The first neutrino mass limit of HOLMES

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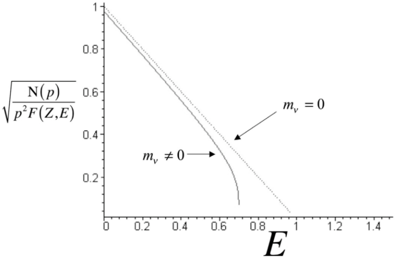
On behalf of HOLMES collaboration

Direct neutrino mass measurements

- **Model-independent** method: kinematic analysis of beta decay;
- Energy spectrum distorted by non-zero ν mass;
- **Spectrometry**:
  - the source is outside the detector;
  - high statistics allowed, no pile-up issue;
  - source systematics;
  - best limit: $m_\beta < 0.45$ eV @ 90% C.L., *KATRIN Collaboration, Science 2025.*
- **Calorimetry** (HOLMES approach):
  - source embedded inside the detectors;
  - all energy measured, except neutrino's;
  - no systematic uncertainty related to the source;
  - trade off between activity and time resolution (pile-up).

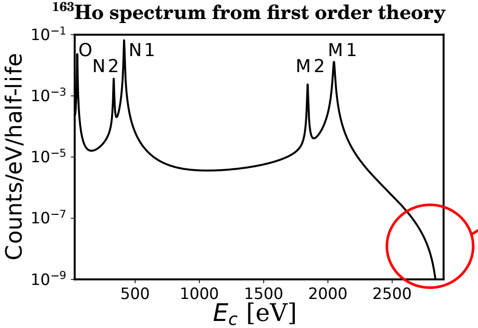
$$m_\beta^2 = \sum_i |U_{ei}|^2 m_{\nu_i}^2$$

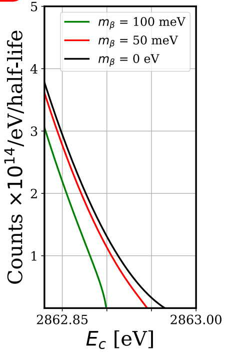


The EC decay of ^{163}Ho

$$^{163}\text{Ho} + e^- \rightarrow \, ^{163}\text{Dy}^H + \nu_e$$
$$^{163}\text{Dy}^H \rightarrow \, ^{163}\text{Dy} + E_C^H$$

$$N(E_c) = \frac{G_\beta^2}{4\pi^2}(Q - E_c)\sqrt{(Q-E_c)^2 - \boldsymbol{m}_\beta^2} \times \sum_i n_i C_i \beta_i^2 B_i \frac{\Gamma_i}{2\pi} \frac{1}{(E_c - E_b(H_i))^2 + \Gamma_{H_i}^2/4}$$





- E_C = atom de-excitation + nuclear recoil;
- Method proposed by *A. De Rújula and M. Lusignoli, Phys. Lett. B 118 (1982) 429*;
- $Q = 2863.2 \pm 0.6$ eV *Ch. Schweiger et al. Nat. Phys. (2024)*;
- $\tau_{1/2} \sim 4570$ y.

The HOLMES experiment

- **Low temperature microcalorimeter** arrays with ion-implanted ^{163}Ho;
- **Proof-of-principles** for a final ^{163}Ho experiment with sub-100 meV m_β sensitivity;
- Gradual approach based on **scalability**.

Currently

HOLMES

- Proved the feasibility of the calorimetric approach
- Multiplexed TES 64-pixel array
- $\approx$ 1 Bq(^{163}Ho)/pixel (6x10^7 decays)
- $\Delta E_{FWHM} \in [5,7]$ eV and $\tau_R \approx 1$ μs

→ m_ν statistical sensitivity *O(10)* eV

2028

HOLMES+

- Mid term (3y) plan
- Optimization of cost/channel
- Preparation of the final scalable competitive module

→ m_ν statistical sensitivity *O(1)* eV

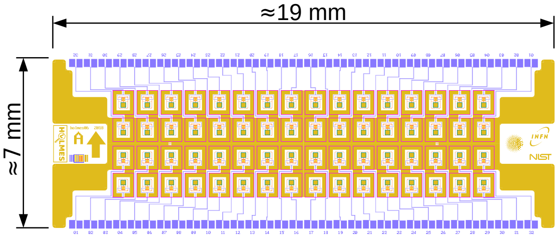
Final Ho experiment

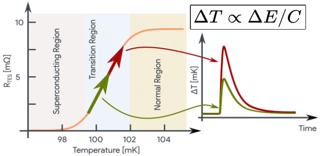
- O(10^6) detectors
- O(10) years
- O(10^{17}) decays
- O(10) Bq detector activity
- $\approx$ 1 eV energy resolution (FWHM)

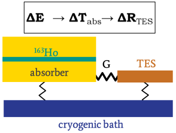
→ m_ν sensitivity: sub-100 meV

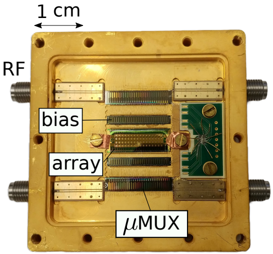
HOLMES detectors

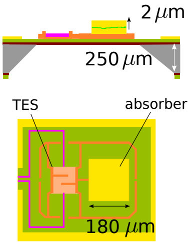
- **Low temperature** (∼ 100 mK) **microcalorimeters**;
- ^{163}Ho implanted gold absorbers each coupled to a Cu/Mo **Transition Edge Sensor**;
- 1+1 μm Au thickness for electrons full absorption;
- μMUXed TES 64-pixel array ∼0.3 Bq/pixel.





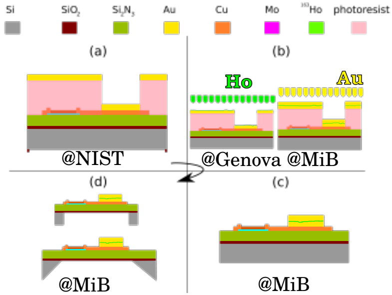


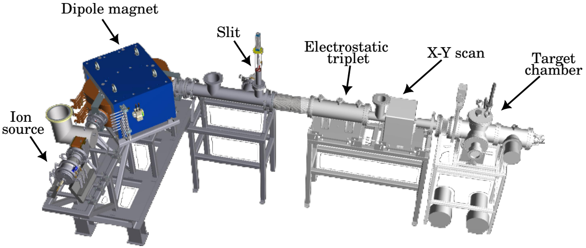


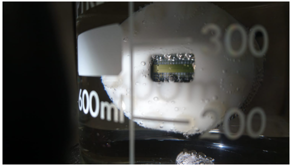


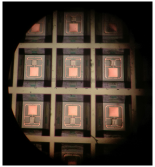
Multistep detector production

- Multiple fabrication steps required for ^{163}Ho implantation;
- TES & first Au layer (NIST), implantation (Ge), Au deposition & membrane release (MiB);
- Ion implanter: source + dipole + slit and FC;
- KOH Si etching (thermal coupling to the bath).



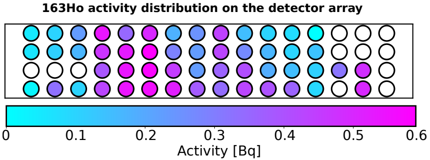


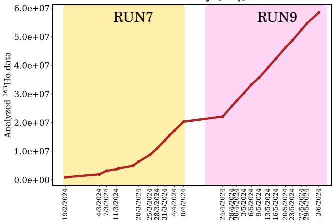

Holmes array chip in KOH solution

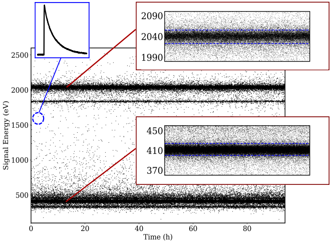

Back of the array after the KOH etching

First data-taking runs (2024)

- **48 measured pixels**[a];
- Average activity ∼0.27 Bq;
- A_{tot} = **15 Bq** ($\sim 3.2 \times 10^{12}$ nuclei);
- $\Delta E_{FWHM} \in [5, 7]$ eV;
- ∼2 months of data taking: 6×10^7 events;
- <1% signals discarded by first level analysis;
- **Duty-cycle** ∼82%;
- Corrected energy gain stability over multiple days.



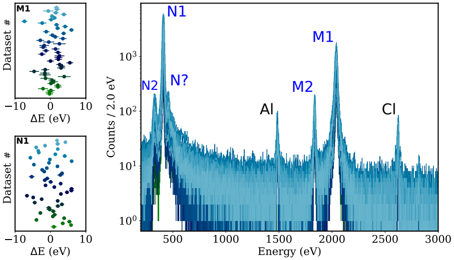




[a]M1 rate high enough for gain drift correction

EC spectrum calibration

- Run with fluorescence X-ray source;
- 2^{nd} order polynomial calibration:
  - $E(A) = a \times A + b \times A^2$.
- Find EC peak energies:
  - Bayesian learning fit accounting for small energy scale deviations.
- Energy calibration for physics runs.



Peak	**Position** E_0 **[eV]**	**Width** Γ **[eV]**	**Asymmetry** δ_{AS}
M1	2040.8 ± 0.3	14.49 ± 0.05	1.306 ± 0.006
M2	1836.4 ± 0.8	8.2 ± 0.3	1.03 ± 0.05
N?	454.5 ± 0.1	22.3 ± 0.4	0.62 ± 0.02
N1	411.7 ± 0.1	5.57 ± 0.03	1.270 ± 0.008
N2	329.0 ± 0.1	16.4 ± 0.2	0.69 ± 0.01
O?	61.0 ± 0.8	6.0 ± 0.5	1.000 ± 0.009
O1	50.9 ± 0.8	2.4 ± 0.4	0.80 ± 0.09

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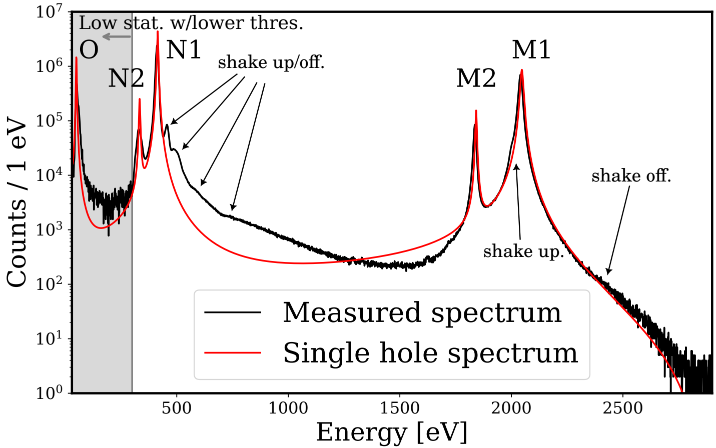
High statistics physics runs

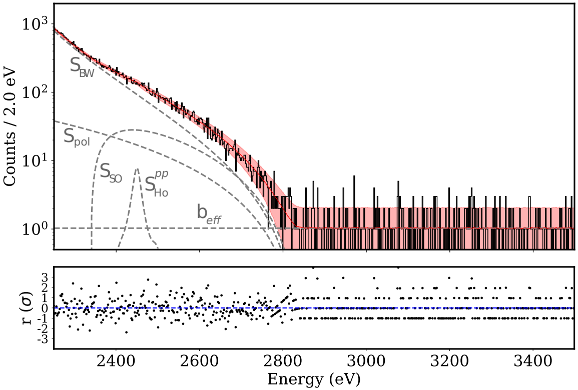


- $\sim 7 \times 10^4$ detector×hour;
- $\sim$ 1000 summed partial datasets;
- Energy calibrated with N1, M1 and M2;
- 300 eV trigger threshold;
- Deviations from single hole spectrum;
- shake up/off contributions[a].

[a] Ho→Dy perturbation "shakens" atomic electron(s) to an upper bound state (SU) or to the continuum (SOF)

Endpoint analysis

- Bayesian analysis with 13 free parameters:
  - ROI: [2250, 3500] eV;
  - $\Delta E_{FWHM} \sim 6$ eV, $f_{pp} \lesssim 10^{-5}$;
  - spectrum as sum of a few terms.



Spectrum @ ROI [2250,3500] eV:

$$\mathcal{S}_{\mathrm{exp}} = \left[N_{tot}\left(\mathcal{S}_{\mathrm{Ho}} + f^{pp}_{eff}\mathcal{S}^{pp}_{\mathrm{Ho}}\right)\right] * \mathcal{R}_{eff} + b_{eff}$$

N_{tot}: number of events;
$\mathcal{S}_{\mathrm{Ho}}$: Ho real spectrum;
$f^{pp}_{eff}\mathcal{S}^{pp}_{\mathrm{Ho}}$: pile-up fraction and pile-up spectrum;
b_{eff} : flat background;
$\mathcal{R}_{eff}$: detector effective resolution.

$$\mathcal{S}_{\mathrm{Ho}} \approx k_0\left(k_{\mathrm{BW}}\mathcal{S}_{\mathrm{BW}} + k_{\mathrm{SO}}\mathcal{S}_{\mathrm{SO}} + \mathcal{S}_{\mathrm{pol}}\right) \times \mathcal{F}_{\mathrm{PS}}$$

$\mathcal{S}_{\mathrm{BW}}$: M1 peak right tail
$\mathcal{S}_{\mathrm{SO}}$: energy spectrum of shake off de-excitation
$\mathcal{S}_{\mathrm{pol}}$: tails of other peaks and shake-offs
$\mathcal{F}_{\mathrm{PS}}$: phase space, only term with $m_\beta \propto (E_0 - E_c)\sqrt{(E_0 - E_c)^2 - m_\beta^2}$

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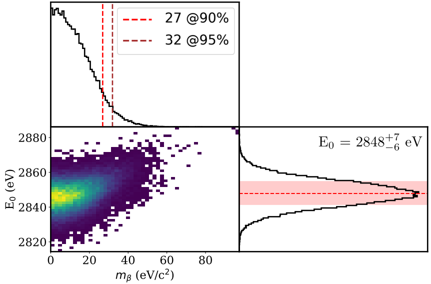
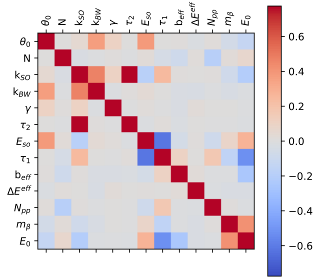
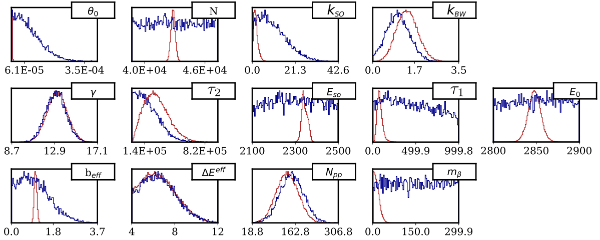
Neutrino mass limit

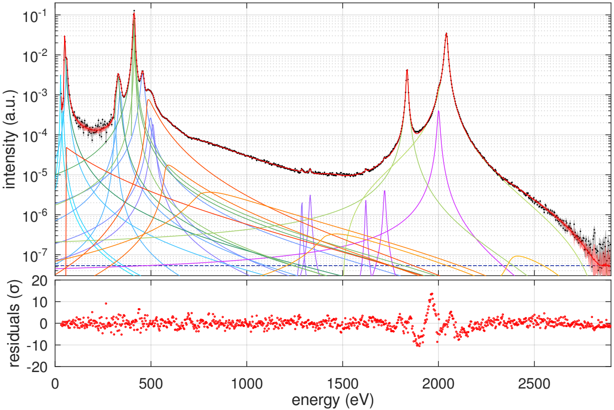
- Posteriors explored via Hamiltonian MCMC (STAN);
- E_0 is a free parameter;
- Upper limit m_β <27 eV (90% CI);
- Best published limit on m_β from EC of ^{163}Ho;
- MC simulations: sensitivity of 40 ± 10 eV;
- m_β is correlated only with E_0.







^{163}Ho EC calorimetric spectrum



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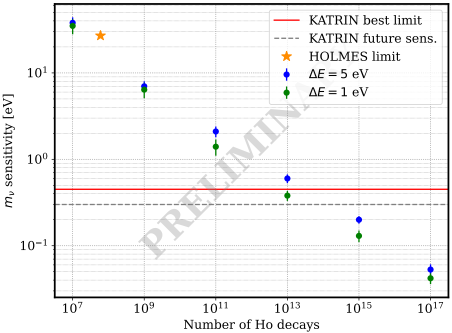
- Bayesian unfolding of all spectra;
- Phenomenological description:
  - asymmetric Lorentzians;
  - shake-up peaks and shake-off spectra.
- EC spectrum deviates from all theoretical predictions;
- ROI signal rate twice higher than with single-hole (shake off + M1 asymmetry);
- ROI: smooth and featureless;
- Assessment of future ^{163}Ho experiments sensitivity.

^{163}Ho future experiment sensitivity (stat. only)



- No background & no pile-up ⇒ need to go to 10^{17} events;
- Still need to establish the systematics;
- $\mathcal{O}(150)$ meV: $N_{ev} \sim \mathcal{O}(10^{15})$, $N_{det} \sim \mathcal{O}(10^{5})$, $A_{det} \sim \mathcal{O}(10)$ Bq, $T \sim \mathcal{O}(10)$ y;
- $\mathcal{O}(50)$ meV: $N_{ev} \sim \mathcal{O}(10^{17})$, $N_{det} \sim \mathcal{O}(10^{7})$, $A_{det} \sim \mathcal{O}(10)$ Bq, $\Delta E_{FWHM} \sim \mathcal{O}(1)$ eV, $T \sim \mathcal{O}(10)$ y.

What's next?

- Achieved the **best published limit** on **neutrino mass** using a ^{163}Ho source;
- Need many detectors and higher activity!
- Increase ^{163}Ho activity per detector — $\mathcal{O}(10)$ Bq:
  - Reduce detector operating temperature to $\lesssim$ 40 mK.
- Lower readout/DAQ costs — few euros per channel:
  - New multiplexing scheme with a higher multiplexing factor;
  - Microwave-multiplexed Kinetic Inductance Current Sensors;
  - Leverage new wide-bandwidth RFSoC boards.
- Improve ion implanter for better control and higher efficiency:
  - Integration of electrostatic triplet, X-Y scan and a target chamber;
  - Upgrading the ion source.
- **Expand international collaboration: happy to chat!**

Thank you for your attention!

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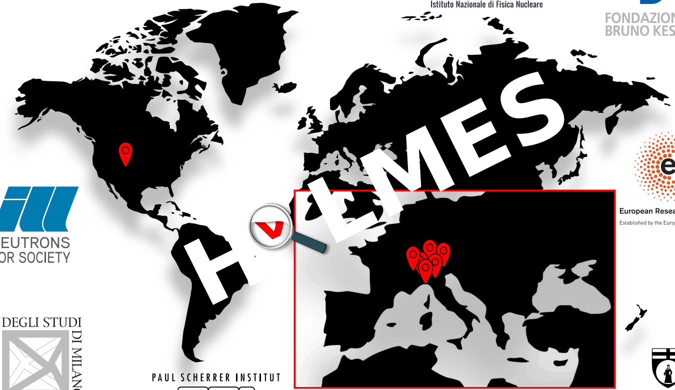

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Backup slides

Neutrino mass fit formula

$$\mathcal{S}_{exp} = \sum_i [N_i(\mathcal{S}_{\text{Ho}} + f_i^{pp}\mathcal{S}_{\text{Ho}}^{pp}) + \mathcal{B}_i] * \mathcal{R}_i$$

$$\mathcal{S}_{\text{exp}} = \left[N_{tot}\left(\mathcal{S}_{\text{Ho}} + f_{eff}^{pp}\mathcal{S}_{\text{Ho}}^{pp}\right)\right] * \mathcal{R}_{eff} + b_{eff}$$

$$\mathcal{S}_{\text{Ho}} \approx k_0\left(k_{\text{BW}}\mathcal{S}_{\text{BW}} + k_{\text{SO}}\mathcal{S}_{\text{SO}} + \mathcal{S}_{\text{pol}}\right) \times \mathcal{F}_{\text{PS}}$$

$$\mathcal{R}_{eff}(E_c) \simeq \mathcal{G}(E_c|0, \Delta E_{eff})$$

$$\mathcal{F}_{PS}(E_c|m_\beta, E_0) = (E_0 - E_c)\sqrt{(E_0 - E_c)^2 - m_\beta^2}$$

$$\mathcal{S}_{BW}(E_c|\gamma, E_{\text{M1}}) = \frac{1}{2\pi}\frac{\gamma}{(E_c - E_{\text{M1}})^2 + \gamma^2/4}$$

$$\mathcal{S}_{pol}(E_c|\vec{\theta}) \simeq \theta_0$$

$$\mathcal{S}_{SO}(E_c|E_{so}, \tau_1, \tau_2) = \frac{1}{\tau_2 - \tau_1}\left(e^{-(E_c - E_{so})/\tau_2} - e^{-(E_c - E_{so})/\tau_1}\right)$$