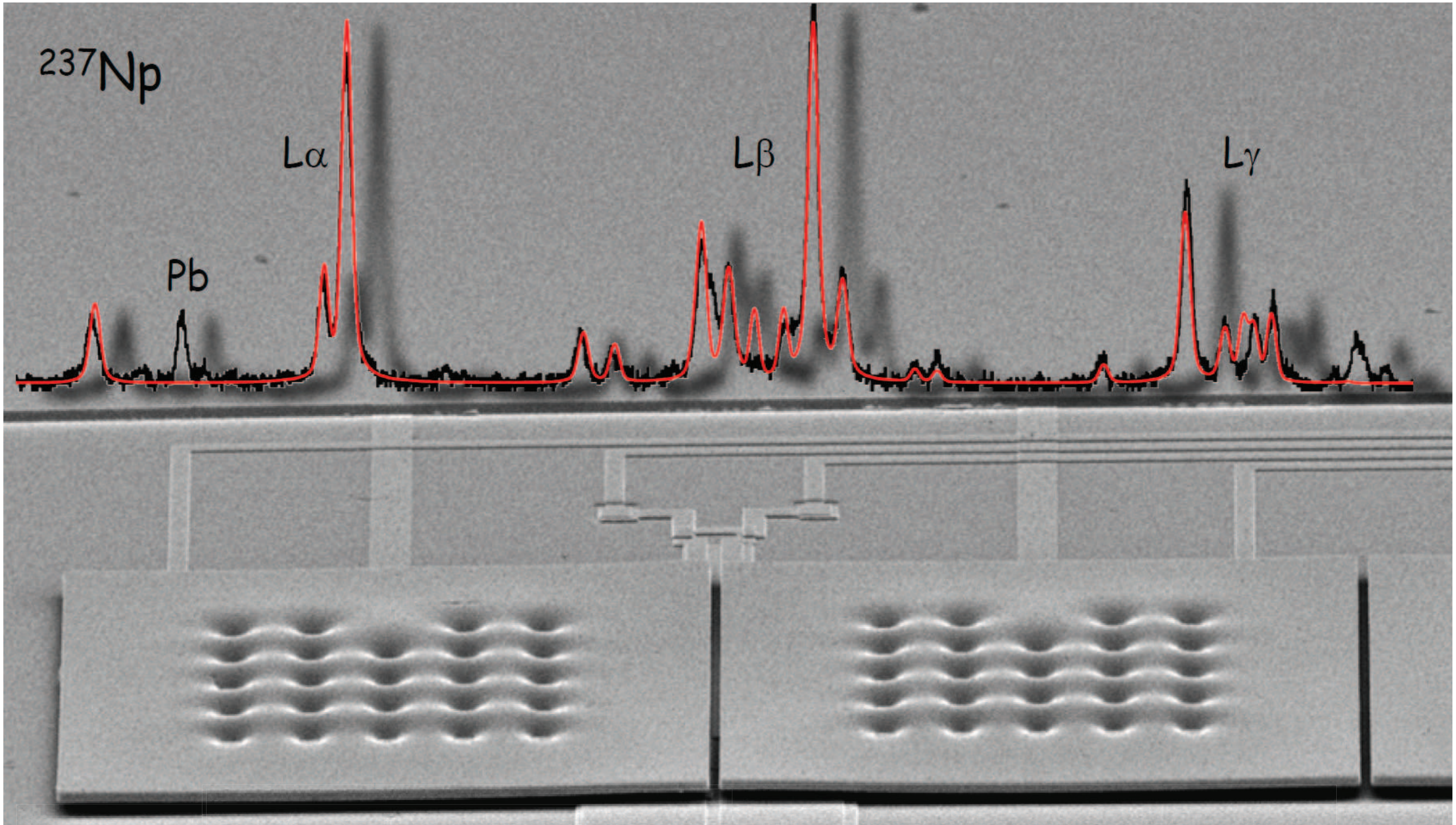
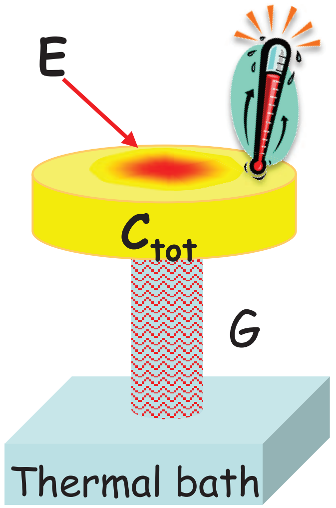


Magnetic Micro-Calorimeters

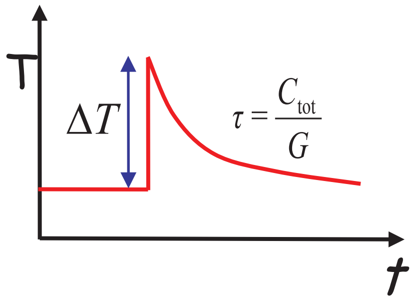
Loredana Gastaldo, S.Allgeier, A.Ferring, L.Gamer, J.Geist, S.Hähnle, C.Hassel, S. Hendricks, D.Hengstler, M.Keller, M.Krantz, W. Köntges, G. Möhl, J. Poller, C.Schötz, D.Schulz, M.Wegner, S.Kempf, A. Fleischmann and C.Enss

Heidelberg University

Low temperature micro-calorimeters



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

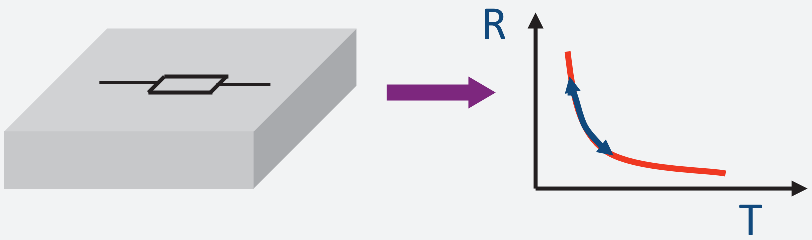


E = 10 keV
C_{tot} = 1 pJ/K
→ ~ 1 mK

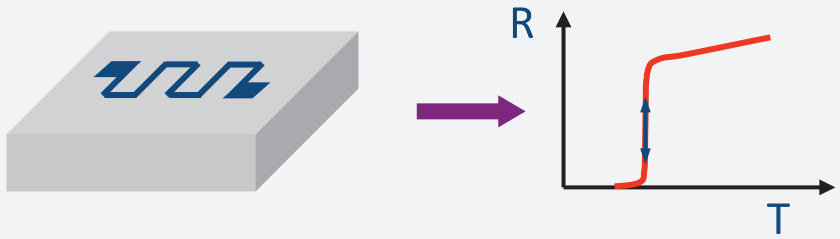
- Very small volume
- Working temperature below 100 mK
  - small specific heat
  - small thermal noise
- **Very sensitive temperature sensor**

Temperature sensors

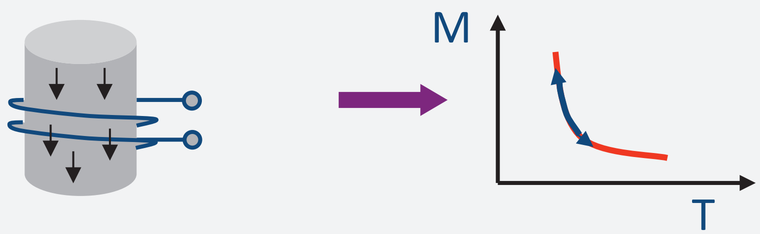
Resistance of highly doped semiconductors



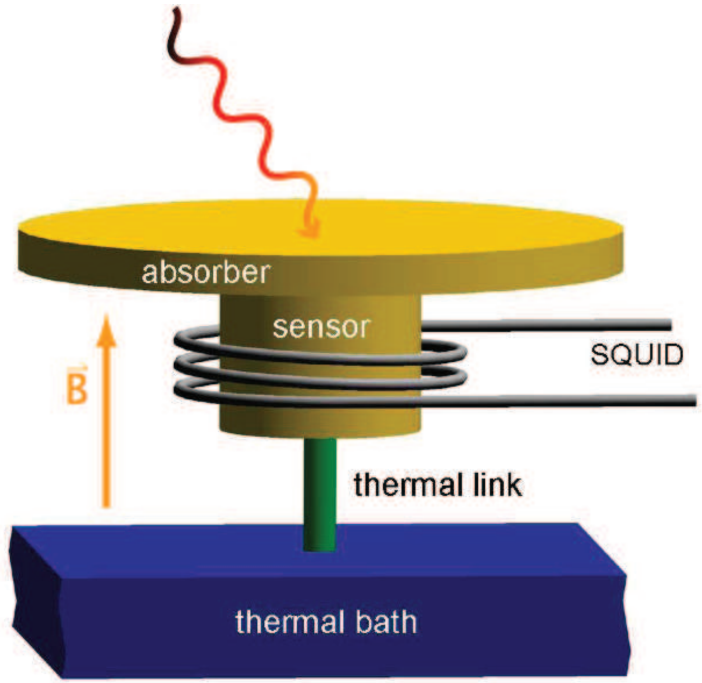
Resistance at superconducting transition,TES



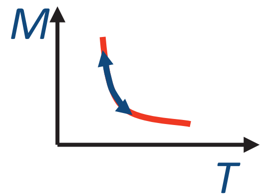
Magnetization of paramagnetic material



Metallic Magnetic Calorimeters - MMC



Paramagnetic sensor: **Au**:Er$_{500ppm}$



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 calorimeters with resistive thermometers

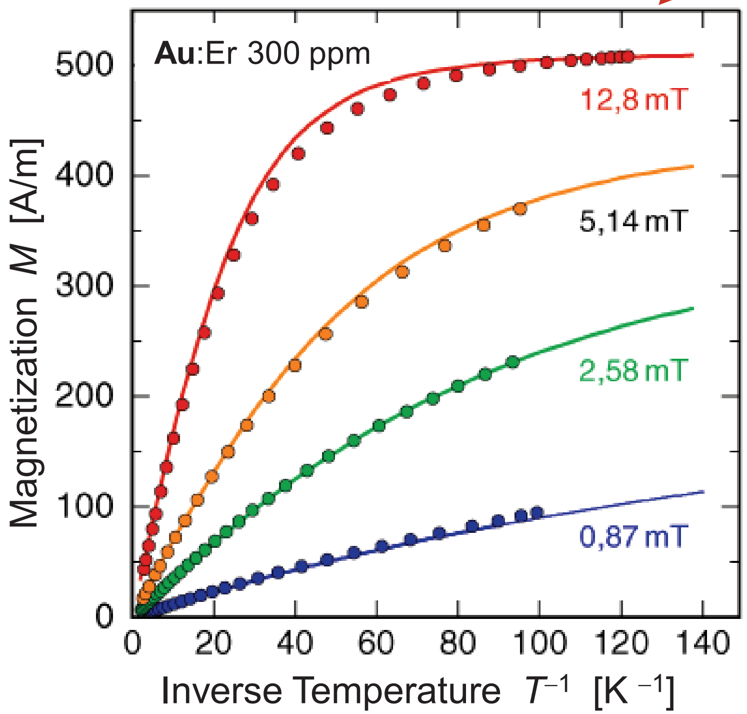
no dissipation in the sensor

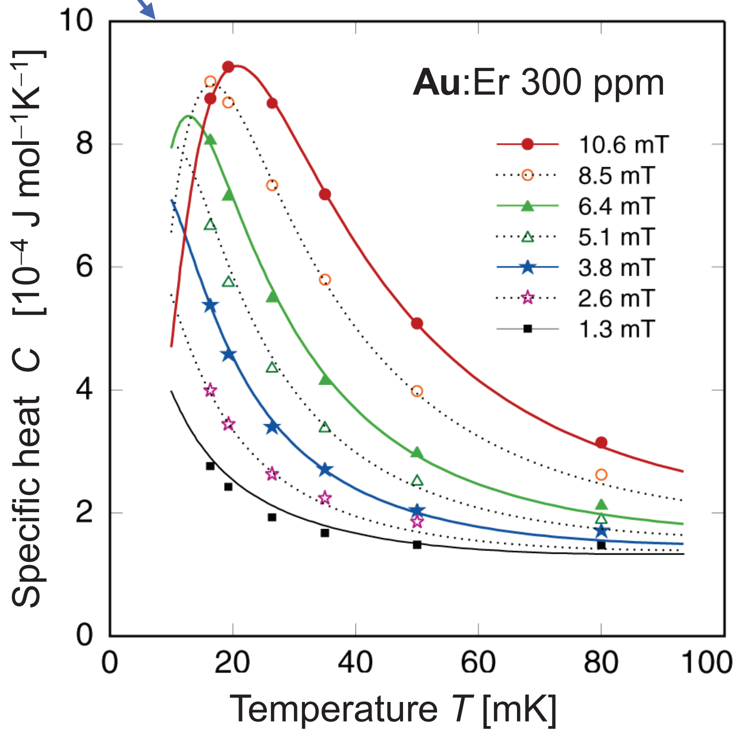
no galvanic contact to the sensor

MMC: signal size

Numerical calculations based on mean field approximation are used to describe thermodynamical properties of interacting spins (RKKY)

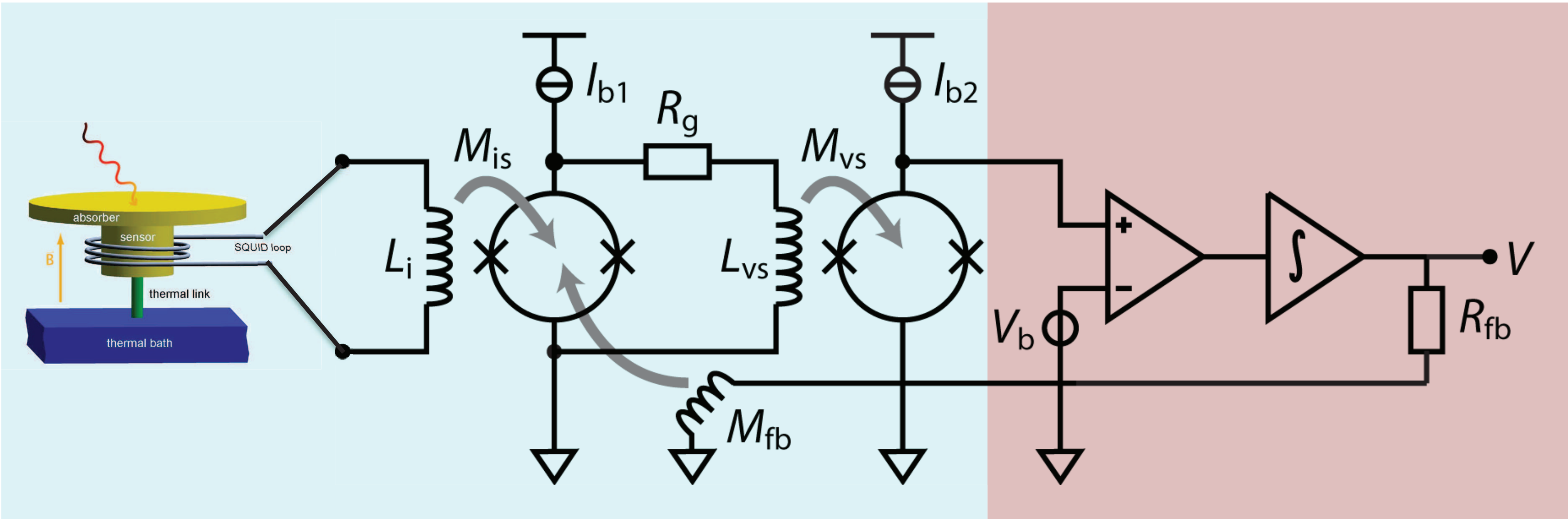
$$\delta \Phi_S \propto \frac{\partial M}{\partial T} \frac{1}{C_{tot}} \delta E$$





MMCs: Readout

T ~ 30 mK　　　　T ~ 300 mK

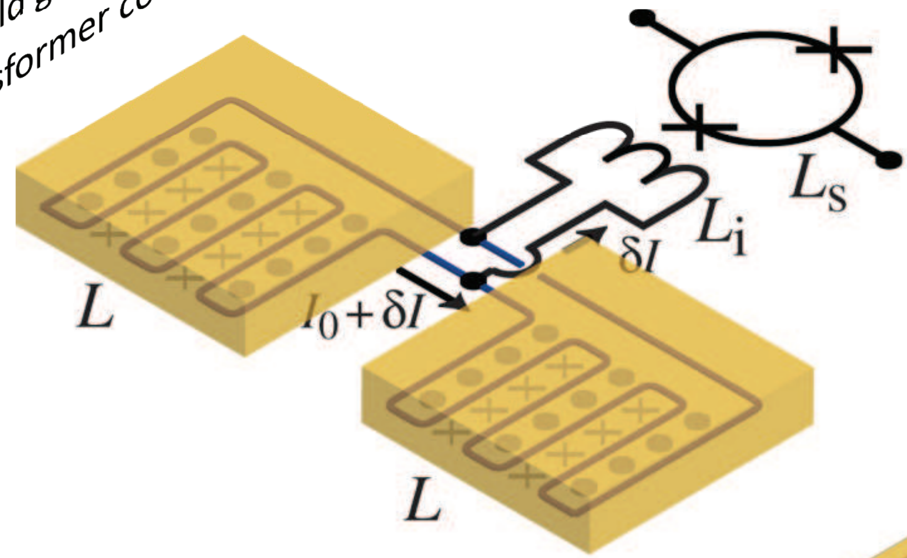


Two-stage SQUID setup with flux locked loop allows for:

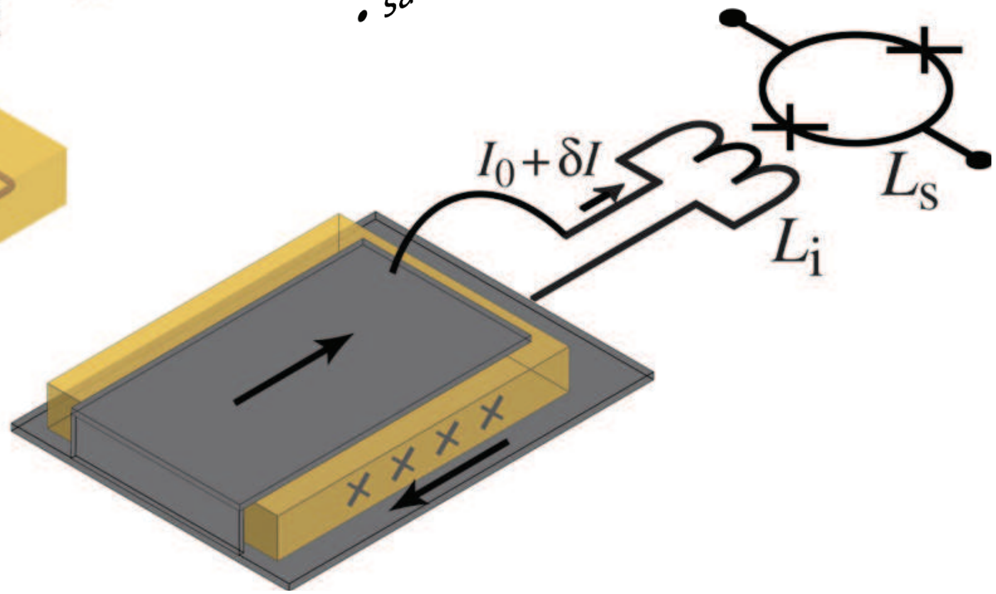
- low noise
- large bandwidth / slewrate
- small power dissipation on detector SQUID chip (voltage bias)

MMCs: Geometries

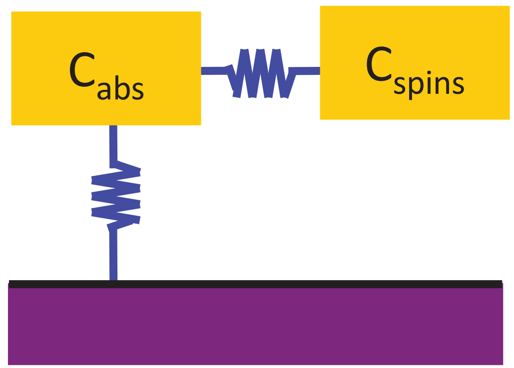
Well established:
- *planar T-sensor*
- *superconducting meander shaped pickup loop*
- *B-field generated by persistent current*
- *transformer coupled to SQUID*



New sandwich geometry:
- *best magn. flux coupling,*
- *planar sensor*
- *sandwiched between stripline*



Energy resolution



- fluctuations of energy between sub-systems

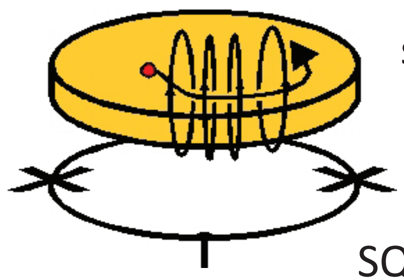
$$\Delta E_{\mathrm{FWHM}} \simeq 2{,}36\sqrt{4k_{\mathrm{B}}C_{\mathrm{Abs}}T^2}\sqrt{2}\left(\frac{\tau_0}{\tau_1}\right)^{1/4}$$

(optimum for $C_{abs} = C_{spins}$)

- flux noise of SQUID-magnetometer

$S_{\Phi} = 2\,\varepsilon\, L$, required: $\varepsilon < 50\,\hbar\,..\,300\,\hbar$

- magnetic Johnson noise
  - thermal currents in the metallic components
  - marginal in all present detectors



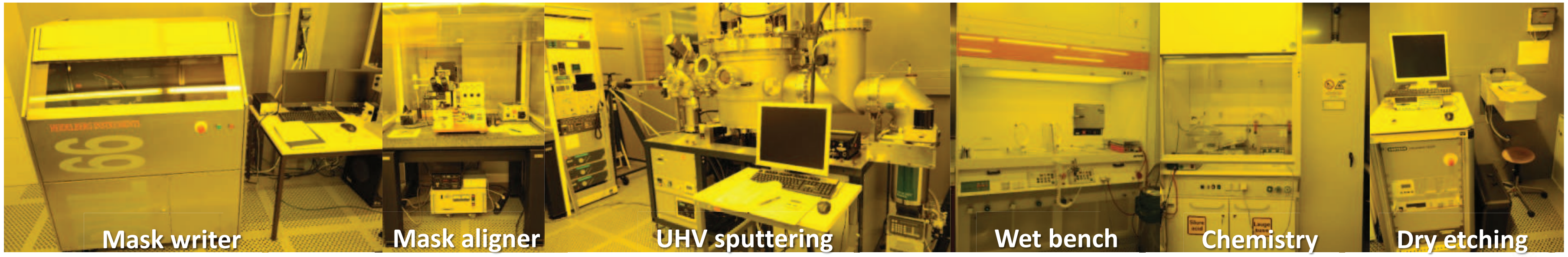
- excess noise $S_{\Phi} \sim N_{\mathrm{Er}}$

$S_{\Phi} \sim 1/f$, $S_m|_{1\mathrm{Hz}} \approx 0.023\ \mu_{\mathrm{Er}}^2/\mathrm{Hz}$

temperature independent (20mK – 4K)

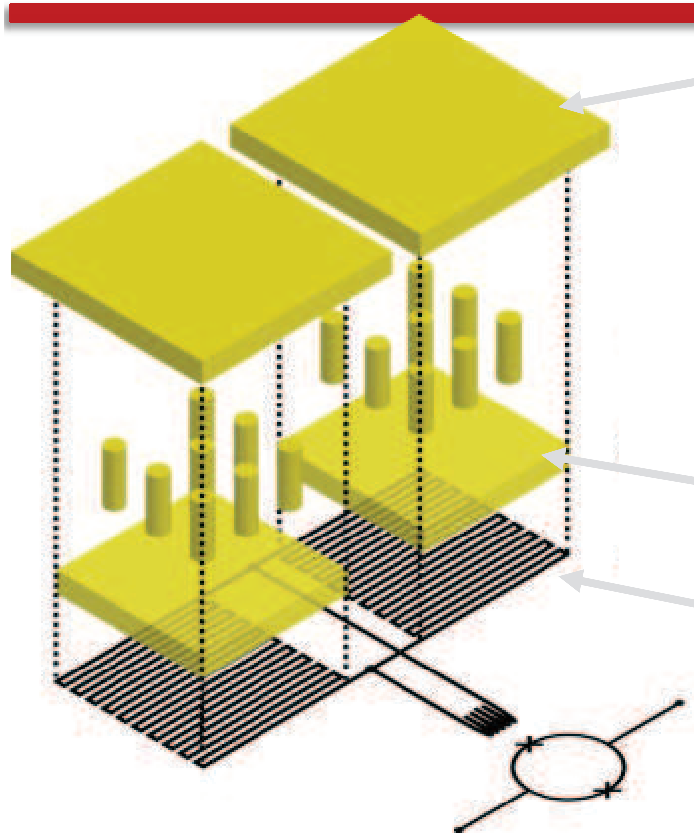
MMCs: Microfabrication

Cleanroom facilities at KIP

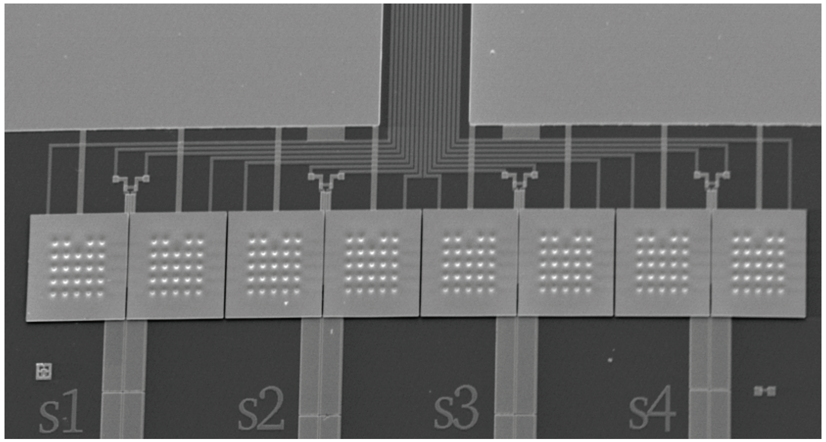


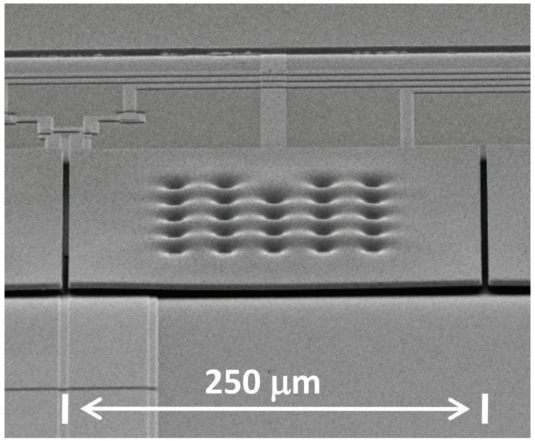
- Flexibility in design and fabrication
- Reliable processes for thin films
- Presently 10 different designs (6-16 layers) processed in parallel

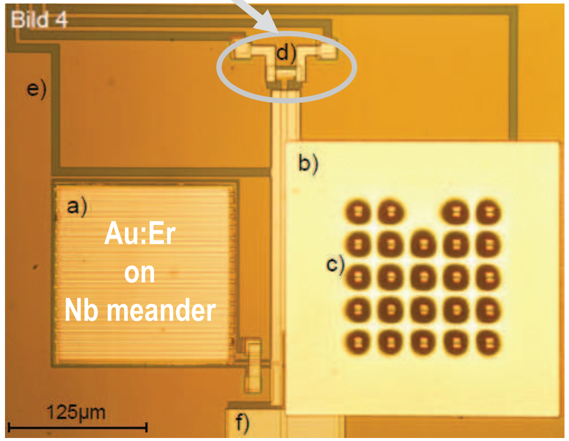
maXs20: 1d-array for soft x-rays



- **1×8 x-ray absorbers**
  - **250µm×250µm** gold**, 5µm thick**
  - **98%** Qu.-Eff. @ 6 keV
  - electroplated into photoresist mold (RRR>15)
  - **mech/therm contact to sensor by stems**
    to prevent loss of initially hot phonons
- **Au:^{166}Er$_{300ppm}$ temperature sensors**
  - co-sputtered from pure Au and high conc. AuEr target
- **Meander shaped pickup coils**
  - 2.5 µm wide Nb lines
  - $I_c \approx$ **100mA**
- **On-chip persistent current switch** (AuPd)







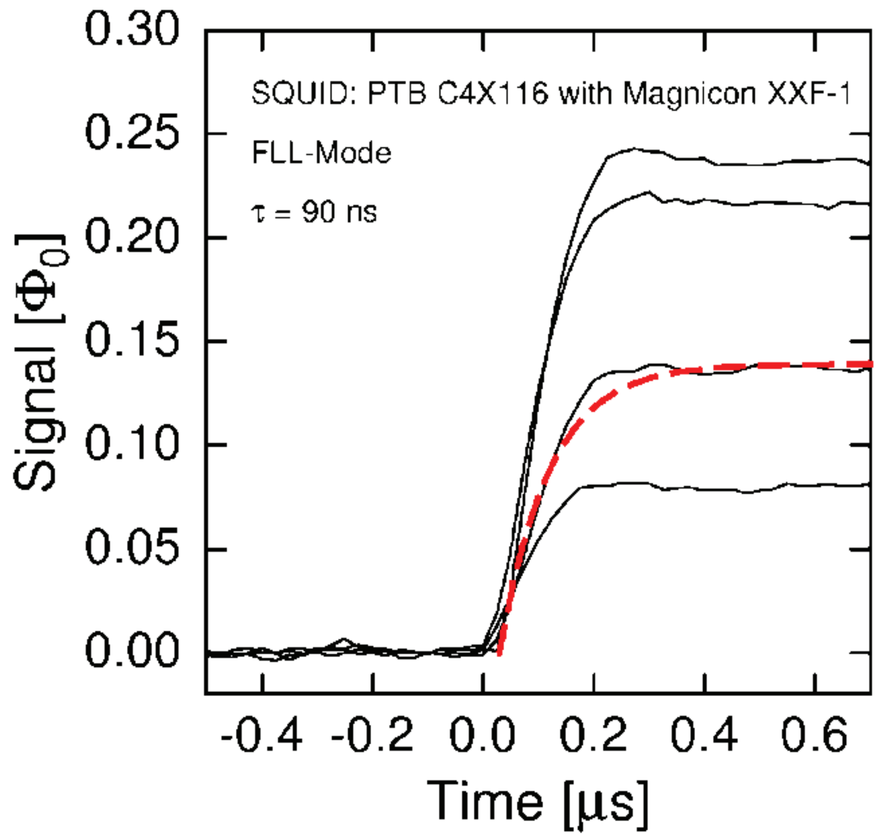
maXs20: 1d-array for soft x-rays

- **rise time: 90 ns** @ 30 mK,

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

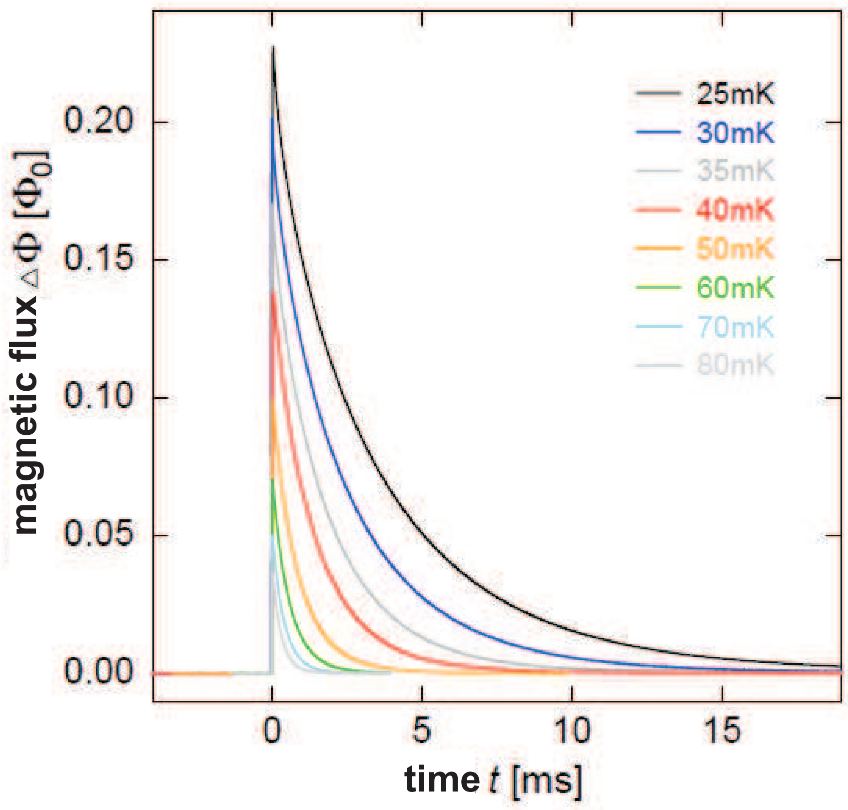
  from Korringa-constant of Er in Au

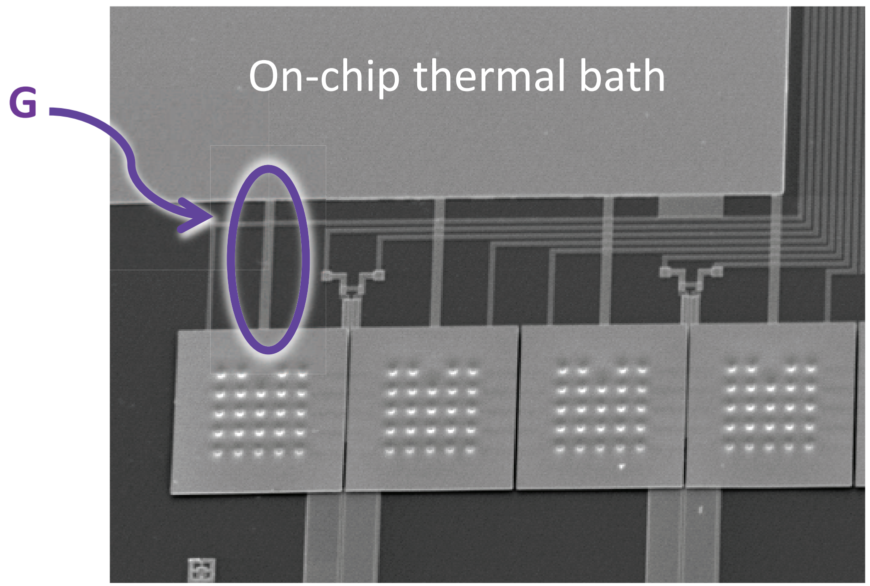
Fastest rise-time among µ-cal for x-ray detection



maXs20: 1d-array for soft x-rays

- **decay time** here: **3 ms @ 30 mK**
- nearly single exponential decay



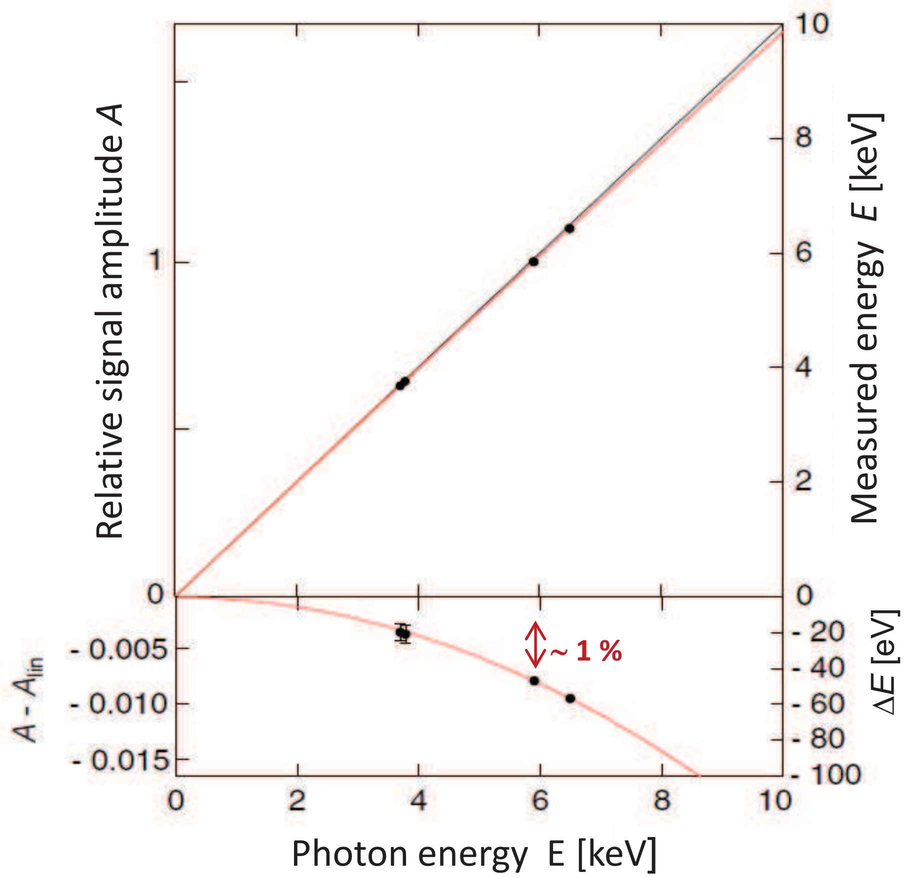


adjusted by sputtered thermal link (Au)

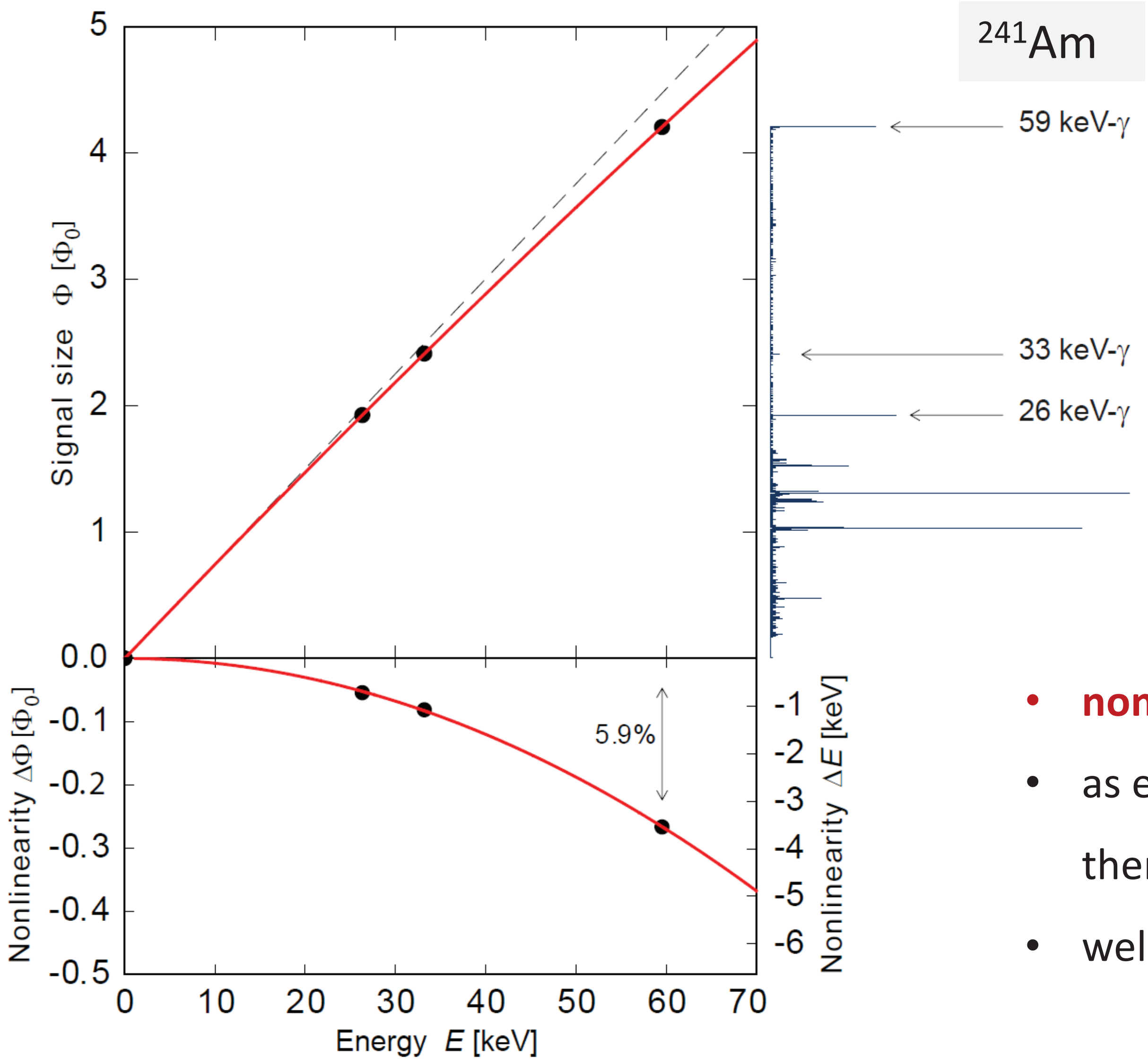
maXs20: 1d-array for soft x-rays

- **non-linearity: 1% at 6 keV**
- as expected from thermodynamical properties
- well described by quadratic term

The energy scale is defined with high precision



maXs20: 1d-array for soft x-rays

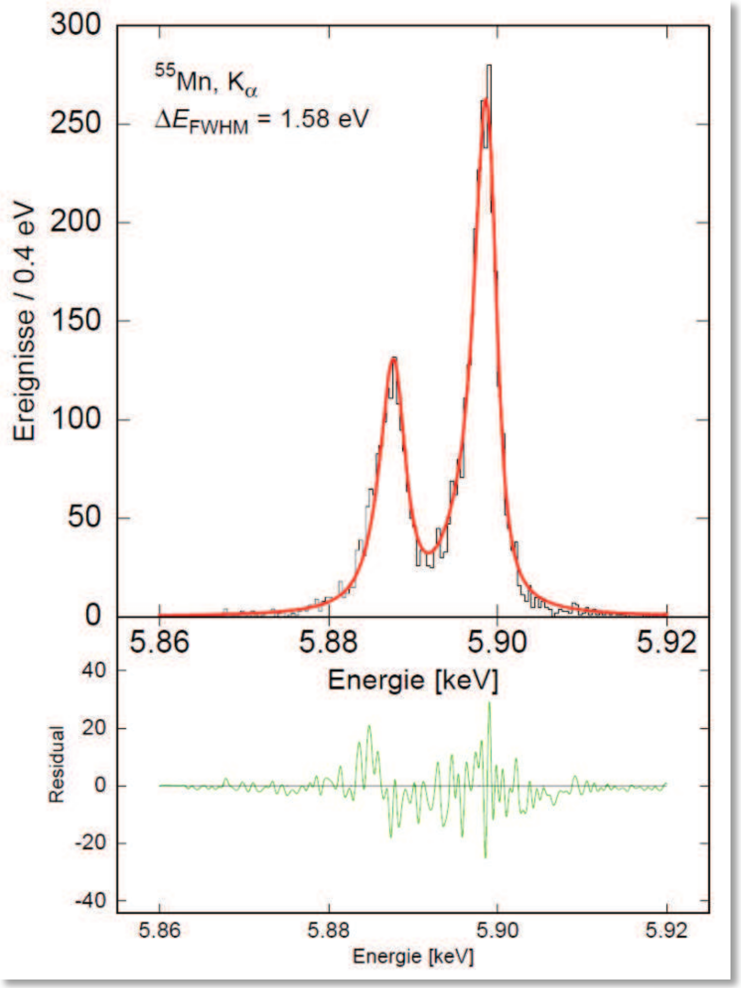


- **non-linearity: 6%** at **60 keV**
- as expected from thermodynamical properties
- well described by quadratic term

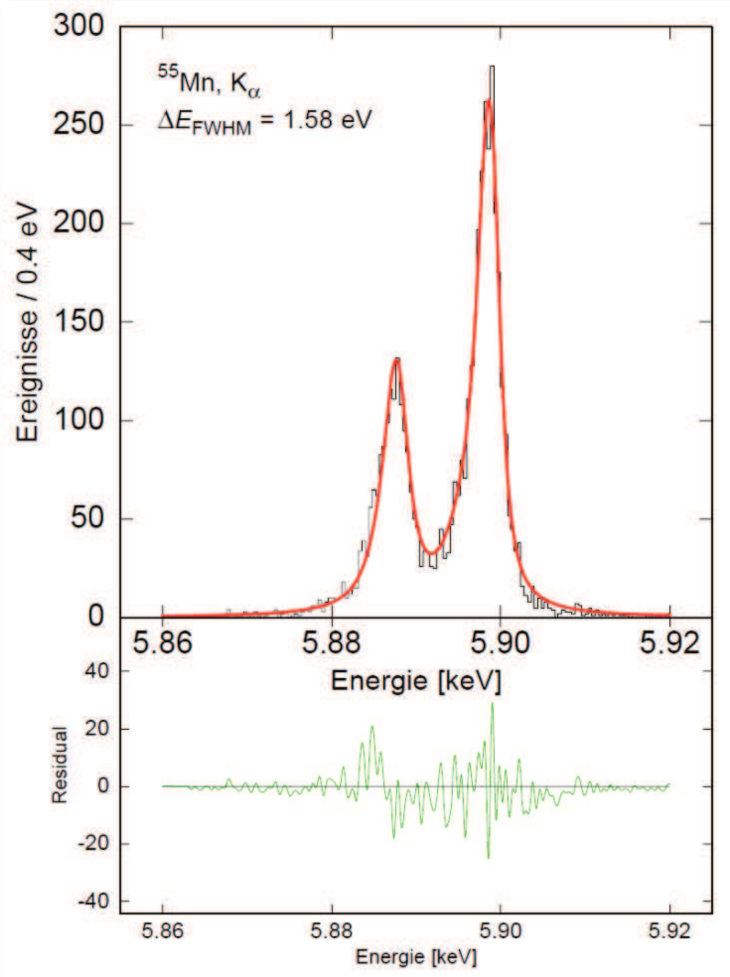
maXs20: 1d-array for soft x-rays (*T*=20 mK)

- Very good energy resolution

  ΔE_{FWHM}= 1.6 eV @ 6 keV



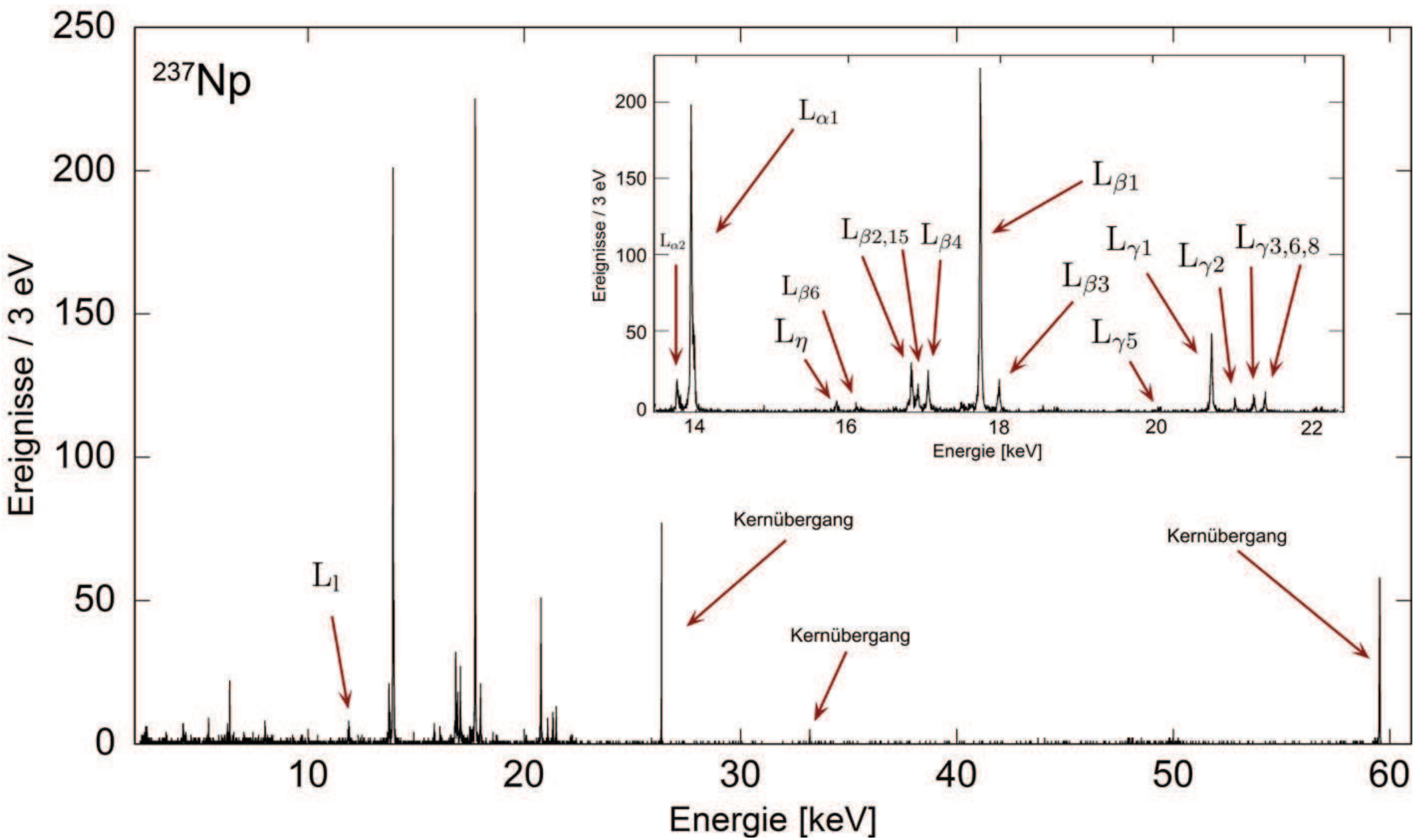
maXs20: 1d-array for soft x-rays (T=20 mK)



World record together with TES-sensors of NASA-GSFC!

maXs20: 1d-array for soft x-rays (T=20 mK)

- Large dynamic range



maXs200: 1d-array for hard x-rays

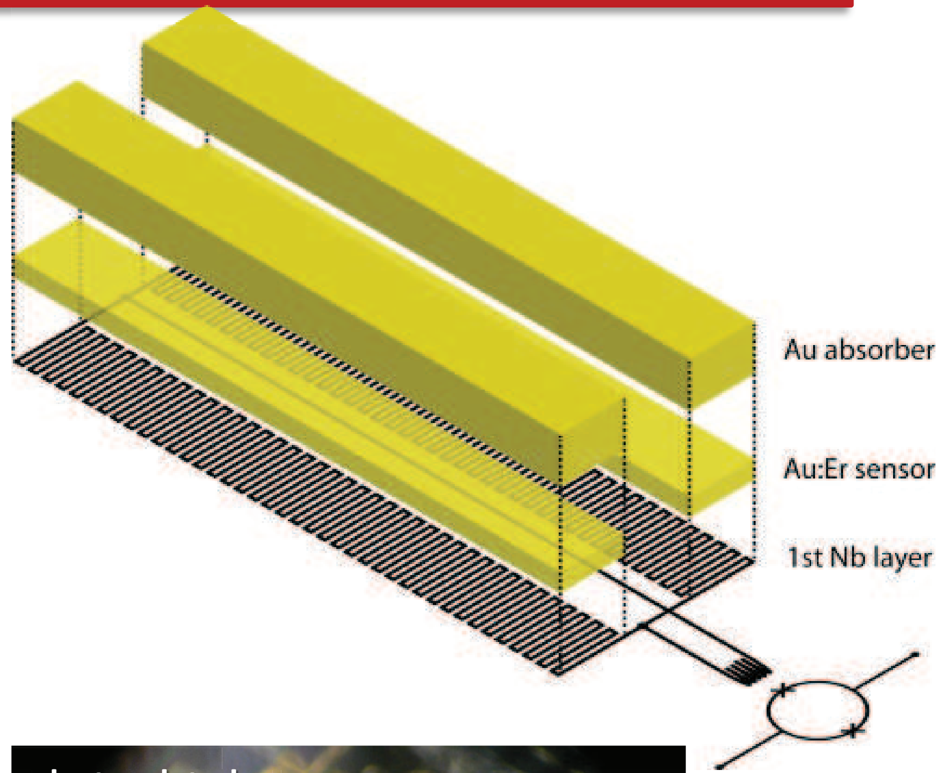
1x8 x-ray absorbers

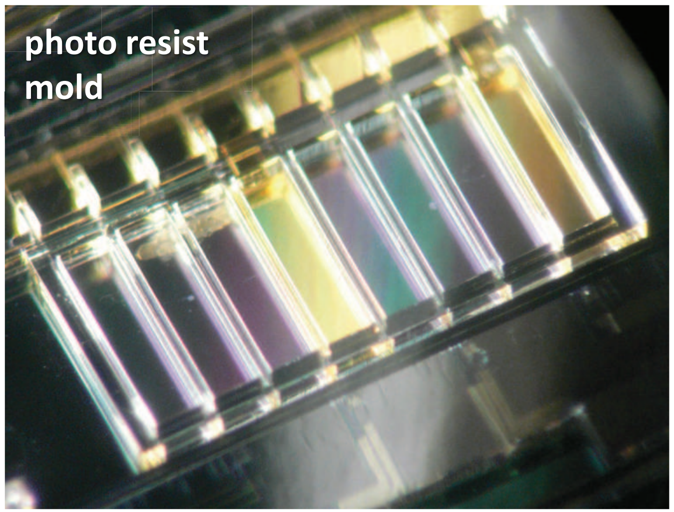
2 mm x 0.5 mm

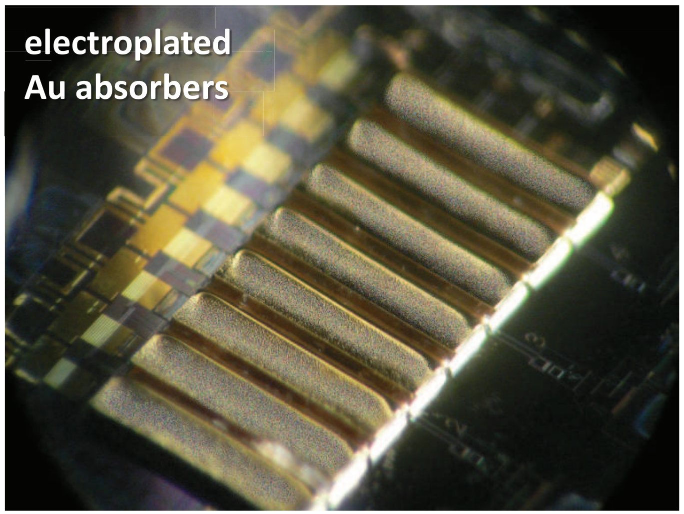
200 μm thick electroplated Au

80% QE at 100 keV

$\Delta E_{FWHM} < 50$ eV

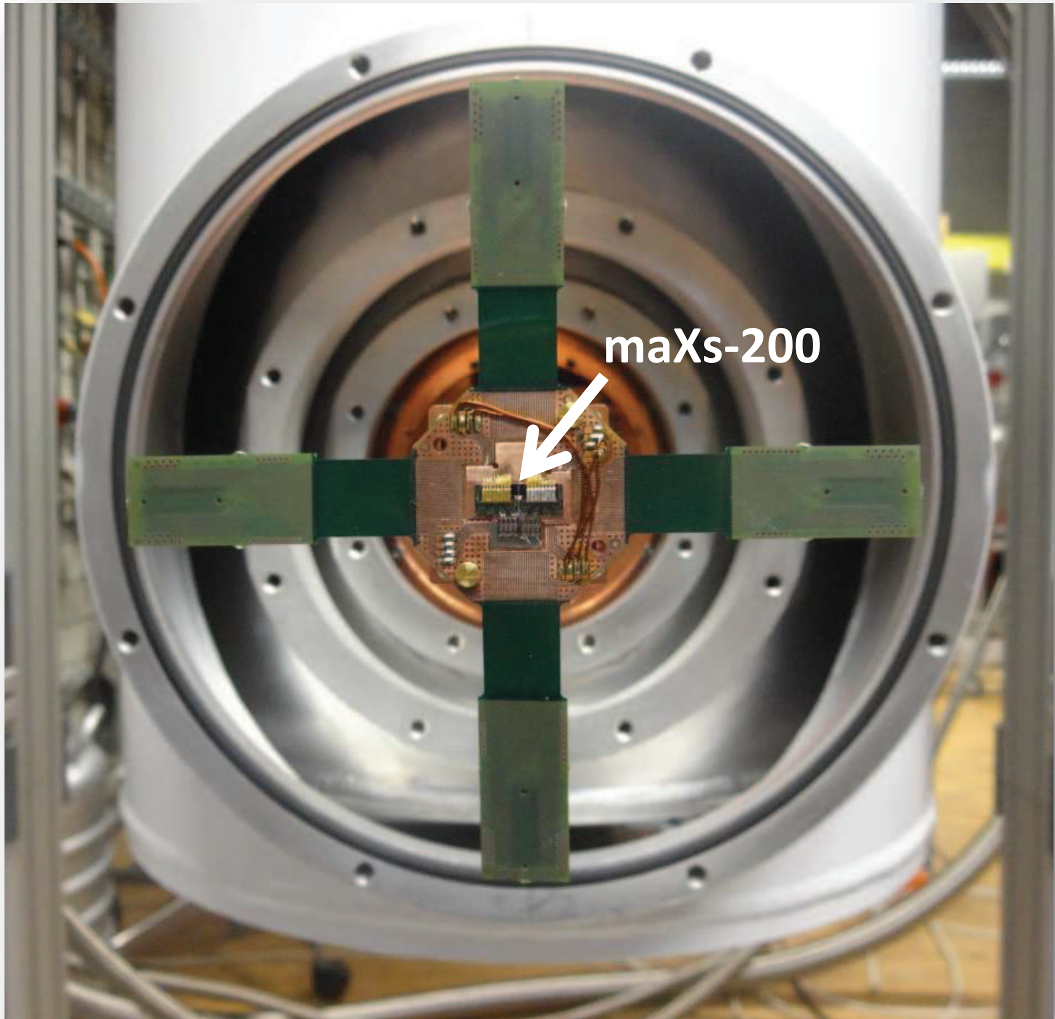




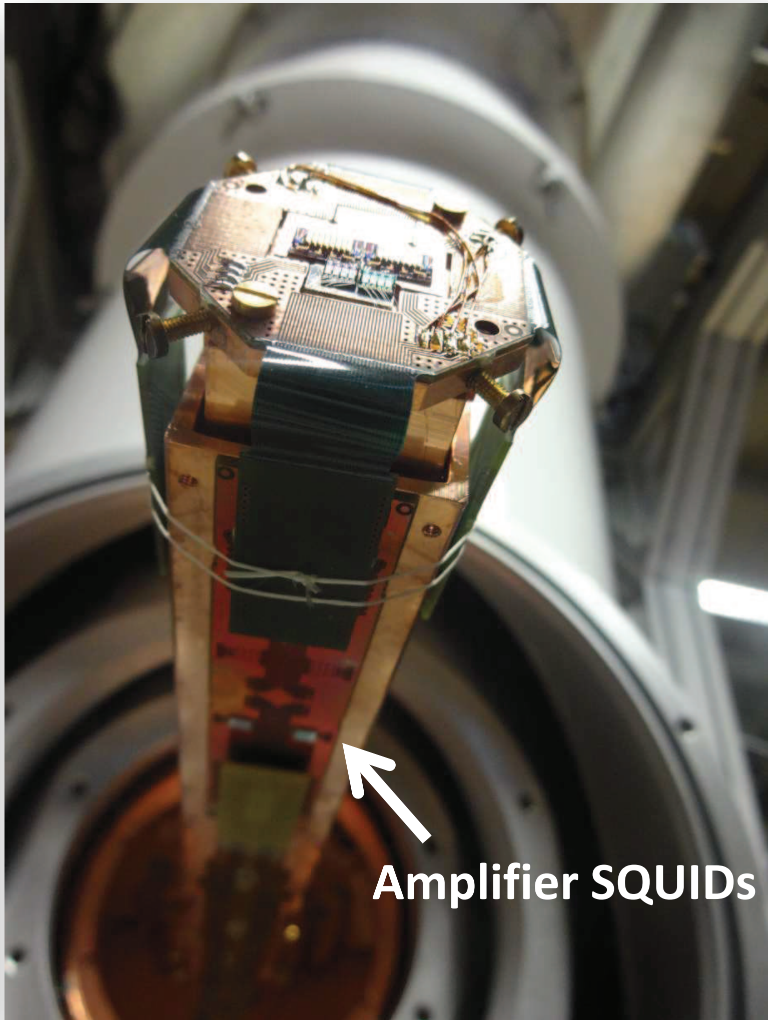


maXs200 on cold finger of a dry cryostat

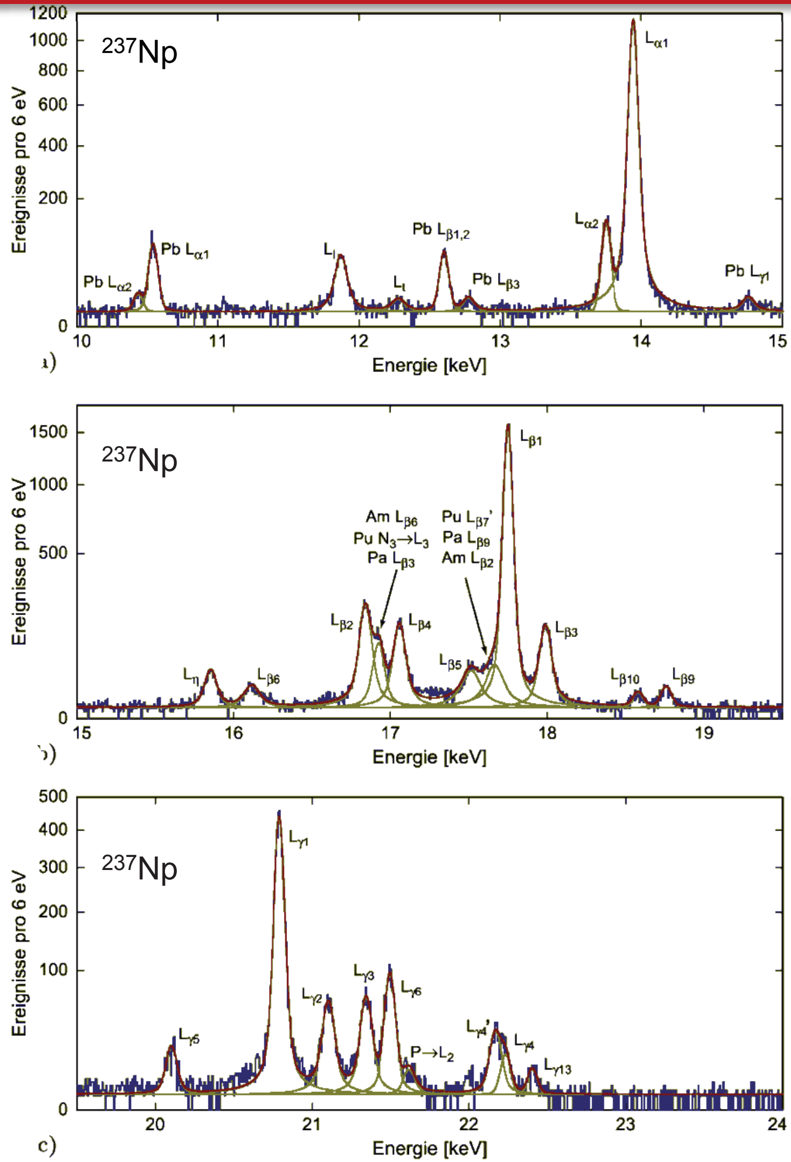
16 pixels **maXs-200** on detector platform



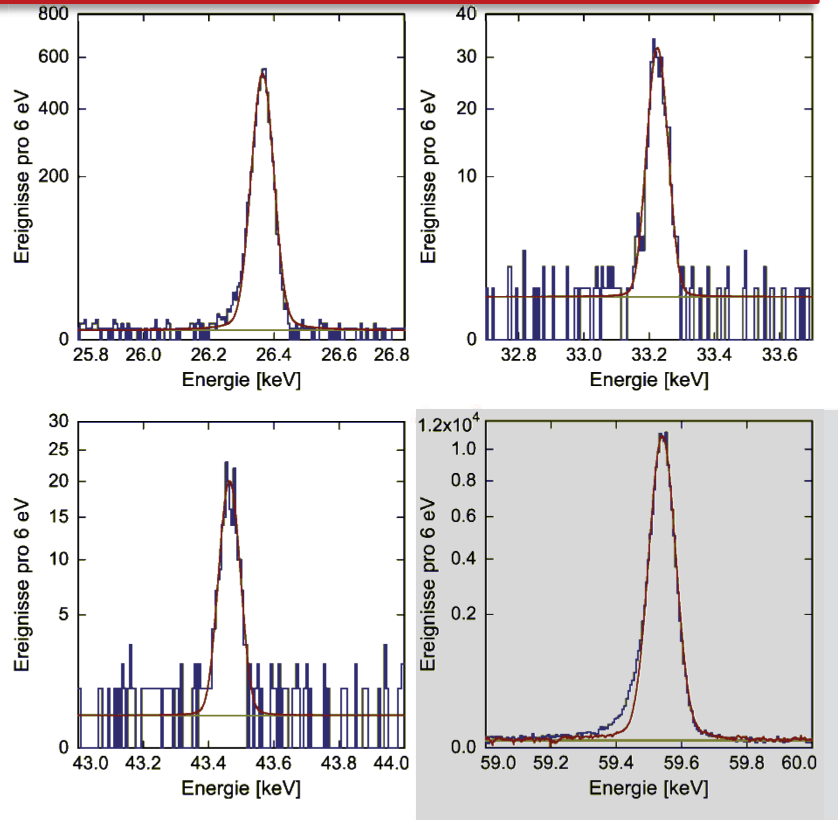
side arm without radiation shields



maXs200 – ^{241}Am calibration source



ΔE$_{FWHM}$ = 40 eV @ 0-20 keV



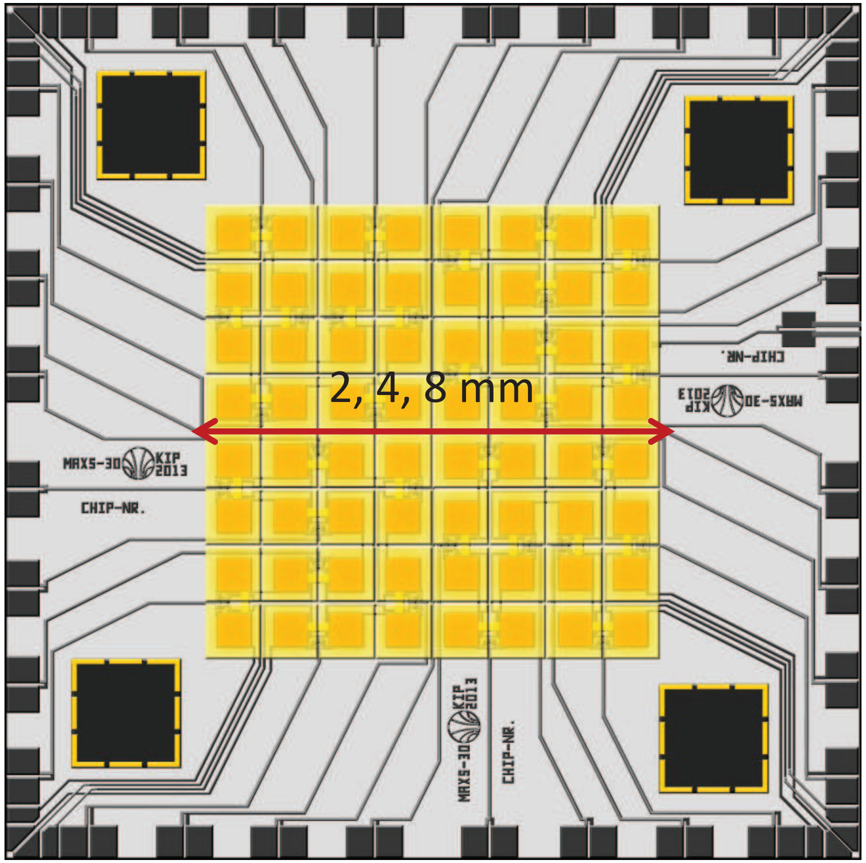
ΔE$_{FWHM}$ = 60 eV @ 60 keV

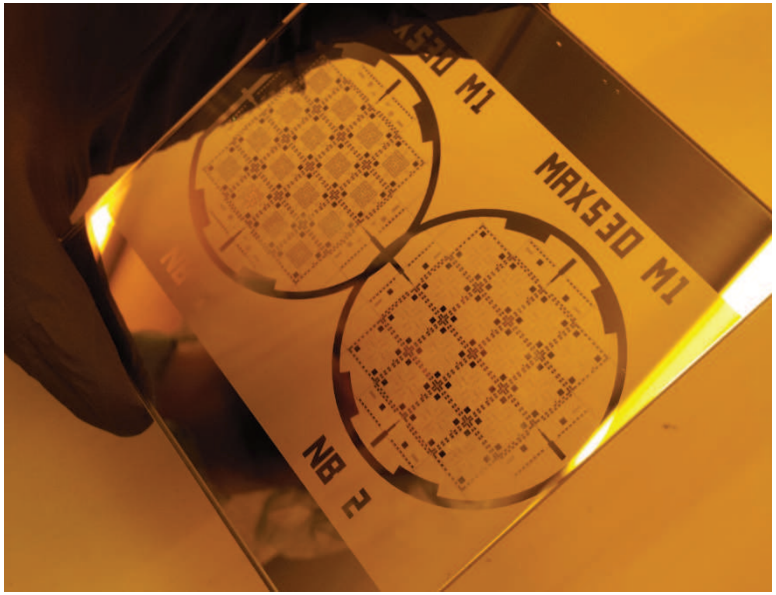
Slight degradation towards higher energies

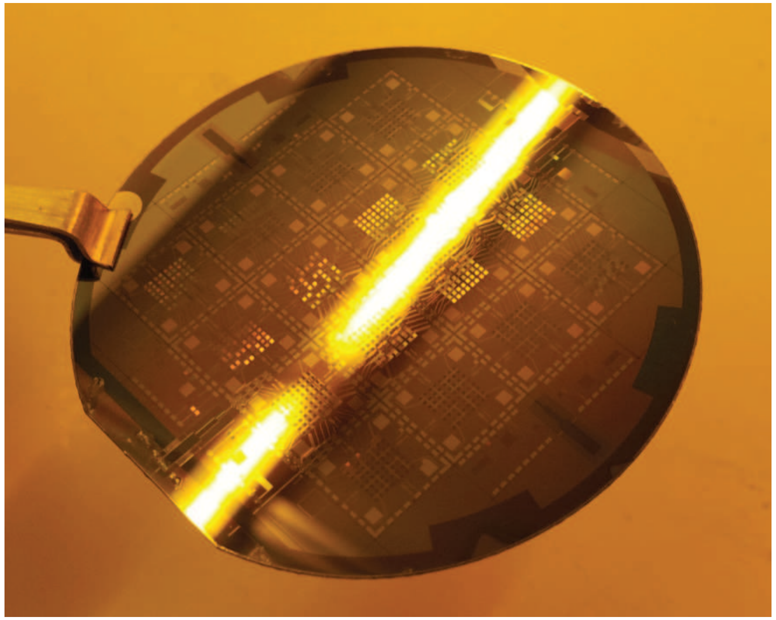
due to **position dependence**,

Meanwhile fixed by stems between absorber and sensor

Large Arrays – parallel read-out





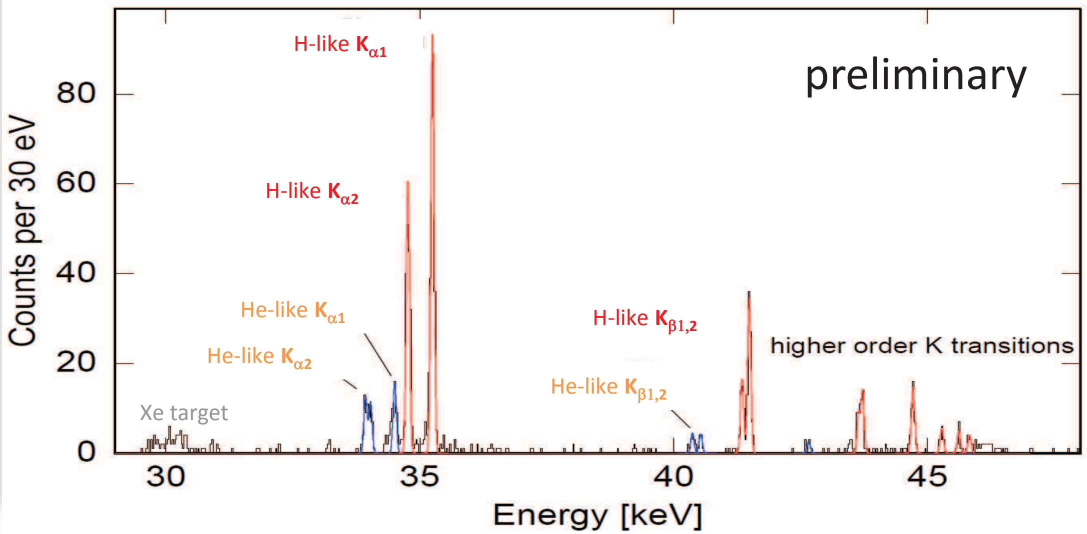


maXs-20/30/200:

- 8×8 pixels for photons up to 20/30/200 keV
- with ΔE_{FWHM} = 2/5/30 eV
- 32 two-stage dc-SQUIDs

MMCs on the road to GSI- Darmstadt

Heidelberg University, Friedrich-Schiller University Jena
and Helmholtz-Institute Jena for SPARC



MMCs meet massive particles from CSR at MPIK

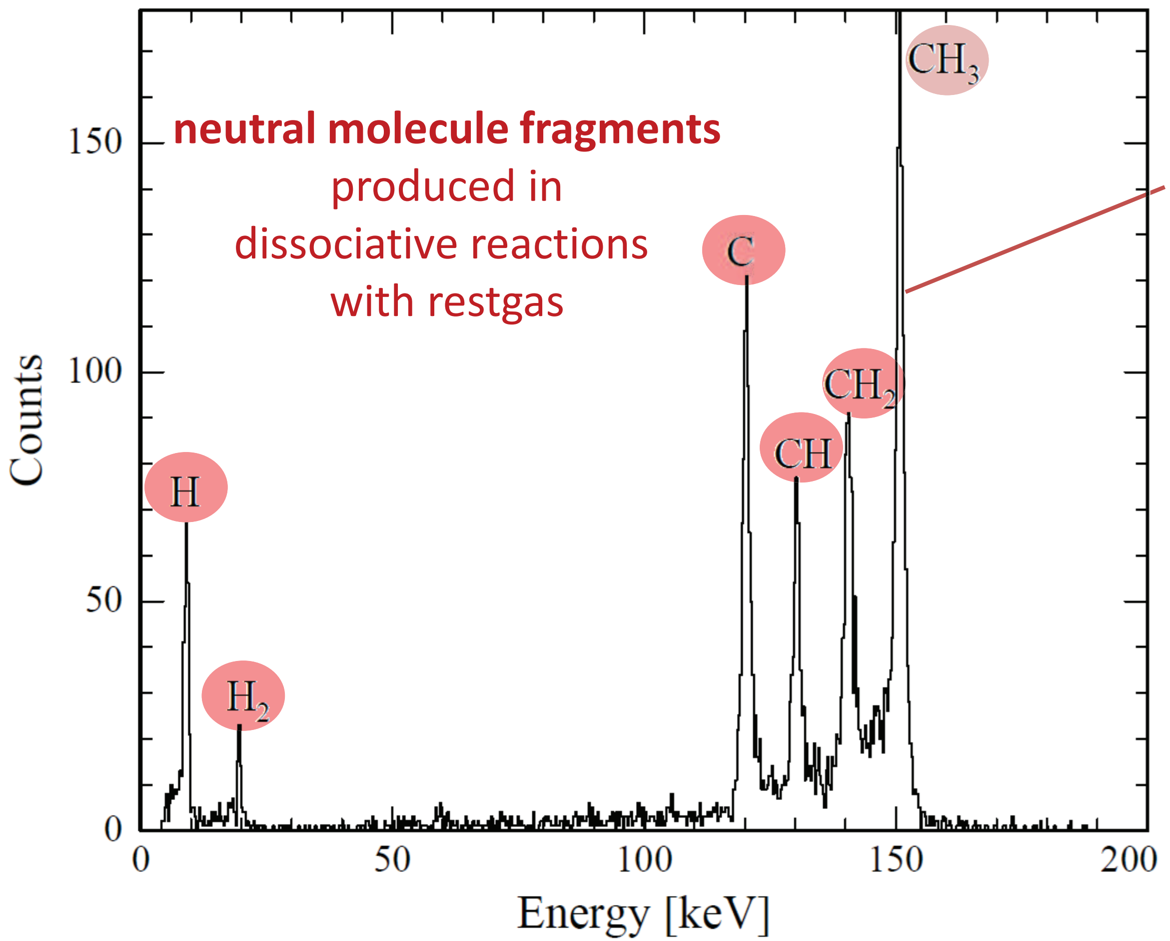
Creation of lattice defects might spoil energy resolution drastically !

→ **first linewidth tests with ions** onto maXs-200 detectors at MPI-K

- atomic ions H^+, C^+, O^+, Ar^+
- molecular ions N_2^+, Ar_2^+, CH_3^+, Acetone$^+$

… accellerated by 0…150 kV

MMCs meet massive particles from CSR at MPIK



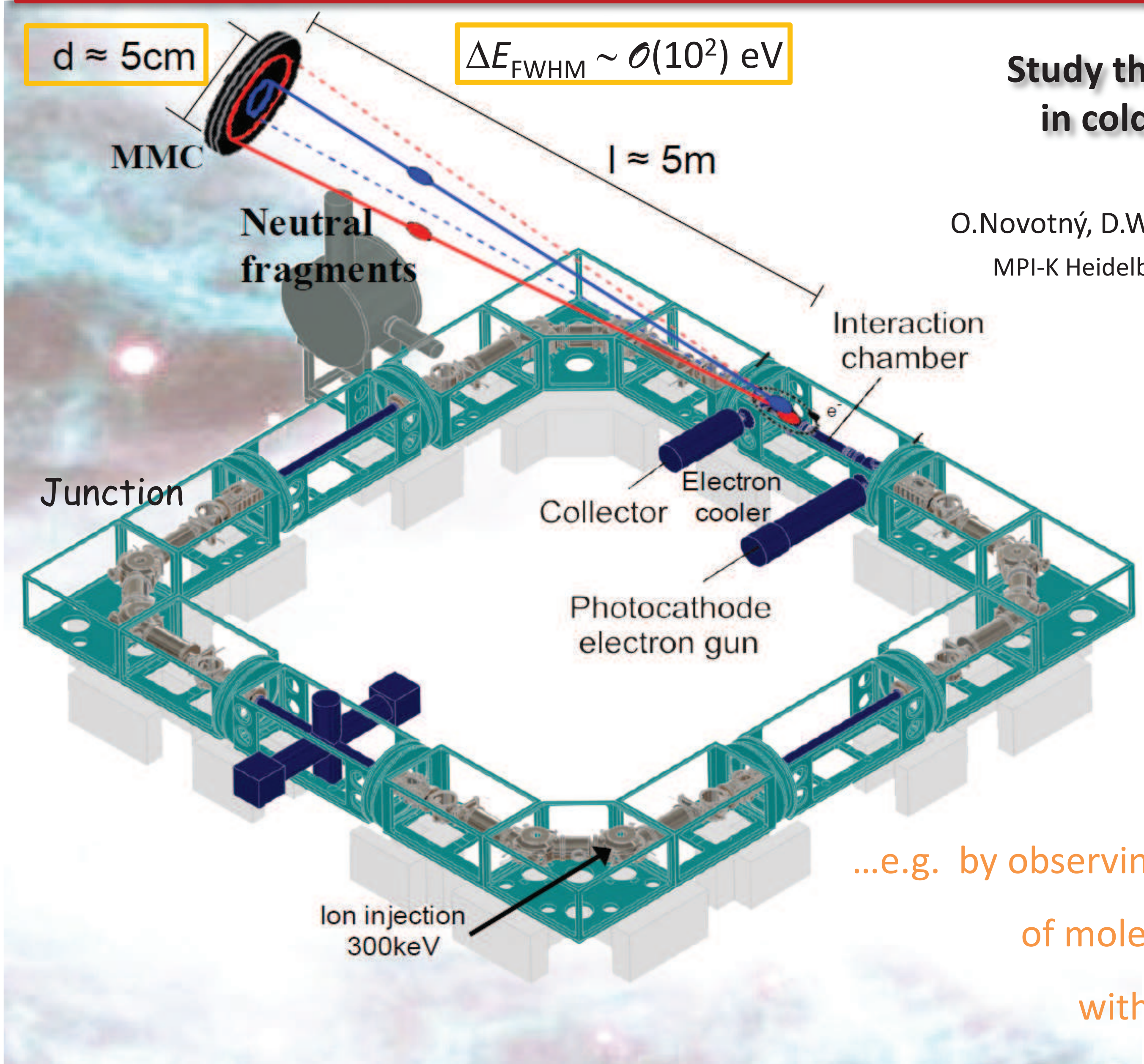
accellerated CH_3^+ ions
or
neutralized CH_3

methyl cation CH_3^+ and its neutral fragments stopped in gold

- **All fragments clearly identified by mass** (= kinetic energy)
- **ΔE_{FWHM}=750eV @ 150keV** allows full identification for molecule masses up to 200

Sometimes nature is more friendly than the simulation ☺

Cold chemistry @ CSR MPI-K



Study the complex chemistry in cold interstellar clouds

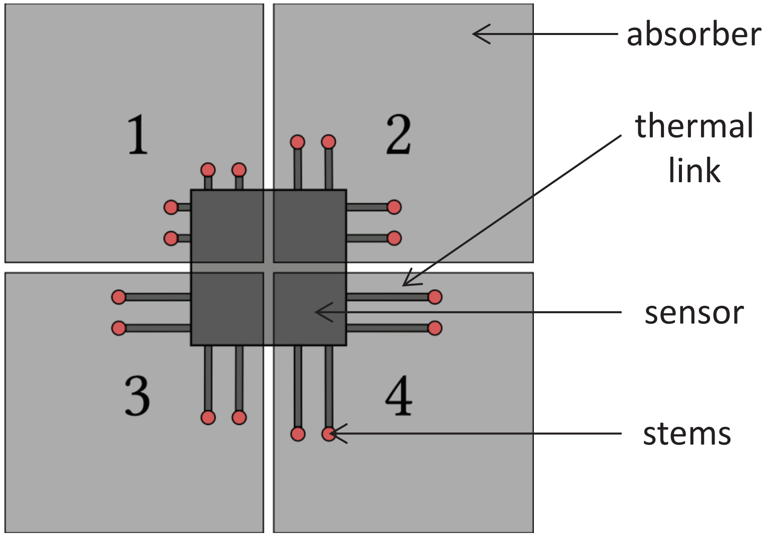
with

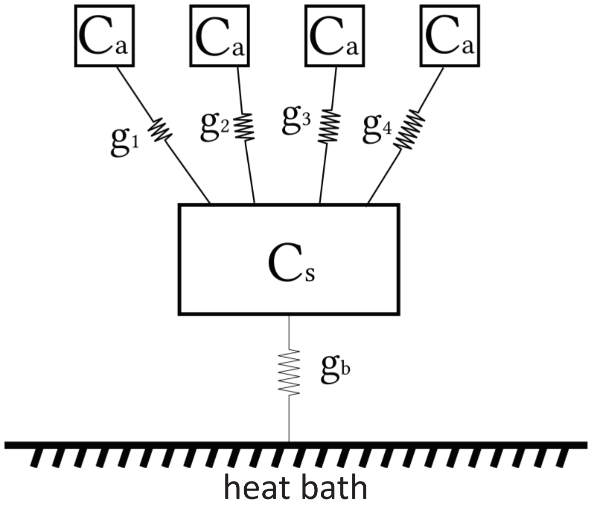
O.Novotný, D.W.Savin, C.Krantz, A.Wolf, K.Blaum,

MPI-K Heidelberg, Columbia Astrophysics Lab NY

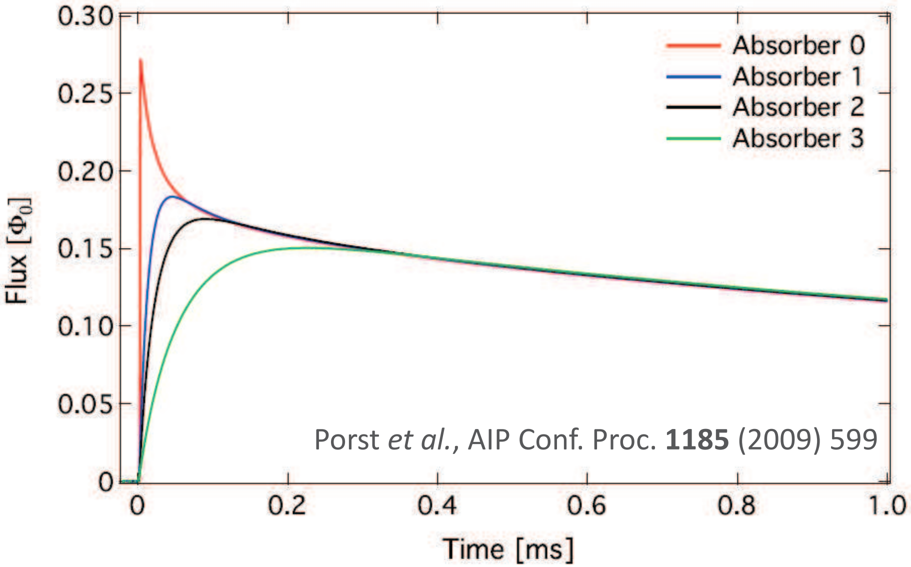
…e.g. by observing neutral reaction products of molecular ions after neutralizing with an electron in the e-cooler

The Hydra principle

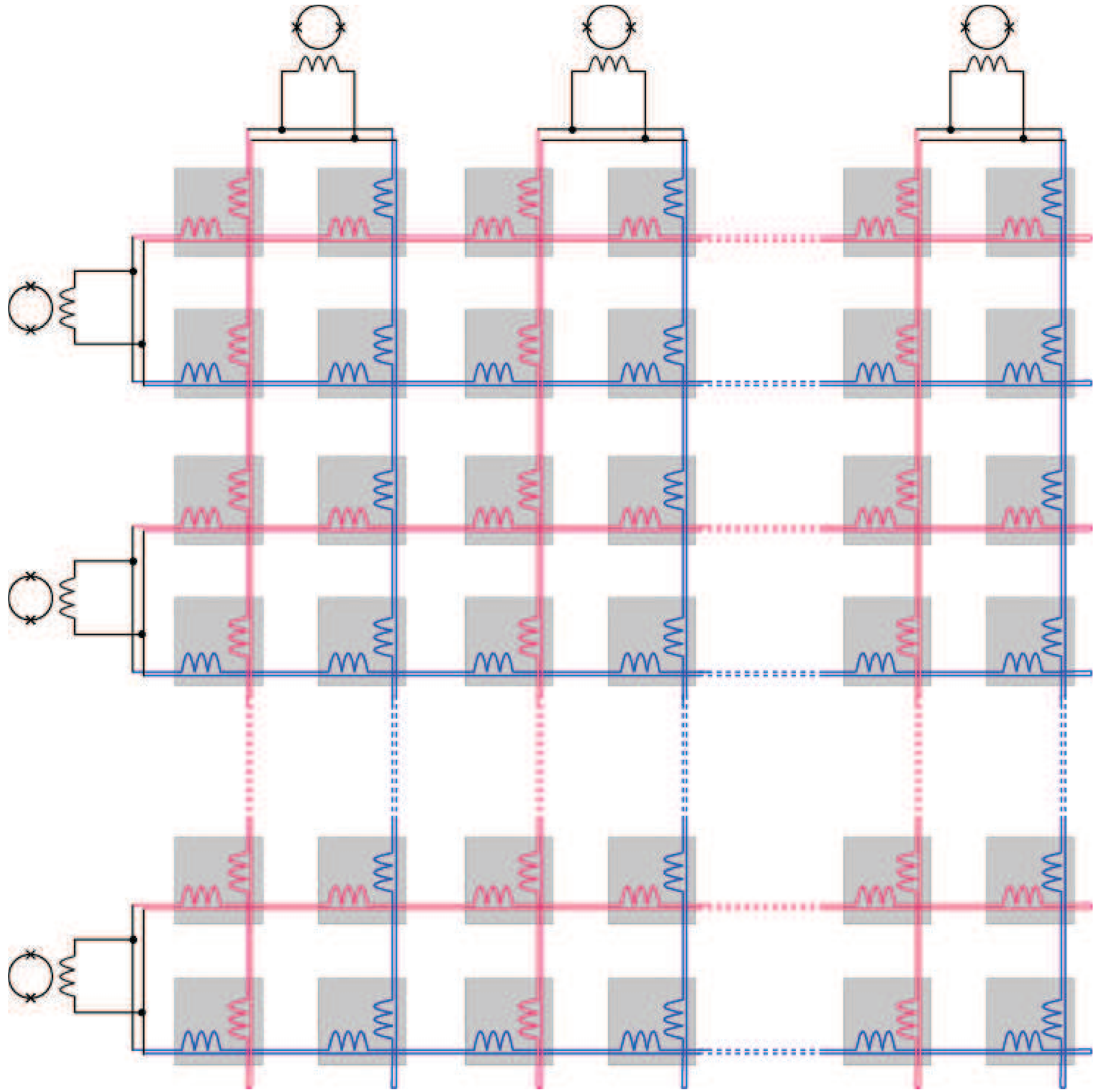




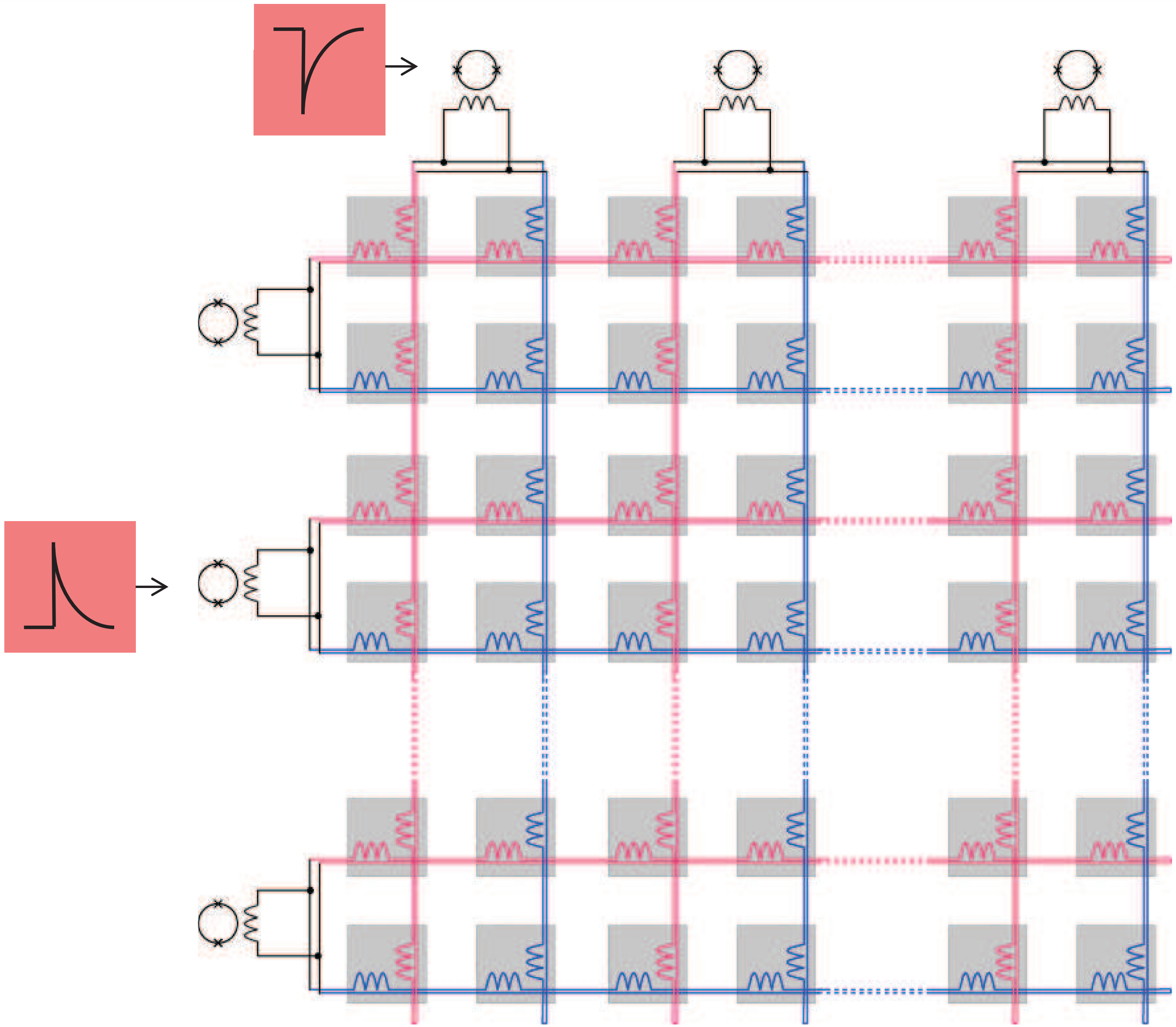
Pixel identification
via rise-time
of the detector signal



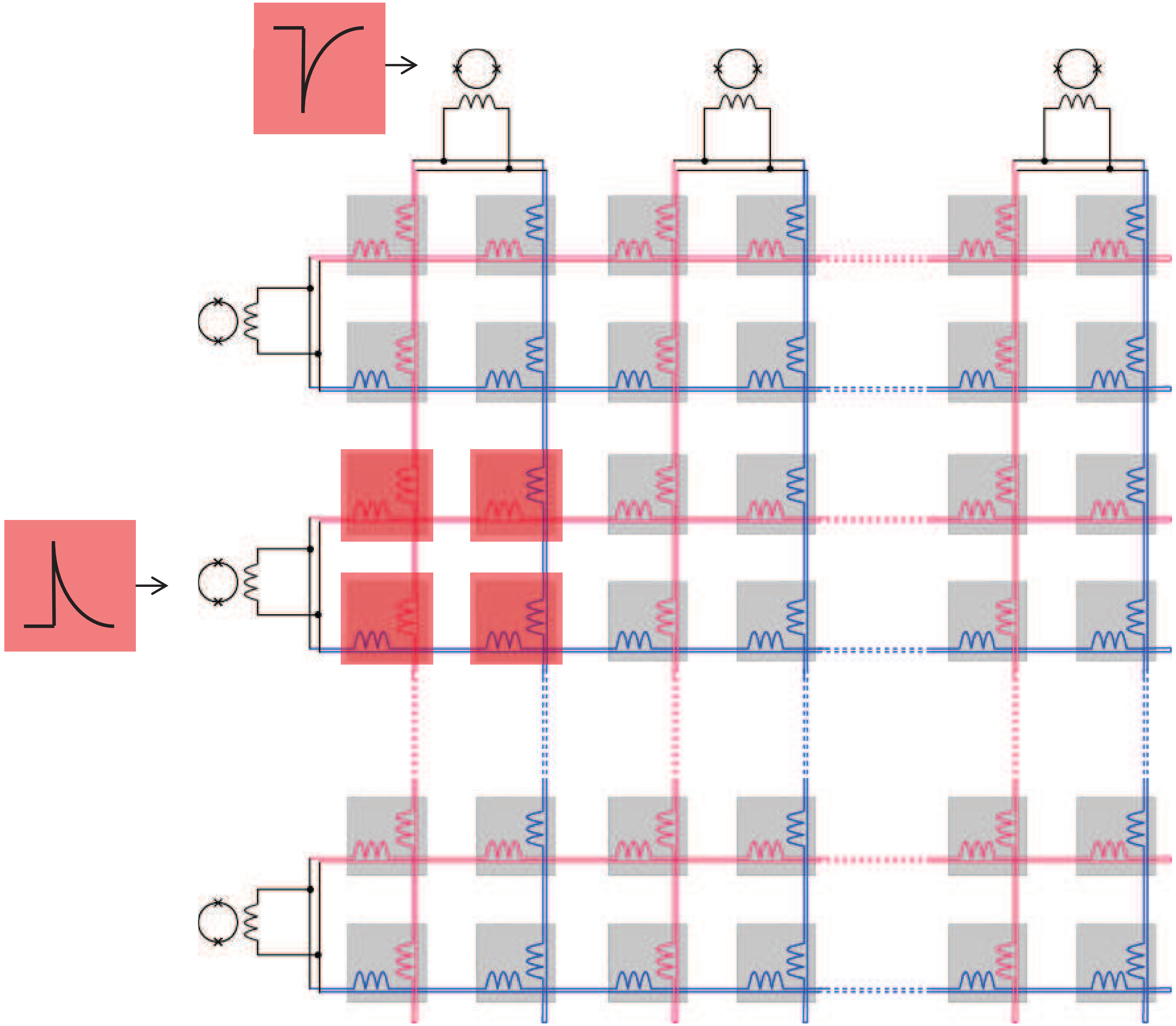
Read out scheme



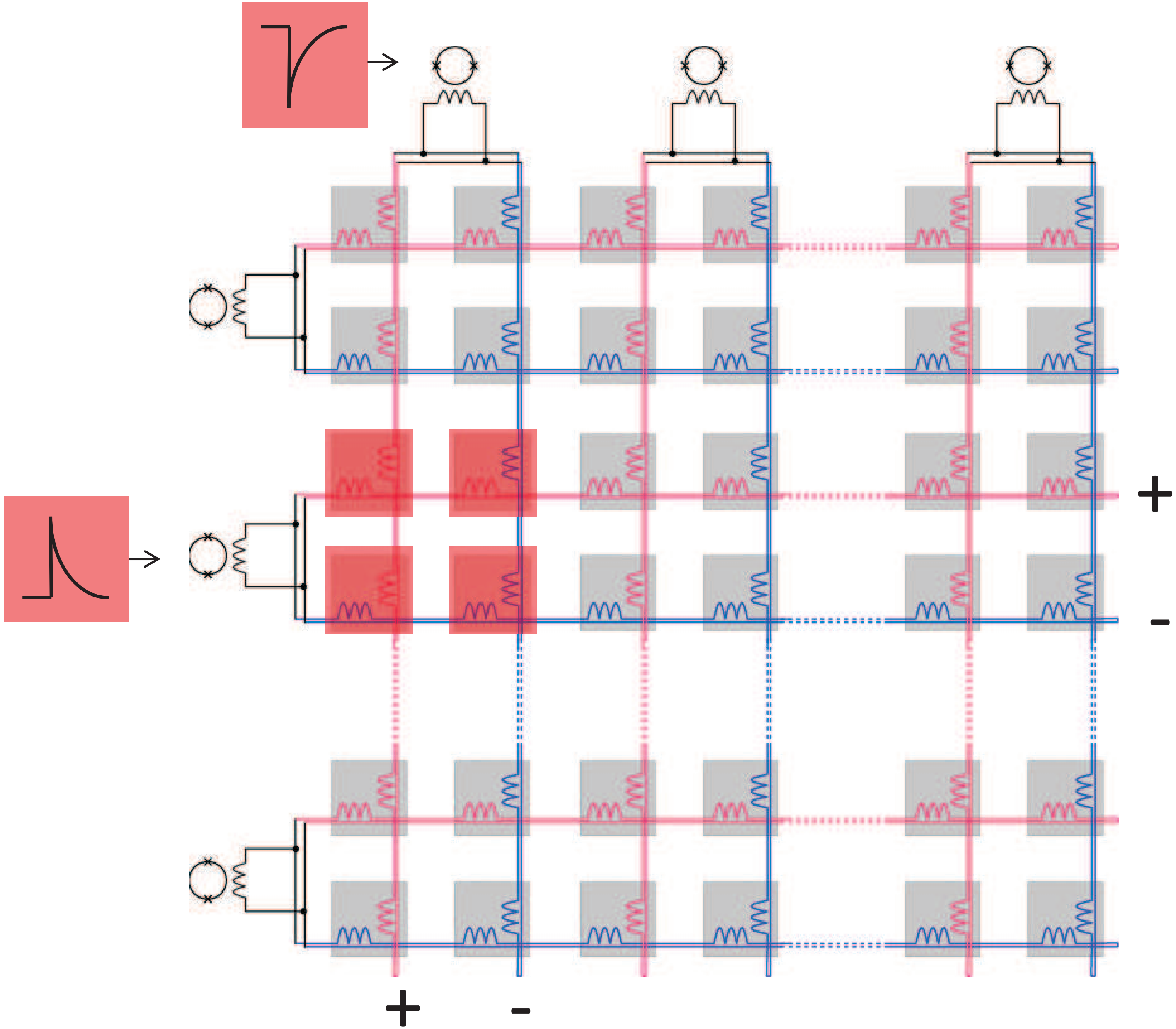
Read out scheme



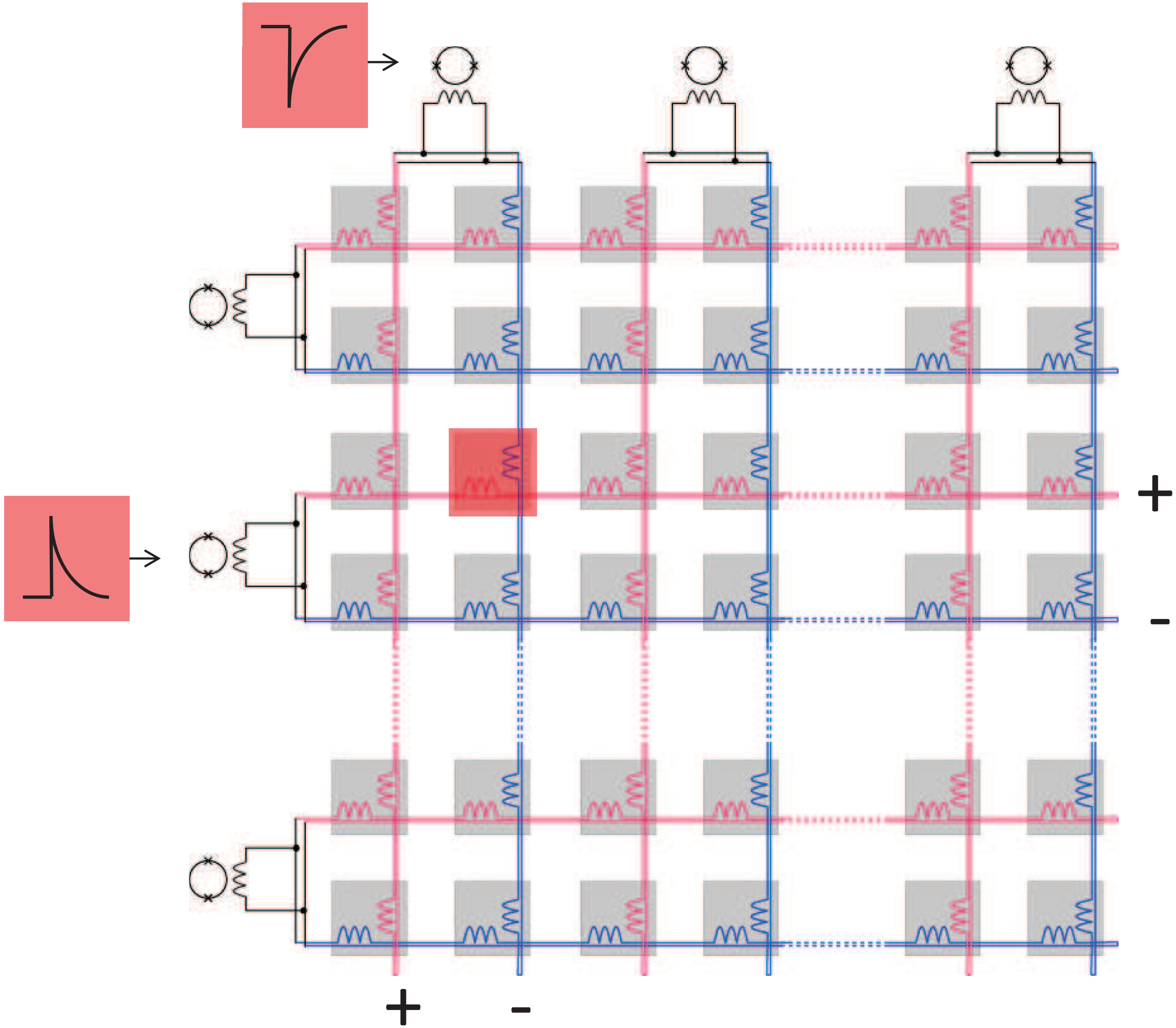
Read out scheme



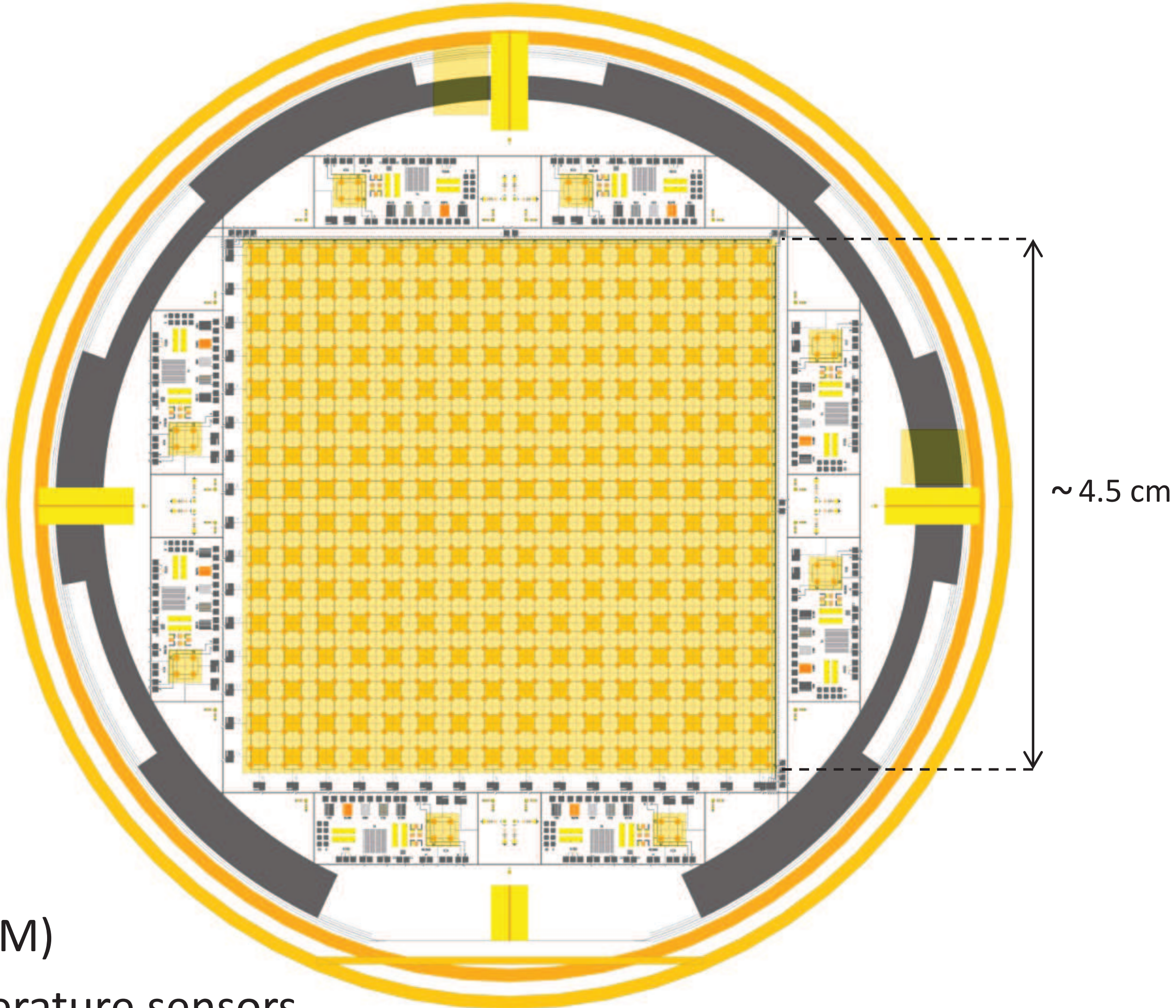
Read out scheme



Read out scheme



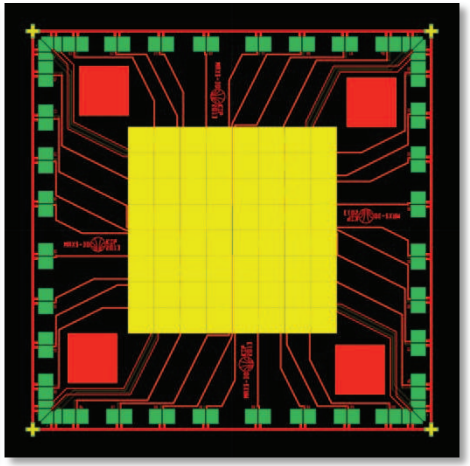
MOCCA: a 4k-pixel MMC camera



- 64×64 pixels
- 200 eV (FWHM)
- 32×32 temperature sensors
- Read out by 16+16 SQUIDs

How to read-out 1000s of detectors?

Simplest idea: duplicate single channel readout



Brute force read-out of 8x8 x-ray detectors

But:

- number of wires
- parasitic heat load
- costs
- complexity

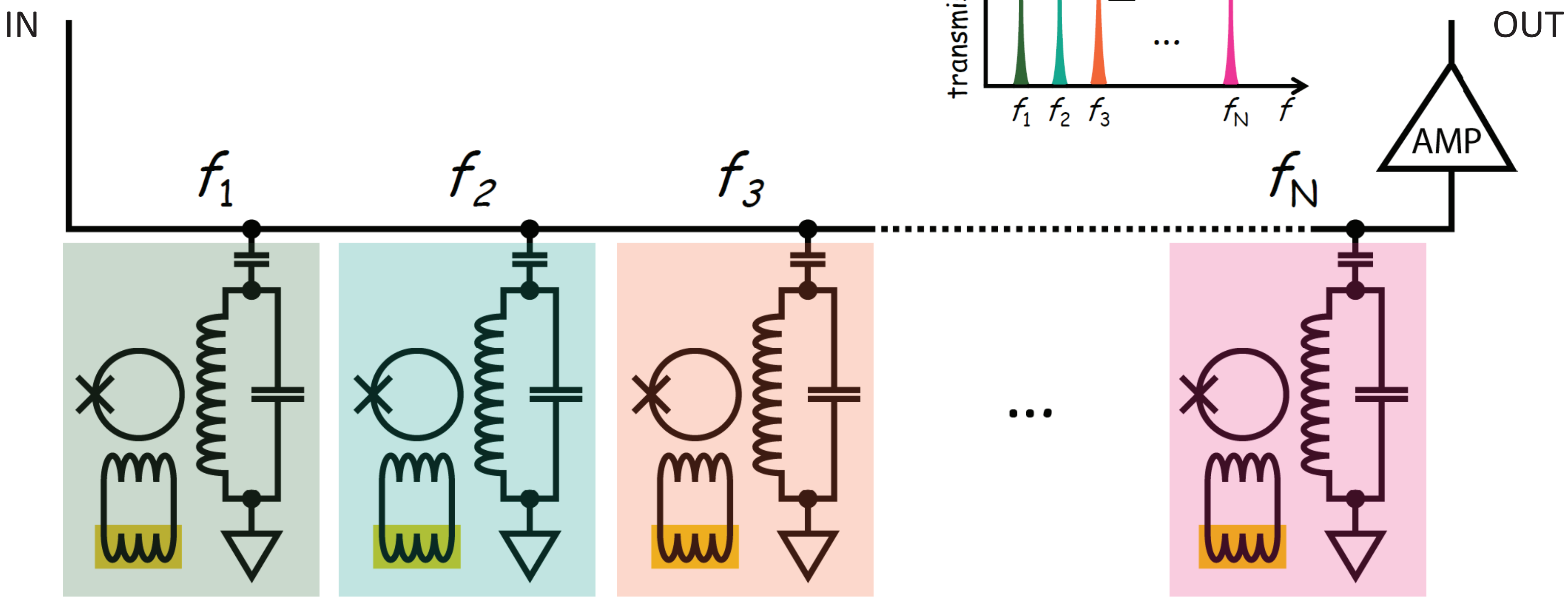
} *~N*

⇨ multiplexing scheme required
(TDM, FDM, CDM, …)

MMCs: Microwave SQUID multiplexing

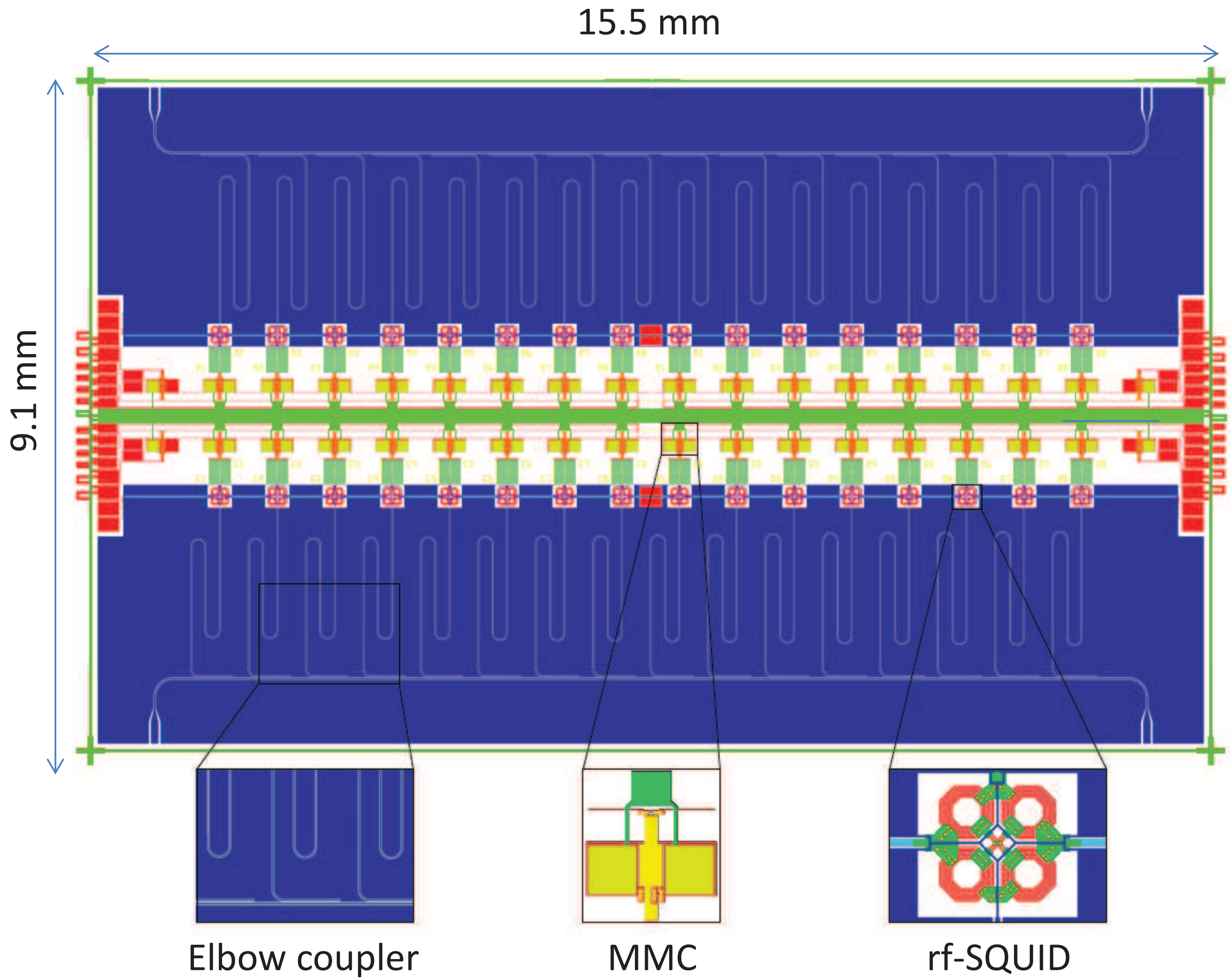
Microwave SQUID multiplexing

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

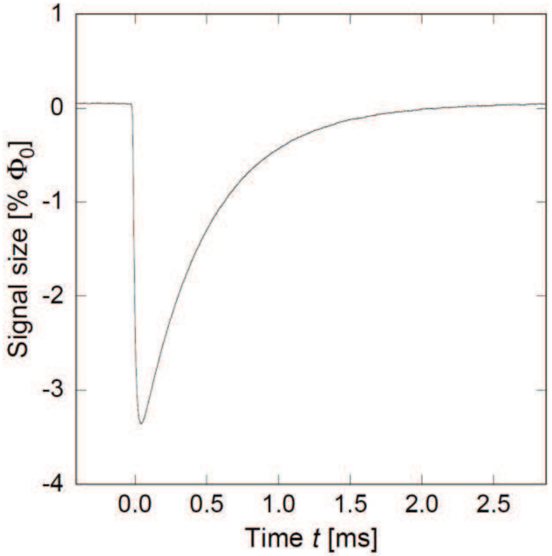


Microwave SQUID Multiplexer for the Readout of Metallic Magnetic Calorimeters
S.Kempf et al., *J. Low. Temp. Phys.* **175** (2014) 850-860

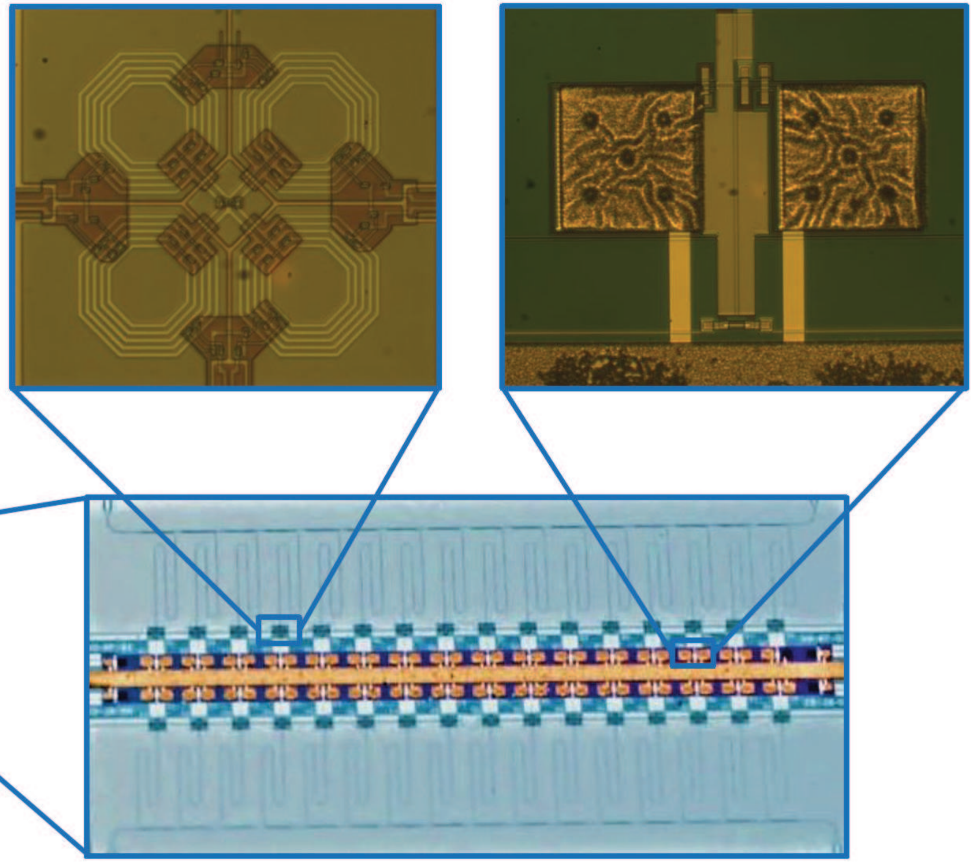
MMCs: Microwave SQUID multiplexing

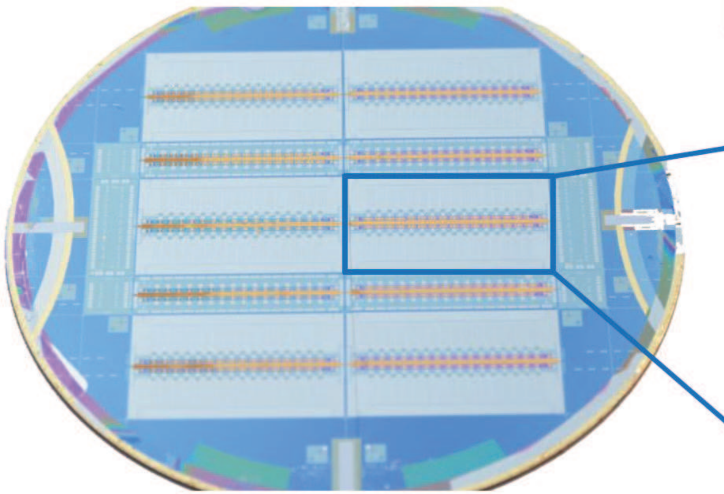


MMCs: Microwave SQUID multiplexing



Successful production and test of the first prototype





M. Wegner et al., in preparation

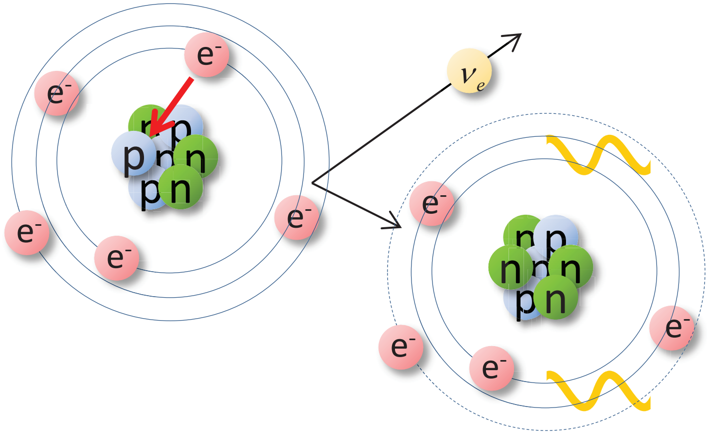
Neutrino mass determination

The Electron Capture in Ho-163 experiment

- Department of Nuclear Physics, Comenius University, Bratislava, Slovakia
- Department of Physics, Indian Institute of Technology Roorkee, India
- Institute for Nuclear Chemistry, Johannes Gutenberg University Mainz
- Institute of Nuclear Research of the Hungarian Academy of Sciences
- Institute of Nuclear and Particle Physics, TU Dresden, Germany
- Institute for Physics, Johannes Gutenberg-Universität
- Institute for Theoretical and Experimental Physics Moscow, Russia
- Institute for Theoretical Physics, University of Tübingen, Germany
- Kirchhoff-Institute for Physics, Heidelberg University, Germany
- Max-Planck Institute for Nuclear Physics Heidelberg, Germany
- Petersburg Nuclear Physics Institute, Russia
- Physics Institute, University of Tübingen, Germany
- Saha Institute of Nuclear Physics, Kolkata, India

The Electron Capture ^{163}Ho Experiment: ECHo
L. Gastaldo *et al.*, JLTP **176 - 5** (2014) 876-884

^{163}Ho and neutrino mass



$$^{163}_{67}\mathrm{Ho} \rightarrow ^{163}_{66}\mathrm{Dy}^{*} + \nu_e$$

$$^{163}_{66}\mathrm{Dy}^{*} \rightarrow ^{163}_{66}\mathrm{Dy} + E_C$$

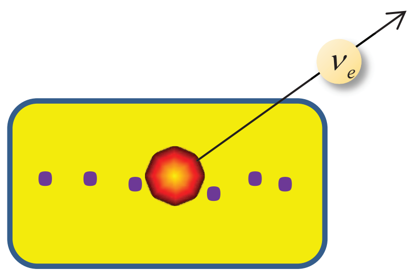
- $\tau_{1/2} \cong$ 4570 years (2*10^{11} atoms for 1 Bq)
- Q_{EC} = (2.555 ± 0.016) keV *

*M. Wang, G. Audi et al., *Chinese Phys. C* **36**, 1603, (2012)

A non- zero neutrino mass affects the de-excitation energy spectrum

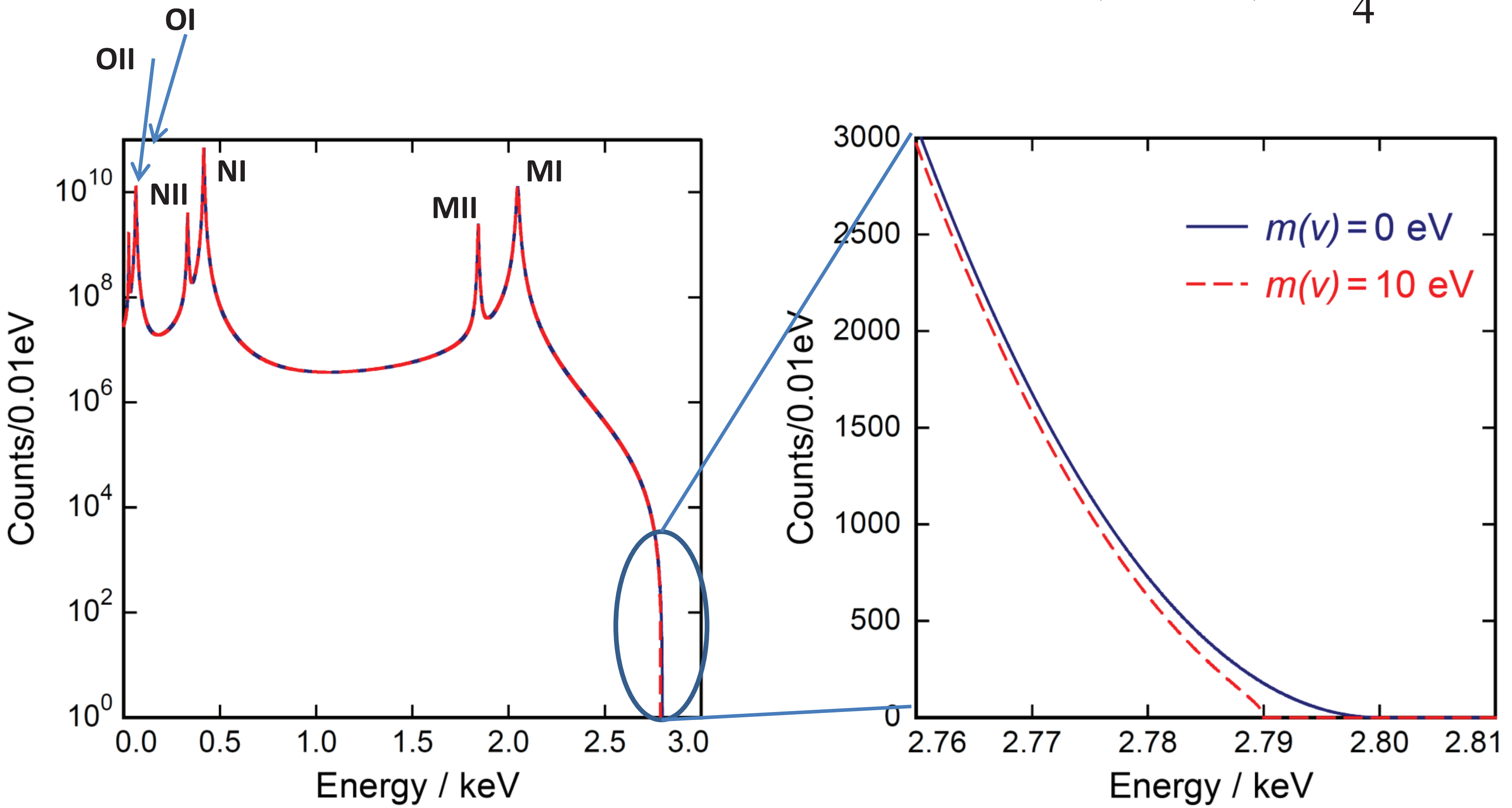
Atomic de-excitation:
•X-ray emission
•Auger electrons
•Coster-Kronig transitions

Calorimetric measurement



^{163}Ho and neutrino mass

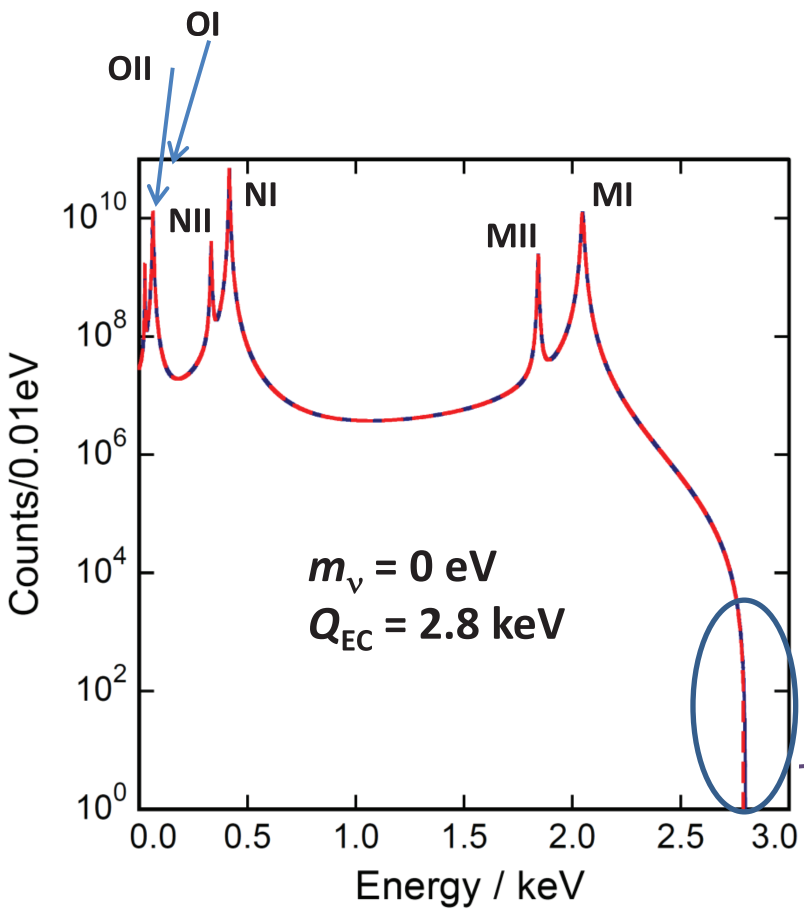
$$\frac{dW}{dE_C} = A(Q_{EC} - E_C)^2 \sqrt{1 - \frac{m_\nu^2}{(Q_{EC} - E_C)^2}} \sum_H B_H \varphi_H^2(0) \frac{\frac{\Gamma_H}{2\pi}}{(E_C - E_H)^2 + \frac{\Gamma_H^2}{4}}$$

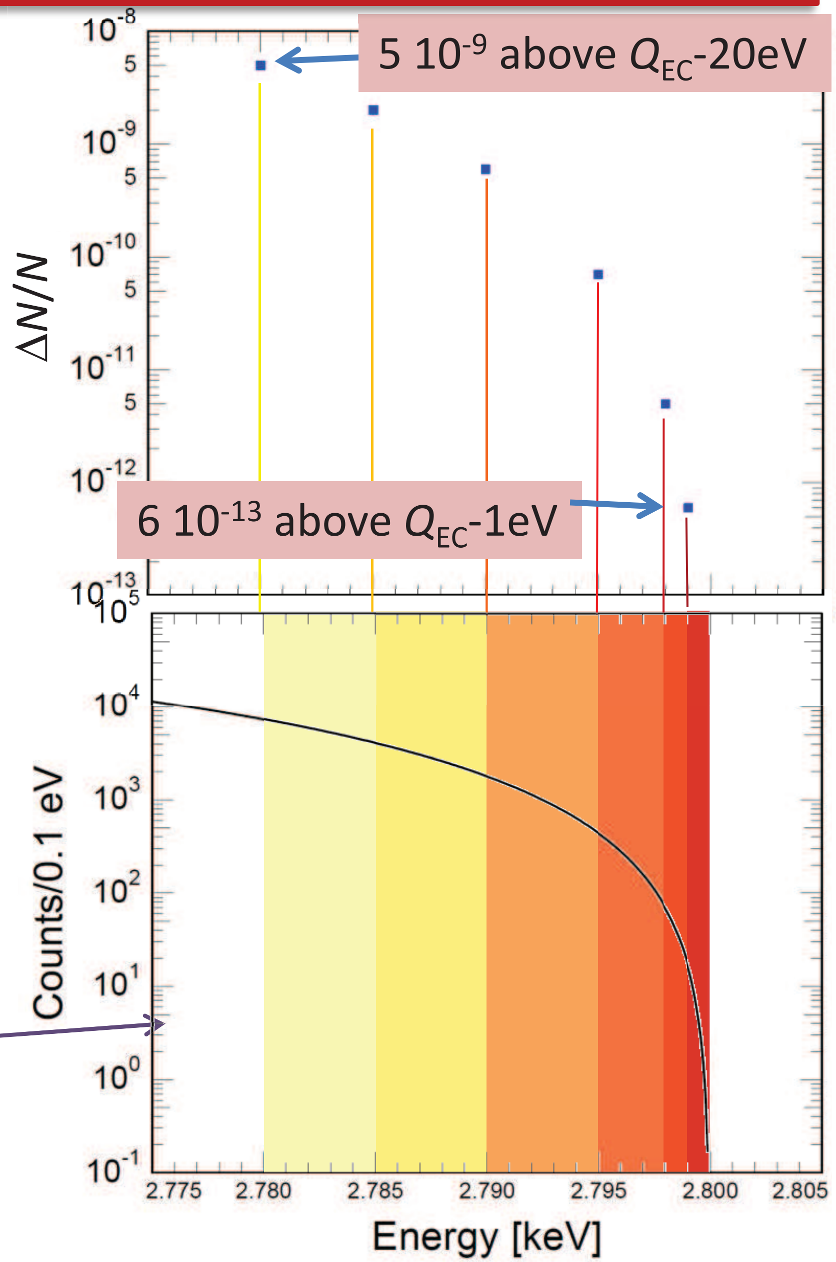


^{163}Ho and neutrino mass: sub-eV sensitivity

Statistics in the end point region

- $N_{ev} > 10^{14}$ → $A \approx 1$ MBq





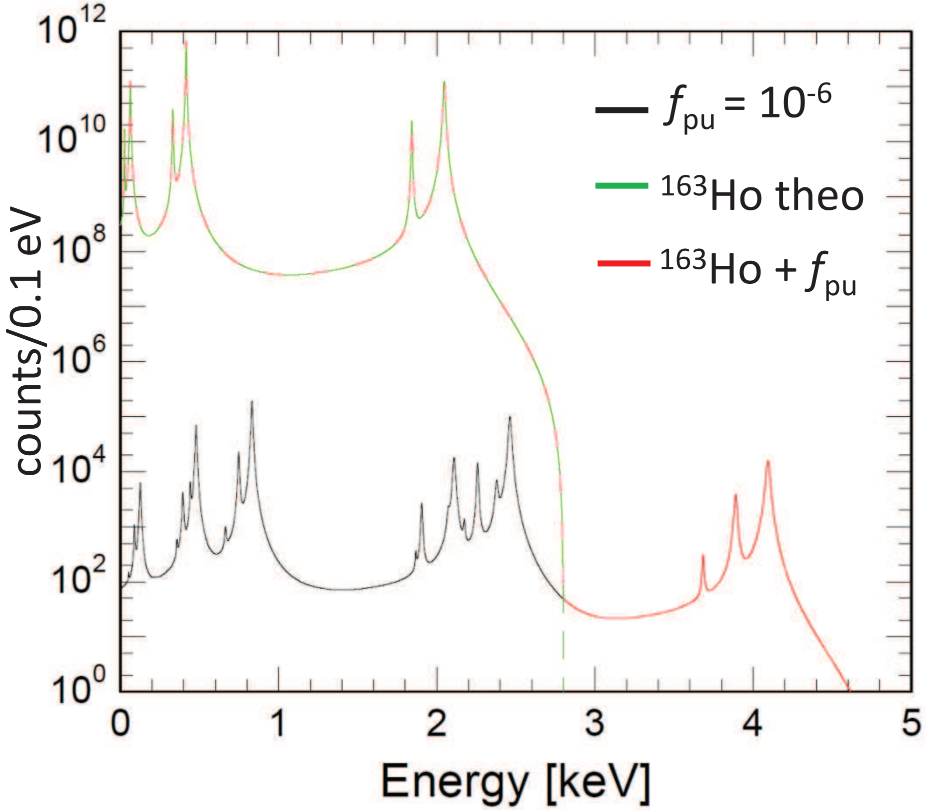
^{163}Ho and neutrino mass: sub-eV sensitivity

Statistics in the end point region

- $N_{ev} > 10^{14}$ → A ≈ 1 MBq

Unresolved pile-up (f_{pu} ~ a · t)

- $f_{pu} < 10^{-5}$
- τ_r < 1 μs → a < 10 Bq
- **10^5 pixels**



^{163}Ho and neutrino mass: sub-eV sensitivity

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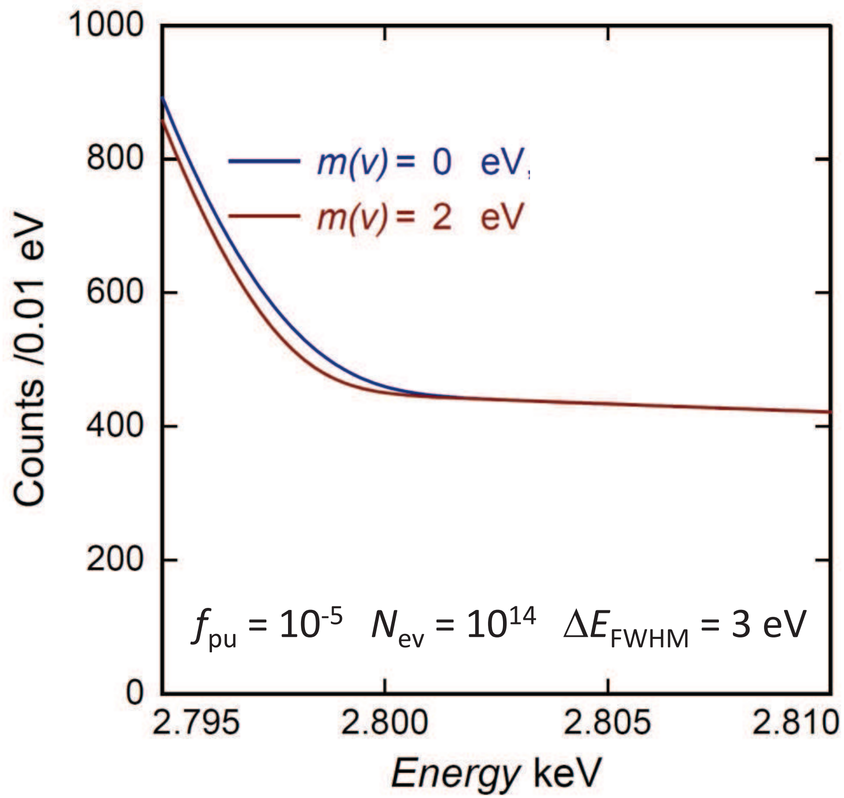
- $\tau_r < 1\ \mu s$ → $a < 10$ Bq
- **10^5 pixels**

Precision characterization of the endpoint region

- $\Delta E_{FWHM} < 2$ eV



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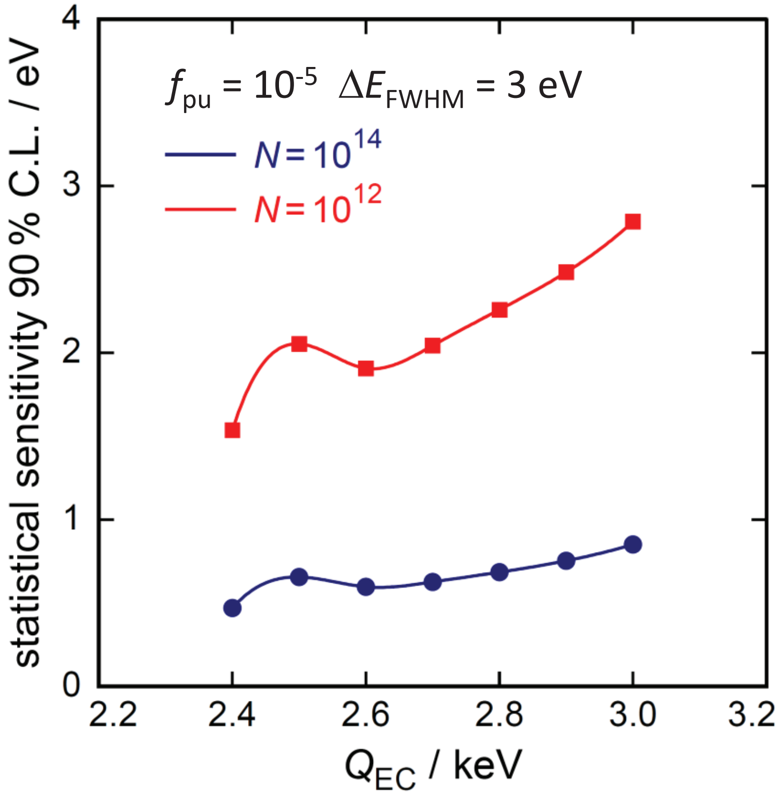
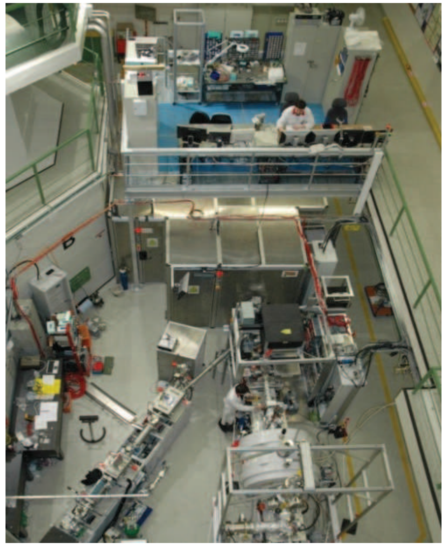


Q_{EC} determination of ^{163}Ho



Penning Trap mass spectrometry

- First experiments at TRIGATRAP (Uni-Mainz) in 2014 *
  - Development of efficient Ho ion source using laser ablation
  - Uncertainties on ^{163}Dy and ^{163}Ho mass reduced by a factor of 2
  - Know-how to be applied in SHIPTRAP

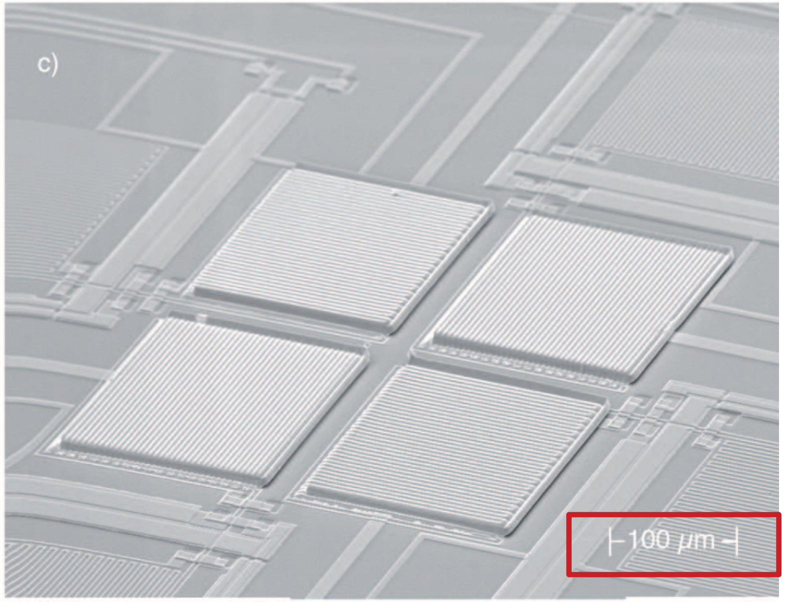
- In a few months: SHIPTRAP (GSI)
  - Q_{EC} determination within 30 - 100 eV

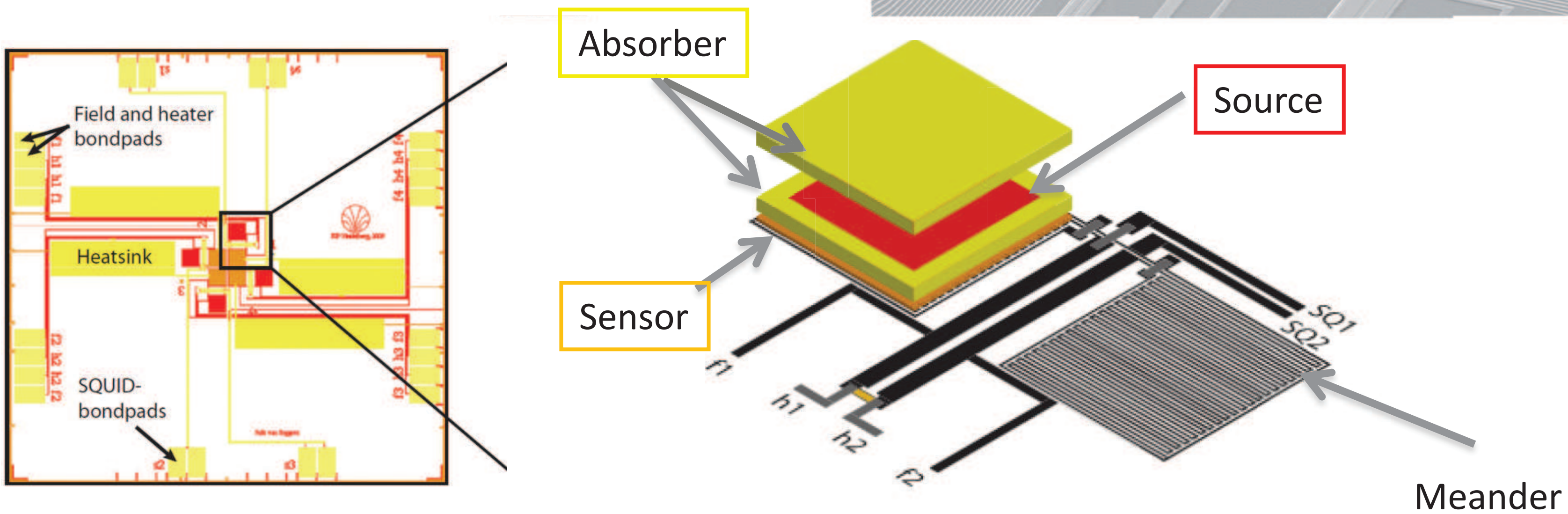
- In a few years: **PENTATRAP** (MPI-K HD)
  - Q_{EC} determination within **1 eV**

*Preparatory studies for a high-precision Penning trap measurement of the 163Ho electron capture Q-value
F. Schneider et al., submitted to EPJ

First detector prototype

- Absorber for calorimetric measurement
  → ion implantation @ ISOLDE-CERN
- About 0.01 Bq per pixel
- Two pixels have been simultaneusly measured





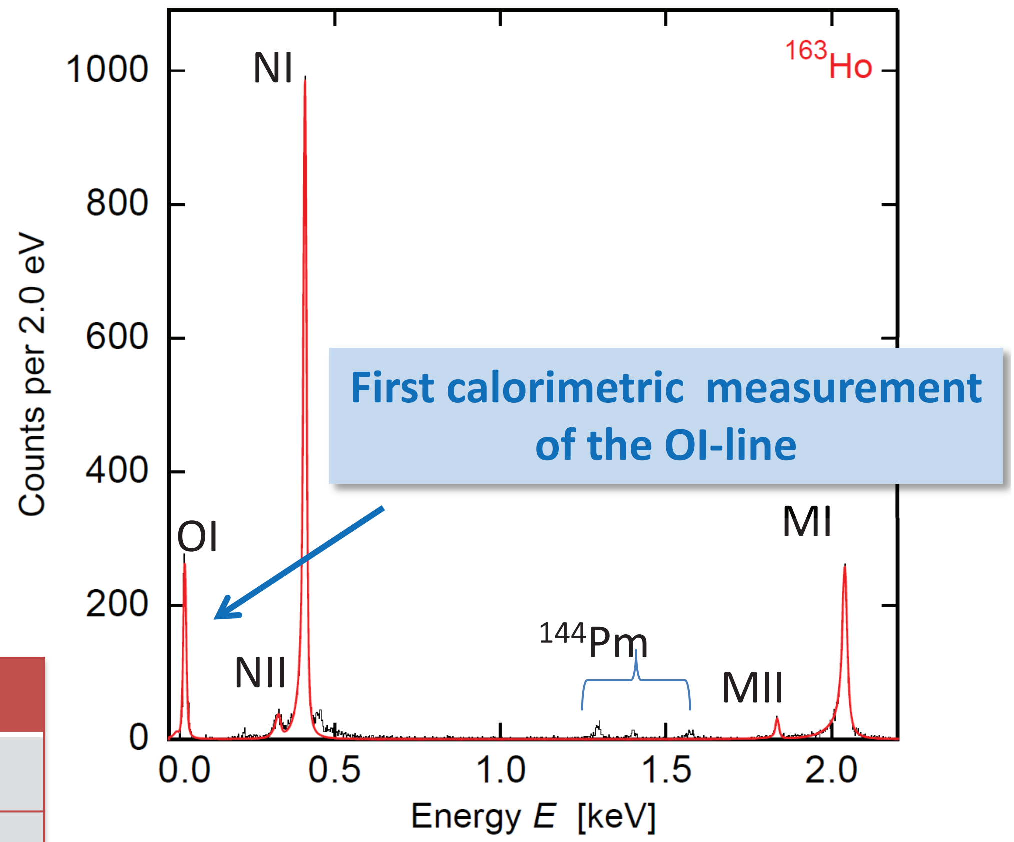
L. Gastaldo et al.,
Nucl. Inst. Meth. A, 711 (2013) 150

P. C.-O. Ranitzsch et al.,
http://arxiv.org/abs/1409.0071v1

Calorimetric spectrum

- Rise Time ~ 130 ns
- ΔE_{FWHM} = 7.6 eV @ 6 keV (2013)
  ΔE_{FWHM} = 2.4 eV @ 0 keV (2014)
- Non-Linearity < 1% @ 6keV
- Synchronized measurement of 2 pixels
- Presently most precise ^{163}Ho spectrum

	E_H bind.	E_H exp.	Γ_H lit.	Γ_H exp
MI	2.047	2.040	13.2	13.7
MII	1.845	1.836	6.0	7.2
NI	0.420	0.411	5.4	5.3
NII	0.340	0.333	5.3	8.0
OI	0.050	0.048	5.0	4.3



Q_{EC} = (2.843 ± 0.009^{stat} - 0.06^{syst}) keV

P. C.-O. Ranitzsch et al ., http://arxiv.org/abs/1409.0071v1)
L. Gastaldo et al., Nucl. Inst. Meth. A, 711, 150-159 (2013)

Where to improve

Detector design and fabrication:

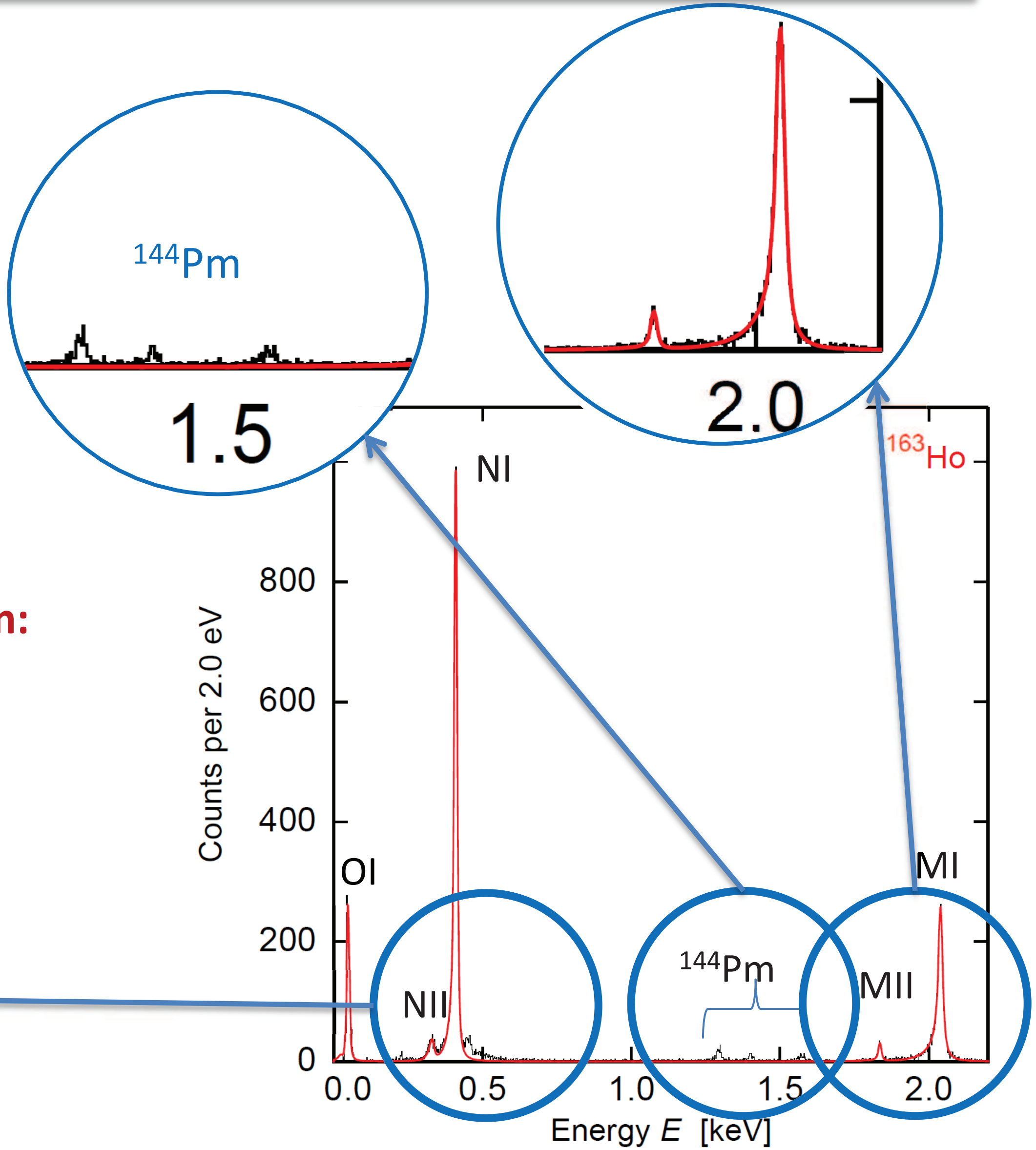
- Increase activity per pixel
- Remove low energy tail

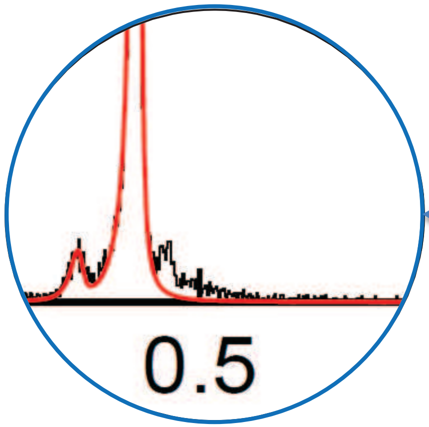
High purity ^{163}Ho source:

- Background reduction

Understanding of the ^{163}Ho spectrum:

- Investigate undefined structures





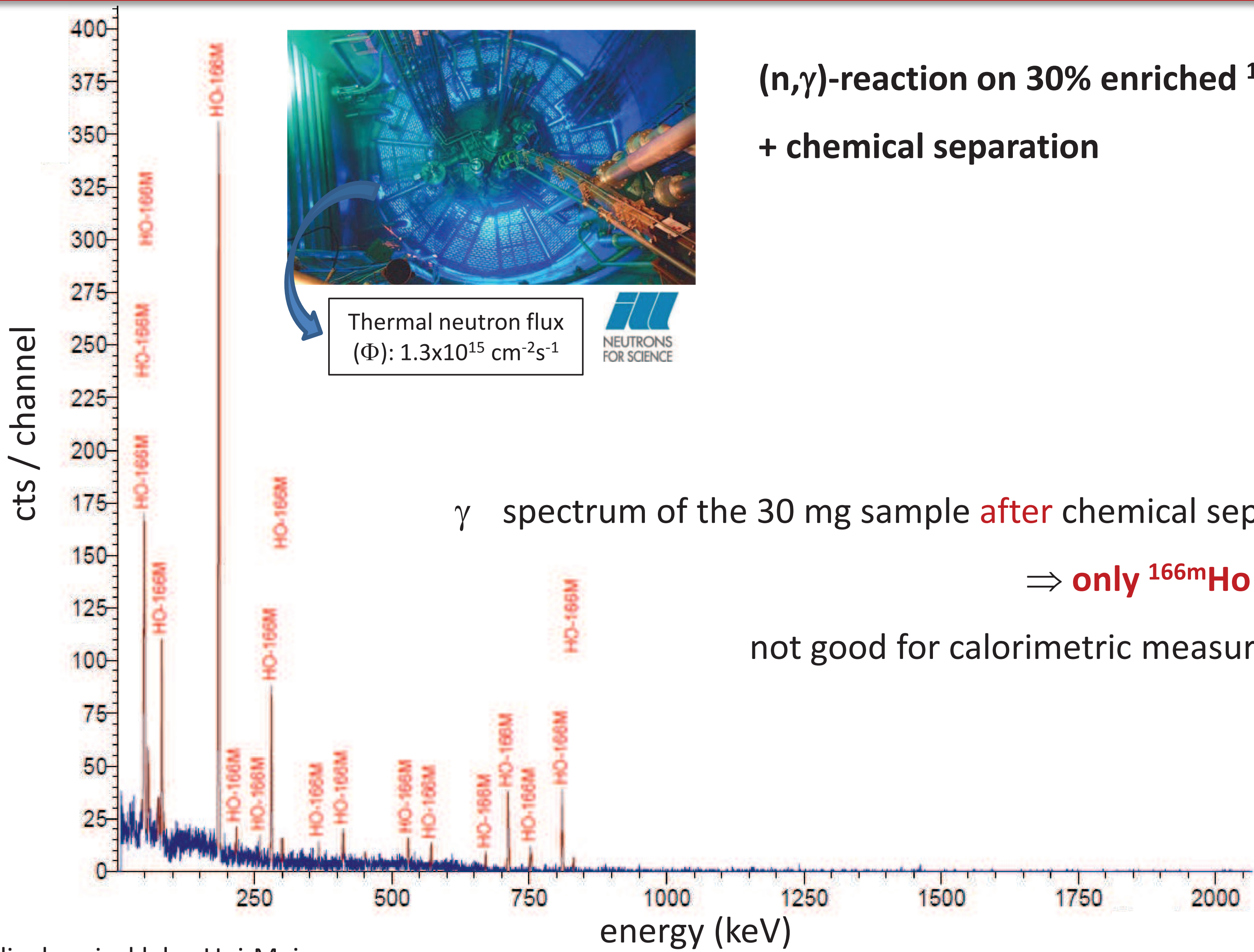
High purity ^{163}Ho source: Chemical separation

Thermal neutron flux (Φ): 1.3×10^{15} $cm^{-2}s^{-1}$

NEUTRONS FOR SCIENCE

(n,γ)-reaction on 30% enriched ^{162}Er

+ chemical separation



γ spectrum of the 30 mg sample after chemical separation:

$\Rightarrow$ **only ^{166m}Ho visible**

not good for calorimetric measurements!

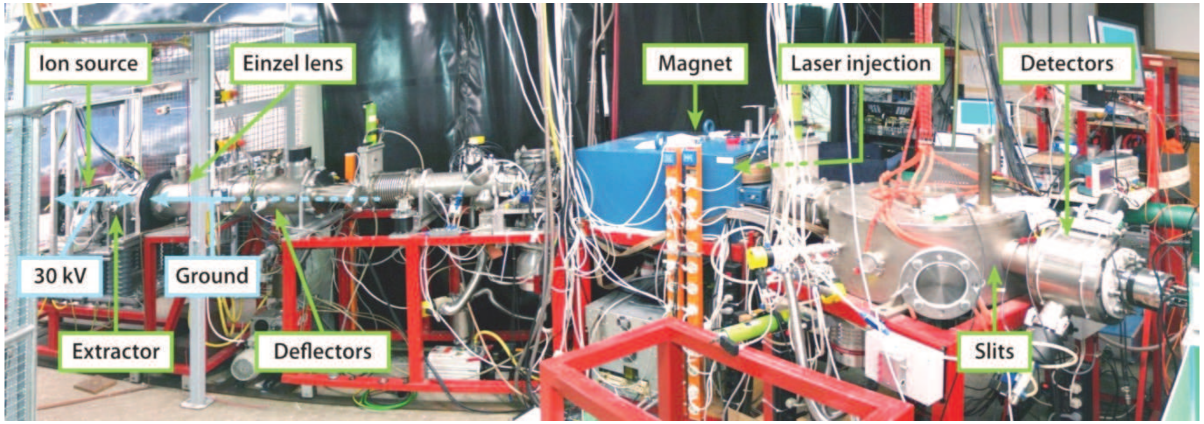
Radiochemical labs, Uni-Mainz

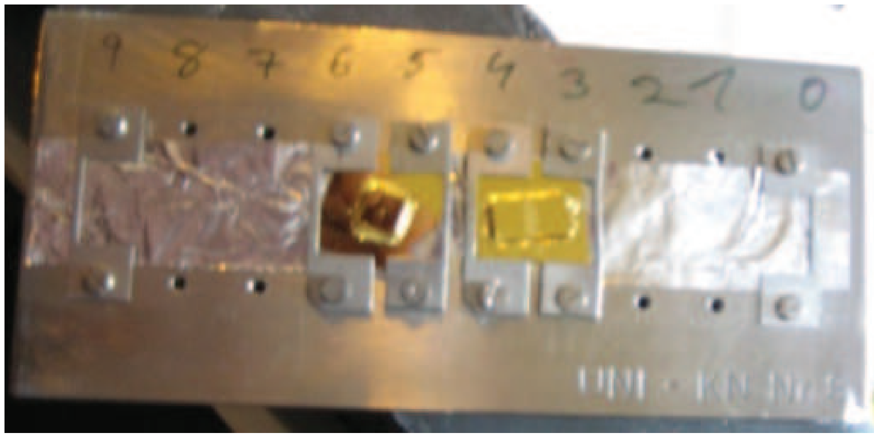
High purity ^{163}Ho source: Mass separation

Goal: $^{166m}Ho/^{163}Ho \leq 10^{-9}$

- RISIKO mass-separator @ Uni-Mainz

  ✓ First successful test with natural Ho





- Separation at CERN/ISOLDE December 2014

  ✓ 2 new chips to test!

  … each with 16 pixel detector arrays for soft x-rays

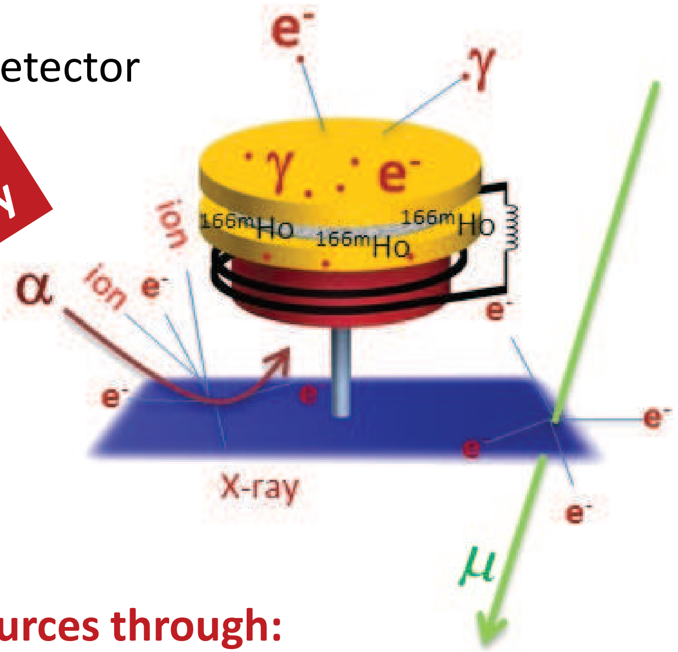
  → higher activity per pixel ≈ 1 Bq

  → no radioactive contaminants

Background

Background sources:

- Environmental radioactivity → Material screening
- Cosmic rays
- Induced secondary radiation by cosmic rays → Underground labs / μ-Veto → Underground measurements in Modane
- Radioactivity in the detector



Background level
5×10^{-5} counts/eV/det/day

Study of background sources through:

- Monte Carlo simulations
- Dedicated experiments

Screening facilities
- Uni-Tübingen
- Felsenkeller

ECHo overview

- Prove scalability with medium large experiment **ECHo-1K**

  - A ~ 1000 Bq — High purity ^{163}Ho source (produced at reactor)
  - $\Delta E_{FWHM} < 5$ eV
  - $\tau_r < 1$ µs
  - multiplexed arrays → microwave SQUID multiplexing

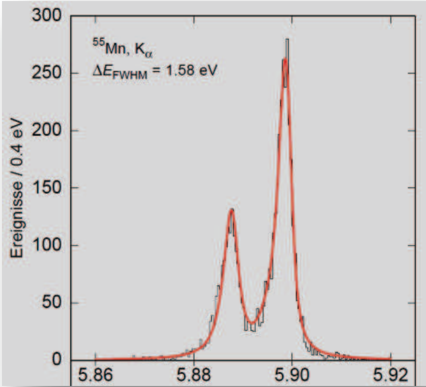
  - 1 year measuring time → 10^{10} counts = Neutrino mass sensitivity $m_\nu < 10$ eV

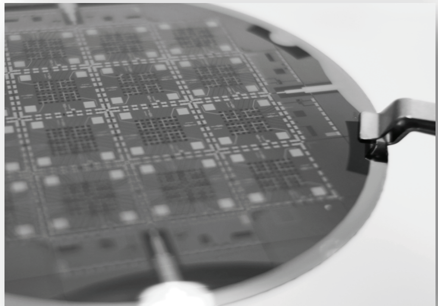
  Just approved

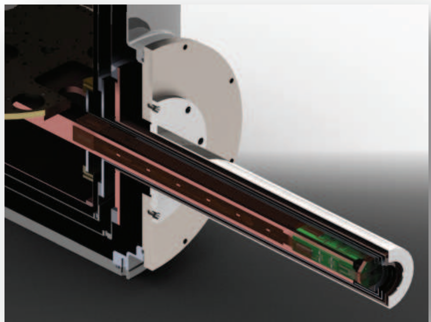
  Research Unit FOR 2202/1
  „Neutrino Mass Determination by Electron Capture in Holmium-163 – ECHo“
  DFG Deutsche Forschungsgemeinschaft

- **ECHo-1M** towards sub-eV sensitivity

Summary and Outlook







metallic magnetic calorimeters

- are versatile low temperature detectors
- high resolution for all kinds of particles
- wide range of energies
- impressive resolving powers in reach

micro-farbrication works

- first detector arrays fabricated
- designed performance is reached
- 2d arrays are on the way

multiplexing

- demonstrated principles

Low temperature physics @KIP

Thank you!