The status of the HOLMES experiment

Luca Origo on the behalf of the collaboration - 7th july 2022

UNIVERSITA' DEGLI STUDI DI MILANO BICOCCA

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Talk outline

1. HOLMES project
2. TES technology
3. TES fabrication
4. TES readout
5. Pulse analysis
6. Parameter estimation
7. Pile-up rejection
8. HOLMES future

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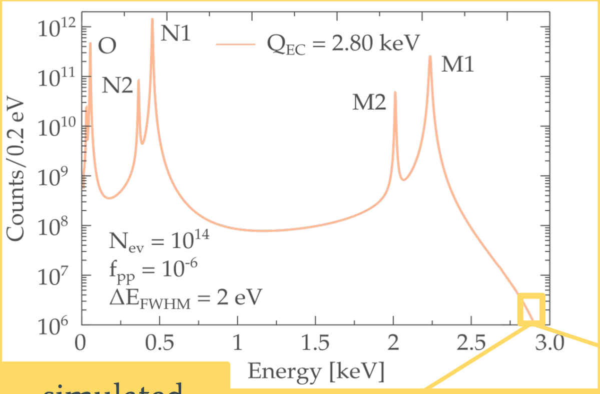
HOLMES project

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

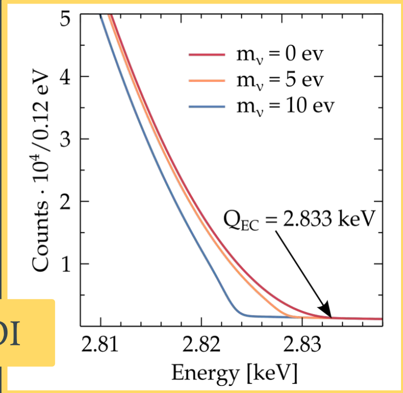
- **direct** & **calorimetric** measurement of the ^{163}Ho electron capture
- the ν_e energy is the only one undetected → purely kinematic assessment of m_ν

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

E_c



simulated spectrum



ROI

a lot of ingredients:

+ very sensitive microcalorimeters (**TESs**)
+ very low temperature (**cryostat ~20mK**)
+ smart readout (**microwaves multiplexing**)

… detector fabrication, holmium implantation, discrimination algorithms, parameter estimation

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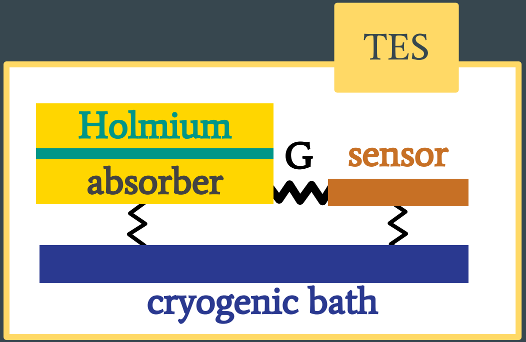
TES technology



+ FWHM(@ 6 keV) ~ 4 eV
+ τ_R ~ 20 µs and τ_D ~ 300 µs
+ suitable for **multiplexing**

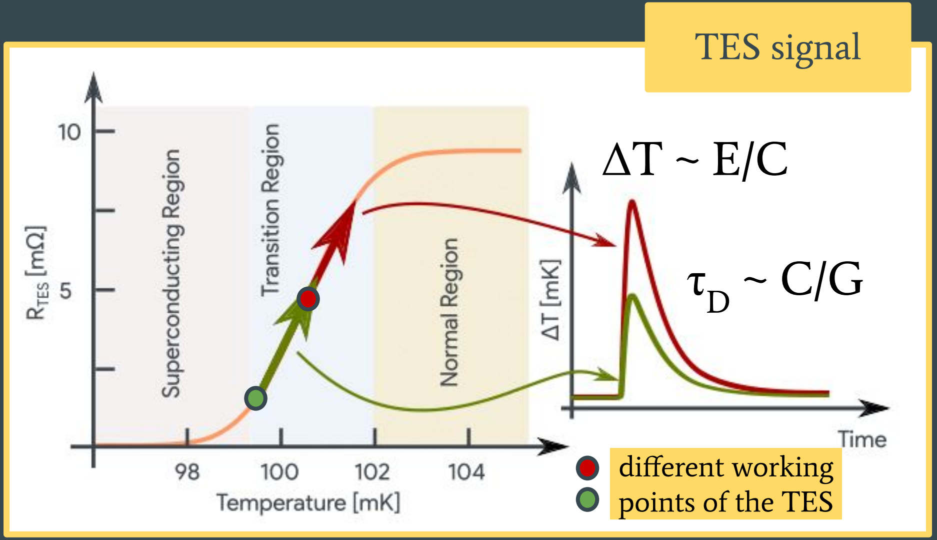
With our pulse analysis:

+ τ_{RES} ~ 1.5 µs
  → lower than t_{sample} ~ 2 µs

Transition Edge Sensors:

- superconducting film coupled to an absorber
  → low T variation leads to high R jumps

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



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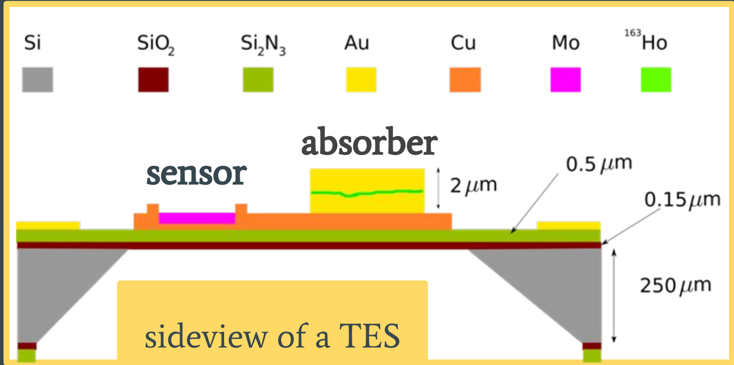
TES fabrication



sideview of a TES

1. Ho implantation
2. Au deposition
3. photoresist lift-off
4. membrane release

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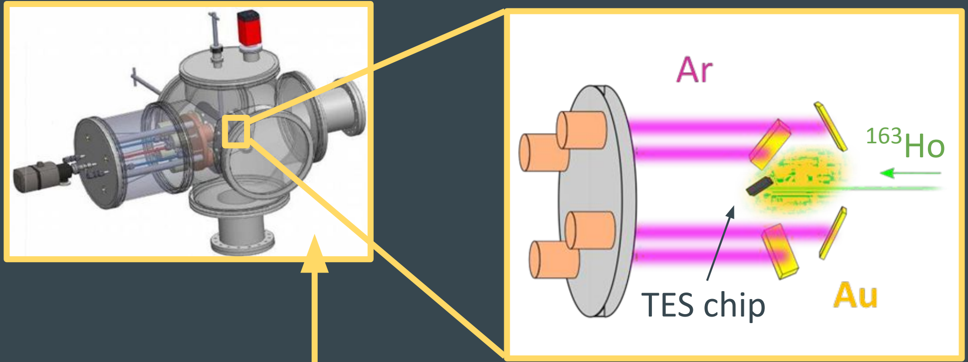
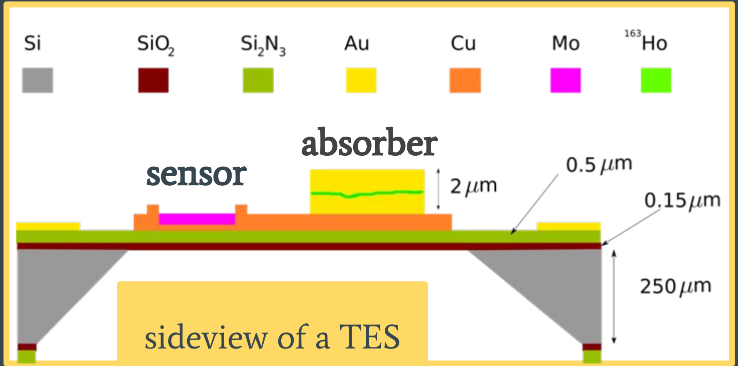
TES fabrication

Target chamber at the end of an electromagnetic mass selector
^{163}Ho atoms are guided through. Implanter set up @ Genova.



1. **Ho implantation**
2. **Au deposition**
3. photoresist lift-off
4. membrane release



sideview of a TES

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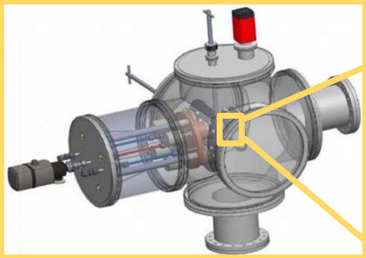
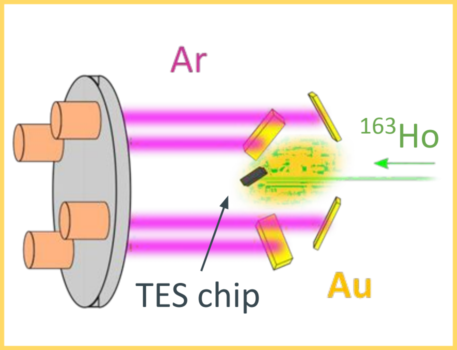
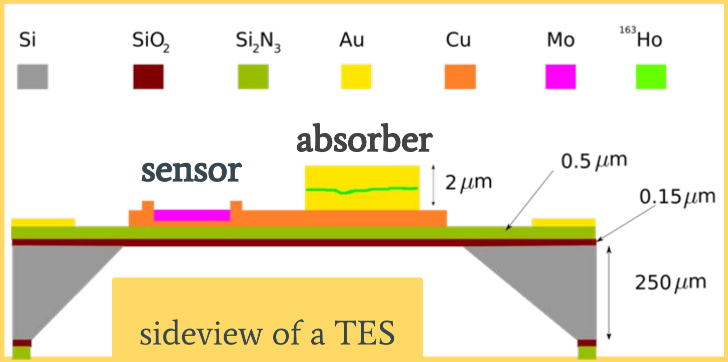
TES fabrication

Target chamber at the end of an electromagnetic mass selector ^{163}Ho atoms are guided through. Implanter set up @ Genova.





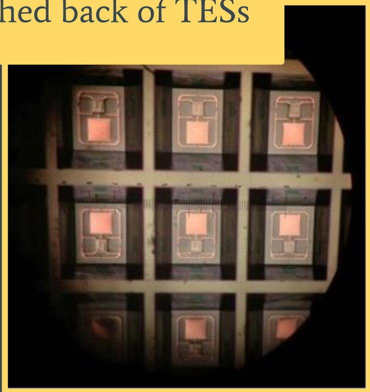


sideview of a TES

1. Ho implantation
2. Au deposition
3. **photoresist lift-off**
4. **membrane release**

Tested @ Milano-Bicocca. Protection film removal and silicon substrate etching to improve thermal coupling to the bath.

etched back of TESs



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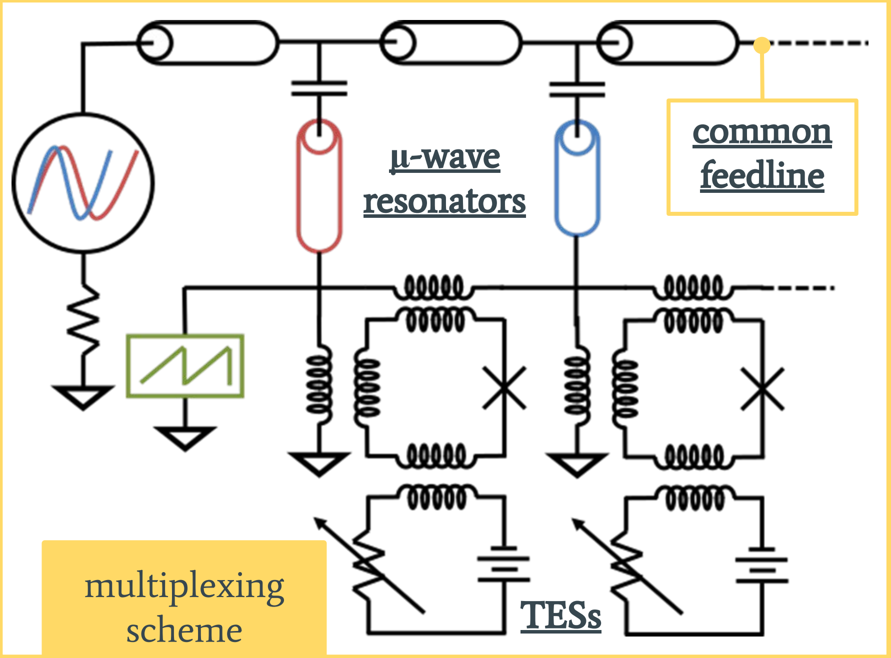
TES readout

It is possible to readout a TES by means of a microwave resonator with a unique f_{res}.

→ **parallel readout is accessible** using N resonators for N detectors, coupled to the same feedline.

$$\Delta E \rightarrow \Delta I_{TES} \rightarrow \Delta f_{res} \rightarrow \Delta \varphi$$

An energy deposition is converted into resonant frequency shift and then into a **phase difference of the traveling signal**.



multiplexing scheme

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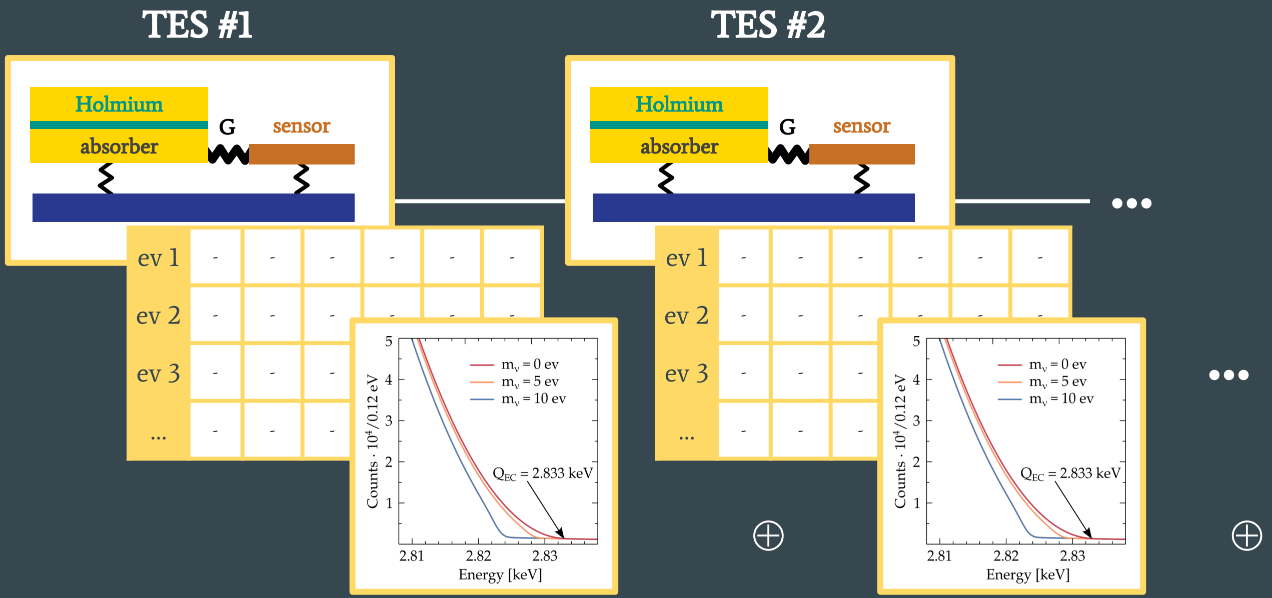
Pulse analysis: data handling

Events collected as arrays in **HDF5 files** and handled with python **matricial operations**.

Each detector can reconstruct the ^{163}Ho EC-spectrum independently.



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Pulse analysis: (first level) data reduction

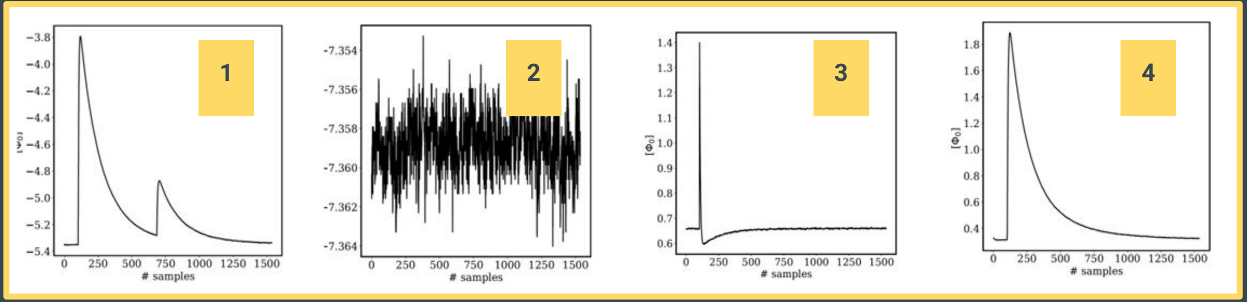
N_{ev} x n_{pts}	pt 1	pt 2	...	...	pt n-1	pt n	t_0
ev 1	-	-	-	-	-	-	-
ev 2	-	-	-	-	-	-	-
...	-	-	-	-	-	-	-
ev N	-	-	-	-	-	-	-

→

N_{ev} x n_{par}	par 1	par 2	...	par n	t_0
ev 1	-	-	-	-	-
ev 2	-	-	-	-	-
...	-	-	-	-	-
ev N	-	-	-	-	-

Data compression by means of parameterization
→ saving **amplitude**, **baseline**, **characteristic times**

Events **tagged** as 'good' or **'bad'**
→ multiple(1), empty(2), strange(3), bad baseline(4)



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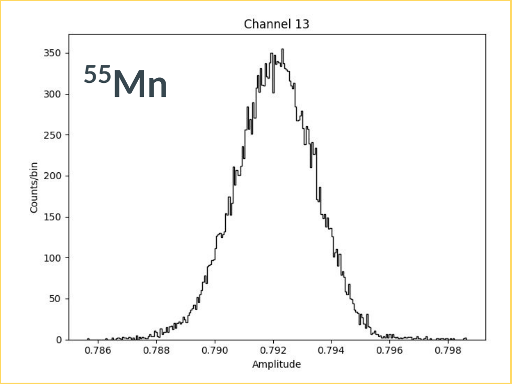
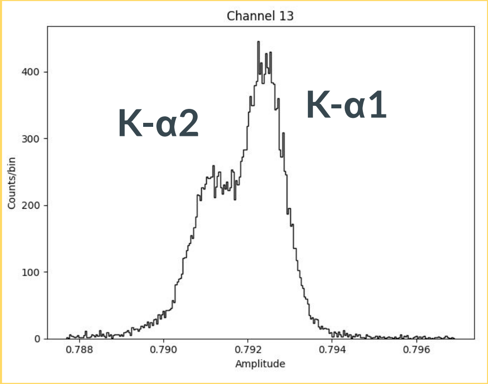
Pulse analysis: energy estimation

Several steps are required to recover a good energy estimation from our TES response
→ best resolution
→ reliable spectrum
→ reliable $\mathbf{m}_\nu$ assessment

- Pass the signals through the optimum filter
- Computing a meaningful arrival time
- Correcting the drift of the detector gain





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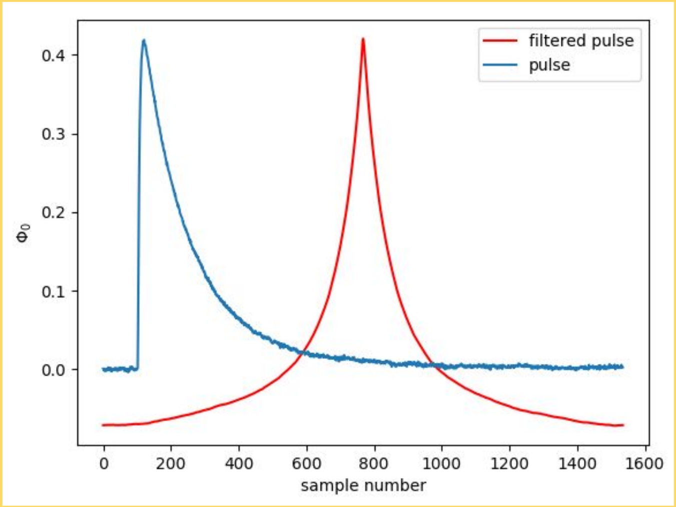
Pulse analysis: energy estimation

Max signal/noise under assumptions:

1. ergodic noise
2. well-chosen sampling window
3. $\mathbf{s}[i] = K(E) \cdot \mathbf{m}[i] + \mathbf{n}[i]$



Pass the signals through the optimum filter

Computing a reasonable arrival time

Correcting the drift of the detector gain

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Pulse analysis: energy estimation

What is the true arrival time of our signals?

$$\Delta t = |t_{true} - t_o|$$

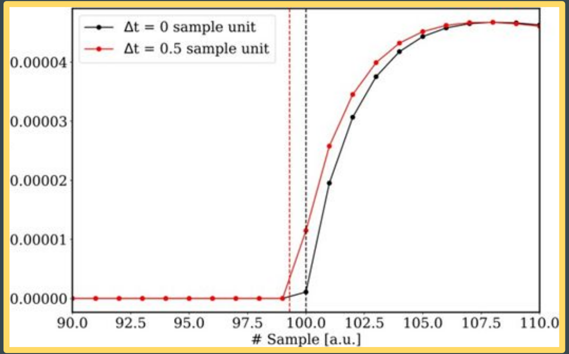
Discrete sampling
→ uncertainty on the rise profile
→ amplitude smearing

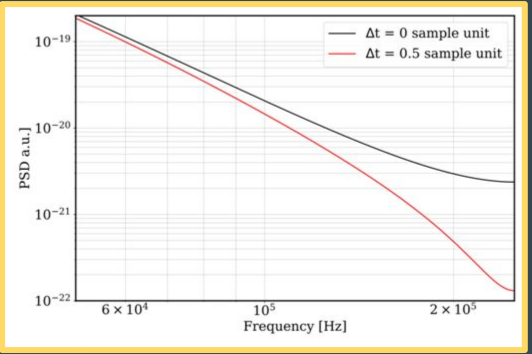
(corrected by smoothing pulses with a moving average)

Pass the signals through the optimum filter

Computing a reasonable arrival time

Correcting the drift of the detector gain





Pulse analysis: energy estimation

TES amplitude response depends on the baseline level

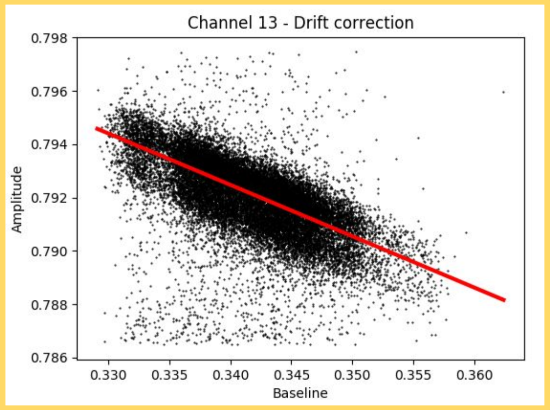
Bath temperature/Voltage bias oscillations
→ Working point variation
→ Observed drift in the data

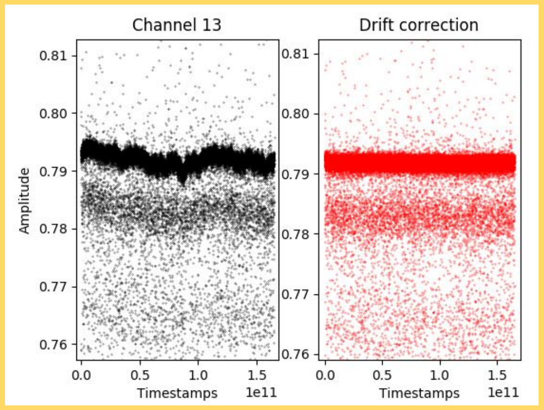
(corrected by fitting with a linear regression)

Pass the signals through the optimum filter

Computing a reasonable arrival time

Correcting the drift of the detector gain





Parameter estimation

Looking forward to the ^{163}Ho spectral fit, a **bayesian** tool for the parameter estimation is under development.

Knowing:

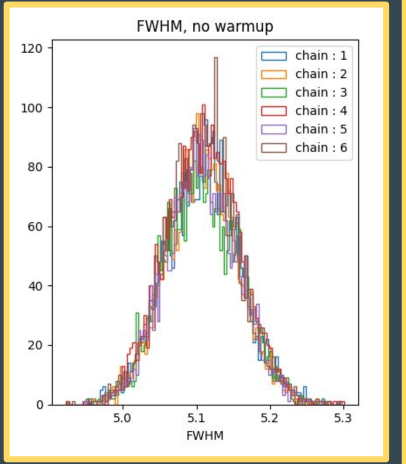
- the **likelihood** of the model
- the parameters **priors**

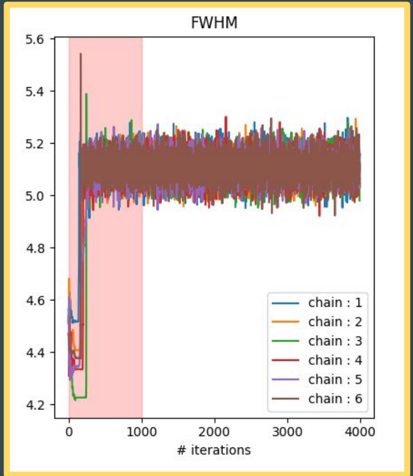
Stan probes the parameter space with the **Markov Chain Monte Carlo technique**.

Once reached a stationary sequence, each iteration is a sample from the **posterior**.

vs Frequentist:

- same performances in simple problems
- natural involvement of systematic errors
- priors ambiguity
- **parameter's 'true value' not fixed**
  → distribution to sample from





Pile-up rejection

HOLMES background sources:

- cosmic rays, natural radioactivity, ^{166m}Ho β-decay
  → negligible/well known contributions
- unresolved pile-up (typically on the rise)
  → complex algorithms required

(assuming ~100Bq/TES)

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Wiener filter:

- + The time profile of the energy deposition is recovered
  → detector response deconvolved
- + Discrimination with shape parameters

DSVP:

- + Discriminating pulses looking at the average data 'morphology'
- + a reduced parameter space is created using a data-set with $N_{good} >> N_{bad}$

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according to simulations:

their combination would provide a time resolution of 1.5 μs

(**pile-up fraction** on the entire EC spectrum **down to 10^{-4}**)

HOLMES future

Looking forward at a **low-dose measurement:**

→ reliable readout ✅
→ stable measurements ✅
} (of 32 TESs)
→ well-tested algorithms ✅
→ detector fabrication ✅
but : ^{163}Ho implantation ❌

HOLMES

2022 → → → 2023

Soon, we will:

- test new Holmium-targets
- find the best operation-mode for the implantation system
- settle a working procedure to handle the radioactive source

Thanks for the attention!

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Backup slides

...

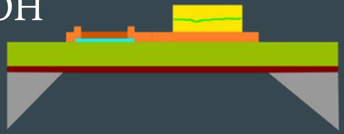
TES fabrication: substrate etching

- how we receive the chip:

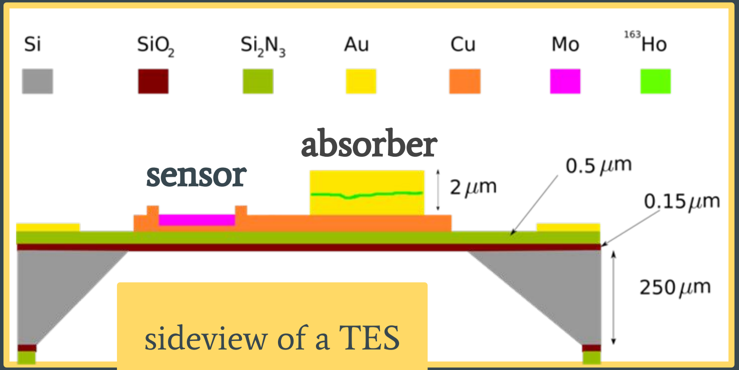
- after implantation/deposition and photoresist lift-off:

DRIE

KOH



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

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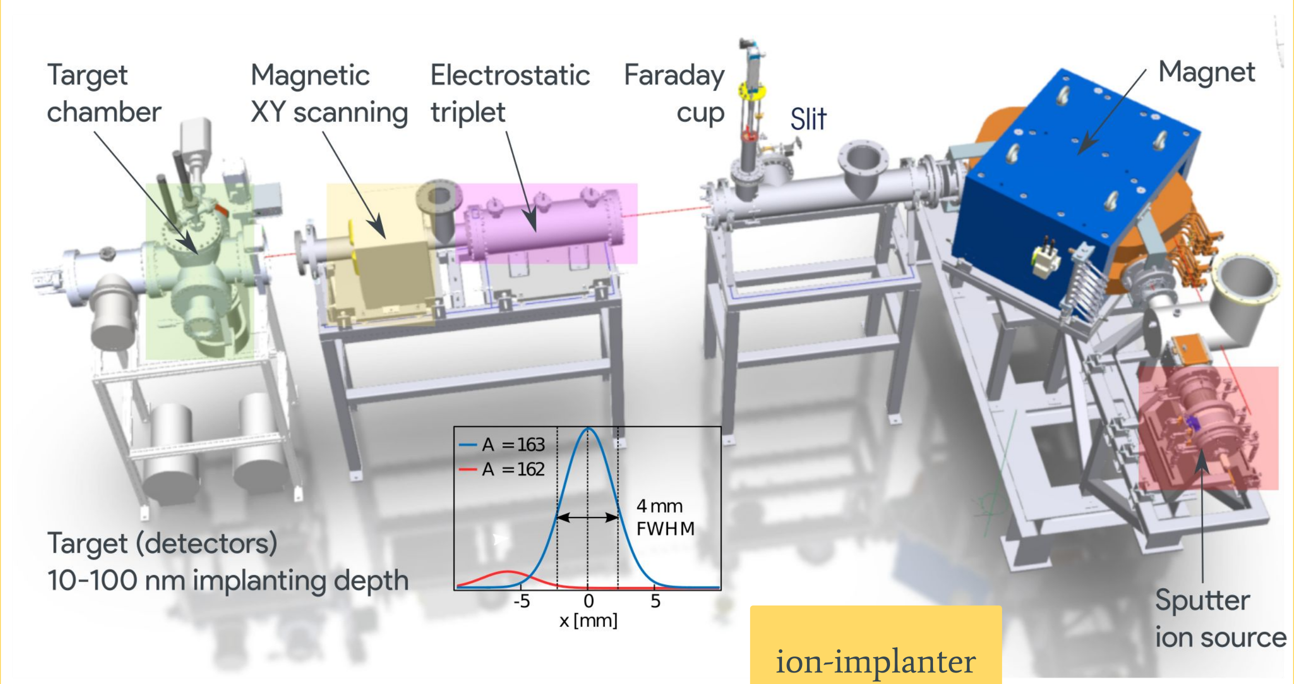
TES fabrication: Ho implantation



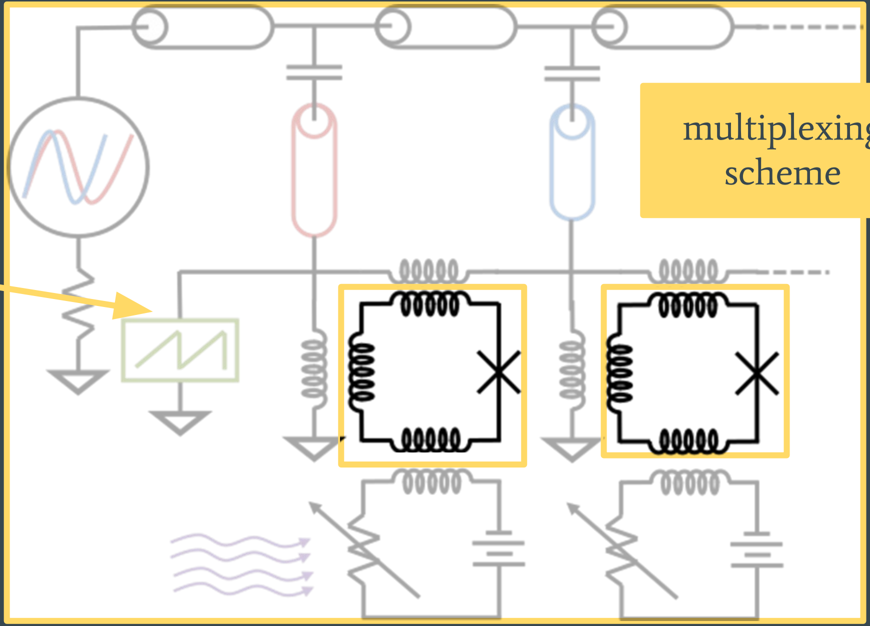
ion-implanter

TES readout: 1/3

$\Delta I_{TES} \rightarrow \Delta\Phi_{SQUID}$

Each TES is coupled to a rf-**SQUID**
- superconductive ring interrupted by a Josephson (insulant) junction
- sensitive magnetometer
- non-linear response

a **sawtooth signal** is used to linearize the SQUID response: $f_{sawtooth} = f_{sample}$



multiplexing scheme

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TES readout: 2/3

$$\Delta I_{TES} \rightarrow \Delta \Phi_{SQUID} \rightarrow \Delta f_{res}$$

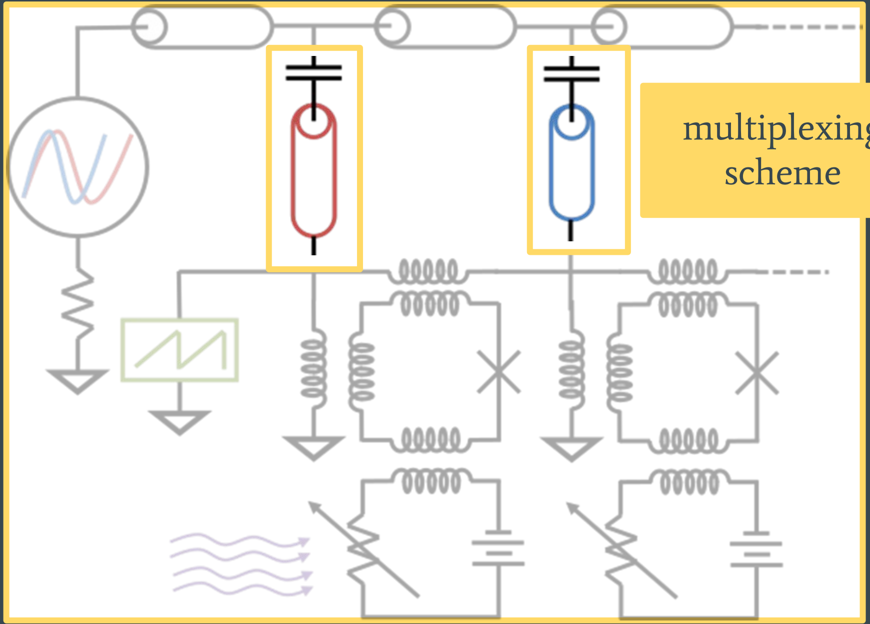
Each TES is coupled with a rf-SQUID

- superconductive ring interrupted by a Josephson (insulant) junction
- sensitive magnetometer
- non-linear response

a sawtooth signal is used to linearize the SQUID response: $f_{sawtooth} = f_{sample}$

Each SQUID is coupled to a **microwave resonator**

- transmission line with unique f_{res}



multiplexing scheme

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TES readout: 3/3

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

Each TES is coupled with a rf-SQUID

- superconductive ring interrupted by a Josephson (insulant) junction
- sensitive magnetometer
- non-linear response

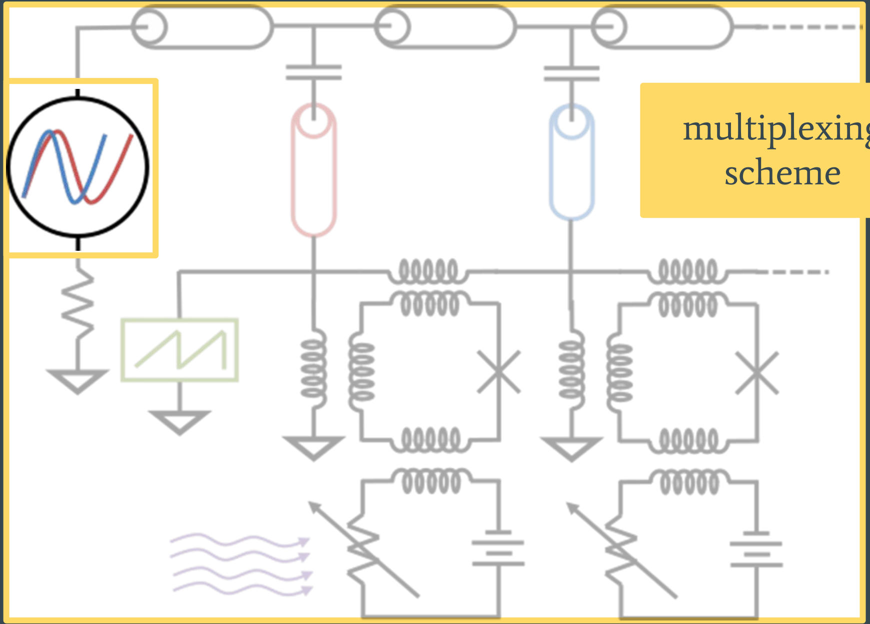
a sawtooth signal is used to linearize the SQUID response: $f_{sawtooth} = f_{sample}$

Each SQUID is coupled with a microwave resonator

- transmission line with unique f_{res}

Each resonator is coupled to a common feedline

- a comb of the resonant frequencies is sent
- the output phase difference is sampled



multiplexing scheme

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Pile-up rejection: Wiener

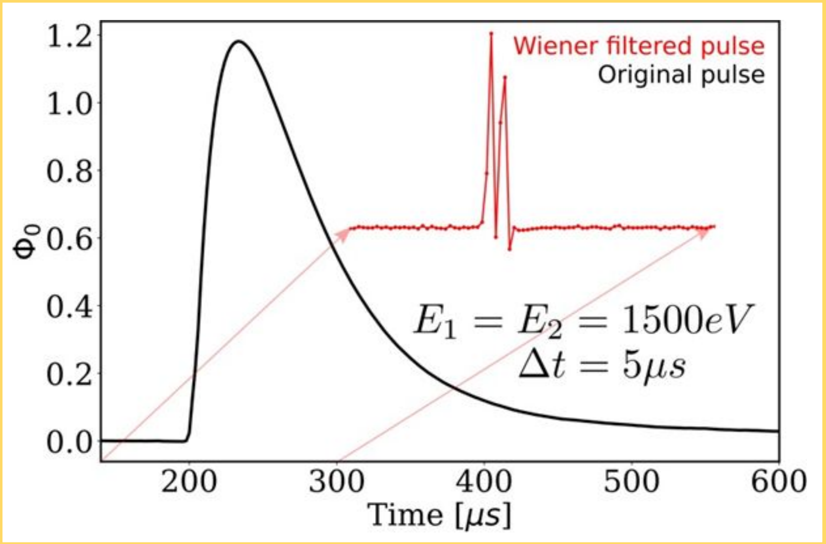
Wiener filter

- Each event is filtered in order to **recover the time profile of the energy deposition**
  ⟶ the detector response is deconvolved

Single event ⟶ single delta pulse

Pile-up event ⟶ multi-delta/broadened delta pulse

- discrimination through **Wiener shape parameters**: delta width at a given height, delta points above the latter and delta maximum



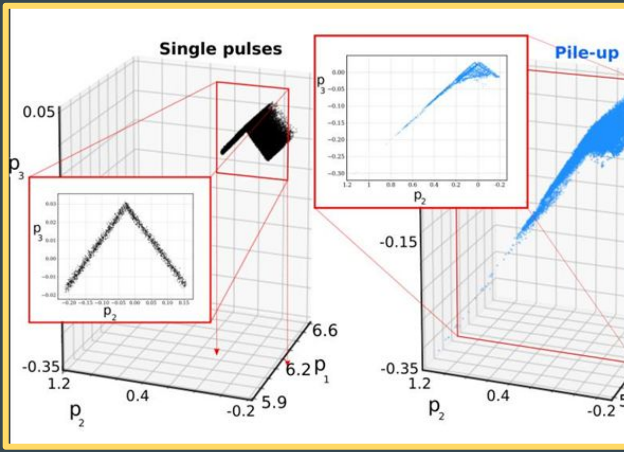
Pile-up rejection: DSVP

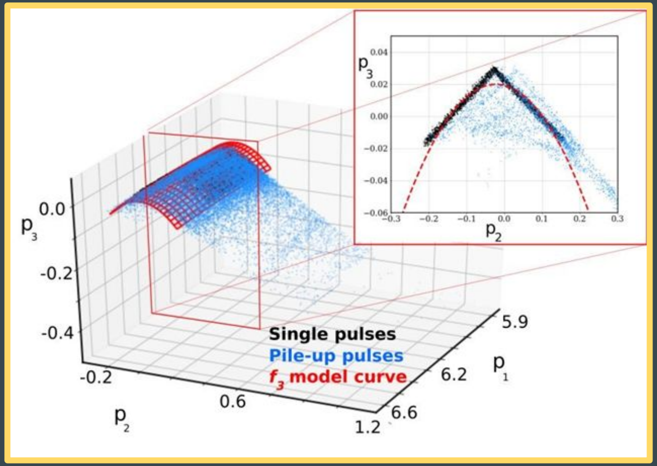
Discrimination through Singular Vectors Projections

- Unsupervised learning technique that discriminate pulses **looking at the average data 'morphology'**
  - a data-set with $N_{good} >> N_{bad}$ is required to create a reduced parameter space

- Iterative procedure that
  - **finds discrimination (hyper-surfaces) thresholds**
  - removes events different from the average

- More on this technique is presented [**Here**].





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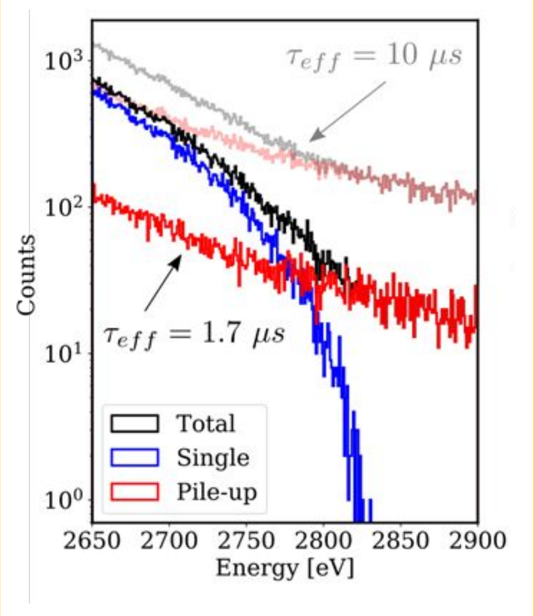
Pile-up rejection: simulations

To evaluate the behavior of our algorithms, we define an **effective time resolution** τ_{eff} :

$$\tau_{eff} = (f_{pp}|_{after} \,/\, f_{pp}|_{before}) \cdot \delta\tau$$

Simulations assume the first level data reduction reached a time resolution ($\delta\tau$) of 10μs, corresponding to f_{pp}~2 (@ **300Hz/TES**)



- **Inside the ROI**:
  - τ_{eff} after **Wiener** ~ 3μs (f_{pp}~0.6)
  - τ_{eff} after **Wiener** + **DSVP** ~ 1.5μs (f_{pp}~0.3)
- The pile-up fraction **over the entire EC spectrum** decreases from 10^{-3} to 10^{-4}