The first neutrino mass measurement of HOLMES

Matteo Borghesi

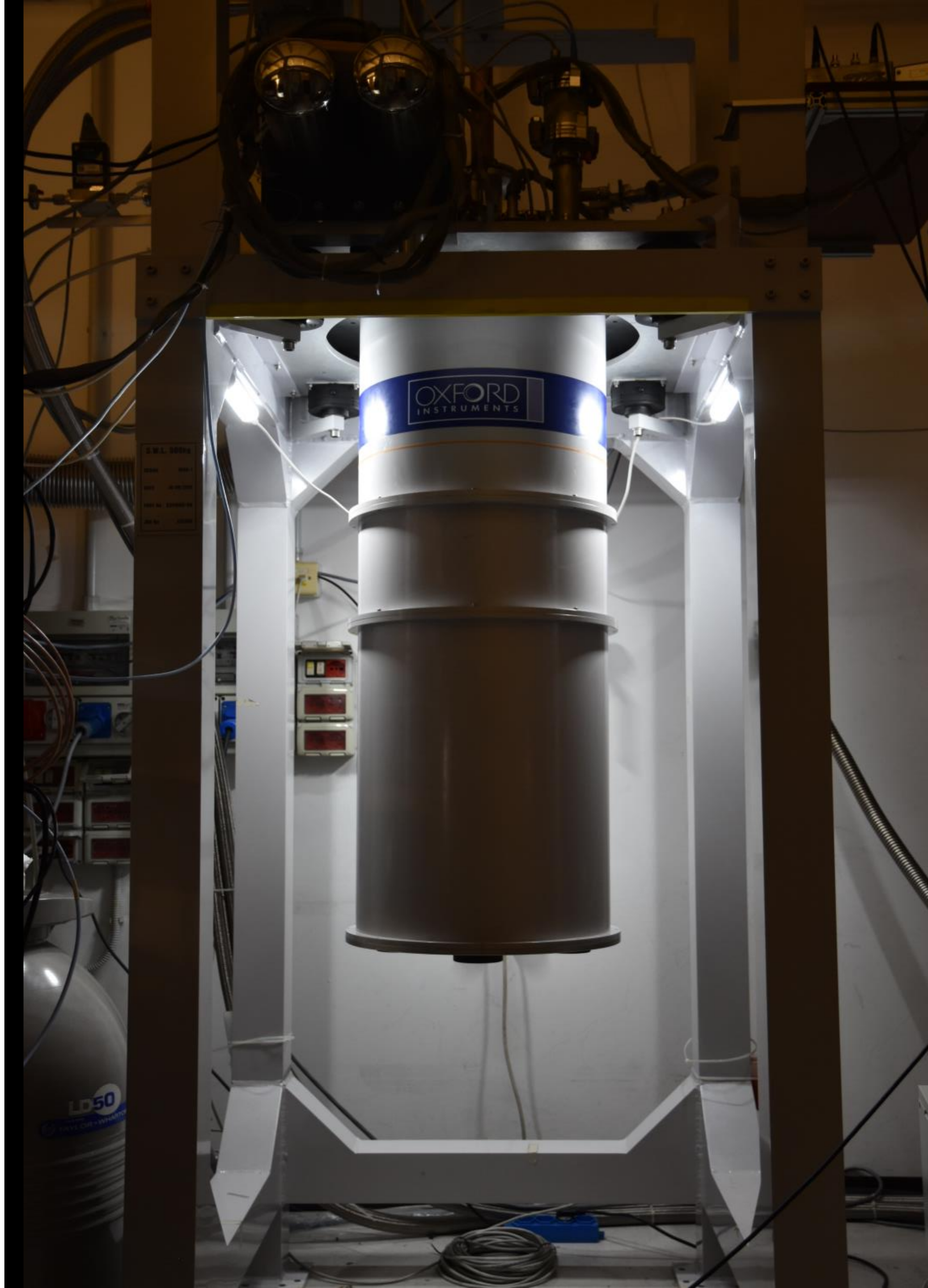
Università & INFN Milano-Bicocca

On behalf of the HOLMES collaboration

INFN Istituto Nazionale di Fisica Nucleare

TAUP VIENNA 2023

UNIVERSITA' DEGLI STUDI DI MILANO BICOCCA



Calorimetric approach: a “new” way to probe sub-eV neutrino mass scale?

- HOLMES is an ambitious project that aims to verify the feasibility of the calorimetric approach to the neutrino mass determination.

- **Pro:** Most of the unwanted source related effects are avoided.

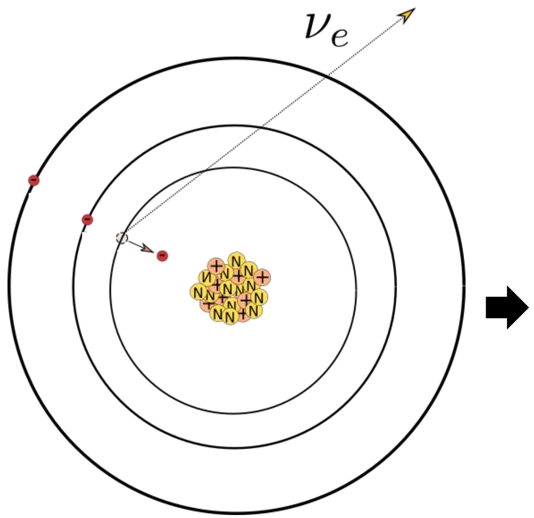
- A good isotope should have:

  Low Q value
  Large portion of events near the ROI → High number of events in the ROI
  Short half life to reduce the experimental challenges

Ideal calorimetric experiment

- The radioactive source is embedded in the detector(s)
- Only the neutrino energy escape detection.
- Important limits on the source intensity (statistics) that can be accumulated
- Activity also limited by the relation between energy resolution and detector size.

- No convincing isotopes alternatives to $^{3}\mathrm{H}$ and $^{163}\mathrm{Ho}$ (yet).

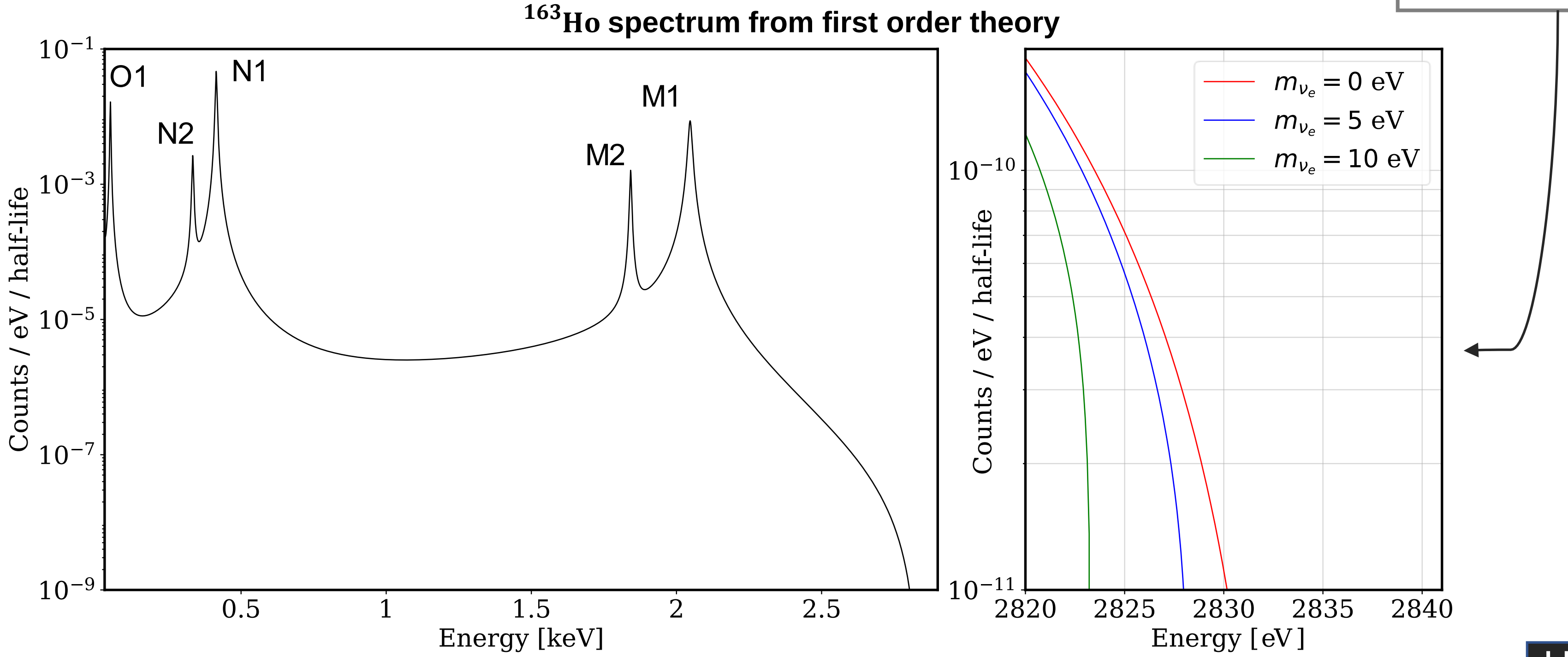


Isotope	Q value [eV]	Half life [y]	Decay	B.R	Experiments
$^{3}\mathrm{H}$	18592.01(7)	12	β^-	1	Simpson’s
$^{187}\mathrm{Re}$	2470.9(13)	4.3×10^{10}	β^-	1	MANU,MIBETA
$^{163}\mathrm{Ho}$	2833(30)	4570	EC	1	Holmes,ECHo
$^{135}\mathrm{Cs}$	440	8.0×10^{11}	?	1.6×10^{-6}	
$^{115}\mathrm{In}$	155	4.3×10^{20}	?	1.1×10^{-6}	

EC decay of ^{163}Ho to measure the neutrino mass

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

$$\frac{d\,\lambda_{EC}}{dE_C} = \text{N}(Q - E_C)\sqrt{\left[(\boldsymbol{Q} - \boldsymbol{E_C})^2 - \boldsymbol{m_{\nu_e}}^2\right]} \times \sum_H \frac{\varphi_H^2(0)(\Gamma_H/2\pi)}{\left[(E_C - E_H)^2 + \Gamma_H{}^2/4\right]}$$



$E_c = nuclear\ recoil + \text{inner bremmstrahlung} + \text{X rays} + \text{auger electrons}$

- High performing detectors are needed, in terms of energy resolution ΔE and time resolution τ_R: **LTD**
- Holmes has adopted a **high-risk/high-gain approach**.

Holmes in a nutshell

- Transition Edge Sensors (TES)
  $\Delta E \approx 1\ eV,\ \ \tau_R < 3\ \mu s$
- Microwave multiplexing readout!
- Target activity (A) of 300 Bq/det
- 6×10^5nuclei of ^{163}Ho
- 3×10^{13} events recorded in three years
- m_{ν_e} sensitivity $O(1)$ eV

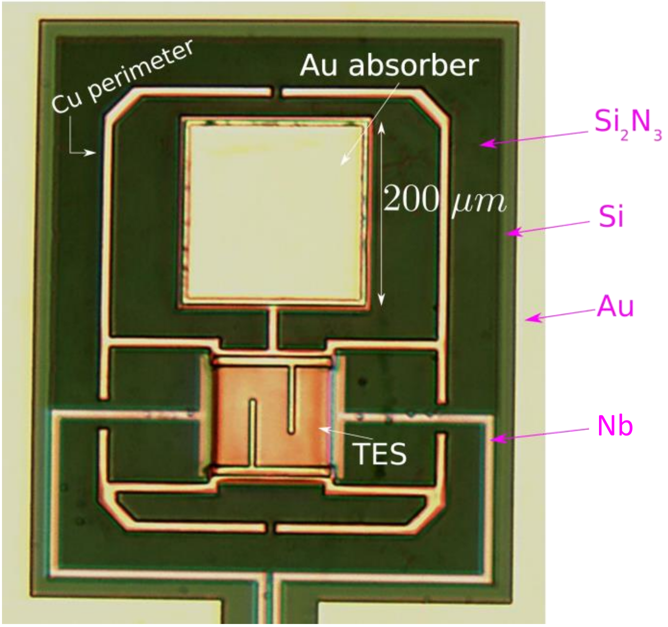
*

HOLMES in 2023

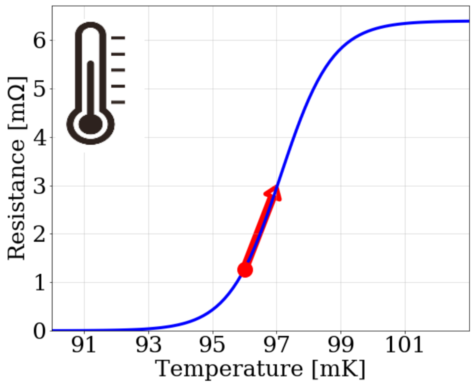
- Final test on the ion implanter
- Optimization of the analysis software
- DAQ setup for the readout of 64 multiplexed detectors
- Holmium implantation
- **26/06/2023 first measurement with the implanted array**

HOLMES detectors

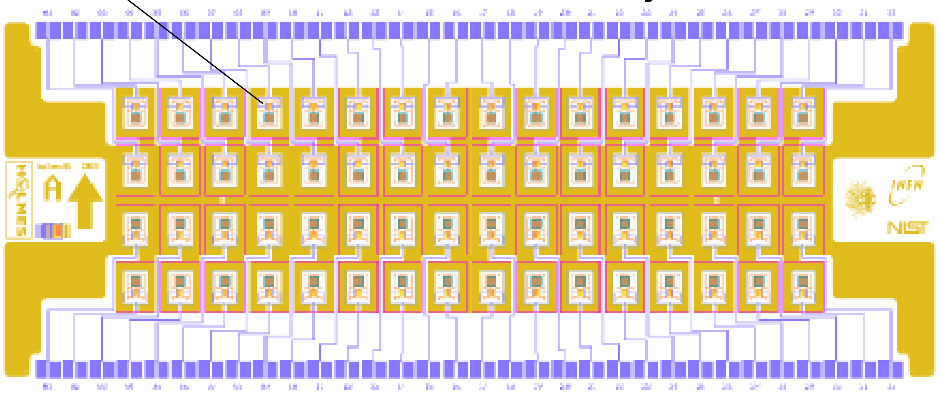
- A TES is a superconductor film operated in the narrow temperature region between the resistive and the superconducting state



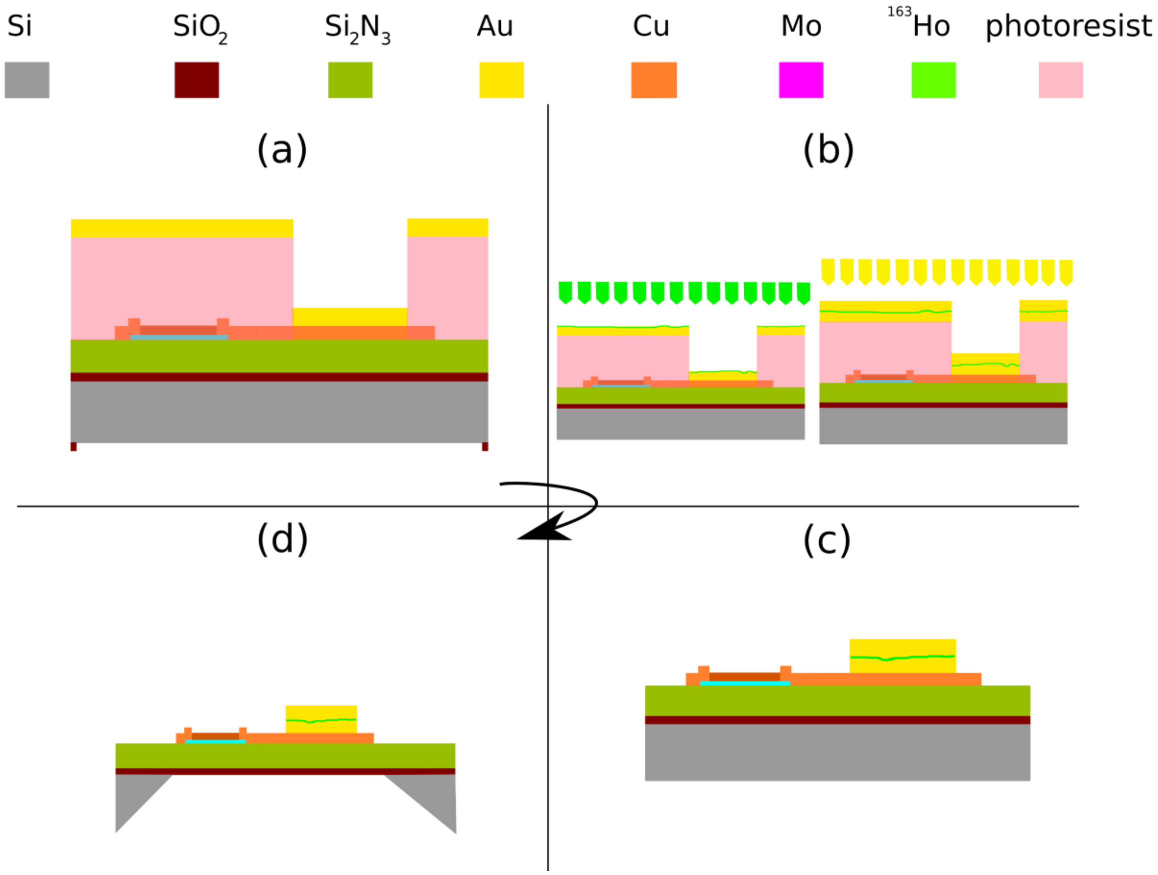
Very sensitive thermometer, able to detect a temperature variation of the order of a fraction of mK



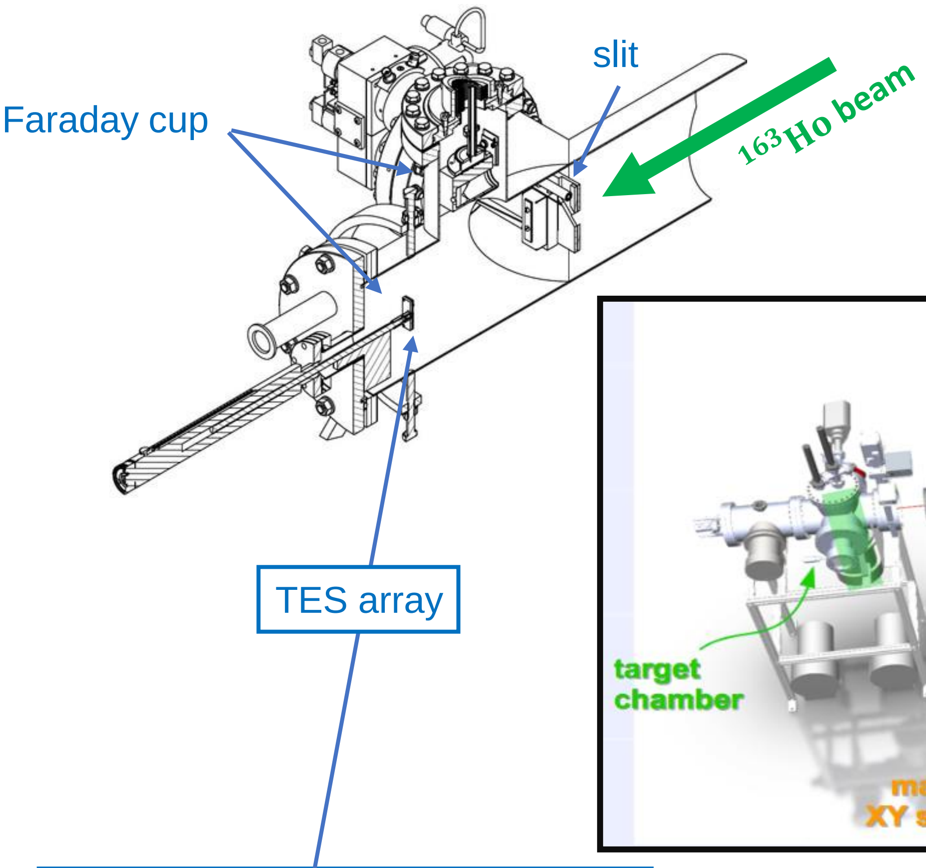
Holmes TES array

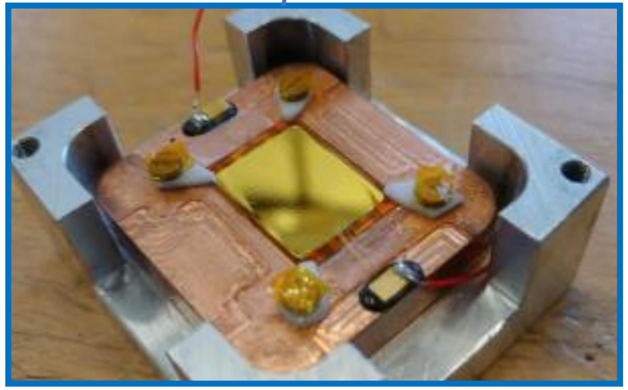


- The HOLMES detectors have to undergo different fabrication steps in order to have the ^{163}Ho implanted inside the gold absorbers.

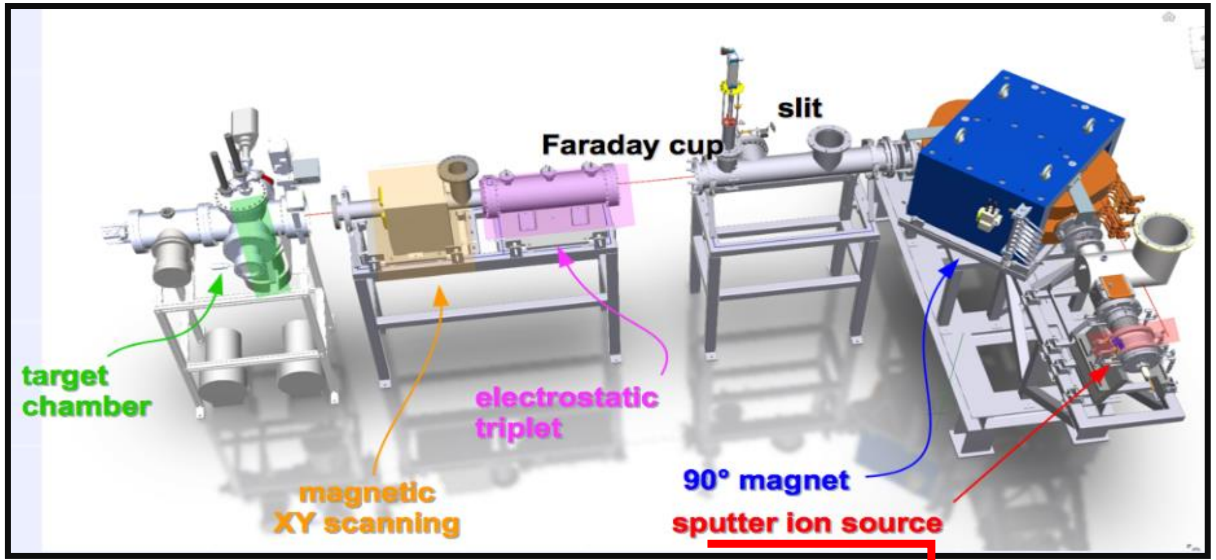


HOLMES TES detector fabrication: implant

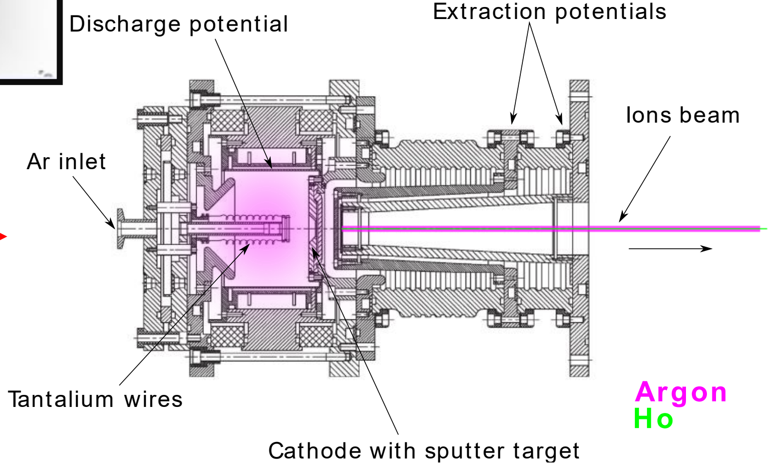




Custom ion implanter @ Genova

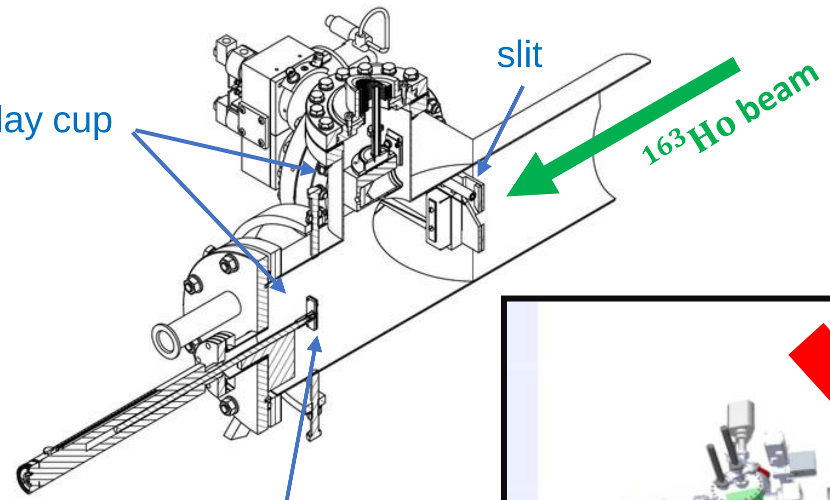


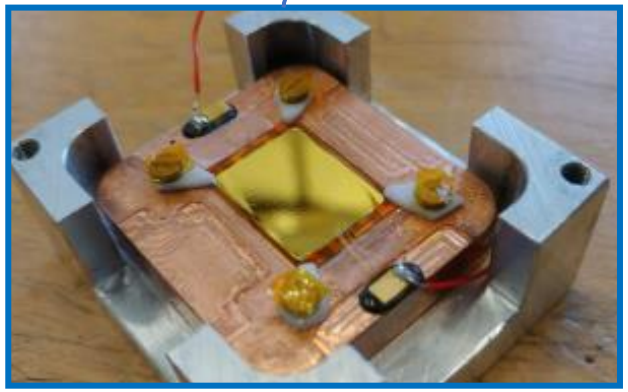
Sputter target: Zr/Bi sintered matrix on Mo + $Ho(NO_3)_3$ dripping



Double system to read out the beam current impinging on the TES array

HOLMES TES detector fabrication: implant





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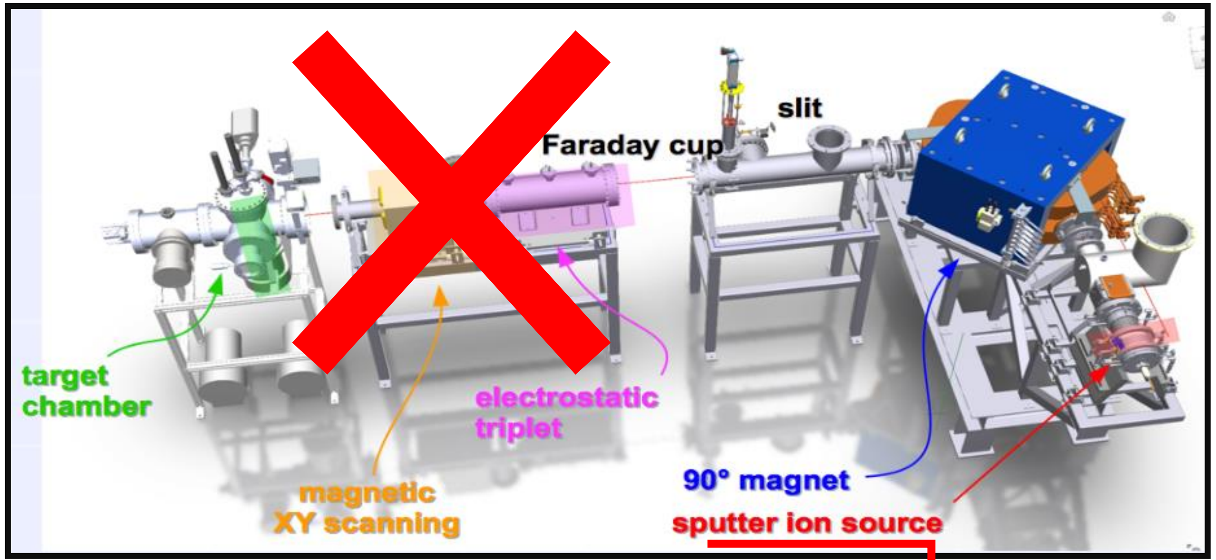

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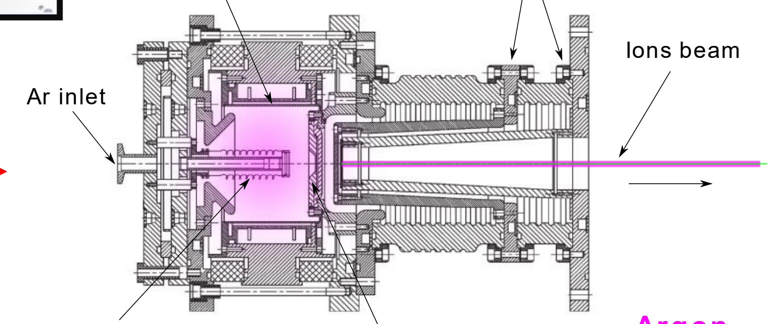
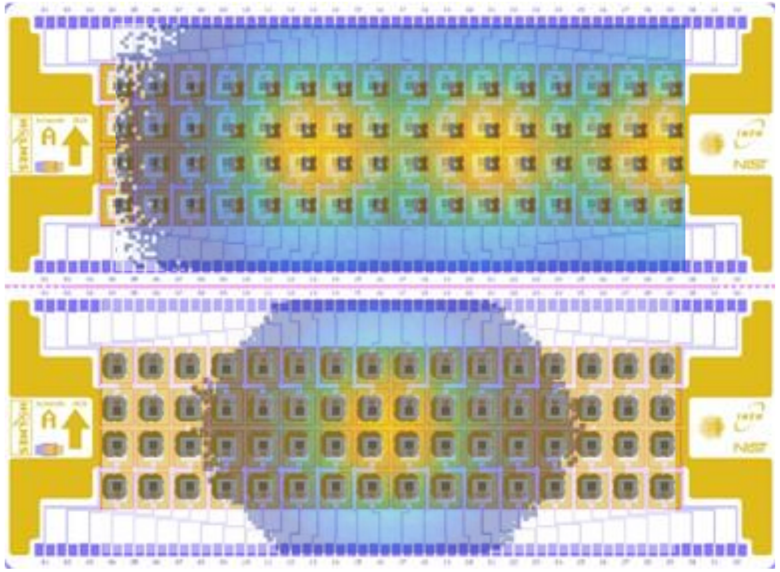


HOLMES TES detector fabrication: implant

Beam profile @ target from simulations

Chip2

Chip1



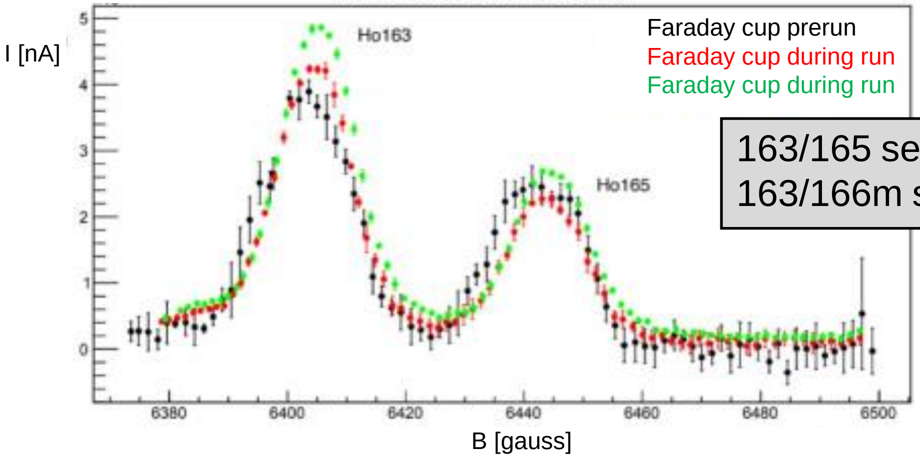
Goals:

- multi-spot (chip 2): uniformity
- single spot (chip 1): beam profile evaluation and assessment of the impact of ^{163}Ho activity on the detectors.

- Sputtered target loaded with 12 Mbq of ^{163}Ho (2.6×10^18 atoms)
- Extraction efficiency from ion source 0.2% (preliminary)
- In our solution ^{163}Ho/ ^{165}Ho/ ^{166m}Ho = 60 / 40 / 0.1

Target loading with ^{163}Ho

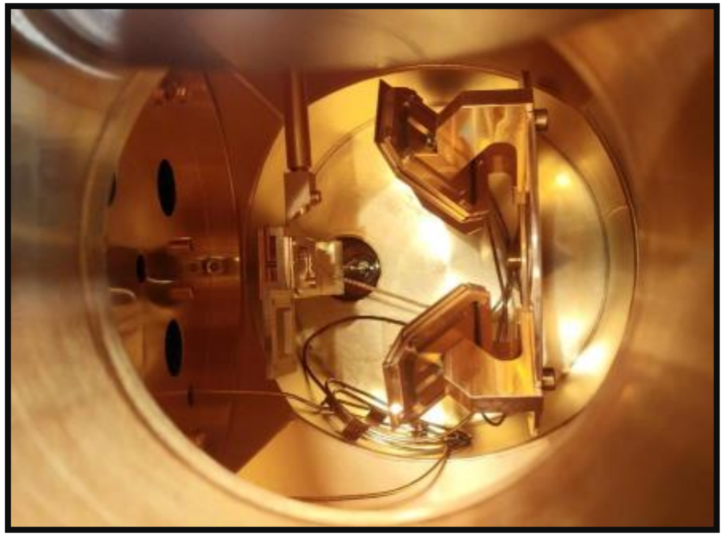
Scan of Ho peaks, 5mm slit opening

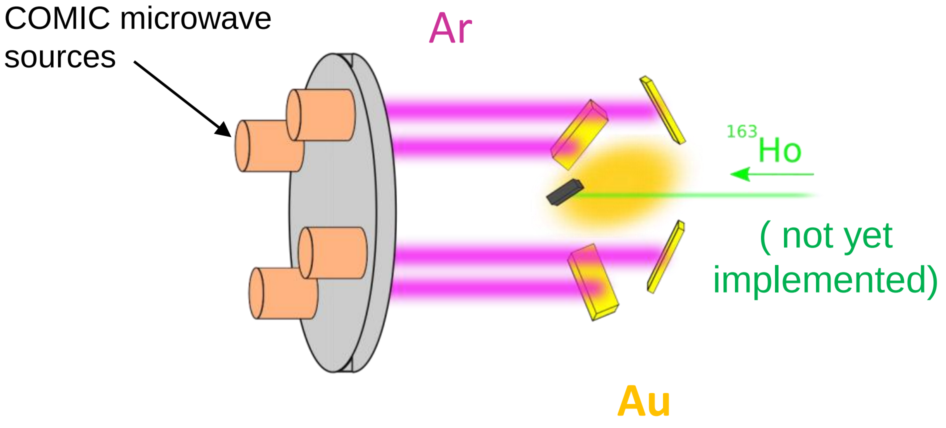


163/165 separated by 15 mm
163/166m separated by 22 mm

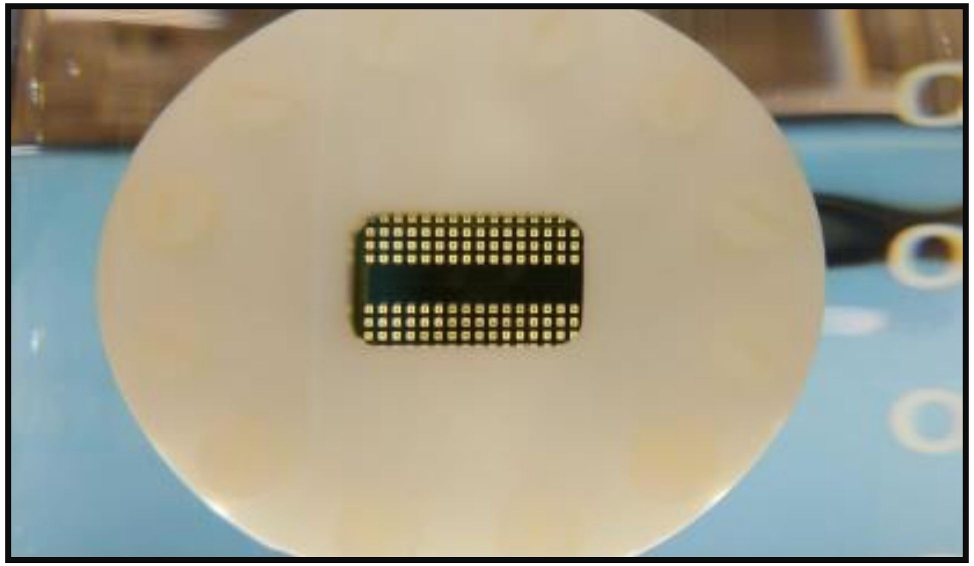
HOLMES TES detector fabrication: incapsulation & finalization

Target chamber @ Milano. Picture and schematic





Back of the TES arrays in KOH solution



- 1 um layer to fully encapsulate ^{163}Ho → probability to stop electron (photon) from Ho decay greater than 99.99% (99.73%)
- 27 hours to complete the process

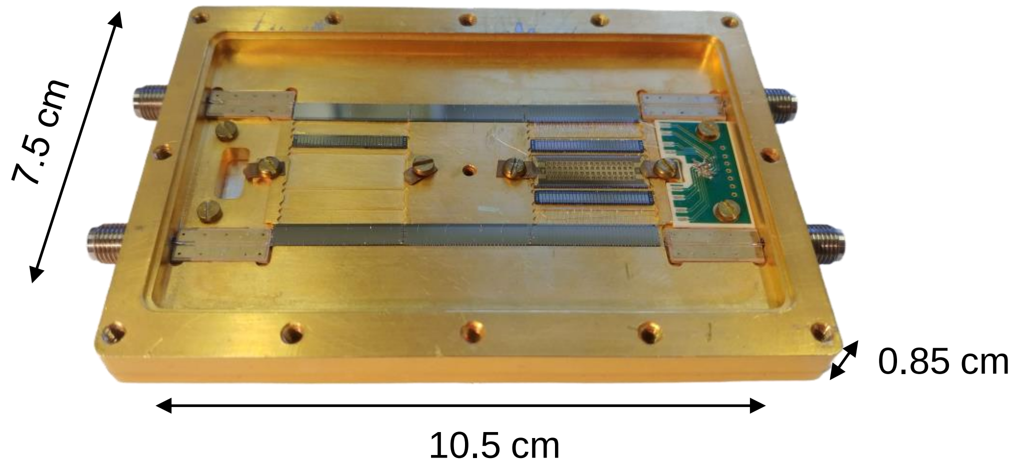
- Membrane release: 5 h silicon anisotropic etching (KOH bath at 80 °C)

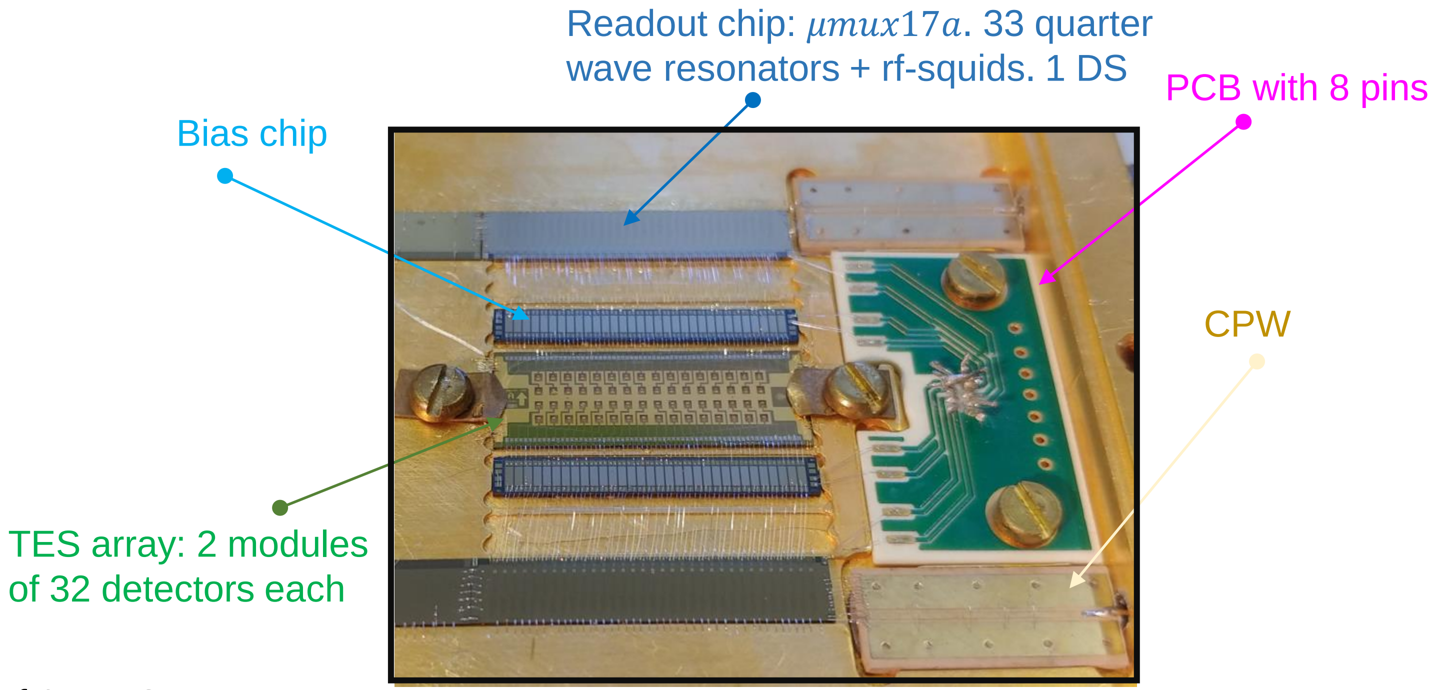
HOLMES TES detector fabrication: holder & general setup

- Each holder can host 2 detectors arrays (4×32 pixels), for a total of 128 detectors with their readout and bias chips.

- At present we can readout 64 detectors at the same time
  - Microwave multiplexing technique (multiplexing factor 256, sampling frequency 500 kHz)
  - ROACH2 boards
  - HEMT amplifier

Detectors holder



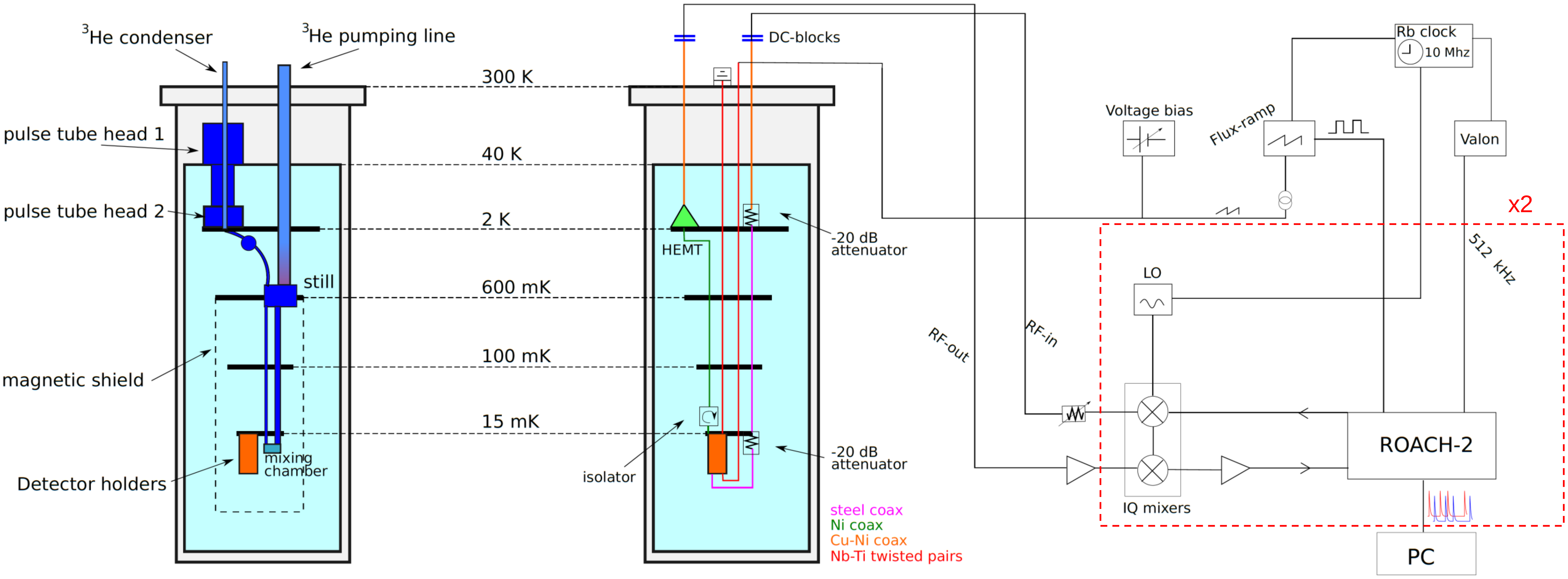


- ~ 350 Al wire bonding for electrical connection of 64 TESs

  ~ 20 Au wire bonding for TES chip thermalization

HOLMES TES detector fabrication: holder & general setup

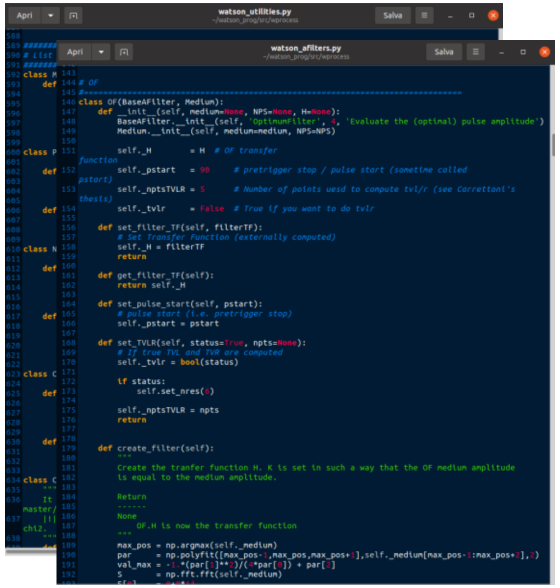
- $^3He/^4He$ diluition refrigerator (200 μW of cooling power @100 mK)

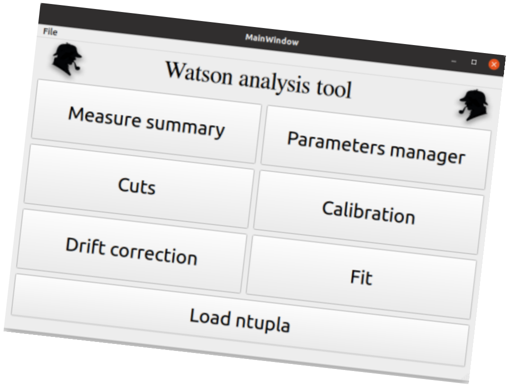


Analysis programs

Watson…

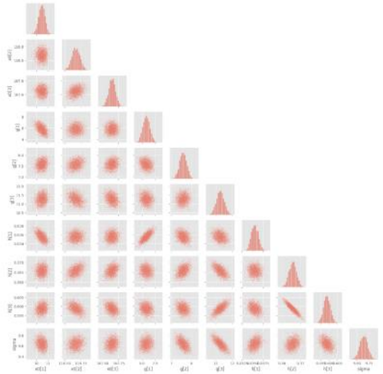
- Software for LTD data analysis
- Object oriented programming. Written in python (numpy and scipy), but still very fast!
- Easy to read, easy to fix code
- GUI with QT5 for handy day to day operations
- Data are stored in hdf5 (hierarchical, filesystem-like data format)
- Signal processing, data reduction and maximum likelihood fit (minuit)
- Machine learning algorithms for data reduction (clustering…) and pile-up discrimination (unsupervised learning with PCA)
- Reinforcement learning algorithms to speed up the calibration process.

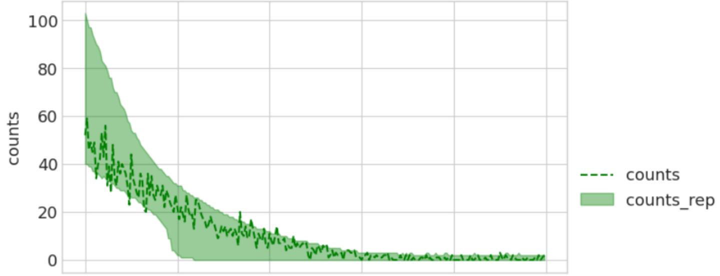


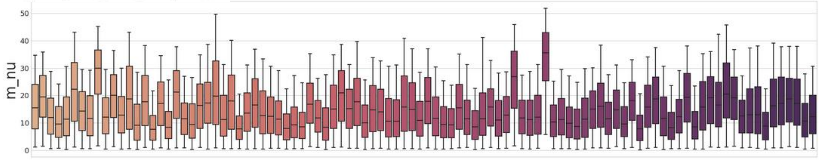


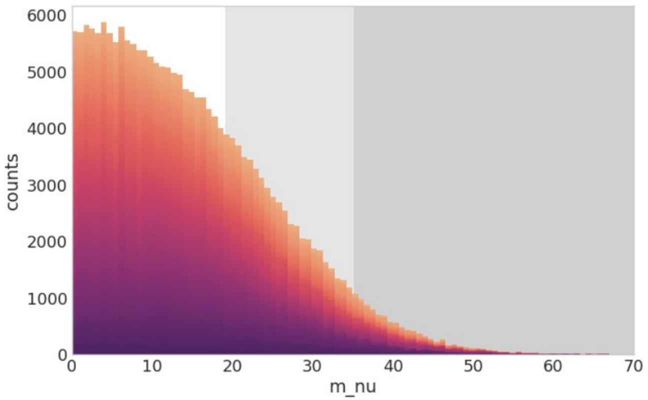
… and Baynes

- Bayesian data analysis with STAN
  - Hamiltonian MCMC
- Parameters estimation, prior predictive check…
- Sensitivity studies!

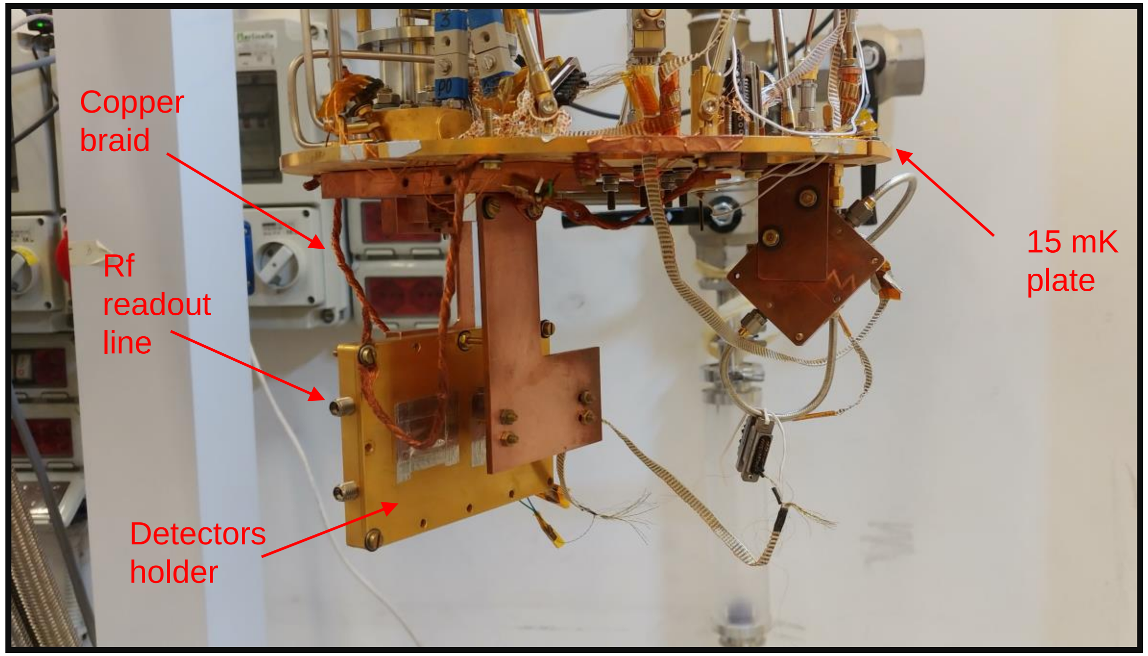




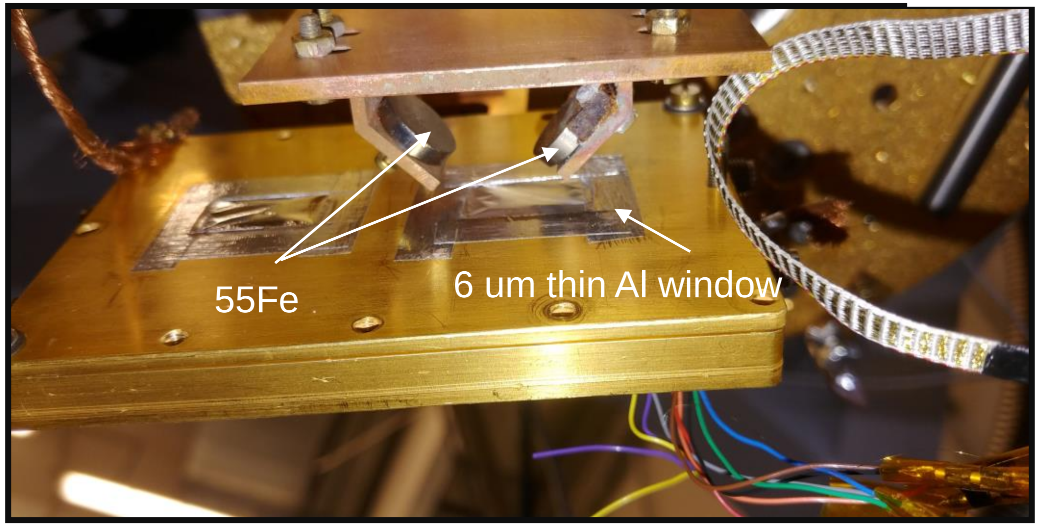




HOLMES TES detector fabrication: holder & general setup

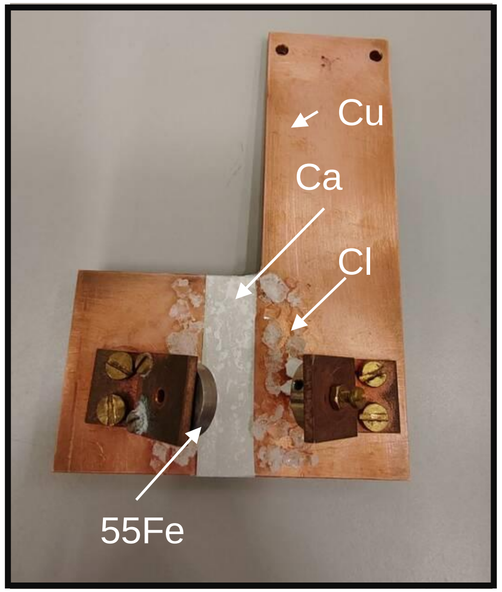


Run 1 setup

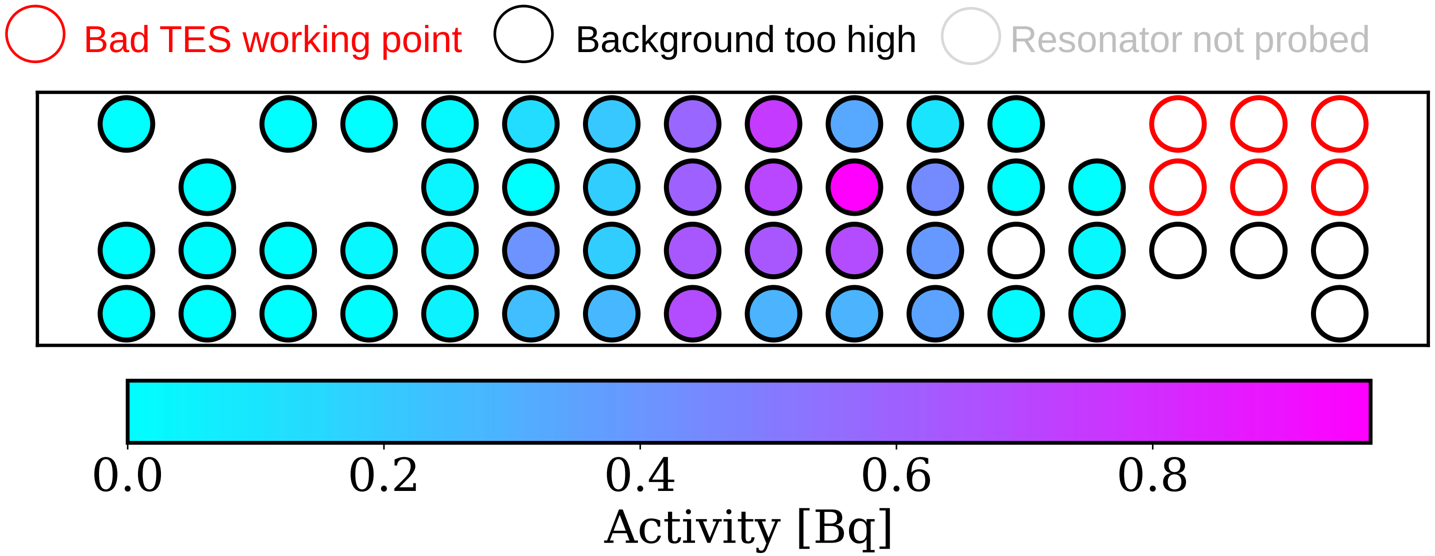


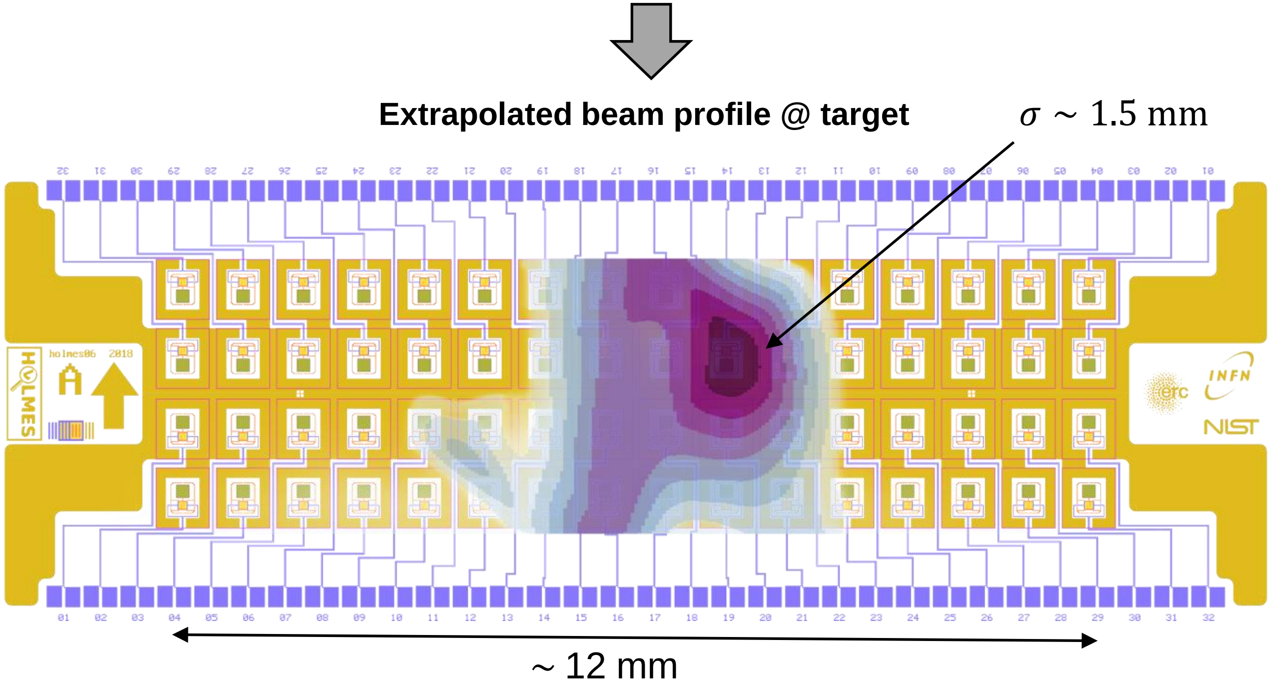
- **Run 1**: (16/06/23 -10/07/23) goals:
  ^{55}Fe calibration source
  - Check the result of the the implantation process
    - Activity map on the first chip
  - Assess the effect of Holmium on the detector response
  - Acquire the **first HOLMIUM spectrum**
- **Run 2**: (17/07/23 – 02/08/23) goals:
  Fluorescence calibration source
  - Describe the main peaks of the Ho spectrum
- **Run 3**: (End of august – tbd) goals:
  No calibration source
  - Activity map on the second chip
  - First physics run!

Run 2 calibration source



Run 1 results: implanted activity map



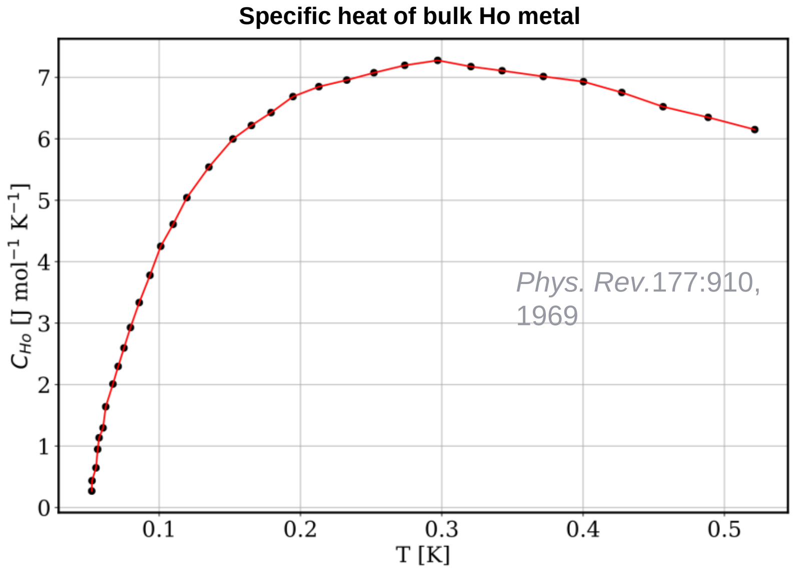


Run 1 results: impact of 163 Ho on TES response

- For a Low Temperature Detector (LTD), the energy resolution and the detector time response is proportional to the detector heat capacity.
- Total detector heat capacity without Ho $C = C_{abs} + C_{sensor}$

e.g. Holmes TES $C_{abs} = 0.55\ pJ/K, C_{sensor} = 0.25\ pJ/K \rightarrow C \sim 0.8\ pJ/K$

- Hyperfine interactions in rare-earth elements (Ho) causes a Schottky anomaly in the (C,T) plot.



- Total detector heat capacity with Ho $C = C_{abs,Au} + C_{sensor} + C_{abs,Ho}$

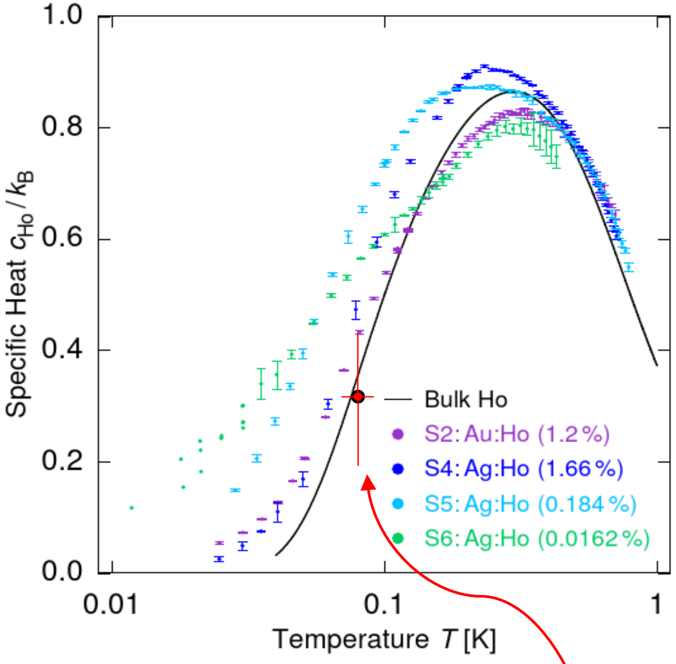
- $C_{abs,Ho}$ could depends on
  - Implantation process
  - Absorber material
  - The chemical species of the implanted ^{163}Ho

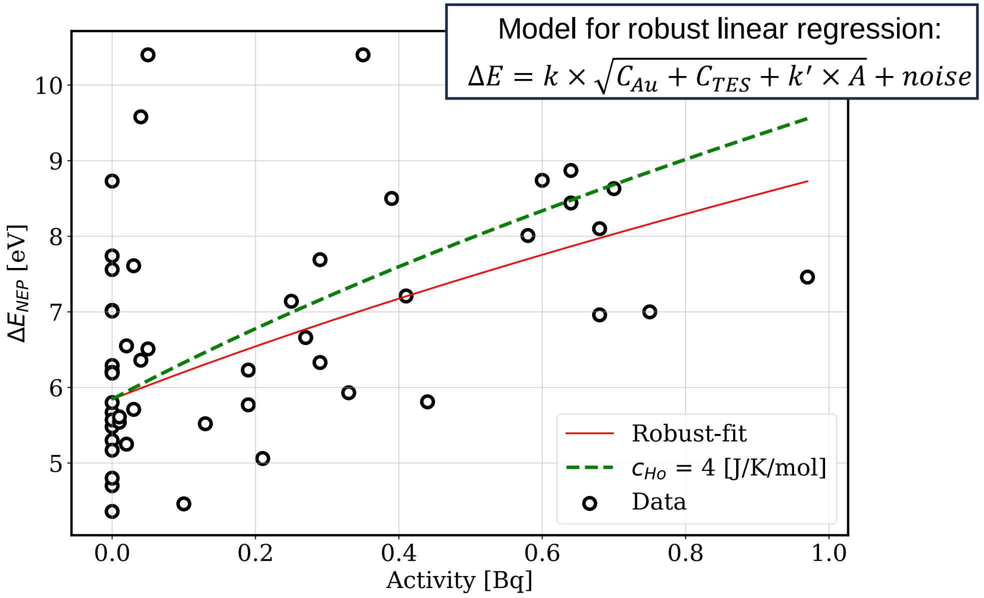
Needs to be assessed for our implantation setup.

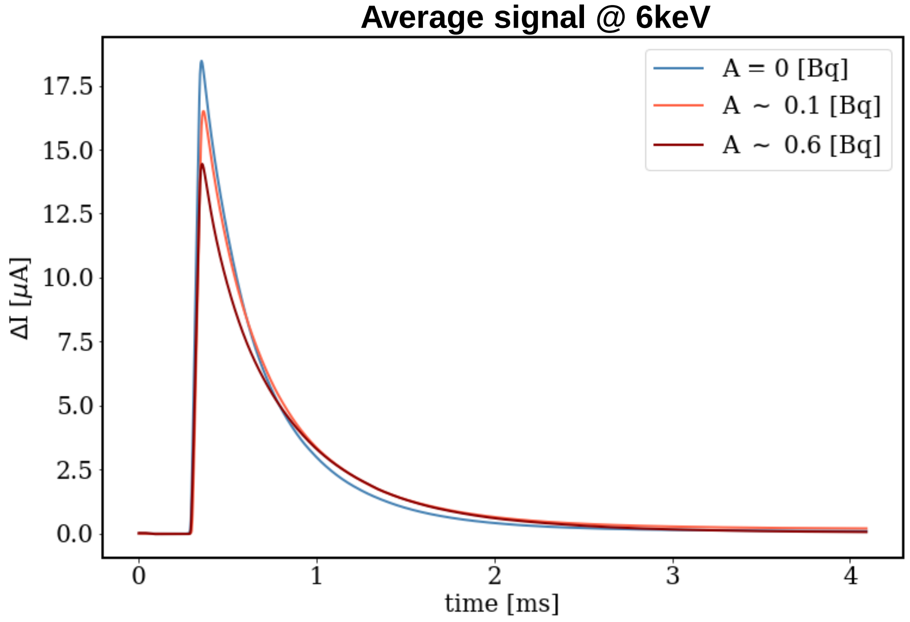
Run 1 results: impact of 163 Ho on TES response

- Bulk Ho ~ 3.6 J/K/mol (@90 mK)
- Data from ECHo

J. Low Temp. Phys. 202, 106-120 (2021)







- Holmes preliminary data (@90 ± 0.16 mK) :

$c_{HO} = 3 \pm 1$ (stat) ± 0.7 (sys) J/K/mol (from energy resolution)

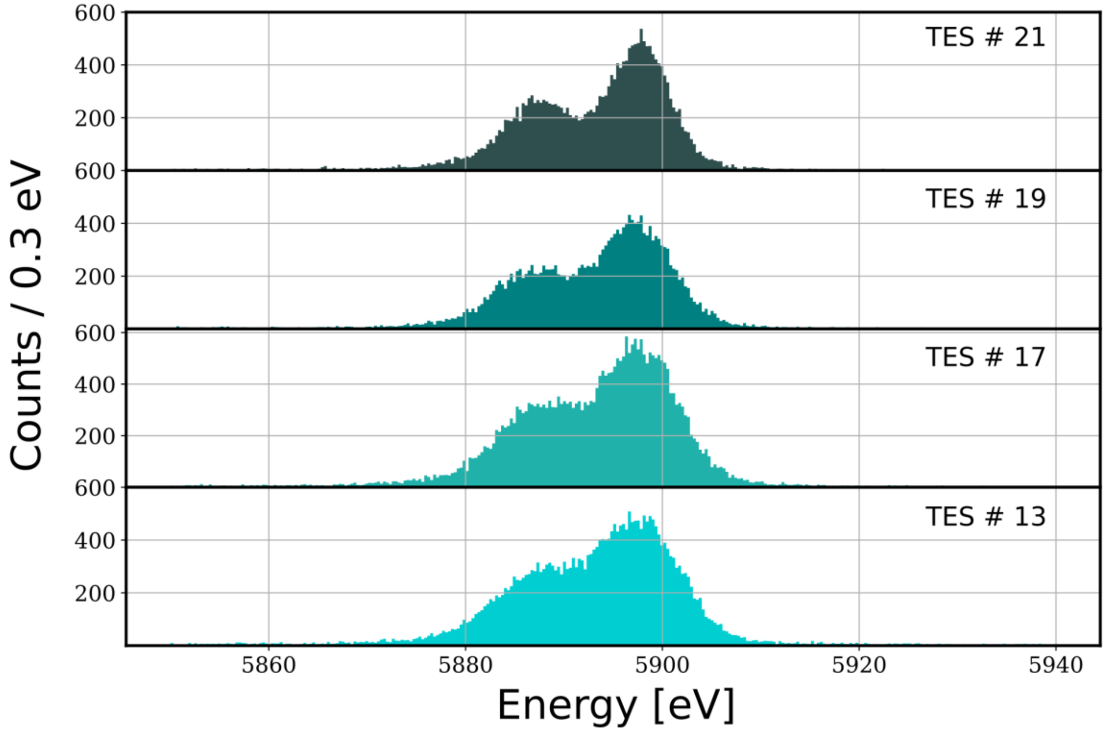
$c_{HO} = 2.5 \pm 0.6$ (stat) J/K/mol (from decay time and thermal conductance)

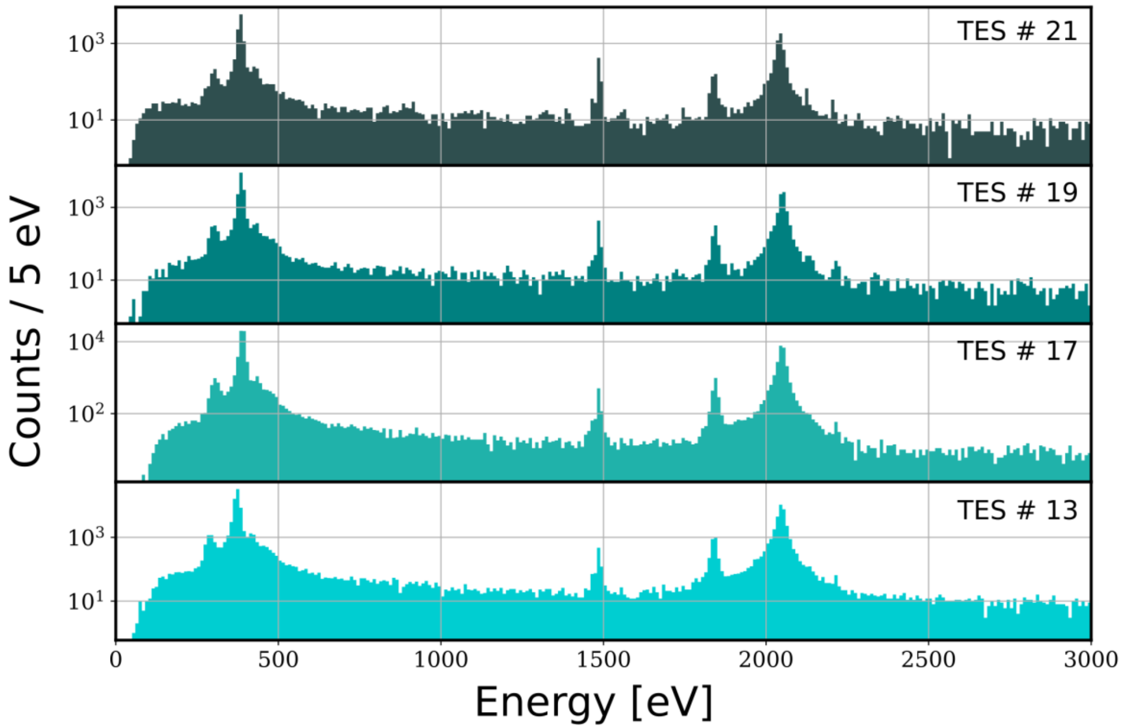
- To reach high activity, lower temperature are needed.

c_{HO} at 40 mK should be ten times lower than @90 mK!

Run 1 results: first Ho spectrum on four selected pixel

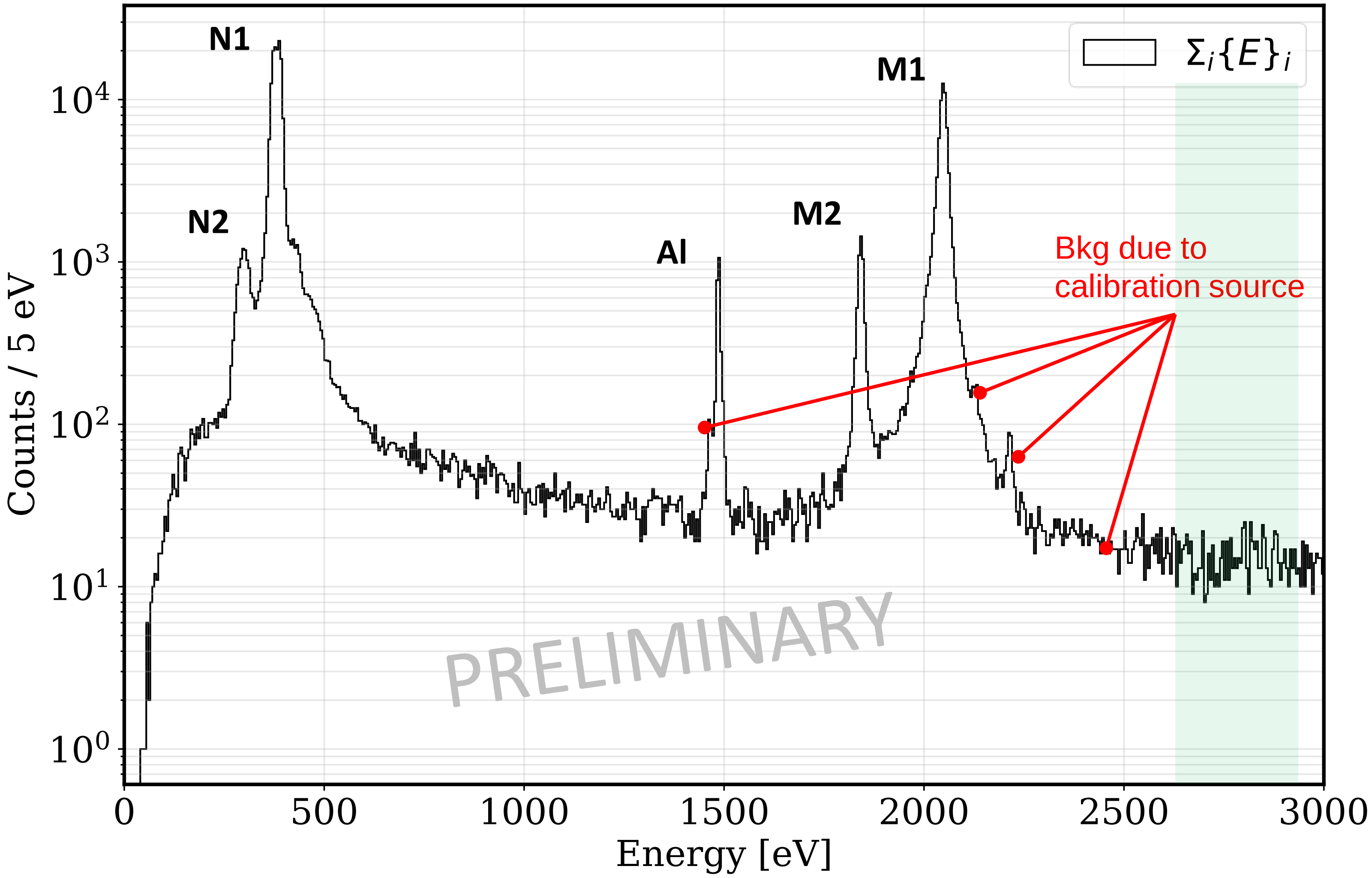
TES #	ΔE_{FWHM}@6 keV [eV]	^{163}Ho activity [Bq]
13	8.36 ± 0.09	0.97
17	7.78 ± 0.08	0.55
19	7.12 ± 0.08	0.21
21	5.76 ± 0.07	0.11





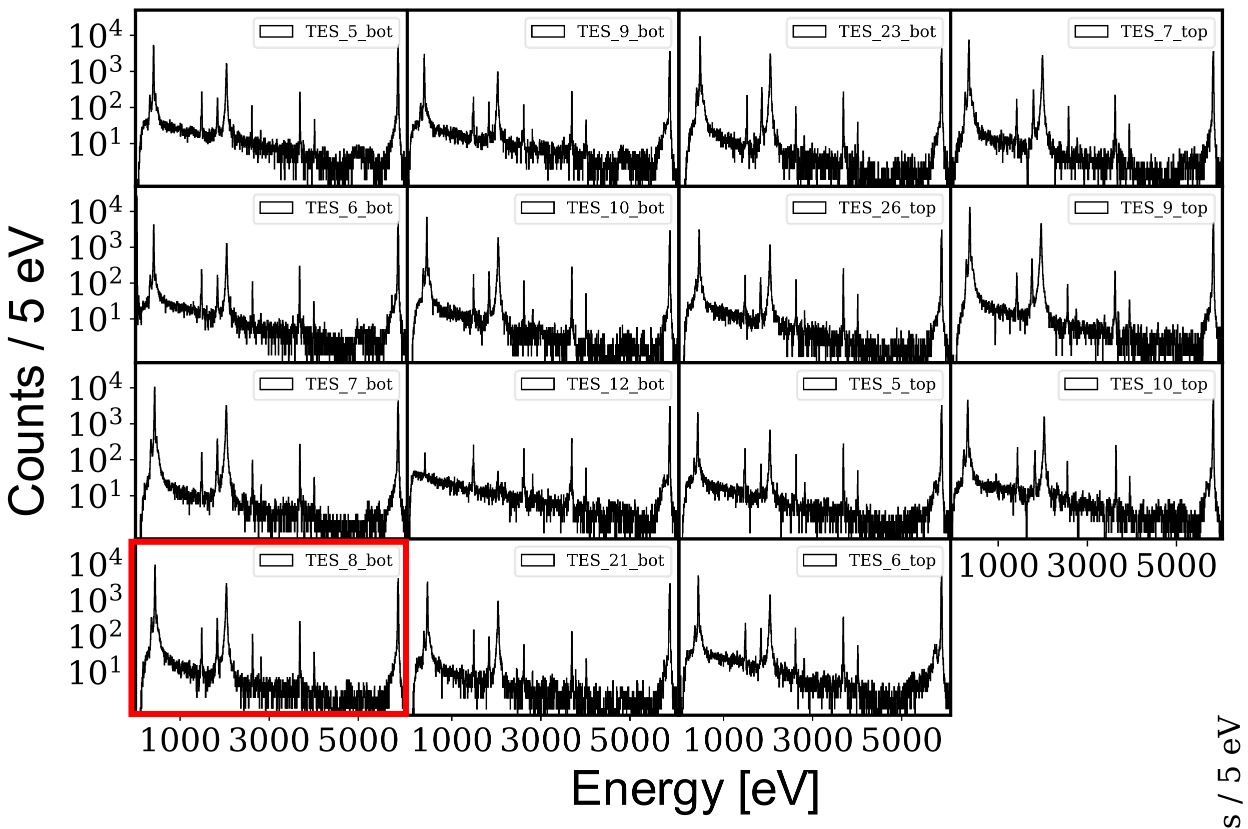
Run 1 results: first Ho spectrum on four selected pixel

- Acquisition time 48.5 hours
- Sum over 4 pixel
- High background due to ^{55}Fe calibration source
- 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.
- $\Delta E_{FWHM} = 6 \div 8$ eV @6 keV

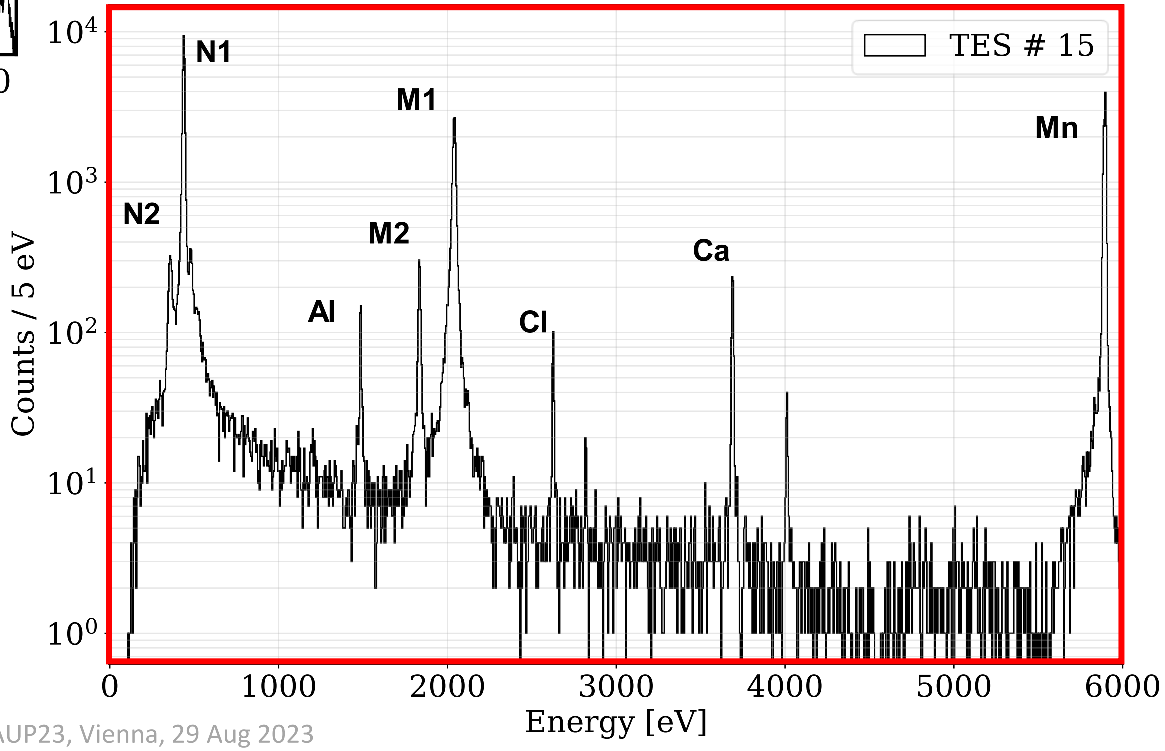


Run 2 results: work in progress

Run 2, measurement 1, 15 pixels with Ho recorded



- Around 60 holmium spectra were recorded, “cleaned” and calibrated.
- Idea: model each ^{163}Ho peak with an asymmetric Lorentzian function



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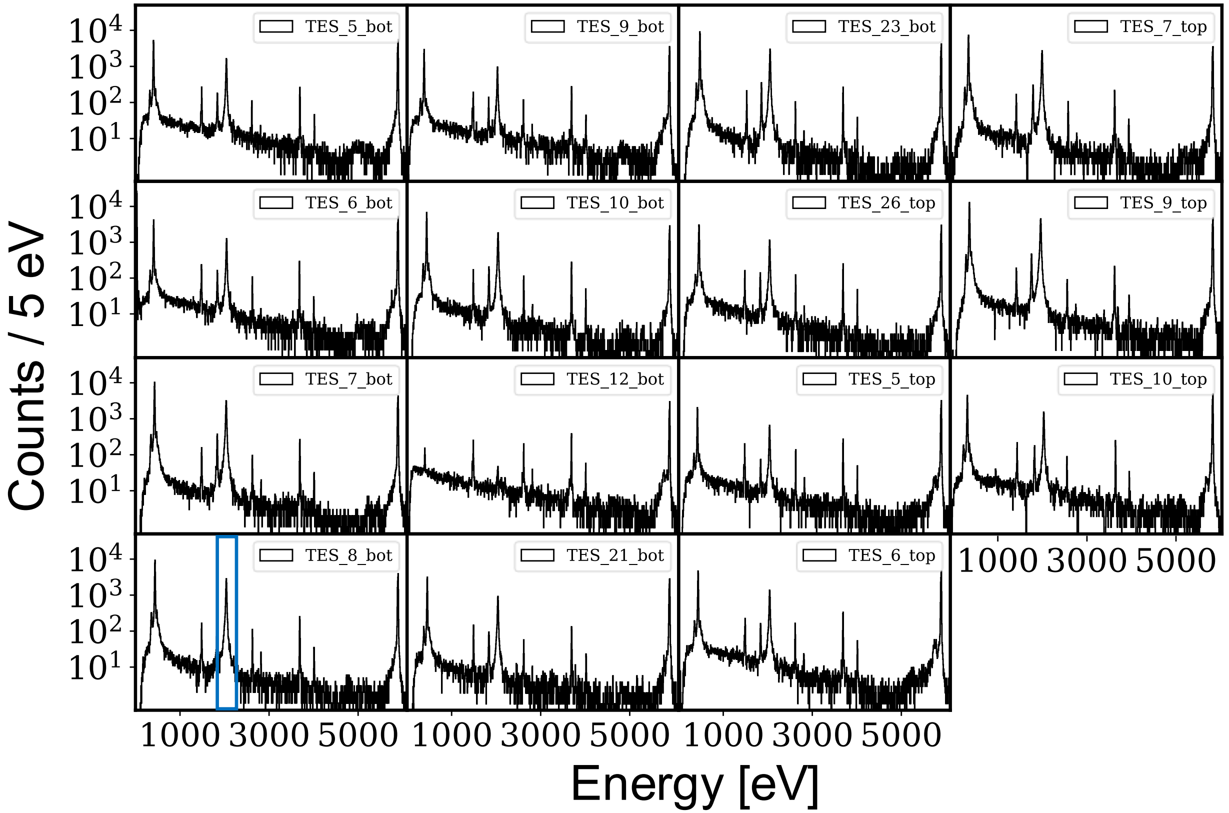

- Data analysis will start in September, using maximum likelihood methods as well as Bayesian parameters estimation

Peak	E [eV]	γ	δ	Intensity
M1	Tbd	Tbd	Tbd	Tbd
M2	Tbd	Tbd	Tbd	Tbd
N1	Tbd	Tbd	Tbd	Tbd
N2	Tbd	Tbd	Tbd	Tbd

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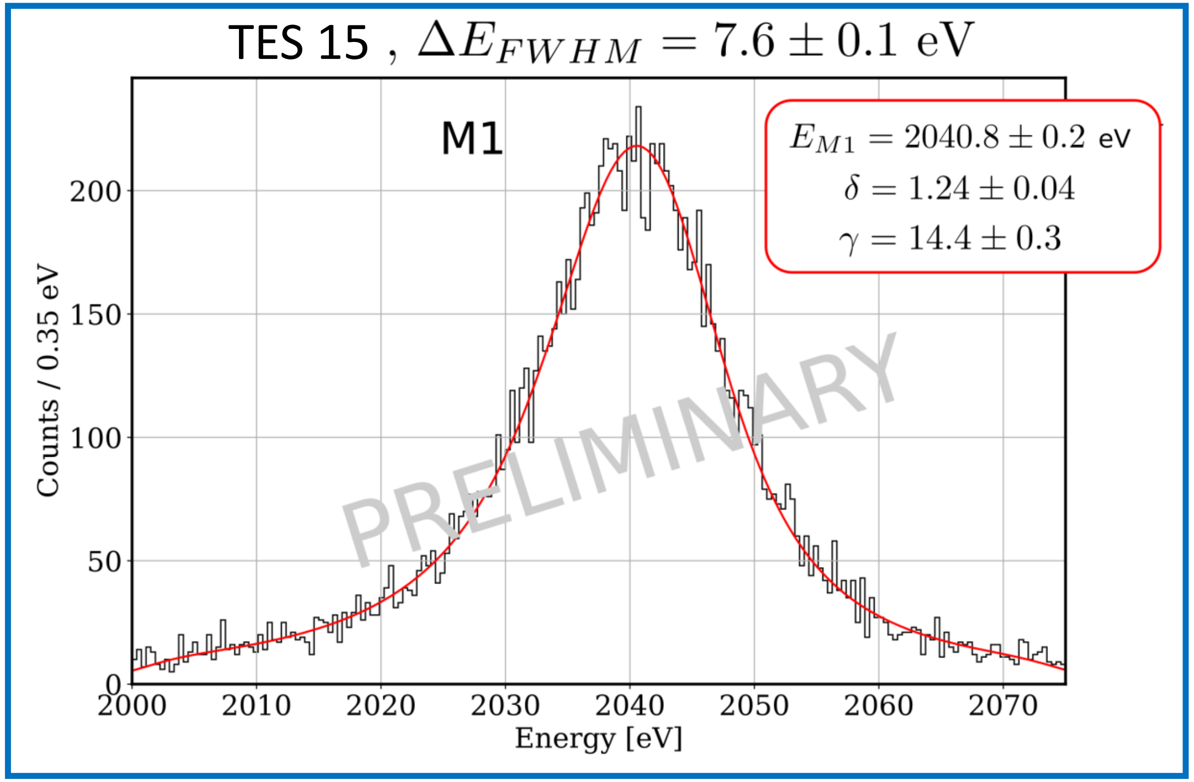
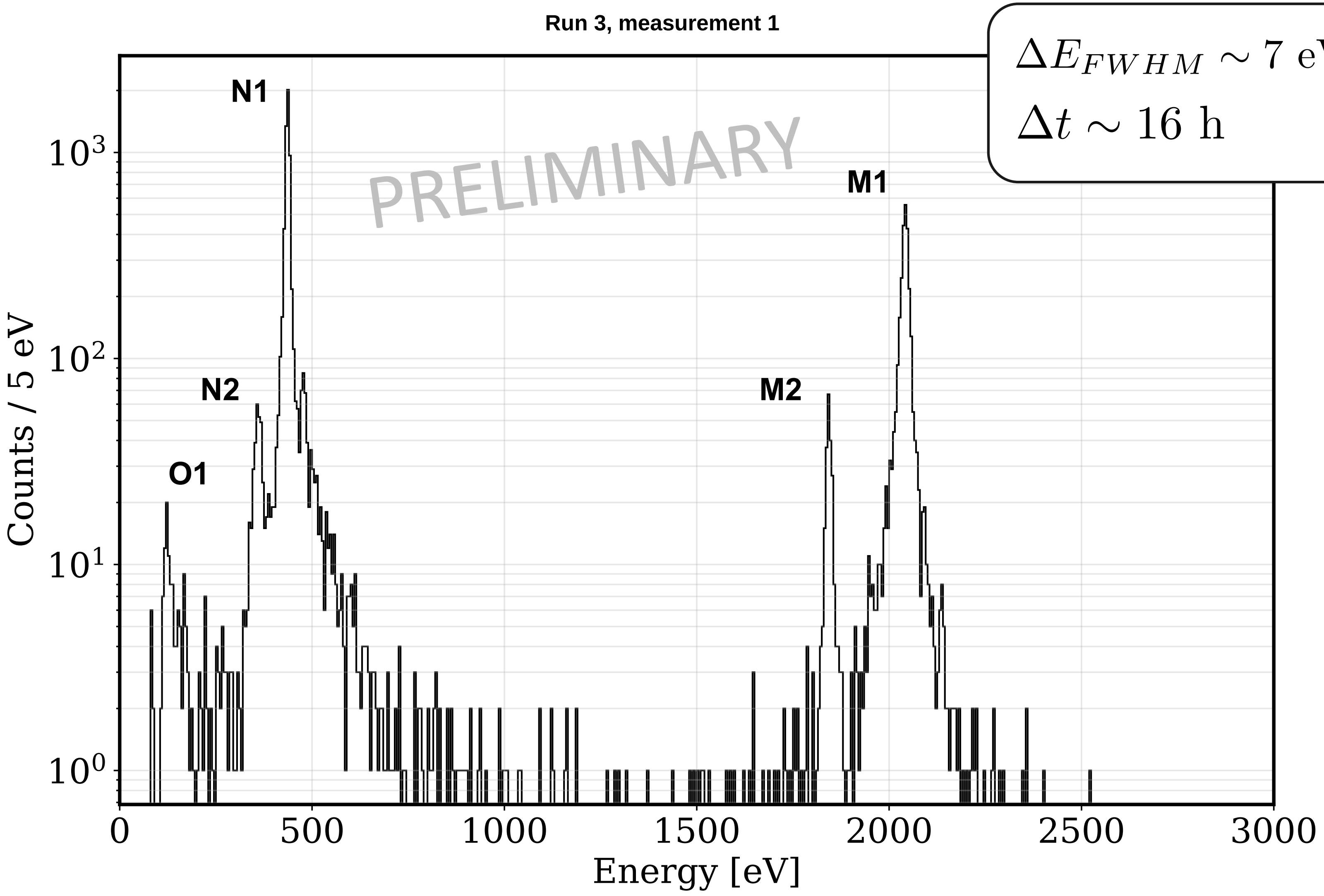


Run 3 results: just a glimpse

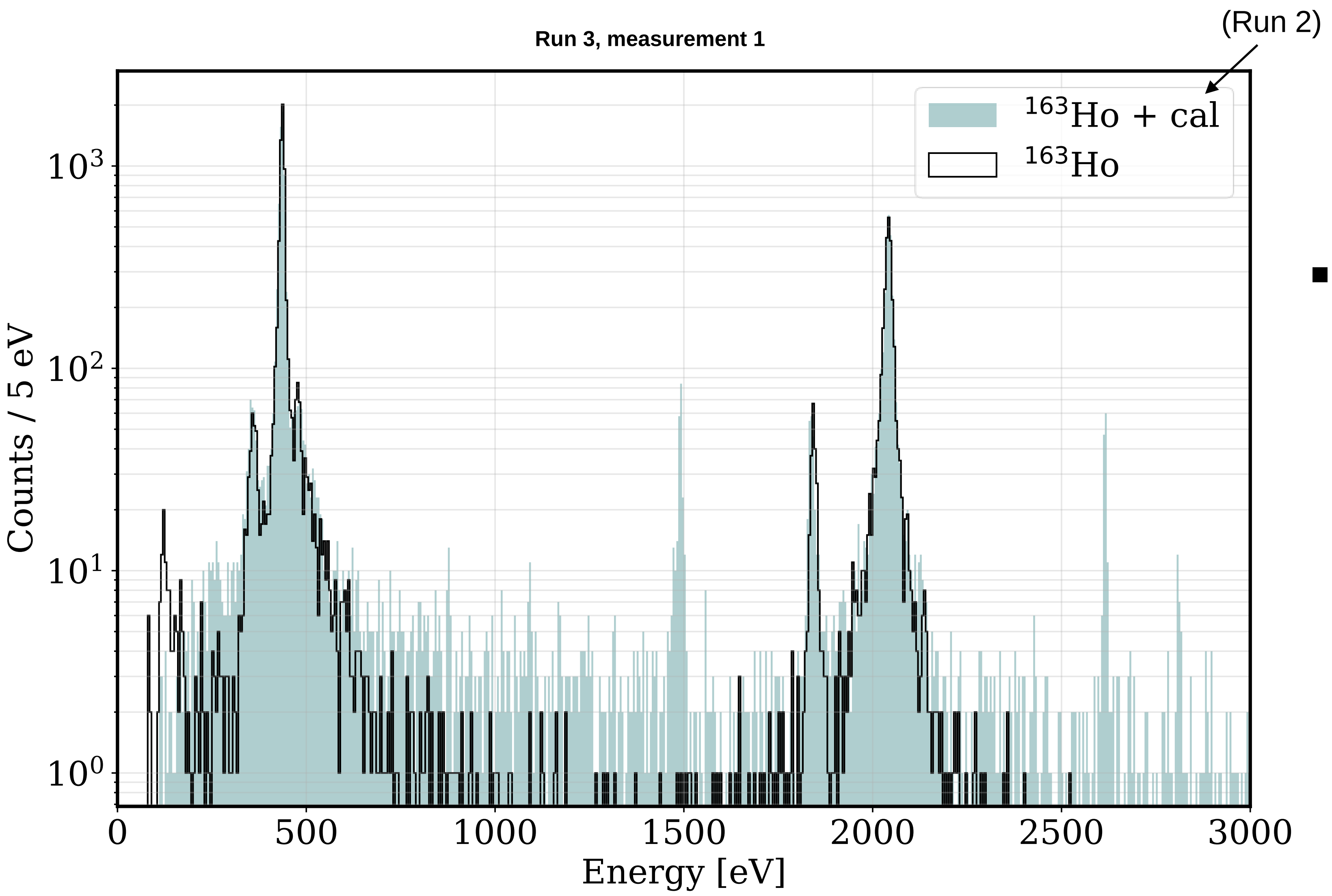


$\Delta E_{FWHM} \sim 7$ eV

$\Delta t \sim 16$ h

- No calibration source

Run 3 results: just a glimpse



- No calibration source

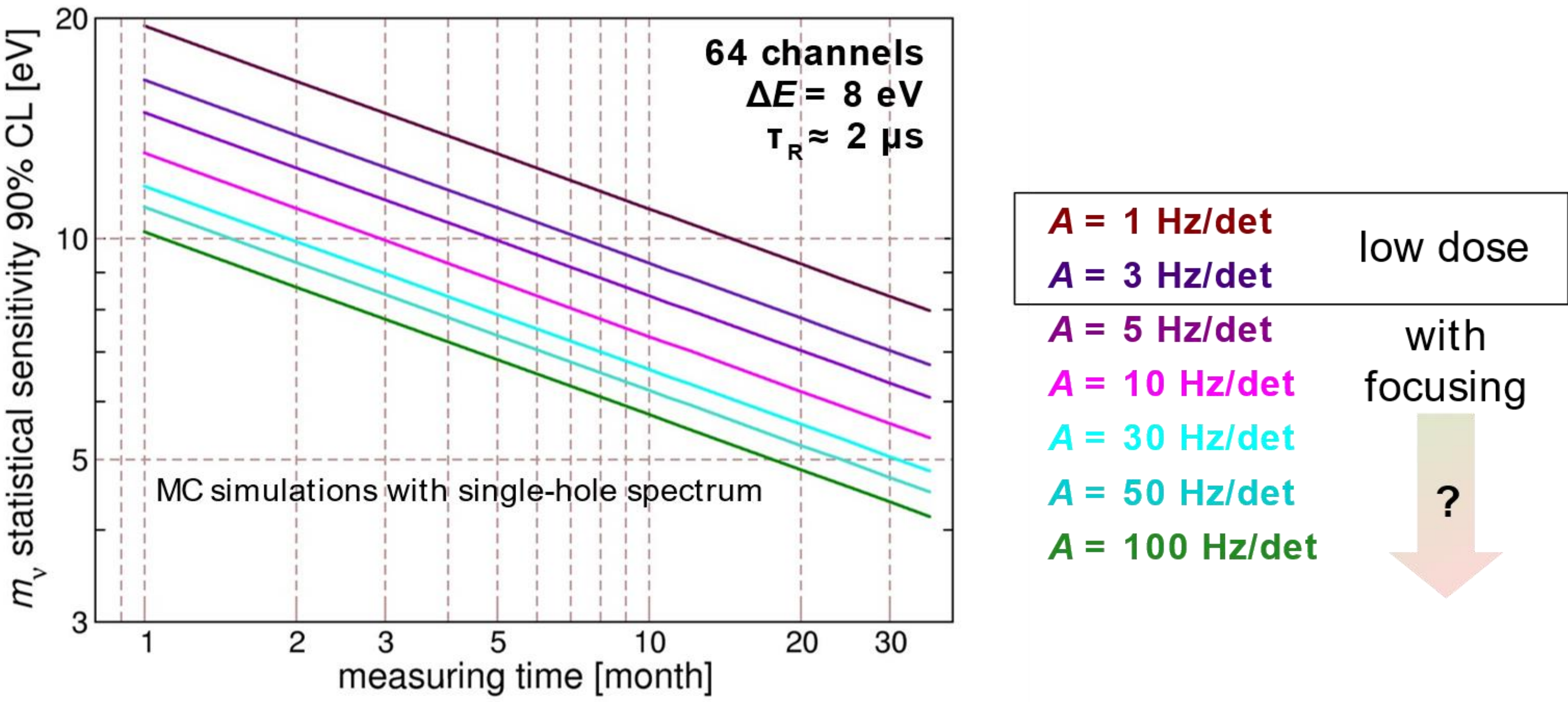
What’s next

- Run 3 will be the first physics run of HOLMES

No external calibration source → Ho lines will be used for calibration

- Implantation of a new array with uniform and maximum achievable activity (last quarter of 2023)

Long measurement and
first limit on neutrino mass around 10 eV



- Upgrade of the ion implanter (focusing stage and co-deposition chamber)

Implantation with higher activities

Acknowledgments

Univ. & INFN Milano-Bicocca

M. Borghesi
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G. Gallucci
F. Gatti
P. Manfrinetti
L. Parodi
F. Siccardi

INFN Roma

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INFN LNGS

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S. Nisi

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

PSI

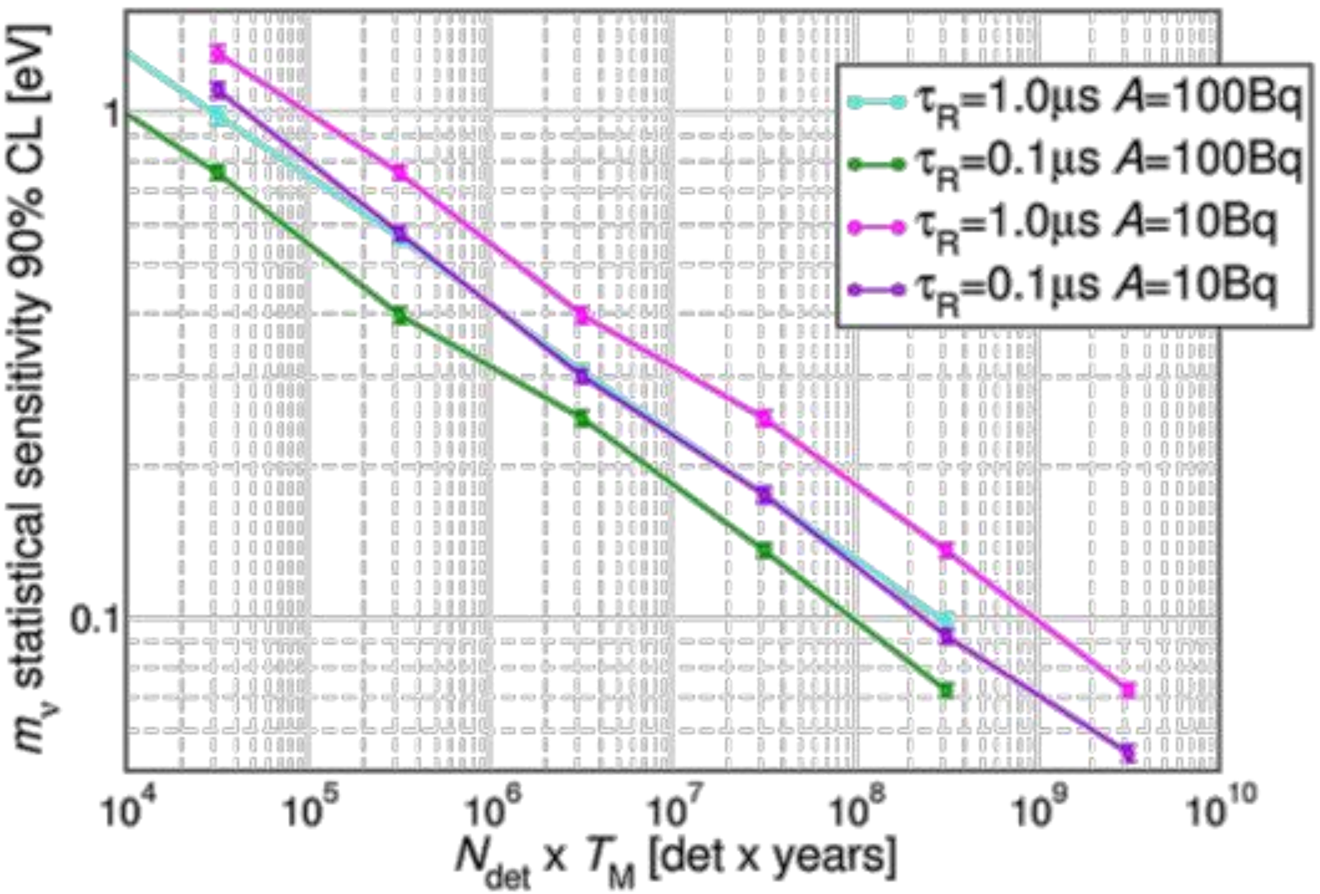
N. Cerboni
R. Dressler
E. Maugeri
D. Shumann

ILL

U. Koester

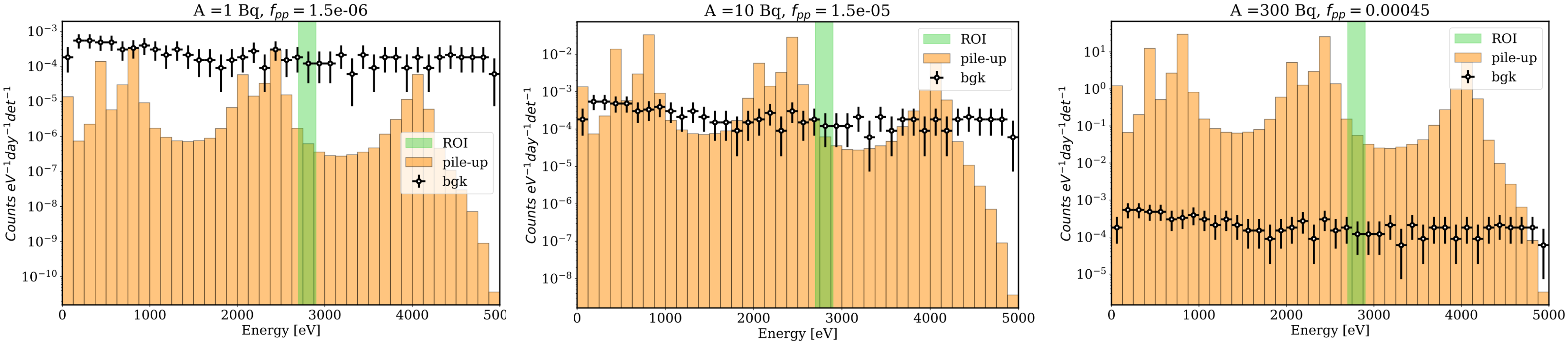
The Milano and Genova group

Backup: What could lie beyond

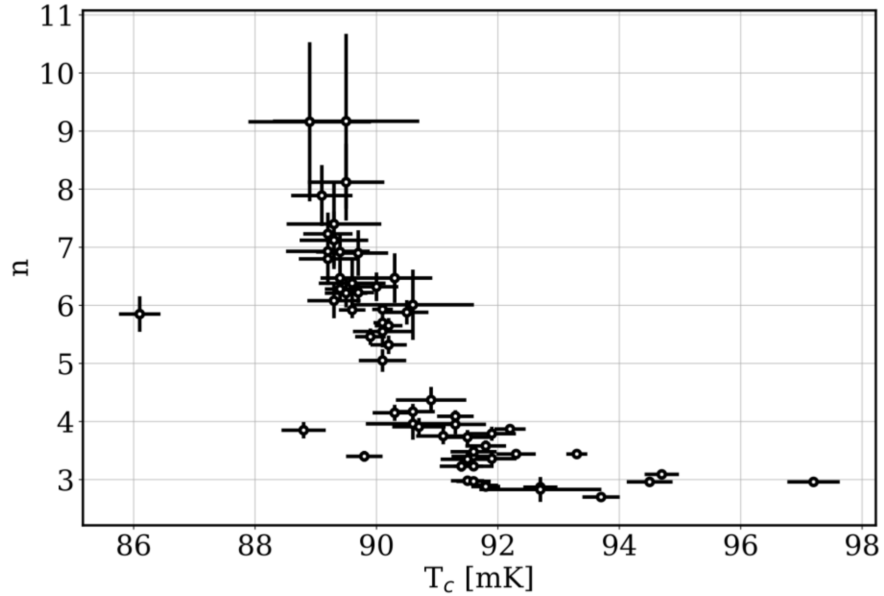


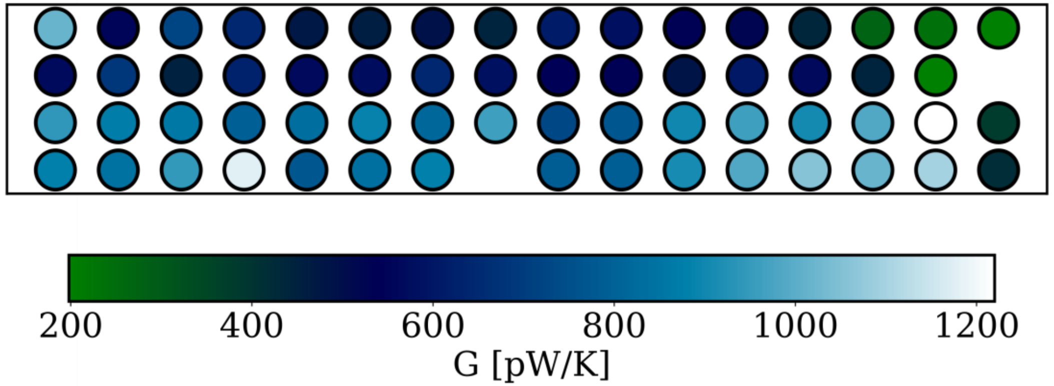
Backup: expected background budget

$$\tau_r = 1.5\ \mu s$$

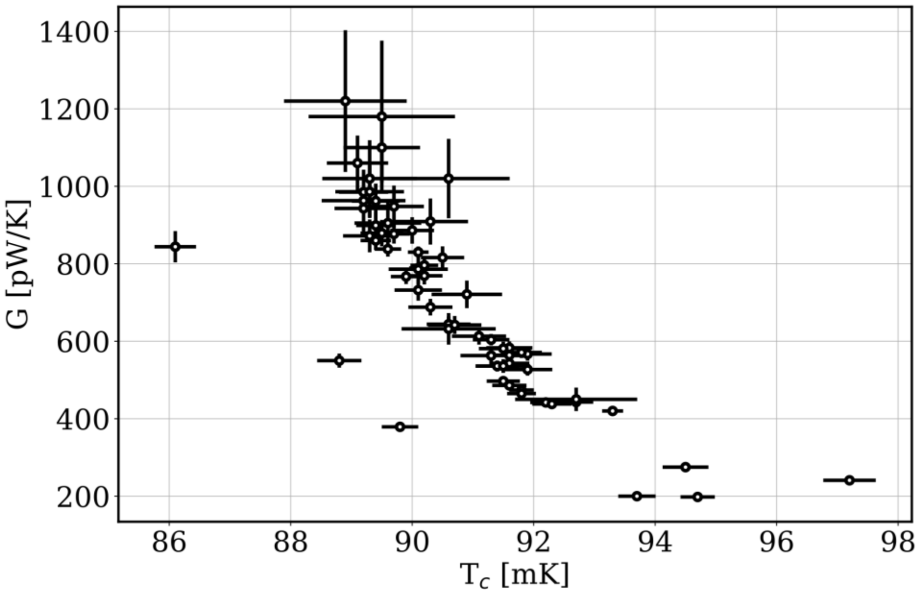


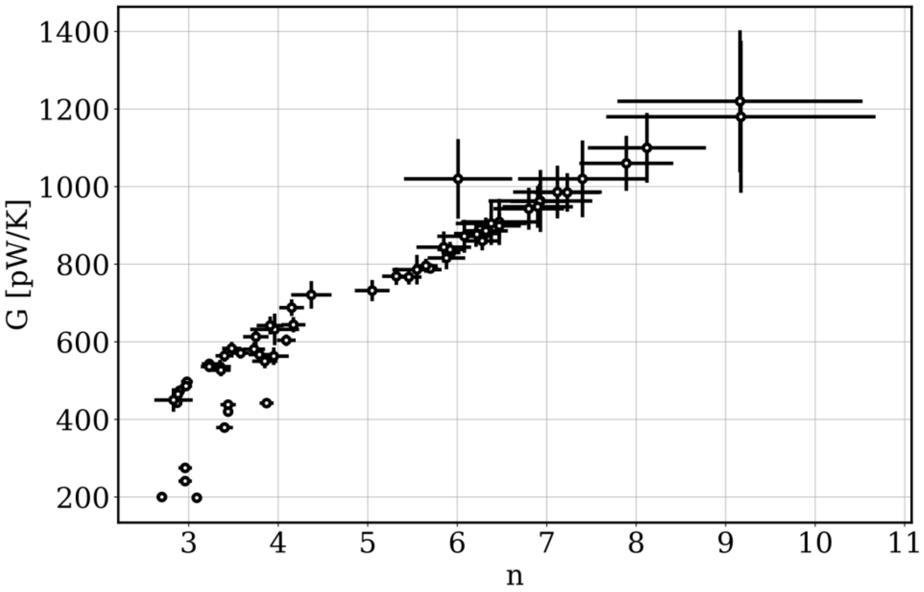
Thermal conductance



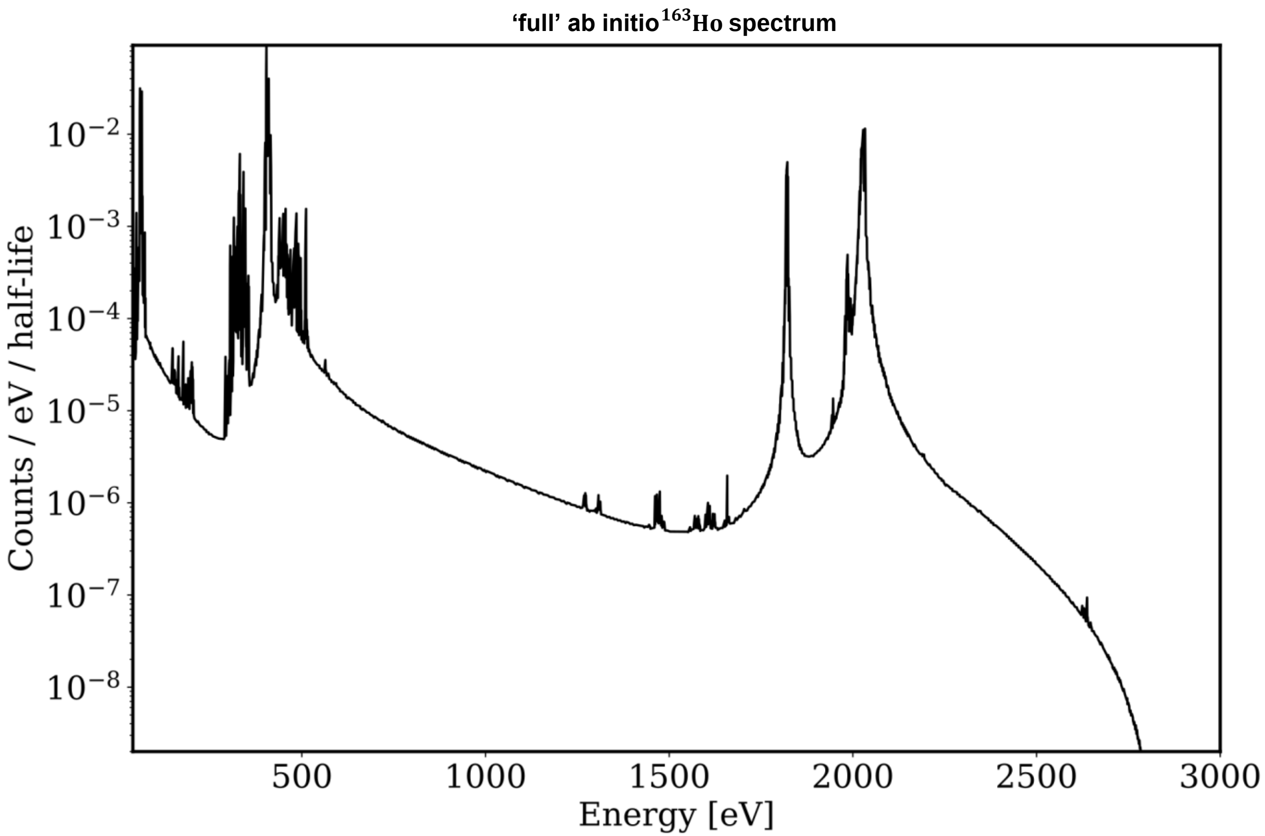


PRELIMINARY

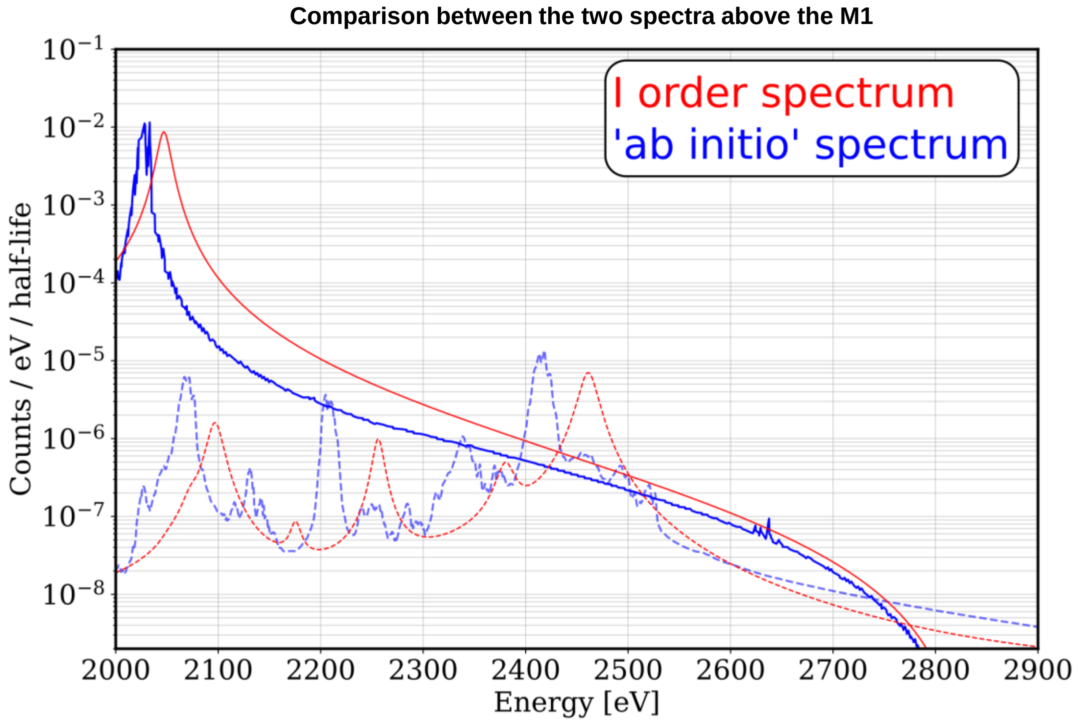




Ho spectrum



'full' ab initio ^{163}Ho spectrum
Counts / eV / half-life
Energy [eV]
500
1000
1500
2000
2500
3000
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}



Comparison between the two spectra above the M1
I order spectrum
'ab initio' spectrum
Counts / eV / half-life
Energy [eV]
2000
2100
2200
2300
2400
2500
2600
2700
2800
2900
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}