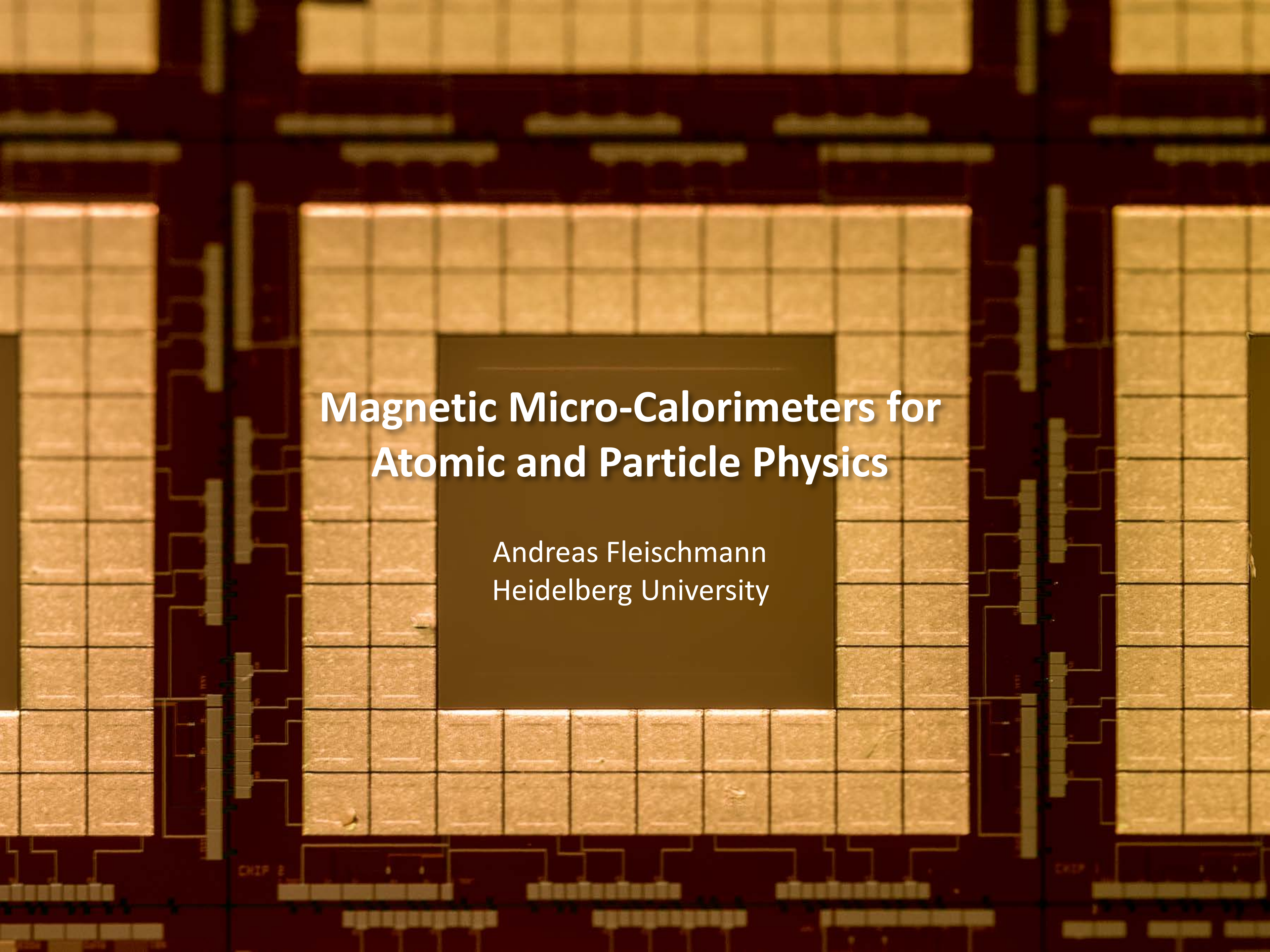
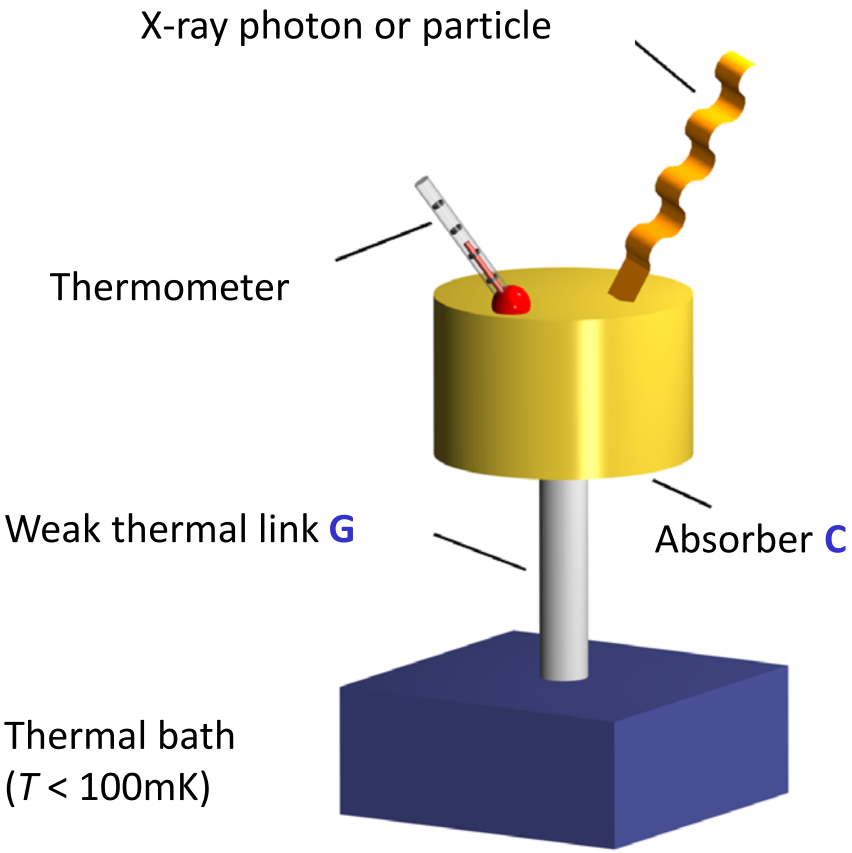


Magnetic Micro-Calorimeters for Atomic and Particle Physics

Andreas Fleischmann
Heidelberg University

micro-calorimeters



Thermal detectors !

Temperature change

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

Relaxation to bath temperature

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

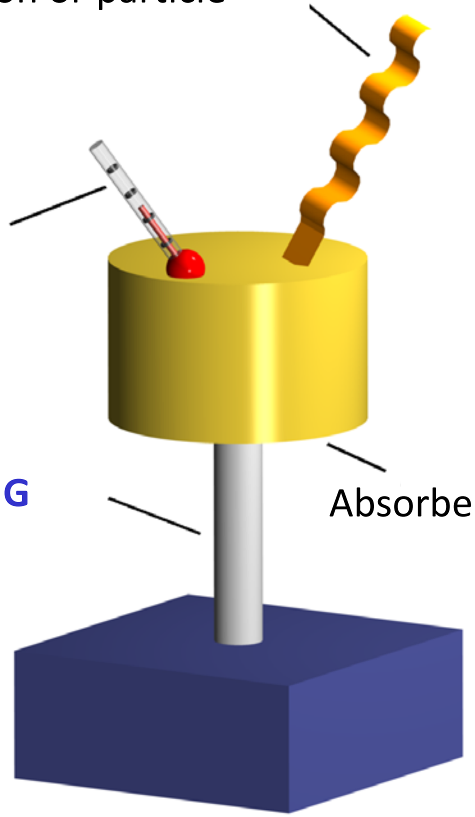
Operation at low temperature ($T < 0.1$ K):

small specific heat

large temperature change

small thermal noise

thermometer concepts



X-ray photon or particle

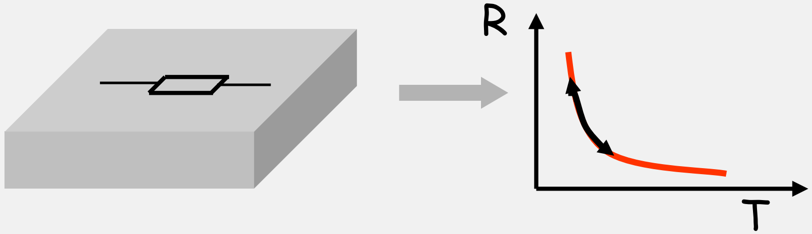
Thermometer

Weak thermal link **G**

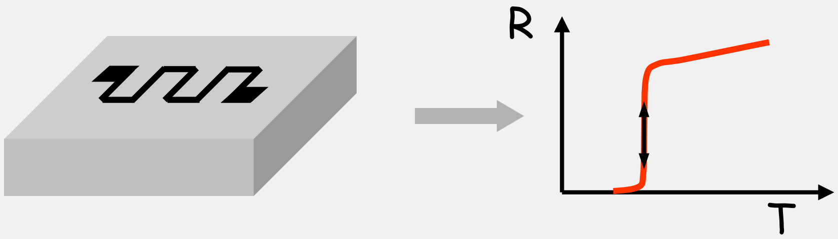
Absorber **C**

Thermal bath
($T < 100$mK)

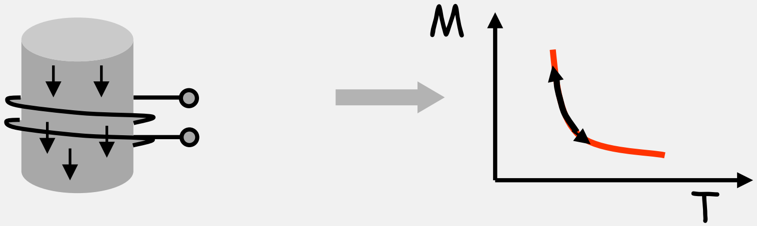
Resistance of highly doped semiconductors



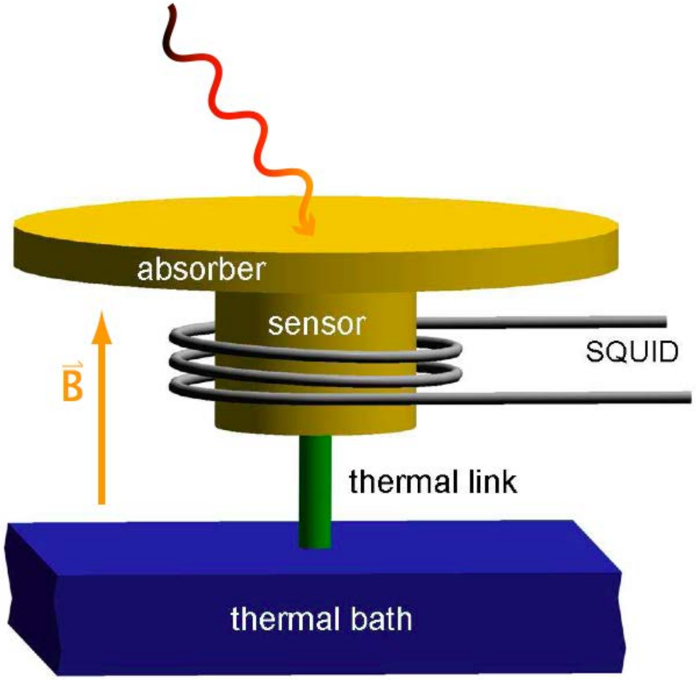
Resistance at superconducting transition,TES



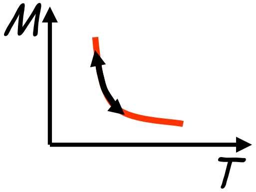
Magnetization of paramagnetic material



metallic magnetic calorimeters



paramagnetic sensor: **Au**:Er$_{500\text{ppm}}$, **Ag**:Er



signal size:

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

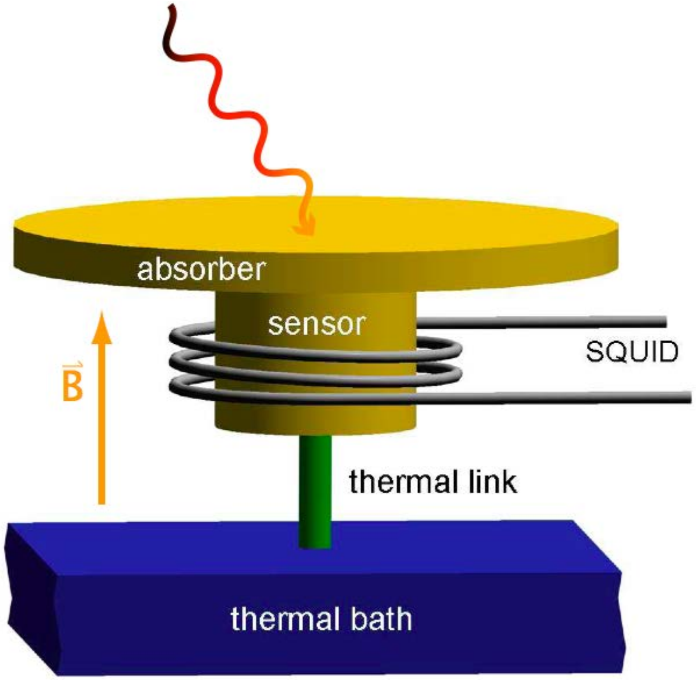
M and **C** of weakly interacting spins
well understood ➡ numerical optimization

main differences to calorimeters with resistive thermometers

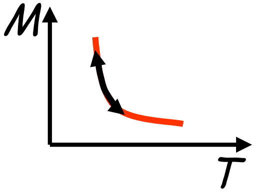
no dissipation in the sensor

no galvanic contact to the sensor

metallic magnetic calorimeters



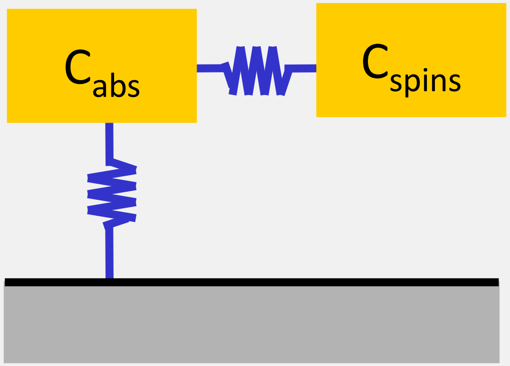
paramagnetic sensor: **Au**:Er$_{500\text{ppm}}$, Ag:Er



signal size:

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

Energy resolution --- Why ‚micro‘-calorimeter

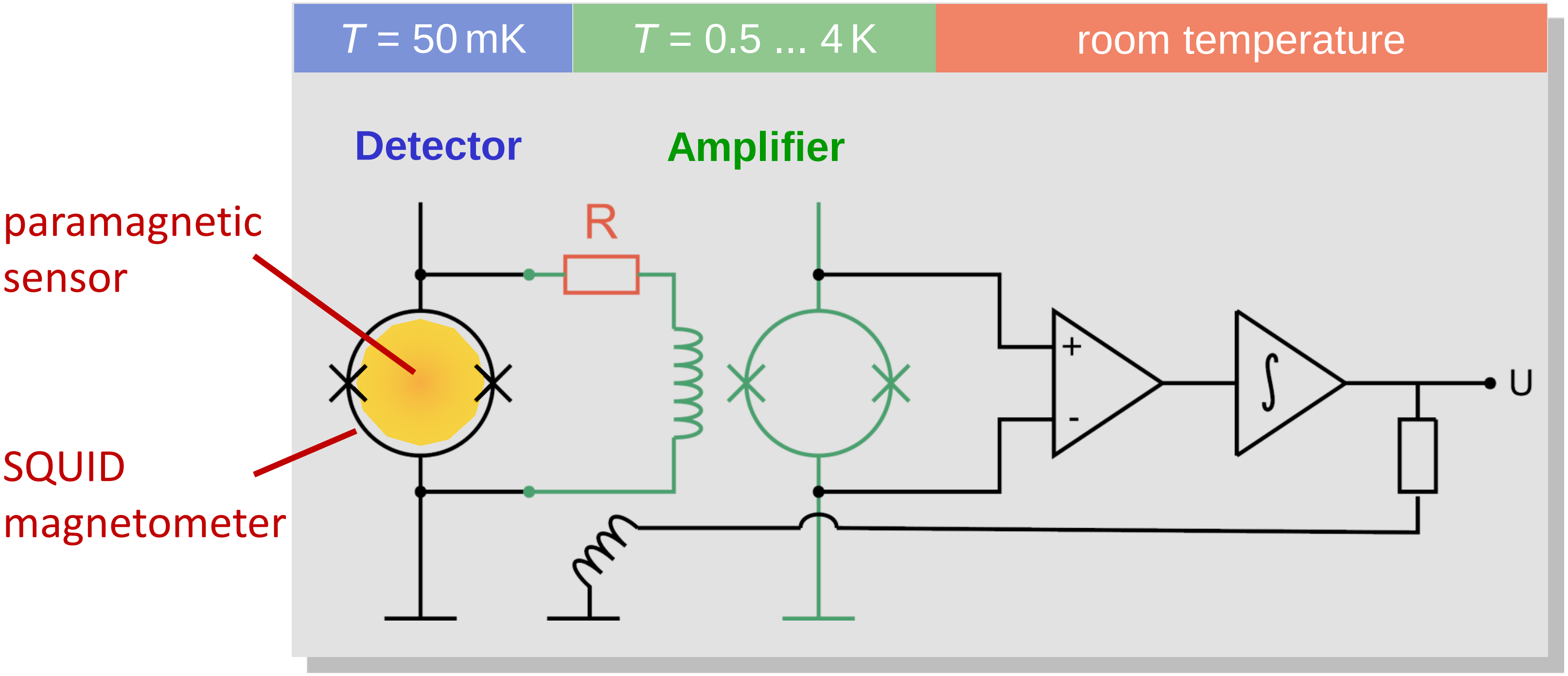


Thermal fluctuations of energy between absorber, thermometer and bath lead to

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

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

readout of magnetic calorimeters

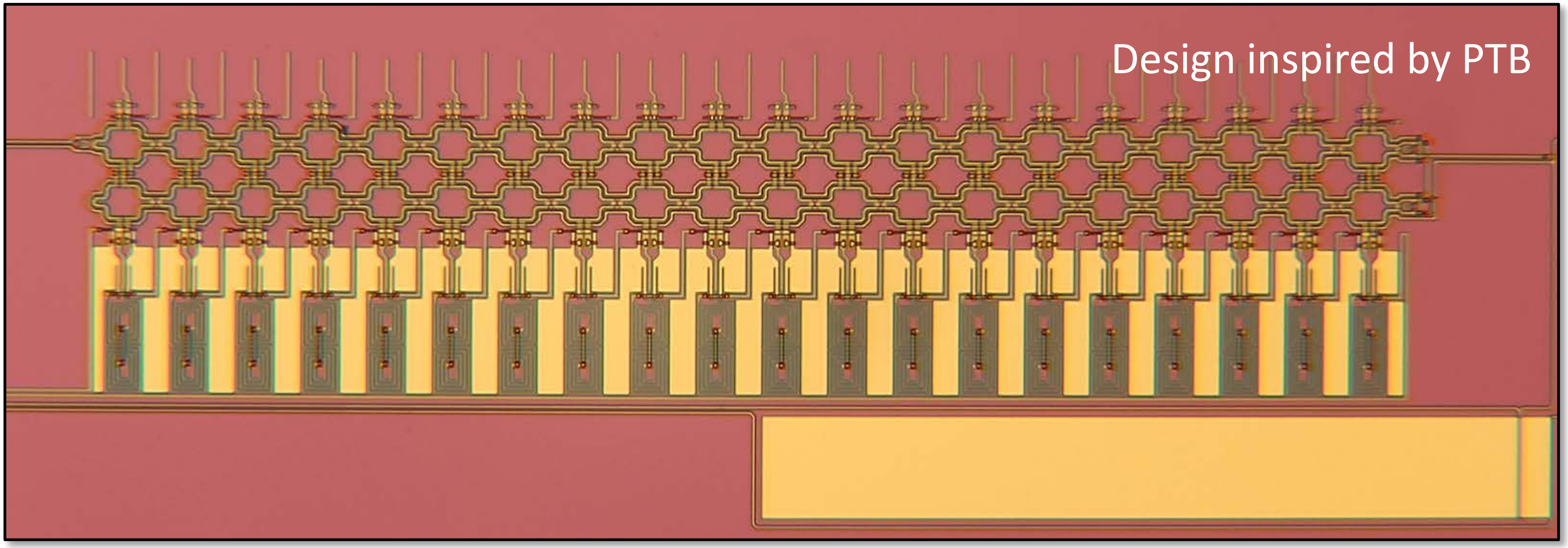


two-stage SQUID setup with flux locked loop to linearize the first stage SQUID

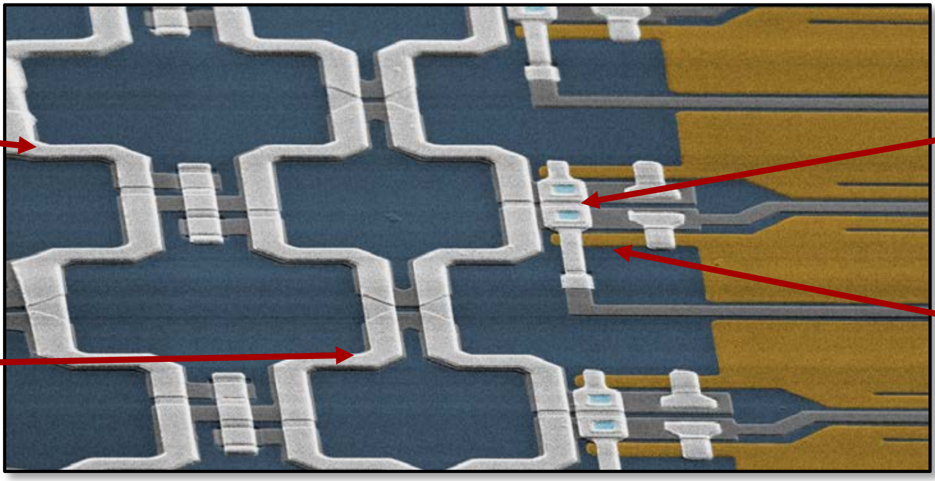
allows for:

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

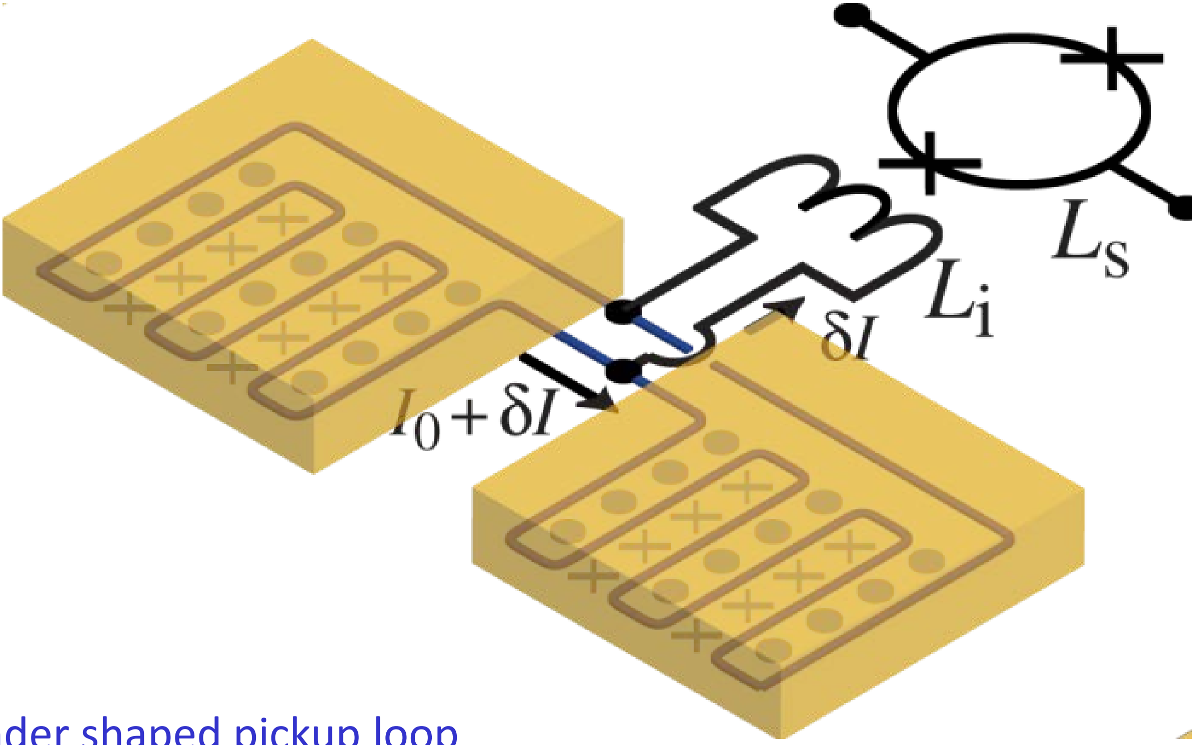
readout of magnetic calorimeters



Design inspired by PTB



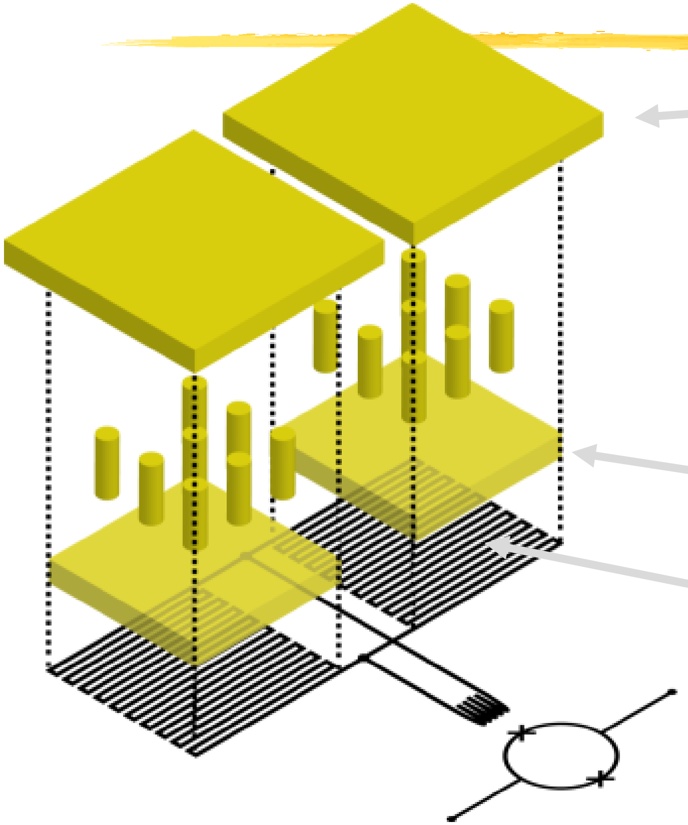
sensor geometry



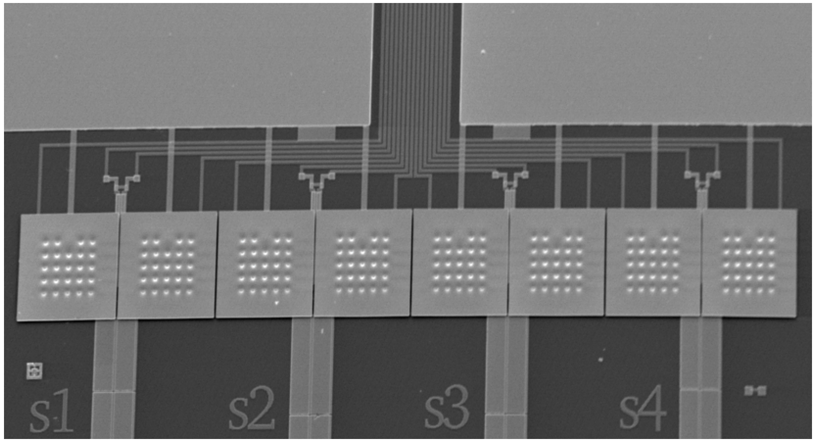
Present working horse:

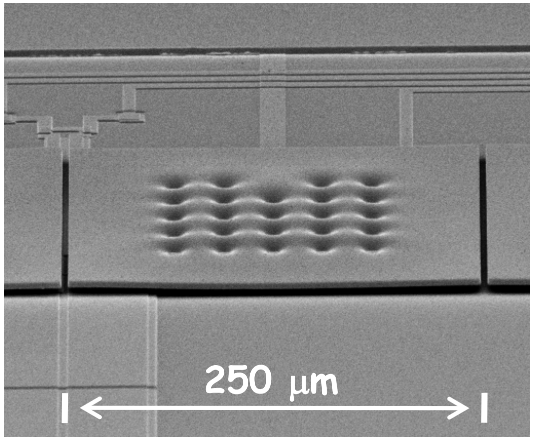
- planar *T*-sensor
- superconducting meander shaped pickup loop
- persistent current to generate B-field
- transformer coupled to SQUID
- two pixels show signals of opposite polarity
  -> fairly insensitive to chip *T*

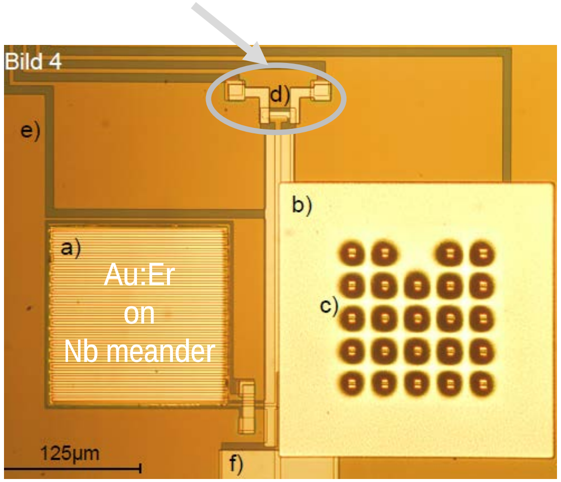
maXs-20: 1×8 array for soft x-rays



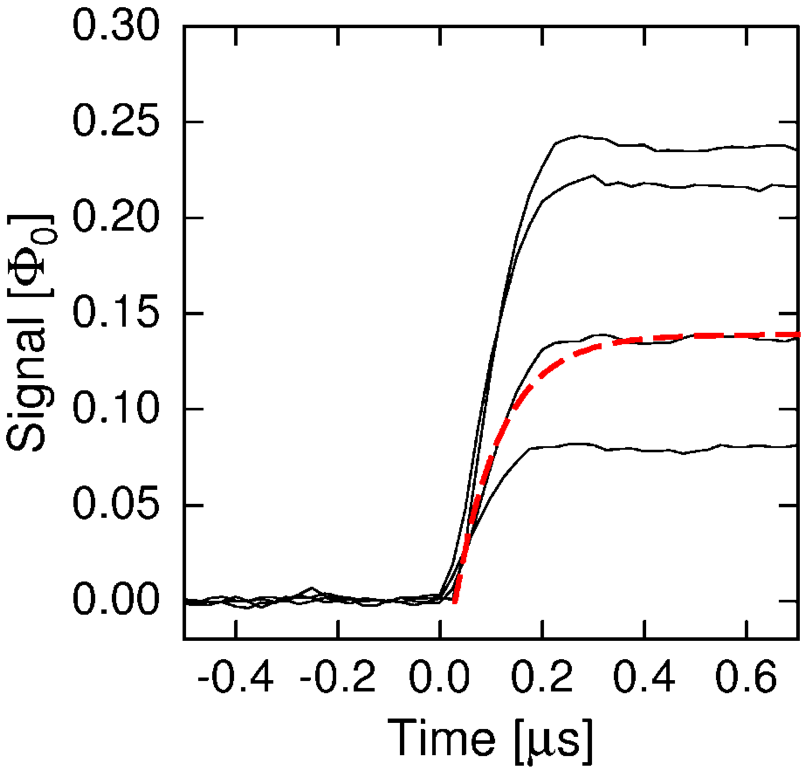
- 1×8 x-ray absorbers
  - **250µm×250 µm** gold**, 5 µm thick**
  - **98%** qu.-eff. @ 6 keV
  - electroplated into photoresist mold
  - **mech/therm contact to sensor by stems** to prevent loss of initially hot phonons
- Au:^{166}Er$_{300ppm}$ temperature sensors
- Superconducting meander shaped pickup 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

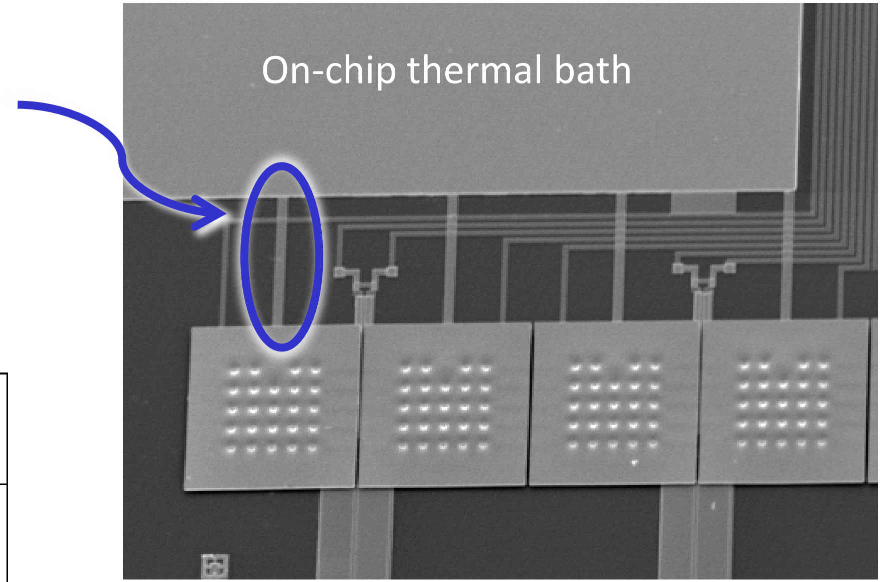
signal decay

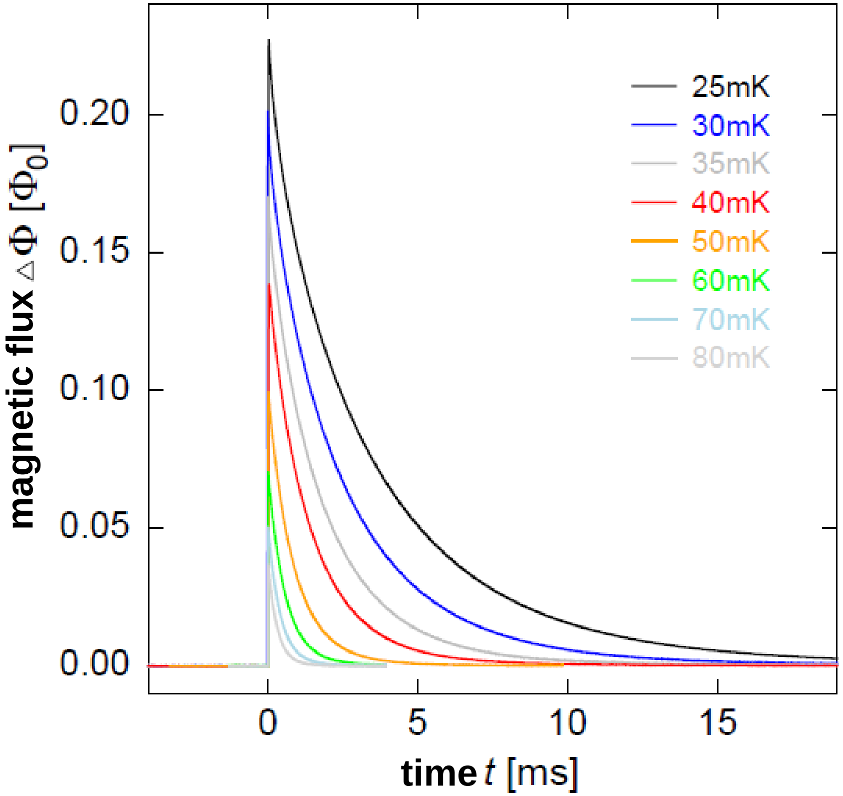
- **decay time**

  adjusted by sputtered thermal link (Au)

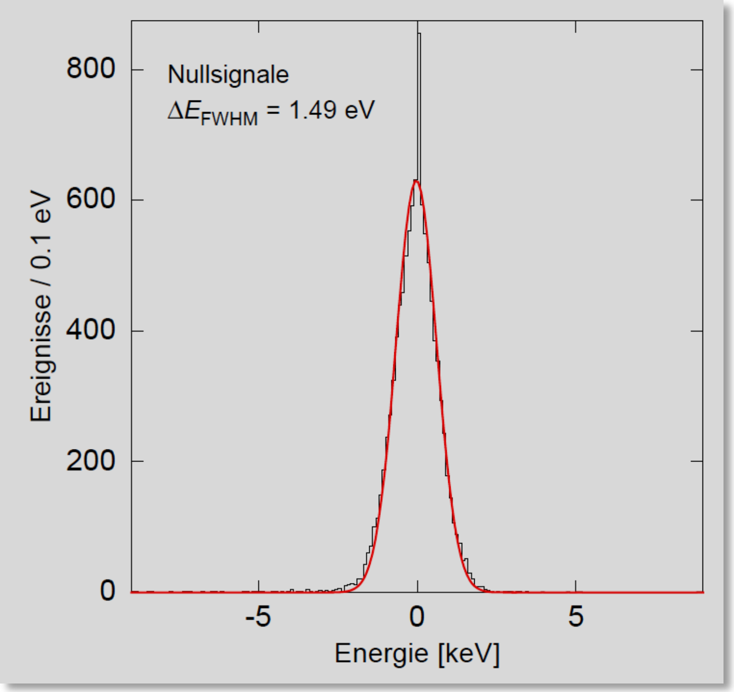
  here: **3 ms @ 30 mK**

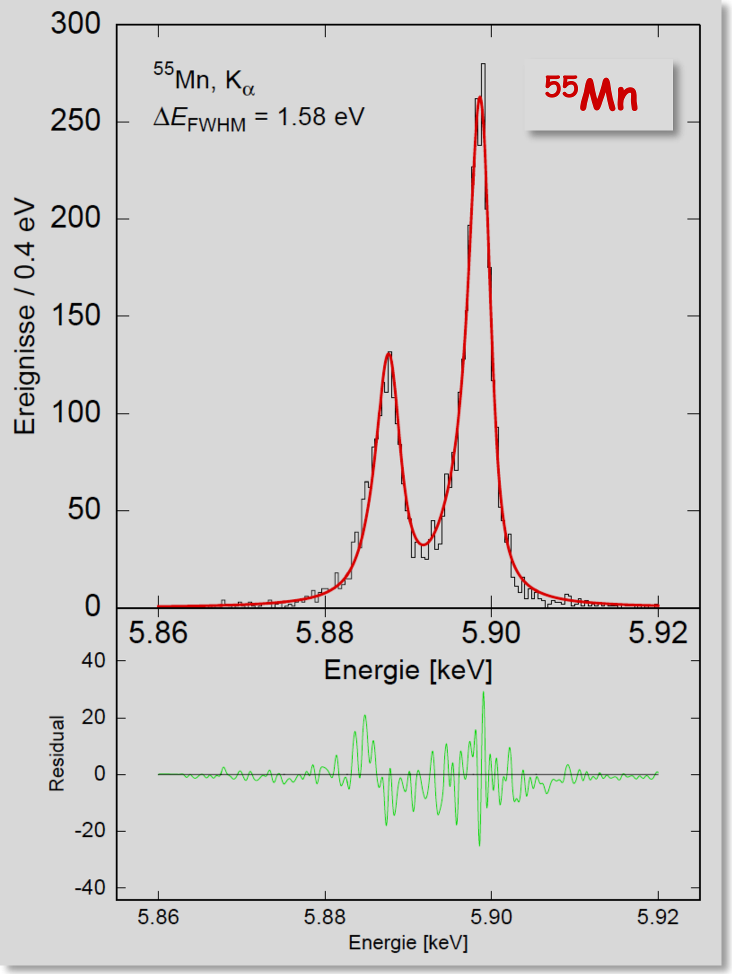
- nearly single exponential decay





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



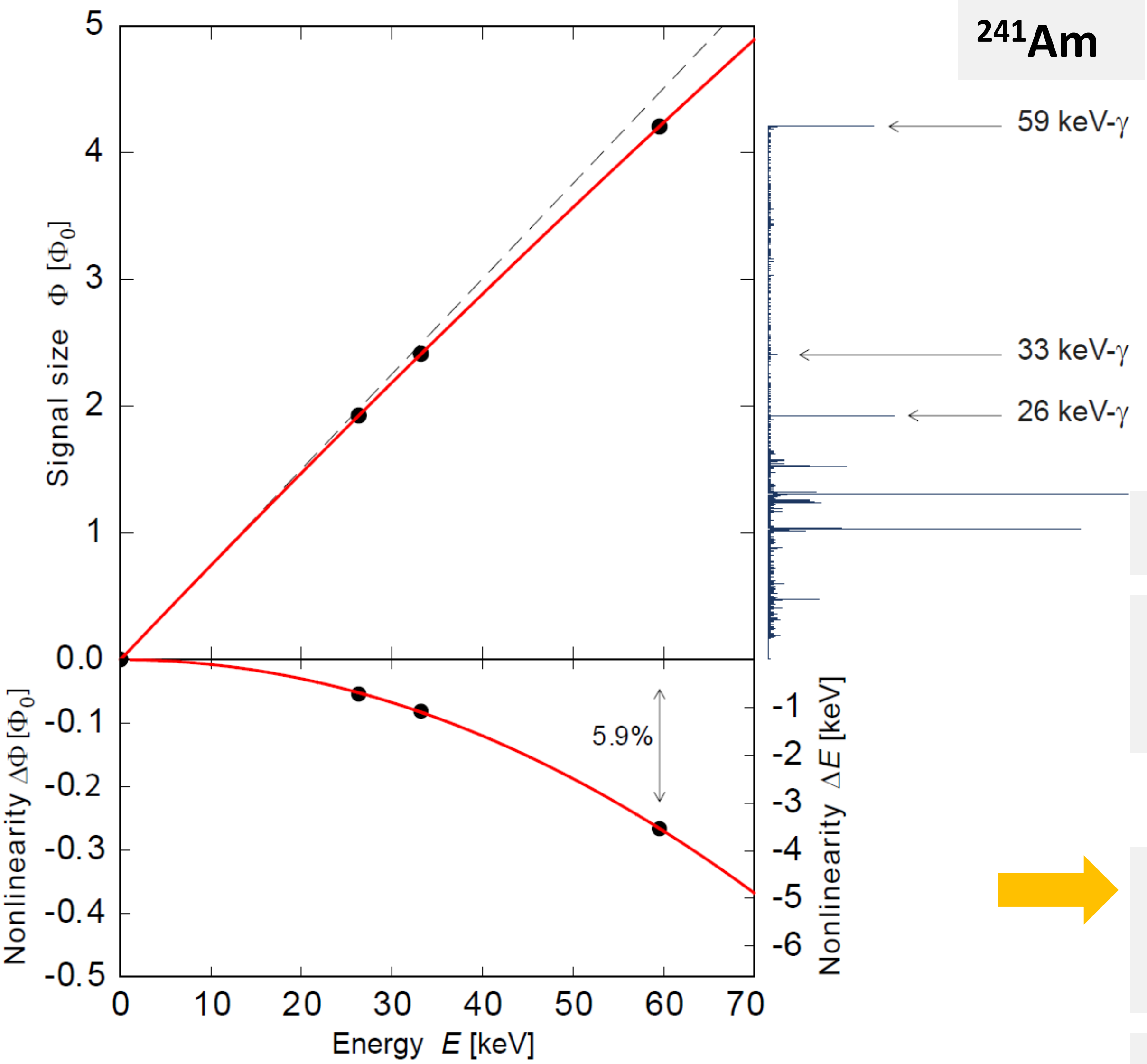


ΔE_{FWHM} = 1.5 eV @ 0 keV

ΔE_{FWHM} = 1.6 eV @ 6 keV

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

maXs-20: no saturation up to 60 keV



non-linearity: 6% @ 60 keV

as expected from

thermodynamical properties

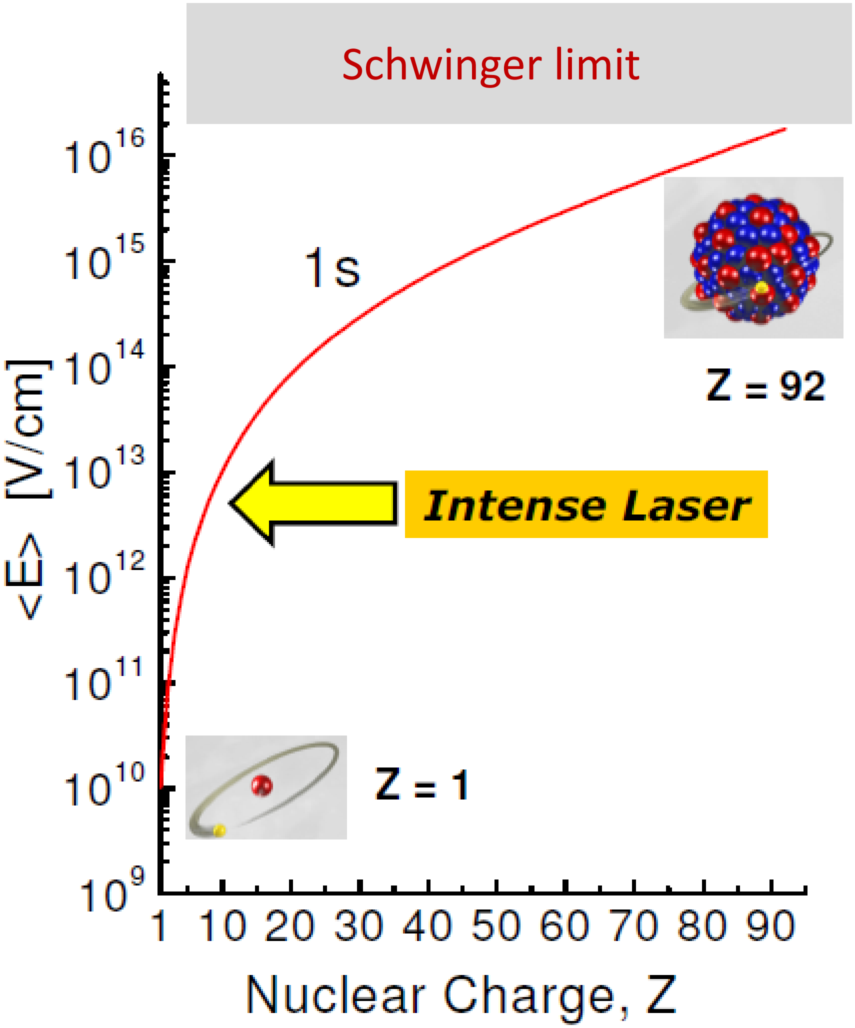
ΔE_{FWHM}= 2eV @ 60 keV

in reach !

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

precision X-ray spectroscopy on highly charged ions

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



Precision tests of QED in high fields

- Lamb-shift of hydrogen-like Uranium
  U^{91+} , Xe^{53+}, …
- Correlations of highly relativistic electrons ín He-like ions

- e.g. H-like Uranium:

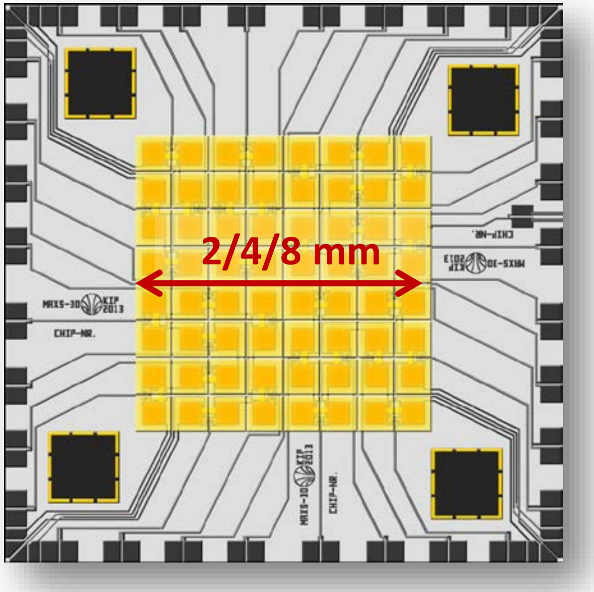
Lyman-α: 100 keV

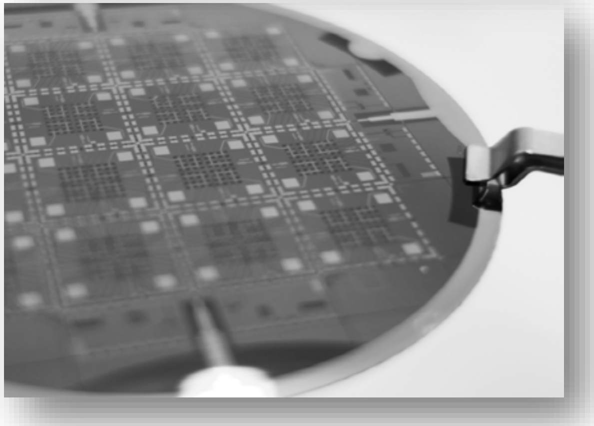
1s Lamb: 0.5 keV ± 0.005keV

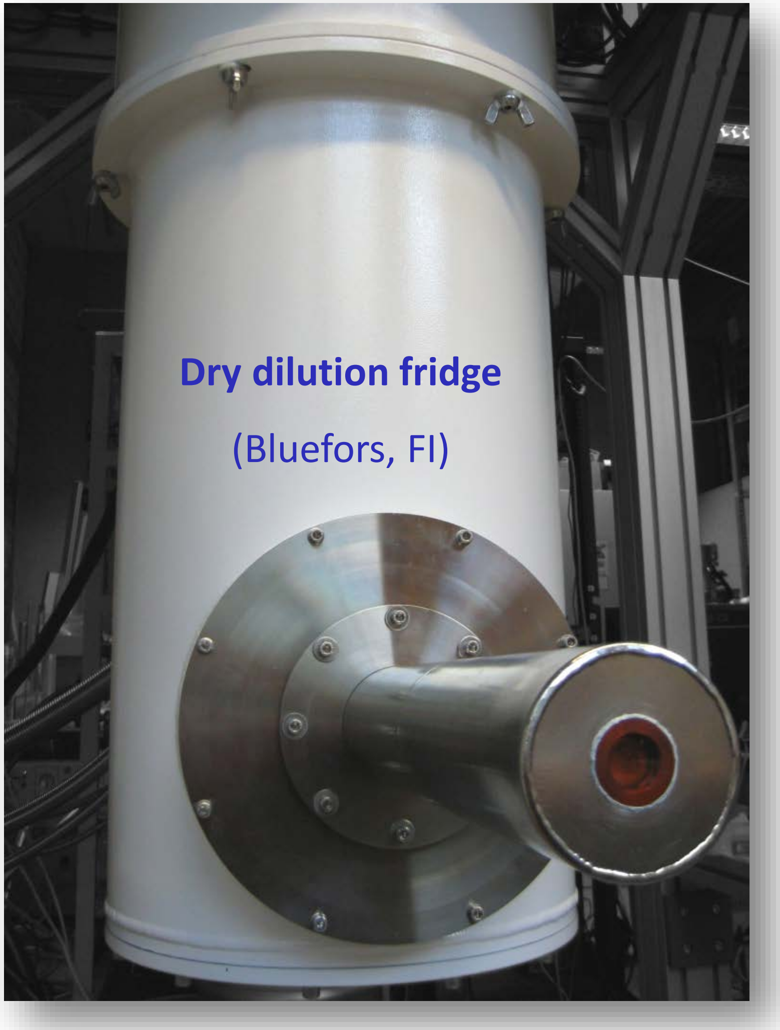
theory challenging, as Zα→1

8×8 arrays of 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



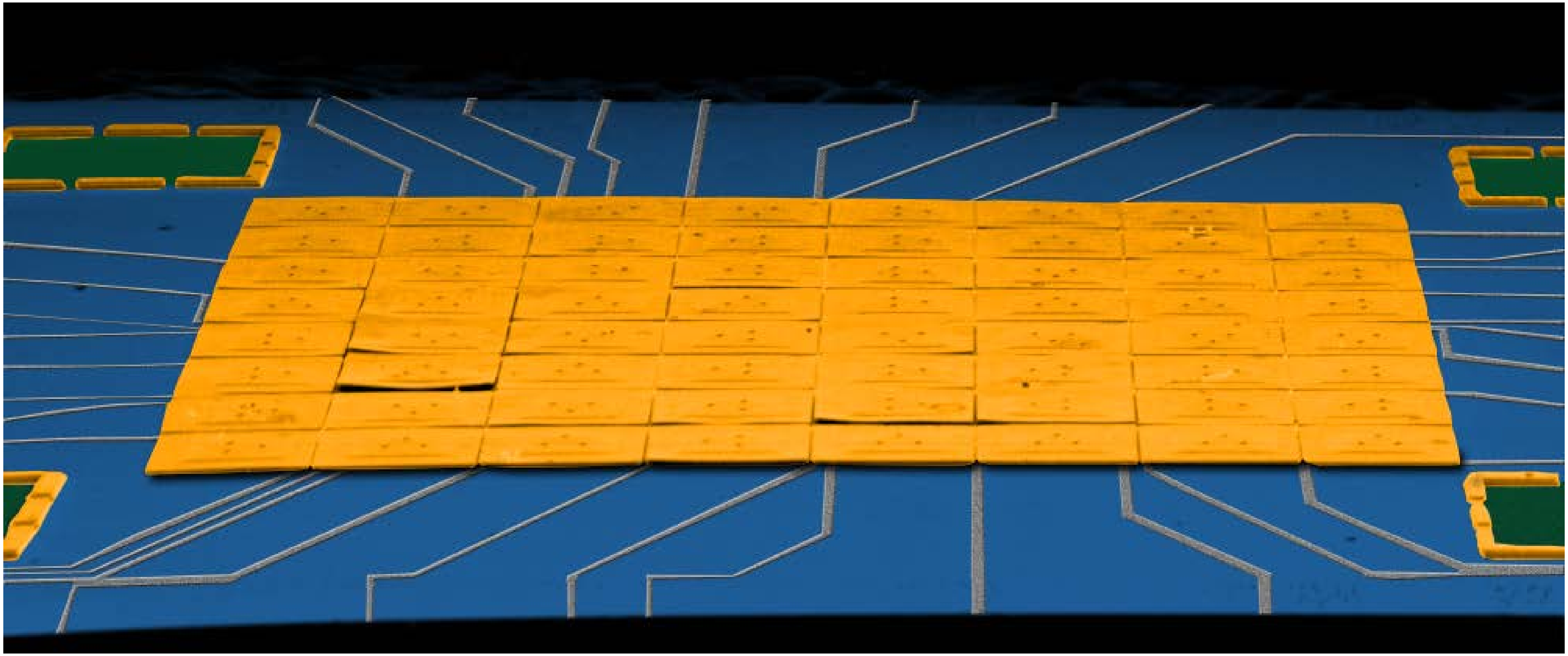



Dry dilution fridge

(Bluefors, FI)

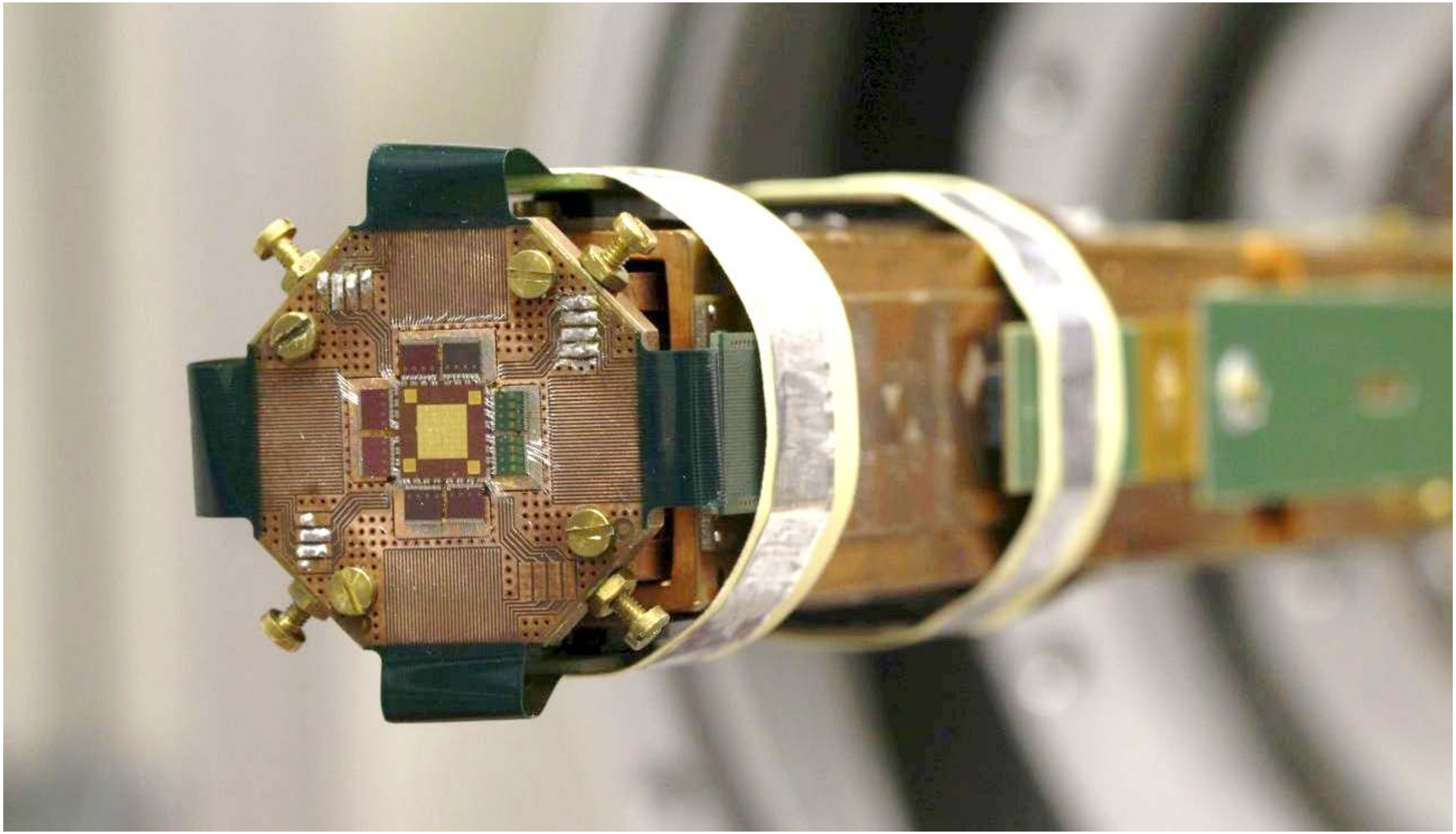
First maXs-30 chips now used

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

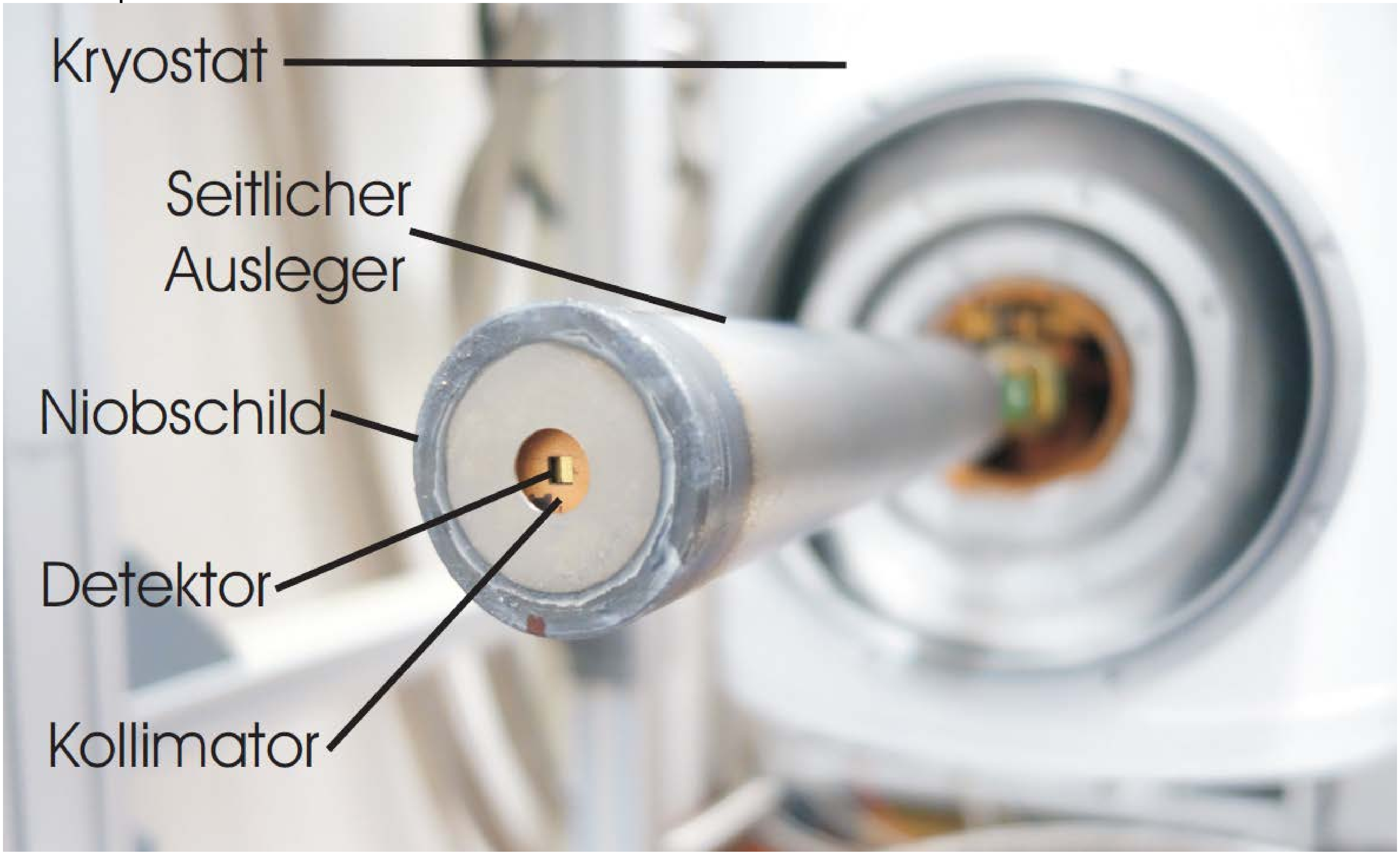


maXs-30

maXs-30 mounted on coldfinger of a dry dilution fridge



maXs-30


Kryostat
Seitlicher Ausleger
Niobschild
Detektor
Kollimator

Hydrogen-like Xenon

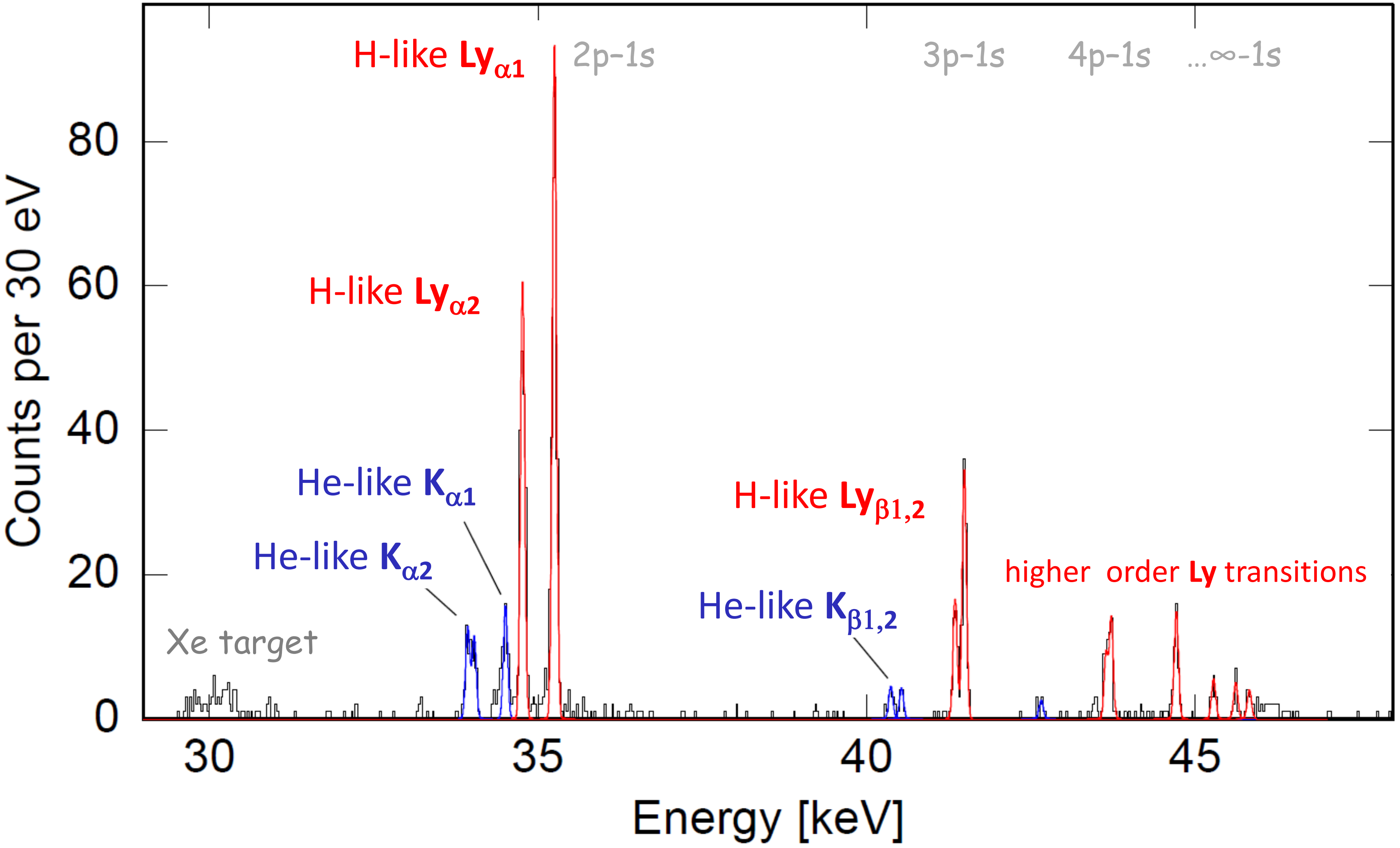
Heidelberg University, Friedrich-Schiller University Jena and Helmholtz-Institute Jena for SPARC

crossing bare Xe^{54+} ions at 50 MeV/u with Xe gas jet

Experimental Storage Ring (ESR) at GSI, Darmstadt, Germany

Hydrogen-like Xenon Helium-like Xenon

bare Xe onto Xe gas jet: **Xe^{54+}** (50 MeV/u) → **Xe**



MOCCA: 4k-pixel molecule camera

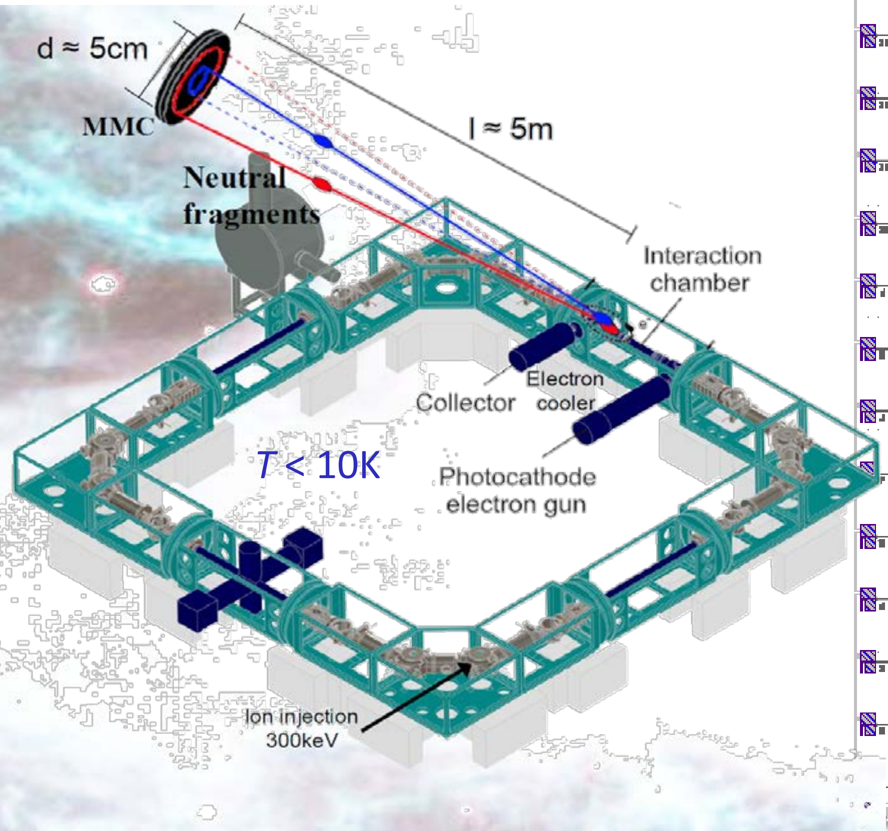
to study reaction cross sections of molecular ions in cold interstellar plasmas

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

Position and energy resolved detection

of neutral molecular fragments

after neutralizing with an electron in the e-cooler



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

MOCCA:

- 44.8mm × 44.8mm
- 64 × 64 pixels
- resolution: ΔE = 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

How to weigh keV neutral atoms/molecules?

Mass from kinetic energy!

beam of
~ keV molecular ions

$v_{\mathrm{frag}} \approx v_{\mathrm{beam}}$

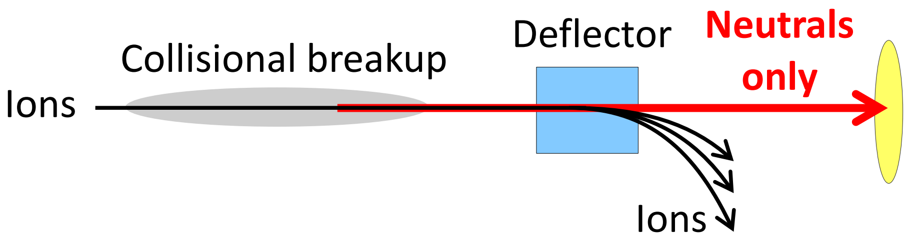
measure
kinetic energies
of products

Fragmentation
reaction

$$\boxed{E_{\mathrm{kin}}^{\mathrm{lab}} \cong \frac{1}{2} m_{\mathrm{frag}} v_{\mathrm{beam}}^{2}}$$

Neutral molecular fragments on a micro-calorimeter

CH_3^+ @ 150 keV: breakup in residual gas collisions



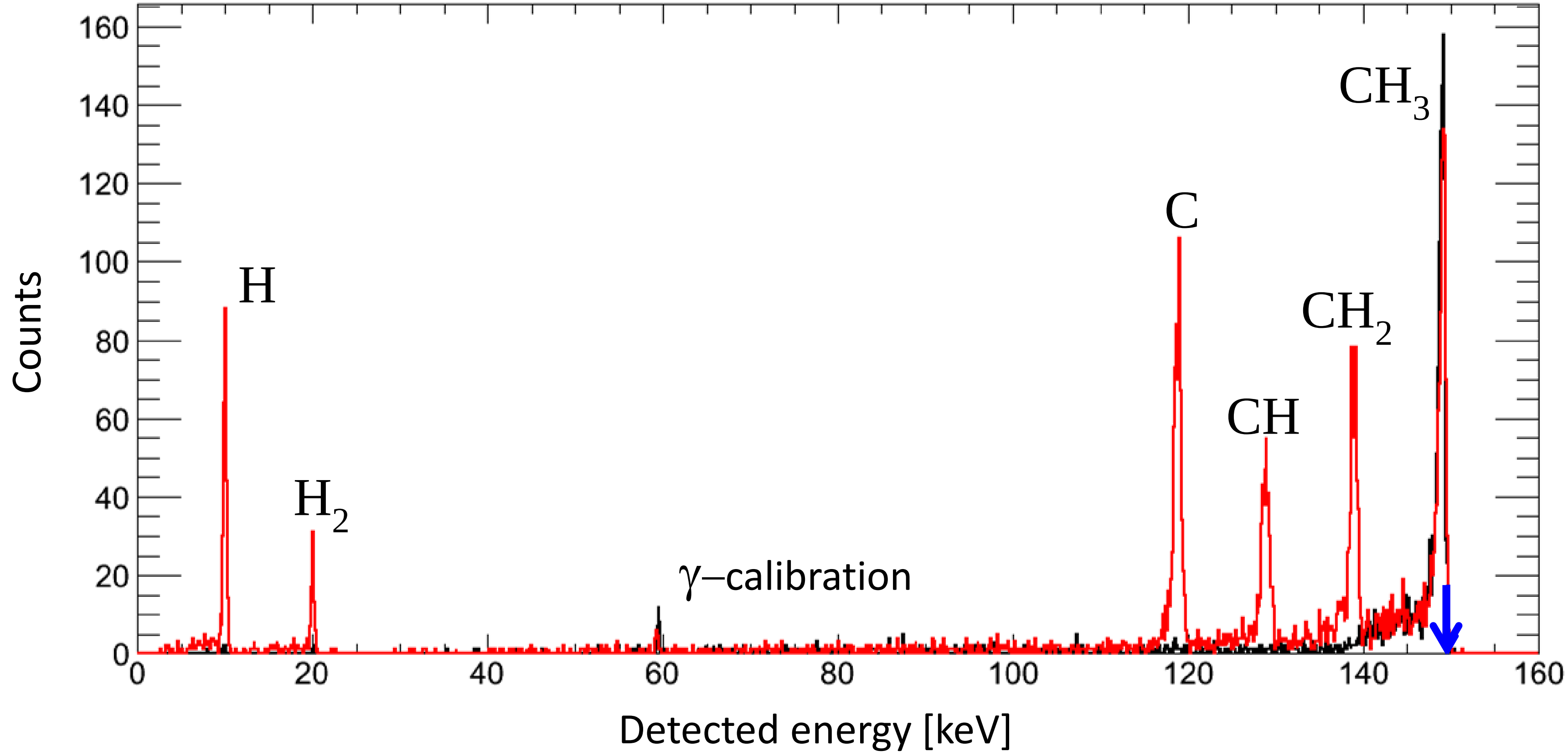
Collisional breakup

Deflector

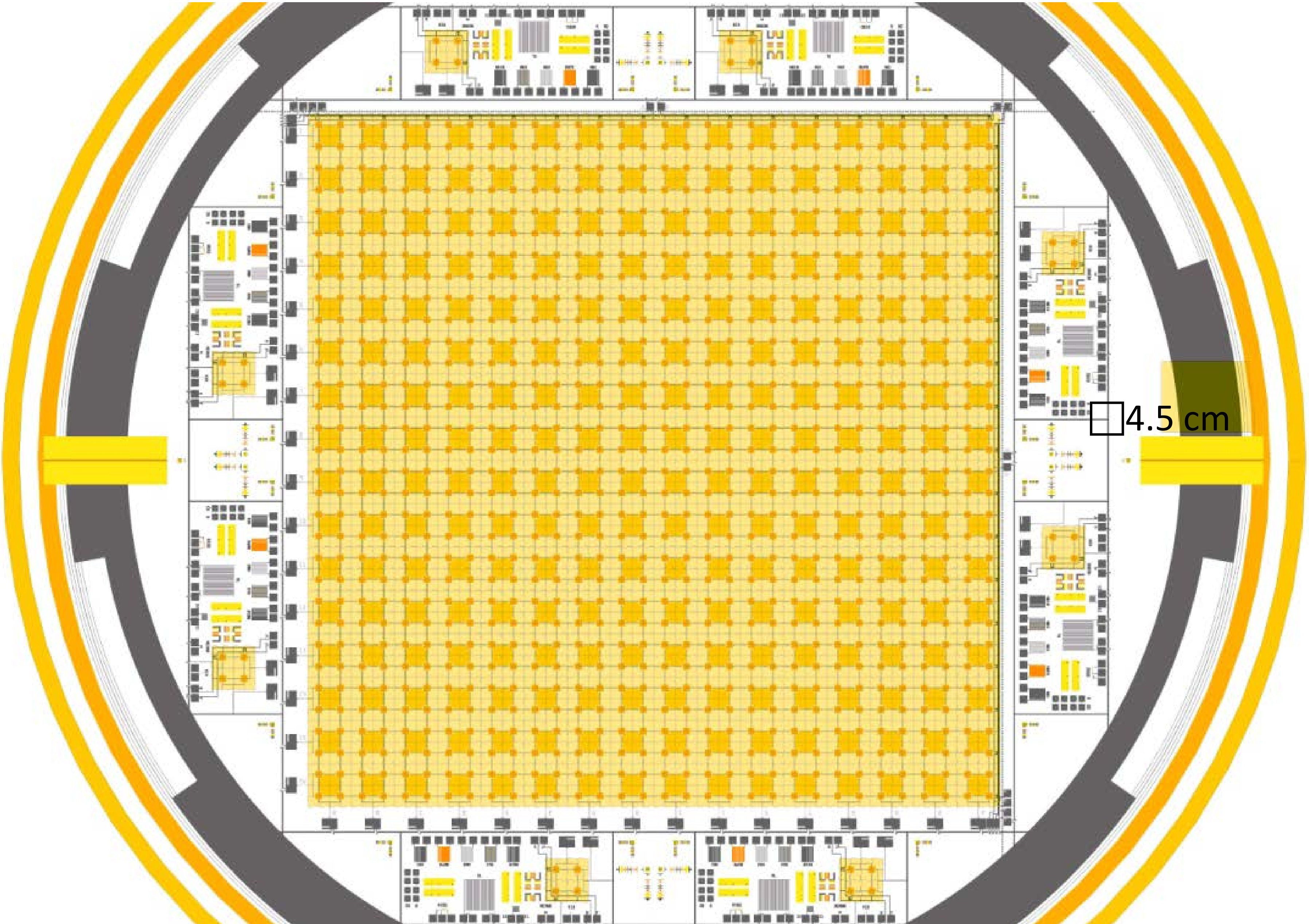
Neutrals only

Ions

Ions



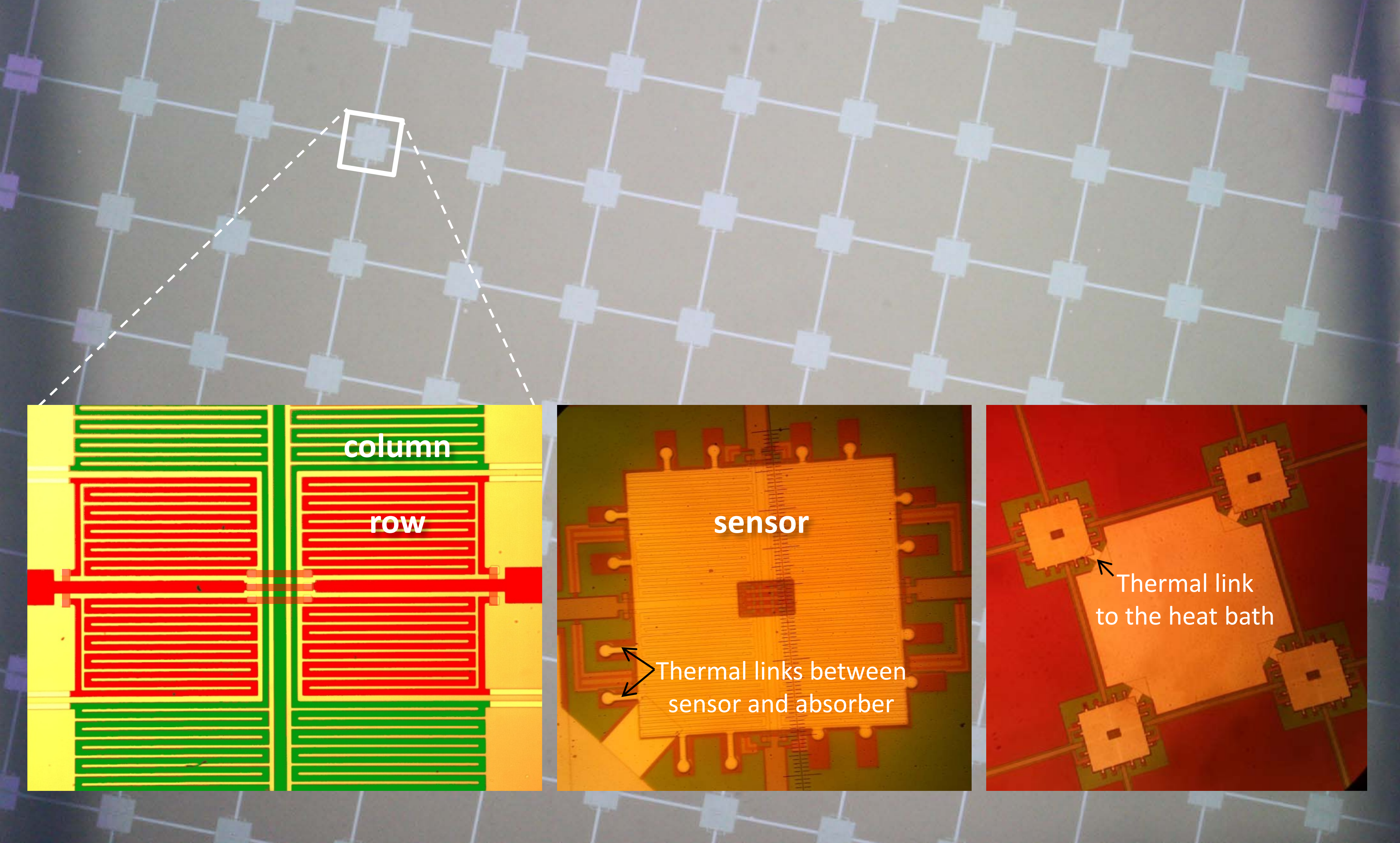
MOCCA: a 4k-pixels molecule camera



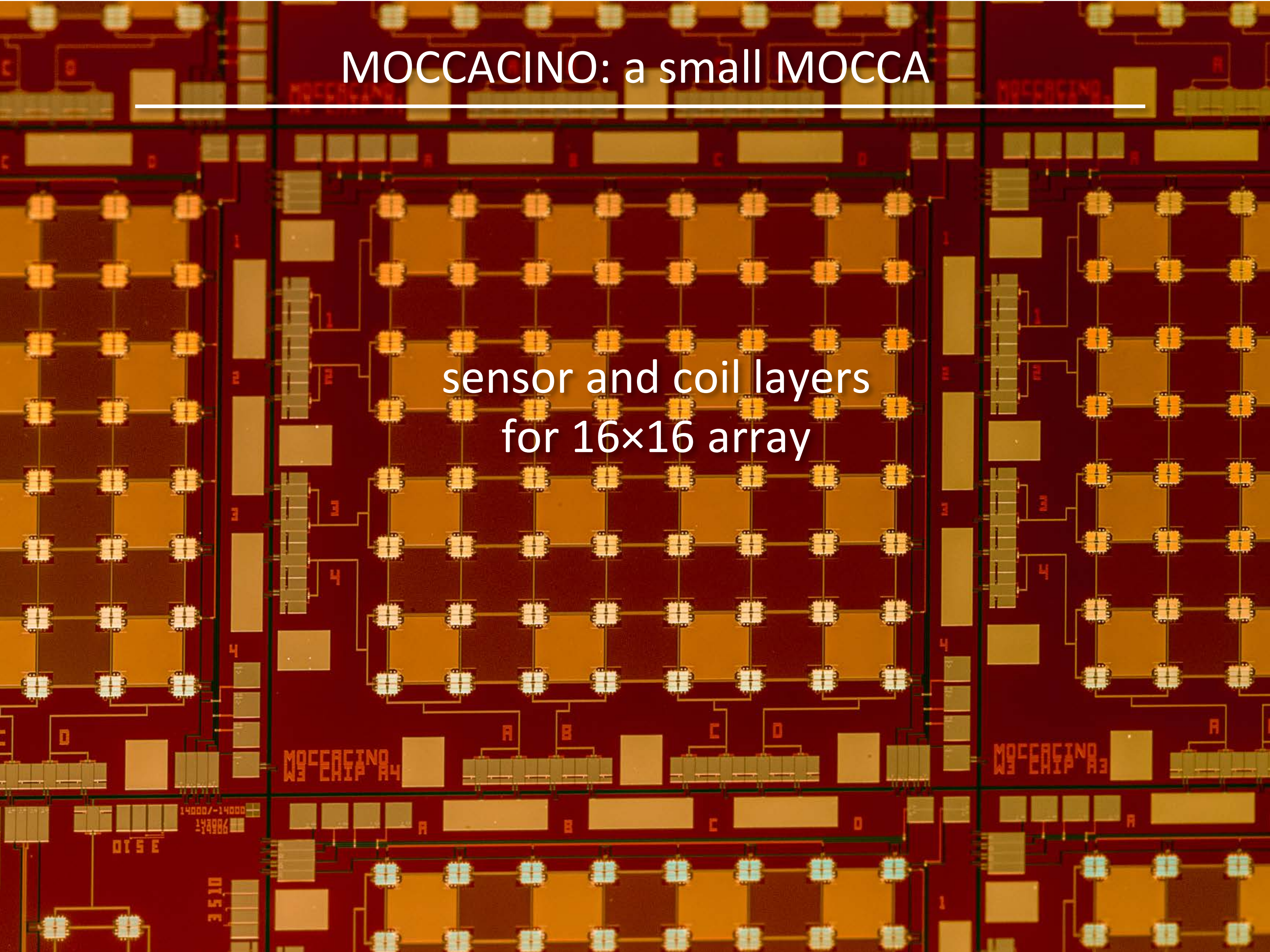
□4.5 cm

Presently in fab: MOCCA´s 2048 pickup coils

- Failure tolerant design

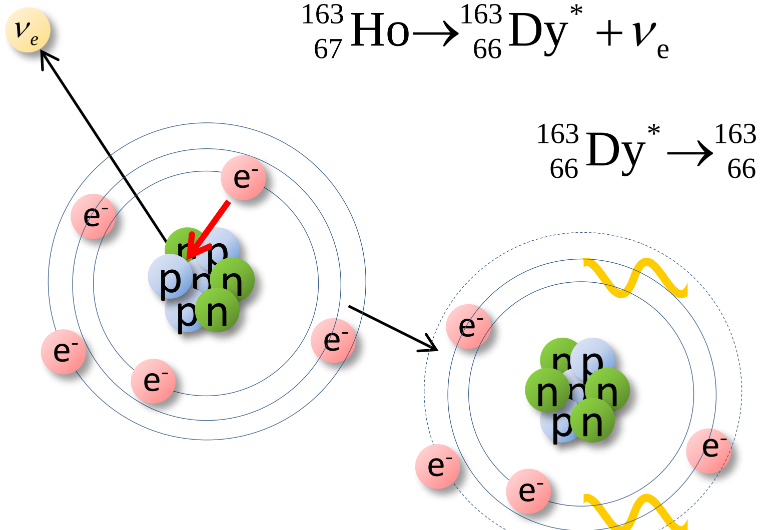


MOCCACINO: a small MOCCA



sensor and coil layers
for 16×16 array

the neutrino mass experiment ECHo



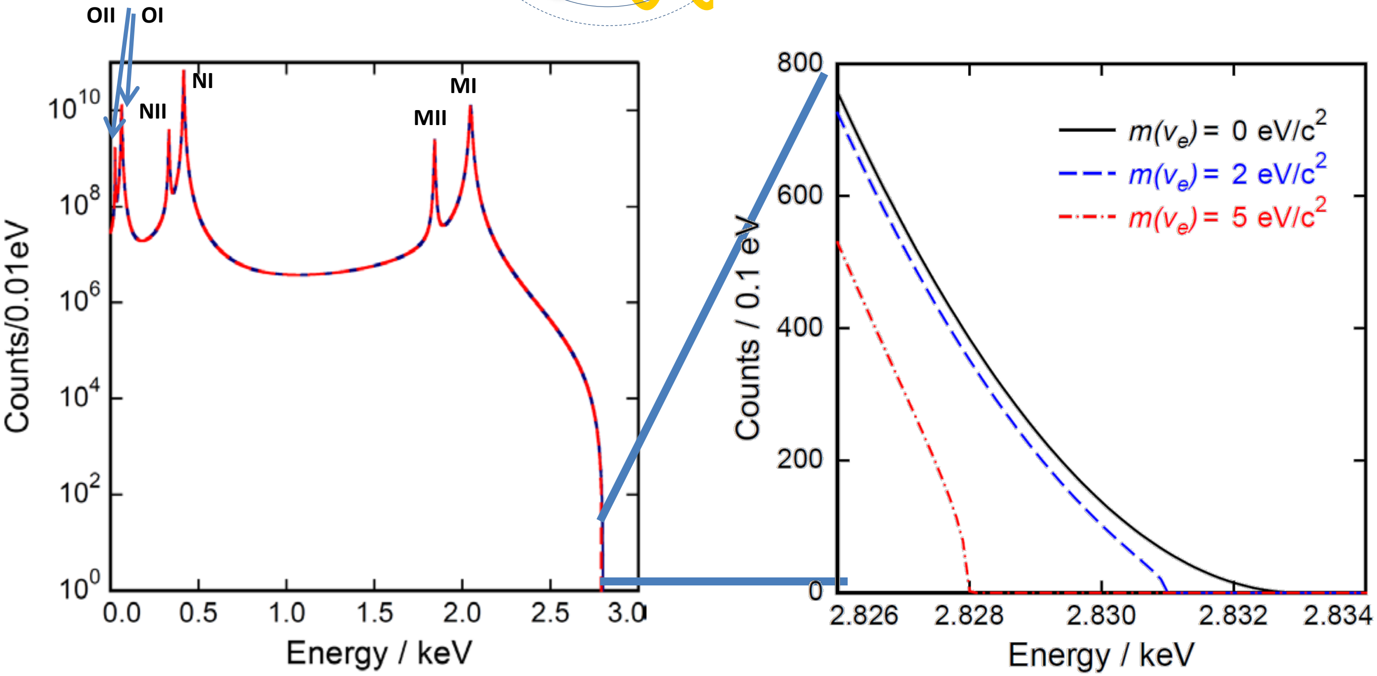
$$^{163}_{67}\mathrm{Ho} \rightarrow {}^{163}_{66}\mathrm{Dy}^{*} + \nu_{\mathrm{e}}$$

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

Implant EC-decaying Holmium-163 into the detector

Spectrum is a spectrum of binding energies of the captured electrons

Endpoint depends on neutrino mass!



requirements for sub-eV sensitivity in ECHo

Statistics in the end point region

- $N_{ev} > 10^{14}$ → **A ≈ 1 MBq**

Unresolved pile-up ($f_{pu} \sim a \cdot \tau_r$)

- **$f_{pu} < 10^{-5}$**
- $\tau_r < 1$ µs → a ~ 10 Bq
- 10^5 pixels → **multiplexing**

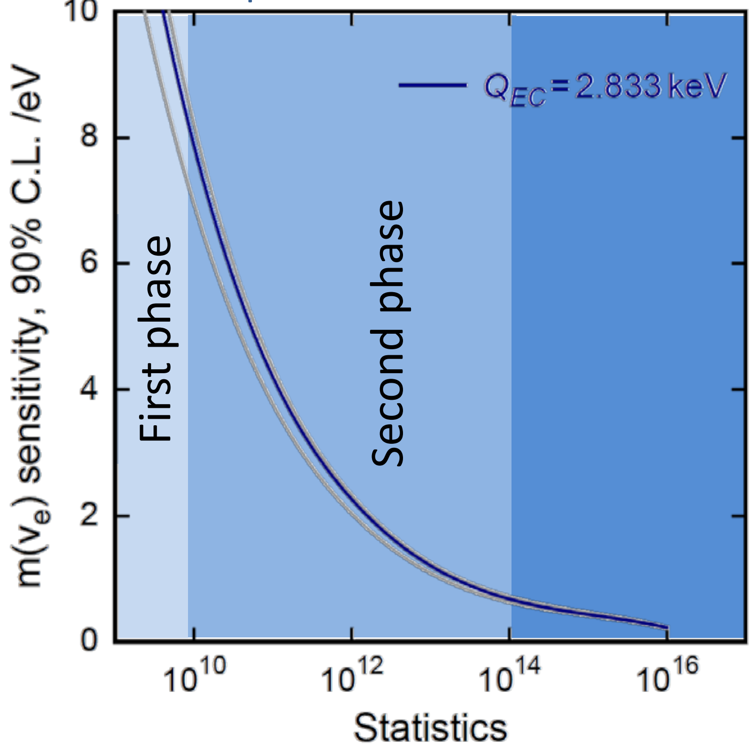
Precision characterization of the endpoint region

- **$\Delta E_{FWHM} < 3$ eV**

Background level

- **$< 10^{-5}$ events/eV/det/day**

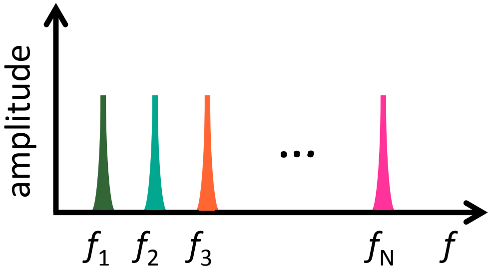
$f_{pu} = 10^{-6}$ $\Delta E_{FWHM} = 2$ eV



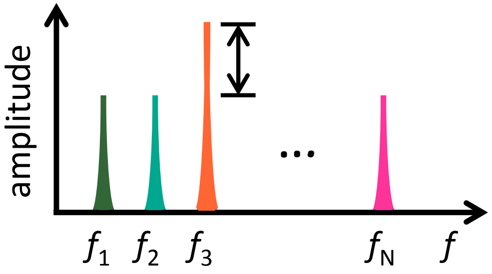
The ECHo Collaboration, *EPJ-ST* **226** 8 (2017) 1623

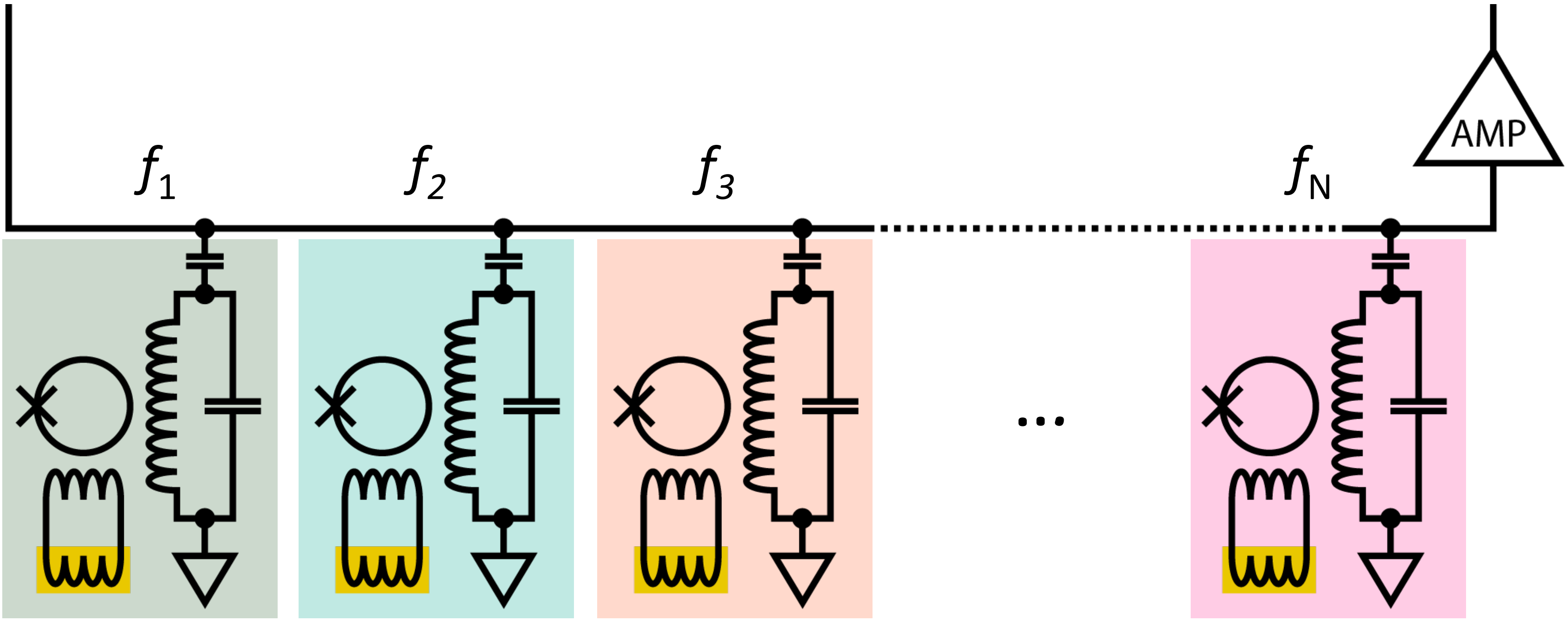
microwave SQUID multiplexer (μMUX)

as pioneeered by NIST group



event in Ch 3

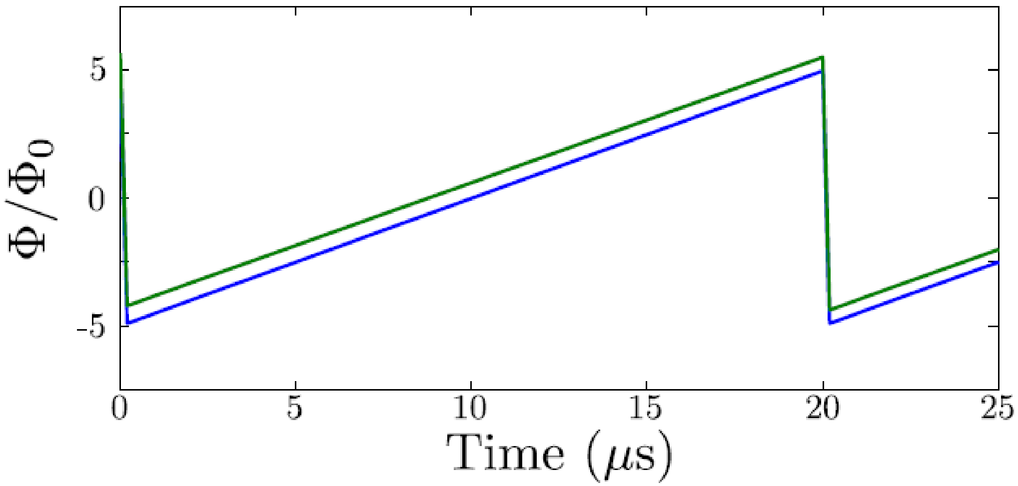




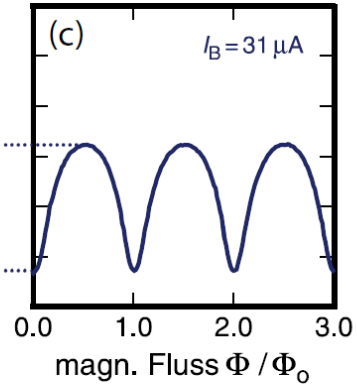
array readout using only one HEMT amplifier and two coaxes

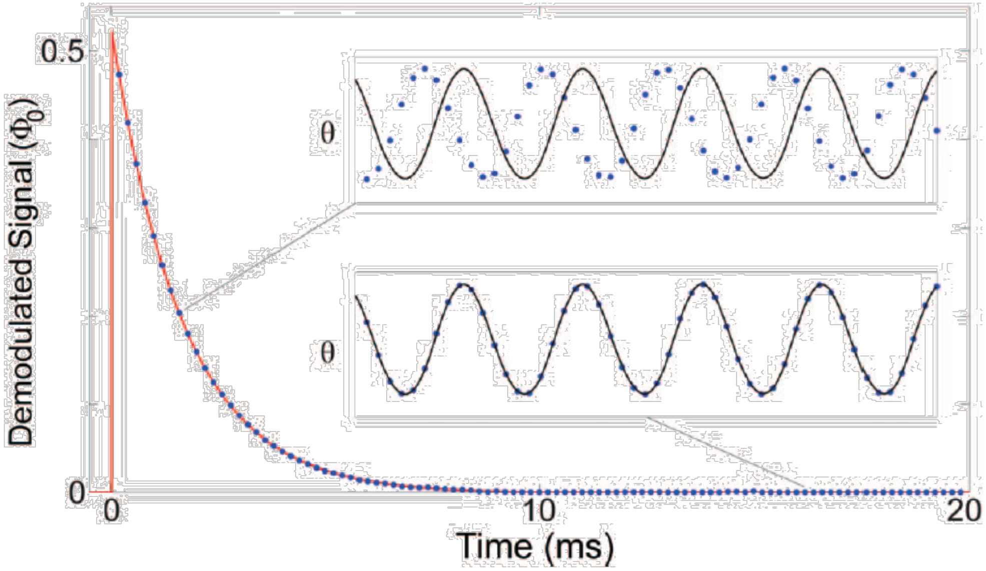
flux ramp modulation

idea: provide common flux ramp to all SQUIDs



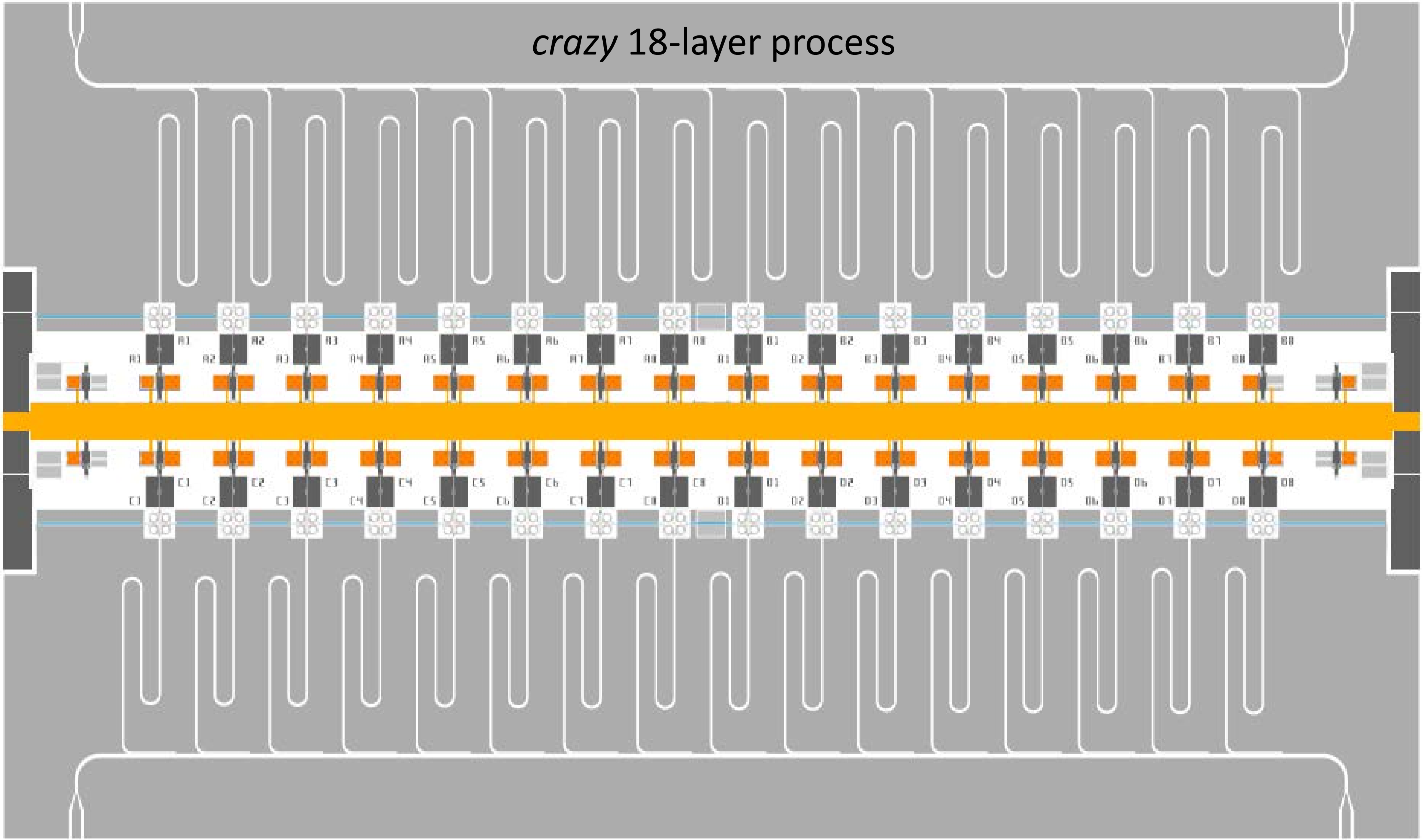
periodic modulation
of the SQUID response





signal can be measured
as a phase change

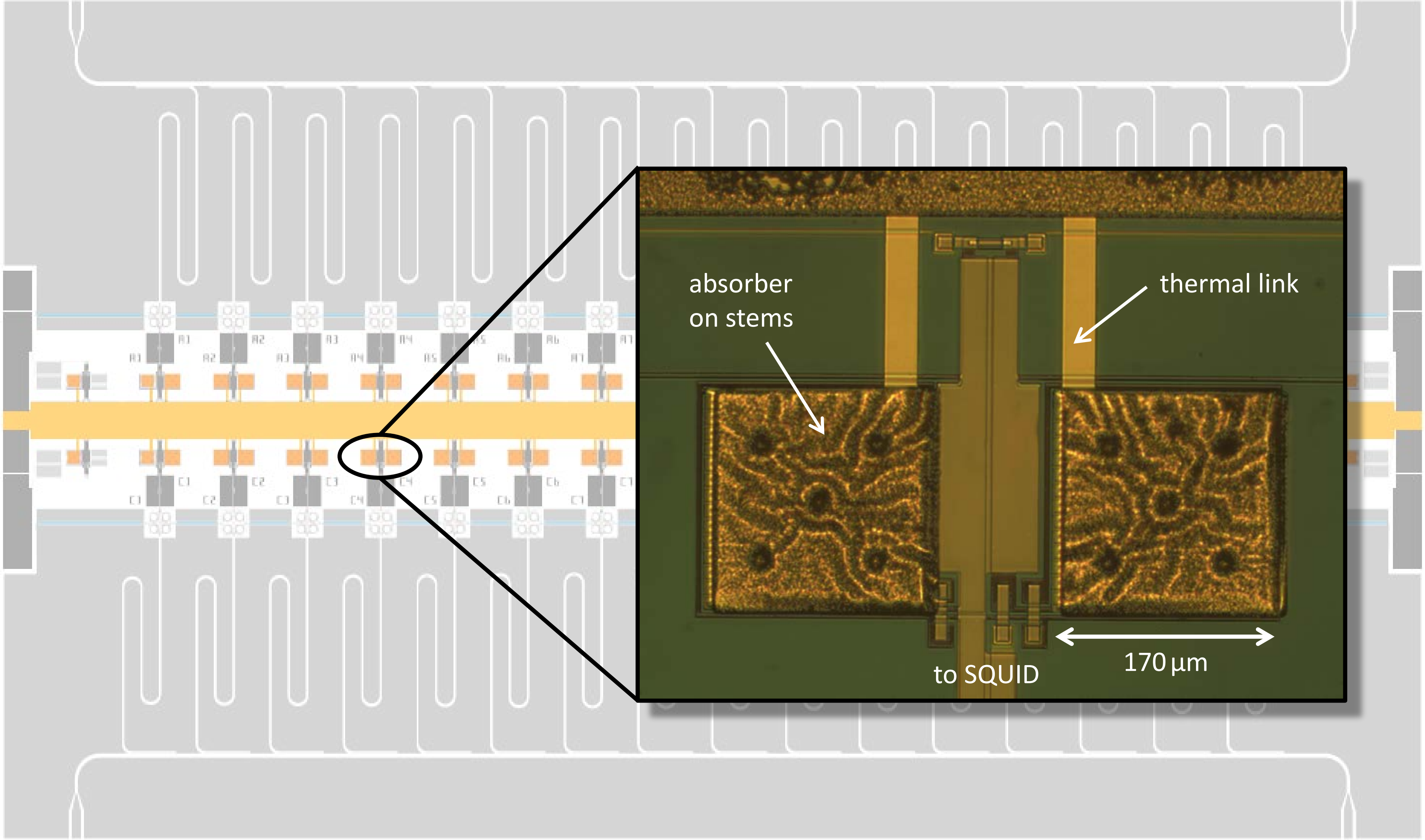
64 pixel detector array with integrated µMUX readout



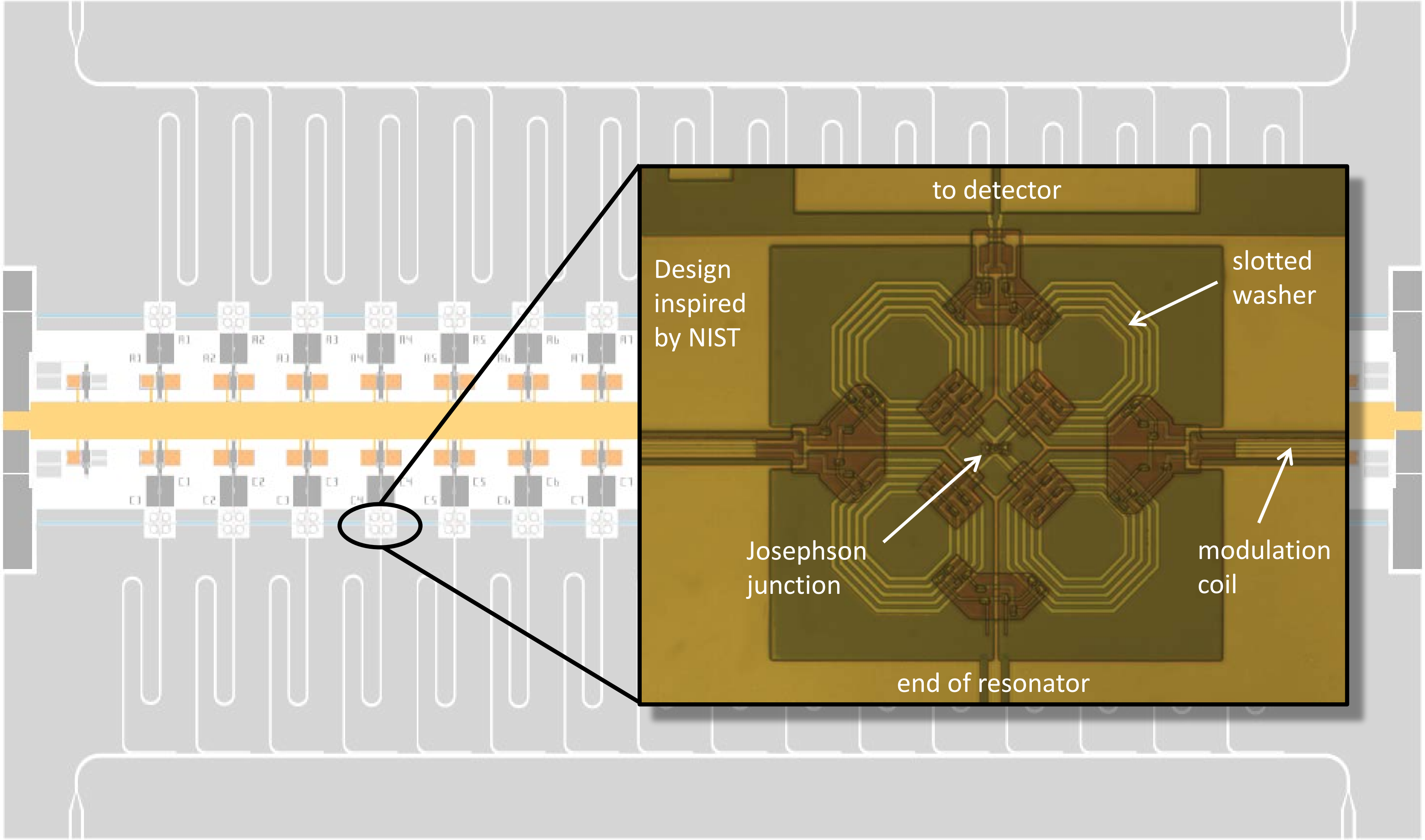
crazy 18-layer process

S.K. *et al.*, J. Low. Temp. Phys. **176** (2014) 426

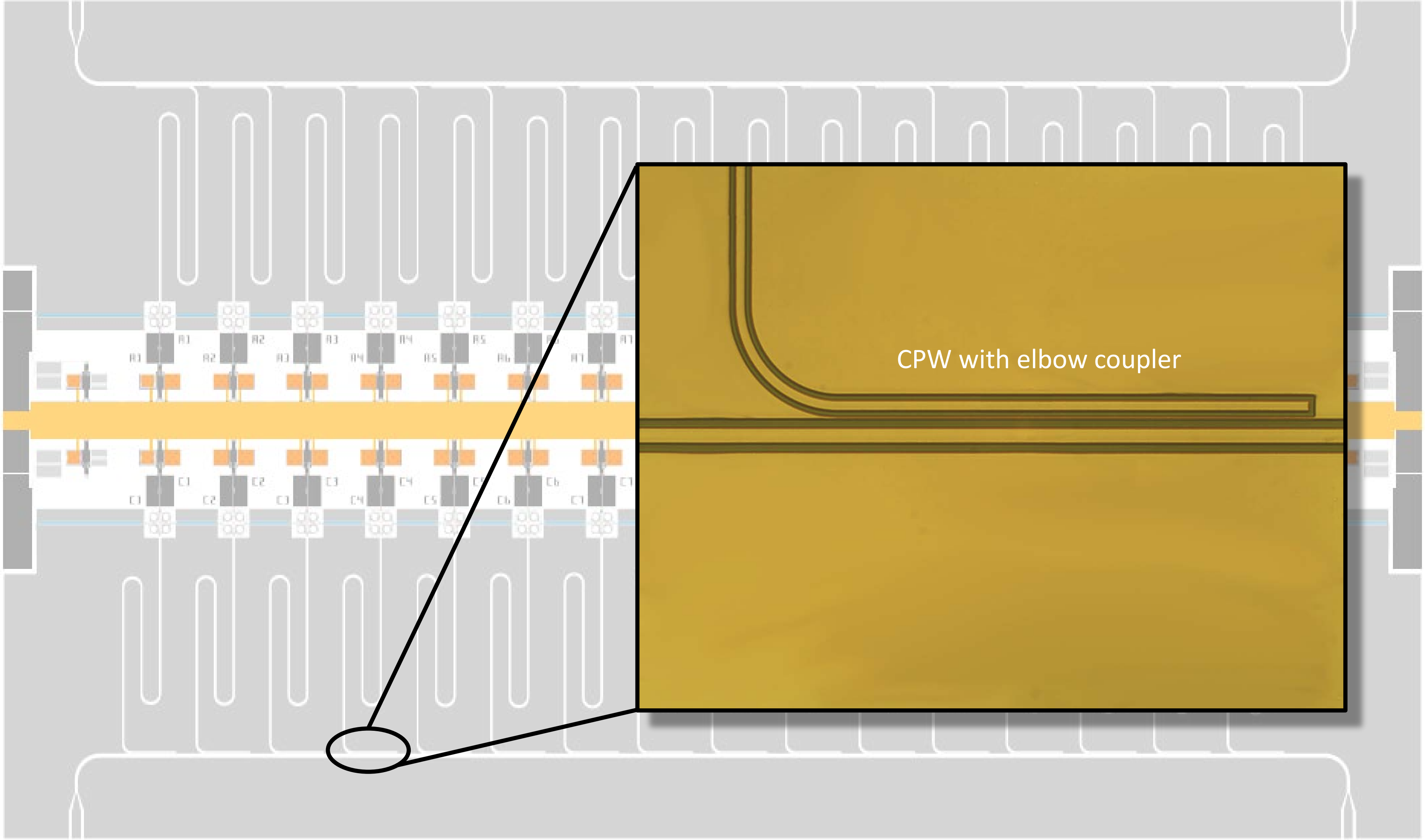
64 pixel detector array with integrated µMUX readout



64 pixel detector array with integrated µMUX readout

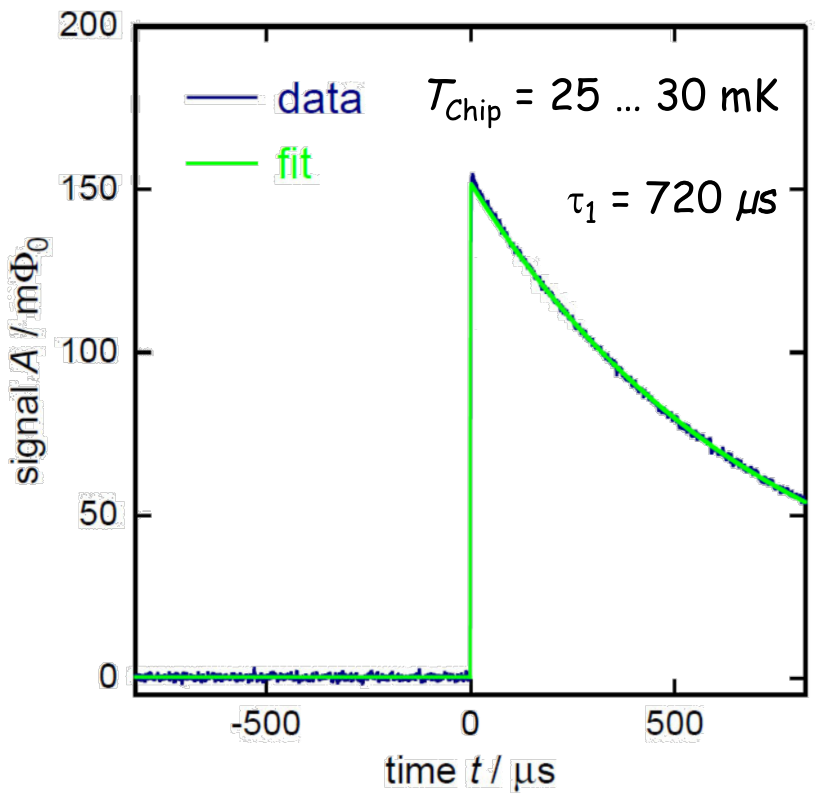


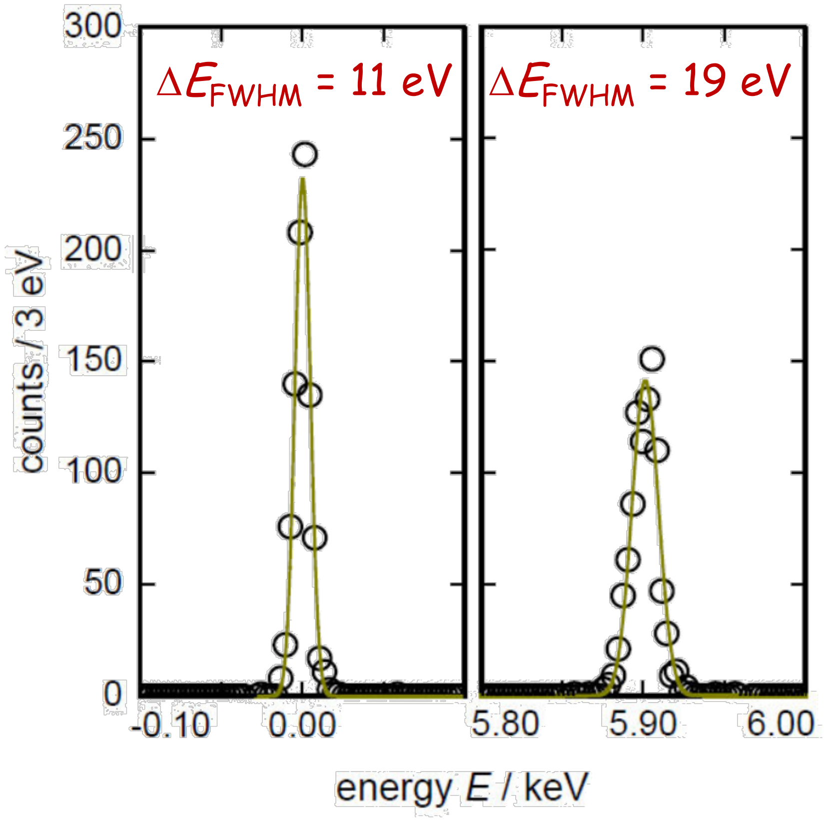
64 pixel detector array with integrated µMUX readout



CPW with elbow coupler

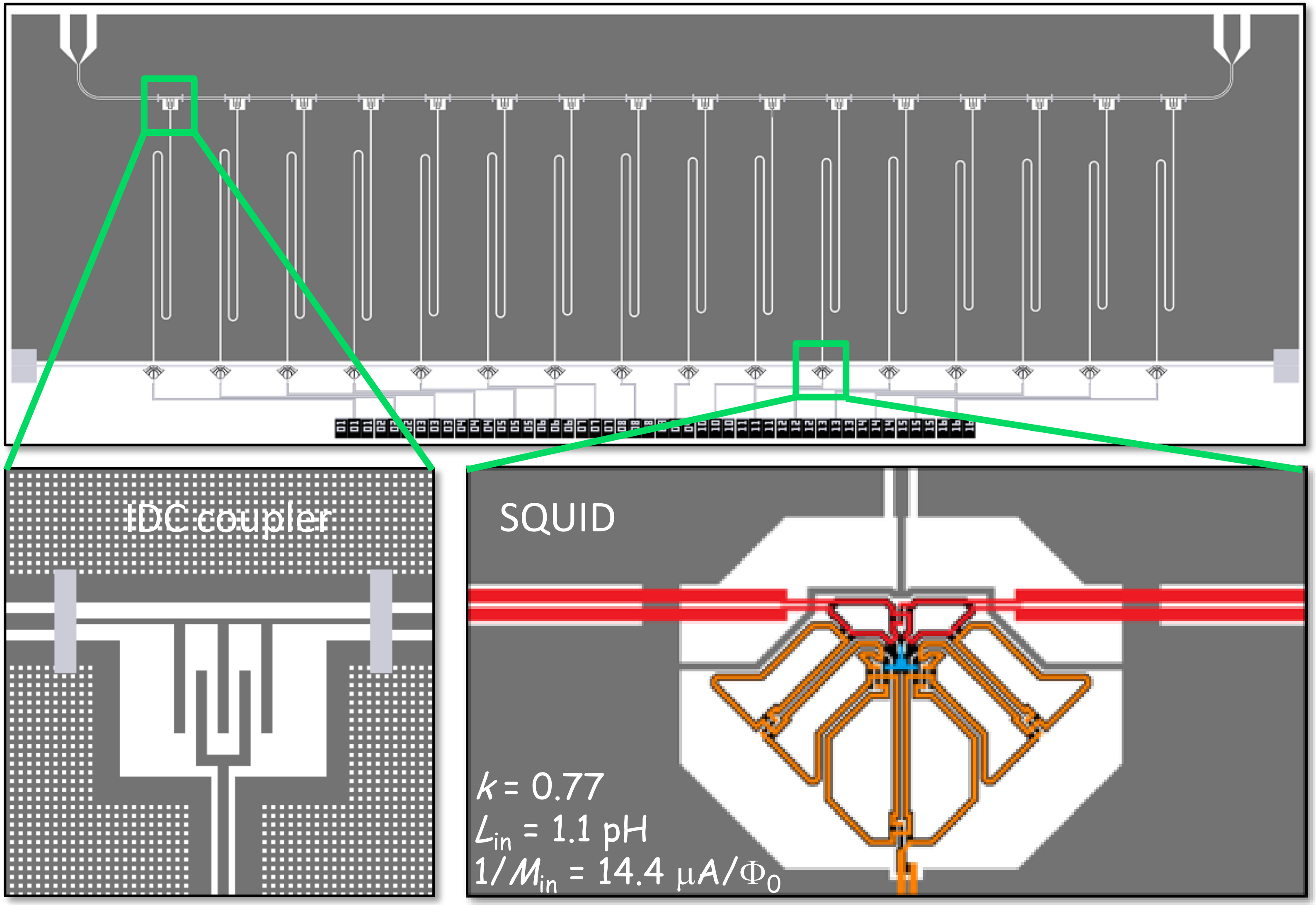
detector performance





- Here: Intrinsic detector rise time t < 100 ns resolvable (low Q resonators)
- Wafer suffered from stress in JJ. Good subgap resistance will bring ×5 improvement!

next-generation multiplexer design



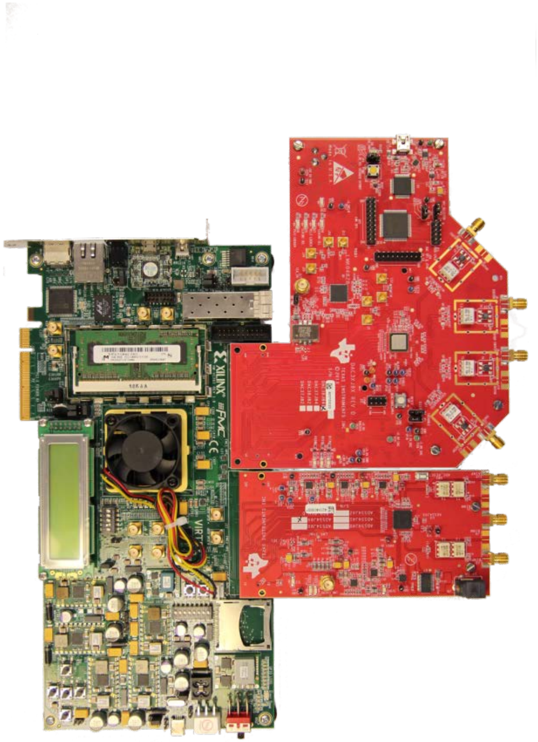
$k = 0.77$

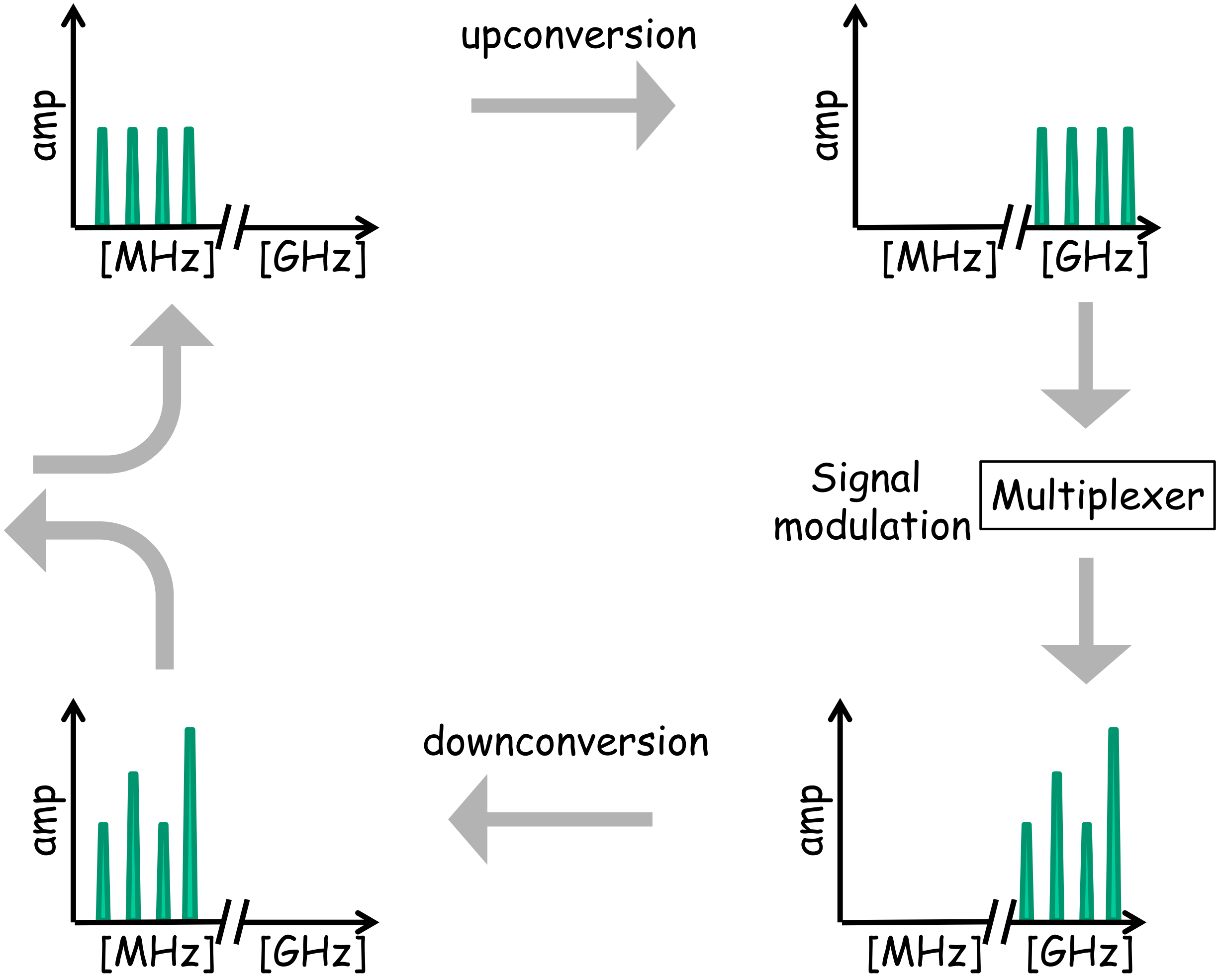
$L_{in} = 1.1\ \mathrm{pH}$

$1/M_{in} = 14.4\ \mu A/\Phi_0$

development of readout electronics

FPGA-based Software Defined Radio in collaboration with KIT





upconversion

Signal modulation

Multiplexer

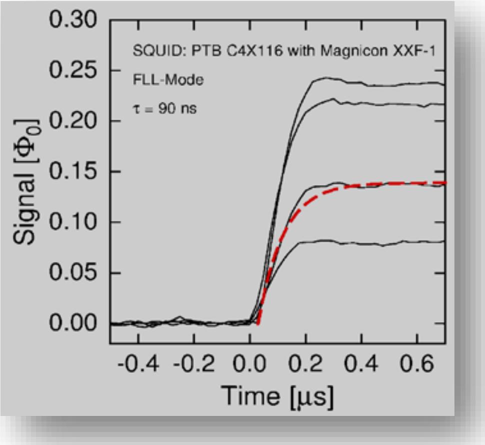
downconversion

MMCs get more and more mobile

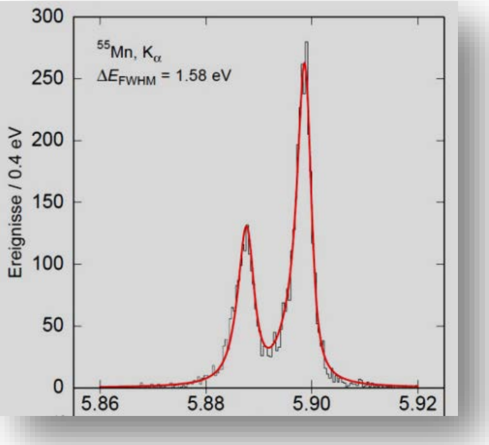
Summary & Outlook

- metallic magnetic calorimeters combine in a unique way

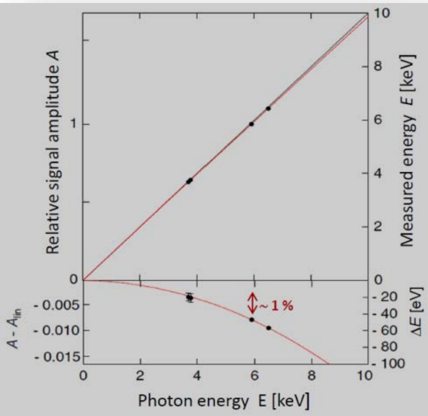
time resolution



energy resolution



linearity



- micro-fabrication works
- ECHo will operate 10k pix in 2021
- hi-res x-ray spectrometer maXs:
    - 256 pixels in 2020
    - > 1k pixel in 2021

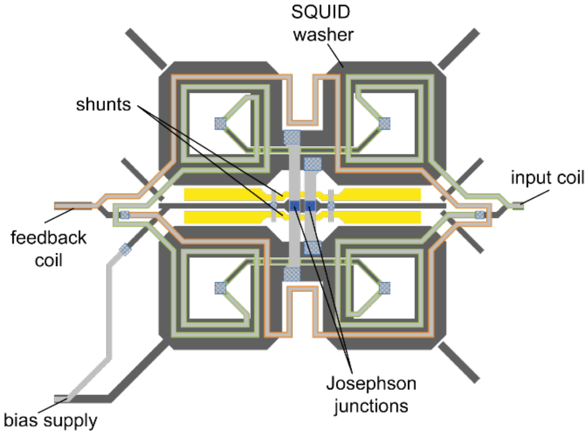
- Joint effort KIP & KIT
    - integrated SDR
      to reduce cost per channel
- After 2022:

  ECHo will aim for >1M channel …

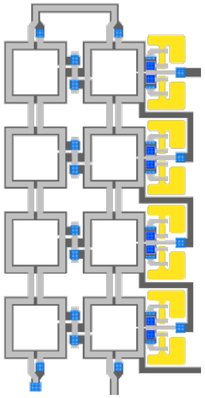
first home-made dc-SQUIDs

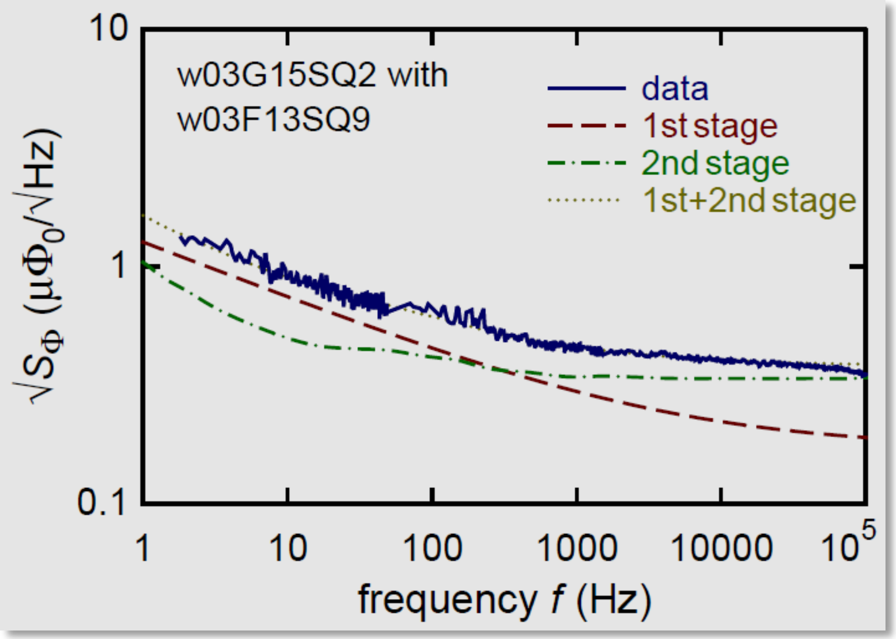
Our first 2-stage dc-SQUIDs:

second-order
parallel gradiometer



series arrays of 4 to 16
series gradiometers





1st stage contribution:

white noise level: $0.17\ \mu\Phi_0/\sqrt{\text{Hz}}$ ⟷ $e_{c,w} = 2.5\,h$

1/f noise at 1 Hz: $1.1\ \mu\Phi_0/\sqrt{\text{Hz}}$ ⟷ $e_{1/f} = 100\,h$

Among the world's finest SQUIDs!

… even if sputtered in the same system as our paramagnetic sensors

Allows for higher level of integration --- important for very soft x-rays