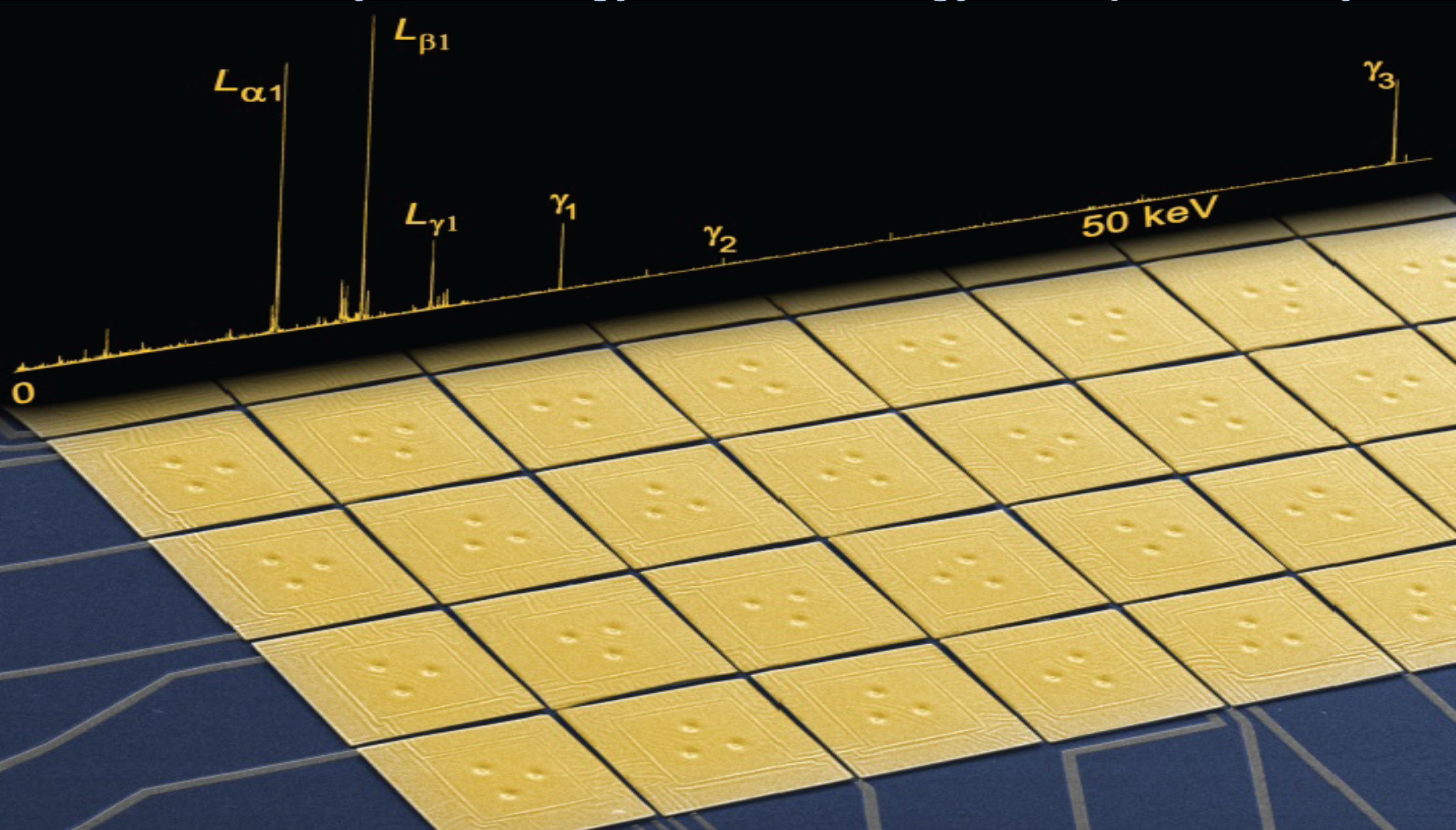
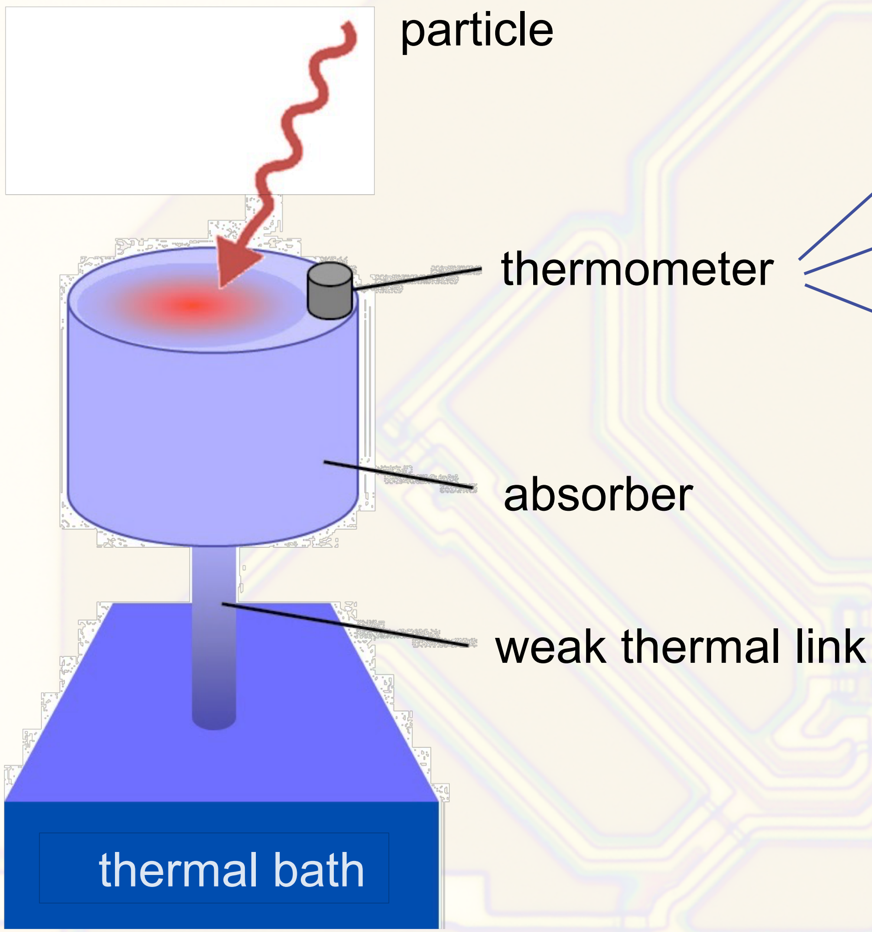
Christian Enss
Heidelberg University

Metallic Magnetic Calorimeters:
A Novel Key Technology for Low Energy Astroparticle Physics



General Concept of a Calorimetric Detector

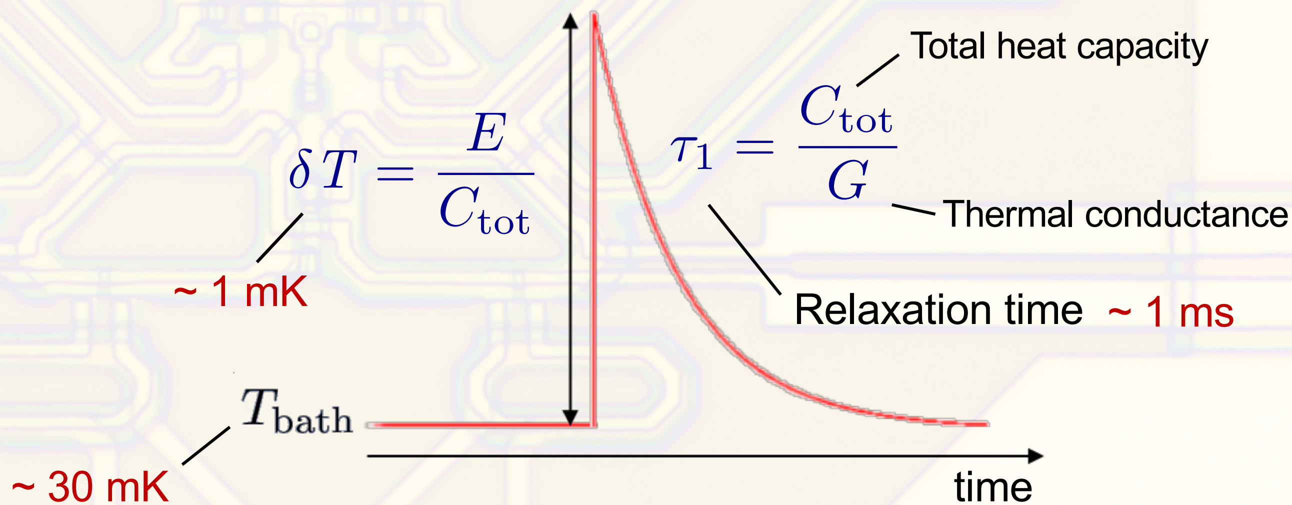


TES

Semiconductor Thermistors

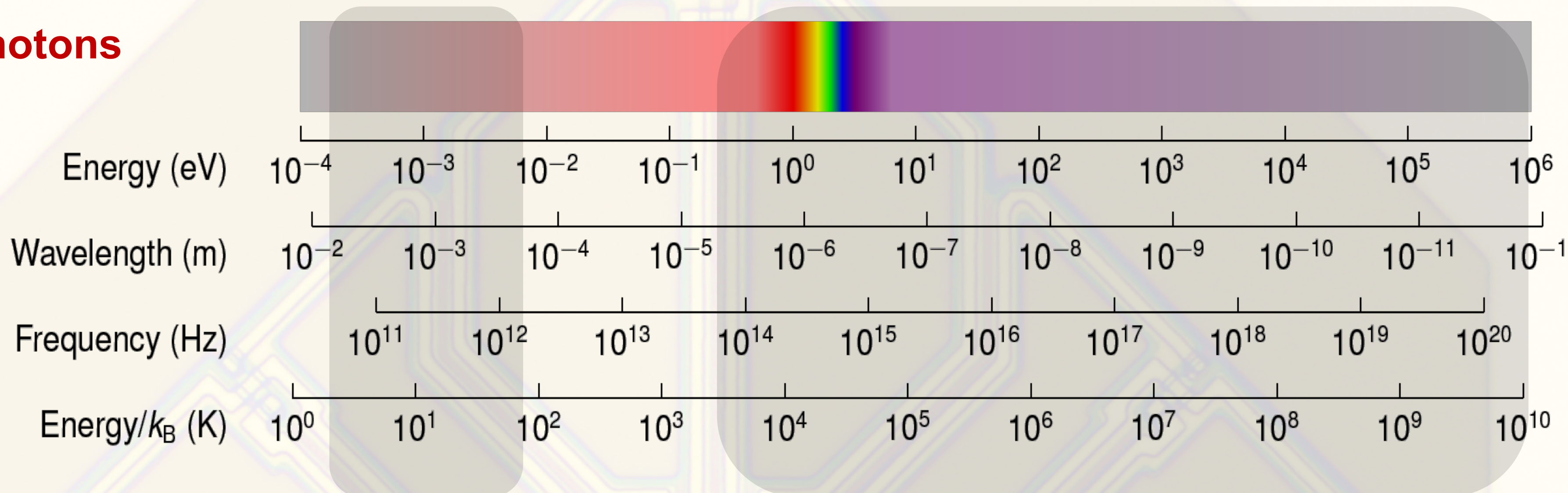
MMC Metallic Magnetic Calorimeters

Single Event



What Can One Measure With Cryogenic Detectors?

Photons



Matter

Mass Spectrometry (Mass 1 – 106 u, Energy 1 – 300 keV)

Heavy Ion Physics (^{4}He – ^{238}U, Energy 0.1 – 400 MeV/u)

α-particles (1 – 10 MeV)

β-particles

Neutinos

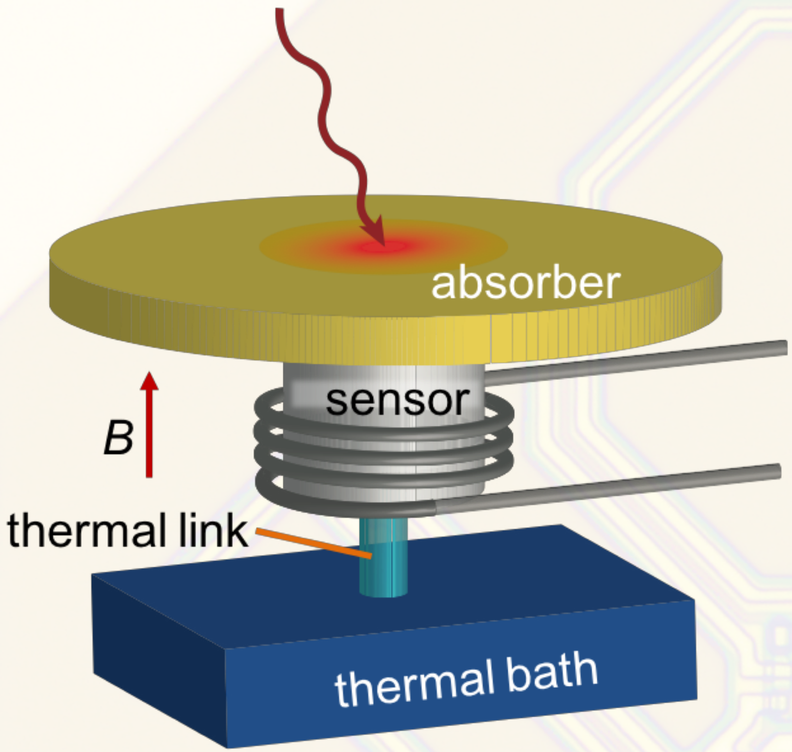
Other

Dark Matter (WIMPs, LDM, Axions, ...)

Primordial gravity waves (indirectly)

...

Metallic Magnetic Calorimeters (MMCs)

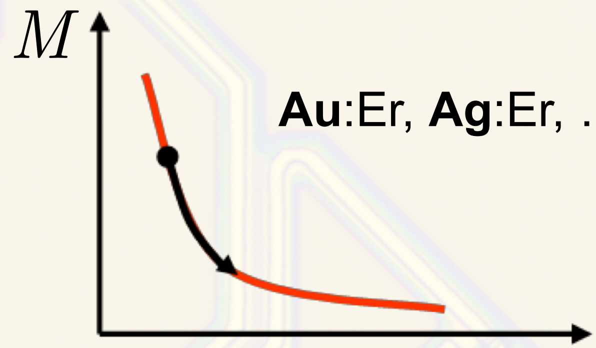


$$\Delta T \propto \Delta M \propto \Delta\phi \propto \Delta U$$

main difference to resistive calorimters:

no dissipation in the sensor
no galvanic contact to the sensor

paramagnetic sensor:



signal size:

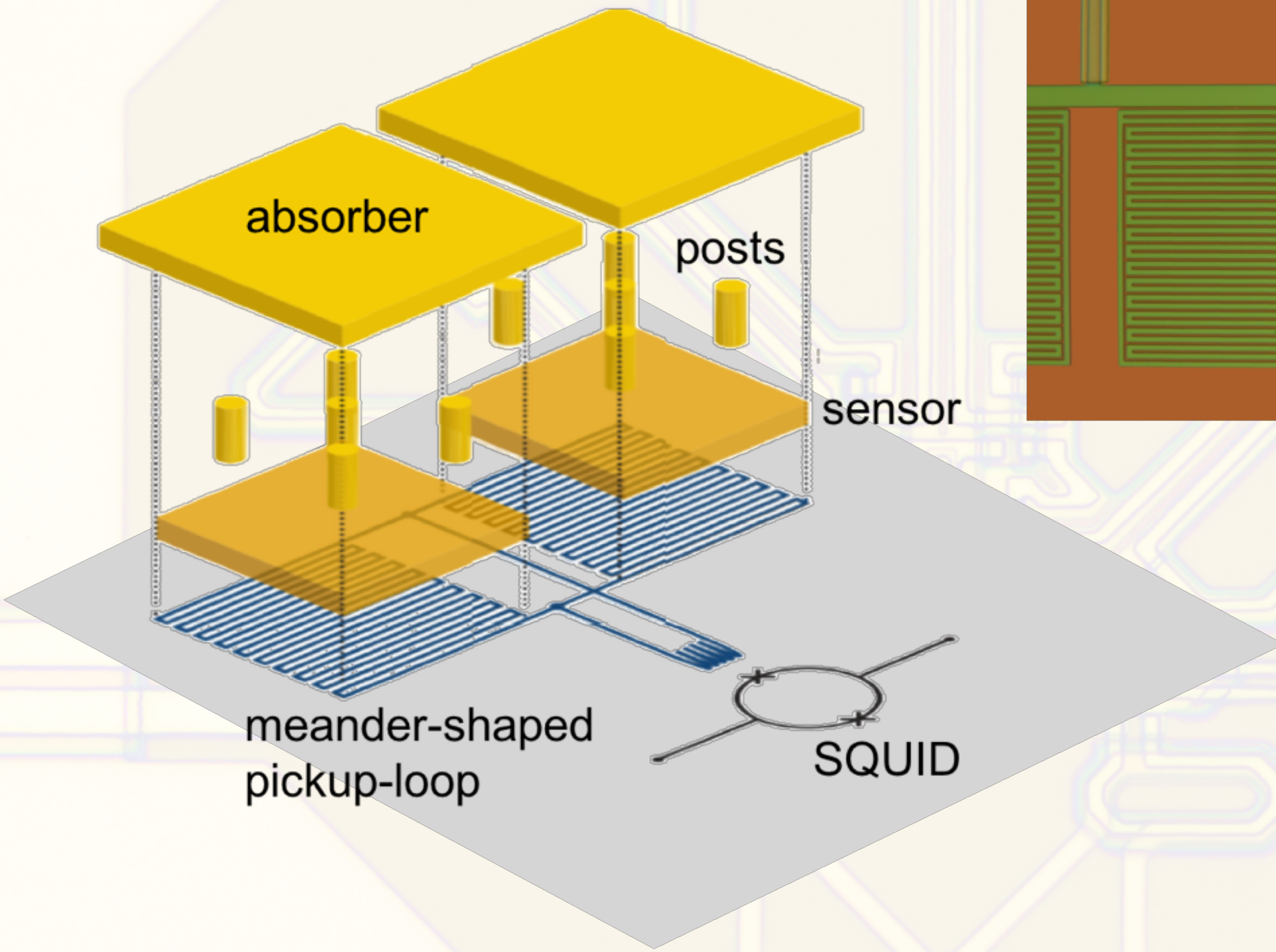
$$\delta M = \frac{\partial M}{\partial T}\delta T = \frac{\partial M}{\partial T}\frac{E}{C_{\mathrm{tot}}}$$

energy resolution:

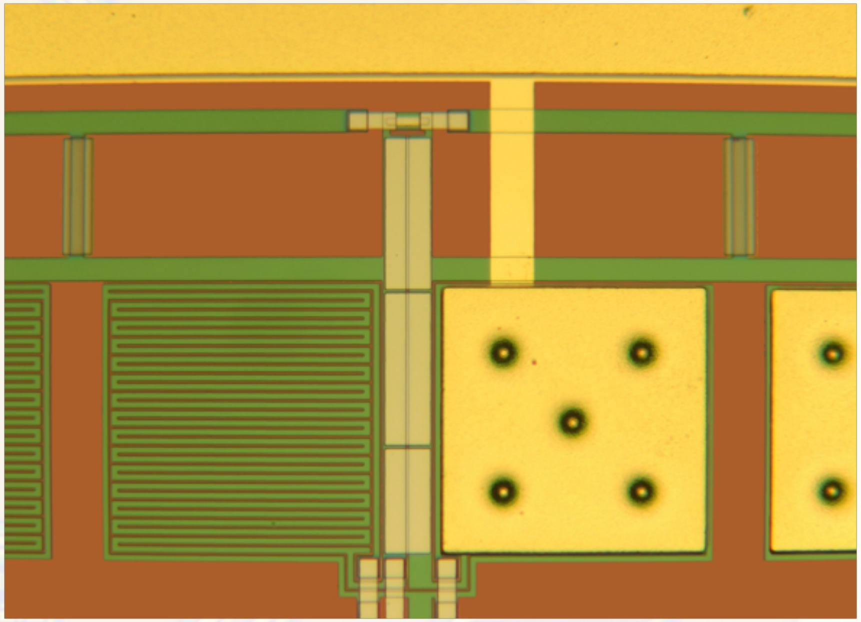
$$\Delta E_{\mathrm{FWHM}} \simeq 2{,}36\sqrt{4k_{\mathrm{B}}C_{\mathrm{Abs}}T^2}\sqrt{2}\left(\frac{\tau_0}{\tau_1}\right)^{1/4}$$

A. Fleischmann, Adv. Solid State Phys. **41**, 577 (2001)

Planar Realisations of MMCs

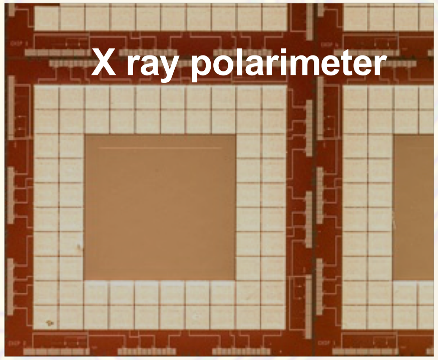


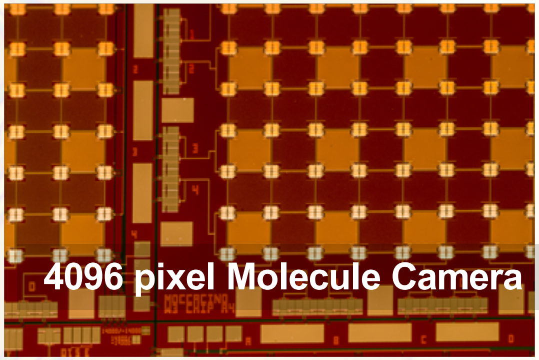
optical image of MMC detector chip

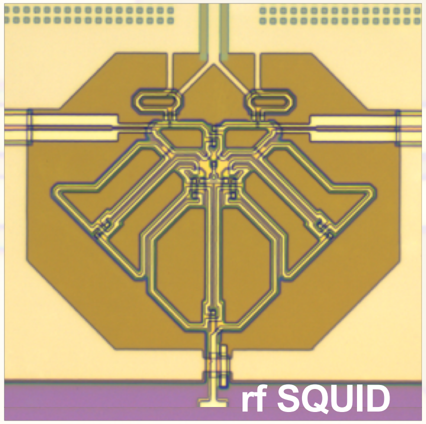


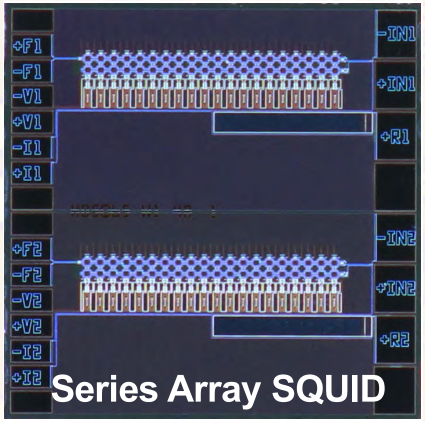
250 μm

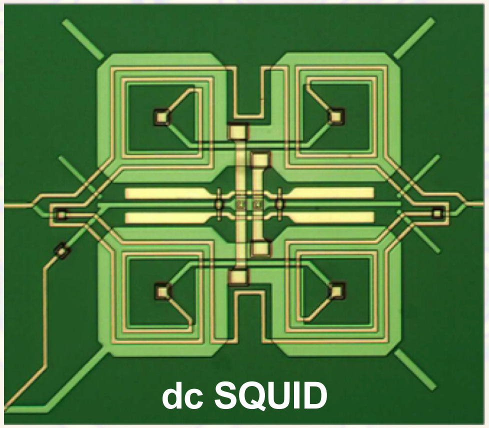
- flexibility in design and fabrication
- reliable processes for thin films
- more than 10 different designs (6-18 layers) processed in parallel

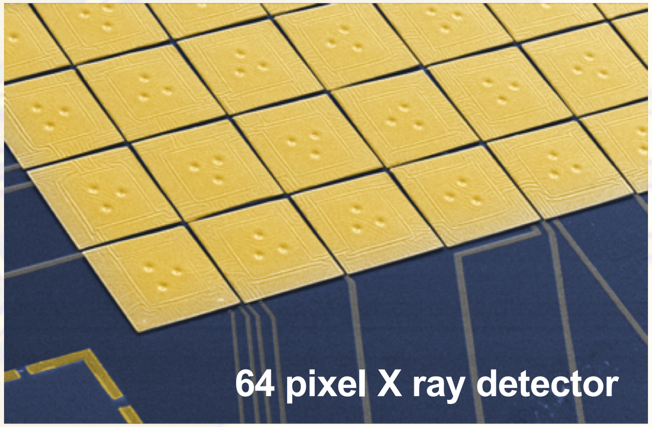

X ray polarimeter


4096 pixel Molecule Camera


rf SQUID

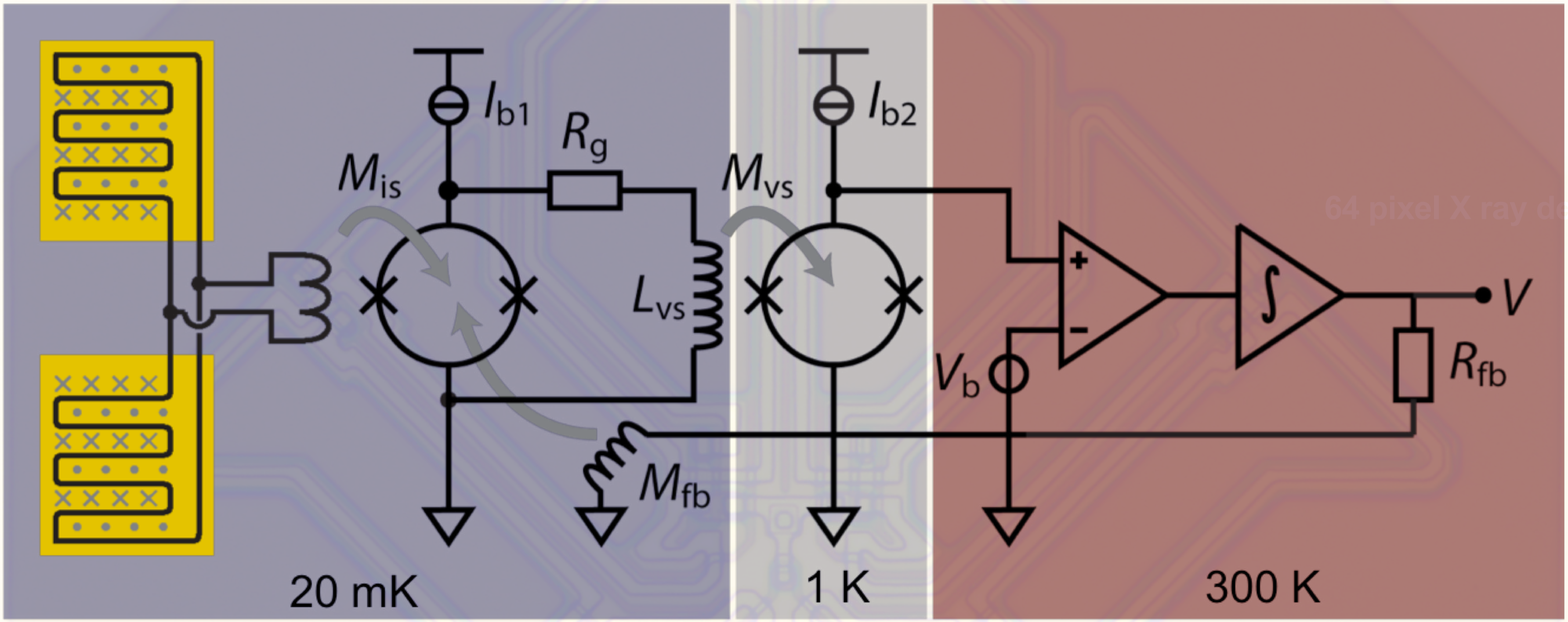

Series Array SQUID


dc SQUID


64 pixel X ray detector

Readout Scheme for MMCs

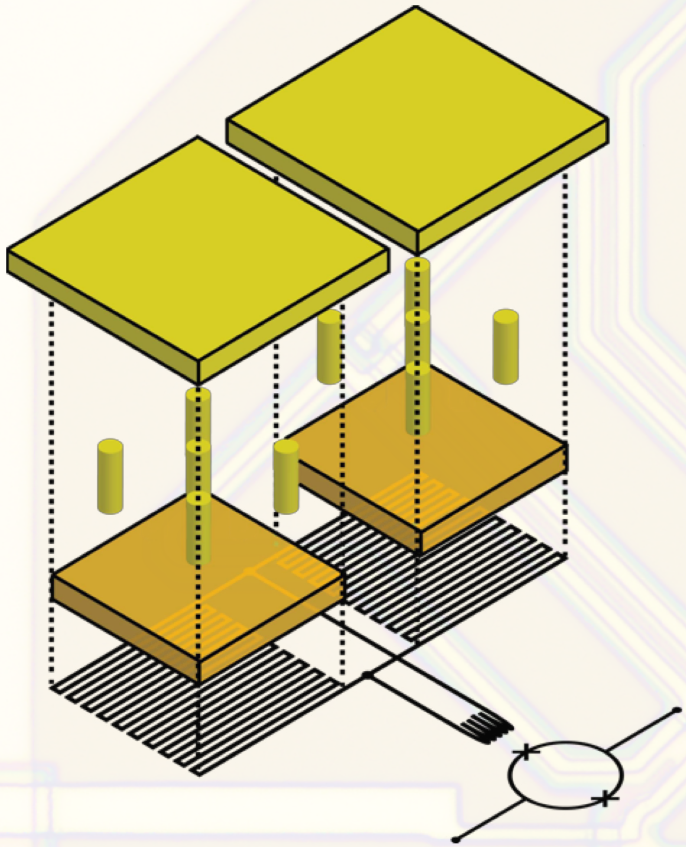
paramagnetic sensor



main advantages:

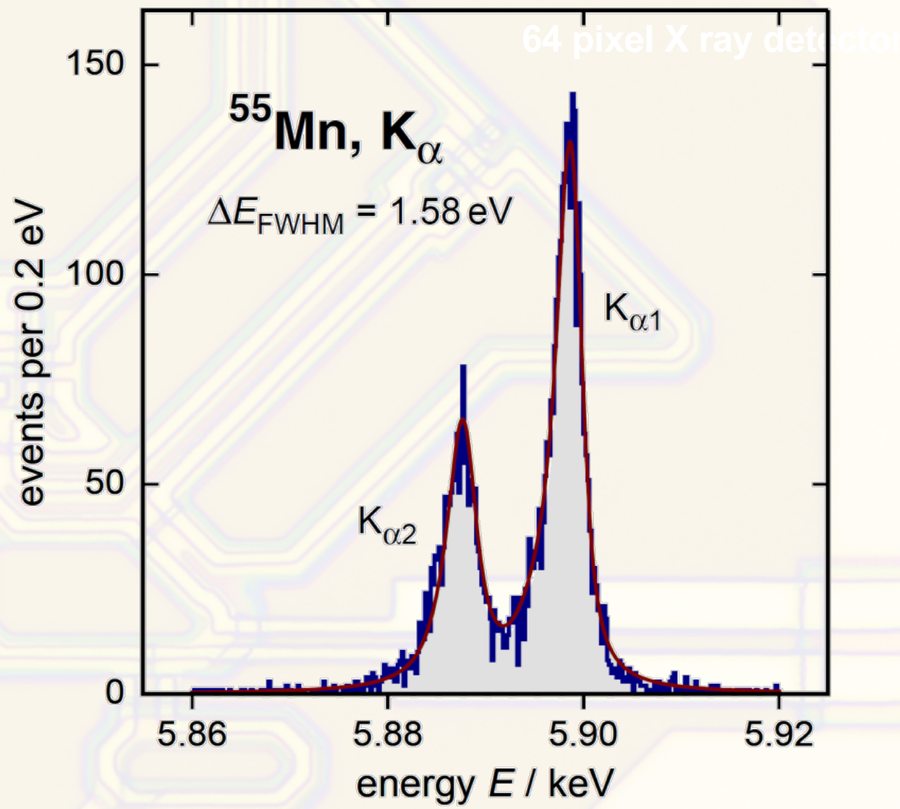
- ► low noise (ε = 50 .. 300 ħ)
- ► large bandwidth / slew rate (MHz)
- ► low power dissipation on detector SQUID chip (nW)
- ► linear signal amplification

Recent Result of a Fully Microfabricated MMC



250 µm × 250 µm Gold, 5 µm thick

98% Quantum Efficiency @ 6 keV



S. Kempf, A. Fleischmann, L. Gastaldo, C.E., J. Low Temp. Phys. **193,** 365 (2018)

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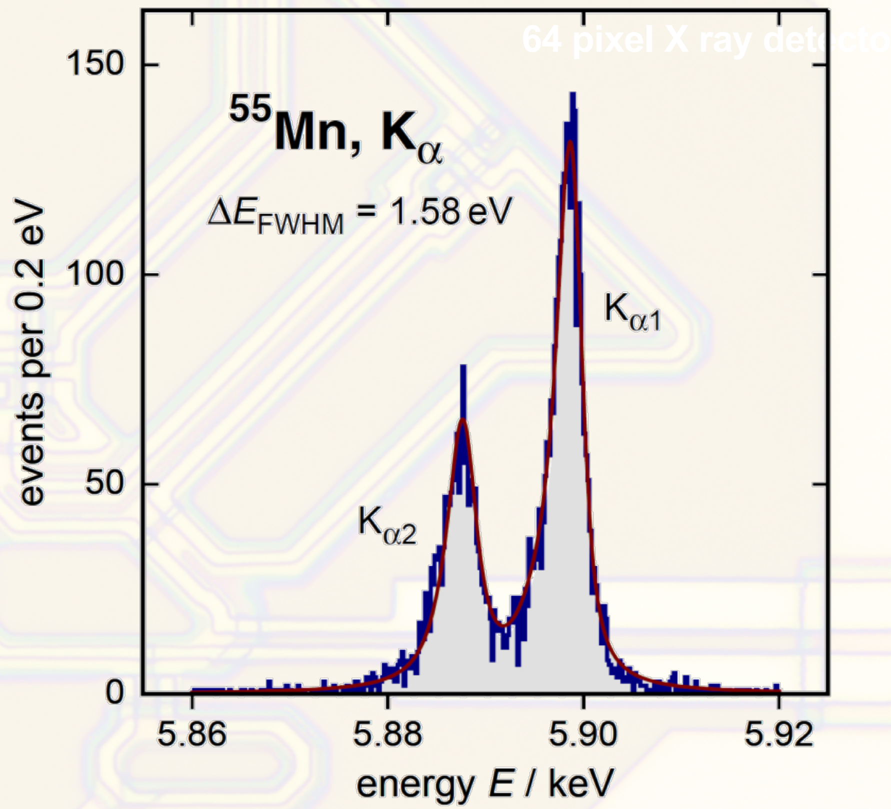
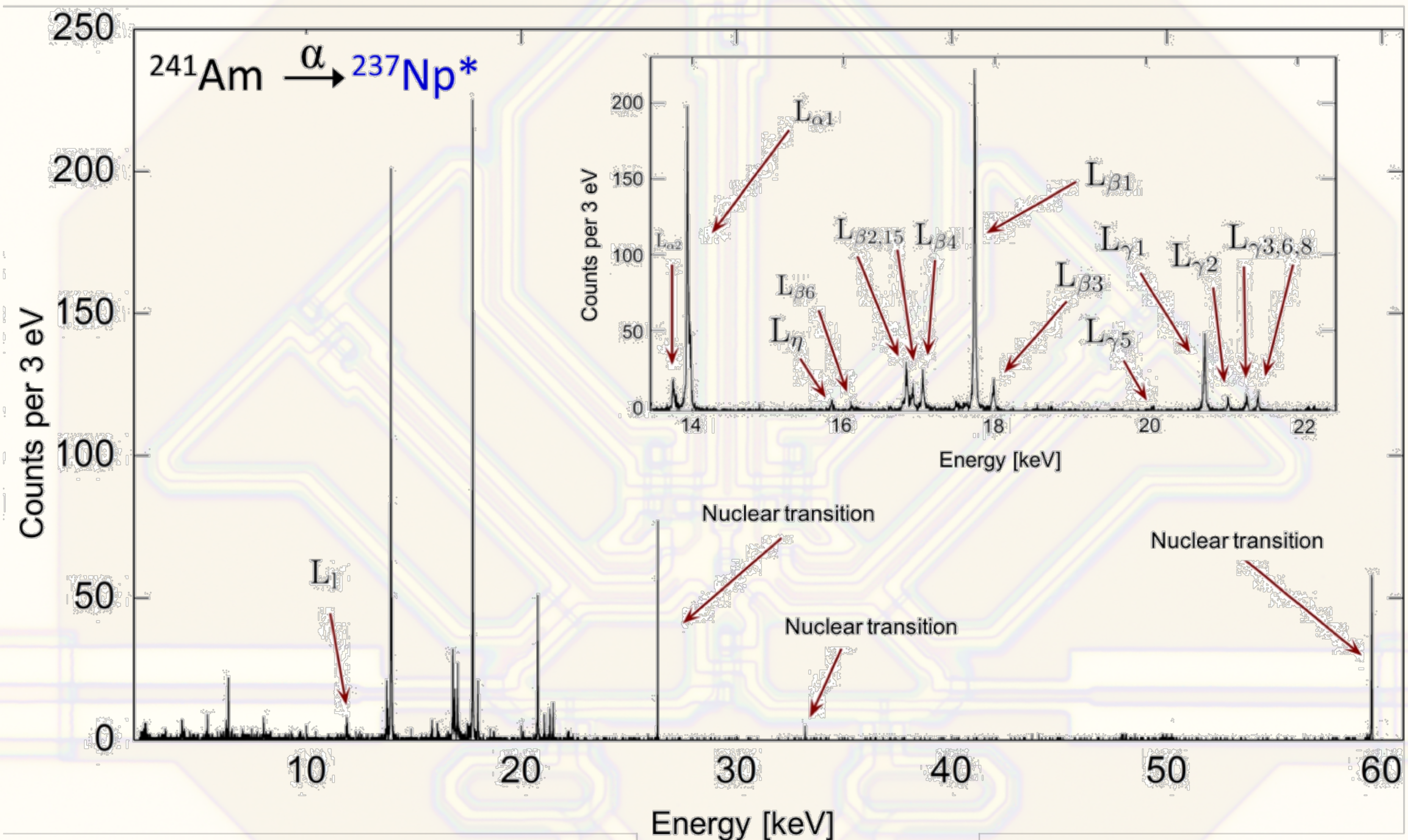


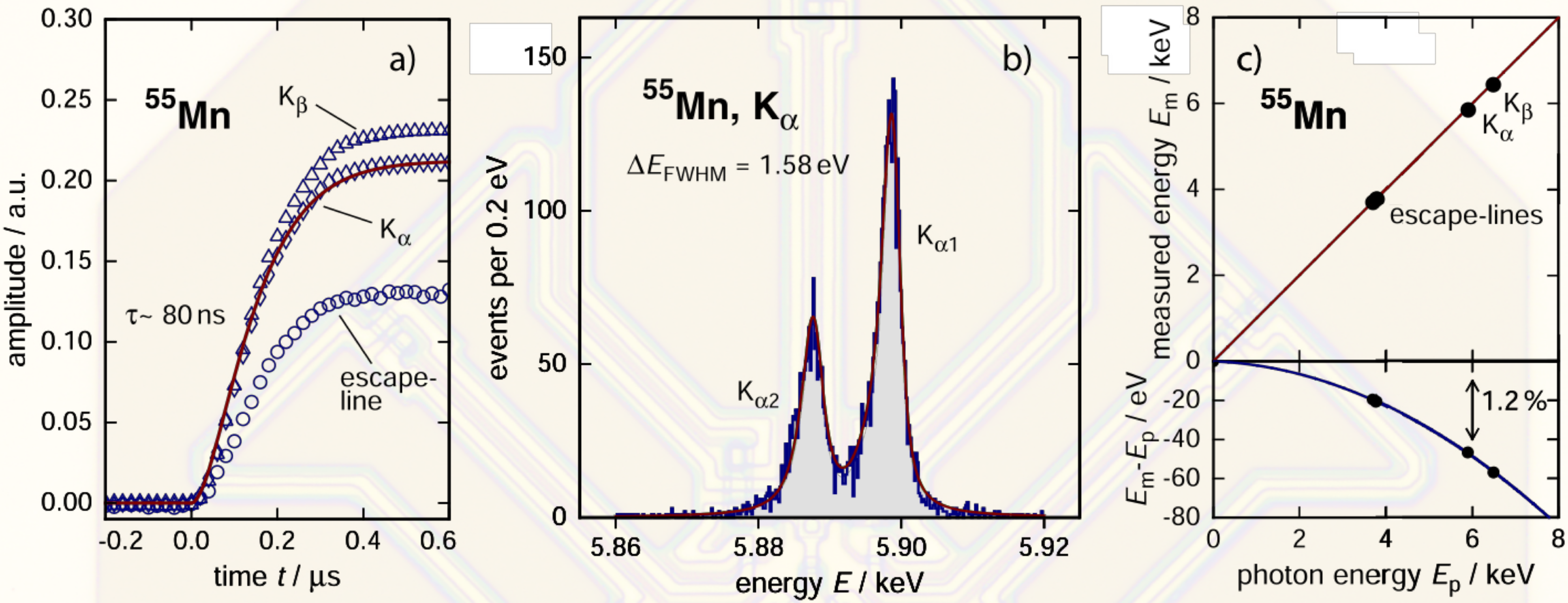
S. Kempf, A. Fleischmann, L. Gastaldo, C.E., J. Low Temp. Phys. **193,** 365 (2018)

Energy Bandwidth



S. Kempf, A. Fleischmann, L. Gastaldo, C.E., J. Low Temp. Phys. **193,** 365 (2018)

Performance of maXs20 Detector at 6 keV



record speed

pileup identification

record resolving power

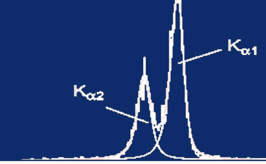
reduction of overlapping lines

record linearity

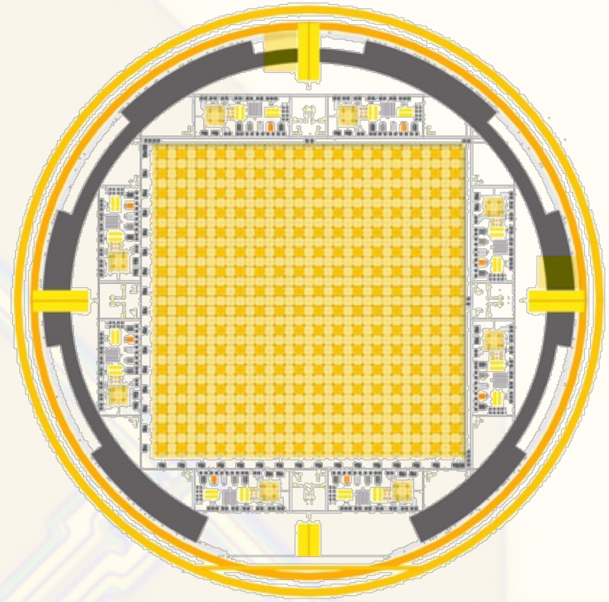
energy scale and calibration

S. Kempf, A. Fleischmann, L. Gastaldo, C.E., J. Low Temp. Phys. **193,** 365 (2018)

Current Projects



atomic and molecular physics	**Funding**
Lamb-shift of highly charged ions (SPARC)	BMBF
X-ray polarimetry (Polar-X)	BMBF
X-ray spectroscopy (HD-EBIT)	MPG
➡ recombination of molecular ions (CSR)	MPG/GIF

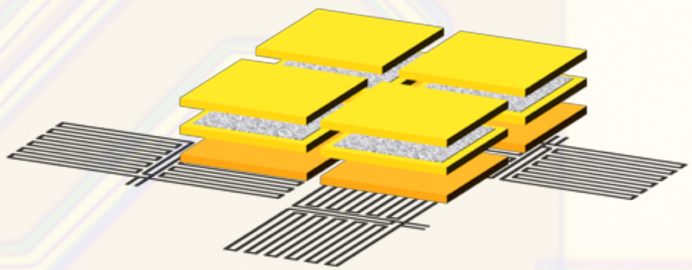


radiation and quantum metrology

α-, β-, and γ-spectroscopy (MetroBeta)	EU
β-spectroscopy (MetroMMC)	EU

nuclear physics

nuclear isomer state of ^{229}Th (nu-Clock)	EU
nuclear forensic (LLNL)	LLNL

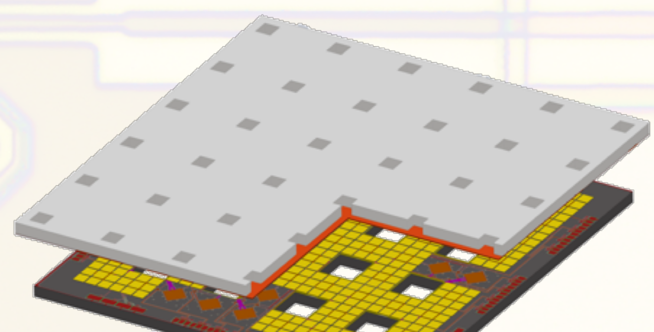


neutrino physics

➡ electron capture of ^{163}Ho (ECHo)	DFG
double beta decay ^{100}Mo (AMoRE)	KRISS
search for steril neutrinos (MATRIX)	

dark matter

search for light dark matter (DELight)	
➡ search for axions (IAXO)	BMBF



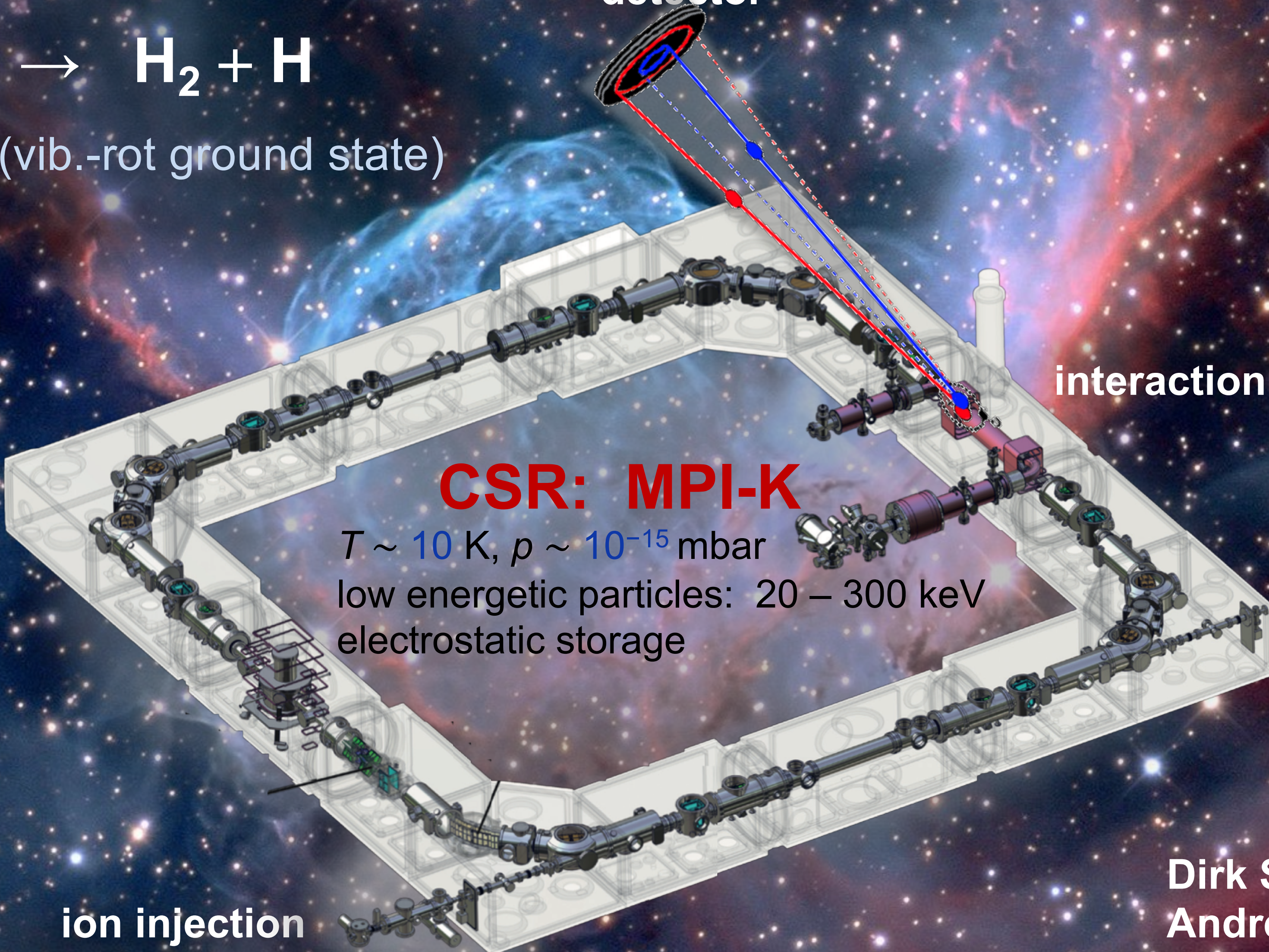
Detection of Molecule Fragments

Andreas Fleischmann

eg. reaction rate of

$$H_3^+ + e^- \rightarrow H_2 + H$$

at $T < 10$ K (vib.-rot ground state)



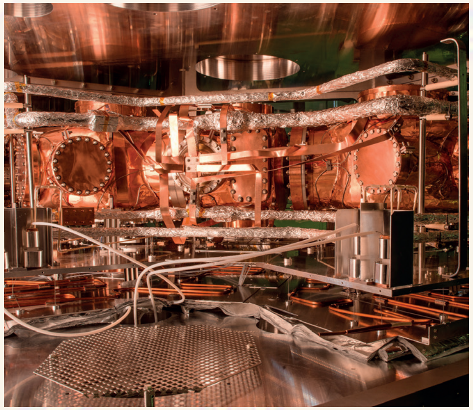
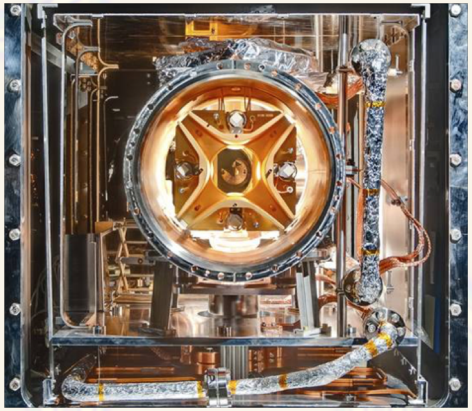
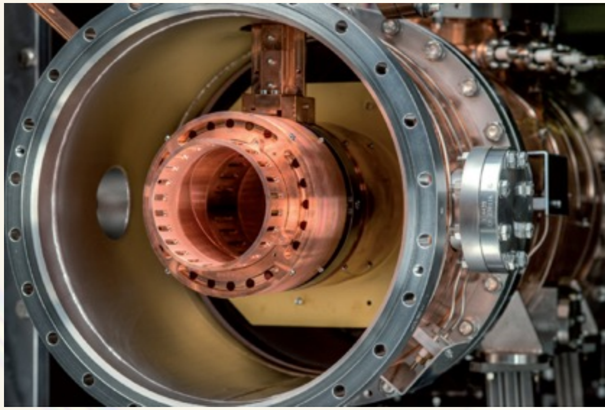
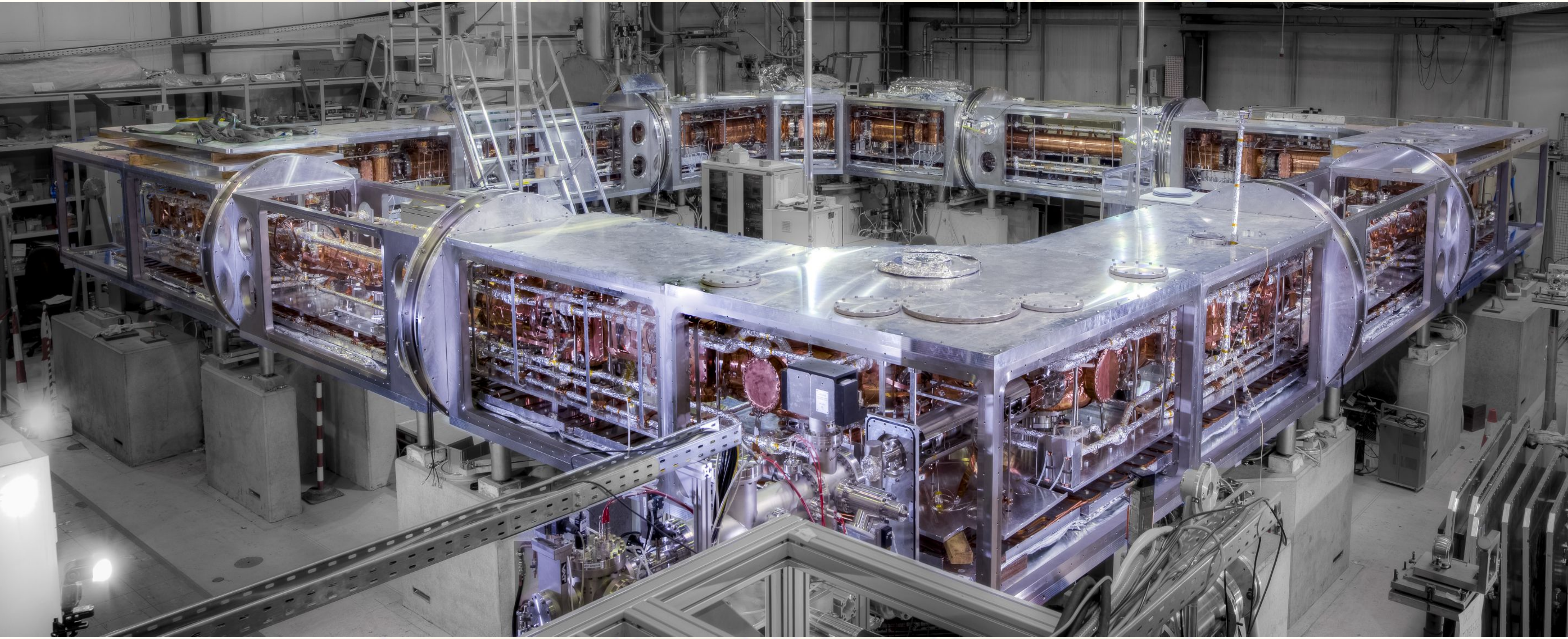
CSR: MPI-K

$T \sim 10$ K, $p \sim 10^{-15}$ mbar
low energetic particles: 20 – 300 keV
electrostatic storage

Dirk Schwalm
Andreas Wolf
Daniel Zajfman

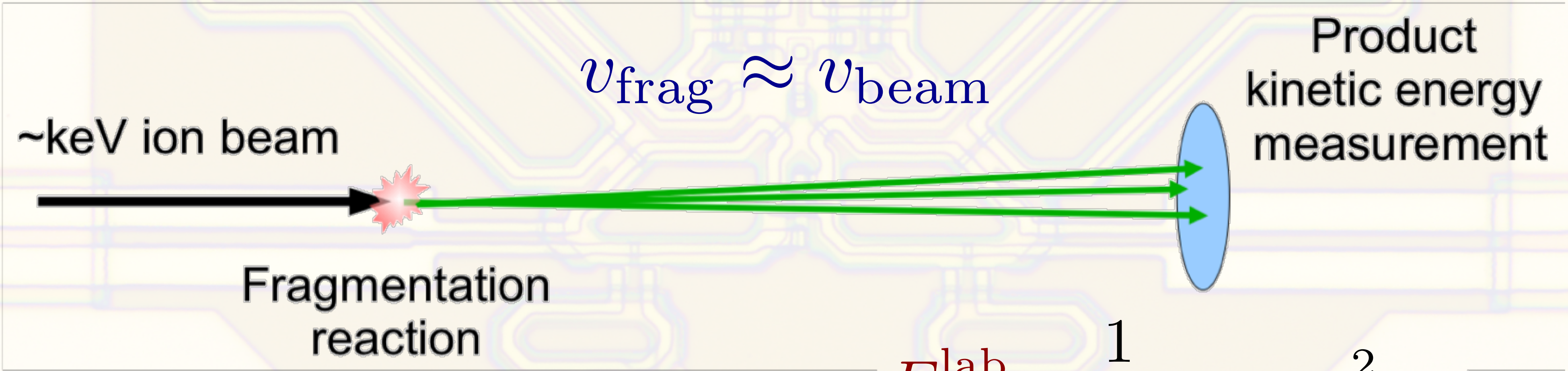
Cryogenic Storage Ring at MPI-K

K. Blaum
A. Wolf
R. v. Hahn
O. Novotny
…

$$\mathrm{ABCD}^{+} + e^{-} \to \mathrm{A} + \mathrm{BCD}$$
$$\to \mathrm{AB} + \mathrm{CD}$$
$$\to \mathrm{A} + \mathrm{B} + \mathrm{C} + \mathrm{D}.$$

mass from kinetic energy

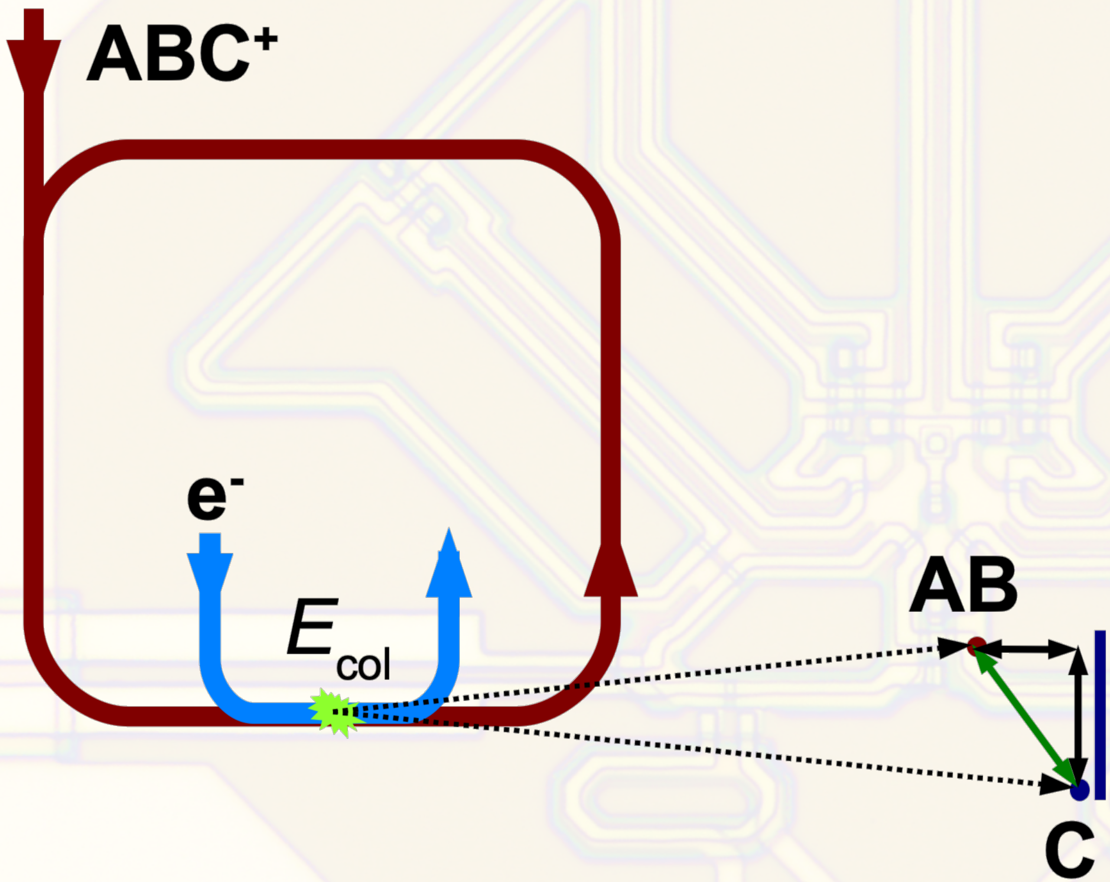


$$v_{\mathrm{frag}} \approx v_{\mathrm{beam}}$$

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

Detector Requirements

- energy resolution
- large detection area
- counting efficiency
- multi-hit capability
- position resolution
- time resolution

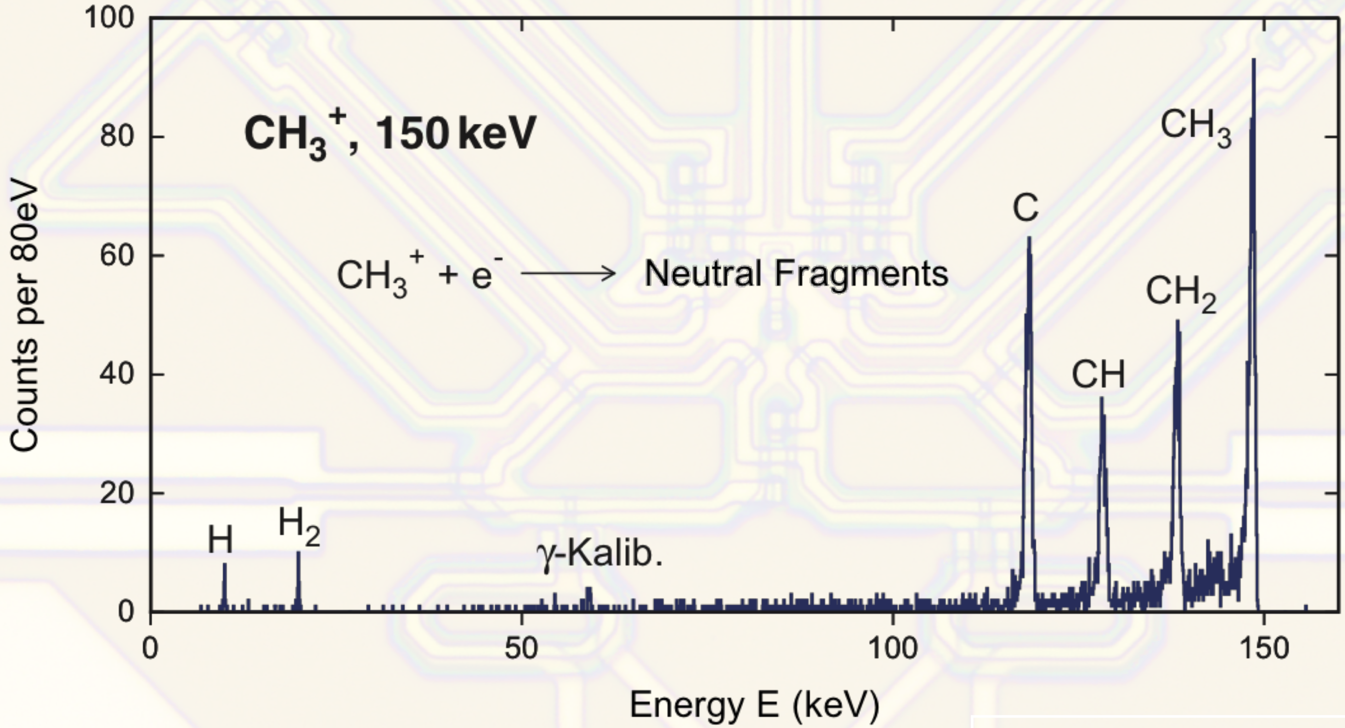


→ MMC

Dissociative Recombination: $CH_3^+ + e^-$

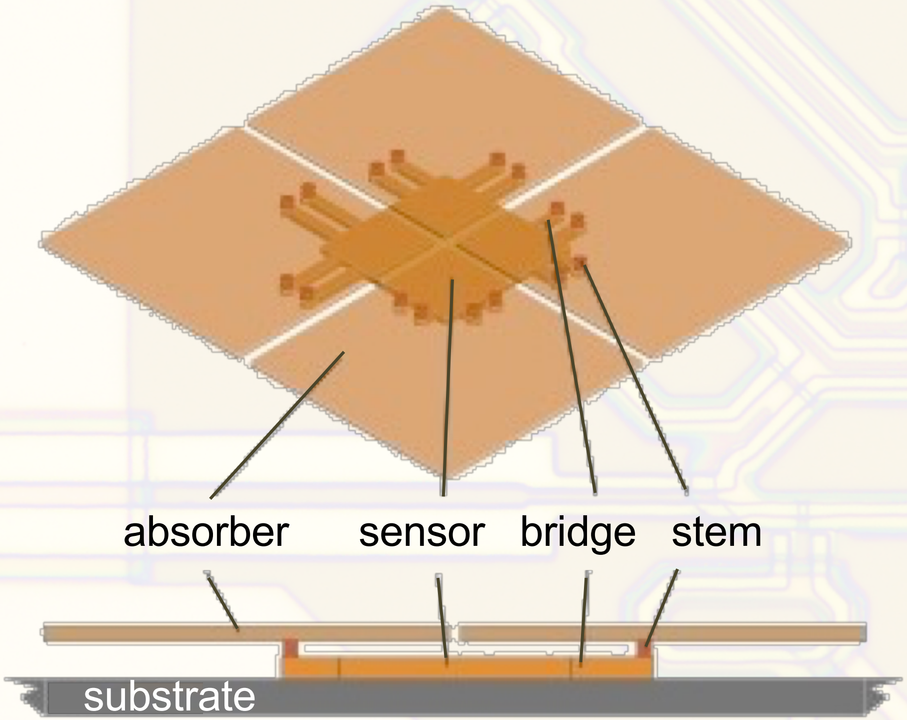
$$ABCD^+ + e^- \to A + BCD$$
$$\to AB + CD$$
$$\to A + B + C + D.$$

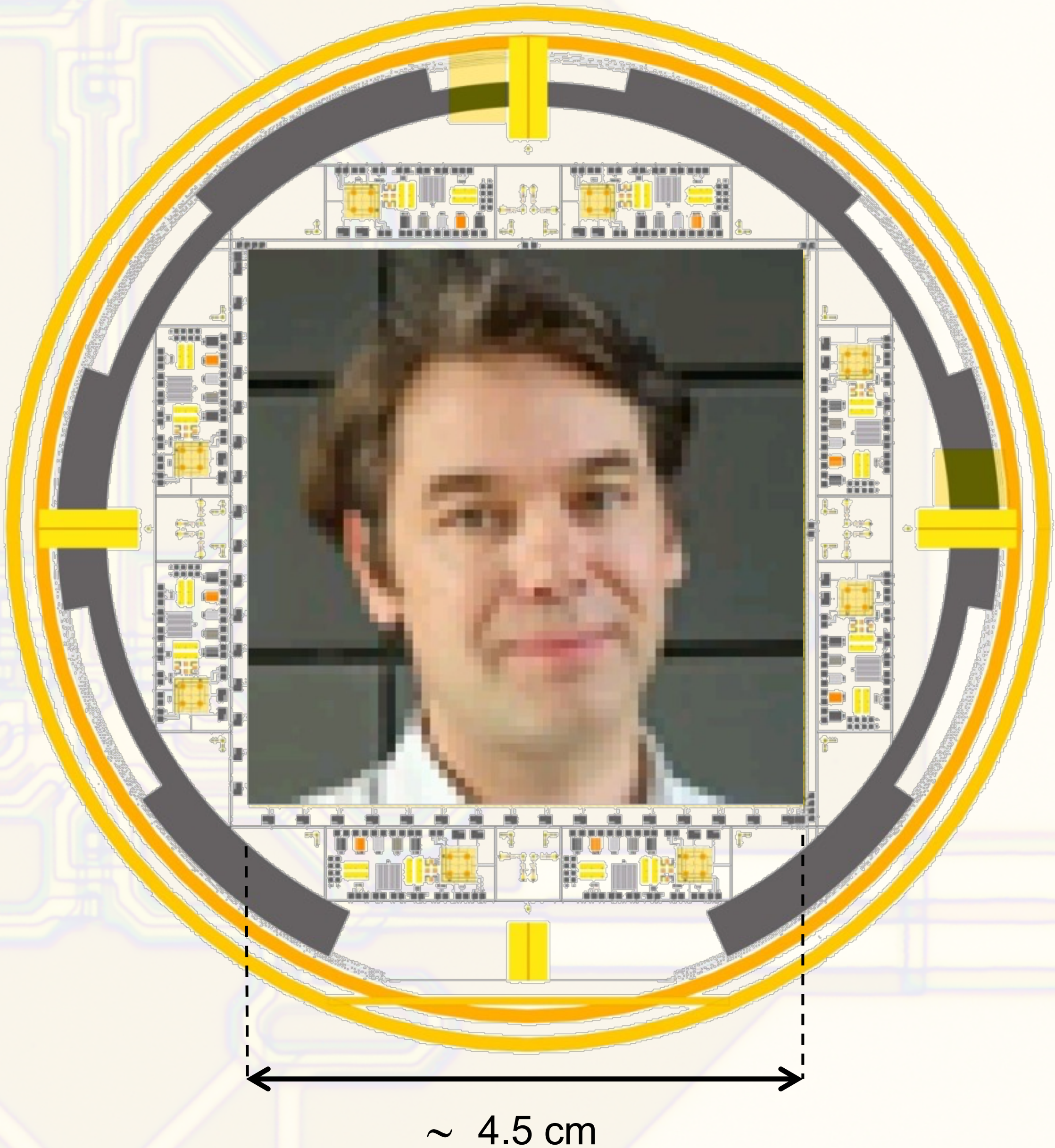
neutral fragments of CH_3^+ accelerated with 150 keV



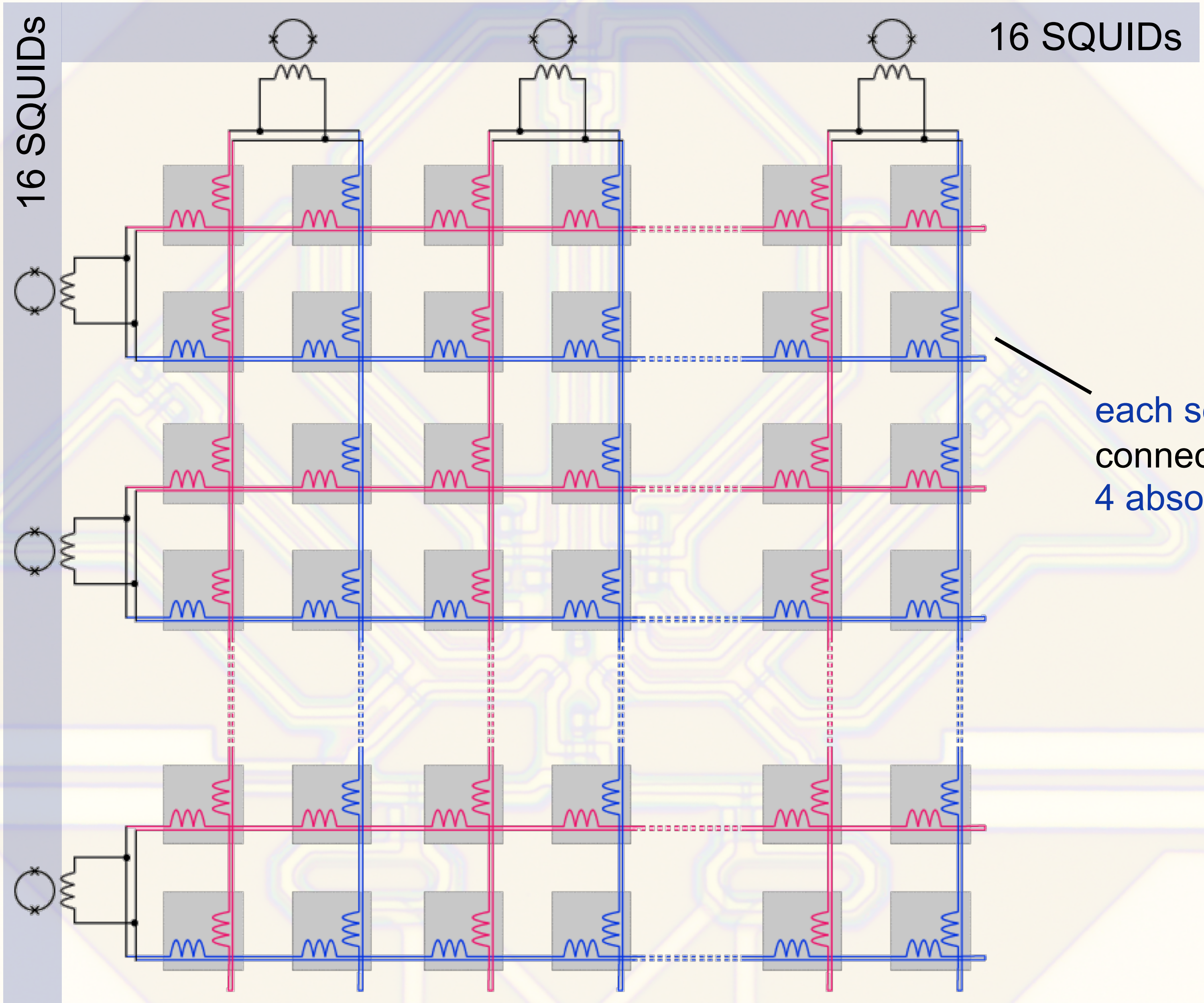
O. Novotný *et al.*, J. Appl. Phys. **118**, 104503 (2015)

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



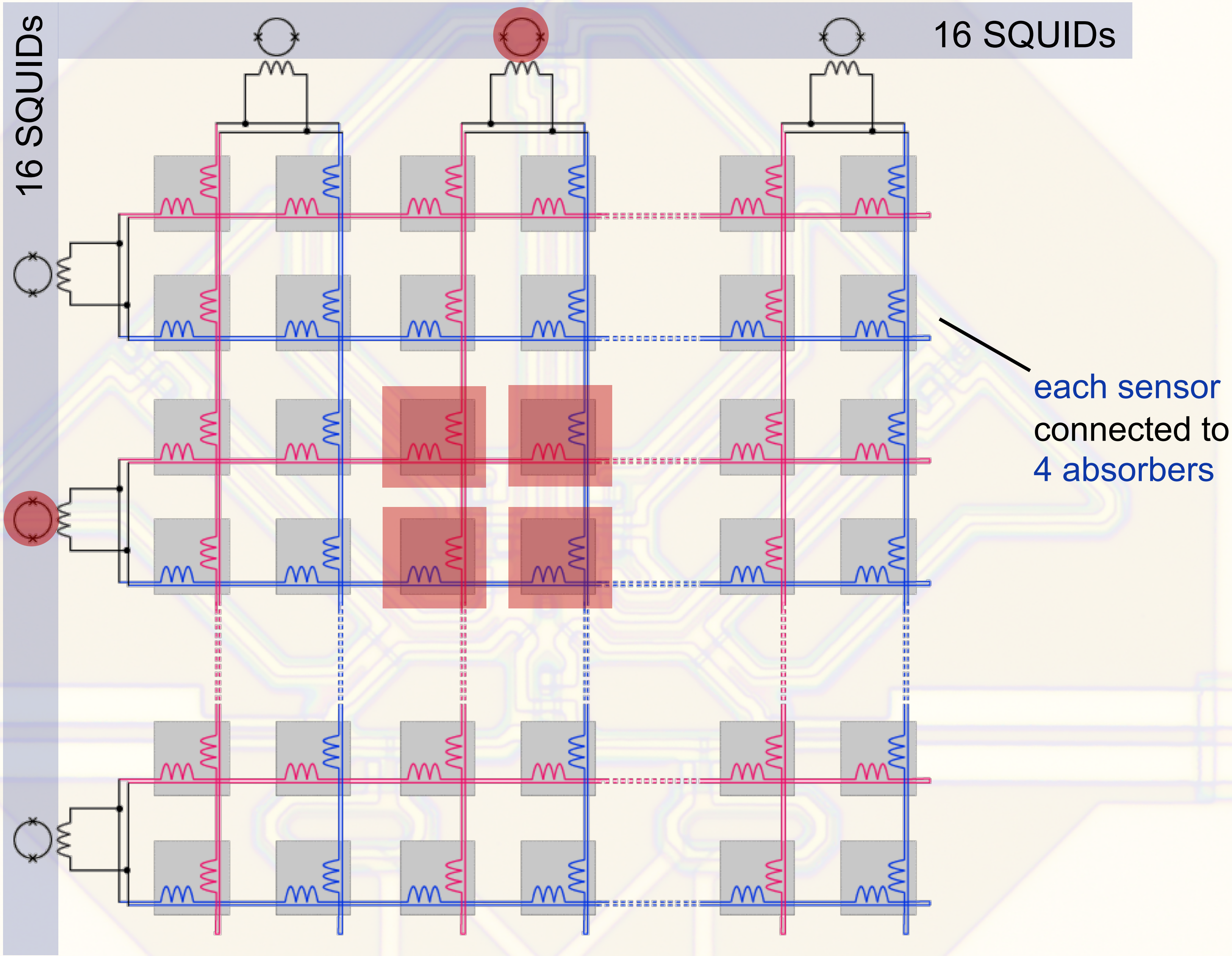


Readout Scheme of MOCCA

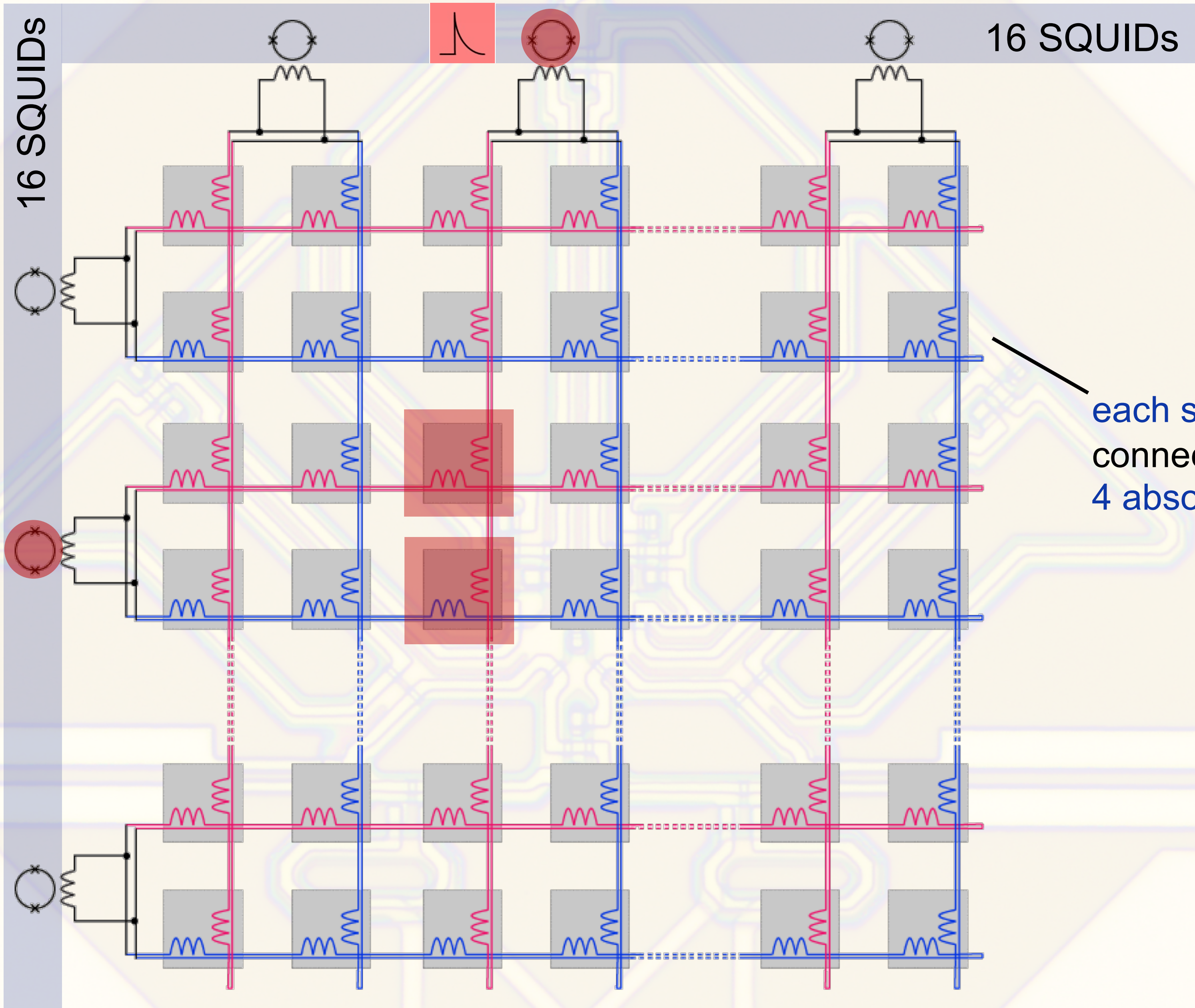


each sensor connected to 4 absorbers

Readout Scheme of MOCCA



Readout Scheme of MOCCA



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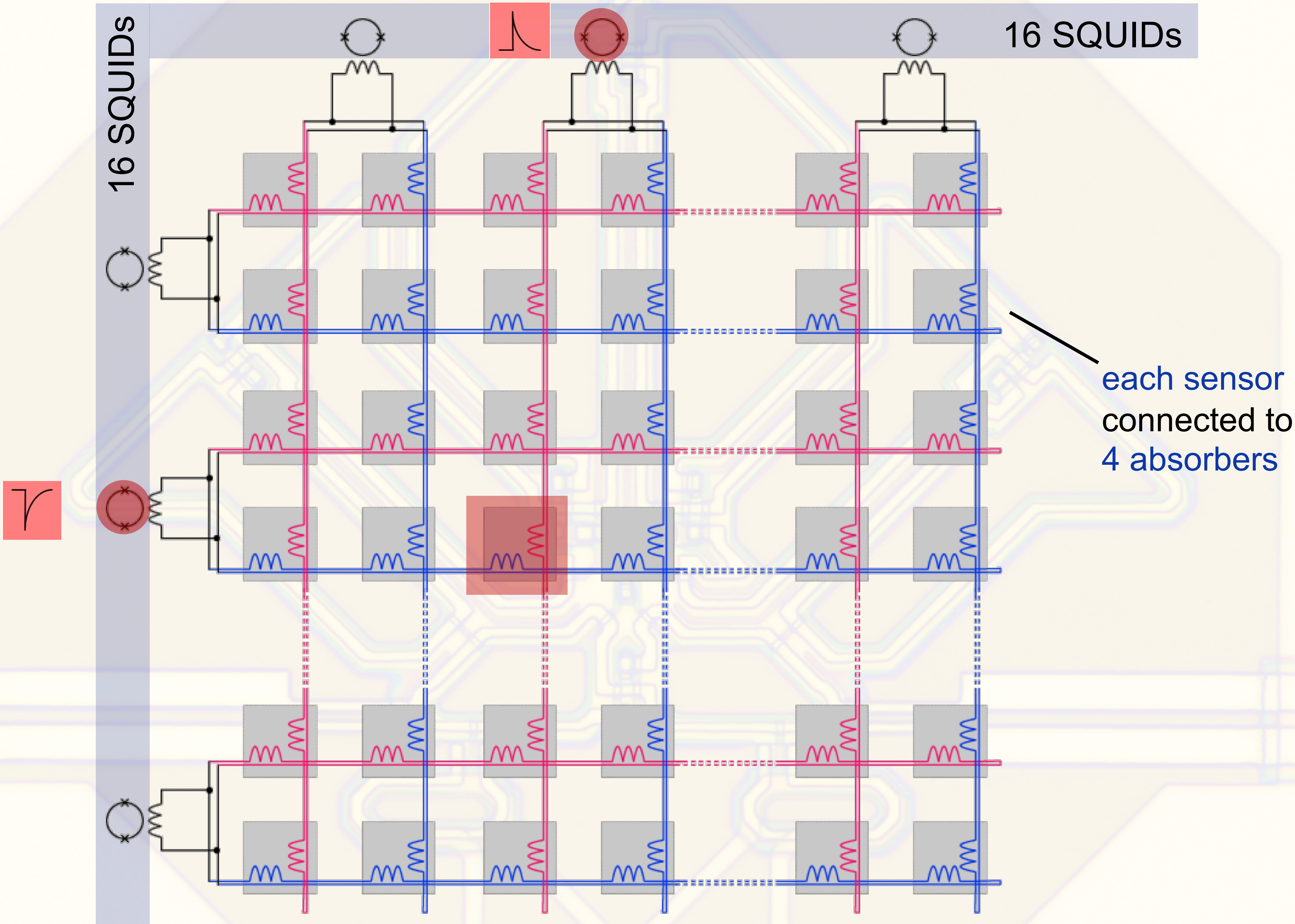
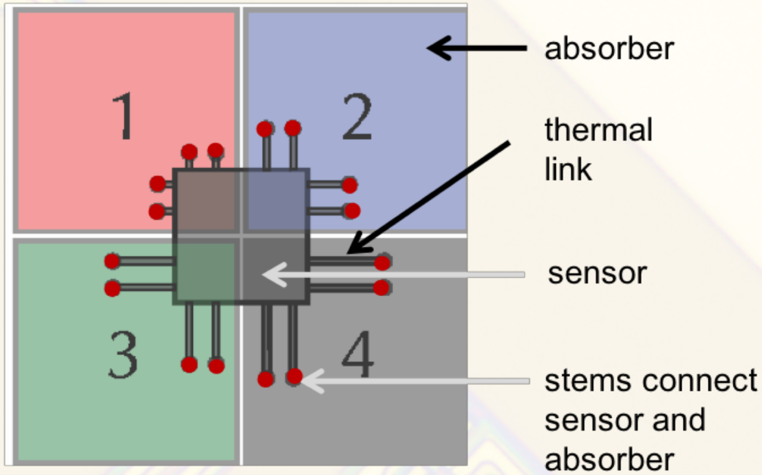
Readout Scheme of MOCCA

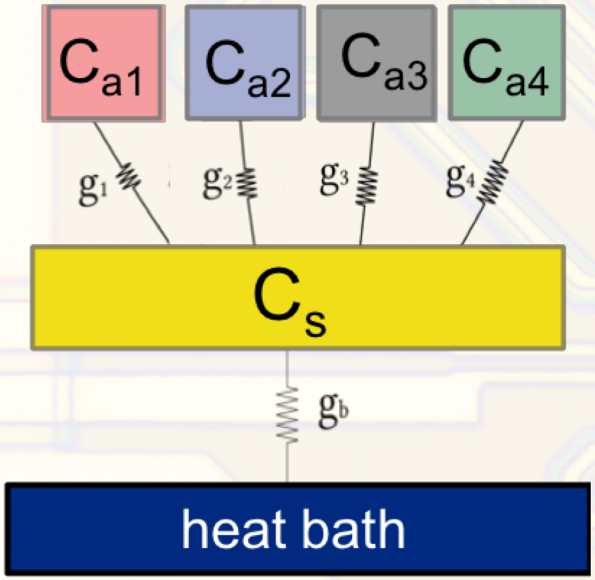


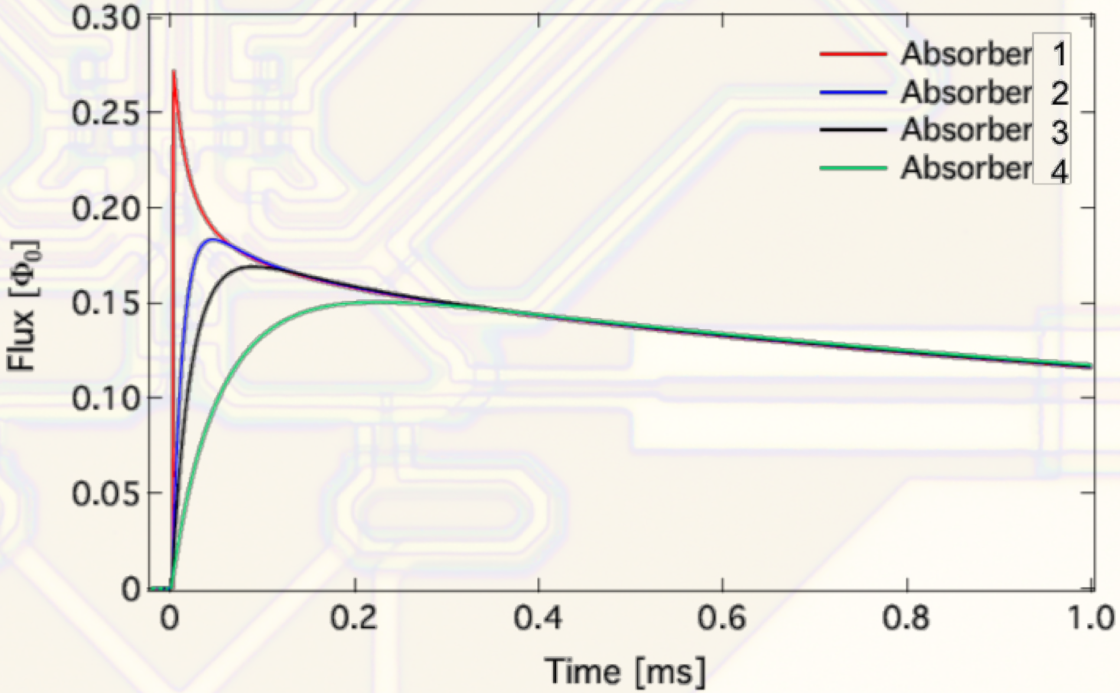
As pioneered by the NASA-Group

Porst *et al.*, AIP Conf. Proc. **1185** (2009) 599

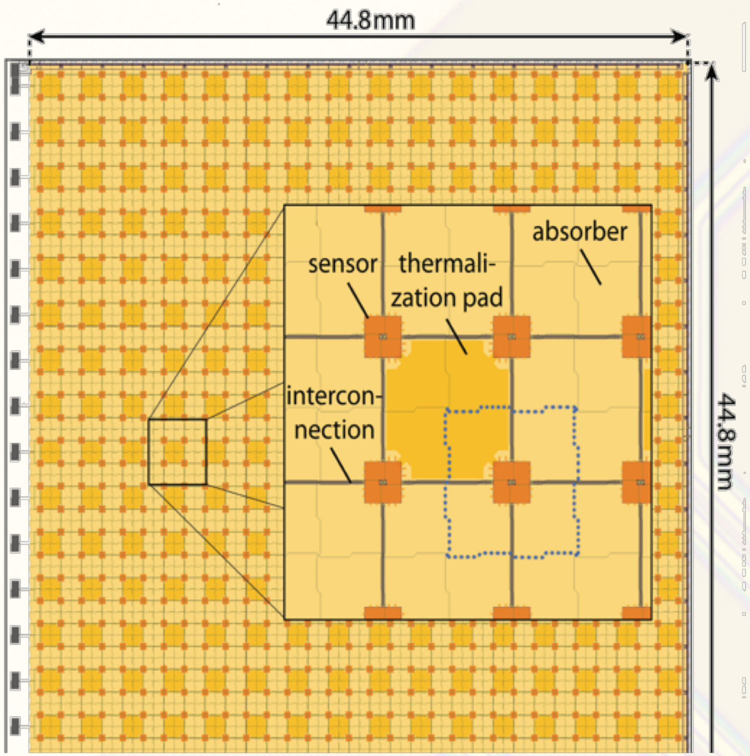


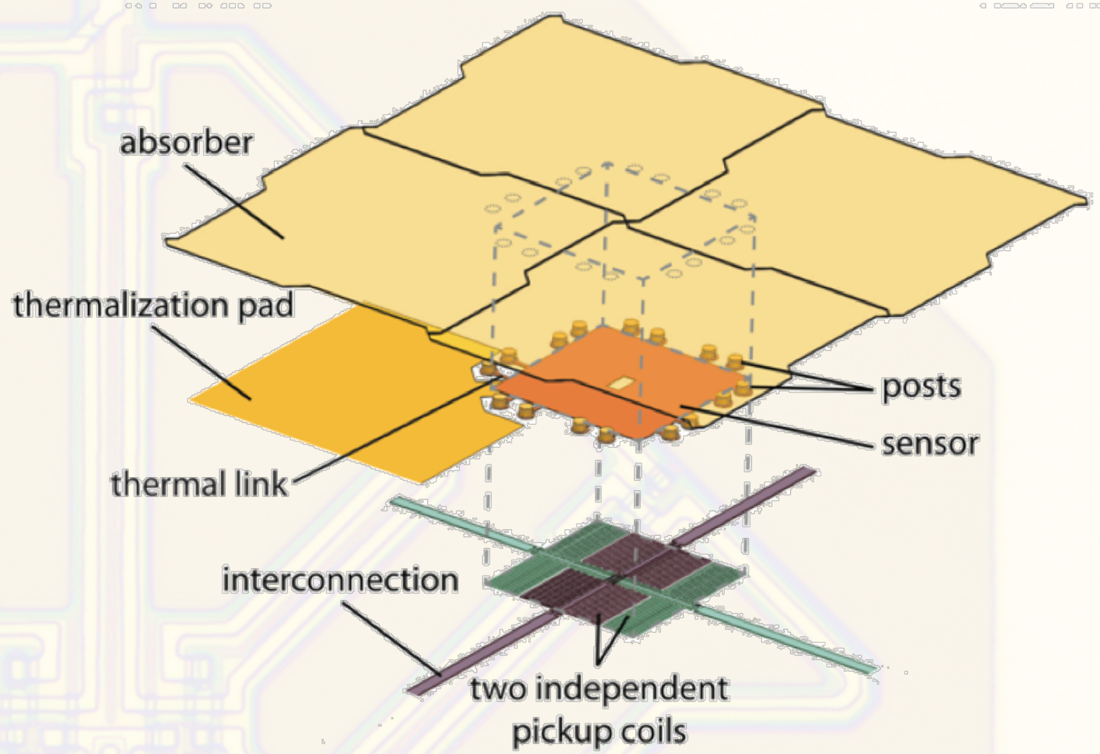
Pixel identification via rise-time of the detector signal

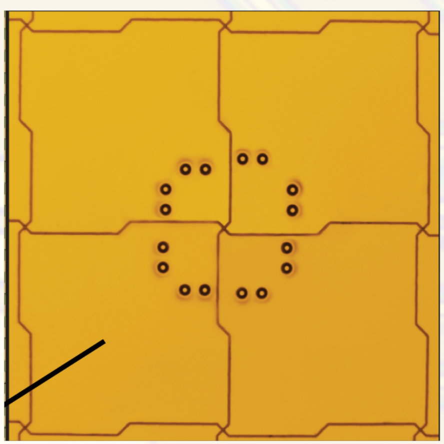




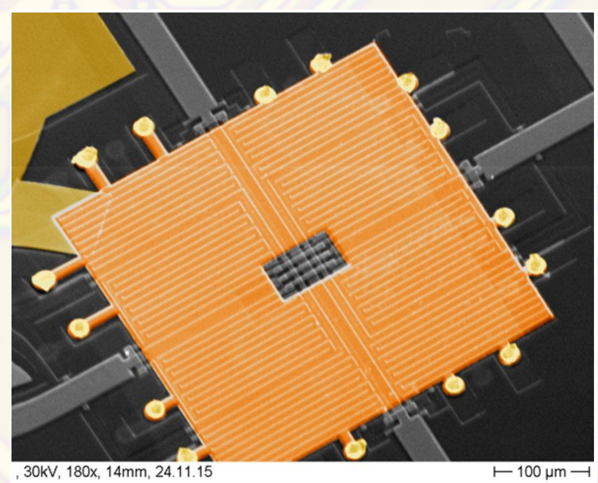
MOCCA Design and Production

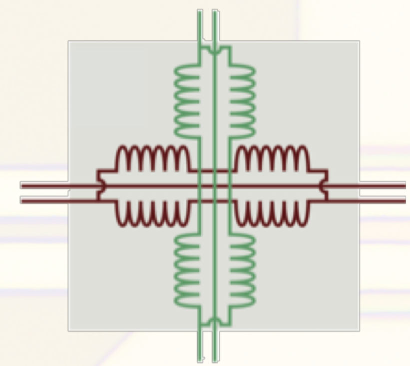




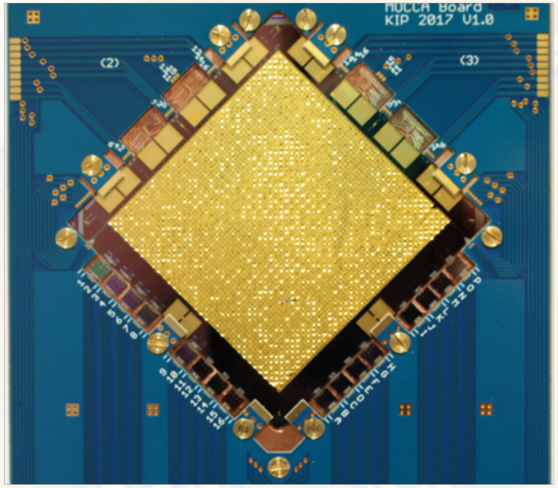


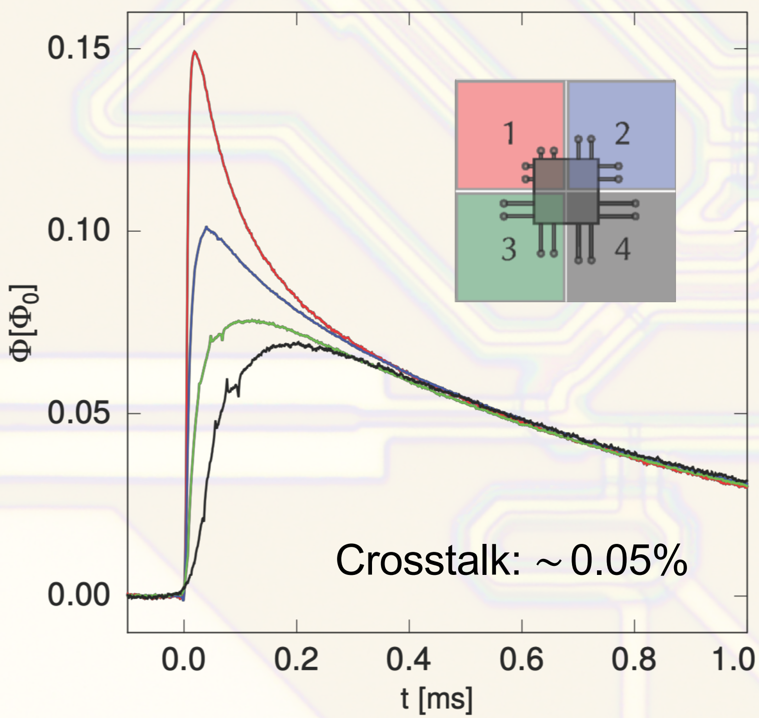
Absorber

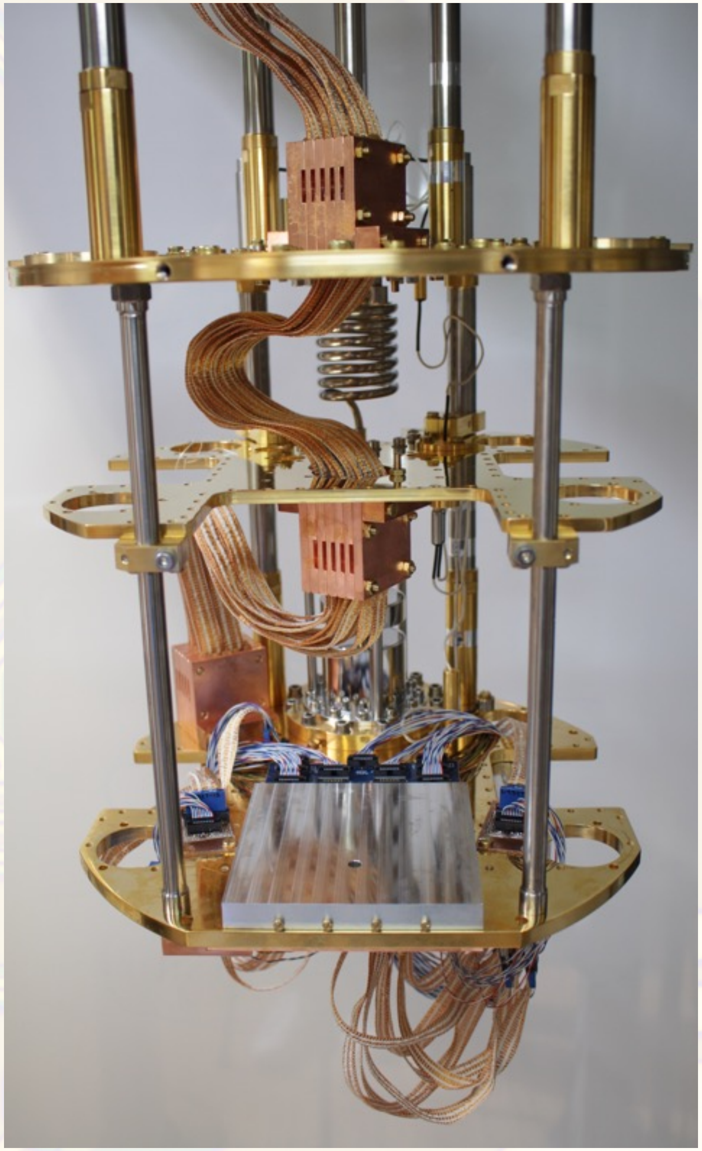




L. Gamer, *et al.*, J. Low. Temp. Phys. (2016)



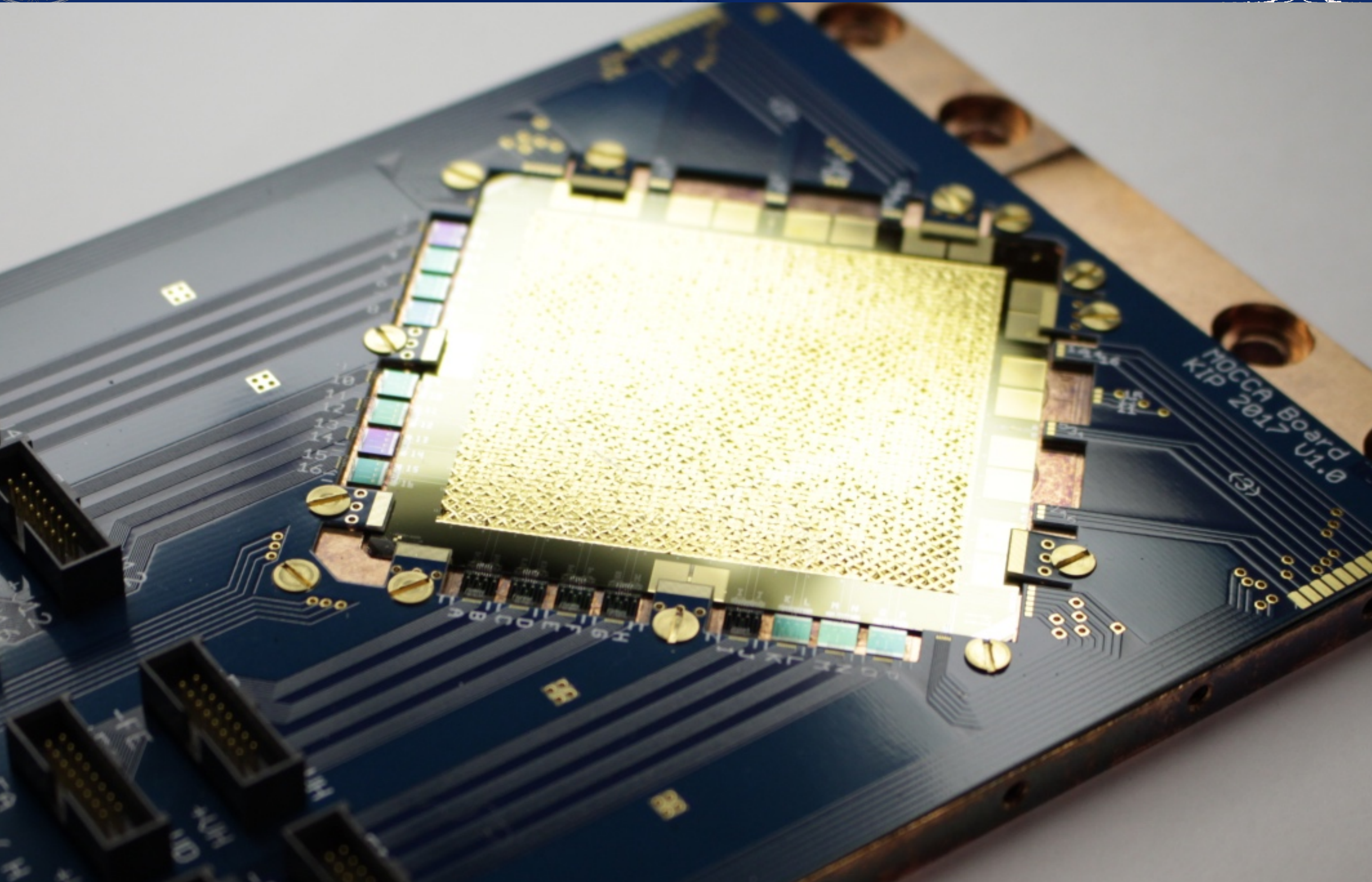




L. Gamer, to be publish (2018)

MOCCA Setup

Full MOCCA Detector



Neutrino, Dark Matter and Axion Experiments

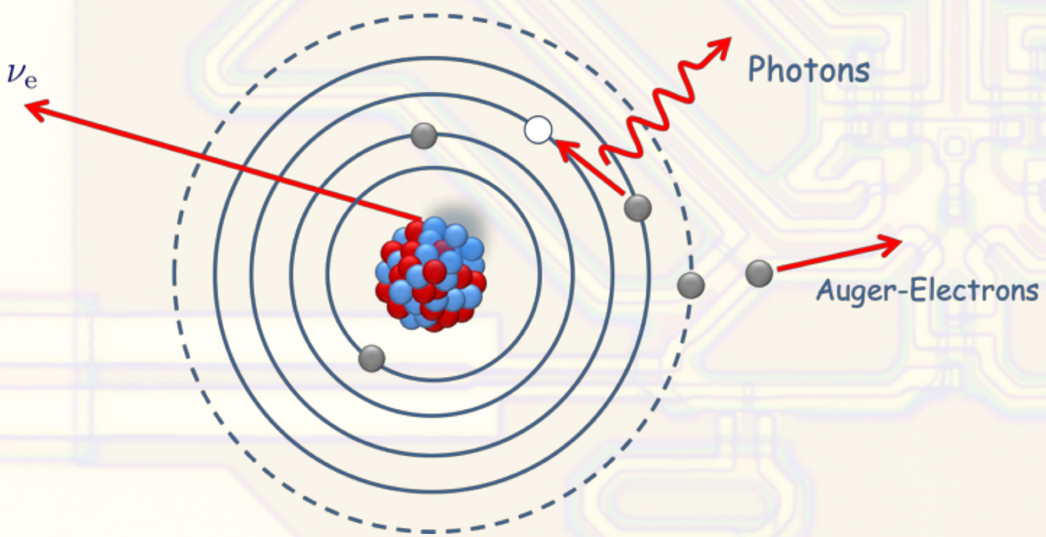
current best limits	$m(\bar{\nu}_e)$	≤	2 eV/c²	beta decay	Tritium
	$m(\nu_e)$	≤	225 eV/c²	beta capture	Holmium

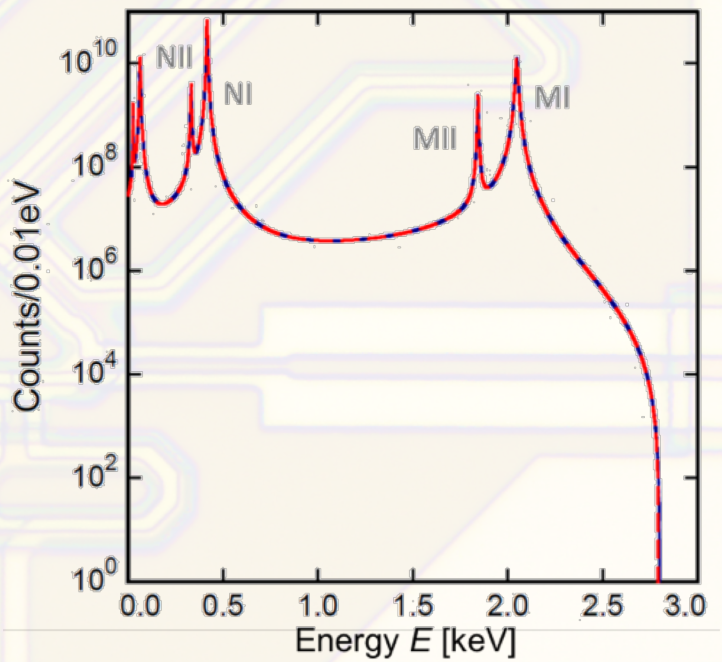
the case of ^{163}Ho

A. De Rujula, M. Lusignoli,
Phys. Lett. B **118** (1982) 429

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

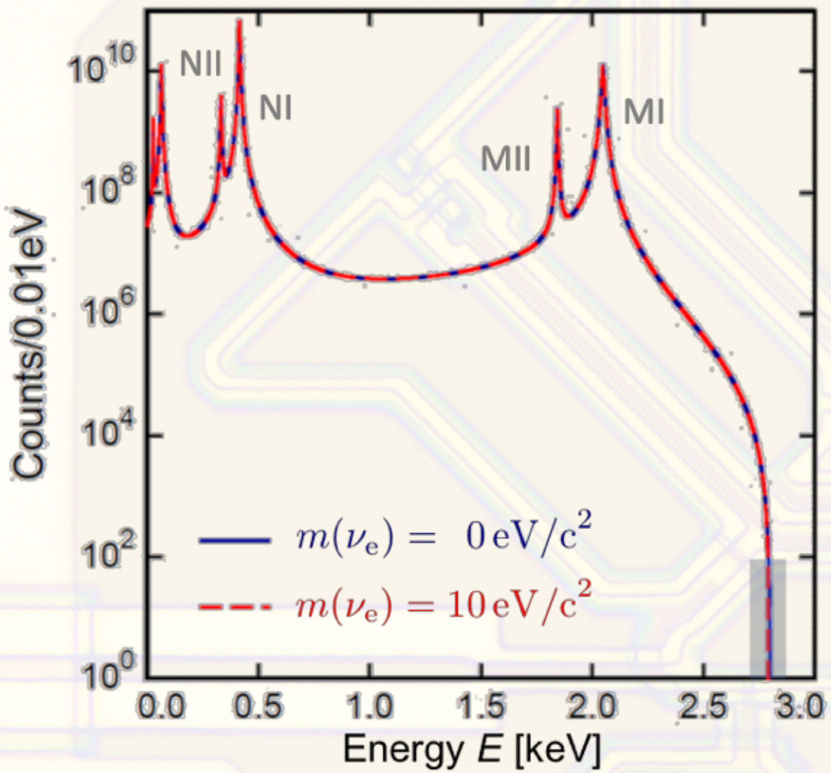
$$\hookrightarrow {}^{163}_{66}\mathrm{Dy} + E_C$$

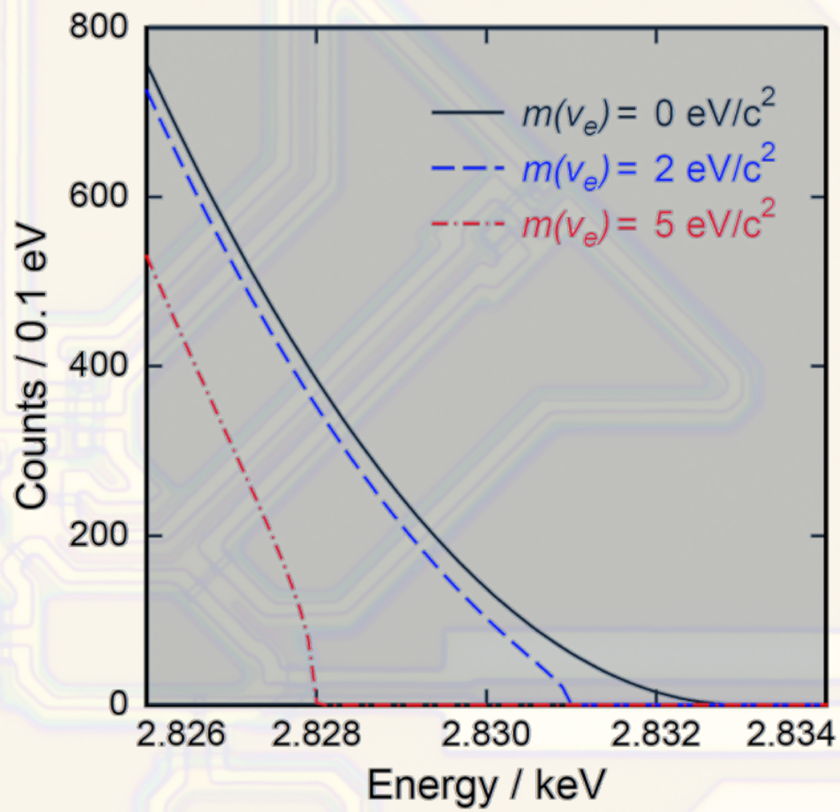




Electron Capture: The Case of ^{163}Ho

$$\frac{\mathrm{d}N}{\mathrm{d}E_\mathrm{C}} = A\,(Q_\mathrm{EC} - E_\mathrm{C})^2 \sqrt{1 - \frac{m_\nu^2}{(Q_\mathrm{EC} - E_\mathrm{C})^2}} \sum_j C_j n_j B_j \phi_j^2(0) \frac{\Gamma_j/2\pi}{(E_\mathrm{C} - E_j)^2 + \Gamma_j^2/4}$$

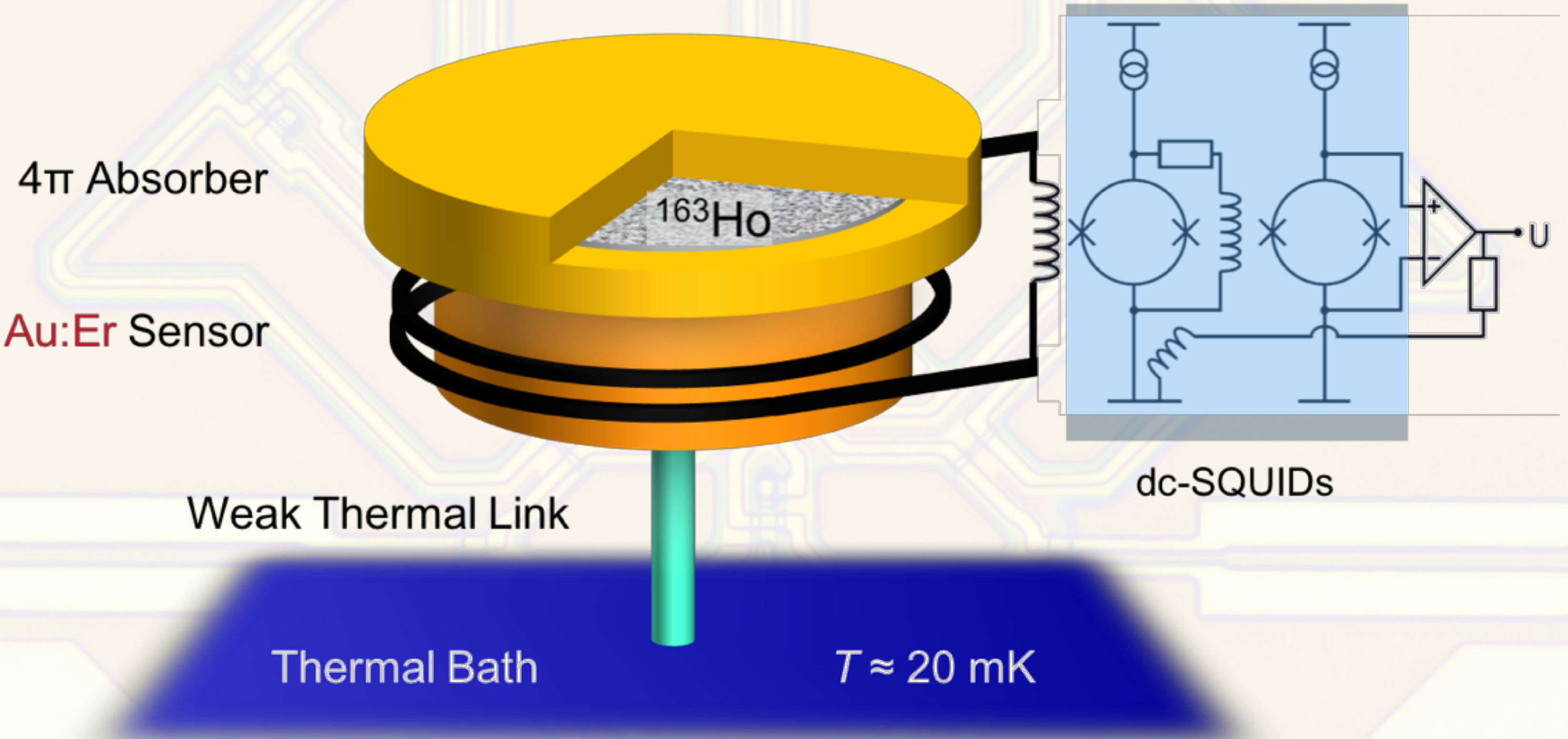




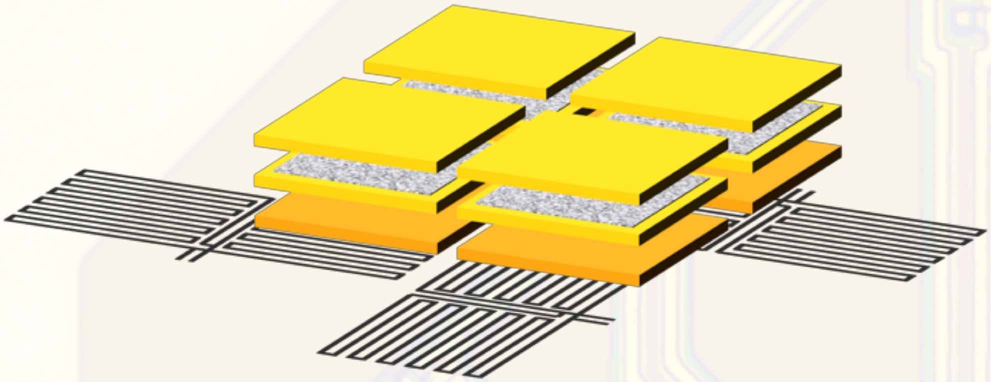
Low Q_EC = (2.833 $\pm$ 0.030$^\mathrm{stat}$ $\pm$ 0.015$^\mathrm{sys}$) keV
(2.858 $\pm$ 0.010$^\mathrm{stat}$ $\pm$ 0.050$^\mathrm{sys}$) keV

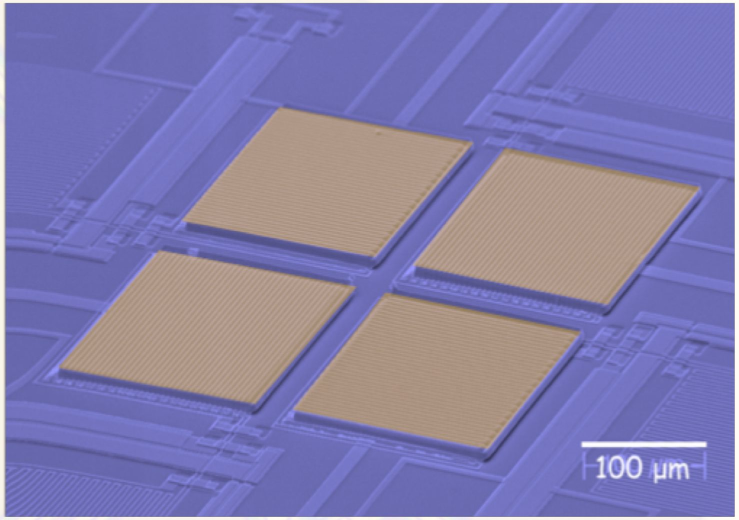
S. Eliseev *et al.*, PRL **115**, 062501 (2015)
P. Ranitzsch *et al.*, PRL **119**, 122501 (2017)

Embedding ^{163}Ho in the absorber of an MMC

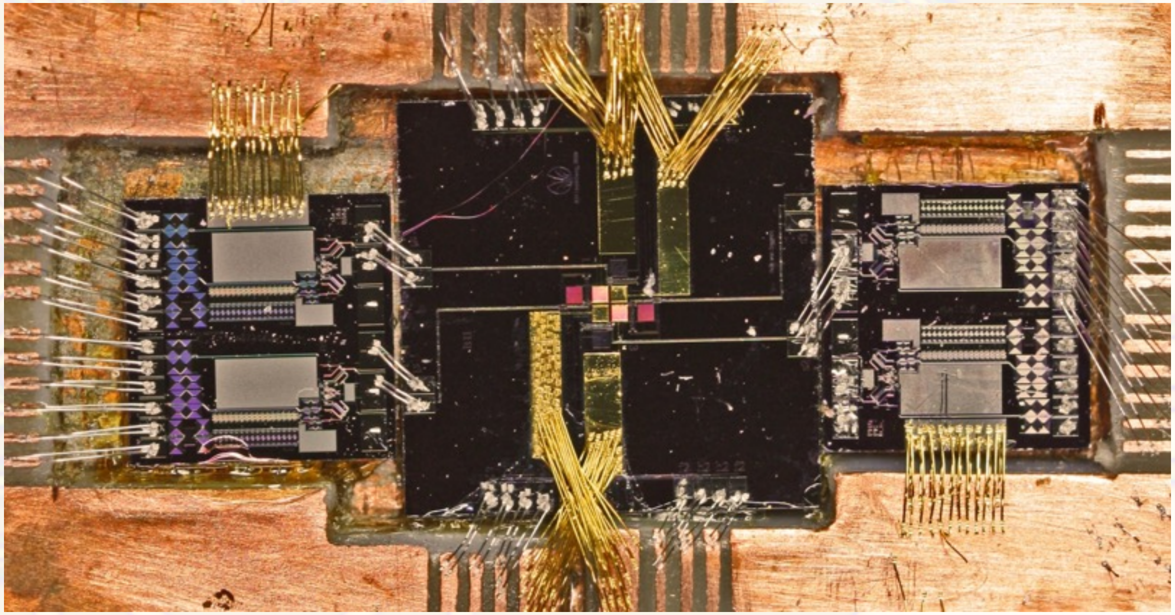


Prototype Detector ECHo-0



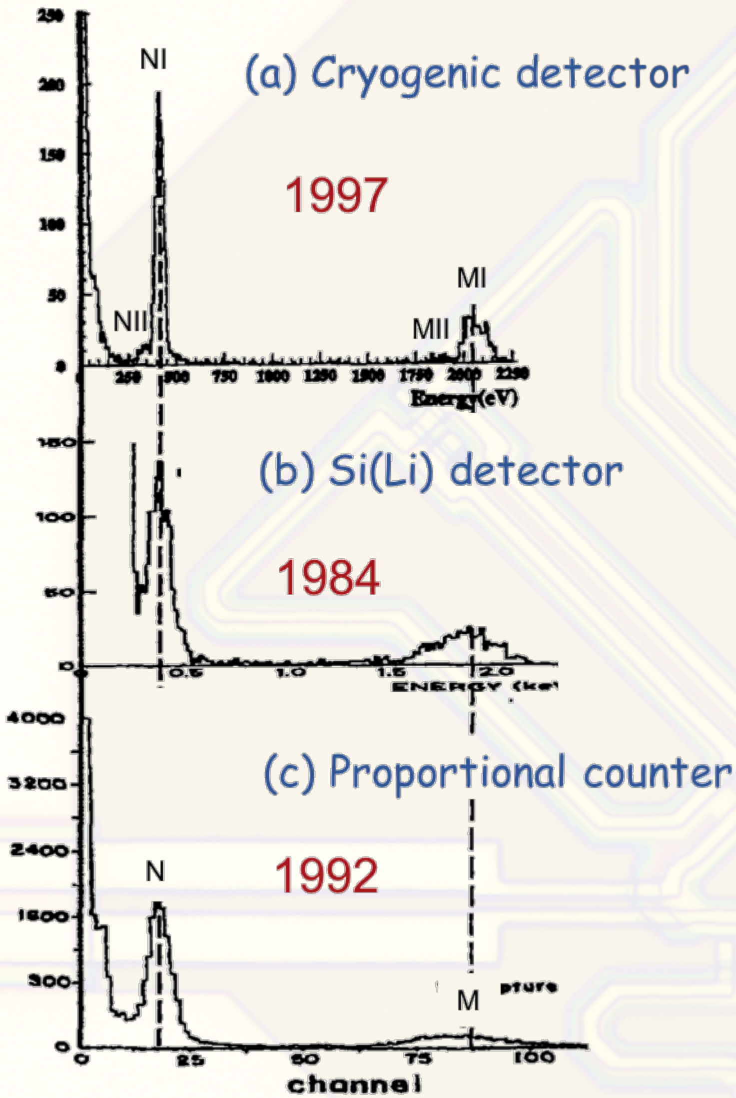


Implantation at CERN 2009



5 mm

Previous Results and First MMC Measurement

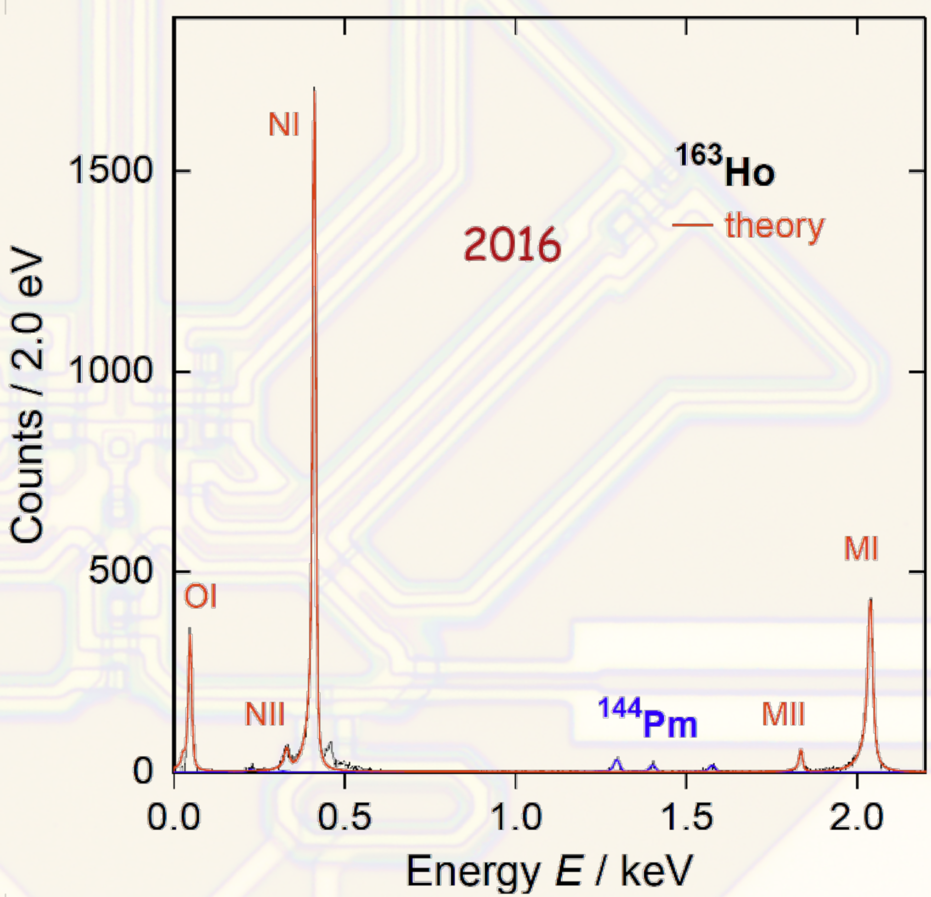


F. Gatti *et al.*, Physics Letters B **398** (1997) 415-419

(a) F. Gatti *et al.*, Physics Letters B **398** (1997) 415-419

(b) E. Laesgaard *et al.*, Proceeding of 7th International Conference on Atomic Masses and Fundamental Constants (AMCO-7), (1984).

(c) F.X. Hartmann and R.A. Naumann, Nucl. Instr. Meth. A **313** (1992) 237.



C. Hassel, *et al.*, J. Low Temp. Phys. **184,** 910 (2016)

ECHo Collaboration

Department of Nuclear Physics, Comenius University, Bratislava, Slovakia
Fedor Simkovic

Department of Physics, Indian Institute of Technology Roorkee, India
Moumita Maiti

Institute for Nuclear Chemistry, Johannes Gutenberg University Mainz
Christoph E. Düllmann, Holger Dorrer, Klaus Eberhard, Fabian Schneider

Institute of Nuclear Research of the Hungarian Academy of Sciences
Zoltán Szúcs

Institute of Nuclear and Particle Physics, TU Dresden, Germany
Kai Zuber

Institute for Physics, Johannes Gutenberg-Universität
Tom Kieck, Klaus Wendt

Institute for Theoretical and Experimental Physics Moscow, Russia
Mikhail Krivoruchenko

Institute for Theoretical Physics, University of Tübingen, Germany
Amand Fäßler

Kirchhoff-Institute for Physics, Heidelberg University, Germany
Christian Enss, Loredana Gastaldo (Spokesperson), Andreas Fleischmann
Clemens Hassel, Sebastian Kempf, Mathias Wegner

Max-Planck Institute for Nuclear Physics Heidelberg, Germany
Klaus Blaum, Andreas Dörr, Sergey Eliseev, Mikhail Goncharov, Yuri N. Novikov, Alexander Rischka, Rima Schüssler

Petersburg Nuclear Physics Institute, Russia
Pavel Filianin, Yuri Novikov

Physics Institute, University of Tübingen, Germany
Josef Jochum, Stephan Scholl

Saha Institute of Nuclear Physics, Kolkata, India
Susanta Lahiri

Institut Laue-Langevin, Grenoble, France
Ulli Köster

Institute for Physics, Humboldt Universität zu Berlin, Germany
Alejandro Saenz

Goethe Universität Frankfurt am Main, Germany
Udo Kebschull, Panagiotis Neroutsos

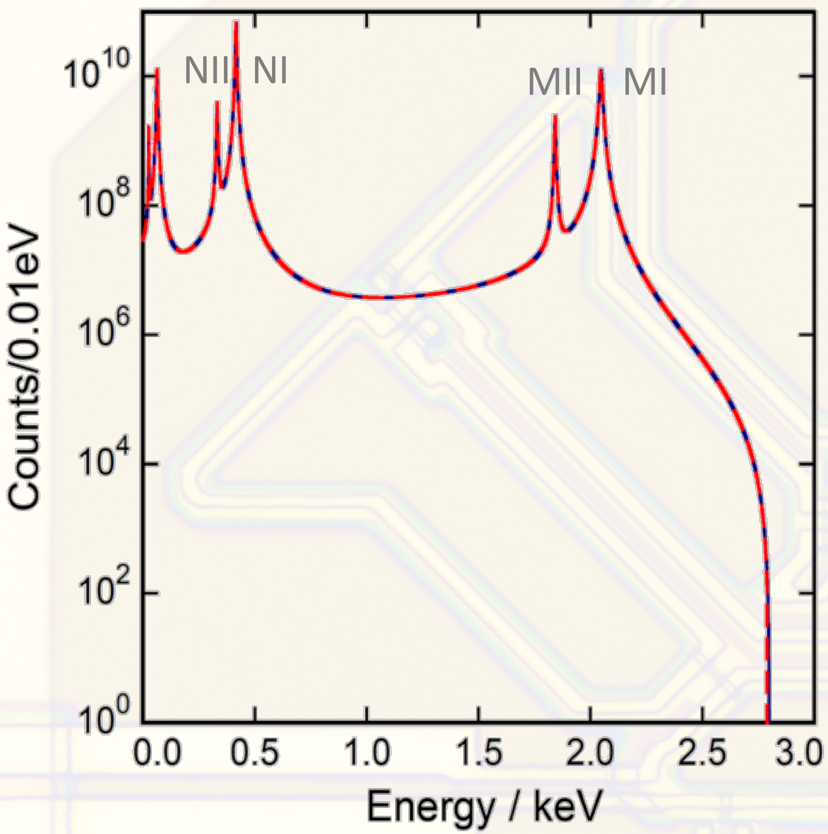
Institute for Theoretical Physics, Heidelberg University, Germany
Maurtis Haverkort, Martin Brass

Funded by the Germany Research Foundation DFG

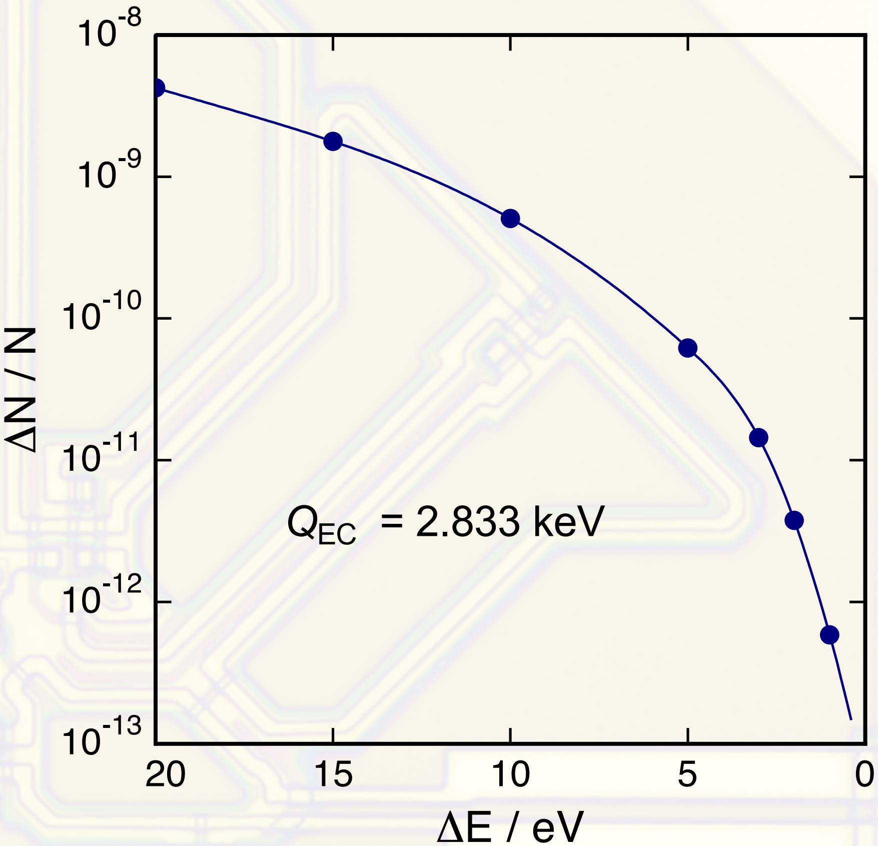
DFG Deutsche Forschungsgemeinschaft

FOR 2202 ECHo

The Electron Capture in ^{163}Ho experiment - ECHo
L. Gastaldo *et al.*, Eur. Phys. J Special Topics. **226** (2017) 1623-1694



fraction of counts in endpoint region



in last 1 eV interval only 6×10^{-13} counts

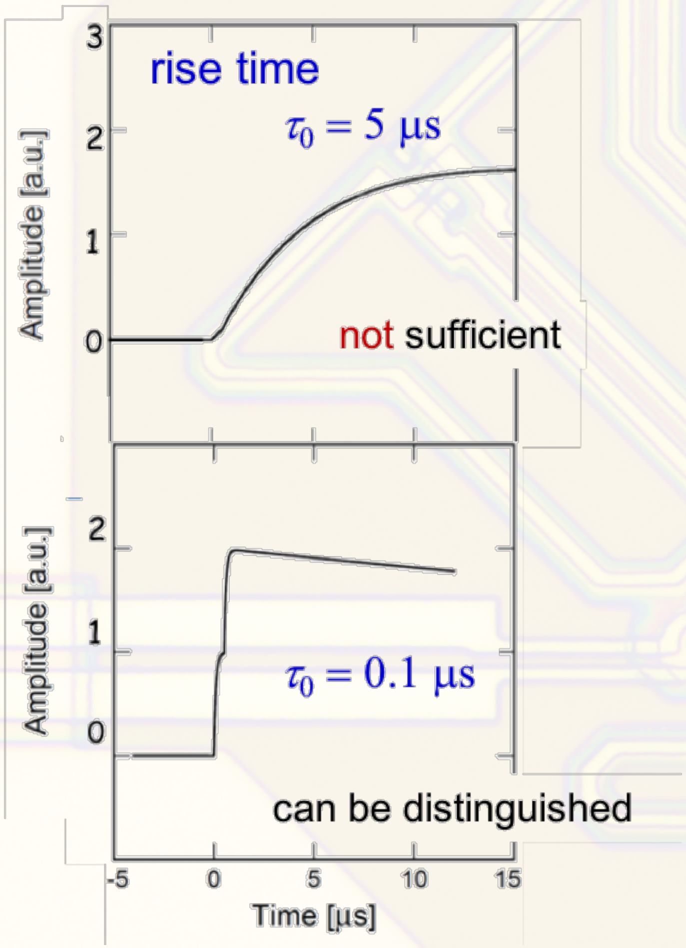
more than 10^{14} total number of counts needed

Requirement For ECHo: Detector Speed

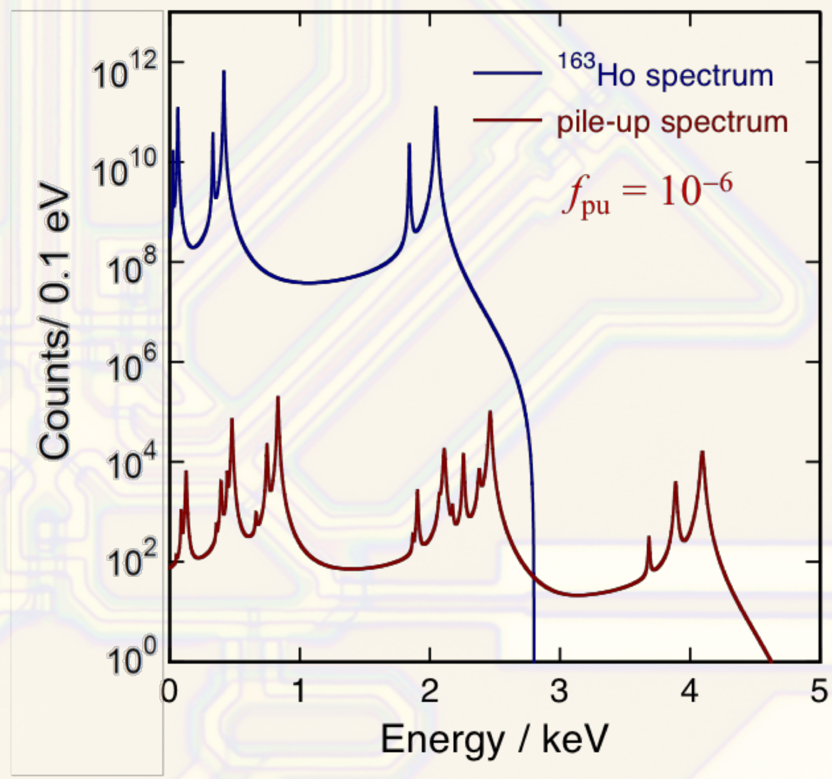
unresolved pile-up fraction: $f_{pu} = A_p \cdot \tau_0$

activity per pixel — signal rise time

two events 0.5 ms apart



pile-up spectrum

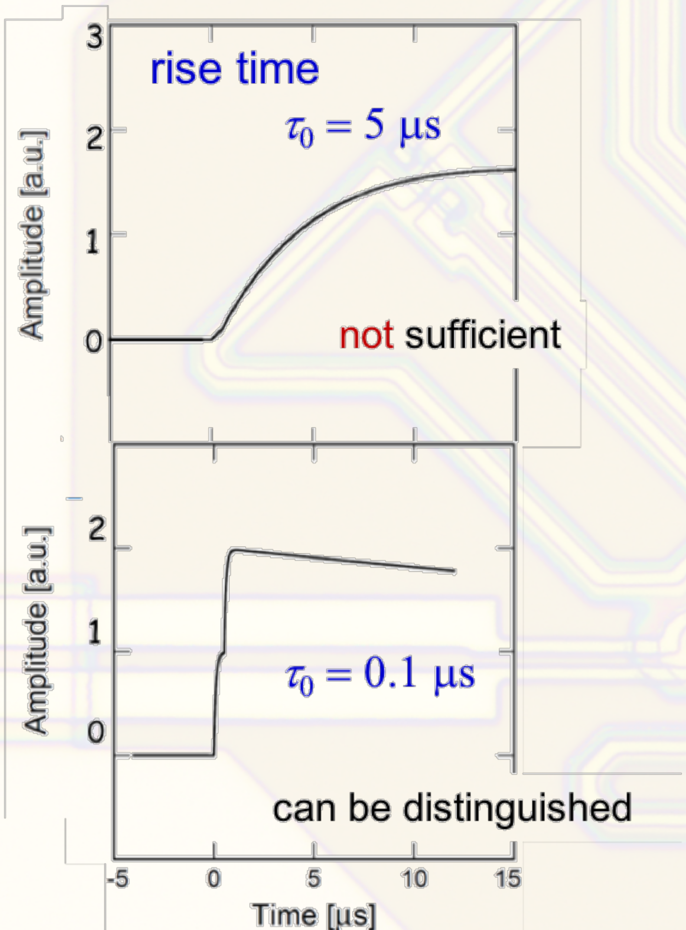


$\Rightarrow$ $f_{pu} < 10^{-5}$ $\Rightarrow$ A_p = 10 Bq, $\tau_0 < 1\mu s$

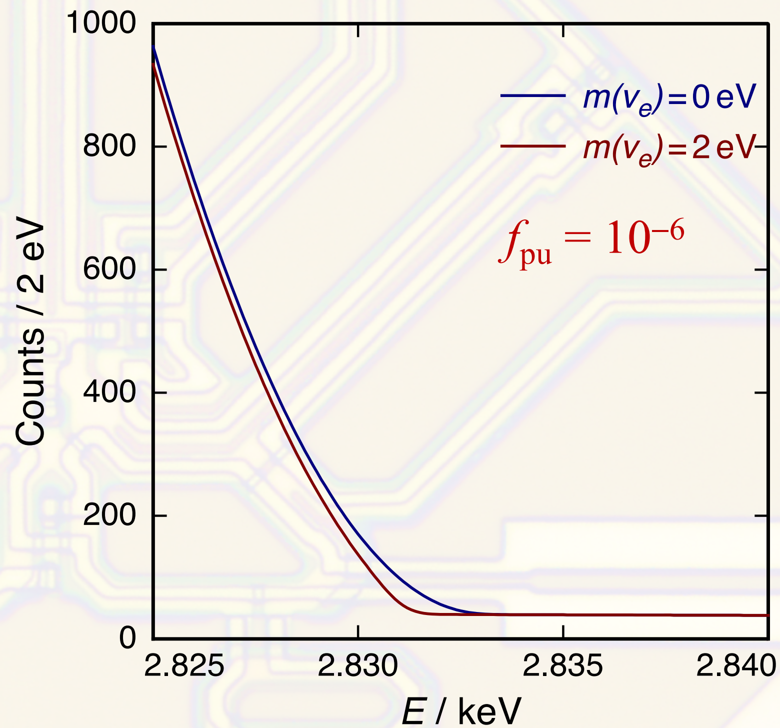
unresolved pile-up fraction: $f_{pu} = A_p \cdot \tau_0$

activity per pixel — signal rise time

two events 0.5 ms apart

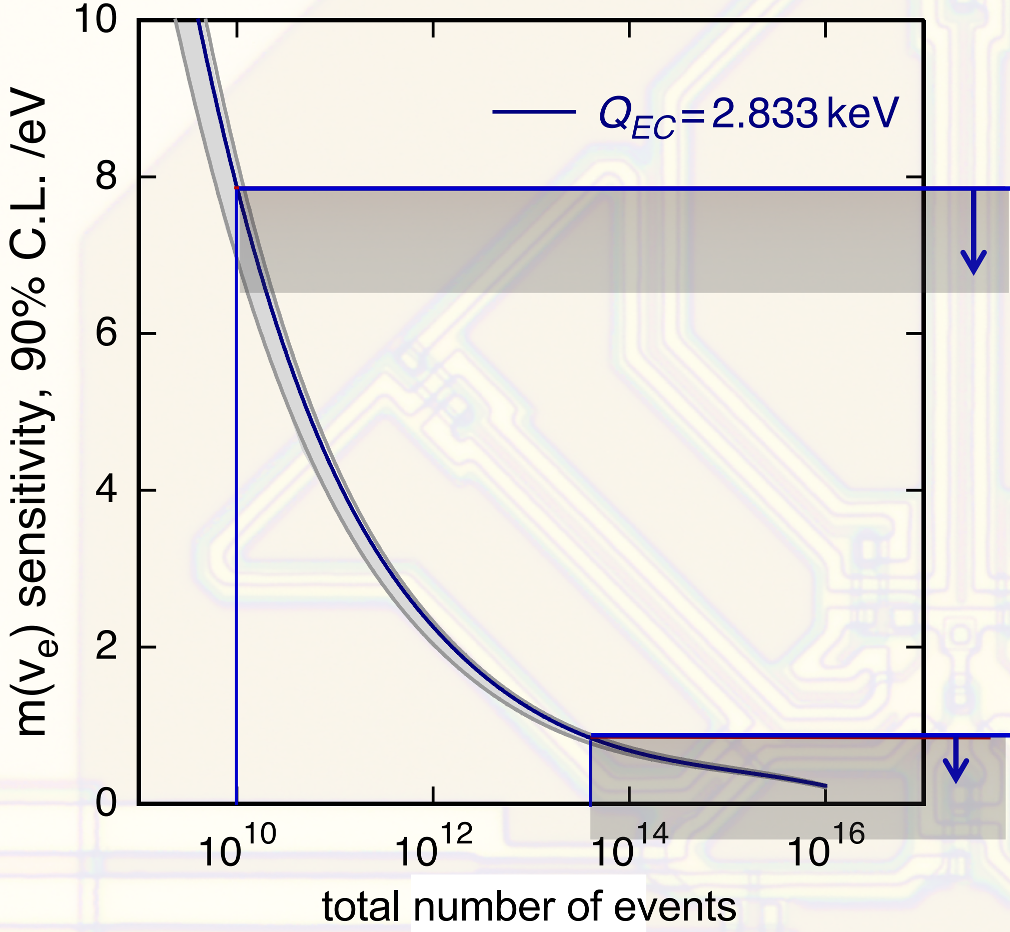


spectrum in endpoint region



$\Rightarrow f_{pu} < 10^{-5} \Rightarrow$ A_p = 10 Bq, $\tau_0 <$ 1µs

Sensitivity for $\Delta E_{\mathrm{FWHM}} = 3\ \mathrm{eV}$ and $f_{pu} = 10^{-5}$



ECHo-1k

2 × 50 pixel × 10 Bq

4 months → 10^{10} events

sub 10 eV resolution

ECHo-100k

50 × 200 pixel × 10 Bq

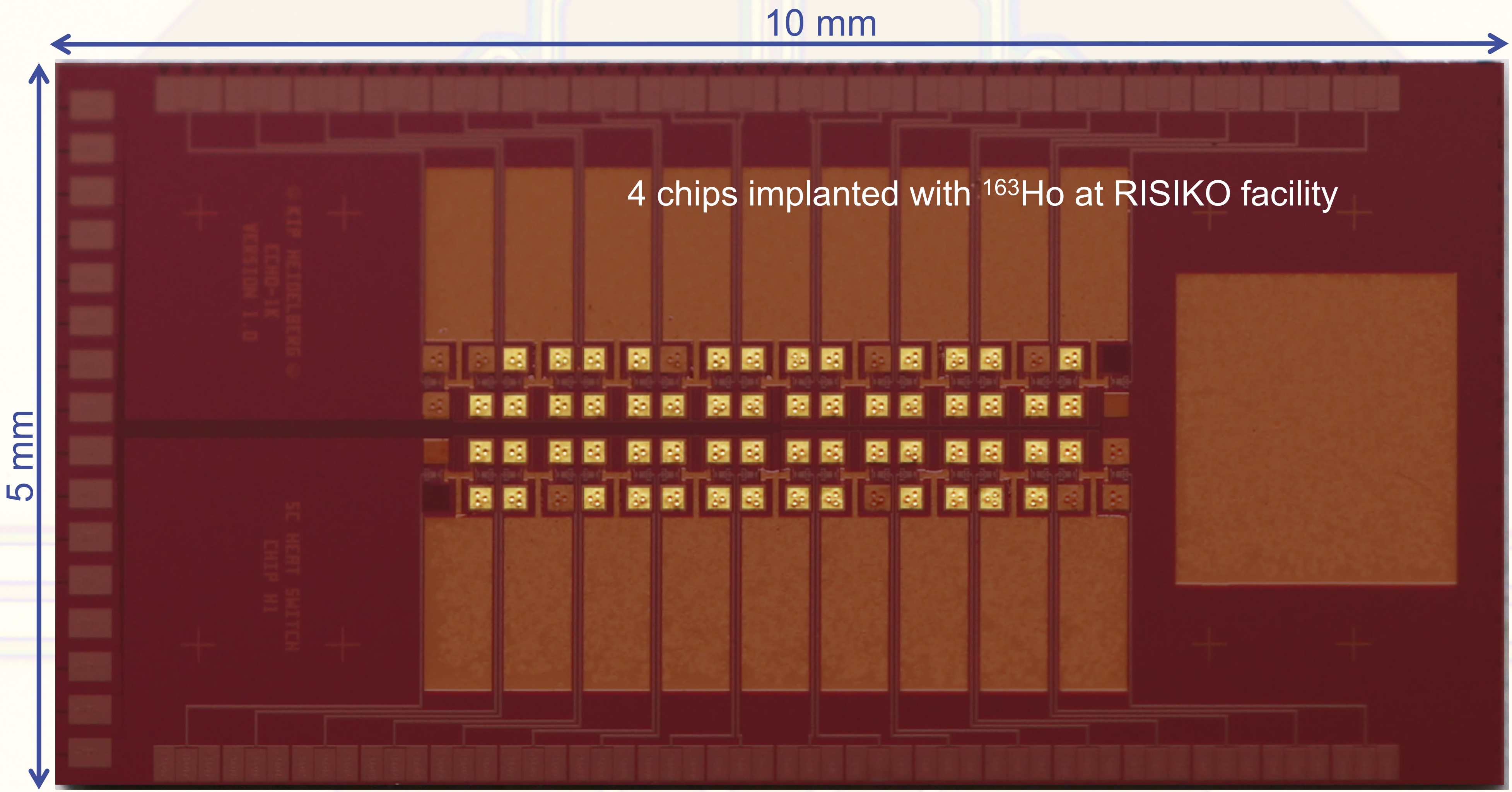
36 months → 3 × 10^{13} events

sub 2 eV resolution

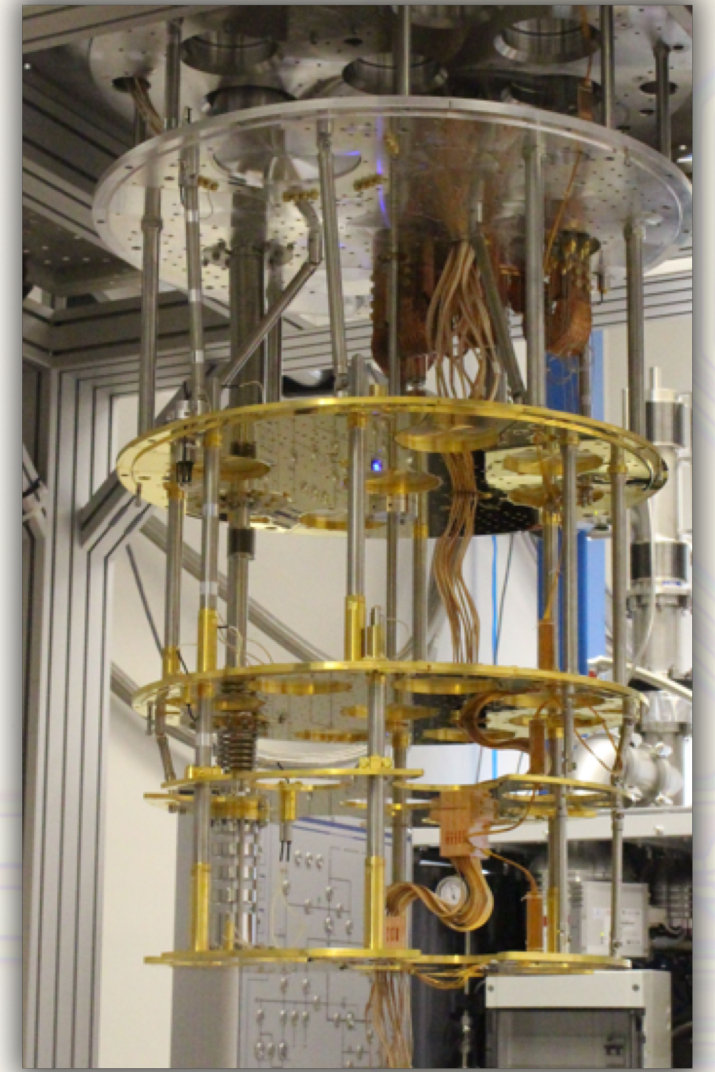
New ECHo-1k Detector Chip

ECHo-1k array: 64 pixels to be loaded with ^{163}Ho

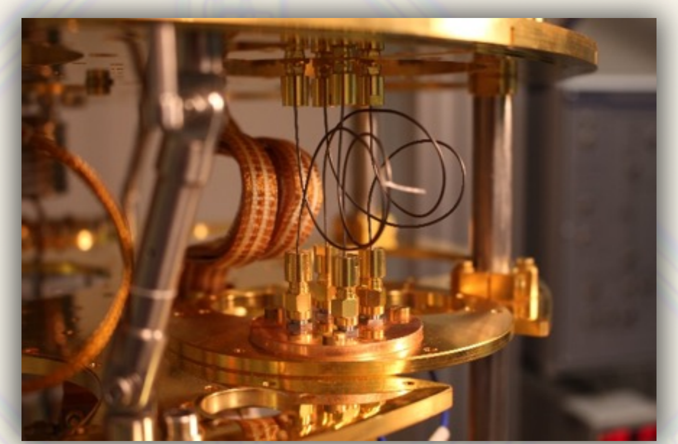
+ 4 detectors for diagnostics

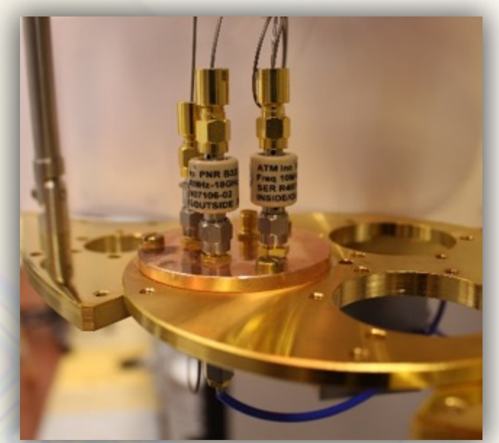


Cryogenic Platform For ECHo

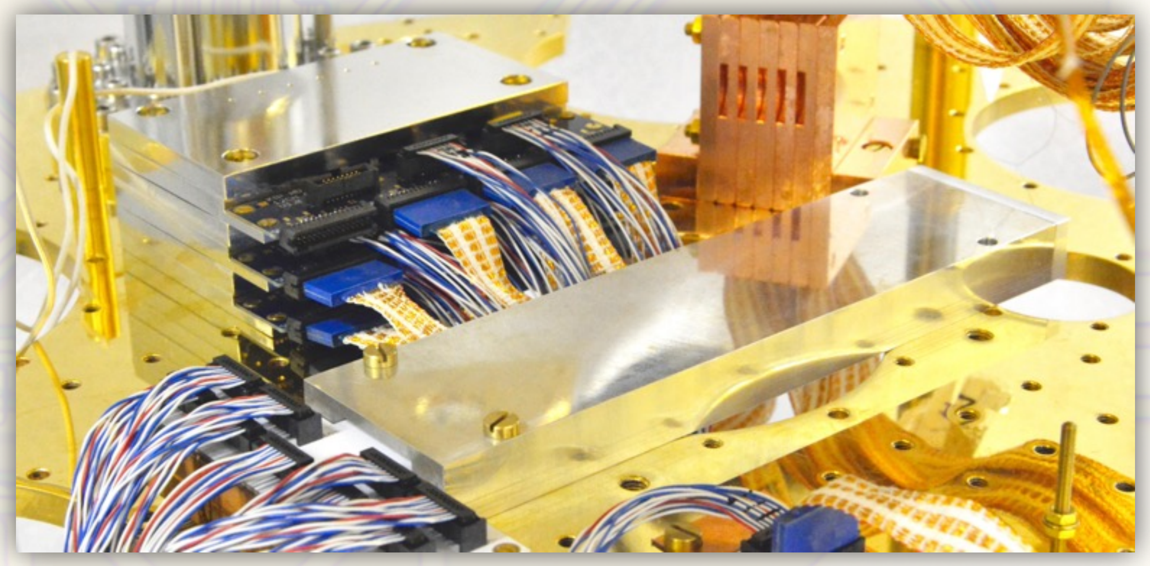


installation of two cryogenic microwave setups





dc wiring and SQUID array installation



ultra-high sensitivity and ultra-fast *T*-stabilization system

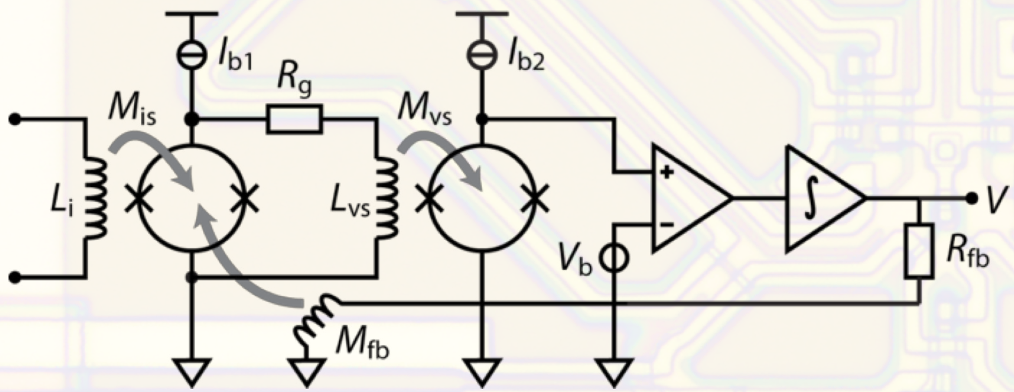
Requirements for ECHo: Scalability

ECHo-1k: ~ 50 detectors → ECHo-100k: > 5.000 detectors → ...

how to read out a large number of detectors ?

single channel readout:

10 wires, 2 SQUIDs, 1 electronics



number of wires
parasitic heat load
costs
complexity

$\Big\} \sim N$

multiplexed readout:

~ 1000 detectors per readout cannel

possible schemes: FDM, CDM, TDM, …

↓

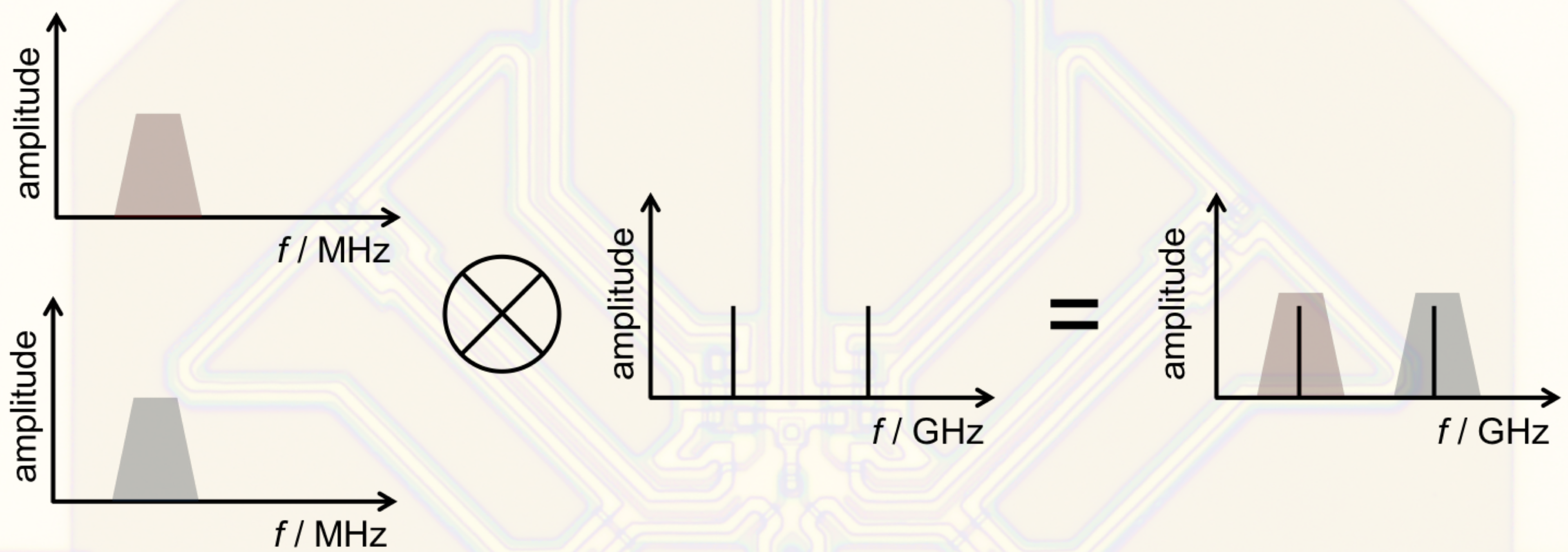
readout techology of ECHo

↓

scalability

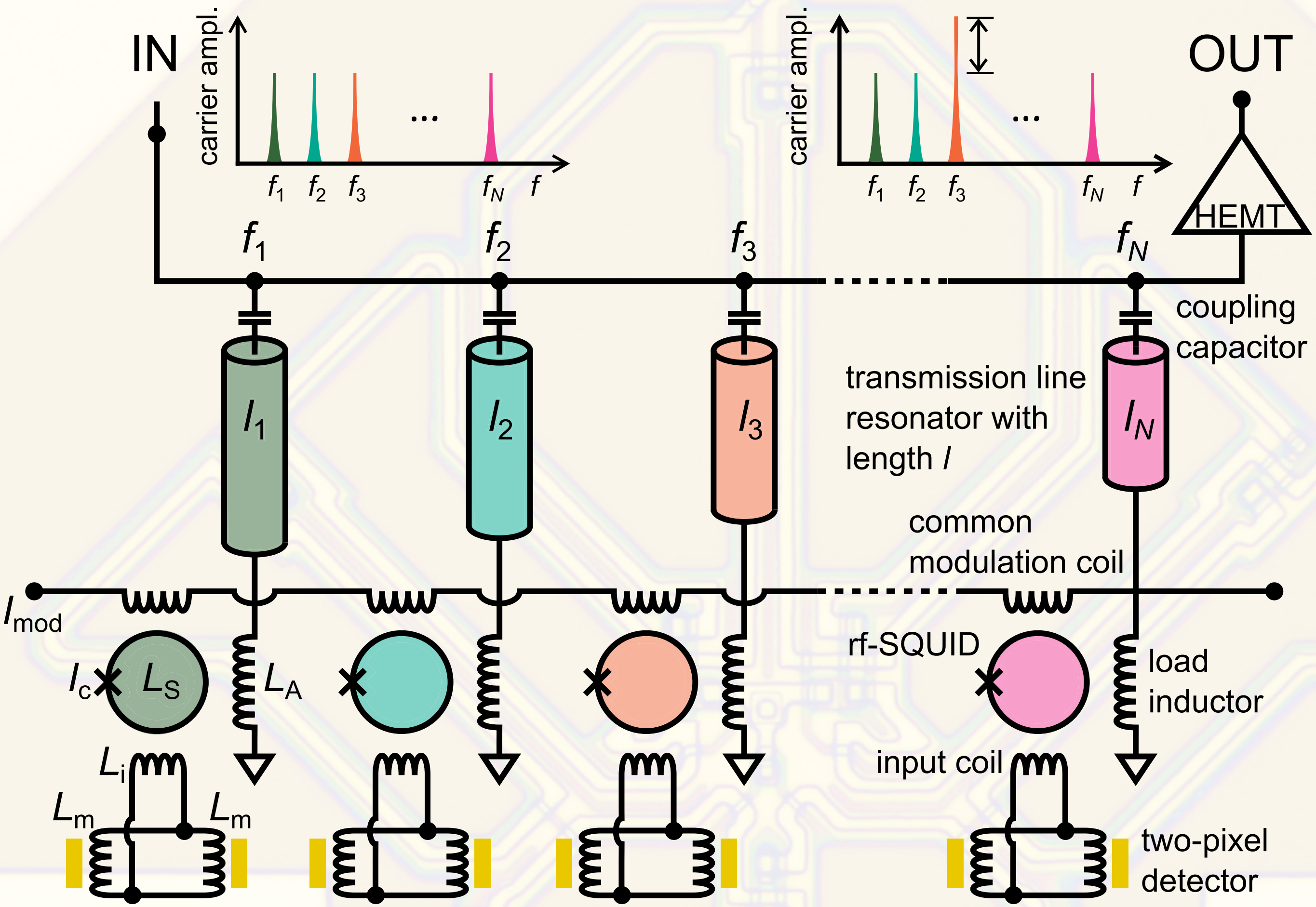
SQUID Multiplexing Techniques

idea: detector signal is modulated on a GHz carrier



- different carrier frequencies
- non-linear element for mixing

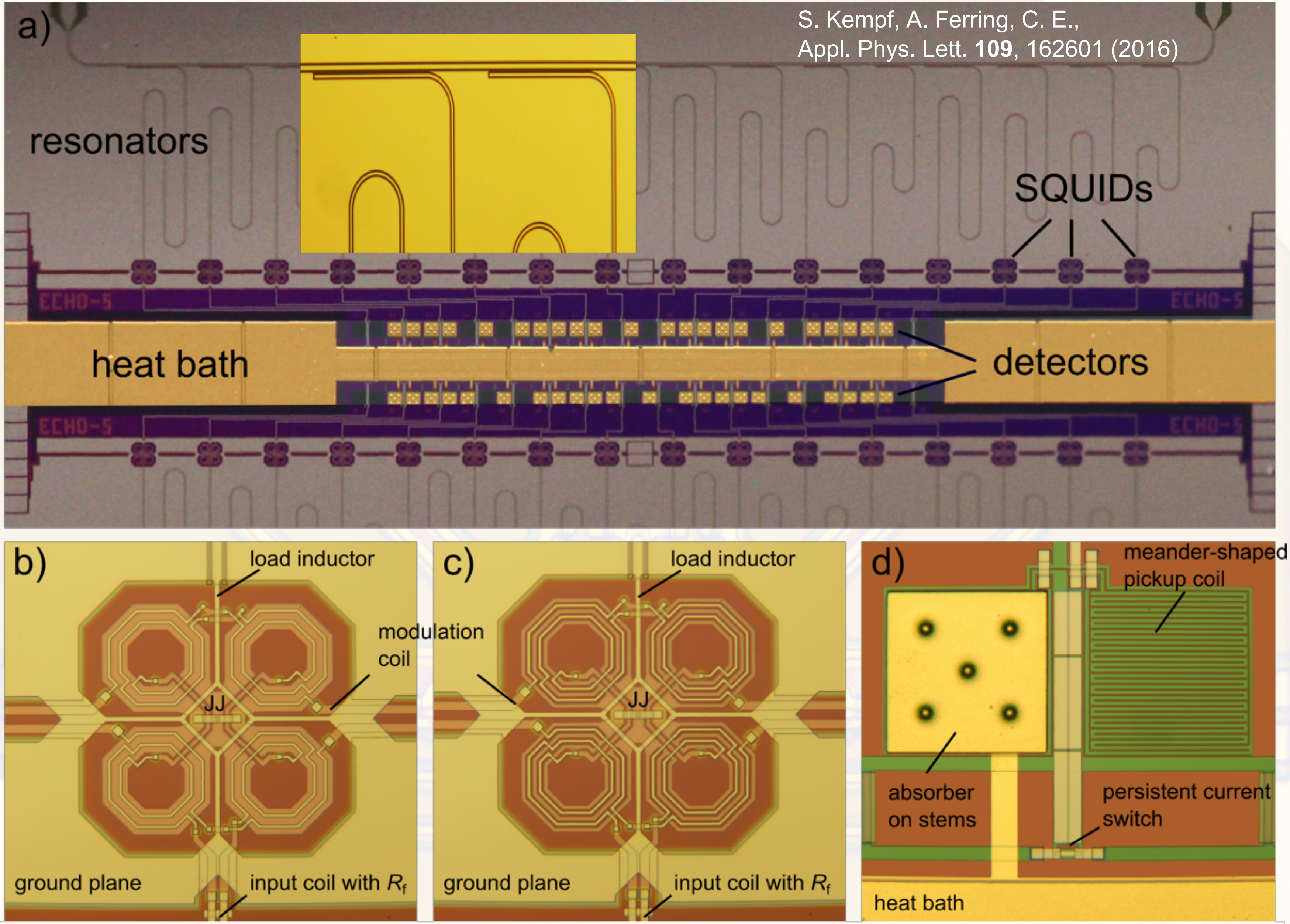
Microwave SQUID Multiplexer (μMUX)



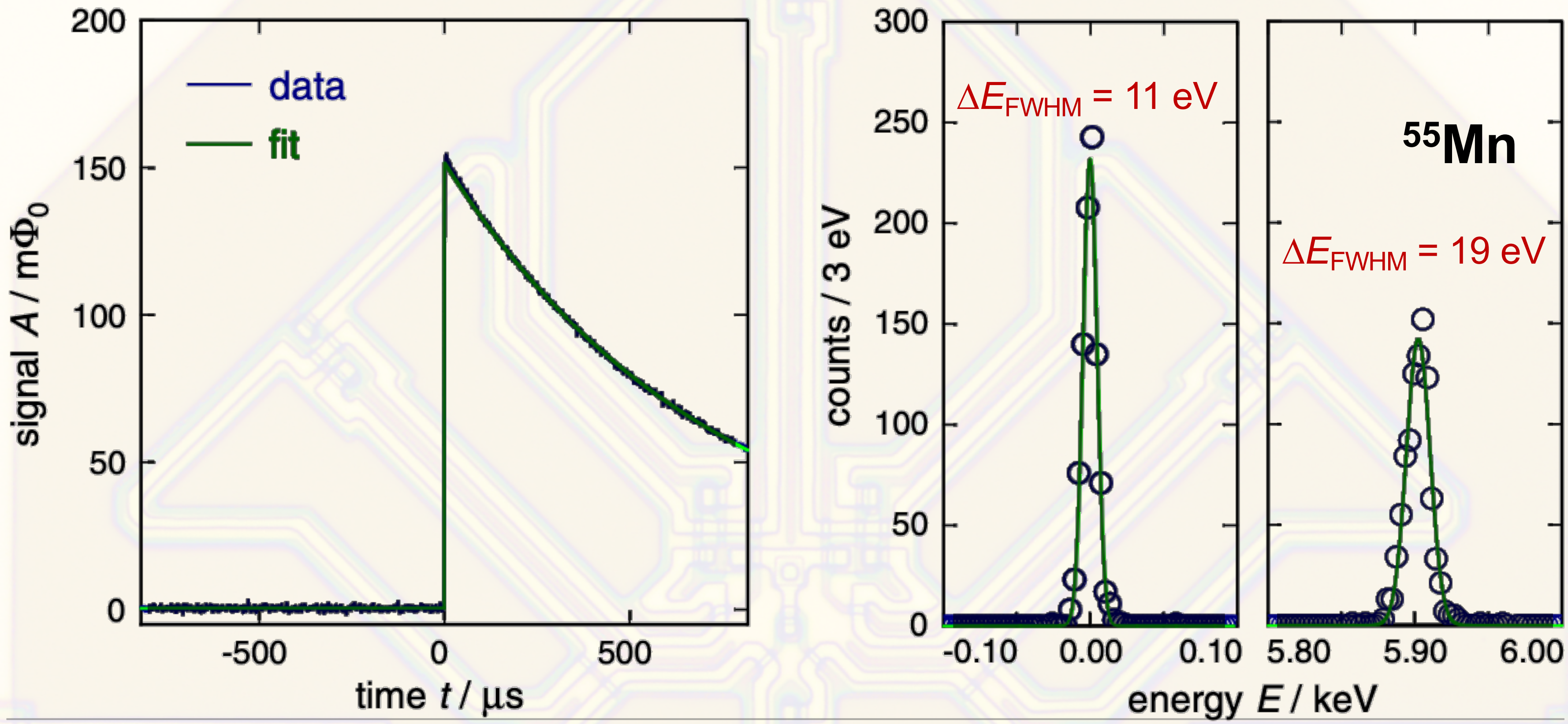
array readout using only one HEMT amplifier and two coaxes

K. Irwin and K. Lehnert, Appl. Phys. Lett. **85**, 2107-9 (2004)
J.A.B. Mates *et al*., Appl. Phys. Lett. **92**, 023514 (2008)
S. Kempf, L. Gastaldo, A. Fleischmann, C. E., J. Low. Temp. Phys. **175,** 850 (2014)
M. Wegner, *et al*., J. Low. Temp. Phys. **193,** 462 (2018)

Microwave SQUID Multiplexer (µMUX01)



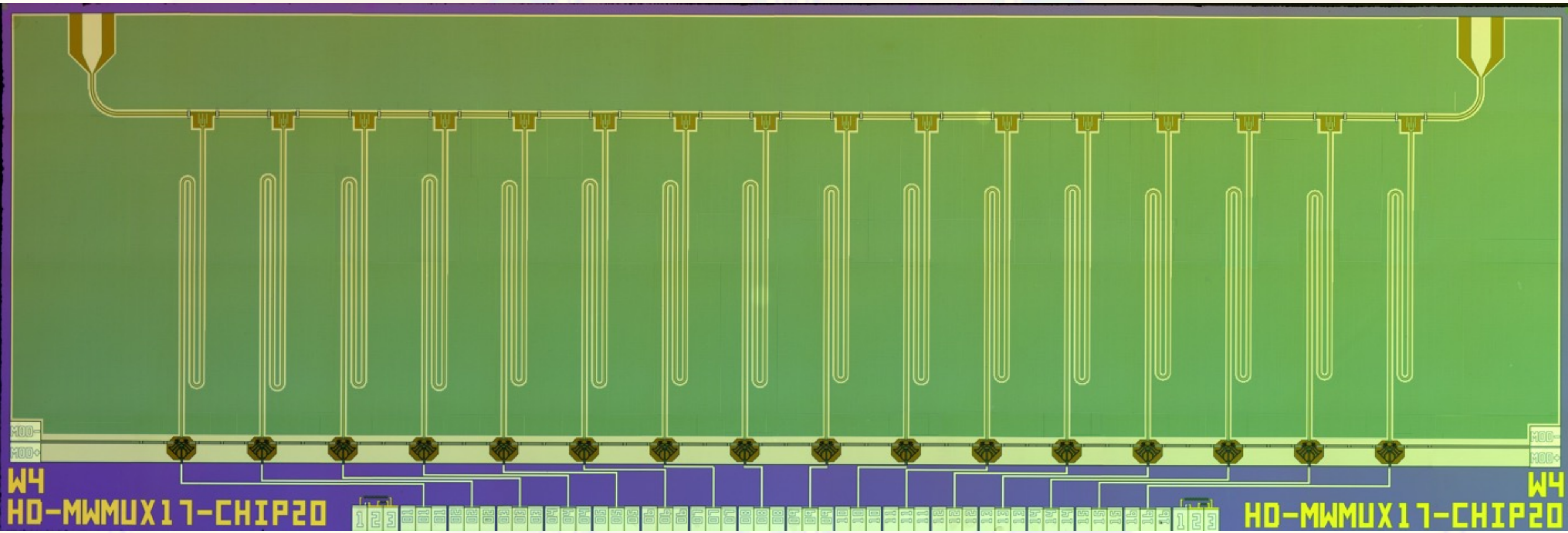
Resolution With First Prototype µMUX01



energy resolution roughly consistent with measured signal size and noise spectra

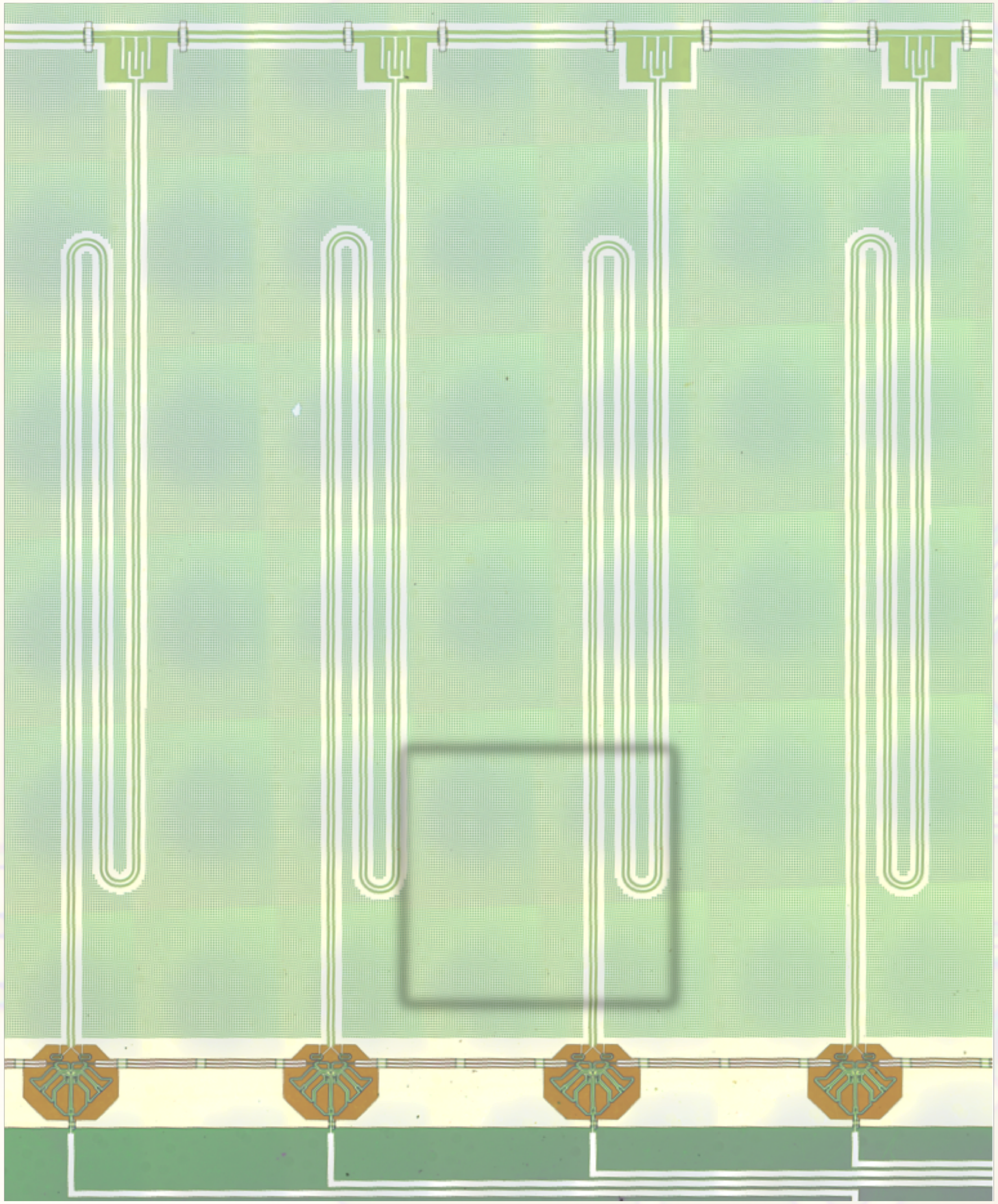
M. Wegner, *et al.*, J. Low. Temp. Phys. **193,** 462 (2018)

2nd Generation Multiplexer µMUX02

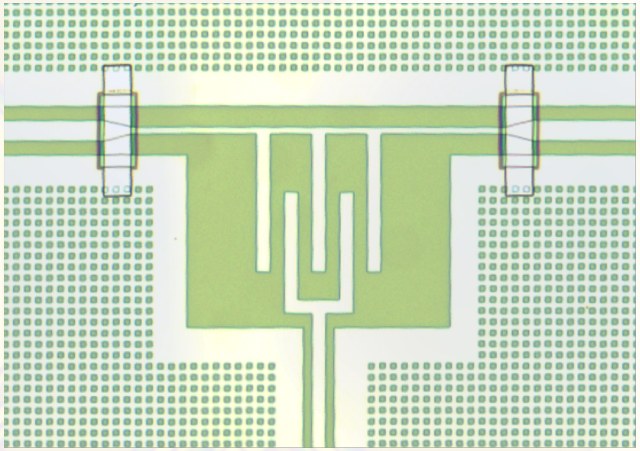


S. Kempf, *et. al.*, to be published

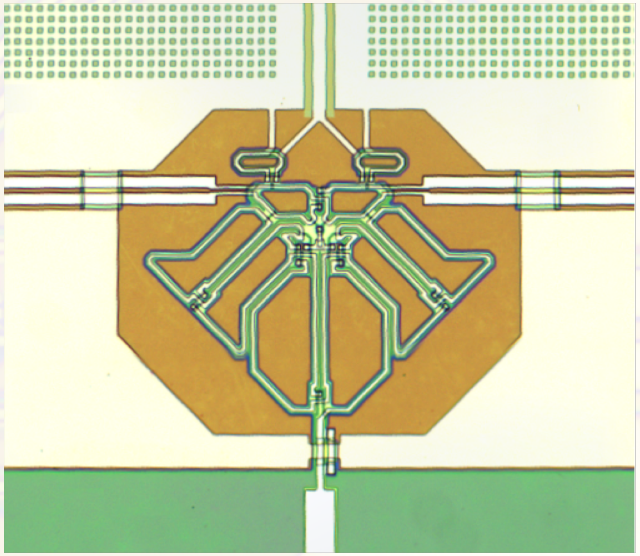
2nd Generation Multiplexer µMUX02



new coupling design

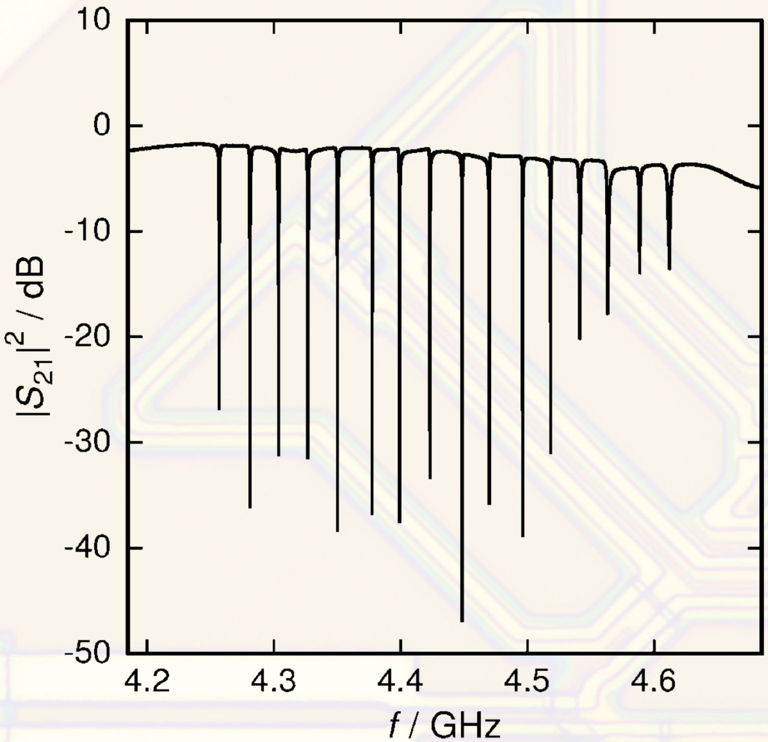


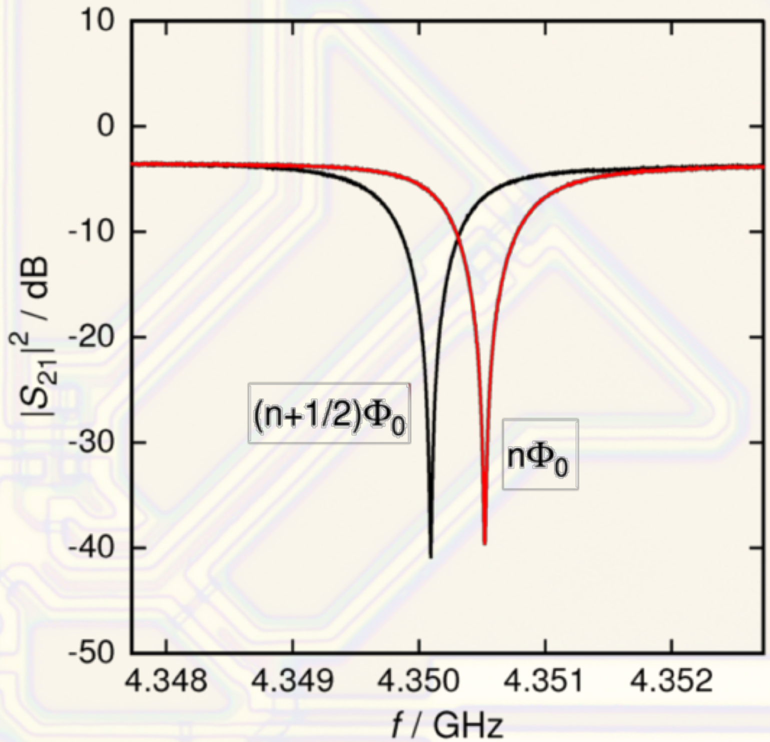
new rf SQUID design



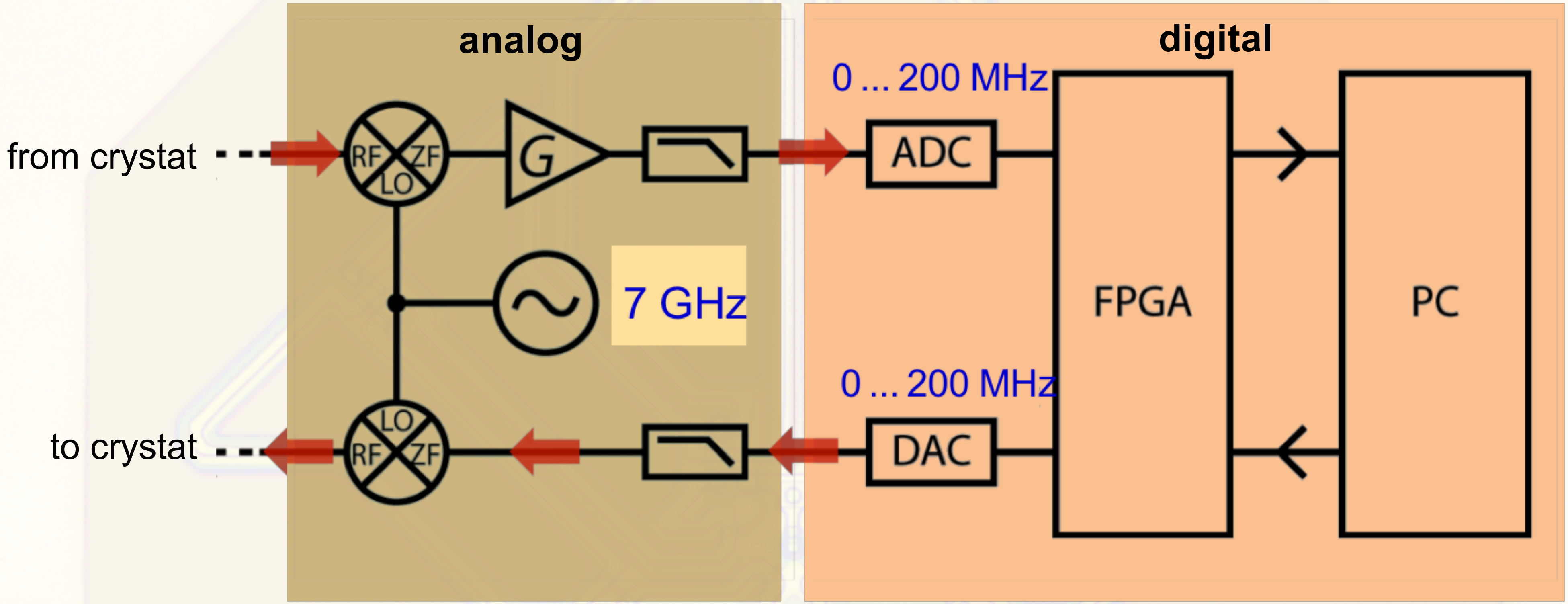
S. Kempf, *et. al.*, to be published

2nd Generation Superconducting Resonators



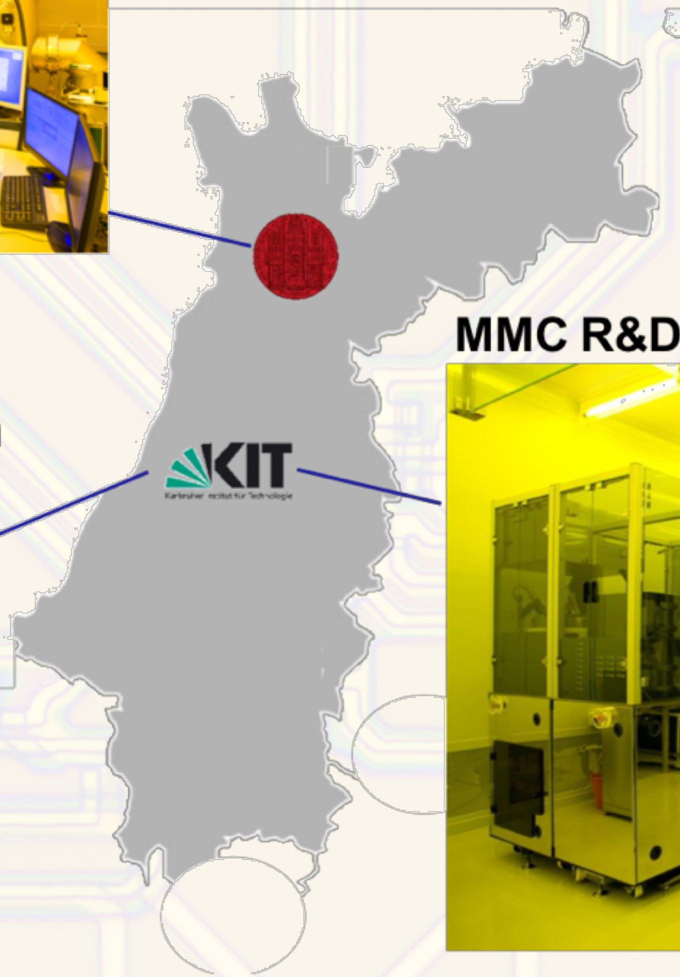


Frequency Division Multiplexing: Software Defined Radio



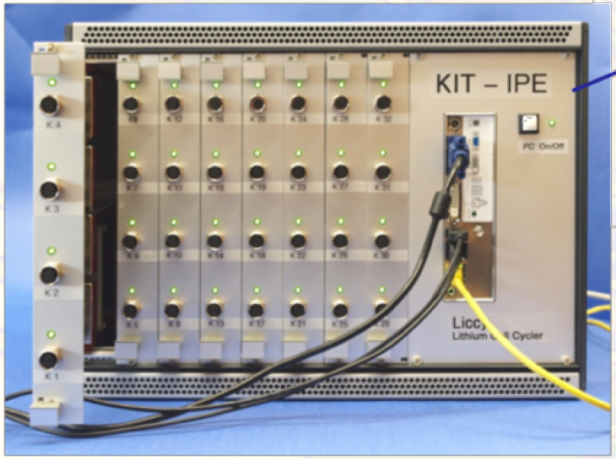
Joint development with
M. Weber, O. Sander, (KIT)
J. Becker (KIT)

MMC R&D Laboratory

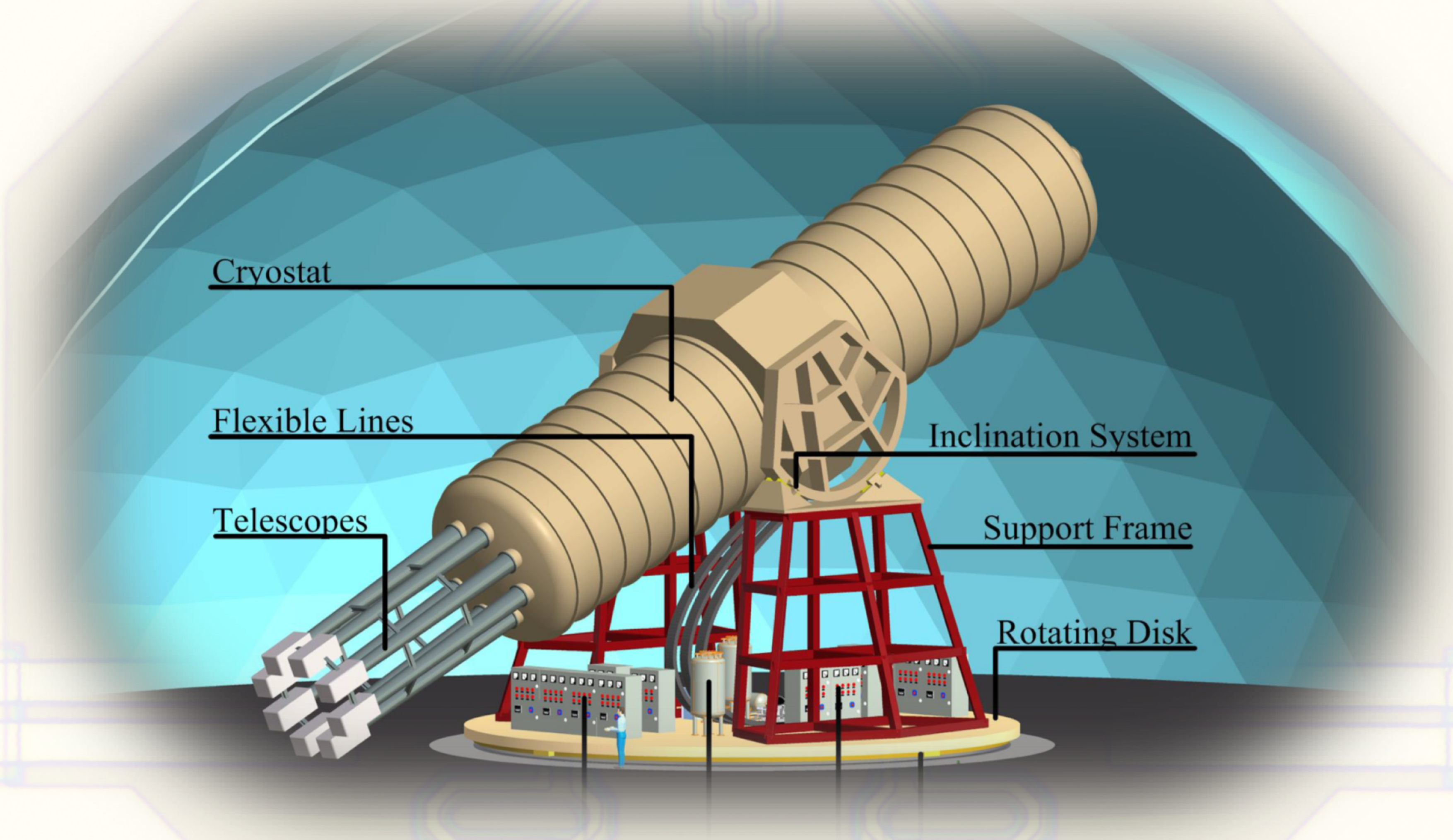


MMC R&D and Production Laboratory

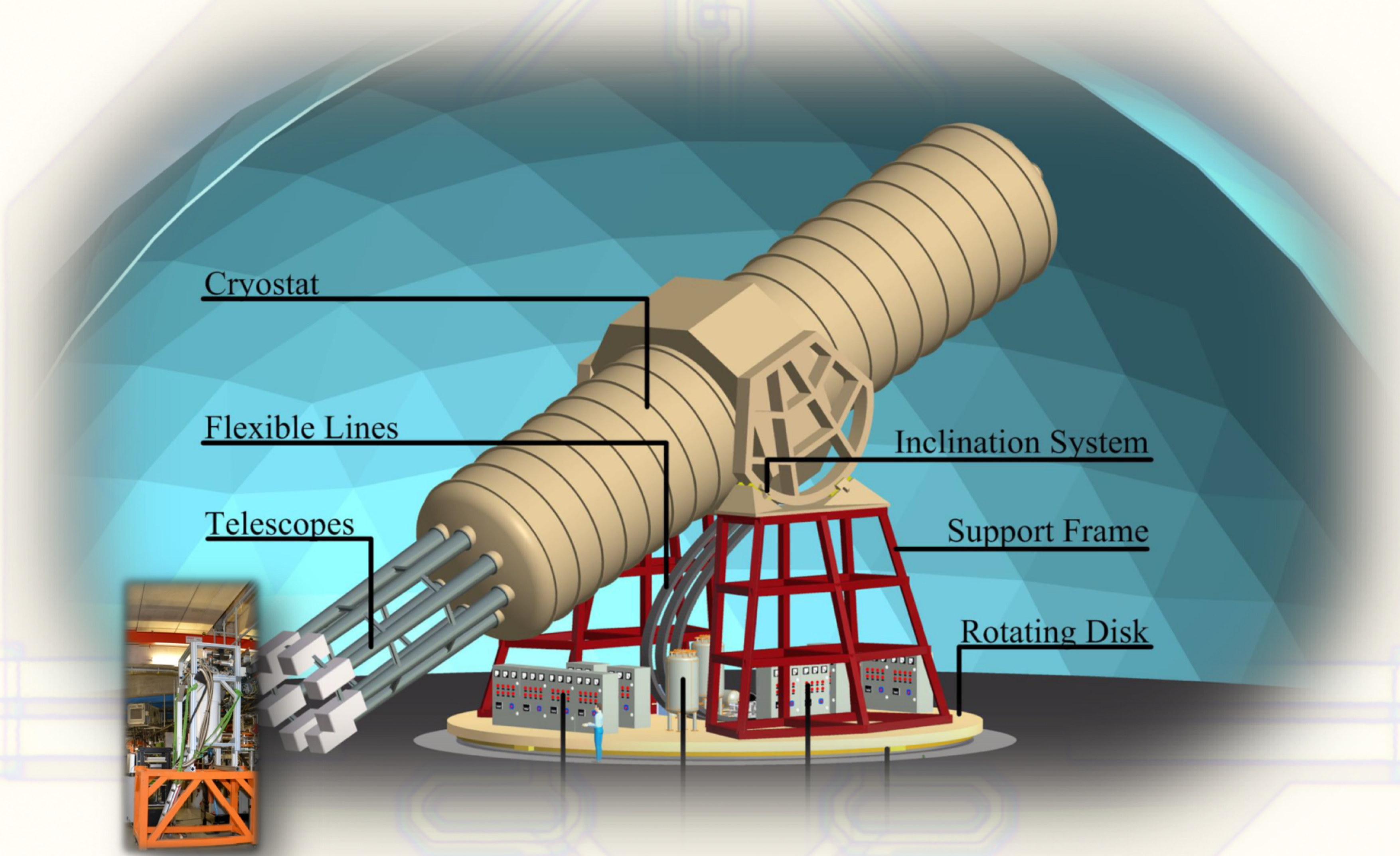
MMC System Integration



MMCs for IAXO The International Axion Observatory

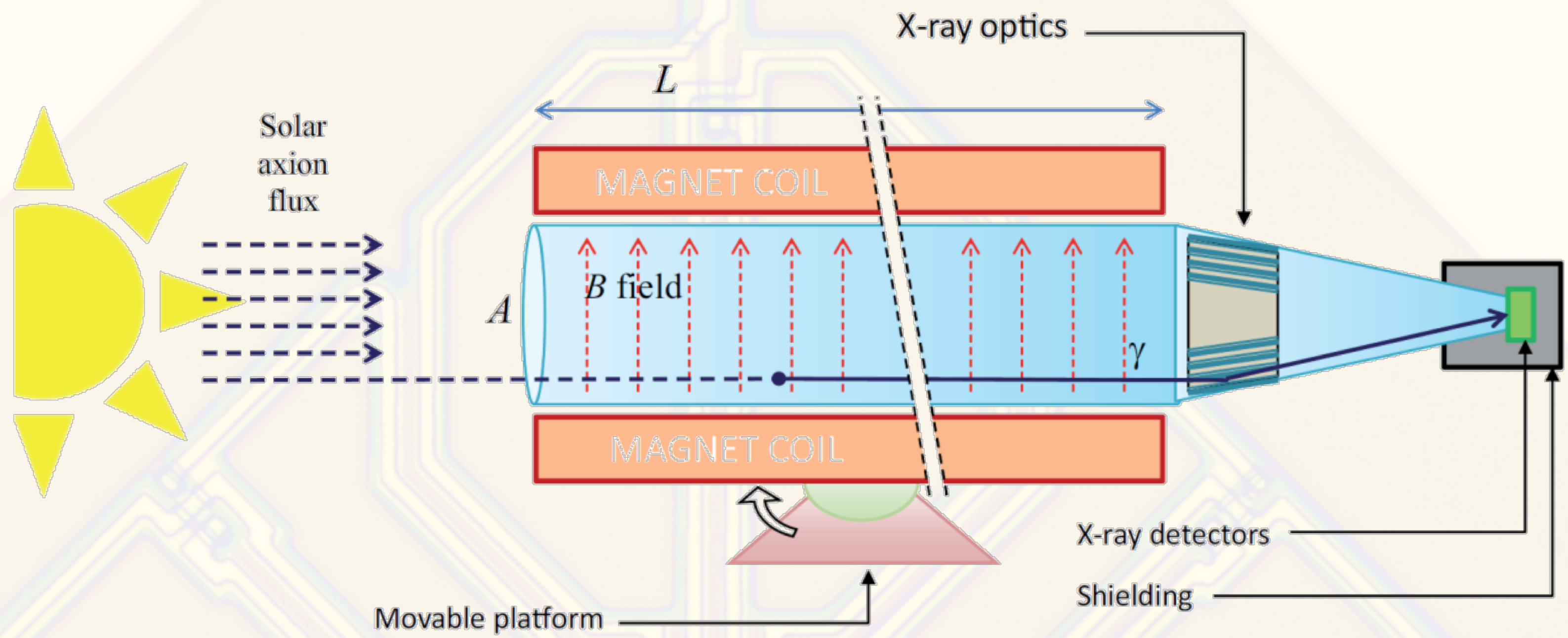


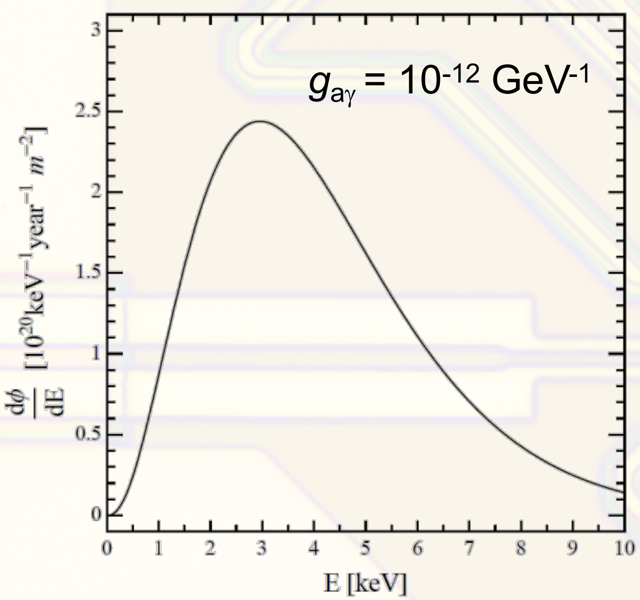
I. Irastorza IAXO LoI CERN 2013



I. Irastorza IAXO LoI CERN 2013

MMCs for IAXO The International Axion Observatory

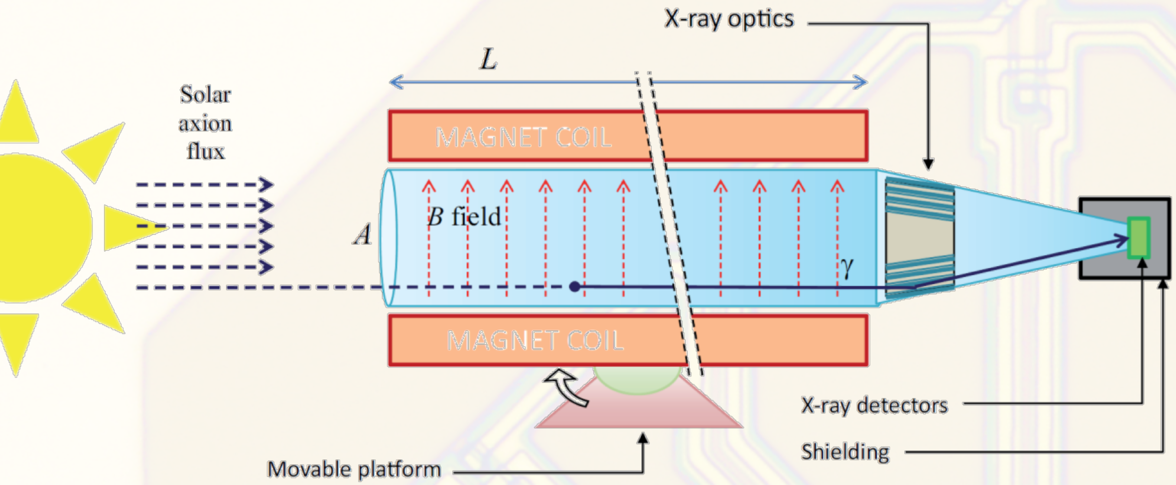


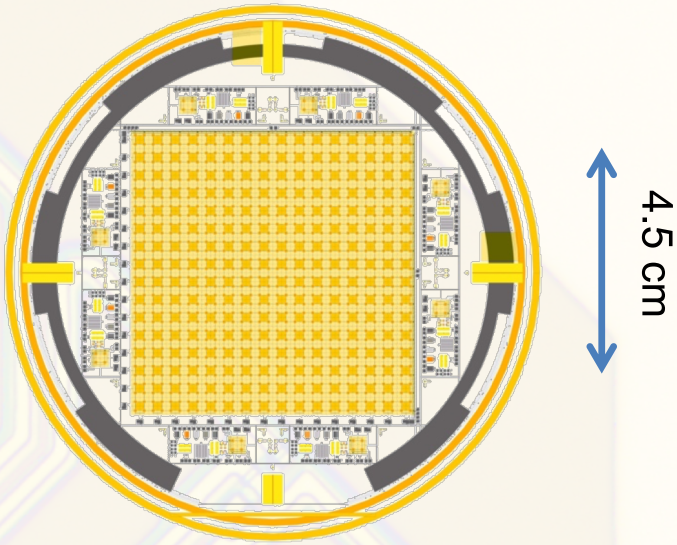


I. Irastorza IAXO LoI CERN 2013

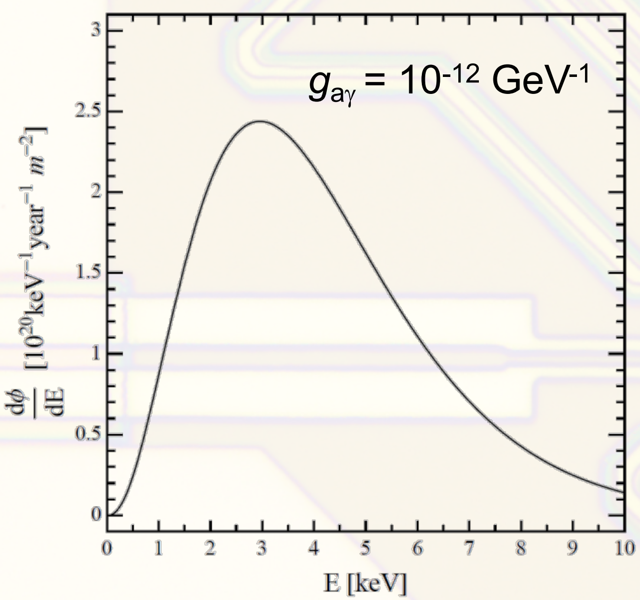
Detector requirements:

- Low rate — OK for MMC
- High QE — OK for MMC
- Low dark count rate — Ok for MMC
- Threshold energy — OK for MMC





I. Irastorza IAXO LoI CERN 2013

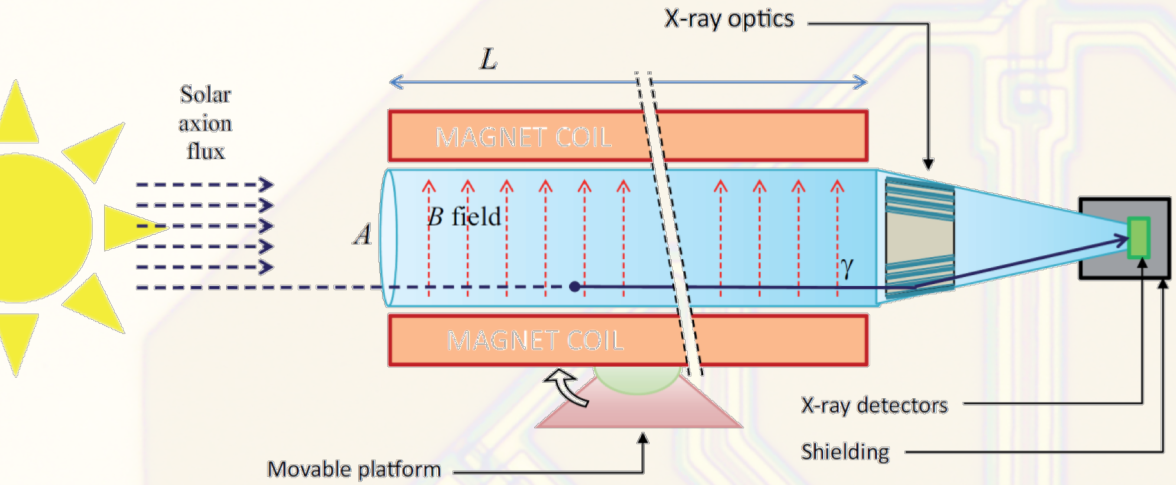


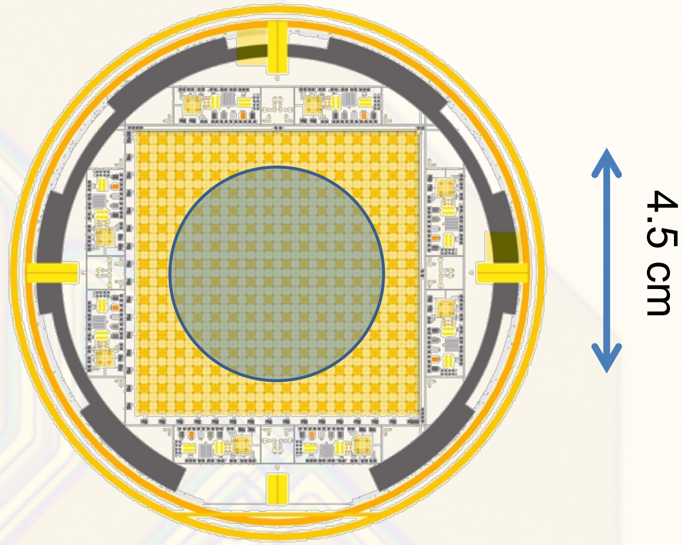
MOCCA Type Detector:

- 32 readout channel
- ΔE_{FWHM} ~ 200 eV
- 4.5 × 4.5 cm^2
- 4096 pixels → 700 μm position resolution

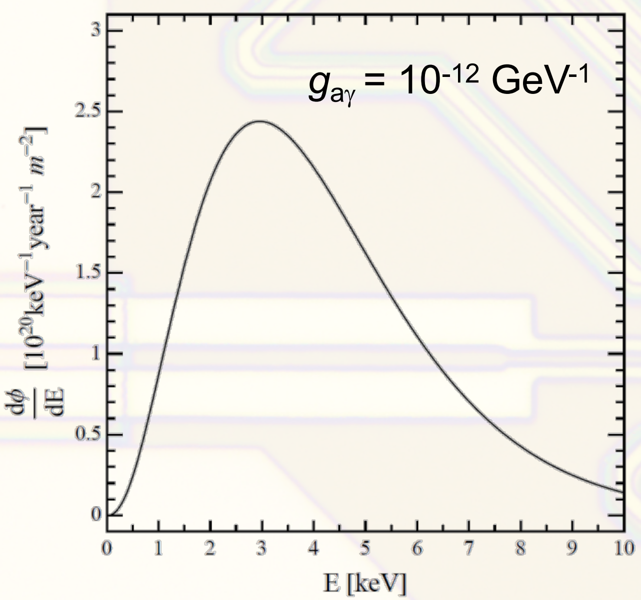
Possibility to be coupled to one of the 8 ports

- about same performance of Micromegas but different systematics





I. Irastorza IAXO LoI CERN 2013

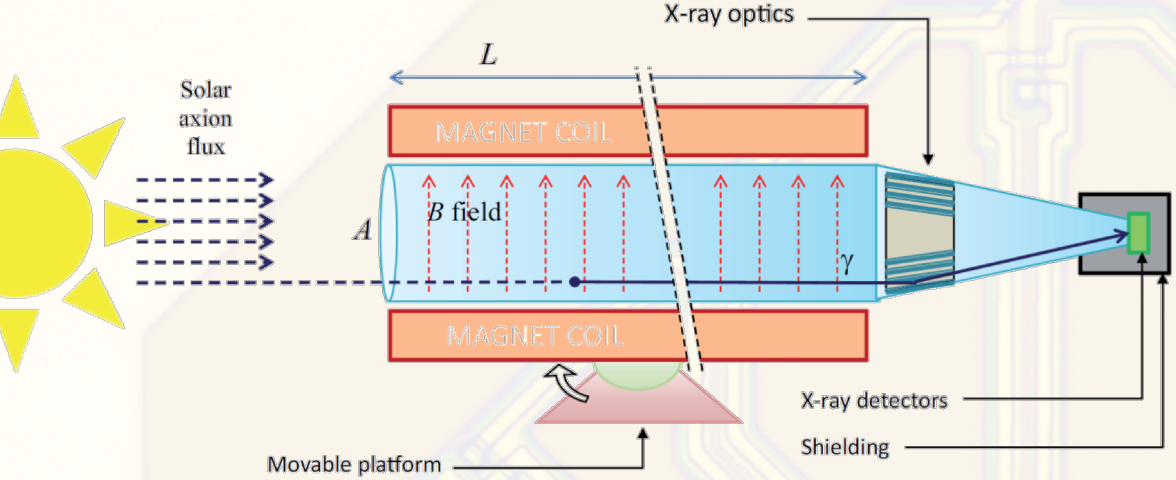


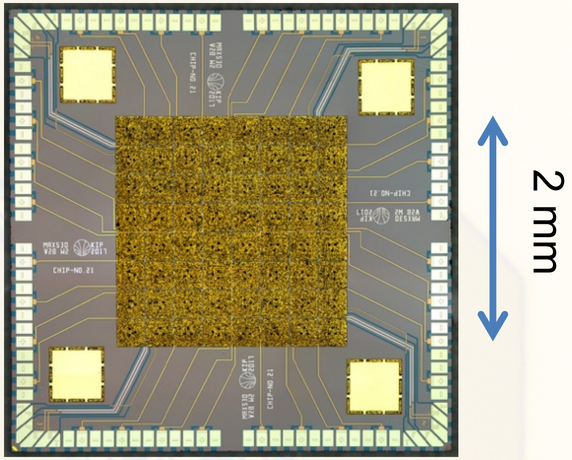
MOCCA Type Detector:

- 32 readout channel
- $\Delta E_{FWHM} \sim 200$ eV
- 4.5×4.5 cm^2
- 4096 pixels → 700 µm position resolution

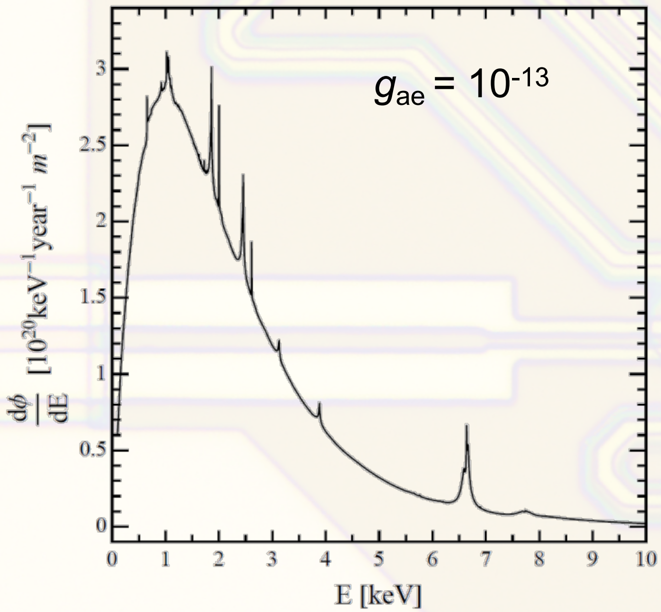
Possibility to be coupled to one of the 8 ports

- about same performance of Micromegas but different systematics
- detection area larger than focused spot → in-situ background measurements





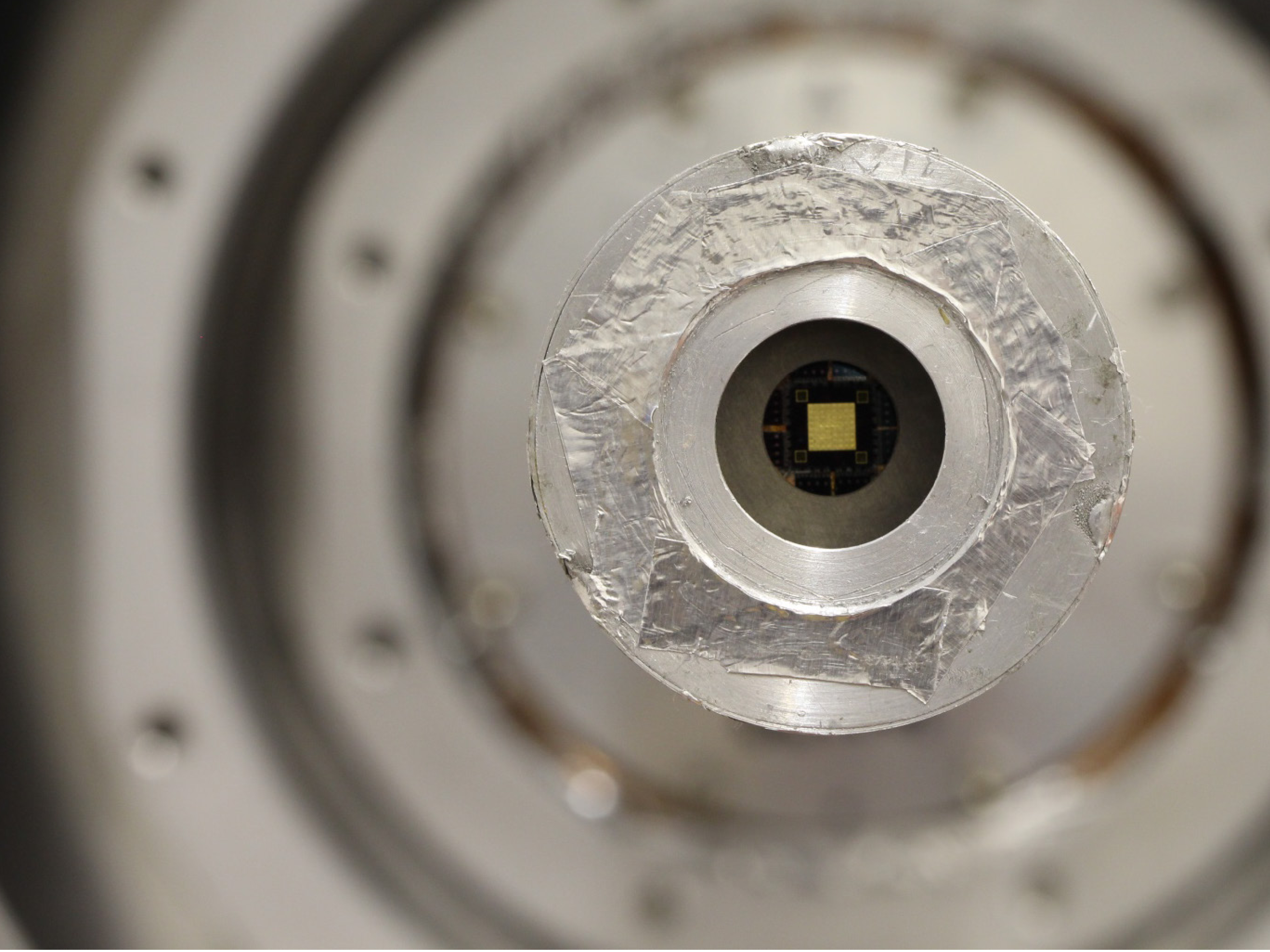
I. Irastorza IAXO LoI CERN 2013



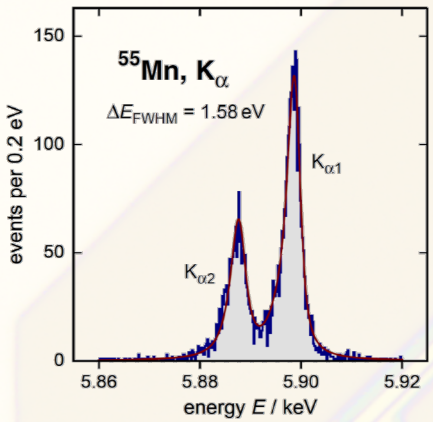
maXs-20: X-ray detector

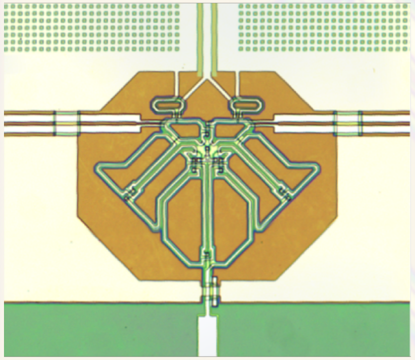
- 32 readout channel
- $\Delta E_{FWHM} = 2$ eV
- 2×2 mm^2
- 64 pixels

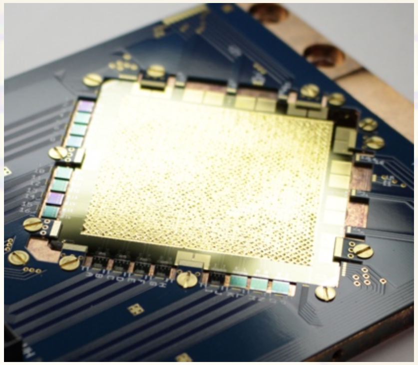
Allows to investigate fine structures in spectrum originating from processes involving electrons, bremsstrahlung, Compton and axion-recombination



Summary & Outlook







Metallic Magnetic Calorimeters

flexible low temperature detectors

described by standard thermodynamics

wide range of applications

Next Steps in Detector Development

optimizing multiplexed read-out

realization of resolving powers > 10.000

$\Delta E_{FWHM} < 1$eV @ 6 keV :-)

Applications

Lamb-shift Measurements at GSI

Commissioning of MOCCA

Realization of ECHo-1K

.....