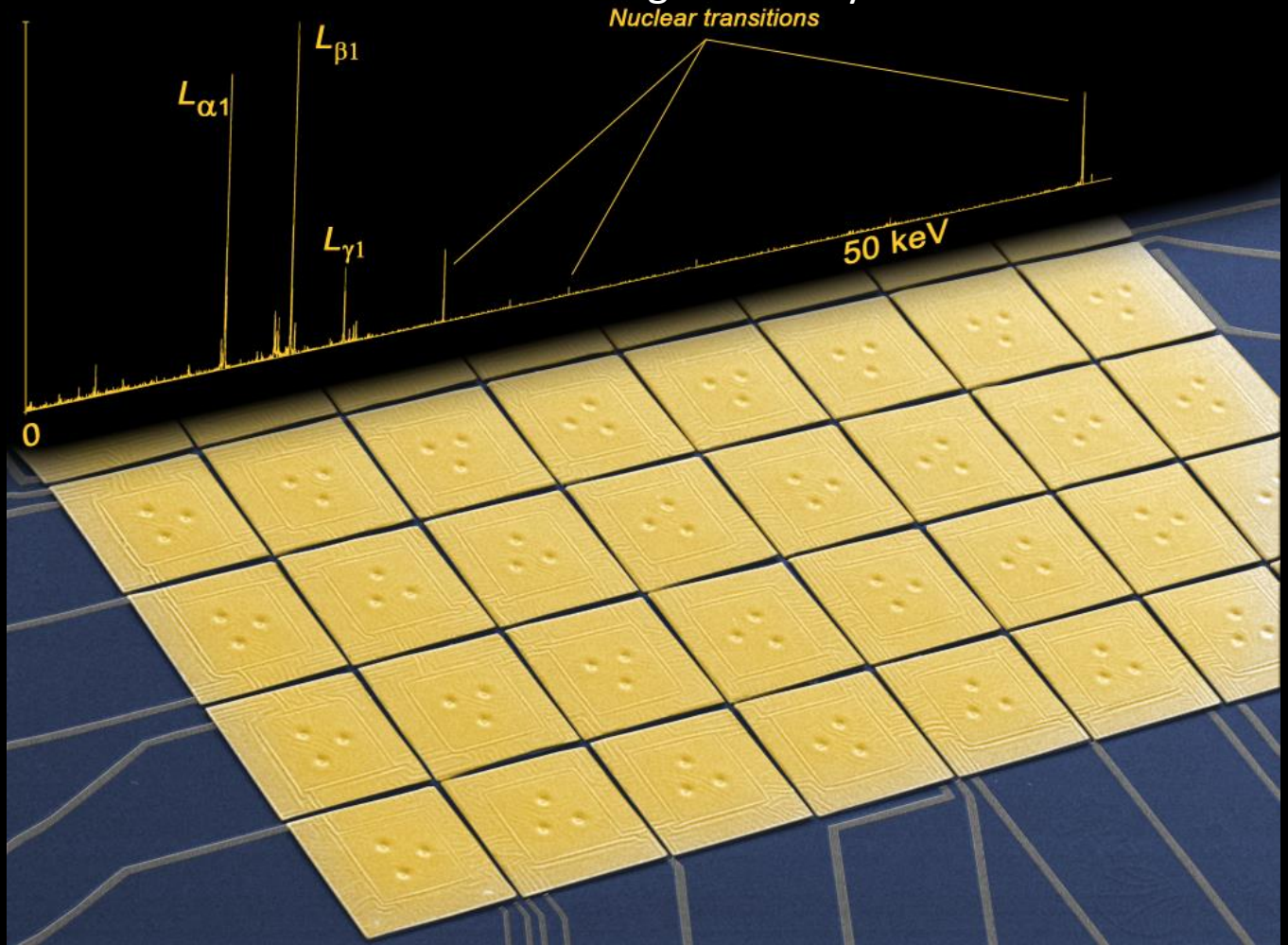
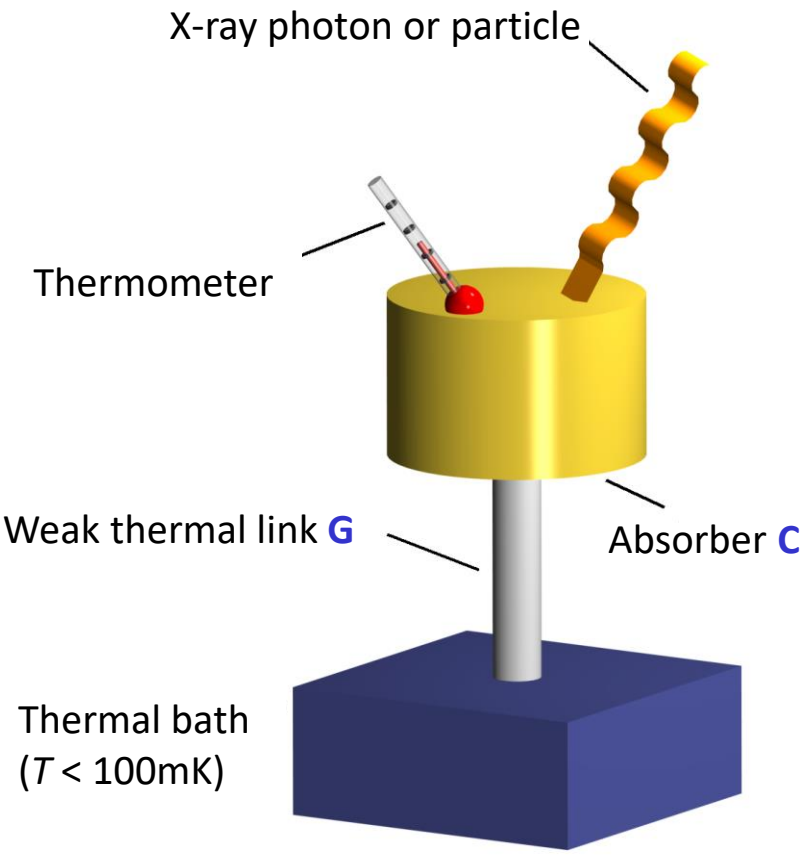
# Metallic Magnetic Micro-Calorimeters to study Exotic Atoms

**Andreas Fleischmann, Loredana Gastaldo, Daniel Hengstler, Christian Enss, Steffen Allgeier, Axel Brunold, …**
Heidelberg University



# micro-calorimeters




Thermal detectors !

Somewhat numb:
Convert good form of energy to heat!

Temperature change

$$\delta T = \frac{E}{C_{\mathrm{tot}}}$$

Relaxation to bath temperature

$$\tau = \frac{C_{\mathrm{tot}}}{G}$$

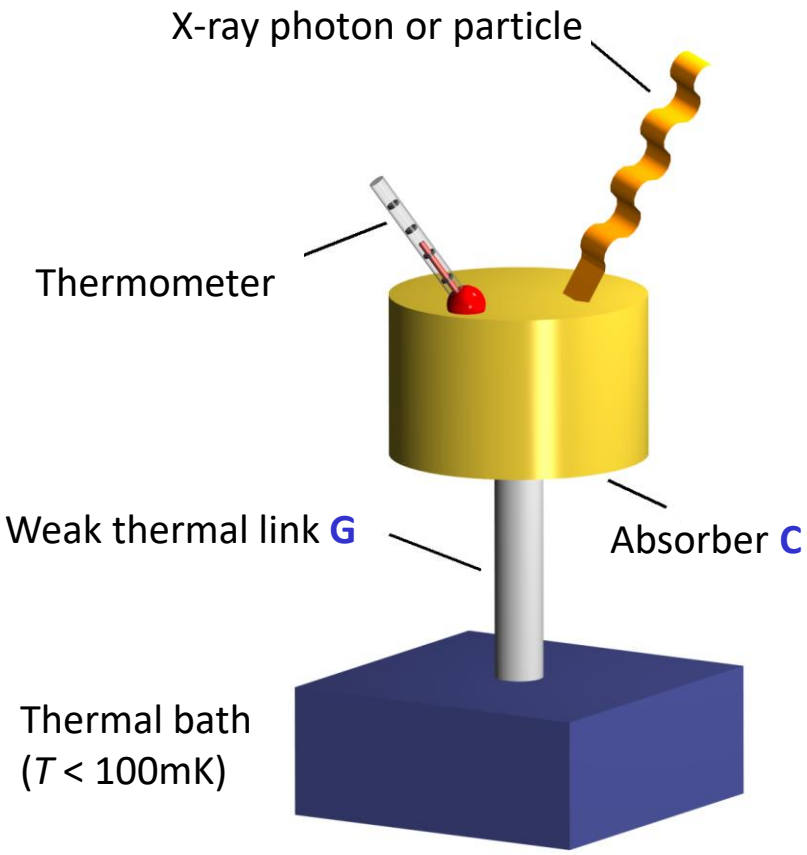
Operation at low temperature ($T$ < 0.1 K):

small specific heat

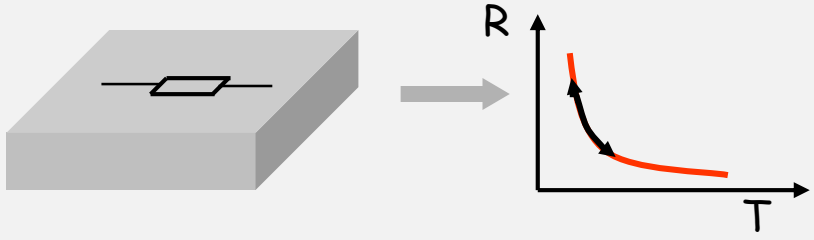
large temperature change

small thermal noise

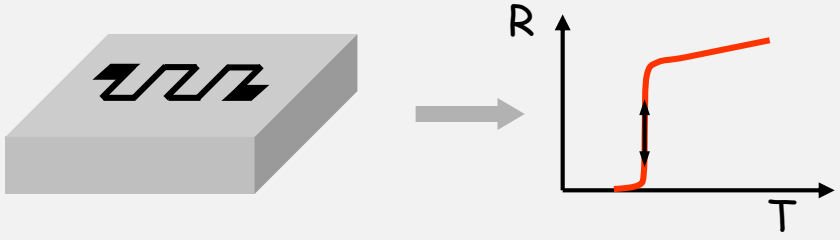
# thermometer concepts



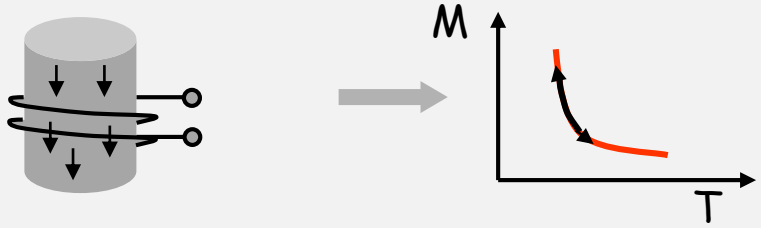

## Resistance of highly doped semiconductors



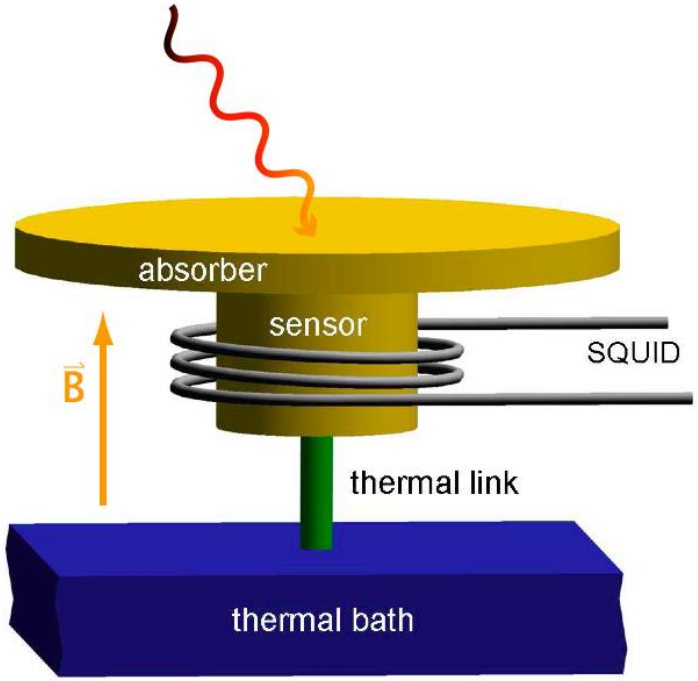

## Resistance at superconducting transition,TES



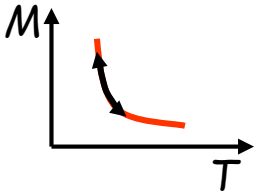

## Magnetization of paramagnetic material



# metallic magnetic calorimeters




paramagnetic sensor: **Au**:$Er_{500ppm}$ , **Ag**:Er




signal size:

$$\delta M = \frac{\partial M}{\partial T}\delta T = \frac{\partial M}{\partial T}\frac{E_\gamma}{C_{\mathrm{tot}}}$$

main differences to TES and thermistors

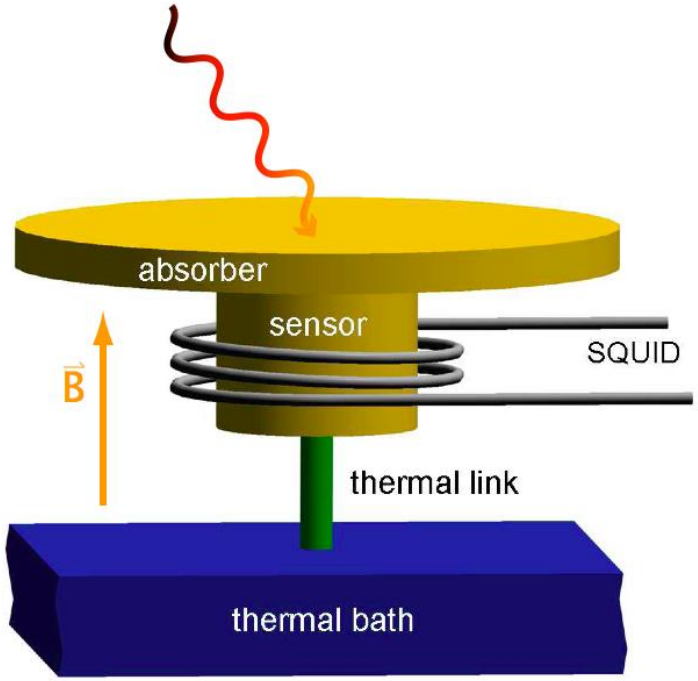
- no dissipation in the sensor
- no galvanic contact to the sensor

} important for large arrays

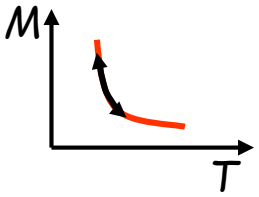
- ***M*** and **C** of weakly interacting spins well understood

➡
- numerical optimization
- non-linearity: **small & understood** from thermodynamics

# metallic magnetic calorimeters



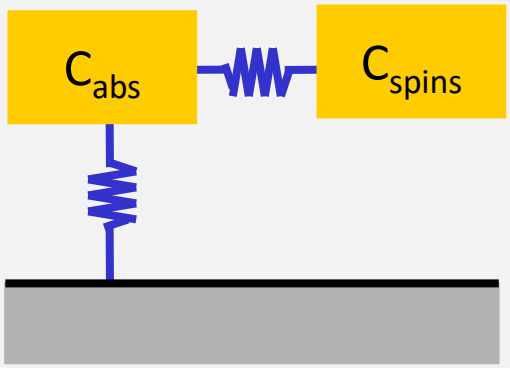

paramagnetic sensor: **Au**:$Er_{500ppm}$ , Ag:Er




signal size:

$$\delta M = \frac{\partial M}{\partial T}\delta T = \frac{\partial M}{\partial T}\frac{E_\gamma}{C_{\mathrm{tot}}}$$

**Energy resolution --- Why ‚micro'-calorimeter**

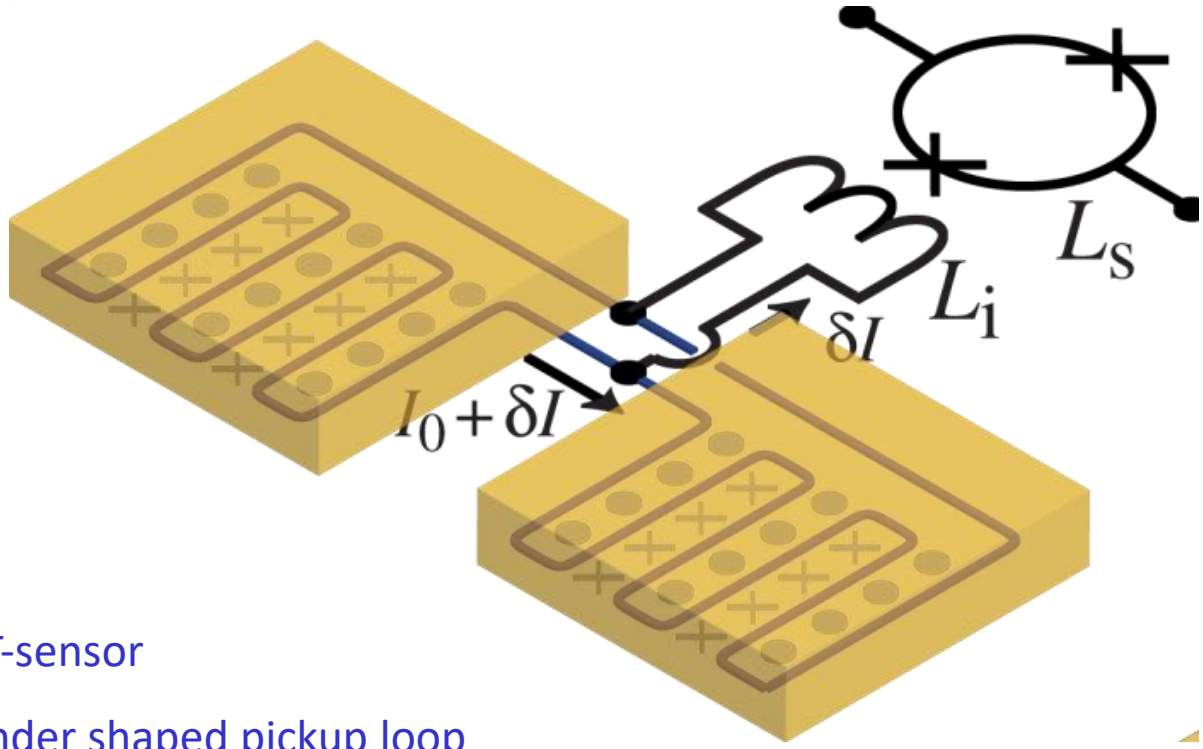



Thermal fluctuations of energy
between absorber, thermometer and bath lead to

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

e.g. **1eV** for C = 1 pJ/K at *T* = 50 mK

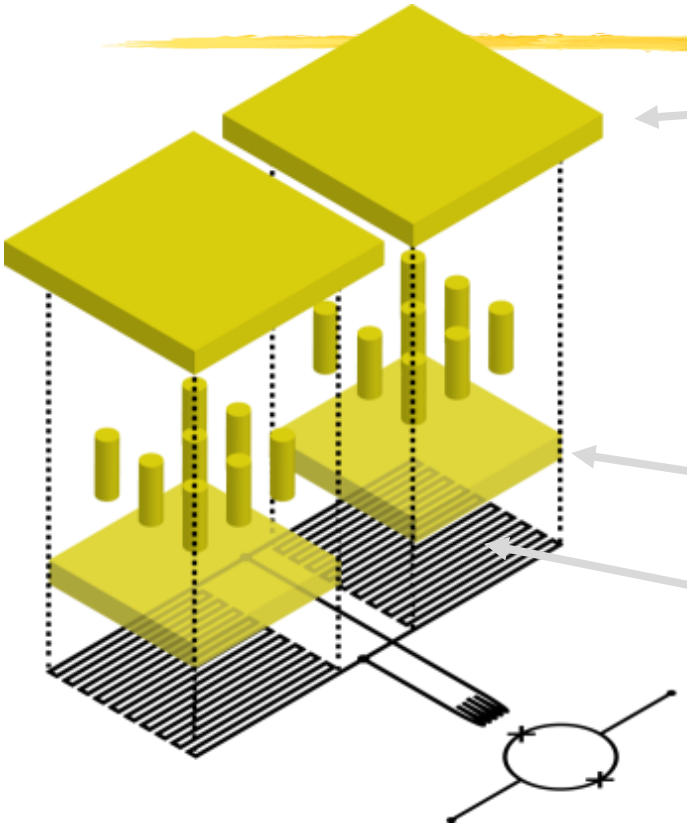
# sensor geometry



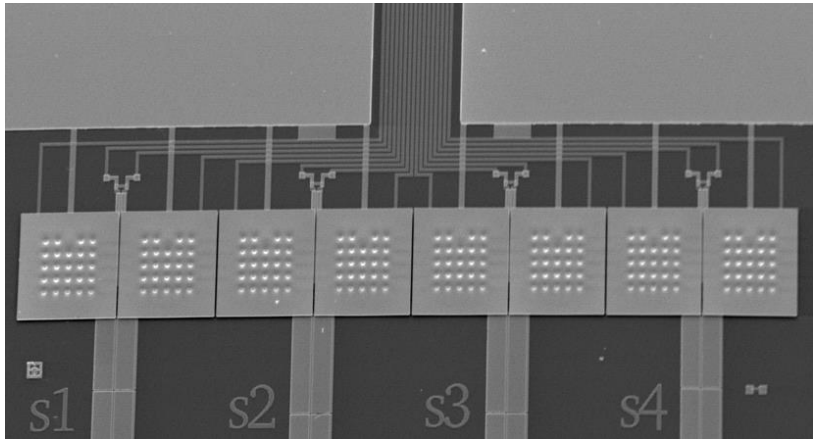

Present working horse:

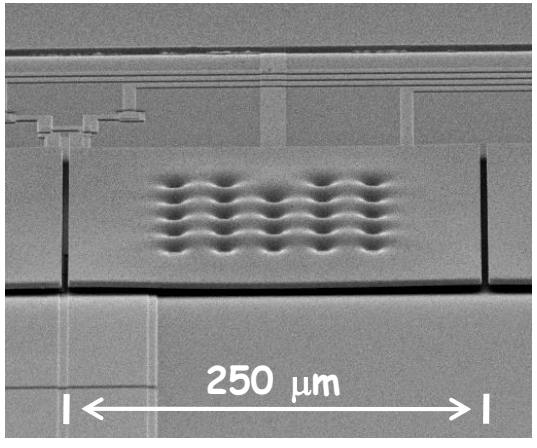
- planar paramagnetic *T*-sensor
- superconducting meander shaped pickup loop
- persistent current to generate bias B-field
- dc-SQUID: magnetic flux to voltage converter,
  close to quantum limit

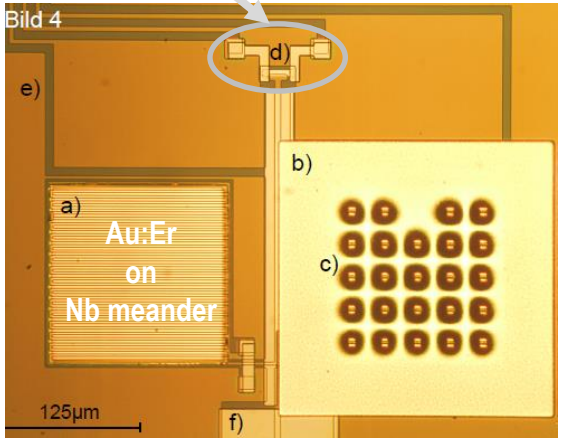
# **maXs-20**: 1×8 array for soft x-rays



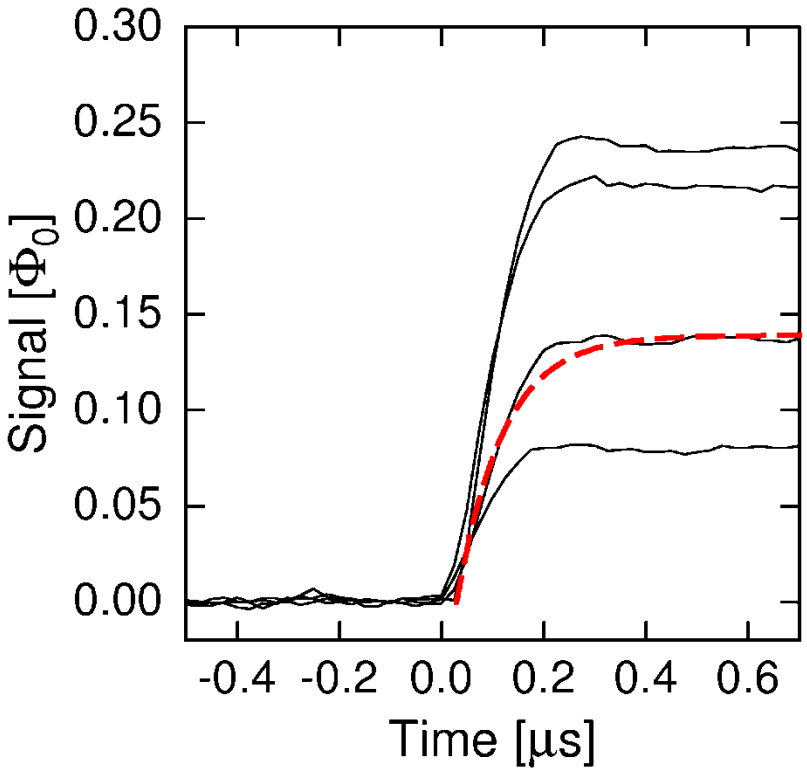
- 1×8 x-ray absorbers
  - **250µm×250 µm** gold**, 5 µm thick**
  - **98%** qu.-eff. @ 6 keV
  - electroplated into photoresist mold
  - **mech/therm contact to sensor by stems**
    to prevent loss of initially hot phonons
- Au:$^{166}Er_{300ppm}$ temperature sensors
- Superconducting meander shaped pickup coils
  - 2.5 µm wide Nb lines
  - $I_c \approx 100mA$
- On-chip persistent current switch (AuPd)



# signal rise




- not affected by stems between absorber and sensor
- **rise time: 90 ns** @ 30 mK,

  as expected for the **spin-electron-relaxation**

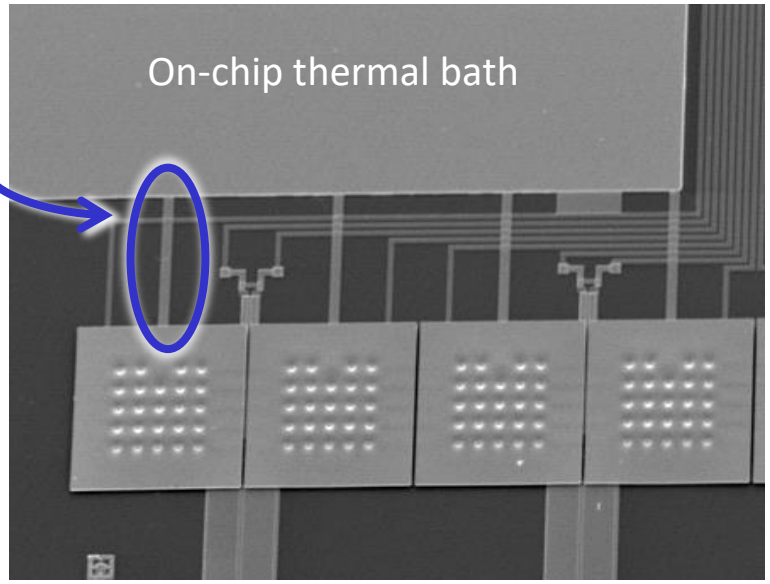
  from Korringa-constant of Er in Au

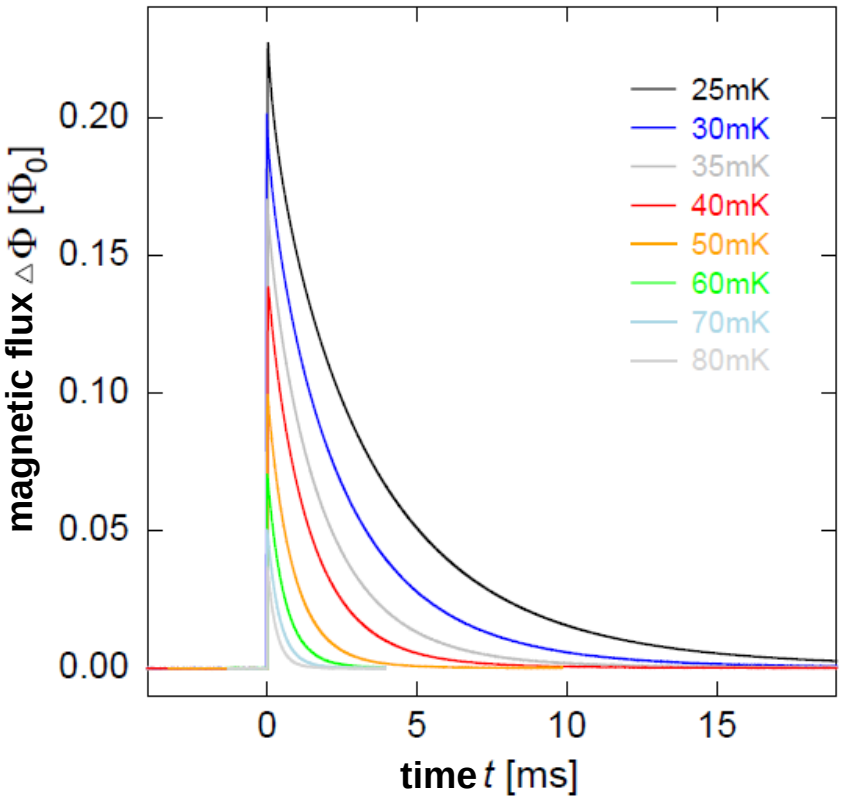
# signal decay

decay time

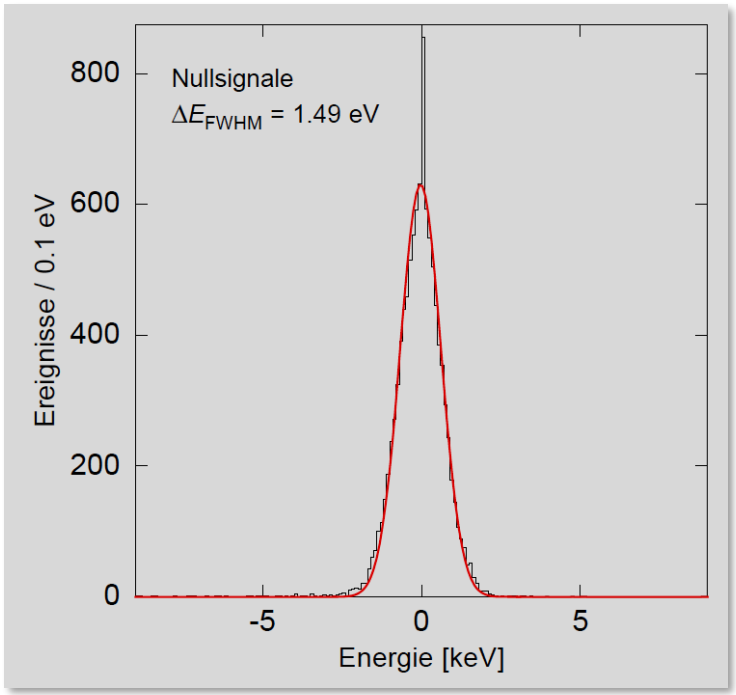
adjusted by sputtered thermal link (Au)

here: 3 ms @ 30 mK

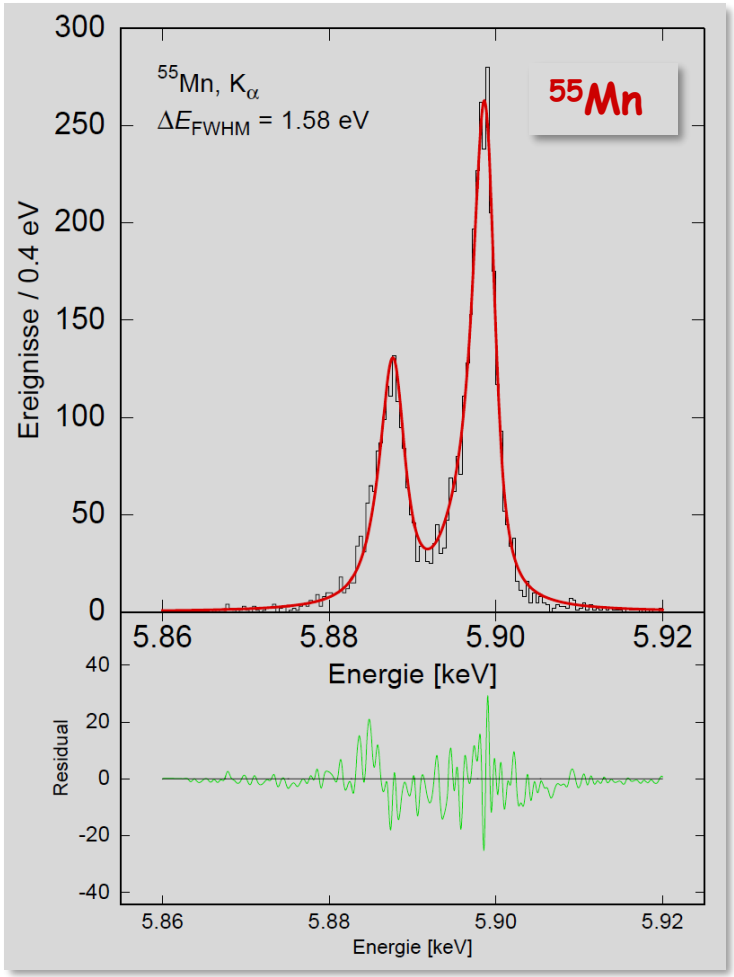


# **maXs-20** operated at 20mK (in dry dilution fridge)



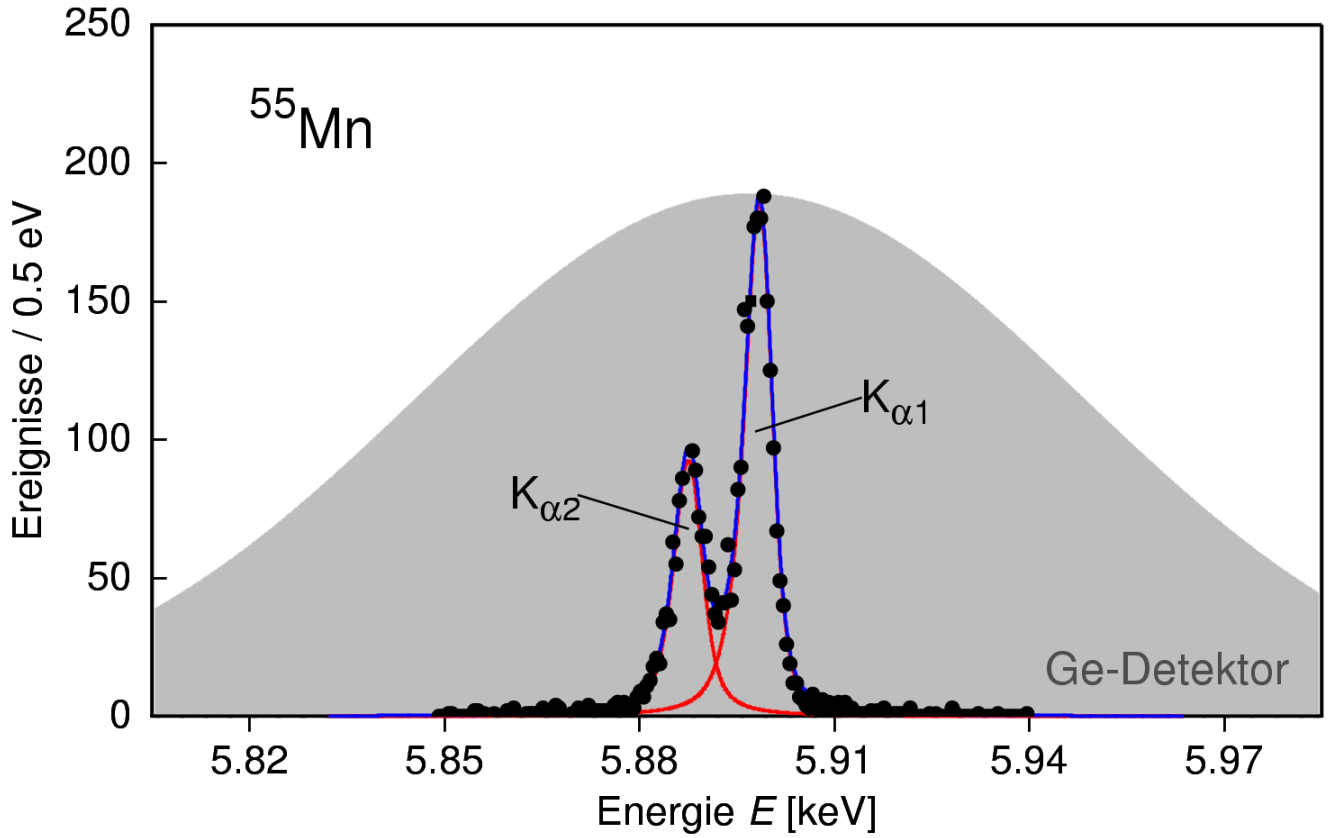

$\Delta E_{FWHM}$ = 1.5 eV @ 0 keV



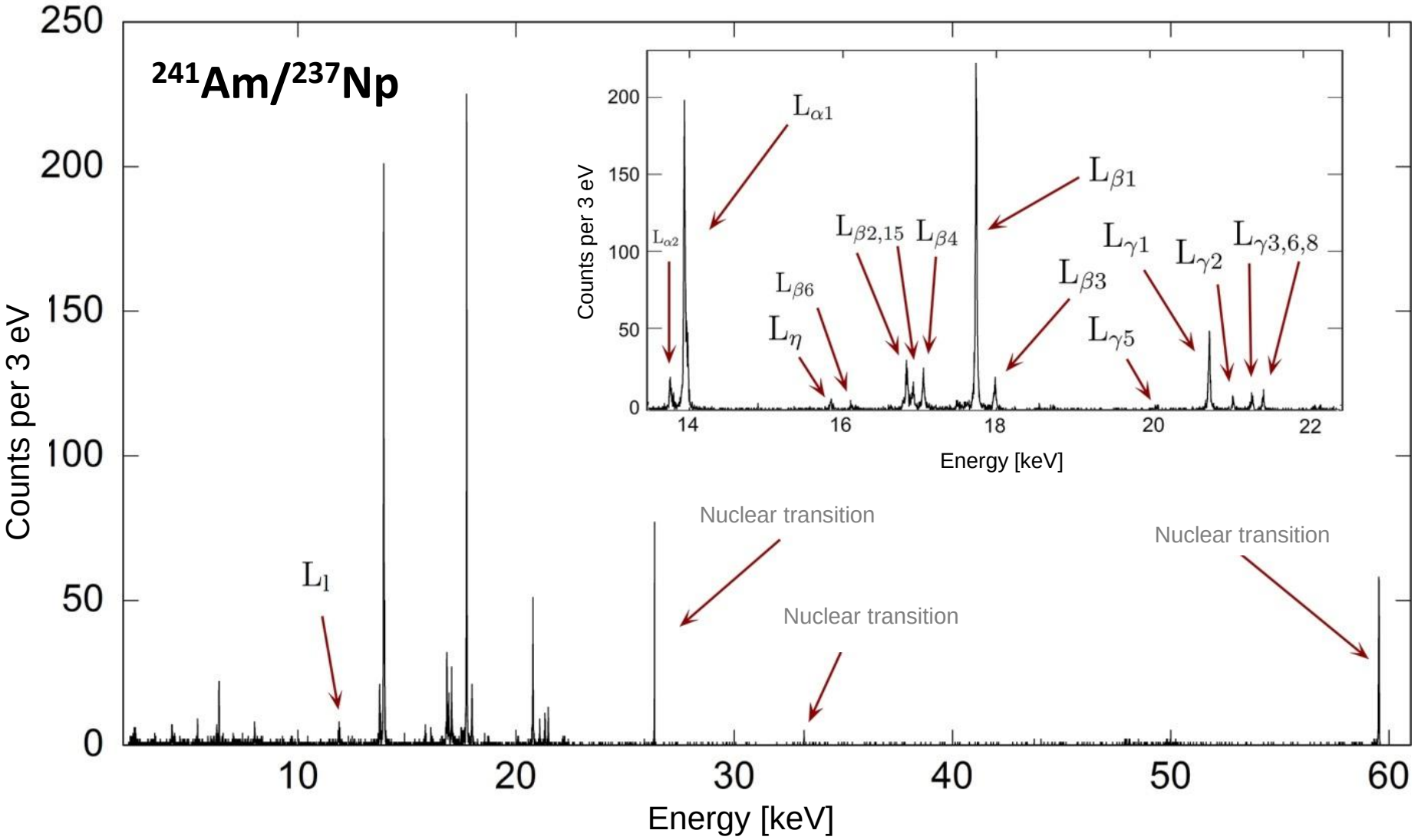

$\Delta E_{FWHM}$ = 1.6 eV @ 6 keV

Defines state-of-the-art together with TES from NIST and NASA

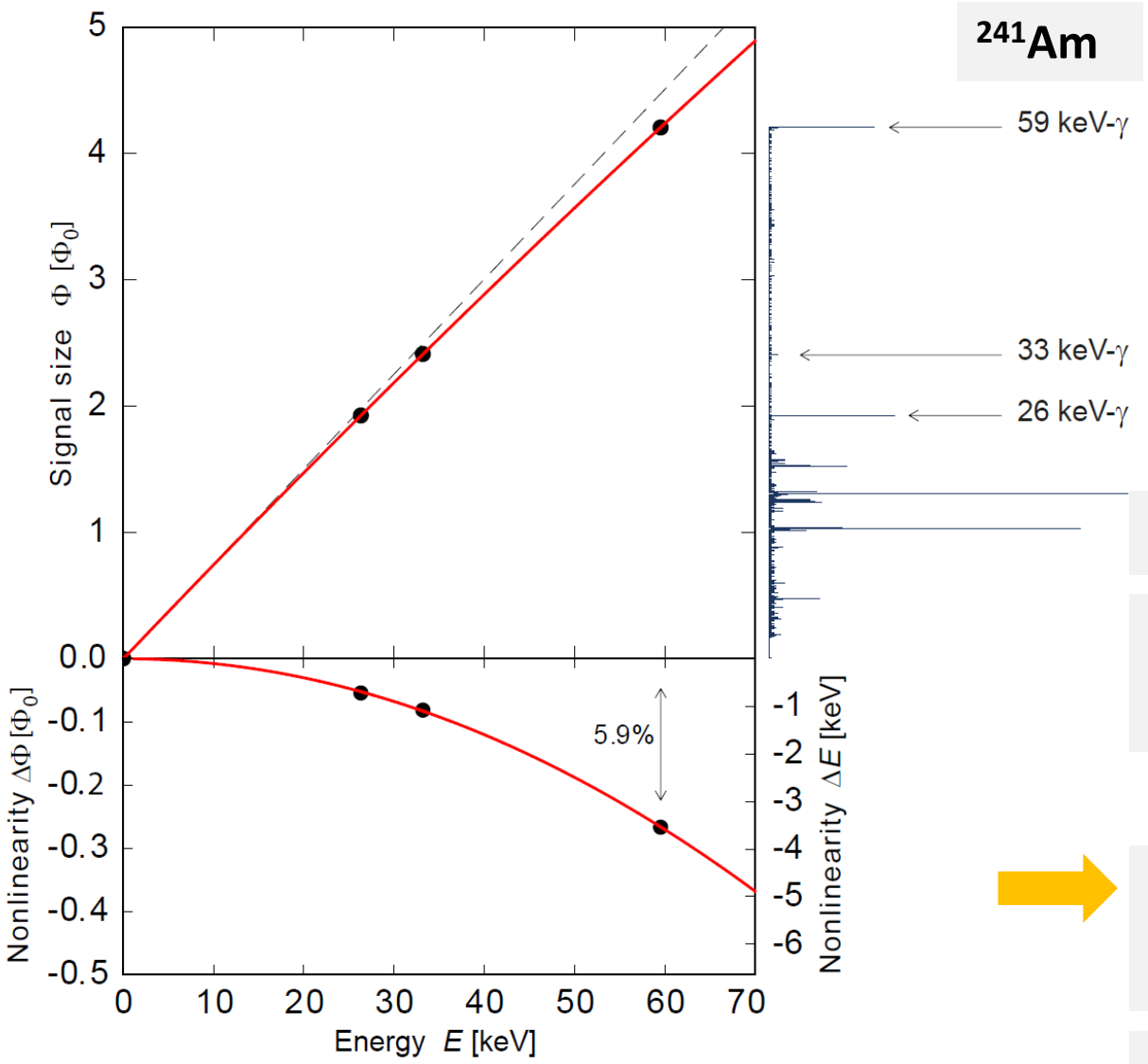
# comparison to ionization detector (120eV)



# **maXs-20** exposed to x-rays and gammas of $^{241}$Am source



# **maXs-20:** no saturation up to 60 keV




**non-linearity: 6% @ 60 keV**

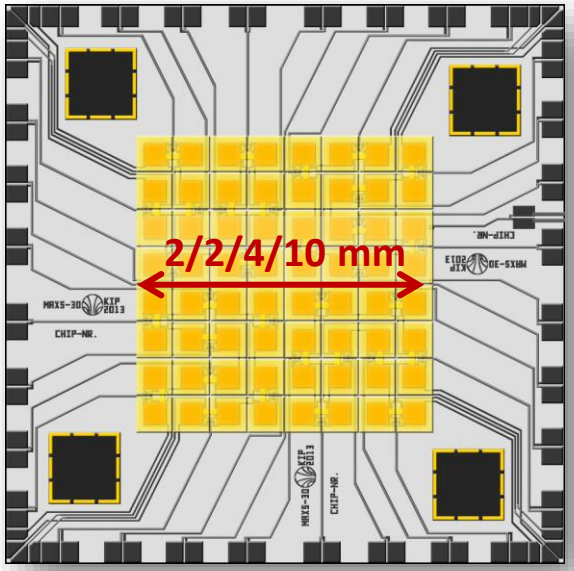
**as expected from thermodynamical properties**

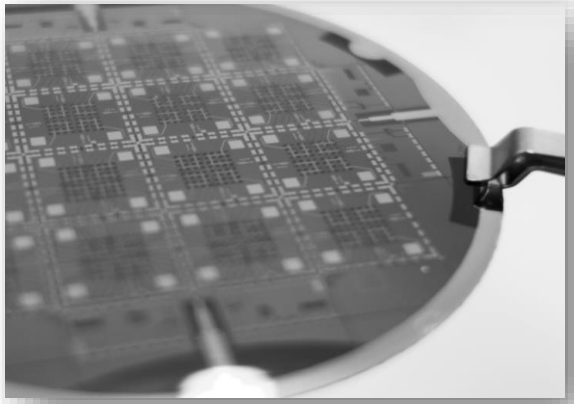
**$\Delta E_{FWHM}$= 2eV @ 60 keV in reach !**

**$E/\Delta E_{FWHM}$ > 30,000 !**

# 8×8 arrays of maXs-1/20/30/200

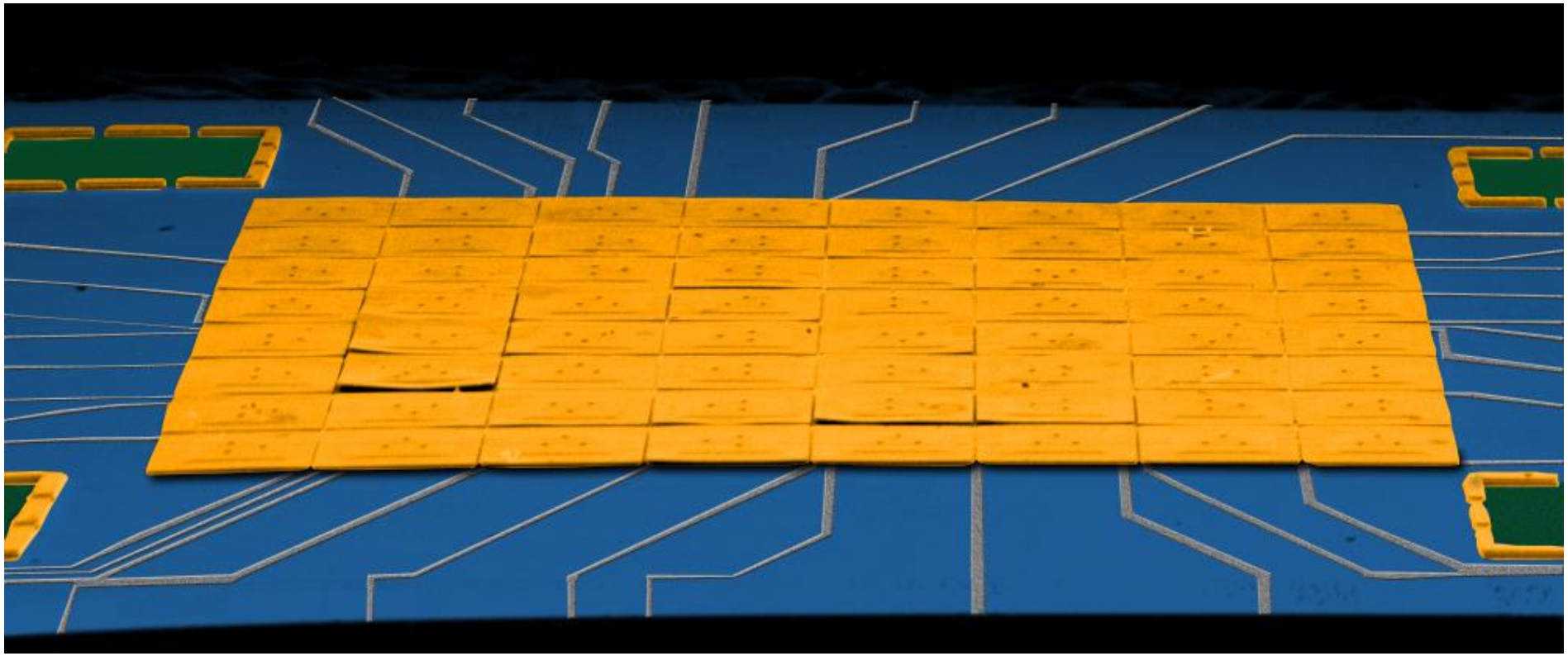
- **8 × 8 pixels** for photons up to **20/30s/30/200 keV** with $\Delta E_{FWHM}$ **= 2/3/5..8/30..50 eV**
- highly symmetric design -> cross-talk $< 10^{-4}$



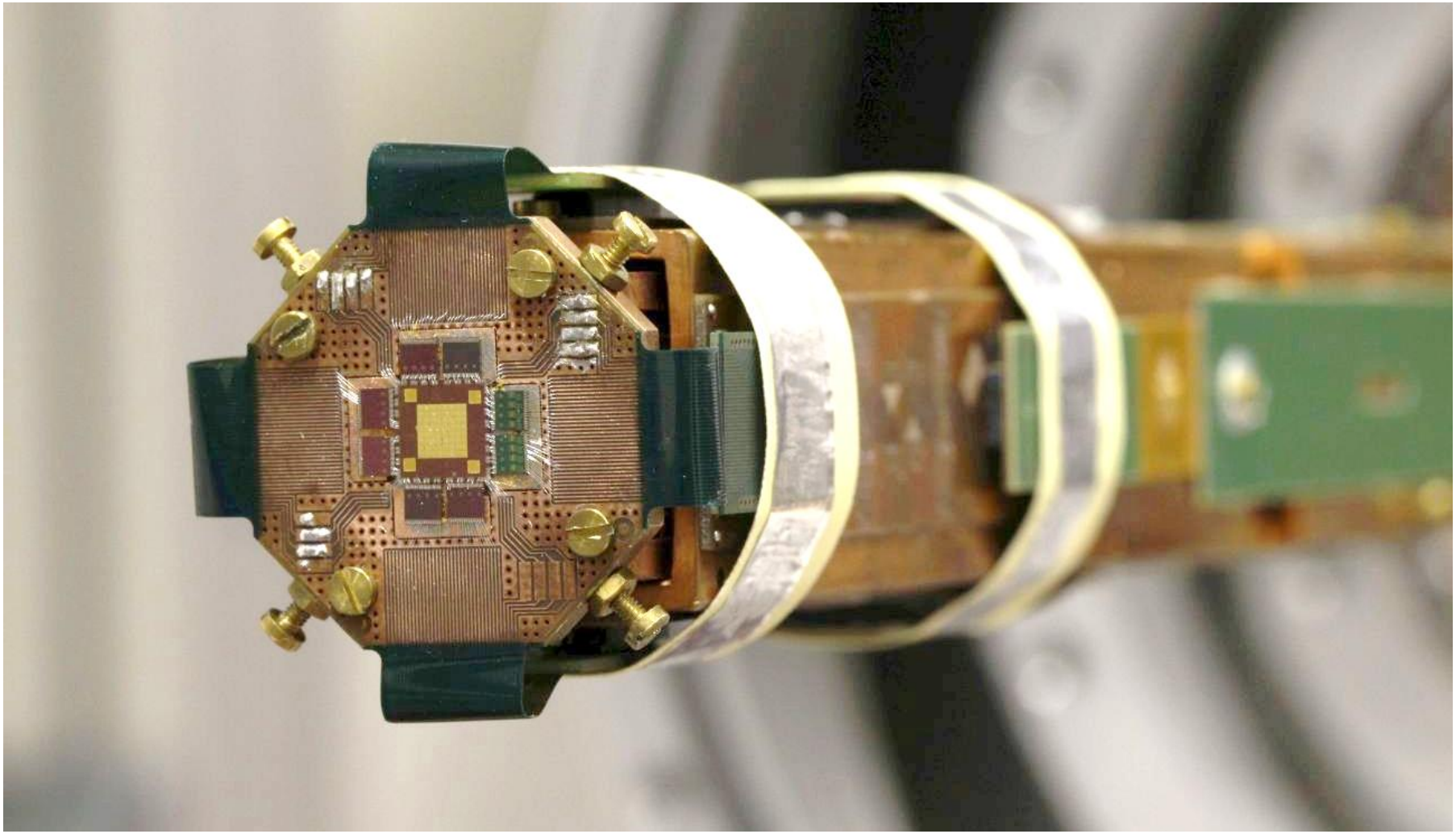
# maXs-30

- 8 × 8 absorbers for photons up to 30 keV
- each 0.5mm × 0.5 mm
- 30 - 50 μm thick gold

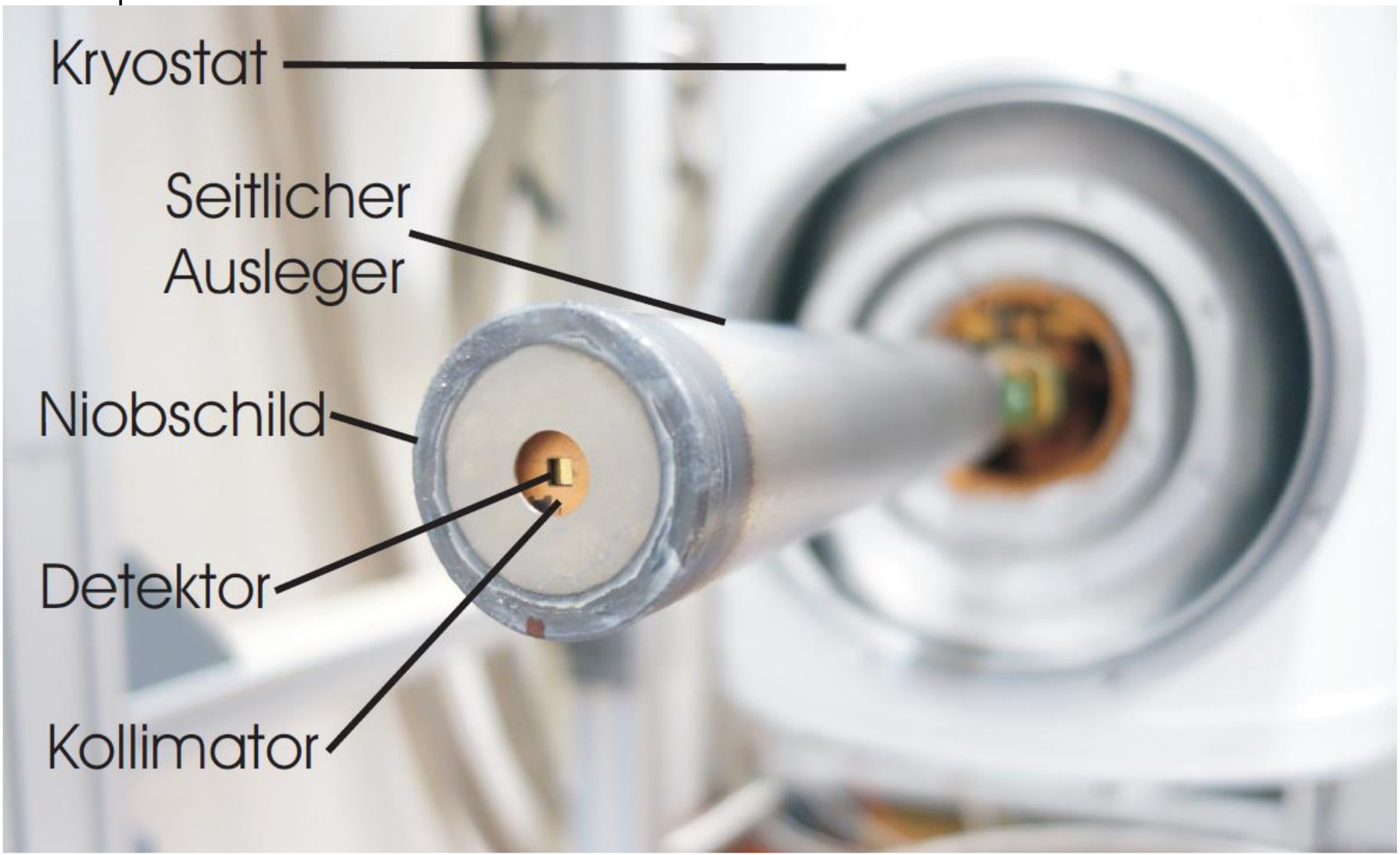


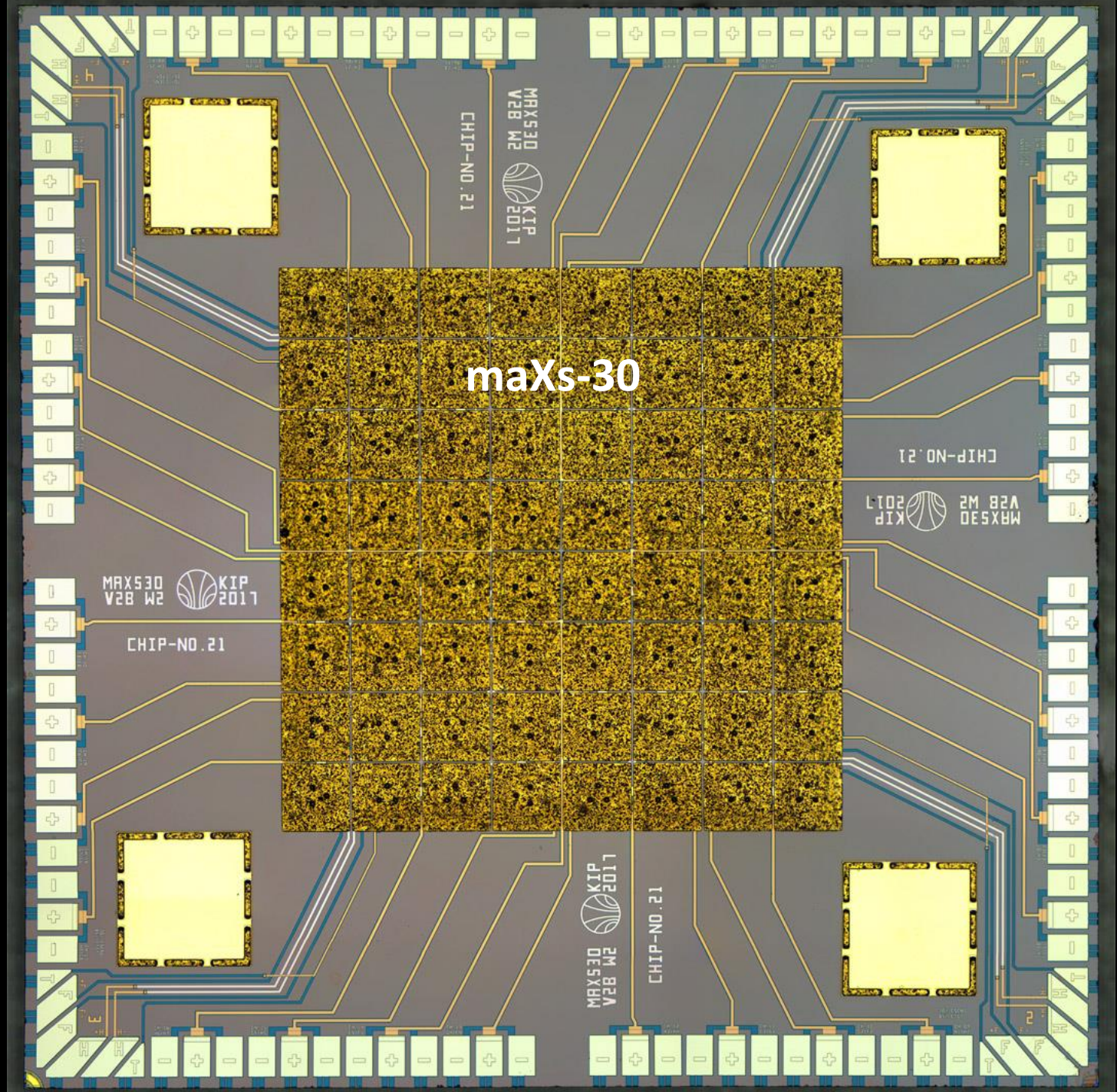
# maXs-30

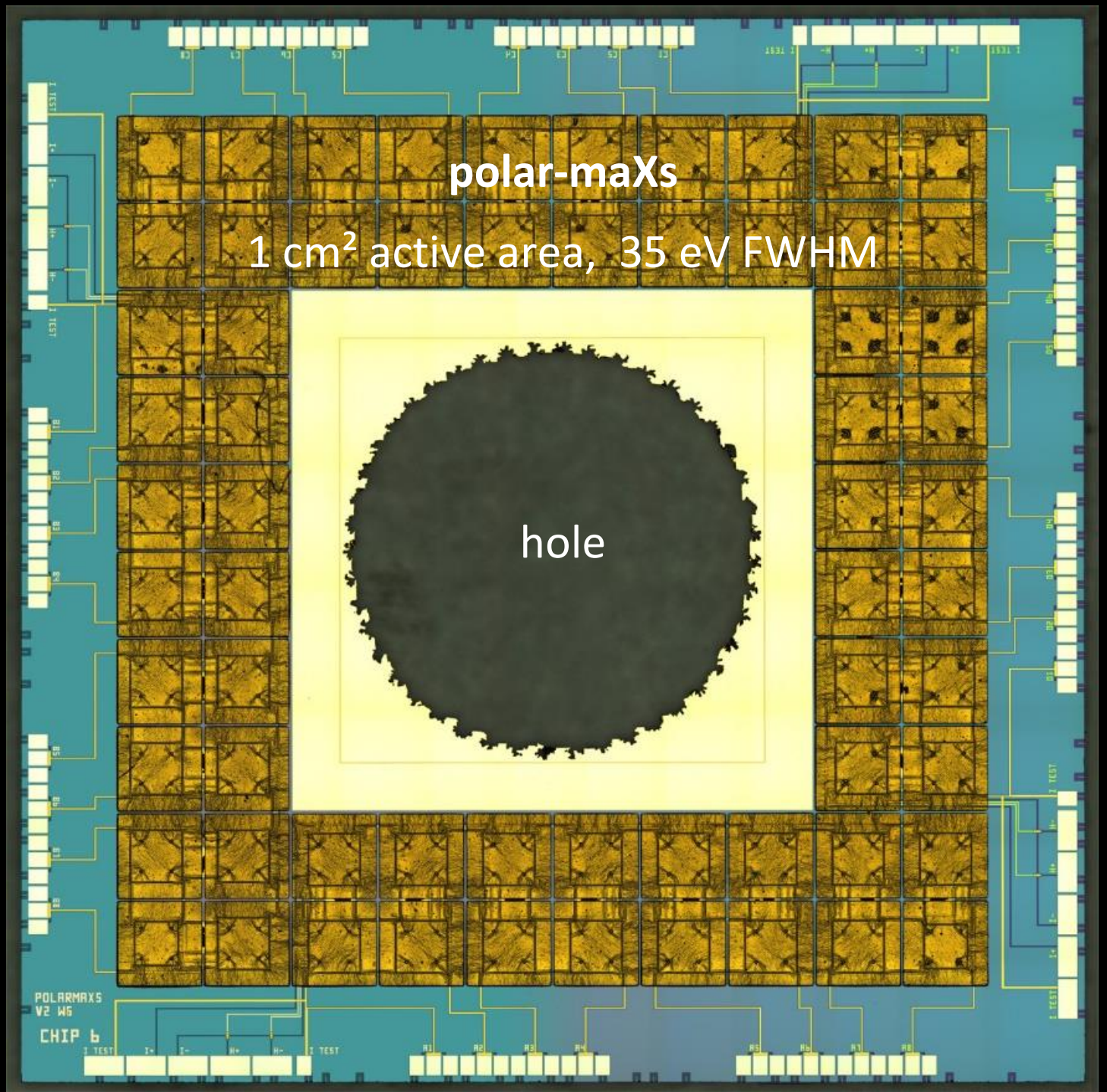
maXs-30 mounted on coldfinger of a dry dilution fridge



# maXs-30


Kryostat
Seitlicher Ausleger
Niobschild
Detektor
Kollimator


maXs-30
MAX530 V28 W2 KIP 2017
CHIP-NO.21

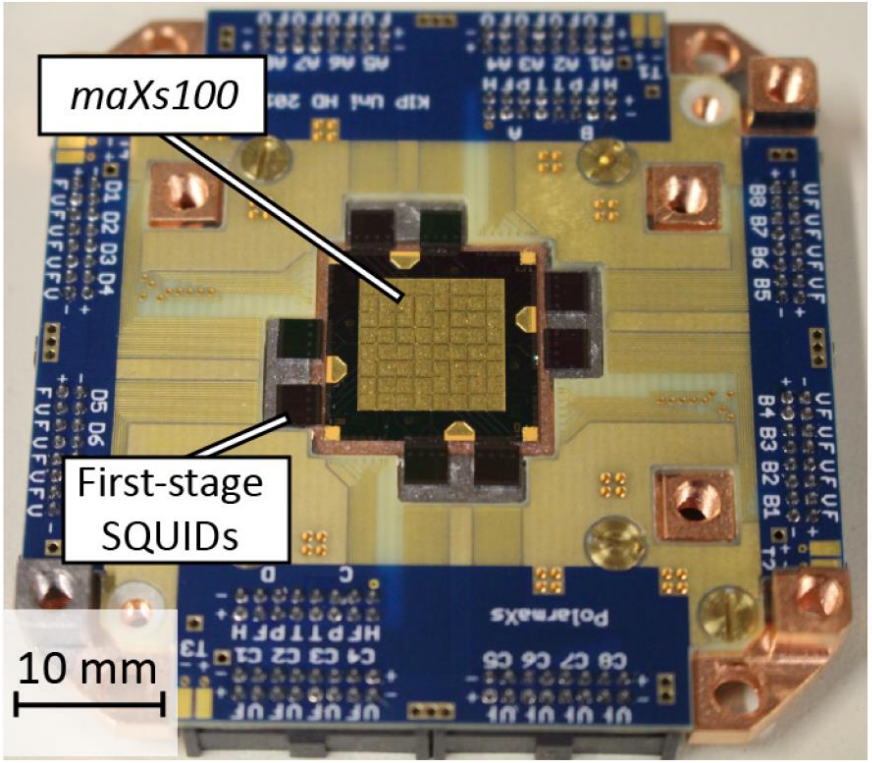

polar-maXs
1 cm² active area, 35 eV FWHM
hole
POLARMAXS
V2 W6
CHIP b

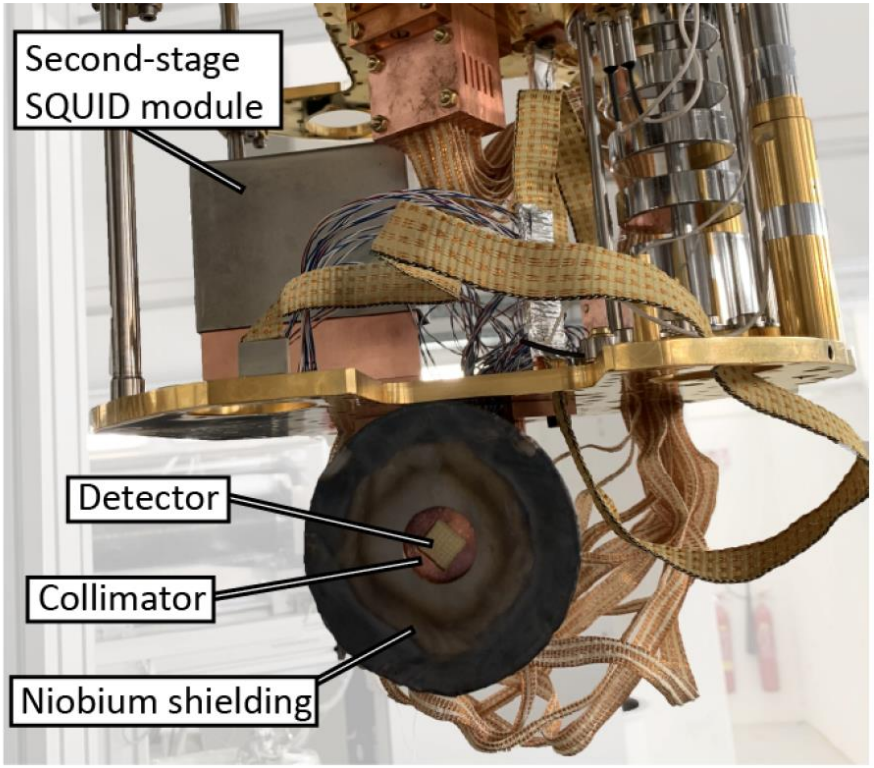
# maXs-100

10mm x 10mm

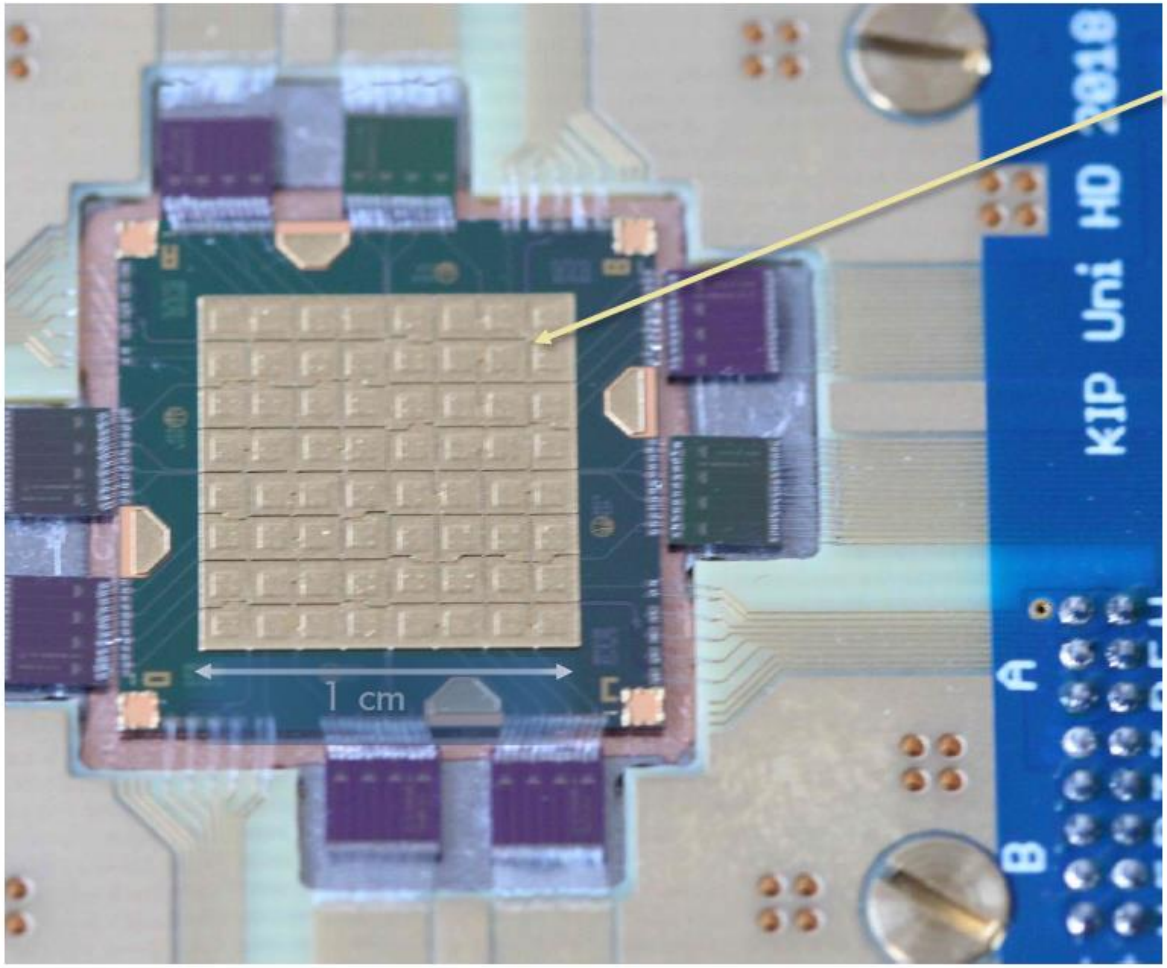
up to 100 μm thick gold

30 .. 50 eV (FWHM)



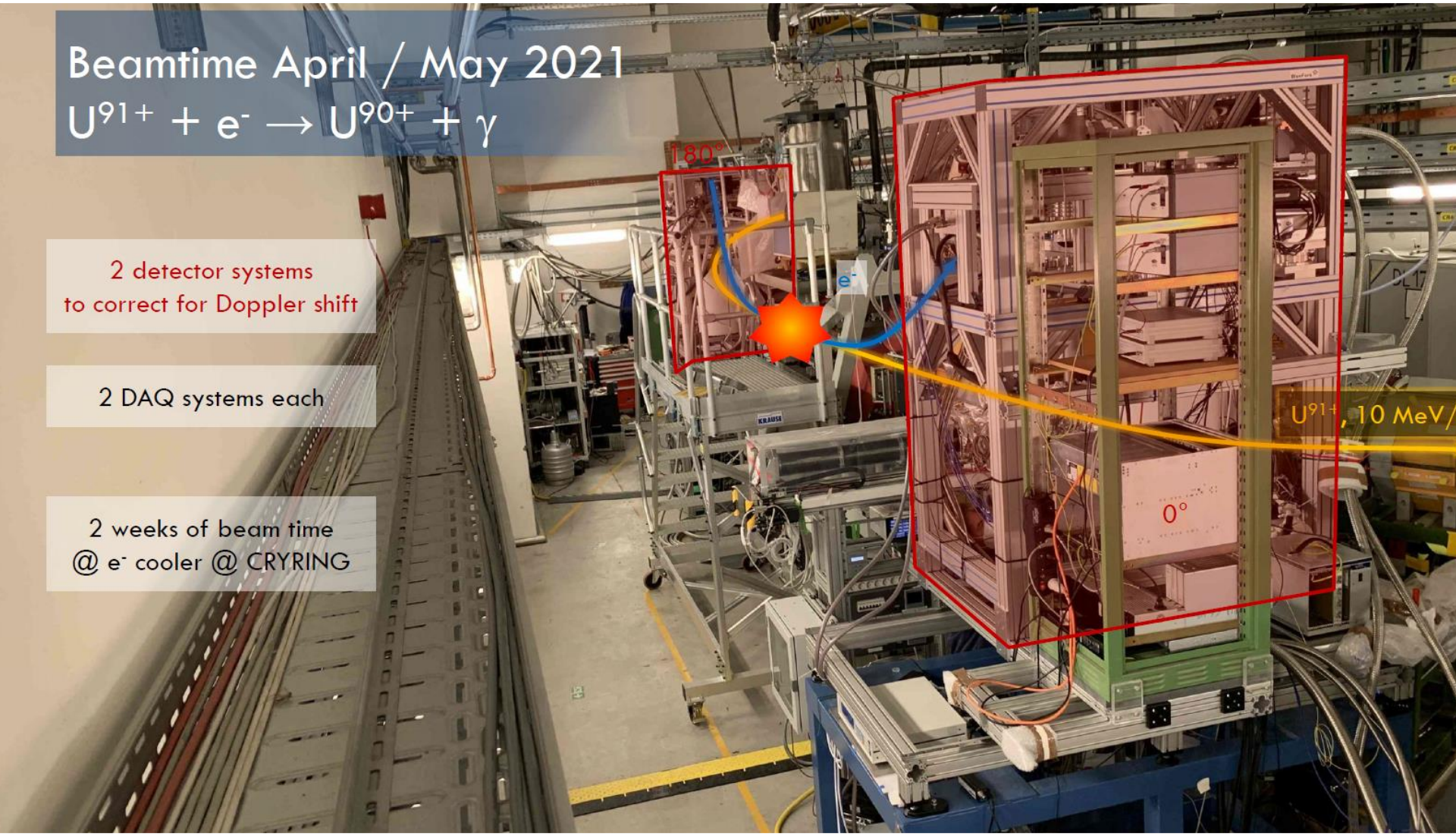
# maXs-100




8x8 absorbers

- Electroplated gold
- Area 1 cm²
- 50 µm thick
- $\Delta E_{FWHM}$ = 40 eV @ 60 keV
- Stopping power:
  - 49 % @ 90 keV
  - 40 % @ 100 keV
  - 34 % @ 110 keV

# maXs-100


Beamtime April / May 2021
$U^{91+} + e^- \rightarrow U^{90+} + \gamma$
2 detector systems
to correct for Doppler shift
2 DAQ systems each
2 weeks of beam time
@ e⁻ cooler @ CRYRING
180°
e⁻
$U^{91+}$, 10 MeV/
0°

# **MOCCA:** 4k-pixel molecule camera

to study reaction cross sections of molecular ions of cold interstellar plasmas

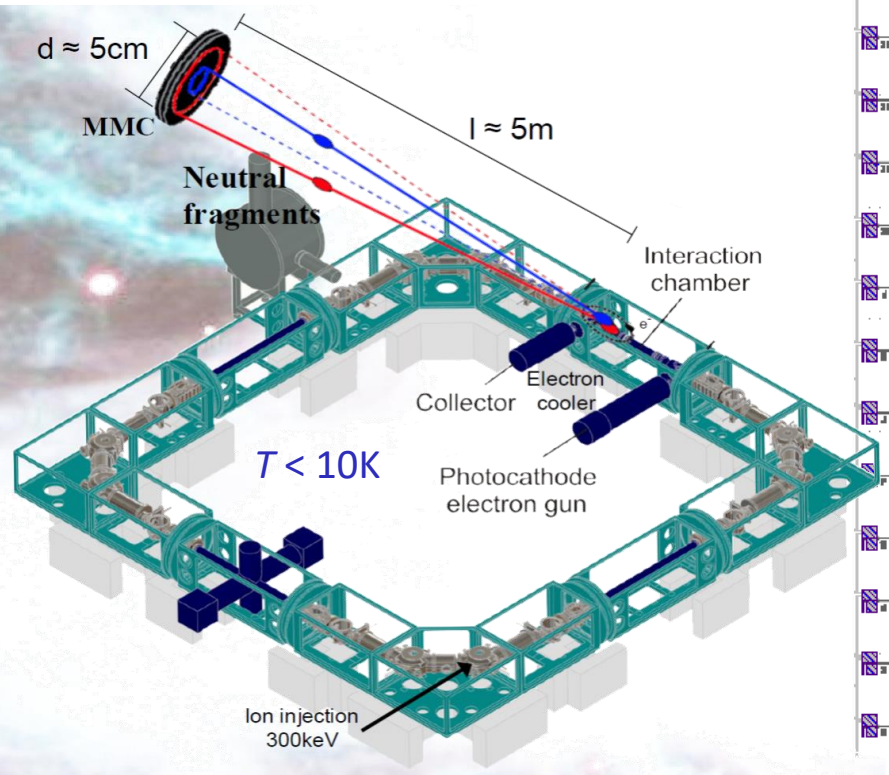
in the cryogenic storage ring CSR at MPI-K, HD

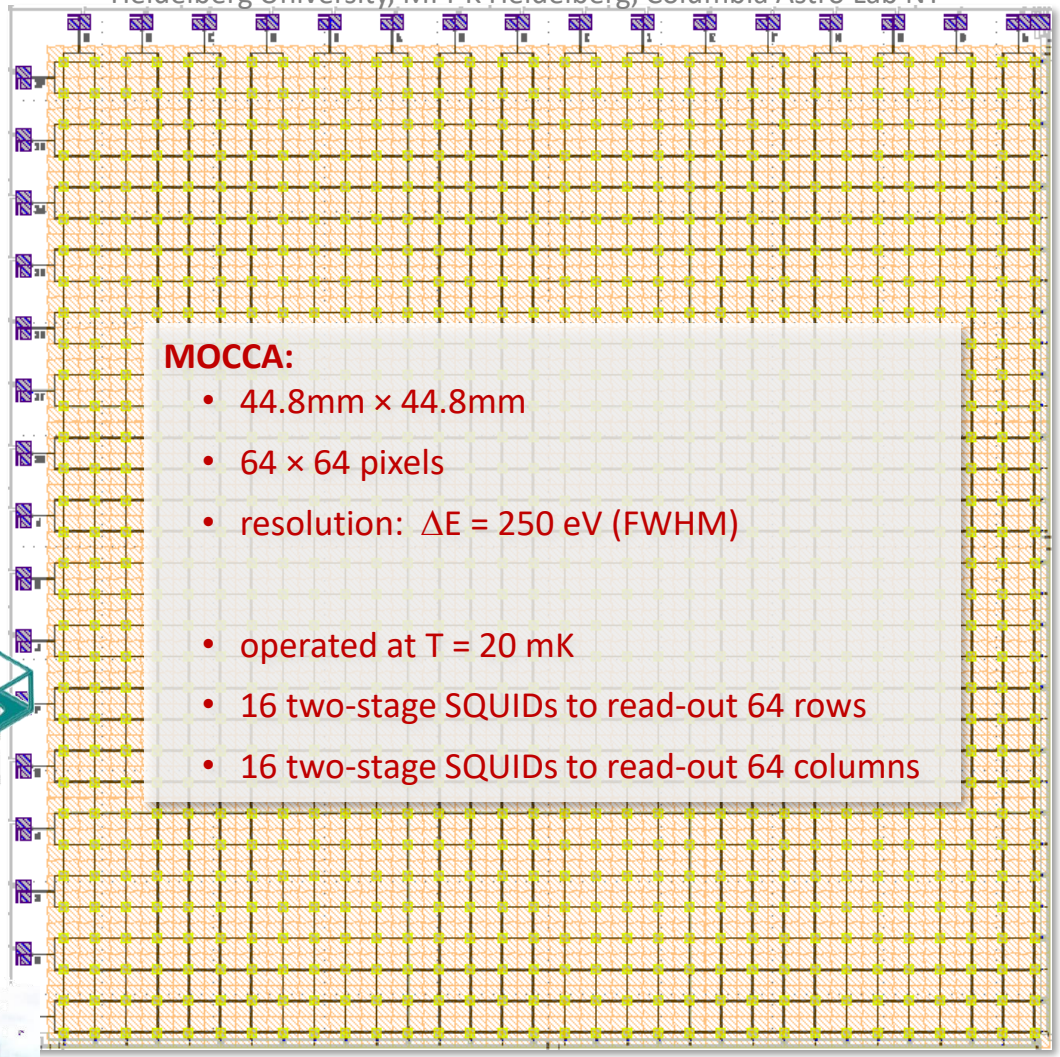
Heidelberg University, MPI-K Heidelberg, Columbia Astro Lab NY

Position and energy resolved detection

of neutral molecular fragments

after neutralizing with an electron in the e-cooler



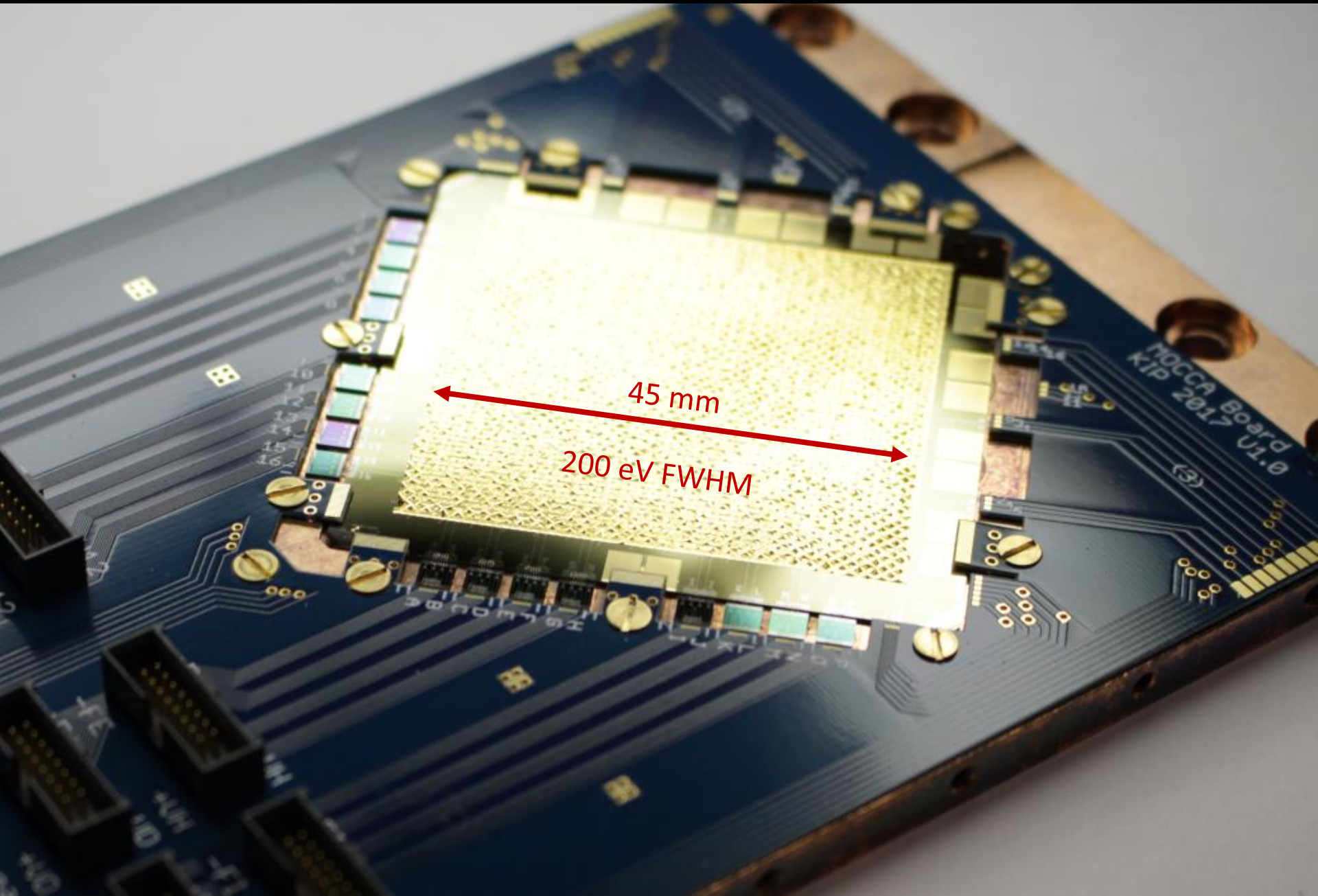



**MOCCA:**

- 44.8mm × 44.8mm
- 64 × 64 pixels
- resolution: $\Delta E$ = 250 eV (FWHM)

- operated at T = 20 mK
- 16 two-stage SQUIDs to read-out 64 rows
- 16 two-stage SQUIDs to read-out 64 columns

# MOCCA: 4k-pixel molecule camera / hi-res alpha detector

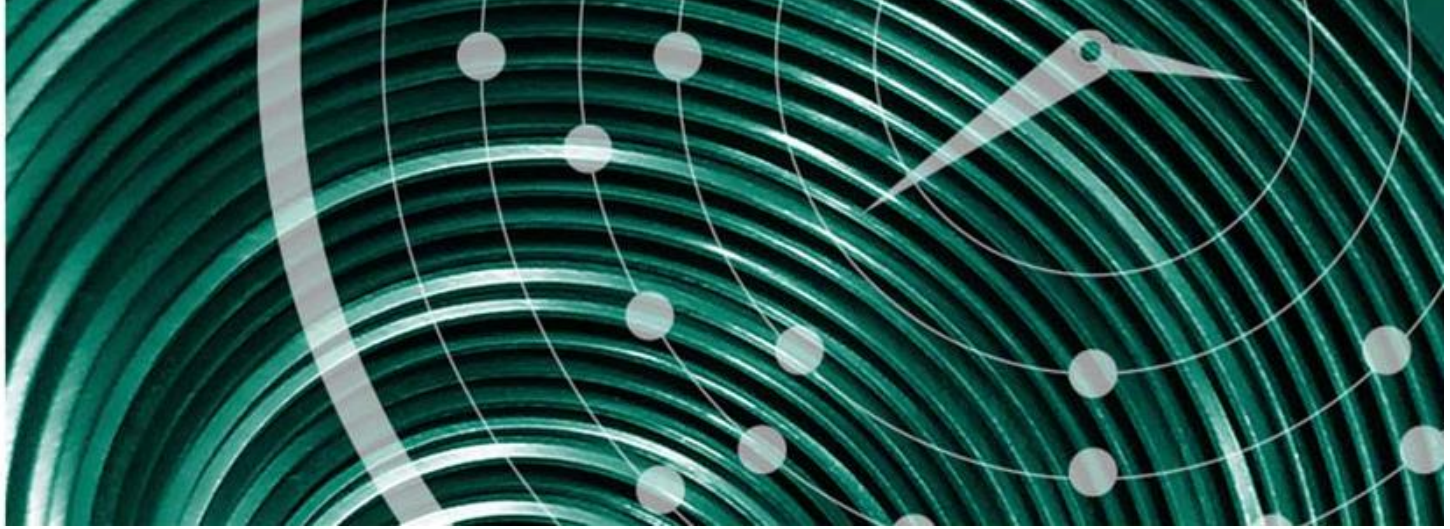


# MMCs get more and more mobile

here @ entrance to Frejus tunnel between Italy and France

nuclock

European Commission



# Development of a nuclear clock using Thorium-229 with one of the lowest nuclear excitation energy

**Isomer energy: 7.8 eV ± 0.5 eV --- too uncertain to build UV-Laser**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**LMU Munich**

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Loredana Gastaldo, Christian Enss
**Heidelberg University**

Christoph Düllmann
**University Mainz, HI Mainz, GSI**


TU WIEN TECHNISCHE UNIVERSITÄT WIEN

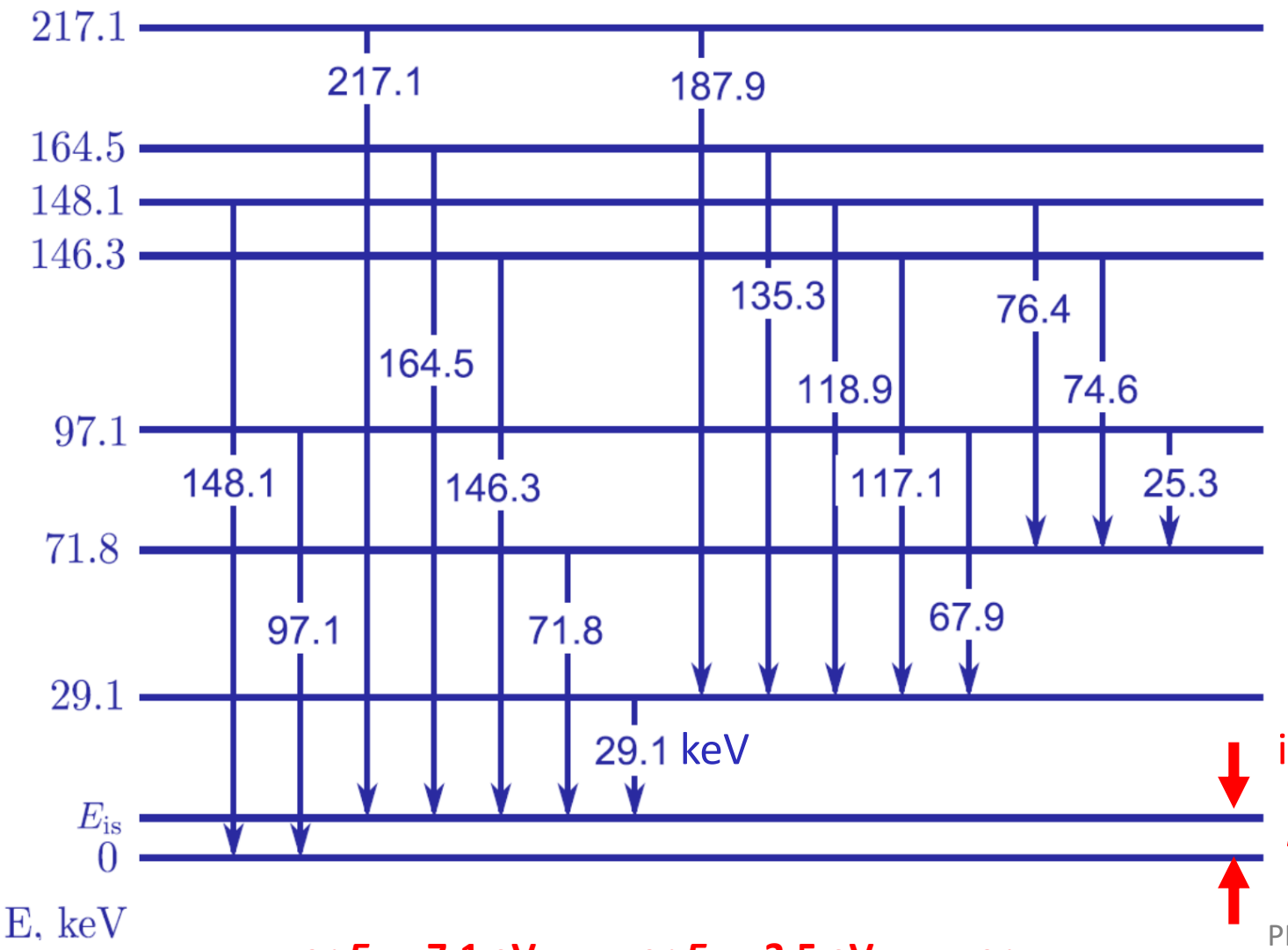
PTB

LMU LUDWIG-MAXIMILIANS-UNIVERSITÄT MÜNCHEN

UNIVERSITÄT HEIDELBERG ZUKUNFT SEIT 1386

TOPTICA PHOTONICS

# isomer state of Th-229




isomer energy

$E_{is}$ = 7.8 eV ?

B.R. Beck et al,
PRL 98, 142501 (2007)

or $E_{is}$ = 7.1 eV,
P.V. Borisyuk et al.,
ArXiv (2018)

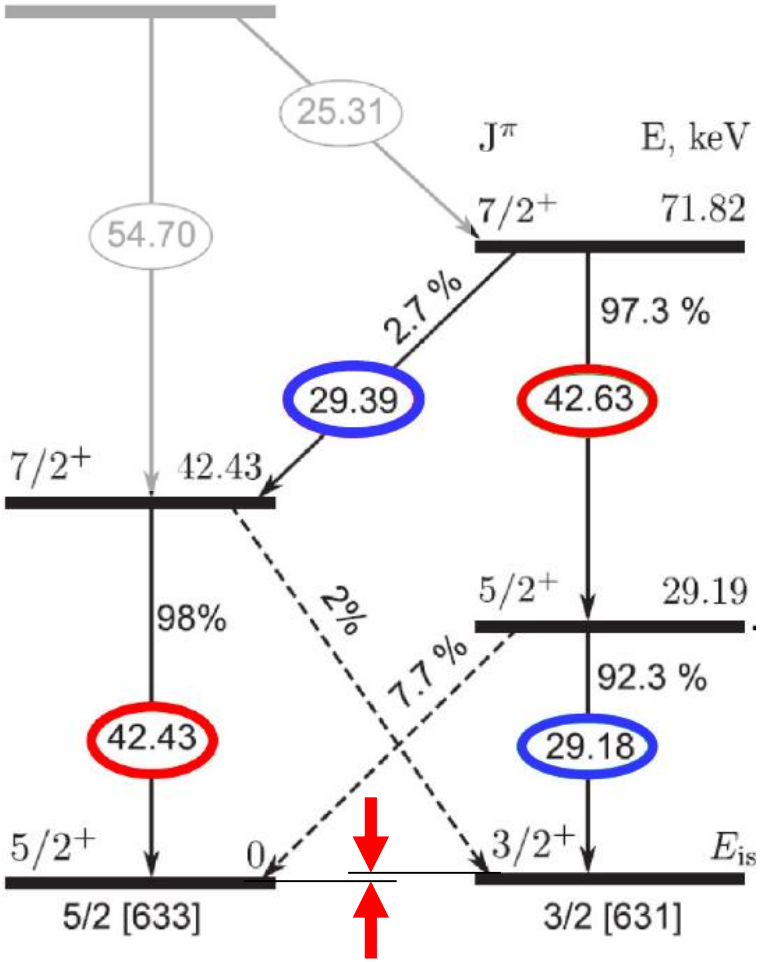
or $E_{is}$ = 3.5 eV,

or …

# indirect determination of isomer energy: 2 strategies

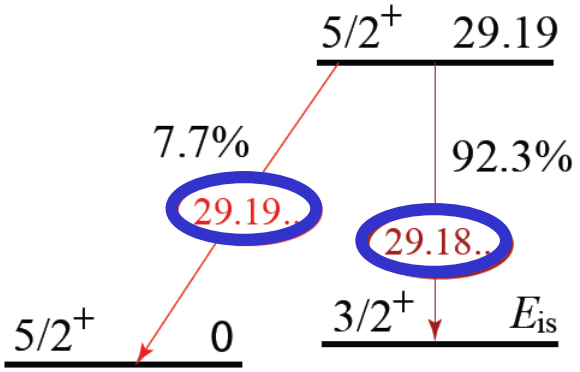
## i) from transitions within lowest 5 states

B.R. Beck et al, PRL 98, 142501 (2007)

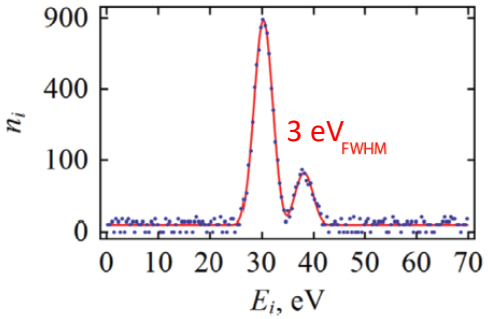


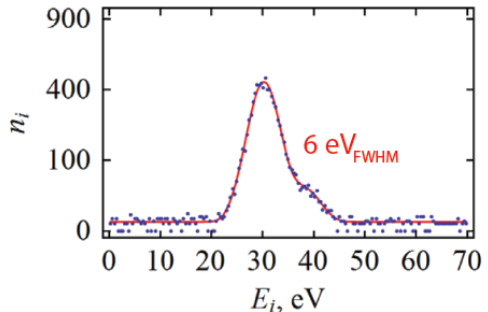

$$E_{\mathrm{iso}} = E_{29.39\,\mathrm{keV}} - E_{29.18\,\mathrm{keV}} - (E_{42.63\,\mathrm{keV}} - E_{42.43\,\mathrm{keV}})$$
$$= \Delta E_{29\,\mathrm{keV}} - \Delta E_{42\,\mathrm{keV}}$$

## ii) resolving the 29.2keV doublet



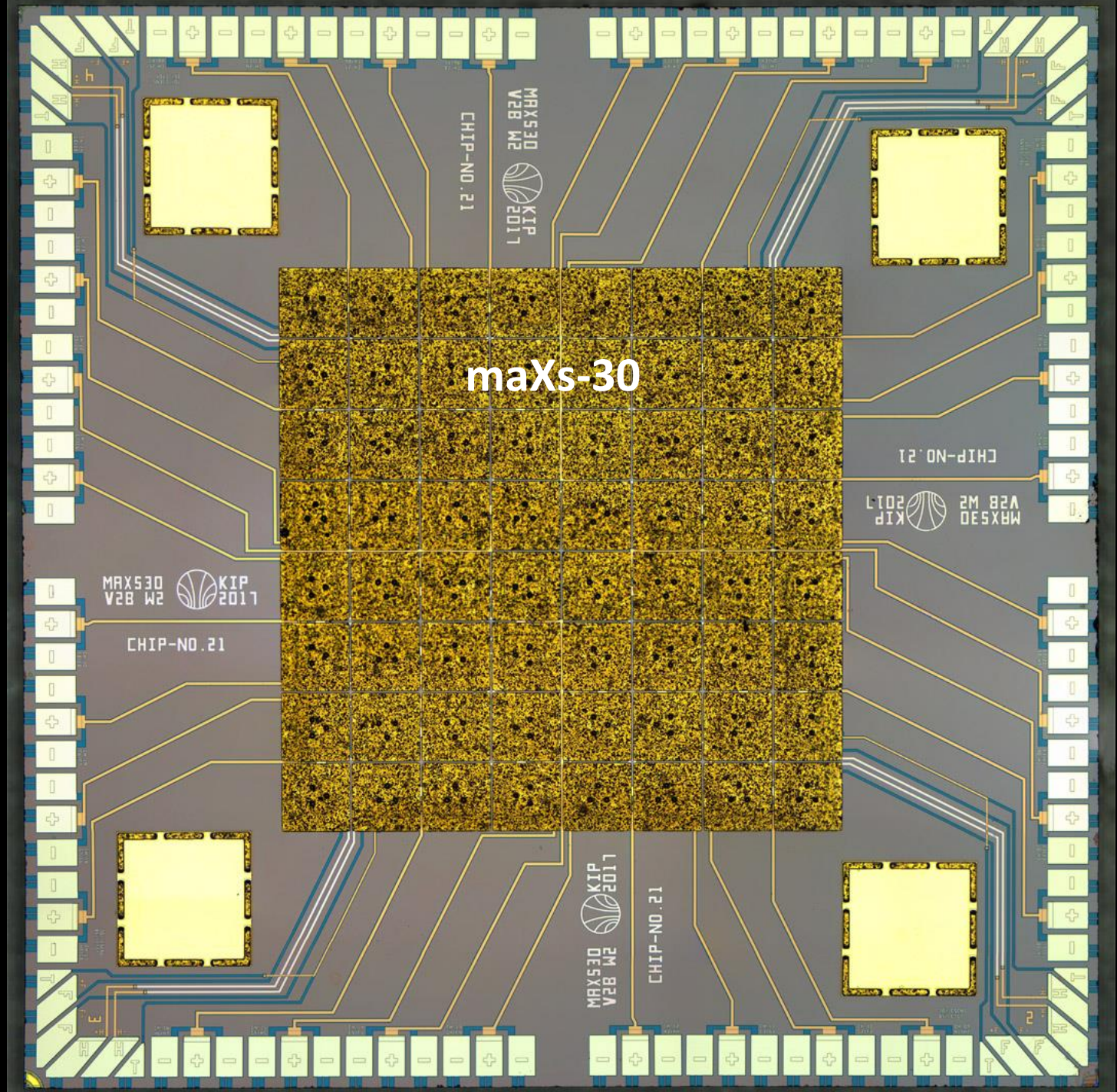

an artist´s Monte Carlo



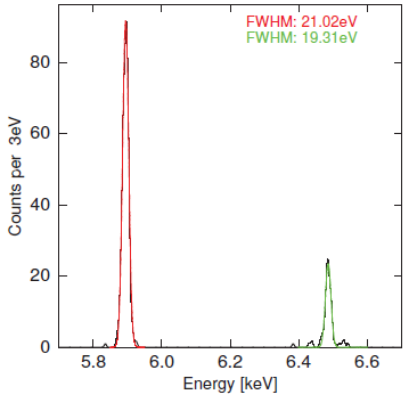



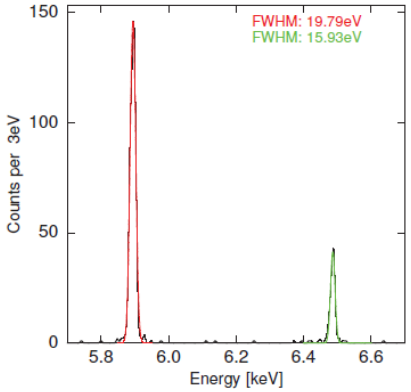
# the challenges

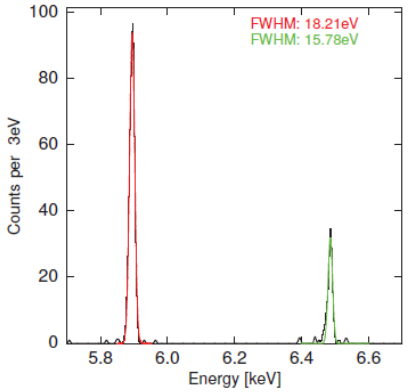
- Excited Th-229 from α-decaying U-233
  - isotopically pure U-233 !
  - with chemically removed daughters (many of them hard β-emitters)
- High *Z* of Uranium
  - strong self-shielding for the interesting 29 keV photons
  - limited, small(!) activity per area
- Detector needs
  - large detector area
  - large solid angle of acceptance
  - high resolving power: 3 – 10 eV @ 30 – 40 keV
  - long time stability
  - pixelized detectors need good co-adding performance
  - excellent linearity!

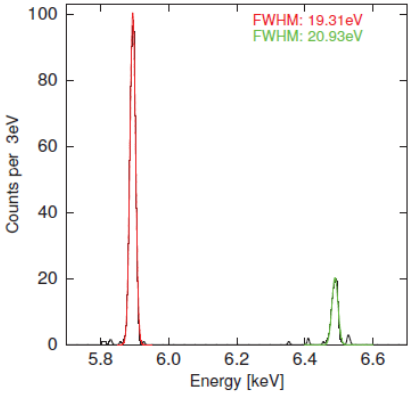

maXs-30
MAX530 V28 W2 KIP 2017
CHIP-NO.21

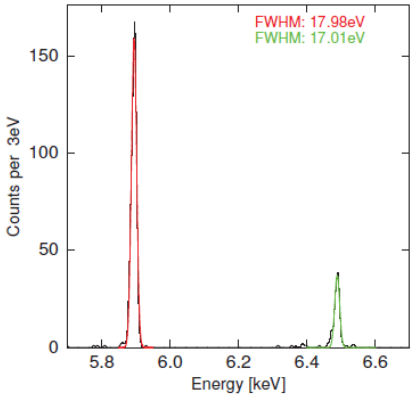
# maXs-30: calibrating and co-adding of spectra

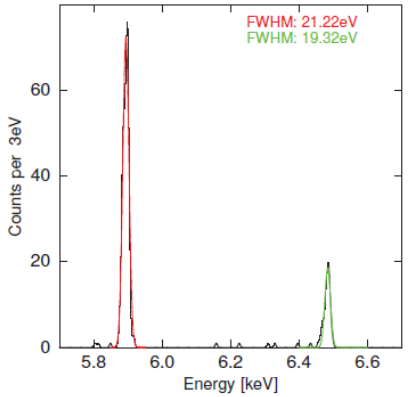


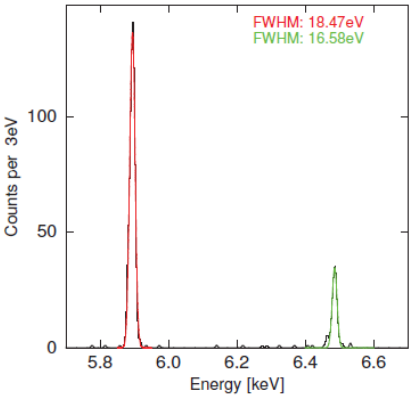



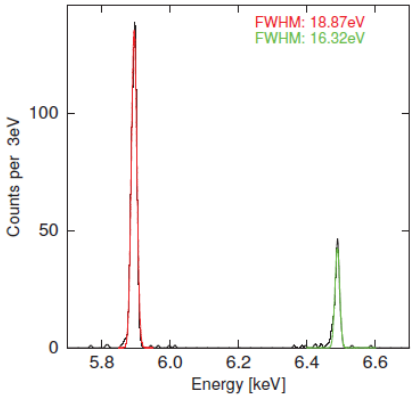



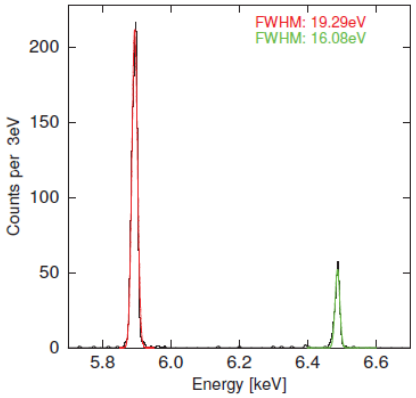



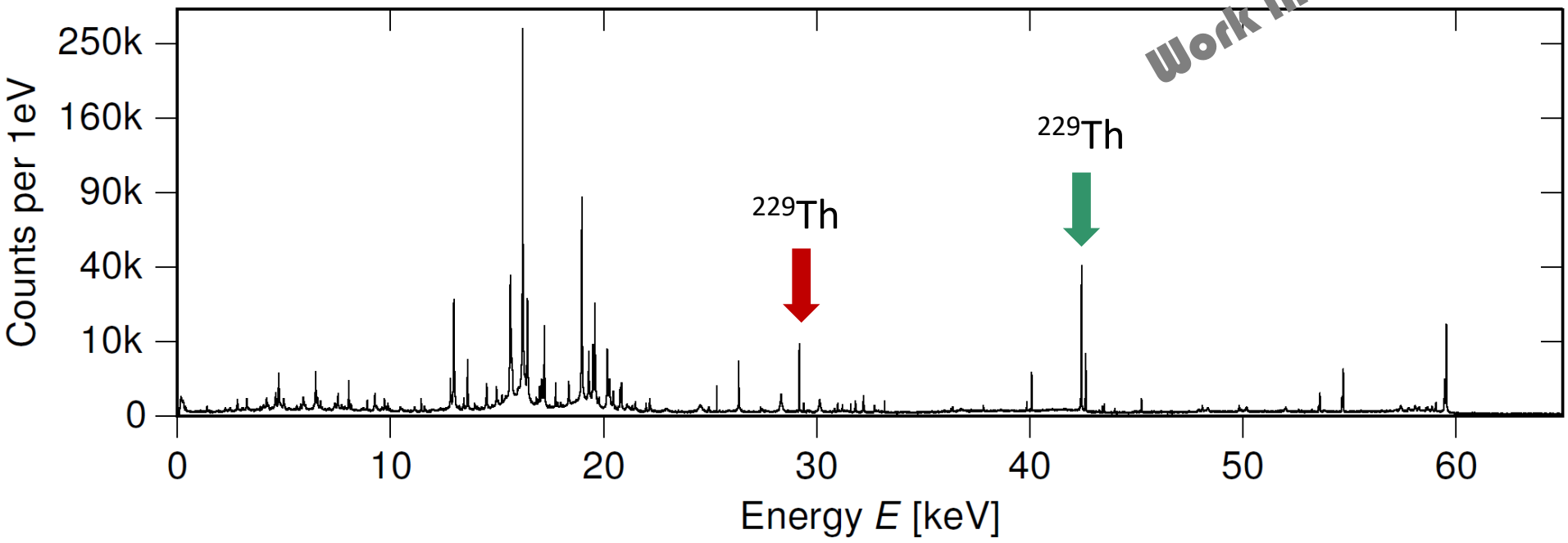



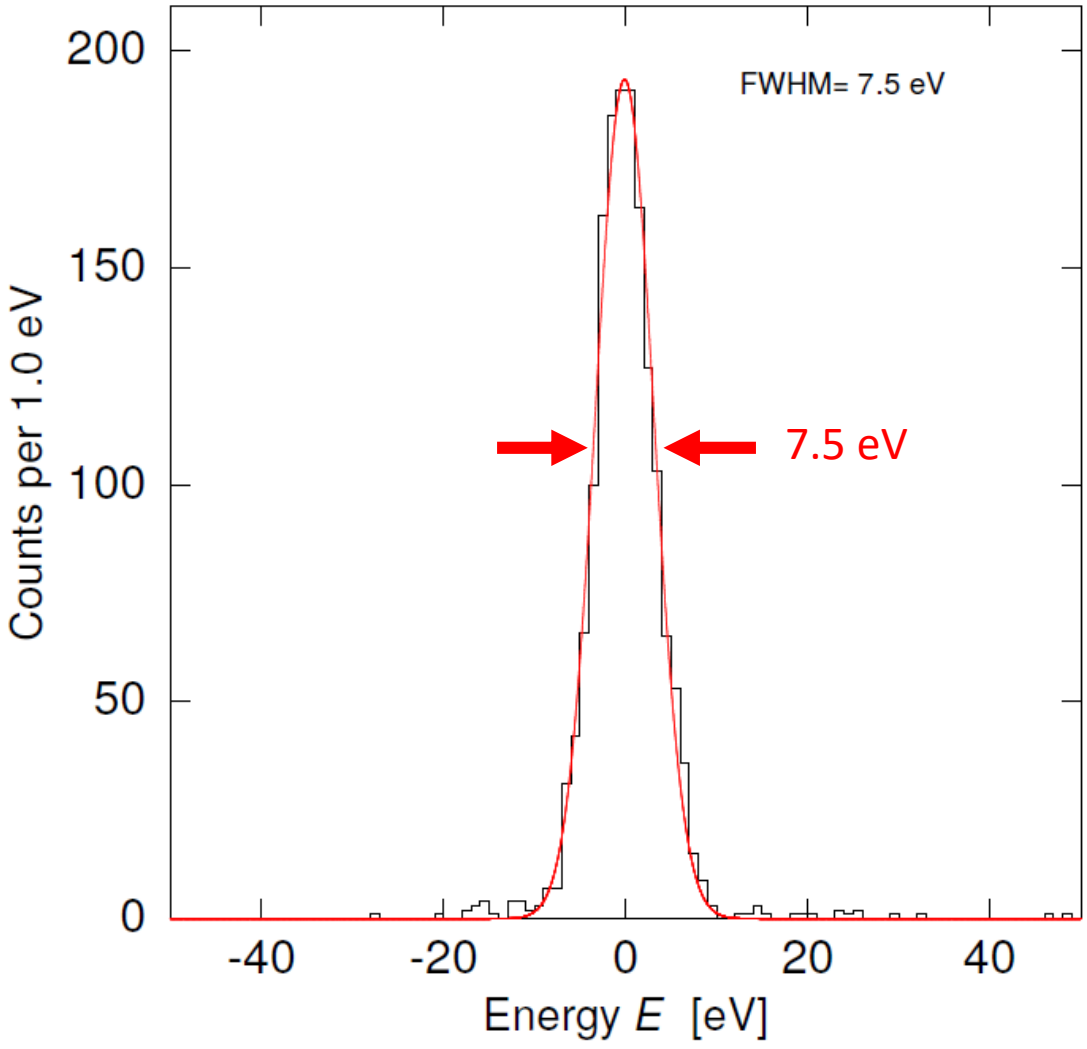



# $^{233}U + ^{241}Am$ spectrum



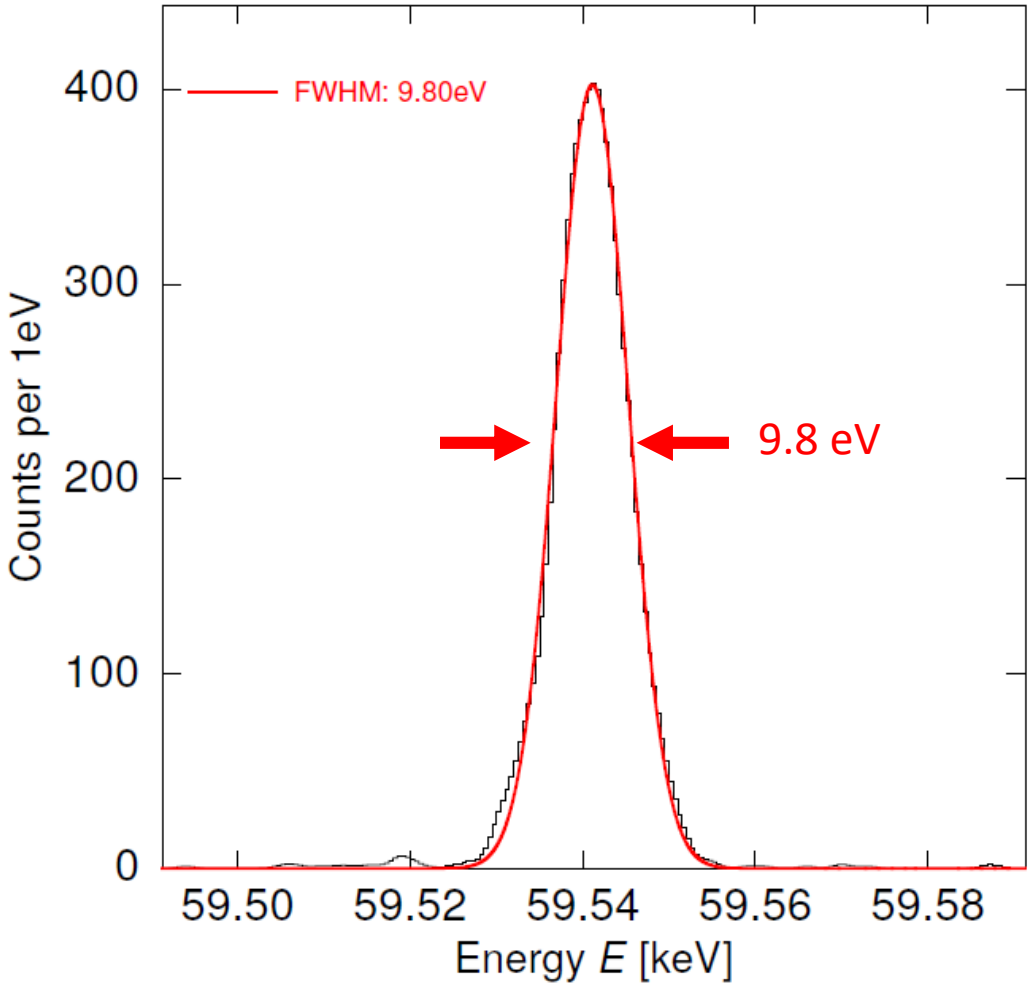

Co-added 20 channels, several weeks

# energy resolution at 0 keV




Very close to design value

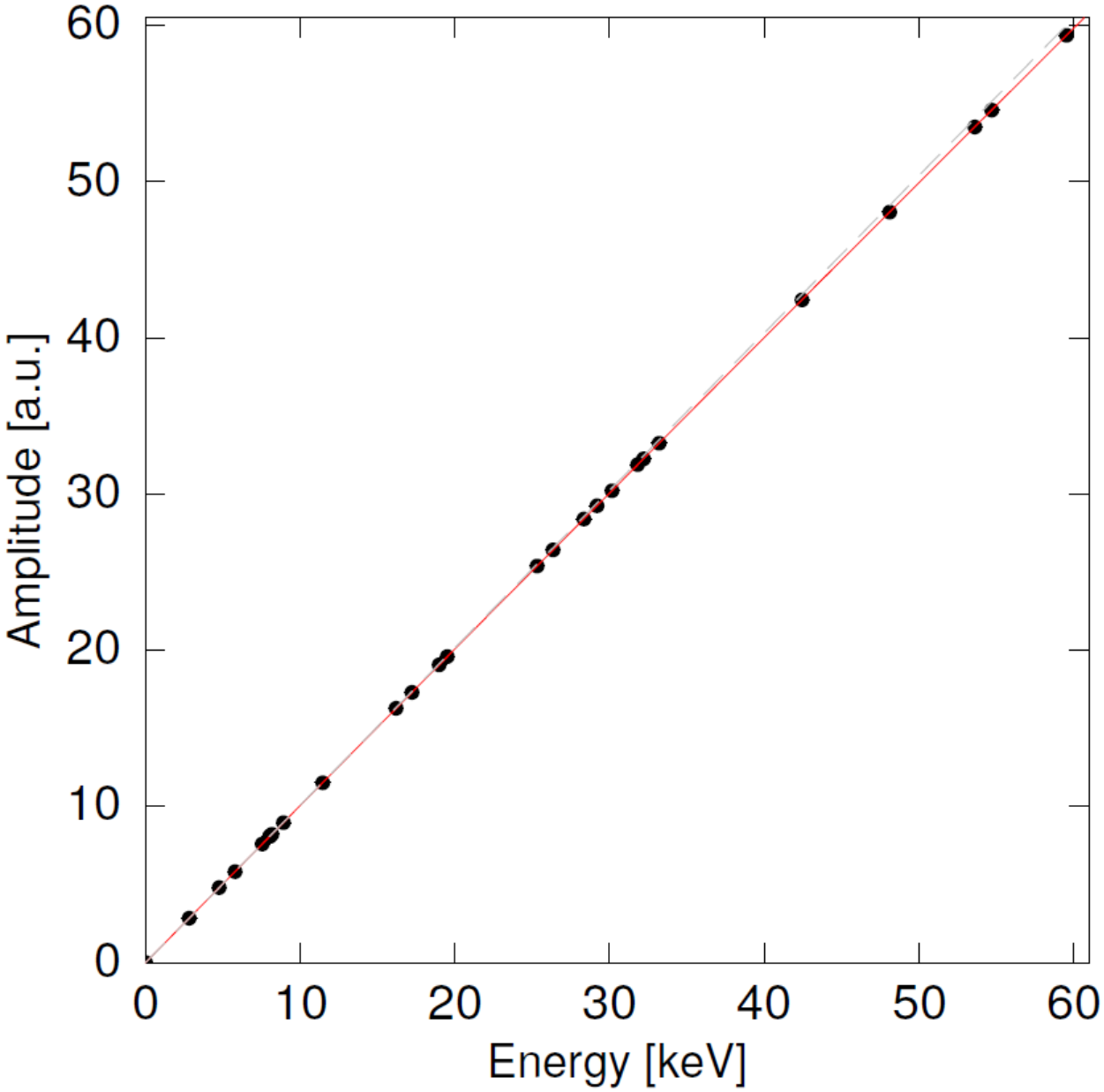
# energy resolution at 60 keV



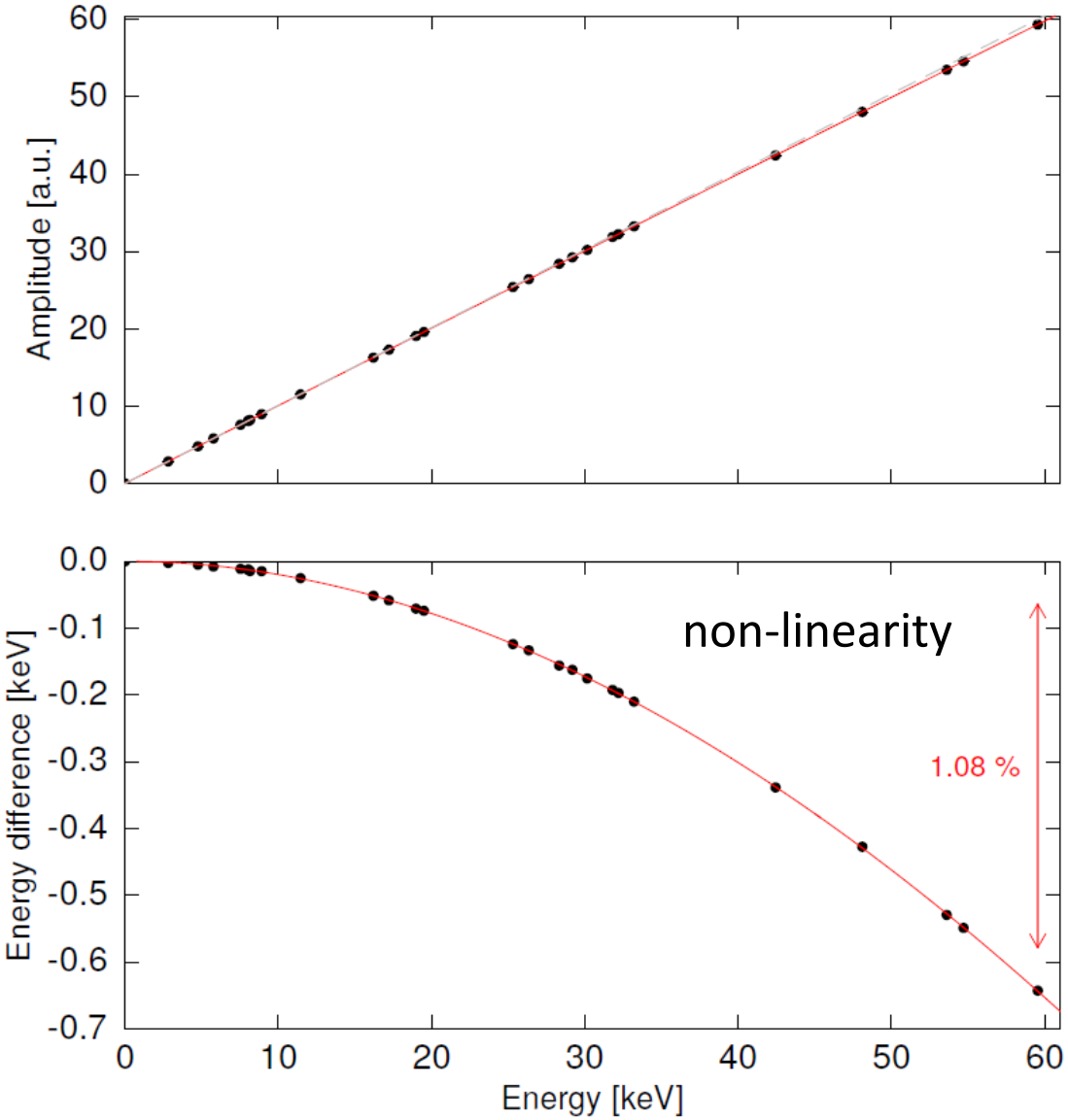

Energy resolution $\Delta E_{FWHM}$ = 9.8 eV @ 59 keV

World record resolving power: 6000

# calibration

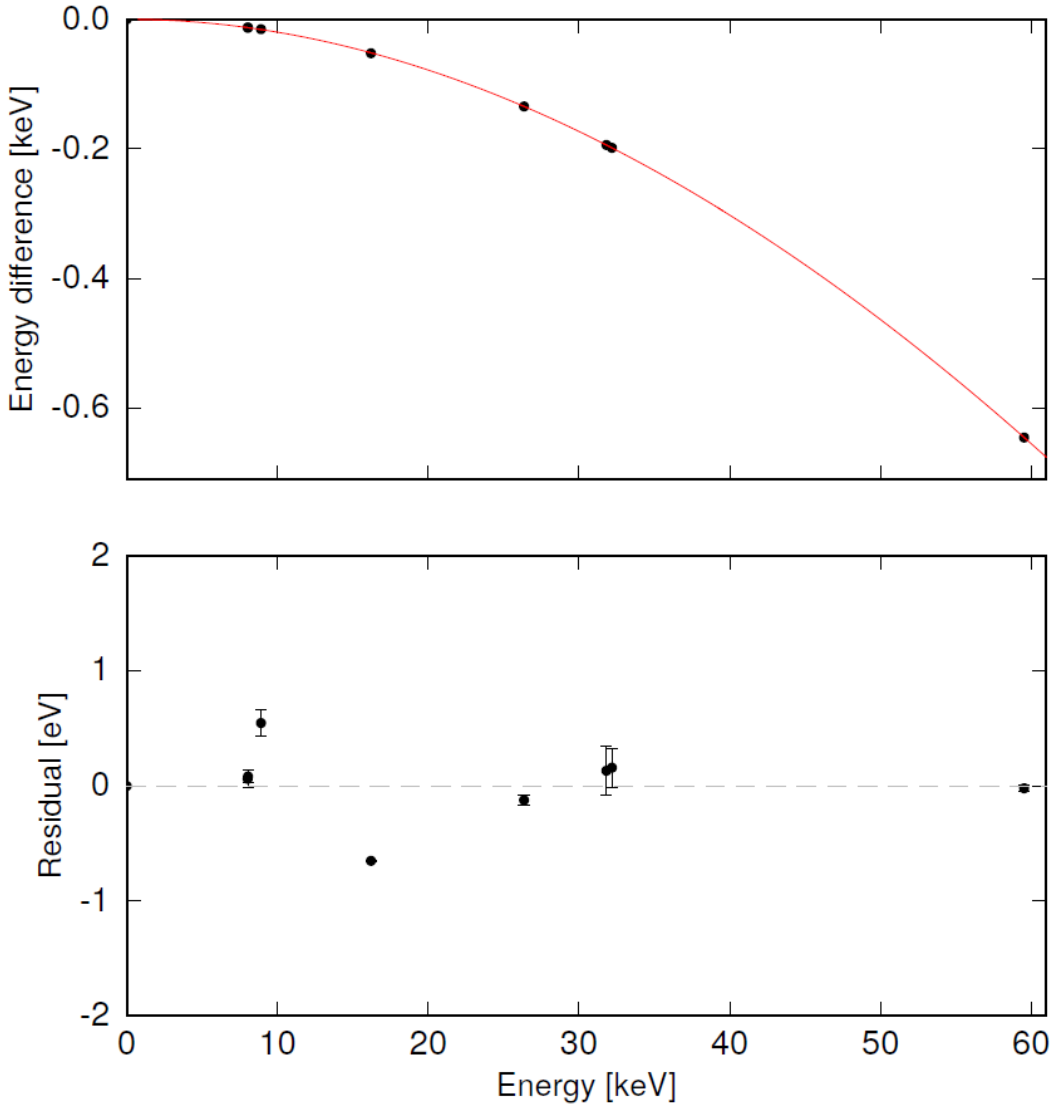


# calibration



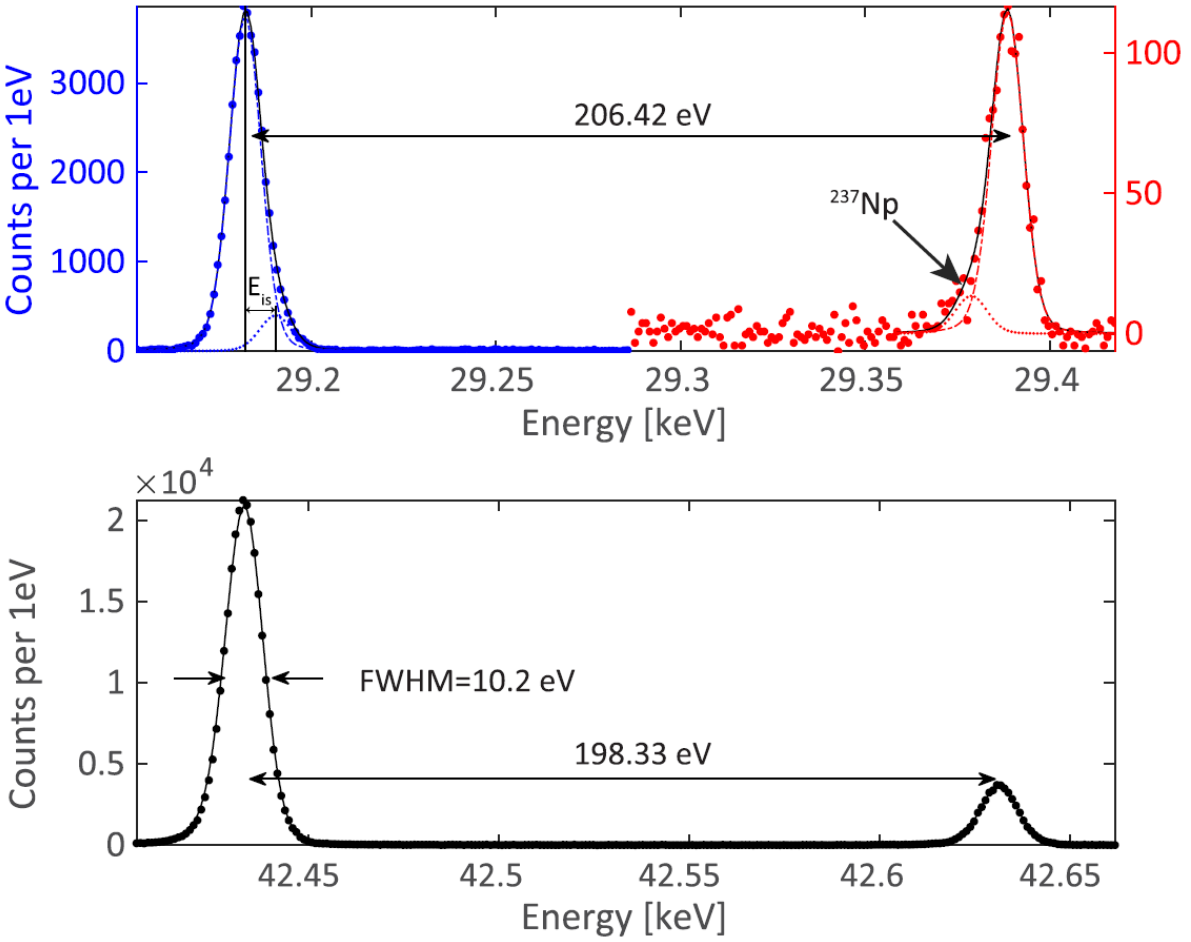

non-linearity as thermodynamically expected!

# non-linearity




Sub-eV agreement for carefully selected calibration lines.
This should be detailed out in future!

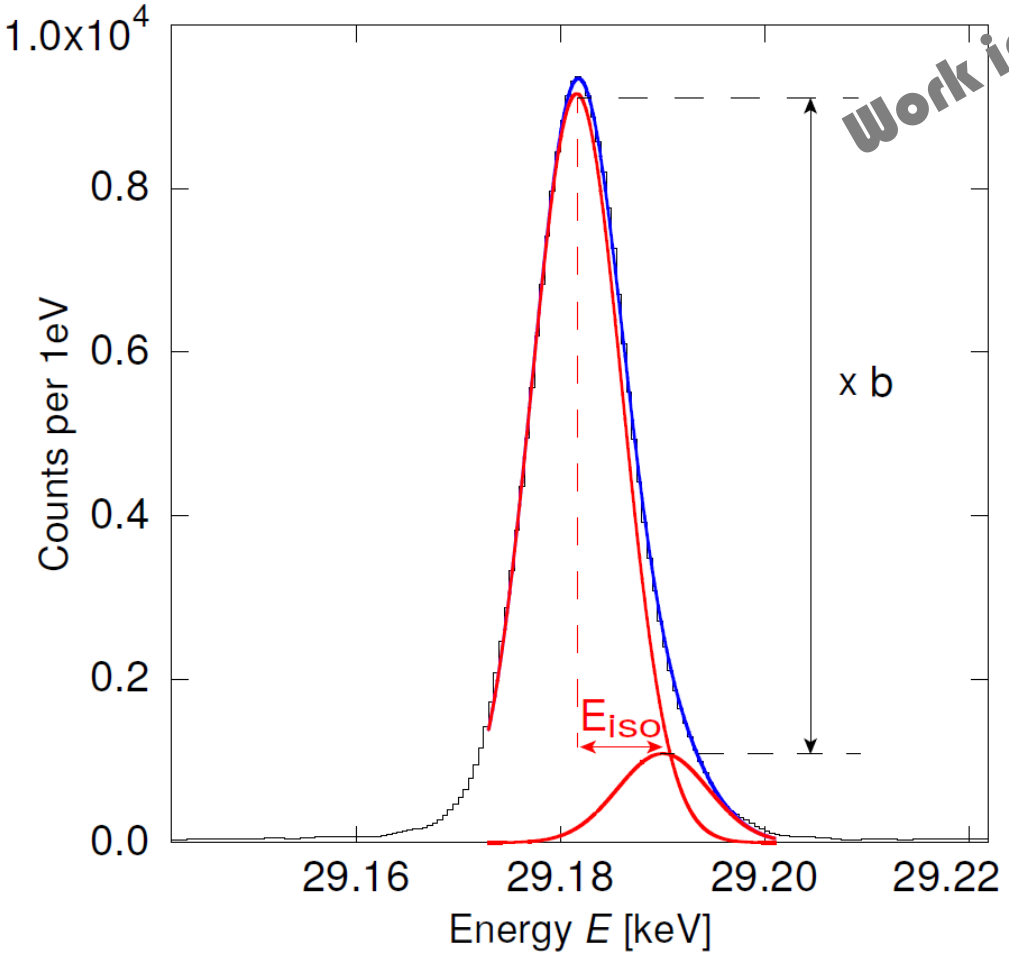
# isomer energy of Th-229 --- 4-line-approach



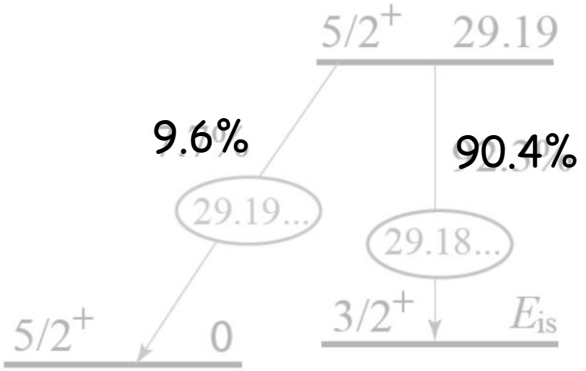

Isomer energy: $\Delta E_{iso}$ = 8.10 eV ± 0.17 eV

in fair agreement with previous result 7.8 eV ± 0.5eV

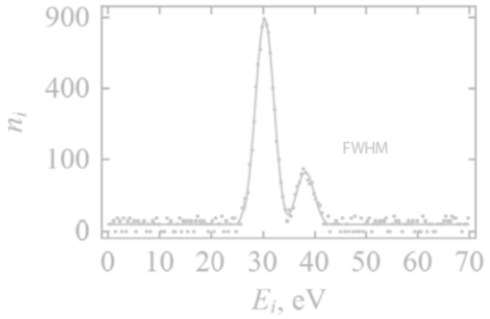
# the 29.2 keV doublet

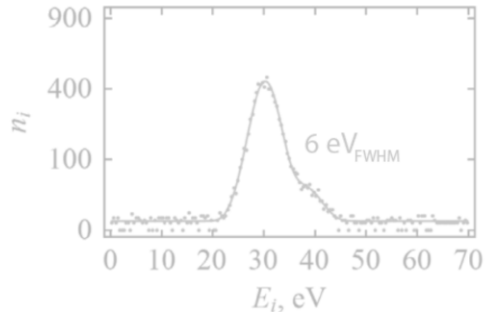



Work in Progress




an artist´s Monte Carlo



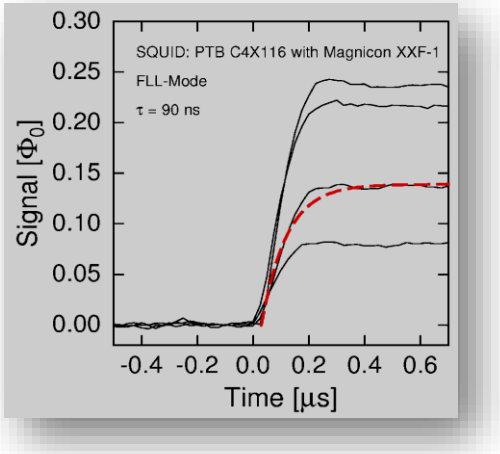

Isomer energy: $E_{iso}$ = 8.2 eV

$\Delta E_{FWHM}$ = 10.5 eV

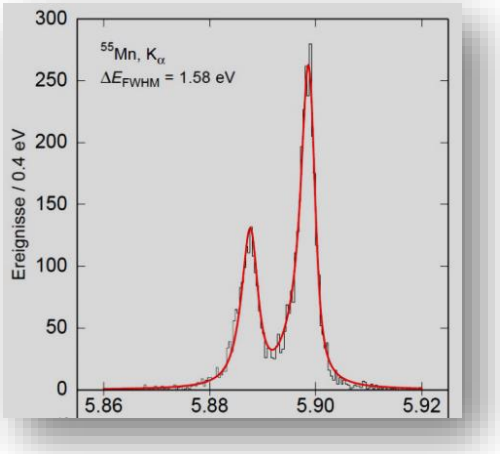
# summary

- metallic magnetic calorimeters combine in a unique way

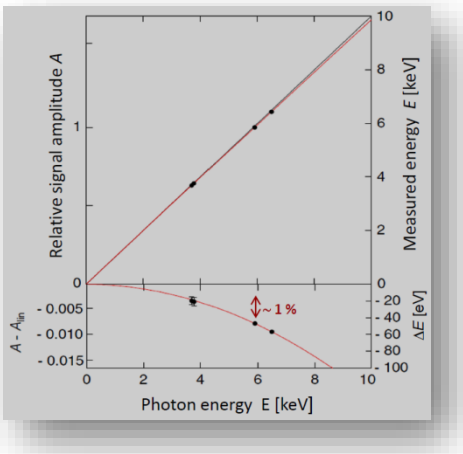
time resolution




energy resolution




linearity




- energy calibration: sparse set of calibration lines allows for sub-eV accuracy in fullrange

- Isomer energy: **8.10 eV ± 0.17 eV** T.S. et al., PRL **125**, 142503 (2020)

  in fair agreement with 8.28 eV ± 0.17 eV

  as found by electron spectroscopy of IC electrons

  B. Seiferle et al. Nature **573**, 243 (2019).

# installation

**Dimensions**

| | |
|---|---|
| Cryostat-frame: | 110cm × 82cm × 172cm (2nd version slightly larger) |
| Gas handling and control | 80cm × 120cm × 190cm |
| $^4$He compressor | size: 50cm × 70cm × 60cm<br>max. distance from cryostat frame: 20 m |

**General infra-structure**

**Access to and area at the beamline**
During installation of maXs at the internal target access to this region is mandatory. During normal operation / data taking all necessary slow control can be done remotely via TCP/IP and no access is foreseen.

At all locations where maXs is to be used, space for the components listed above is required, most of which within a circle of about 5m around the cryostat.

# installation

**Media requirements**

**Electricity**

| | |
|---|---|
| $^4$He compressor | 3-phase, 10 kW, maintenance interval 30 000 h |
| gas handling and pumps | 220 V, 2×16A single phase |
| electronics, DAQ | 220 V, 1×16A, single phase |

**Cooling water**

$^4$He compressor (CryoMech CP2880 for PT410RM)

temperatur non-condensing to 25 °C
flow 7-9 l/s,
typ 15L/min at 3.5bar pressure drop
max power 10 kW

$^3$He turbo pump (Pfeiffer HiPace400)

temperature non-condensing to 25 °C
flow typ 2L/min at 3.5bar pressure drop
max power 500 W

# installation

**Pressurized gases**

Pressurized air for vacuum valve actuation and the air springs of the cryostat table:

| | | |
|---|---|---|
| pressurized air: | pressure: | > 4 bar, negligible flow<br>mostly static pressure |

Further use of pressurized gases besides the $^4$He circuit (25 bar) of the pulse tube cooler is not planned.

**Cryogenics**

The pulse tube cooled dilution refrigerator is a closed cycle cooler and does not require the transfer of cryogenic liquids. In case of subtle leaks in the $^3$He circuit, a liq. $N_2$ cold trap with a hold-time longer one week might serve as temporary solution.

**Exhausts**

During standard operation no exhausts are required. During cool-down (24h-48h) the system gets evacuated and an exhaust line for the vacuum pump is desirable.

# Effects of ADC non-linearity scaled to the Lamb-shift experiment (worst case)

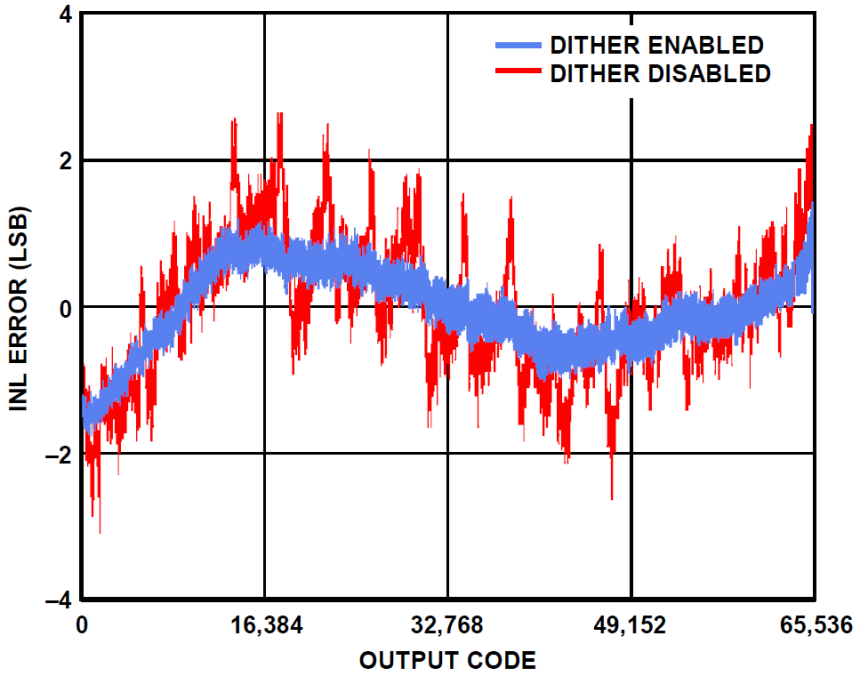
- 16 bit for +/- 120 keV (1 LSB = 3.7eV)
- „no missing codes“, i.e. bits are up to ± 0.5 LSB off: 1 → 0.7

  2 → 2.1
- Struck SIS3316 uses AD9268

  4 → 3.6

  8 → 8.2

  ...




| Parameter | AD9268BCPZ-125 Min | Typ | Max | Unit |
|---|---|---|---|---|
| RESOLUTION | 16 | | | Bits |
| ACCURACY | | | | |
| No Missing Codes | | Guaranteed | | |
| Offset Error | | ±0.4 | ±0.65 | % FSR |
| Gain Error | | ±0.4 | ±2.5 | % FSR |
| Differential Nonlinearity (DNL)[1] | –1.0 | | +1.2 | LSB |
| | | ±0.7 | | LSB |
| Integral Nonlinearity (INL)[1] | | | ±5.5 | LSB |
| | | ±3.0 | | LSB |

# Effects of ADC non-linearity

- 16 bit for +/- 120 keV
- „no missing codes“, i.e. bits are up to ± 0.5 LSB off:

1 → 0.7

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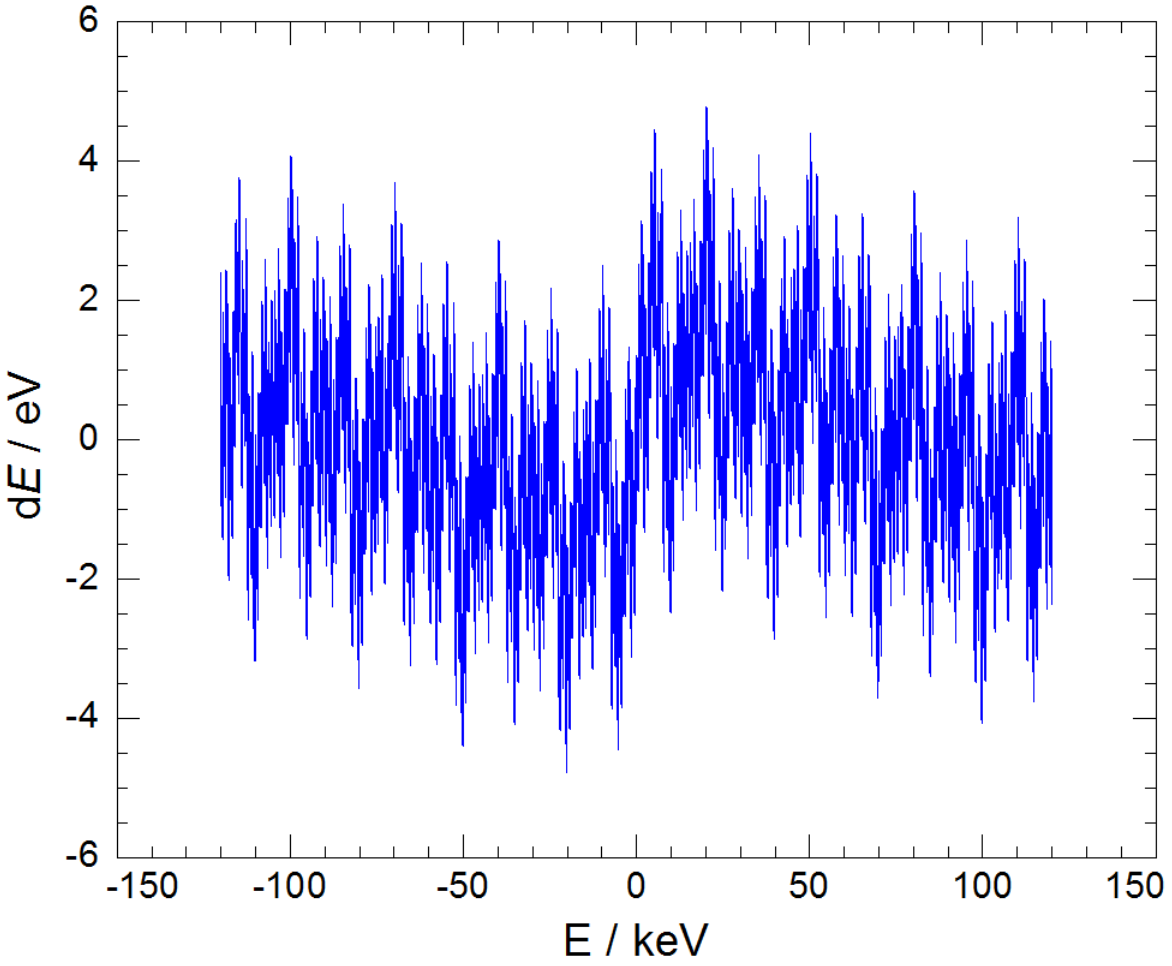
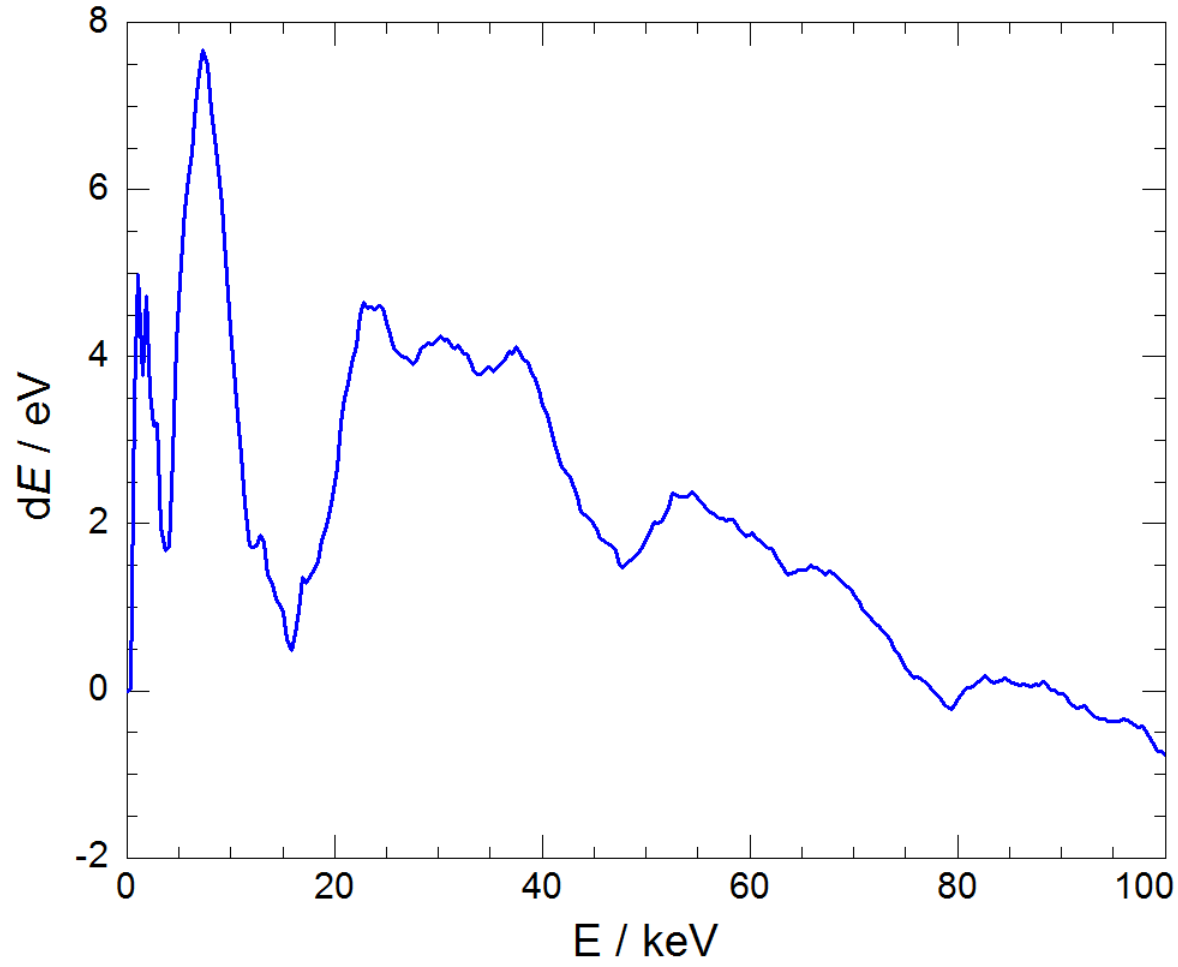
…



# Effects of ADC non-linearity

- 16 bit for +/- 120 keV
- overall nonlinearity for processed, simulated pulses:



# Effects of ADC non-linearity

- 16 bit for +/- 120 keV
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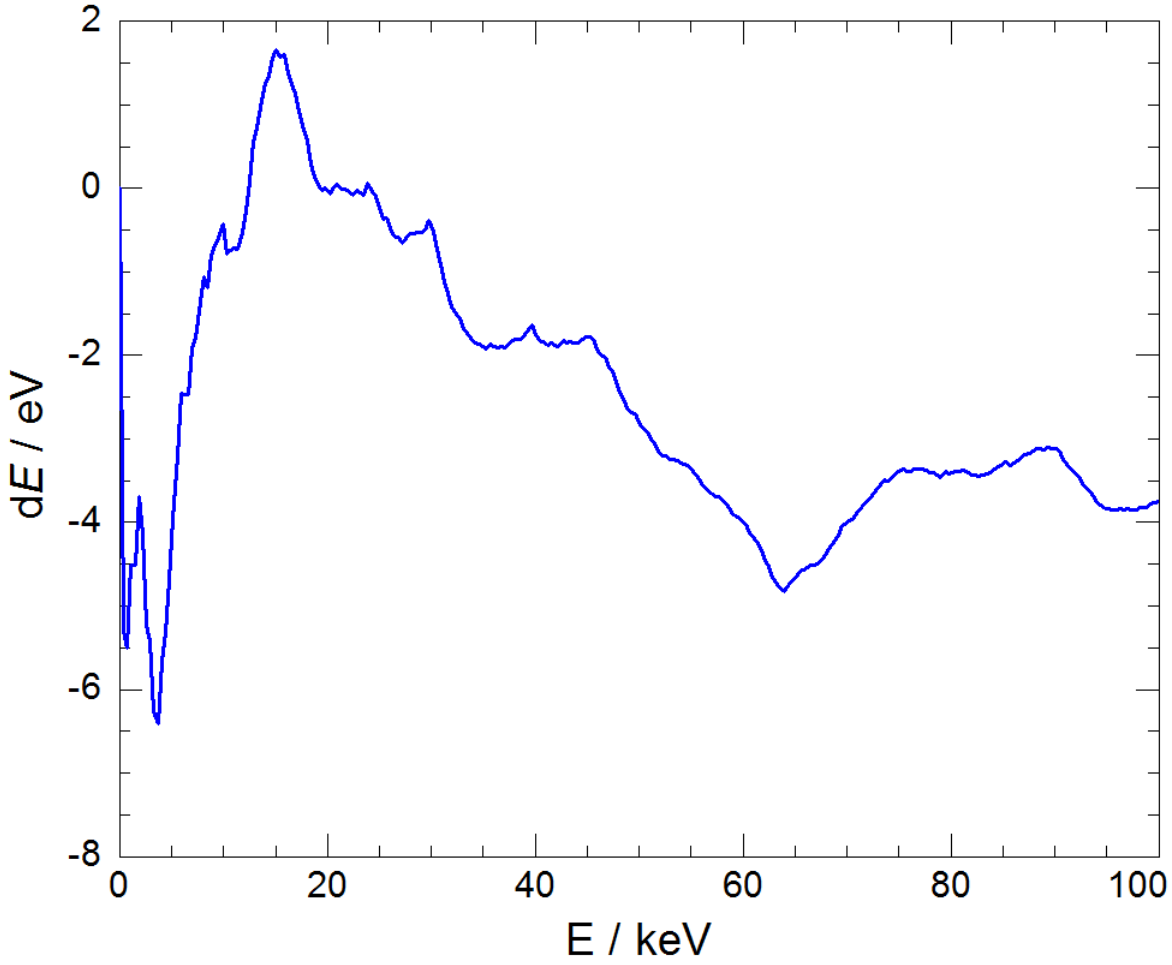
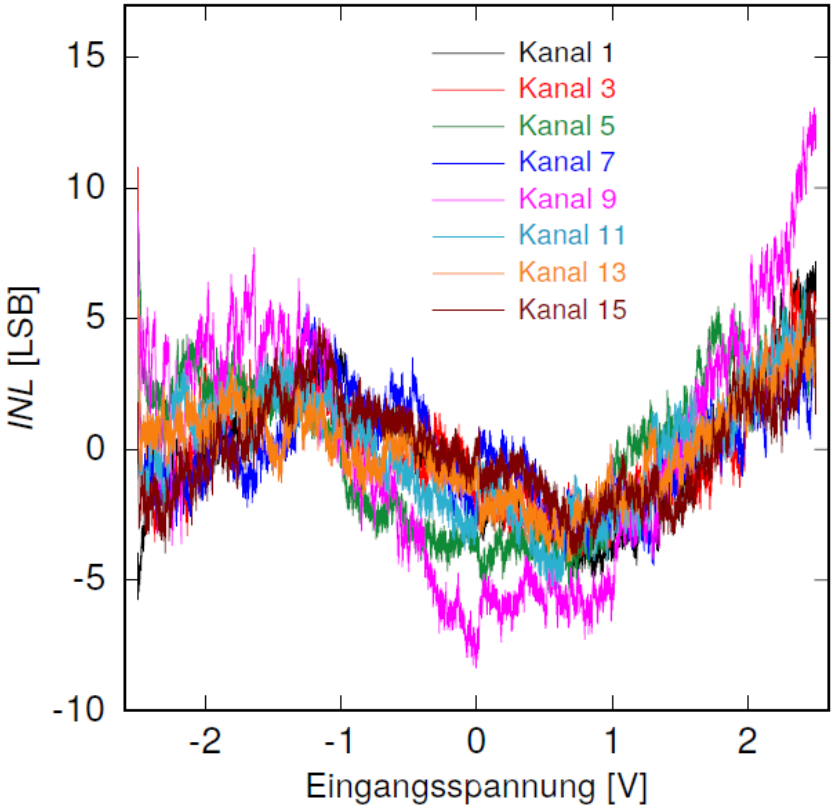
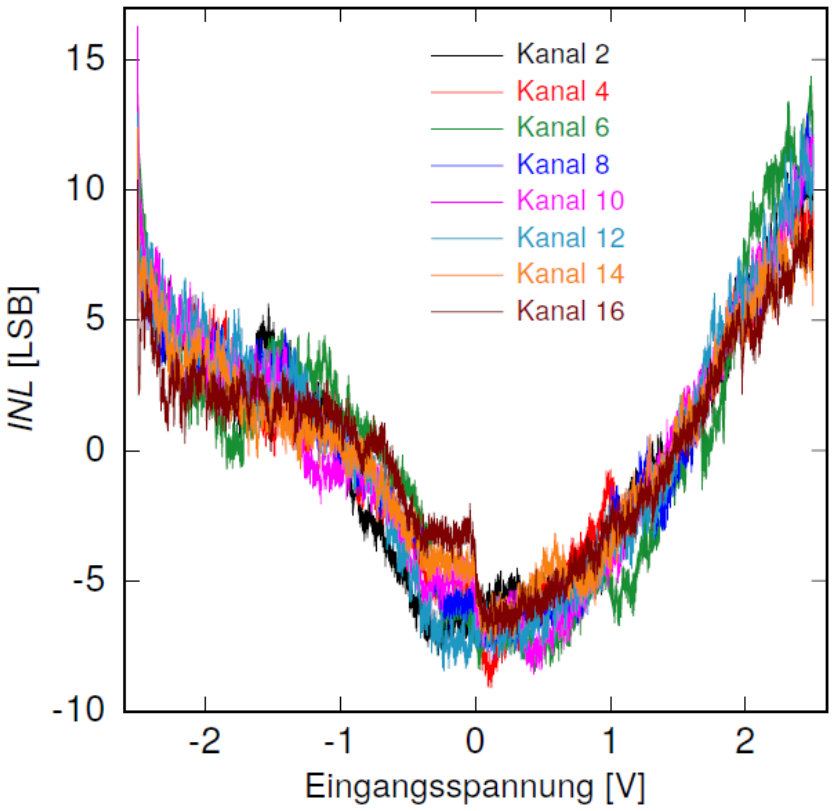


# Measured ADC non-linearity

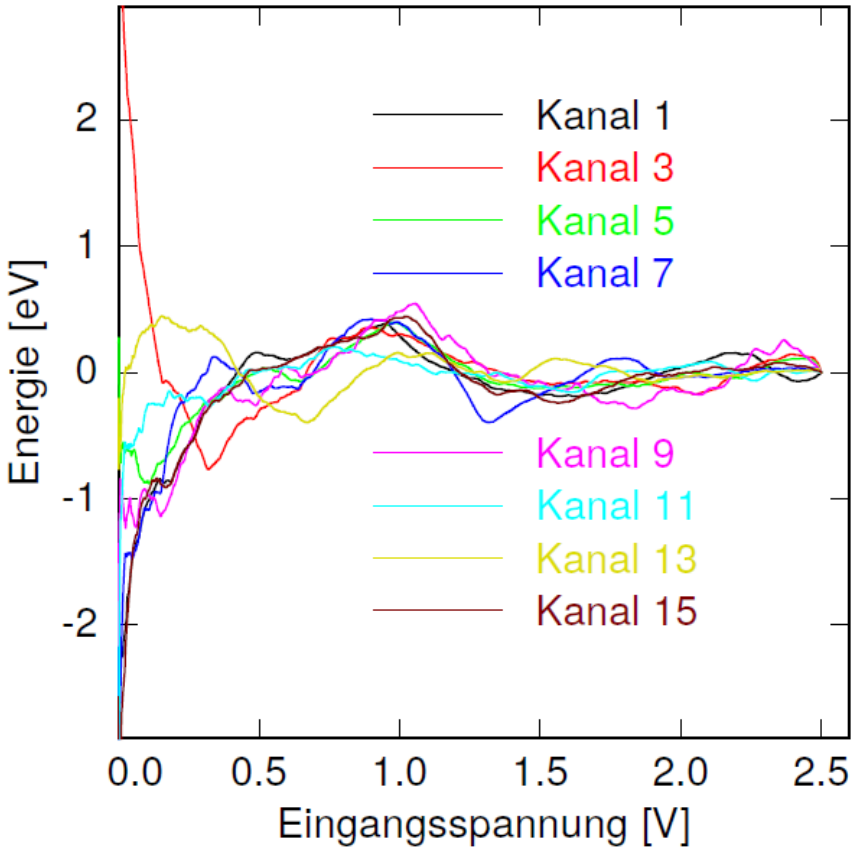
- 16 bit for +/- 60 keV
- measured non-linearity of SIS-3316:

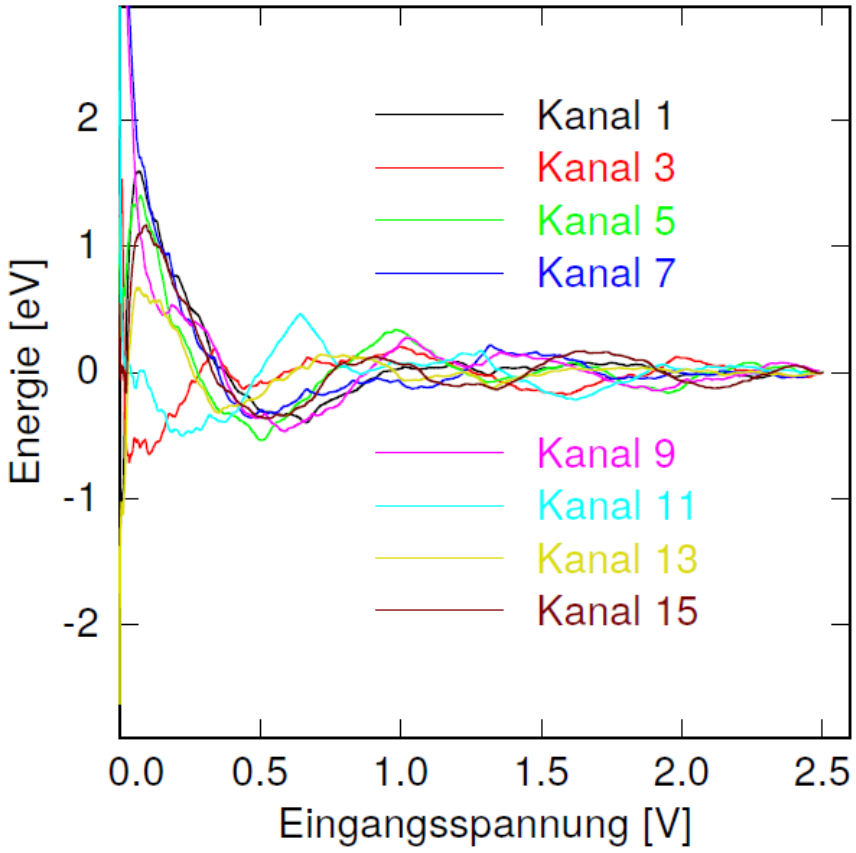


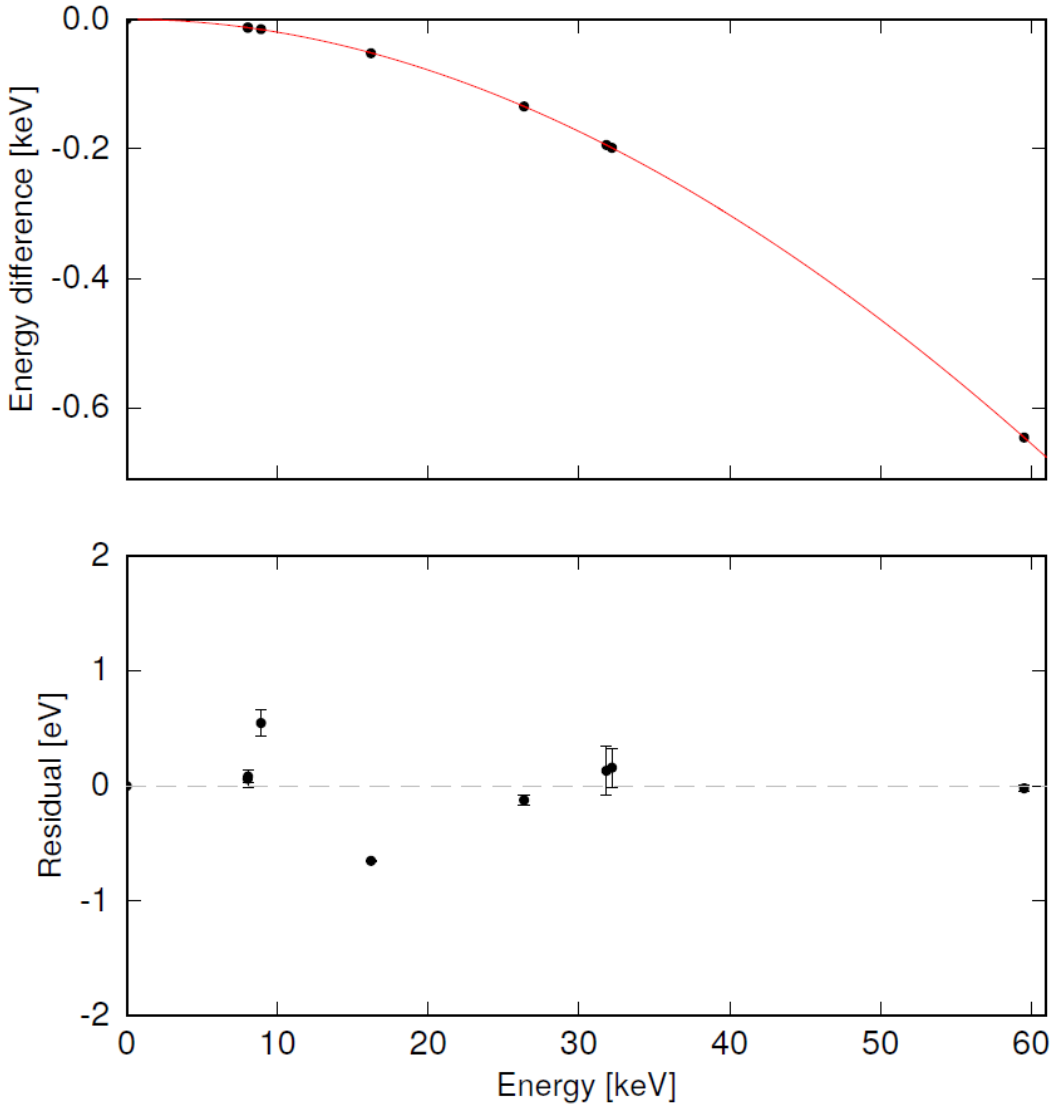
# Effects of ADC non-linearity on energy calibration

- 16 bit for +/- 60 keV
- based on measured non-linearity of SIS-3316.
- pulses average over large voltage ranges removing errors of small bits



# non-linearity




Sub-eV agreement for carefully selected calibration lines.
This should be detailed out in future!

# Effects of ADC non-linearity

- 16 bit for +/- 120 keV
- „no missing codes“, i.e. bits are up to ± 0.5 LSB off:

1 → 0.7

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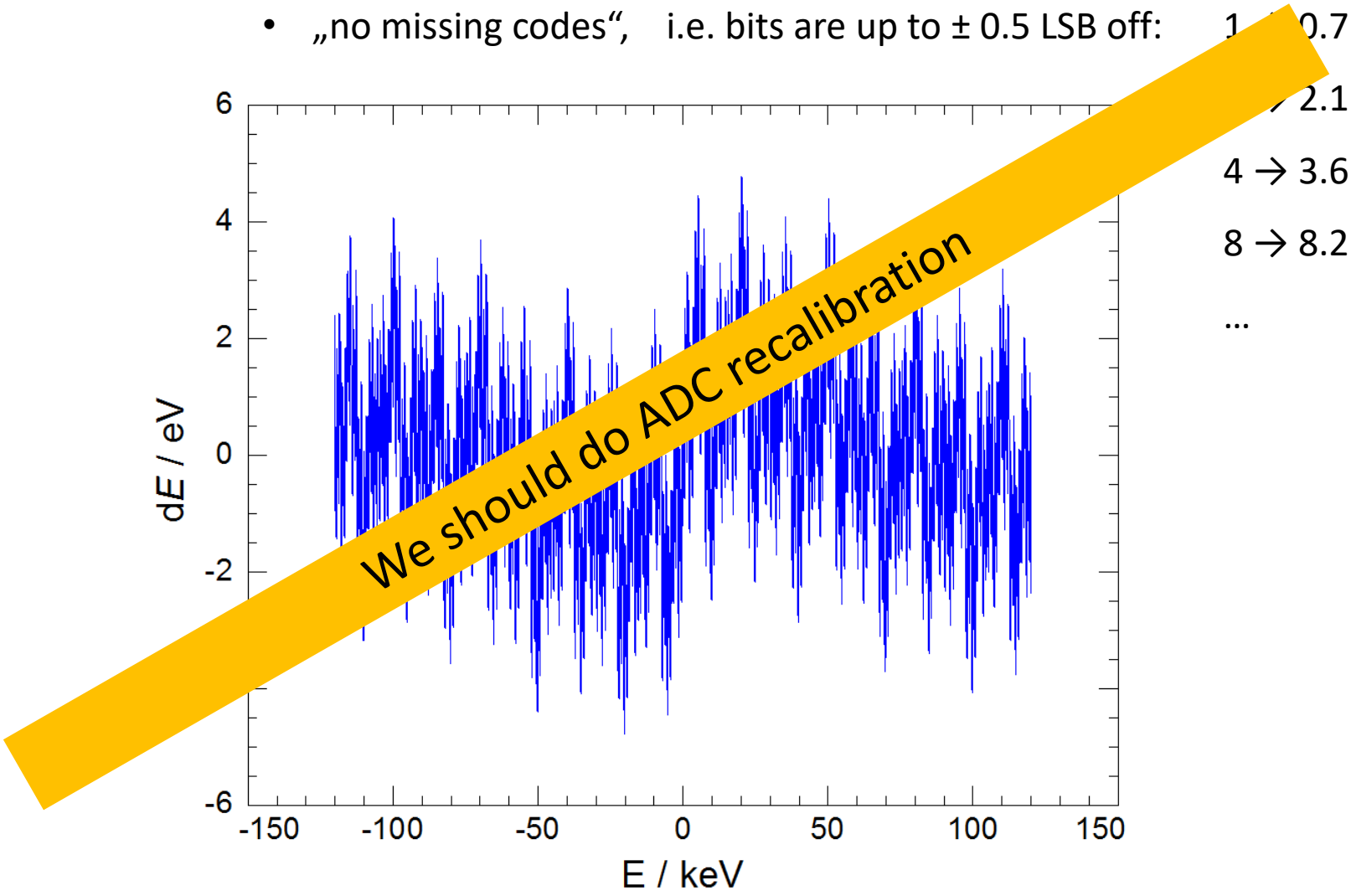
4 → 3.6

8 → 8.2

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