The first neutrino mass measurement of HOLMES experiment

Lorenzo Ferrari Barusso
on behalf of the HOLMES collaboration

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Outline

- A Direct neutrino mass measurement: calorimetric approach
- ^{163}Ho and neutrino mass: the HOLMES experiment
- First results from HOLMES
- Next phase HOLMES+ and future on m_ν

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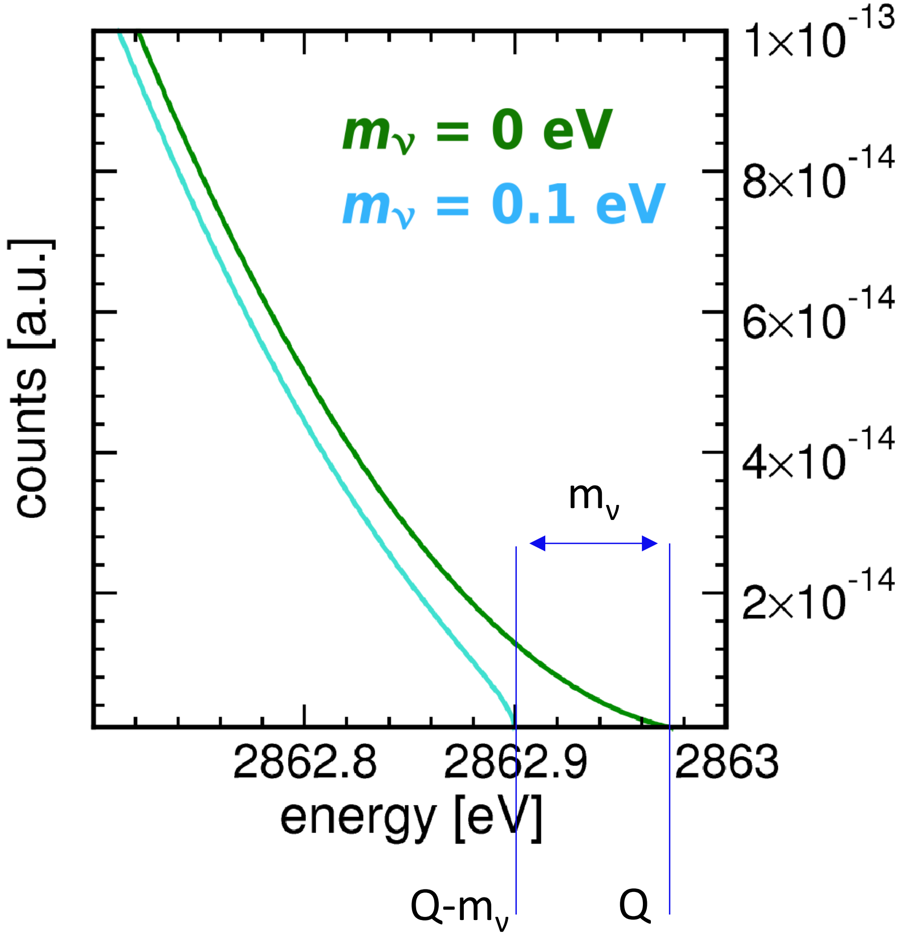
Direct Neutrino mass measurements

model independent: study of weak decays kinematics
β and EC decays where $\boldsymbol{\nu_e}$ or $\boldsymbol{\bar{\nu}_e}$ are emitted

Low-Q β/EC decay isotopes (^{3}H, ^{187}Re, ^{163}Ho) needed;

Two main possibilities:

- Spectroscopic approach (KATRIN)
- Calorimetric approach (HOLMES)



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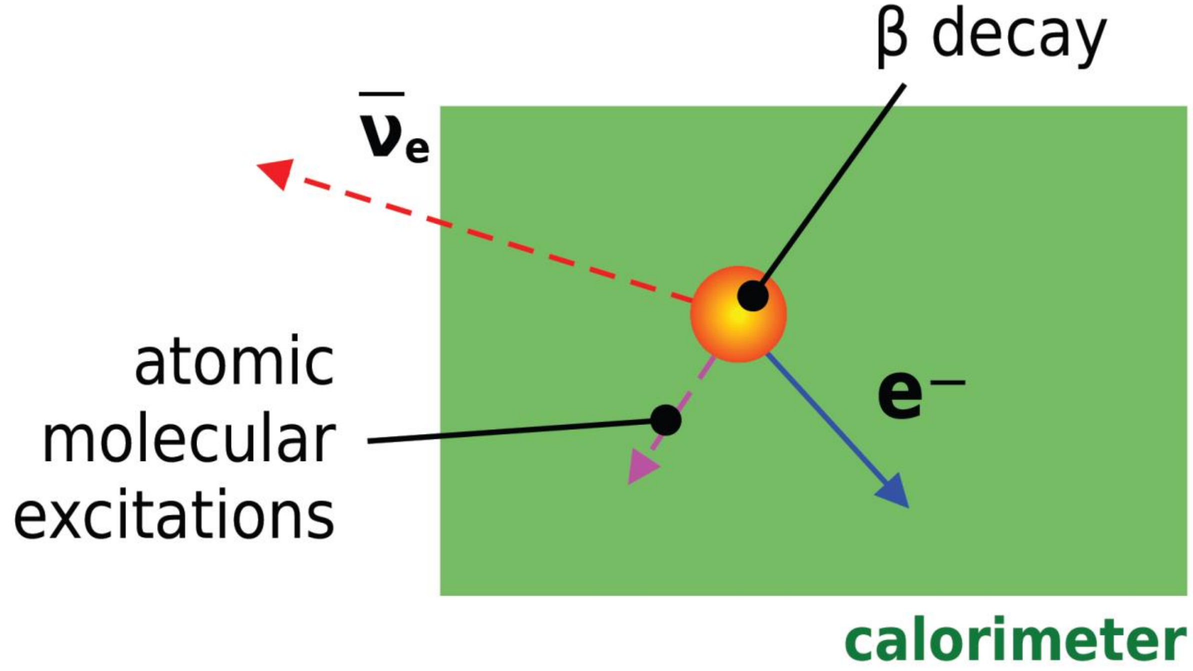
Calorimetric approach

- Low Q and Low $\tau_{1/2}$ ➡ ^{163}Ho

Source embedded → **Ec = Q – Ev**

Electron Capture

Calorimetric measurement of Dy* de-excitation spectrum



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

$$\frac{d\lambda_{EC}}{dE_c} = \frac{G_\beta^2}{4\pi^2}(Q-E_c)\sqrt{(Q-E_c)^2 - m_\nu^2} \times \sum n_i C_i \beta_i^2 B_i \frac{\Gamma_i}{2\pi}\frac{1}{(E_c-E_i)^2+\Gamma_i^2/4}$$

Q~2.8 keV, capture only from shell ≥ M1
De Rujula & Lusignoli, Phys. Lett. B 118 (1982) 429

same phase space factor as β decay
(total de-excitation energy E_c instead of E_e)

Breit-Wigner shape

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Calorimetric approach

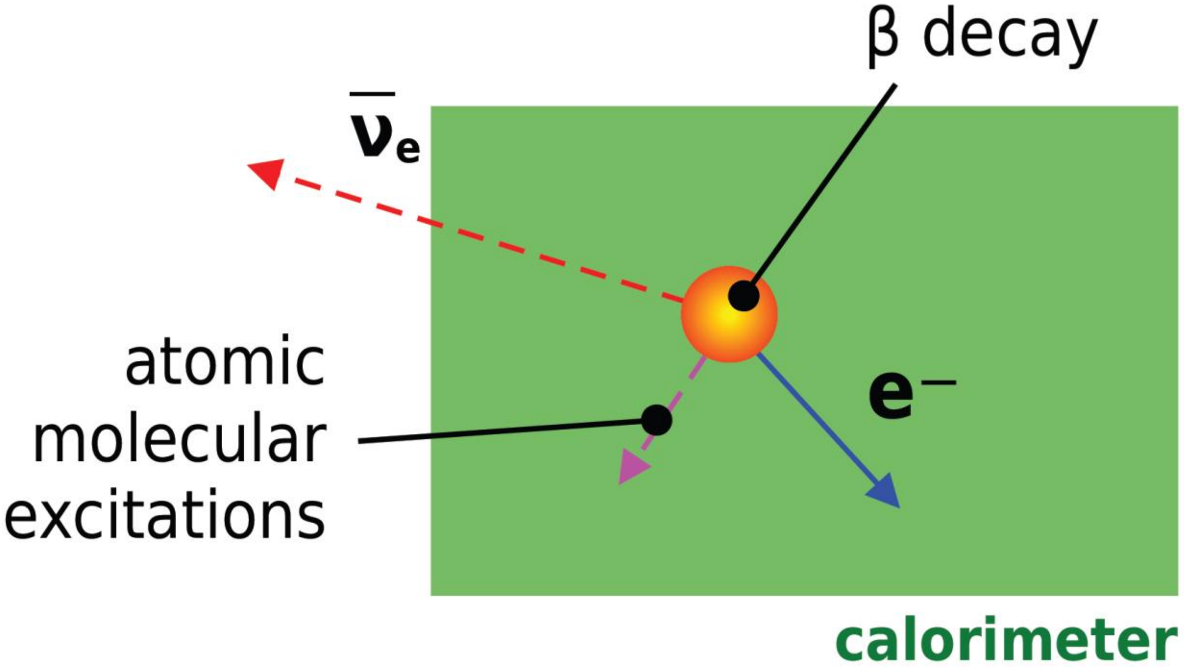
- Low Q and Low $\tau_{1/2}$ ➡ ^{163}Ho

Electron Capture

Calorimetric measurement of Dy* de-excitation spectrum

- m_ν sensitivity depends on Q-value

Source embedded → **Ec = Q – Eν**



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Calorimetric approach

- Low Q and Low $\tau_{1/2}$ → ^{163}Ho

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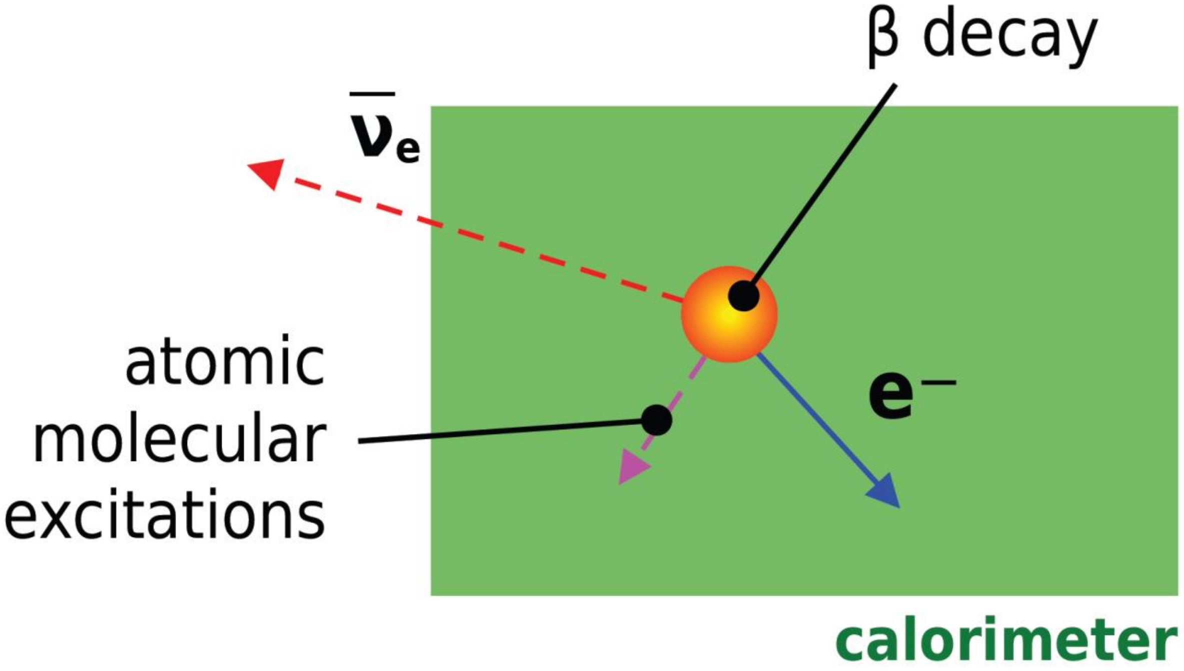

Electron Capture

Calorimetric measurement of Dy* de-excitation spectrum

- m_ν sensitivity depends on Q-value
- $\tau_{1/2}$ ~ 4570 years → high specific activity, avoid to spoil detector performances by adding too much ^{163}Ho (Pile-up vs statistics trade-off)

$$^{163}Ho + e^- \rightarrow Dy^* + \nu_e$$

$$\frac{d\lambda_{EC}}{dE_c} = \frac{G_\beta^2}{4\pi^2}(Q-E_c)\sqrt{(Q-E_c)^2 - m_\nu^2} \times \sum n_i C_i \beta_i^2 B_i \frac{\Gamma_i}{2\pi}\frac{1}{(E_c-E_i)^2+\Gamma_i^2/4}$$

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Breit-Wigner shape

The HOLMES experiment: low temperature **microcalorimeter arrays** with ion-implanted ^{163}Ho

scalable proof-of-principle for an experiment with **≲ 0.1 eV m_ν sensitivity**

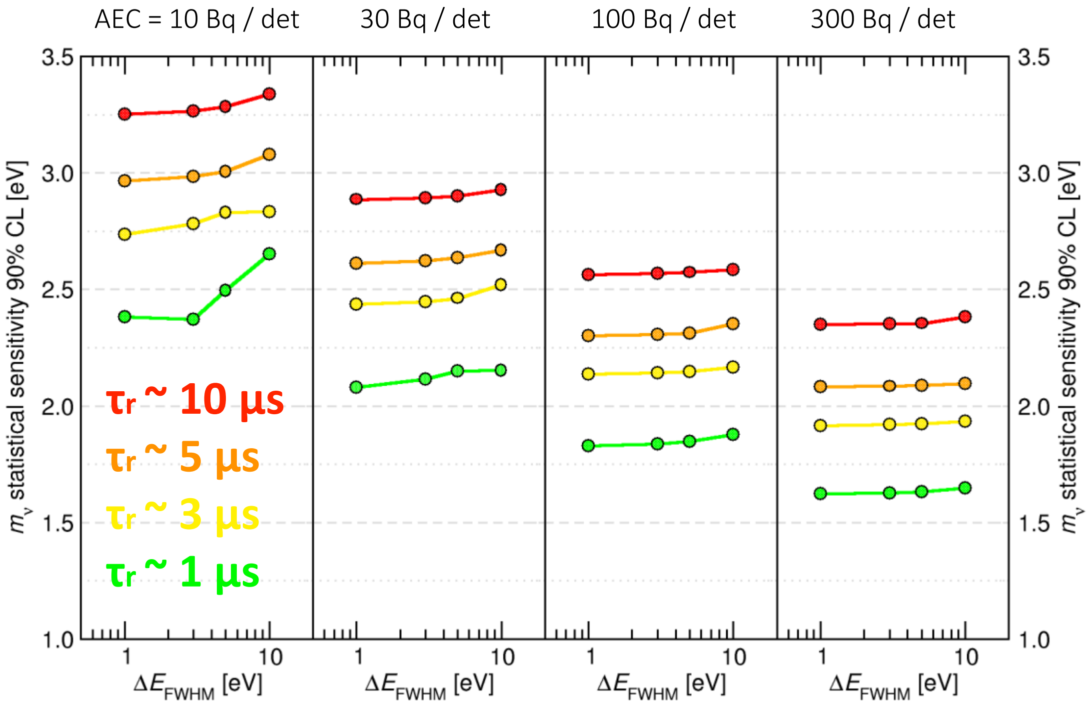
Started as ERC Advanced Grant (2013)

B. Alpert et al., Eur. Phys. J. C, (2015) 75:112

Direct neutrino mass measurement with statistical sensitivity around 1 eV based on **Transition Edge Sensor (TES) micro-calorimeters** arrays with ^{163}Ho implanted Au absorber and multiplexed readout.

Proposal:

- 1k channels, A_{EC} ~ 300 Bq / det
- ΔE ~ few eV → weak dependance from energy reso
- Δt ~ 1 - 10 µs → to get rid of pile up
- Needed at least O(10^{13}) events to explore eV region



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Started as ERC Advanced Grant (2013)

B. Alpert et al., Eur. Phys. J. C, (2015) 75:112

64 chs prototype
with almost 1 Bq/ch activity

HOLMES

Probe of the full chain, assessment of implanted Ho effect on detector signals, first high statistic spectrum (analysis tool, spectrum evaluation…)

First limit on neutrino mass

HOLMES collab., Phys. Rev. Lett. 135 (2025)

256 chs
maximum achievable activity
with current setup (1 - 3 Bq)

m_ν extraction with sensitivity O(10 eV)

HOLMES+

1k chs arrays with high activity O(100 Bq/ch)

- 6.5×10^{16} total nuclei
- O(10^{13}) events / year
- $m_\nu \sim 1$ eV

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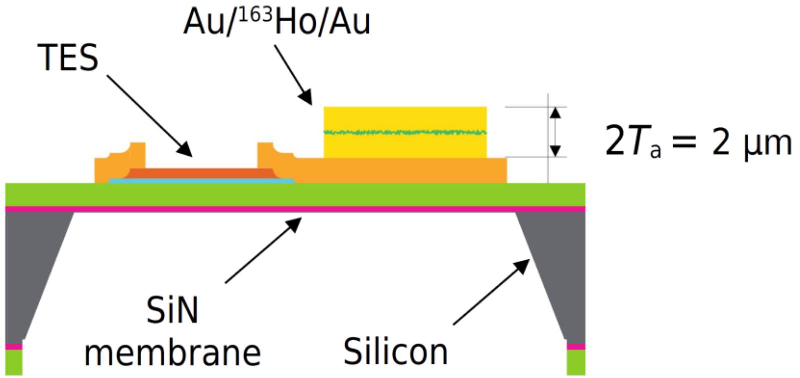
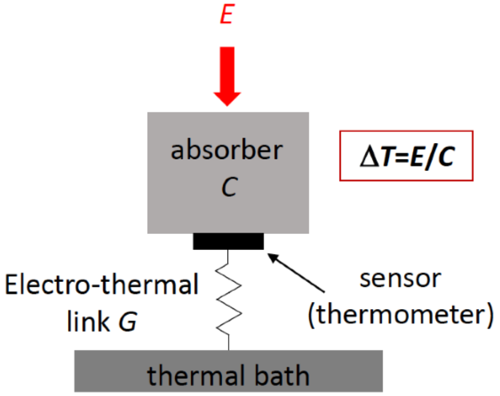
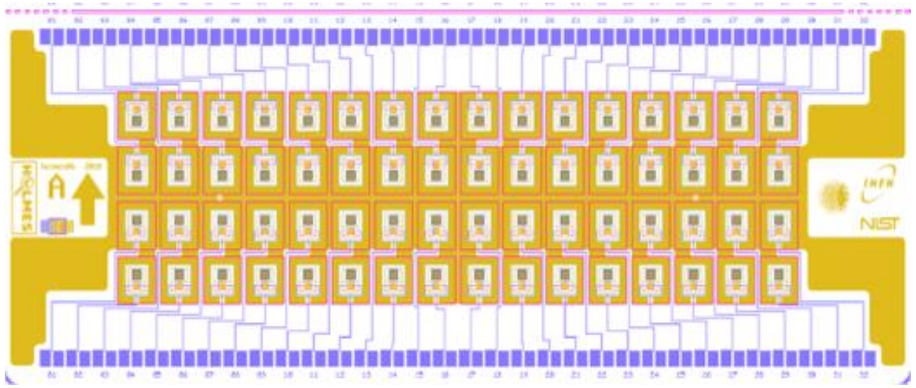
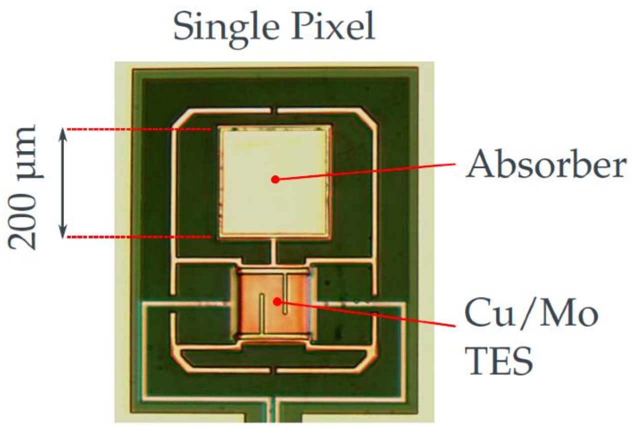
TES Microcalorimeters

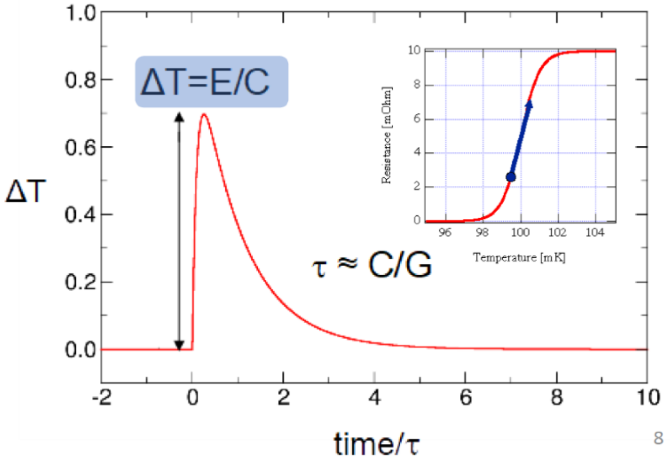
- Gold absorber coupled to superconductive Cu/Mo sensor in transition region,
- energy release in absorber
  → temperature increase in TES
  → variation of TES resistance;
- 100 mK operating point
- 1 eV FWHM
- τ_R = 1 μS











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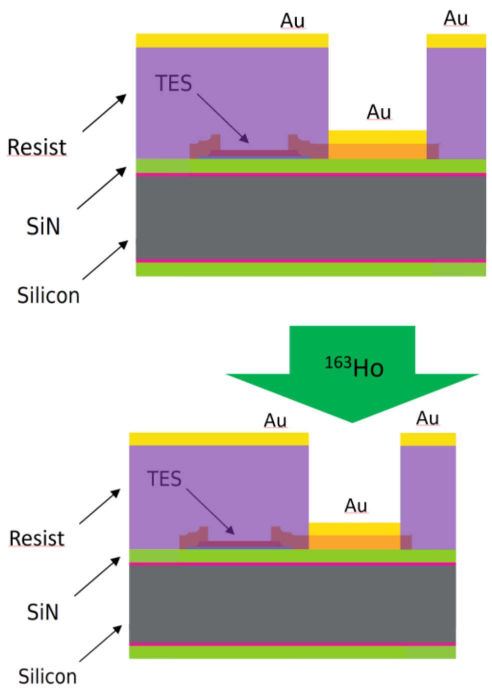
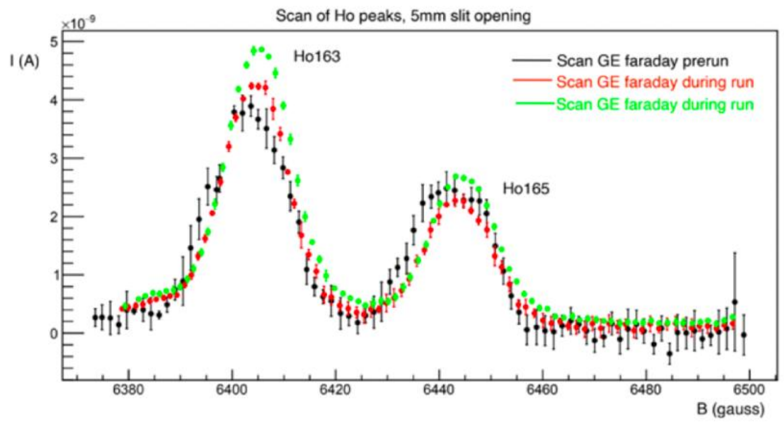
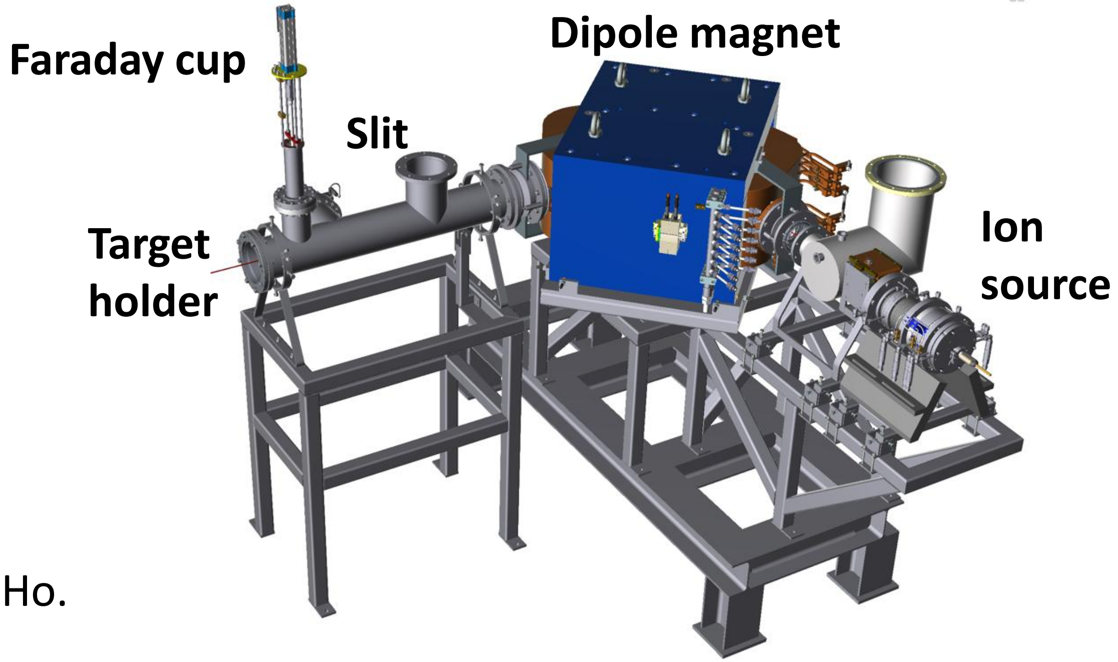
Implantation of ^{163}Ho in the absorber

An **ion implanter** has been designed and commissioned to embed ^{163}Ho in the μ-calorimeters and **to remove ^{166m}Ho residuals.**







First setup (50 keV penning sputter ion source + dipole + slit and FC)

A **chemical purification** is needed to remove contaminants other than Ho.

- **beam size σ ~ 1.5 mm**
- **163 / 166 mass separation > 5 σ;**
- **efficiency ~ 0.2%. Even if efficiency is very low, it was still enough to implant the first array for physics DAQ!**

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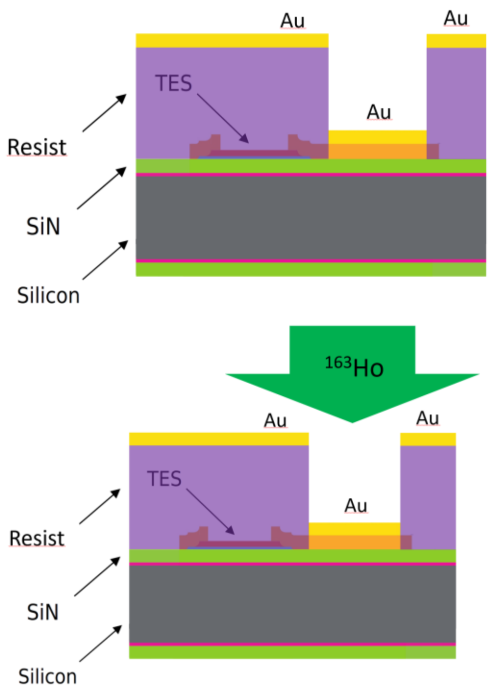
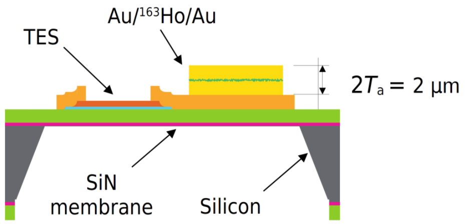
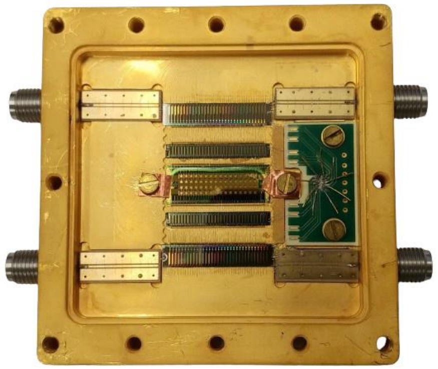
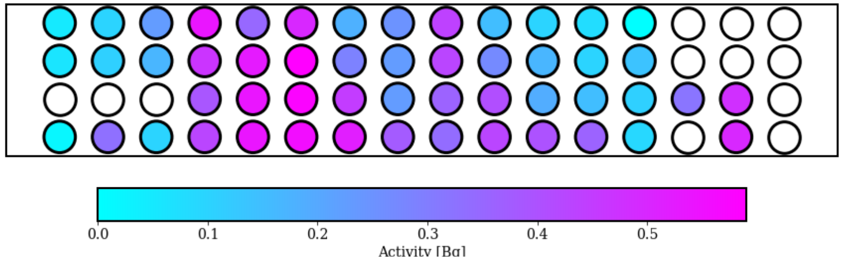




The array is then completed by adding a 1 µm Au layer to fully encapsulate the source and membrane is released with KOH wet etching.



Activity map of the *^{163}Ho ion implantation*



4 spots for a uniform **≲ 2 Bq** activity → neutrino mass measurement integrated currents correspond to ≈ **6×10^{14} ^{163}Ho ions**

48 active pixels (activity above threshold)
average activity **⟨*A*⟩ = 0.27 Bq**
total activity **A_{tot} = 13 Bq**
peak activity **A_{max}≈0.6 Bq**

non-uniform and too low activity
to be understood/improved:

- beam profile and position
- beam current measurement

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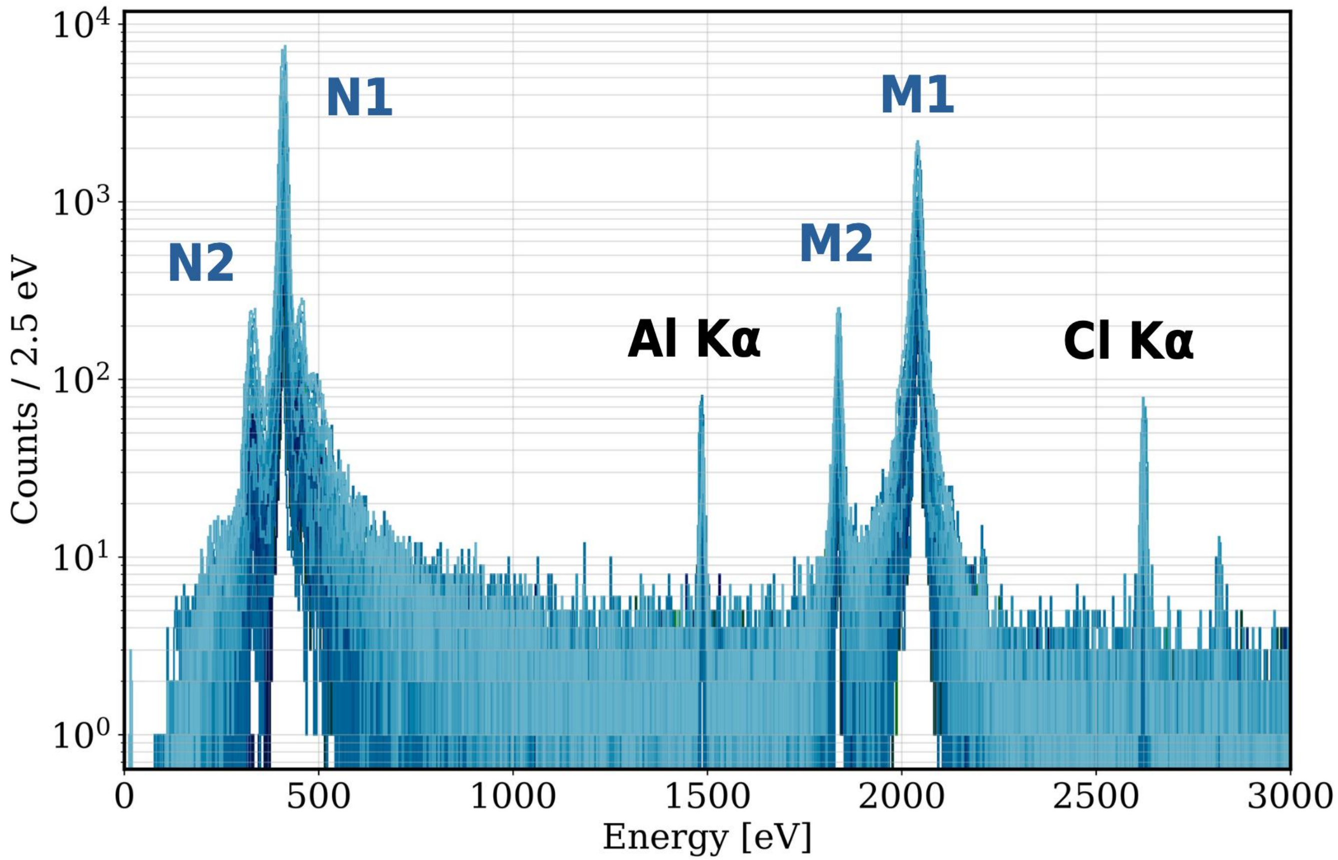
EC peak and detector characterization with fluorescence X-ray source

Peak	Position [eV]	Gamma [eV]	Asymmetry
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	411.72 ± 0.1	5.57 ± 0.03	1.270 ± 0.008
N2	329.0 ± 0.1	16.4 ± 0.2	0.69 ± 0.01

- 48 active μ-calorimeters
- ΔE_{FWHM} = 5.4 ~ 8.0 eV
- 2nd order polynomial calibration
- $E(A) = a_1A + a_2A^2$

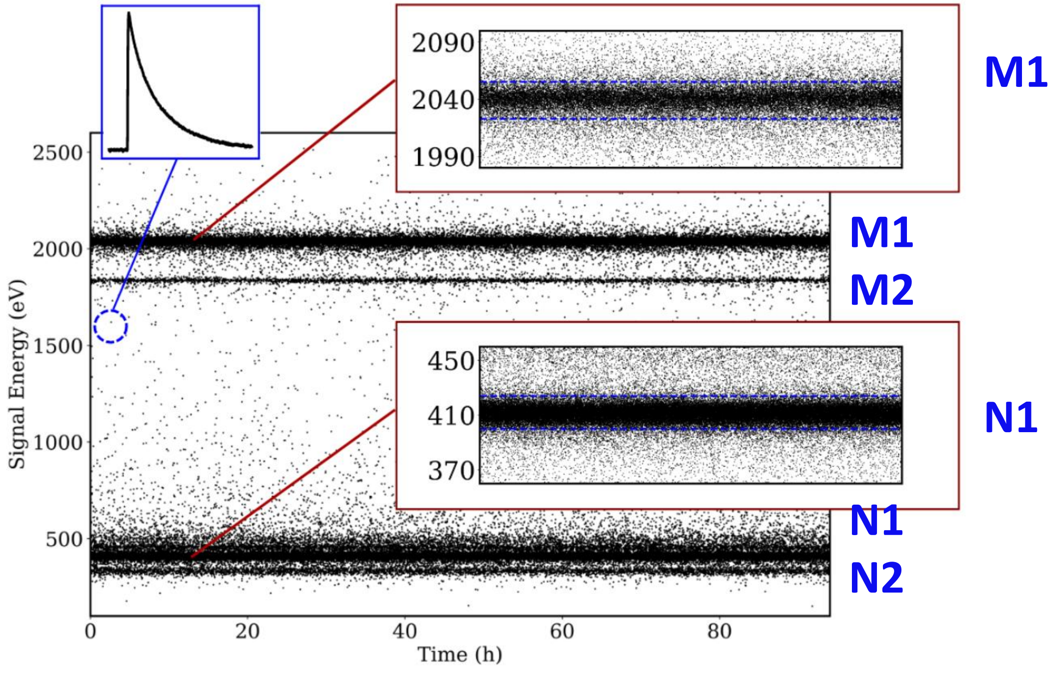
Find EC peak energies: calibration for physics run, needed to merge spectra from different μ-calorimeters

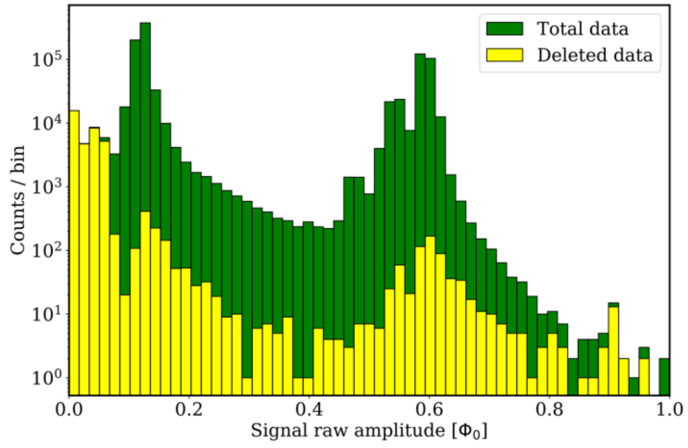


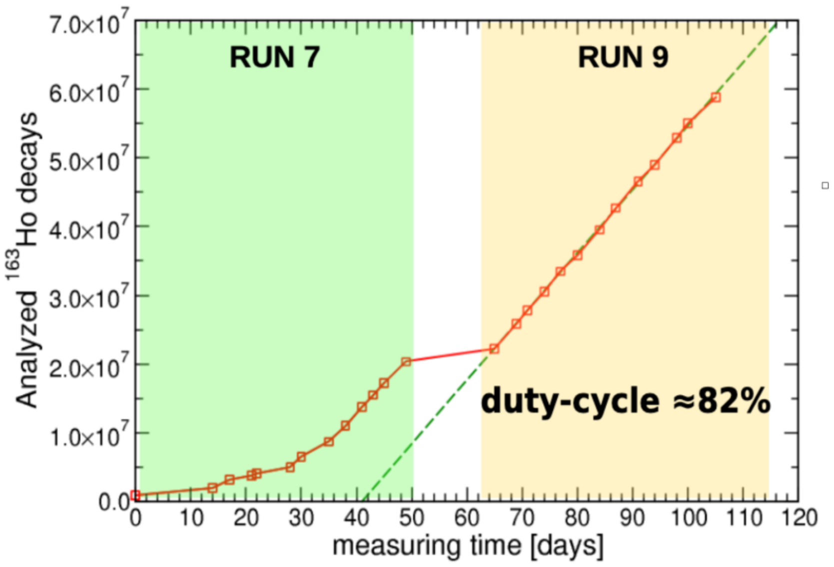
Holmes Collaboration: «Phenomenological Modeling of the ^{163}Ho Calorimetric Electron Capture Spectrum from the HOLMES Experiment» arXiv

^{163}Ho high statistics measurement

- data taking without calibration source **2 months live time** between February and June 2024
- < 1% signals discarded by first level analysis







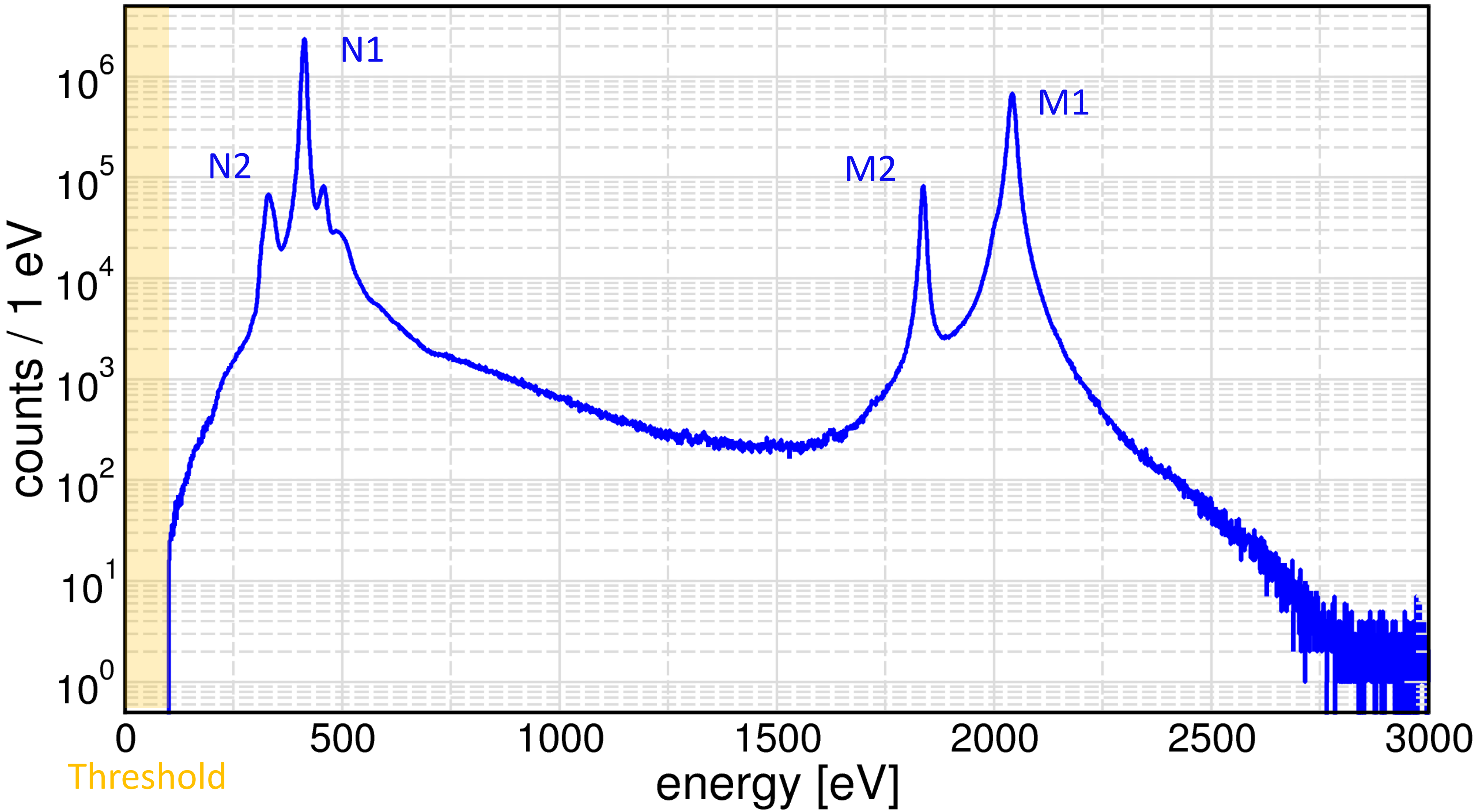
^{163}high statistics spectrum

48 selected pixels
<A> = 0.27 Bq
A_{tot} = 13 Bq
3.2 x 10^{12} ^{163}Ho nuclei

$\langle \Delta E_{FWHM} \rangle$ = 6 ± 1 eV
7×10^4 detector × hour
6×10^7 events in spectrum
≈ 7×10^7 ^{163}Ho decays

≈ 1000 partial data sets
(48 det x 25 runs)

- gain drift correction
- energy calibration using N1, M1 and M2 lines



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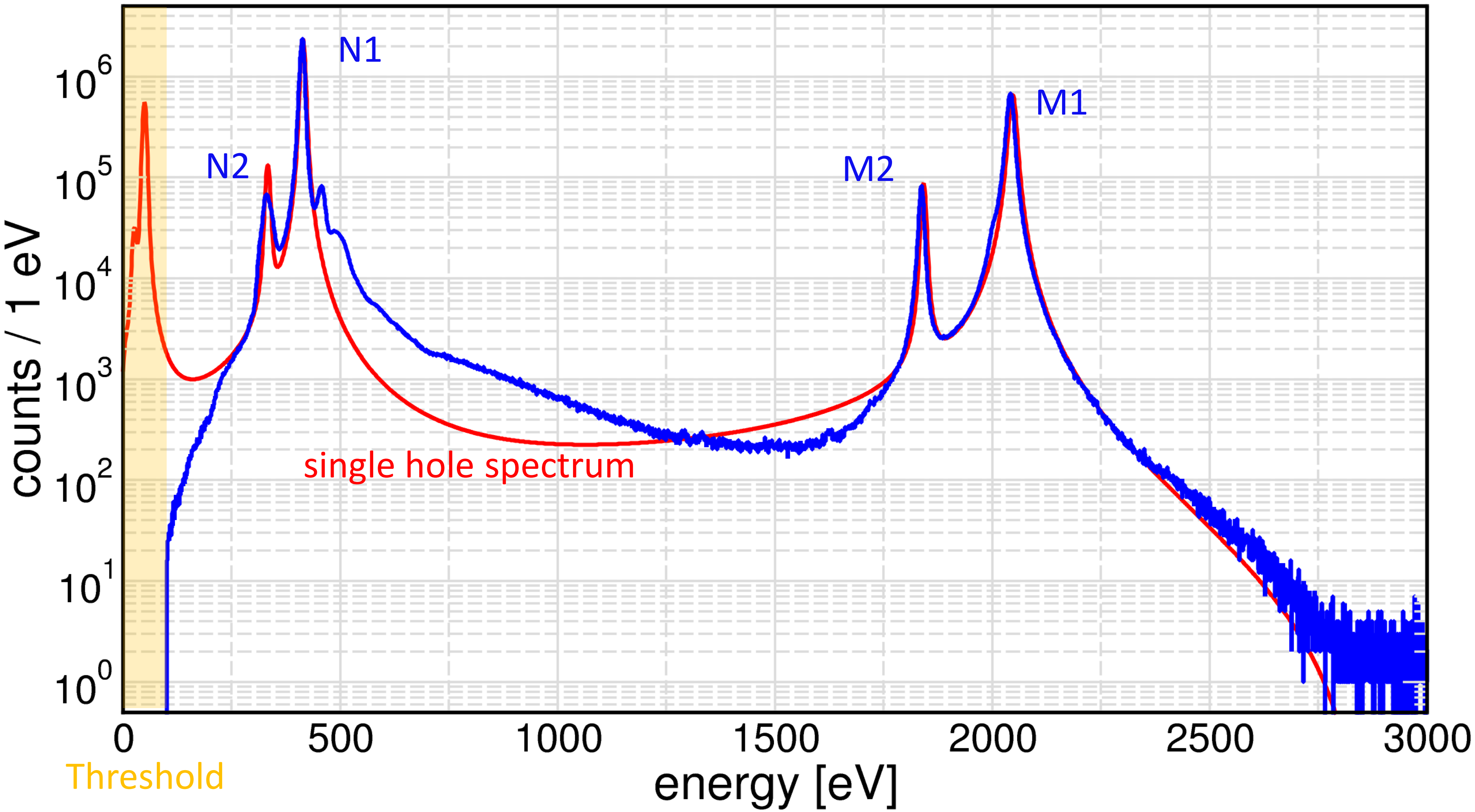
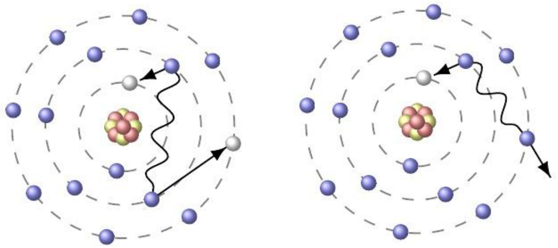
Single hole spectrum doesn't explain data…



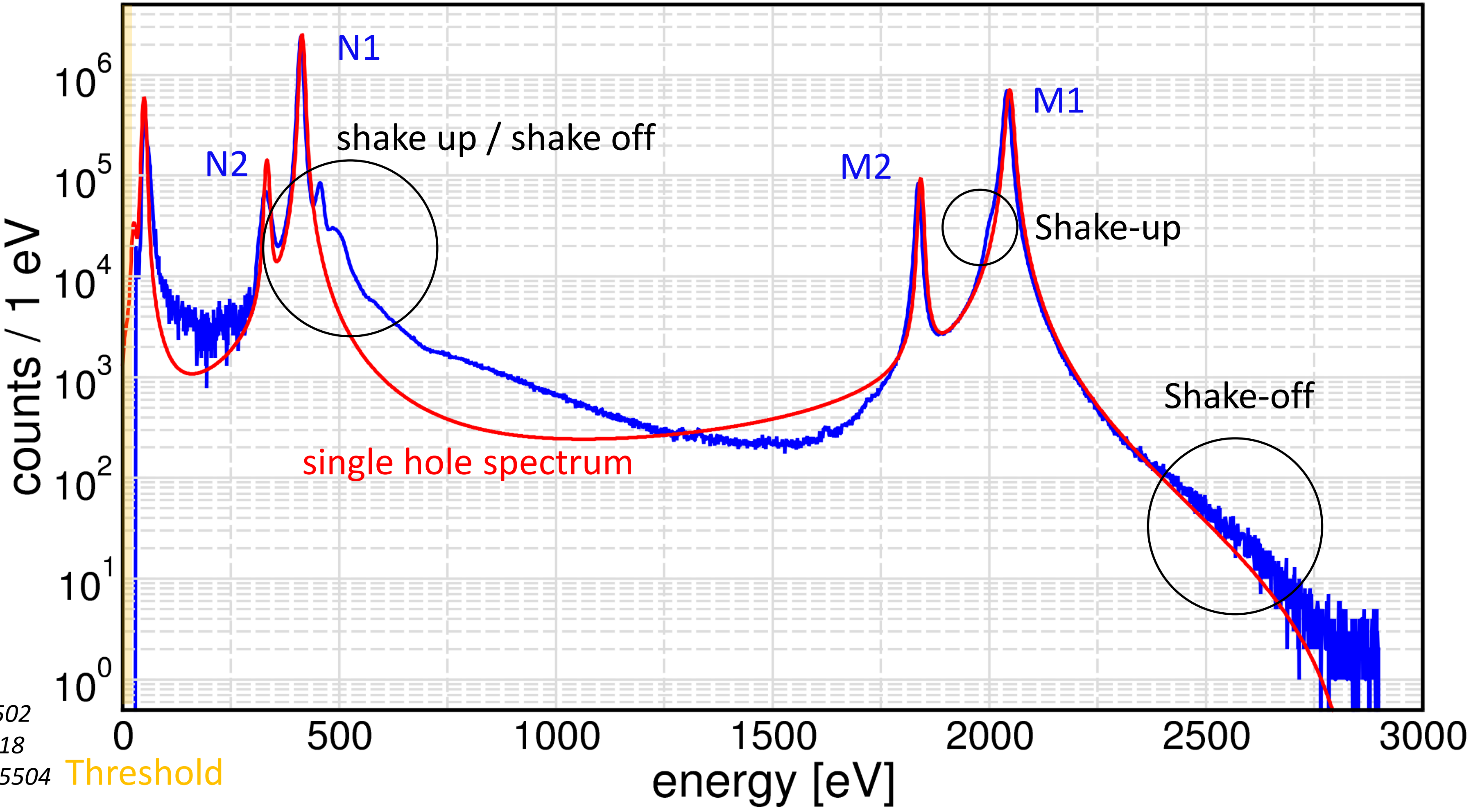
^{163}high statistics spectrum

Additional data taking with lower threshold



shake-up   shake-off

experimental EC spectrum deviates from all theoretical predictions



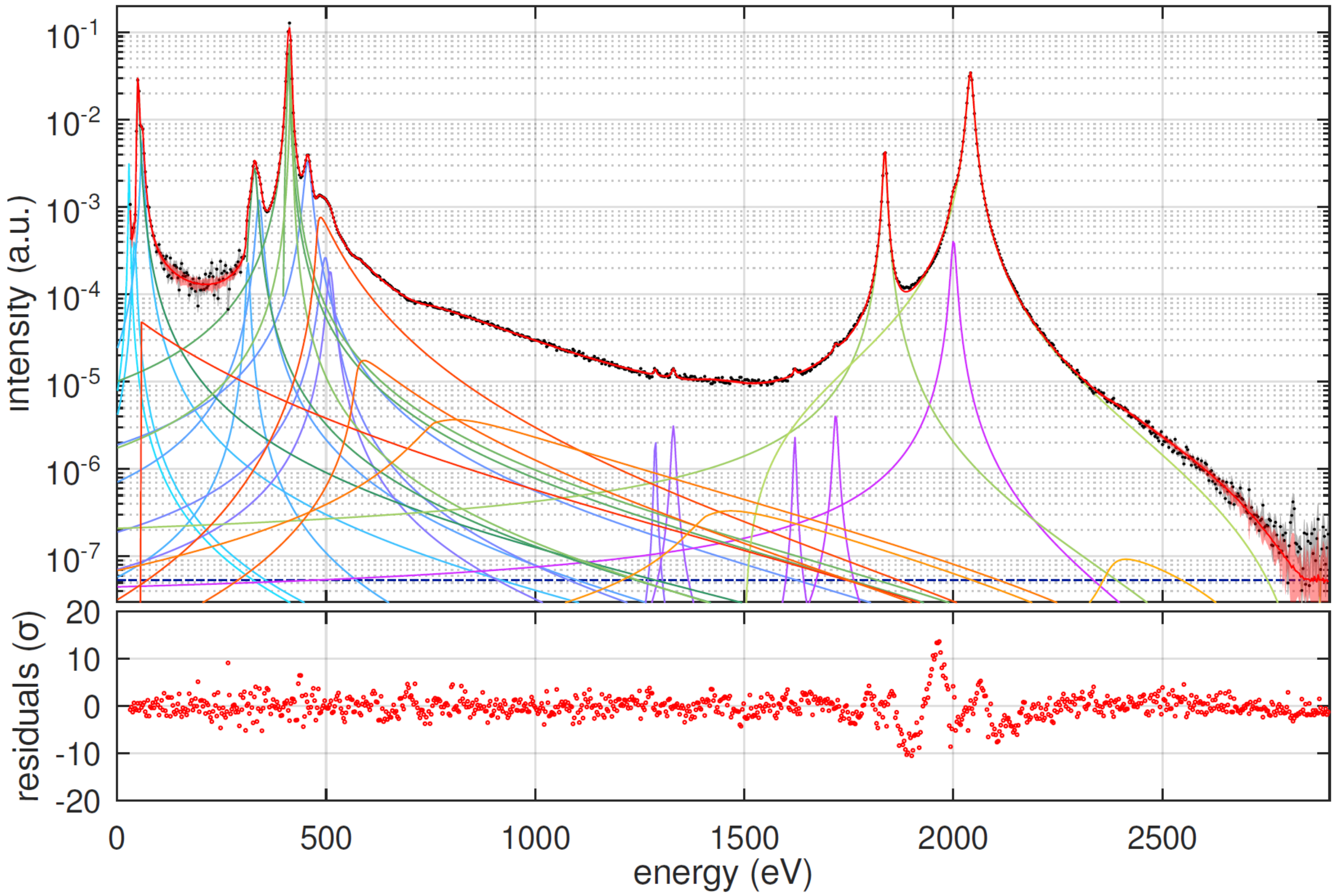
A. De Rújula et al., J. High Energ. Phys., 2016 (2016) 15
A. Faessler et al., Phys. Rev. C, 95 (2017) 045502
M. Brass et al.t, New J. Phys., 22 (2020) 093018
R. G. H. Robertson, Phys. Rev. C, 91 (2015) 035504

Unfolding experimental ^{163}Ho spectrum

Signal rate higher than single hole spectrum → impact on m_ν sensitivity?

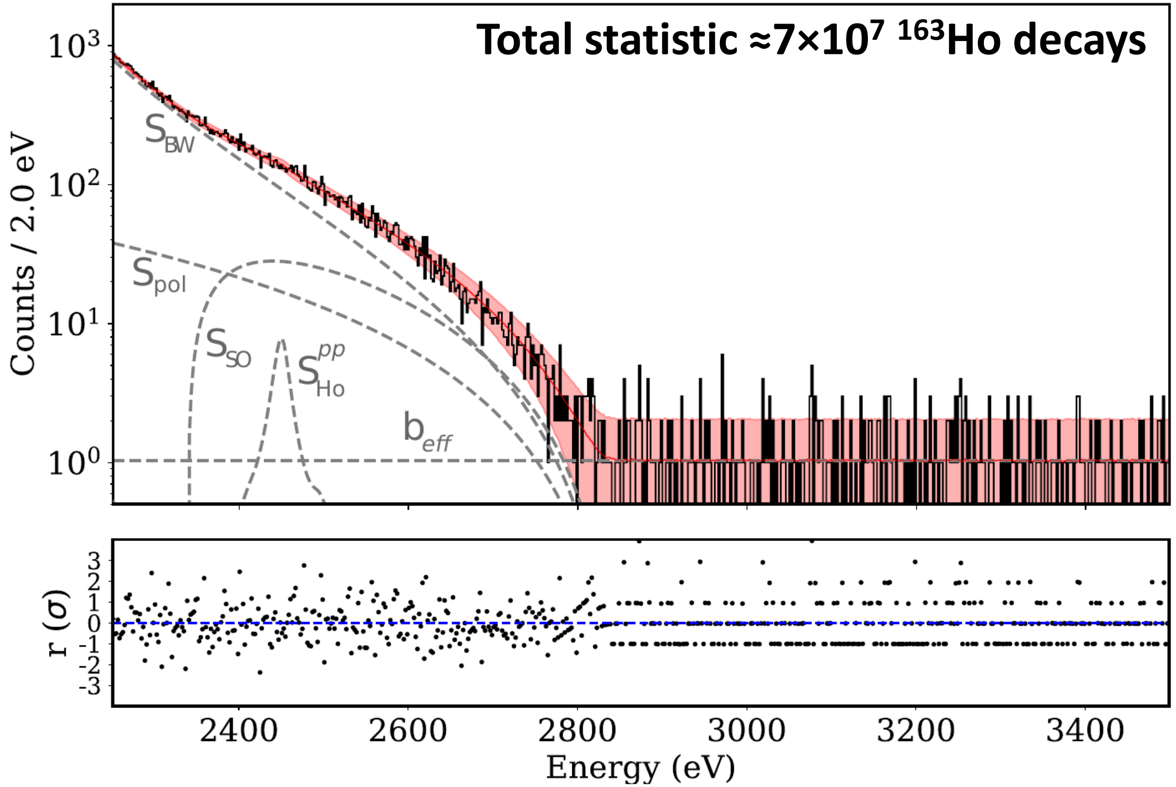
Experimental EC spectrum deviates from theoretical predictions → phenomenological description of the EC spectrum is now under study

- shake-up peaks and shake-off spectra
- strongly asymmetric Lorentzians needed for assessing sensitivity of future ^{163}Ho experiments



Bayesian analysis with 13 free parameters: ROI 2250 – 3500 eV

- ^{163}Ho spectrum modelled as sum of only few terms
- $\langle \Delta E_{FWHM} \rangle$ = 6 eV, pile-up fraction < 10^{-5}
- Statistical sensitivity from toy MC ~ 40 ± 10 eV

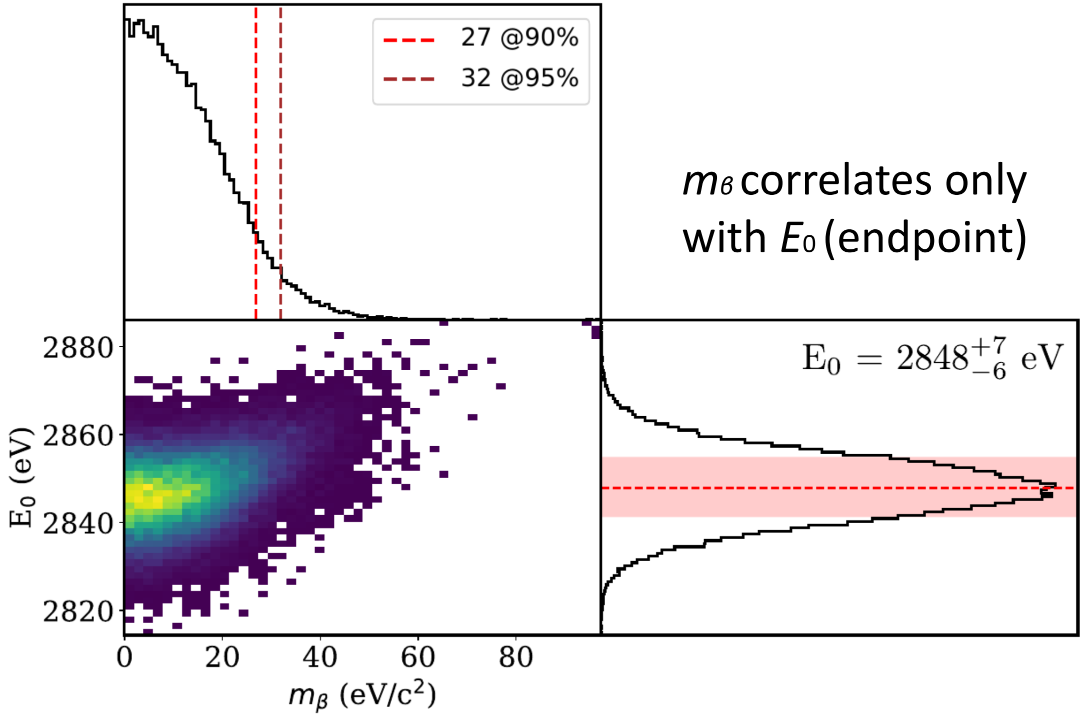


Limit on the neutrino mass

HOLMES collab., Phys. Rev. Lett. 135 (2025) 10.1103/s9vl-7n24

m_ν < 27 eV @ 90% CI

$E_0 = 2848^{+7}_{-6}$ eV



m_β correlates only with *E_0* (endpoint)

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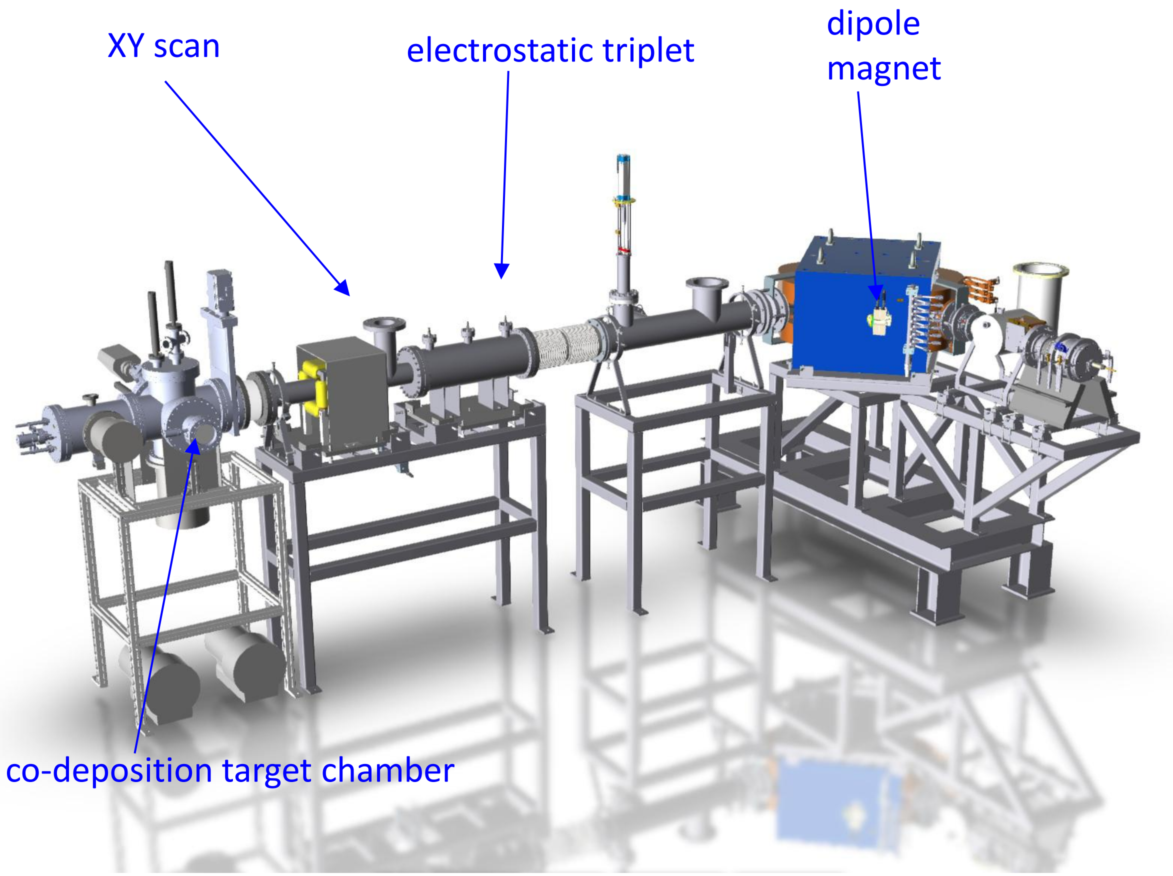
HOLMES+
3 year program activities:

- **Improve ion implanter for better beam control and higher efficiency**

Toward sub eV sensitivity:
- Major upgrade of ion source new (much) more efficient ionization technique under study

- Reduce detector operating temperature down to 30 mK
- **Increase the number of channel and reduce readout/DAQ cost → few €/ch**

HOLMES+ and beyond toward eV and sub eV



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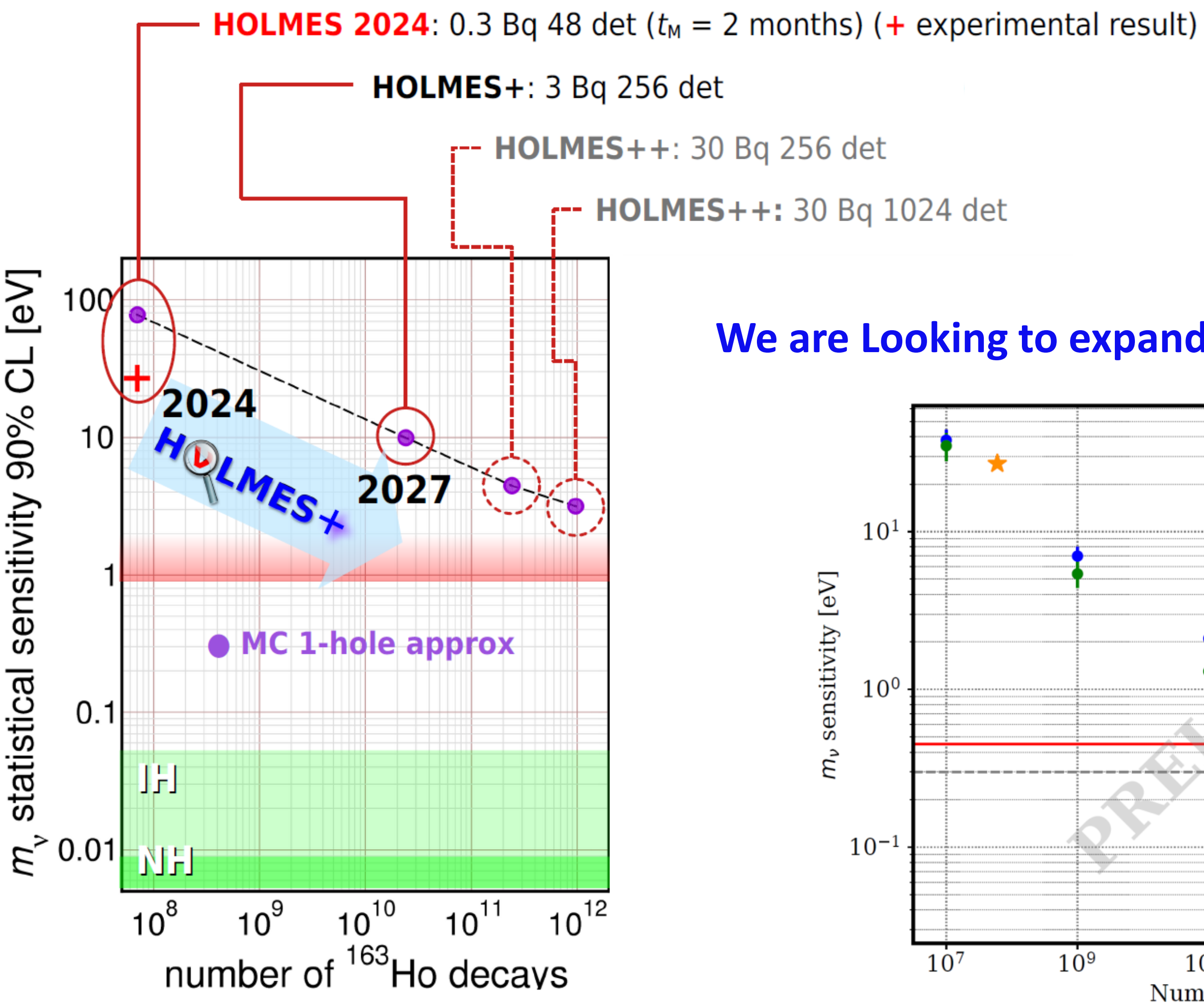
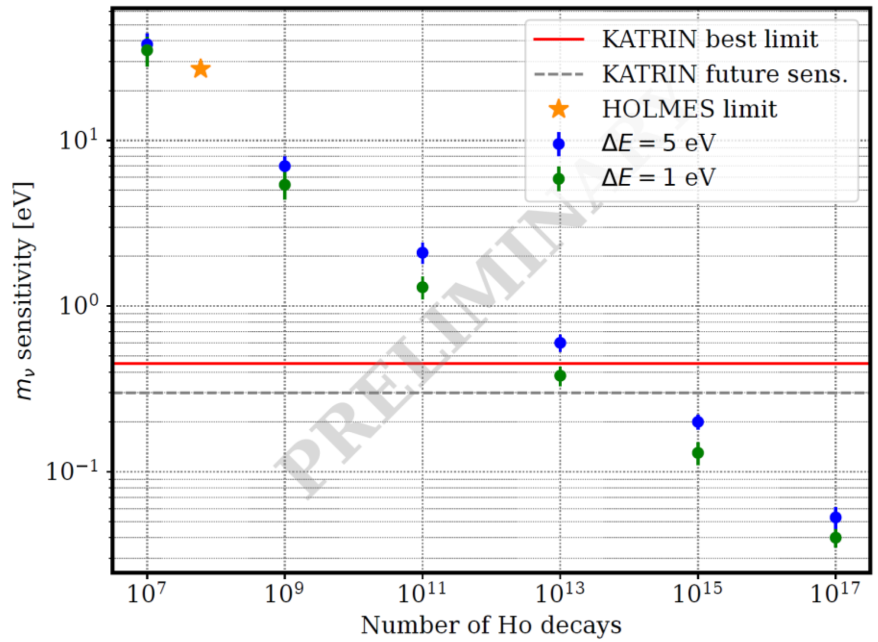


ΔE_{FWHM} = 5 eV
τ_R = 2 μs
b = 2×10^{-4} c/eV/day/det
t_M = 1 y

We are Looking to expand international collaboration



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Conclusions

HOLMES has successfully demonstrated the feasibility of the calorimetric measurement of ^{163}Ho EC decay spectrum.

The calorimetric measurement is mature for next-generation holmium-based experiments targeting **sub eV sensitivity.**

- Scalable detector and readout architecture.

Improved understanding of the ^{163}Ho decay spectrum enables:

- Precise end-point analysis
- Refined sensitivity projections for future experiments

HOLMES+ drives the technological optimization for future holmium-based neutrino mass measurements

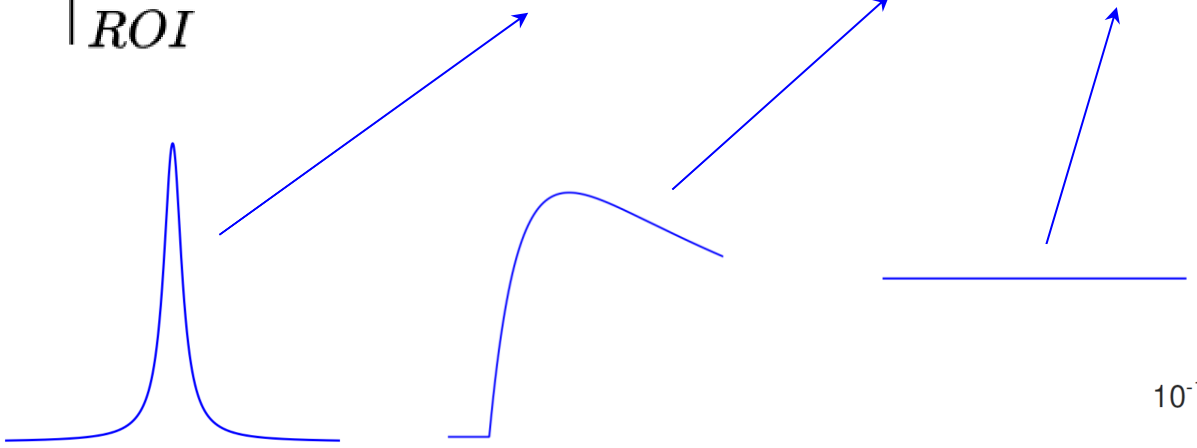
In the next years, we plan to increase our sensitivity with a step by step approach.
New results will come (hopefully) soon!

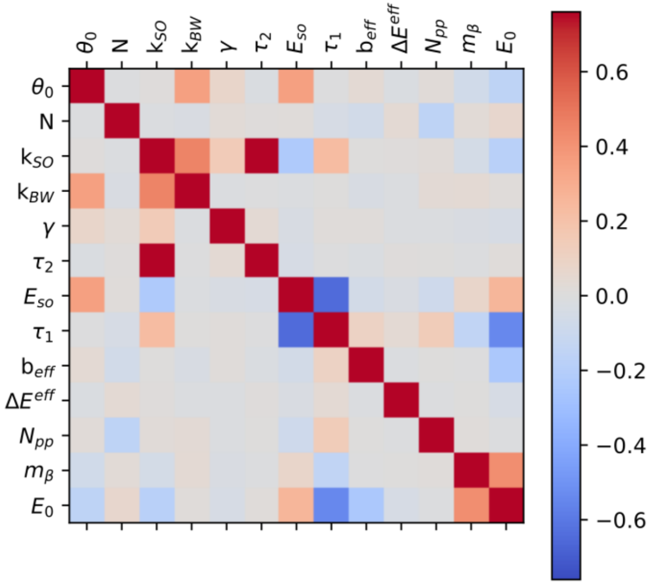
Backup

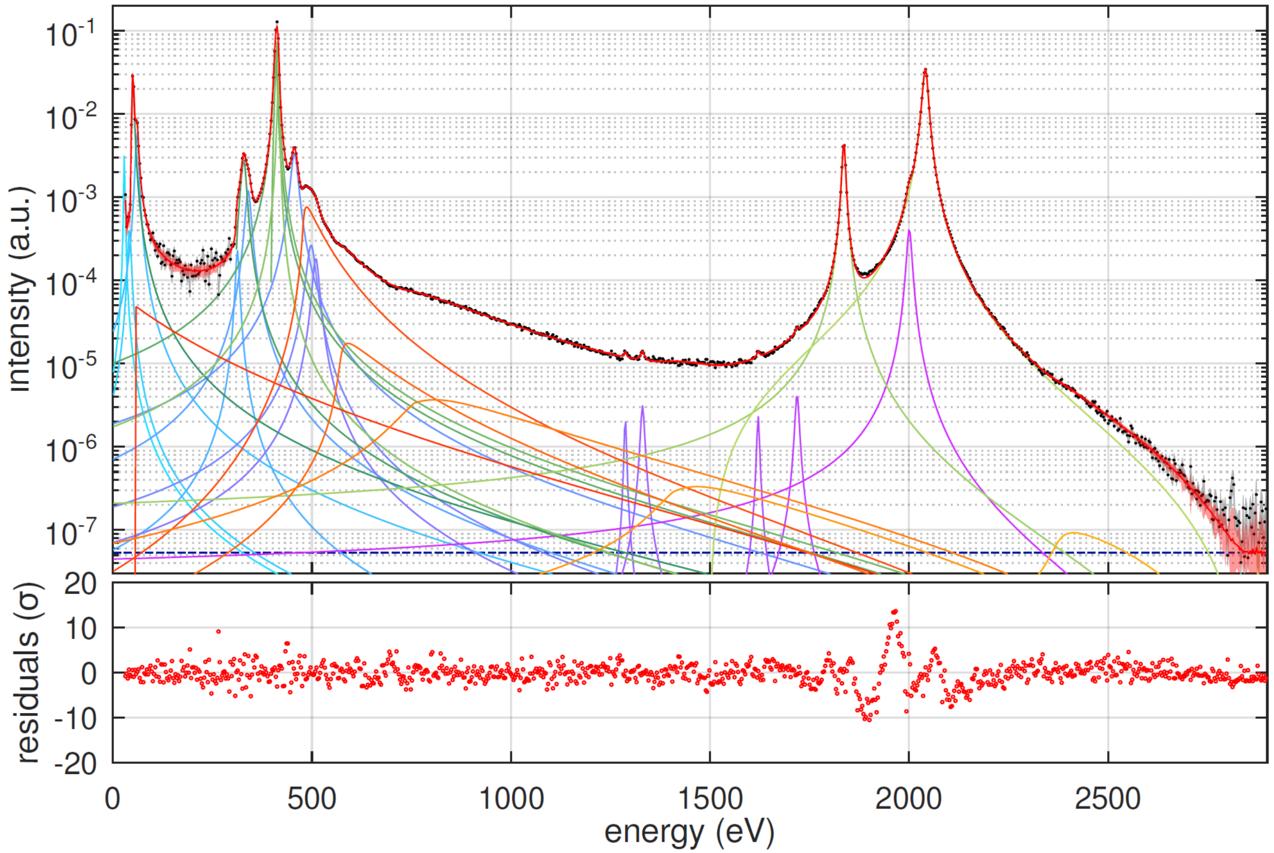
$$S_{Ho}\Big|_{ROI} \sim k_0(k_{BW}S_{BW} + k_{SO}S_{SO} + S_{pol}) \times F$$

- Phase space (***F***) is the only term with explicit m_β dependance

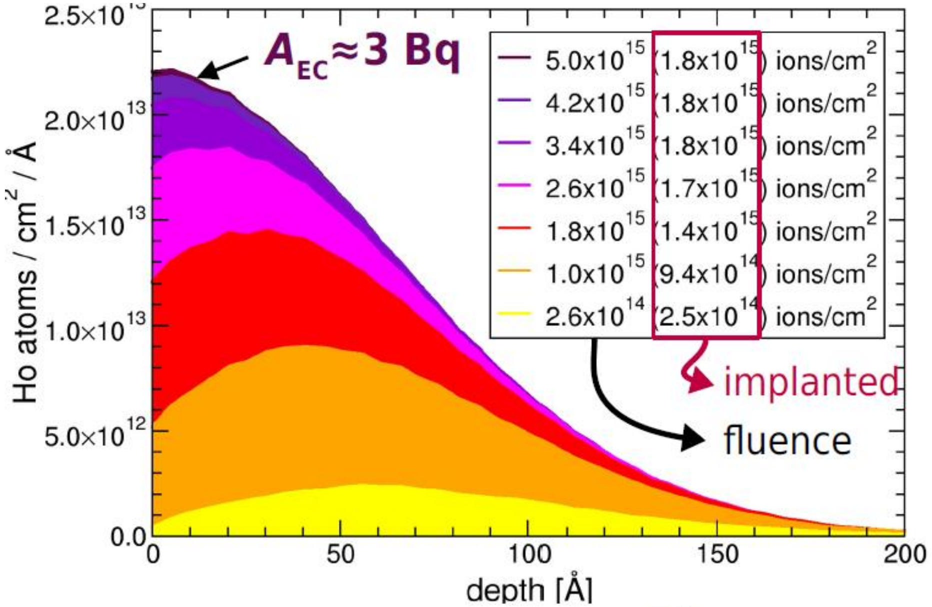
$$F = (Q - E)\sqrt{(Q-E)^2 - m_\beta^2}$$



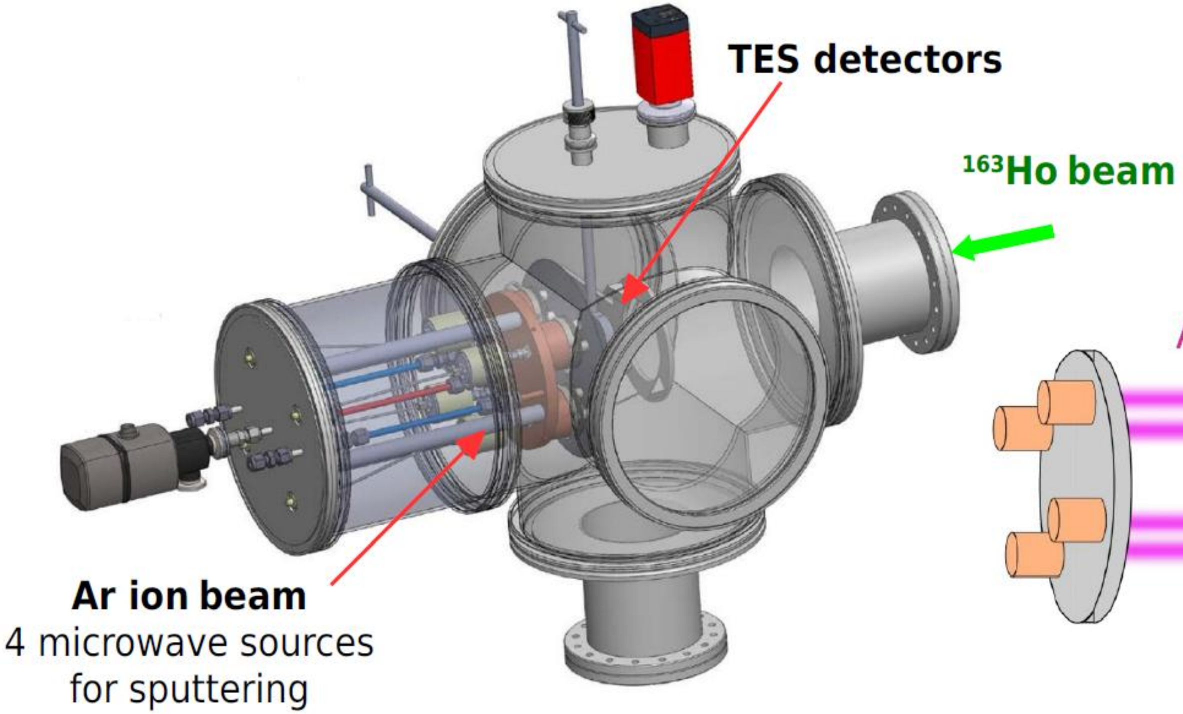


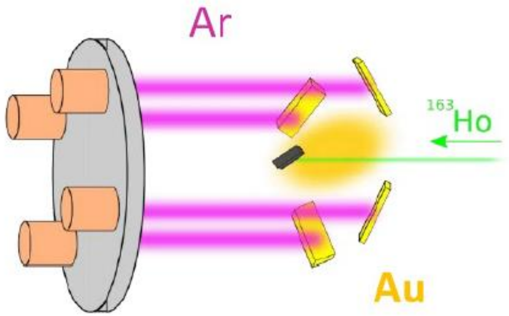


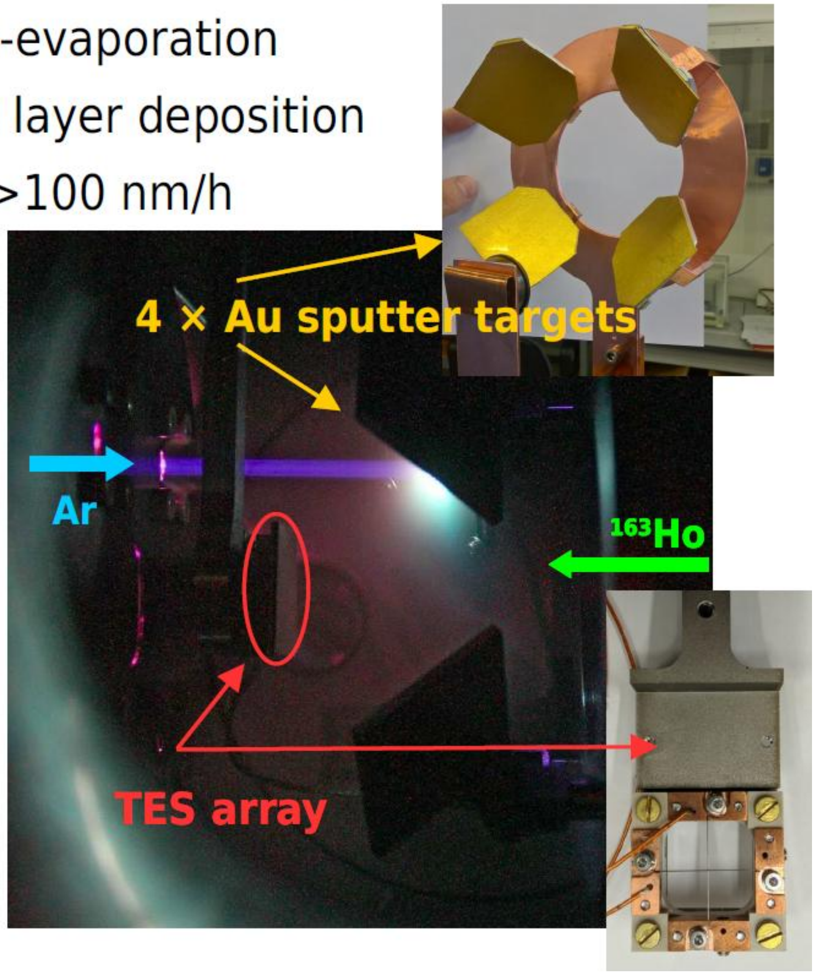
HOLMES co-depositon system



- ion implant simulation with SRIM2013
- **^{163}Ho ions on Au (E_{ion} = 50 keV)**
- ^{163}Ho ion beam sputters off Au from absorber (≈26 Au/Ho)
  - implanted ^{163}Ho saturates at A_{EC}≈3 Bq (HOLMES design)
  - compensate by Au co-evaporation
  - in situ upper 1 µm Au layer deposition
    → with 4 ion sources >100 nm/h

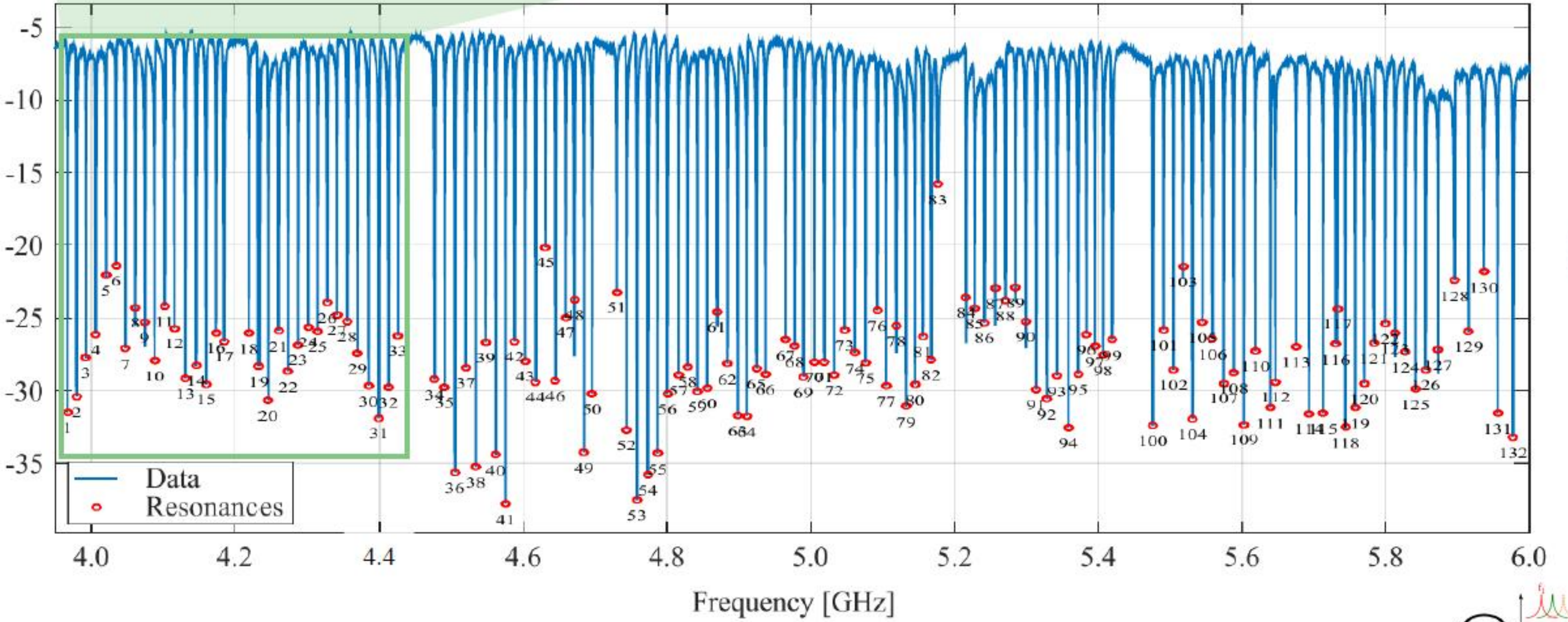


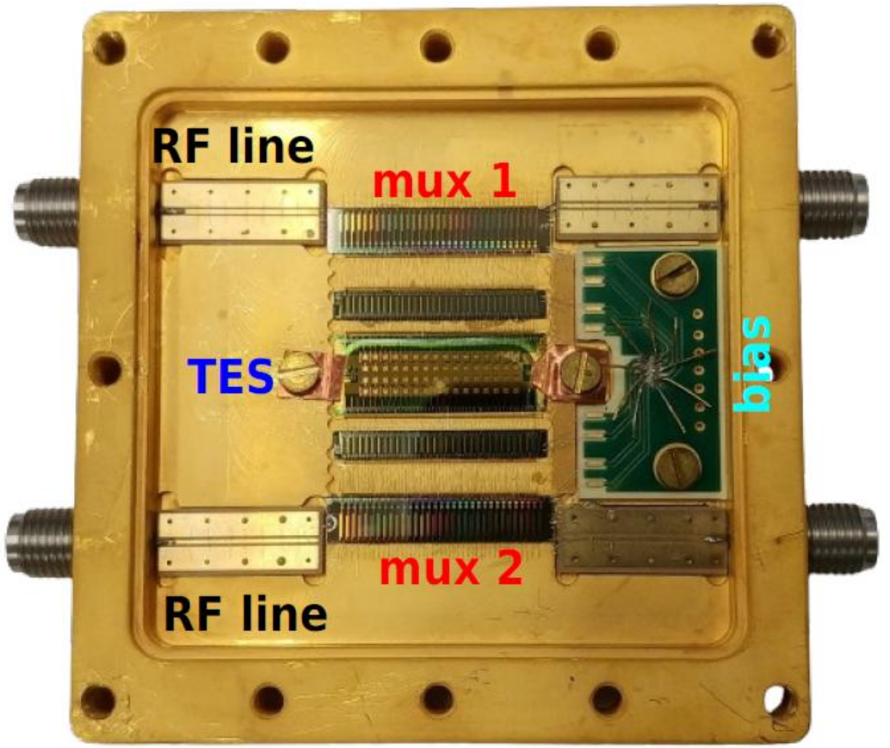




HOLMES Multiplexing

4 µmux chips in series
→ 132 resonances in 2 GHz

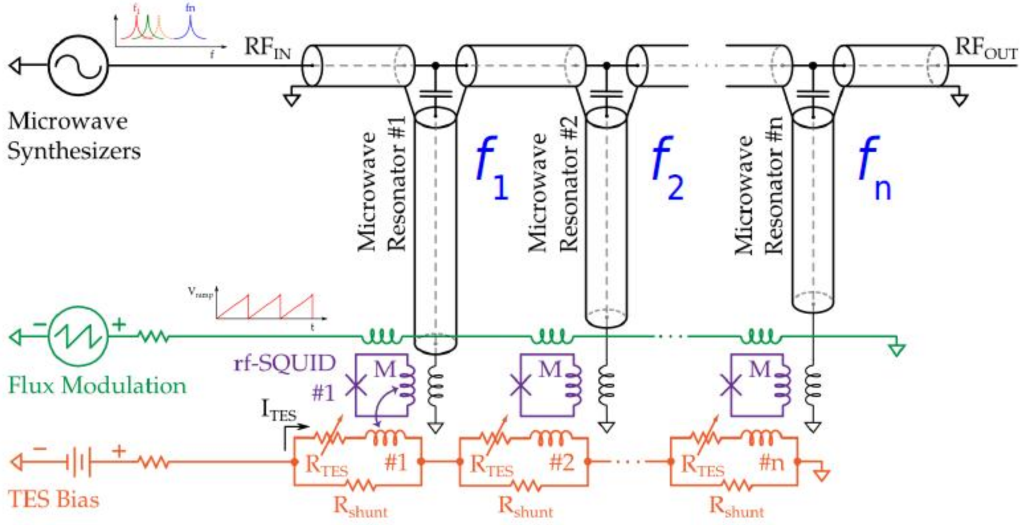




pulse τ_{rise}, x-talk, ... → **64 carrier tones / GHz**
→ DAQ multiplexing factor $\boldsymbol{n_{TES}}$ per ADC module

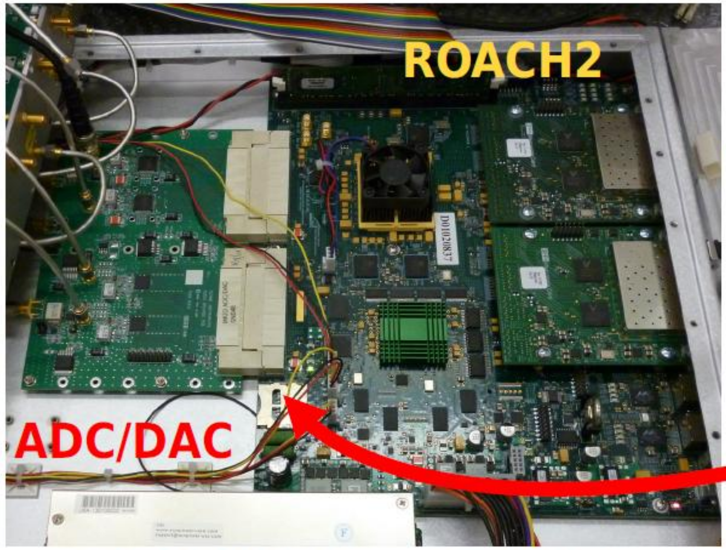
$$n_{\mathrm{TES}} \approx \frac{1}{140}\ \tau_{\mathrm{rise}}[\mu s]\ f_{\mathrm{ADC}}[\mathrm{MS/s}]$$

for f_{ADC}=512 MS/s and τ_{rise}≈10 µs → $\boldsymbol{n_{TES}}$**≈32**



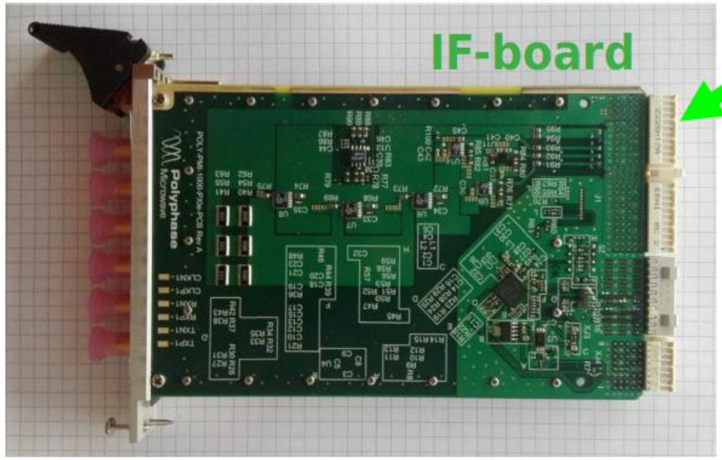
DAQ

Software Defined Radio generates RF tones and demodulates output RFsignals

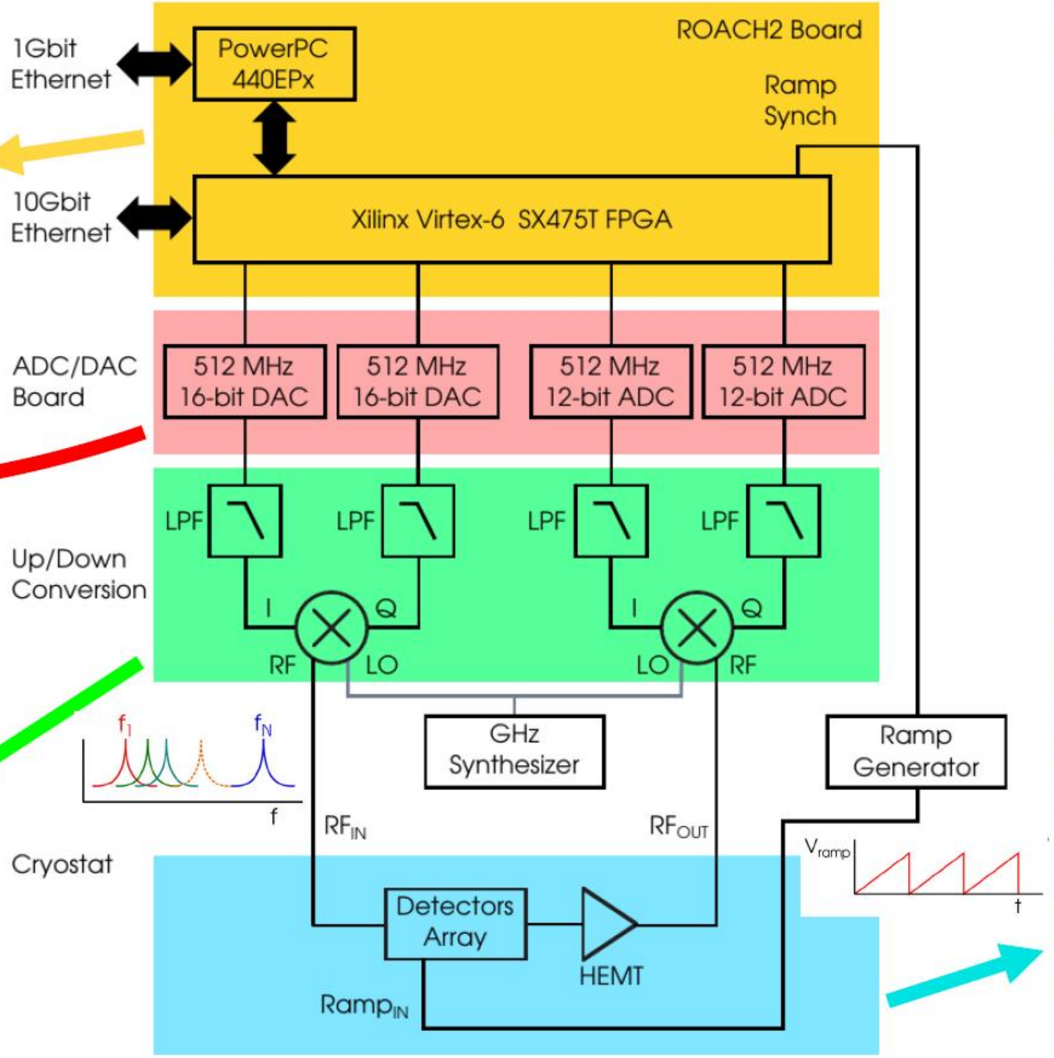


2 ROACH2 (f_{ADC}=512 MS/s)

for 64 detectors

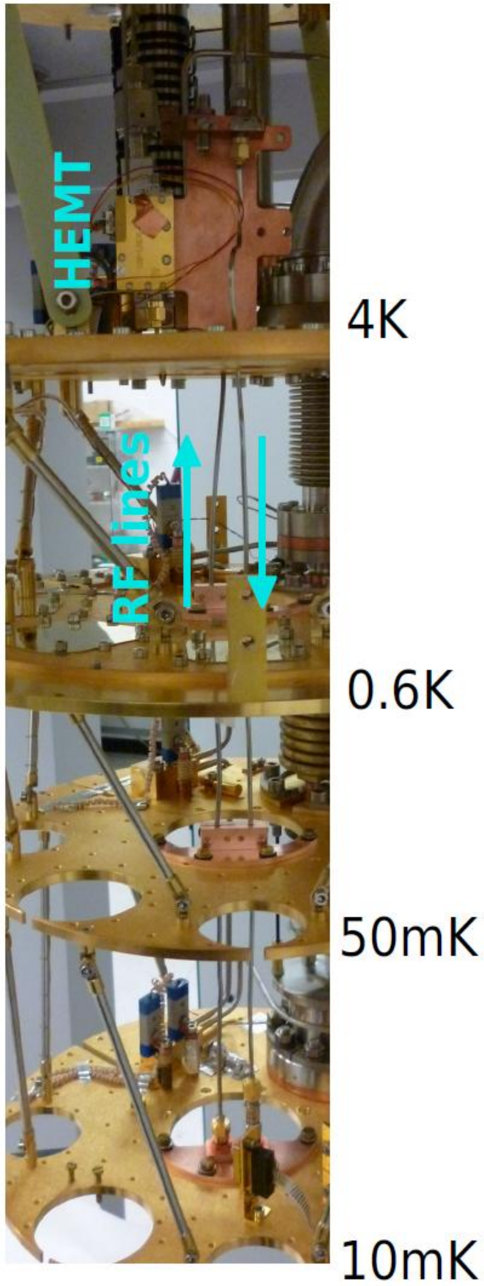


2 IF-board for 64 detectors



1 HEMT (BW 4-8 GHz)

for up to 256 detectors

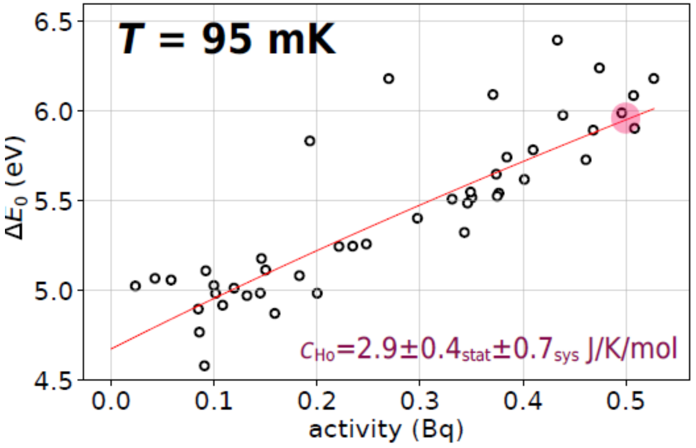


Lower Tc TES development

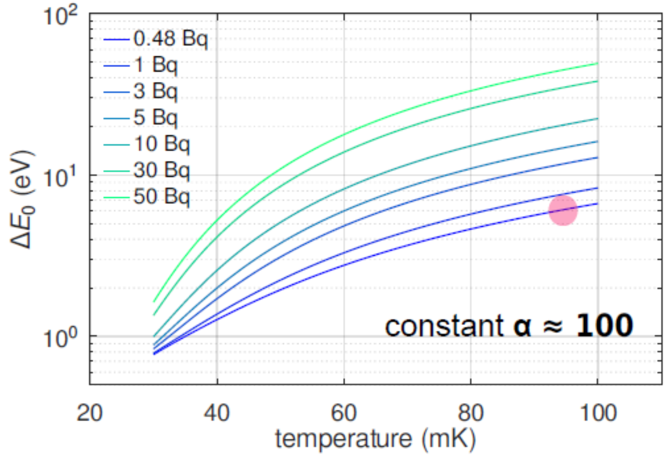
increase ^{163}Ho activity per detector → up to 50 Bq

- reduce detector operating temperature to ≲ 40mK

from HOLMES array with embedded ^{163}Ho



$$\Delta E_0 \propto \sqrt{T^2\left(C_{\mathrm{TES}}(T) + \frac{A_{\mathrm{Ho}}}{\lambda N_{\mathrm{Av}}} c_{\mathrm{Ho}}(T)\right)} \;*$$



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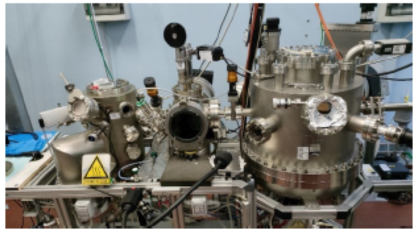
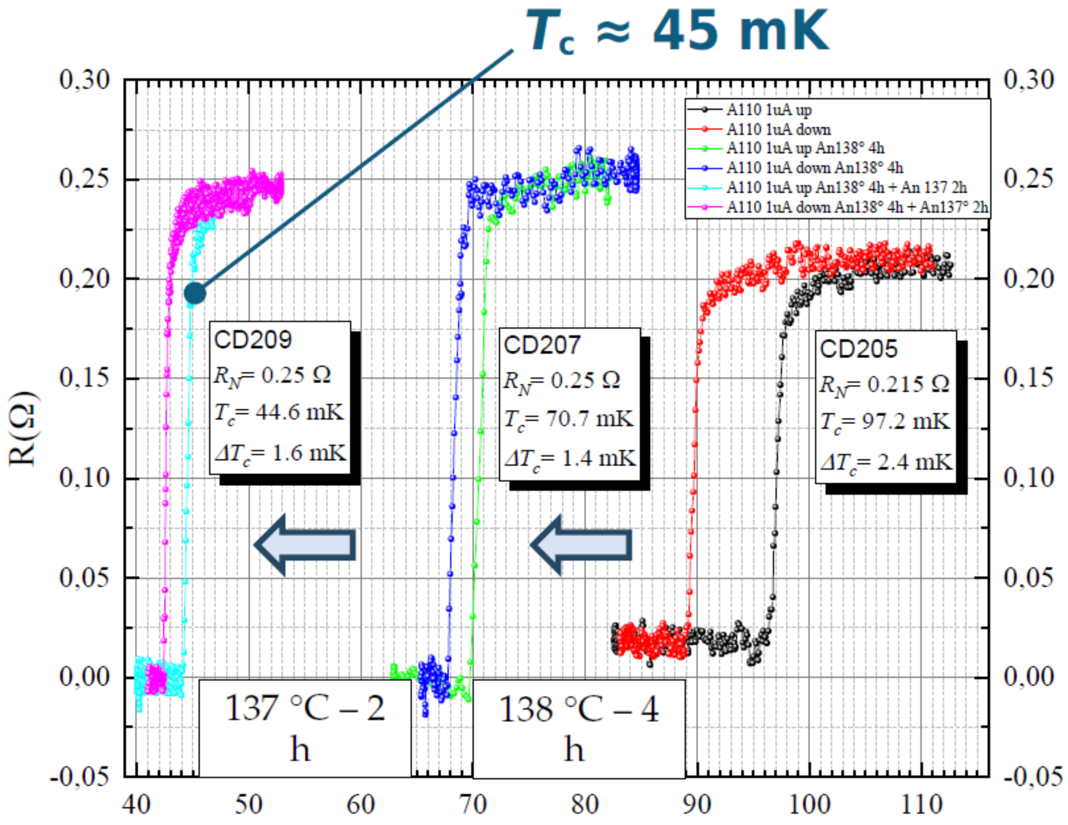




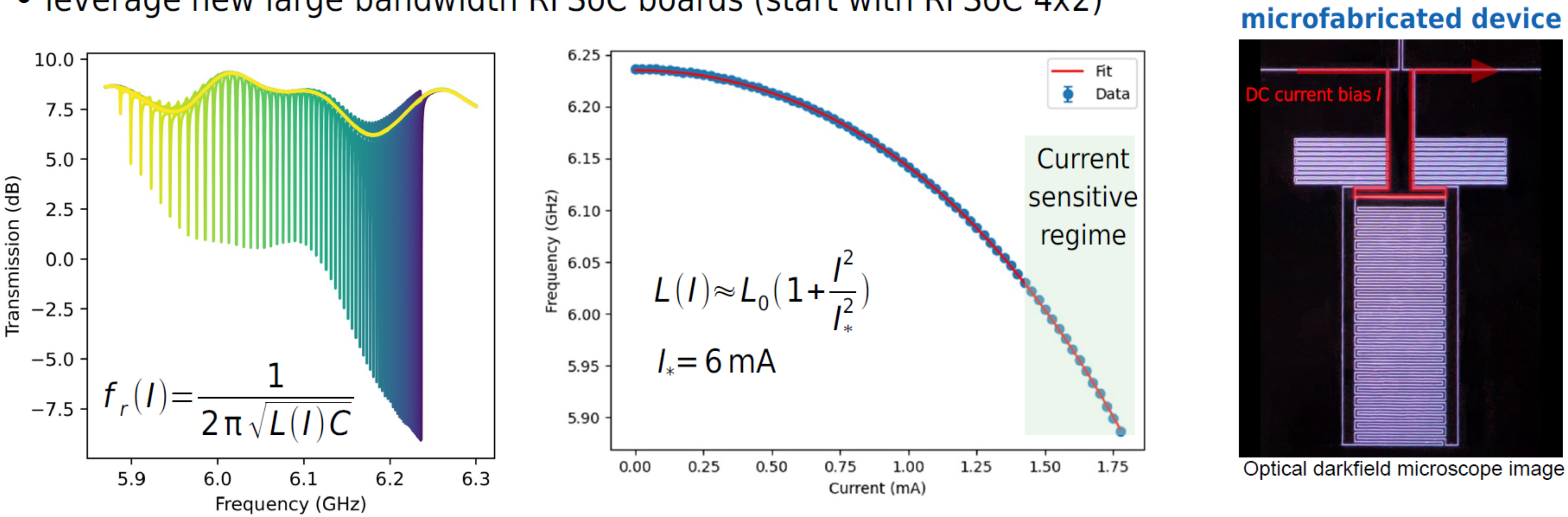
Ti/Au bilayers with T_c ≈ 100 mK

reduce T_c by annealing at ≈150 °C

New KICS readout development

reduce readout/DAQ cost → few € per channel

- new multiplexing scheme w/o rfSQUIDs and larger multiplexing factor
  - microwave multiplexed Kinetic Inductance Current Sensor *P. Szypryt et al., Commun Eng, 3 (2024) 1-9*
  - up to a 10-fold increase in frequency multiplexing factor (pixel/GHz)
- leverage new large bandwidth RFSoC boards (start with RFSoC 4x2)



first **current tunable resonator** prototypes with **≈10nm NbTiN**

- successful resonance tuning with persistent current

in progress: KICS designed to readout HOLMES TESs