Multiplexed superconducting detectors for neutrino mass measurement

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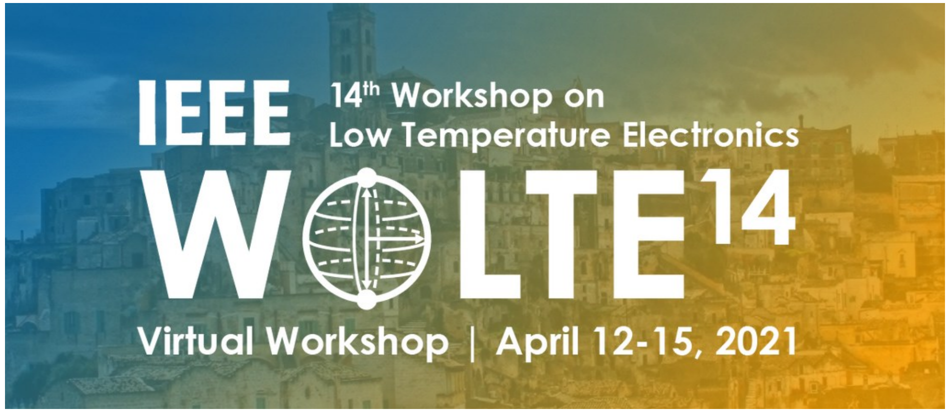
on behalf of the HOLMES collaboration



^{163}Ho electron capture

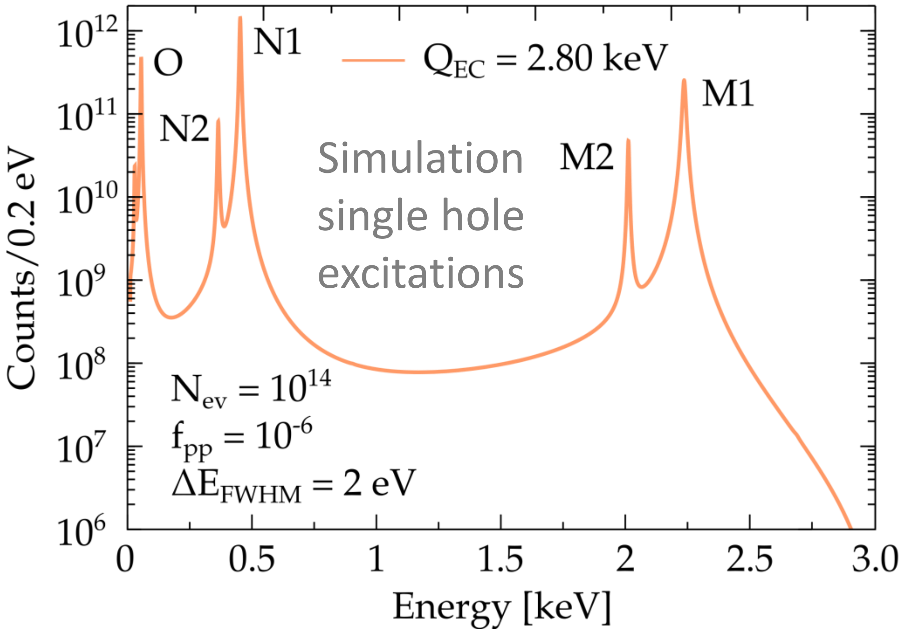
$^{163}Ho + e^- \rightarrow {}^{163}Dy^* + \nu_e$

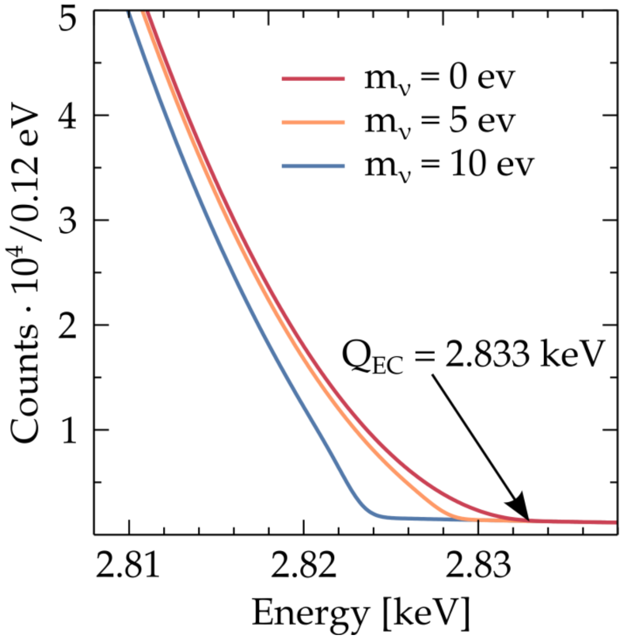
^{163}Ho decay via EC from shell ≥ M1, with $Q_{EC} \sim 2.8$keV

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 (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
  - $\Delta E \sim 1$ eV, $\tau_R \sim 1$ µs
- 300 Hz/det of ^{163}Ho
- 6.5x10^{16} nuclei of ^{163}Ho
- $f_{pp} \approx A_{EC} \cdot \tau_R$
- 3x10^{13} in 3 years

- sensitivity on $m_\nu \sim$ eV

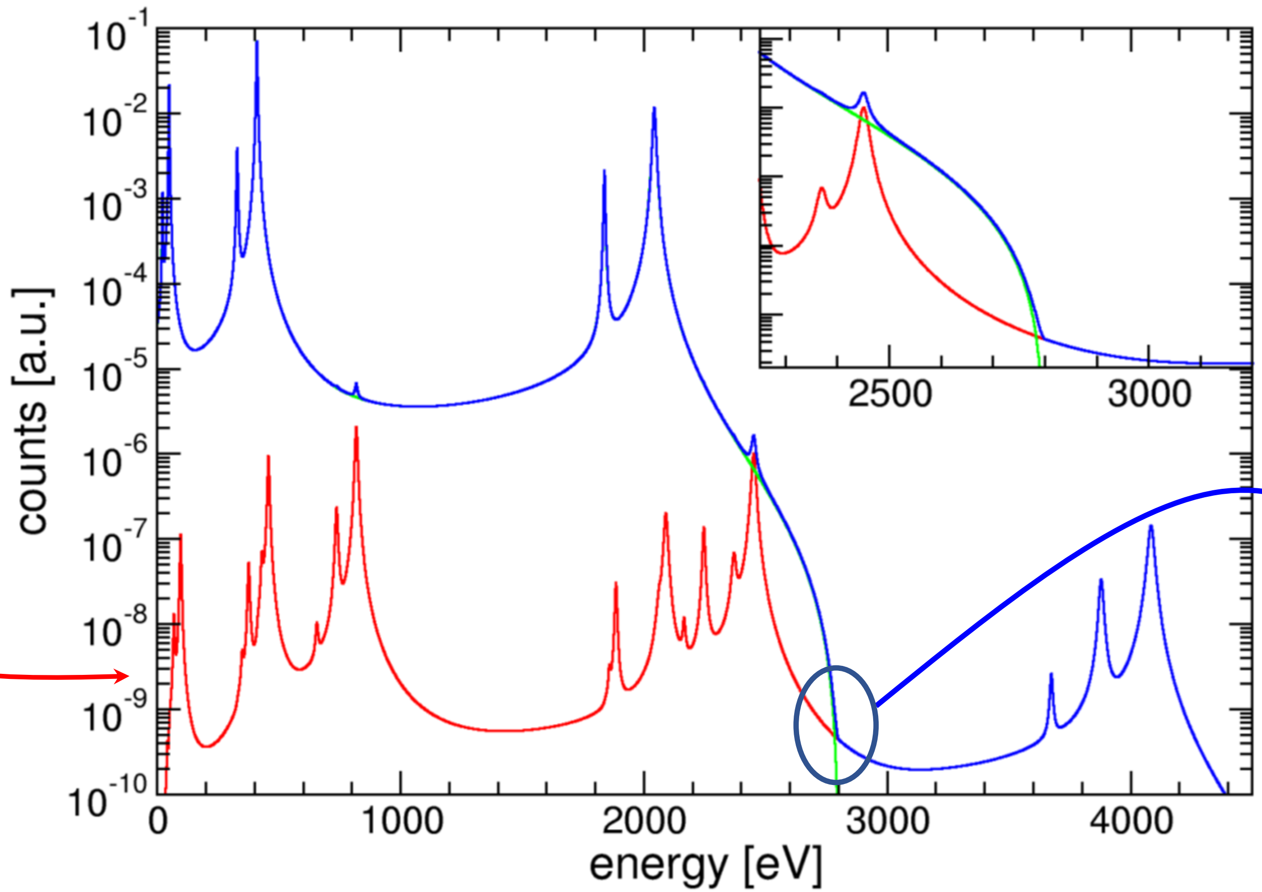
Pile-up

- 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

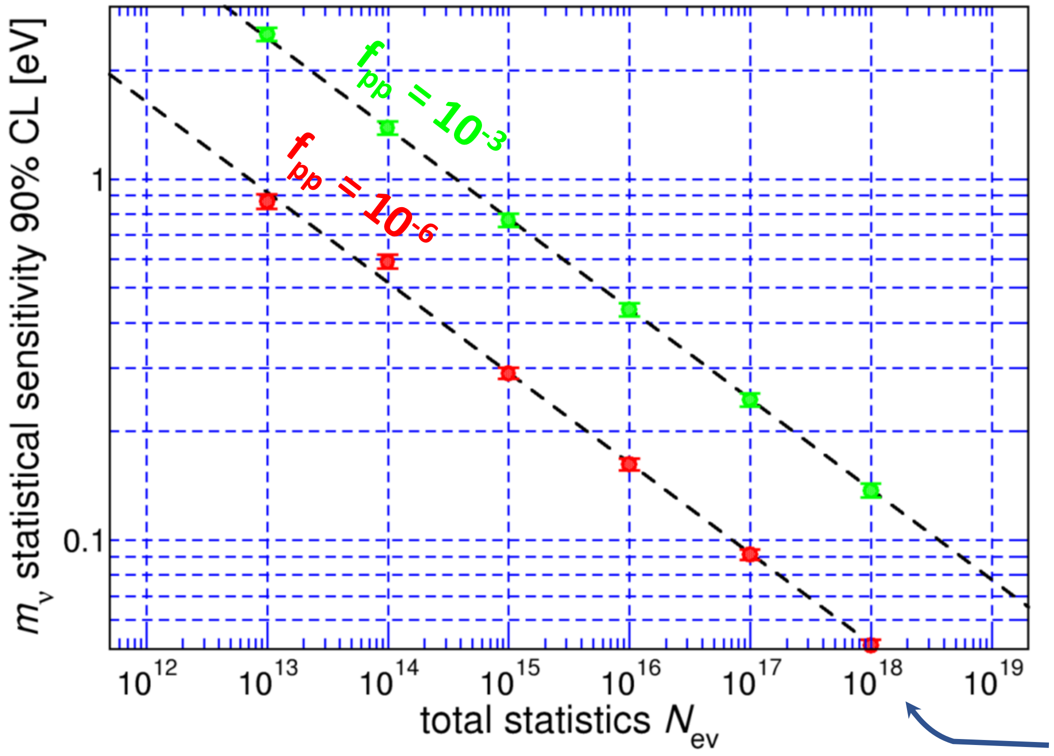
parallelization over large number of detectors



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

Impairing effect on the end-point measurement

Statistical sensitivity



$\propto \sqrt[4]{1/N_{ev}}$

MC simulation

- Q = 2.8 keV
- ΔE = 1 eV
- τ_R = 1 μs

to obtain $\Sigma(m_\nu) \leq 0.1$ eV

- A = 1 Bq, $f_{pp} = 10^{-6}$
- $N_{det} t_M \approx 2\text{x}10^9$ det · y

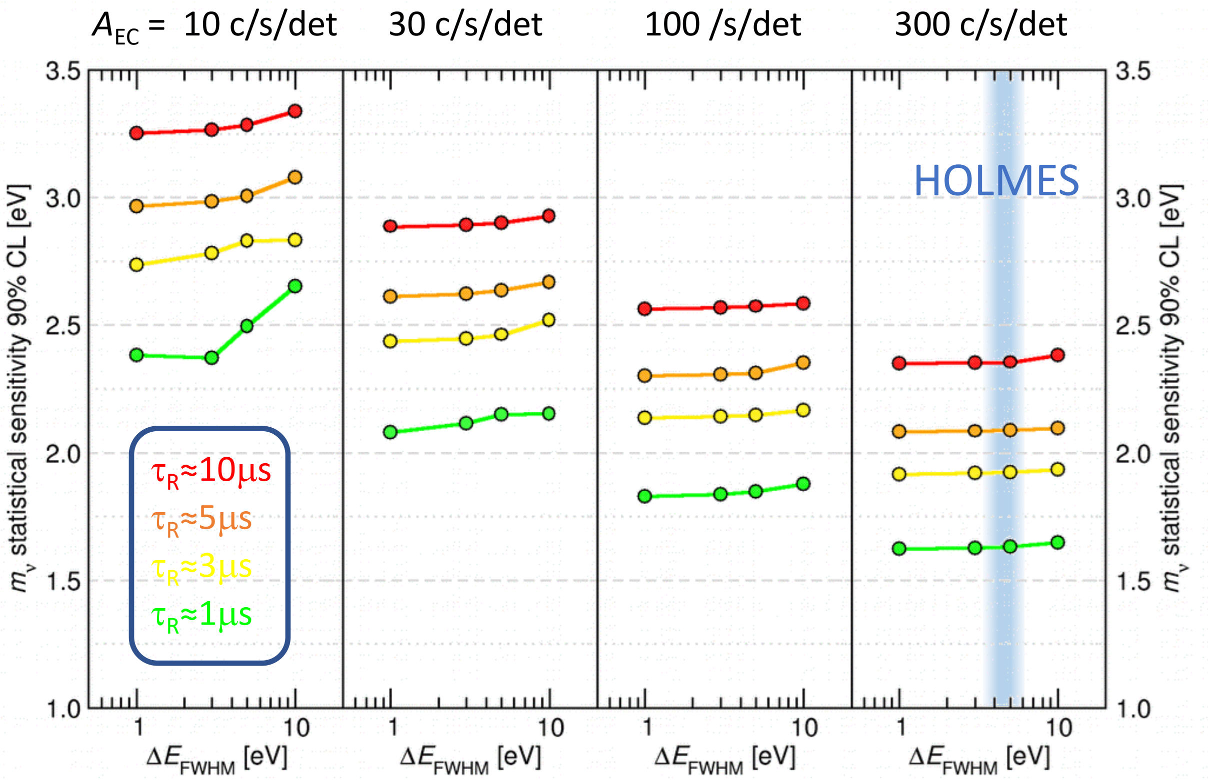
- A = 1000 Bq, $f_{pp} = 10^{-3}$
- $N_{det} t_M \approx 10^8$ det · y

Detectors:
- **time resolution τ_R = 1μs**
- **ΔE = 1eV @ 2.8 keV**
- **Extremely large detector array!!**

M. Galeazzi et al., arXiv:1202.4763v2
A. Nucciotti, Eur. Phys. J. C (2014) 74:3161

HOLMES (ERC-Adv. Grant) 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:

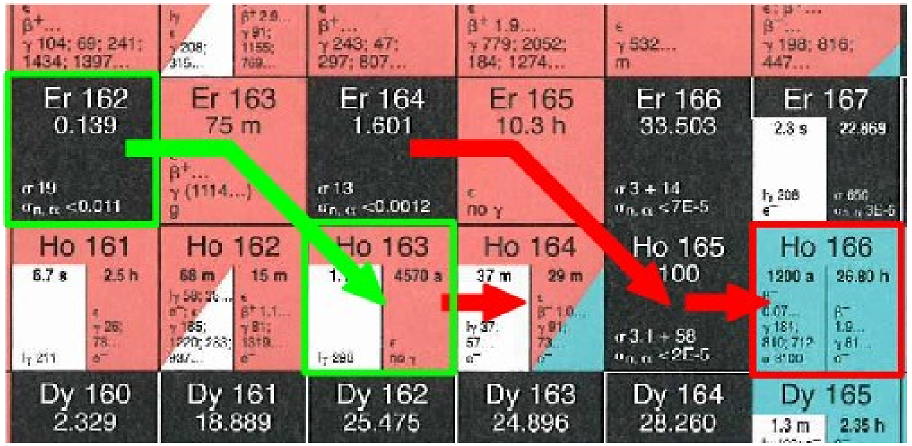
- Neutrino mass determination with a sensitivity as low as ~ 1 eV
- proof potential and scalability of the approach
- precise calorimetric determination of *Q*
- systematic errors assessment

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 1.3×10^{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**

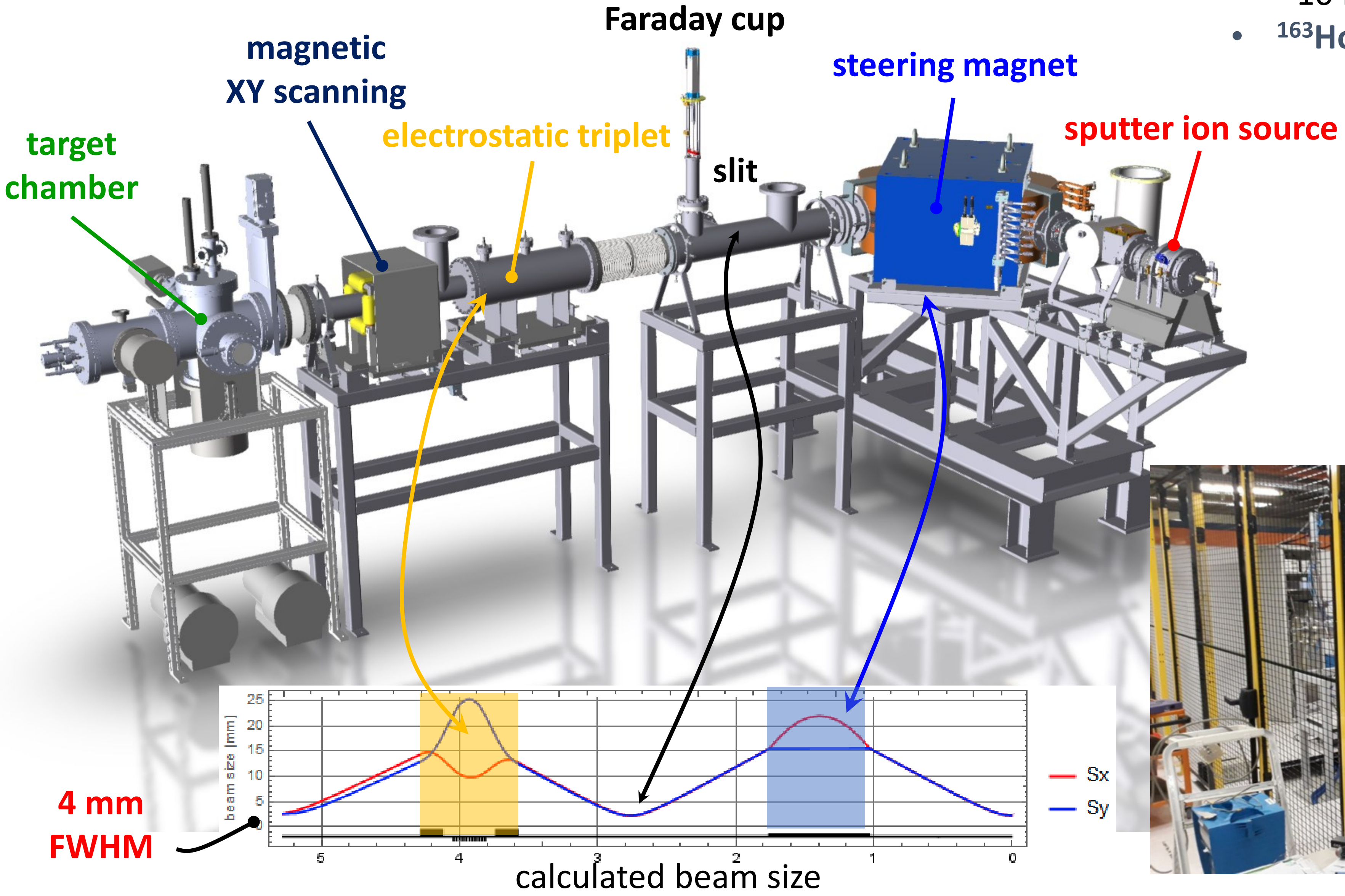
HOLMES ^{163}Ho inventory:

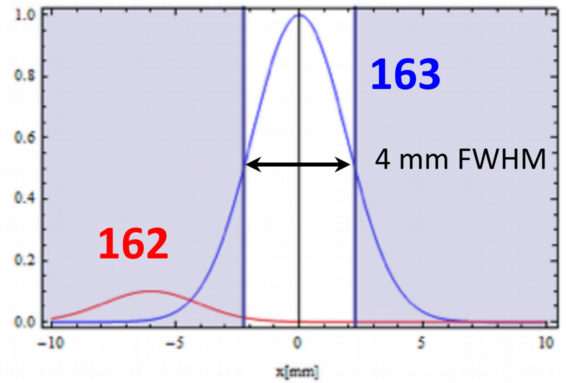
- ❑ ≈ 110 MBq of purified ^{163}Ho available at INFN in Genova
- ❑ ≈ 250 kBq of ^{166m}Ho
- ❑ more ^{162}Er available to produce 80 MBq of ^{163}Ho

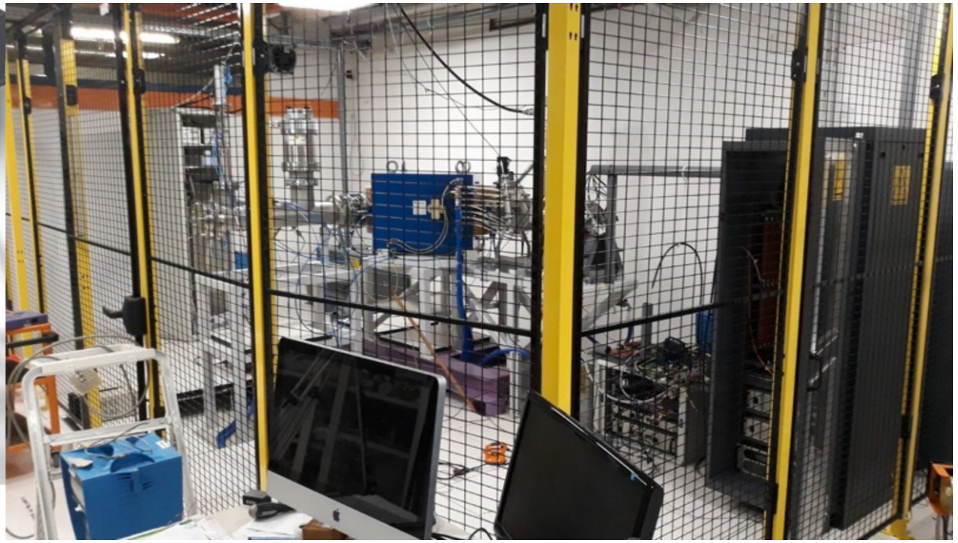
*depends on the actual global embedding process efficiency

HOLMES mass separation/ion implantation

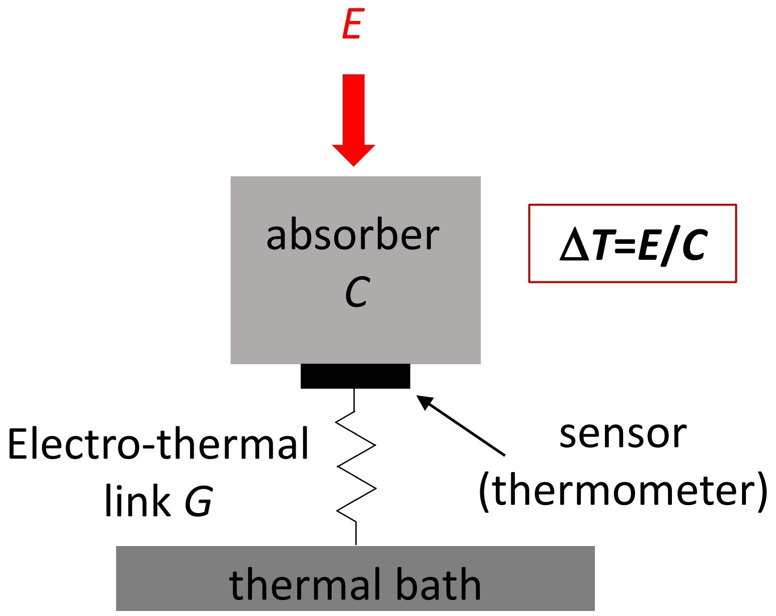
- extraction voltage 30-50 kV
- ~10 nm implanting depth
- **^{163}Ho/^{166m}Ho separation better than 10^5**







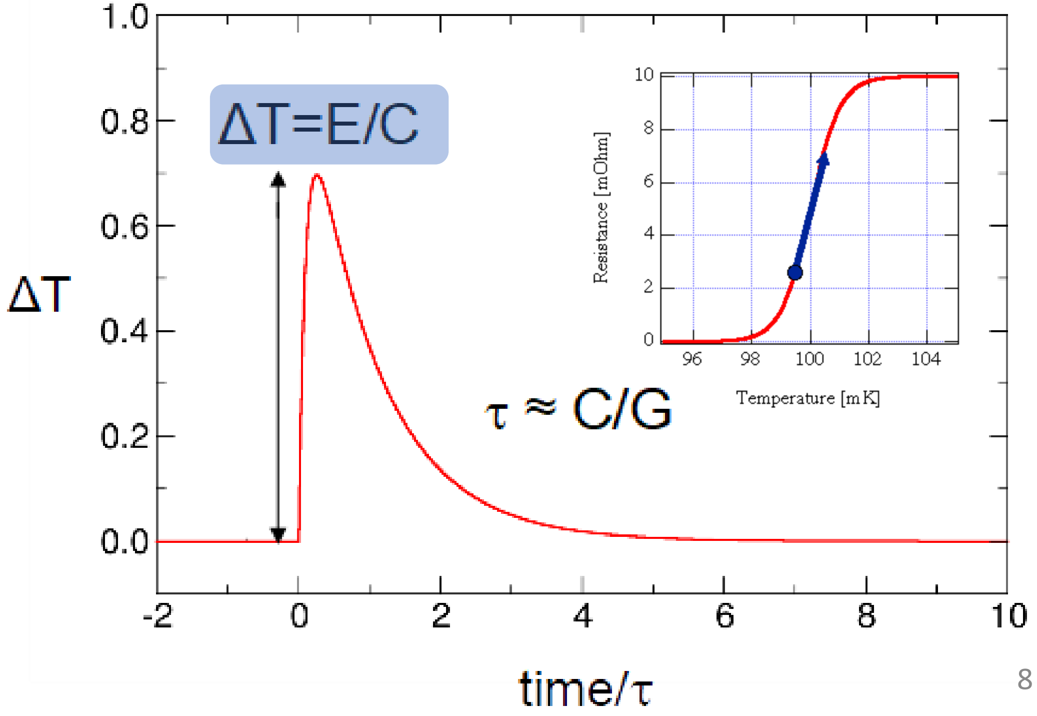
Transition Edge Sensors



Low temperature detectors

- (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



Transition Edge Sensors (TES)

- 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

HOLMES detectors & readout

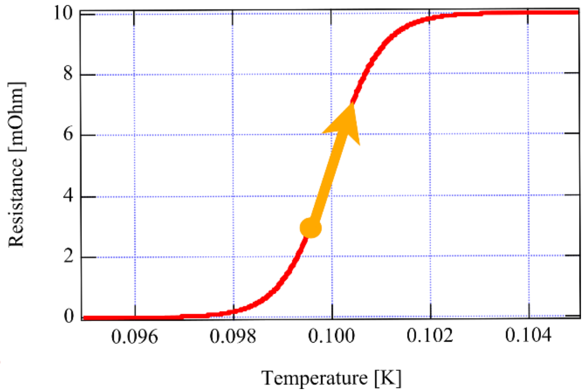
- **transition edge sensors**
  - ➢ good energy resolution: few eVs @ *Q*-value
  - ➢ compatible with ion-implanting
  - ➢ detectors intrinsically fast *O*(100 ns) – slowed down to ~ 20 μs for bandwidth limitations
    - ➢ effective time resolution better than rise time ⟶ pile-up discrimination
  - ➢ 300 Hz/pixel: excess of heat capacity? Degradation of detector performances? To be investigated…

- **microwave multiplexing**
  - ➢ rather simple readout scheme
  - ➢ compatible with fast sampling rate & intrinsic energy resolution

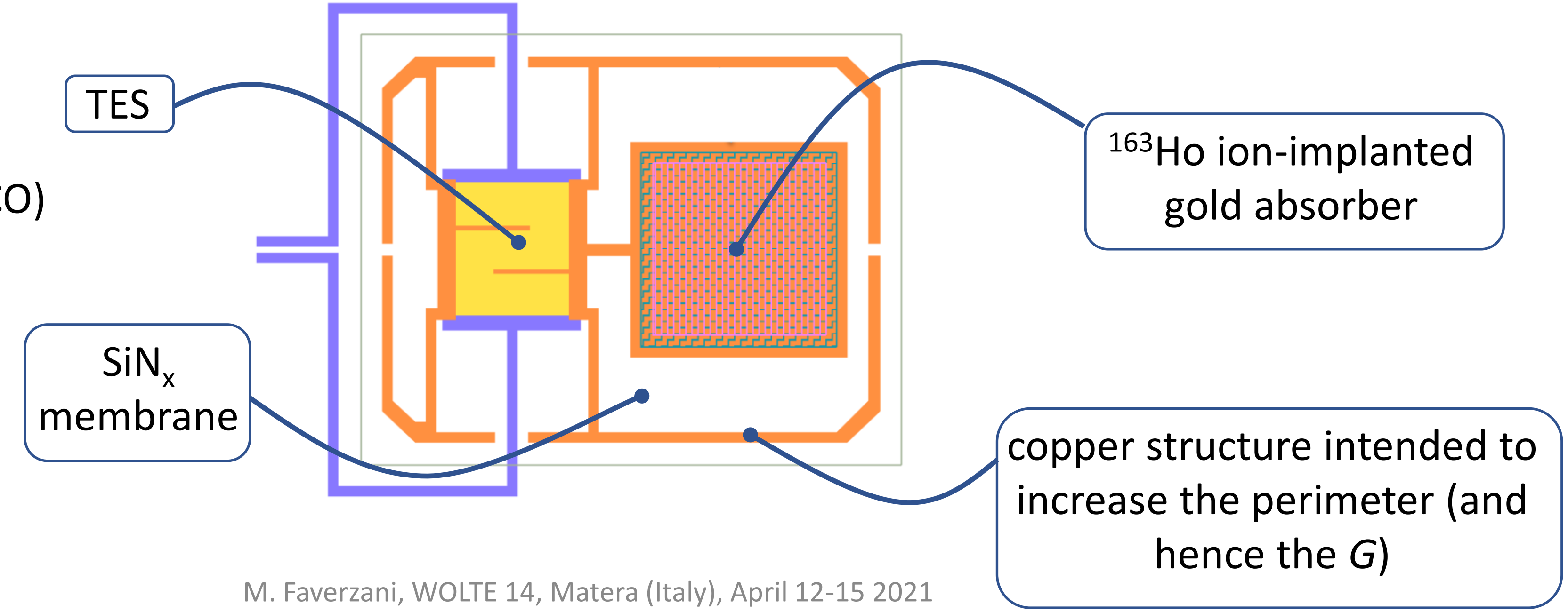
- **DAQ based on Software Defined Radio**
  - ➢ multiplexing factor limited by bandwidth of the ADC

Transition Edge Sensors for HOLMES

- Transition Edge Sensors: exploit the strong dependence of *R* vs *T* of a superconductor kept in its transition
- ^{163}Ho ion-implanted gold absorber thermally coupled to the sensor
- “side-car” geometry to prevent proximity effect
- absorber thickness determined by stopping power of electrons and photons
- fast detector response for high counting rate
  - ➢ signal rise time determined by electrical cut-off (*L*/*R*)
  - ➢ signal decay time (at the first order) set by *C*/*G*: large *G* to reduce dead time



- ✓ production @NIST (Boulder, CO)
- ✓ test at NIST and Milano
- ➢ ion-implanted in Genova
- ➢ production completion in Genova+Milano



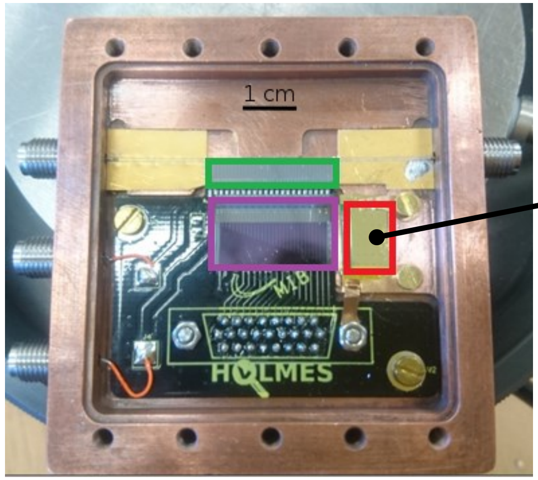
Detectors testing

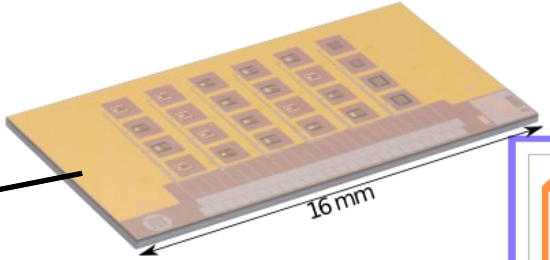
- tested several geometries
- produced entirely at NIST
- **Not implanted with Holmium!**
- ^{55}Fe (5.9 keV) + fluorescence source (Ca – 3.7 keV; **Cl – 2.6 keV**; Al – 1.5 keV)
- selected stray inductance to obtain $\tau_{rise} \approx 13\ \mu s$

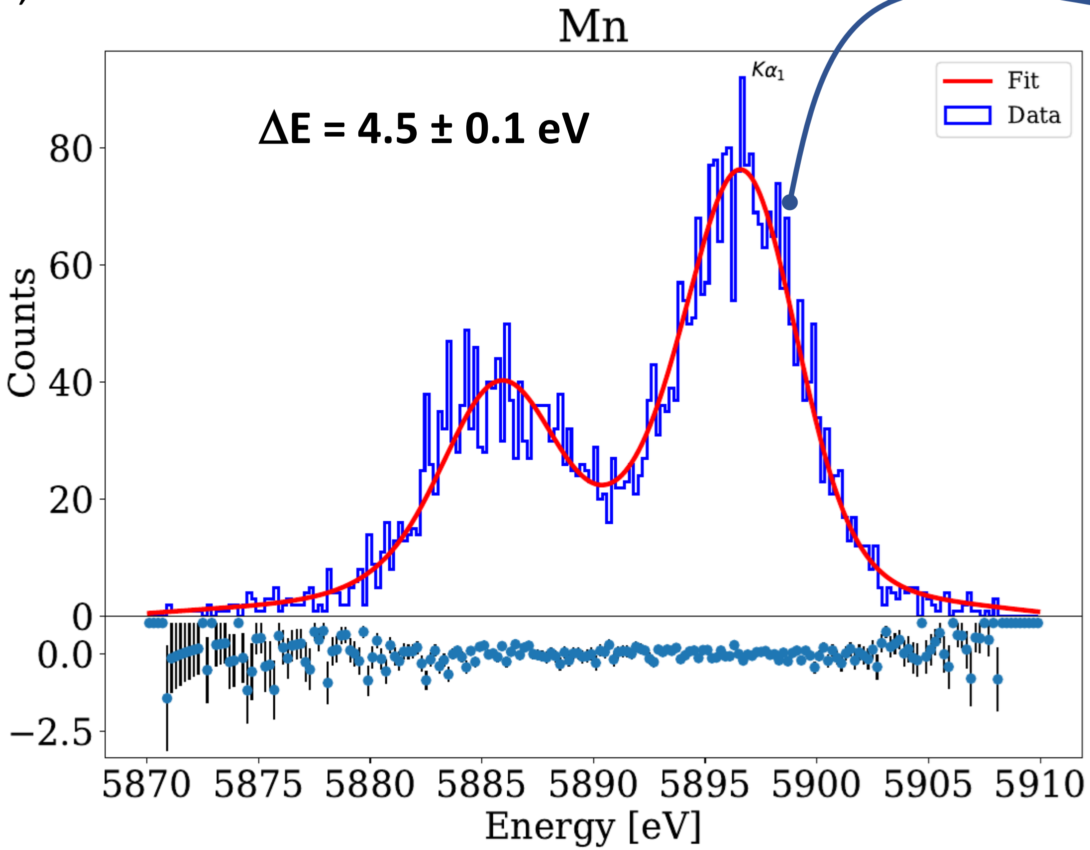
test @Milano **with μ–wave multiplexing**

f_{samp} = 500 kHz

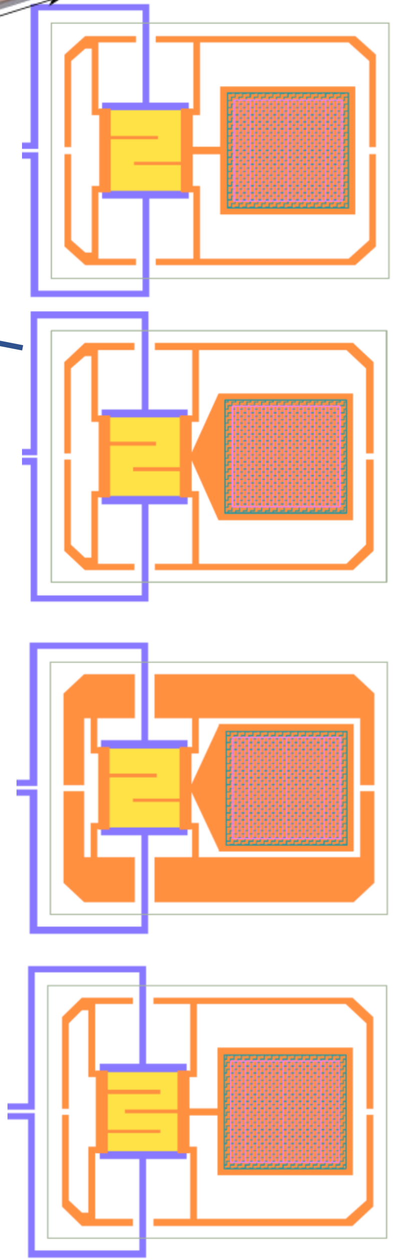
E [keV]	ΔE [eV]
1.49	4.3±0.3
2.62	4.5±0.3
3.69	4.6±0.3







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



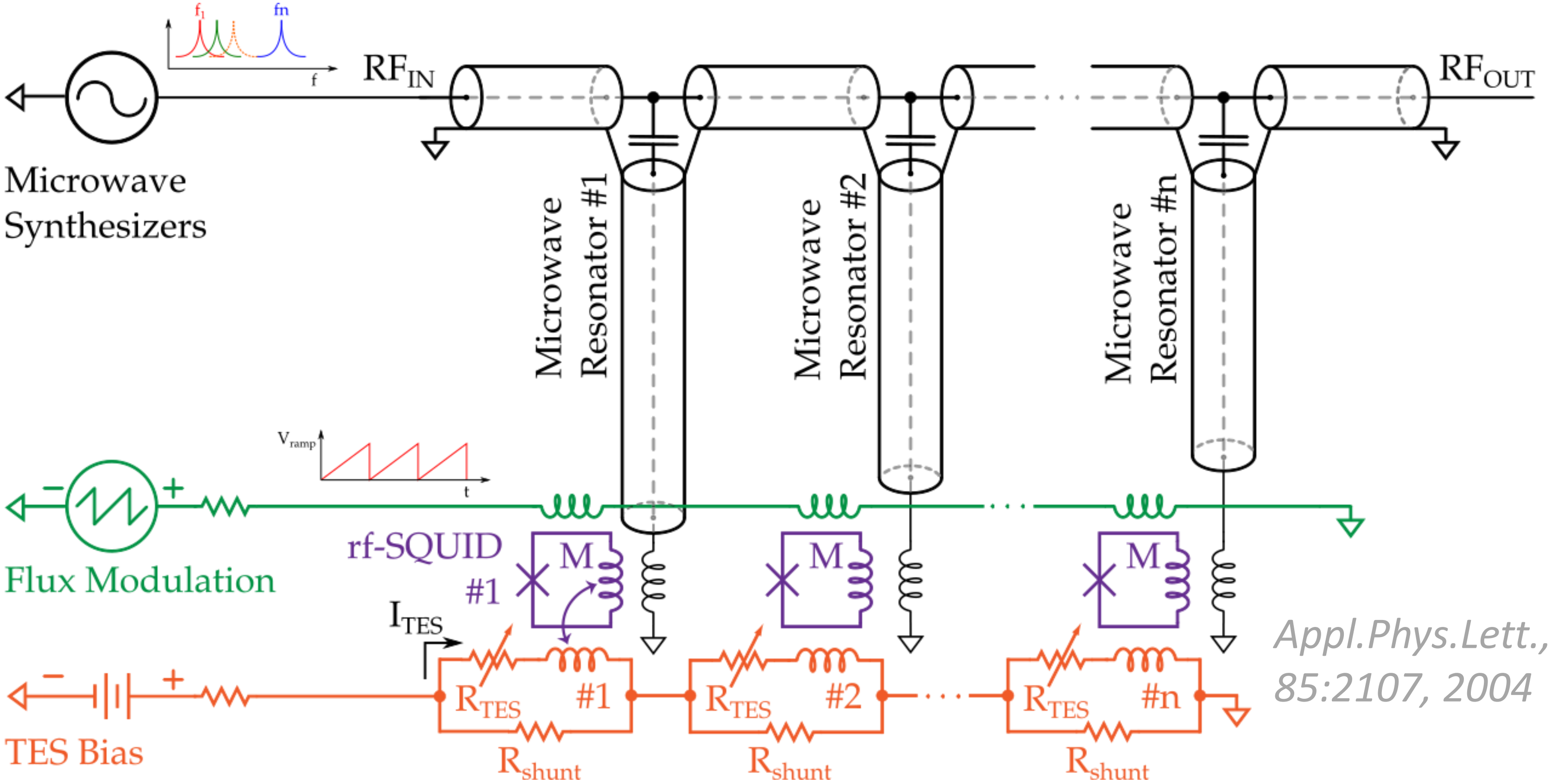
Microwave multiplexing readout

TESs readout with microwave multiplexing (produced by NIST)

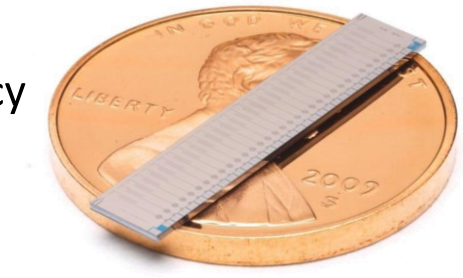
- each sensor inductively coupled to a RF-squid part of a $\lambda/4$ resonator
- a comb of signals probe the resonators at their characteristic resonant frequency

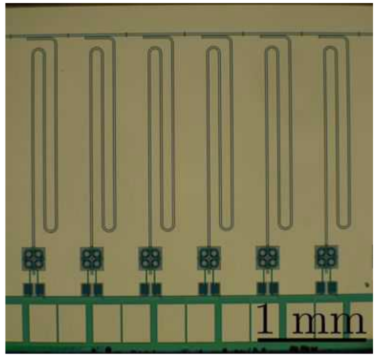
$$E \longrightarrow \delta T_{\mathrm{TES}} \longrightarrow \delta I_{\mathrm{TES}} \longrightarrow \delta\phi_{\mathrm{squid}} \longrightarrow \delta f_{\mathrm{resonator}}$$

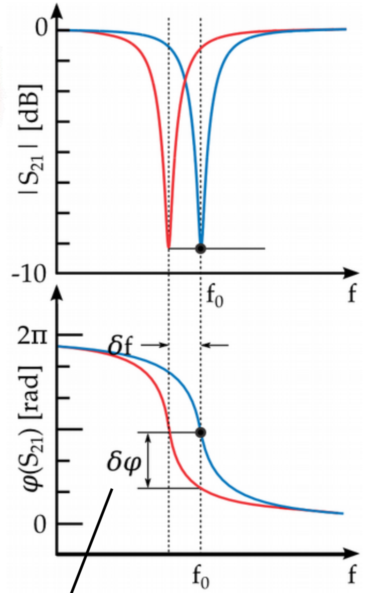
- a ramp signal added to the squids in order to linearize the response

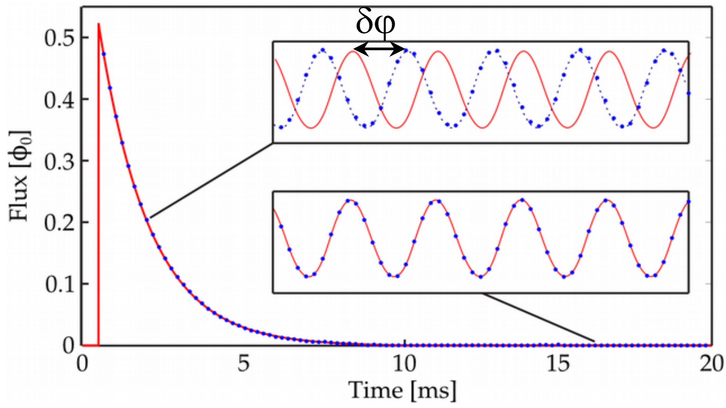


Appl.Phys.Lett., 85:2107, 2004

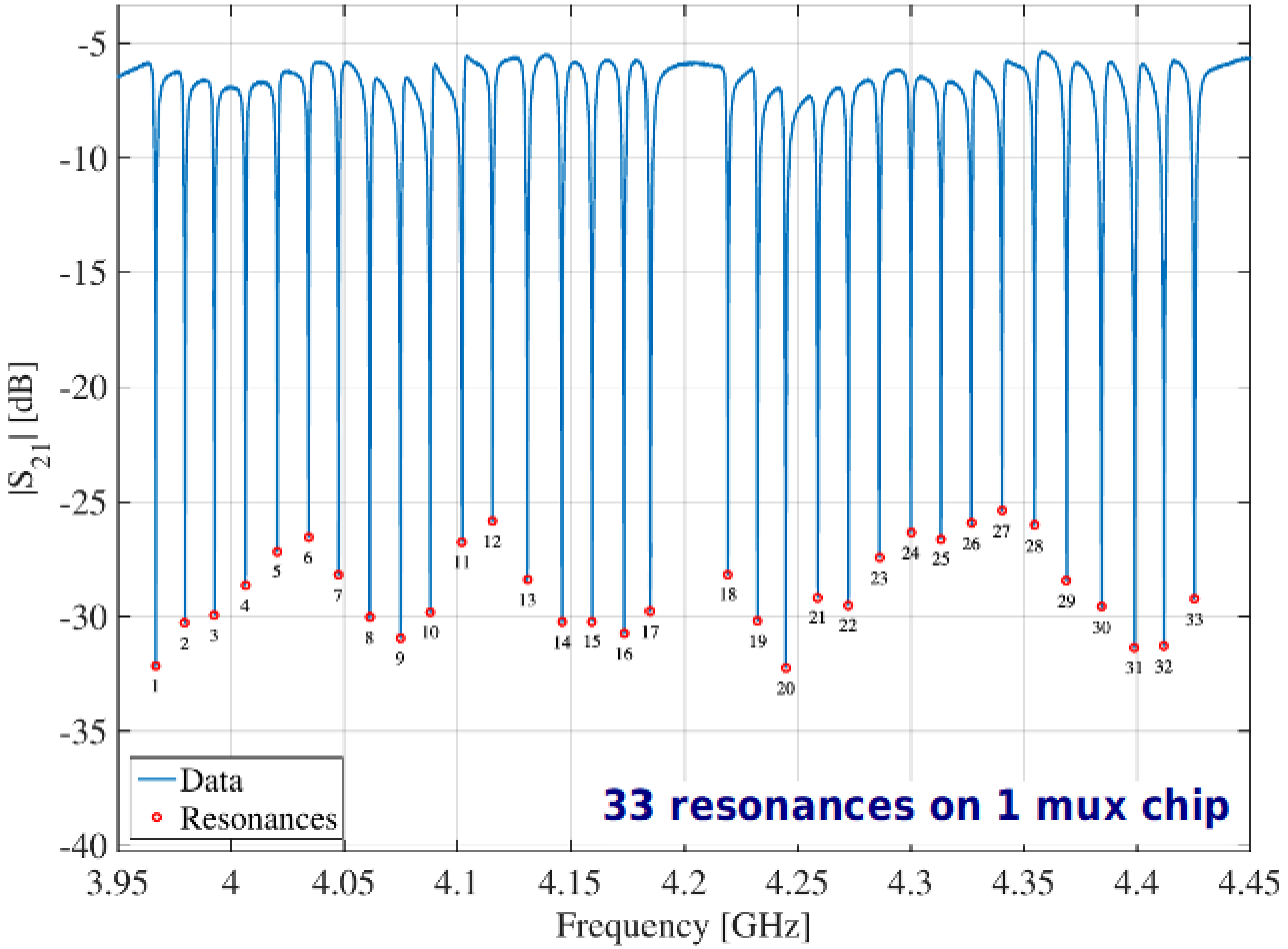


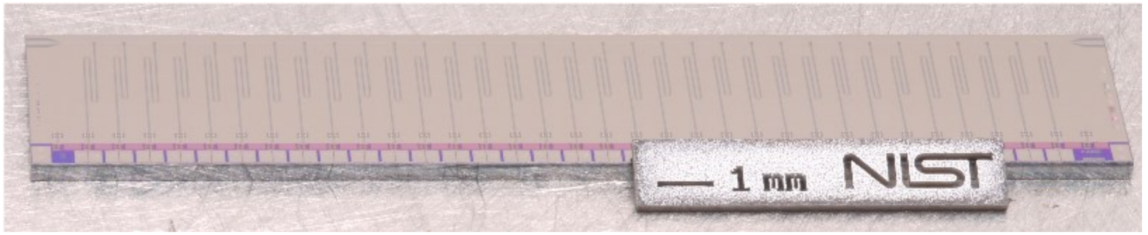






Microwave multiplexing readout

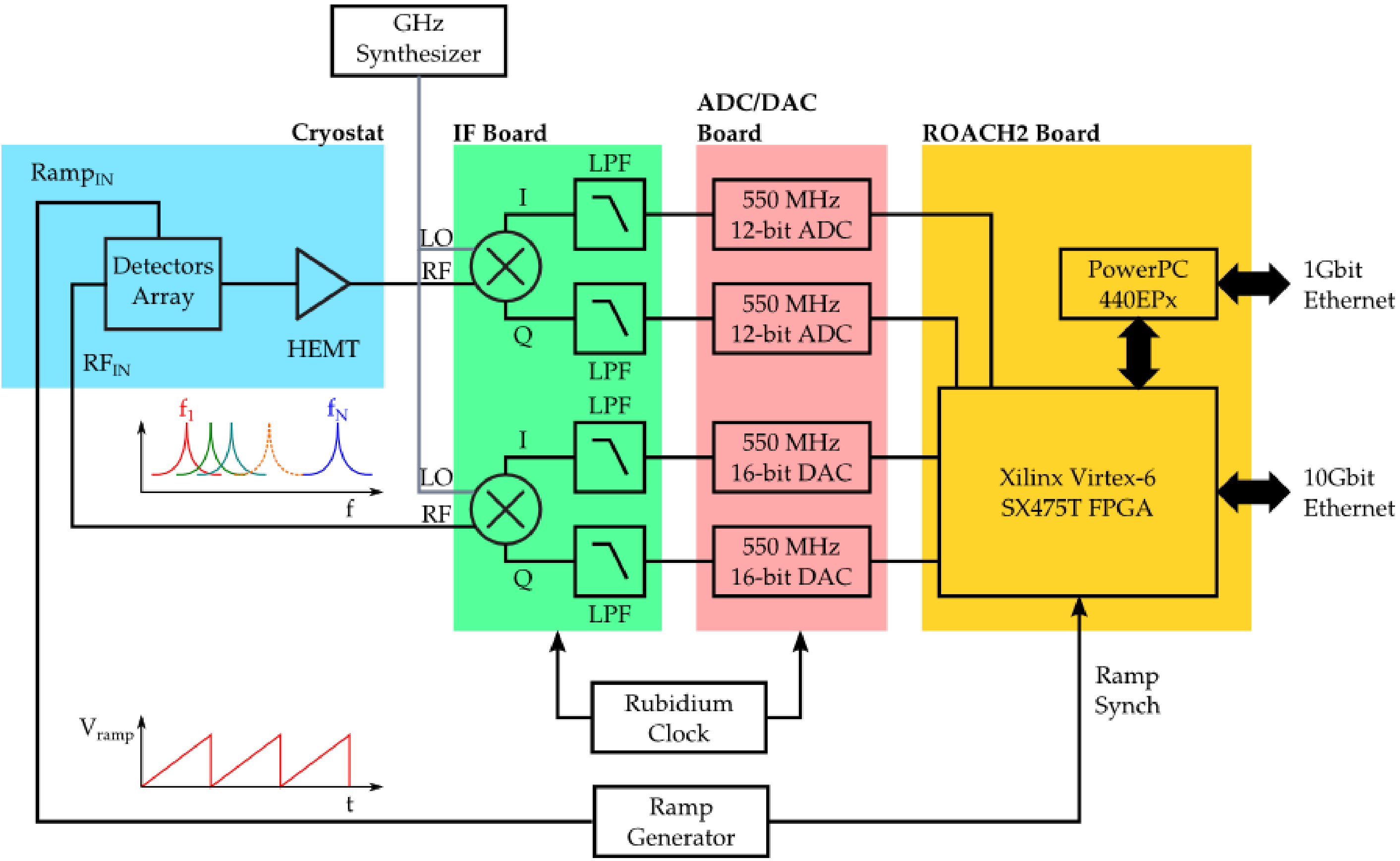


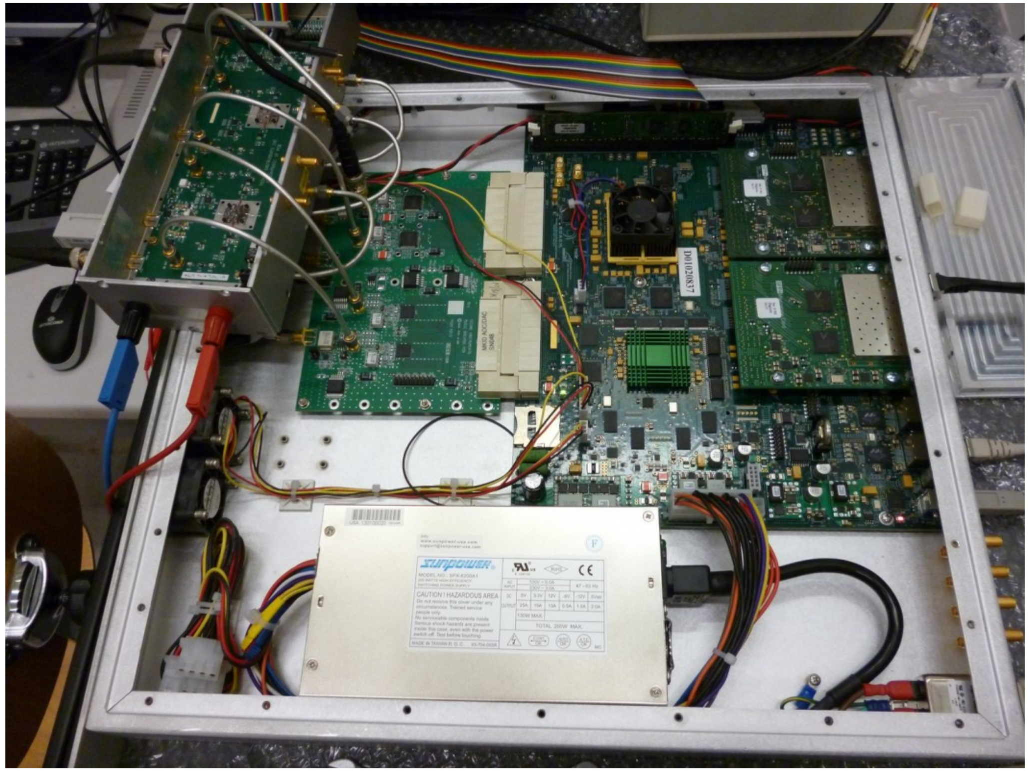


- 33 resonances/chip over 500 MHz
- BW = 2 MHz per resonator
- separation between resonances 14 MHz (to prevent crosstalk)
- depth greater than 10 dB
- SQUID equivalent noise: ≤ 2 $\mu\phi_0/\sqrt{Hz}$

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

DAQ with the ROACH2





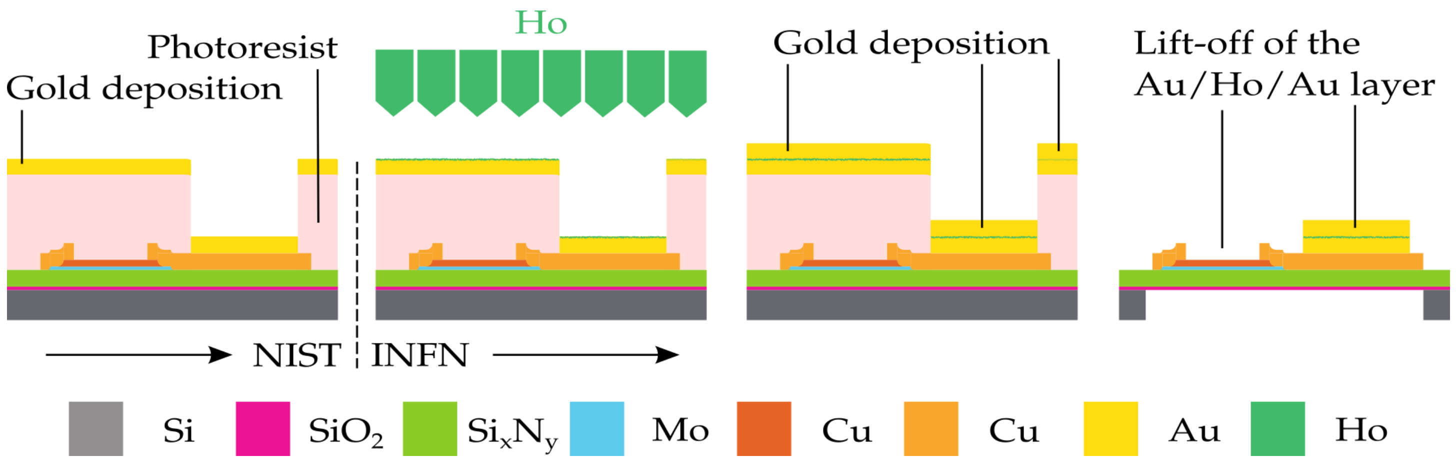
- Software Defined Radio with the open system ROACH2 (Casper collaboration)
- ADC BW 550 MHz
- real time pulse reconstruction
- ➢ at the moment readout available for 64 channels

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

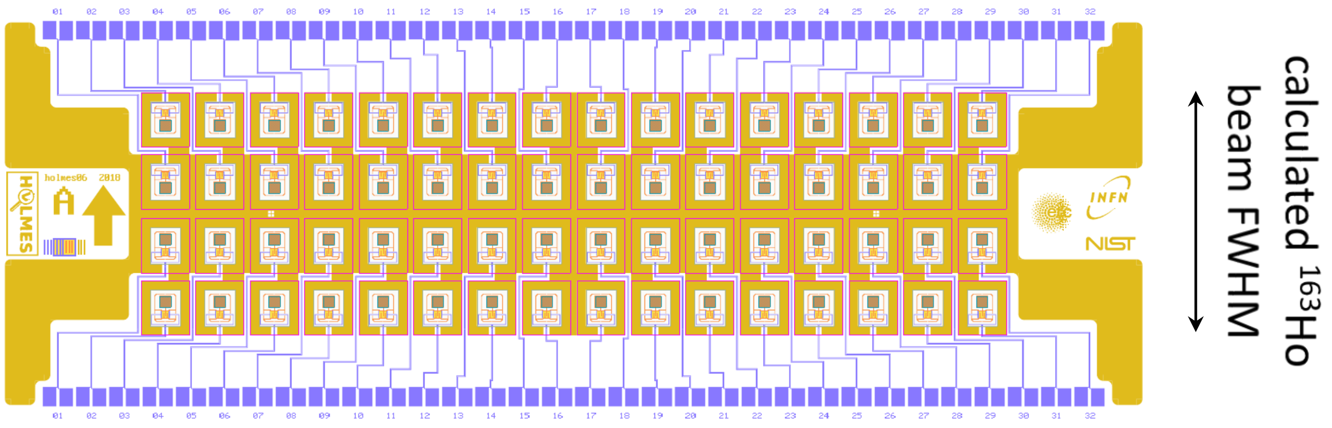
requiring τ_{rise} = 10 μs

$n_{TES} \approx 34$

Detectors fabrication

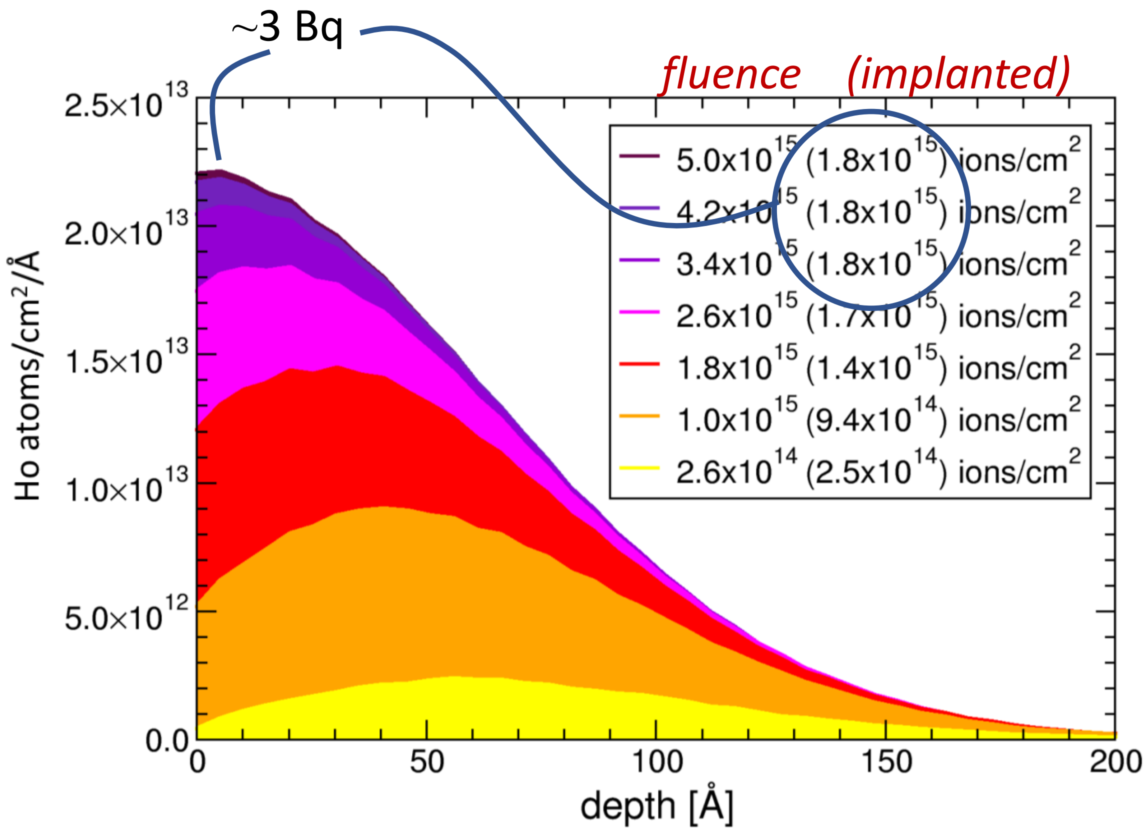


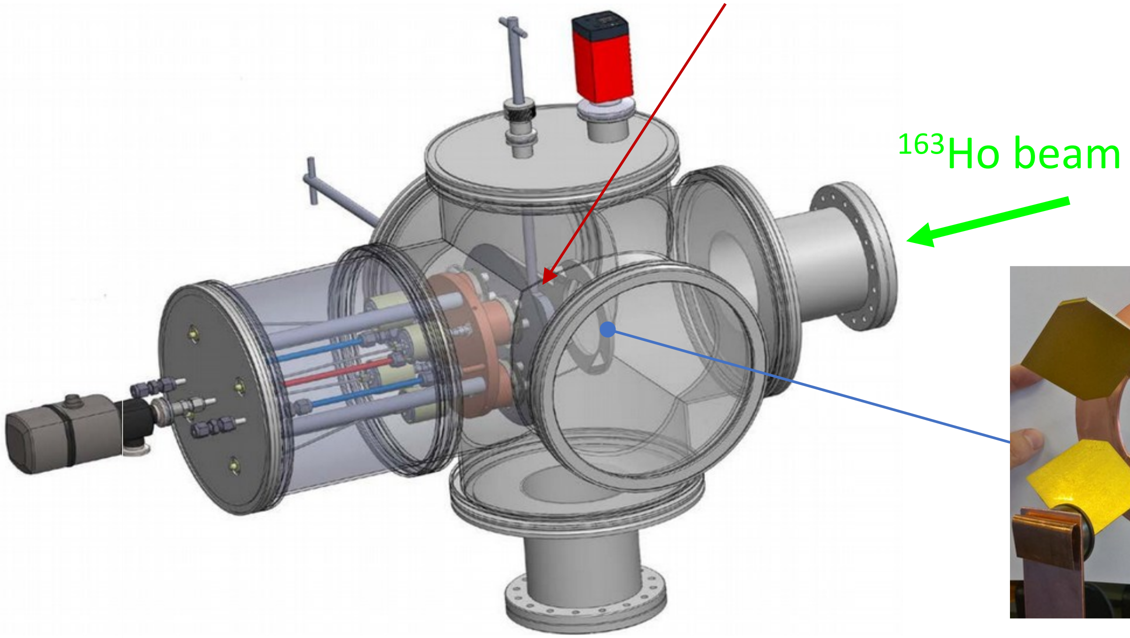
- TES originally fabricated at NIST, Boulder, CO, USA
- ^{163}Ho implantation at INFN, Genova, Italy
- 1 μm Au final layer deposited at INFN, Genova, Italy
- final fabrication process: release of the membrane with KOH in Milano or DRIE
- HOLMES 4 x 16 linear sub-array for low parasitic *L* and high implant efficiency

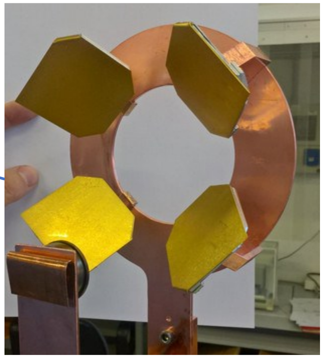


Target chamber

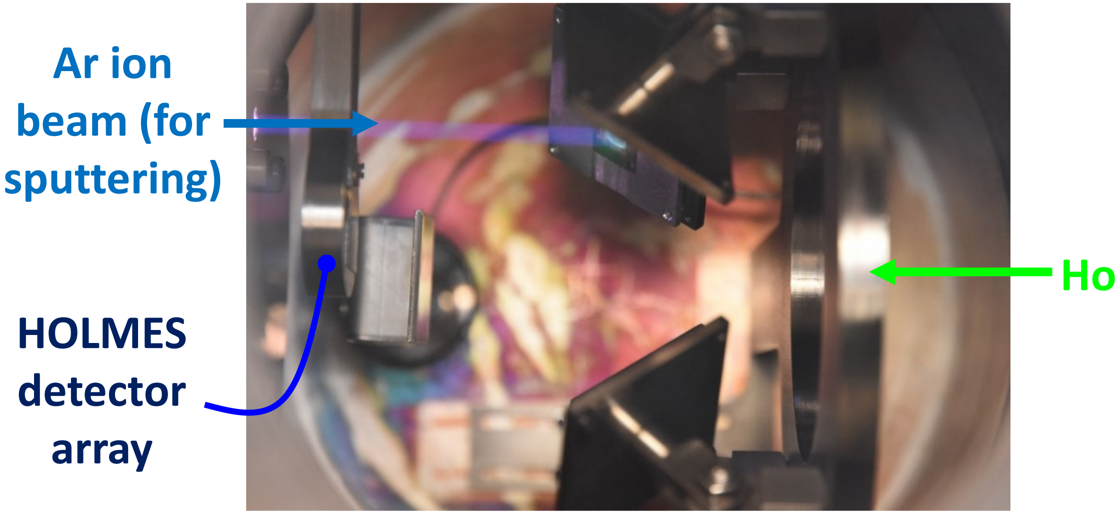
ion implantation (SRIM2013) – energy beam 50 keV







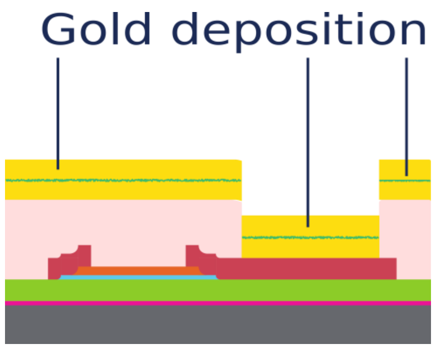
deposition rate (with 4 sputter sources) > 100 nm/h
~ 10 hours to deposit 1 μm



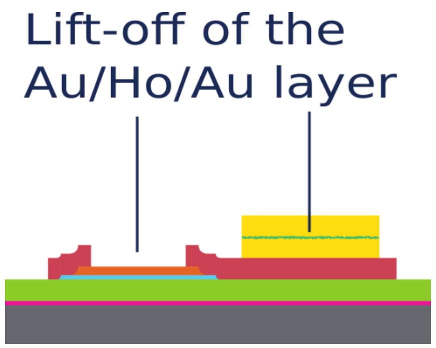
- ^{163}Ho concentration in absorbers saturate because ^{163}Ho sputters off Au from absorber
- effect compensated by Au co-evaporation (also for heat capacity reasons)
- final 1 μm Au layer deposited in situ to avoid oxidation

Detectors fabrication @ Milano-Bicocca

1)

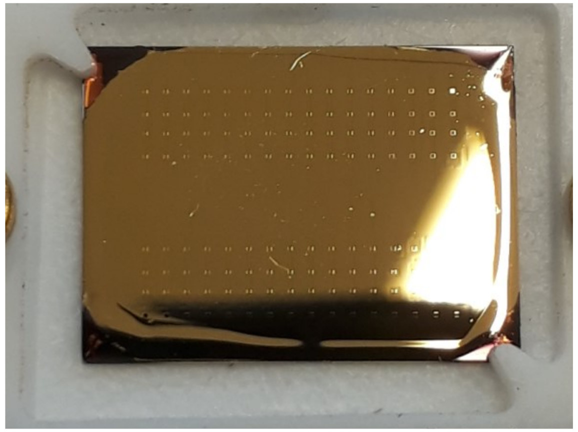


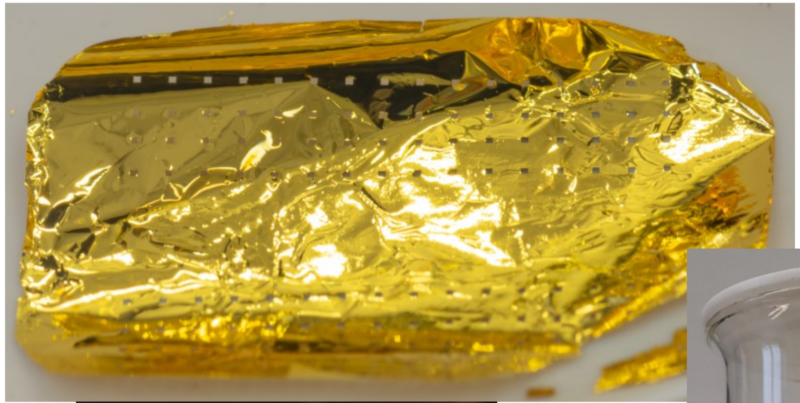
2)

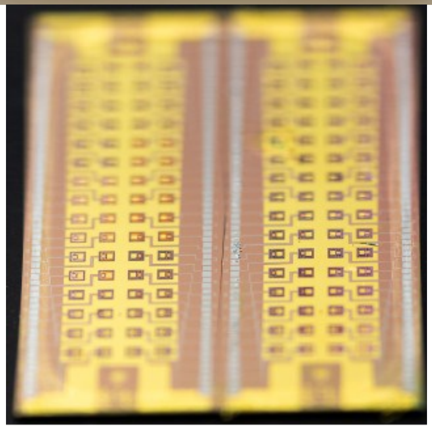


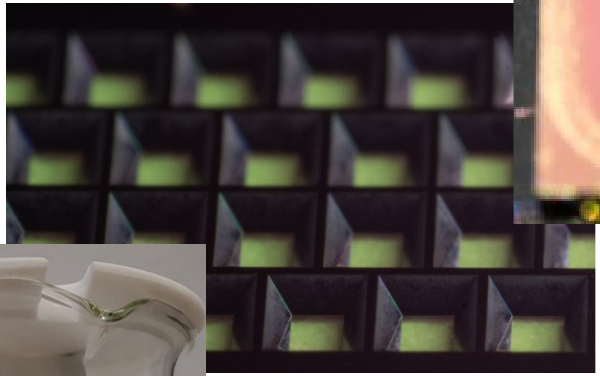
3)

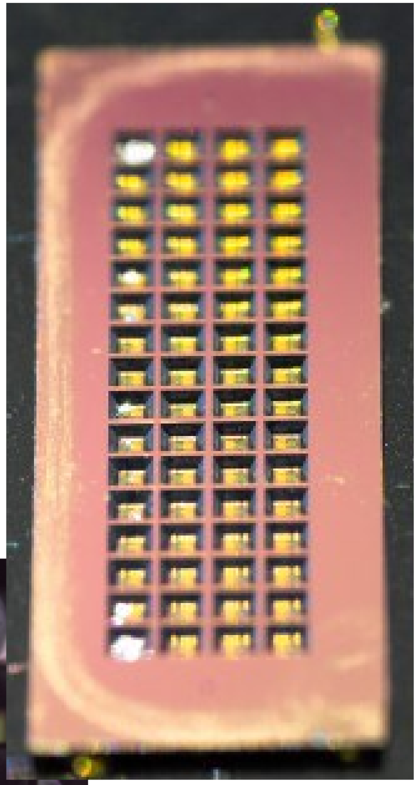
KOH…











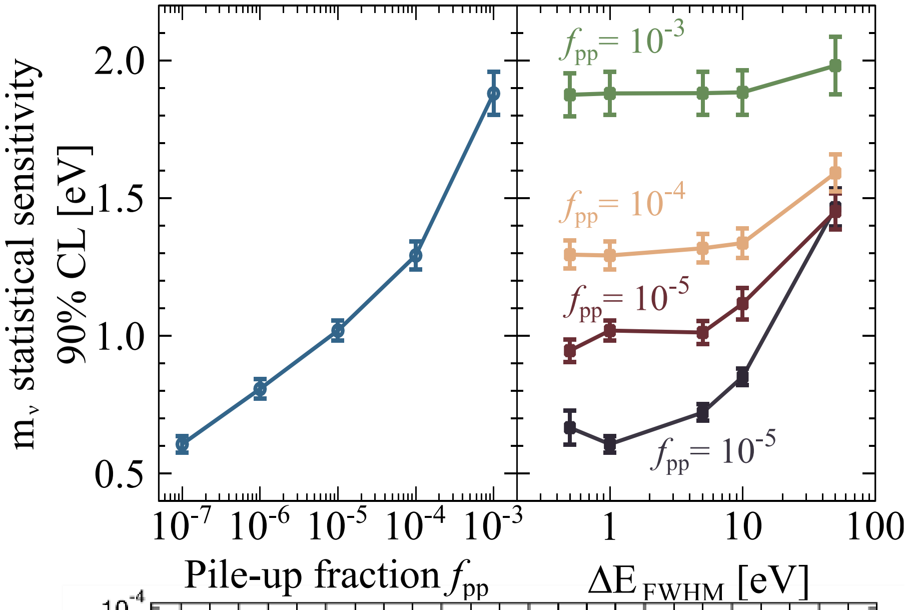
… vs DRIE

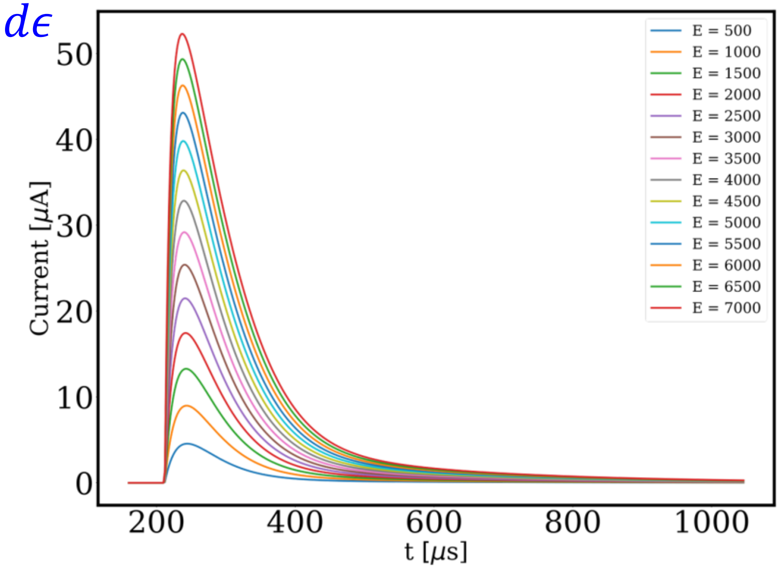
- ✓ gold thickness uniformity measured: $\sigma_t/t \sim 4\,\%$
- ✓ full fab tested on 2 arrays
- ✓ arrays characterized at low temp → ΔE_{FWHM} = (4.64±0.14) eV @ 6 keV

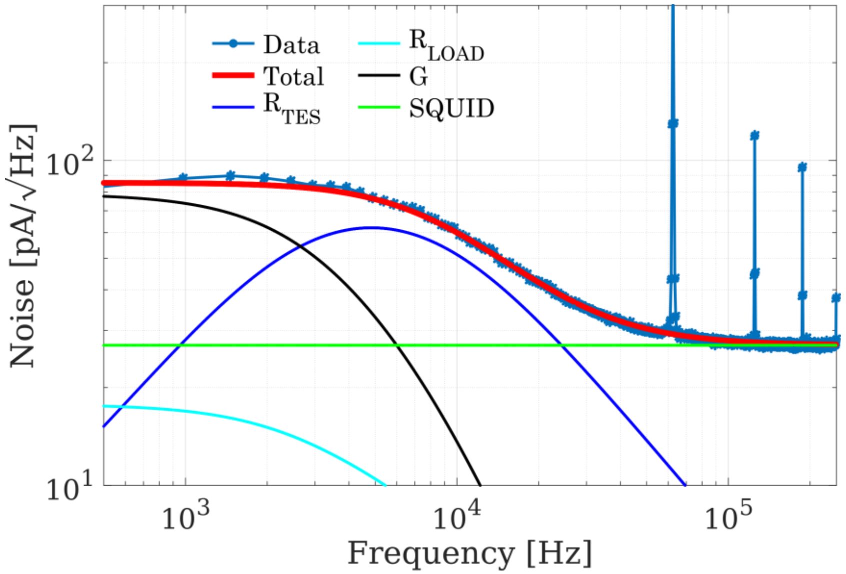
Detector time resolution (MC simulations)

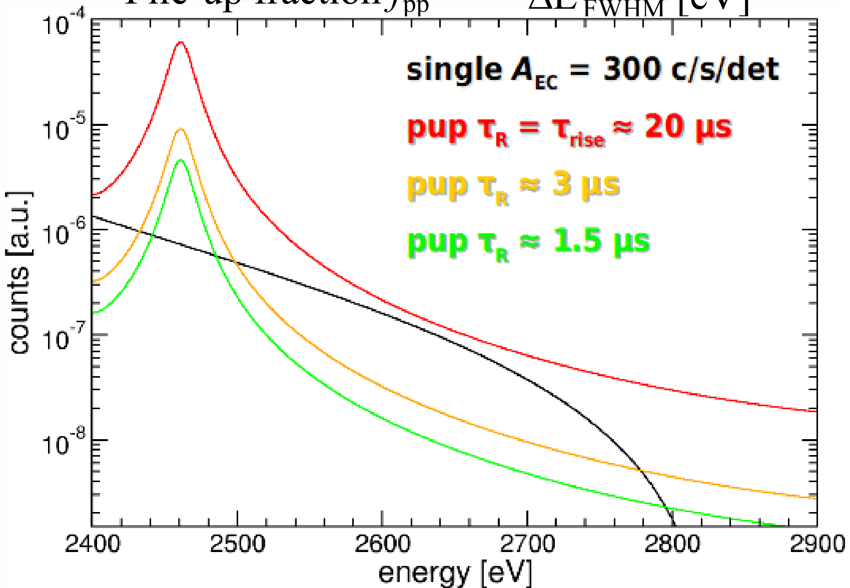
pile-up spectrum with a time resolution τ_R:

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









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 → $\tau_R \approx 2$ 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 2021
  - ➢ 64 high-activity channels will start data taking by beginning of 2022

long term

- ✓ large scale ^{163}Ho production
- ✓ TES performance
- ✓ large bandwidth μwave multiplexing
- ✓ pile-up rejection algorithm
- ✓ embedding efficiency
- ✓ high dose implantation
- ✓ running of 1000 detectors and data analysis