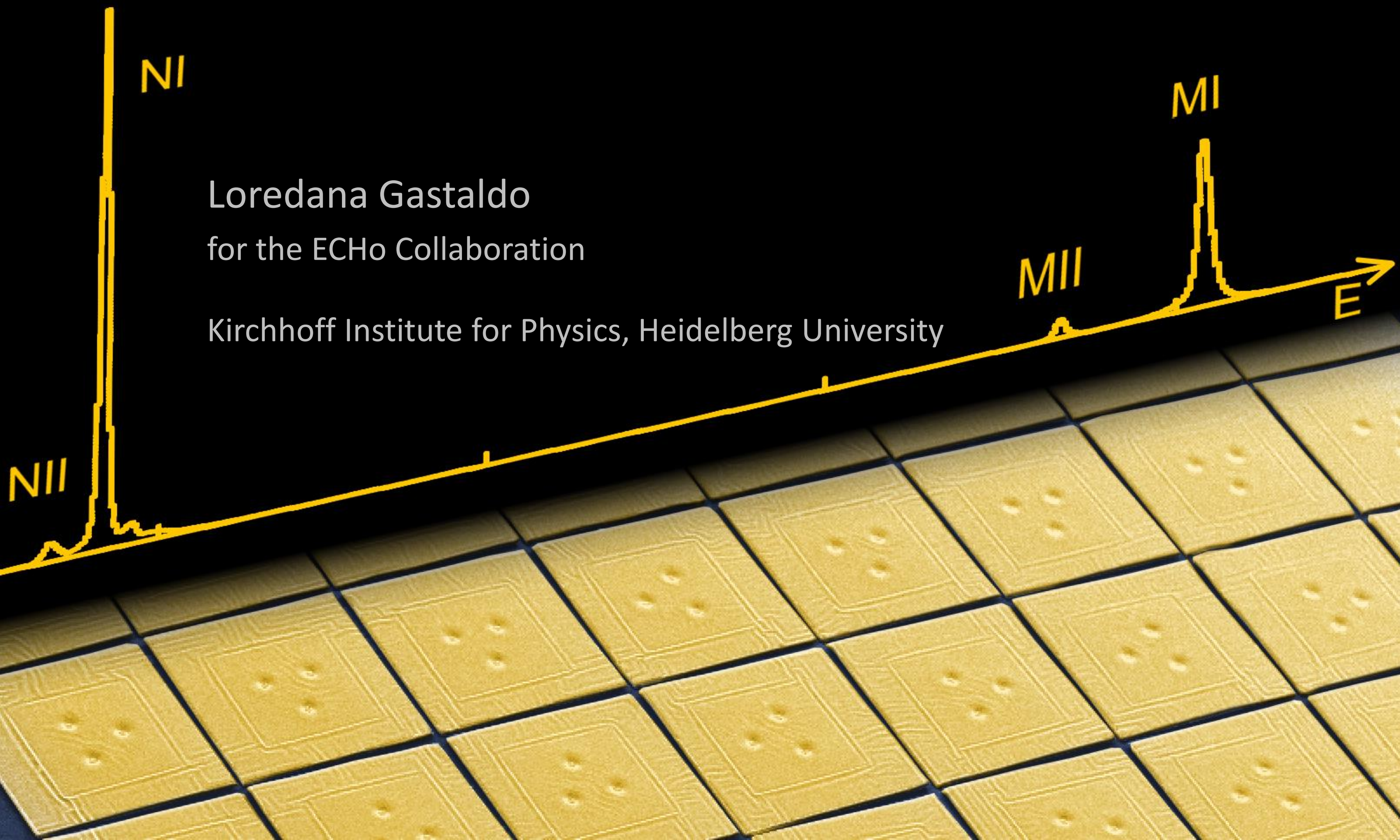
# The Electron Capture in $^{163}$Ho experiment - ECHo

Loredana Gastaldo
for the ECHo Collaboration

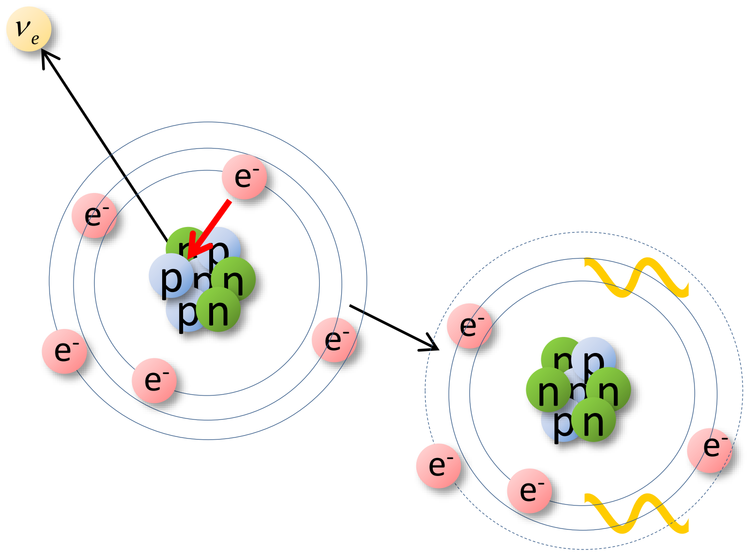
Kirchhoff Institute for Physics, Heidelberg University



# Outline

- Electron capture in $^{163}$Ho and neutrino mass
  - Energy spectrum
  - Sensitivity to a finite neutrino mass
- Experimental challenges
  - Detectors
  - $^{163}$Ho Source
- Theory challenges
- Recent results
- Conclusions

# $^{163}$Ho electron capture decay




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

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

- $\tau_{1/2} \cong 4570$ 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

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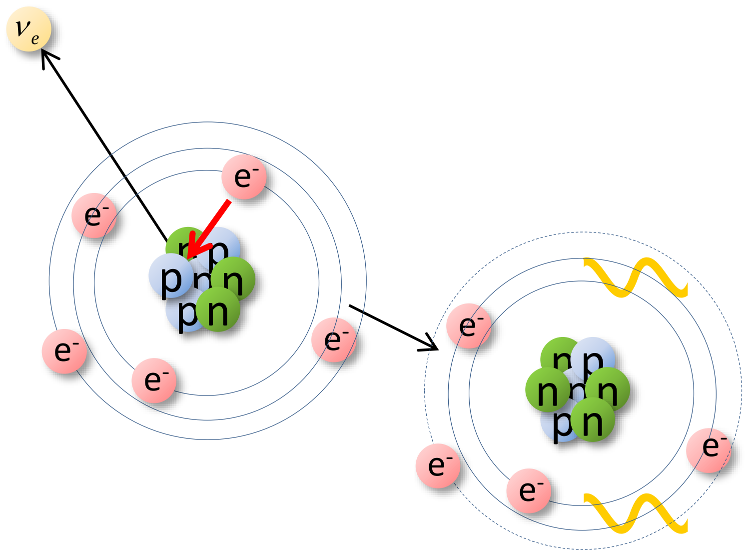

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$$Q_{EC} = m(^{163}\mathrm{Ho}) - m(^{163}\mathrm{Dy})$$

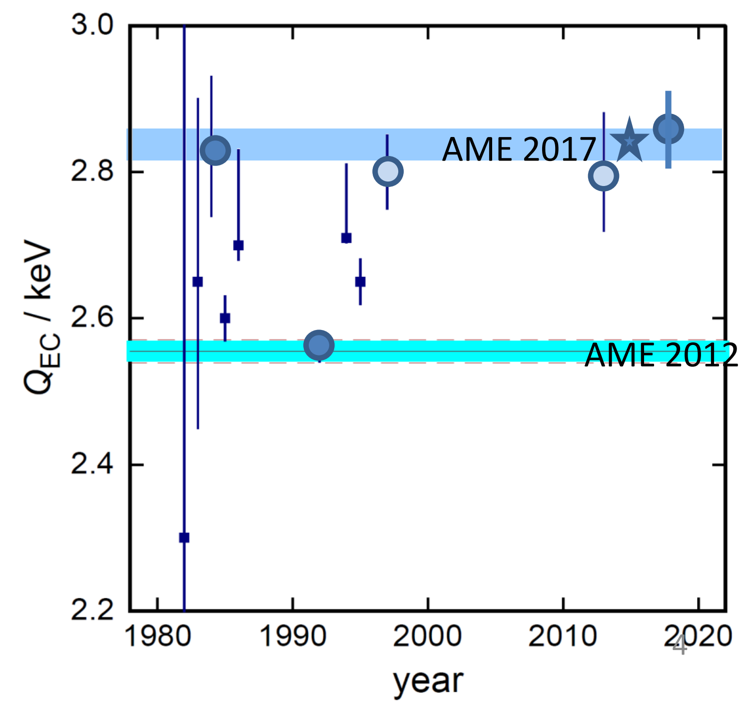
Penning Trap Mass Spectroscopy

@TRIGA TRAP (Uni-Mainz) (♦)

@SHIPTRAP (GSI – Darmstadt) (♦♦)

Future goal: 1 eV precision:

**PENTATRAP** @MPIK, Heidelberg (*)




(♦) F. Schneider et al., Eur. Phys. J. A **51** (2015) 89

(♦♦) S. Eliseev et al., *Phys. Rev. Lett.* **115** (2015) 062501

(*) J. Repp et al., Appl. Phys. B **107** (2012) 983

(*) C. Roux et al., Appl. Phys. B **107** (2012) 997

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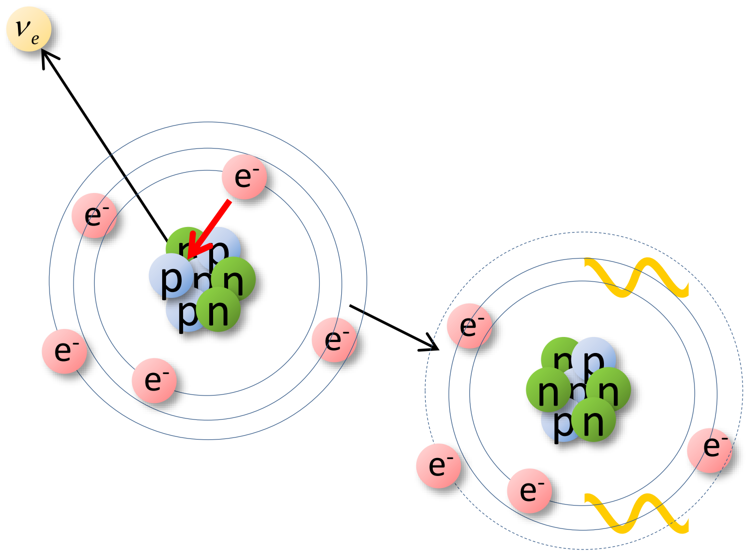


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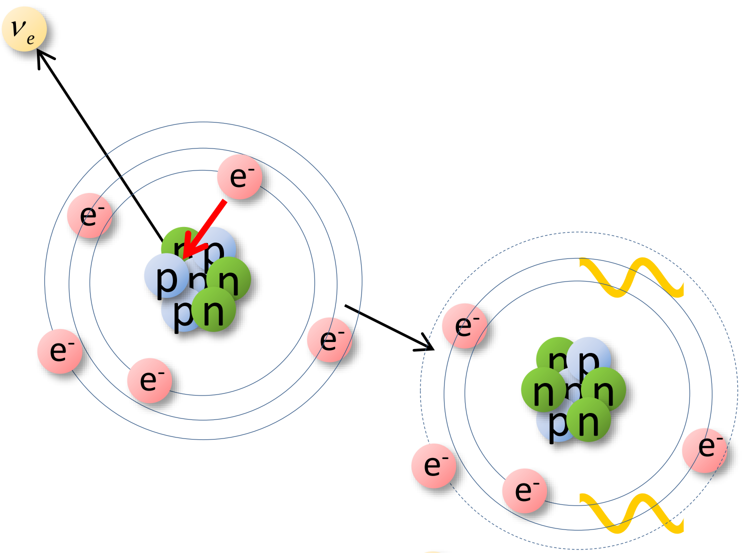


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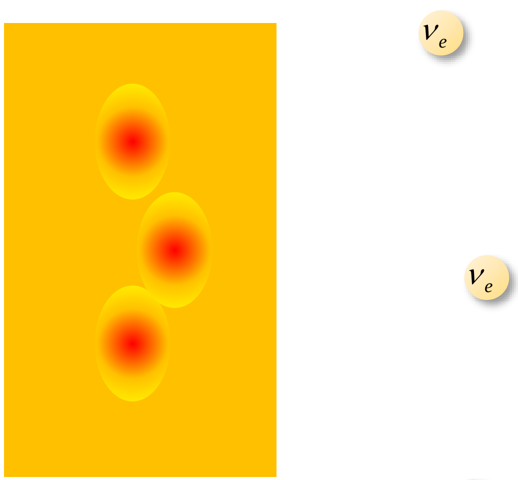
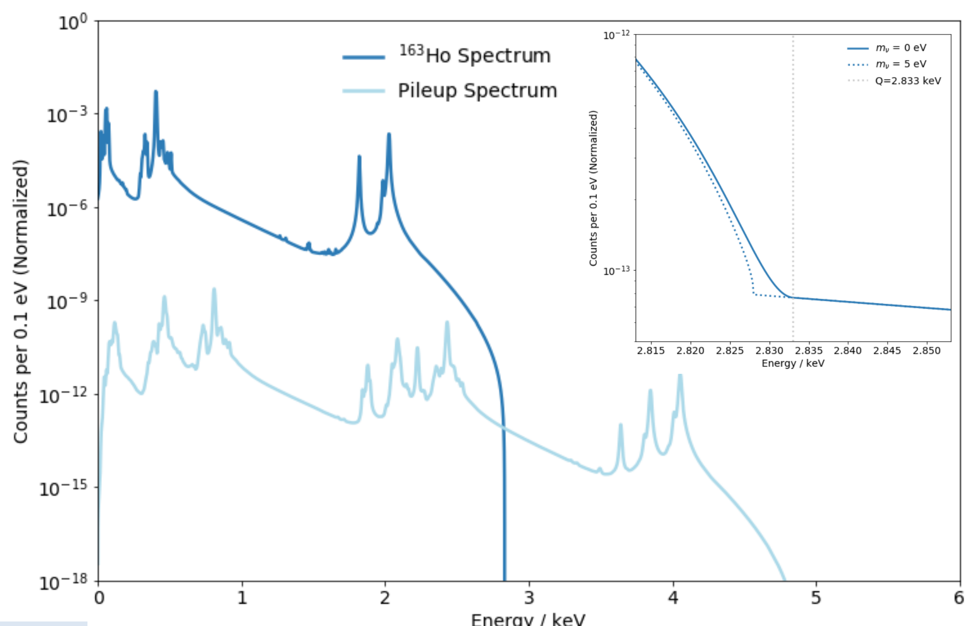



Source = Detector

**Calorimetric measurement**

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

Brass and Haverkort, arXiv:2002.05989 [nucl-th]

# Requirements for sub-eV $\nu$ mass sensitivity

Statistics in the end point region

- $N_{ev} > 10^{14}$ → **A ≈ 1 MBq**

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

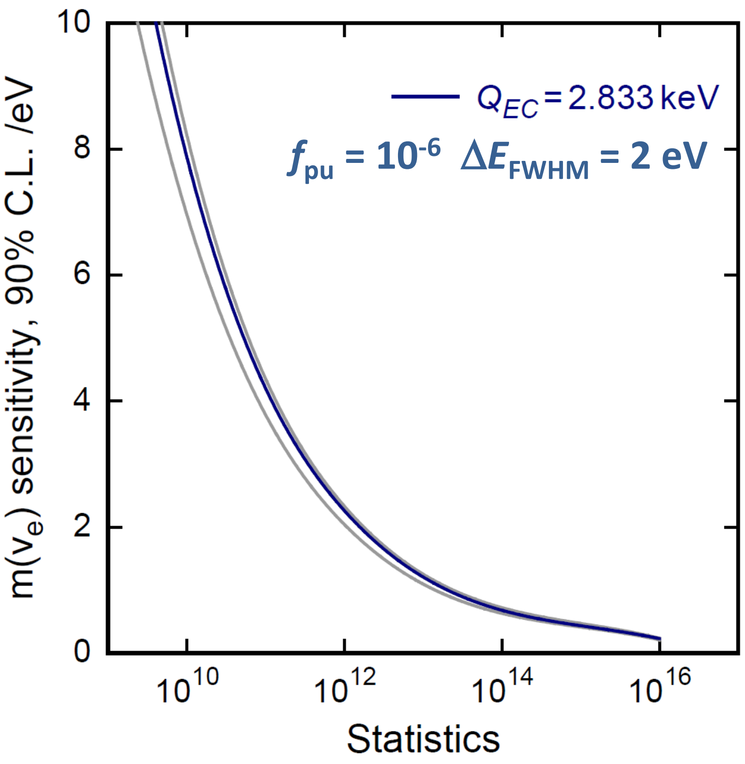
- $f_{pu} < 10^{-5}$
- $\tau_r < 1\ \mu s$ → $\boldsymbol{a \sim 10\ \mathrm{Bq}}$
- **$10^5$ pixels**

Precision characterization of the endpoint region

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

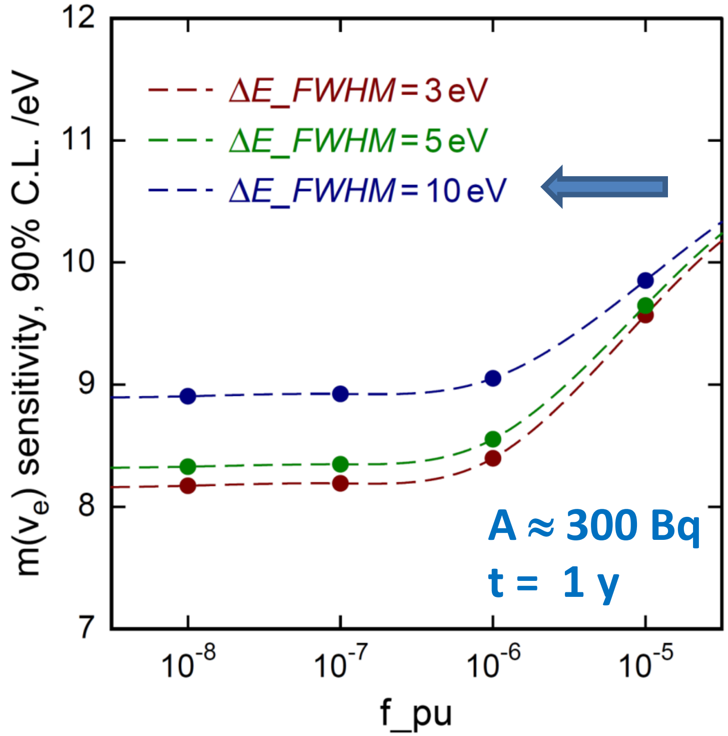
Background level

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



# Sensitivity of $^{163}$Ho based experiments - ECHo

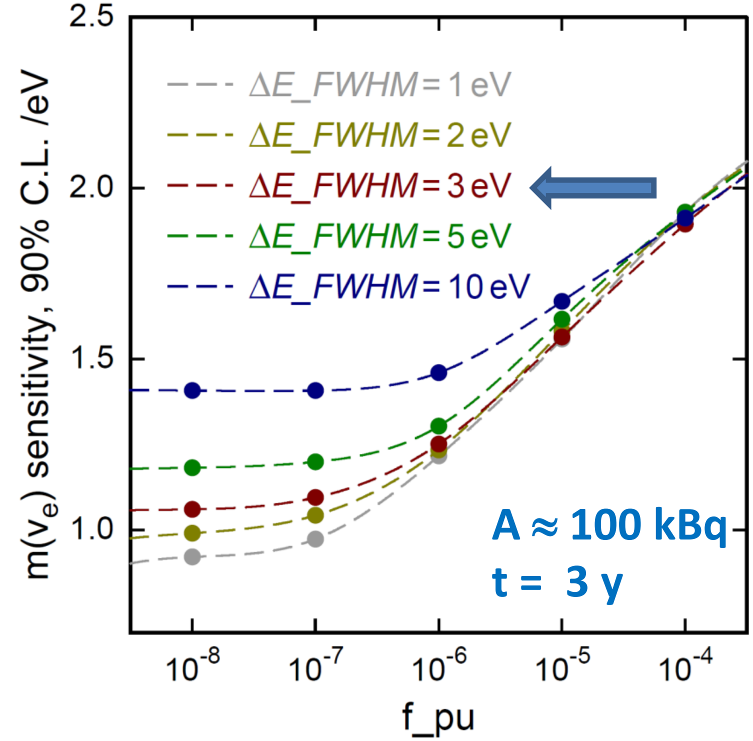
**ECHo-1k** – revised (2015 – 2018+)




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

Activity per pixel: 1 - 5 Bq
Number of detectors: 60 - 100
Readout: parallel two stage SQUID

**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 2022/1

Supported by DFG Research Unit FOR 2022/2

# Experimental aspects

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

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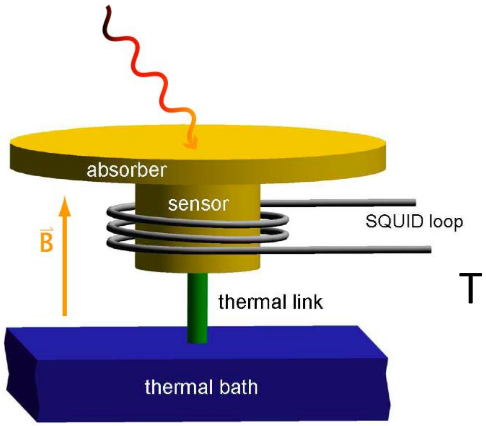
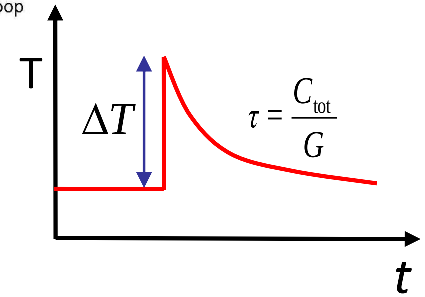



$$\Delta T \cong \frac{E}{C_{tot}}$$




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

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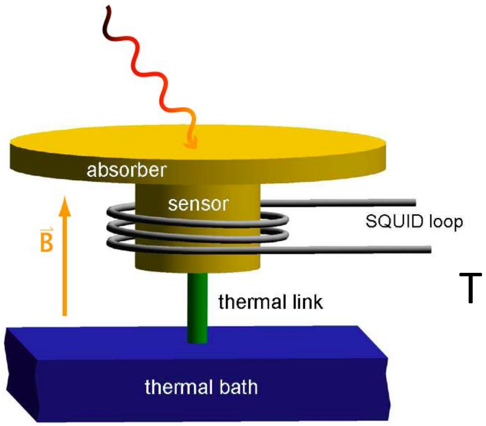


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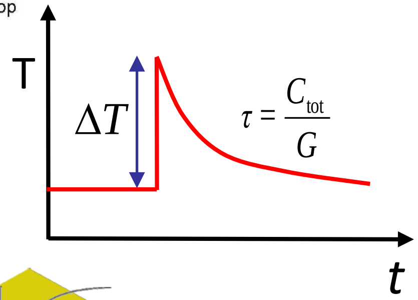


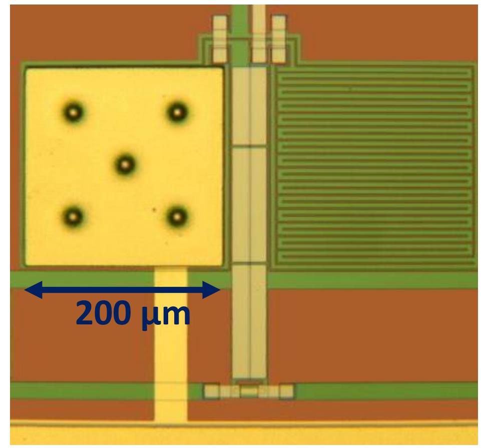



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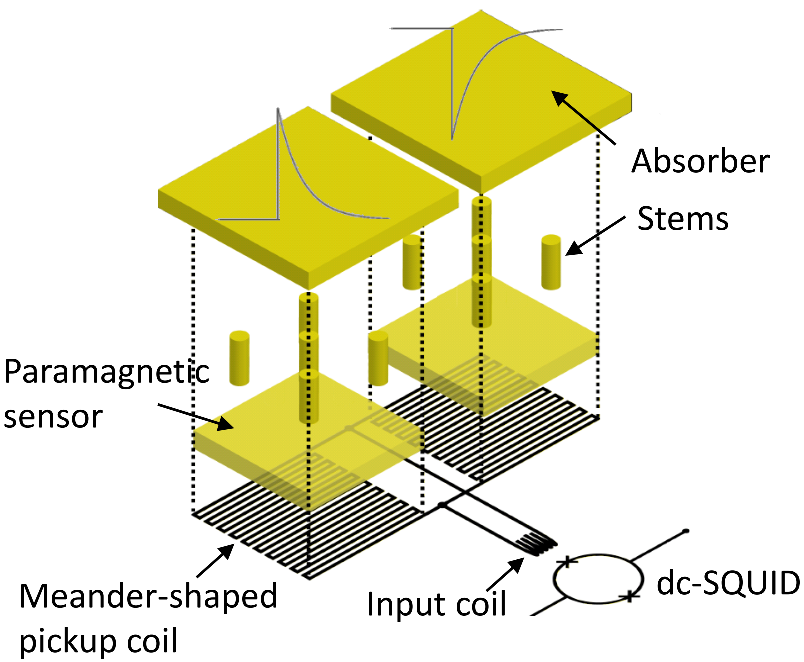

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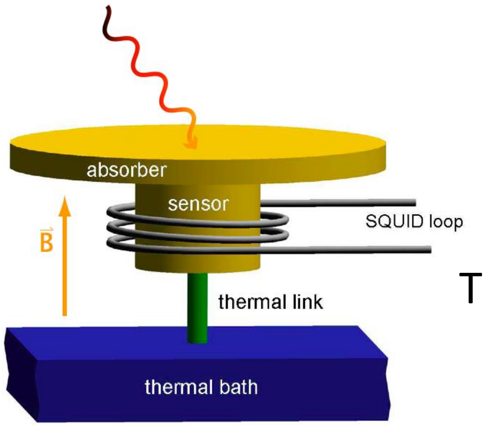
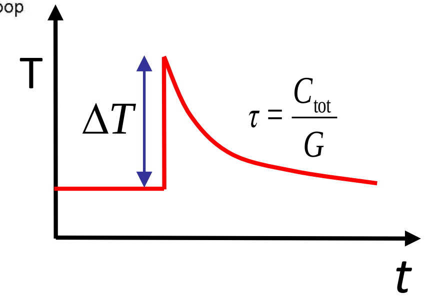
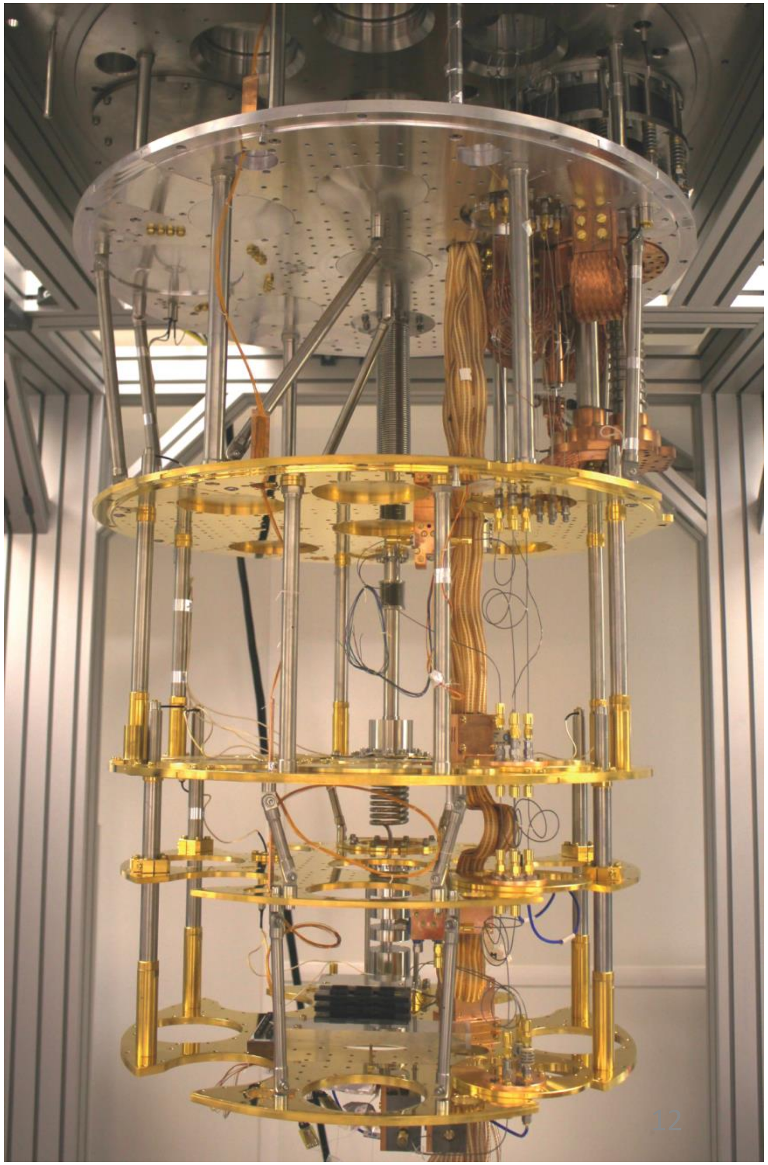



$$\Delta T \simeq \frac{E}{C_{tot}}$$



Operated at T ≅ 20 mK

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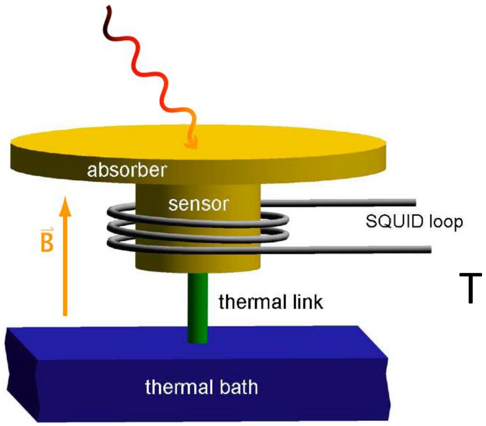


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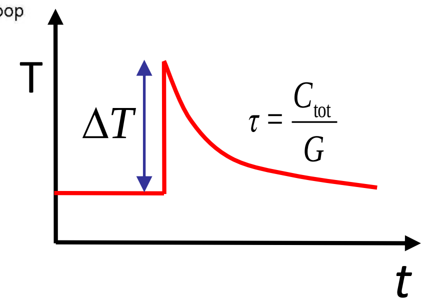



Fast risetime

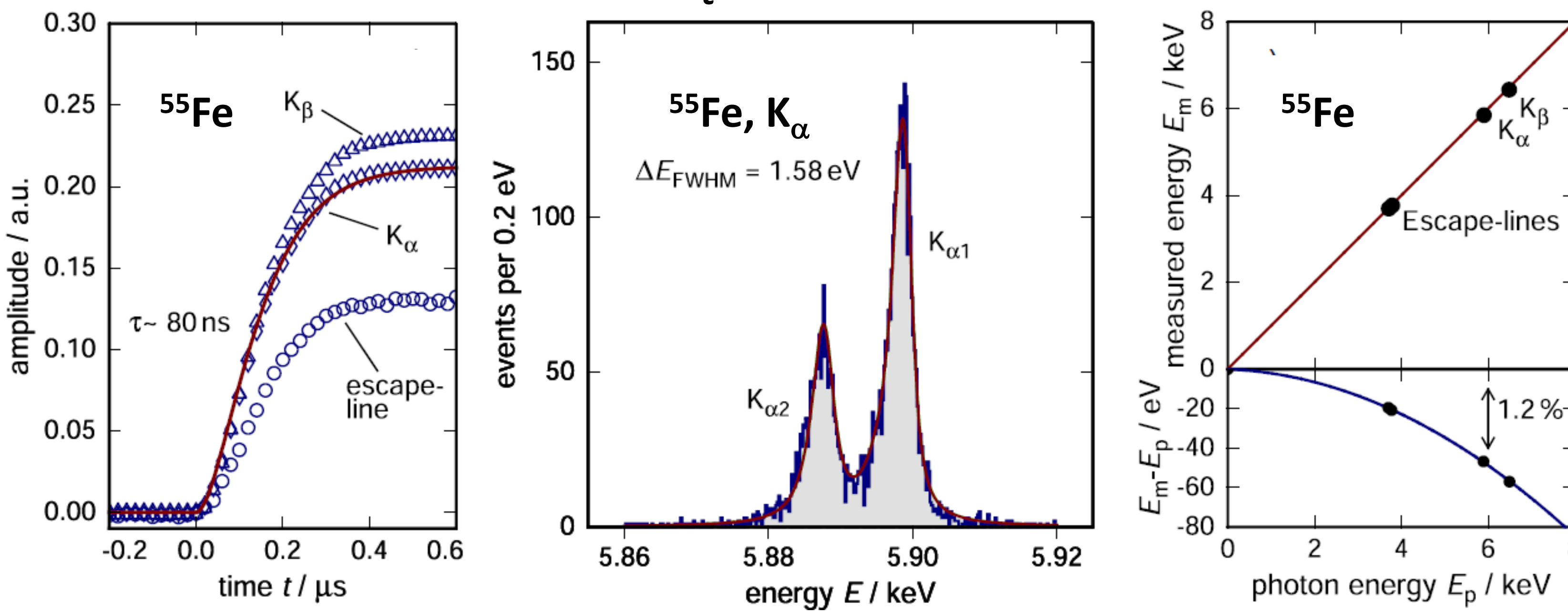
→ Reduction un-resolved pile-up

Extremely good energy resolution

→Reduced smearing in the end point region

Excellent linearity

→ precise definition of the energy scale



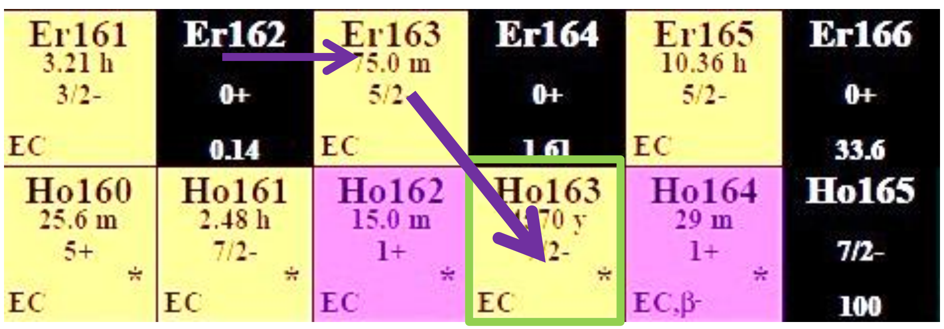
# Experimental aspects: $^{163}$Ho source

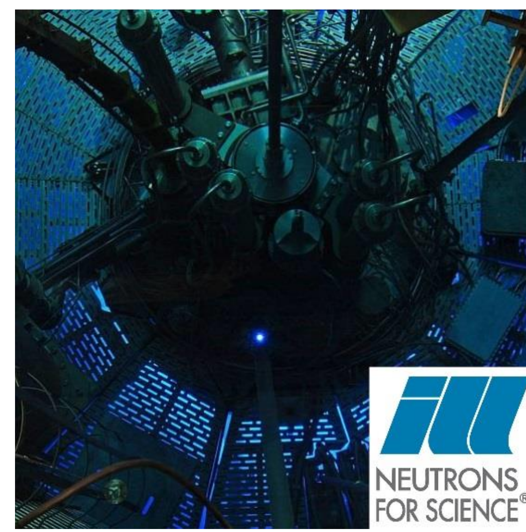
ECHo uses large arrays of low T metallic magnetic calorimeters with enclosed $^{163}$Ho

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 ~ $2 \times 10^{18}$ atoms (10 MBq)




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

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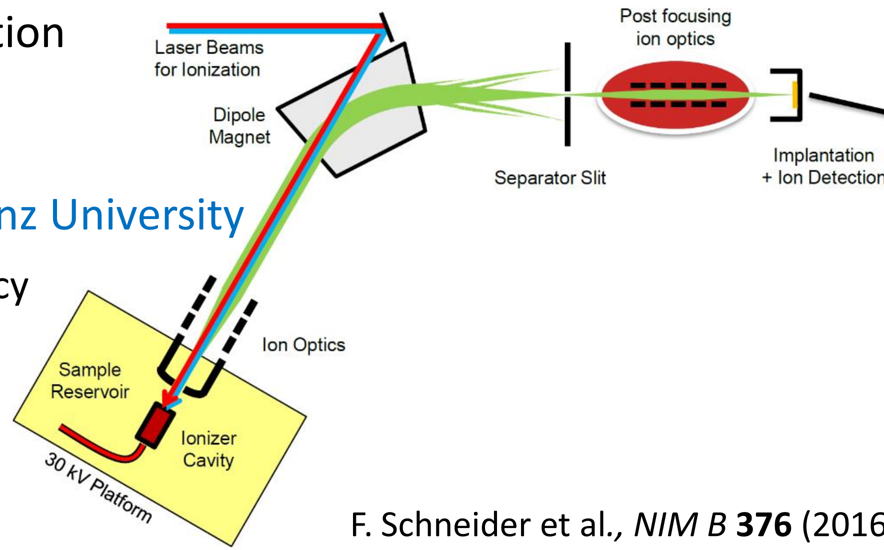
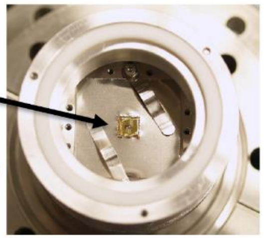
Mass separation and ion implantation in MMC pixels



RISIKO @ Institute of Physics, Mainz University

- Resonant laser ion source efficiency

  **$(69 \pm 5^{stat} \pm 4^{syst})\%$**

- Reduction of $^{166m}$Ho in MMC

  **$^{166m}Ho/^{163}Ho < 4(2)10^{-9}$**

- Optimization of beam focalization

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
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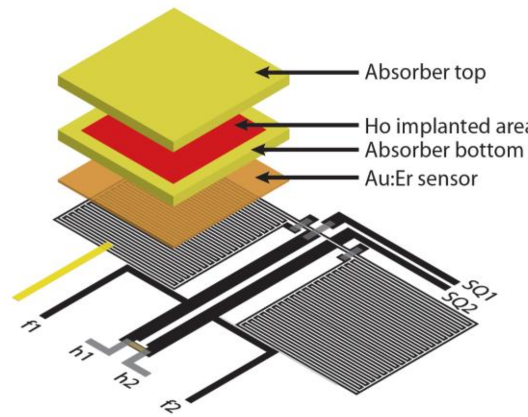



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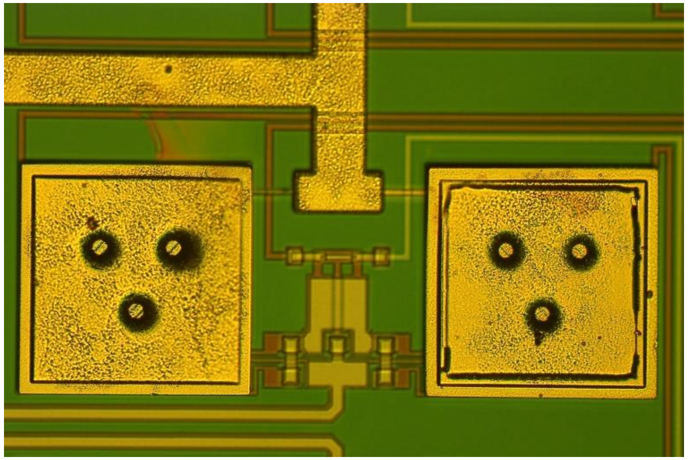

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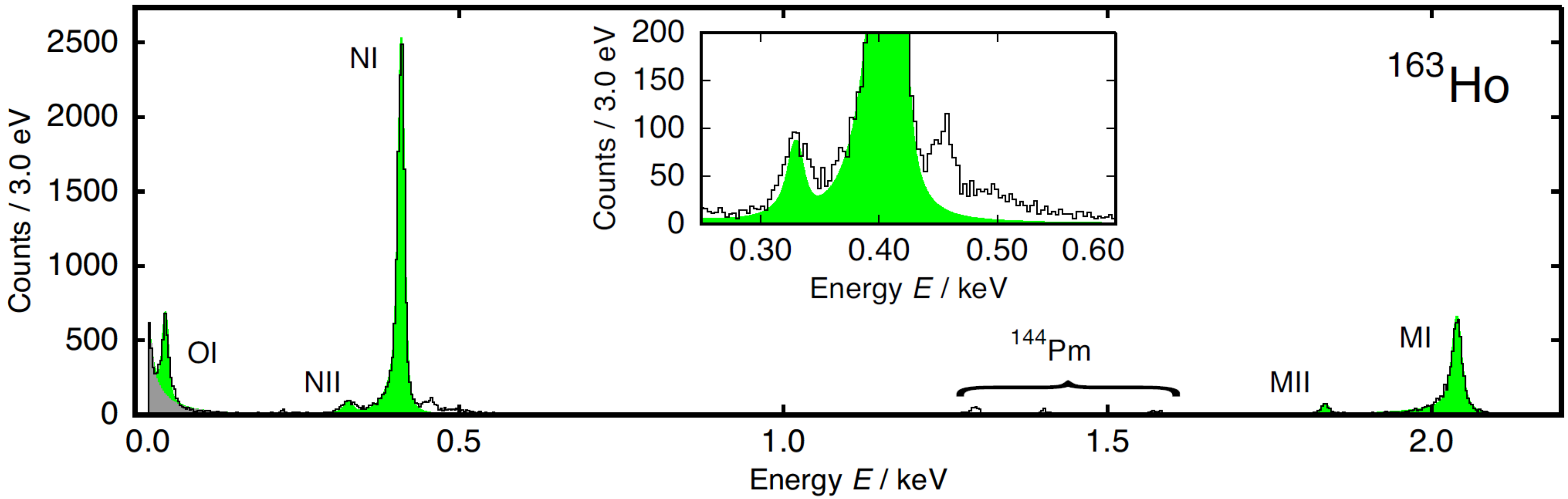
T. Kieck et al., NIM A 945 (2019) 162602
H. Dorrer et al, Radiochim. Acta 106(7) (2018) 535–48

# Theoretical aspects: $^{163}$Ho spectrum (2015 -2017)




A large number of theoretical works to interpret the $^{163}$Ho spectral shape

- A. Faessler et al., *J. Phys. G* **42** (2015) 015108
- R. G. H. Robertson, Phys. Rev. C **91**, 035504 (2015)
- A. Faessler and F. Simkovic, Phys. Rev. C 91, 045505 (2015)
- A. Faessler et al., Phys. Rev. C **91**, 064302 (2015)
- A. Faessler et al., Phys. Rev. C **95**, (2017) 045502
- A. De Rujula  and  M. Lusignoli, JHEP 05 (2016) 015

P. C.-O. Ranitzsch et al., Phys. Rev. Lett. **119** (2017) 122501

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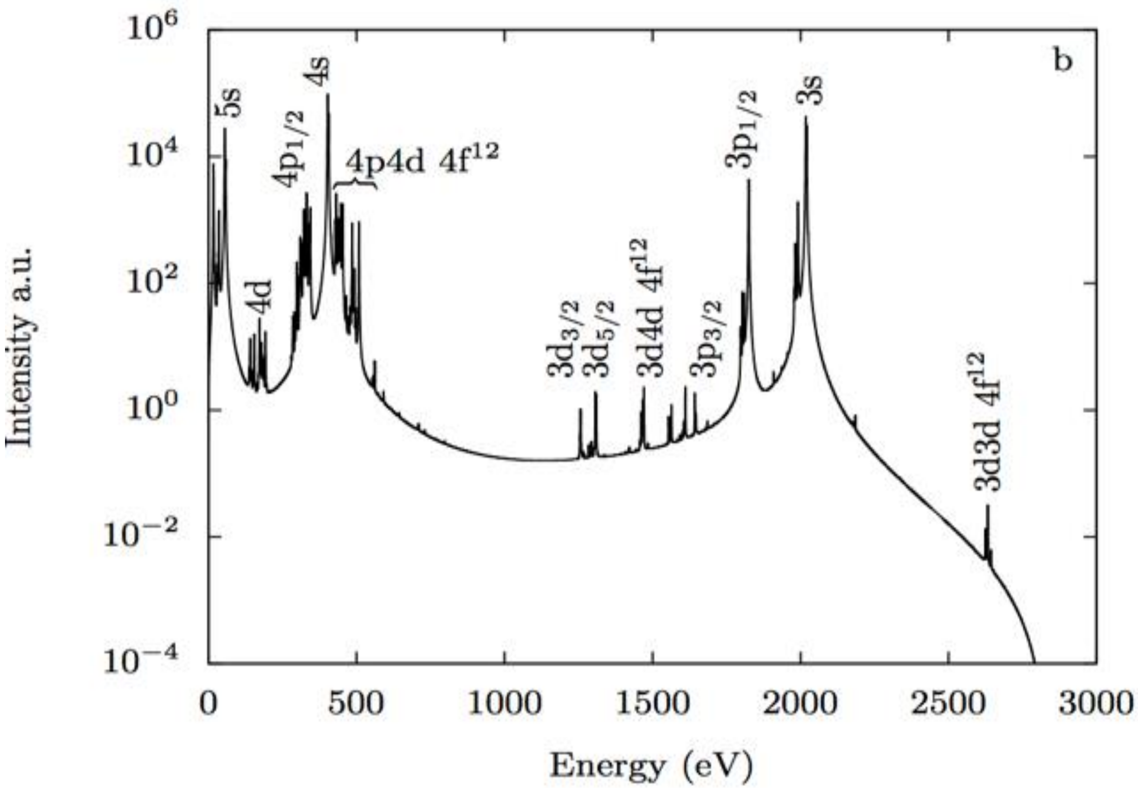



New approach

*Ab inito* calculation of the $^{163}$Ho electron capture spectrum

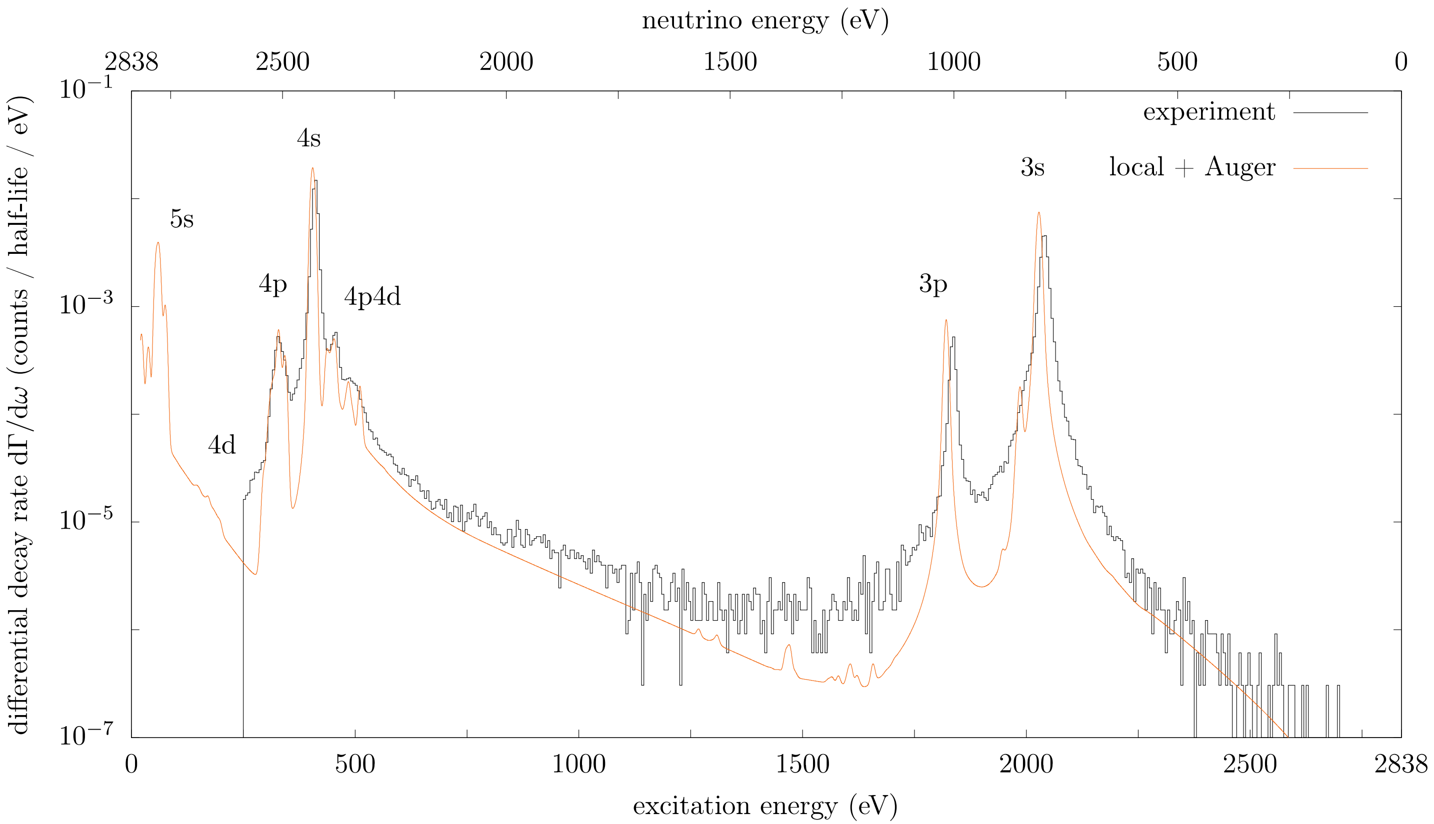
Restricted to bound-states only, i.e. the spectrum is given by a finite number of resonances

- Broadening of the 4p1/2 line
- Additional structures above the 4s line
- Additional line just below the 3s resonance



Brass et al., *Phys. Rev. C* **97** (2018) 054620

# Theoretical aspects: $^{163}$Ho spectrum (2020)




Ab-initio calculations have being used for calculating the $^{163}$Ho spectrum:

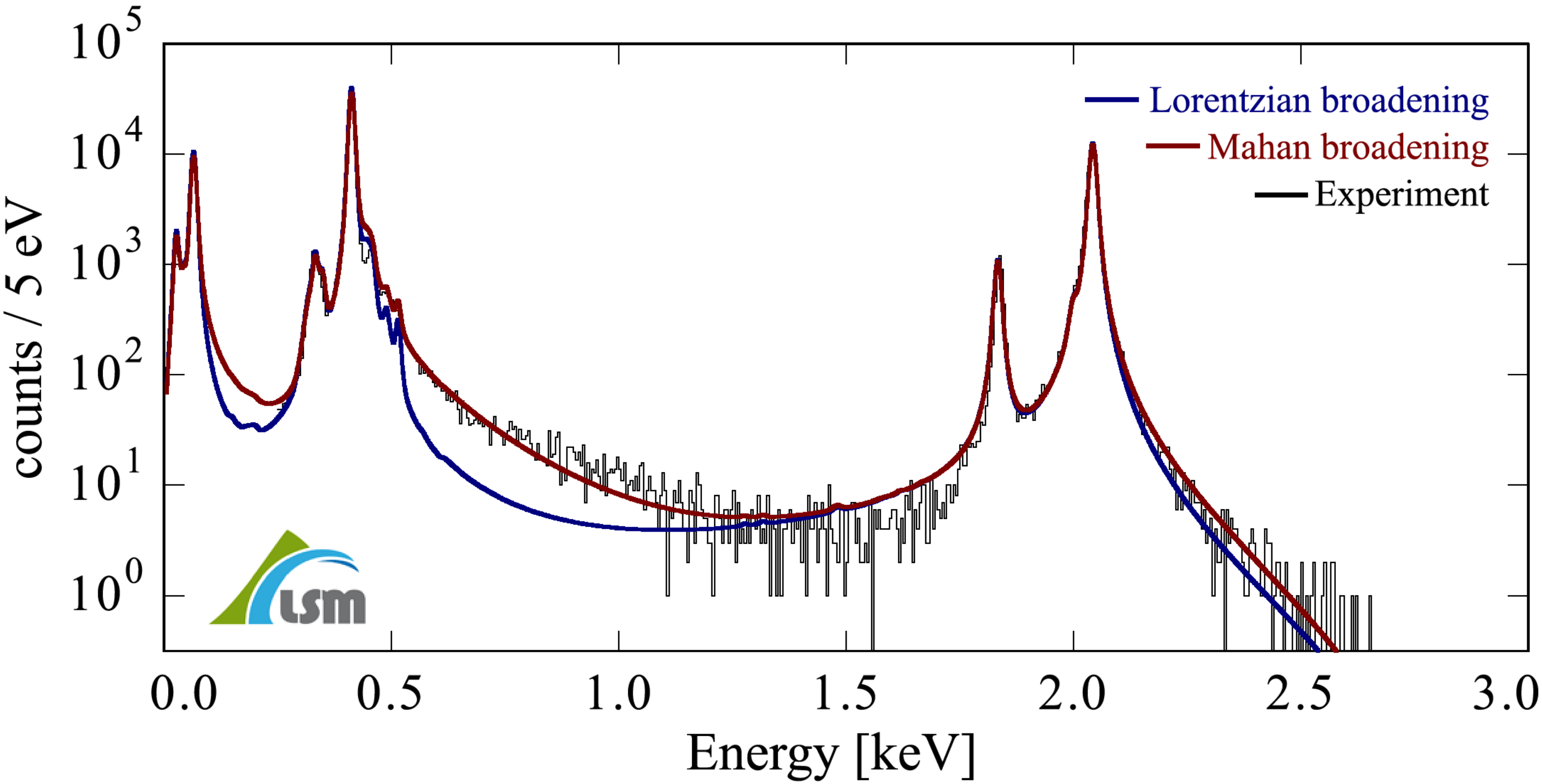
- The $^{163}$Ho spectrum is dominated by resonances due to local atomic multiplet states with core holes.
- Coulomb scattering between electrons couples the discrete atomic states, via Auger-Meitner decay, to final states with free electrons.

The present theory justifies the enhancement in countrate observed at the endpoint region



Brass and Haverkort, arXiv:2002.05989 [nucl-th]

# Recent results



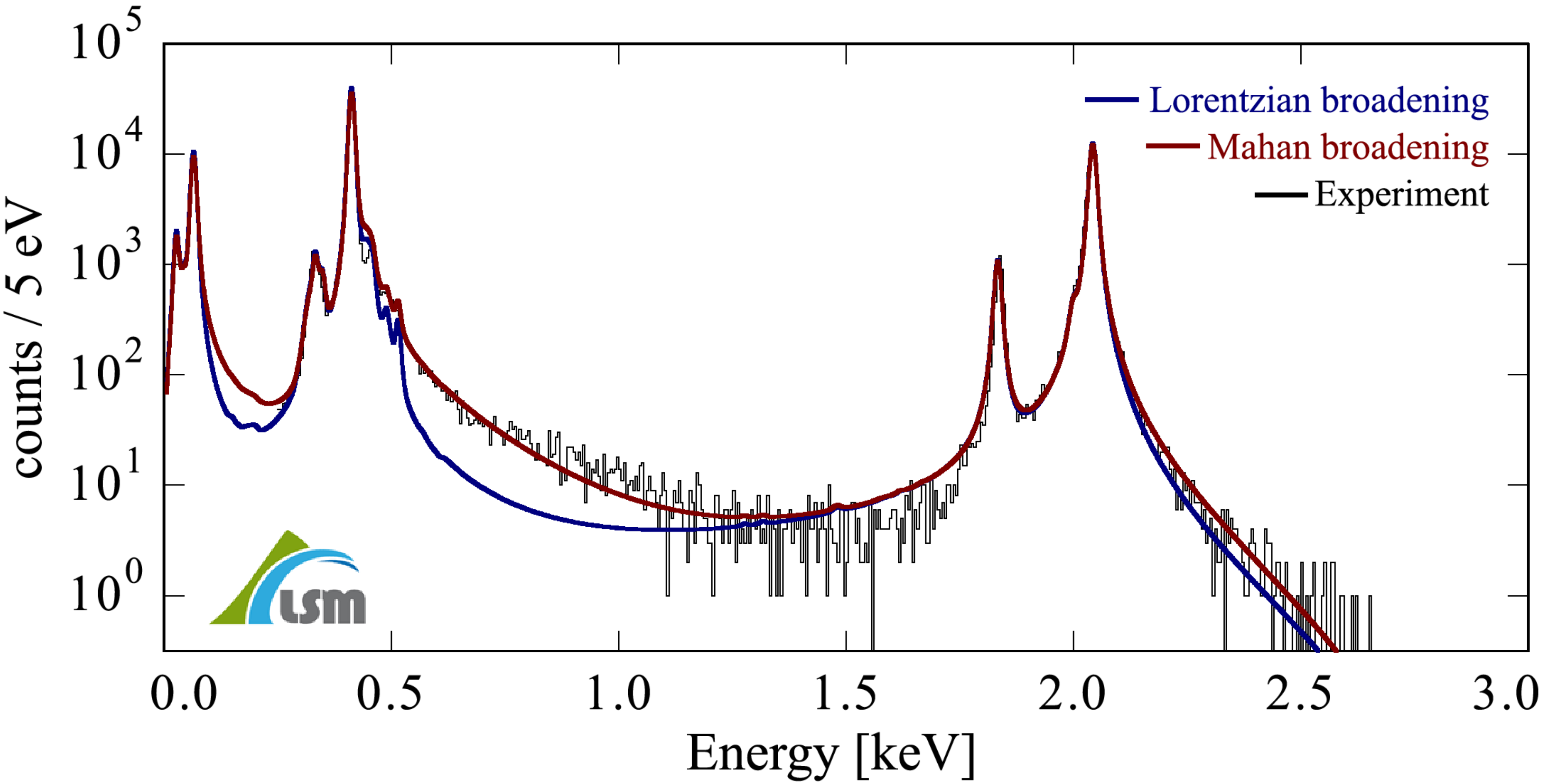

4 day measurement with 4 pixels loaded with ~0.2 Bq $^{163}$Ho

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



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

# Recent results




Energy resolution
$\Delta E_{FWHM}$ = 9.2 eV


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

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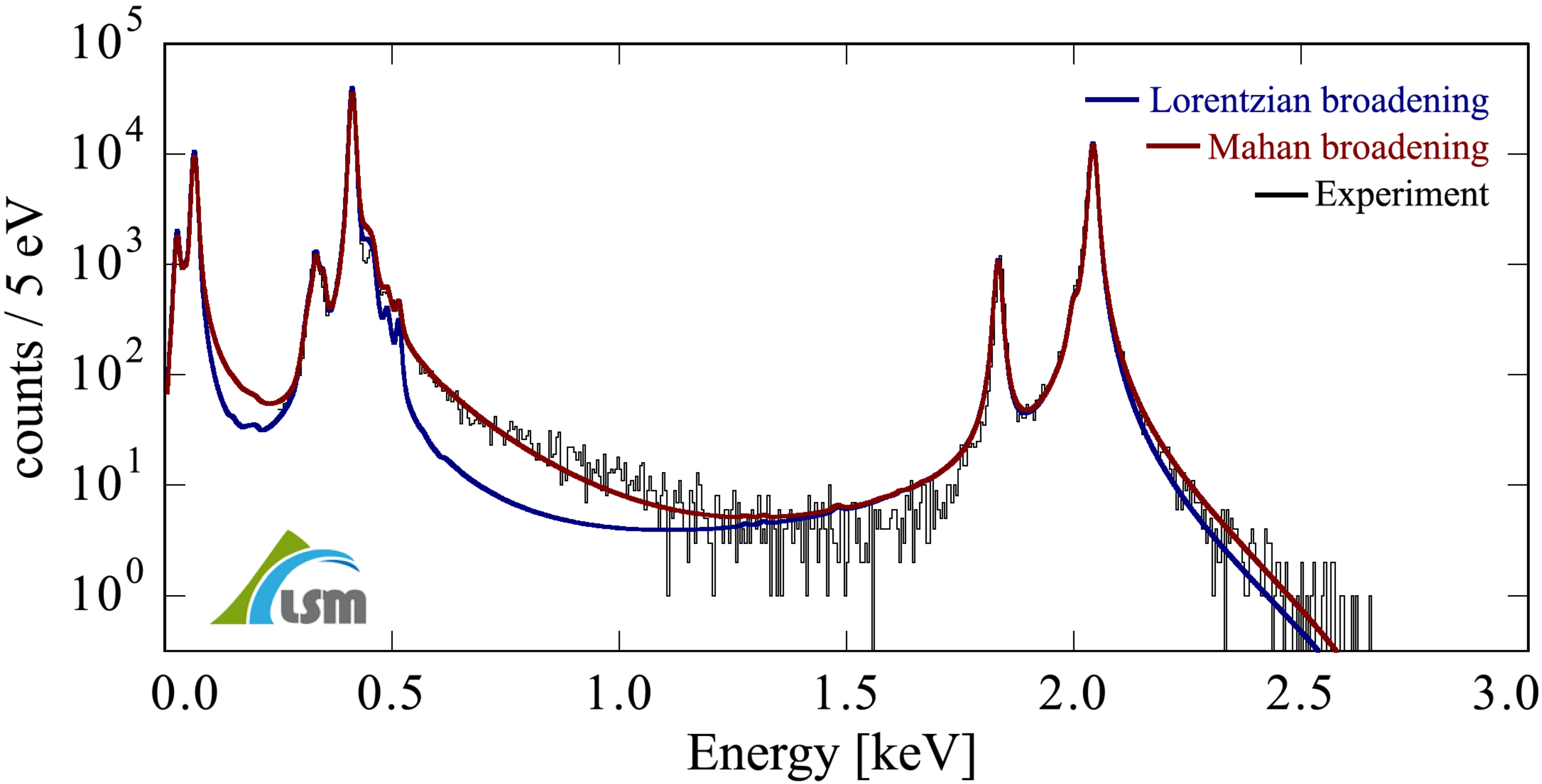


Two background events:
@ 3.742 keV
@ 6.250 keV

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



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

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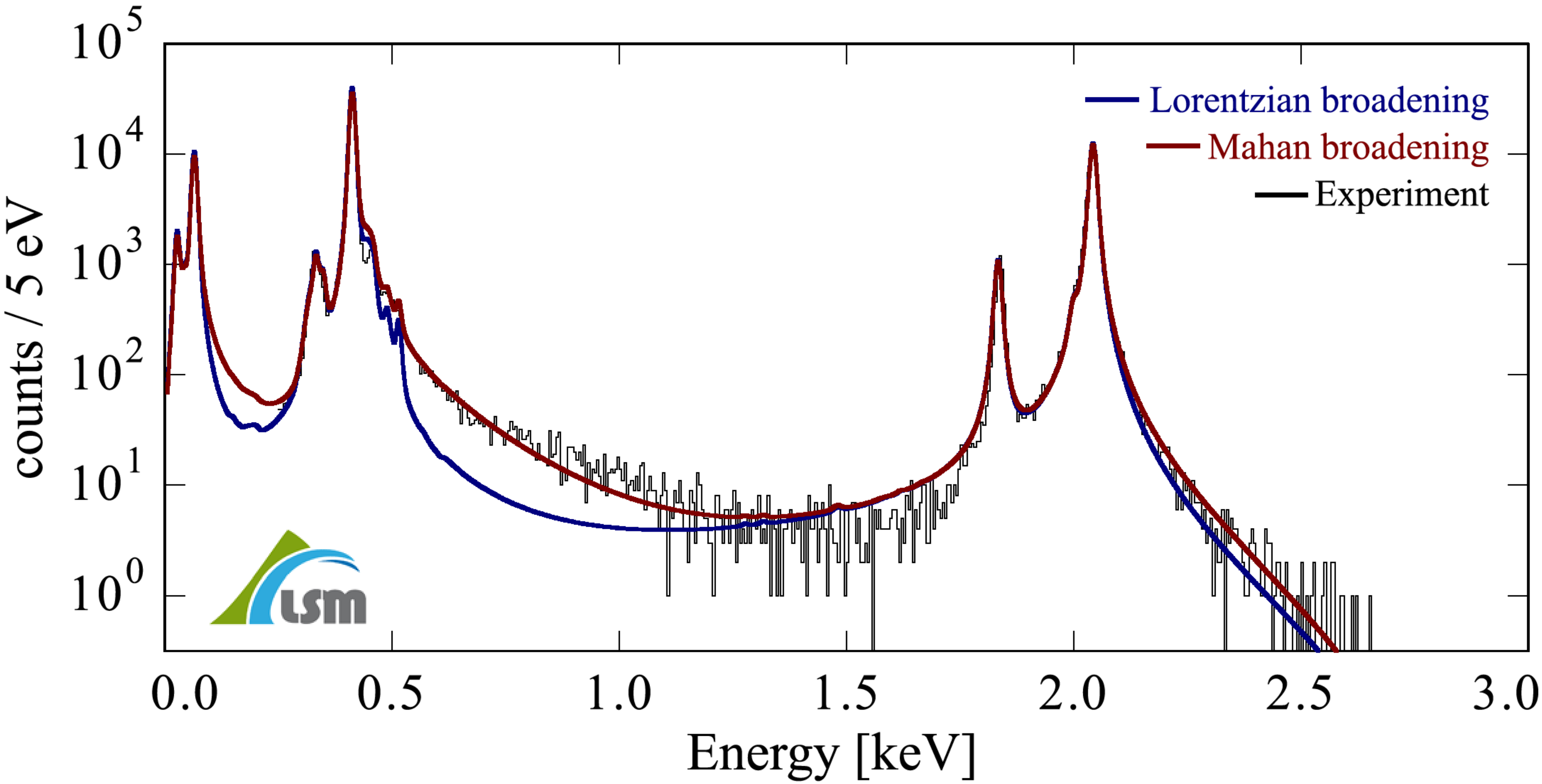


test of analysis routines: $Q_{EC}$ = (2838 ± 14) eV

$m(\nu_e)$ < 150 eV (95% C.L.) profile log-likelihood ratio hypothesis test



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

# ECHo-1K phase

## ECHo-1k chip-Au

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

## ECHo-1k chip-Ag

- $^{163}$Ho activity per pixel $a \approx 0.7$ Bq average activity
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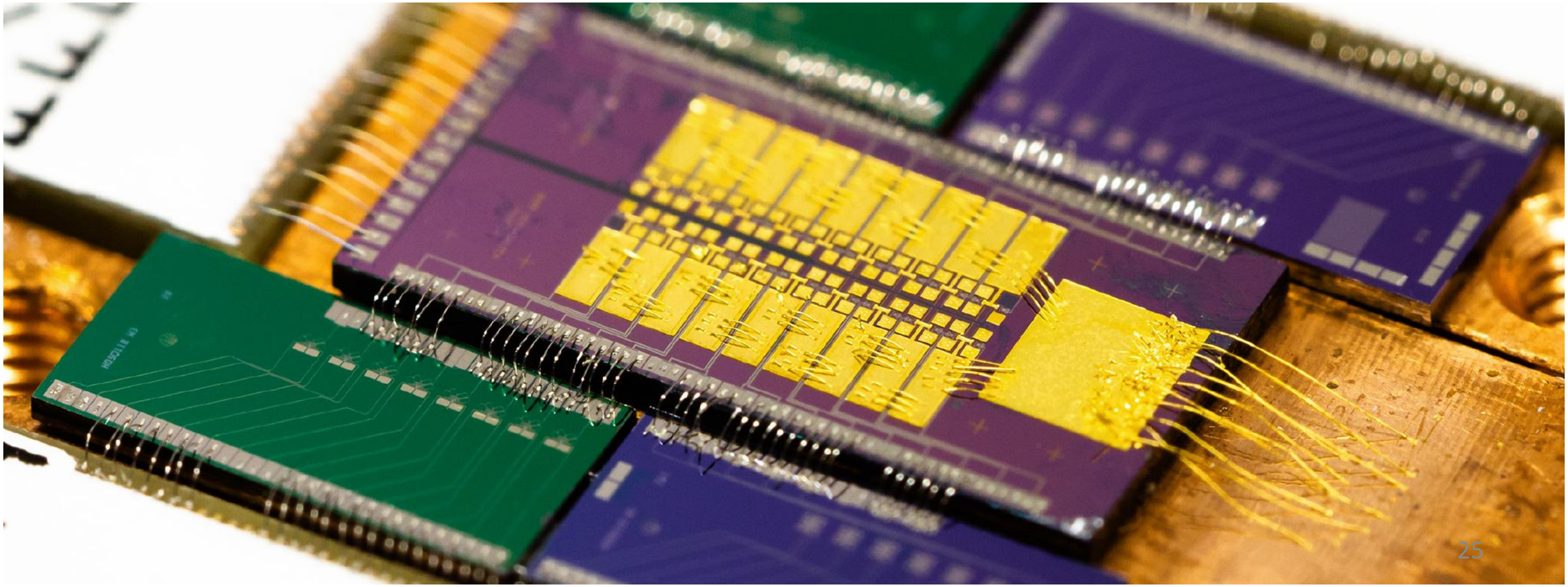

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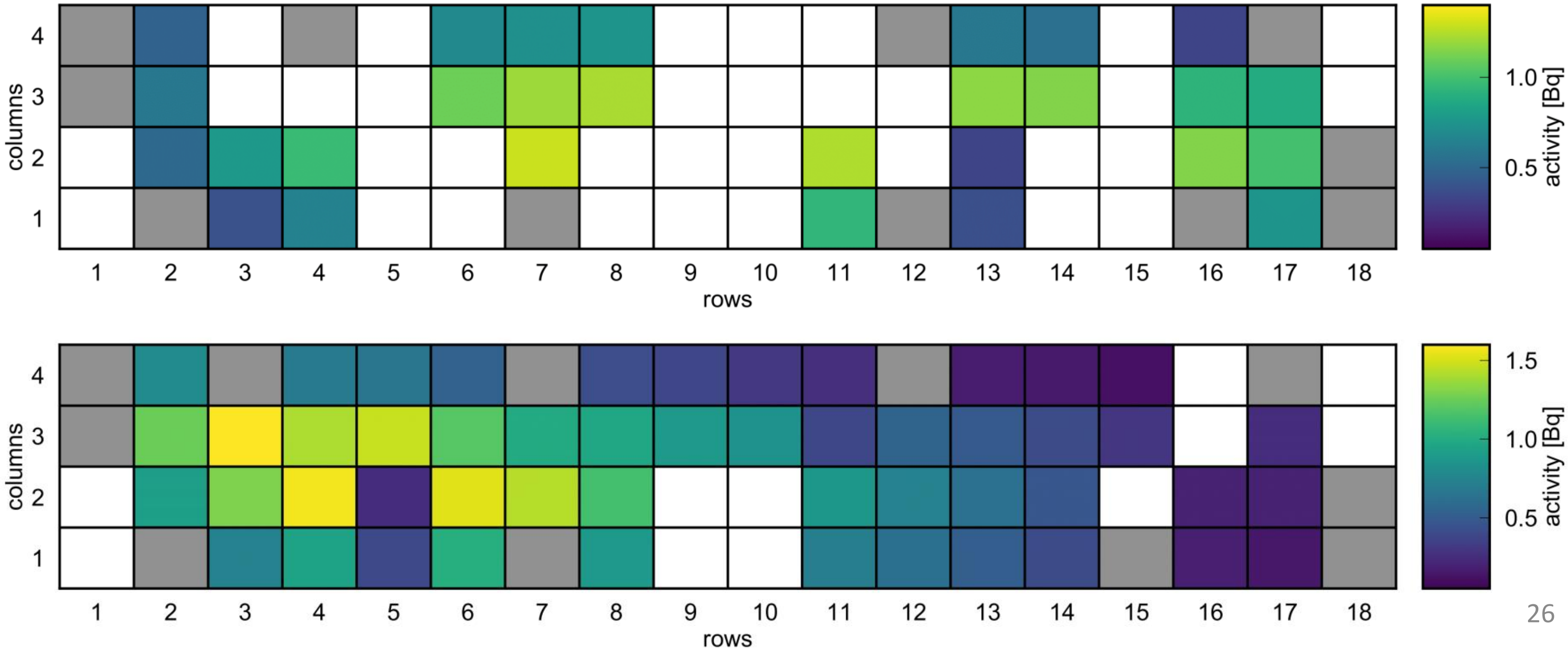

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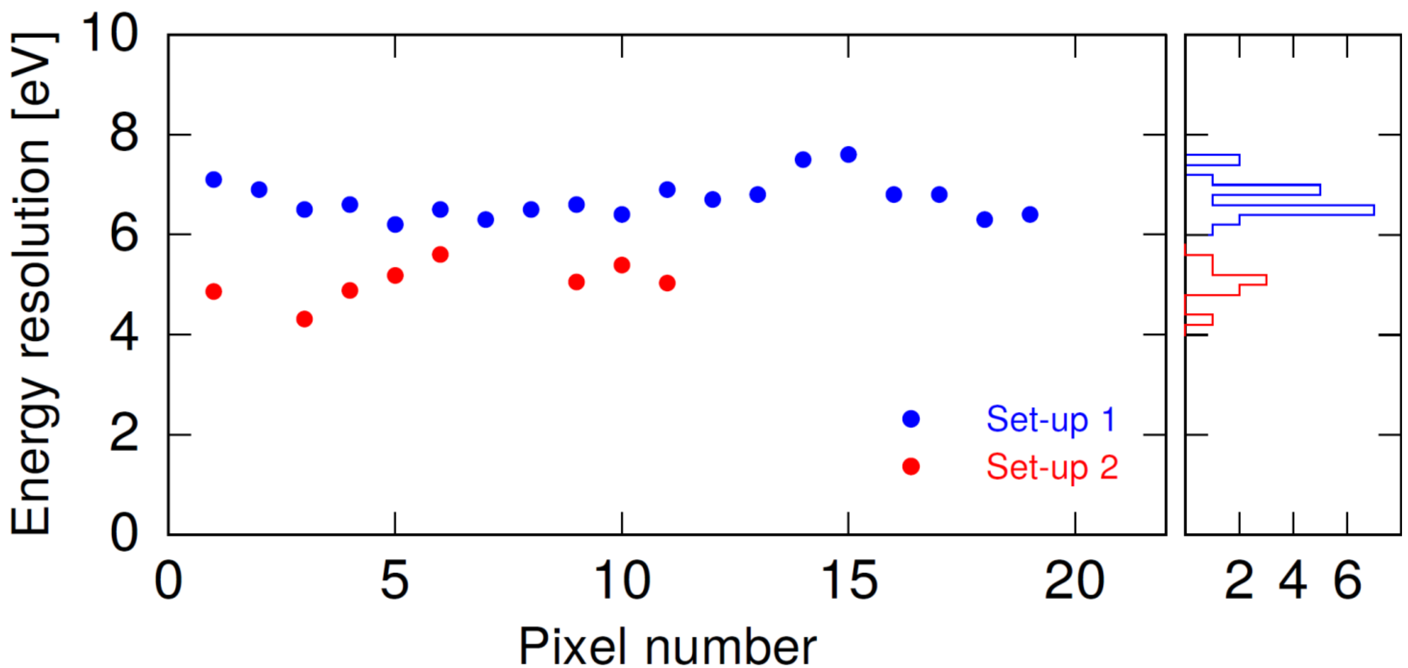

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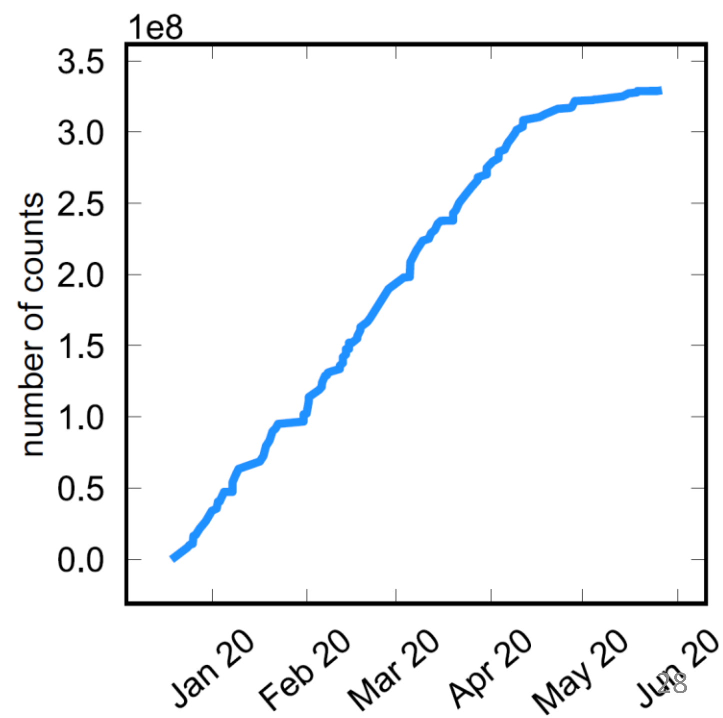
A number of $^{163}$Ho events larger than 108 has been acquired in the first months of 2020

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

Data analysis is on going

New limit on the electron neutrino effective mass before end 2020



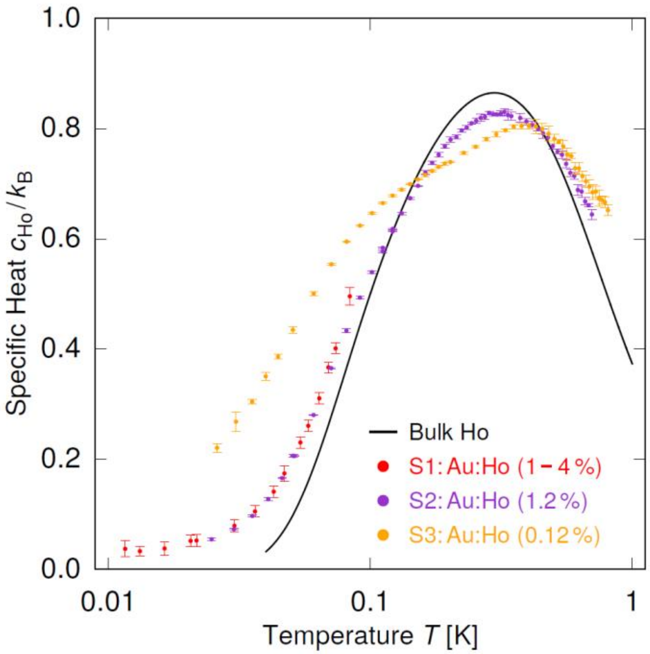
# Towards ECHo-100k

ECHo-100k chip design

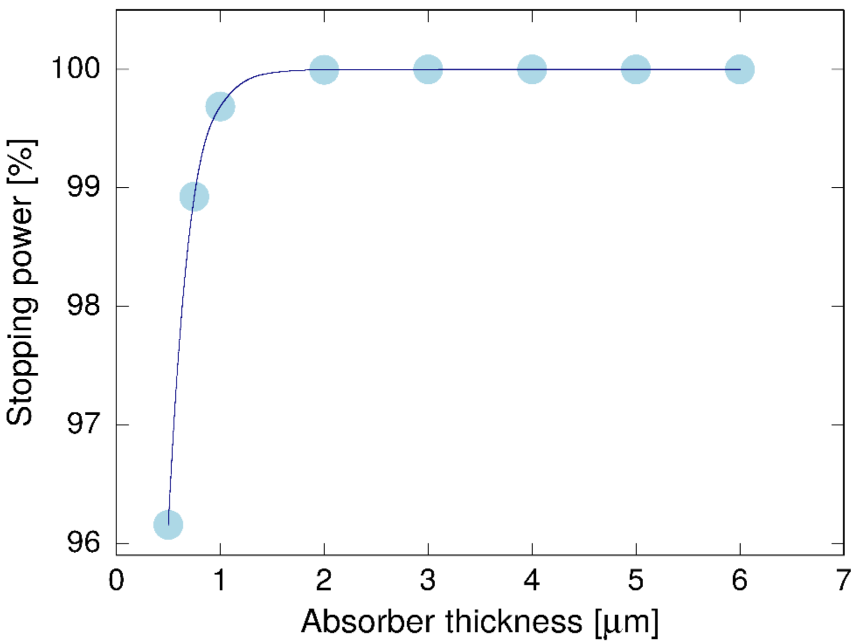
- single pixel optimization:

$^{163}$Ho activity per pixel $a \approx 10$ Bq
determination of the specific heat per Ho ion

optimization absorber thickness → increase signal to noise ratio
$^{163}$Ho sandwiched between two 3 µm Au layer




M. Herbst et al., submitted to JLTP
arXiv:1912.09354 [cond-mat.mtrl-sci]



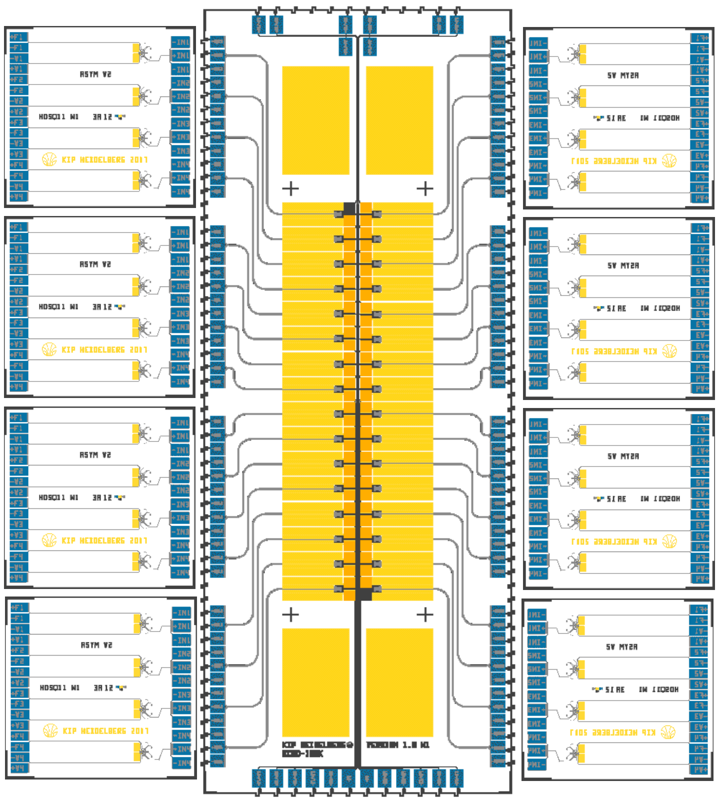

F. Mantegazzini et al., in preparation

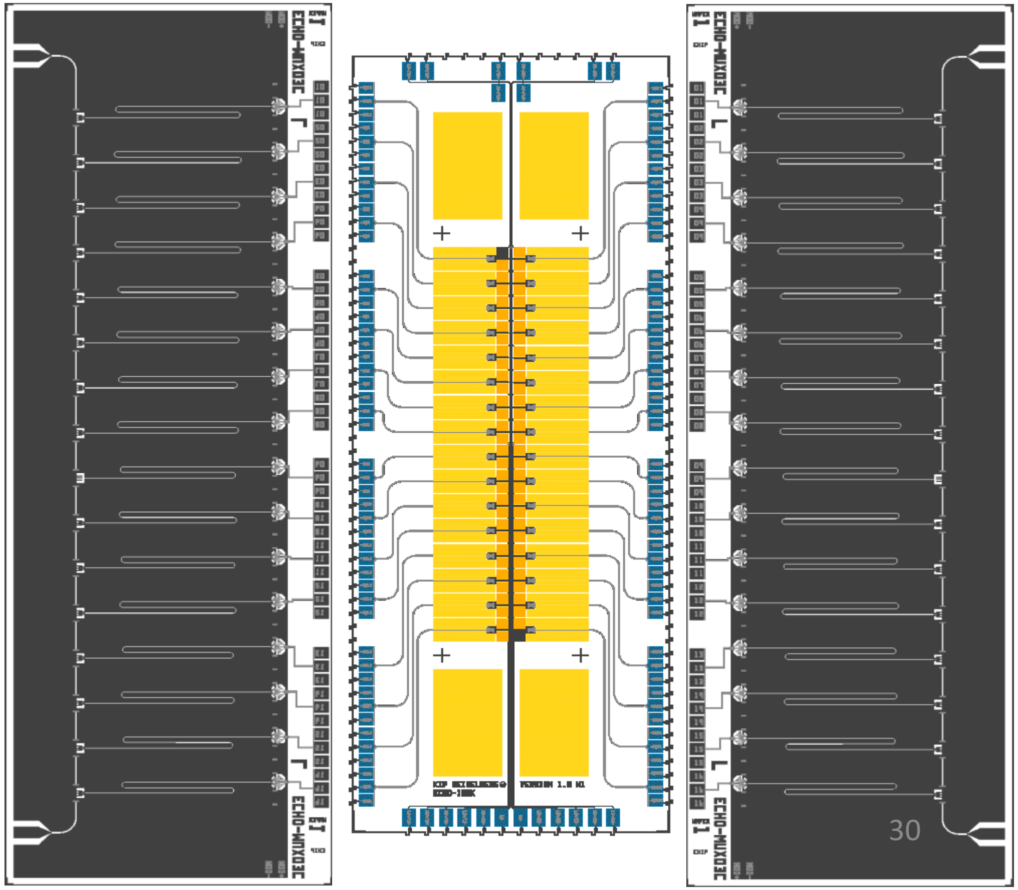
# Towards ECHo-100k

ECHo-100k chip design

- single pixel optimization: $^{163}$Ho activity per pixel $a \approx 10$ Bq

  optimization absorber thickness → increase signal to noise ratio
- suitable for parallel and multiplexed readout





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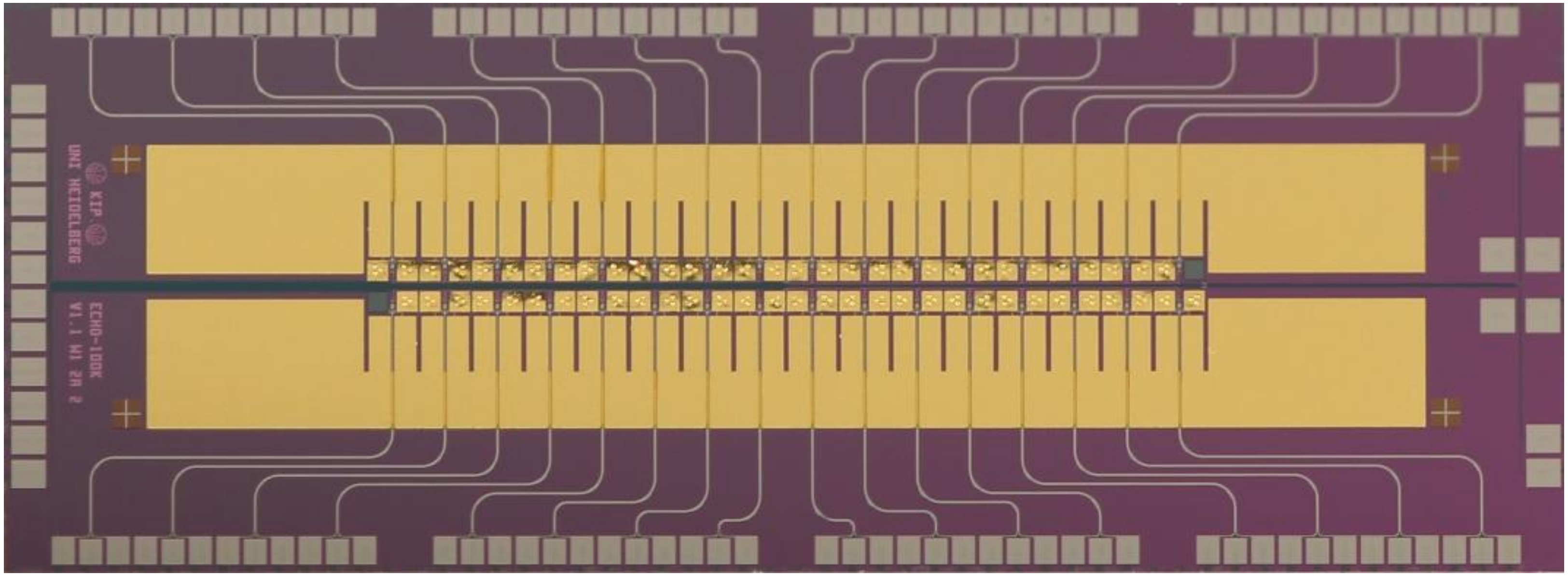

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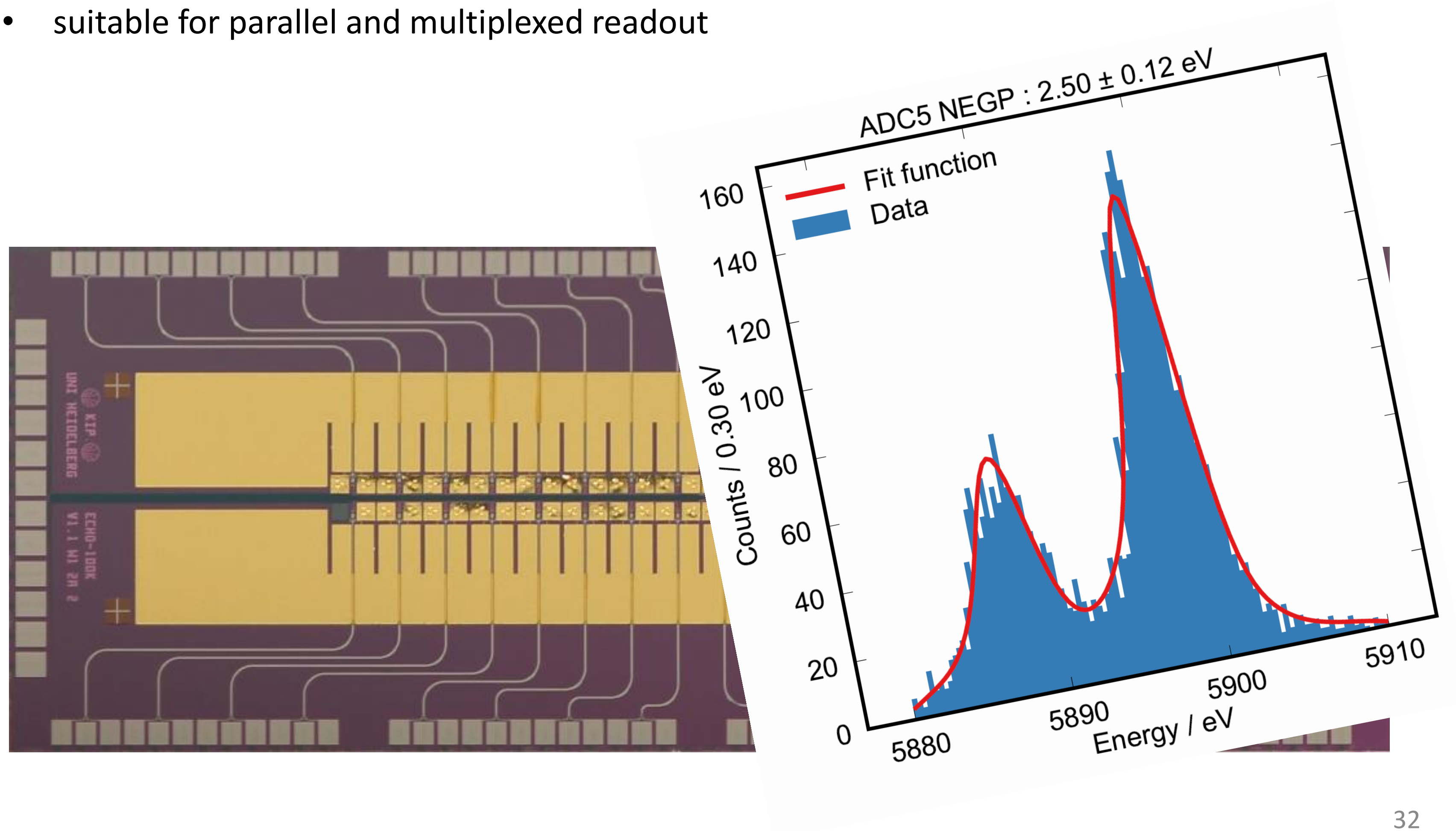

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ECHo-100k chip

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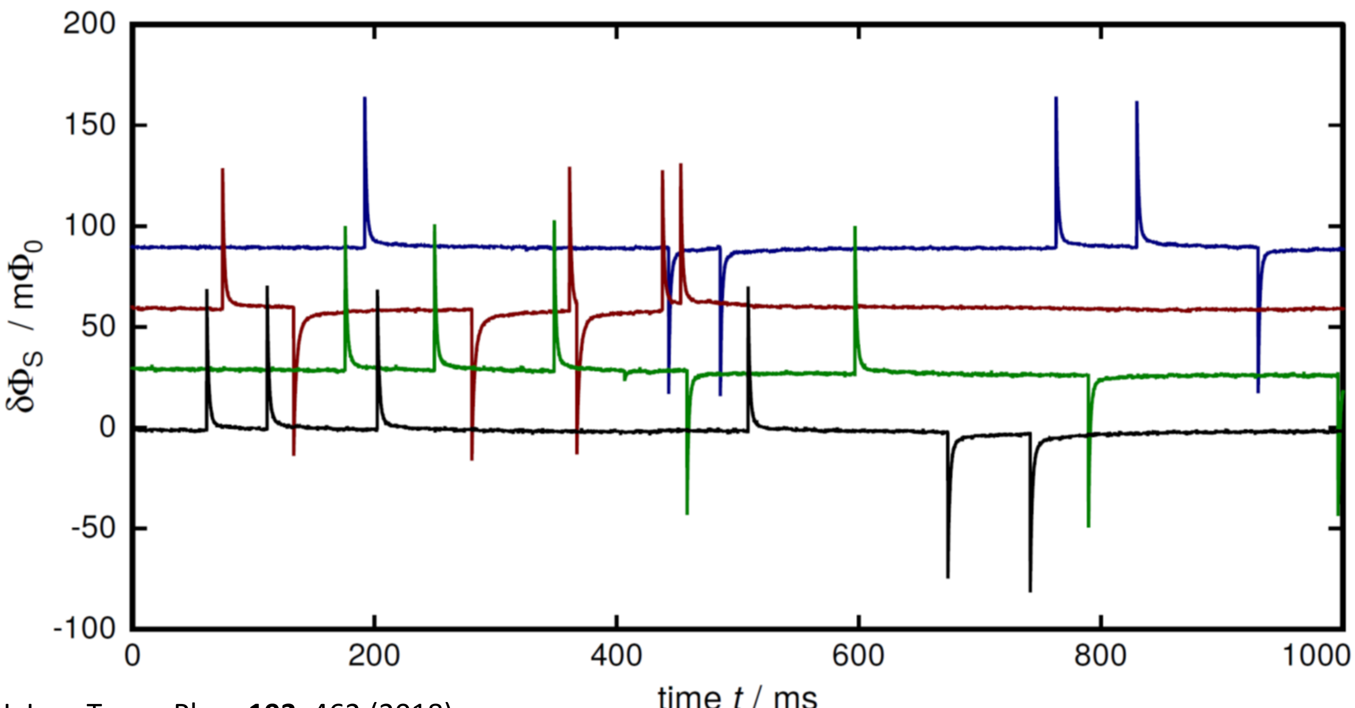
Microwave multiplexed readout of MMC demonstrated




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

# Towards ECHo-100k

ECHo-100k chip

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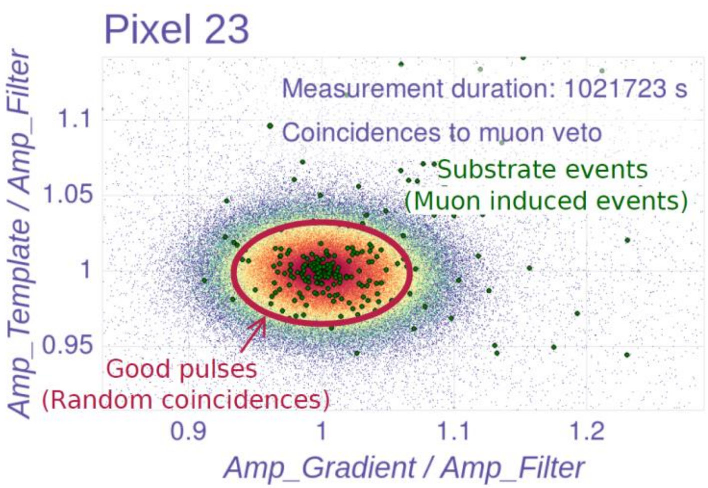
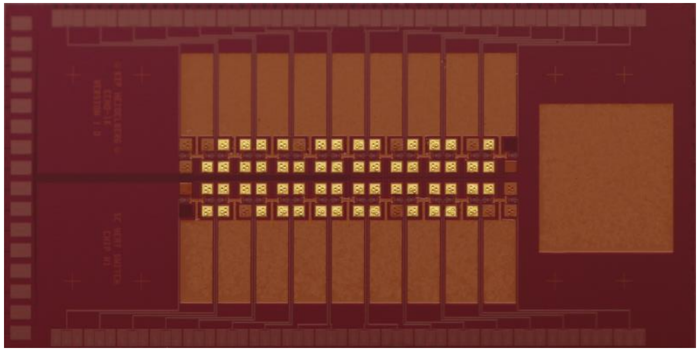
Microwave multiplexed readout of MMC demonstrated

Preparation of background model for ECHo

- Experiments with muon veto demonstrate that muon related events discriminated via pulse shape
- Effect of low energy secondary radiation is being investigated via Monte Carlo simulations
- In-situ background measurement over the full acquisition time



A. Göggelmann et al. Muon induced background in ECHo, in preparation

# Towards ECHo-100k

ECHo-100k chip

- single pixel optimization: $^{163}$Ho activity per pixel $a \approx 10$ Bq
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ECHo-100k starting in 2021

Microwave multiplexed readout of MMC demonstrated

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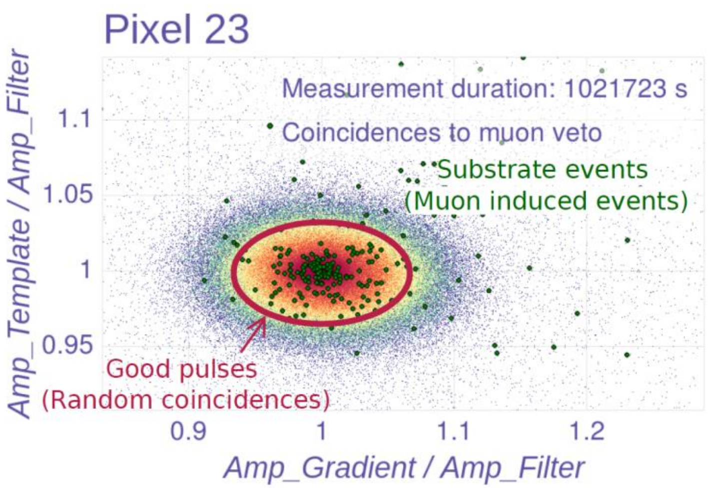
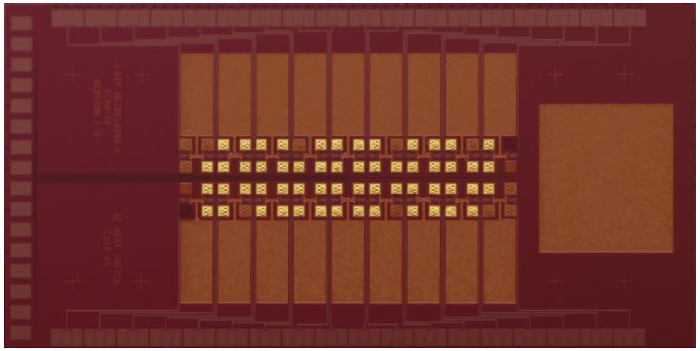


A. Göggelmann et al. Muon induced background in ECHo, in preparation

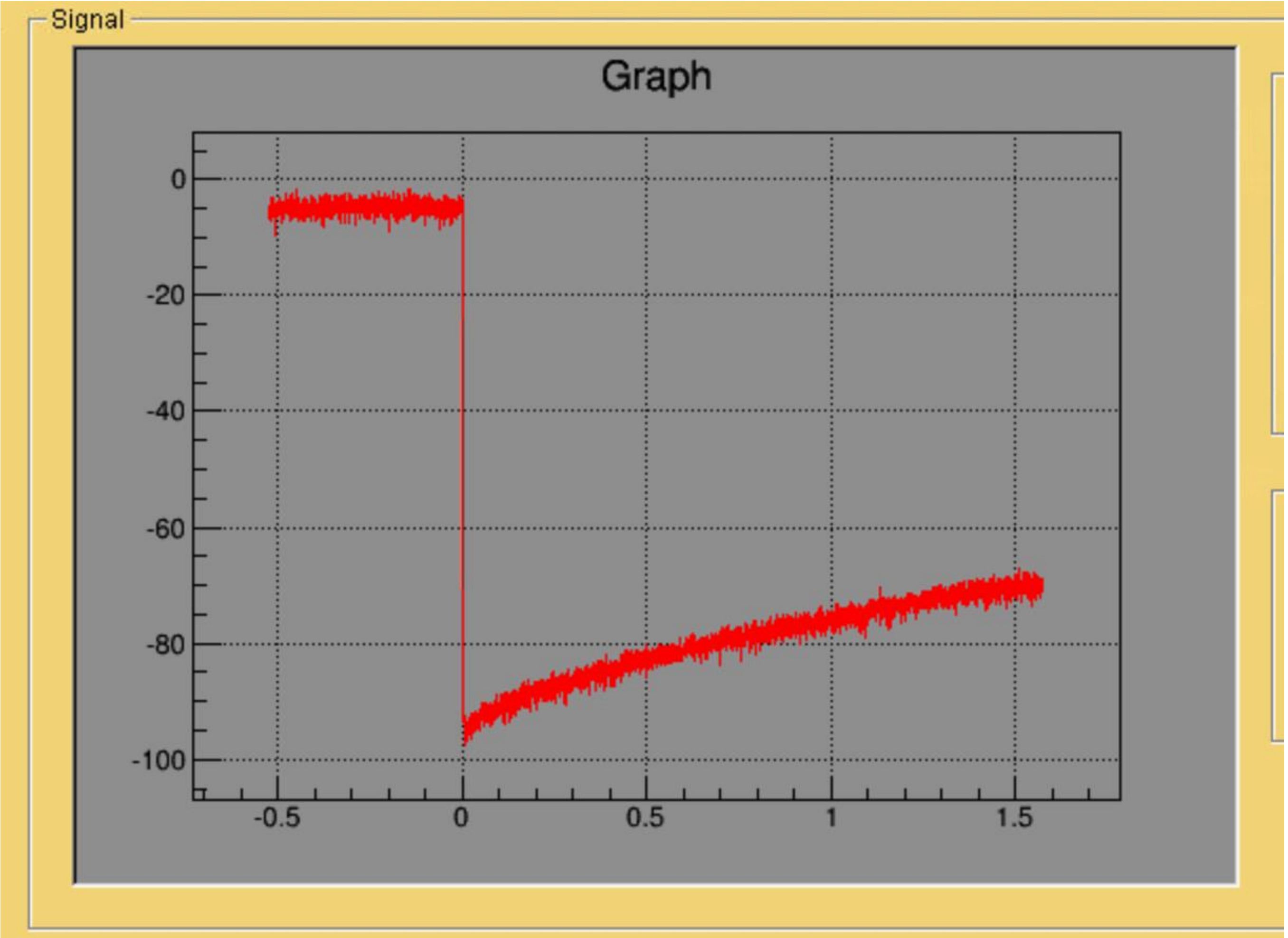
# Conclusions

- The determination of the electron neutrino effective mass with $^{163}Ho$ is complementary to the determination of the electron antineutrino effective mass with $^{3}H$

- ECHo has already demonstrated:
  - production and purification of mg-size sample of $^{163}Ho$
  - operation of large arrays of high resolution low temperature detectors
  - first low energy background studies

- Determination of the $^{163}Ho$ spectral shape is of major importance
  - ab-initio calculation → smooth end-point region
  - precise independent determination of $Q_{EC}$ via PTMS

- ECHo is now a running experiment on the way to provide a new limit on the electron neutrino mass and ready for upgrades to larger arrays

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EBERHARD KARLS UNIVERSITÄT TÜBINGEN

TECHNISCHE UNIVERSITÄT DRESDEN

NEUTRONS FOR SCIENCE

Thank you!

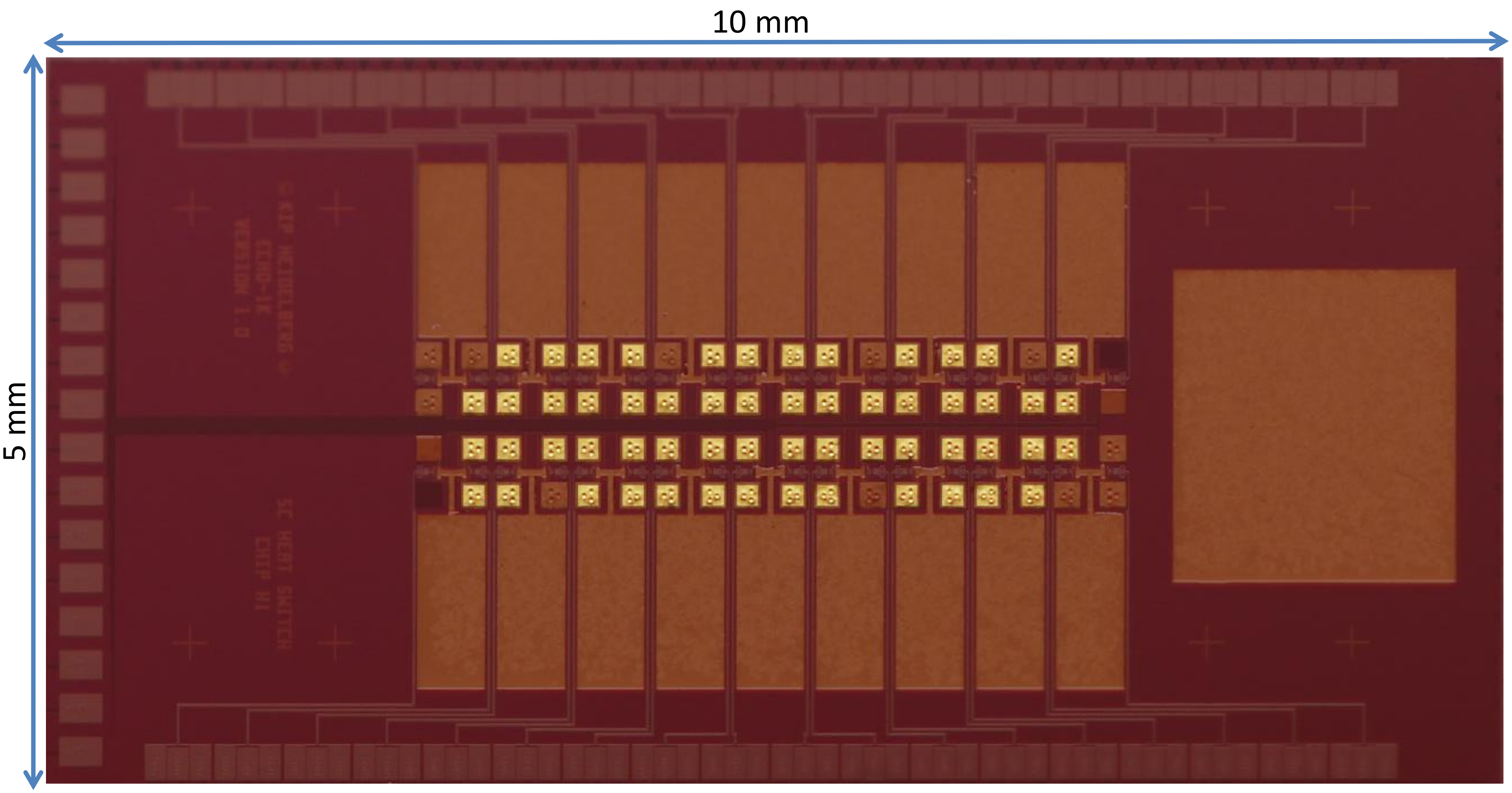
JG|U JOHANNES GUTENBERG UNIVERSITÄT MAINZ

ISOLDE

DFG Deutsche Forschungsgemeinschaft

# ECHo-1k array

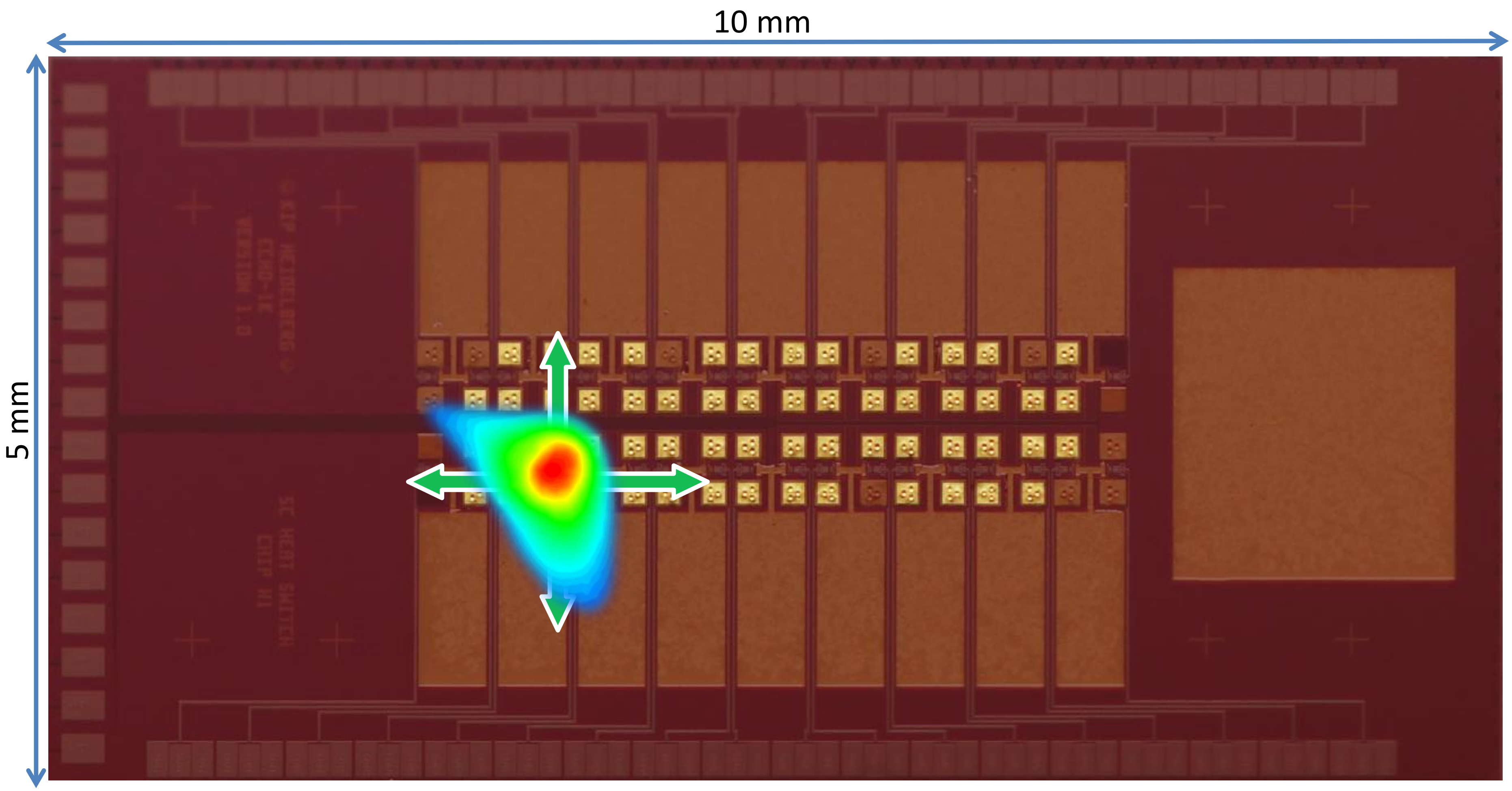
presence of non-implanted pixels for in-situ background determination



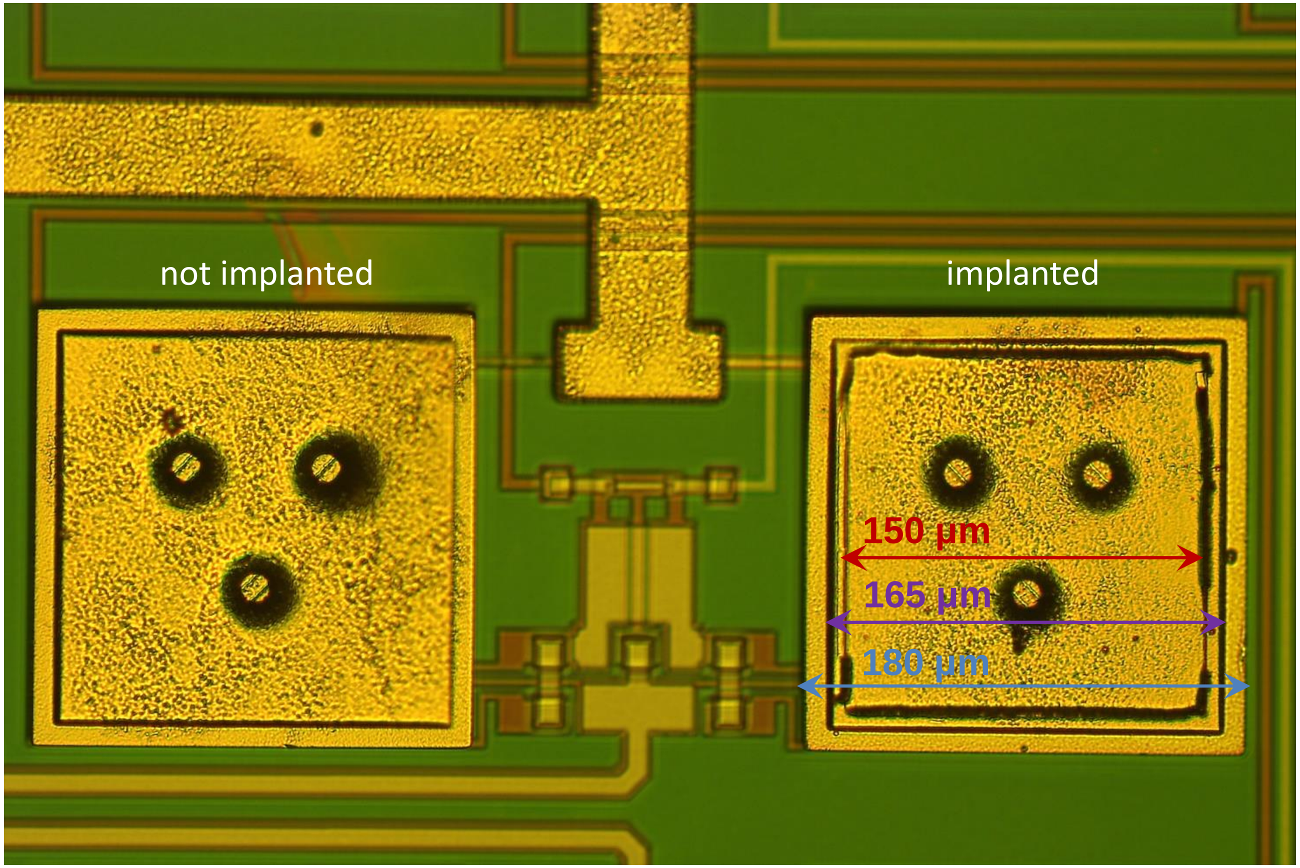
# ECHo-1k array

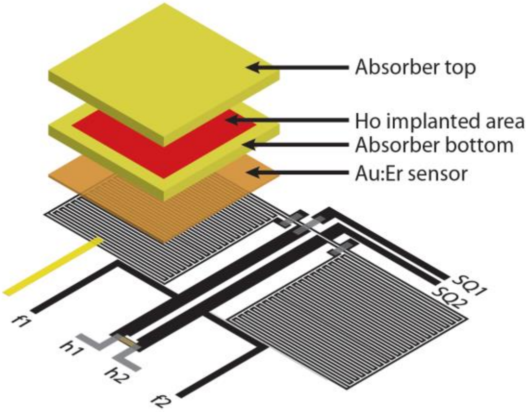
presence of non-implanted pixels for in-situ background determination

high geometrical efficiency for $^{163}$Ho implantation



# ECHo-1k array



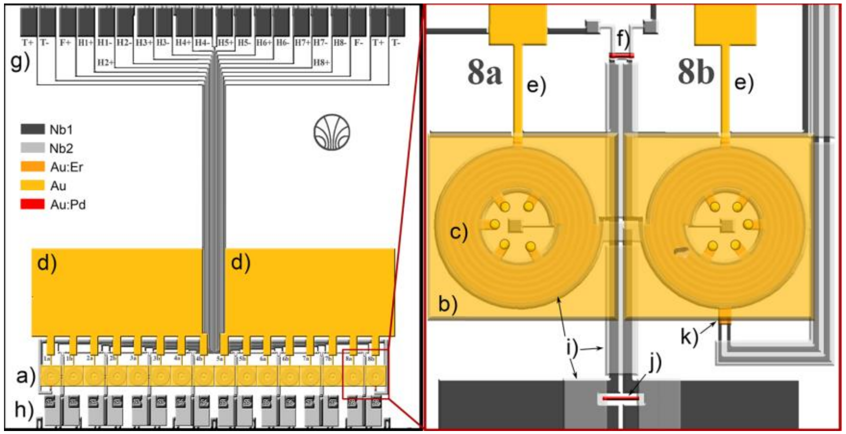

Implantation square:
150 µm x 150 µm

Second absorber:
165 µm x 165 µm

First absorber:
180 µm x 180 µm

# Experimental aspects

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

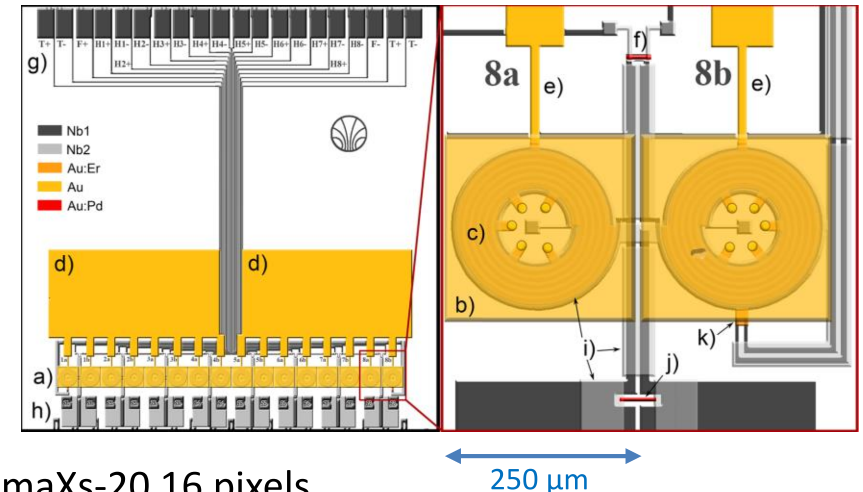



250 µm

maXs-20 16 pixels
4 pixels used for low background experiment

# Experimental aspects

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

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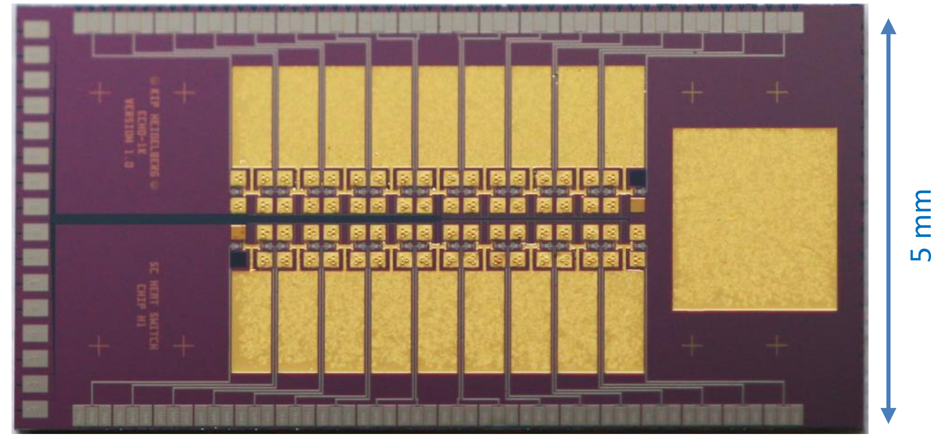
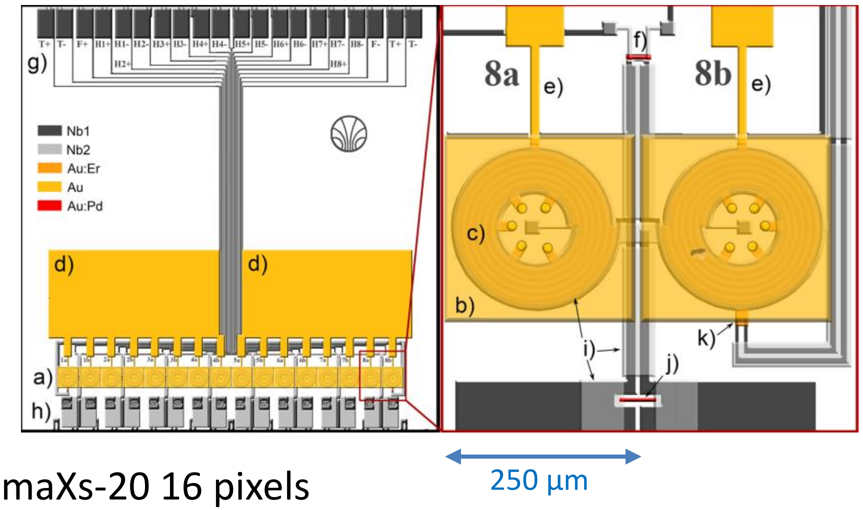
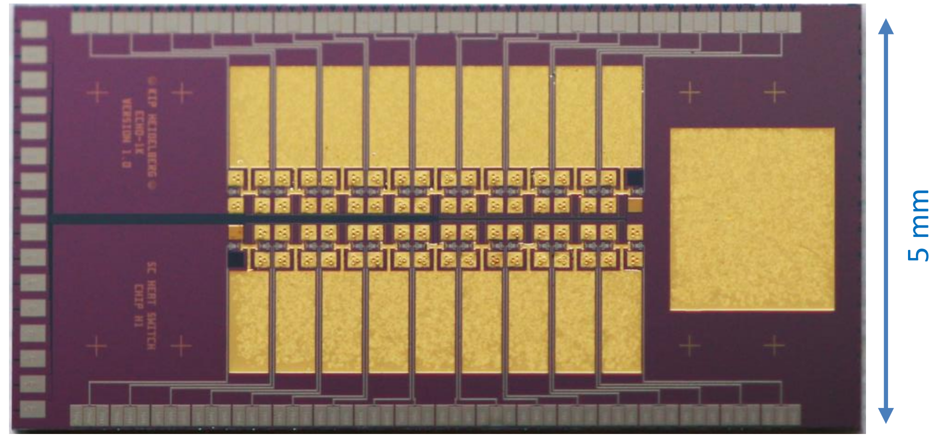



ECHo-1k 32 channels + 4 for diagnostics
present working horse

# Experimental aspects

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

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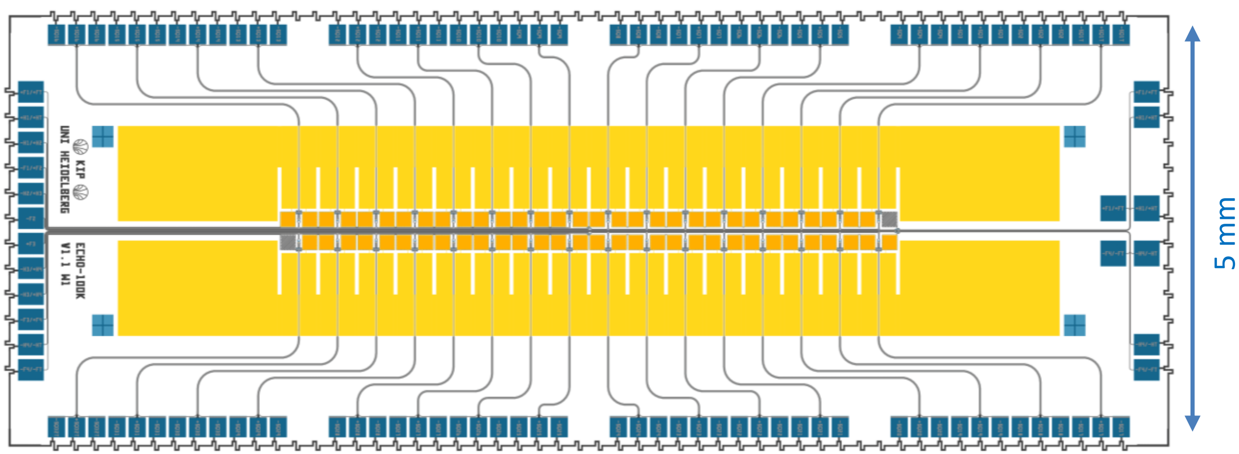
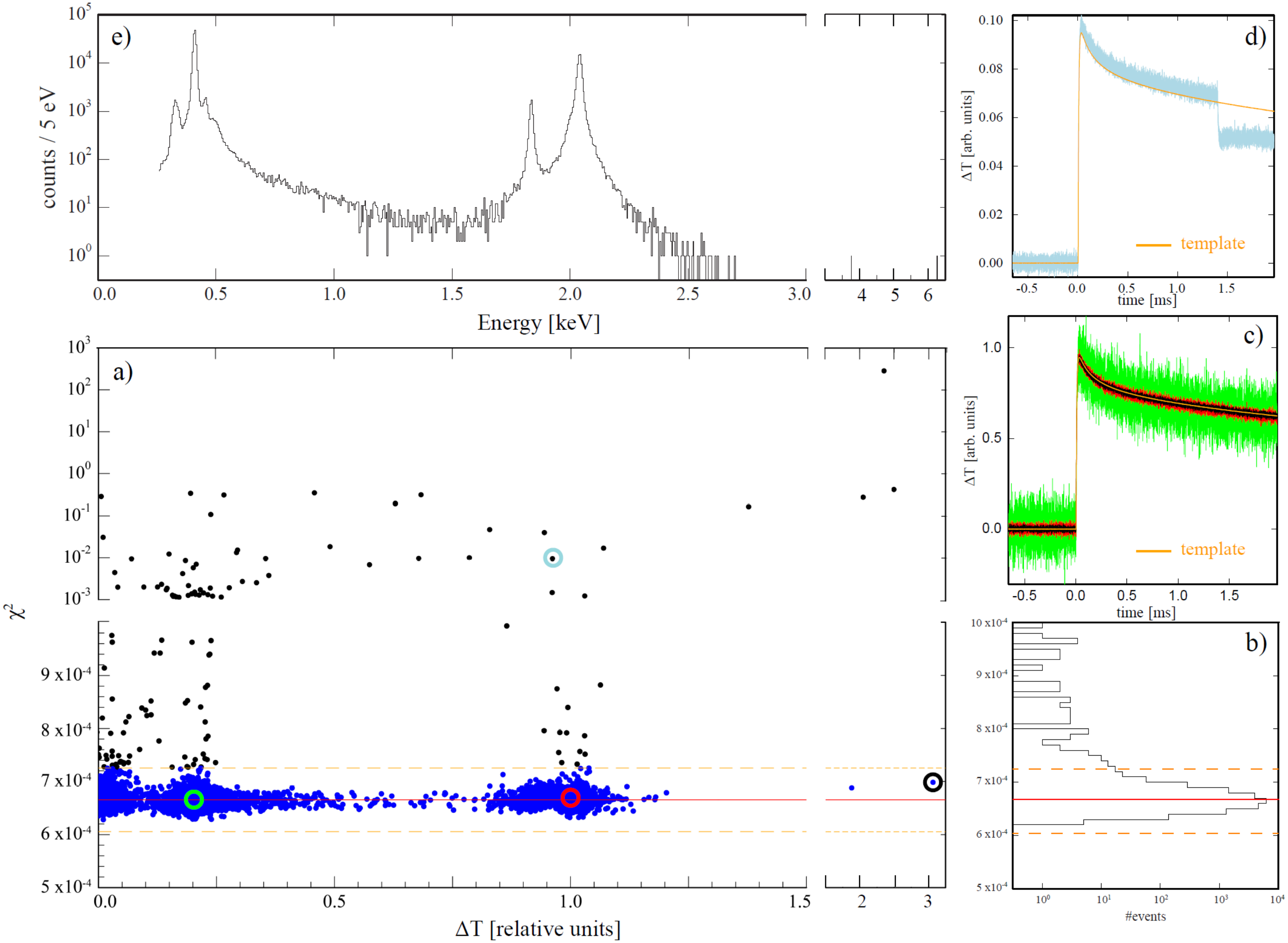



ECHo-100k 32 channels - in fabrication

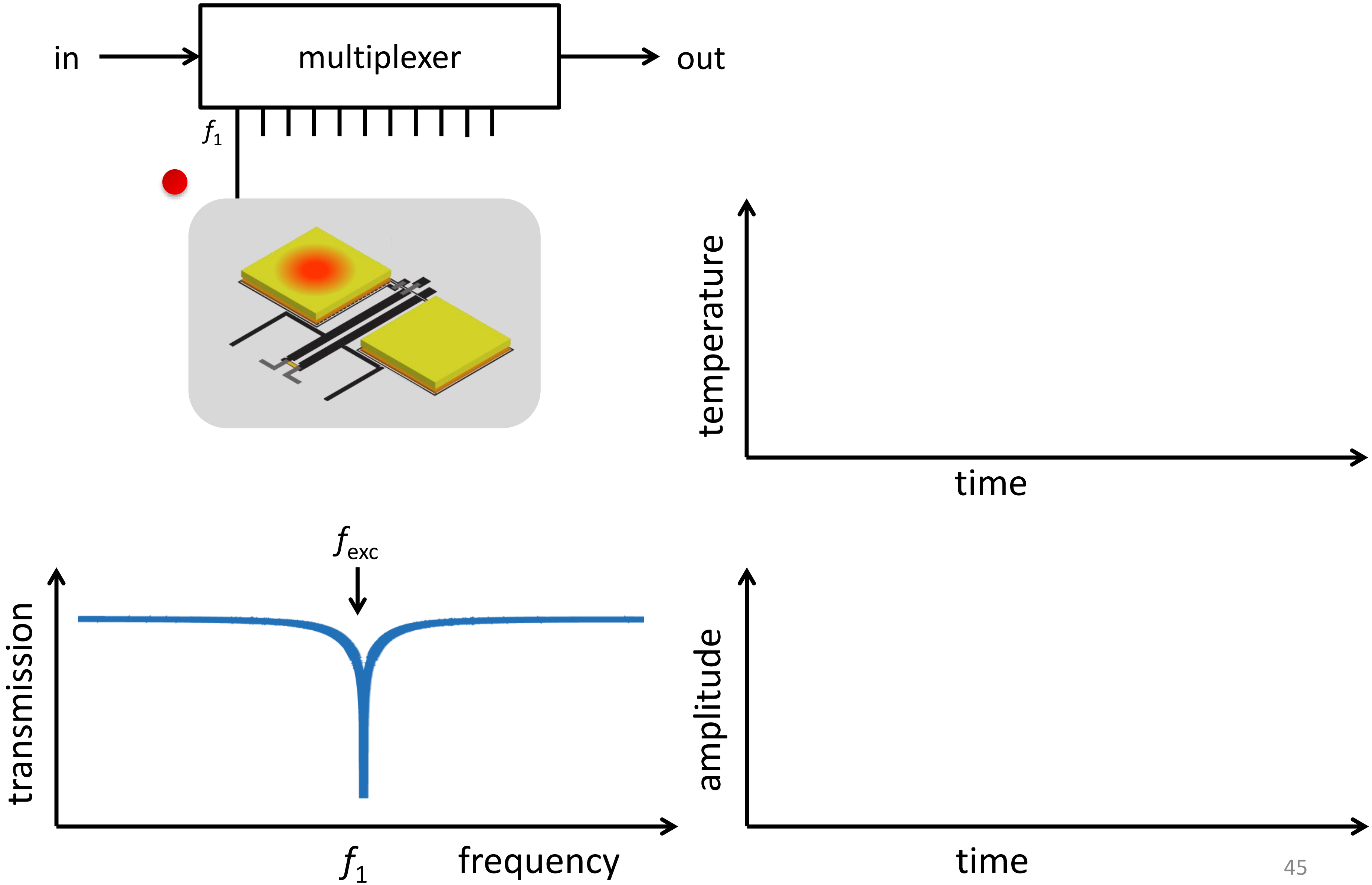
# From signal to spectrum






C. Velte et al., submitted to EPJC

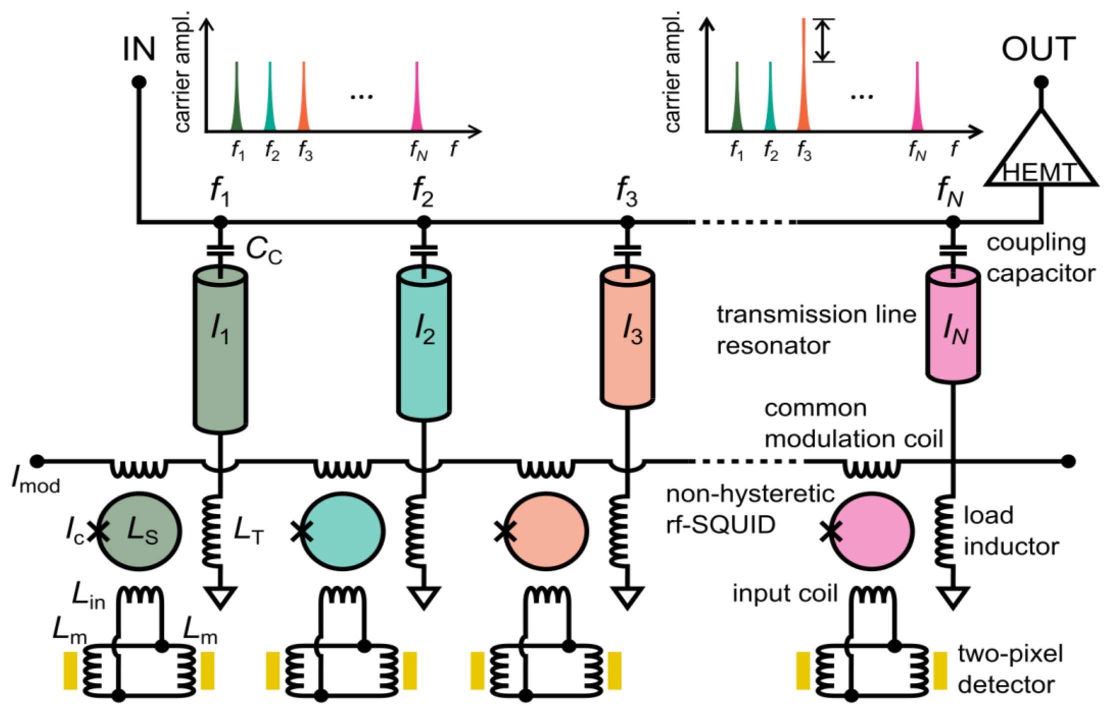
# MMCs: Microwave SQUID multiplexing



# Multiplexing readout

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

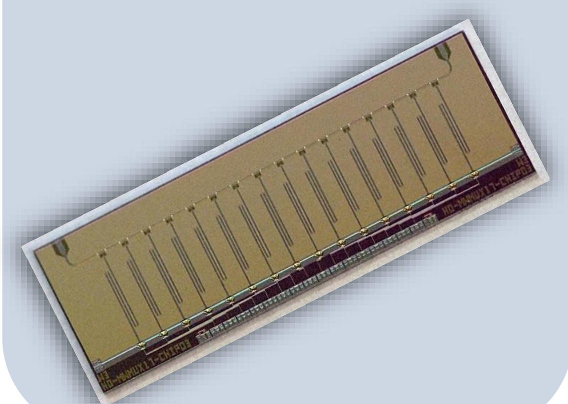
- Reliable fabrication of 64-pixel array
- Successful characterization of first prototypes
  → optimization of design parameters




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

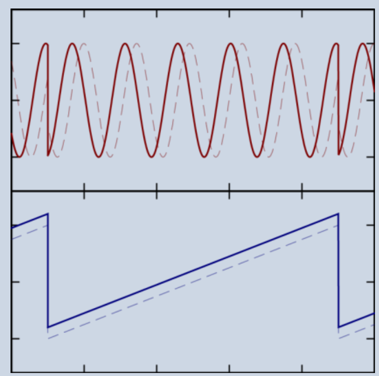
# Multiplexing readout

microwave SQUID multiplexer



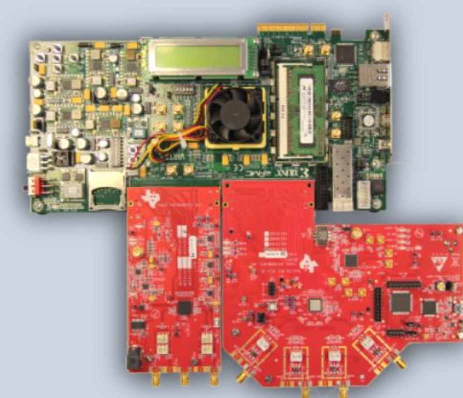
+

flux ramp modulation



+

software defined radio



combination of signals from multiple detectors into single readout line

output signal linearization

multiplexer operation

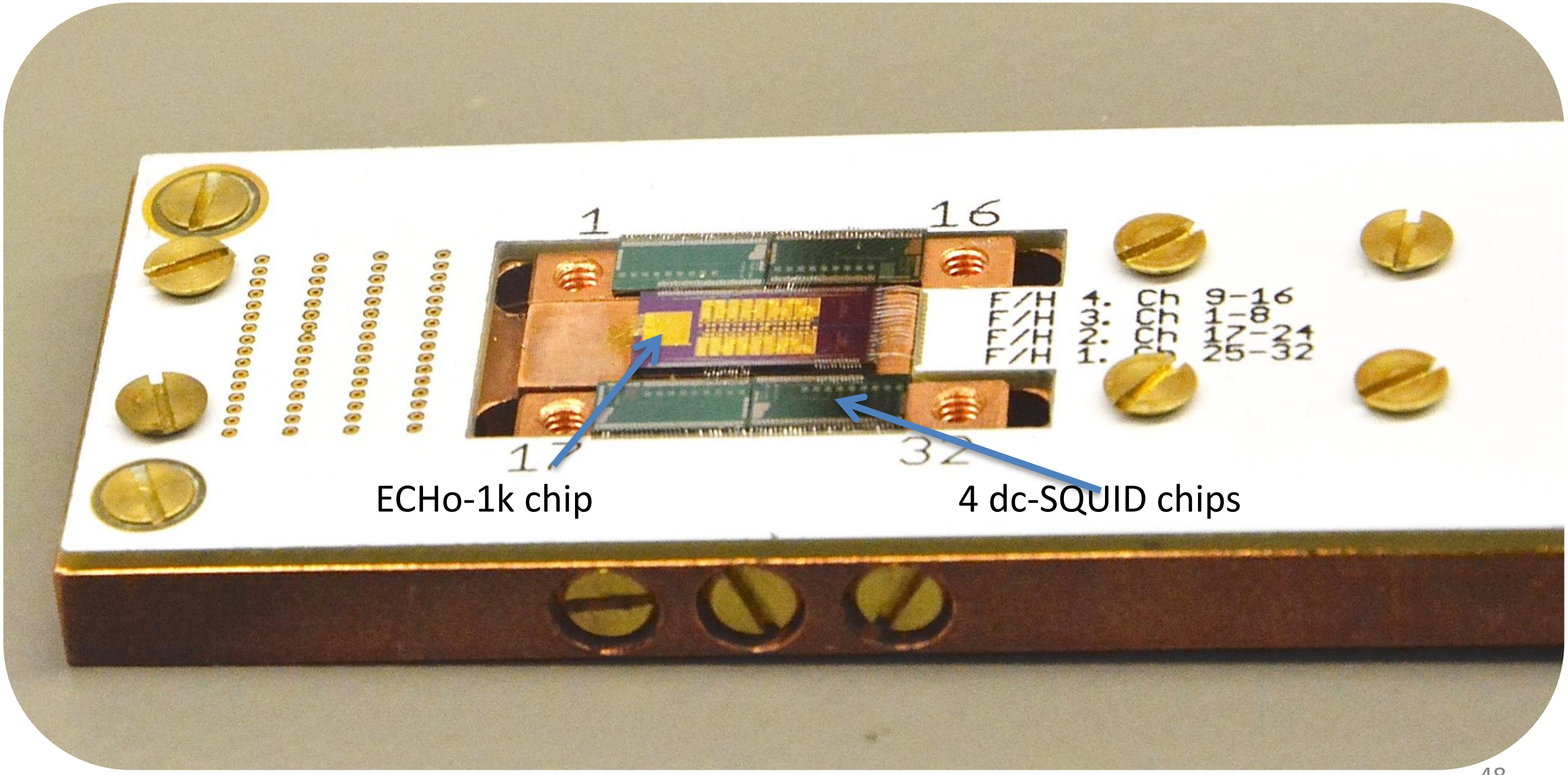
first time: full operation of multiplexed readout including µMUX, flux ramp modulation + SDR

# Detector set-up

- ECHo-1k chip implanted at RISIKO Uni-Mainz

  → $^{163}$Ho activity per pixel $a \approx 1$ Bq (total activity $A \approx 50$ Bq)

- 4 Front-end chips each with 8 dc-SQUIDs



# Detector module and amplifier module