Determination of the effective neutrino mass from the ^{163}Ho EC spectrum

International School of Nuclear Physics, 47th Course

Erice

Lorenzo Calza for the ECHo-LE Collaboration

18 September 2026

Electron Capture in ^{163}Ho

Introduction

- Search for neutrino mass at sub-eV scale
- Energy spectrum of electron capture in ^{163}Ho

$$^{163}\text{Ho} \rightarrow {}^{163}\text{Dy}^* + \nu_e \rightarrow {}^{163}\text{Dy}^* + \nu_e + E_{EC}$$

- Low Q value Q = 2863.2(6) eV [1]
- Half-life of decay: $T_{1/2}$ = 4570(25) y [2]

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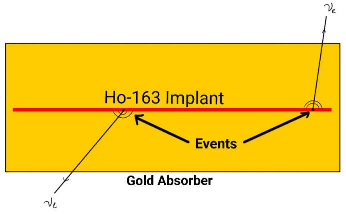
- Calorimetric measurement → Embed ^{163}Ho inside detector



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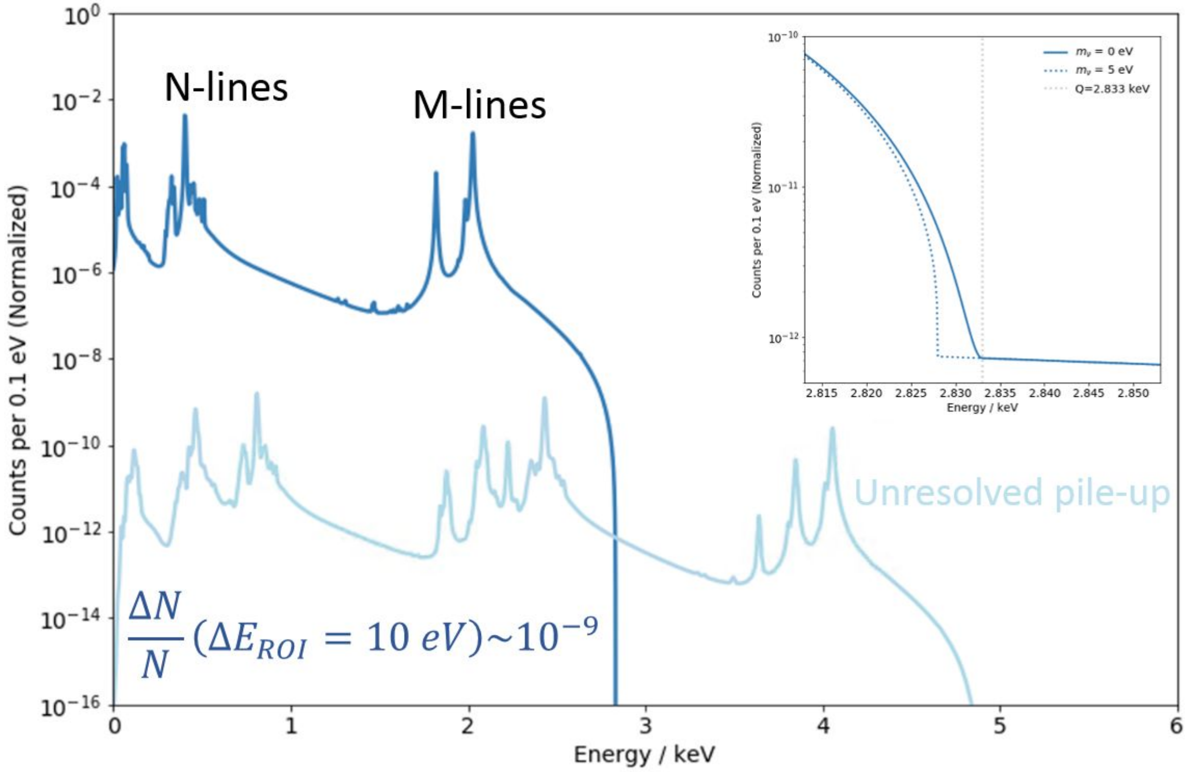
Calorimetric Spectrum of ^{163}Ho



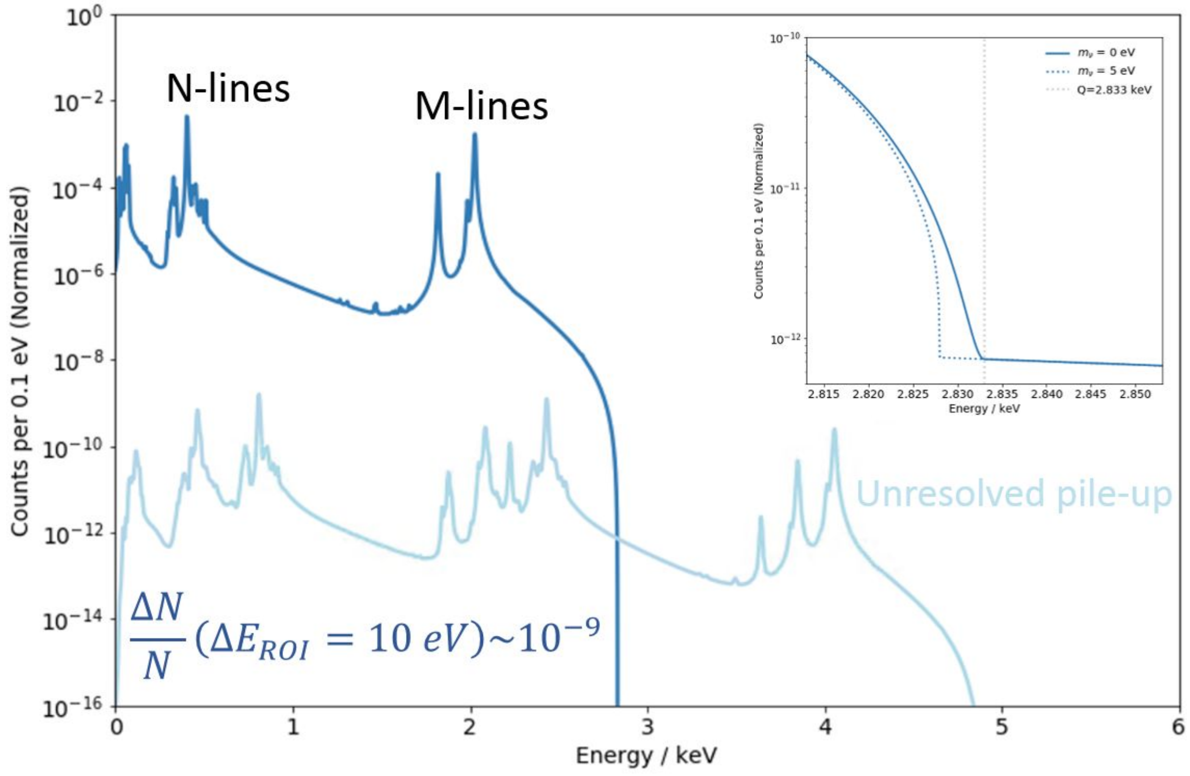
M. Braß and M. W. Haverkort, *New J. Phys.* (2020) 093018

Electron Capture in ^{163}Ho

Requirements

- High energy resolution
- Reliable calibration
- 100% quantum efficiency

Solution:
Metallic Magnetic Calorimeters (MMCs)



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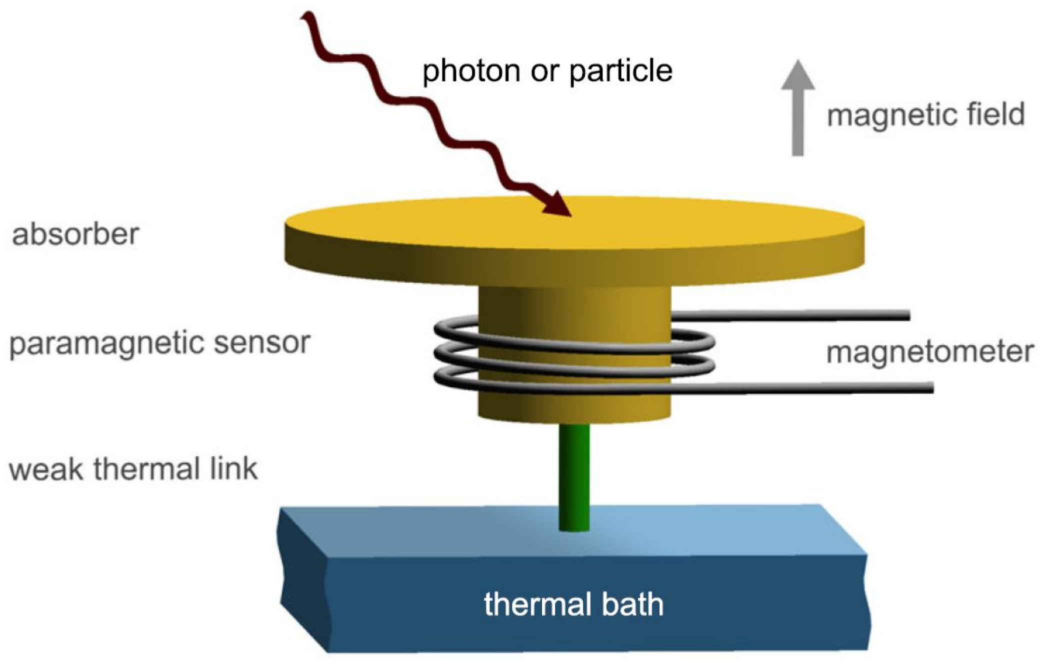
Metallic Magnetic Calorimeters

- Low temperature micro-calorimeters
- Particle absorption $\longrightarrow$ Temperature increase $\delta T = \frac{E}{C}$
- Change in T-dep magnetisation and change of flux in pick-up coil

$$\delta\Phi \propto \delta M \propto \delta T \propto E$$

- Current in superconducting pick-up coil, measured by SQUID-magnetometer $\delta V \propto \delta\Phi \propto E$
- Weak thermal link restores original operating temperature T_0



A. Fleischmann et al., In: C. Enss (eds) *Cryogenic Particle Detection*. Topics in Applied Physics

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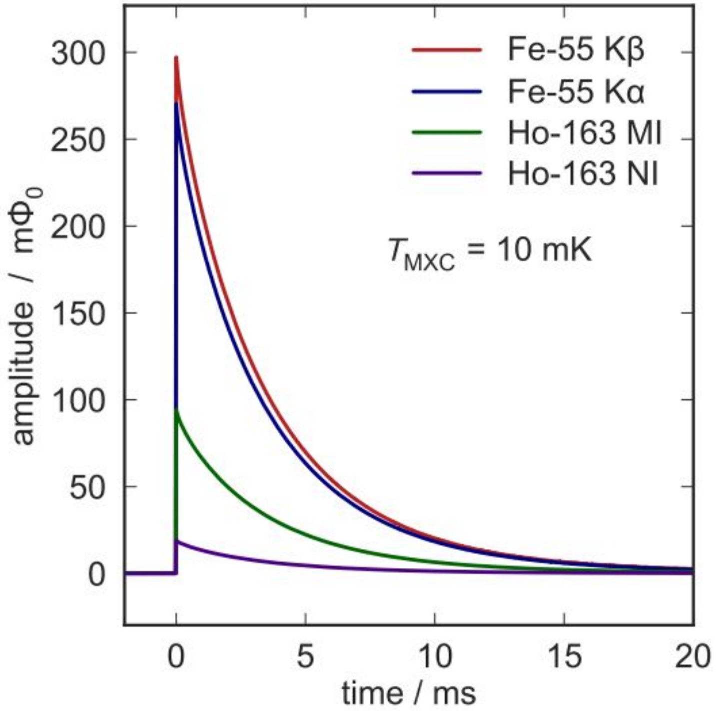

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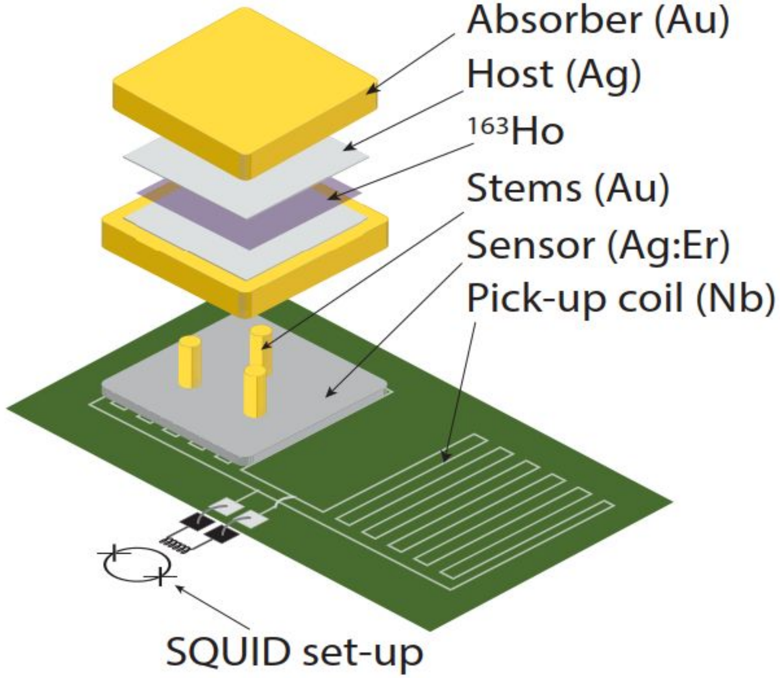
^{163}Ho source implanted in absorber



Gastaldo et al., *Nucl. Instrum. Methods Phys. Res. A* (2012)
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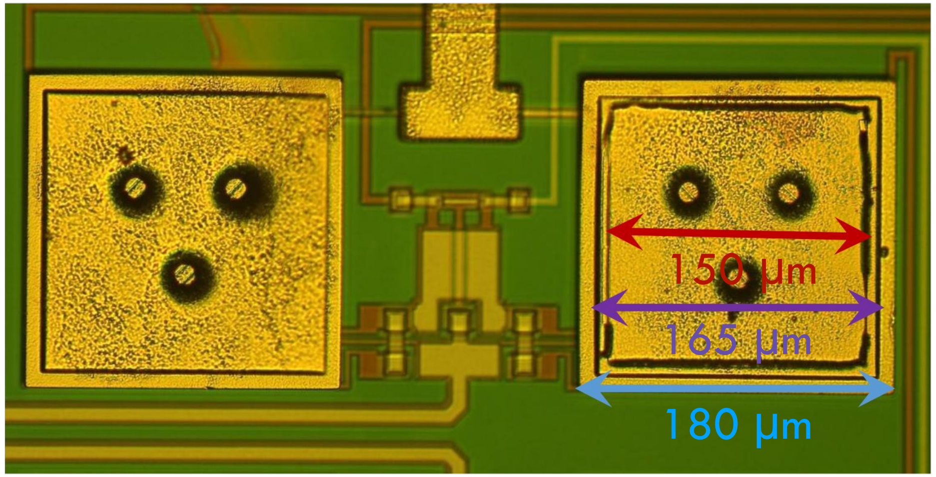
F. Adam et al., *Phys. Rev. Lett.* (2026)

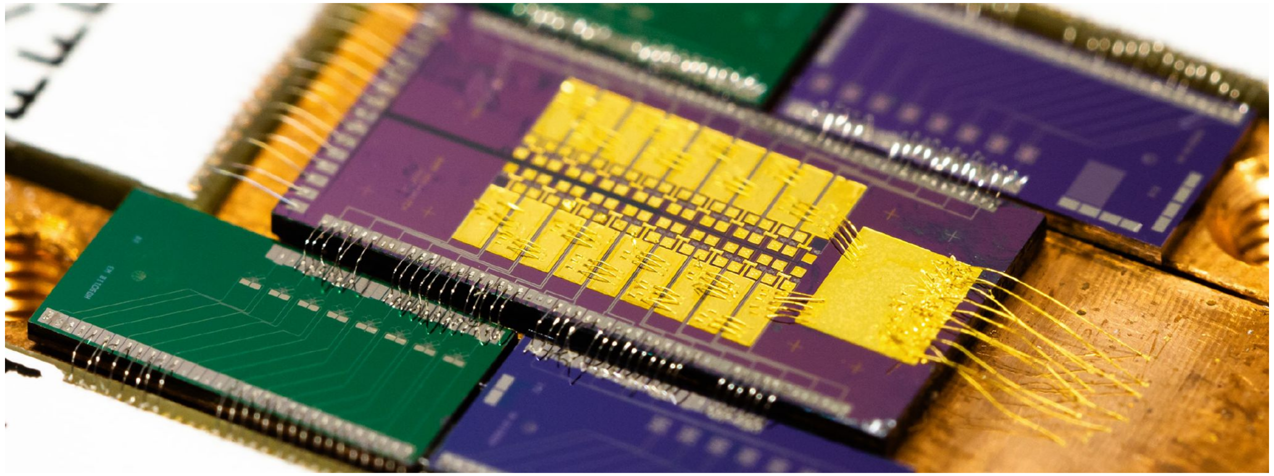
ECHo-1k Experiment

- 57 pixels implanted with ^{163}Ho
- 10 background pixel

- Average activity 0.71 Bq per pixel
- Total activity ~ 40 Bq

- 300 million events acquired
- (Dec 2019 - June 2020)





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ECHo-1k Experiment

Background Elimination

R. Hammann et al., *Eur. Phys. J.* C (2021)

Raw Data

- ^{163}Ho decays
- Unresolved pileup
- Pile-up on Tail
- Mobile Phone Signal
- Triggered Noise
- Muon Event
- Natural radioactivity

ECHo-1k Experiment

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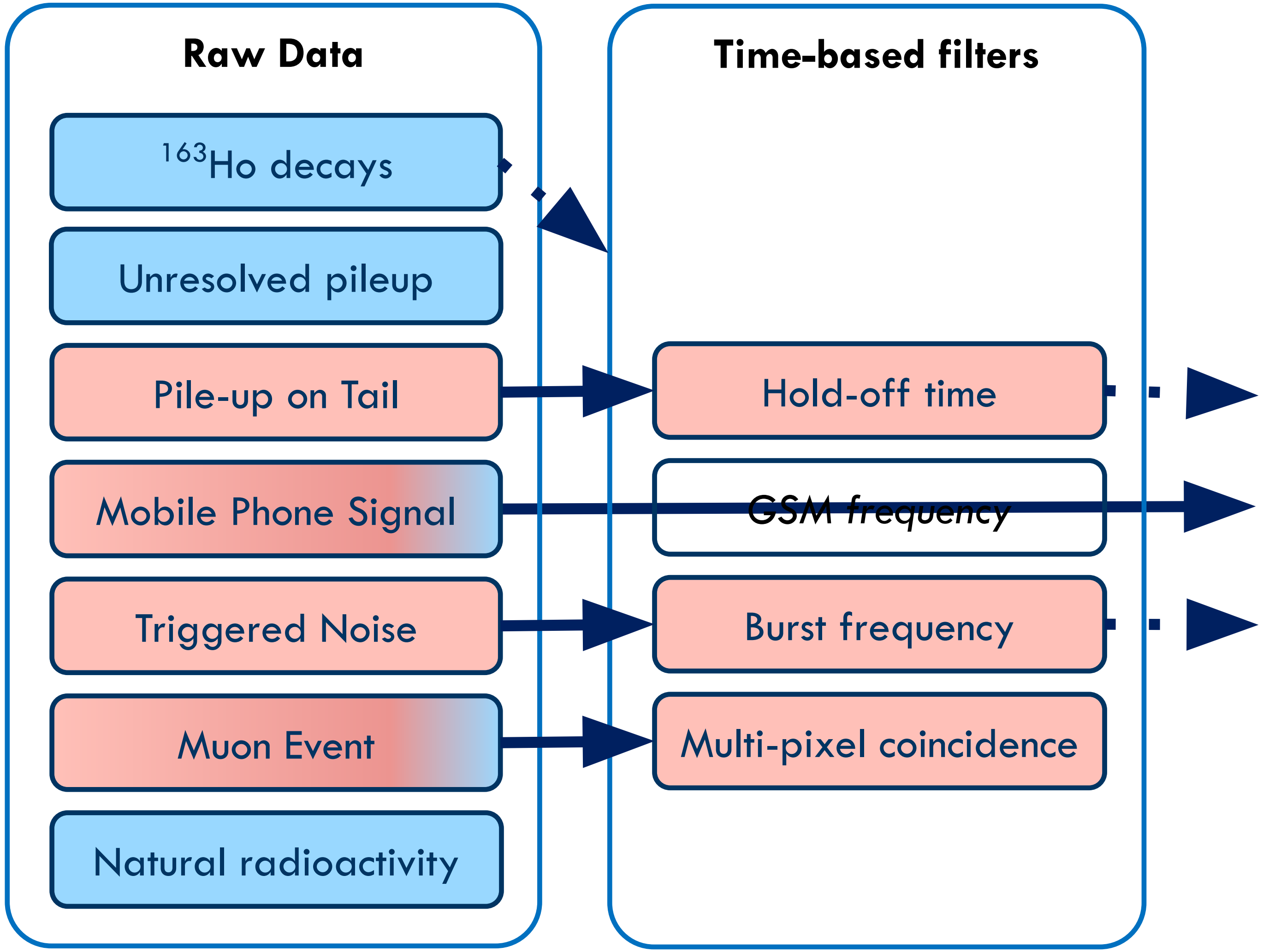
R. Hammann et al., *Eur. Phys. J.* C (2021)



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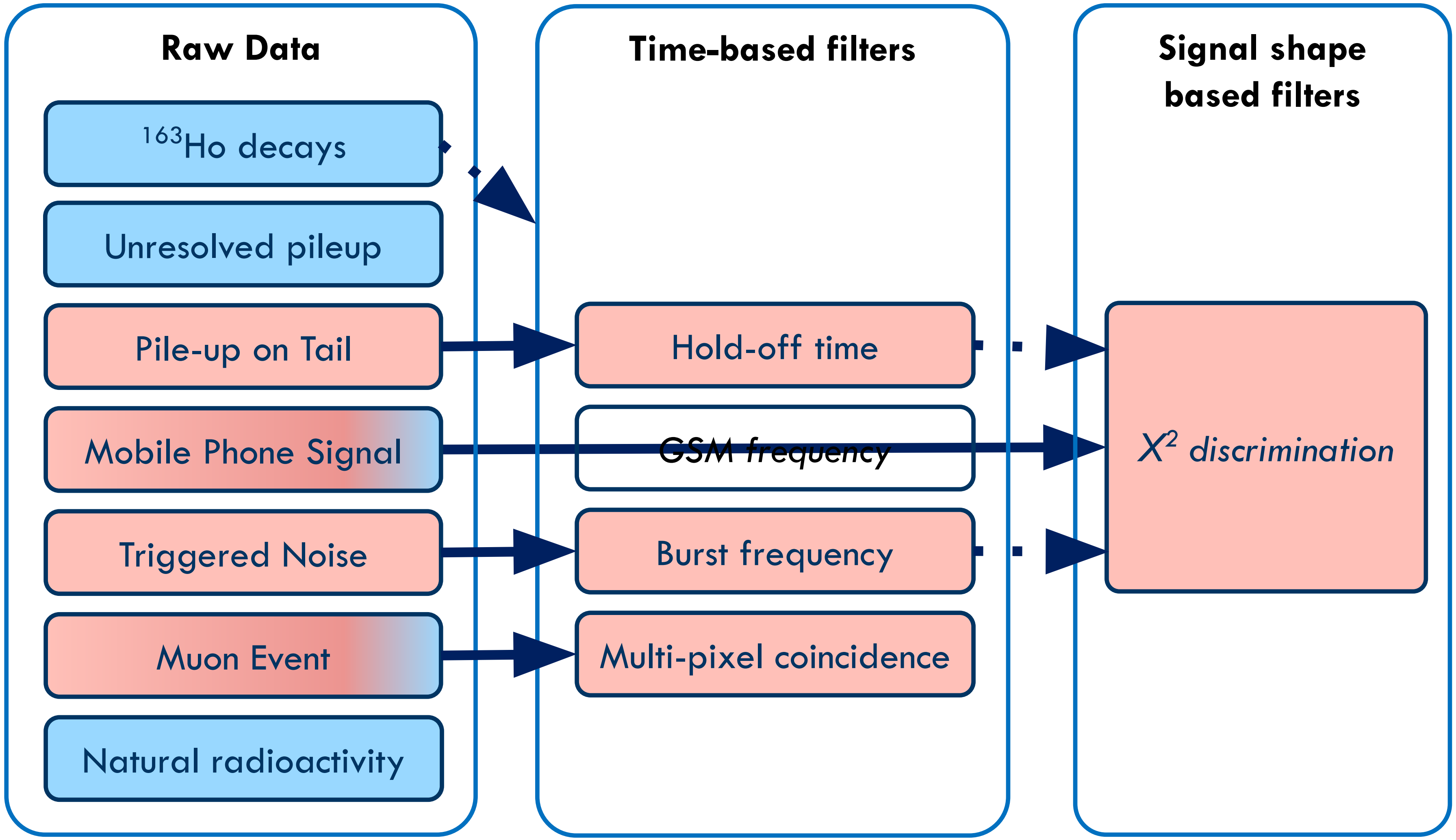

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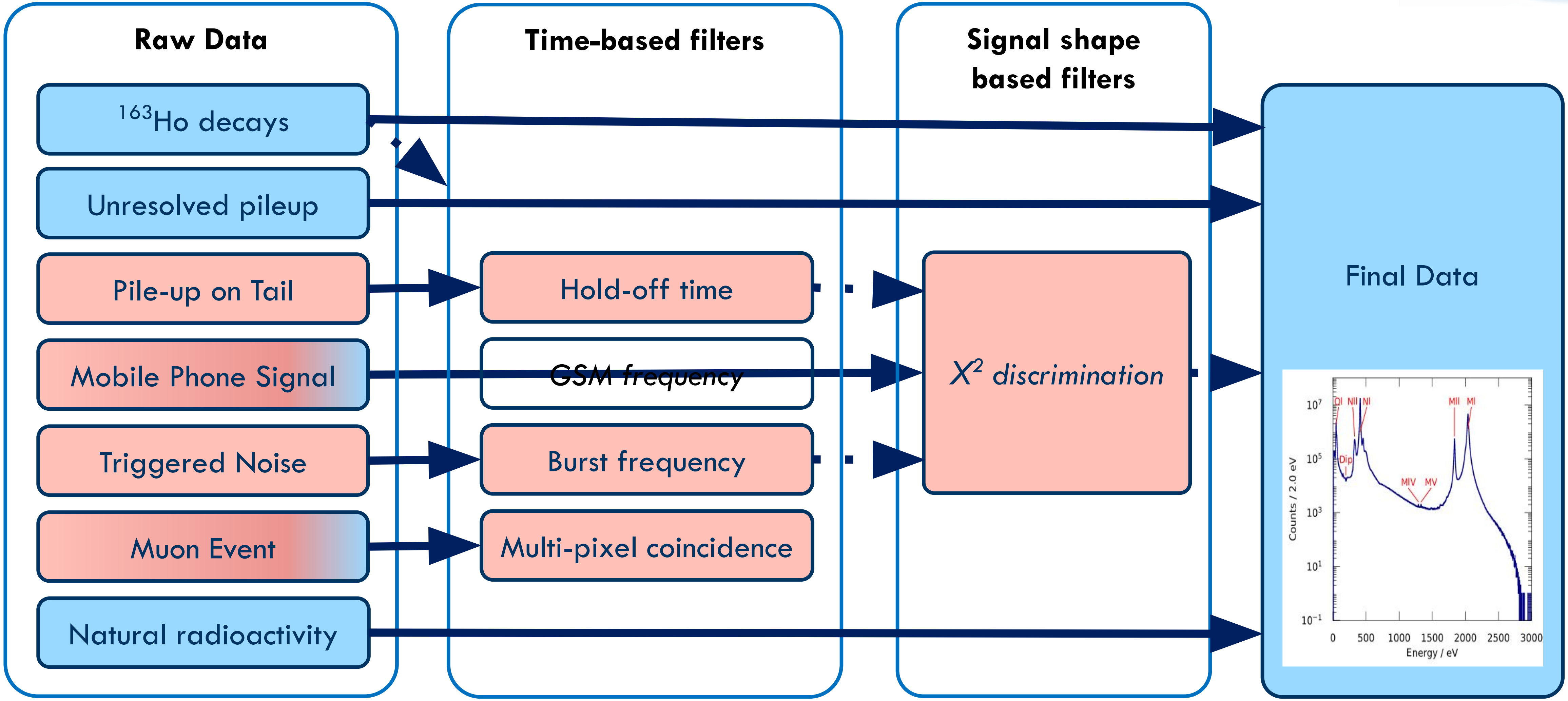
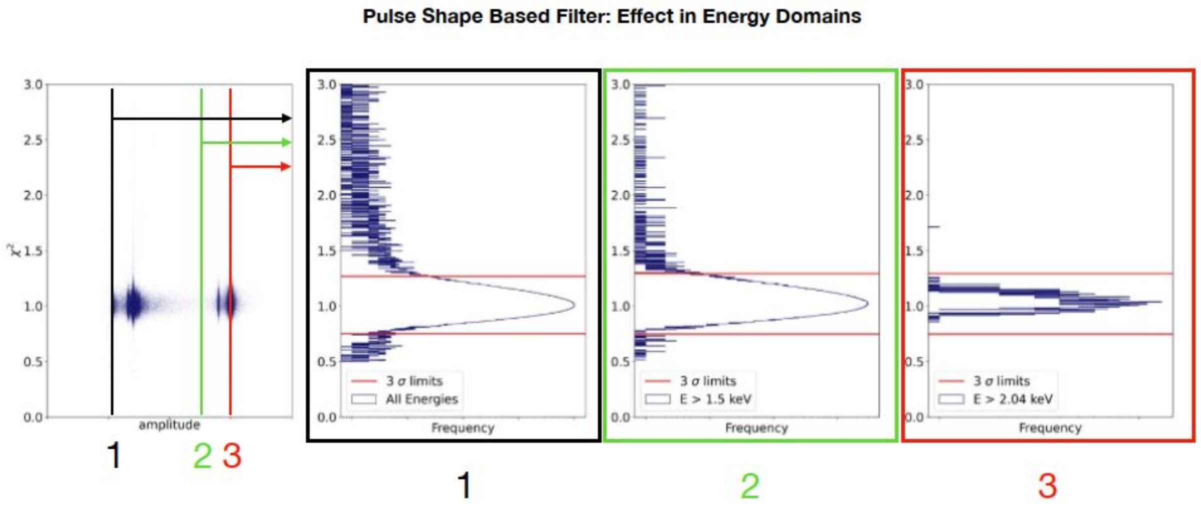
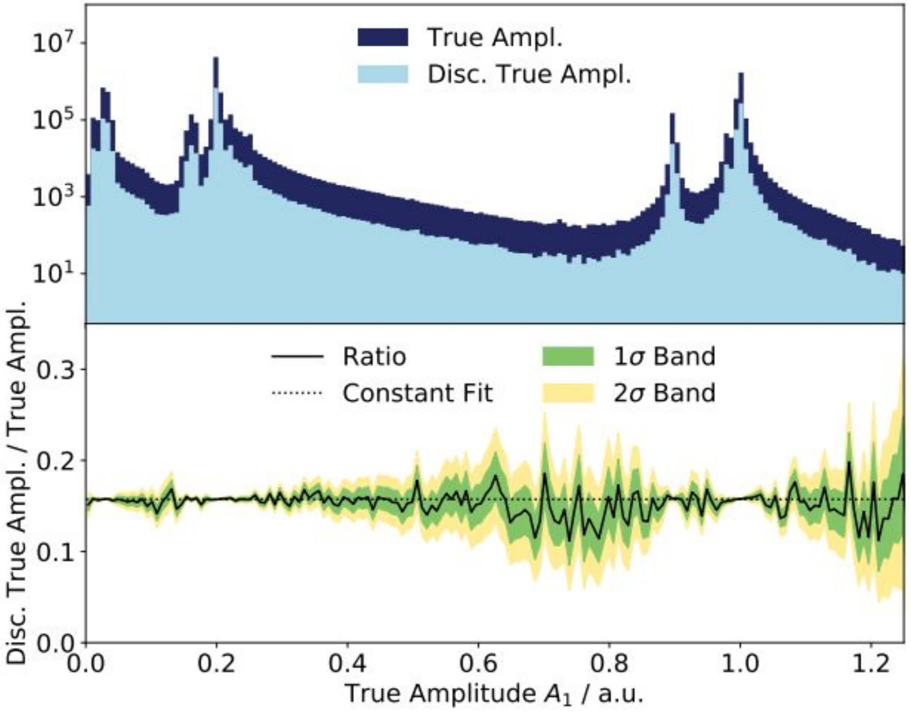


ECHo-1k Experiment

Control Parameters for the Data Reduction

- Filtering process has been tested with simulated events, confirmed energy-independence





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Control Parameters for the Data Reduction

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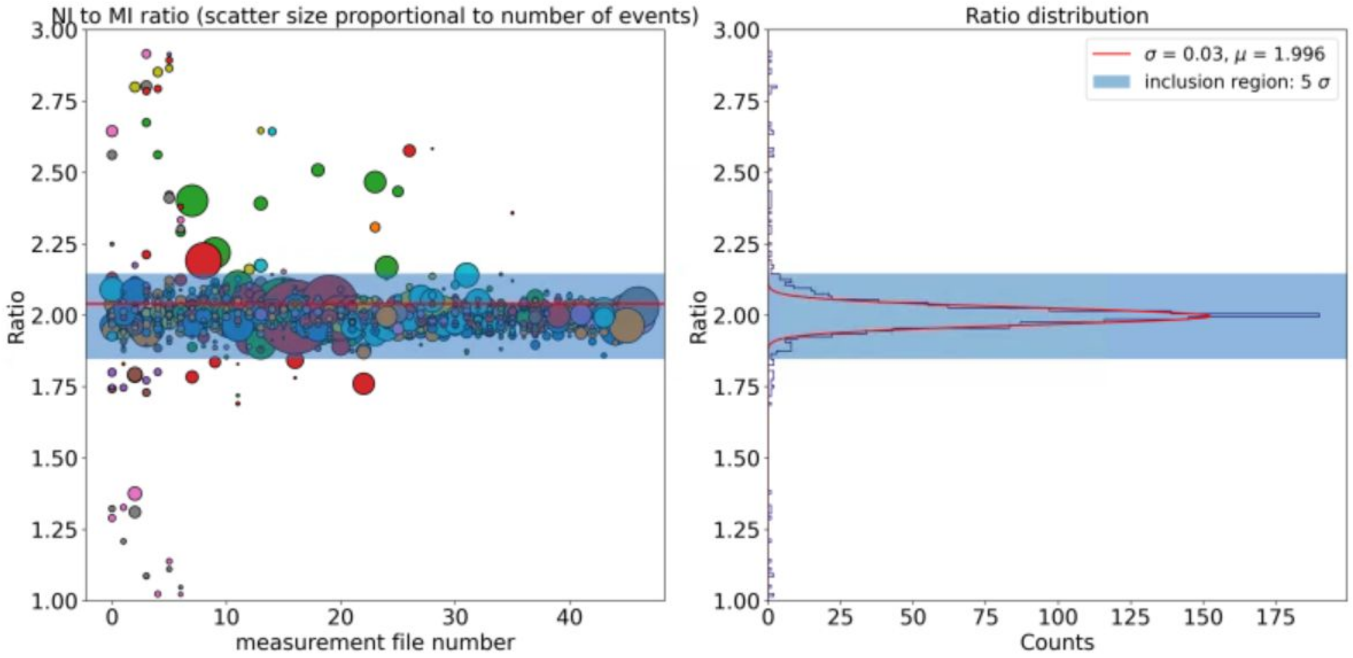
- Monitor fraction of discarded events over time

- Monitor fraction of events in MI and NI line



^{163}Ho Spectrum

Spectral Features and Past Descriptions

- Endpoint region dominated by MI line at 2.04 keV
- Other lines negligible in ROI

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- Satellite peaks and tails
- Atomic shake-up and shake-off
- Increased intensity near endpoint wrt. Lorentzian profile

- A. De Rújula, M. Lusignoli, *Phys. Lett. B* (1982)
- A. Faessler, *J. Phys. G: Nucl. Part. Phys* (2014)
- R. G. H. Robertson, *Phys. Rev.* C (2015)
- A. Faessler et al., *Phys. Rev.* C (2015)
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- No prediction for line widths
- No analytical form for the decay rate

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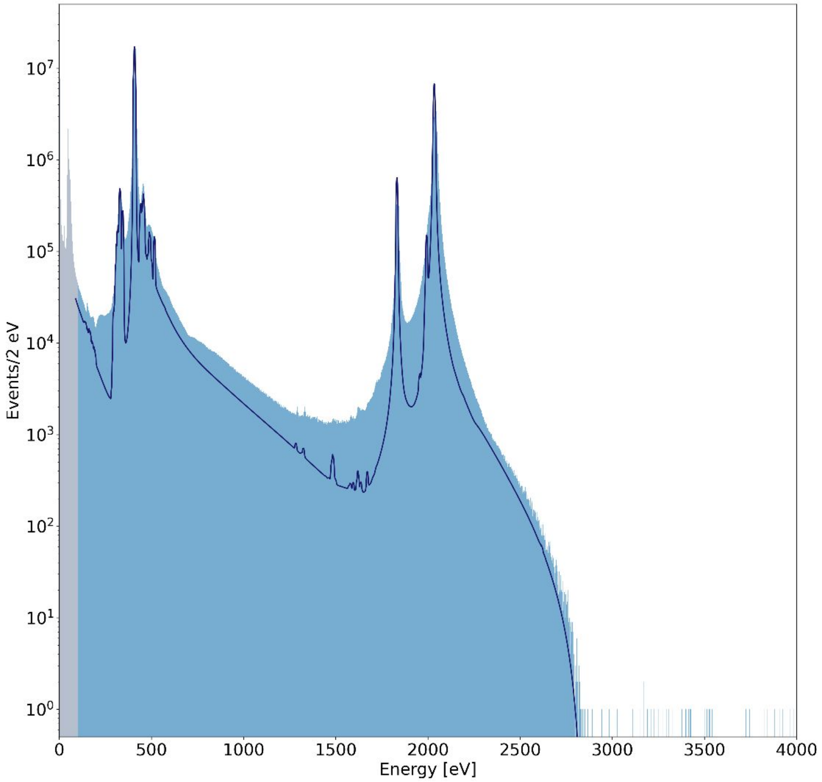
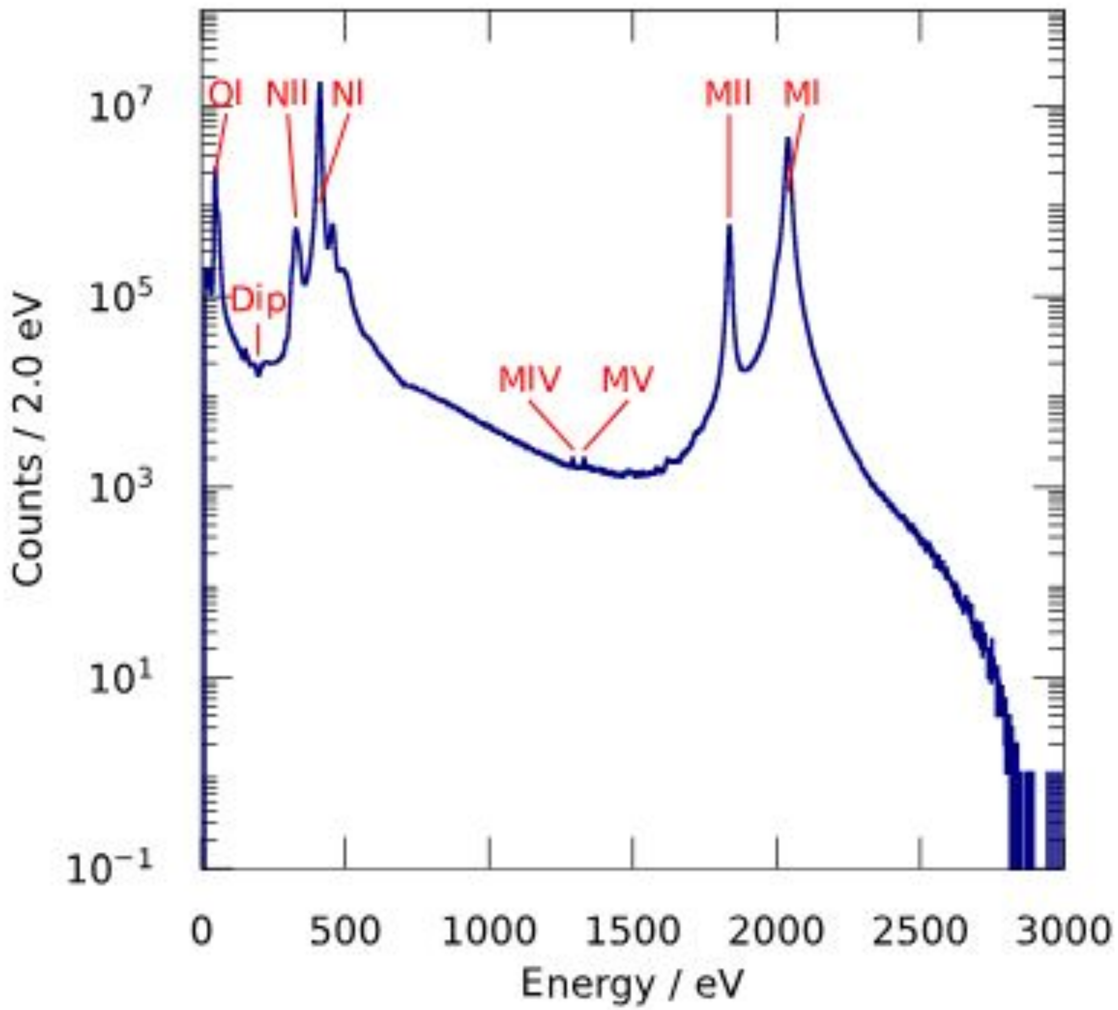
Theory (Braß 2020) vs. ECHo-1k data



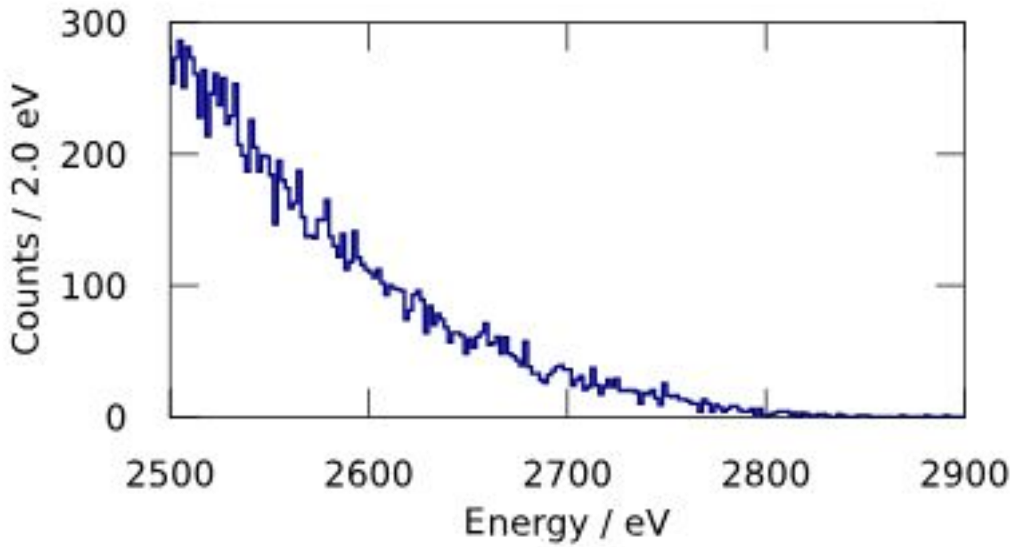
- M. Braß et al., *Phys. Rev.* C (2018)
- M. Braß, M. W. Haverkort, *NJP* (2020)

ECHo-1k Experiment

High Statistics Spectrum



200 million events after data reduction



F. Adam et al., *Phys. Rev. Lett.* (2026)

ECHo-1k Experiment

Phenomenological Model of the Endpoint Region

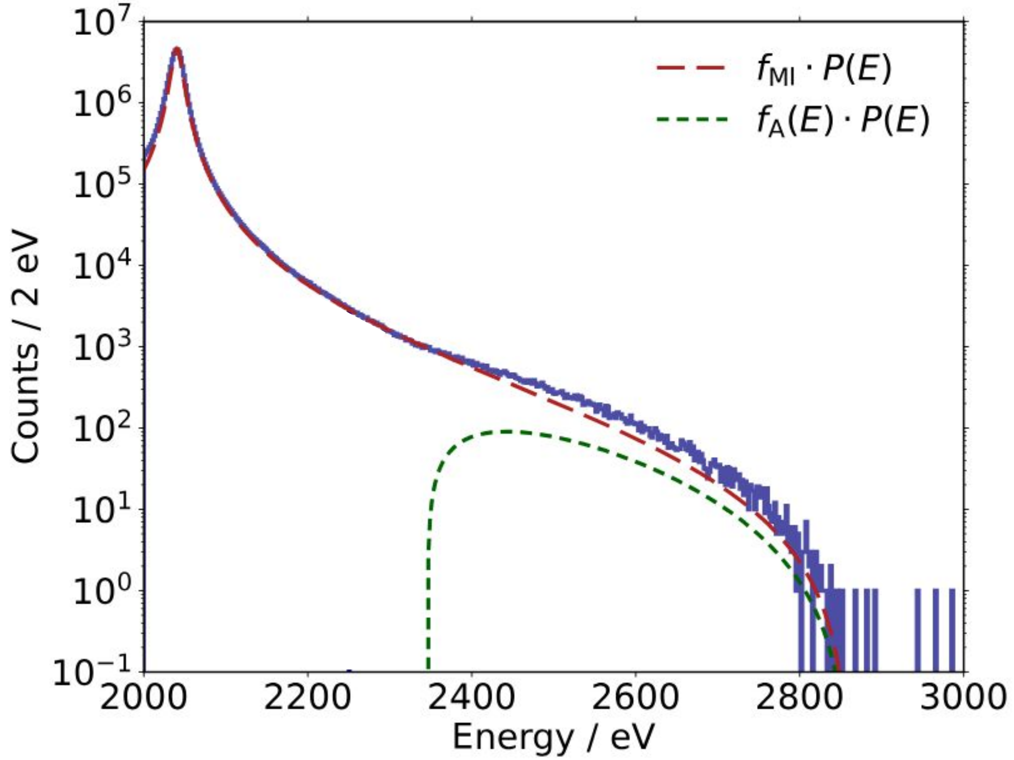
- Spectral shape comprised of:
  - Atomic Physics Function: Lorentzian (MI) + Bump

    $A(E) = f_{MI}(E) + k\,[\exp(-(E - E_{so})/\tau_1) - \exp(-(E - E_{so})/\tau_2)]$

  - Phase Space Factor

    $P(E) \propto (Q - E)\sqrt{((Q - E)^2 - m^2)}$

- Overall spectrum: $S(E) = A(E) \times P(E)$



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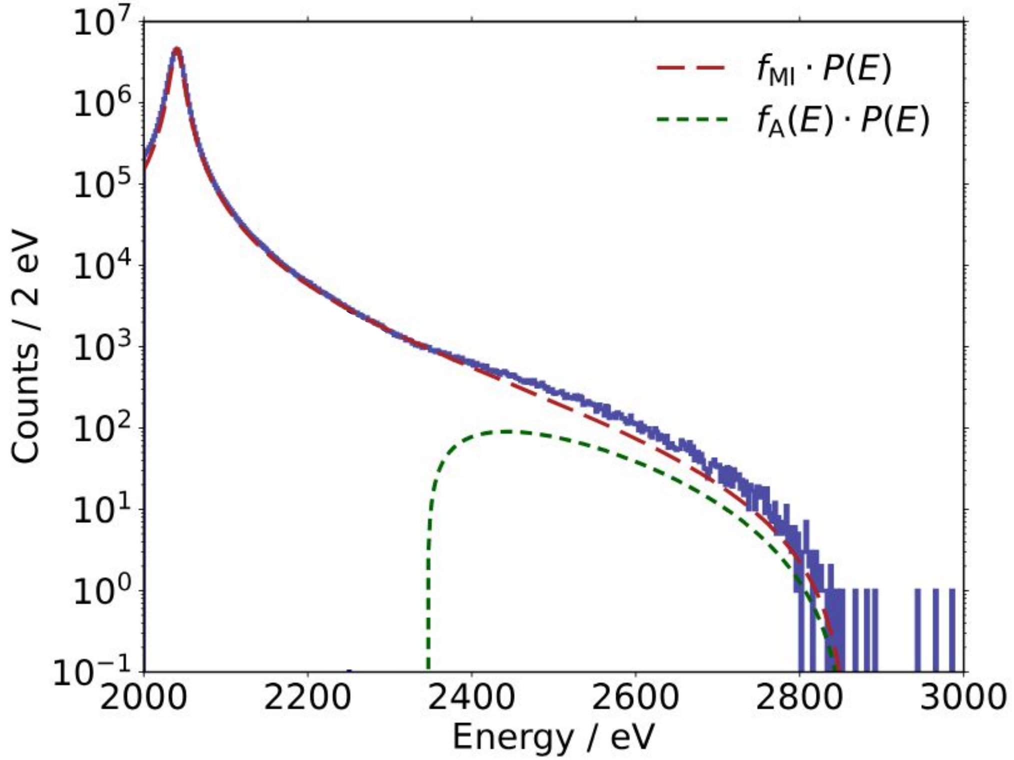
- Overall spectrum: $S(E) = A(E) \times P(E)$
- Gaussian detector response: resolution $\Delta E = 6.95(16)$ eV
- Background:
  - unresolved pile-up of ^{163}Ho events ($f_{pu} = 10^{-7}$)
  - natural radioactivity (9×10^{-6} / eV / pixel / day)



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ECHo-1k Experiment

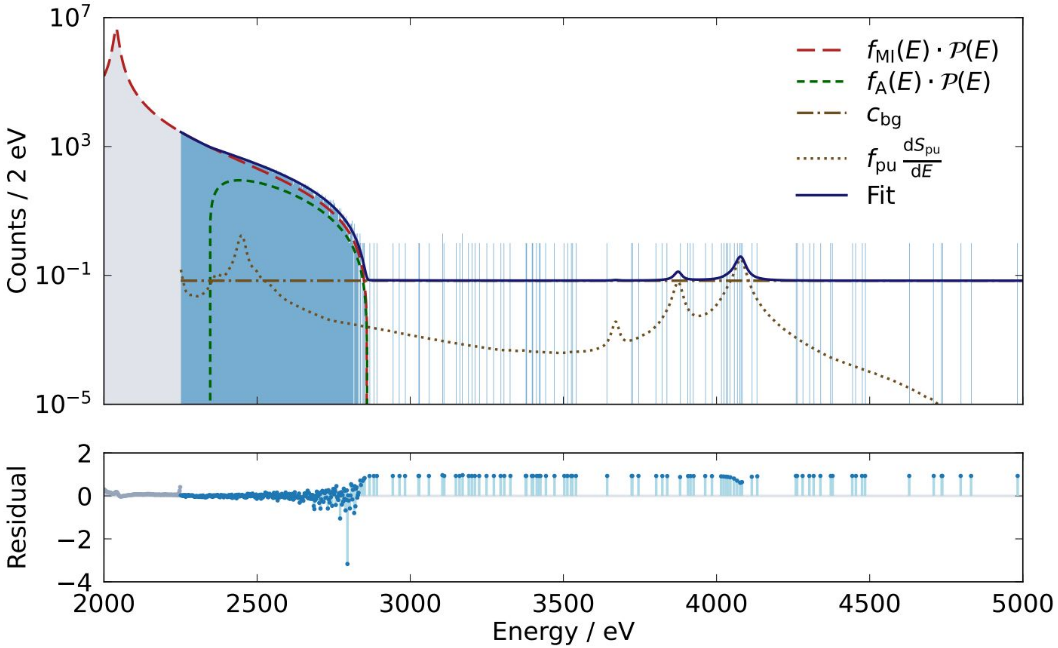
Final Result

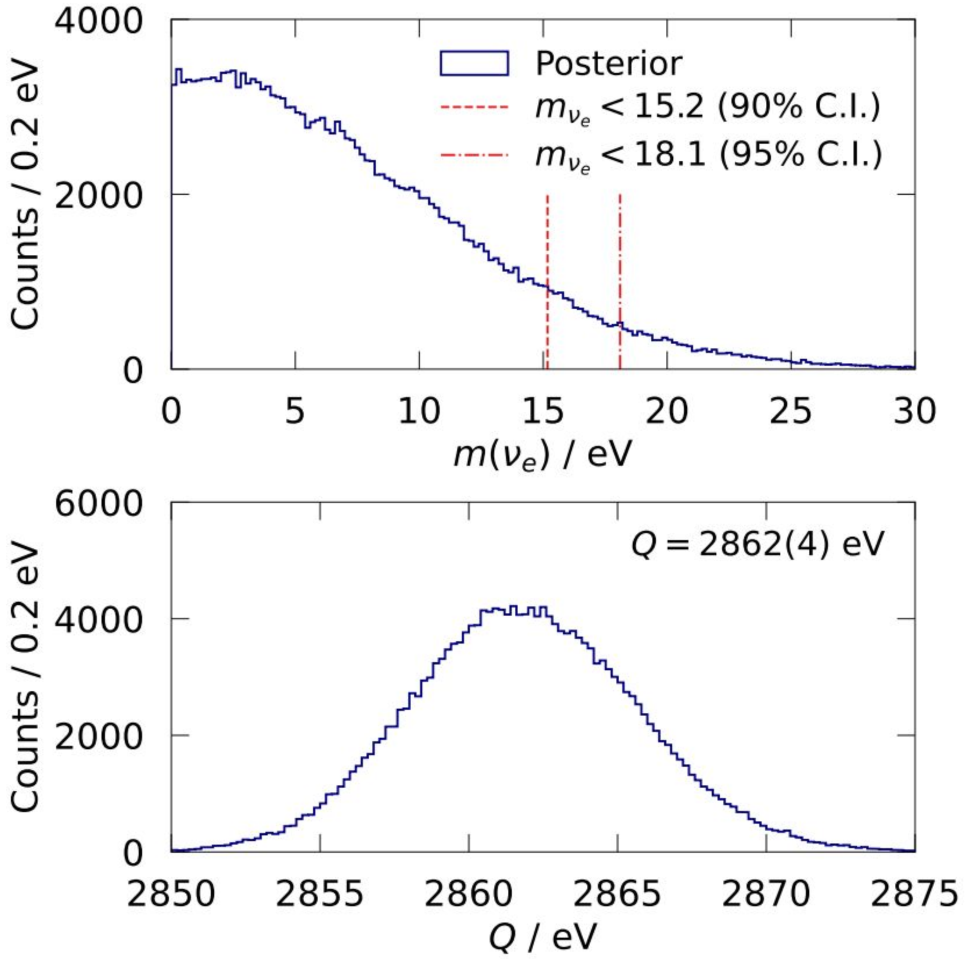
[1] F. Adam et al., *Phys. Rev. Lett.* (2026)
[2] C. Schweiger et al., *Nature Physics* (2024) **20**, 921-927

- 2×10^{8} ^{163}Ho decays in the final spectrum
- Current best limit on $m(\nu_e)$ from direct measurement [1]

$m(\nu_e) < 15$ eV 90 % C.I. (18 eV 95 %)
Q = 2862(4) eV

- Q in agreement with PENTATRAP result: 2863.2(6) eV [2]





ECHo-1k Experiment

Stability of the Final Result

- Final result is independent of initial parameters or width of prior distributions
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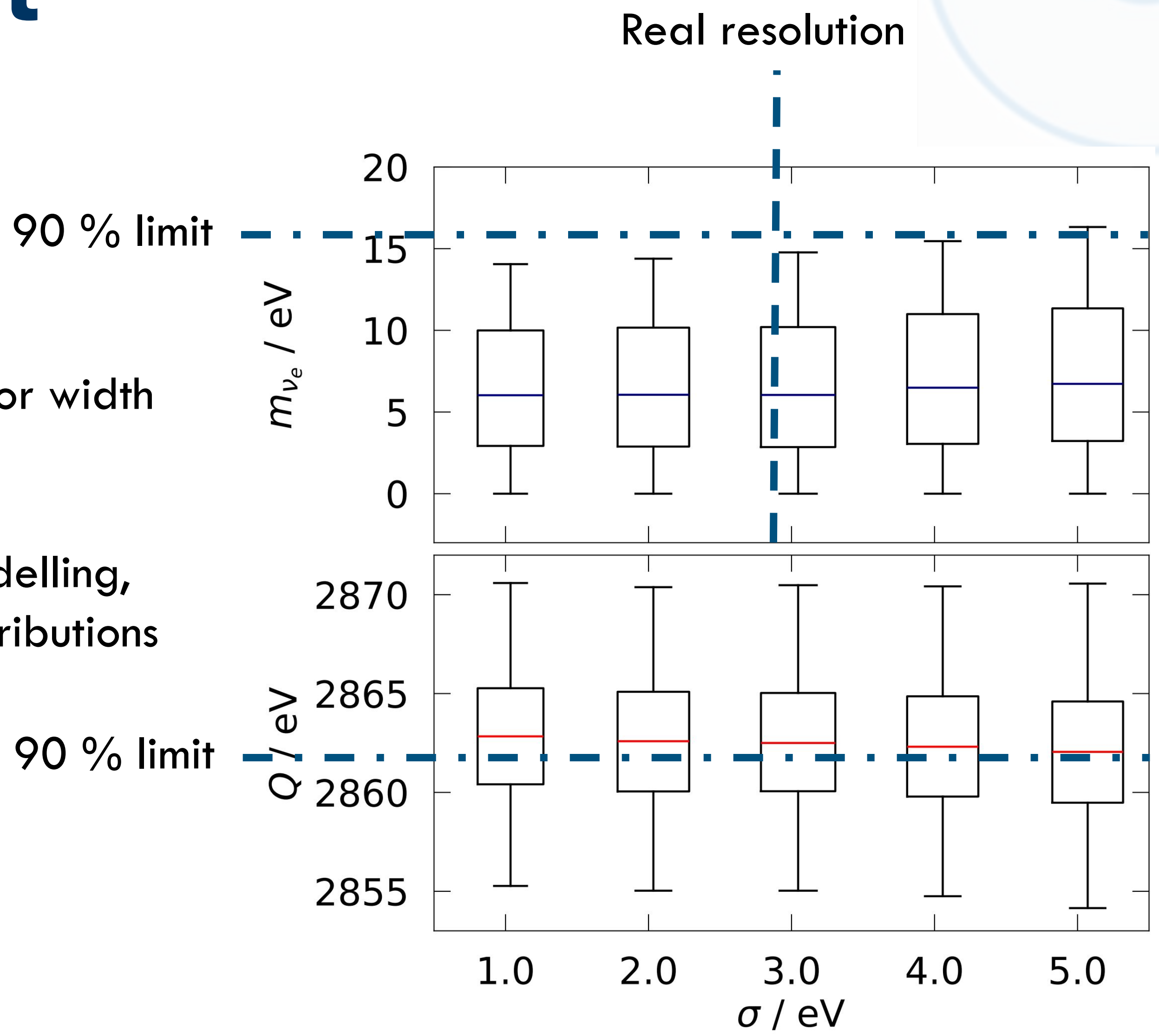
- Final result is independent of initial parameters or width of prior distributions
- Main systematic error due to spectral shape modelling, was quantified to 1 eV by varying the prior distributions
- Test of biased energy resolution yields very stable limit



ECHo-LE

Goal of the ECHo-LE Phase

- Goal: limit < 1 eV on neutrino mass (90% C.I.)

- Need $O(10^{13})$ total ^{163}Ho decays with energy resolution better than 5 eV FWHM
- Statistics can be achieved with 20 000 MMC pixels (10 Bq/pixel)

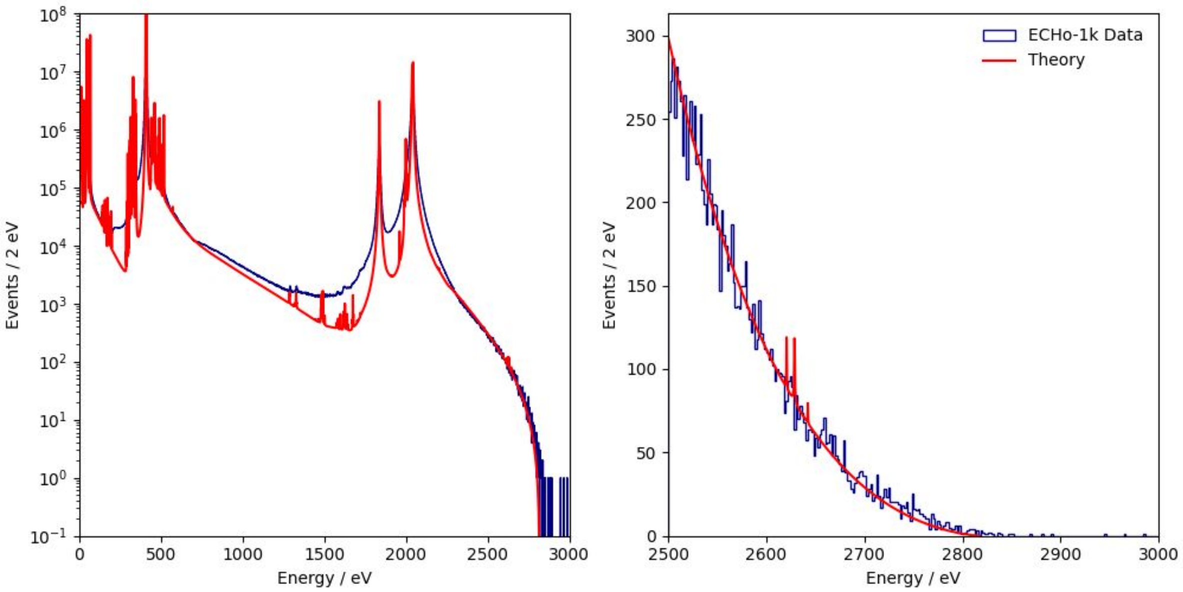
- Optimised detector arrays following years of R&D
- Read-out via microwave SQUID multiplexing in development

Next contribution:
Raghav Pandey
on ECHo-LE

ECHo-LE

Modelling the Endpoint Region

- Theory by M. Braß and M. W. Haverkort predicts pure exponential behaviour above 2.6 keV
- With O(10^{13}) events, a narrower energy range can be fitted
- Significant reduction of model parameters and correlations



Theory: M. Braß and M. W. Haverkort, *New J. Phys.* (2020) 093018
Data: F. Adam et al., *Phys. Rev. Lett.* (2026)

ECHo-LE

Work in Progress: Systematics Influencing the Sensitivity

- Final spectrum will be comprised of many sub-spectra

- Ongoing studies on systematic effects of
    - Spread in energy resolution
    - Calibration uncertainty
    - Uncertainty in background profile

→ Monte Carlo using theory of Braß & Haverkort (2020) and Bayesian methods developed for ECHo-1k

- Reliable and flexible algorithms for:
    - investigate bias in endpoint analysis
    - quantification of systematic errors based on detector performance and current background models [1,2]

[1] A. Göggelmann et al., *Eur. Phys. J. C* (2021)
[2] A. Göggelmann et al., *Eur. Phys. J. C* (2022)

Summary & Outlook

ECHo-1k:

- 2×10^8 ^{163}Ho decays in the final spectrum (3×10^8 acquired)
- Reliable data reduction and building of the high statistic spectrum
- Phenomenological modelling of the endpoint region yields stable posterior distributions
- Current best limit on the (effective) neutrino mass: $m(\nu_e) < 15$ eV (90% C.I.) from direct measurement

Deutsche Forschungsgemeinschaft
European Research Council
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ECHo-LE: 10^{13} decays

- Detector arrays optimised for sensitivity < 1 eV
- Studies of systematic uncertainties are ongoing
- New data acquisition scheme needed to address high data sizes

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Deutsche Forschungsgemeinschaft

European Research Council
Established by the European Commission

Backup

Stability of Calibration Parameters

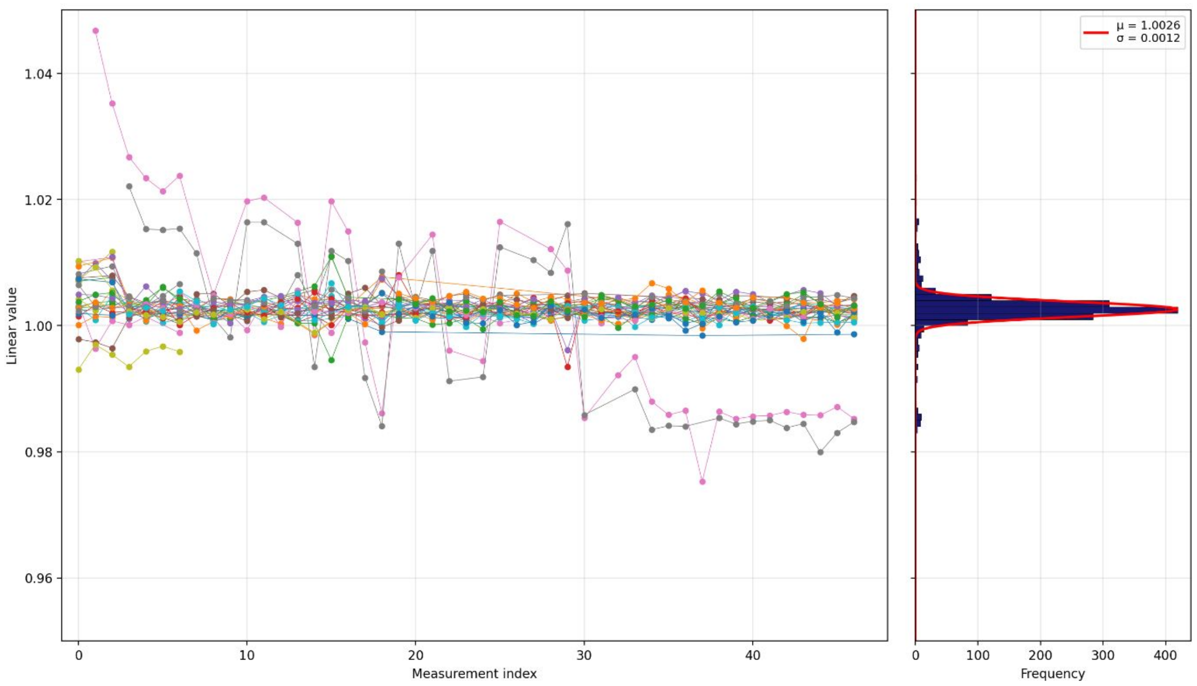
- Calibration parameters constant with time
- Different pixels show the same calibration parameters

 Reproducibility and stability of detector performance

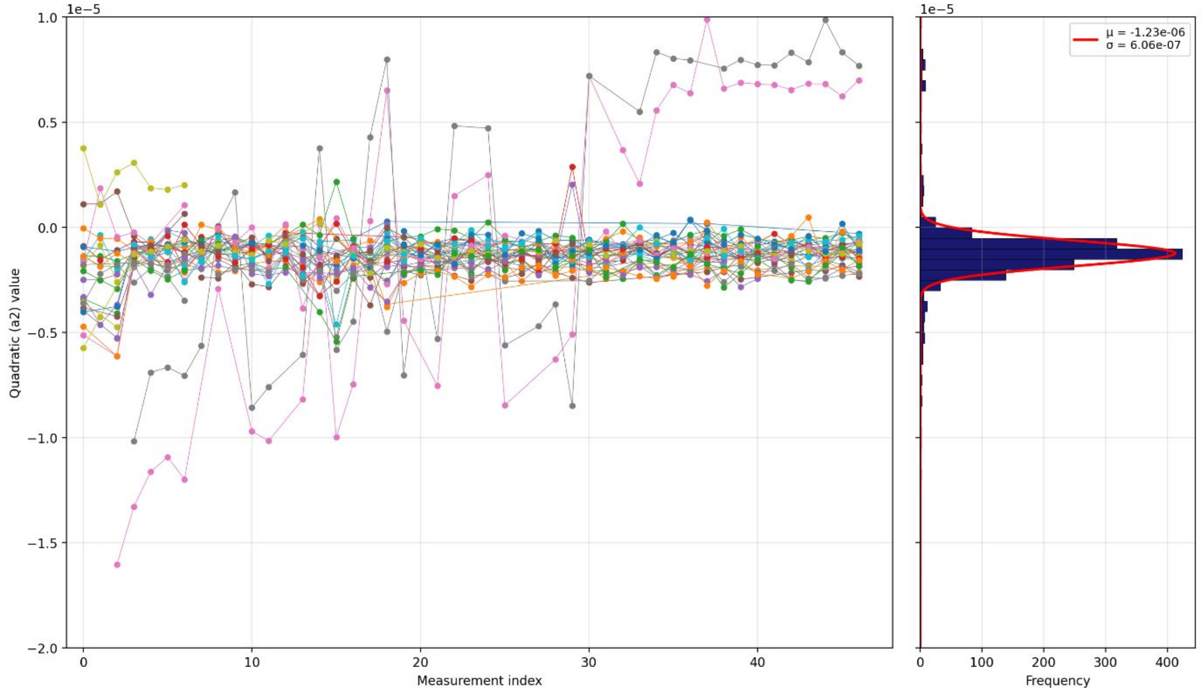
Quadratic calibration fit:

$$A(E) = aE + bE^2$$

a



b



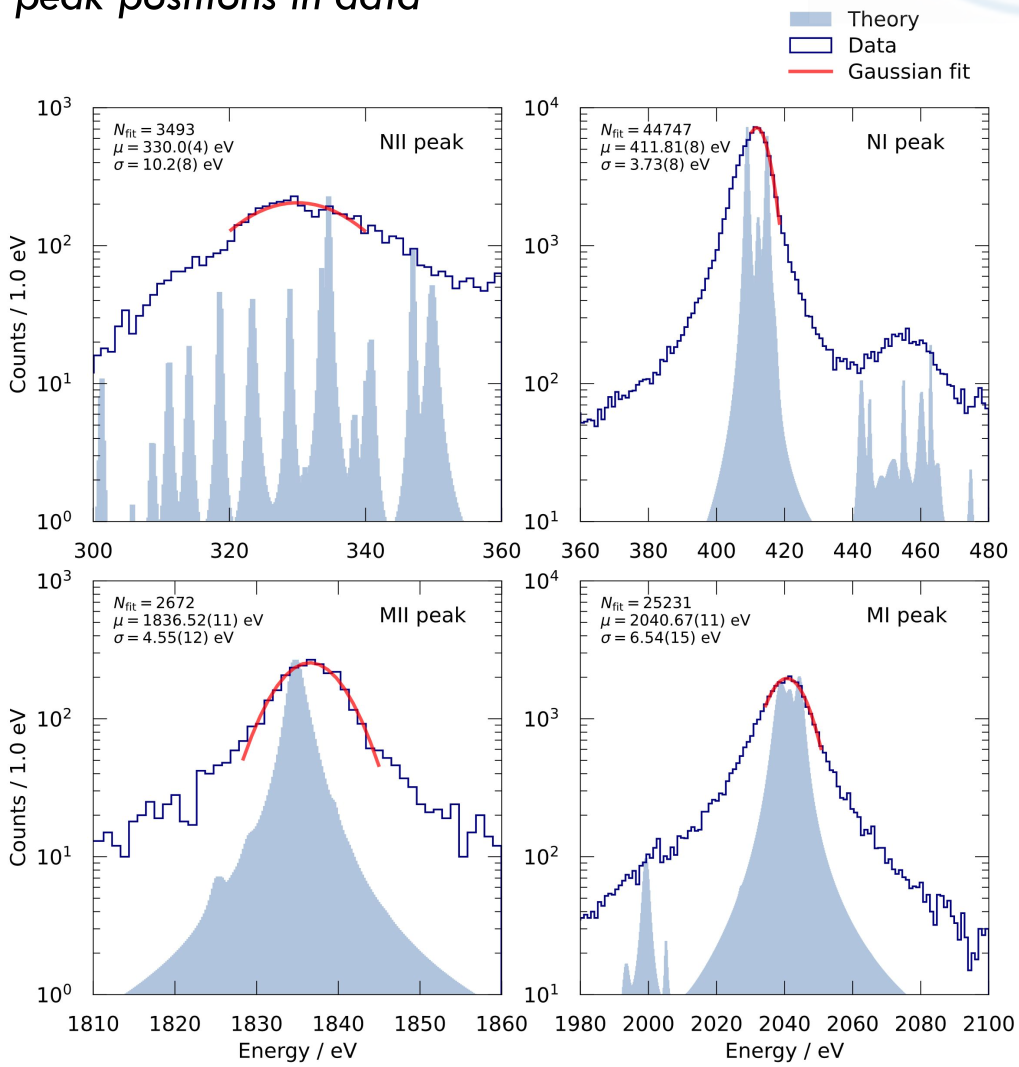
ECHo-1k Experiment

Energy Calibration

- Auxiliary high precision measurement with ^{55}Fe
  - Extraction of effective line positions

- Energy calibration of high statistic spectrum via effective line positions

Theoretical spectrum – quadratic recalibration to match peak positions in data



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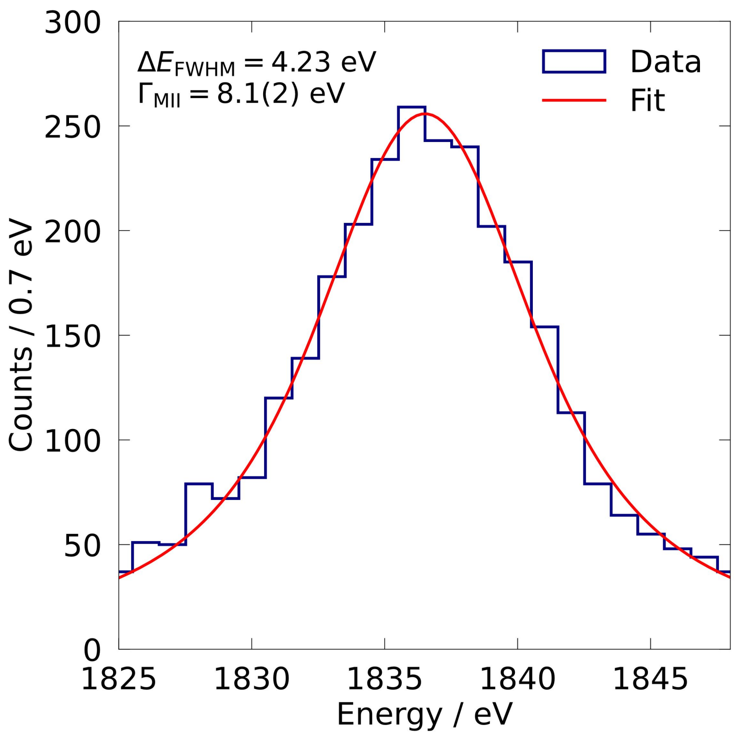
- M. Braß, M. W. Haverkort, *New J. Phys.* (2020)
- F. Adam et al., *Phys. Rev. Lett.* (2026)
- Dedicated publication in progress

Energy Resolution

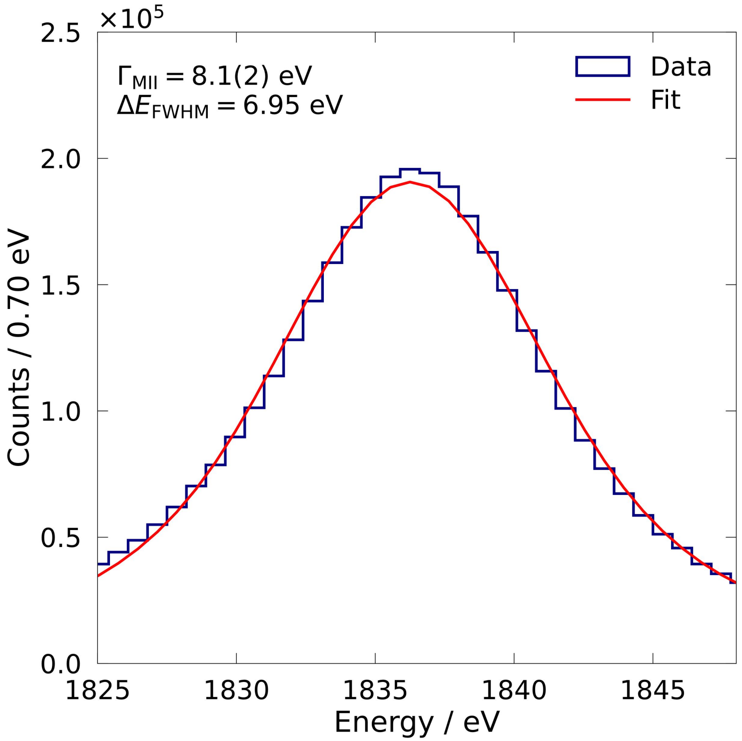
Calibration Data

Get MI line width



High Statistics

Get detector response



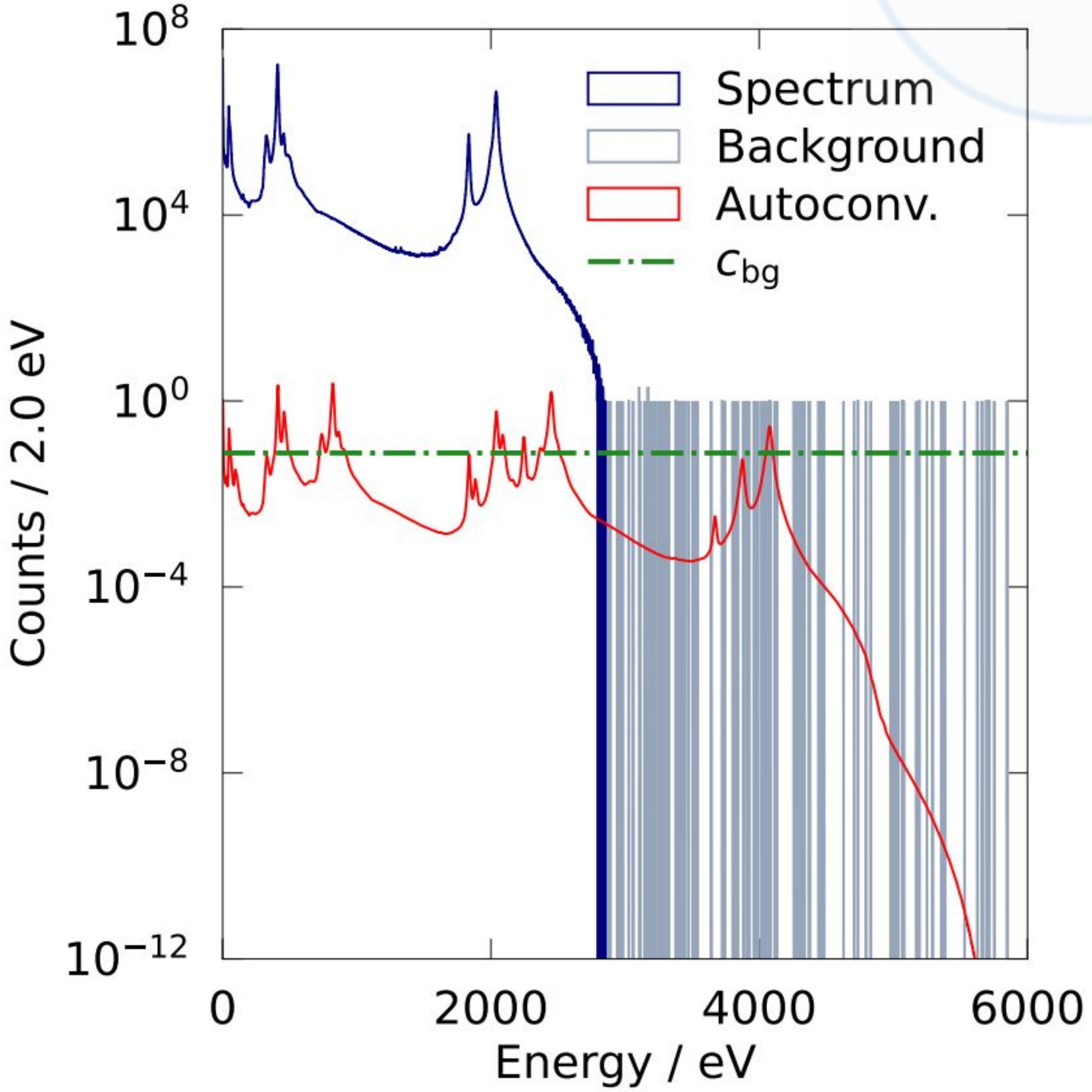
ECHo-1k

Background Quantification

Background fit (2.9 – 5.0 keV):

$$f_{\mathrm{bg}} = c_{\mathrm{bg}} + f_{\mathrm{pu}} \frac{\mathrm{d}N}{\mathrm{d}E} * \frac{\mathrm{d}N}{\mathrm{d}E}$$

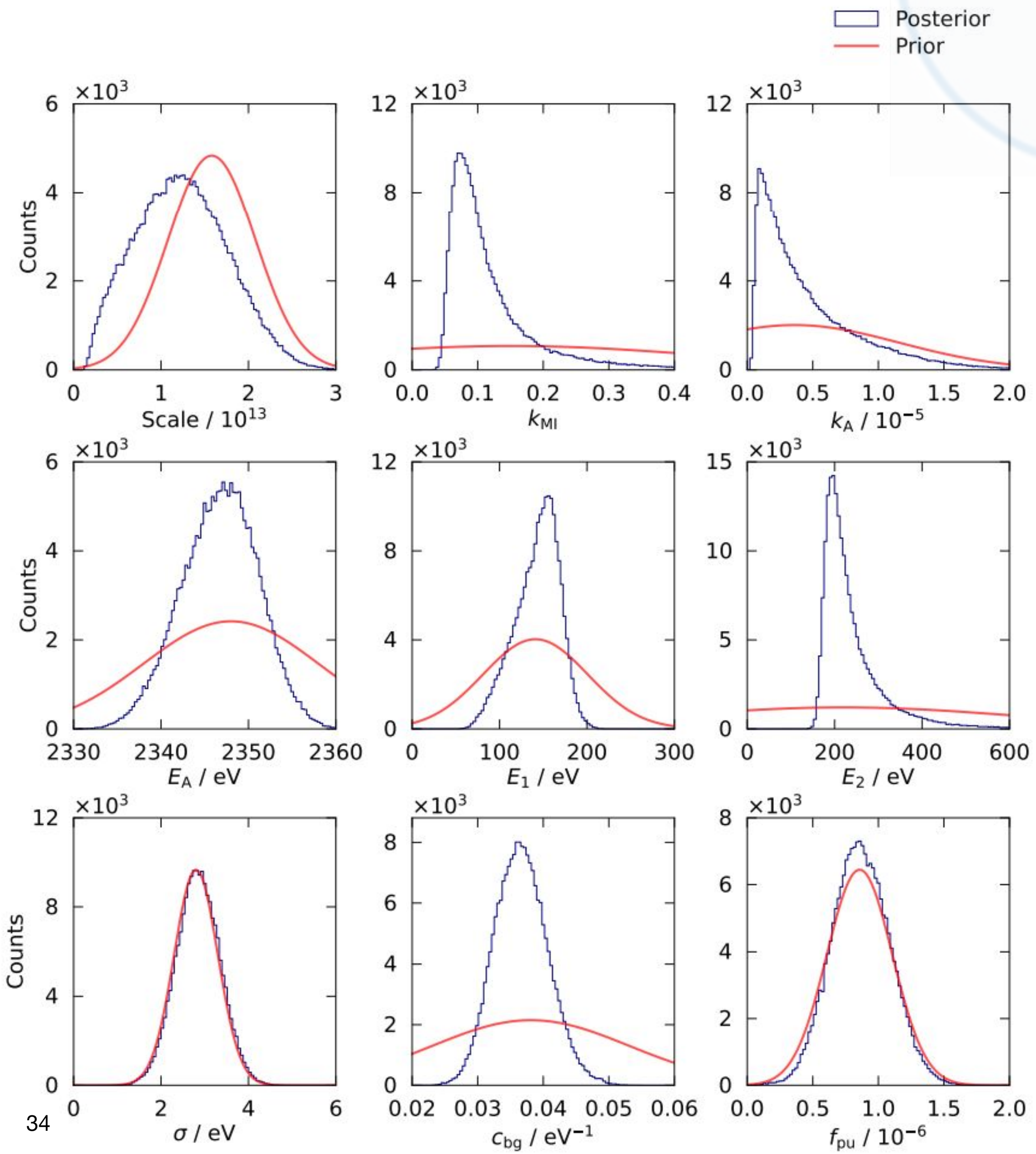
- Constant rate c_{bg} for random radioactivity
  $c_{\mathrm{bg}} = 0.038$ / eV
- Pile-up as autoconvolution of spectrum weighted by $f_{\mathrm{pu}} \sim 8 \times 10^{-7}$ with respect to main spectrum



^{163}Ho Spectrum

Fit of the Endpoint Region

- Coarse grid search to estimate bump parameters
  2250 eV – 2750 eV
- Bayesian priors defined based on grid
- Markov Chain Monte Carlo (MCMC)
  2250 eV – 5000 eV
- Infer posterior distributions for each parameter
- MCMC not very sensitive to σ and f_{pu}



Acquisition at mK in Dilution Refrigerator