Status of the HOLMES neutrino mass experiment

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erc

INFN
Istituto Nazionale di Fisica Nucleare

UNIVERSITA' DEGLI STUDI DI MILANO BICOCCA

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Outline

- ^{163}Ho decay calorimetry and neutrino mass measurement
- HOLMES experiment goal and design
- HOLMES tasks status
  - isotope production and chemical purification
  - isotope mass separation and embedding
  - single detector design
  - detector read-out and DAQ
  - detector array fabrication
- conclusions and perspectives

Electron capture calorimetric experiments

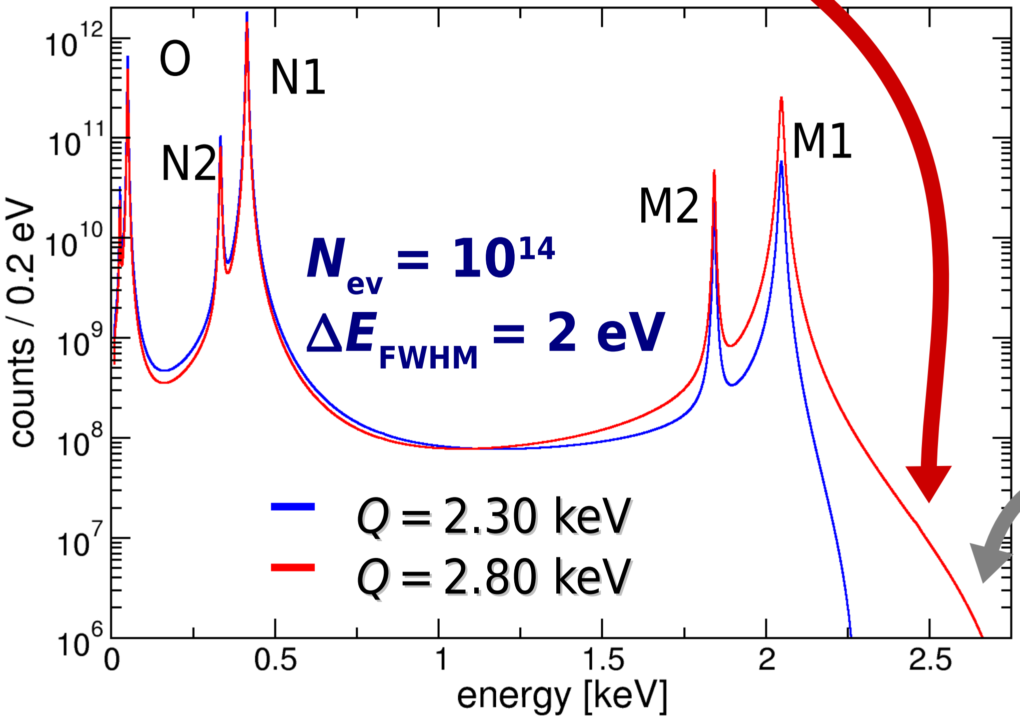
$^{163}\mathrm{Ho} + e^- \rightarrow {}^{163}\mathrm{Dy}^* + \nu_e$

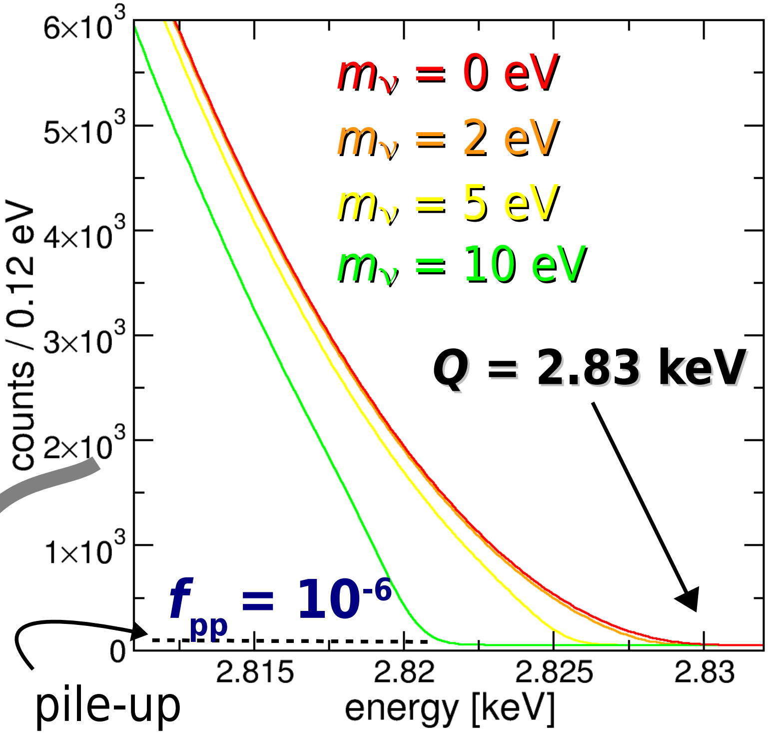
electron capture from shell ≥ M1

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

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

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

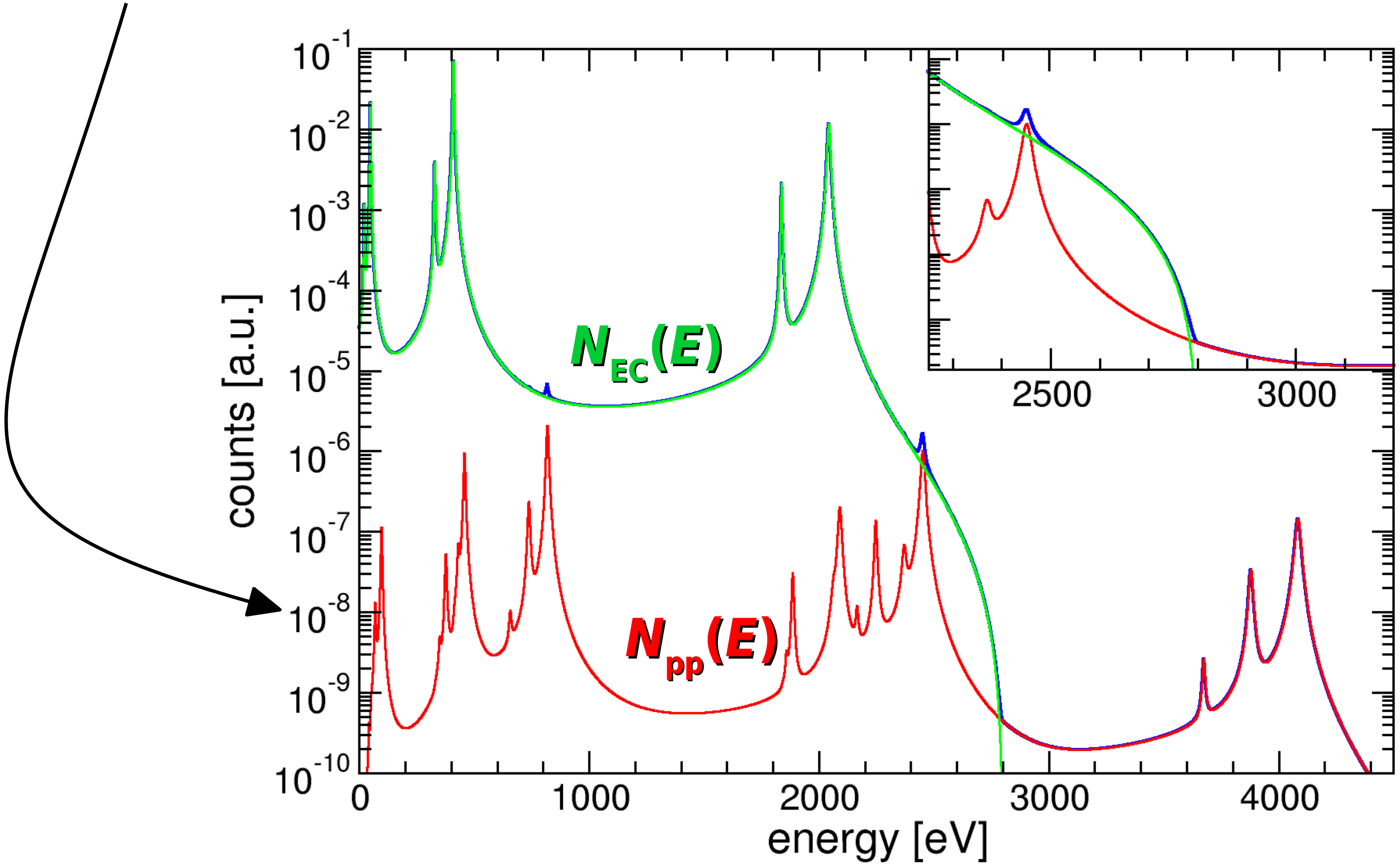




Electron capture calorimetric experiments

- 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

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

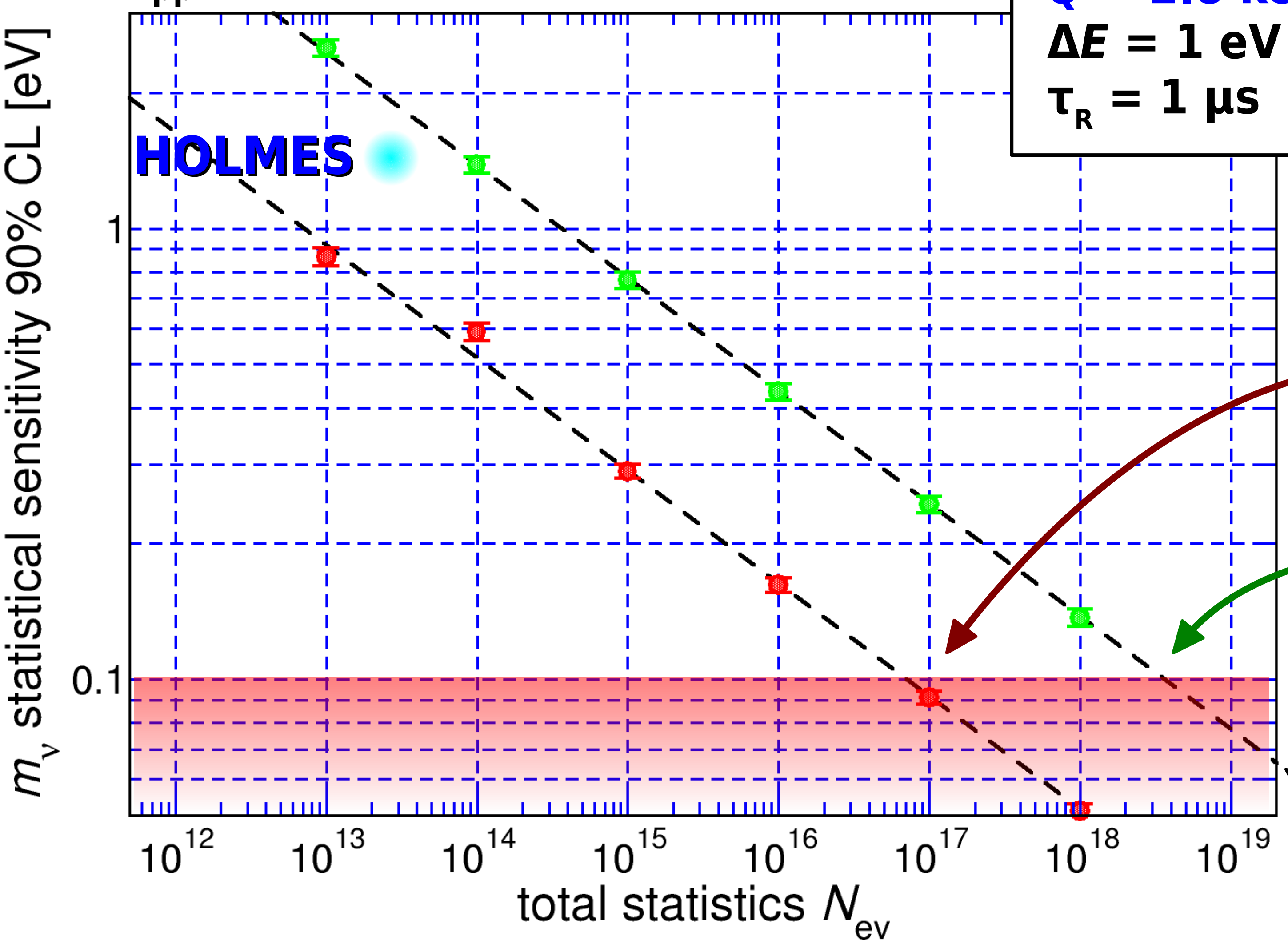
$N_{EC}(E)$ without higher order processes (shake up / shake off)

Montecarlo simulations: ^{163}Ho sensitivity potential

m_ν sensitivity mostly depends on:
- ▲ total statistics $N_{ev} = A_{EC} N_{det} t_M$
- ▼ pile fraction $f_{pp} = A_{EC} \tau_R$

t_M measuring time
N_{det} number of detectors

f_{pp} = 10^{-6}, 10^{-3}



Q = 2.8 keV
ΔE = 1 eV
τ_R = 1 µs

for $\Sigma(m_\nu) \leq 0.1$ eV

A_{EC} = 1 Bq
$N_{det} t_M \approx 2 \times 10^9$ det×y

A_{EC} = 1000 Bq
$N_{det} t_M \approx 10^8$ det×y

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

A. Nucciotti, Eur. Phys. J. C (2014) 74:3161

HOLMES *(ERC-Advanced Grant n. 340321)*

HOLMES

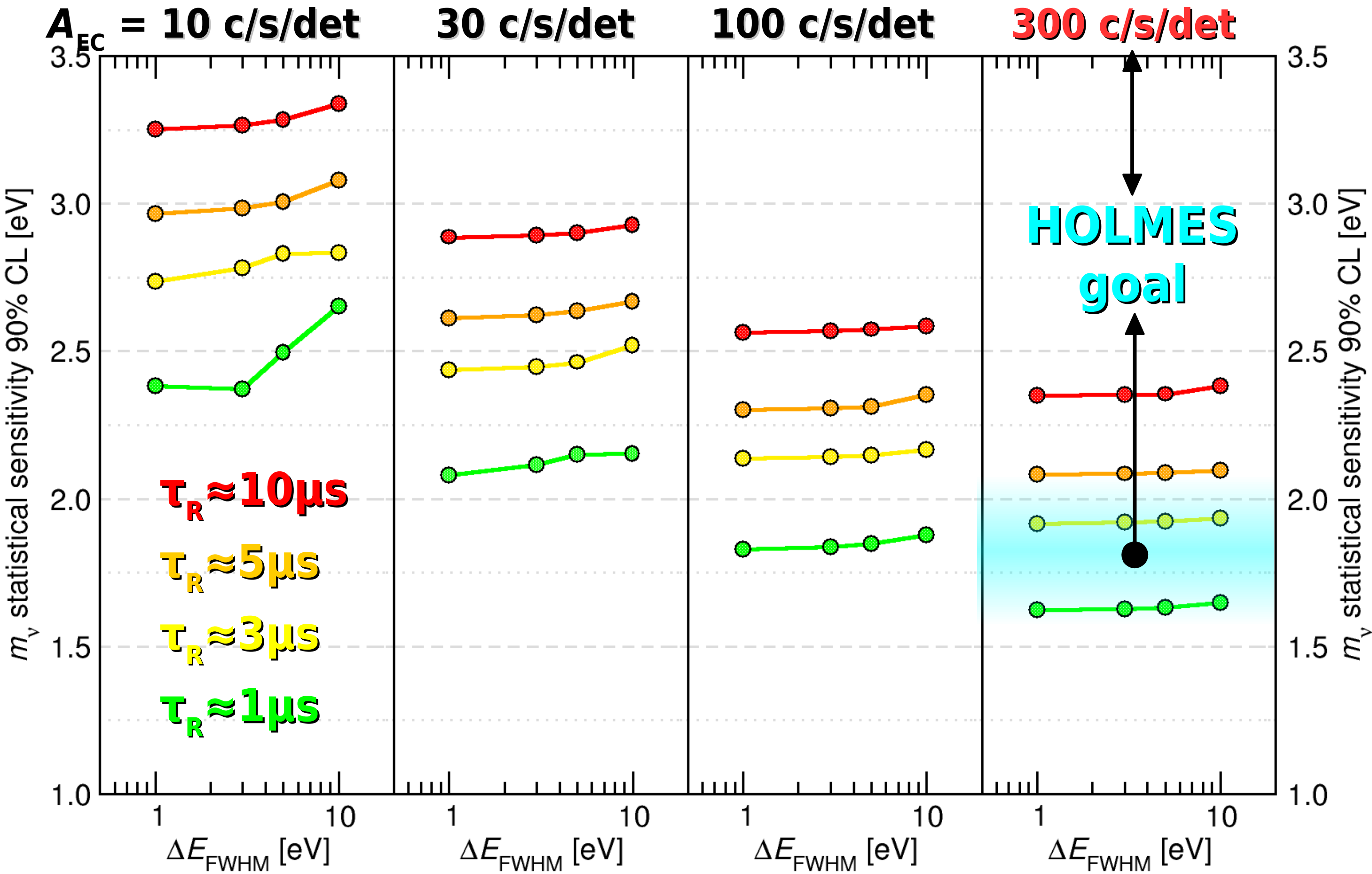
goal

- direct neutrino mass measurement: **m_ν statistical sensitivity around 1 eV**
- prove potential and scalability:
  - assess EC spectral shape
  - assess systematic errors

baseline

- **low T microcalorimeters** with **implanted ^{163}Ho**
  - 6.5×10^{13} atom/det → **A_{EC}=300 c/s/det**
  - **ΔE ≈ 1 eV** and **τ_R ≈ 1 μs**
- **1000 channel** array
  - 6.5×10^{16} ^{163}Ho nuclei → ≈18 μg
  - 3×10^{13} events in **3 years**

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



5 years project started on February 1st 2014 (now extended by 1 year)

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

HOLMES collaboration

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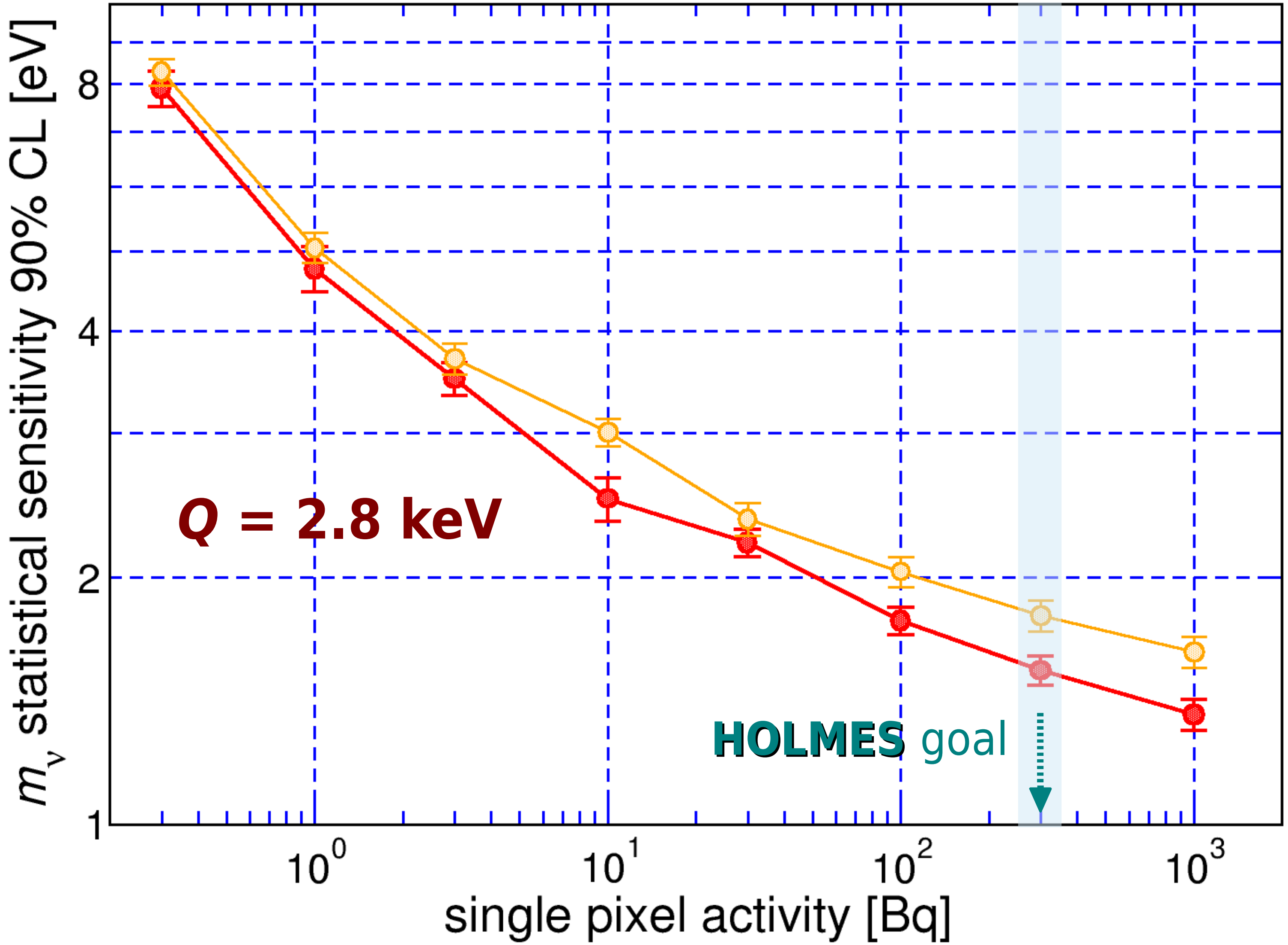
Statistical sensitivity and single pixel activity

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



ΔE =1 eV
τ_R = 1 µs

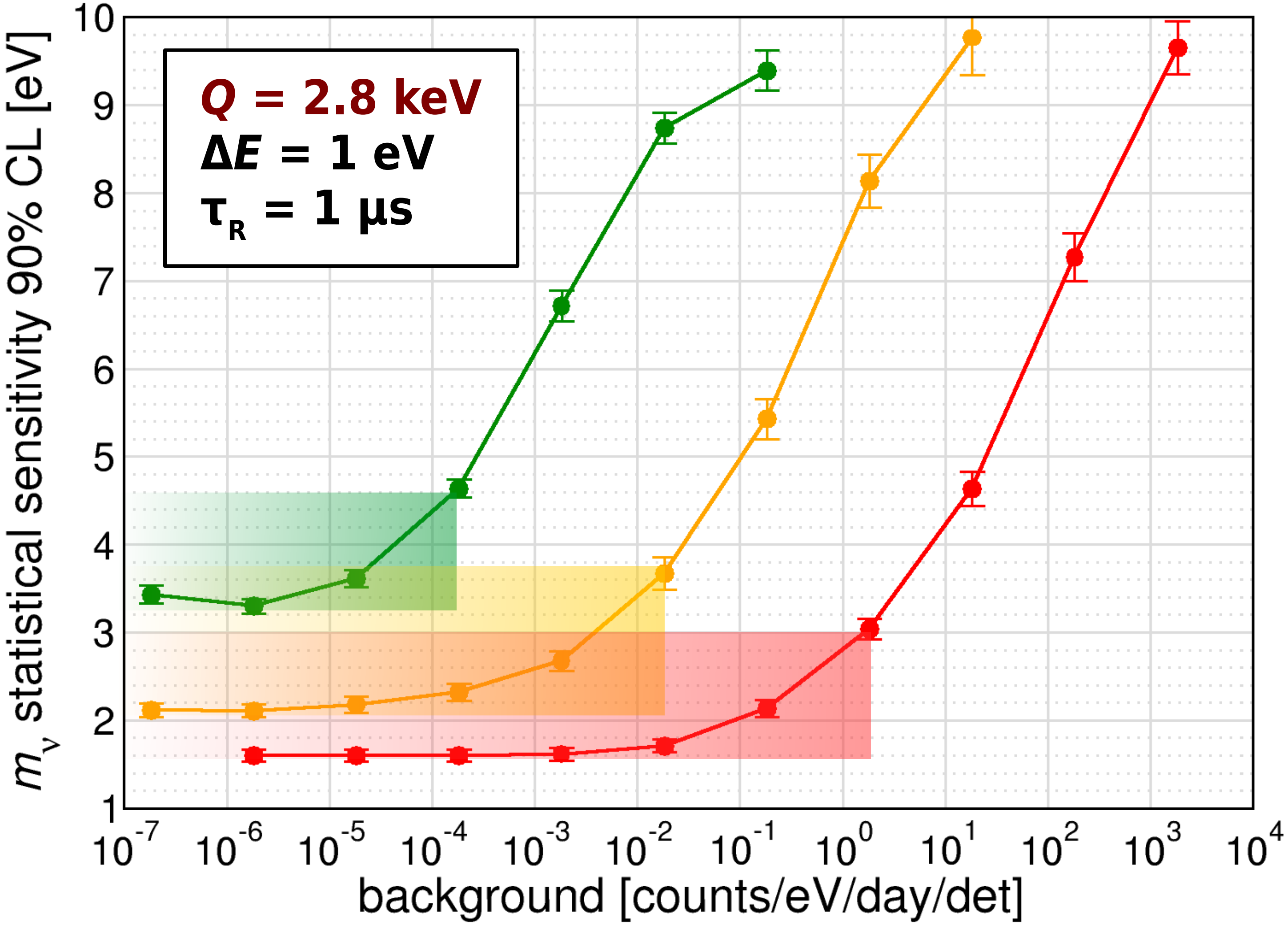
ΔE =3 eV
τ_R = 3 µs

high activity → robustness against (flat) background

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

Effect of background on sensitivity

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



A_{EC}=3 Bq/det
$f_{pp} = 3\times10^{-6}$

A_{EC}=30 Bq/det
$f_{pp} = 3\times10^{-5}$

A_{EC}=300 Bq/det
$f_{pp} = 3\times10^{-4}$

pile-up background ≈ average rate $\langle r_{pp} \rangle$

$\langle r_{pp} \rangle = A_{EC} f_{pp} / 2Q =$ **1.5×10^{-4}** **1.5×10^{-2}** **1.5** c/eV/day/det

Low energy background

HOLMES target

for $A_{EC} = 300$ Bq

bkg **< ≈0.1 c/eV/day/det**

Au pixel 200×200×2 μm^3

- **environmental γ radiation**
- **γ, X and β from close surroundings**
- **cosmic rays**
  - ▷ GEANT4 **→ *bkg* ≈ 5×10^{-5} c/eV/day/det (0 - 4 keV)**

MIBETA experiment: 300×300×150 μm^3 AgReO$_4$ crystals at **sea level**

***bkg*(2-5keV)≈1.5×10^{-4} c/eV/day/det**

- **internal radionuclides**
  - ▷ ^{166m}**Ho** (β⁻, Q = 1.8 MeV, $\tau_{1/2}$ = 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)

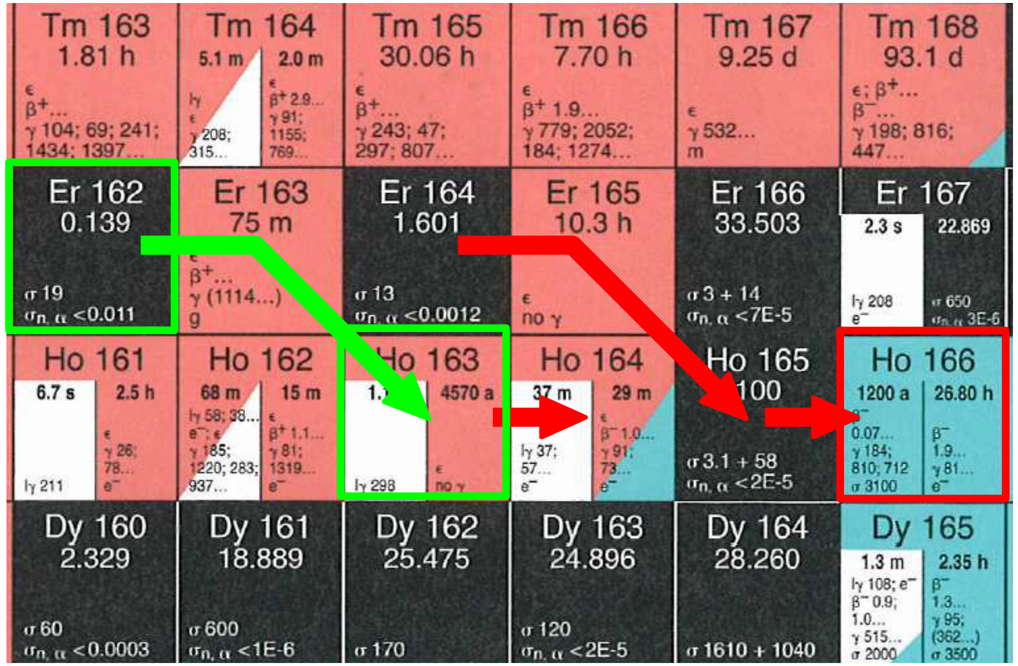
***bkg*(^{166m}Ho) < 0.1 c/eV/day/det → *A*(^{163}Ho)/*A*(^{166m}Ho) > 1500**

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

^{163}Ho production by neutron activation

^{162}Er (n,γ) ^{163}Er $\sigma_{thermal} \approx 20$b

^{163}Er → ^{163}Ho + ν_e $\tau_{½}^{EC} \approx 75$min



- **HOLMES needs ≈ 200 MBq of ^{163}Ho**

  with *reasonable* assumptions on the (unknown) global embedding process efficiency...

- ^{162}Er irradiation at **ILL nuclear reactor** (Grenoble, France)
  - thermal neutron flux at **ILL**: 1.3×10^{15} n/cm^2/s
  - burn up ^{163}Ho(n,γ)^{164}Ho: $\sigma_{burn\text{-}up} \approx 200$b (preliminary result from **PSI** analysis)
  - ^{165}Ho(n,γ) (mostly from ^{164}Er(n,γ)) → **^{166m}Ho** (β, $\tau_{½}$=1200y) → $A(^{163}\text{Ho})/A(^{166m}\text{Ho})$=100~1000
- chemical pre-purification and post-separation at **PSI** (Villigen, CH)

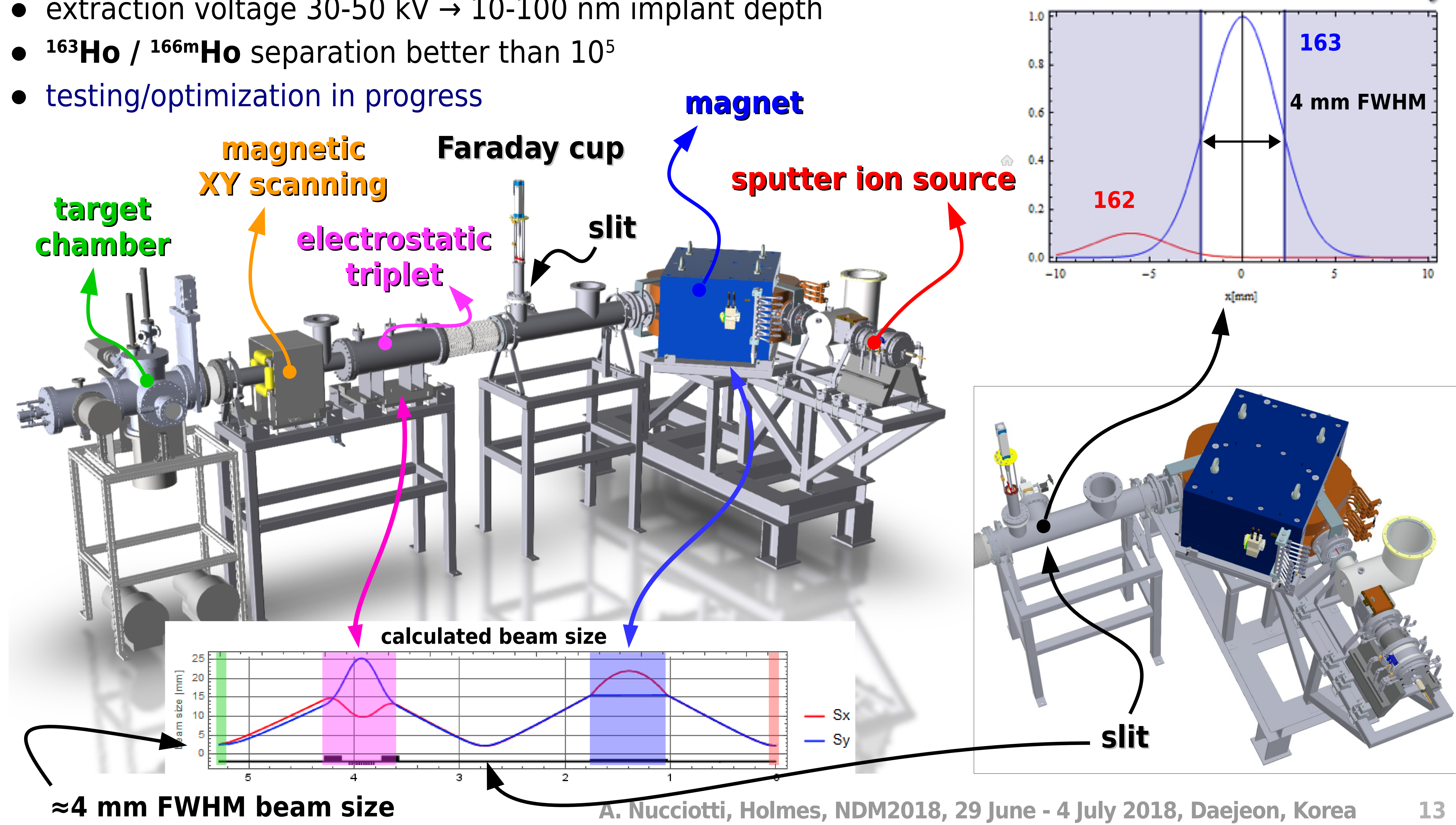
HOLMES source production

- **enriched Er_2O_3** samples irradiated at **ILL** and pre-/post-processed at **PSI**
  - 25 mg irradiated for 55 days (2014) → **$A(^{163}Ho) \approx 5$ MBq** ($A(^{166m}Ho) \approx 10$kBq)
  - 150 mg irradiated for 50 days (2015) → **$A(^{163}Ho) \approx 23$ MBq** ($A(^{166m}Ho) \approx 37$kBq)
- **Ho radiochemical separation** with ion-exchange resins in hot-cell at **PSI**
  - **efficiency ≳79%** (preliminary)
- **540 mg of 25% enriched Er_2O_3** irradiated 50 days at **ILL** in 2017 (separation in progress)
  - **$A(^{163}Ho)_{theo} \approx 100$ MBq** (enough for R&D and 500 pixels) ($A(^{166m}Ho) \approx 180$kBq)

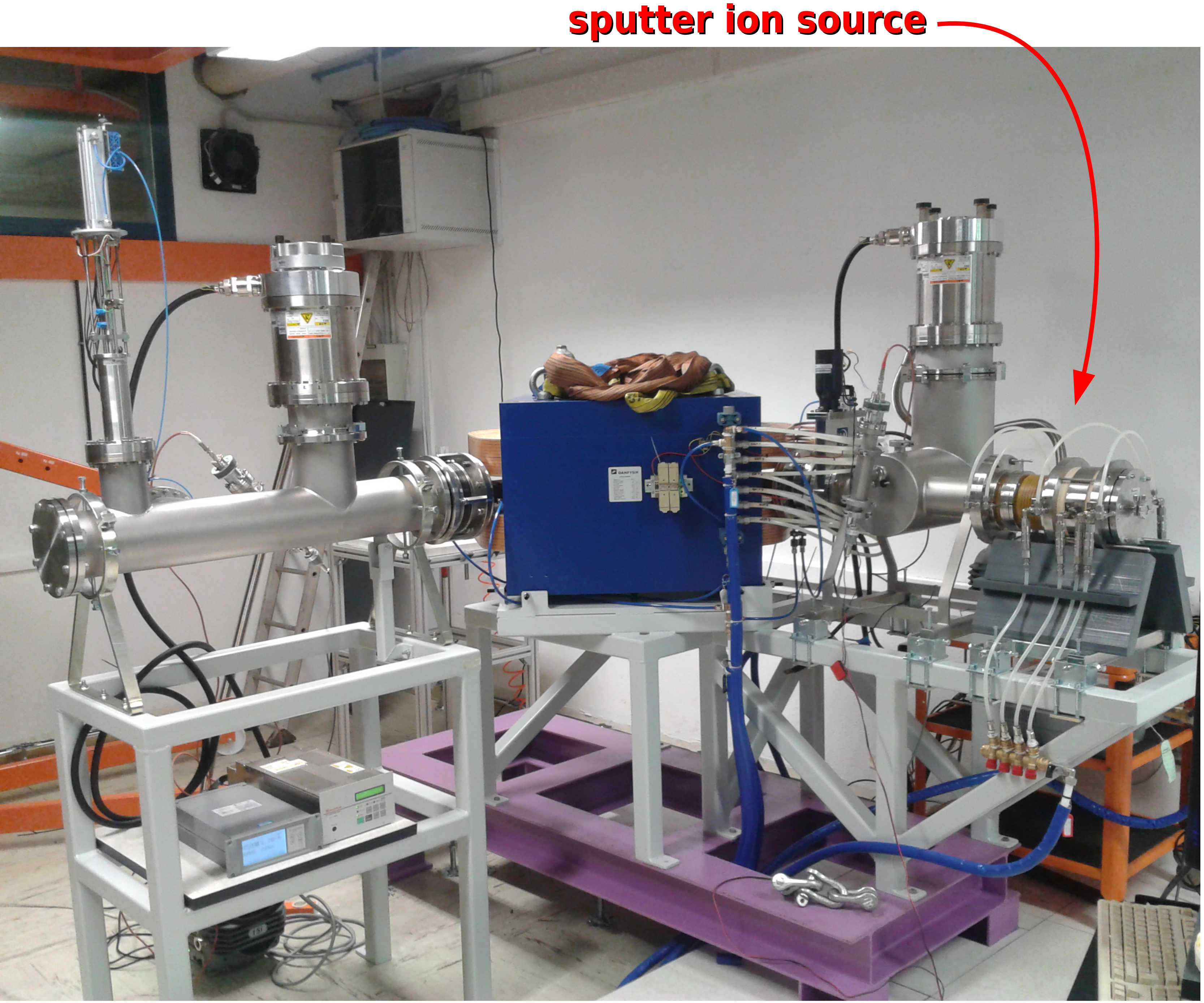
S. Heinitz et al., submitted to PLOSE ONE

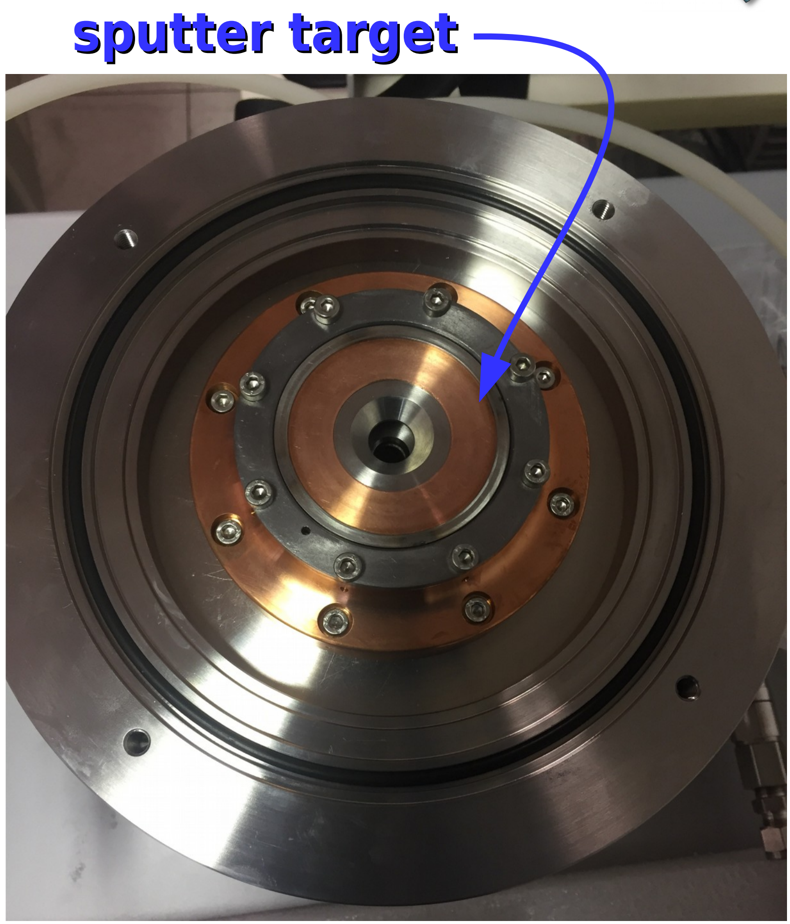
HOLMES mass separation and ion implantation

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



HOLMES ion implantation system testing

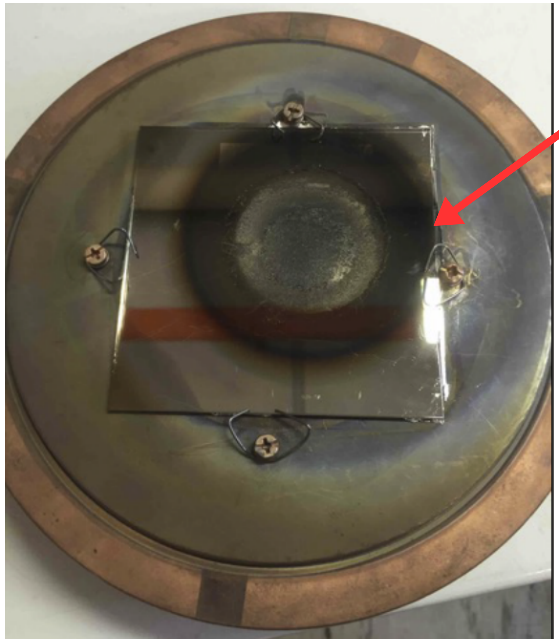




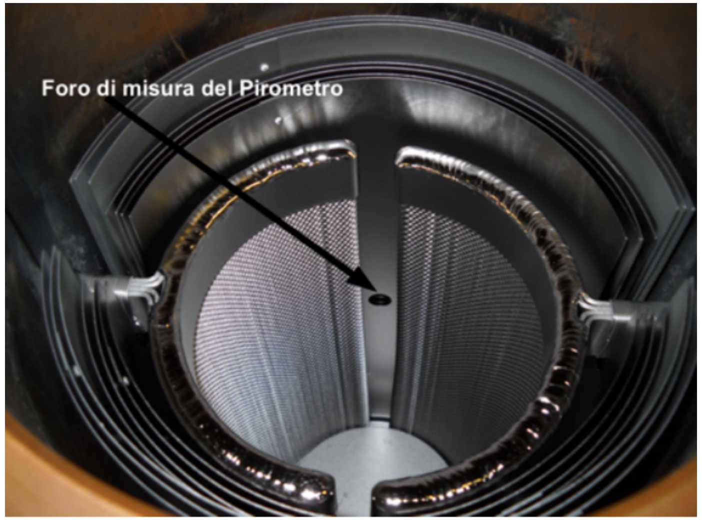
- tests in progress
  - without focussing
  - with natural Ho
- triplet and scanning stages ready to be installed

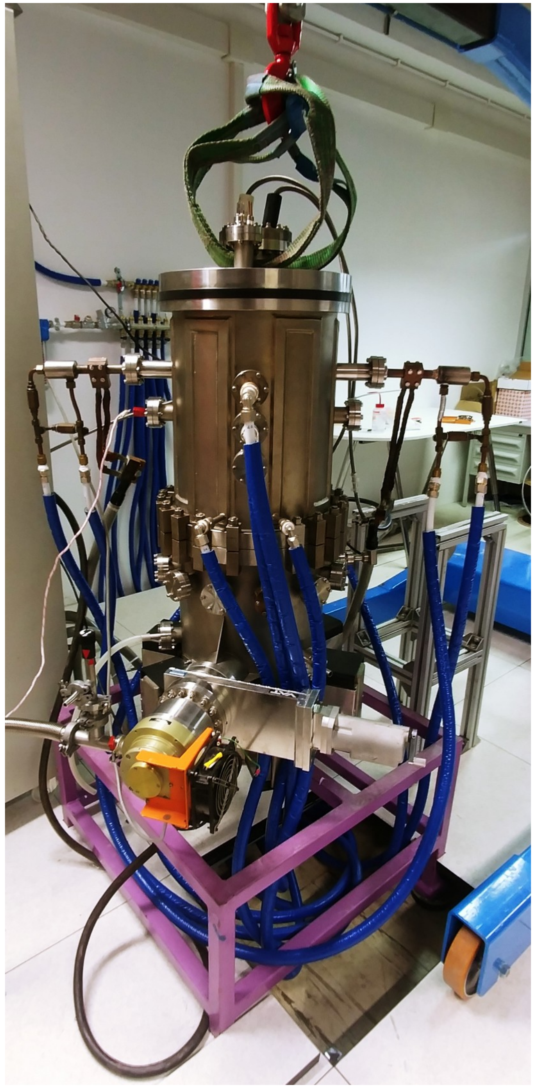
Ion source sputter target production / 1

- **metallic holmium sputter target** for implanter ion source
- enriched Er_2O_3 → Ho_2O_3
- thermoreduction/distillation in furnace
  - **$Ho_2O_3+2Y(\mathit{met}) \rightarrow 2Ho(\mathit{met})+Y_2O_3$ at $T>1600°C$**
- new furnace set-up in 2016
- work in progress to
  - optimize the process
  - measure efficiency (≈**70%**, preliminary)



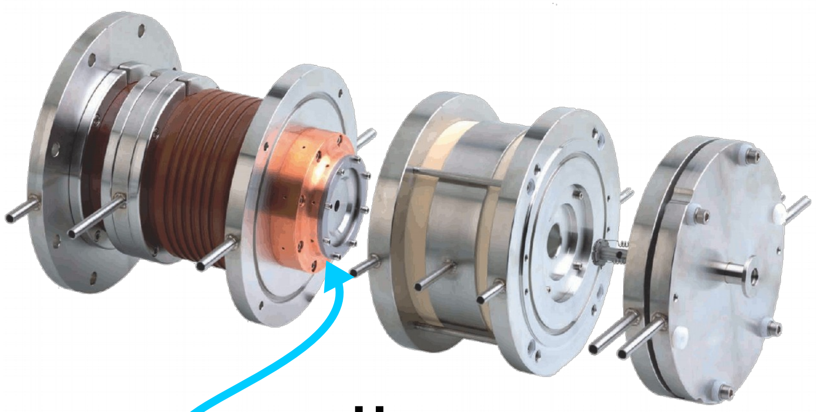
evaportated metallic holmium



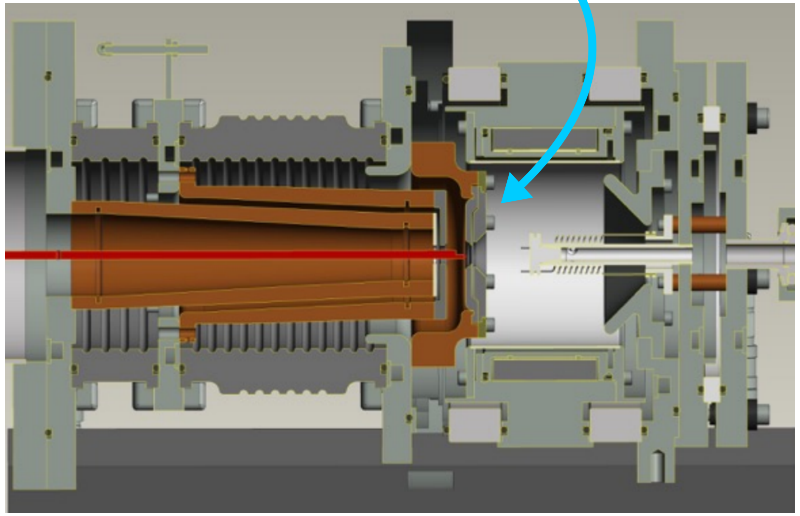


Ion source sputter target production / 2

- **metallic holmium sputter target** for implanter ion source
  - ▸ work is in progress to produce the sputter target
  - ▸ sintering Ho with other metals



sputter target



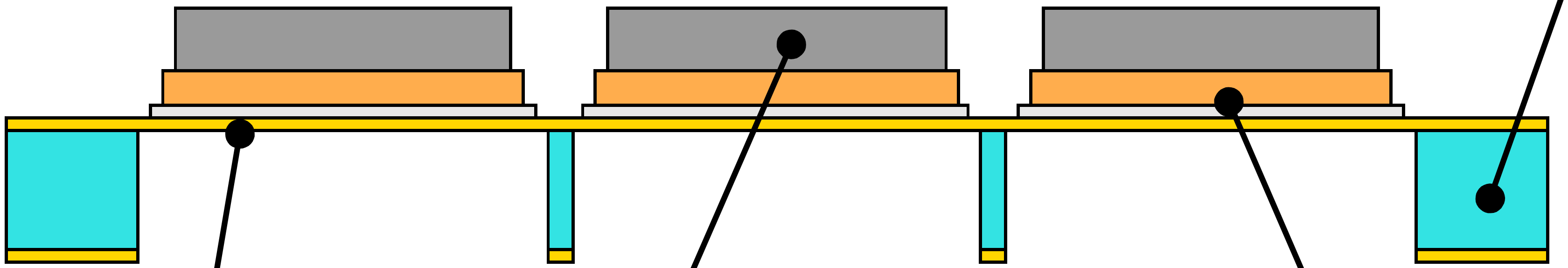
high pressure

+

heat treatment

TES low temperature microcalorimeters

NIST TES arrays for X-ray spectroscopy

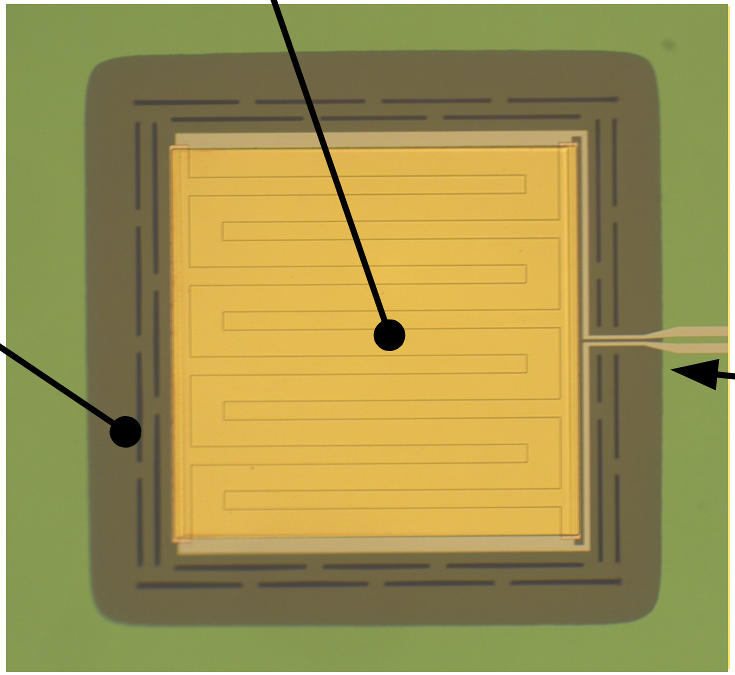


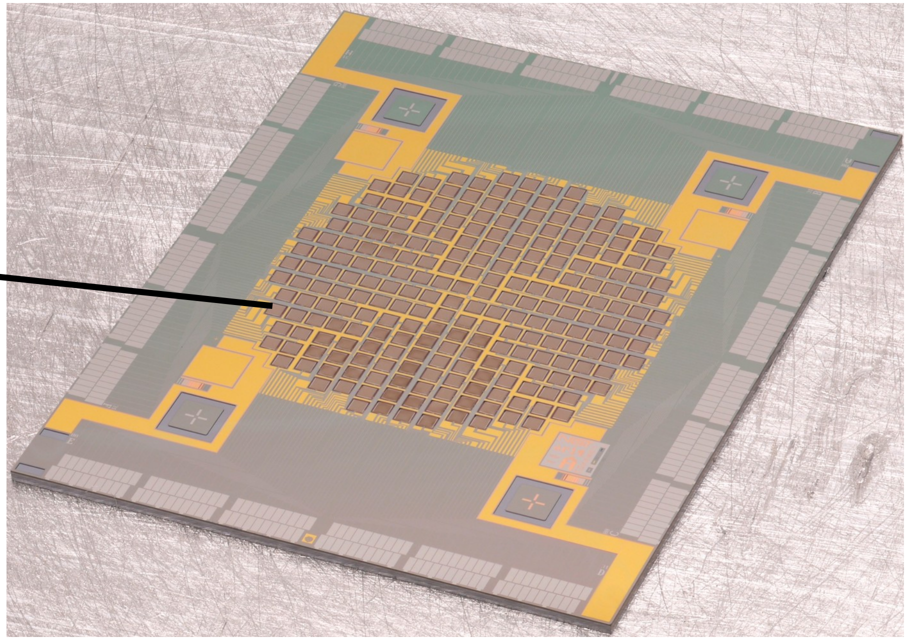
micromachined silicon substrate

Au absorber

TES Mo/Cu bilayer
(thermometer)

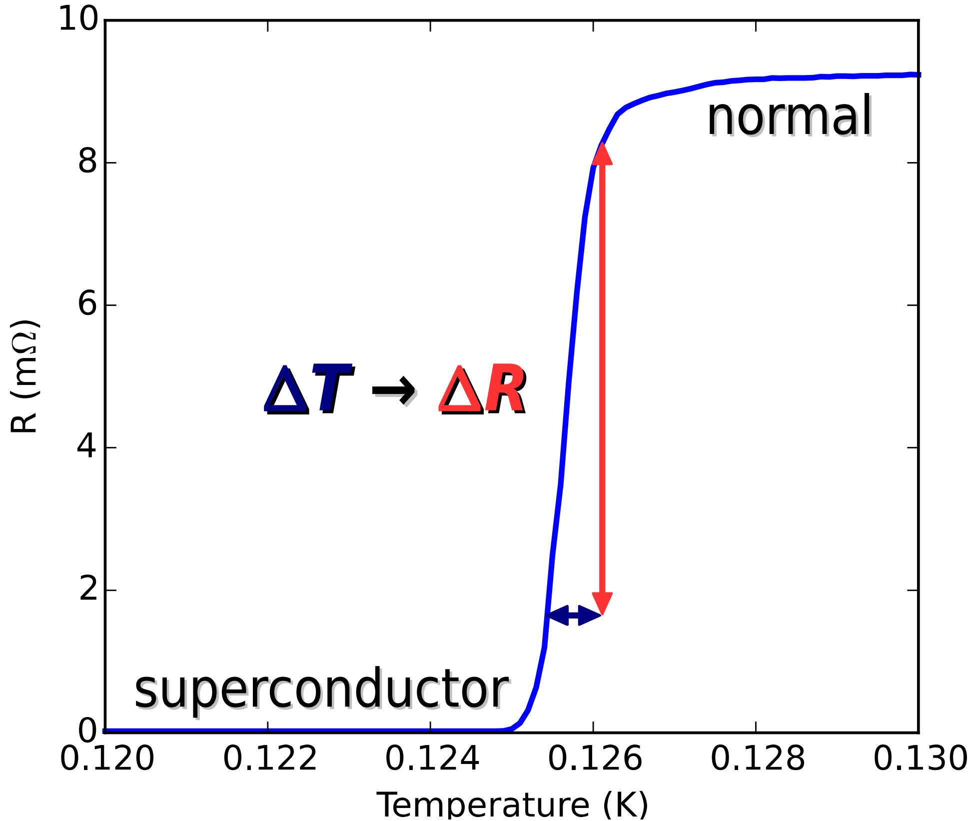
SiN$_x$ membrane
(thermal link)



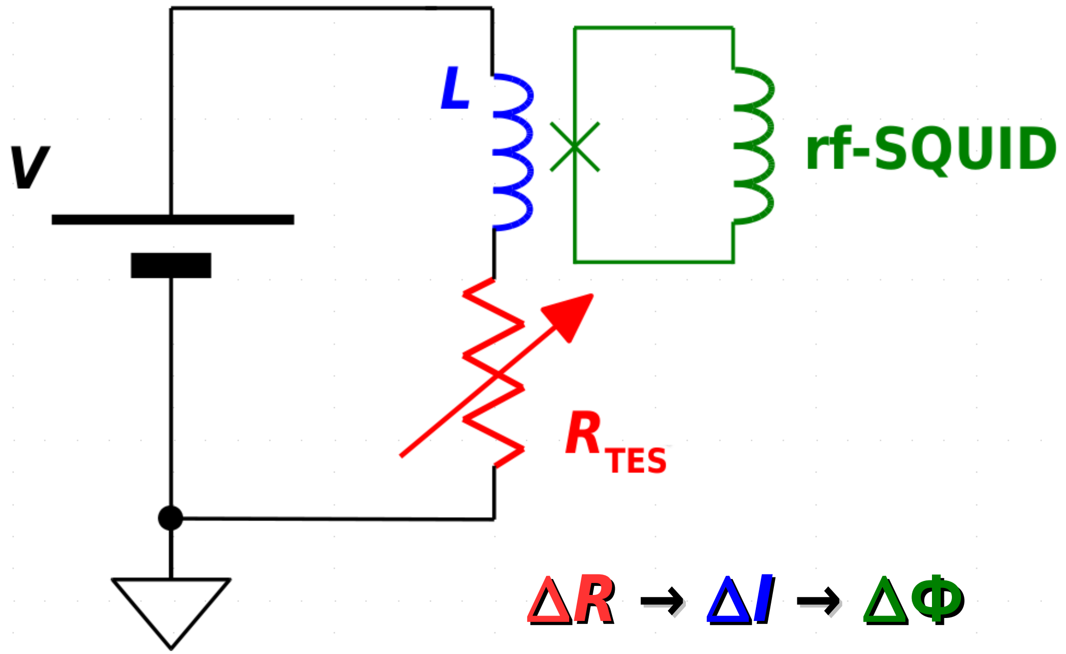


Superconducting transition edge sensors (TES)

- **superconductor thin films** operated inside the phase transition at T_c
  - metal-superconductor bilayers → tunable T_c (20÷200 mK) : Mo/Cu, Ti/Au, Ir/Au, ...
- high sensitivity $T dR/(R dT) \approx 100$) → **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**



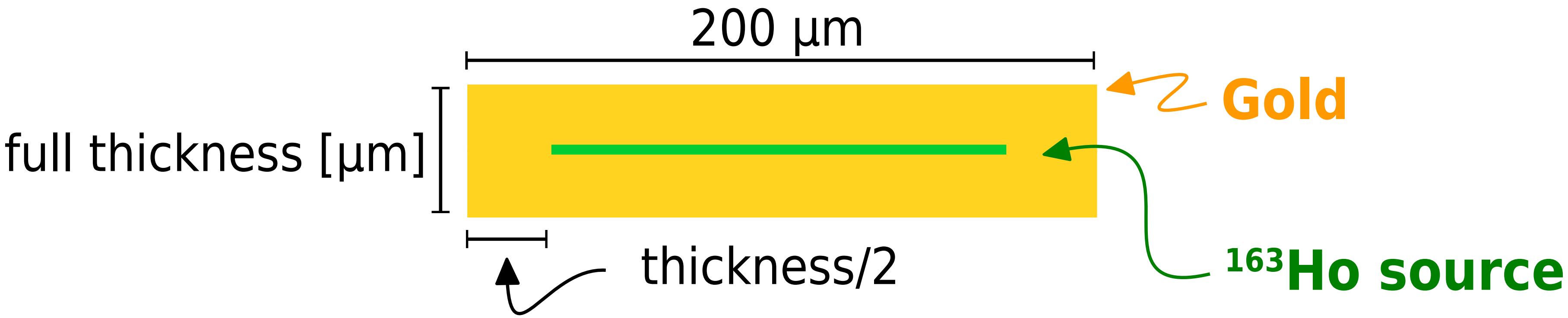
TES read-out: costant voltage bias



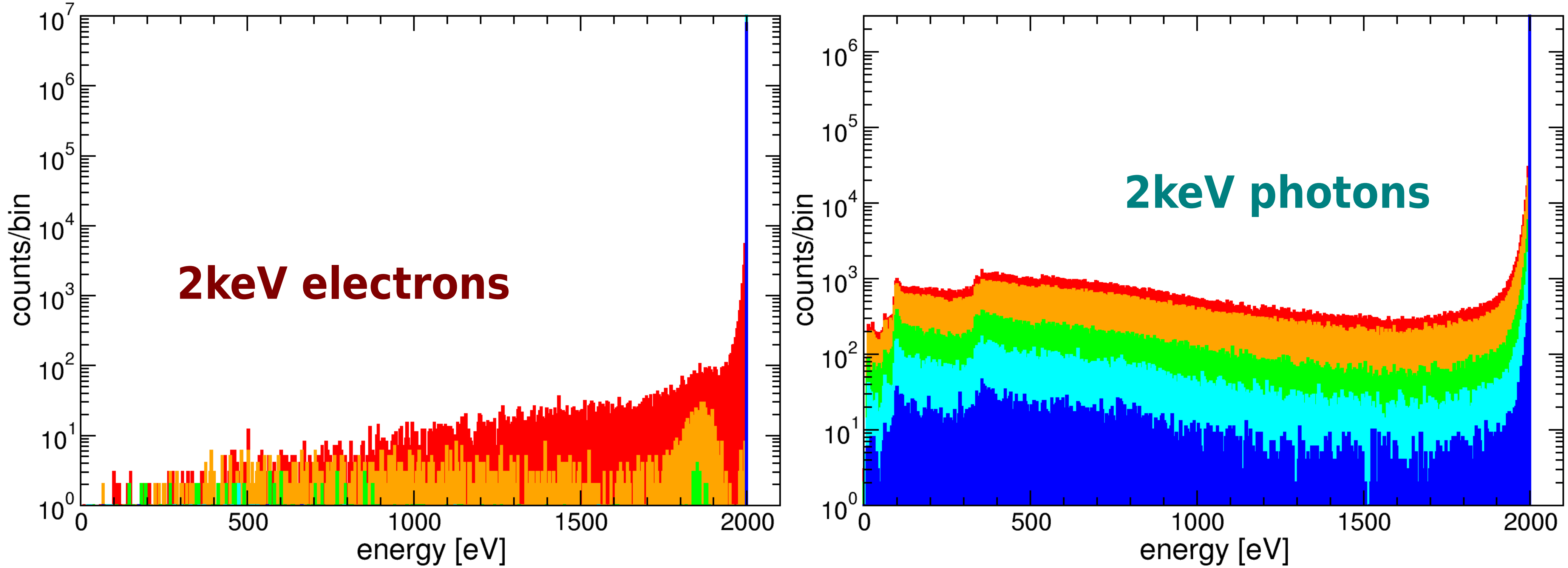
$\Delta R \rightarrow \Delta I \rightarrow \Delta \Phi$

TES absorber design: stopping EC radiation / 1

Geant4 + LowEnergyEM MC simulation



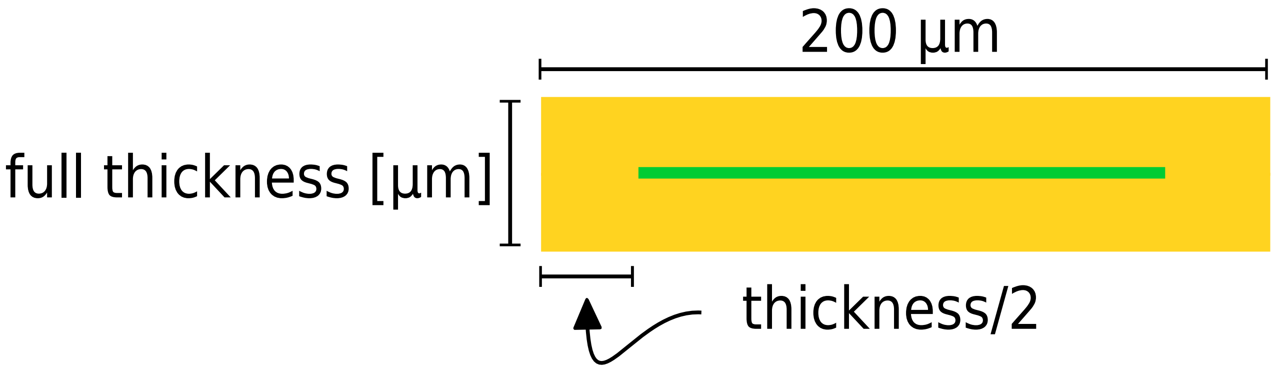
full thickness: 0.05, 0.1, 0.5, 1, 2 µm

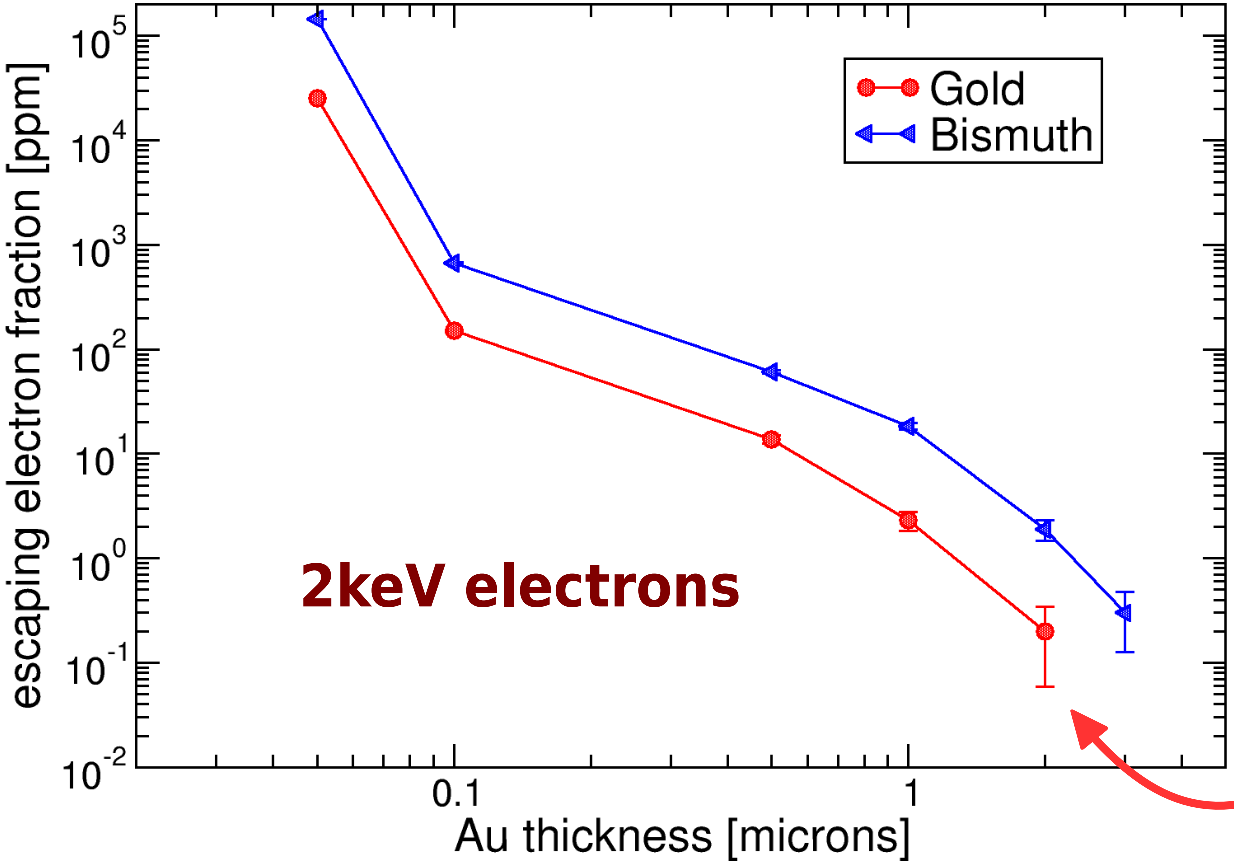


$I_x \approx 10^{-5} I_e$

TES absorber design: stopping EC radiation / 2

Geant4 + LowEnergyEM MC simulation

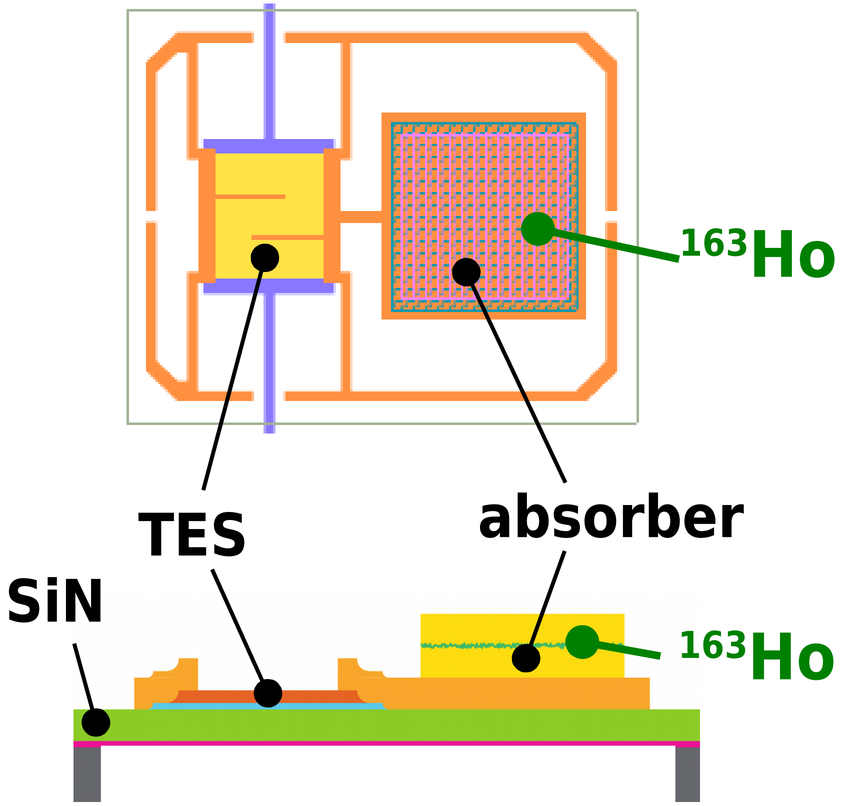


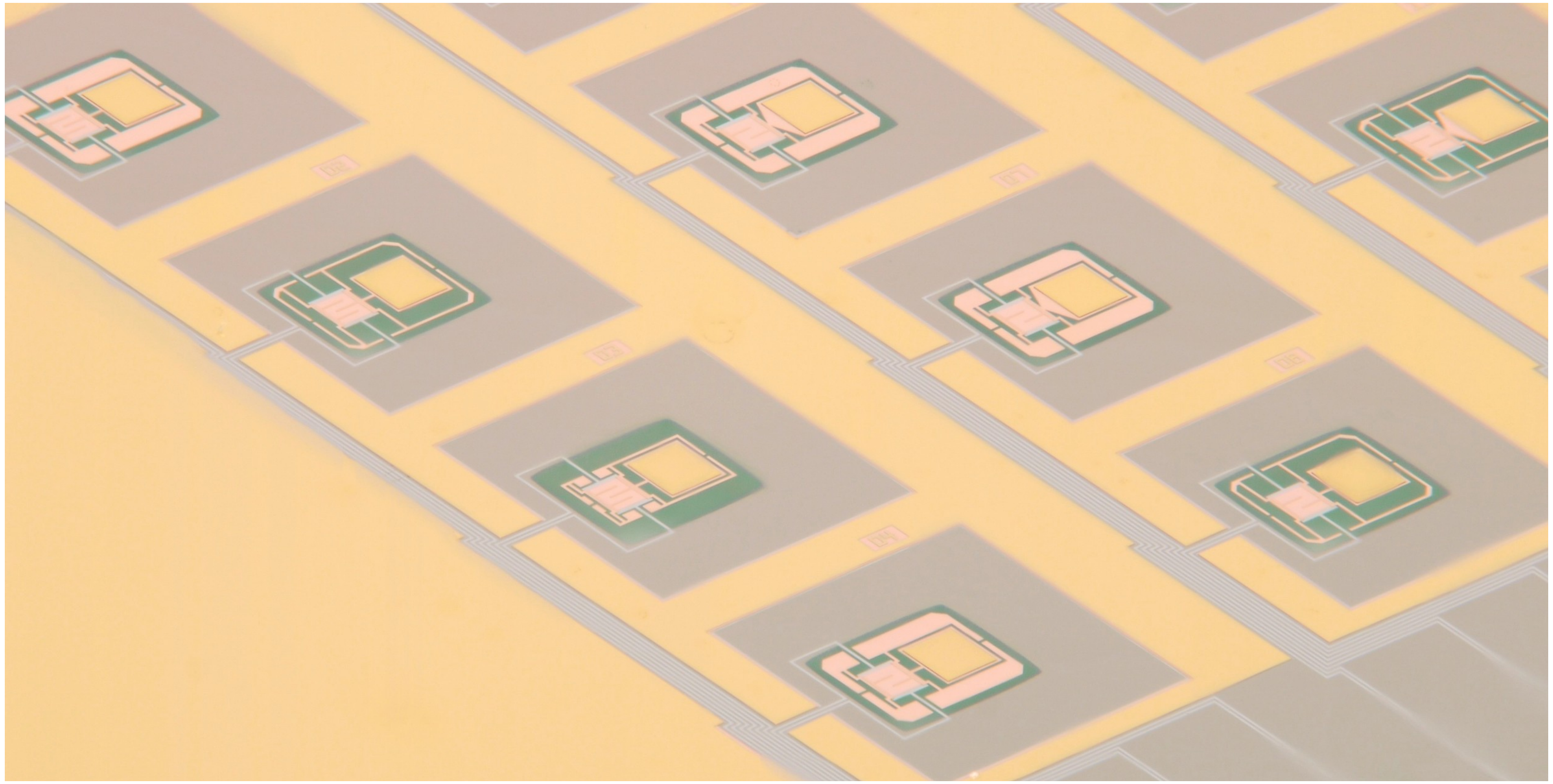


99.99998%
full stopping
for 2keV electrons

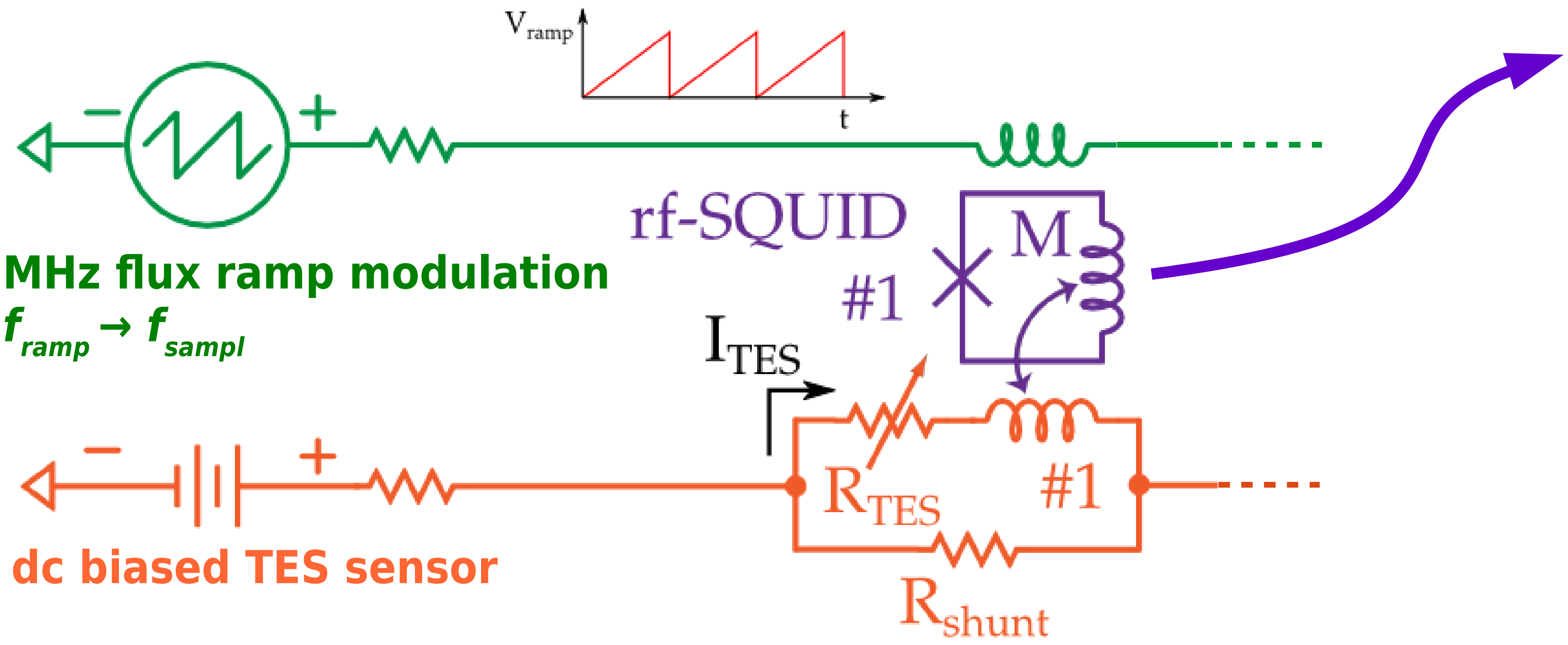
HOLMES pixel design and test

- optimize design for speed and resolution
  - ▷ **specs @3keV : $\Delta E_{FWHM} \approx 1\text{eV}$, $\tau_{rise} \approx 10\mu s$, $\tau_{decay} \approx 100\mu s$**
- **2 μm Au** thickness for *full* electron and photon absorption
- ***side-car*** design to avoid TES proximitation and *G* engineering for τ_{decay} control
- **NIST** designed and fabricated 4×6 arrays of **TES prototypes** for optimization **w/o ^{163}Ho**





HOLMES array read-out: rf-SQUID



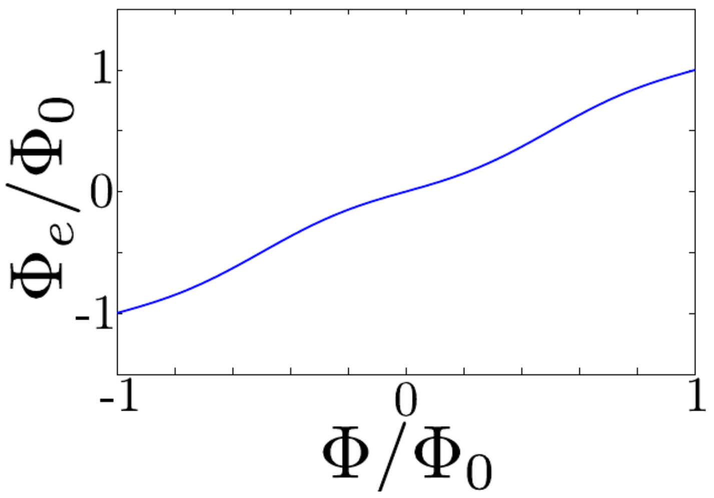
MHz flux ramp modulation

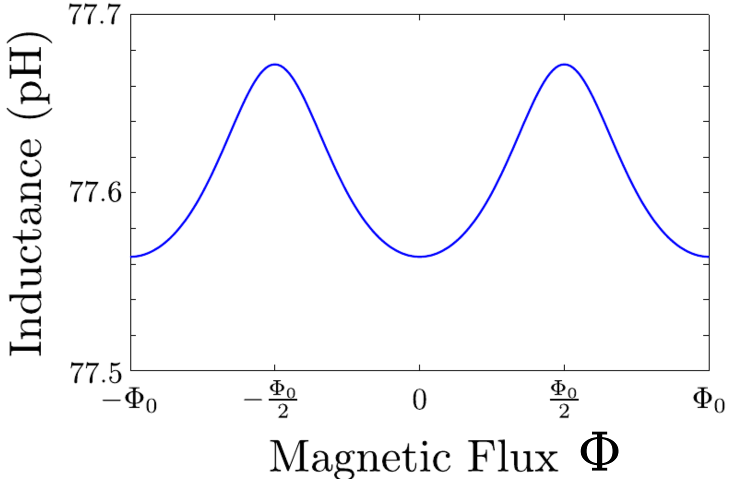
$f_{ramp} \rightarrow f_{sampl}$

dc biased TES sensor

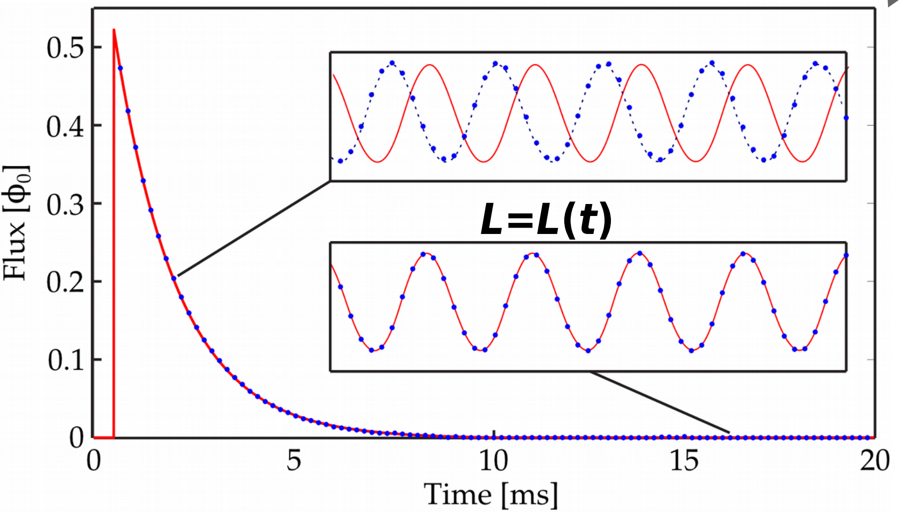
non-hysteretic rf-SQUID

Φ_e vs. Φ and L vs. Φ responses



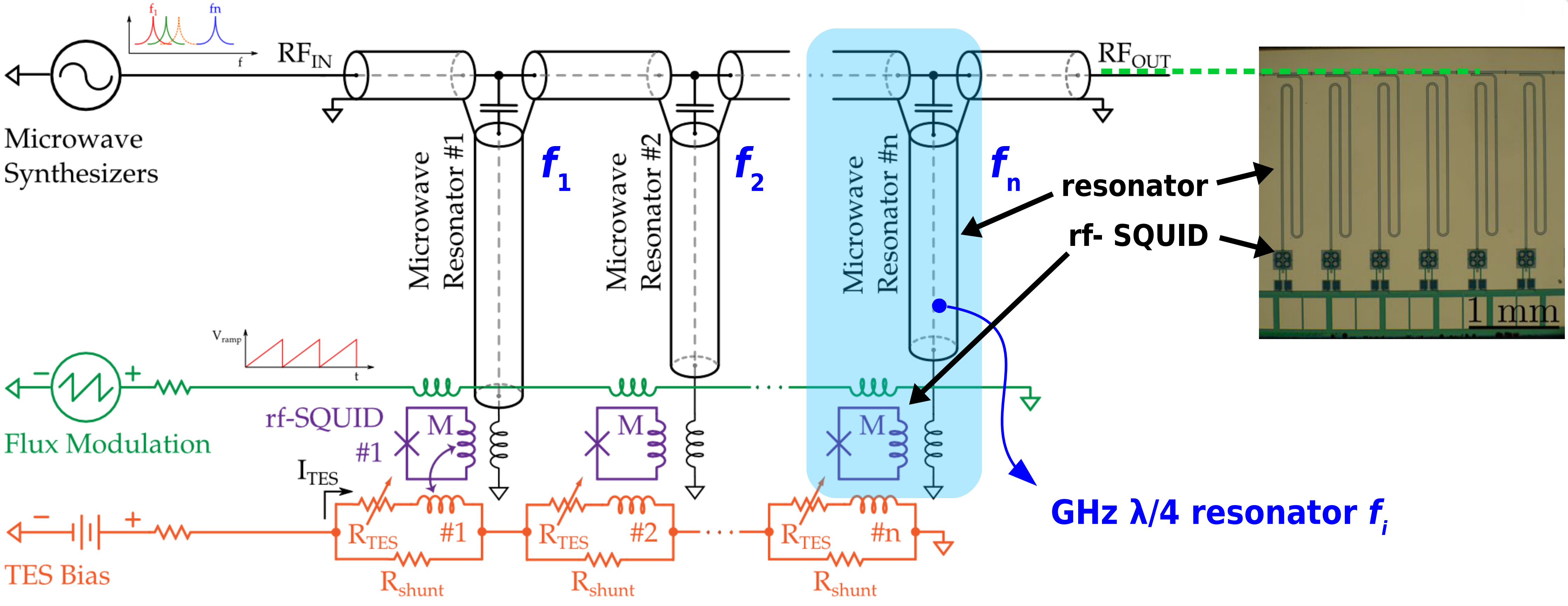


$$\Delta T \rightarrow \Delta R_{TES} \rightarrow \Delta I_{TES} \rightarrow \Delta\Phi_e \rightarrow \Delta\Phi \rightarrow \Delta L$$

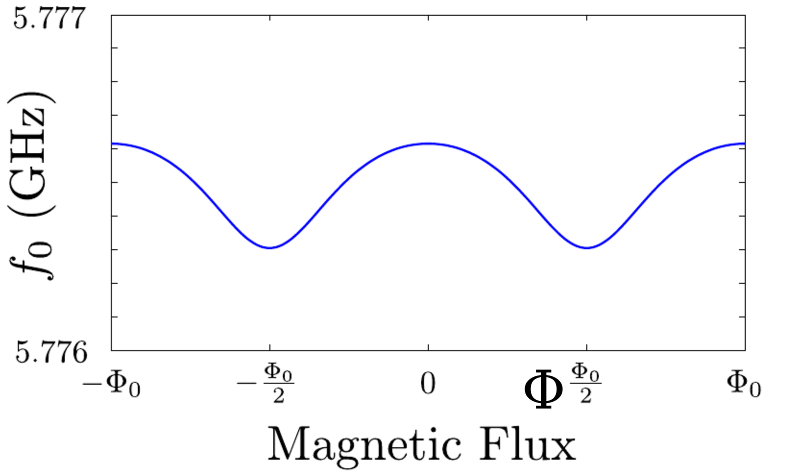


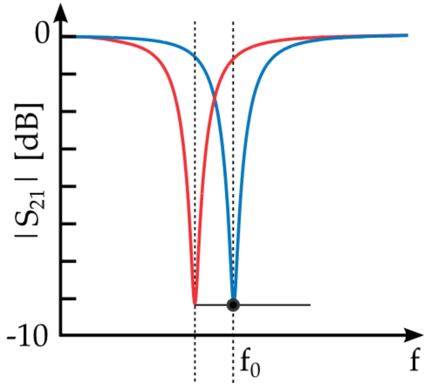
- **$\Phi_e = \Phi_{TES} + \Phi_{ramp}$**
- **flux-ramp modulation**
  - phase modulated MHz signal $L(t)$
  - linearized non-hysteretic rf-SQUID response
  - avoid low frequency noise sources

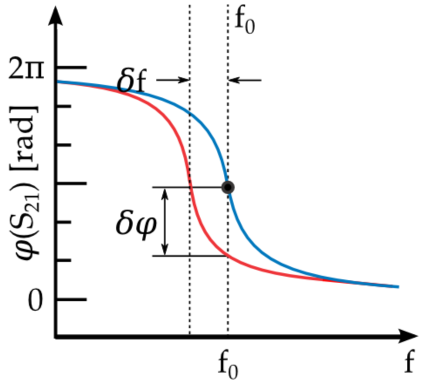
HOLMES array read-out: microwave multiplexing



$\ldots \rightarrow \Delta\Phi \rightarrow \Delta L \rightarrow \Delta f_0 \rightarrow (\Delta A, \Delta\varphi) \rightarrow (\Delta I, \Delta Q)$

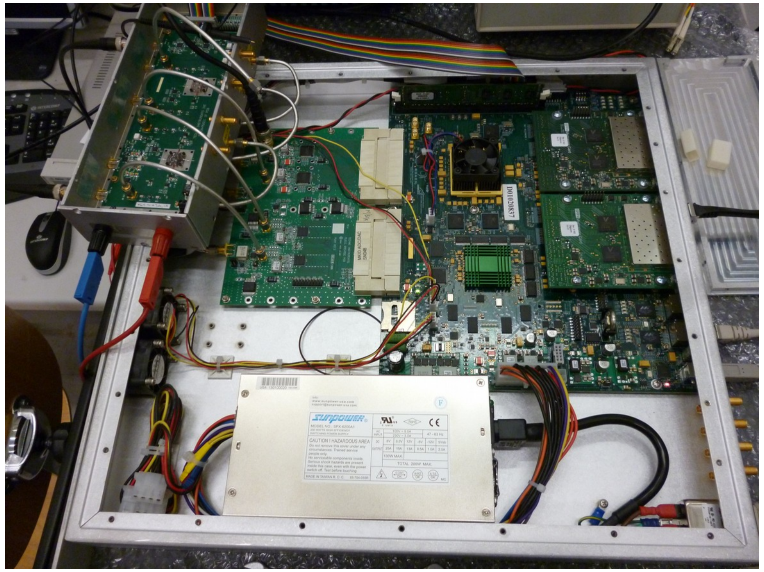


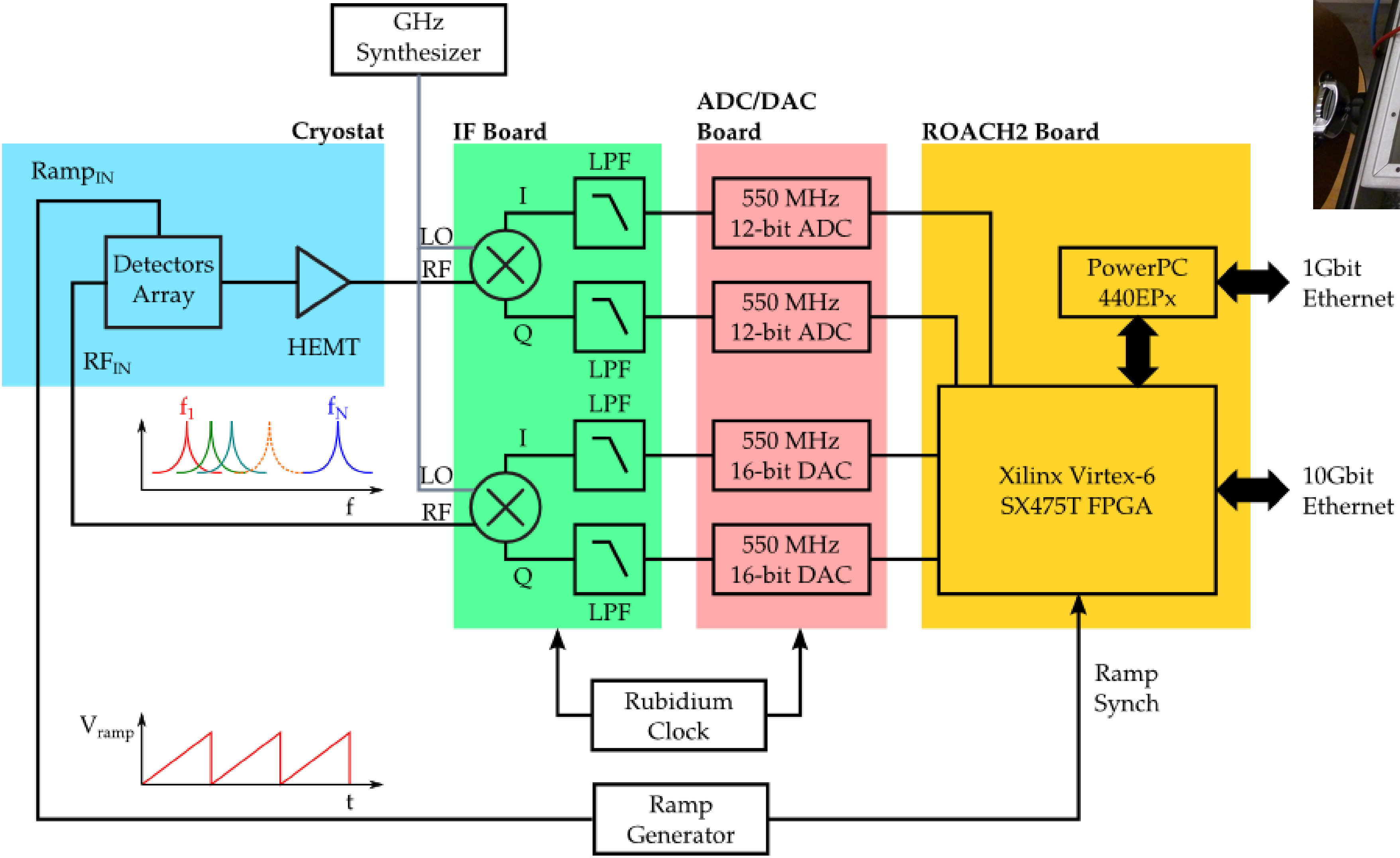




HOLMES DAQ: Software Defined Radio

- base-band tone generation (0-512MHz)
- up- / down-conversion (base-band → 4-8 GHz → base-band)
- base-band tone IQ de-modulation (0-512MHz)
- rf-SQUID phase signal de-modulation by Fourier analysis





HOLMES detector design

design mostly driven by **read-out bandwith** requirements

- TES microwave multiplexing with rf-SQUID ramp modulation + Software Defined Radio (SDR)

read-out specs
SDR ADC f_{ADC}
multiplexing factor n_{TES}

→

signal sampling f_{samp}
signal rise time τ_{rise}

→

HOLMES targets
τ_R ΔE N_{det}

$$f_{samp} \geq \frac{R_d}{\tau_{rise}} \approx \frac{5}{\tau_{rise}}$$

detector signal sampling (signal BW)

$$f_{res} \geq 2 n_{\Phi_0} f_{samp}$$

flux ramp modulated signal BW (resonator BW)

$$f_n \geq g_f f_{res} = \frac{2 R_d g_f n_{\Phi_0}}{\tau_{rise}}$$

microwave tones separation ($g_f \gtrsim 7$)

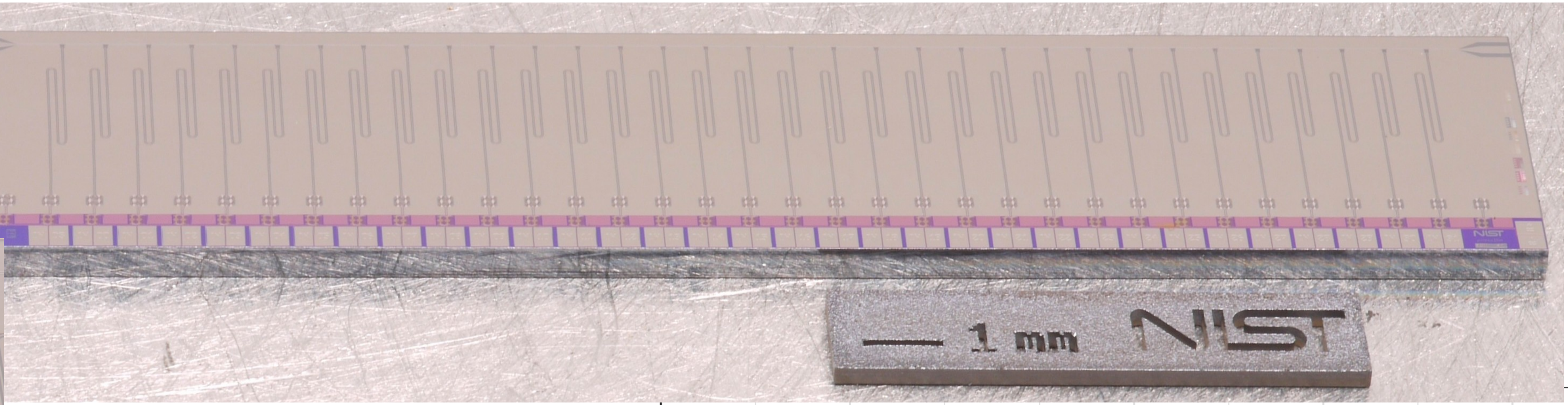
multiplexing factor →

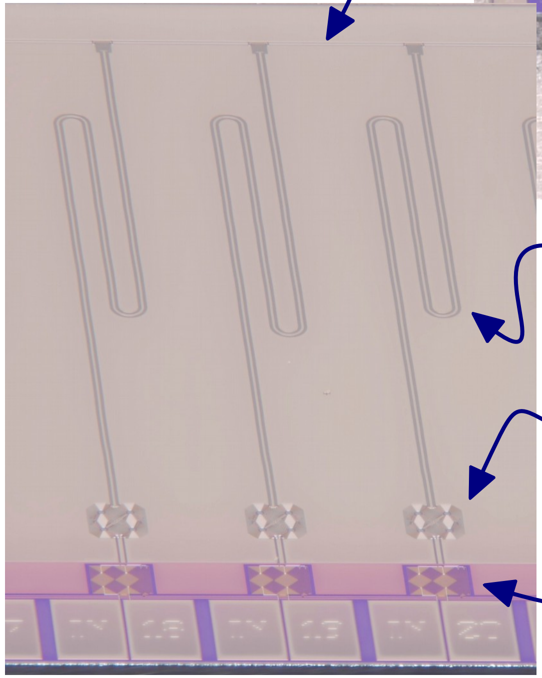
$$n_{TES} = \frac{f_{ADC}}{f_n} \leq \frac{f_{ADC} \tau_{rise}}{2 R_d g_f n_{\Phi_0}} \approx \frac{f_{ADC} \tau_{rise}}{140}$$

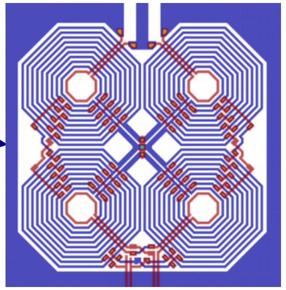
for fixed **f_{ADC}=512MHz** and **n_{TES}=32** ↔ **τ_{rise}≈10µs** with **f_{samp}=0.5MHz**

→ check for slew rate, τ_R and *ΔE*...

HOLMES µwave multiplexed TES read-out





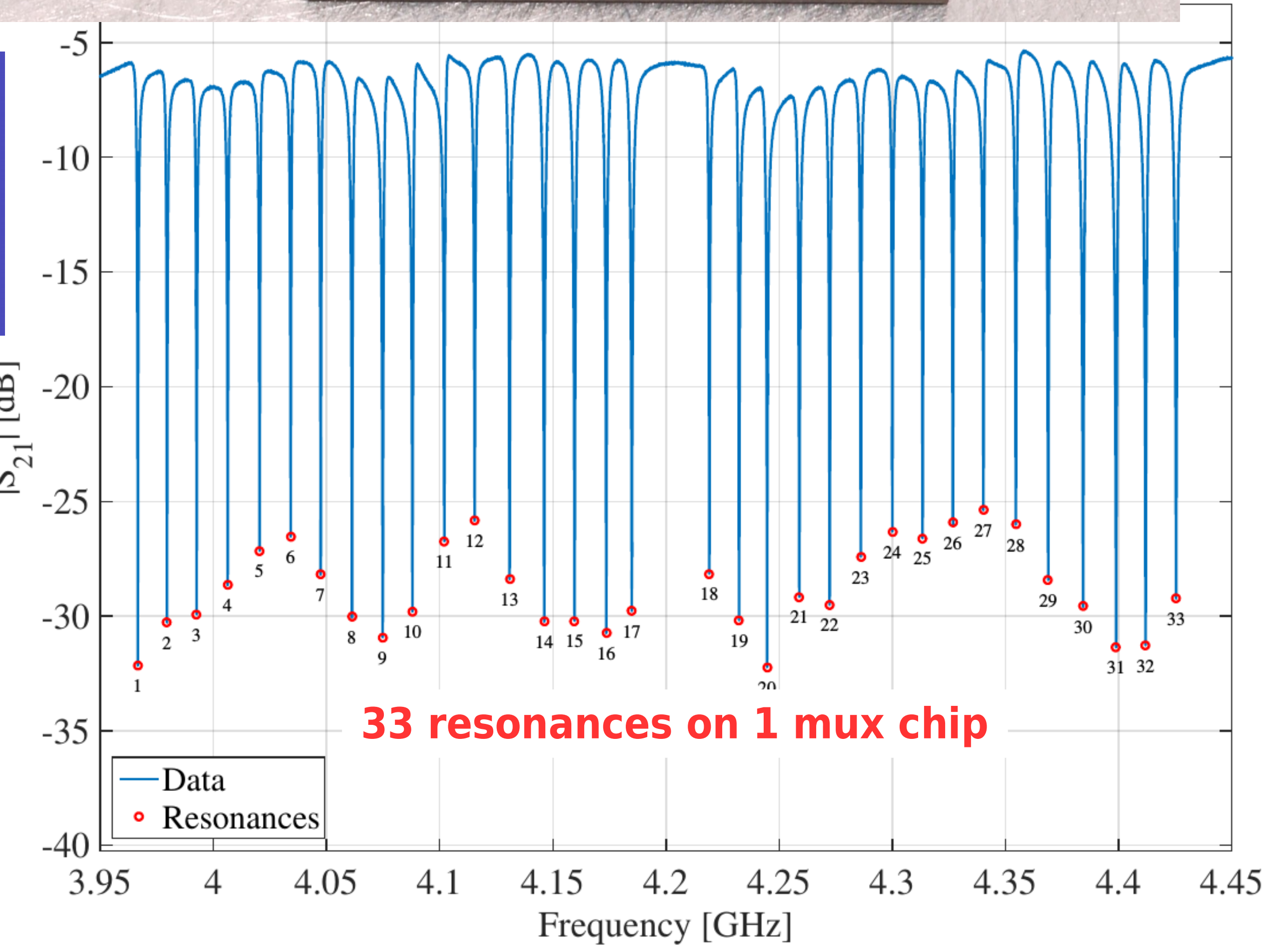


feedline

λ/4 resonator

rf-SQUID

filter



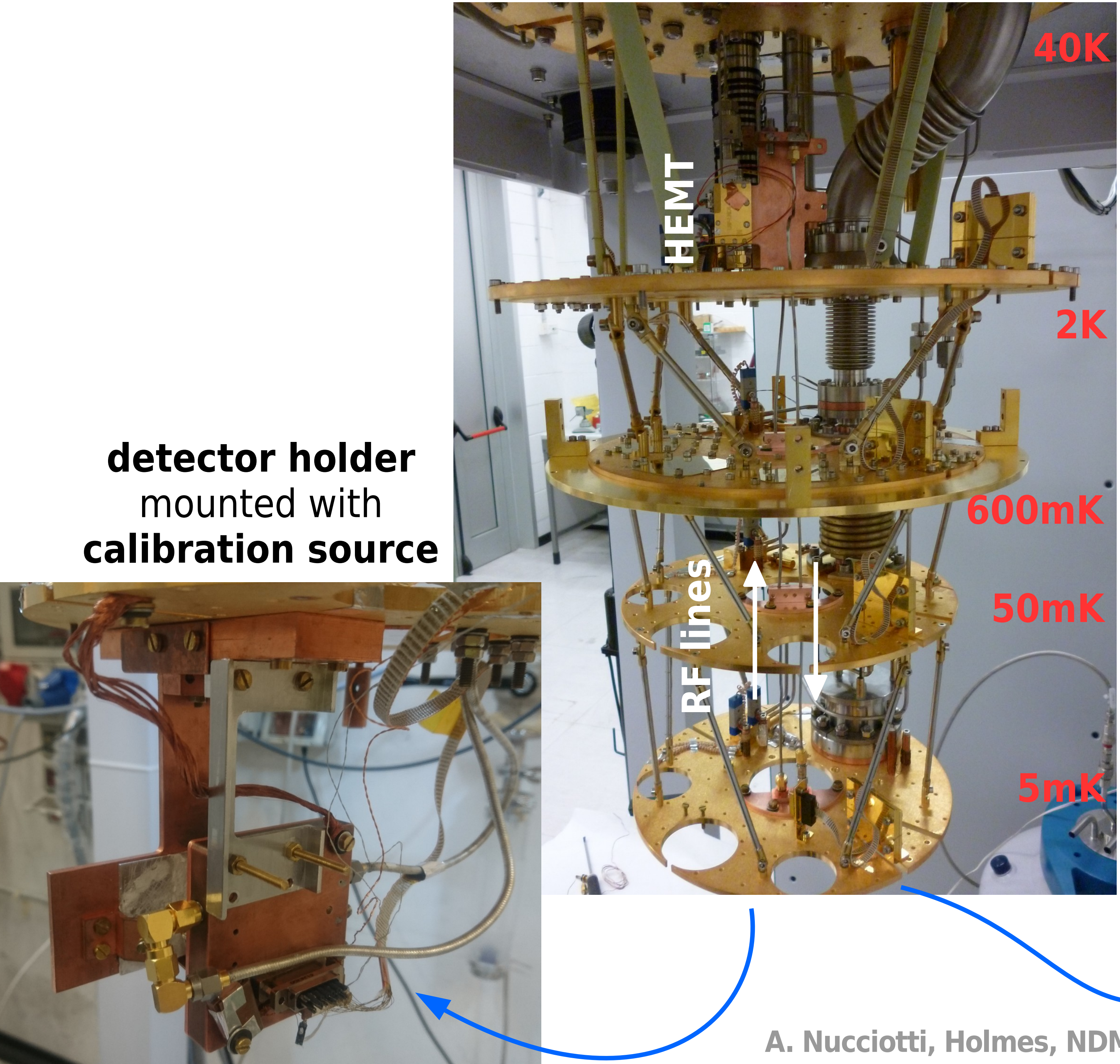
33 resonances on 1 mux chip

- **µMUX17A** optimized for **HOLMES**
- 33 resonances in 500 MHz
  - width f_{res} = 2 MHz
  - separation 14 MHz (g_f = 7)
- squid noise <≈2 $\mu\Phi_0/\sqrt{\mathrm{Hz}}$

Cryogenic set-up

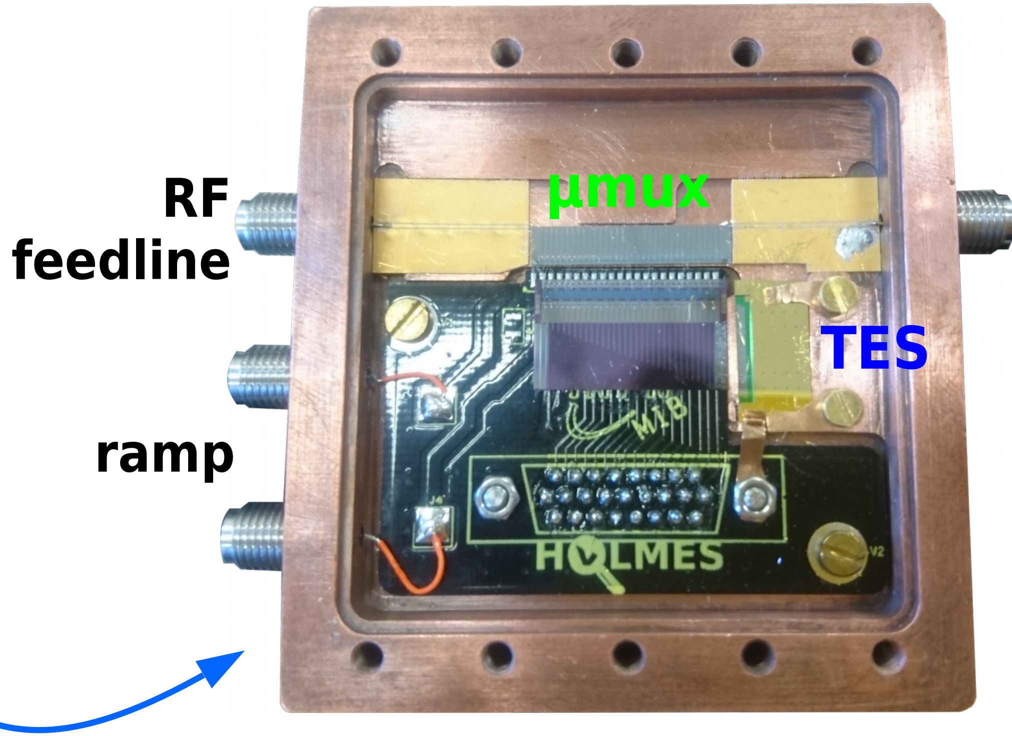
LHe-free dilution fridge

1 HEMT + 2 coax RF lines
→ **8** µmux chips
→ **256** detectors

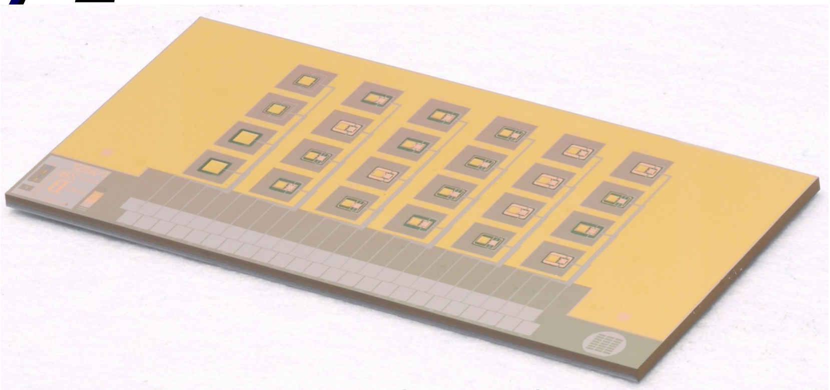


detector holder
mounted with
calibration source

detector holder



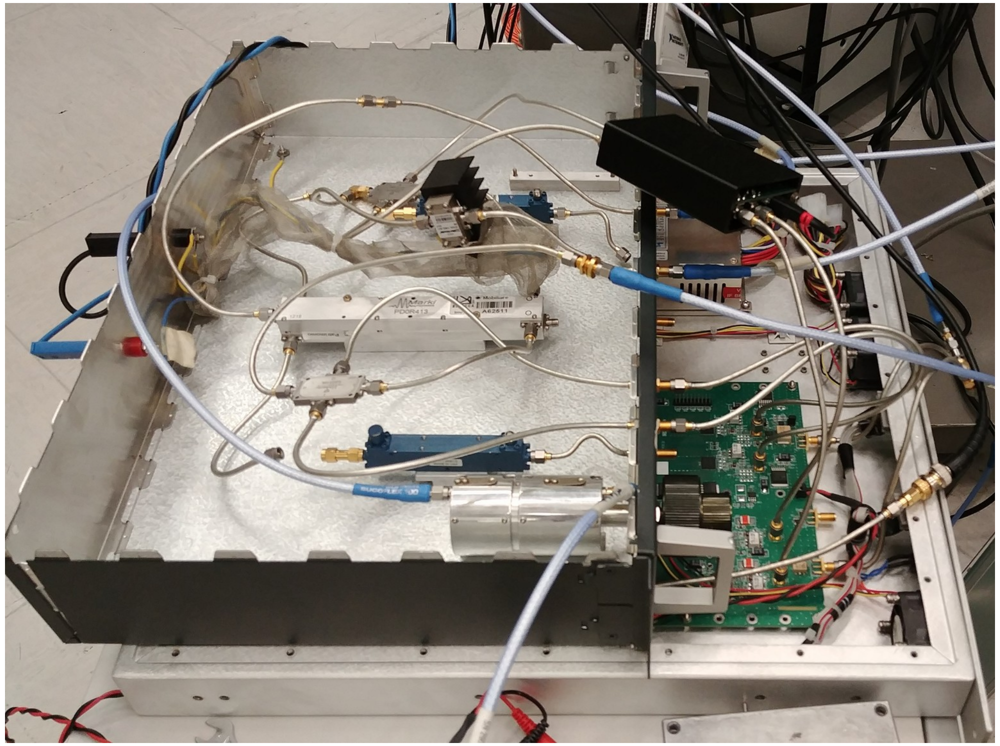
TES pixel testing with HOLMES DAQ / 1



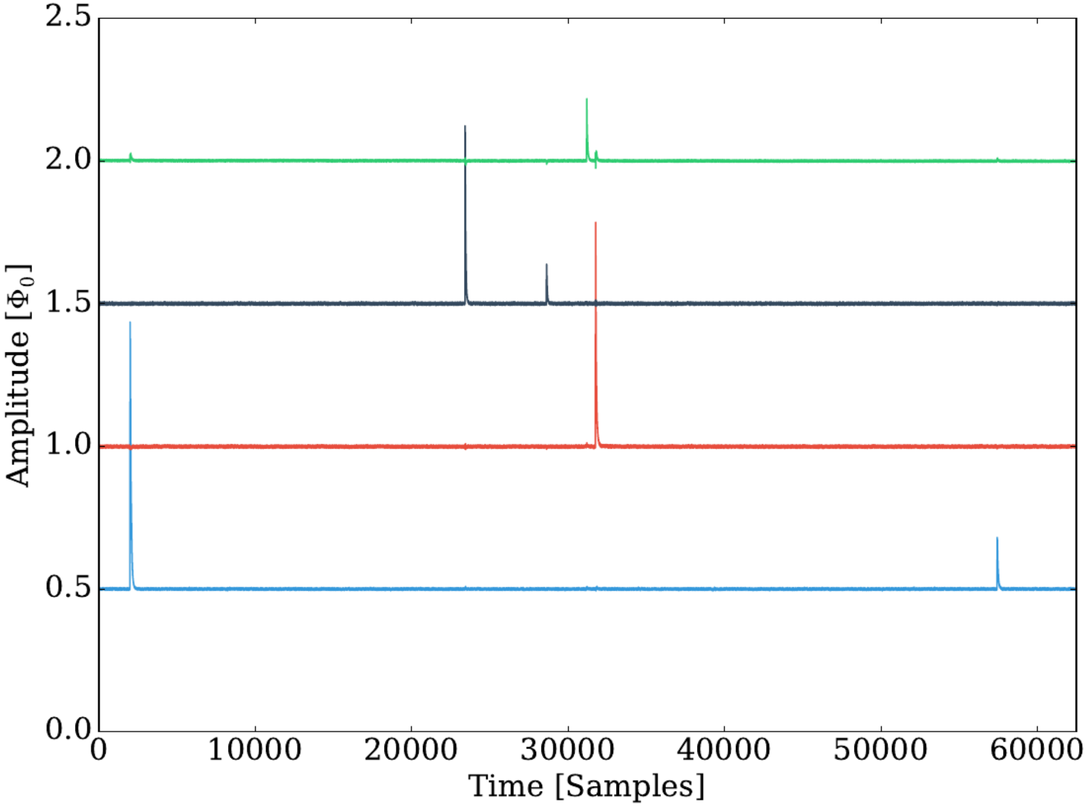
HOLMES prototypes

ROACH-2 based Software Defined Radio

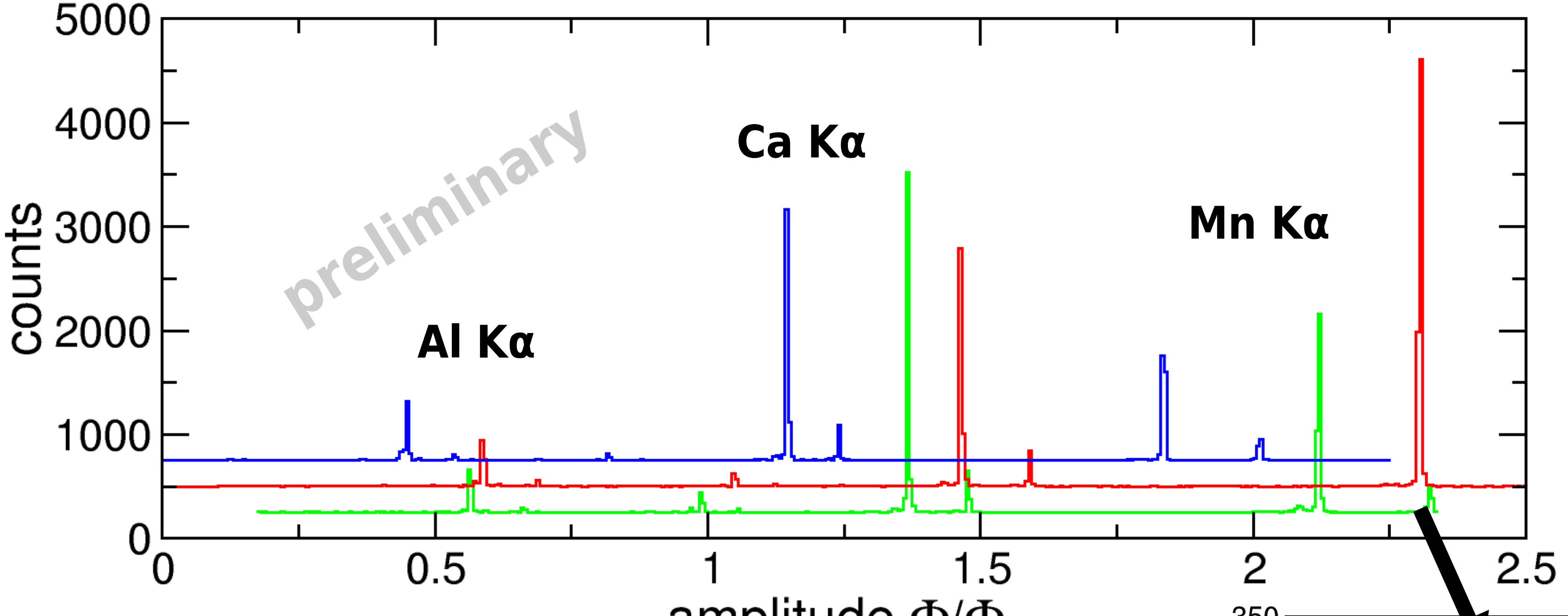
- ADC (550 MS/s 12bit) / DAC (1 GS/s 16bit)
- discrete components IF circuitry (up- / down- conversion)
- $n_{\Phi 0} = 2$, $f_{\mathrm{samp}} = 500$ kS/s
- 16 ch firmware from NIST (uses only half of available ADC bandwidth)
- 4 HOLMES prototypes acquired ↔ limited by available tone power
- **goals**: check algorithms, noise, ΔE, τ_R and slew rate

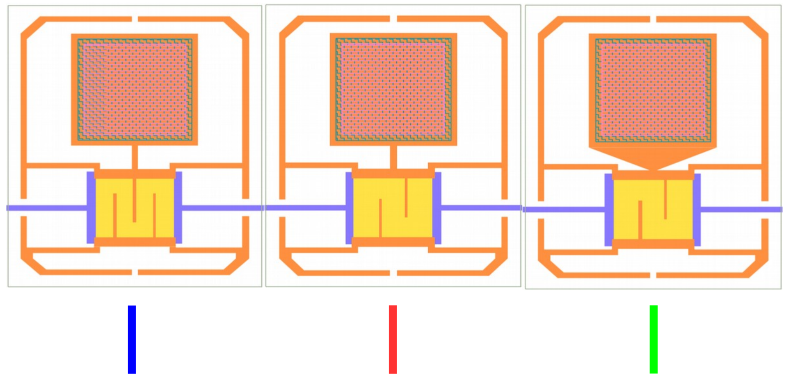


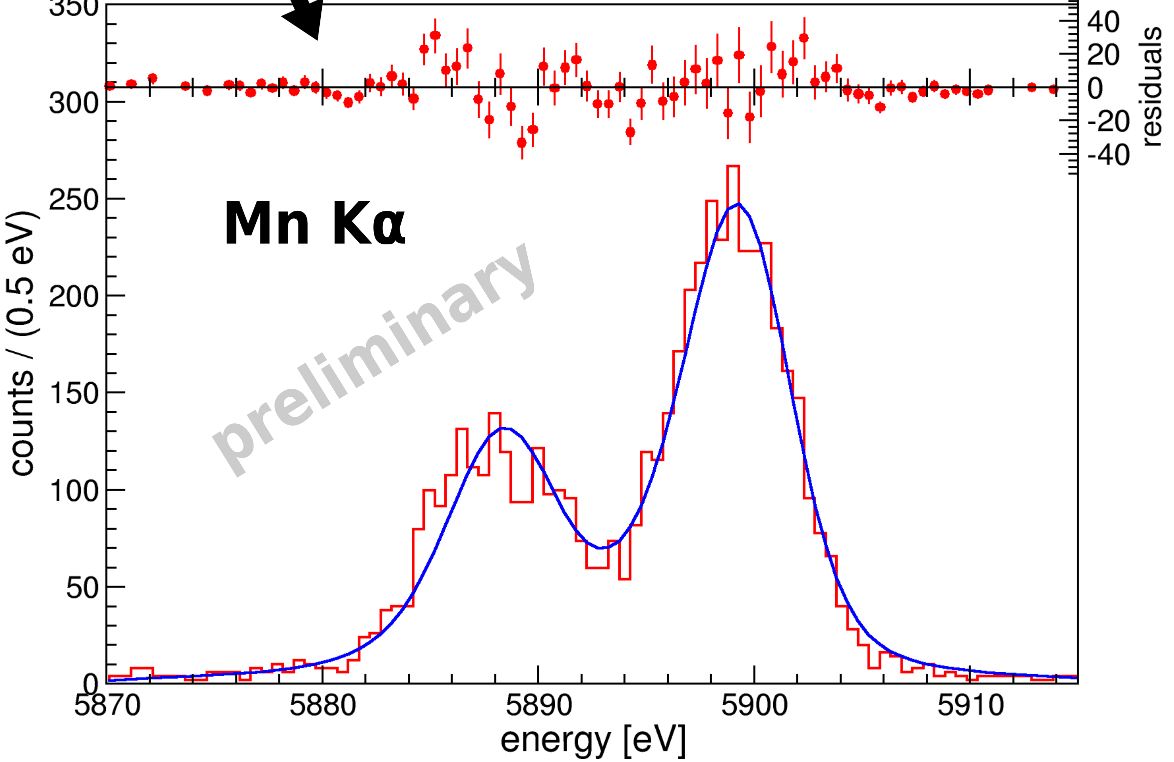
ROACH + IF circuit



TES pixel testing with HOLMES DAQ / 2







- $\Delta E_0 \approx$ **3.3 eV**
- ΔE_{FWHM} **= 4.5±0.1 eV @ 6 keV**
- $\tau_{\mathrm{rise}} \approx$ **13 µs**
- $\tau_{\mathrm{decay}} \approx$ **54 µs**

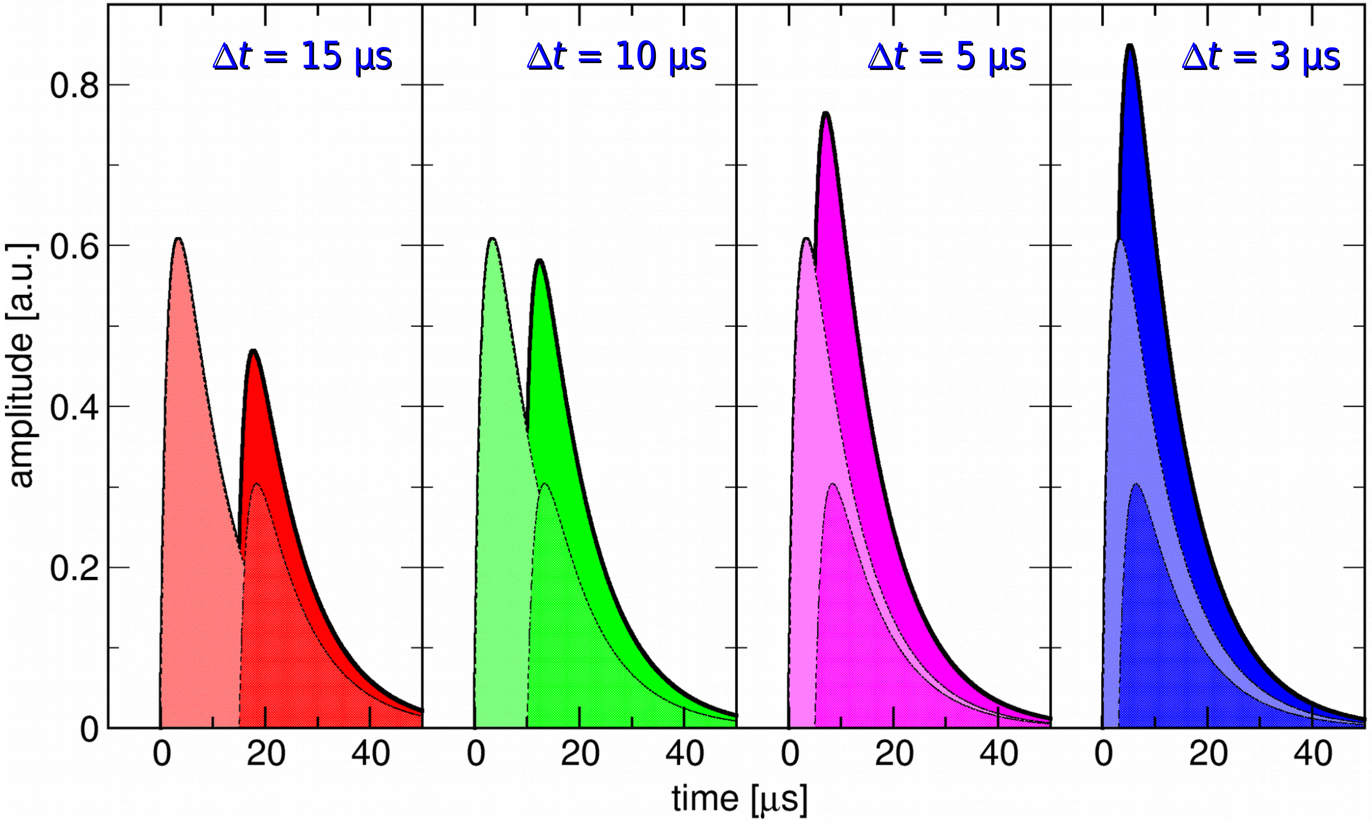
Rise time pile-up

simple pulse model

$$A(t) = A\left(e^{-t/\tau_{decay}} - e^{-t/\tau_{rise}}\right)$$

2 pulses with:

- $\tau_{rise} = 1.5\ \mu s$
- $\tau_{decay} = 10\ \mu s$
- $A_2/A_1 = 0.5$



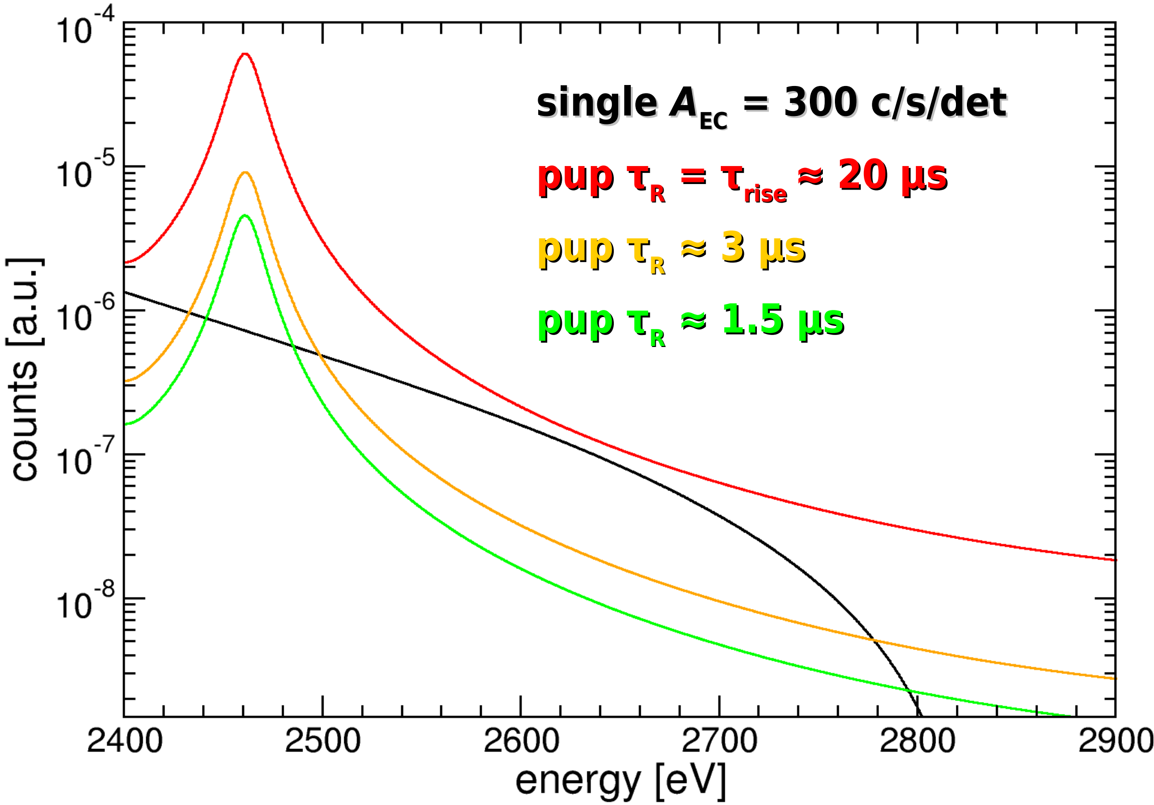
resolving time $\boldsymbol{\tau_R} \approx$ pulse rise time $\boldsymbol{\tau_{rise}}$

Detector time resolution

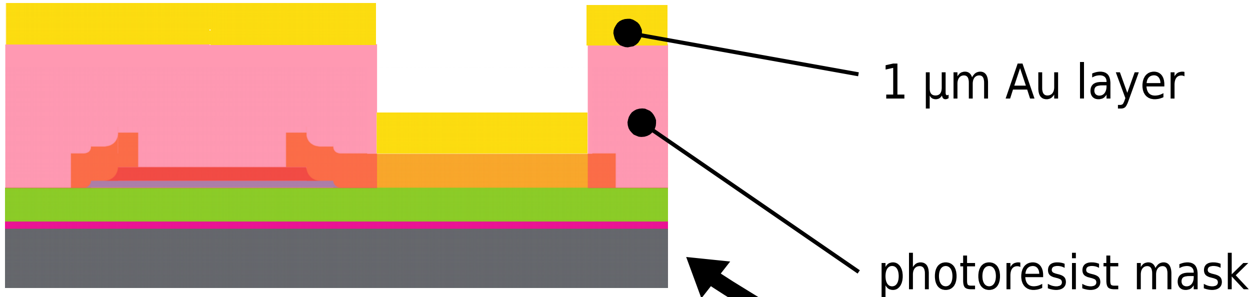
- for subsequent (Δt) events with energy E_1 and E_2: time resolution $\boldsymbol{\tau_R = \tau_R(E_1, E_2)}$

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

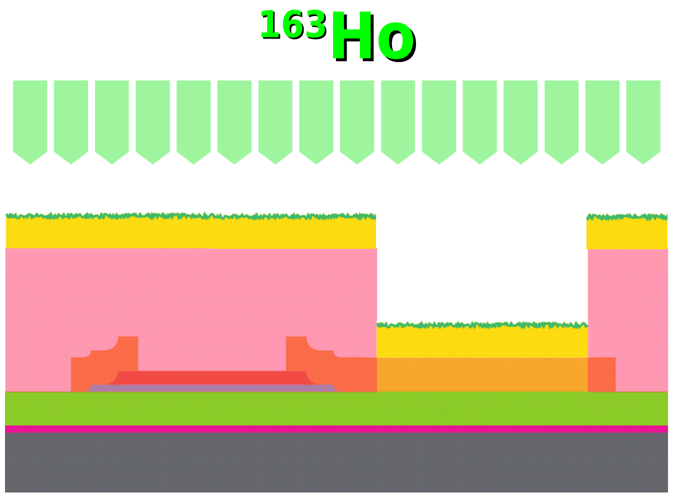
- **Montecarlo pile-up spectrum simulations**
  - ▷ event pairs with $E_1+E_2 \in [2.4\text{ keV}, 2.9\text{ keV}]$ (drawn from ^{163}Ho spectrum), $\Delta t \in [0, 10\mu s]$
  - ▷ pulse shape and noise from NIST TES model, sampled with f_{samp}, record length, and n bit
- **process with pile-up detection algorithms:**
  - ▷ for $\boldsymbol{f_{samp} = 0.5\text{MHz}, \tau_{rise} \approx 20\mu s}$
    - **Wiener Filtering**
      - → $\boldsymbol{\tau_R \approx 3\ \mu s}$
    - **Singular Value Decomposition**
      - → $\boldsymbol{\tau_R \approx 1.5\ \mu s}$



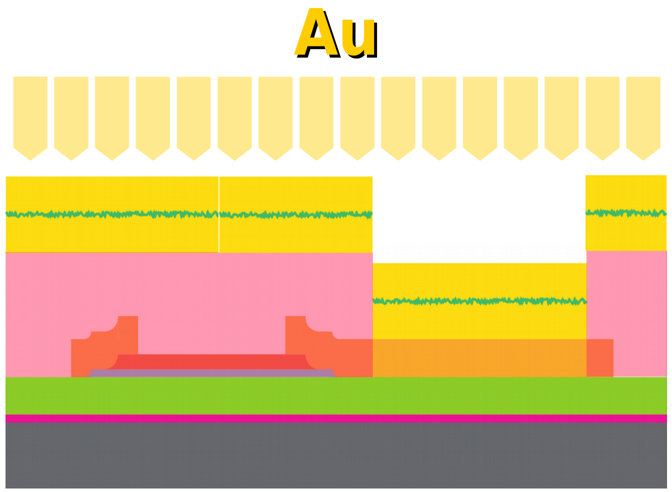
HOLMES array design and fabrication



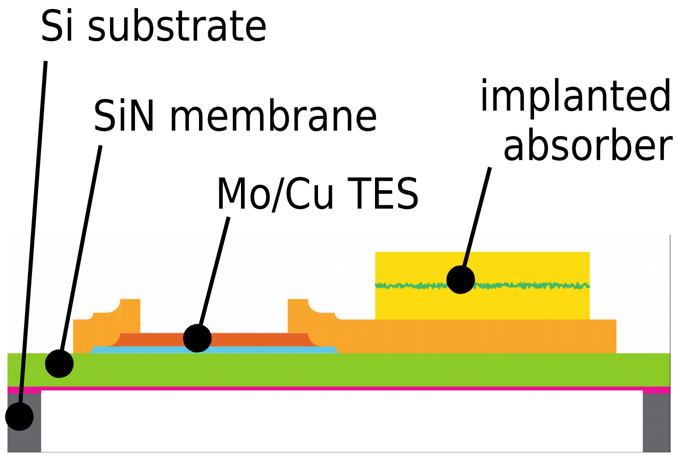
- TES array fabrication after first steps at **NIST**
- ^{163}**Ho** implantation and final 1 µm **Au** layer deposition
- final micromachining step definition in progress
- **4×16 sub-array** for low parasitic *L* and high implant efficiency



ion implantation



full incapsulation by sputtering

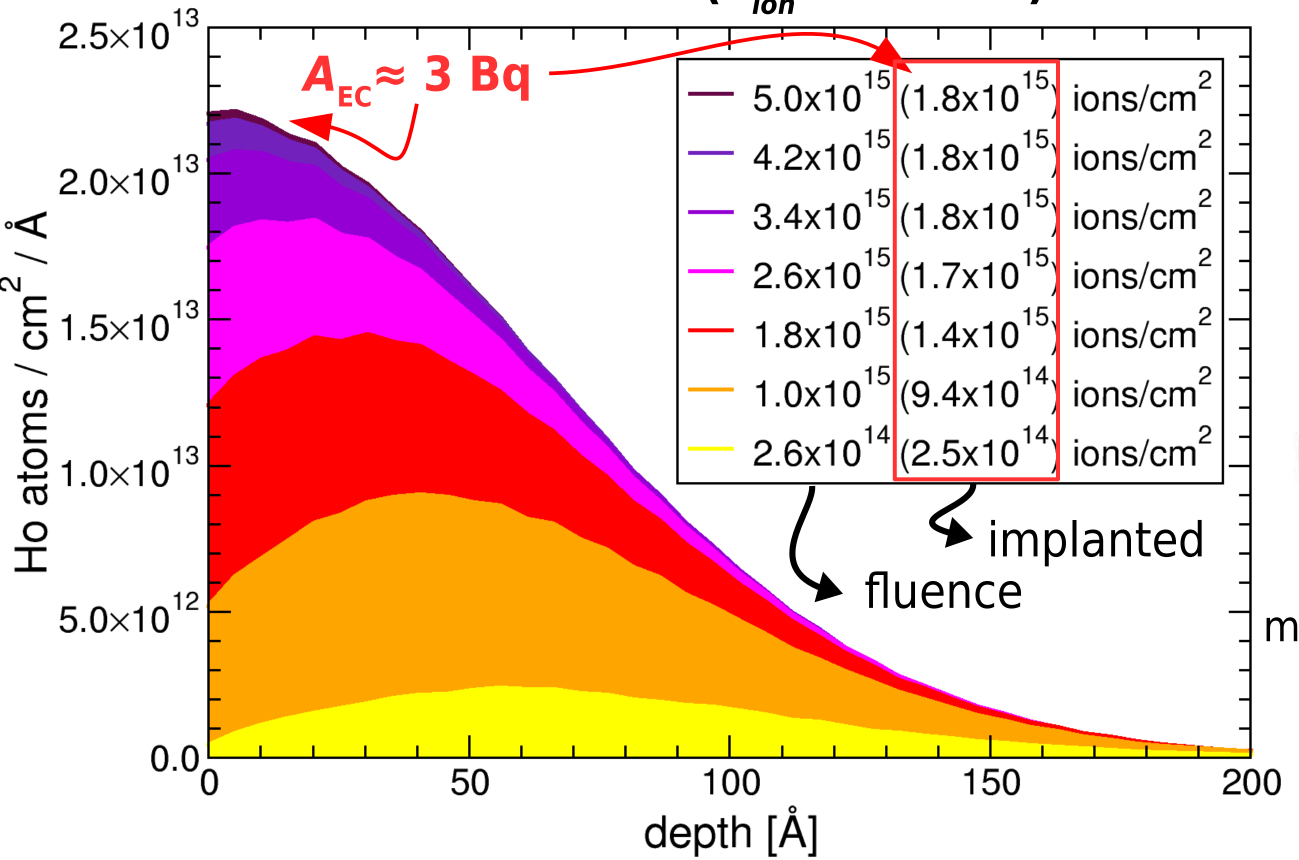


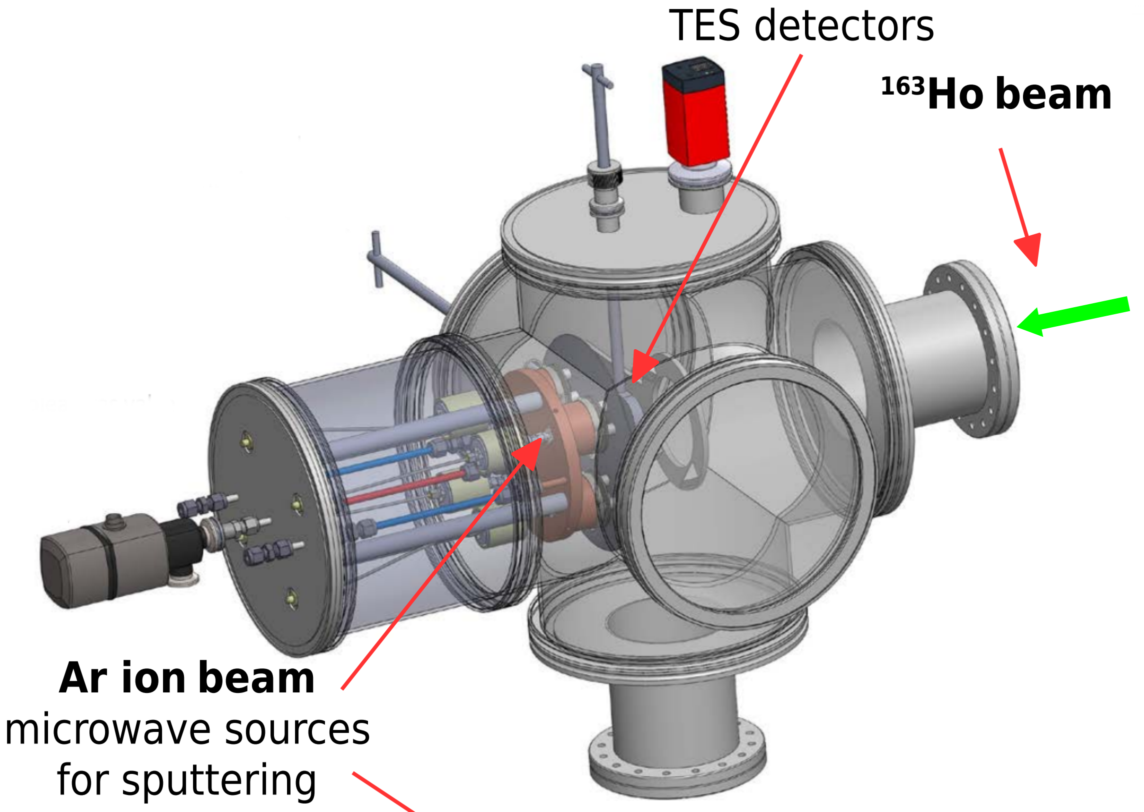
SiN membrane release

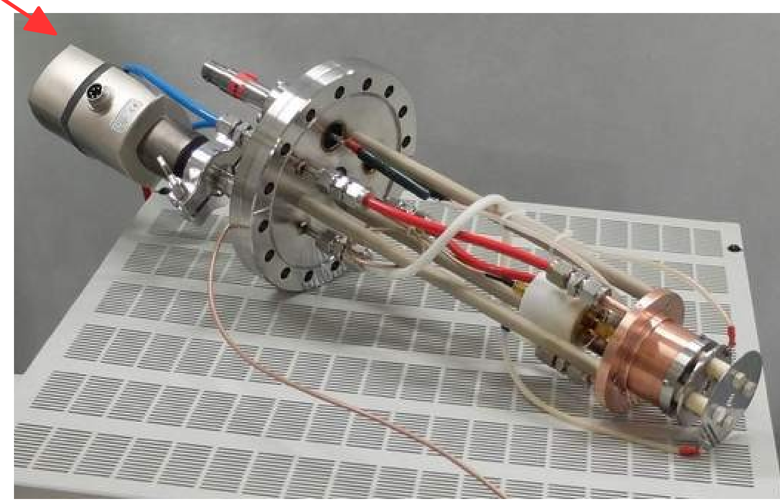
Target chamber for absorber fabrication / 1

ion implant simulation with SRIM2013

^{163}Ho ions on Au (E_{ion} = 50 keV)



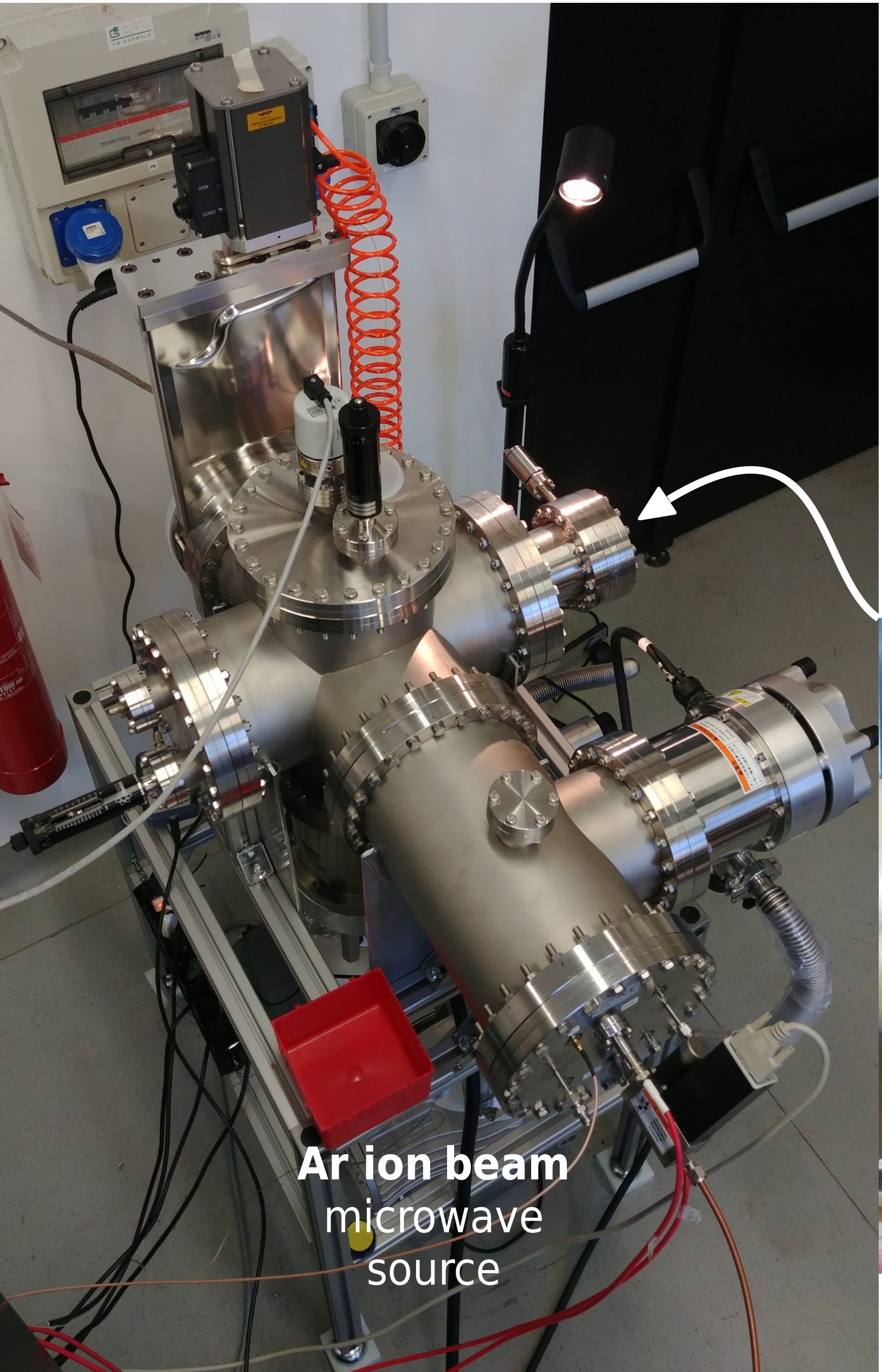


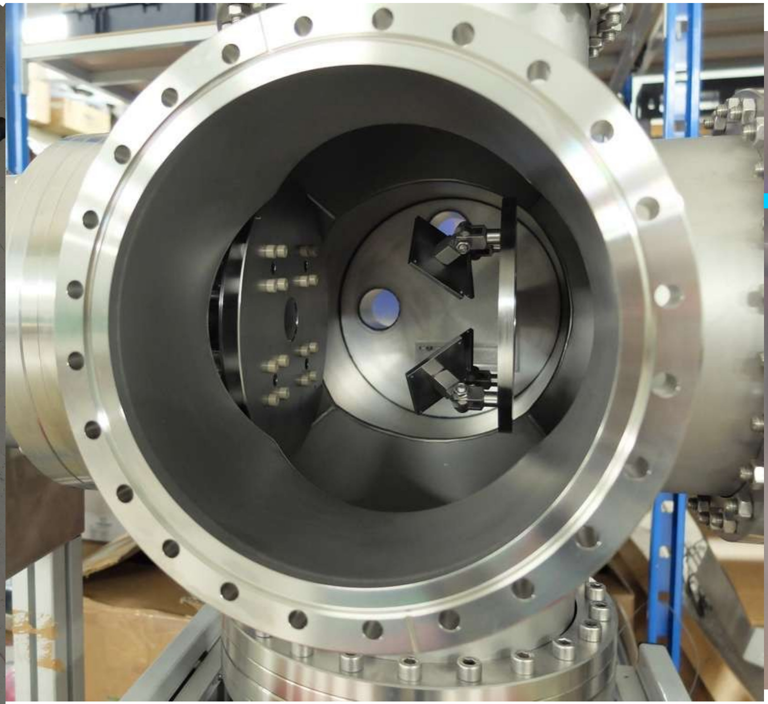


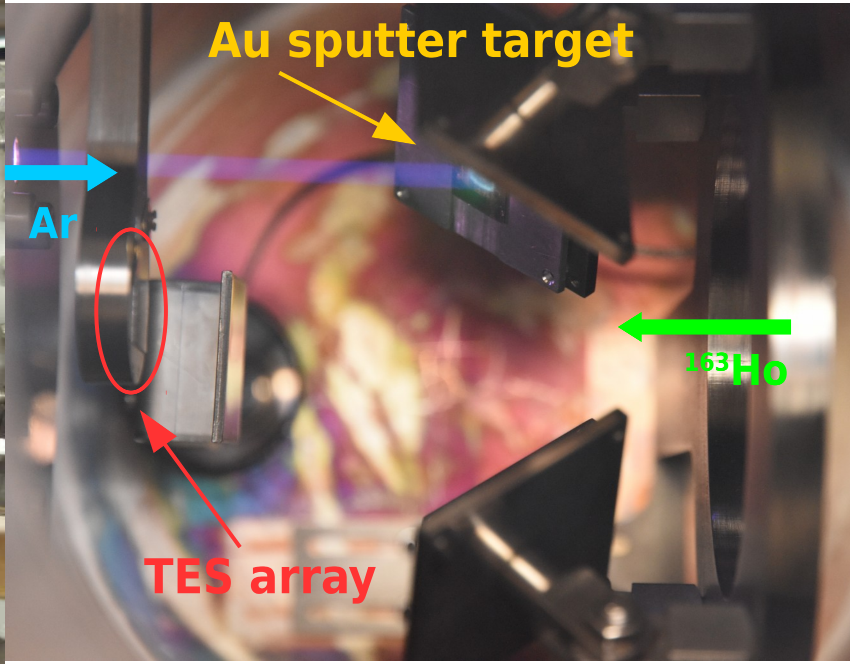
- ^{163}Ho ion beam sputters off Au from absorber (≈26 Au/Ho)
  - implanted ^{163}Ho concentration in absorber saturates
  - compensate by Au co-evaporation
- final 1 µm Au layer in situ deposition
  - to prevent Ho oxidization

Target chamber for absorber fabrication / 2

- Ion Beam Sputtering system for on-line deposition
- up to 4 ECR ion beam sources
- testing / optimization in progress with 1 ECR source
  - Au deposition rate control and maximization
  - Au film quality and uniformity characterization

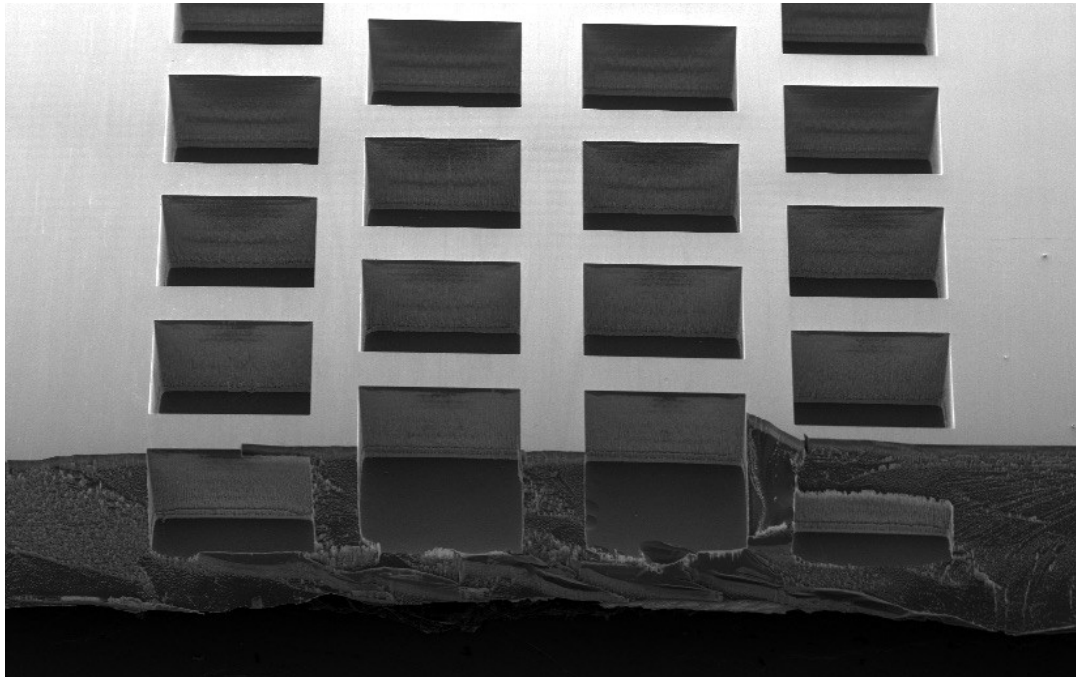




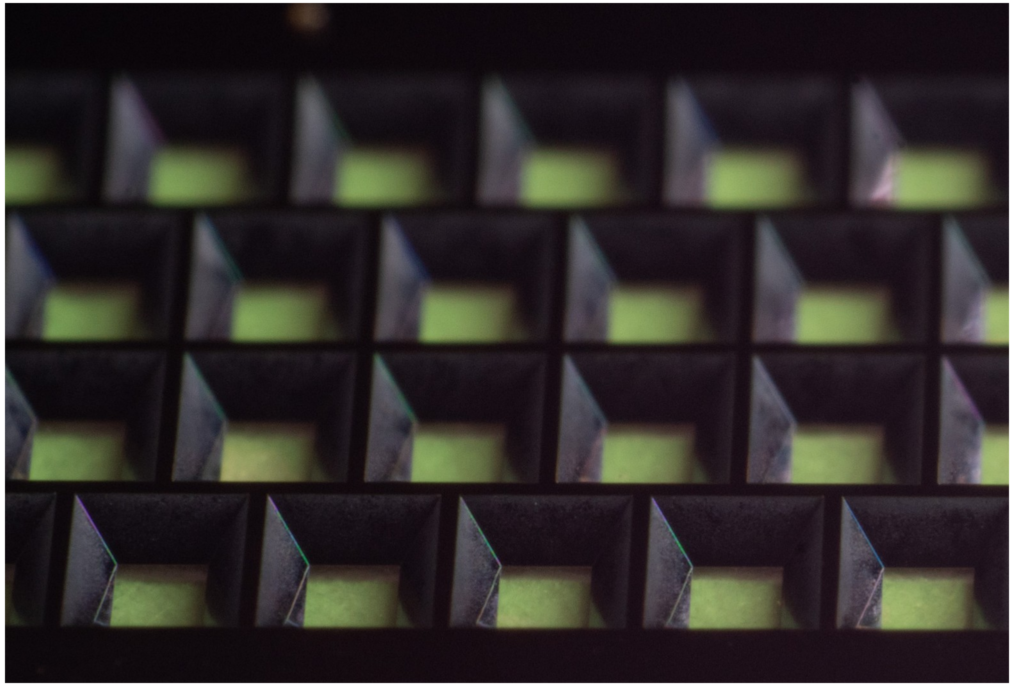


Detector array fabrication

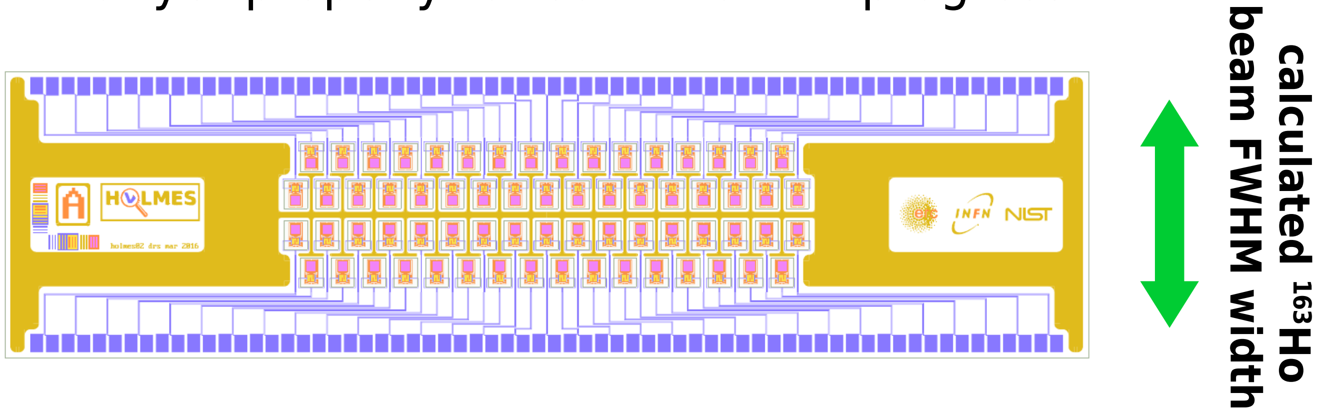
two options for membrane release (i.e. final array fabrication step)

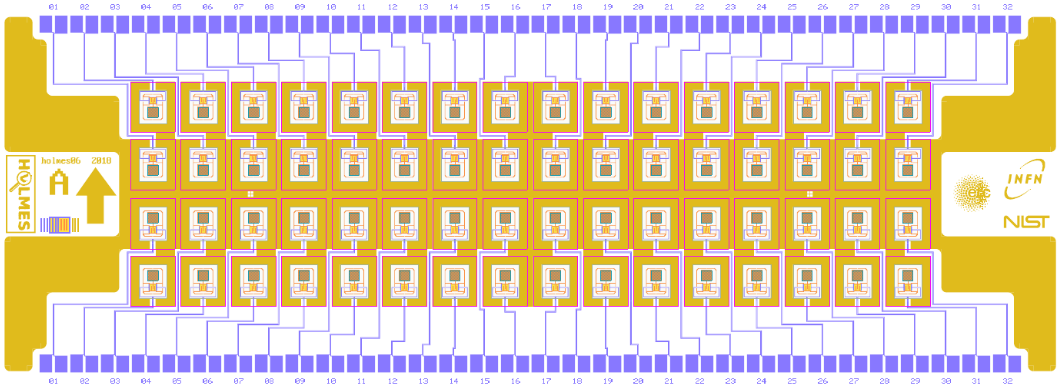


- Silicon Deep Reactive Ion Etching (DRIE)
- best for close packing and high implant efficiency
- not yet properly tuned → work in progress



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



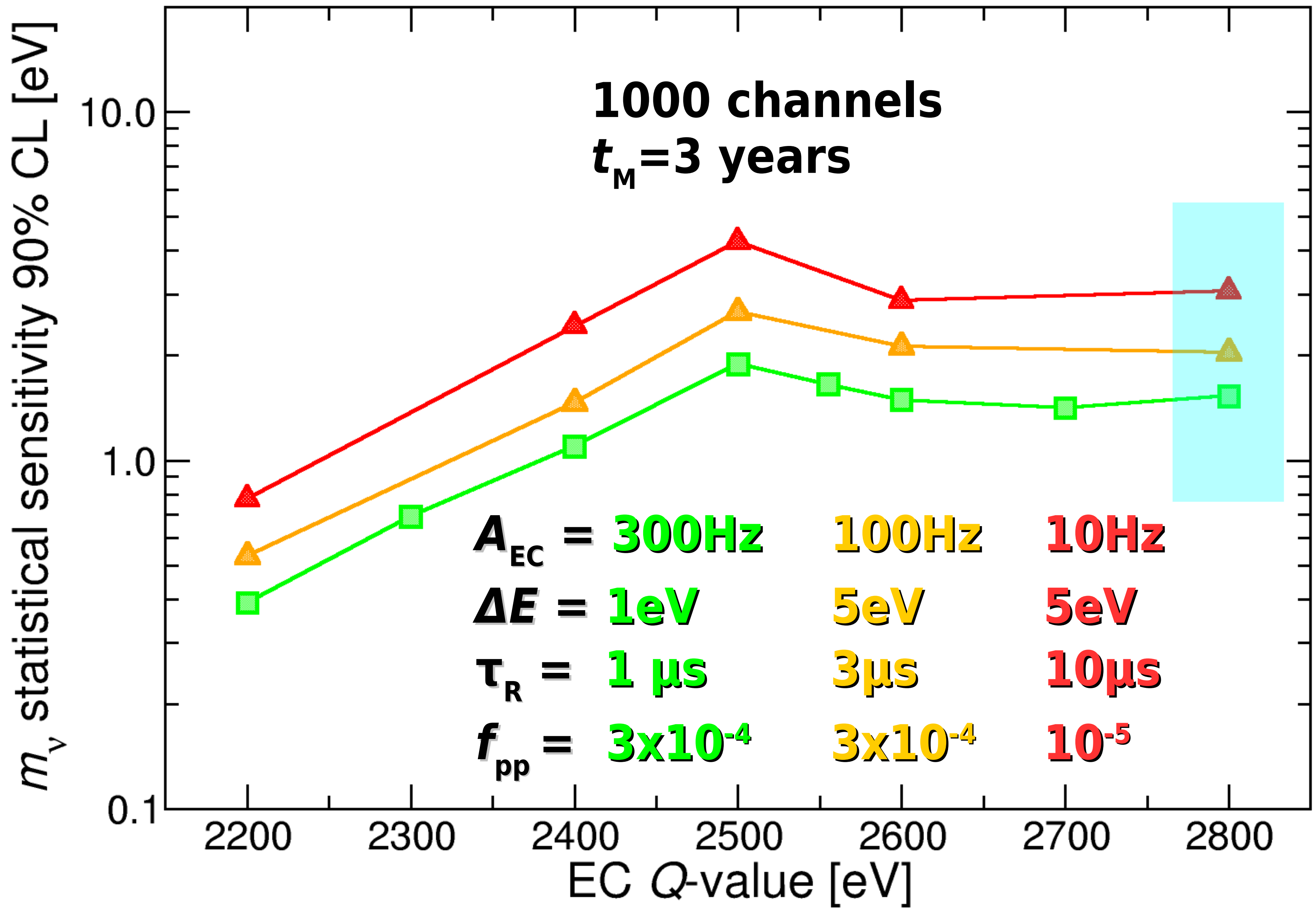


Conclusions

- first detector arrays are being fabricated at NIST
- first ion implantation tests with ^{163}Ho before the end of 2018
  - first not-optimized ion implanted detectors late in 2018
- ^{163}Ho implanted activity optimized during 2019
  - first high ^{163}Ho activity array running in 2019
  - 1 month data taking can provide a m_ν statistical sensitivity ≈10 eV
  - full array deployment will follow

Backup…

Worst case scenarios...

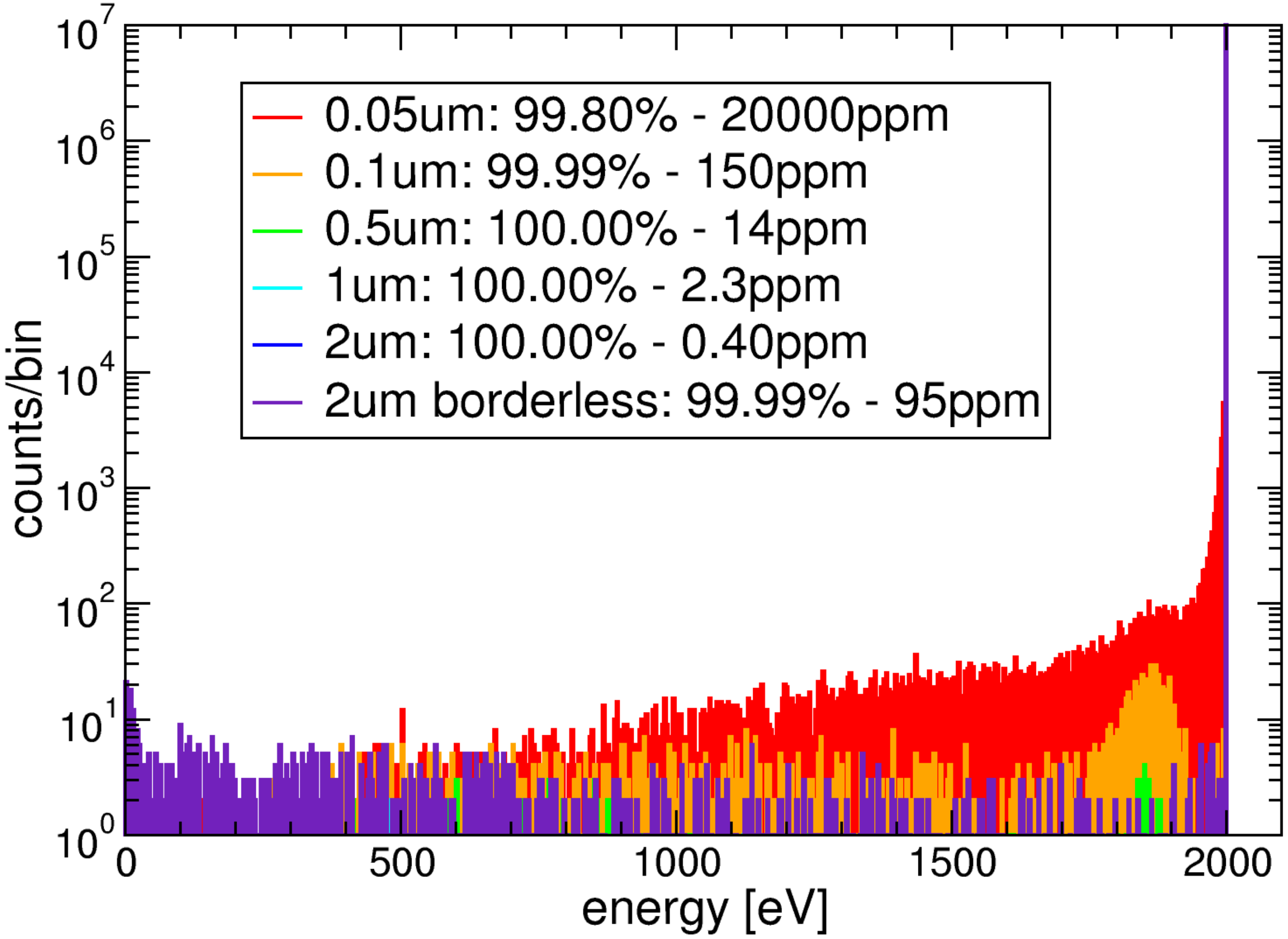


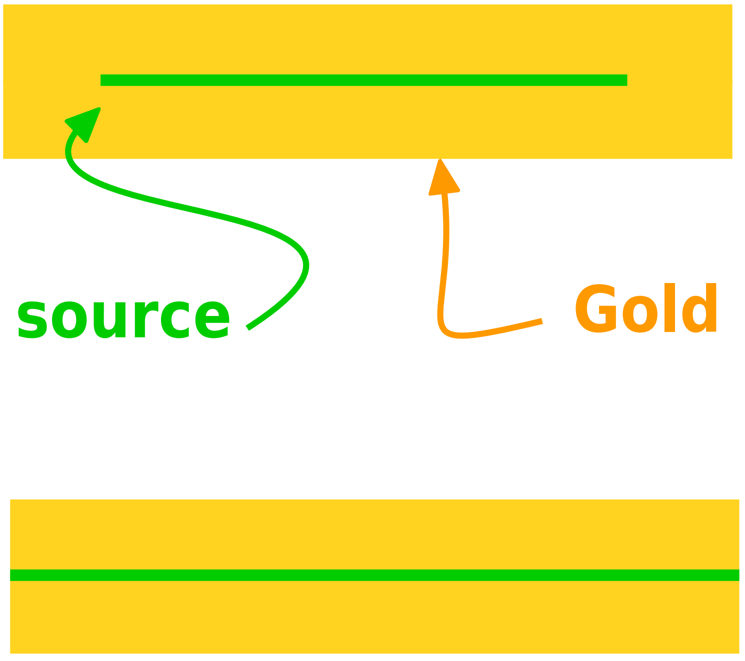
TES absorber design: stopping EC radiation / 1 b

Geant4 + LowEnergyEM MC simulation

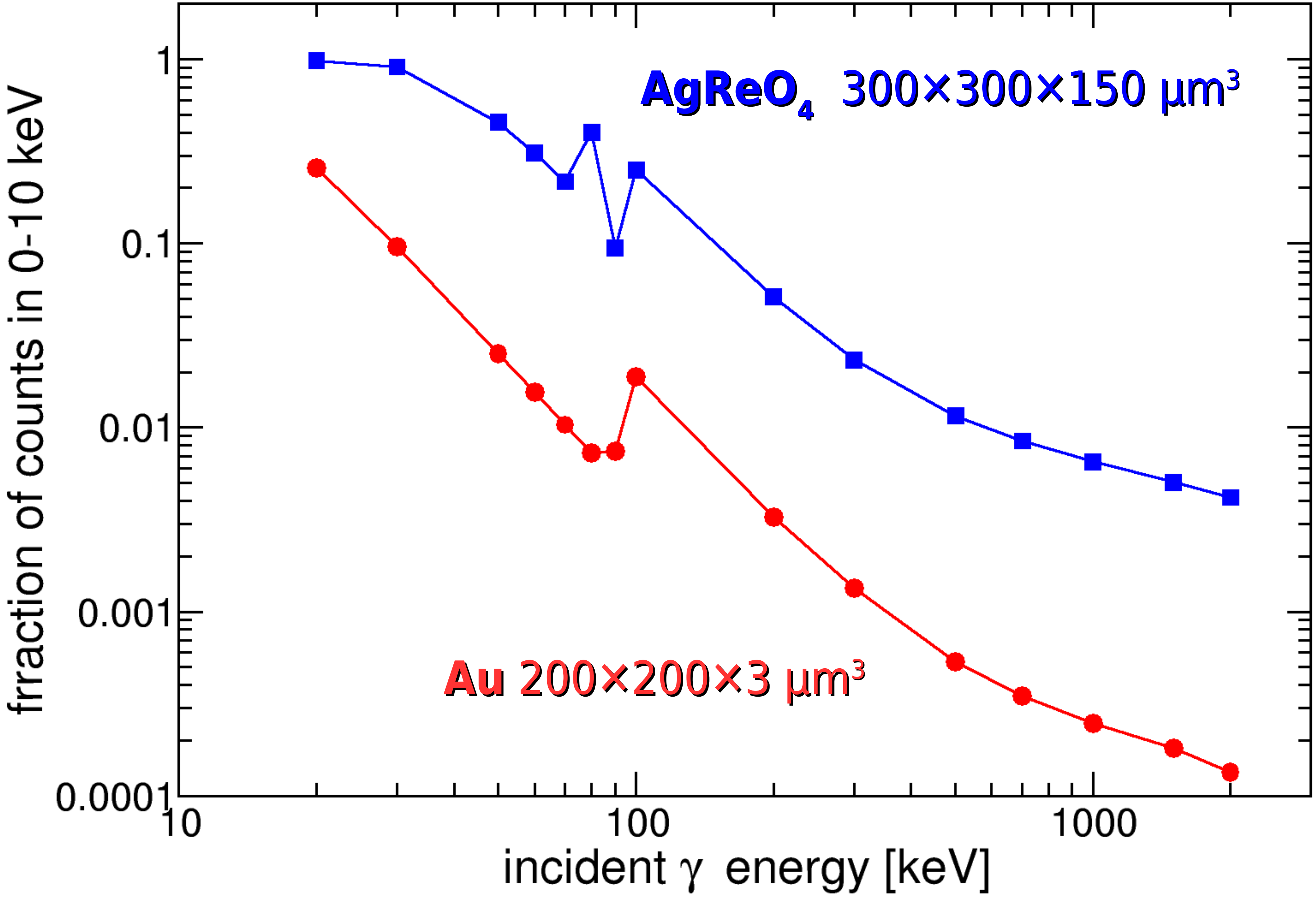
2keV electrons

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





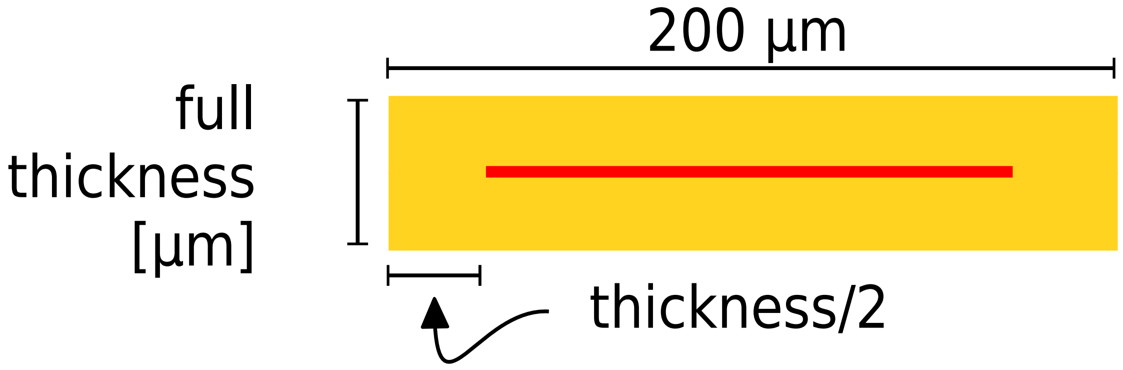
Low energy background: γ sources



^{166m}Ho background

Geant4 + LowEnergyEM

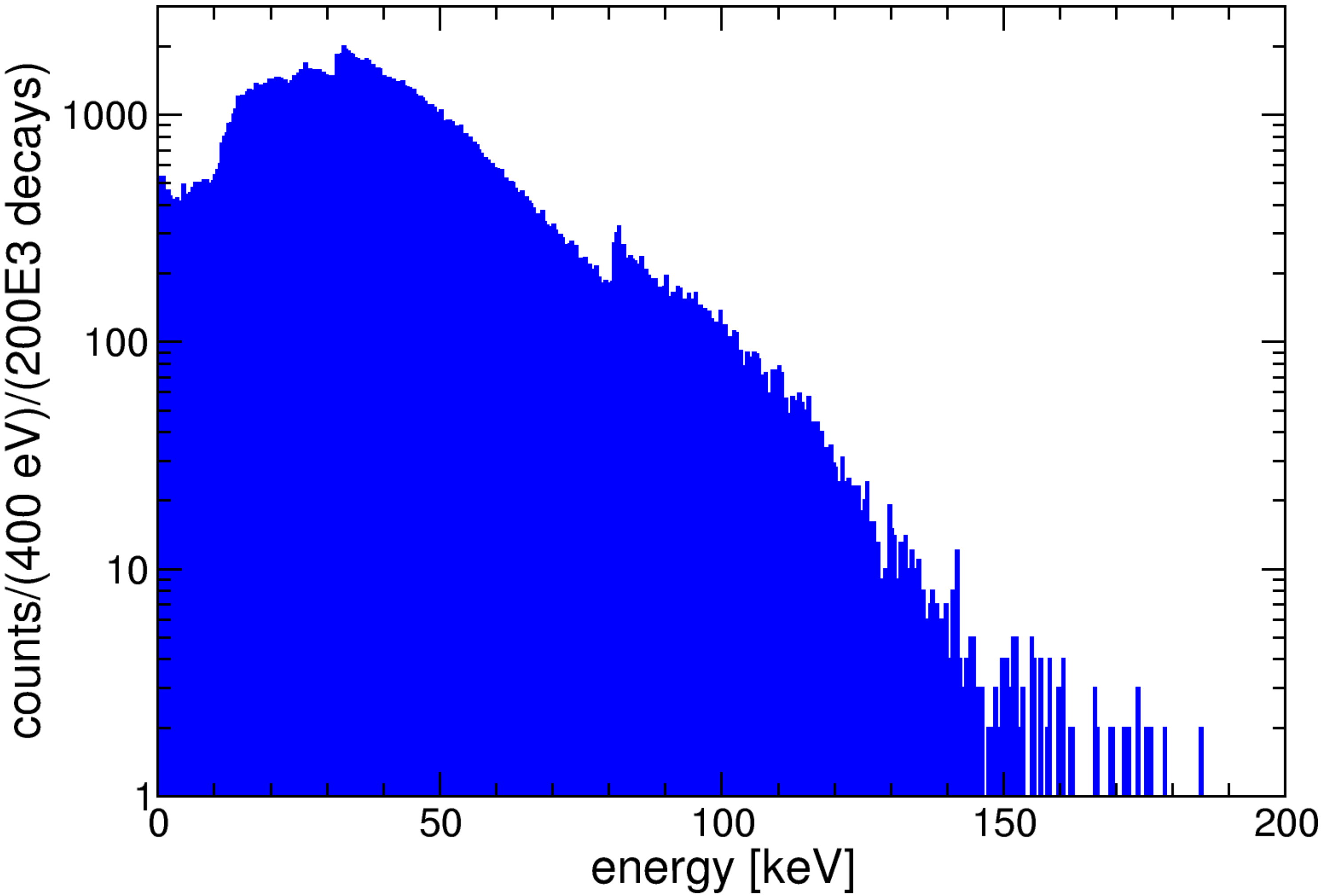
2 10^5 events

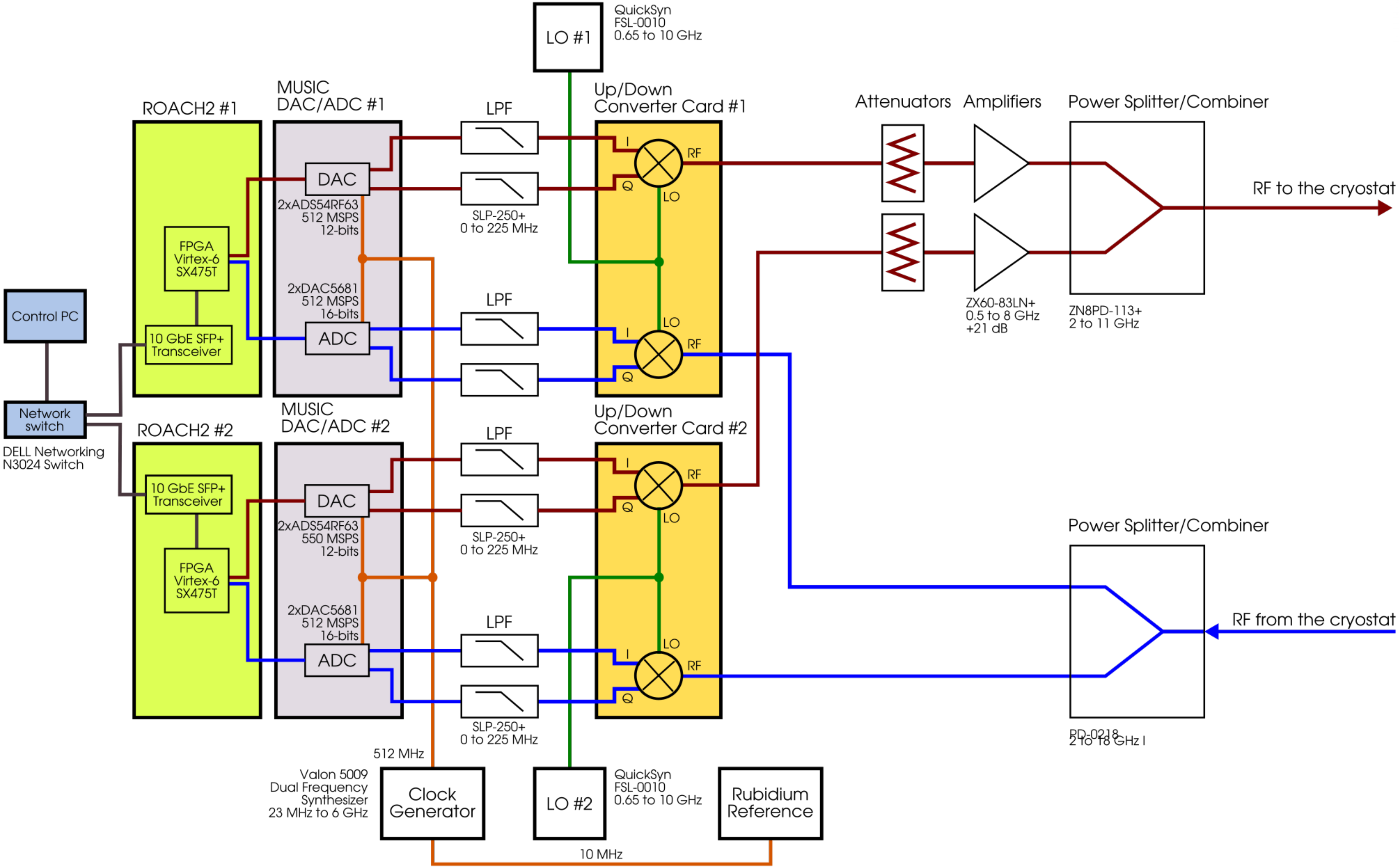


200 µm

full thickness [µm]

thickness/2





LO #1

QuickSyn
FSL-0010
0.65 to 10 GHz

ROACH2 #1

FPGA
Virtex-6
SX475T

10 GbE SFP+
Transceiver

MUSIC
DAC/ADC #1

DAC
2xADS54RF63
512 MSPS
12-bits

2xDAC5681
512 MSPS
16-bits
ADC

LPF

SLP-250+
0 to 225 MHz

LPF

Up/Down
Converter Card #1

I
Q
RF
LO

LO
I
RF
Q

Attenuators

Amplifiers

Power Splitter/Combiner

RF to the cryostat

ZX60-83LN+
0.5 to 8 GHz
+21 dB

ZN8PD-113+
2 to 11 GHz

Control PC

Network
switch

DELL Networking
N3024 Switch

ROACH2 #2

10 GbE SFP+
Transceiver

FPGA
Virtex-6
SX475T

MUSIC
DAC/ADC #2

DAC
2xADS54RF63
550 MSPS
12-bits

2xDAC5681
512 MSPS
16-bits
ADC

LPF

SLP-250+
0 to 225 MHz

LPF

SLP-250+
0 to 225 MHz

Up/Down
Converter Card #2

I
Q
RF
LO

LO
I
RF
Q

Power Splitter/Combiner

RF from the cryostat

PD-0218
2 to 18 GHz I

512 MHz

Valon 5009
Dual Frequency
Synthesizer
23 MHz to 6 GHz

Clock
Generator

LO #2

QuickSyn
FSL-0010
0.65 to 10 GHz

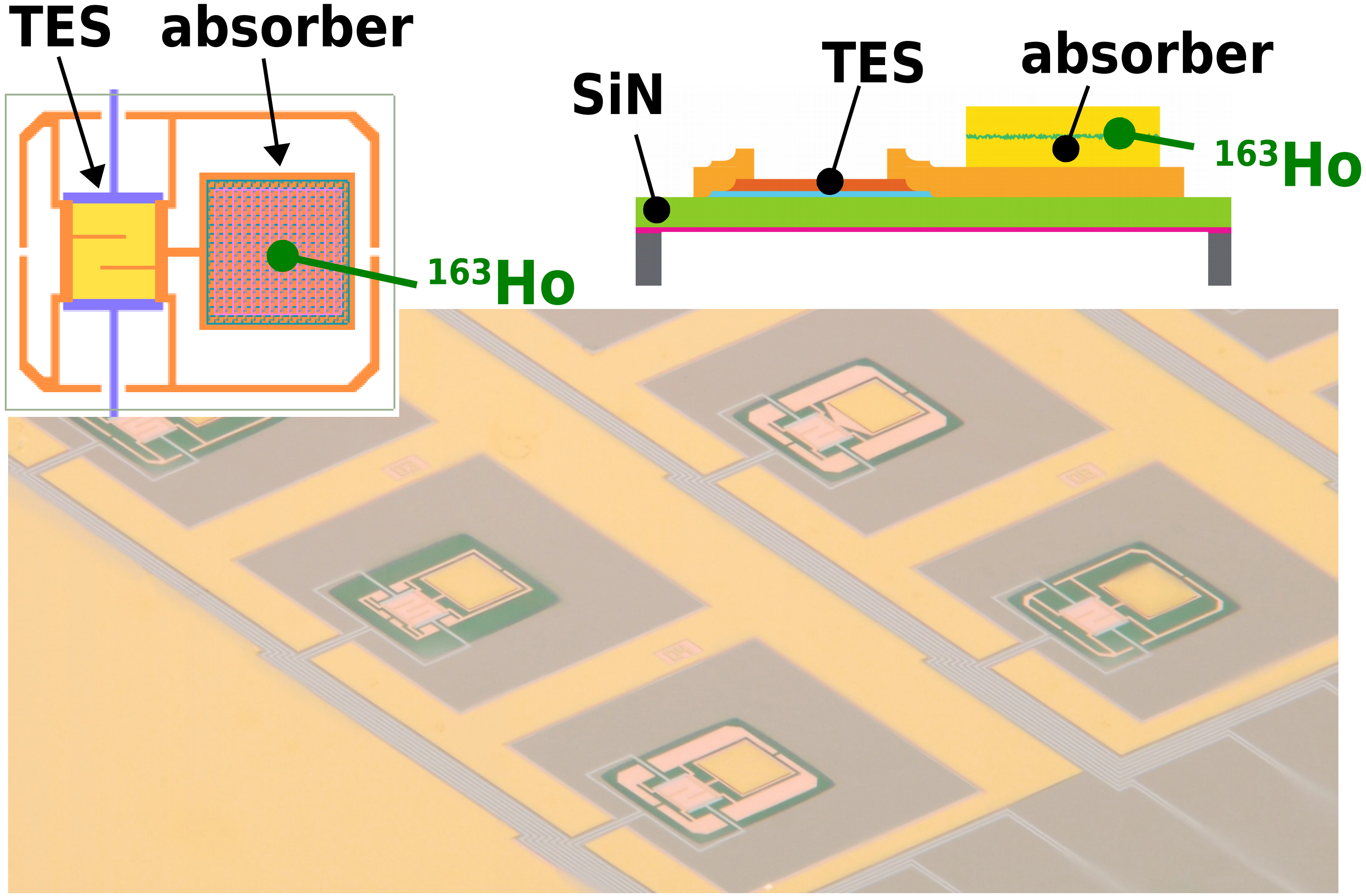
Rubidium
Reference

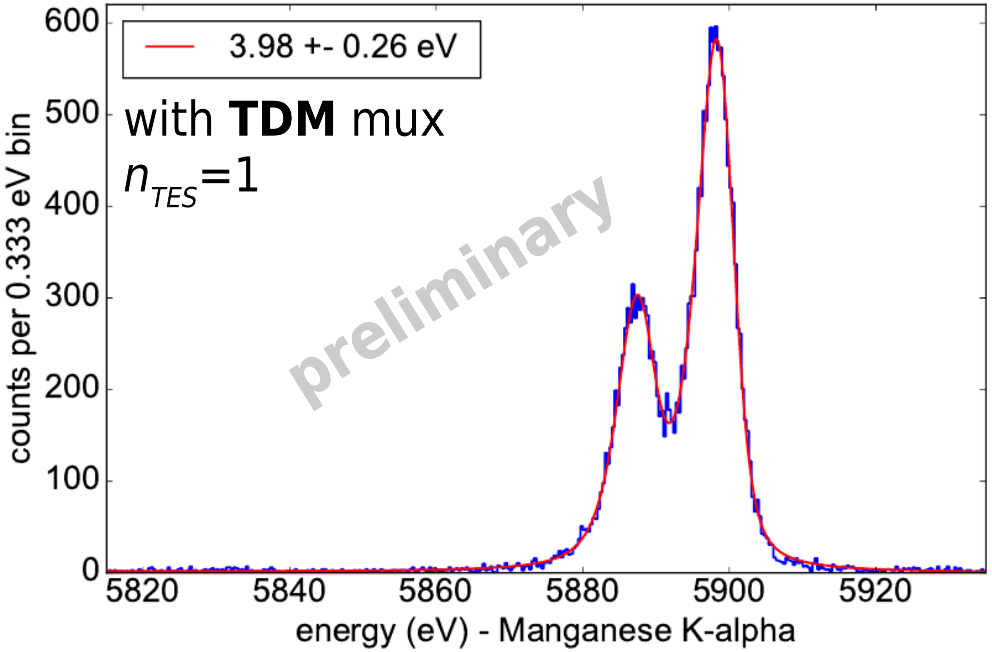
10 MHz

HOLMES pixel design and test

- optimize design for speed and resolution
  - ▷ **specs @3keV : $\Delta E_{\mathrm{FWHM}} \approx$ 1eV, $\tau_{\mathrm{rise}} \approx$ 10μs, $\tau_{\mathrm{decay}} \approx$ 100μs**
- **2 μm Au** thickness for *full* electron and photon absorption
- ***side-car*** design to avoid TES proximitation and *G* engineering for τ_{decay} control

TES prototypes w/o ^{163}Ho: fabrication & test @ **NIST**





- ▷ **$\Delta E_{\mathrm{FWHM}} \lesssim$ 4 eV** @ 6 keV (→ **≈3 eV** @ Q_{EC})
- ▷ **$\tau_{\mathrm{rise}} \approx$ 6 μs** (with L=38nH → to be slowed)
- ▷ **$\tau_{\mathrm{decay}} \approx$ 130 μs** (still tunable)