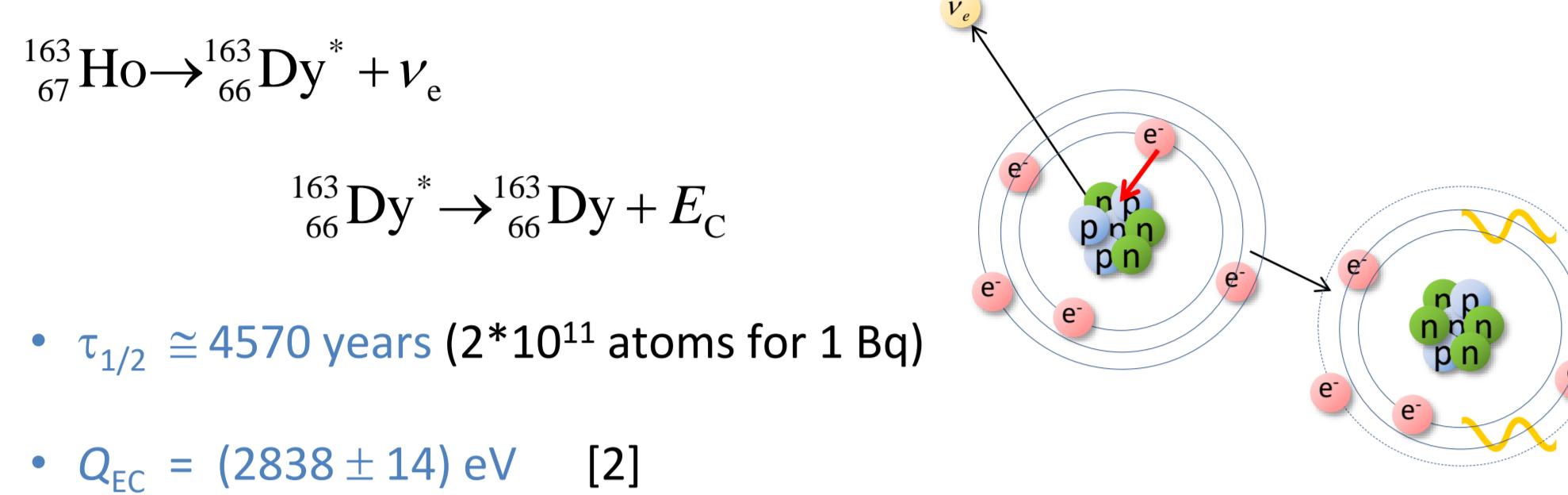


# The Electron Capture in $^{163}\text{Ho}$ Experiment

L. Gastaldo, F. Ahrens, A. Barth, C. Enss, A. Fleischmann, R. Hammann, D. Hengstler, S. Kempf, F. Mantegazzini, A. Reifenberger, D. Richter, C. Velte, M. Wegner, T. Wieckenhäuser Kirchhoff Institute for Physics, Heidelberg University; M. Brass, M. Haverkort, Institute for theoretical physics, Heidelberg University; K. Blaum, M. Door, S. Eliseev, P. Filianin, A. Rischka, R. Schüssler, C. Schweiger, Max-Planck-Institut für Kernphysik; Y. Novikov Petersburg Nuclear Physics Institute, Gatchina; J. Jochum and A. Göggelmann, Physikalisches Institut, Eberhard Karls Universität Tübingen; Ch. E. Düllmann, H. Dorrer, T. Kieck, N. Kneip, K. Wendt Johannes Gutenberg-Universität Mainz; Institute of Physics; K. Johnston, B. Marsh, S. Rothe, T. Stora ISOLDE, CERN; U. Köster Institut Laue-Langevin, Grenoble; N. Karcher, O. Sander, M. Weber Institut für Prozessdatenverarbeitung und Elektronik, Karlsruher Institut für Technologie

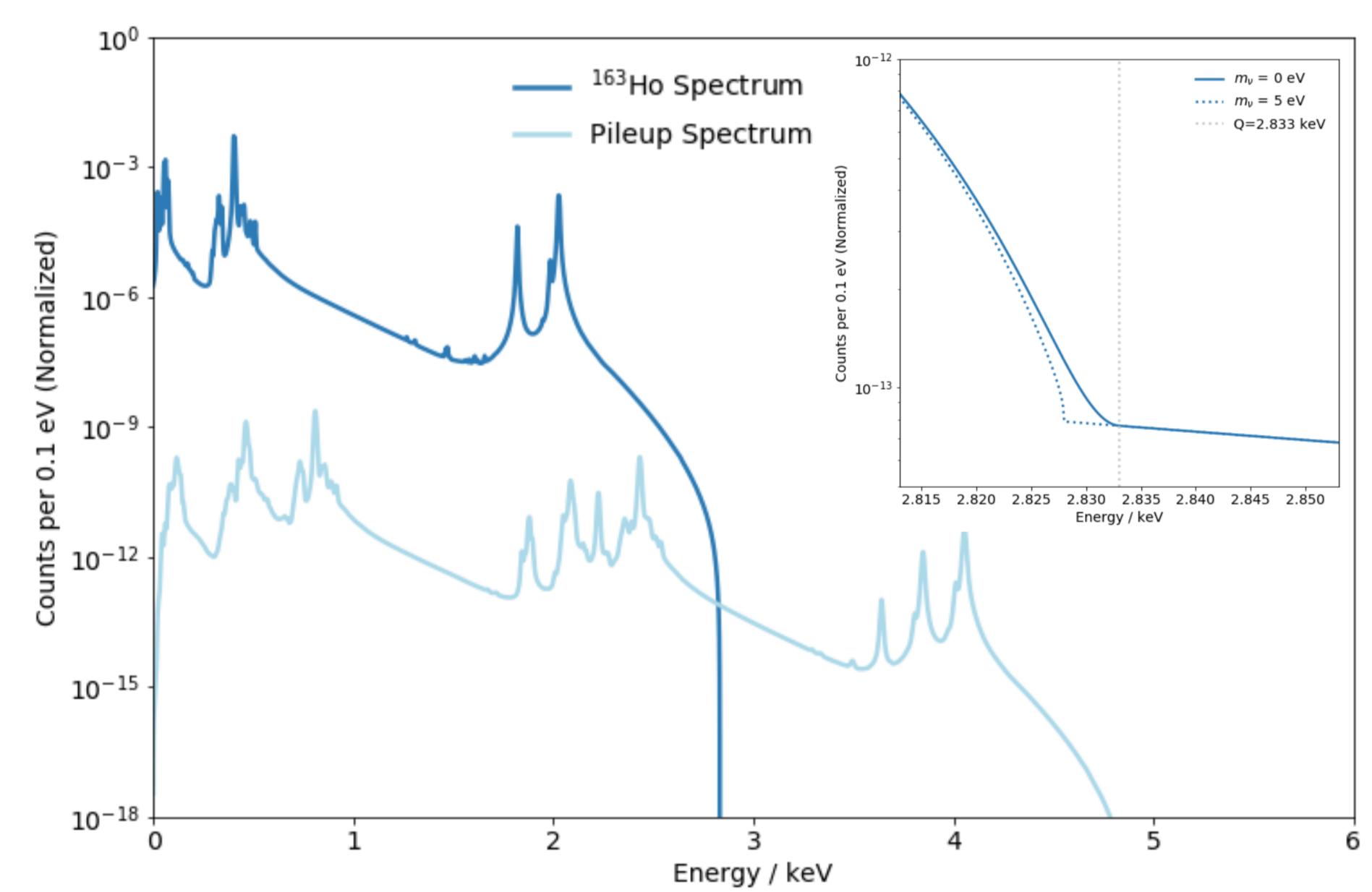
## The ECHO experiment



The energy available to the decay  $Q_{EC}$  is shared between the  $\nu_e$  and the excited state of the daughter  $^{163}\text{Dy}$  atom (plus a negligible fraction nuclear recoil)

Calorimetric measurement with  $^{163}\text{Ho}$  source enclosed in a detector able to stop 100% of the energy released during the EC process besides the energy of the  $\nu_e$  allows for a reduction of systematic uncertainties due to energy losses and branching ratios for different de-excitation processes [3]

A precise knowledge of the  $^{163}\text{Ho}$  spectrum relies in the understanding of the possible final states a  $^{163}\text{Dy}$  atom can be left in after EC in  $^{163}\text{Ho}$  [4]



Challenges to reach sub-eV sensitivity with  $^{163}\text{Ho}$  based experiments:

Statistics in the end point region

- $N_{ev} > 10^{14} \rightarrow A \approx 1 \text{ MBq}$

Precision characterization of the endpoint region

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

Precise determination of the energy scale

- Less than 1 eV uncertainty in the endpoint region

Background reduction (natural radioactivity, including muon related events, and pile-up)

- Background level  $< 10^{-6}$  events/eV/det/day
- Unresolved pile-up fraction  $f_{pu} < 10^{-6}$

Limit on activity per detector due to un-resolved pile-up

- $f_{pu} < 10^{-6}$
- $\tau_r < 1 \mu\text{s} \rightarrow a < 10 \text{ Bq}$

ECHO is designed to reach sub-eV sensitivity on the  $\nu_e$  mass by using large arrays of multiplexed metallic magnetic calorimeters (MMCs) with enclosed high purity  $^{163}\text{Ho}$  source

## ECHO in a nutshell

### $^{163}\text{Ho}$ high purity source production

Er161	Er162	Er163	Er164	Er165	Er166
3.21 h	0+	5.2 h	0+	10.36 h	0+
3/2-	EC	5/2-	EC	5/2-	100
Ho160	Ho161	Ho162	Ho163	Ho164	Ho165
25.6 m	2.48 h	15.0 m	1.70 y	29 m	72-
5+*	7-*	1+*	EC	1+*	
EC	EC	EC	EC	EC	

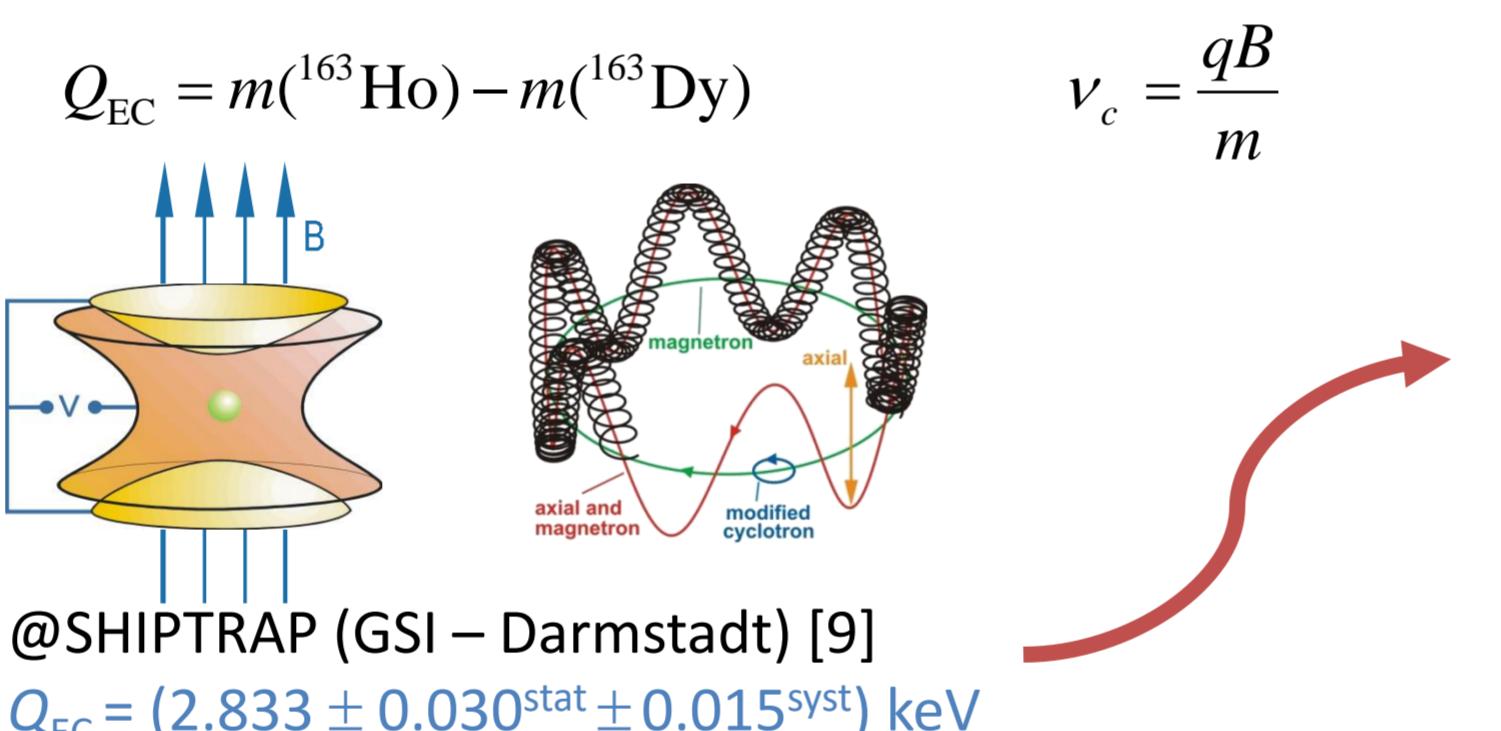
Neutron irradiation:  $(n,\gamma)$ -reaction on enriched  $^{162}\text{Er}$  at ILL Grenoble

- Excellent chemical separation: 95% efficiency
- Available  $^{163}\text{Ho} \sim 2 \times 10^{18}$  atoms (10 MBq – 300  $\mu\text{g}$ )
- Detailed sample characterization performed [5]

### $^{163}\text{Ho}$ $Q_{EC}$ -value determination:

Penning Trap Mass Spectroscopy using high purity  $^{163}\text{Ho}$  samples

- Measurement which does not depend on EC process
- Important parameter for validation of the analysis of the  $^{163}\text{Ho}$  EC spectrum in the endpoint region



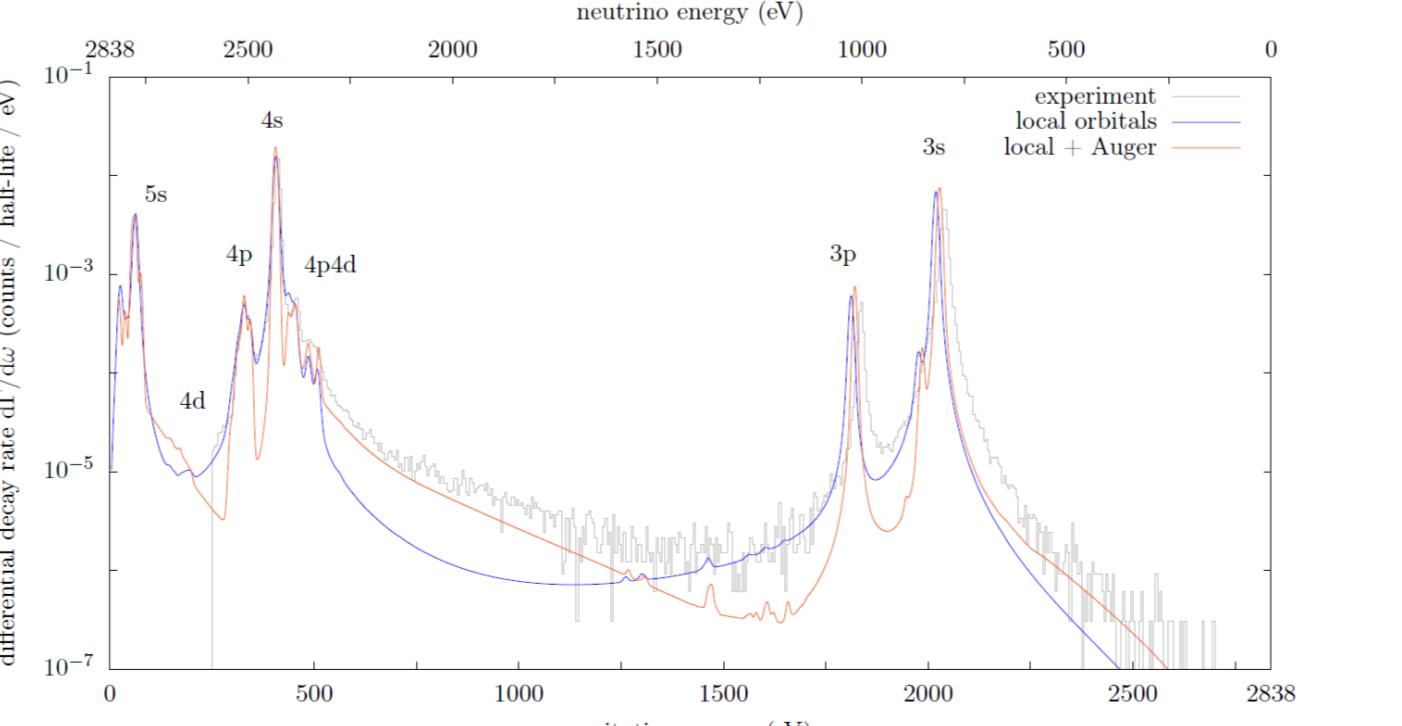
Perfect agreement with  $Q_{EC}$  derived from the analysis of the calorimetric spectrum

Future goal: 1 eV precision:  
PENTATRAP @MPIK, Heidelberg [10,11]

### Theoretical description of the $^{163}\text{Ho}$ spectrum

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

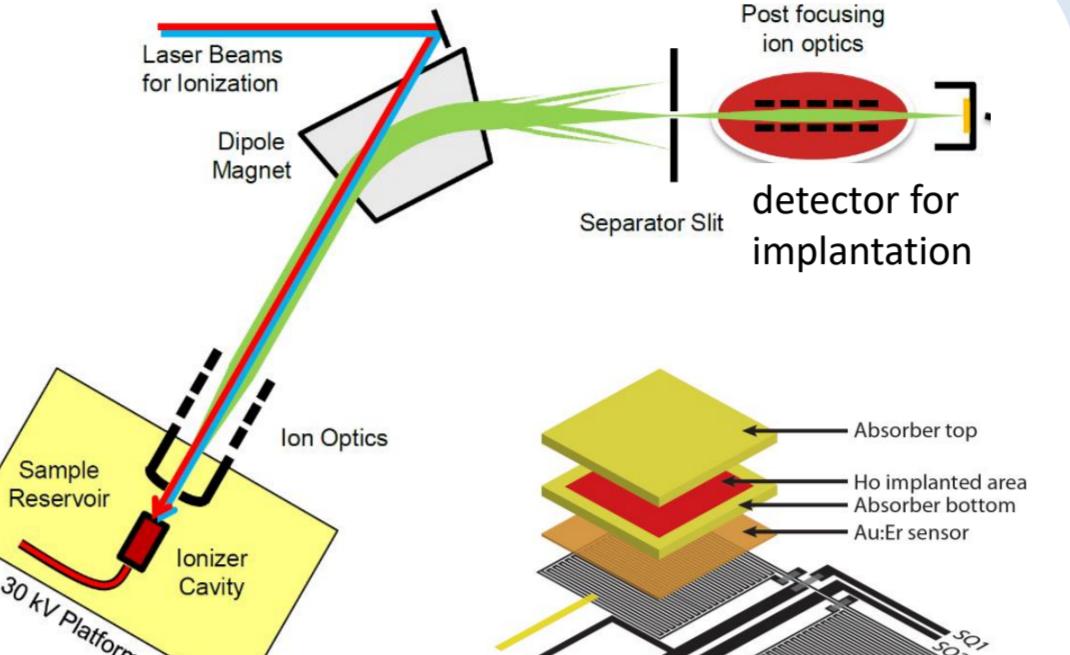
- The  $^{163}\text{Ho}$  spectrum is dominated by resonances due to local atomic multiplet states with core holes.
- Coulomb scattering between electrons couples the discrete atomic states, via Auger-Meitner decay, to final states with free electrons.



The present theory justifies the enhancement in count rate observed at the endpoint region [2, 4, 15]

### Mass separation and $^{163}\text{Ho}$ ion implantation

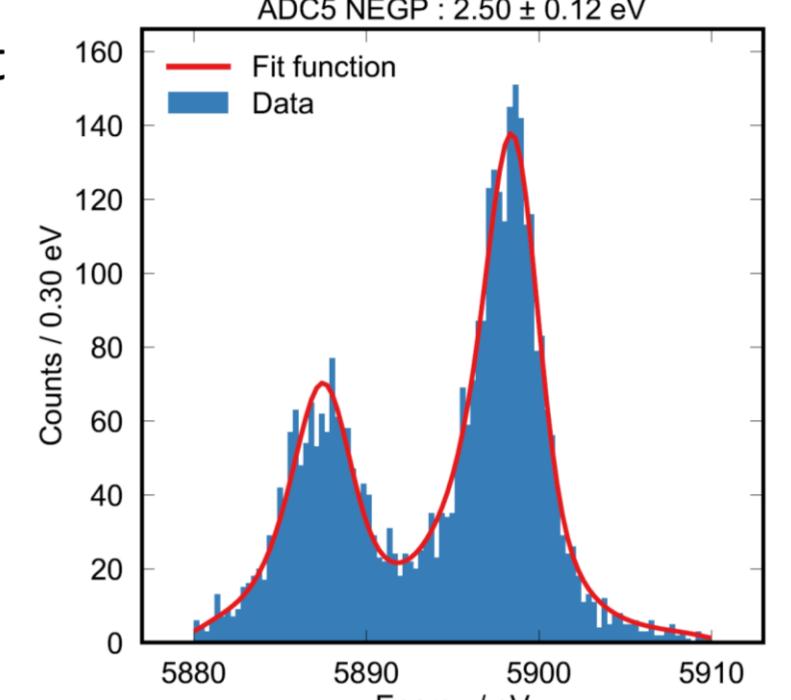
- RISIKO @Institute of Physics, Mainz University [6, 7, 8]
- Fraction of high purity  $^{163}\text{Ho}$  source as starting sample
  - Resonant laser ion source efficiency:  $(69 \pm 5^{\text{stat}} \pm 4^{\text{syst}})\%$
  - Reduction of  $^{166}\text{Ho}$  in MMC:  $^{166}\text{Ho}/^{163}\text{Ho} < 4(2)10^{-9}$
  - Optimization of beam focalization



### MMC with enclosed $^{163}\text{Ho}$ [12]

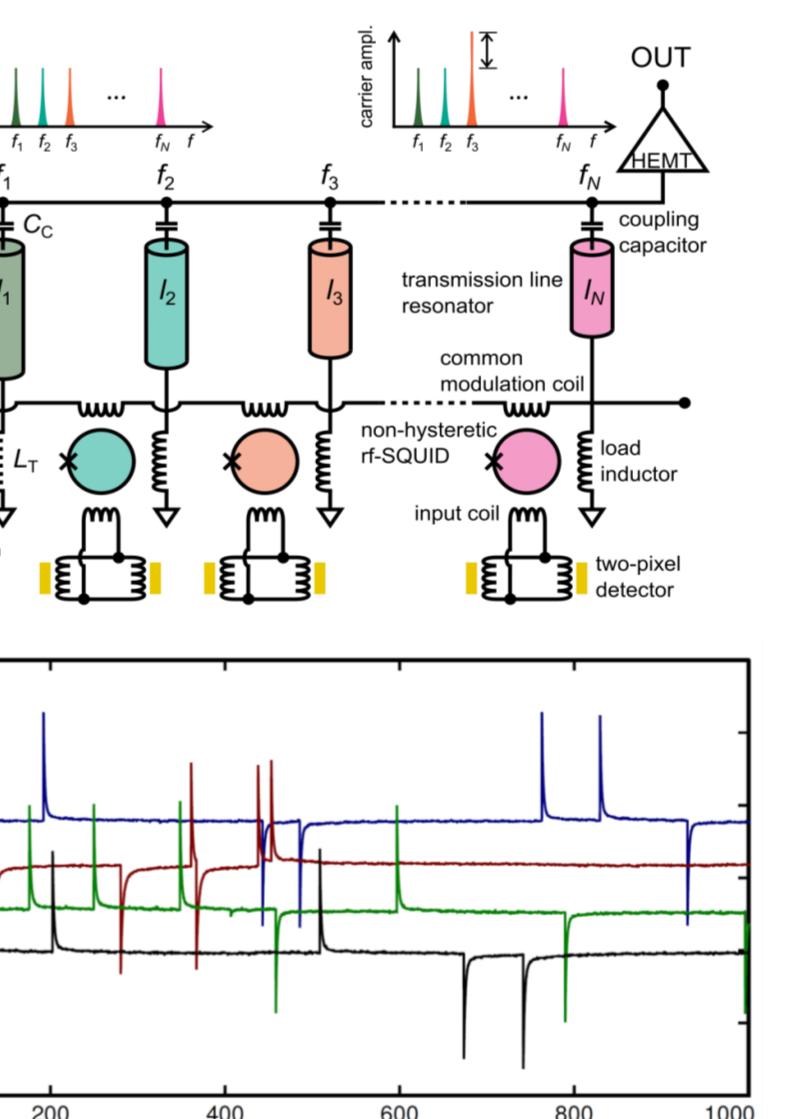
Microcalorimeters operated at  $\sim 20$  mK in a dedicated dilution cryostat

- Fabrication of large MMC arrays and post-processing after ion-implantation are well-established
- Achieved energy resolution below 3 eV FWHM
- Reliable operation over several months
- Reliable data reduction



### Multiplexed readout of MMC arrays

- Microwave multiplexed readout of MMC demonstrated [13]
- Room temperature electronics for larger number of detectors/channel (goal 400 det/ch) [14]



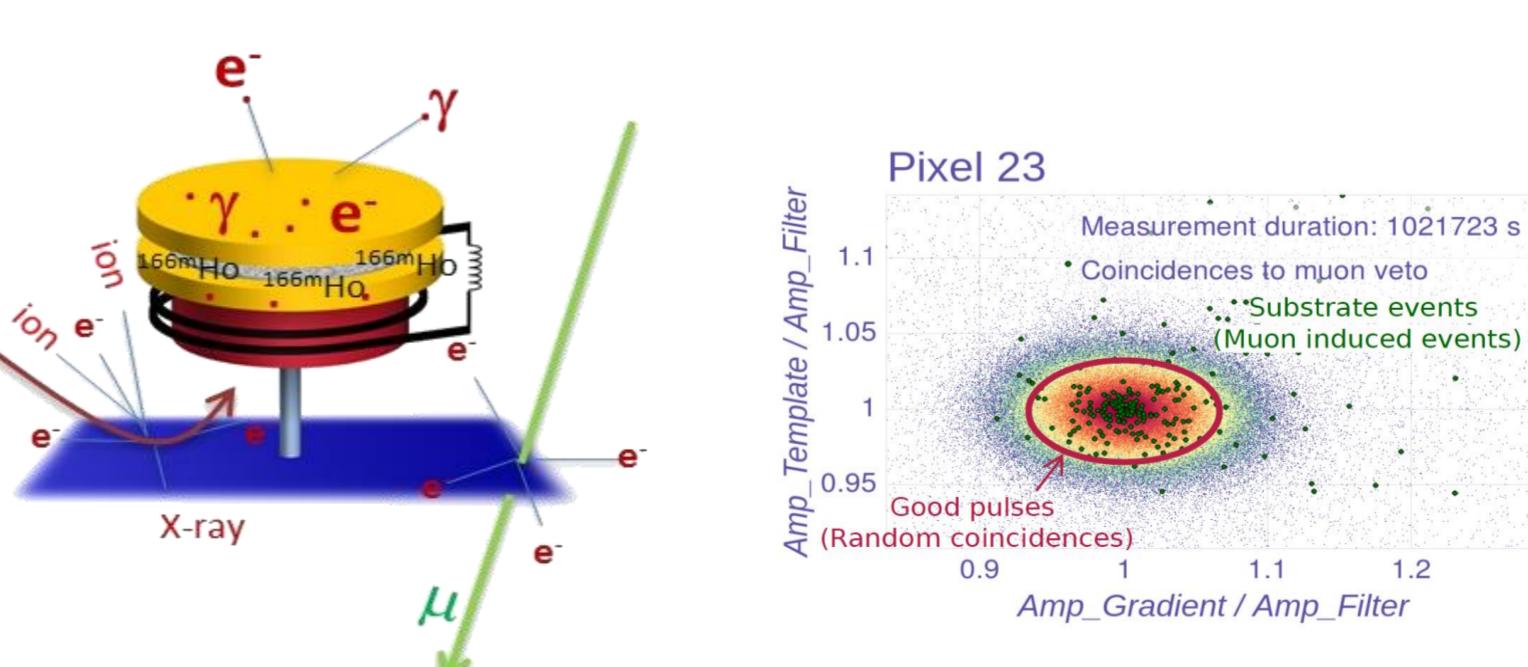
### Data Analysis with input from:

- $^{163}\text{Ho}$  source characterization
- Detector properties: energy resolution, response time and activity per pixels
- Background model
- Theoretical spectral shape
- Independent  $Q_{EC}$ -value

### Background sources identification and suppression

Preparation of background model for ECHO [16]

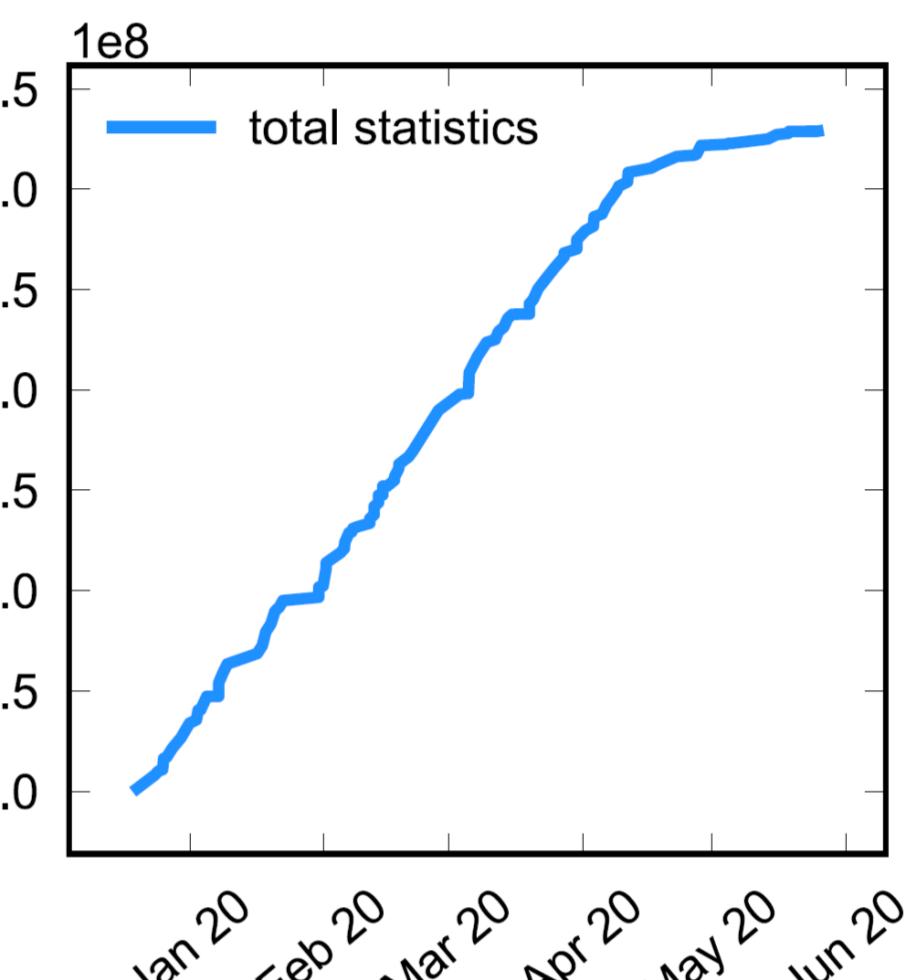
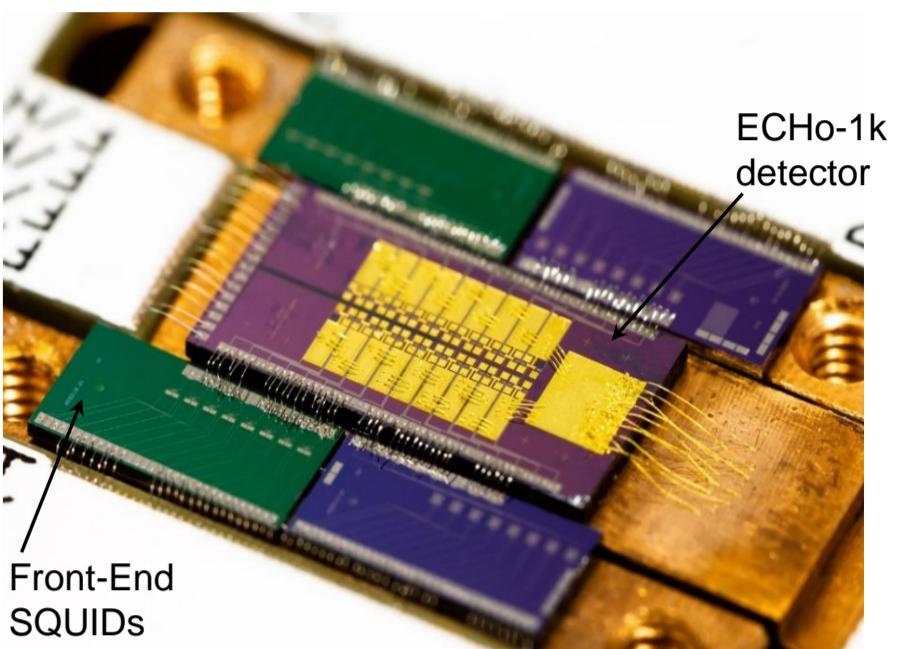
- Effect of natural radioactivity studied via material screening and Monte Carlo simulation
- Experiments with muon veto demonstrate that muon related events discriminated via pulse shape
- Effect of low energy secondary radiation is being investigated via Monte Carlo simulations



## ECHO experiment phases

### ECHO-1k:

- Activity per pixel:  $\sim 1$  Bq
- Number of detectors:  $\sim 60$
- Readout: parallel two stage SQUID
- Data Acquisition completed
- Data Analysis on-going



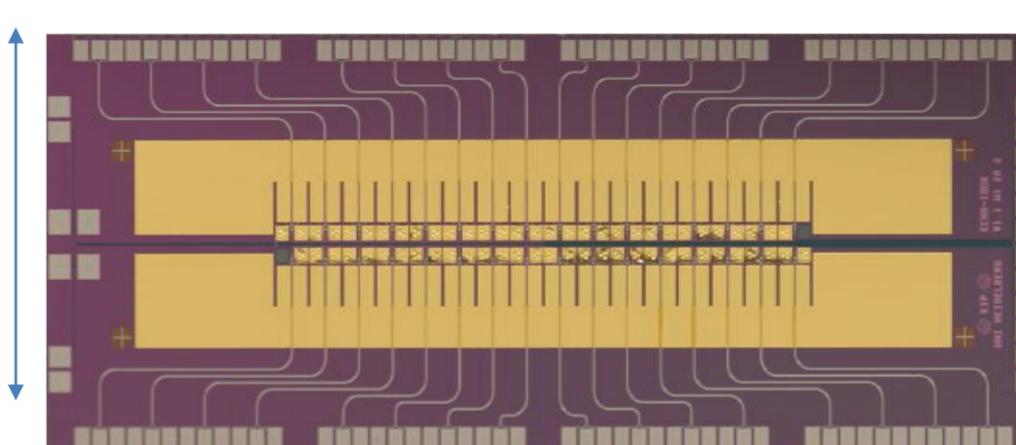
Total number of counts for the ECHO-1k experiment before applying any cut ( $\sim 10\%$  loss)

- The goal to reach  $10^8$   $^{163}\text{Ho}$  events has been reached
- Achievable sensitivity  $m(\nu_e) < 20$  eV

### Towards ECHO-100k

#### ECHO-100k chip have been fabricated [12]

- Single pixel optimization:  $^{163}\text{Ho}$  activity per pixel  $\alpha \approx 10$  Bq
- Suitable for parallel and multiplexed readout
- Upgrade of RISIKO system for 10 Bq/pixel  $^{163}\text{Ho}$ -implantation



Microwave multiplexed readout for about 12000 pixels

- New microwave channels in ECHO cryostat

### Description of the $^{163}\text{Ho}$ spectrum

- Background model based on the results of ECHO-1k
- 1 eV precision on the  $Q_{EC}$  value from Penning trap mass spectrometry
- Effect of the host material on the EC process

### Target sensitivity:

- About  $10^{13}$  events can be acquired over three years of measurements
- Achievable sensitivity  $m(\nu_e) < 2$  eV

### References

- [1] L. Gastaldo et al., *EPL-ST* **226** (2017) 1623
- [2] C. Velte et al., *Eur. Phys. J. C* **79** (2019) 1026
- [3] A. De Rujula, M. Lusignoli, *Phys. Lett. B* **118** (1982) 429
- [4] M. Brass, M. Haverkort, [arXiv:2002.05989](https://arxiv.org/abs/2002.05989)
- [5] H. Dorrer et al., *Radiochim. Acta* **106**(7) (2018) 535
- [6] F. Schneider et al., *NIM B* **376** (2016) 388
- [7] T. Kieck et al., *Rev. Sci. Inst.* **90** (2019) 053304
- [8] T. Kieck et al., *NIM A* **945** (2019) 162602
- [9] S. Eliseev et al., *Phys. Rev. Lett.* **115** (2015) 062501
- [10] J. Repp et al., *Appl. Phys. B* **107** (2012) 983
- [11] C. Roux et al., *Appl. Phys. B* **107** (2012) 997
- [12] F. Mantegazzini et al., to be submitted
- [13] M. Wegner et al., *J. Low Temp. Phys.* **193** (2018) 462
- [14] O. Sander, *IEEE TRANSACTIONS ON NUCLEAR SCIENCE* **66** (2019) 1204
- [15] M. Brass, M. Haverkort, *Phys. Rev. C* **97** (2018) 054620
- [16] A. Göggelmann et al., to be submitted

V  
e