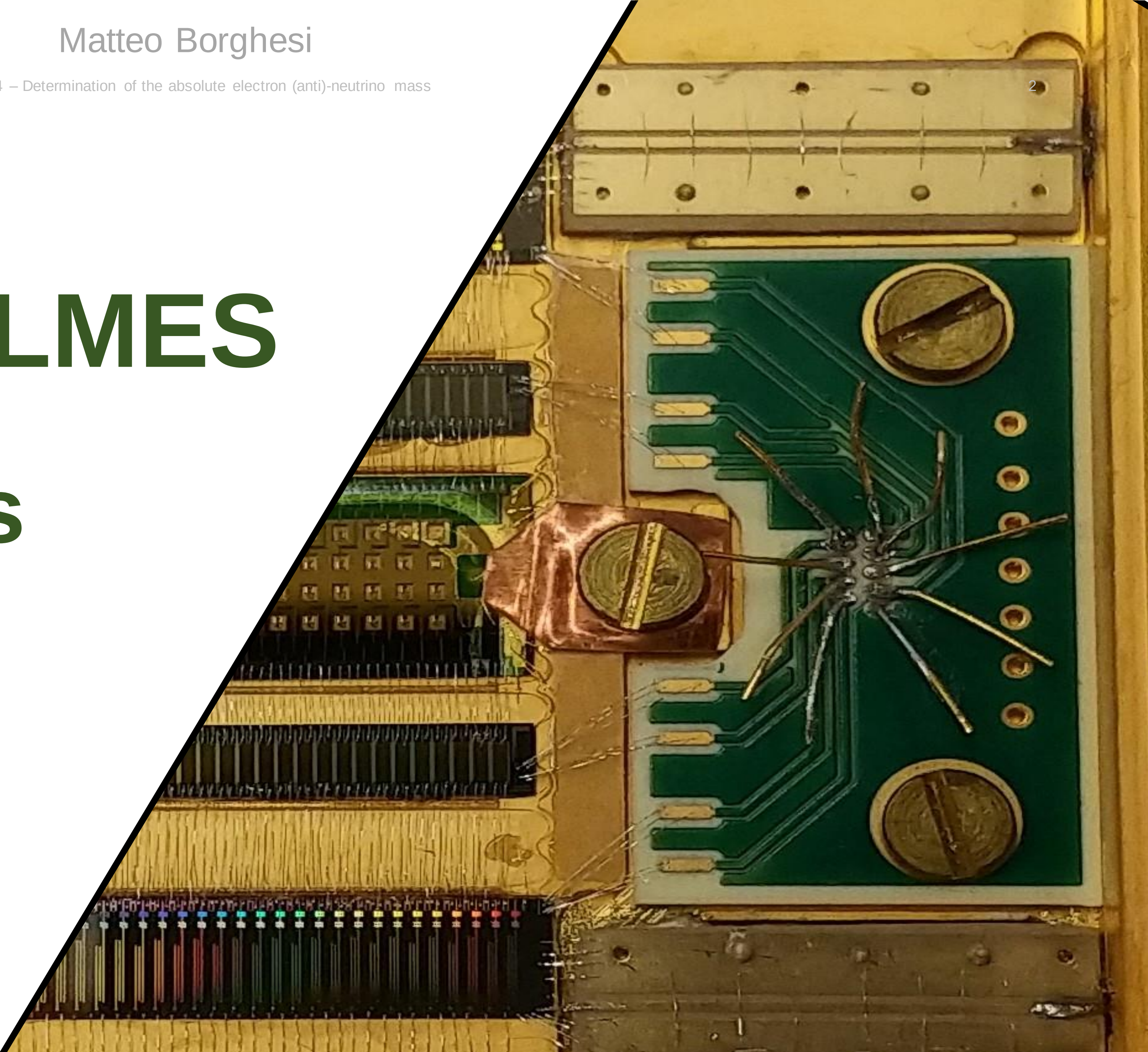
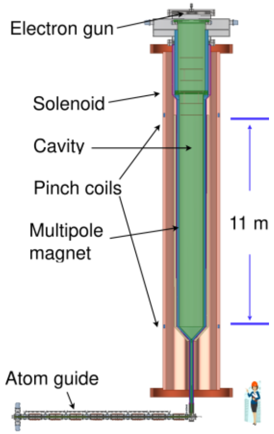
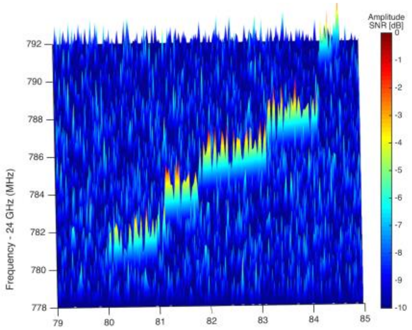
HOLMES

status

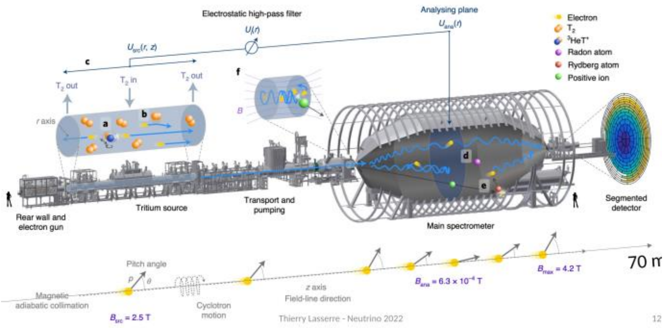


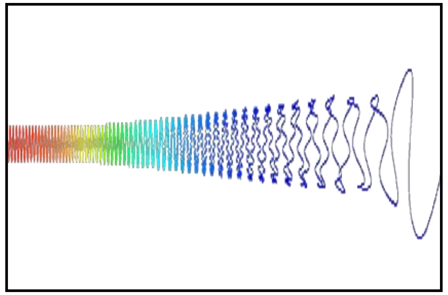
The hunt for the neutrino mass





CRES

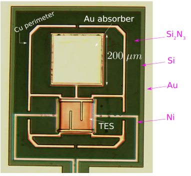


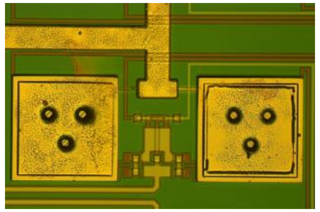


P on-
T ecorvo
O bservatory for
L ight,
E arly-universe,
M assive-neutrino
Y ield

Low Temperature Detectors

Electromagnetic Filters





The hunters

Calorimetric measurement: pro & cons

- The radioactive source is embedded in the detector(s). ⇨ **Most of the unwanted source related effects are avoided.**

- Only the neutrino energy escape detection.

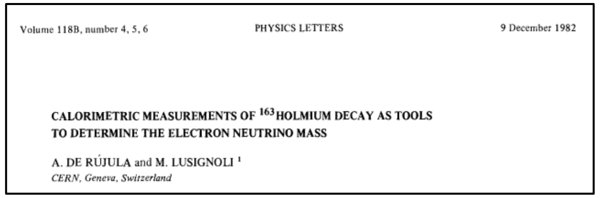
- Important limits on the single pixel activity (pile-up).

- Activity also limited by the correlation between energy resolution and detector size.

EC decay spectrum of Ho163

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

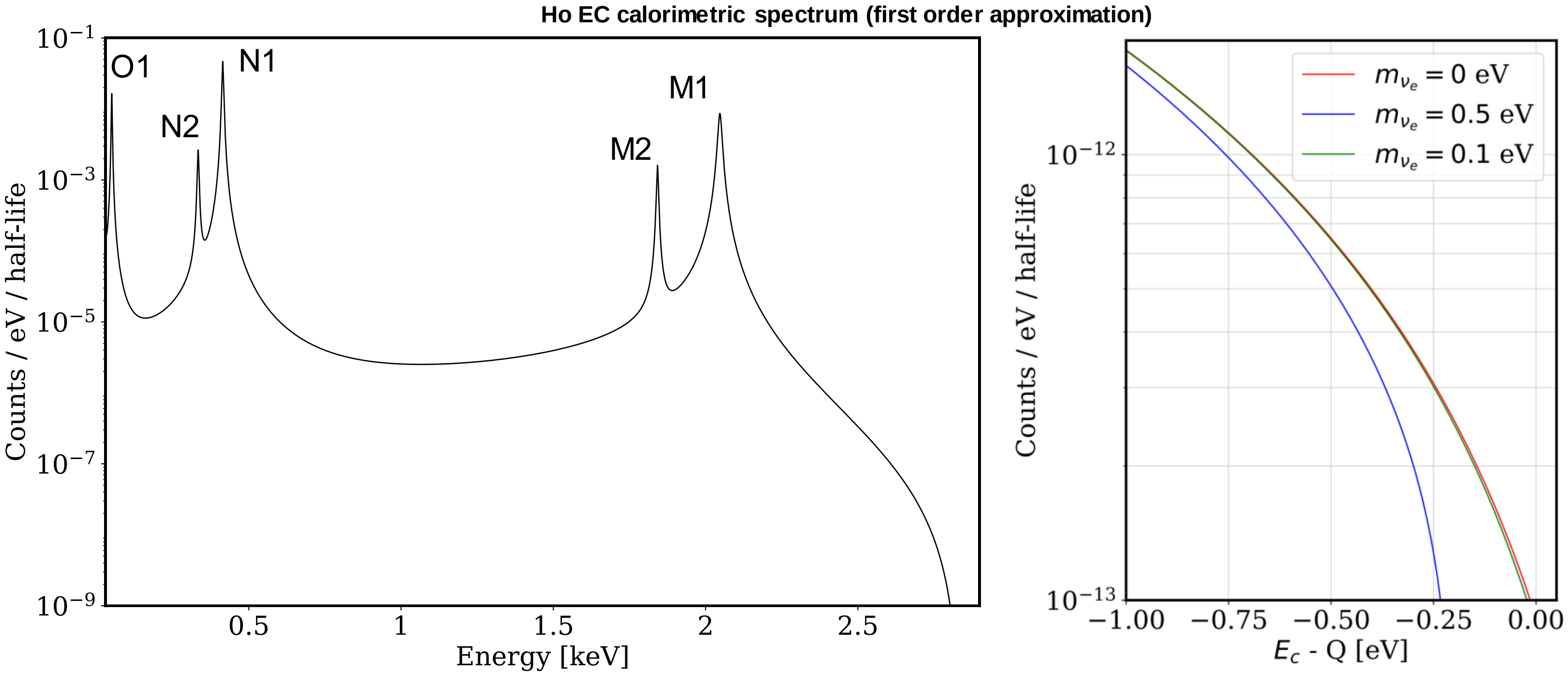
$$\frac{d\,\lambda_{EC}}{dE_C} = \mathrm{N}(Q - E_C)\sqrt{[(Q-E_C)^2 - m_\nu{}^2]} \times \sum_H \frac{\varphi_H^2(0)(\Gamma_H/2\pi)}{[(E_C - E_H)^2 + \Gamma_H{}^2/4]}$$


Volume 118B, number 4, 5, 6 PHYSICS LETTERS 9 December 1982

CALORIMETRIC MEASUREMENTS OF ^{163}HOLMIUM DECAY AS TOOLS TO DETERMINE THE ELECTRON NEUTRINO MASS

A. DE RÚJULA and M. LUSIGNOLI [1]

CERN, Geneva, Switzerland



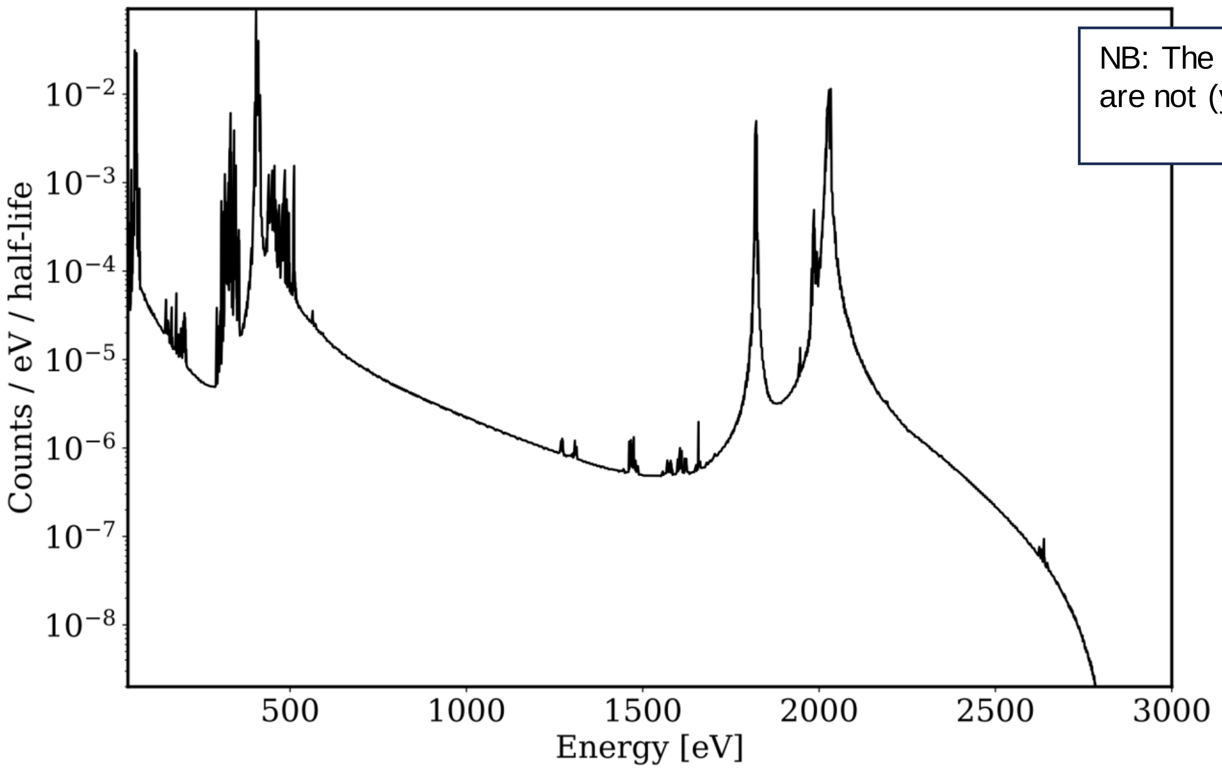
$$E_c = nuclear\ recoil + \text{inner bremmstrahlung} + \text{X rays} + \text{auger electrons}$$

EC decay spectrum of Ho163

- Additional calculations *(e.g. Ab initio calculation)* predict several additional features.
  - Shake-up, shake-off

M. Braß, C. Enss, L. Gastaldo, R. J. Green, and M. W. Haverkort
https://doi.org/10.1103/PhysRevC.97.054620

'full' ab initio ^{163}Ho spectrum



NB: The FWHM of the peaks are not (yet) fully known

- The exact shape of the Ho163 spectrum is yet not known.

The event rate at the endpoint can be quite different to the one predicted by first order theory

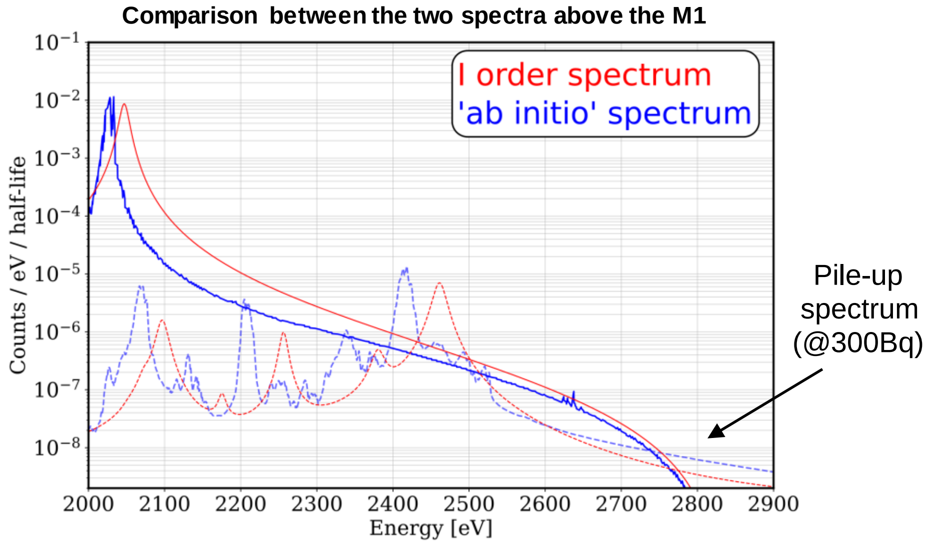
Ho163 spectral shape, is it important?

- What we must know:

+ (importance) -

- Energy of the main peaks. — Calibration
- Shape of M1 peak. — Detector response (FWHM)
- Shape of the entire Ho spectrum. — Sensitivity studies

Ho163 spectral shape, is it important?



- In all the available models, the Ho163 **calorimetric** spectrum appears **smooth** in the ROI.

True Ho163 spectrum

$$\left(f(E,\vec{\theta}) \times g(E,Q,m_\nu)\right) + bkg(E) + pup(E)$$

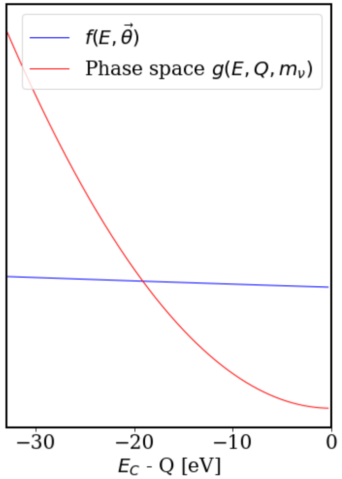
$f(E,\vec{\theta})$: Sum of *n* Lorentzian peaks + shake-off

$g(E,Q,m_\nu)$: Phase space

⇨

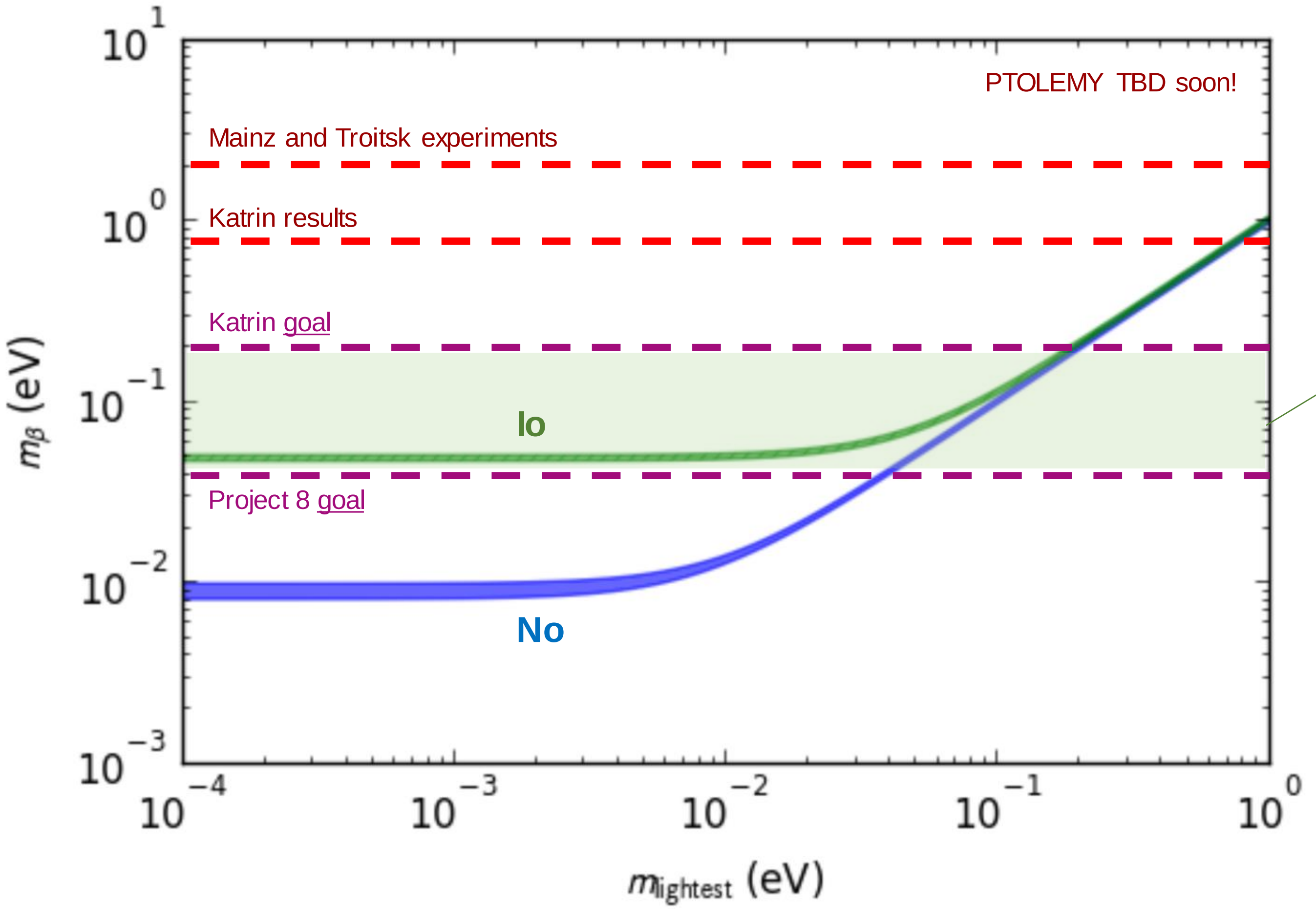
Approximated 163Ho spectra

$$\left([a_1 + a_2E + a_3E^2 + ...] \times g(E,Q,m_\nu)\right) + bkg(E) + pup(E)$$



"model-free" estimation of the neutrino mass?

Next-gen calorimetric experiments, requirements & sensitivity



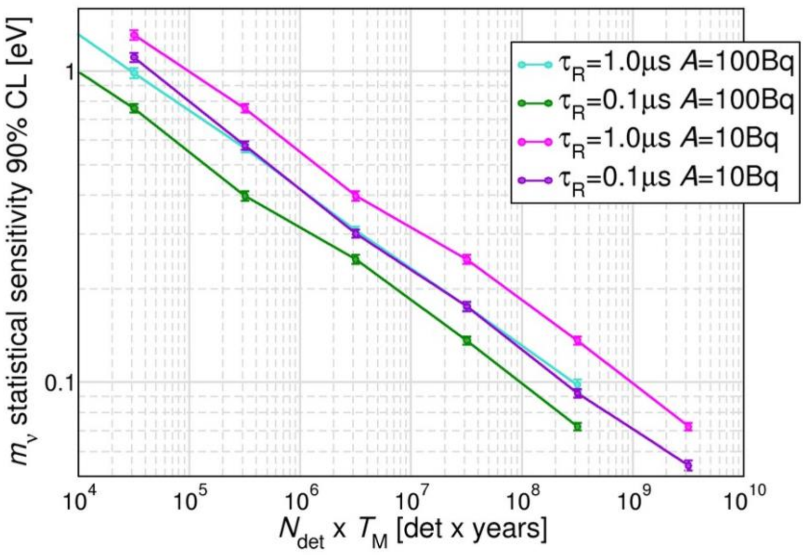
Target sensitivity region for the next-gen calorimetric experiment

How?

Next-gen calorimetric experiments, requirements & sensitivity

- … it depends on the expected rate in the ROI.

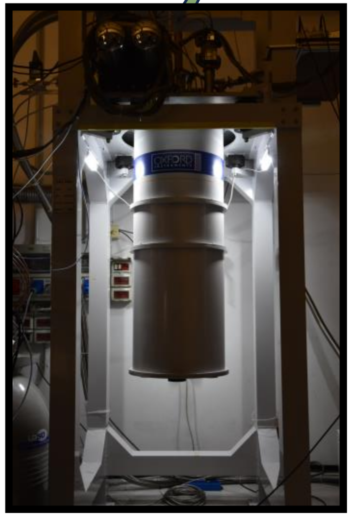
Worst case scenario: I order theory



- Pixel activity ~ 100 Bq/det
- Time resolution below 0.1 us
- Energy resolution = 1 eV
- About 1M pixels, 10 y measurement for ~ **200-100 meV** sensitivity

Next-gen calorimetric experiments, requirements & sensitivity

- Requirements:
  - LTD working at low temperature (e.g. @30mK).
  - LTD with fast rise (reduce pup fraction) and fast decay time (reduce dead time).
  - Affordable multiplexing technique with large BW.
  - Efficient implantation technique.
  - Large cryogenic infrastructure.



- If you want to increase the sensitivity, you need (as always) to go

BIG

HOLMES goal

- Evaluate the feasibility of this approach.

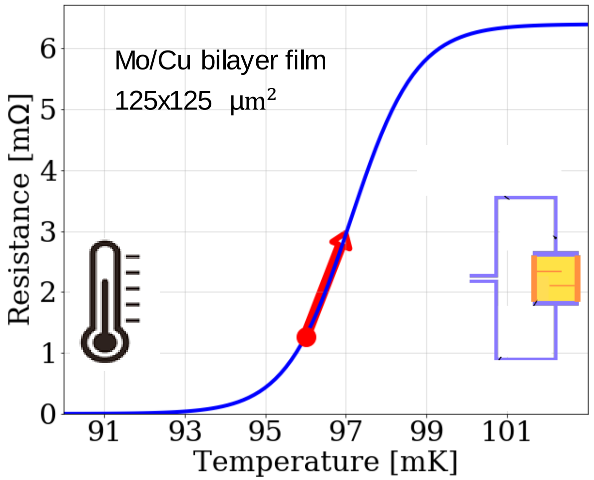
  - ✓ Desing robust analysis routines for LTD data-handling, pile-up rejection and data analysis of *n* independent detectors.
  - ✓ Test the performance of fast TES detectors, readout with proper multiplexing technique.
  - ✓ Implant the Holmium inside a TES detectors.
  - ✓ Study the Ho163 spectral shape.
  - ✓ Perform a first “test” measurement of the neutrino mass.
  - ❑ Increase the single pixel activity.

Done
Ongoing

TES for HOLMES

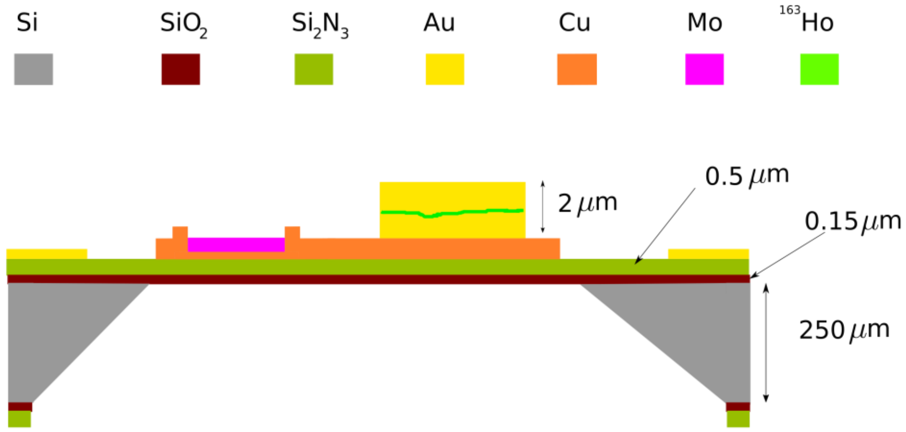
- TES: superconductor film operated in the narrow temperature region between the resistive and the superconducting state

Transition shape of an Holmes-like TES

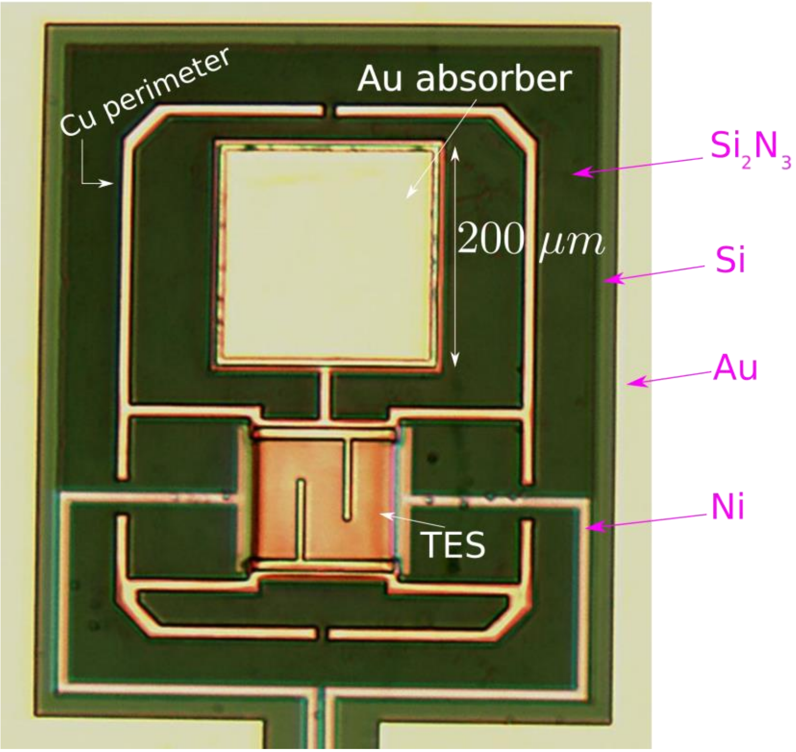


- Designed to be fast: additional copper perimeter to decrease the recovery time of the signal

L. Origo talk: “163Ho-implanted TES for a calorimetric m_nu measurement”

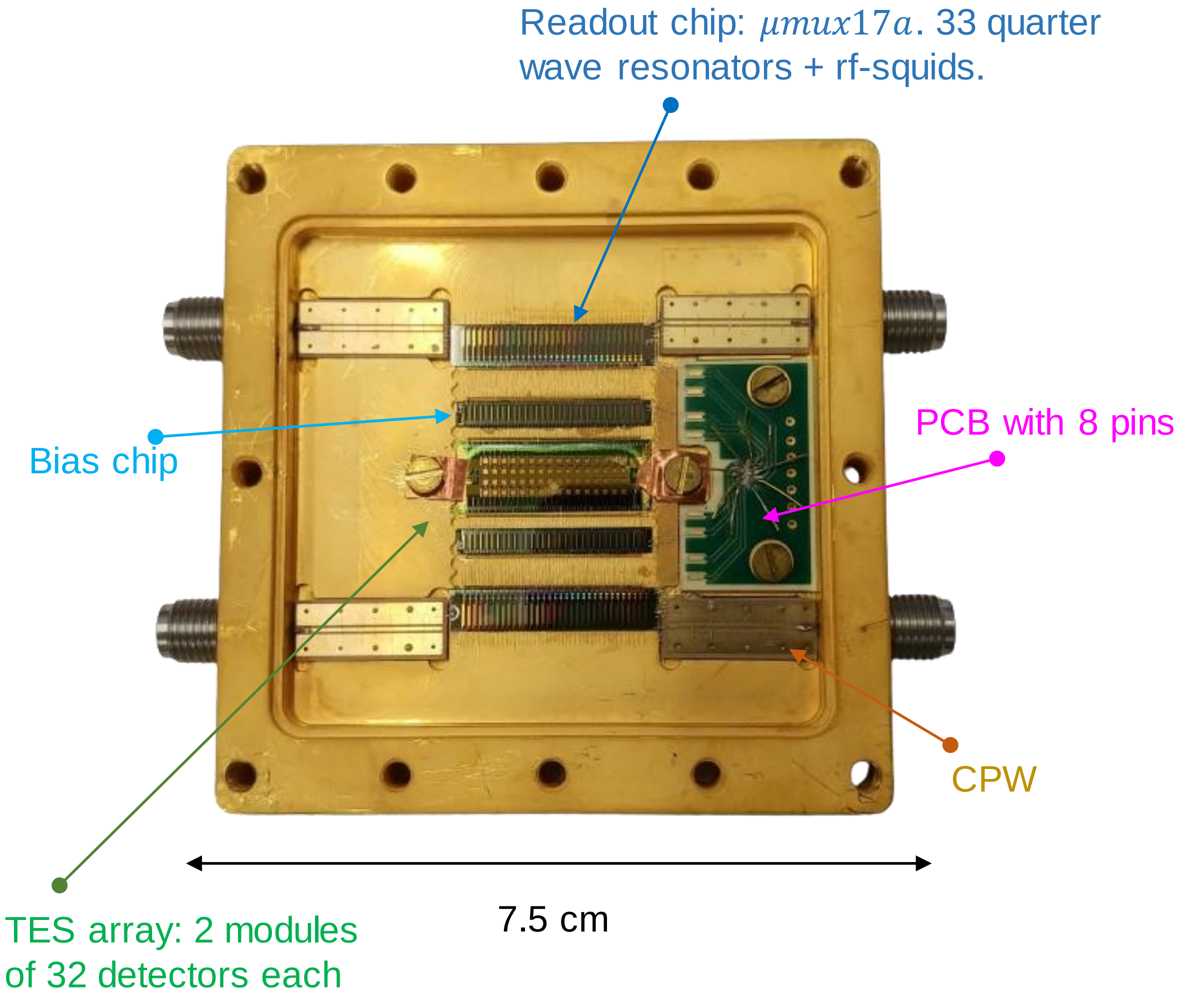


Sideview and topview of the Holmes detector design

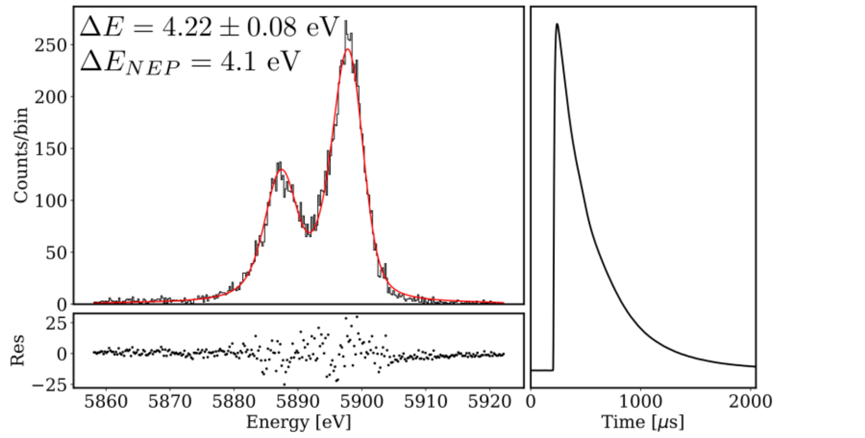


The detector array

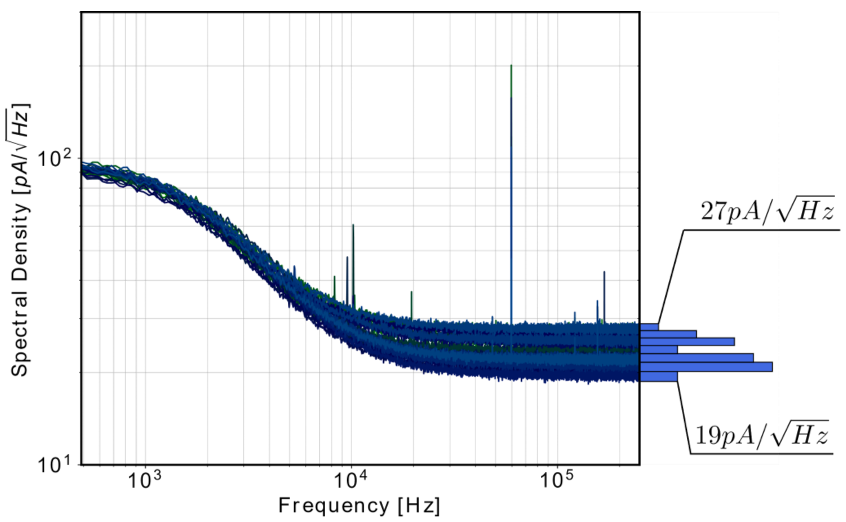
- At present we can readout 64 detectors simultaneously.



Detector resolution @6000 eV readout with μmux (w/o 163Ho)

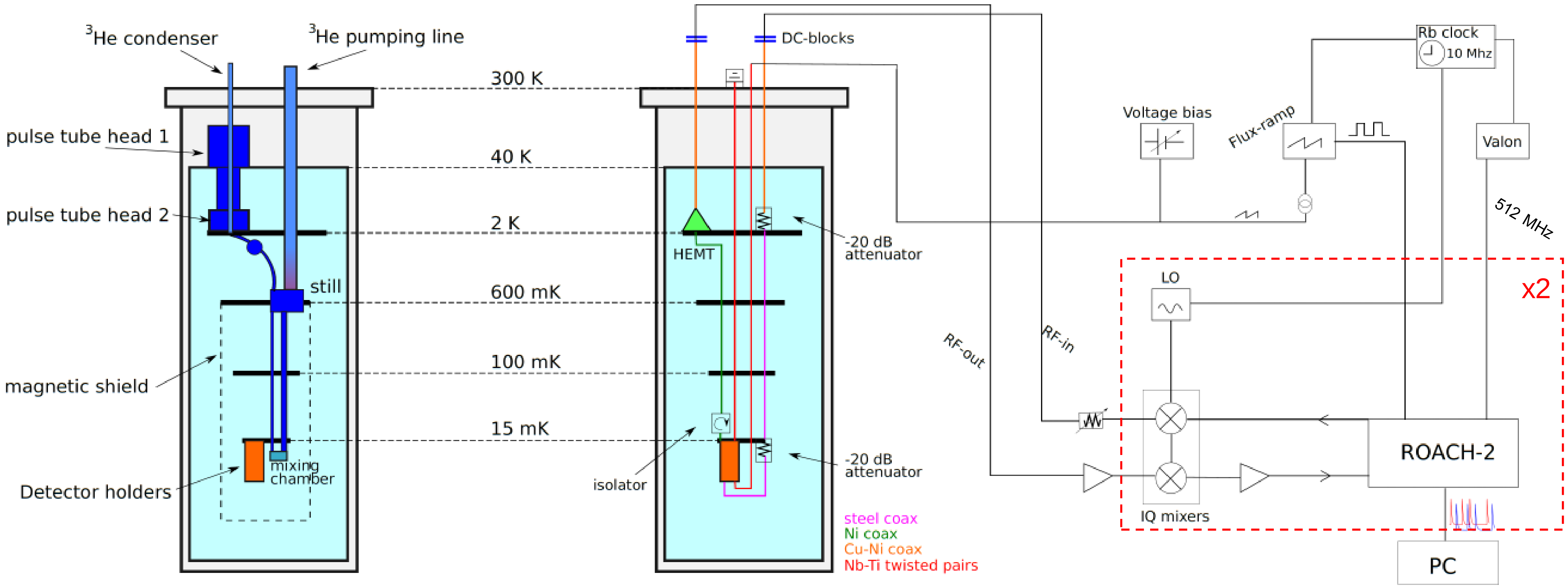


Noise of a 32 TES detectors readout with μmux



Measurement setup

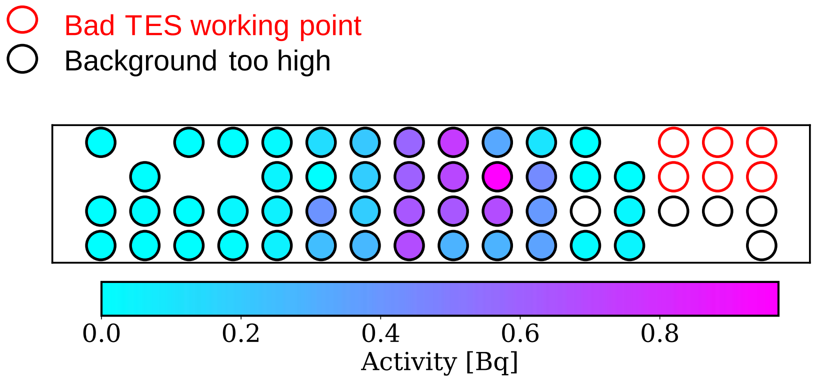
- $^3He/\ ^4He$ diluition refrigerator (200 μW of cooling power @100 mK)

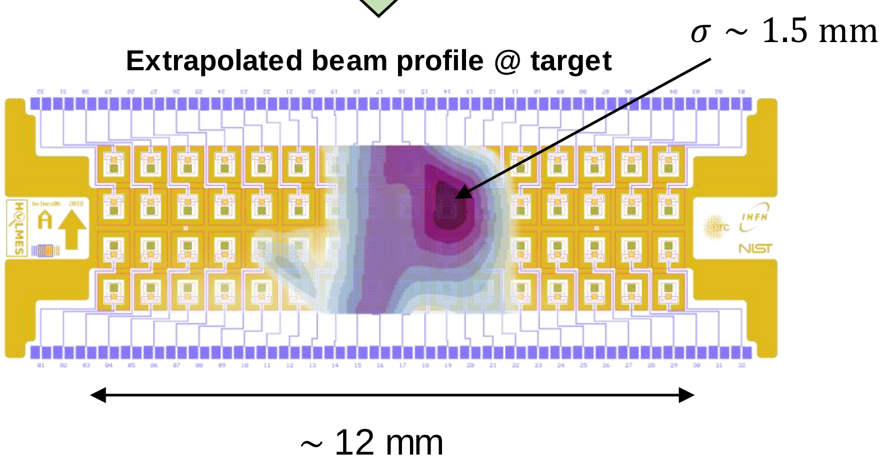


Implantation results so far

G. Gallucci talk: “The HOLMES low activity implantation”

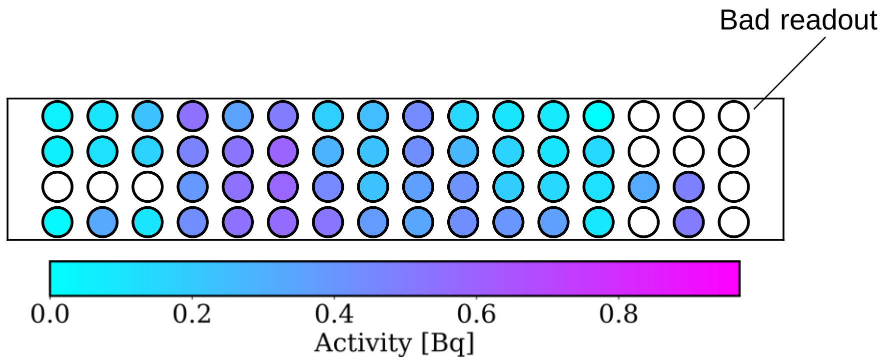
First implantation





- Mean activity ≃ 0.24 Bq
- Total activity ≃ 10 Bq

Second implantation



- Mean activity ≃ 0.30 Bq
- Total activity > 15.4 Bq

Runs summary

Run 1 | Run 2 | Run 3 | Run *n* | Run 6 | Run 7

Jun 2023

- With external ^{55}Fe calibration source.
- Goal: Observe the **first HOLMIUM spectrum.**

July 2023

- With external Fluorescence calibration source
- Goal: Characterize the main peaks of the Ho spectrum**.**

August 2023

- **Just Ho163.**
- **First Physics run!**

Jan 2024

Feb 2024

Runs summary

Run 1 | Run 2 | Run 3 | Run *n* | Run 6 | Run 7

Jun 2023

- With external ^{55}Fe calibration source.
- Goal: Observe the **first HOLMIUM spectrum.**

July 2023

- With external fluorescence calibration source
- Goal: characterize the main peaks of the Ho spectrum**.**

August 2023

- **Just Ho163.**
- **First Physics run!**

Jan 2024

- With external fluorescence calibration source
- Goal: Describe the main peaks of the Ho spectrum**.**

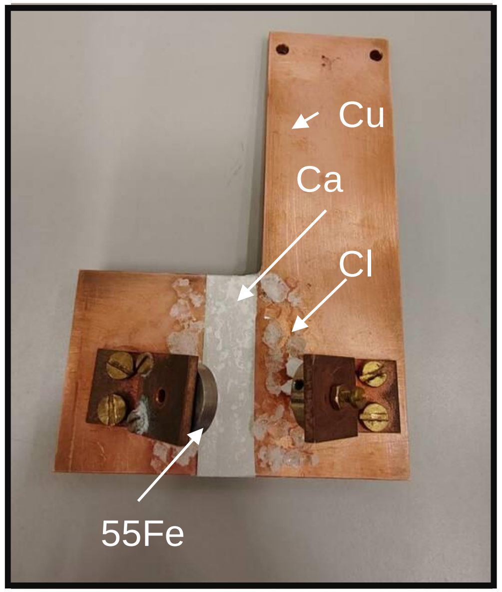
Feb 2024

- **Just 163Ho.**
- **First Physics run!**

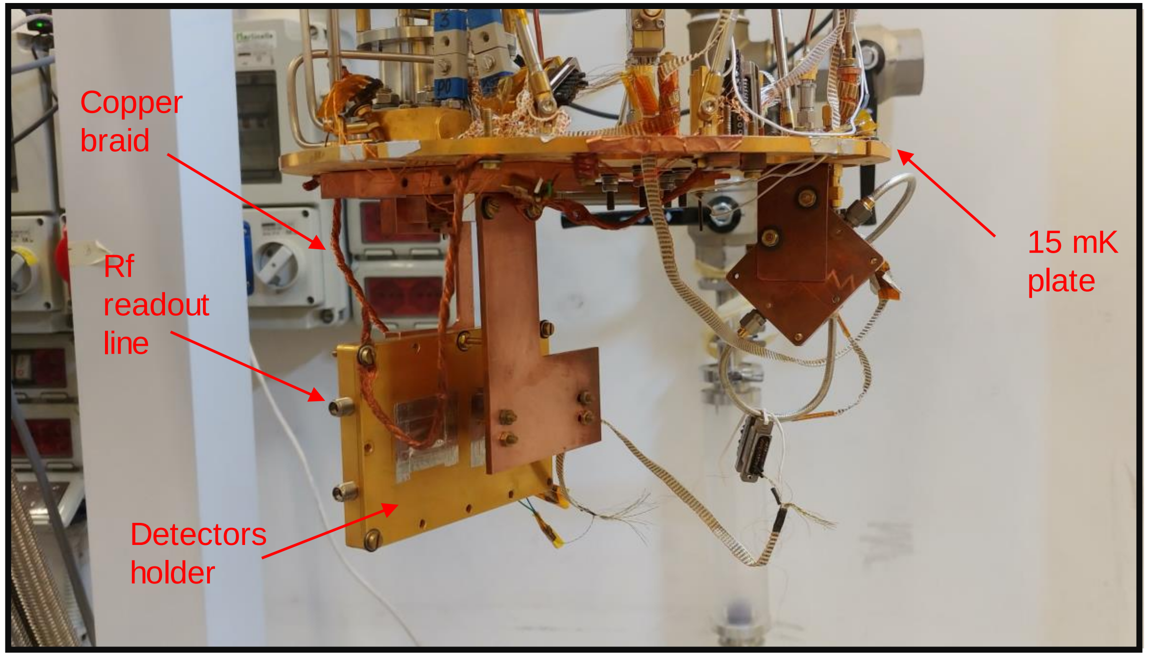
Characterization of the Ho163 spectrum (I)

- **Goal**: find a good model to <u>locally</u> describe the main Ho163 peaks
- Only ½ of the chip used (32 detectors) (one of our amplifiers failed, now fixed!)
- We use an external fluorescence calibration source

Fluo calibration source



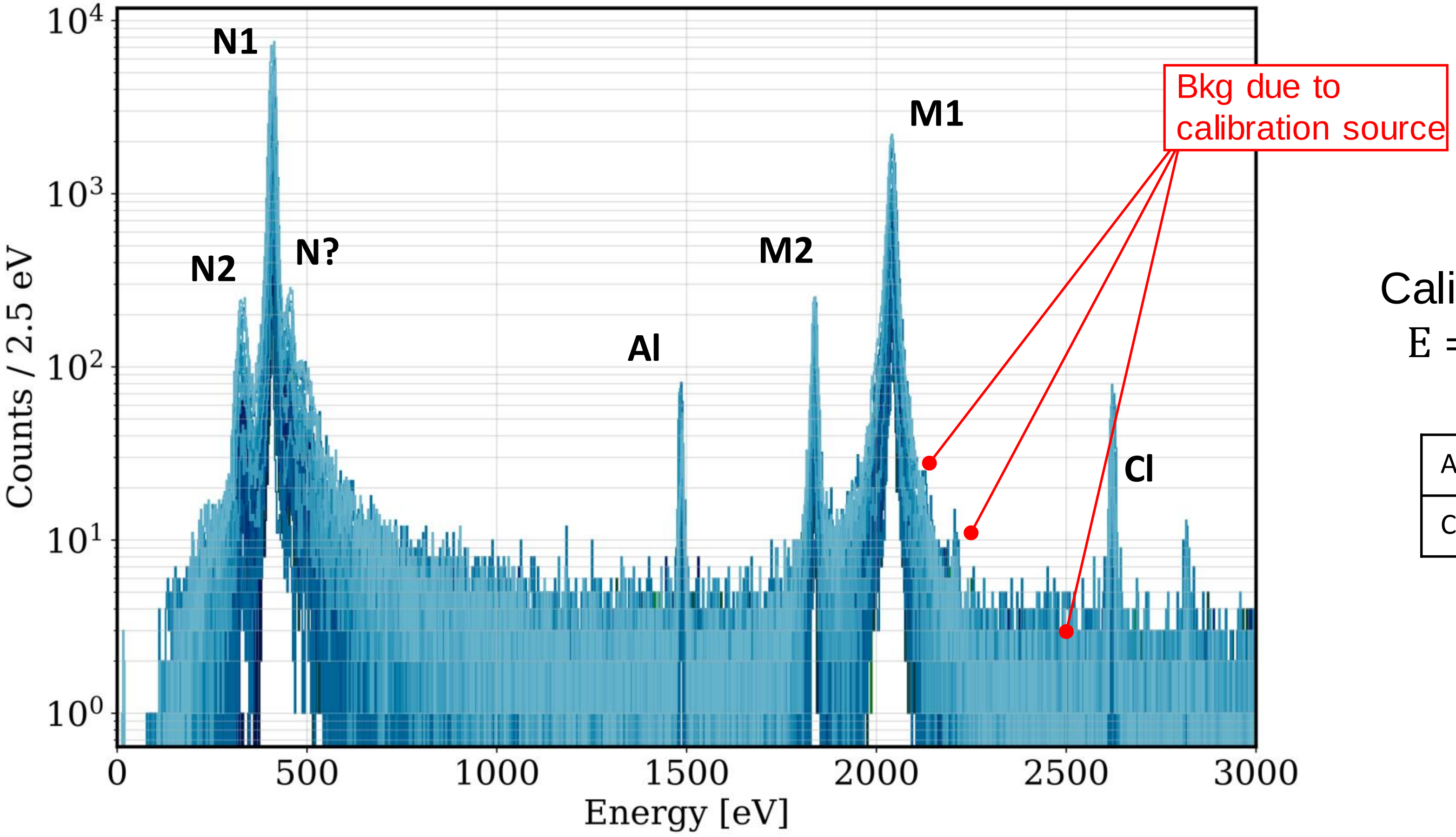
Setup @MC plate



Characterization of the Ho163 spectrum (II)

- 50 holmium spectra were recorded, “cleaned” and calibrated.

$\Delta E_{FWHM} \sim (5.4 \div 8)$eV



Calibration function used:

$$E = f(x) = a_1 x + a_2 x^2$$

Al Ka1	1486.706 (10) eV
Cl Ka1	2622.39 (9) eV

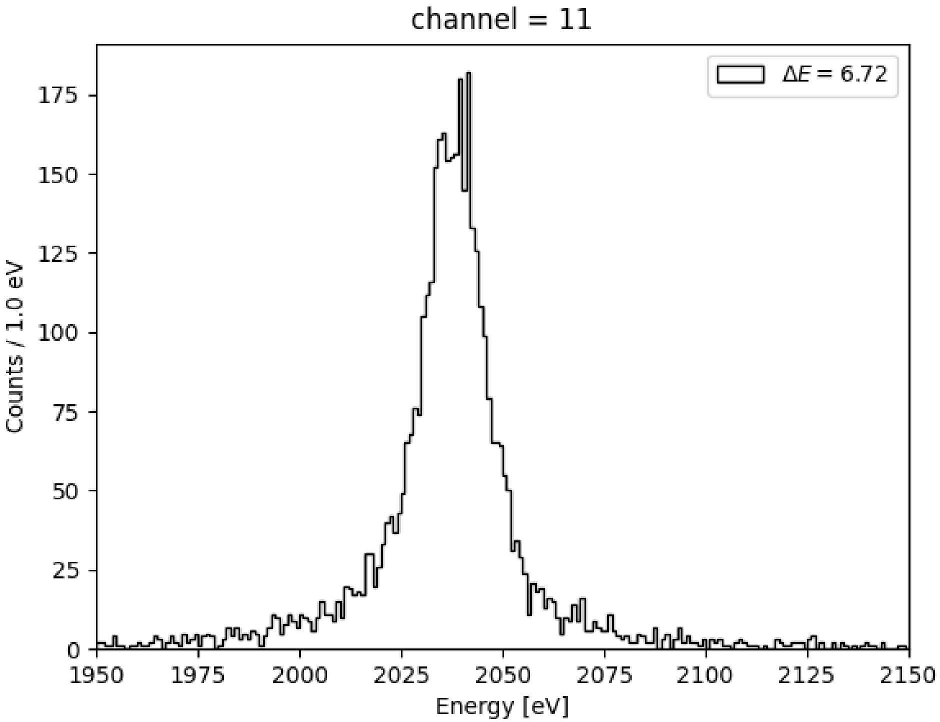
Characterization of the Ho163 spectrum (III)

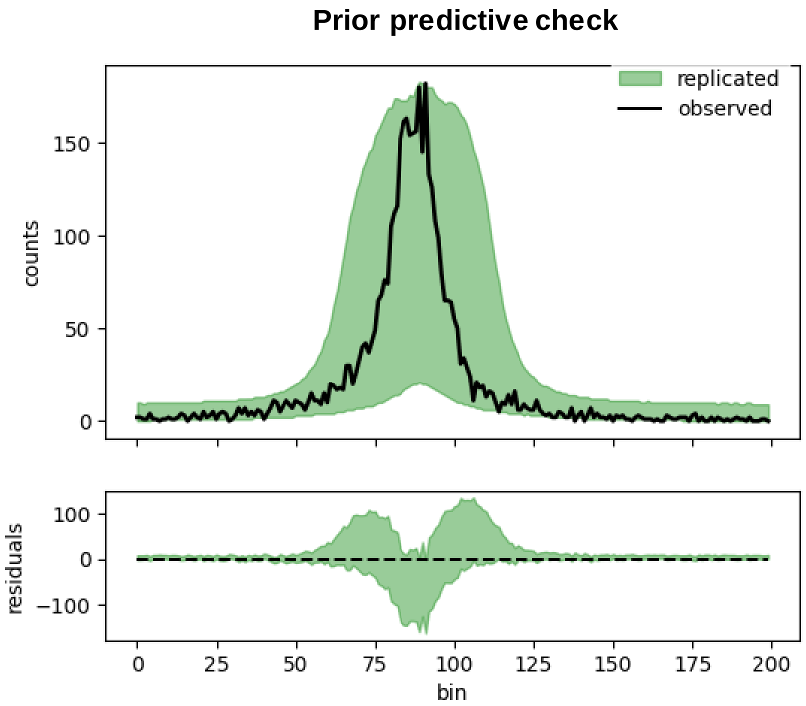
- Bayesian parameter estimation.

$$spectra = gaus(0,\boldsymbol{\sigma}) \otimes [\boldsymbol{I} \times cauchy_{asym}(E,\boldsymbol{E_0},\boldsymbol{\gamma},\boldsymbol{\xi}) + \boldsymbol{bkg}]$$

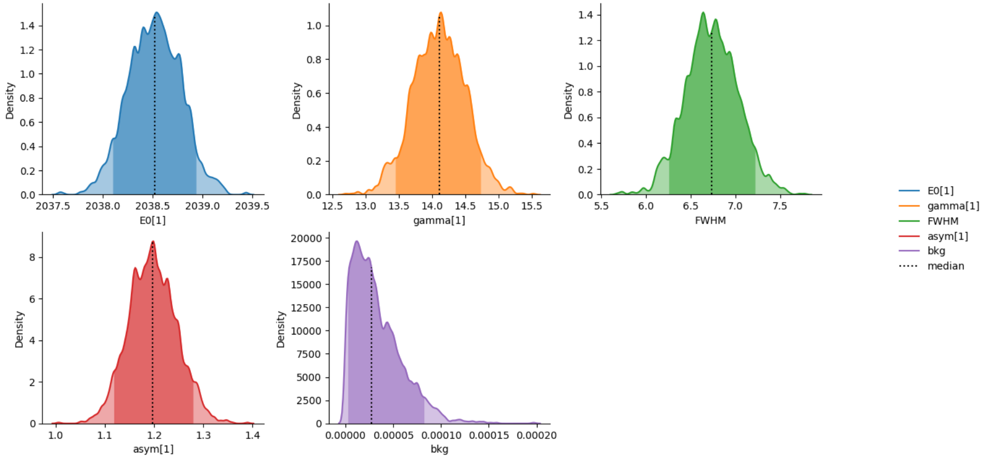
$$likelihood \sim poisson(spectra)$$

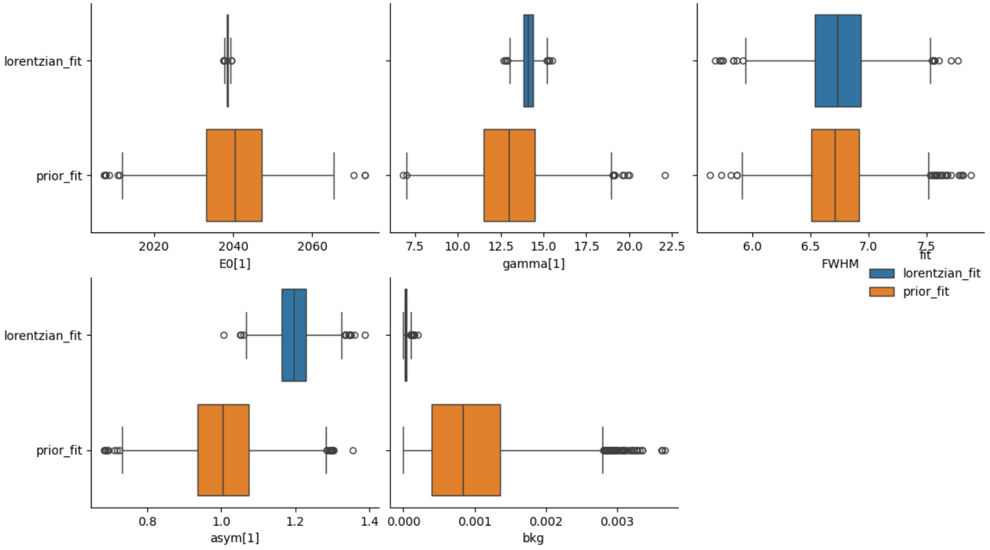
$$cauchy_{asym} \propto \begin{cases} cauchy(E,E_0,\gamma_L) & E \leq E_0 \\ cauchy(E,E_0,\gamma_R) & E > E_0 \end{cases} \qquad \gamma_L = \frac{\gamma \times \xi}{\xi + 1} \qquad \gamma_R = \frac{\gamma}{\xi + 1}$$

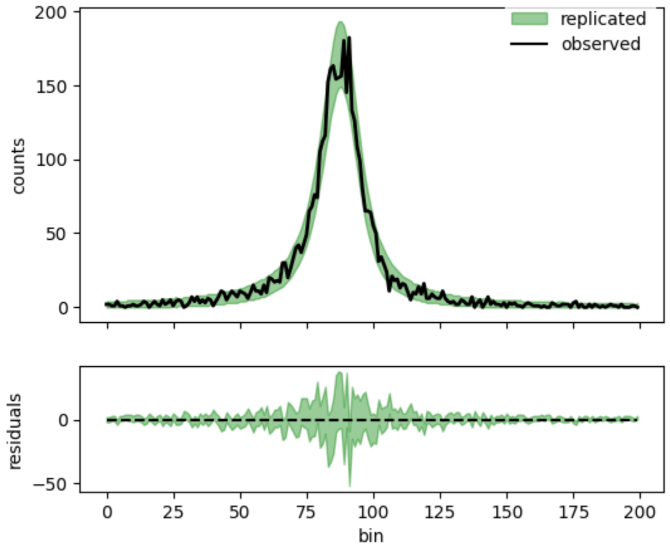


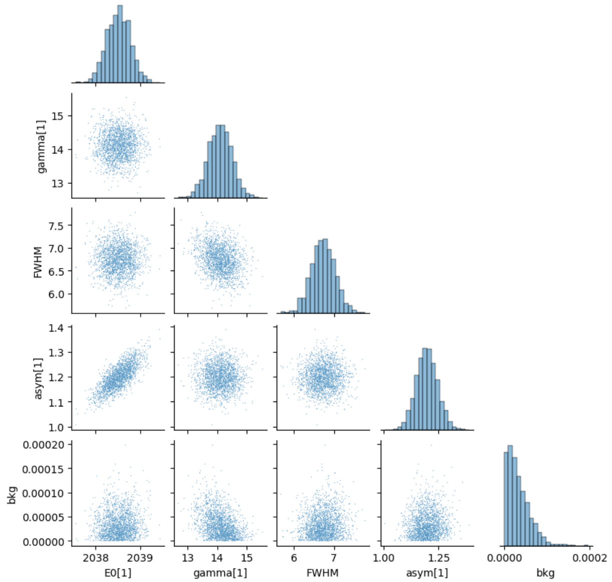


Characterization of the Ho163 spectrum (III)



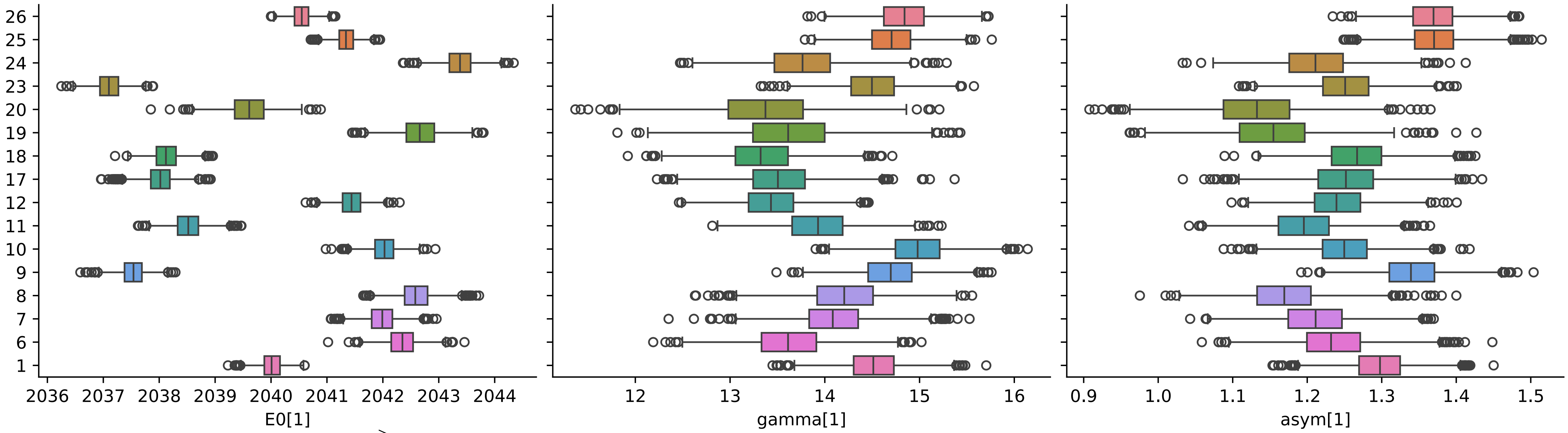






Characterization of the Ho163 spectrum (IV)

- How can we achieve a robust estimation of the peak position?



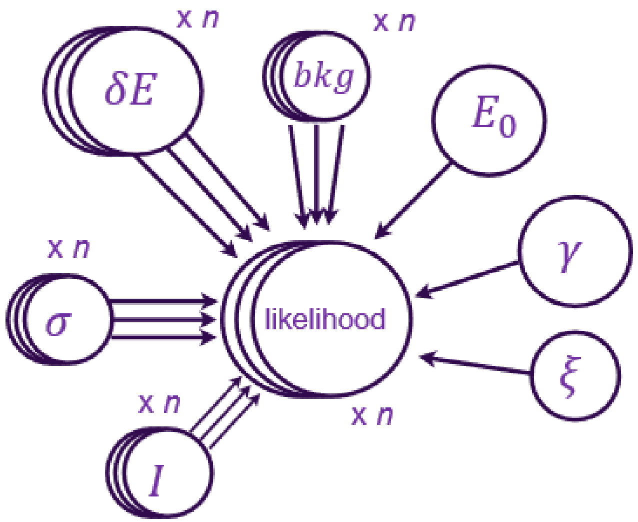
Energy shift due to calibration

Characterization of the Ho163 spectrum (IV)

Assumption: the energy shifts δE are normally distributed around 0 (prior)

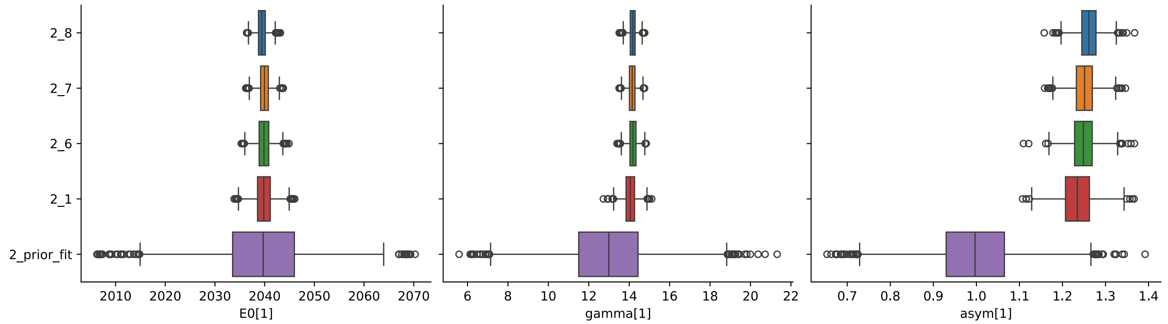
Global fit

- Fit spectra from *n* detectors at the same time.
- Probably the most accurate method. But computationally expensive!
- Four parameters for each detector: resolution (σ), bkg (bkg), peak intensity (I), energy shift (δE).
- Peak position (E_0), gamma (γ) and asymmetry (ξ) are common parameters.

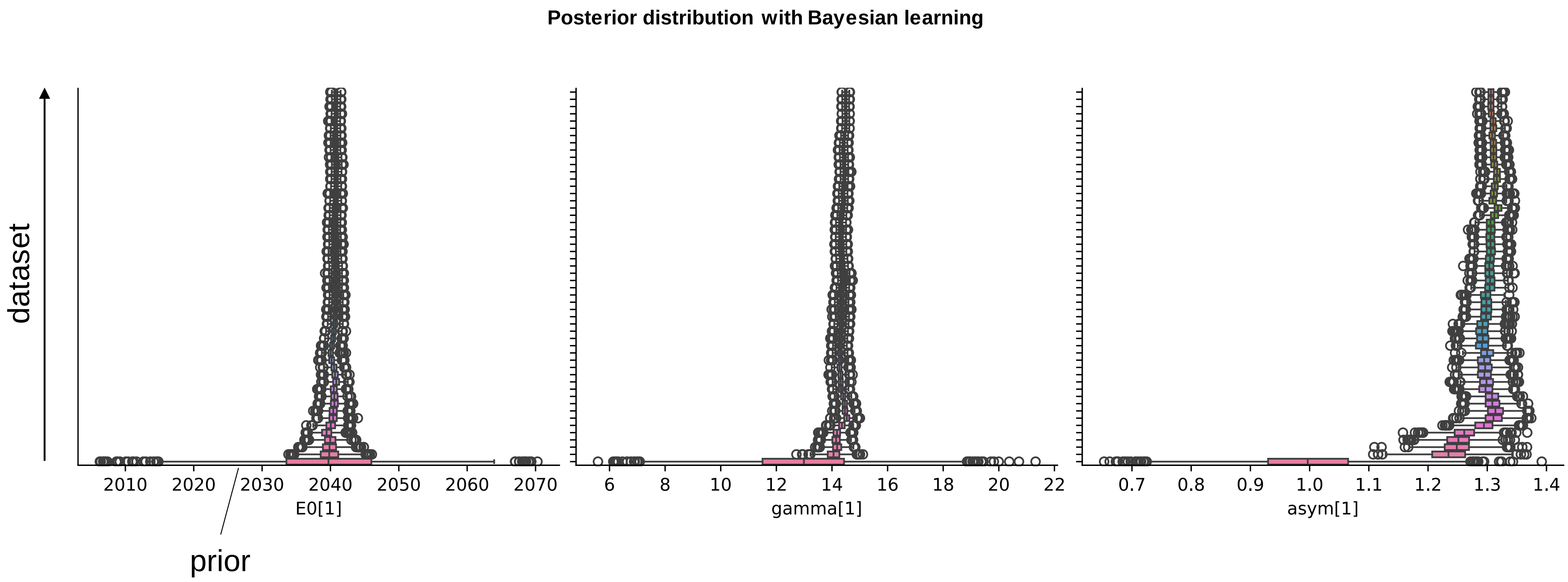


Bayesian learning

- Fit spectra from *n* detectors recursively. The posterior of the former is prior for the latter.
- The single peak model has to be modified in order to take into account the energy shift.
- Update the prior just for the common parameters: Peak position (E_0), gamma (γ) and asymmetry (ξ).
- Assumption (reasonable): model the posterior distribution for the common parameters as gaussian.



Characterization of the Ho163 spectrum (IV)



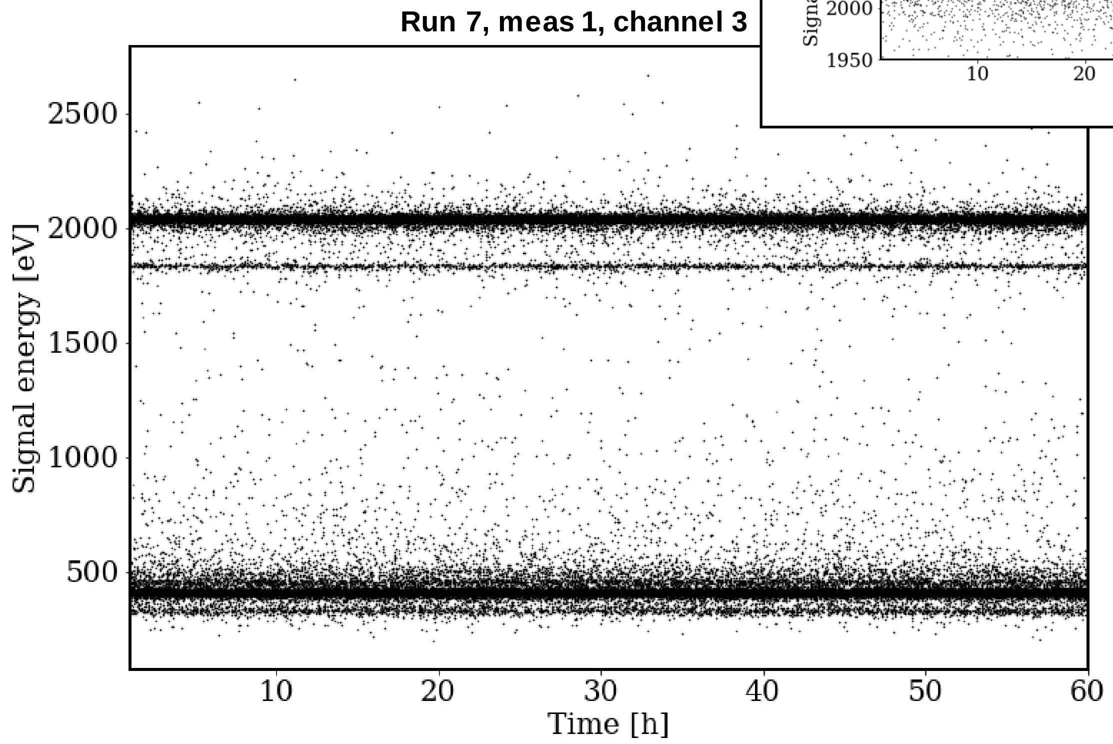
Characterization of the Ho163 spectrum (V)

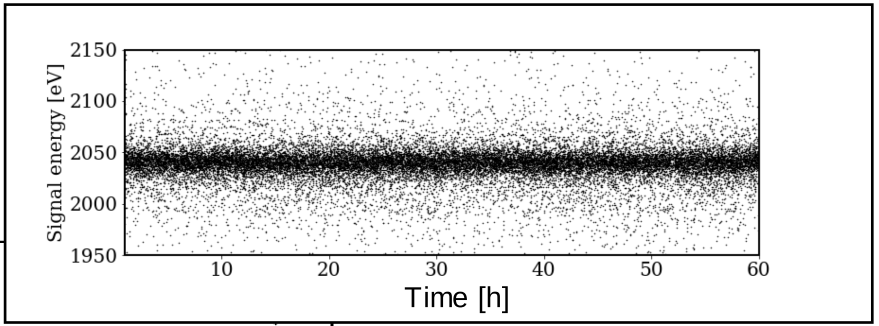
Peak	Position [eV]	Gamma [eV]	Asymmetry
M1	2040.8 ± 0.3	14.49 ± 0.05	1.306 ± 0.006
M2	1836.4 ± 0.8	8.2 ± 0.3	1.03 ± 0.05
N?	454.5 ± 0.1	22.3 ± 0.4	0.62 ± 0.02
N1	411.72 ± 0.1	5.57 ± 0.03	1.270 ± 0.008
N2	329.0 ± 0.1	16.4 ± 0.2	0.69 ± 0.01

Using those peak positions to calibrate a dataset, we get for Al and Cl 1486 ± 1 eV (1486.706 (10) eV) and 2623 ± 1.2 (2622.39 (9) eV) eV, respectively

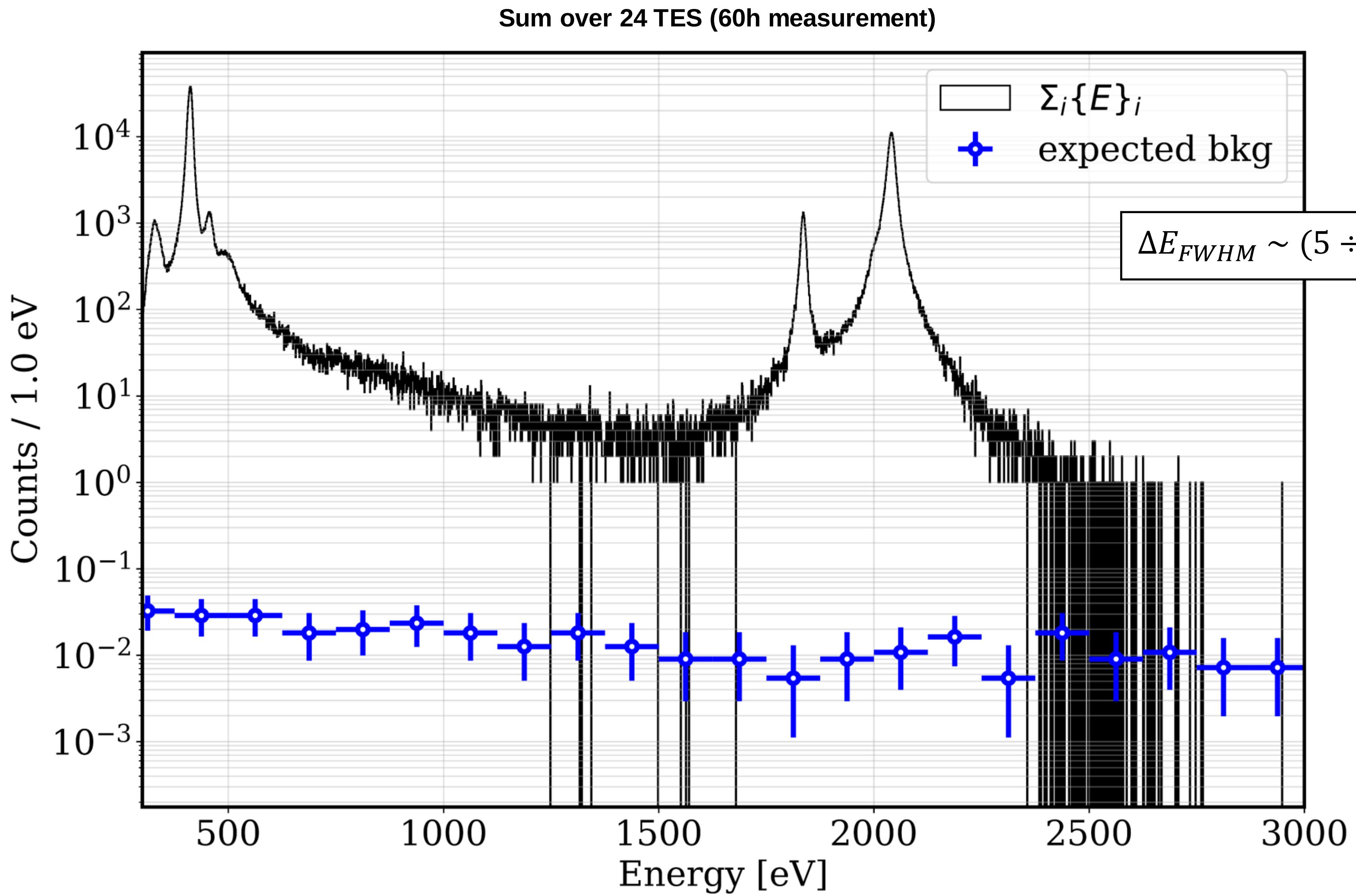
Study of the Ho163 spectrum

- No external fluorescence calibration source.
- Run started last week!
    - 1 measurement acquired so far: 24 channels, 60 continuous hours



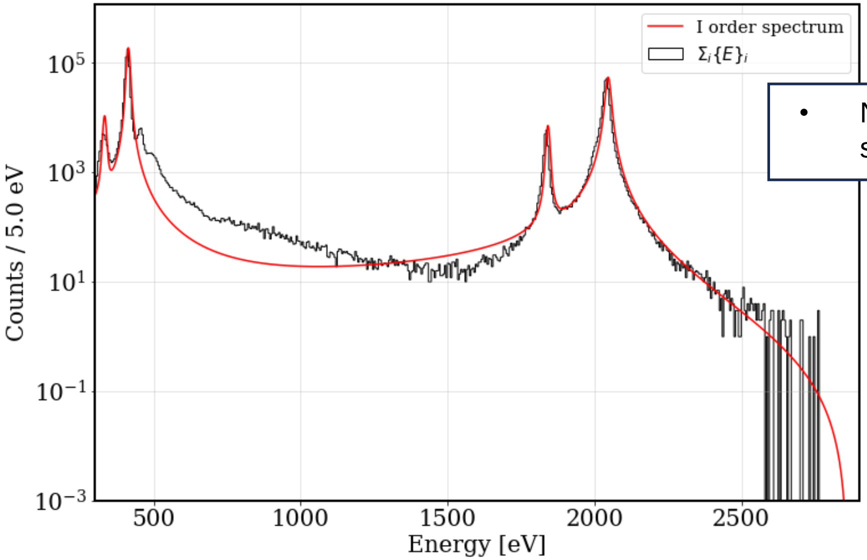


Study of the Ho163 spectrum



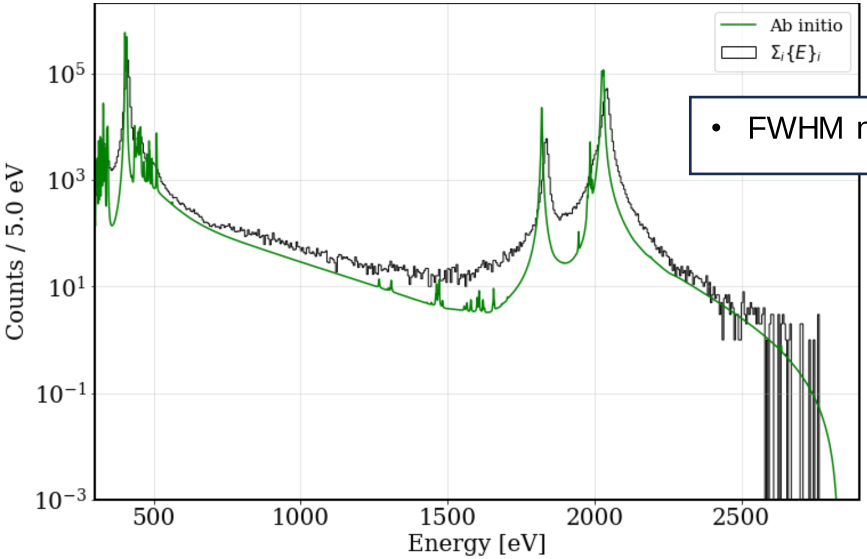
$\Delta E_{FWHM} \sim (5 \div 7\,)\text{eV}$

Study of the Ho163 spectrum

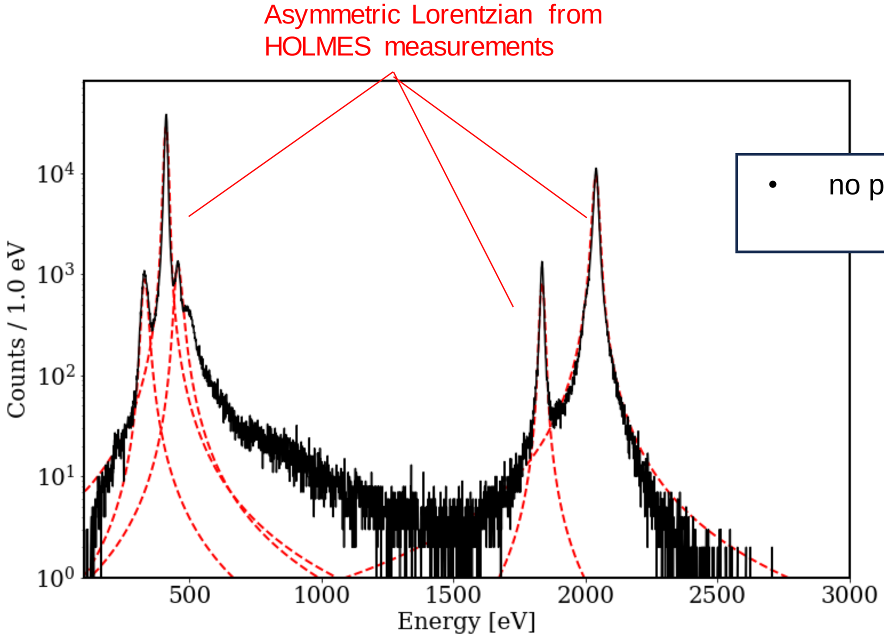


- No shake-off and shake up

(qualitative comparison)



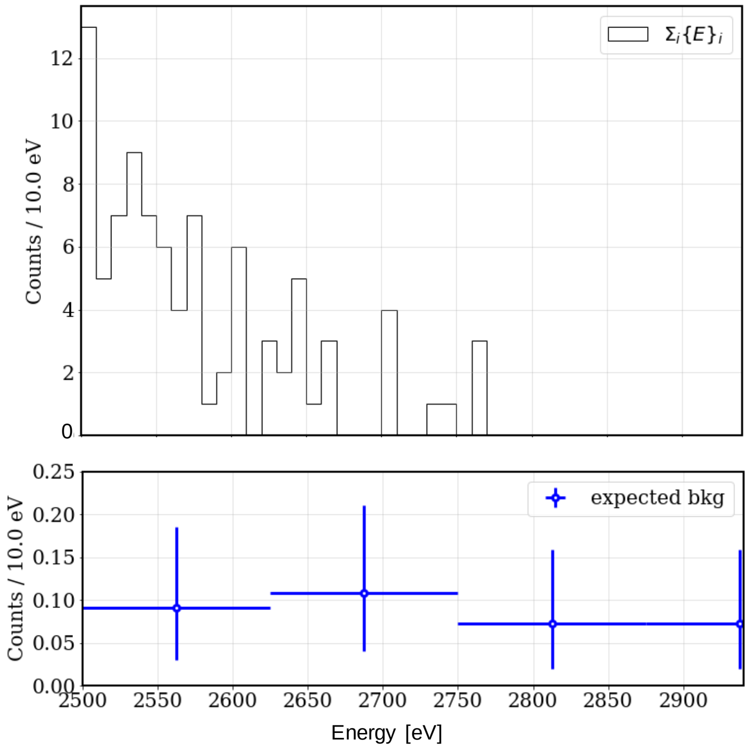
- FWHM not complete



- no phase space

Study of the Ho163 spectrum

- Event rate in the ROI could be higher than predicted?



Energy interval [eV]	Expected events*	Measured events
2500-2860	50 ± 7	90
2600-2860	15.5 ± 4	30
2700-2860	3 ± 1.7	9

* From I order theory

- Needs to be investigated.

Conclusion

- We are ready to start our very first physics run.

- HOLMES and ECHo are laying down the fundamentals for the next-gen calorimetric experiment.