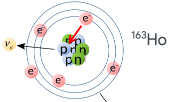
HOLMES , an experiment for measuring the neutrino mass

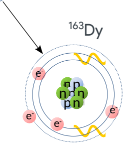
Elena Ferri

INFN of Milano-Bicocca
on behalf of HOLMES collaboration

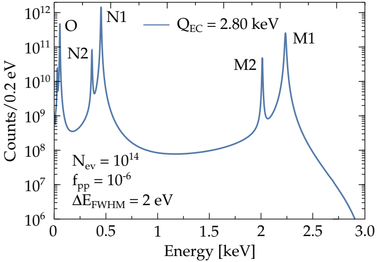
^{163}Ho Electron Capture for measuring the neutrino mass

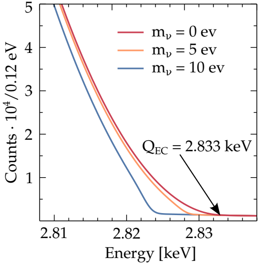
$$^{163}\mathrm{Ho} + e^- \rightarrow {}^{163}\mathrm{Dy}^* + \nu_e(E_c) \quad \text{electron capture from shell} \geqslant \mathrm{M1}$$





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

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

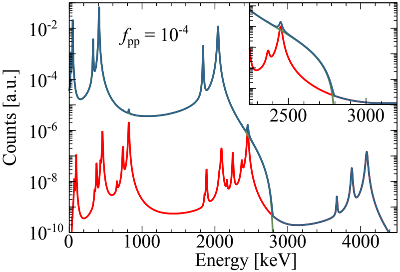
HOLMES

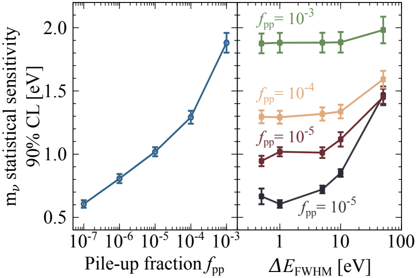
Neutrino mass determination with a sensitivity as low as ≈ 1 eV

- Microcalorimeters based on Transition Edge Sensors with ^{163}Ho implanted Au absorber
- Pixel activity of $A_{EC} \sim 300$ Bq/det
- Energy resolution: $O(\mathrm{eV})$
- Time resolution: $\tau_{res} \sim 3\ \mu s$ ($\tau_{rise} = 10 - 20\ \mu s$);
- 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





Ion implanter

Ion implanter designed to embed Ho inside the detectors' absorbers and to perform a mass separation of the ^{163}Ho from the other contaminants.

- extraction voltage 30-50 kV $\rightarrow$ 10-100 nm implant depth
- ^{163}Ho/^{166m}Ho separation better than 10^5

Main components:

- Ar penning sputter ion source
- magnetic dipole mass analyzer ($B_{max} = 1$ T)
- faraday cup and slit
- target chamber for Au co-evaporation

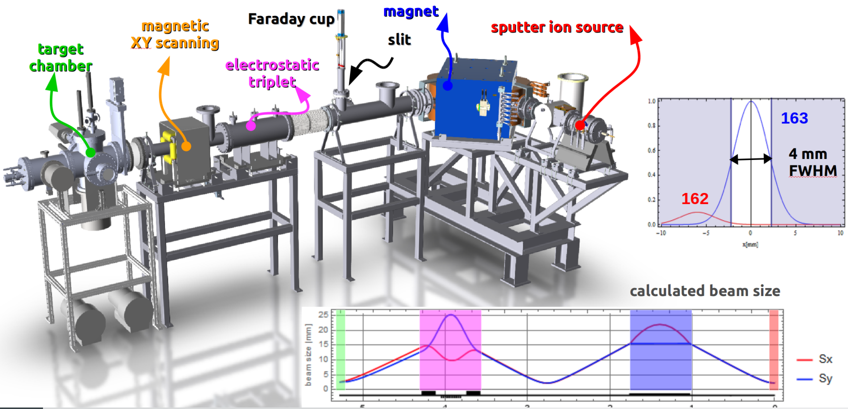
Au co-evaporation:

- to fully encapsulate the source
- to compensate the saturation of the ^{163}Ho concentration in the absorber
- to avoid oxidation
- heat capacity

Target chamber:

- 4 COMIC microwave sources
- 4 Ar beams hit on 4 Au targets

$\rightarrow$ 4 in order to increase the deposition rate and uniformity

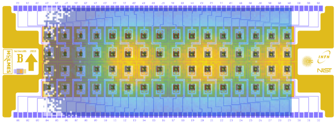


Isotope embedding @INFN-Genova

- Focusing stage and co-deposition chamber still to be integrated in the system
- produced an ad hoc holder to implant just after the slit
- sputter target with ^{nat}Ho used to evaluate extraction efficiency from source: $\approx 0.2\%$ (preliminary)
- separation at the slit 163Ho from 165Ho and 166mHo (in our solution: 163Ho/165Ho/166mHo = 60/40/0.1) evaluated with simulations:
  - 163/165Ho separated by 15 mm
  - 163/166mHo separated by 22 mm

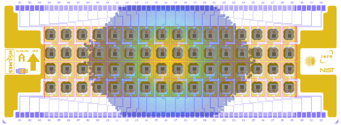
Multi-spots

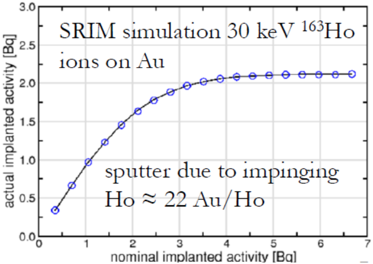
- integrated current to achieve 2 Bq/det peak activity (neglecting sputter)
- 3 spots of implantation to test uniformity of activity

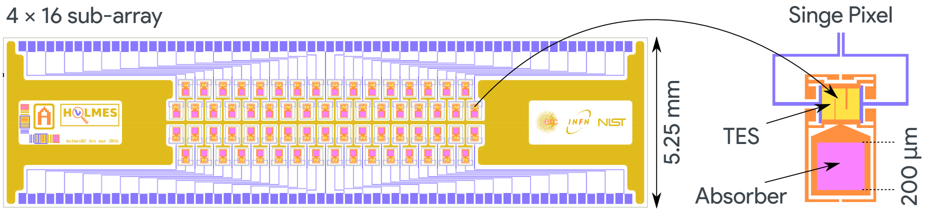


Single spot

- integrated current to achieve 4 Bq/det peak activity (neglecting sputter)
- evaluation of 163Ho activity on TES
- beam profile





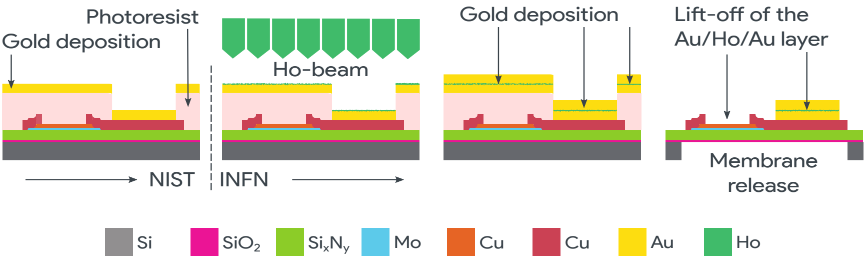


- Mo/Cu TES coupled to Gold absorbers where ^{163}Ho is ion-implanted
- 2 µm Gold thickness for full e/γ absorption
- Side-car design to avoid TES proximitation effect
- Thermal conductance G engineering for τ_{decay} control
- 4 $\times$ 16 linear sub-array designed for high implant efficiency and low parasitic L
- Optimized design for high speed and high resolution:

$$\text{Specs @ } 2.8\,\text{keV} : \Delta E_{FWHM} \simeq 3-4\,\text{eV}\,,\ \tau_{rise} \simeq 10\,\mu\text{s}\,,\ \tau_{decay} \simeq 100\,\mu\text{s}$$

HOLMES: detectors fabrication process

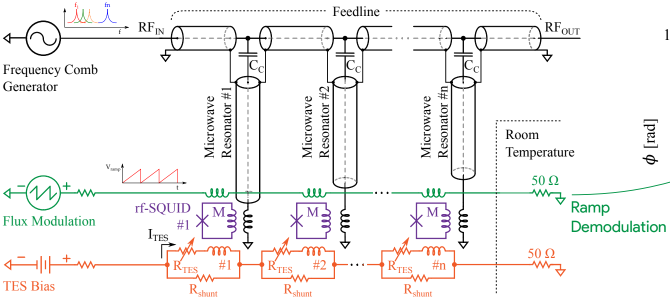
^{163}Ho isotopes embedded in metallic absorbers (through ion-implantation)

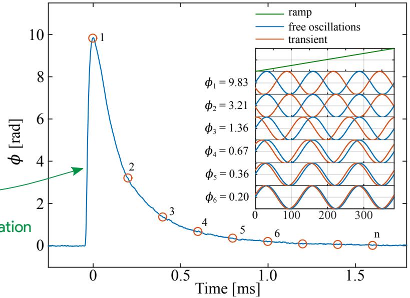


- Fabrication in two steps:
  - NIST: TES fabrication with 1 μm Au absorber
  - INFN: ^{163}Ho implantation, final deposition of 1 μm Au and SiN membrane release

Microwave rf-SQUID multiplexing

HOLMES TESs readout is based on microwave rf-SQUID multiplexing





Appl. Phys. Lett., 85:2107, 2004

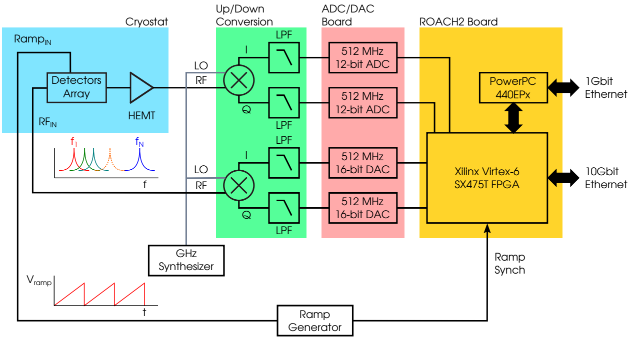
- voltage bias TES $\Delta T = \Delta I$
- Change in TES current $\Rightarrow$ change in the input flux to the rf-SQUID
- The rf-SQUID transduces a change in input flux into a variation of resonant frequency and phase
- Ramp modulation for linearization $\Delta f_r = \Delta \phi$

rf-Microwave readout with flux rump modulation

- $f_{ramp} = f_{samp}$ (= 500 kHz)
- allows to readout many detectors with one common RF line and HEMT amplifier: 1 HEMT (4-8 GHz) = 256 TESs

JINST 14 P10035 (2019)

HOLMES DAQ with the ROACH2



- Software Defined Radio with the open system ROACH2 (Casper collaboration)
- ADC BW 550 MHz
- real time pulse reconstruction

  → at the moment readout available for 64 channels

Multiplexing factor proportional to the target rise time

- $n_{TES} \approx 3.4 \cdot \tau_{rise}$
- requiring $\tau_{rise} = 10\mu s$

Event reconstruction

First level data reduction

Evaluation of pulse information

Energy estimation

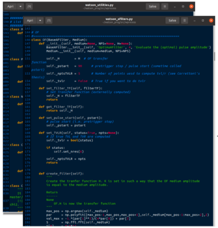
- Optimum filter
- Arrival time correction
- Gain drift correction
- Energy calibration

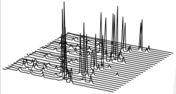
Second level data reduction

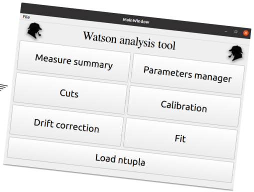
- Robust analysis is mandatory for achieving the expected microcalorimeter intrinsic energy resolution.
- The data from each pixel need to be processed separately.

Watson toolkit

- Software for low temperature detector data analysis
- Object oriented programming. Written in python (numpy and scipy)
- Fast, easy to read, easy to fix code
- GUI with QT5 for handy day to day operations
- Data are stored in hdf5 (hierarchical, filesystem-like data format)







Fabrication of the first HOLMES detectors

First ^{163}Ho implant on TES array

- sputter target loaded with 12 MBq of ^{163}Ho (= 2.6 x10^{18} ^{163}Ho atoms)
- ^{163}Ho beam current stable at 5 nA for 3 hours
- integrated current corresponds to $\approx$ 3x10^{14} ^{163}Ho ions

sputter target: Zr/Bi (98%/2%) sintered matrix on Mo + $Ho(NO_3)_3$ dripping

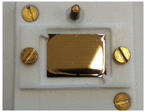
Lift-off

Removal of the resist mask (7 μm thickness)

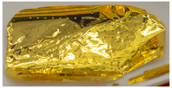
- sample in acetone at 50°C for 2 h

$\rightarrow$ the Au deposited remains only on the absorber:

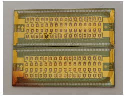
- $\rightarrow$ minimal crowning



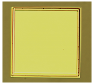
Au removed with the lift-off



Arrays after the lift-off



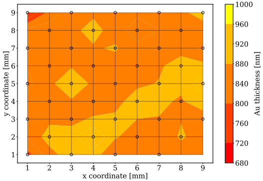
Zoom of a single absorber



Au deposition

1 μm of Au deposited

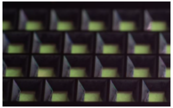
- with Ion beam sputter system
- $\approx$ 27 hours for 1 μm
- gold thickness uniformity $\rightarrow \sigma_t / t \sim 4\%$

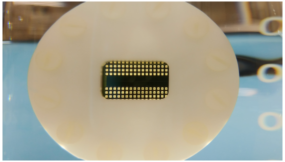


Membrane release

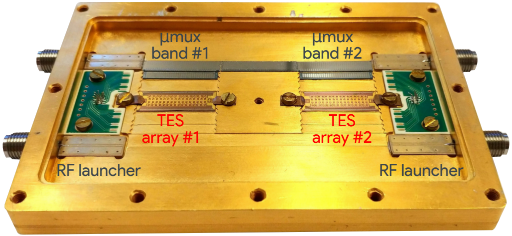
Anisotropic wet etching

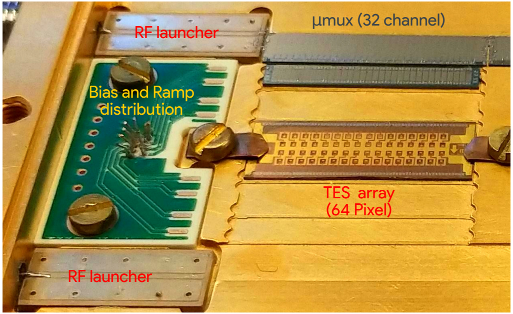
- 5 h in KOH bath at 80°C





Experimental setup & Runs





An holder can host 2 detectors array, for a total of 128 detectors with their readout and bias chips.

At present we can readout 64 detectors at the same time

RUN1 with ^{55}Fe calibration source

- Check the result of the the implantation process
  - $\rightarrow$ activity map of the chip with single spot
- Assess the effect of Holmium on the detector response
- Acquire **the first HOLMIUM spectrum**

RUN2 with fluorescence calibration source

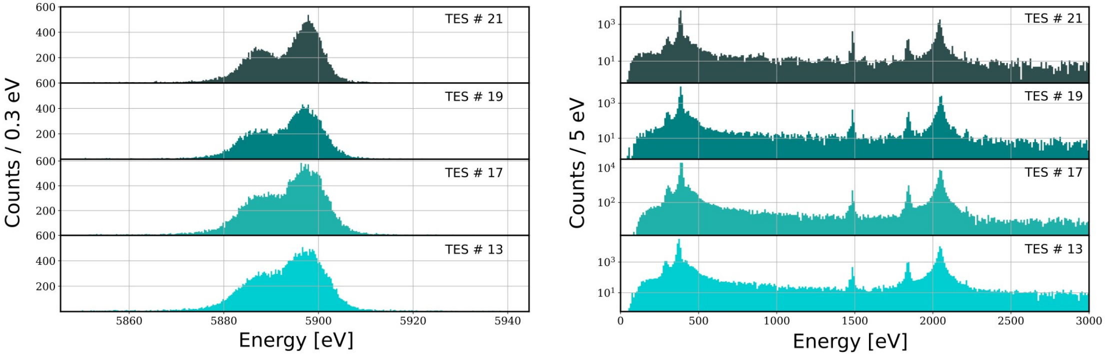
- Describe the main peaks of the Ho spectrum

RUN3 without calibration source

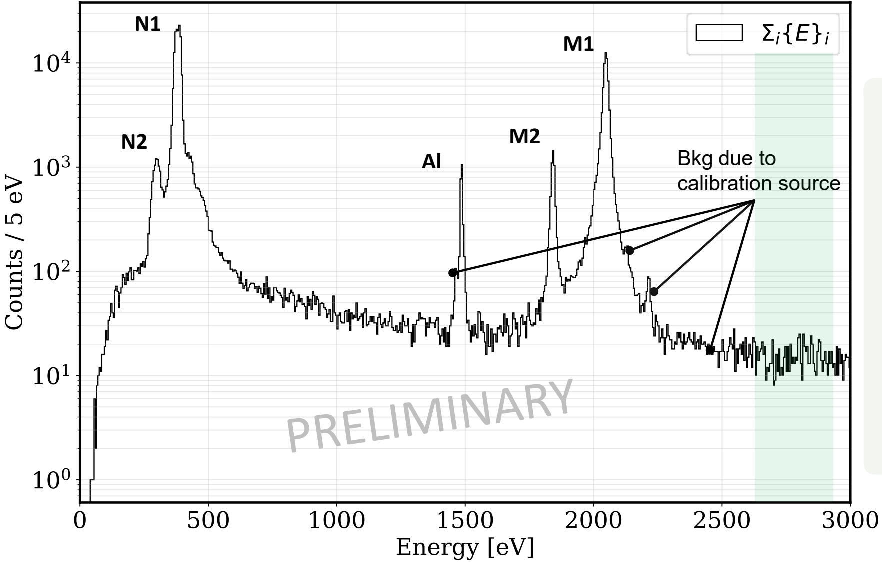
- Activity map on the second chip
- First physics run!

Run 1 results: first Ho spectrum on four selected pixel

TES	ΔE_{FWHM} at 6 kev [eV]	^{163}Ho activity [Bq]
13	8.36 ± 0.09	0.97
17	7.78 ± 0.08	0.55
19	7.12 ± 0.08	0.21
21	5.76 ± 0.07	0.11

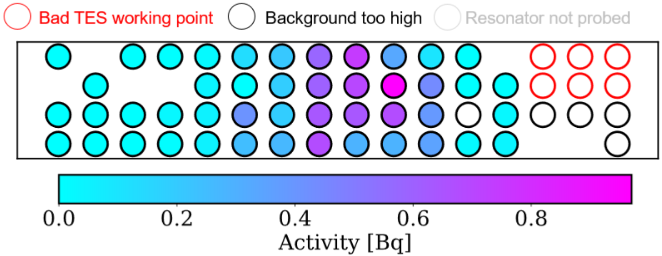


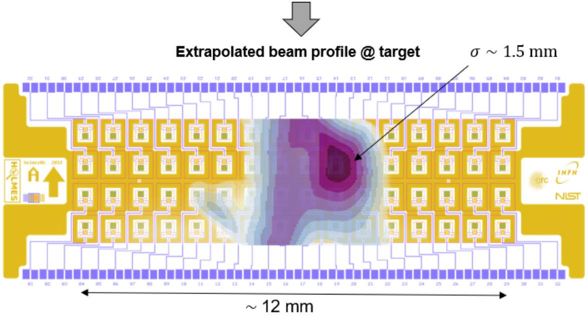
Run1 results: first Ho spectrum on four selected pixels

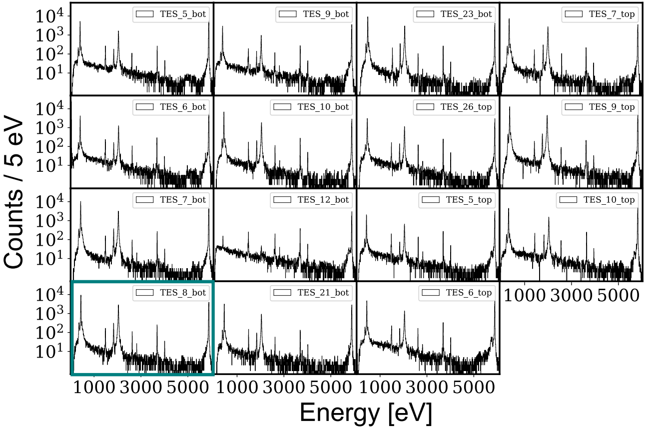


- Sum over 4 pixels
- acquisition time 48.5 h
- high background due to ^{55}Fe calibration source
- ΔE_{FWHM} 6 − 8 eV at 6 keV
- $< A > \approx$ 0.5 Bq (0.1 - 1 Bq)
- Expected background due to cosmic rays and natural radioactivity in the ROI lower than 0.01 counts / eV (From previous measurement campaign and MC simulations)

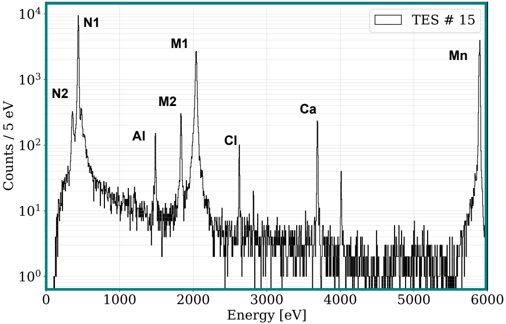
Run1: implanted activity results





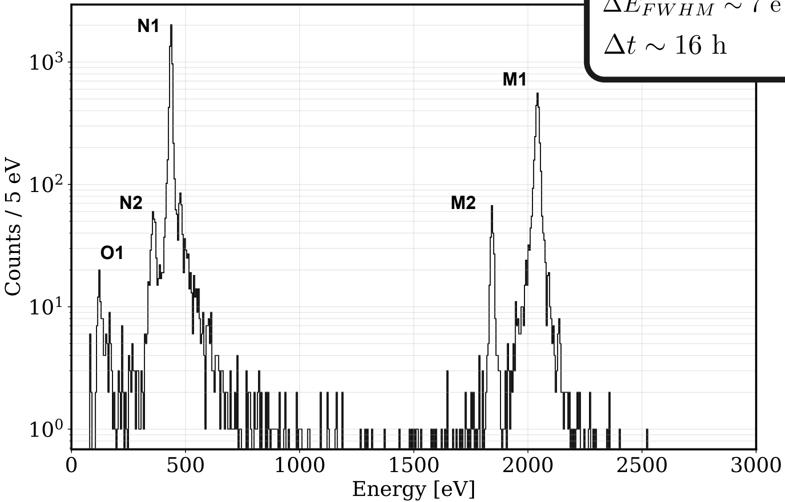


- Around 60 spectra were recorded, "cleaned" and calibrated
- Idea: model each ^{163}Ho peak with an asymmetric Lorentzian function
- Analysis in progress



No calibration source

$\Delta E_{FWHM} \sim 7$ eV
$\Delta t \sim 16$ h



Upcoming plans

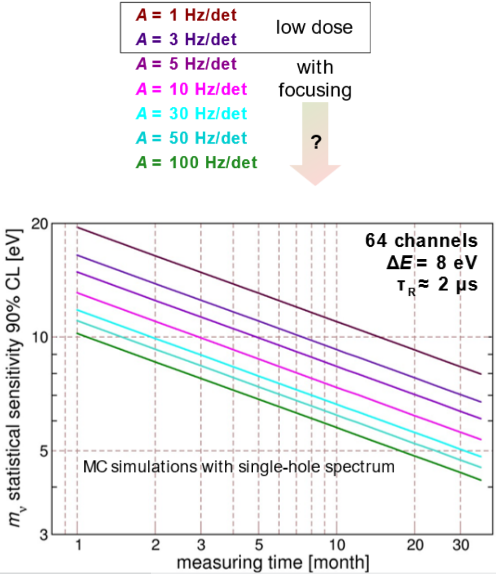
Next ion implantation:

- implantation of a new array with uniform and maximum achievable activity (end of 2023)
- integration of focusing stage & co-deposition chamber (Nov 2023 ≈ 6 months)

  → implantation with higher activities

Next measurements:

- long measurement and **first limit on the neutrino mass around 10 eV** with the new array with uniform and maximum achievable activity



Summery and acknowledgement

- ^{163}Ho embedded inside the HOLMES TES absorber
- first HOLMES ^{163}Ho spectrum measured
- new physics measurements coming in the next few months

Univ. & INFN Milano-Bicocca

M. Borghesi
G. Ceruti
M. Faverzani
E. Ferri
A. Giachero
D. Labranca
R. Moretti
A. Nucciotti
L. Origo
G. Pessina
S. Ragazzi

INFN & Univ. Genova

A. Bevilacqua
M. De Gerone
M. Fedkevych
G. Gallucci
F. Gatti
P. Manfrinetti
L. Parodi
F. Siccardi

INFN Roma

M. Lusignoli

INFN LNGS

M. Balata
S. Nisi

NIST (Boulder, CO)

B. Alpert
D. Becker
D. Bennet
J. Fowler
J. Gard
G. Hilton
J. Mates
C. Reintsema
D. Schmidt
D. Swetz
J. Ullom
L. Vale

PSI

N. Cerboni
R. Dressler
E. Maugeri
D. Shumann

ILL

U. Koester

The Milano and Genova group