A limit on neutrino mass with the first HOLMES dataset

EUROPEAN PHYSICAL SOCIETY EPS HEP2025 MARSEILLE

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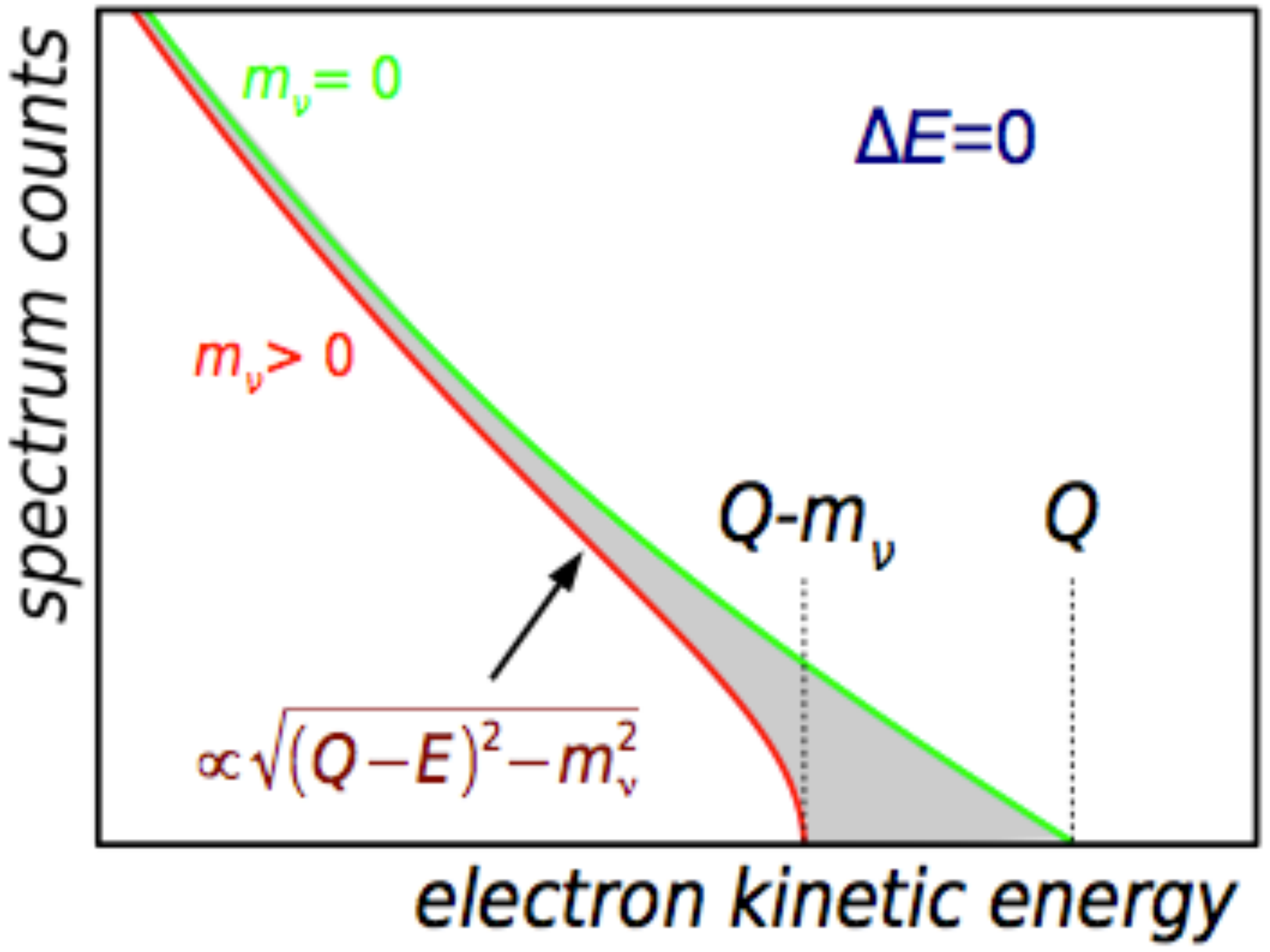
Outline

- Direct neutrino mass measurements
- ^{163}Ho and neutrino mass: the HOLMES experiment
- First results from HOLMES
- Next steps to improve m_ν sensitivity

Direct neutrino mass measurements



- **Low-Q β/EC decay isotopes** (^{3}H, ^{187}Re, ^{163}Ho) needed;
- **model independent**: relies only on E, p conservation
- ν mass appears as a **distortion at the end point of the electron energy spectrum;**
- 2 different approaches.

Spectrometry:

- source ⊄ detector (**KATRIN** like).
  - High statistics allowed, **no pile-up issue.**
  - Main systematics sources:
    - **decay on excited states**;
    - **energy losses in source**.
- **Currently, gives the best limit: $m_\nu < 0.45$ eV**
- **Sensitivity down to 0.3 eV**

Calorimetry:

- source ⊂ detector (**HOLMES** approach)
  - Remove systematics related to energy loss in the source, **but implies pile-up issue!**
  - Need a trade off between activity and time reso + pile-up rejection algorithm.
  - **Could explore region below 0.3 eV**
  - **Complementary to spectrometry**

^{163}Ho electron capture and ν mass

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

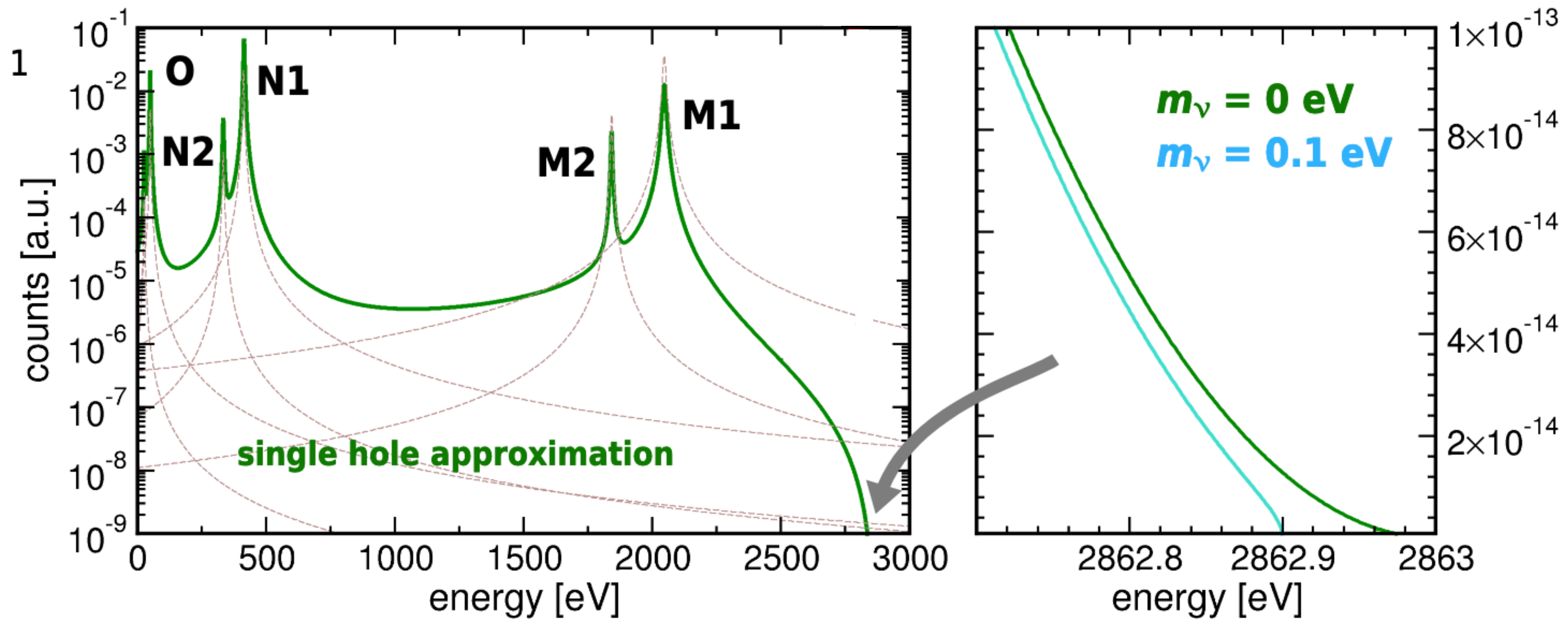
$$\frac{d\lambda_{EC}}{dE_c} = \frac{G_\beta^2}{4\pi^2}(Q-E_c)\sqrt{(Q-E_c)^2 - m_\nu^2} \times \sum n_i C_i \beta_i^2 B_i \frac{\Gamma_i}{2\pi}\frac{1}{(E_c-E_i)^2+\Gamma_i^2/4}$$

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)

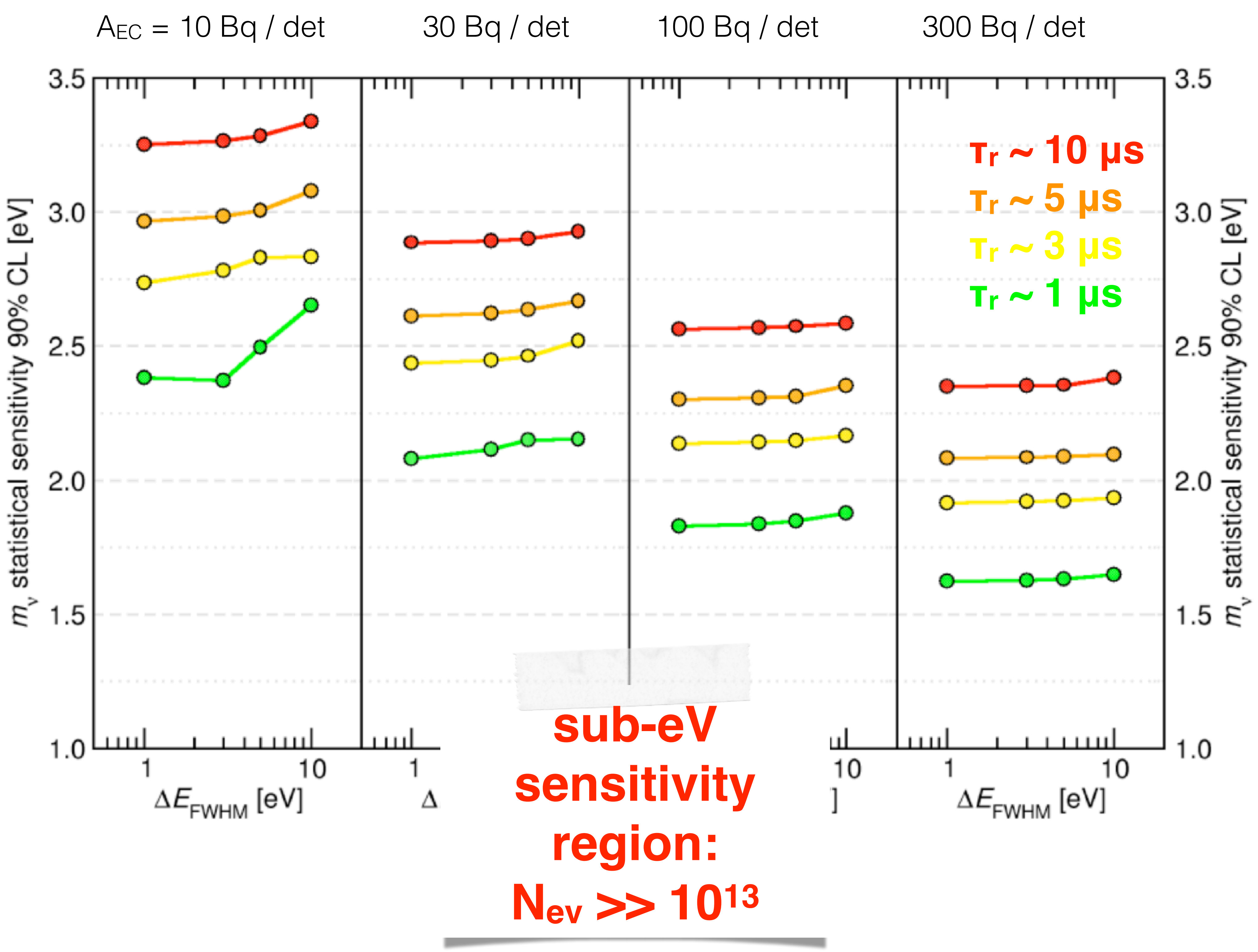
Breit-Wigner shape

- Calorimetric measurement of Dy* de-excitation spectrum;
- m_ν sensitivity depends on Q-value
- M1 line close to end-point could enhance “good” statistics?
- $\tau_{1/2}$ ~ 4570 years → high specific activity, avoid to spoil detector performances by adding too much ^{163}Ho.



The HOLMES experiment

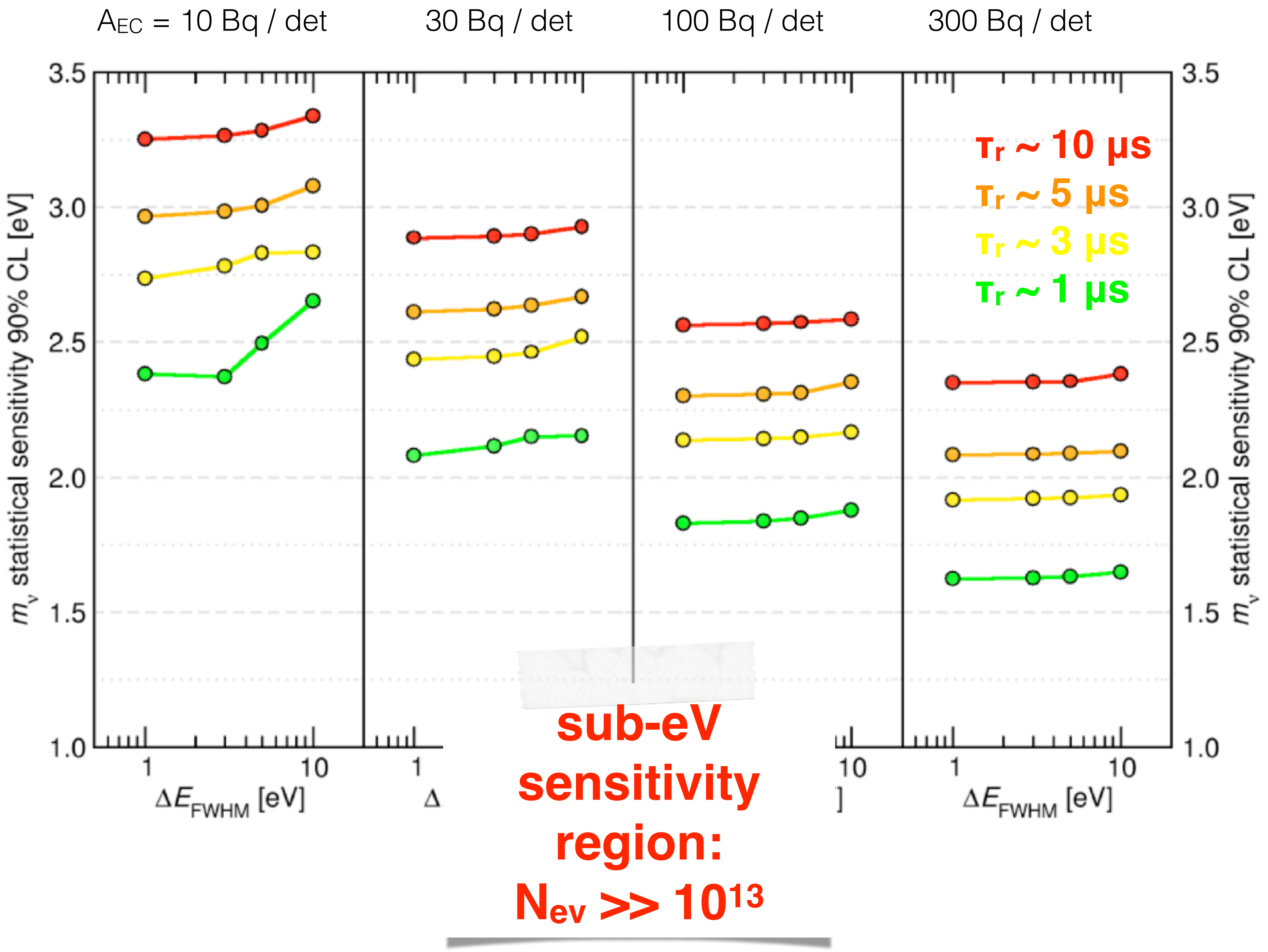
- Started as ERC Advanced Grant (2013)
- **Direct neutrino mass measurement** with statistical sensitivity around 1 eV
- Based on **Transition Edge Sensor (TES) micro-calorimeters** arrays with ^{163}Ho implanted Au absorber.
- Multiplexed readout
- Proposal:
  - 1k channels, A_{EC} ~ 300 Bq / det
  - 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



Multi-step approach to prove the feasibility of the project…

The HOLMES experiment

- **Multi steps approach:**
  - **64 chs prototype, ~ 1 Bq/ch (this talk)**
    - Probe of the full chain, assessment of implanted Ho effect on detector signals, first high statistic spectrum (analysis tool, spectrum evaluation…)
  - **256 chs, implanted with maximum achievable activity with current setup (1 - 3 Bq)**
    - t_m = 1 month, m_ν extraction with sensitivity O(10 eV)
  - **1k chs arrays with high activity O(100 Bq/ch):**
    - 6.5 x 10^{16} total nuclei
    - O(10^{13}) events / year
    - m_ν ~ 1 eV



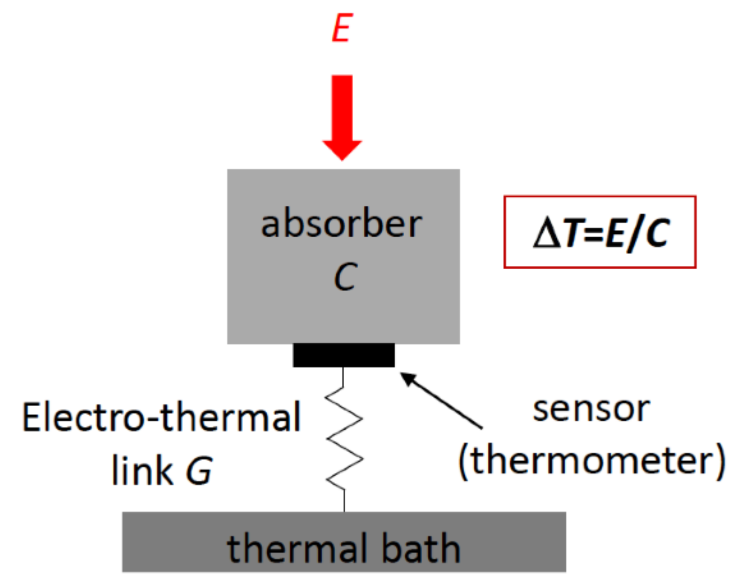
TES-based μ-calorimeters

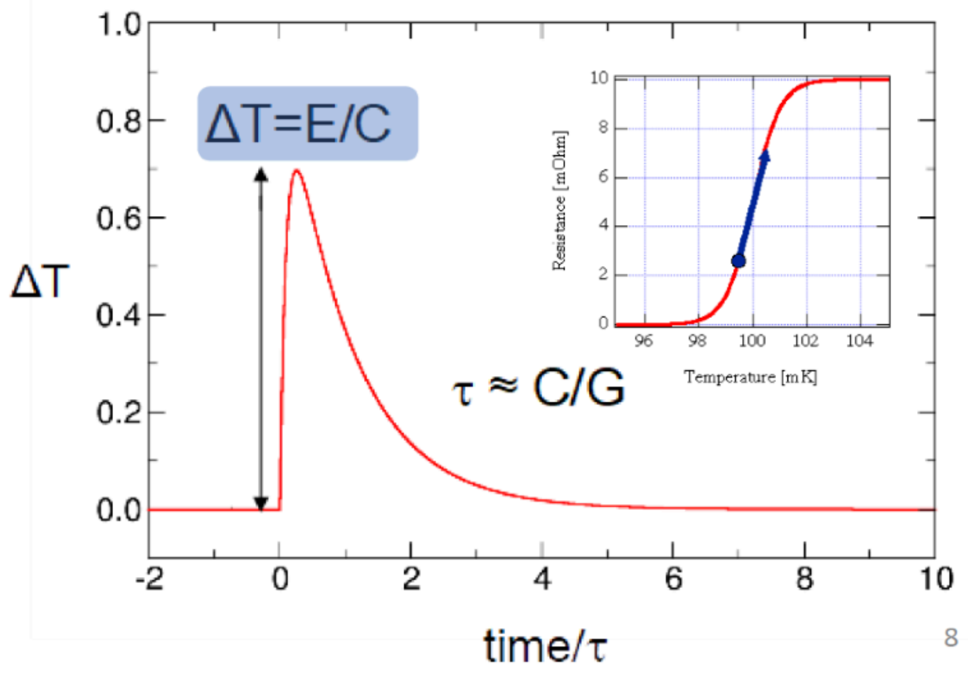
Transition edge sensors based *μ*-calorimeters:

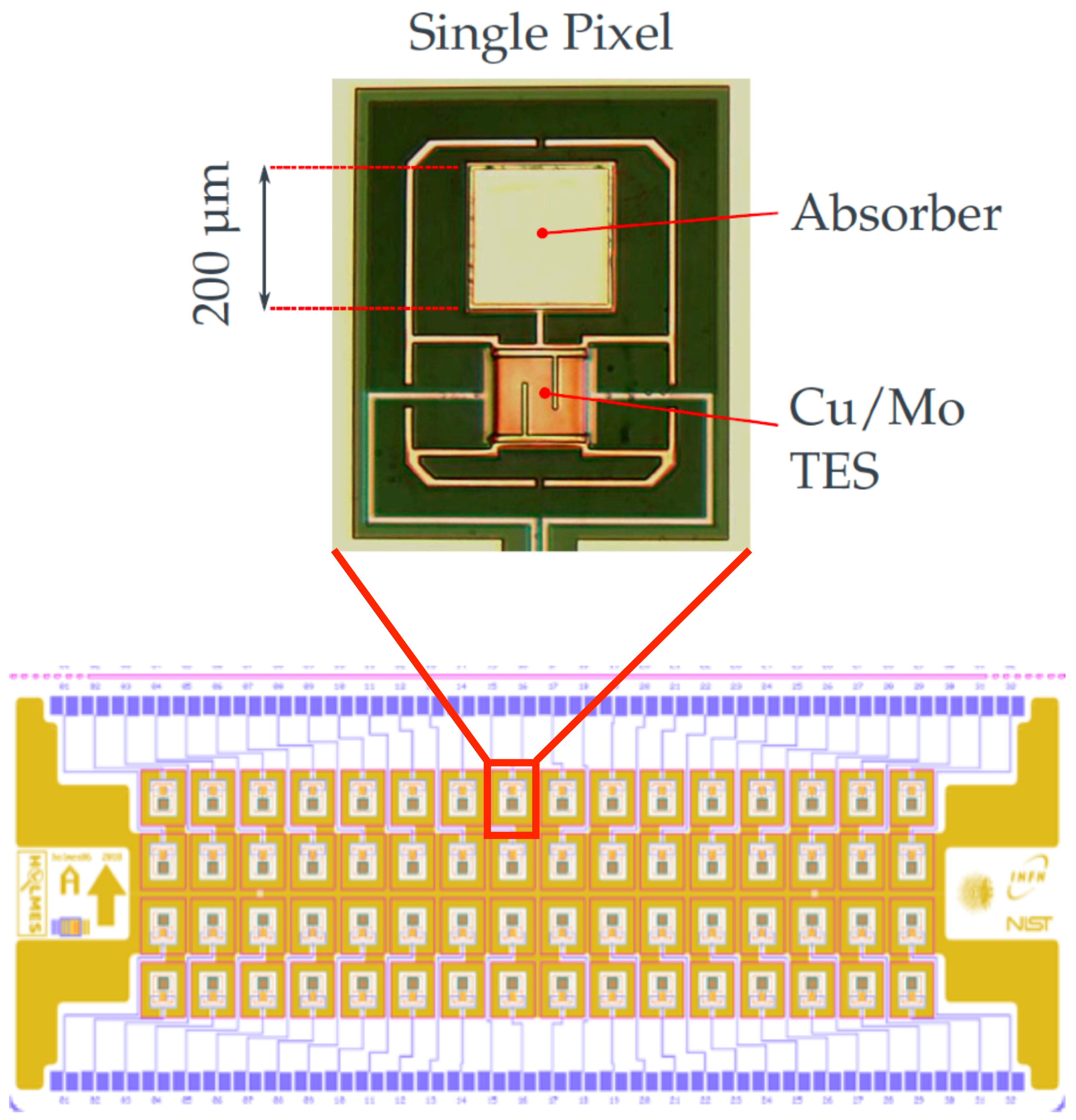
- Gold absorber coupled to superconductive Cu/Mo sensor in transition region,
- energy release in absorber → temperature increase in TES → variation of TES resistance;
- 2 μm Au thickness for full energy absorption
- Operating point at 100 mK

Multi step production procedure:

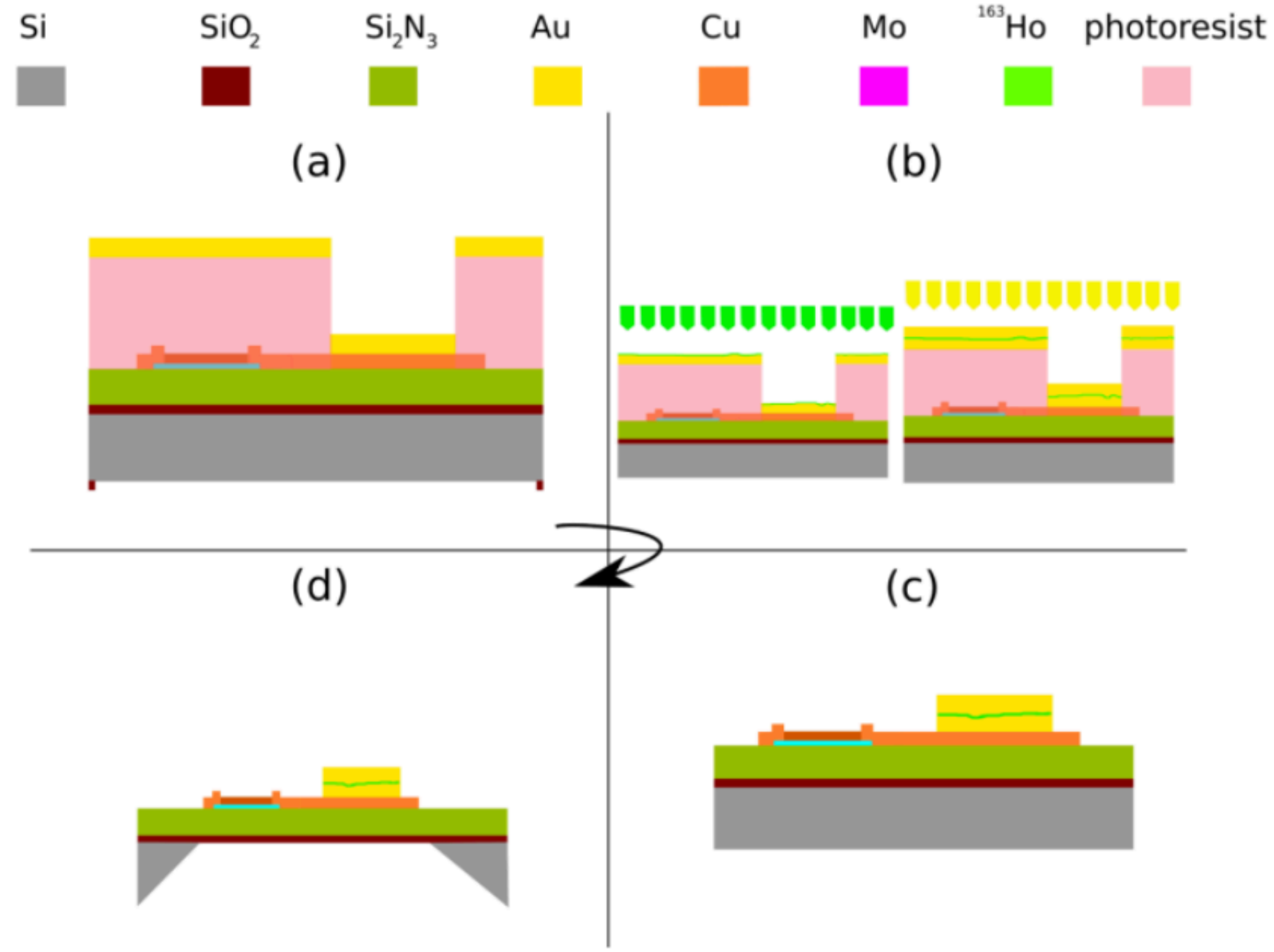
- Up to first 1um of Au at NIST;
- Ho implantation in Genova;
- absorber completion, bonding and membrane release in Milano.







64 chs array



^{163}Ho embedding

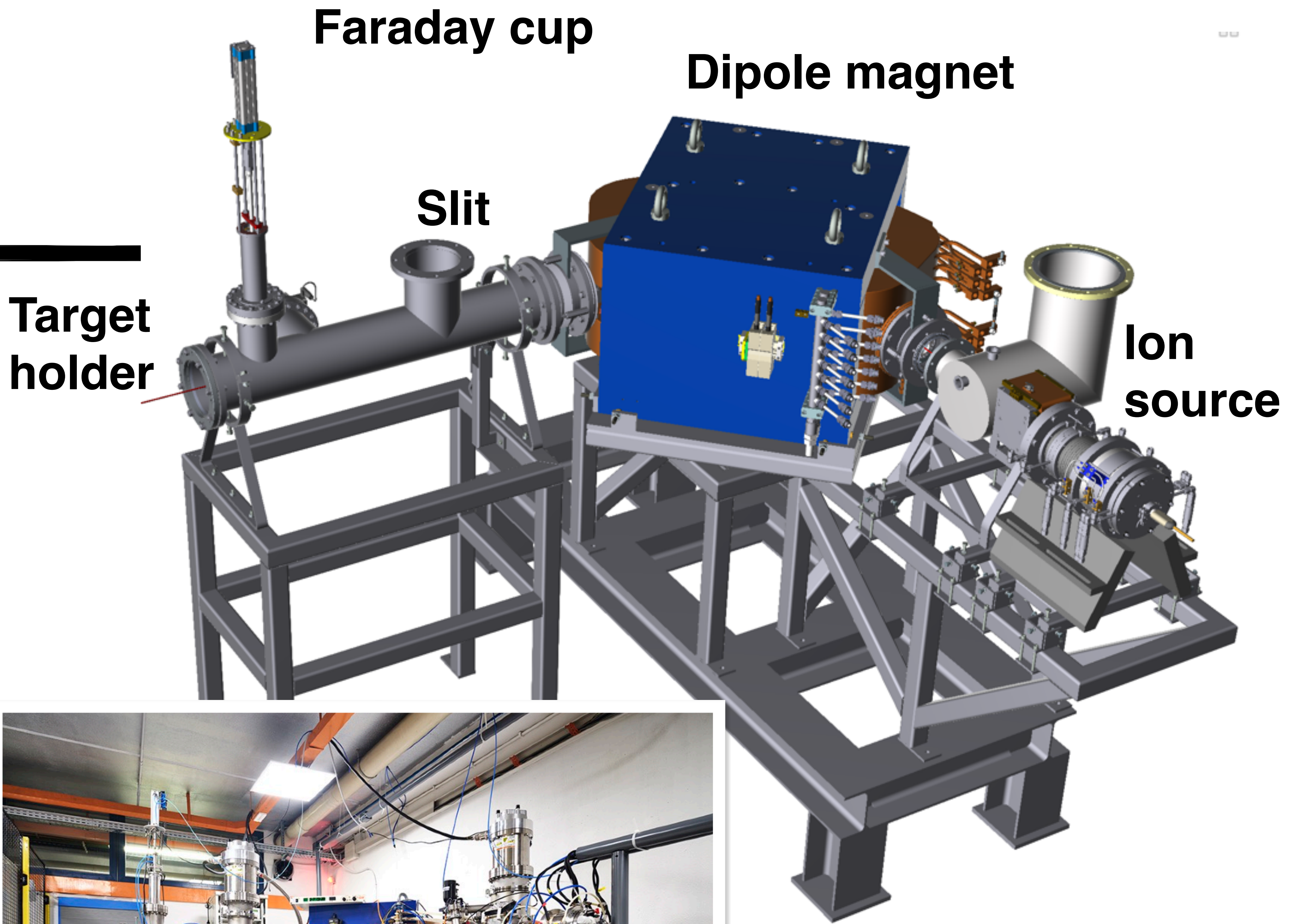
A **chemical purification** before and after the activation is needed to remove contaminants other than Ho.

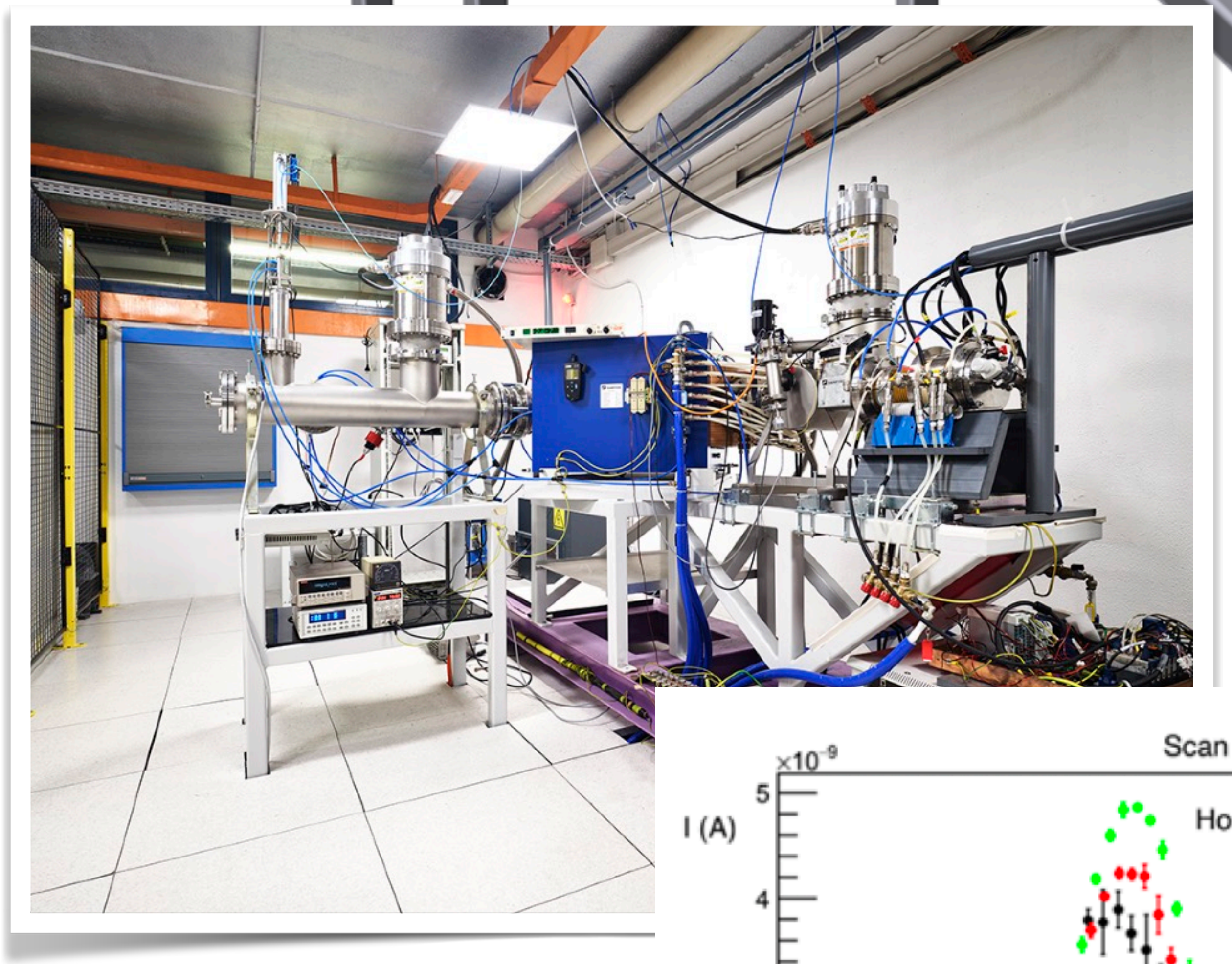
An **ion implanter** has been designed and commissioned to embed ^{163}Ho in the μ-calorimeters and **to remove ^{166m}Ho residuals.**

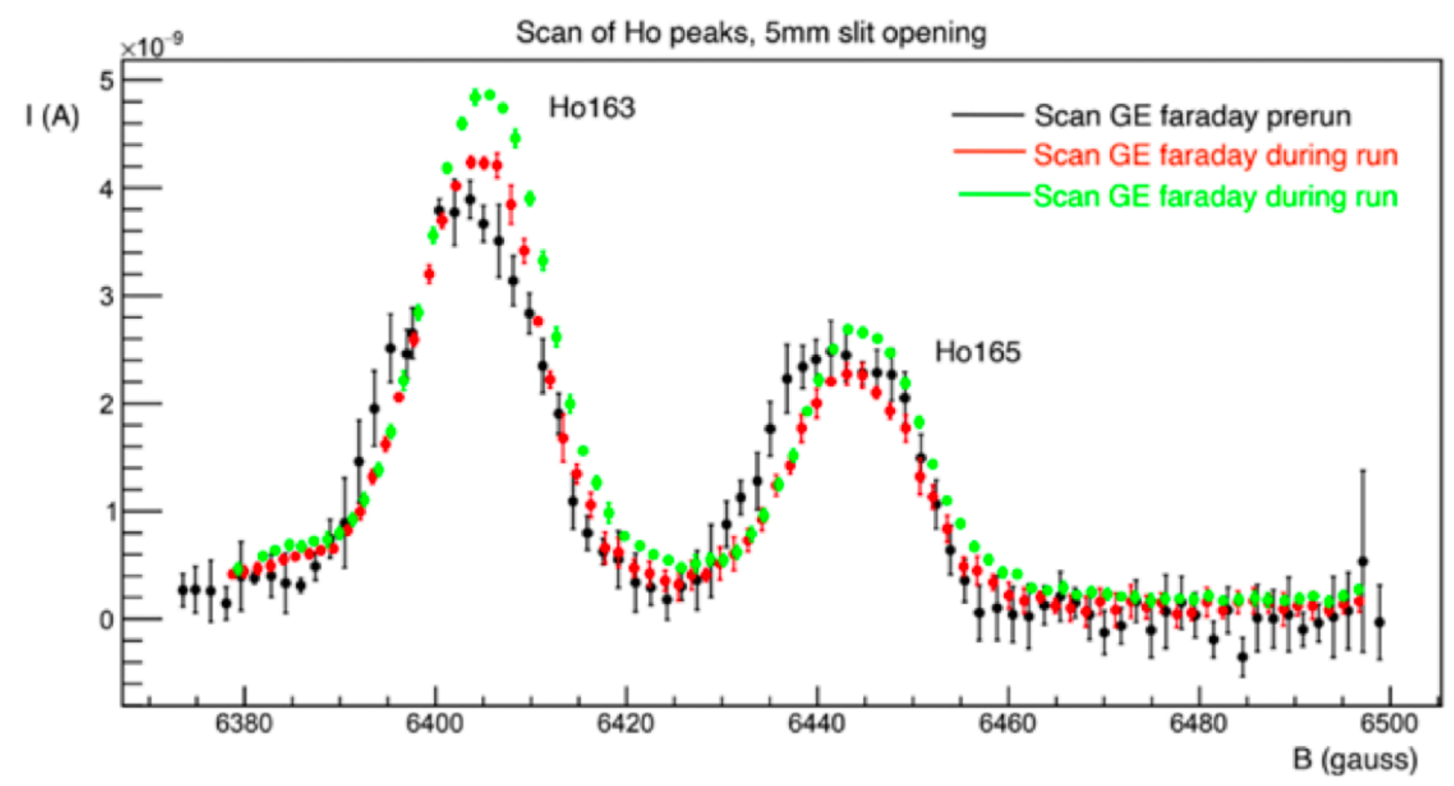
With a quite simple setup (50 keV penning sputter ion source + dipole + slit and FC) we obtained:

- **beam size σ ~ 1.5 mm;**
- **163 / 166 mass separation > 5 σ;**
- **efficiency ~ 0.2%.**

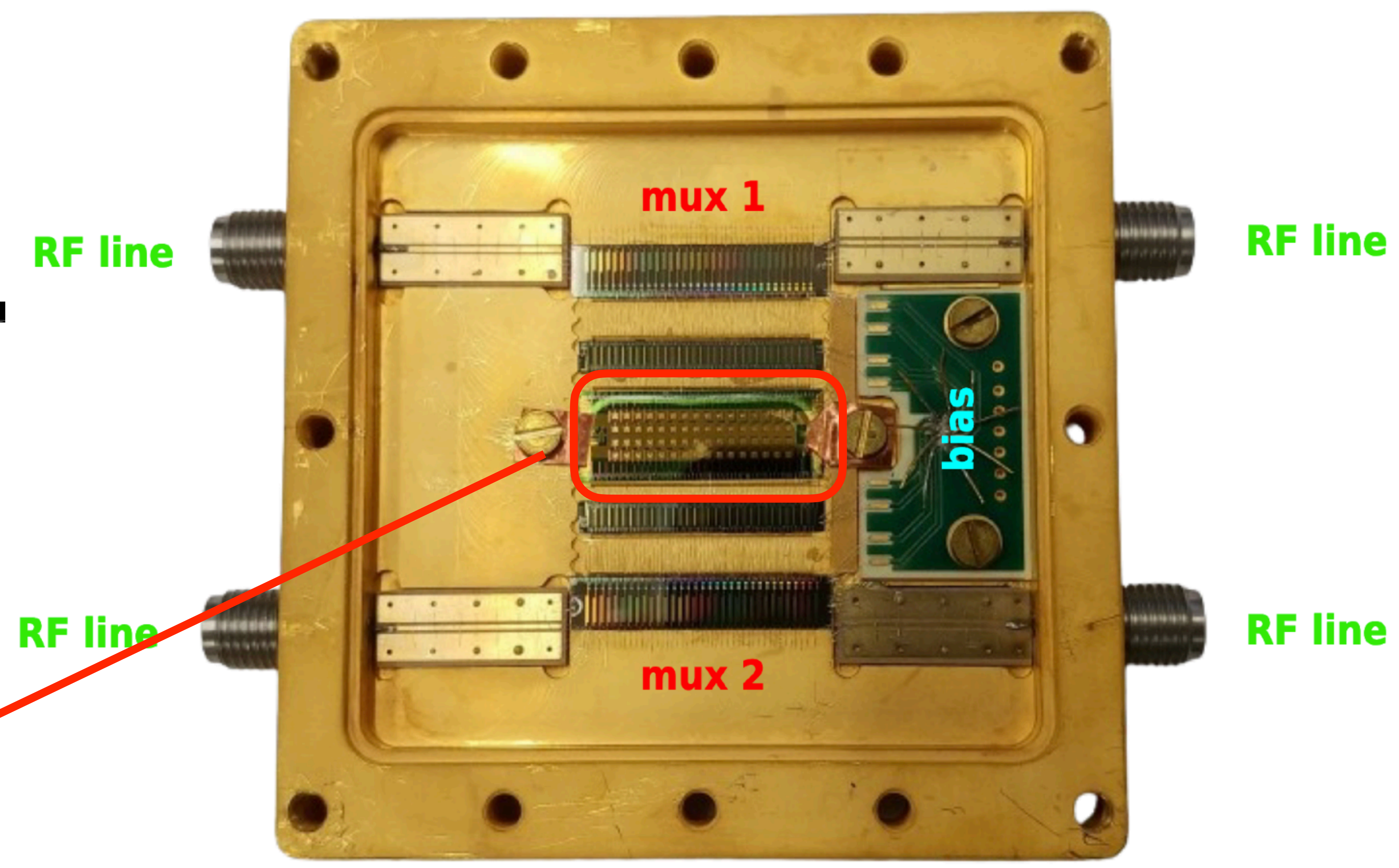
Even if efficiency is very low, it was still enough to implant the first array for physics DAQ!



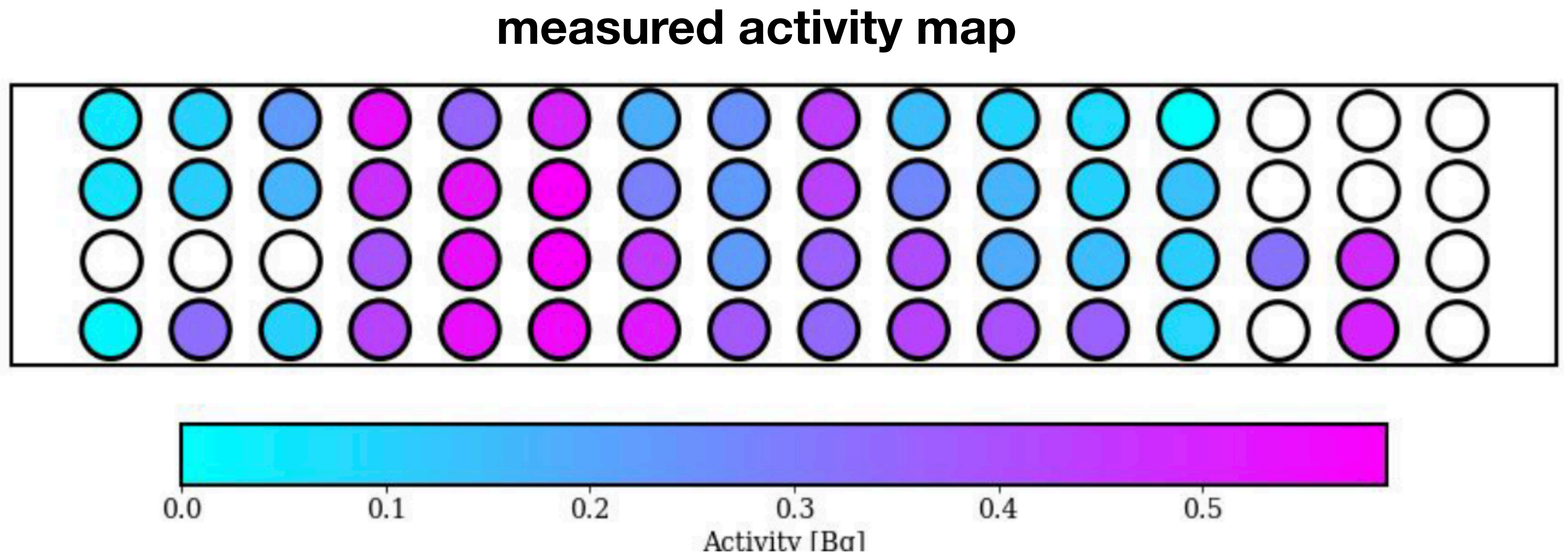


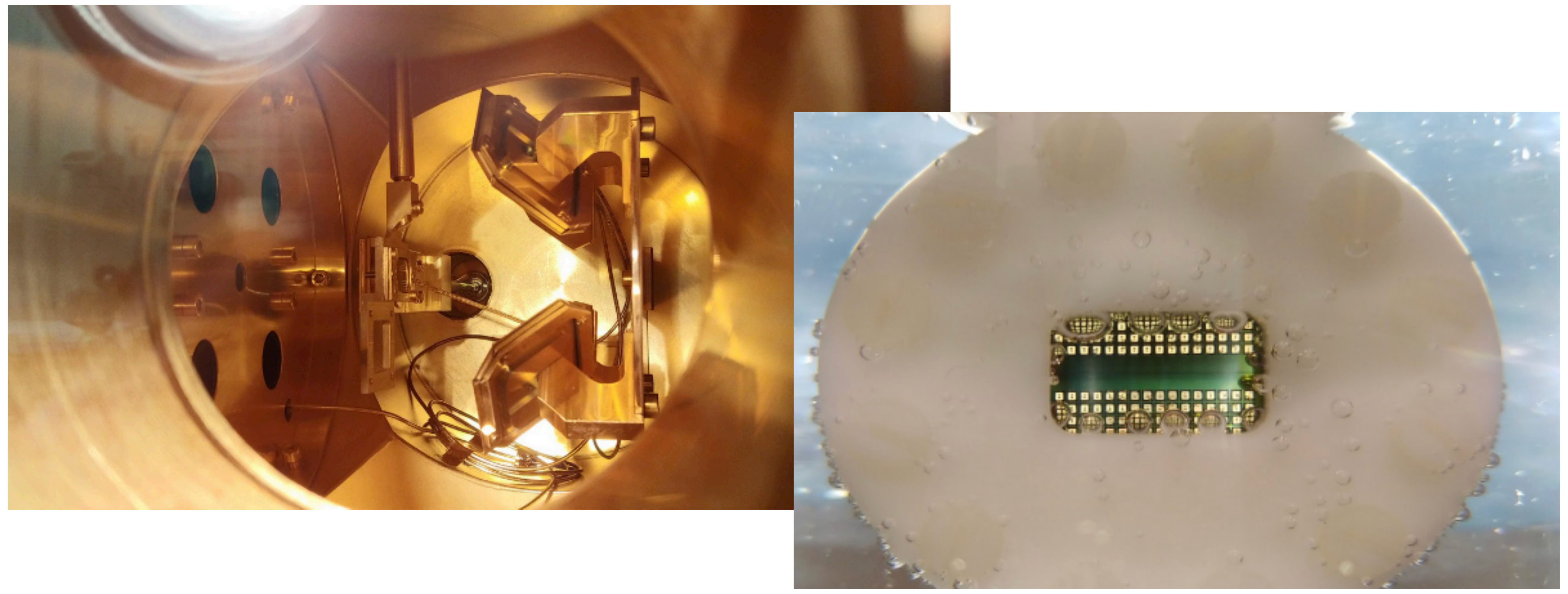


Arrays for physics data taking



After a long commissioning phase, we finally implanted our first arrays for physics data taking aiming for uniform ~ 1Bq / detector activity…





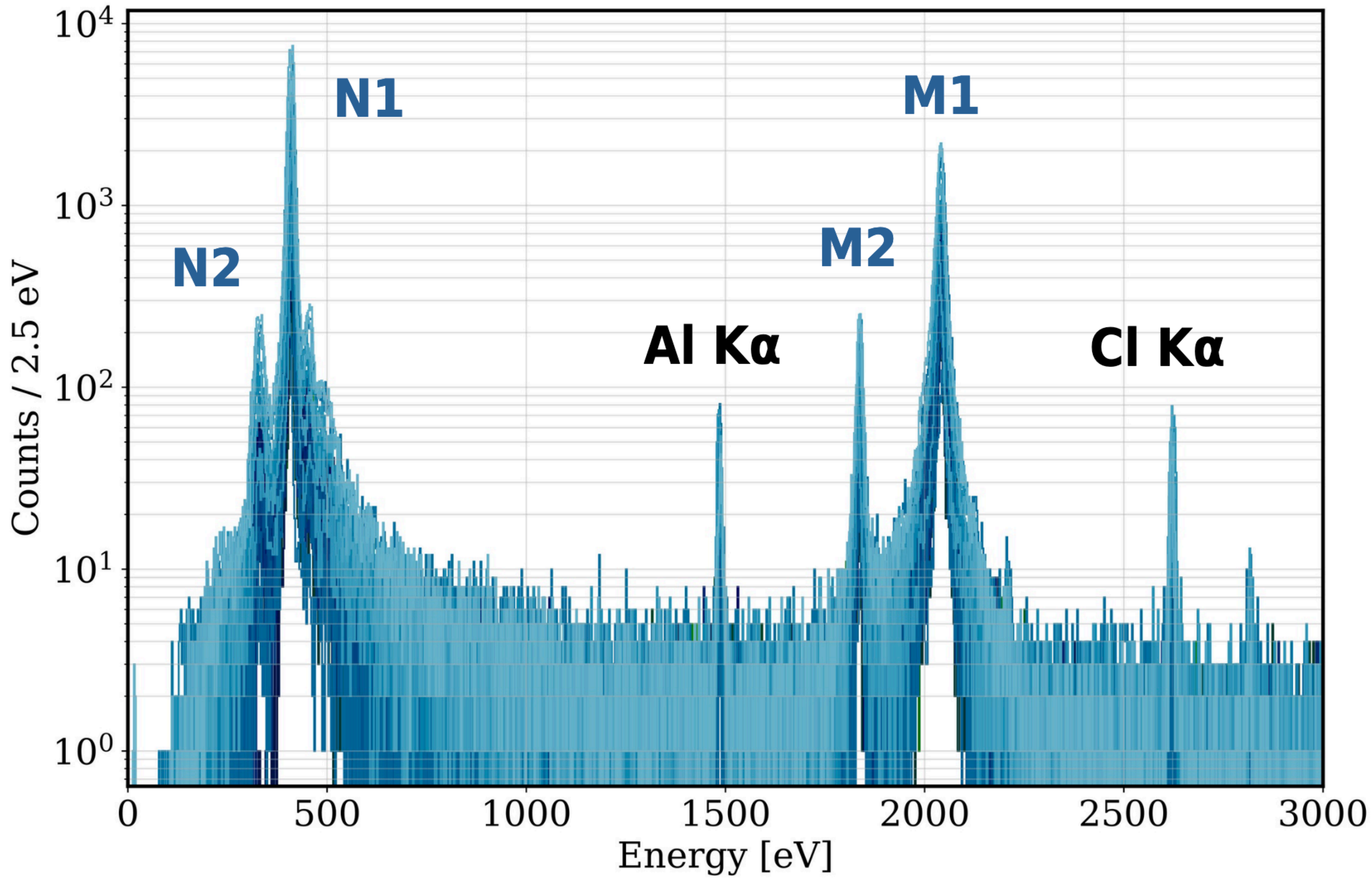
At the end of the implantation run we got:
48 active detectors (activity above threshold);
average activity $< A > = 0.27$ Bq;
total activity $A_{tot} = 13$ Bq;
peak activity $A_{max} \sim 0.6$ Bq

After implantation, the array is completed by adding a 1 um Au layer to fully encapsulate the source, then membrane is released by means of KOH wet etching.

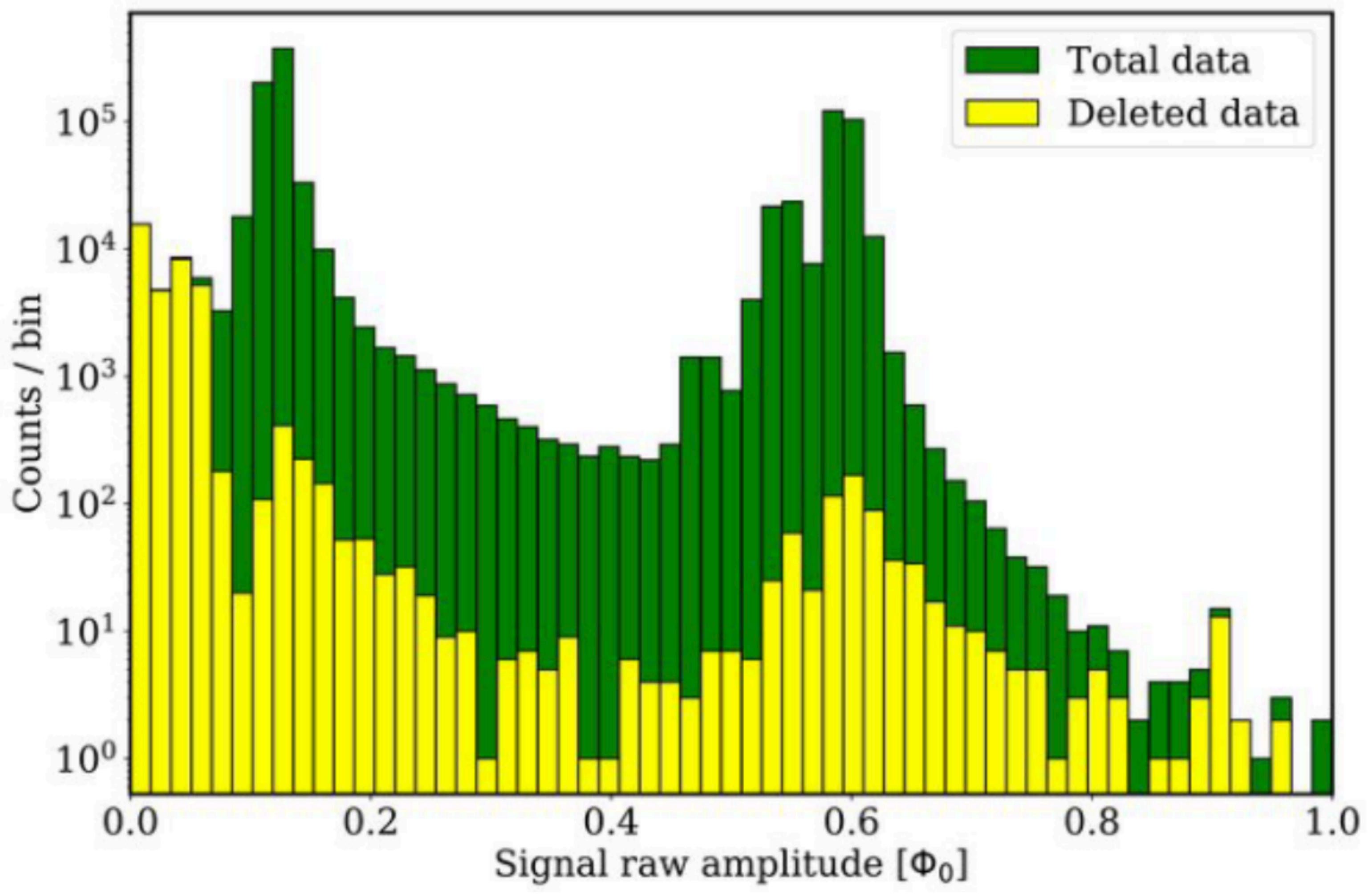
EC peak and detectors characterization

- Run with fluorescence X-ray source
- 48 active μ-calorimeters
  - ΔE_{FWHM} = 5.4 ~ 8.0 eV
- 2nd order polynomial calibration
  - $E(A) = a_1 A + a_2 A^2$
- Find EC peak energies: calibration for physics run, needed to merge spectra from different μ-calorimeters

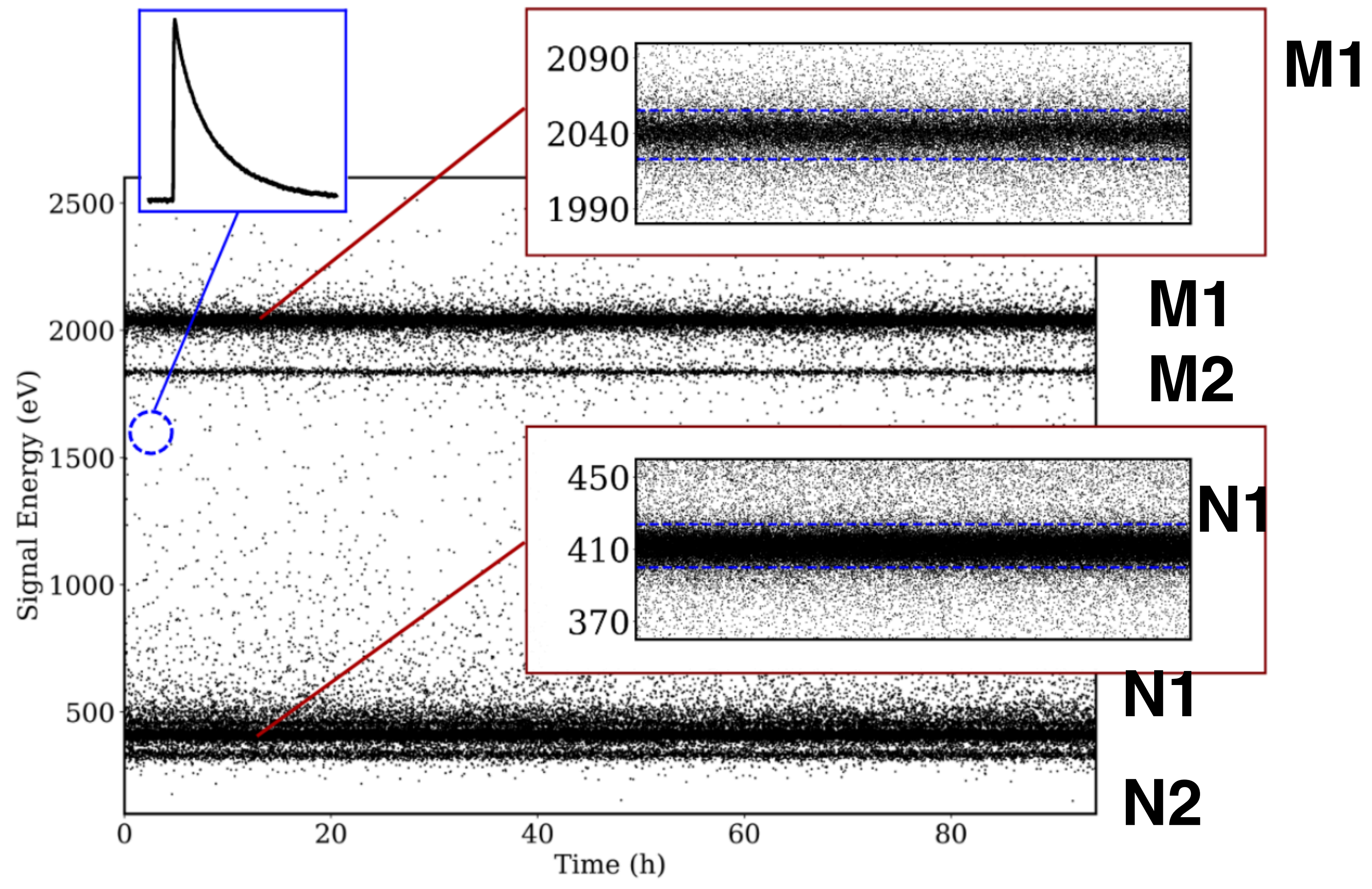
Peak	Position [eV]	Gamma [eV]	Asymmetry
M1	2040.8 ± 0.3	14.49 ± 0.05	1.306 ± 0.006
M2	1836.4 ± 0.8	8.2 ± 0.3	1.03 ± 0.05
N?	454.5 ± 0.1	22.3 ± 0.4	0.62 ± 0.02
N1	411.72 ± 0.1	5.57 ± 0.03	1.270 ± 0.008
N2	329.0 ± 0.1	16.4 ± 0.2	0.69 ± 0.01



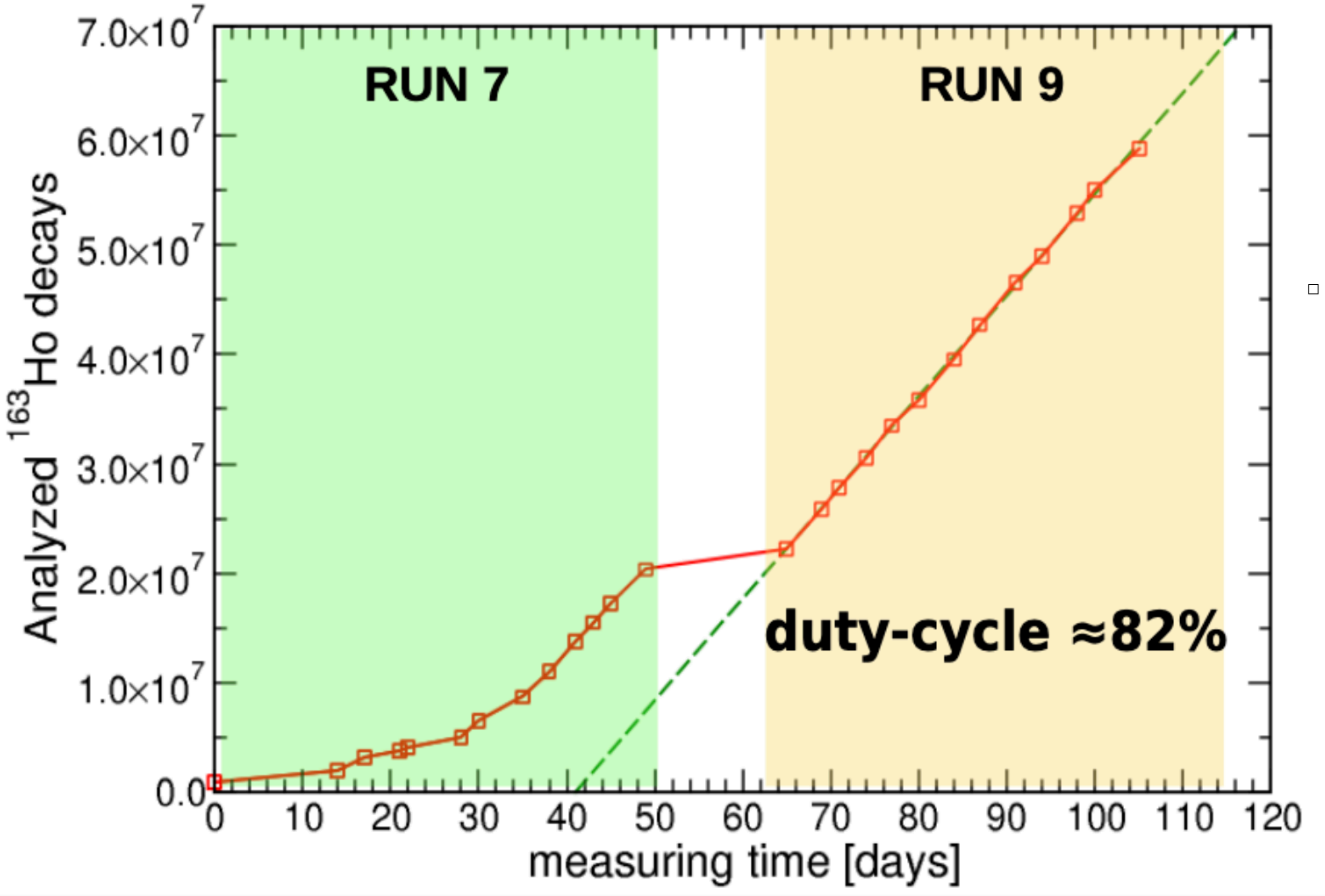
First ^{163}Ho high statistics spectrum



- **Physics data taking in 2024, about 2 months live time**
- < 1% signals discarded by first level analysis (based on pulse shape)

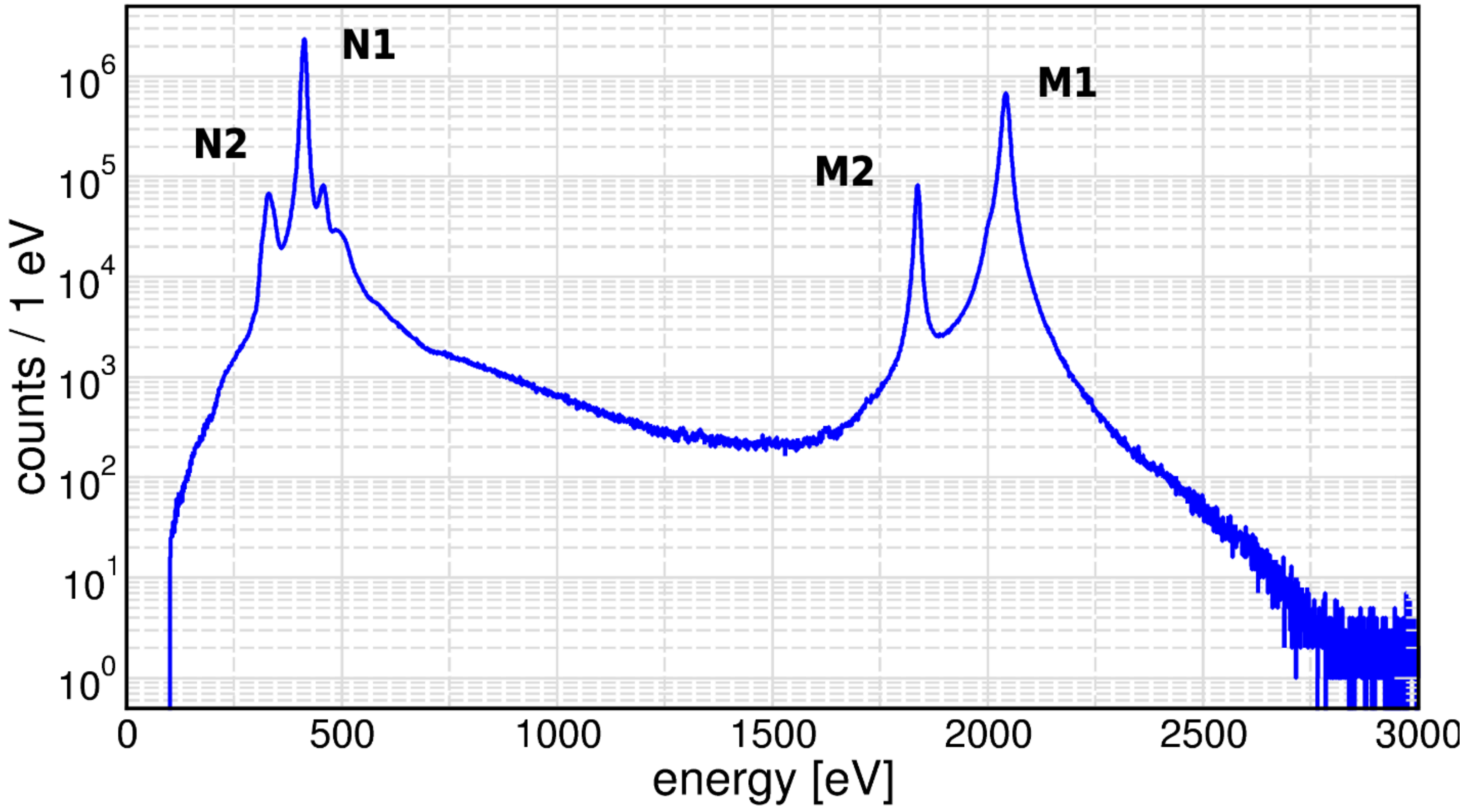


Gain drift correction



First ^{163}Ho high statistics spectrum

- 48 selected pixels
- Average activity <A> = 0.27 Bq → total activity A_{tot} = 13 Bq (3.2 x 10^{12} ^{163}Ho nuclei)



- ΔE_{FWHM} ~ 7 eV
- 7 x 10^4 detector x hour
- ~ 7 x 10^7 ^{163}Ho decays

Sum of 1000 partial data sets (48 det x 25 runs) with:

- Gain drift correction
- Energy calibrated using N1, M1 and M2 lines

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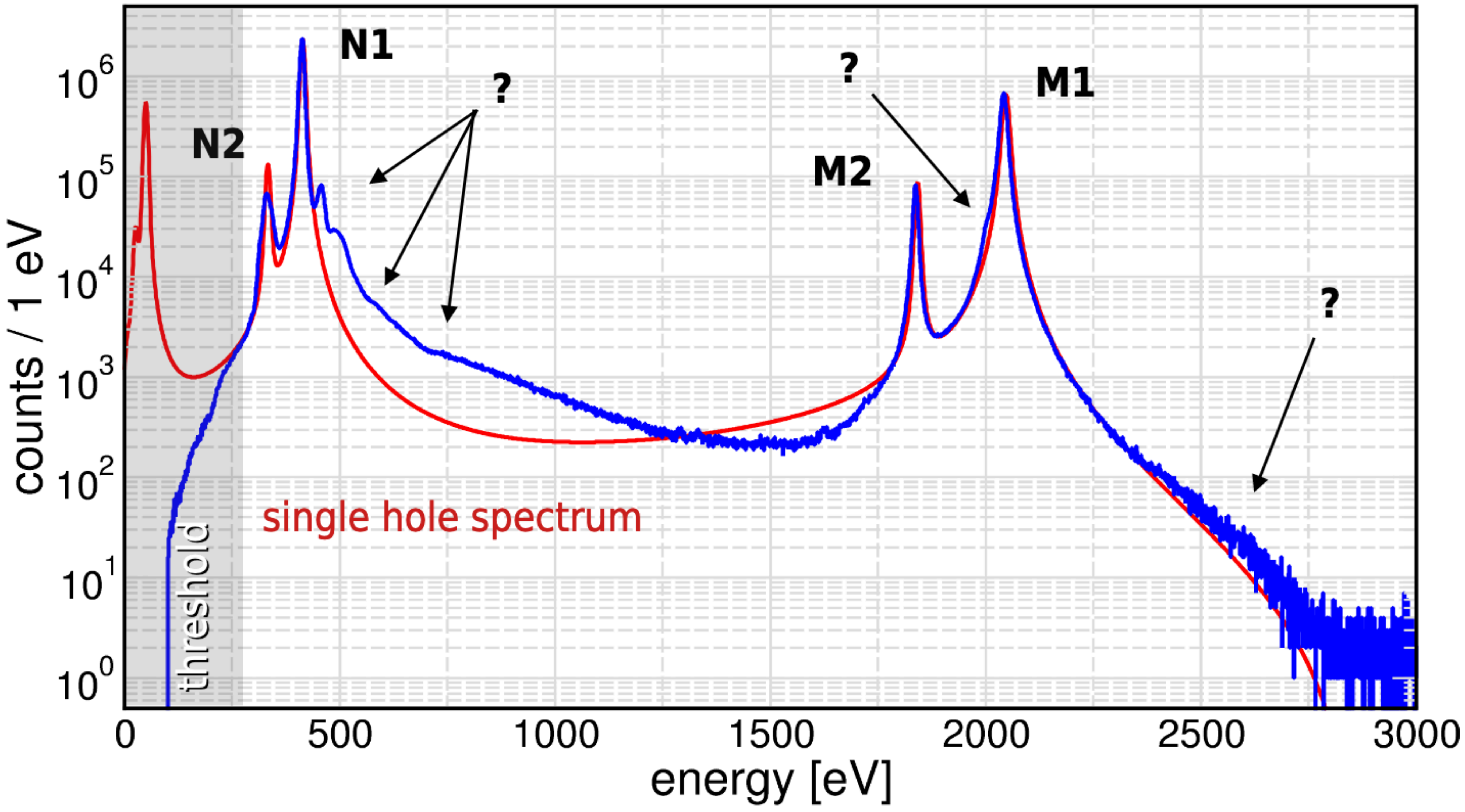

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Single hole spectrum doesn't explain data…

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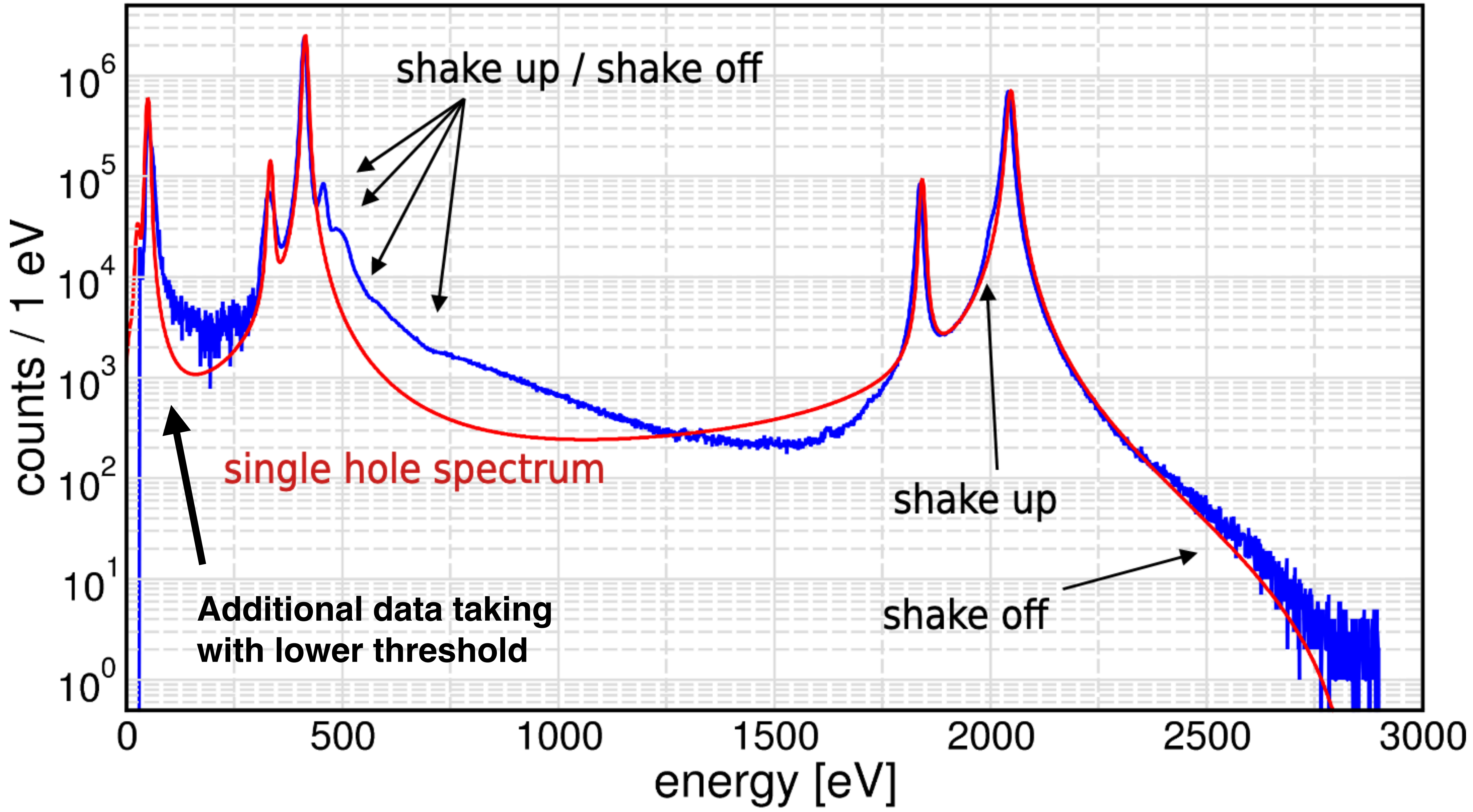

- ΔE_{FWHM} ~ 7 eV
- 7 x 10^4 detector x hour
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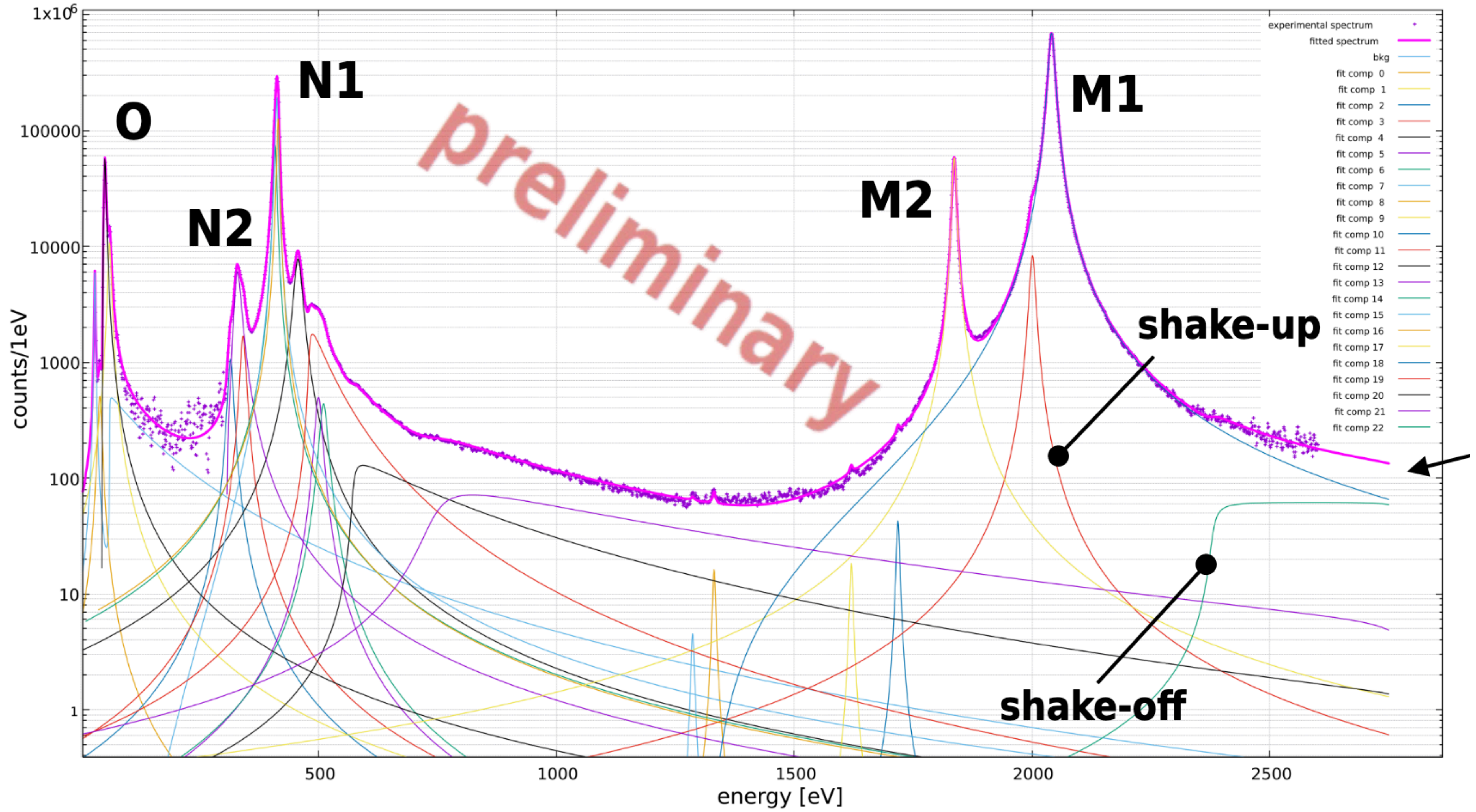
Single hole spectrum doesn't explain data…

2 holes excitation: the perturbation due to the Ho→Dy transition "shakens" one or more additional atomic electron to an upper bound state (**shake-up**) or to the continuum (**shake-off**).

Unfolding experimental ^{163}Ho spectrum…



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

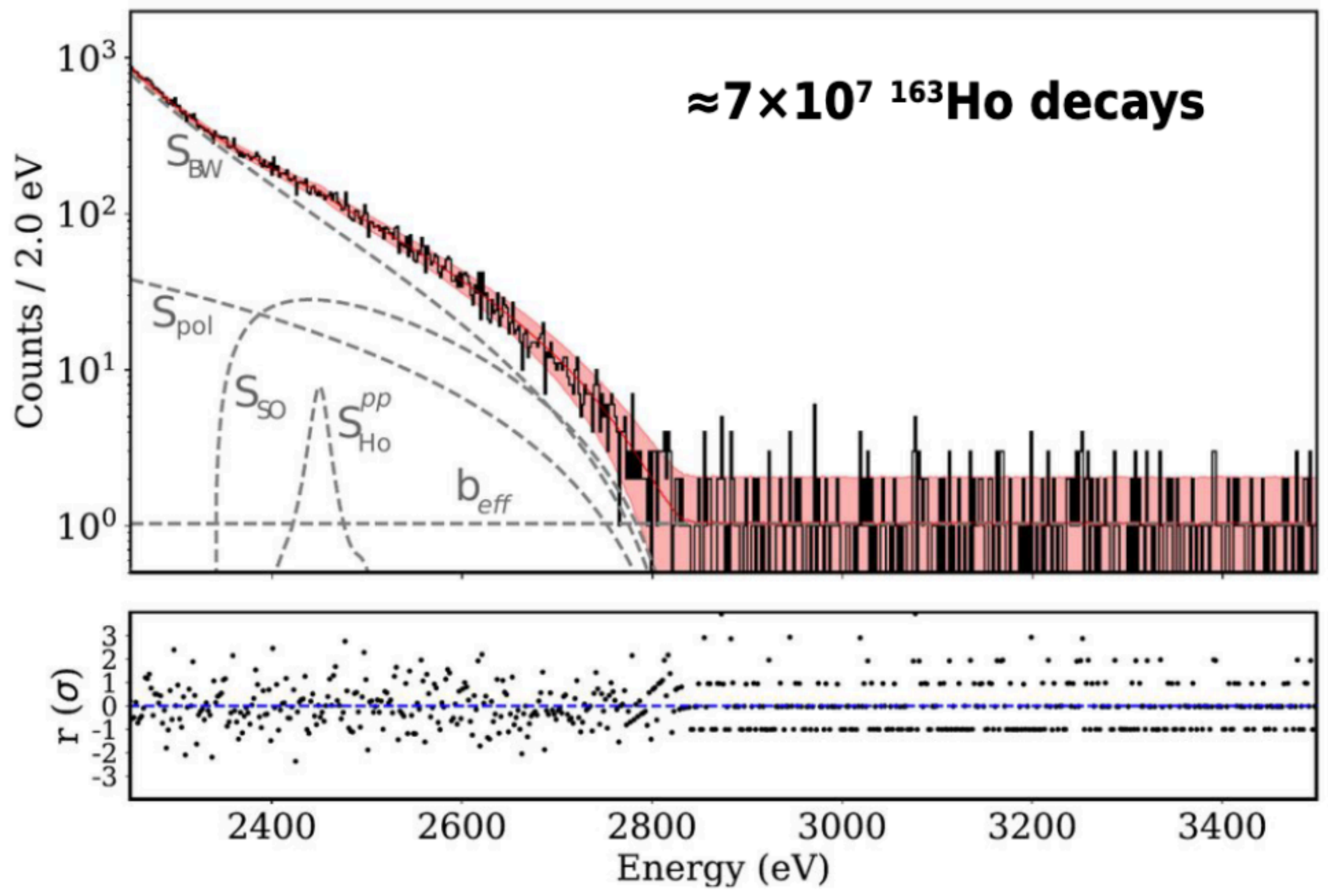
Experimental EC spectrum deviates from theoretical predictions
→ phenomenological description of the EC spectrum is now under study

- shake-up peaks and shake-off spectra
- strongly asymmetric Lorentzians

needed for assessing sensitivity of future ^{163}Ho experiments

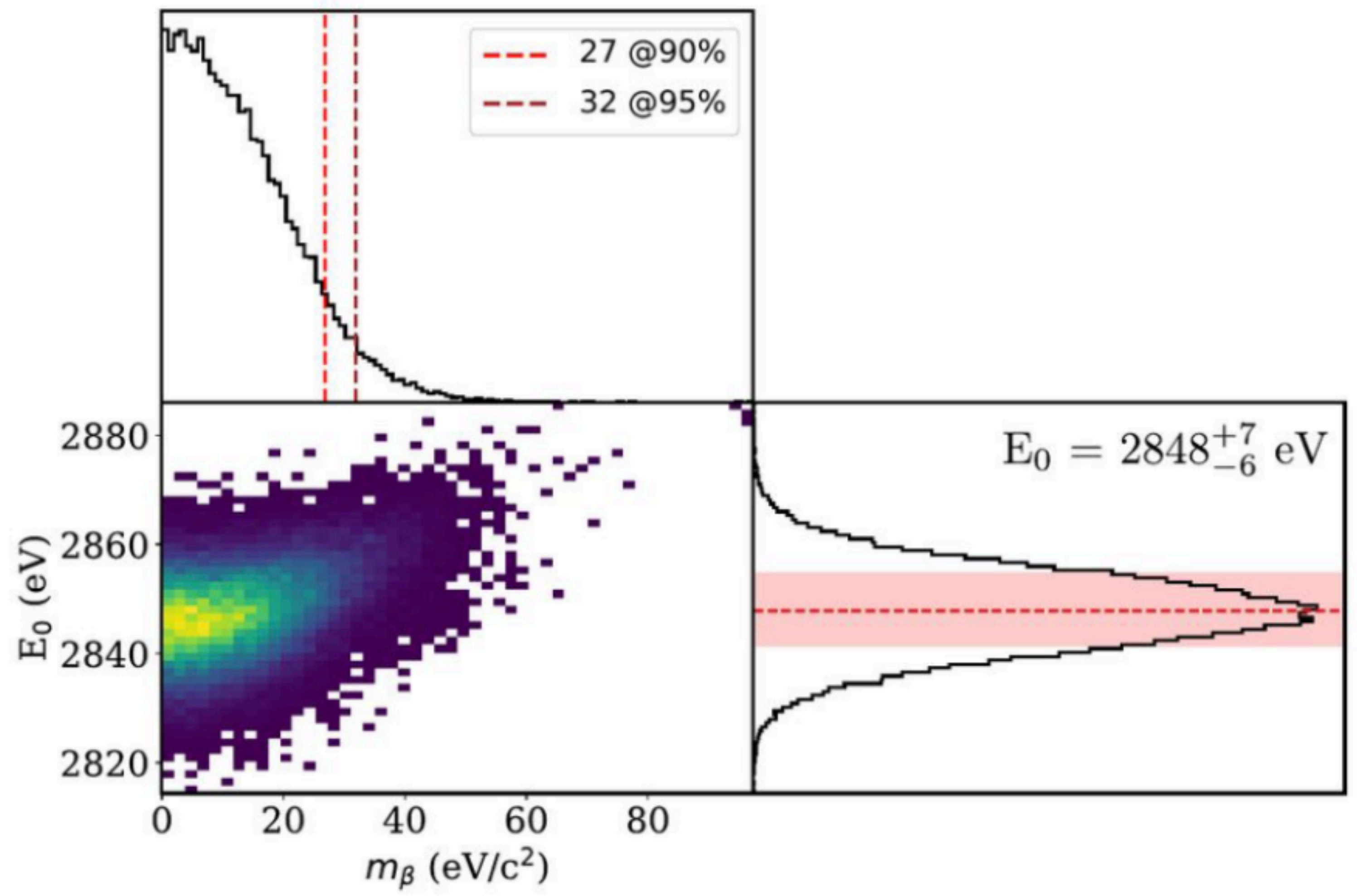
Limit on neutrino mass

- **Bayesian analysis with 13 free parameters** performed in the ROI: (2250 - 3500) eV
- ^{163}Ho spectrum modeled as sum of few terms
- Posterior distributions explored through a Hamiltonian Markov chain Monte Carlo using STAN
- ΔE_{FWHM} ~ 7 eV, $f_{pp} < 10^{-5}$
- Background count rate (1.7 ± 0.1) x 10^{-4} counts/eV/day/det
- **m_ν correlated only with E_0** (endpoint)
- Statistical sensitivity from toy MC ~ 40 ± 10 eV



m_ν < 27 eV @ 90% CI

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



What next?

To reach the (sub) eV sensitivity we must:

- **Improve ion implanter for better beam control and higher efficiency**
  - Integrating 4poles + x-y stirring magnet + diagnostic elements + target co-evaporation chamber
  - Major upgrade of ion source → new (much) more efficient ionization technique is under study

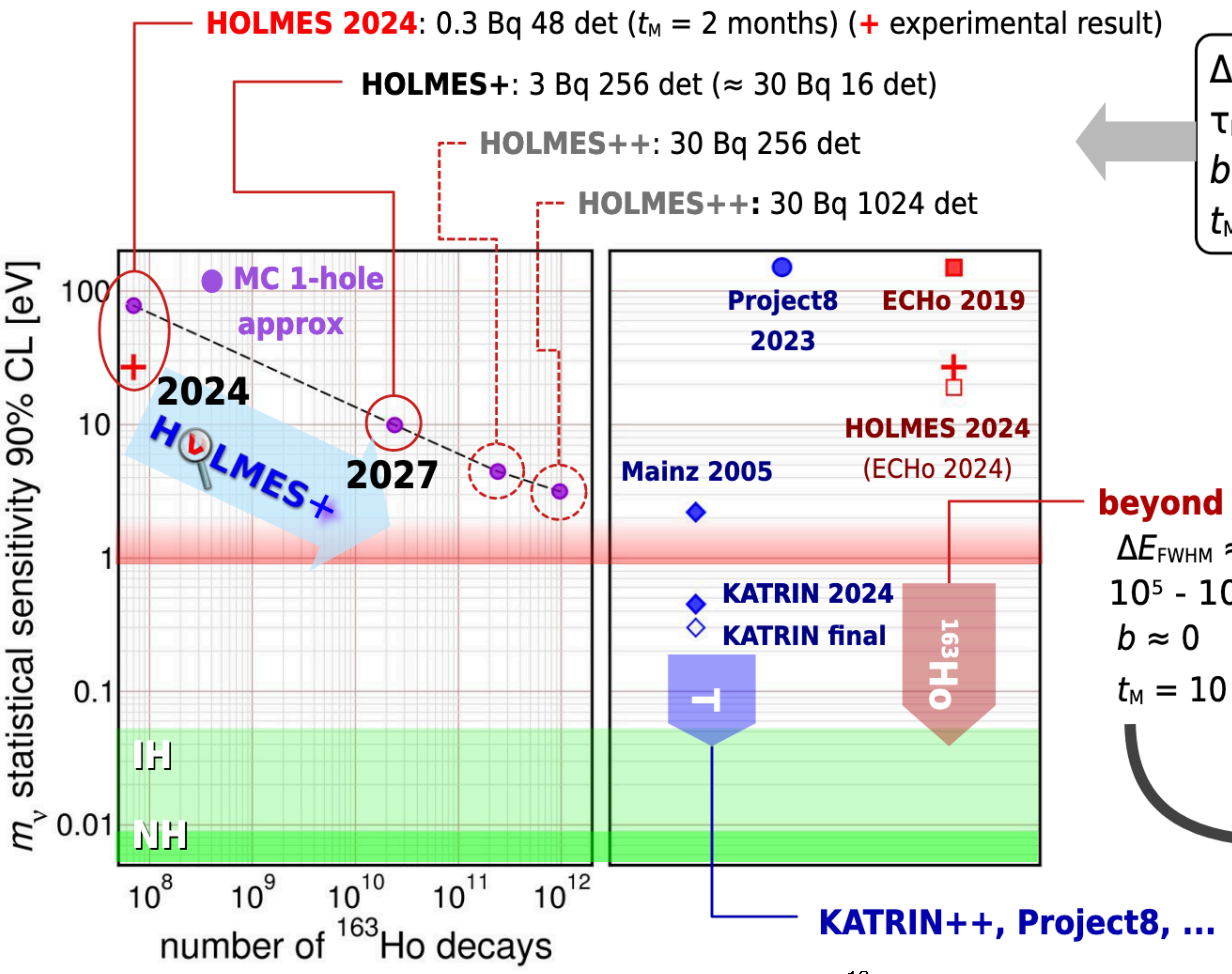
→ **Increase detector activity by 2 order of magnitude**

- **Reduce detector operating temperature down to 30 mK**
  - Addition of ^{163}Ho could spoil detector performance, must be recovered by lowering operating T

- **Increase the number of channel and reduce readout/DAQ cost → few €/ch**

- **0.1 eV sensitivity on m_ν requires scaling up HOLMES experiment by a factor $O(10^9)$…very aggressive but feasible!**

A possible roadmap towards sub eV sensitivity…



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

beyond HOLMES/ECHo:
ΔE_{FWHM} ≈ 1 eV, $\tau_R \lesssim$ 1 µs
10^5 - 10^6 det with up to 100 Bq
b ≈ 0
t_M = 10 y

sensitivity studies for true spectral shape are in progess…

Summary

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

- Even if still not competitive with the current best limit, this first result shows that the μ-calorimeters technology is ready and built the foundations for sub-eV sensitivity.

- In the next years, we plan to increase our sensitivity with a step by step approach

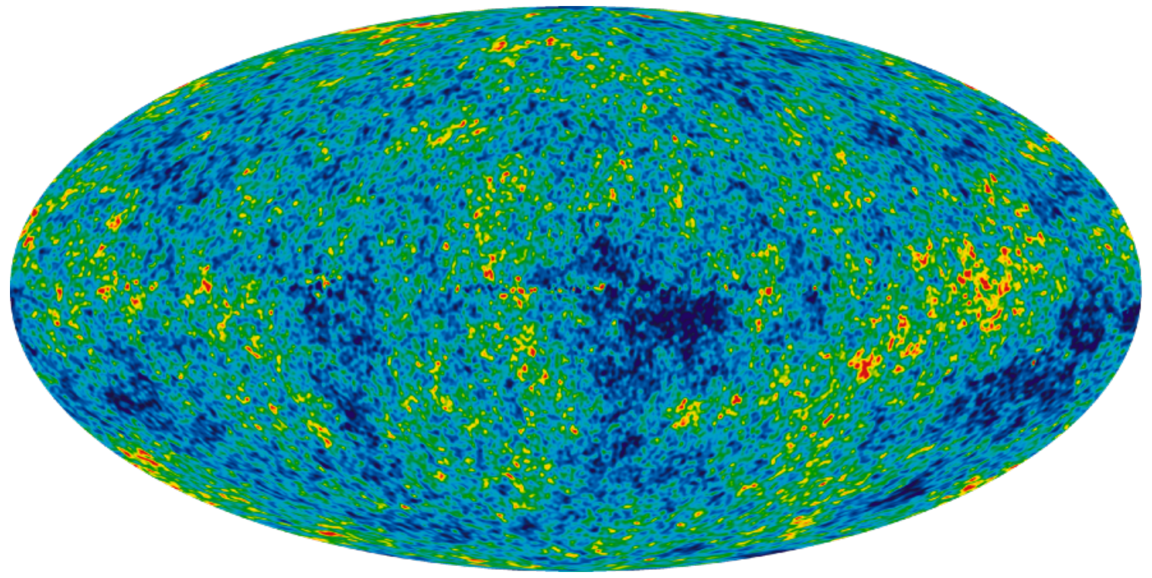
- New results will come (hopefully) soon!

Back-up

Neutrino mass measurements

Cosmological

$$M_\nu = \sum_i m_i$$



Best limit : 0.07 eV - analysis of CMB and structure formation data - model dependent

DESI + CMB + PLANCK

neutrino mass measurements

Neutrino mass measurements

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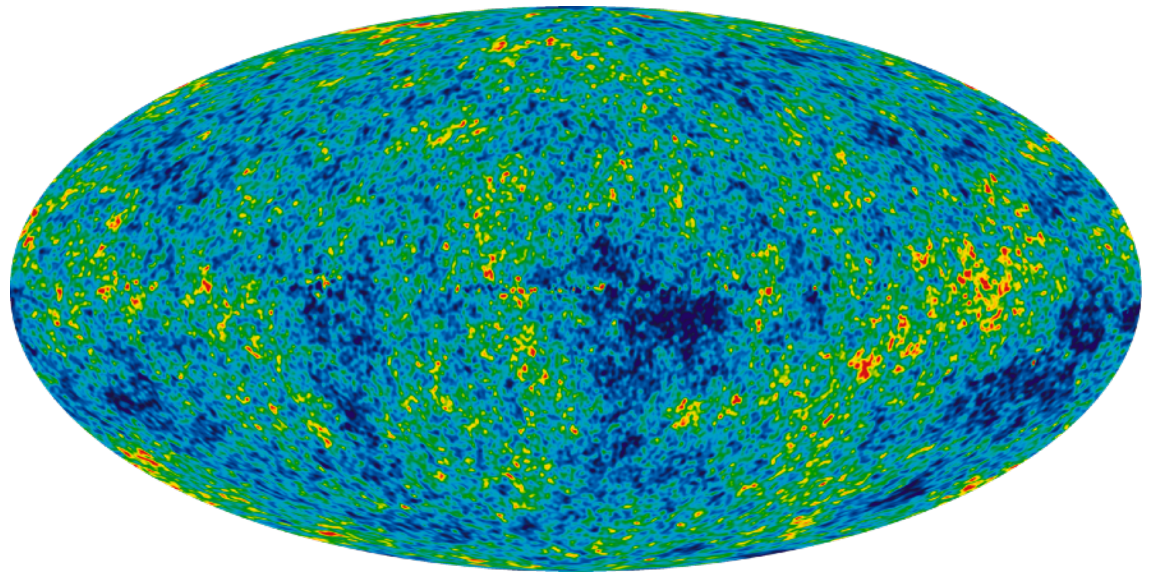

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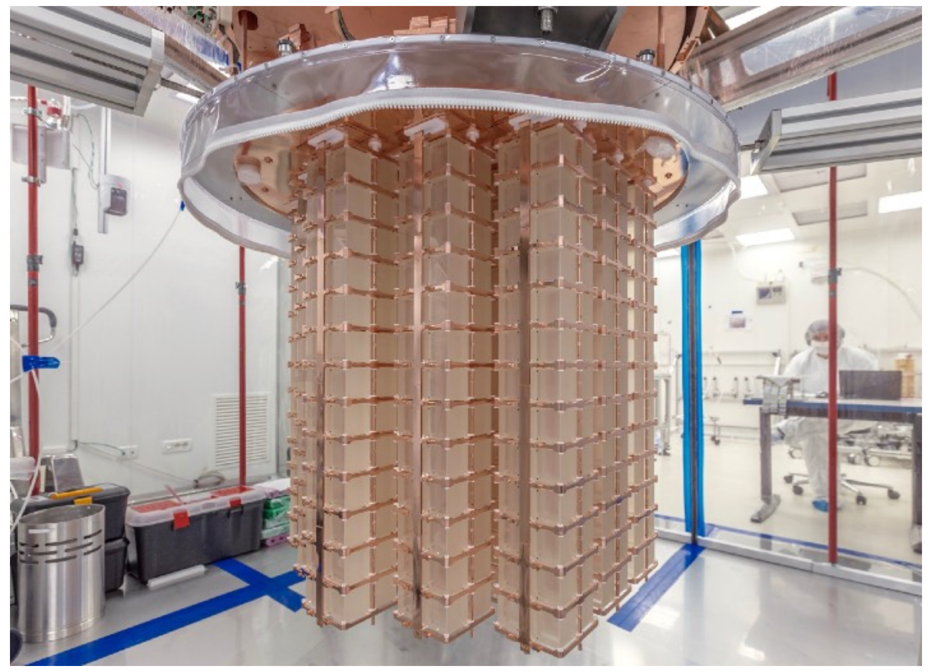

0νββ

$$m_{\beta\beta}^2 = \left| \sum_i U_{ei}^2 m_i \right|^2$$

Best limit : 0.05 - 0.15 eV, inference neutrino mass from 0νββ decay, model-dependent

KamLAND-Zen, GERDA, CUORE, EXO, SNO+, Majorana, Nemo 3, COBRA…

Neutrino mass measurements

Cosmological

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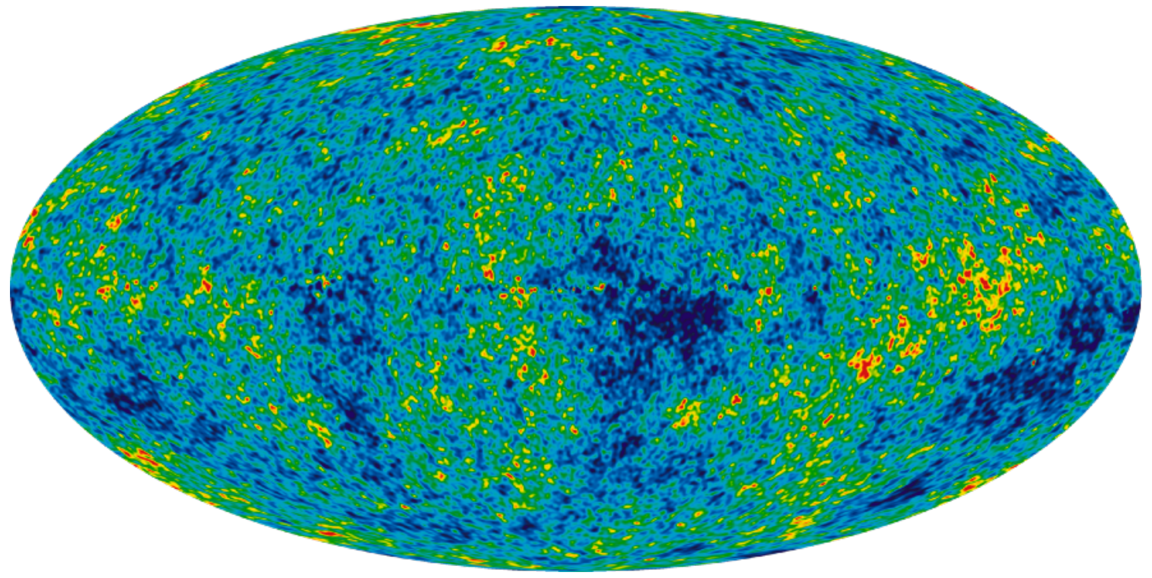

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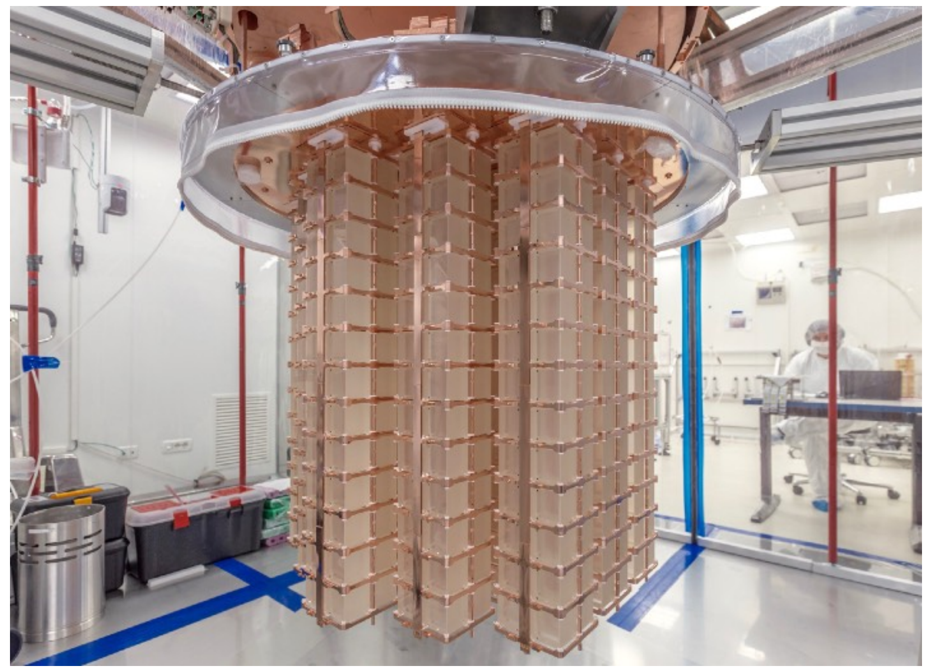
0νββ



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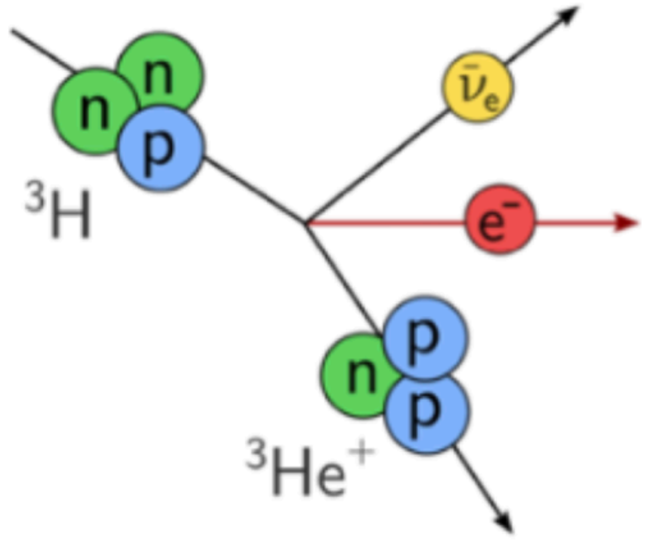
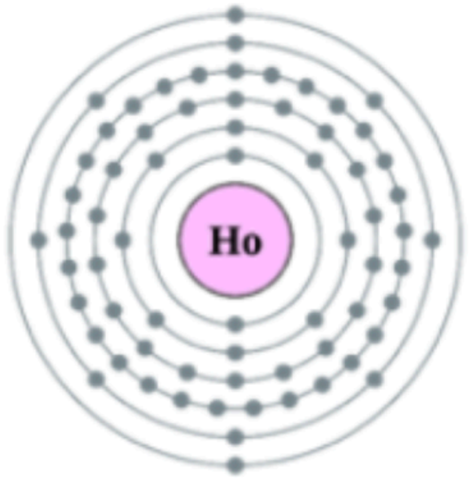
KamLAND-Zen, GERDA, CUORE, EXO, SNO+, Majorana, Nemo 3, COBRA…

neutrino mass measurements

Direct measurements

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

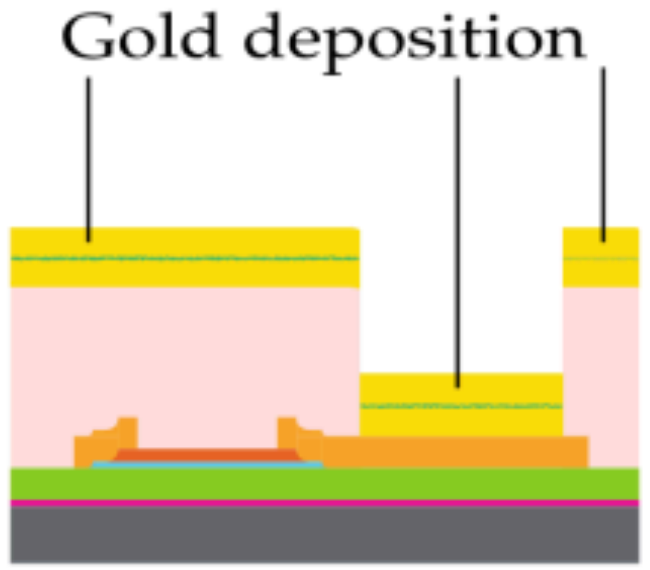


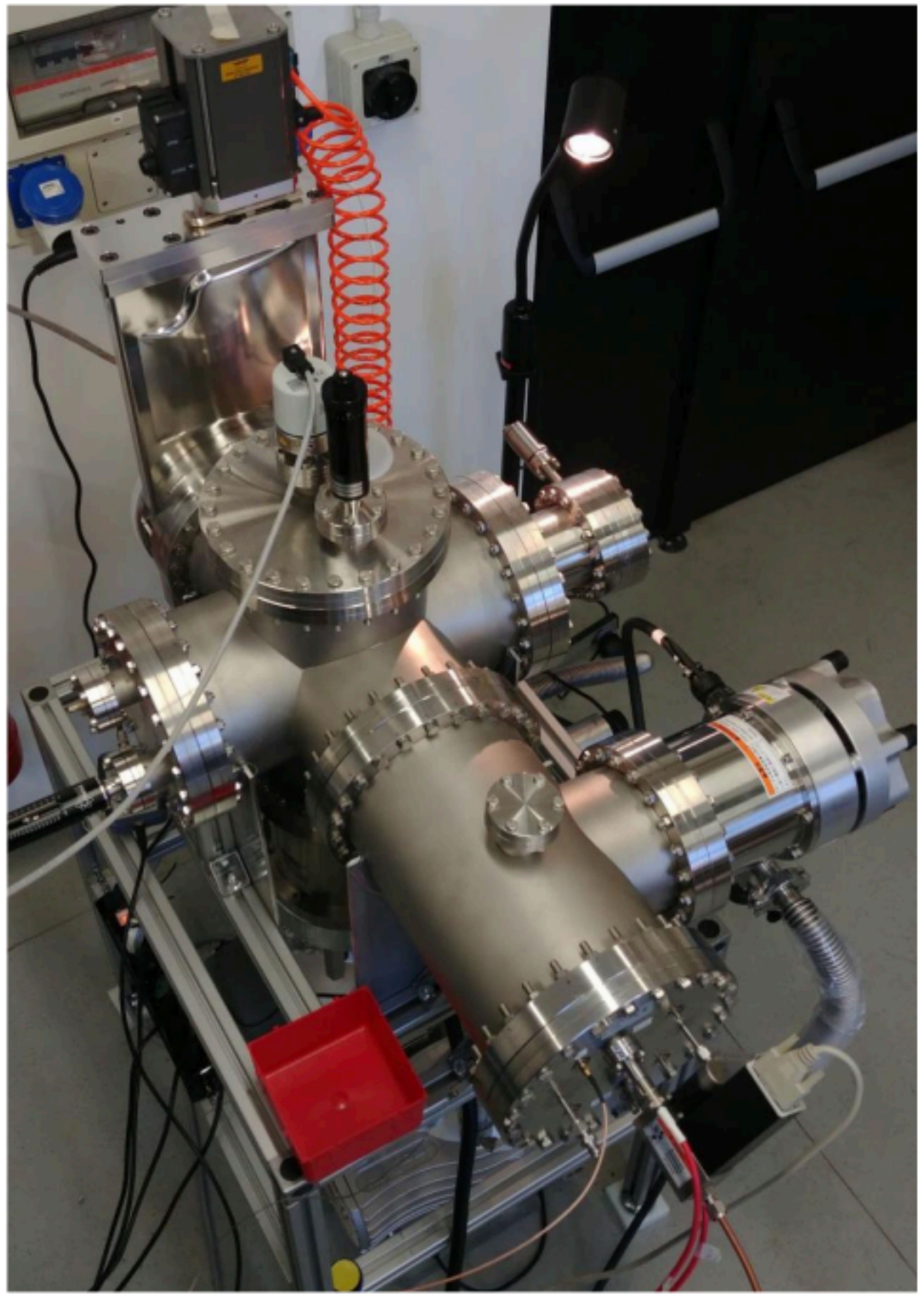


Best limit: 0.45 eV, exploit kinematics of weak decays, model independent

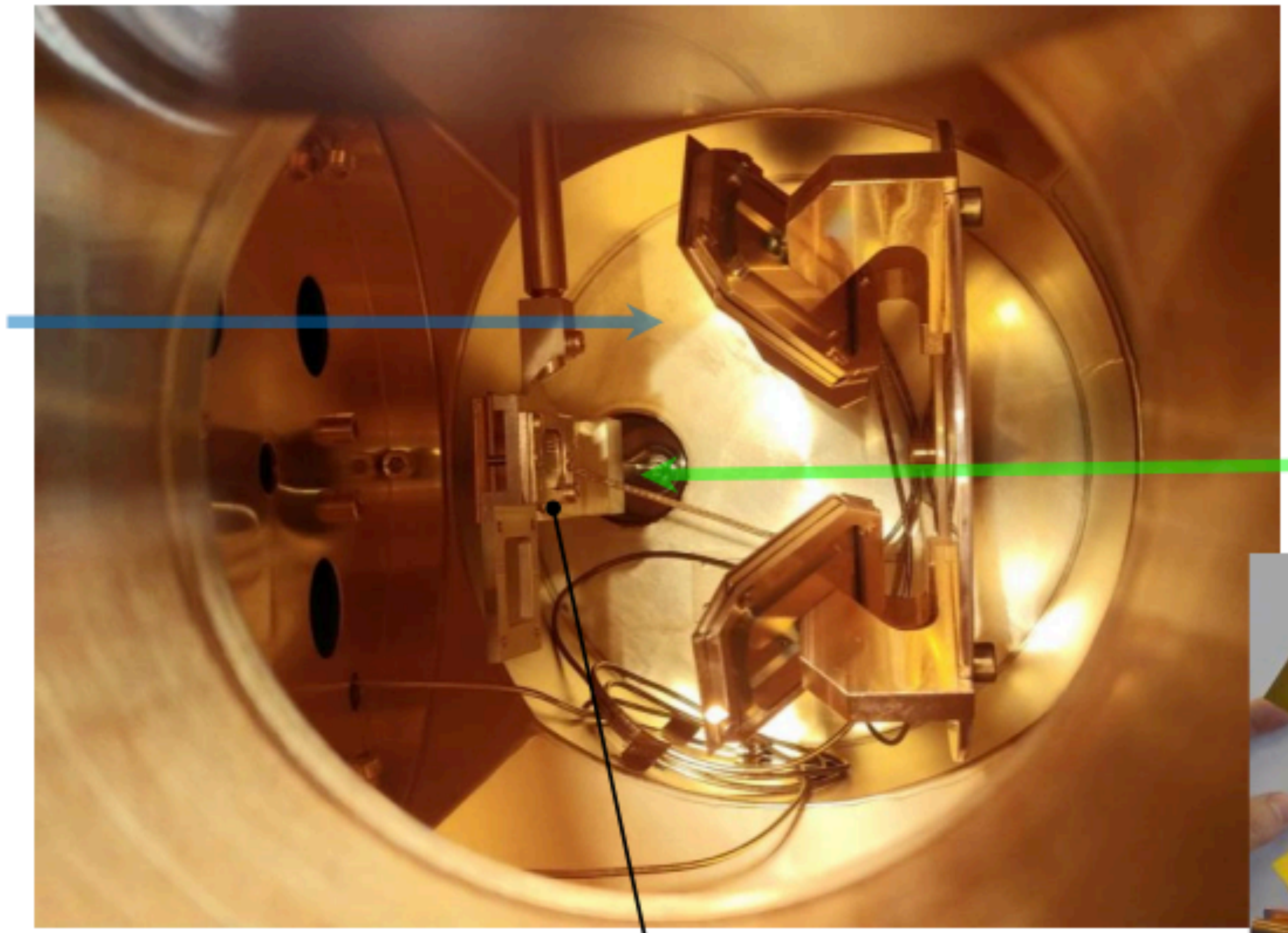
KATRIN, HOLMES, ECHO, Project-8, NuMECS…

Full encapsulation @Milano-Bicocca



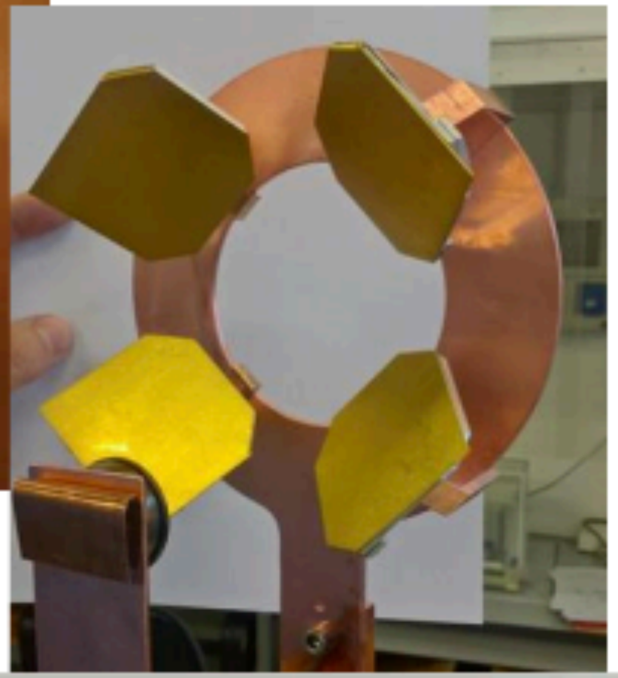


Ar ion beam (for sputtering)



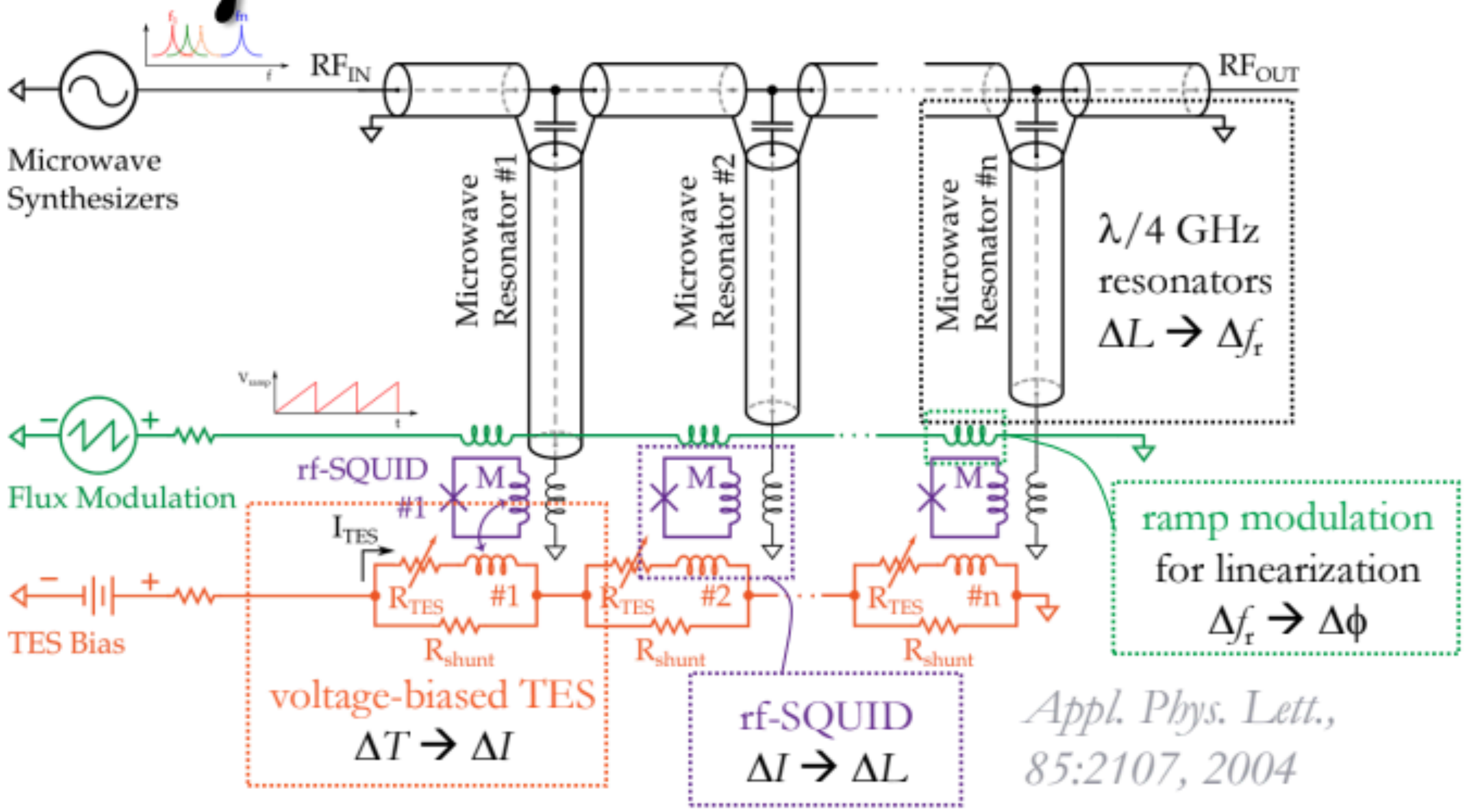
^{163}Ho (not implemented yet)

TES array

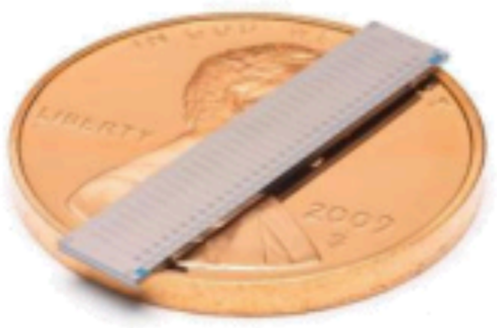


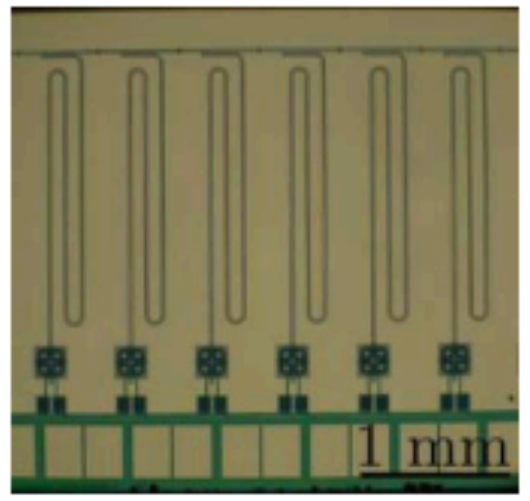
- 1 μm layer to fully encapsulate the ^{163}Ho
- ≈ 27 hours to complete the process
- soon will be integrated with the ion-implanter to compensate sputter and avoid oxidation

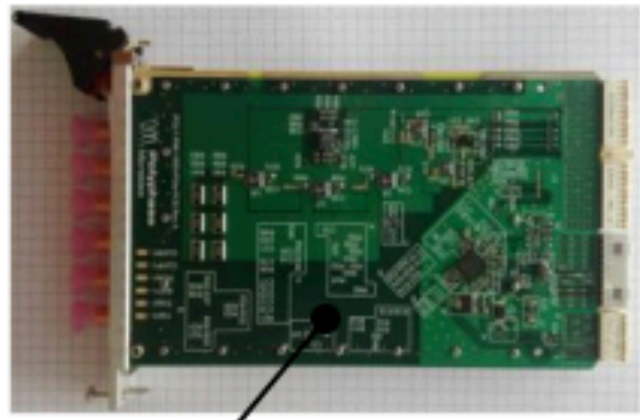
µwave mux readout & DAQ



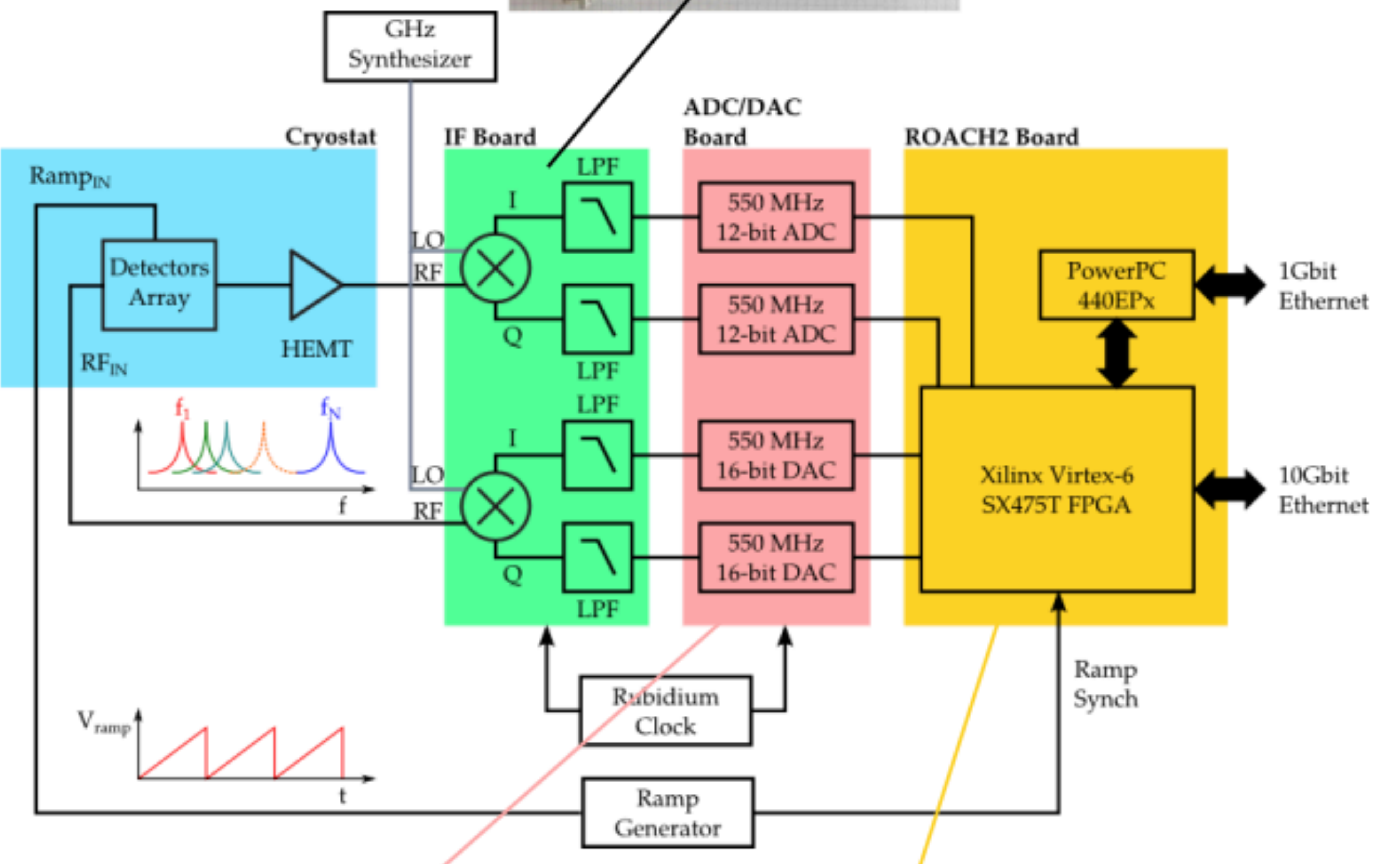
Appl. Phys. Lett., 85:2107, 2004



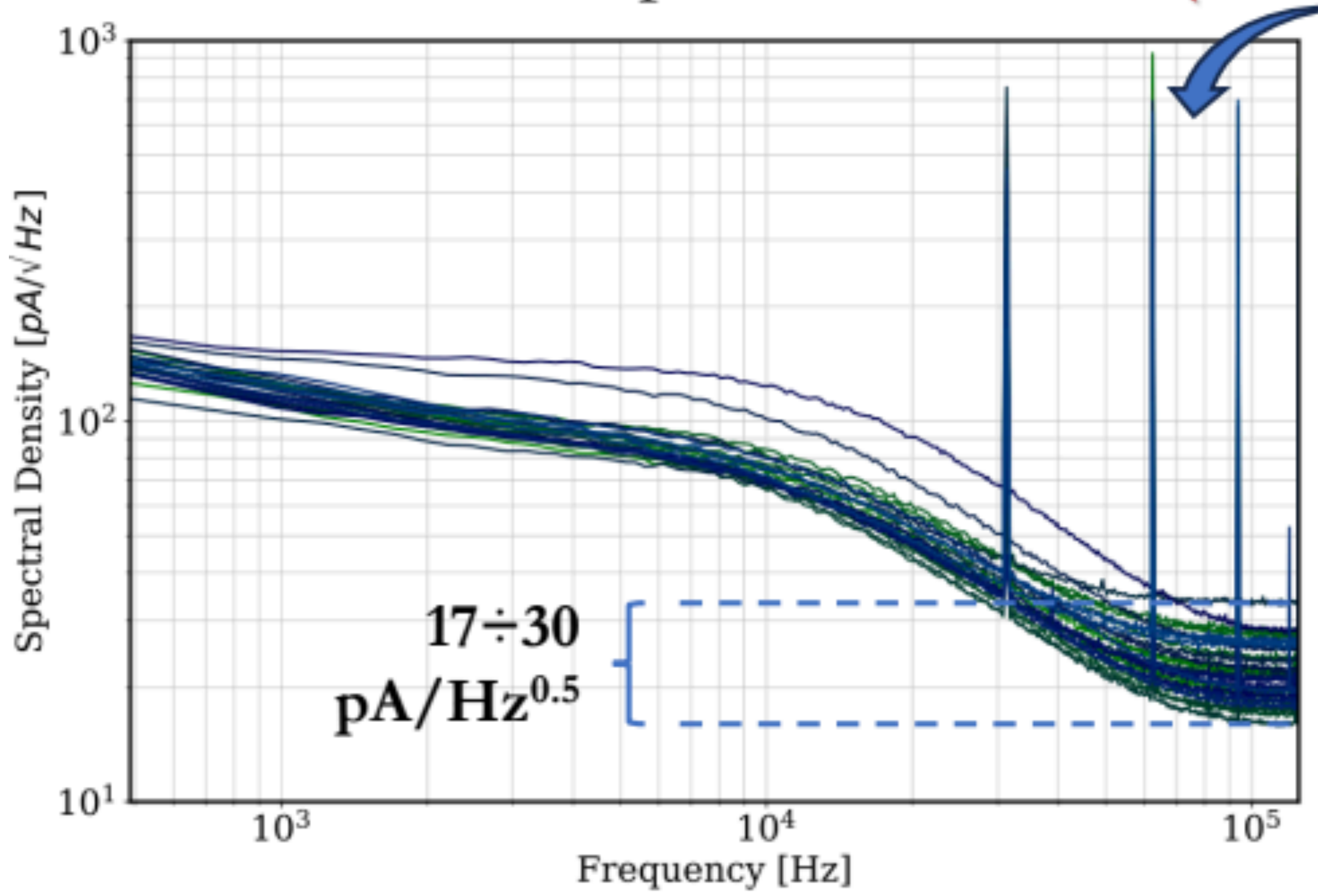


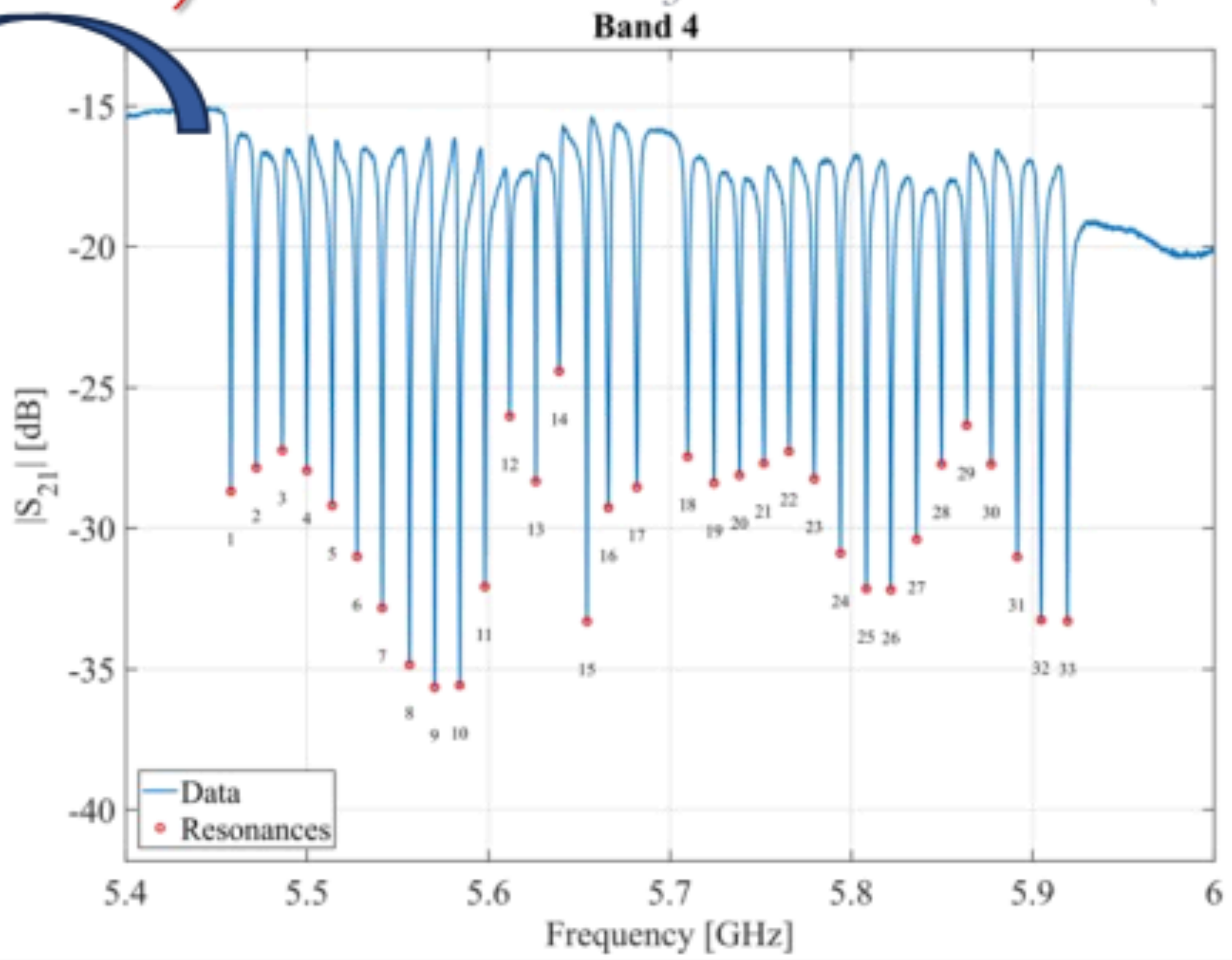


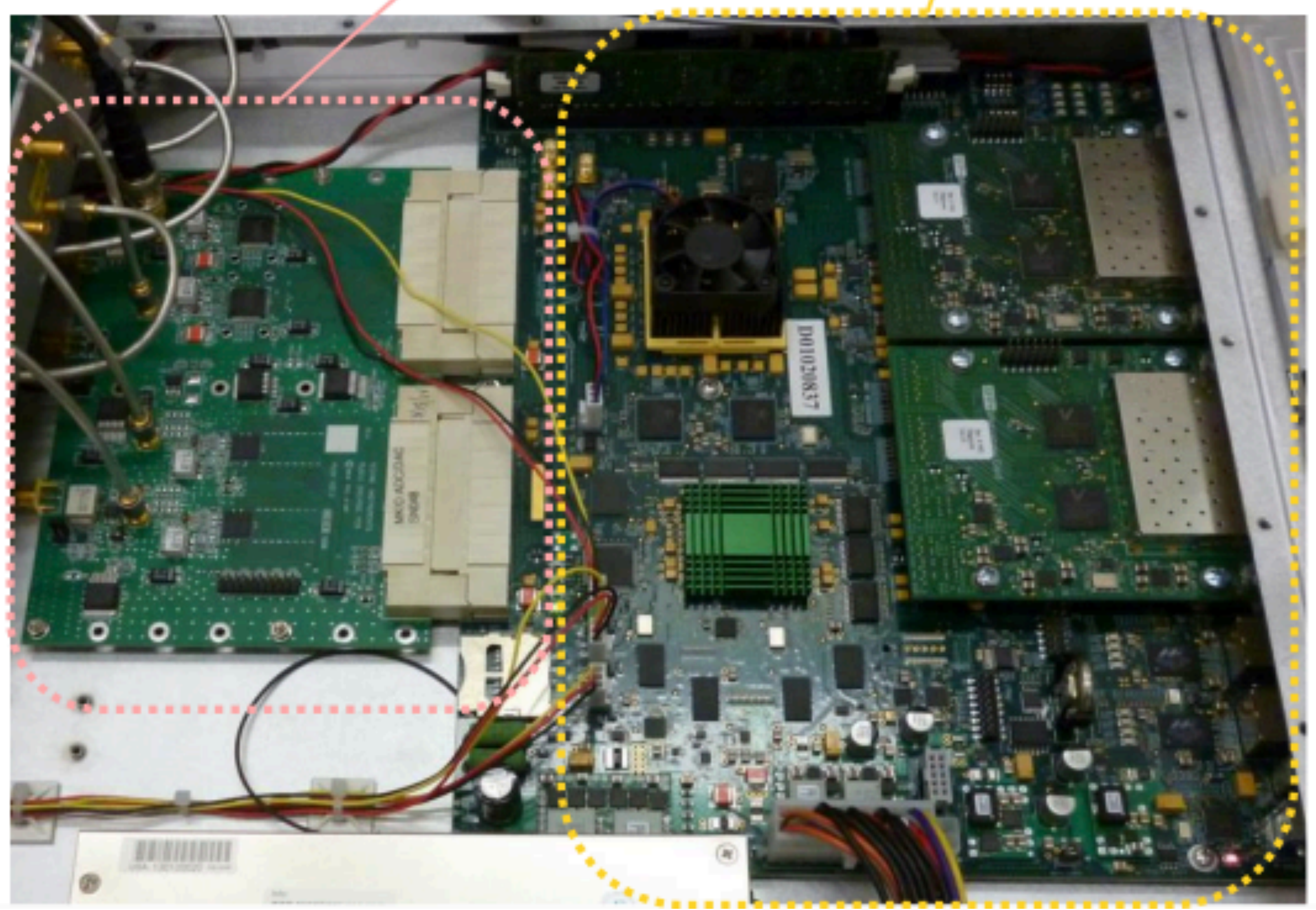
64 channels already available



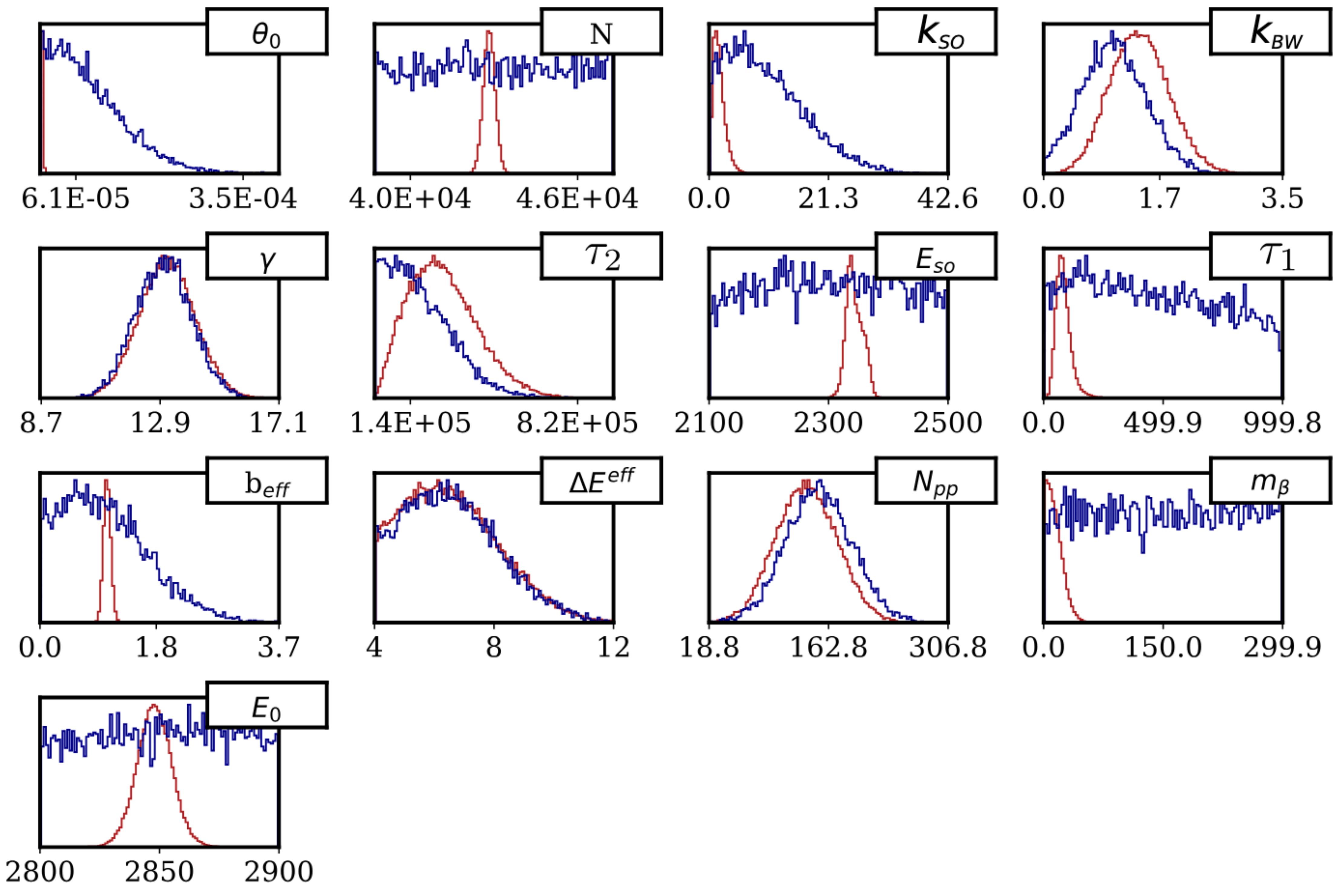
- $f_{ramp} = f_{samp}$ (= 500 kHz)
- allows to readout many detectors with one common RF line and HEMT amplifier: 1 HEMT (4-8 GHz) = 256 TESs *JINST 14 P10035 (2019)*

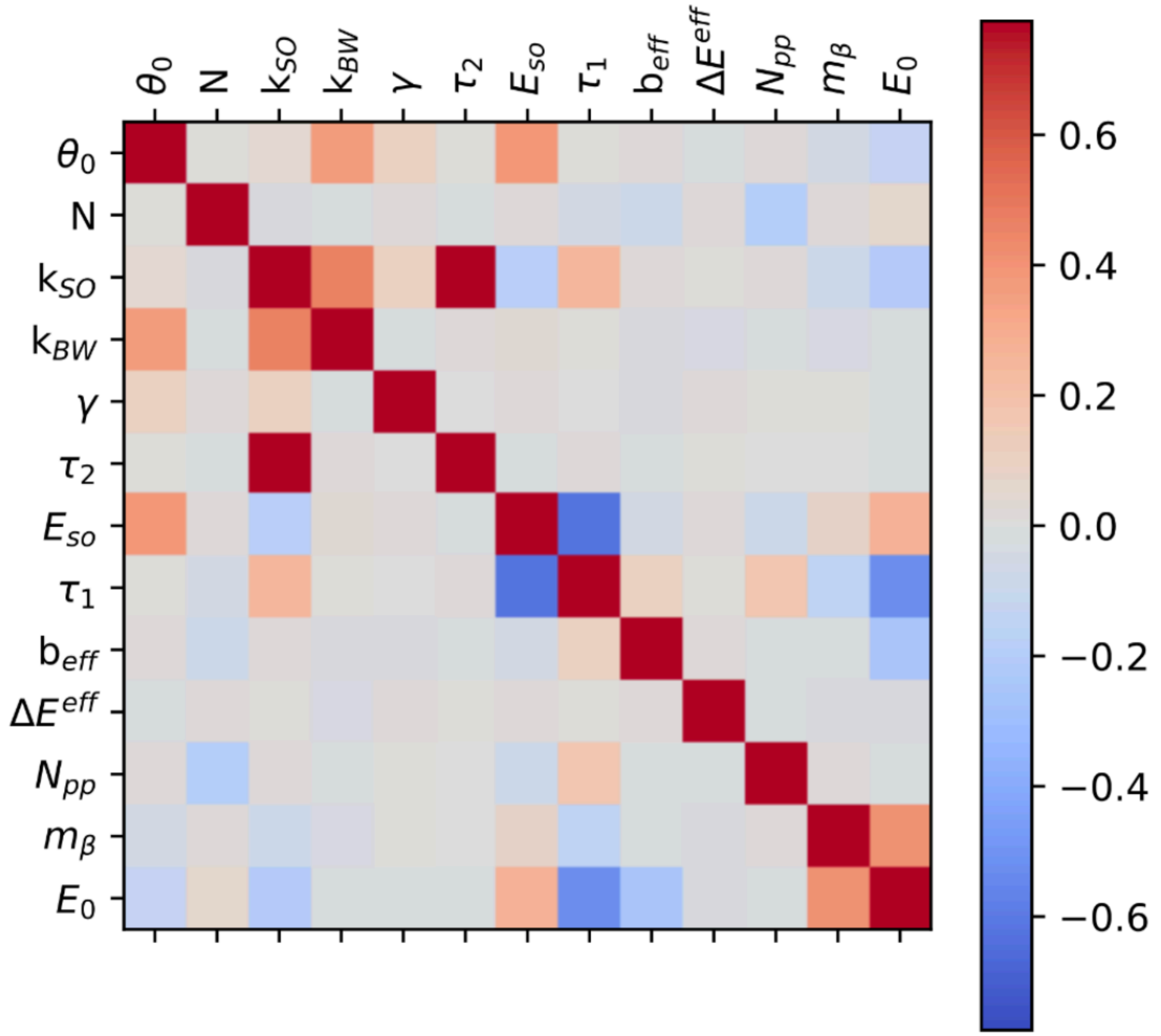






Parameters distributions and correlations





What next?

HOLMES

- Proved:
  - Multiplexed TES 64 pixel array
  - ~ 1Bq/det
  - ΔE_{FWHM} = 5 - 8 eV
  - $\tau \sim 1\ \mu s$

→ m_ν stat sensitivity ~ 20 eV

HOLMES+

- Mid term (3 years) plan for:
  - m_ν stat sensitivity < 10 eV
  - up to 256 detectors
  - up to 3 Bq / detector