HOLMES

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DIRECT NEUTRINO MASS MEASUREMENTS

Università di Roma "La Sapienza", July 8th, 2020

HOLMES collaboration

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https://holmes0.mib.infn.it/

Outline

- ^{163}Ho decay calorimetry and neutrino mass measurement
- HOLMES status
  - isotope production and chemical purification
  - isotope mass separation and implantation
  - single detector R&D
  - detector array fabrication
  - detector read-out and DAQ
  - background measurements
- short and mid term program: 2020-2023
- beyond HOLMES: future of ^{163}Ho experiments
- PTOLEMY-0 as neutrino mass experiment: a quick overview

Electron capture calorimetric experiments

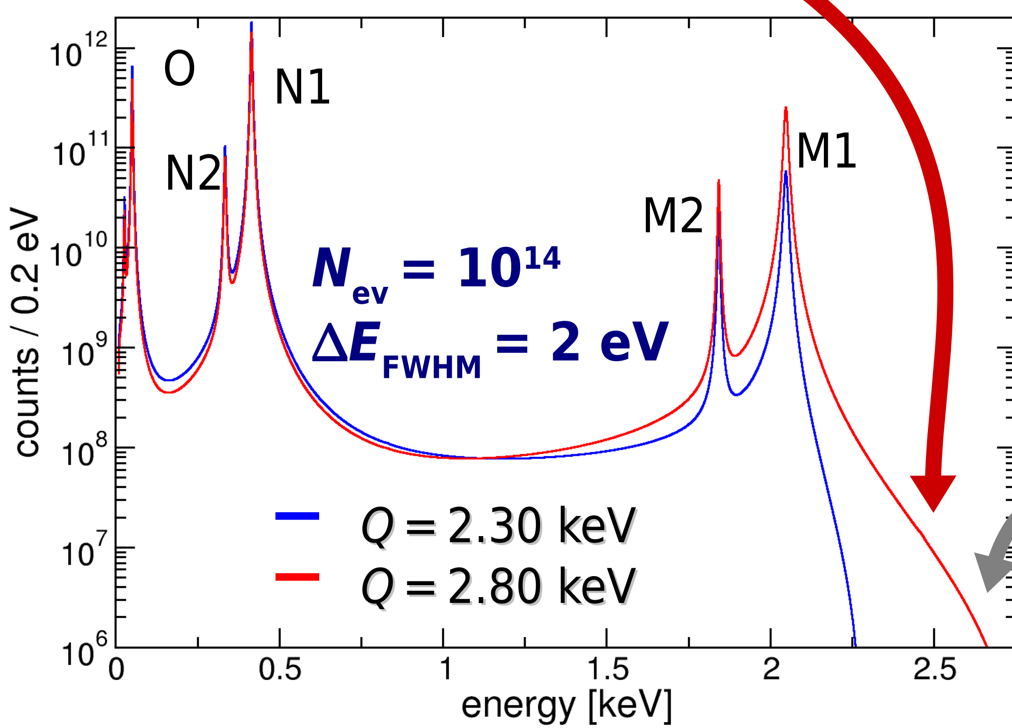
$^{163}Ho + e^- \rightarrow {}^{163}Dy^* + \nu_e$

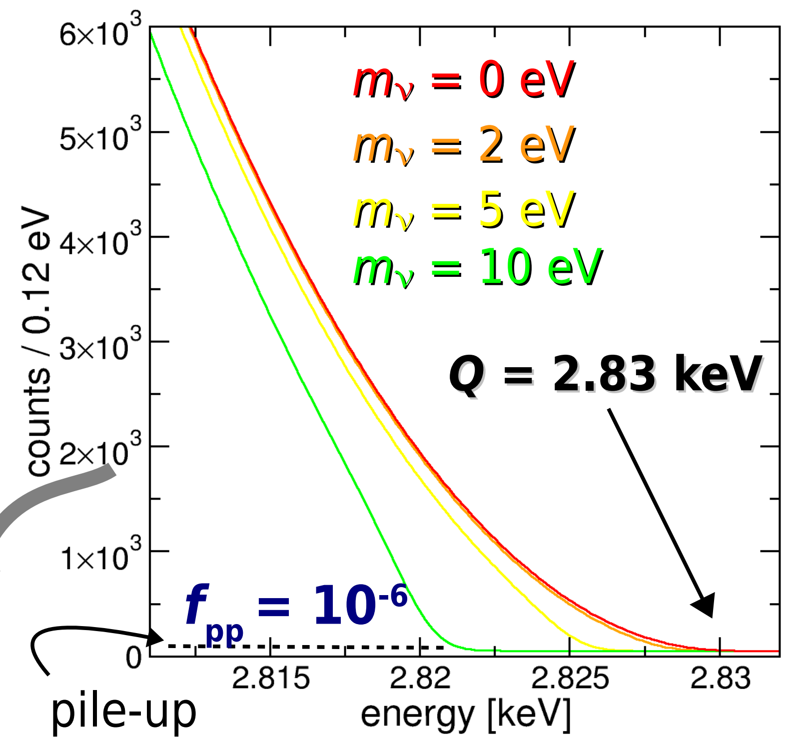
electron capture from shell ≥ M1

A. De Rújula and M. Lusignoli, Phys. Lett. B 118 (1982) 429

- **calorimetric measurement of Dy atomic de-excitations** (mostly non-radiative)
- ***Q* = 2.83 keV** (determined with Penning trap in 2015)
  - end-point rate and **ν mass sensitivity** depend on $Q - E_{M1}$
- $\tau_{1/2}$ **≈ 4570 years** → 2×10^{11} ^{163}Ho nuclei ↔ 1Bq

$$N(E_c) = \frac{G_\beta^2}{4\pi^2}(Q-E_c)\sqrt{(Q-E_c)^2 - m_\nu^2} \times \sum_i n_i C_i \beta_i^2 B_i \frac{\Gamma_i}{2\pi}\frac{1}{(E_c-E_i)^2+\Gamma_i^2/4}$$

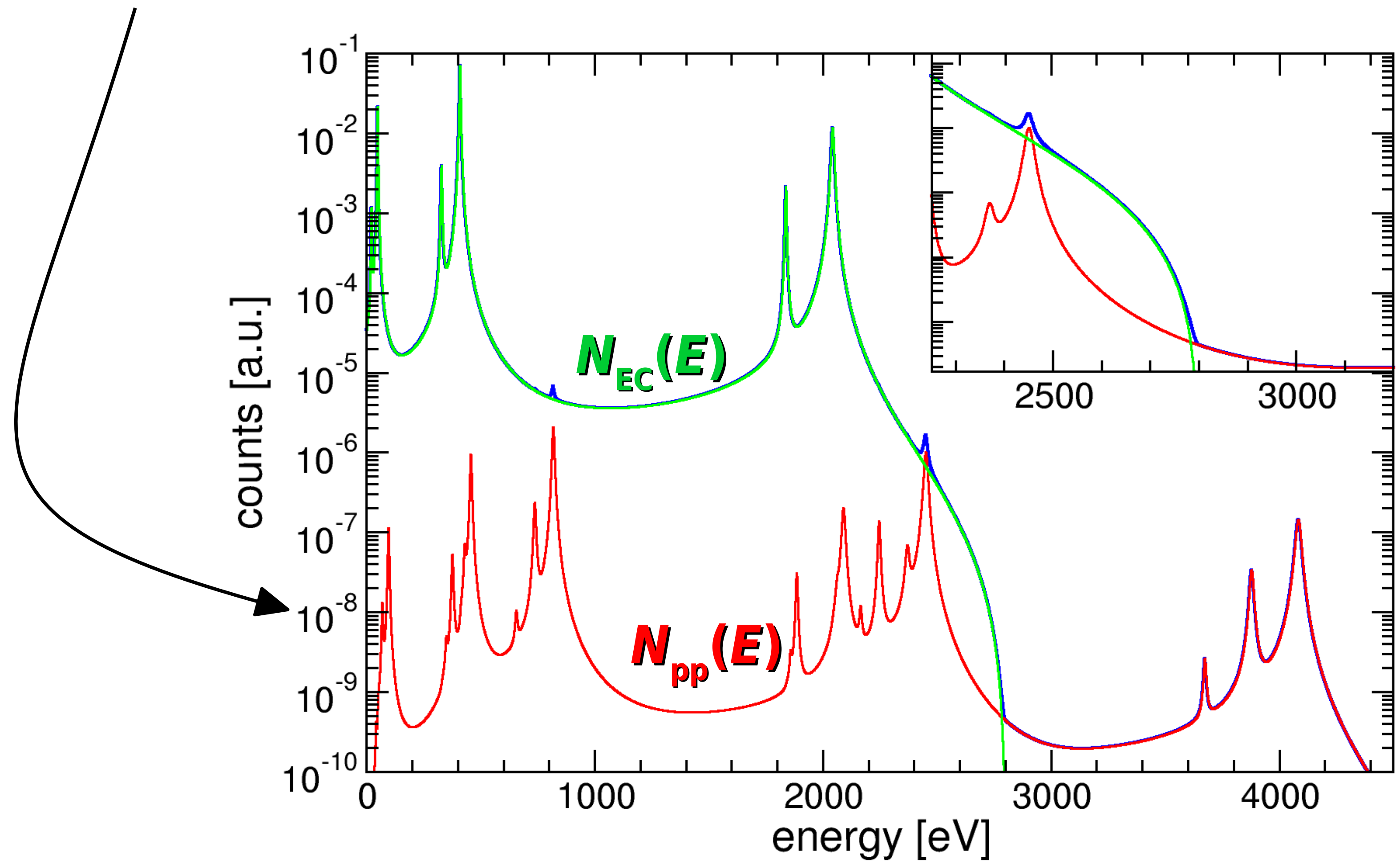




Electron capture calorimetric experiments

- calorimetric measurement ↔ **detector speed is critical**
- accidental coincidences → complex pile-up spectrum
  - $N_{pp}(E) = f_{pp}\, N_{EC}(E) \otimes N_{EC}(E)$ with $f_{pp} \approx A_{EC}\, \tau_R$

A_{EC} EC activity per detector
τ_R time resolution (≈rise time)



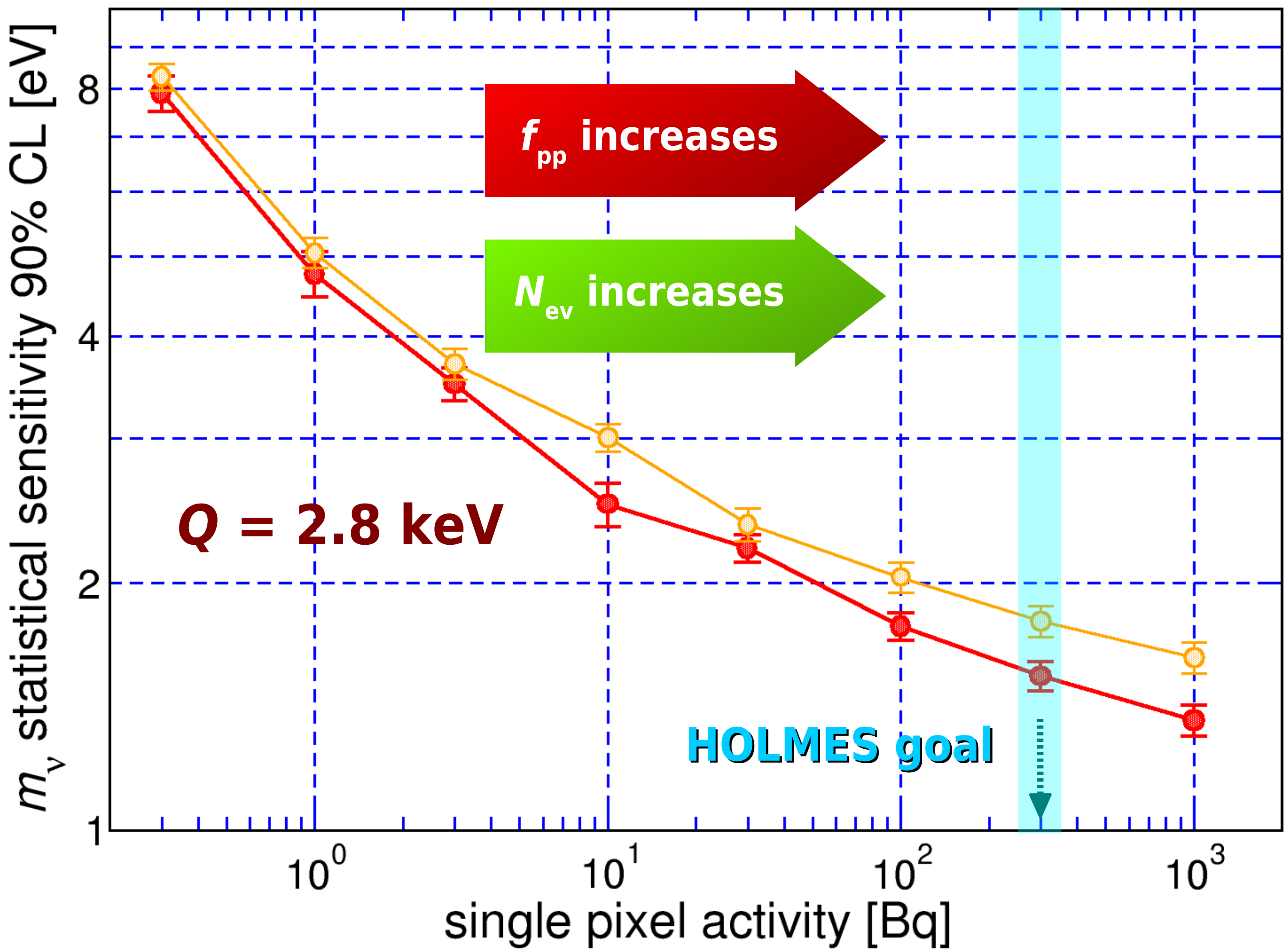
Q = 2800 eV

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

$N_{EC}(E)$ without higher order processes (shake up / shake off)

Statistical sensitivity and single pixel activity

exposure $N_{det} t_M$ = 1000 det × 3 y



ΔE =1 eV
τ_R = 1 μs

ΔE =3 eV
τ_R = 3 μs

high activity → robustness against (flat) background

A_{EC}=300 Bq → *bkg*<≈0.1 counts/eV/day/det

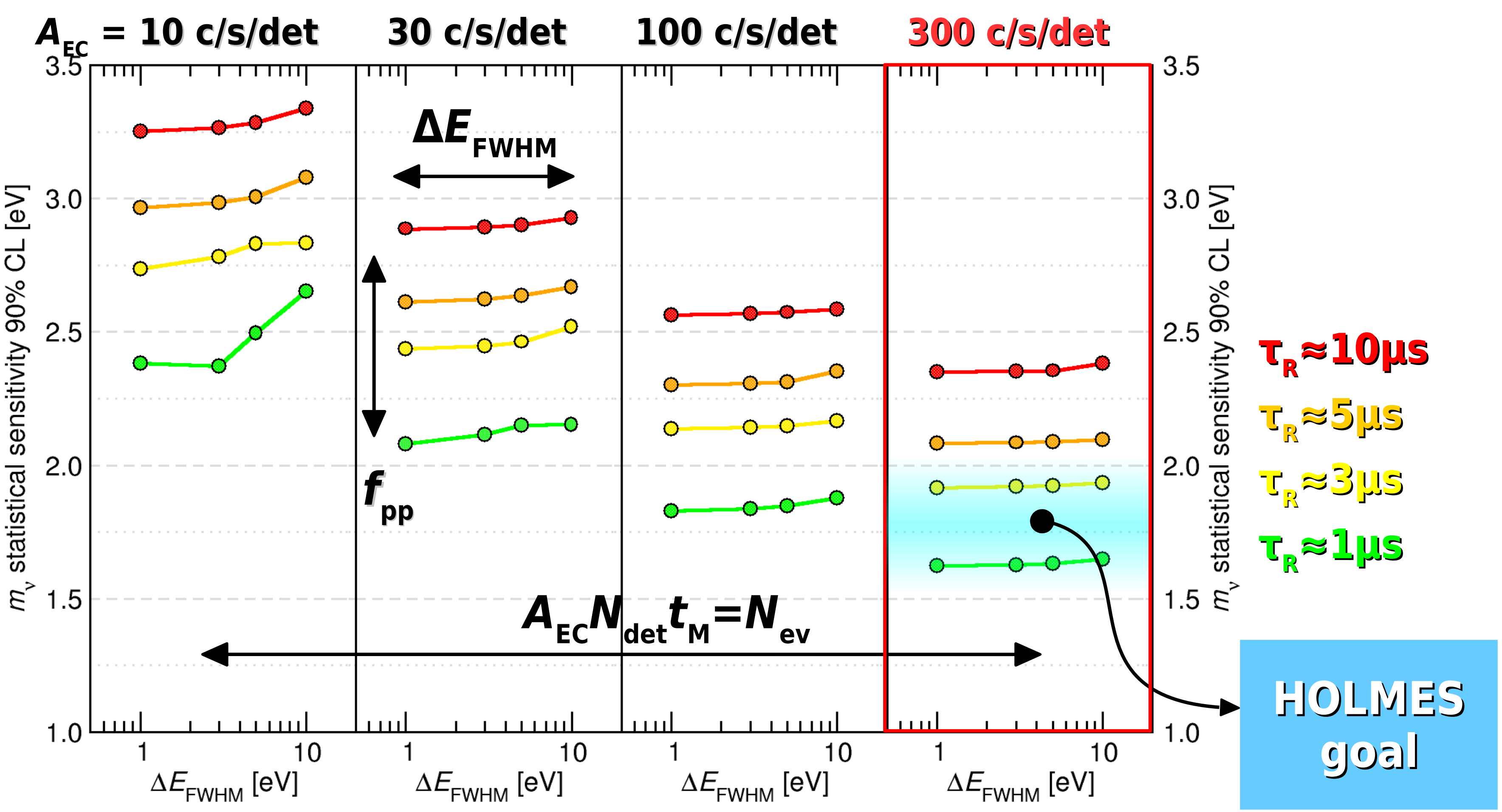
A. Nucciotti, Eur. Phys. J. C 74.11 (2014)

Statistical sensitivity and single pixel perfomances

low *T* microcalorimeters with **implanted ^{163}Ho**

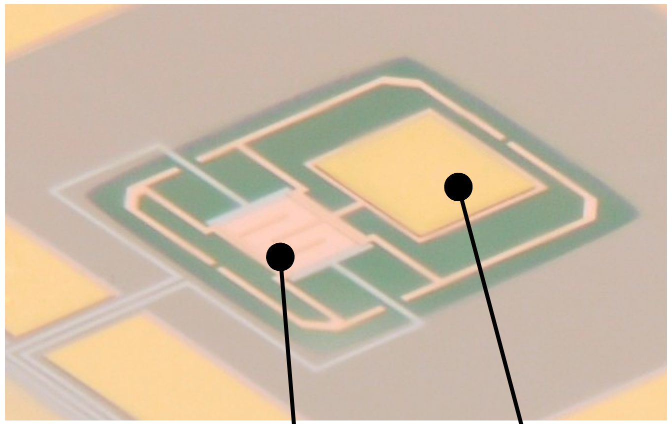
- 6.5×10^{13} atom/det → A_{EC}**=300 c/s/det**
- $\Delta E \approx 1$ **eV** and $\tau_R \approx 1$ **µs**

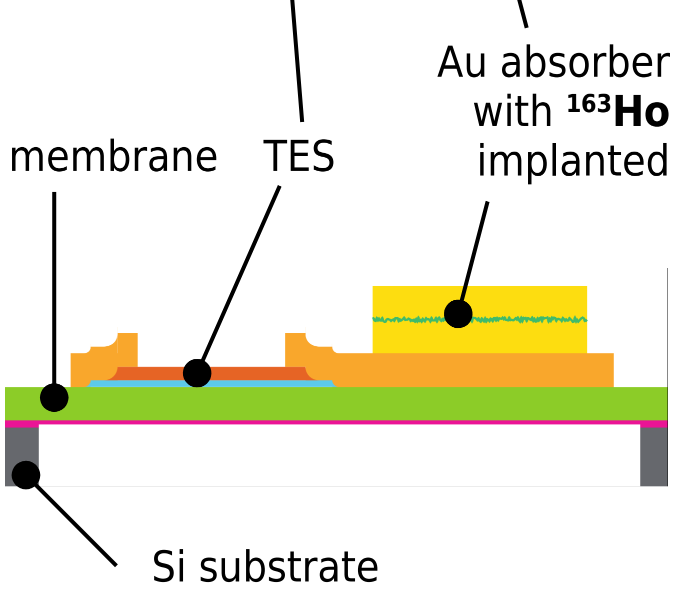
exposure $N_{det} t_M$ **= 1000 det × 3 y**



1000 detector array

- 6.5×10^{16} ^{163}Ho nuclei → ≈18 µg
- A_{tot} **= 300 kBq**
- 3×10^{13} events in **3 years**

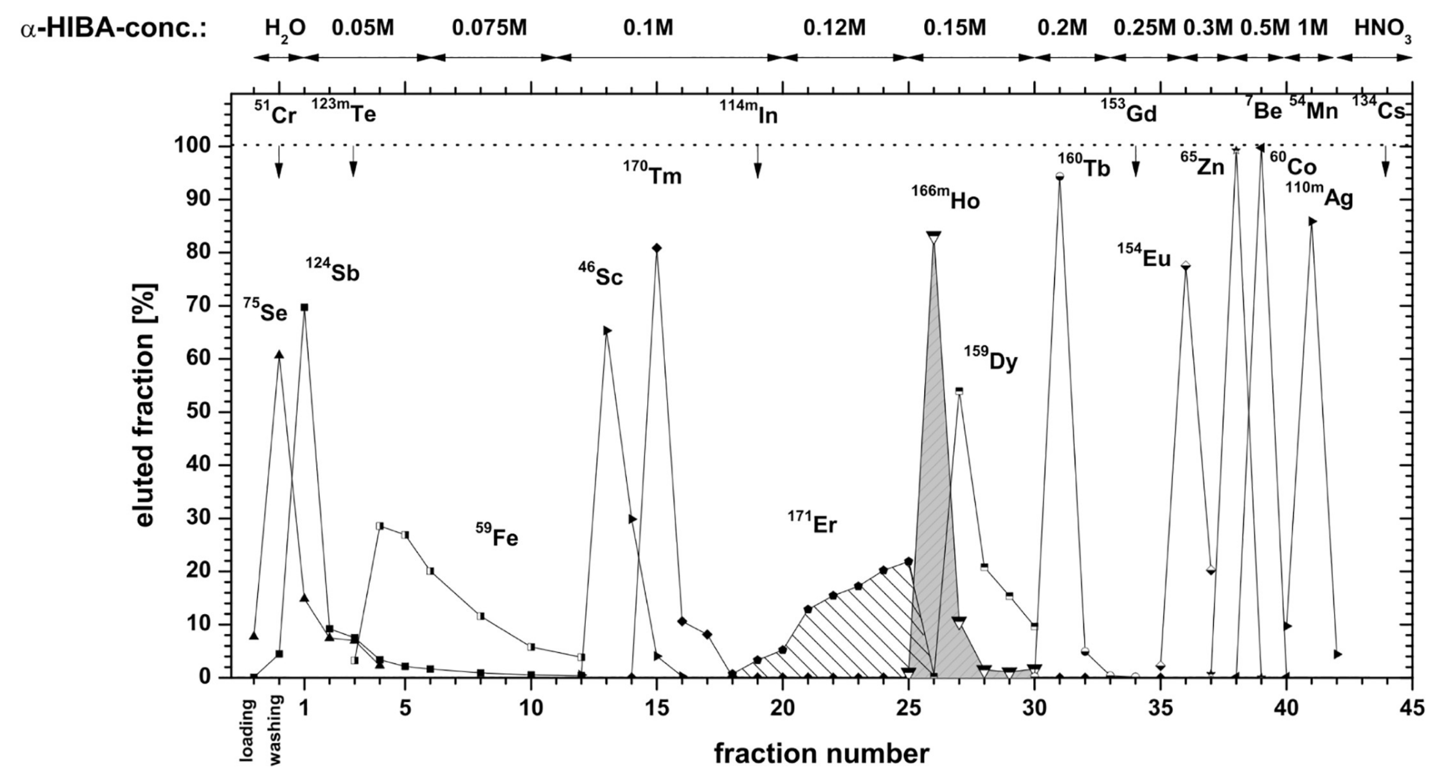




B. Alpert et al., Eur. Phys. J. C, (2015) 75:112

^{163}Ho production and purification

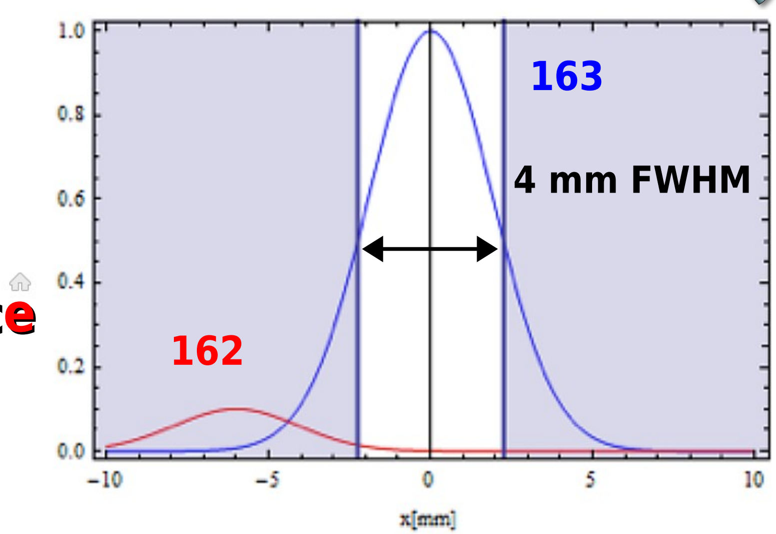
- **HOLMES might need ≈300 MBq of ^{163}Ho**
  (for conservative 0.1% global embedding efficiency)
- ^{162}Er neutron irradiation at ILL nuclear reactor
- ^{163}Ho chemical purification at PSI
- **≈110 MBq** of purified ^{163}Ho available at Genova
- ≈250 kBq of co-produced ^{166m}Ho
- more ^{162}Er available to produce other **80 MBq** of ^{163}Ho

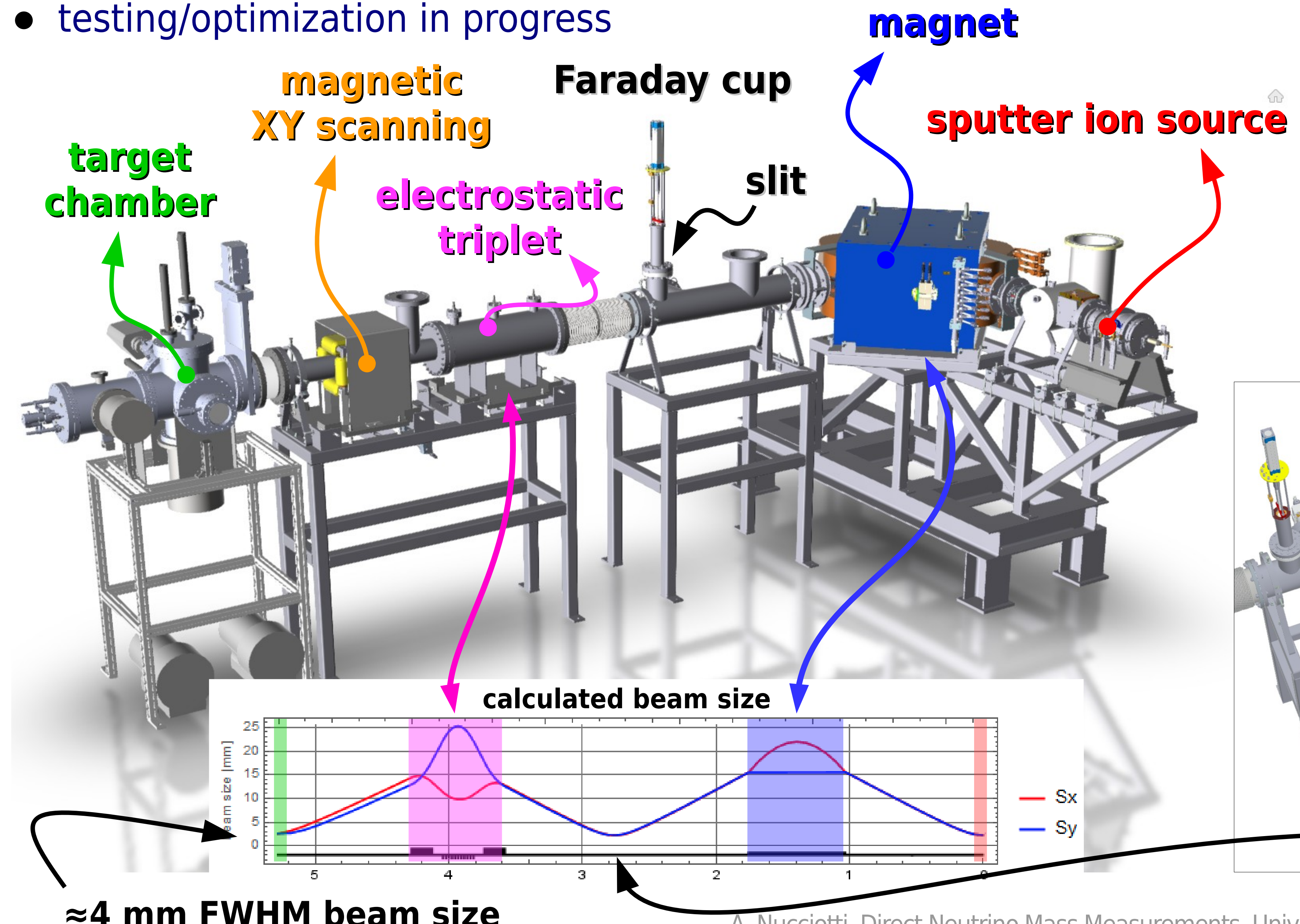


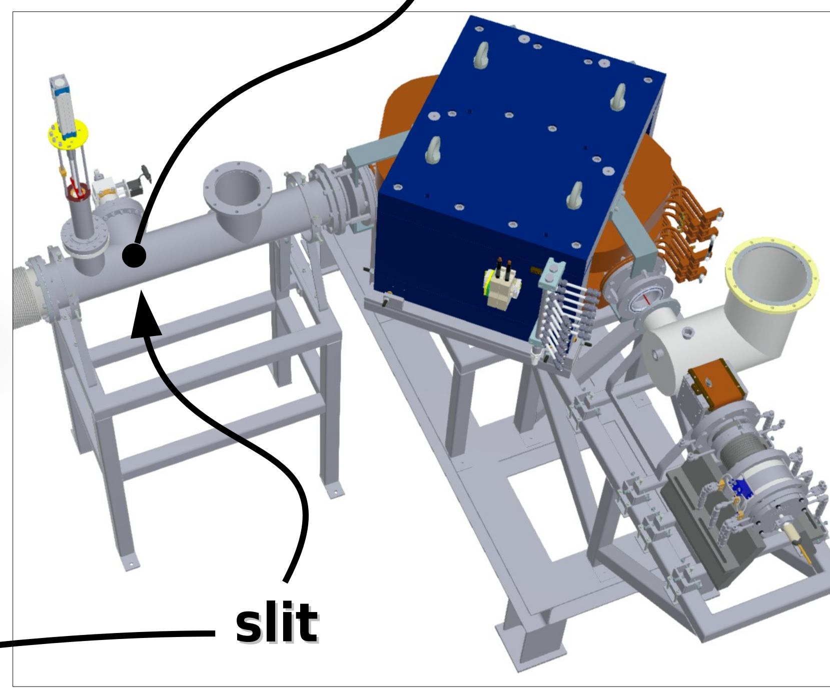
S. Heinitz et al., PLoS ONE 13(8): e0200910

HOLMES mass separation and ion implantation

- extraction voltage 30-50 kV → 10-100 Å implant depth
- ^{163}**Ho** / ^{166m}**Ho** separation better than 10^5
- testing/optimization in progress

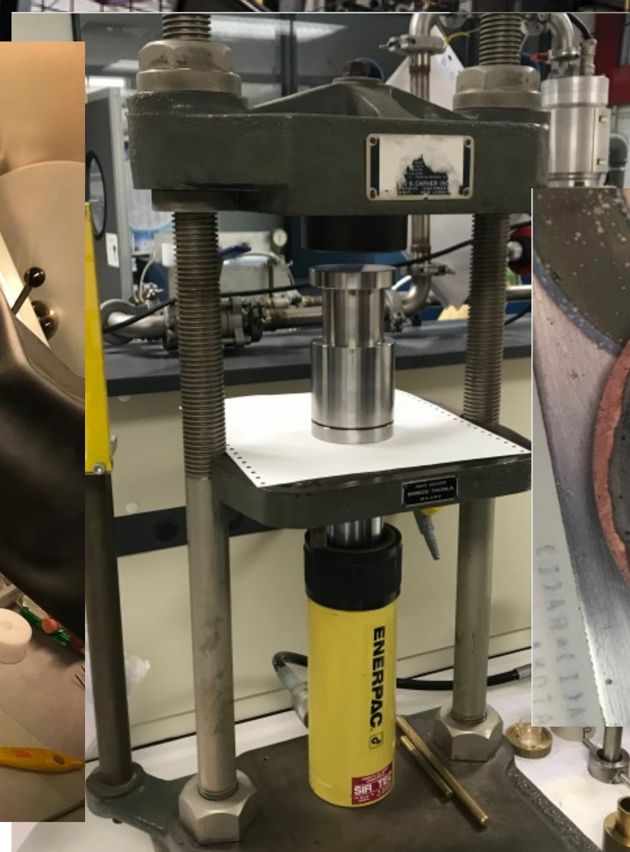




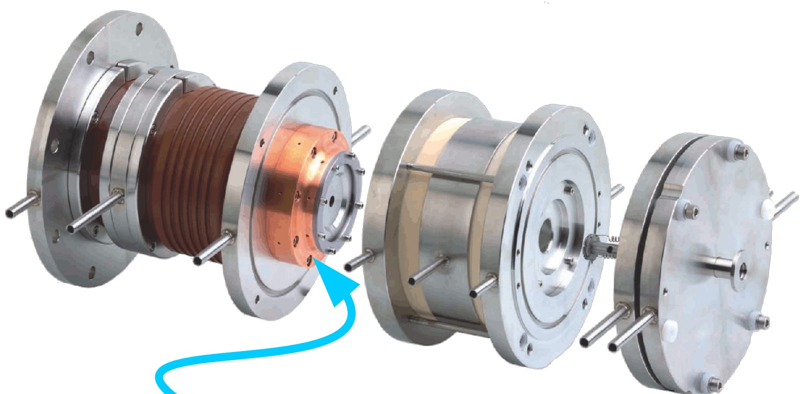


HOLMES ion implantation system / 1

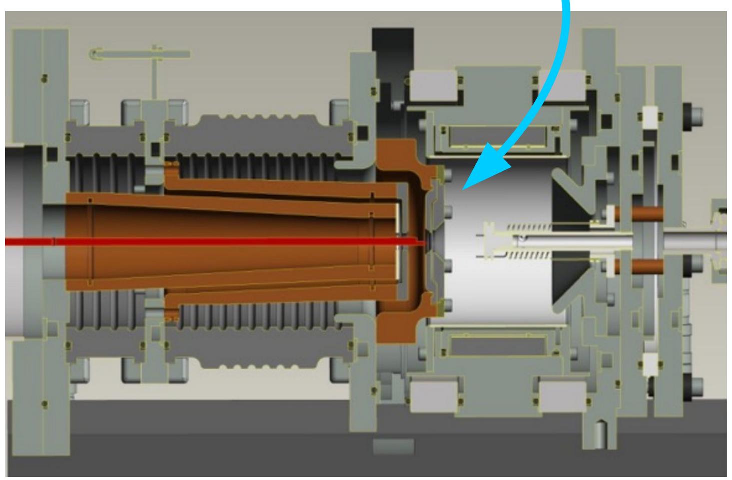
- HV power supply tested up to 50kV
- HV safety & optical fiber remote control
- tests with Cu ion beam in progress
- target from metallic ^{nat}Ho ready
  - intermetallic Ti_2Ni_2Sn/HoNiSn
  - high pressure and temperature sintering



HOLMES ion implantation system / 2

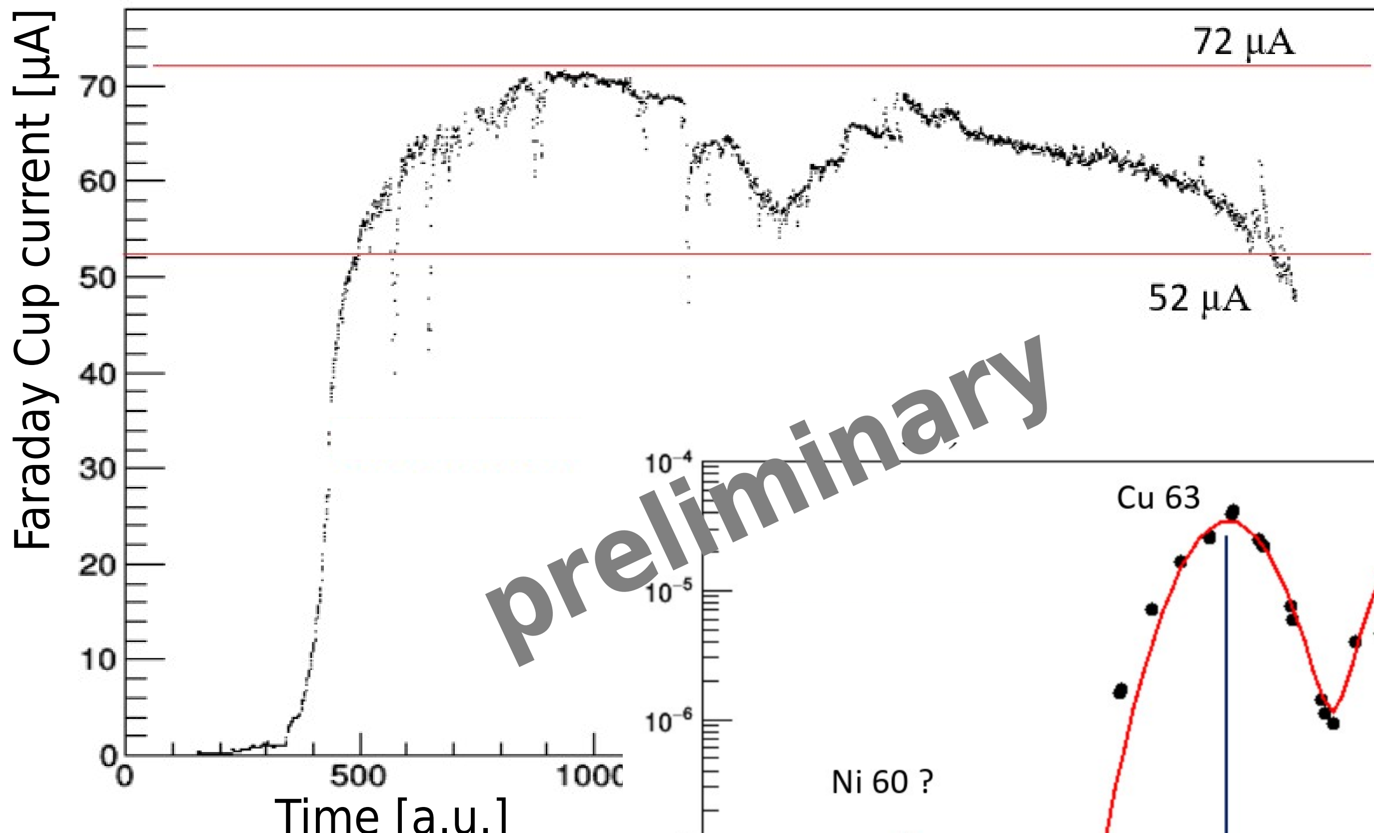


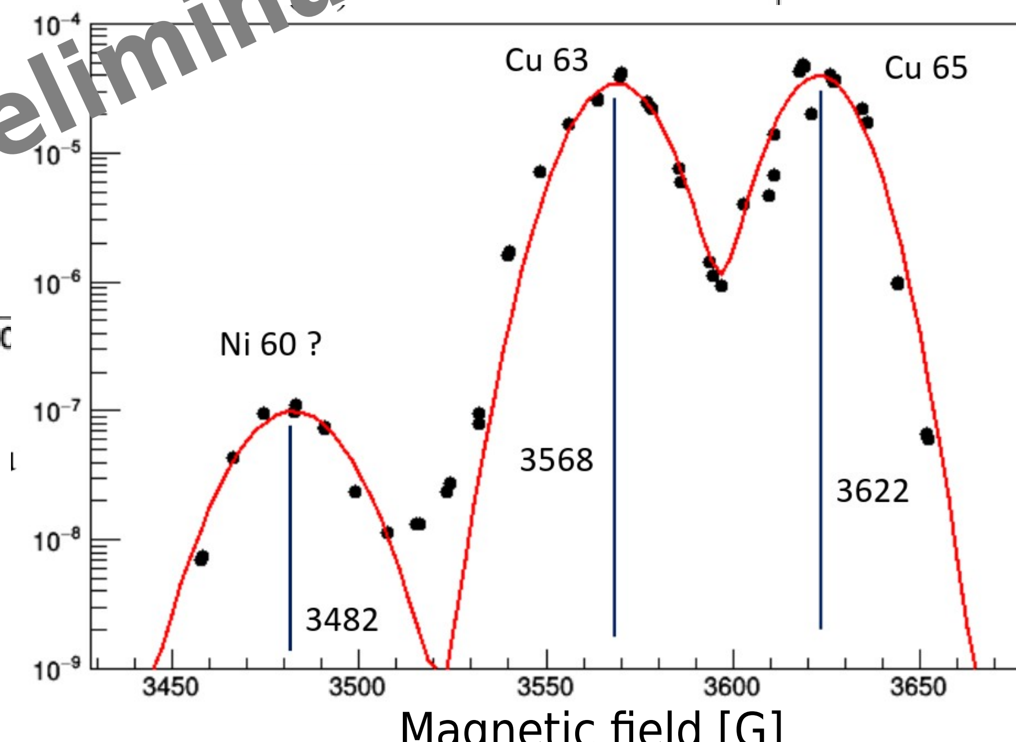
target



ion source

- first ion beam tests with Cu target
- ≈2 hours measurement of ion beam current

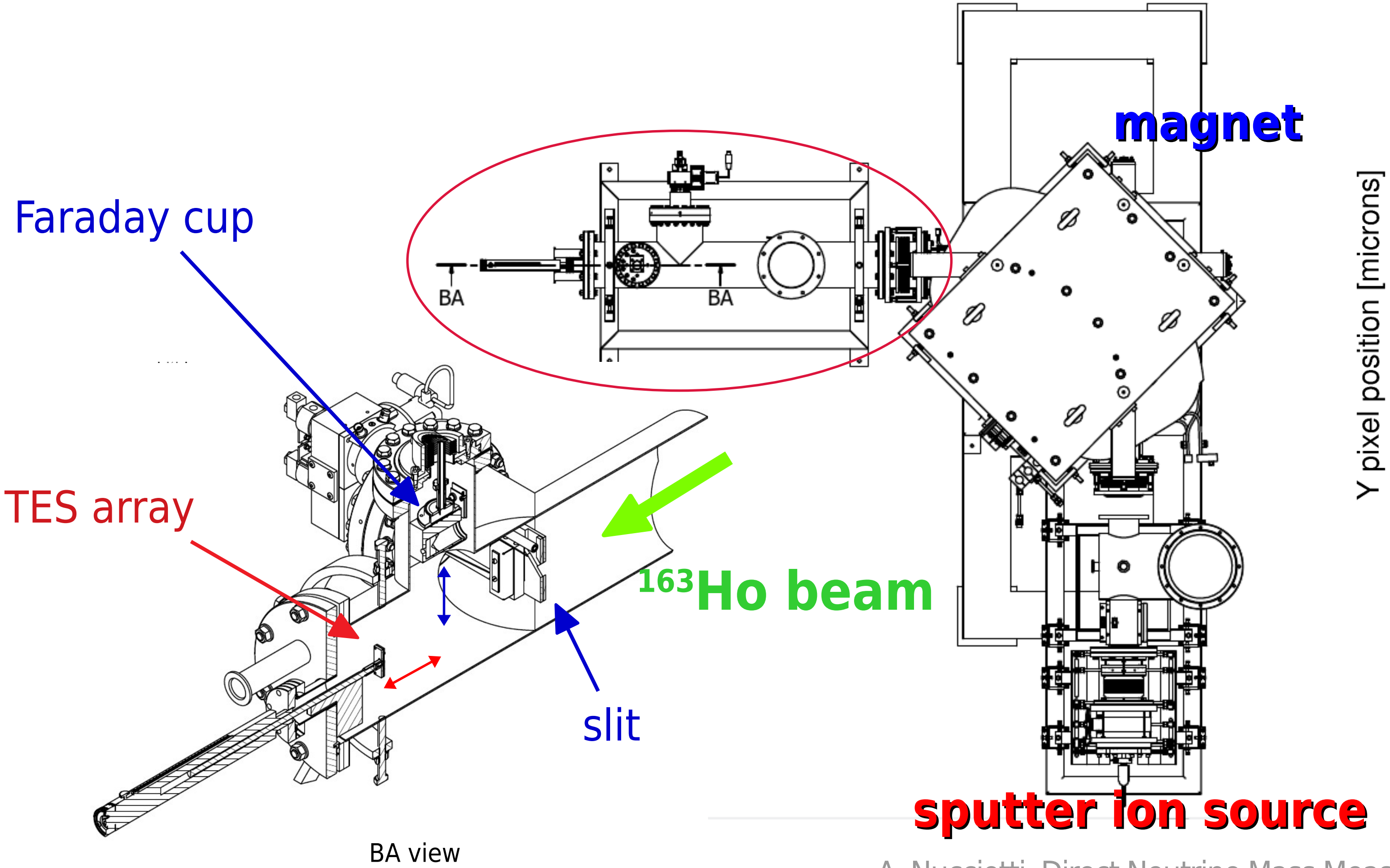


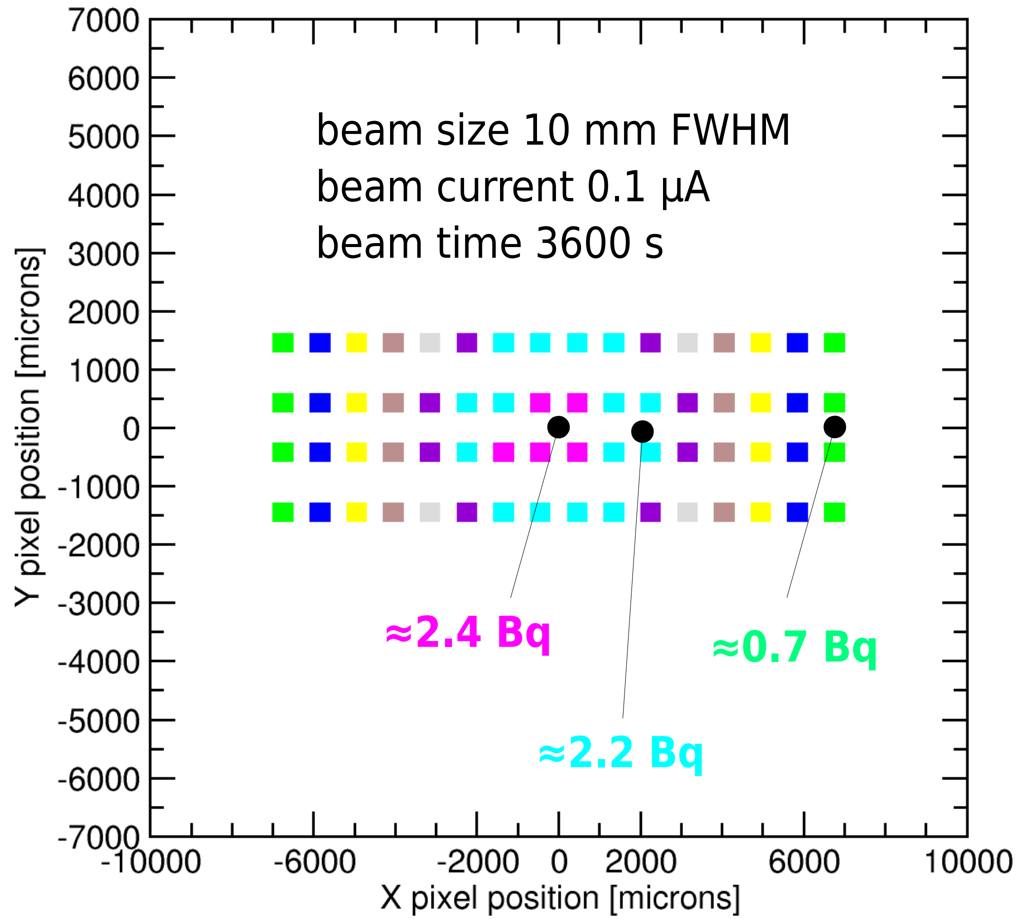


HOLMES needs 1-10 μA ^{163}Ho beam current

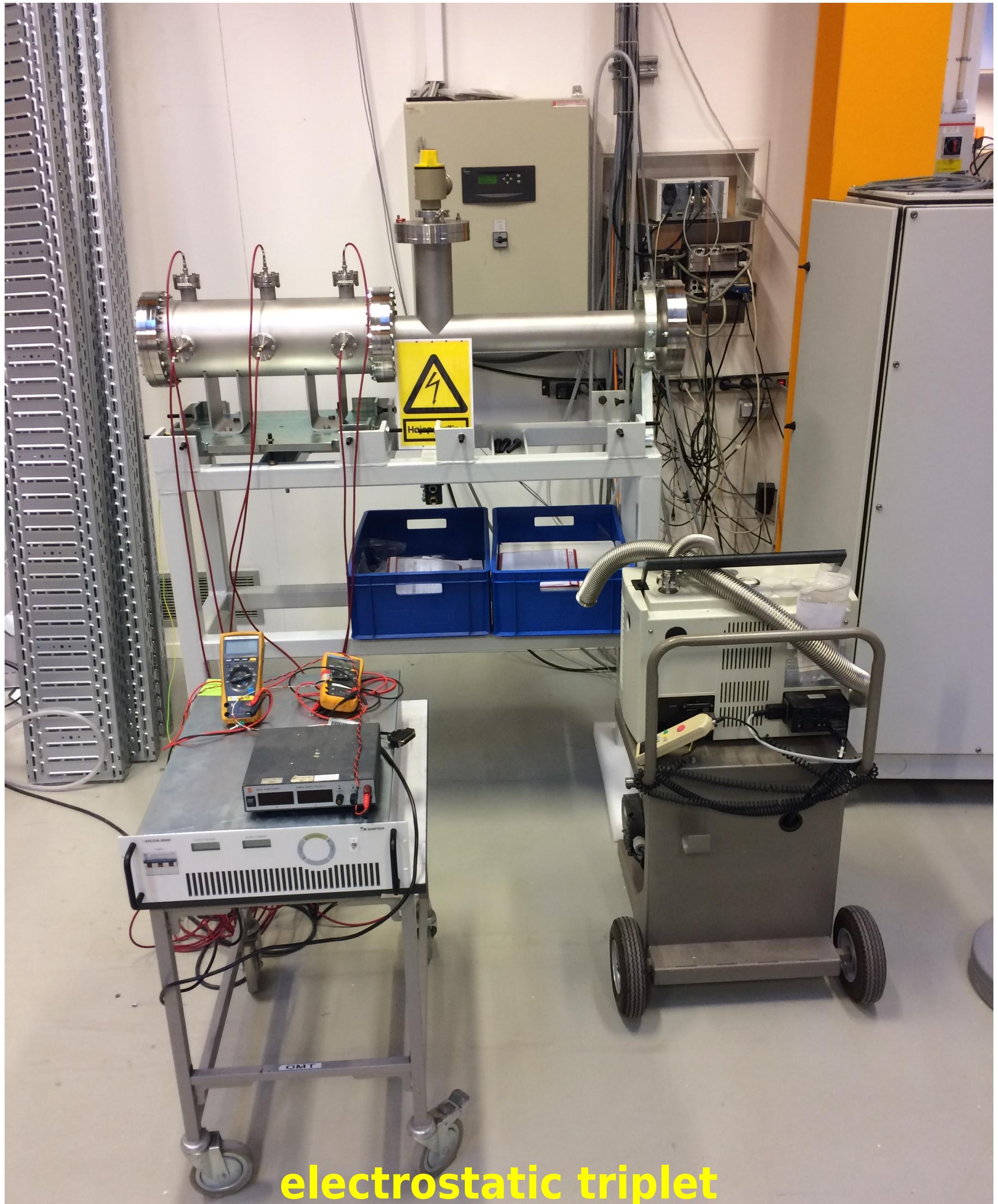
HOLMES ion implantation system / 3

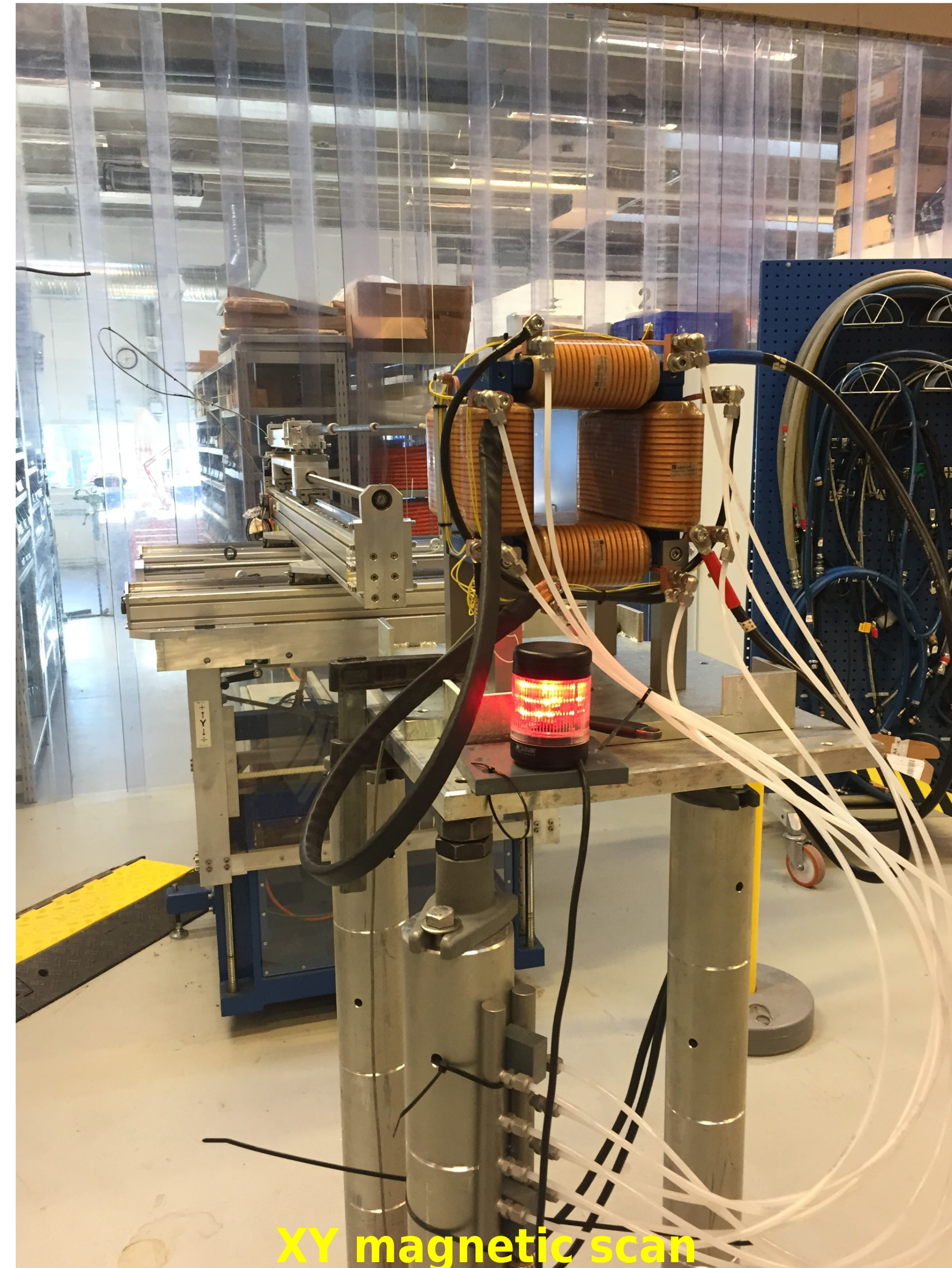
- next steps with present ion implanter configuration
  - optimize ^{nat}Ho ion beam and assess efficiency
  - test different ion source sputter targets with ^{nat}Ho (sintered in Ge and molecular plated from PSI)
  - switch to enriched ^{163}Ho target
  - array low dose ^{163}Ho implantation (≈1Bq/det)





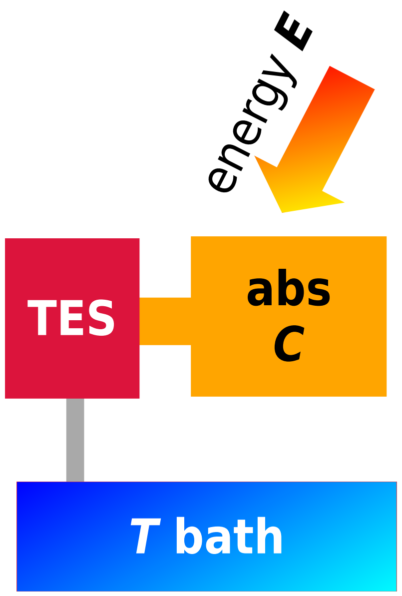
HOLMES ion implantation system extension



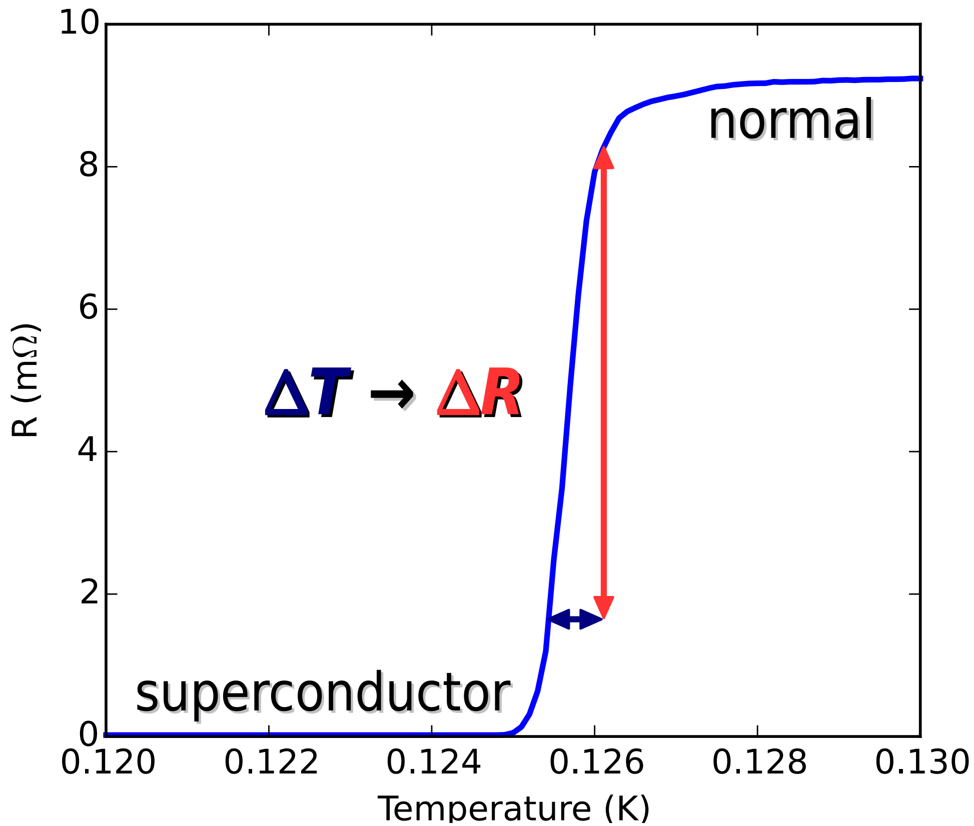


Superconducting transition edge sensors (TES)

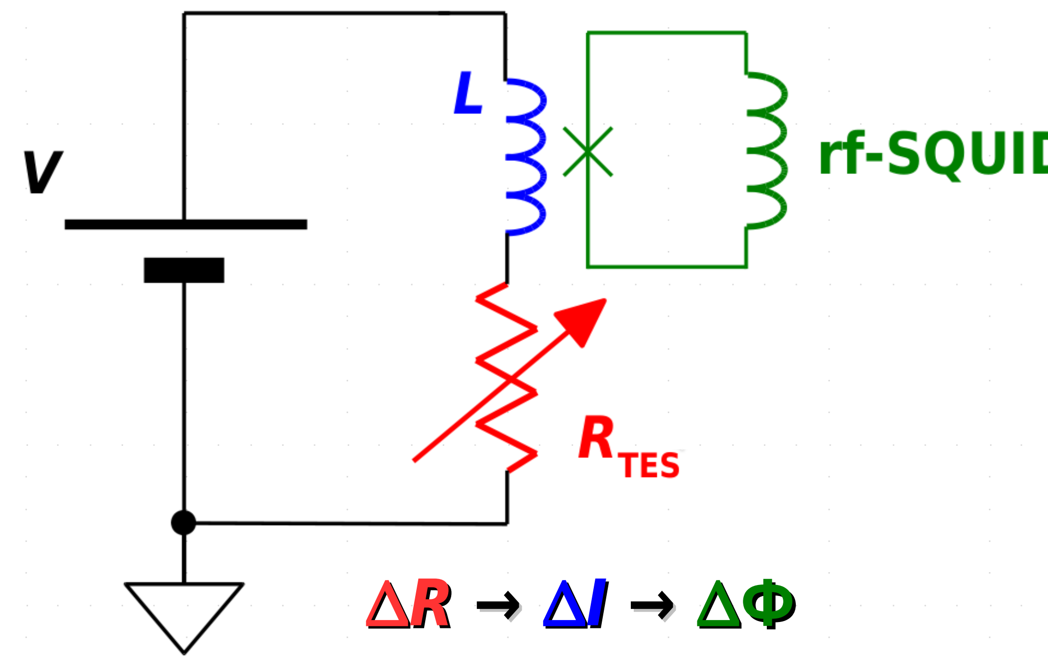
- **superconducting thin films** operated inside the phase transition at T_c
  - Mo/Cu bilayers → tunable T_c (20÷200 mK)
- high sensitivity $TdR/(RdT)\approx100$) → **high energy resolution**
  - as thermal sensors → thermodynamical fluctuation limited → $\sigma_E^2 \approx \xi^2 k_B T^2 C$
- strong electron-phonon coupling → **high intrinsic speed**
- low impedance → SQUID read-out → **multiplexing for large arrays**



$\Delta T \approx E / C$

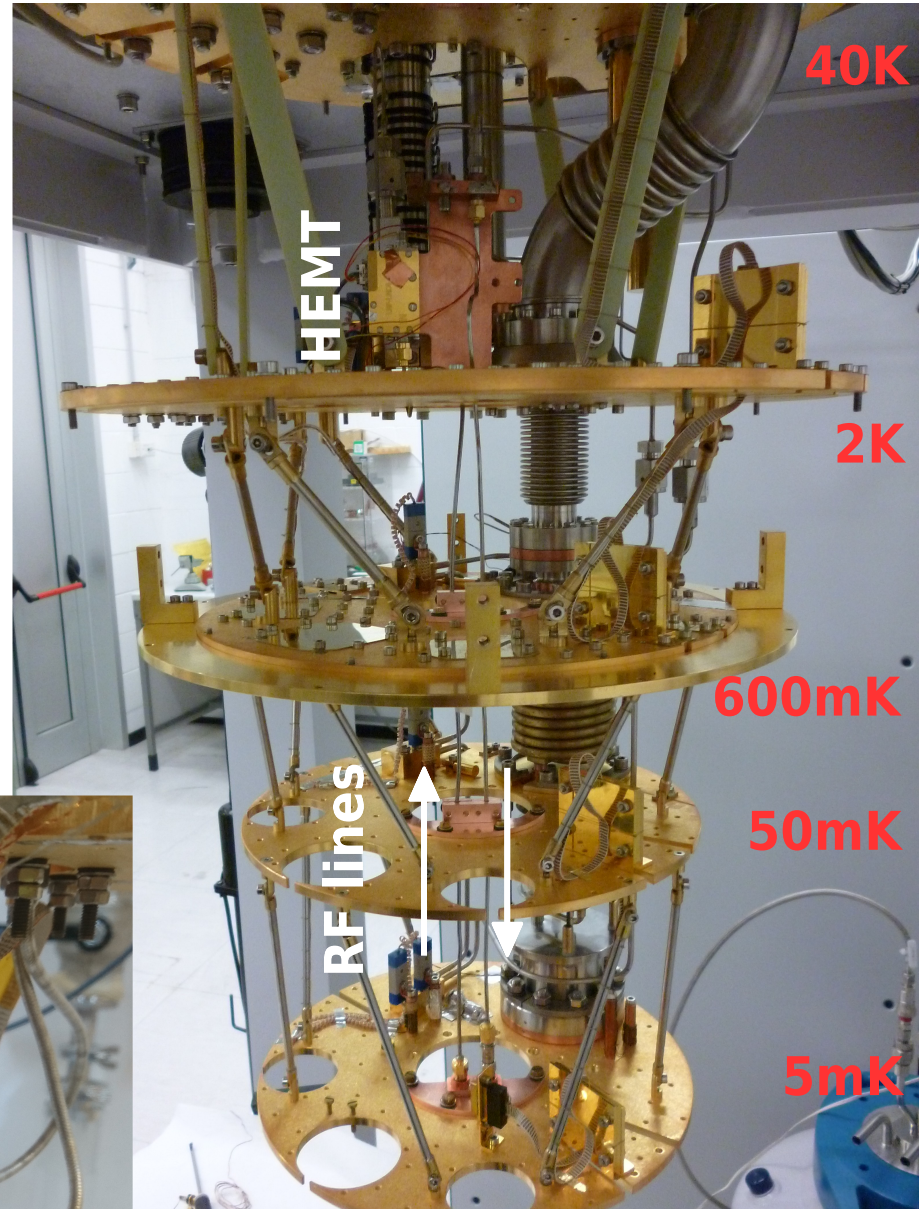


TES read-out: costant voltage bias



Cryogenic set-up

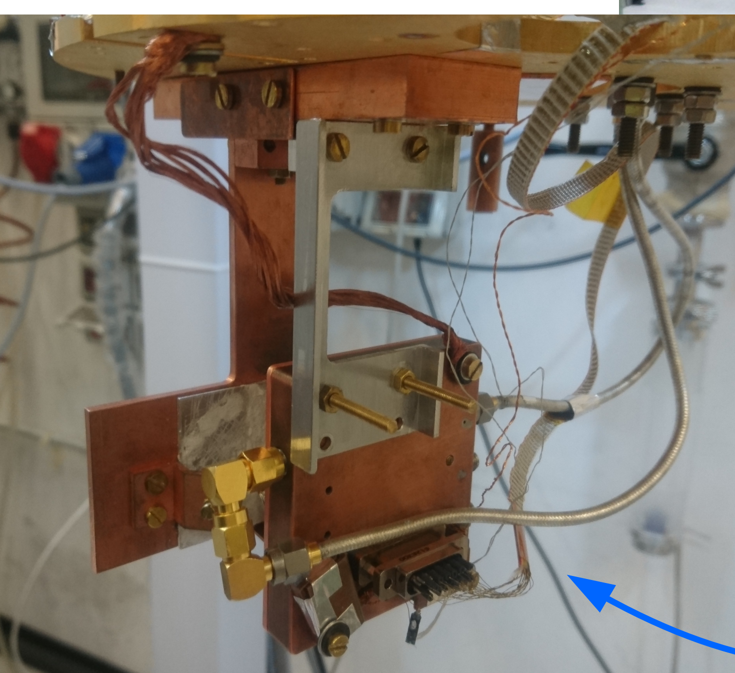
LHe-free dilution fridge



instrumented for
microwave multiplexed readout of rf-SQUIDs
→ 1 HEMT + 2 coax RF lines
→ **8** µwave multiplexing chips
→ **256** detectors

4 HEMTs available → 1024 ch

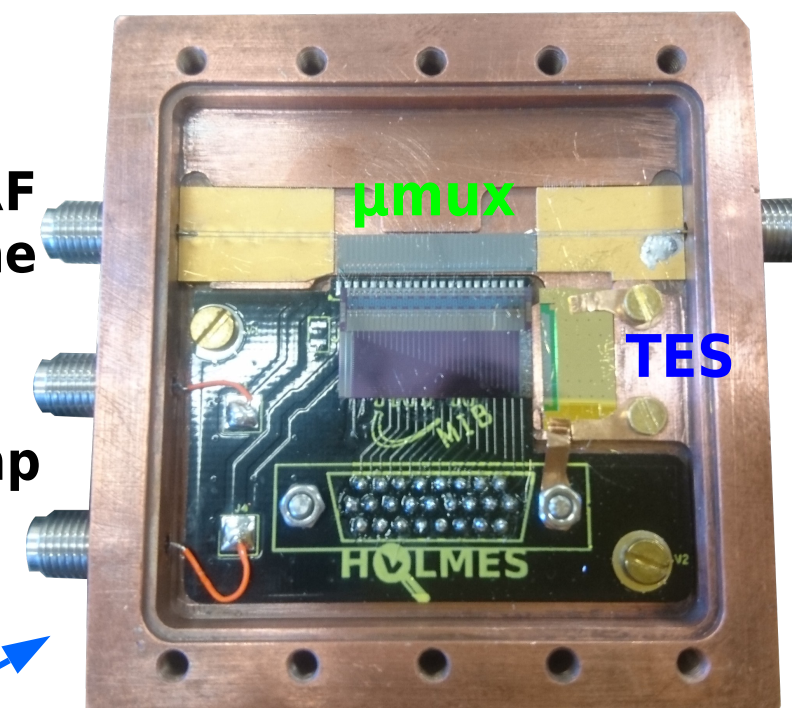
detector holder mounted with **calibration source**



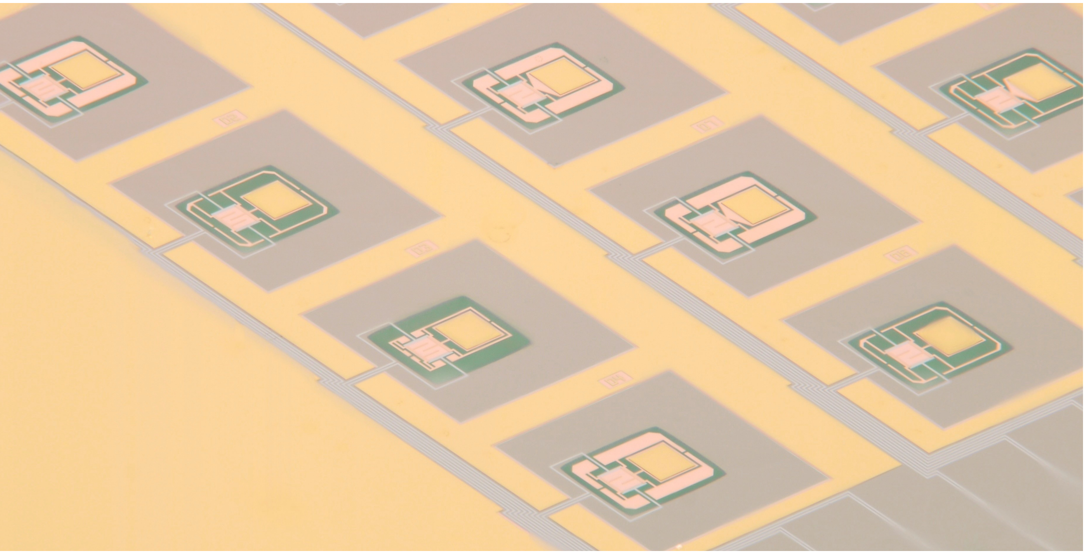
detector holder

RF feedline

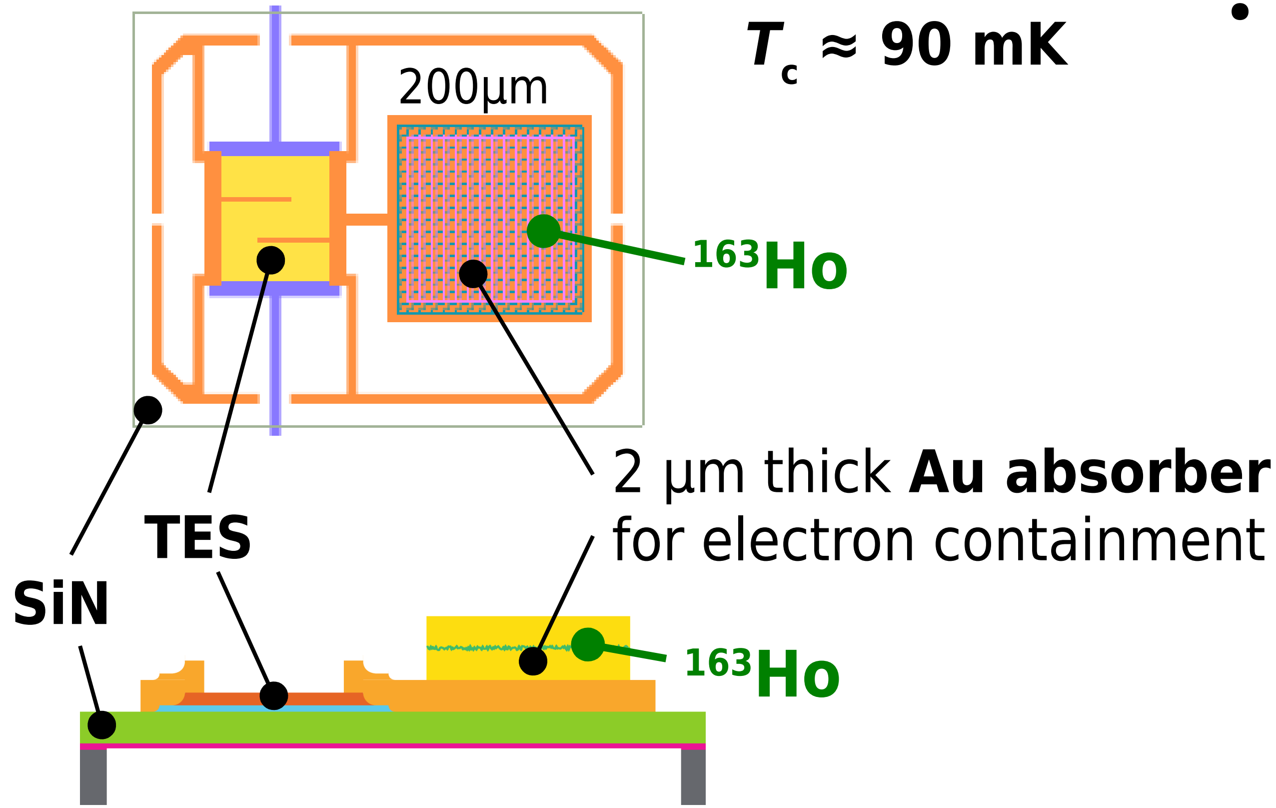
ramp

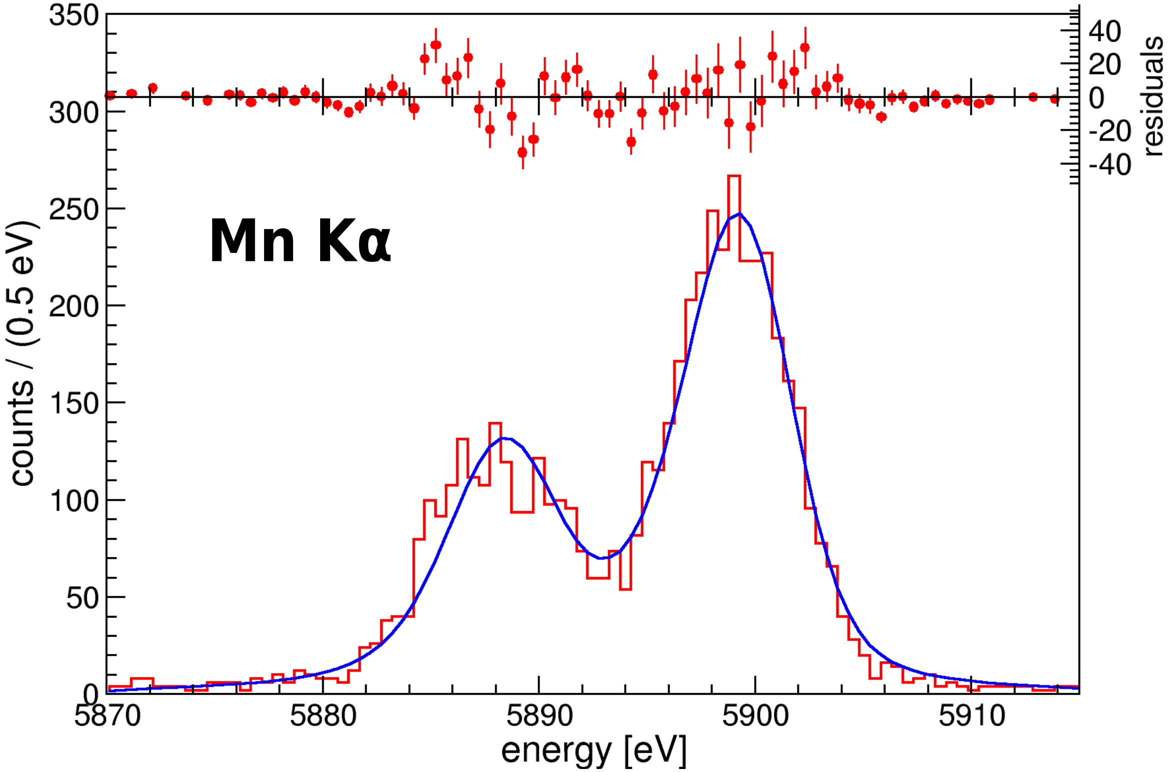


Single TES detector R&D



- prototypes w/o ^{163}Ho
- $\Delta E_0 \approx 3.3$ eV
- **ΔE_{FWHM} = 4.5±0.1 eV @ 6 keV**
- **$\tau_{rise} \approx$ 13 μs** (limited to match read-out)
- $\tau_{decay} \approx 54$ μs
- pile-up detection algorithms (*work in progress*):
  - for f_{samp} = 0.5MHz, $\tau_{rise} \approx$ 20μs
  - Singular Value Decomposition → $\tau_R \approx$ 1.8 μs

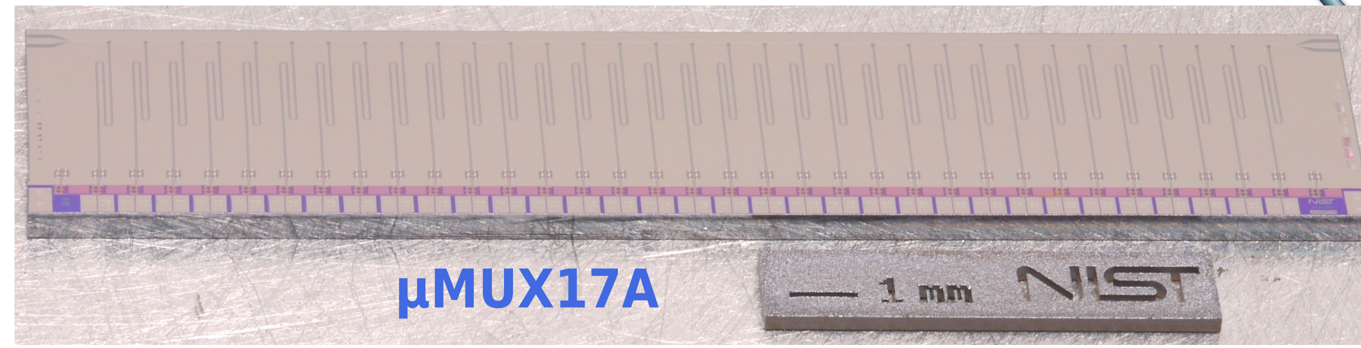


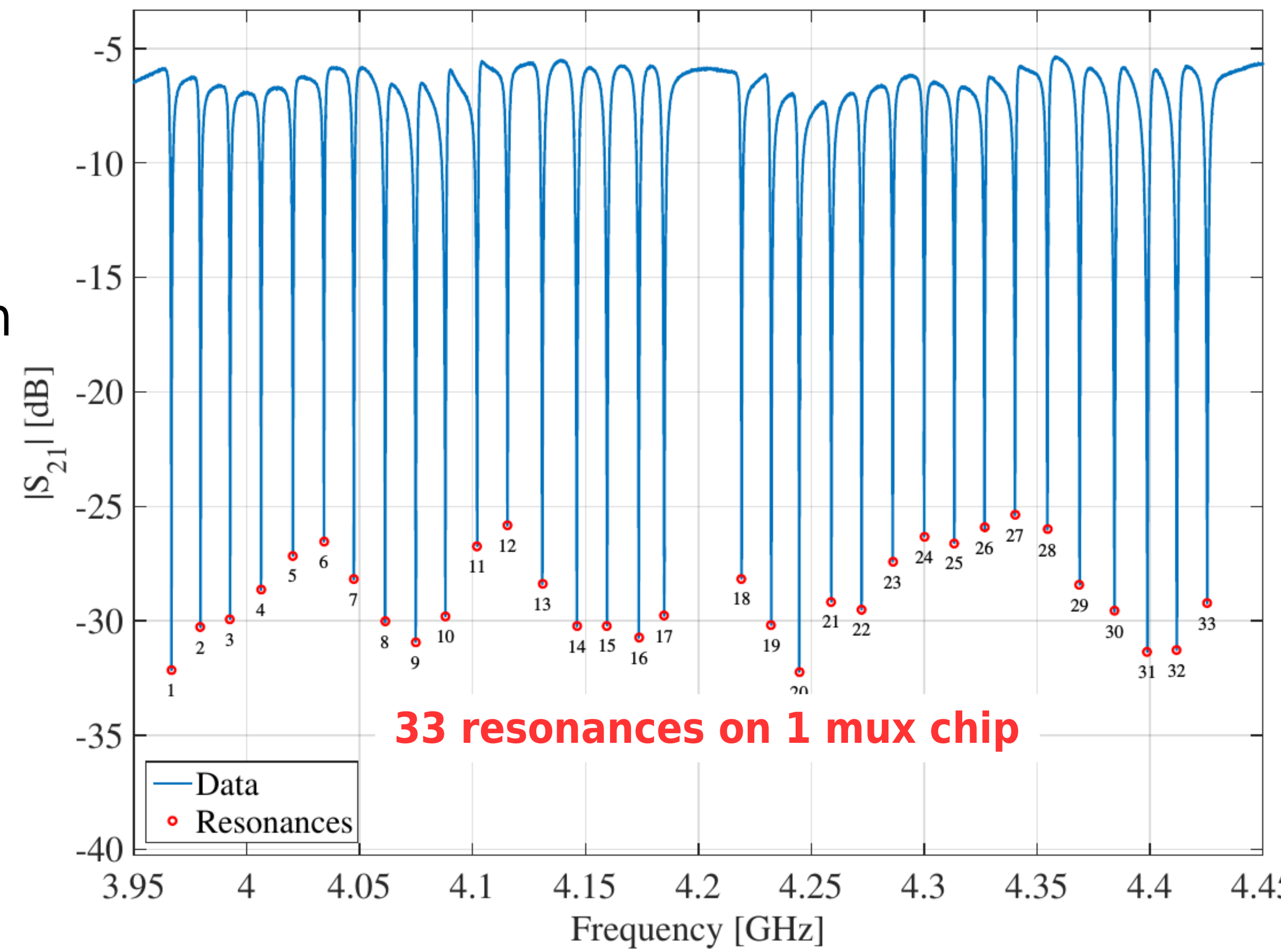


Alpert B. et al., Eur. Phys. J. C (2019) 79:304

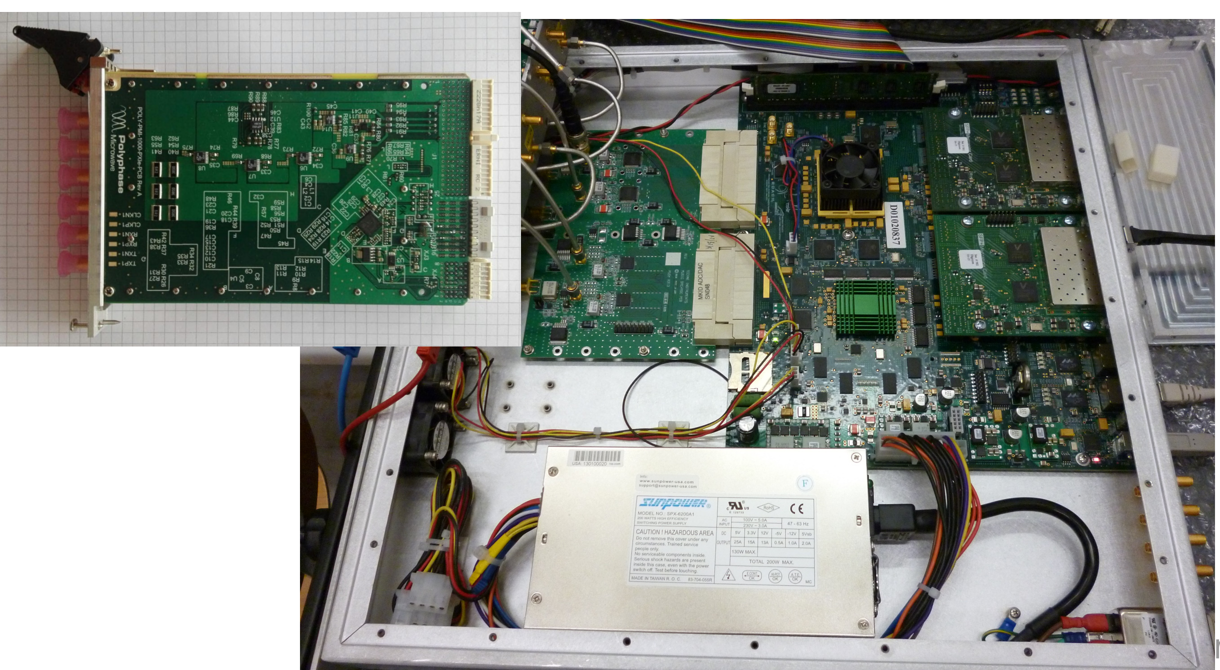
Detector read-out and DAQ

- read-out: **µwave rf-SQUID multiplexing**
- µMUX17A optimized for HOLMES
  - 33 resonances in 500 MHz (4→8 GHz band)
- DAQ: **Software Defined Radio**
- ROACH2/ADC (32 channel fw)
  - base-band tone generation (0-512MHz)
  - base-band tone IQ de-modulation (0-512MHz)
  - rf-SQUID phase signal de-modulation
- custom IF-board → C-band up- / down-conversion
- **read-out / DAQ ready for 64 channels**

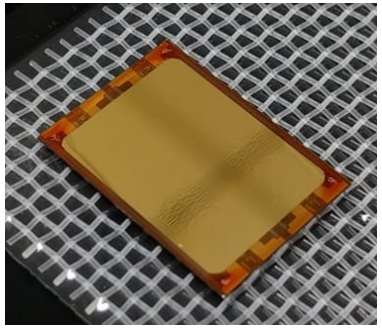


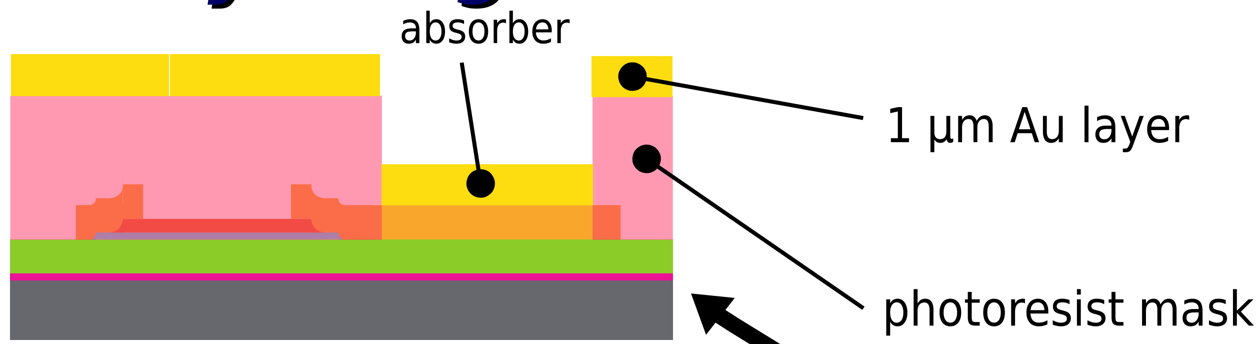


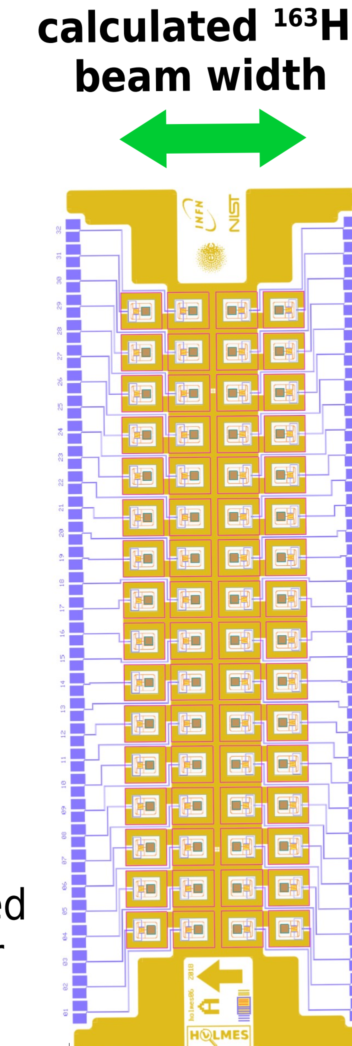
D.T. Becker et al, JINST 14 (2019) P10035



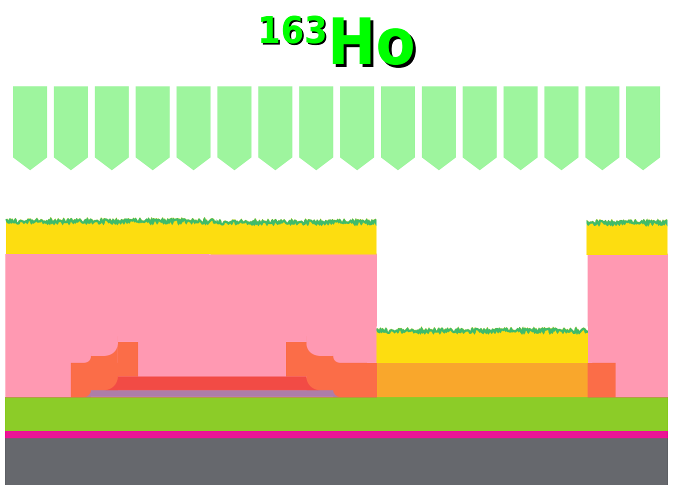
HOLMES detector array design and fabrication



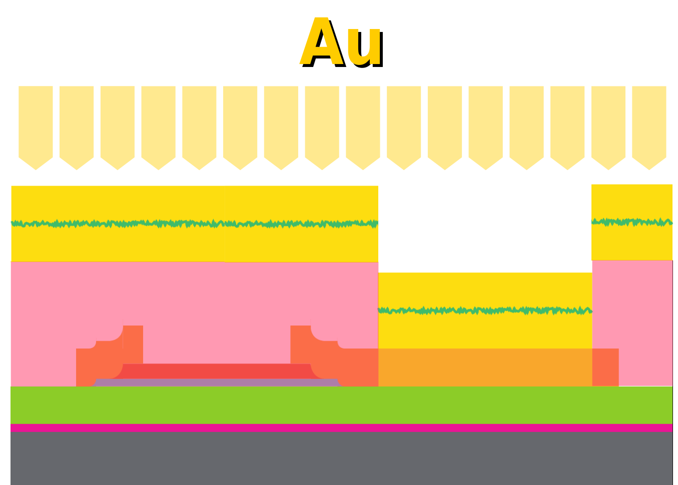




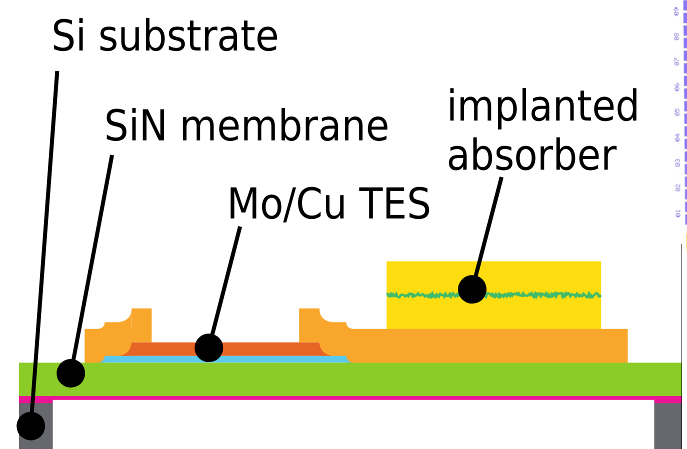
- TES array fabrication after first steps at **NIST**
- **^{163}Ho** implantation and final 1 μm **Au** layer deposition
- final micromachining step definition in progress
- **4×16 sub-array** for low parasitic *L* and high implant efficiency



ion implantation



full encapsulation by sputtering

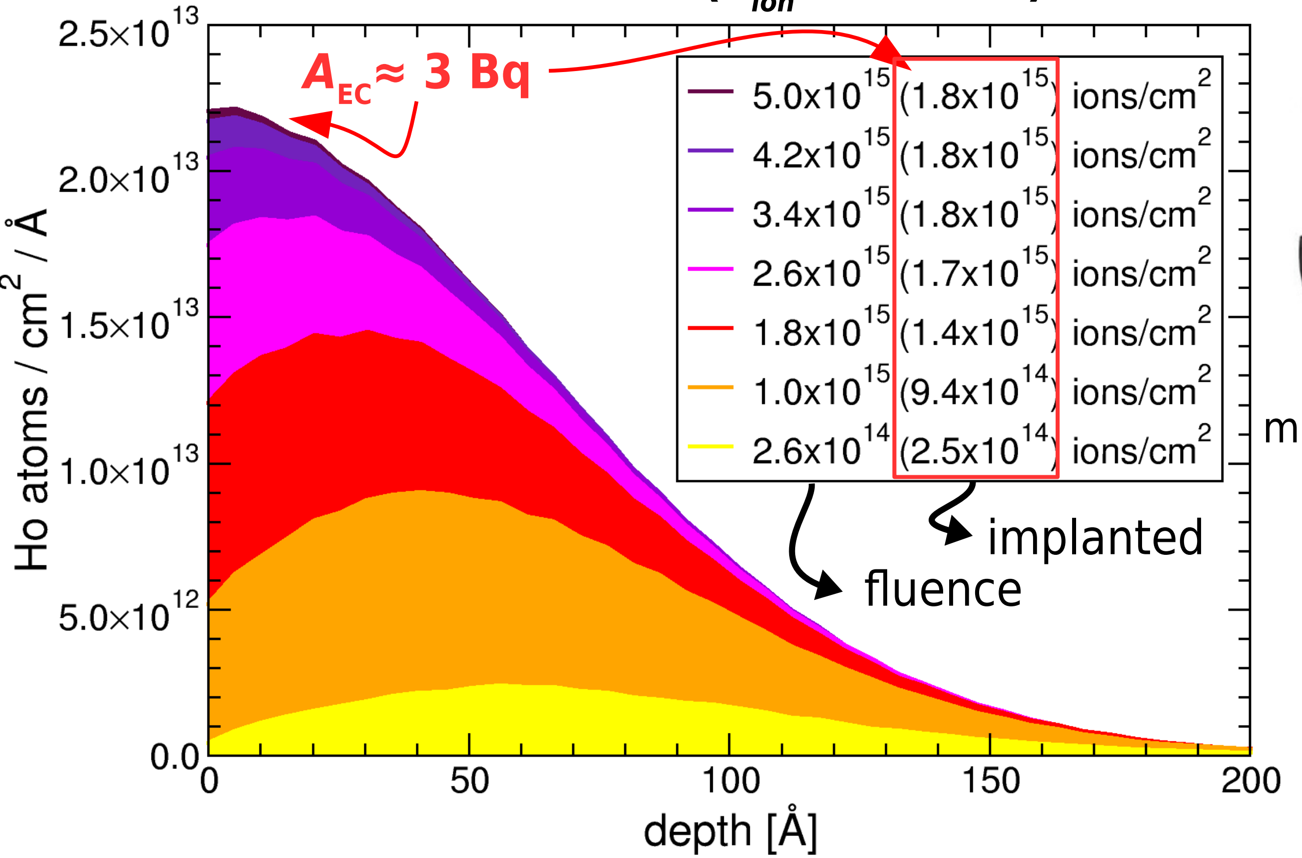


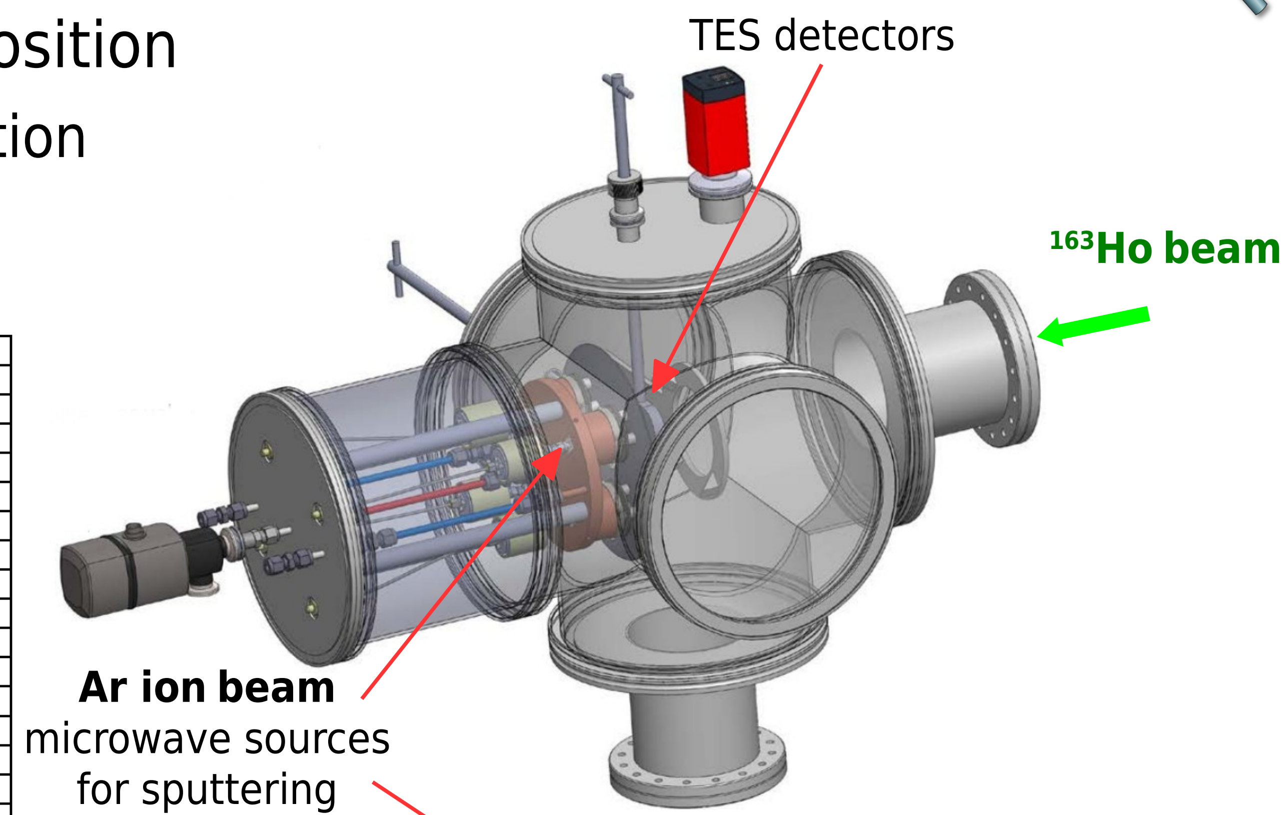
photoresist lift-off and SiN membrane release

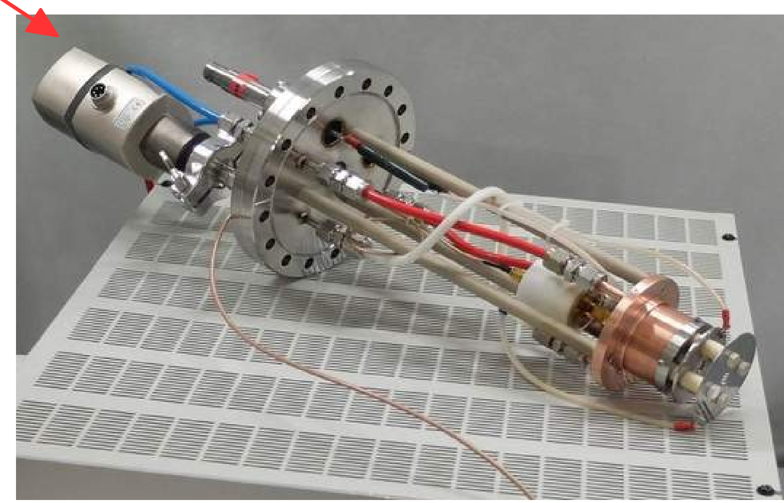
Target chamber for absorber fabrication / 1

- final 1 µm Au capping layer in situ deposition
  - for calorimetry and to prevent Ho oxidization

ion implant simulation with SRIM2013
^{163}Ho ions on Au (E_{ion} = 50 keV)

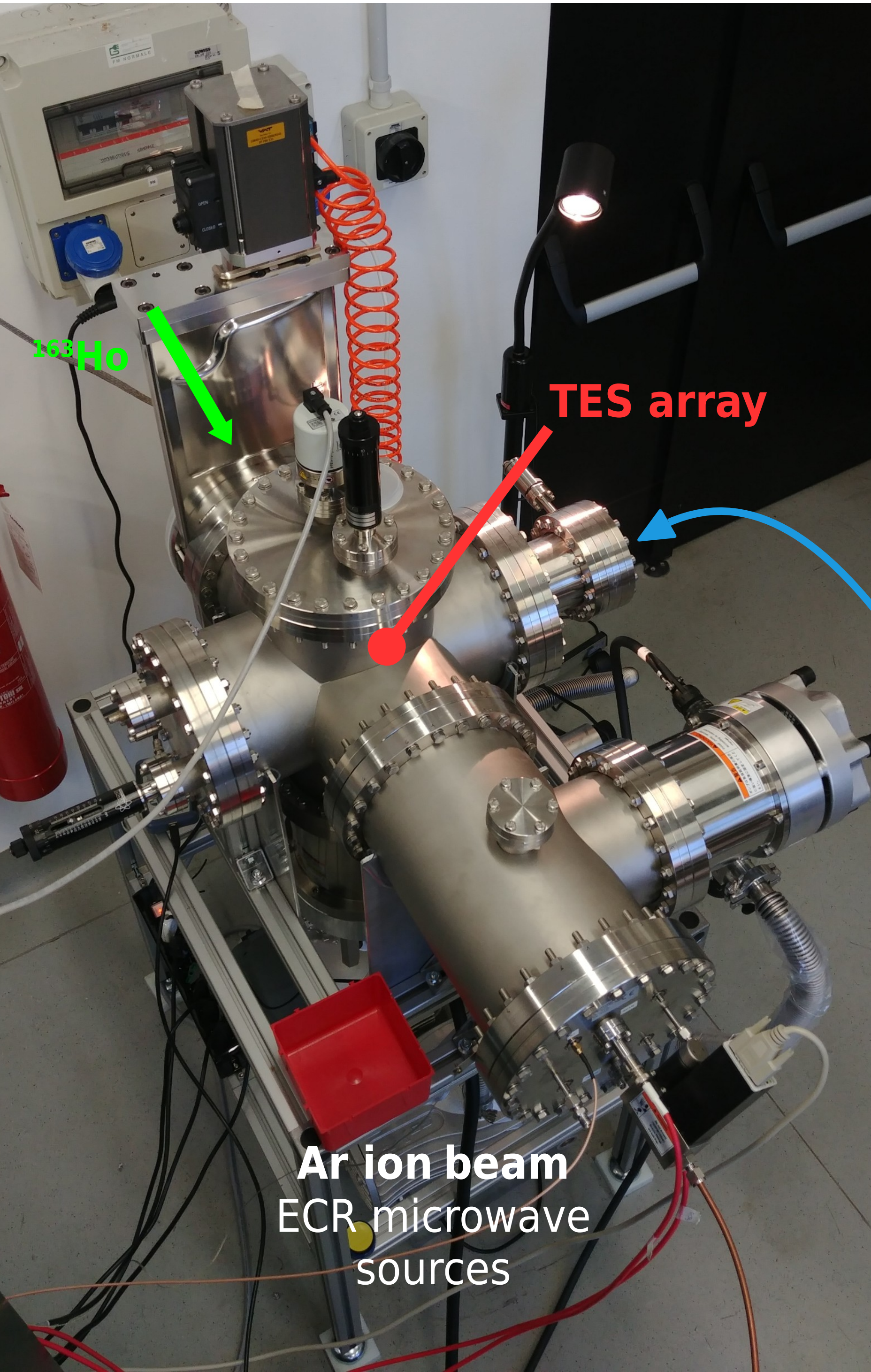




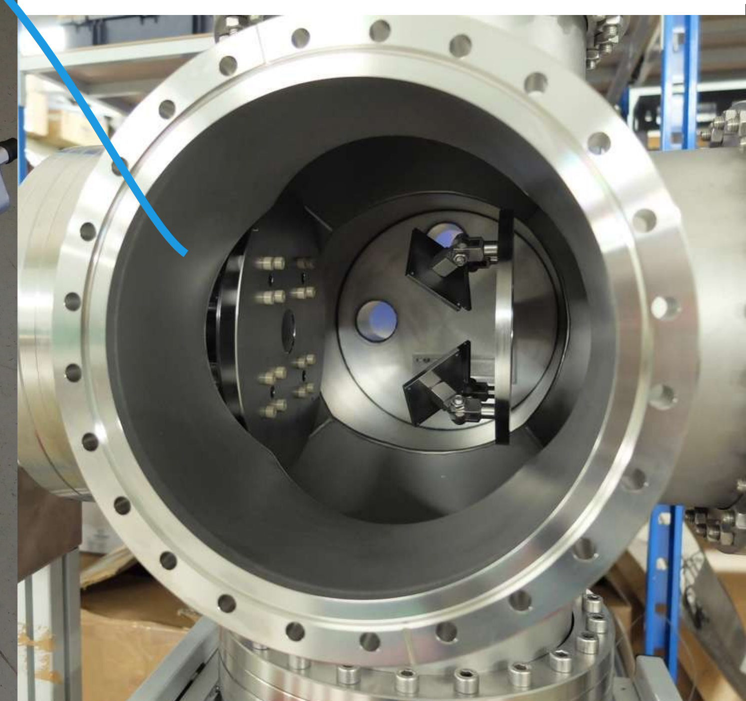


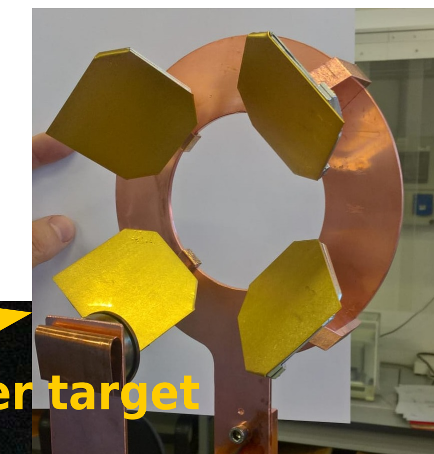
- ^{163}Ho ion beam sputters off Au from absorber (≈26 Au/Ho)
  - implanted ^{163}Ho concentration in absorber saturates
  - compensate by Au co-evaporation

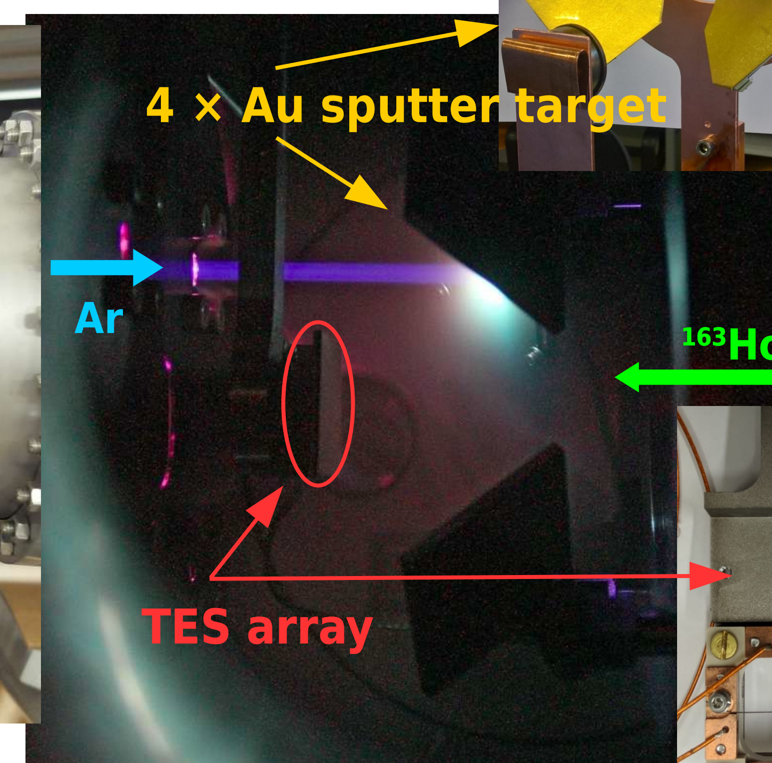
Target chamber for absorber fabrication / 2

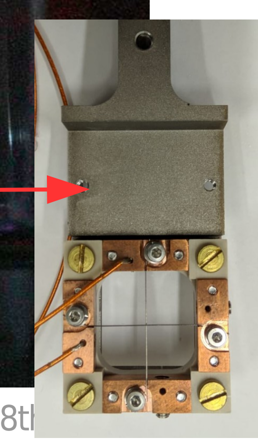


- 4 ECR ion beam sources
- background pressure ≈10^{-8} mbar
- Ar ion current ≈175 µA/source (without water cooling)
  - Au deposition rate with 4 ion sources **>100nm/h**
- remote control for use with ion-implanter
- ^{163}Ho beam diagnostic:
  - wire cross + Faraday cup



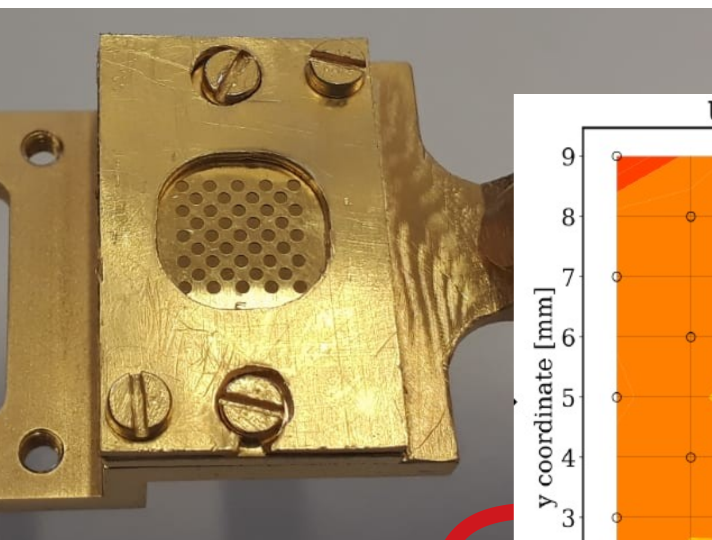


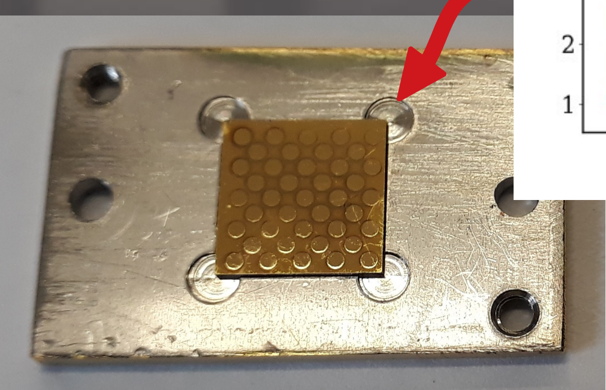


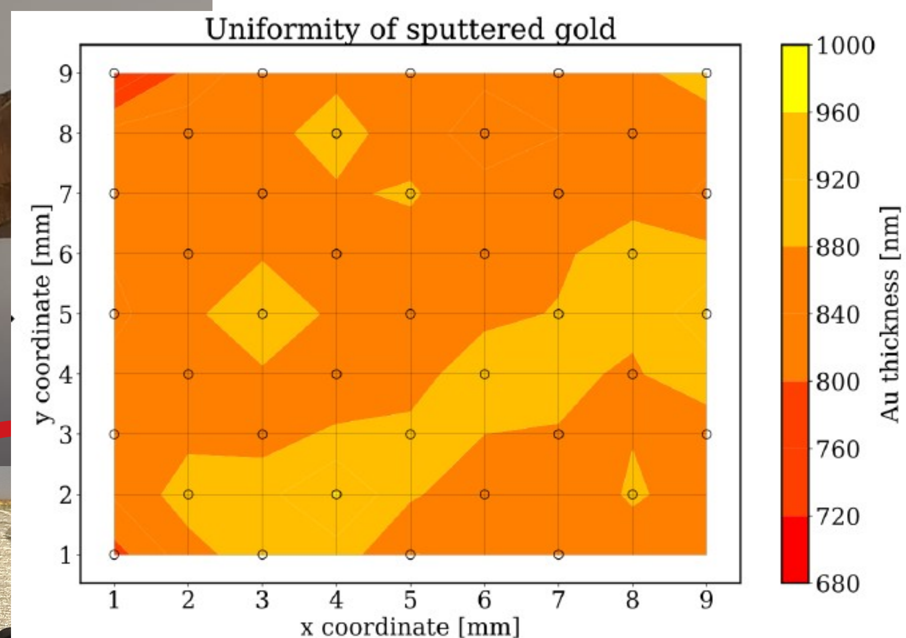


Detector array fabrication / 1

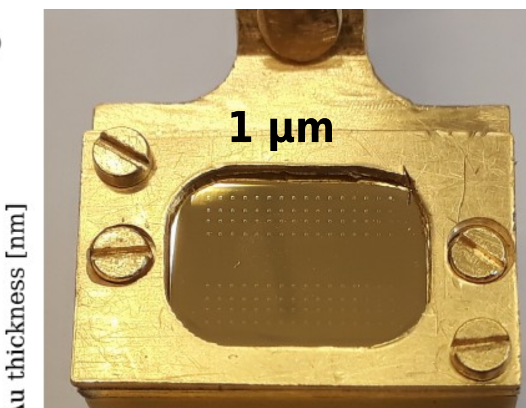
- 1 µm Au final layer deposition in Target Chamber
  - deposition rate calibrated
  - uniformity tested with 4 sources
- Au layer patterned by lift-off
- full fabrication process successfully tested on 2 arrays
  - arrays characterized at low temperature → Au quality and sticking are OK

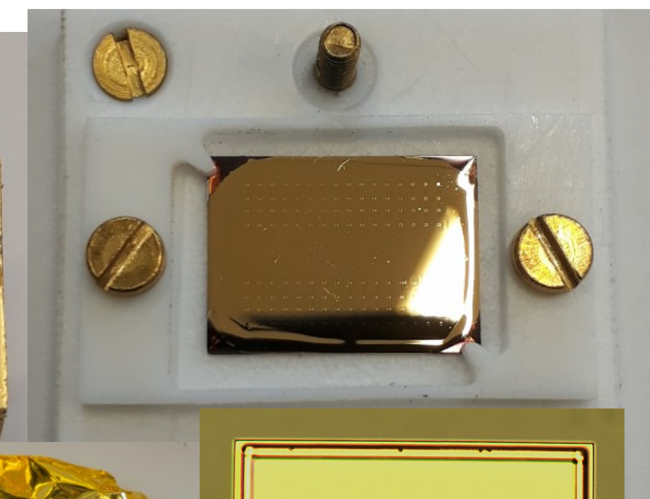


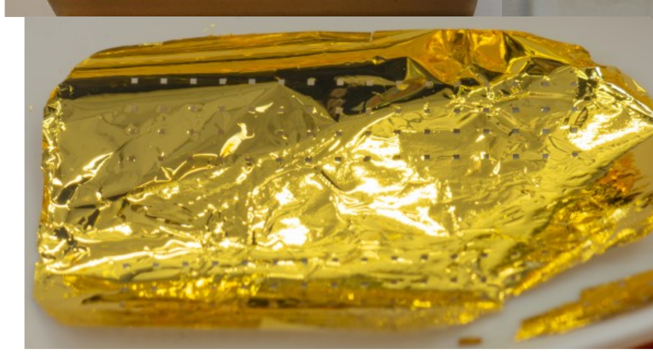


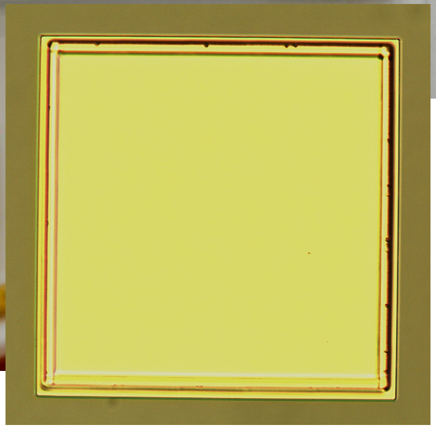


***d* = 865±40 nm**

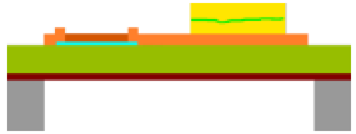




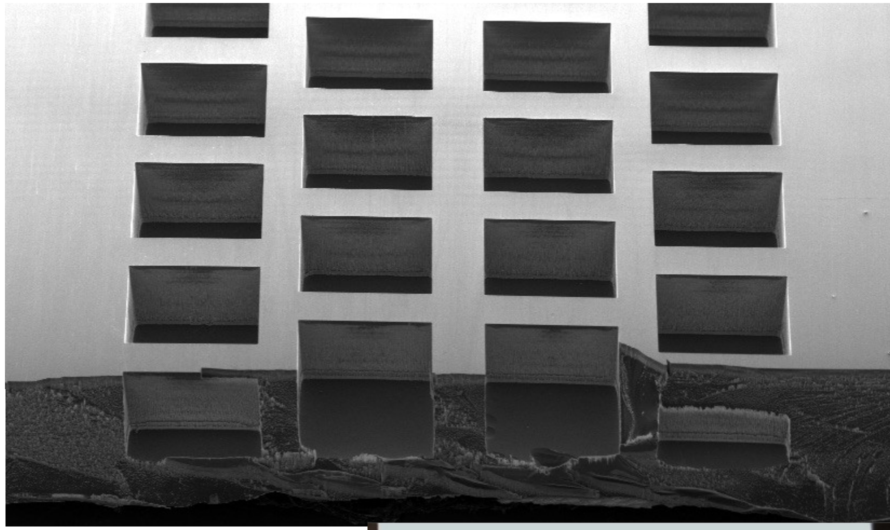




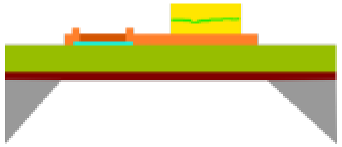
Detector array fabrication / 2

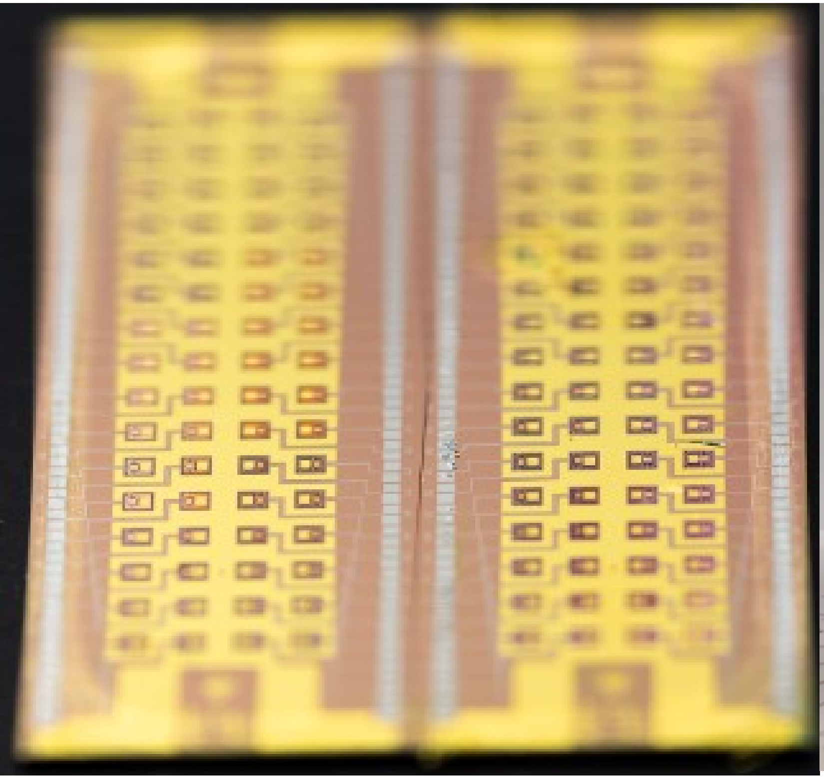


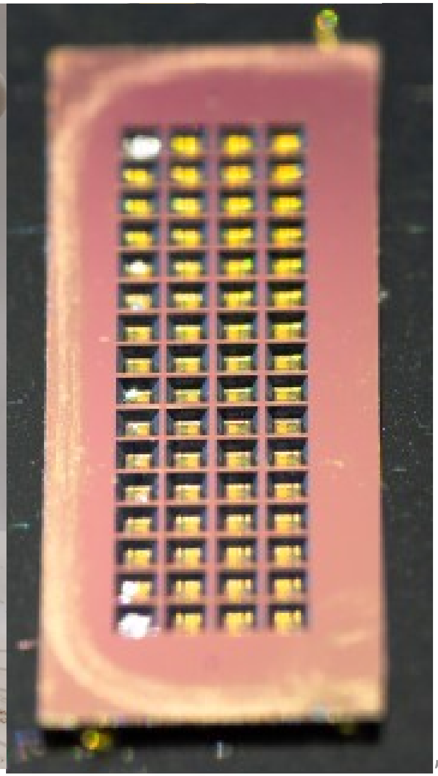
- two options for membrane release (i.e. final array fabrication step)
- Silicon Deep Reactive Ion Etching (DRIE)
  - best for close packing and high implant efficiency
  - R&D almost complete

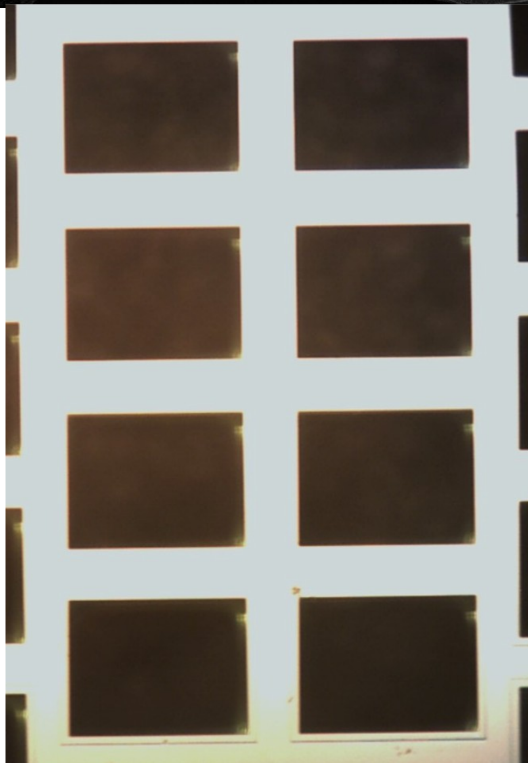


- Silicon KOH anisotropic wet etching
  - requires more spacing between pixels
  - succesfully tuned → **HOLMES baseline**



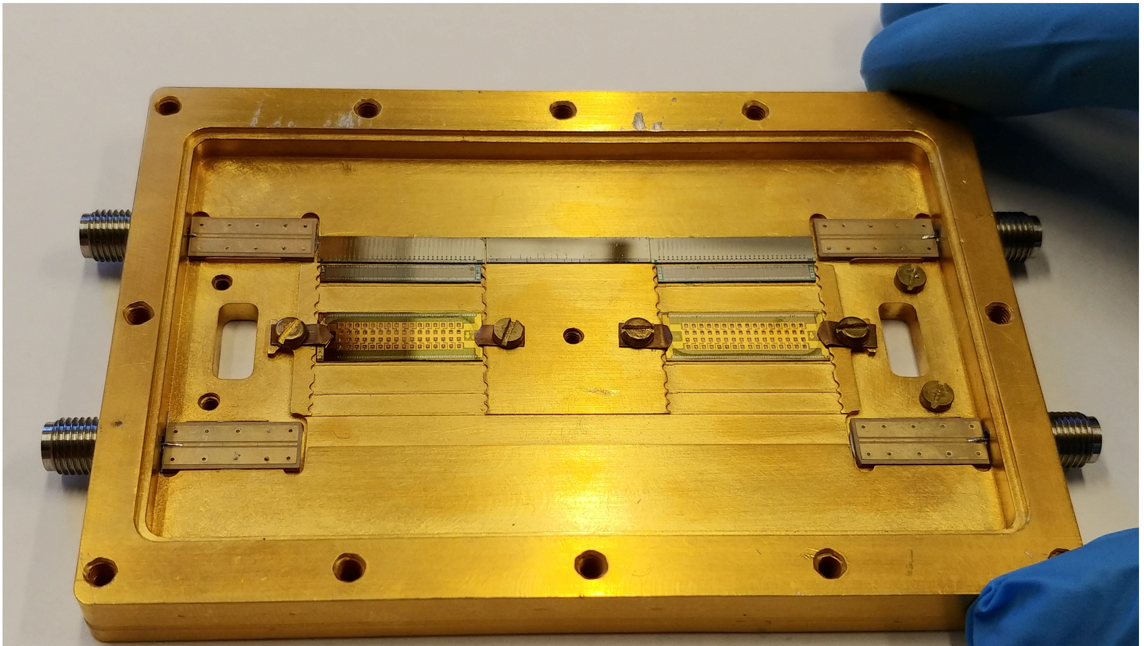


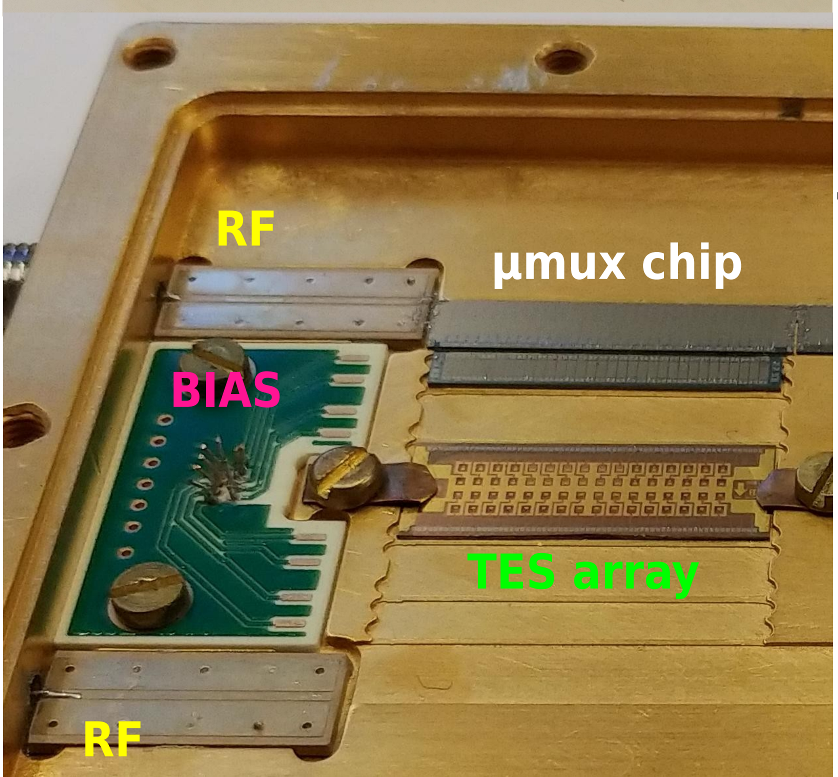




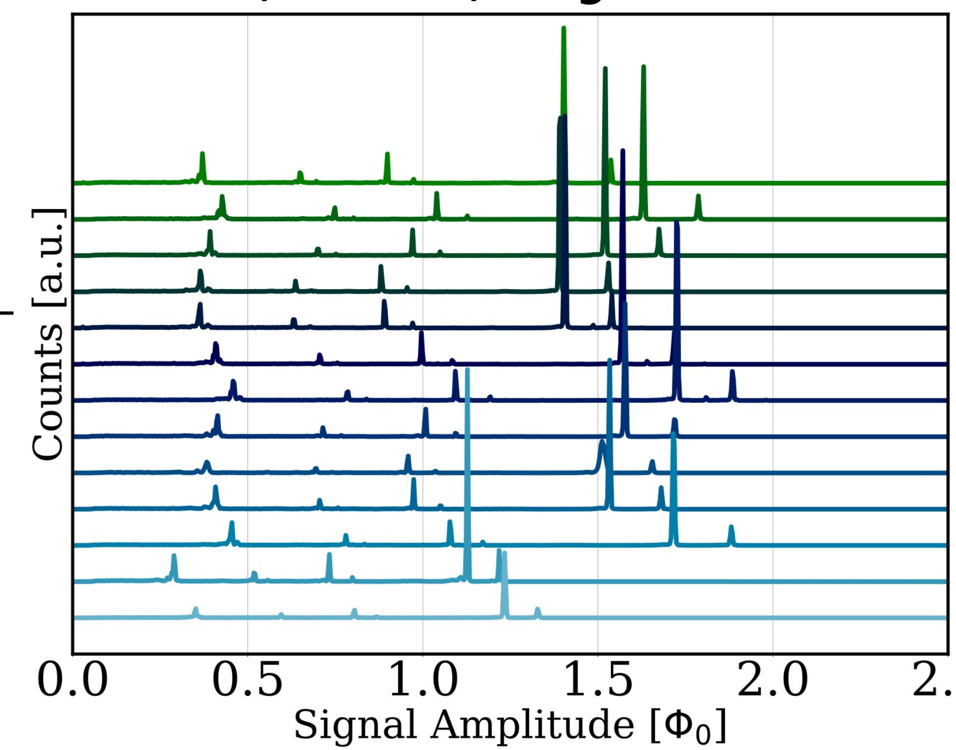
Fully processed detector array testing

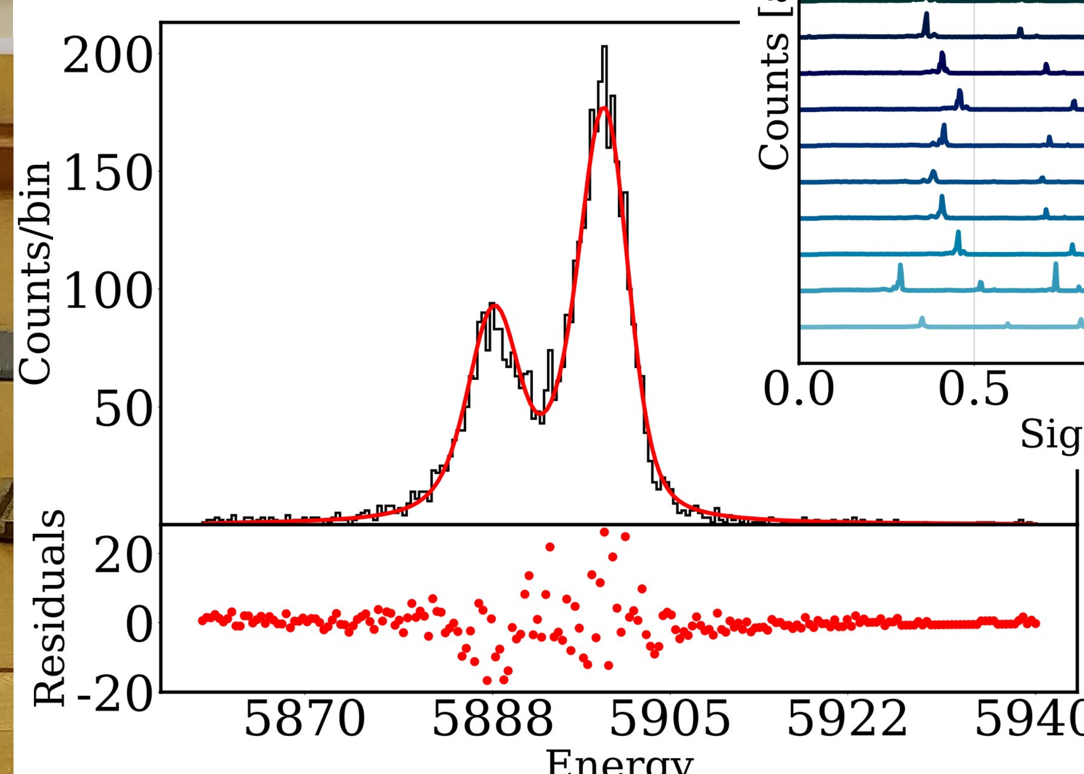
- low temperature test of **fully processed arrays**
- 32+32 pixels bonded
- analysis in progress: ΔE_{FWHM} 4~5 eV
- still w/o ^{163}Ho





raw data, no cuts, no gain corrections





ΔE_{FWHM} = 4.2±0.1 eV

Low energy background

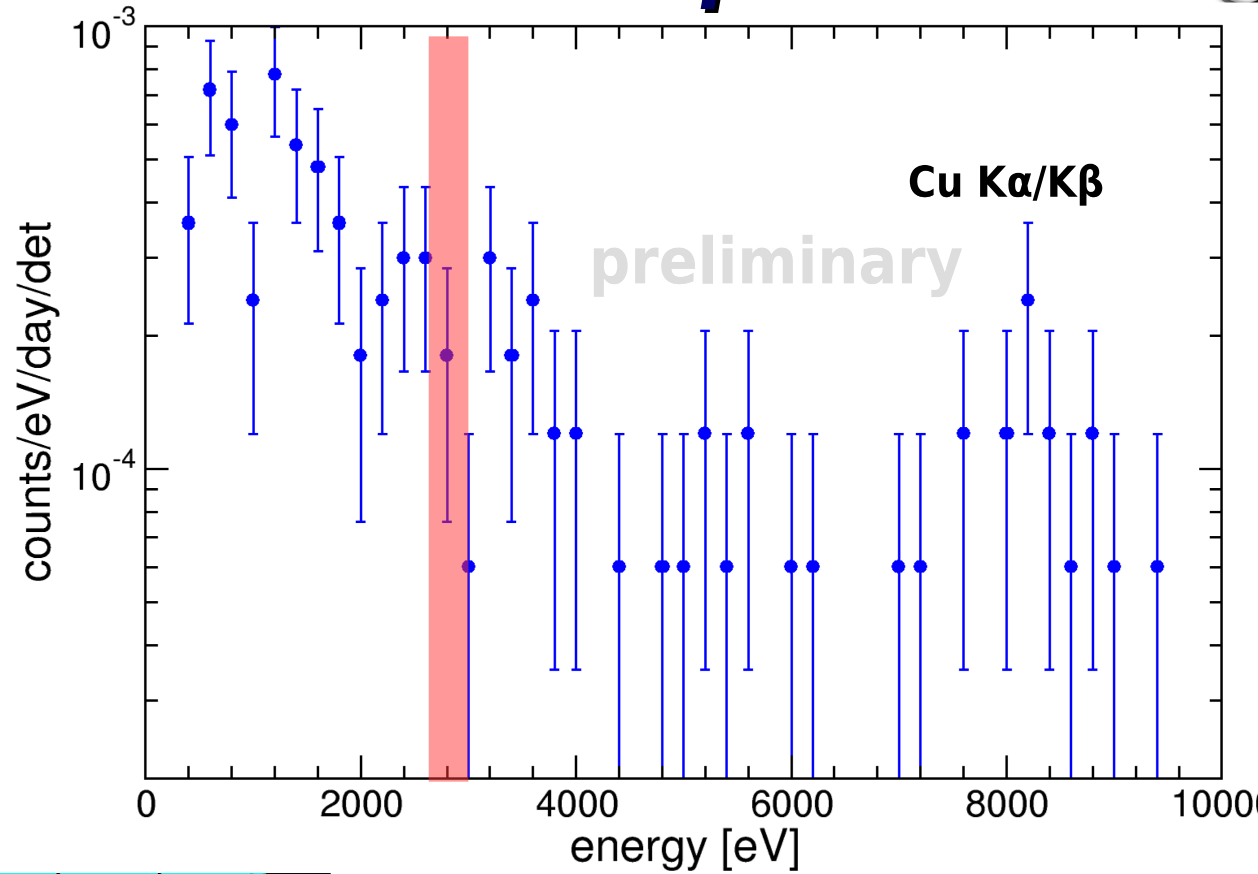
- environmental γ radiation
- γ, X and β from close surroundings
- cosmic rays
  - ▷ GEANT4 **→ *bkg* ≈ 10^{-5} c/eV/day/det** (0 - 4 keV)
- internal radionuclides
  - ▷ **^{166m}Ho** (β⁻, *Q* = 1.8 MeV, $\tau_{½}$ = 1200 y, produced along with ^{163}Ho)
  - ▷ GEANT4 **→ *bkg* ≈ 0.5 c/eV/day/det/Bq(^{166m}Ho)**
  - ▷ *A*(^{163}Ho) = 300Bq/det (↔ ≈6.5×10^{13} nuclei/det)

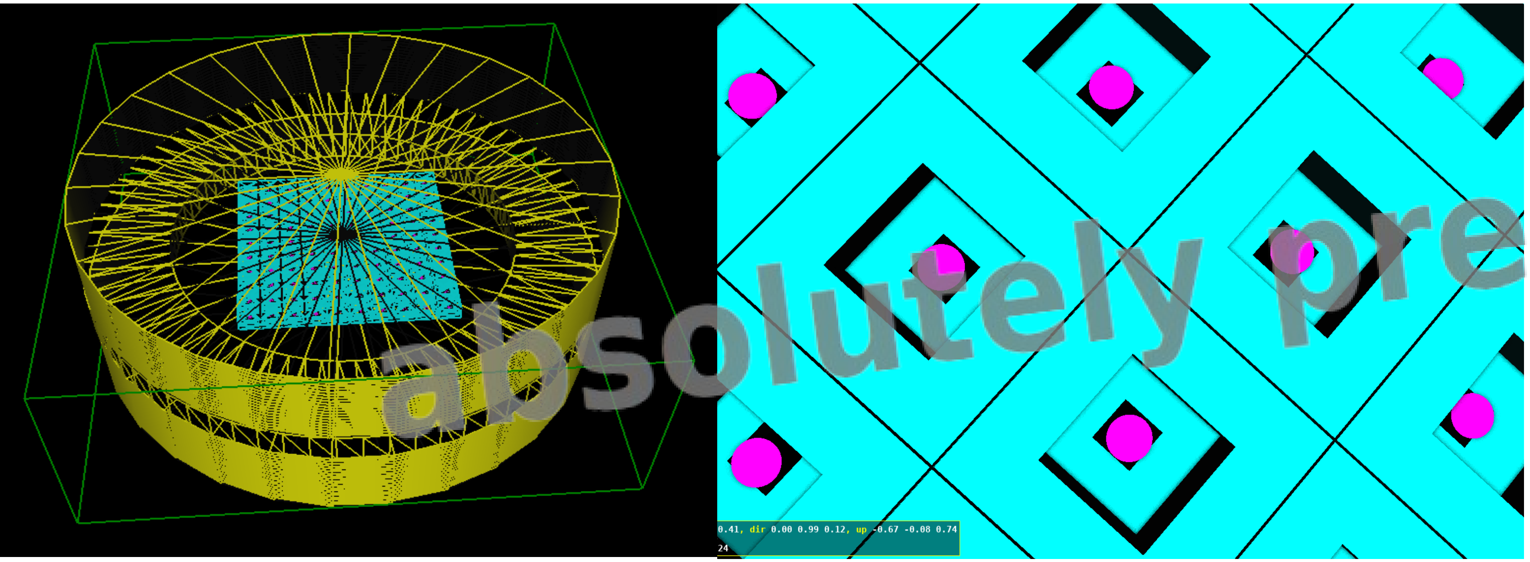
bkg(^{166m}Ho) < 0.1 c/eV/day/det → _A_(^{163}Ho)/_A_(^{166m}Ho) > 1500

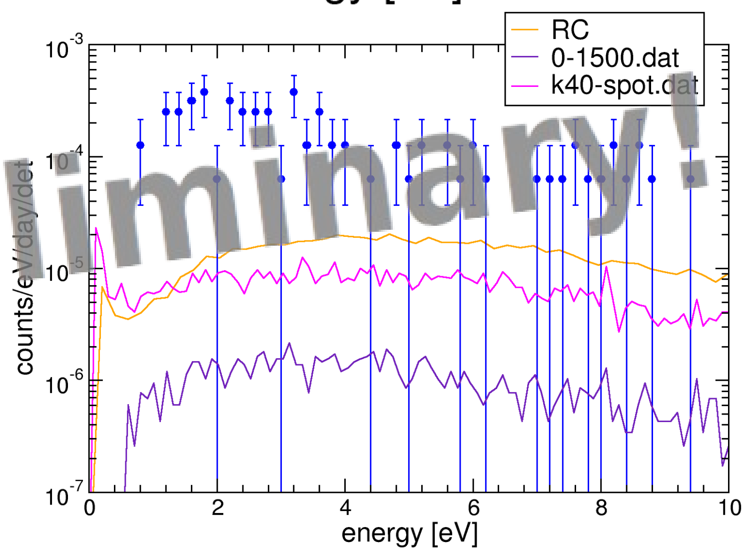
→ *N*(^{163}Ho)/*N*(^{166m}Ho)>6000

Background measurement in HOLMES set-up

- **HOLMES** detectors (≈90 day×det)
  - 200×200×2 μm³ Au absorbers
  - vertical placement (→ ≈no RC?)
  - sea level no material selection, no shielding
  - ***bkg*(4-10keV)≈1.1×10⁻⁴ c/eV/day/det**
- Geant4 simulations are in progress
  - cosmic rays (only muons), ^{238}U, ^{232}Th, ^{40}K, radon, environmental γ, …
- on-site γ measurements with HPGe detector
- more background measurement (w/o ^{163}Ho)

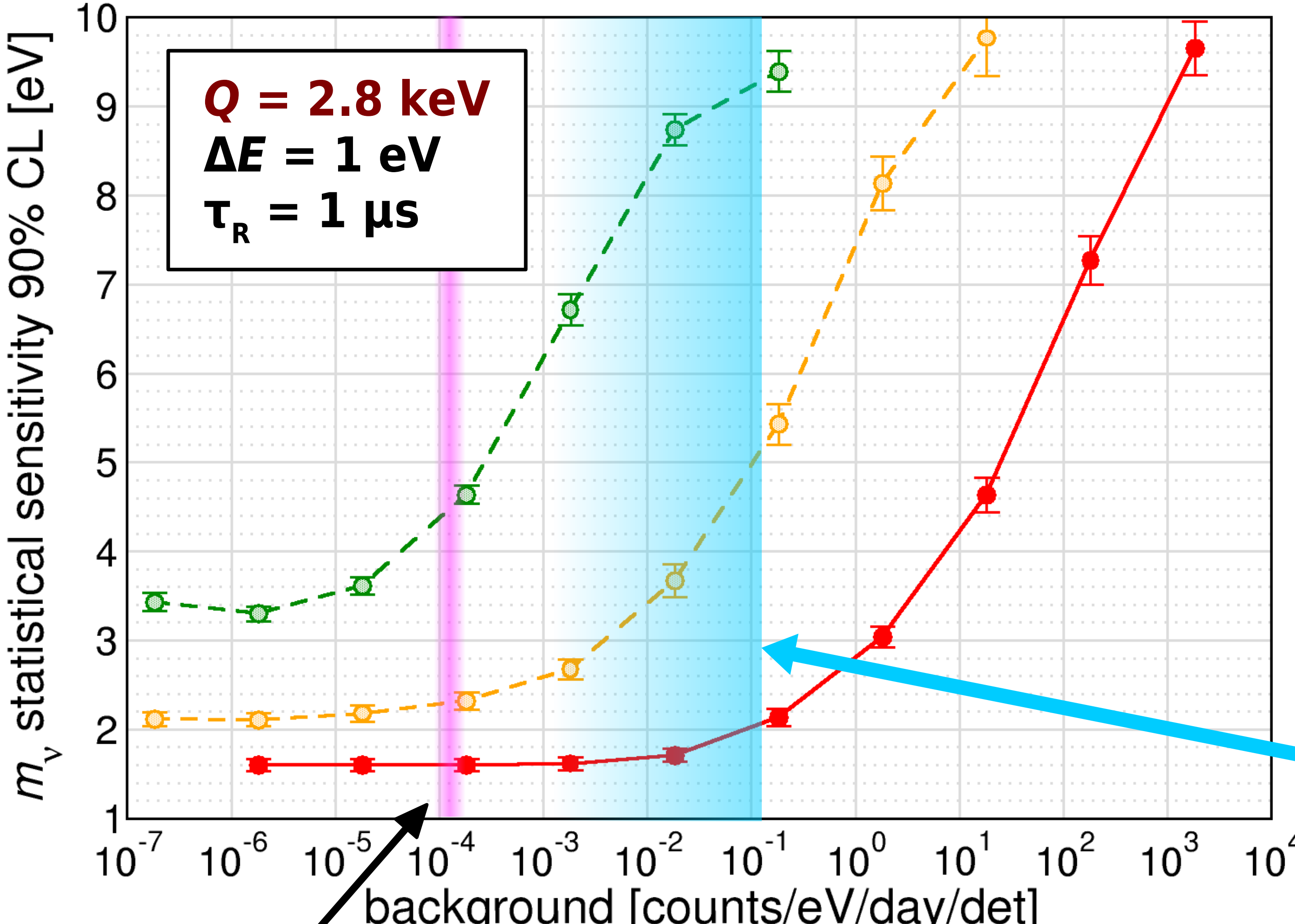






Effect of flat background on sensitivity

exposure $N_{det} t_M$ = 1000 det × 3 y



A_{EC}=3 Bq/det
f_{pp} = 3×10^{-6}

A_{EC}=30 Bq/det
f_{pp} = 3×10^{-5}

A_{EC}=300 Bq/det
f_{pp} = 3×10^{-4}

HOLMES target
for A_{EC} = 300 Bq
***bkg* < ≈0.1 c/eV/day/det**

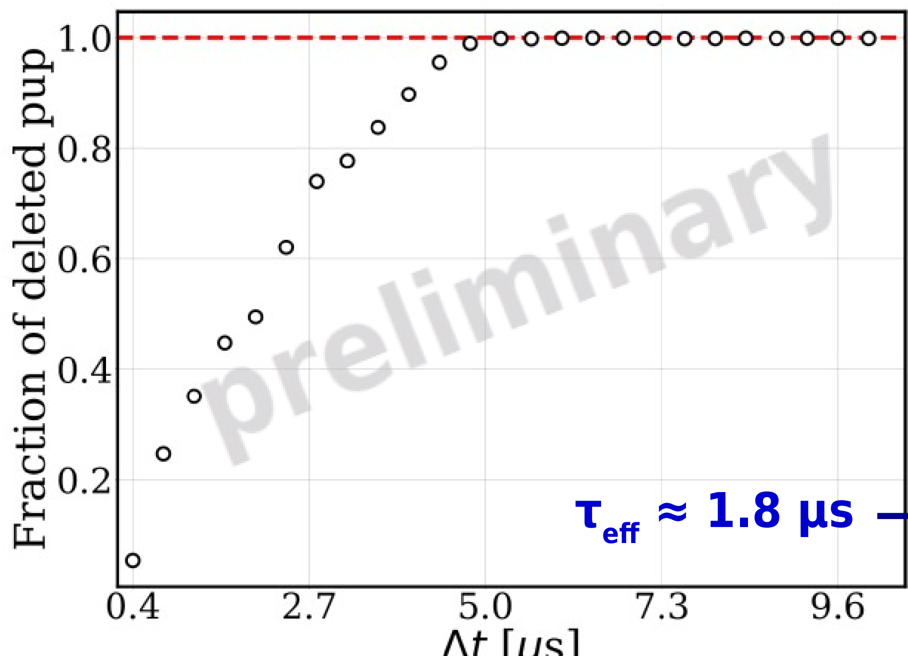
HOLMES preliminary background measurement

Detector time resolution

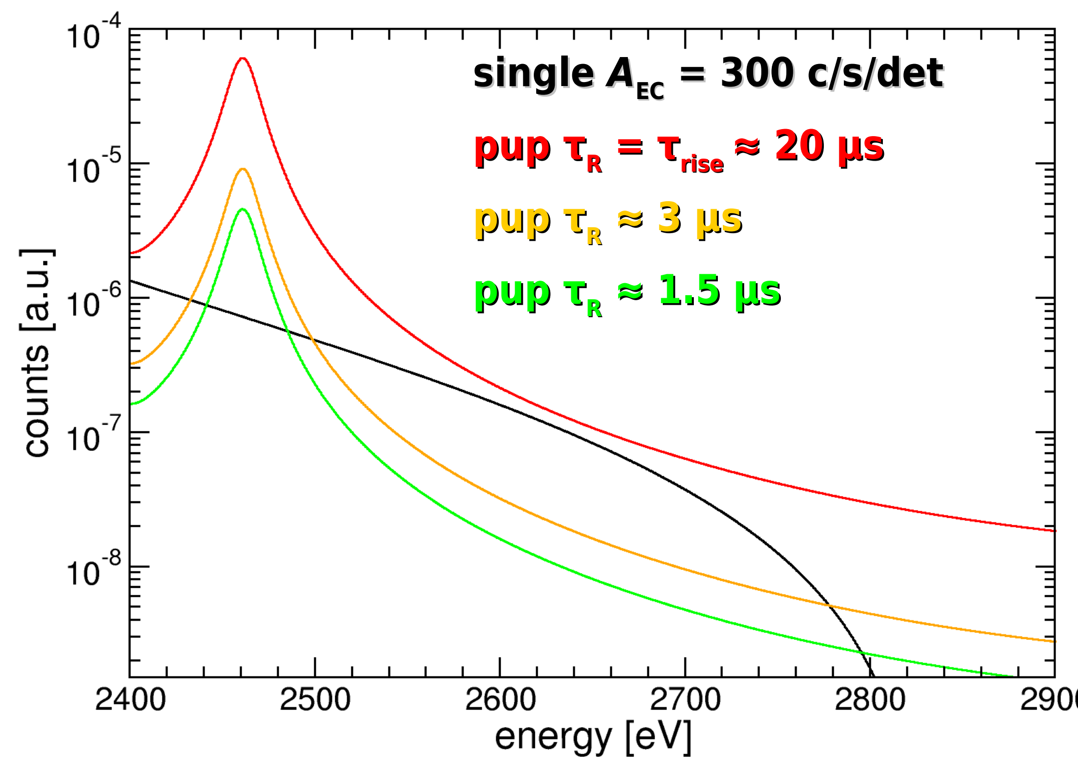
- for subsequent (Δt) events with energy E_1 and E_2: time resolution $\boldsymbol{\tau_R = \tau_R(E_1, E_2)}$

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

- **Montecarlo pile-up spectrum simulations**
  - ▷ event pairs with $E_1+E_2 \in [2.6\text{ keV}, 2.9\text{ keV}]$ (drawn from ^{163}Ho spectrum), $\Delta t \in [0, 10\mu s]$
  - ▷ pulse shape and noise from NIST TES model, sampled with f_{samp}, record length, and n bit
  - ▷ $\boldsymbol{f_{samp} = 0.5\text{MHz}, \tau_{rise} \approx 20\mu s}$
- ***mycroft*** a tool to discriminate **pile-up** based on PCA, SVD and multidimensional linear regression



sub-sample time resolution

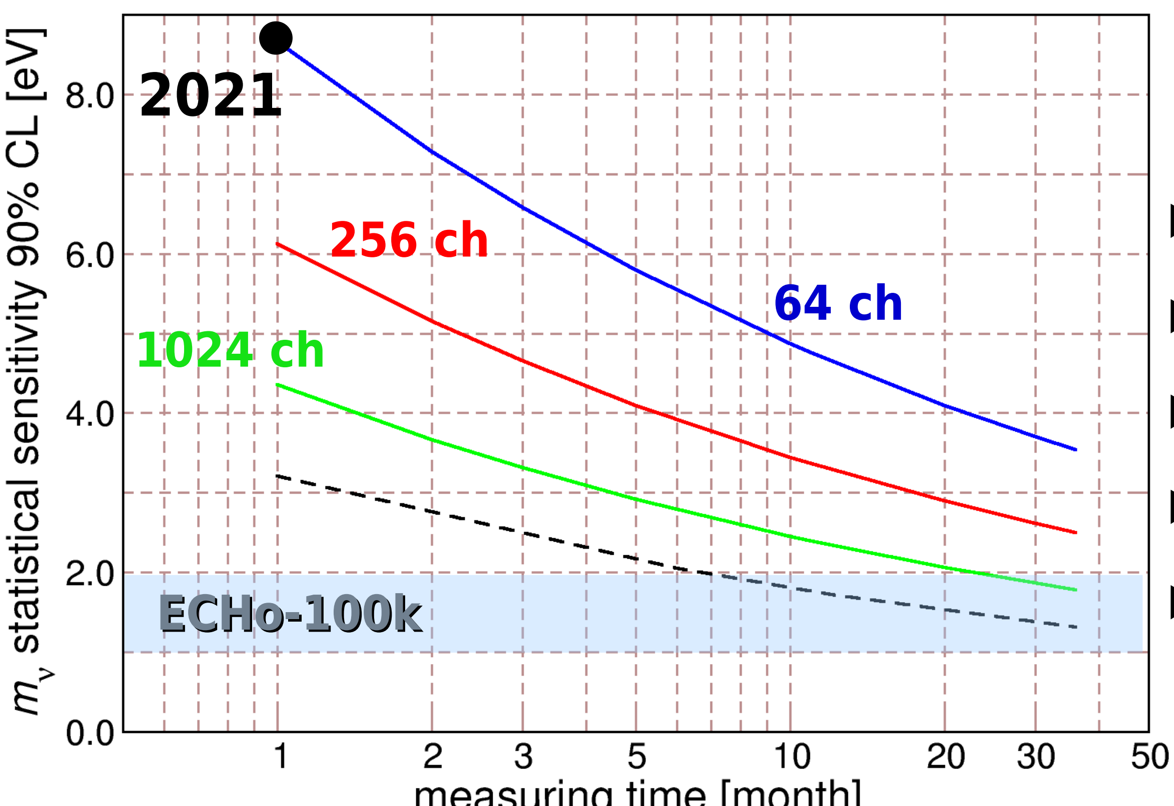


HOLMES status summary

- ✔ **purified ^{163}Ho to ion implant 300Bq in ≈300 detectors (+ tests)**
- ✔ **ion implanting system**
  - ✔ ion source and magnetic mass separation
  - ✔ ion source optimization with Ho → 2020
  - ✔ implanter/focusing/target chamber integration for high dose ion implantation → 2021
- ✔ **single TES pixel suitable for HOLMES**
- ✔ **64 pixel array fabrication**
  - ✔ first wafer produced by NIST → 22 arrays
  - ✔ KOH backside etching (R&D on DRIE in progress)
  - ✔ target chamber for Au co-depostion
  - ✔ full array fabrication without ion implantation
  - ✔ array fabrication with implanted ^{163}Ho → low dose in 2020, high dose in 2021
- ✔ **MUX & DAQ**
  - ✔ SDR firmware for 32 channels
  - ✔ HW for 64 channels (mux chip, HEMT/coax, IF board, ROACH2)
- ✔ **analysis tools**

HOLMES short and mid term program (2020-2023)

- optimize ^{nat}Ho ion beam with different targets
- first low dose ^{163}Ho implantation (≈1 Bq) in array (w/o focusing) → 2020
  - 1 month data taking can provide a m_ν statistical sensitivity ≈10 eV
- focusing stage and target chamber integration
- optimize high dose ^{163}Ho implantation (≈300 Bq?) → 2021
  - **start high statistics measurement with 64 channels → 2021**

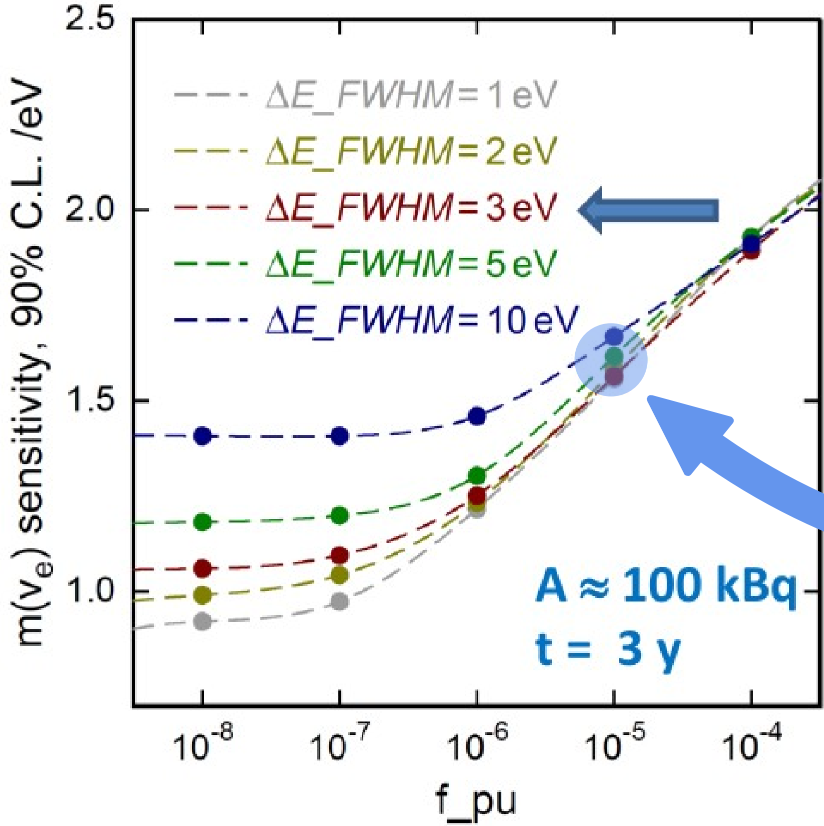


2021 → 2023 program

- increase number of deployed arrays
- end-point measurement ≈1 eV sensitivity
- compare HOLMES vs. ECHo (high vs. low activity)
- check shape and enhancements above M1 peak
- high statistics systematic effects analysis

ECHo-100k vs. HOLMES (Montecarlo simulations)

ECHo-100k (2018 – 2021)



$m(\nu_e) < 1.5$ eV 90% C.L.

Activity per pixel 10 Bq

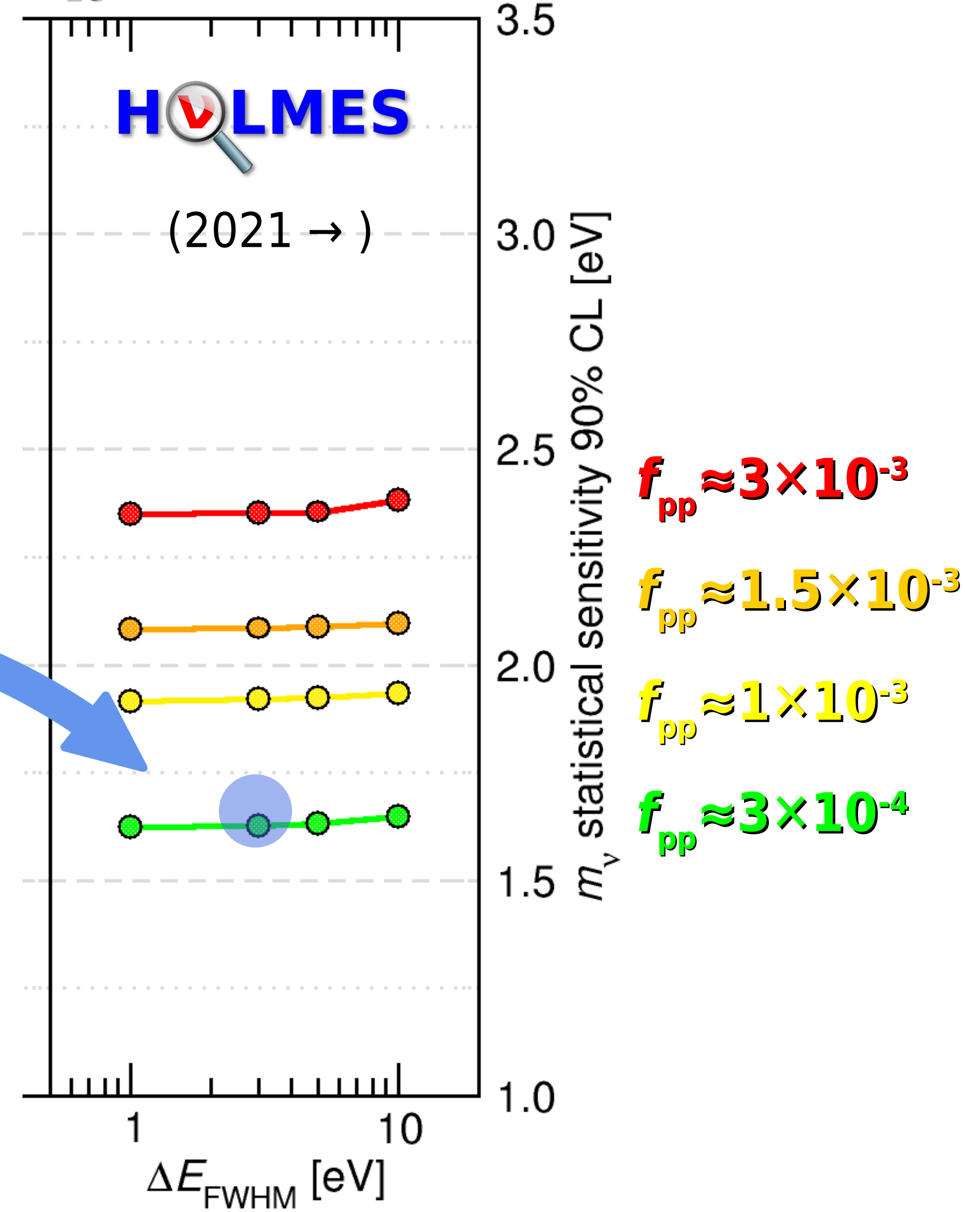
Number of detectors 12000

Readout: microwave SQUID multiplexing

possibly similar statistical sensitivity (≈2eV) by 2022?

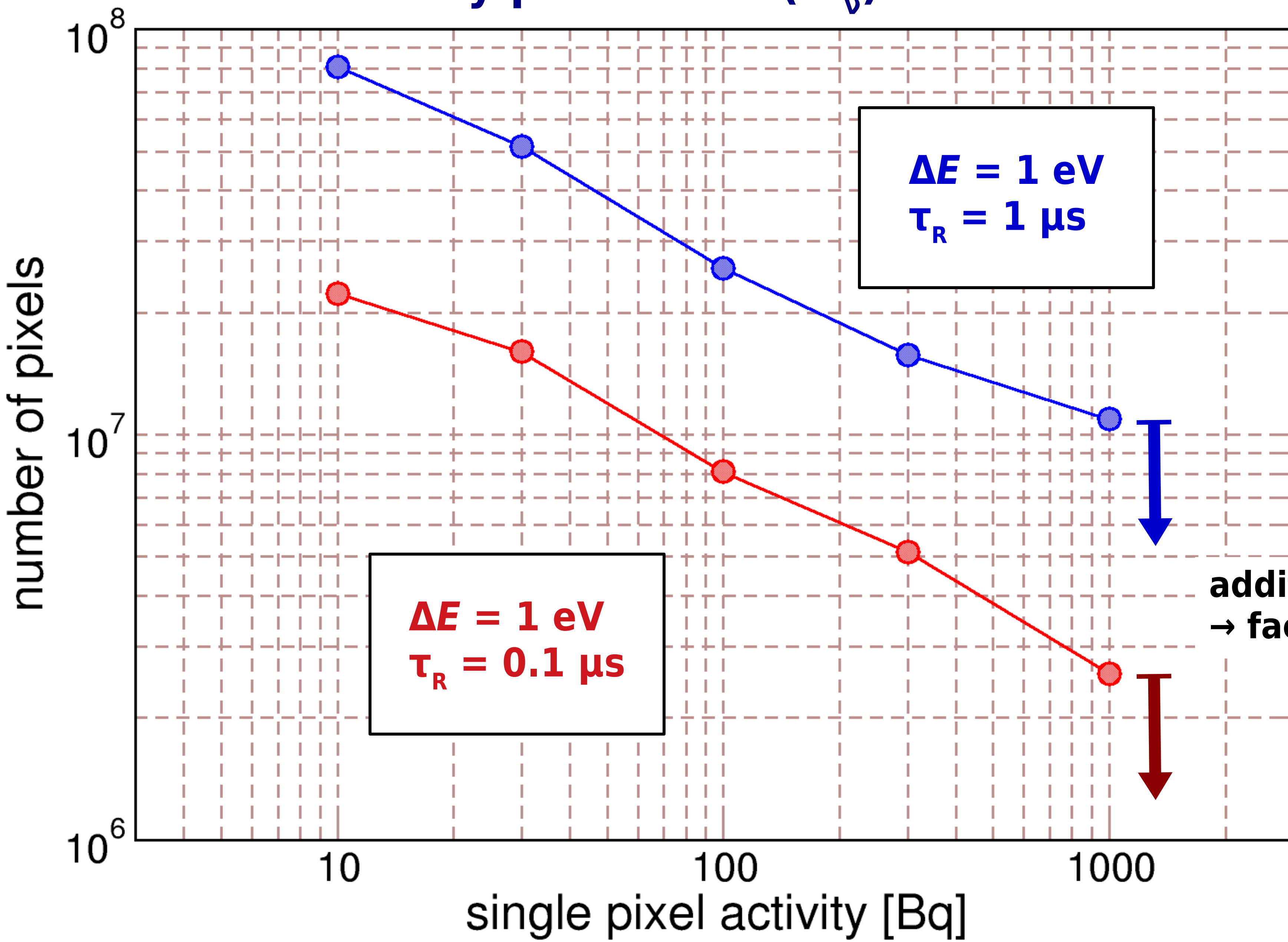
$N_{det}t_M$ = 1000 det × 3 y

A_{EC} = 300 c/s/det



From HOLMES to a 0.1eV experiment

how many pixels for $\Sigma(m_\nu) \leq 0.1$ eV ?



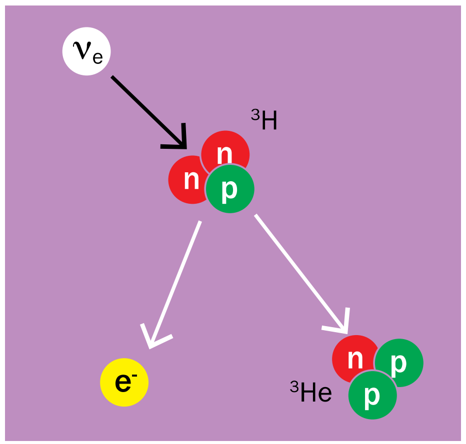
t_M = 10 years

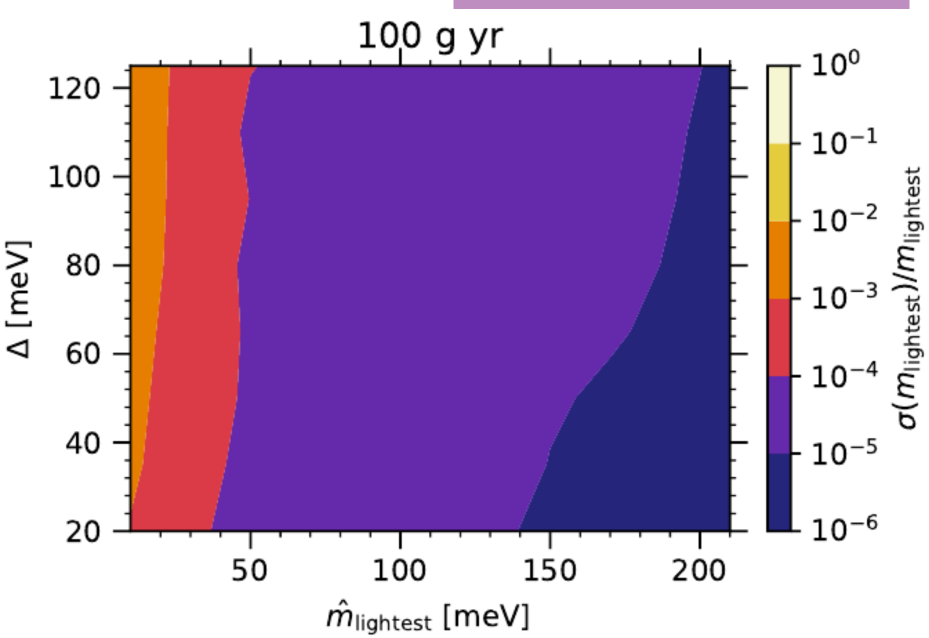
additional rate due to shake-off
→ factor 2-3 gain

PTOLEMY project

- **PonTecorvo Observatory for Light, Early-universe, Massive-neutrino Yield**
- PTOLEMY concept: Relic Neutrino Capture on Tritium Nuclei
- S. Weinberg in 1962 [Phys. Rev. 128:3, 1457] and Cocco, Mangano, Messina in 2007 [JCAP06(2007)015]

https://ptolemy.lngs.infn.it/

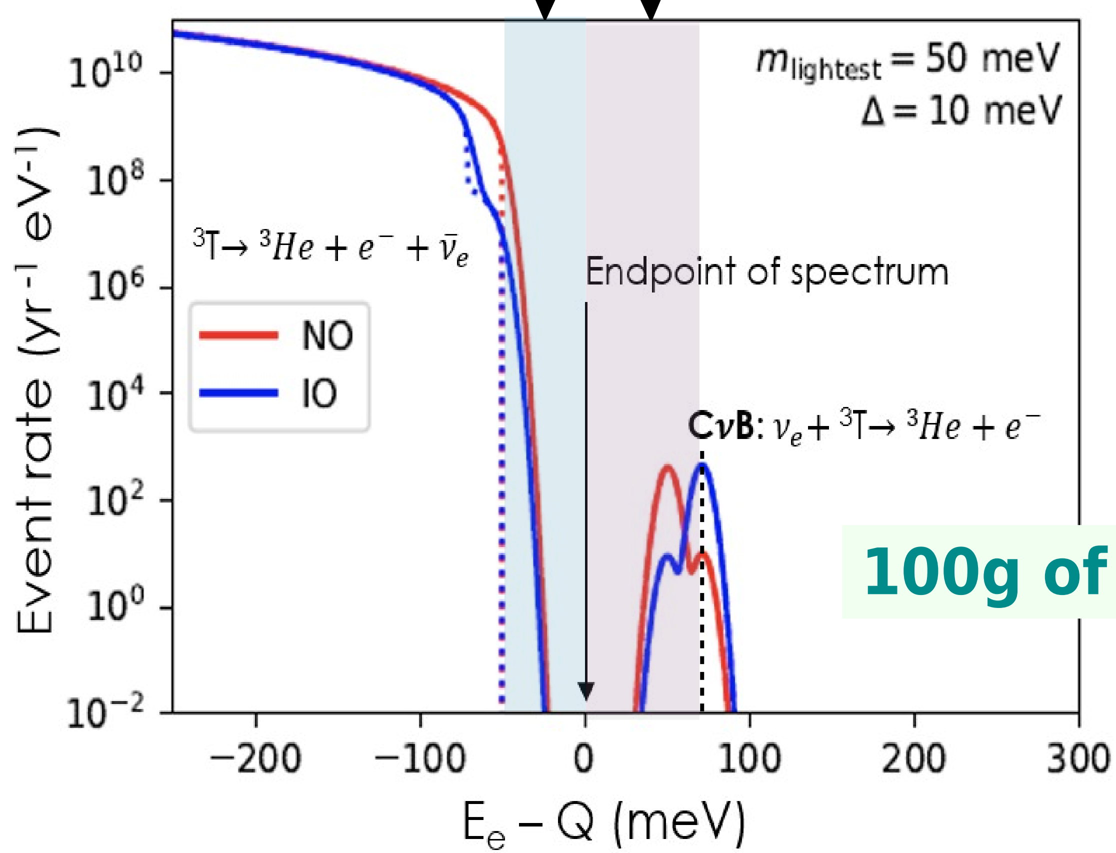




M.G. Betti et al., JCAP 1907 (2019).

from oscillations

$\gtrsim m_{lightest}$ **$\gtrsim$ 50meV**



Q = 18.6 keV

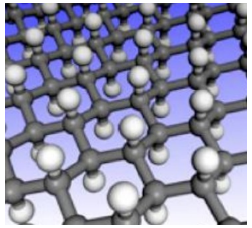
100g of tritium

→ potentially a very sensitive neutrino mass experiment

PTOLEMY demonstrator: PTOLEMY-0

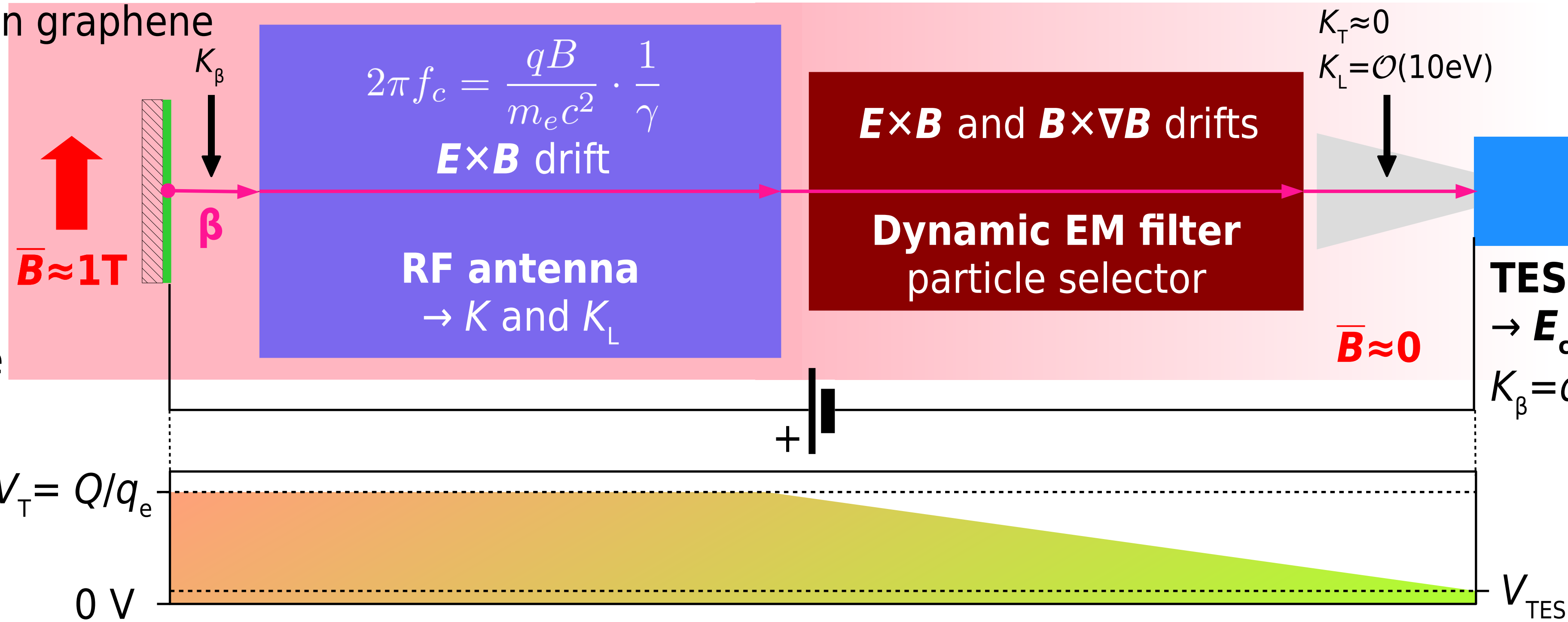
M.G. Betti et al., Prog. Part. Nucl. Phys, 106 (2019)

monoatomic T on graphene



1 µg T monolayer on graphene

→ **370MBq**



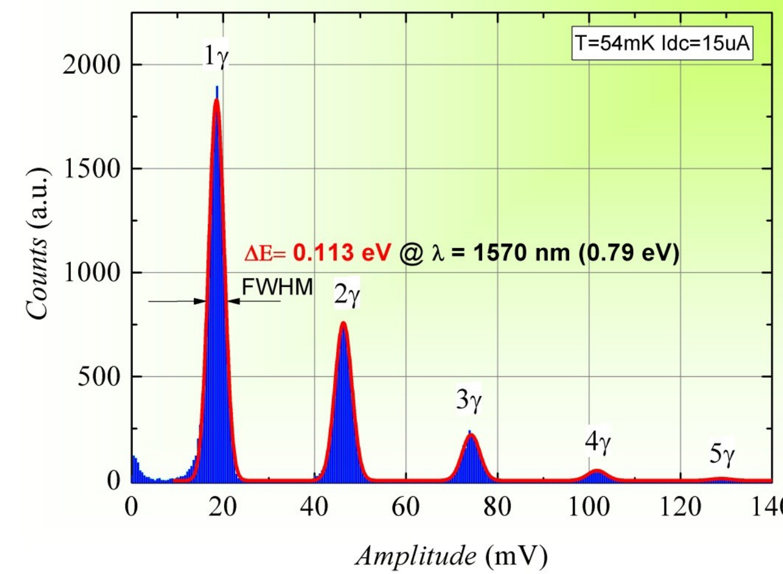
TES µcalorimeters

→ $E_{cal} = K_T + K_L$

$K_\beta = q_e(V_{TES} - V_T) + \Delta E_{RF} + E_{cal}$

- Electrons from weakly-bound tritium originate from a cold target surface.
- Electrons drift through the RF Antenna region

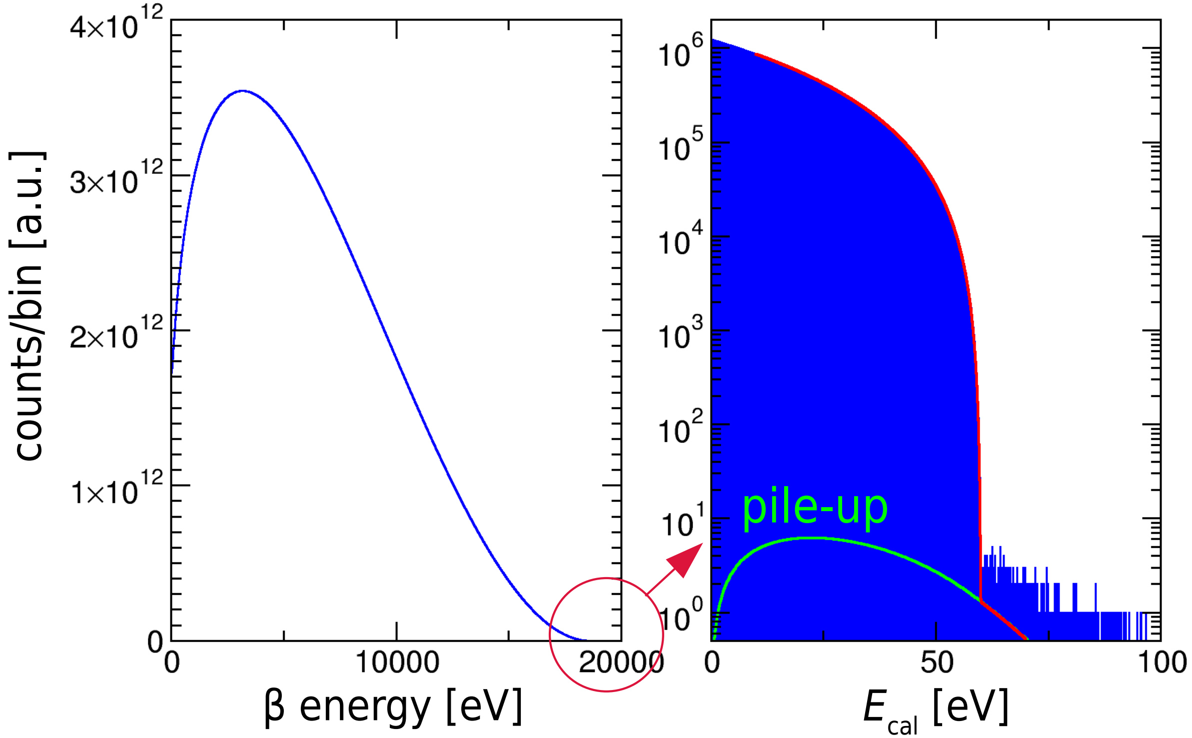
  → electron momentum components are measured to $\mathcal{O}$(eV) resolution by Cyclotron Radiation Electron Spectroscopy in 1T
- EM Filter electrodes are set ~1 msec before electrons enter
- Kinetic energy of electrons drained as they climb a potential under ***E*×*B*** and ***B*×∇*B*** drifts.
- Electrons with energy $>q_e(V_{TES}-V_T)=Q-\mathcal{O}(10\text{eV})$ in low B field region are transported into TES µcalorimeters with $\Delta E \approx 0.05$ eV



L. Lolli et al. Appl. Phys. Lett. 103, 041107 (2013)

PTOLEMY-0 and neutrino mass sensitivity

$q_e(V_{TES}-V_T) = Q - 60$ eV



- 1 µg tritium → 370MBq
- 3 years measurement → N_{ev}=3.5×10^{16} decays
- 18 β/s on µcalorimeters → N'_{ev}=1.8×10^{9} counts
- 32 pixel array, τ_R= 10 µs → f_{pp}≈ 10^{-5}
- ΔE_{FWHM} = 0.1 eV