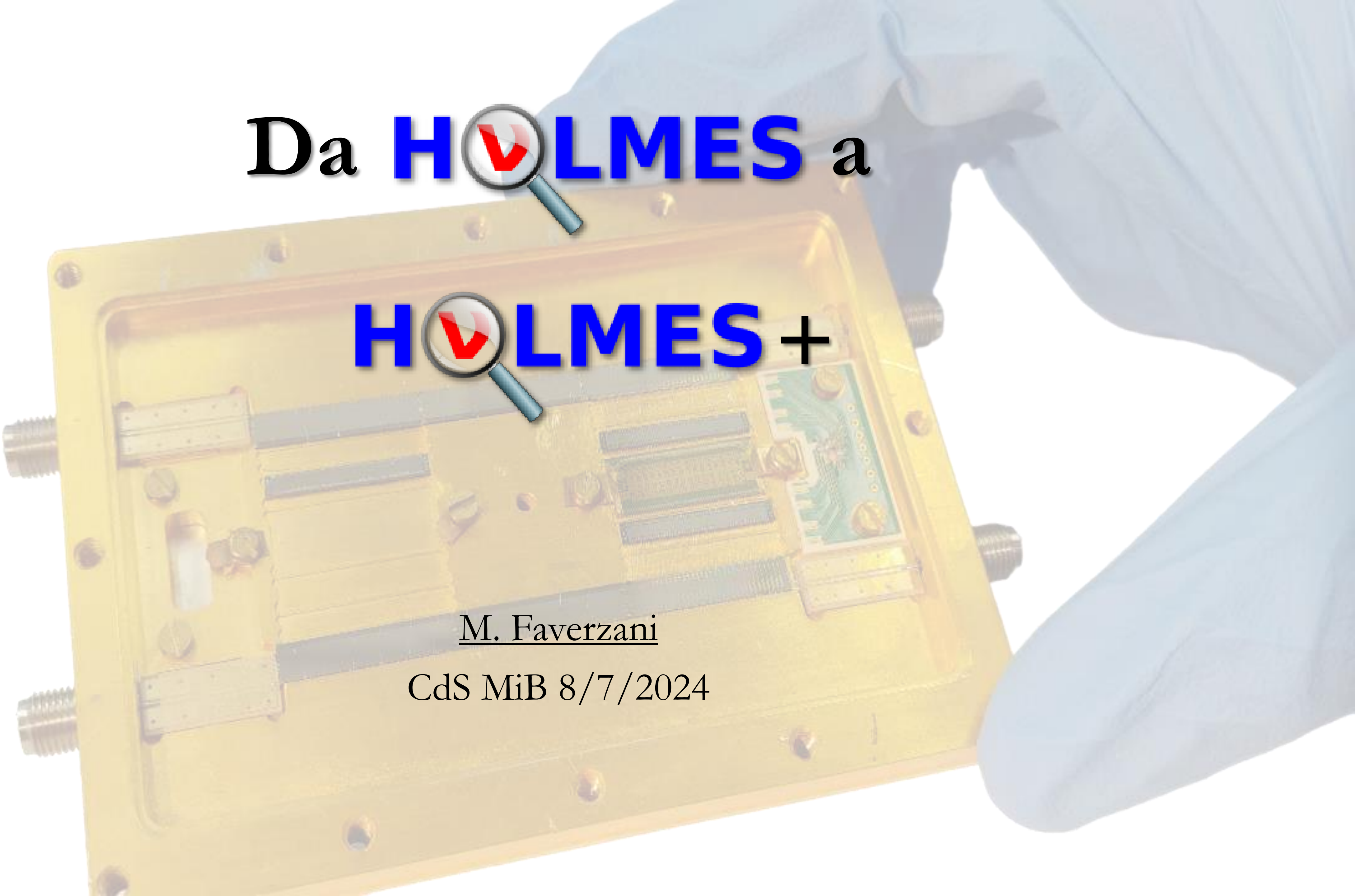
Da HOLMES a HOLMES+



M. Faverzani

CdS MiB 8/7/2024

Physics case

- Direct neutrino mass measurement is the only theory-unrelated method of accessing the neutrino mass
  - ➢ benchmark for Λ-CDM model

- KATRIN has reached m_ν<0.45 eV [arXiv:2406.13516] and aims at 0.3 eV
  - ➢ maximum size and complexity achievable with **spectrometers**
  - ➢ only way to increase sensitivity is through differential measurement and/or atomic **tritium** source
- other projects
  - ➢ Project8: m_ν < 150 eV with cm3-scale apparatus
  - ➢ QTNM
  - ➢ Ptolemy
- calorimetry
  - ➢ HOLMES m_ν< 28 eV @ 90% CI
  - ➢ ECHo m_ν< 19 eV @ 90 CL

^{163}Ho electron capture

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

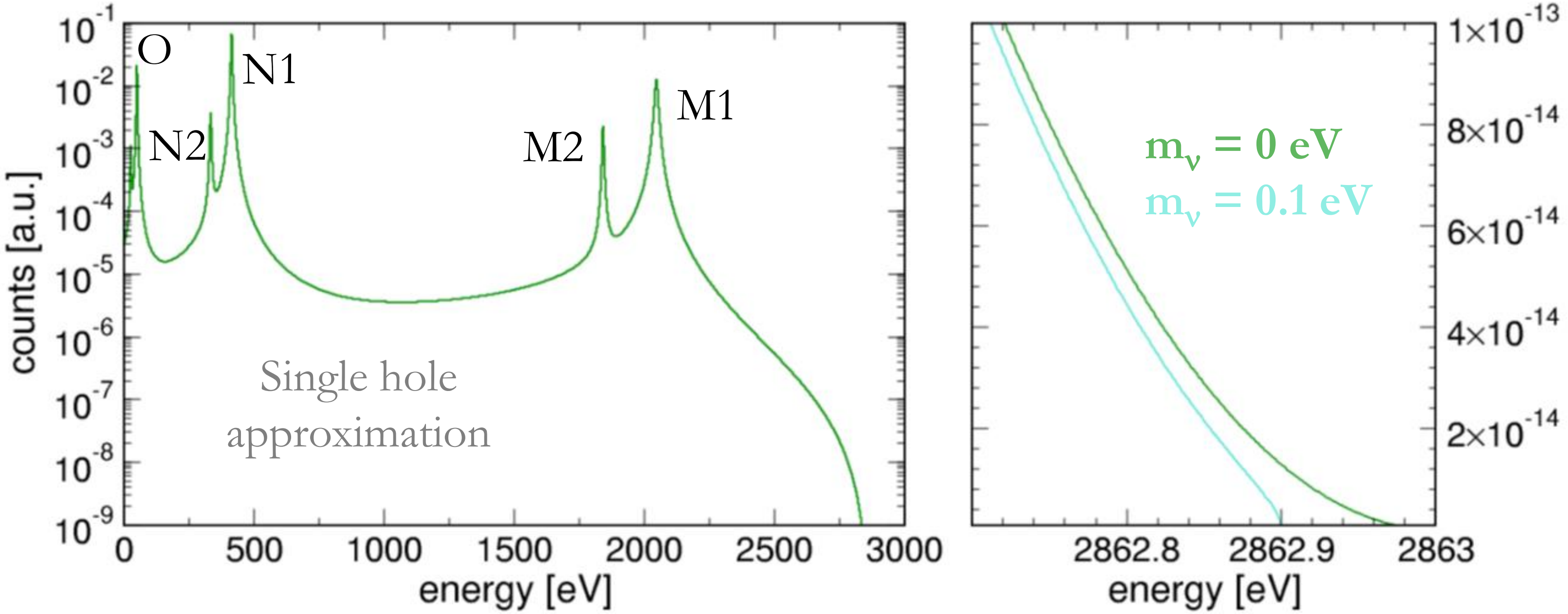
$\hookrightarrow {}^{163}Dy + E_c$

^{163}Ho decay via EC from shell ≥ M1, with $Q_{EC} \sim 2.8$keV

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

- calorimetric measurement of the Dy atomic de-excitation (mostly non-radiative)
- rate at the end point and ν mass sensitivity depend on **($Q - E_{M_1}$)**, where $E_{M1} = 2.05$ keV
- $\tau_{1/2} \sim 4570$ years: few nuclei are needed ($2\text{x}10^{11}$ ^{163}Ho nuclei = 1 Bq)

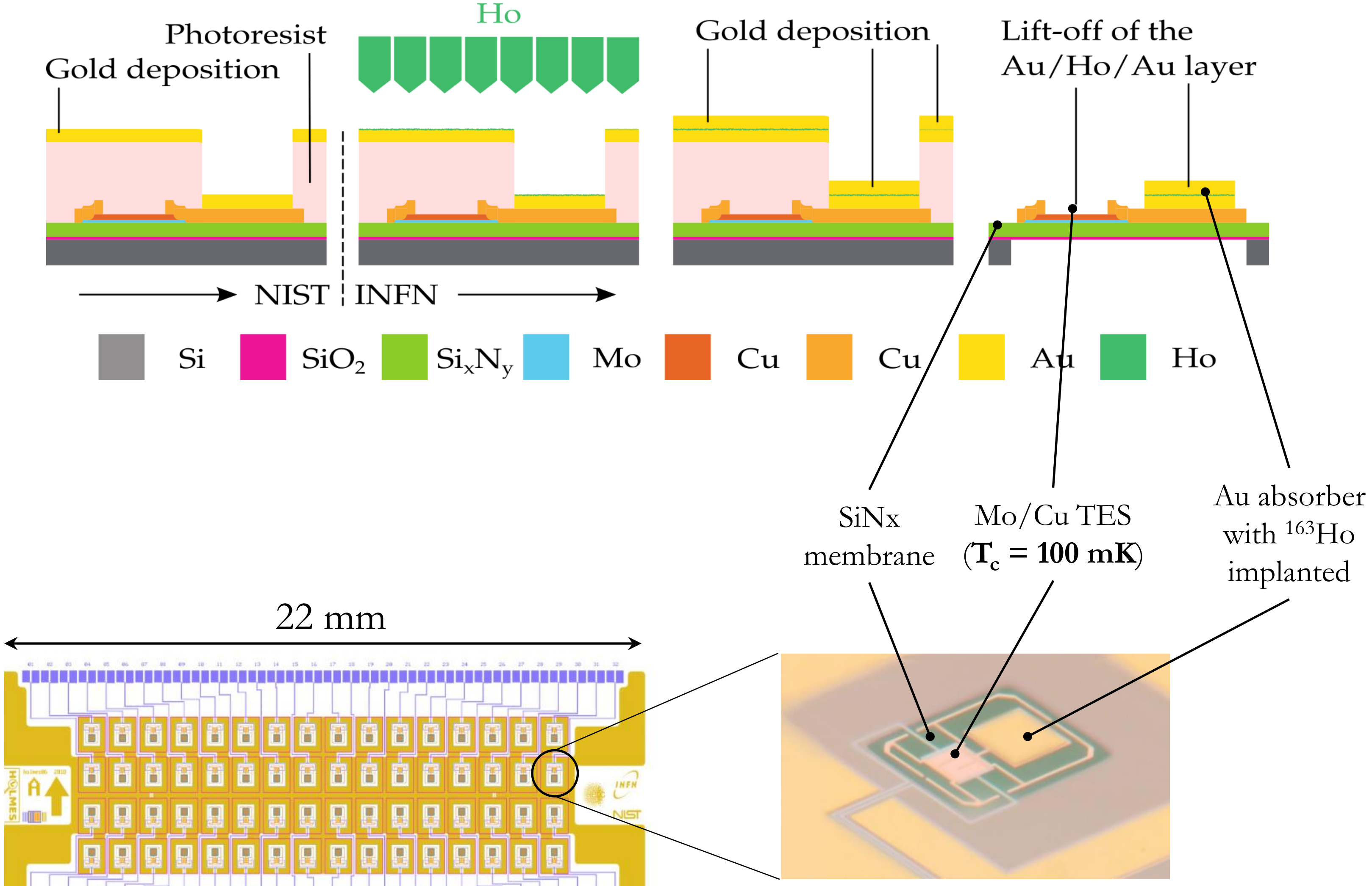
$$\frac{d\lambda_{\mathrm{EC}}}{dE_c} = \frac{G_\beta^2}{4\pi^2} \boxed{(Q-E_c)\sqrt{(Q-E_c)^2 - m_\nu^2}} \times \Sigma_i n_i C_i \beta_i^2 \frac{\Gamma_i}{2\pi} \frac{1}{(E_c - E_i)^2 + \Gamma_i^2/4}$$

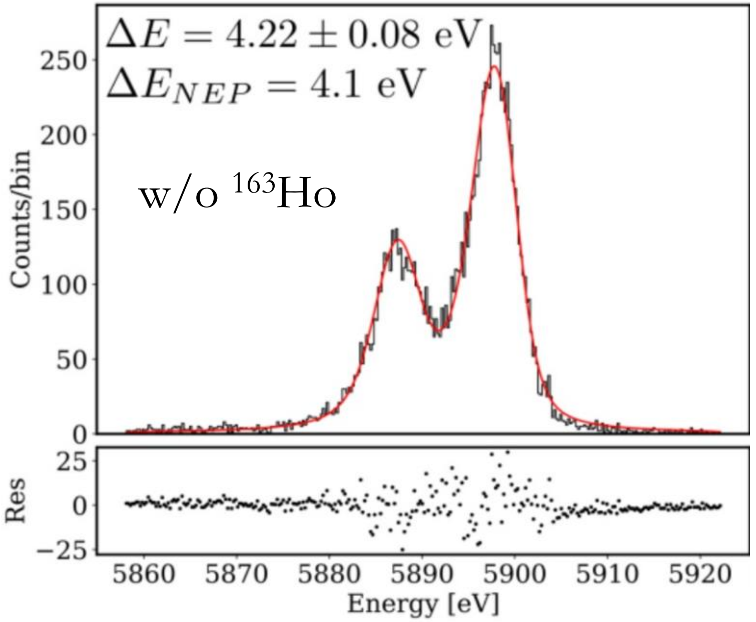


HOLMES funding
- ERC AdG 2014
- since 2020 INFN CSN2

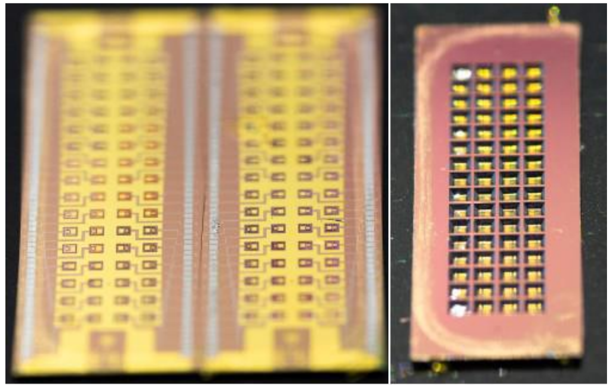
ECHo funding
- two DFG grants (mainly)

HOLMES TES detectors



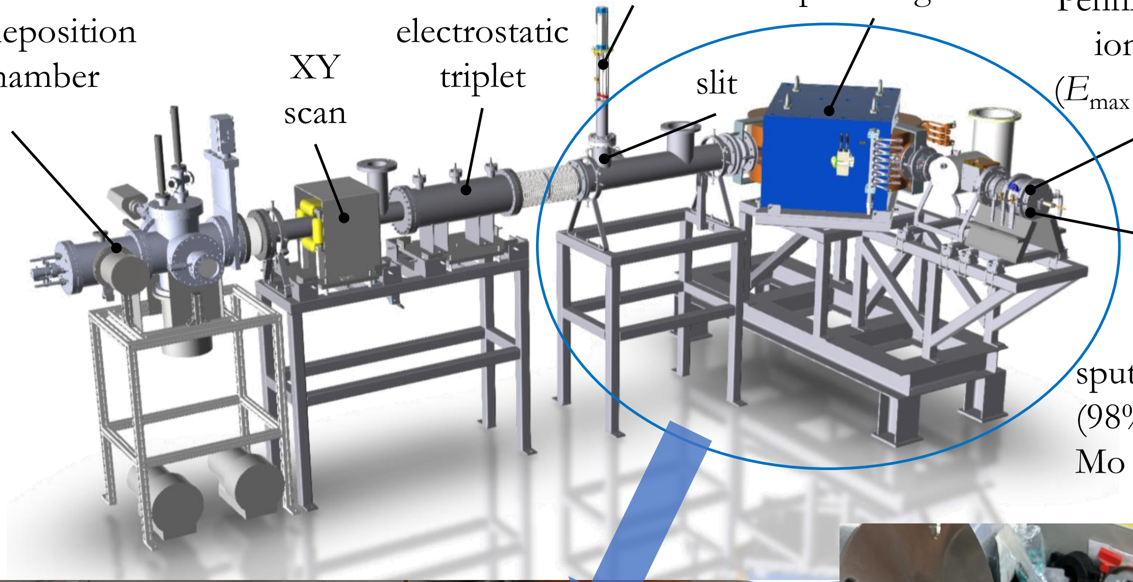


Eur. Phys. J. C, 79:304 (2019)



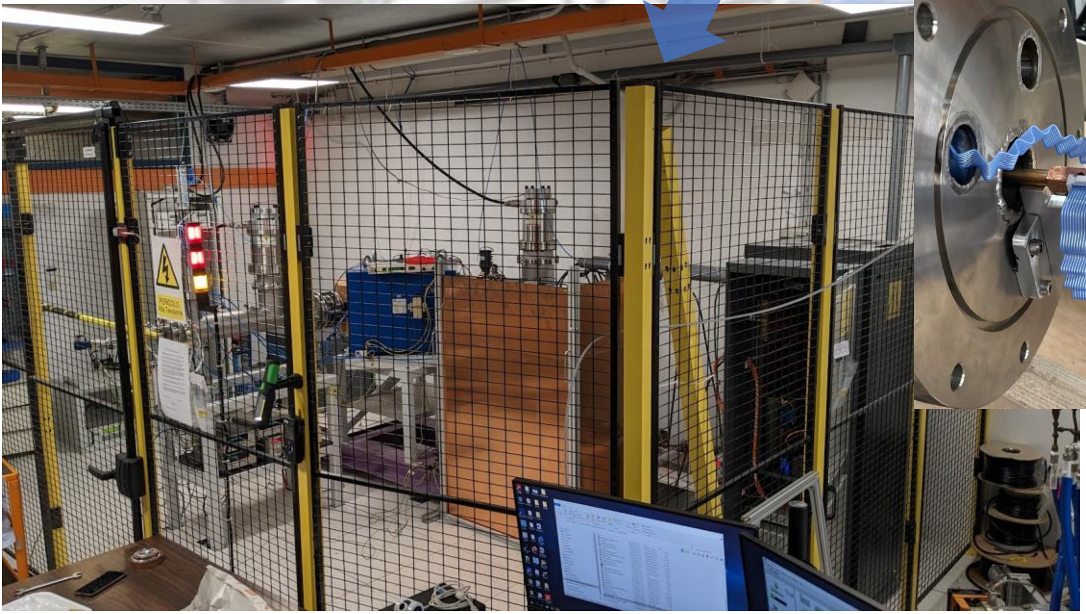
64 pixels/die

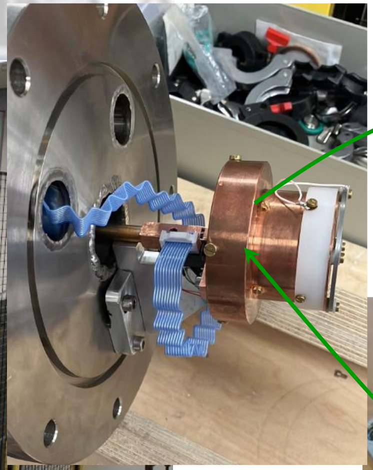
Isotope embedding @INFN-Genova

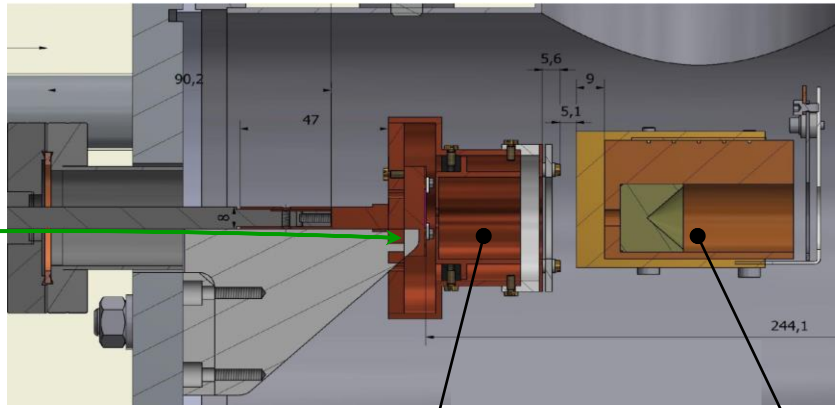


sputter target: Zr/Bi (98%/2%) sintered matrix on Mo + $Ho(NO_3)_3$ dripping

- Focusing stage and co-deposition chamber still to be integrated in the system
- produced an *ad hoc* holder to implant just after the slit
- double system to read the beam current impinging on the TES array (FC “MiB” + bonding wires)

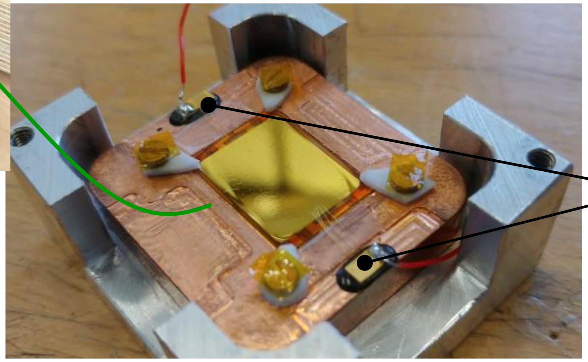






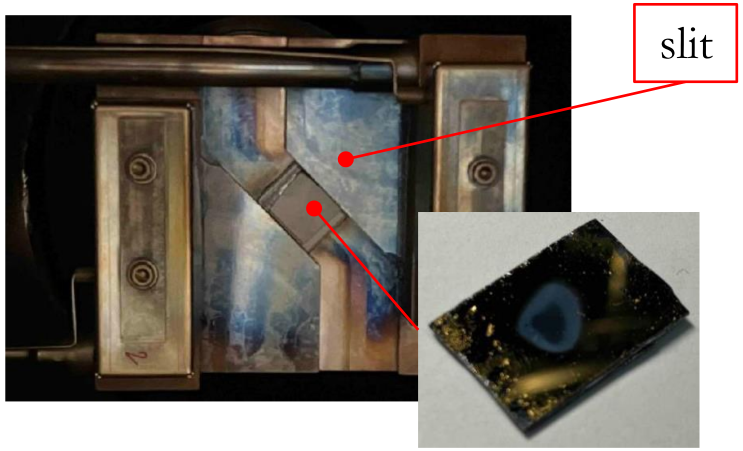
secondary FC “MiB” + TES array

FC Danpysik (interlock with TESs)

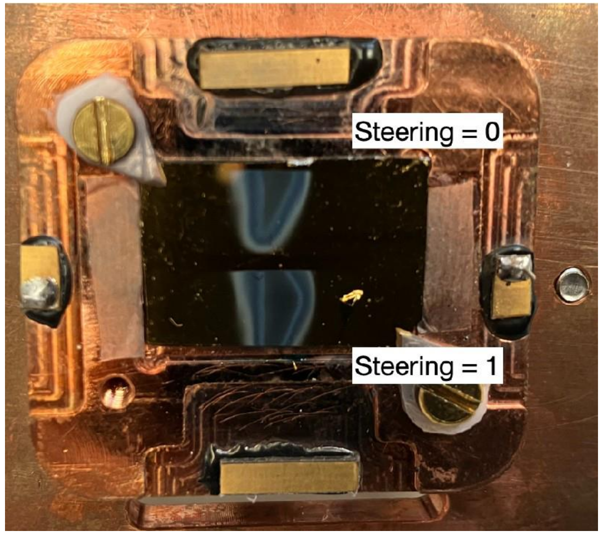


beam current readout

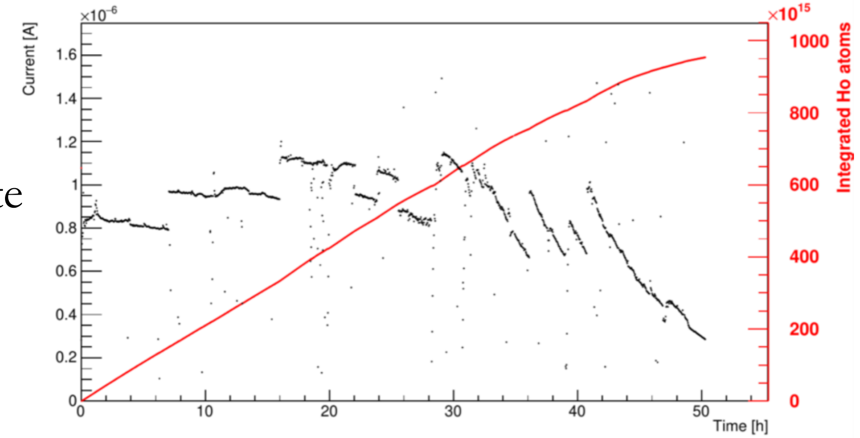
Isotope embedding @INFN-Genova



- Beam centering with high current footprint on Au plated silicon substrate both at the slit and at the array holder

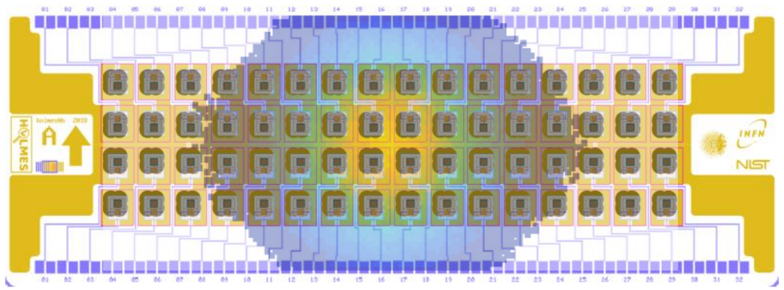


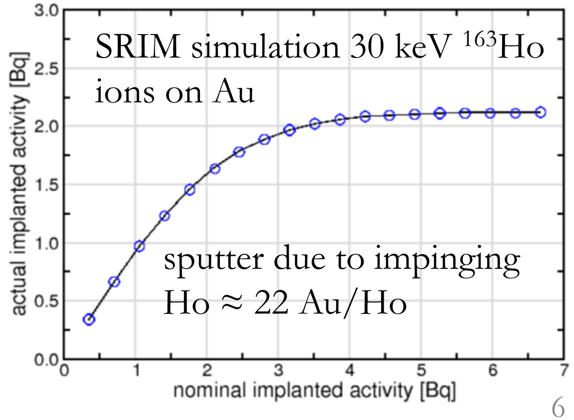
- sputter target source efficiency (with ^{nat}Ho): ε ~ 0.2%
- **most of the Ho deposits on the walls of the chamber before being ionized**



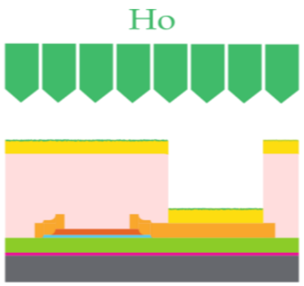
- separation at the slit ^{163}Ho from ^{165}Ho and ^{166m}Ho (in our solution: ^{163}Ho/^{165}Ho/^{166m}Ho = 60/40/0.1) evaluated with simulations:
  - ➢ $^{163/165}$Ho separated by 15 mm
  - ➢ $^{163/166m}$Ho separated by 22 mm

- single spot
  - ➢ integrated current to achieve 4 Bq/det peak activity (neglecting sputter)
  - ➢ evaluation of ^{163}Ho activity on TES
  - ➢ beam profile
  - ➢ evaluation of ^{163}Ho activity effect on TESs

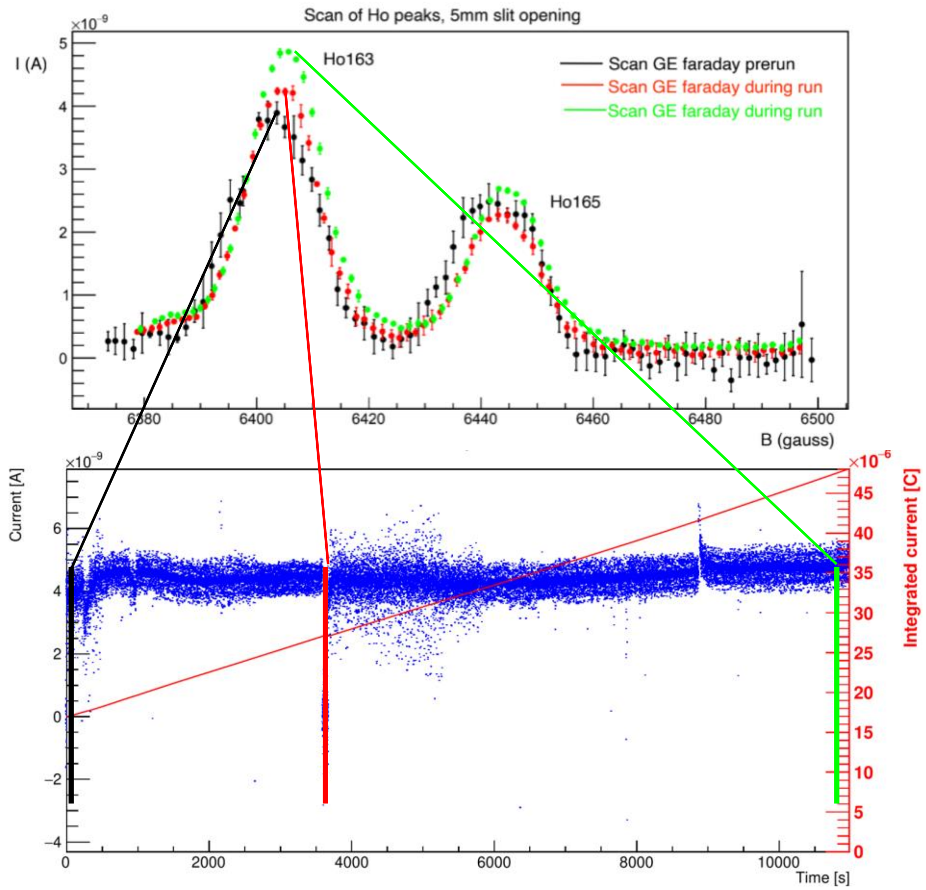




First ^{163}Ho implant on TES array

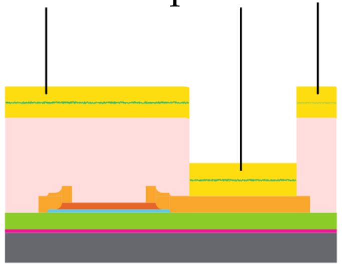


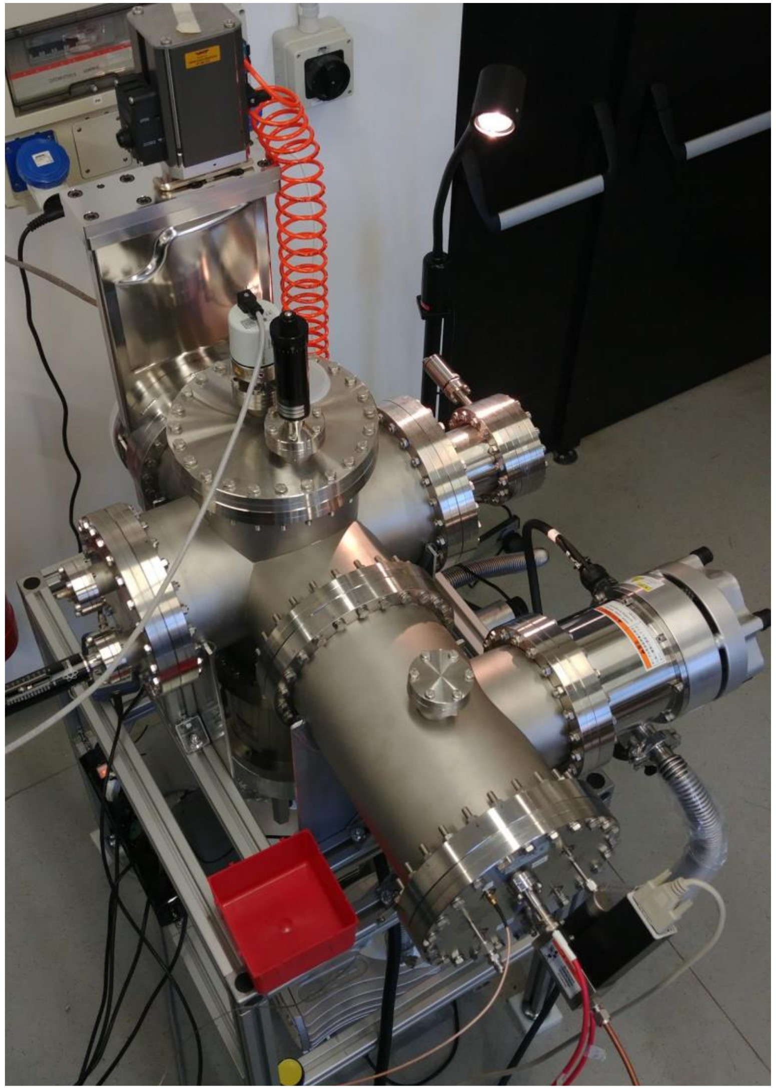
- sputter target loaded with **12 MBq of ^{163}Ho** (= 2.6 x 10^{18} ^{163}Ho atoms)
- ^{163}Ho beam current stable at ≈ 5 nA for 3 hours
- integrated current corresponds to ≈ 3 x 10^{14} ^{163}Ho ions



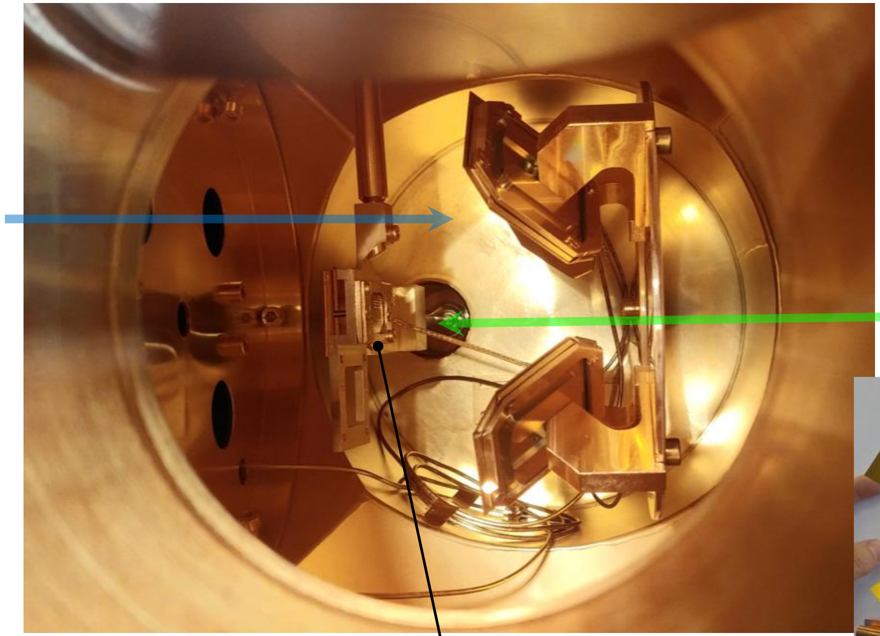
Full encapsulation @Milano-Bicocca

Gold deposition

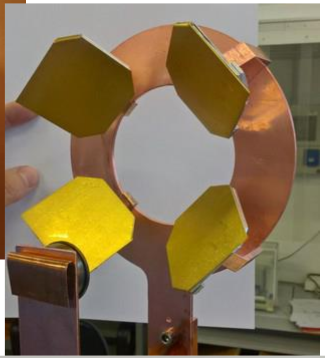




Ar ion **beam** (for sputtering)



^{163}**Ho** (not implemented yet)

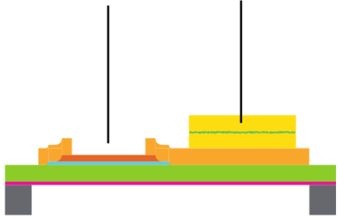


TES array

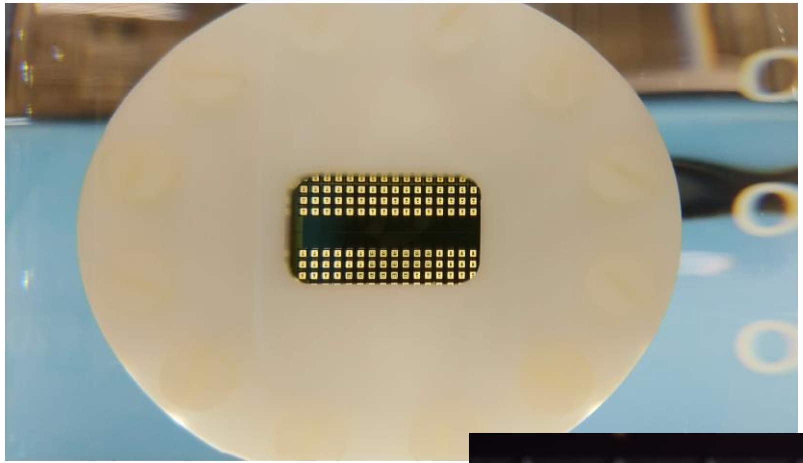
- 1 μm layer to fully encapsulate the ^{163}Ho
- ≈ 27 hours to complete the process
- soon will be integrated with the ion-implanter to compensate sputter and avoid oxidation

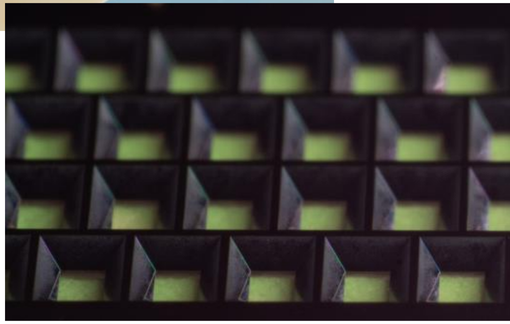
TESs finalization

Lift-off of the
Au/Ho/Au layer

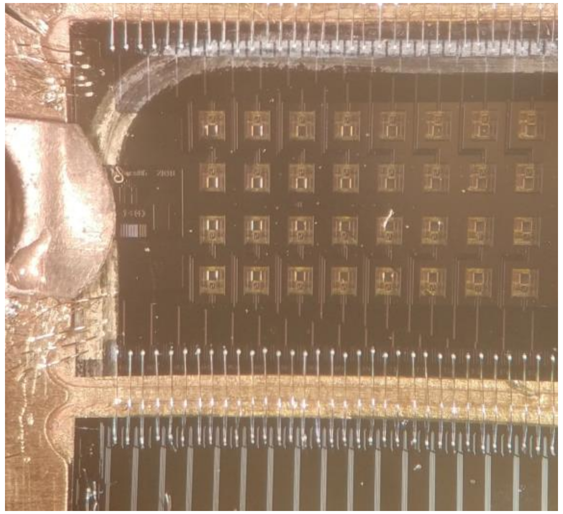


Membrane release: ≈ 5 h silicon anisotropic etching
KOH bath at 80°C



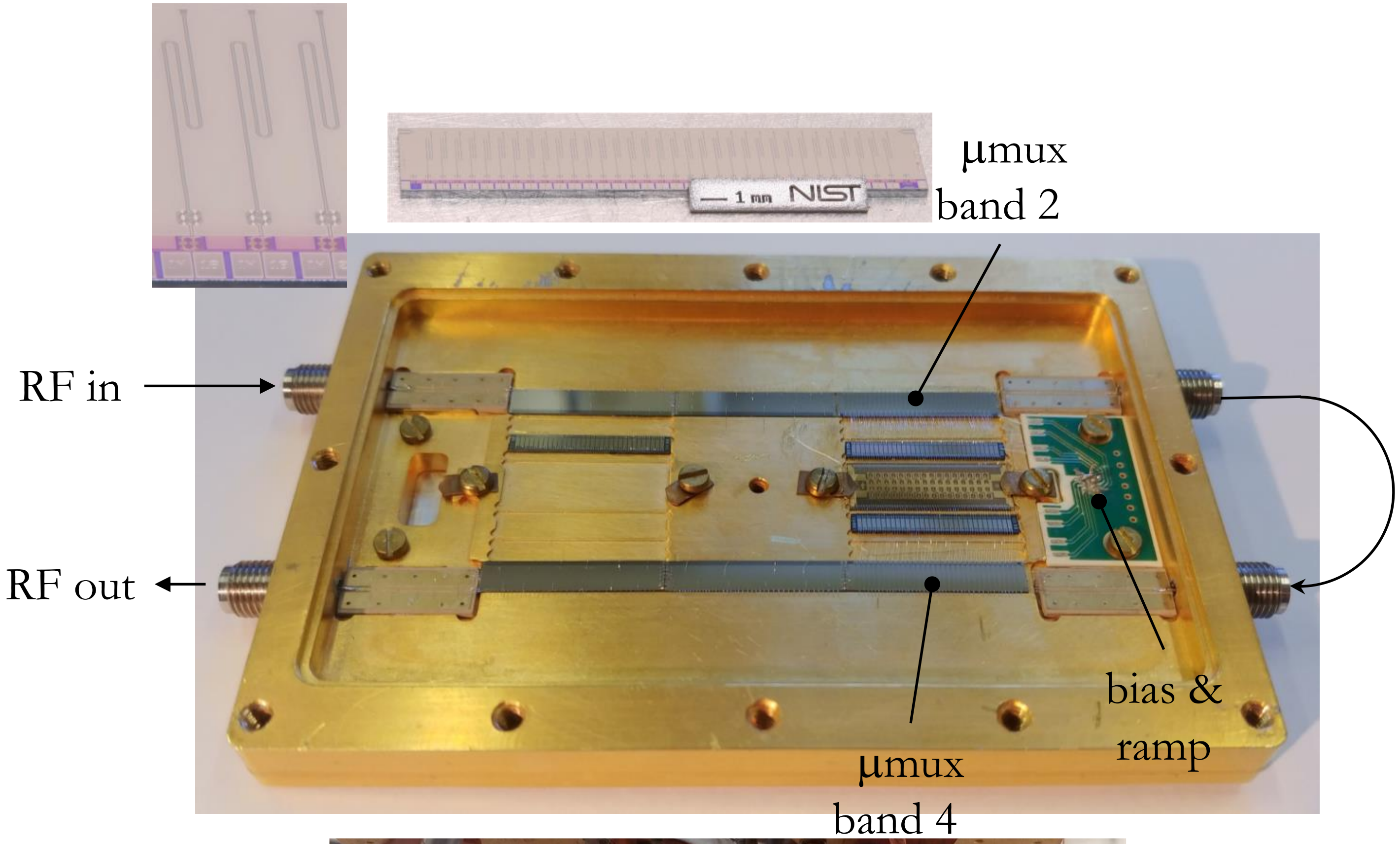


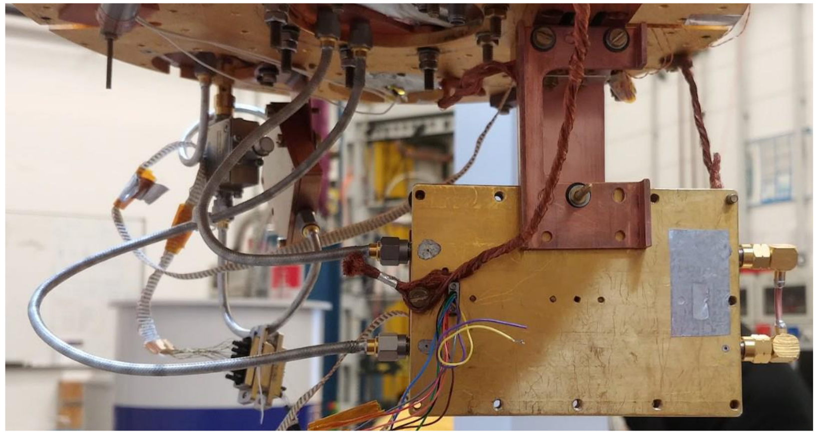
Au lift-off:
≈ 2 h acetone bath at 50°C

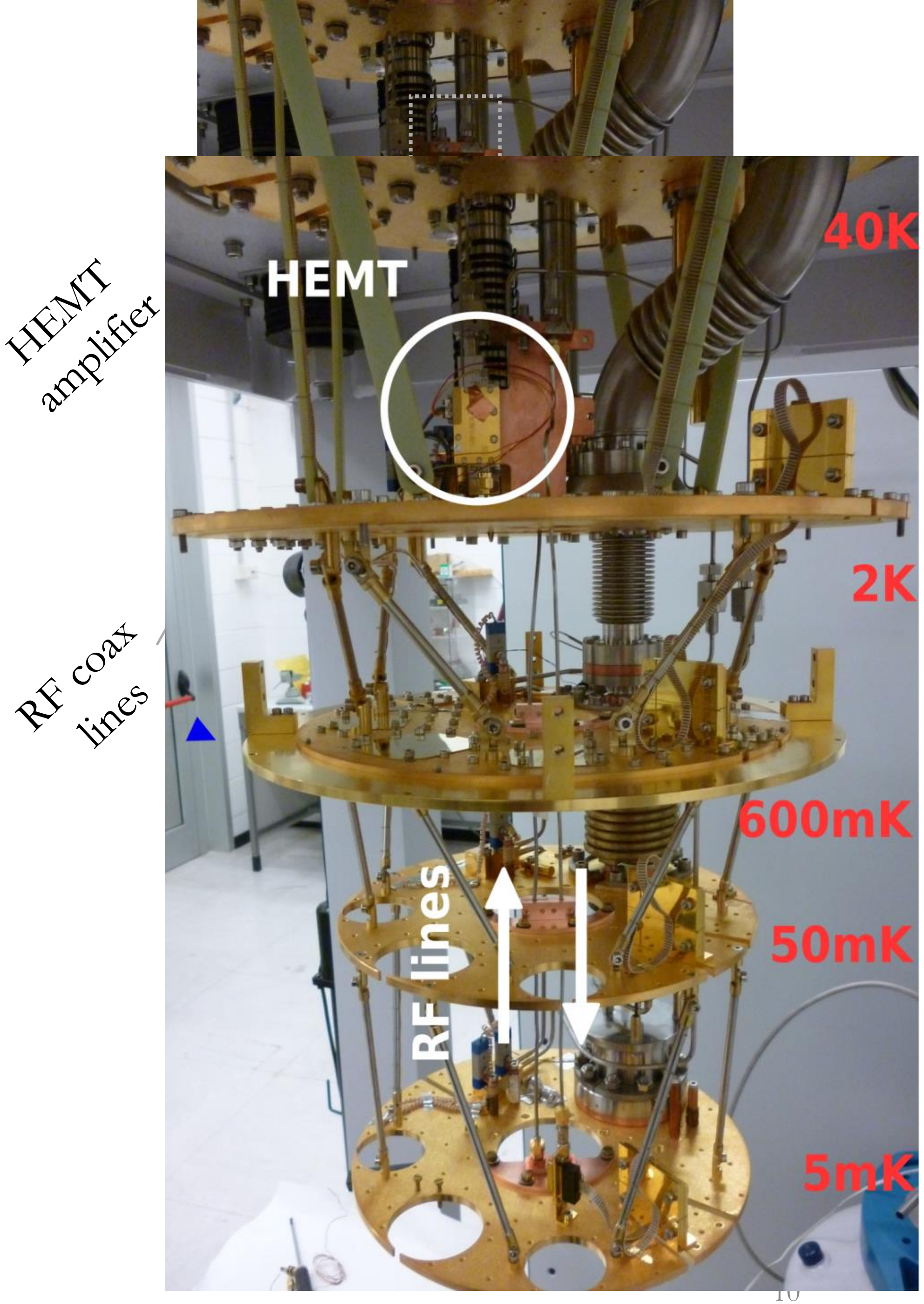


- ~ 350 Al wire bonding for electrical connections for 64 TESs
- ~ 20 Au wire bonding for TES chip thermalization

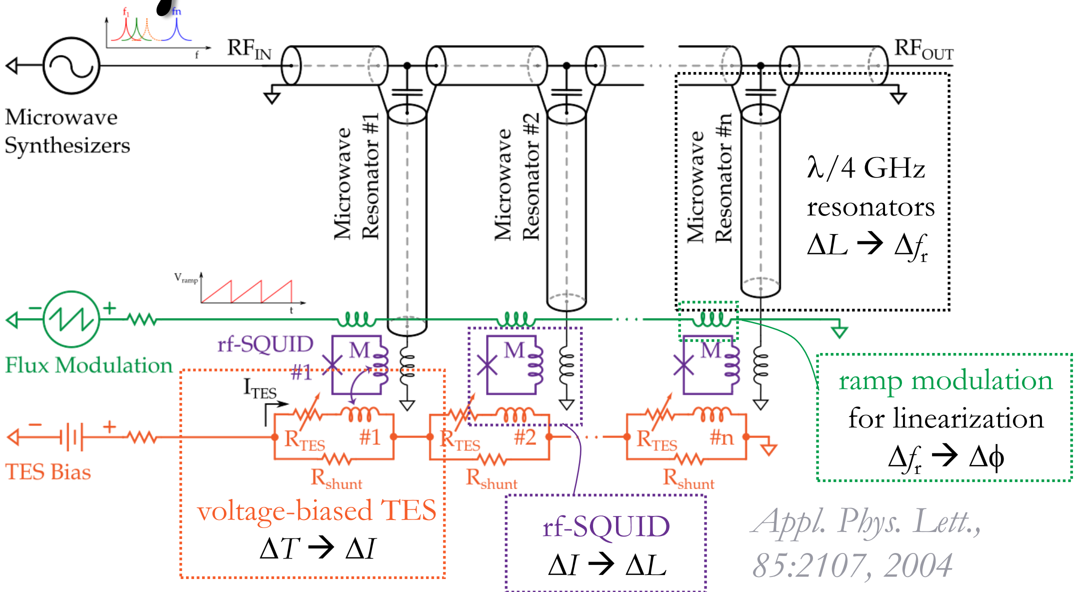
Experimental setup



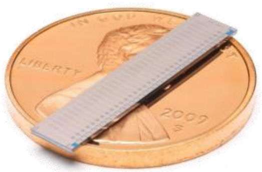


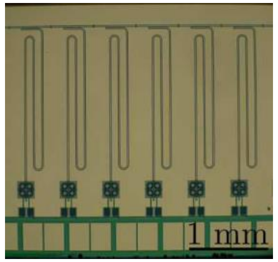


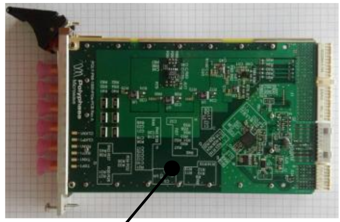
µwave mux readout & DAQ



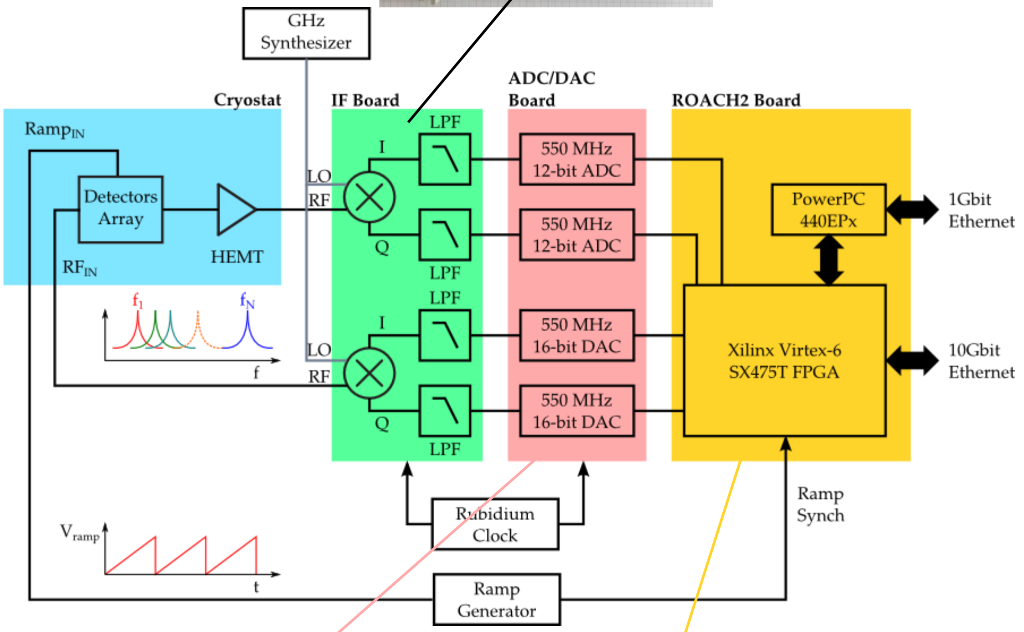
Appl. Phys. Lett., 85:2107, 2004



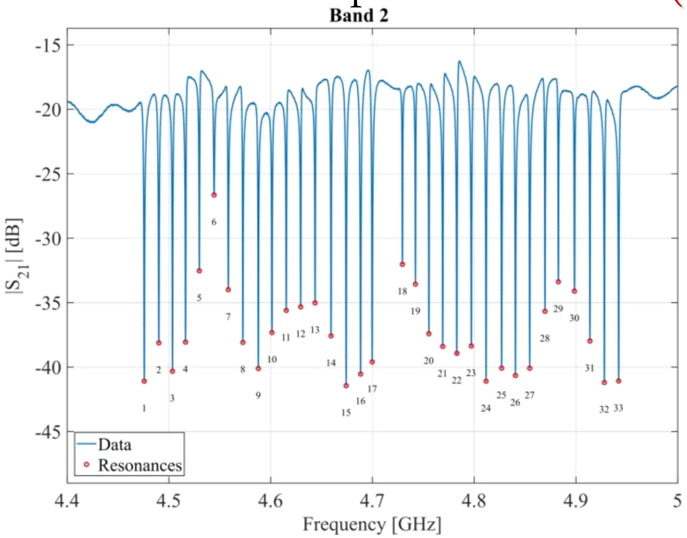


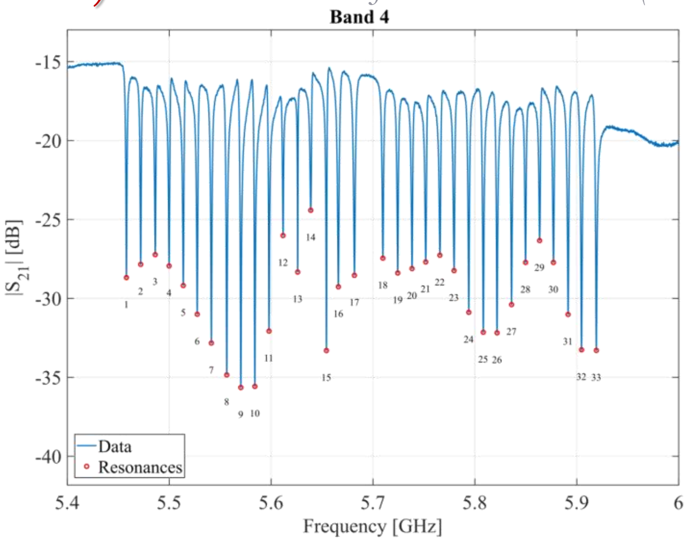


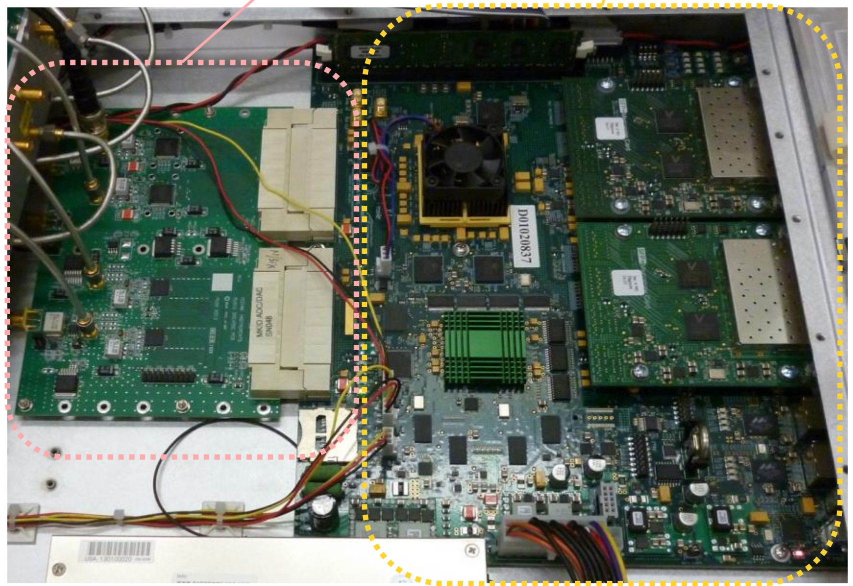
64 channels already available



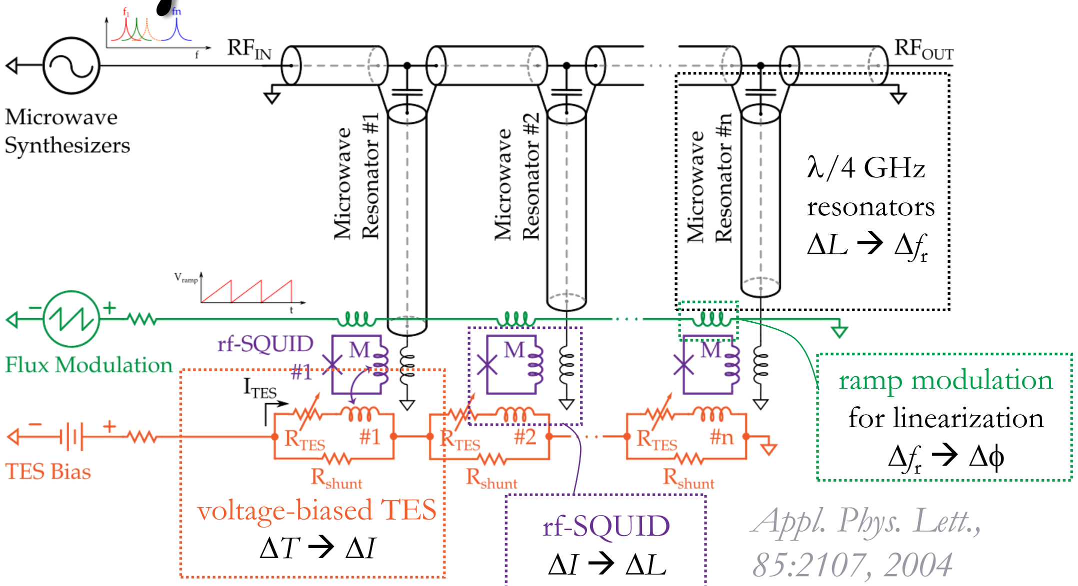
- $f_{ramp} = f_{samp}$ (= 500 kHz)
- allows to readout many detectors with one common RF line and HEMT amplifier: 1 HEMT (4-8 GHz) = 256 TESs *JINST 14 P10035 (2019)*







μwave mux readout & DAQ



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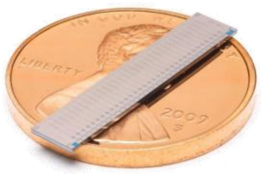

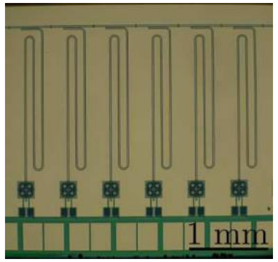

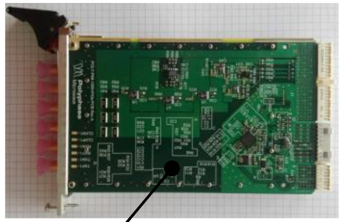

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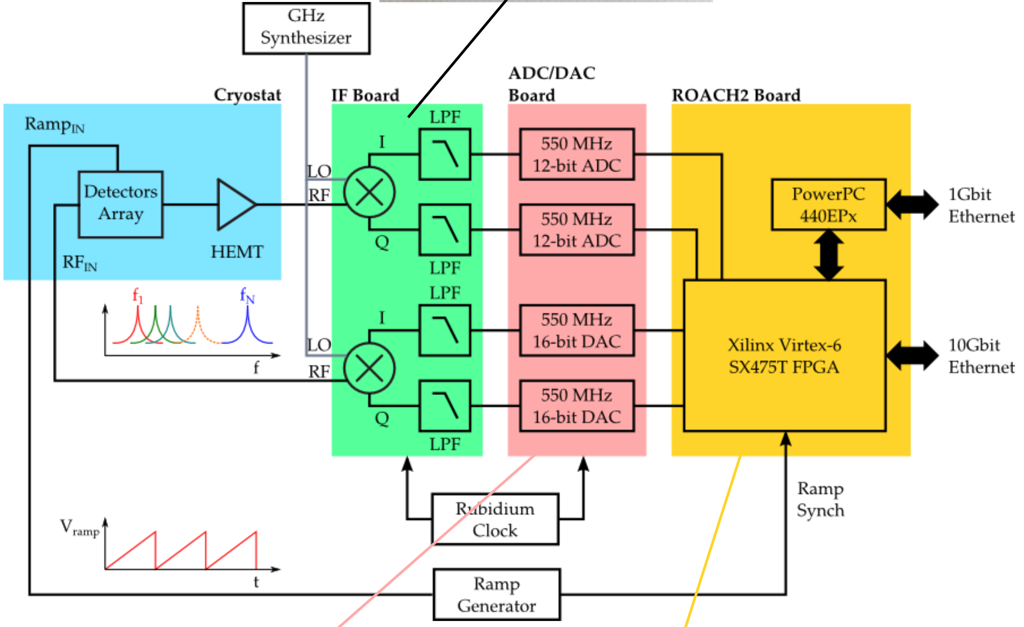

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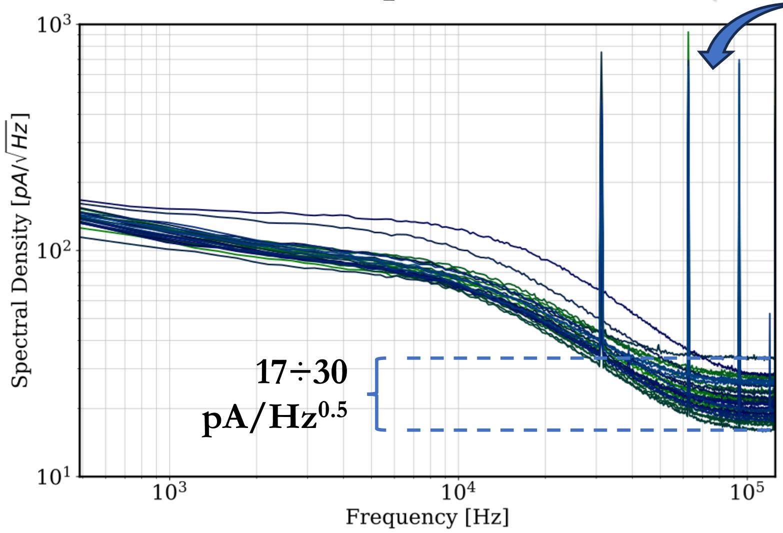
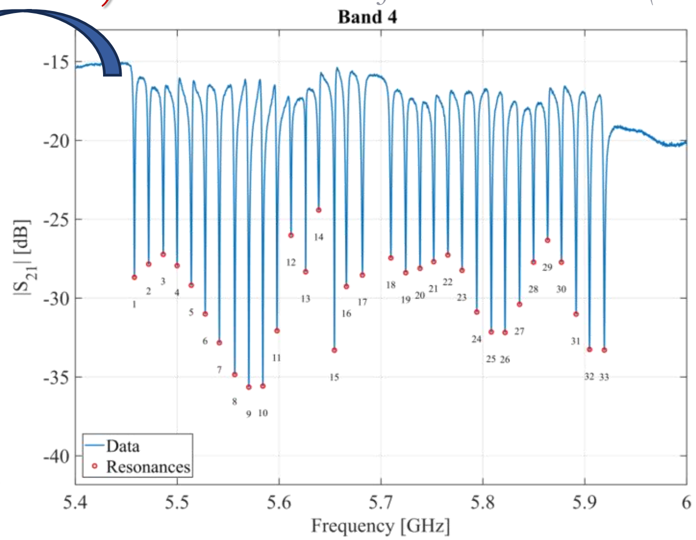
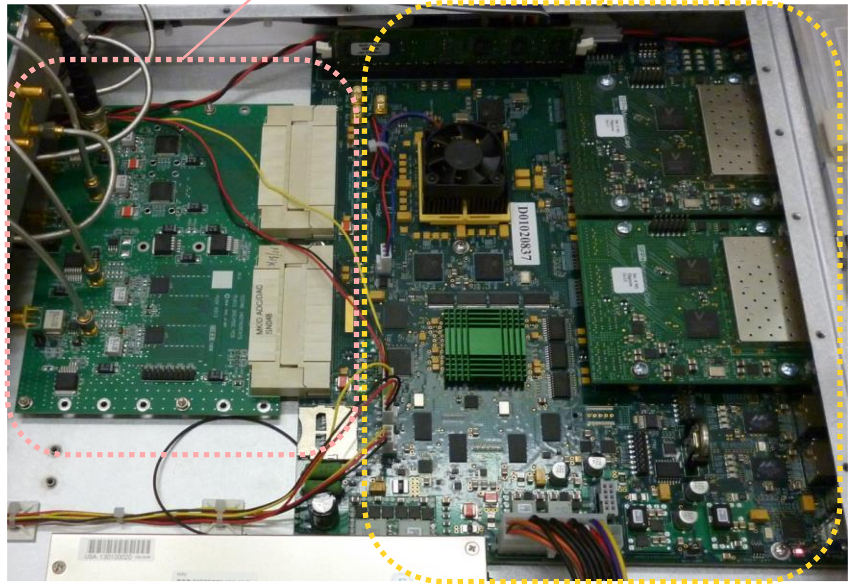
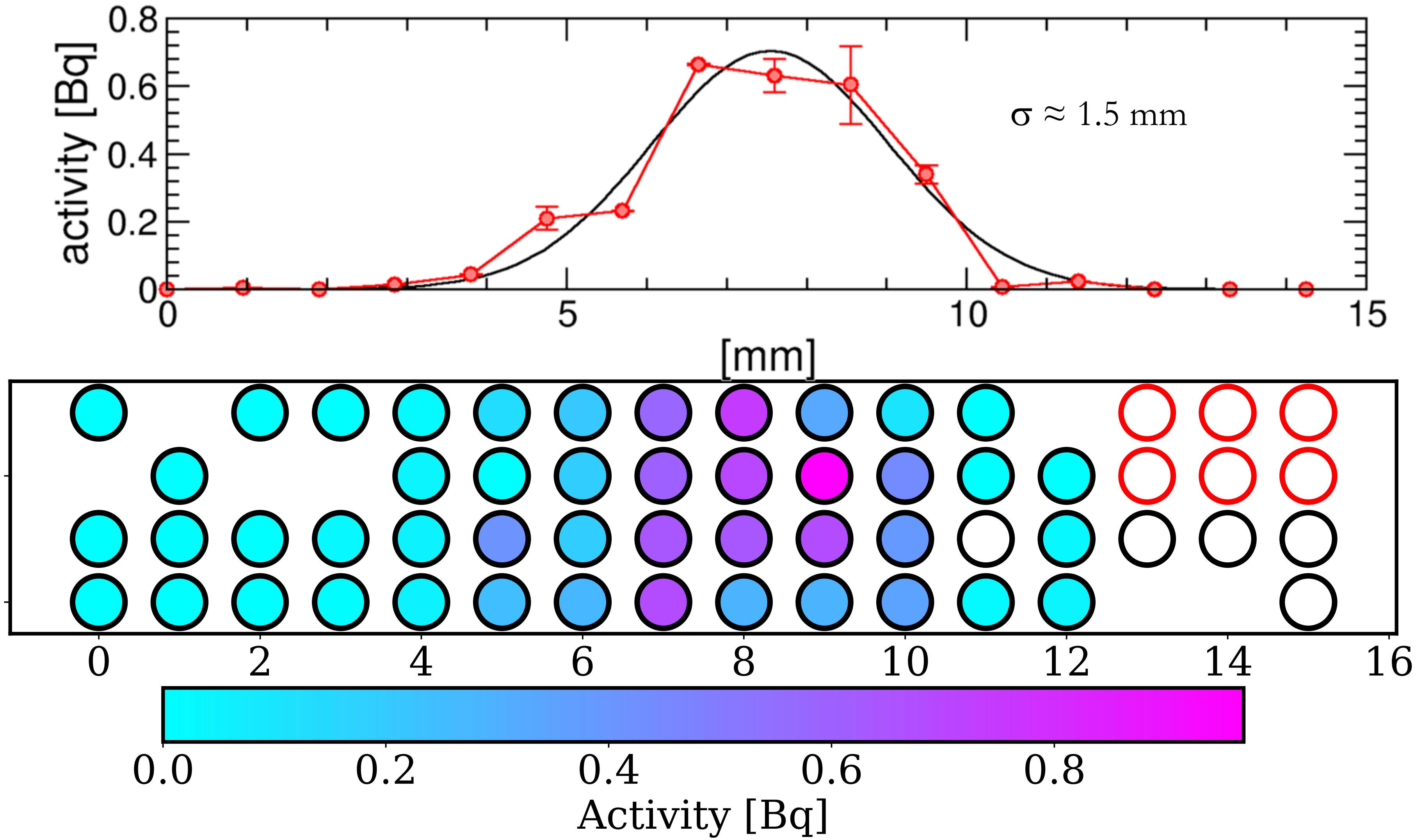






^{163}Ho implanted activity map – RUN1

- 1 spot implantation
- A_{target} = 4 Bq
- $A_{measured}$ = 1 Bq

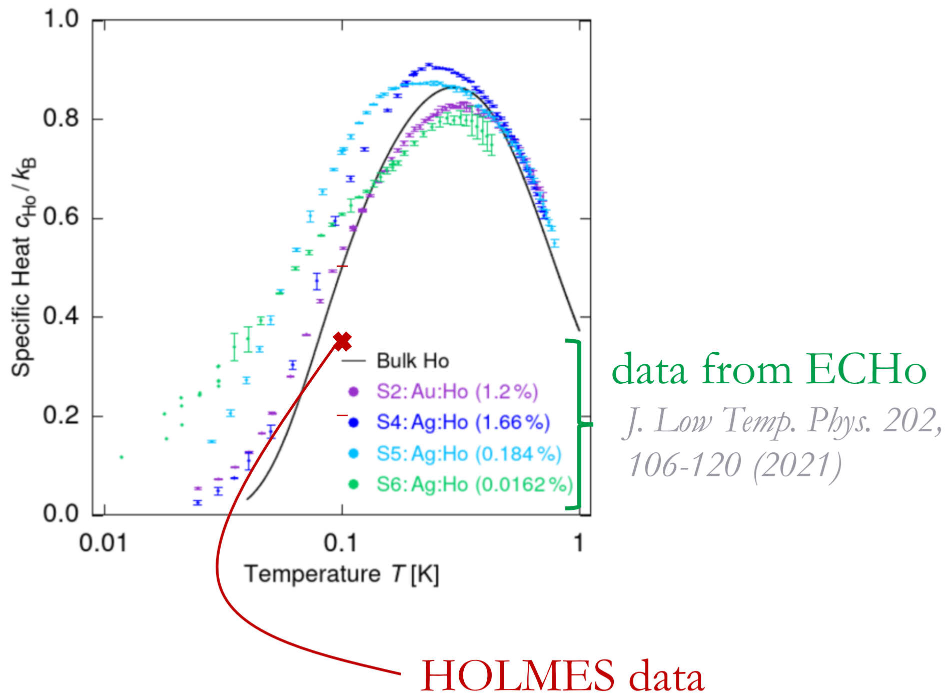


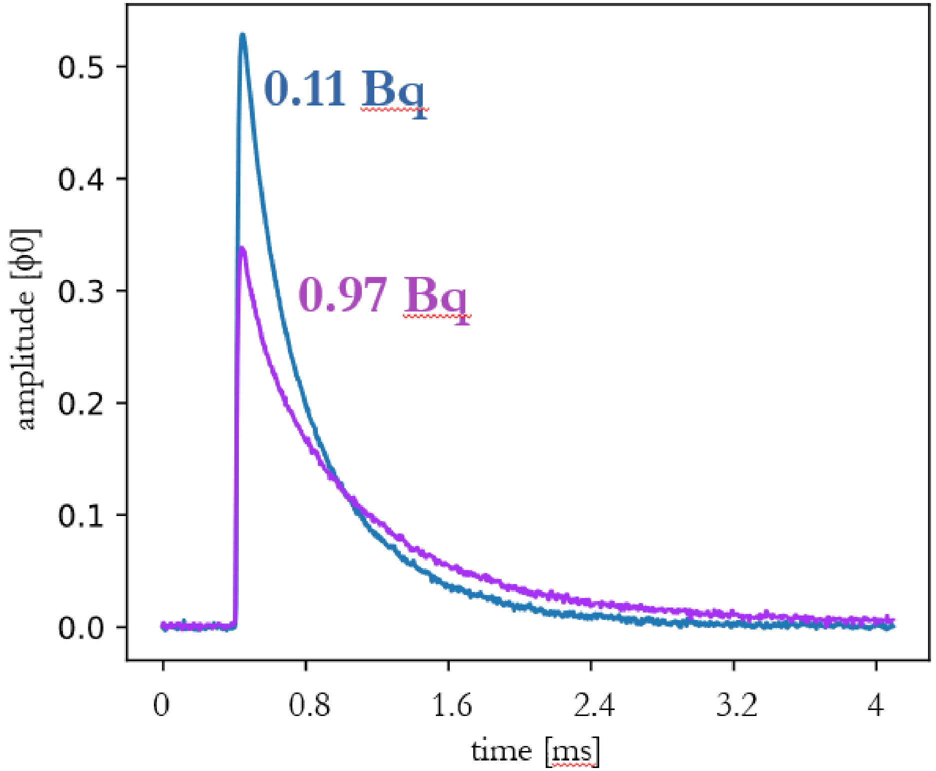
bad TES working point

too high ^{55}Fe background

detuned readout tone

^{163}Ho impact on TESs





- Ho heat capacity is dominated by Schottky anomaly
- peak at ≈ 250 mK
- high activity manageable at ***T* ≤ 50 mK**

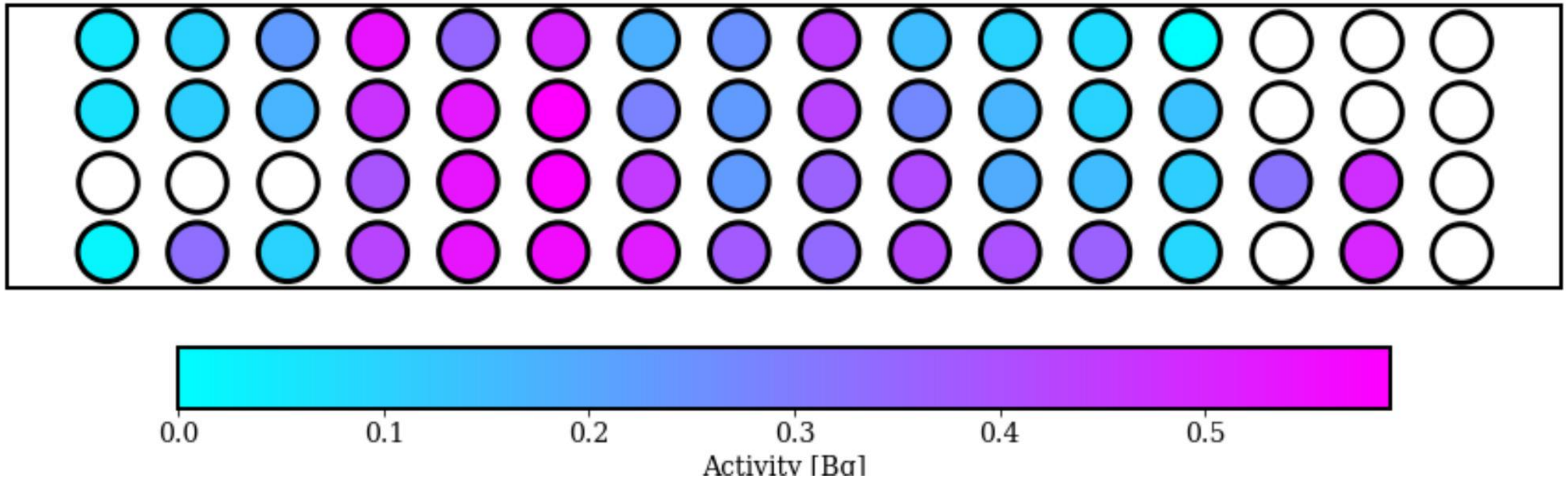
- from HOLMES pulses decay time:

c_{Ho} = 3 J/K/mol

- ➢ bulk value 4.2 J/K/mol
- ➢ ECHo between 4 and 5 J/K/mol

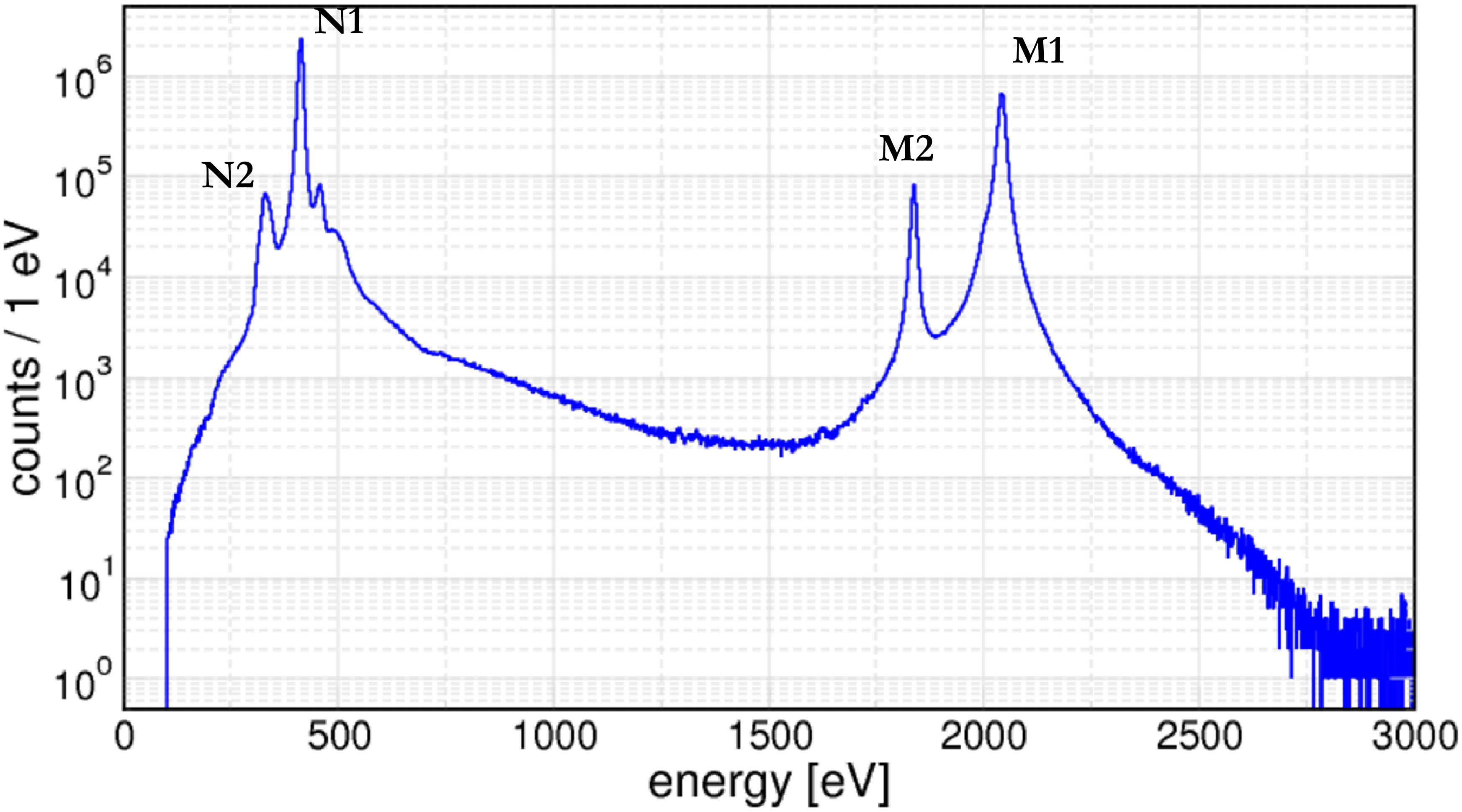
^{163}Ho implanted activity map – RUN2

- 4 spots implantation
- A_{target} = 2 Bq
- A_{measured} = 0.27 Bq (avg)
- A_{measured} = 0.6 Bq (peak)
- not as uniform as expected



^{163}Ho measured spectrum

- 2.5 months measuring time
- preliminary calibration with fluorescence source
- physics runs calibrated with Ho peaks
- $6x10^7$ events collected
- ΔE_{FWHM} = 7 eV



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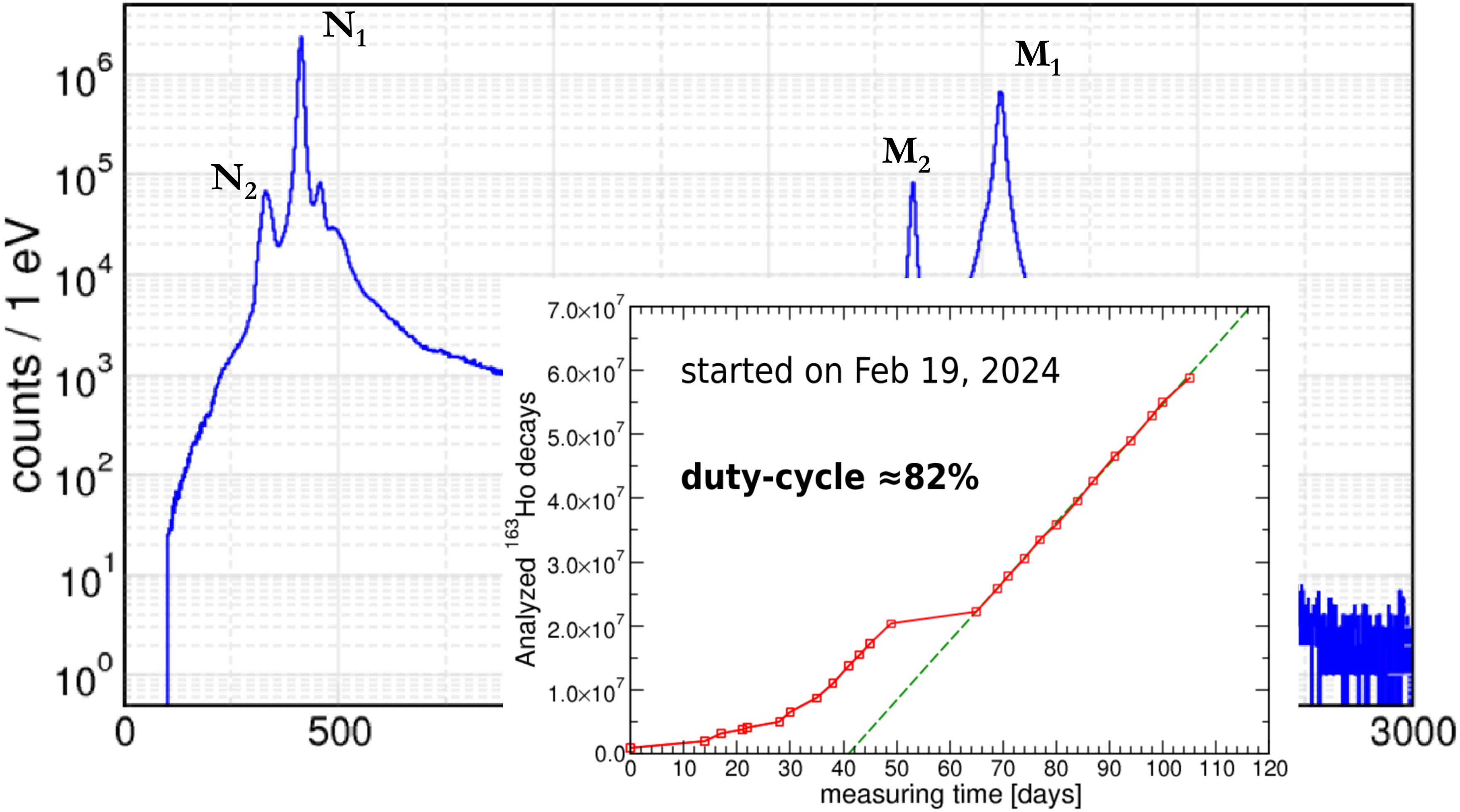

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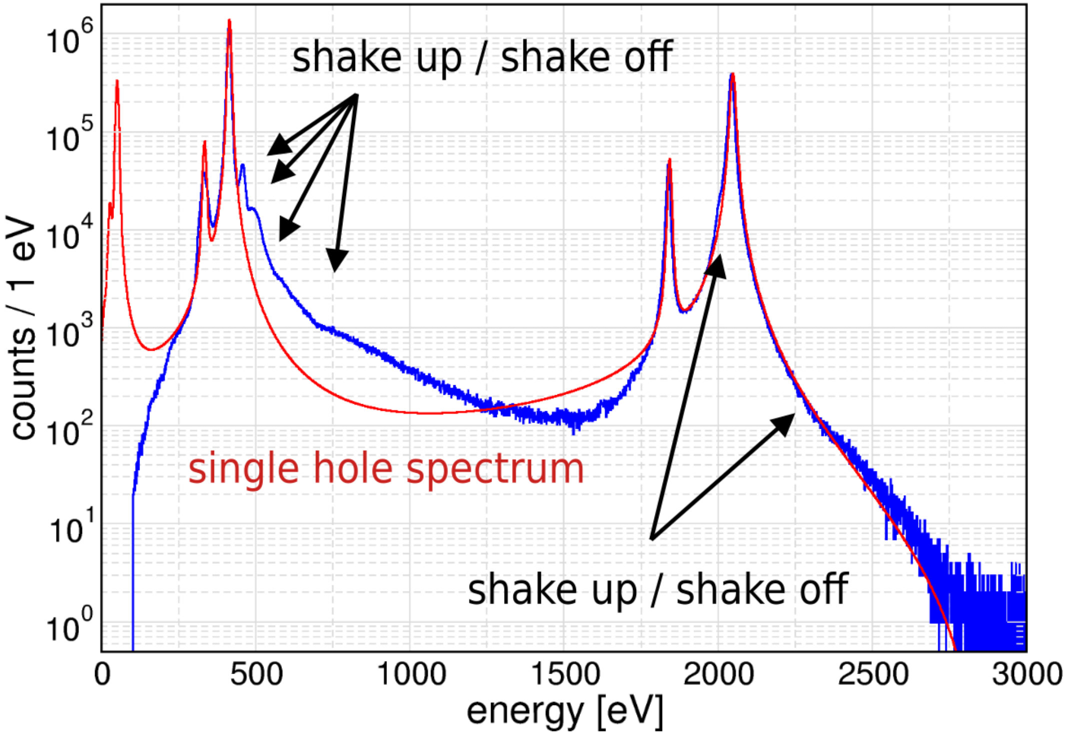
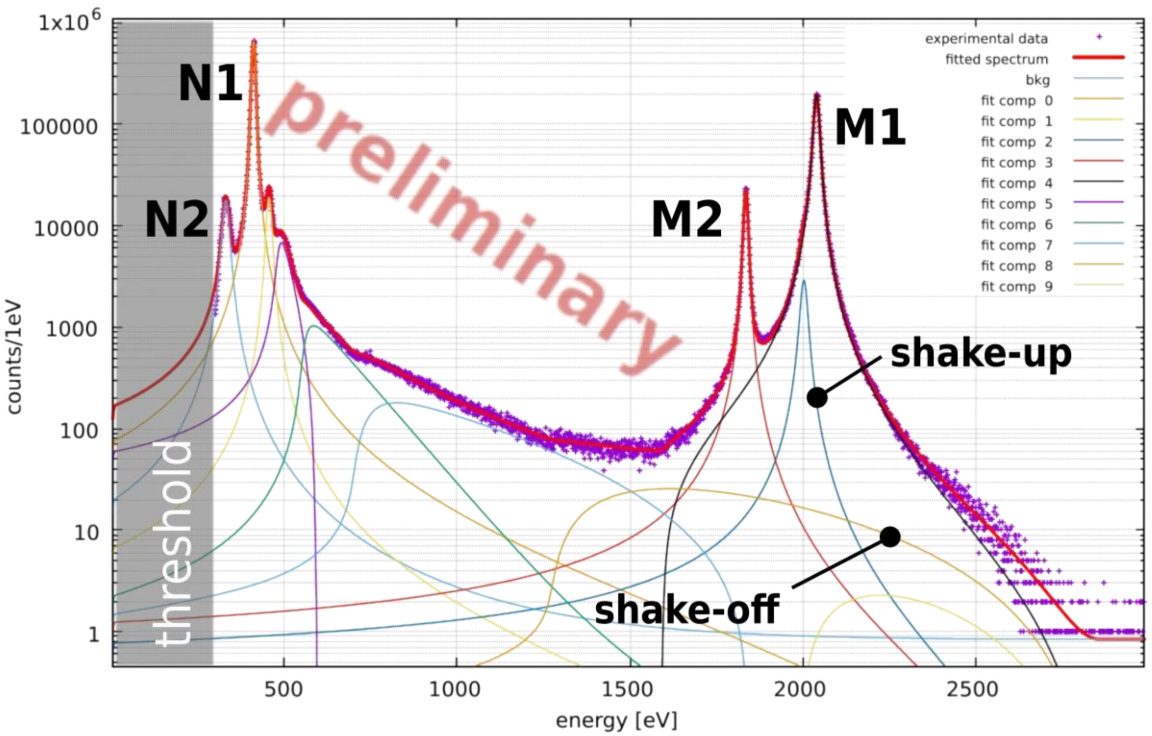




experimental EC spectrum deviates from all theoretical predictions

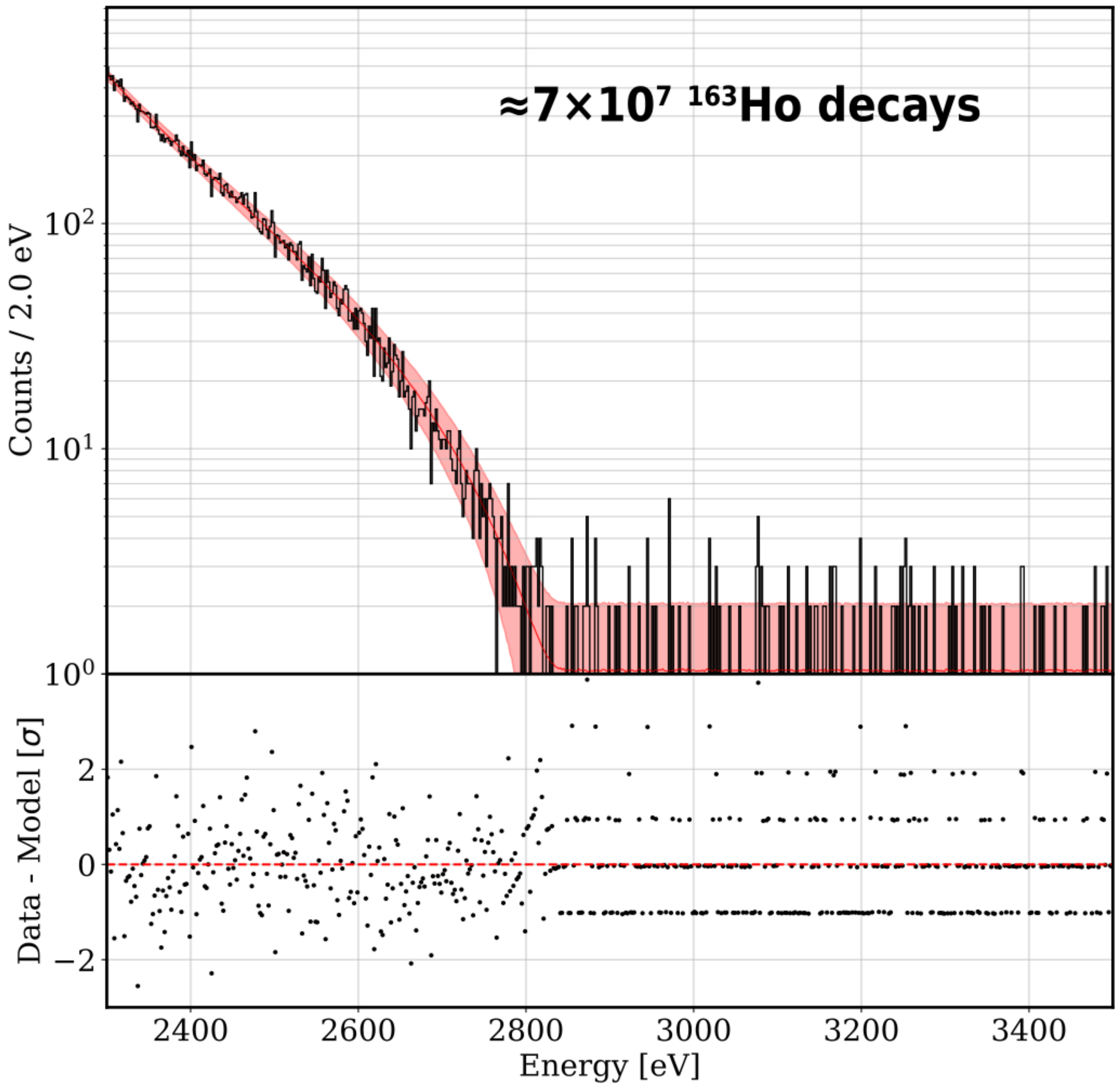
→ phenomenological description of the EC spectrum

- shake-up peaks and shake-off spectra
- strongly asymmetric Lorentzians (Fano-like interference?)

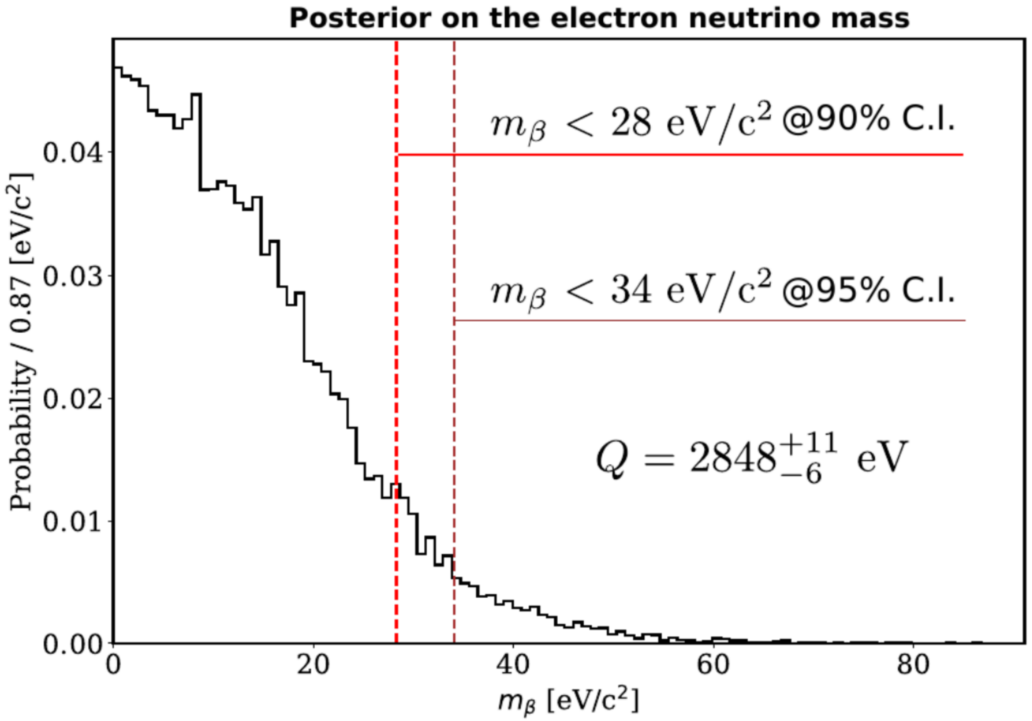
needed for assessing sensitivity of future ^{163}Ho experiments

end-point region is smooth and featureless

^{163}Ho measured spectrum



preliminary Bayesian end-point analysis with phenomenological model
$m_\beta < 28$ eV @ 90% CI
Q = 2848+11−6 eV (only stat error)



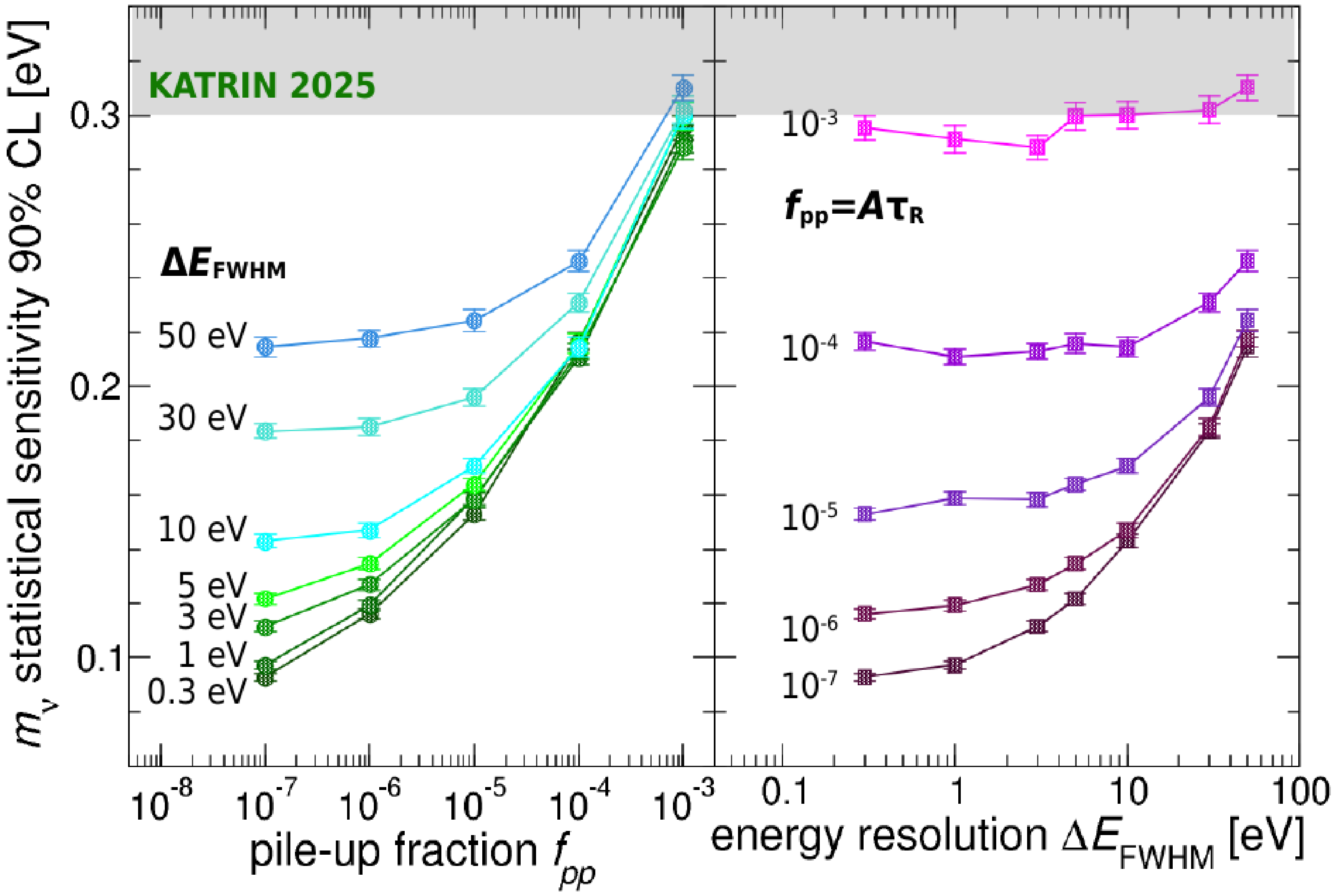
HOLMES+

proposed activity for 3 years (CDR) in CSN2

aims:

- **<u>prepare for a 100 meV sensitivity experiment</u>**
- achieve sensitivity on m_ν of a few eVs
  - ➢ deployment of **256 HOLMES TESs** with and activity of $\geq$ 1Bq
  - ➢ readout with the current cold readout scheme + new readout boards
- produce and deploy **a small number (9-16) of low Tc TESs**
  - ➢ $T_c \leq 40$ mK
  - ➢ $A_{^{163}Ho}$/det $\approx$ 30Bq
  - ➢ readout with new cold readout scheme + HOLMES readout boards
- improve the readout cost/channel
  - ➢ new readout boards
  - ➢ novel cold readout technique
- improve embedding efficiency
  - ➢ heated cavity for atomization
  - ➢ different ionization process → FEBIAD vs RILIS
- exploit and expand synergies with ECHo, NIST, Colorado School of Mines, LANL

HOLMES+ aiming at nex-gen experiment



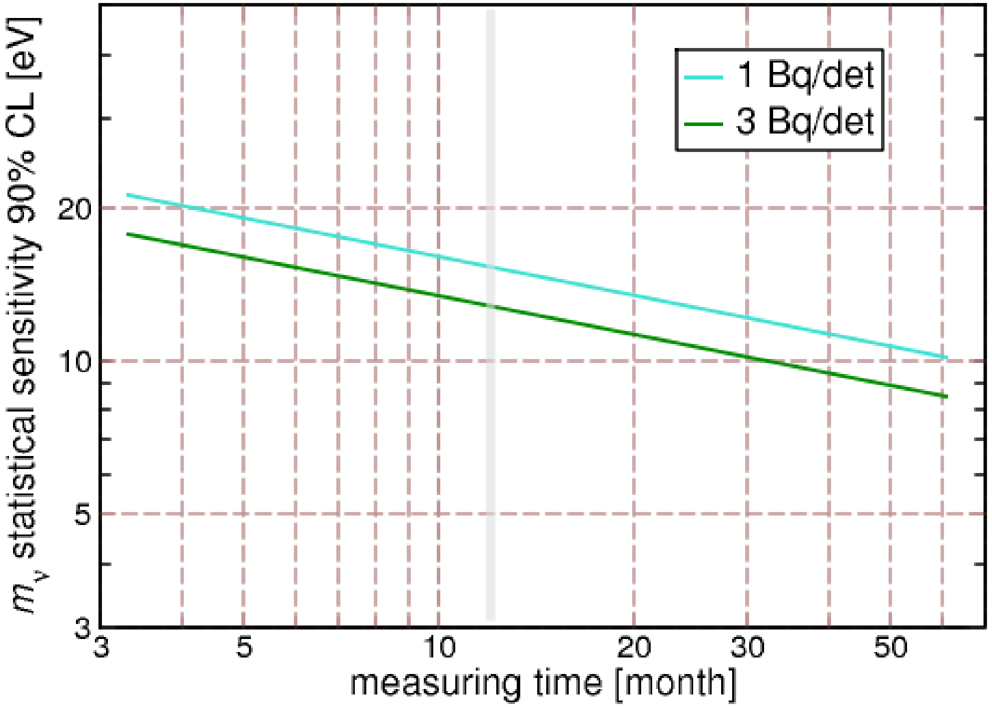
MC simulations based on one-hole approximation

improvement on m_ν sensitivity due to excess statistics yet to be quantified (with HOLMES at least a factor 2 better)

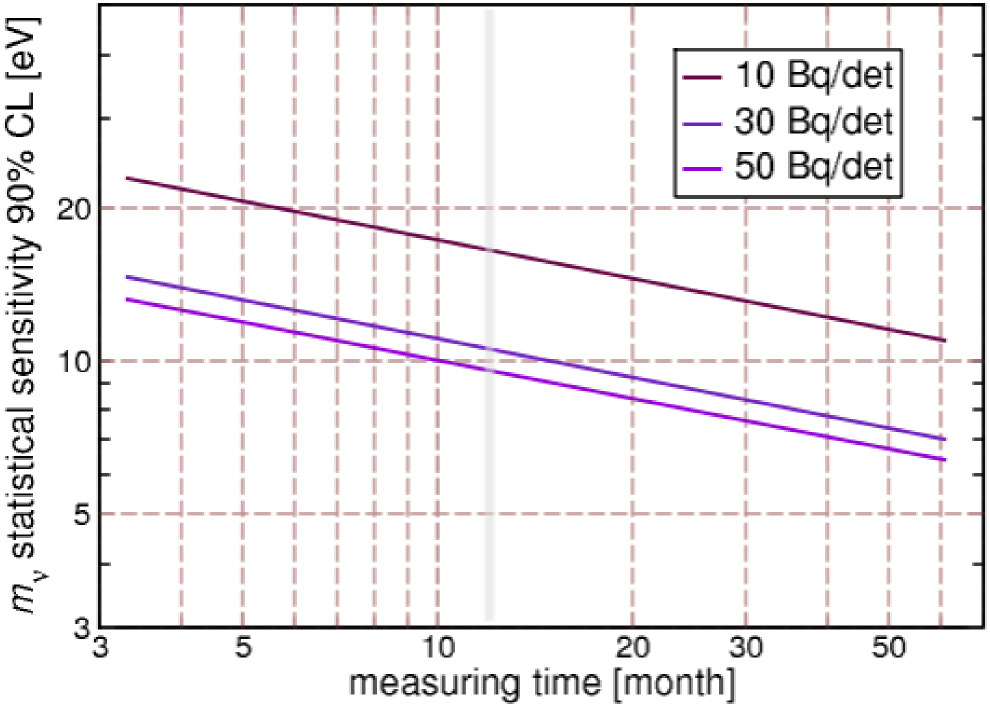
- 5×10^{16} events
- $\Sigma_{90}(m_\nu) \propto \sqrt[4]{1/N_{ev}}$

HOLMES+: 256 + 16 TESs

simulations based on one-hole approximation

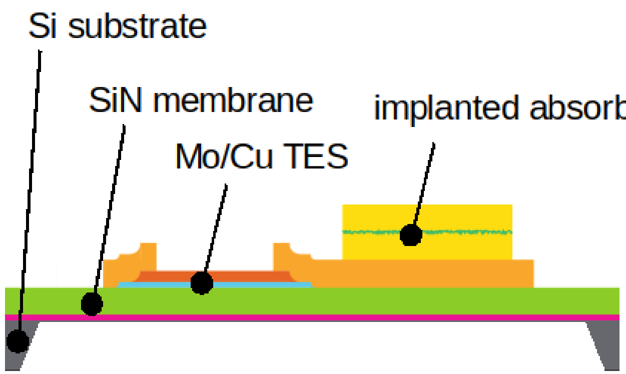


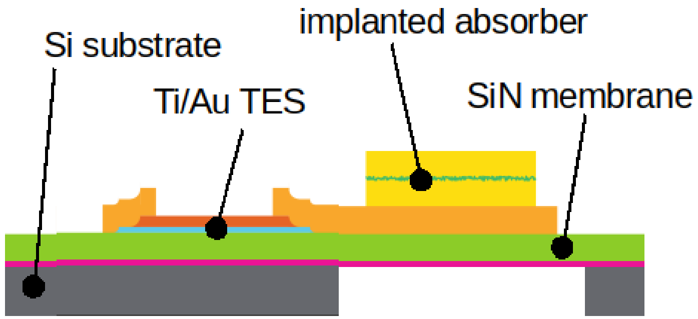
256 ‘old’ HOLMES-style TESs



16 ‘new’ HOLMES+ TESs

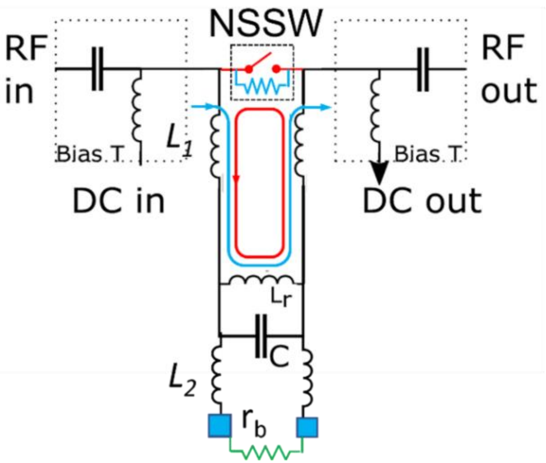
HOLMES+: TESs and cold readout

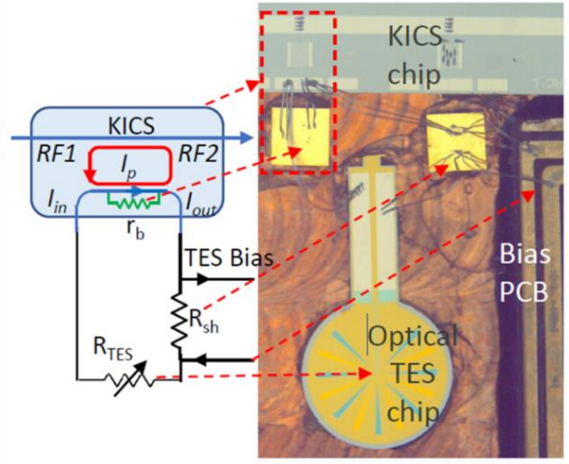




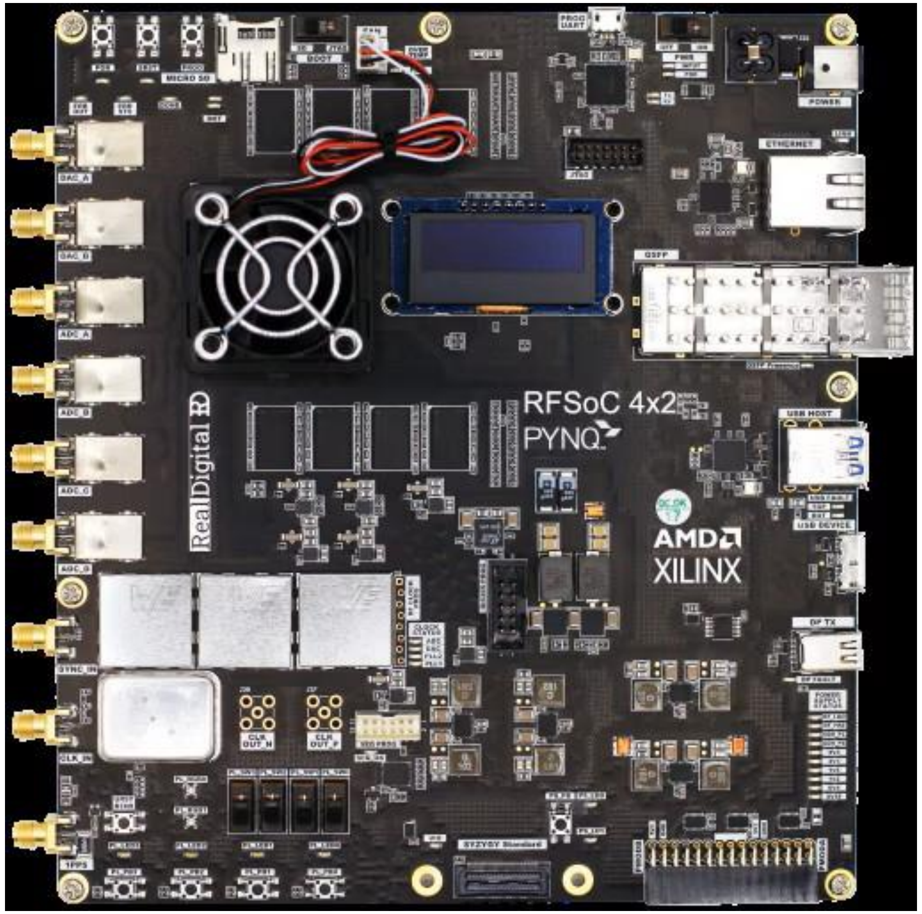
- low T_c TESs developed and produced at INRiM with support of NIST
- Ti/Au bilayer
- sensor deposited on Si substrate → conductivity determined by e-ph
- absorber on SiN membrane to avoid leakage of energetic phonons

- novel technique demonstrated at NIST
- exploits non-linearity of superconductors (experience with DARTWARS, ICSC and NQSTI)
- more efficient usage of the bandwidth
- easy to fabricate
- possibility to integrate on the TES chip
- will be produced at FBK with support of NIST
- will be used to readout the 9/16 low T_c TESs





HOLMES+: readout and DAQ



Since HOLMES' proposal many new readout boards

Interesting the RFSoC 4x2

- low cost (educational/research)
- 5 GSPS, 14-bit ADC
- 9.85 GSPS, 14-bit DAC

- coupled with new IF board (2 GHz BW) → 256 channels HOLMES-style multiplexing

- will be used to readout the 256 low activity TESs

- Synergy with ECHo: possibility to use their MPSoC boards and compare performances

HOLMES+: ion implanter upgrade

Aim: improve the overall embedding efficiency

1. integrate the co-deposition chamber (currently @MiB) in the ion implanter
2. install the focus stage
3. upgrade the ion source
   - heated cavity for evaporation of Ho (and avoid deposition of Ho before ionization)
   - more efficient ionization technique: FEBIAD
     - Forced Electron Beam Induced Arc Discharge Ion Source
     - established technology
     - low cost (~150 k€)
     - less efficient than RILIS
   - RILIS
     - Resonance Ionization Laser Ion Source
     - used at Mainz with high efficiency with 70% efficiency
     - expensive (~1M€)

HOLMES+ baseline: FEBIAD, leaving a possible future (post-HOLMES+) upgrade to RILIS

Collaboration with ECHo/Mainz and support from LNL (which will join the collaboration starting from 2026)

HOLMES+ collaboration and synergies

European institutions:

- INFN units:
    - MiB
    - Ge
    - To (INRiM)
    - TIFPA (FBK)
- LNL support for 2025, will ufficially join the collaboration with FTE starting from 2026
- ECHo collaboration (including Mainz)

US institutions:

- NIST Boulder
- Colorado School of Mines (BeEST)
    - Kyle Leach will submit proposal to NSF in December (~200k$/y)

HOLMES+ WPs

- WP1: Experimental set-up 76 k€
  - INFN-MiB
- WP2: Embedding system 190 k€
  - INFN-Ge, INFN-MiB, INFN-To (INRiM)
- WP3: TES detectors 165 k€
  - INFN-To (INRiM), INFN-MiB, INFN-Ge
- WP4: KICS readout 95 k€
  - TIFPA (FBK), INFN-MiB, INFN-To (INRiM)
- WP5: DAQ, data analysis and simulations 60k€
  - INFN-MiB, all