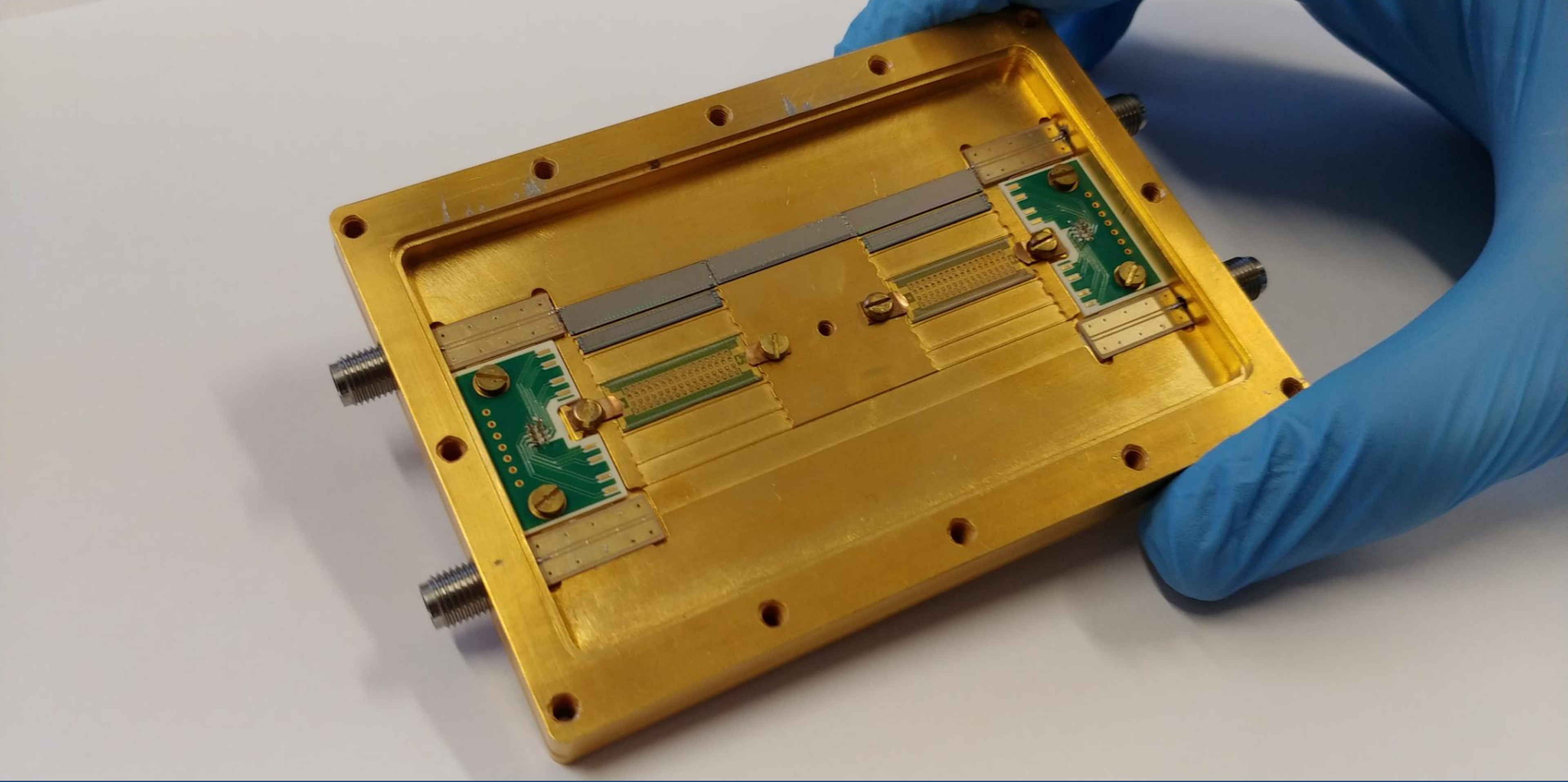


Updates on the HOLMES detector array fabrication

Matteo Borghesi

Introduction to HOLMES: EC and neutrino mass measurement

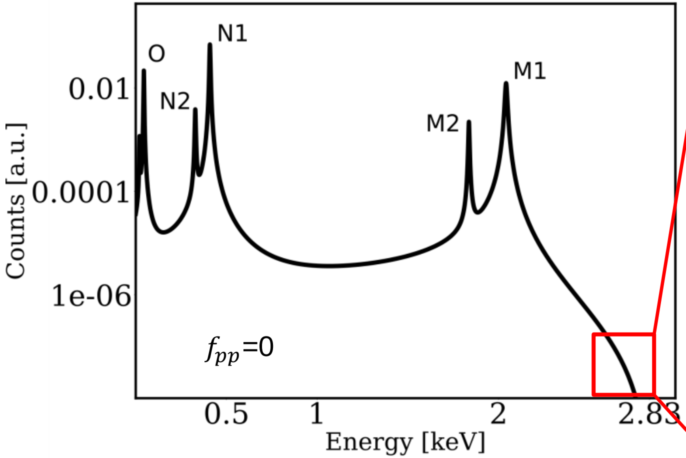
- Direct measurement of the electron neutrino mass studying the EC decay of $^{163}\mathrm{Ho}$

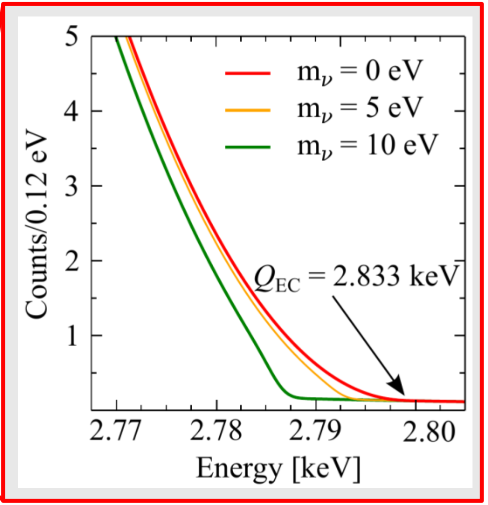
$$^{163}Ho \rightarrow {}^{163}Dy^{H} + \nu_e \rightarrow {}^{163}Dy + E_c$$

($2 \cdot 10^{11}$ $^{163}\mathrm{Ho}$ nuclei = 1 Bq)

- Pro: low Q value (2.833 keV), “short” half life ($\tau_{1/2} \sim 4570$ years) and the proximity of the M1 peak to the end-point

$$\frac{d\,\lambda_{EC}}{dE_C} = \mathrm{N}(Q - E_C)\boxed{\sqrt{[(Q - E_C)^2 - m_\nu{}^2]}}\,x \sum_H \frac{\varphi_H^2(0)(\Gamma_H/2\pi)}{[(E_C - E_H)^2 + \Gamma_H{}^2/4]}$$





HOLMES in a nutshell

- Transition Edge Sensors
  $\Delta E \sim 1$eV, $\tau_{eff} < 3\mu s$
- Target activity (A) 300 Hz/det
- $6.5 \cdot 10^{16}$ nuclei of $^{163}\mathrm{Ho}$
- $3 \cdot 10^{13}$ events in 3 years
- m_ν sensitivity ~eV

- Neutrino mass sensitivity strongly depends on the number of the events at the endpoint $\Longrightarrow$ $\Sigma(m_\nu) \simeq N_{ev}^{\frac{1}{4}}$

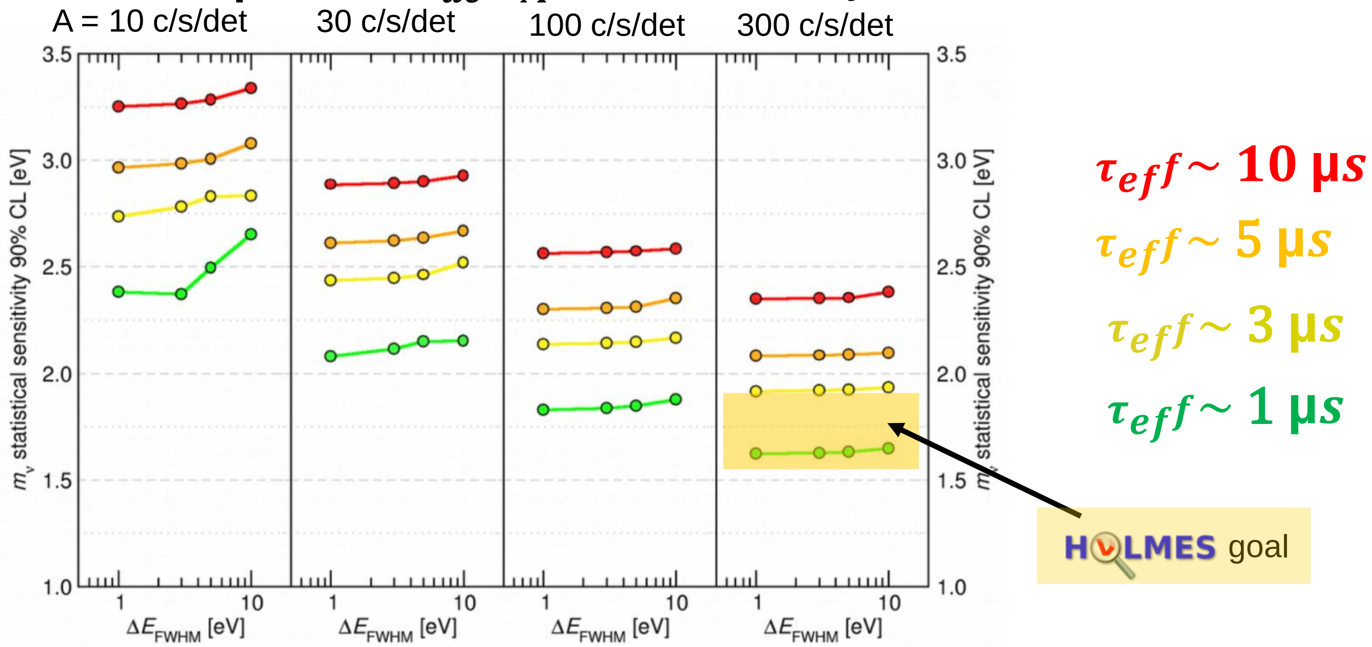
$$N_{ev} = A\, N_{det} t_M$$

Measurement time [3 years]

Single detector activity [300 Hz]

Number of detectors [1000]

Exposure $N_{det}t_M$= 1000 det x 3 y

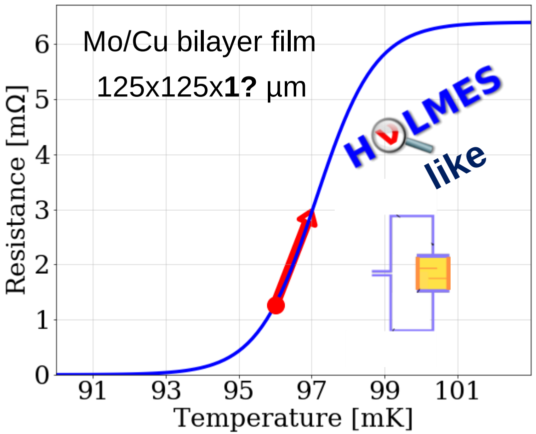


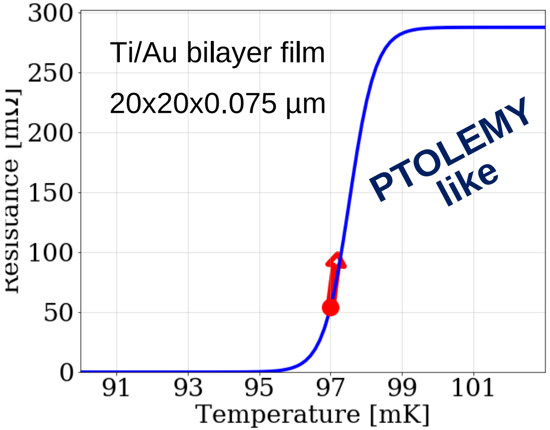
Transition Edge Sensors

- A TES is a superconductor film operated in the narrow temperature region between the resistive and the superconducting state

➡ The resistance is strongly dependent on temperature ➡ It is a very sensitive termometer, able to detect a temperature variation of the order of a fraction of mK

- The R vs T curve depends on different things, such as: the material and the dimension of the film, the geometry of the TES, ...



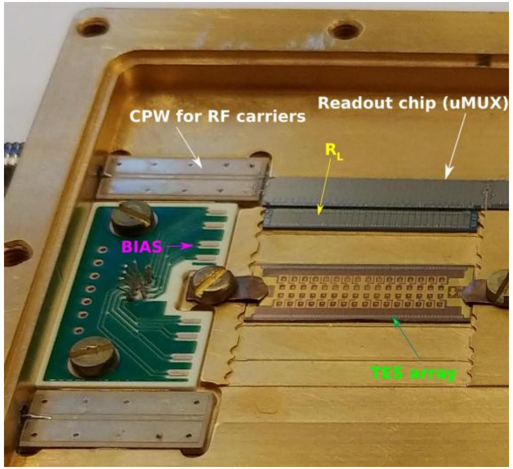


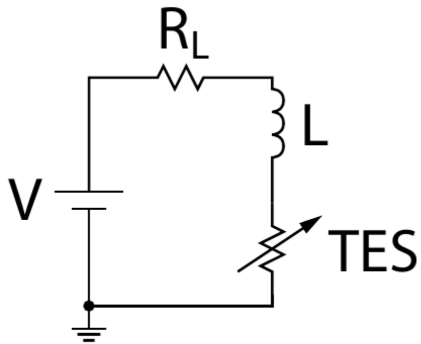
- Work aimed at finding the optimal TES parameters for HOLMES has been carried out and <u>concluded</u> during the last year

Transition Edge Sensors: electrical and thermal response

- After defining a model, the TES behavior can be described by a set of differential equations....

  ... but determining which thermal model to use is no easy task!

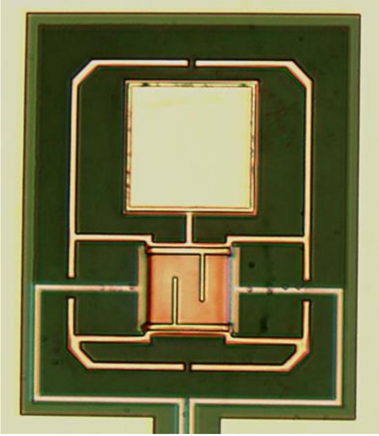




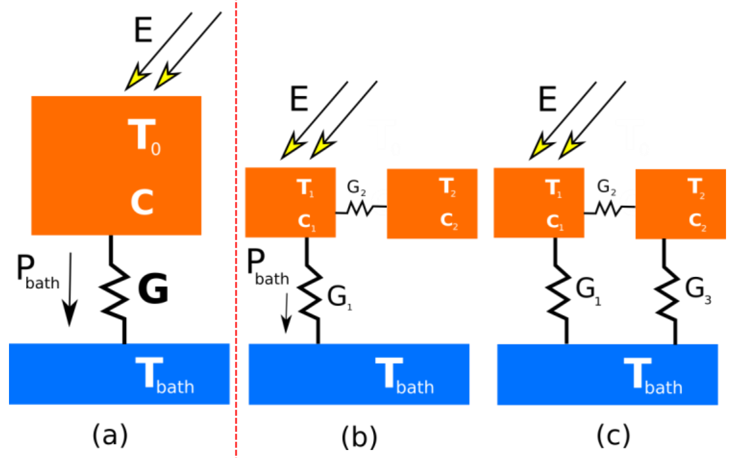
- We are currently using the simplest one, the so called **one body model** (a)

$$L\frac{dI}{dt} = V - IR_{SH} - IR_{TES}(T, I)$$

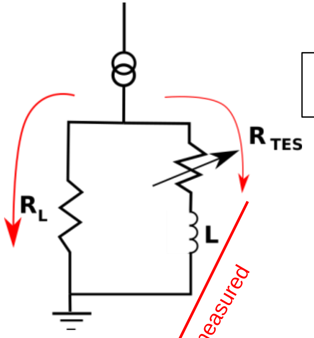
$$C\frac{dT}{dt} = -P_{bath} + P_J + P$$



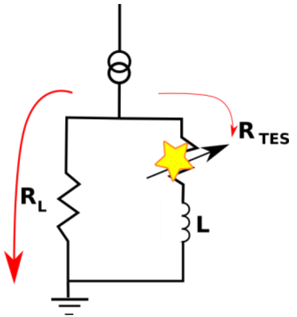
?



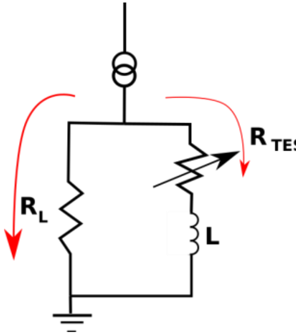
Transition Edge Sensors: signal shape & useful formulas



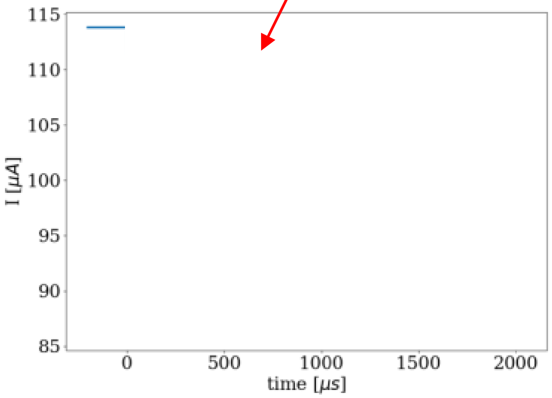
$$R_{TES} \propto R_{TES}(I, T, \alpha, \beta)$$

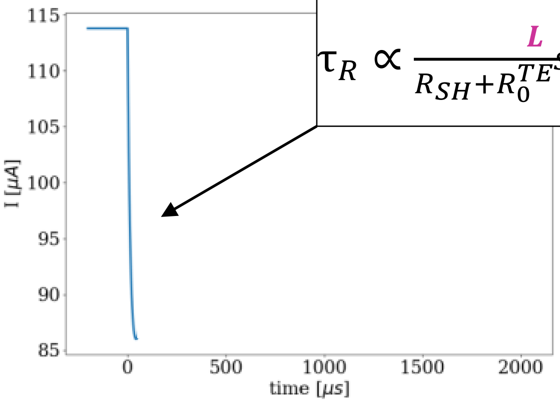


Energy interaction in the TES

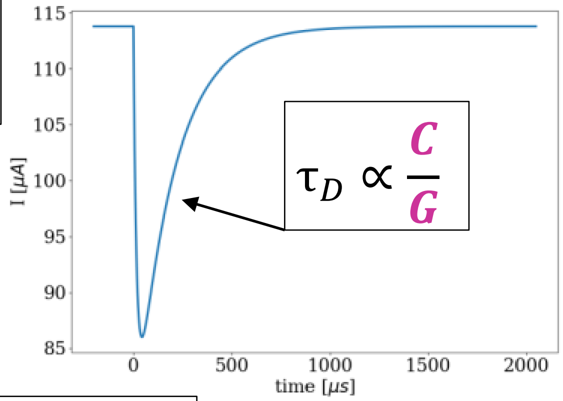


Electrothermal feedback kicks in





$$\tau_R \propto \frac{L}{R_{SH} + R_0^{TES}(1+\beta)}$$



$$\tau_D \propto \frac{C}{G}$$

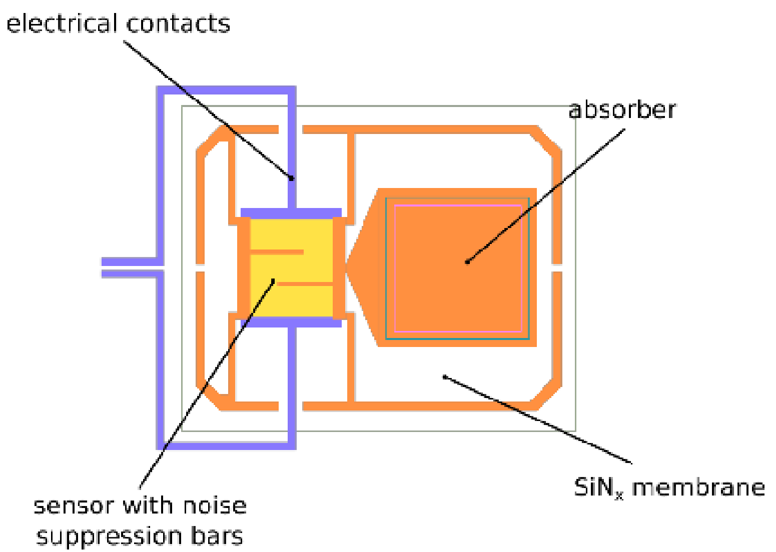
Deduced from the one body model (and some approximations)

$$\Delta E_{FWHM} \propto \sqrt{\frac{T_0^2 C}{\alpha}}$$

HOLMES

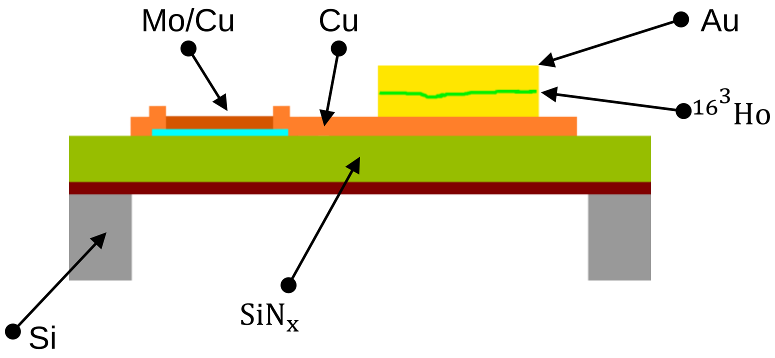
Transition Edge Sensors: the design for HOLMES

- TES + absorber with a sidecar geometry
- Au absorber 200x200x2 μm^3 . It will ensure 99.99998% (99.9277%) probability of stopping the electrons (photons) from the ^{163}Ho decay
- The TES surface is shaped using copper bars (increase ETF and reduce the excess electrical noise)
- SiN membrane + copper perimeter to control the thermal conductance toward the thermal bath *G*



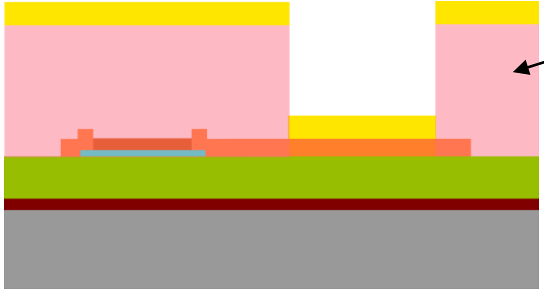
- G, $I_{TE}{}^{S}(I_{bias})$, $R_{TE}{}^{S}(I_{TE}{}^{S})$ have been measured
- C, L, α, β have been evaluated through the noise spectra fit and NIST preliminary estimation

Not very accurate → Full TES characterization through complex impedance measurement is scheduled!

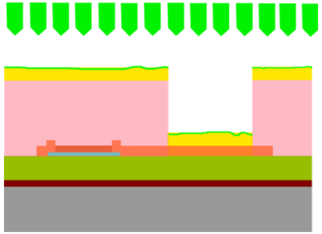


Transition Edge Sensors: production

- TES for preliminary tests fabricated at NIST, Boulder, CO, USA
  With 2 um Au absorber and DRIE etched
- Proper HOLMES detectors finalized @Genova & @ Milano -> processes currently being setup

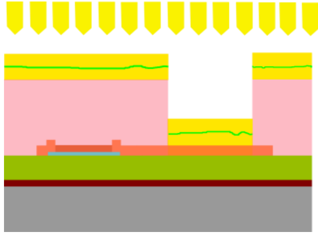


Photoresist



<u>Ho implantation</u>

See Gallucci's talk tomorrow

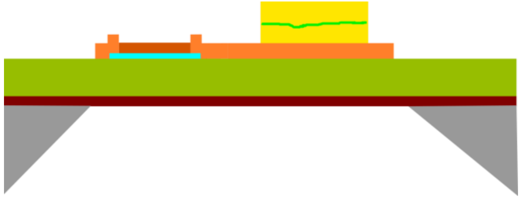


<u>Gold sputtering</u>

☑ Succesfully tested

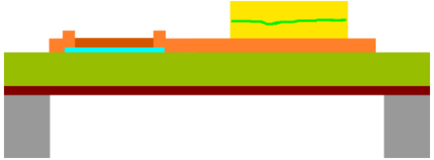
<u>Lift off</u>

☑ Succesfully tested



<u>KOH etching</u>

☑ Succesfully tested



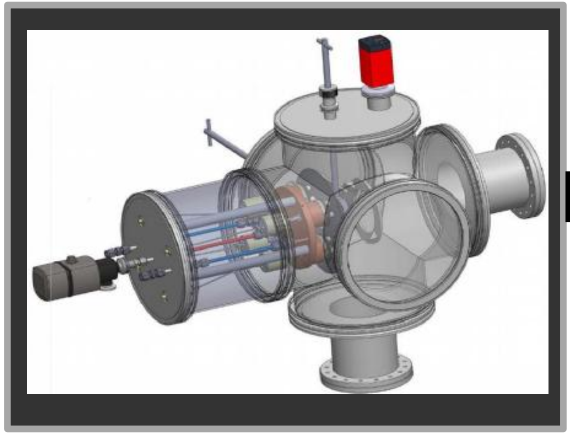
<u>DRIE etching</u>

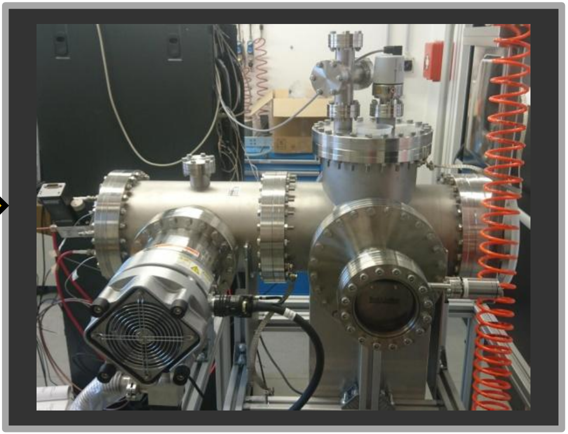
☐ Work in progress @ Trustech

Target chamber

Why Au co-evaporation?

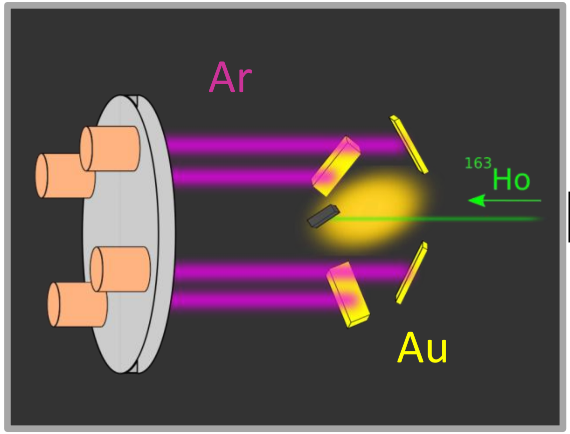
- ^{163}Ho concentration in absorber saturates
- Au deposited in situ to avoid oxidation
- Heat capacity

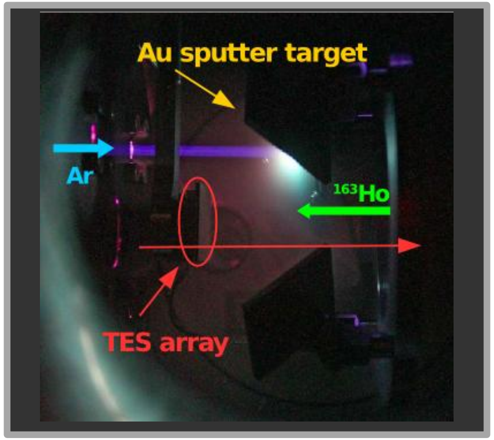


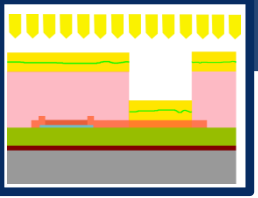


Test goals:

- Beam parameters optimization
- Calibration
- Deposition rate estimation
- Evaluation of the uniformity of the sputtered gold







Target chamber test @ Milano Bicocca: deposition rate

- 4 COMIC microwave sources

  4 argon beams

  4 Au targets

  - Increase deposition uniformity
  - Increase deposition rate

- Target Chamber Pressure: $\sim 10^{-8}$mbar
  Total Argon ion current achieved: ~ 250 µA
  Rate measured with a quartz microbalance near the target

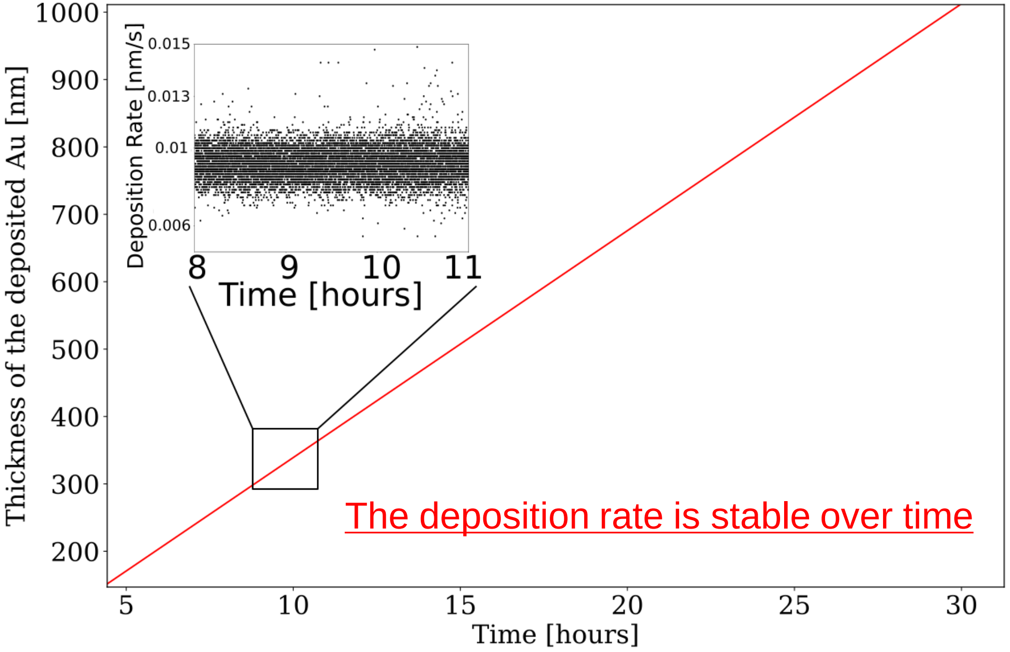
- With ~ 250 µA total Ar current

< rate @ microbalance > = 39 ± 2 nm/h

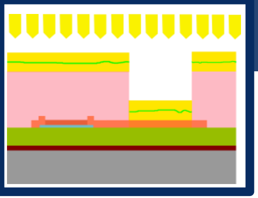
< rate @ target > = 52 ± 4 nm/h

~ 20 h for 1 um deposition

With < 250 µA total Ar current

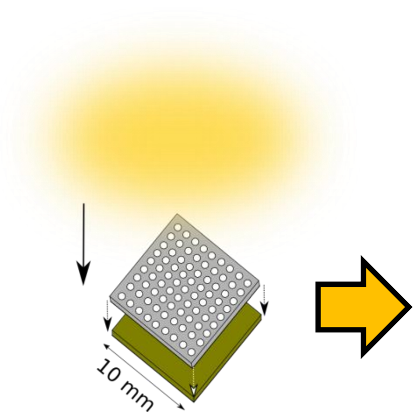


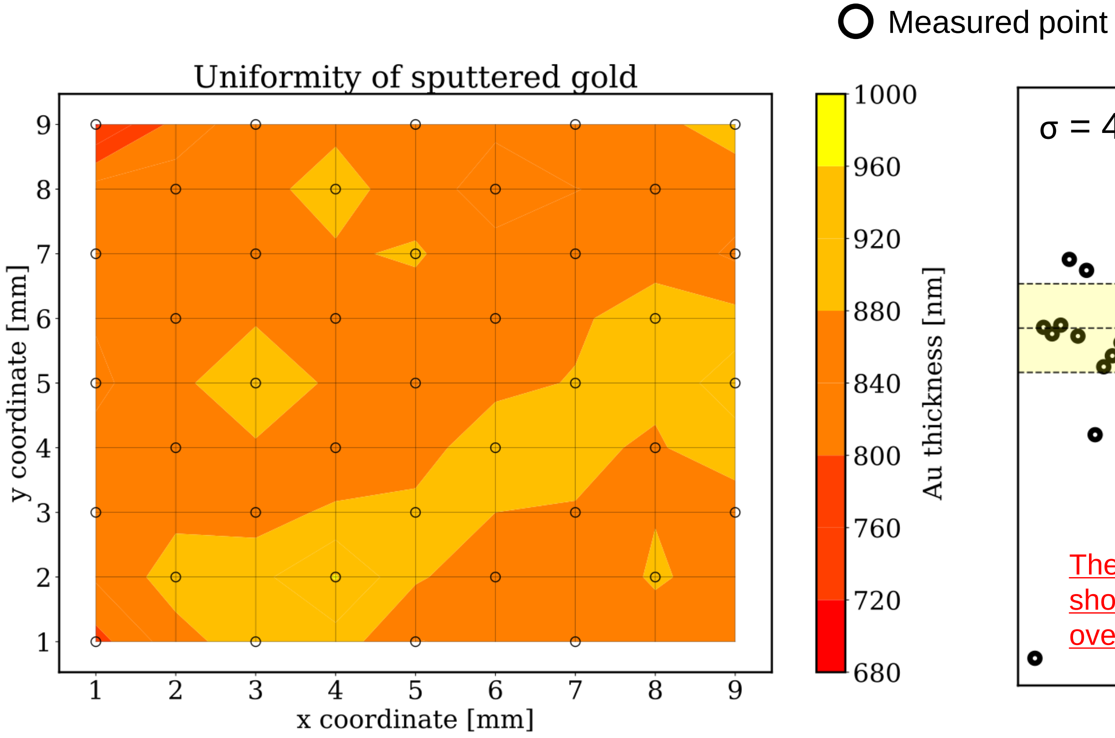
The deposition rate is stable over time

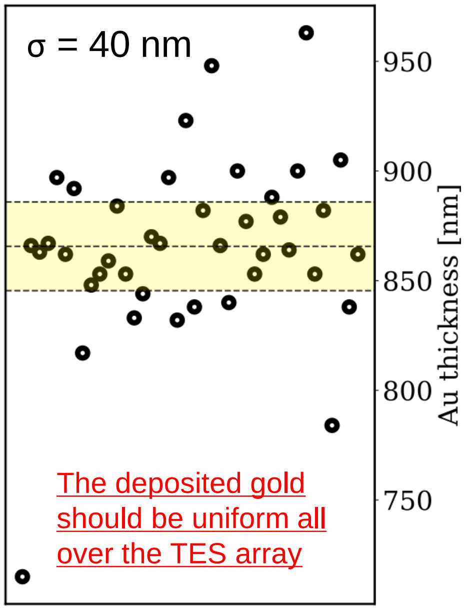


Target chamber test @ Milano Bicocca: uniformity

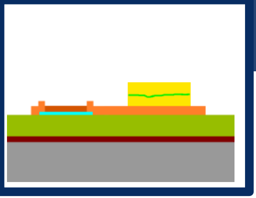
- Au sputtered for ~ 22 hours on a Si slab 1x1cm^2 → with a drilled mask with 9x9 holes on top
- The thickness in the center of the circles were measured with a profilometer







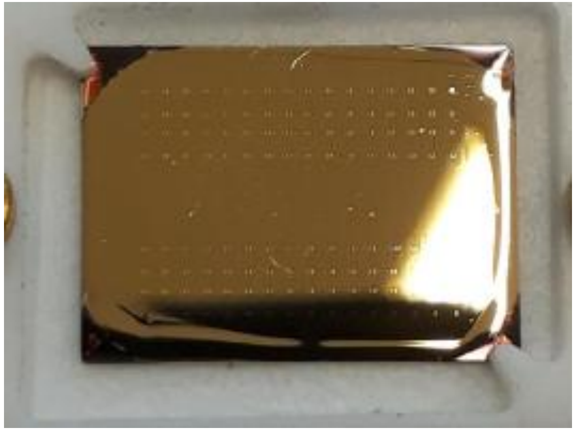
The deposited gold should be uniform all over the TES array

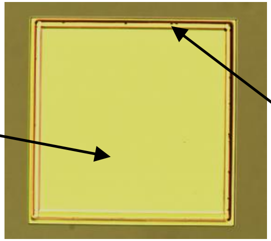


Lift-off

- After the gold deposition on the absorbers, the photoresist mask (7 µm thickness) must be removed
- Sample in acetone (40˚C) for 24h

After the lift-off, the Au deposited remains only on the absorber

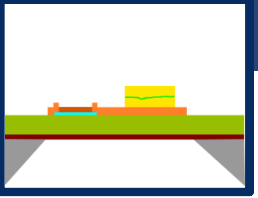




Au absorber

Minimal crowning

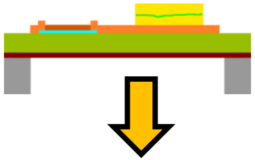
KOH vs DRIE

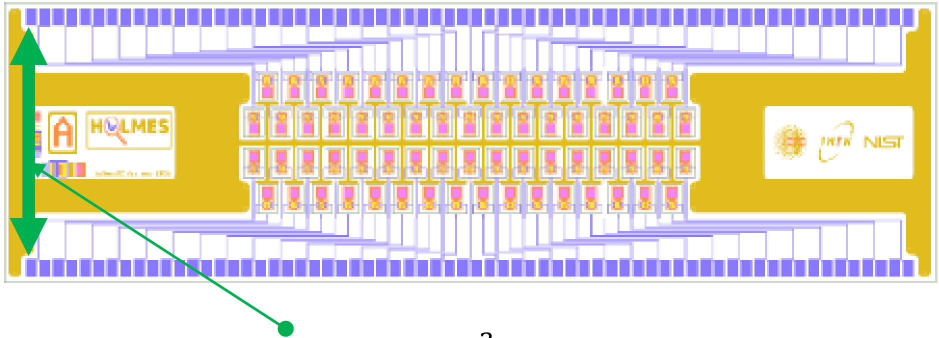


Silicon Deep Reactive Ion Etching (DRIE)

- Best for close packing and high implant efficiency
- Not yet properly tuned

Work in progress @ Trustech

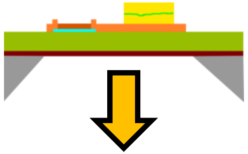


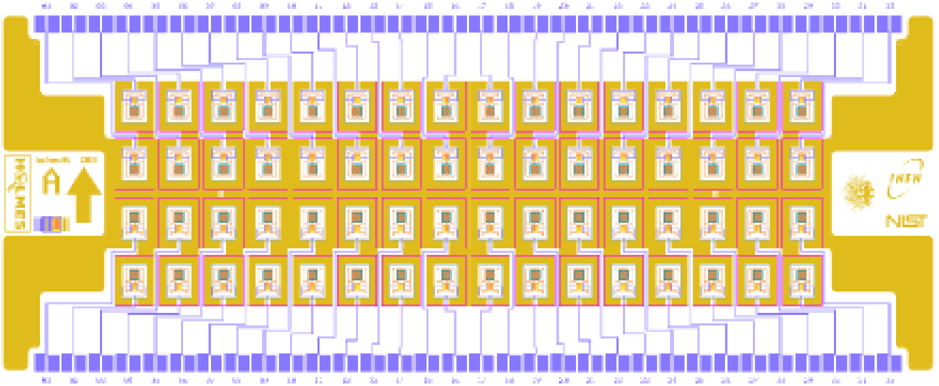


Calculated $^{163}\mathrm{Ho}$ beam FWHM

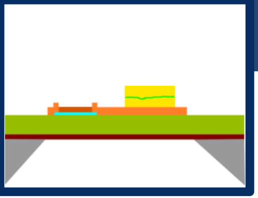
Silicon KOH anisotropic wet etching

- Requires more spacing between pixels
- Succesfully tuned

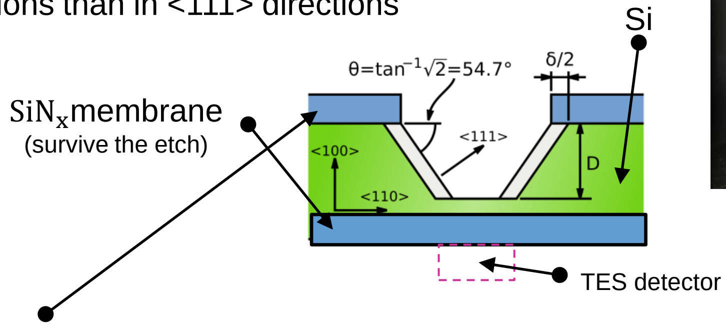


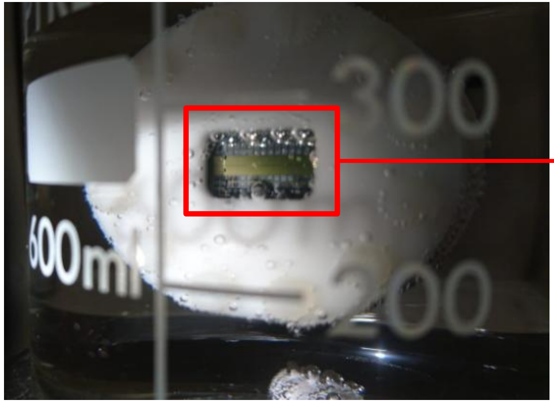


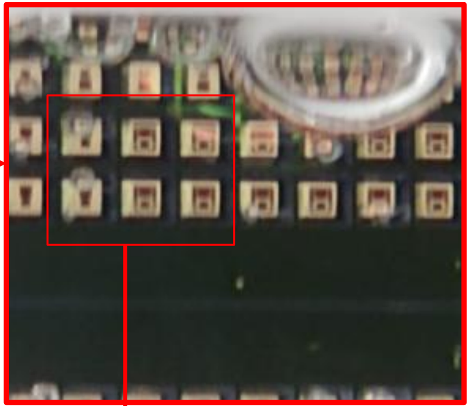
KOH etching test

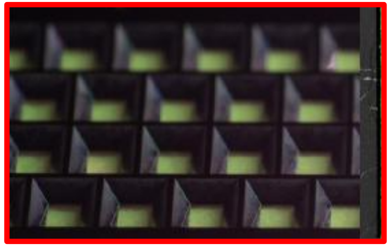


- Potassium hydroxide (KOH) displays an etch rate selectivity dozens of times higher in <100> crystal directions than in <111> directions









- New SiNx mask was designed at NIST to match the thermal performance of the DRIE array

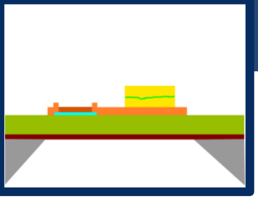
- The TES arrays were placed in a 33% KOH with isopropanol solution

- smoothen the <100> surface
- increase the anisotropy in the etch

Estimated ETCH rate @ 80 ˚C~ 1 µm/minute

(after some tests) **The etching procedure was a success!**

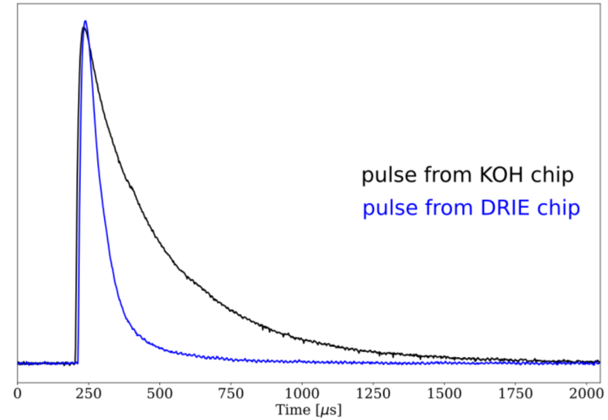
- The temperature was mainteined 65 ˚C <T< 70˚C to avoid turbolent motion in the solution



Pulse decay time

- But…

  … the measured pulses were ~ 3 times slower than the ones from the *baseline* detector (entirely produced at NIST)



Something went wrong during the etching procedures?

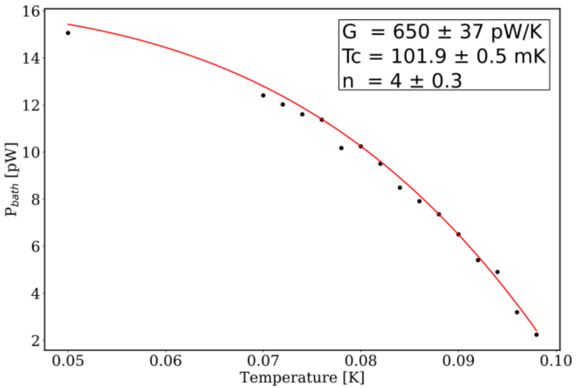
- How to evaluate the thermal conductance of a TES
  (assuming one body model)

Measured with IV curves

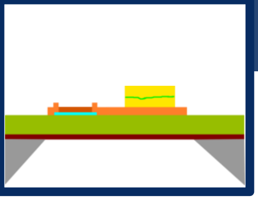
$$P_{bath} = I_{TES}^2 R_{TES}$$

$$P_{bath} = k(T_{TES}^n - T_{bath}^n)$$

$$= \frac{G T_{TES}}{n}\left[1 - \left(\frac{T_{bath}}{T_{TES}}\right)^n\right]$$



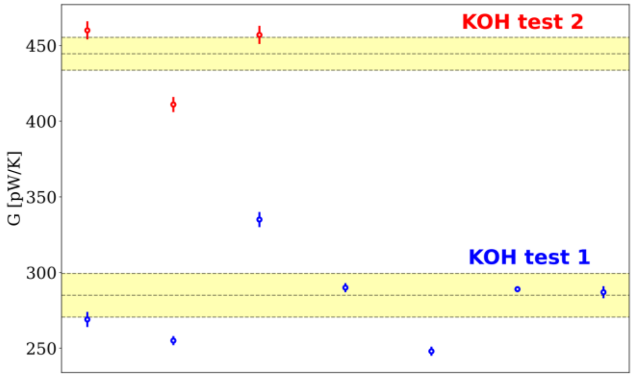
G and dead time



- G was 25-50% lower than the target one (~600 pW/K)

The etched area measured is the correct one

The Tc does not justify such a low G (it should be ~ 70 mK)

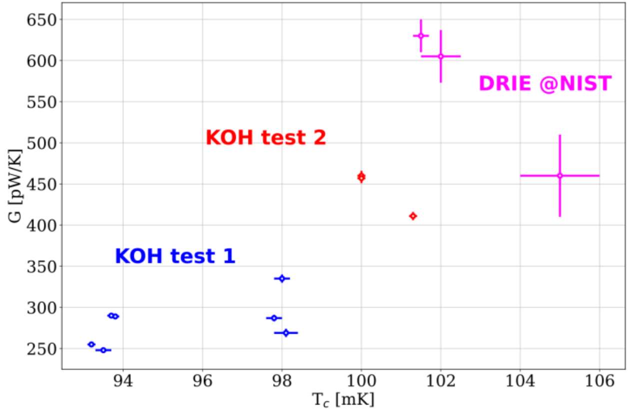


- Issues with the membrane production?

We are currently working with NIST to fix this problem for the future

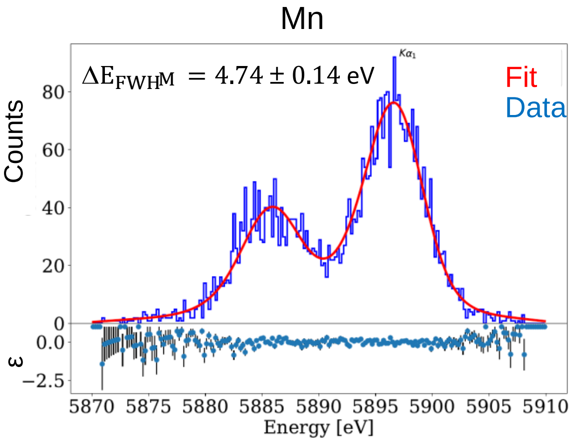
- % of discarded events

	DT (90-30) [µs]	Single detector activity [Hz]	Discarded events [%]
<G> ~ 300 pW/K →	350	300	27
	350	10	1
<G> ~ 600 pW/K →	100	300	8
	100	10	0.3

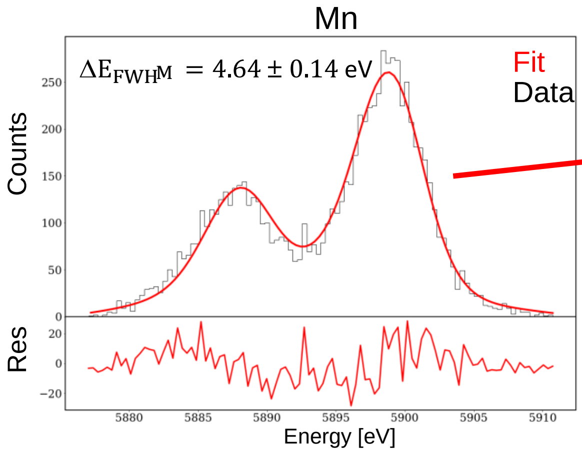


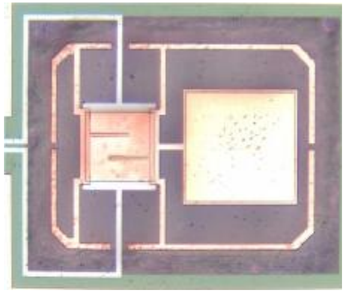
Energy resolution

- Test @Milano with μ-wave multiplexing ($f_{samp} = 500$ kHz)
- Mn (5.9 keV) + fluorescence source (Ca – 3.7 keV; Cl – 2.6 keV ; Al – 1.5 keV)
- Signals RT ~ 15 μs (@Ca)



Detector entirely produced @NIST





Detector with KOH and Au deposition @Milano

<u>The detectors have the same performance in terms of energy resolution</u>

Pulse rise time & fast signals

- Faster the pulse rise time, the better is the time resolution of the device

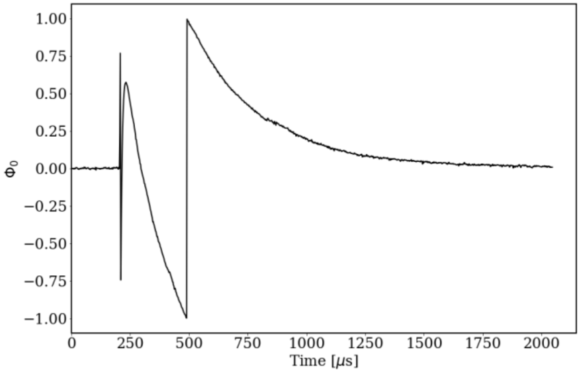
Pile-Up Discrimination Algorithms for the HOLMES Experiment
E. Ferri et al.
Algorithms for Identification of Nearly-Coincident Events in Calorimetric Sensors
B. Alpert et al.

- The pulse rise time can be tuned at will** $\tau_R \propto L$

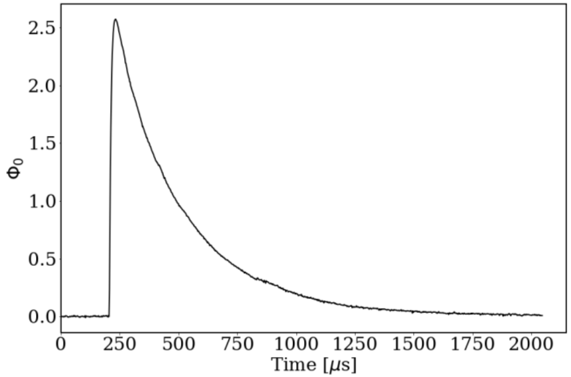
As long as:
- the readout bandwidth is enough to reconstruct the rise edge the signals
- the sampling time is much faster than the signal itself

- With the uMUX readout system, the points in a signal that are acquired are phase differences

Signal read by the ROACH2 FPGA



Signal acquired



Pulse rise time & fast signals

- Faster the pulse rise time, the better is the time resolution of the device

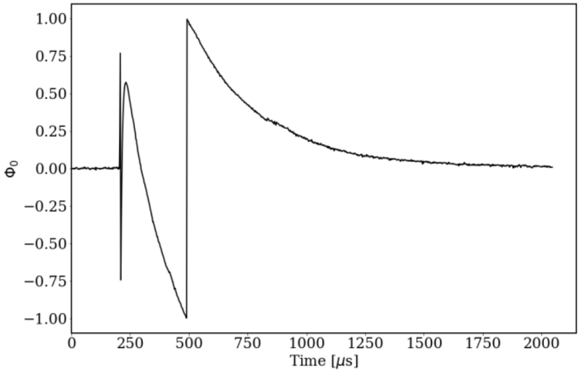
Pile-Up Discrimination Algorithms for the HOLMES Experiment
E. Ferri et al.
Algorithms for Identification of Nearly-Coincident Events in Calorimetric Sensors
B. Alpert et al.

- The pulse rise time can be tuned at will** $\tau_R \propto L$

As long as:
- the readout bandwidth is enough to reconstruct the rise edge the signals
- the sampling time is much faster than the signal itself

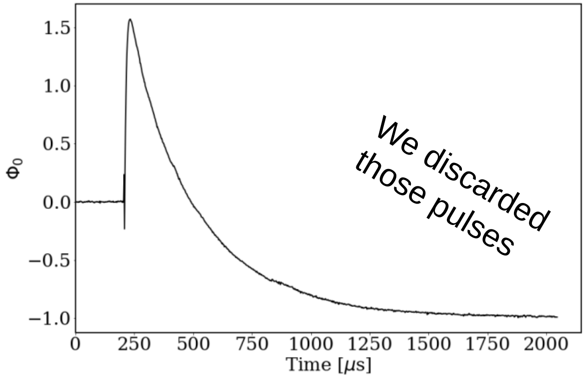
- With the uMUX readout system, the points in a signal that are acquired are phase differences

Signal read by the ROACH2 FPGA

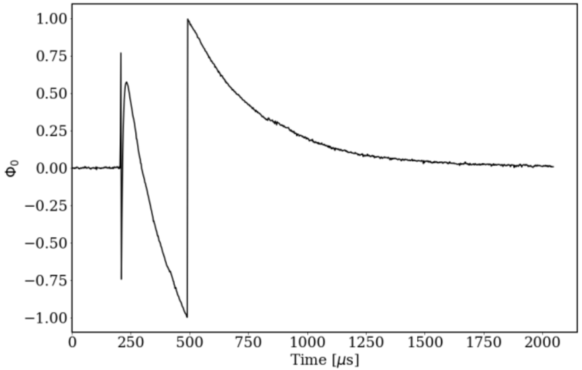


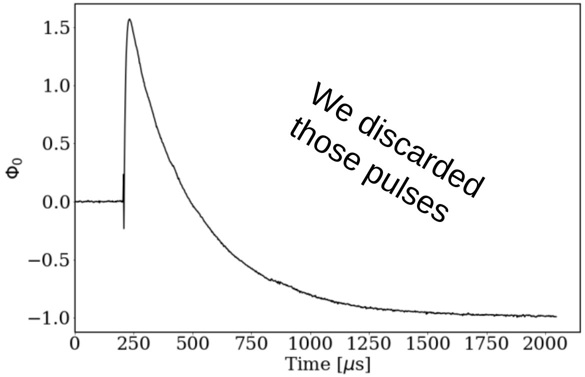
The probability of those events depends on:
- The rise time of the pulse
- The energy of the signal
- The difference between the arrival time of the pulse and the sampling time

Signal acquired

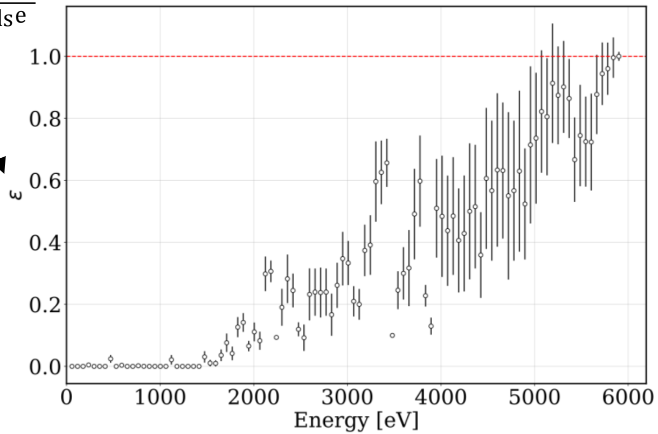


Pulse rise time & fast signals





The probability for those events depends on:
- The rise time of the pulse
- **The energy of the signal**
- The difference between the arrival time of the pulse and the sampling time



- Discarding those events would have introduced a deformation in the final ^{163}Ho spectrum

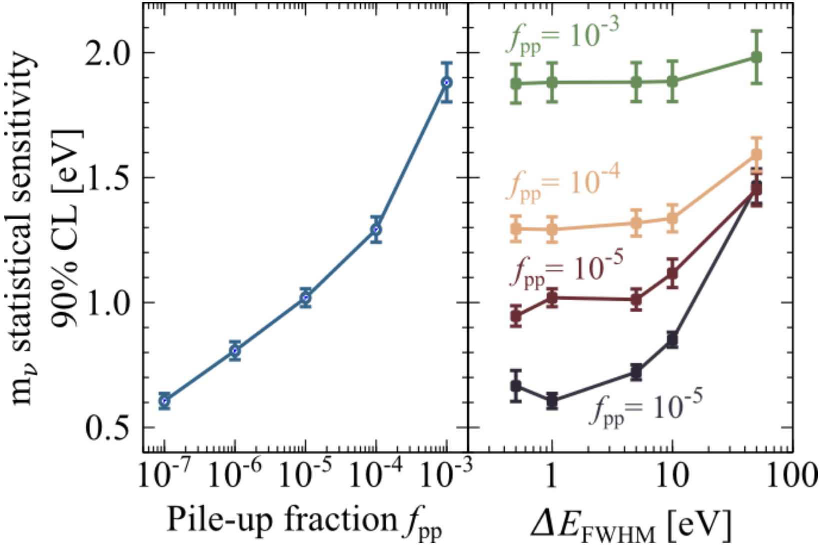
<u>We wrote an algorithm that successfully identifies and corrects the 100% of these pulses</u>

Pulses rise time & pileup discrimination algorithms (work in progress)

- Pile up (pup): two events of energies E_1 and E_2 which occur within a time span shorter than the time resolution of the detector and are recorded as a single event with an energy E ~ $E_1 + E_2$

τ_{eff} =effective time resolution = is the ratio of number of retained pup pulses to single pulse, divided by that ratio of original events, times Δt → Simulated time interval between two consecutive pulses

- With an activity A_{EC} of 300 Hz, random coincidence events are one of the main sources which impairs the ability to identify the effect of a non vanishing neutrino mass



$$f_{pp} = \frac{number\ of\ pup\ pulses}{number\ of\ single\ pulses} \simeq A_{EC} \cdot \tau_{eff}$$

Pulses rise time & pileup discrimination algorithms (work in progress)

- We want to use an approach similar to Alpert's ⟶ but without using an external source with $E_{sourc} \sim E_{ROI}$

Algorithms for Identification of Nearly-Coincident Events in Calorimetric Sensors
B. Alpert et al.

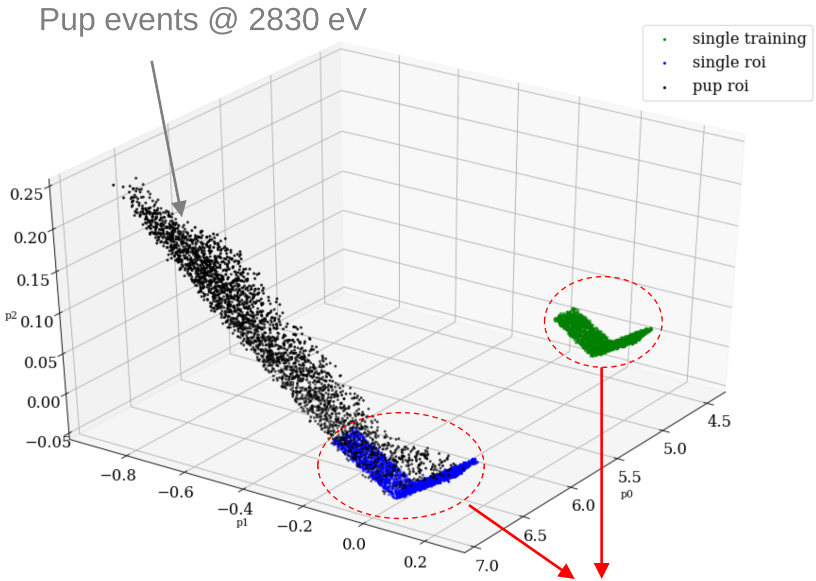
- Briefly (**very briefly**), the idea:

<u>Dimensional reduction:</u>

Using the Singular Value Decomposition (SVD) to switch from a 1024 dimensional space to 4-6 dimensional space

<u>Pup discrimination:</u>

With the SVD basis of this vector space we should be able to recognize between the single pulses and the pup pulses



Single events
- events @2000 eV
- events @ 2830 eV

Conclusion

- We have successfully tested the last steps in the fabrication of the TES array

We are very close to have the Ho implanted in the detectors

- We are ready to measure the first 64 detector array

- We are finishing developing the analysis and signal processing program (in Python , numpy)

(Almost done!)

- A background measurement with 16 TESs will start soon, and will last for ~ 1 month

BACKUP

READOUT uMux

Cose da fare

Misura di pup con autocalibrazione

....