NuMass ν

^{163}Ho-implanted TES for a calorimetric m_ν measurement

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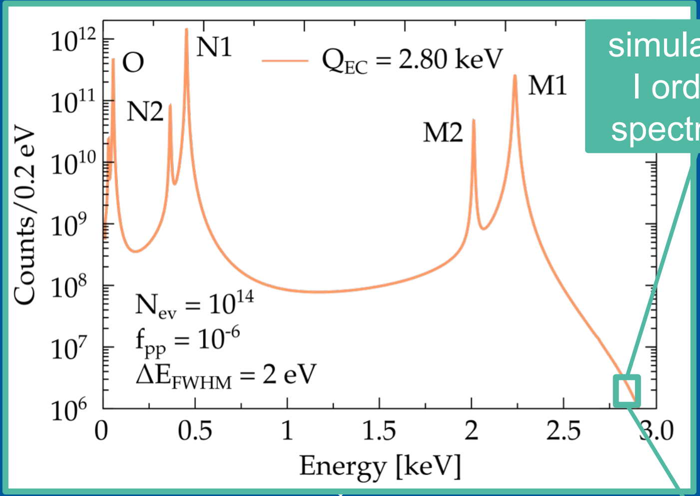
E_c

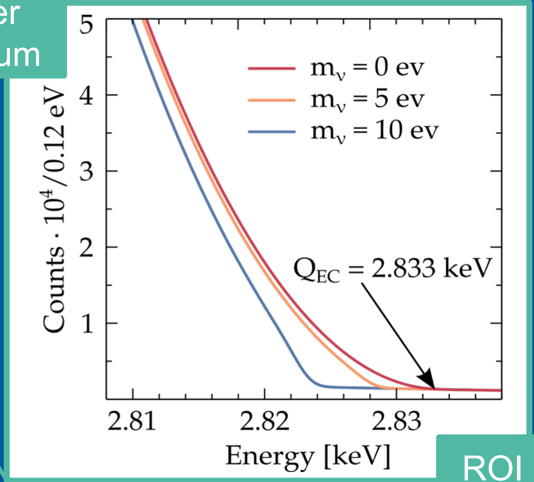
$^{163}\text{Ho} + e^- \rightarrow {}^{163}\text{Dy}^{(*)} + \nu_e$

$\text{ROI}(E_c) \propto \sqrt{(Q-E_c)^2 - m_\nu^2}$

- endpoint statistics
  - Q-value ~2.8 keV
  - M1 peak ~2 keV
- few nuclei needed
  - $t_{1/2}$ ~ 4570 yr

simulated I order spectrum





ROI

m_ν **calorimetric** measurement
- purely kinematic assessment
- embedded source

→ direct approach

→ systematics avoided

Outline

I. TES for the HOLMES experiment

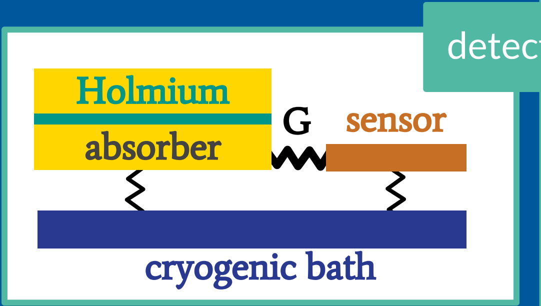
II. TES fabrication

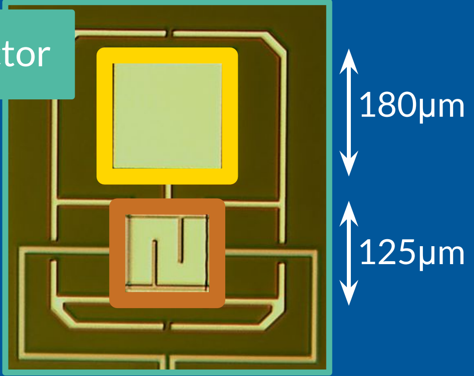
III. TES characterization

What's next?

microcalorimeters

$$\Delta E \rightarrow \Delta T_{abs} \rightarrow \Delta R_{TES} \rightarrow \dots$$

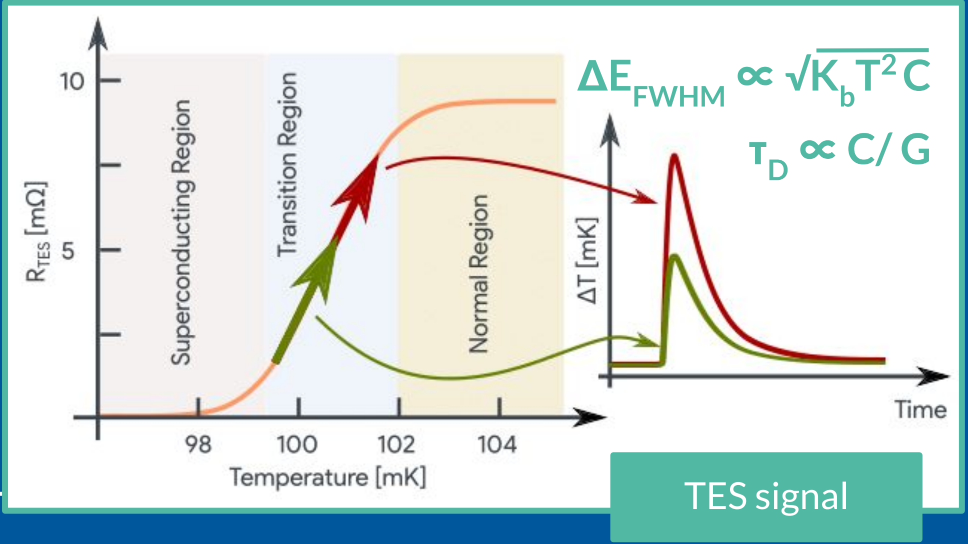




Mo/Cu superconducting film linked to an Au absorber, **very sensitive thermometers** (low T variation → high R jumps)

many reasons:

- state of the art performances
  - time, energy resolutions
- tunable devices
- suitable for multiplexing



$$\Delta E_{FWHM} \propto \sqrt{K_b T^2 C}$$

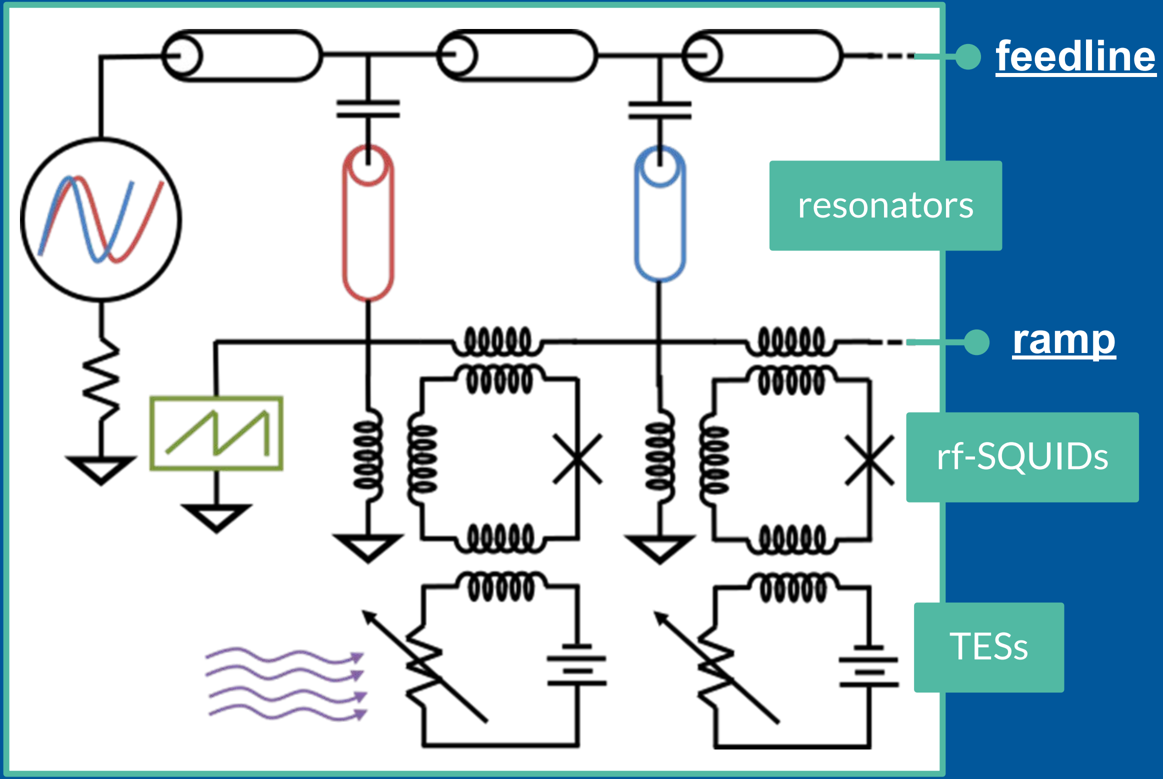
$$\tau_D \propto C/G$$

I. TES for HOLMES **readout scheme**

$$\ldots \rightarrow \Delta I_{TES} \rightarrow \Delta L_{SQUID} \rightarrow \Delta f_{res} \rightarrow \Delta\varphi$$

multiple TESs **readout** with a unique feedline (N depends on the HEMT amplifier bandwidth)

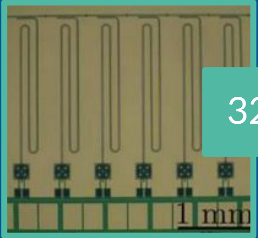
- rf-SQUIDs
- microwave resonators
- ramp (flux modulation)



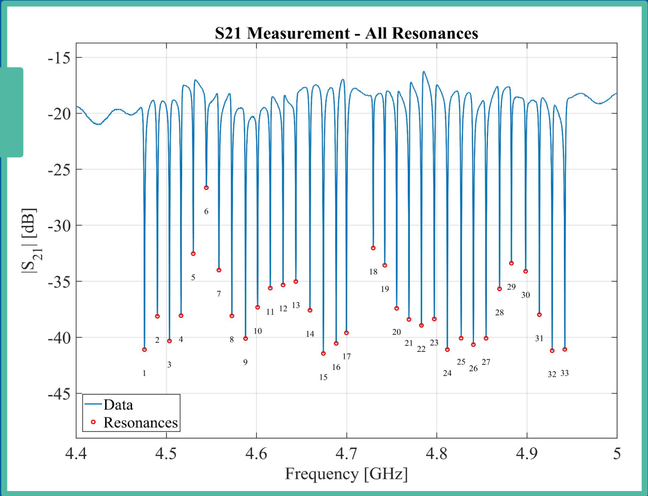
I. TES for HOLMES **readout scheme**

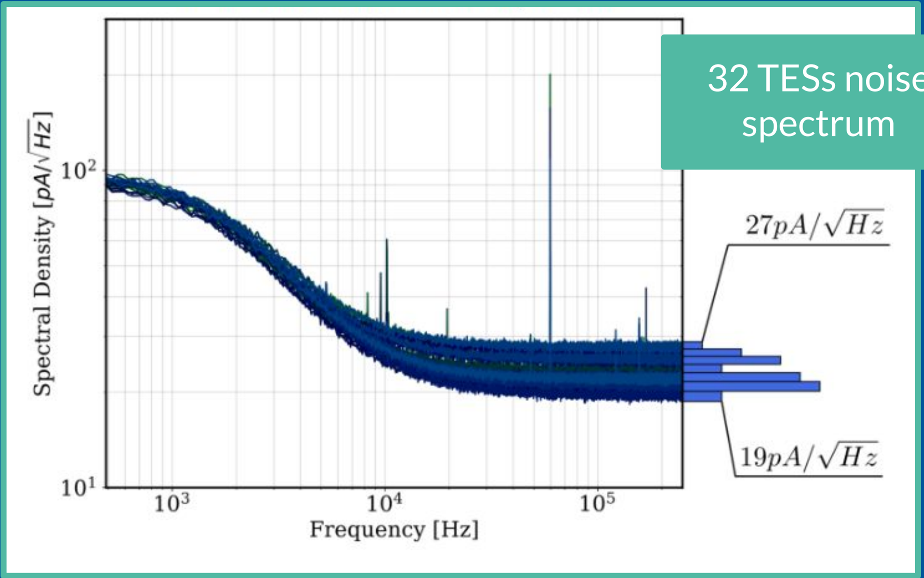
32 TESs bandwidth: ~500 MHz

HEMT in 4-8 GHZ:
potentially 32 x 8 TESs



32 resonators





32 TESs noise spectrum

low freq. → load resistance noise
+ TES noise

high freq. → SQUID noise

(peaks → acquisition firmware)

TESs without Ho (old characterization):

- ΔE_{FWHM} ~ 4eV (@6keV)
- τ_R ~ 20 µs
  - electrical parameters of the TES circuit
- τ_D ~ 300 µs
  - thermal parameters of the TES circuit
- Δt ~ 1.5 µs
  - unresolved pile-up fraction of events

… how do they change after ^{163}Ho implantation?

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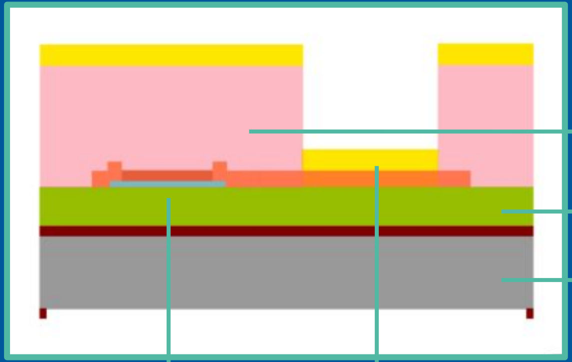
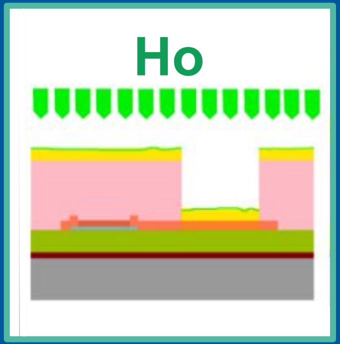
II. TES fabrication

pre-implantation

initial chip fabrication @NIST

Ho implantation @ Genova





detector finalization @ Milano

. . .

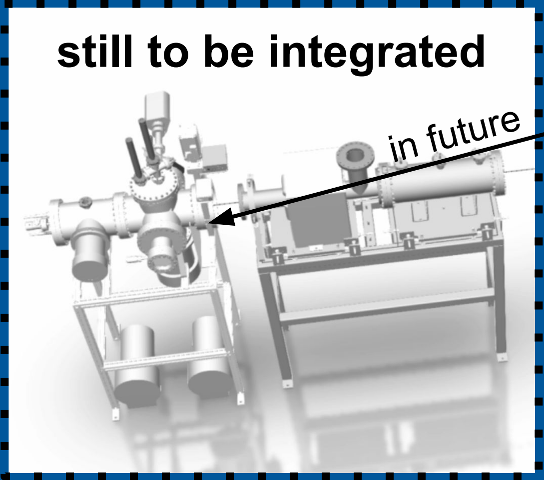
^{163}Ho implantation

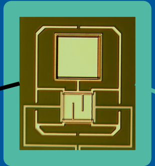
^{163}Ho ion-implantation @ Genova lab

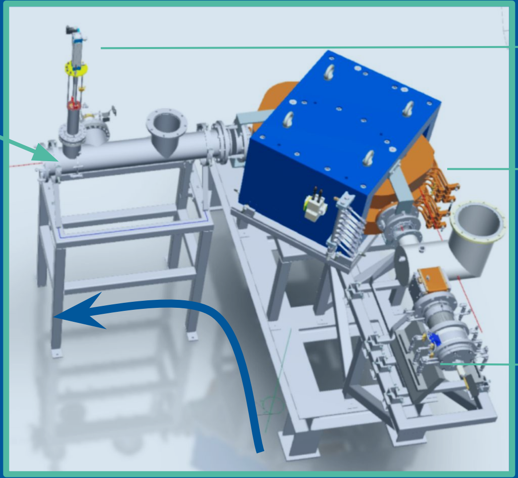
- Ar plasma sputters the source target
- mass selector bending magnet
- FC read the selected current


TES array holder


sintered target
Mo + Ho$(NO_3)_3$


still to be integrated


TESs location for implantation



^{163}Ho ion-implantation @ Genova lab

- Ar plasma sputters the source target
- mass selector bending magnet
- FC read the selected current

“The HOLMES low activity implantation”

by Giovanni Gallucci

(second talk in the afternoon)

sintered target
Mo + Ho(NO$_3$)$_3$

araday cup

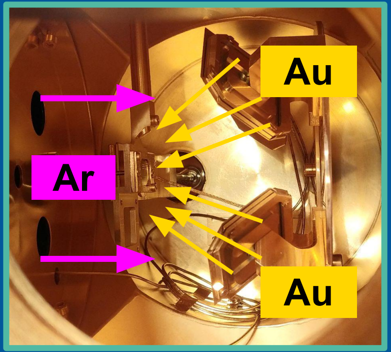
dipole magnet

still to be i

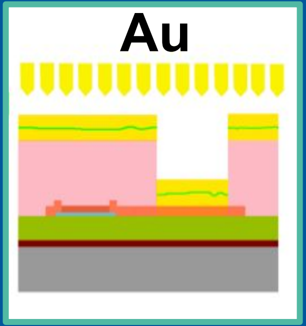
for implantation

sputter ion source

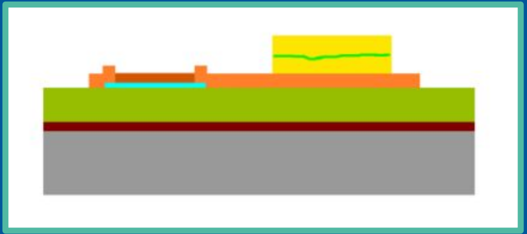
II. TES fabrication finalization

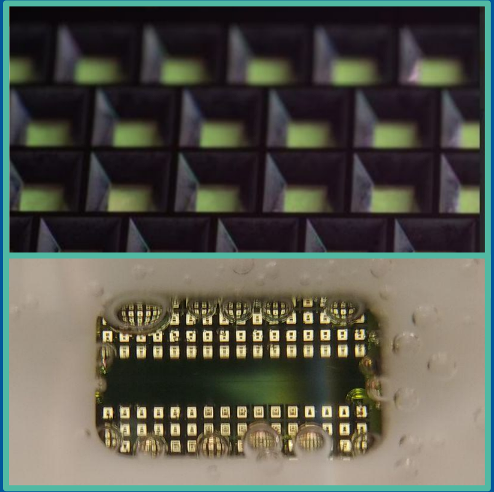


Au deposition

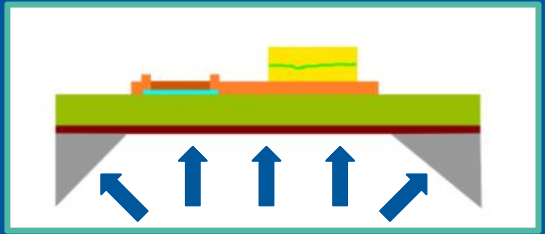


lift-off (acetone)

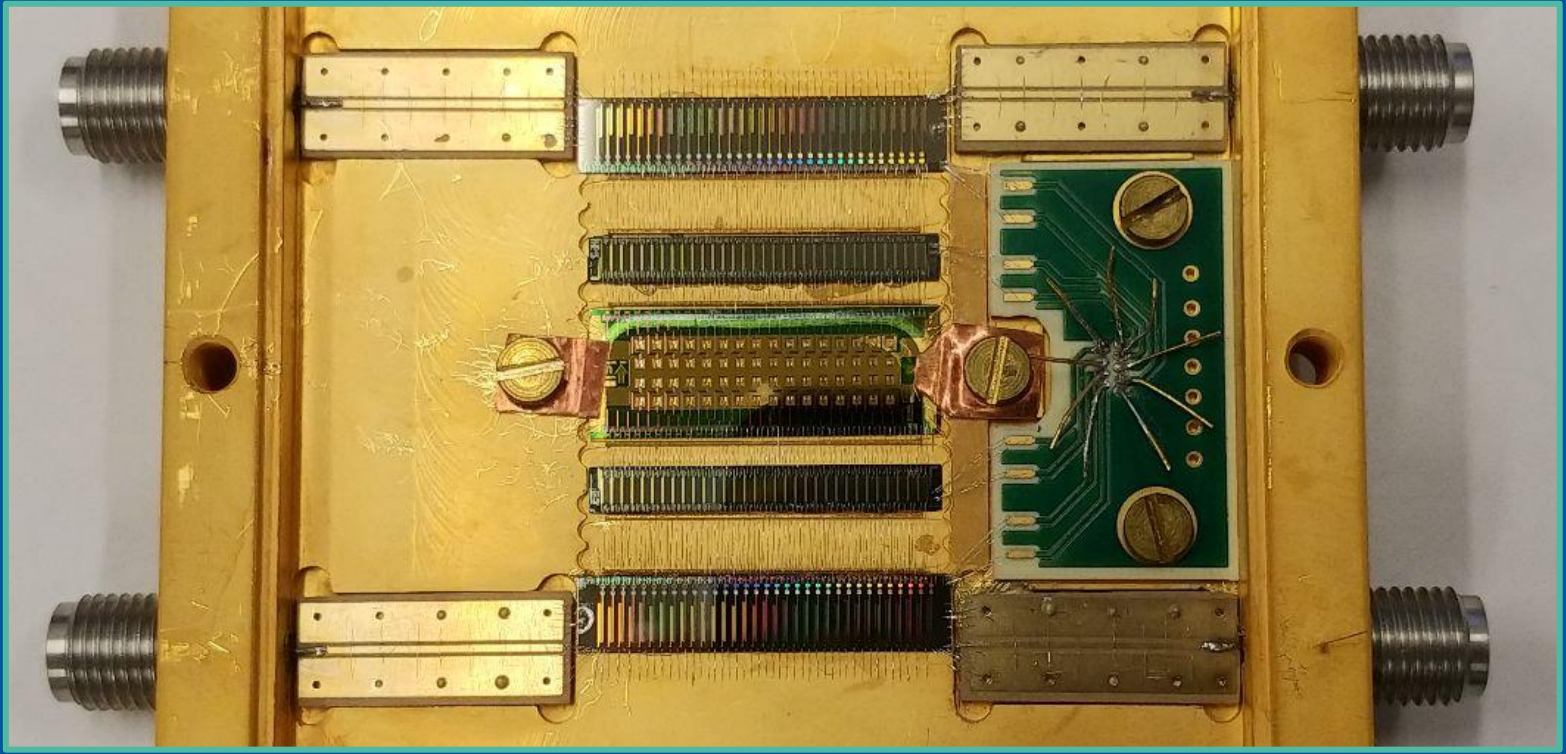




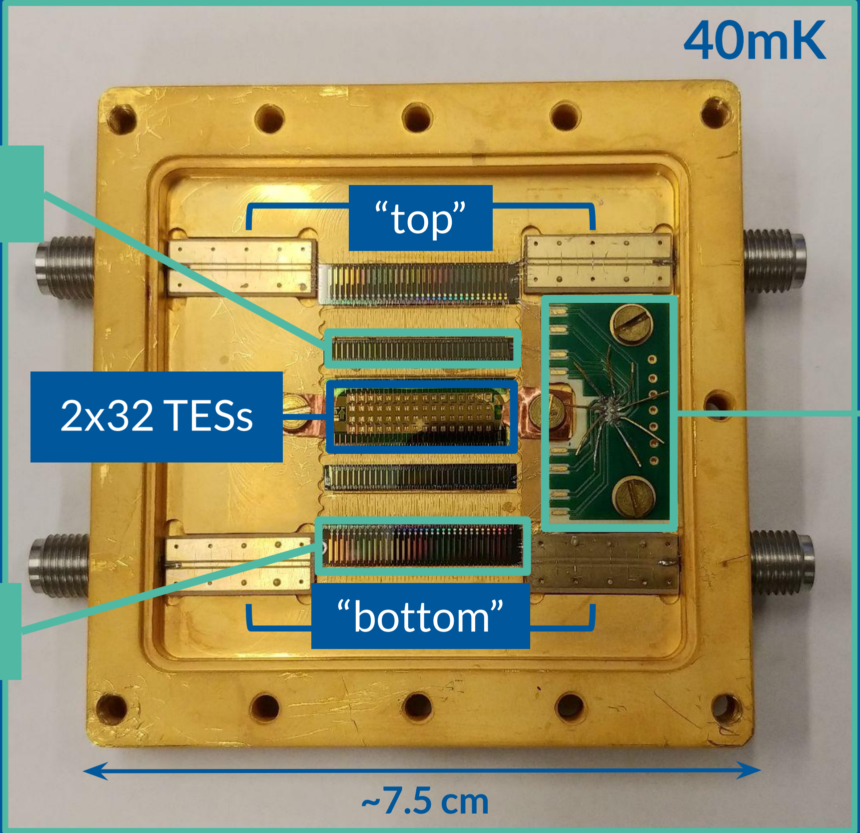
substrate etching (KOH)



detector holder



II. TES fabrication **detector holder**



32 shunting resonances

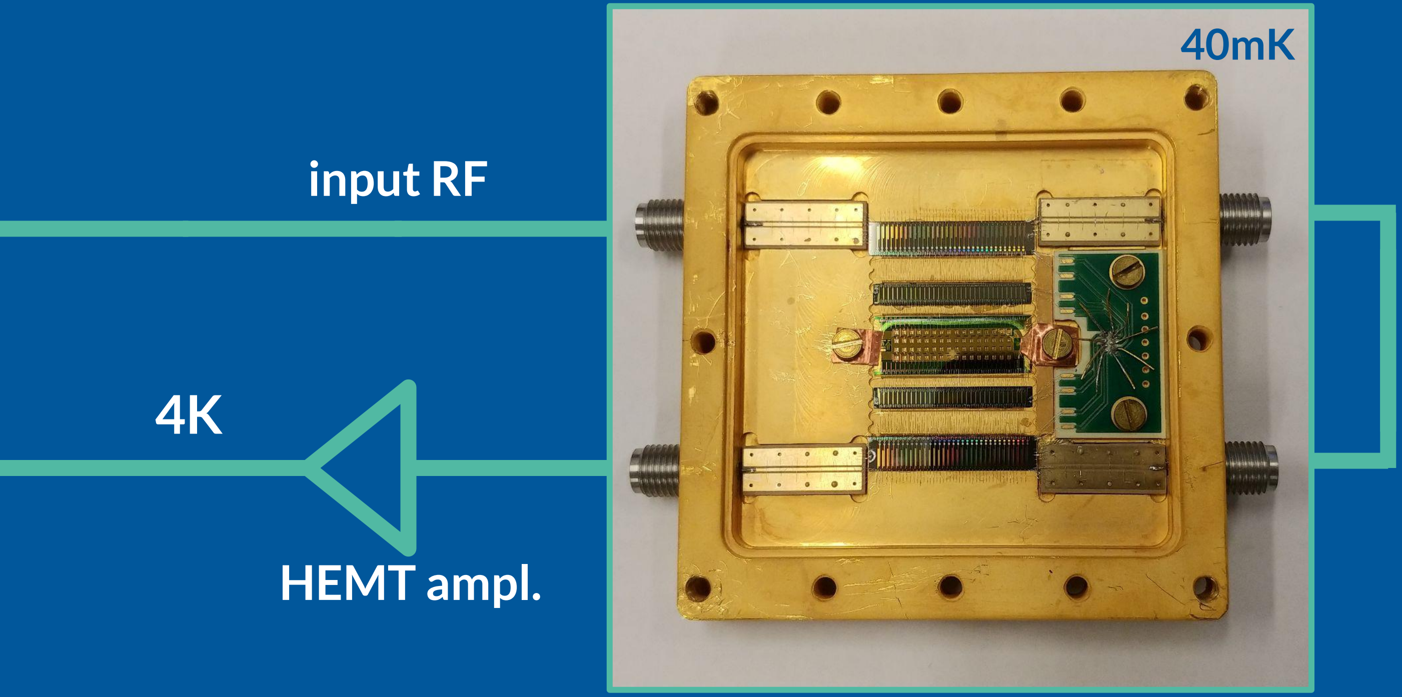
bias chip

32 resonators/ SQUIDs pairs

μMUX chip

PCB with bias and ramp inputs

voltage bias O(1V)
ramp signal 250 kHz



40mK

input RF

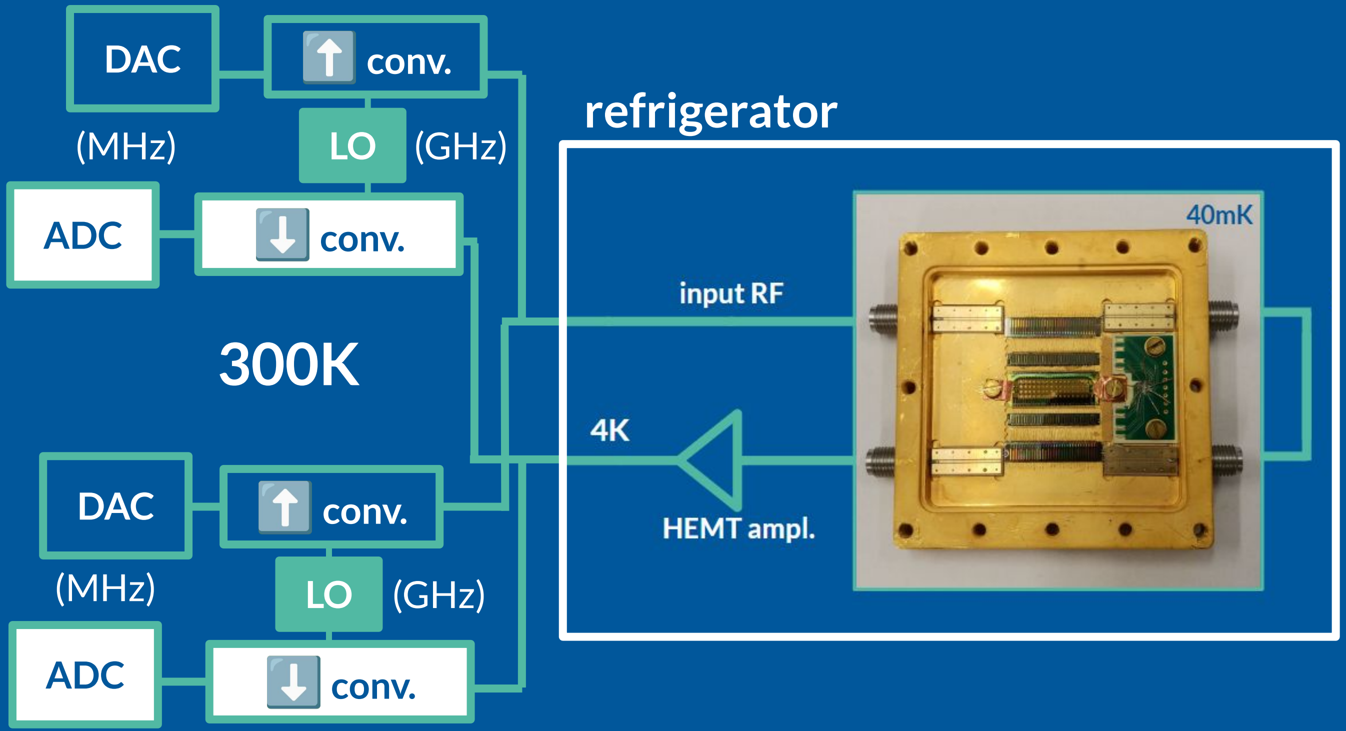
4K

HEMT ampl.

“top” “bottom”

2 x 32 TESs readout:

- x1 RF line
  - x1 HEMT



2 x 32 TESs readout:

- x1 RF line
  - x1 HEMT
- x2 FPGAs
  - DAC/ADC
- x2 IQ mixers
  - ⬆️/⬇️ conv.
- x2 LO generators

Outline

I. TES for the HOLMES experiment

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What’s next?

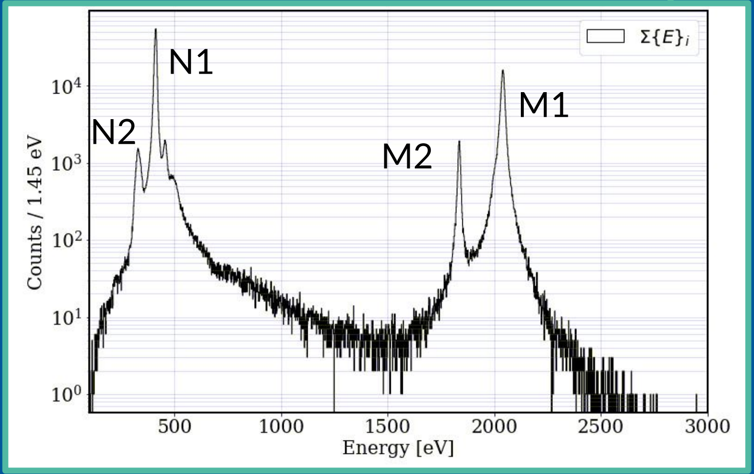
2024 measurements

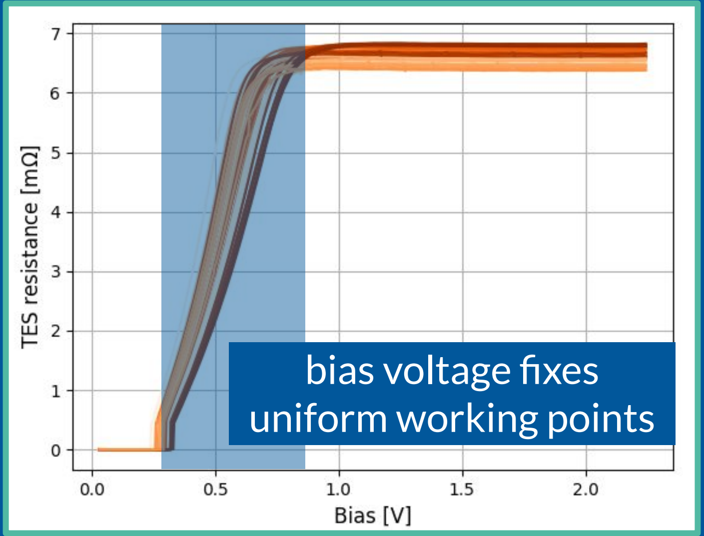
1^{st} run

spectral features calibration
(with external sources)

2^{nd} run

measurement w/ 64 pixels
without fluorescence source

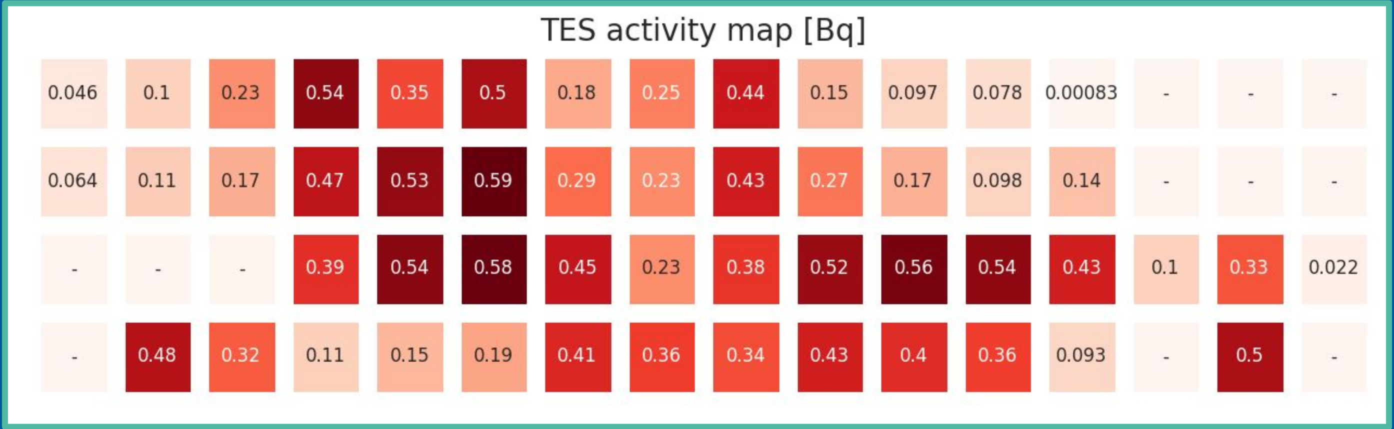




bias voltage fixes
uniform working points

- implanted ^{163}Ho activity
- TES performances (τ_D, τ_R and ΔE_{FWHM})
- estimation of G
- estimation of C_{Ho}

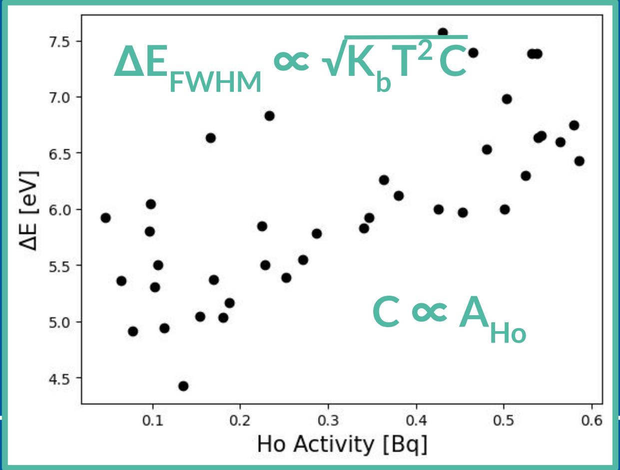
– III. TES charcaterization implanted activity



TES activity map [Bq]

0.046	0.1	0.23	0.54	0.35	0.5	0.18	0.25	0.44	0.15	0.097	0.078	0.00083	-	-	-
0.064	0.11	0.17	0.47	0.53	0.59	0.29	0.23	0.43	0.27	0.17	0.098	0.14	-	-	-
-	-	-	0.39	0.54	0.58	0.45	0.23	0.38	0.52	0.56	0.54	0.43	0.1	0.33	0.022
-	0.48	0.32	0.11	0.15	0.19	0.41	0.36	0.34	0.43	0.4	0.36	0.093	-	0.5	-

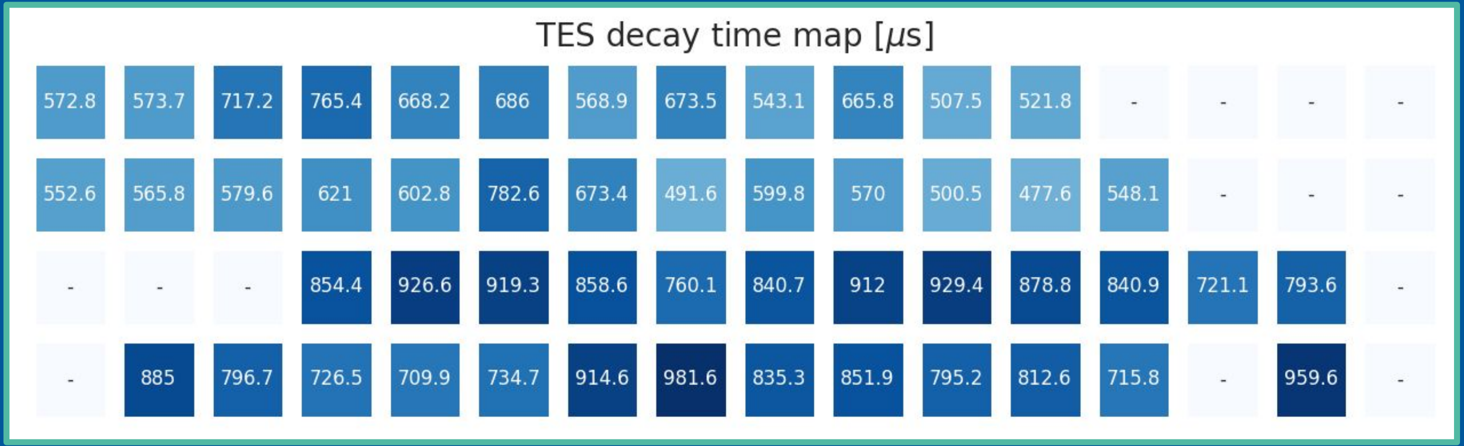
- 12 pixels not measured
- $\langle A_{Ho} \rangle \cong 0.3$ Bq
- $A_{tot} \cong 16$ Bq
- studying different implanted activities



$\Delta E_{FWHM} \propto \sqrt{K_b T^2 C}$

$C \propto A_{Ho}$

– III. TES charcaterization **signal decay times**



TES decay time map [μs]

572.8	573.7	717.2	765.4	668.2	686	568.9	673.5	543.1	665.8	507.5	521.8	-	-	-	-
552.6	565.8	579.6	621	602.8	782.6	673.4	491.6	599.8	570	500.5	477.6	548.1	-	-	-
-	-	-	854.4	926.6	919.3	858.6	760.1	840.7	912	929.4	878.8	840.9	721.1	793.6	-
-	885	796.7	726.5	709.9	734.7	914.6	981.6	835.3	851.9	795.2	812.6	715.8	-	959.6	-

- non-uniform distribution
- $<\tau_D> \sim 700\ \mu s$ (two times longer)
- combination of effects:
  - **G** ← substrate etching procedure
  - **C** ← implanted activity of Ho

$<\tau_R> \sim 20\ \mu s$

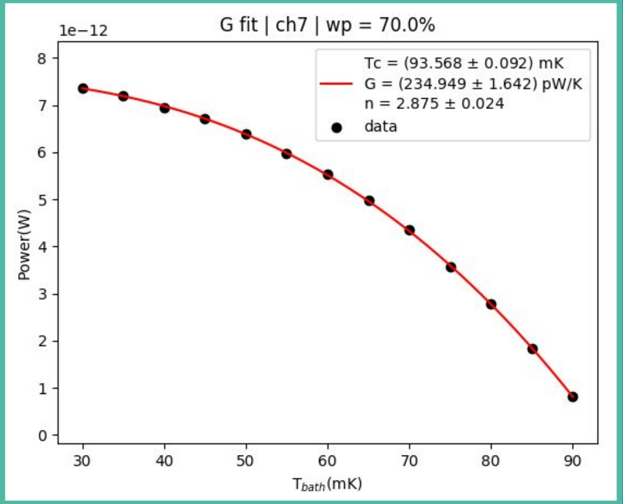
$t_{sampling} = 4\ \mu s$
(250 kHz ramp)

$t_{window} \cong 4$ ms

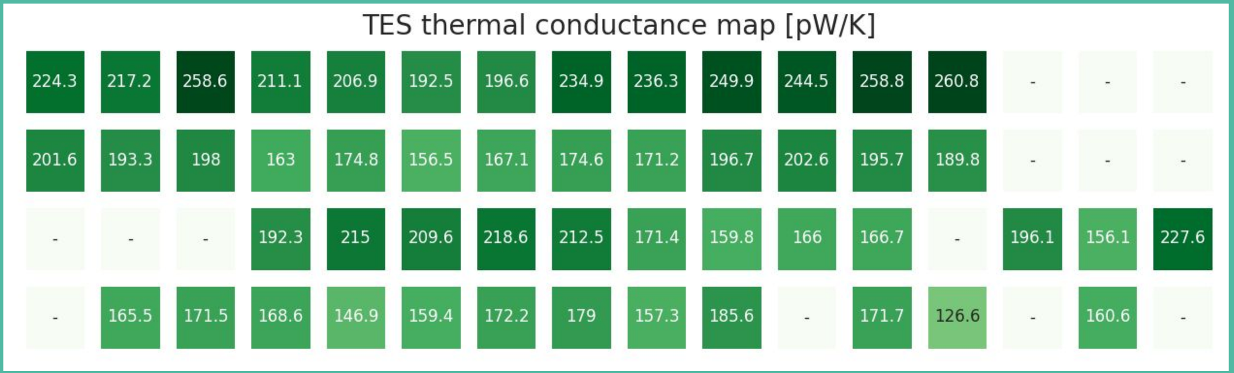
– III. TES charcaterization **thermal conductance**

TES response at fixed R_{TES} (and therefore the P flowing through the bath) depends on T_{bath}

$\langle G \rangle \cong 200$ pW/K	$\sigma_G \cong 30$ pW/K
$\langle T_c \rangle \cong 94$ mK	$\sigma_T \cong 0.8$ mK



$$P(T_{bath}) = \frac{G}{n\,T_c^{\,n-1}}\left(T_c^{\,n} - T_{bath}^{\,n}\right)$$



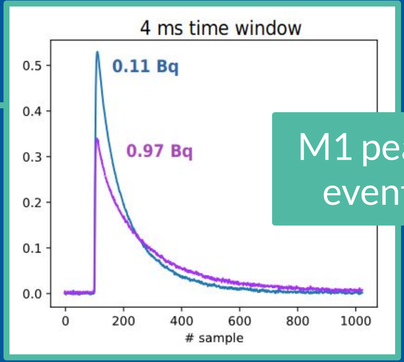
TES thermal conductance map [pW/K]

224.3	217.2	258.6	211.1	206.9	192.5	196.6	234.9	236.3	249.9	244.5	258.8	260.8	-	-	-
201.6	193.3	198	163	174.8	156.5	167.1	174.6	171.2	196.7	202.6	195.7	189.8	-	-	-
-	-	-	192.3	215	209.6	218.6	212.5	171.4	159.8	166	166.7	-	196.1	156.1	227.6
-	165.5	171.5	168.6	146.9	159.4	172.2	179	157.3	185.6	-	171.7	126.6	-	160.6	-

– III. TES charcaterization heat capacity of Ho

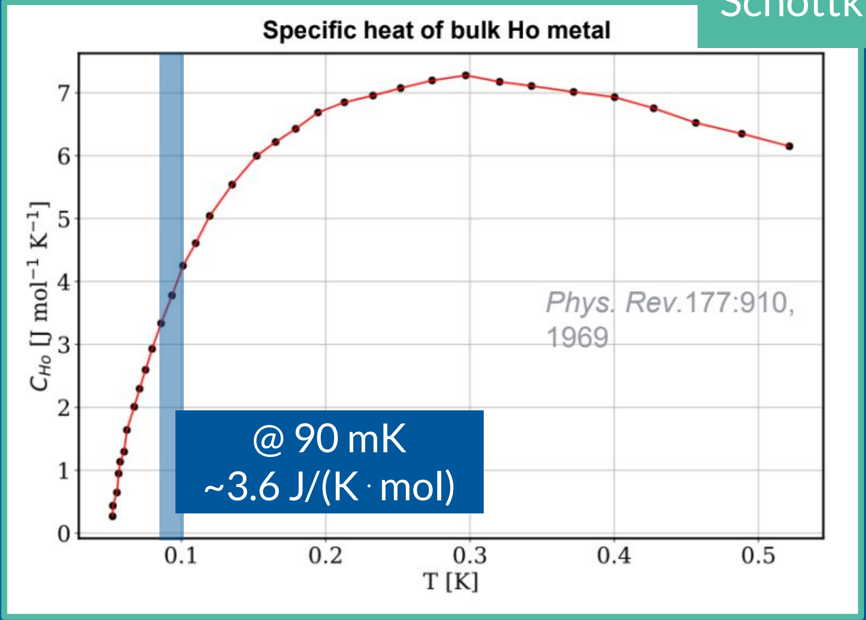
Holmium heat capacity effect on TES performances is not negligible →

- worst ΔE_{FWHM}
- longer τ_D



M1 peak event

Schottky anomaly



@ 90 mK
~3.6 J/(K · mol)

$$C_{tot} = \overbrace{C_{abs,\,Au} + C_{TES}}^{\sim\,0.8\ \text{pJ/K}} + C_{abs,\,Ho}$$

$C_{abs,\,Ho}$ estimated from data:

1) $\tau_D \propto C_{tot} / G$
2) $C_{Ho} \propto A_{Ho}$

$C_{abs,\,Ho} = (2.77 \pm 0.9)$ J/(K · mol)

PRELIMINARY

agreement with ECHo study

Herbst, M. et al., J Low Temp Phys 202, 106–120 (2021)

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II. TES fabrication

III. TES characterization

What's next?

NOW!

Data collection is ongoing: first results with increased statistics will be soon available establishing the first m_ν upper limit assessment of the HOLMES experiment

… SOON

new TES implantation run

- maximizing ^{163}Ho implanted activity
- more statistics and new m_ν assessments…

and

ion-implanter update

- electromagnetic focusing stage
- co-deposition target chamber

new TESs ?

lowering the transition temperature would improve performances

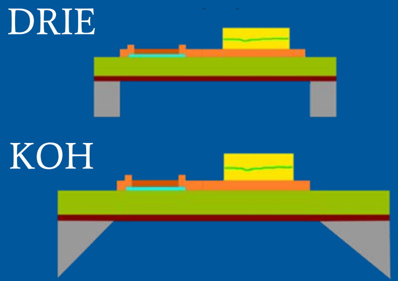
Thanks for the attention :)

Backup slides…

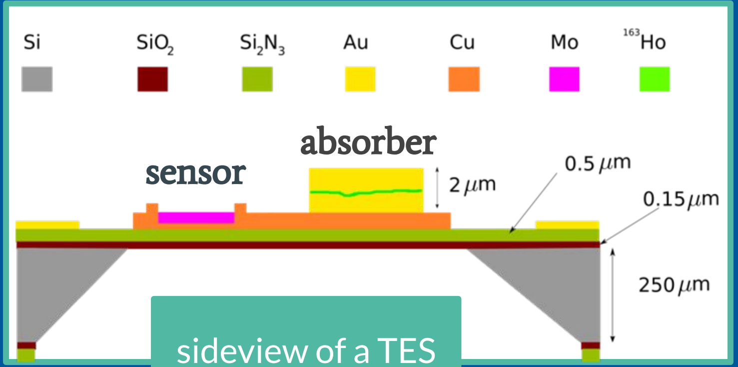
Backup slides

- how we receive the chip:

- after implantation/deposition and photoresist lift-off:



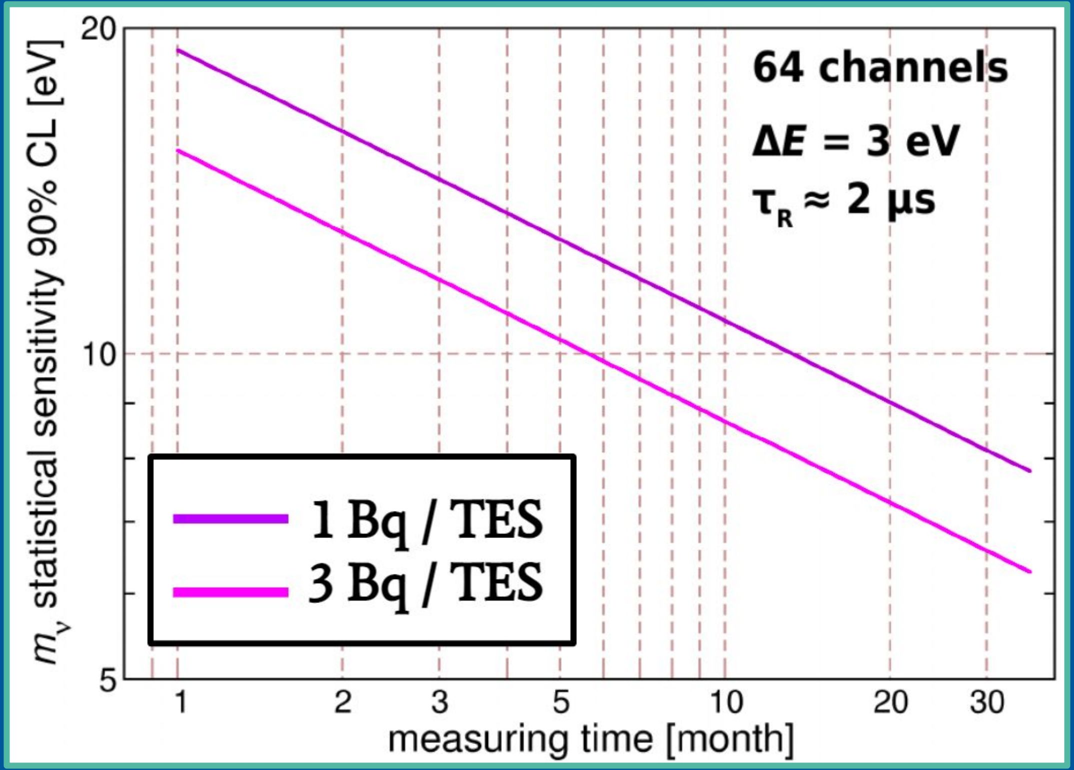
after substrate etching



sideview of a TES

2 techniques:

- KOH → more space required between TESs, tested succesfully @ MiB
- Deep Reactive Ion Etching (DRIE) → perpendicular etching, not properly tuned yet

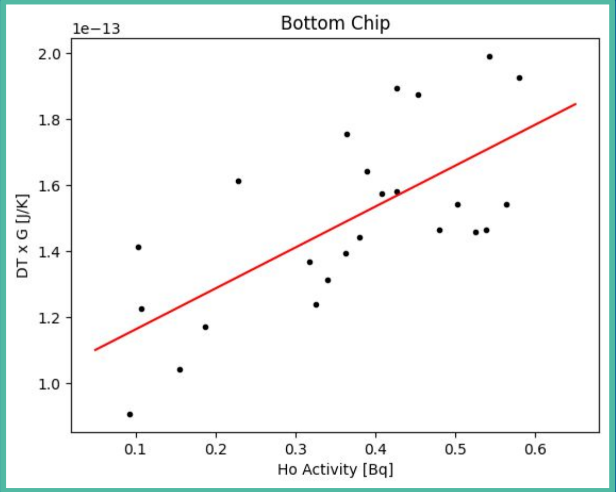

64 channels
ΔE = 3 eV
$\tau_R \approx 2\ \mu s$
1 Bq / TES
3 Bq / TES
m_ν statistical sensitivity 90% CL [eV]
20
10
5
1
2
3
5
10
20
30
measuring time [month]

Bottom chip TESs

$\langle G\rangle \cong 170$ pW/K

$\langle \sigma_G/G\rangle \cong 1\%$

$\langle T_d\rangle \cong 875$ μs



Assumptions:

1) $\tau_d \propto C_{tot}/G$

2) $C_{Ho} \propto A_{Ho}$

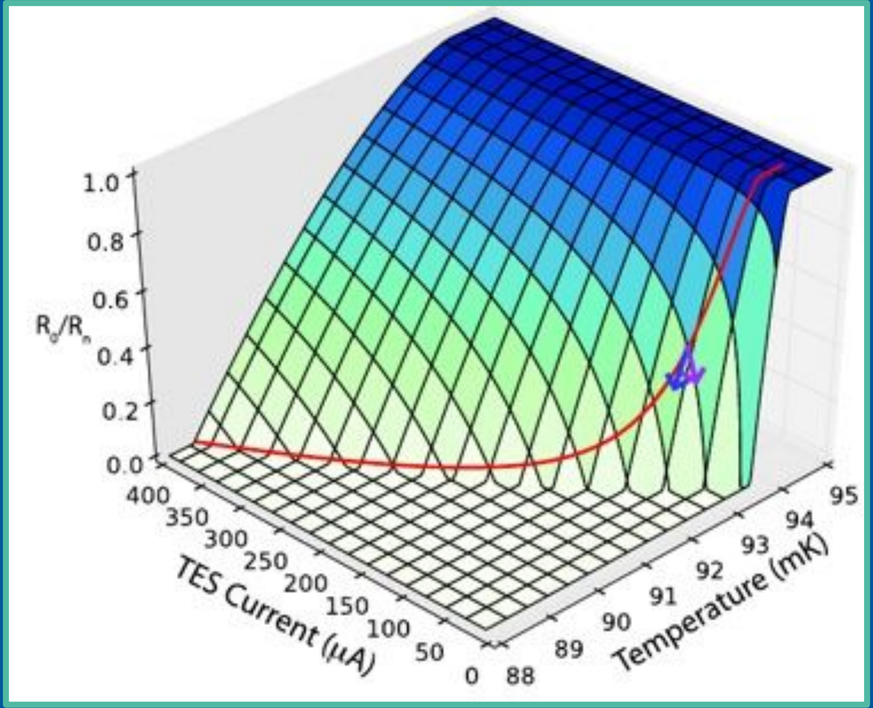
$$\tau_d[s] \times G[W\,K^{-1}] = K_0\,(C_{det+Au} + \boxed{K_1\,A_{Ho}[s^{-1}]})$$

$$\boxed{K_1\,A_{Ho}\,[J\,K^{-1}]} \Rightarrow K_1\,[sJ\,K^{-1}] = C_{Ho}\,[J\,K^{-1}mol^{-1}]\,\tau_{Ho}[s]\,/\,N_{Av}\,[mol^{-1}]$$

we can fix C_{det+Au} at ~ 0.8 pJ/K

C_{Ho} is computed from the linear relation ($\tau_d \times G$) vs A_{Ho}

$$C_{Ho} = (2.77 \pm 0.9)\ J/(K \cdot mol)$$


1.0
0.8
0.6
0.4
0.2
0.0
R_0/R_n
400
350
300
250
200
150
100
50
0
TES Current (μA)
88
89
90
91
92
93
94
95
Temperature (mK)

Backup slides

A spectral fit is performed over each TES dataset

Multi-spectrum analysis with neutrino mass as shared parameter

Stan-based software for bayesian inference through Markov Chain Monte Carlo