Direct neutrino mass measurement with cryo-detectors

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HOLMES

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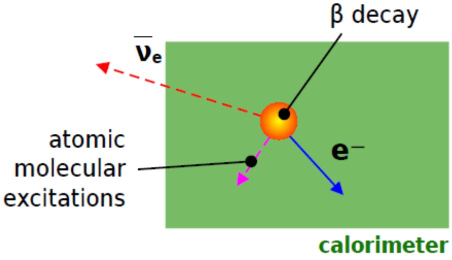
Direct neutrino mass with calorimeters

Kinematics of weak decays

- nuclear decay involving neutrinos
- only energy and momentum conservation
- no further assumptions



Calorimeters:

- the β source is embedded in the detector
- ideally they measure all the energy E released in the decay except for the ν_e energy
- calorimeters measure the entire spectrum at once

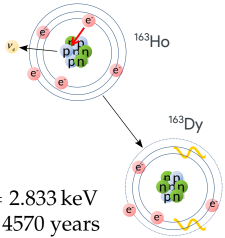
Isotope	Q [eV]	$\tau_{1/2}$ [y]	Decay	Experiments
^{3}H	18592.01(7)	12	β^-	Simpsons's
^{187}Re	2470.9(13)	4.3×10^{10}	β^-	MANU, MIBETA
^{183}Ho	2863.2(6)	4570	EC	Holmes, ECHo

for an udated analysis of low Q candidates
D. K. Keblbeck et al., Phys. Rev. C, 107 (2023) 015504

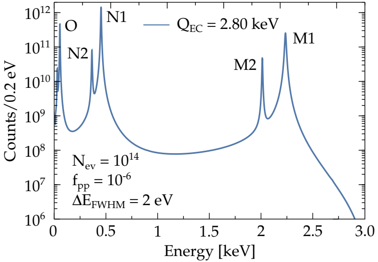
Ideal isotope has:

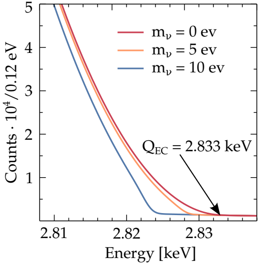
- low Q
  - → larger fraction of decays in ROI
  - → easier calorimetry
- short half life
- for EC: capture peak close to end-point

$$^{163}\mathrm{Ho} + e^- \rightarrow {}^{163}\mathrm{Dy}^* + \nu_e(E_c)$$ electron capture from shell $\geqslant$ M1



$Q_{EC} = 2.833\,\mathrm{keV}$
$\tau_{1/2} \simeq 4570$ years





proposed for the first time
by A. De Rujula e M. Lusignoli in 1982
Phys. Lett. 118B (1982) 429
Nucl. Phys. B219 (1983) 277-301

- Calorimetric measurement of Dy atomic de-excitations (mostly non-radiative)

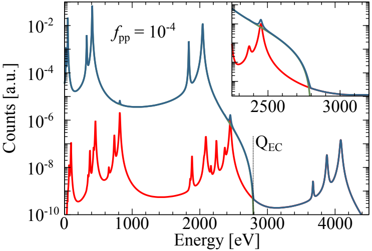
  $\Rightarrow$ measurement of the entire energy released except the ν energy

- rate at the end point depends on $(Q - E_{M1})$: the proximity to M1 resonance peak enhances the statistics at the end point (i.e. sensitivity on m_ν)

- Searching for a tiny deformation caused by a non-zero neutrino mass to the spectrum near its end point

^{163}Ho: pile-up spectrum

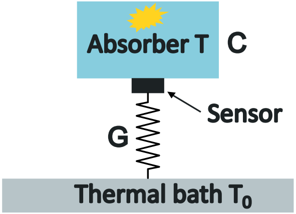
$$S(E_c) = \left[N_{ev}(N_{EC}(E_c, m_\nu) + f_{pp} \times N_{EC}(E_c,0) \otimes N_{EC}(E_c,0)) + B(E_c)\right] \otimes R_{\Delta E}(E_c)$$

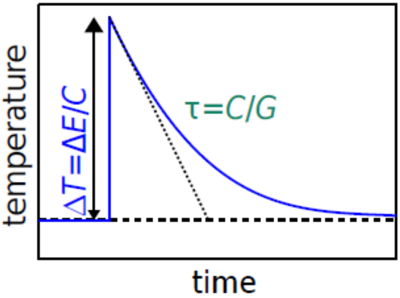


N_{ev}	: total number of events
$N_{EC}(E_c, m_\nu)$	: ^{163}Ho spectrum
$B(E)$	: background energy spectrum
$R_{\Delta E}(E_c)$	: detector energy response function
f_{pp}	: fraction of pile-up events
$R_{\Delta E}(E_c)$	: detector energy response function
ΔE	Energy interval

- Pile-up pulses occur when multiple events arrive within the resolving time of the detector
- Unresolved pile-up events close to the end-point impair m_ν measurement
- ^{163}Ho pile-up spectrum is quite complex and presents a number of peaks close to the end-point
- To resolve pile-up:
  - Detector with fast signal rise-time τ_{rise}
  - Pile-up recognition algorithm (i.e. Wiener filter, Singular Value Decomposition)

LTDs were initially proposed as perfect calorimeters, i.e. as devices able to thermalize thoroughly the energy released by the impinging particle.





$$C(T)\frac{dT}{dt} + G(T, T_0) = P(t)$$

$$P(T) = \Delta E \delta(t) \rightarrow T = T_0 + \frac{\Delta E}{C} e^{-t/\tau}$$

for $t > 0$ and $\tau = C/G$

The only requirements are to operate the device at low temperatures (< 0.1 K) in order to make the C low enough, and to have a sensitive enough temperature sensor.
Energy resolution limited by thermodynamic fluctuation noise (TFN):

$$\sigma_E = \sqrt{k_B T^2 C}$$

k_B is the Boltzman constant.

The HOLMES experiment (ERC-2013-AdG no. 340321)

The m_ν statistical sensitivity has:

- **Strong** dependence on statistic: $\Sigma(m_\nu) \propto N_{events}^{1/4}$
- **Strong** dependence on pile-up: $f_{pp} \simeq A_{EC} \cdot \tau_{res}$
  (A_{EC}: pixel activity, τ_{res}: time resolution)
- **Weak** dependence on energy resolution ΔE;

Multiplaxable detectors with fast response are required

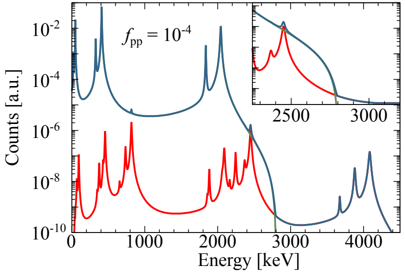
HOLMES

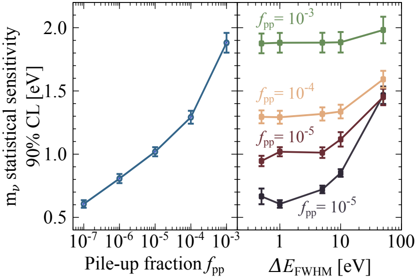
Neutrino mass determination with a sensitivity as low as ≈ 1 eV

- Microcalorimeters based on Transition Edge Sensors with ^{163}Ho implanted Au absorber
- Pixel activity of $A_{EC} \sim 300$ Bq/det
- Energy resolution: $O(\text{eV})$
- Time resolution: $\tau_{res} \sim 1.5\ \mu s$ ($\tau_{rise} = 10 - 20\ \mu s$);
- 1000 channels for $3 \cdot 10^{13}$ events collected in $T_M = 3$ years

more details on
Eur. Phys. J. C (2015) 75: 112

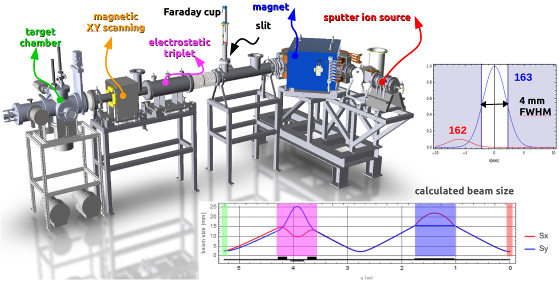
Pile-up Spectrum





Isotope production and embedding

- ^{163}Ho produced from ^{162}Er neutron activation
- Chemical purification before and after the irradiation
- **Ion implanter** designed to embed Ho and to perform a mass separation of the ^{163}Ho from the other contaminants
  - → Ar plasma sputter ion source
  - → efficiency $\approx 0.2\%$
  - → A $\approx$1 Bq/det



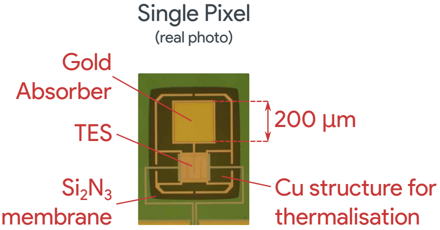
HOLMES detectors and read out

Mo/Cu TES coupled to Gold absorbers where ^{163}Ho is ion-implanted

Optimized design for high speed and high resolution:

- $\Delta E_{FWHM} \simeq 3 - 4\,\text{eV}$ @ 2.8 keV
- $\tau_{rise} \simeq 20\ \mu s$
- $\tau_{decay} \simeq 600\ \mu s$

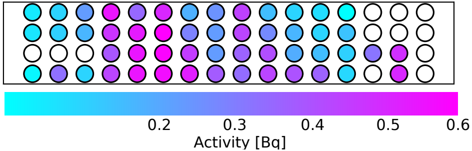
Readout: microwave rf-SQUID multiplexing with a multiplexing factor ≈ 256 and a maximum sampling time of 2 μs

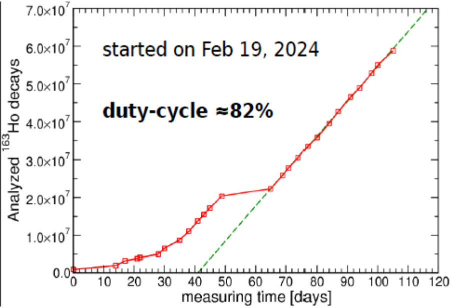


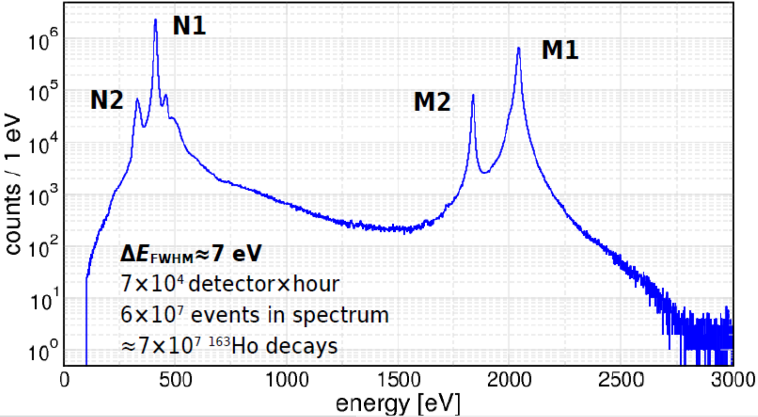
High statistics spectrum

- 48 active detectors
- average activity* $< A > = 0.27$ Bq
- total activity* $Atot = 13$ Bq
- peak activity* $Amax \approx 0.6$ Bq

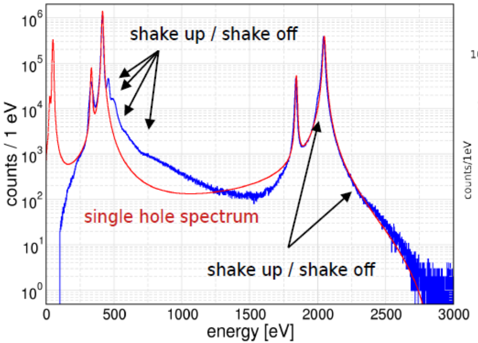
** all activities above threshold*

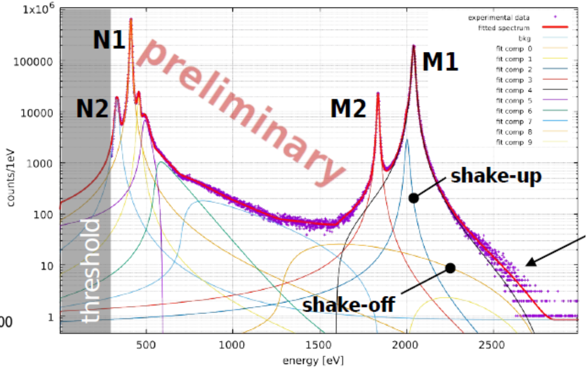






HOLMES high statistics measurement: spectral shape





signal rate higher than single-hole

impact on m_β sensitivity?

Experimental EC spectrum deviates from all theoretical predictions

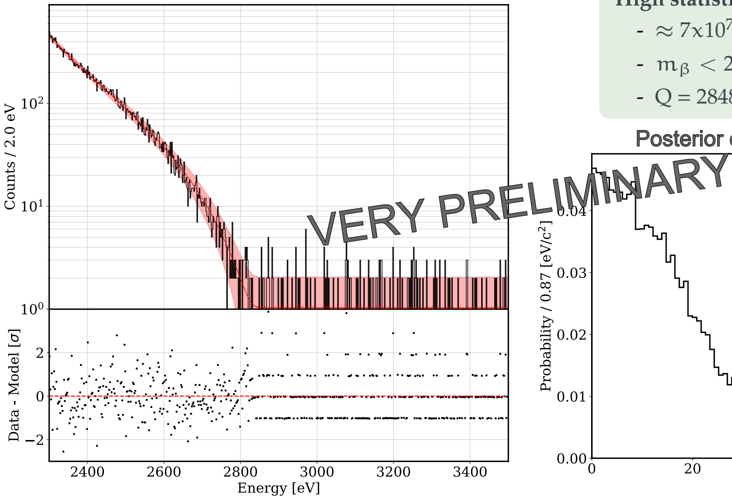
→ phenomenological description of the EC spectrum

End-point region is smooth and featureless

JHEP 05 (2016) 015
Phys. Rev. C, 95 (2017) 045502
New J. Phys., 22 (2020) 093018
Phys. Rev. C, 91 (2015) 035504

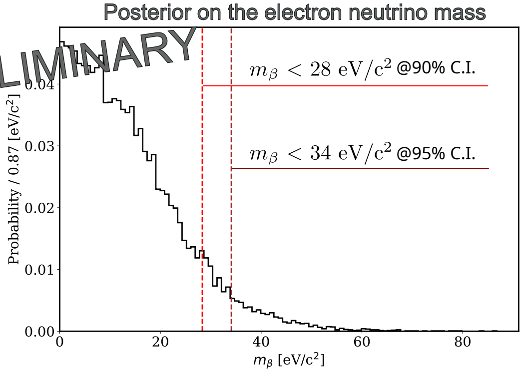
NOW 2024 Neutrino Oscillation Workshop

Preliminary Bayesian end-point analysis with phenomenological model



High statistic spectrum

- ≈ 7x10^7 ^{163}Ho decays
- m_β < 28 eV 90% CI
- Q = 2848+11-6 eV (only stat error)



ECHo-0

Magnetic Metallic Calorimeters (First Protype)

- 4 detectors
- 0.01 Bq per pixel
- operated over more than 4 years

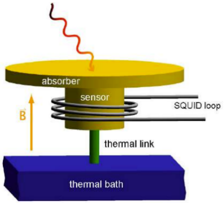
more details on
Eur. Phys. J. Special Topics 226, 1623 (2017)

ECHo-100k

Multiplexed Magnetic Metallic Calorimeters

- 12000 detectors
- ~ 10 Bq(^{163}Ho)/det
- $\Delta E_{FWHM} < 5$ eV

Sensitivity on $m_\nu \leqslant 1.50$ eV



ECHo-1k

Magnetic Metallic Calorimeters

- 60~100 detectors
- ~ 15 Bq(^{163}Ho)/det
- $\Delta E_{FWHM} < 10$ eV

Sensitivity on $m_\nu \leqslant 20$ eV

Mass separation and isotope embedding

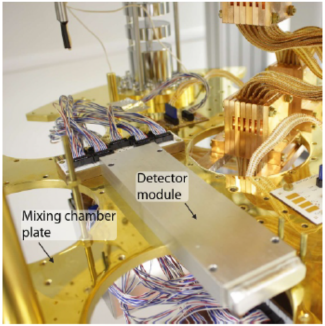
ECHo: resonant laser ionization source

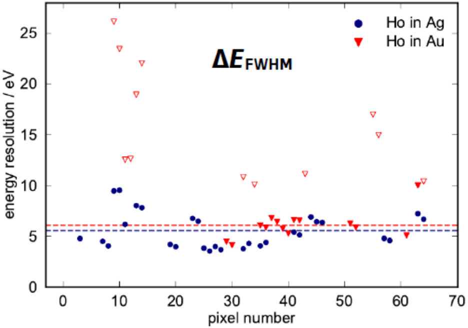
- RISIKO at Mainz University
- efficiency: $(69 \pm 5\text{stat} \pm 4\text{syst})\%$
- demonstrated A(^{163}Ho)max≈ 3 Bq/det

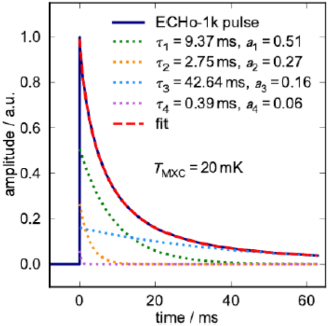
more details on
NIM A, 945, 2019, 162602

2x64 detector modules with ^{163}Ho in Au and Ag host material parallel dc-SQUID readout

more details on
NIM A 1030 (2022) 166406
J. Inst. 16 (2021) P08003







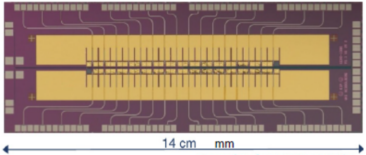
host	Ho pixels	bck pixeld	$< A >$ [Bq]	A_{tot} [Bq]
Au	23	3	0.94	28.1
Ag	34	6	0.71	25.9

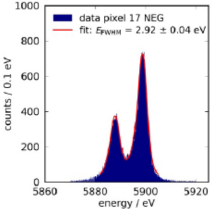
- $\tau_r \approx 1$ µs limited by SQUID bandwidth
- complex decays time: mostly $\tau_1 \approx 10$ ms

ECHo-1k status: high statistic measurement

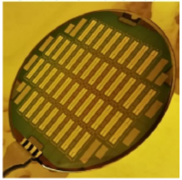
High statistic spectrum

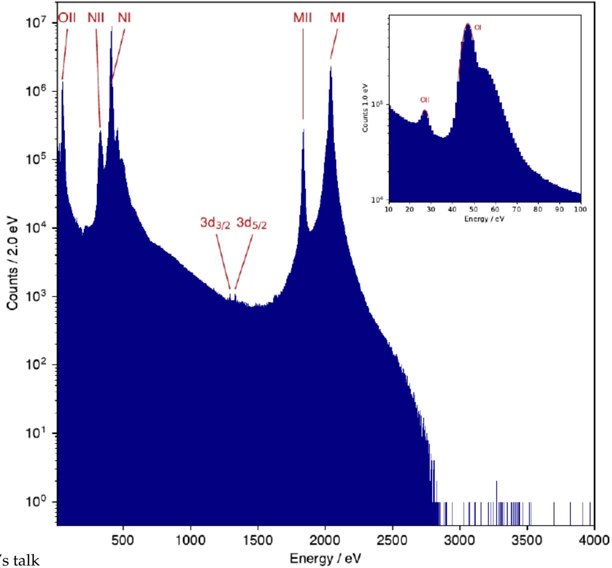
- Bayesian end-point analysis in progress
- 1.26×10^8 events from detectors with ^{163}Ho in Ag host material
- now preparing ECHo-100k





6 wafer for ECHo-100k



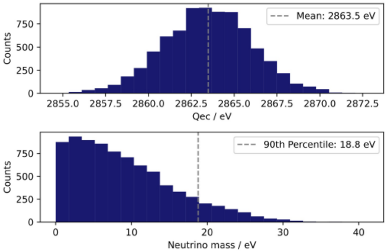


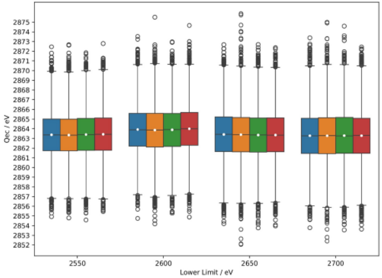
from NEUTRINO 2024, Nucciotti's talk

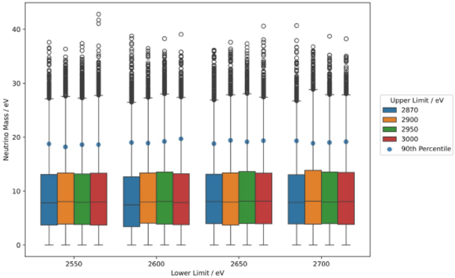
ECHo-1k status: high statistic measurement (cont.)

$Q = (2862.1 \pm 1.7)$ eV

$m_\nu < 19$ eV 90% CL







from NEUTRINO 2024, Nucciotti's talk

Beyond ECHo and HOLMES: a sub-eV experiment

ECHo and HOLMES proved

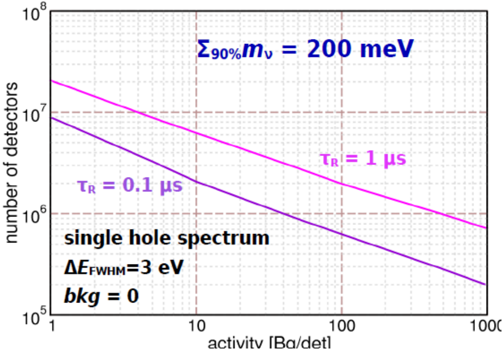
- production of large and pure ^{163}Ho isotope samples
- efficient embedding technology
- large bandwith array multiplexed readout
- performing microcalorimeters with Ho
- high duty-cyle high-statistics data taking
- spectrum endpoint analysis

to go beyond

New collaboration for a sub-eV experiment

- increased pixel activity (impact of ^{163}Ho heat capacity)
- multiplexing and DAQ bandwidth
- about 1M pixels

Estimated cost is only O(10M€)



Conclusion

The ECHo and HOLMES experiments:

- low temperature microcalorimeter arrays with ion-implanted 163Ho
- scalable proof-of-principles for an experiment with $\leqslant$0.1 eV m_ν sensitivity

Ho calorimetric experiments are a solid and readily available alternative to tritium experiment

- different systematics
- individual projects are reaching order of 10 eV sensitivities on m_β
- ready to reach statistical sensitivities of order of 1 eV on m_β in few years
- potential to go beyond KATRIN with more R&D and a large international collaboration