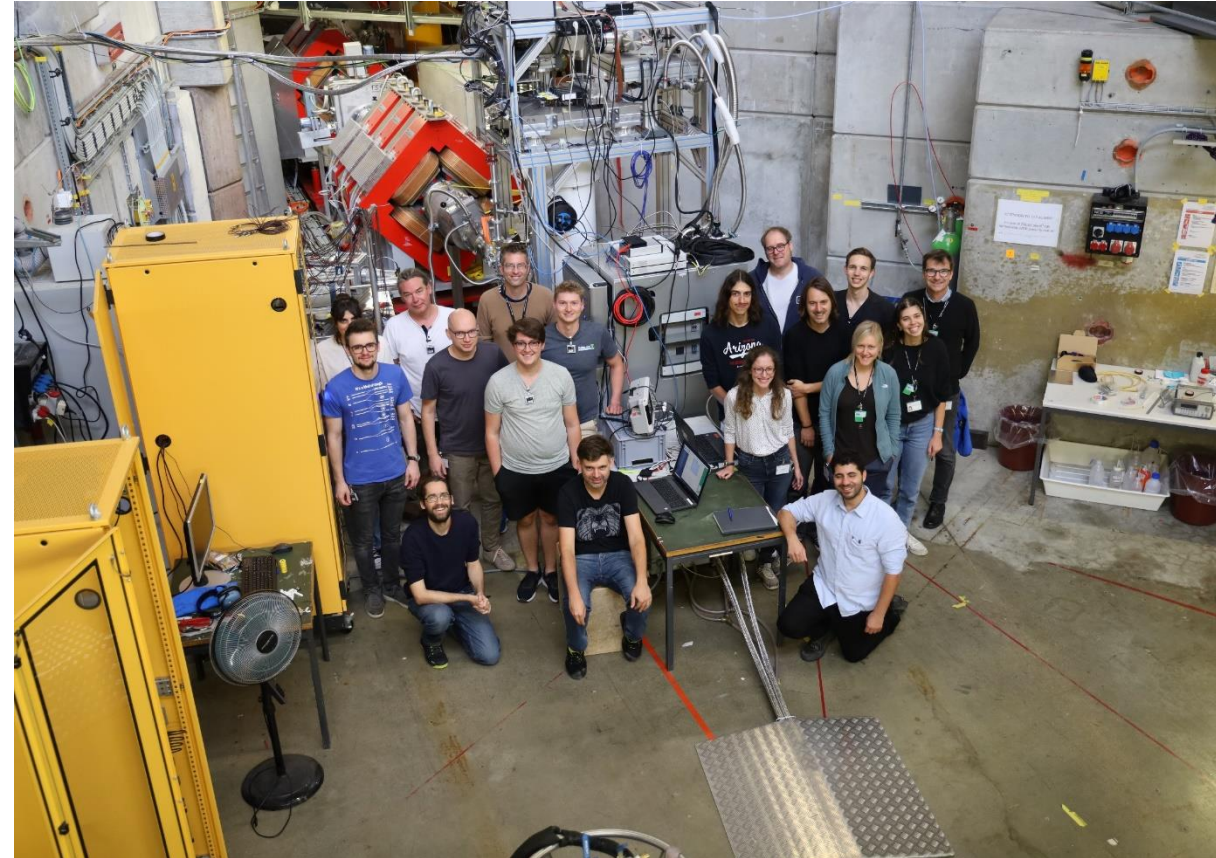
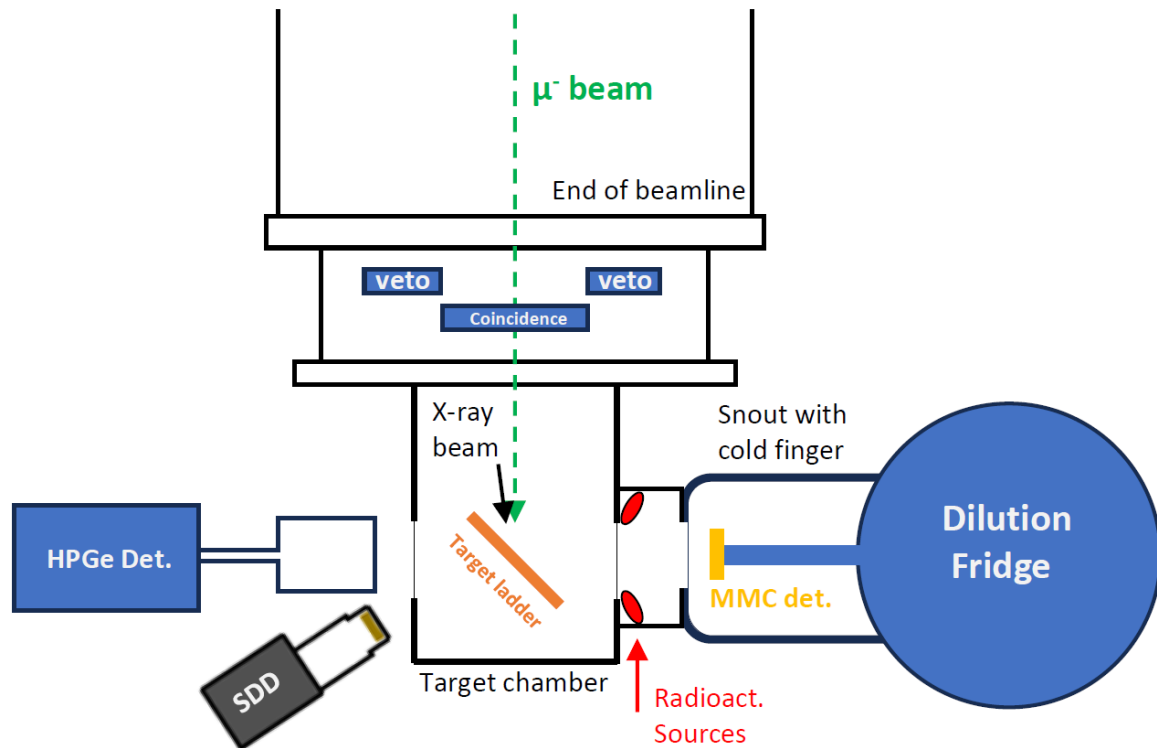


QUARTET – Beamtime 2023



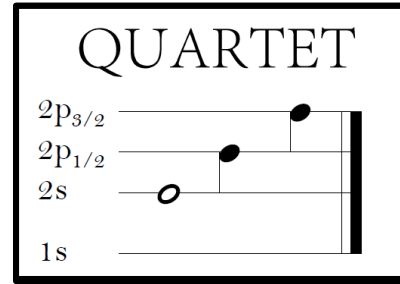
Cryogenic system integrated with existing muon, electron and photon detector

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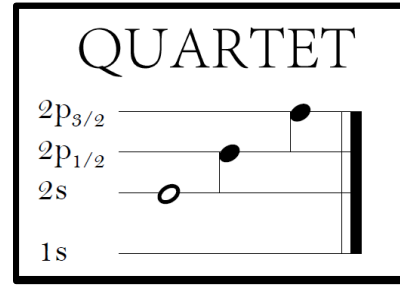
QUARTET – Preliminary results

- Detector operation > 95% of the time
- Excellent energy resolution
- Good rate for high precision line determination for Li, Be, B
- Rate for C should be increased → target optimization
→ single pixel optimization



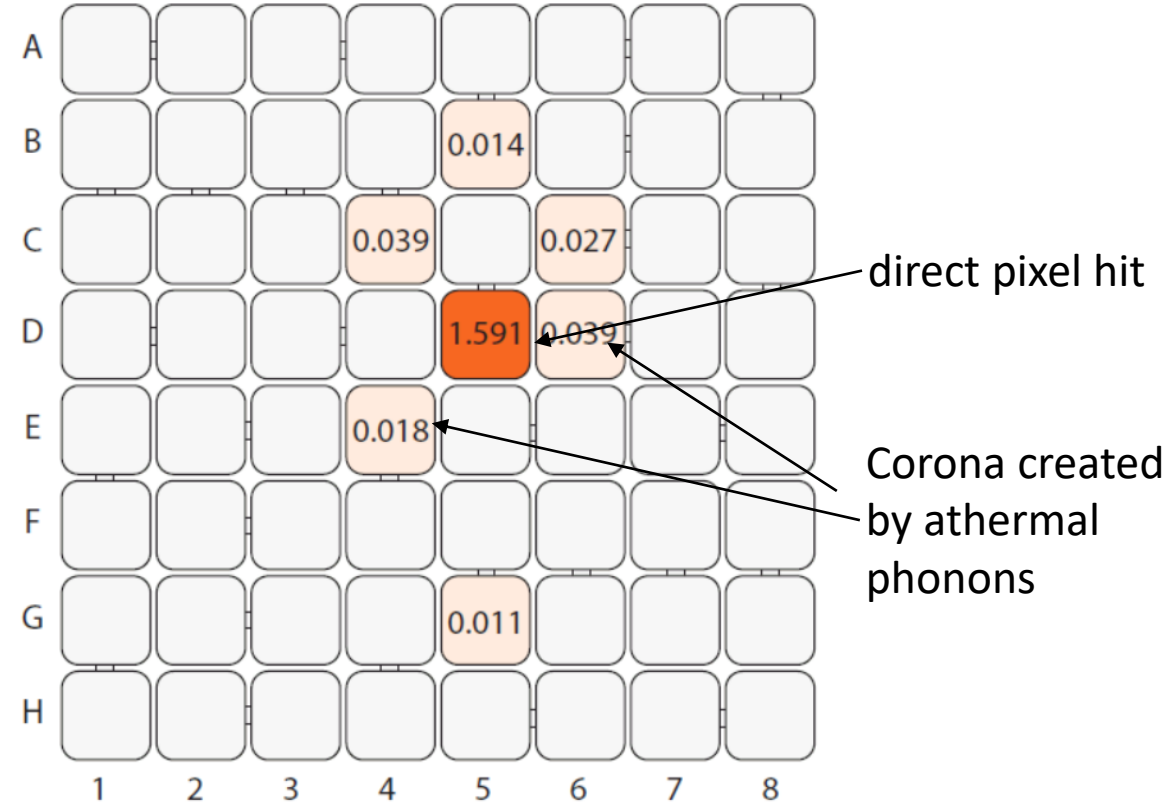
Target	E_{2p-1s} keV	ΔE_{FWHM} eV	Rate Hz	Expected Hz	BGD Hz keV ⁻¹	Calib. source
Base	0	12				
⁶ Li	19	14	0.17	0.17	0.003	Mo K_{α}
⁷ Li	19	15	0.16	0.17	0.002	Mo K_{α}
⁹ Be	33	24	0.11	0.11	0.005	¹³⁷ Cs → Ba K_{α}
^{10,11} B	52	29	0.036	0.040	0.003	²⁴¹ Am
¹² C	75	~ 40	0.005	0.006	0.002	

QUARTET – Preliminary results



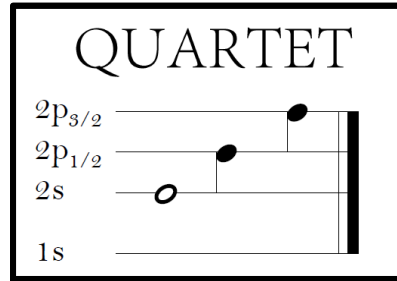
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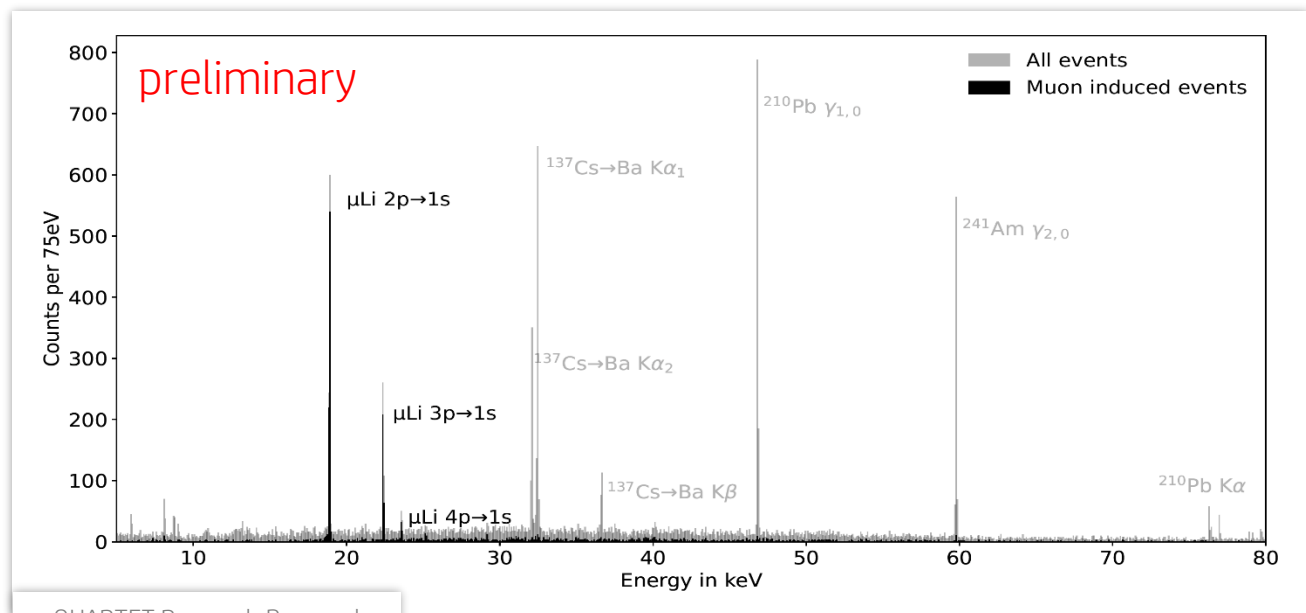
- Resulting from muon decay
- Deposit ~ 150 keV energy in the Si substrate
- Identified by signal shape and clustering

QUARTET – Preliminary results

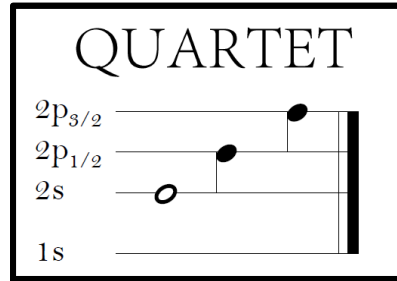


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 - Muon coincidence allows for effective background suppression
 - $\mu\text{Li } np \rightarrow 1s$ transitions detected

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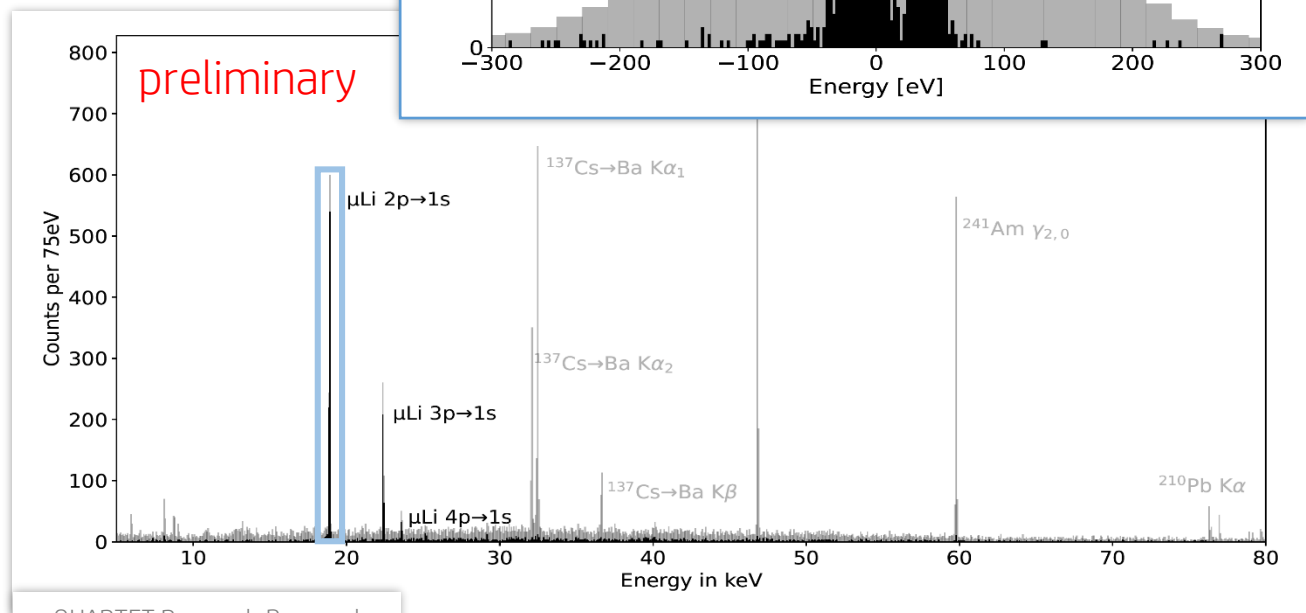
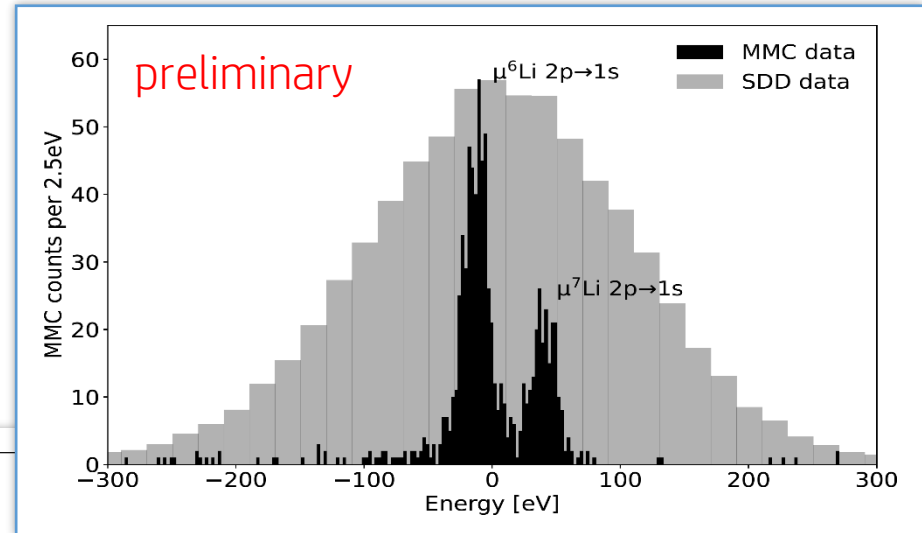


QUARTET – Preliminary results



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

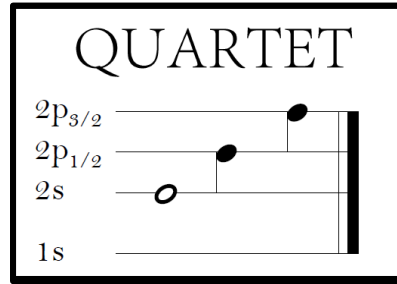
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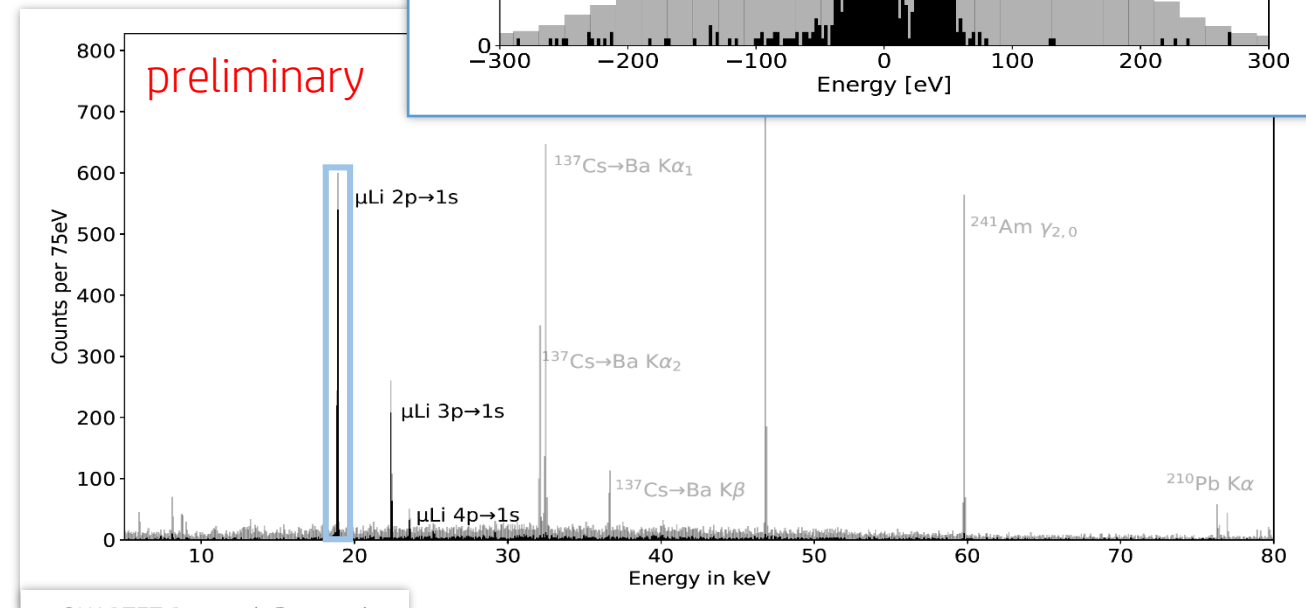
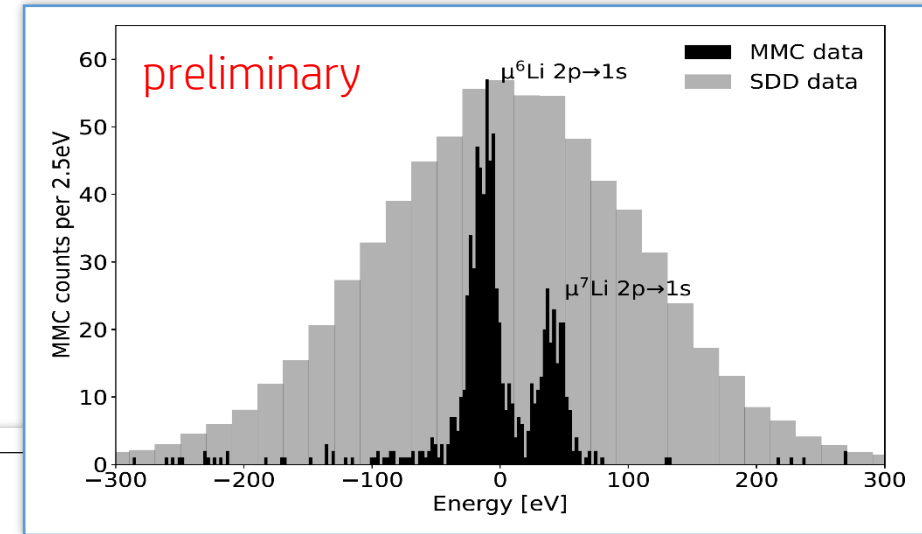
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QUARTET – Open questions

- Investigate optimized calibration strategy over different energy ranges
- Compromise between energy resolution and quantum efficiency



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

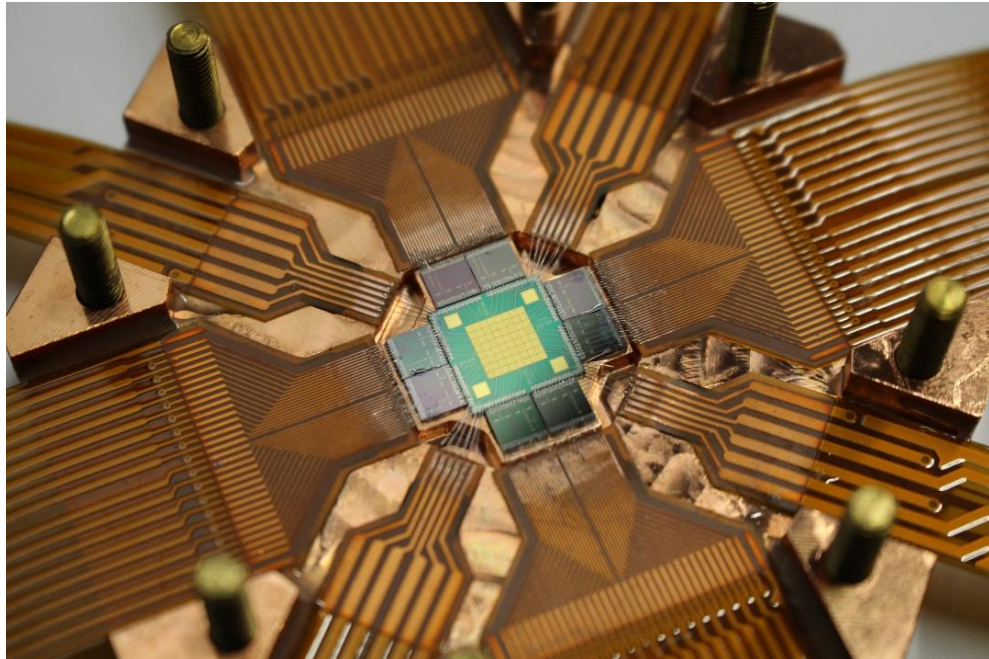
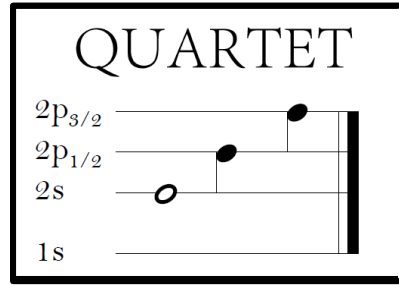


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QUARTET – maXs-30 – Beamtime 2024

Goal: High precision spectroscopy of [muonic Li](#), [Be](#) and [B](#)

Calibration strategy optimized for the different elements

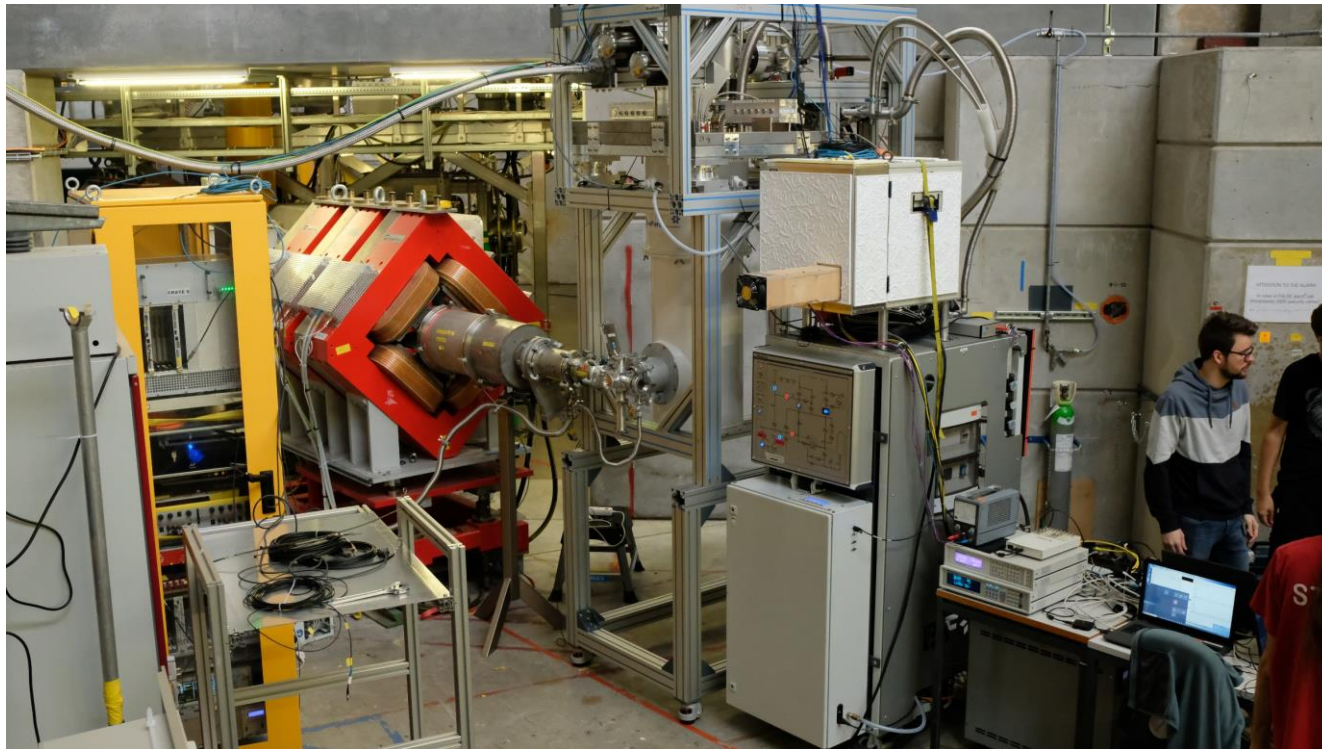
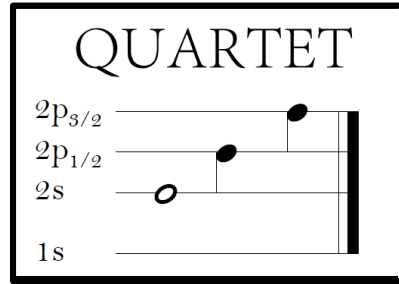


QUARTET – maXs-30 – Beamtime 2024

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[Detector system moved to PiE1 yesterday](#)

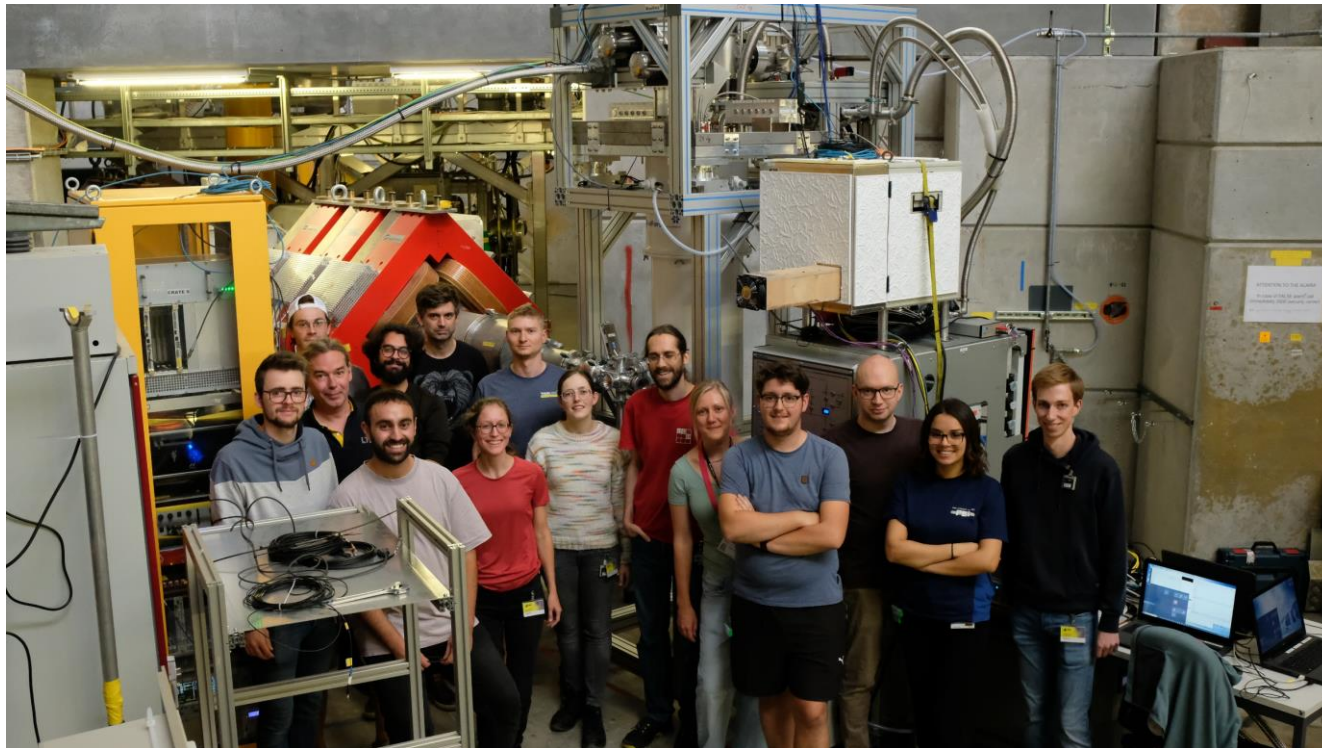
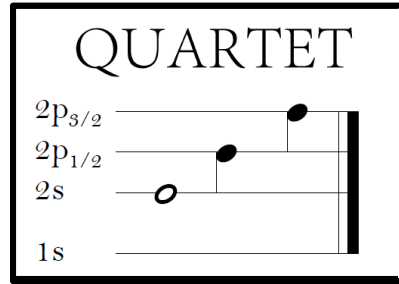


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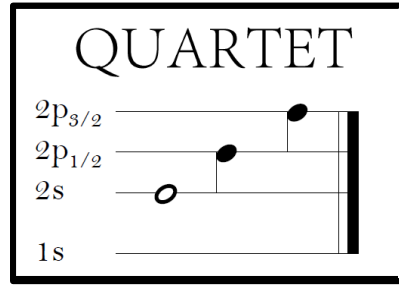


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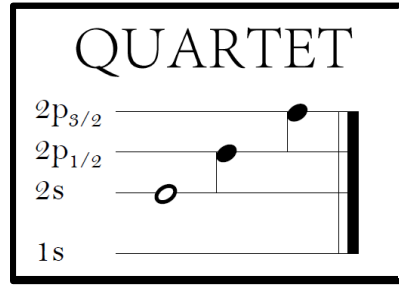
[and we are excited to see the first photons tonight!](#)

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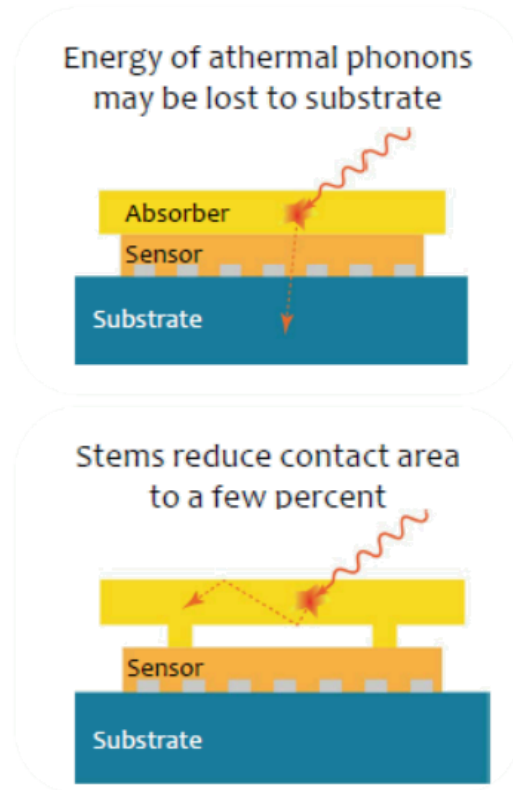
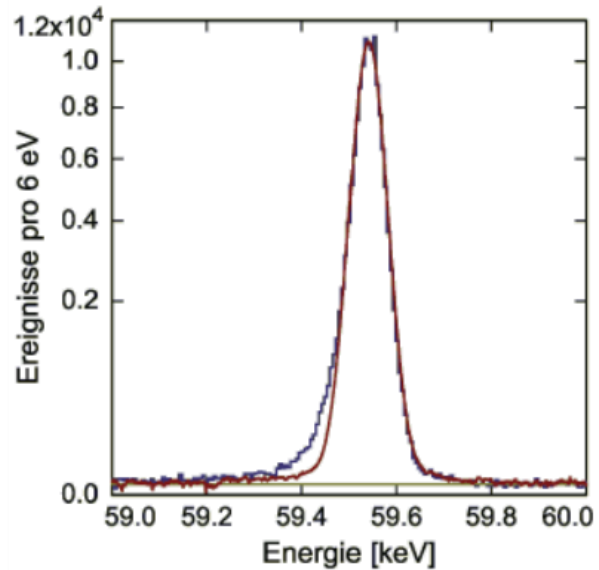
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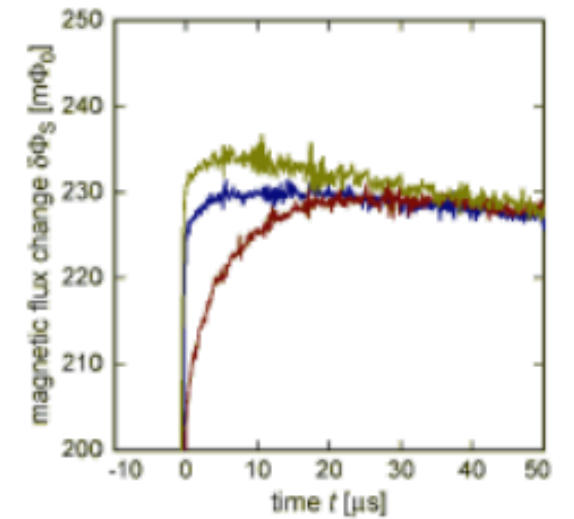
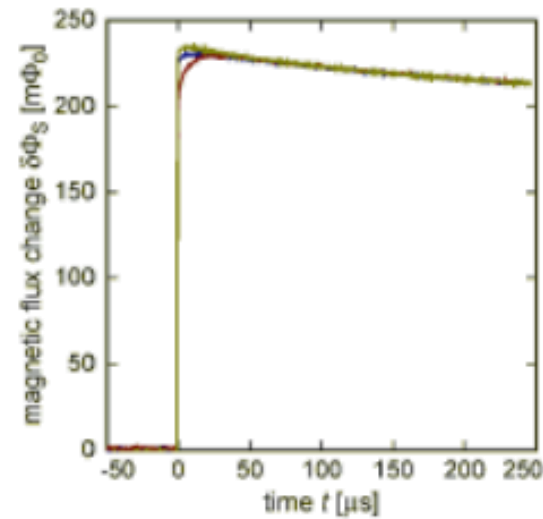
Thank you for
your attention!

Loss of **athermal phonons** to the substrate



→ reduce contact area between sensor and absorber

In large absorbers: signal rise time limited by **thermal diffusion**



→ add thermal bottleneck between absorber and sensor

Challenge: remove heat from pixels in a closely p



Electroplate Au heat bath on front-side



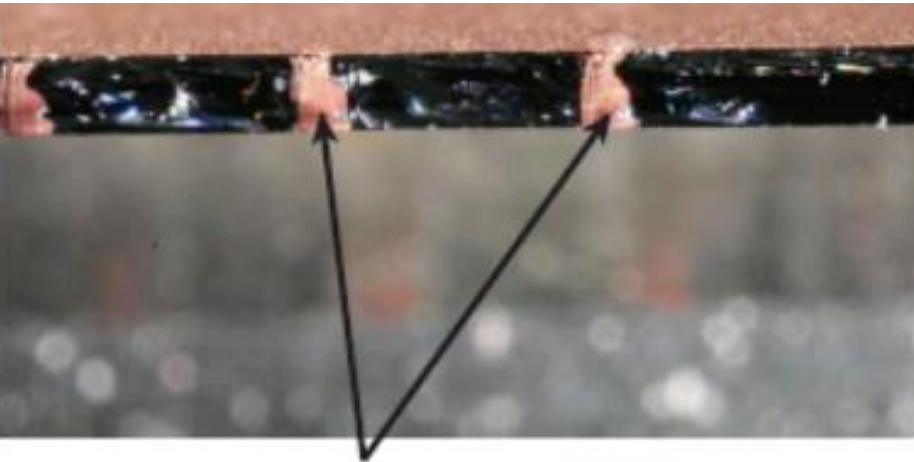
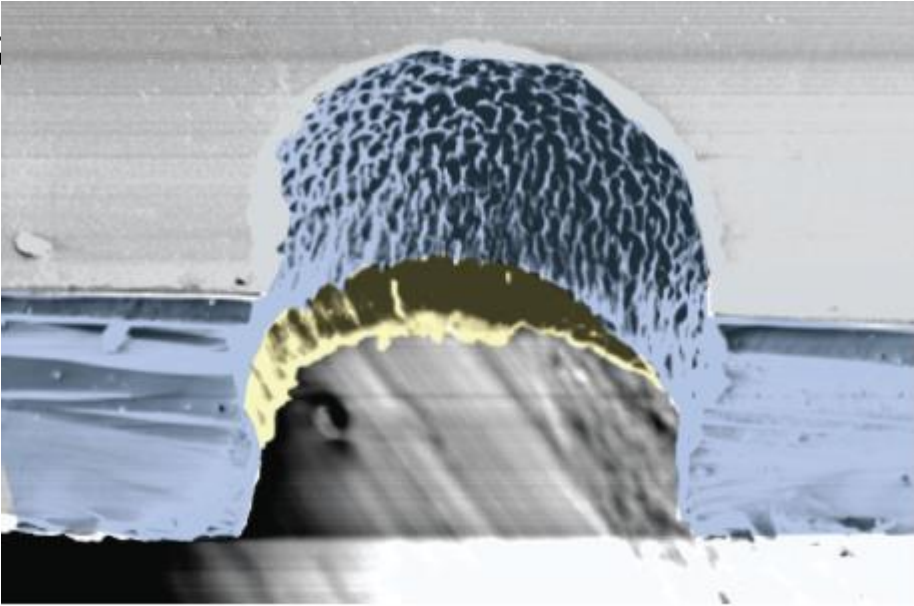
Au contact layer (FS) and etch mask (BS)



Bosch process from BS



Electroplate Cu on back-side



Completely filled TWV