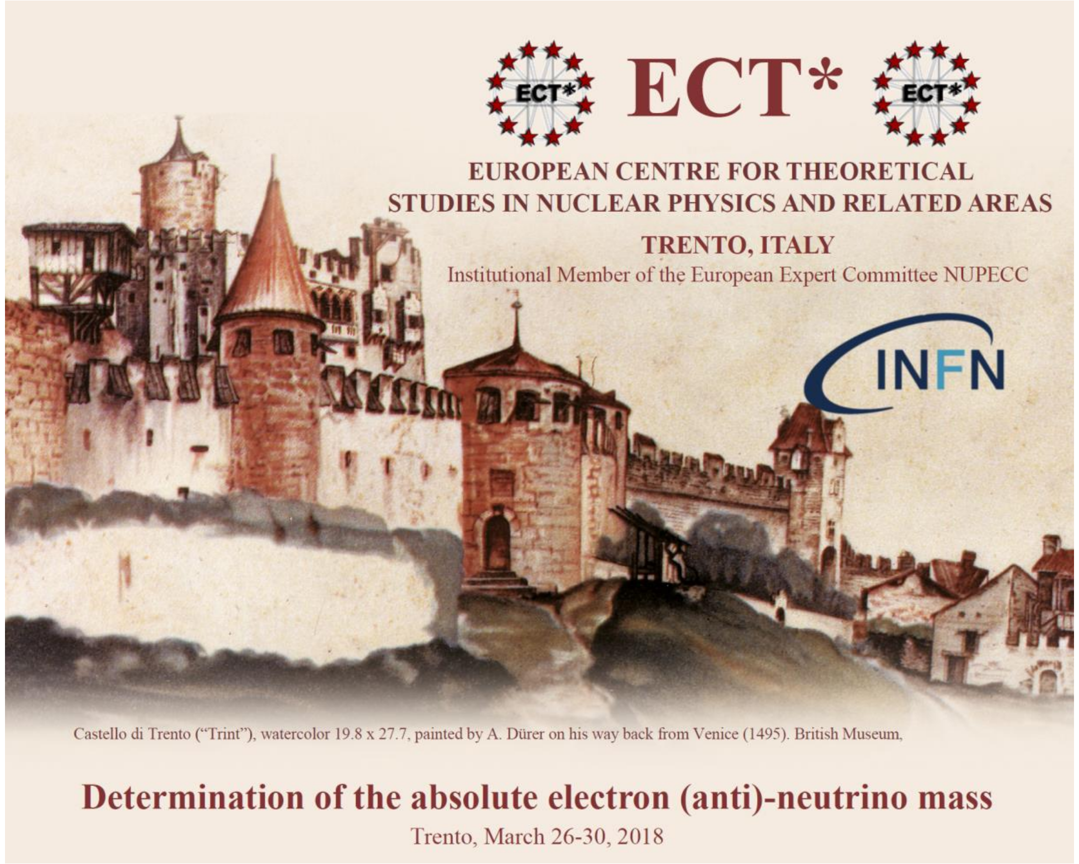
The HOLMES experiment

Marco Faverzani

Università & INFN Milano-Bicocca

on behalf of the HOLMES collaboration



Outline

- Neutrino mass
- Direct and calorimetric measurement of m_ν with ^{163}Ho
- HOLMES
    - Experimental statistical sensitivity
    - Experiment design and baseline
    - Technical tasks status
- Conclusions

HOLMES collaboration

Univ. Milano-Bicocca
INFN Milano-Bicocca
G. Ceruti
M. Faverzani
E. Ferri
A. Giachero
A. Nucciotti
A. Orlando
G. Pessina
A. Puiu
S. Ragazzi

INFN Genova
A. Bevilacqua
M. Biasotti
V. Ceriale
M. De Gerone
G. Gallucci
F. Gatti
L. Parodi
F. Siccardi

INFN Roma
M. Lusignoli

INFN LNGS
M. Balata
S. Nisi

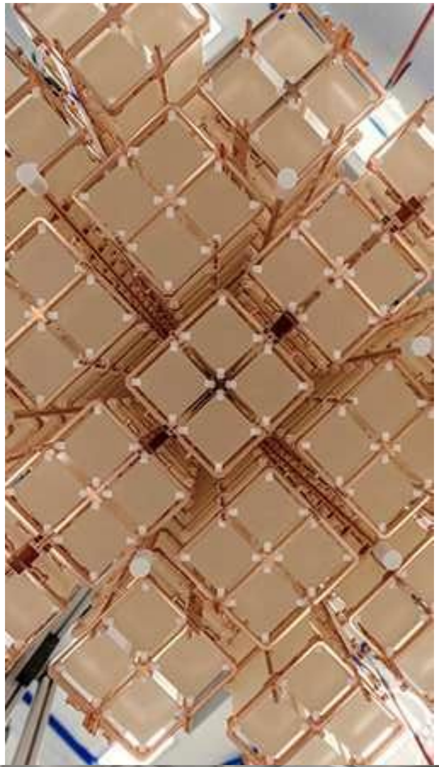
NIST (Boulder, CO)
B. Alpert
D. Becker
D. Bennet
J. Fowler
J. Gard
J. Hays-Wehle
G. Hilton
J. Mates
C. Reintsema
D. Schmidt
D. Swetz
J. Ullom
L. Vale

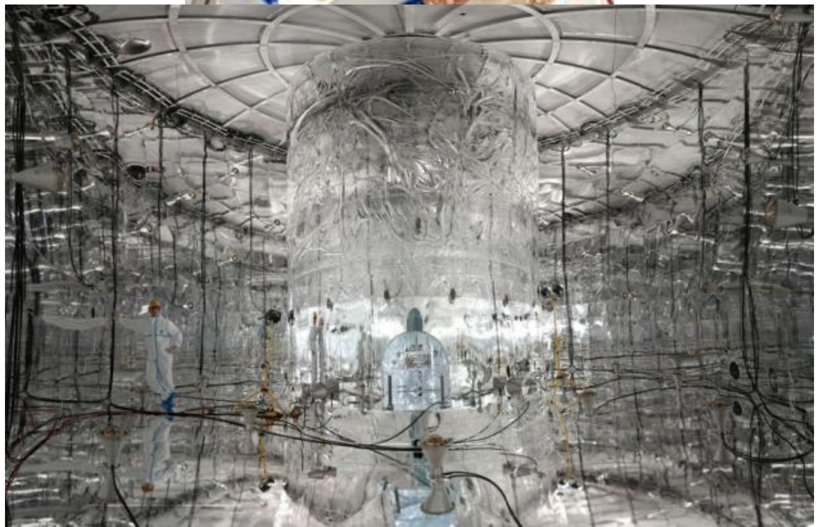
PSI
R. Dressler
S. Heinitz
D. Shumann

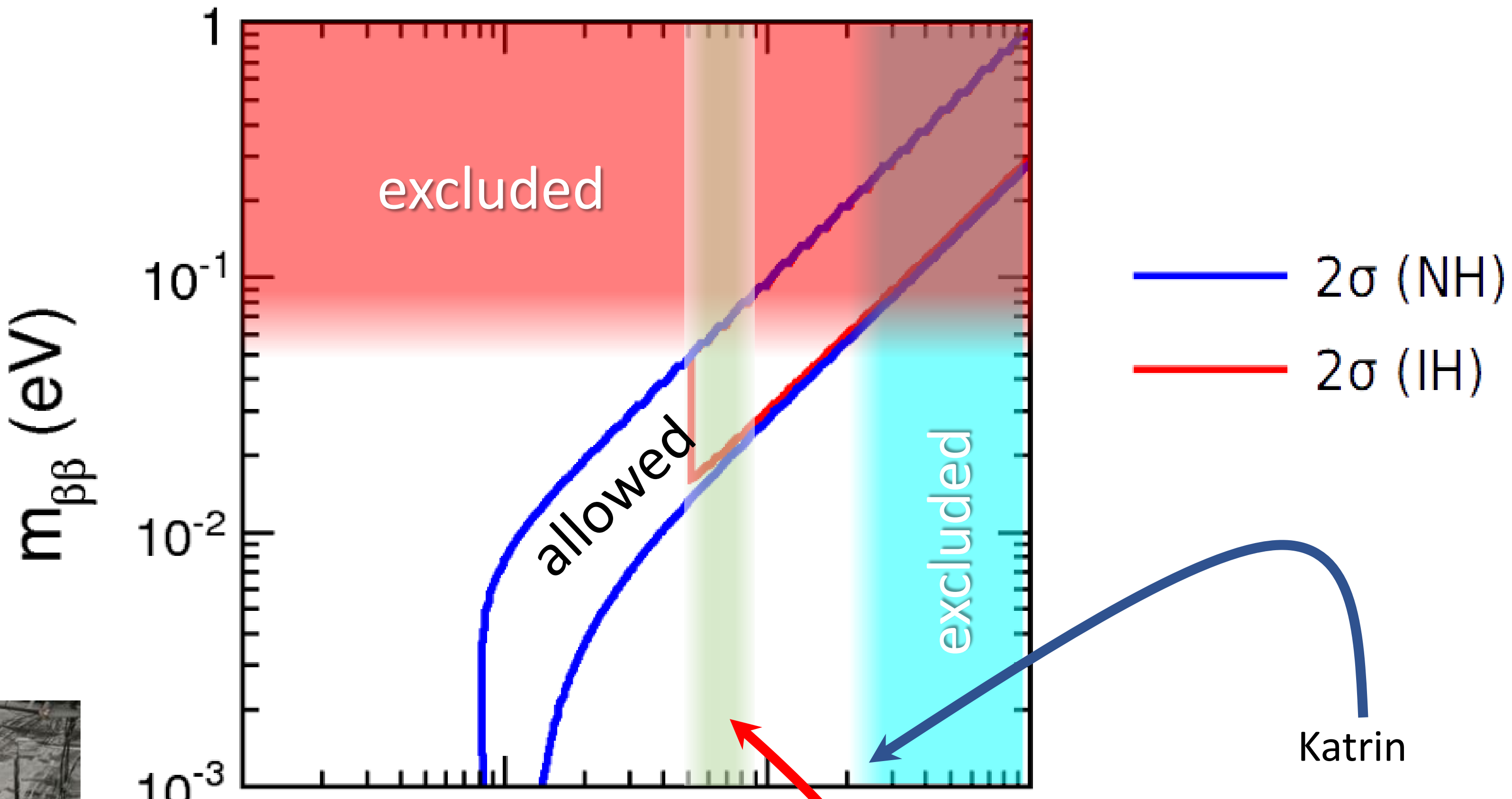
CENTRA-IST
M. Ribeiro-Gomes

ILL
U. Koester

Absolute neutrino mass







^{163}Ho electron capture

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

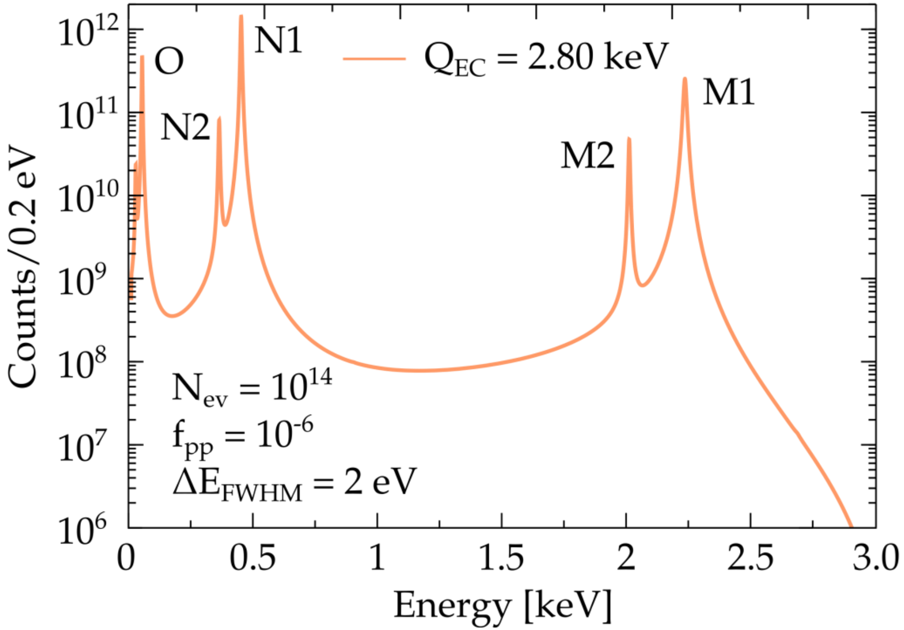
^{163}Ho decay via EC from shell ≥ M1, with $Q_{EC} \sim 2.8$keV

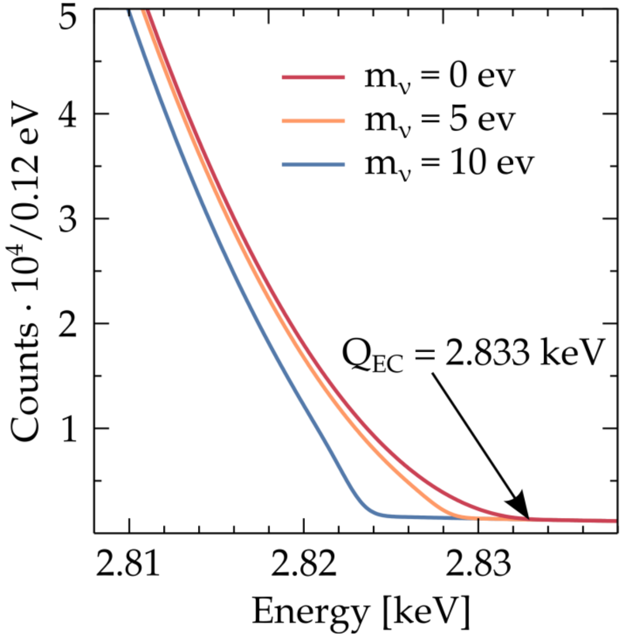
Proposed by *A. De Rujula and M. Lusignoli, Phys. Lett. B 118 (1982) 429*

- calorimetric measurement of the Dy atomic de-excitation (mostly non-radiative)
- rate at the end point depends on $\boldsymbol{(Q - E_{M_1})}$: 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)

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

Simulation with single hole excitations





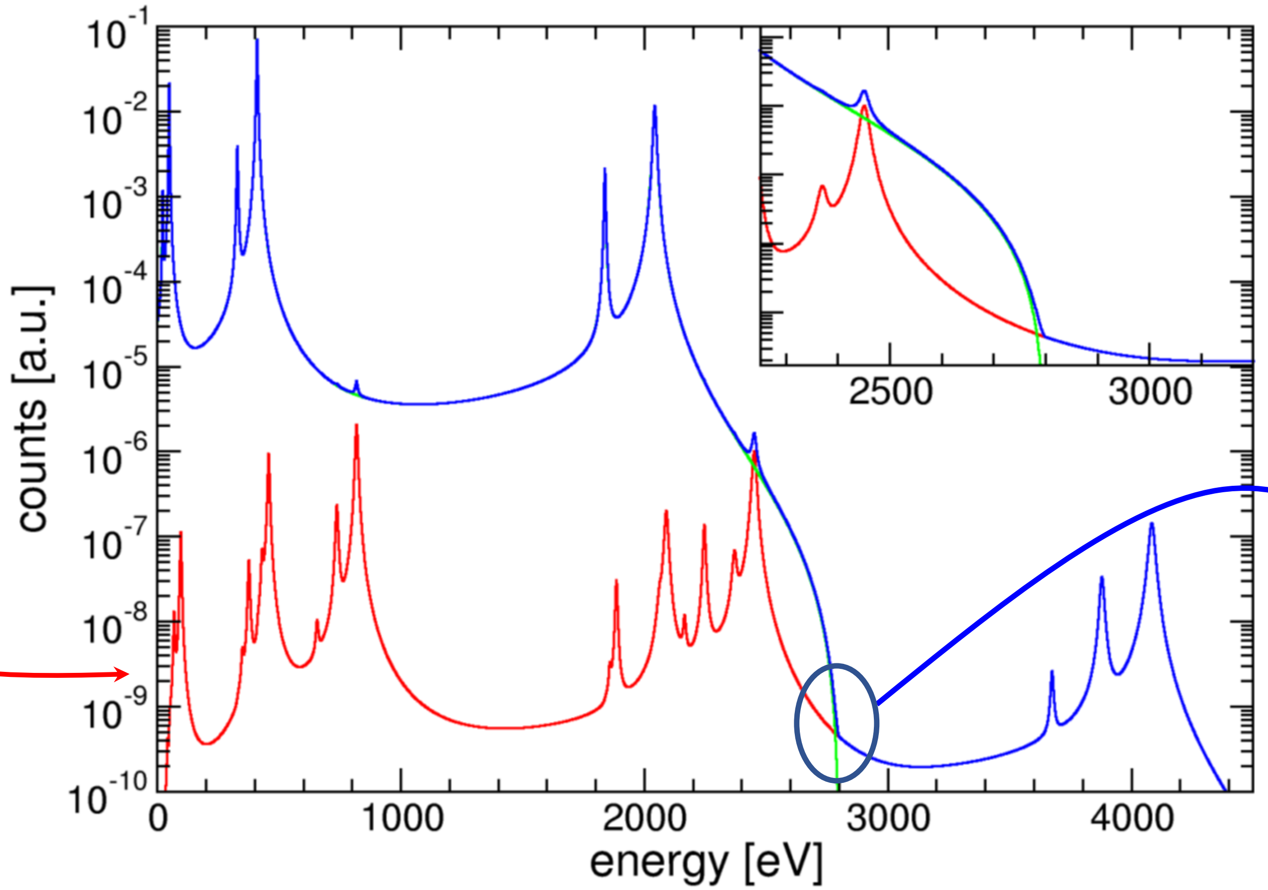
Pile-up

- no direct calorimetric measurement of Q (end-point) so far
- 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 (~ rise time)

- 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

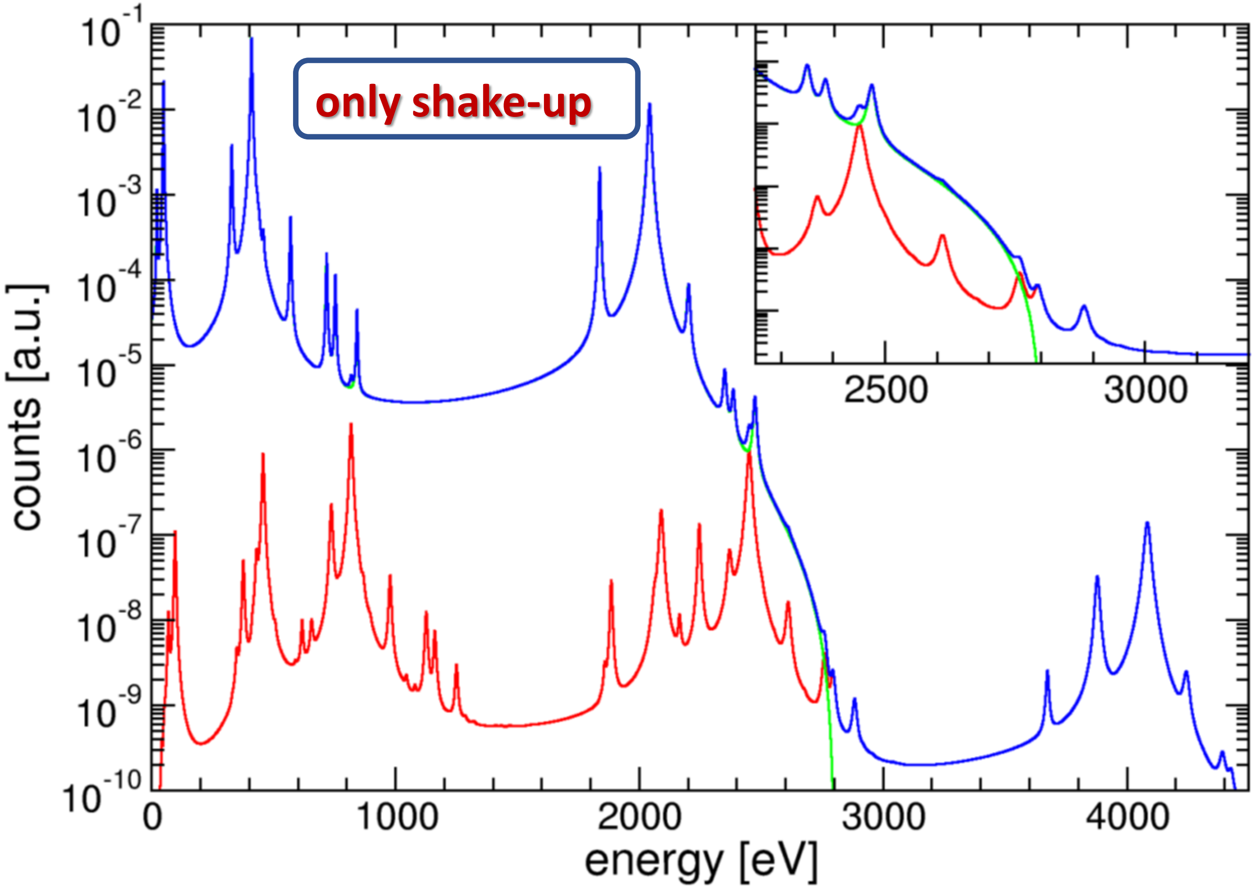
Pile-up/2

- shake-up/shake-off due to two holes excitations
  - *n*-hole possible, but less probable
  - energies and probabilities are still uncertain

Double hole excitations

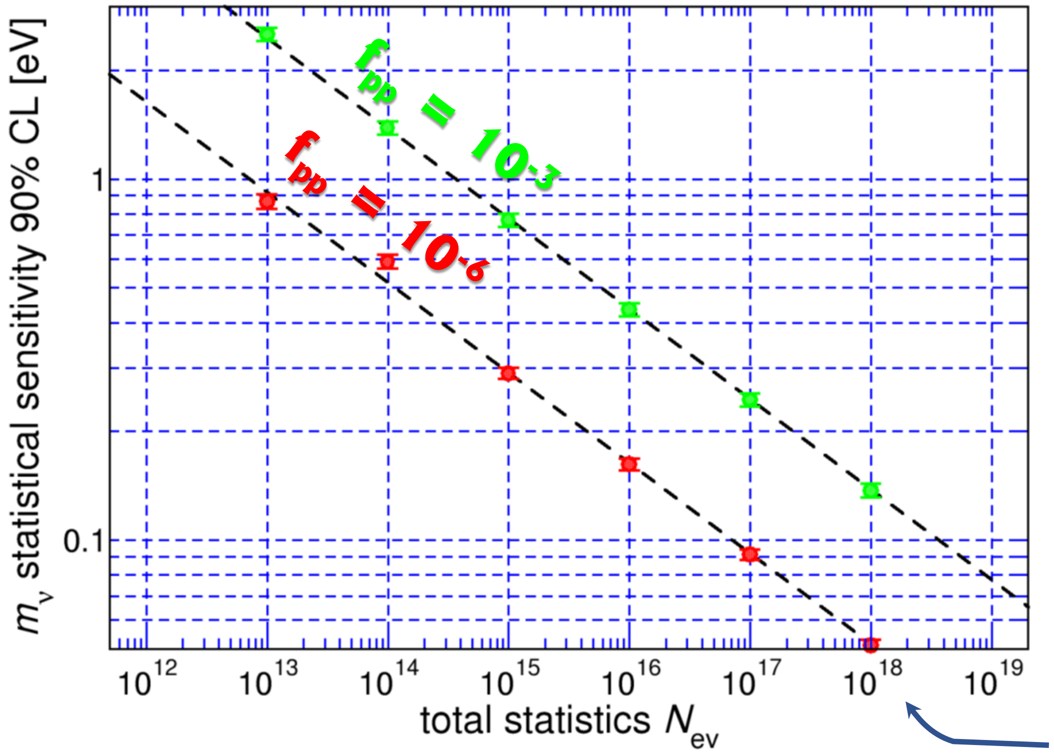
Q = 2800 eV

$f_{pp} = 10^{-4}$



more complex structure at the end-point might require a $\boldsymbol{f_{pp}}$ **even lower than 10^{-4}**

Statistical sensitivity



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

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!!**

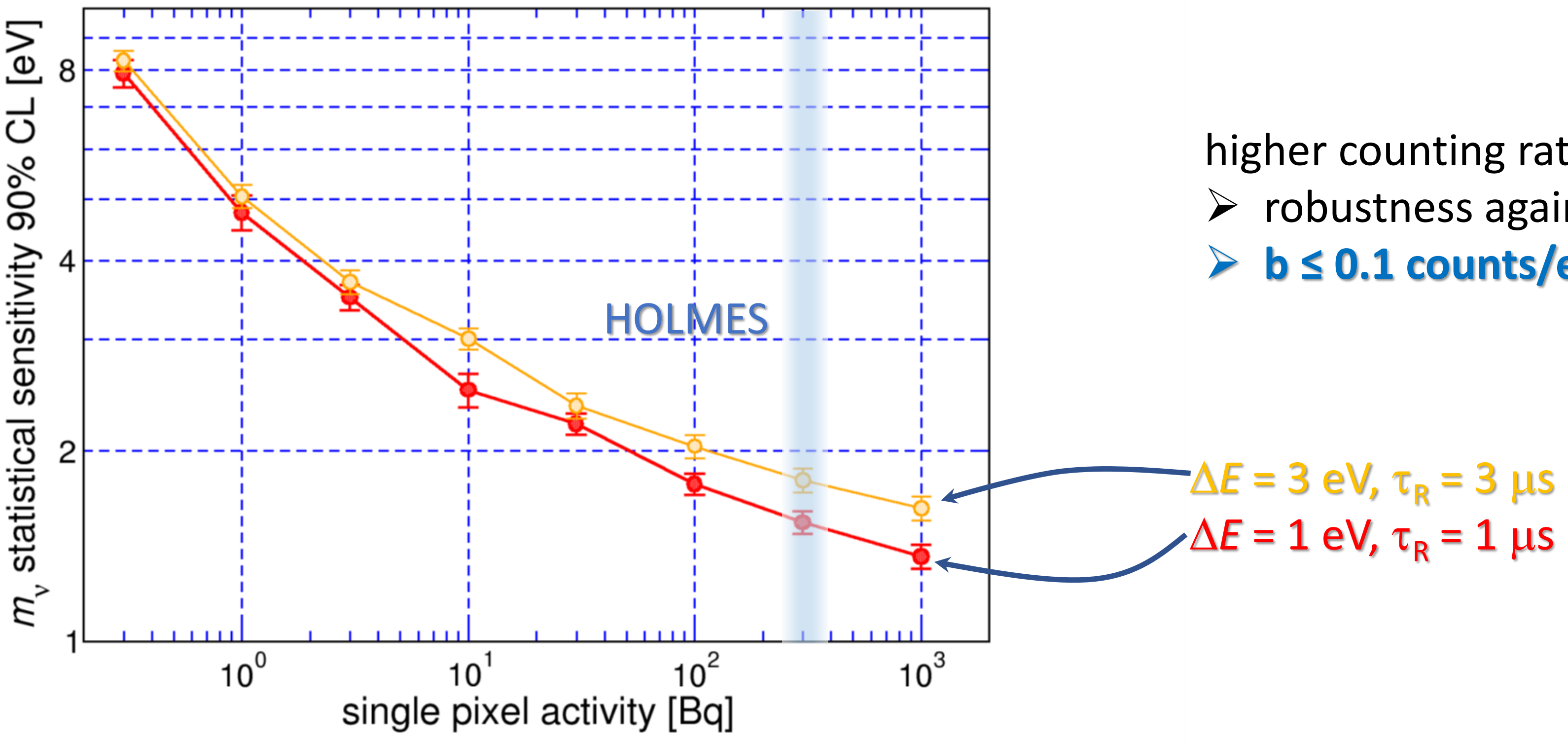
MC simulation

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

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

Statistical sensitivity vs pixel activity

1000 channels, t_M = 3 years

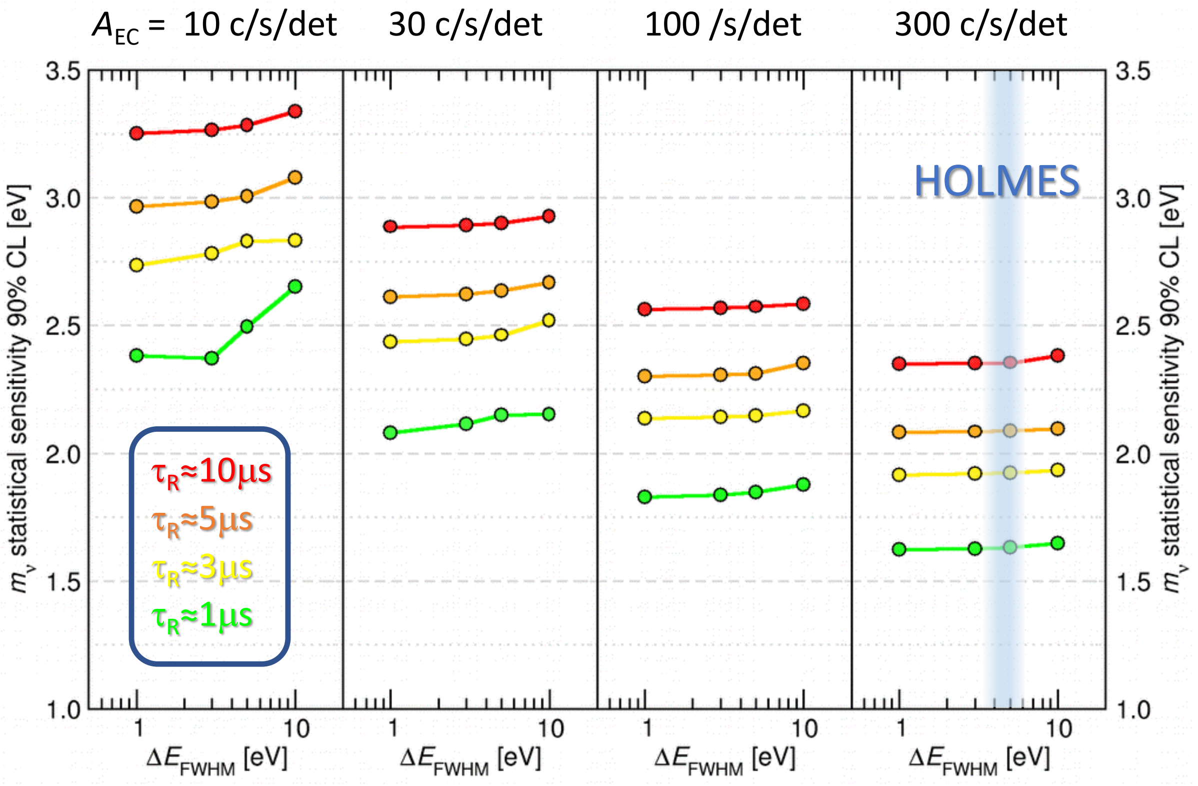


higher counting rates provide higher sensitivity

- robustness against background
- **b ≤ 0.1 counts/eV/day/det** (flat background)

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:

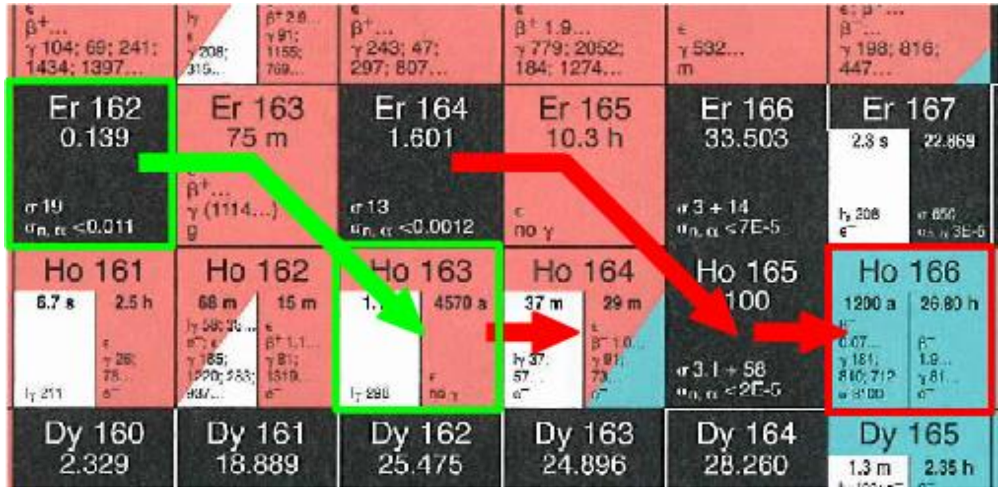
- Neutrino mass determination with a sensitivity as low as ~ 1 eV
- proof potential and scalability of the approach
- precise calorimetric determination of *Q*
- systematic errors assessment

Two steps approach:

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

5 years project started on Feb. 1st 2014

^{163}Ho production



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

- 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 = 5.97 keV**
  - $A(^{163}Ho)/A(^{166m}Ho)$ = 100 ~ 1000
- chemical pre-purification and post-separation at PSI (Villigen, Switzerland)
- **HOLMES needs ~ 200 MBq of ^{163}Ho***

*depends on the actual global embedding process efficiency

^{163}Ho production/2

- So far three batches* of enriched Er_2O_3 irradiated @ILL, pre/post processed @PSI and analyzed with ICP-OES, NAA (PSI) and ICP-MS (PSI+LNGS):
  - 18 mg (enriched ~28%) irradiated for 55 days @ILL ⟶ **5 MBq** (**6 kBq**) of **^{163}Ho** (**^{166m}Ho**)
  - 120 mg (enriched ~26.5%) irradiated for 53 days @ILL ⟶ **23 MBq** (**37 kBq**) of **^{163}Ho** (**^{166m}Ho**)
  - 544 mg (enriched ~25%) irradiated for 50 days @ILL. *Expected in 2018:* **108 MBq** (**200 kBq**) of **^{163}Ho** (**^{166m}Ho**)
- total of **~108 MBq** (**243 kBq**) of **^{163}Ho** (**^{166m}Ho**): enough for R&D and 500 pixels
- Ho radiochemical separation with ion-exchange resins in hot-cells at PSI
  - efficiency ≥ 79%

*from INFN, Uni Milano-Bicocca and CENTRA (Lisbon)

Background

- environmental γ radiation
- γ, X and β from surroundings
- **cosmic rays**
  - GEANT4 simulation for cosmic rays (muons) at sea level
  - 200x200x2 μm^3 Au absorber produce **bkg ≈ 5x10^{-5} c/eV/day/det** (0 – 4 keV)

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

MIBETA experiment: 300x300x150 μm^3 $AgReO_4$ absorber → bkg (2 – 5 keV) ≈ 1.5x10^{-4} c/eV/day/det

- **internal radionuclides (^{166m}Ho)**
  - GEANT4 simulation for ^{166m}Ho (β^-, Q = 1856 keV, $\tau_{1/2}$ = 1200 y)
  - 200x200x2 μm^3 Au absorber produce a **bkg ≈ 10^{-11} c/eV/day/det/(^{166m}Ho nucleus)**

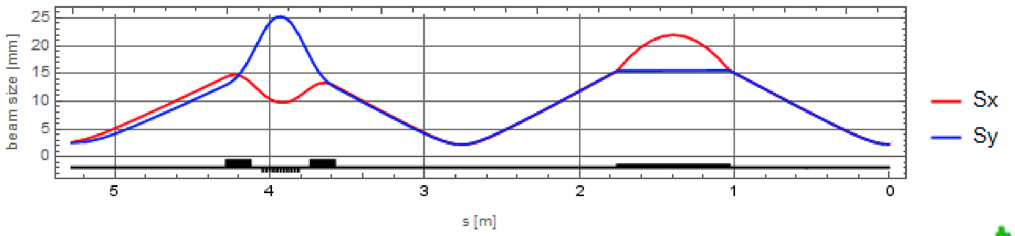
if ***A*** **(^{163}Ho) = 300 Bq** and requiring ***bkg*****(^{166m}Ho) < 0.1 c/eV/day/det**

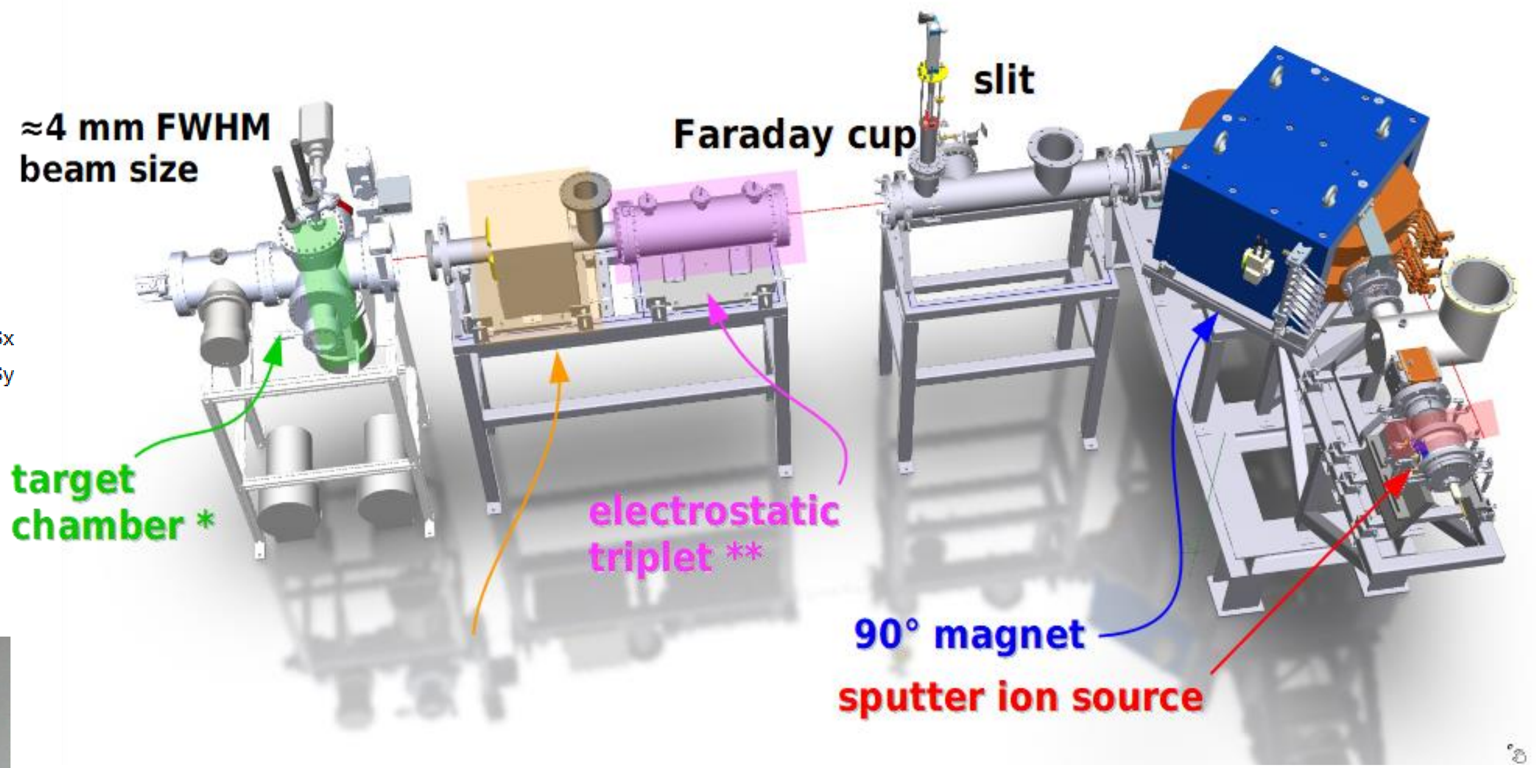
$N(^{163}Ho)/N(^{166m}Ho) > 6000$

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

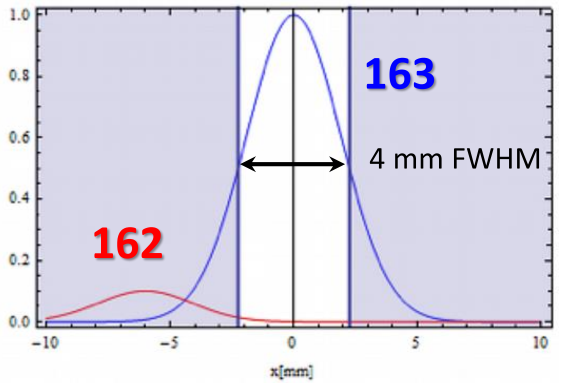
Ion implanter

calculated beam size





*delivered in July 2017
**delivered in January 2018



- extraction voltage 30-50 kV
- 10-100 nm implanting depth
- **^{163}Ho/^{166m}Ho separation better than 10^5**

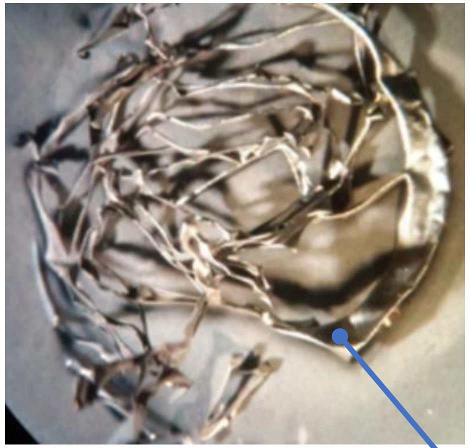
See G. Gallucci (Tuesday talk)
M. De Gerone (poster)

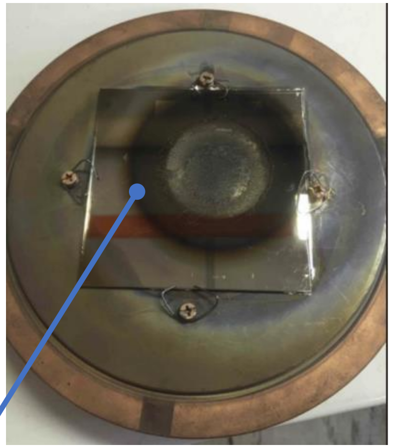
Ion source sputter target production

- sputter target for ion-implanting has to be in metallic form for possible extraction efficiency loss
- enriched Er_2O_3 ⟶ Ho_2O_3
- thermoreduction/distillation in furnace:

  Ho_2O_3 + 2Y(*met*) ⟶ 2Ho(*met*) + Y_2O_3 @T > 1600 °C
- distillation efficiency ≈ 70% (preliminary)

See G. Gallucci (Tuesday talk)
M. De Gerone (poster)



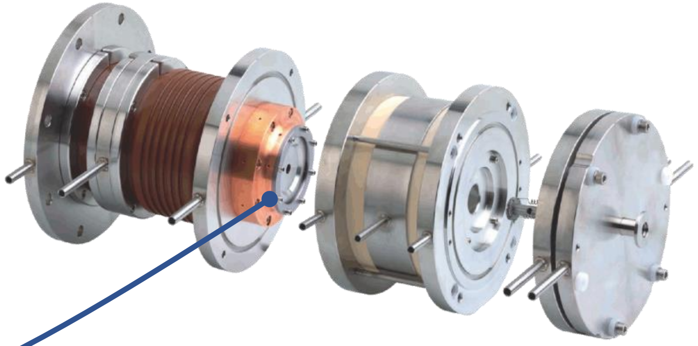


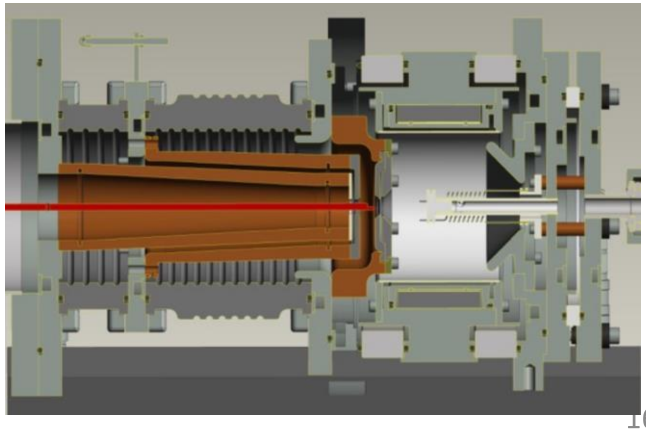
evaporated metallic holmium

Ion source sputter target production/2

- sputter target for ion-implanting has to be in metallic form for possible extraction efficiency loss
  - work in progress to produce the sputter target
  - sintering of Ho with other metals
  - production of targets with different metals to test the implanting efficiency

Ho target





HOLMES detectors & readout

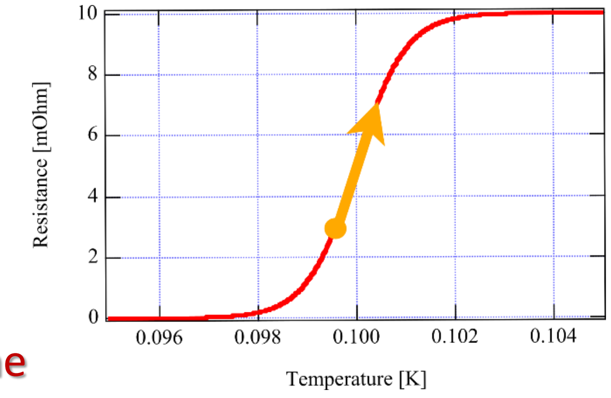
- **transition edge sensors**
  - ➢ good energy resolution: few eVs @ *Q*-value
  - ➢ compatible with ion-implanting
  - ➢ detectors intrinsically fast *O*(100 ns) – slowed down to ~ 20 μs for bandwidth limitations
    - ➢ effective time resolution better than rise time ⟶ pile-up discrimination
  - ➢ 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

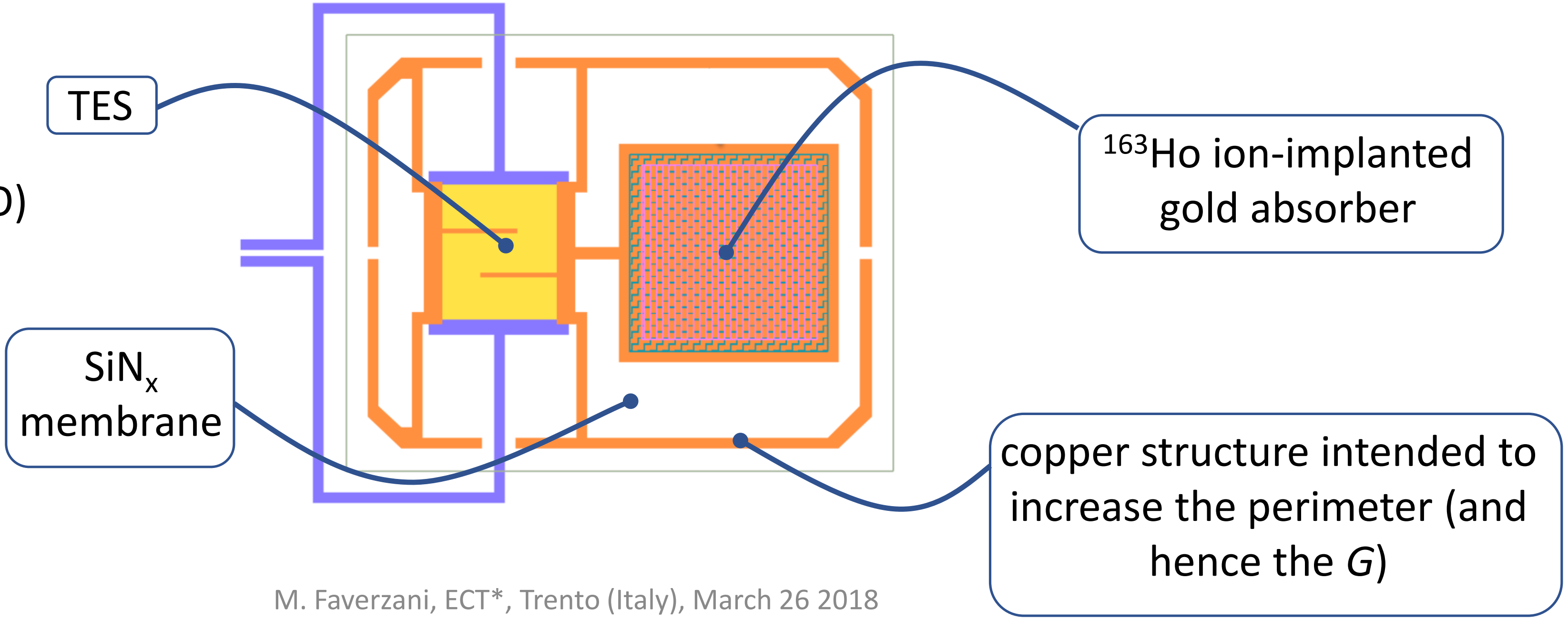
- **DAQ based on Software Defined Radio**
  - ➢ multiplexing factor limited by bandwidth of the ADC

Detectors

- 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



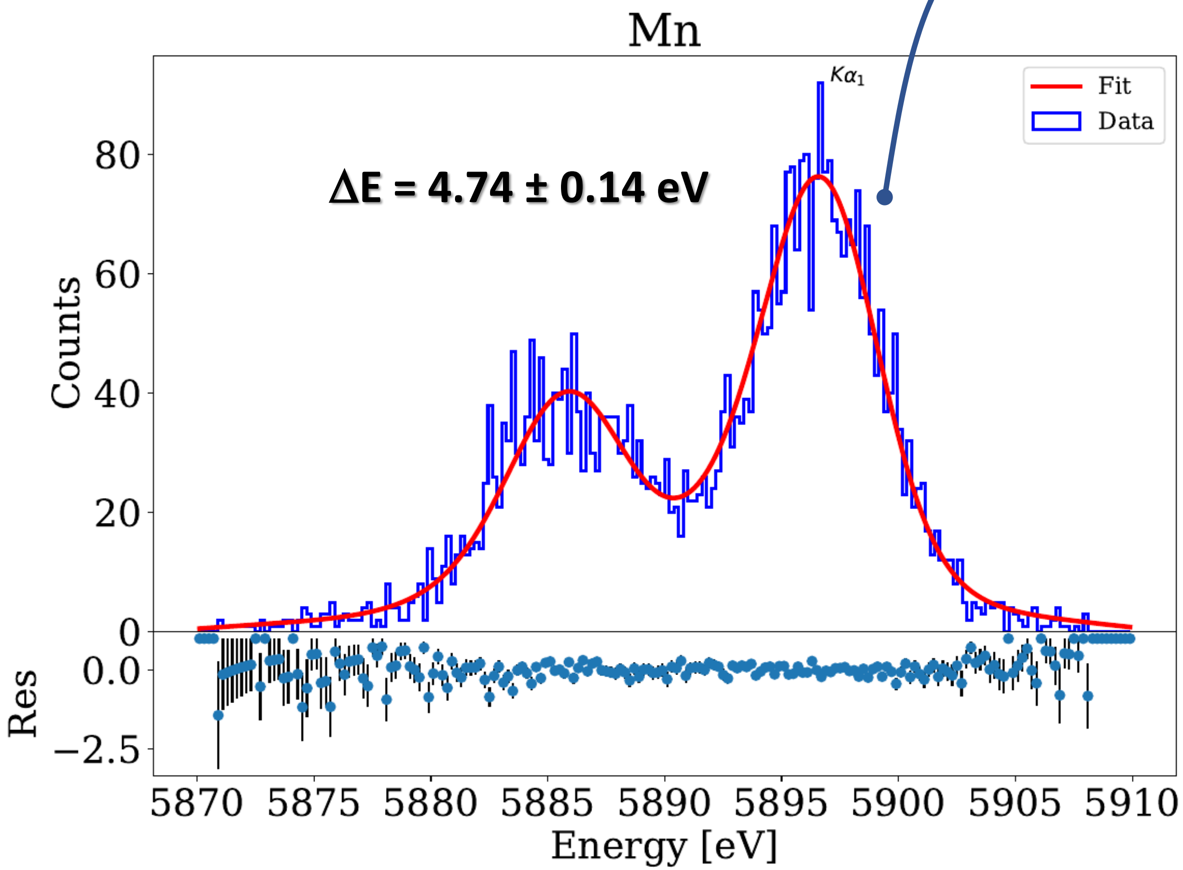
See E. Ferri (Wednesday talk)

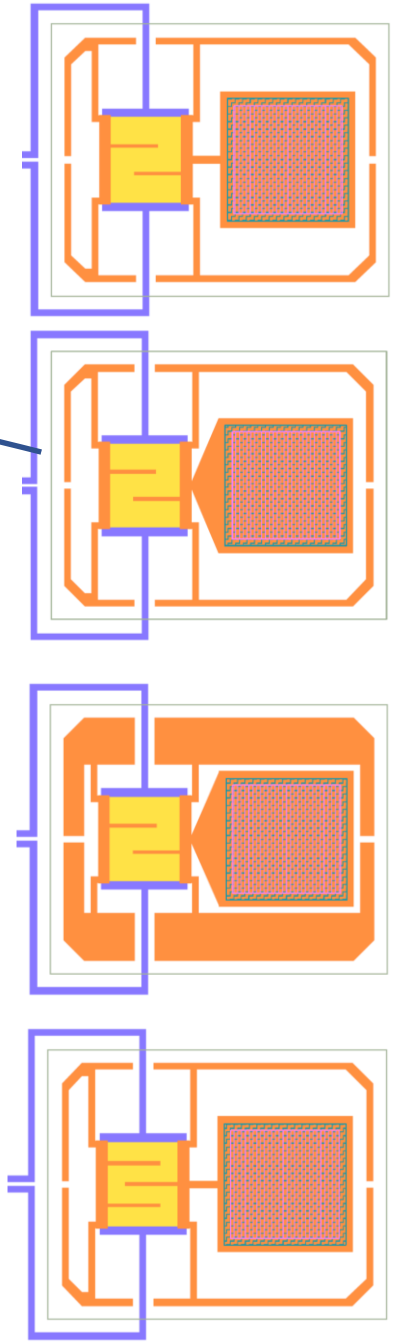
Detectors testing

- 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 $\tau_R \approx 10\ \mu s$

test @Milano with f_{samp} = 500 kHz

E [keV]	ΔE [eV]
1.49	4.6
2.62	5.3
3.69	4.6

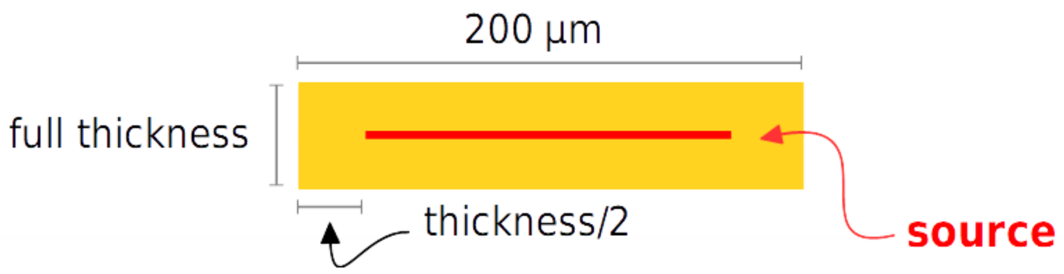




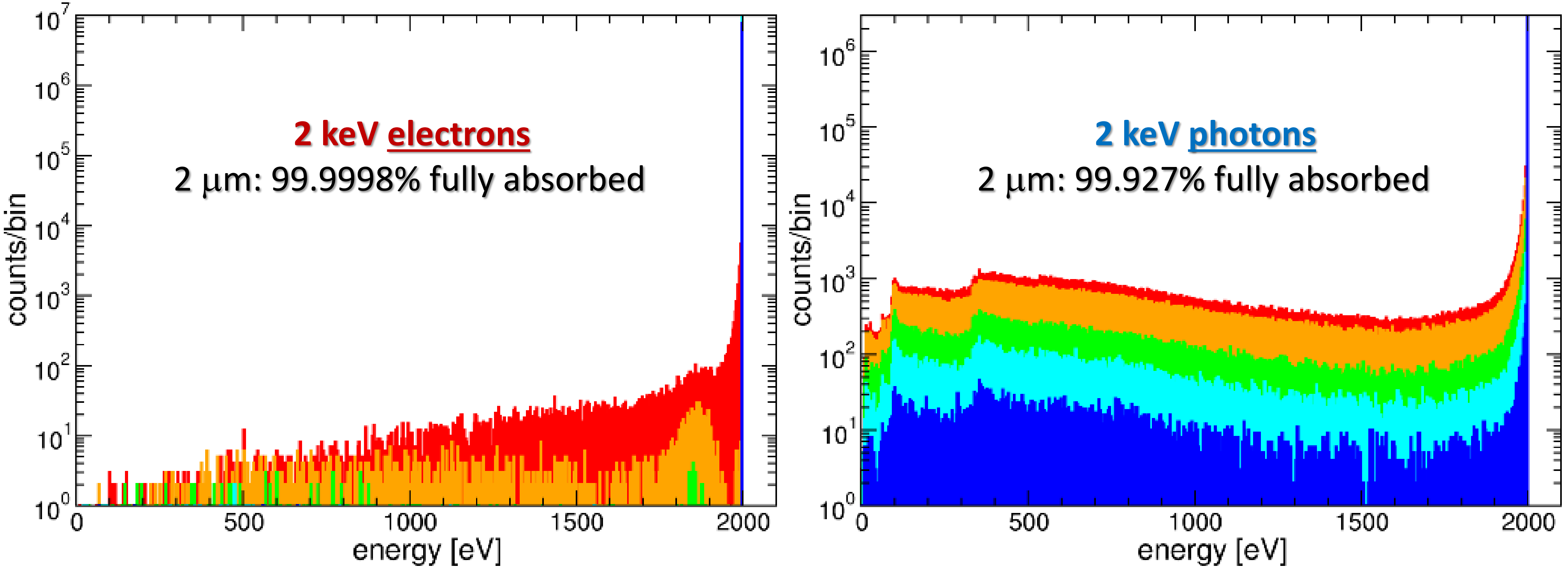
See E. Ferri (Wednesday talk)

Gold absorber - simulations

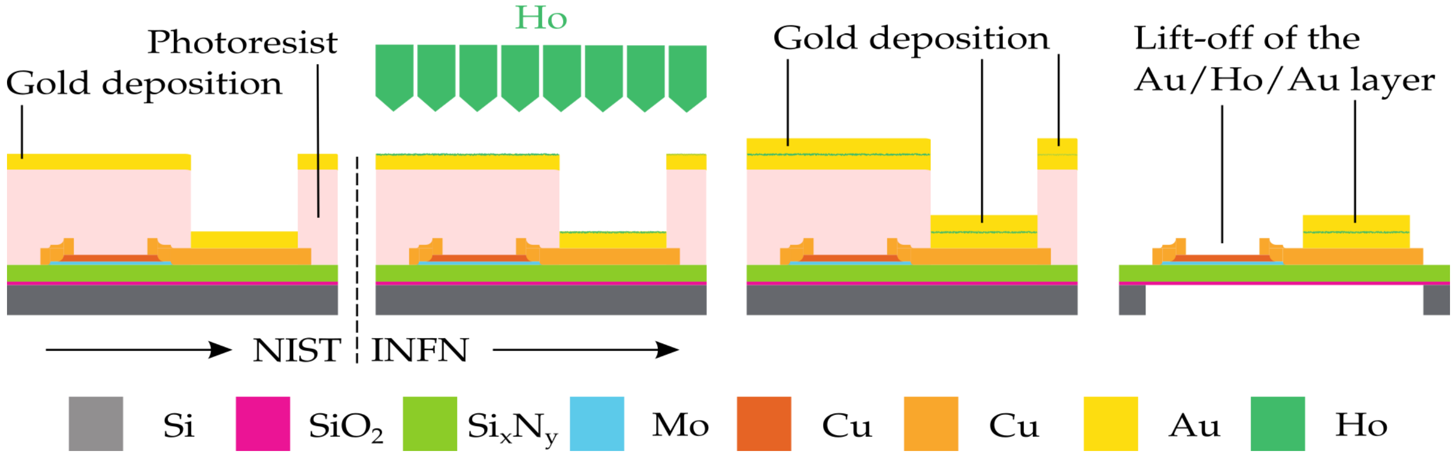
Geant4 + LowEnergyEM MC simulation: 10^7 events



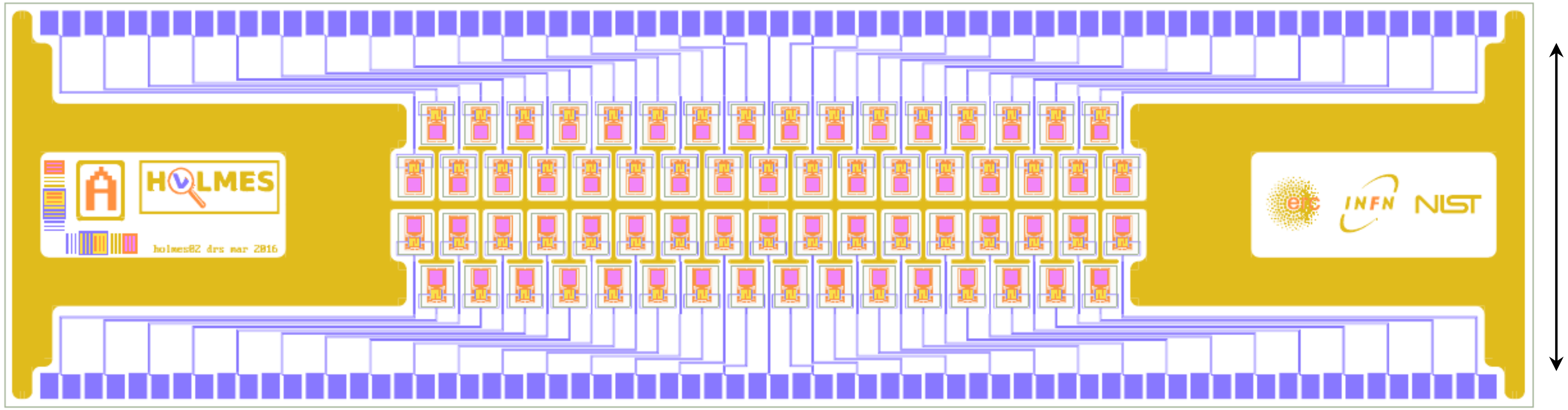
full thickness: 0.05, 0.1, 0.5, 1, 2 μm



Detectors fabrication

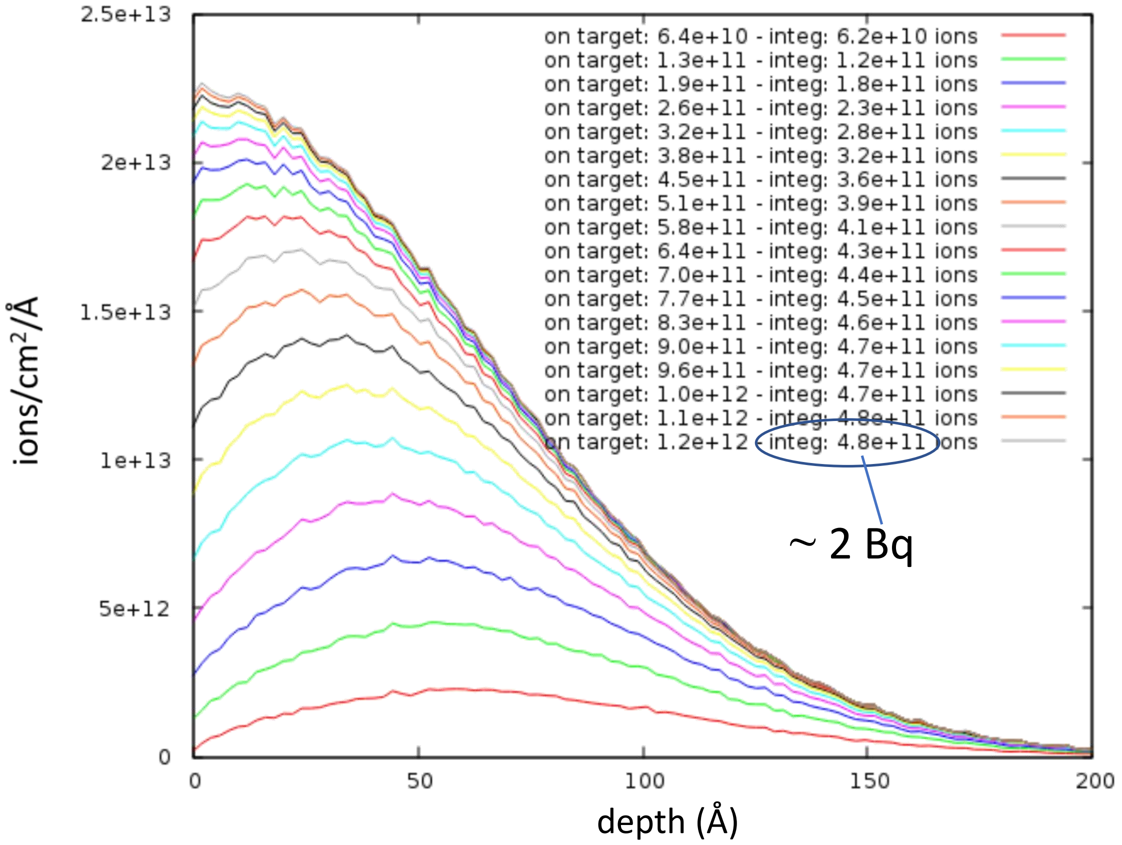


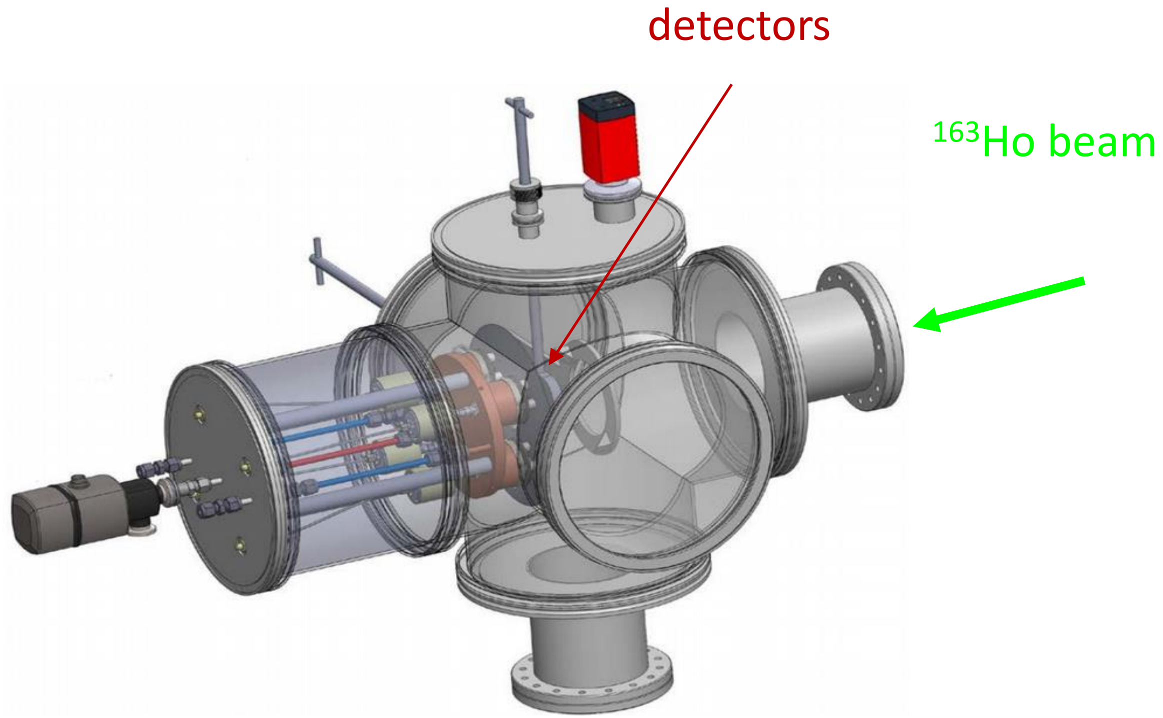
- TES originally fabricated at NIST, Boulder, CO, USA
- ^{163}Ho implantation at INFN, Genova, Italy
- 1 μm Au final layer deposited at INFN, Genova, Italy
- final fabrication process: release of the membrane with KOH in Milano or DRIE
- HOLMES 4 x 16 linear sub-array for low parasitic *L* and high implant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

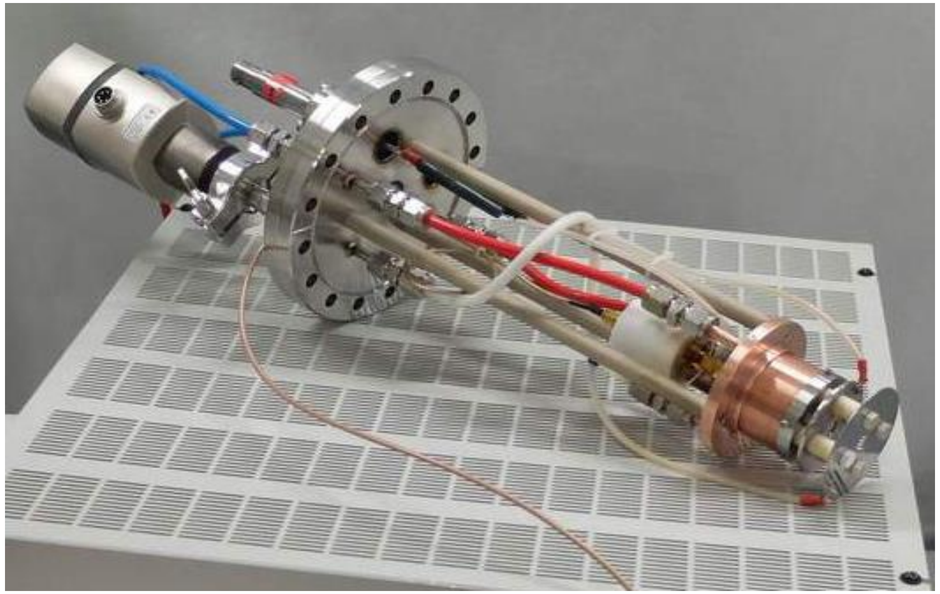


calculated ^{163}Ho beam FWHM

Target chamber



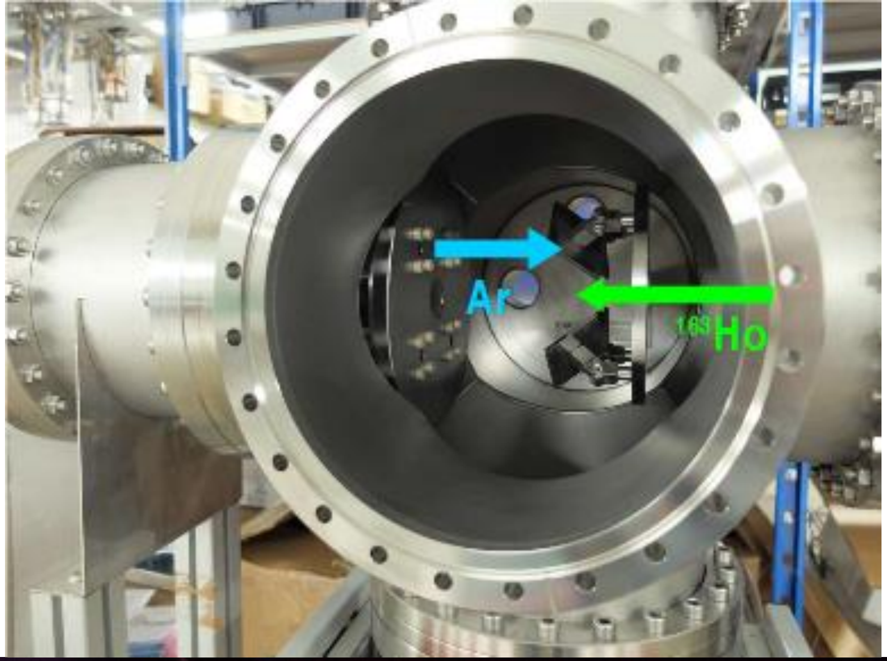


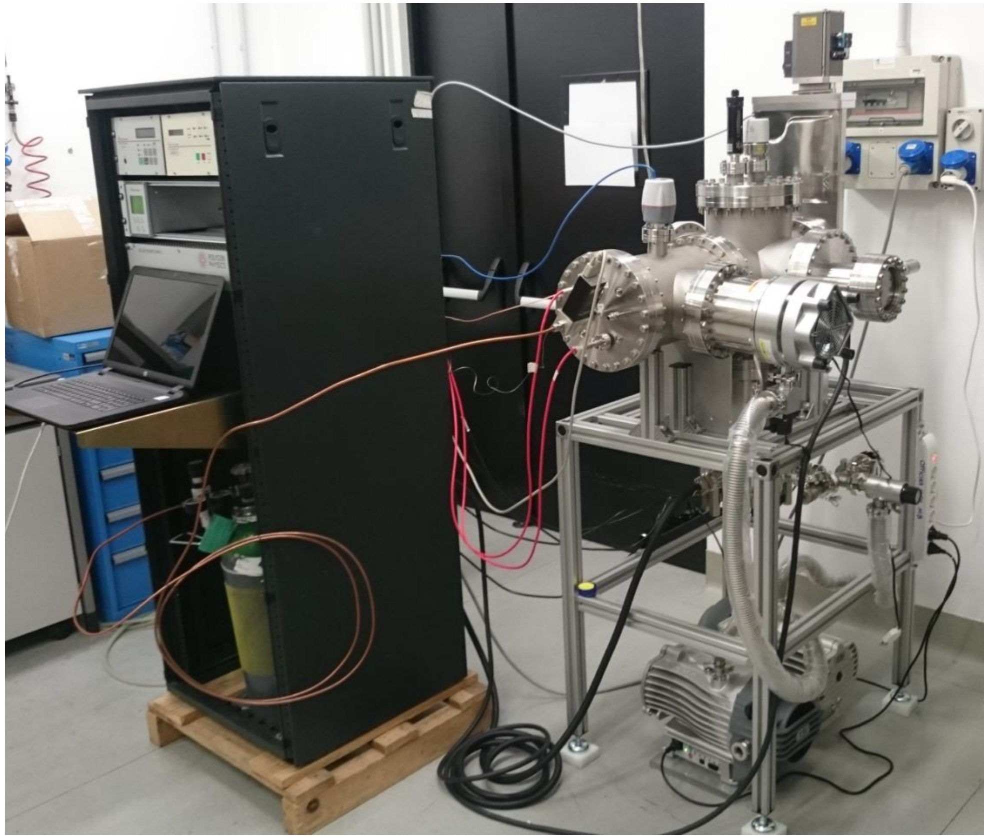


- ^{163}Ho concentration in absorbers saturate because ^{163}Ho sputters off Au from absorber
- effect compensated by Au co-evaporation (also for heat capacity reasons)
- final 1 μm Au layer deposited in situ to avoid oxidation

Target chamber/2

gold deposition rate ≈ 100 nm/hour
(tunable with RF power or with Ar energy)





Microwave multiplexing readout

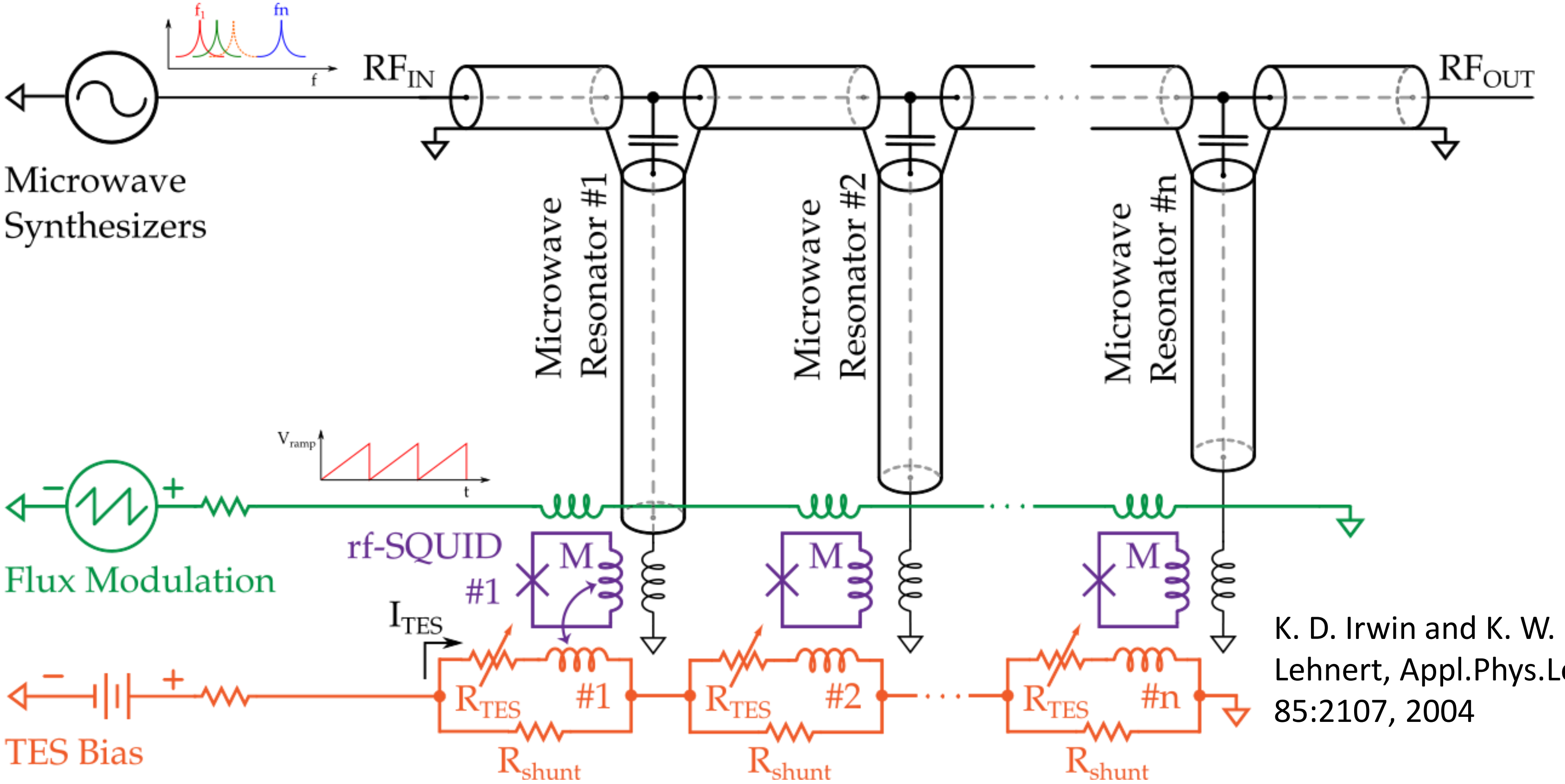
See E. Ferri (Wednesday talk)

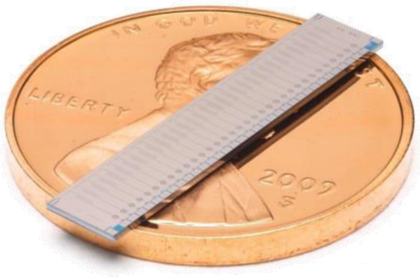
TESs readout with microwave multiplexing (produced by NIST)

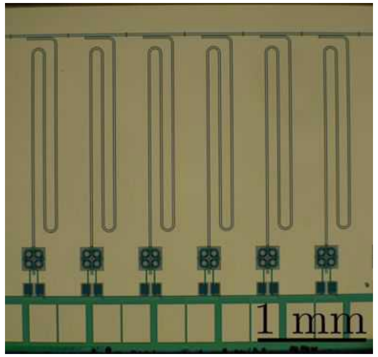
- each sensor inductively coupled to a RF-squid part of a $\lambda/4$ resonator
- a comb of signals probe the resonators at their characteristic resonant frequency

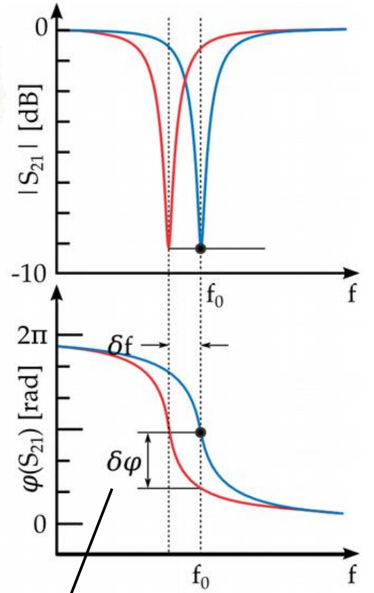
$$E \longrightarrow \delta T_{TES} \longrightarrow \delta I_{TES} \longrightarrow \delta\phi_{squid} \longrightarrow \delta f_{resonator}$$

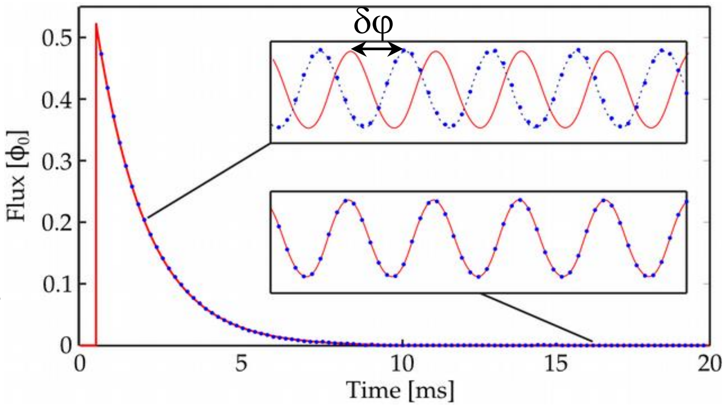
- a ramp signal added to the squids in order to linearize the response





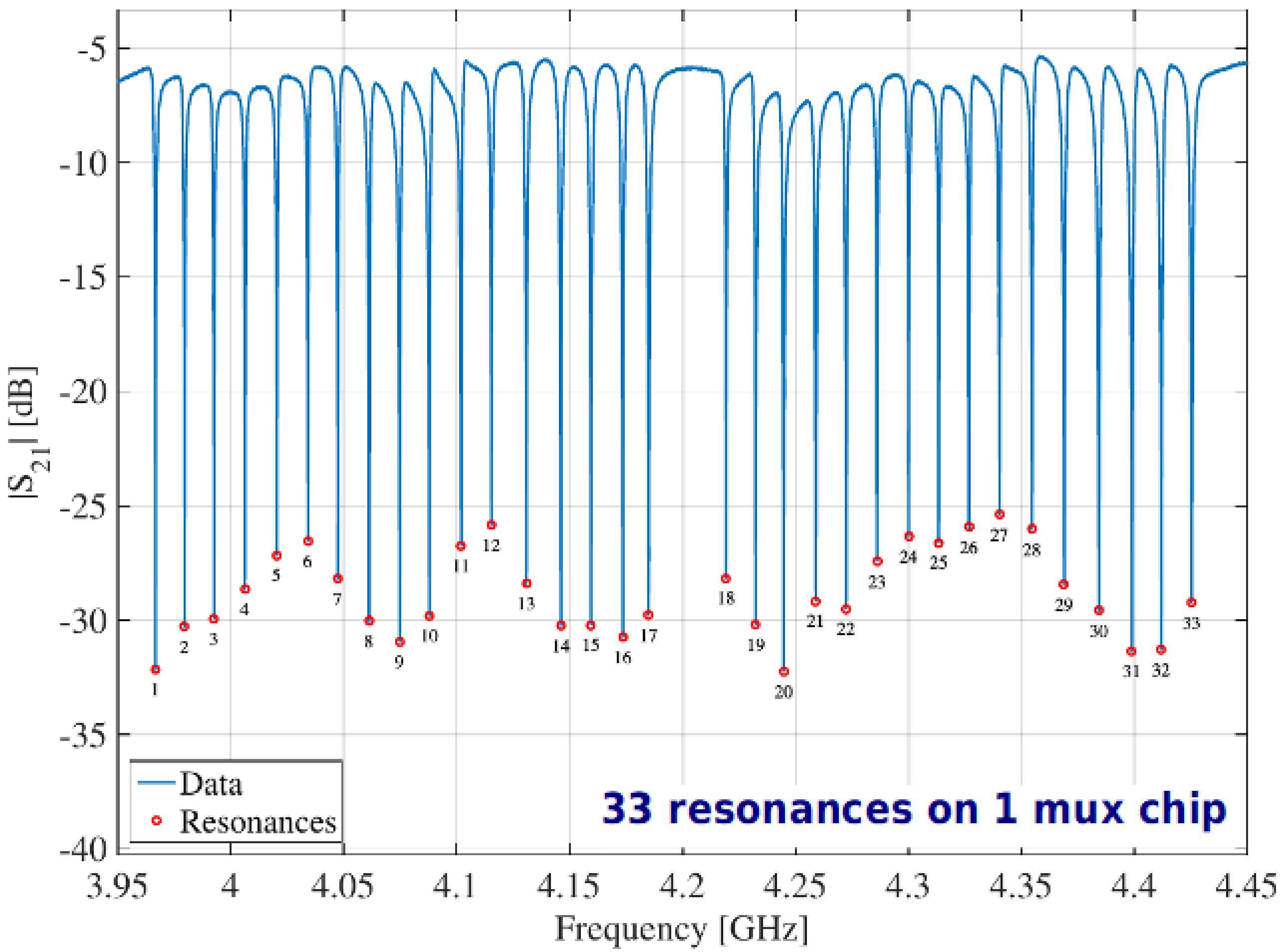


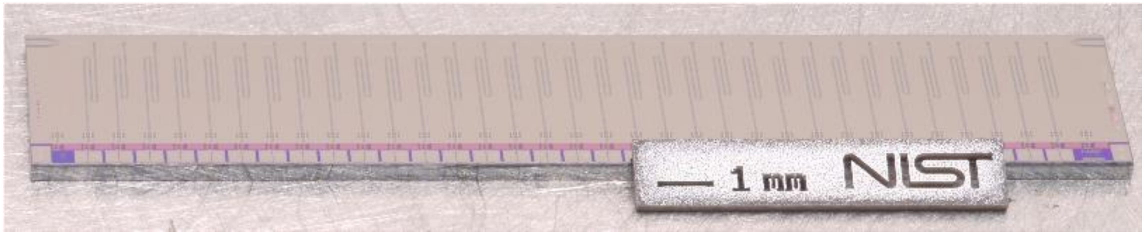




K. D. Irwin and K. W. Lehnert, Appl.Phys.Lett., 85:2107, 2004

Microwave multiplexing readout



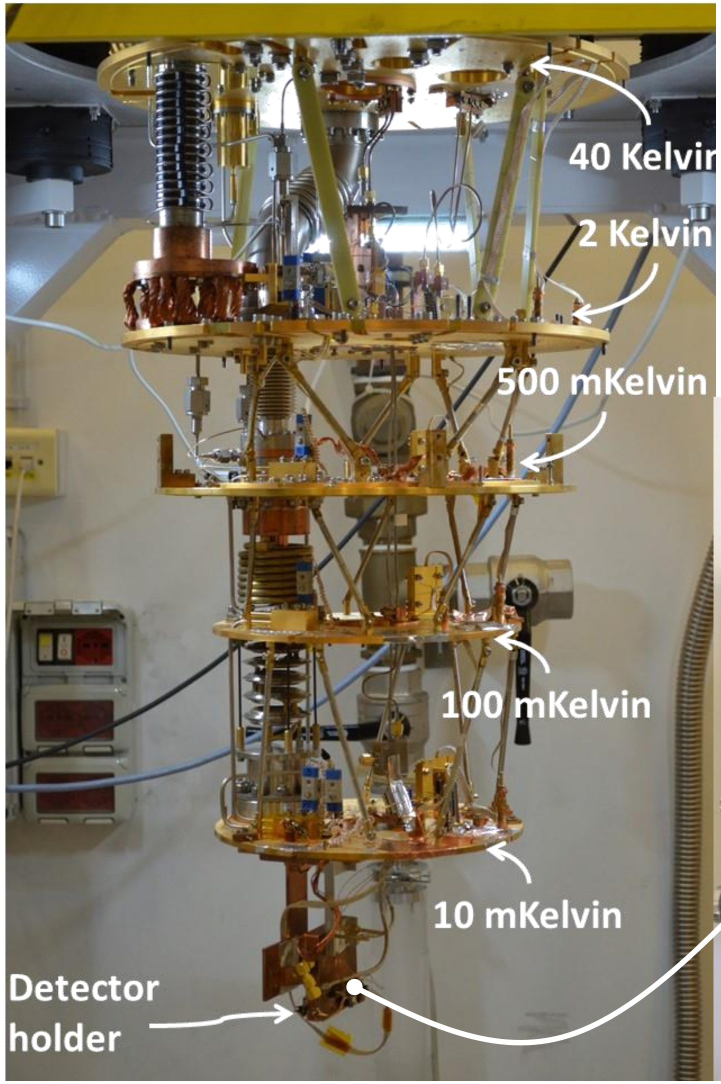


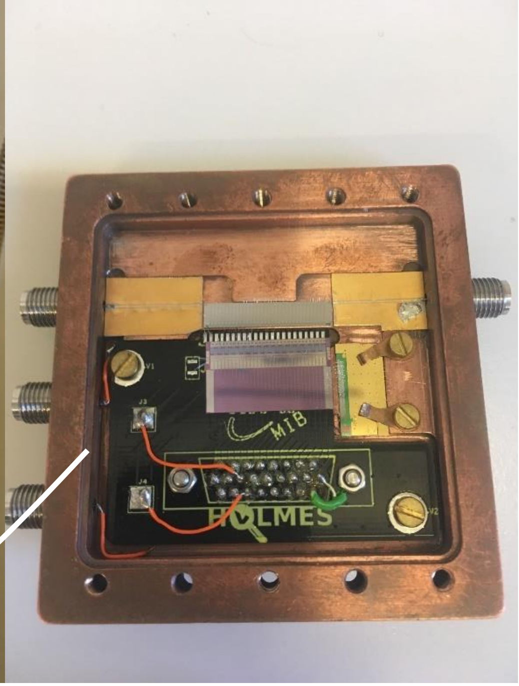
- 33 resonances/chip over 500 MHz
- BW = 2 MHz per resonator
- separation between resonances 14 MHz (to prevent crosstalk)
- depth greater than 10 dB
- SQUID equivalent noise: ≤ 2 $\mu\phi_0/\sqrt{Hz}$

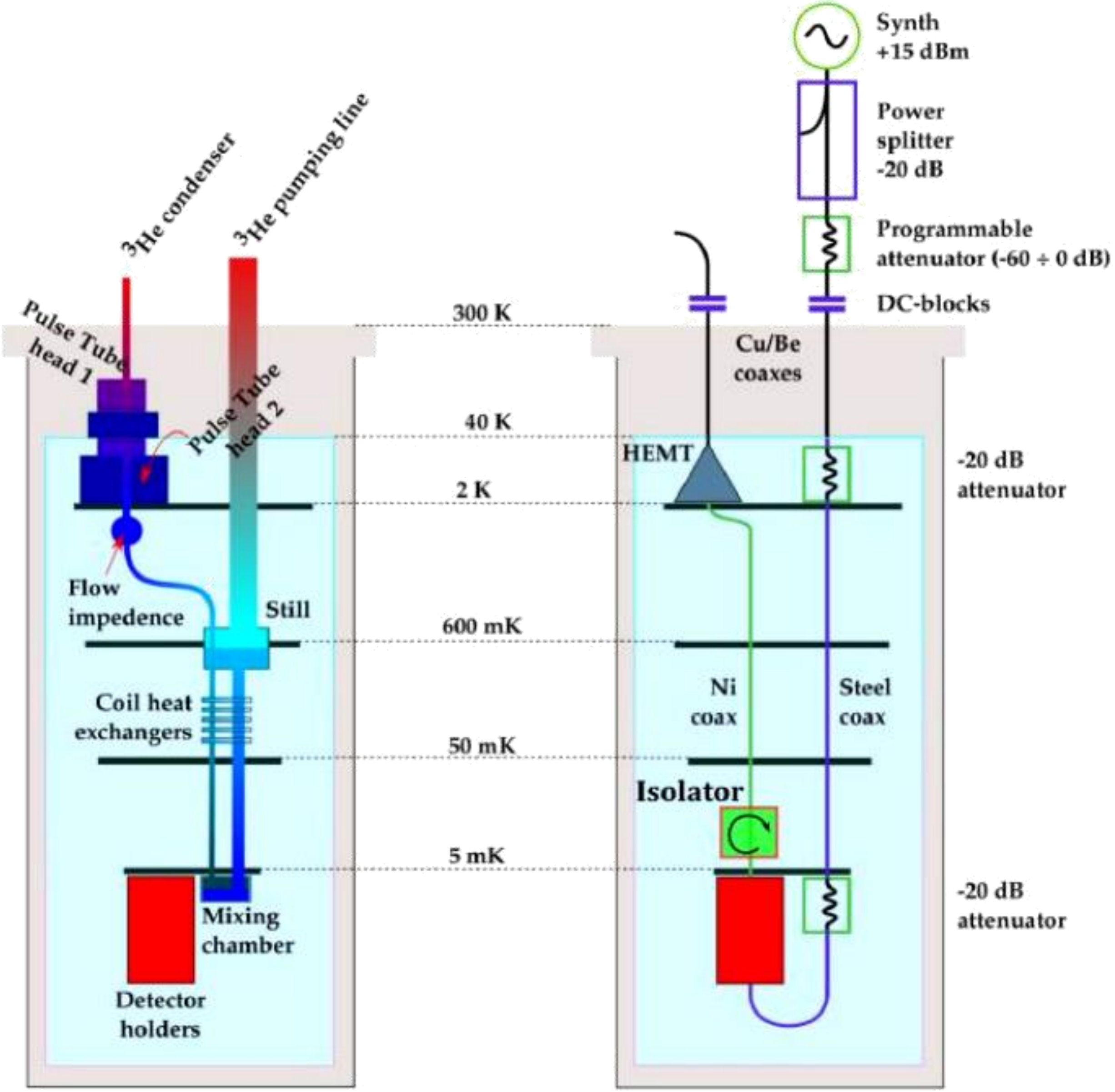
See E. Ferri (Wednesday talk)

Cryogenic set-up

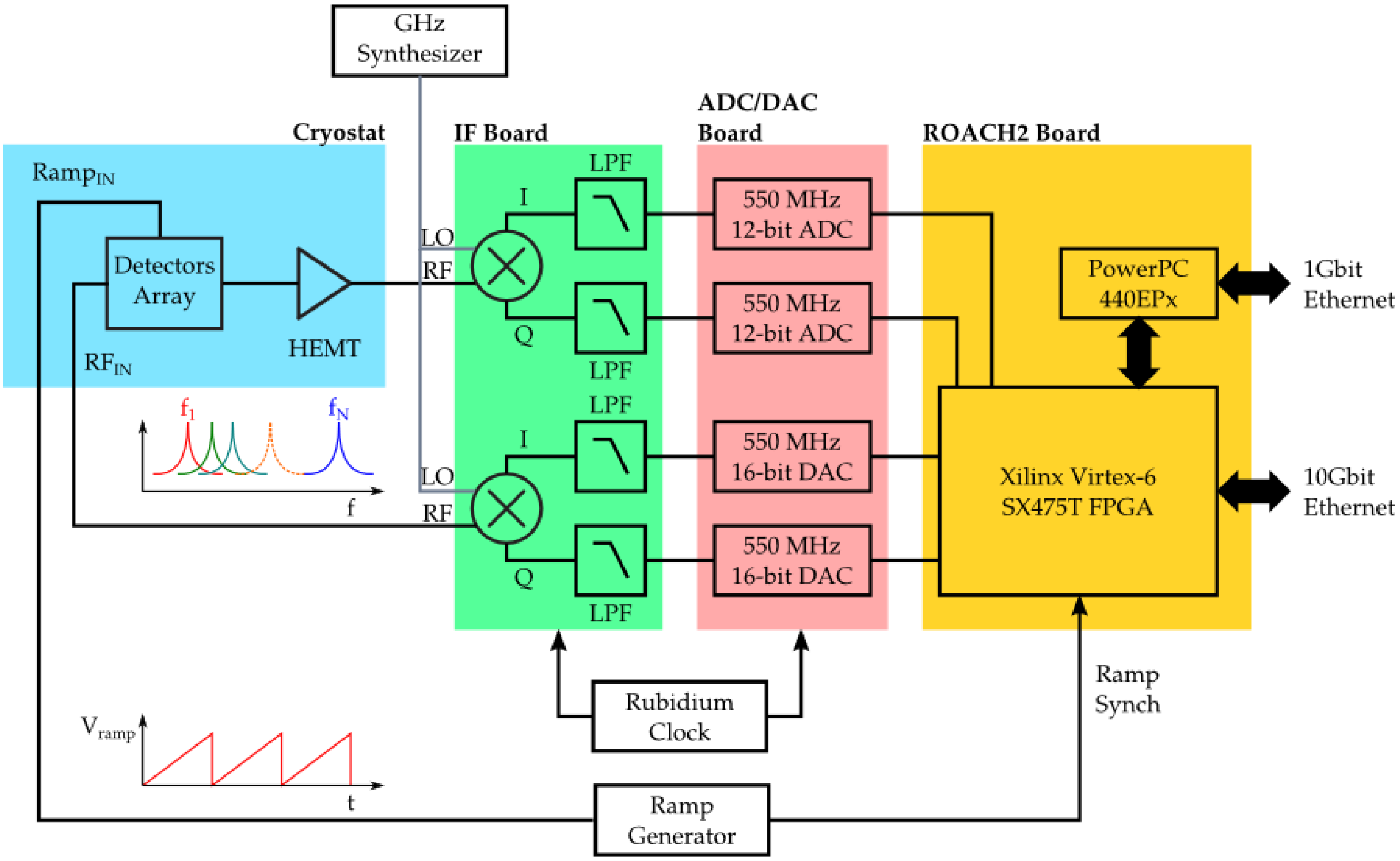
dry dilution refrigerator







DAQ with the ROACH2



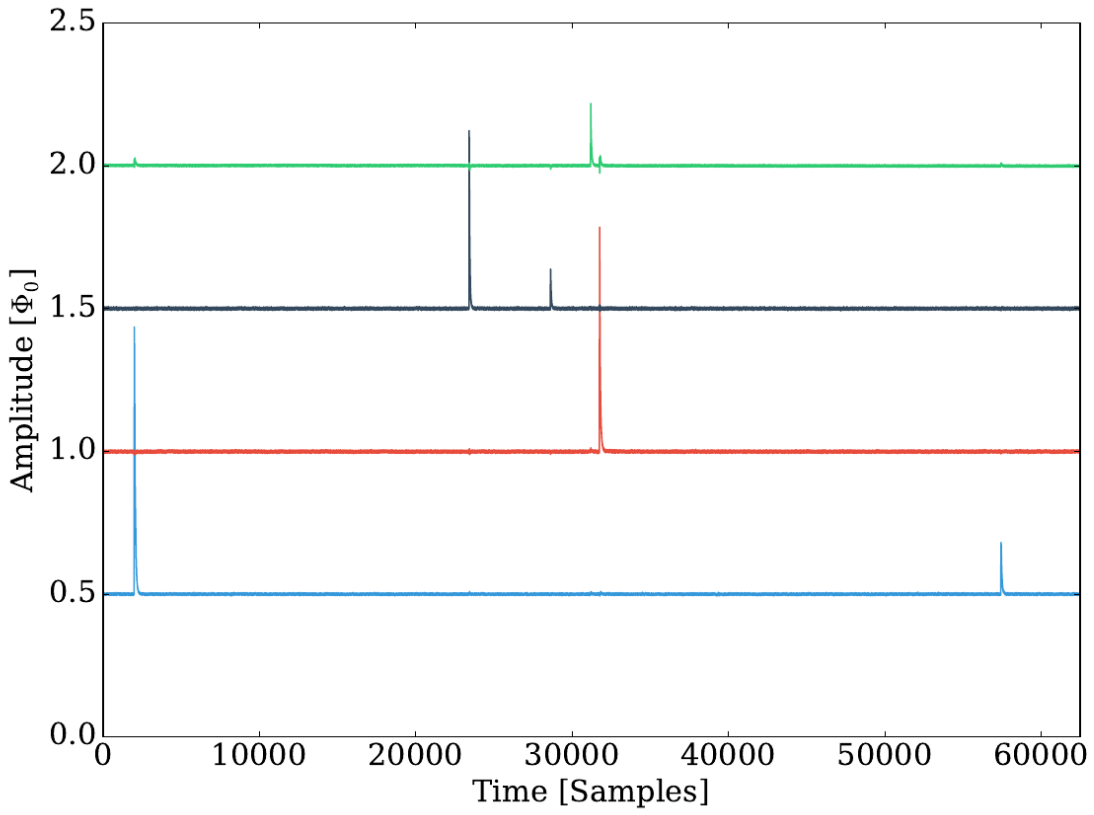
- Software Defined Radio with the open system ROACH2 (Casper collaboration)
- ADC BW 550 MHz
- real time pulse reconstruction

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

requiring τ_R = 10 μs

$n_{TES} \approx 34$

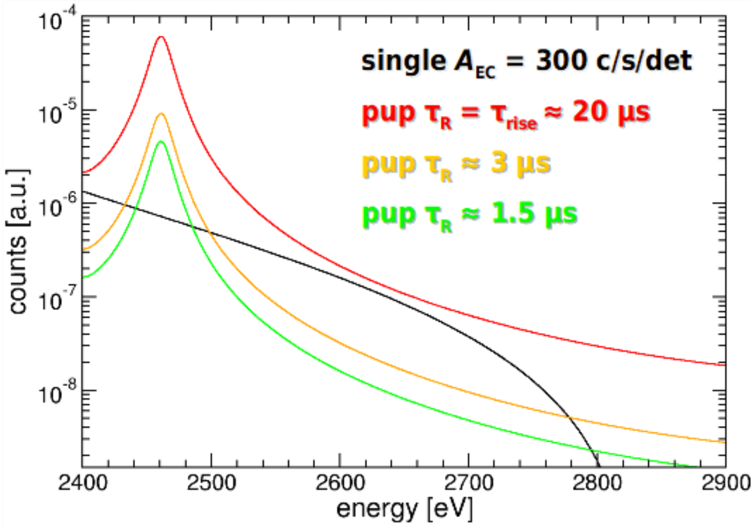
At the moment n_{TES} is limited by the readout power of the RF probe signals

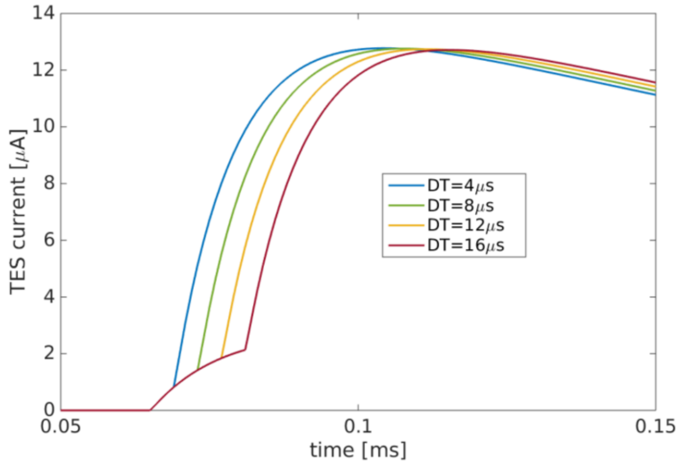


Detector time resolution (MC simulations)

pile-up spectrum with a time resolution τ_R:

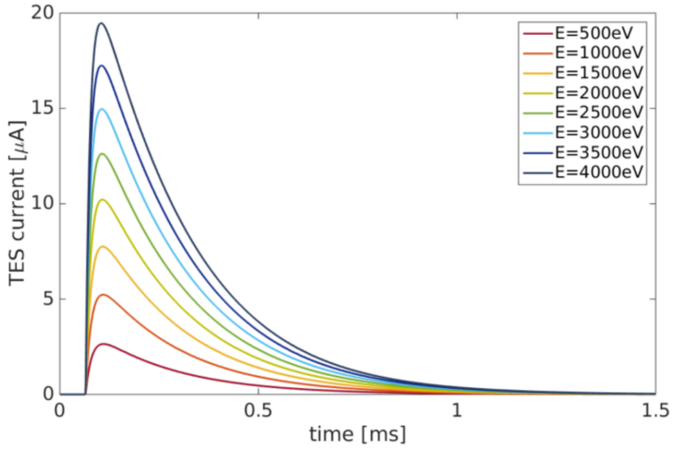
$$N_{pp}(E) = A_{EC}\int_0^{\infty}\tau_R(E,\epsilon)N_{EC}(\epsilon)N_{EC}(E-\epsilon)d\epsilon$$

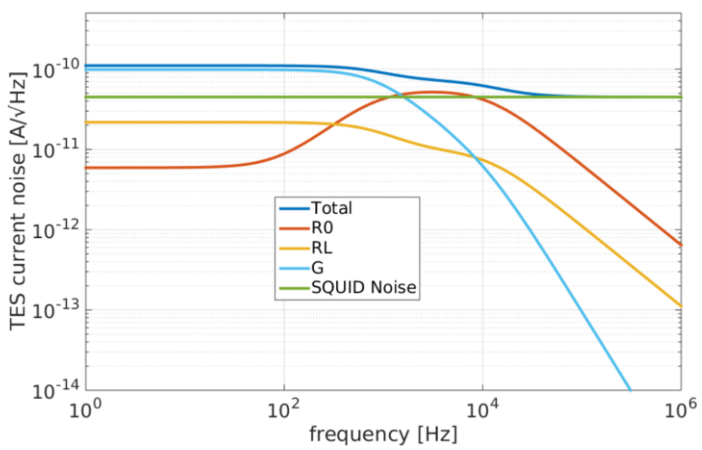




E1 + E2 ∈ (2.4 ÷ 2.9) keV (from ^{163}Ho spectrum), $\Delta t \in [0 \div 10]$ μs

pulse shape and noise from NIST TES model, sampled with f_{samp}, record length, and *n* bit





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

- Wiener Filter → $\tau_R \approx$ 3μs
- Single Value Decomposition → $\tau_R \approx$ 1.5 μs

Signal processing

- normal data taking (hypothetical configuration)
  - ❑ Save only *n*-tuples (6 x 4 byte words)
  - ❑ high threshold ($E_{th} \approx 2.022$ keV < E_{M_1}, 21% of spectrum)
  - ➢ **about 150 TB 3 years of data-taking**
- periodic minimum bias samples (temporary storage)
  - ❑ tune parameter for real time pulse processing
  - ❑ full waveform for immediate off-line analysis (512 samples x 12 bits)
  - ❑ full spectrum ⟶ **20 TB/day**

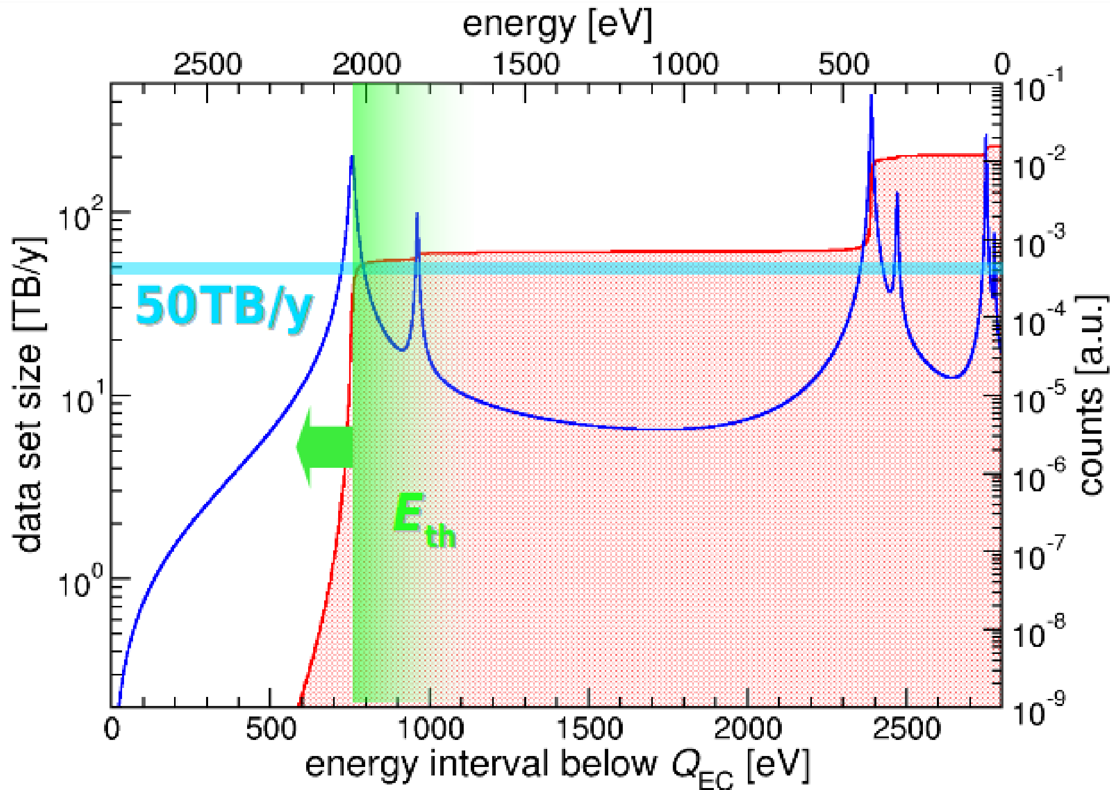
ROACH2 real-time

pulse processing + threshold cut

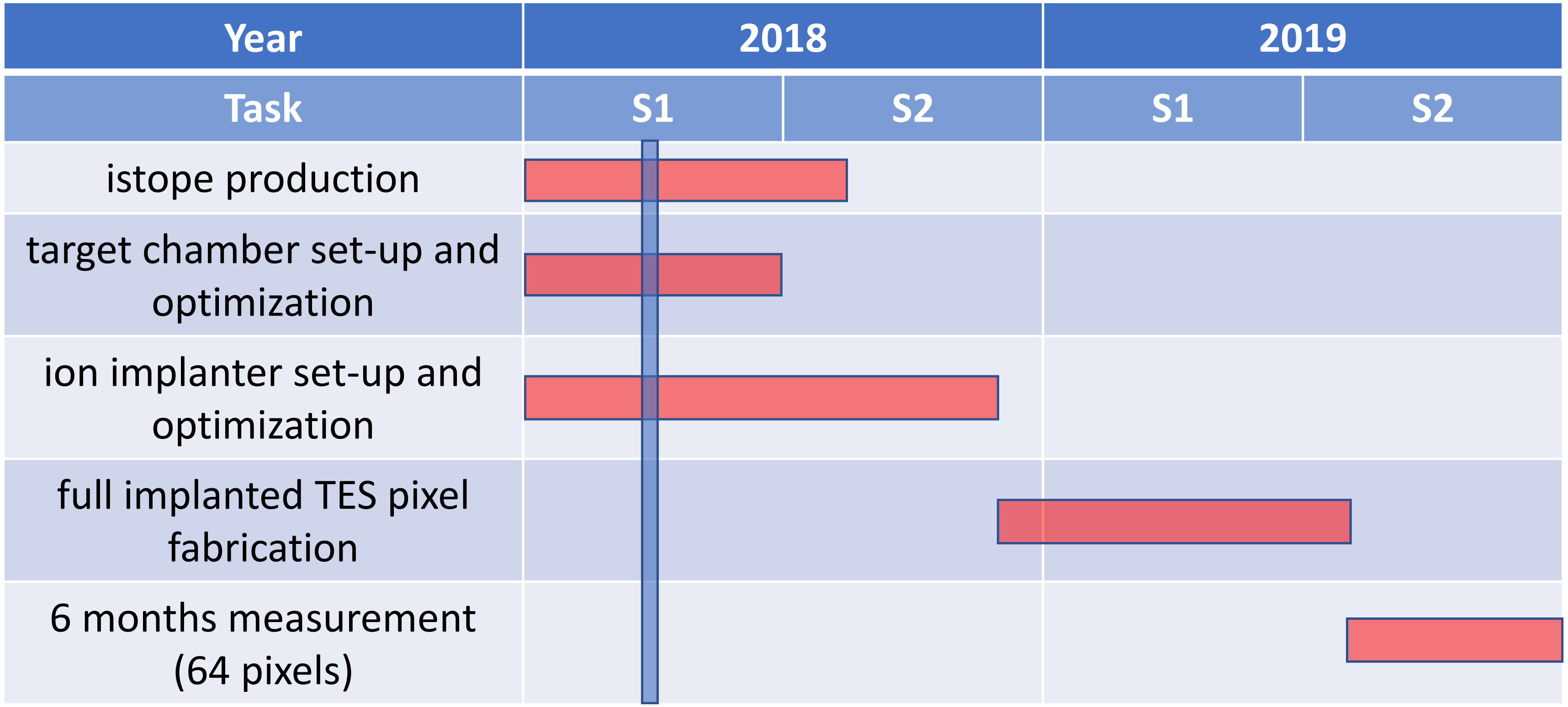
Server quasi real-time

pulse processing:

- OF analysis
- pile-up detection
- …



Schedule



Project status:

- TES detectors and DAQ ready
- ion implanting and target chamber are being setting up
- first spectrum measurement with 64 channles will start in mid 2019
  - ➢ 1 month of data-taking → $\Sigma_{m_\nu} \approx 10$ eV