Status of the HOLMES experiment

Marco Faverzani

Università & INFN Milano-Bicocca

on behalf of the HOLMES collaboration

^{163}Ho electron capture

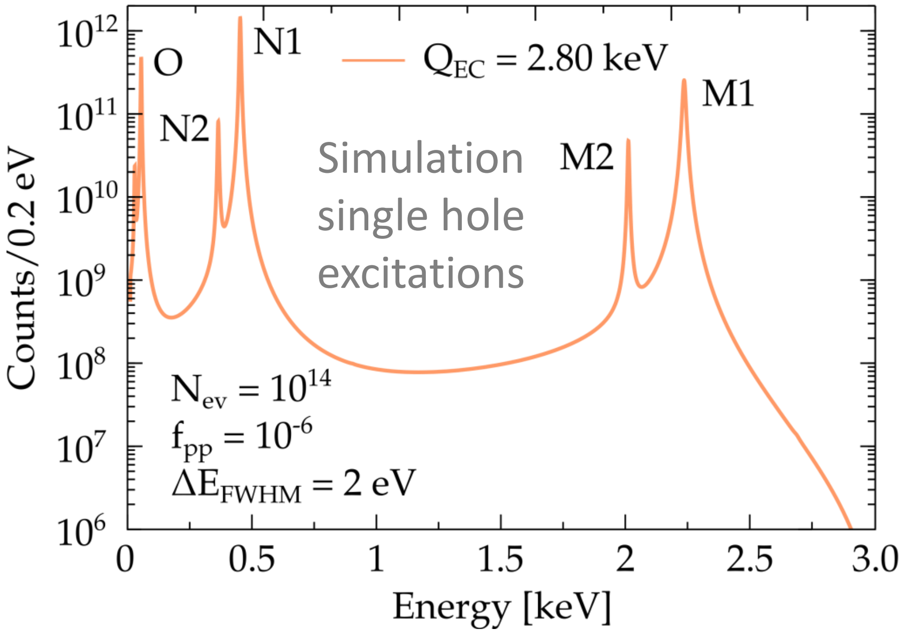
$^{163}Ho + e^- \rightarrow {}^{163}Dy^* + \nu_e$

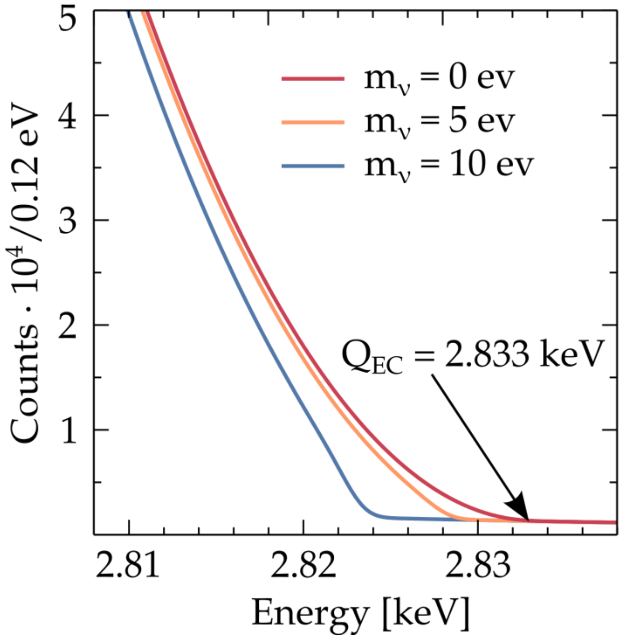
^{163}Ho decay via EC from shell ≥ M1, with $Q_{EC} \sim 2.8$keV

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 depends on $(Q - E_{M_1})$: the proximity to M1 resonance peak enhances the statistics at the end point (i.e. sensitivity on m_ν)
- $\tau_{1/2} \sim 4570$ years: few nuclei are needed (2×10^{11} ^{163}Ho nuclei = 1 Bq)

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





HOLMES (ERC Grant 340321):

- Transition Edge Sensors
  - $\Delta E \sim 1$ eV, $\tau_R \sim 1$ µs
- 300 Hz/det of ^{163}Ho
- 6.5×10^{16} nuclei of ^{163}Ho
- $f_{pp} \approx A_{EC} \cdot \tau_R$
- 3×10^{13} in 3 years
- sensitivity on $m_\nu \sim$ eV

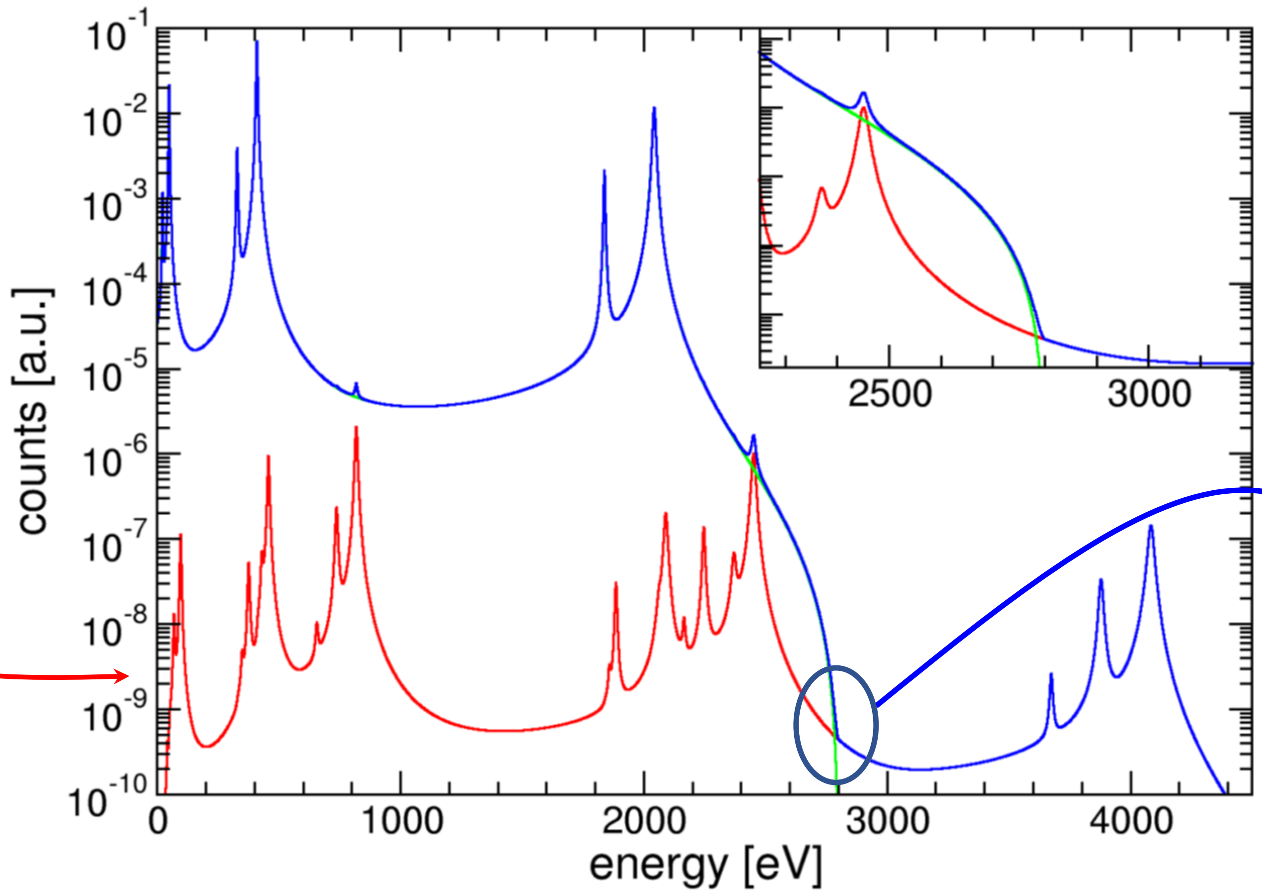
Pile-up

- pile-up is a major systematics of the calorimetric approach
  - $N_{pp}(E) = f_{pp} N_{EC}(E) \otimes N_{EC}(E)$, with $f_{pp} \approx A_{EC} \tau_R$

A_{EC} activity/detector
τ_R time resolution

- fast detectors
- limited activity/det

parallelization over large number of detectors

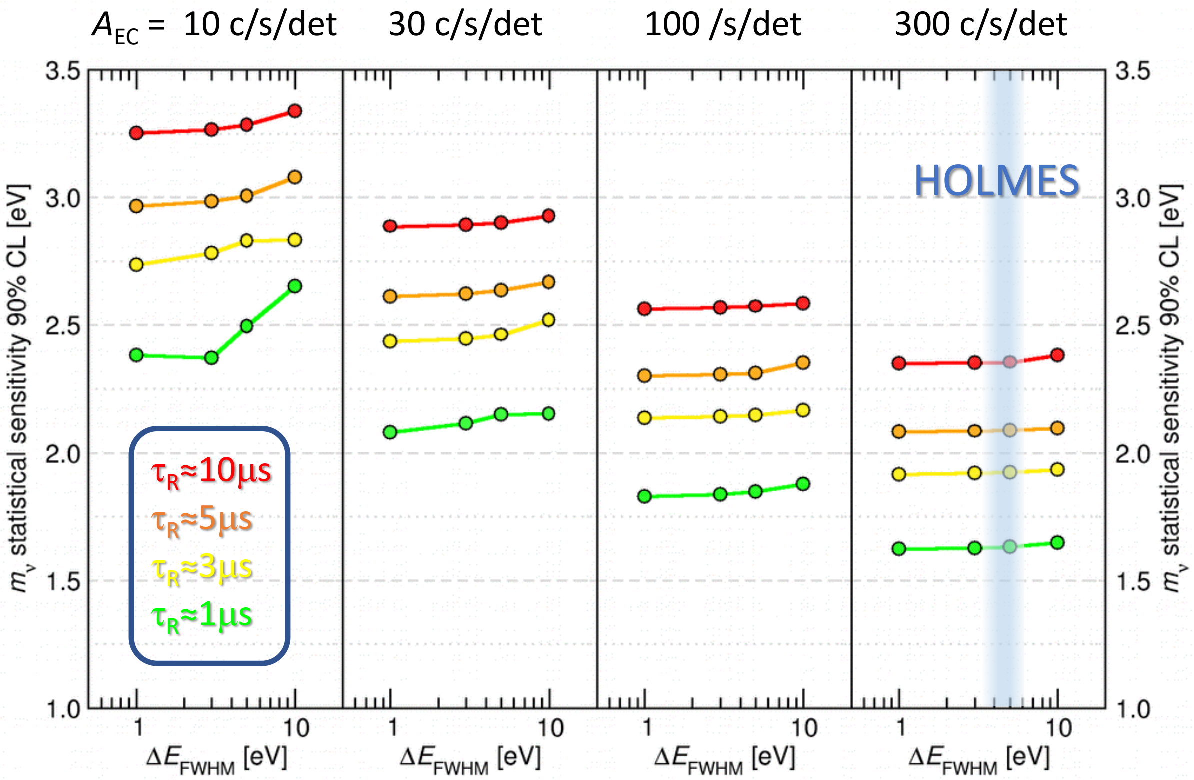


Single hole excitations
Q = 2800 eV
$f_{pp} = 10^{-4}$

Impairing effect on the end-point measurement

HOLMES (ERC-Adv. Grant 340321) PI:S.Ragazzi

MonteCarlo with 1000 detectors x 3 years



B. Alpert et al., Eur. Phys. J. C, (2015) 75:112
http://artico.mib.infn.it/holmes

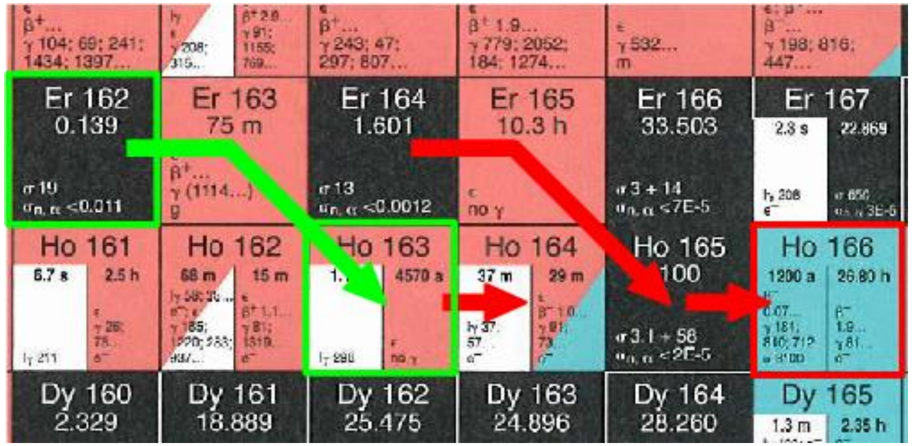
Goals:

- Neutrino mass determination with a sensitivity as low as ~ 1 eV
- proof potential and scalability of the approach
- precise calorimetric determination of *Q*
- systematic errors assessment

Two steps approach:

- 64 channels mid-term prototype, t_M = 1 month (m_ν < 10 eV)
- full scale: **1000 channels** (Transition Edge Sensors)
- 300 Hz/detector → $3x10^{13}$ events collected in 3 years
- $6.5x10^{16}$ ^{163}Ho nuclei (≈18 μg)

^{163}Ho production & purification



$^{162}Er(n,\gamma)^{163}Er$	$\sigma_{thermal} \approx 20b$
$^{163}Er \longrightarrow {}^{163}Ho + \nu_e$	$\tau_{½}^{EC} \approx 75min$

- ILL nuclear reactor @ Grenoble: high **thermal n flux 1.3x10^{15} n/cm^2/s**
- **cross section burn up** $^{163}Ho(n,\gamma)^{164}Ho$ not negligible (~ 200 b)
- $^{165}Ho(n,\gamma)$ (mostly from $^{164}Er(n,\gamma)$) → **^{166m}Ho, β^-, $\tau_{½}$ = 1200 y, Q = 1856 keV**
  - $A(^{163}Ho)/A(^{166m}Ho)$ = 100 ~ 1000
- chemical pre-purification and post-separation at PSI (Villigen, Switzerland)
  - *S. Heiniz et al., PLoS ONE 13(8):e0200910*
- **HOLMES needs ~ 300 MBq of ^{163}Ho* for 1000 detectors**

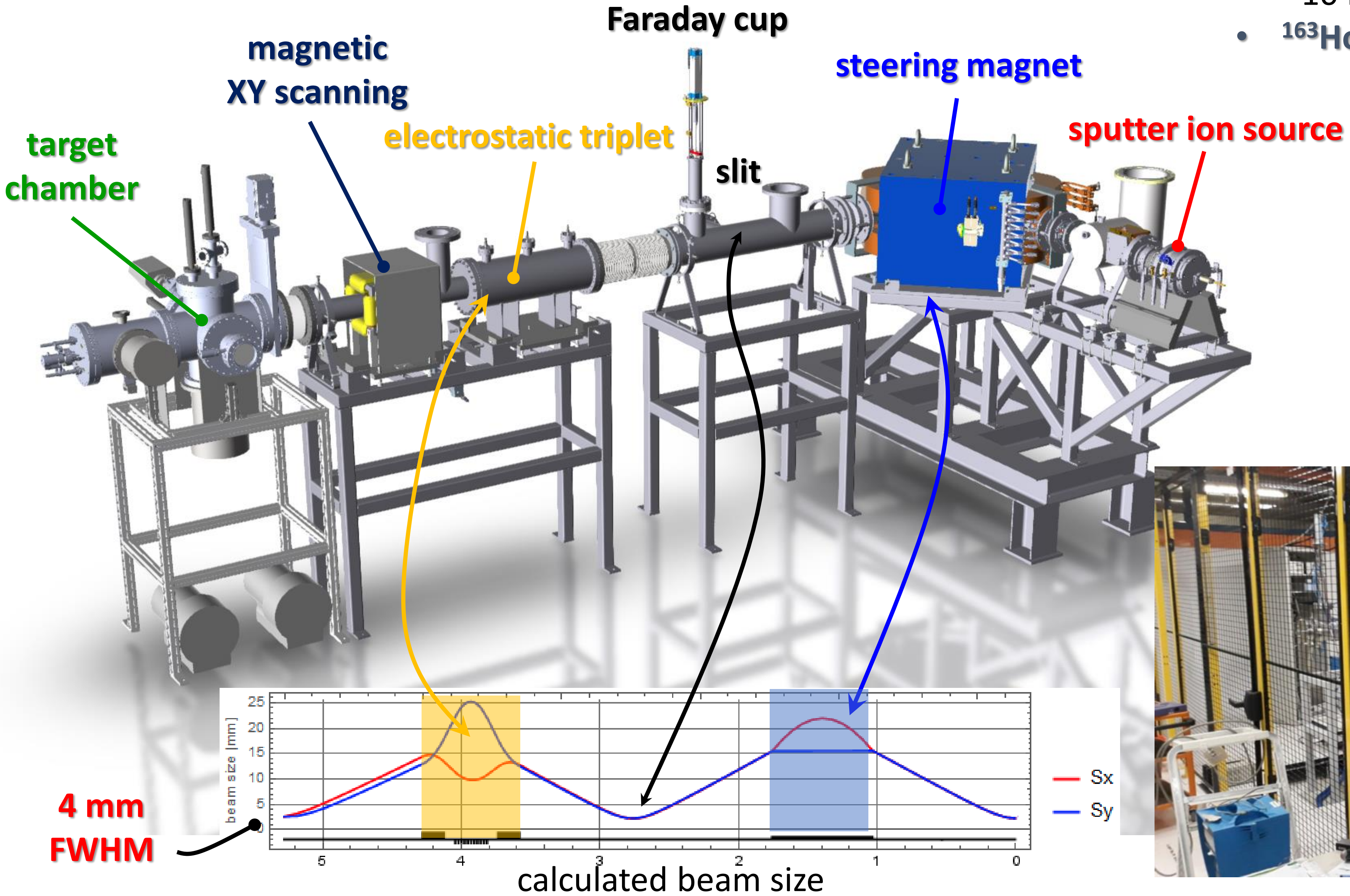
HOLMES ^{163}Ho inventory:

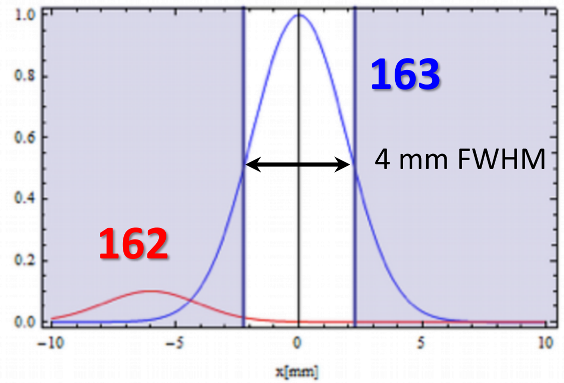
- ≈ 110 MBq of purified ^{163}Ho available at INFN in Genova
- ≈ 250 kBq of ^{166m}Ho
- more ^{162}Er available to produce 80 MBq of ^{163}Ho
  - ILL shutdown until 2022

*depends on the actual global embedding process efficiency

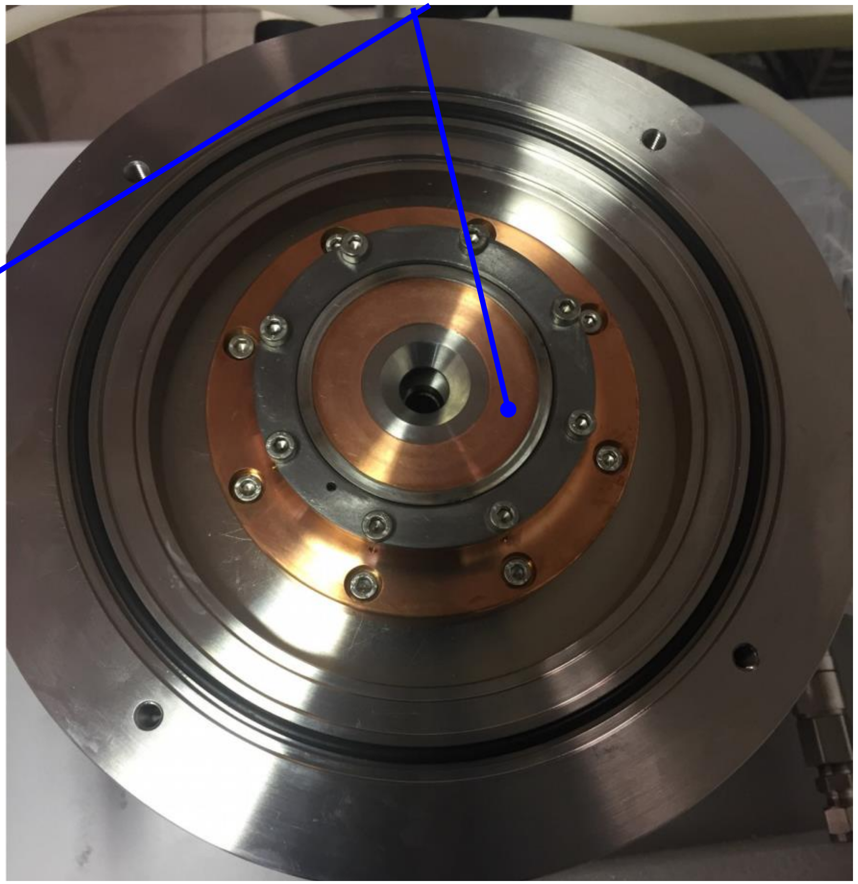
HOLMES mass separation and ion implantation

- extraction voltage 30-50 kV
- ~10 nm implanting depth
- **^{163}Ho/^{166m}Ho separation better than 10^5**





HOLMES Ion implanter: testing



- test in progress at INFN Genova
  - no focusing
  - sputter target made in Cu
- **Cu ion beam current > 30 μA (HOLMES requires 1-10 μA of ^{163}Ho)**

next steps:

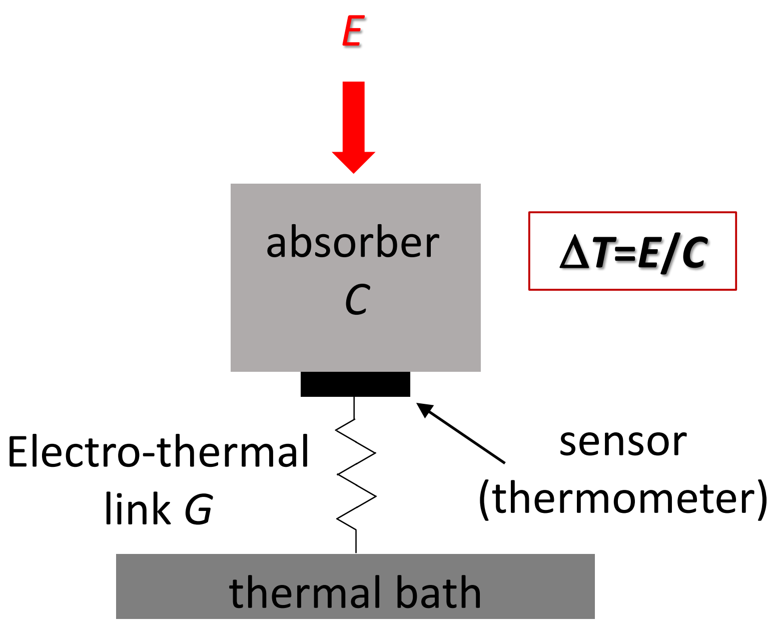
- tests with natural holmium
- tests with ^{163}Ho (sintered with other metals)

Transition Edge Sensors

<u>Low temperature detectors</u>

- (quasi-)equilibrium thermal detector
- complete energy thermalization → calorimetry
- $\Delta T = E / C$ → low C
  - low T (T << 1K)
  - preferable dielectrics or superconductors

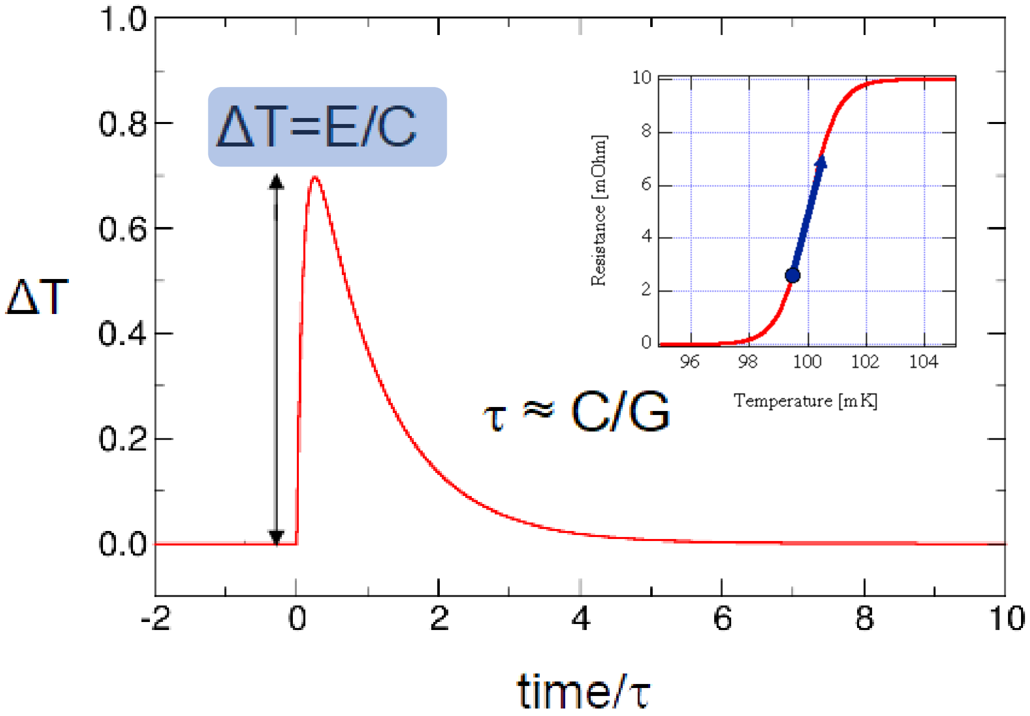
➢ good energy resolution
➢ wide choice of materials
➢ slow time response



<u>Transition Edge Sensors (TES)</u>

- exploit the steepness of $R(T)$ of a superconductor kept in its transition to measure ΔT

➢ state of the art energy resolution
➢ multiplexing scheme available
➢ limited dynamics → design optimized for a specific application



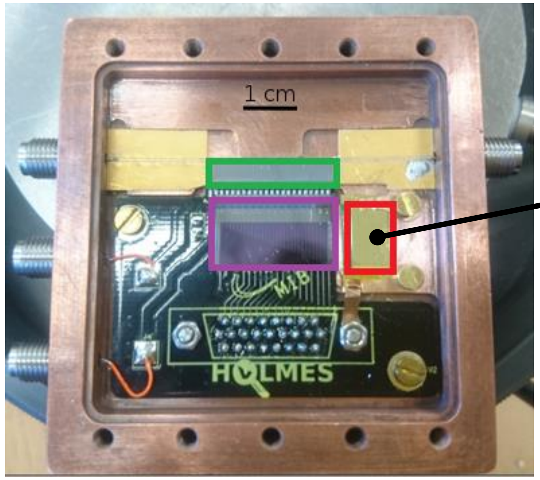
Detectors testing

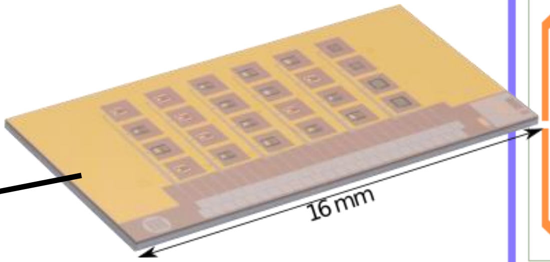
- tested several geometries
- produced entirely at NIST
- **Not implanted with Holmium!**
- ^{55}Fe (5.9 keV) + fluorescence source (Ca – 3.7 keV; **Cl – 2.6 keV**; Al – 1.5 keV)
- selected stray inductance to obtain $\tau_{rise} \approx 13\ \mu s$

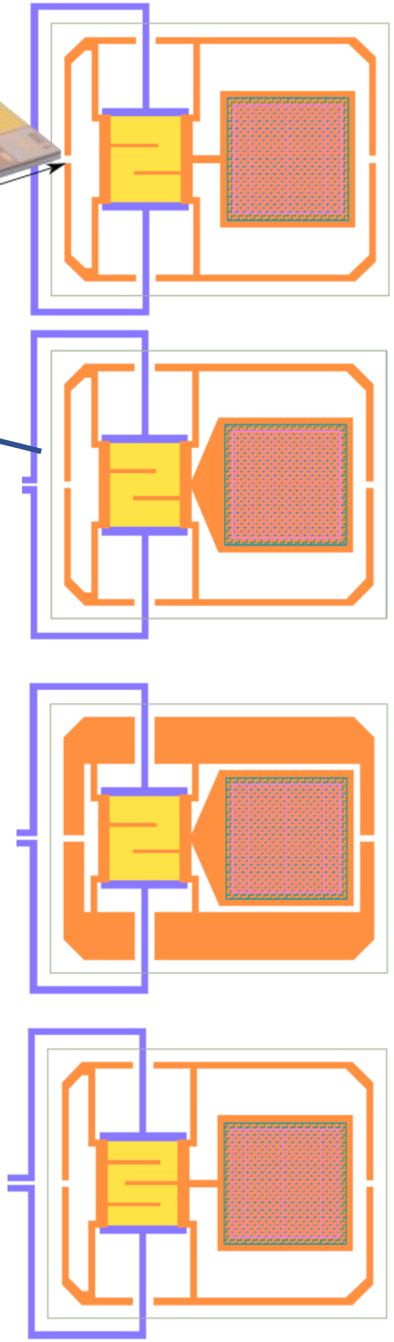
test @Milano **with μ–wave multiplexing**

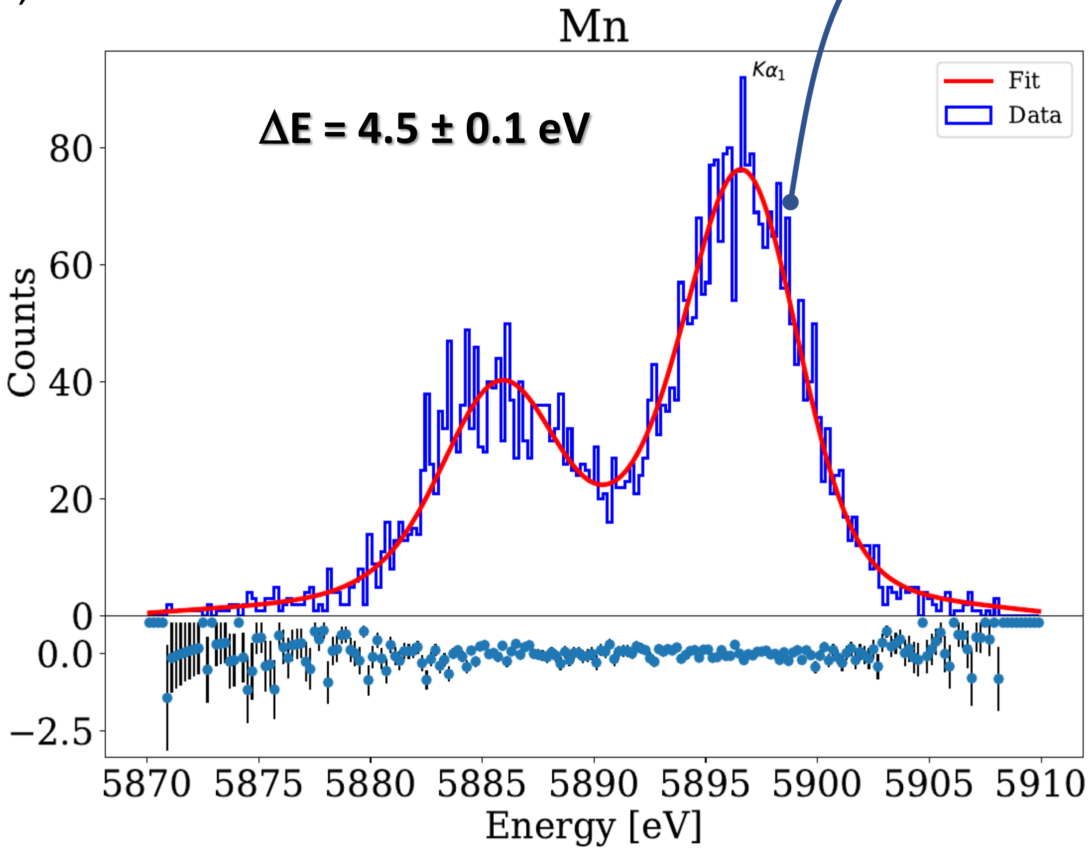
f_{samp} = 500 kHz

E [keV]	ΔE [eV]
1.49	4.3±0.3
2.62	4.5±0.3
3.69	4.6±0.3









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

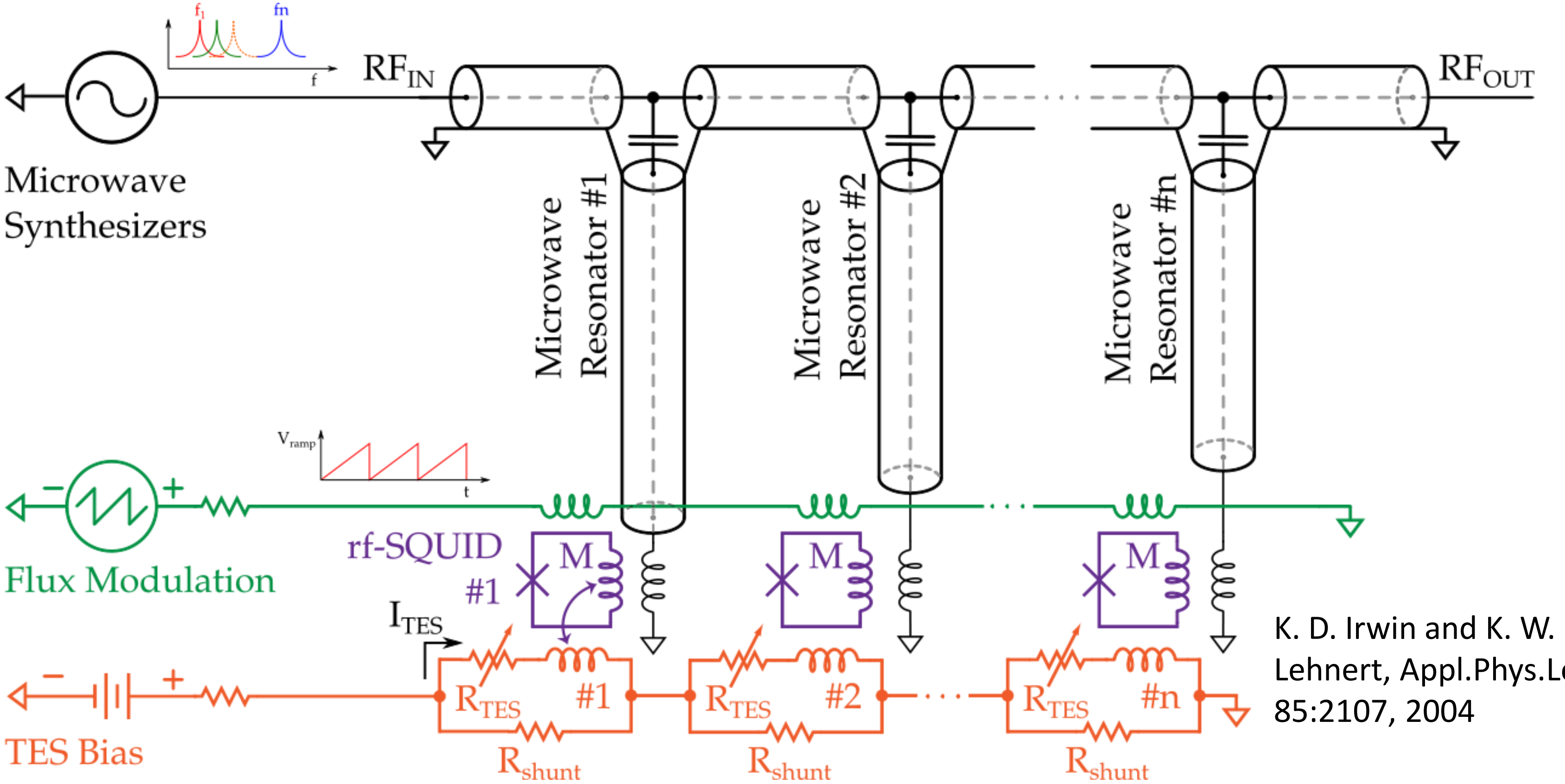
Microwave multiplexing readout

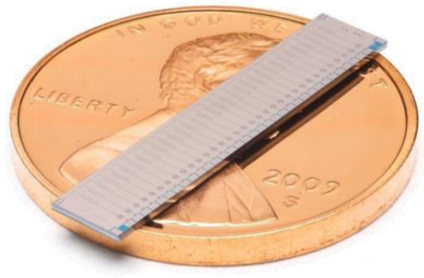
TESs readout with microwave multiplexing (produced by NIST)

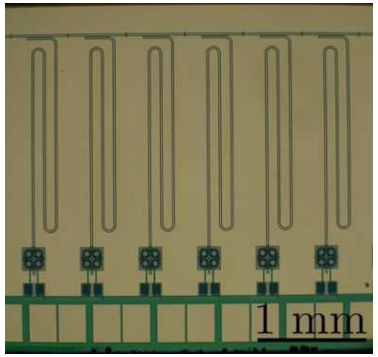
- each sensor inductively coupled to a RF-squid part of a $\lambda/4$ resonator
- a comb of signals probe the resonators at their characteristic resonant frequency

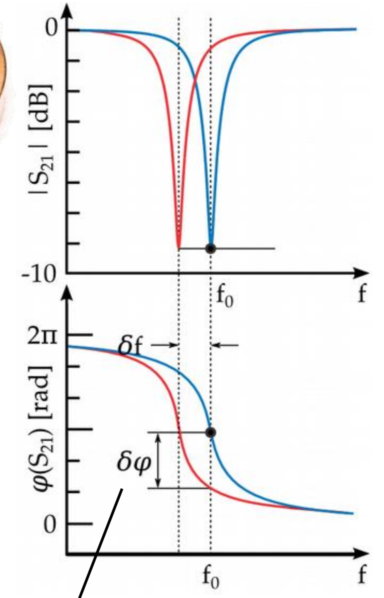
$$E \longrightarrow \delta T_{\mathrm{TES}} \longrightarrow \delta I_{\mathrm{TES}} \longrightarrow \delta\phi_{\mathrm{squid}} \longrightarrow \delta f_{\mathrm{resonator}}$$

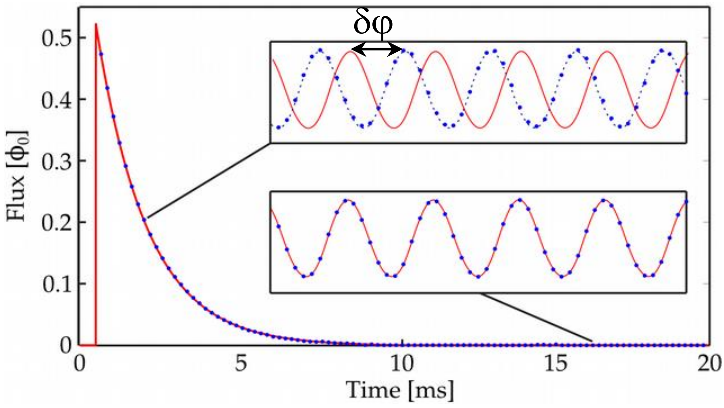
- a ramp signal added to the squids in order to linearize the response





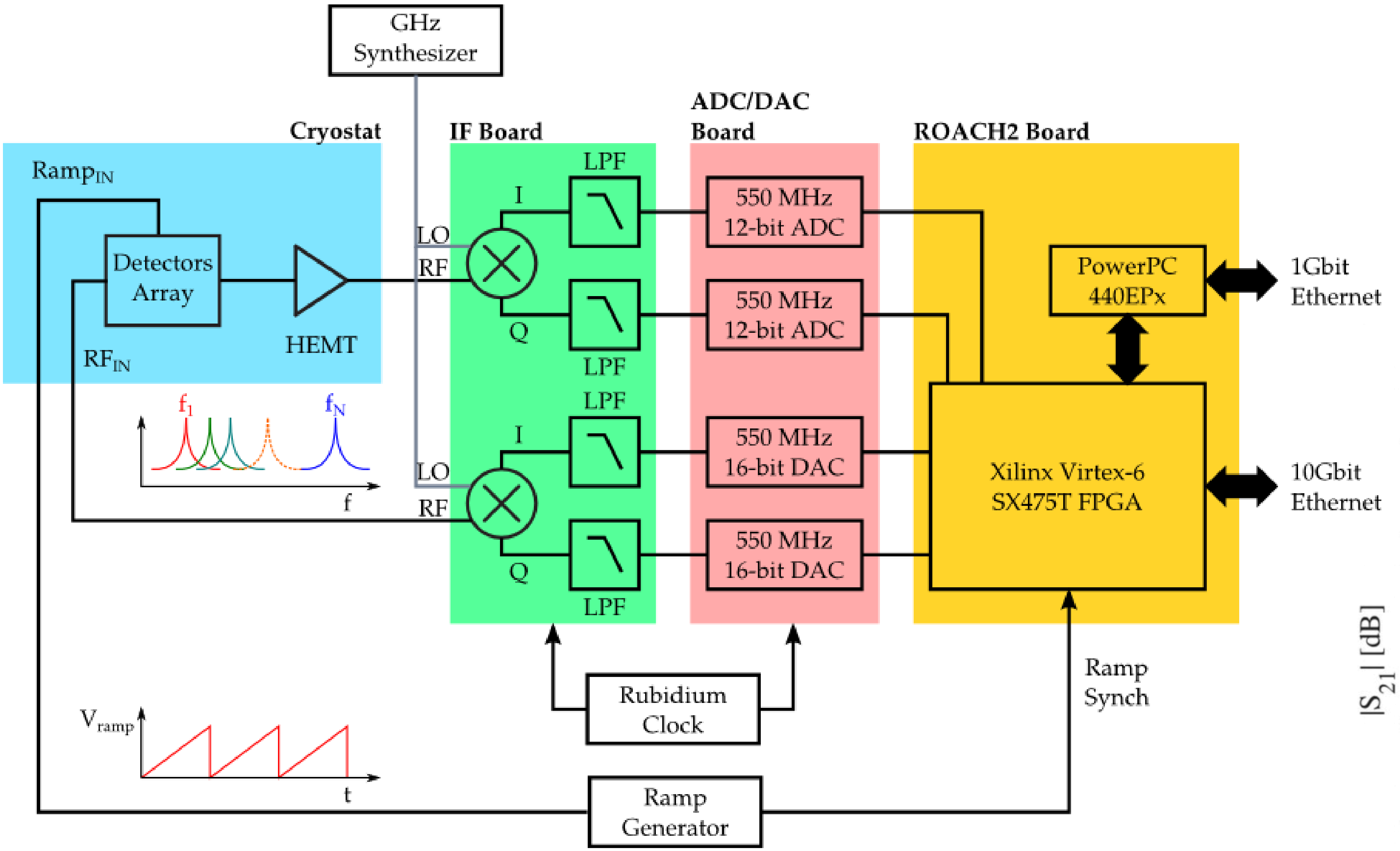






K. D. Irwin and K. W. Lehnert, Appl.Phys.Lett., 85:2107, 2004

DAQ with the ROACH2

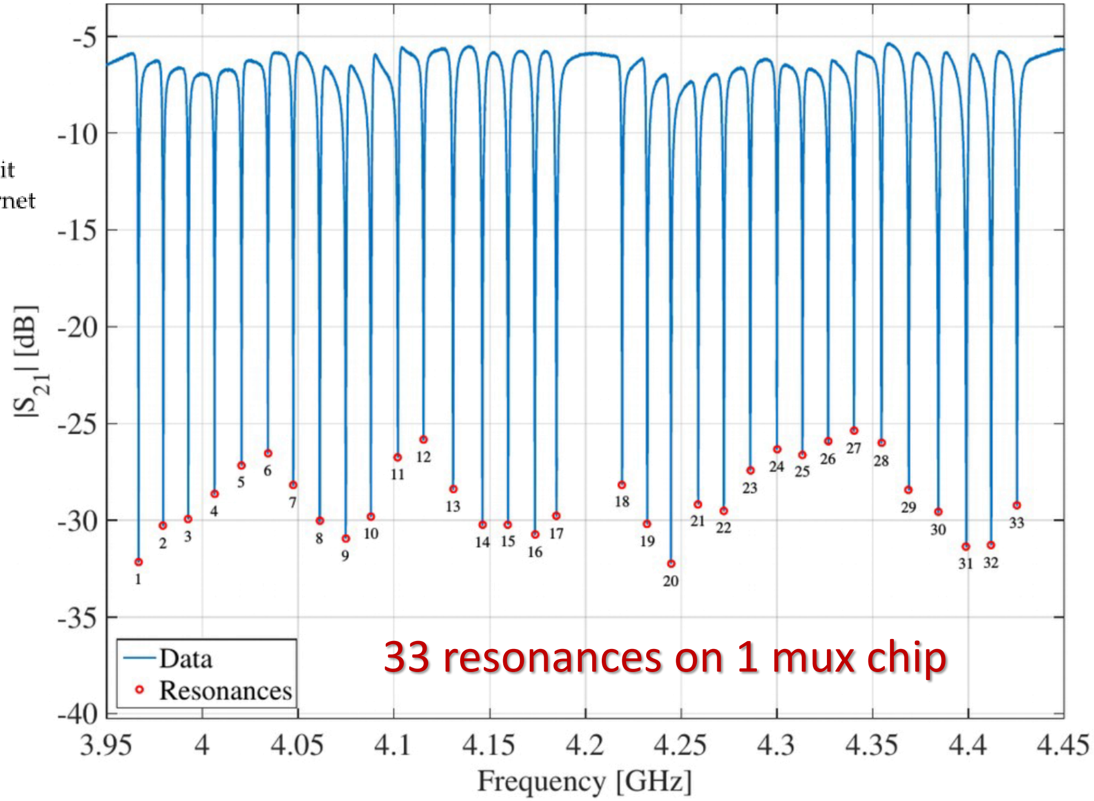


- Software Defined Radio with the open system ROACH2 (Casper collaboration)
- ADC BW 550 MHz
- real time pulse reconstruction
- ➢ at the moment readout available for 64 channels

Multiplexing factor proportional to the target rise time: $n_{TES} \approx 3.4 \cdot 10^{-6} \tau_{rise}$

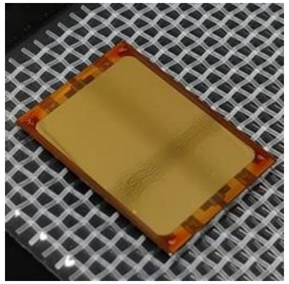
requiring τ_{rise} = 10 µs

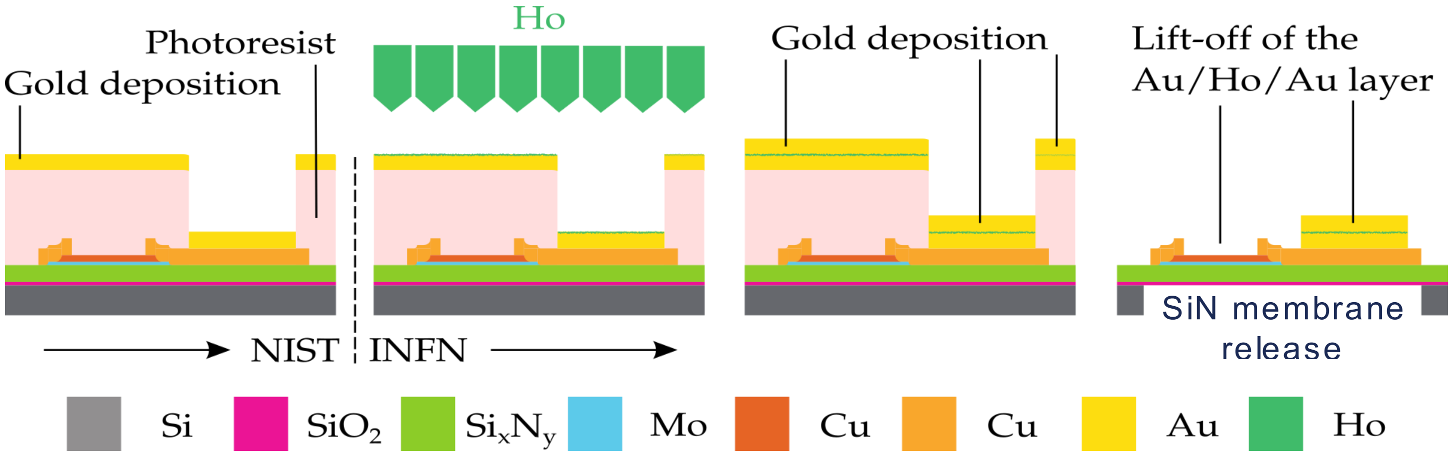
$n_{TES} \approx 34$

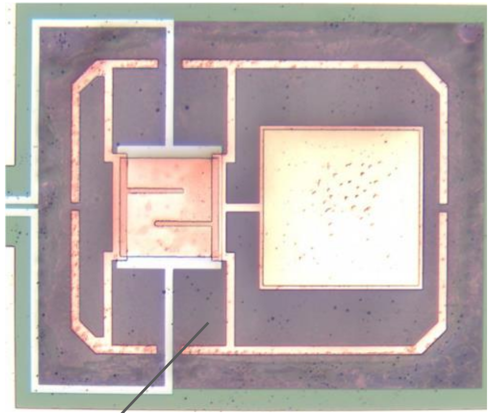


D.T. Becker at al., JINST 14 (2019) P10035

Detectors fabrication

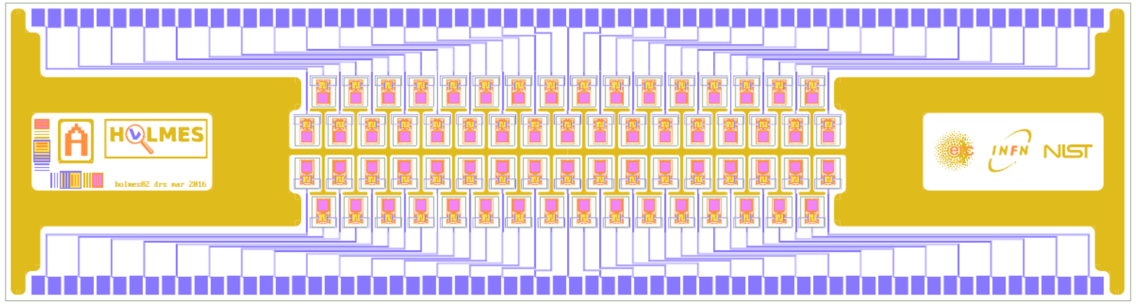






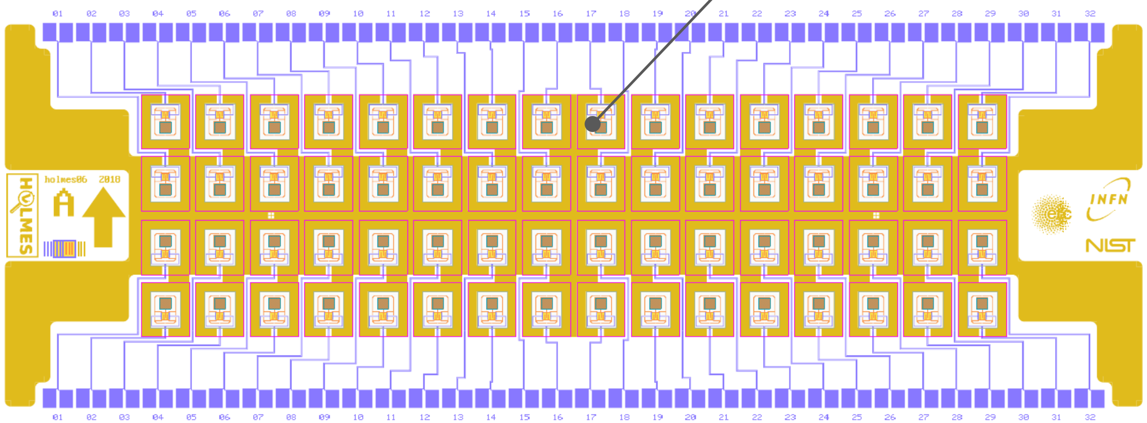
- TES originally fabricated at NIST, Boulder, CO, USA
- ^{163}Ho implantation at INFN, Genova, Italy
- 1 µm Au final layer deposited at INFN, Genova, Italy
- final fabrication process: release of the membrane with KOH in Milano or DRIE

DRIE



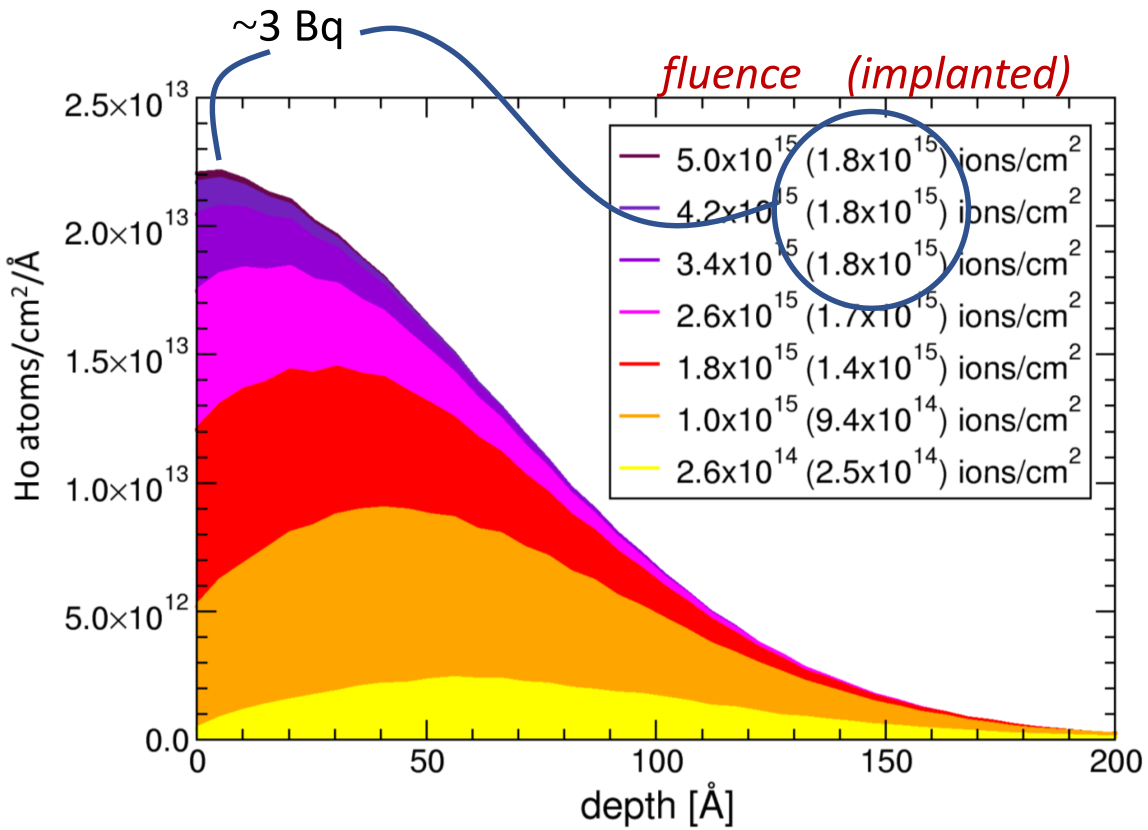
beam FWHM
calculated ^{163}Ho

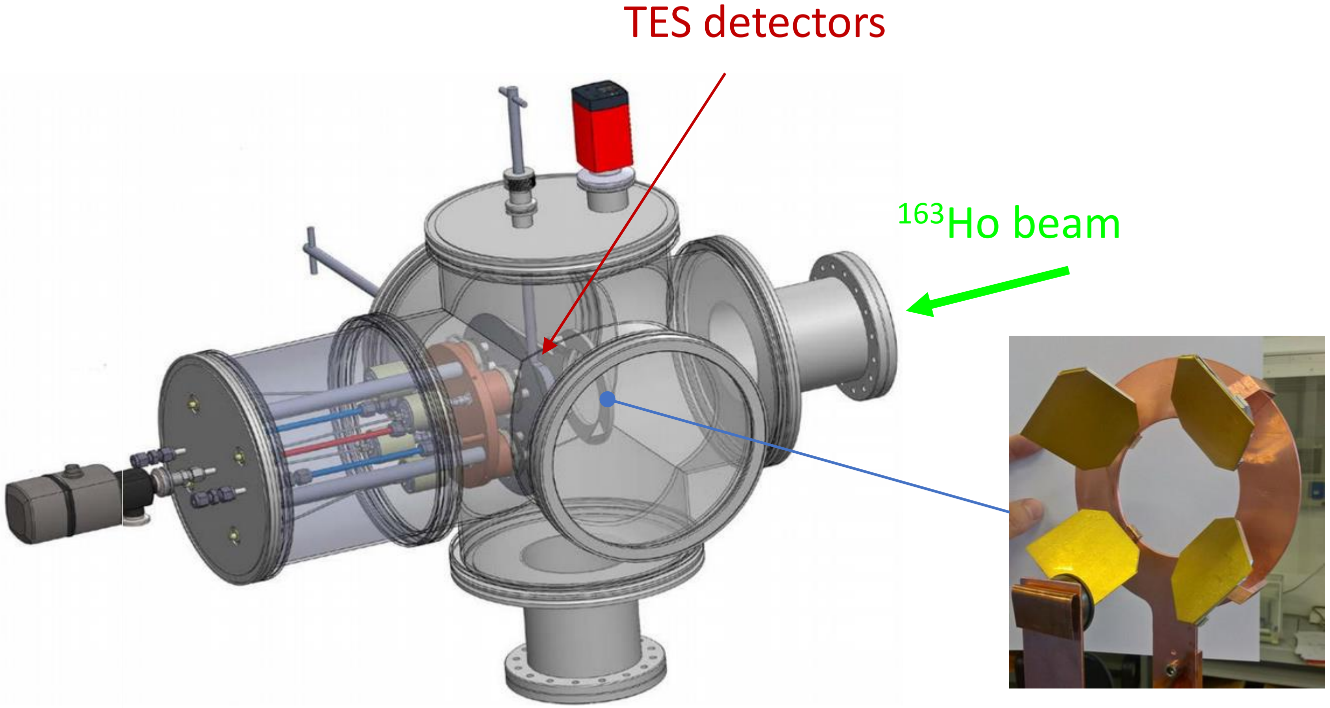
KOH



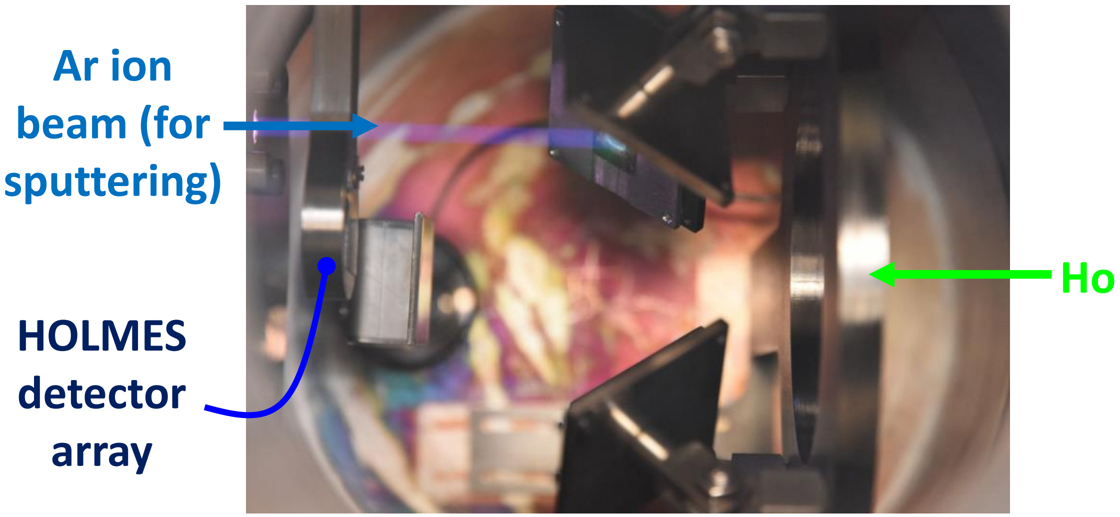
Target chamber

ion implantation (SRIM2013) – energy beam 50 keV





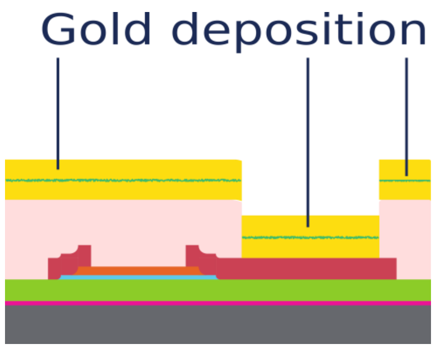
deposition rate (with 4 sputter sources) > 100 nm/h
~ 10 hours to deposit 1 μm



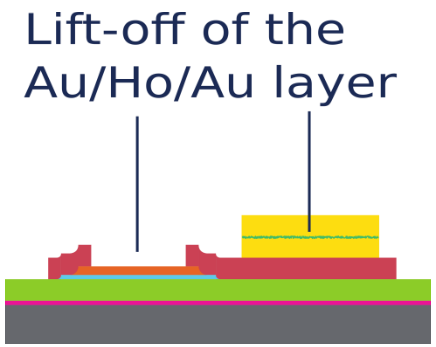
- ^{163}Ho concentration in absorbers saturate because ^{163}Ho sputters off Au from absorber
- effect compensated by Au co-evaporation (also for heat capacity reasons)
- final 1 μm Au layer deposited in situ to avoid oxidation

Detectors fabrication @ Milano-Bicocca

1)

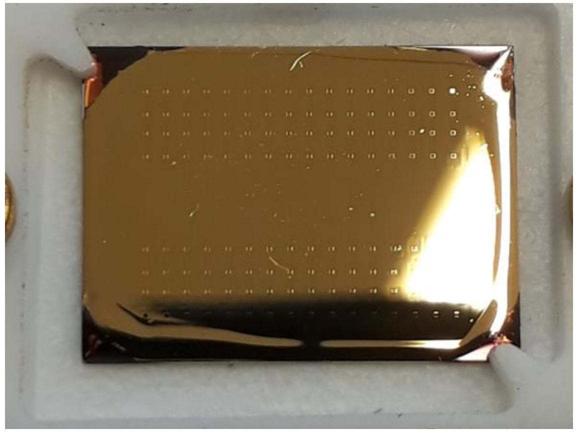


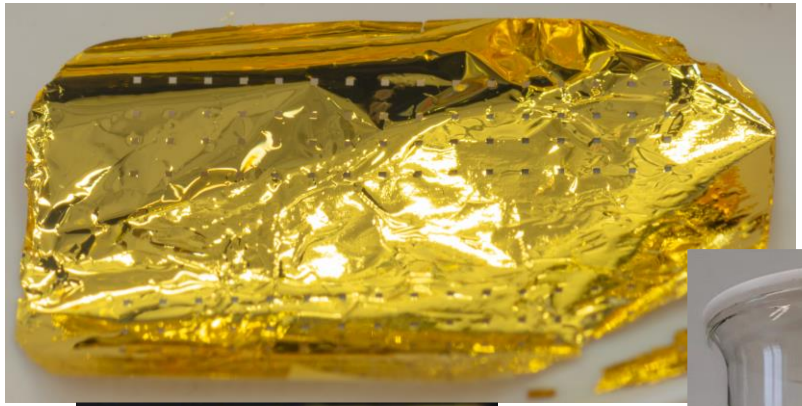
2)

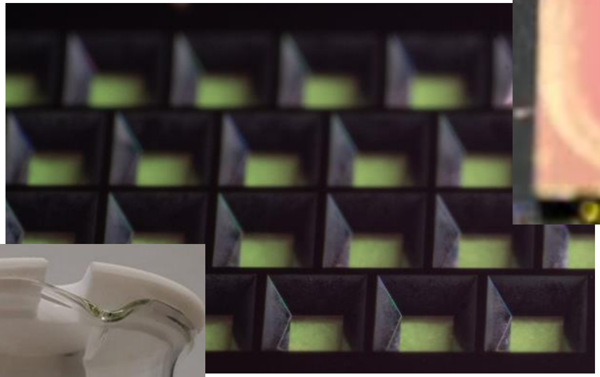


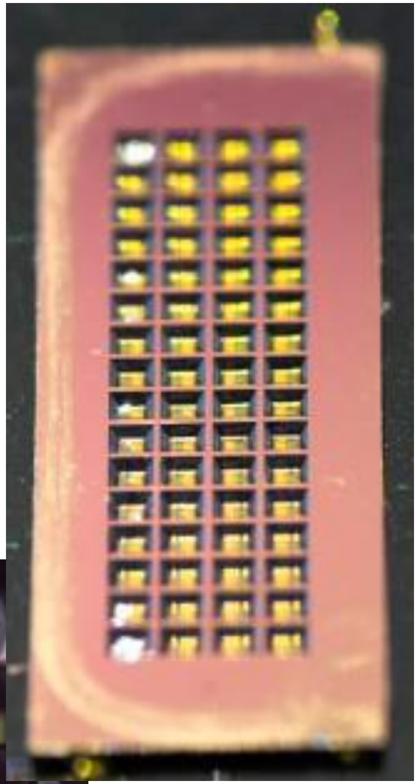
3)

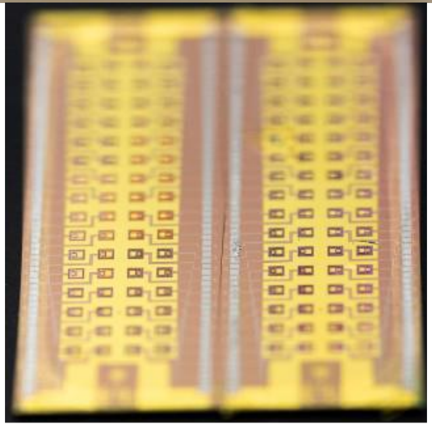
KOH…

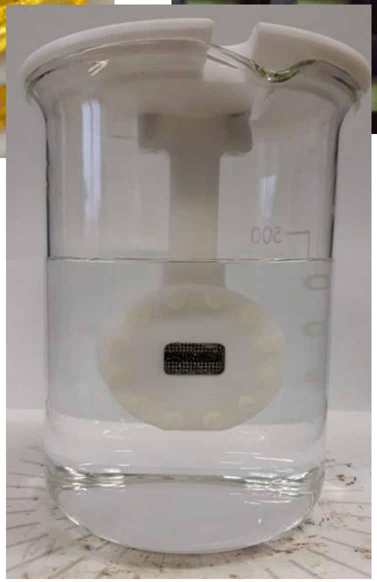












… vs DRIE

- ✓ gold thickness uniformity measured: $\sigma_t/_t \sim 4\,\%$
- ✓ full fab tested on 2 arrays
- ✓ arrays characterized at low temp → ΔE_{FWHM} = (4.64±0.14) eV @ 6 keV

Background

- environmental γ radiation
- γ, X and β from close surroundings
- **cosmic rays**
  - GEANT4 simulation for cosmic rays (muons) at sea level
  - 200x200x2 μm^3 Au absorber produce **bkg ≈ 10^{-4} c/eV/day/det** (0 – 10 keV)

HOLMES baseline: ^{163}Ho pile-up rate
$<r_{pp}> = A \cdot f_{pp}/2Q = 300$ Bq x $3 \cdot 10^{-4}/2Q$ =
1.5 c/eV/day/det

Measured: 200x200x2 μm^3 Au absorber (HOLMES-like) → bkg (1 – 10 keV) ≈ 5×10^{-3} c/eV/day/det

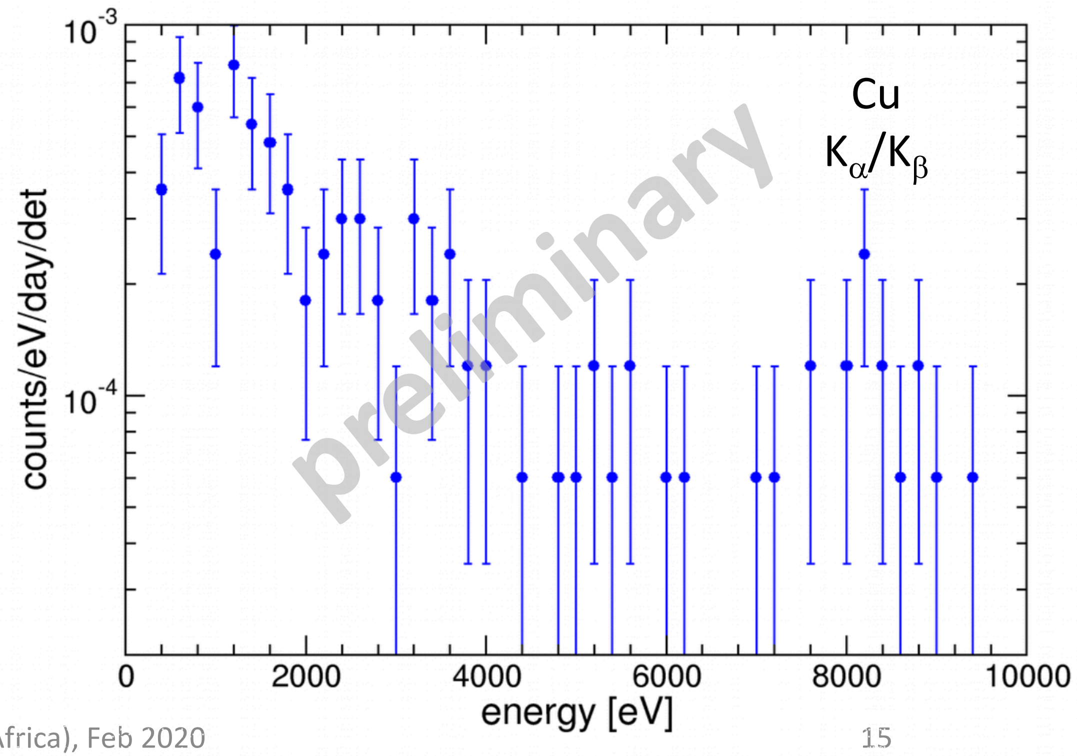
- **internal radionuclides (^{166m}Ho, byproduct of ^{163}Ho production)**
  - GEANT4 simulation for ^{166m}Ho (β^-, Q = 1856 keV, $\tau_{1/2}$ = 1200 y)
  - 200x200x2 μm^3 Au absorber produce

  bkg ≈ 10^{-11} c/eV/day/det/(^{166m}Ho nucleus)

if ***A*** **(^{163}Ho) = 300 Bq** and requiring ***bkg*****(^{166m}Ho) < 0.1 c/eV/day/det**

***N*(^{163}Ho)/*N*(^{166m}Ho) > 6000**

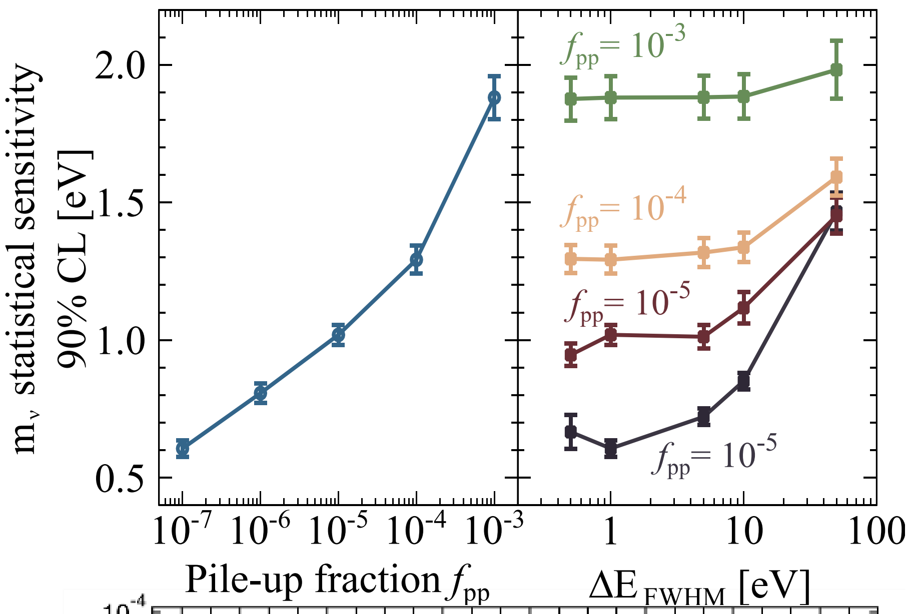
***A*(^{163}Ho)/*A*(^{166m}Ho) > 1500**

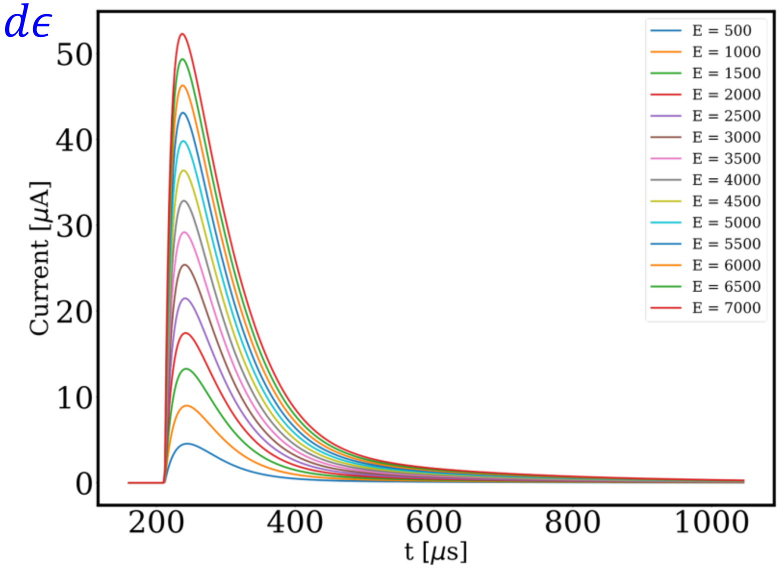


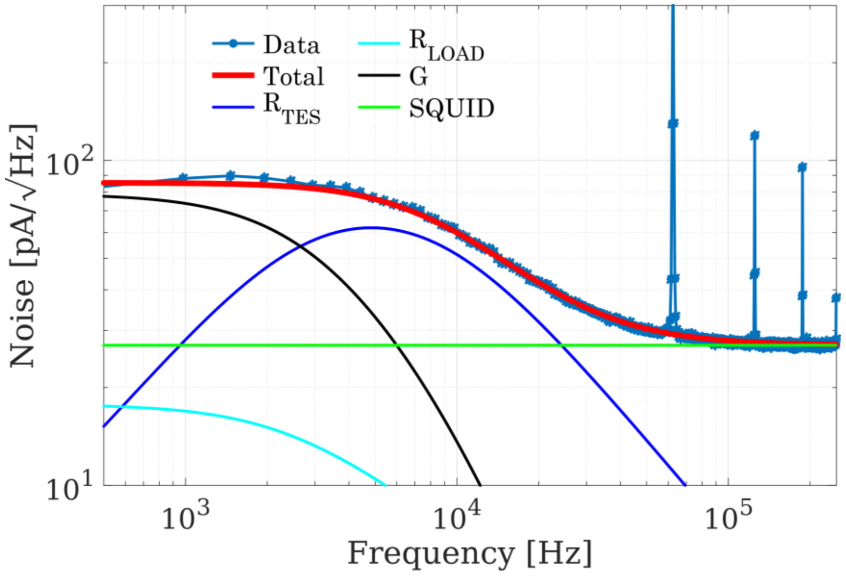
Detector time resolution (MC simulations)

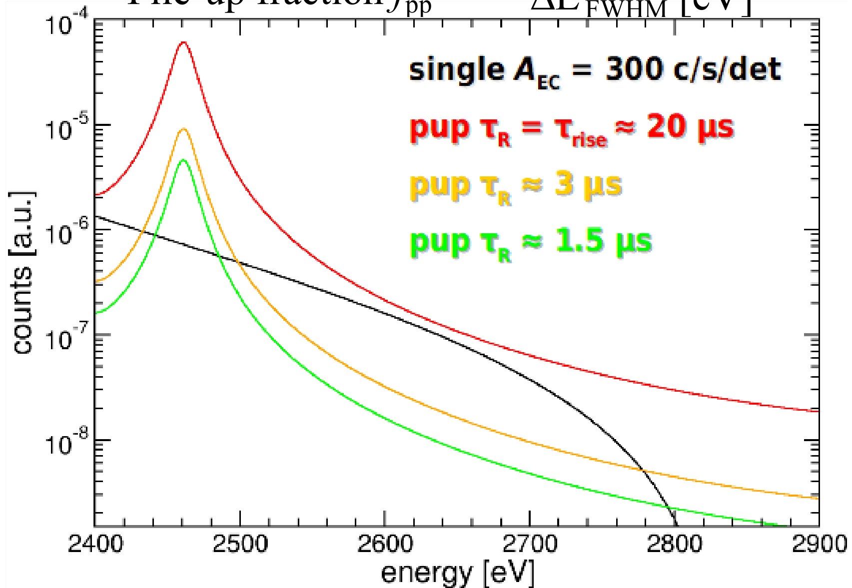
pile-up spectrum with a time resolution τ_R:

$$N_{pp}(E) = A_{EC}\int_0^{\infty}\tau_R(E,\epsilon)N_{EC}(\epsilon)N_{EC}(E-\epsilon)d\epsilon$$









E1 + E2 ∈ (2.7 ÷ 2.9) keV (from ^{163}Ho spectrum), $\Delta t \in [0 \div 10]$ μs

pile-up detection algorithms for f_{samp} = 0.5 MHz, $\tau_{rise} \approx$ 20 μs:

- Wiener Filter → **$\tau_R \approx$ 3 μs**
- Singular Value Decomposition → $\tau_R \approx$ **2.8 μs** (preliminary)

HOLMES short/long term program

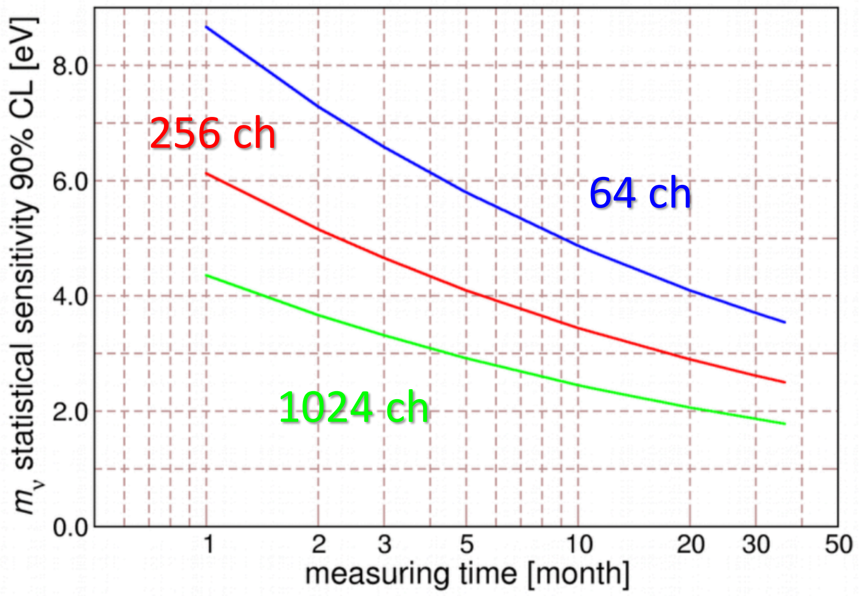
2020/2021

- optimize ion beam with ^{nat}Ho and ^{163}Ho
- implant of first TES array with low dose (≈ 1 Bq) without focusing
  - ➢ statistical sensitivity on $m_\nu \approx 10$ eV in one month of data taking
- focusing stage and target chamber integration
- optimize high dose (up to 300 Bq) ^{163}Ho implantation by the end of 2020
  - ➢ 64 high-activity channels will start data taking by beginning of 2021

long term

✓ large scale ^{163}Ho production
✓ TES performance
✓ large bandwidth μwave multiplexing

✓ embedding efficiency
✓ high dose implantation
✓ running of 1000 detectors and data analysis
✓ pile-up rejection algorithm



Summary

- available ^{163}Ho to implant 300 Bq in ≈ 300 detectors
- ion implanting system is being setup
- single detector performance demonstrated
- array fabrication ready with KOH (R&D on DRIE in progress)
- readout ready and available for 64 channels

the first ^{163}Ho measurement is scheduled to begin at the beginning of 2021