# Status of the HOLMES experiment

Marco Faverzani

Università & INFN Milano-Bicocca

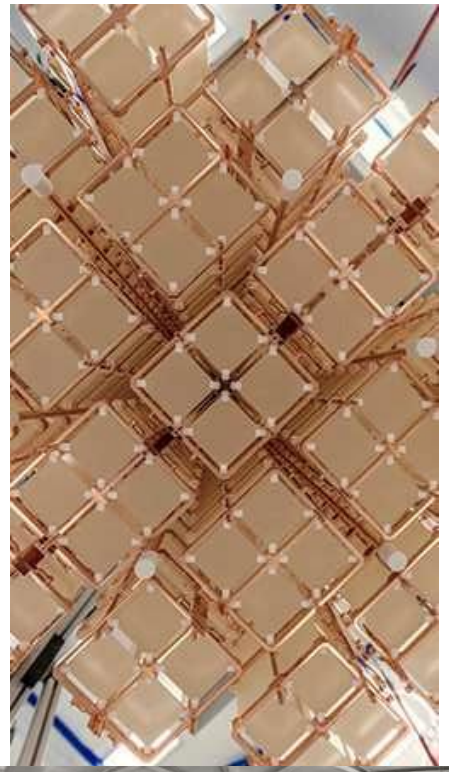
on behalf of the HOLMES collaboration

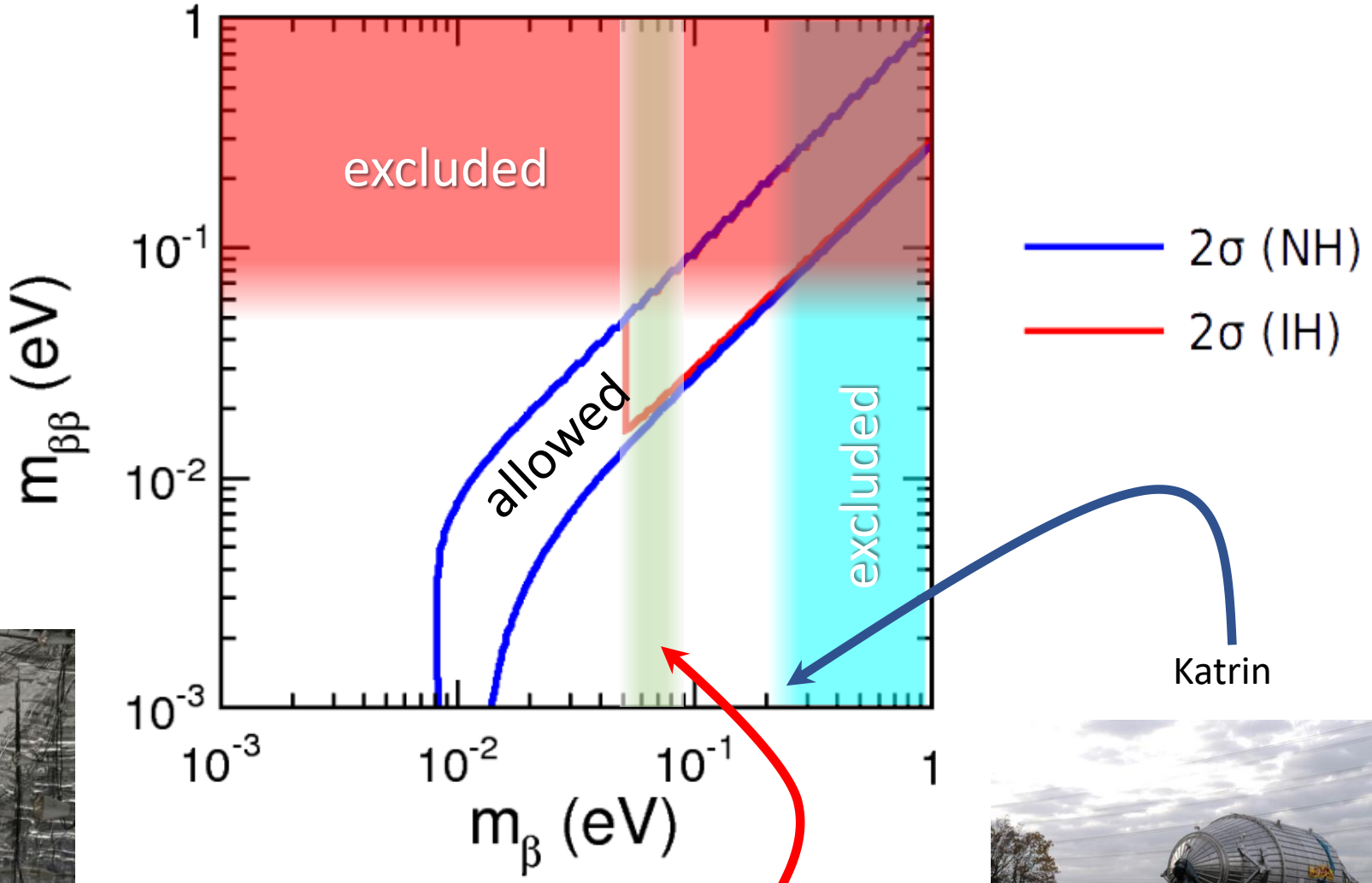






# *Absolute neutrino mass*






# $^{163}$Ho electron capture

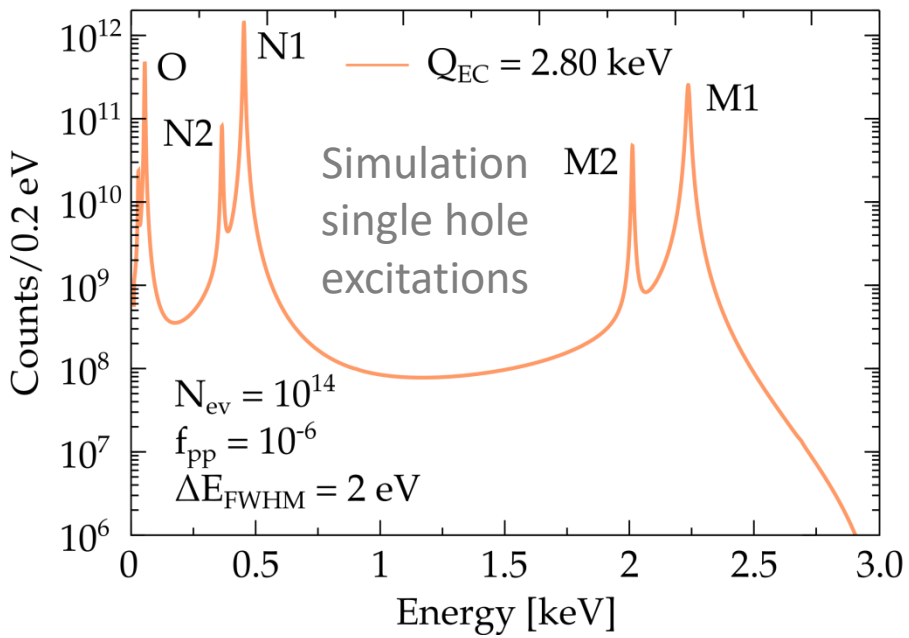
$^{163}Ho + e^- \longrightarrow {}^{163}Dy^* + \nu_e$

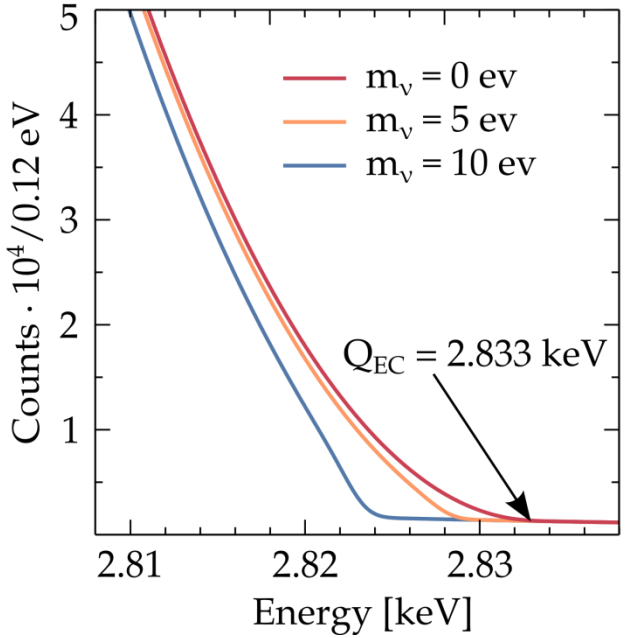
$^{163}$Ho decay via EC from shell ≥ M1, with $Q_{EC}$ ~ 2.8keV

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 $m_\nu$)
- $\tau_{1/2}$ ~ 4570 years: few nuclei are needed (2x10$^{11}$ $^{163}$Ho nuclei = 1 Bq)

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



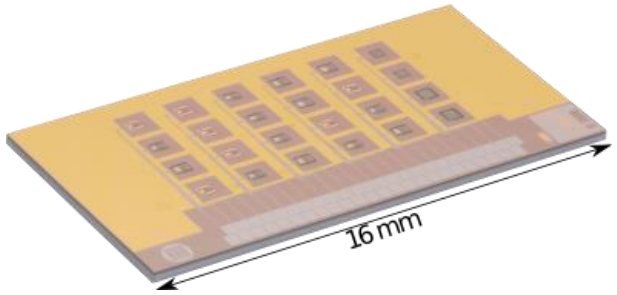




**HOLMES (ERC Grant 340321):**

- Transition Edge Sensors
  - $\Delta E$ ~ 1 eV, $\Delta t$ ~ 1 μs
- 300 Hz/det of $^{163}$Ho
- 6.5x10$^{16}$ nuclei of $^{163}$Ho
- $f_{pp} \approx A \cdot \Delta t$
- 3x10$^{13}$ in 3 years

- sensitivity on $m_\nu$ ~ eV

# Detectors testing



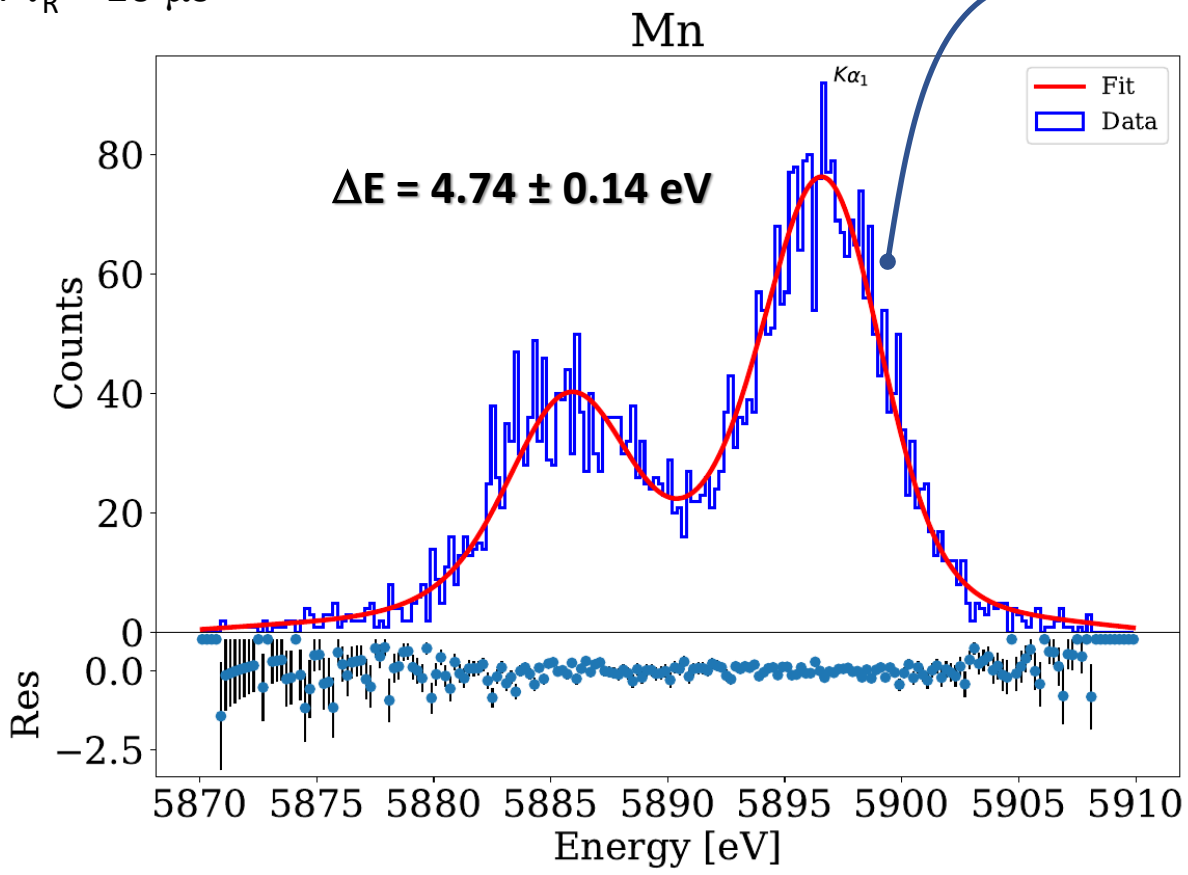

- tested several geometries
- **Not implanted with Holmium!**
- $^{55}$Fe (5.9 keV) + fluorescence source (Ca – 3.7 keV; **Cl – 2.6 keV**; Al – 1.5 keV)
- selected stray inductance to obtain $\tau_R \approx 10$ μs

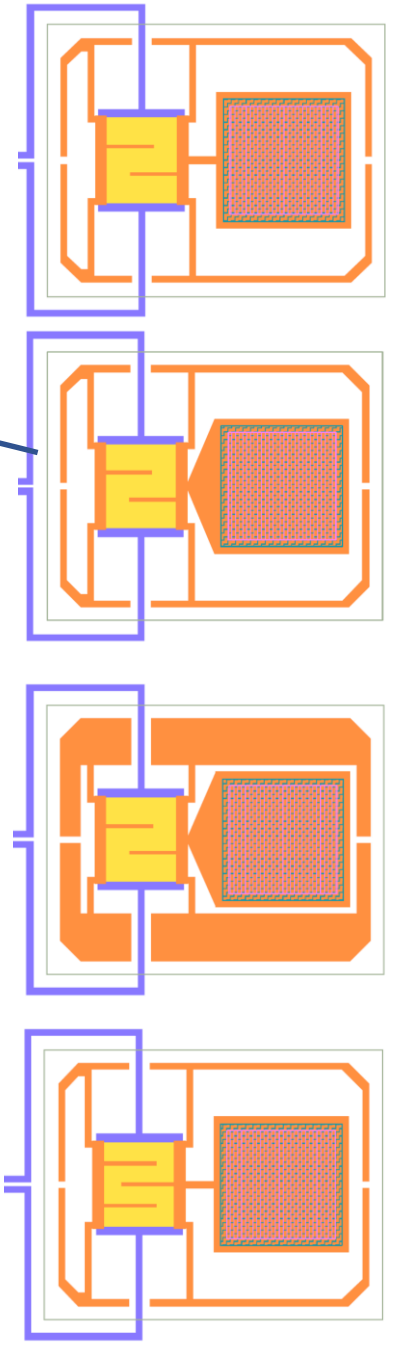
test @Milano **with μ–wave multiplexing**

$f_{samp}$ = 500 kHz

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

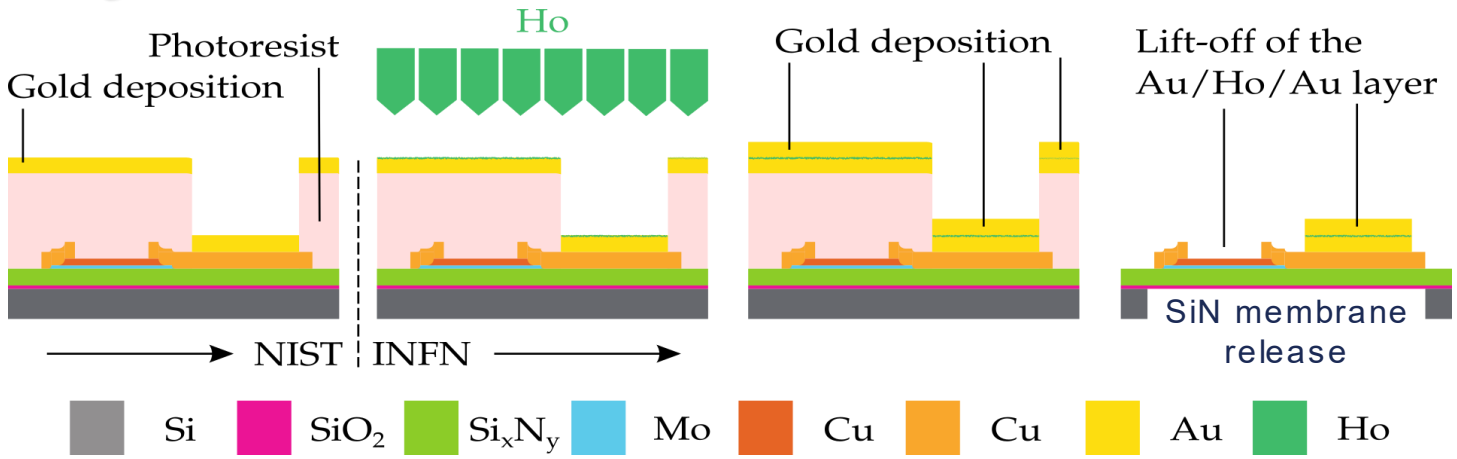
**See A. Puiu's talk (#393)**



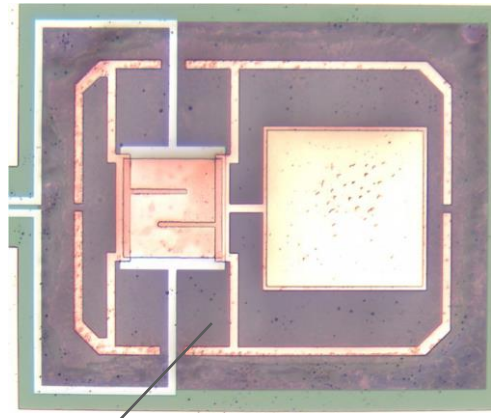



*Eur. Phys. J. C, 79:304 (2019)*

# Detectors fabrication

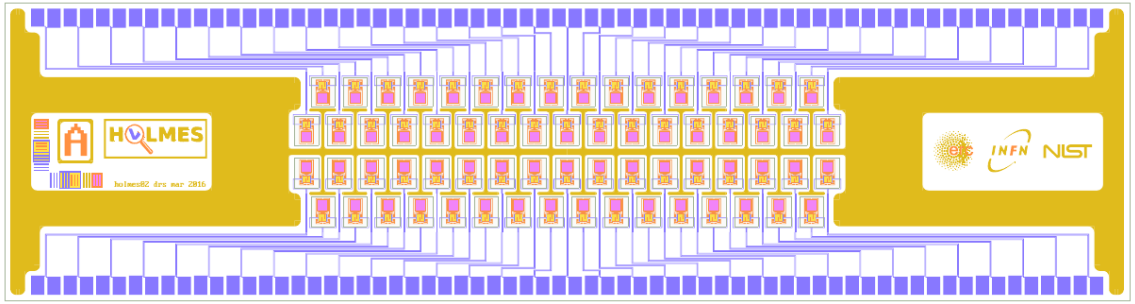



- TES originally fabricated at NIST, Boulder, CO, USA
- $^{163}$Ho implantation at INFN, Genova, Italy
- 1 μm Au final layer deposited at INFN, Genova, Italy
- final fabrication process: release of the membrane with KOH in Milano or DRIE

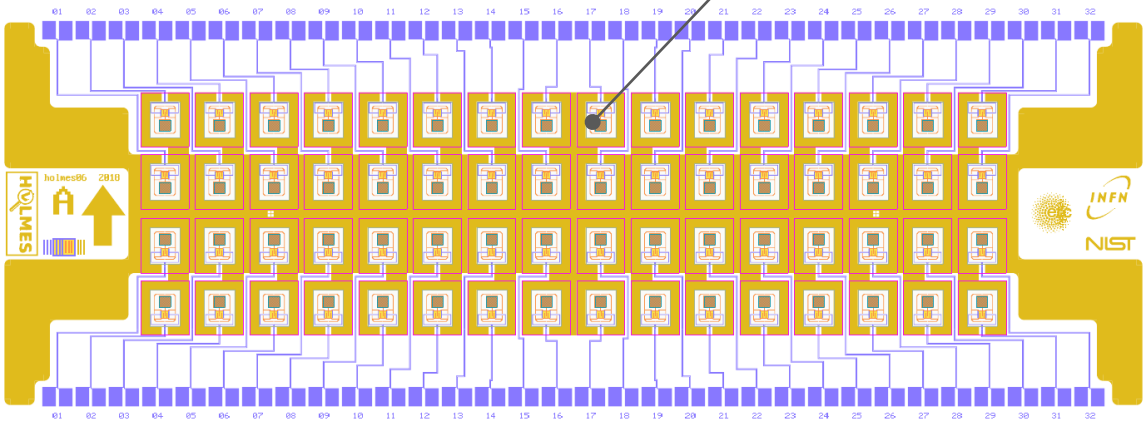


**KOH**

**DRIE**

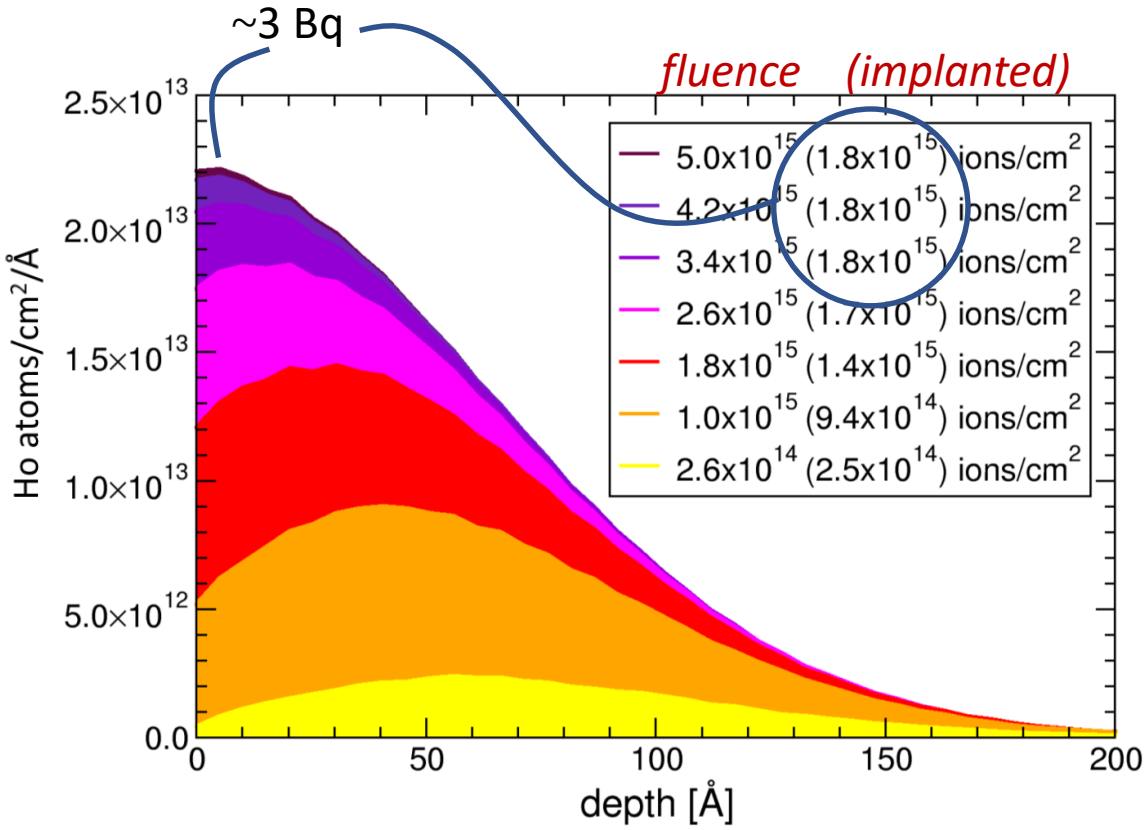



calculated $^{163}$Ho beam FWHM

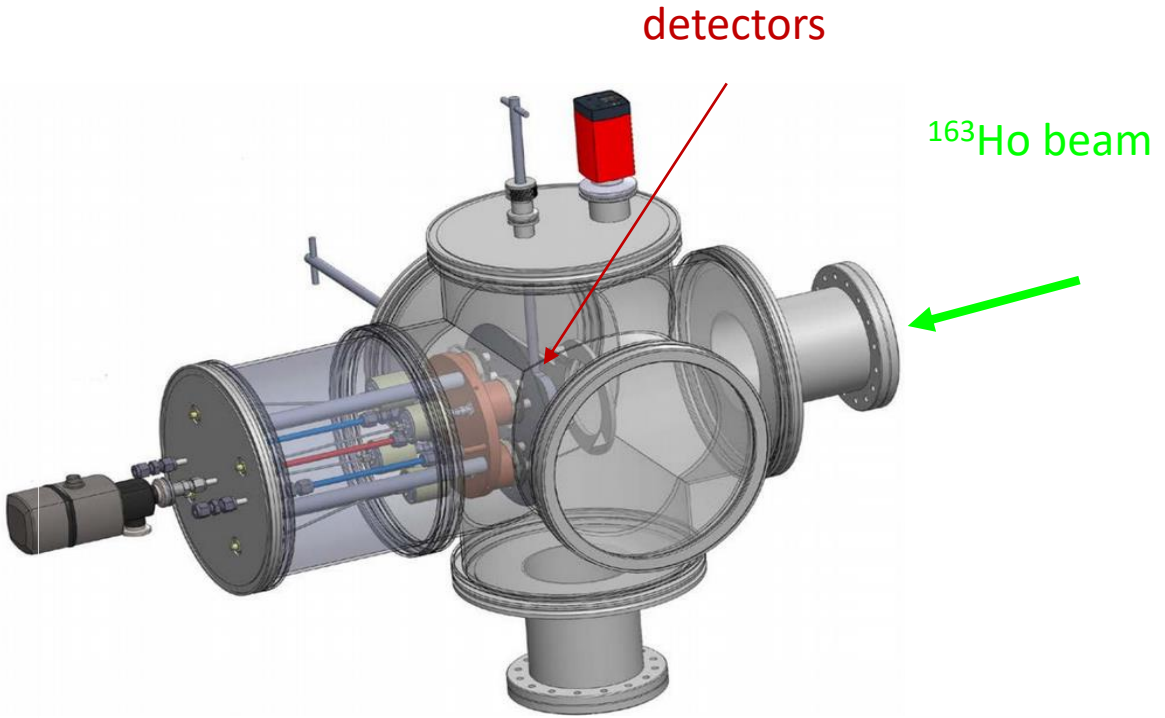


# Target chamber

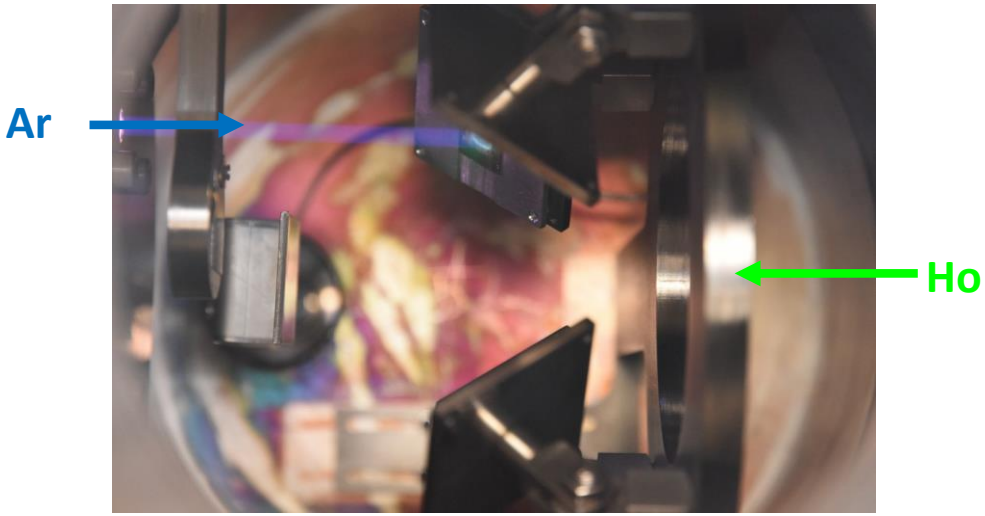
ion implantation (SRIM2013) – energy beam 50 keV




- $^{163}$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

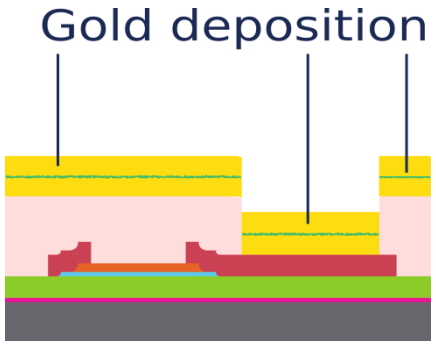



**deposition rate (with 4 sputter sources) ≈ 50 nm/h**
**~ 20 hours to deposit 1 μm**



# Detectors fabrication @ Milano-Bicocca

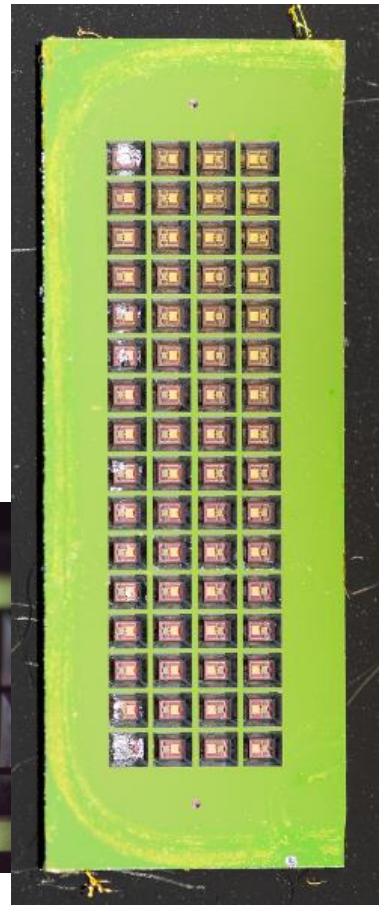
1)

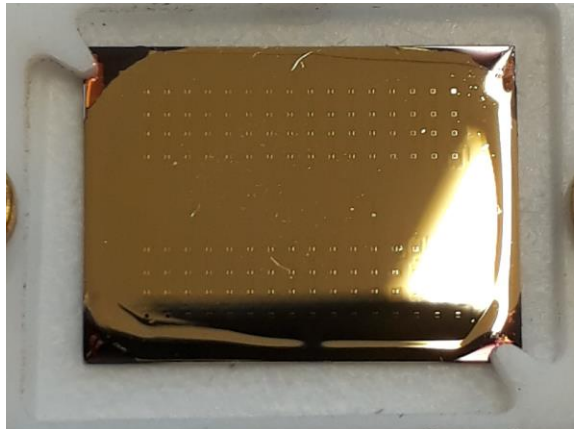


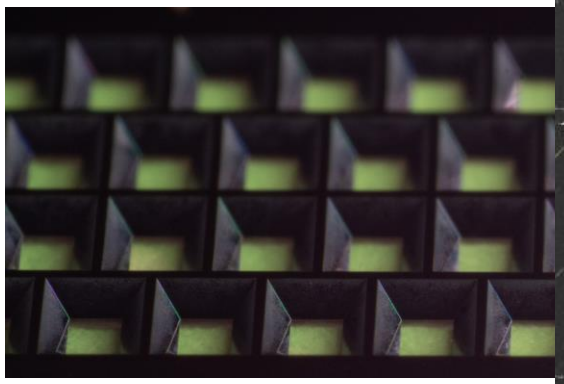

2)

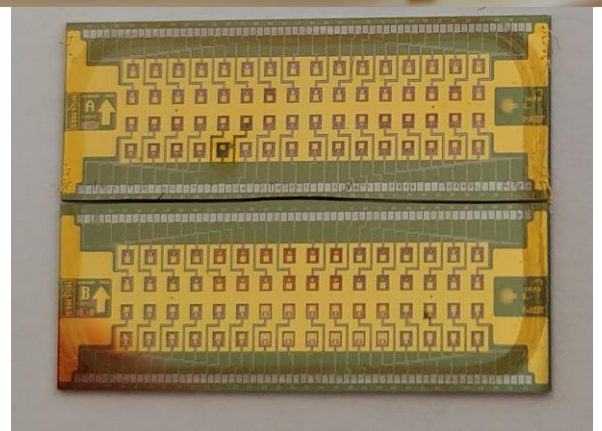

3)


**KOH…**



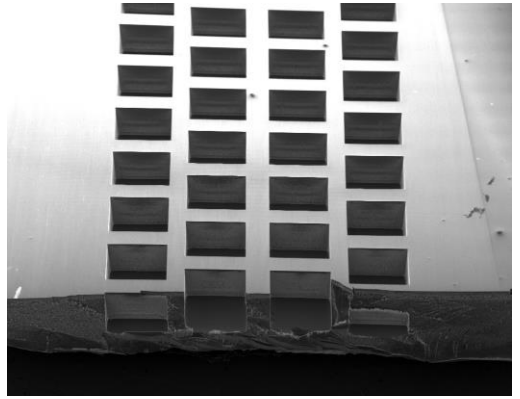






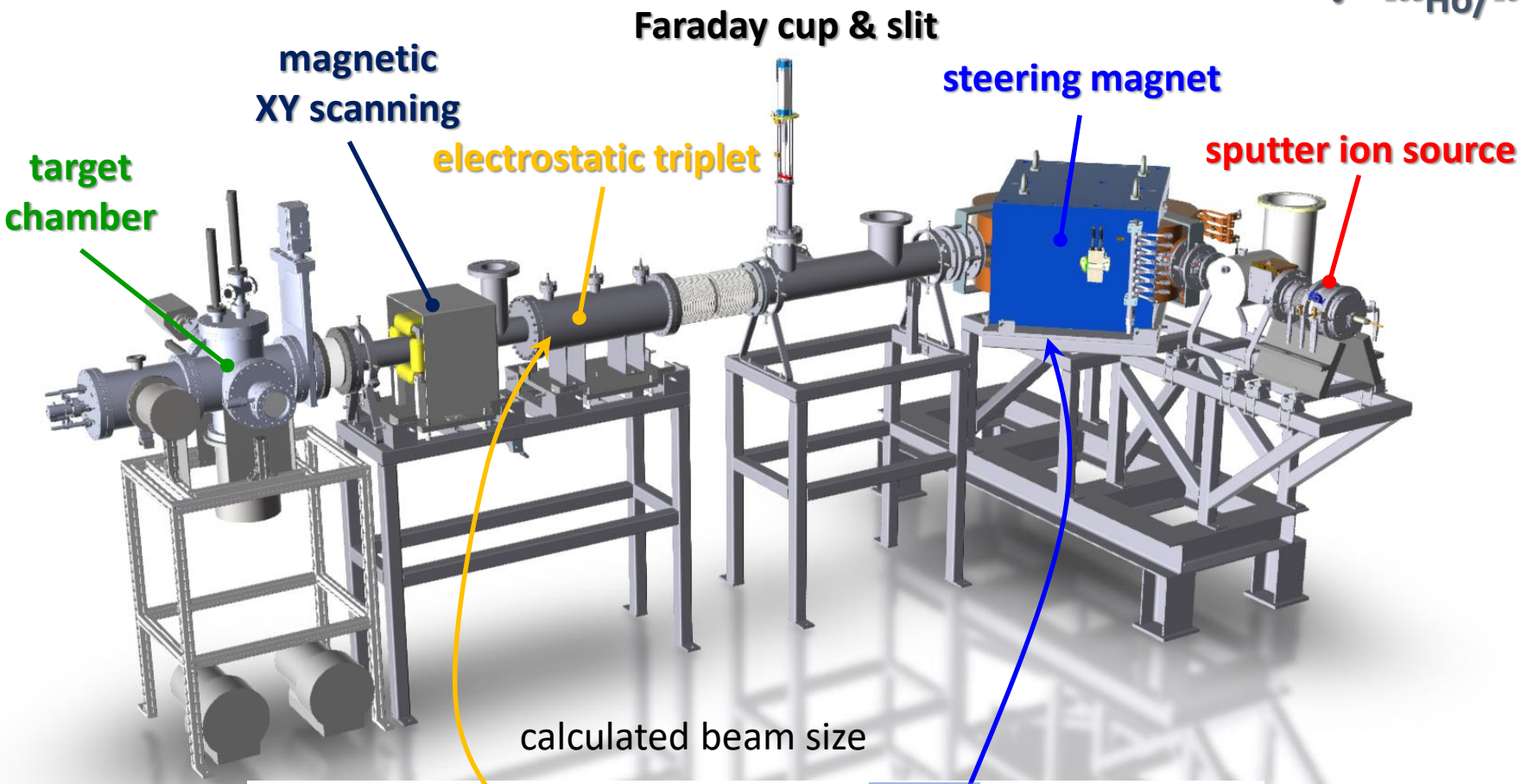
**See E. Ferri's poster**
**(Session A - ID 221-408)**

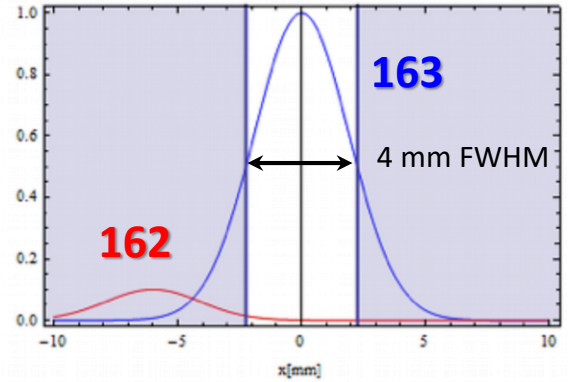
**… vs DRIE**

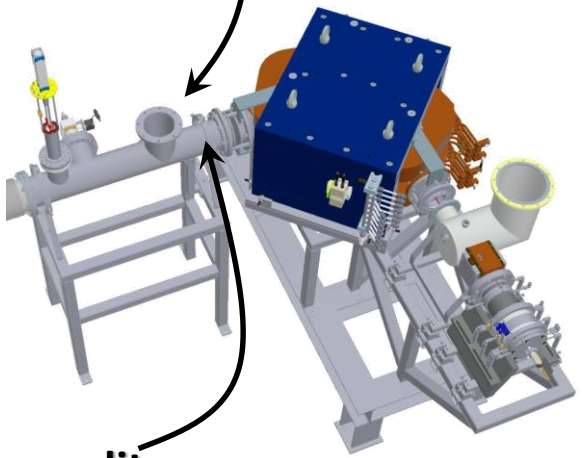


# *HOLMES ion implanter*

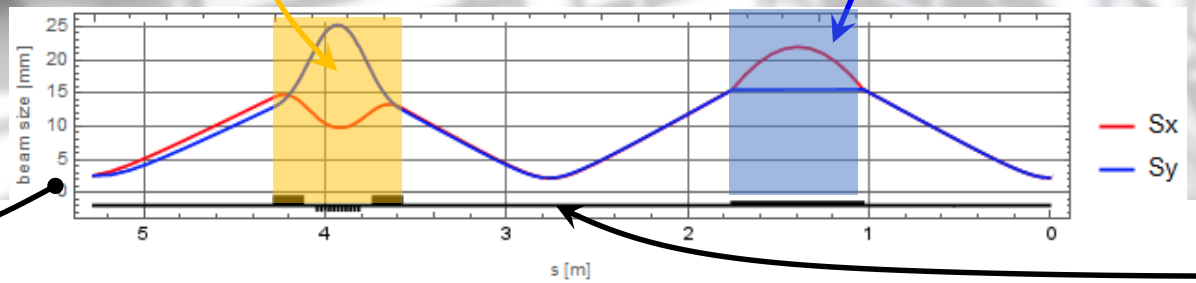
- extraction voltage 30-50 kV
- ~10 nm implanting depth
- **$^{163}$Ho/$^{166m}$Ho separation better than $10^5$**



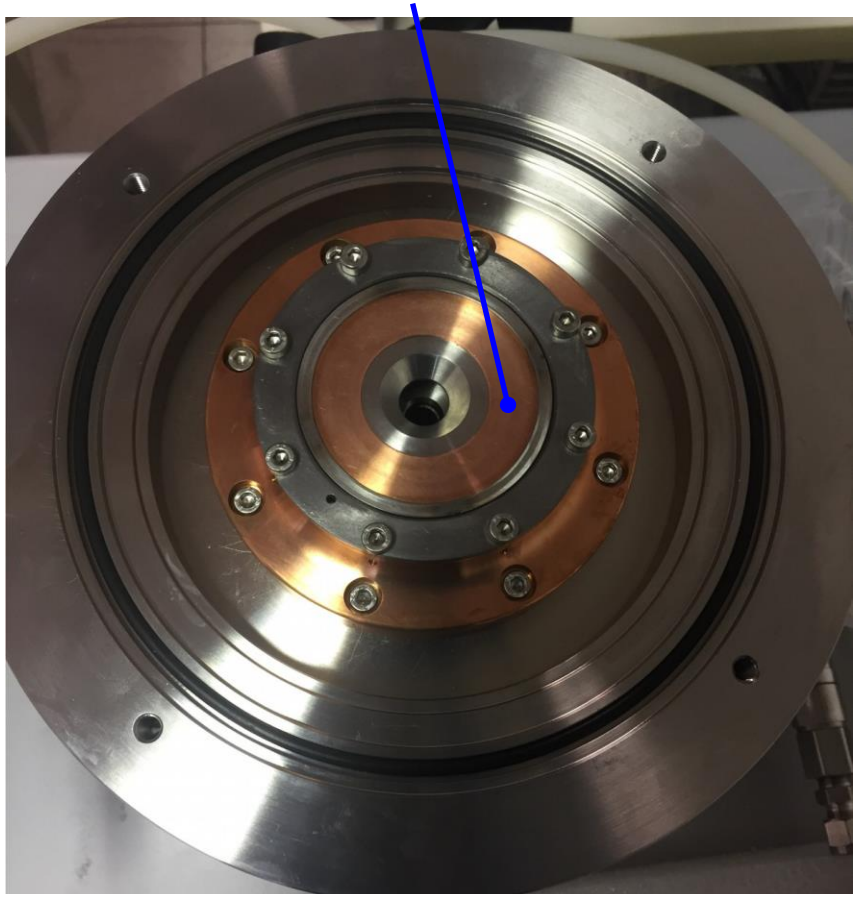




calculated beam size




**4 mm FWHM**

# HOLMES Ion implanter: testing




- test in progress at INFN Genova
  - no focusing
  - sputter target made in Cu
- **measured current of 100 μA (preliminary)**

next steps:

- tests with natural holmium
- tests with $^{163}$Ho

**See M. De Gerone's poster (session B - ID 192-389)**

# Background

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

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

**Measured**: 200x200x2 $\mu m^3$ Au absorber (HOLMES-like) → bkg (1 – 10 keV) ≈ $5 \times 10^{-3}$ c/eV/day/det

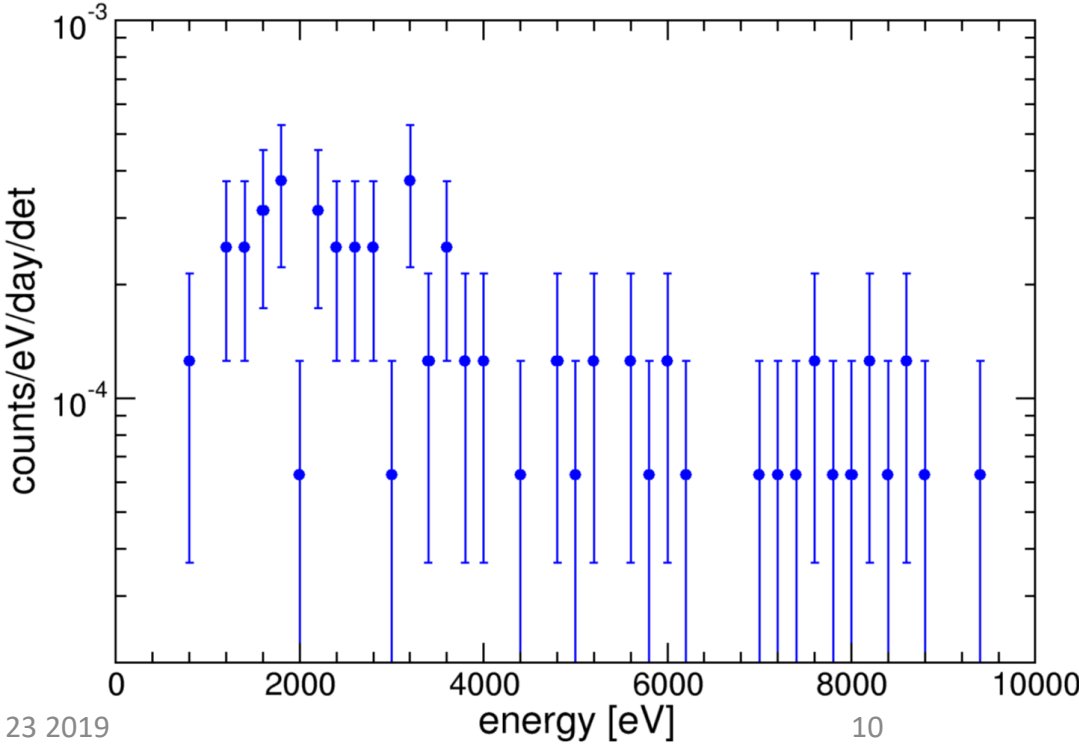
- **internal radionuclides ($^{166m}$Ho, byproduct of $^{163}$Ho production)**
  - GEANT4 simulation for $^{166m}$Ho ($\beta^-$, $Q$ = 1856 keV, $\tau_{1/2}$ = 1200 y)
  - 200x200x2 $\mu m^3$ Au absorber produce

  **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



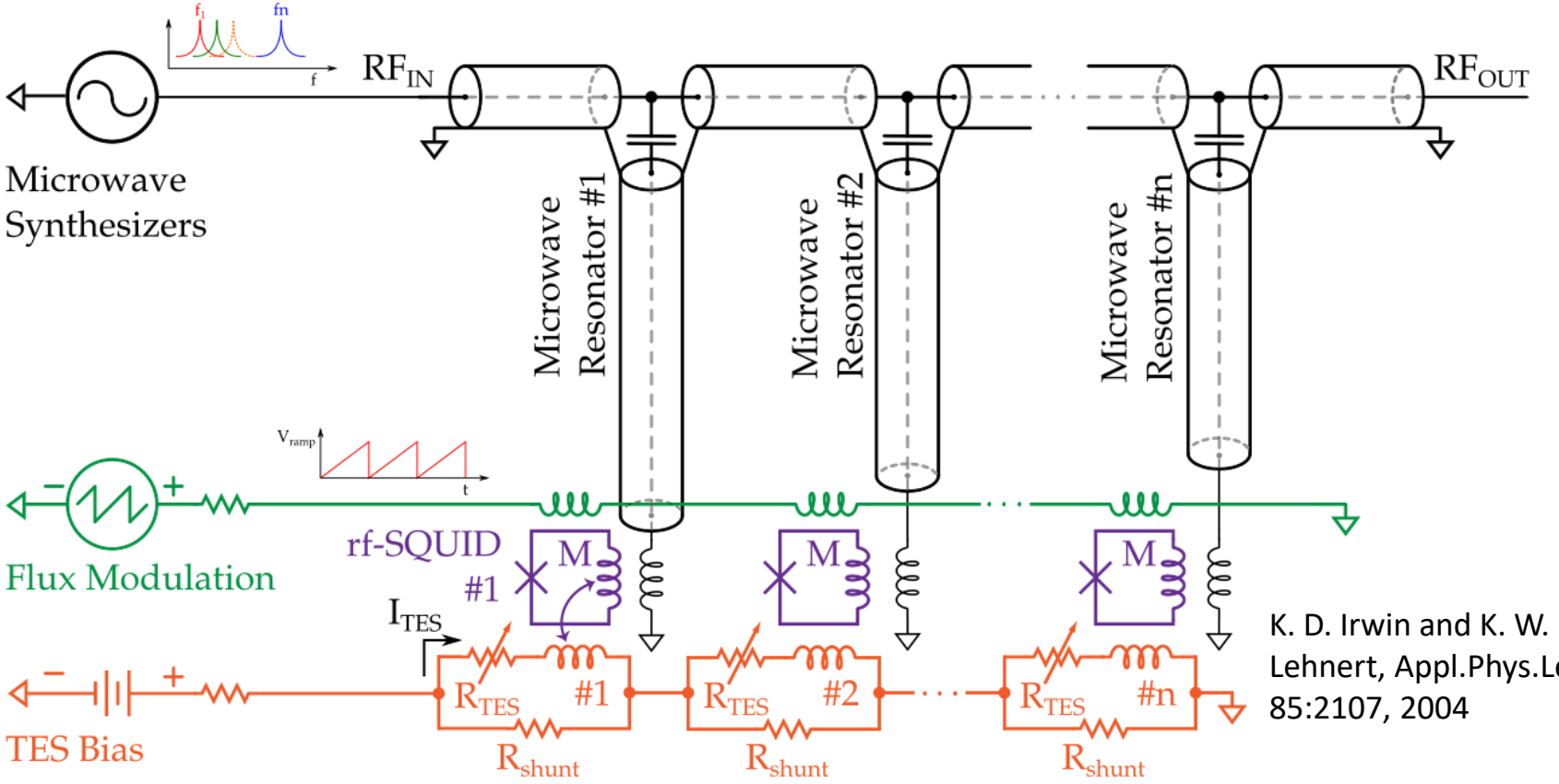
# Microwave multiplexing readout

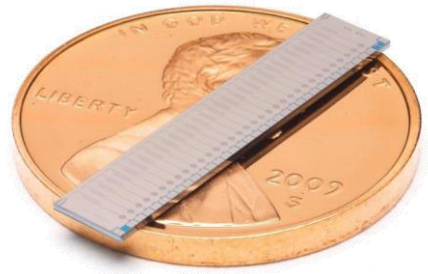
## TESs readout with microwave multiplexing (produced by NIST)

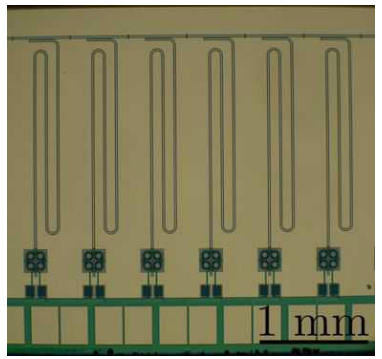
- each sensor inductively coupled to a RF-squid part of a λ/4 resonator
- a comb of signals probe the resonators at their characteristic resonant frequency

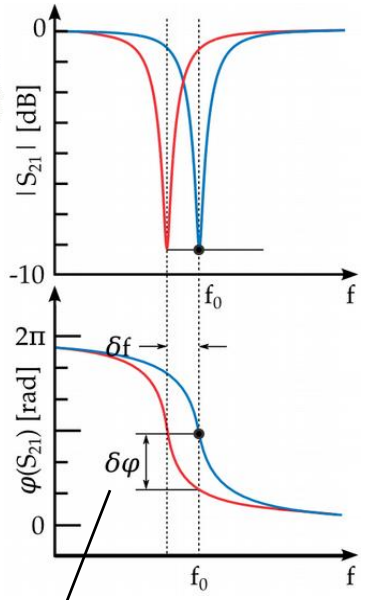
$$E \longrightarrow \delta T_{TES} \longrightarrow \delta I_{TES} \longrightarrow \delta \phi_{squid} \longrightarrow \delta f_{resonator}$$

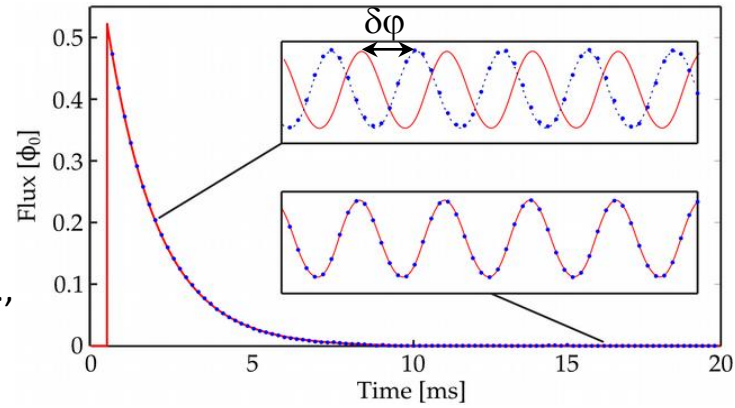
- a ramp signal added to the squids in order to linearize the response



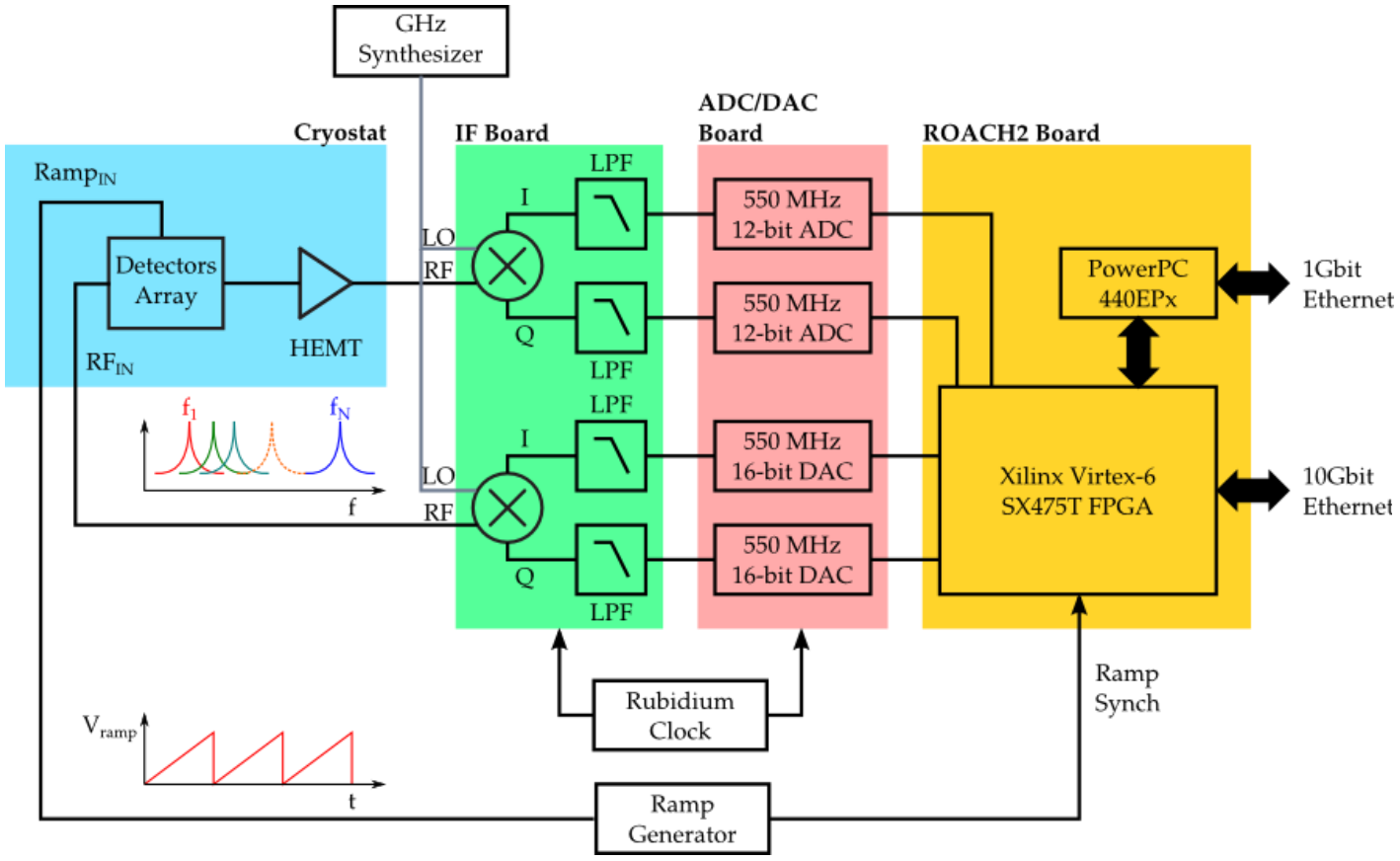



K. D. Irwin and K. W. Lehnert, Appl.Phys.Lett., 85:2107, 2004

# DAQ with the ROACH2



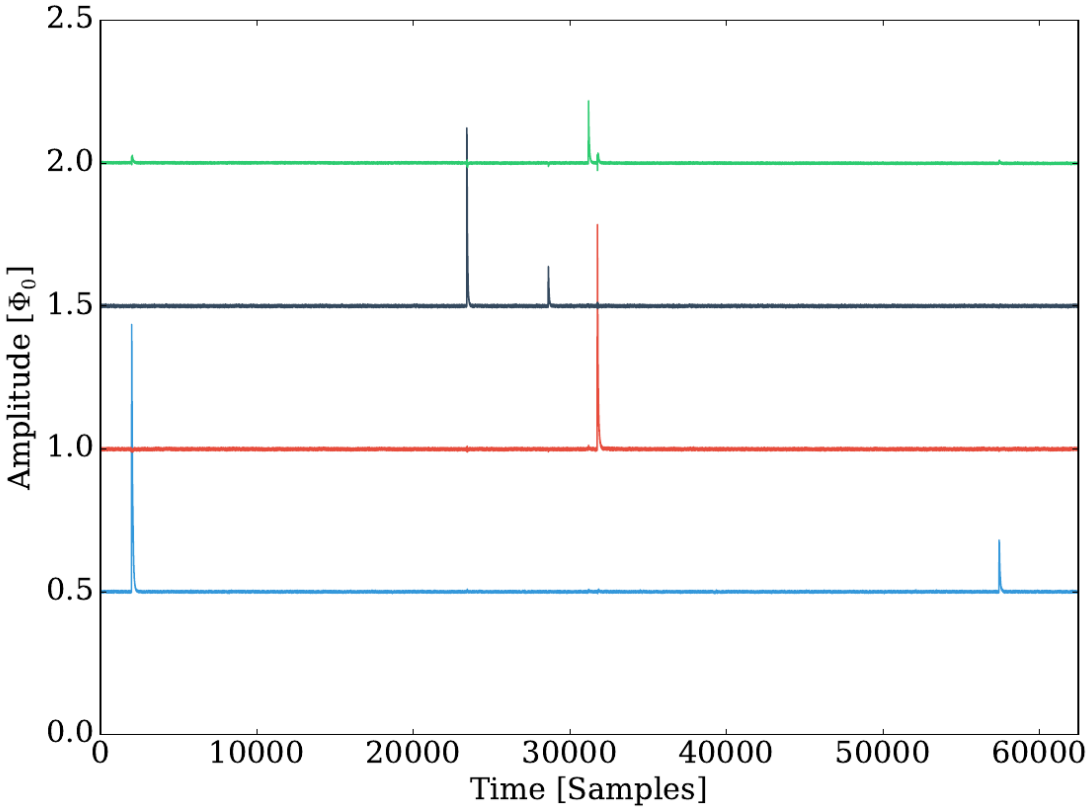

- Software Defined Radio with the open system ROACH2 (Casper collaboration)
- ADC BW 550 MHz
- real time pulse reconstruction

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

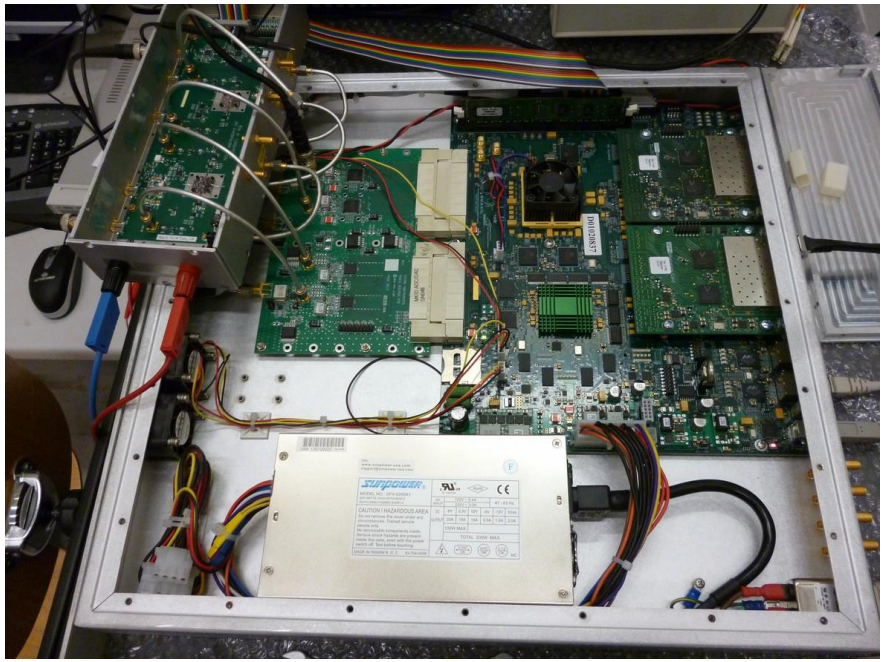
requiring $\tau_R = 10\ \mu s$

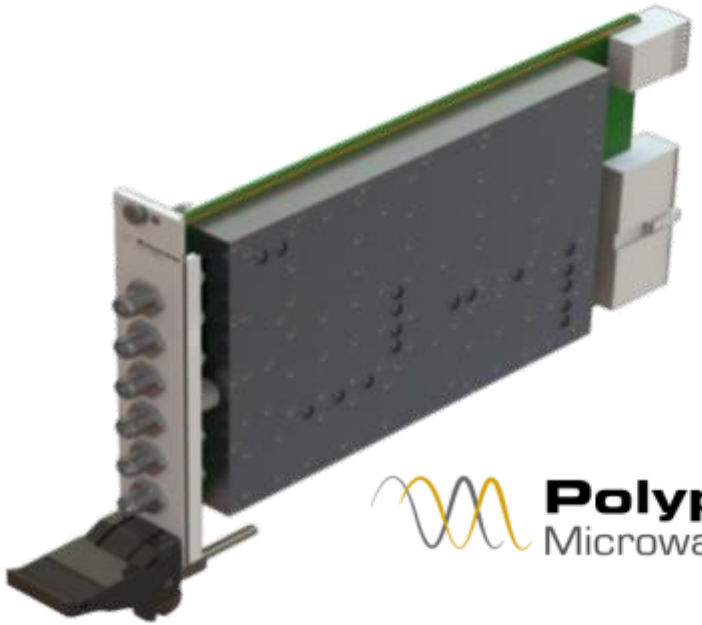
$n_{TES} \approx 34$

At the moment $n_{TES}$ is limited by the readout power of the RF probe signals



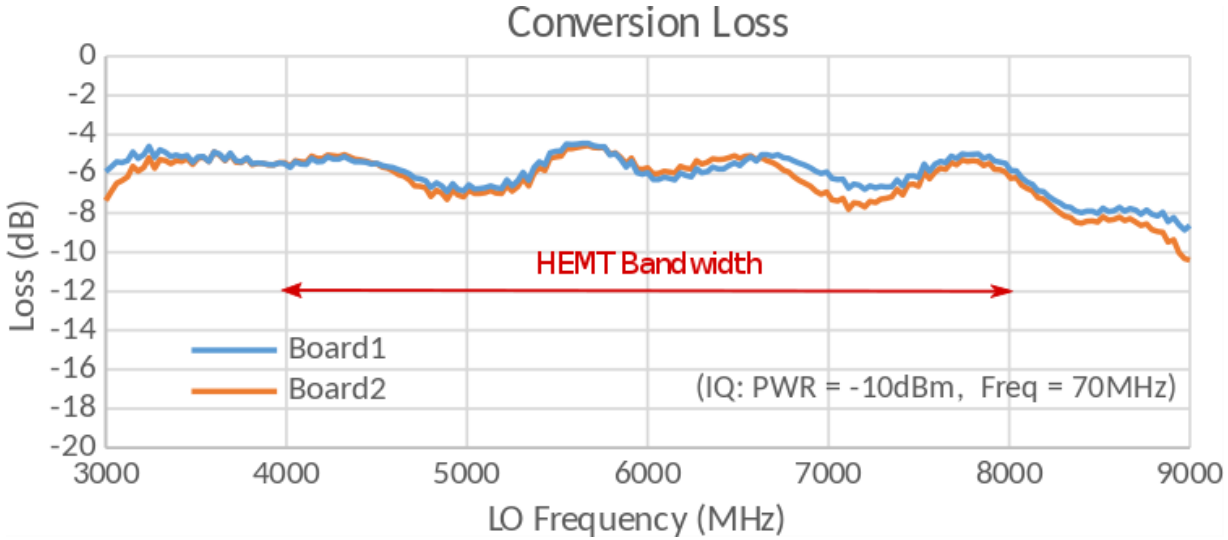
# DAQ with the ROACH2 (cont'd)






New semi-commercial up/down conversion board

- Commercial design but customized to match the HOLMES requirements
- 16 channels measured at the same time (firmware limited)
- white noise level ≈ **2-3 $\phi_0$/Hz$^{0.5}$ = 23-35 pA /Hz$^{0.5}$** (preliminary)
- total readout power -7 dBm, compatible for reading out 32 resonators
- two boards delivered and currently being characterized

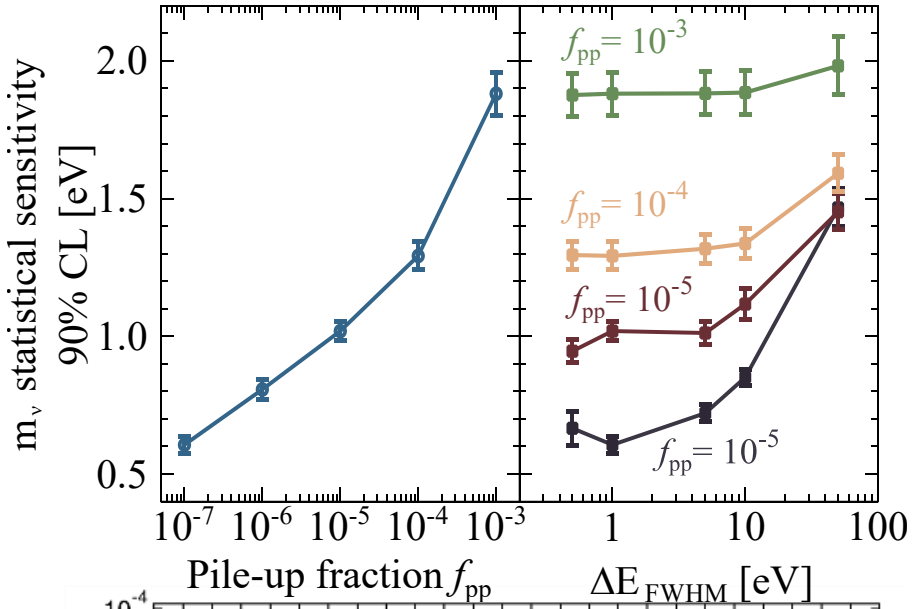


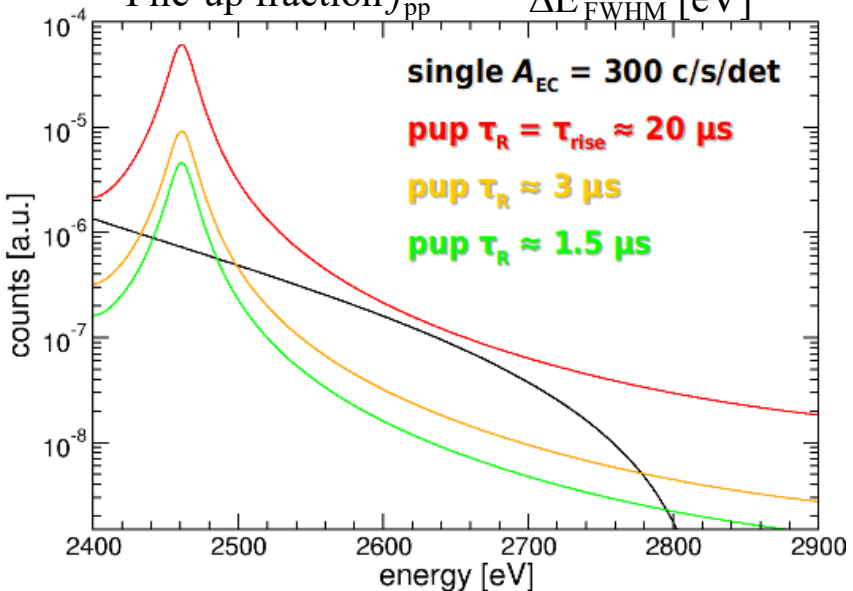

**See A. Giachero's poster (session B - ID 150-397)**

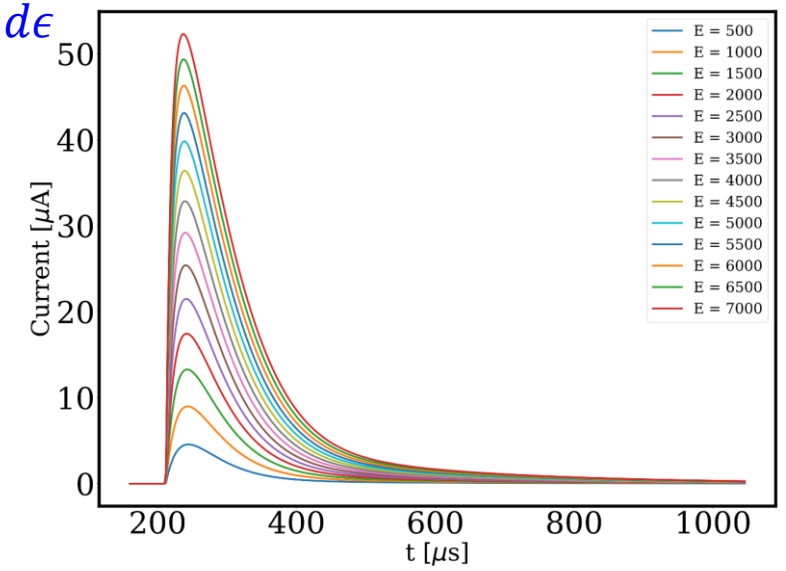
# Detector time resolution (MC simulations)

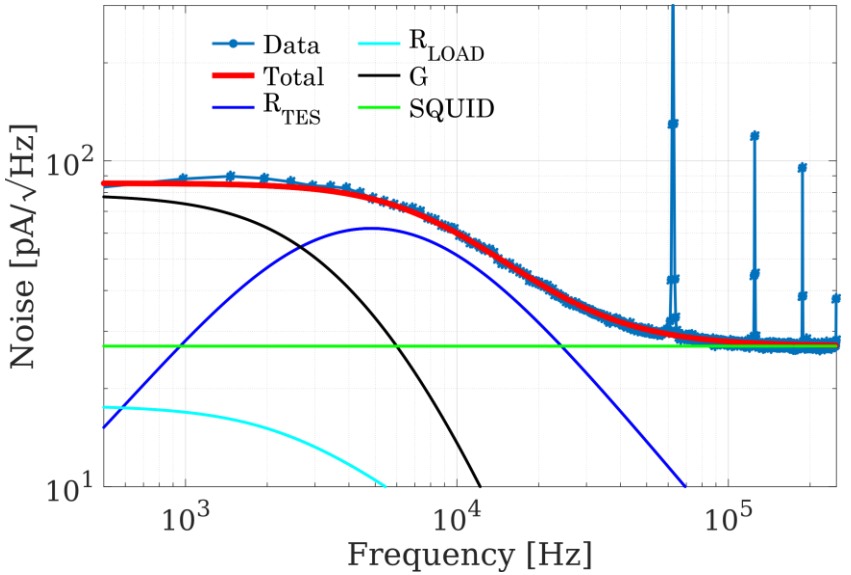
pile-up spectrum with a time resolution $\tau_R$:

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




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)

**See M. Borghesi's poster (session B - ID 120-398)**

# *Summary*

- The detector design has been chosen
- HOLMES detector production procedure defined
  - Firsts detectors are being characterized
- Ion implanter
  - Observed a current of 100 μA with Cu target
- Readout for 16 channels, ready to be scaled up with the new firmware
- Pile-up simulations show time resolution of ~ 2.8 μs