Direct neutrino mass measurement by the HOLMES experiment

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on behalf of the HOLMES collaboration

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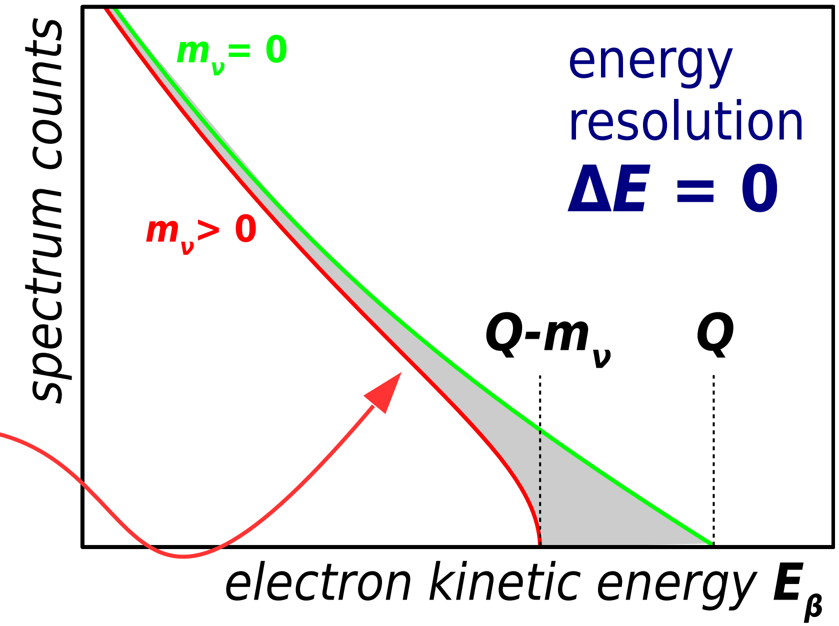
Direct neutrino mass measurements

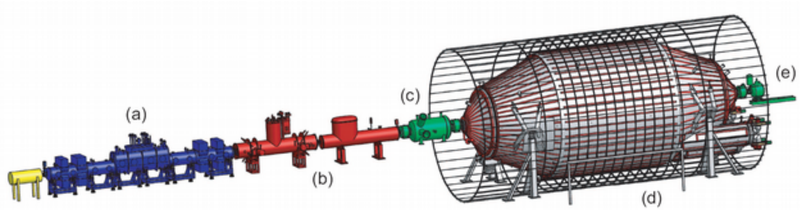
- **kinematics of weak decays with ν emission**
  - low Q nuclear beta decays (^{3}H, ^{187}Re...)
  - only energy and momentum conservation
  - no further assumptions

$$(A,Z) \rightarrow (A,Z+1) + e^{-} + \bar{\nu}_e$$

$$N(E_\beta) \propto p_\beta E_\beta (Q-E_\beta)\sqrt{((Q-E_\beta)-m_\nu^2)}\,F(z,E_\beta)\,S(E_\beta)$$

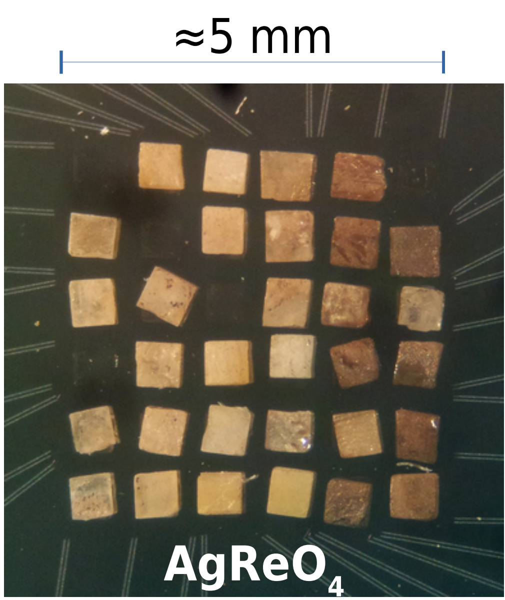


- **2 approaches with different systematics:**
  - **spectrometry** with the β source outside
  - **calorimetry** with the β source inside



KATRIN
large MAC-E filter spectrometer with ^{3}H
→ results from 2018

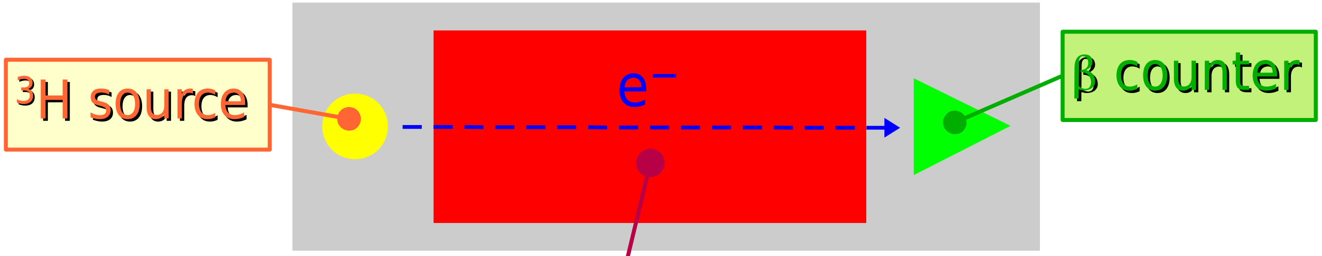
MARE/ECHO/HOLMES
array of low temperature microcalorimeters
with ^{187}Re or ^{163}Ho



A. Nucciotti, Adv. High Energy Physics, 2016, 915304

Direct ν mass measurements: experimental

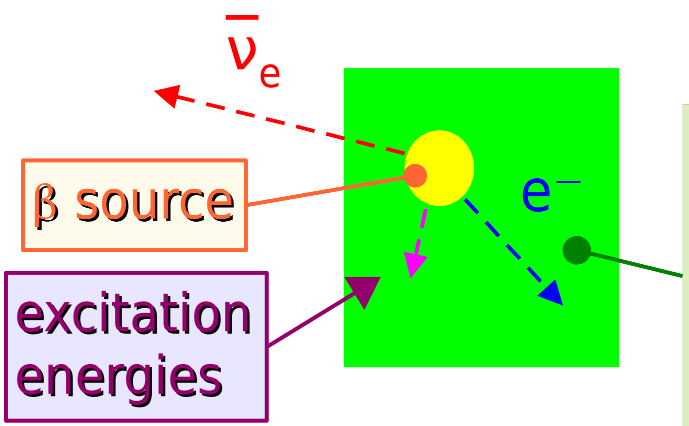
Spectrometers: source ≠ detector



β differential or integral spectrometer
βs from the ^{3}H spectrum are magnetically and/or electrostatically selected in *E* and transported to the counter

- ▲ high statistics
- ▲ high energy resolution
- ▼ source effects
- ▼ decays to excited states

Calorimeters: source ⊆ detector



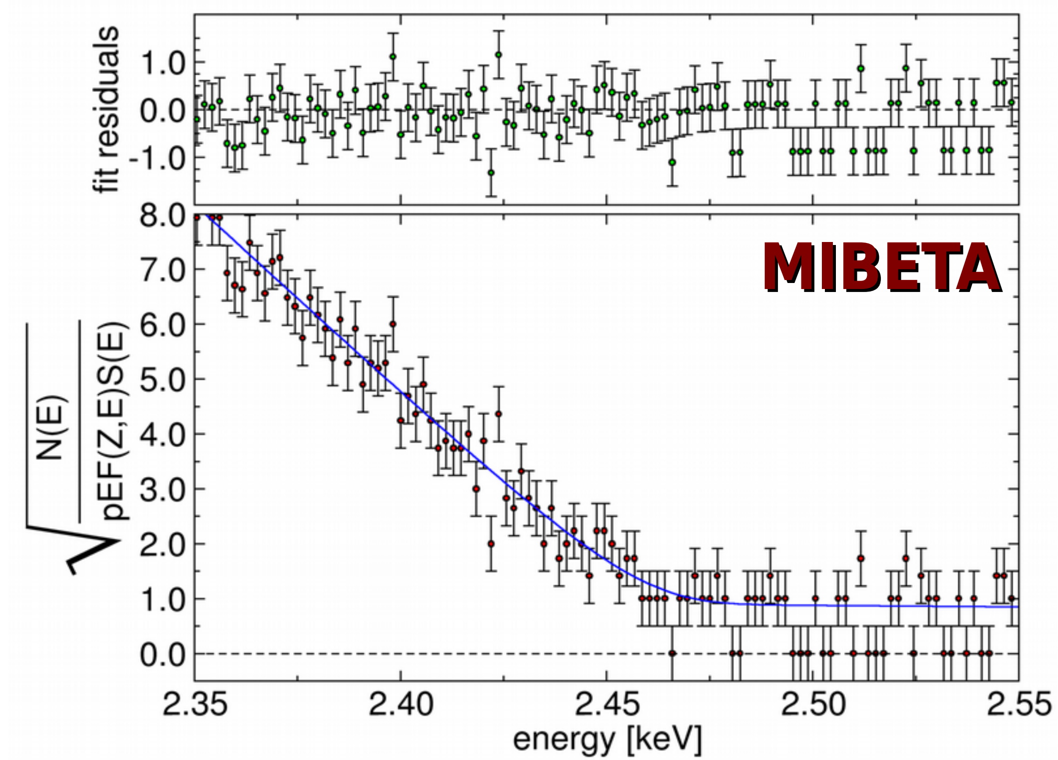
β calorimeter
ideally measures all the energy *E* released in the decay except for the $\bar{\nu}_e$ energy: $E=Q-E_\nu$

- ▲ no backscattering
- ▲ no energy losses in source
- ▲ no decay final state effects
- ▲ no solid state excitation
- ▼ limited statistics
- ▼ pile-up background

Rhenium calorimetric experiments

$^{187}_{75}Re \rightarrow\, ^{187}_{76}Os + e^- + \bar{\nu}_e$

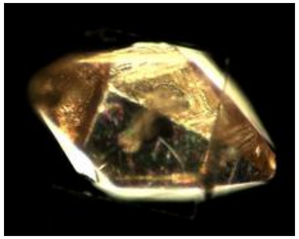
- $5/2^+ \rightarrow 1/2^-$ unique first forbidden
- end point Q = 2.47 keV
- half-life time $\tau_{1/2}$ = 43.2 Gy
- natural abundance a.i. = 63%
  - 1 mg of Rhenium → ≈1.0 decay/s



- **metallic rhenium** single crystals
  - superconductor with T_c=1.6K
  - NTD thermistors
  - **MANU experiment (Genova)**

→ m_ν < ≈15 eV

- **dielectric rhenium compound** ($AgReO_4$) crystals
  - Silicon implanted thermistors
  - **MIBETA experiment (Milano)**



MARE

→ sub-eV m_ν sensitivity

A. Nucciotti, Adv. High Energy Physics, 2016, 915304

Electron capture calorimetric experiments / 1

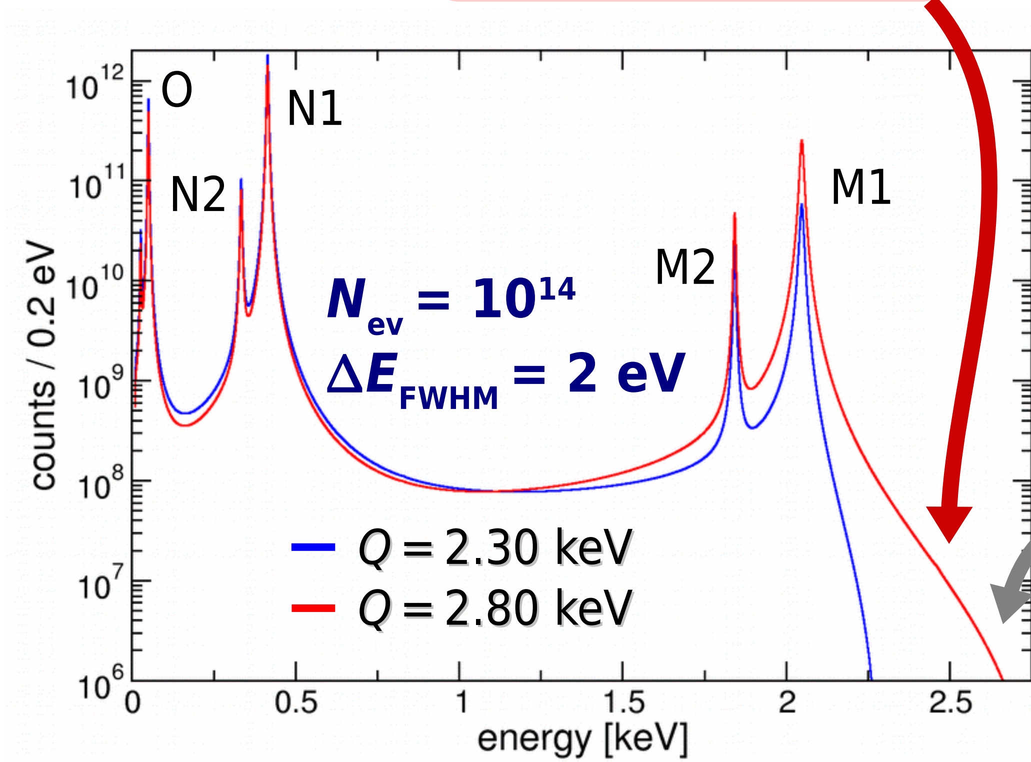
$^{163}Ho + e^{-} \rightarrow {}^{163}Dy^{*} + \nu_e$

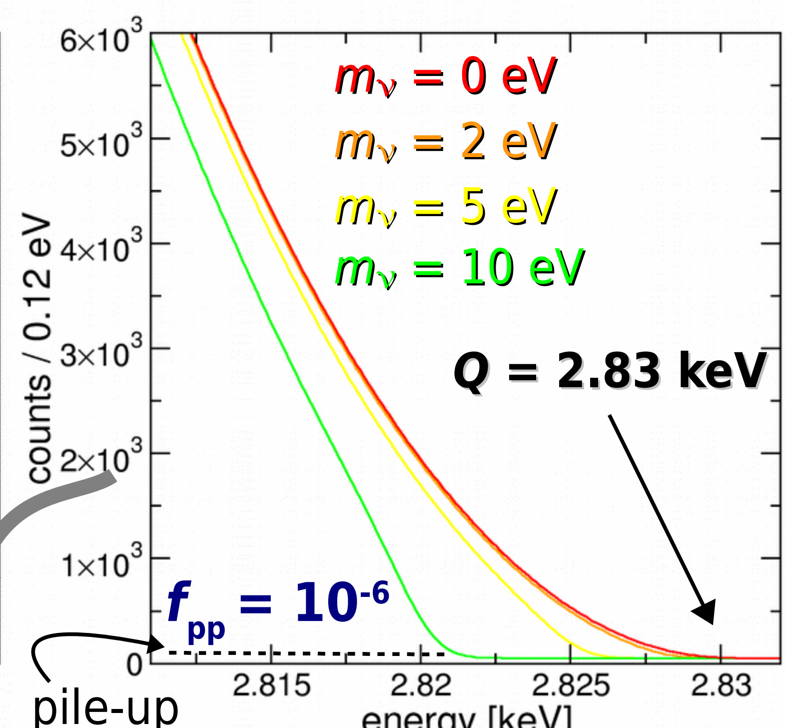
electron capture from shell ≥ M1

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** (measured with Penning trap)
  - end-point rate and ν mass sensitivity depend on $Q - E_{M1}$
- $\tau_{1/2}$ **≈ 4570 years** → 2×10^{11} ^{163}Ho nuclei ↔ 1Bq

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

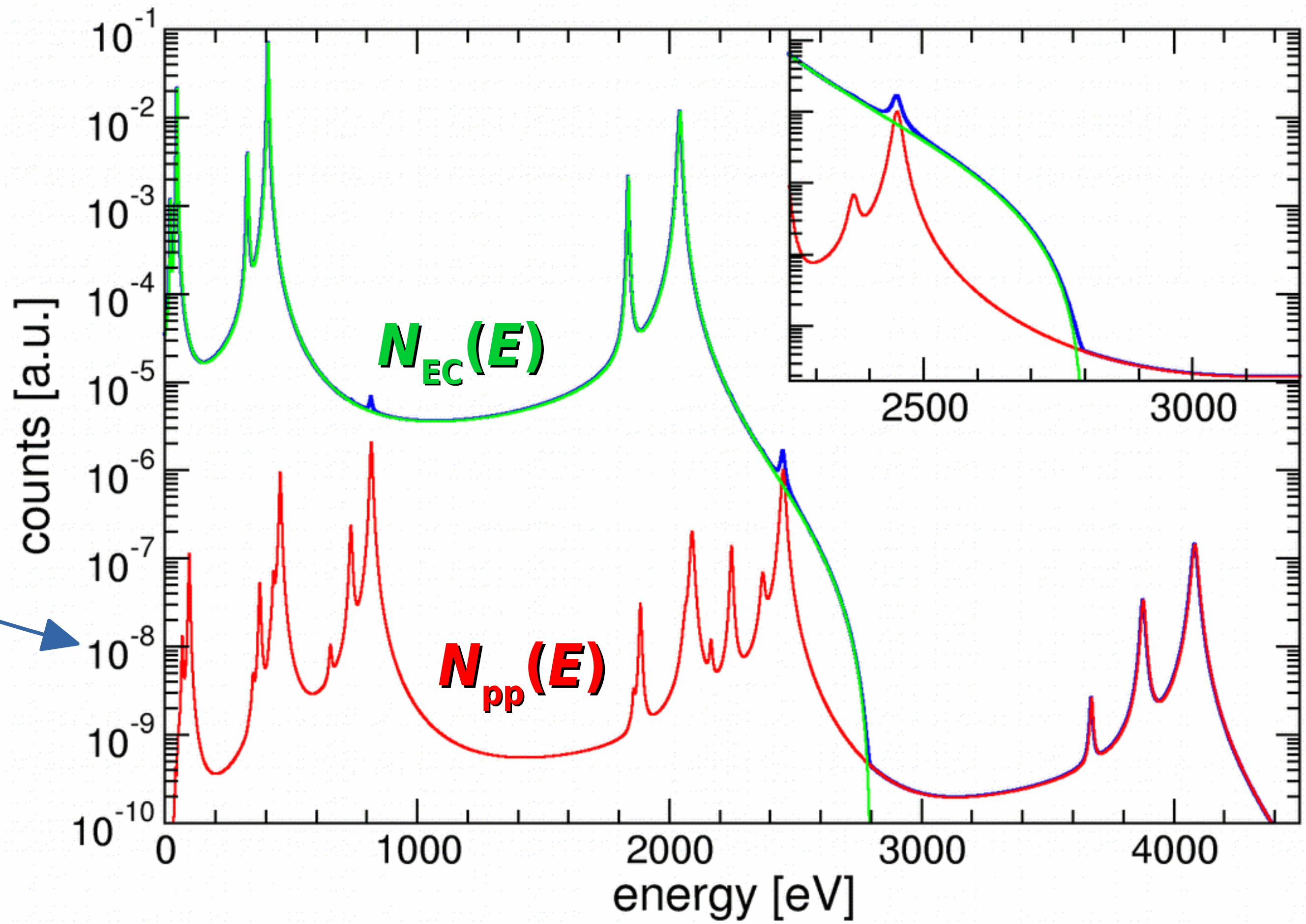




Electron capture calorimetric experiments / 2

- 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)



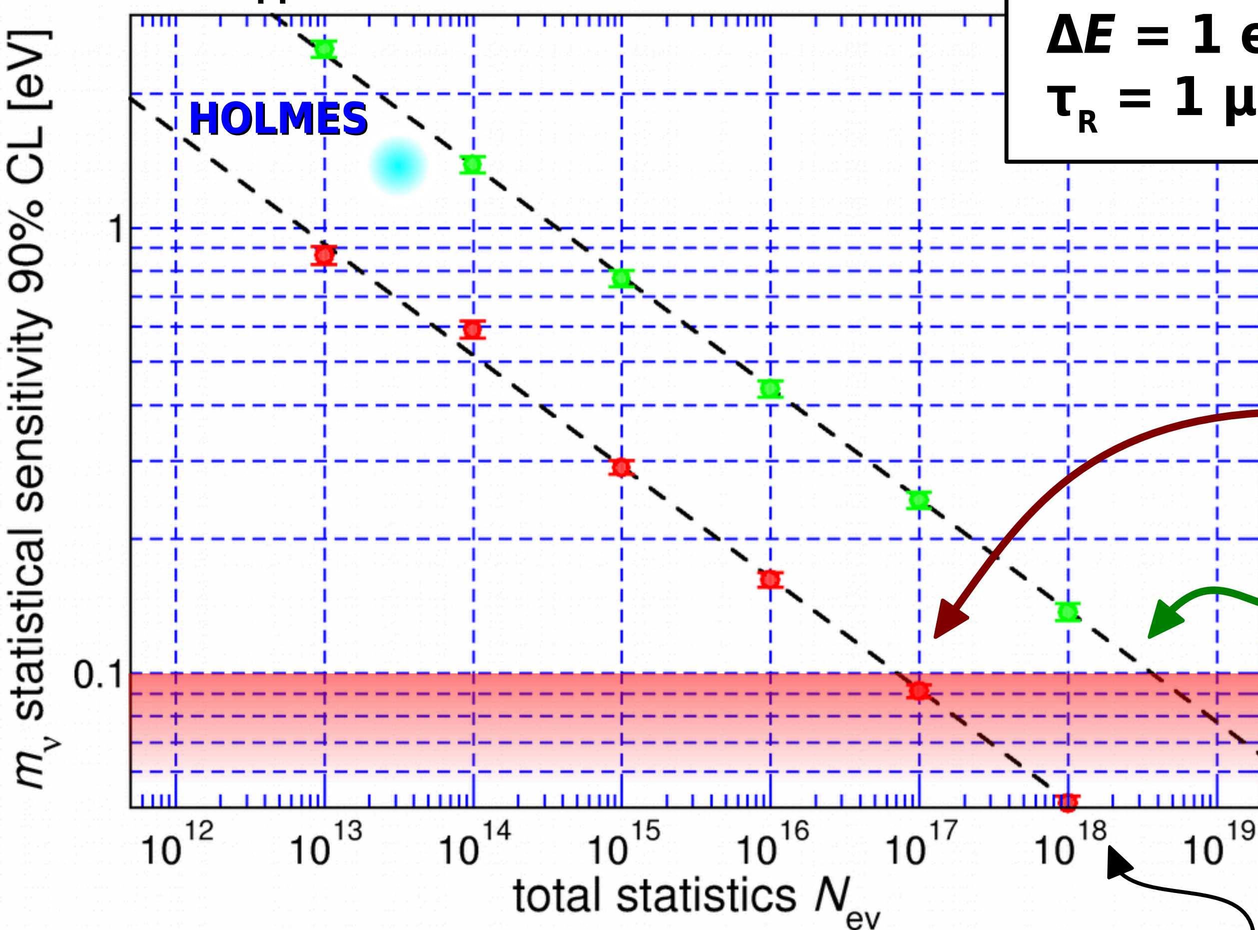
Q = 2800 eV

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

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

Montecarlo simulations: ^{163}Ho sensitivity potential

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
$N_{det} t_M \approx 2\times10^9$ 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

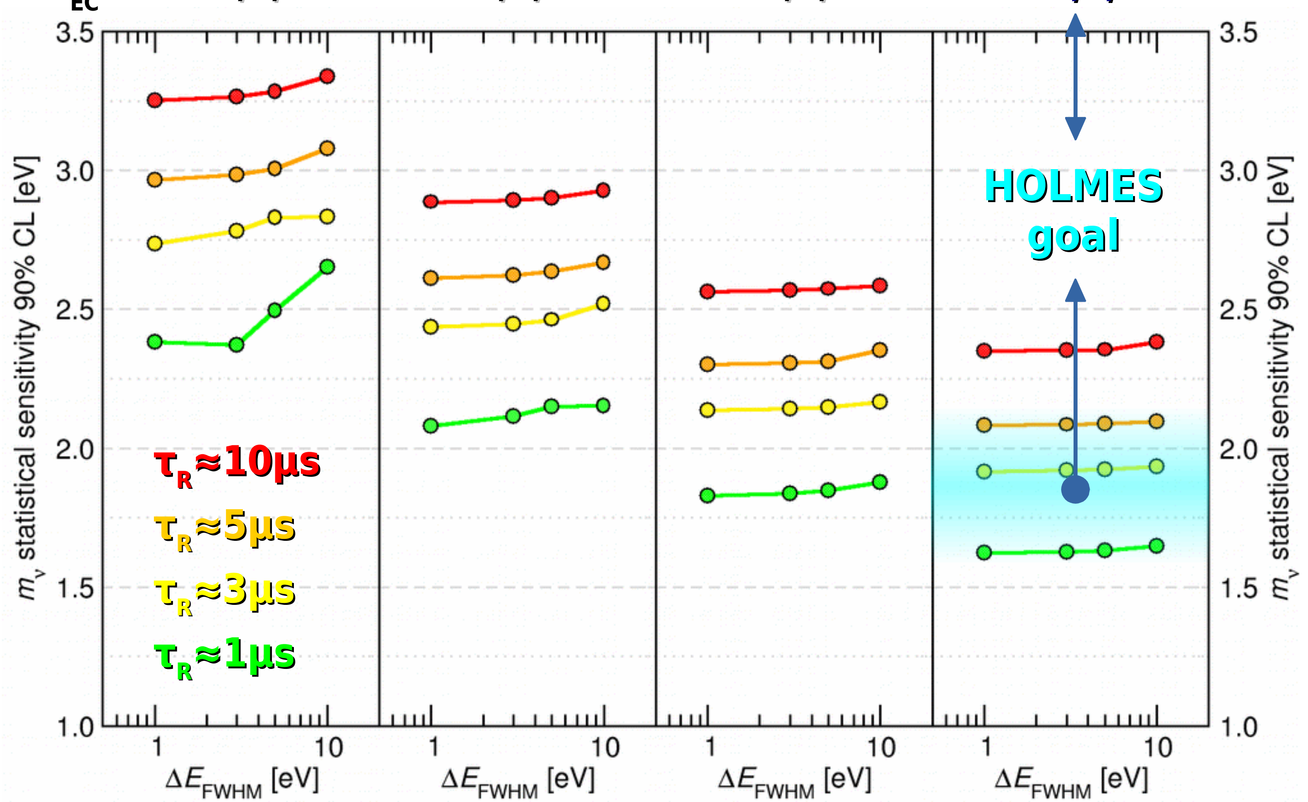
goal

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

baseline

- **TES microcalorimeters** with **implanted ^{163}Ho**
  - 6.5×10^{13} nuclei per pixel
    A_{EC} = 300 c/s/det
  - **$\Delta E \approx 1$ eV** and **$\tau_R \approx 1\ \mu s$**
- **1000 channel** array
  - 6.5×10^{16} ^{163}Ho nuclei
    → ≈18 µg
  - 3×10^{13} events in **3 years**

exposure = 1000 det × 3 y



5 years project started on February 1st 2014

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

HOLMES collaboration

Univ. Milano-Bicocca INFN Milano-Bicocca	INFN Genova	NIST	PSI
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	INFN LNGS	J.Ullom	
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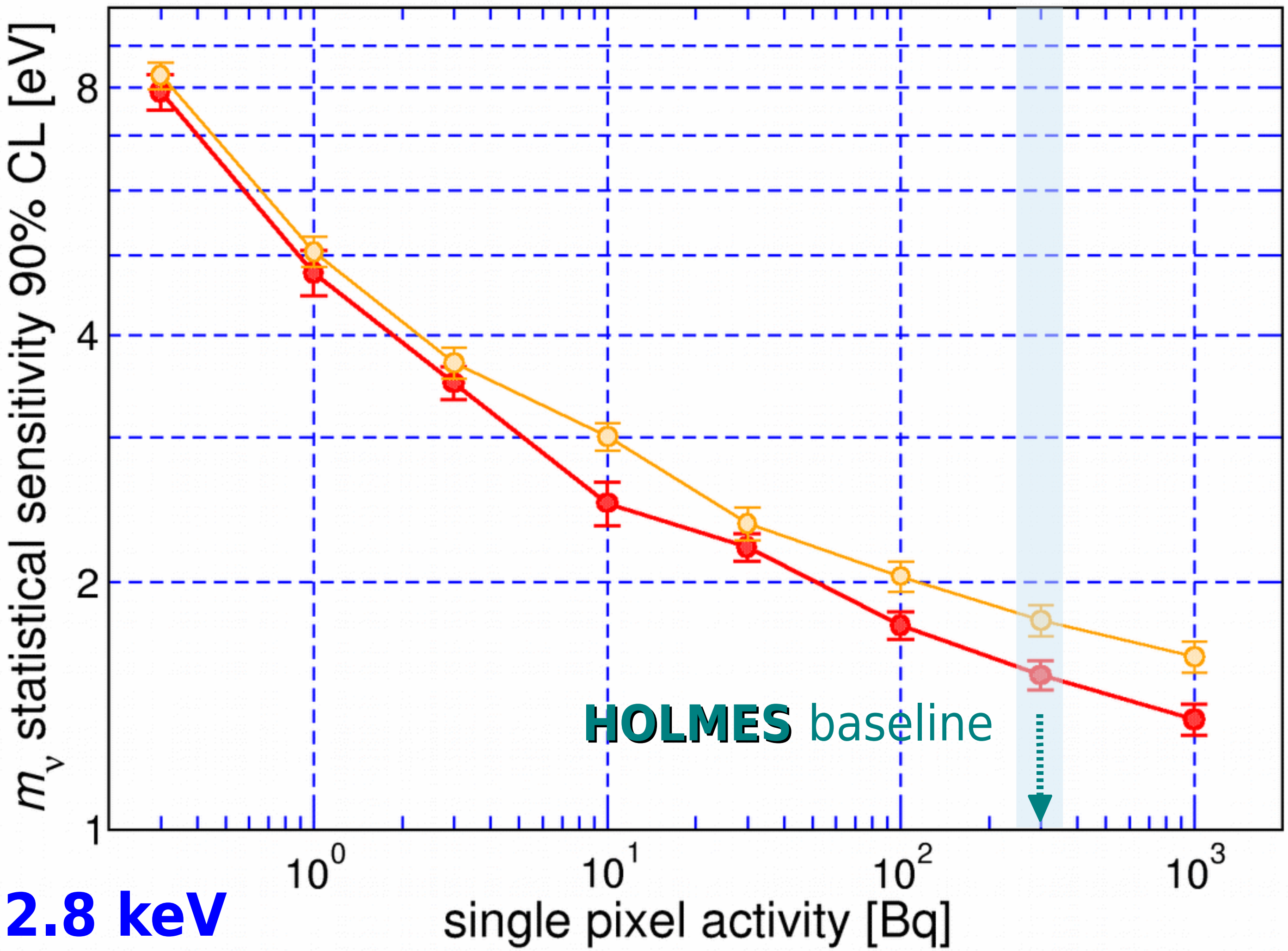
http://artico.mib.infn.it/holmes

Statistical sensitivity and single pixel activity

fixed exposure $N_{det}t_M$



1000 channels
t_M=3 years

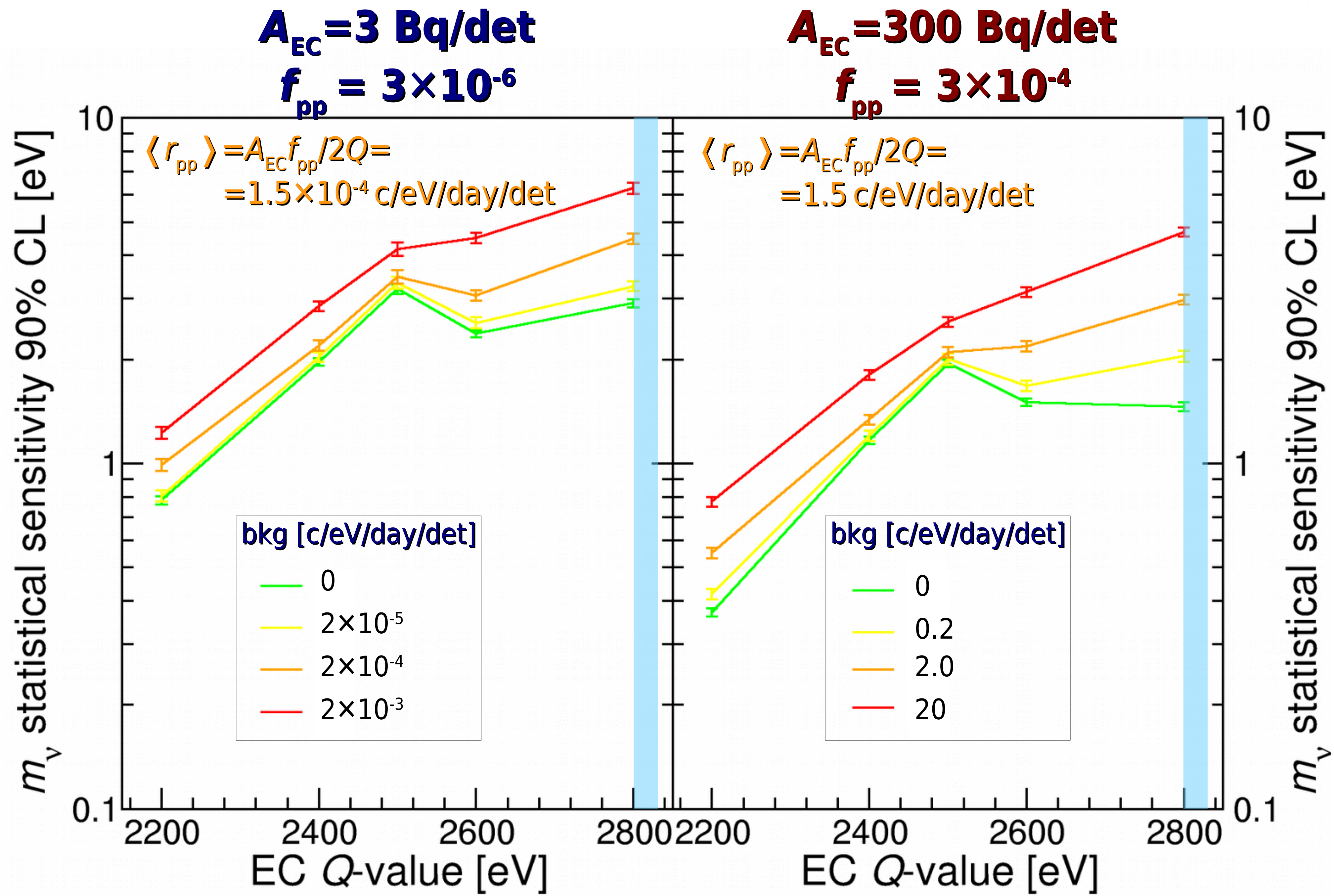
ΔE =1 eV
τ_R = 1 μs

ΔE =3 eV
τ_R = 3 μs

Q = 2.8 keV

high activity → robustness against (flat) background
A_{EC}=300 Bq → *bkg*<≈0.1 counts/eV/day/det

Effect of background on sensitivity



Low energy background

- **environmental γ radiation**
- **γ, X and β from close surroundings**
- **cosmic rays**
  - ▷ GEANT4 simulation for CR at sea level (only **muons**)
  - ▷ **Au pixel 200×200×2 μm³ → *bkg* ≈ 5×10⁻⁵ c/eV/day/det (0 - 4 keV)**

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

MIBETA experiment: 300×300×150 μm³ $AgReO_4$ crystals at **sea level**
***bkg*(2-5keV)≈1.5×10⁻⁴ c/eV/day/det**

- **internal radionuclides**
  - ▷ **^{166m}Ho** (β⁻, *Q* = 1.8 MeV, $\tau_{½}$ = 1200 y, produced along with ^{163}Ho)
  - ▷ **Au pixel 200×200×2 μm³**
    GEANT4 simulation → ***bkg* ≈ 0.5 c/eV/day/det/Bq(^{166m}Ho)**
  - ▷ *A*(^{163}Ho) = 300Bq/det (↔ ≈6.5×10¹³ 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

^{163}Ho production by neutron activation

^{162}Er (n,γ) ^{163}Er	$\sigma_{thermal} \approx 20$b
^{163}Er → ^{163}Ho + ν_e	$\tau_{1/2}^{EC} \approx 75$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, $\tau_{1/2}$=1200y) → A(^{163}Ho)/A(^{166m}Ho)=100~1000
- chemical pre-purification and post-separation at **PSI** (Villigen, CH)

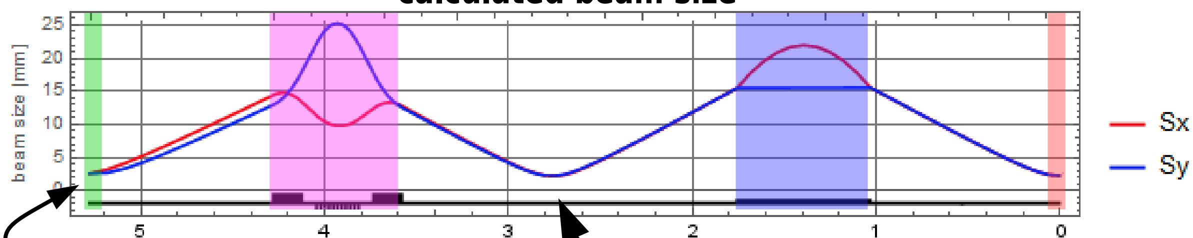
HOLMES source production

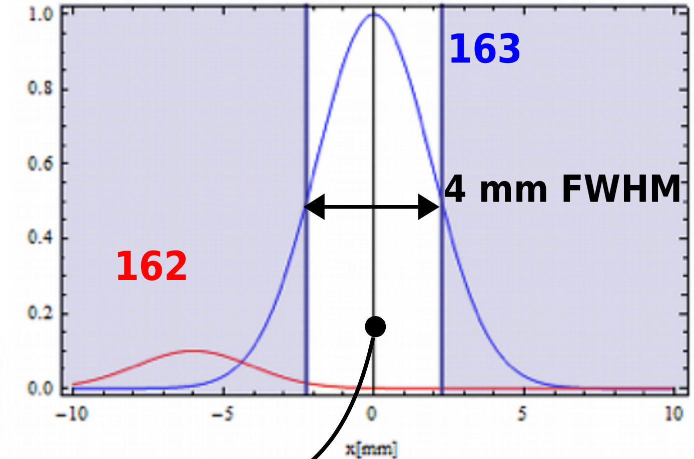
- **enriched Er_2O_3** samples irradiated at **ILL** and pre-/post-processed at **PSI**
  - 25 mg irradiated for 55 days (2014) → ***A*(^{163}Ho) ≈ 5 MBq** (*A*(^{166m}Ho)≈10kBq)
  - 150 mg irradiated for 50 days (2015) → ***A*(^{163}Ho) ≈ 38 MBq** (*A*(^{166m}Ho)≈37kBq)
- **Ho radiochemical separation** 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** early in 2017
  - ***A*(^{163}Ho)$_{theo}$ ≈ 130 MBq** (enough for R&D and 500 pixels) (*A*(^{166m}Ho)≈180kBq)

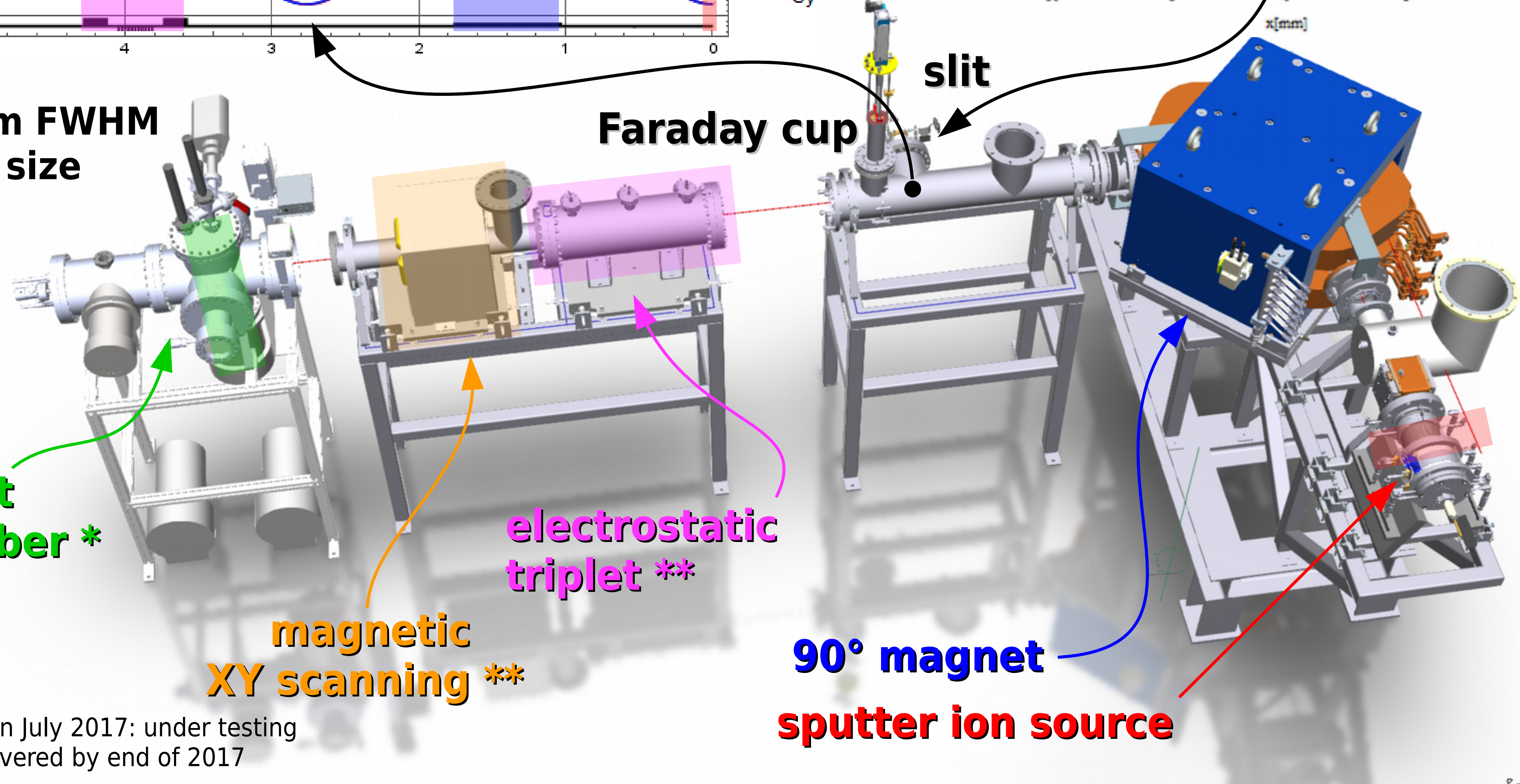
HOLMES mass separation and ion implantation

- extraction voltage 30-50 kV → 10-100 nm implant depth
- **^{163}Ho / ^{166m}Ho** separation better than 10^5
- **ion source**, **magnet** and **slit** delivered end **2016**

calculated beam size

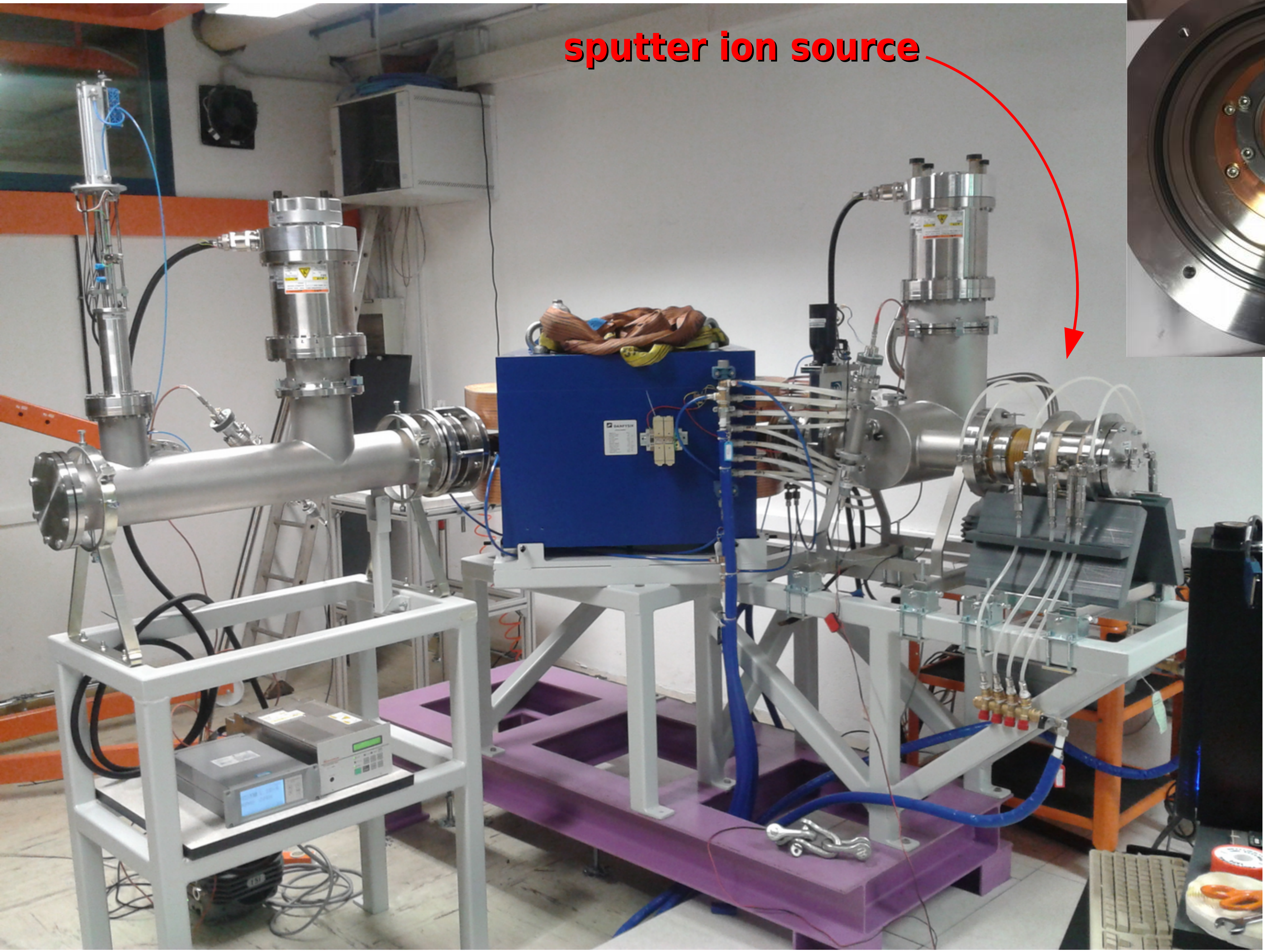


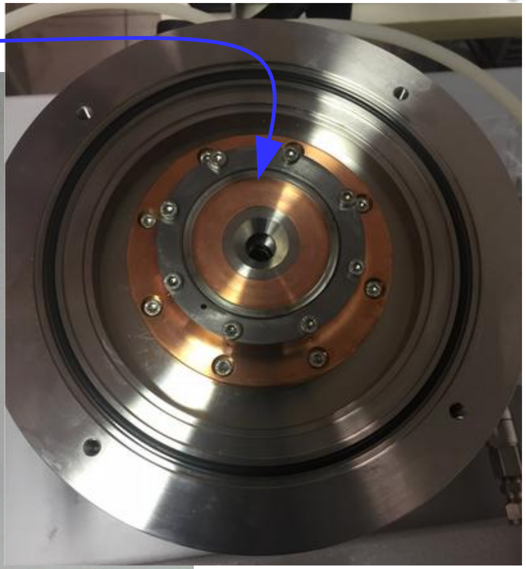




* delivered in July 2017: under testing
** to be delivered by end of 2017

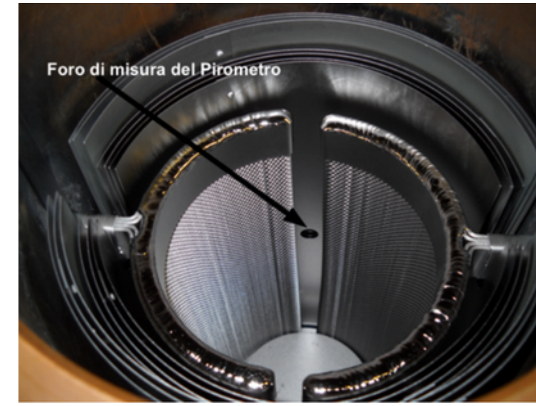
HOLMES ion implantation system testing

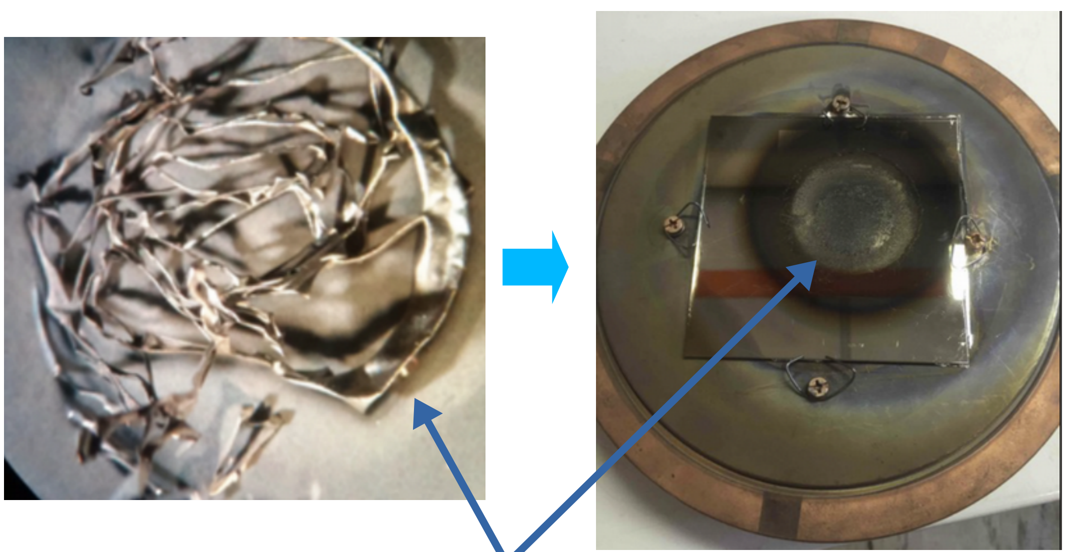




Ion source sputter target production / 1

- **metallic holmium sputter target** for implanter ion source
- enriched $Er_2O_3 \rightarrow Ho_2O_3$
- thermoreduction/distillation in furnace
  - **Ho_2O_3+2Y(*met*) → 2Ho(*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)

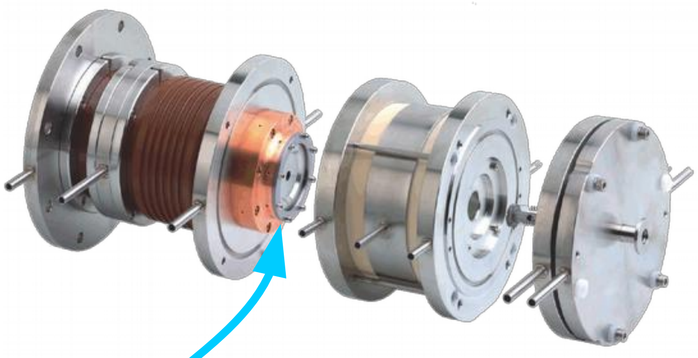




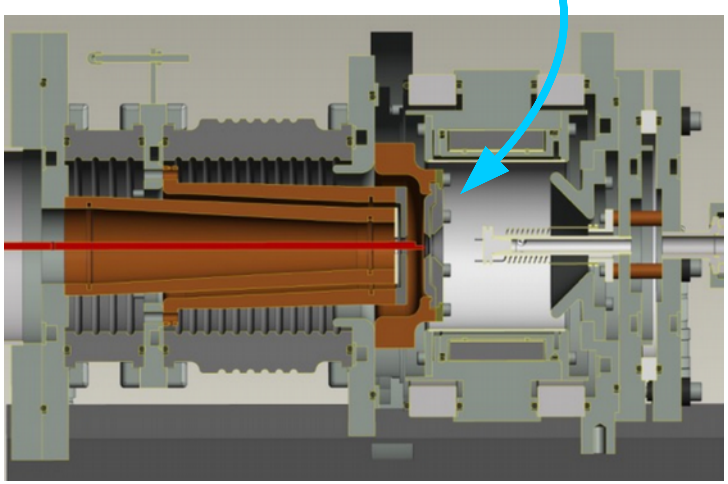
evaportated metallic holmium

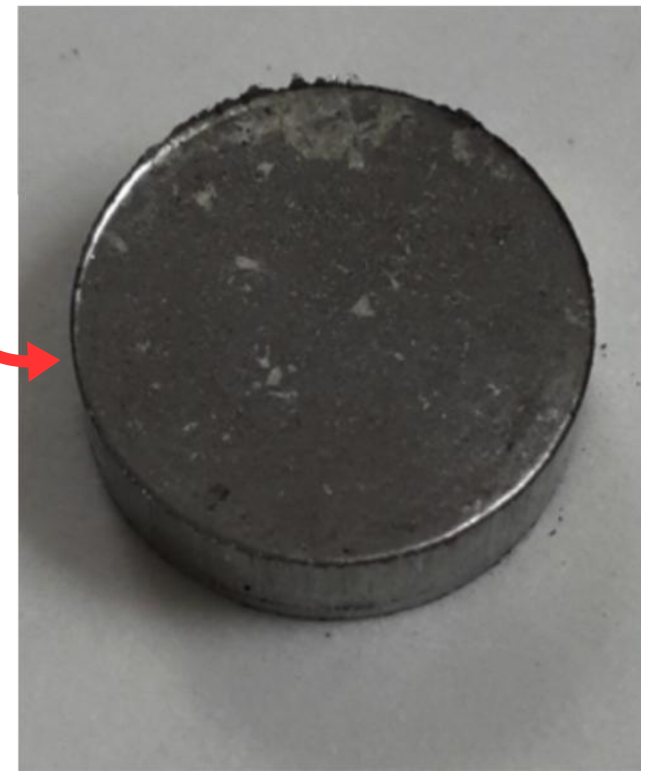
Ion source sputter target production / 2

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

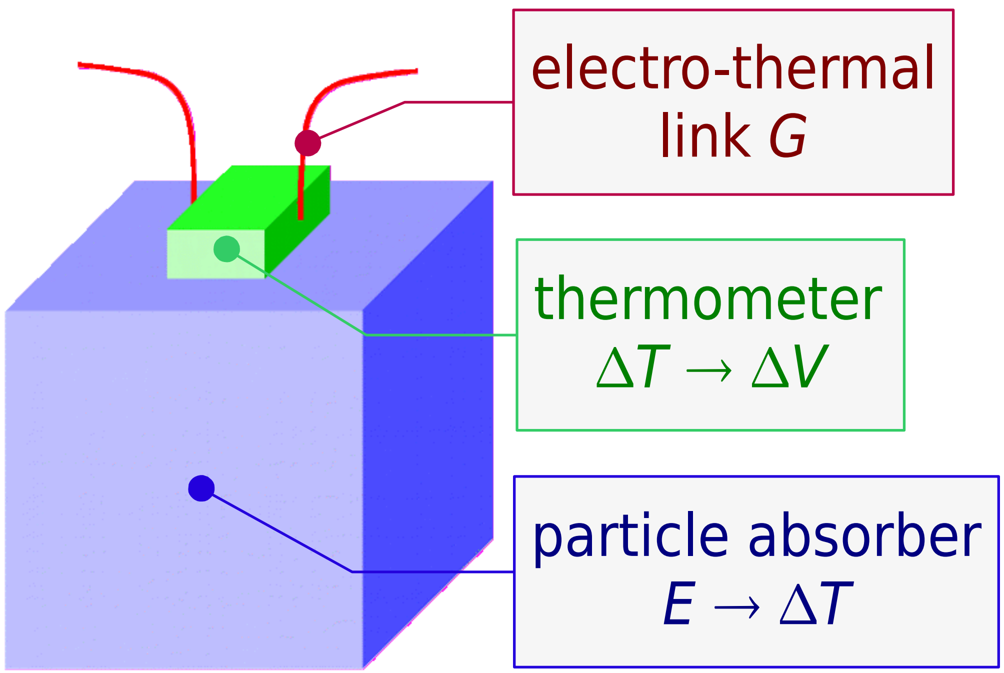


target





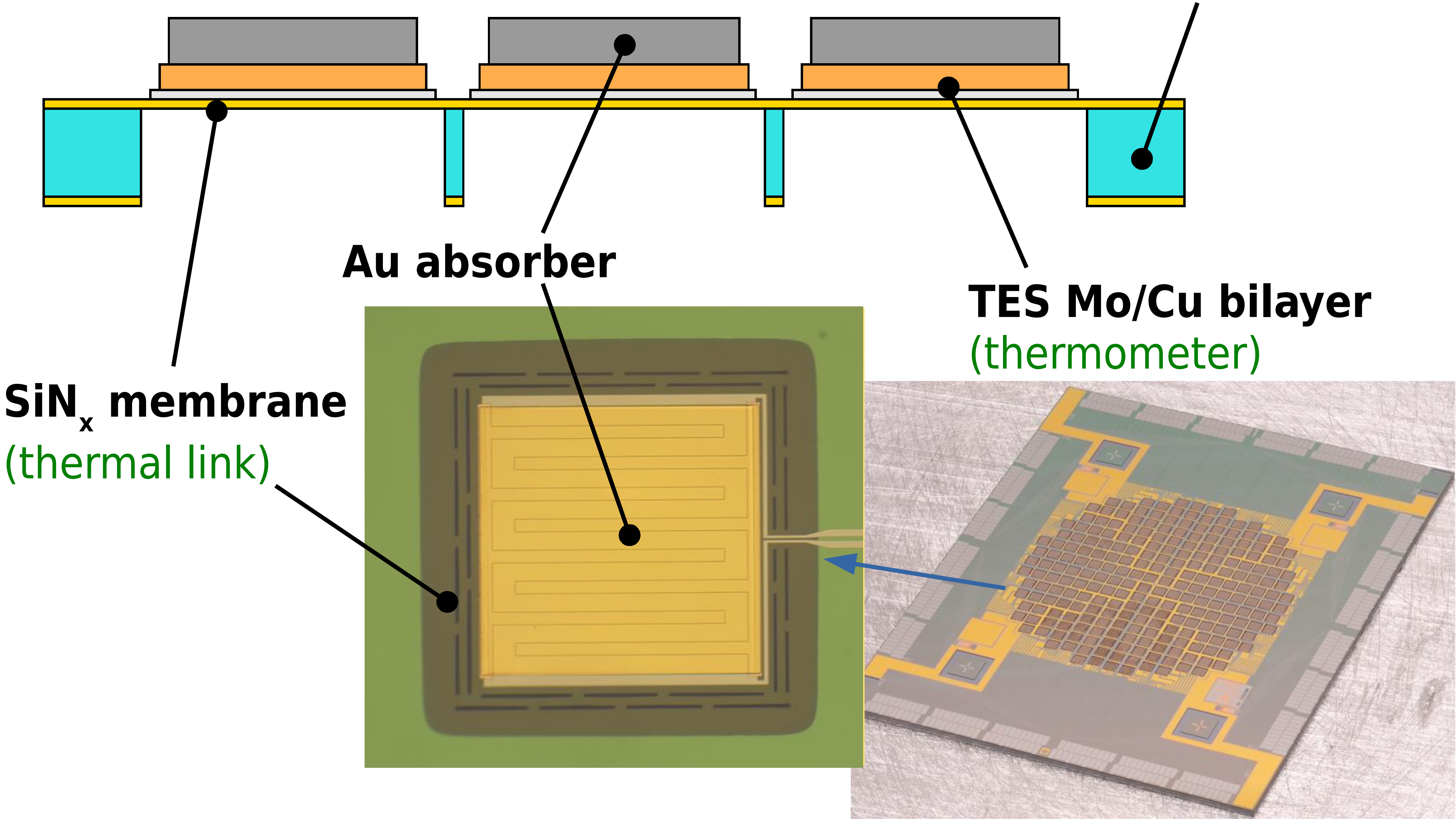
Low temperature detectors as calorimeters



- (quasi-)equilibrium thermal detector
- complete energy *thermalization*
  - **calorimetry**
- $\Delta T = E/C$ (C thermal capacity)
  - low C
    - low T (i.e. $T \ll 1$K)
    - dielectrics, superconductors
- Pros and cons
  - ▲ high energy resolution
  - ▲ large choice of absorber materials
  - ▲ true calorimeters
  - ▼ only energy and time informations
  - ▼ slow time response

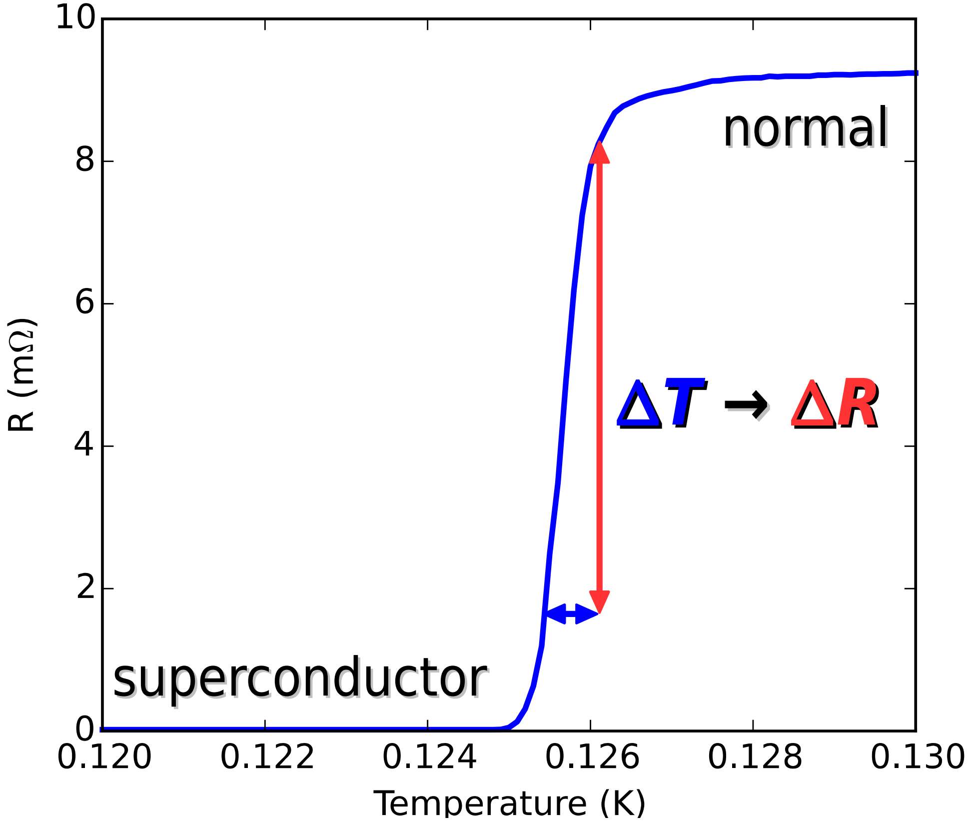
TES microcalorimeters

NIST TES arrays for X-ray spectroscopy

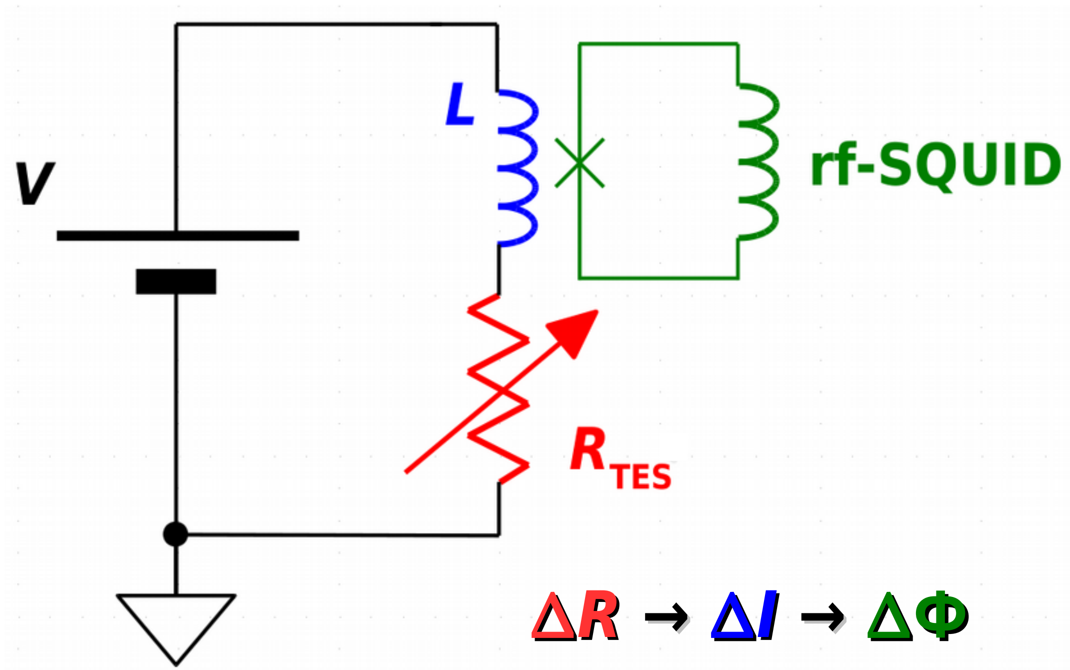


Superconducting transition edge sensors (TES)

- **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 $TdR/(RdT) \approx 100$ → **high energy resolution**
  - as thermal sensors → $\sigma_E^2 \approx \xi^2 k_B T^2 C$
- strong electron-phonon coupling → **high intrinsic speed**
- low impedance → SQUID read-out → **multiplexing for large arrays**

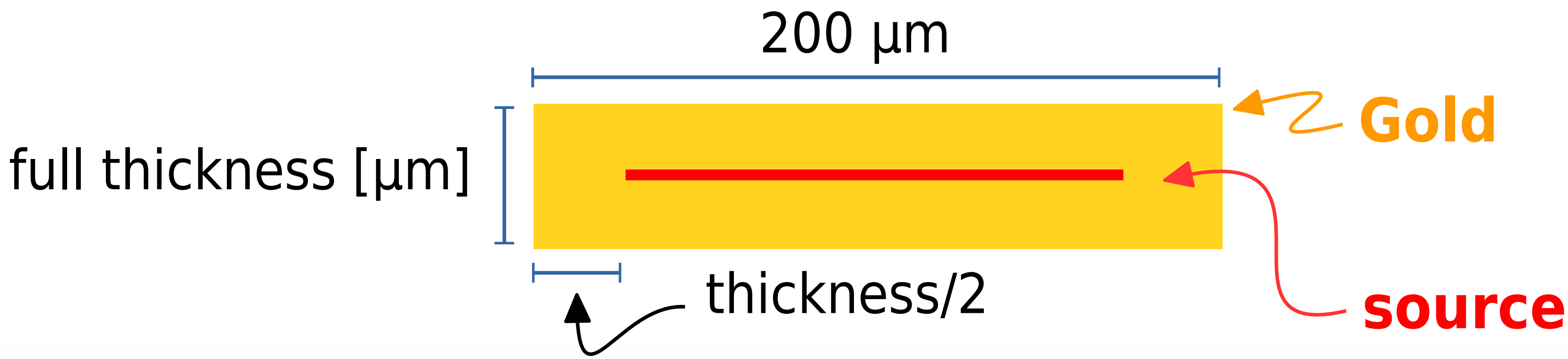


TES read-out: costant voltage bias

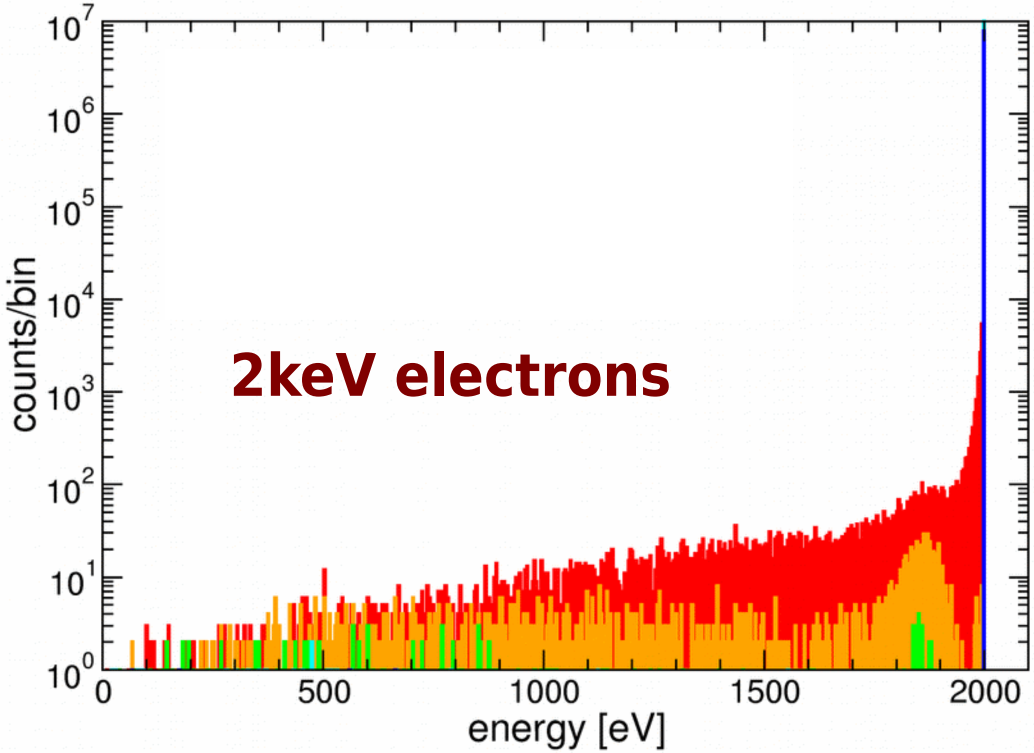


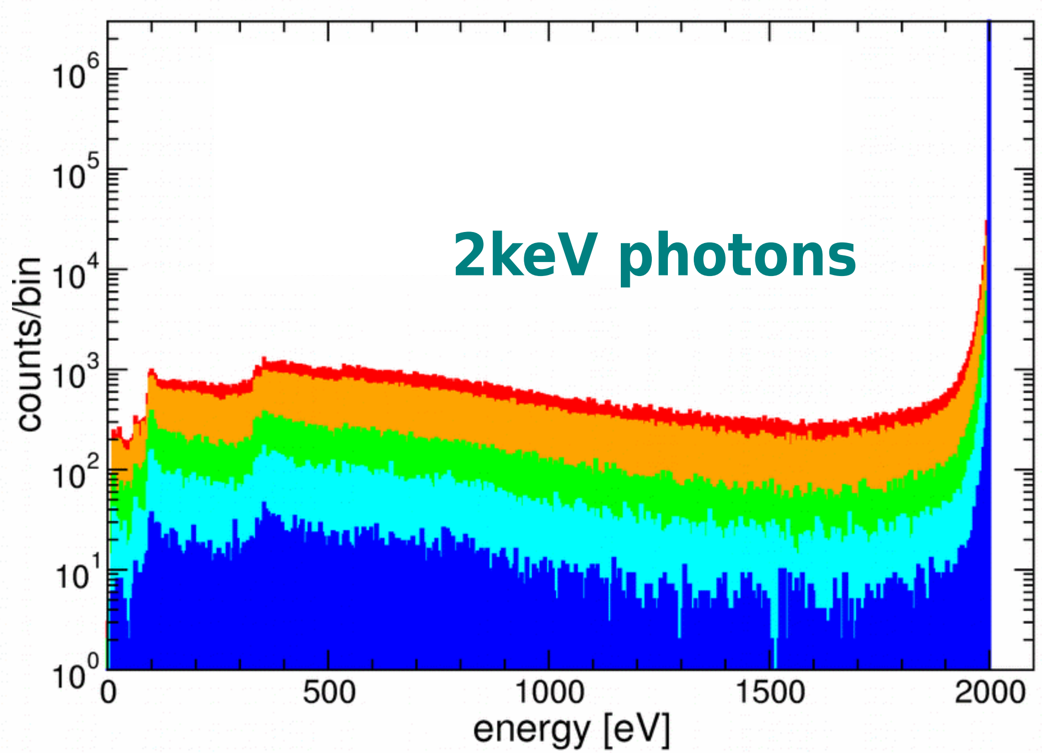
TES absorber design: stopping EC radiation / 1

Geant4 + LowEnergyEM MC simulation



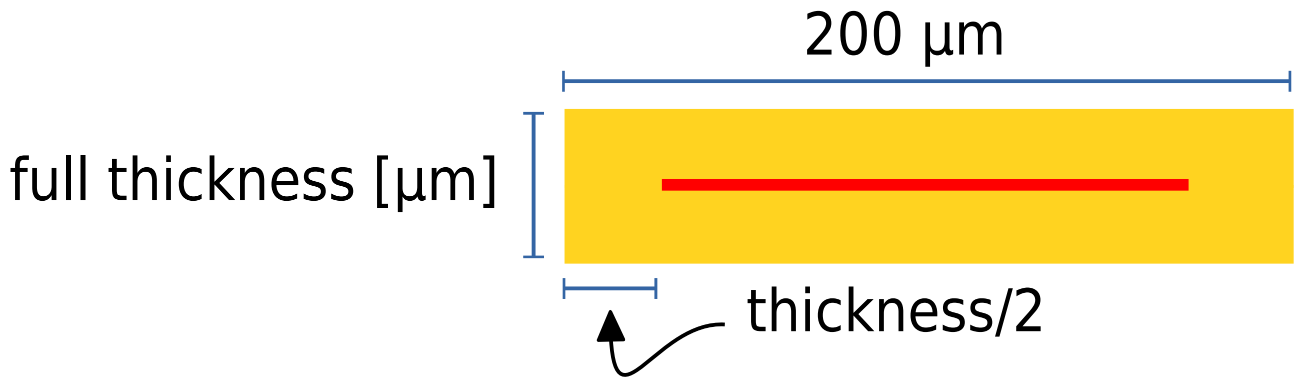
full thickness: 0.05, 0.1, 0.5, 1, 2 µm

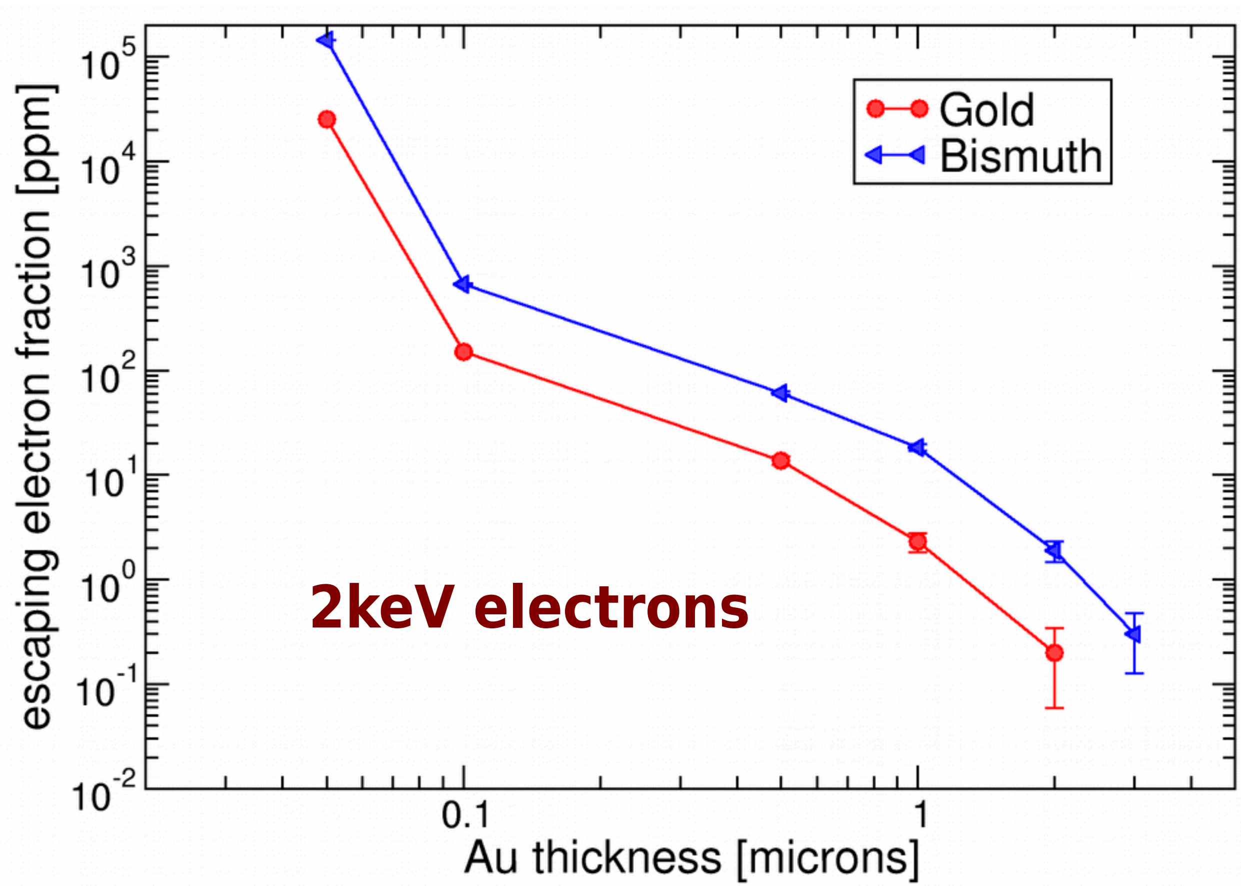




TES absorber design: stopping EC radiation / 2

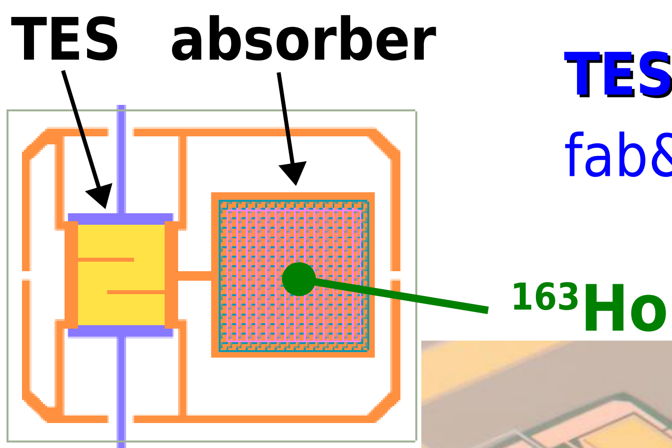
Geant4 + LowEnergyEM MC simulation





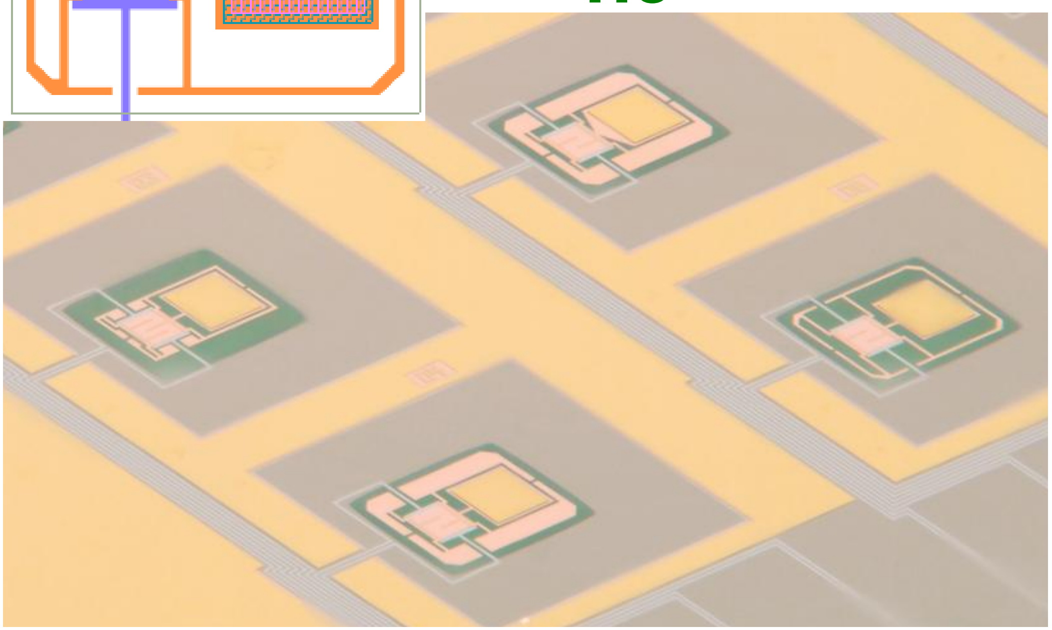
HOLMES pixel design and test

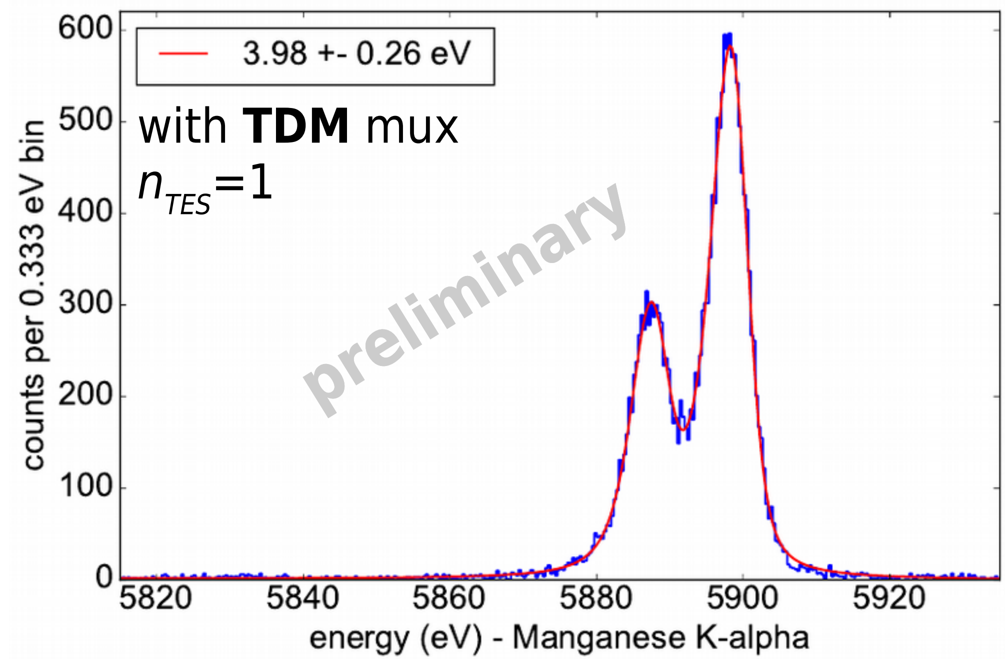
- optimize design for speed and resolution
  - ▷ **specs @3keV : $\Delta E_{FWHM} \approx 1$eV, $\tau_{rise} \approx 10\mu$s, $\tau_{decay} \approx 100\mu$s**
- **2 µm Au** thickness for *full* electron and photon absorption
  - ▷ GEANT4 simulation: 99.99998% / 99.927% full stopping for 2 keV electrons / photons
- ***side-car*** design to avoid TES proximitation and *G* engineering for τ_{decay} control



TES prototypes

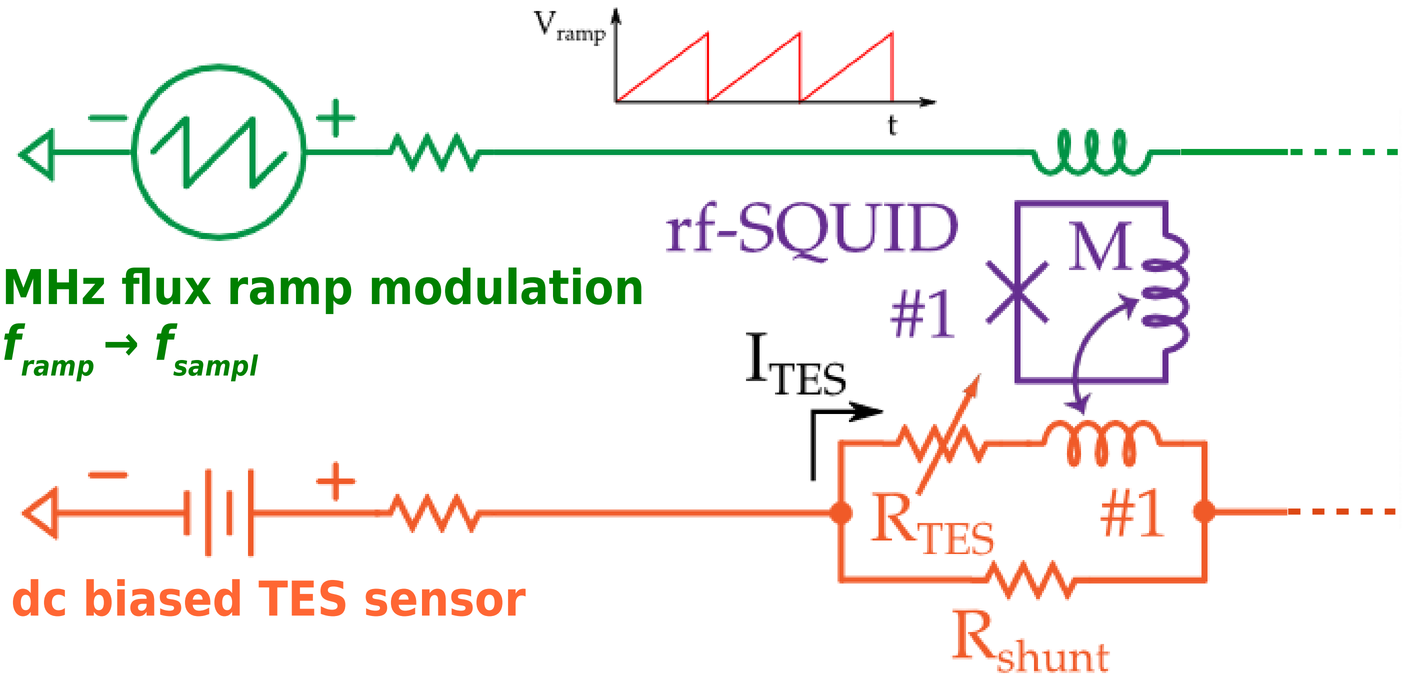
fab&test @ **NIST**





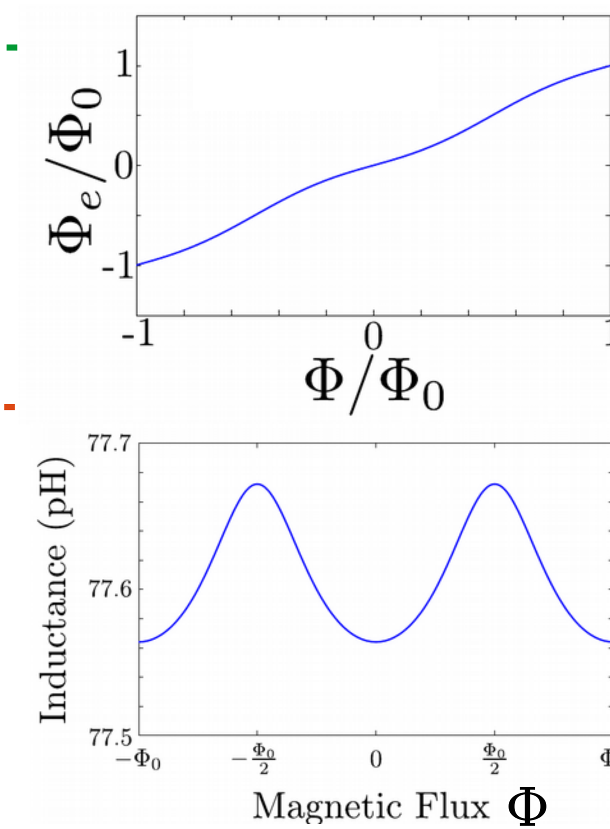
- ▷ $\Delta E_{FWHM} \lesssim$ **4 eV** @ 6 keV (→ **≈3 eV** @ Q_{EC})
- ▷ $\tau_{rise} \approx$ **6 µs** (with L=38nH → to be slowed)
- ▷ $\tau_{decay} \approx$ **130 µs** (still tunable)

HOLMES array read-out: rf-SQUID

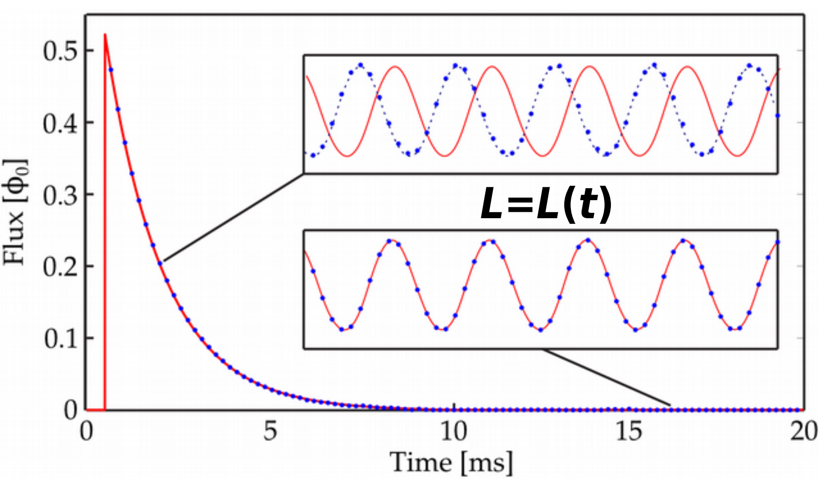


non-hysteretic rf-SQUID

Φ_e vs. Φ / L vs. Φ responses

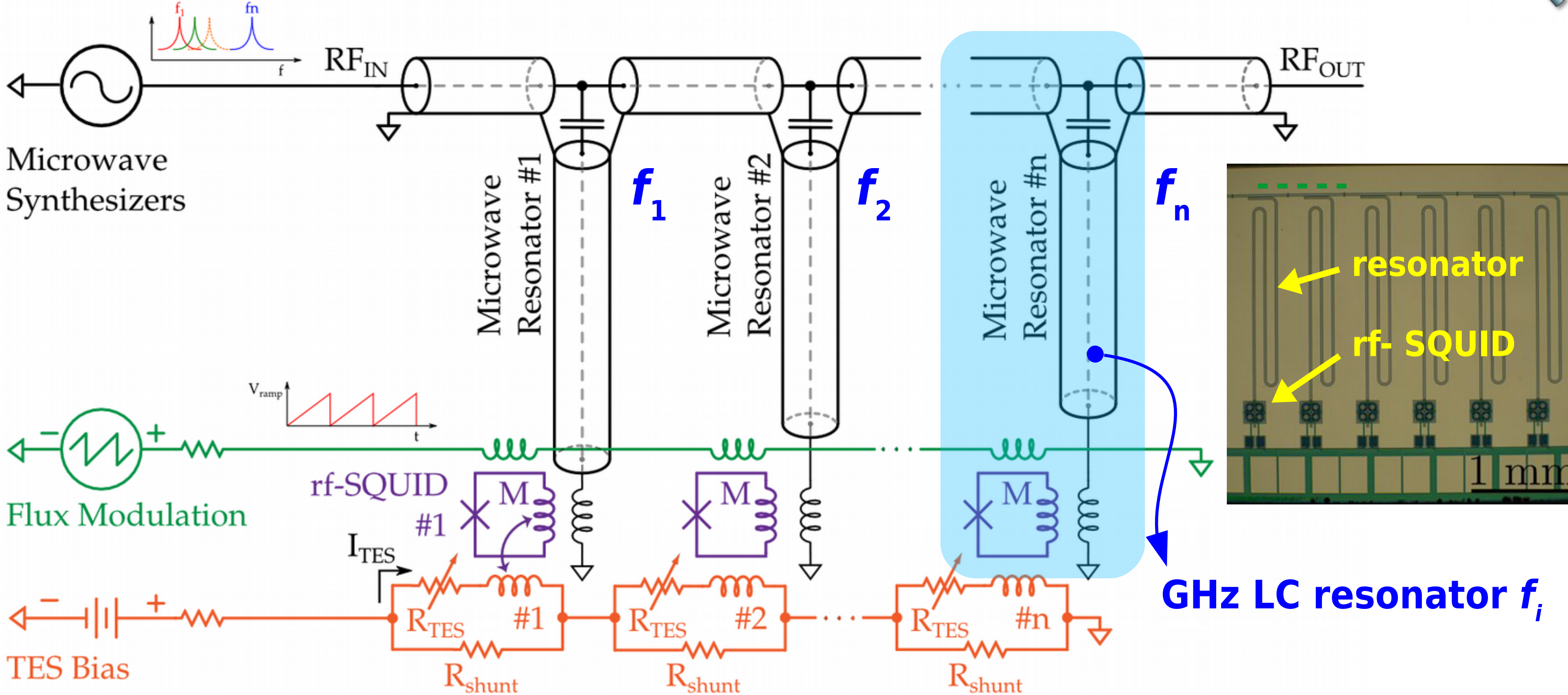


$$\Delta T \rightarrow \Delta R_{TES} \rightarrow \Delta I_{TES} \rightarrow \Delta \Phi_e \rightarrow \Delta \Phi \rightarrow \Delta L$$

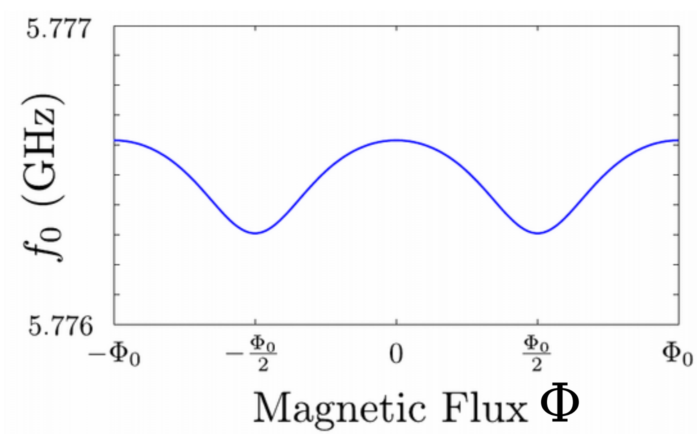


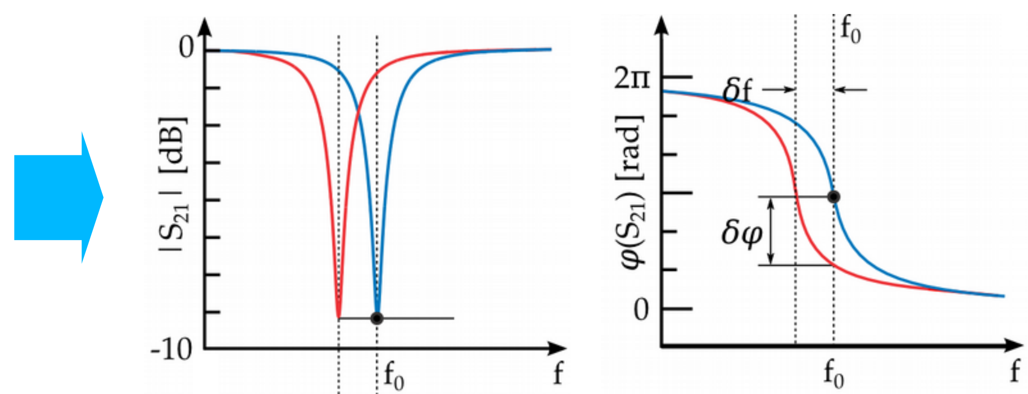
- $\Phi_e = \Phi_{TES} + \Phi_{ramp}$
- **flux-ramp modulation**
  - phase modulated MHz signal $L(t)$
  - linearized non-hysteretic rf-SQUID response
  - avoid low frequency noise sources

HOLMES array read-out: μwave mux

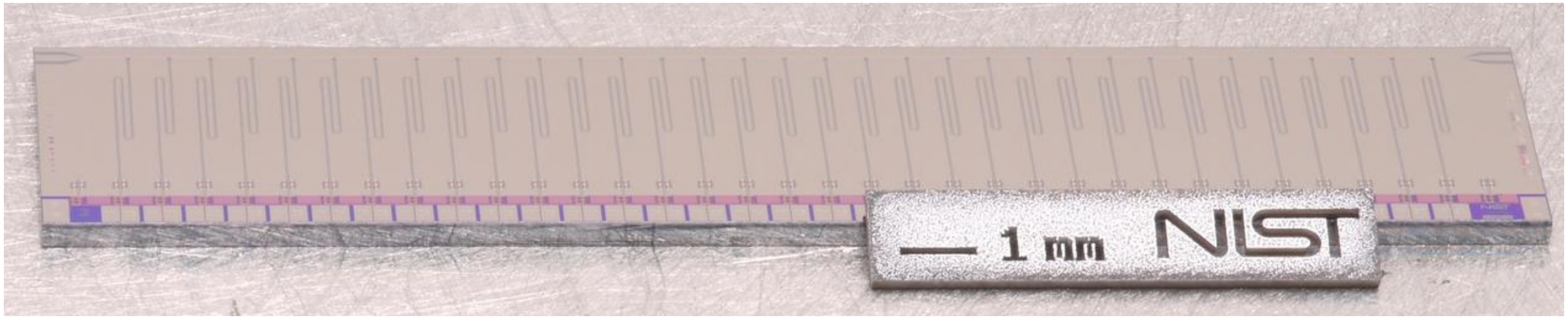


… → ΔΦ → ΔL → Δf_0 → ΔA, Δφ → ΔQ

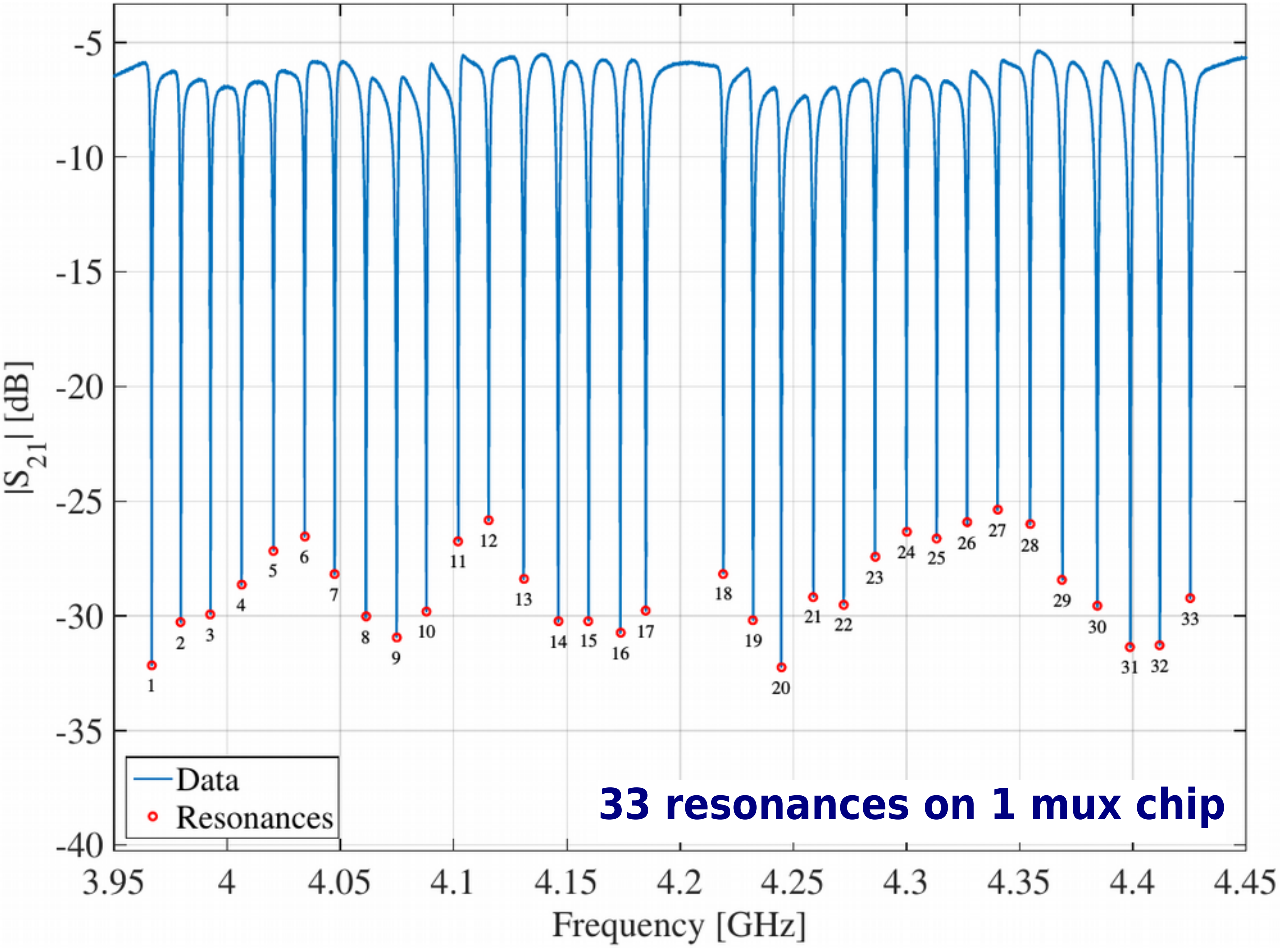




HOLMES μwave multiplexed TES read-out

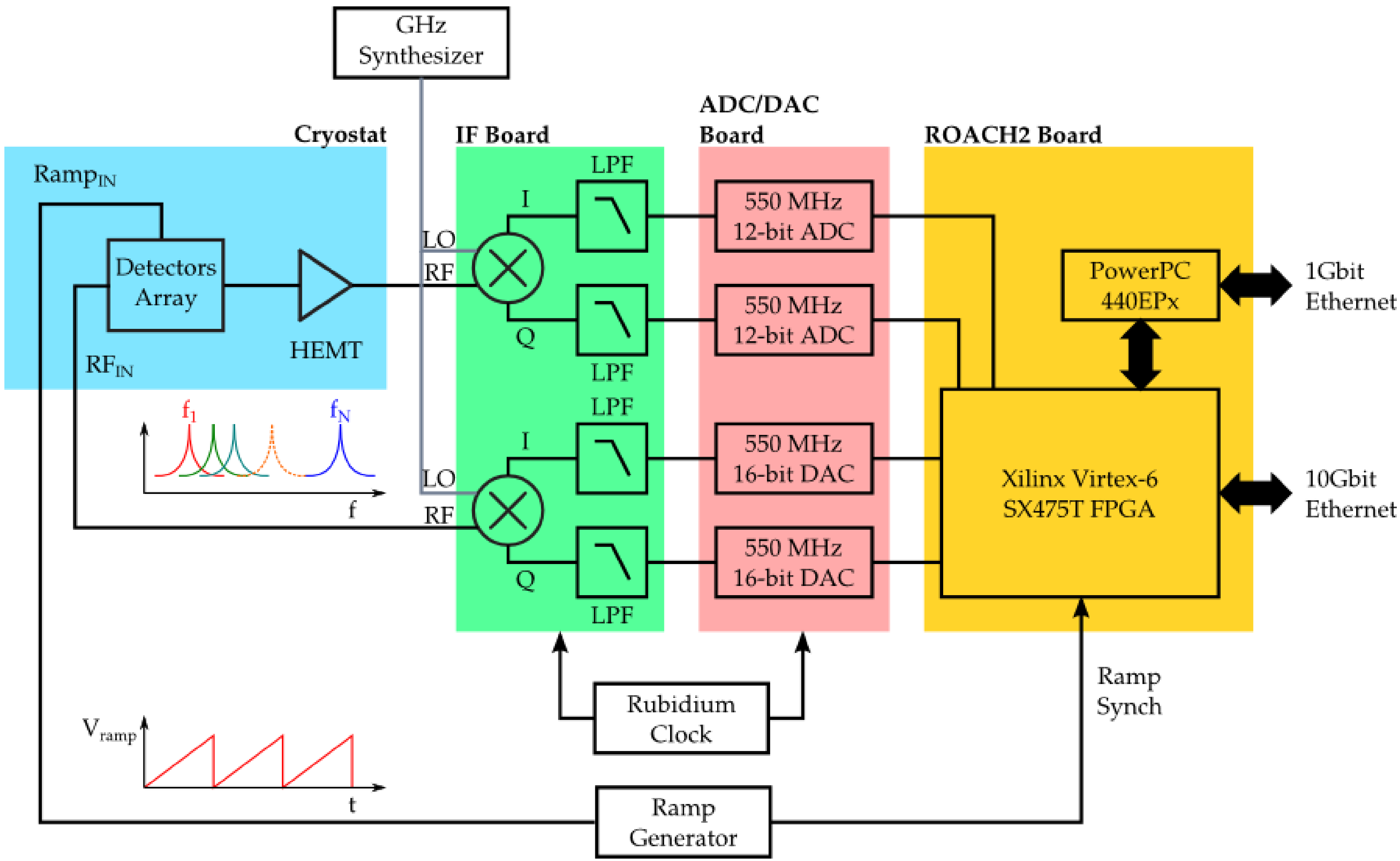


- chip **μMUX17A**
- optimized for HOLMES
- 33 resonances in 500 MHz
  - width 2 MHz
  - separation 14 MHz
- squid noise <≈2 $\mu\Phi_0/\sqrt{Hz}$



HOLMES DAQ: Software Defined Radio

- base-band tone generation (0-550MHz)
- up- / down-conversion (base-band → 4-8 GHz → base-band)
- base-band tone IQ de-modulation (0-550MHz)
- 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 ($g_f \gtrsim 10$)

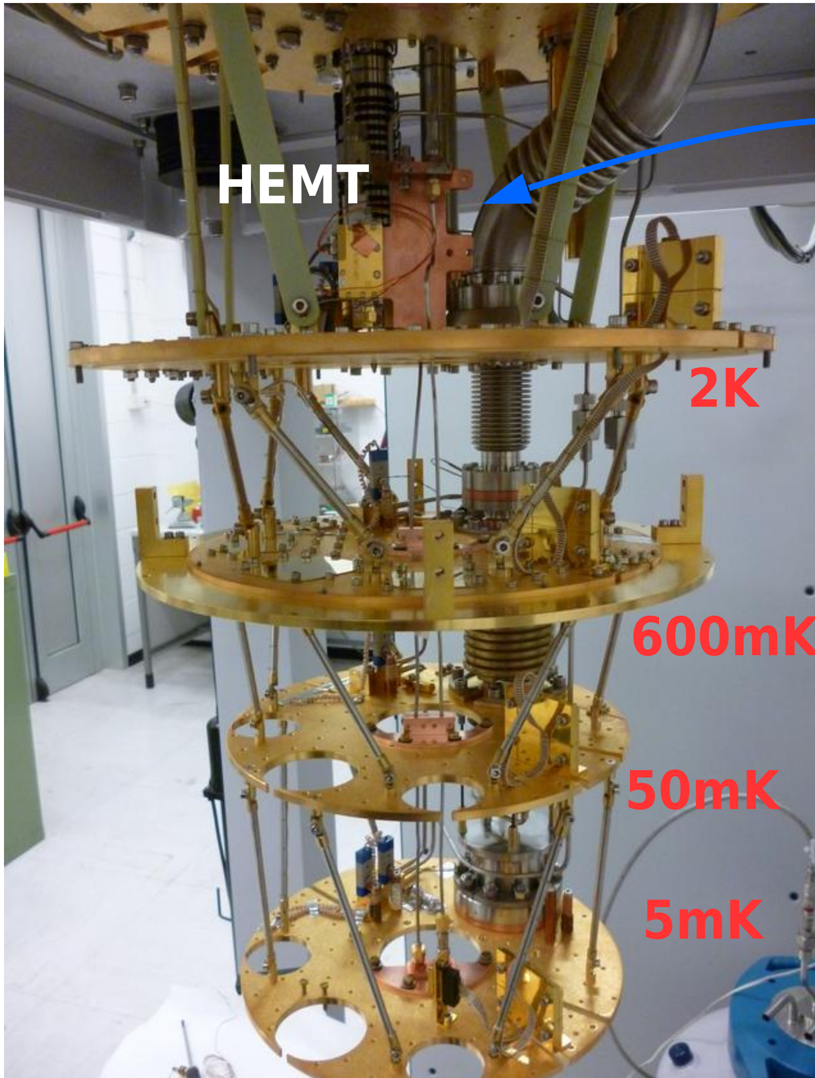
multiplexing factor

$$n_{TES} = \frac{f_{ADC}}{f_n} \leq \frac{f_{ADC}\,\tau_{rise}}{2 R_d g_f n_{\Phi_0}} \approx \frac{f_{ADC}\,\tau_{rise}}{200}$$

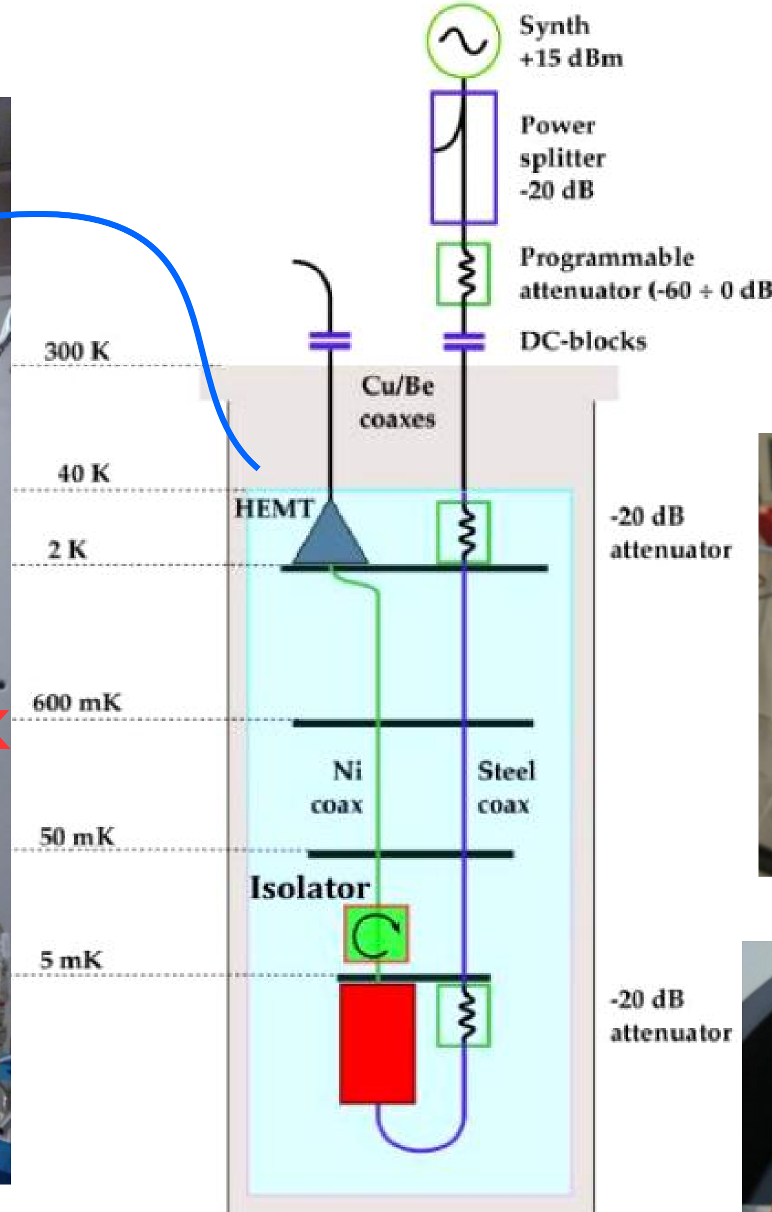
for fixed f_{ADC}**=550MHz** and n_{TES}**≈30** ↔ τ_{rise}**≈10µs** with f_{samp}**=0.5MHz**

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

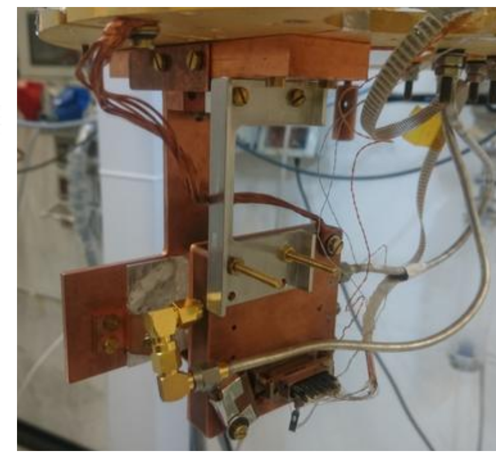
Cryogenic set-up

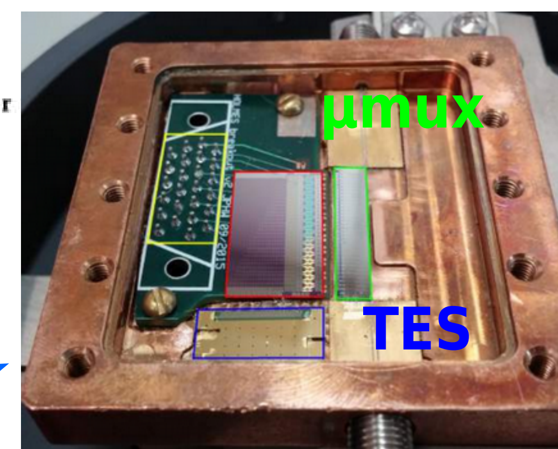


LHe-free dilution refrigerator



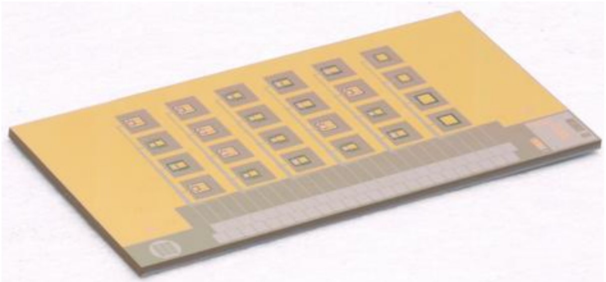
detector holder



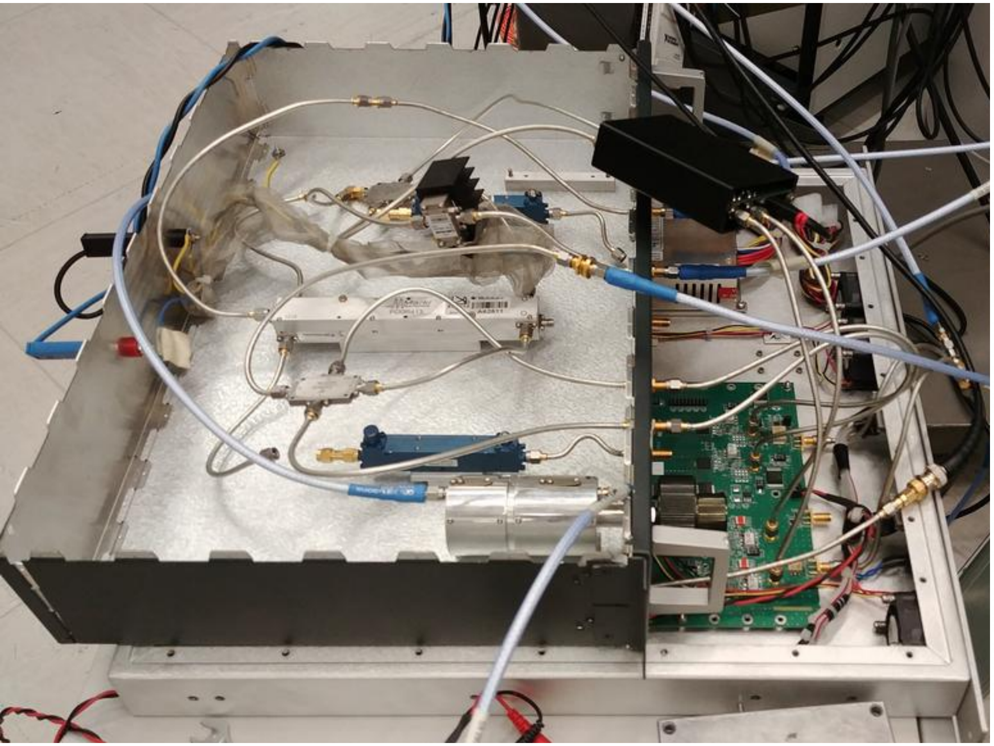


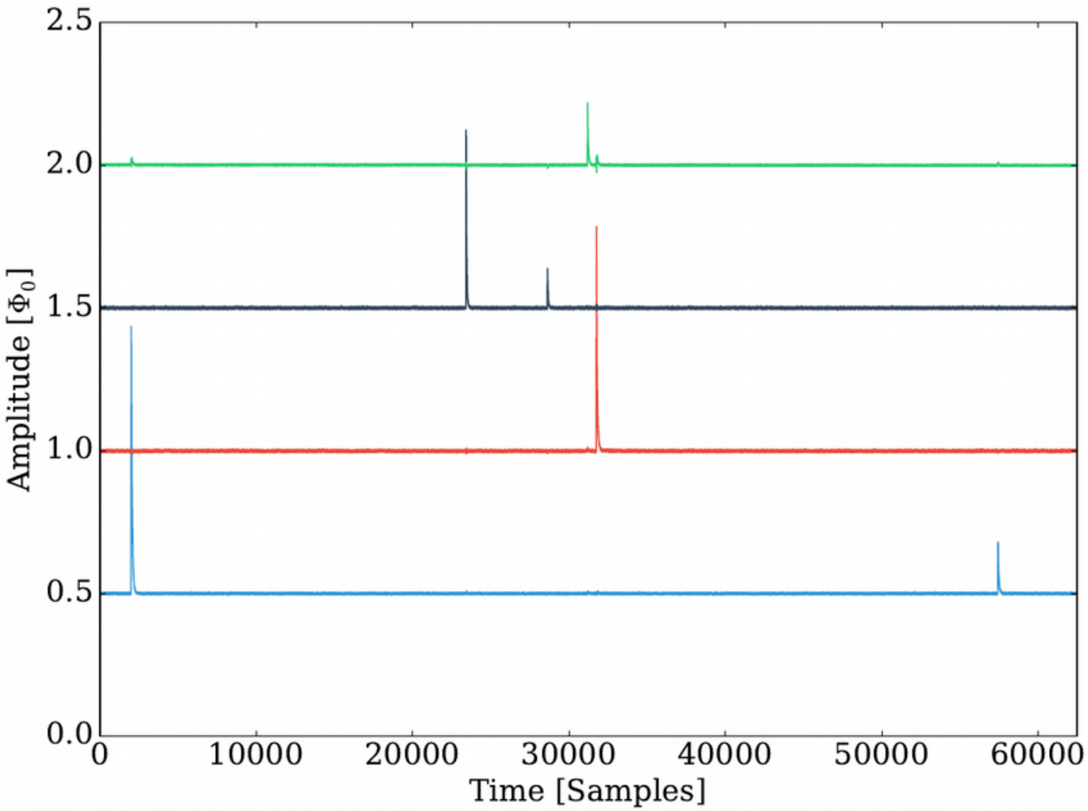
TES pixel testing with HOLMES DAQ / 1

ROACH-2 based Software Defined Radio

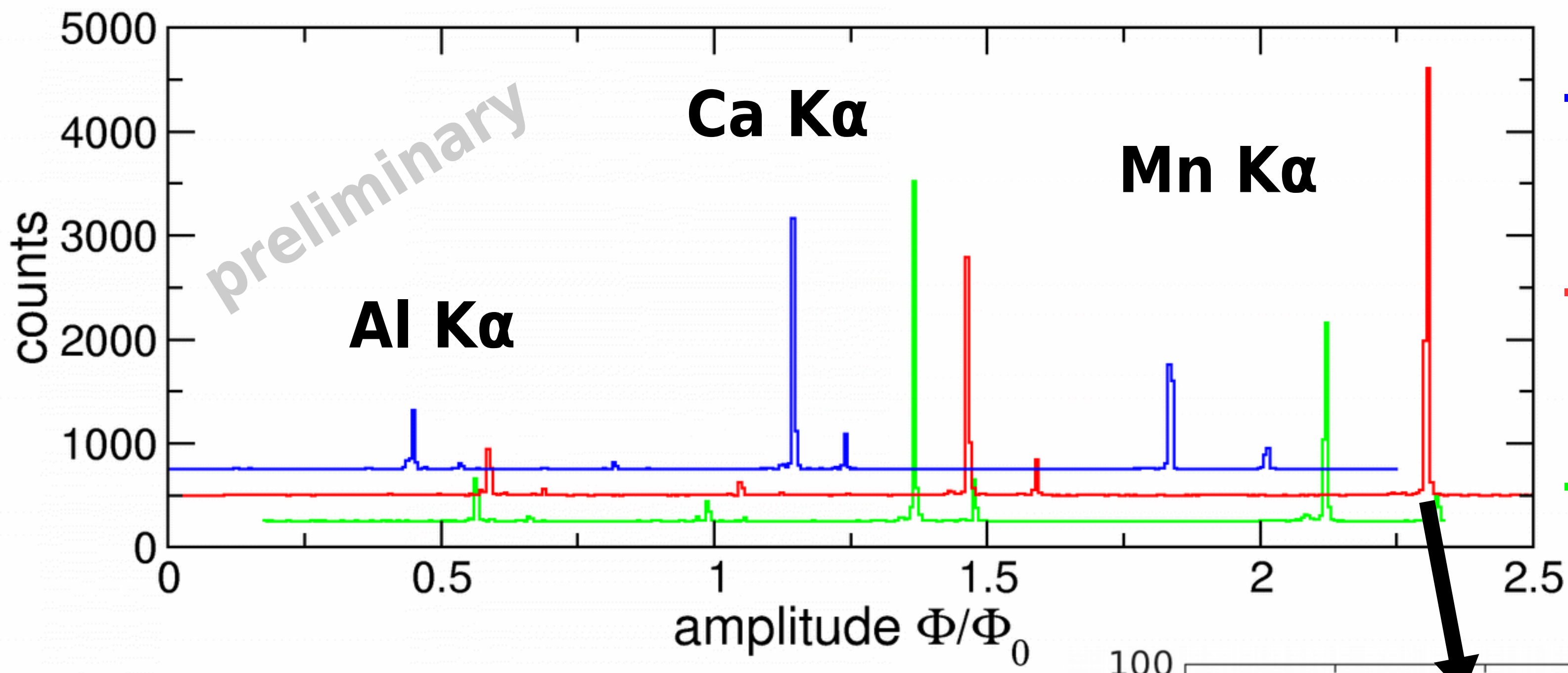


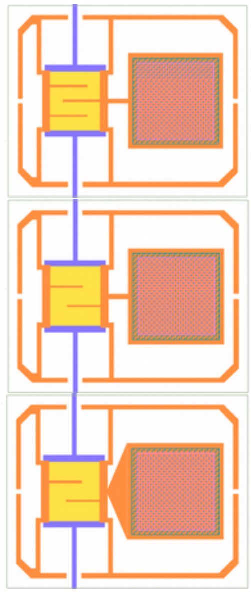
- ADC (550 MS/s 12bit) / DAC (1 GS/s 16bit)
- discrete components IF circuitry (up- / down- conversion)
- $n_{\Phi 0}$= 2 , f_{samp}= 500 kS/s
- 16 ch firmware from NIST (uses only half of available ADC bandwidth)
- 4 HOLMES prototypes acquired ↔ limited by available tone power
- goals: check algorithms,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

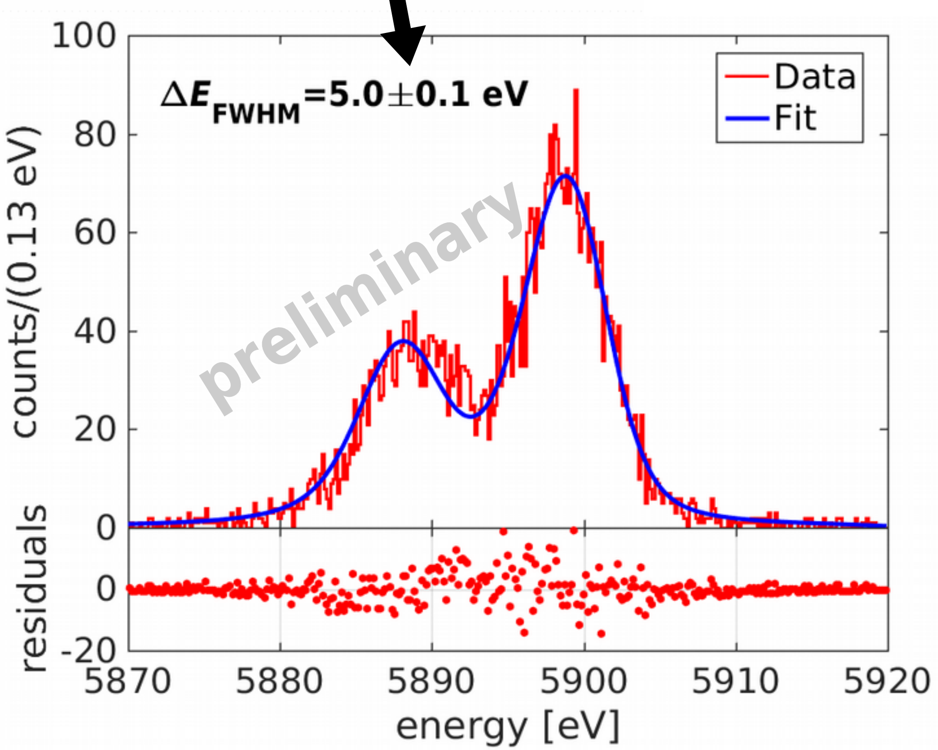




TES pixel testing with HOLMES DAQ / 2







- $\Delta E_0 \approx 4.5$ eV
- $\Delta E_{FWHM} = 5.0 \pm 0.1$ eV @ 6 keV
- $\tau_{rise} \approx 15$ μs
- $\tau_{decay} \approx 70$ μs
- slew rate ≈ 0.15 Φ_0/S @ 2.6 keV

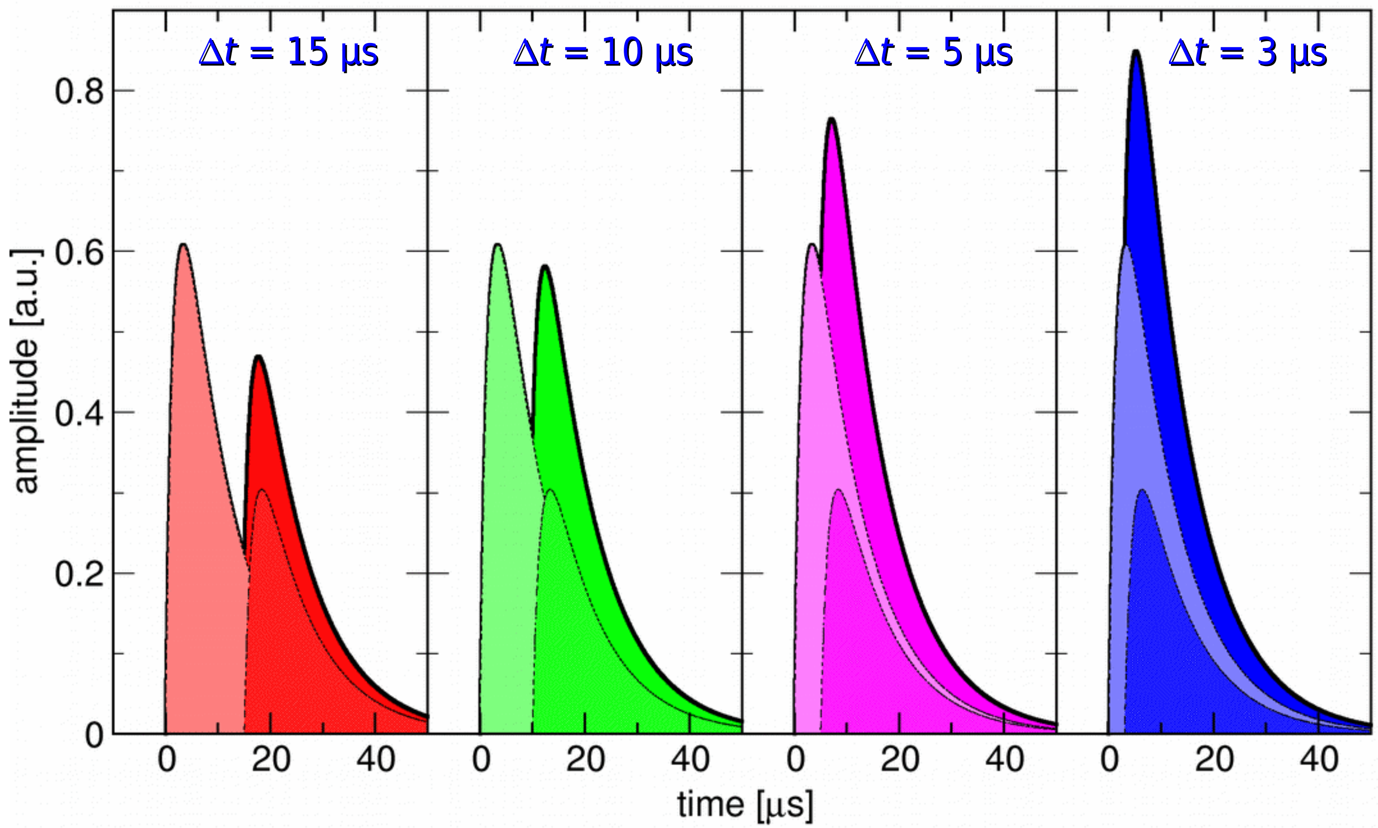
Rise time pile-up

simple pulse model

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

2 pulses with:

- τ_{rise} = 1.5 µs
- τ_{decay} = 10 µs
- A_2/A_1 = 0.5



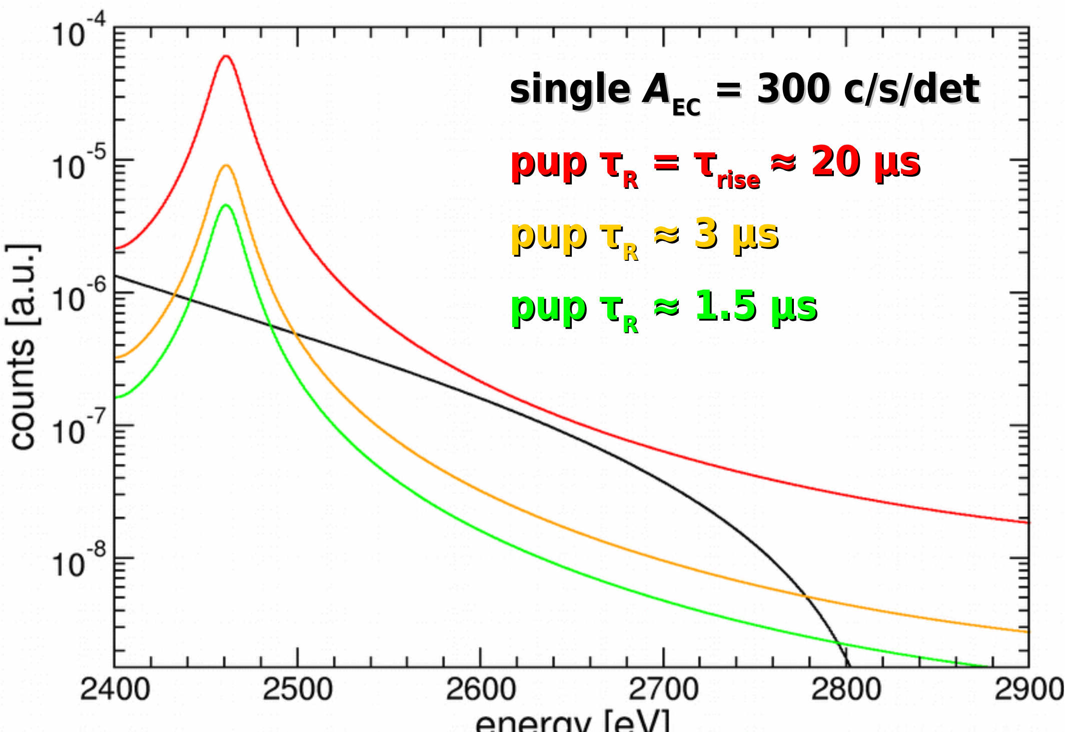
resolving time $\boldsymbol{\tau_R}$ ≈ pulse rise time $\boldsymbol{\tau_{rise}}$

Detector time resolution

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

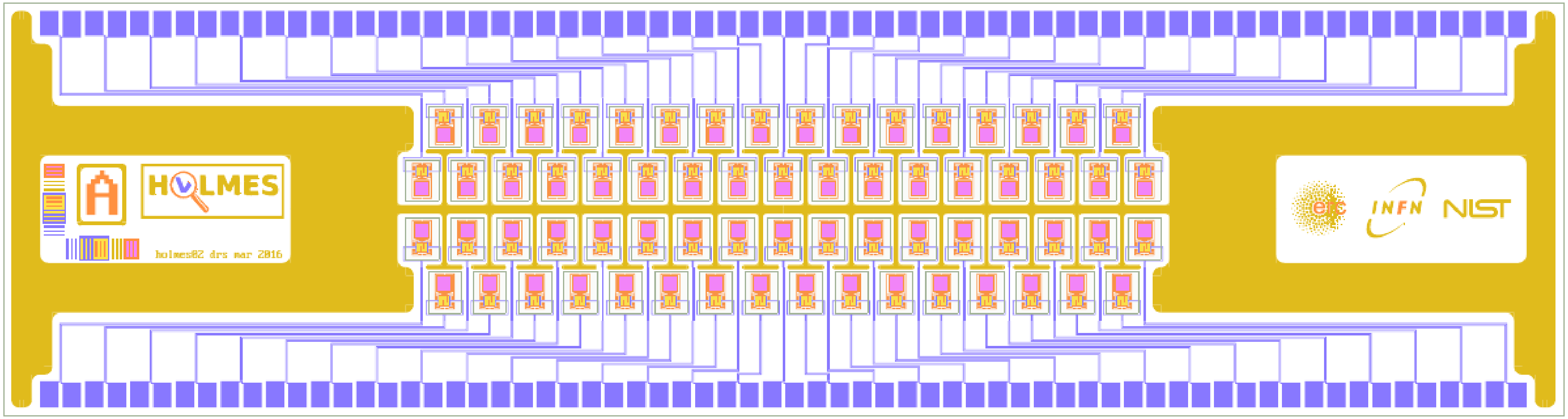
$$N_{pp}(E) = A_{EC} \int_0^\infty \tau_R(E, \epsilon) N_{EC}(\epsilon) N_{EC}(E-\epsilon) d\epsilon$$

- **Montecarlo pile-up spectrum simulations**
  - ▷ event pairs with $E_1+E_2 \in [2.4\ \mathrm{keV}, 2.9\ \mathrm{keV}]$ (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:**
  - ▷ **Wiener Filter WF** or **Singular Value Decomposition SVD**
  - ▷ for $\boldsymbol{f_{samp} = 0.5\mathrm{MHz}, \tau_{rise} \approx 20\mu s}$
    - **WF → $\boldsymbol{\tau_R \approx 3\ \mu s}$**
    - **SVD → $\boldsymbol{\tau_R \approx 1.5\ \mu s}$**



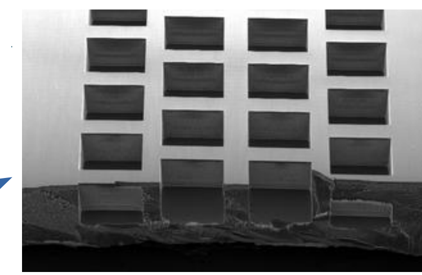
HOLMES array design and fabrication

HOLMES **4×16 sub-array** for low parasitic *L* and high implant efficiency



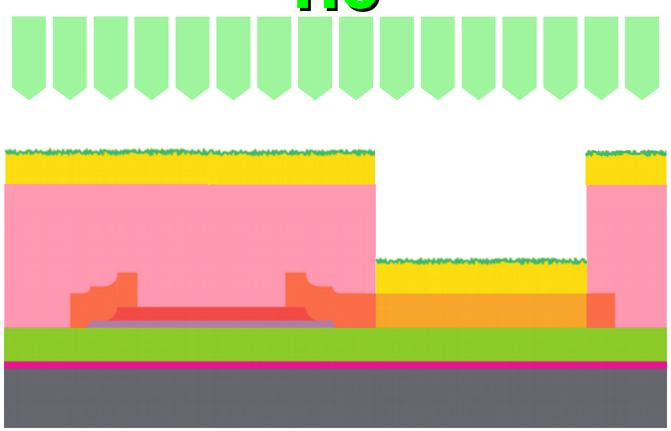
calculated ^{163}Ho beam FWHM width

- TES array fabrication after first steps at **NIST**
- ^{163}Ho implantation and final 1 µm Au layer deposition
- final micromachining step definition in progress



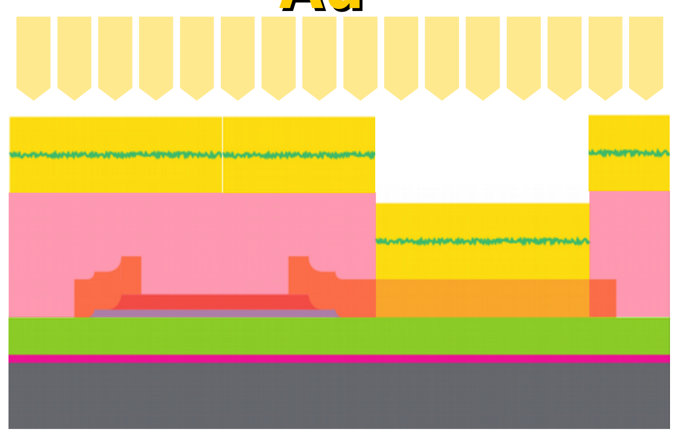
ion implantation

^{163}Ho

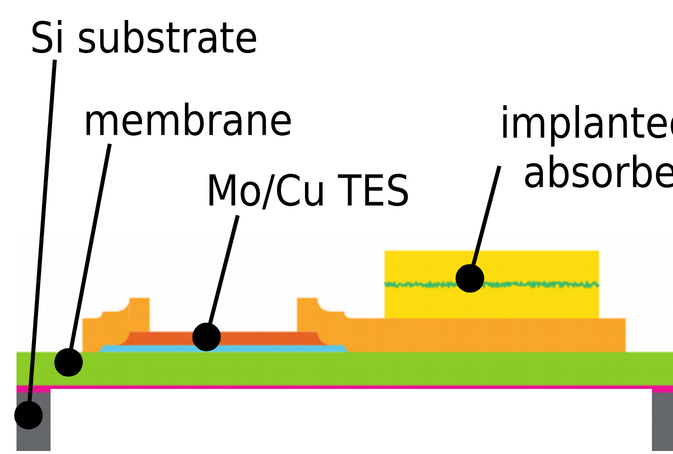


full incapsulation by sputtering

Au

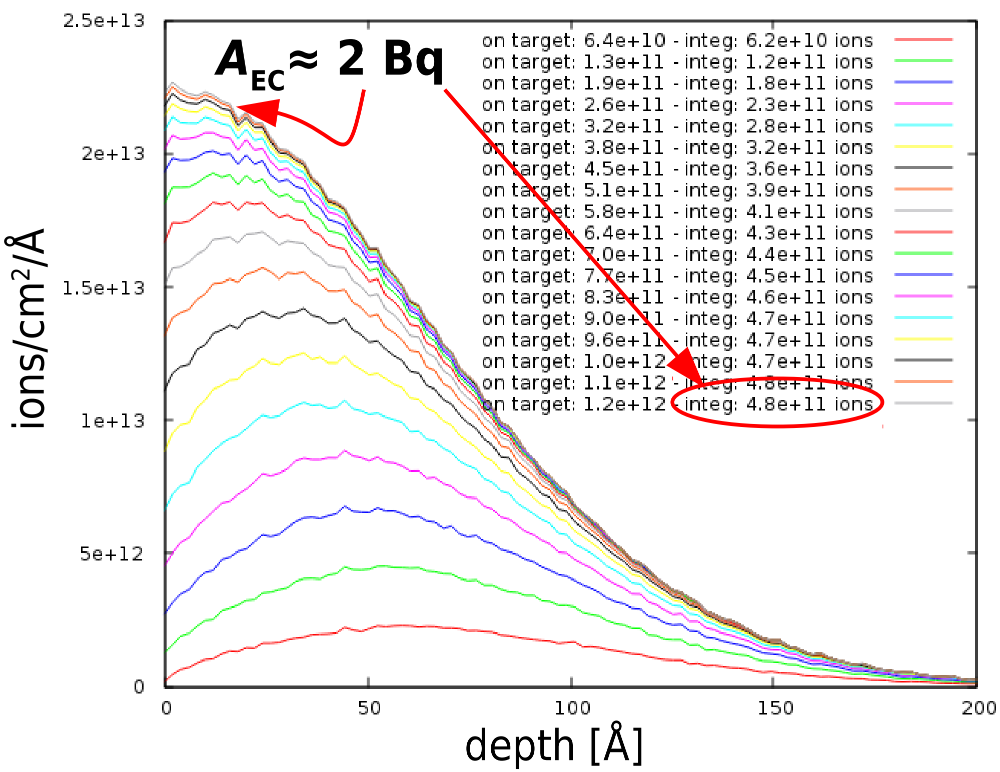


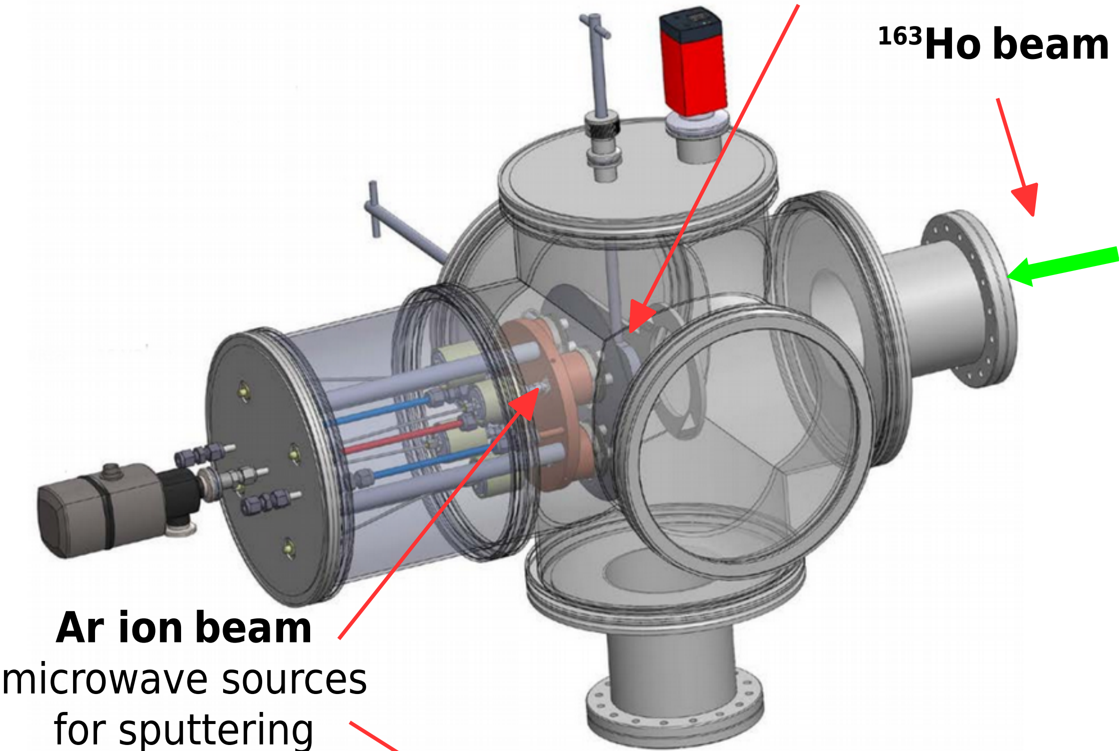
membrane release by DRIE



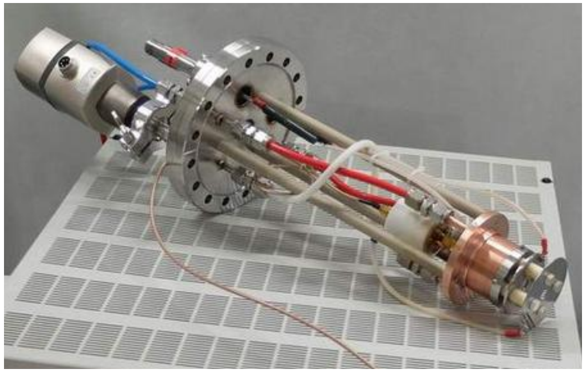
Target chamber for absorber fabrication / 1

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



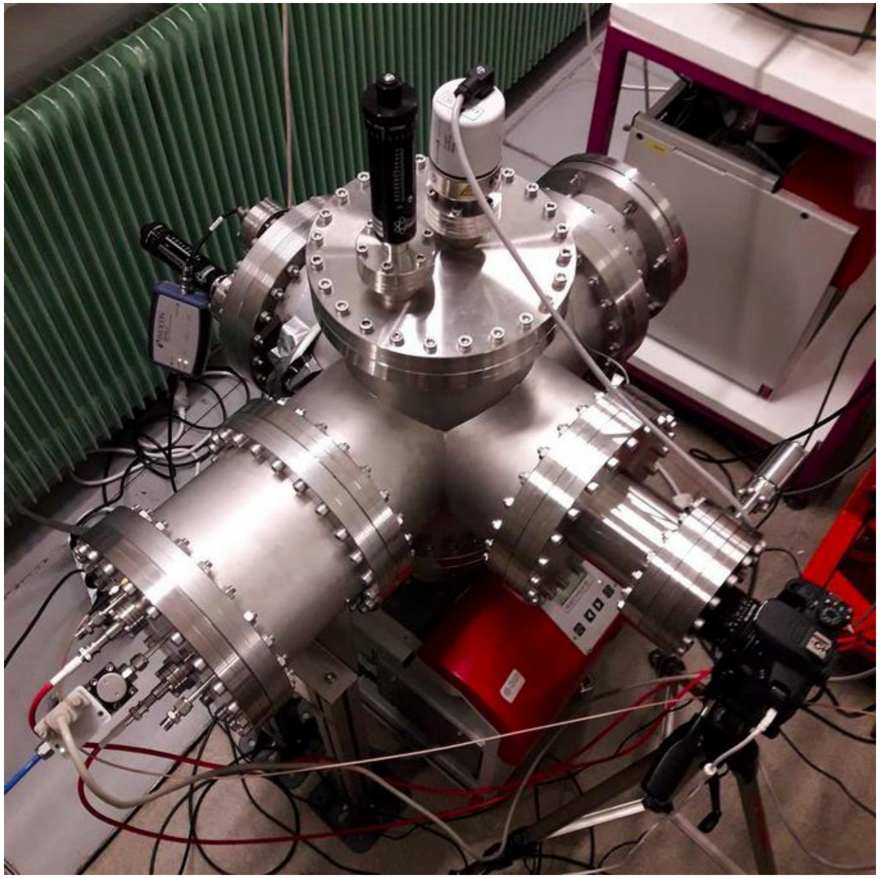


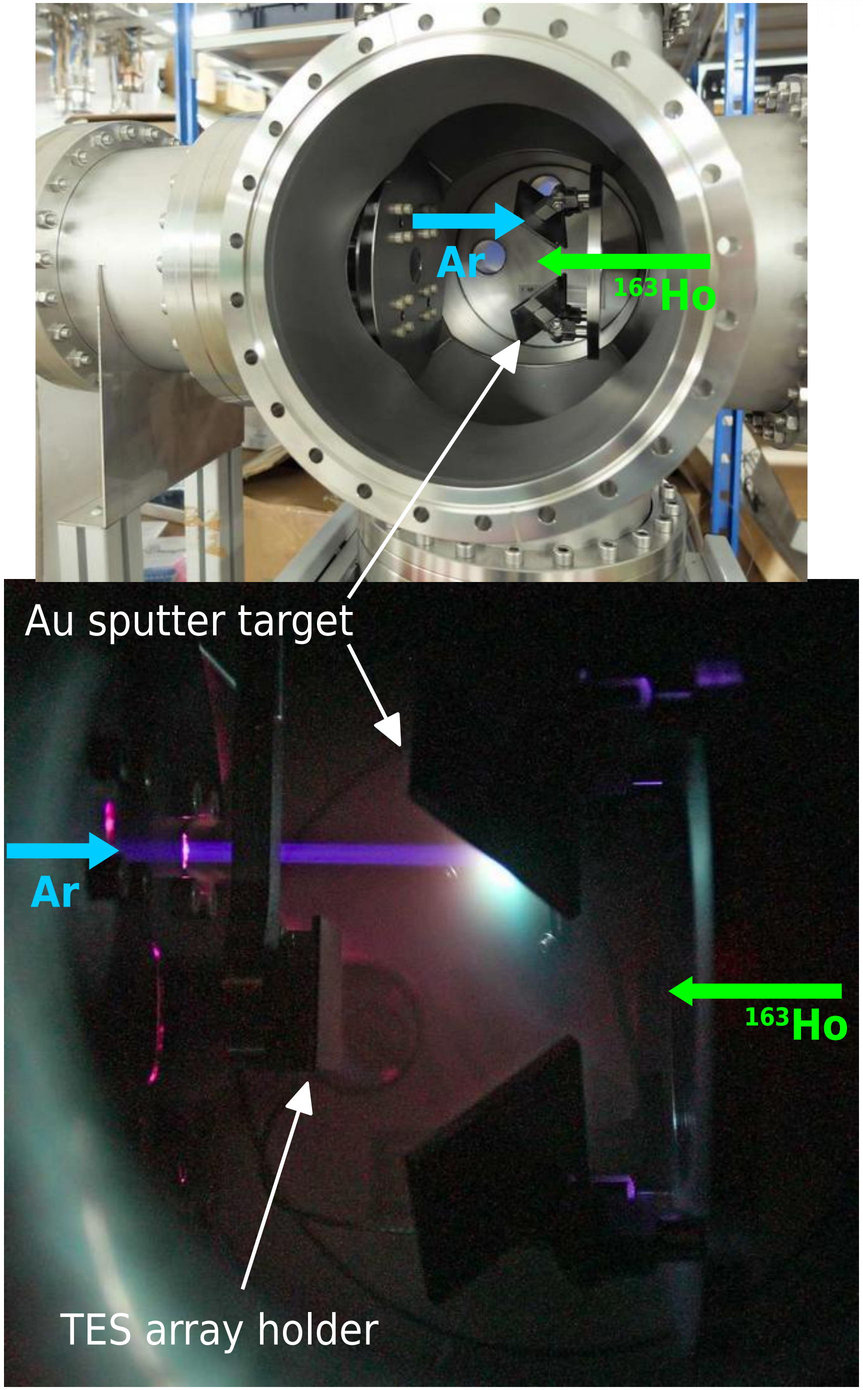
- ^{163}Ho ion beam sputters off Au from absorber
  - ^{163}Ho concentration in absorber saturates
  - compensate by Au co-evaporation
- final 1 µm Au layer in situ deposition
  - to prevent Ho oxidization



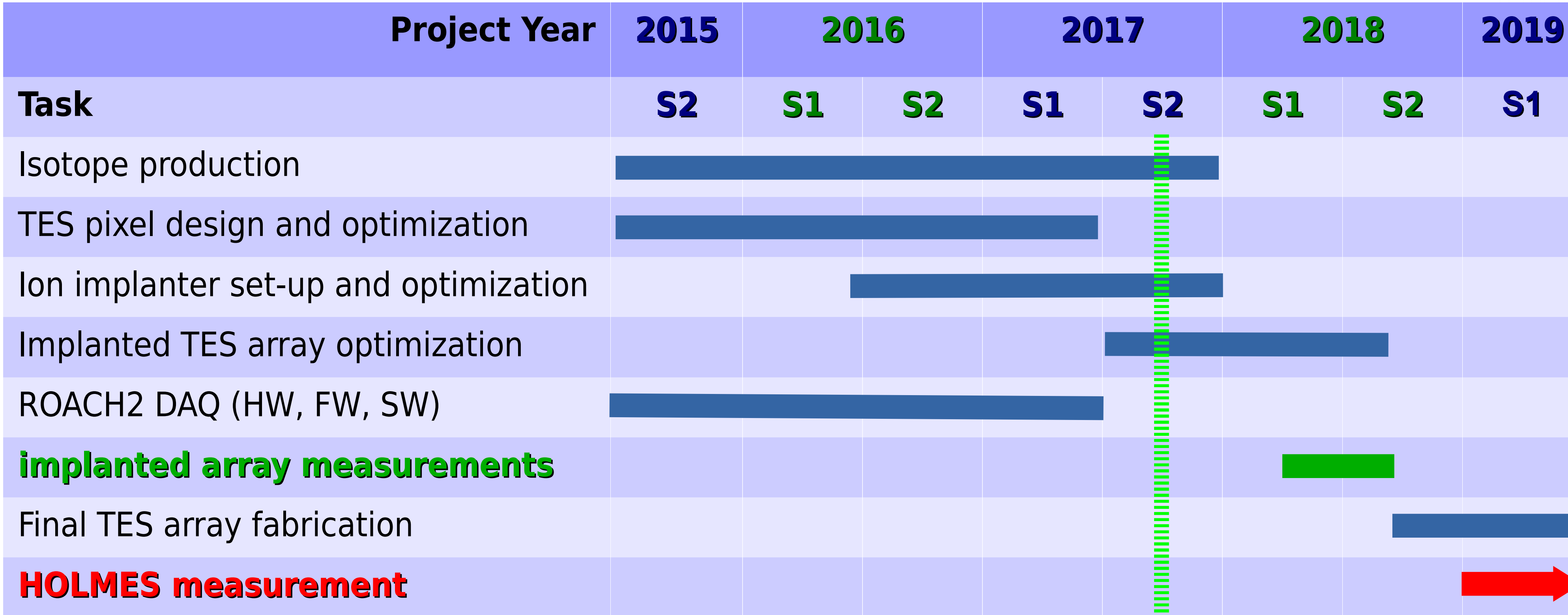
Target chamber for absorber fabrication / 2

- system just delivered
- **tests are in progress**





HOLMES schedule and conclusions



- **HOLMES project status**
  - TES array design and DAQ ready
  - ion implanter optimization is in progress
  - first ^{163}Ho implantation coming shortly
  - ^{163}Ho spectrum measurements will begin in 2018
    - **32 pixels for 1 month → m_ν sensitivity ≈10 eV**