# HOLMES

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*on behalf of the HOLMES collaboration*

GA n. 340321

HOLMES is an experiment to directly measure the neutrino mass with a sensitivity as low as ~1 eV. HOLMES will perform a calorimetric measurement of the energy released in the electron capture decay of $^{163}$Ho (A. De Rujula and M. Lusignoli, Phys. Lett. B 118 (1982) 429). The calorimetric measurement eliminates systematic uncertainties arising from the use of external beta sources, as in experiments with beta spectrometers. HOLMES will deploy a large array of low temperature microcalorimeters with implanted $^{163}$Ho nuclei. We outline here the project technical challenges and the present status of the development.

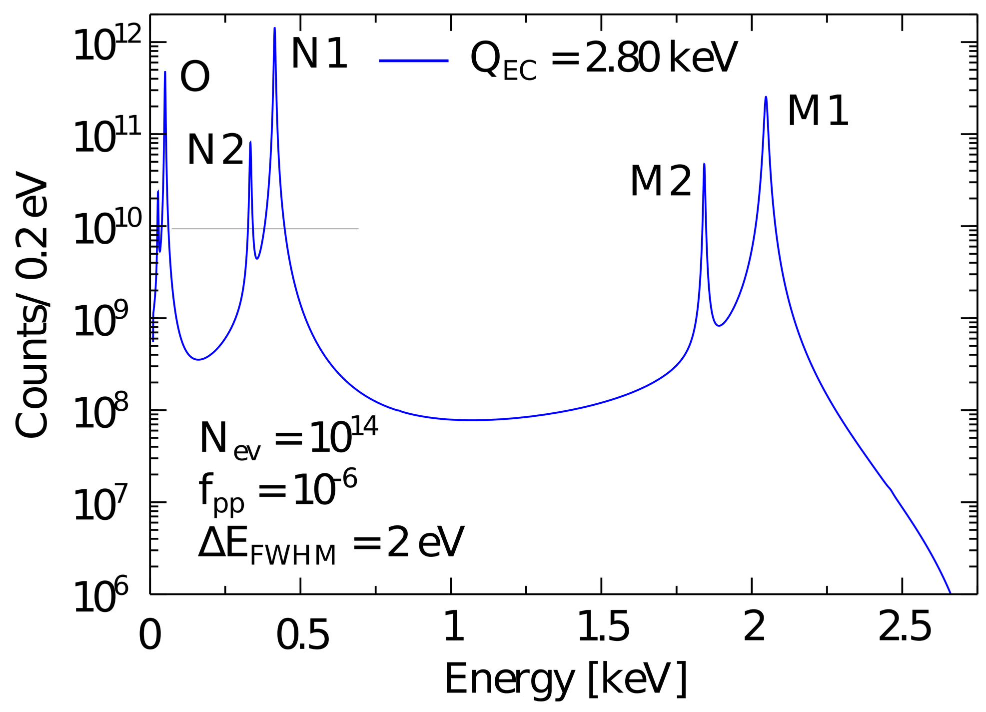
## $^{163}Ho + e \longrightarrow {}^{163}Dy^* + \nu_e$ Electron capture from shell ≥ M1

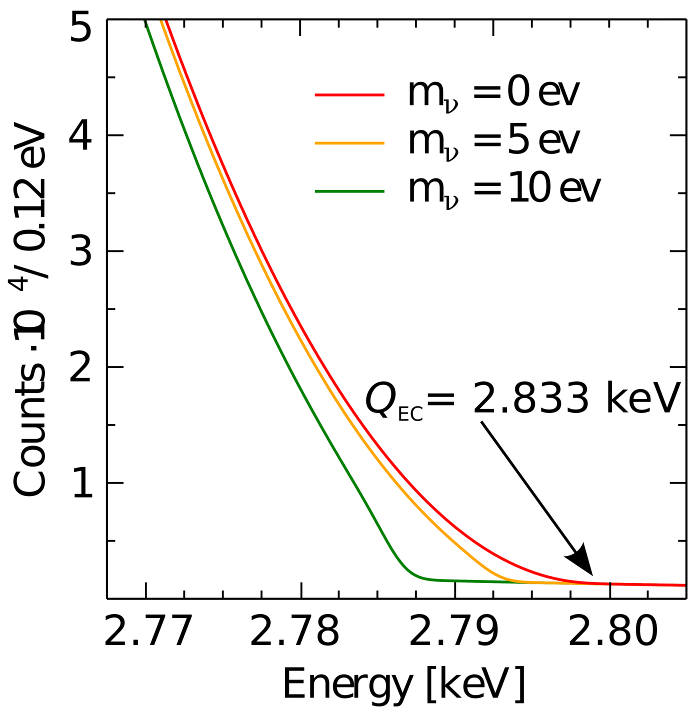
*A. De Rujula and M. Lusignoli, Phys. Lett. B 118 (1982) 429*

- **Calorimetric measurement of the (mostly non-radiative) de-excitation of Dy**
- Rate at the end-point depends on $Q$
  - ▸ Measured with Penning trap: $\boldsymbol{Q}$ **= 2.833 keV** Phys.Rev.Lett., 115:062501 (2015)

$\tau_{1/2} \approx 4570$ years ⟶ **few nuclei are needed**

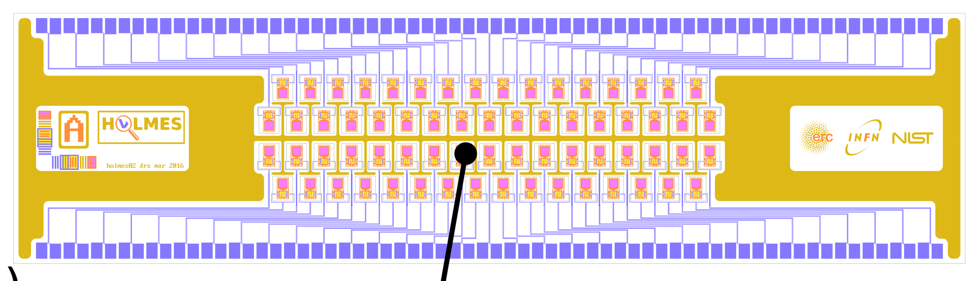
$$\frac{d\lambda}{dE_c} = \frac{G_\beta^2}{4\pi^2}(Q-E_c)\sqrt{(Q-E_c)^2-m_\nu^2} \times \Sigma_i n_i C_i \beta_i \frac{\Gamma_i}{2\pi}\frac{1}{(E_c-E_i)^2+\Gamma_i^2/4}$$

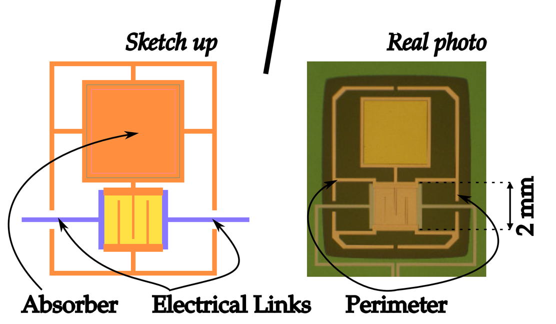


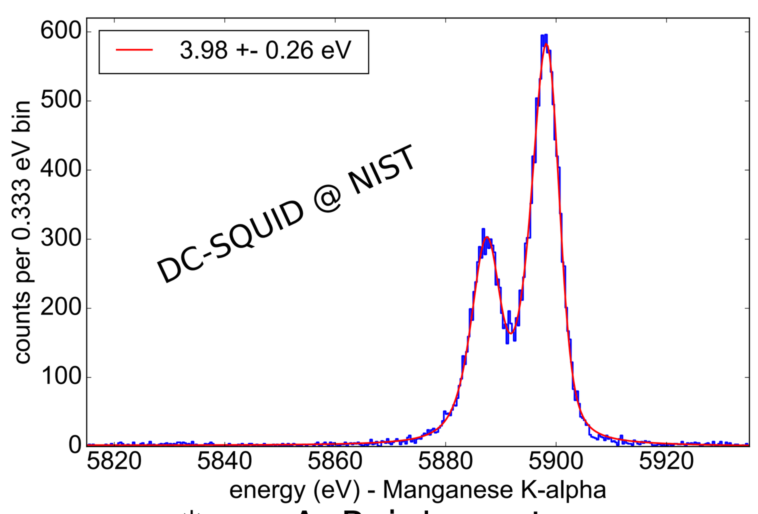




## Transition edge sensors (TES)

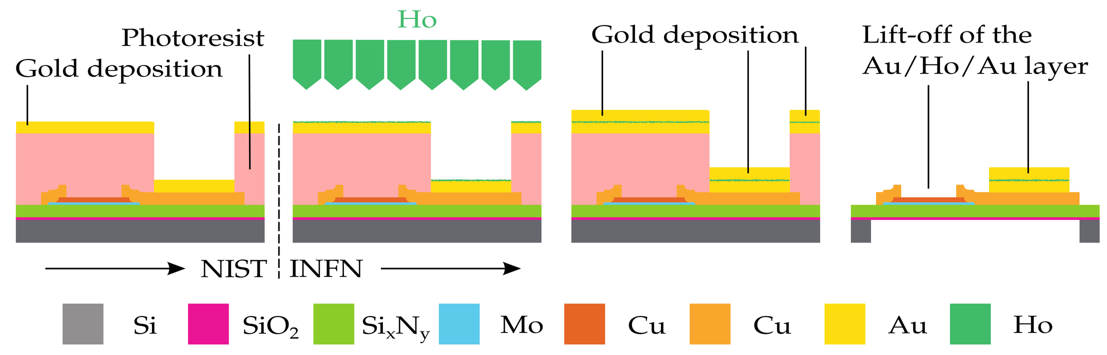
- Thermal microcalorimeters
- Mo/Cu bilayers: $Tc \approx 100$ mK
- 2 µm thick gold absorbers
- produced @ NIST (Boulder, CO, USA)
- Implanted **$^{163}$Ho** (INFN)



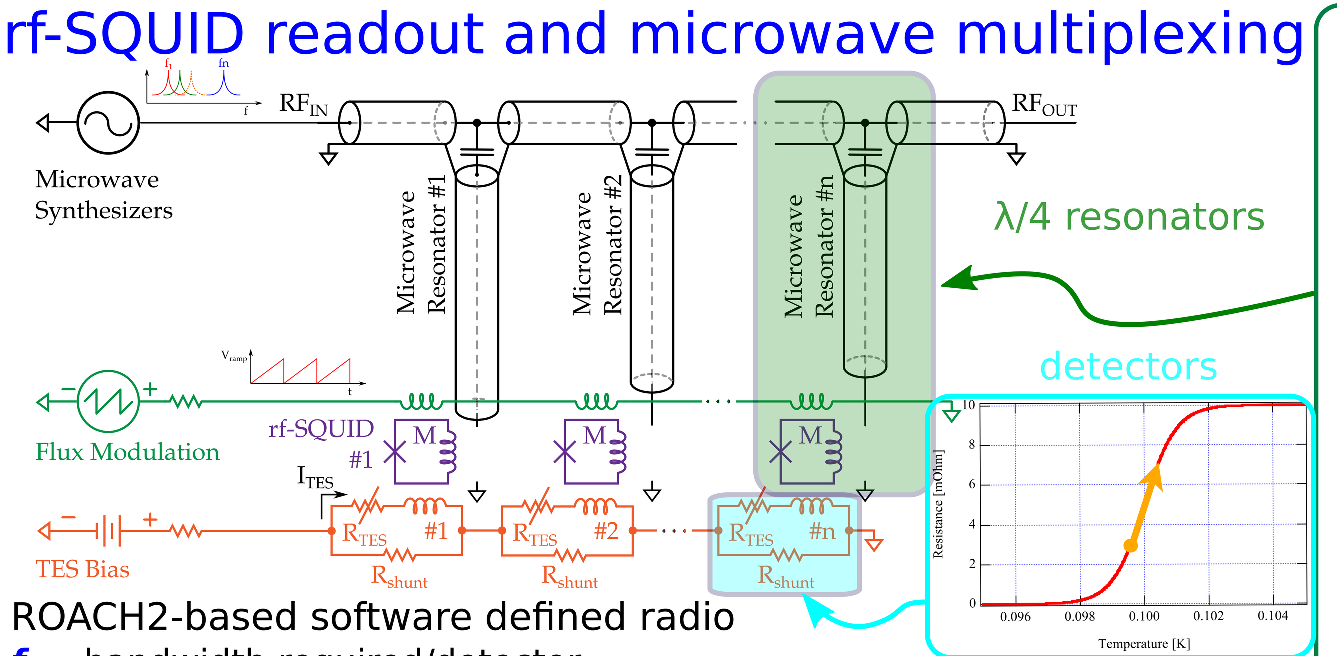



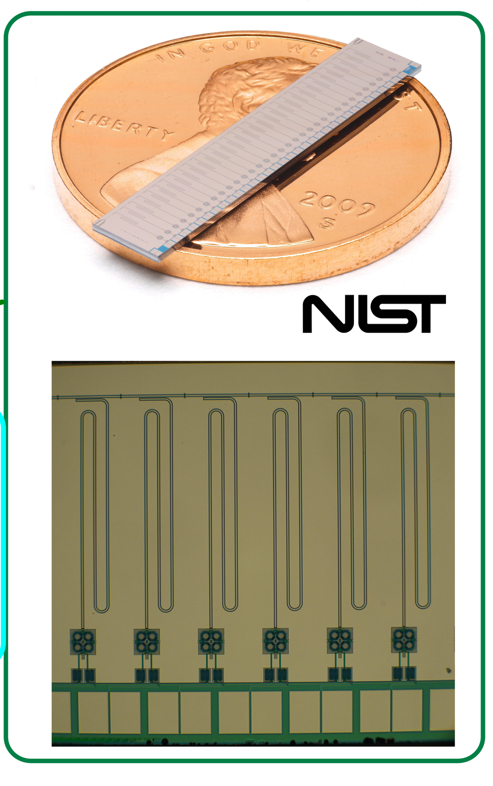




* see A. Puiu's poster




## rf-SQUID readout and microwave multiplexing




ROACH2-based software defined radio

- $f_{TES}$ bandwidth required/detector
- $f_{TES} \geq 2\, n_{\Phi_0} f_{sampl}$ ; $f_{sampl} \geq 5/\tau_R$
- $N_{mux} \leq f_{ADC} / 10 f_{TES}$ ; $f_{sampl}$ = 0.5 MHz, $n_{\Phi_0}$ = 2

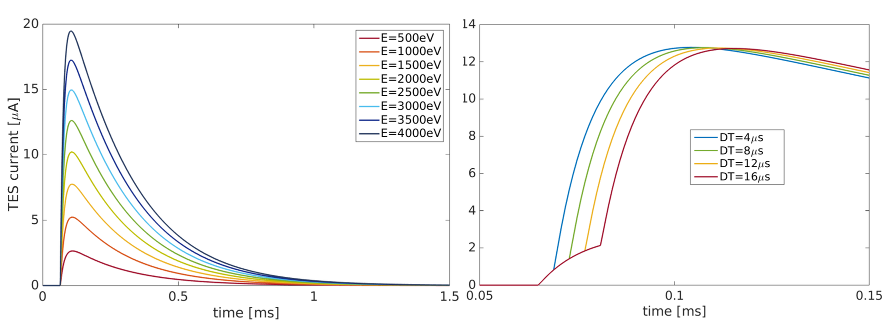
$N_{mux} \approx 30$

## MC simulations for effective time resolution

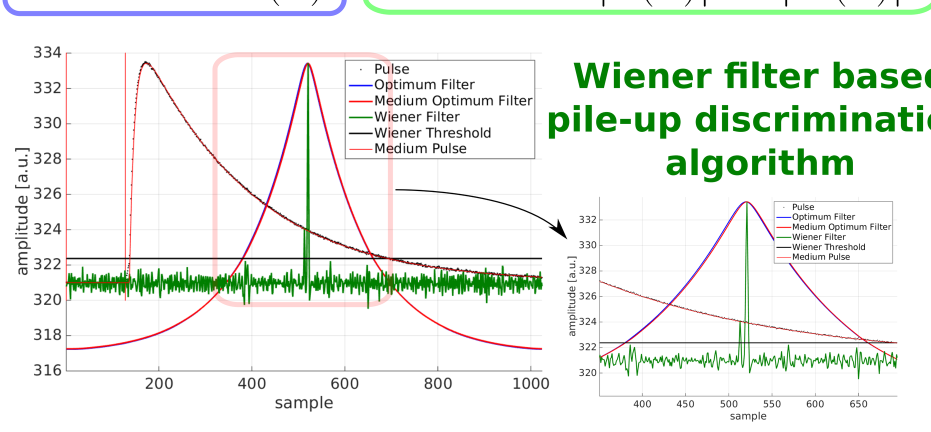
- generate realistic TES signals from differential equations
- $E_1+E_2 \in Q \pm 0.1$ keV
- sampled records with realistic noise ($\Delta E$)
- signal $S(\omega)$, noise $N(\omega)$

$$H_{OF}(\omega) \propto \frac{S^*(\omega)}{N(\omega)} \qquad H_{WF}(\omega) \propto \frac{S^*(\omega)}{|S(\omega)|^2+|N(\omega)|^2}$$

$$f_{pp} = A_{EC}\Delta t_{max}\left[1-\int_0^{\Delta t_{max}}\frac{\eta(x)}{\Delta t_{max}}dx\right] = A_{EC}\tau_{eff}$$




E. Ferri et al. J.Low Temp. Phys 184:405 (2016)




**Wiener filter based pile-up discrimination algorithm**

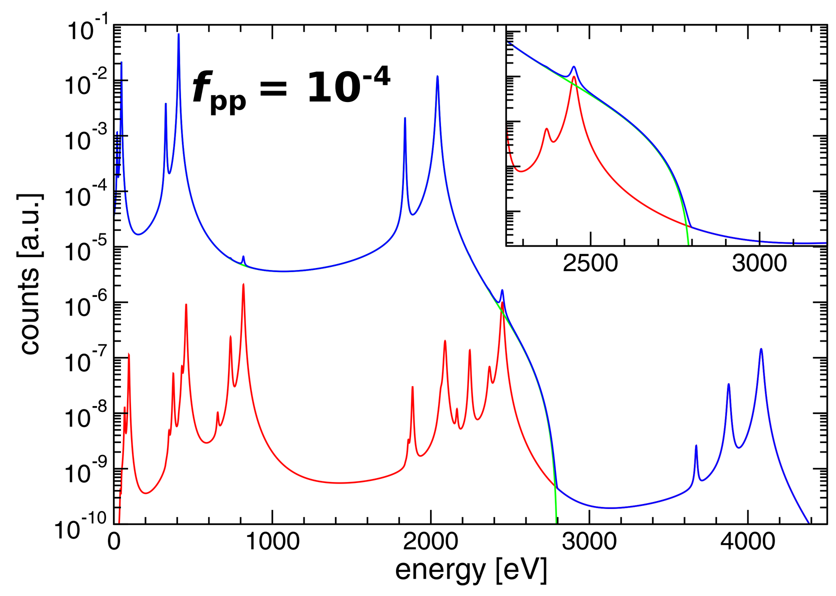
| $f_{sam}$ | reclen | L | $\tau_{rise\ (10\text{-}90)}$ | $\tau_{decay}$ | false + | $\tau_{eff}$ | ΔE |
|---|---|---|---|---|---|---|---|
| [MHz] | [sample] | [nH] | [us] | [us] | % | [us] | [eV] |
| 1 | 1024 | 45 | 18 | 262 | 3 | 3.4 | 2.4 |
| 1 | 1024 | 84 | 31 | 225 | 4.5 | 3.7 | 2.4 |

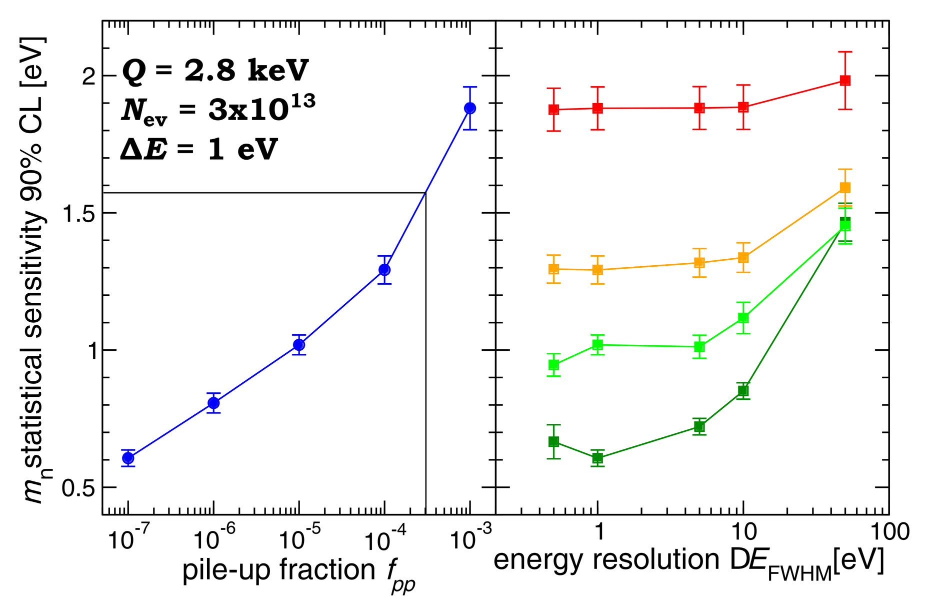
Single value decomposition also under study B.Alpert et al. J.Low Temp. Phys 184:263 (2016)

## Statistical sensitivity Σ($m_\nu$) from MC simulations

- strong on statistics $N_{ev} = A_{EC}N_{det}T_M$: $\Sigma(m_\nu) \propto N_{ev}^{1/4}$
- strong on rise time pile-up (probability $f_{pp} \approx A_{EC}\tau_R$)
- weak on energy resolution $\Delta E$

A. Nucciotti, Eur. Phys. J. C (2014) 74:3161

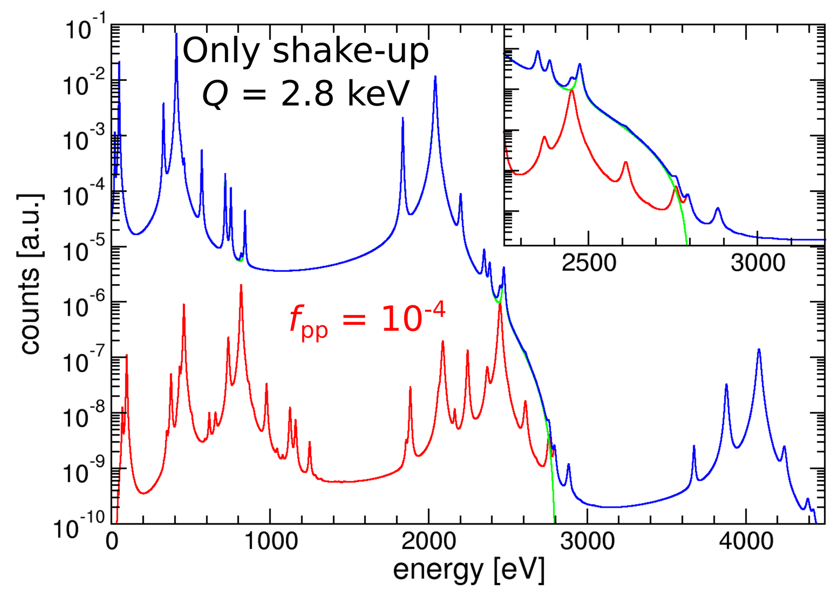


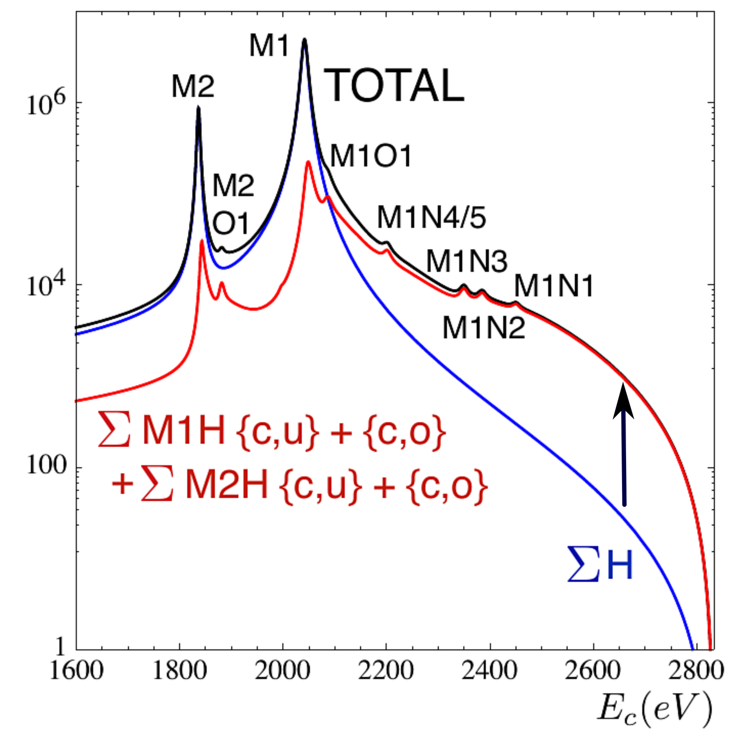




### Shake up/shake off → double hole excitations

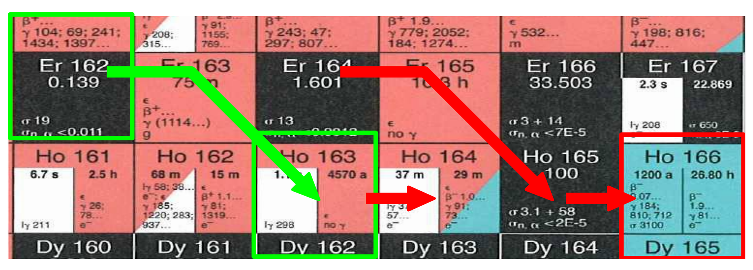
- Even more complex pile-up spectrum
- Statistics enhanced (shake-off)
  - ▸ Best predictions: factor 40

A. De Rújula and M. Lusignoli arXiv:1601:04990




## $^{163}$Ho production and embedding



≈**200 MBq** of $^{163}$Ho required

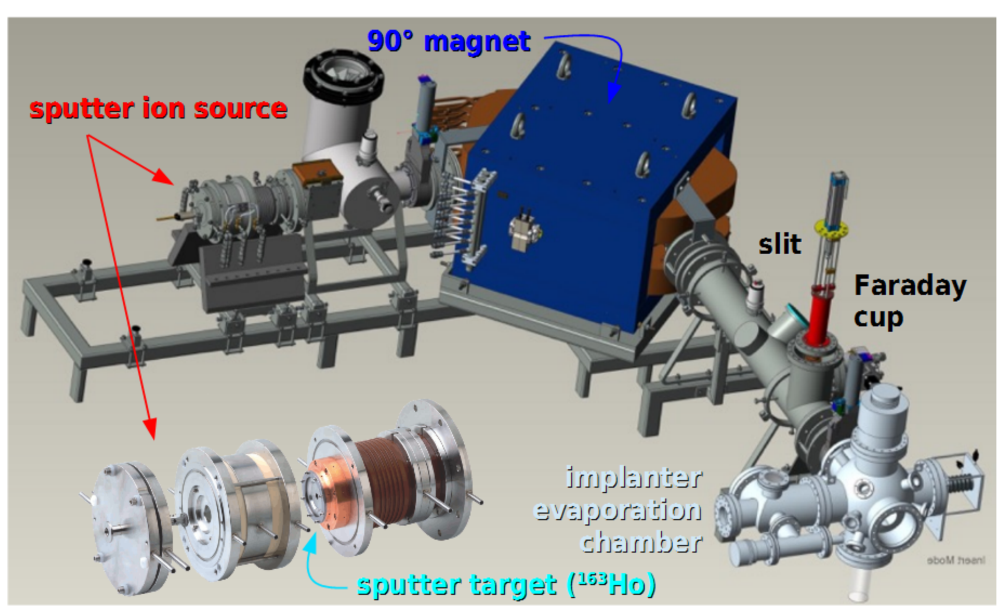
- **$^{162}$Er (n,γ) $^{163}$Er** $\sigma_{thermal} \approx 20$b
- **$^{163}$Er ⟶ $^{163}$Ho** $\tau^{1/2}_{EC} \approx 75$ min
- ILL reactor (Grenoble, France) thermal neutron flux = 1.3x10$^{15}$ n/cm$^2$/s

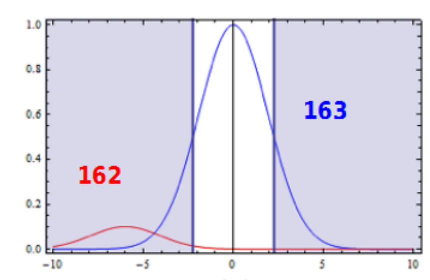
**≈ 270 kBq($^{163}$Ho)/mg($^{162}$Er)/week**

- **burnup** $^{163}$Ho(n,γ)$^{164}$Ho reduces yield, σ ≈ 220b
- $^{165}$Ho(n,γ)$^{166m}$Ho (from contaminations of $^{164}$Er), $\tau_{1/2}$ = 1200 y

100 mg ($^{162}$Er) for 7 weeks ⟶ ~ 100 kBq of $^{166m}$Ho (∝$^{164}$Er abundance)

- **500 mg** of 30% enriched $Er_2O_3$ are required for HOLMES




- Implanter from Danfysik
- extraction voltage 30-50 kV
- 10-100 nm implation depth
- $^{163}$Ho/$^{166m}$Ho mass separation better than 10$^5$
- delivery by Sept 2016

Evaporation of gold simultaneous to the implantation to reduce sputtering effects of the ions on gold and to prevent excess of heat capacities

- **Enriched $Er_2O_3$ samples* pre/post processed at PSI**

25mg irradiatied for 55 days ⟶ $A(^{163}Ho)_{theo} \approx 10$ MBq, $A(^{163}Ho)_{meas} \approx 10$ kBq

150mg irradiated for 50 days ⟶ $A(^{163}Ho)_{theo} \approx 70$ MBq, $A(^{163}Ho)_{meas} \approx 500$ kBq

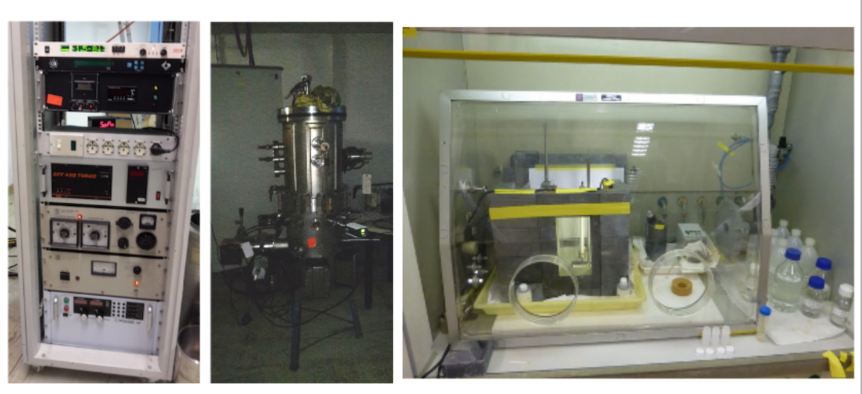
- **Holmium chemical separation**

efficiency ≈ 79%

- **Metallic holmium sputter target**

thermoreduction/distillation in furnace @ INFN Genoa

$Ho_2O_3 + 2Y(met) \quad 2Ho(met) + Y_2O_3$ at 2000°



* from CENTRA, Lisbon