Metallic Magnetic Calorimeters for the ECHo experiment

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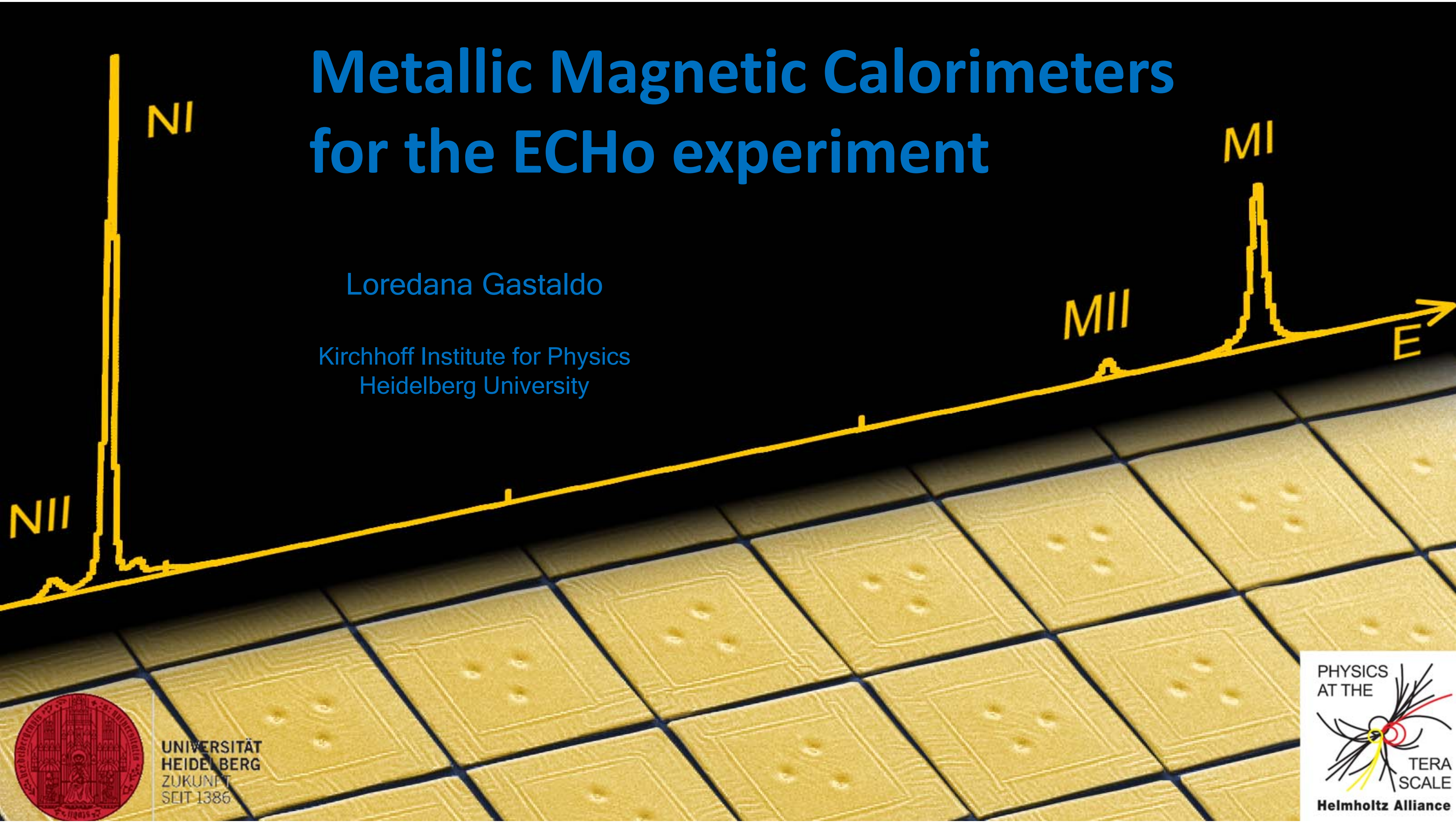
Kirchhoff Institute for Physics
Heidelberg University



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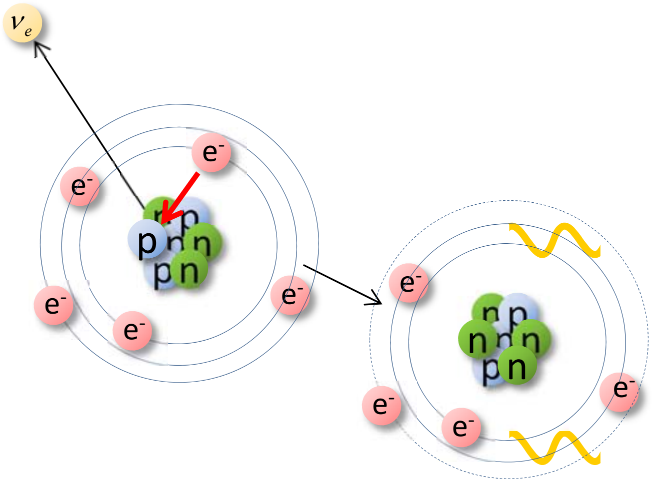
PHYSICS AT THE TERA SCALE
Helmholtz Alliance

Outline

- ^{163}Ho and neutrino mass
- Technological challenges
- Metallic magnetic calorimeters with enclosed ^{163}Ho
- Conclusions

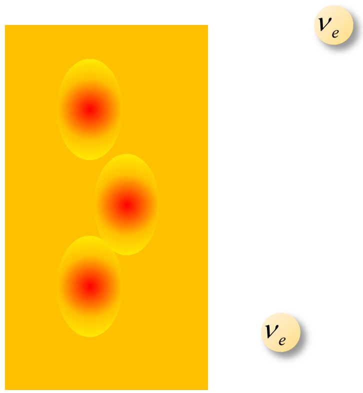
^{163}Ho calorimetric spectrum



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

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

- $\tau_{1/2} \cong$ 4570 years (2*10^{11} atoms for 1 Bq)
- Q_{EC} = $(2.833 \pm 0.030^{stat} \pm 0.015^{syst})$ keV
  S. Eliseev et al., *Phys. Rev. Lett.* **115** (2015) 062501



Source = Detector

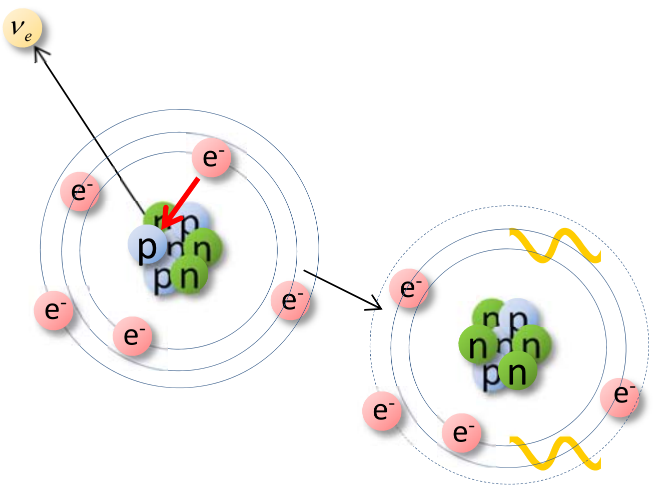
Calorimetric measurement

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

Advantages: Measured neutrino complementary spectrum
No final state problems

Disadvantages: Unresolved pile-up

^{163}Ho calorimetric spectrum



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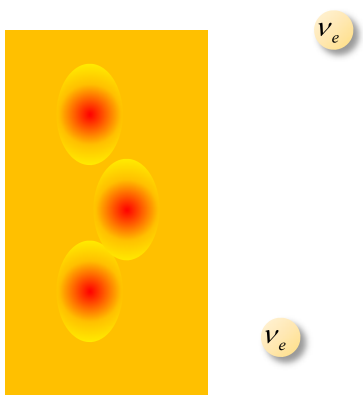
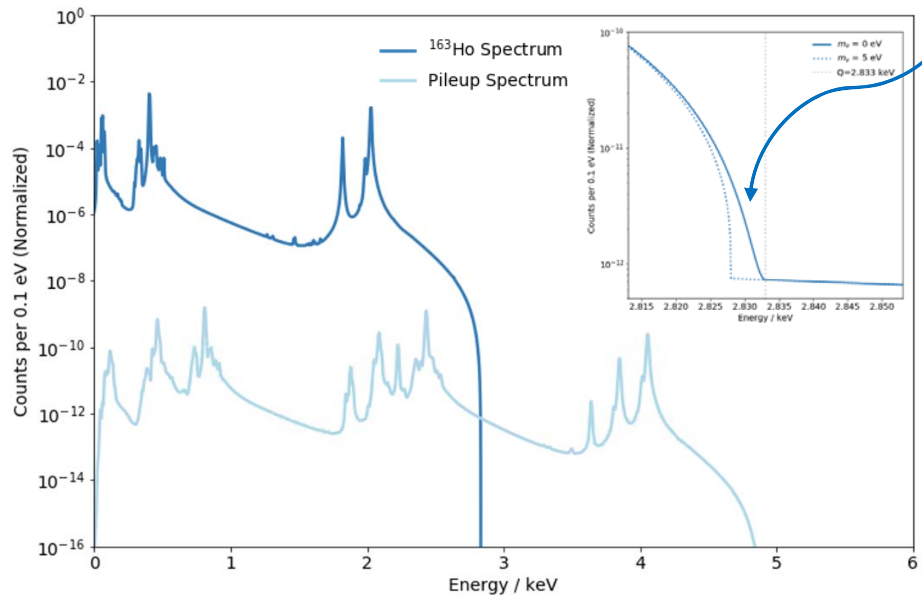


Source = Detector

Calorimetric measurement

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

Fraction of events in the last eV ~10^{-12}



M. Braß and M. W. Haverkort, *New J. Phys.* **22** (2020) 093018

Requirements for sub-eV sensitivity

Statistics in the end point region

- $N_{ev} > 10^{14}$ → **A ≈ 1 MBq**

→ Large amount of high purity ^{163}Ho source

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

- $f_{pu} < 10^{-5}$
- $\tau_r \sim 1\ \mu s$ → ***a* ~ 10 Bq**
- **10^5 pixels**

→ Fast and multiplexable detectors

Background level below unresolved pile-up

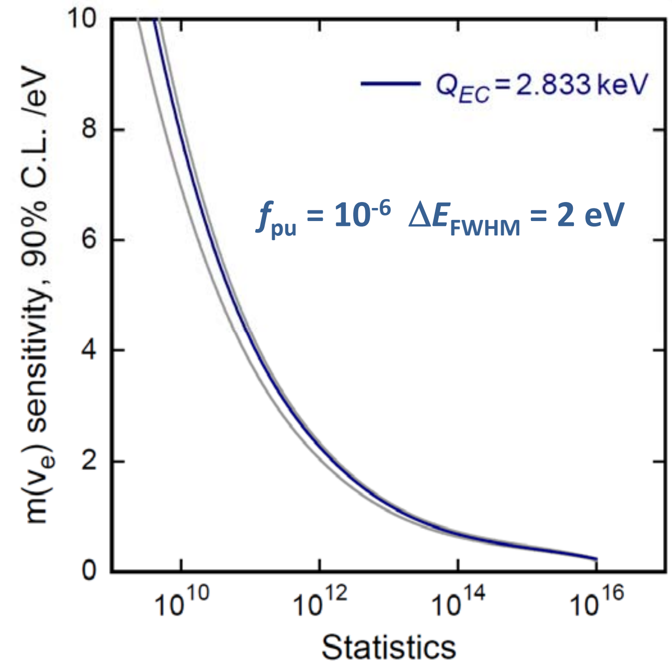
- **< 10^{-6} events/eV/det/day**

→ Identification and suppression of background sources

Precise characterization of the endpoint region

- **ΔE_{FWHM} < 3 eV**

→ High energy resolution low temperature microcalorimeters with enclosed ^{163}Ho

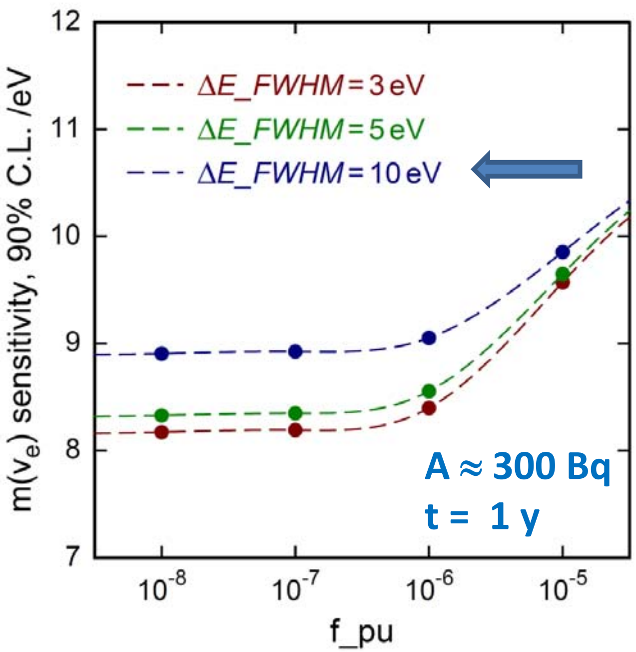


The ECHo Collaboration
EPJ-ST 226 8 (2017) 1623

B. Alpert et al.,
Eur. Phys. J. C 75 (2015) 112

ECHo phases

ECHo-1k – revised (2015 – 2018+)

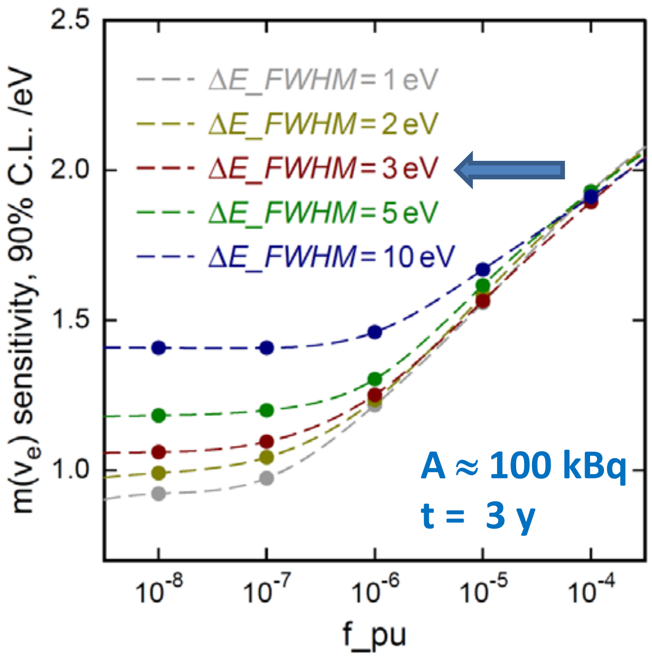


$m(\nu_e) < 20$ eV 90% C.L.

Activity per pixel: ~ 1 Bq
Number of detectors: ~ 60
Readout: parallel two stage SQUID

Supported by DFG Research Unit FOR 2202/1

ECHo-100k (2018 – 2021+)



$m(\nu_e) < 1.5$ eV 90% C.L.

Activity per pixel: 10 Bq
Number of detectors: 12000
Readout: microwave SQUID multiplexing

Supported by DFG Research Unit FOR 2202/2

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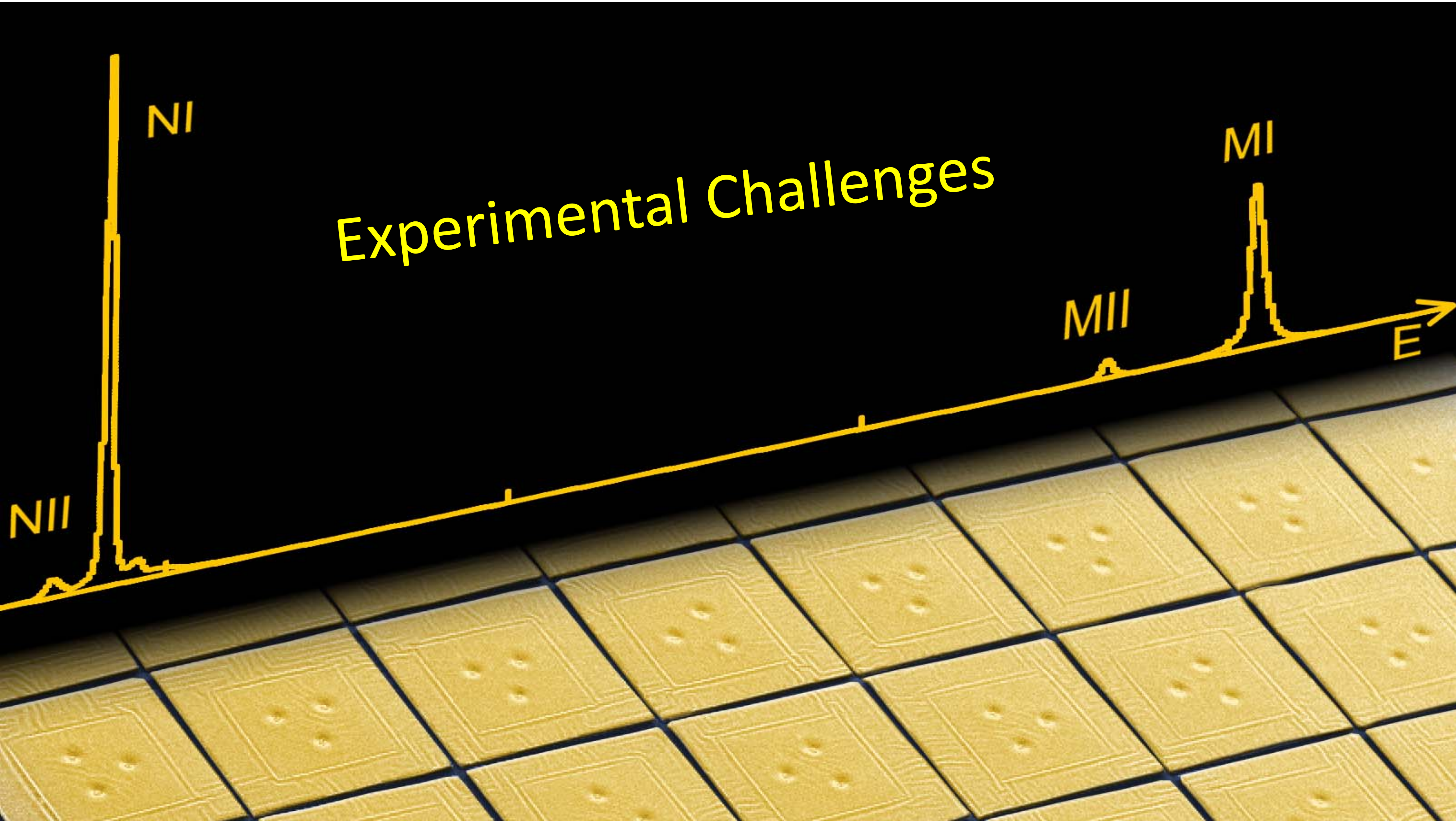
Experimental Challenges

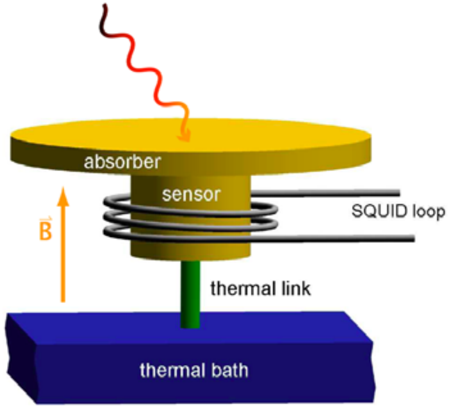


Calorimetric measurement

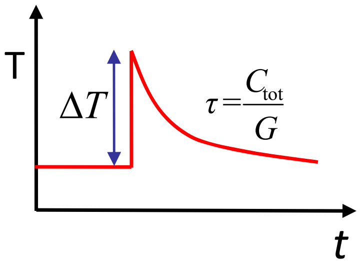
ECHo uses large arrays of low T metallic magnetic calorimeters with enclosed ^{163}Ho

Calorimetric measurement – Detectors

ECHo uses large arrays of low T metallic magnetic calorimeters with enclosed ^{163}Ho



$$\Delta T \cong \frac{E}{C_{tot}} \xrightarrow{\text{MMC}} \Delta\Phi_S \propto \frac{\partial M}{\partial T}\Delta T \rightarrow \Delta\Phi_S \propto \frac{\partial M}{\partial T}\frac{E}{C_{tot}}$$

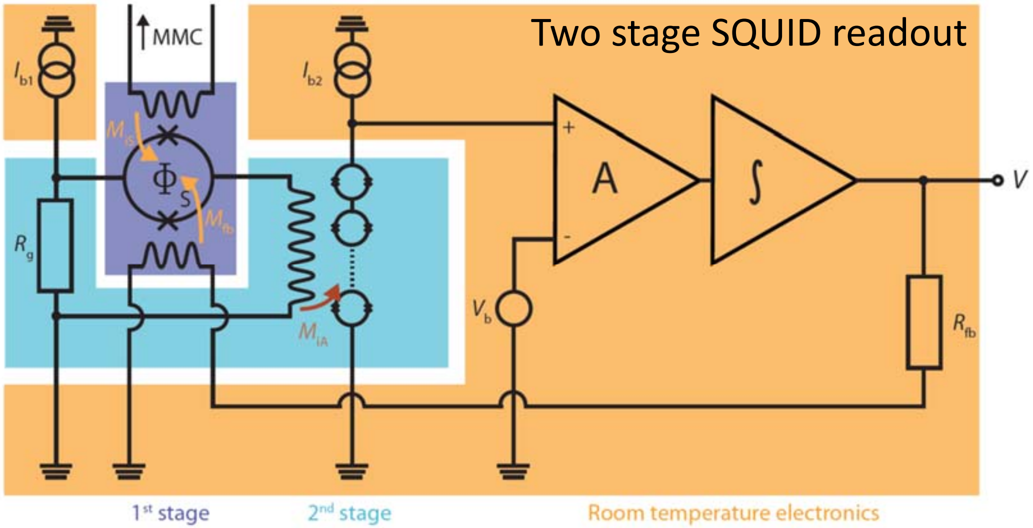


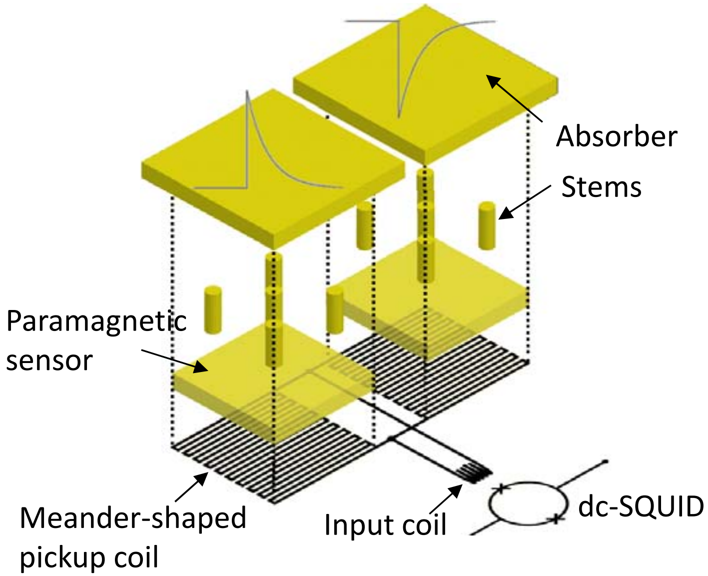
Paramagnetic Ag:Er sensor

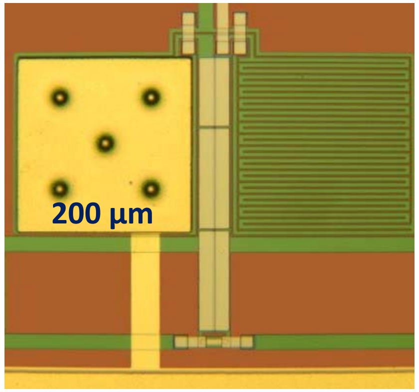
A.Fleischmann, C. Enss and G. M. Seidel, Topics in Applied Physics **99** (2005) 63

A.Fleischmann et al., *AIP Conf. Proc.* **1185** (2009) 571

L. Gastaldo et al., Nucl. *Inst. Meth. A*, **711** (2013) 1

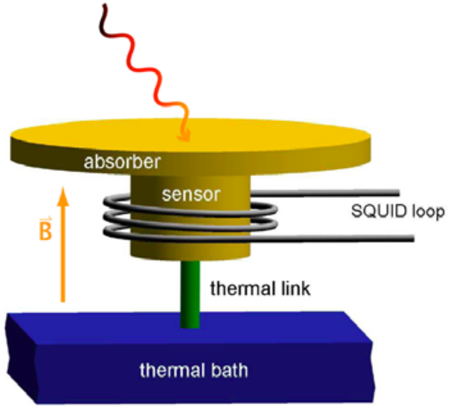




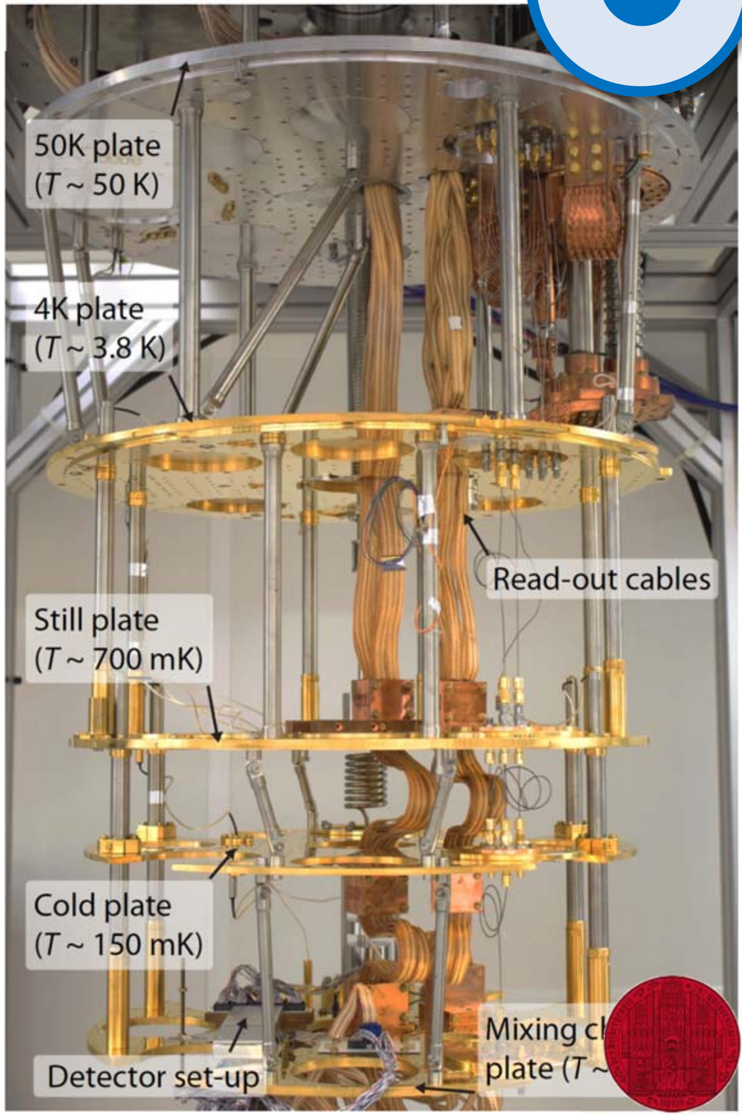


Calorimetric measurement – Detectors

ECHo uses large arrays of low T metallic magnetic calorimeters with enclosed ^{163}Ho



MMC are operated at T < 30 mK in cryostats



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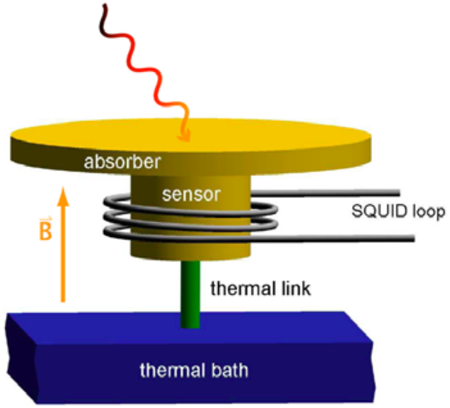
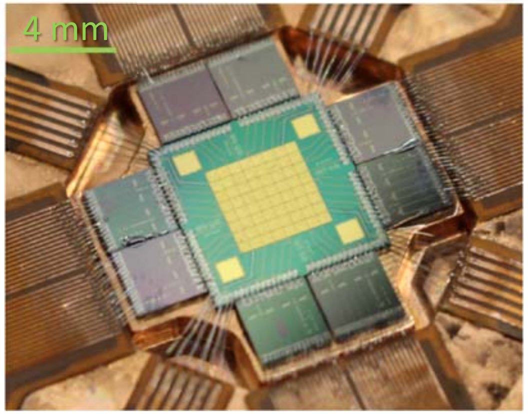


Fast risetime
→ Reduction un-resolved pile-up

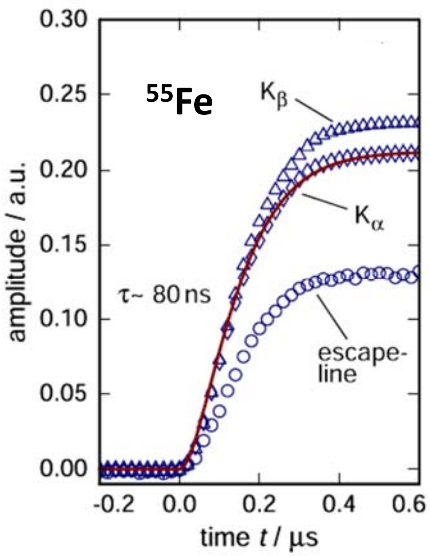
Extremely good energy resolution
→Reduced smearing in the end point region

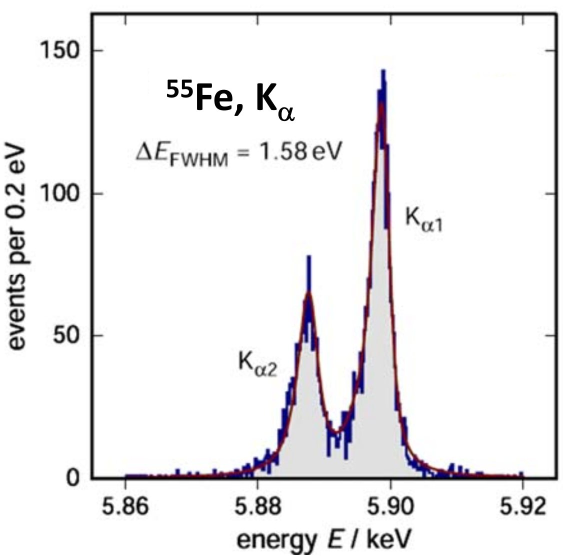
Excellent linearity
→ precise definition of the energy scale

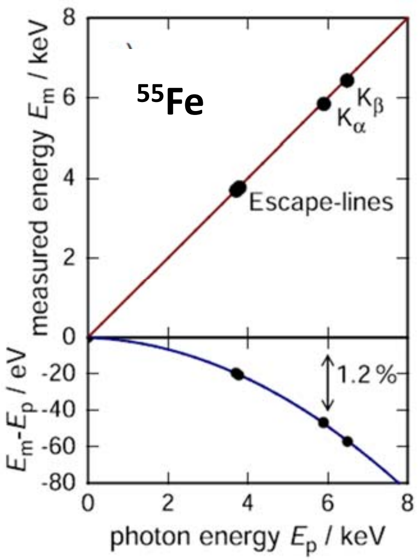


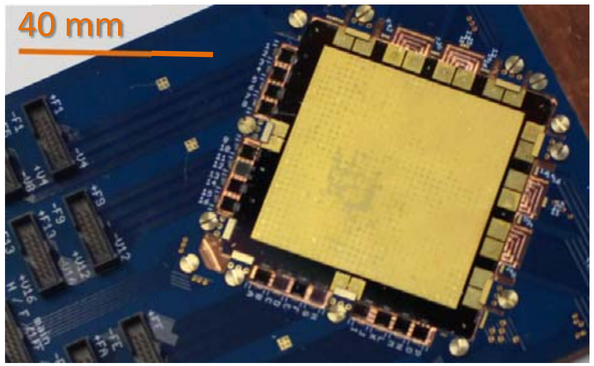
4 mm

Focal plane detector for IAXO 64 pixels









40 mm

MOCCA system for
mass spectrometry @CSR
4096 pixels

Calorimetric measurement – Source

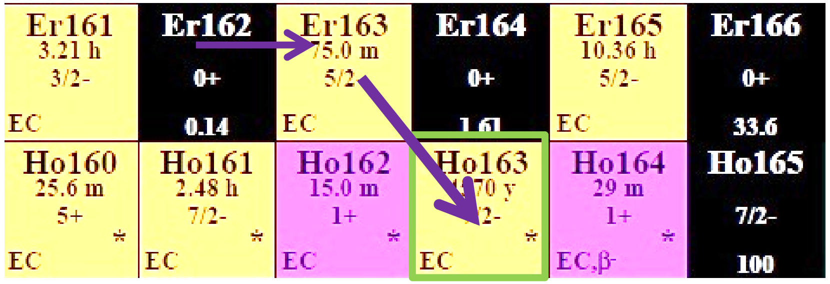
ECHo uses large arrays of low T metallic magnetic calorimeters with enclosed ^{163}Ho

Required activity in the detectors for sub-eV → >10^6 Bq → >10^{17} atoms → >27 µg

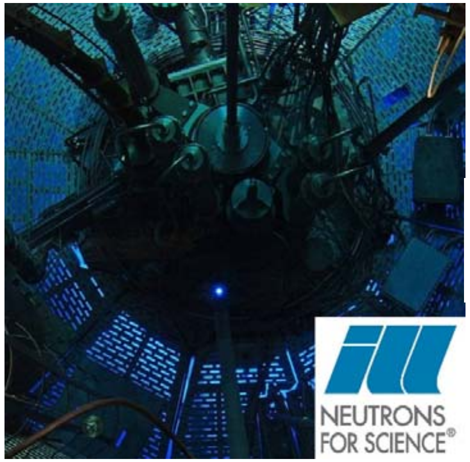
Neutron irradiation
(n,γ)-reaction on ^{162}Er

→

Excellent chemical separation
95% efficiency



Available ^{163}Ho for ECHo
~ 2×10^{18} atoms (10 MBq)



ISOLDE

NEUTRONS FOR SCIENCE

JG|U JOHANNES GUTENBERG UNIVERSITÄT MAINZ

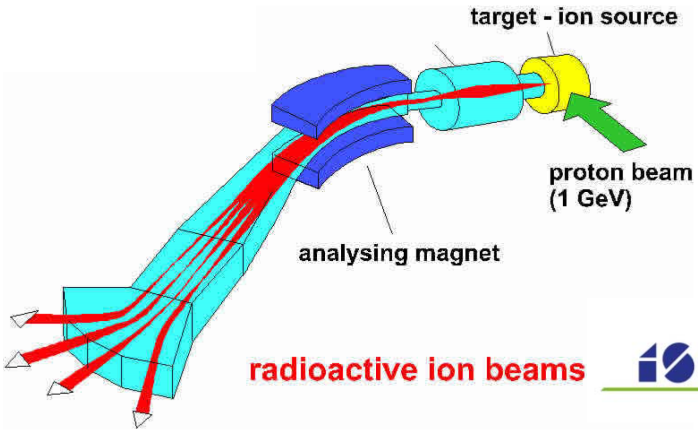
H. Dorrer et al, Radiochim. Acta 106(7) (2018) 535–48

Calorimetric measurement – ^{163}Ho implantation

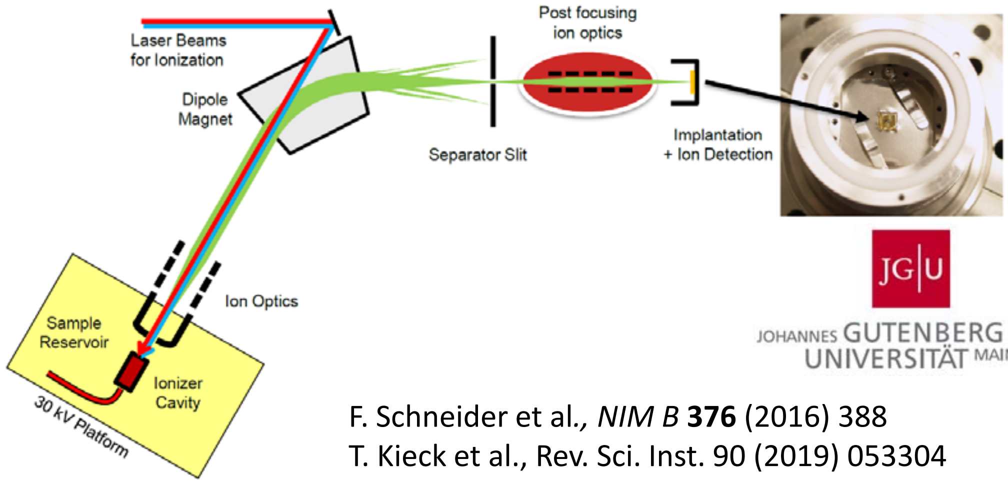
ECHo uses large arrays of low T metallic magnetic calorimeters with enclosed ^{163}Ho

Mass separation and ion implantation in MMC pixels

- Demonstrated in 2009: on-line implantation @ISOLDE-CERN
  L. Gastaldo et al., *Nucl. Inst. Meth. A* **711** (2013) 150



- Optimization of ^{163}Ho beam production and control at
  RISIKO @ Institute of Physics, Mainz University
  - Resonant laser ion source efficiency
    $(69 \pm 5^{stat} \pm 4^{syst})\%$
  - Reduction of ^{166m}Ho in MMC
    $^{166m}Ho/^{163}Ho < 4(2)10^{-9}$
  - Beam focalization

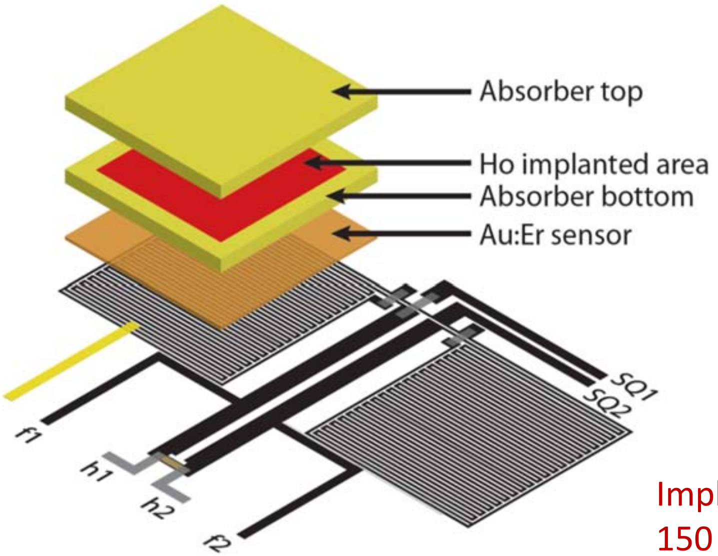


JOHANNES GUTENBERG UNIVERSITÄT MAINZ

F. Schneider et al., *NIM B* **376** (2016) 388
T. Kieck et al., Rev. Sci. Inst. 90 (2019) 053304
T. Kieck et al., NIM A 945 (2019) 162602

Calorimetric measurement – 4π geometry

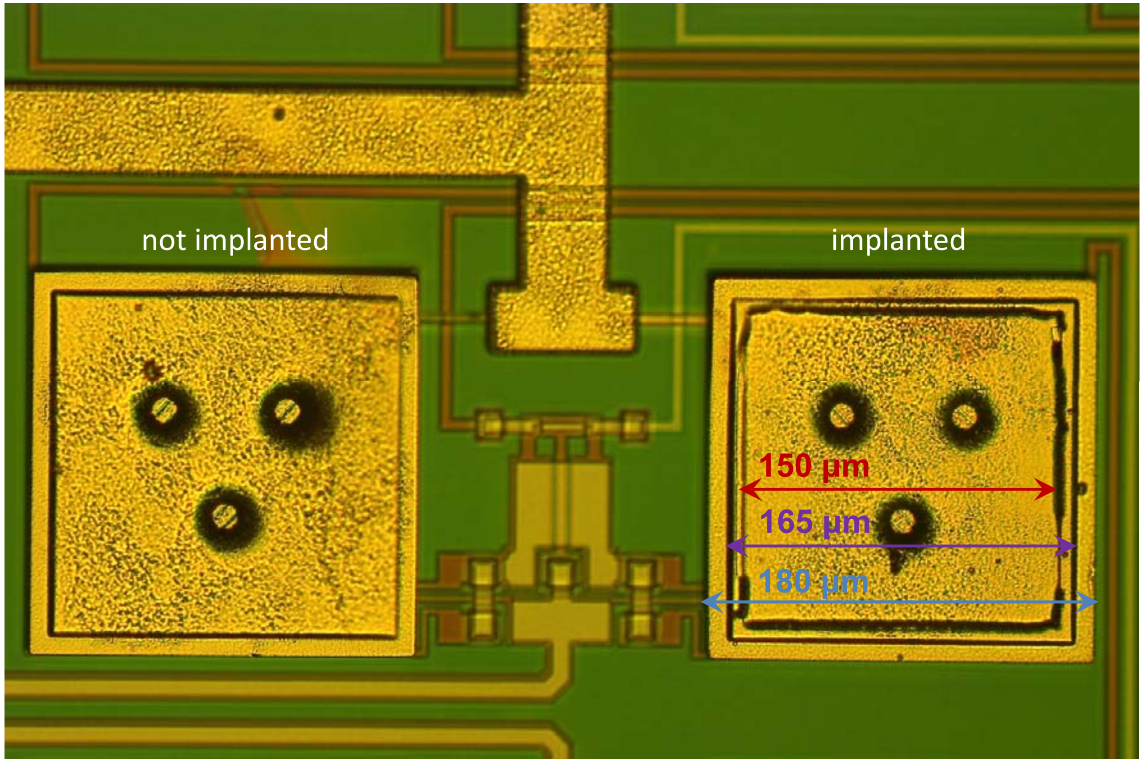
ECHo uses large arrays of low T metallic magnetic calorimeters with enclosed ^{163}Ho



Implantation square:
150 µm x 150 µm

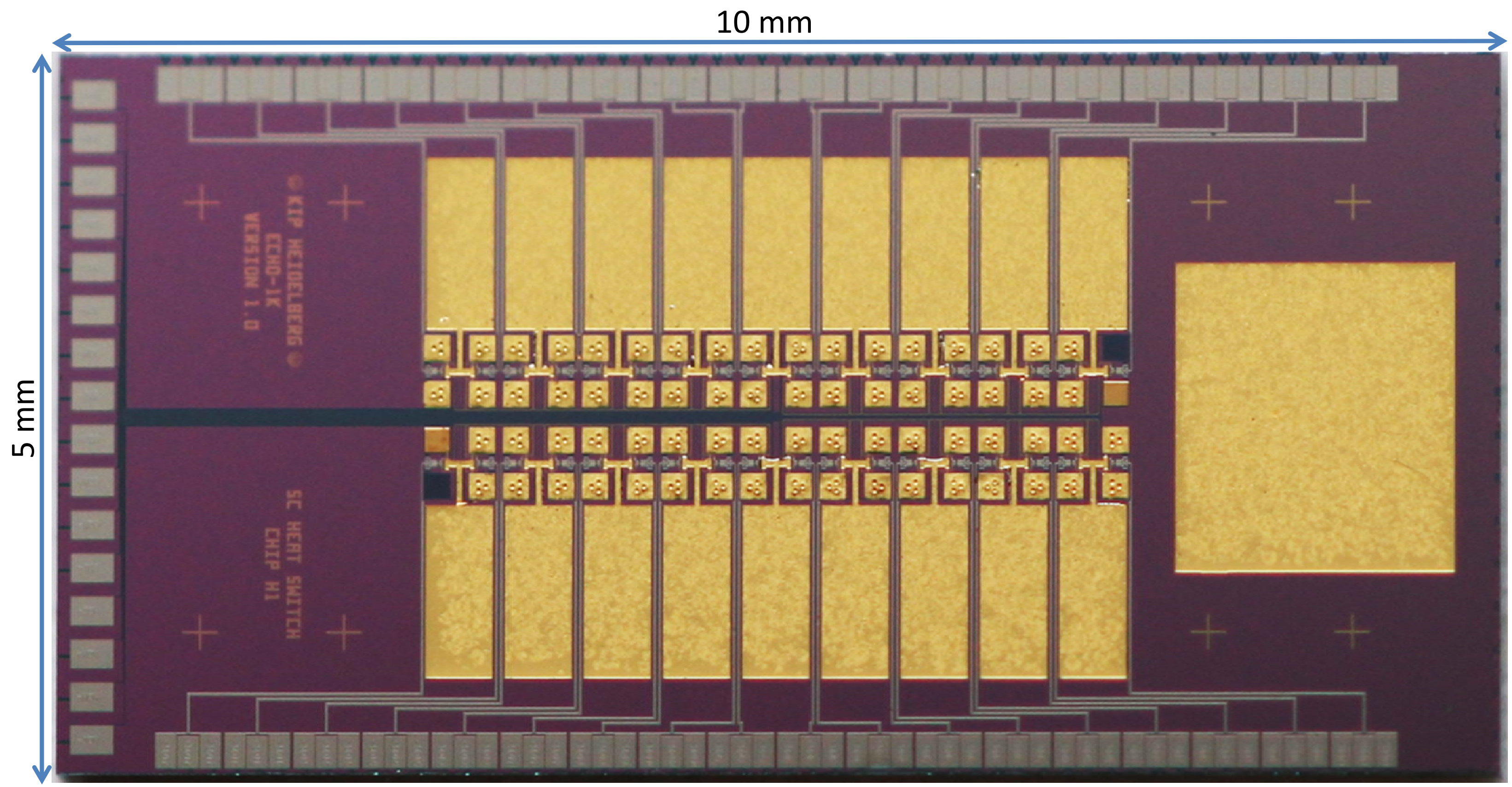
Second absorber:
165 µm x 165 µm

First absorber:
180 µm x 180 µm



F. Mantegazzini, to be submitted to JINST (2021)

ECHo-1k array

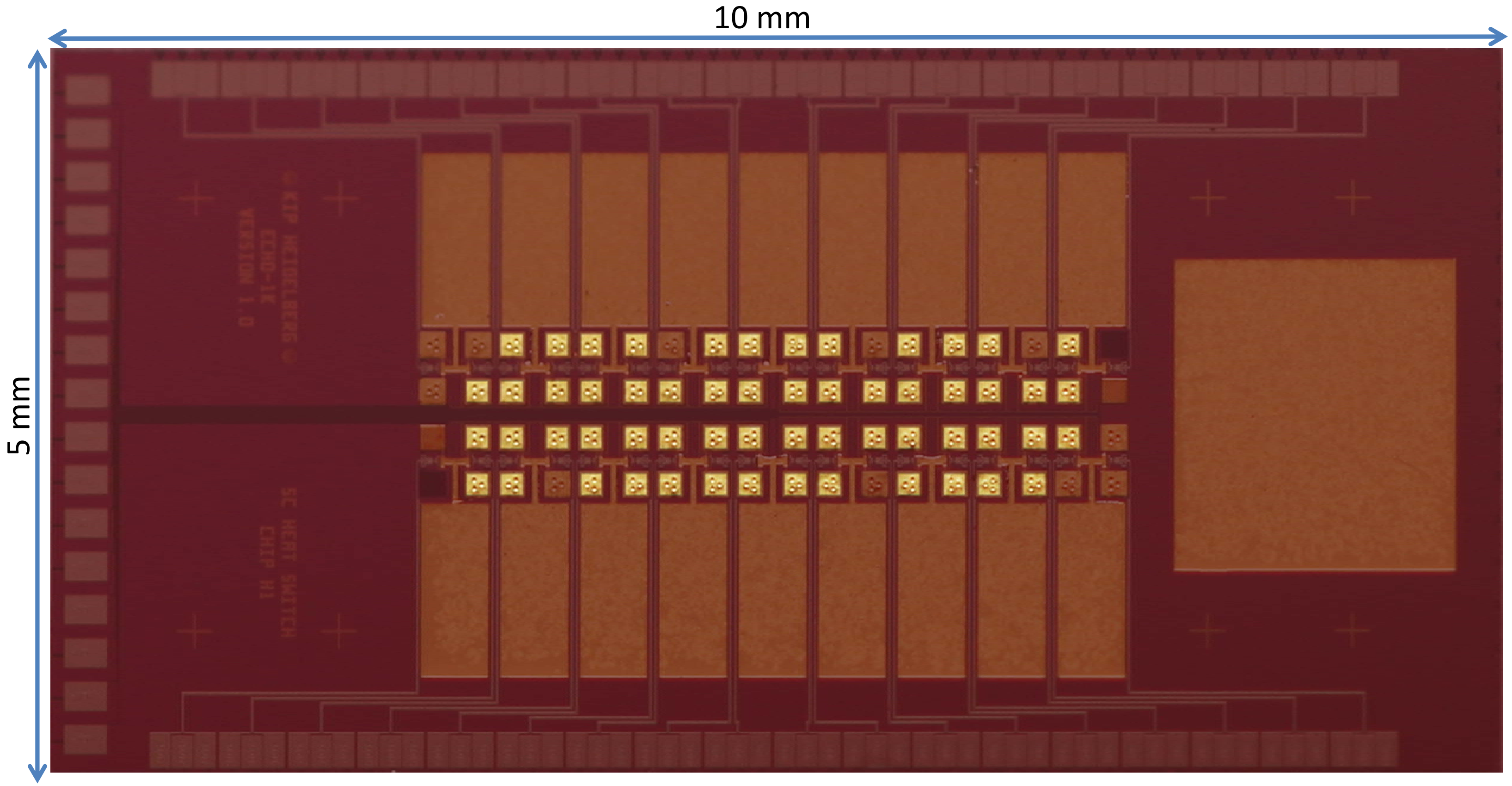


64 pixels can be loaded with ^{163}Ho
+ 2 temperature pixels
+ 2 detectors for diagnostics

Design performance:
ΔE_{FWHM} ~ 5 eV
τ_r ~ 90 ns (single channel readout)

F. Mantegazzini, to be submitted to JINST (2021)

ECHo-1k array



64 pixels can be loaded with ^{163}Ho
+ 2 temperature pixels
+ 2 detectors for diagnostics

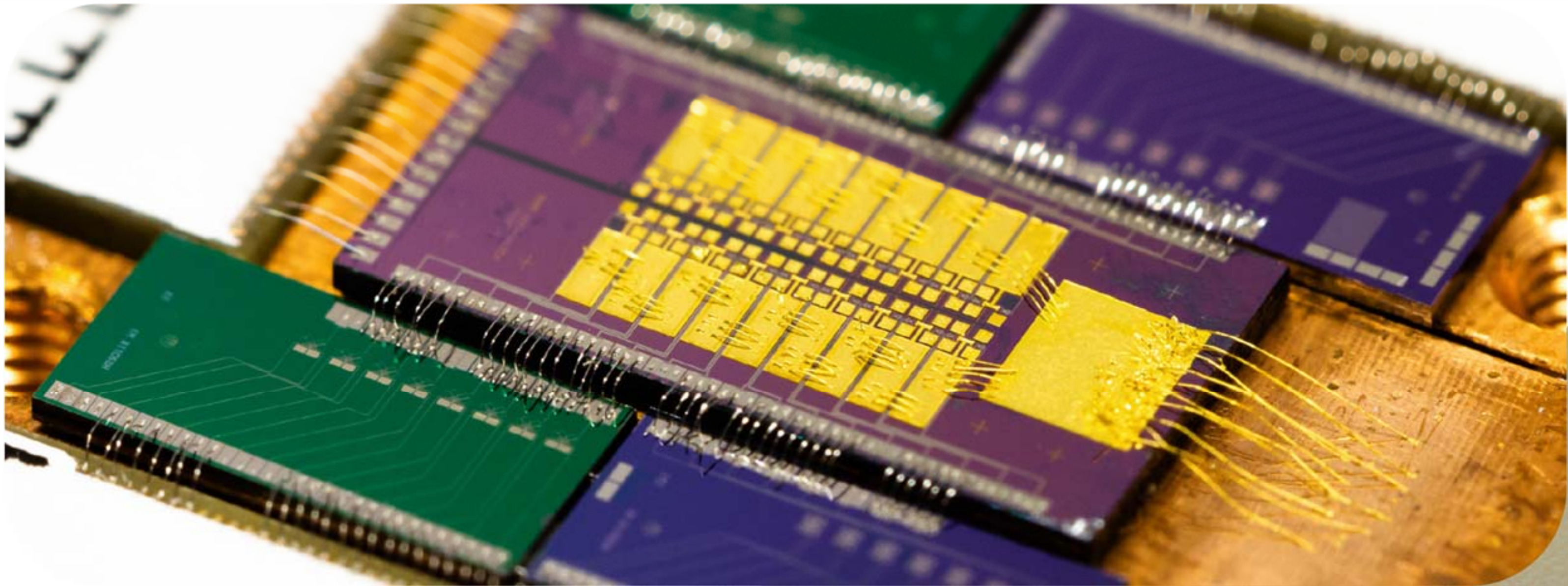
Design performance:
ΔE_{FWHM} ~ 5 eV
τ_r ~ 90 ns (single channel readout)

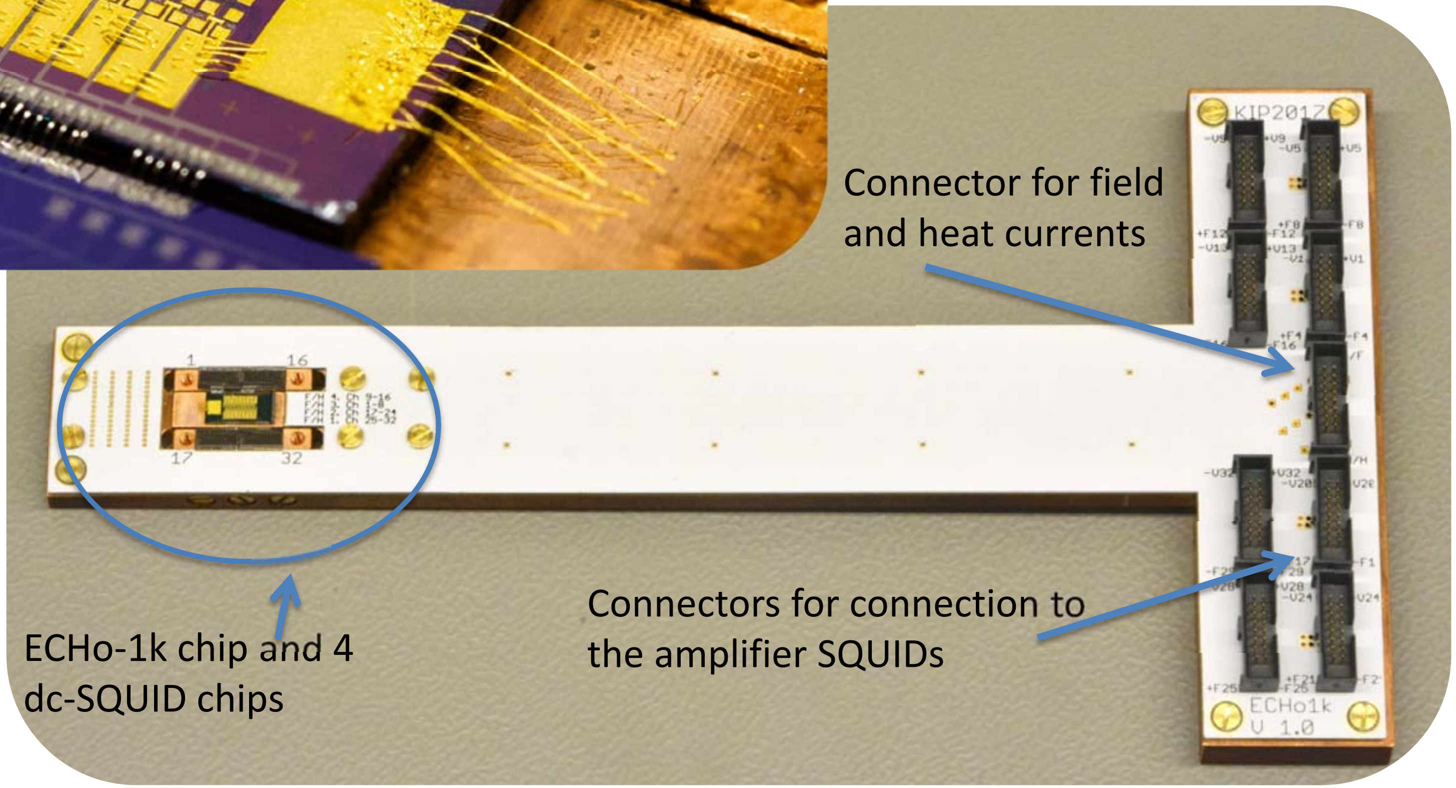
✓ presence of non-implanted chips for in-situ background determination

6 ECHo-1k chips implantanted @RISIKO

F. Mantegazzini, to be submitted to JINST (2021)

ECHo-1k read-out



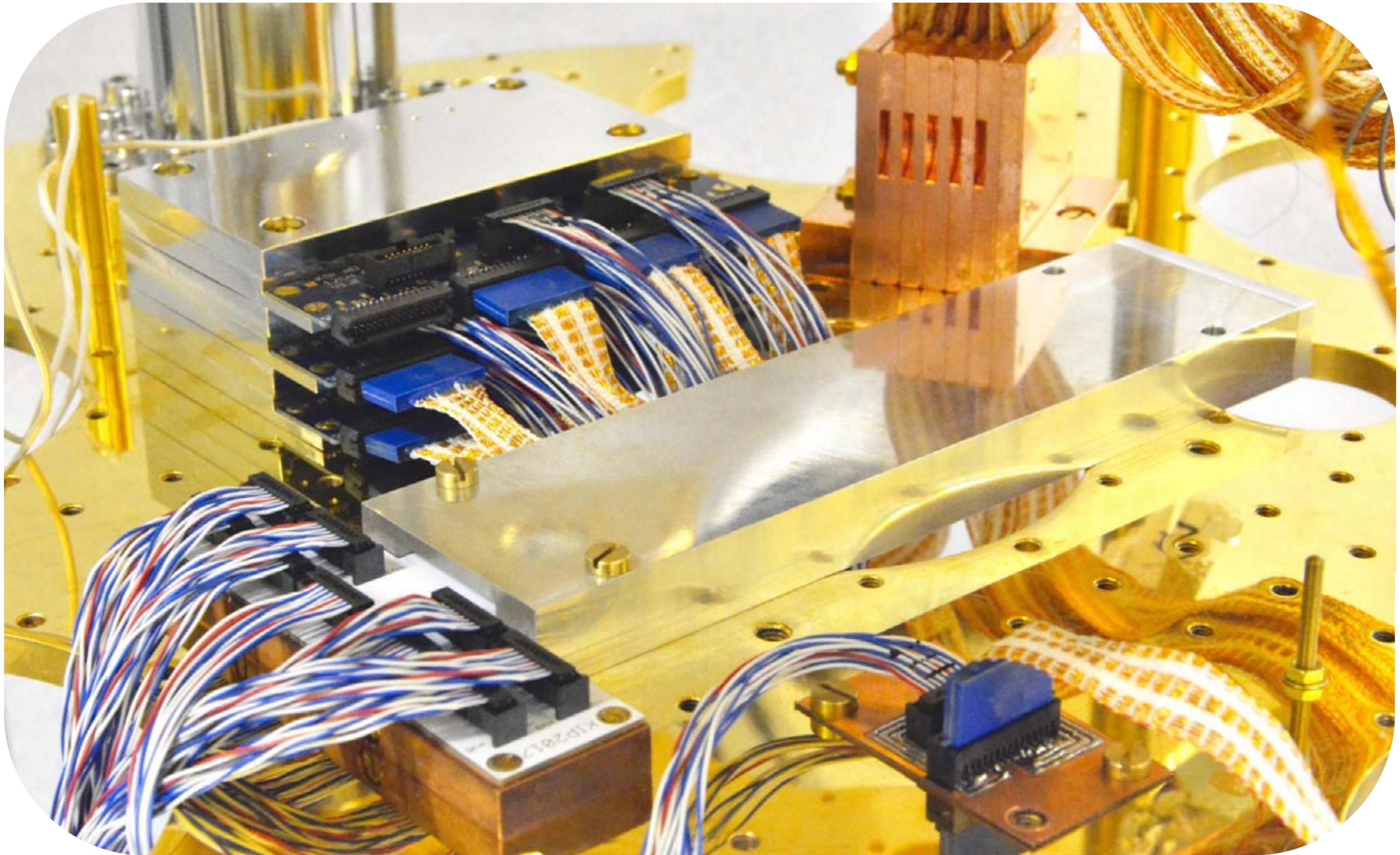


ECHo-1k chip-Au implanted @RISIKO

- High purity ^{163}Ho source
  → activity per pixel $a \approx 1$ Bq
- 4 Front-end chips each with 8 dc-SQUIDs for parallel readout

F. Mantegazzini, submitted to NIM A (2021), arXiv:2102.11100 [physics.ins-det]

ECHo-1k read-out



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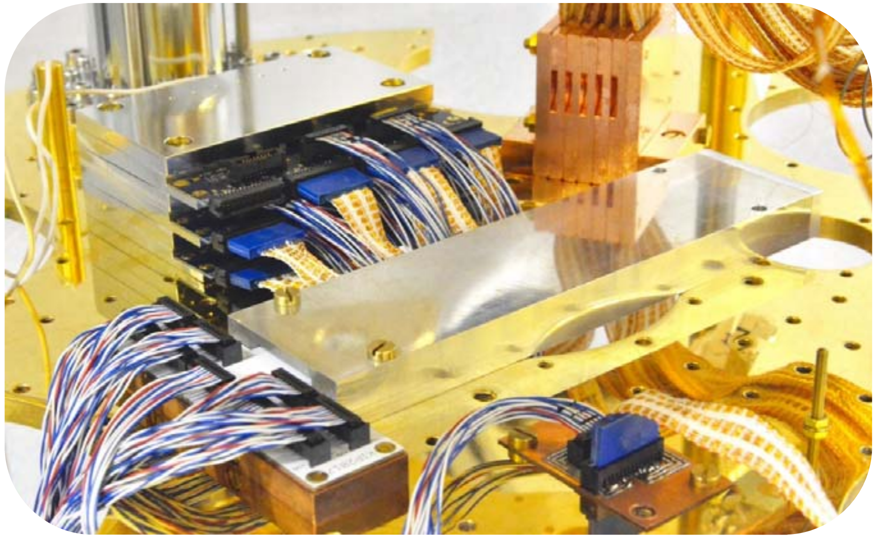

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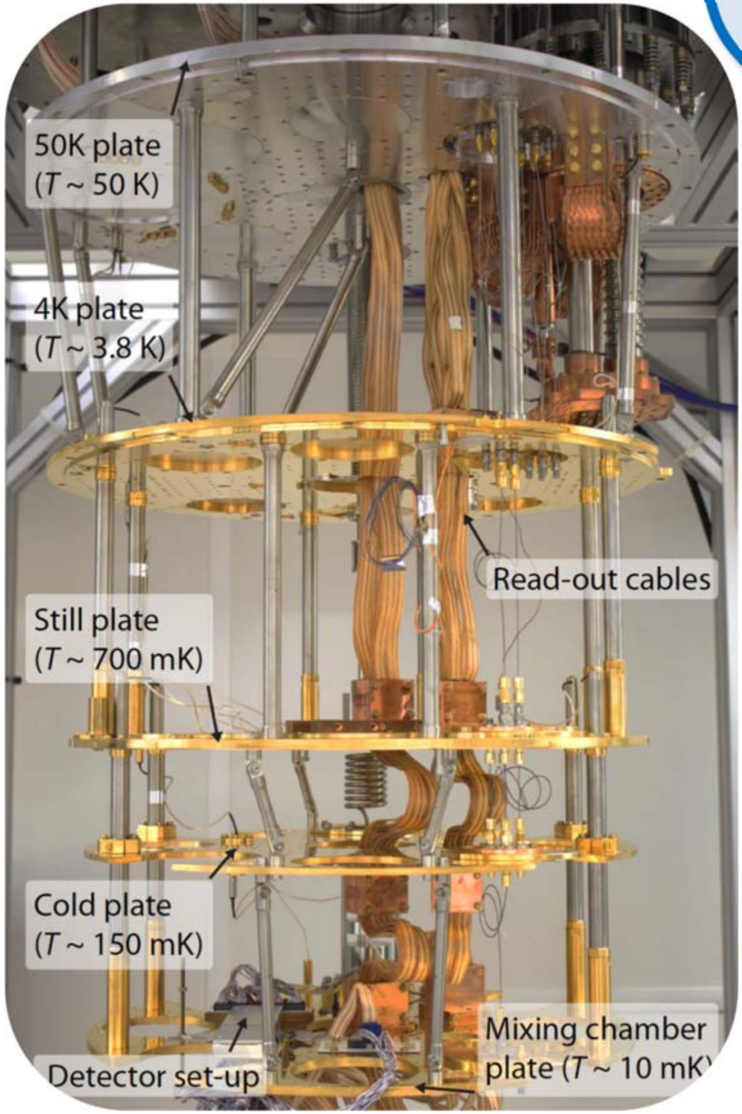
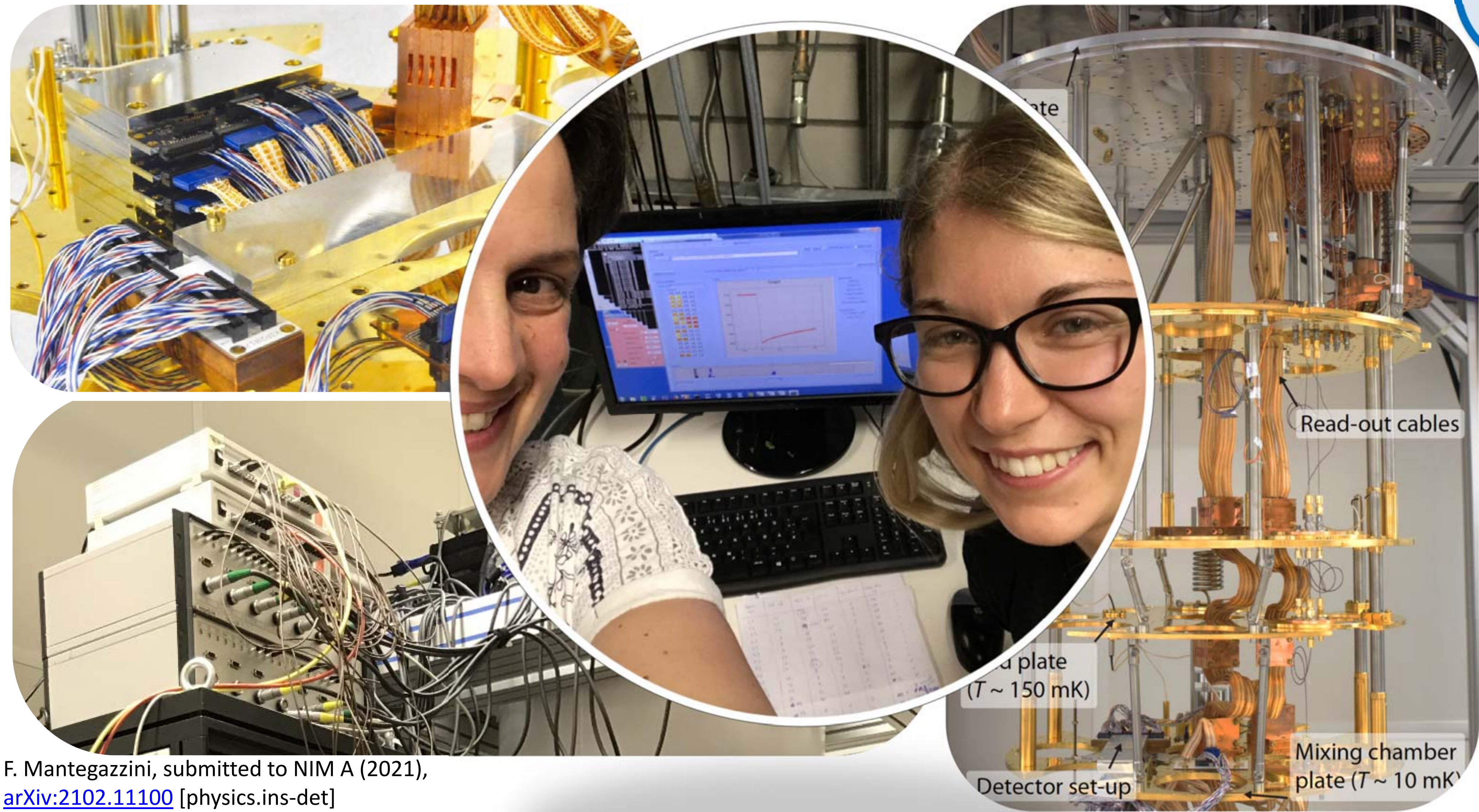
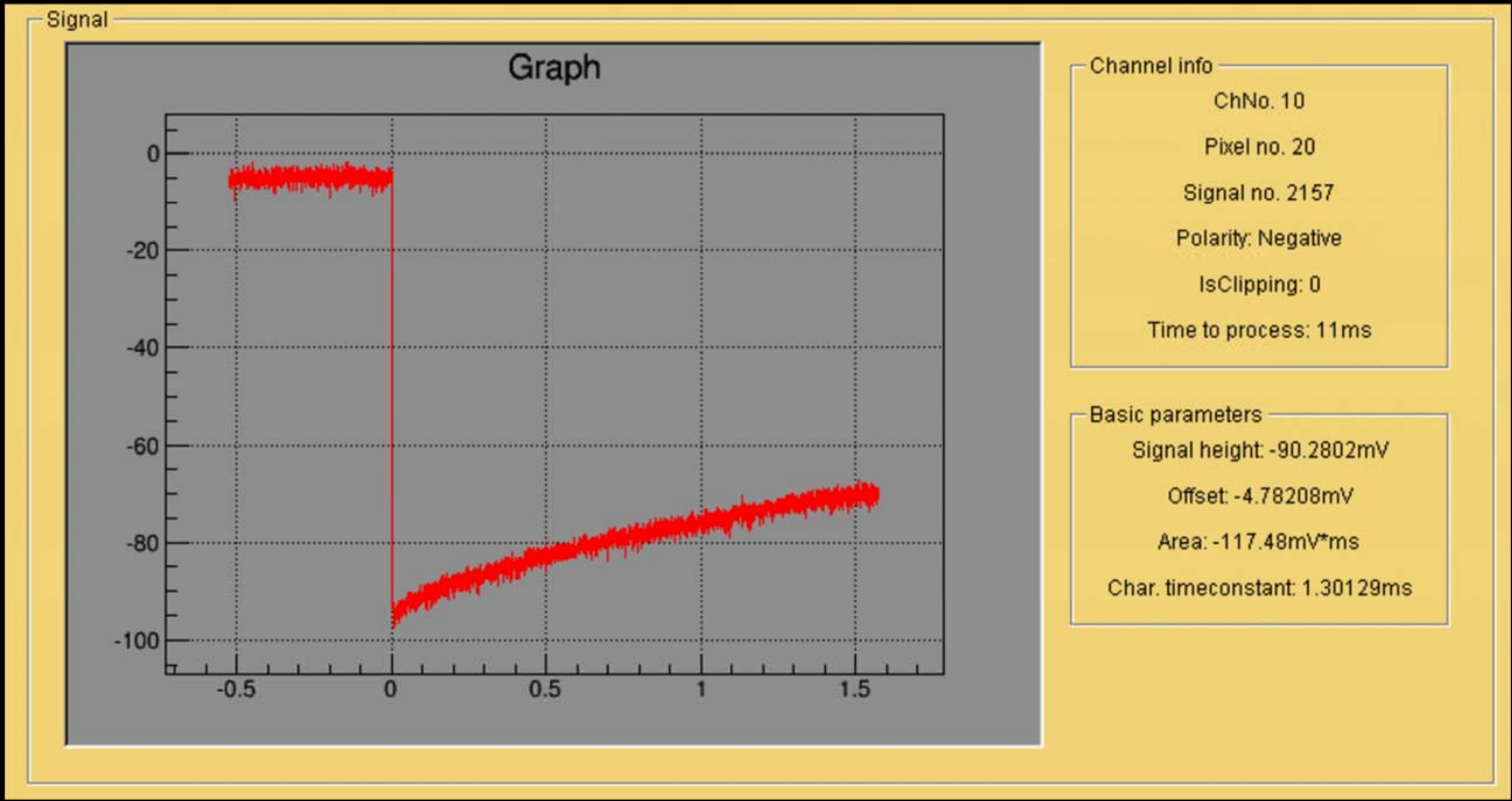


ECHo-1k read-out

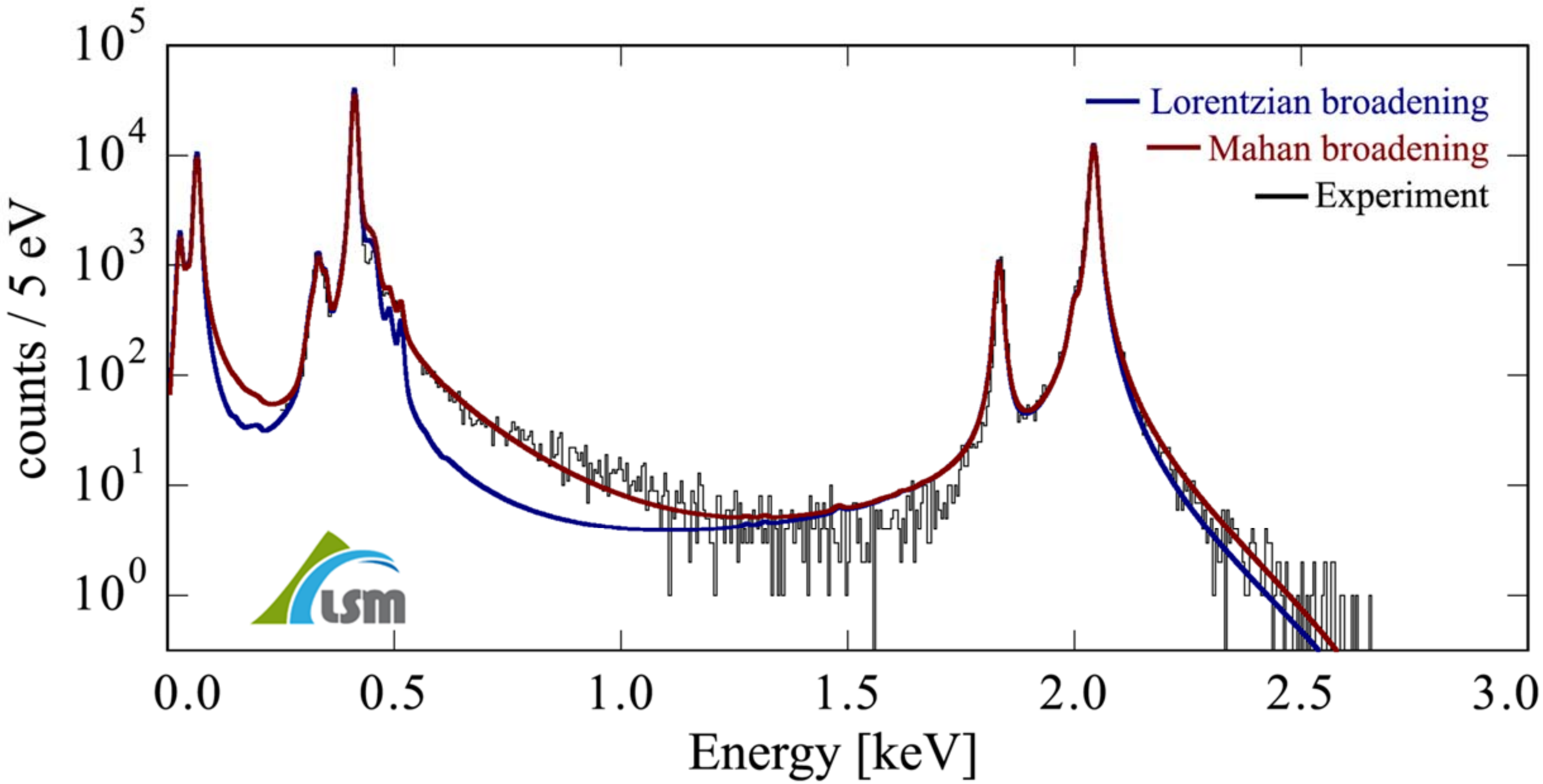


F. Mantegazzini, submitted to NIM A (2021), arXiv:2102.11100 [physics.ins-det]

ECHo-1k data – Live!



Proof of concept



C. Velte et al., EPJC **79** (2019) 1026

Energy resolution
ΔE_{FWHM} = 9.2 eV

Background level
b < 1.6 × 10^{-4} events/eV/pixel/day

4 day measurement with 4 pixels loaded with ~0.2 Bq ^{163}Ho

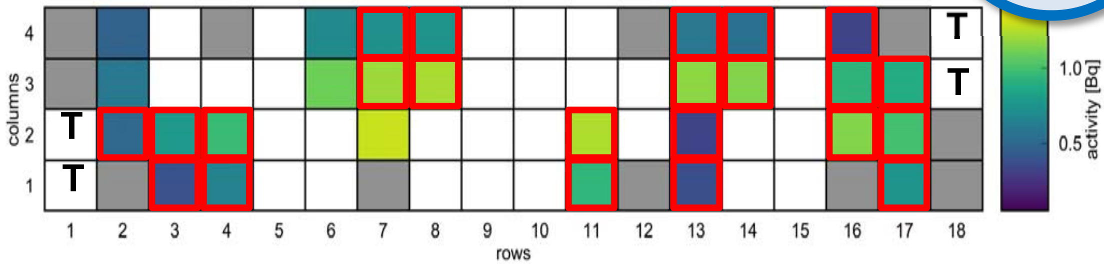
- measurement performed underground
- test for data reduction and spectral shape analysis

- Q_{EC} = (2838 ± 14) eV
- $m(\nu_e)$ < 150 eV (95% C.L.)

ECHo-1k high statistics spectrum

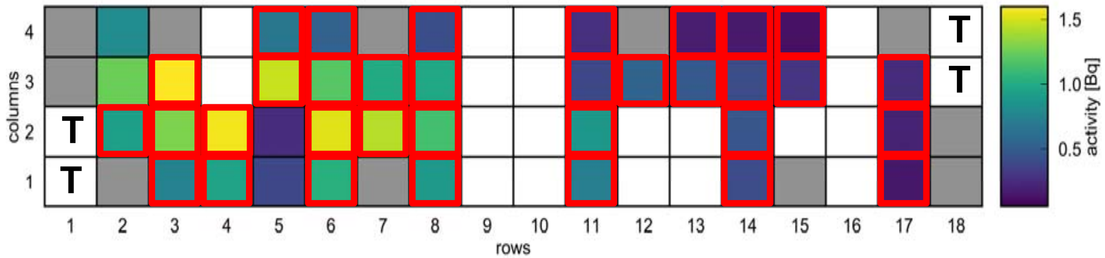
ECHo-1k chip-Au

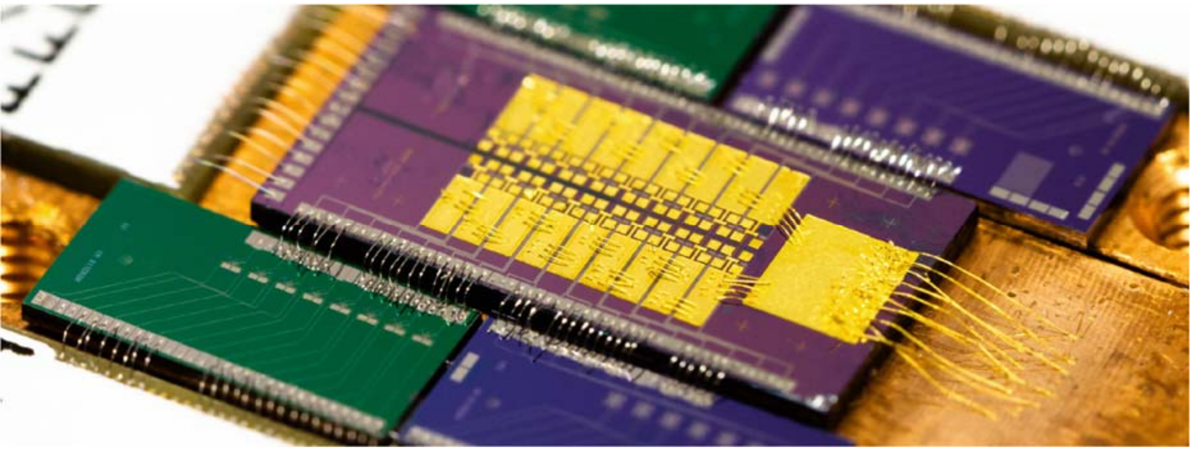
15 channels
2 temperature channels
23 pixel with implanted ^{163}Ho
3 background pixels
average activity = 0.94 Bq
total activity of 28.1 Bq



ECHo-1k chip-Ag

22 channels
2 temperature channels
34 pixel with implanted ^{163}Ho
6 background pixels
average activity = 0.71 Bq
total activity of 25.9 Bq





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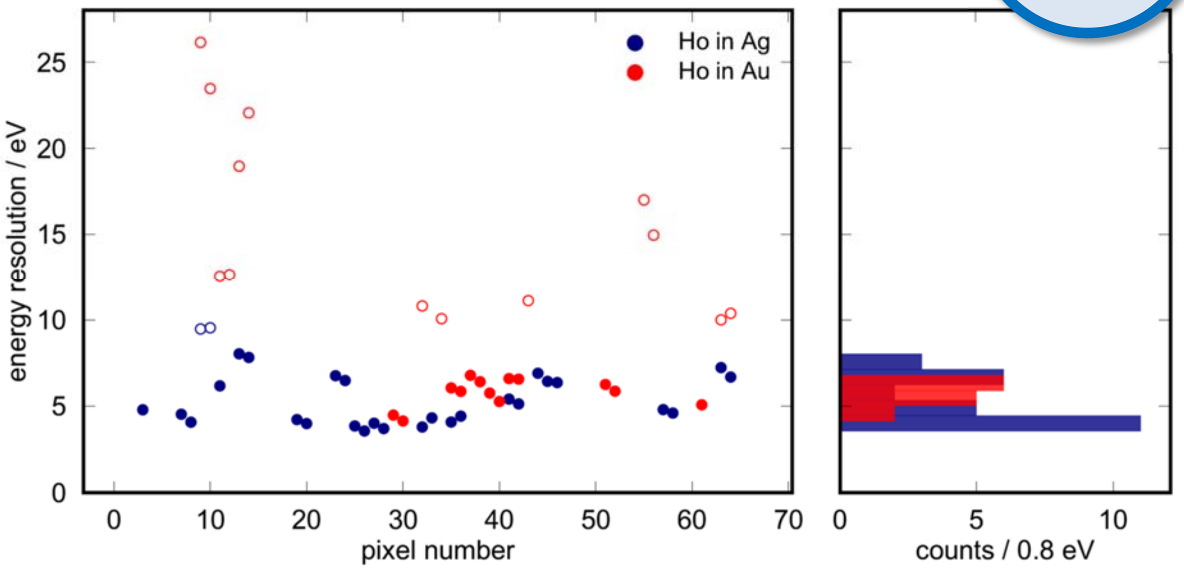

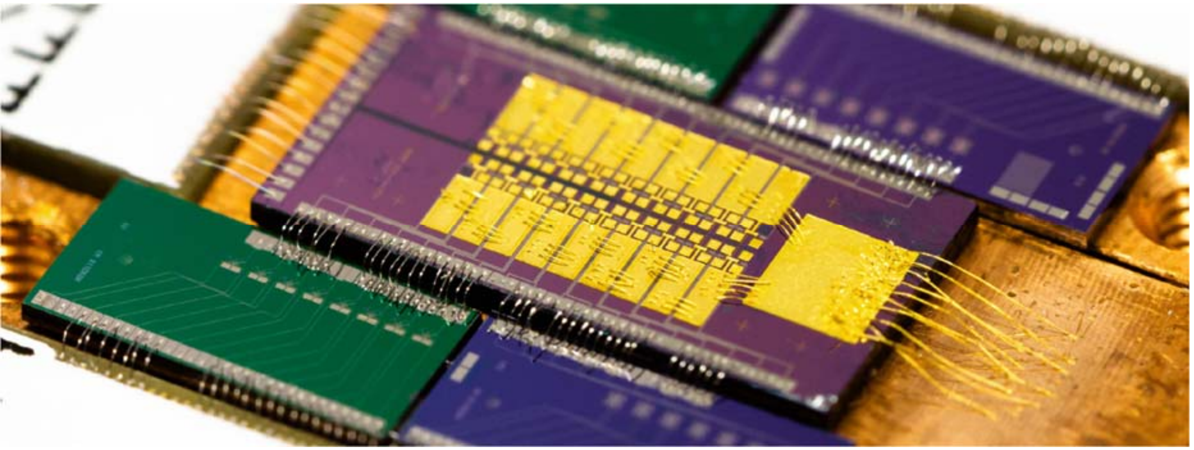

Further characterization

- Thermodynamical properties of single pixels
- Readout performance

ECHo-1k high statistics spectrum

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2 temperature channels
23 pixel with implanted ^{163}Ho
3 background pixels
average activity = 0.94 Bq
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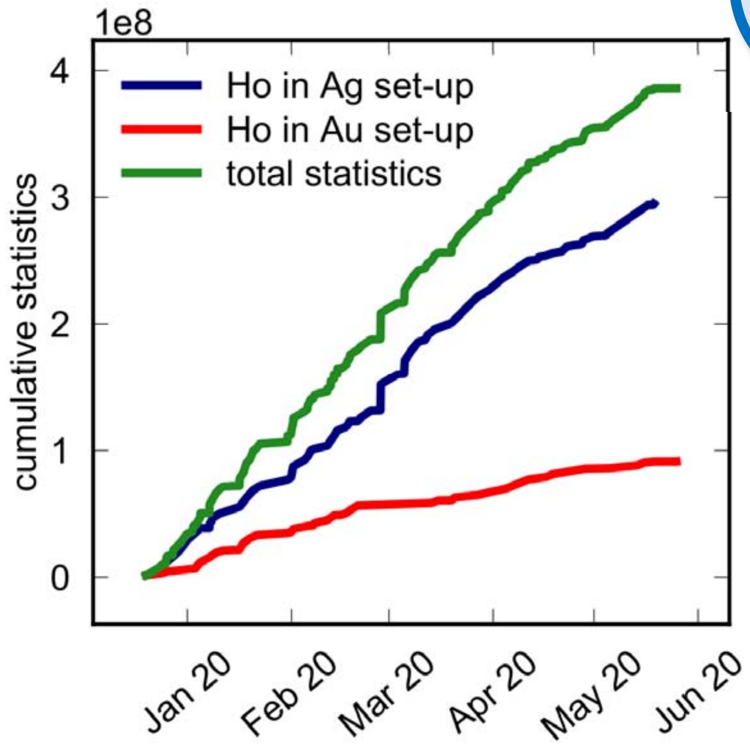


A number of ^{163}Ho events larger than 10^8 has been acquired in the first months of 2020

This statistics allow for investigating the value of the electron neutrino effective mass down to **20 eV**

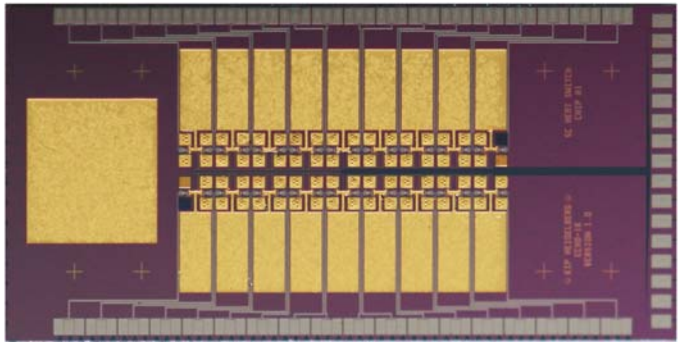
Data reduction started:
new limit for m_β si coming soon!

Towards ECHo-100k – MMC array

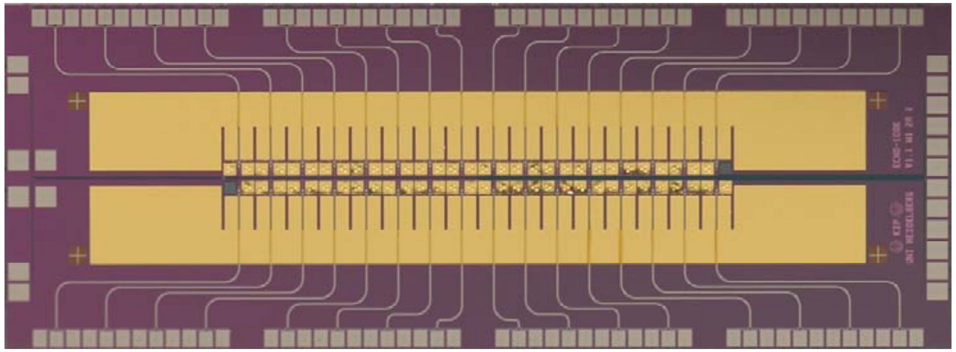
ECHo-1k
~1 Bq / pixel
57 MMCs

ECHo-100k
10 Bq / pixel
12000 MMCs

5 cm



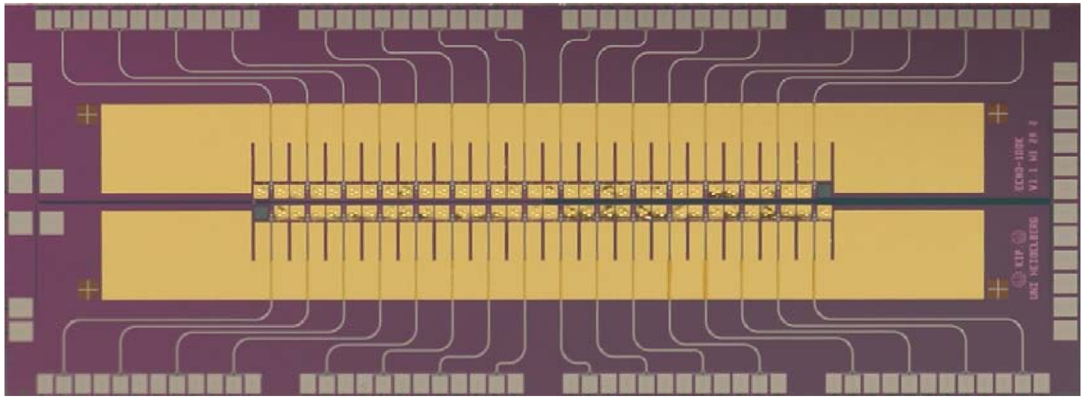
10 cm

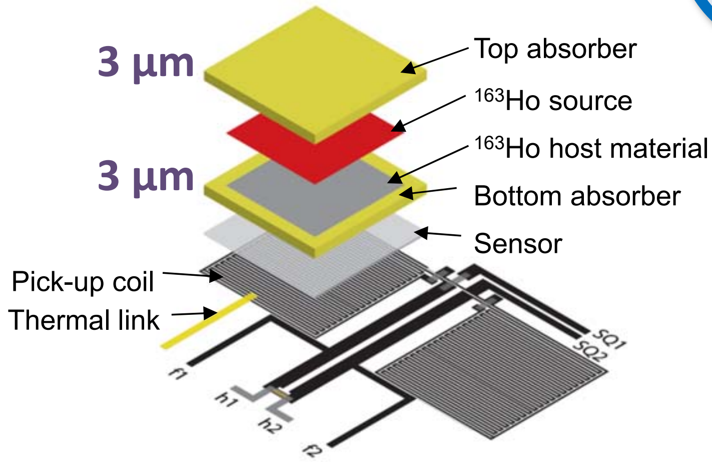


14 cm

- ✓ **Design and fabrication** completed
- ✓ **Characterised** with ^{55}Fe external source

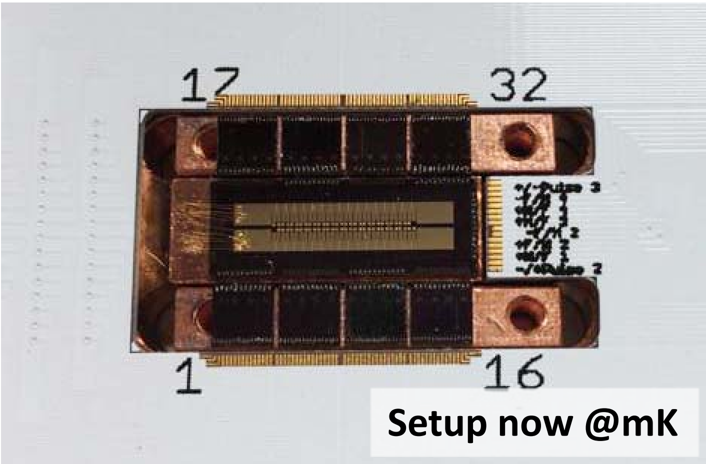
Towards ECHo-100k – MMC array



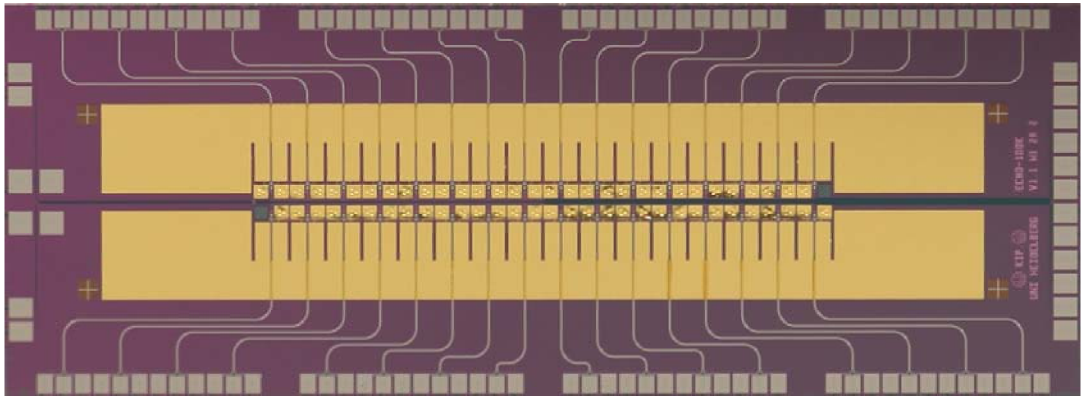


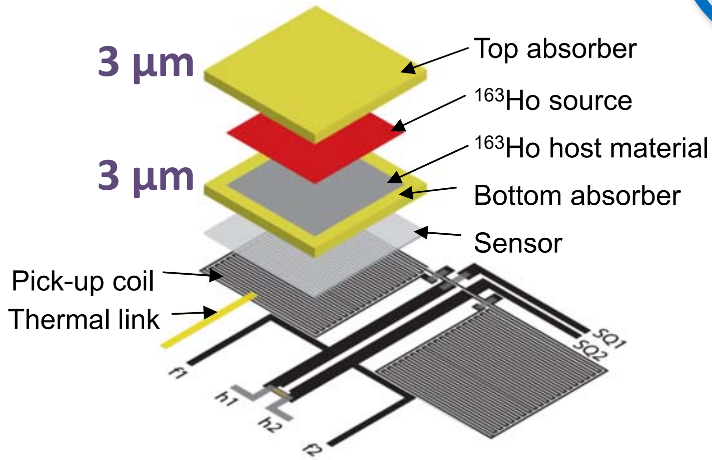
What is new in ECHo-100k?

- Optimised performances:
  - Lower heat capacity → **higher energy resolution**
  - Optimised thermalisation with gold bridges → **better thermalisation**
- Optimised pixel ordering for **efficient implantation**



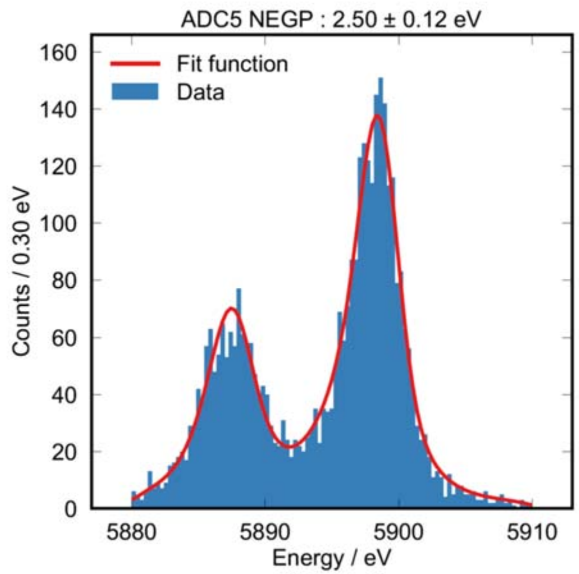
Towards ECHo-100k – MMC array



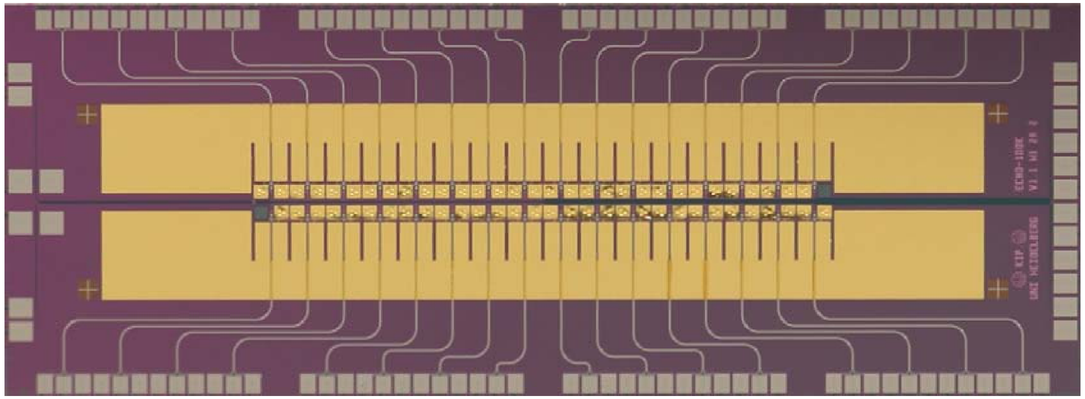


What is new in ECHo-100k?

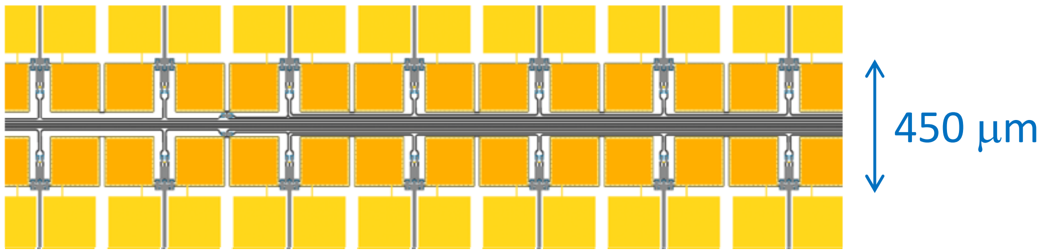
- Optimised performances:
  - Lower heat capacity → **higher energy resolution**
  - Optimised thermalisation with gold bridges → **better thermalisation**
- Optimised pixel ordering for **efficient implantation**

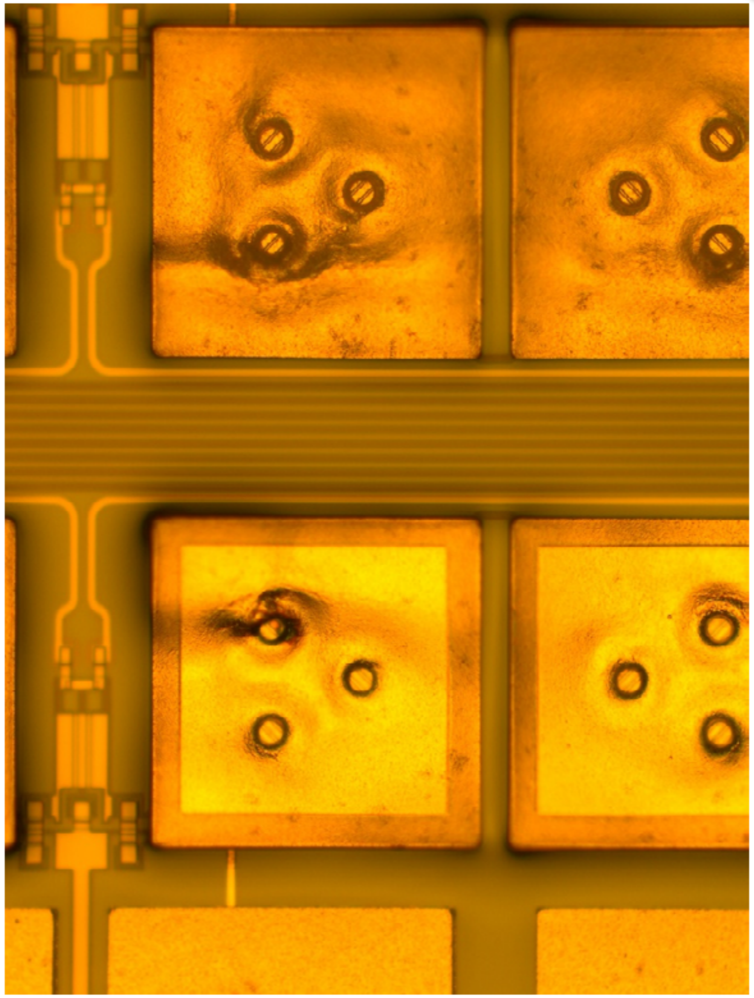


Towards ECHo-100k – MMC array



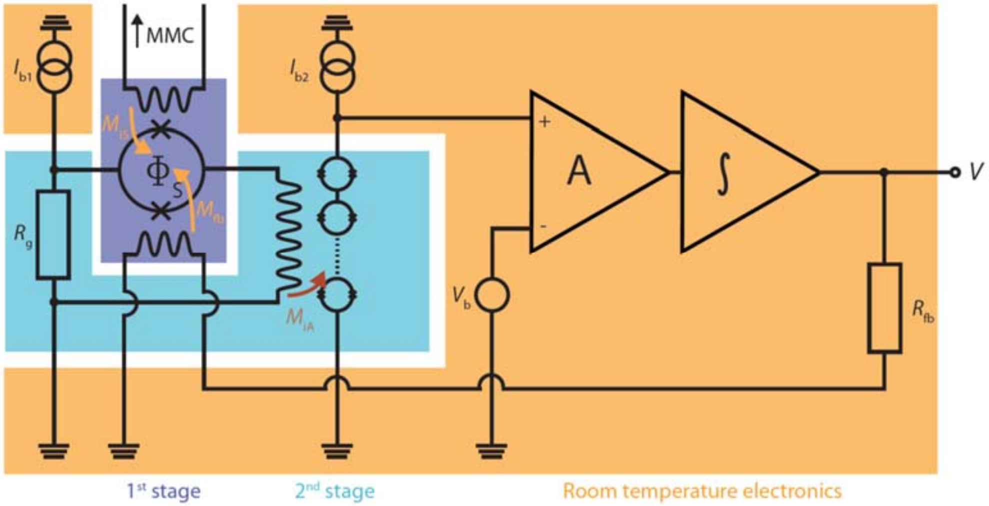
2 chips have been implanted
@RISIKO in January – 10 Bq/pixel





Towards ECHo-100k – Multiplexing

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



Single channel readout – two stage SQUID scheme:

10 wires per channels

SQUID electronics

Not scalable → parasitic heat load, number of wires, costs, complexity ~N

How to read out a large number of detectors ?

Multiplexed readout:

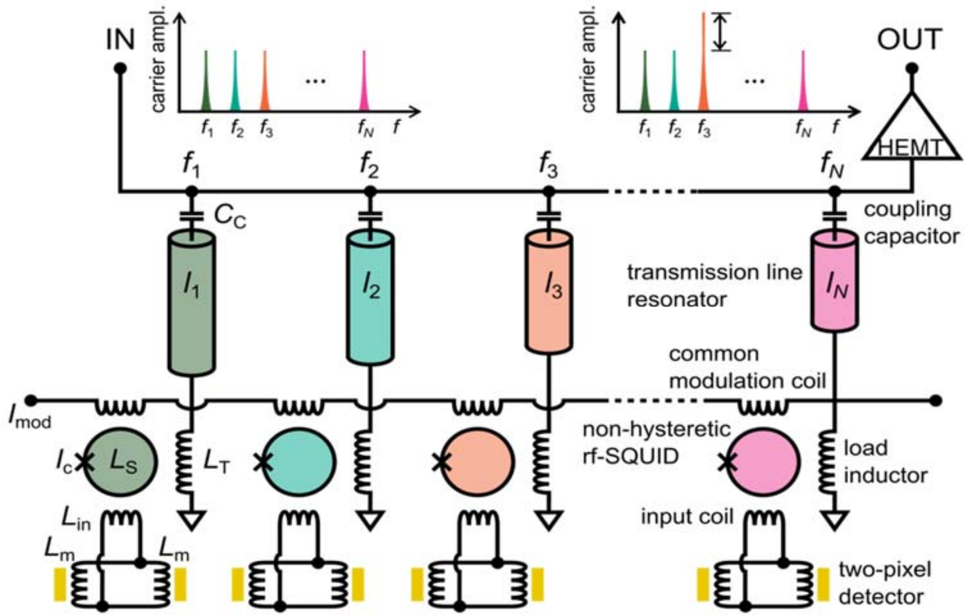
~ 500 detectors per readout channel

For ECHo → Microwave SQUID multiplexing

Scalability

Towards ECHo-100k – Multiplexing

Microwave SQUID multiplexing
Single HEMT amplifier and 2 coaxes
to read out **100 - 1000** detectors

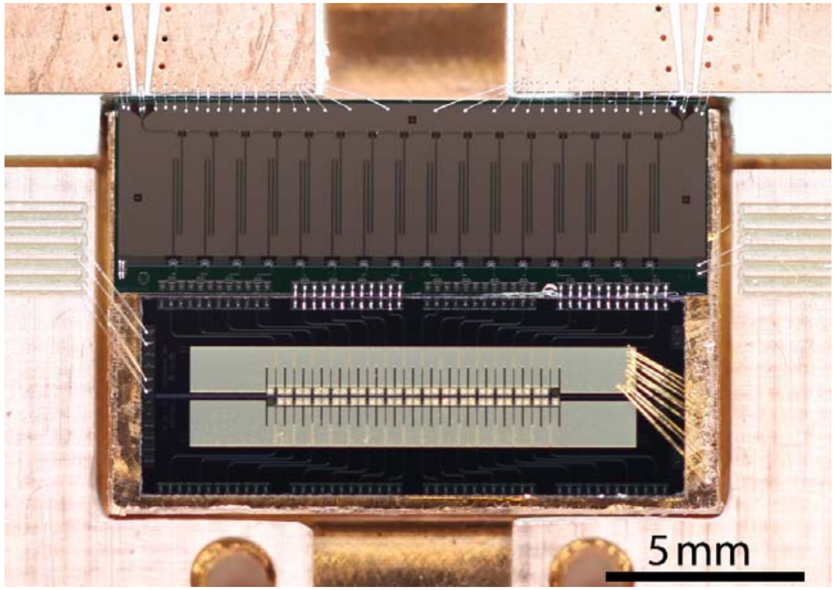


S.Kempf et al., *J. Low. Temp. Phys.* **175** (2014) 850-860

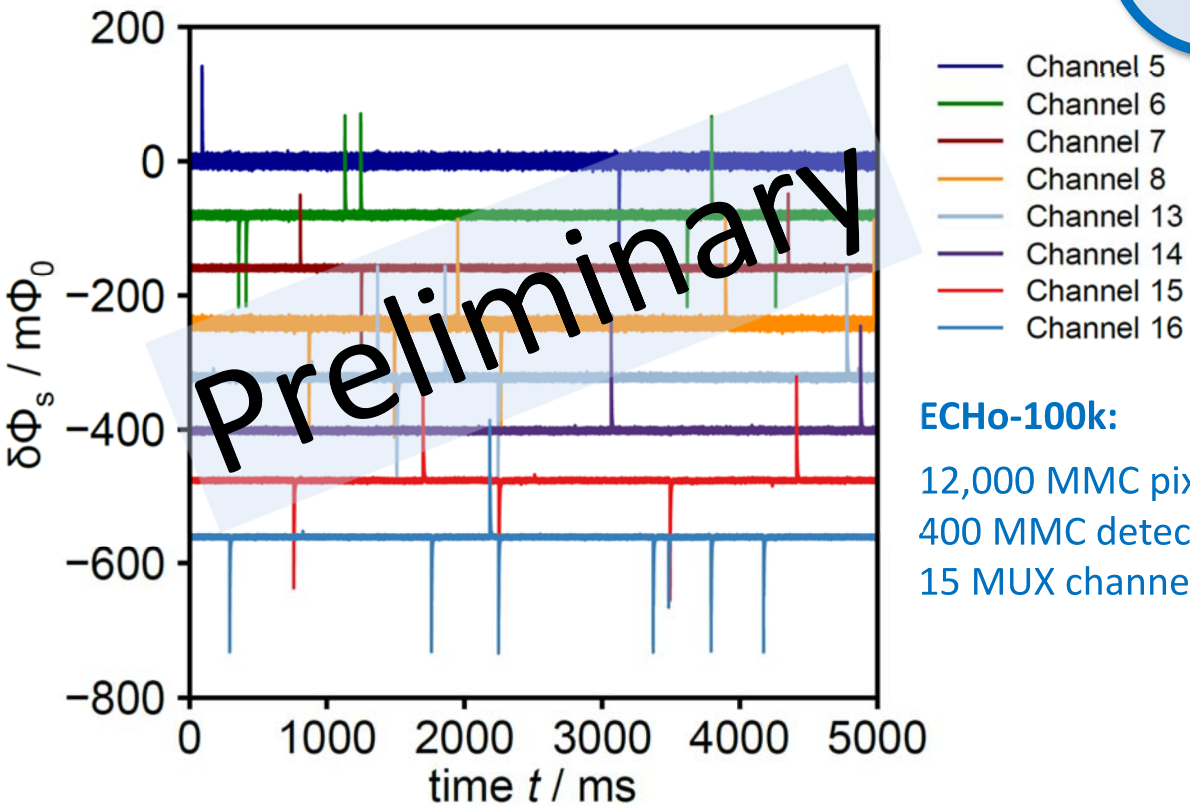
Towards ECHo-100k – Multiplexing

Microwave SQUID multiplexing
Single HEMT amplifier and 2 coaxes to read out **100 - 1000** detectors

- Successful characterization of first prototypes with external ^{55}Fe
  → Very promising results:
  8 channels (16 pixels)



S.Kempf et al., *AIP Advances* **7** (2017) 015007
M. Wegner et al., J. Low Temp. Phys. **193**, 462 (2018)



ECHo-100k:
12,000 MMC pixels = 400 MMC detectors × 15 MUX channels

Soon tests with ^{163}Ho loaded MMC arrays

Karlsruher Institut für Technologie
UNIVERSITÄT HEIDELBERG ZUKUNFT SEIT 1386

Conclusions

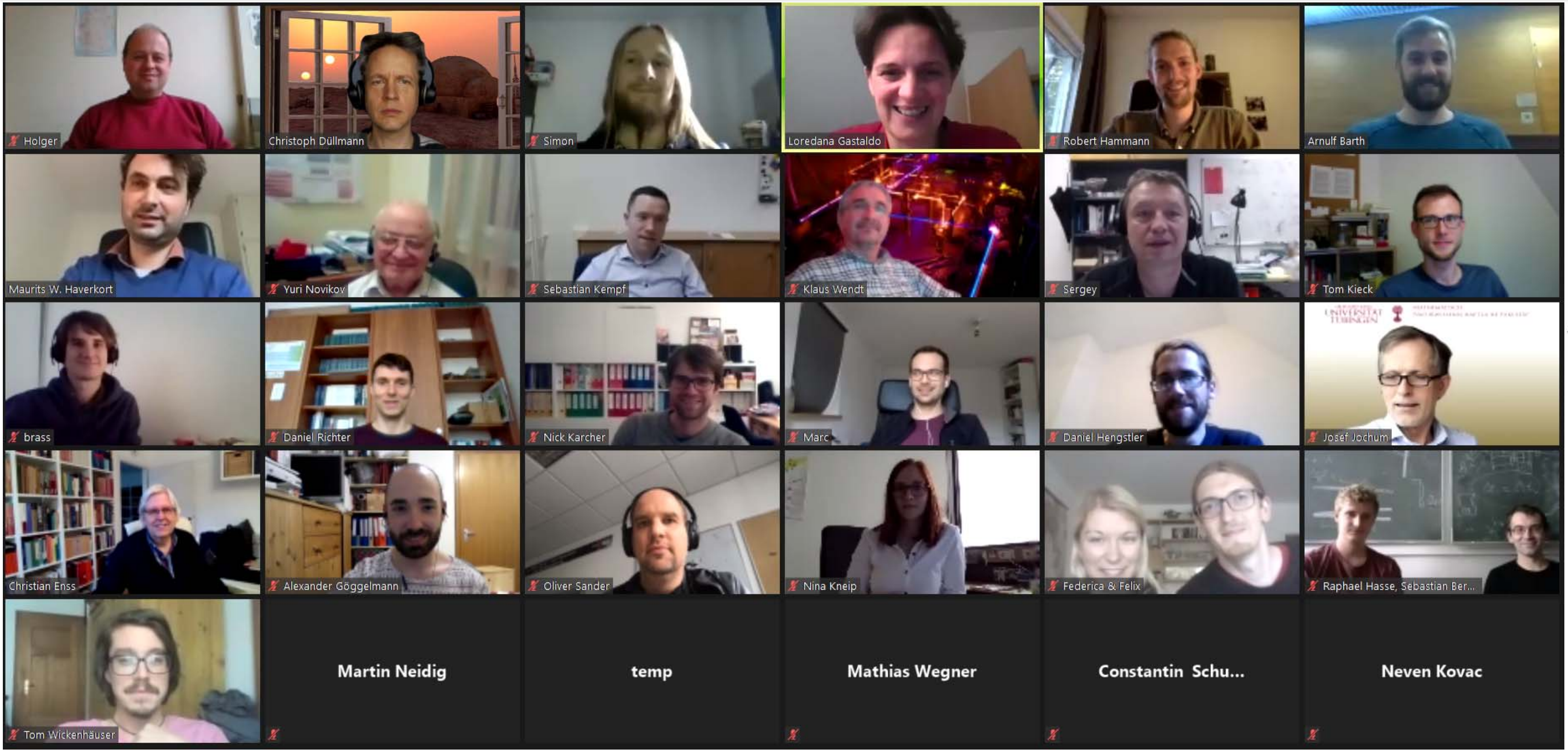
- The results obtained with ^{163}Ho loaded MMCs paved the way to large scale neutrino mass experiments based on ^{163}Ho

- A first improvement on the effective electron neutrino mass limit has been obtained in a proof of concept measurement

- More than 10^8 ^{163}Ho events have been acquired within the ECHo-1k phase → A new limit at the level of 20 eV on the effective electron neutrino mass is coming soon

- Important steps towards ECHo-100k have been demonstrated: new ECHo-100k array + multiplexed readout

The ECHo Collaboration (Coll. Meeting October 2020)



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DFG Deutsche Forschungsgemeinschaft

Research Unit FOR 2202

Thank you!

ISOLDE

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