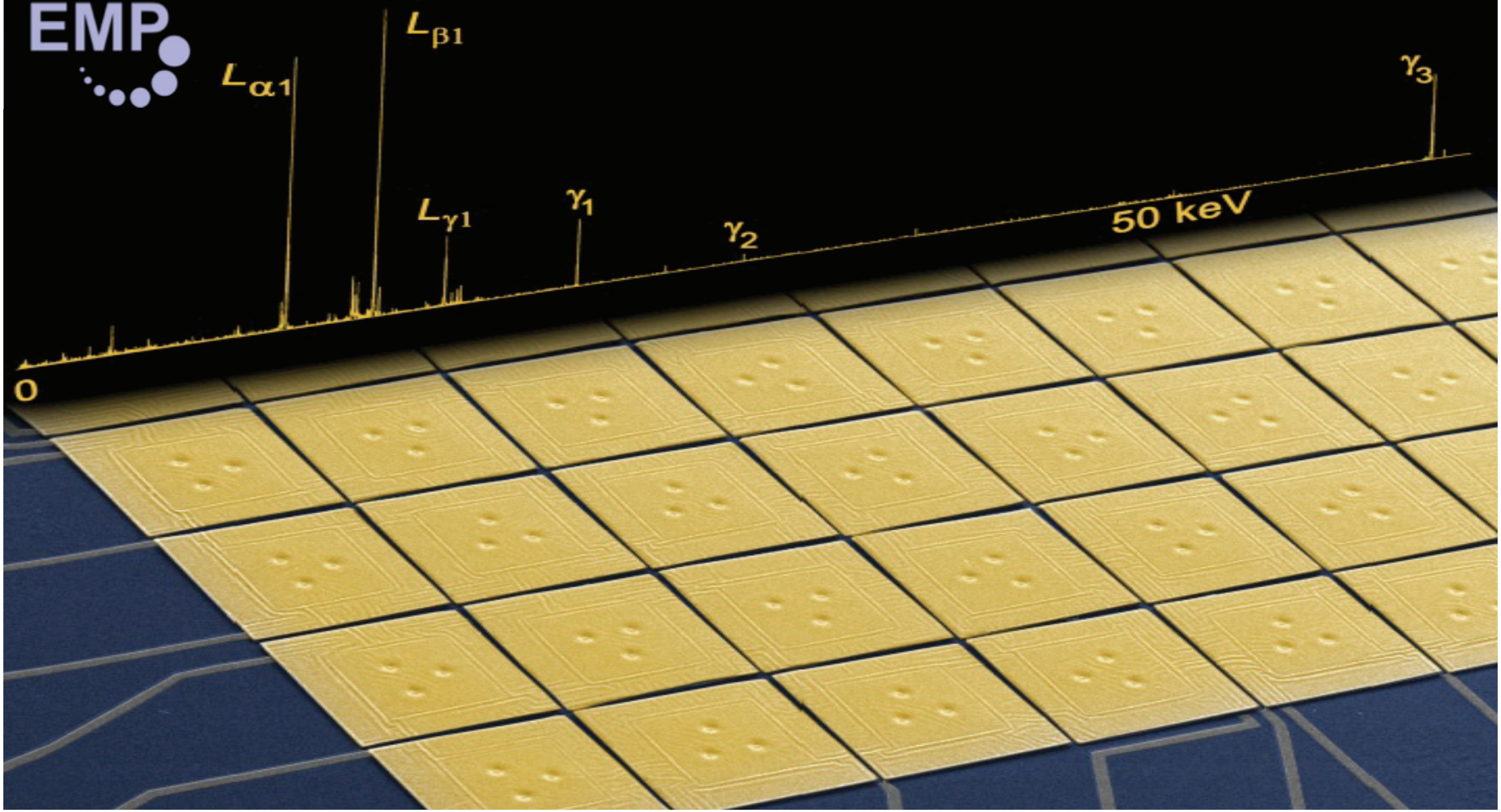
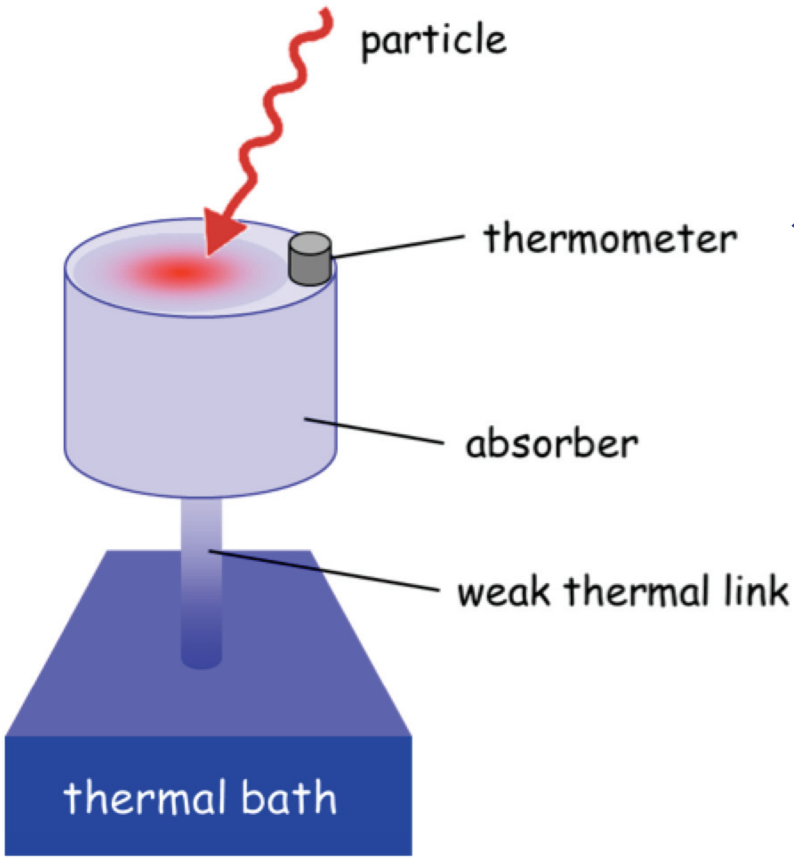
Christian Enss, Heidelberg University

MMC Based Cryogenic Micro-Calorimeters:

A New Key Technology for Particle Detection

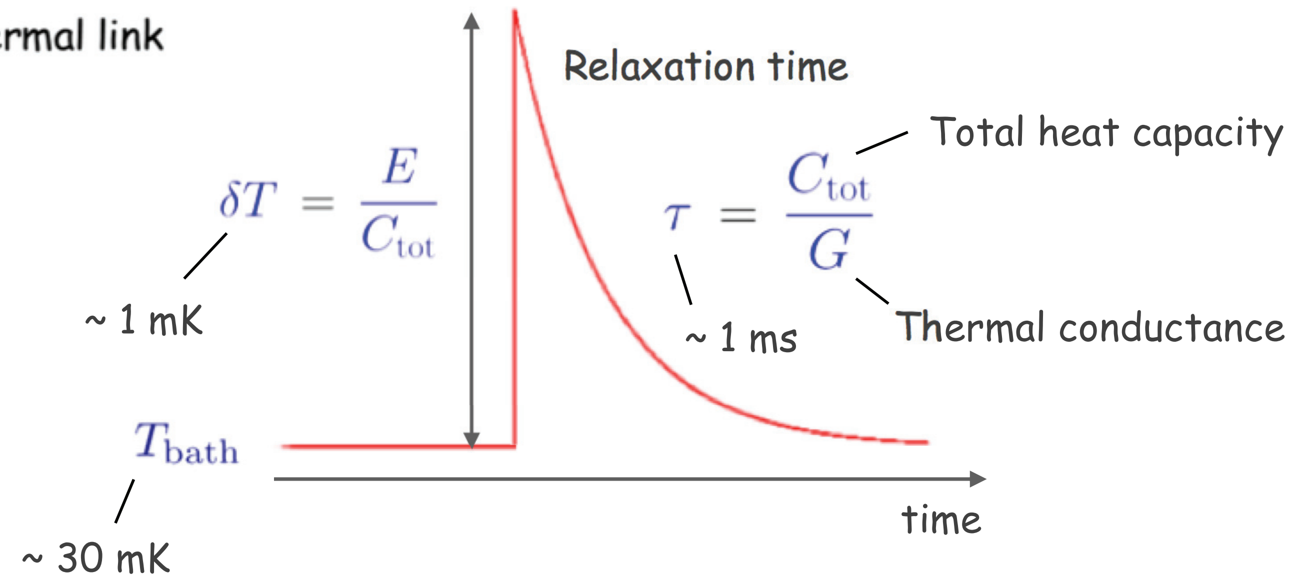


General Concept of a Calorimetric Particle Detector

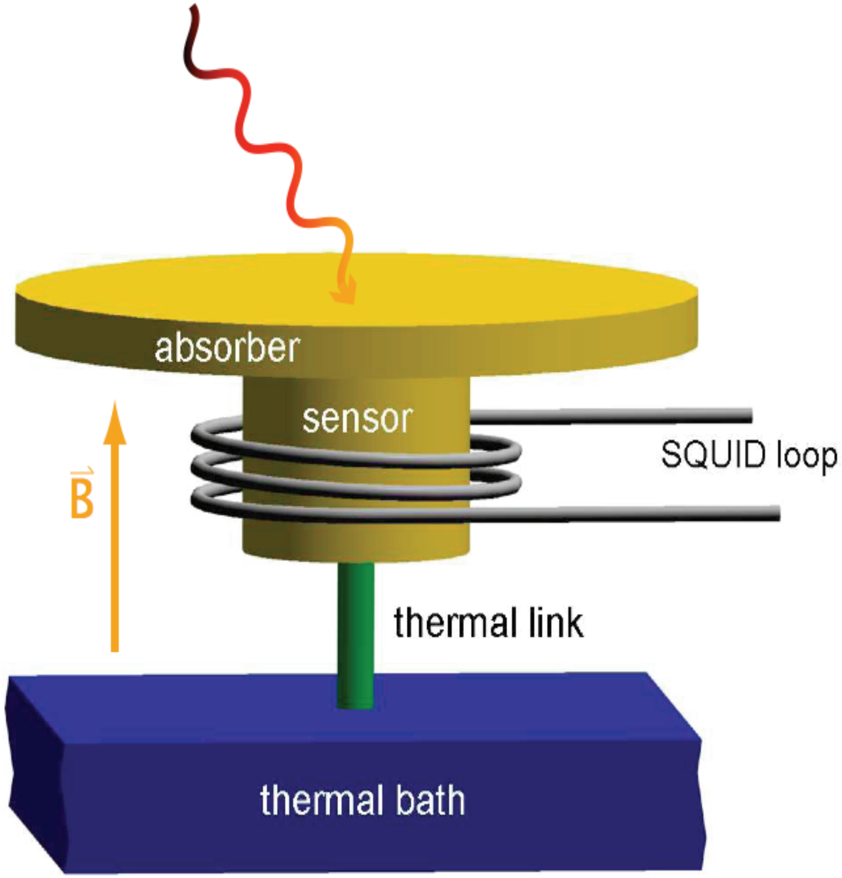


- TES
- MMC Metallic Magnetic Calorimeter
- NTD

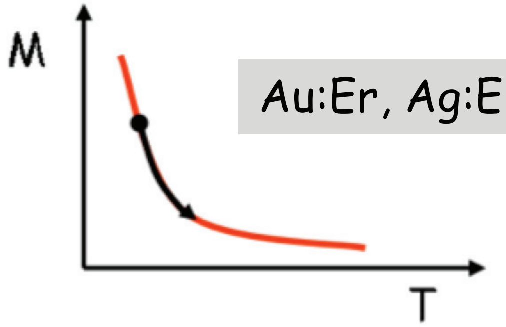
Single Event



Metallic Magnetic Calorimeter (MMC)



paramagnetic sensor:



Au:Er, Ag:Er, ...

signal size:

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

energy resolution:

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

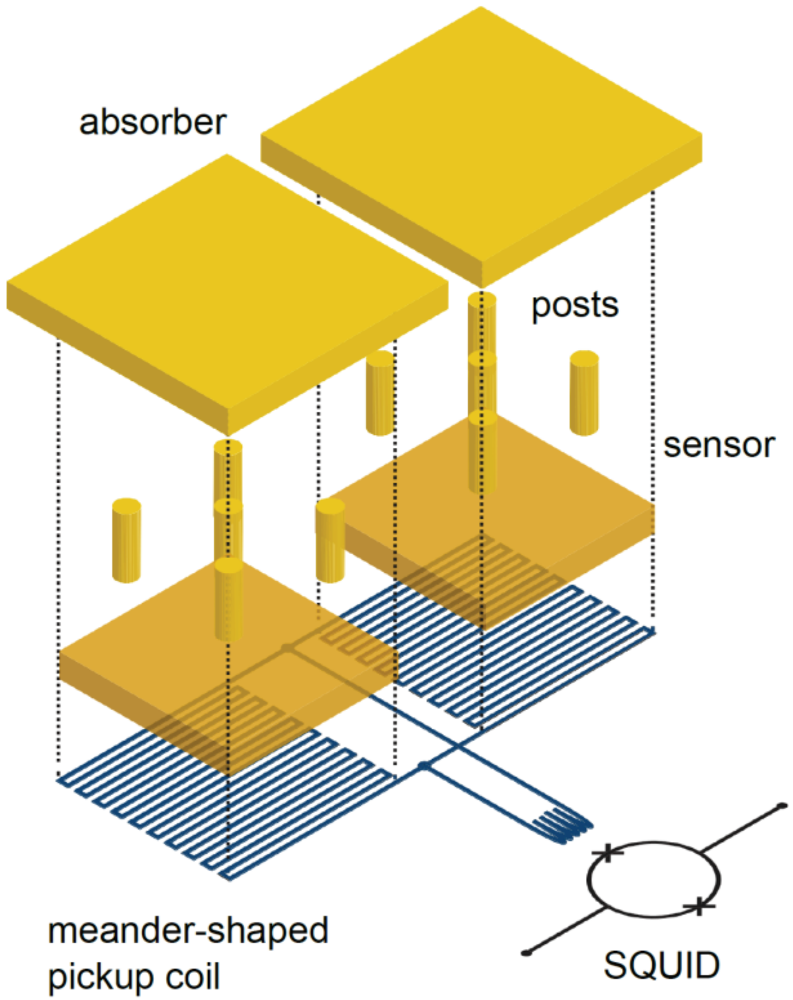
A. Fleischmann, Adv. Solid State Phys. **41**, 577 (2001)

main difference to resistive calorimters:

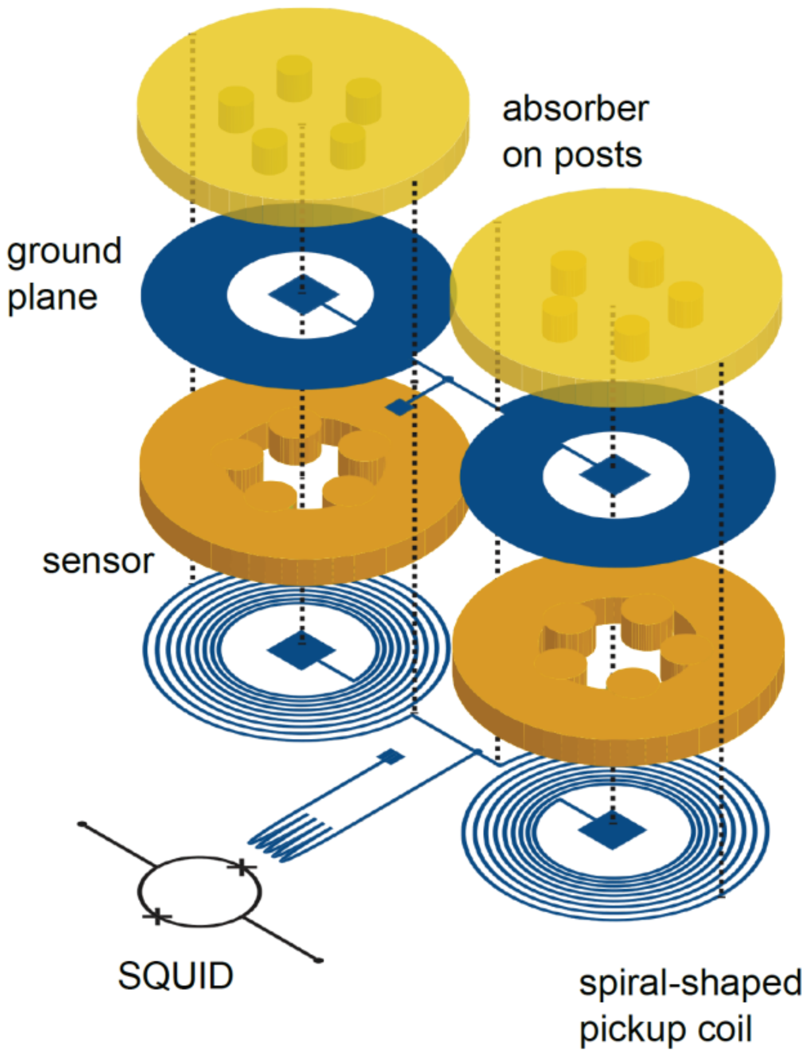
no dissipation in the sensor
no galvanic contact to the sensor

MMCs: Geometries

meander-shaped pick-up



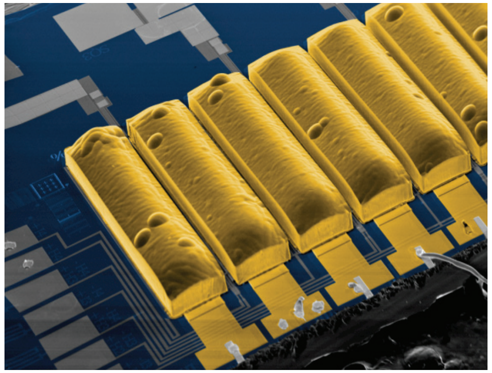
stripline (sandwich) design

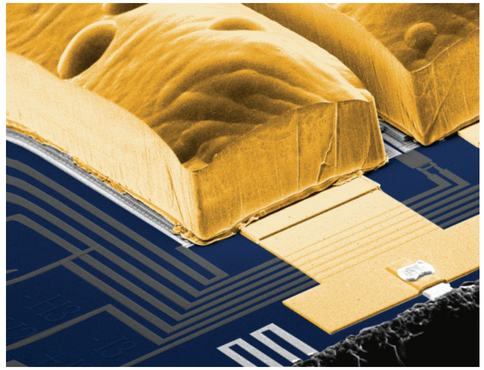


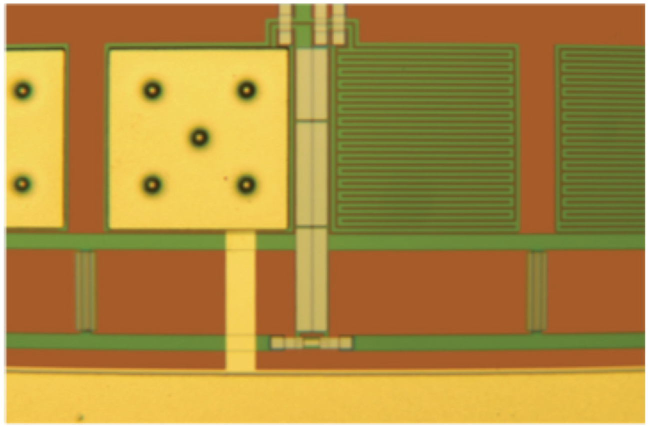
MMCs: Micro-fabrication at KIP in Heidelberg

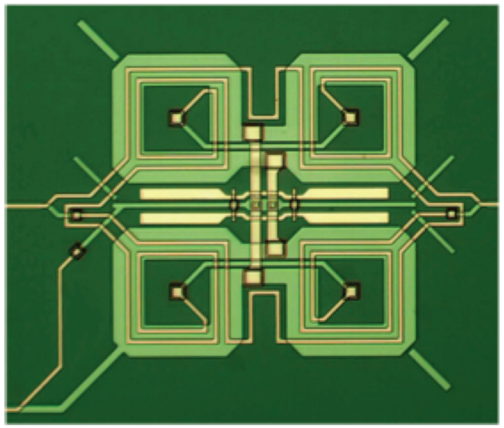
Mask writer | Mask aligner | Mask less aligner | UHV sputtering | Wet bench | Chemistry | Dry etching

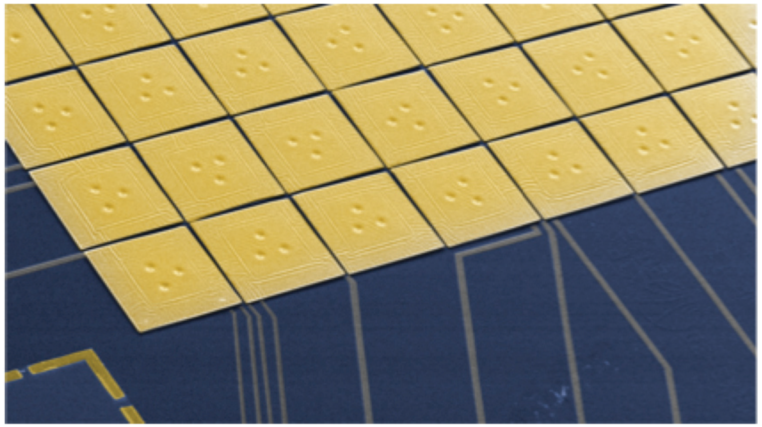
- flexibility in design and fabrication
- reliable processes for thin films
- more than 10 different designs
  (6-18 layers) processed in parallel



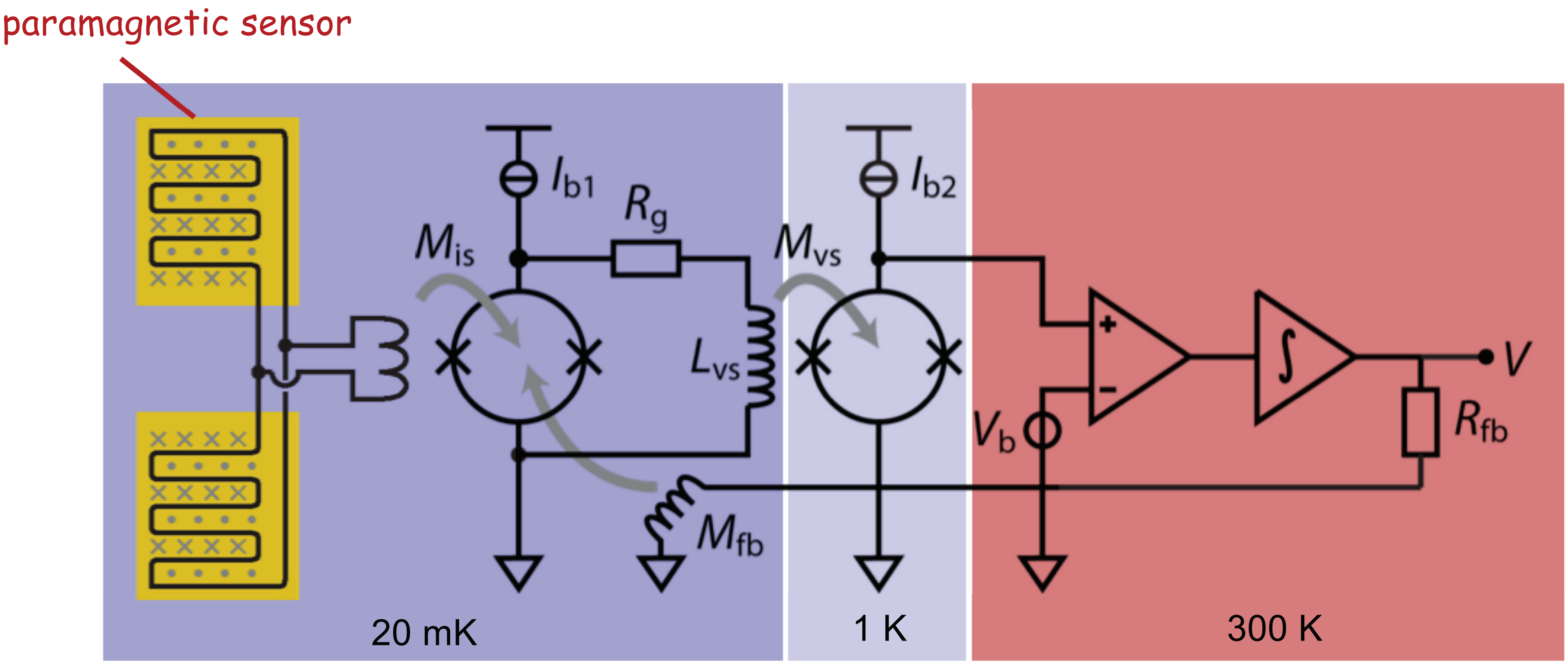








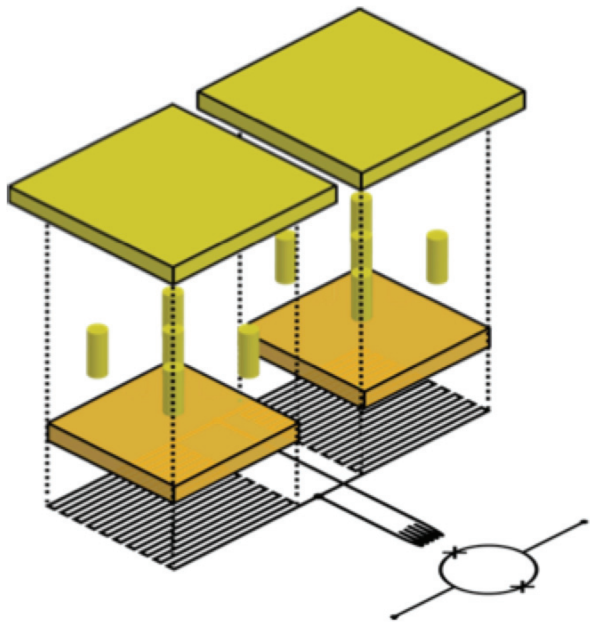
Readout Scheme For MMCs: two-stage SQUID Setup

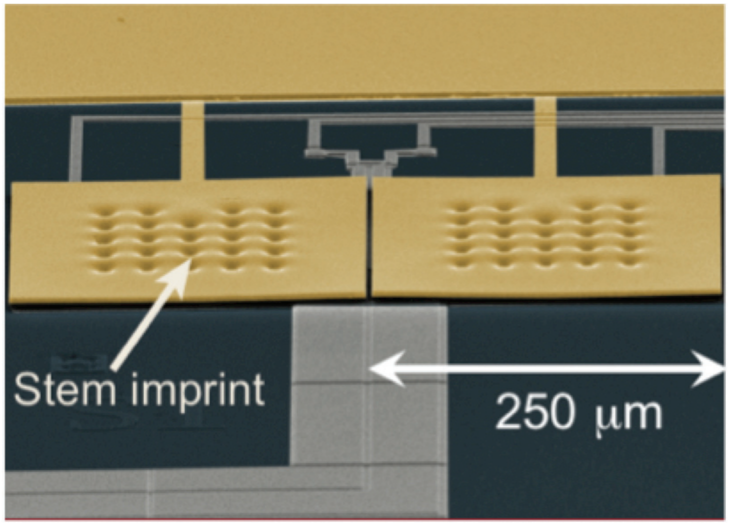


main advantages:

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

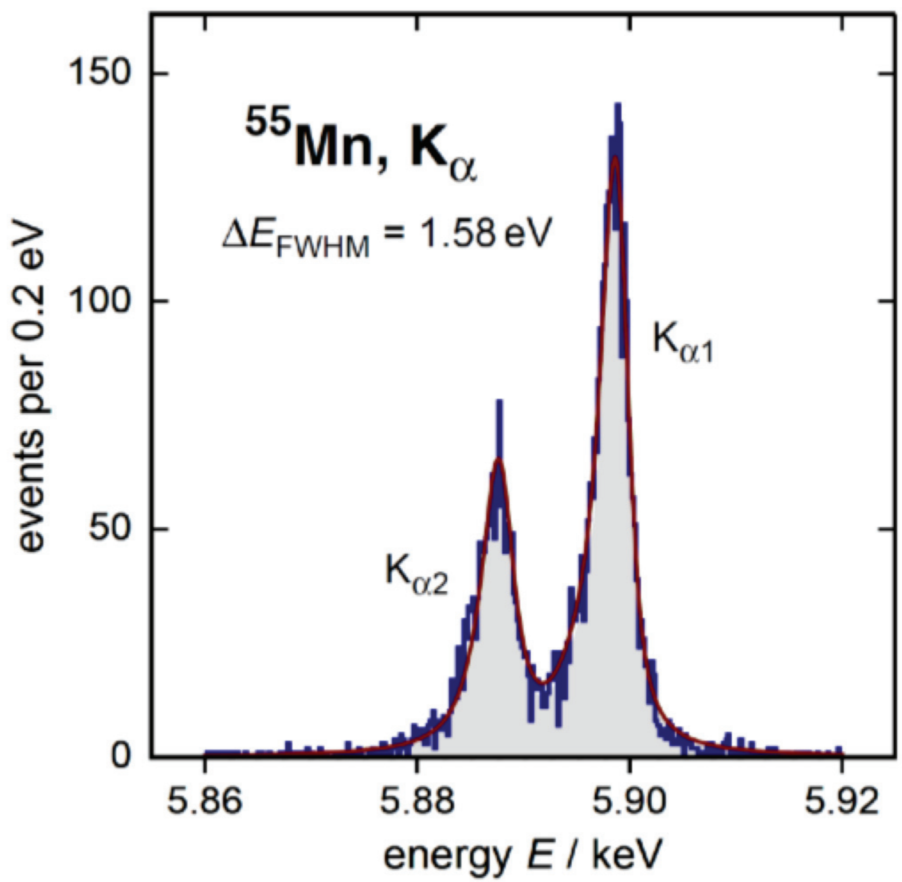
Recent Result of a Fully Microfabricated MMC





250 µm × 250 µm Gold, 5 µm thick

98% Quantum Efficiency @ 6 keV



Recent Result of a Fully Microfabricated MMC

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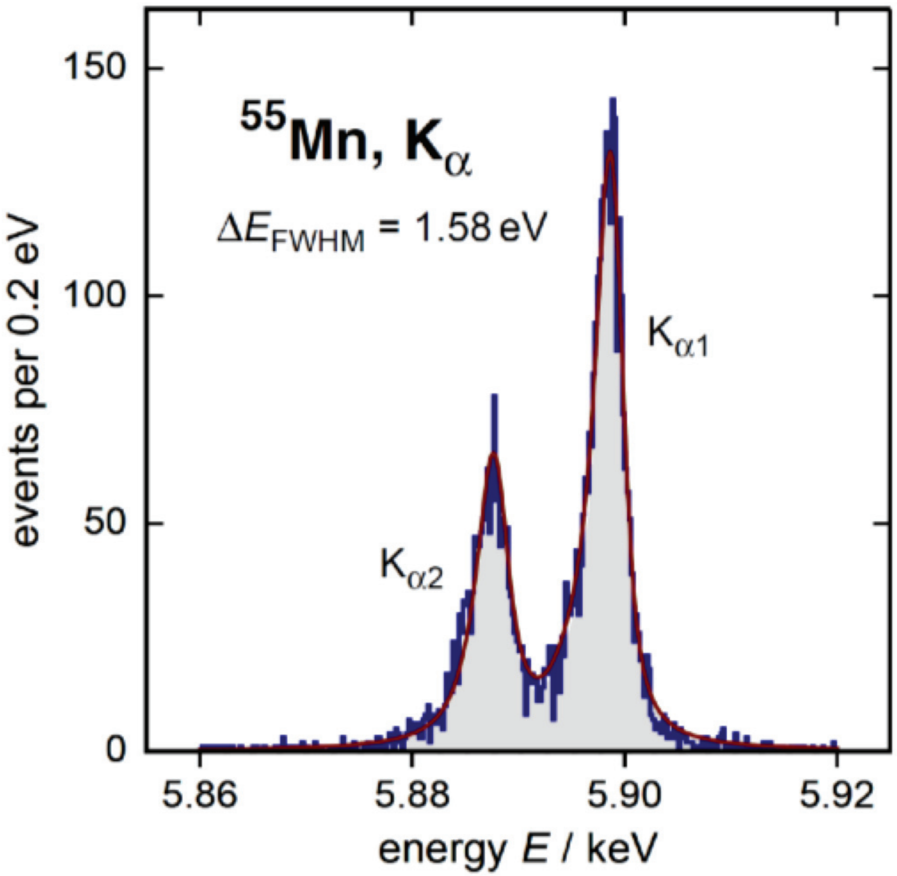
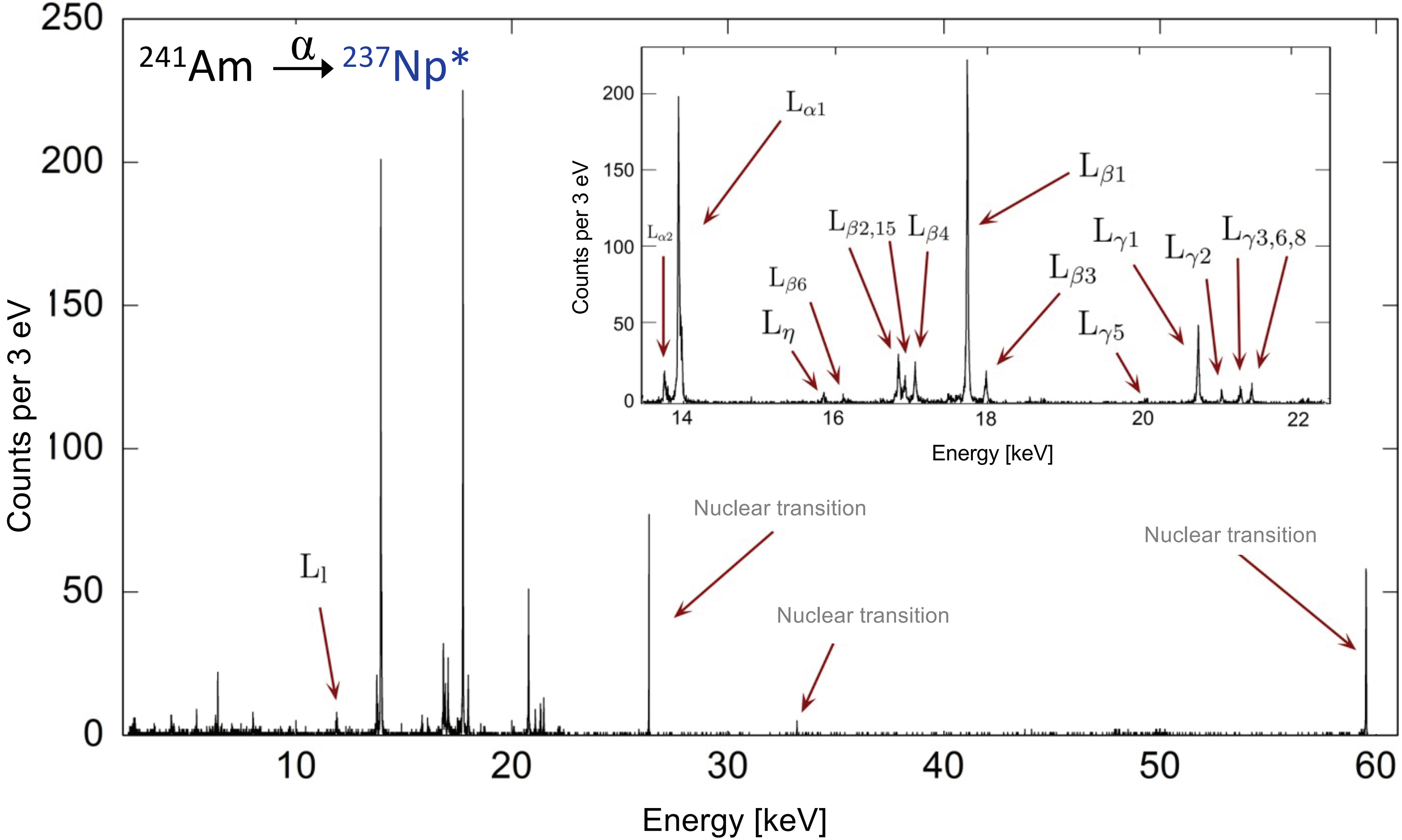
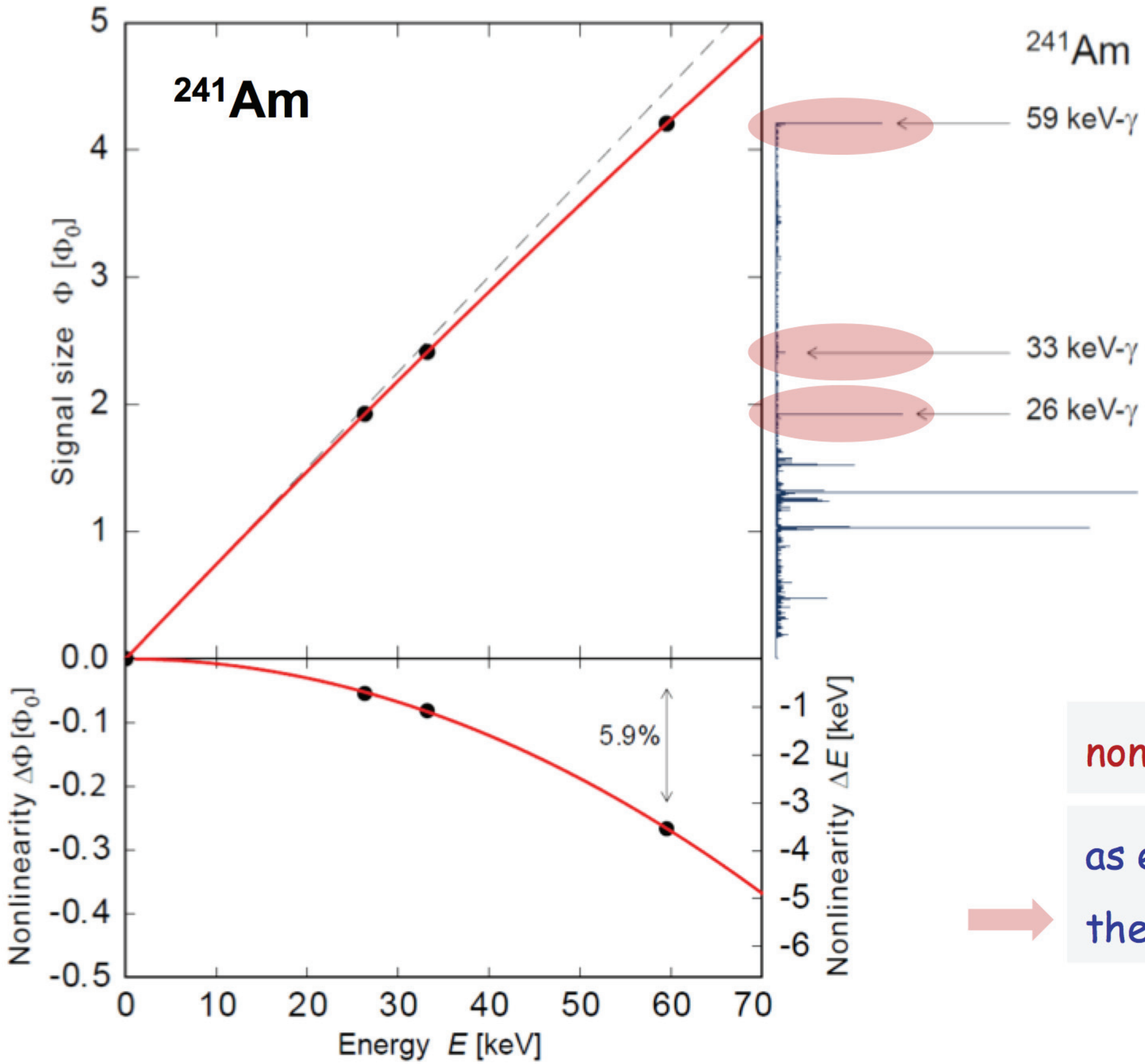


Energy Bandwidth



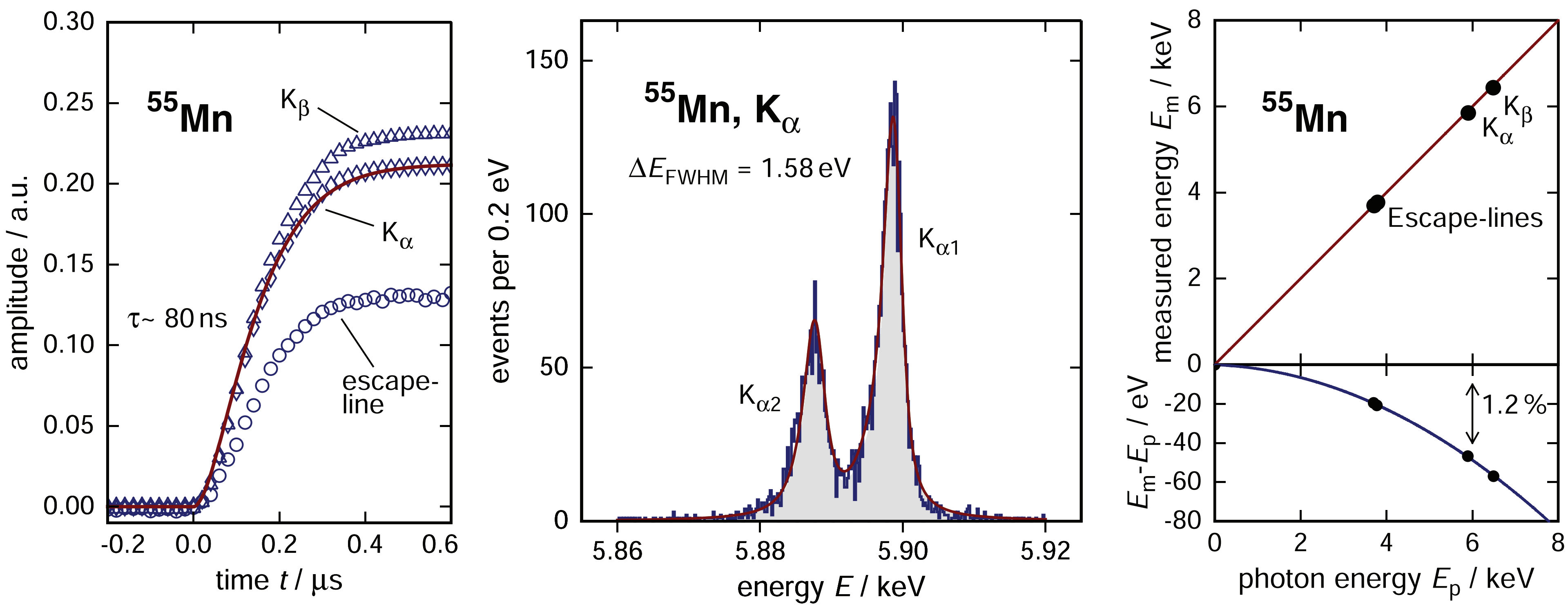
Excellent Linearity



non-linearity: 6% @ 60 keV

as expected from thermodynamical properties

Performance of maXs20 Detector at 6 keV



record speed

record resolving power

record linearity

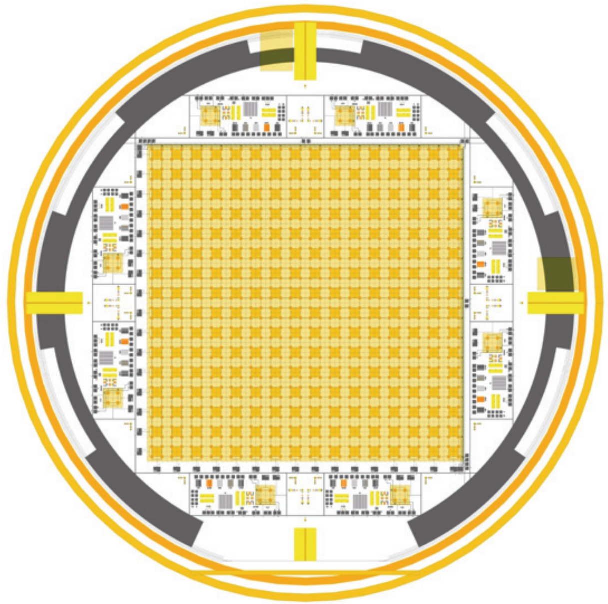
pileup identification

reduction of overlapping lines

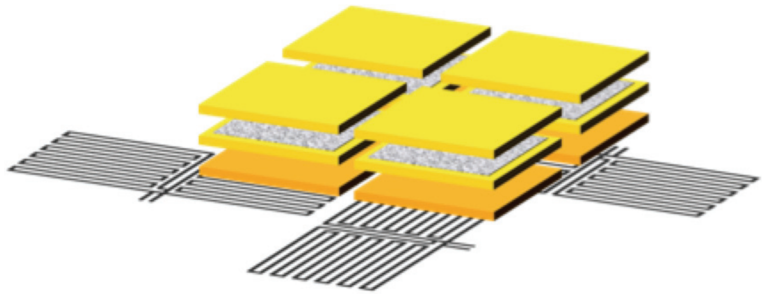
energy scale and calibration

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

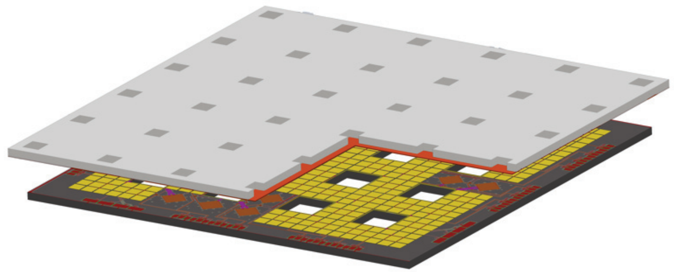


radiation and quantum metrology	
α-, β-, and γ-spectroscopy (MetroBeta)	EU
β-spectroscopy (MetroMMC)	EU



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

neutrino mass experiments			
electron capture of	^{163}Ho	(ECHo)	DFG
double beta decay	^{100}Mo	(AMoRE)	KRISS
double beta decay	^{100}Mo	(LUMINEU)	CEA

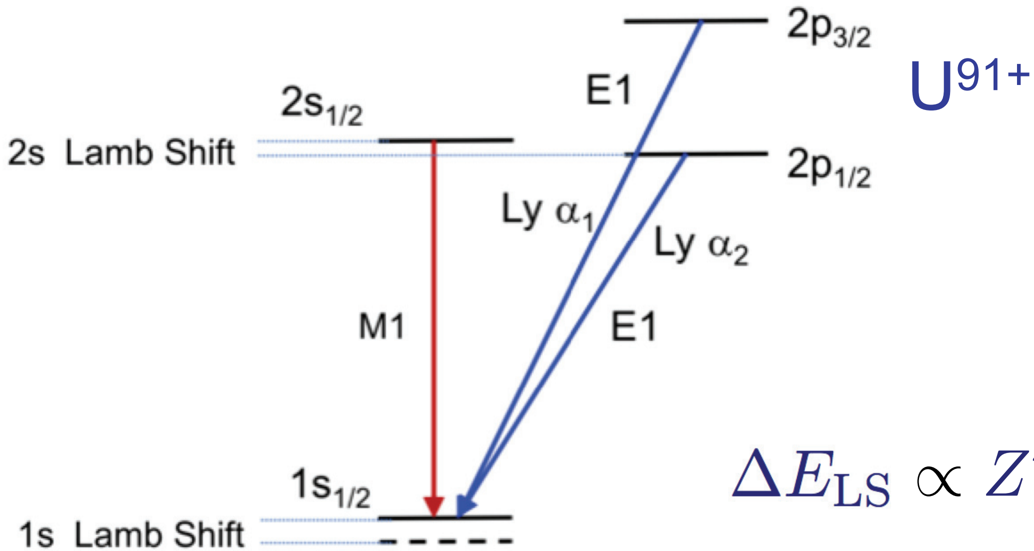


Atomic and Molecular Physics Experiments

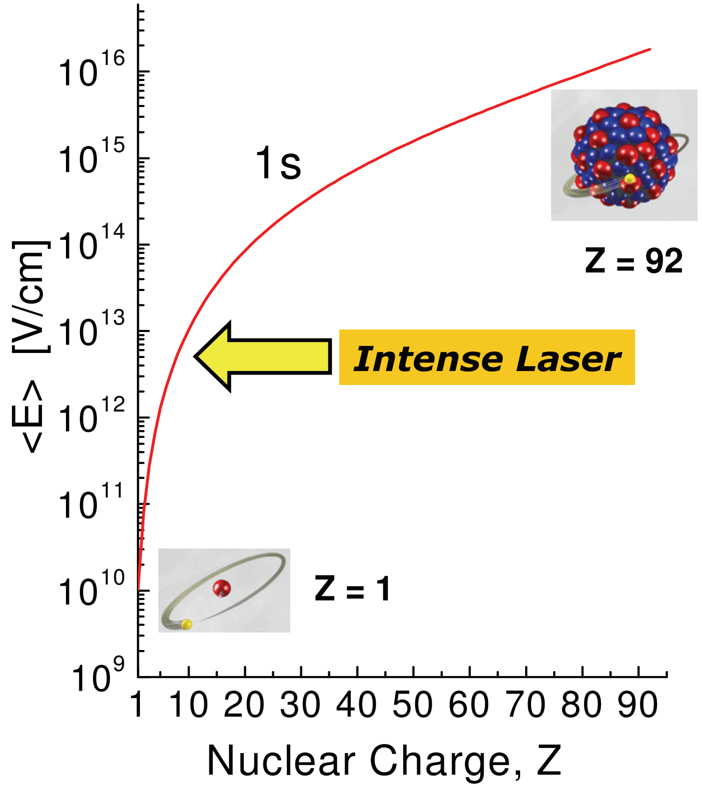
QED Test with Highly Charged Ions

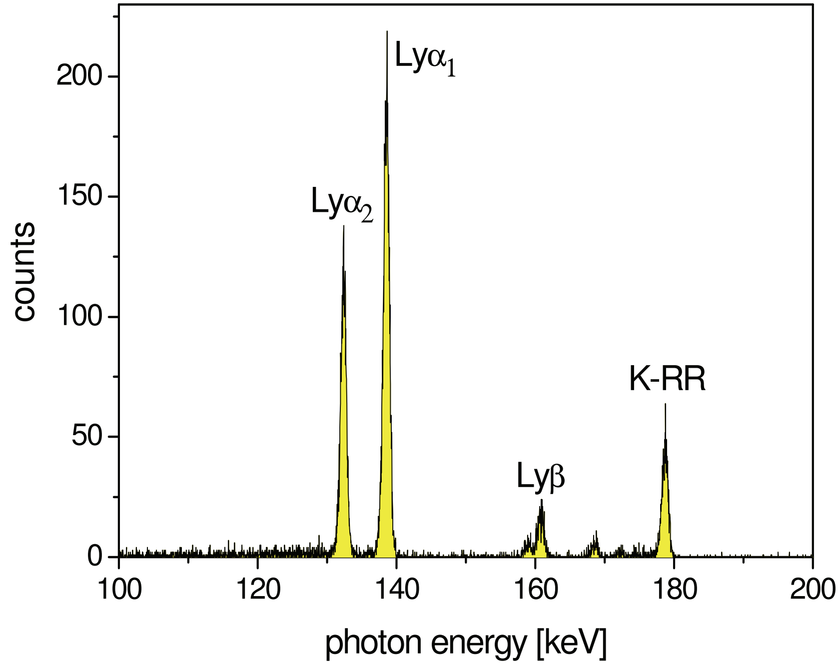
Chemistry of Interstellar Clouds

Lamb-shift of Highly Charged Ions (SPARC)

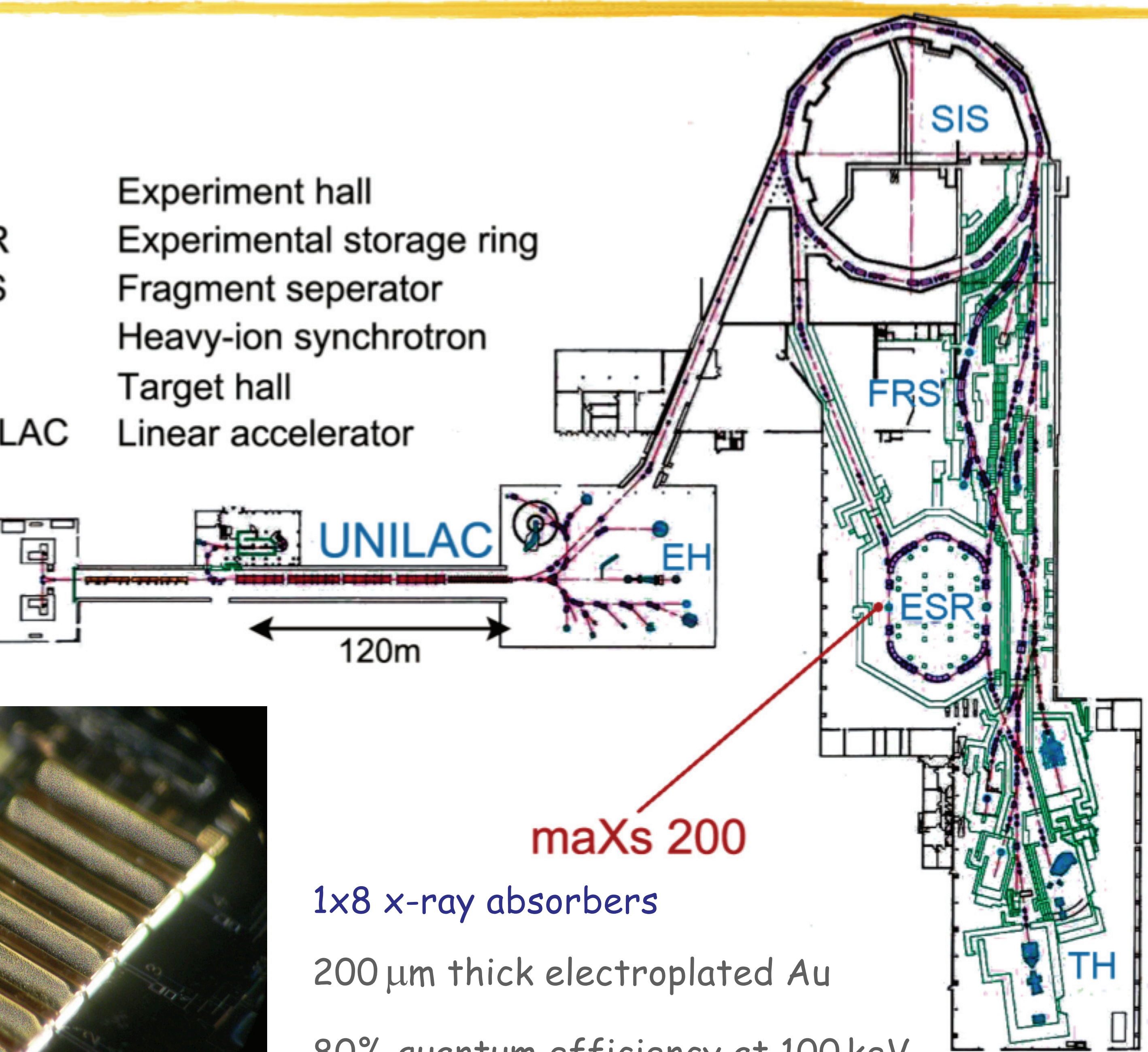


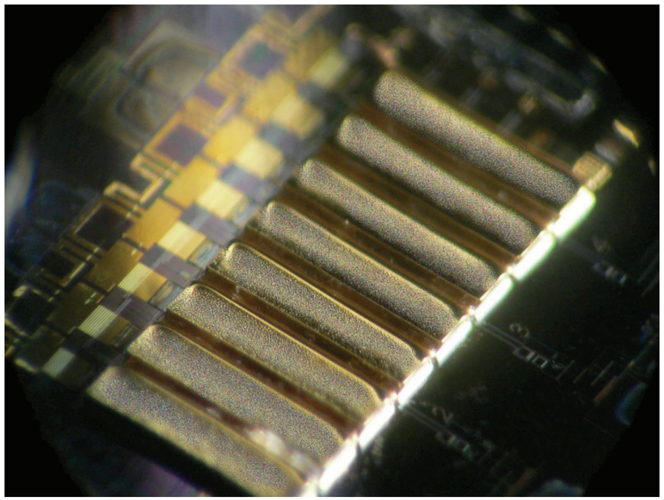
$$\Delta E_{\mathrm{LS}} \propto Z^4/n^3$$





GSI Accelerator Facility



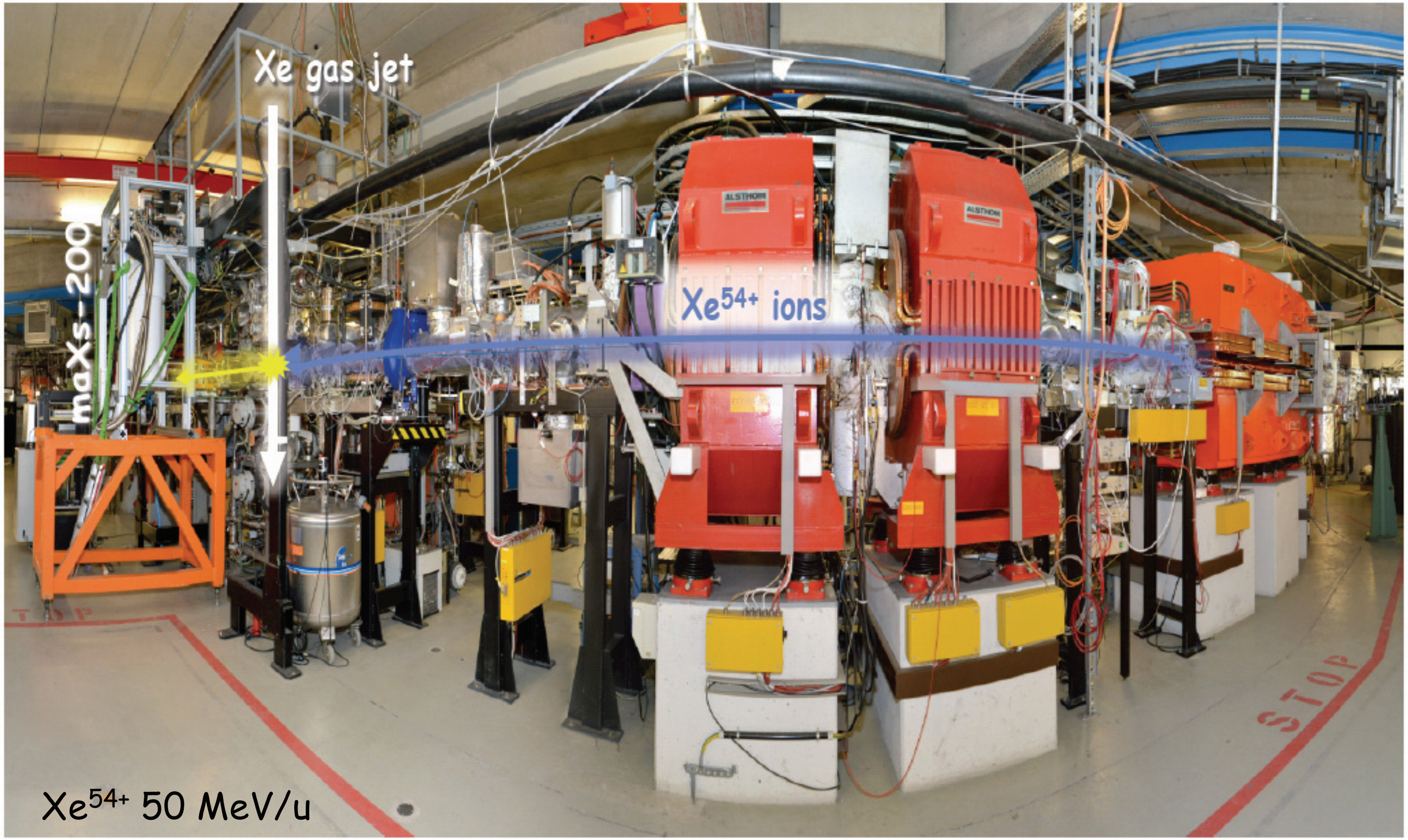


1x8 x-ray absorbers

200 μm thick electroplated Au

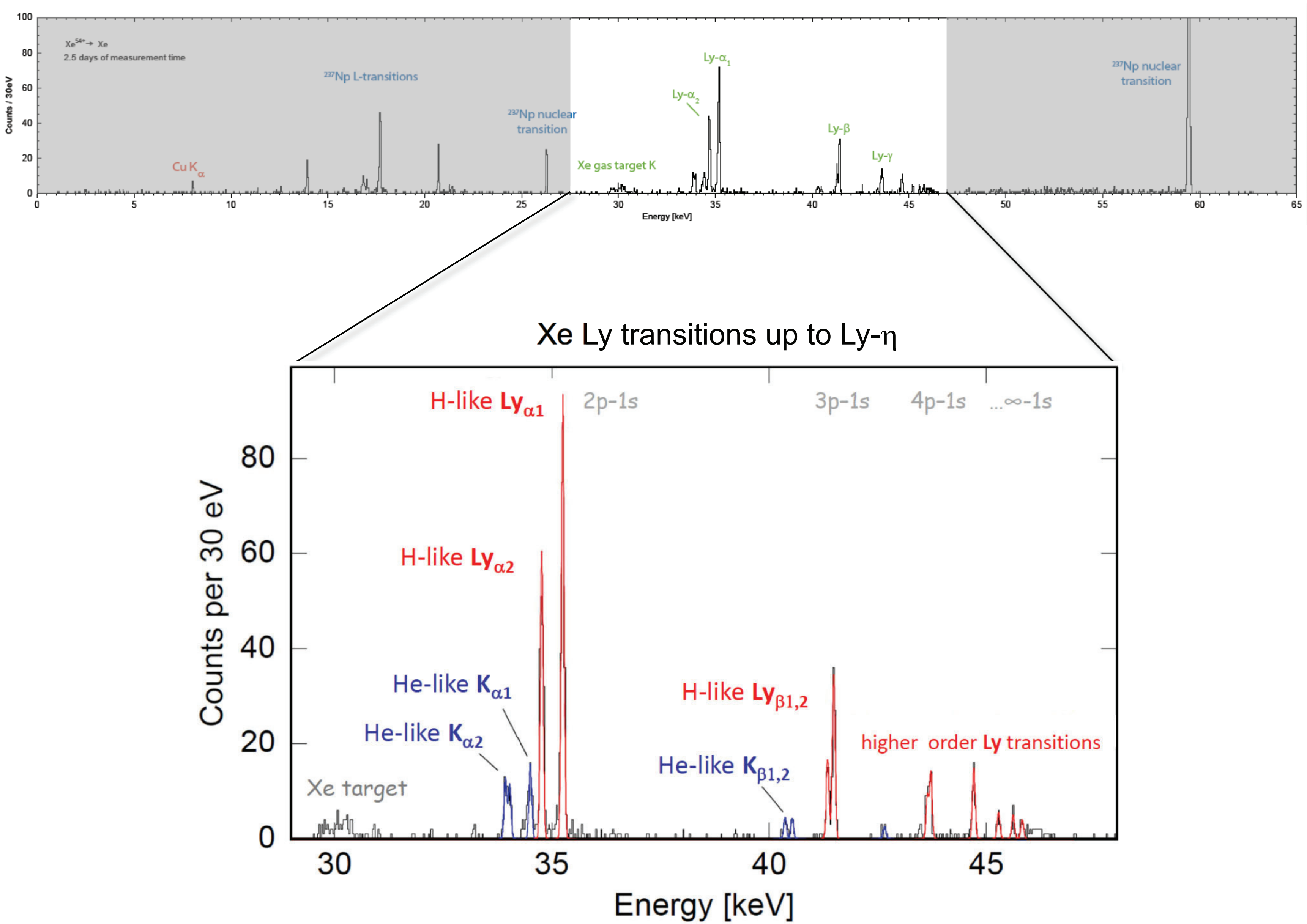
80% quantum efficiency at 100 keV

Investigation of H-like and He-like Xe at the ESR



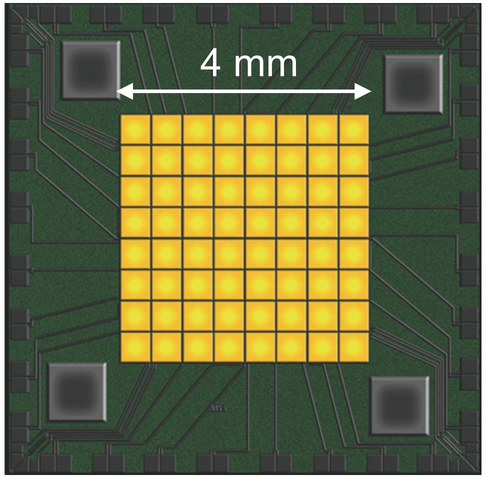
From disassembly to first pulse: 80 hours

H-like $^{53+}$Xe



D. Hengstler, *et al.*, Physica Spripta **T166**, 014054 (2015)

maXs-30 Detector (8 x 8 Array)

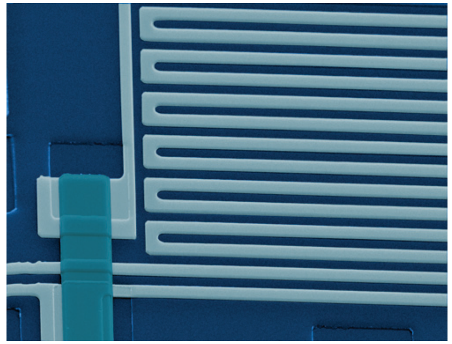


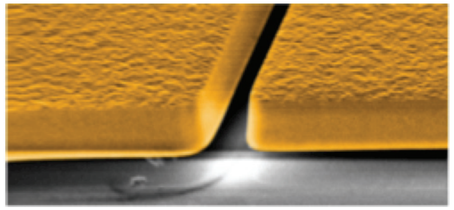
8 x 8 array of X-ray absorbers

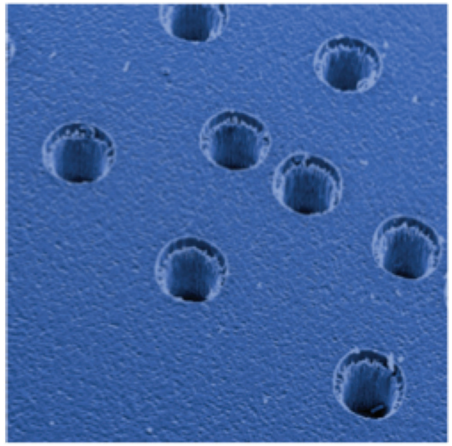
500 x 500 μm, 30 μm thick gold

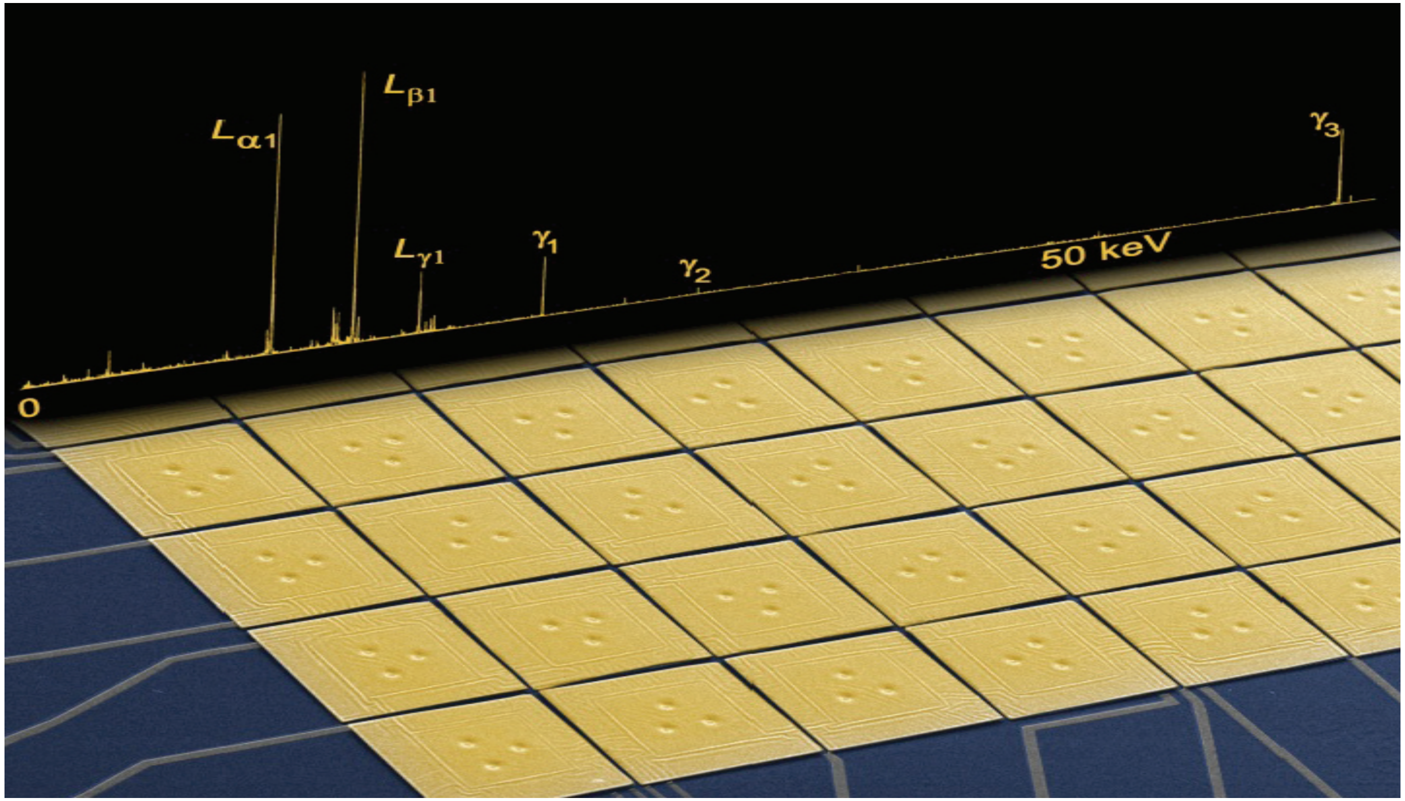
Quantum effeciency	~ 100 %	@	20 keV
	80 %	@	30 keV
	20 %	@	60 keV

Energy resolution $\Delta E_{FWHM} < 6$ eV







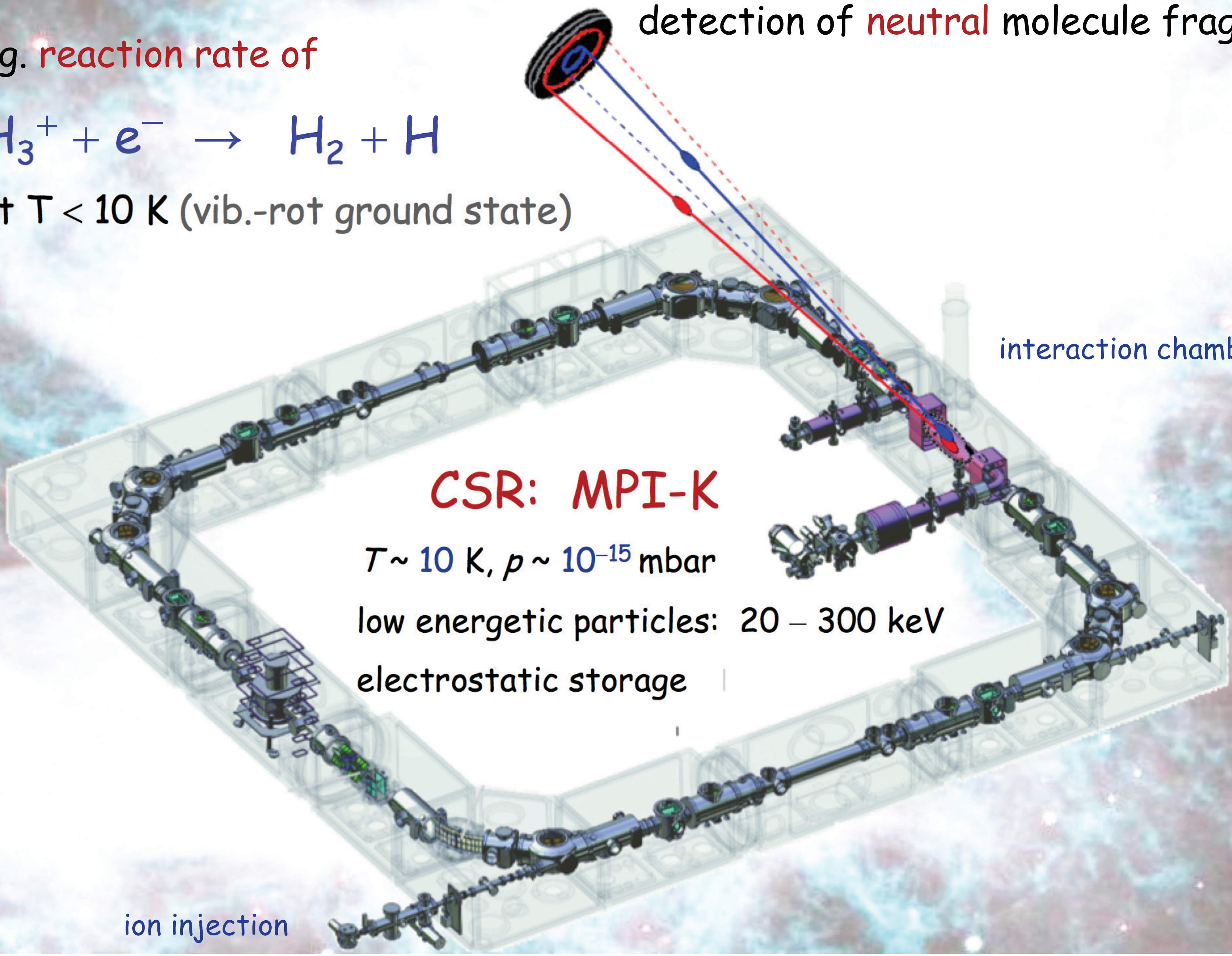


Chemistry of Interstellar Clouds

eg. reaction rate of

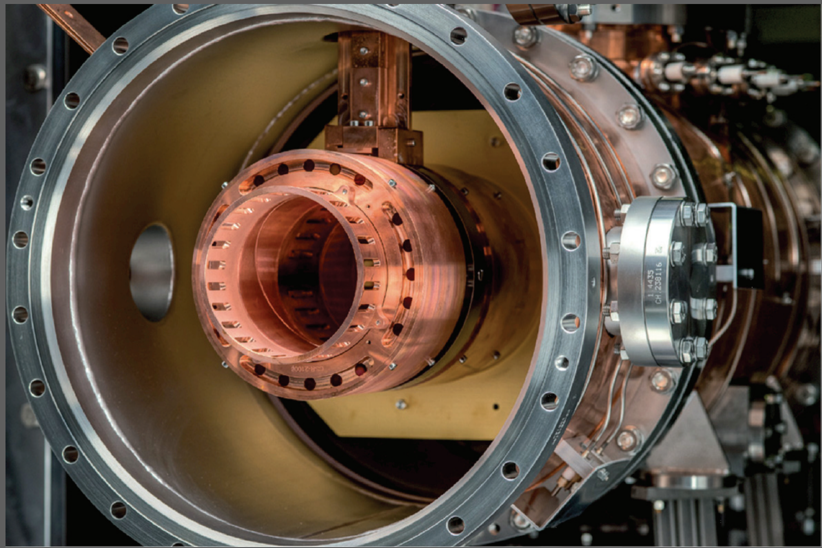
$$H_3^+ + e^- \rightarrow H_2 + H$$

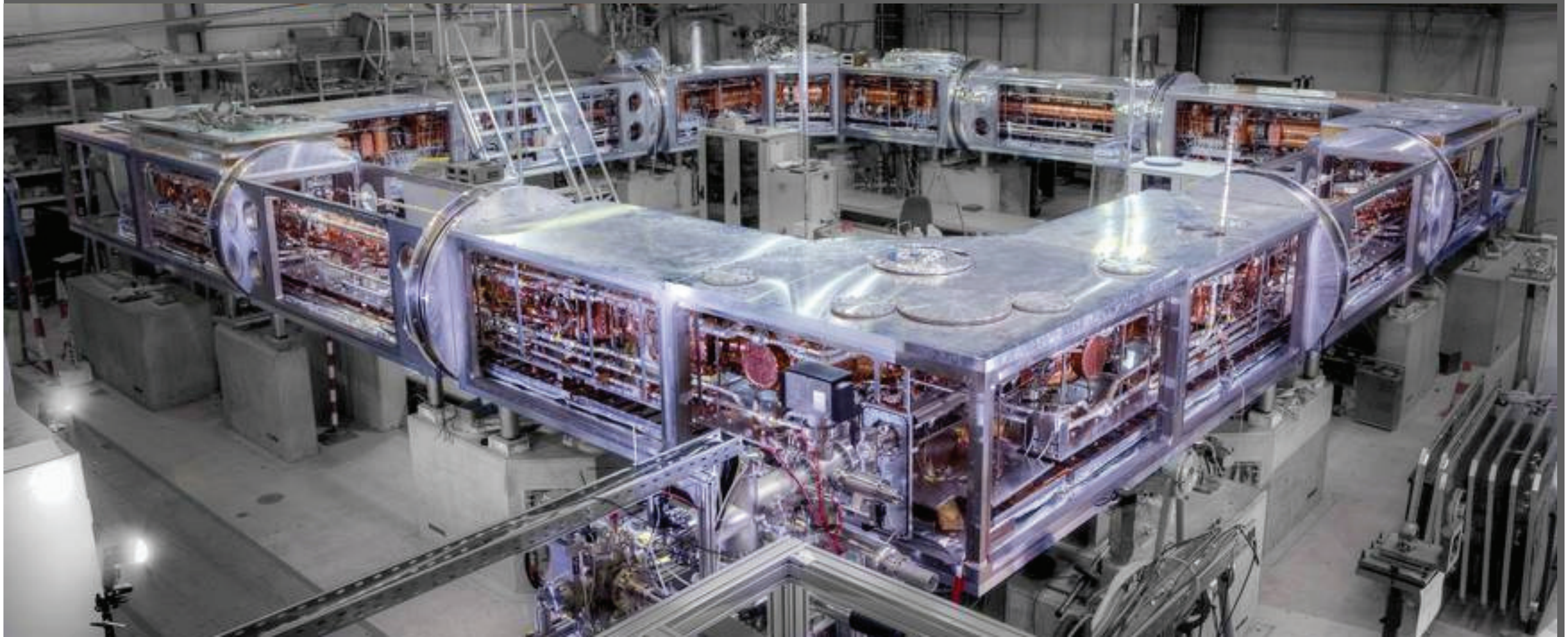
at $T < 10$ K (vib.-rot ground state)



Cryogenic Storage Ring at MPI-K

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

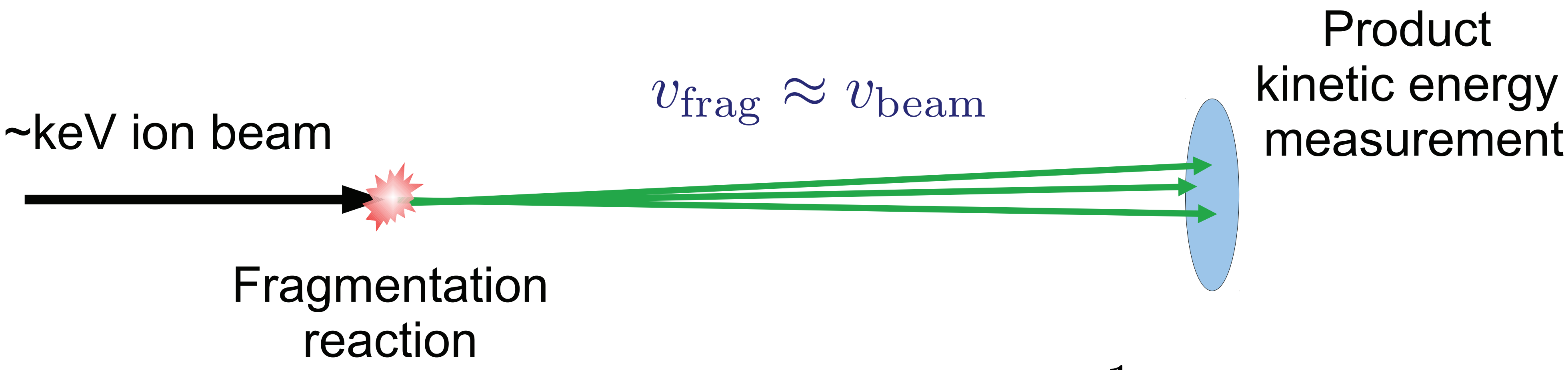




Dissociative Recombination

$$
\begin{aligned}
\mathrm{ABCD}^+ + e^- &\rightarrow \mathrm{A} + \mathrm{BCD} \\
&\rightarrow \mathrm{AB} + \mathrm{CD} \\
&\rightarrow \mathrm{A} + \mathrm{B} + \mathrm{C} + \mathrm{D}.
\end{aligned}
$$

mass from kinetic energy



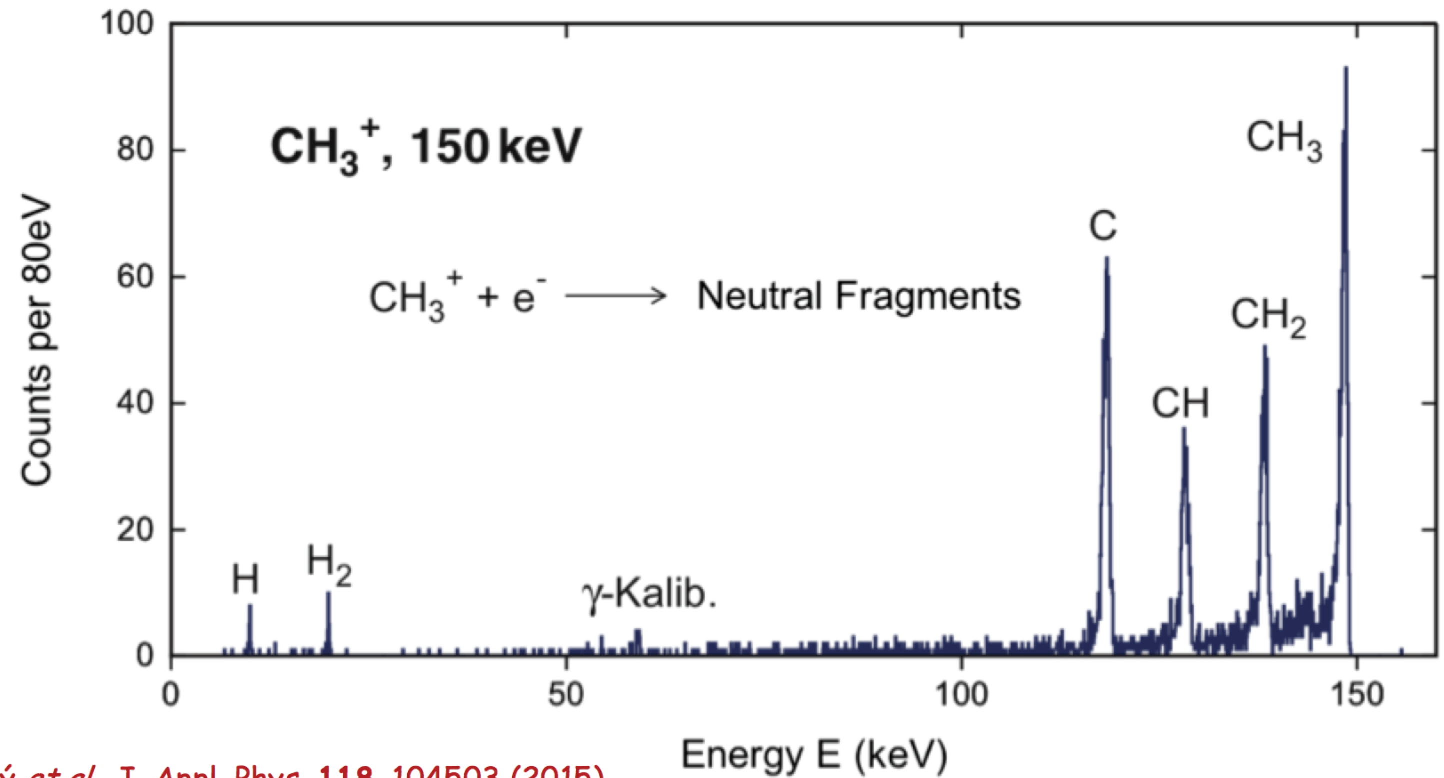
$$v_{\mathrm{frag}} \approx v_{\mathrm{beam}}$$

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

First Measurements at MPI for Nuclear Physics

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

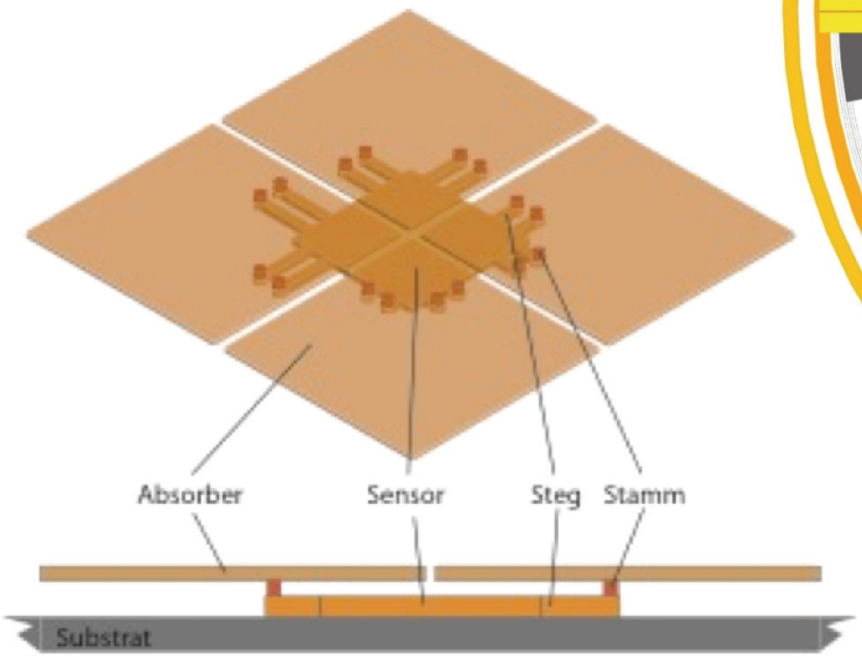
neutral fragments of CH_3^+ accelerated with 150 keV

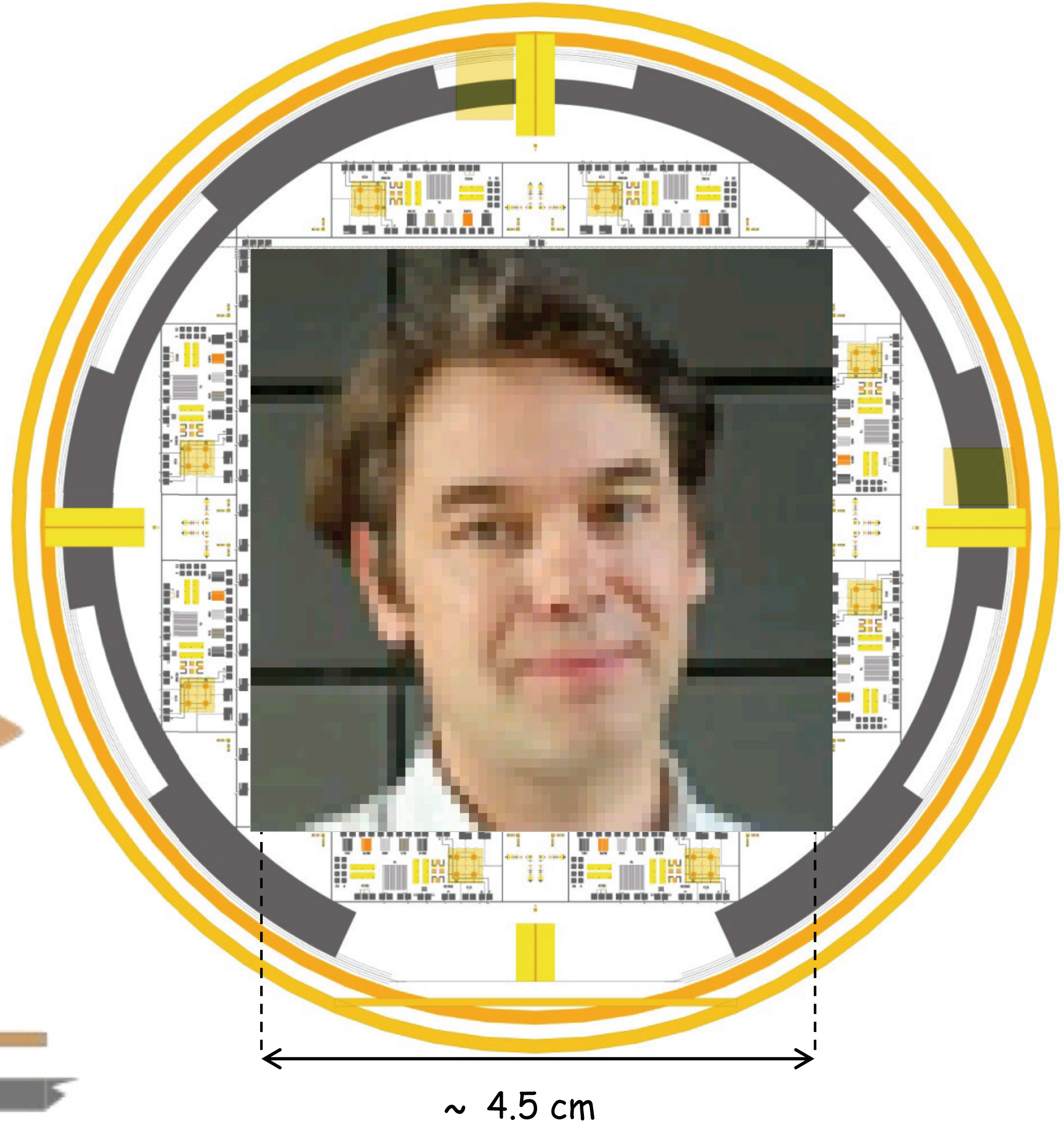


O. Novotný *et al.*, J. Appl. Phys. **118**, 104503 (2015)

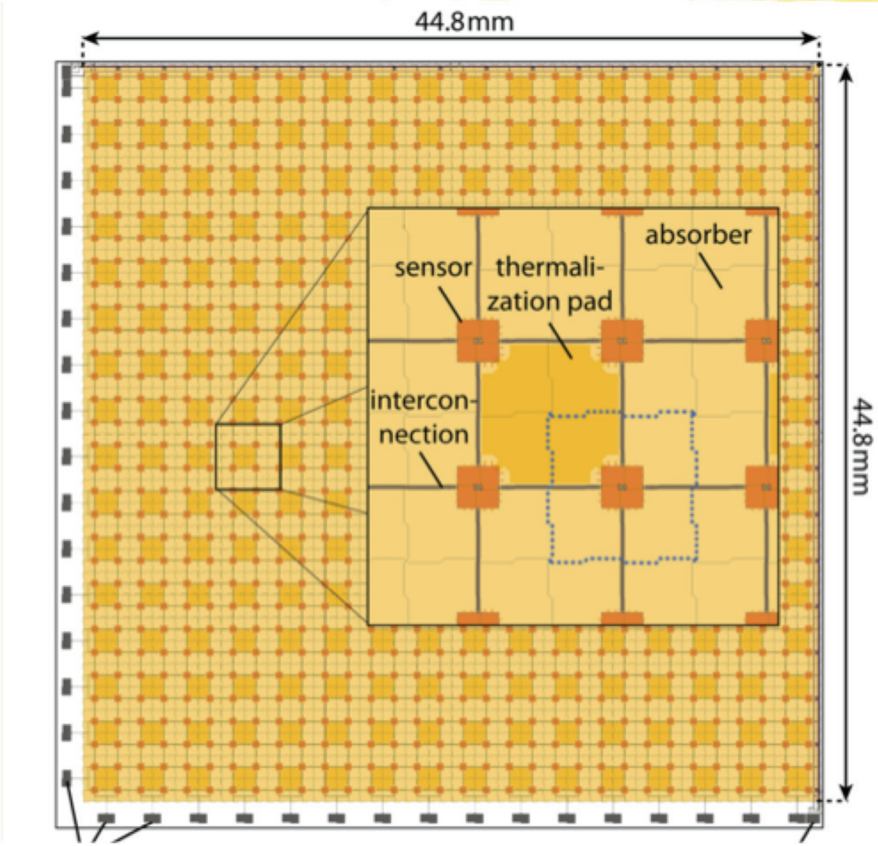
MOCCA: a 4k-pixel molecule camera

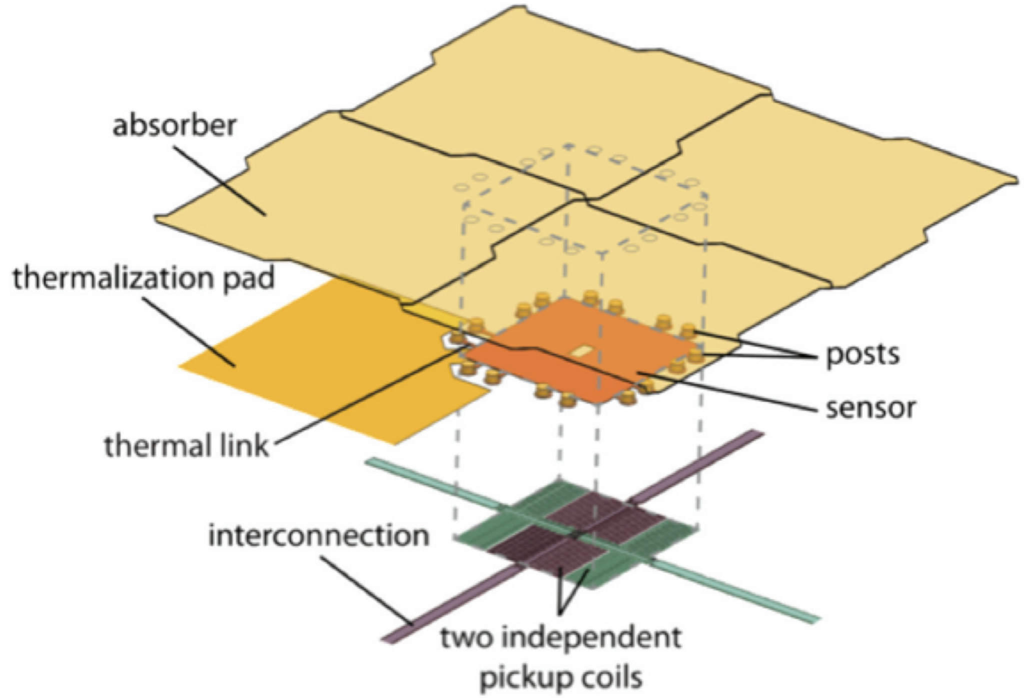
64 × 64 pixels
200 eV (FWHM)
32 × 32 temperature sensors
Read out by 16+16 SQUIDs



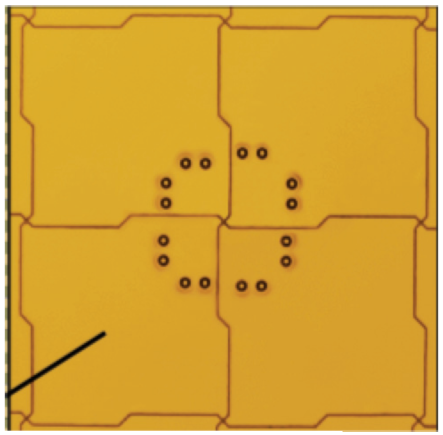


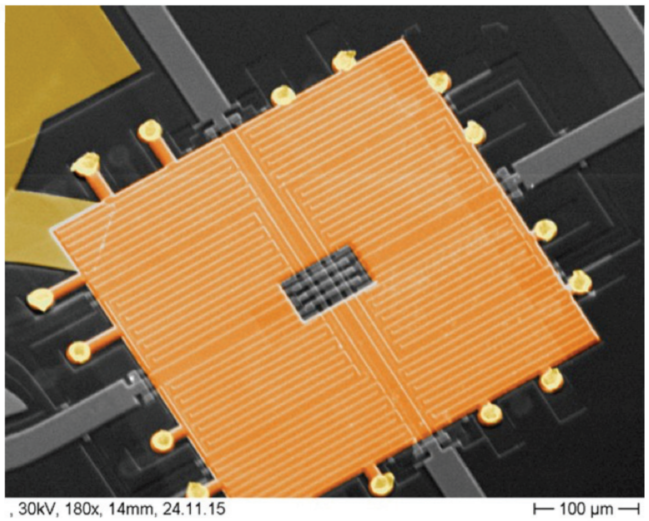
MOCCA Design and Production

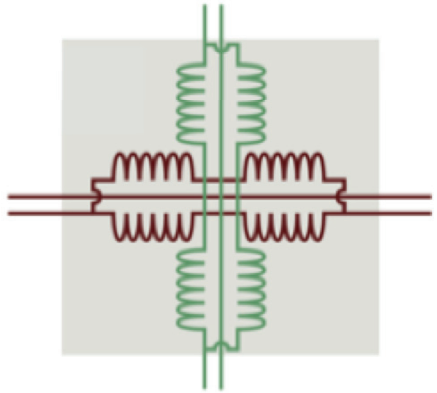




Absorber



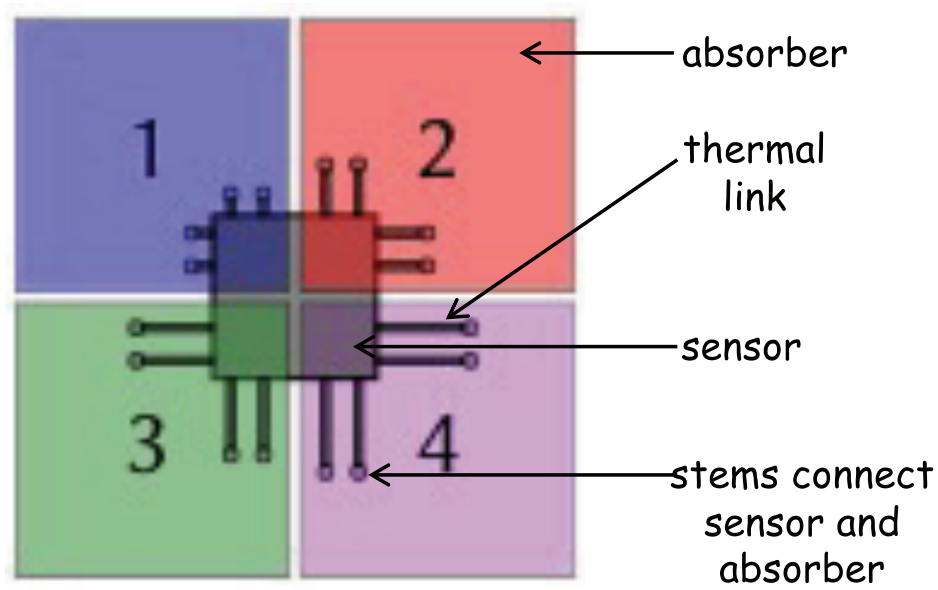


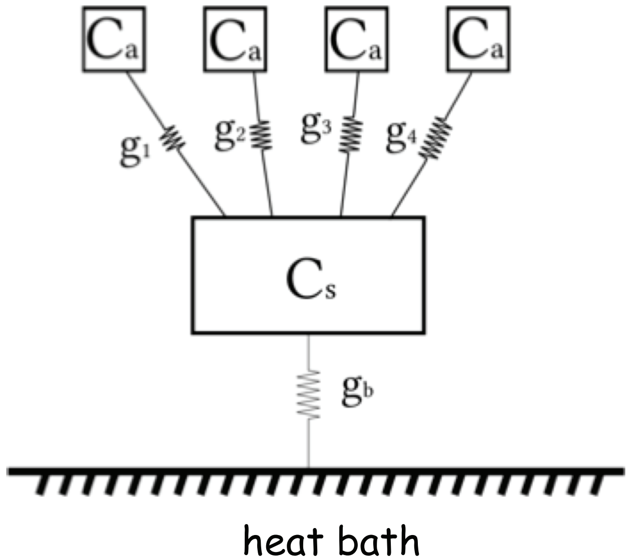


L. Gamer, *et al.*, J. Low. Temp. Phys. (2016)

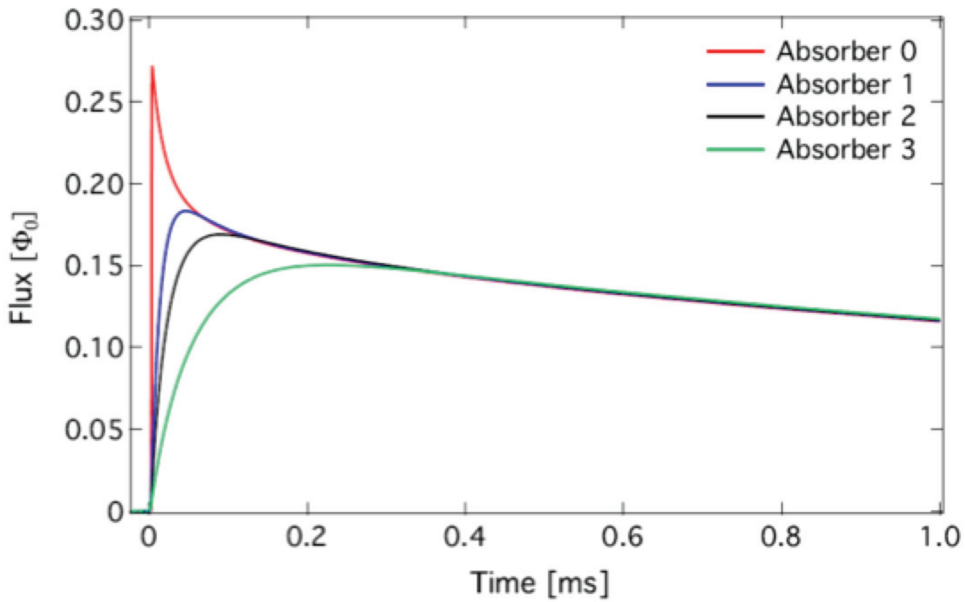
The Hydra Principle

As pioneered by the NASA-Group



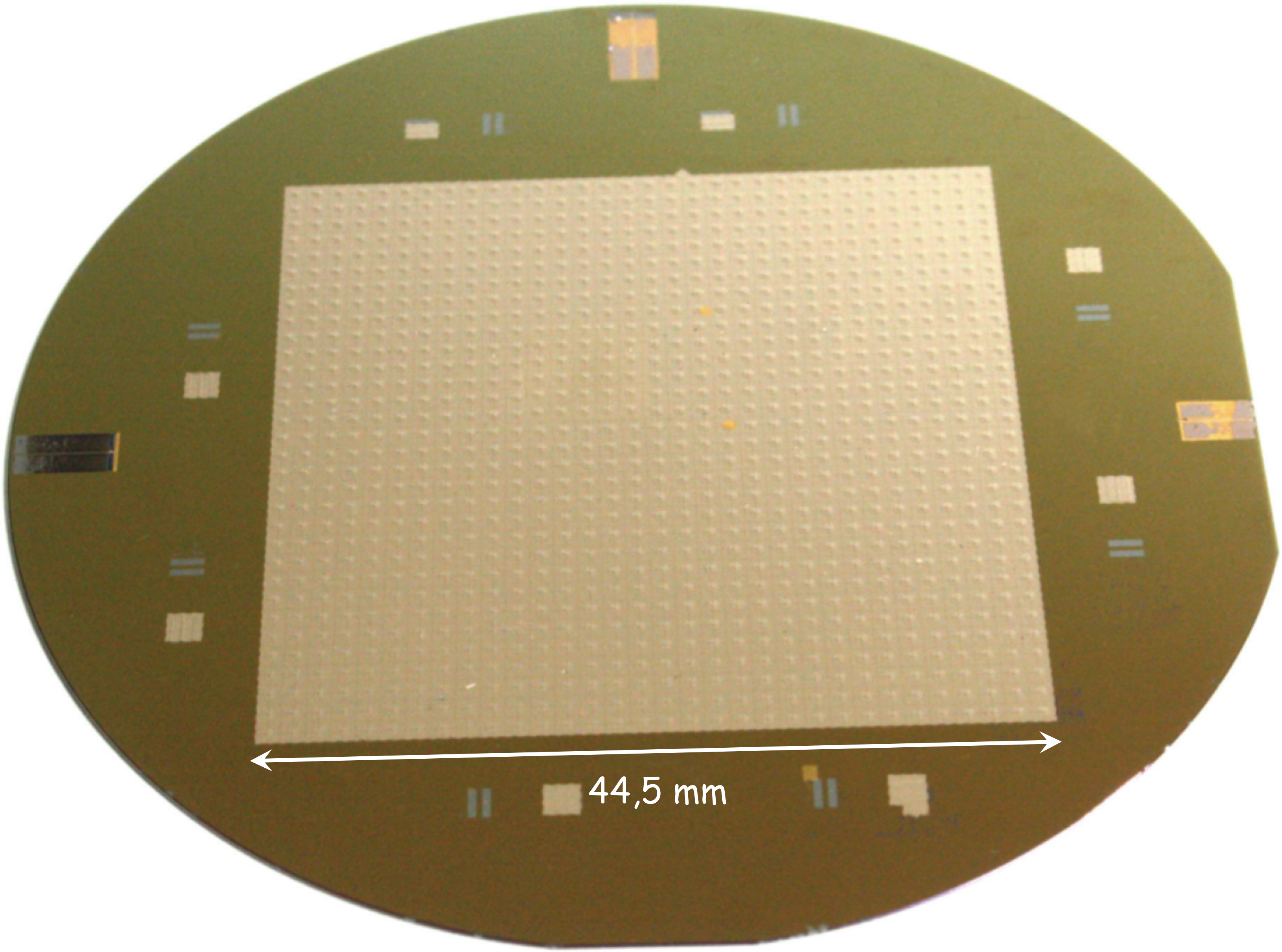


Pixel identification via rise-time of the detector signal



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

MOCCA in Production



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

Particle Physics

Direct Determination of Neutrino Mass

Neutrinoless Double Beta Decay

Direct Neutrino Mass Determination

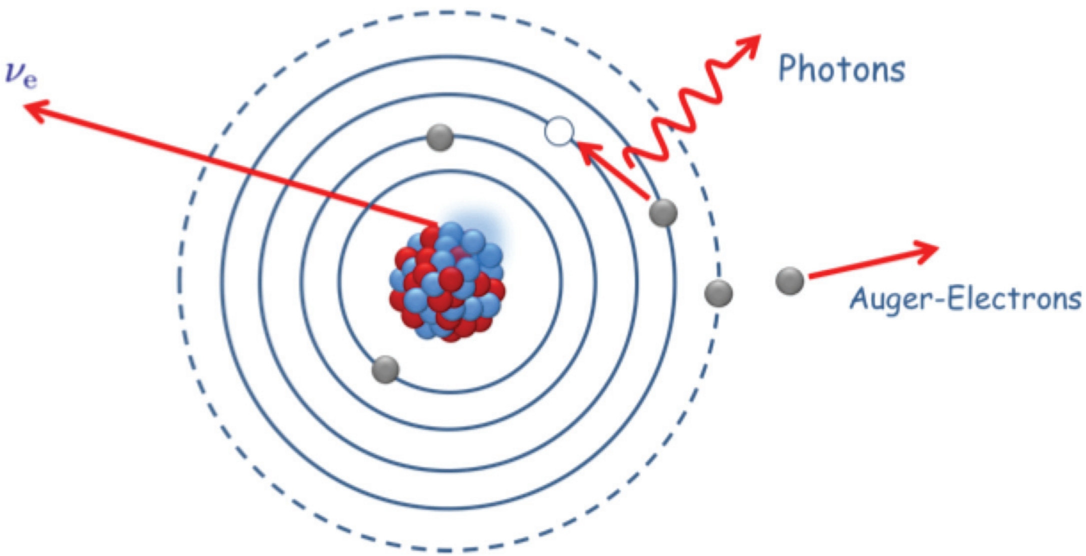
current best limits	$m(\overline{\nu}_e) \leq$	2 eV/c²	beta decay	Tritium
	$m(\nu_e) \leq$	225 eV/c²	beta capture	Holmium

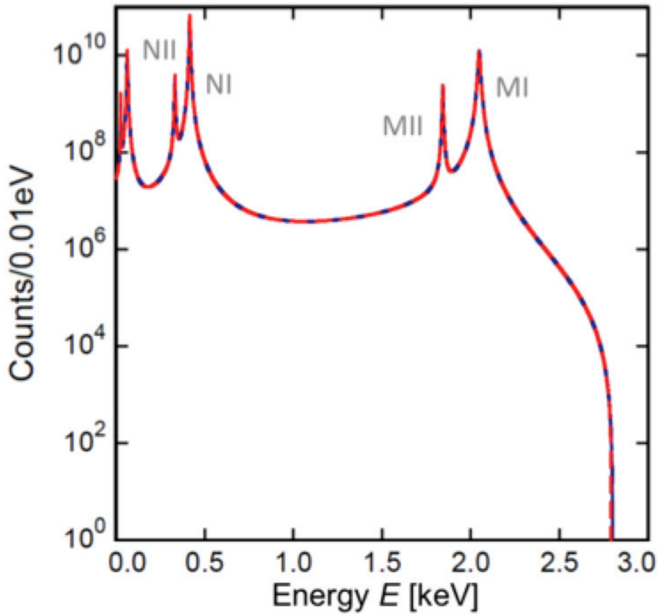
the case of ^{163}Ho

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

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

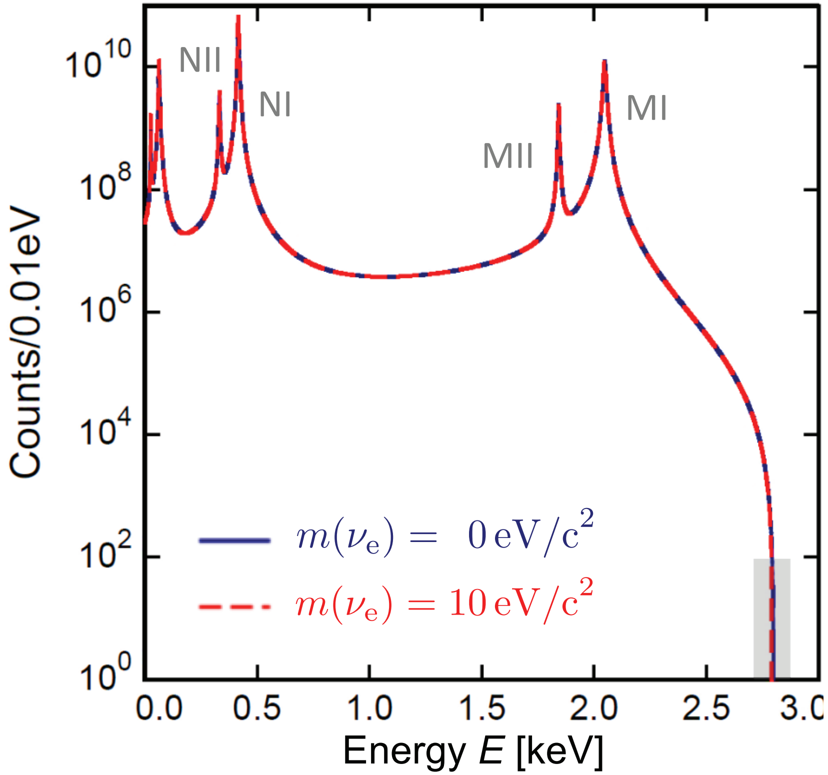
$$\hookrightarrow {}^{163}_{66}\mathrm{Dy} + E_C$$

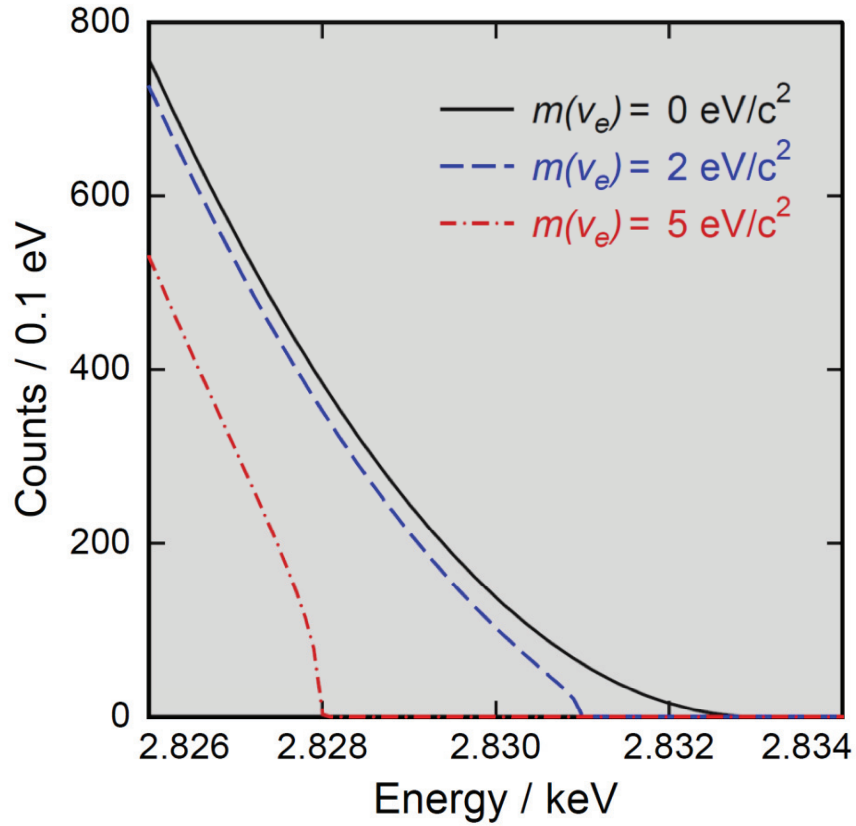




Electron Capture Spectrum of ^{163}Ho

$$\frac{dN}{dE_C} = A\,(Q_{EC}-E_C)^2\sqrt{1-\frac{m_\nu^2}{(Q_{EC}-E_C)^2}}\sum_j C_j n_j B_j \phi_j^2(0)\frac{\Gamma_j/2\pi}{(E_C-E_j)^2+\Gamma_j^2/4}$$



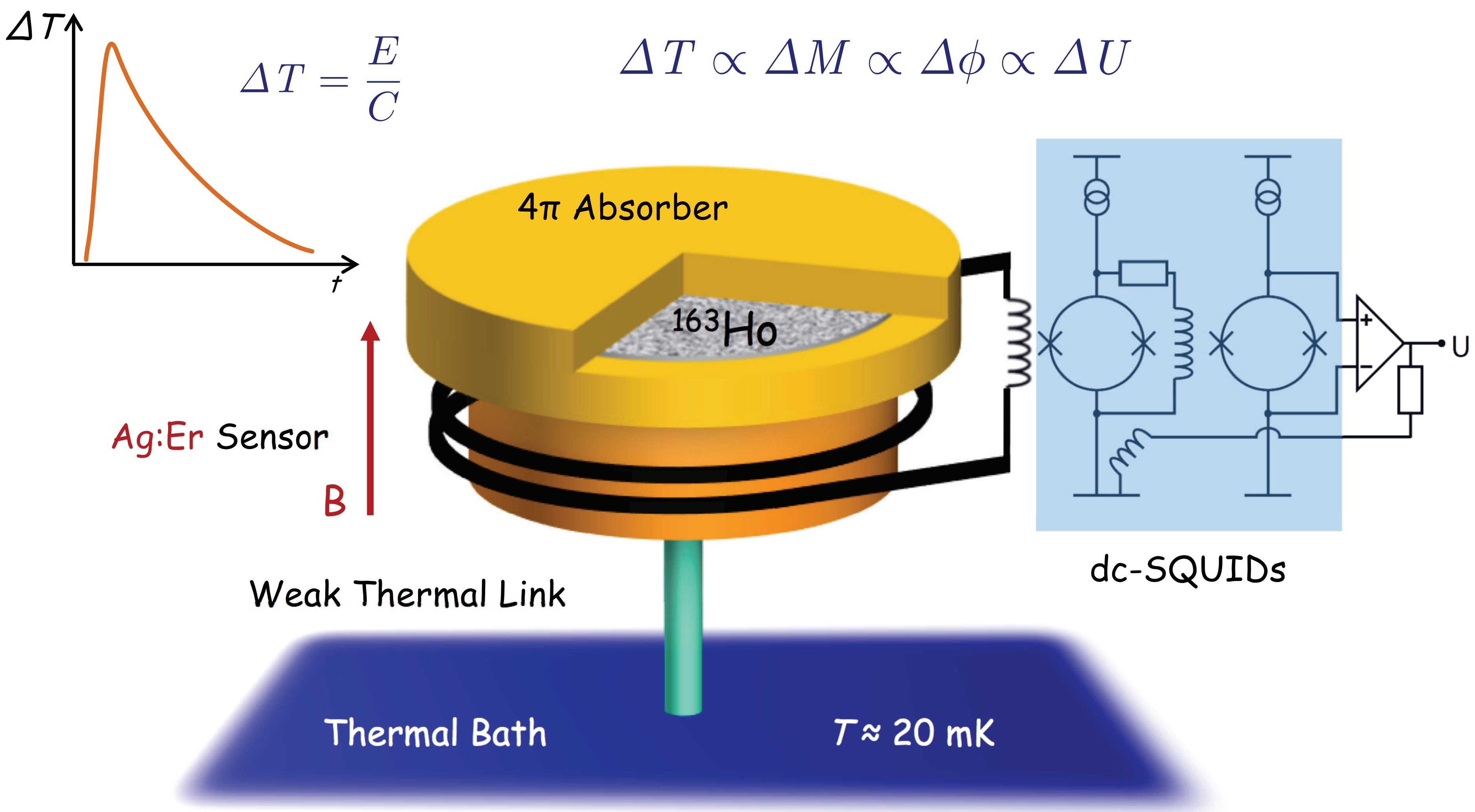


Low Q_{EC} = $(2.833 \pm 0.030^{stat} \pm 0.015^{sys})$ keV S. Eliseev *et al.*, PRL**115**, 062501 (2015)

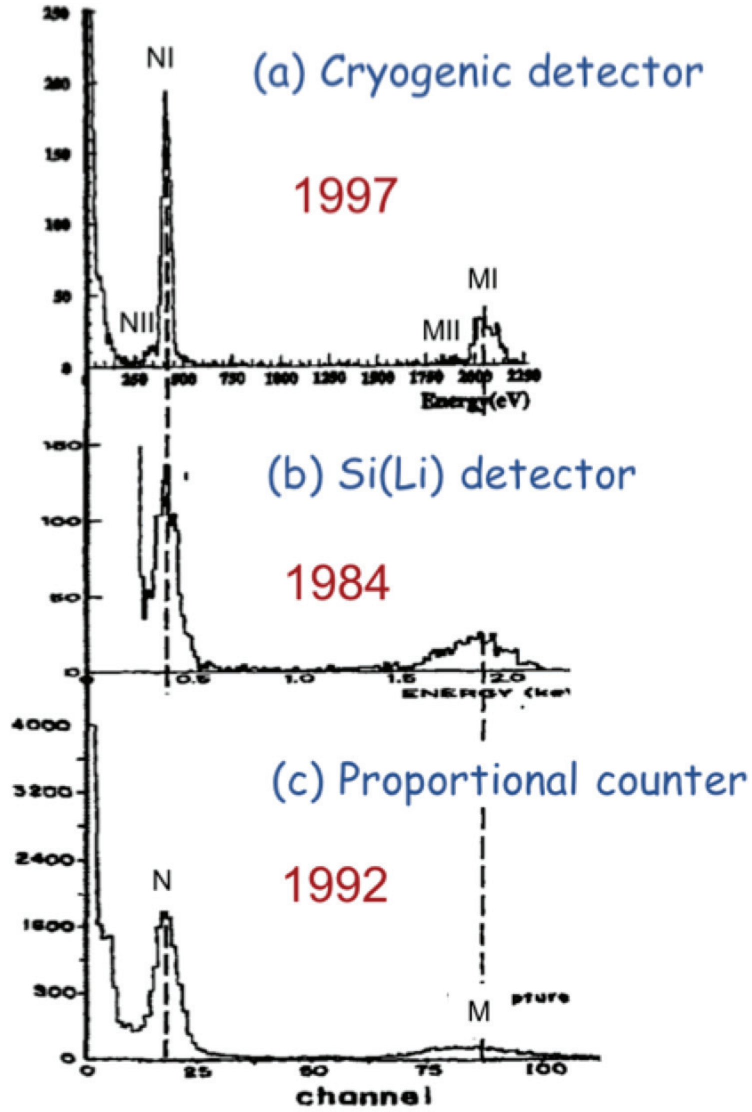
$(2.858 \pm 0.010^{stat} \pm 0.050^{sys})$ keV P. Ranitzsch *et al.*, PRL **119**, 122501 (2017)

Calorimetric Detection of E_C

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



Previous Results and First MMC Measurement

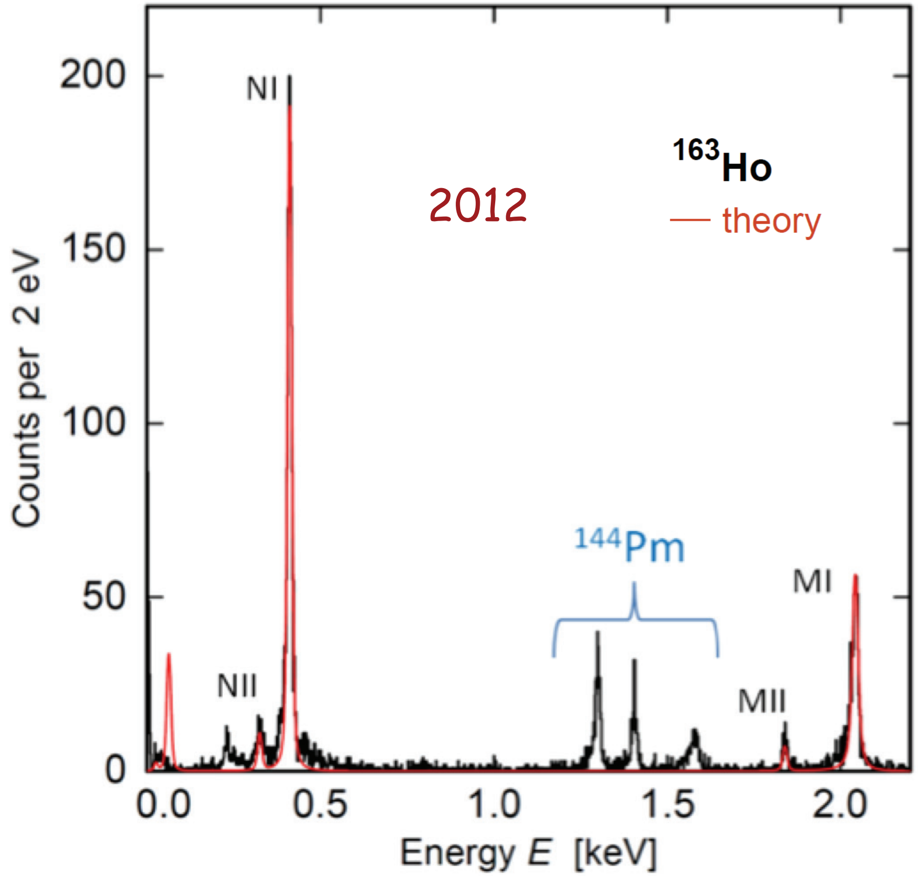


F. Gatti *et al.*, Physics Letters B **398** (1997) 415-419

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

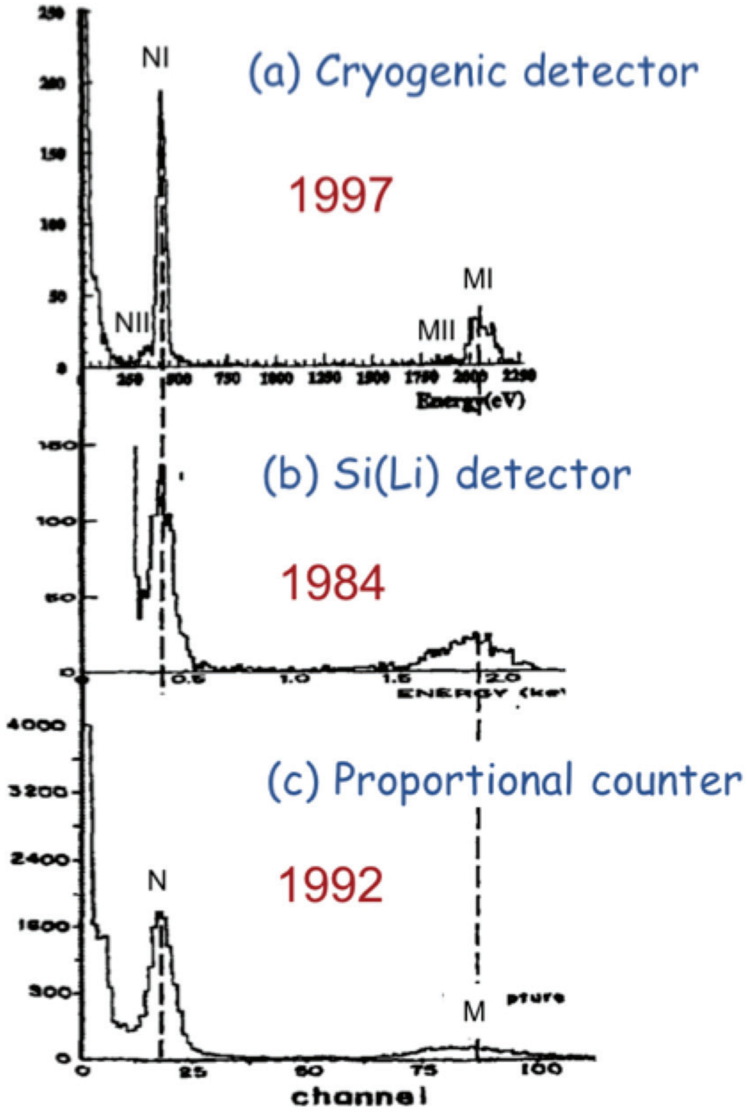
(b) E. Laesgaard *et al.*, Proceeding of 7th International Conference on Atomic Masses and Fundamental Constants (AMCO-7), (1984).

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



P.C.-O. Ranitzsch, *et al.*, J. Low Temp. Phys. **167**, 1004 (2012)

Previous Results and First MMC Measurement

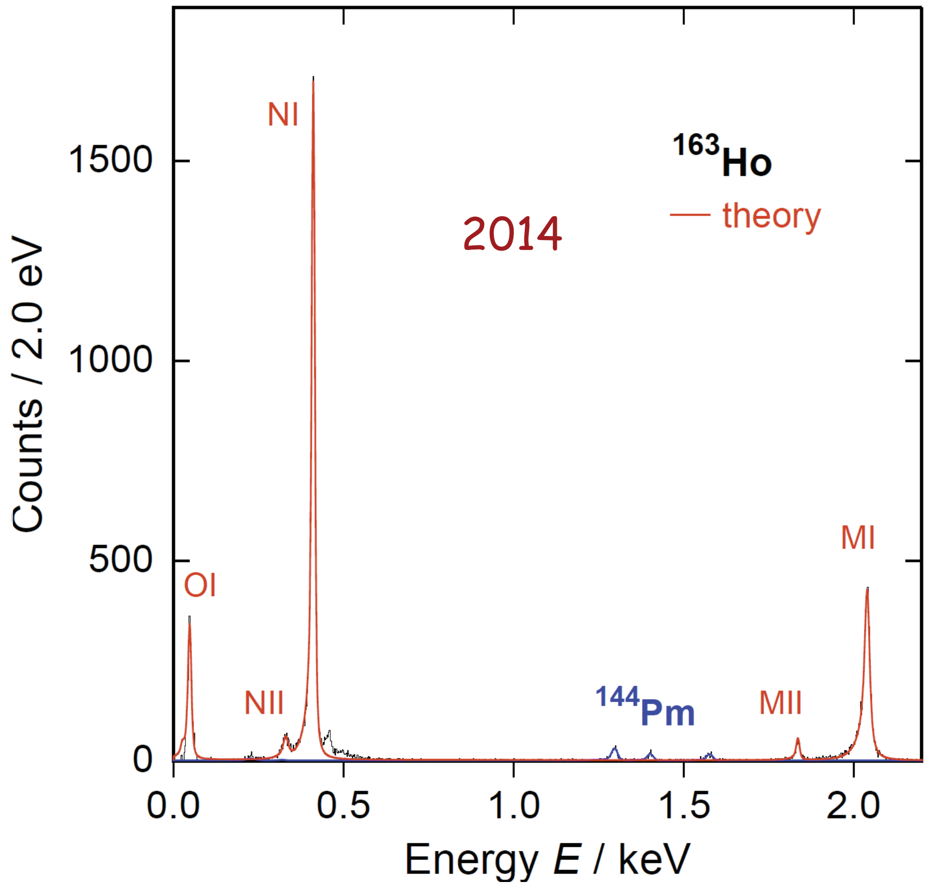


F. Gatti *et al.*, Physics Letters B **398** (1997) 415-419

(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)

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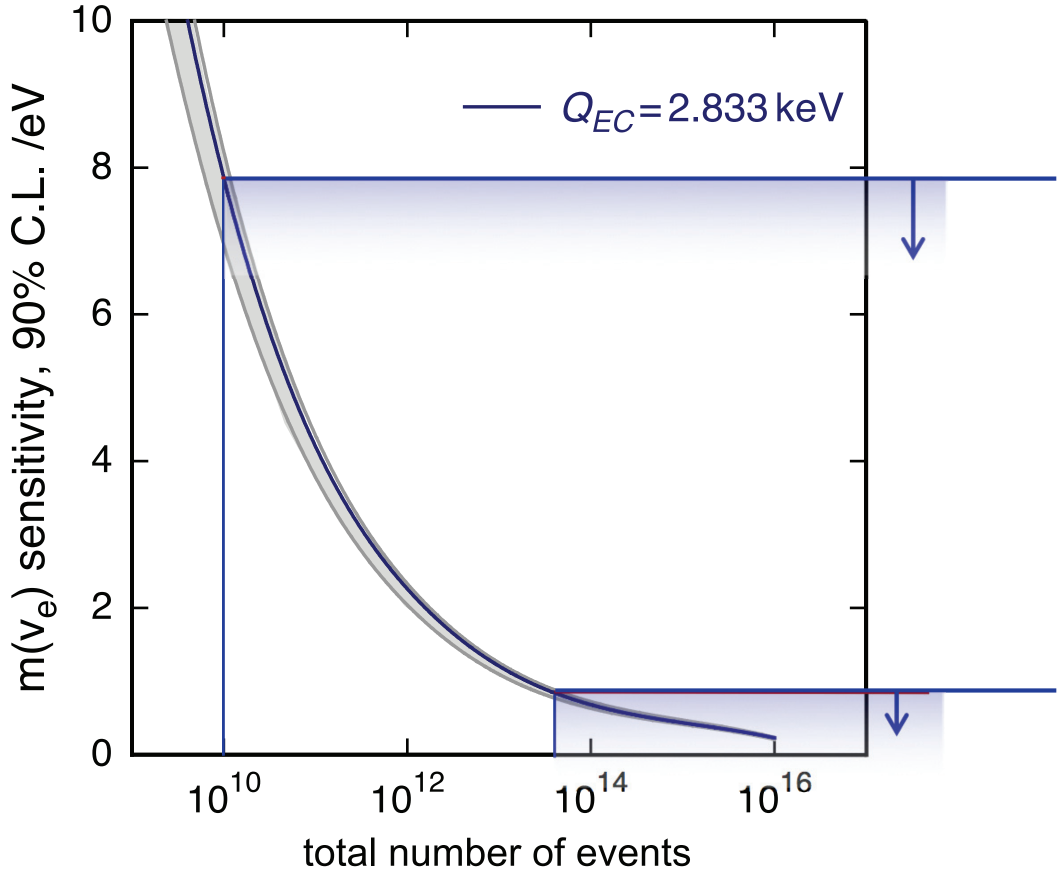
Funded by the Germany Research Foundation DFG

FOR 2202

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



ECHo-1k

2 x 50 pixel x 10 Bq

4 months → 10^{10} events

↓

sub 10 eV resolution

ECHo-100k

50 x 200 pixel x 10 Bq

36 months → 3×10^{13} events

↓

sub 2 eV resolution

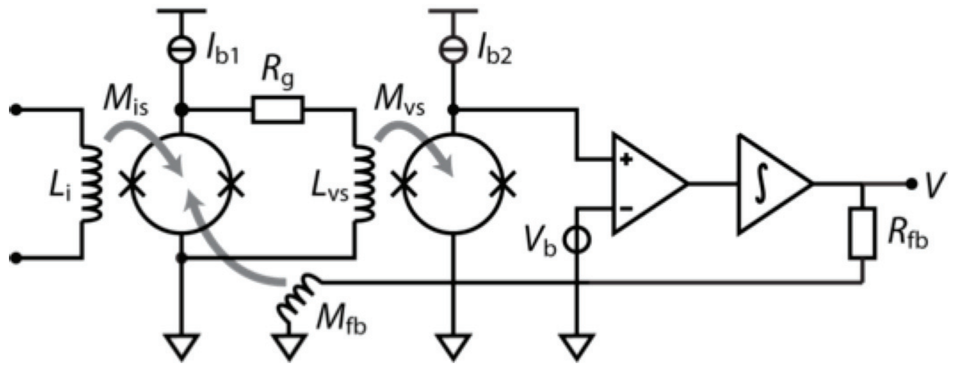
Requirements For Sub-eV Sensitivity: Scalability

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

} ~ N

multiplexed readout:

~ 1000 detectors per readout cannel

possible schemes: FDM, CDM, TDM, ...

↓

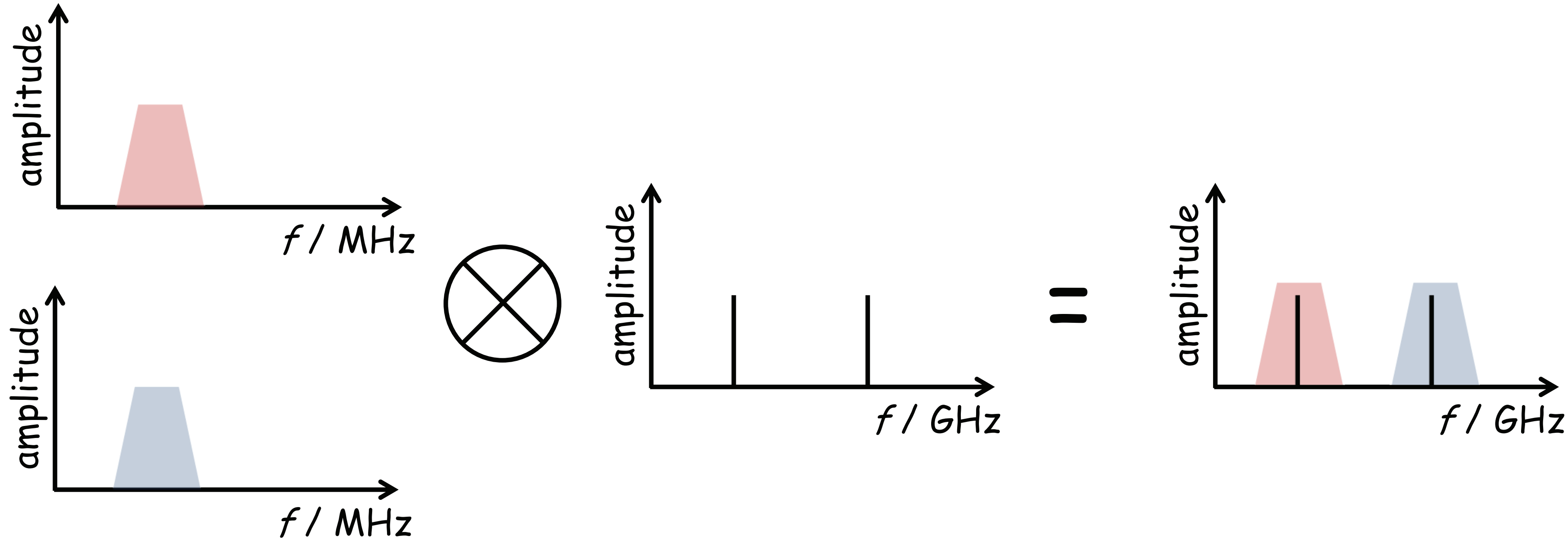
readout techology of ECHo

↓

scalability

Frequency Domain Multiplexing

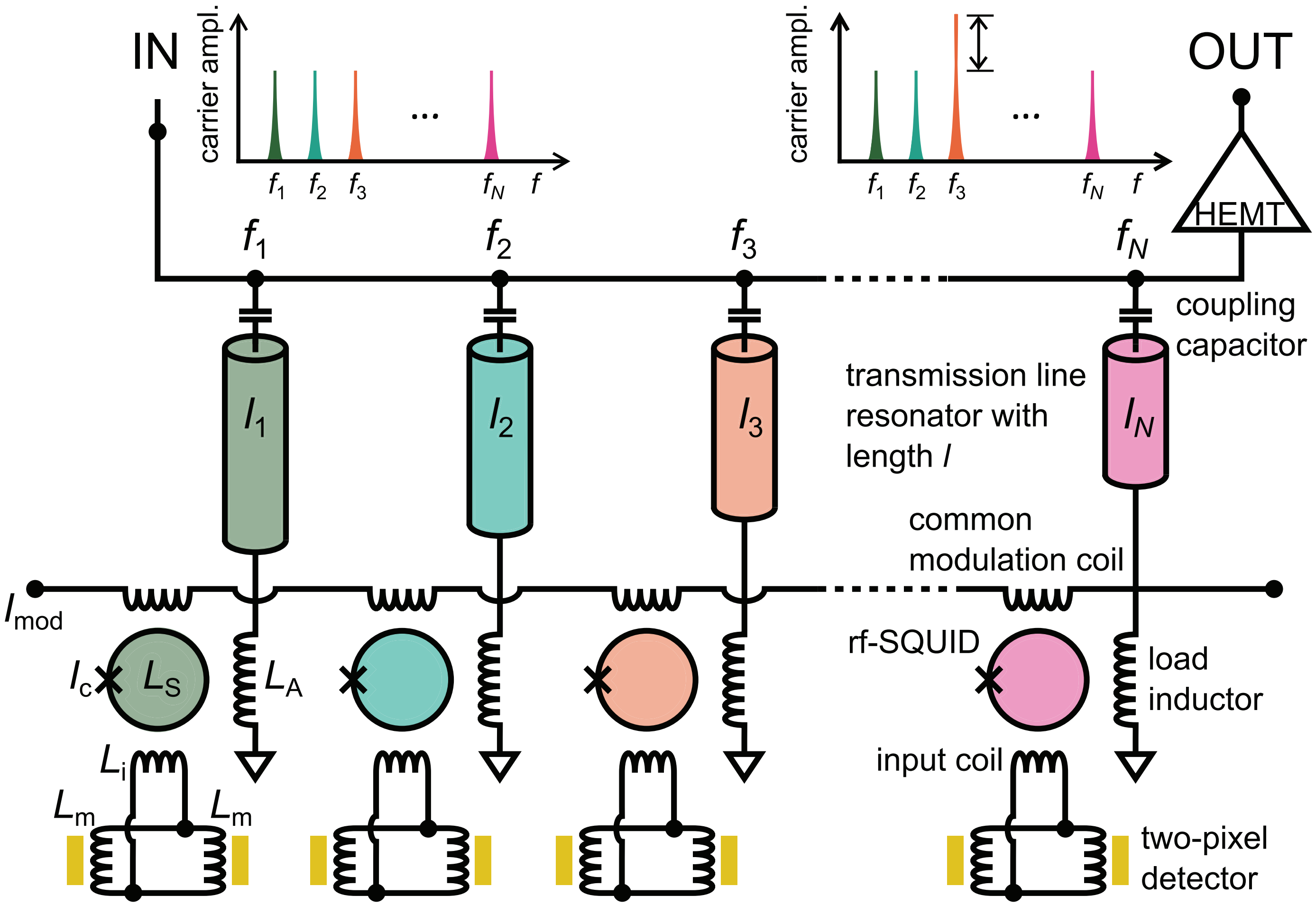
idea: detector signal is modulated on a GHz carrier



→ different carrier frequencies

→ non-linear element for mixing

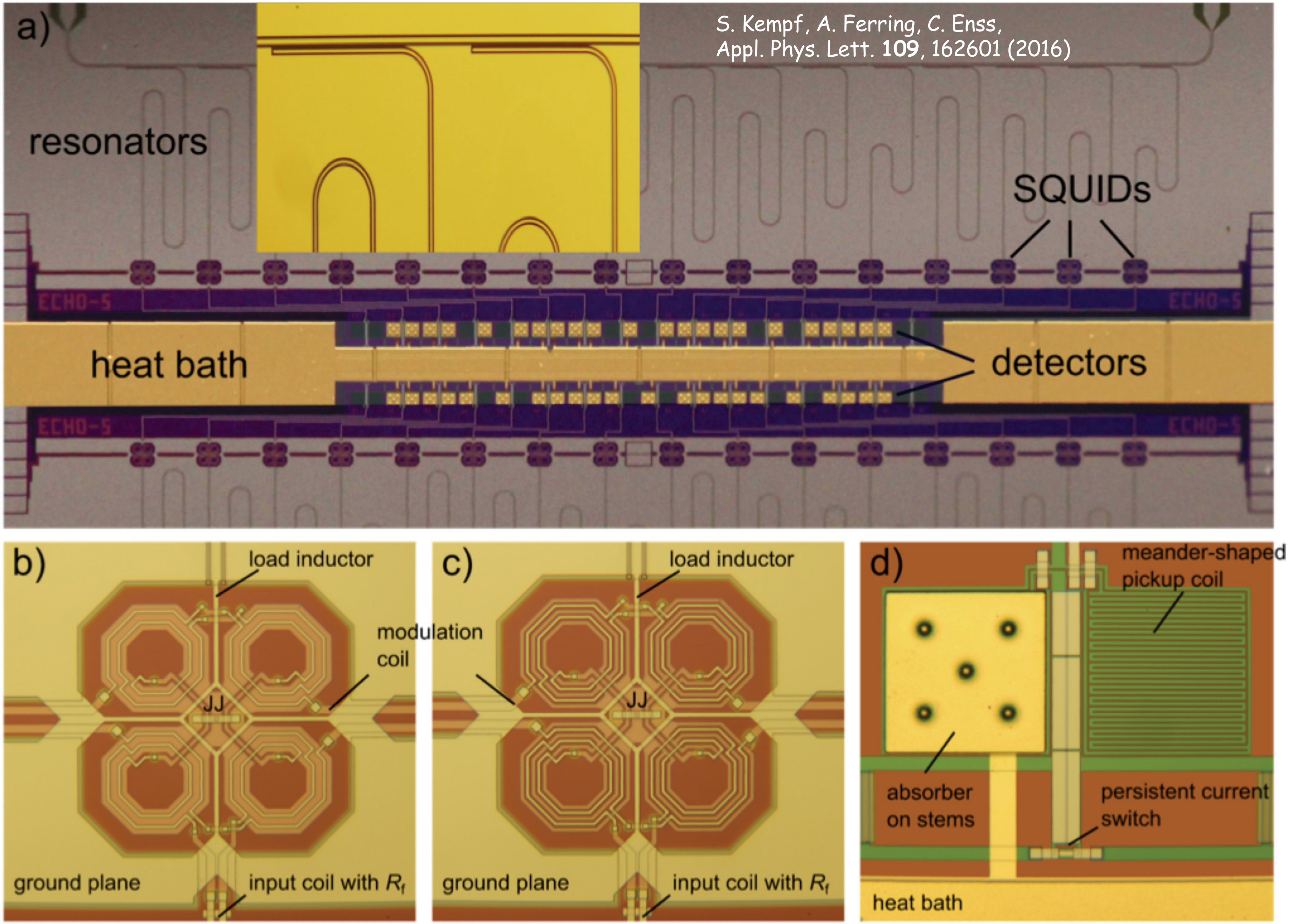
Microwave SQUID Multiplexer (μMUX)



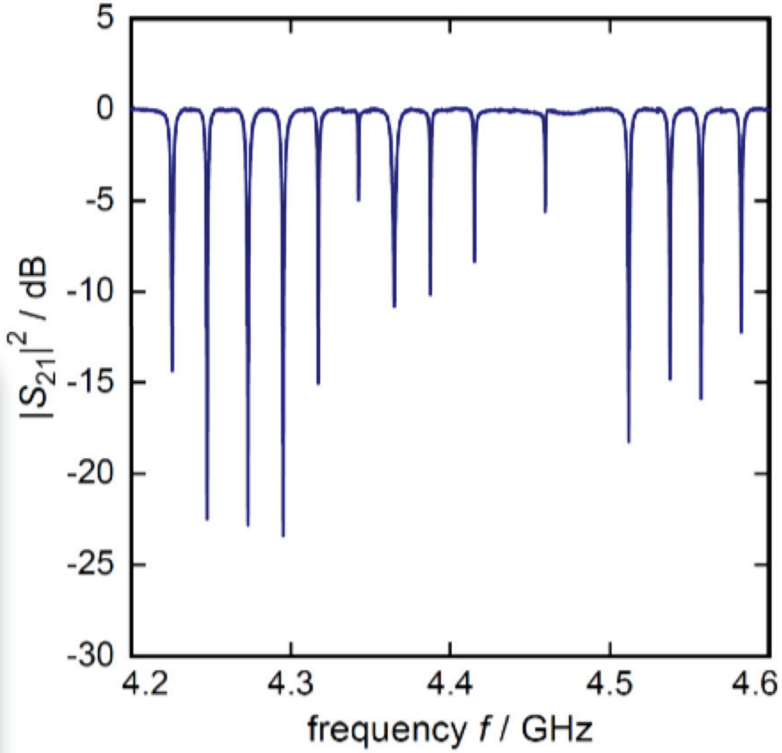
array readout using only one HEMT amplifier and two coaxes

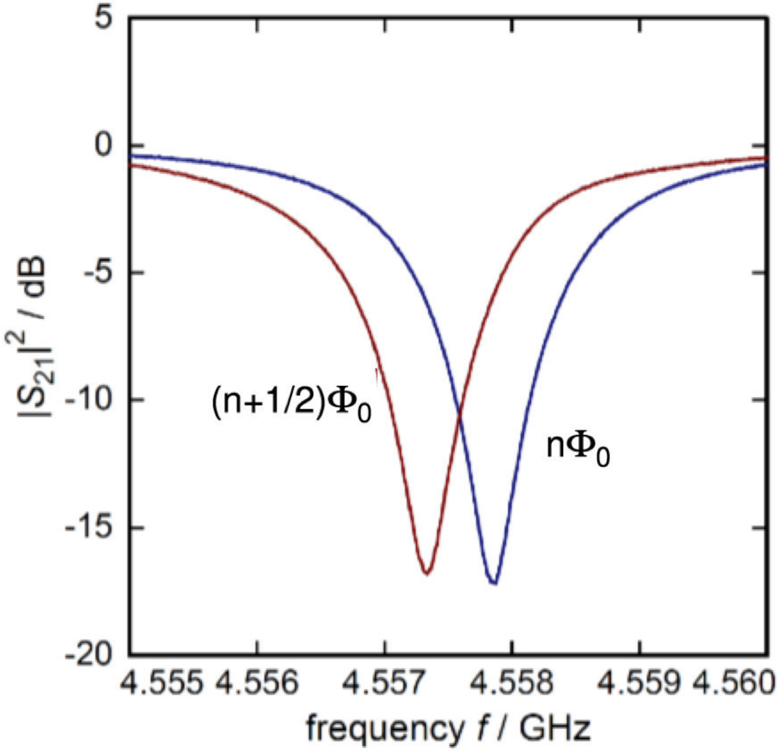
K. Irwin and K. Lehnert, Appl. Phys. Lett. **85** (2004), 2107-9
J. A. B. Mates et al., Appl. Phys. Lett. **92** (2008), 023514
S. Kempf, L. Gastaldo, A. Fleischmann, C. Enss, J. Low. Temp. Phys. **175**, 850 (2014)

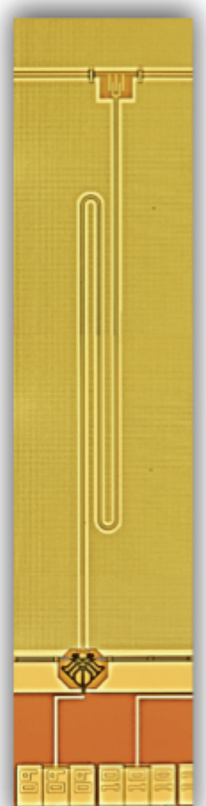
Microwave SQUID Multiplexer (µMUX)

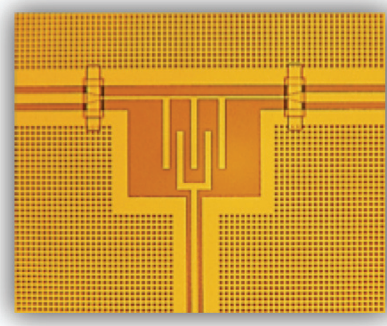


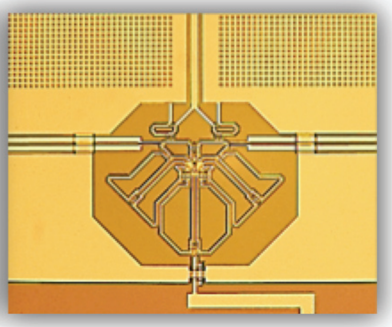
2nd Generation Superconducting Resonators





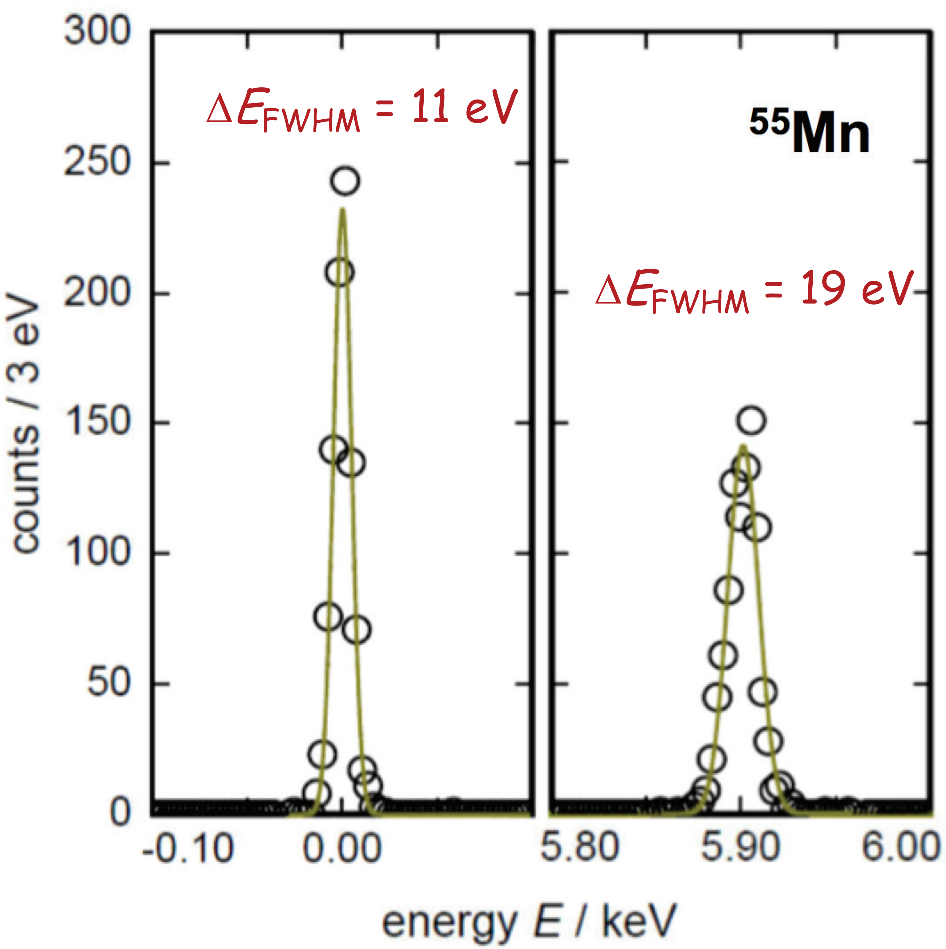






S. Kempf, et. al., AIP ADVANCES **7**, 015007 (2017)

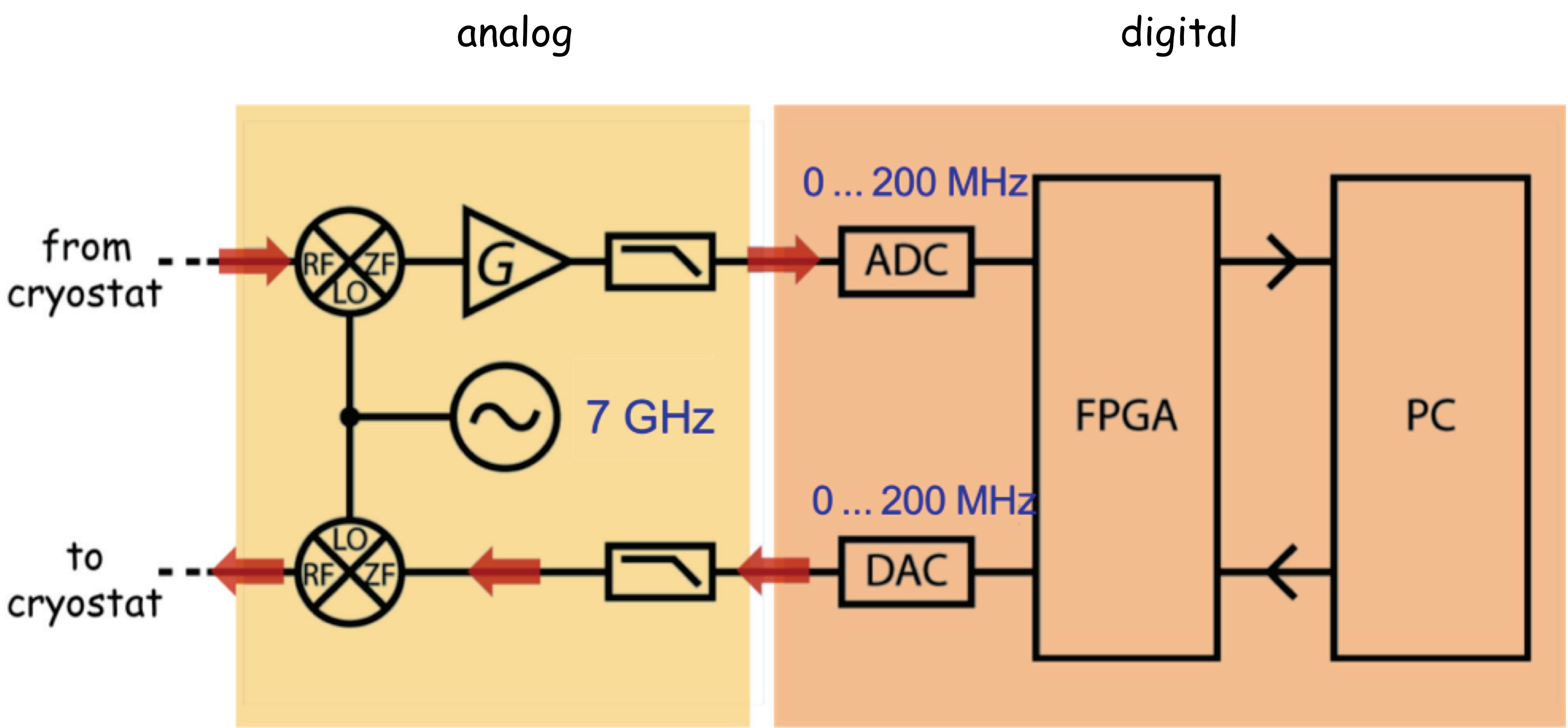
First Results



energy resolution roughly consistent with measured signal size and noise spectra

S. Kempf, et. al., AIP ADVANCES **7**, 015007 (2017)

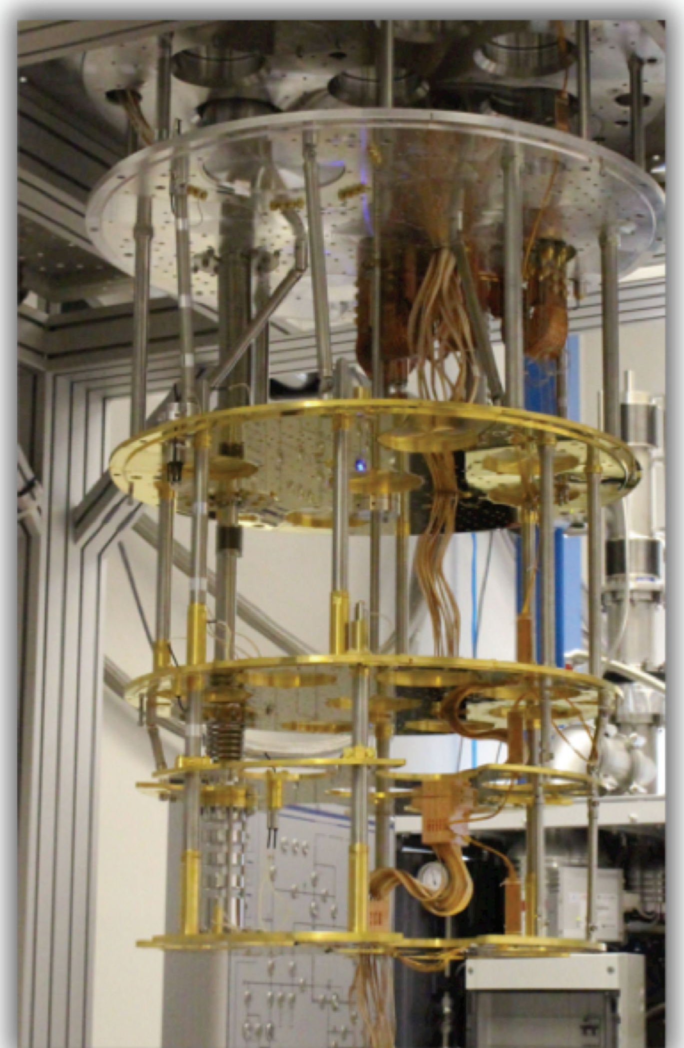
Frequency Domain Multiplexing: Software Defined Radio



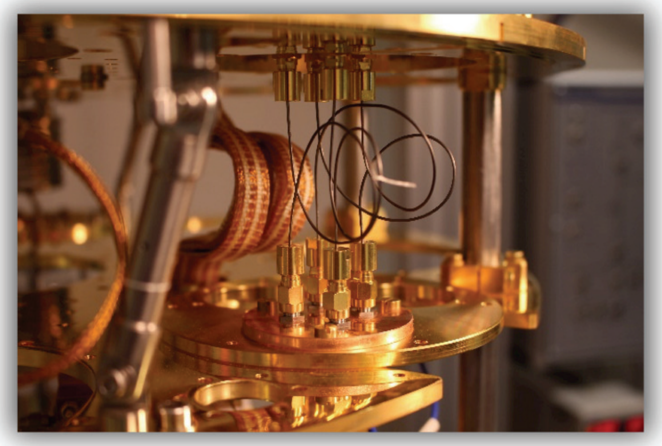
➡ first fully functional system expected in a few months

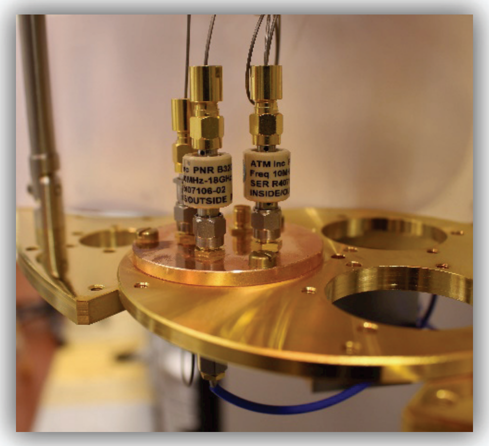
Joint development with
M. Weber, (KIT)
J. Becker (KIT)
U. Kebschull (Uni Frankfurt)

Cryogenic Platform For ECHo

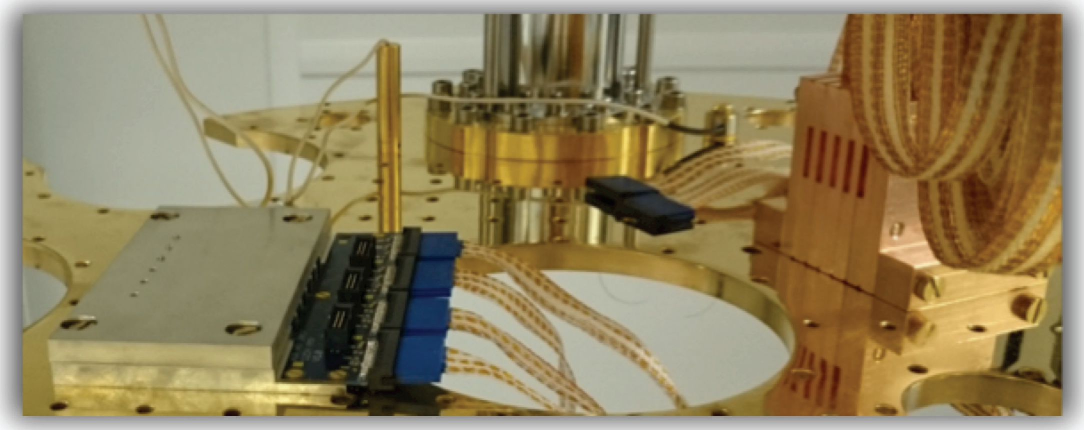


installation of two cryogenic microwave setups



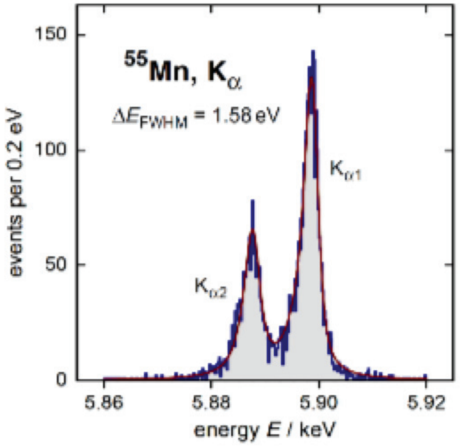


dc wiring and SQUID array installation



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

Summary & Outlook

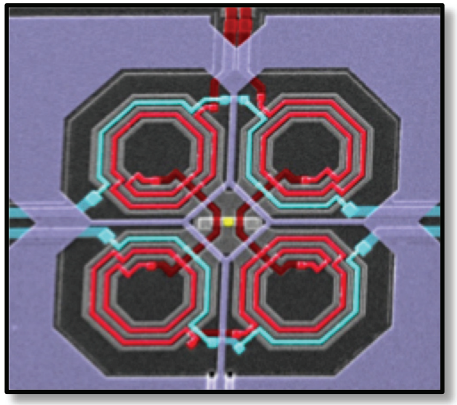


Metallic Magnetic Calorimeters

flexible low temperature detectors

described by standard thermodynamics

wide range of applications

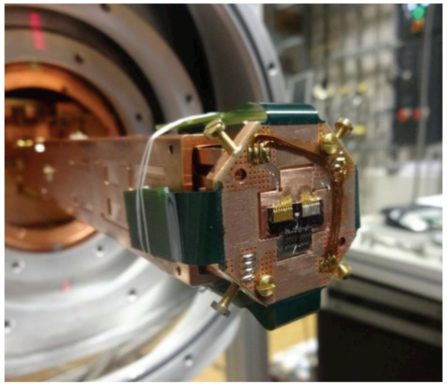


Next Steps in Detector Development

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

.....

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SEVENTH FRAMEWORK PROGRAMME

Thank you!

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