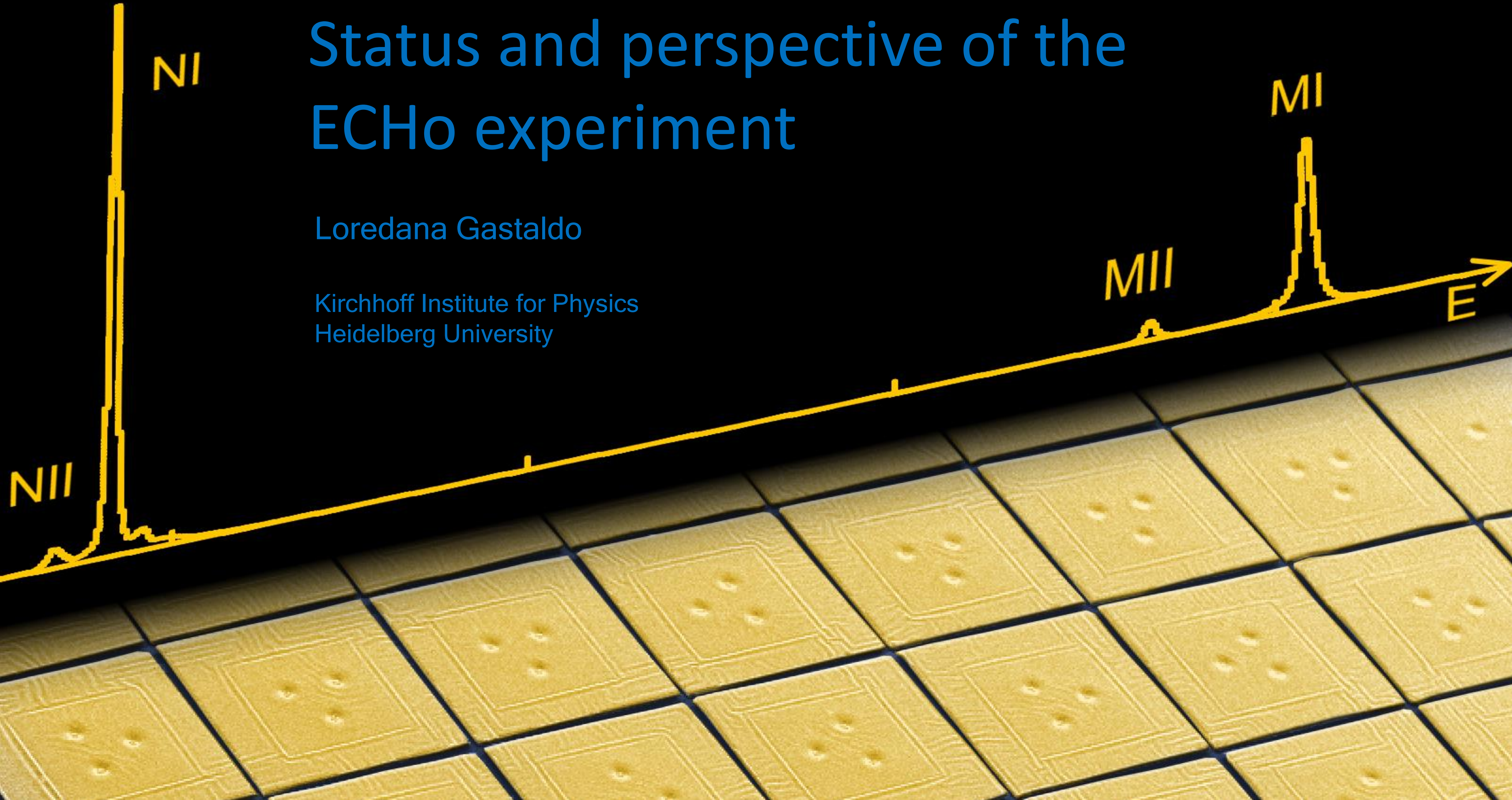
Status and perspective of the ECHo experiment

Loredana Gastaldo

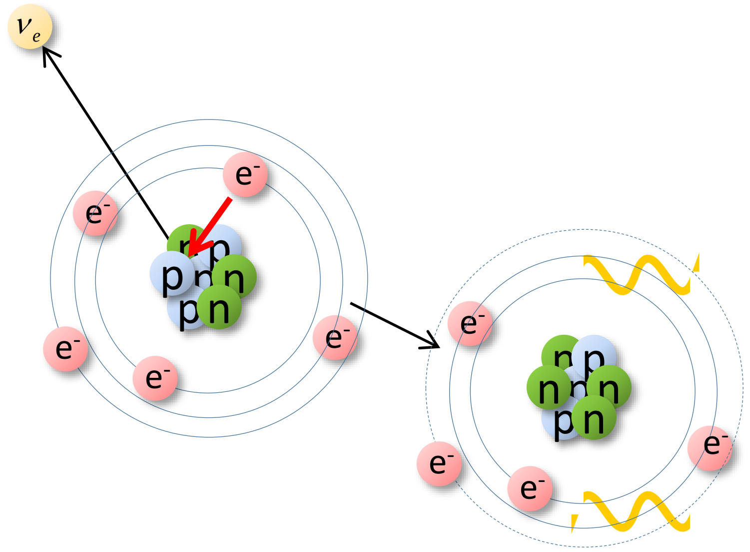
Kirchhoff Institute for Physics
Heidelberg University



Outline

- Electron Capture in ^{163}Ho and neutrino mass
- The ECHo experiment
  - Technological challenges
  - Status of ECHo-1k
  - Towards ECHo-100k
- Conclusions

Electron Capture in ^{163}Ho – 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} = (2863.2 $\pm$ 0.6) eV

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  https://doi.org/10.48550/arXiv.2402.06464

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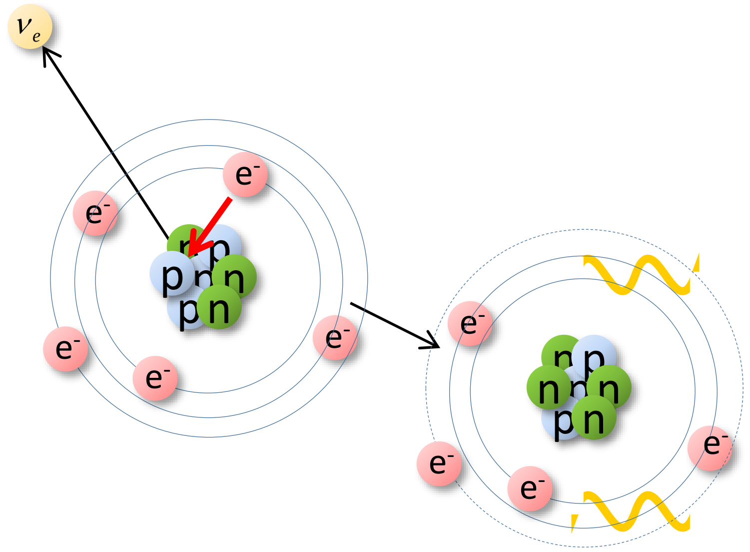

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To be publisched in Nature Physics

…more at the end of my talk

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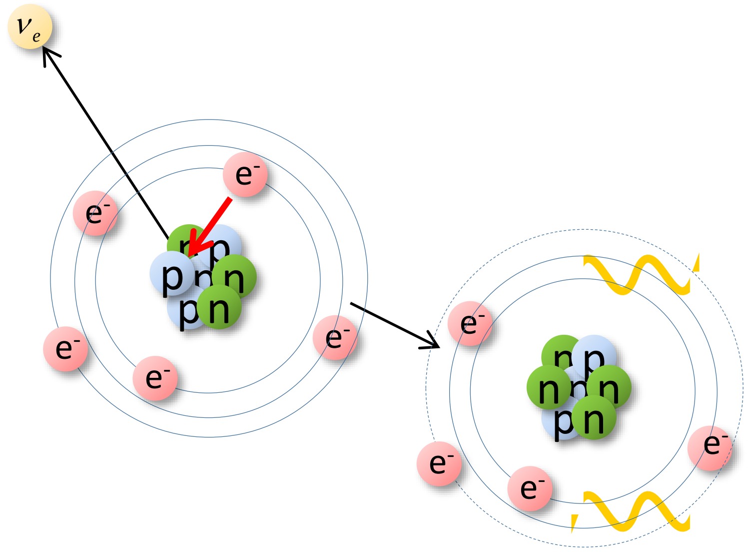

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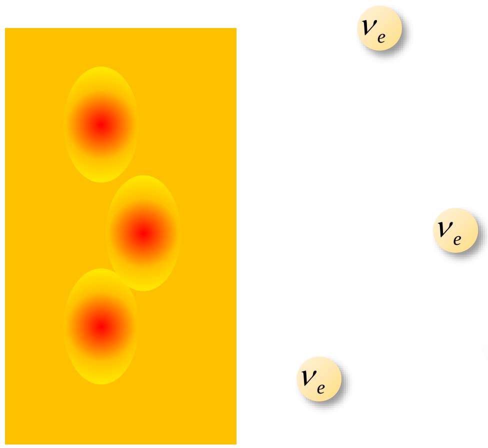

Source = Detector

Calorimetric measurement

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

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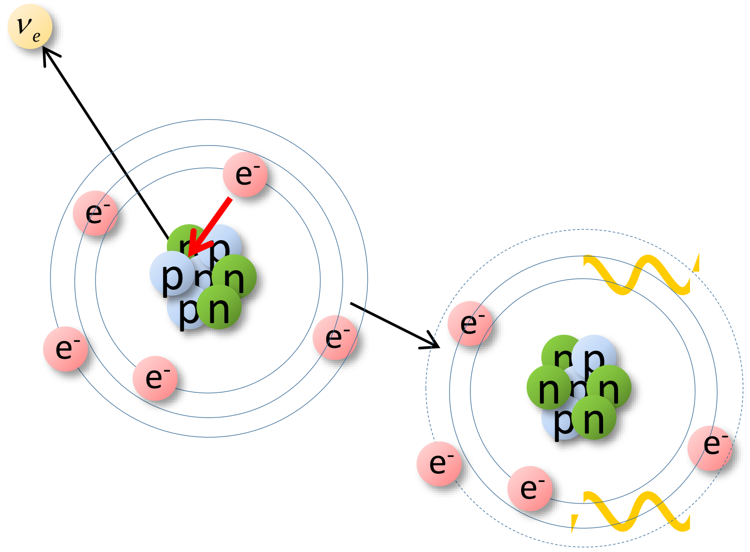

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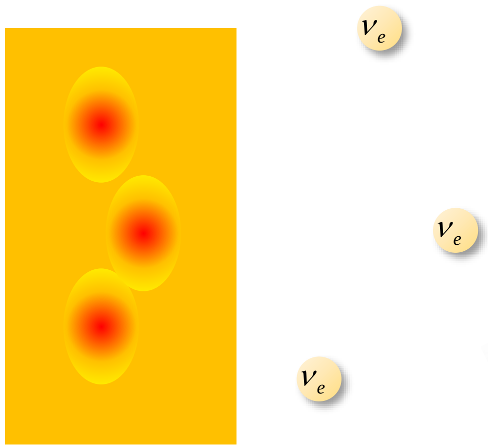

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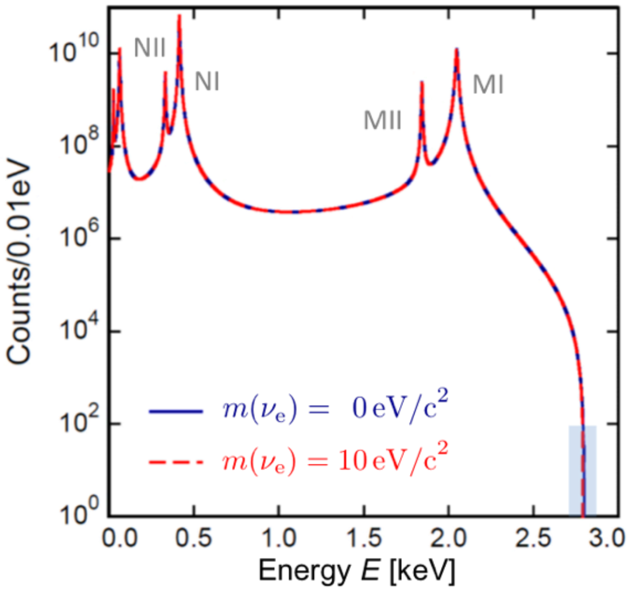

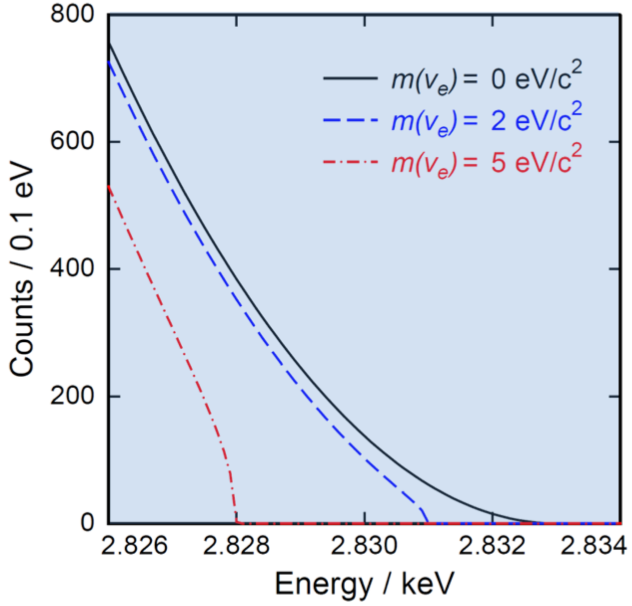

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Electron Capture in ^{163}Ho - Timeline

ECHo HOLMES

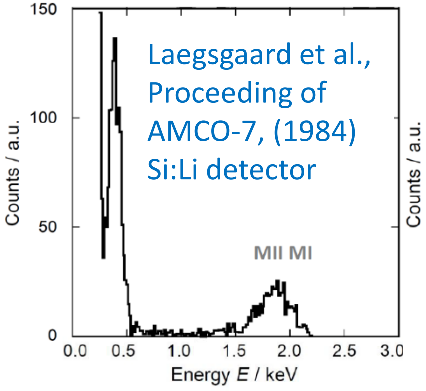
$m(\nu_e) < 225\ eV$ **

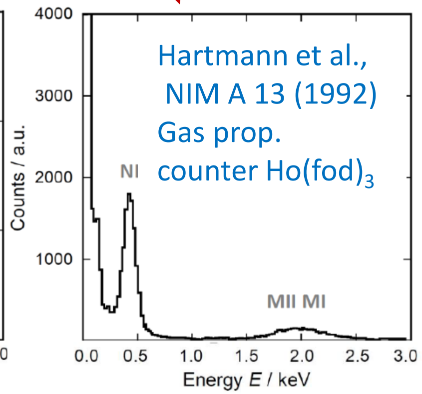
1980 1990 2000 2010 2020

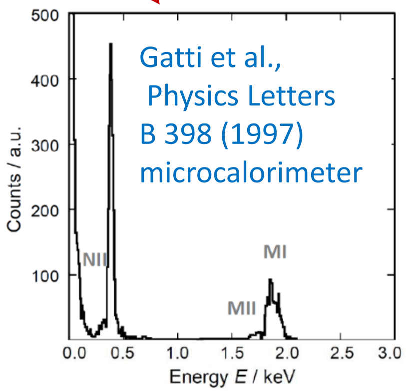
Modern ^{163}Ho experiments

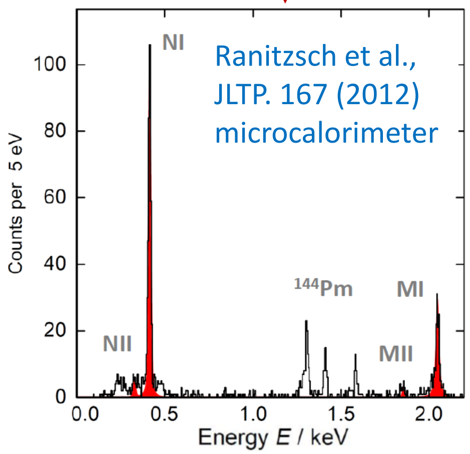
$m(\nu_e) < 150\ eV$ ***

* Proposal for calorimetric measurements







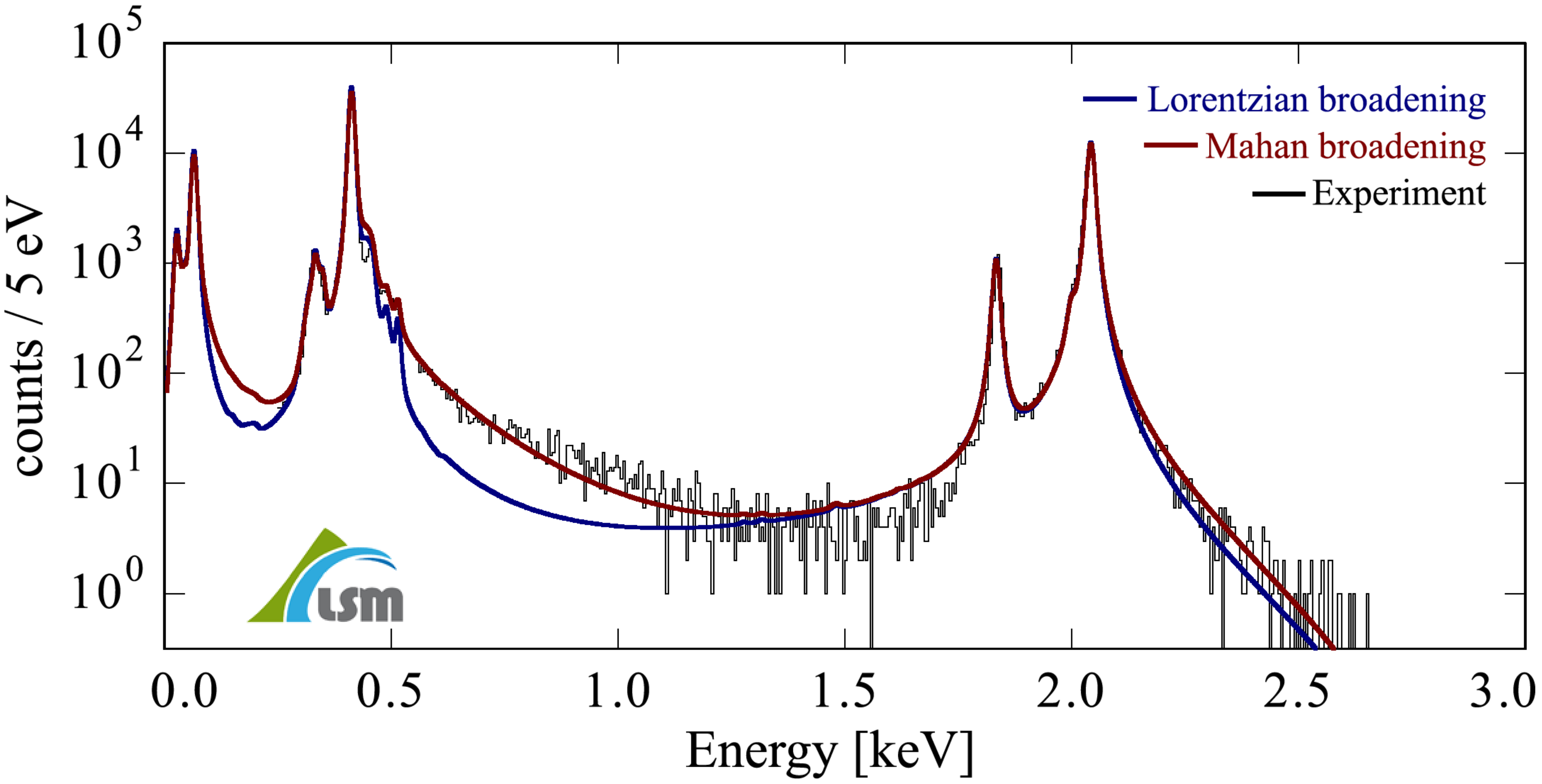


ECHo: EPJ-ST 226 8 (2017) 1623
HOLMES: Eur. Phys. J. C 75 (2015) 112

* A. De Rujula and M. Lusignoli, *Phys. Lett.* **118B** (1982)
** P. T. Springer, C. L. Bennett, and P. A. Baisden Phys. Rev. A 35 (1987) 679

*** C. Velte et al., (The ECHo Collaboration) *Eur. Phys. J. C* **79** (2019) 1026

Proof of ECHo concept



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Energy resolution
ΔE_{FWHM} = 9.2 eV

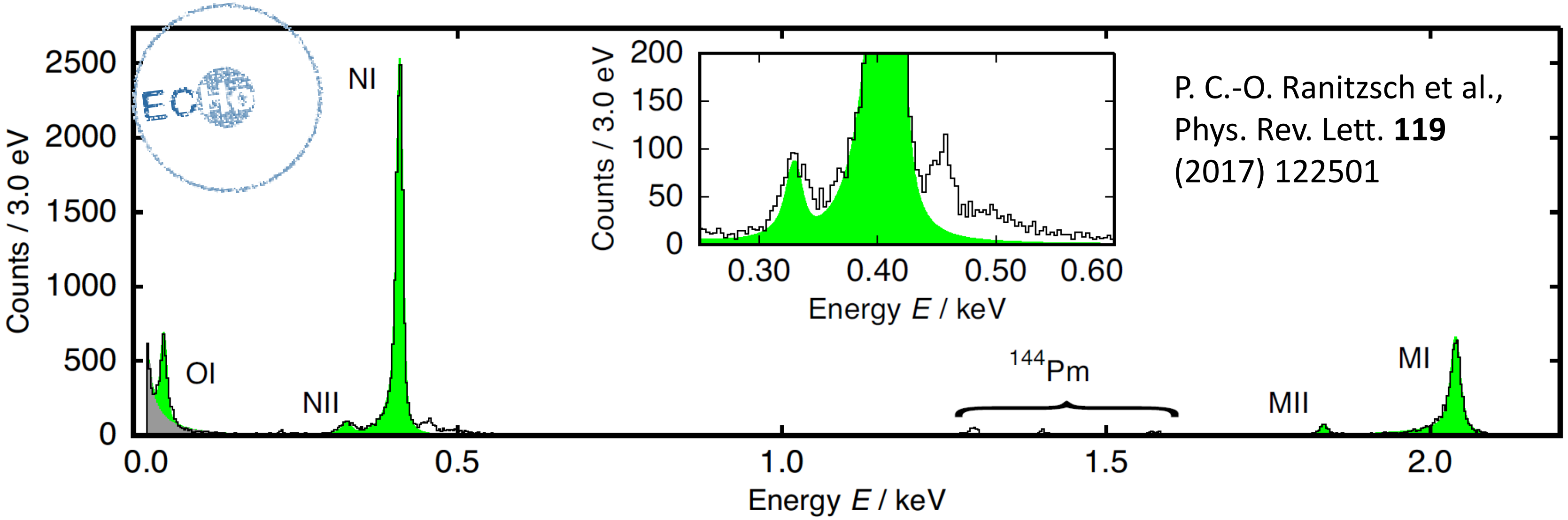
Background level
b < 1.6 × 10^{-4} events/eV/pixel/day

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

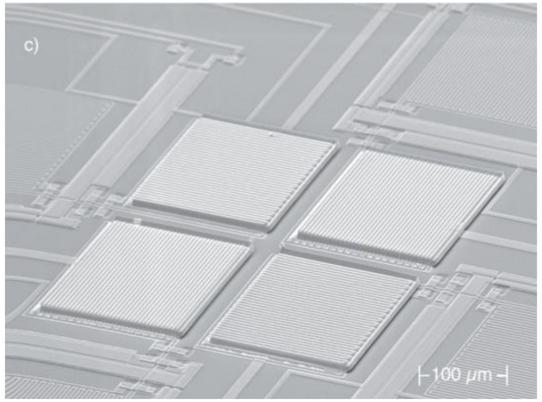
- measurement performed underground
- test for data reduction and spectral shape analysis

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

Systematic uncertainties – spectral shape

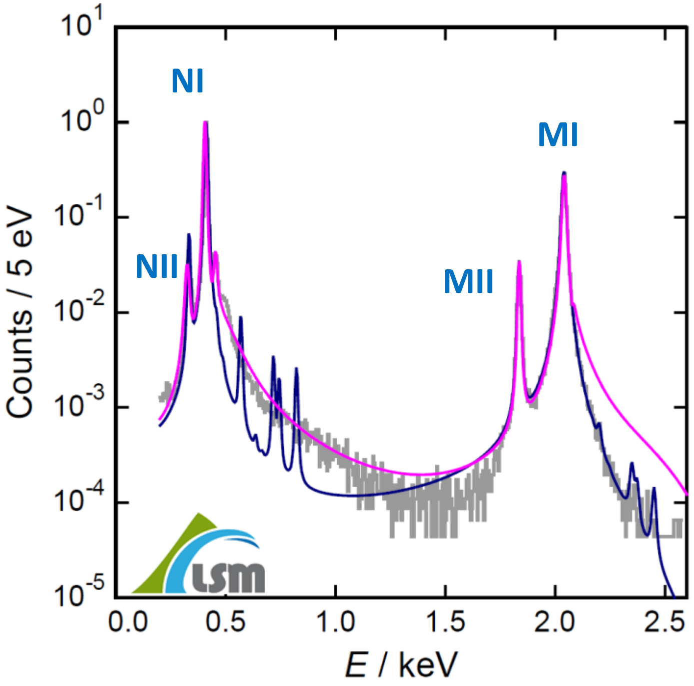


P. C.-O. Ranitzsch et al., Phys. Rev. Lett. **119** (2017) 122501



Identification of non-expected structures in the spectrum

- A. Faessler et al.
  J. Phys. G **42** (2015) 015108
- R. G. H. Robertson
  Phys. Rev. C **91**, 035504 (2015)
- A. Faessler et al.
  Phys. Rev. C **91**, 064302 (2015)
- A. Faessler and F. Simkovic
  Phys. Rev. C **91**, 045505 (2015)
- A. De Rujula and M. Lusignoli
  JHEP 05 (2016) 015, arXiv:1601.04990v1
- A. Faessler et al.
  Phys. Rev. C **95**, (2017) 045502



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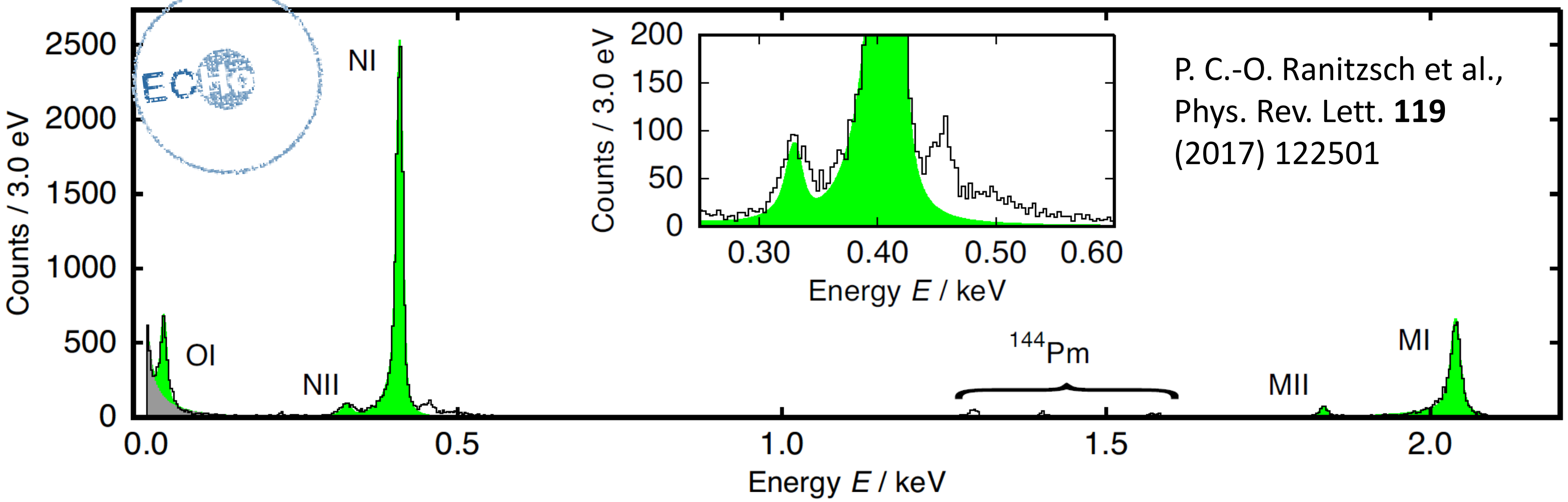

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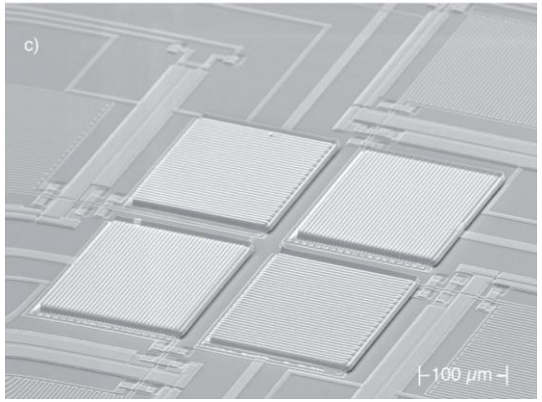

Identification of non-expected structures in the spectrum

New approach

Ab initio 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

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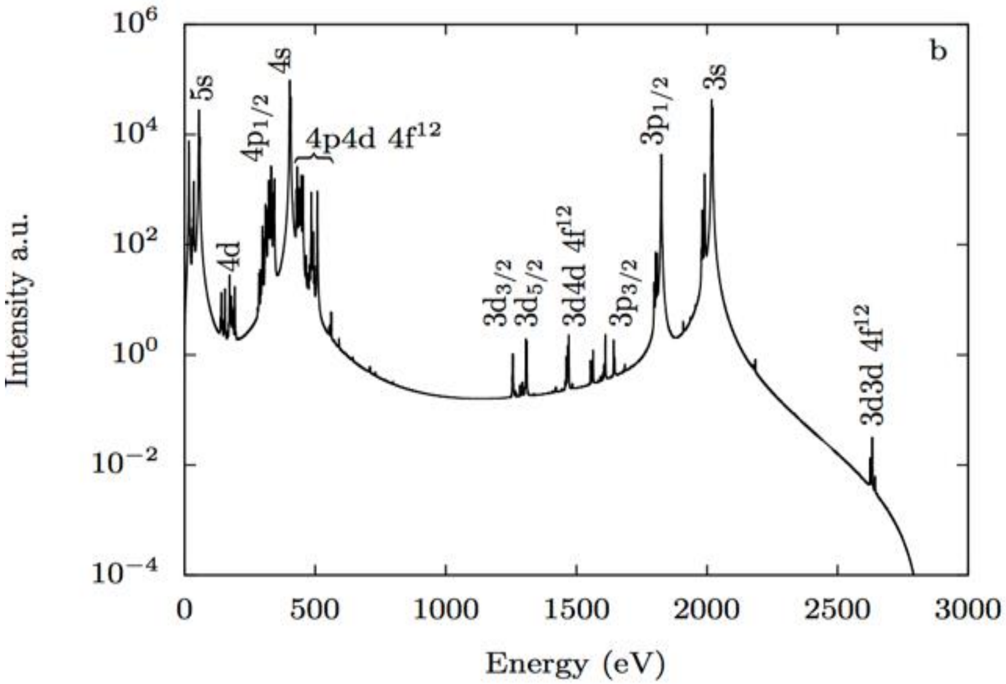

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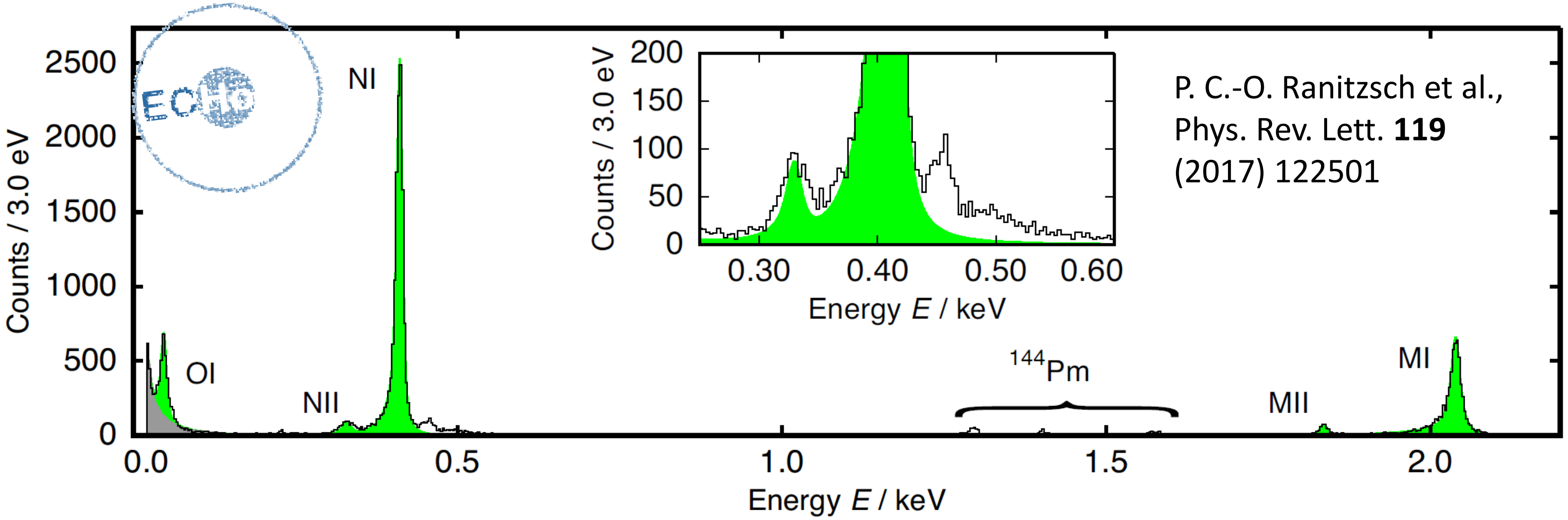

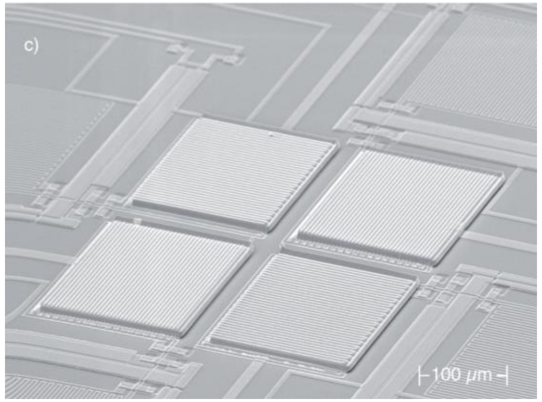

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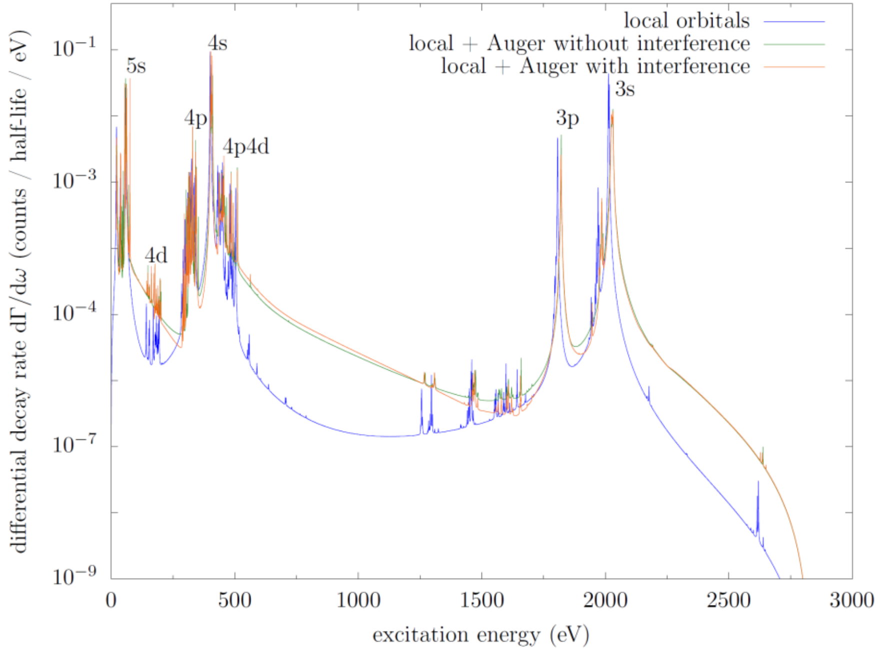
Including states with multiple correlated holes in local atomic orbitals interacting with unbound Auger-Meitner electrons

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



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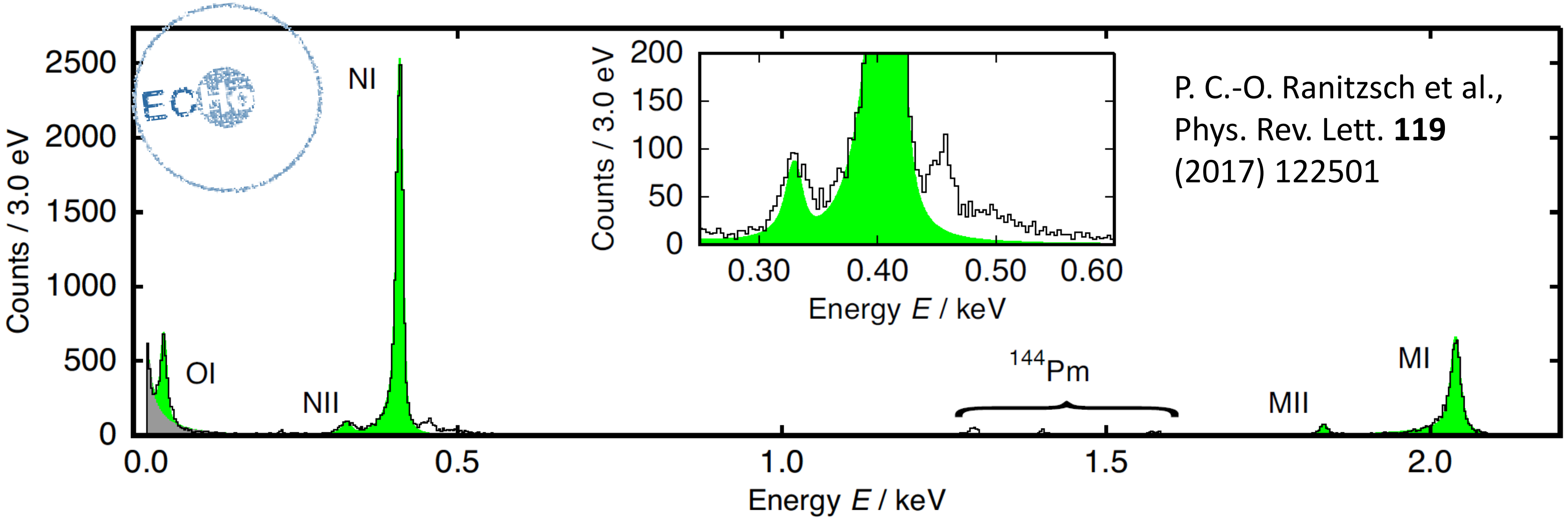

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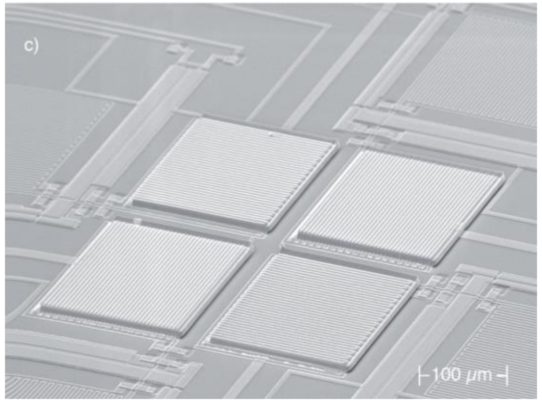

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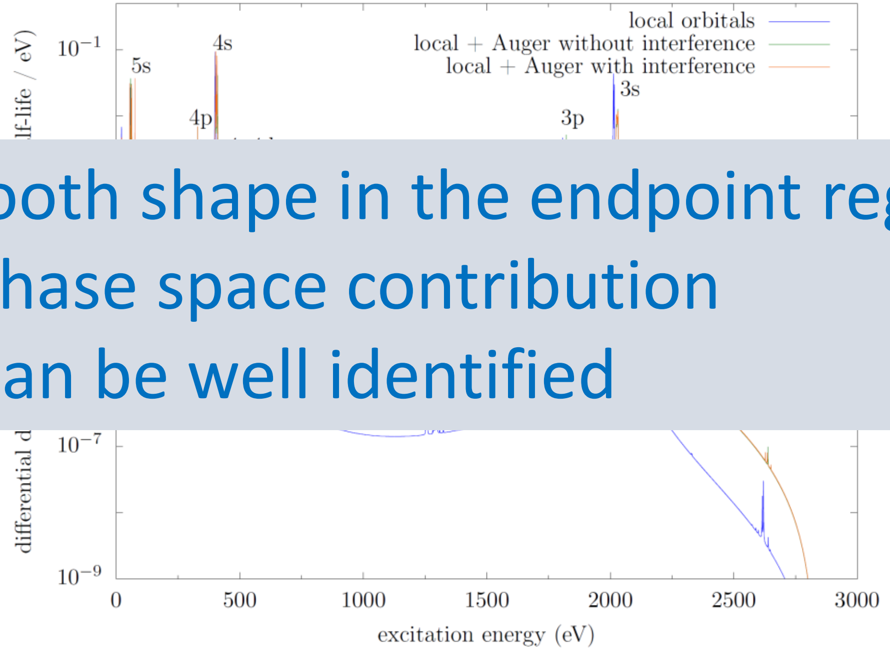

Smooth shape in the endpoint region
→phase space contribution
can be well identified

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

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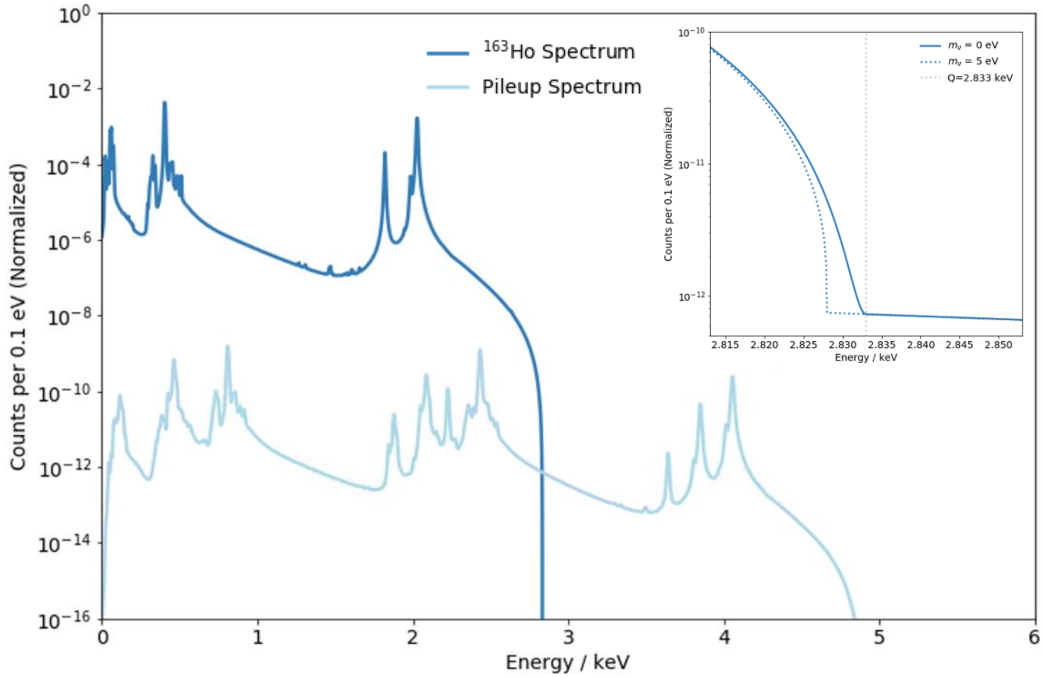
Unresolved pile-up ($f_{pu} \sim a \cdot \tau_r$)

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

→ Fast and multiplexable detectors

Pile-up fraction f_{pu} depends on activity per pixels a and time resolution of the detector τ_r



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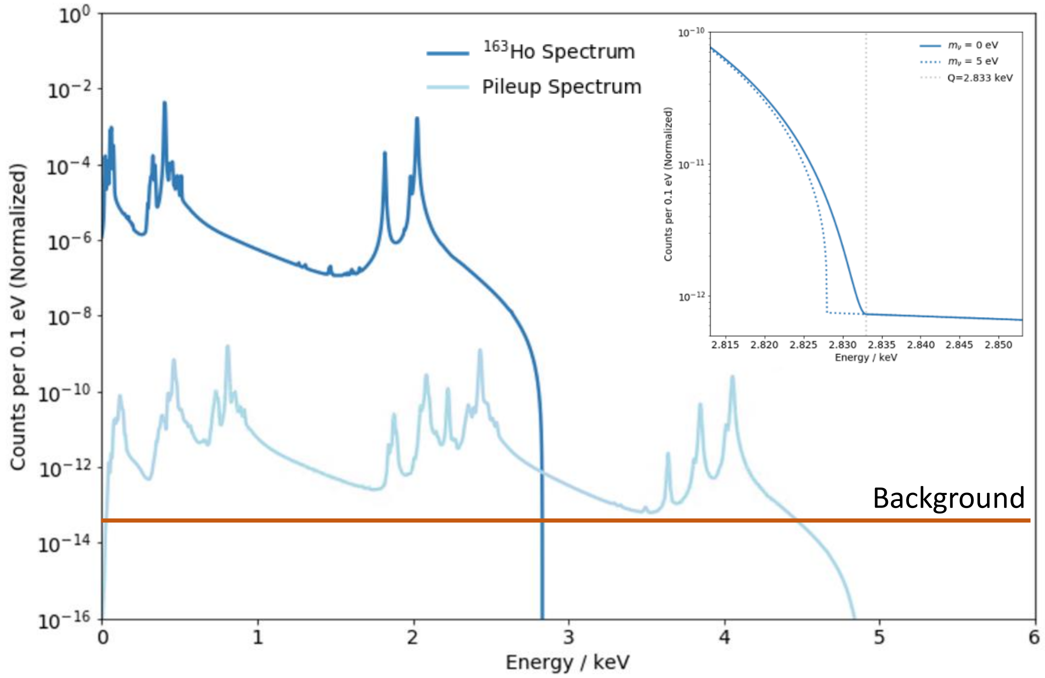
Background level below unresolved pile-up

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

→ Identification and suppression of background sources



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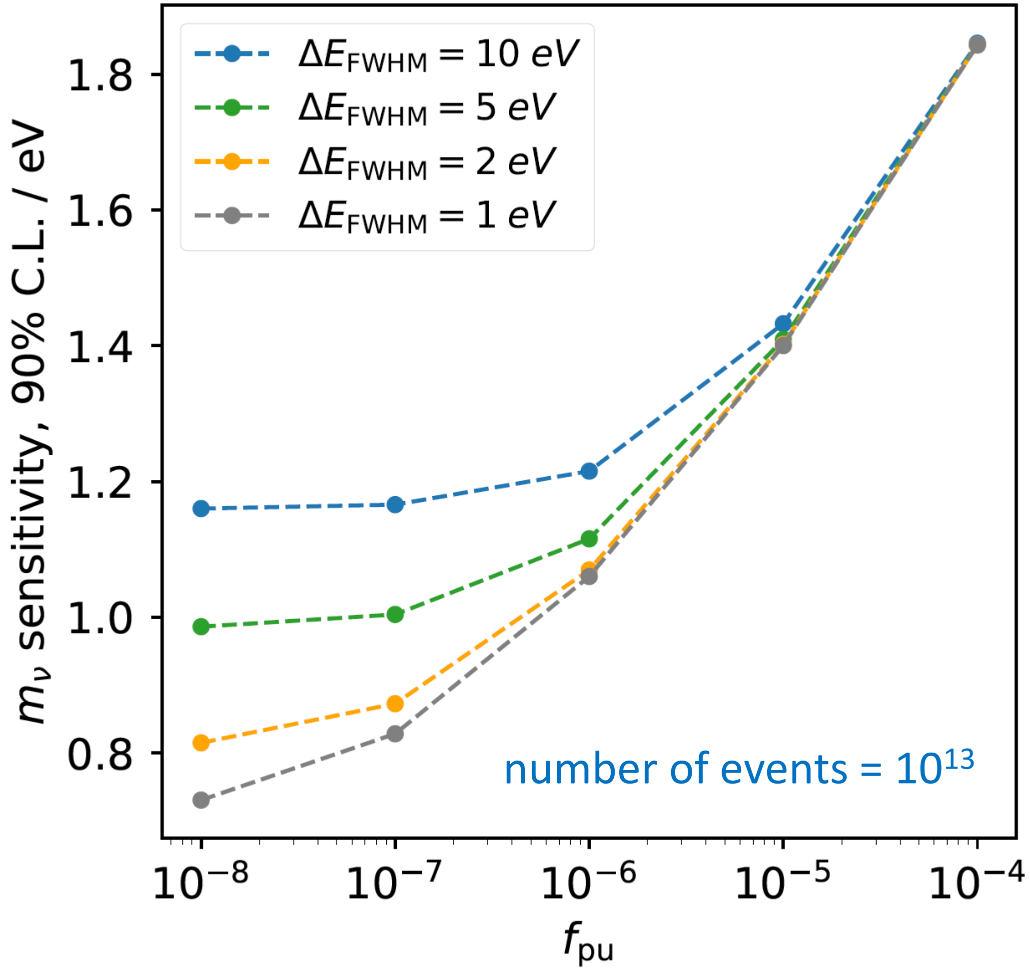
Precise characterization of the endpoint region

- **ΔE_{FWHM} < 3 eV**

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



ECHo Phases

ECHo-1k

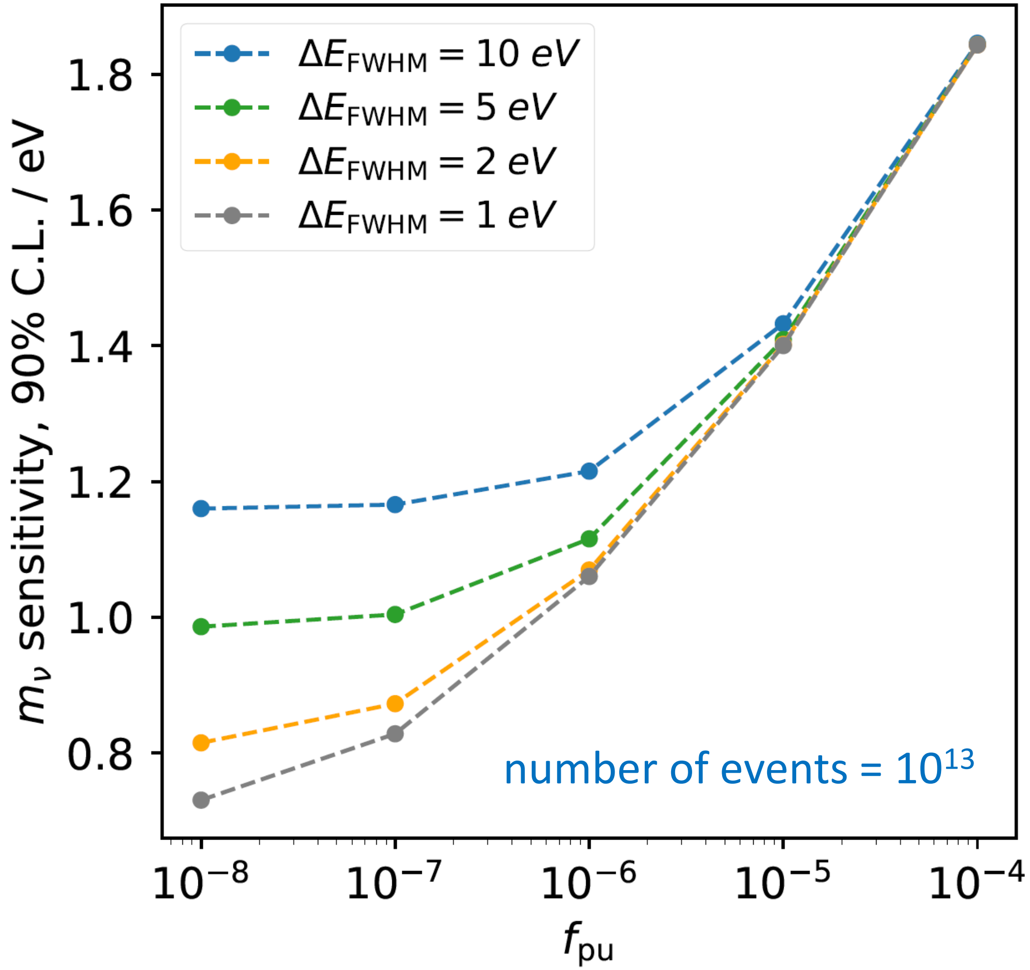
Activity per pixel: 1 Bq
Number of detectors: 60 - 100
Readout: parallel two stage SQUID

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

ECHo-100k

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

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



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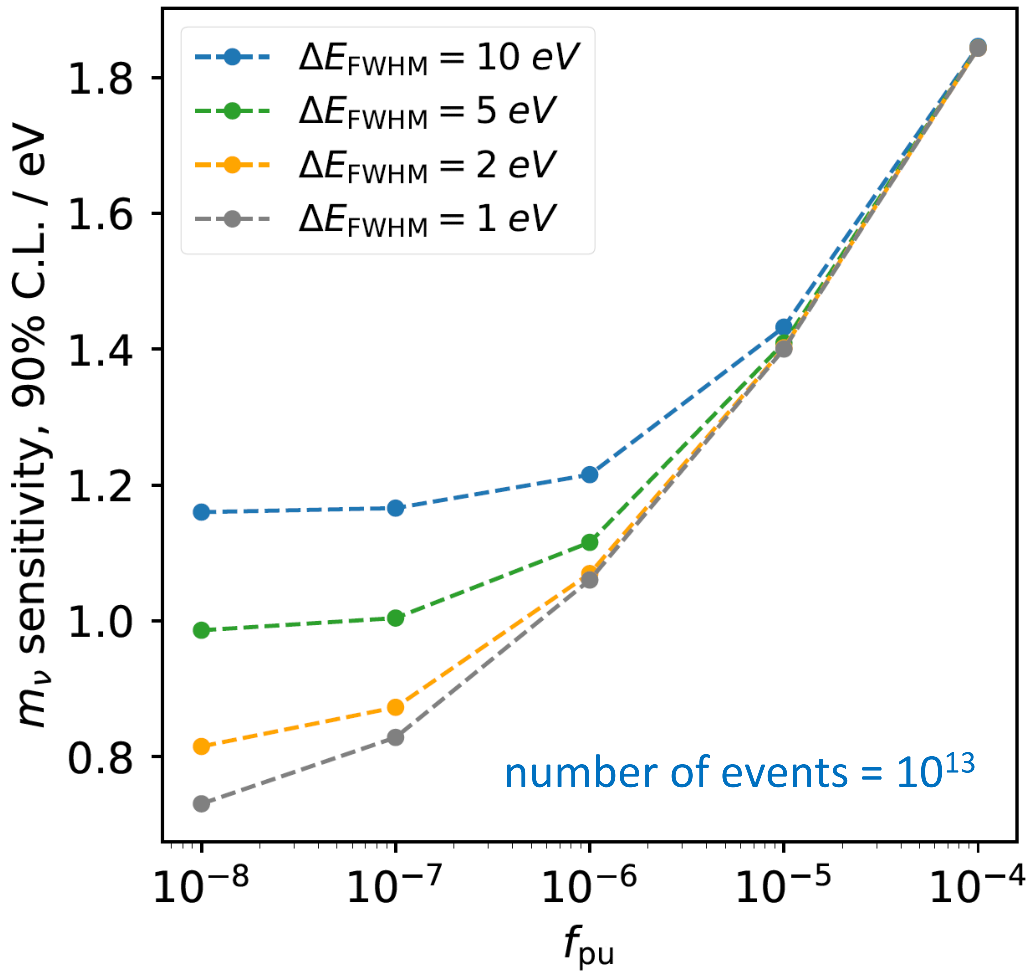
Preparation of all components



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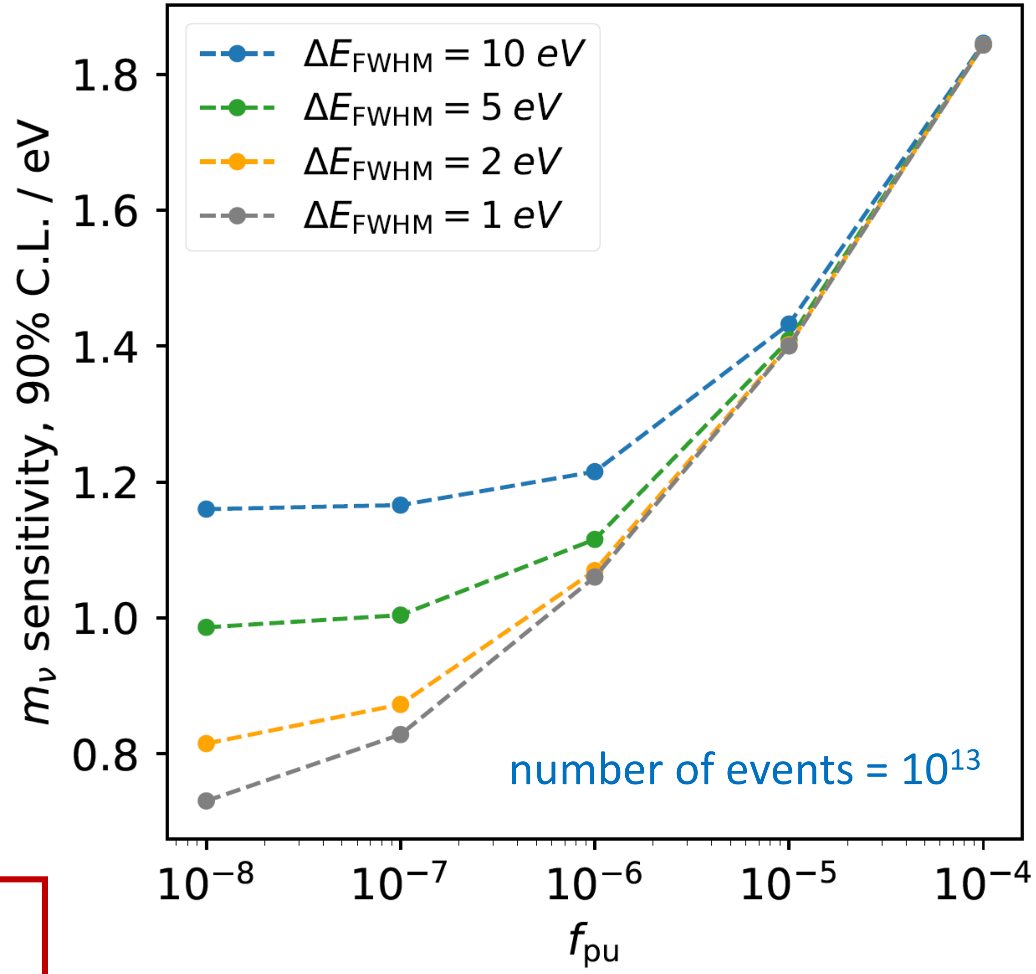
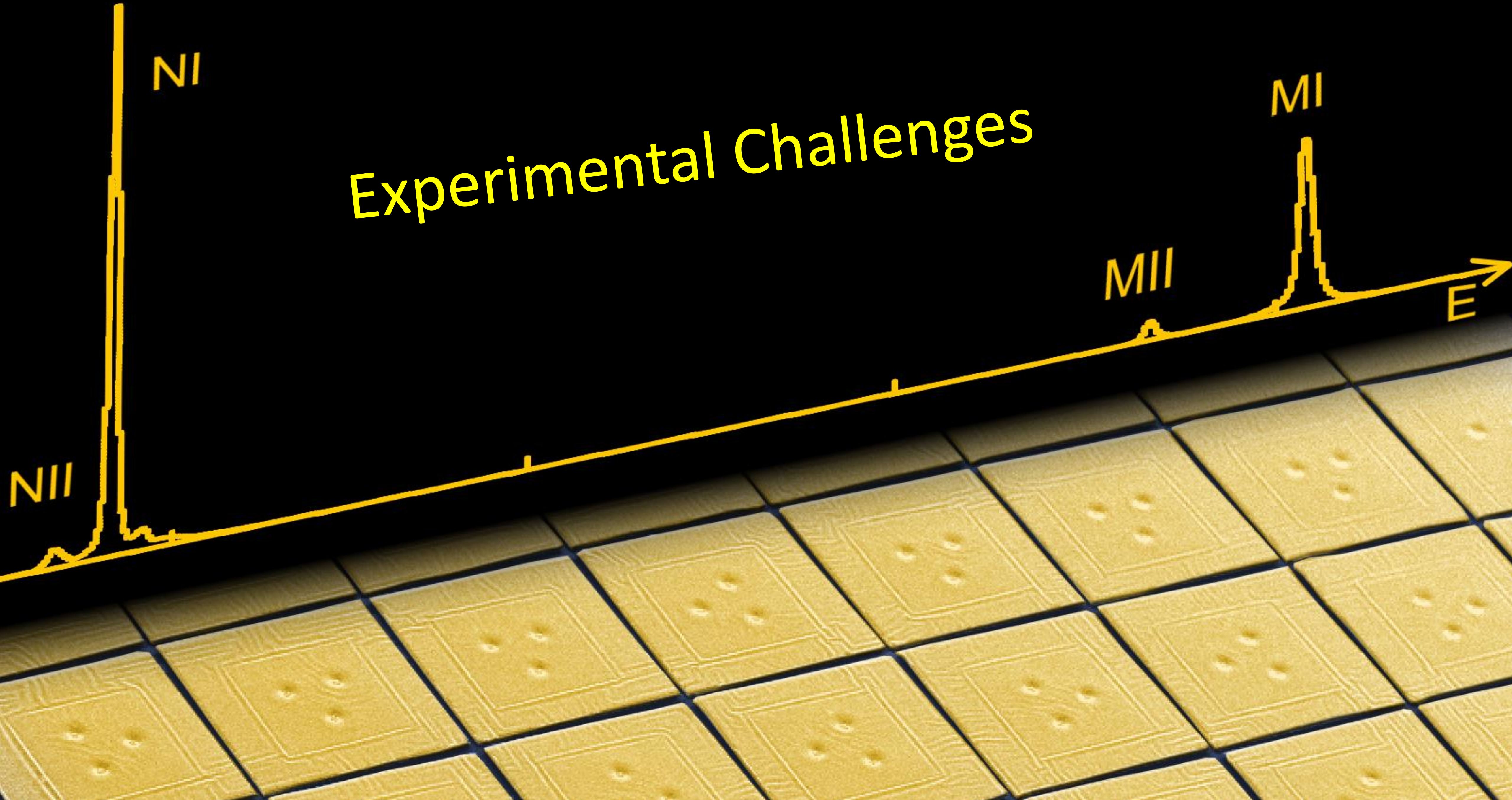


ECHo-XXk

Achievable scale to be determined after ECHo-100k + HOLMES results

Experimental Challenges



Calorimetric measurement

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

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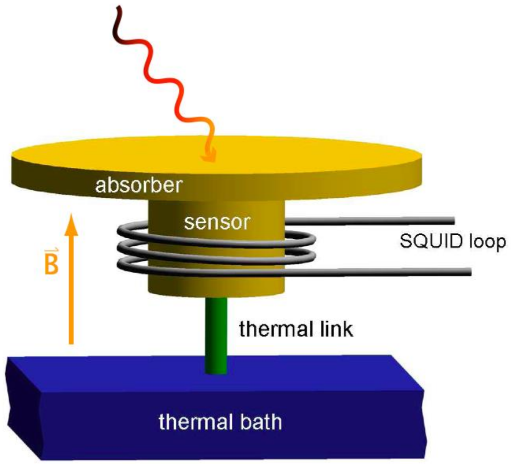
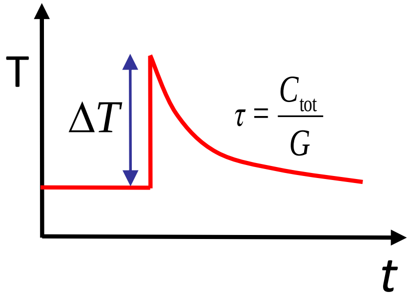


$$\Delta T \cong \frac{E}{C_{tot}}$$



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

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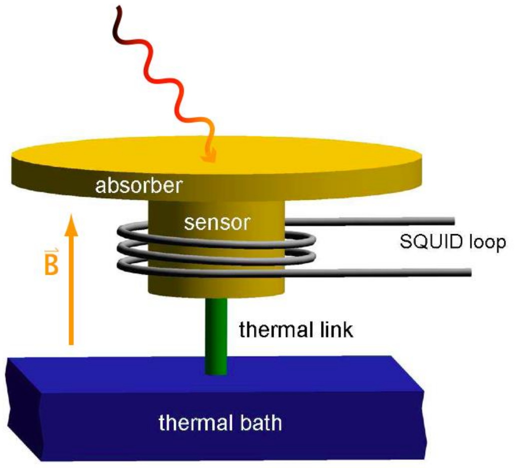

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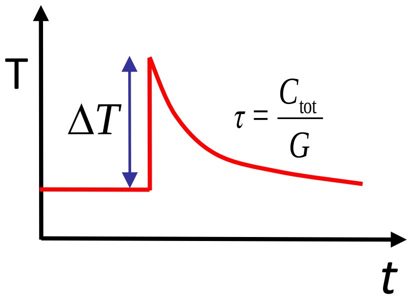

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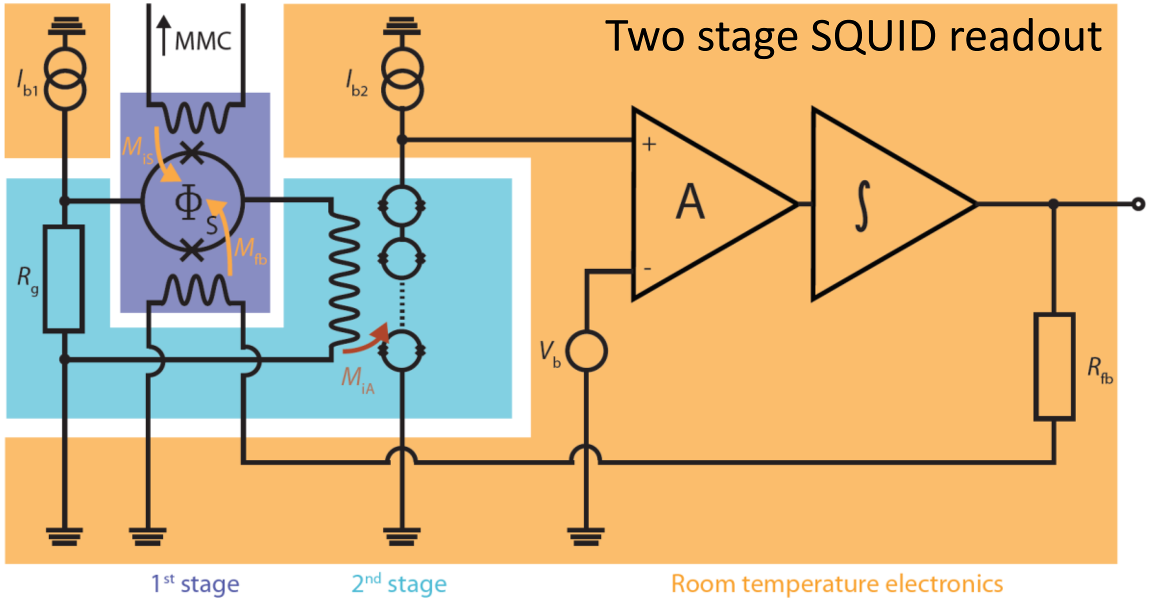

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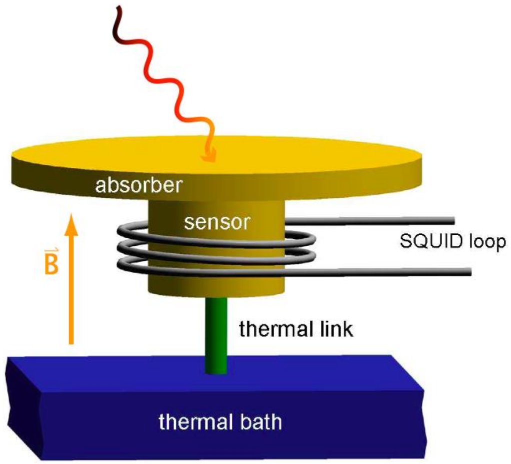

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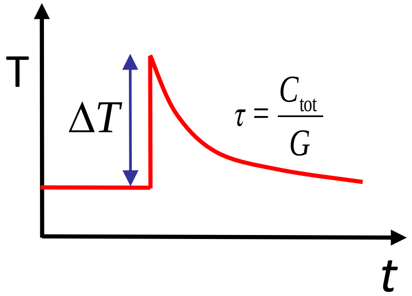

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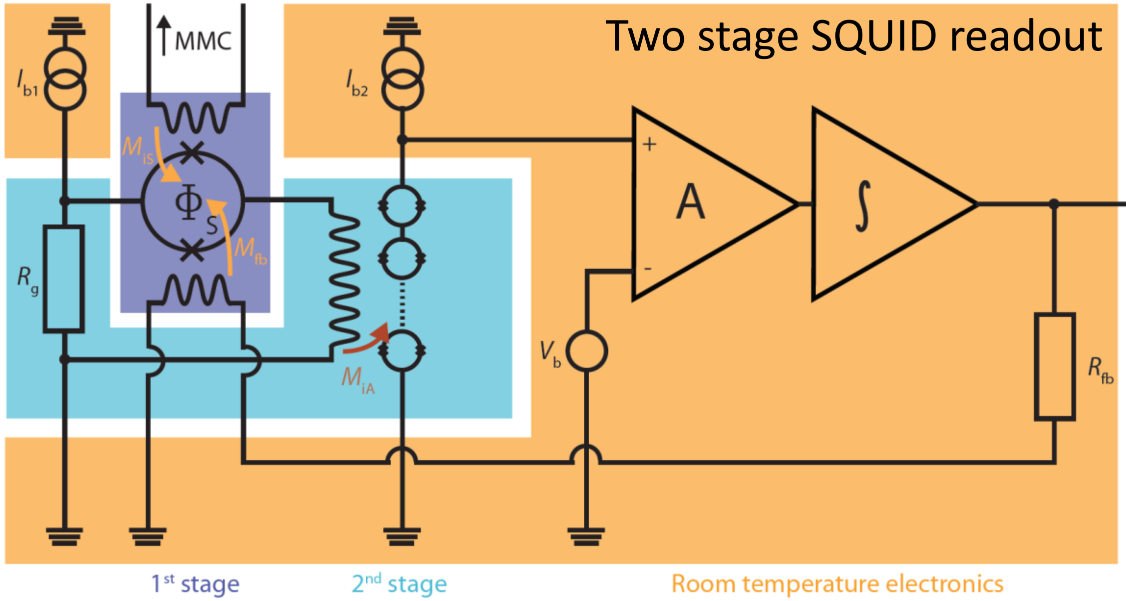

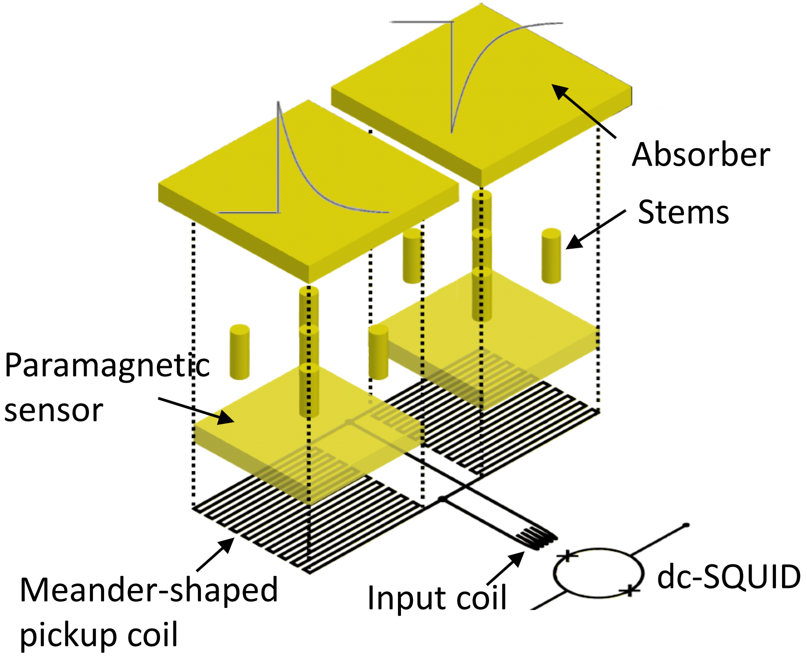

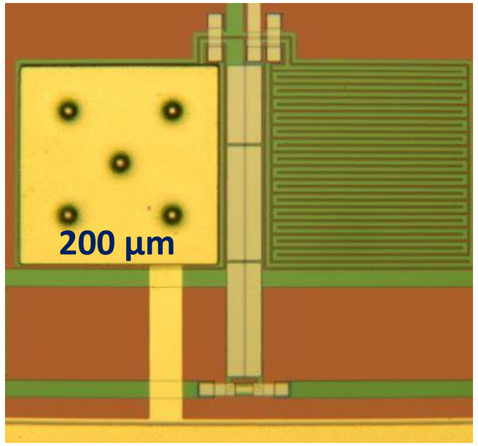

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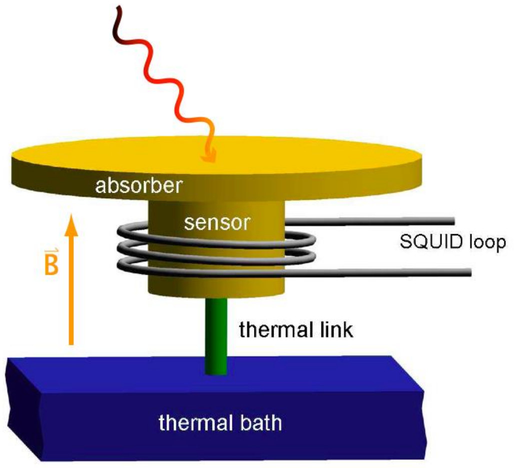
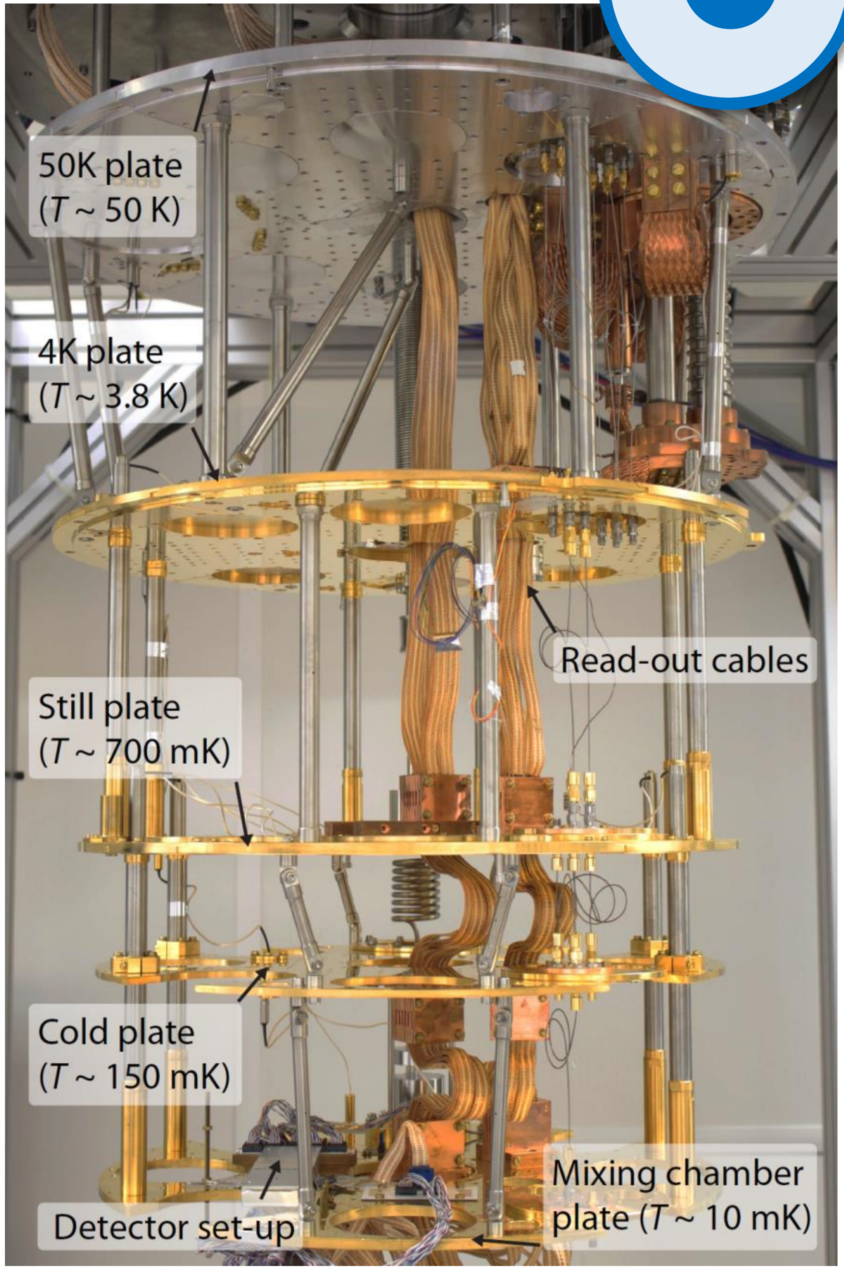
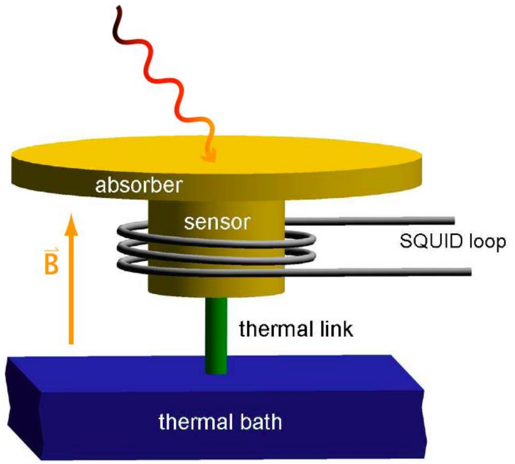


MMC are operated at T < 30 mK in cryostats



Calorimetric measurement – Detectors

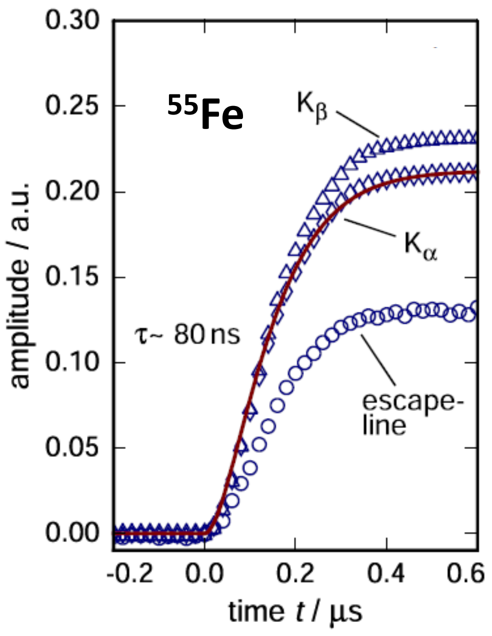
ECHo uses large arrays of low T metallic magnetic calorimeters with enclosed ^{163}Ho

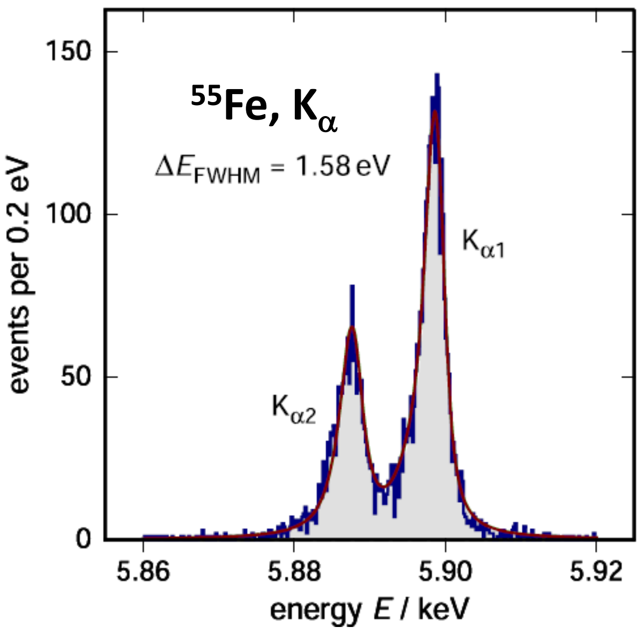


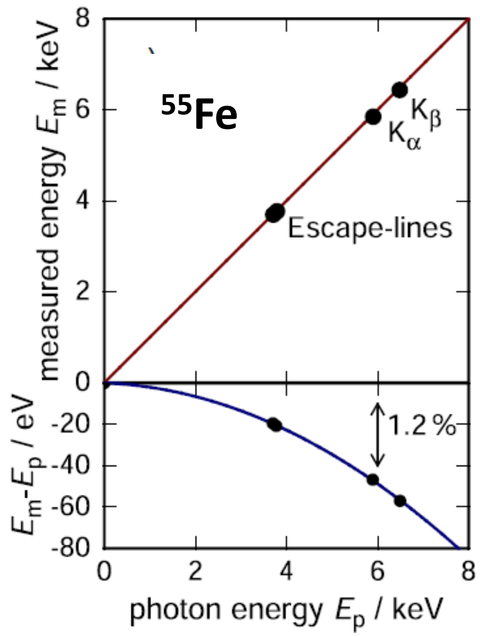
Fast risetime
→ Reduction un-resolved pile-up

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

Excellent linearity
→ precise definition of the energy scale

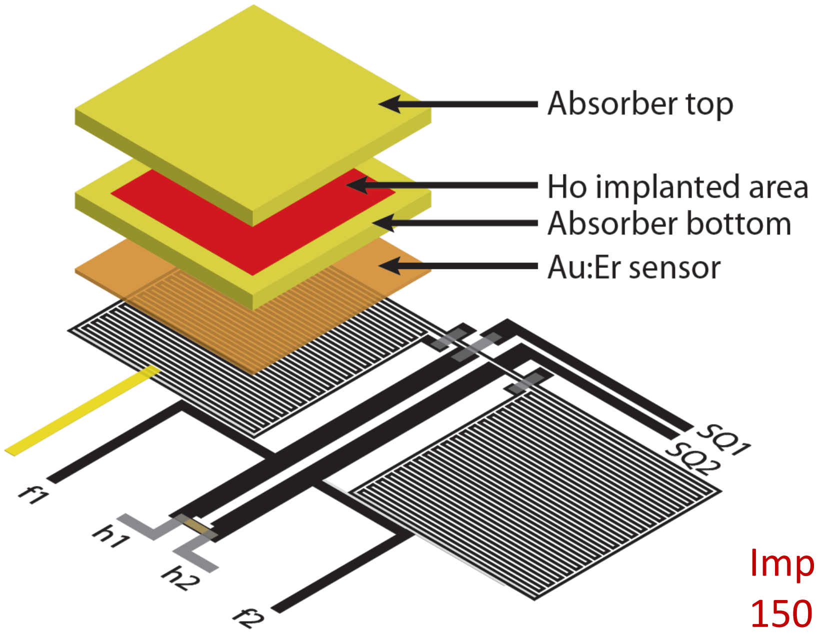






Calorimetric measurement – 4π geometry

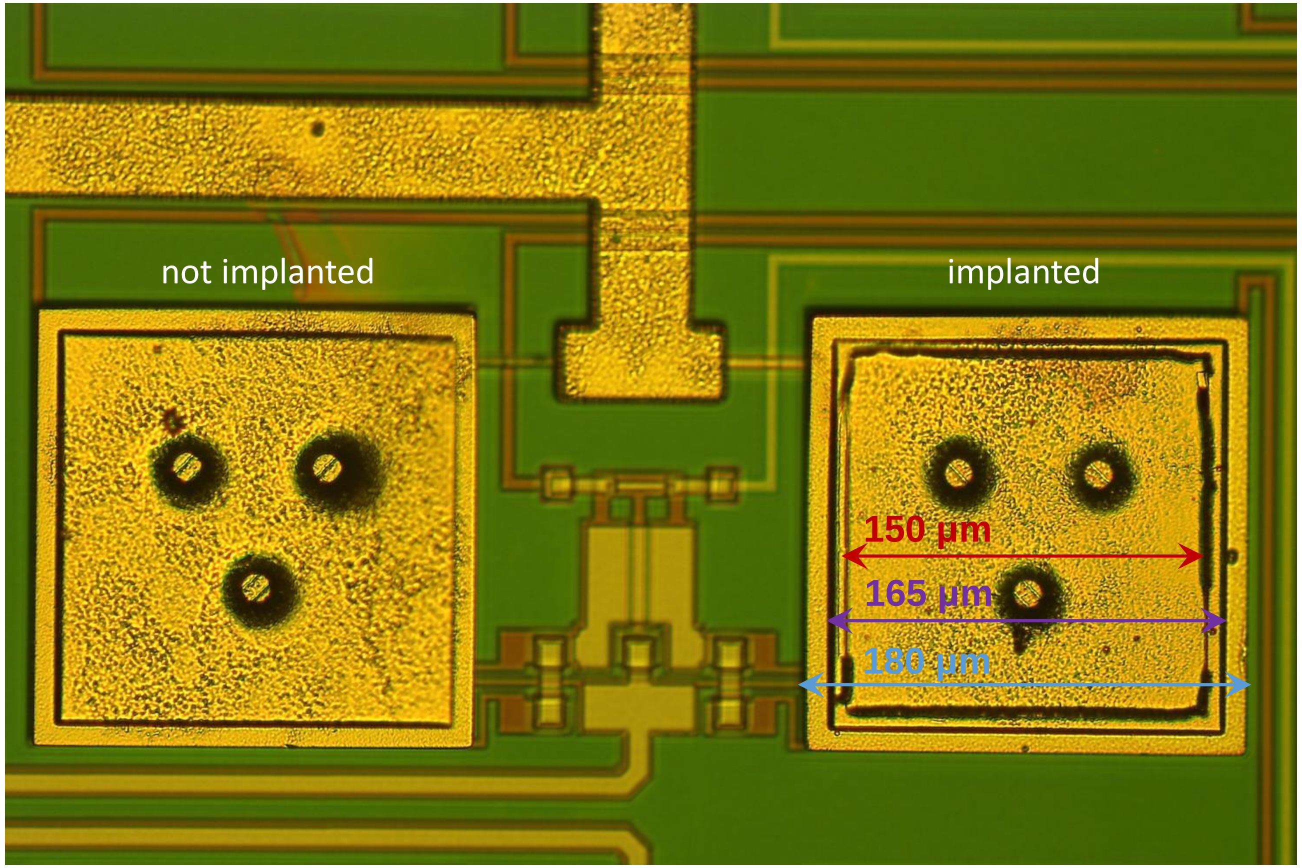
ECHo uses large arrays of low T metallic magnetic calorimeters with enclosed ^{163}Ho



Implantation square:
150 µm x 150 µm

Second absorber:
165 µm x 165 µm

First absorber:
180 µm x 180 µm

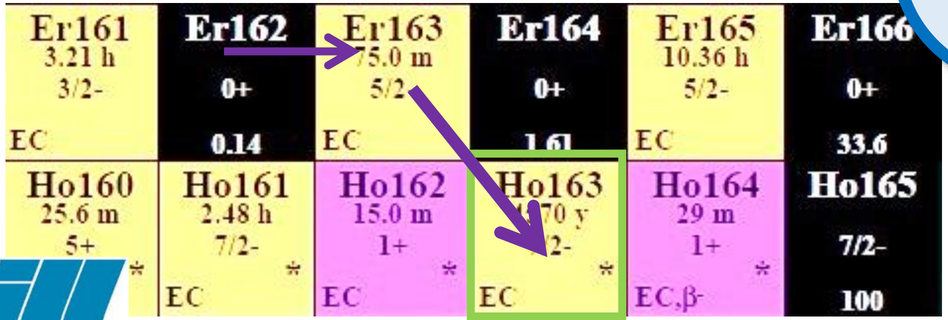


F. Mantegazzini et al., *Nucl. Instrum. Meth. A* **1030** (2022) 166406

^{163}Ho Source Production + Implantation

^{163}Ho production via neutron irradiation → (n,γ)-reaction on ^{162}Er

Excellent chemical separation → 95% efficiency



NEUTRONS FOR SCIENCE

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

^{163}Ho available for coming experiments
$\sim 6 \times 10^{18}$ atoms (30 MBq)

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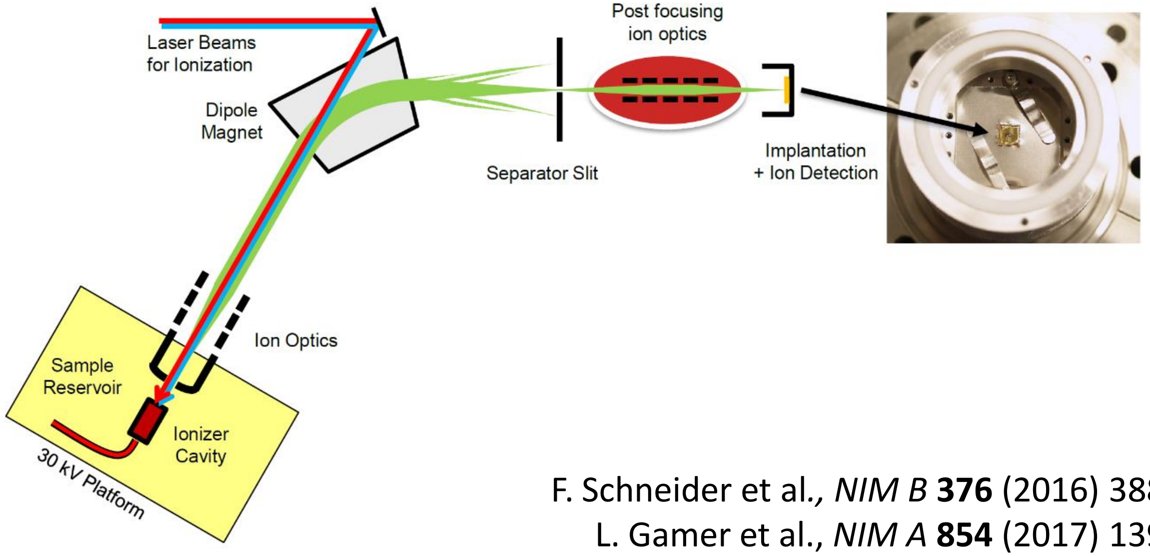

F. Schneider et al., *NIM B* **376** (2016) 388
L. Gamer et al., *NIM A* **854** (2017) 139
T. Kieck et al., *Rev. Sci. Inst.* **90** (2019) 053304
T. Kieck et al., *NIM A* **945** (2019) 162602

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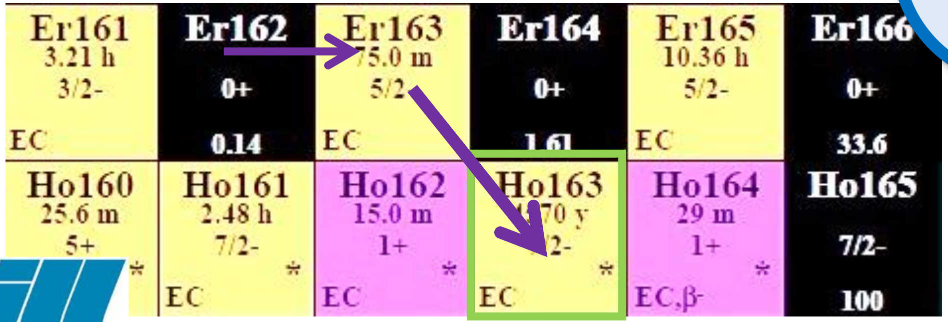

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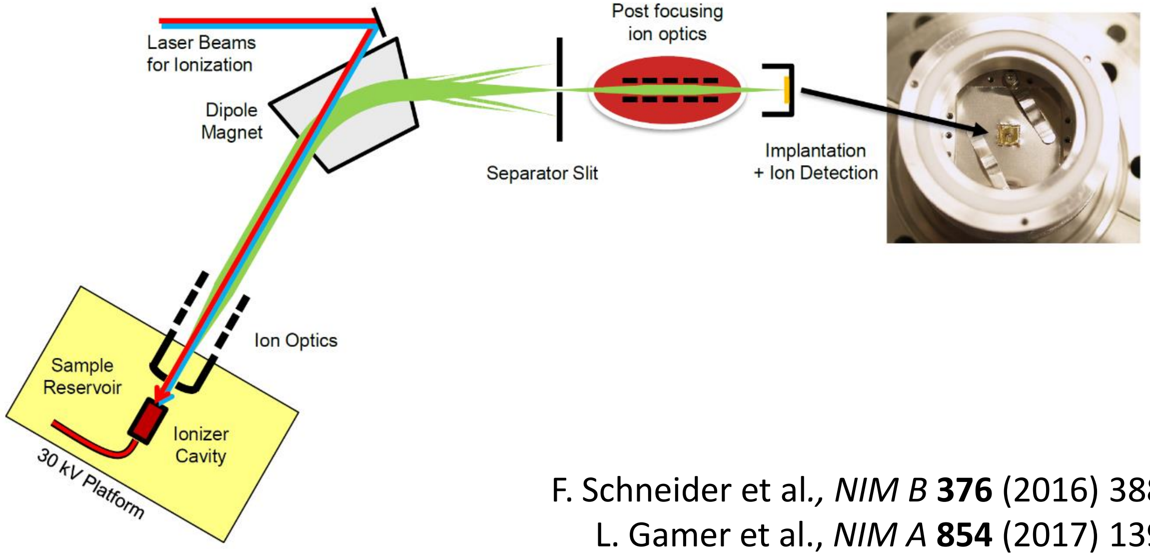

More in Raphael Hasse's talk tomorrow

F. Schneider et al., *NIM B* **376** (2016) 388
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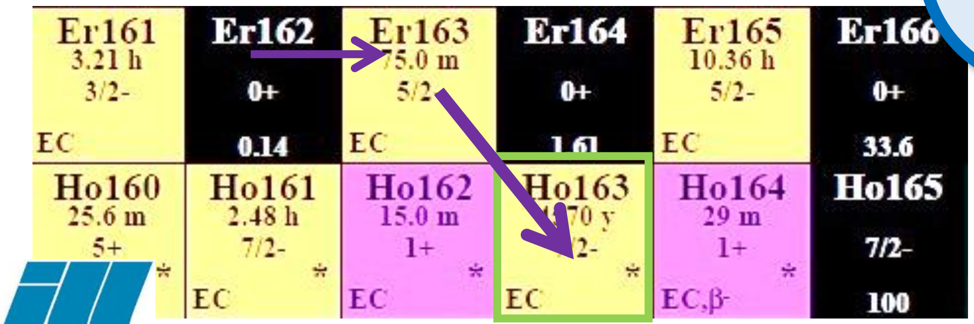

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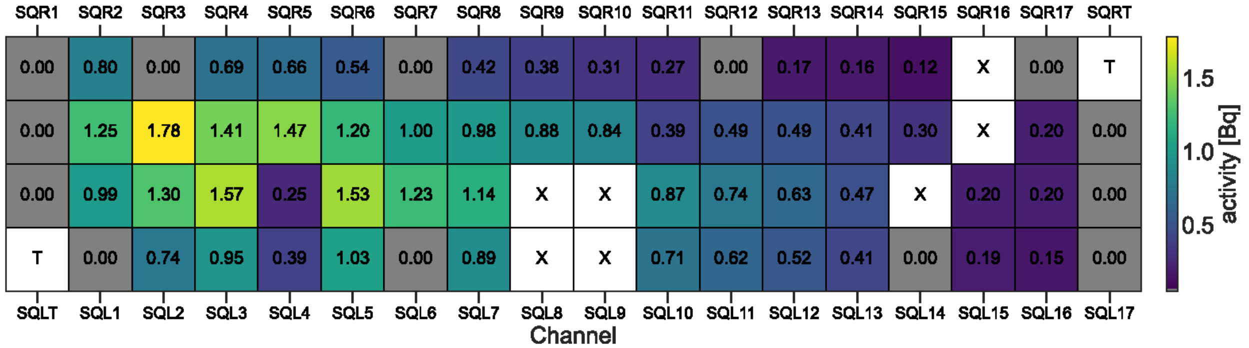
ECHo-1k single chip implantation

Activity map



N. Kovac, Master Thesis Heidelberg University

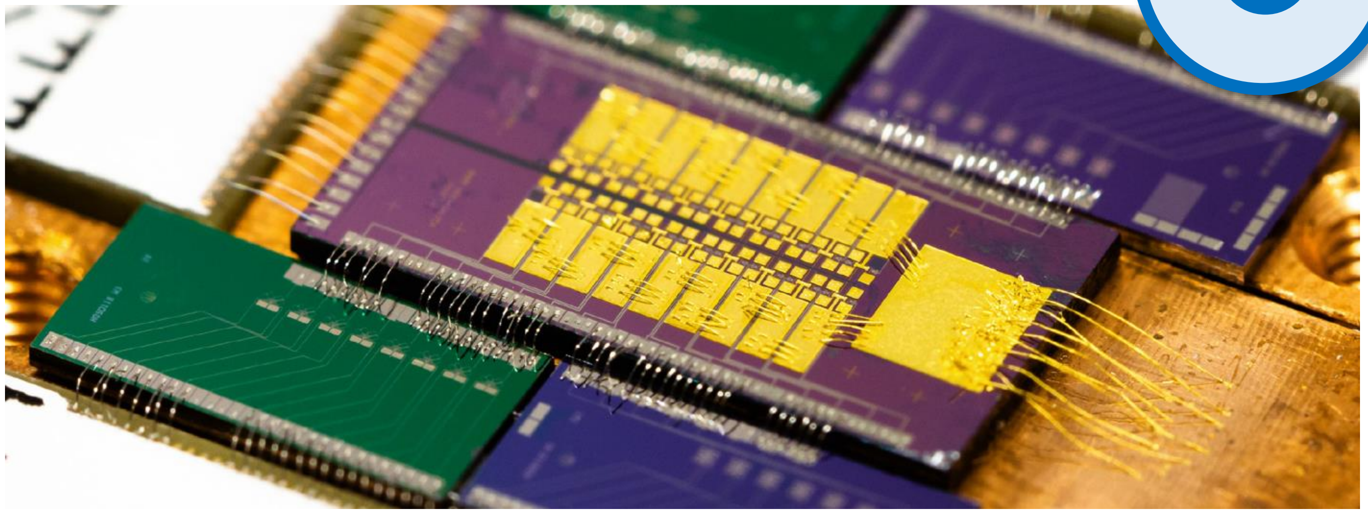
ECHo-1k high statistics spectrum

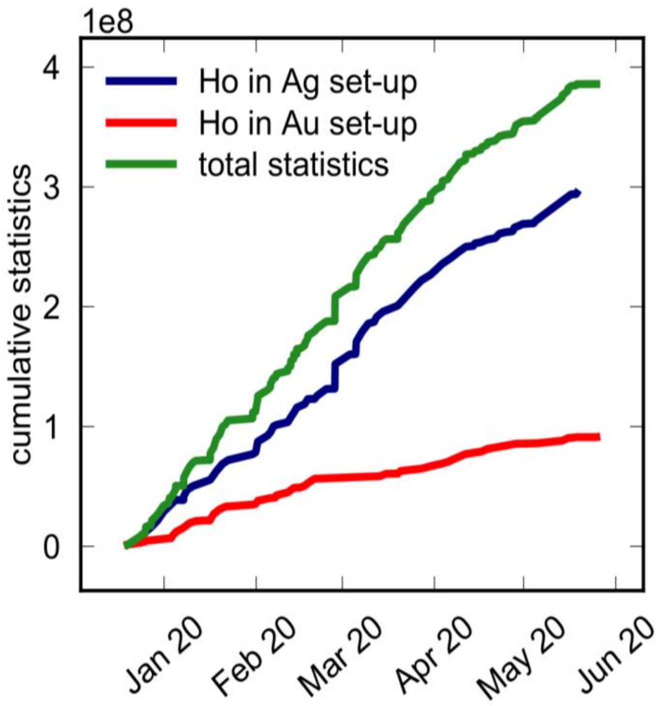
ECHo-1k chip-Au

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

ECHo-1k chip-Ag

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





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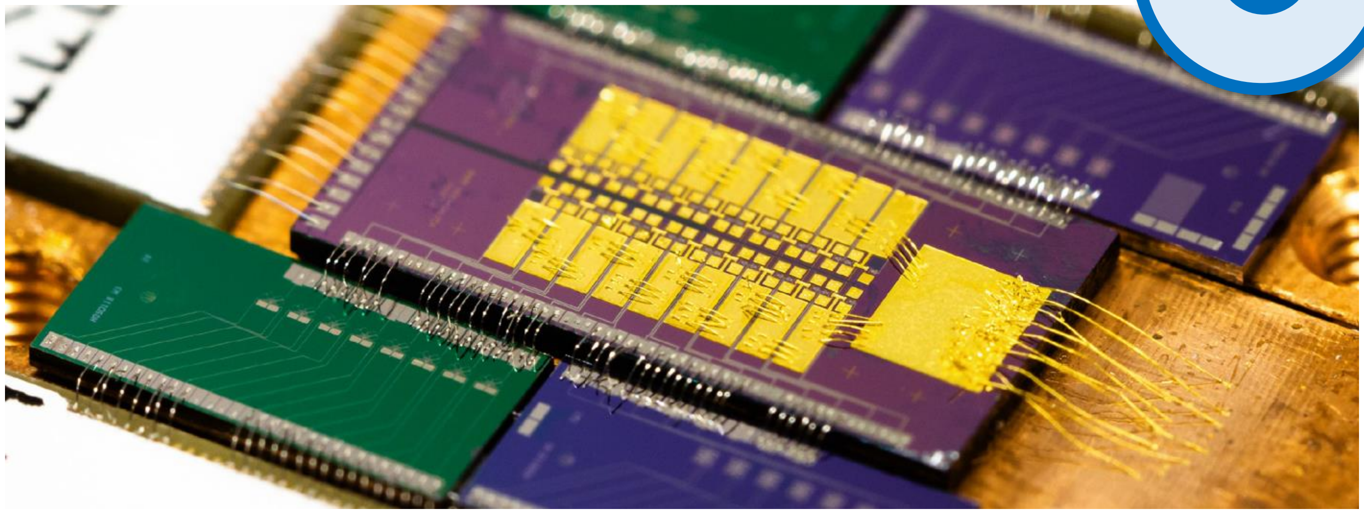
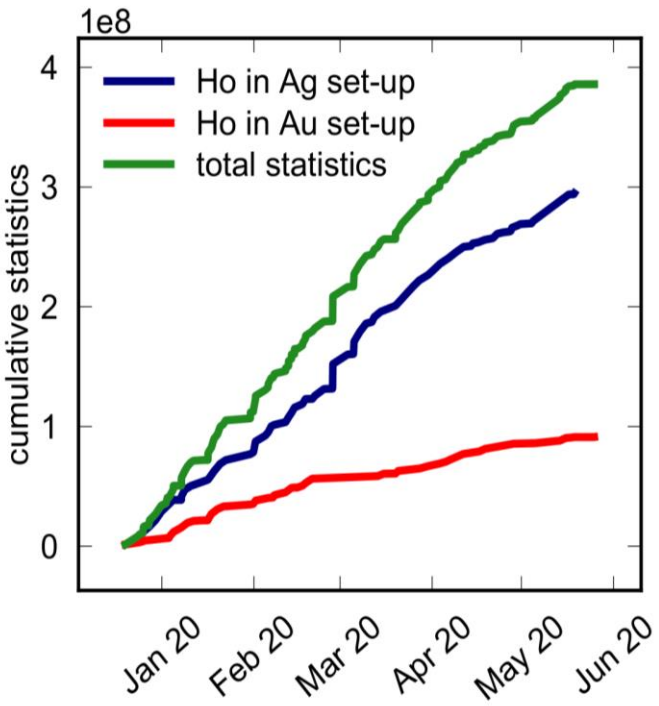




Data Reduction

First Level: Time Information Filter

Holdoff Filter

Discard traces with $\Delta T_{Ch} < T_{Holdoff}$

Burst Filter

Discard time intervals with abnormally high rate

Coincidence Filter

Discard traces with $\Delta T < T_{Coincidence}$

GSM Filter

Discard traces with ΔT associated to GSM pulse frequencies

Second Level:

Template Fit

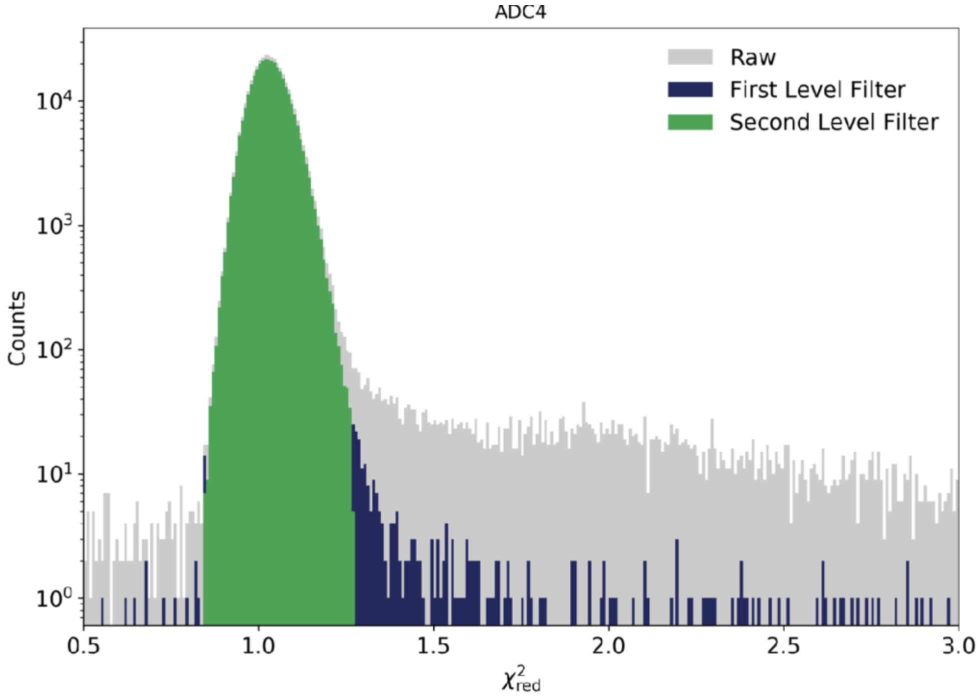
- Create mean pulse from traces by cross-fitting traces in batches
- Fit traces to template to recover amplitude and χ_{red}^2

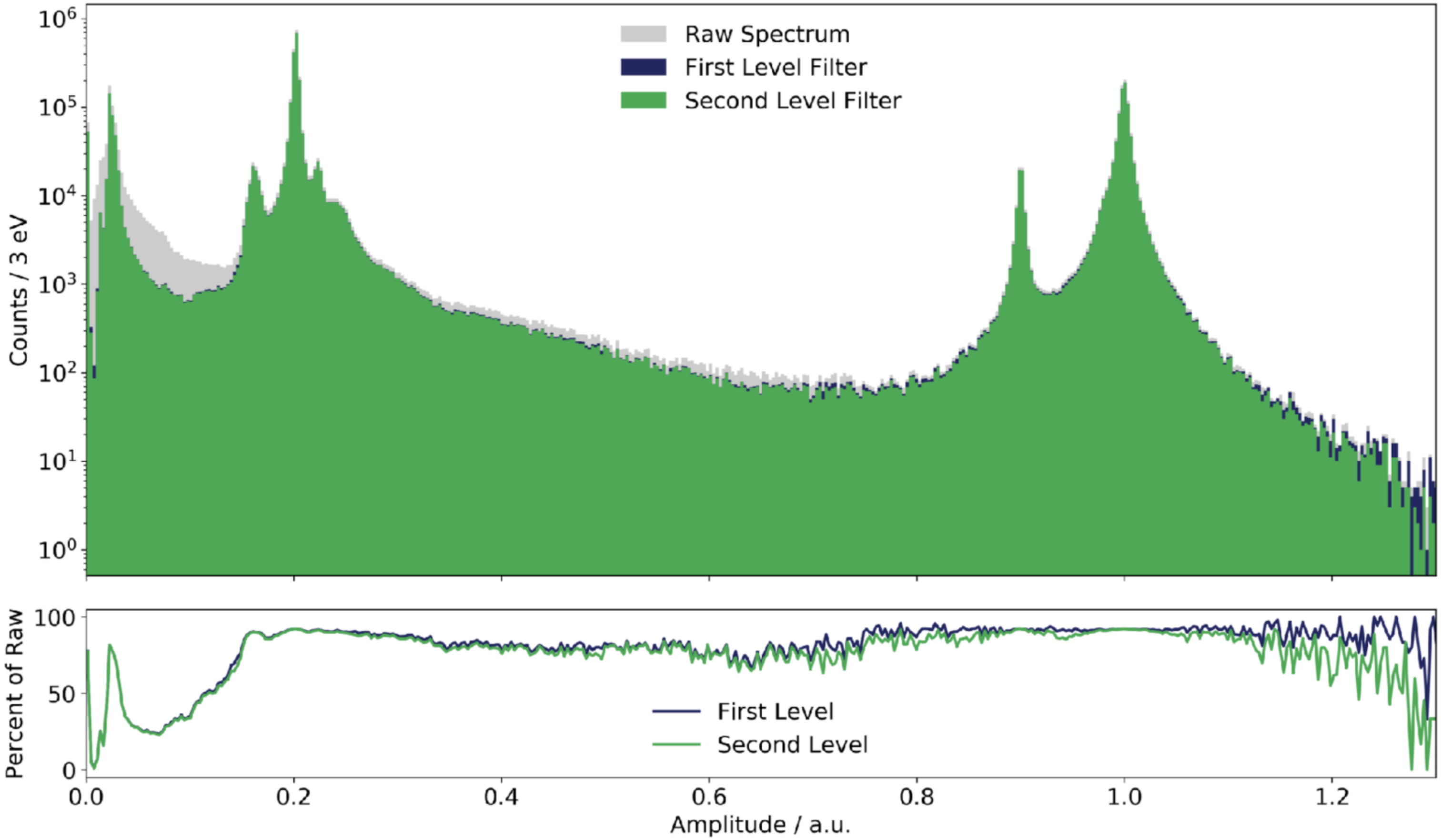
Pulse Shape Filter

Discard traces with high deviation from template

R. Hammann et al., Eur. Phys. J. C (2021) 81:963

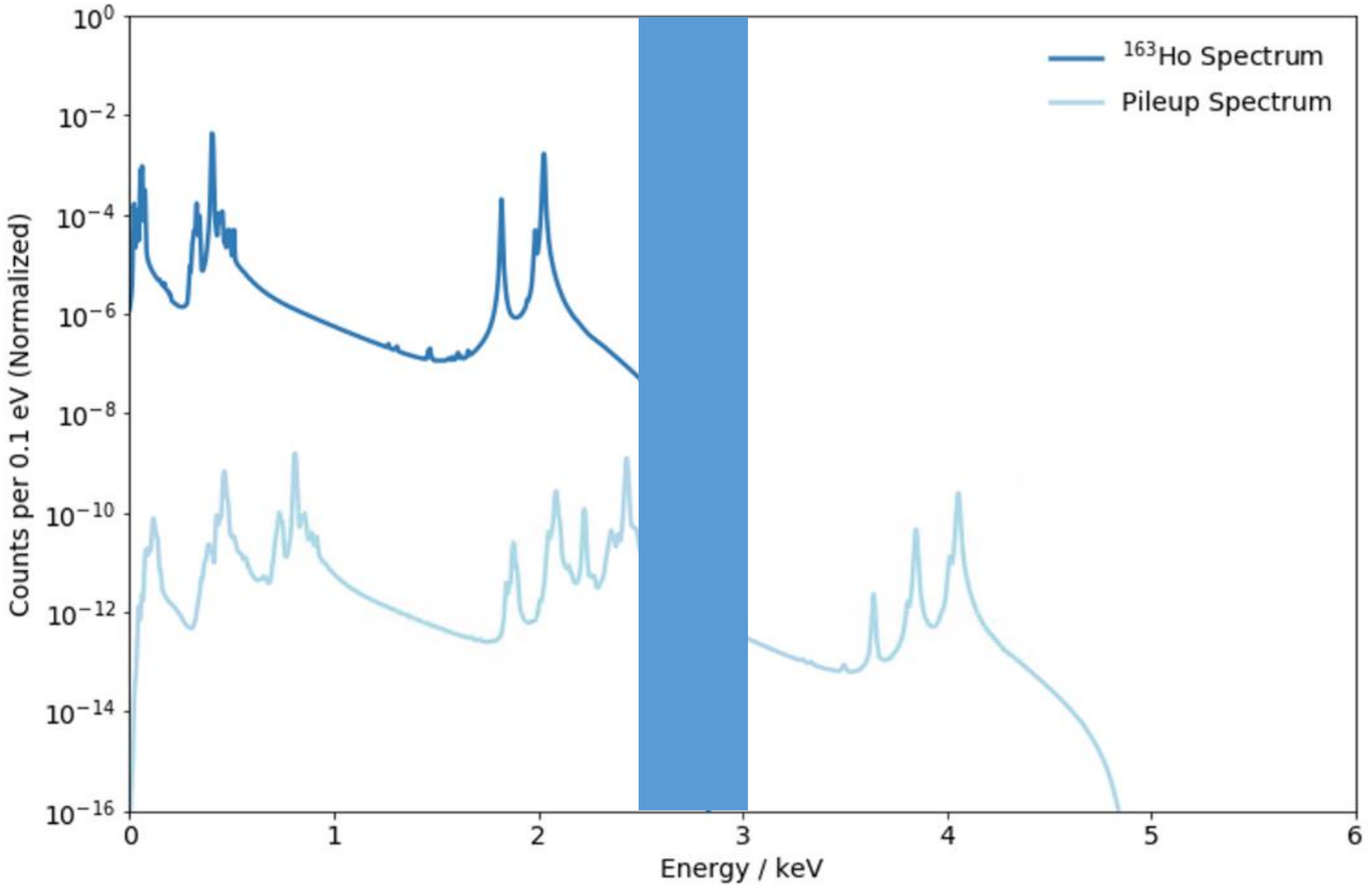
Example of data reduction





Determination of efficiency for filters

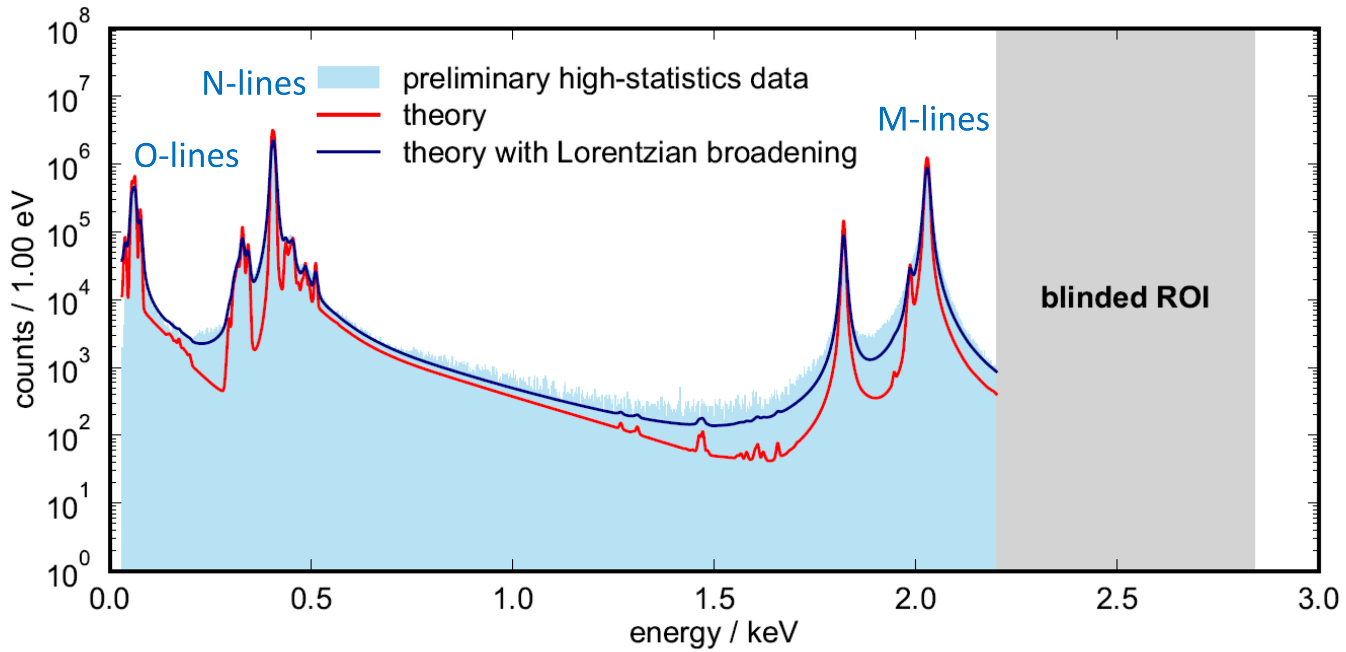
Analysis of the ^{163}Ho electron capture spectrum



$E \leq 2.5$ keV
determination spectrum parameters
(intensity, peak energies, widths, Q-value)

$E \geq 3$ keV
determination unresolved pile-up spectrum
and natural background

$E < 2.5$ keV



Fraction of data corresponding to 6×10^7 events acquired with detectors having ^{163}Ho in Ag

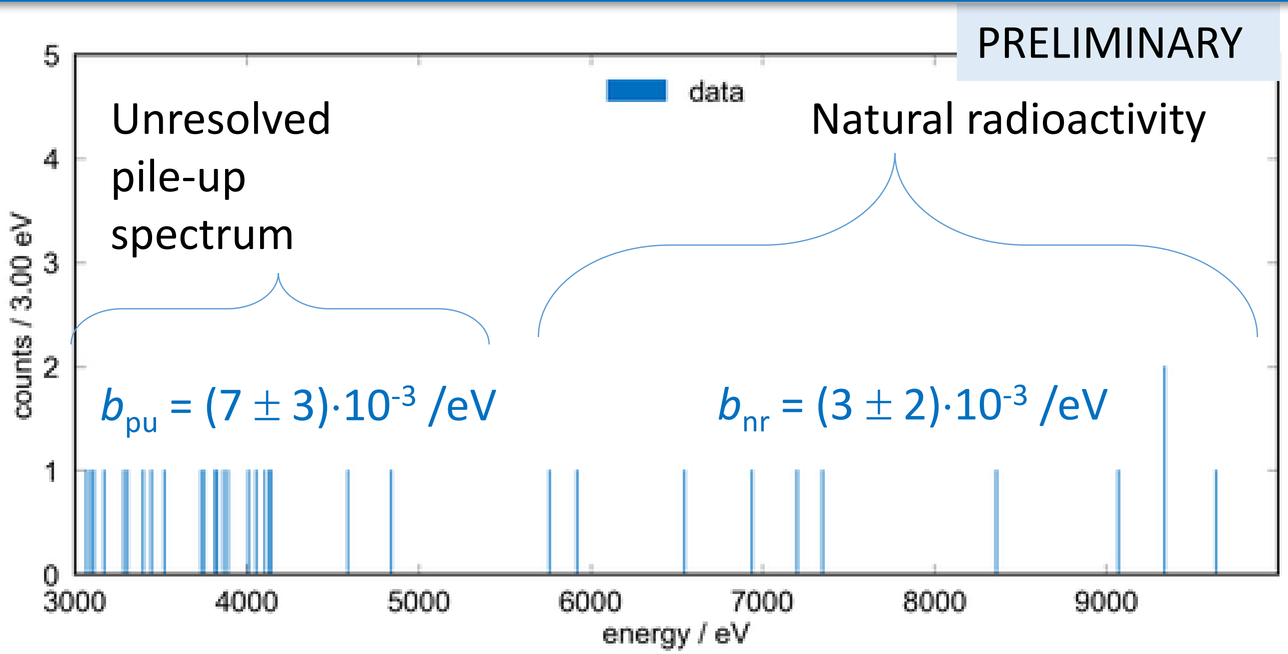
- Only data passing quality checks
- Energy scale defined in a new calibration measurement

New theory describes well the complex structure of line multiplets but tails are still not perfect

- more work is on extending the theoretical description and EC spectra measurements

M. Braß et al., *Phys. Rev. C* **97** (2018) 054620,
M. Braß M. W. Haverkort, *New J. Phys.* **22** (2020) 093018
M. Merstorf et al, arXiv:2307.13812 [physics.atom-ph]

E > 3 keV

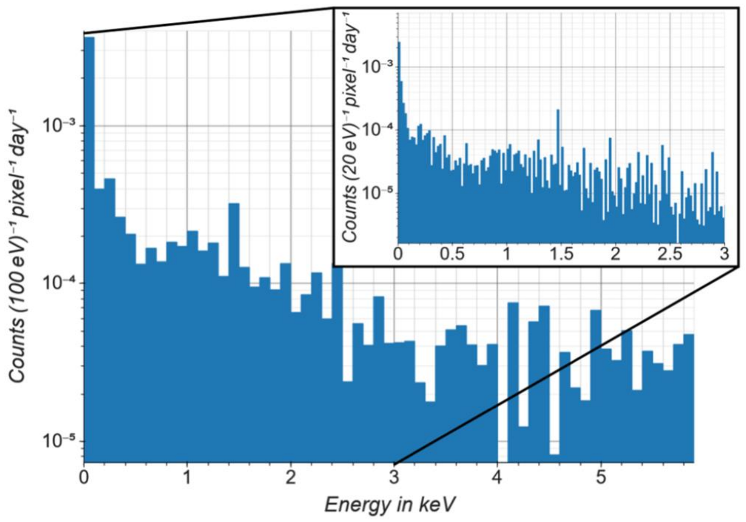


Two major contributions

- unresolved pile-up for $E < 5.7$ keV
- natural radioactivity + muon related events for $E > 5.7$ keV

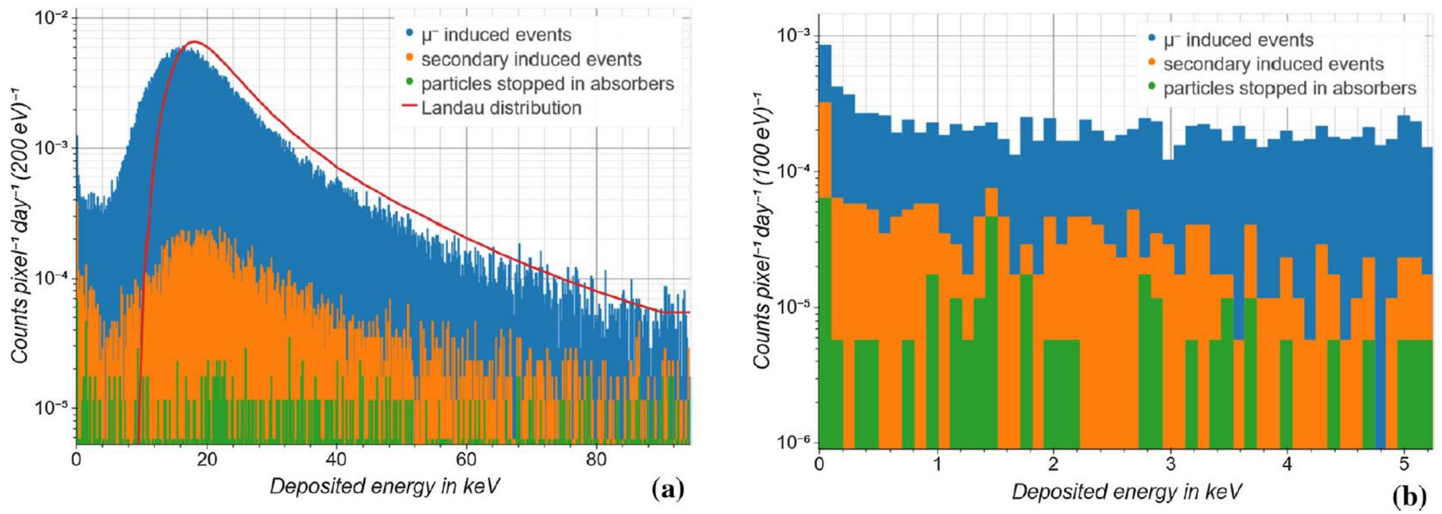
Comparison with simulation on-going

Natural radioactivity

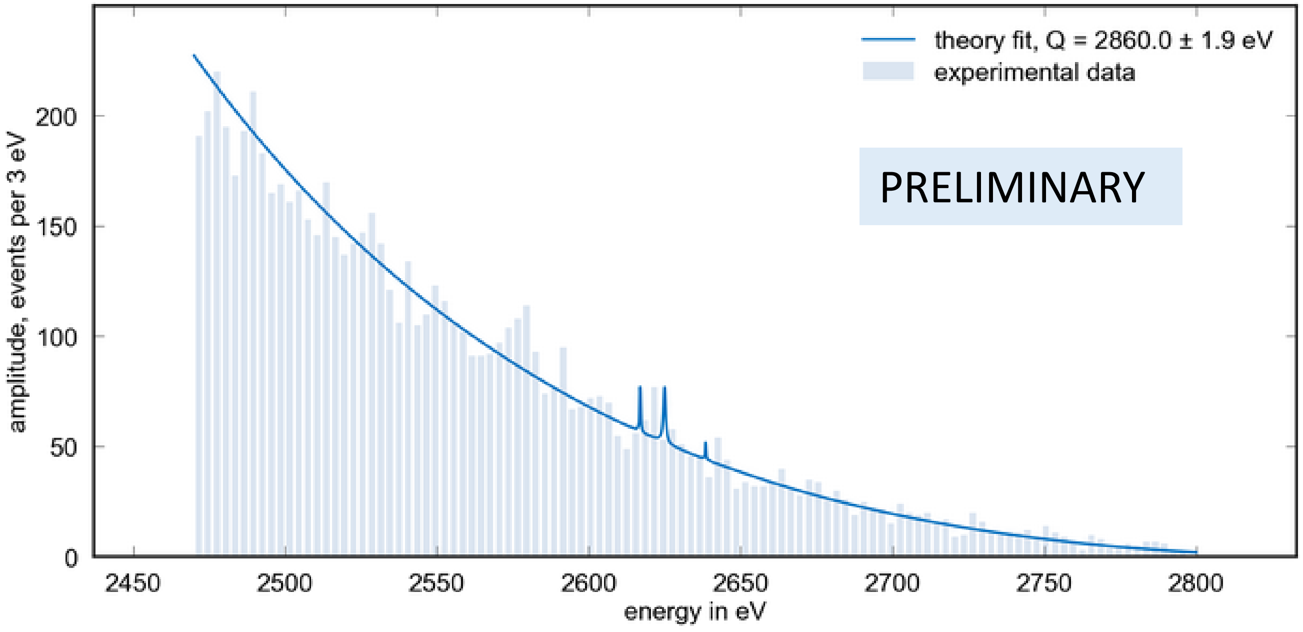


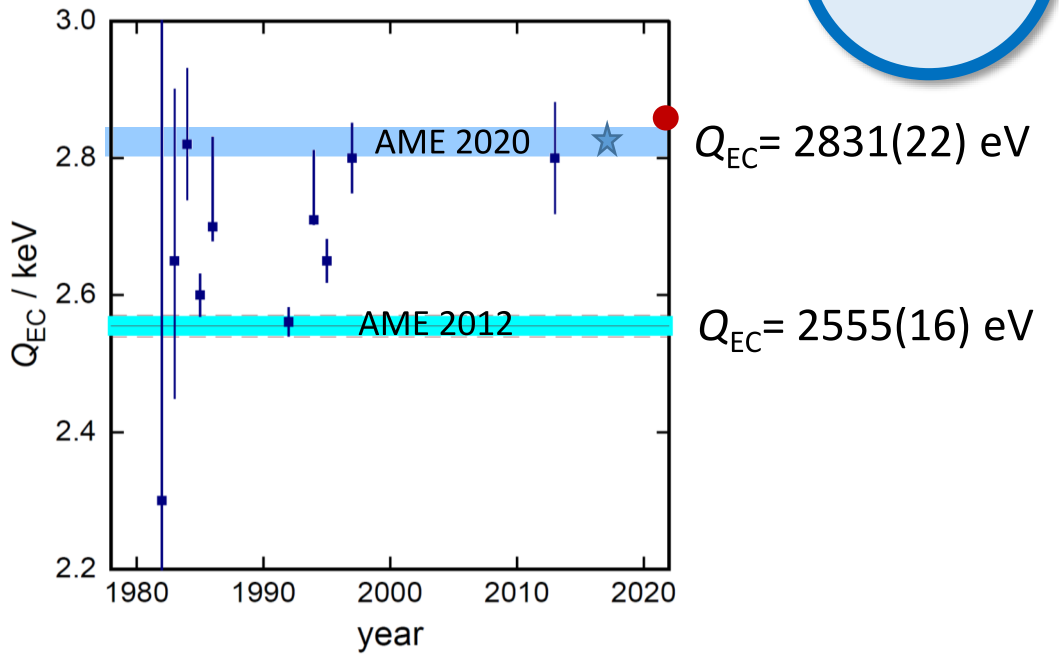
Muon related background

A. Goeggelmann et al., *Eur.Phys.J.C* **81** (2021) 363
A. Goeggelmann et al., *Eur.Phys.J.C* **82** (2022) 139



2.5 keV < *E* < 2.8 keV





★ $Q_{EC} = (2.833 \pm 0.030^{stat} \pm 0.015^{syst})$ keV

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

Determination of Q_{EC} by fitting the spectrum using:

- Brass & Haverkort theory
- Flat background

$Q_{EC} = (2860 \pm 2_{stat} \pm 5_{syst})$ eV

!

In perfect agreement with new PENTATRAP* results

$Q_{EC} = (2863.2 \pm 0.6)$ eV

Ch. Schweiger et al.
https://doi.org/10.48550/arXiv.2402.06464

(*) J. Repp et al., Appl. Phys. B **107** (2012) 983
C. Roux et al., Appl. Phys. B **107** (2012) 997

Towards ECHo-100k

ECHo-1k

~1 Bq / pixel

60 MMCs

→

ECHo-100k

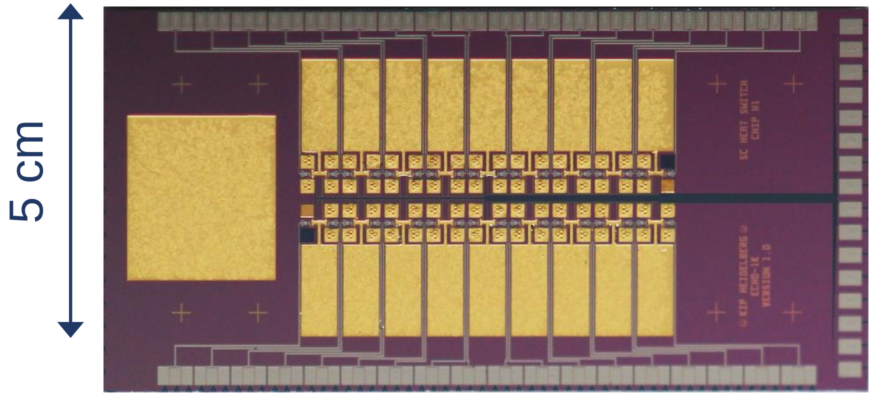
10 Bq / pixel

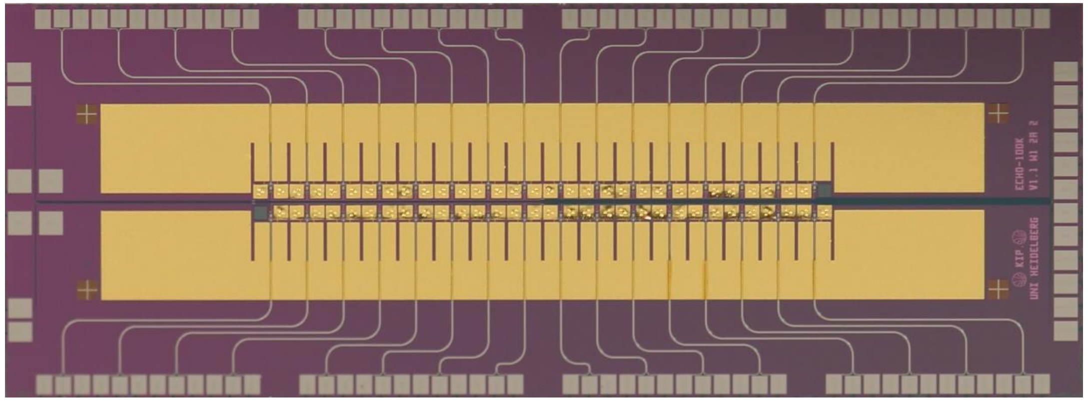
12000 MMCs

- New ECHo-100k
- More efficient ^{163}Ho implantation
- Multiplexed readout

ECHo-100k – MMC array

ECHo-1k		ECHo-100k
~1 Bq / pixel	→	10 Bq / pixel
60 MMCs		12000 MMCs





- ✓ **Design and fabrication** completed
- ✓ **Characterised** with Fe-55 and implanted Ho-163

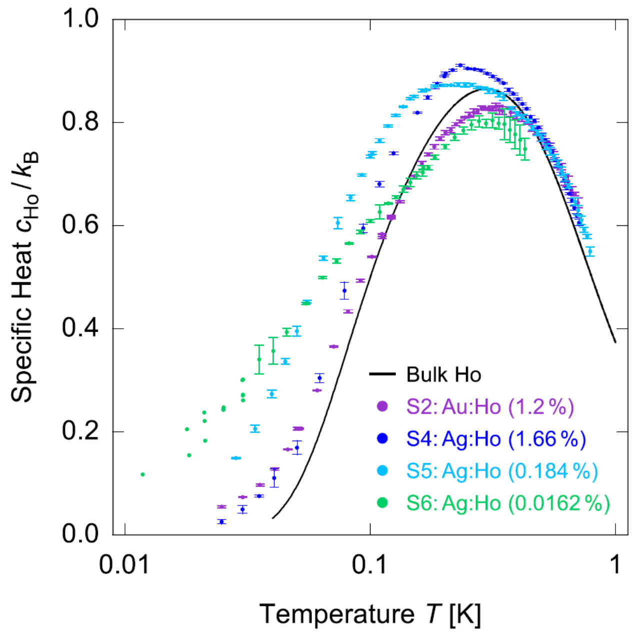
ECHo-100k – MMC array

Maximum activity per pixel

Maximum ^{163}Ho activity in microcalorimeters is affected by:

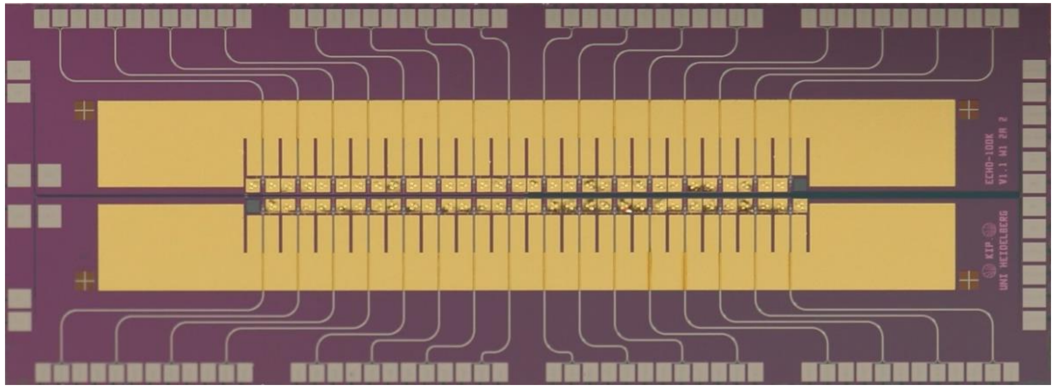
- specific heat per ^{163}Ho atom ($2*10^{11}$ atoms for 1 Bq)
  compromise detector performance
- allowed unresolved pile-up
  unavoidable background in the endpoint region

10 Bq per pixel for ECHo-100k

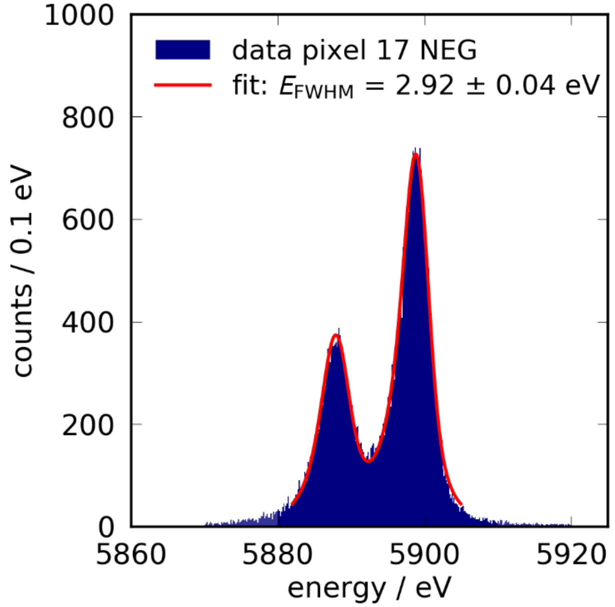


M. Herbst et al., *Journal of Low Temperature Physics* **202** (2021) 106

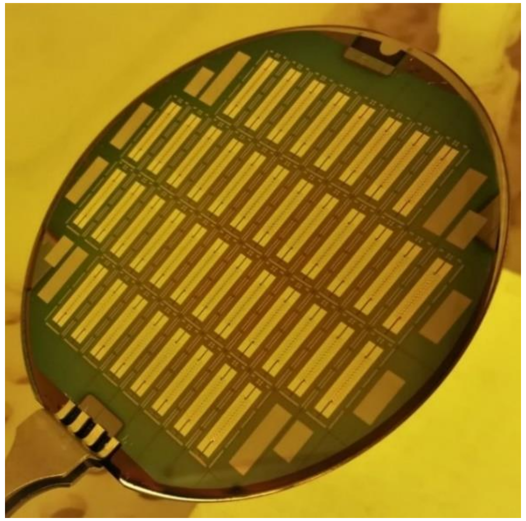
New ECHo-100k chip design



14 cm



6 wafer for ECHo-100k



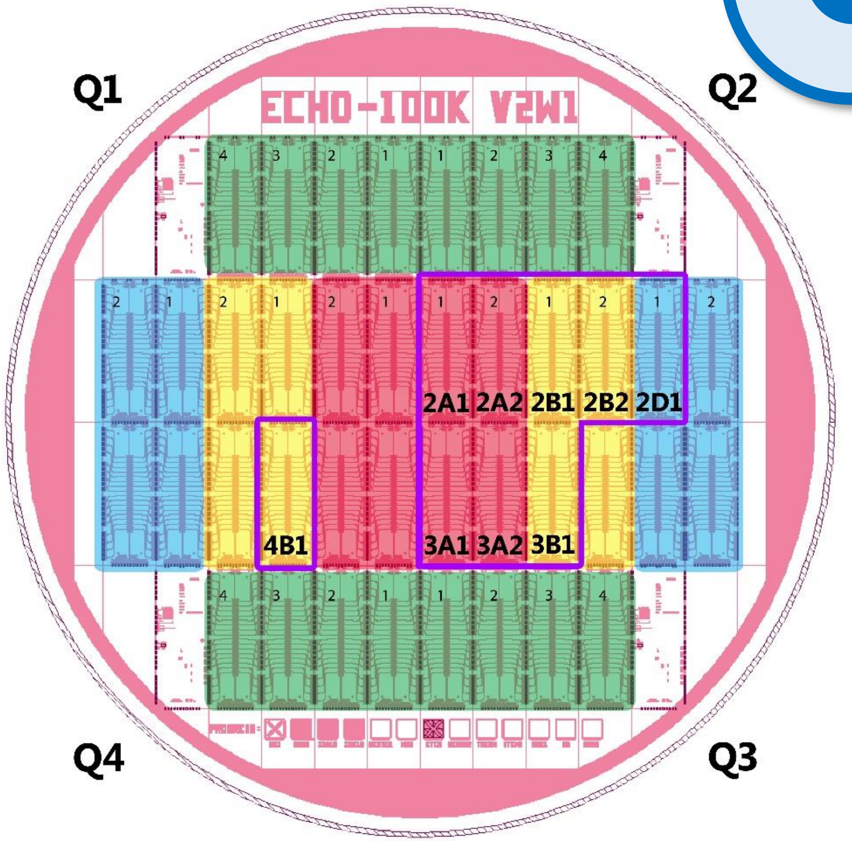
F. Mantegazzini et al., *NIM A* **1055** (2023) 168564

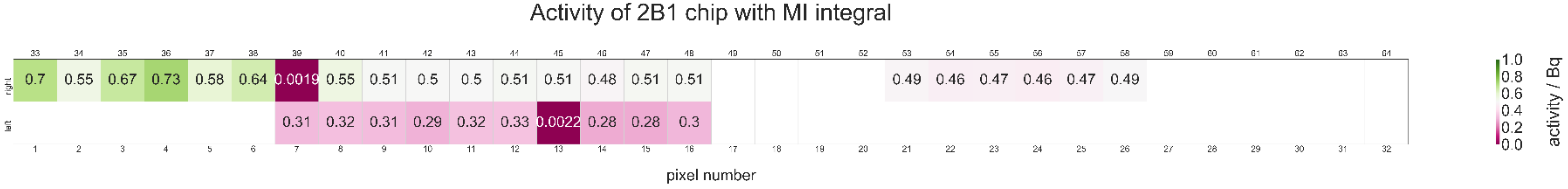
^{163}Ho Implantation for ECHo-100k

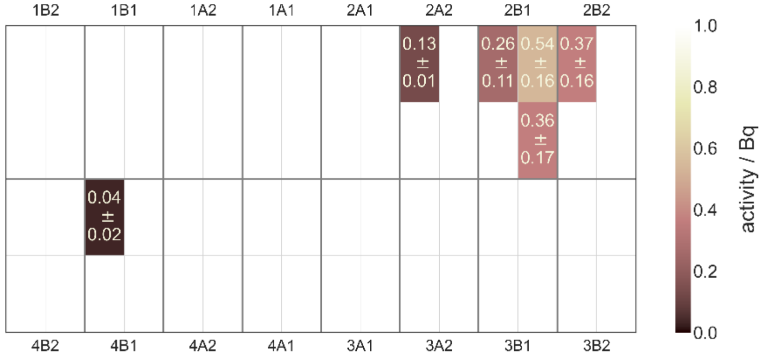
^{163}Ho available for coming experiments: 6×10^{18} atoms (30 MBq)

Ion implantation @ RISIKO, Institute of Physics, Mainz University

- Resonant laser ion source → $(69 \pm 5^{stat} \pm 4^{syst})$% efficiency
- Reduction of ^{166m}Ho in MMC → $^{166m}Ho/^{163}Ho < 4(2)10^{-9}$
- Optimization of beam focalization
- Implantation on wafer scale demonstrated







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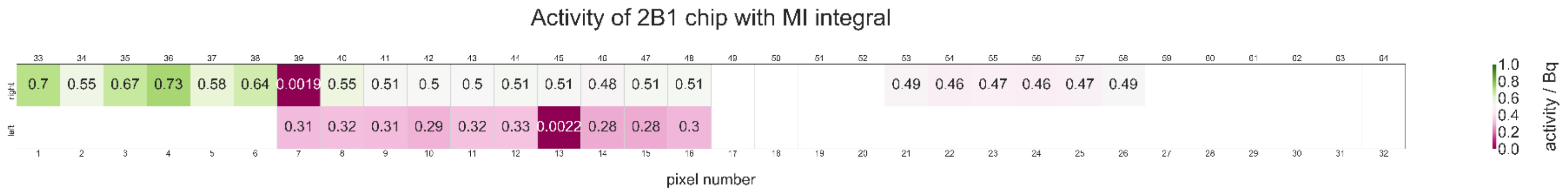
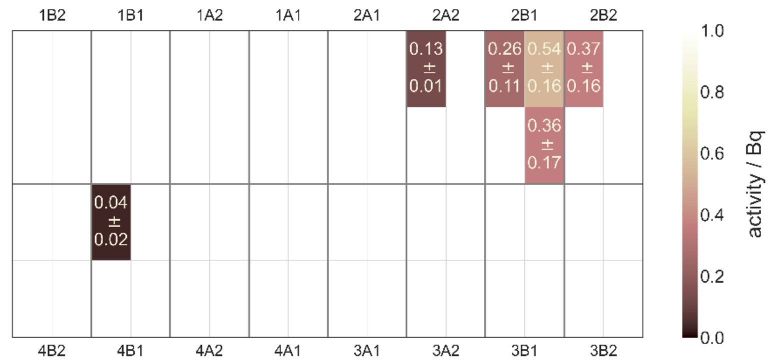


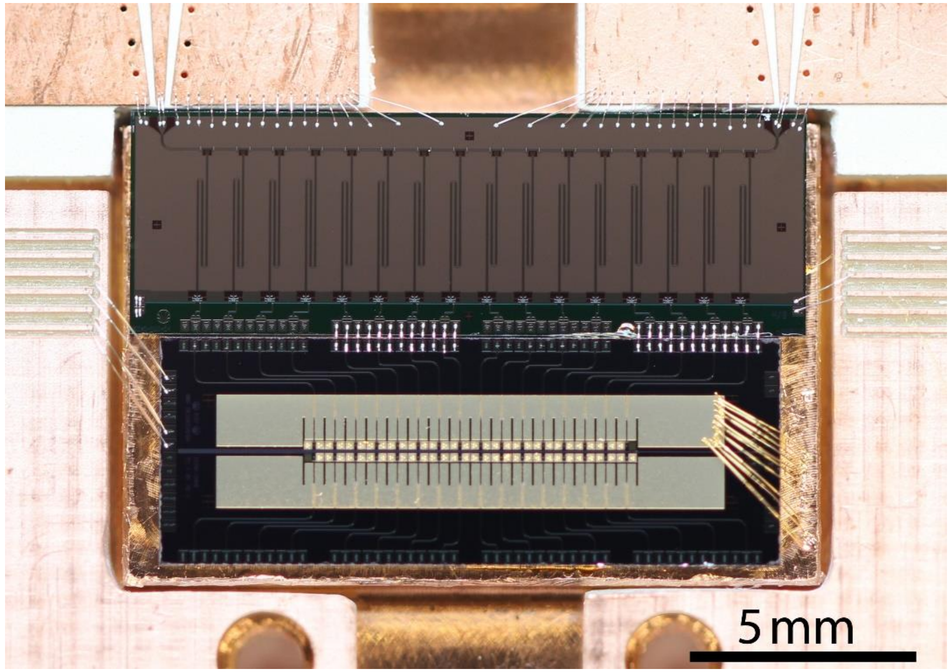


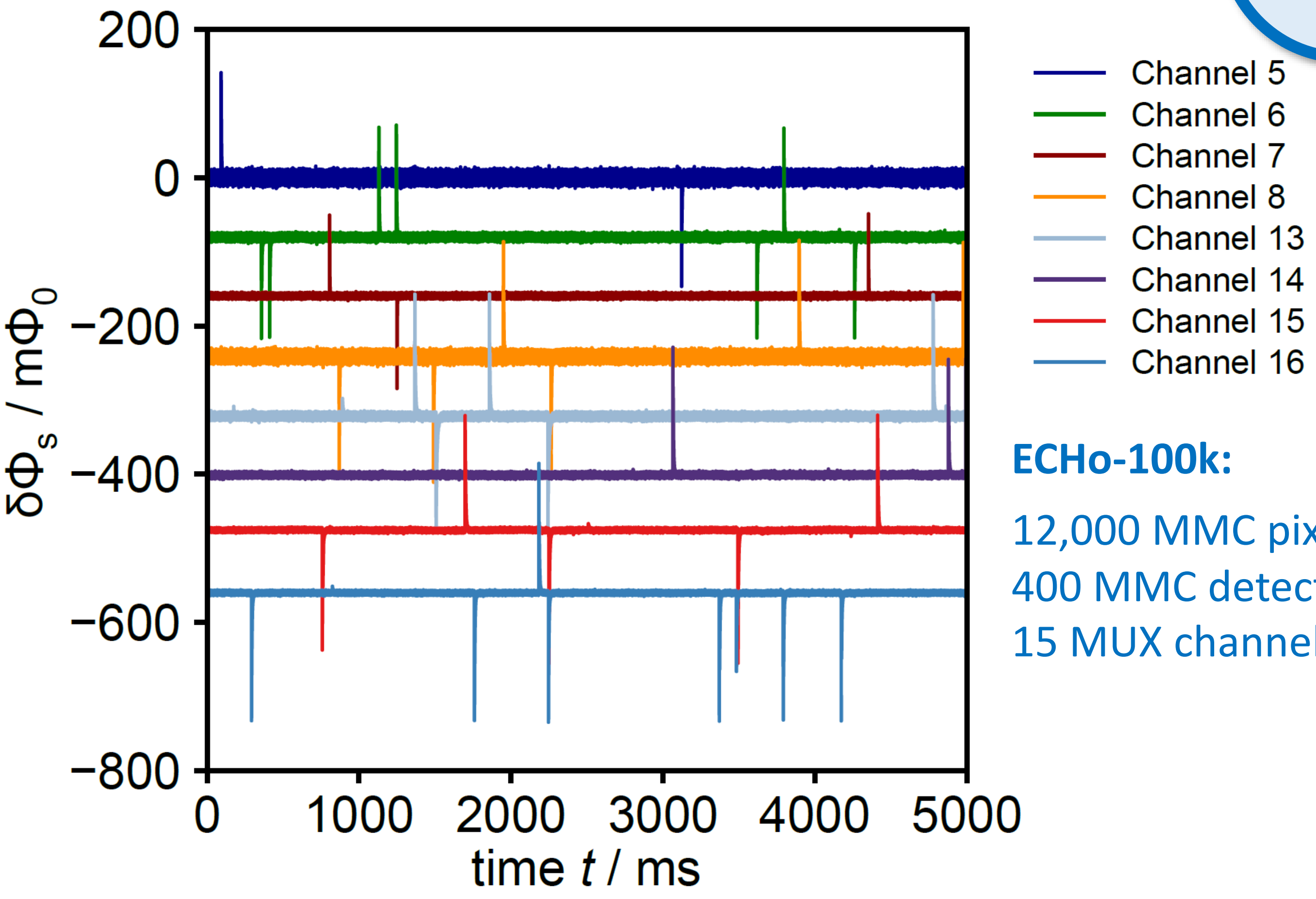
More in Raphael Hasse's talk tomorrow

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)





ECHo-100k:

12,000 MMC pixels = 400 MMC detectors × 15 MUX channels

S.Kempf et al., *J. Low. Temp. Phys.* **175** (2014) 850-860
M. Wegner et al., J. Low Temp. Phys. **193**, 462 (2018)

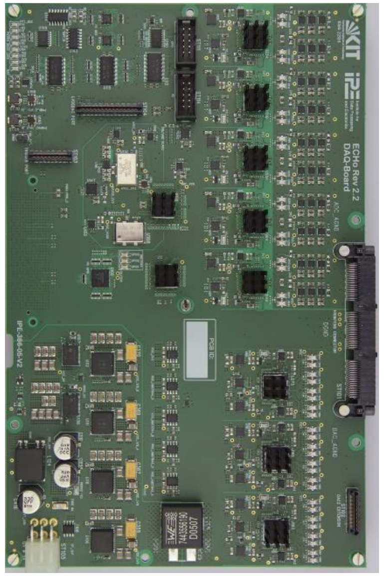
ECHo-100k – Multiplexing

- Full-scale readout electronics system ready for production of 15 units
- System would read 12000 sensors
- Real-time digital signal processing firmware is ready
- Capable of processing in the 160 Gb/s of raw data to just 30 Mb/s of demodulated sensor information

Muscheid, et. al. JINST 2022

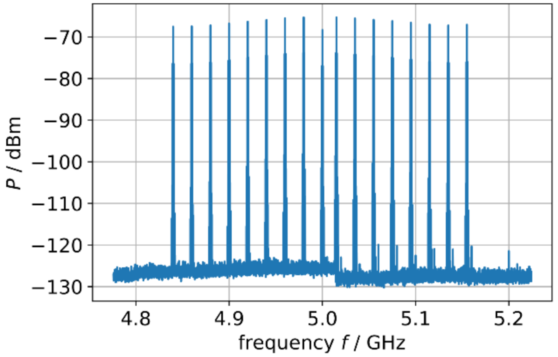
MMC + mux

RF Board

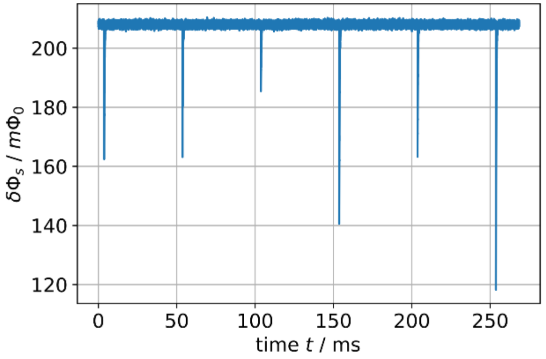


DAC + ADC

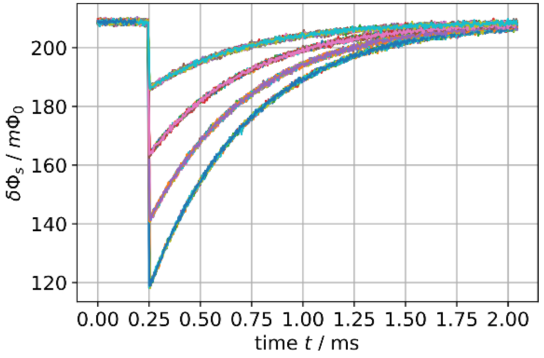
ZynqUS+ Board (DTS-100G)



Input HF signal



Demodulated detector signal



Extracted pulses

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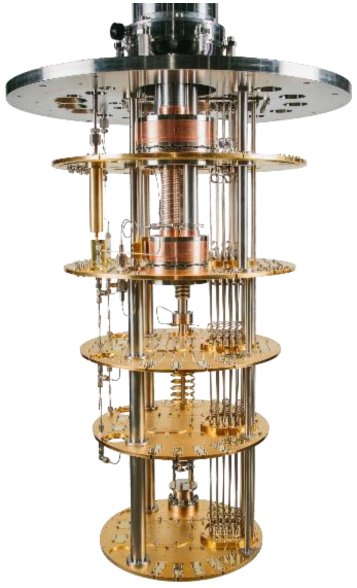
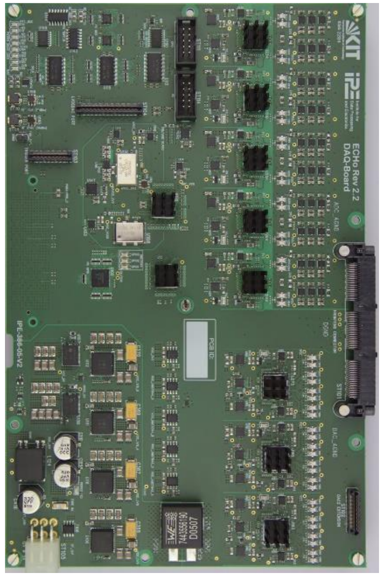
More in Robert Gartmann's talk tomorrow

Muscheid, et. al. JINST 2022



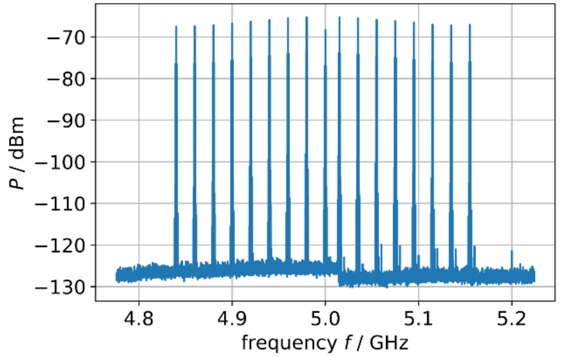
MMC + mux

RF Board

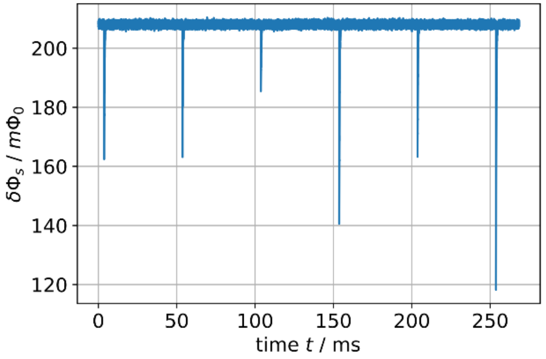


DAC + ADC

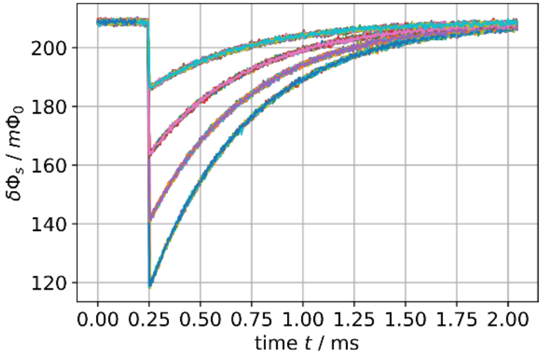
ZynqUS+ Board (DTS-100G)



Input HF signal

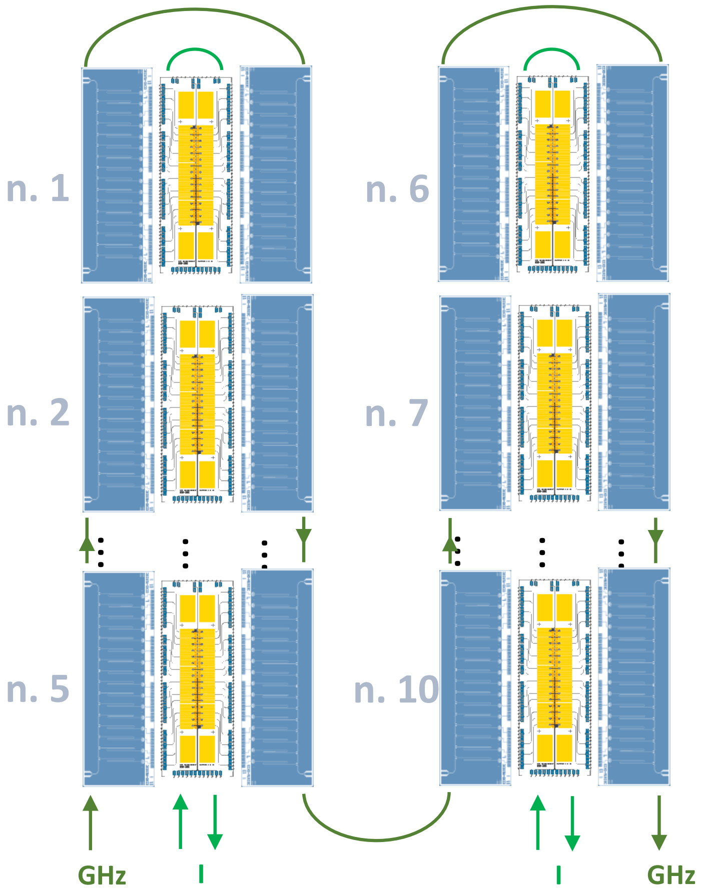


Demodulated detector signal



Extracted pulses

ECHo-100k for eV-scale sensitivity



Deutsche Forschungsgemeinschaft

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

ECHo-100k baseline: large arrays of metallic magnetic calorimeters

Number of detectors: 12000

Activity per pixel: 10 Bq (2 × 10^{12} ^{163}Ho atoms)

Present status:

High Purity ^{163}Ho source:

- available about 30 MBq

Ion implantation system:

- demostrated and continuously optimized

Metallic magnetic calorimeters

- reliable fabrication of large MMC array
- succesfull characterization of arrays with ^{163}Ho

Multiplexing and data acquisition:

- demostrated for 8 channels
- development of the SDR electronics
- Test with ^{163}Ho loaded MMC array on the way

Data reduction

- optimized energy independent algorithm to identify spurious traces

Conclusions

- The results obtained with ^{163}Ho loaded MMCs paved the way to large scale neutrino mass experiments based on ^{163}Ho
- The ECHo collaboration has already contributed to a more precise description of the ^{163}Ho spectrum
- 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
  - New analysis with clear quality control parameters on-going
  - Goal: 20 eV on the effective electron neutrino mass
- Important steps towards ECHo-100k have been demonstrated
  new ECHo-100k array + implantation of wafer scale + multiplexed readout

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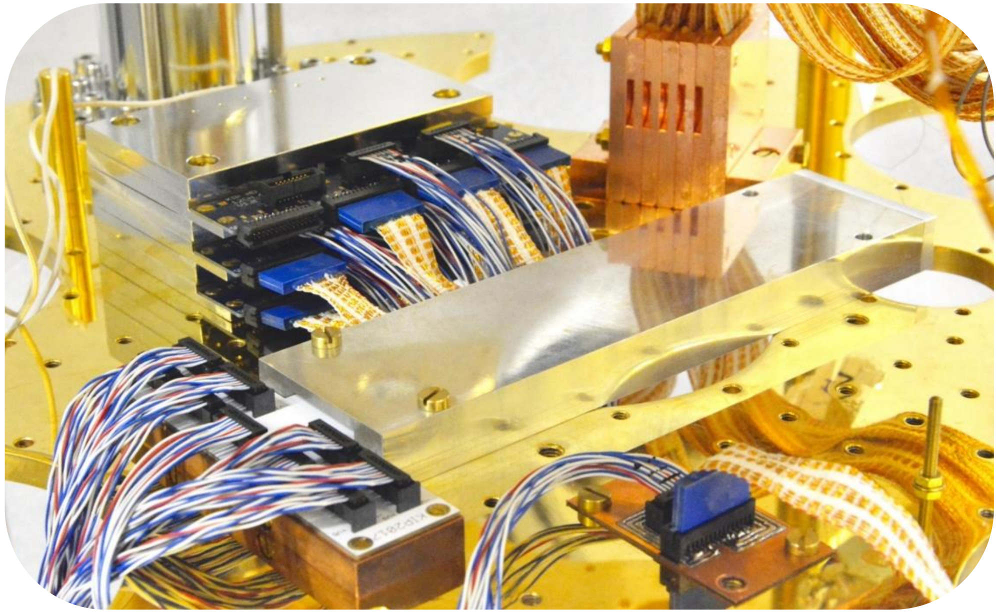
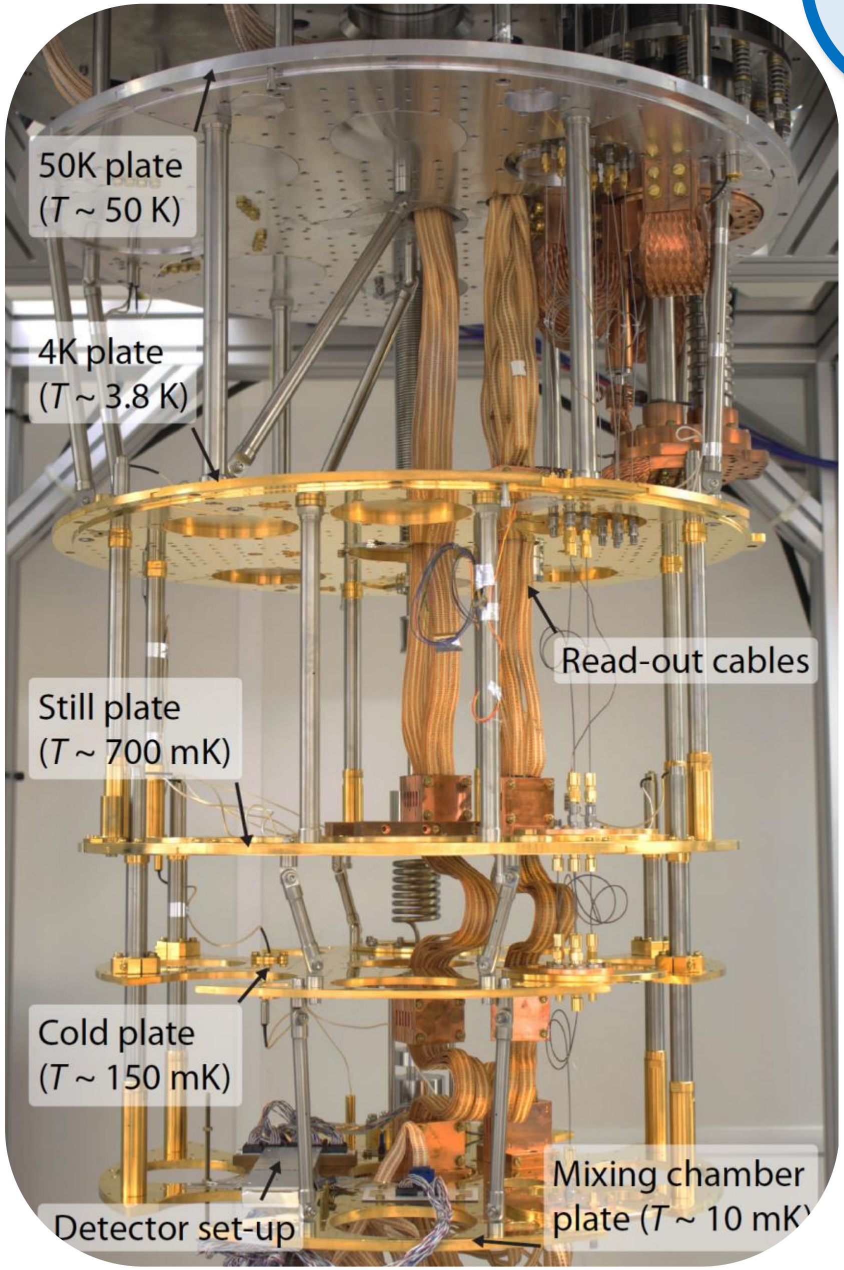
DFG Deutsche Forschungsgemeinschaft
Research Unit FOR 2202

Thank you!

ECHo-1k read-out



F. Mantegazzini et al., *JINST* **16** (2021) P08003



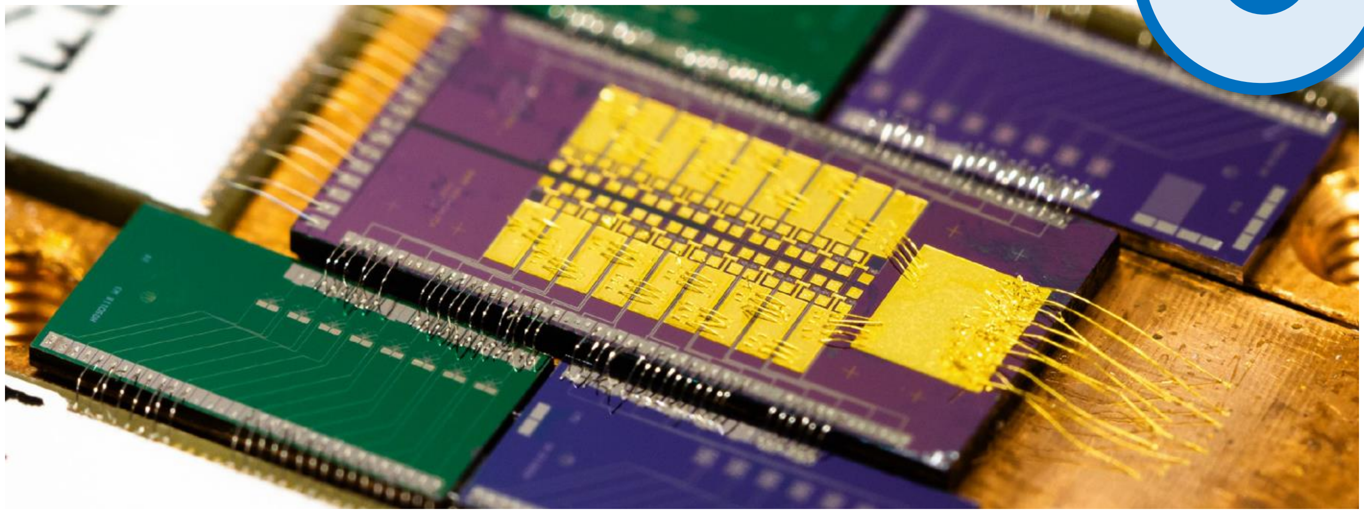
ECHo-1k high statistics spectrum

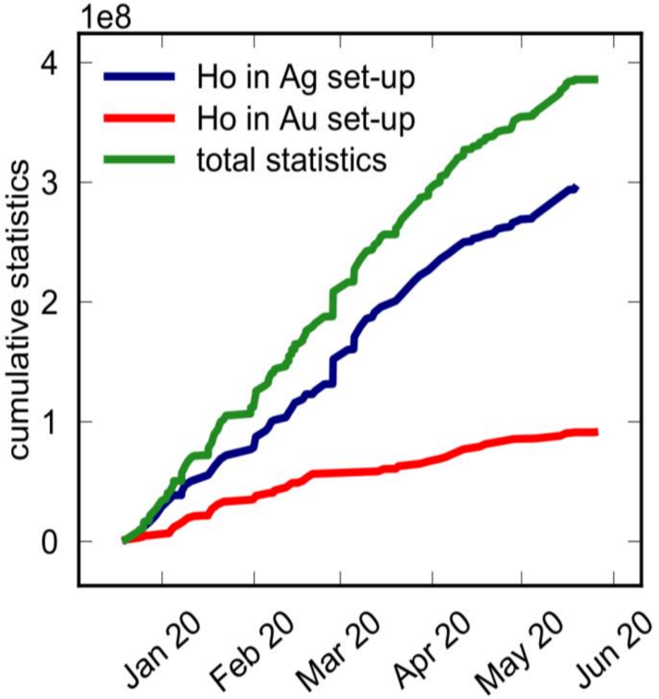
ECHo-1k chip-Au

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

ECHo-1k chip-Ag

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





Quality checks on data reduction cuts and spectra features