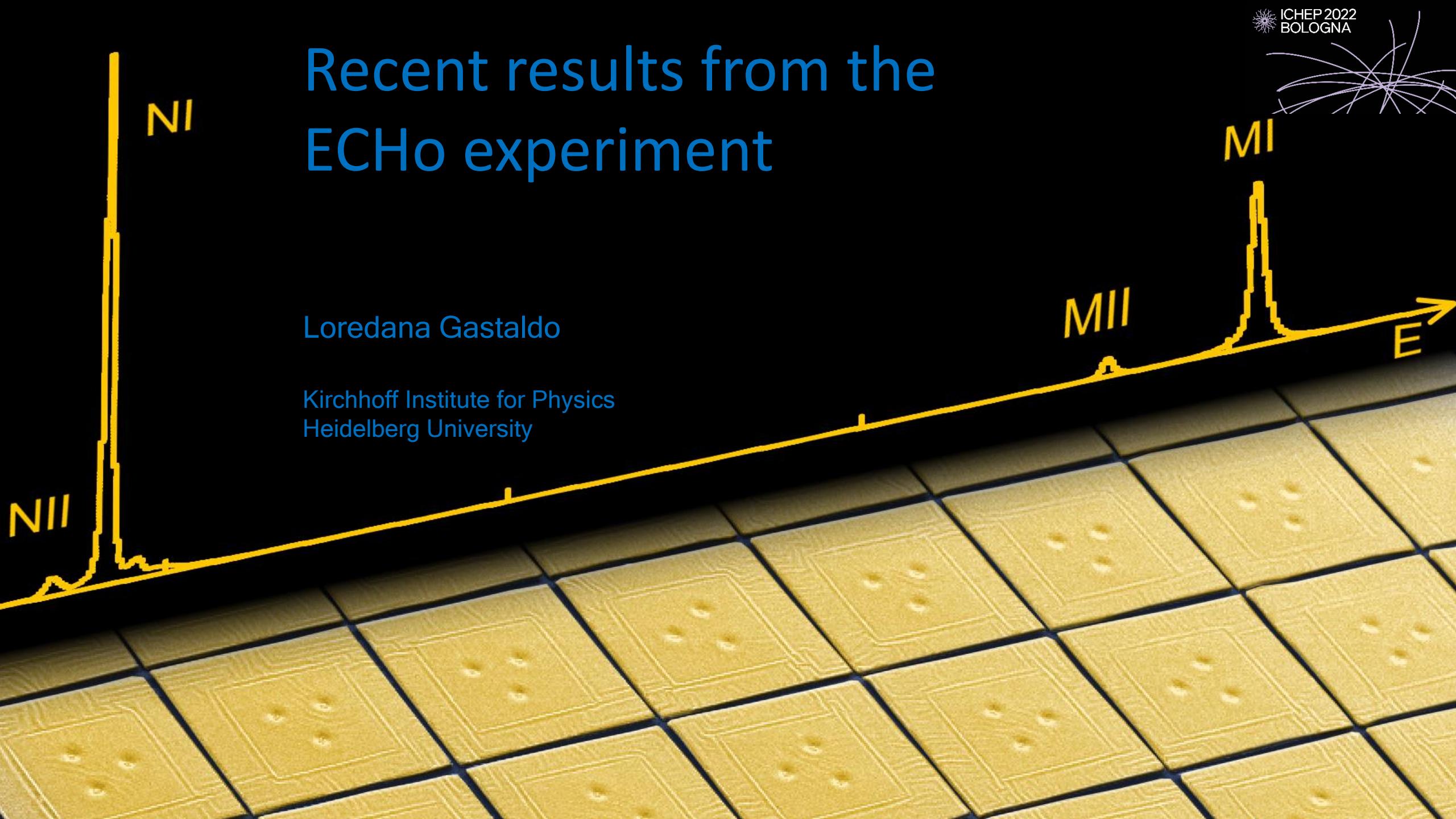


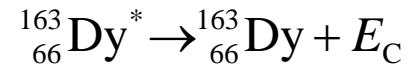
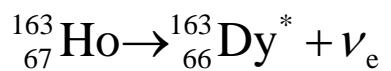
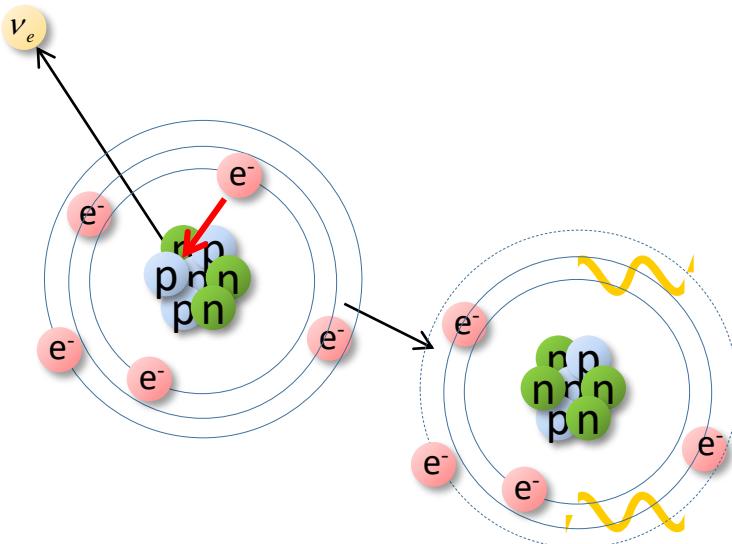
Recent results from the ECHO experiment

Loredana Gastaldo

Kirchhoff Institute for Physics
Heidelberg University

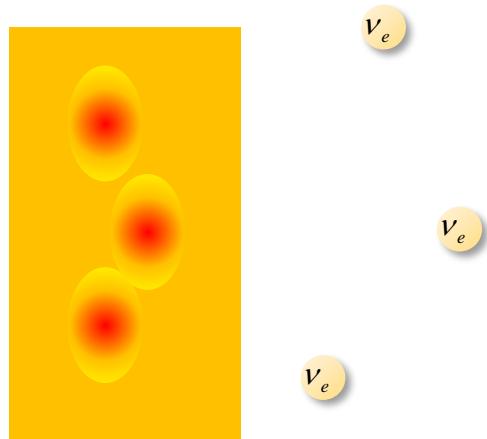


Electron Capture in ^{163}Ho – Spectrum



- $\tau_{1/2} \cong 4570 \text{ years}$ (2×10^{11} atoms for 1 Bq)
- $Q_{EC} = (2.833 \pm 0.030^{\text{stat}} \pm 0.015^{\text{syst}}) \text{ keV}$

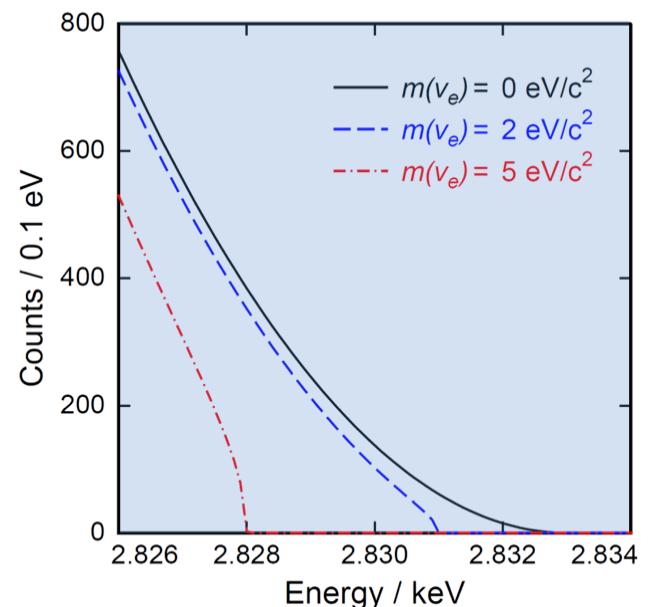
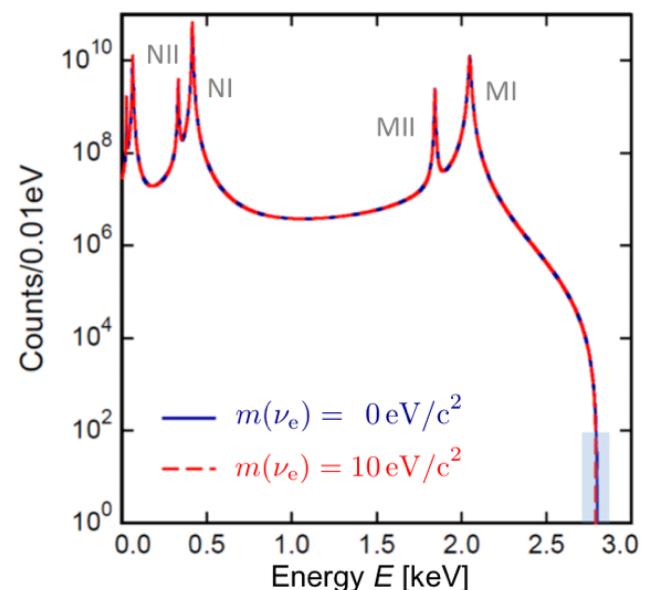
S. Eliseev et al., *Phys. Rev. Lett.* **115** (2015) 062501



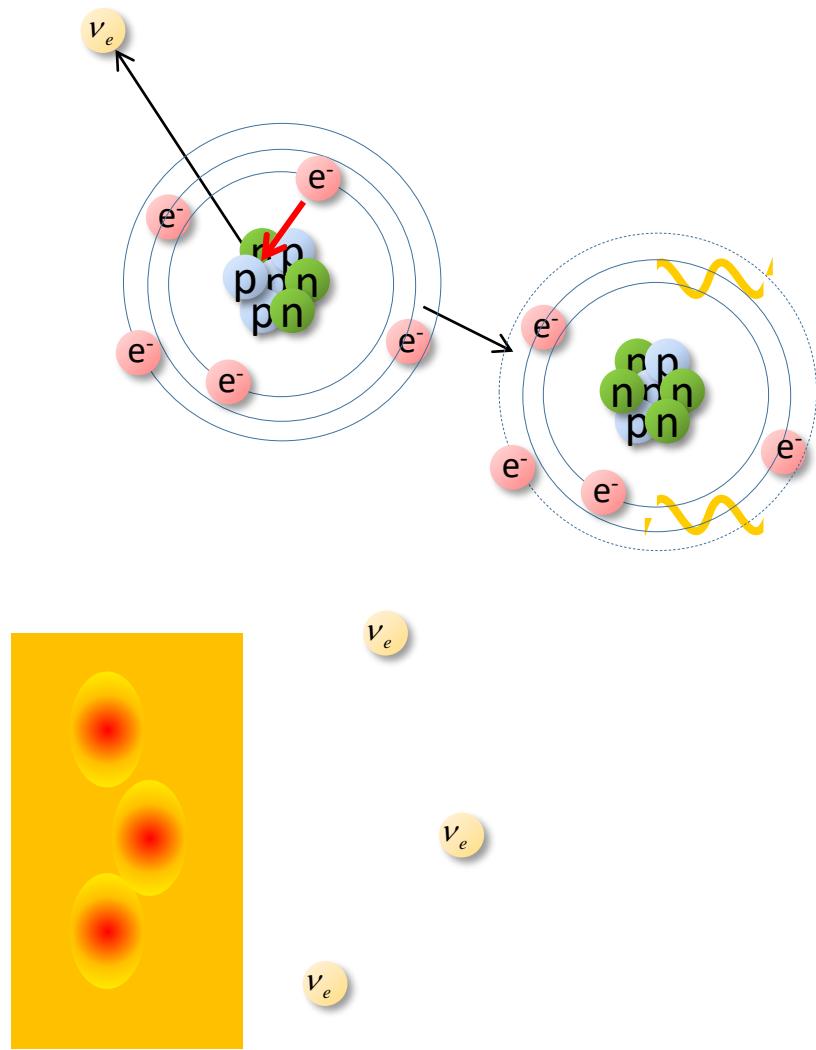
Source = Detector

Calorimetric measurement

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



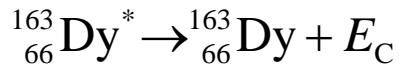
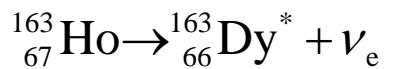
Electron Capture in ^{163}Ho – Spectrum



Source = Detector

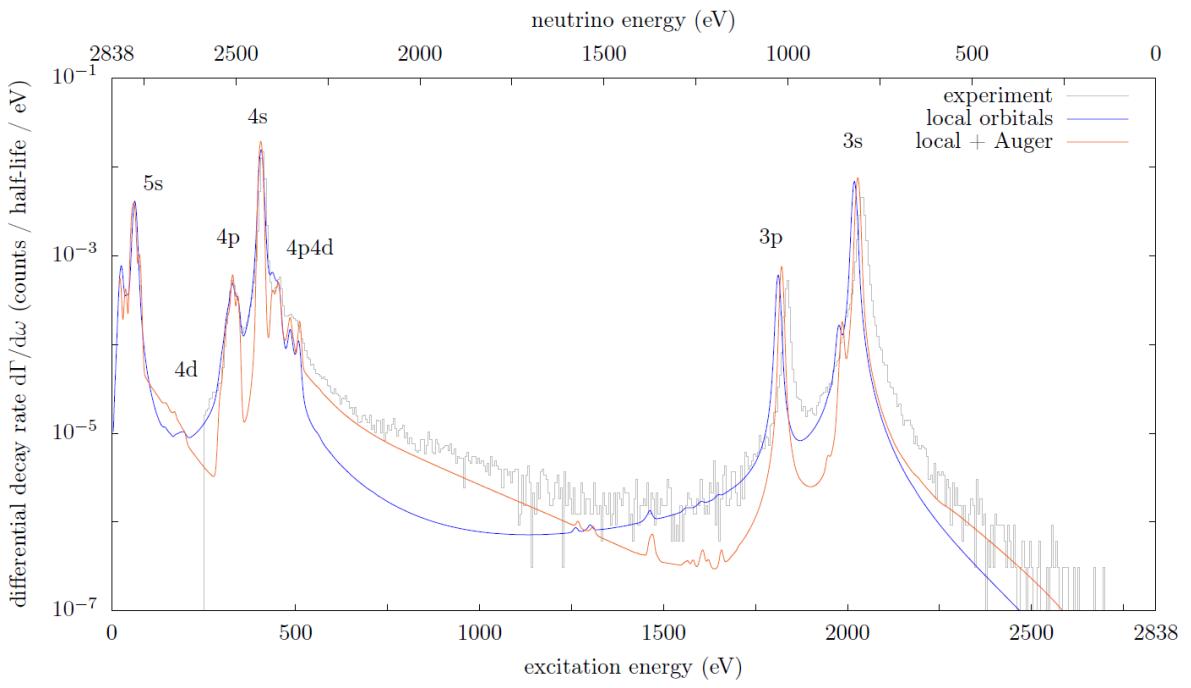
Calorimetric measurement

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



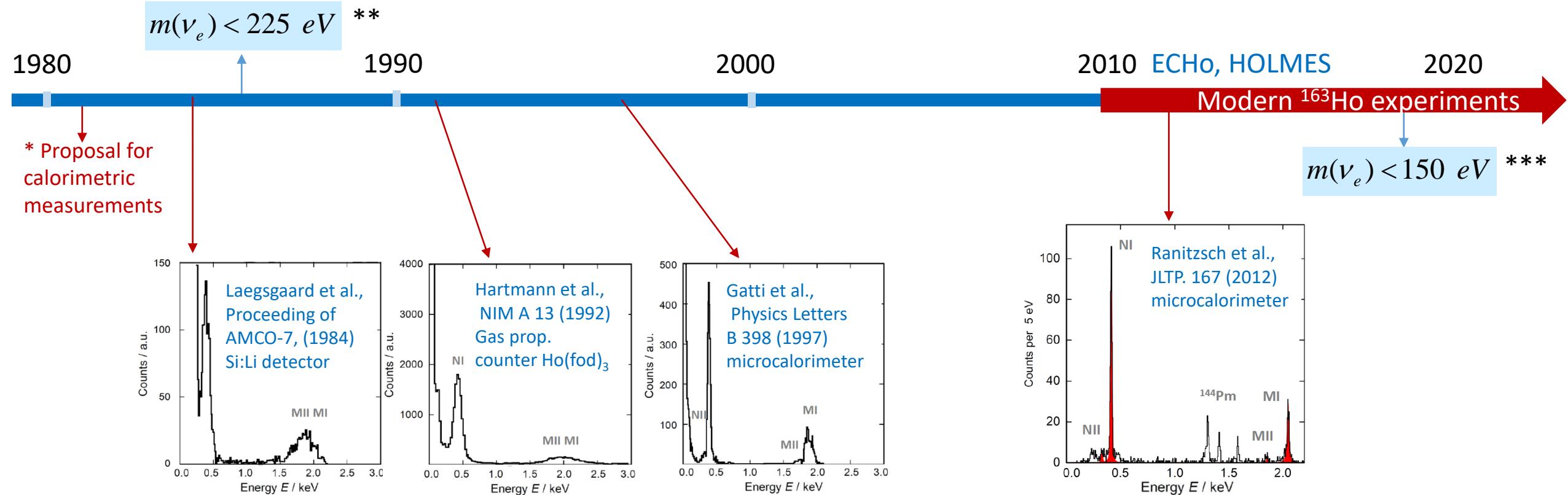
- $\tau_{1/2} \approx 4570 \text{ years}$ ($2 \times 10^{11} \text{ atoms for 1 Bq}$)
- $Q_{EC} = (2.833 \pm 0.030^{\text{stat}} \pm 0.015^{\text{syst}}) \text{ keV}$

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



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

Electron Capture in ^{163}Ho - Timeline

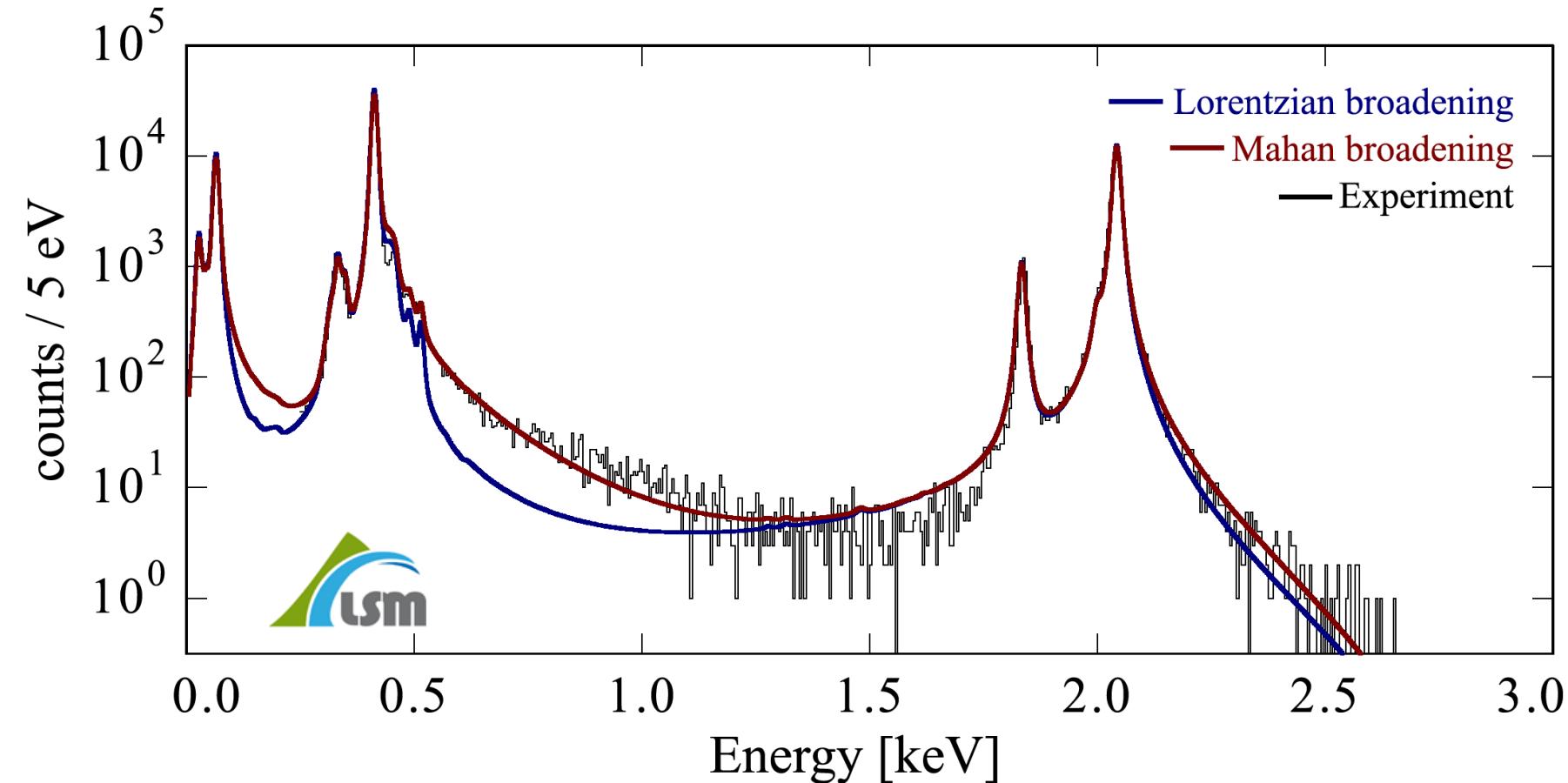


* A. De Rujula and M. Lusignoli, *Phys. Lett.* **118B** (1982)

** 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 concept



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

Energy resolution

$$\Delta E_{FWHM} = 9.2 \text{ eV}$$

Background level

$$b < 1.6 \times 10^{-4} \text{ events/eV/pixel/day}$$

- 4 day measurement with 4 pixels loaded with $\sim 0.2 \text{ Bq}^{163}\text{Ho}$
- measurement performed underground
- test for data reduction and spectral shape analysis

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

Requirements for sub-eV sensitivity

Statistics in the end point region

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

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

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

- $f_{pu} < 10^{-5}$
- $\tau_r \sim 1 \mu\text{s} \rightarrow a \sim 10 \text{ Bq}$
- 10^5 pixels

→ Fast and multiplexable detectors

Background level below unresolved pile-up

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

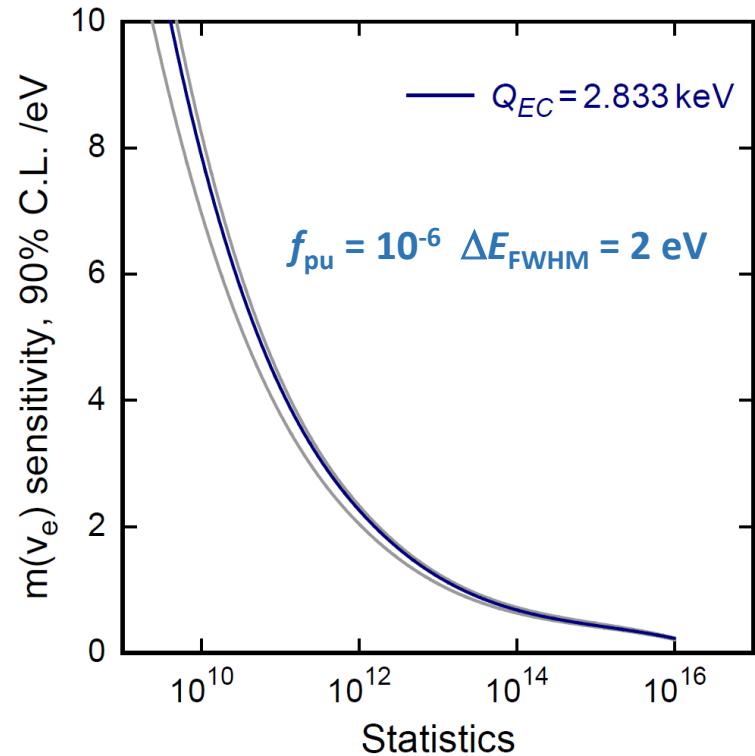
→ Identification and suppression of background sources

Precise characterization of the endpoint region

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

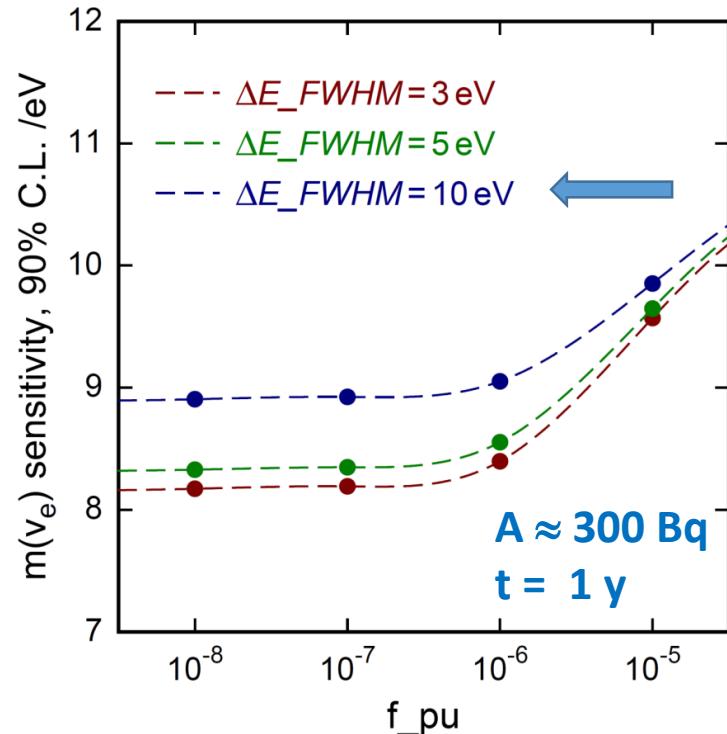
→ High energy resolution low temperature microcalorimeters with enclosed ^{163}Ho

Sensitivity curve based on old theory



ECHO phases

ECHO-1k – almost concluded



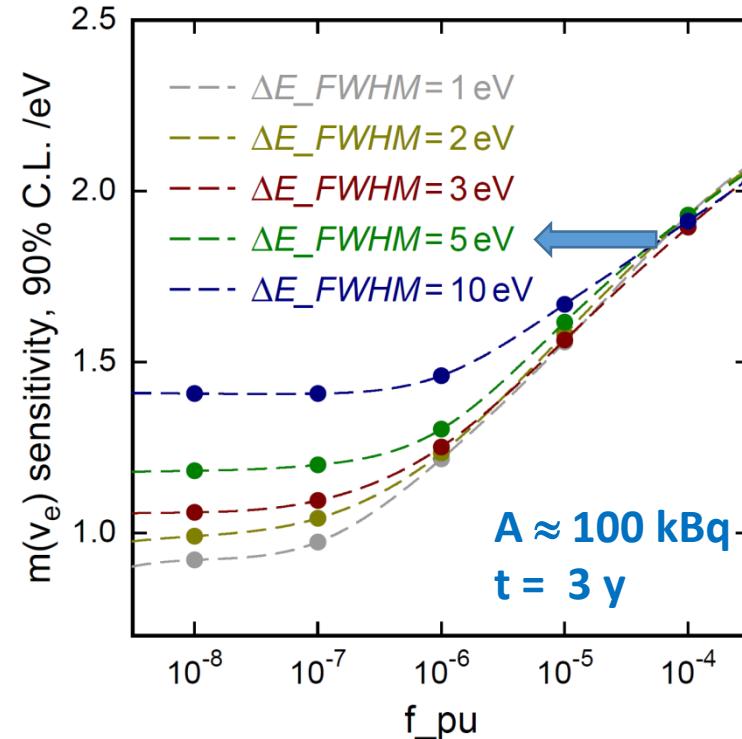
$m(v_e) < 20 \text{ eV} \text{ 90\% C.L.}$

Activity per pixel: 1 - 5 Bq

Number of detectors: 60 - 100

Readout: parallel two stage SQUID

ECHO-100k on-going



$m(v_e) < 1.5 \text{ eV} \text{ 90\% C.L.}$

Activity per pixel: 10 Bq

Number of detectors: 12000

Readout: microwave SQUID multiplexing

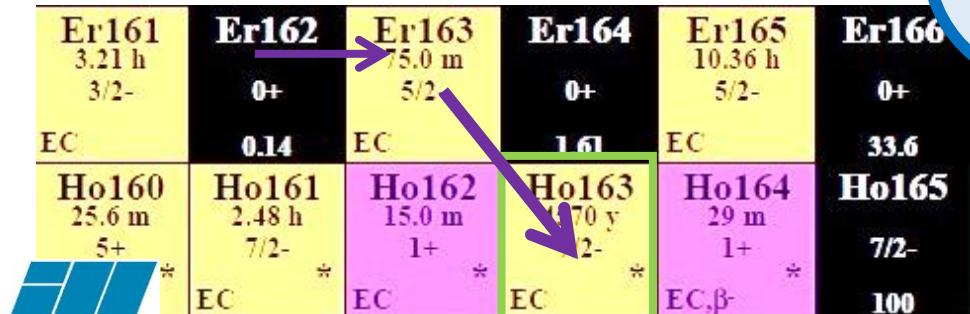
^{163}Ho Source

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

Excellent chemical separation \rightarrow 95% efficiency

^{163}Ho available for coming experiments

ECHO $\sim 6 \times 10^{18}$ atoms (30 MBq)



NEUTRONS
FOR SCIENCE

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

Ion implantation @ RISIKO, Institute of Physics, Mainz University

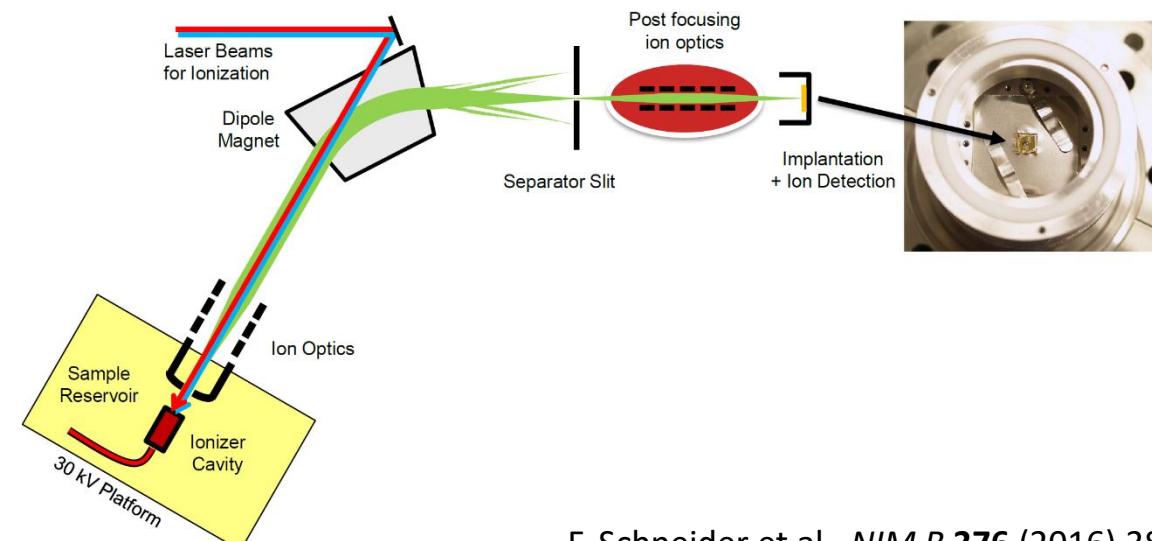
- Resonant laser ion source $\rightarrow (69 \pm 5^{\text{stat}} \pm 4^{\text{syst}})\%$ efficiency

- Reduction of $^{166\text{m}}\text{Ho}$ in MMC $\rightarrow {}^{166\text{m}}\text{Ho}/{}^{163}\text{Ho} < 4(2)10^{-9}$

Validation via AMS measurement @HZDR DREAMS

- Optimization of beam focalization

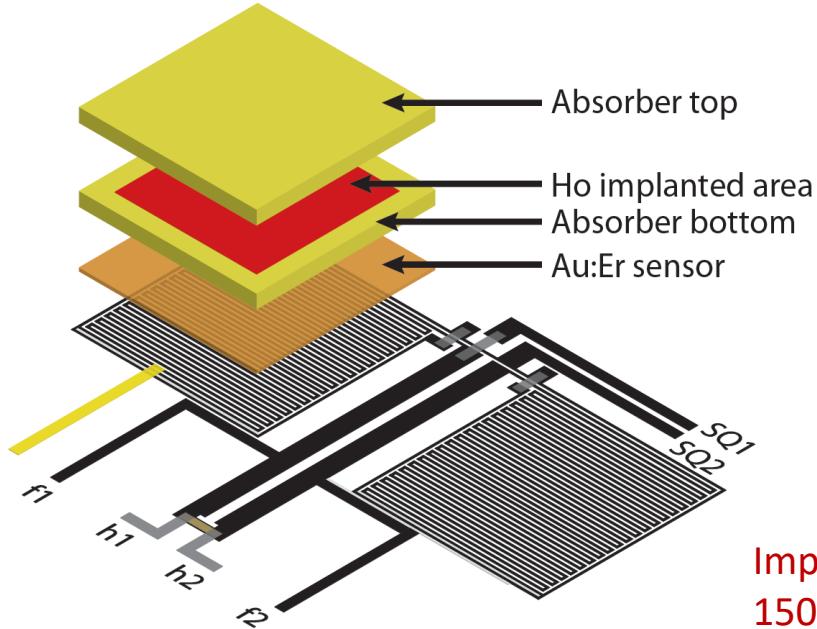
\rightarrow Coming soon: implantation on wafer scale



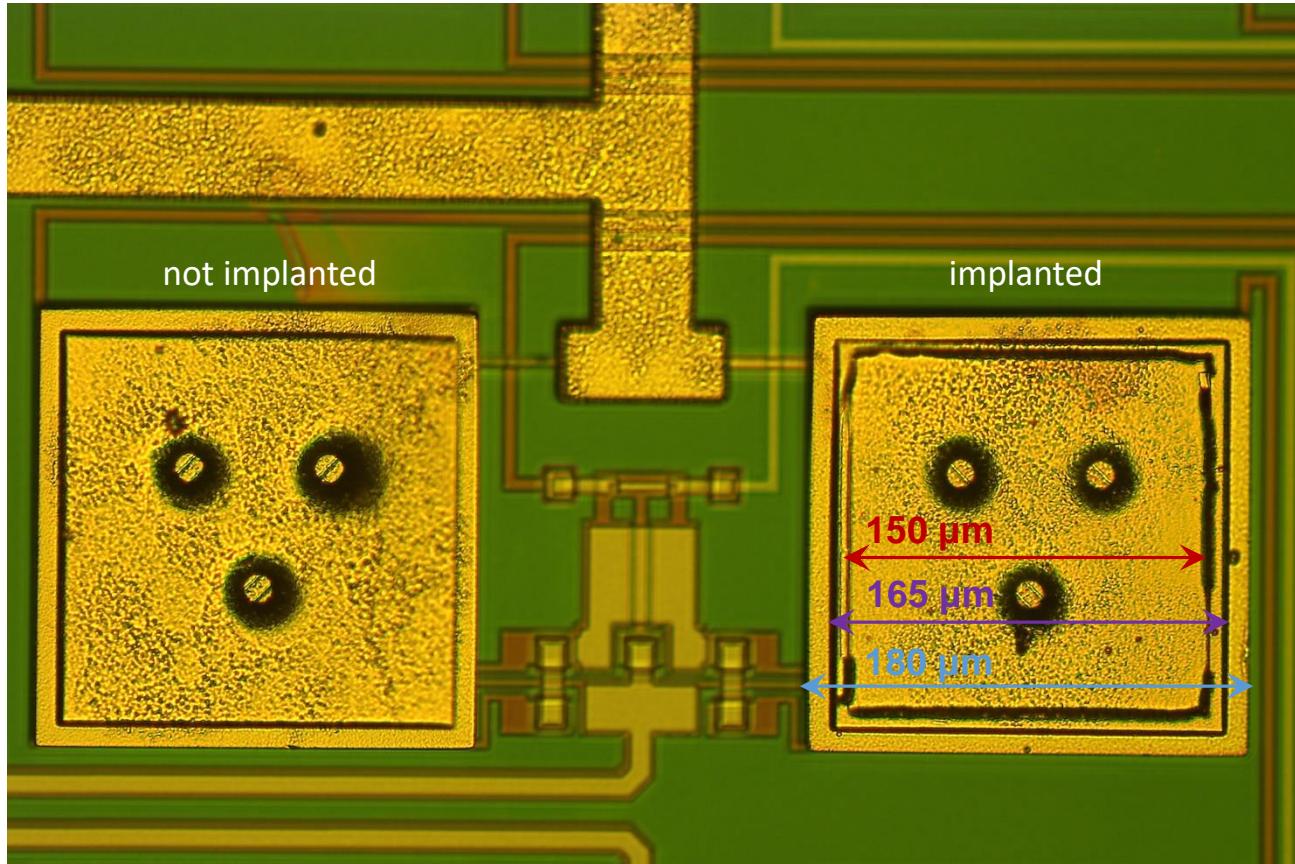
F. Schneider et al., NIM B 376 (2016) 388
T. Kieck et al., Rev. Sci. Inst. 90 (2019) 053304
T. Kieck et al., NIM A 945 (2019) 162602

Calorimetric measurement – 4π geometry

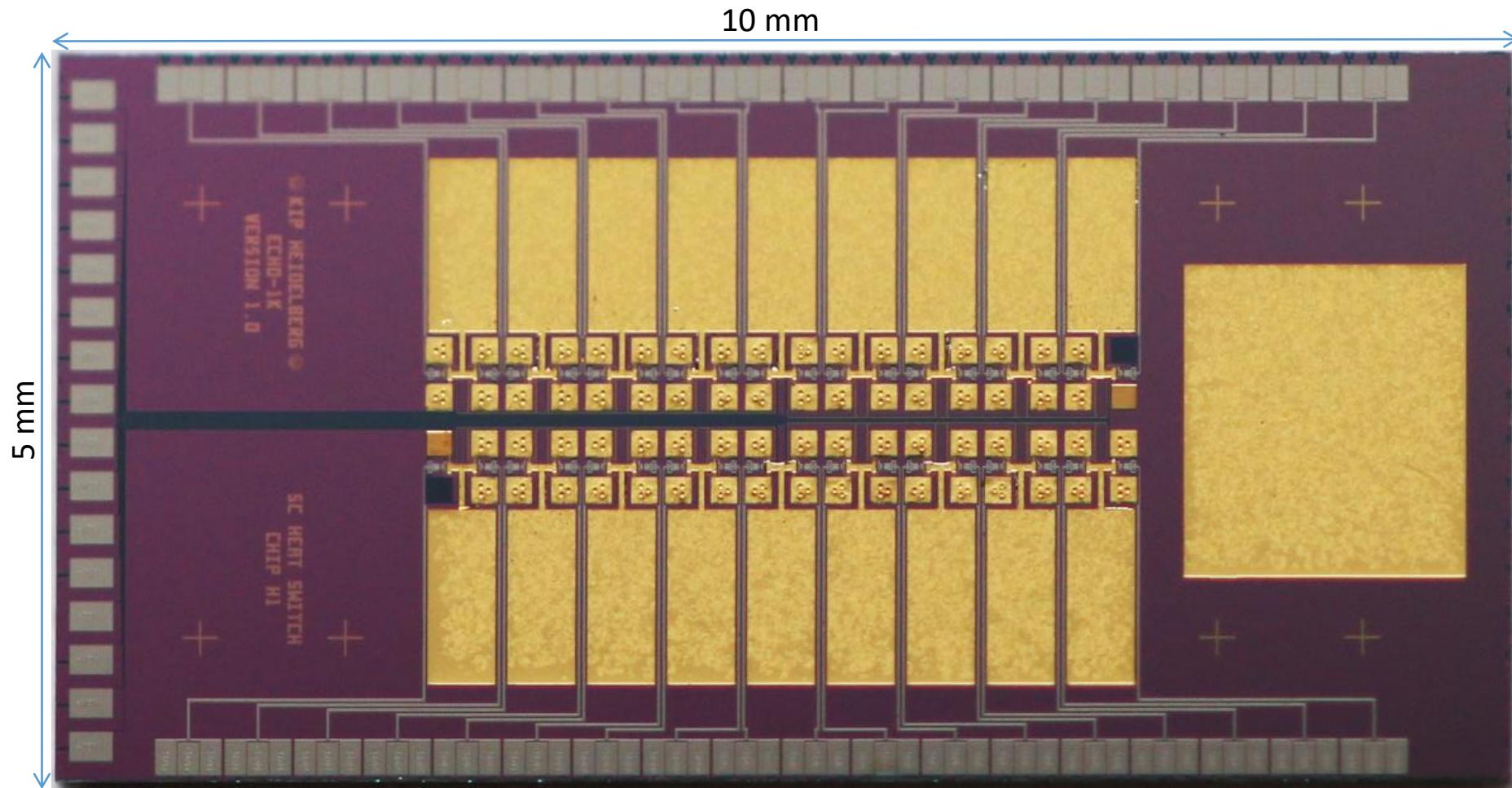
ECHO uses large arrays of low T metallic magnetic calorimeters with enclosed ^{163}Ho



Implantation square:
150 $\mu\text{m} \times$ 150 μm
Second absorber:
165 $\mu\text{m} \times$ 165 μm
First absorber:
180 $\mu\text{m} \times$ 180 μm



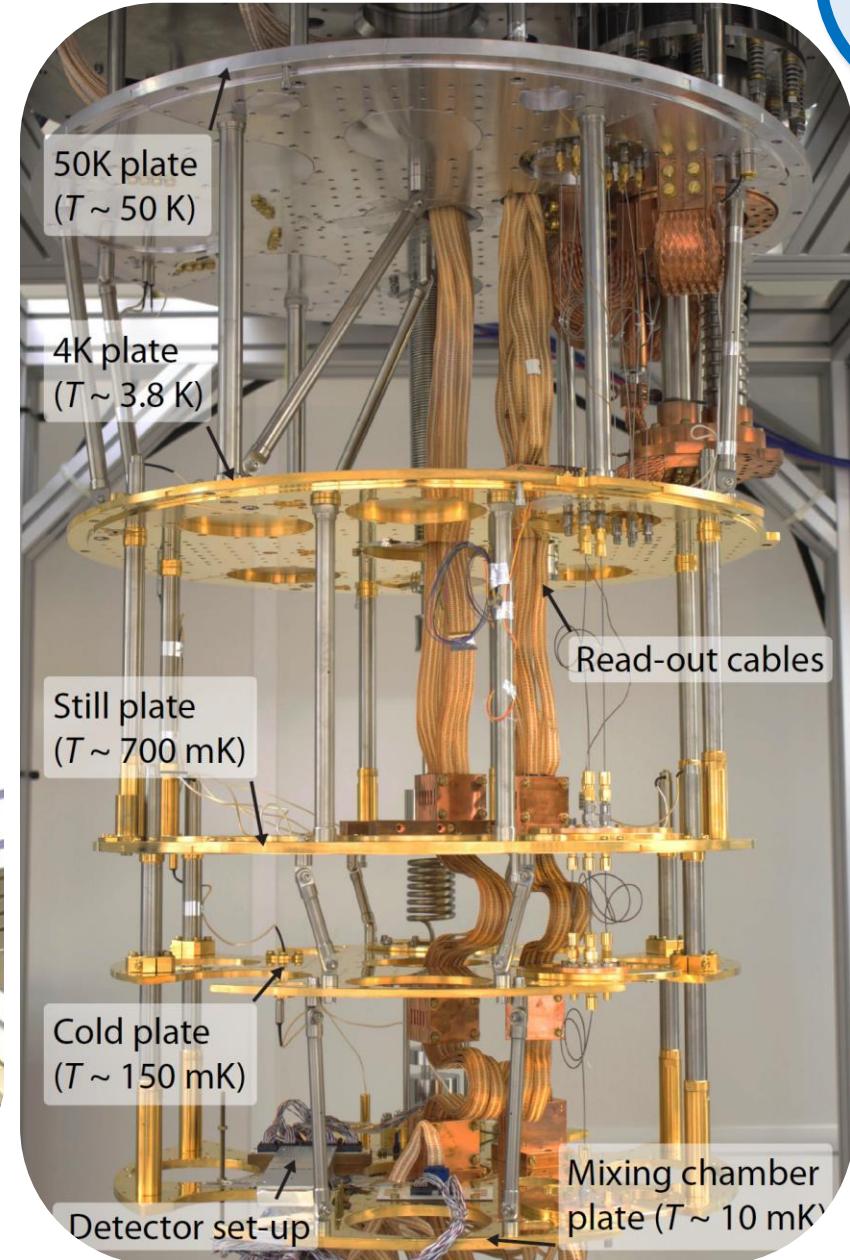
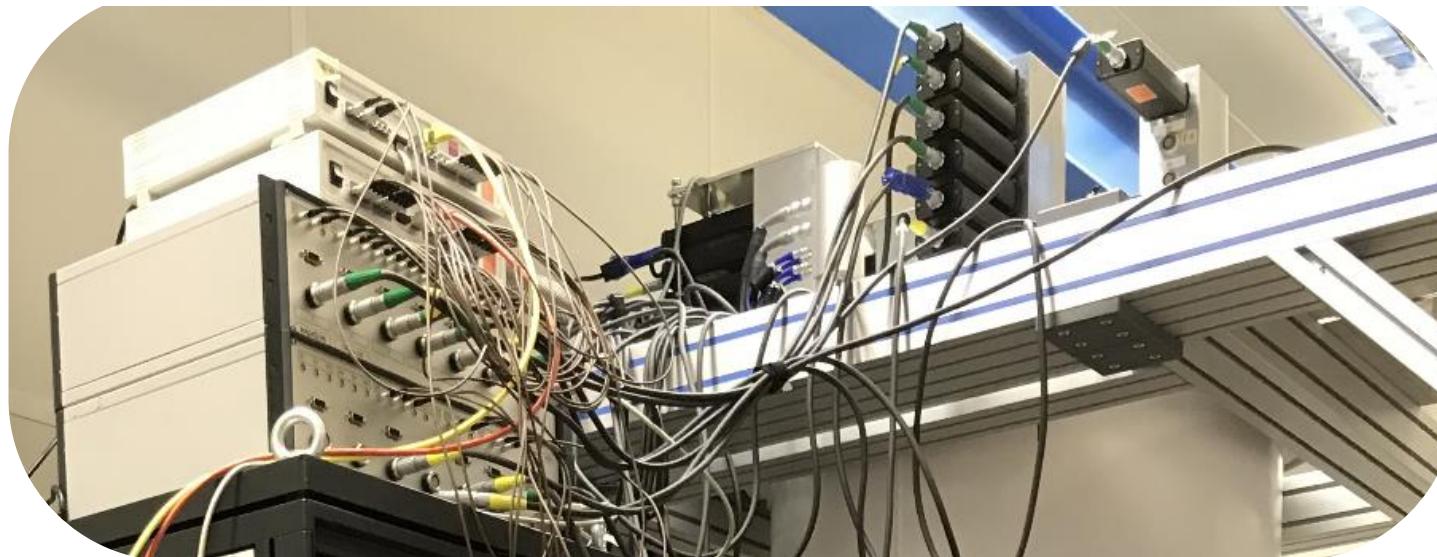
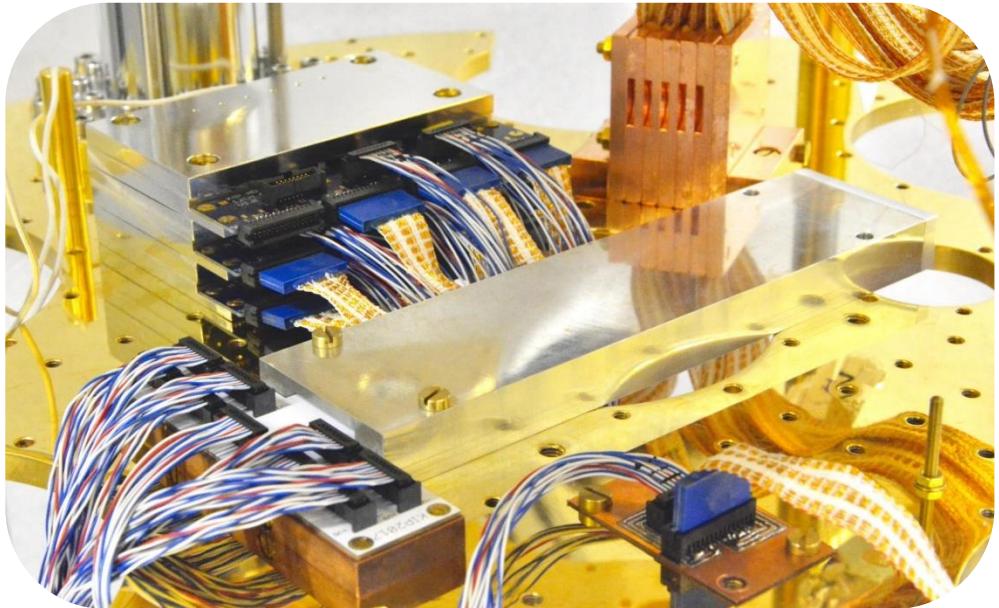
ECHO-1k array



Design performance:
 $\Delta E_{FWHM} \sim 5 \text{ eV}$
 $\tau_r \sim 90 \text{ ns}$ (single channel readout)

ECHO-1k read-out

10



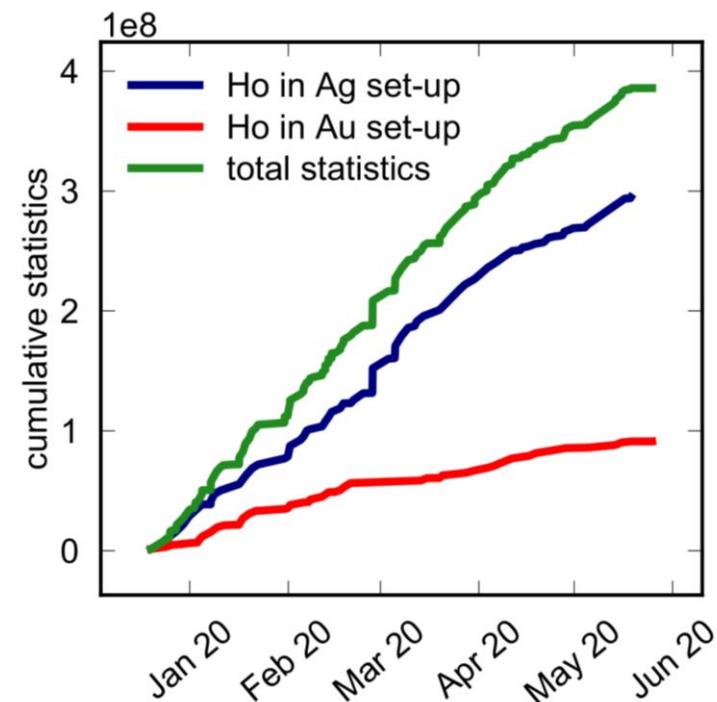
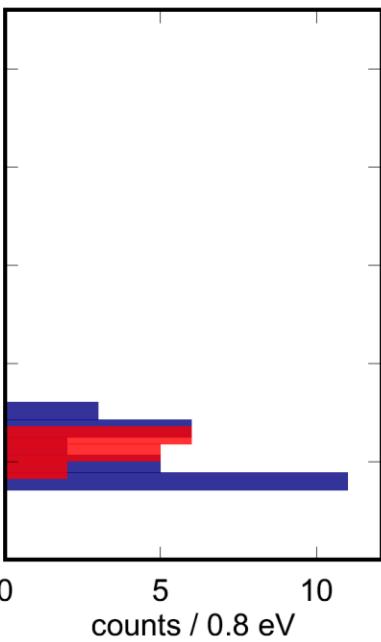
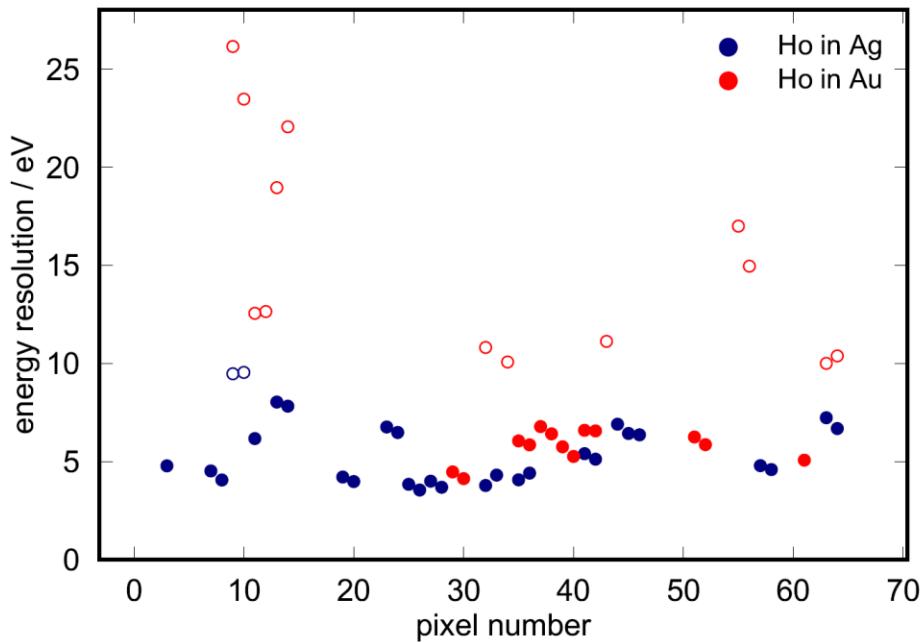
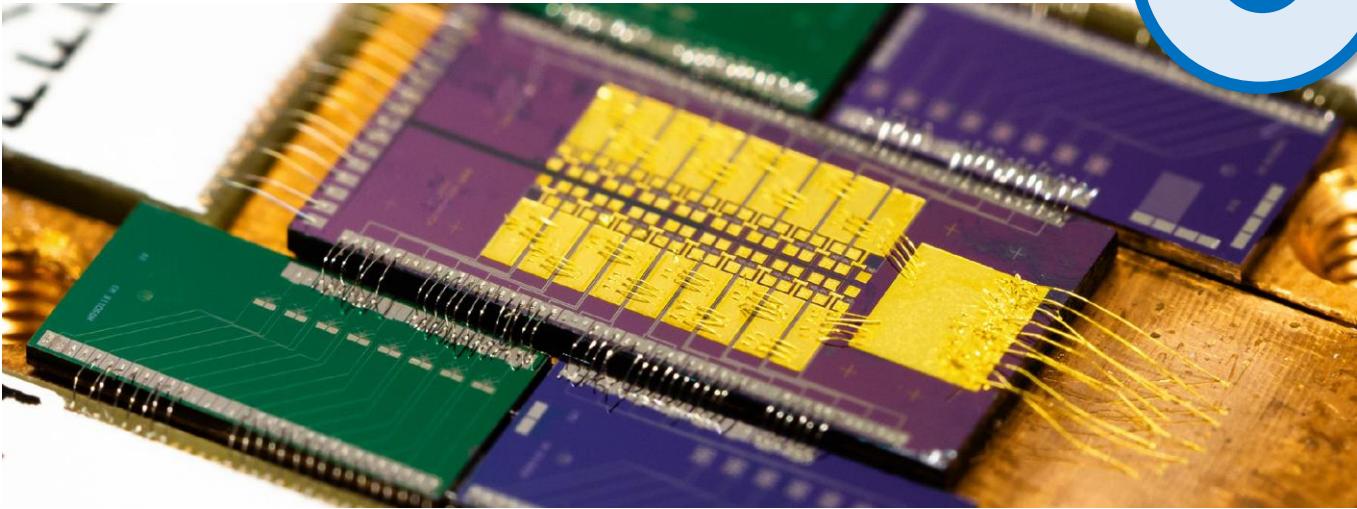
ECHO-1k high statistics spectrum

ECHO-1k chip-Au

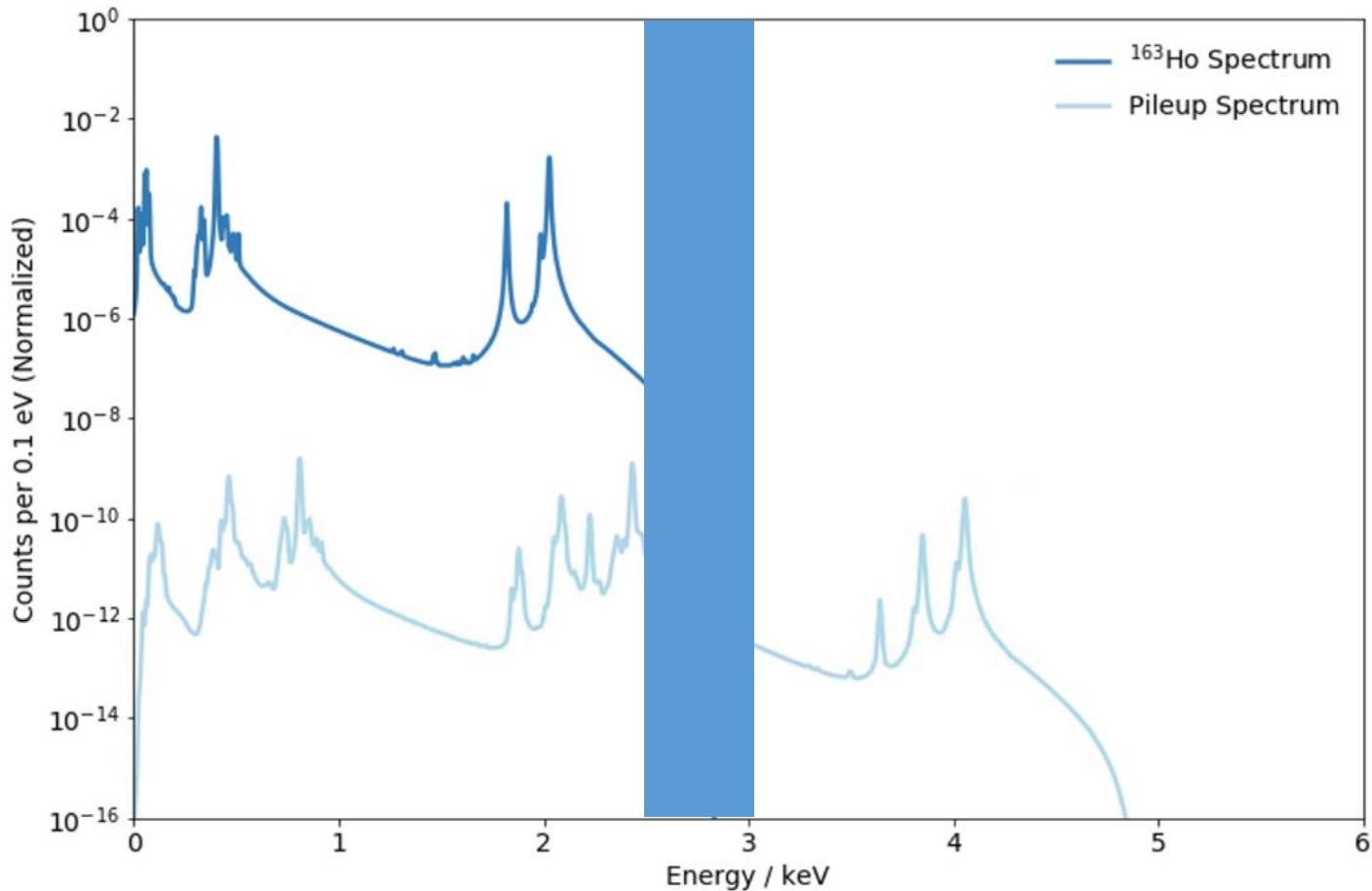
23 pixel with implanted ^{163}Ho
 3 background pixels
 average activity = 0.94 Bq
 total activity of 28.1 Bq

ECHO-1k chip-Ag

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



Analysis of the ^{163}Ho electron capture spectrum

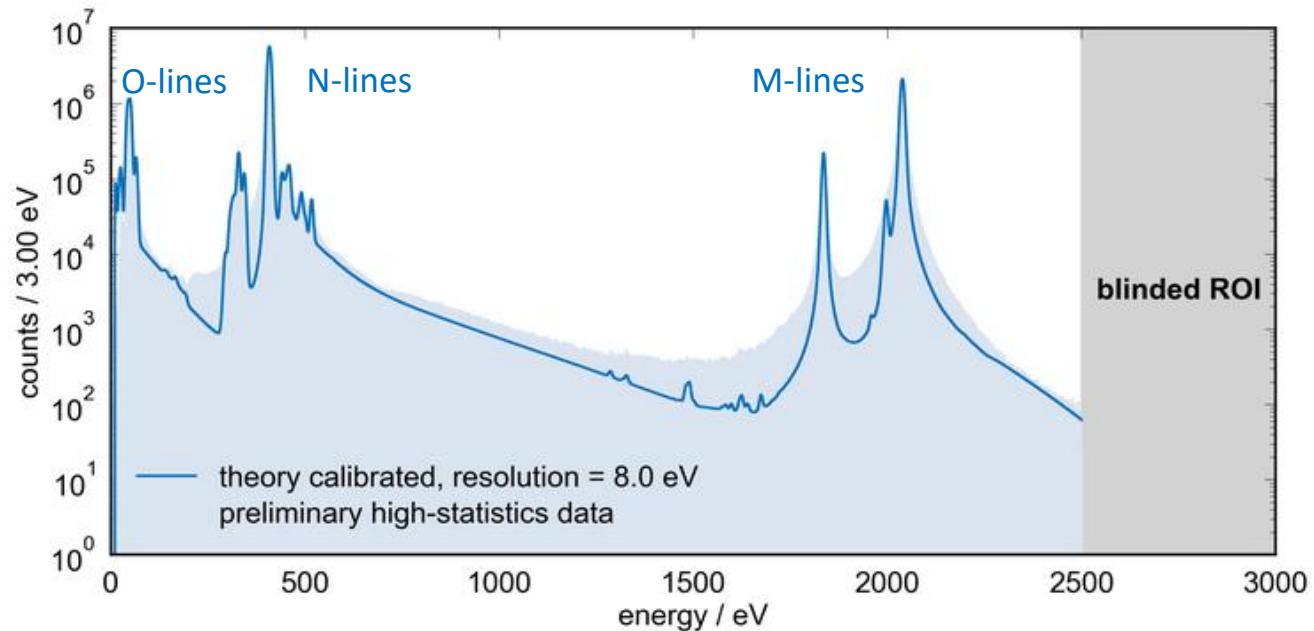


$E \leq 2.5 \text{ keV}$

determination spectrum parameters
(intensity, peak energies, widths, Q -value)

$E \geq 3 \text{ keV}$

determination unresolved pile-up spectrum
and natural background

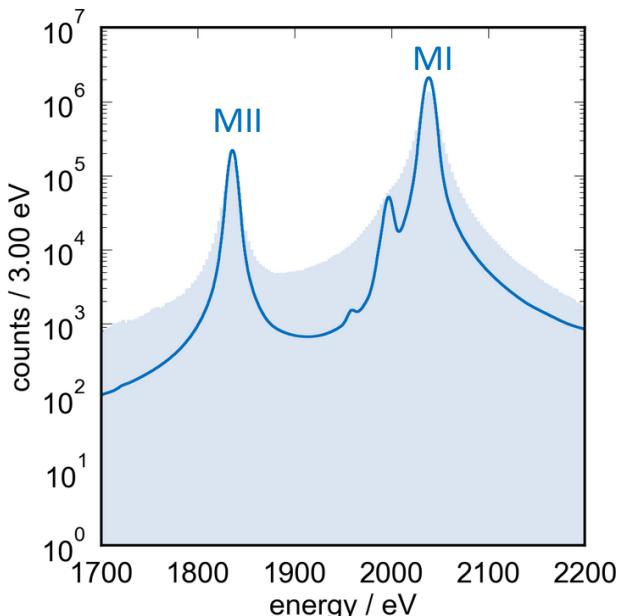
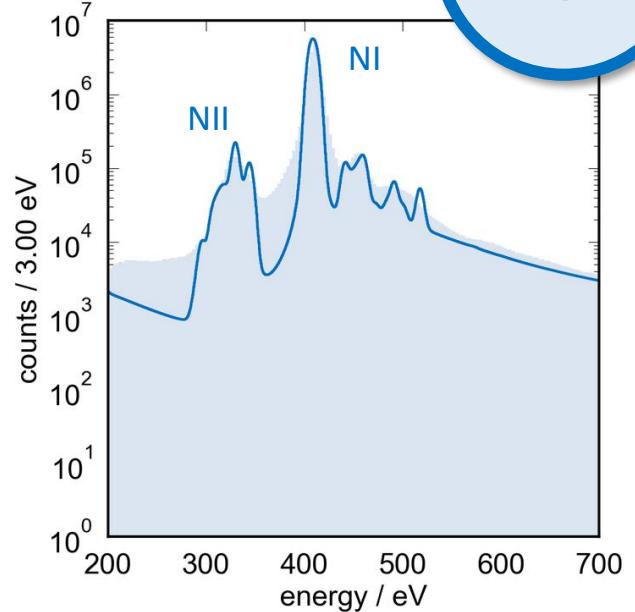


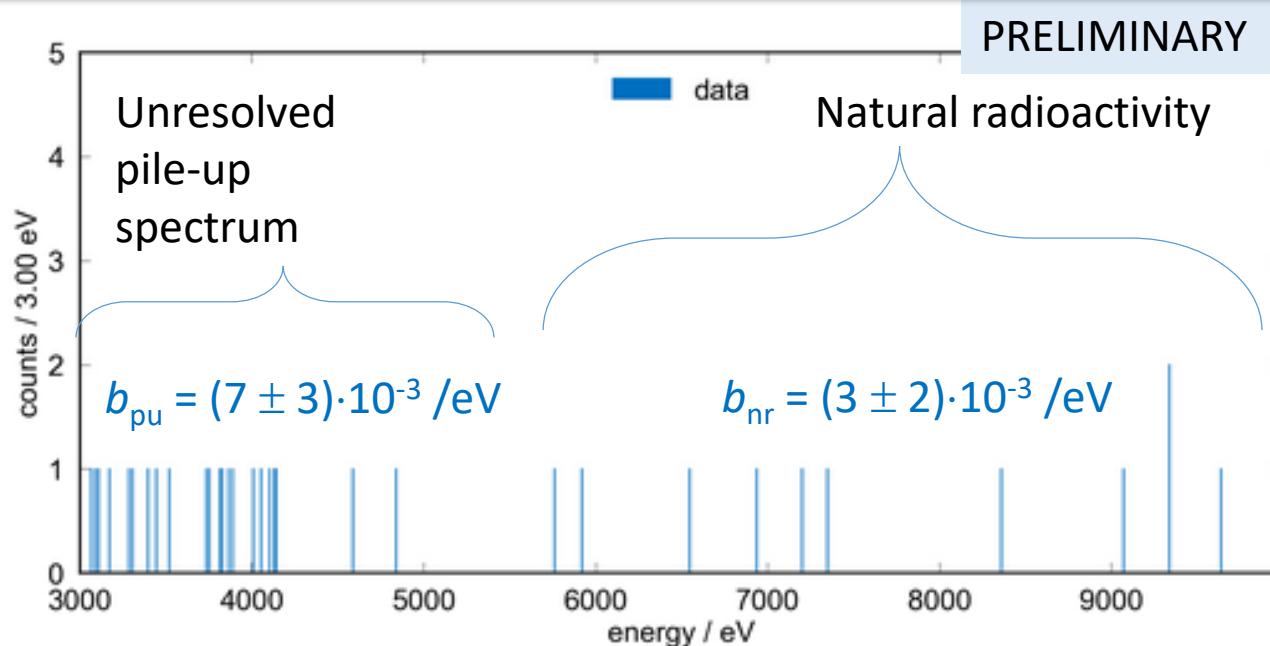
Fraction of data corresponding to 6×10^7 events acquired with detectors having ^{163}Ho in Ag

- 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

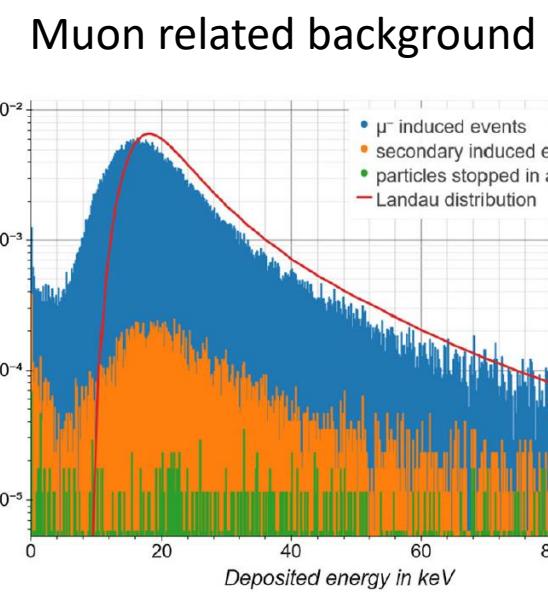
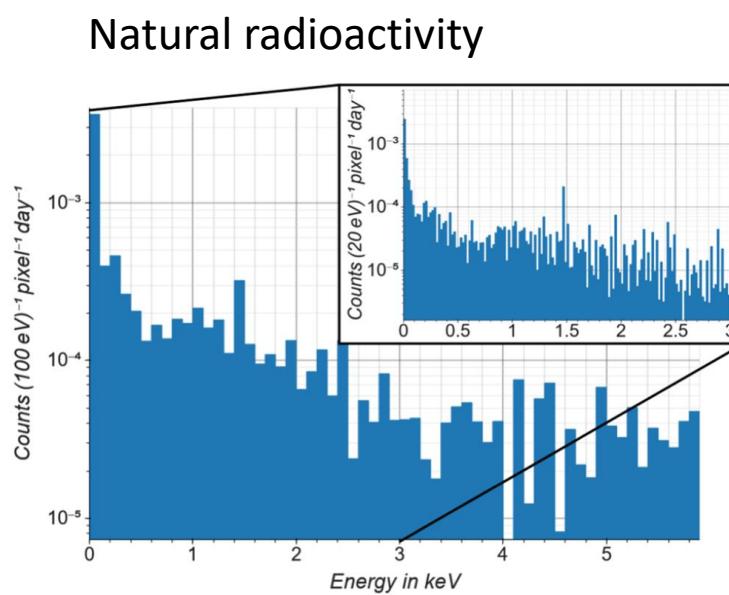




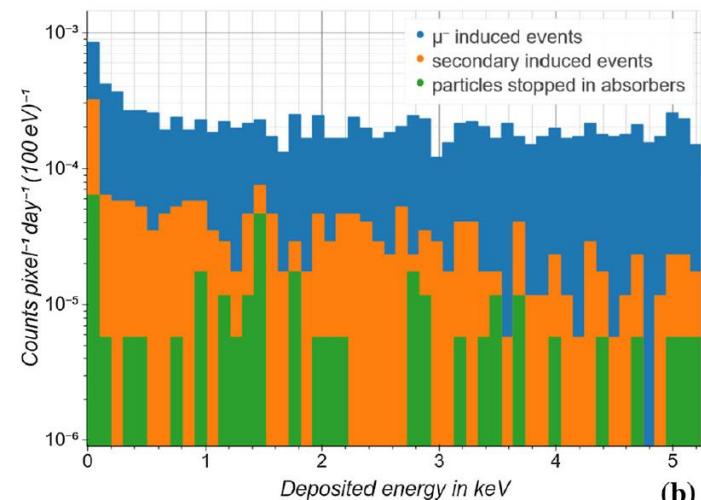
Two major contributions

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

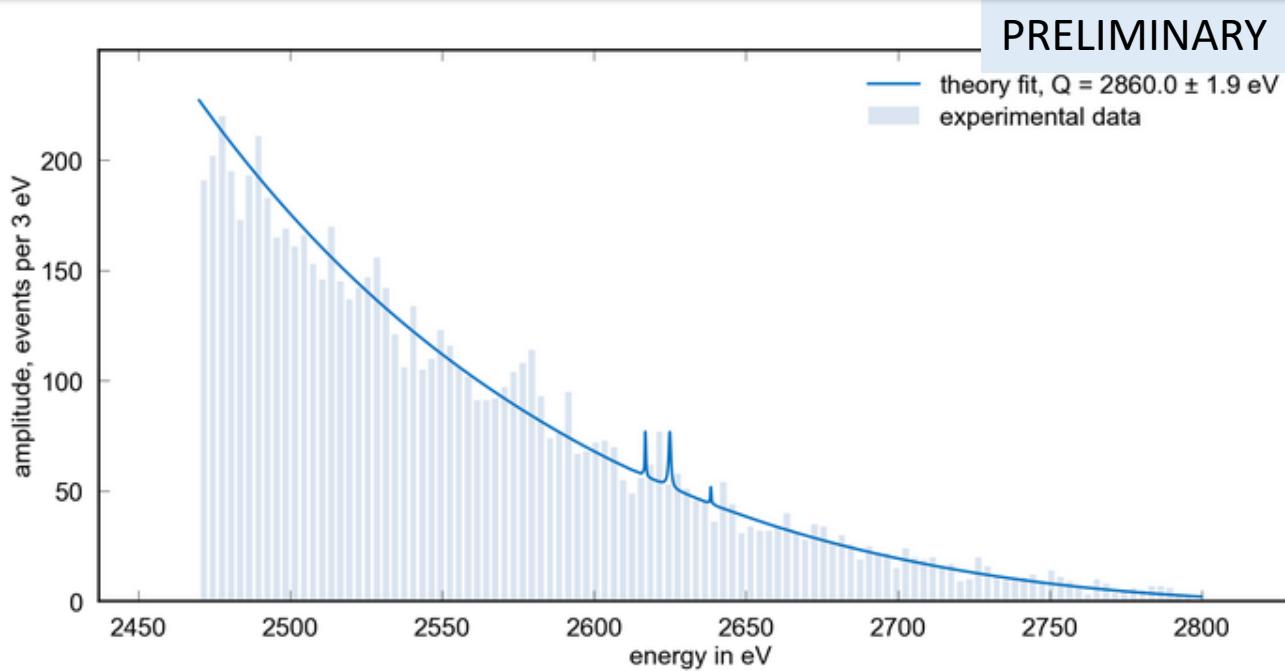
Comparison with simulation on-going



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



$2.5 \text{ keV} < E < 2.8 \text{ keV}$

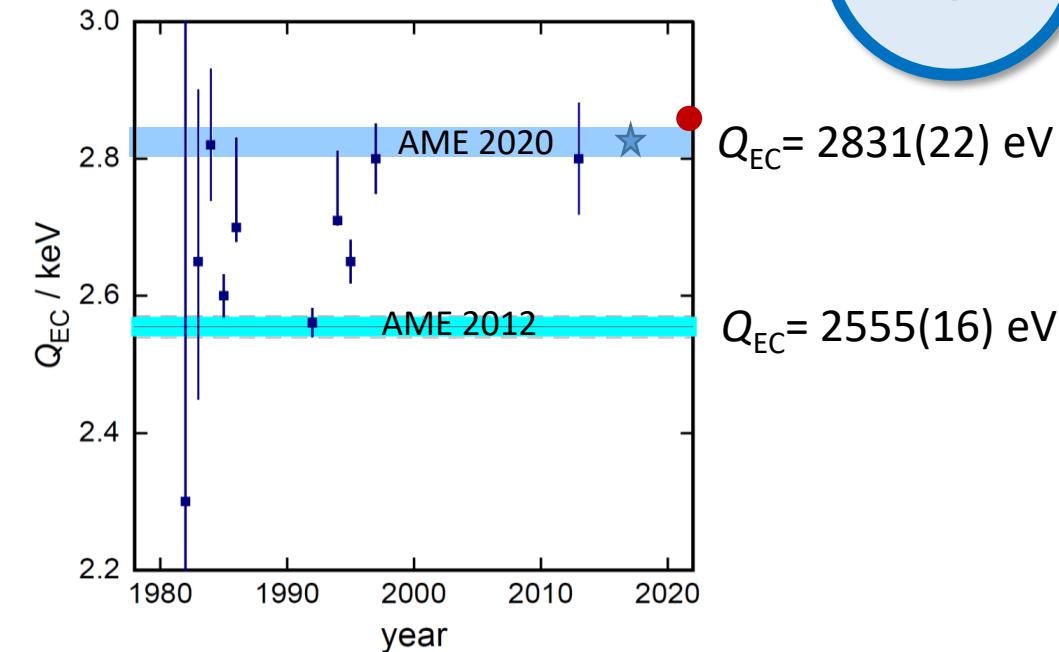


Determination of Q_{EC} by fitting the spectrum using:

- Brass & Haverkort theory
- Flat background

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

Systematic uncertainties related to theoretical spectral shape and Q -value
...still too large for analysis of smaller endpoint region



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

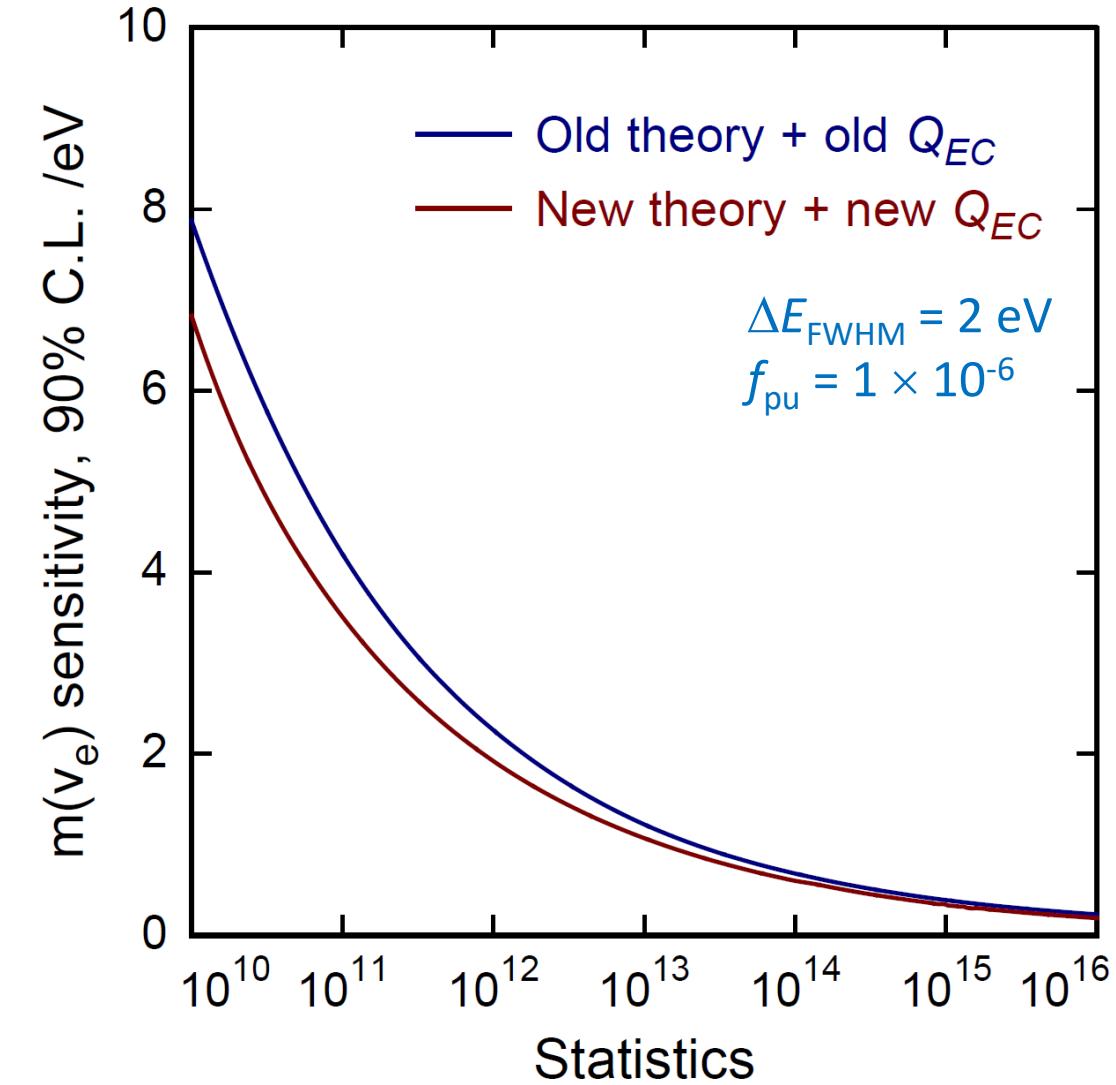
S. Eliseev et al., *Phys. Rev. Lett.* **115** (2015) 062501

Waiting for new PENTATRAP* results

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

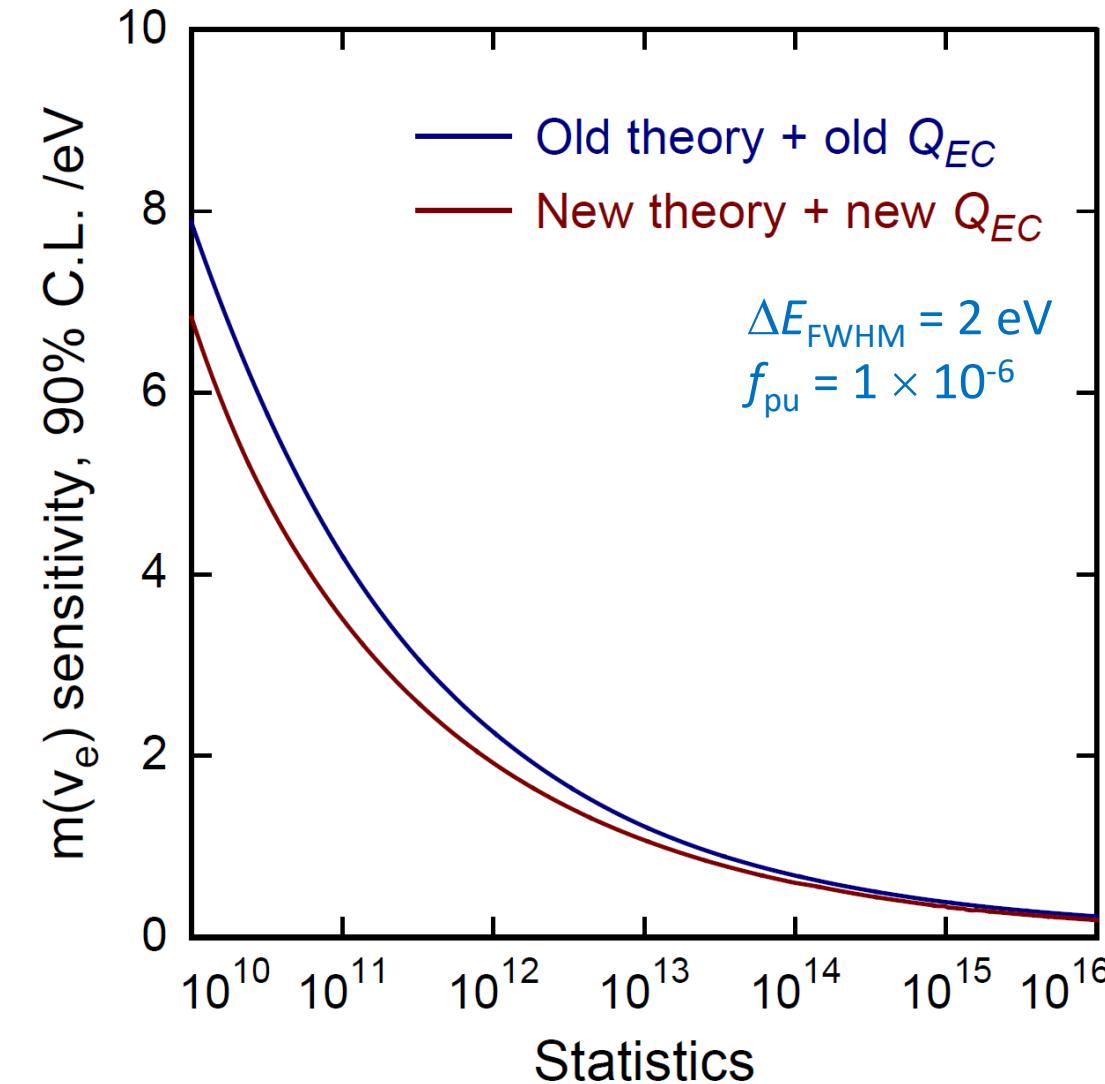
Updated sensitivity

Brass & Haverkort theoretical model + new Q_{EC} -value

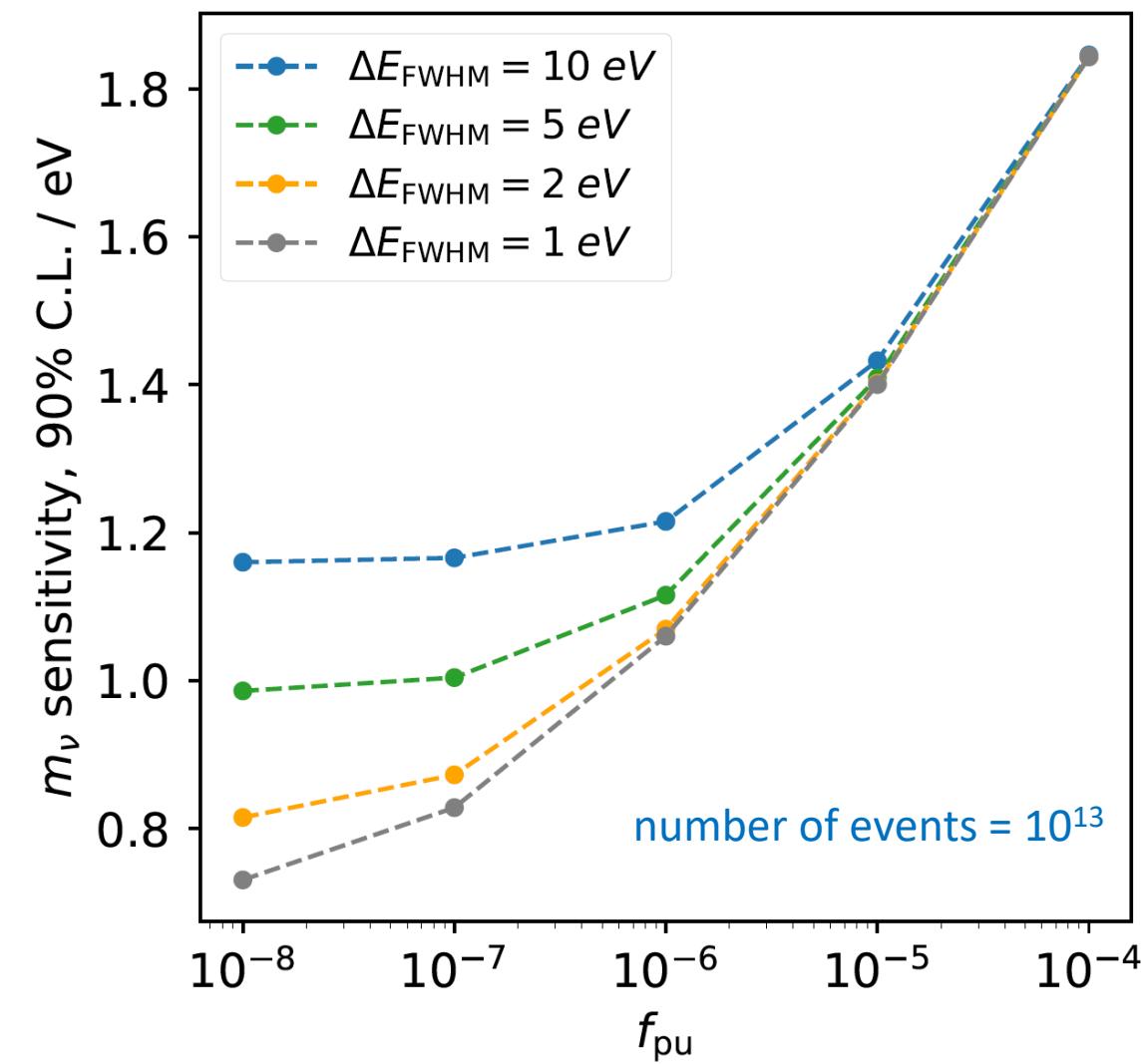


Updated sensitivity

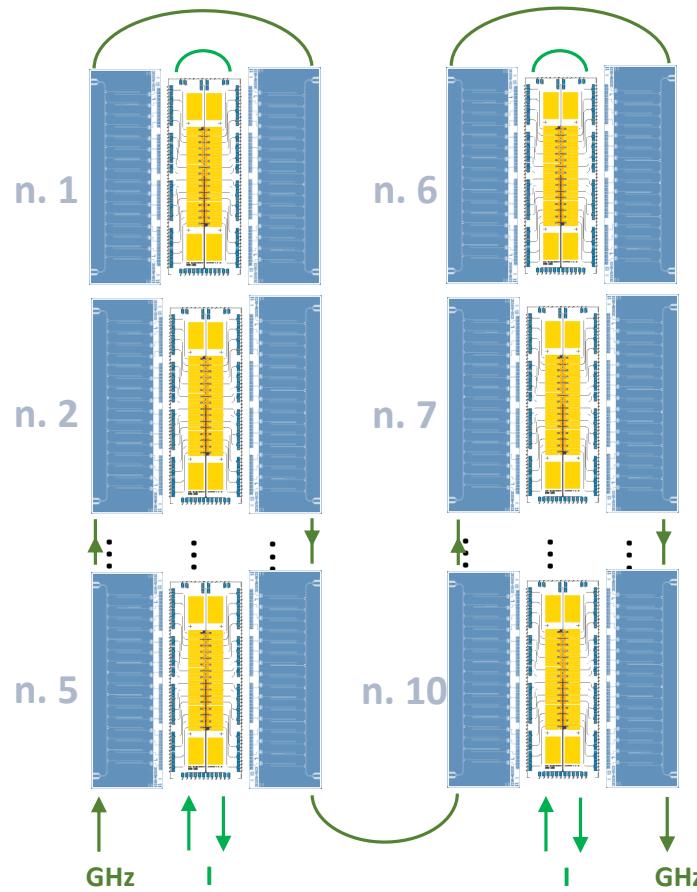
Brass & Haverkort theoretical model + new Q_{EC} -value



Sensitivity for the coming phase of ECHO



ECHo-100k for eV-scale sensitivity



DFG

Deutsche
Forschungsgemeinschaft

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

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

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

Number of detectors: 12000

Activity per pixel: 10 Bq ($2 \times 10^{12} {}^{163}\text{Ho}$ atoms)

Present status:

High Purity ${}^{163}\text{Ho}$ source:

- available about 30 MBq

Ion implantation system:

- demonstrated and continuously optimized

Metallic magnetic calorimeters

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

Multiplexing and data acquisition:

- demonstrated for 8 channels
- development of the SDR electronics
- still to show scaling of the system

Data reduction

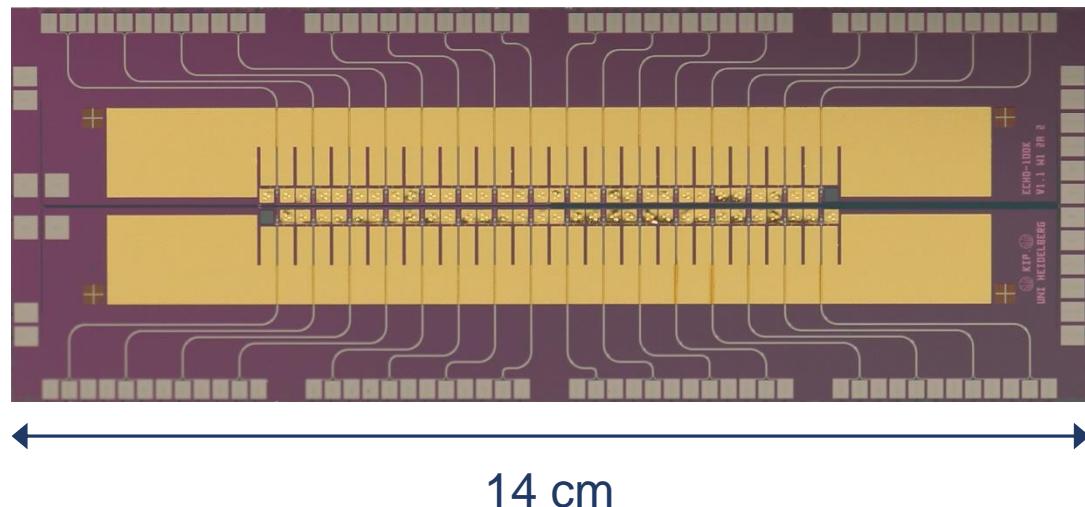
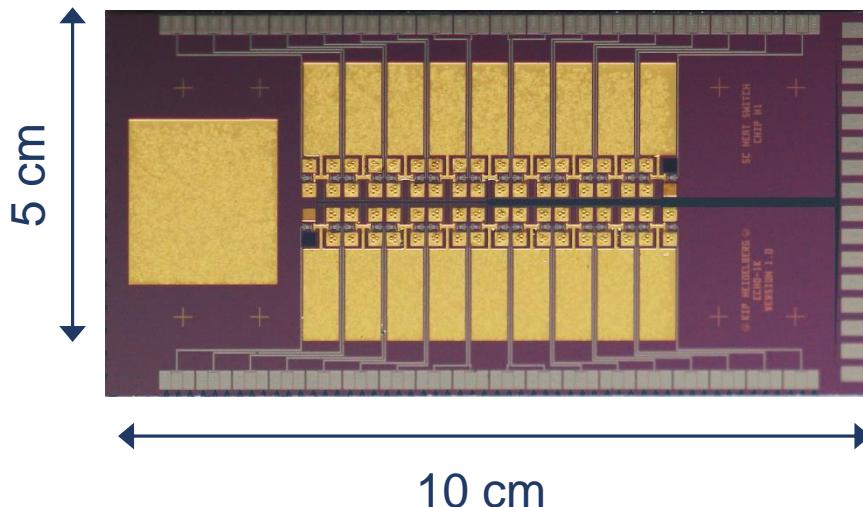
- optimized energy independent algorithm to identify spurious traces

ECHo-100k – MMC array

ECHo-1k
~1 Bq / pixel
57 MMCs



ECHo-100k
10 Bq / pixel
12000 MMCs



- ✓ **Design and fabrication completed**
- ✓ **Characterised with**

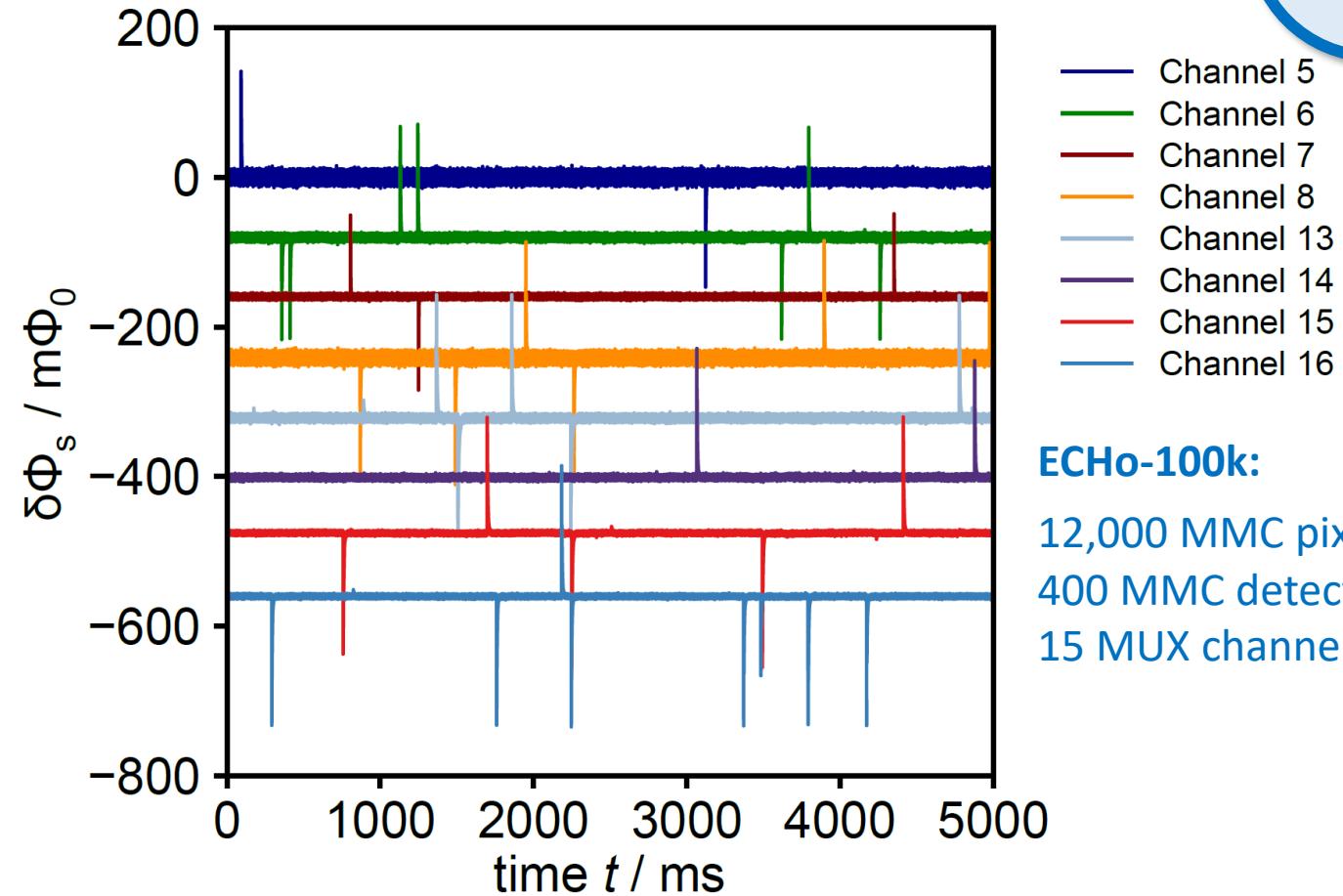
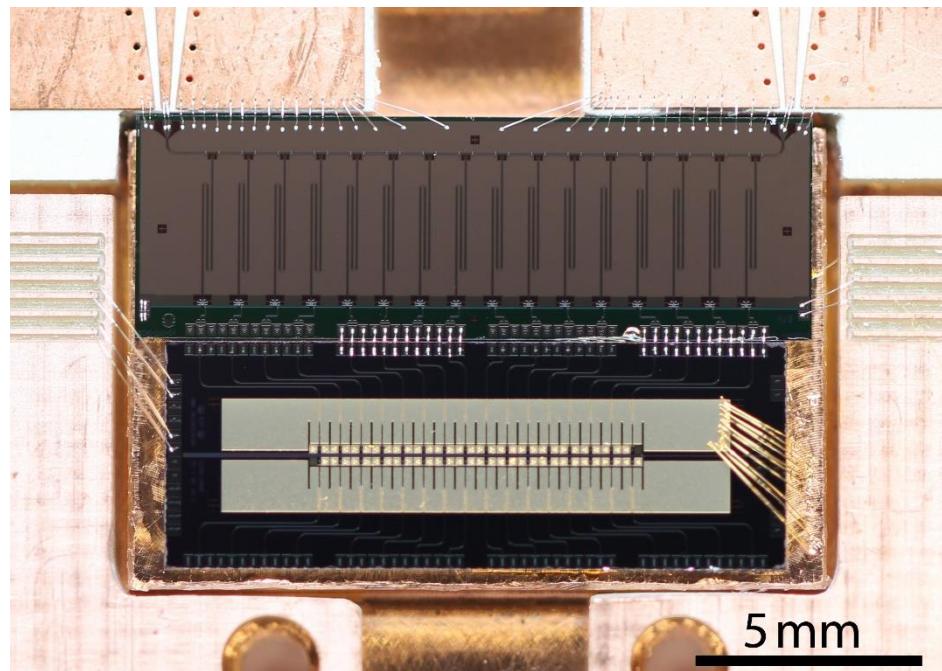
^{55}Fe external source
implanted ^{163}Ho

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)

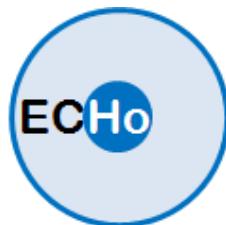


ECHO-100k:

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

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 →
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



... not only cool because of mK temperature



The ECHo Collaboration (Coll. Meeting October 2020)



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UNIVERSITÄT MAINZ



MAX-PLANCK-INSTITUT
FÜR KERNPHYSIK

EBERHARD KARLS
UNIVERSITÄT
TÜBINGEN



KIT
Karlsruher Institut für Technologie

GU

DFG Deutsche
Forschungsgemeinschaft
Research Unit FOR 2202

Thank you!

ISOLDE

**NEUTRONS
FOR SCIENCE**