Update on the ECHo Experiment

TAUP 2025, Xichang

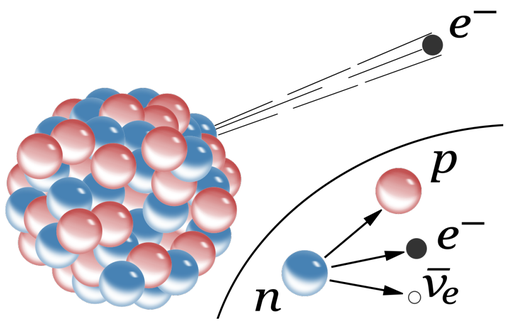
Raghav Pandey, 28 August 2025

Neutrino mass

Direct Measurement

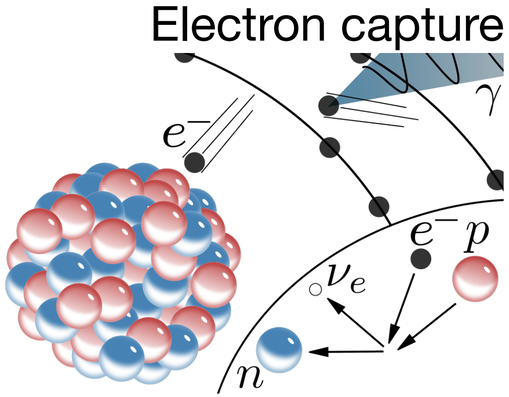
- Kinematic study of radioactive decays (beta decay, electron capture) are model independent investigations of m_{ν_e}

$$\frac{dW}{dE} \propto (Q-E)^2 \sqrt{1-\frac{m_{\nu_e}^2}{(Q-E)^2}}$$

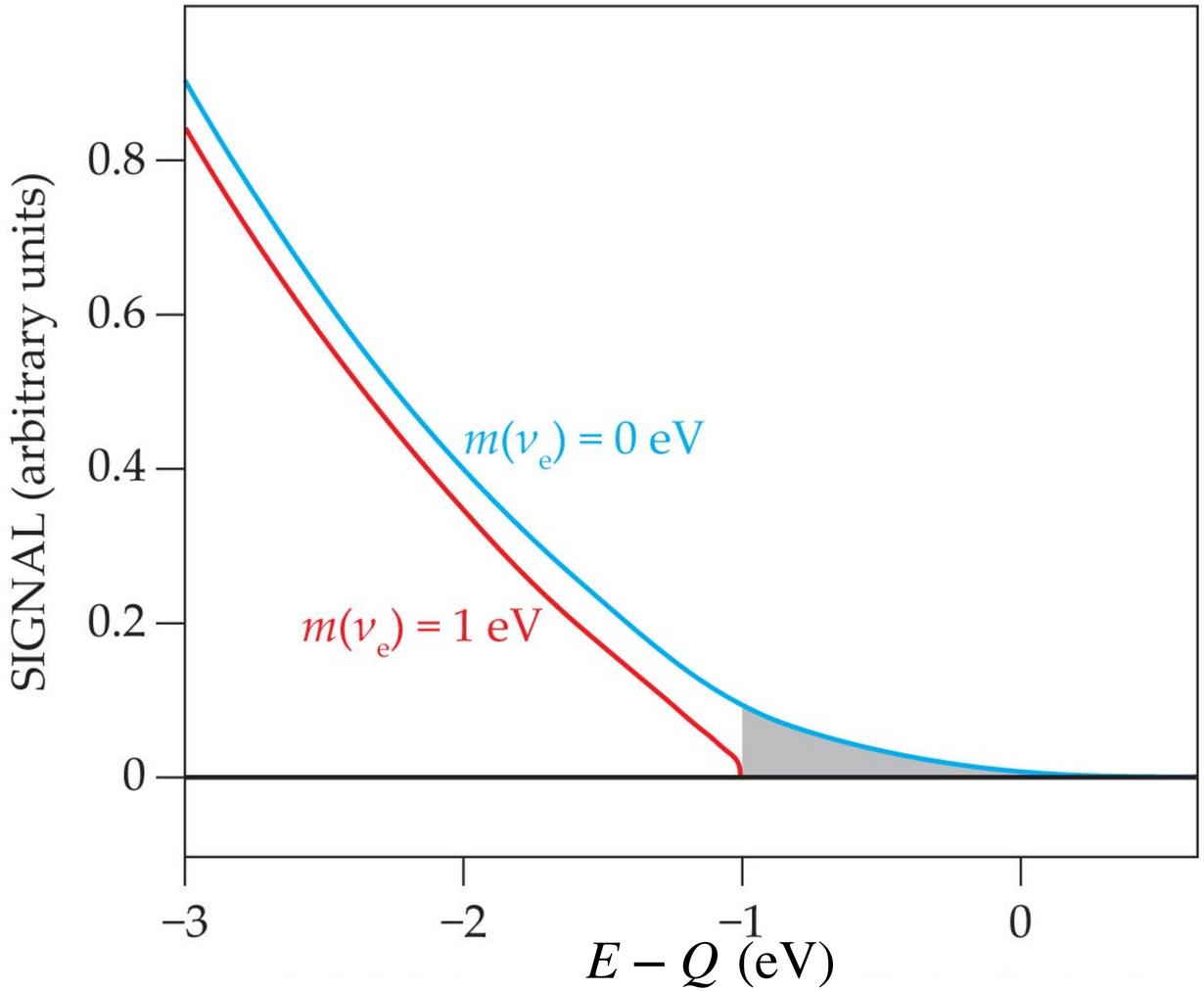


https://en.wikipedia.org/wiki/Beta_decay#/media/File:Beta-minus_Decay.svg

Beta decay



https://commons.wikimedia.org/wiki/File:Electron_capture.svg



https://medium.com/starts-with-a-bang/the-mystery-of-neutrino-mass-is-now-smaller-than-ever-a98138731900

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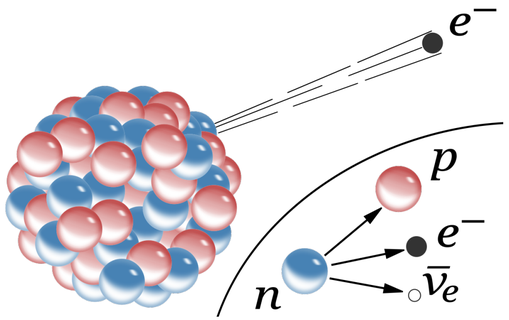

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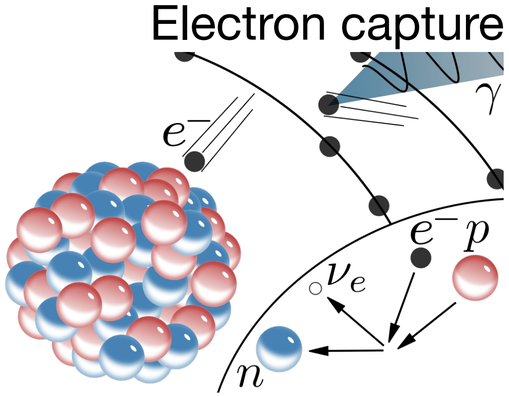
Beta decay



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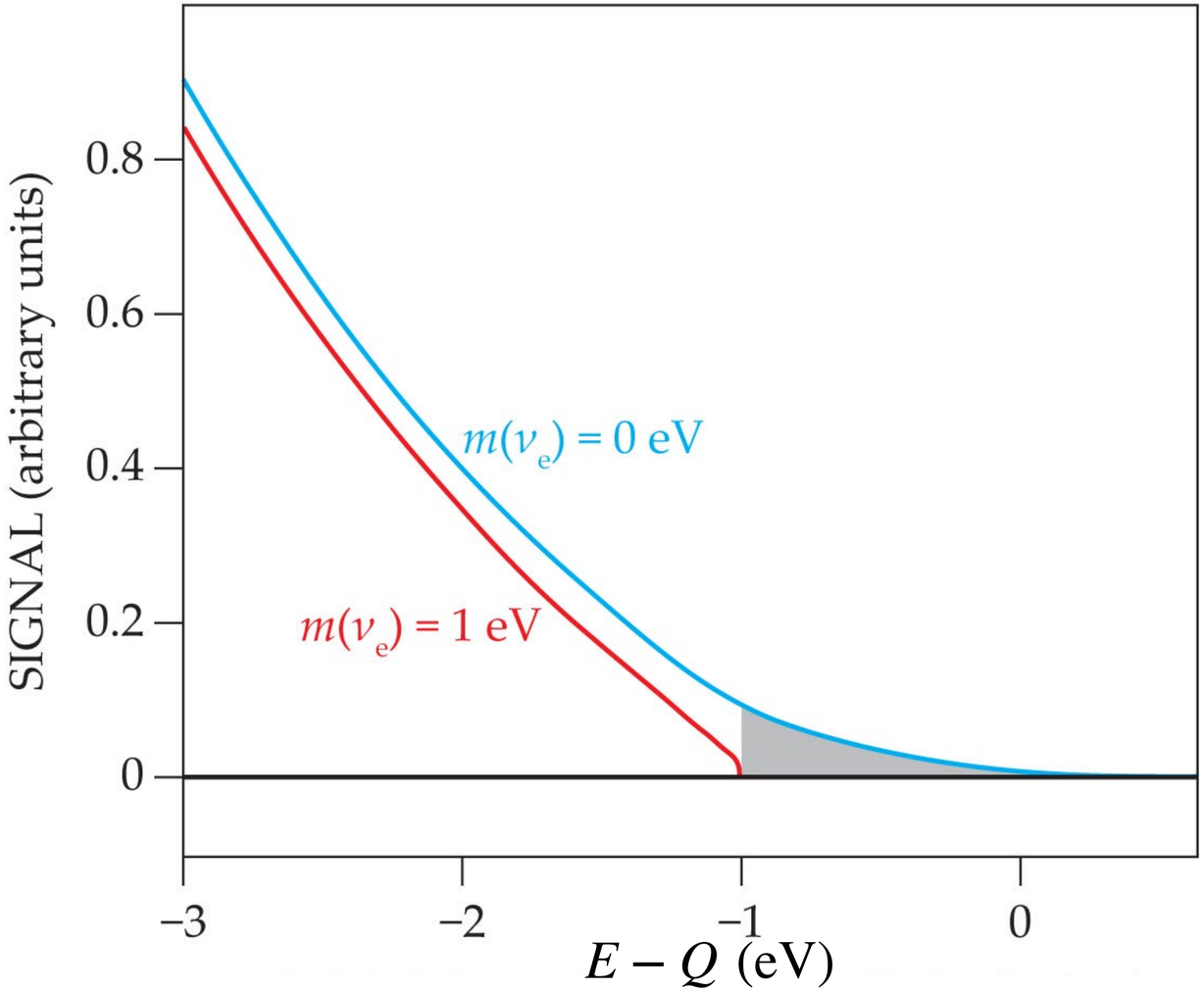

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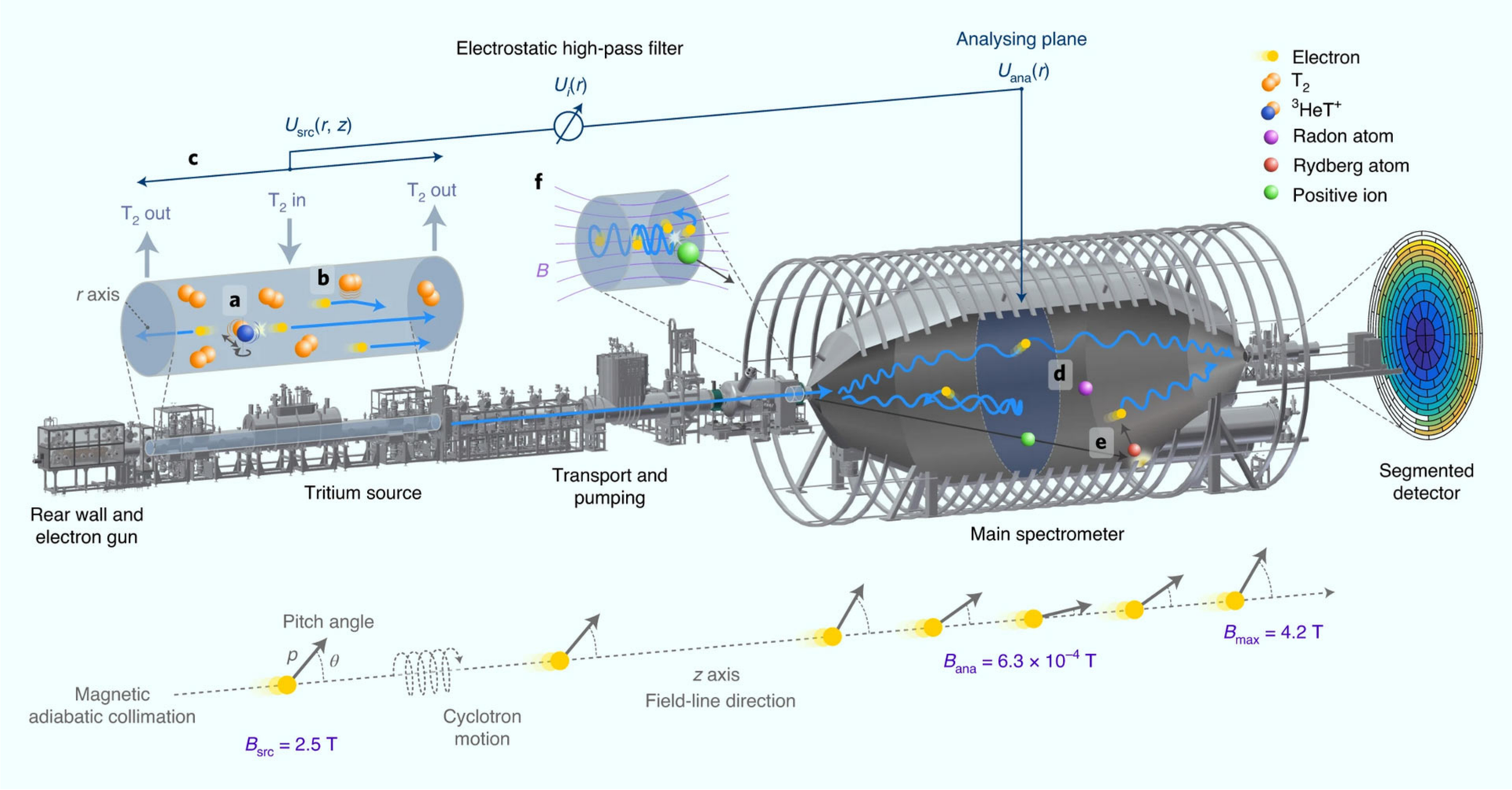
KATRIN

Most stringent limit on effective electron anti-neutrino mass $m_\beta < 0.45$ eV (90 % C.L.)

KATRIN Collaboration† et al..Science388,180-185(2025).DOI:10.1126/science.adq9592



$$T_2 \rightarrow {}^3HeT^+ + e^- + \bar{\nu}_e$$

The KATRIN Collaboration. *Nat. Phys.* **18**, 160–166 (2022)

$$(Q \sim 18.5 \text{ keV}, \tau_{1/2} \sim 12.3 \text{ y})$$

Electron Capture in Holmium-163

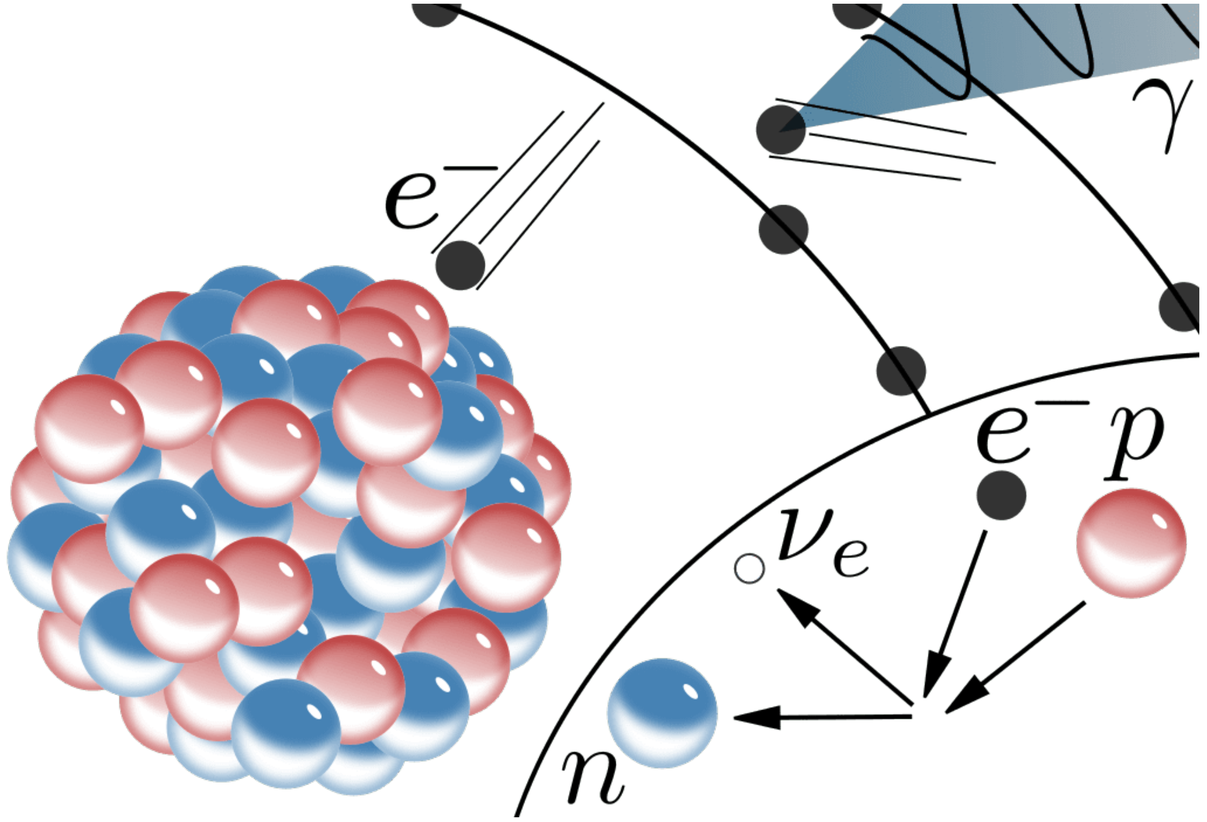
$$^{163}\mathrm{Ho} \rightarrow {}^{163}\mathrm{Dy}^{*} + \nu_e$$

$$^{163}\mathrm{Dy}^{*} \rightarrow {}^{163}\mathrm{Dy} + E_c$$

$$\tau_{1/2} \simeq 4570 \text{ y}$$

$$Q = 2863.2 \pm 0.6 \text{ eV}$$

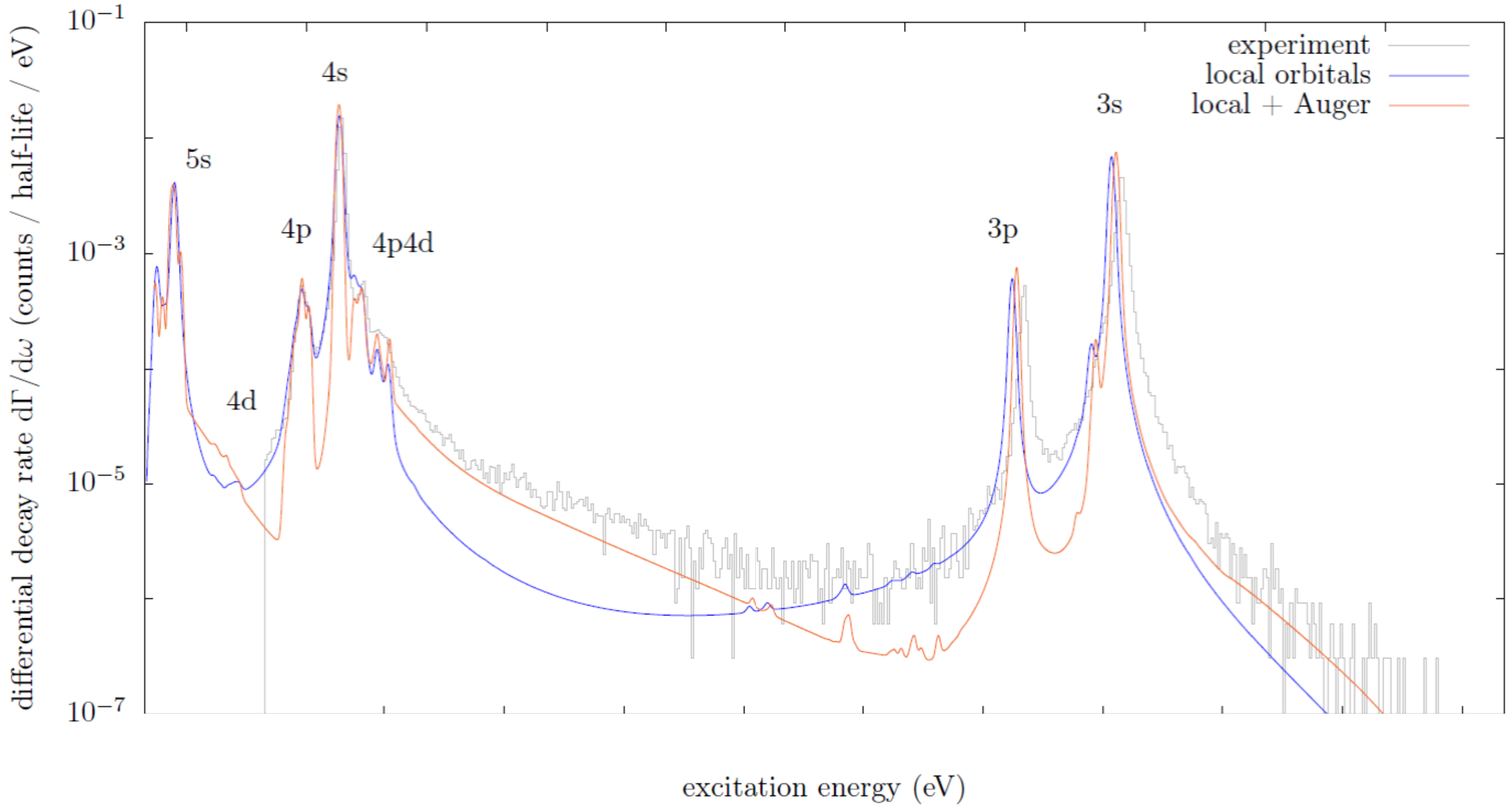
Schweiger, C., Braß, M., Debierre, V. *et al.* *Nat. Phys.* **20**, 921–927 (2024).



https://commons.wikimedia.org/wiki/File:Electron_capture.svg

Electron Capture in Holmium-163

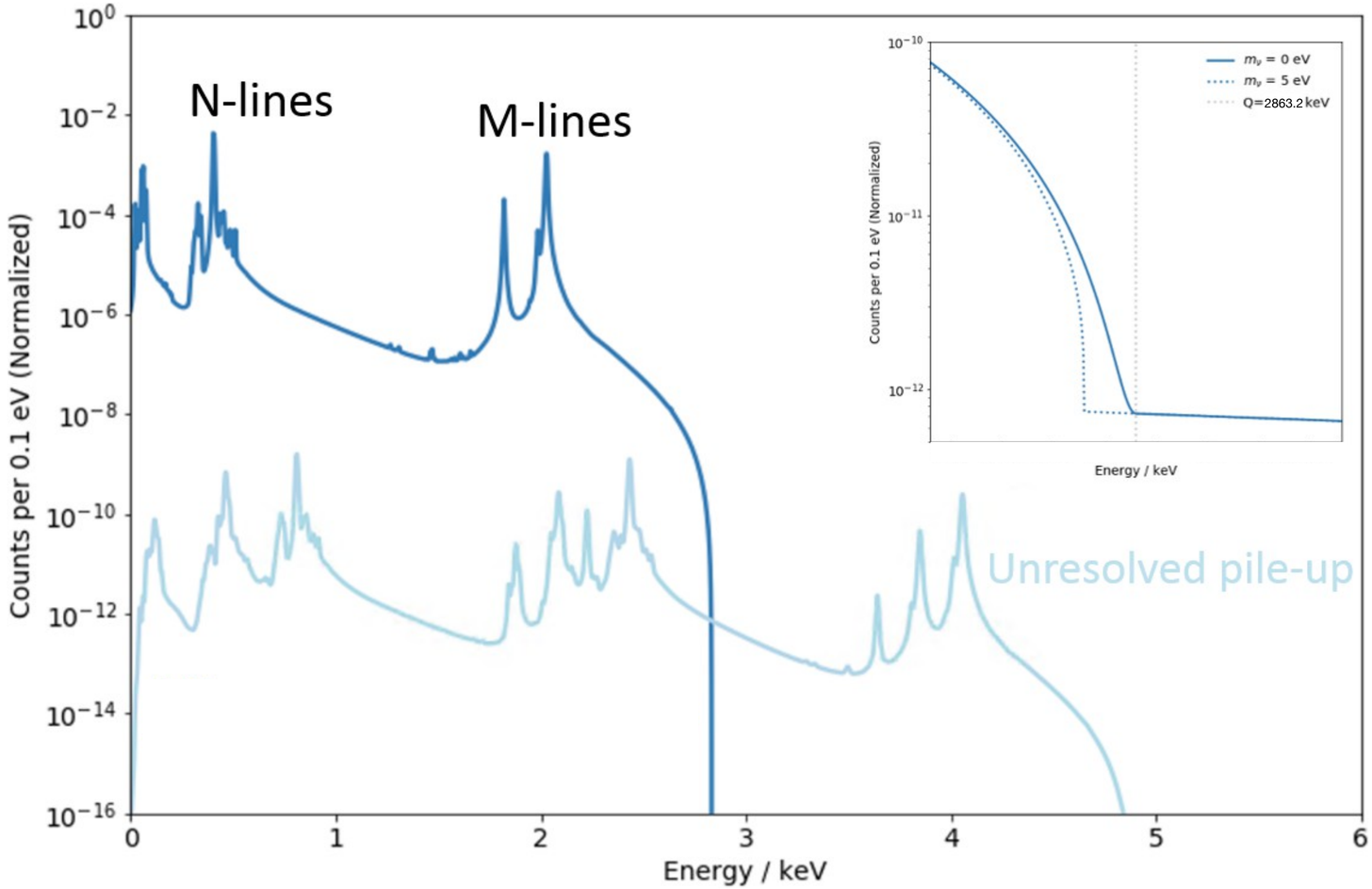
- **Theoretical Spectrum calculated based on:**
  - Phase space factor $\left(\frac{dW}{dE} \propto (Q-E)^2 \sqrt{1-\frac{m_{\nu_e}^2}{(Q-E)^2}}\right)$
  - Modified potentials
  - Coulombic repulsions
  - Auger, Auger-Meitner effects
- **Unaccounted tail effects:**
  - Double Auger effects
  - Condensed Matter effects of implantation



M. Brass, M.W. Haverkort, New J. Phys. 22 093018 (2020)

Electron Capture in Holmium-163

- $Q = 2863.2 \pm 0.6$ eV
- Low Q-value necessitates **implantation**
- Significant fraction of background from pile-up:
  - **fast time response needed**
  - **Limited activity of Ho-163 in detector**
- **High Energy resolution**



M. Brass, M.W. Haverkort, New J. Phys. 22 093018 (2020)

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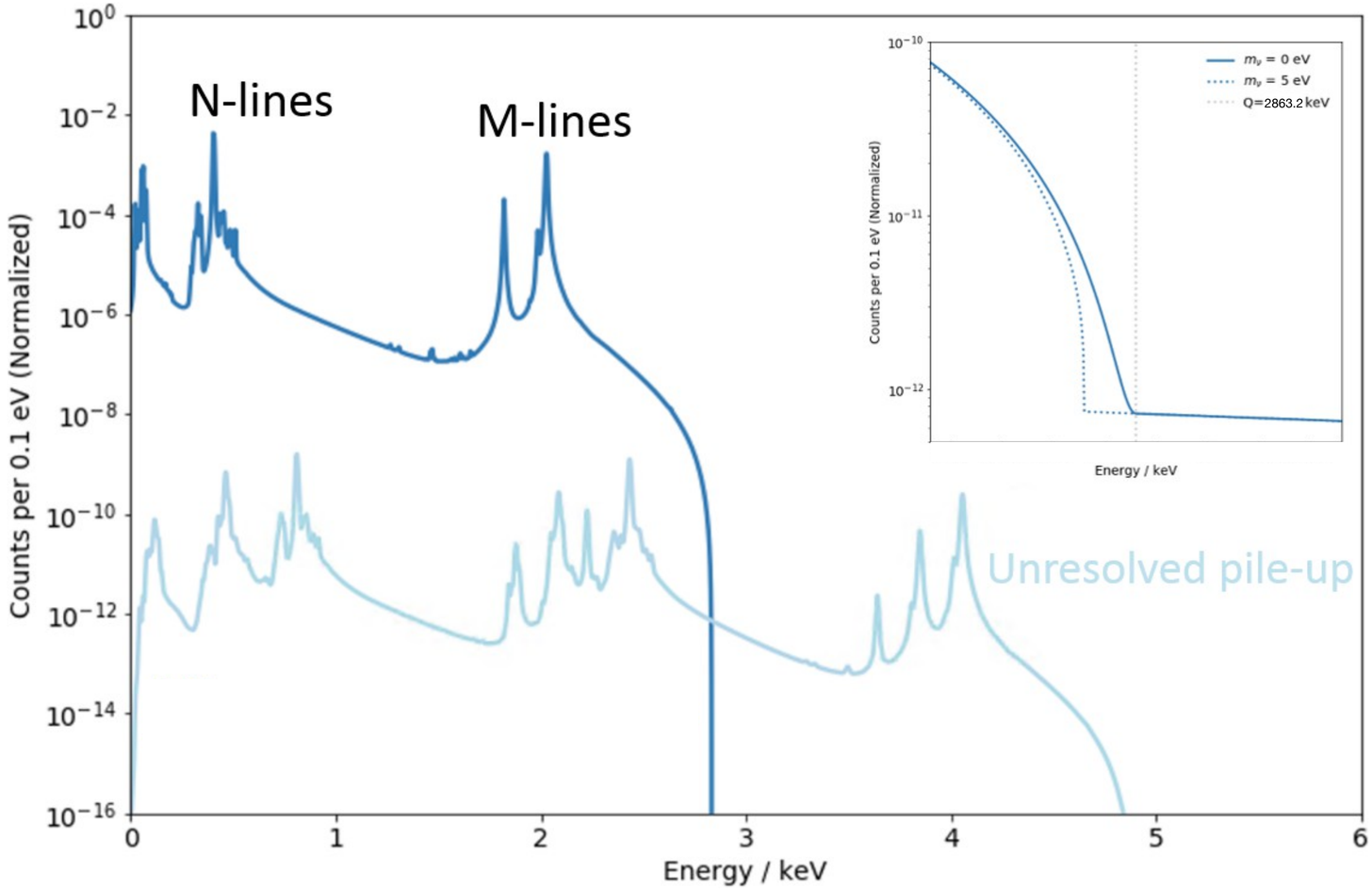


M. Brass, M.W. Haverkort, New J. Phys. 22 093018 (2020)

Metallic Magnetic Calorimeters

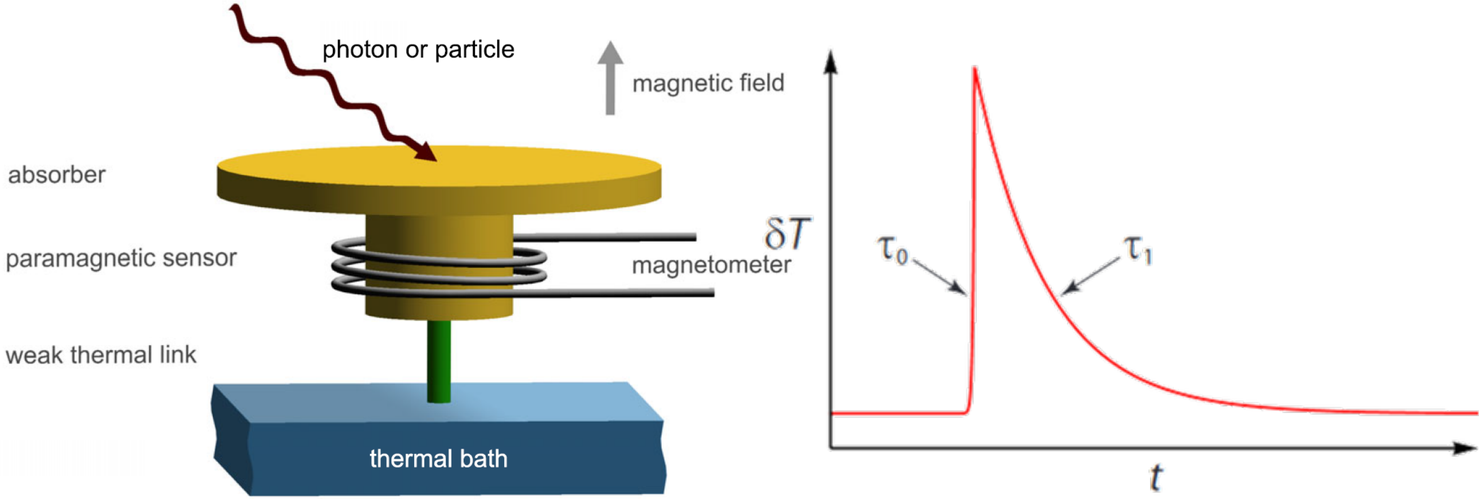
Metallic Magnetic Calorimeters (MMCs)

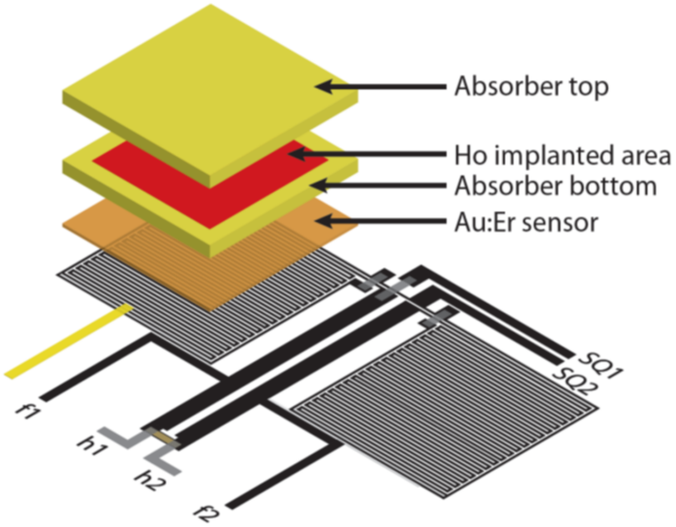
- MMCs are low-temperature calorimeters

$$\delta E \rightarrow \frac{\delta E}{C} = \delta T \rightarrow \frac{\partial M}{\partial T}\delta T = \delta M \rightarrow \delta M \propto \delta \Phi$$

- Change in Flux detected by SuperConducting Quantum Interference Devices (SQUIDs)

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





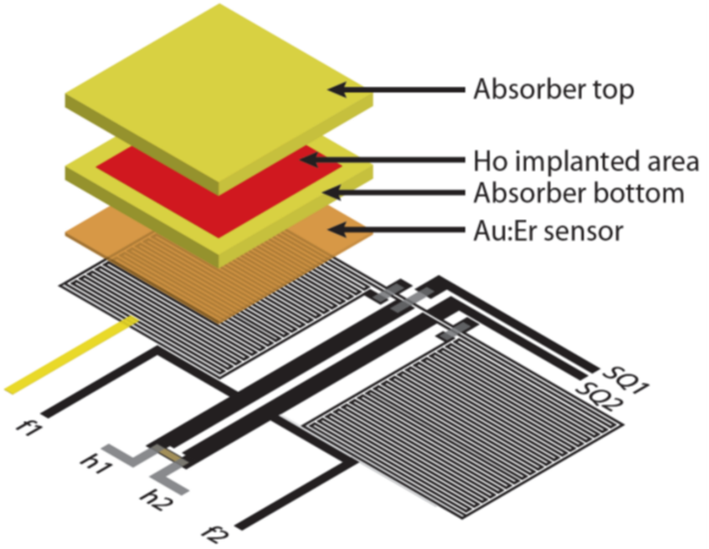
L. Gastaldo et. al, Eur. Phys. J. Special Topics 226, 1623–1694 (2017)

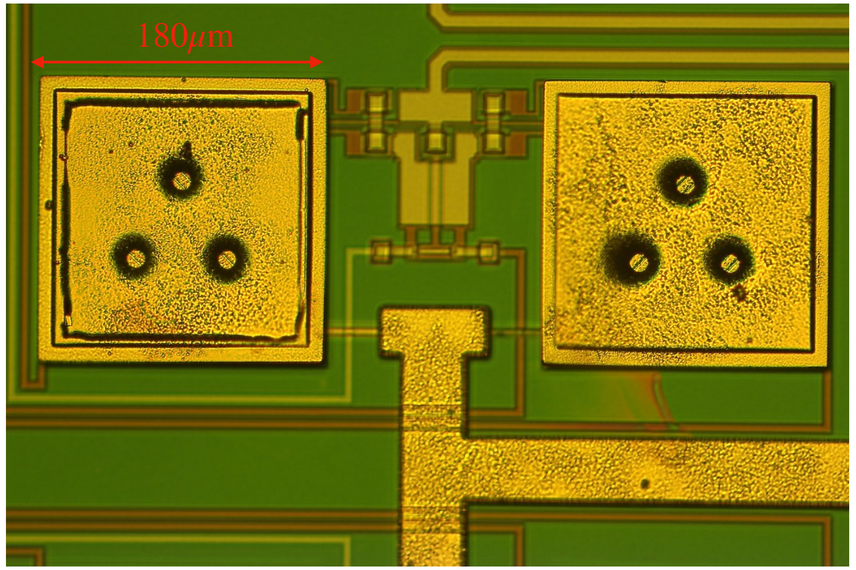
ECHo-1k

- Array of Metallic Magnetic Calorimeters with Ho-163 embedded inside particle absorber

- Fabricated in-house in Kirchhoff Institute for Physics, Heidelberg

- Implantation of Ho-163 done in RISIKO, Institute of Physics, Mainz University





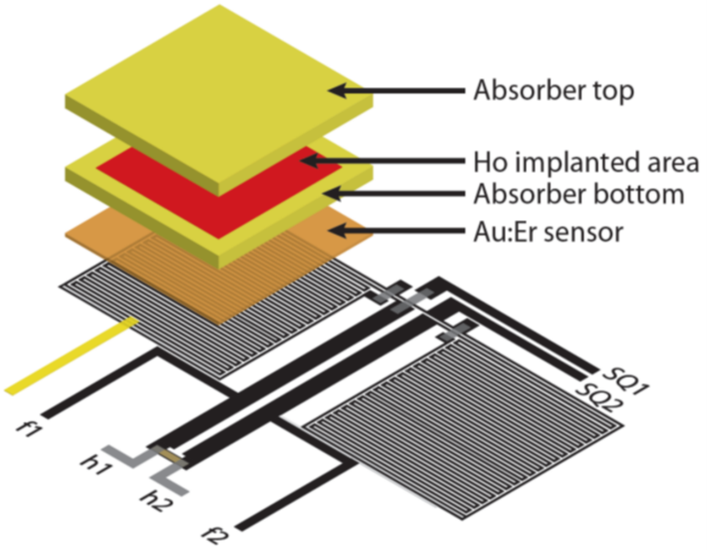
Implantation:
150 µm x 150 µm

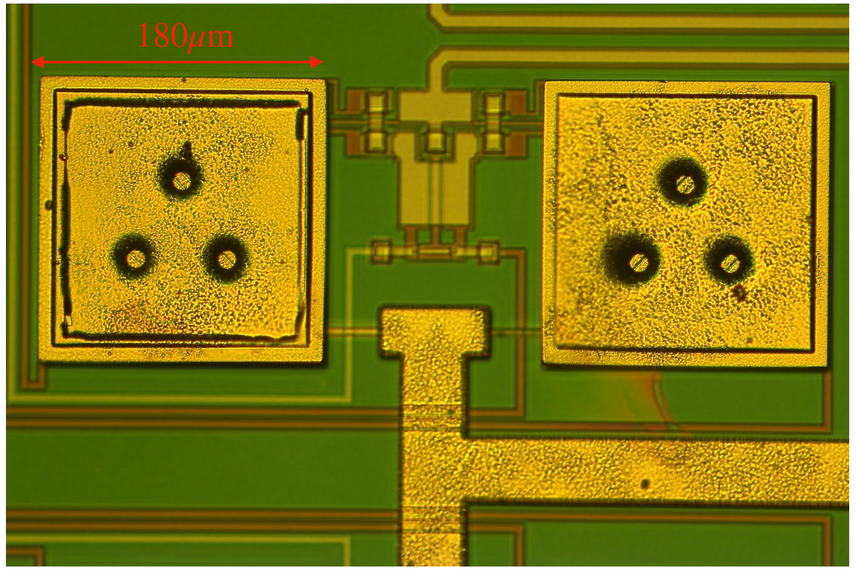
Second absorber:
165 µm x 165 µm

First absorber:
180 µm x 180 µm

ECHo-1k

- Energy Resolution < 7 eV
- Linear energy response (non linear component $\sim 10^{-5}$eV @ 2 keV)
- High statistics with low unresolved pile-up fraction





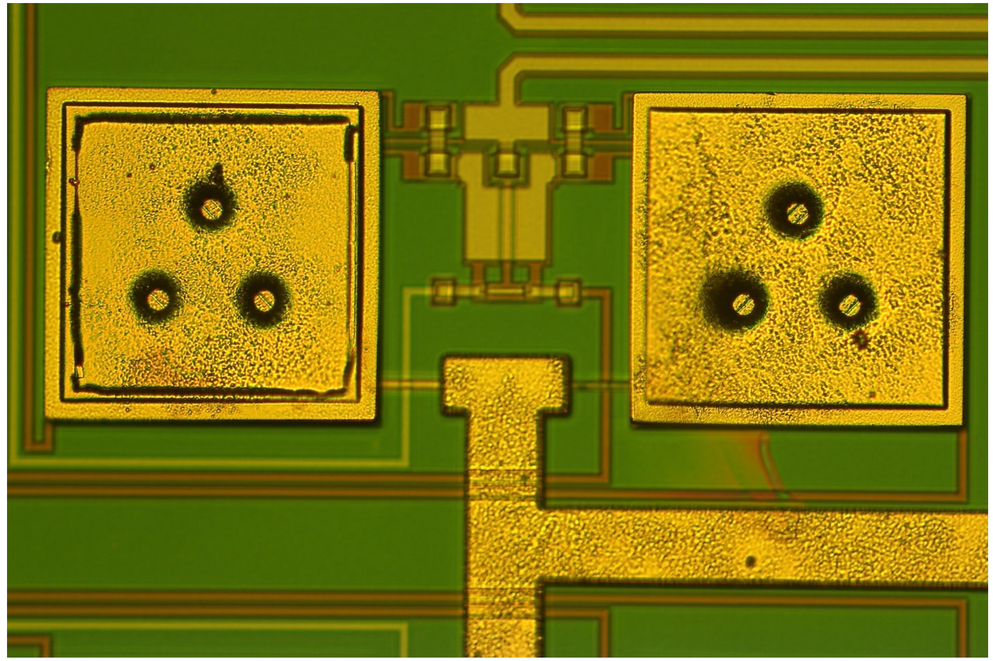
Implantation:
150 µm x 150 µm

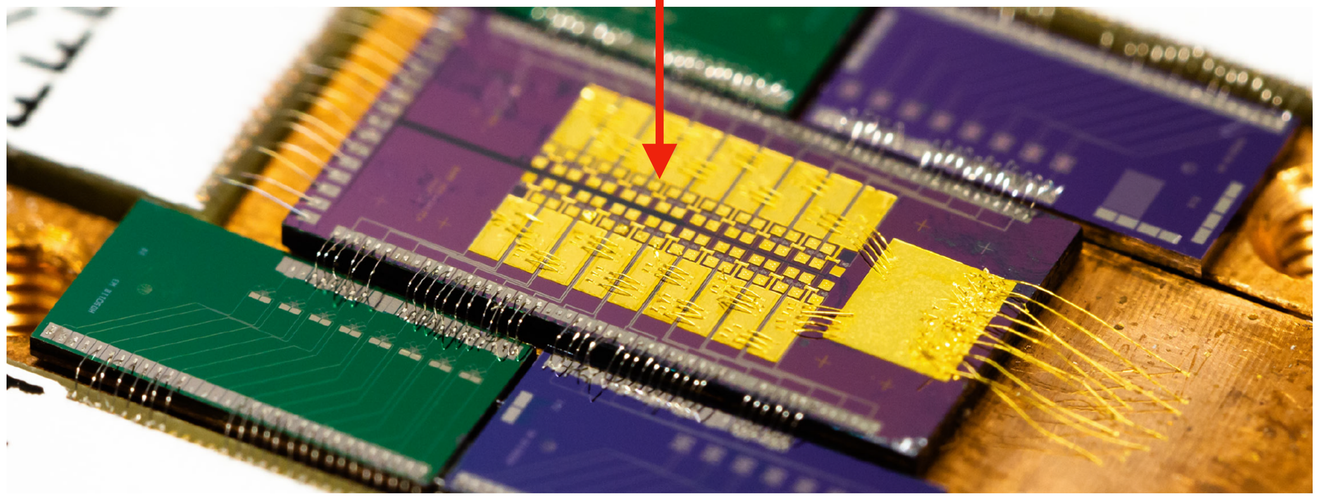
Second absorber:
165 µm x 165 µm

First absorber:
180 µm x 180 µm

ECHo-1k

- 57 pixels implanted with Ho-163
- Average activity = 0.71 Bq
- Total activity ~ 40 Bq
- **Data corresponding to ~ 3×10^8 events acquired in Dec 2019 - June 2020**
- >1000 independently stored data files





Data reduction and analysis

Time Filters

Data reduction and analysis

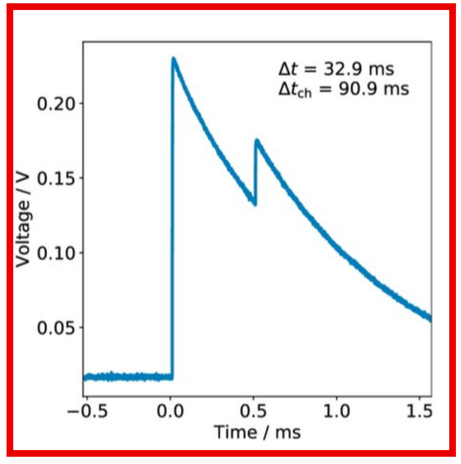
Time Filters

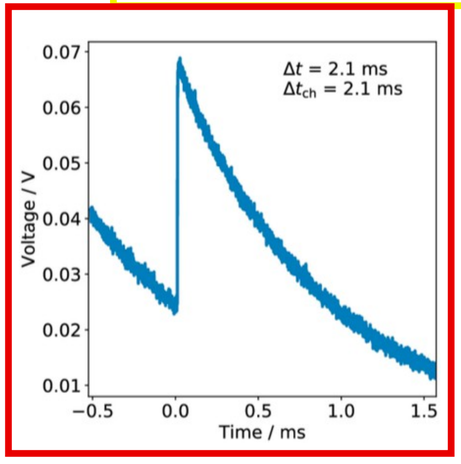
Acquired Data

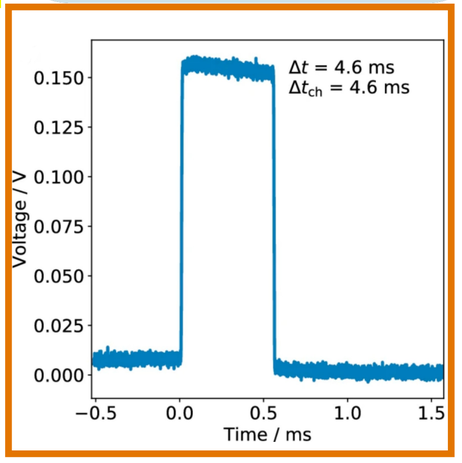
^{163}Ho Events

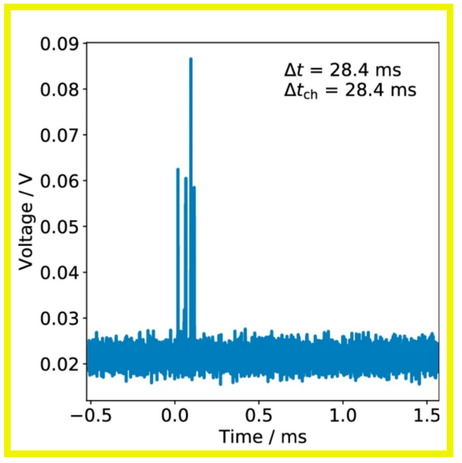
Pileup on Tail	Hold-off Filter
Phone Signal	GSM Filter
Muon Event	Coincidence Filter
Triggered Noise	Burst Filter

time-info Filter





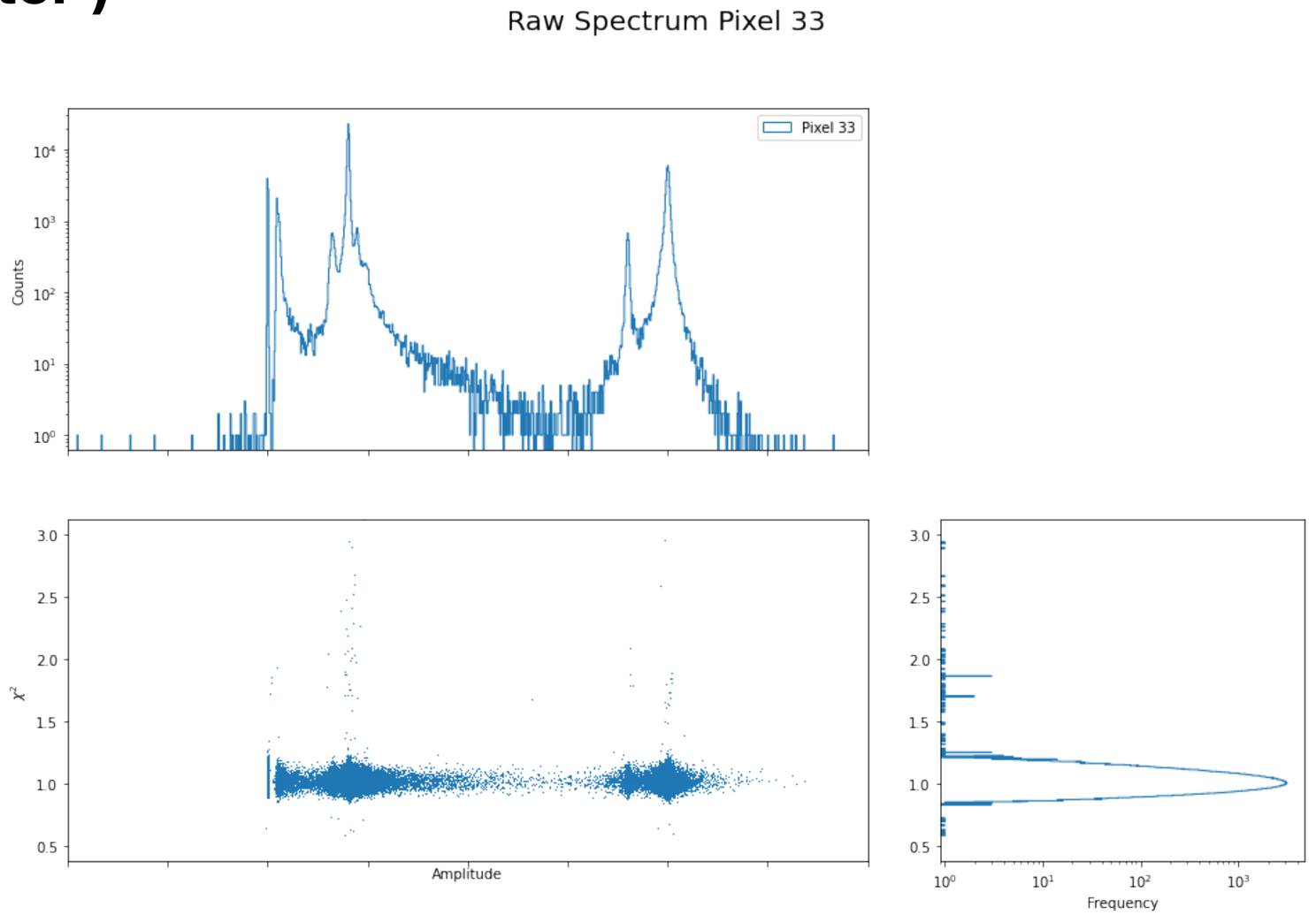




Data reduction and analysis

Pulse Shape Analysis (χ^2 Filter)

- Second level filter created on the basis of pulse shape.
- “Template Pulse” created by cross-fitting traces in batches
- Fit each trace to a template; data stored as relative ‘amplitude’s
- χ^2 of each signal calculated from mean trace



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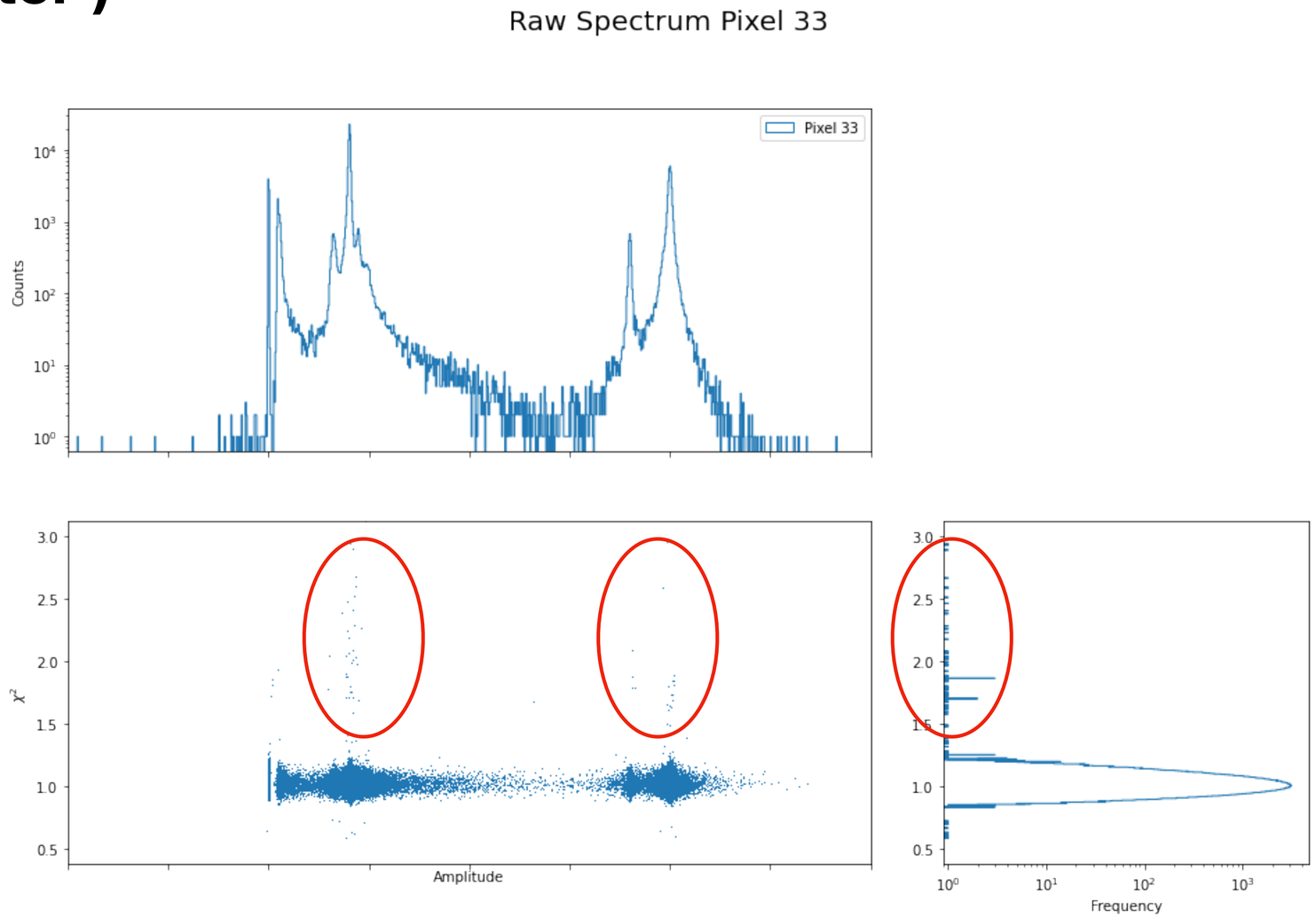
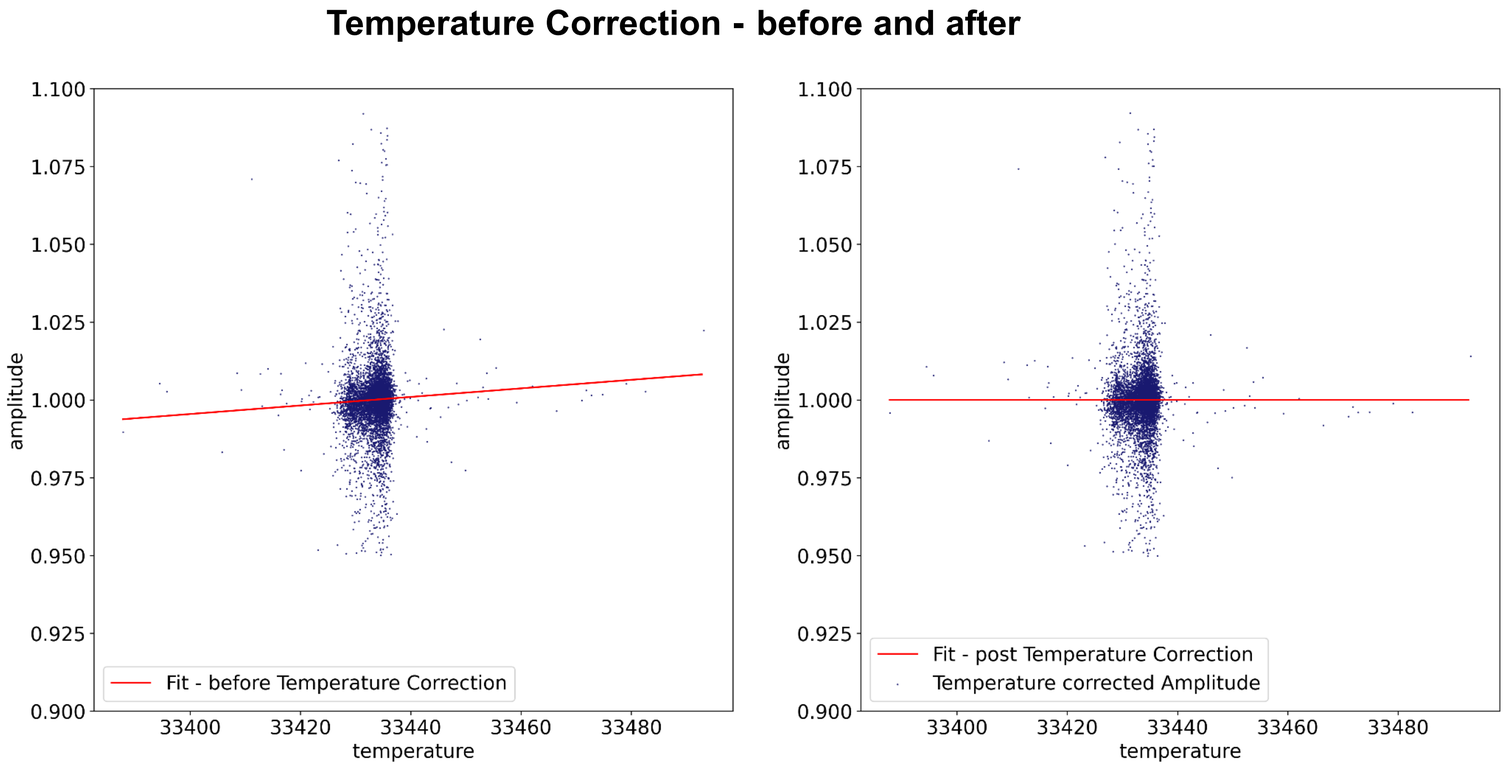


Further Data Processing

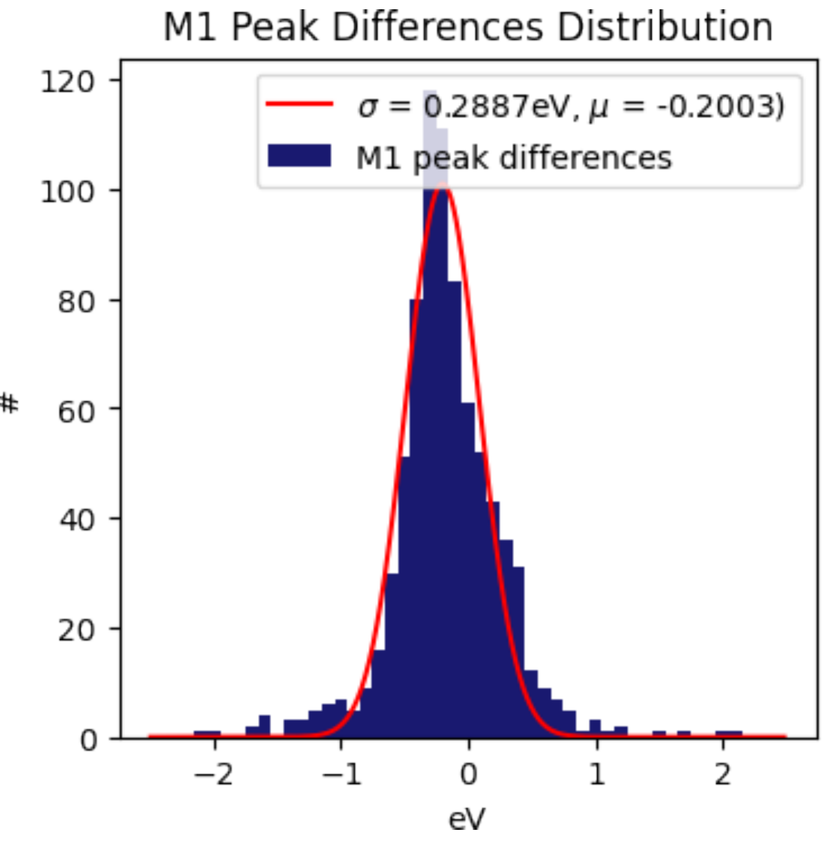
Temperature Correction

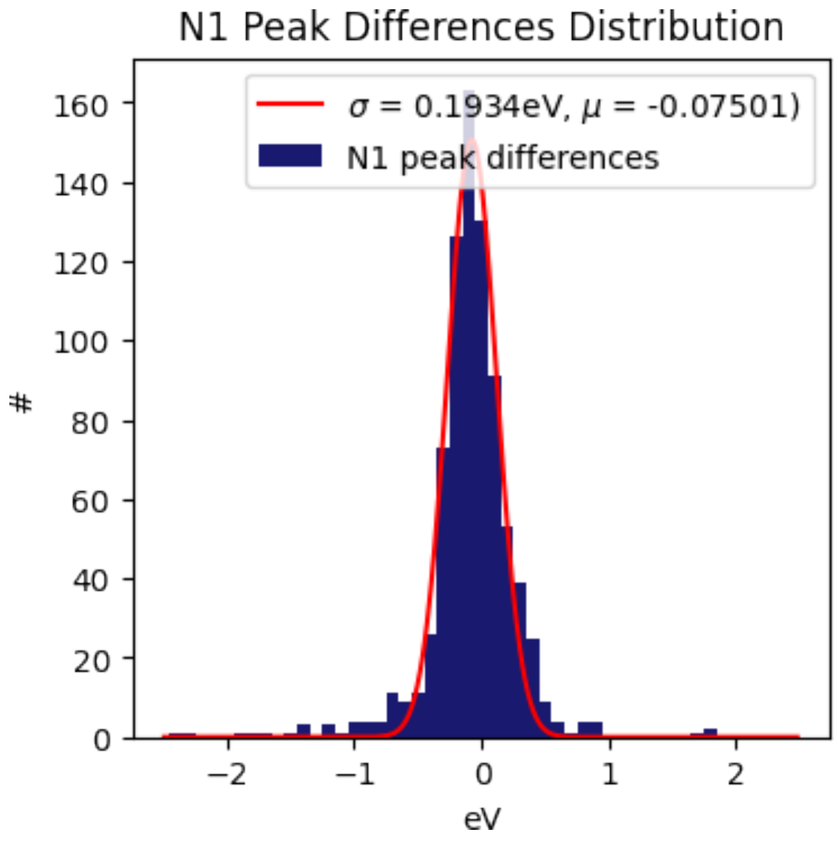


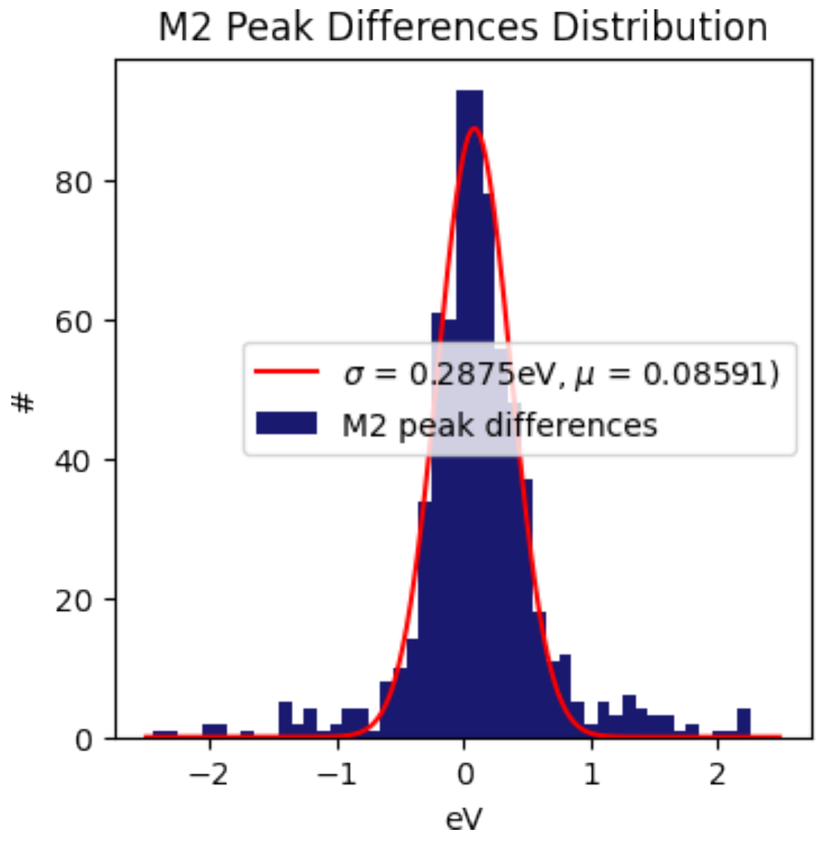
1 2

Energy calibration

Energy calibration







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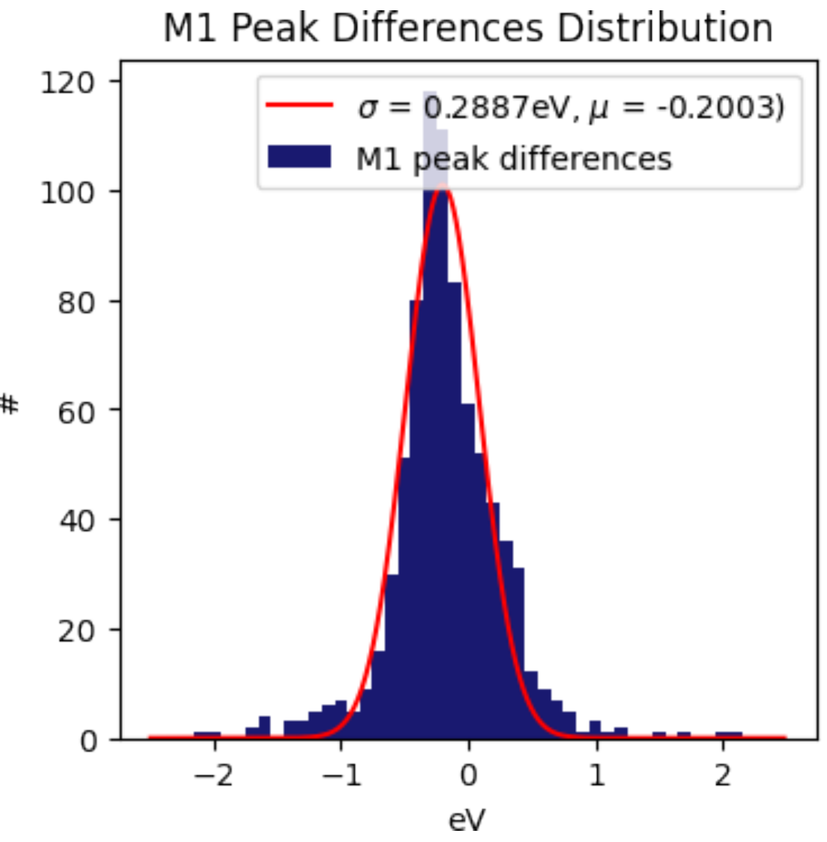
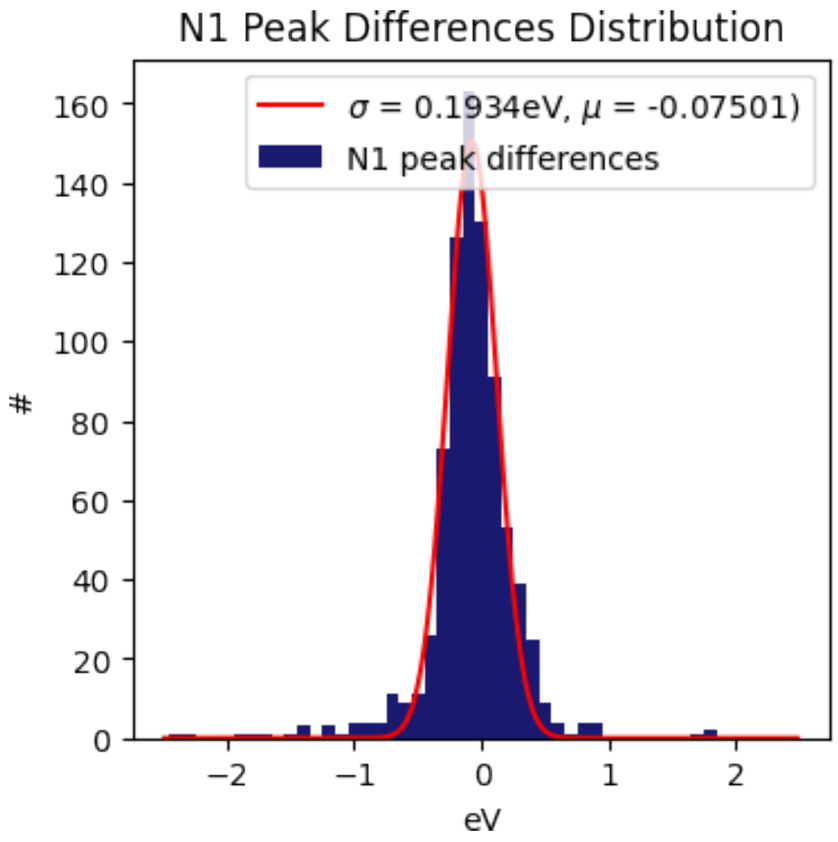
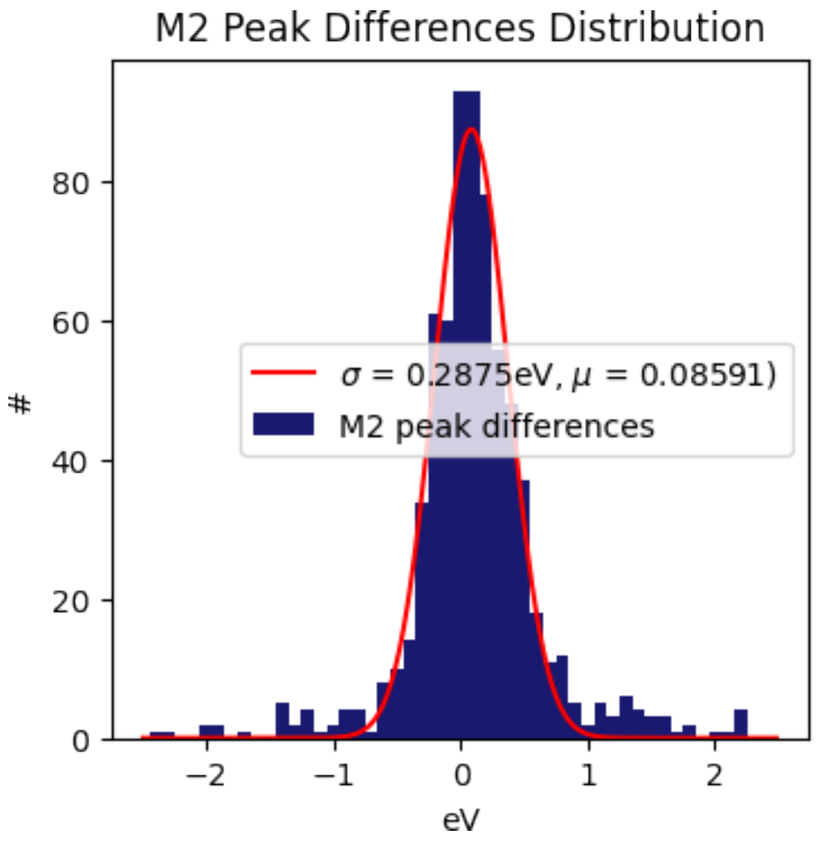
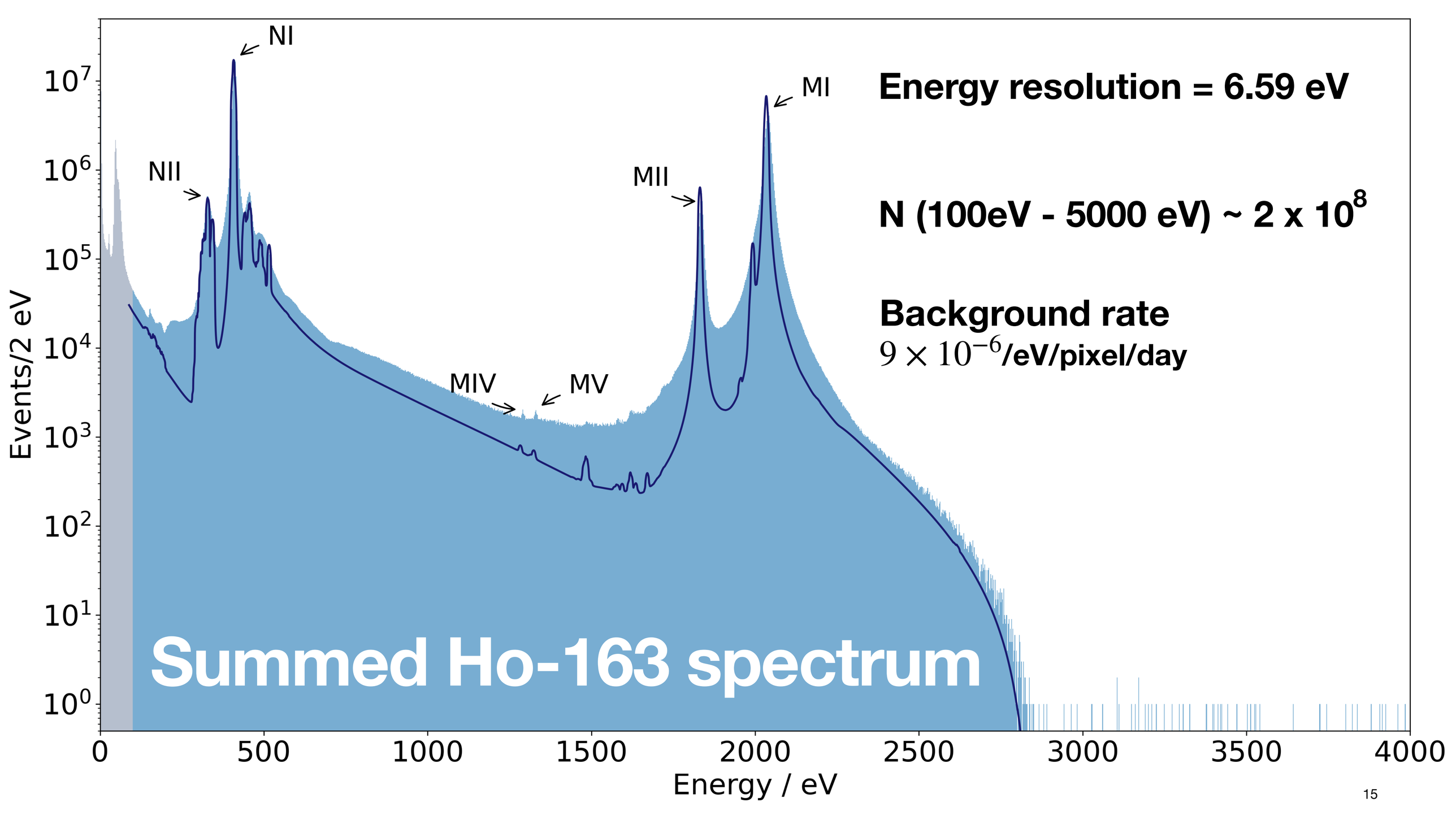


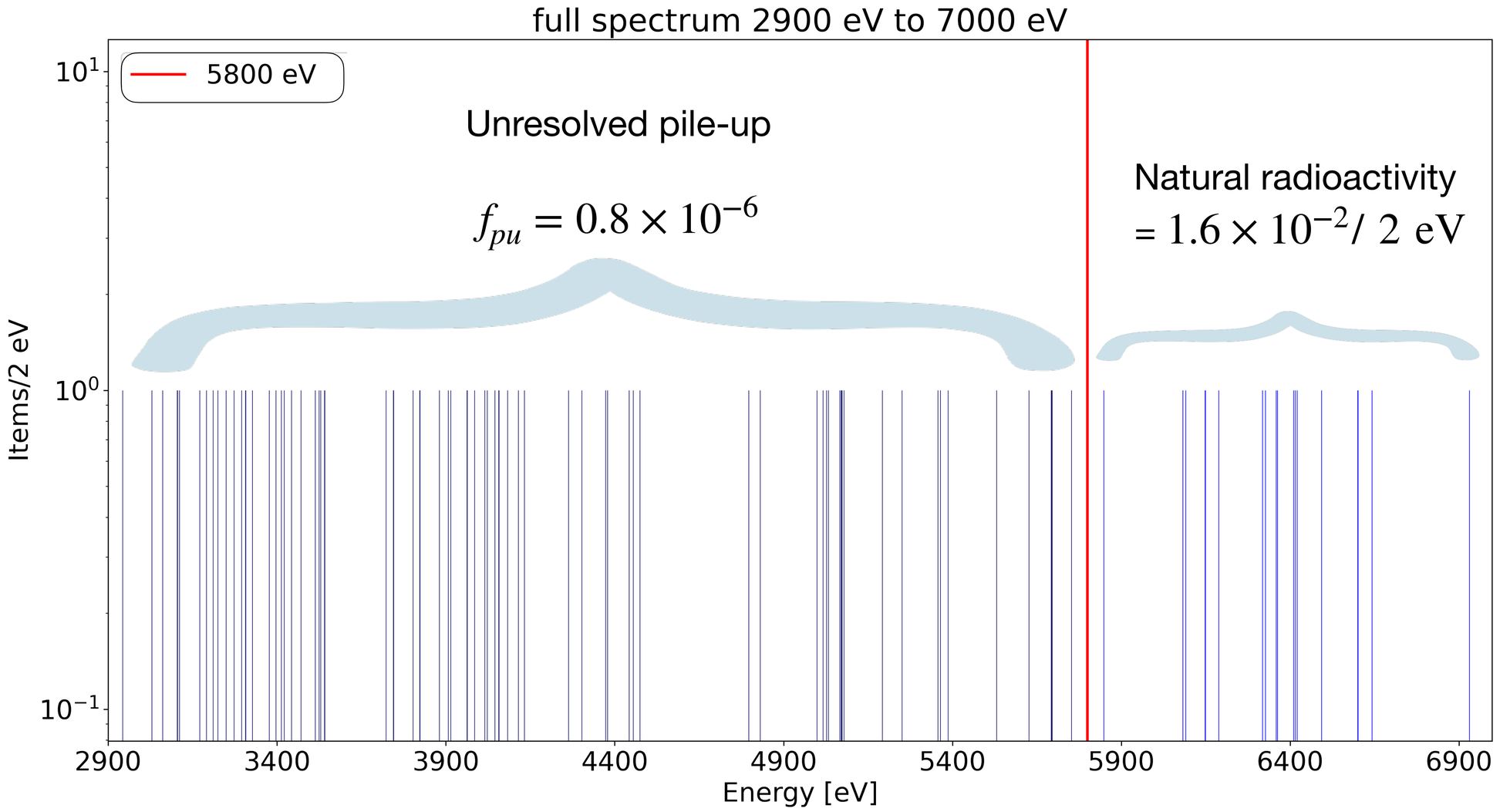




Calibrated peak position distribution σ < bin-size used (2 eV)


NI
NII
MI
MII
MIV
MV
Energy resolution = 6.59 eV
N (100eV - 5000 eV) ~ 2 x 10^8
Background rate
9 × 10^−6/eV/pixel/day
Summed Ho-163 spectrum
Events/2 eV
Energy / eV
10^0
10^1
10^2
10^3
10^4
10^5
10^6
10^7
0
500
1000
1500
2000
2500
3000
3500
4000

End Spectrum Region

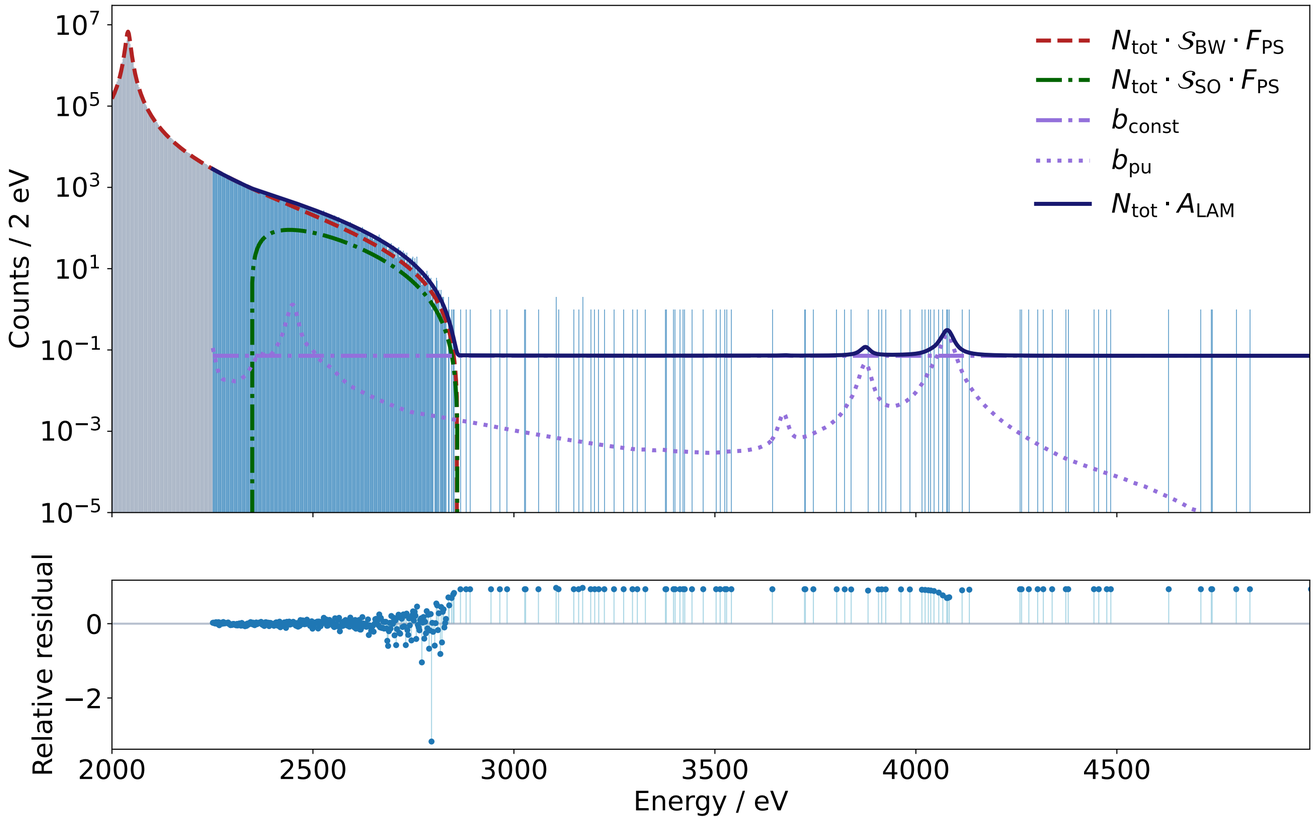


Can be modelled as a constant background

Fitting the end spectrum

$$\frac{\mathrm{d}N}{\mathrm{d}E} = C \times [A(E) \times F_{\mathrm{PS}}(E, Q)] \otimes g(E, \sigma) + b(E)$$

B. K. Alpert et al., (HOLMES Collaboration), arXiv:2503.19920v2 [hep-ex] (2025)



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B. K. Alpert et al., (HOLMES Collaboration), arXiv:2503.19920v2 [hep-ex] (2025)

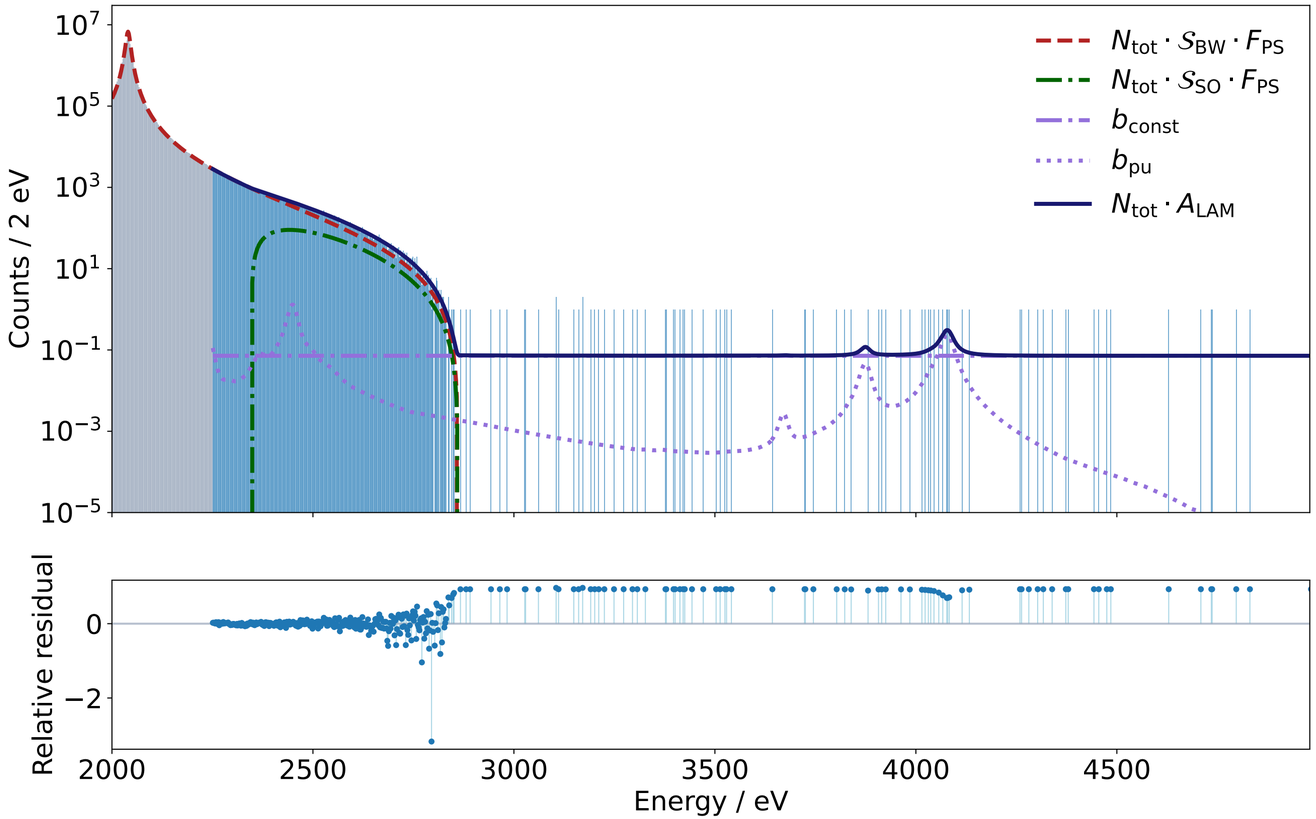
Scaling constant

Atomic Physics Descriptor

Phase Space Factor

Convolved with gaussian

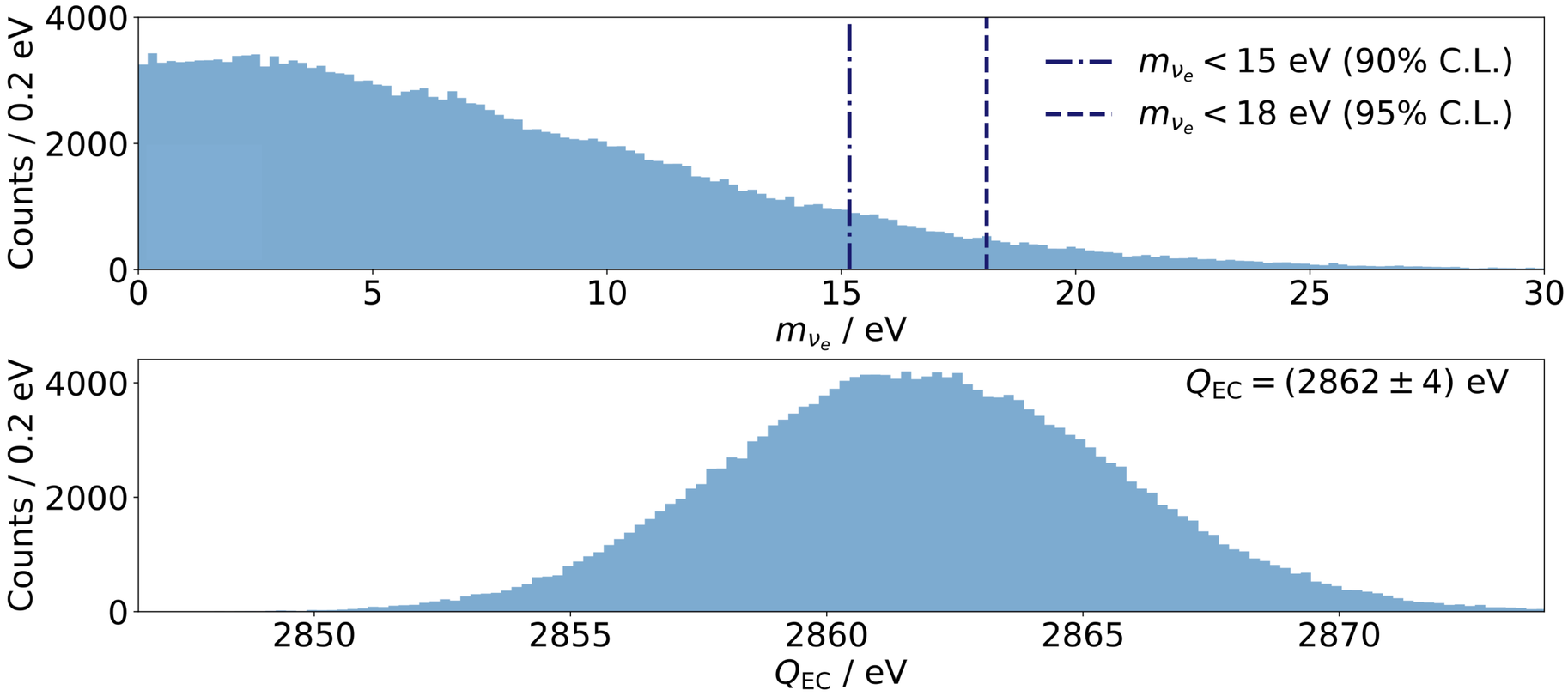
Background



Result

$$Q_{fit} = 2862 \pm 4 \text{ eV} \qquad m_{\nu_e} < 15 \text{ eV (90 \% C.L.)}$$

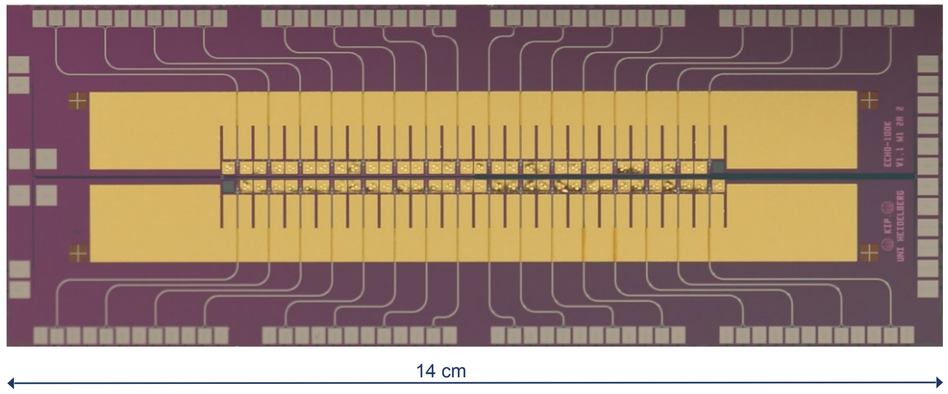
$$Q_{PTMS} = 2863.2 \pm 0.6 \text{ eV}$$

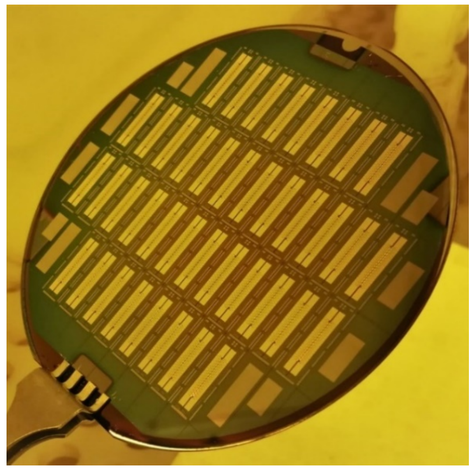


- Best limit on effective electron neutrino mass
- Complete agreement between measured and fit-based Q-value

Outlook

New ECHo-100k chip design





Present status:

High Purity ^{163}Ho source:

- ~ 10 MBq available

Ion implantation system:

- demonstrated and continuously optimised

Metallic magnetic calorimeters

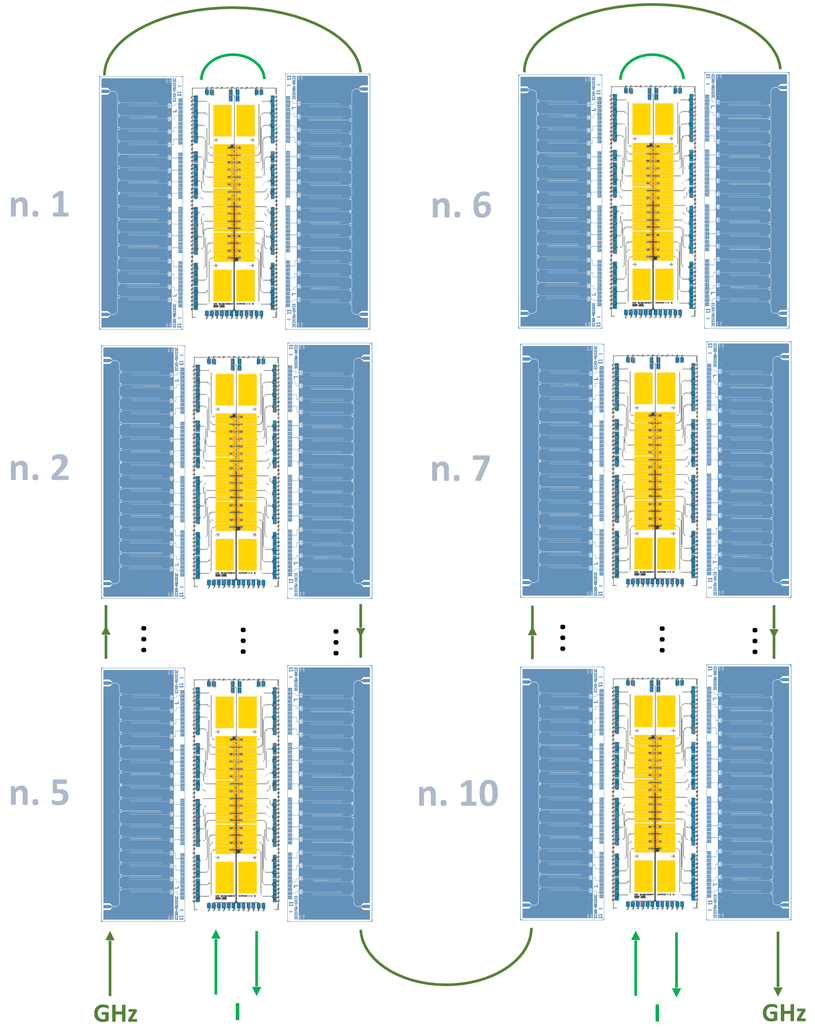
- fabrication of large MMC array underway
- successful characterisation of arrays with ^{163}Ho

Multiplexing and data acquisition:

- demonstrated for 8 channels
- Electronics ready
- Test with ^{163}Ho loaded MMC array on the way

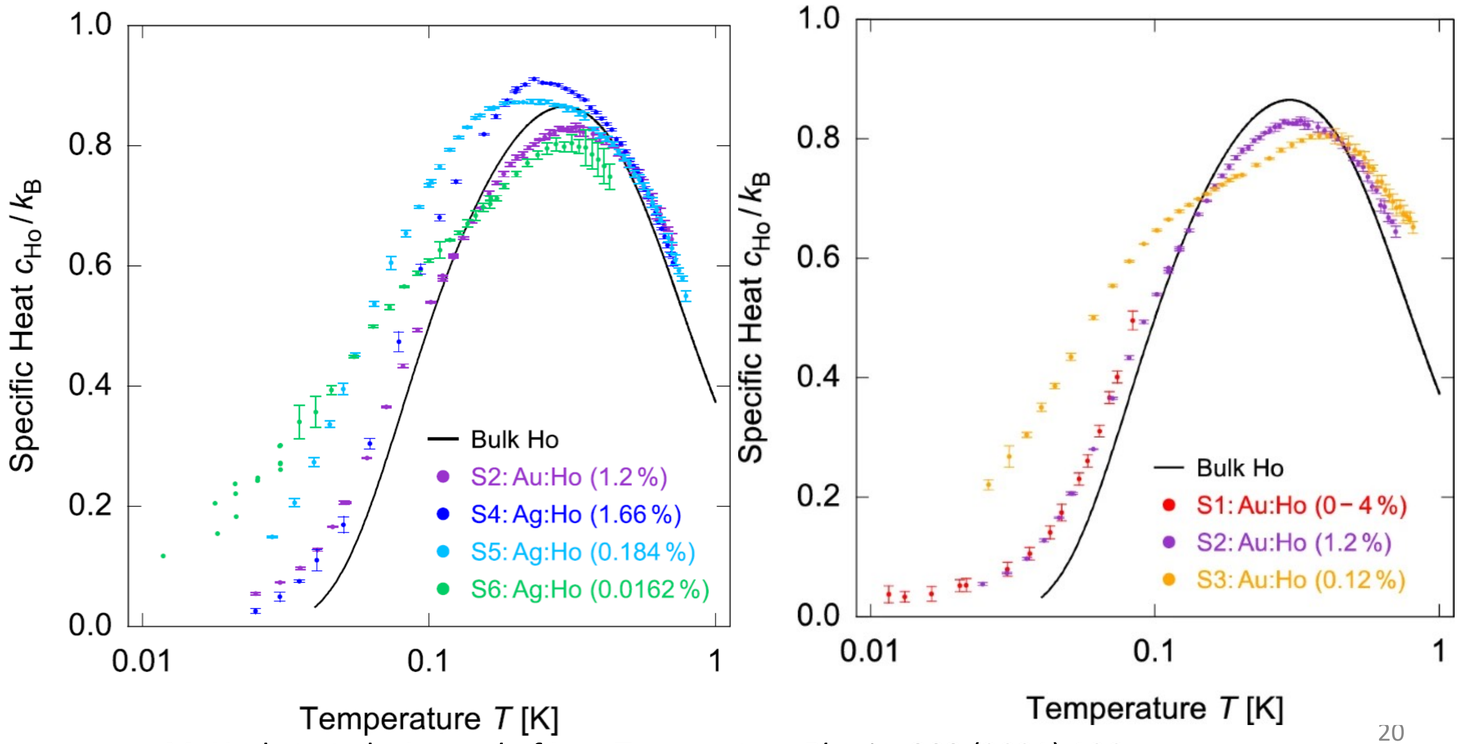
F. Mantegazzini et al., *NIM A* **1055** (2023) 168564

Outlook



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

- Baseline: large arrays of metallic magnetic calorimeters
- Number of detectors ~20,000
- Activity per pixel: 10 Bq (2 × 10^{12} ^{163}Ho atoms)



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

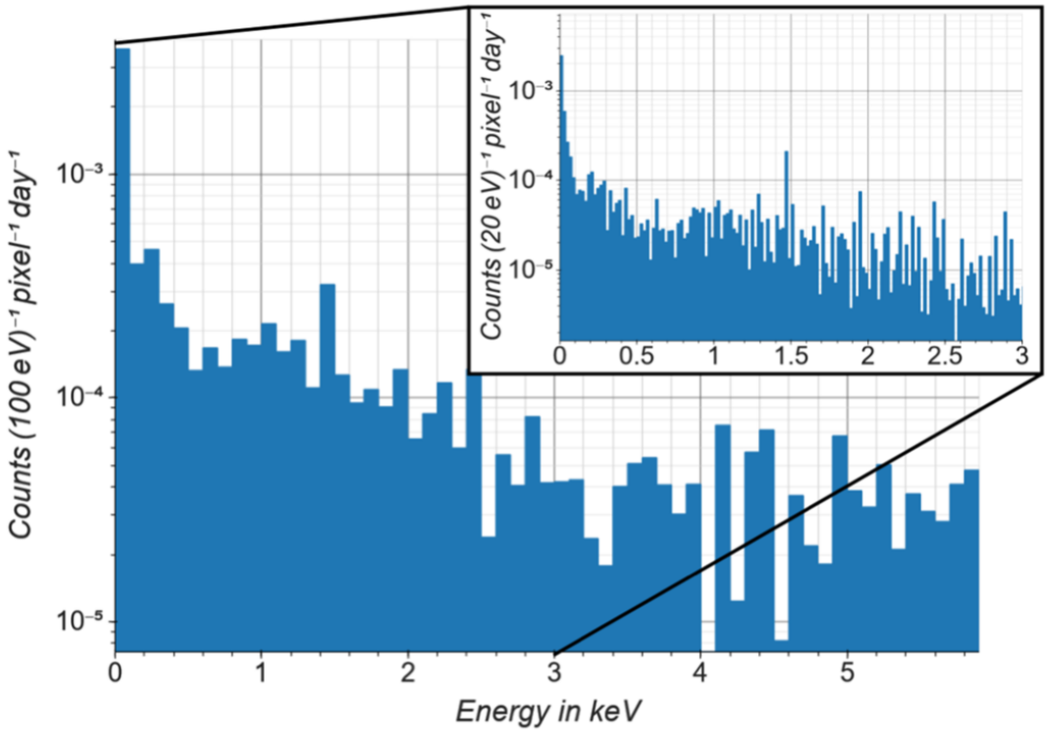
Summary

- Model Independent determination of $m_{\nu_e}/m_{\bar{\nu}_e}$ done with kinematic studies of β-decay and electron capture
- Best limits
  - KATRIN: $m_{\bar{\nu}_e} < 0.45 \text{ eV } (90\,\% \text{ C.L.})$
  - ECHo: $m_{\nu_e} < 15 \text{ eV } (90\,\% \text{ C.L.})$
- Excellent agreement between Q-value measured by Pentatrap ($Q_{\text{PTMS}} = 2863.2 \text{ eV}$) and ECHo fit ($Q_{EC} = 2862 \pm 4 \text{ eV}$)
- Next stage: ECHo-LE aims to measure ~ 20,000 detectors with 10 Bq implanted Ho-163, to achieve sub-eV sensitivity on m_{ν_e} with 10^{13} events

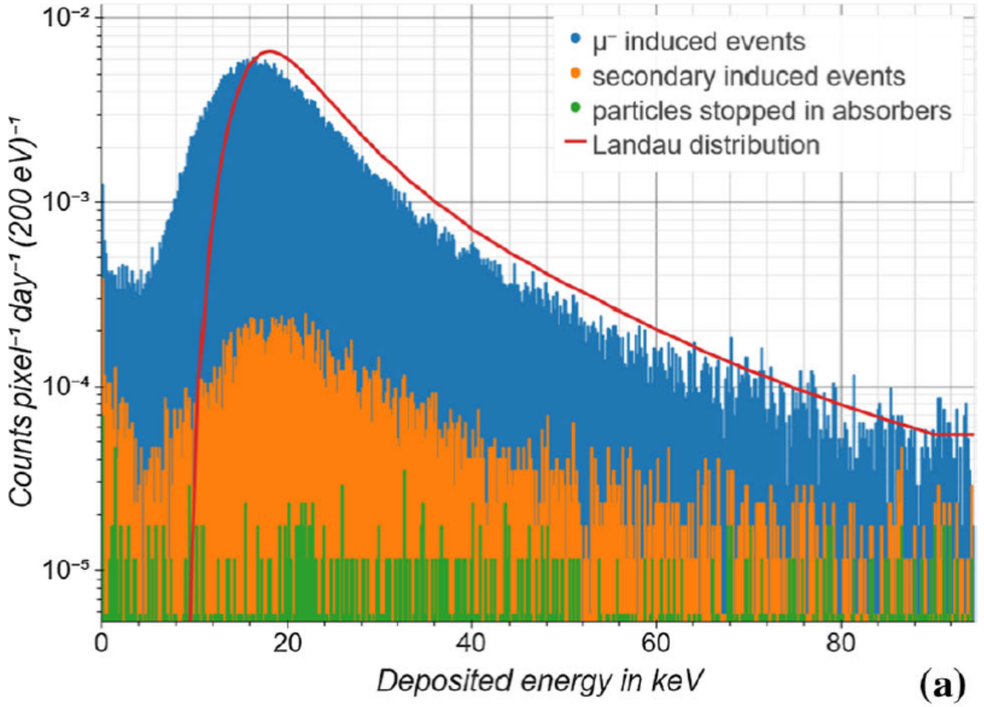
Thank you!

Backup

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

Penning Trap Mass Spectrometry

- Pure samples of highly charged ions of both $^{163}\mathrm{Ho}$ and $^{163}\mathrm{Dy}$ trapped in uniform magnetic field region
- Modified cyclotron frequencies measured

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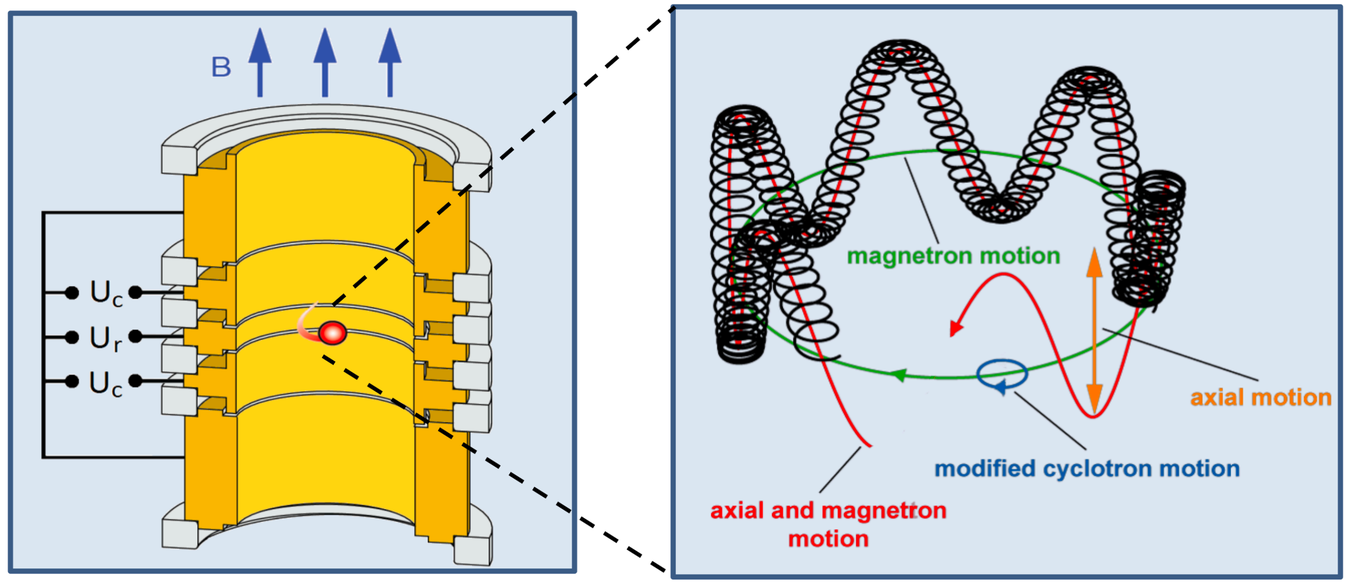

Schweiger, C., Braß, M., Debierre, V. *et al.* *Nat. Phys.* **20**, 921–927 (2024).

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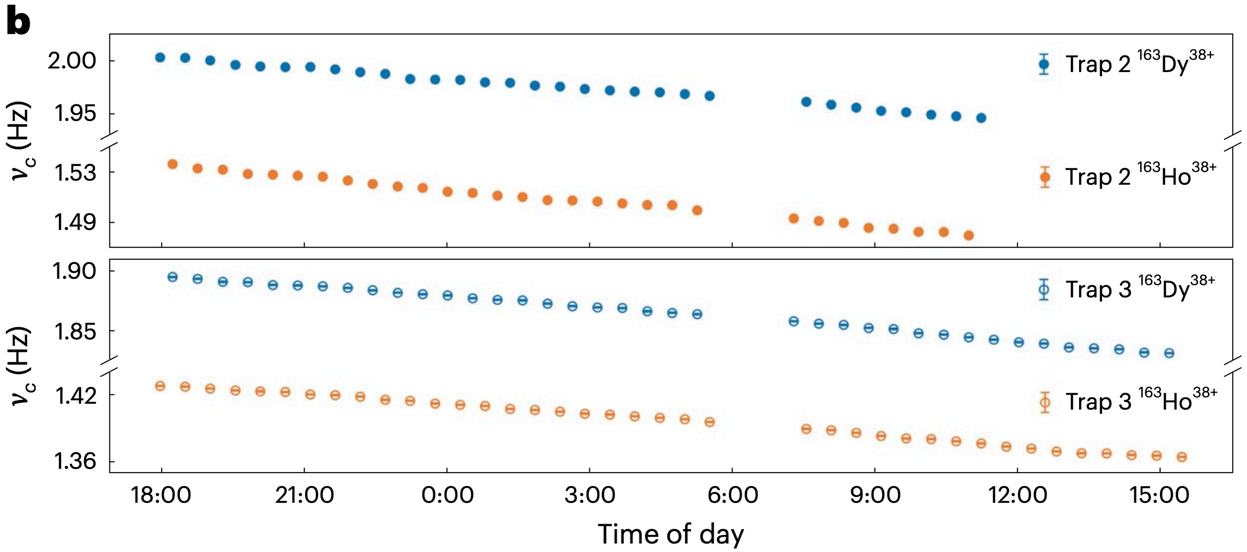
PENTATRAP



q/e	R	δR	ΔE_B^{q+} (eV)	Q (eVc^{-2})
38	1.000000018623	3.0×10^{-12}	37.4±1.4	2,863.4±1.5
39	1.000000011307	4.1×10^{-12}	1,147.3±0.7	2,863.2±0.9
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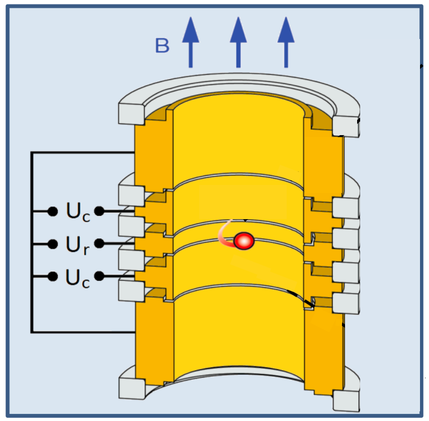
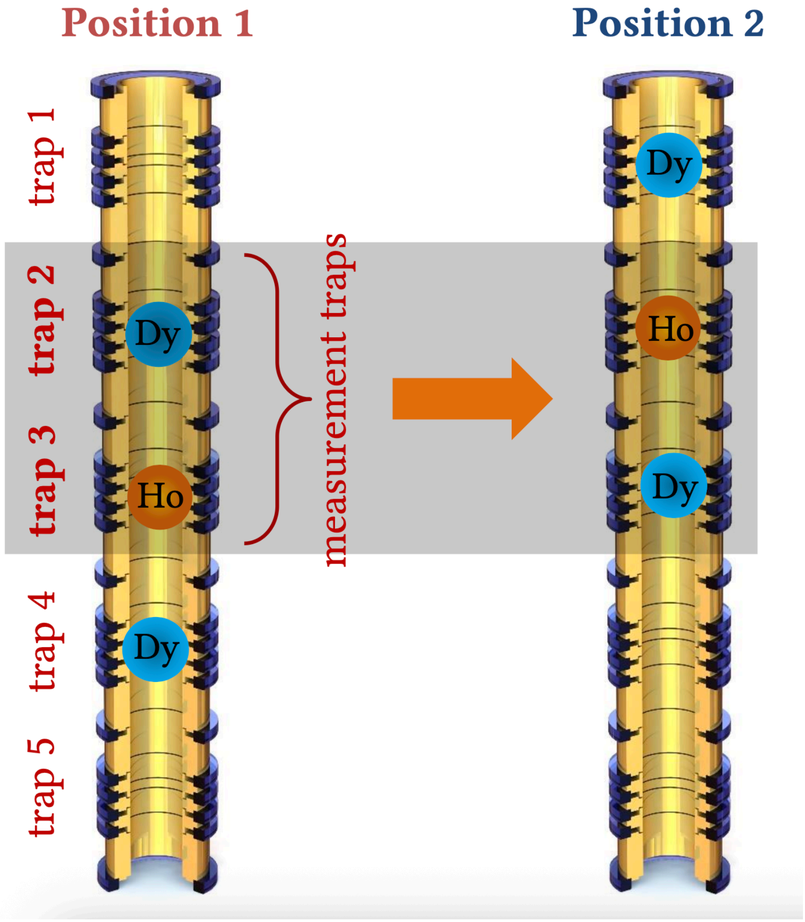
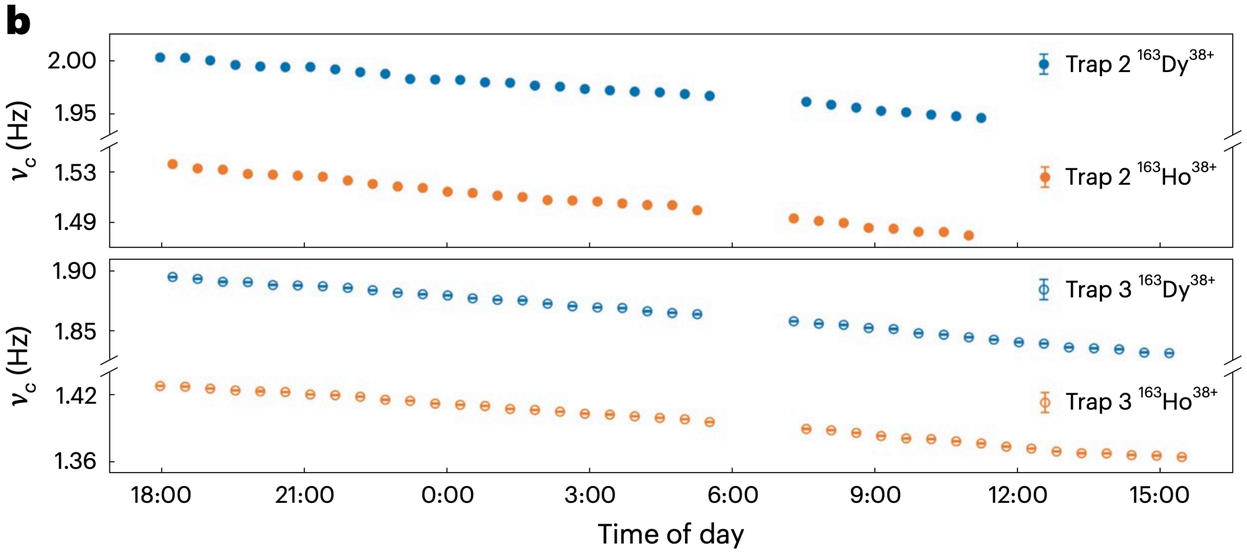
$$Q = 2863.2 \pm 0.6 \text{ eV}$$





PENTATRAP



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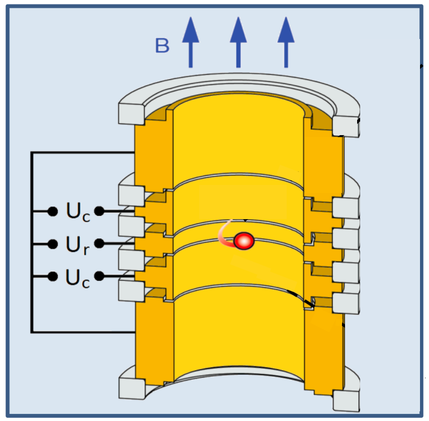
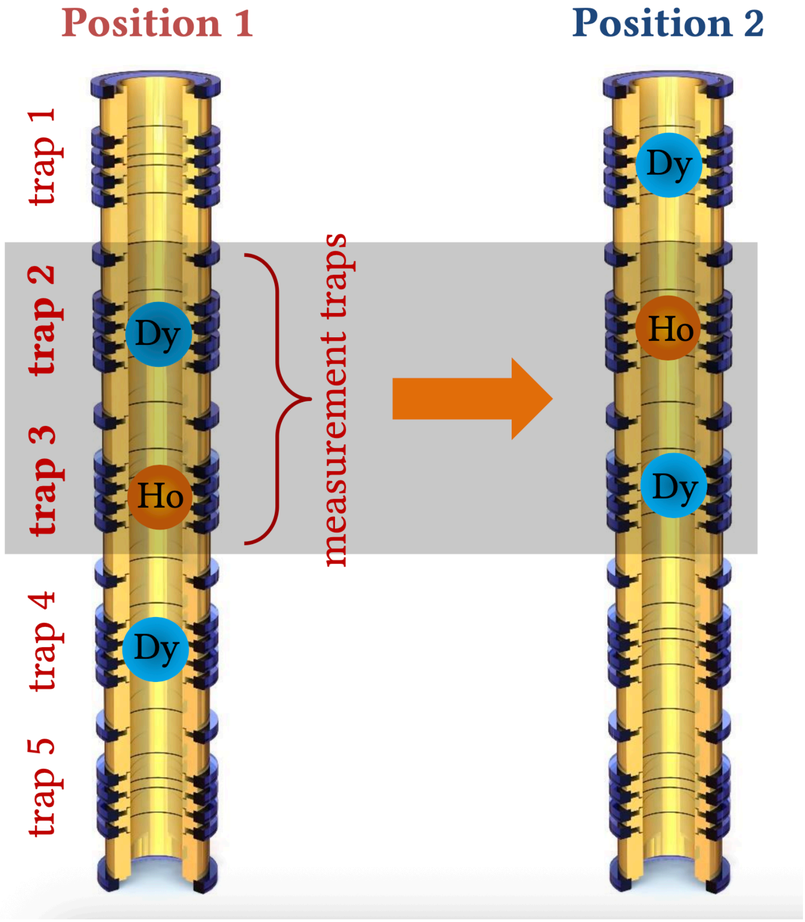
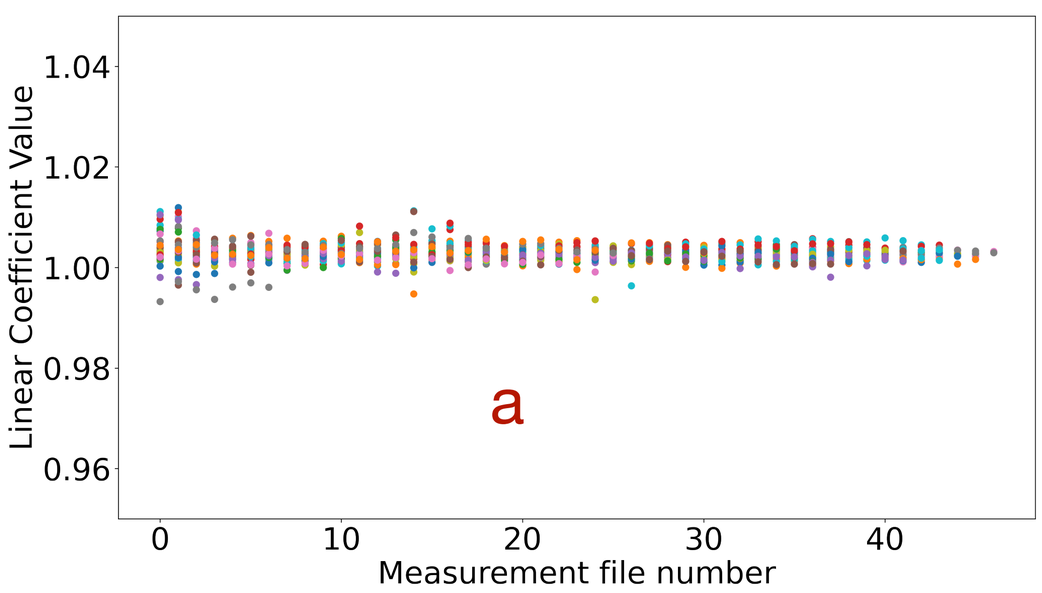
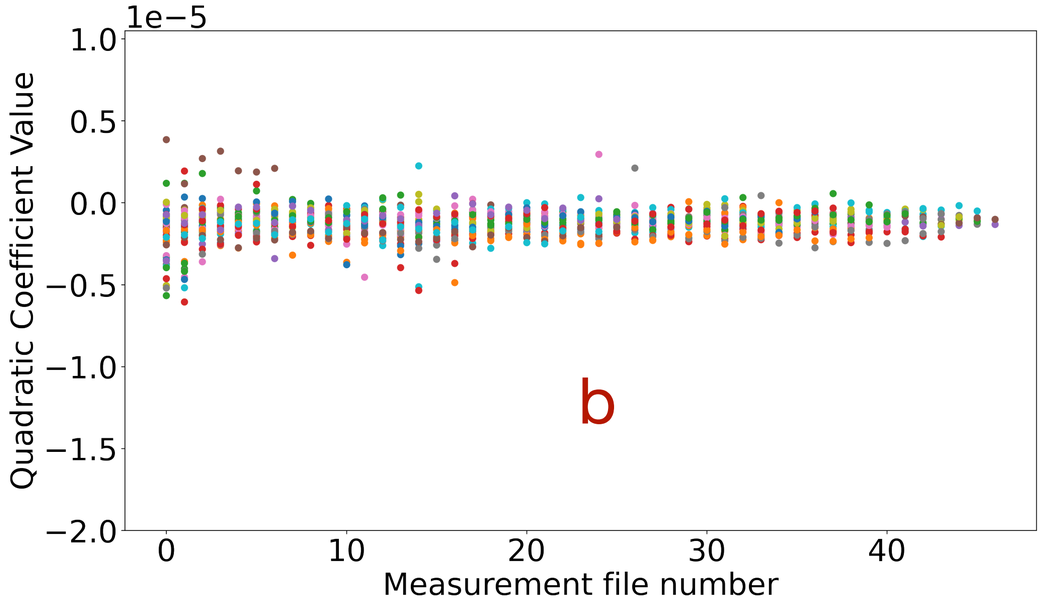




Further Work

- ECHo-100k is the current stage of the ECHo project
- Fabrication and characterisation of 240 ECHo-100k detector chips.
  - Work underway as part of a Master’s Thesis
- Prepare ECHo-100k detector setup
  - 10,000 pixels, multiplexed signal readout





$$E_{exp} = aE_{theo} + bE_{theo}^2$$

Current Work

- HiWi with ECHo, continuation of Research from Master’s studies, supervising bachelor’s students with focus on data analysis
- Implementation of full Data reduction + quality check for data acquired from pixels with gold host
  - Comparison High Energy resolution - spectral shape - artefacts from host

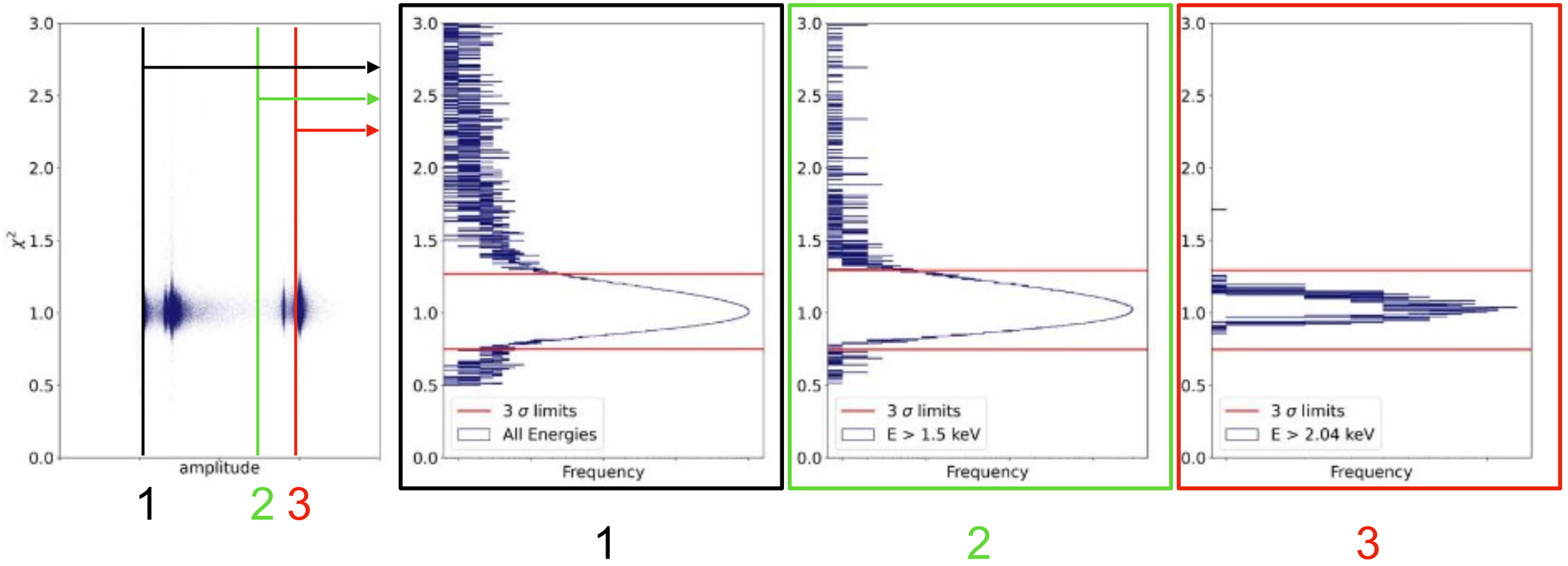
Achievement

Of the Masters Thesis

- Data Analysis pipeline: from raw data to calibrated, compiled spectrum.
  - Data reduction
    - Temperature Correction
    - Energy Calibration
  - Data Quality parameters

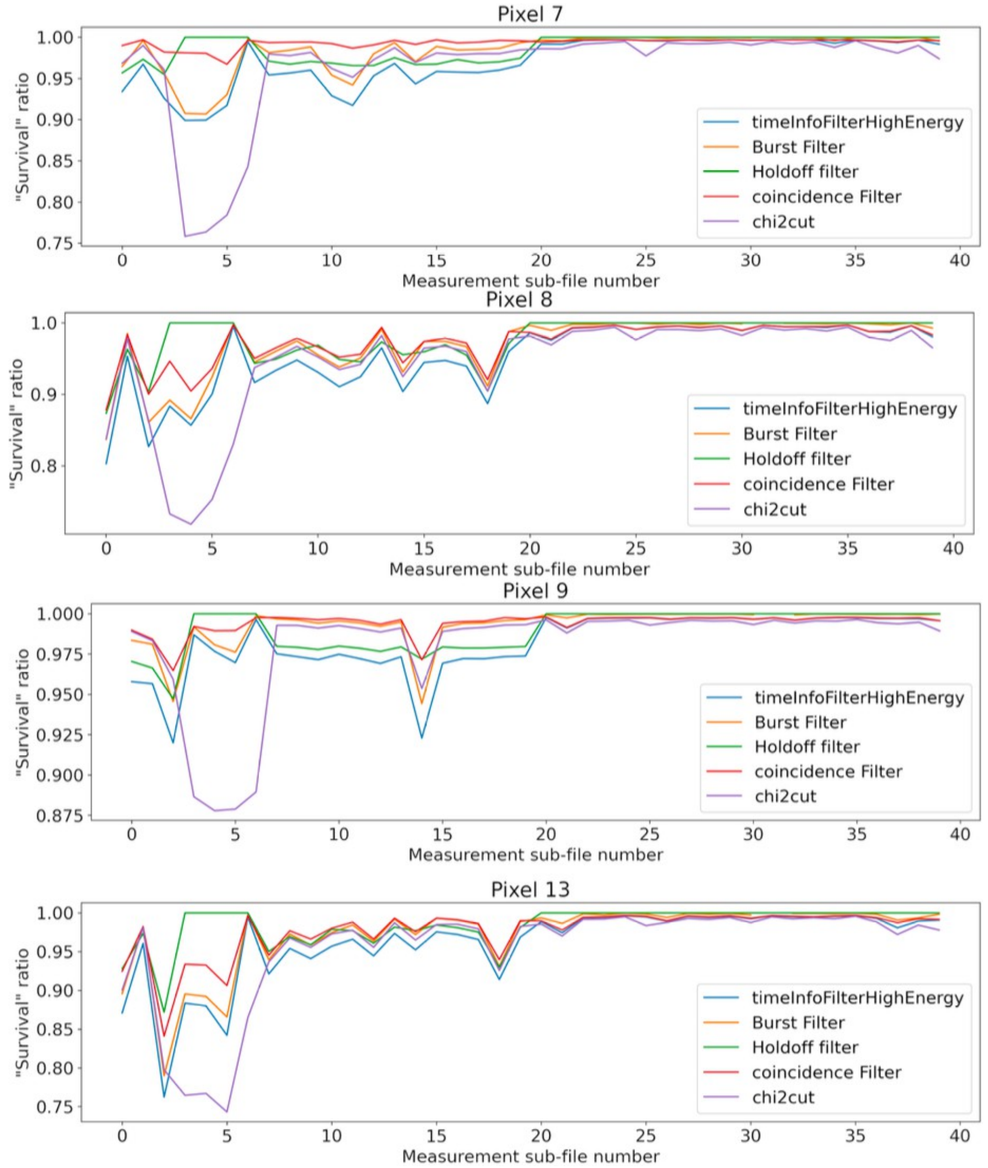
Data Reduction Summaries

Pulse Shape Based Filter: Effect in Energy Domains



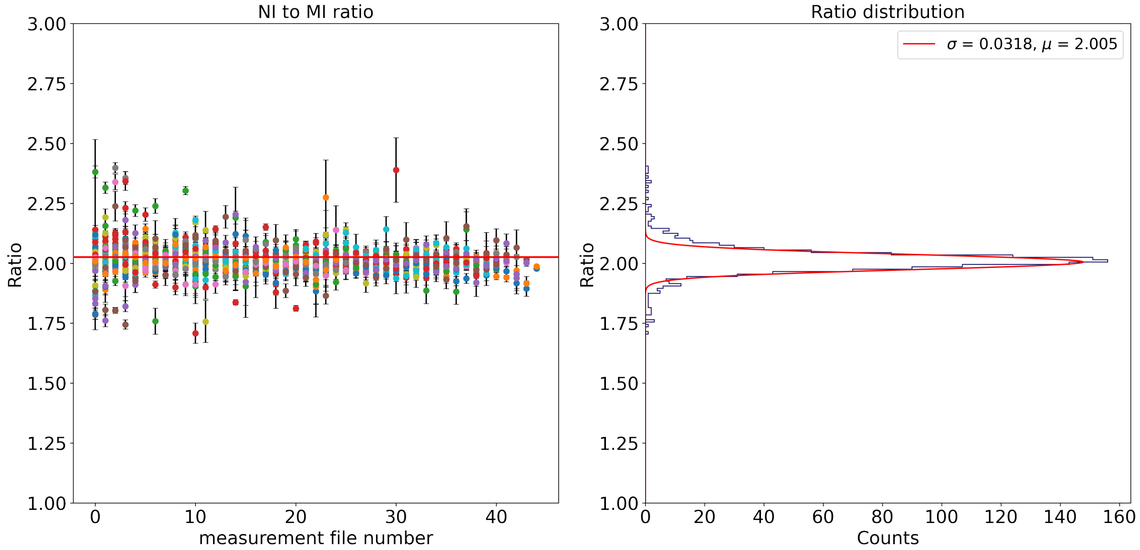
Data Reduction Summaries

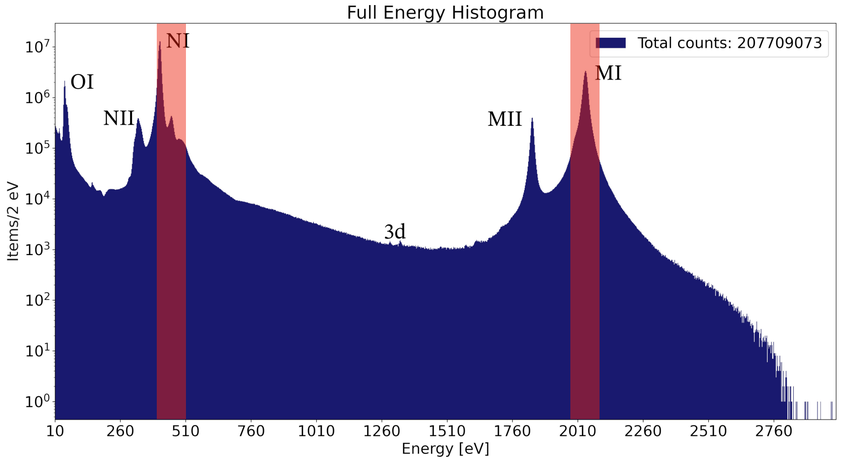
Survival Ratio

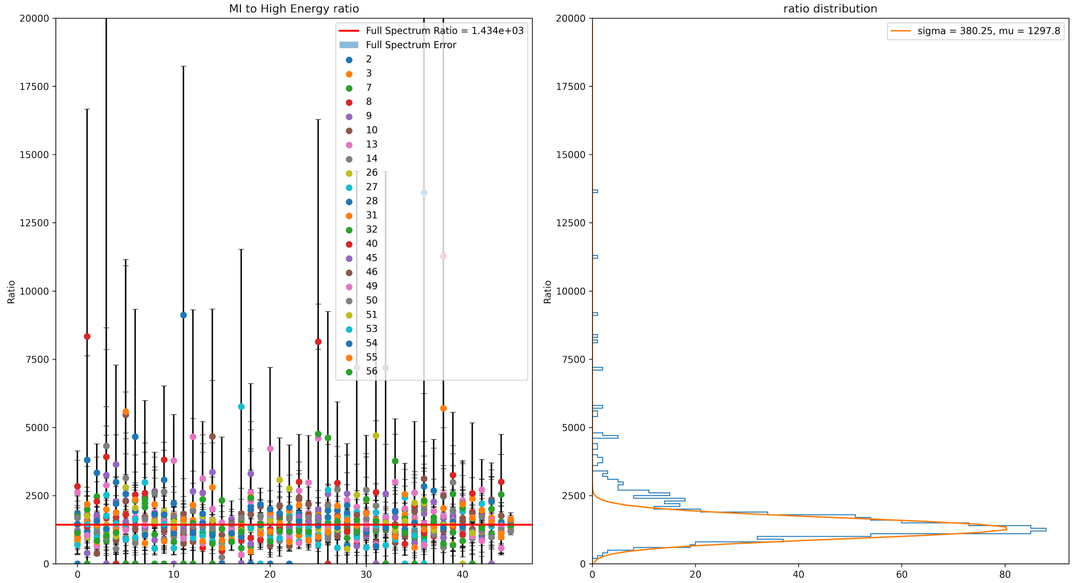


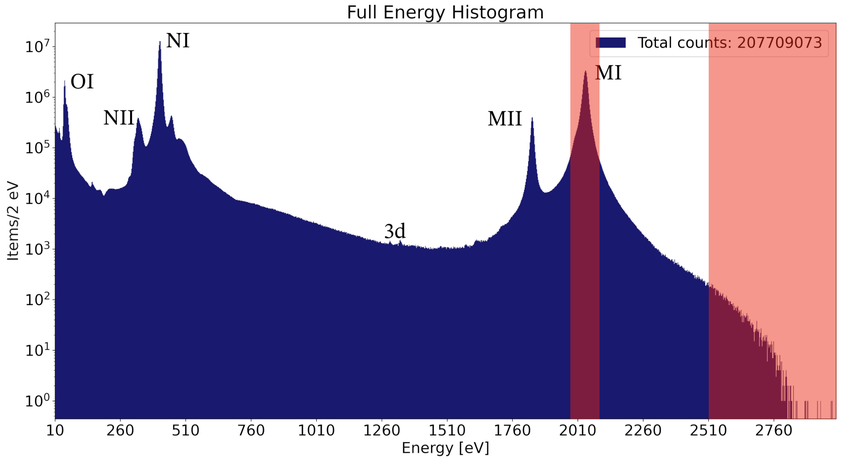
Time/2 days

Quality Parameters









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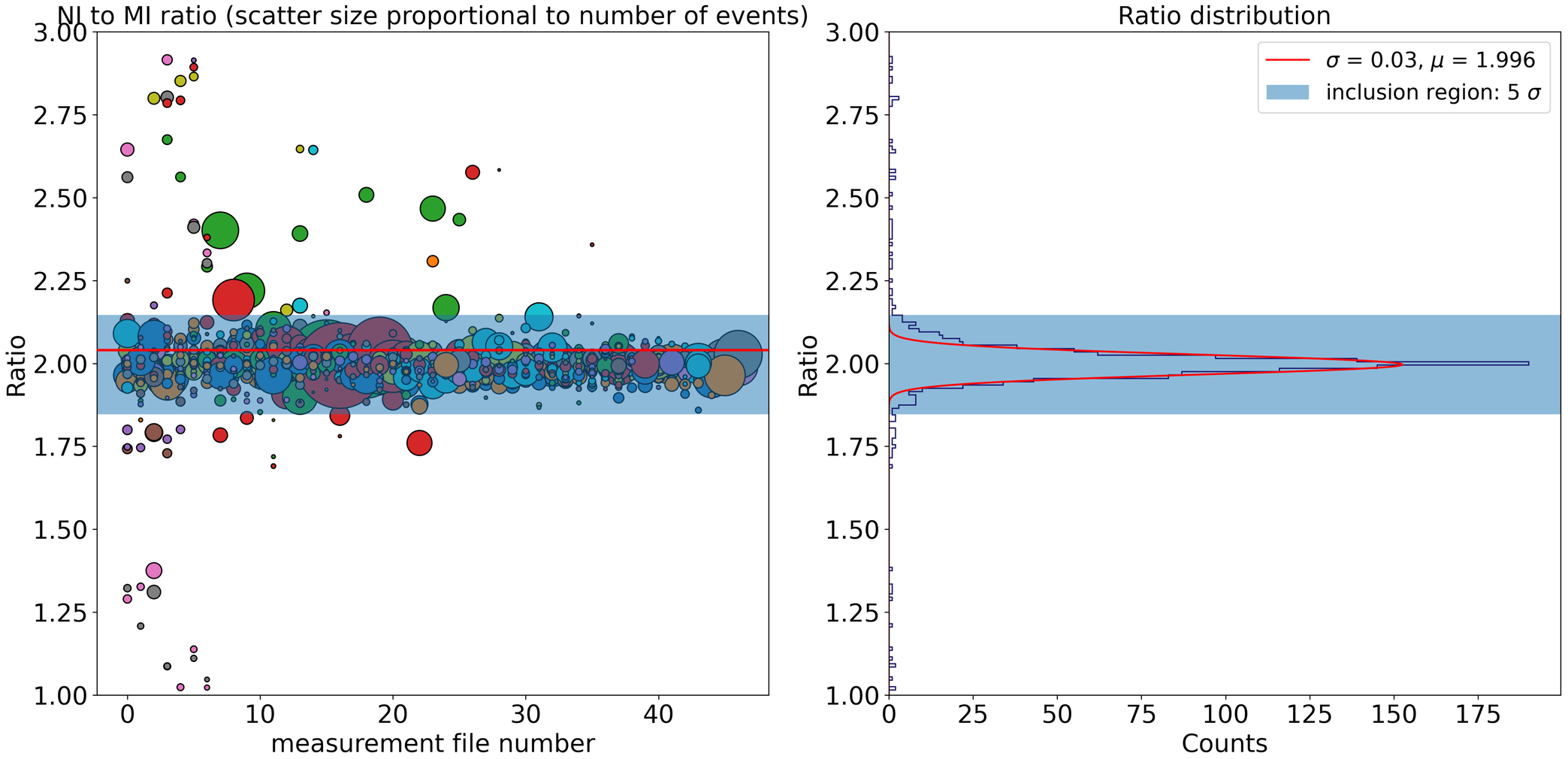

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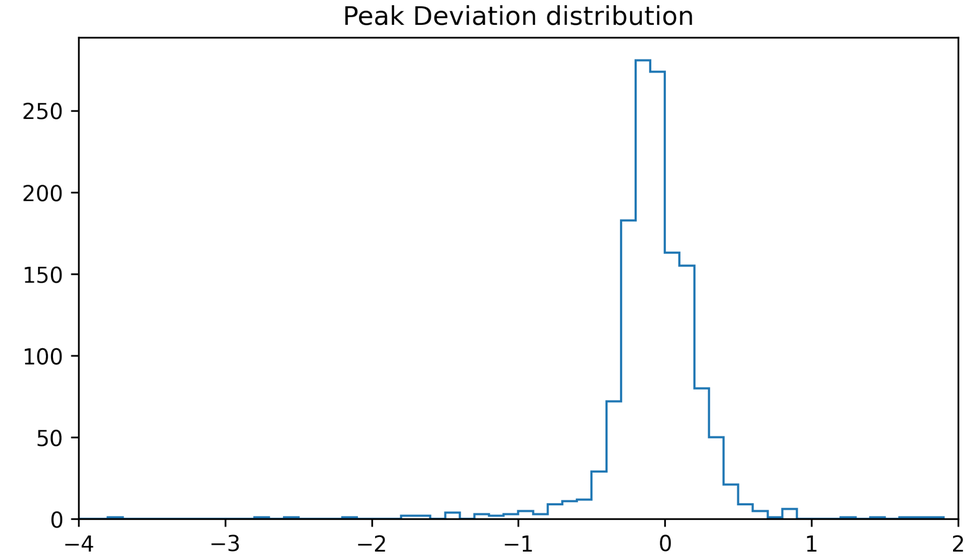

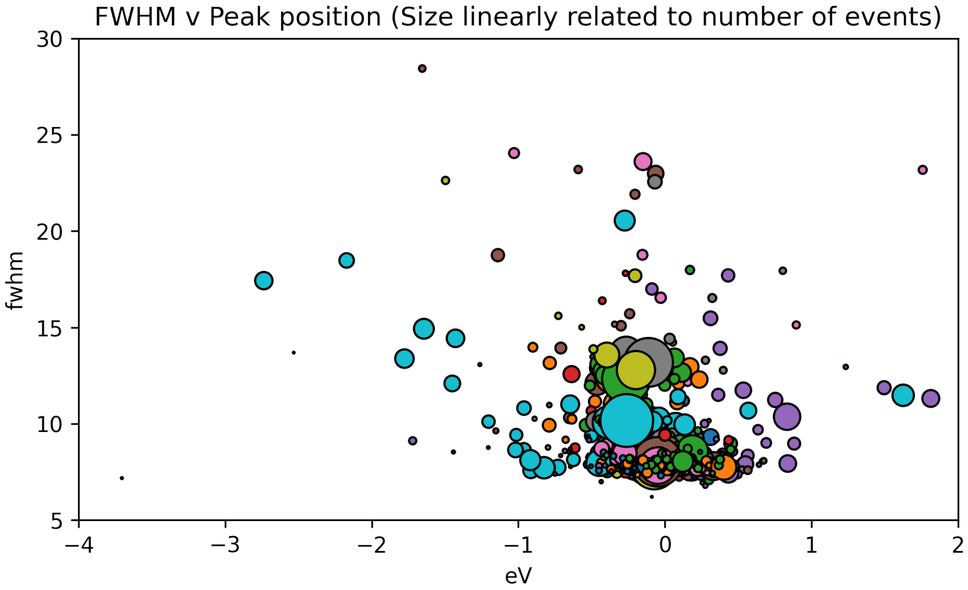

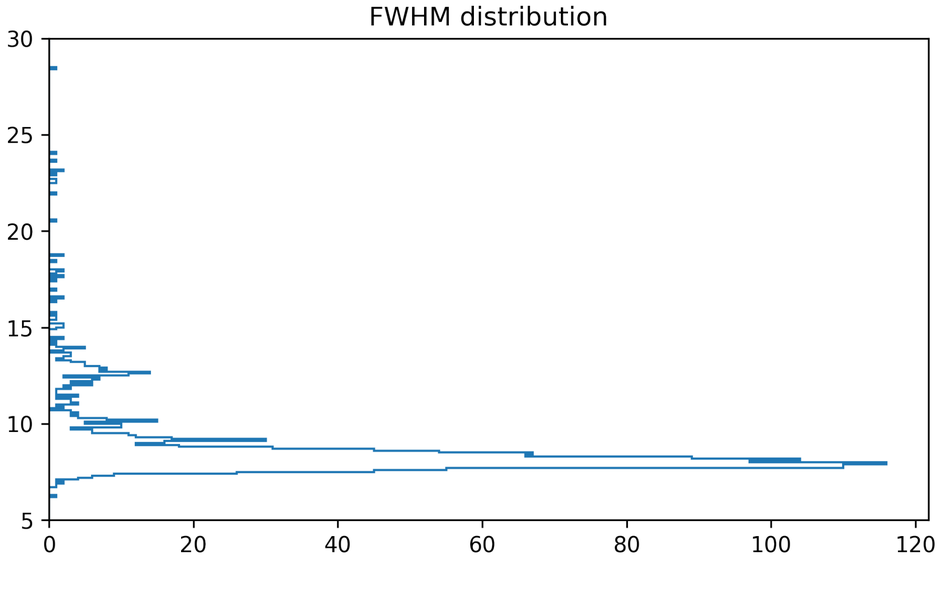

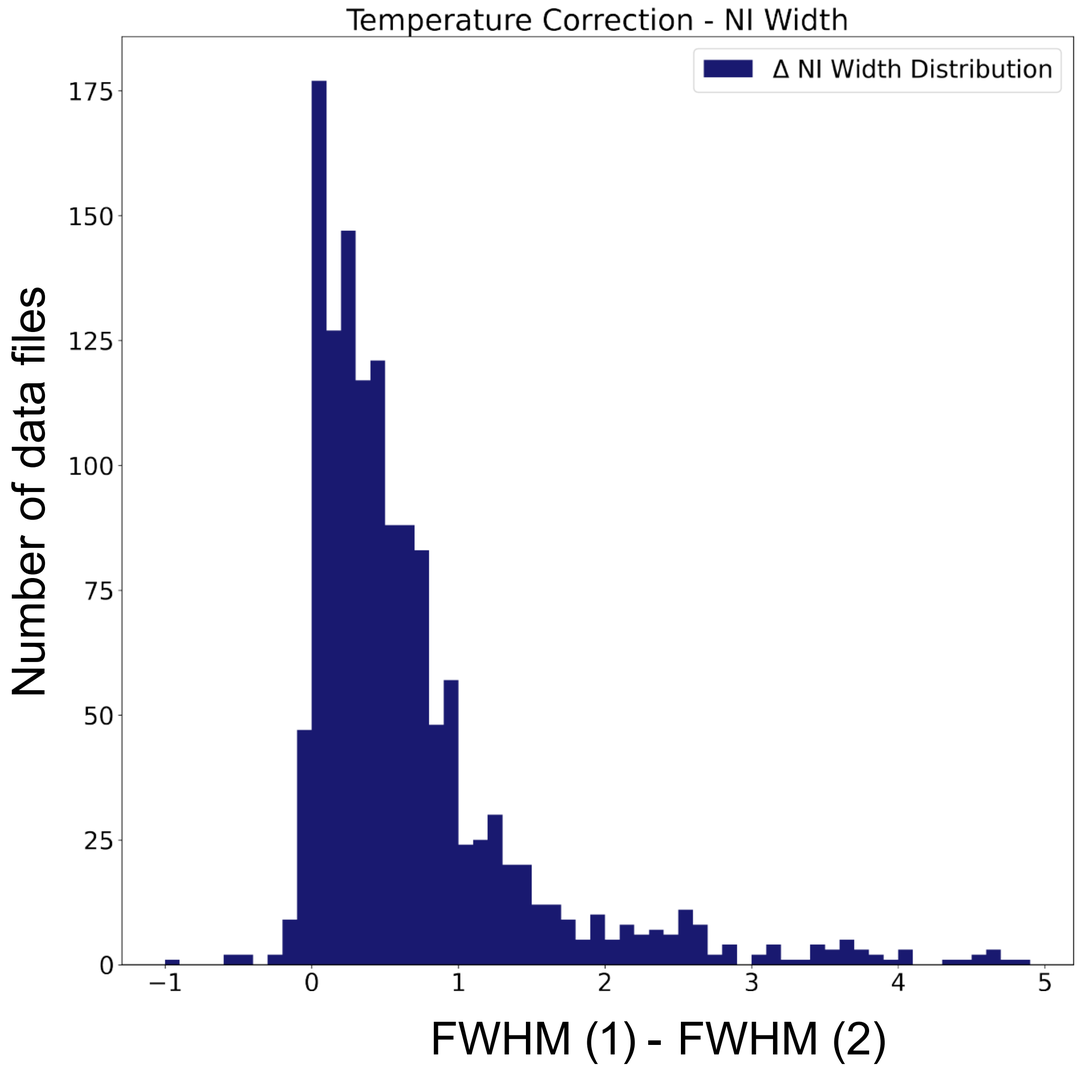

FWHM(1) - FWHM(2) > 0 implies Improvement in Energy Resolution

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 limit on the effective electron neutrino mass limit has been obtained in a proof of concept measurement and this limit has been improved with ECHo-1k by almost one order of magnitude to $m(\nu_e) <$ 19 eV/c^2 90% C.L.
- Important steps towards ECHo-100k have been demonstrated
  new ECHo-100k array + implantation of wafer scale + multiplexed readout