# First measurements of the HOLMES neutrino mass experiment

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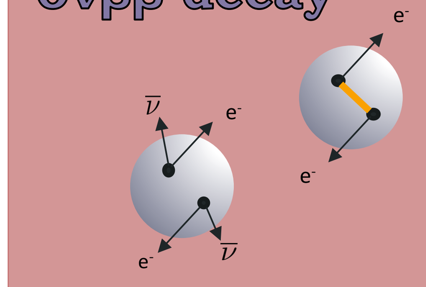
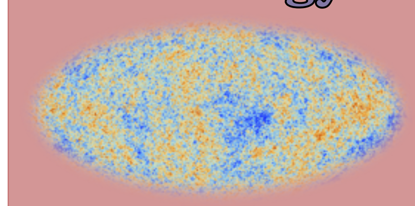


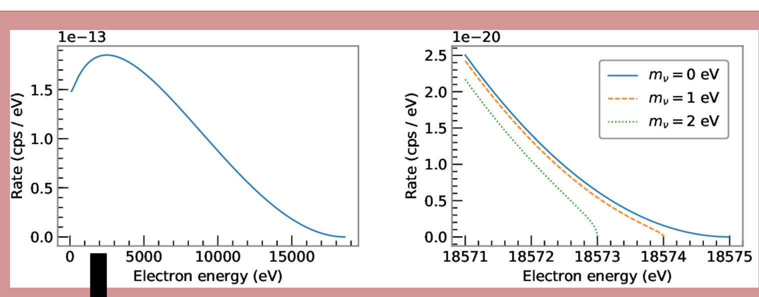

**indirect observables**

$m_{\beta\beta} = |\Sigma\, U_{ek}^2\, m_k|$

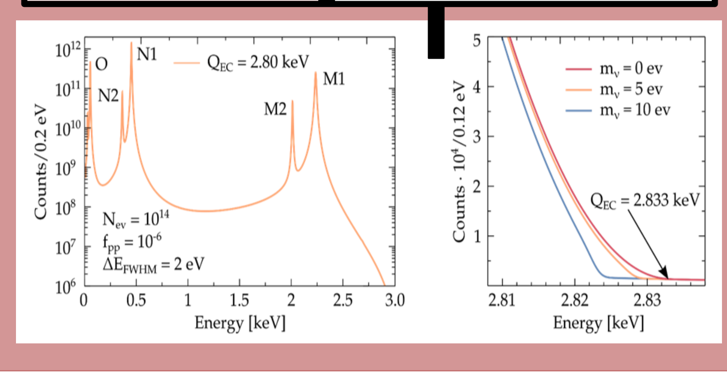
$\Sigma_m = m_1 + m_2 + m_3$

**direct observable**

$m_\beta = (\Sigma\, |U_{ek}|^2\, m_k^2)^{1/2} = m_\nu$



$^3H \rightarrow {}^3He + e^- + \bar{\nu}_e$ | $^{163}Ho + e^- \rightarrow {}^{163}Dy^{(*)} + \nu_e$

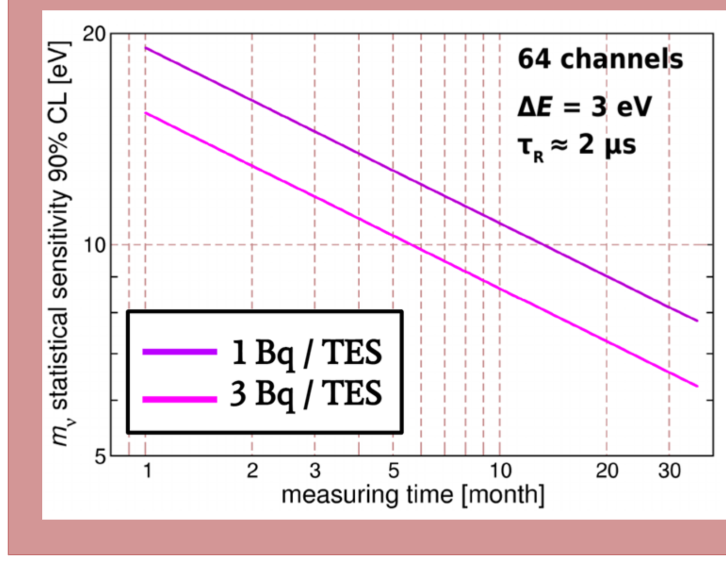



## Direct measurement of $m_\nu$

It is possible to infer neutrino mass by several methods. Some of them rely on specific theoretical models: cosmological measurements and 0νββ experiments

A model-independent assessment of the absolute neutrino mass is given by the analysis of a β spectrum endpoint. KATRIN is the leading experiment in this field. It is currently taking data improving its sub-eV upper boundary.

Calorimetry emerges as the main alternative approach to the Katrin spectrometer. By encapsulating the β isotope inside the detector it is possible to avoid several systematic errors also ensuring future experiments scalability.

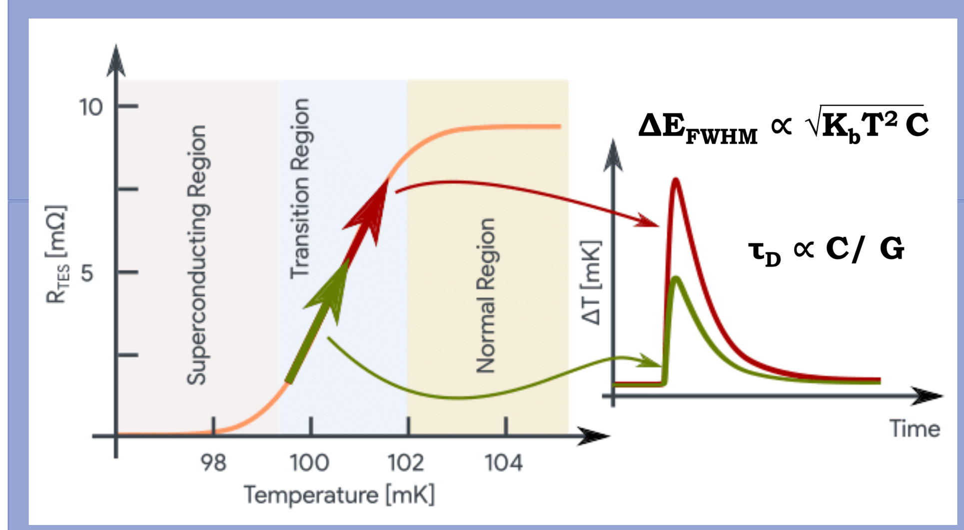


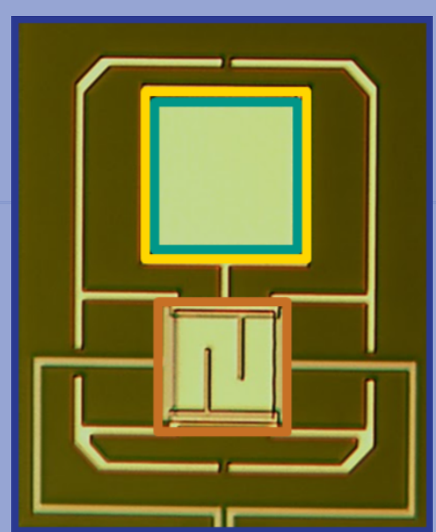

$^{163}$Ho electron capture (EC) has been proposed for direct neutrino mass determination because of its low Q-value (~2.83 keV) that increases the fraction of endpoint events. The HOLMES experiment is benchmarking this approach by ion-implanting the source in array of Transition Edge Sensors (TESs).

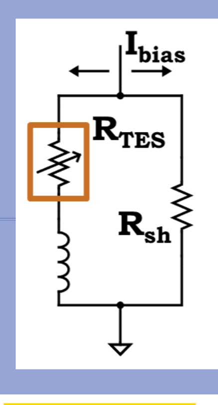
HOLMES is currently taking data and it is close to assess a calorimetric upper limit on the electron neutrino mass of ~30eV.

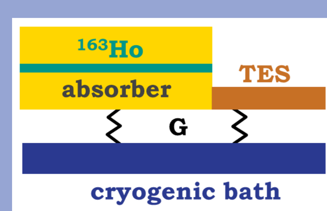
## Transition Edge Sensors

TES microcalorimeters act like very sensitive thermometers when cooled down to their ***critical temperature*** $T_C$. A rise in local temperature (such as the one caused by any energy deposition) leads the TES from superconductive to resistive. To increase the detection efficiency, the β source is enclosed in a metal absorber.





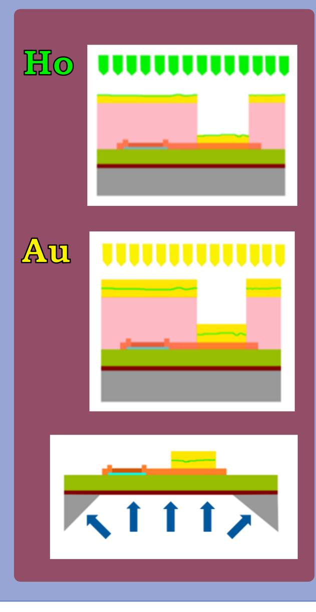

HOLMES TESs are Mo-Cu bilayer whose $T_C$ is ~100 mK. These are thermally coupled to a gold absborber 2 µm thick and both are deposed on a silicate membrane. A silicon substrate provides the thermal link to the $T_{bath}$ set by a dilution refrigerator. These detectors ensure high energy resolutions, while the time resolution depends on the fraction of unresolved pile-up events.

| | |
|---|---|
| $\Delta E_{FWHM}$~5 eV (@6keV) | Δt~1.5 µs |
| $\tau_R$~20 µs | $\tau_D$~300 µs |

TESs allow a distribution of the total activity over a large number of pixels that are read out using the microwave multiplexing technique. Pulses rise time is tunable by adjusting the electrical parameters of the TES circuit while their decays depend on the thermal coupling to the bath.

Important parameters are:

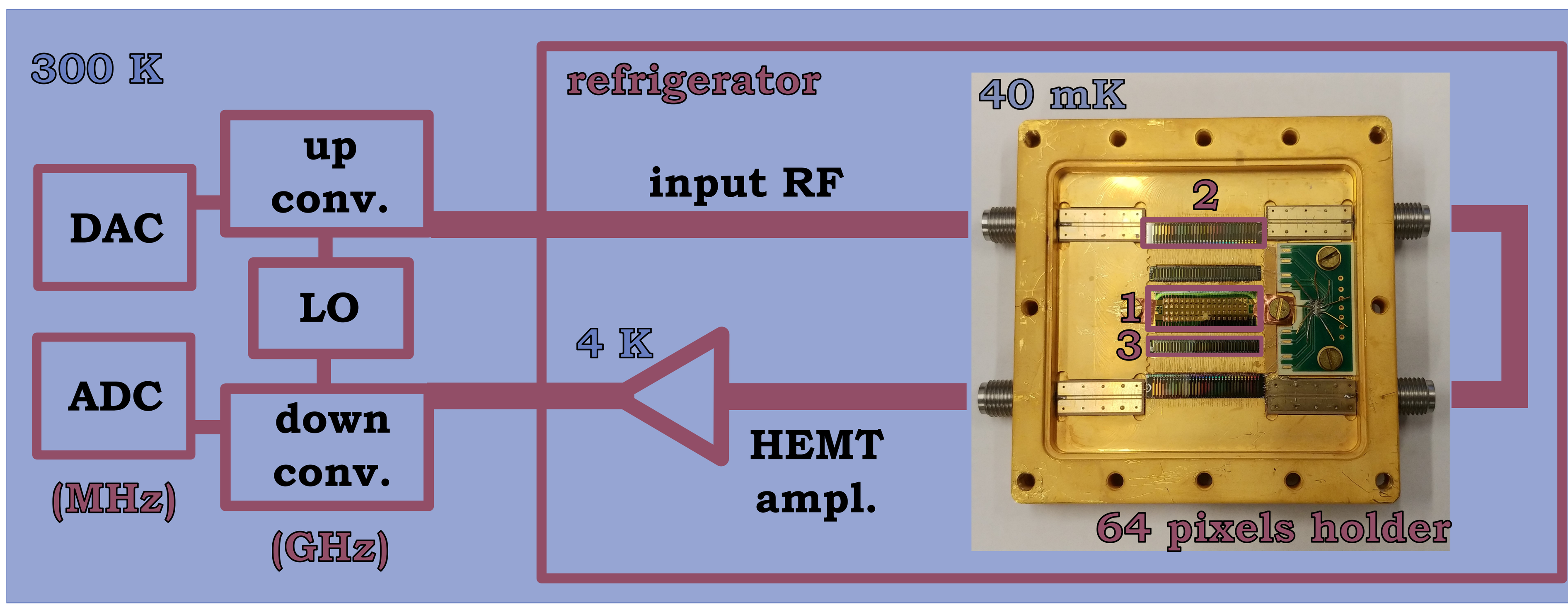
- ***Heat capacity (C)***: it affects the energy resolution and it strongly depends on the implanted Ho activity;
- ***Thermal conductance (G)***: it affects the relaxation time of TES pulses and it is defined during the substrate etching.




@ NIST — **TES production**

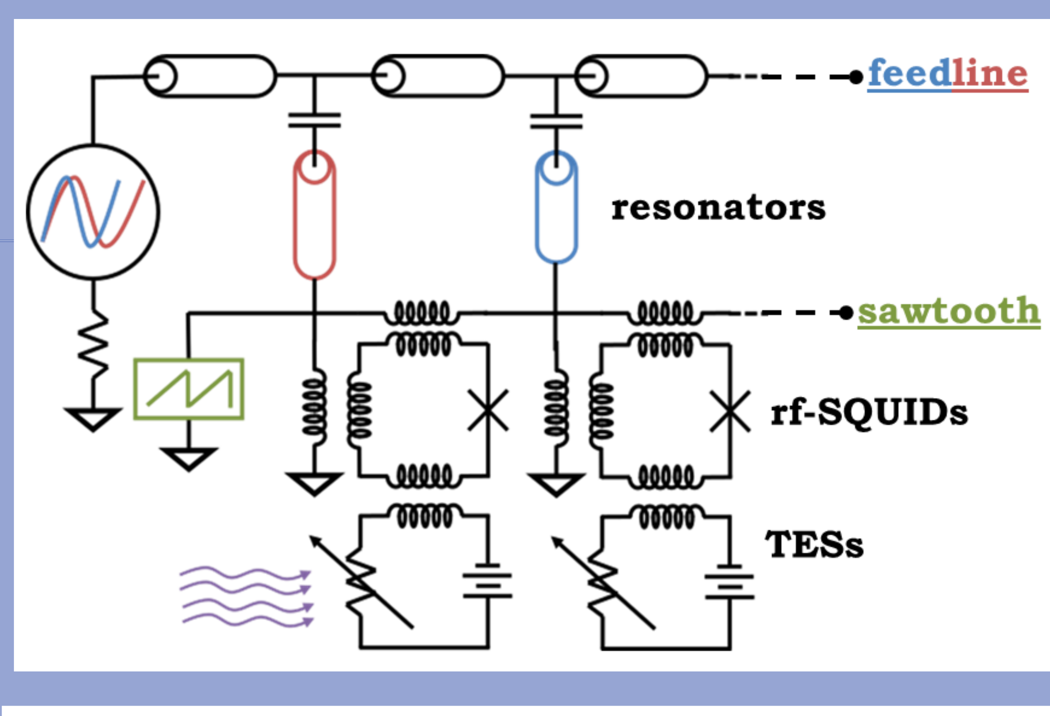
@ UniGe — **ion implantation**, **gold deposition**

@ UniMIB — **membrane release**




## HOLMES setup

Currently, the device under measurement is an array of 64 TESs **(1)**. Each TES is coupled to a rf-SQUID magnetometer and to a λ/4 resonator in the GHz. The readout scheme exploits two uMUX chips **(2)** coupled to the same RF line. These chips also carry the sawtooth signal used to linearize the rf-SQUID response with the HOLMES sampling rate (250 kHz). Two other chips **(3)** with shunting resistors are required to bias the pixel array with a constant voltage.



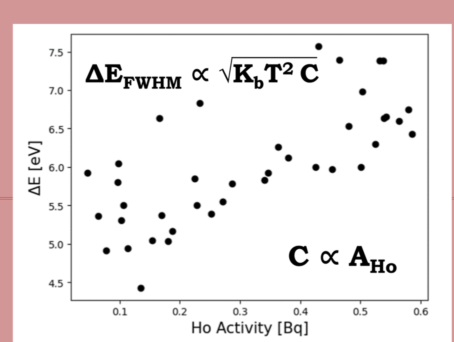

$\Delta E \rightarrow \Delta T_{abs} \rightarrow \Delta R_{TES} \rightarrow \Delta I_{TES} \rightarrow \Delta L_{SQUID} \rightarrow \Delta f_{res} \rightarrow \Delta\varphi$

## Characterization and results

The ion implantation process was verified during the first physics run of HOLMES. A total activity of ~15 Bq has been measured for an array of 64 pixels (spread over 52 operating ones). Low-dose values in (0-1) Bq allow the study of Ho abundance impact on the TES performances.

TES activity map [Bq]

| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.046 | 0.103 | 0.225 | 0.539 | 0.347 | 0.501 | 0.180 | 0.253 | 0.441 | 0.152 | 0.097 | 0.078 | 0.001 | - | - | - |
| 0.064 | 0.113 | 0.170 | 0.465 | 0.533 | 0.586 | 0.287 | 0.233 | 0.431 | 0.271 | 0.166 | 0.098 | 0.135 | - | - | - |
| - | - | - | 0.389 | 0.543 | 0.580 | 0.453 | 0.228 | 0.364 | 0.408 | 0.188 | 0.155 | 0.107 | 0.317 | 0.481 | - |
| 0.022 | 0.326 | 0.103 | 0.427 | 0.538 | 0.564 | 0.525 | 0.380 | 0.340 | 0.426 | 0.396 | 0.362 | 0.093 | - | 0.503 | - |




TES thermal conductance was estimated from the power flowing through the bath by biasing the TESs at a fixed working point and varying the bath temperature. The critical temperature of the TESs was another important free parameter.

TES thermal conductance map [pW/K]

| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 224.3 | 217.2 | 258.6 | 211.1 | 206.9 | 192.5 | 196.6 | 234.9 | 236.3 | 249.9 | 244.5 | 258.8 | 260.8 | - | - | - |
| 201.6 | 193.3 | 198.0 | 163.0 | 174.8 | 156.5 | 167.1 | 174.6 | 171.2 | 196.7 | 202.6 | 195.7 | 189.8 | - | - | - |
| - | - | - | 192.3 | 215.0 | 209.6 | 218.6 | 212.5 | 179.0 | 172.2 | 159.4 | 146.9 | 168.6 | 171.5 | 165.5 | - |
| 227.6 | 156.1 | 196.1 | - | 166.7 | 166.0 | 159.8 | 171.4 | 157.3 | 185.6 | - | 171.7 | 126.6 | - | 160.6 | - |

| | |
|---|---|
| <G>≅200 pW/K | $\sigma_G$≅30 pW/K |
| <$T_c$>≅94 mK | $\sigma_T$≅0.8 mK |

$P(T_{bath}) = \frac{G}{n\, T_c^{n-1}}(T_c^n - T_{bath}^n)$

HOLMES data taking started at the end of 2023. During the 1st run the parameters of the EC spectral features were estimated thanks to an external calibration source.

The 2nd run started in February 2024. This physics run will lead to a low-dose $m_\nu$ assessment by the end of the 2024.