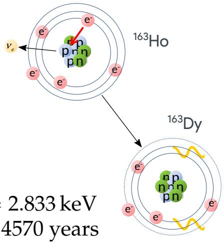
Status of HOLMES, an experiment for measuring the neutrino mass

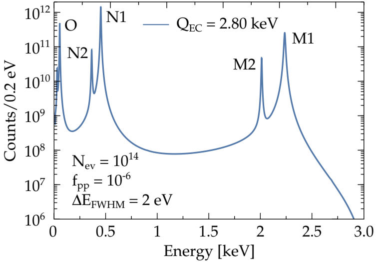
Elena Ferri

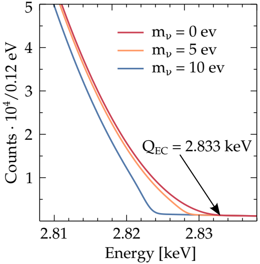
INFN of Milano-Bicocca
on behalf of HOLMES collaboration

$$^{163}\mathrm{Ho} + e^- \rightarrow {}^{163}\mathrm{Dy}^* + \nu_e(E_c)$$ electron capture from shell $\geqslant$ M1



$Q_{EC} = 2.833\,\mathrm{keV}$
$\tau_{1/2} \simeq 4570$ years





proposed for the first time
by A. De Rujula e M. Lusignoli in 1982
Phys. Lett. 118B (1982) 429
Nucl. Phys. B219 (1983) 277-301

- Calorimetric measurement of Dy atomic de-excitations (mostly non-radiative)

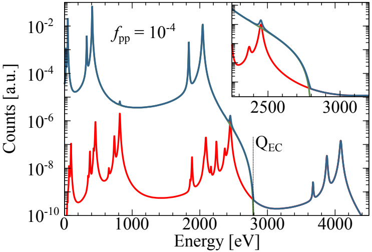
  $\Rightarrow$ measurement of the entire energy released except the ν energy

- rate at the end point depends on $(Q - E_{M1})$: the proximity to M1 resonance peak enhances the statistics at the end point (i.e. sensitivity on m_ν)

- Searching for a tiny deformation caused by a non-zero neutrino mass to the spectrum near its end point

^{163}Ho: pile-up spectra

$$S(E_c) = \left[N_{ev}(N_{EC}(E_c, m_\nu) + f_{pp} \times N_{EC}(E_c, 0) \otimes N_{EC}(E_c, 0)) + B(E_c)\right] \otimes R_{\Delta E}(E_c)$$



N_{ev}	: total number of events
$N_{EC}(E_c, m_\nu)$	: ^{163}Ho spectrum
$B(E)$	: background energy spectrum
$R_{\Delta E}(E_c)$	: detector energy response function
f_{pp}	: fraction of pile-up events
$R_{\Delta E}(E_c)$	: detector energy response function
ΔE	intervall of energy

more details on
Eur. Phys. J. C 74 (2014) 3161

- Pulse pile-up occurs when multiple events arrive within the temporal resolving time of the detector
- Unresolved pile-up events close to the end-point impairing effect on the end-point measurement
- The ^{163}Ho pile-up events spectrum is quite complex and presents a number of peaks at the end-point
- To resolve pile-up:
  - Detector with fast signal rise-time τ_{rise}
  - Pile-up recognition algorithm (i.e. Wiener filter, Singular Value Decomposition)

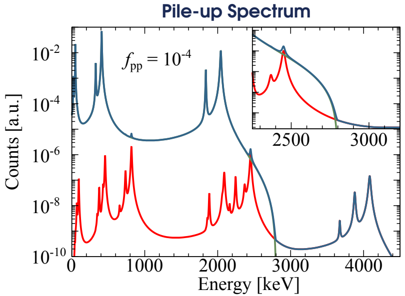
The HOLMES experiment (ERC-2013-AdG no. 340321)

The m_ν statistical sensitivity has:

- **Strong** dependence on statistic: $\Sigma(m_\nu) \propto N_{events}{}^{1/4}$
- **Strong** dependence on pile-up: $f_{pp} \simeq A_{EC} \cdot \tau_{res}$

  (A_{EC}: pixel activity, τ_{res}: time resolution)
- **Weak** dependence on energy resolution ΔE;

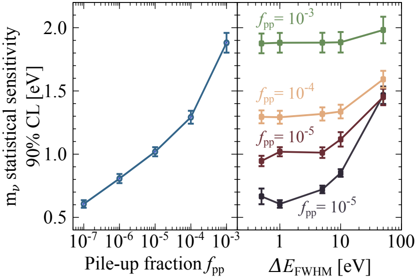
Multiplaxable detectors with fast response are required



HOLMES

Neutrino mass determination with a sensitivity as low as ≈ 1 eV

- Microcalorimeters based on Transition Edge Sensors with ^{163}Ho implanted Au absorber
- Pixel activity of $A_{EC} \sim 300$ Bq/det
- Energy resolution: $O(eV)$
- Time resolution: $\tau_{res} \sim 3\ \mu s$ ($\tau_{rise} = 10 - 20\ \mu s$);
- 1000 channels for $3 \cdot 10^{13}$ events collected in $T_M = 3$ years



more details on
Eur. Phys. J. C (2015) 75: 112

^{163}Ho production and chemical purification

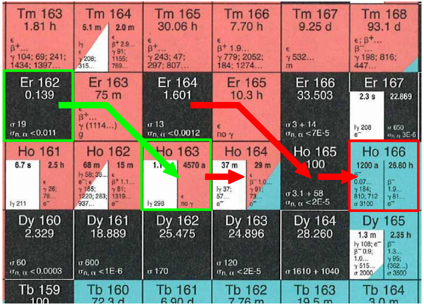
Production

^{163}Ho production from ^{162}Er neutron activation

$$^{162}Er(n,\gamma)^{163}Er \qquad \sigma_{therm} \approx 20b$$

$$^{163}Er + e^{-} \rightarrow ^{163}Ho + \nu_e \qquad \tau_{1/2} \approx 75m$$

- ^{162}Er irradiation at ILL nuclear reactor @ Grenoble: high thermal n flux
- cross section burn up $^{163}Ho(n,\gamma)^{164}Ho$ not negligible (~200 b)
- $^{165}Ho(n,\gamma)^{166m}Ho$ (β,$\tau_{1/2} \sim 1200y$) from Ho contamination or ^{164}Er



Purification

Chemical purification @ PSI before and after the irradiation

- radiochemical separation with ion-exchange chromatography
- efficiency better than 79%
- Expected ^{166m}Ho contamination fraction: $\sim 10^{-3}$

Sample processed

Enriched Er_2O_3 samples irradiated @ ILL, pre and post processed @ PSI:

- 25 mg, 55 days irradiation, A(^{163}Ho) ~ 5 MBq
- 150 mg, 53 days irradiation, A(^{163}Ho) ~ 38 MBq
- 544 mg, 50 days irradiation, A(^{163}Ho) ~ 120 MBq

* ~ 100 MBq enough for R&D and 500 pixels

Ion implanter designed to embed Ho inside the detectors absorbers and to perform a mass separation of the ^{163}Ho from the other contaminants.

- extraction voltage 30-50 kV $\rightarrow$ 10-100 nm implant depth
- ^{163}Ho/^{166m}Ho separation better than 10^5

Main components:

- Ar penning sputter ion source
- magnetic dipole mass analyzer ($B_{max} = 1$ T)
- faraday cup and slit
- target chamber for Au co-evaporation

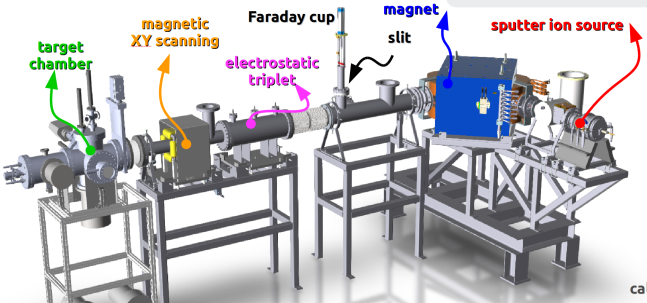
Au co-evaporation:

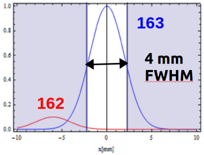
- to fully encapsulate the source
- to compensate the saturation of the ^{163}Ho concentration in the absorber
- to avoid oxidation
- heat capacity

Target chamber:

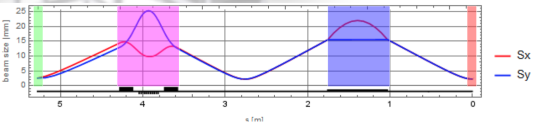
- 4 COMIC microwave sources
- 4 Ar beams hit on 4 Au targets

$\rightarrow$ 4 in order to increase the deposition rate and uniformity



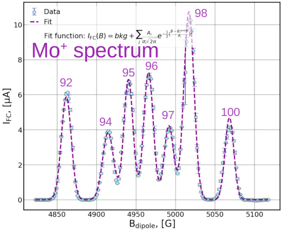


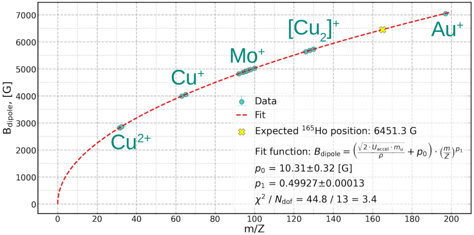
calculated beam size



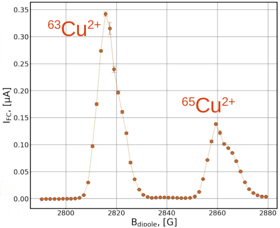
Ion implanter calibration

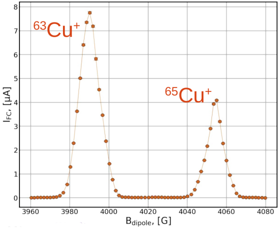
Magnetic field vs mass-to-charge ratio calibration with Cu, Au and Mo peaks.

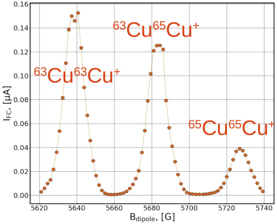




- Cu/Au from sputter target/holder
- Mo from the anode
- The source produces also multiple-ionized and dimeric ions from the same material, which can also be used for calibration







for more details
Mariia Fedkevych's talk @ NuMass 2022

Ion source sputter target

Efforts are put to build the most suitable target for the Ho sputtering

$\rightarrow$ different techniques for target fabrication are tested

Molecular plating

Electrodeposition of Ho complexes in an organic solvent at high voltages with high uniformity and efficiency (>90%)

Drop-on-demand inkjet printing

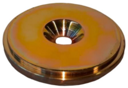
put droplets of solution containing compound and let solvent evaporate to deposit the dissolved compound

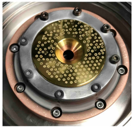
Sintered targets

$Ho(NO_3)_3$ in a metallic mixture of Zr and Y fine-grained powder preparade pressed at 350 bar/cm^2 and baked at 950°C

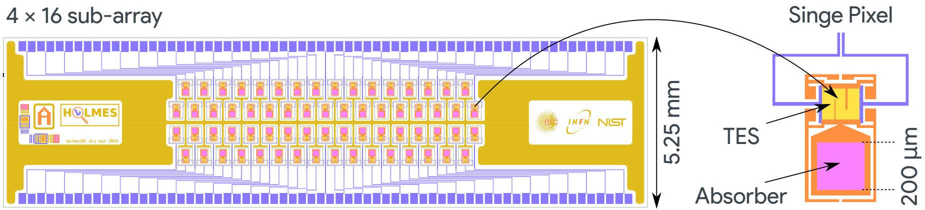
Coupled reduction

Ho reduction and diffusion into backing material due to thermodynamically favourable formation of intermetallic compound

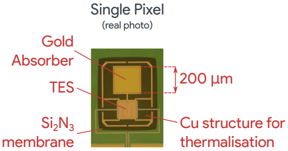




With **sintered target** we obtained the best current-stability:O(200) nA over 15 h!

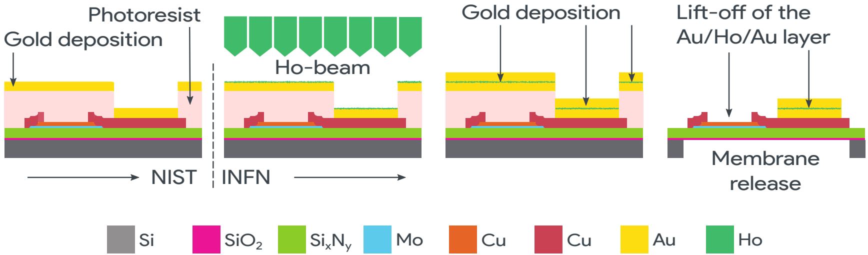


- Mo/Cu TES coupled to Gold absorbers where ^{163}Ho will be ion-implanted
- 2 µm Gold thickness for full e/γ absorption
- Side-car design to avoid TES proximitation effect
- Thermal conductance G engineering for τ_{decay} control
- 4 × 16 linear sub-array designed for high implant efficiency and low parasitic L
- Optimized design for high speed and high resolution:



$$\text{Specs @ } 2.8\,\text{keV} : \Delta E_{FWHM} \simeq 3-4\,\text{eV}\,,\ \tau_{rise} \simeq 10\ \mu\text{s}\,,\ \tau_{decay} \simeq 100\ \mu\text{s}$$

^{163}Ho isotopes embedded in metallic absorbers (through ion-implantation)



- Fabrication in two steps:
  - NIST: TES fabrication with 1 μm Au absorber
  - INFN: ^{163}Ho implantation, final deposition of 1 μm Au and SiN membrane release
- final micromachining step definition in progress

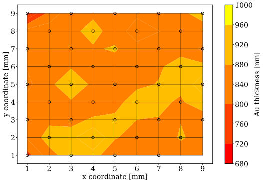
  ⇒ KOH vs DRIE machining

HOLMES: detectors fabrication process (cont.)

Au deposition

1 μm of Au deposited

- with Ion beam sputter system
- at rate of around 52 nm/h
  → about 20 h for 1 μm
- gold thickness uniformity
  → $\sigma_t / t \sim 4\%$

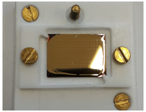


Lift-off

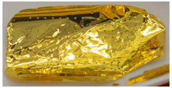
Removal of the resist mask (7 μm thickness)

- sample in acetone at 40°C for 24 h

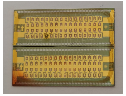
After the lift-off, the Au deposited remains only on the absorber:
→ Minimal crowning and almost isotropical deposition thanks to the 4 ion beam sources



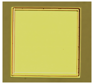
Au removed with the lift-off



Arrays after the lift-off



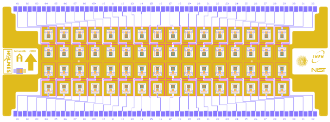
Zoom of a single absorber

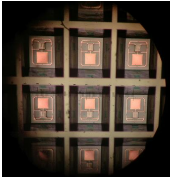


Membrane release

KOH

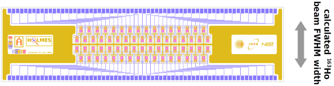
- Anisotropic wet etching
- Requires more spacing between pixels
- Sucessfully tested

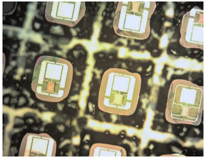




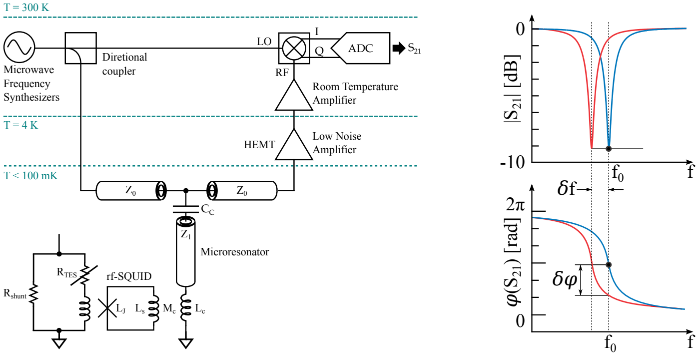
DRIE

- Silicon Deep Reactive Ion Etching
- Best for close packing
- High implant efficiency
- Not yet tuned

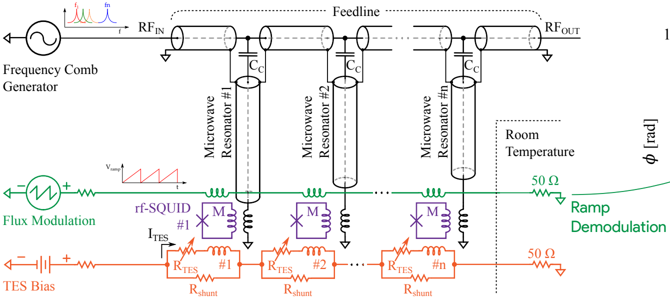


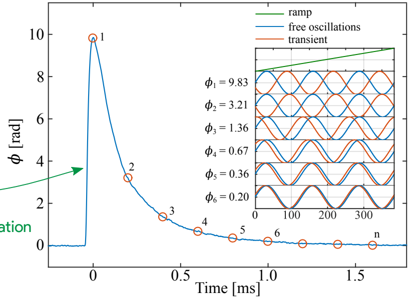


HOLMES TESs readout is based on microwave rf-SQUID multiplexing



- rf-SQUID inductively coupled to a dc-biased TES and to a high-Q superconducting $\lambda/4$-wave resonator
- Change in TES current $\Rightarrow$ change in the input flux to the SQUID
- The rf-SQUID transduces a change in input flux into a variation of resonant frequency and phase
- Each micro-resonator can be continuously monitored by a probe tone

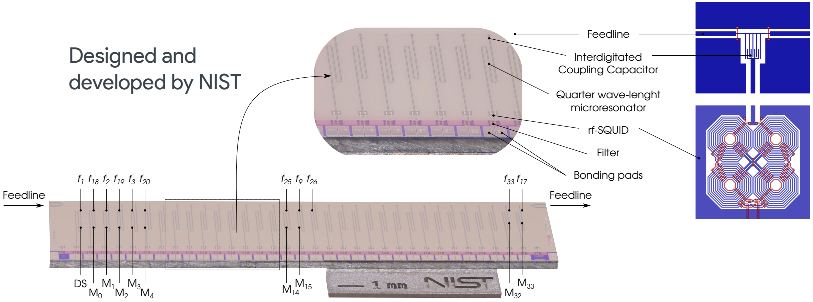




- By coupling many resonators to a single microwave feedline it is possible to readout multiple detectors
- Sensors are monitored by a set of sinusoidal probe tones (frequency comb)
- At equilibrium, the resonator frequencies are matched to the probe tone frequencies, and so each resonator acts as a short to ground
- The ramp induces a controlled flux variation in the rf-SQUID, which is crucial for linearizing the response
- Large multiplexing factor (> 100) and bandwidth, currently limited by the digitizer bandwidth

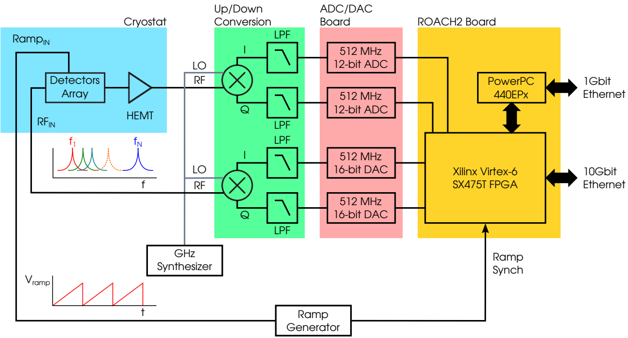
The Multiplexing chip

The core of the microwave multiplexing is the multiplexer chip



- Superconducting 33 quarter-wave coplanar waveguide (CPW) microwave resonators covering 500 MHz in the 4-8 GHz frequency range
- 200 nm thick Nb film deposited on high-resistivity silicon ($\rho > 10\,k\Omega\cdot cm$)
- each resonator has a trombone-like shape with slightly different length
- 2 MHz bandwidth per resonator
- separation beetween resonances 14 MHz (to prevent cross-talk)
- resonance depth greater than 10 dB
- squid equivalent noise less than $2\mu\phi_o/\sqrt{Hz}$

HOLMES DAQ with the ROACH2

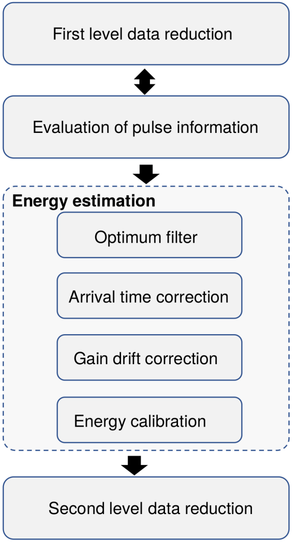


- Software Defined Radio with the open system ROACH2 (Casper collaboration)
- ADC BW 550 MHz
- real time pulse reconstruction

  $\rightarrow$ at the moment readout available for 64 channels

Multiplexing factor proportional to the target rise time

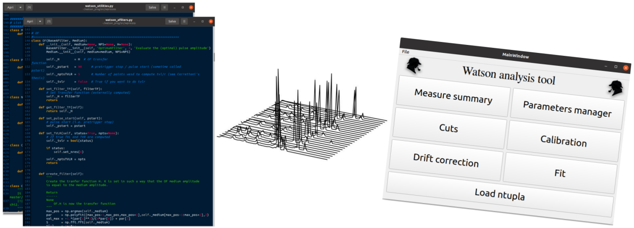
- $n_{TES} \approx 3.4 \cdot \tau_{rise}$
- requiring $\tau_{rise} = 10\mu s$



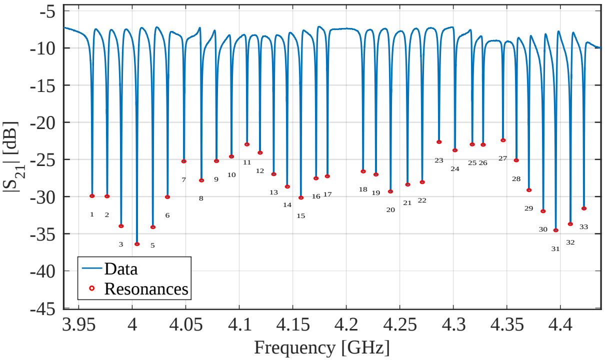
- Robust analysis is mandatory for achieving the expected microcalorimeter intrinsic energy resolution.
- The data from each pixel need to be processed separately.

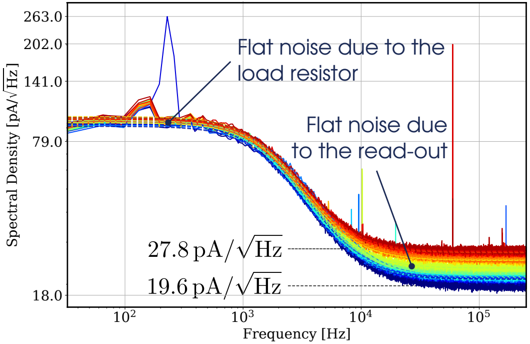
Watson toolkit

- Software for low temperature detector data analysis
- Object oriented programming. Written in python (numpy and scipy)
- Fast, easy to read, easy to fix code
- GUI with QT5 for handy day to day operations
- Data are stored in hdf5 (hierarchical, filesystem-like data format)



Multiplexing: characterization results





		Required	Measured
Resonators bandwidth	Δf_{BW} [MHz]	2	2 ± 1
Resonators spacing	Δf [MHz]	14	14 ± 1
Resonators depth	ΔS [dB]	> 10	29 ± 6

All the microresonator parameters match the HOLMES specification

Improved read out noise

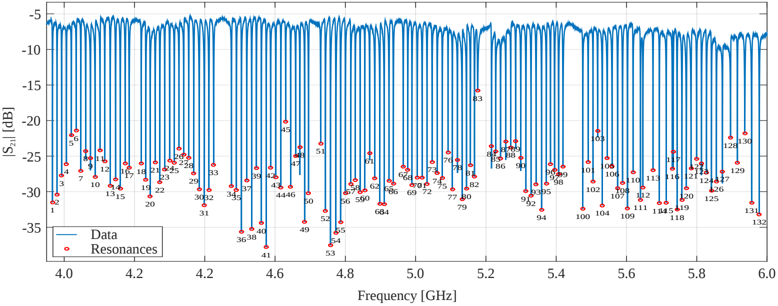
$\rightarrow n_s = (23 \pm 2) pA/\sqrt{(Hz)}$

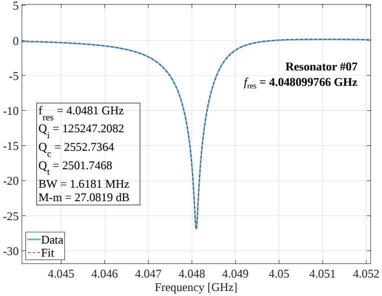
Previous work

$\rightarrow n_s = (26 \pm 7) pA/\sqrt{(Hz)}$

more details on
IEEE TAS 31 (2021) 5, 2100205

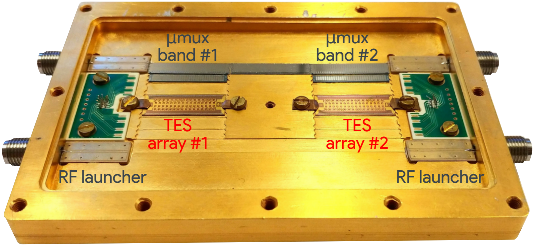
Forward transmissiom S_{21} of 4 different band chips wired in series and an example of resonce fit

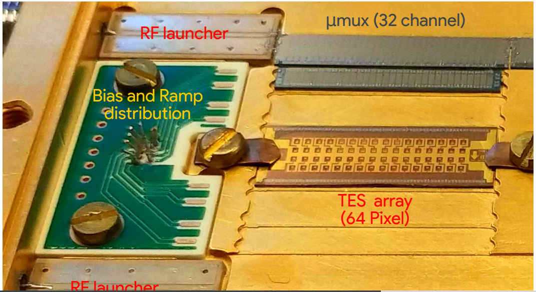




Four µmux in series are able to cover a wide frequency range from 4 to 6 GHz

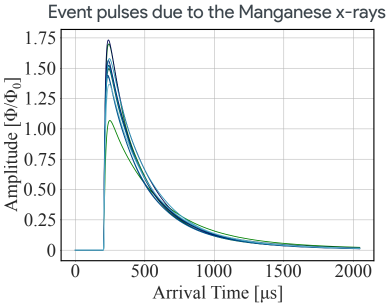
HOLMES: test on the processed detectors

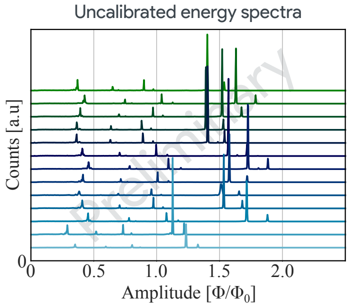


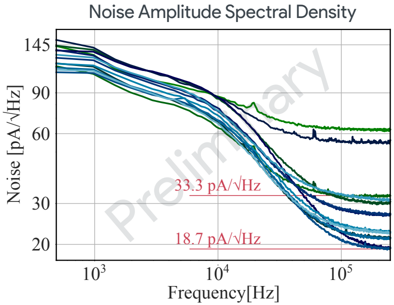


- Holder designed to host 128 Channels:
  - $2\times$ (4×16) sub arrays
  - $4\times$ μmux multiplexer chips with 4 bands
- 8 holders will cover the entire HOLMES in its final configuration (1024 channels);
- Preliminary low temperature tests performed with fully processed arrays (with KOH):
  - detector with (1 μm) absorber at NIST
  - absorber finalized (1 μm) at MIB
  - wet etching at MIB
- 32+32 TES pixels bonded (half of the available)
- Absorbers without the ^{163}Ho implanted
- New SDR firmwares for 16 and 32 channels:
  16-channel version fully operational
  32-channel version under testing
- New up/down-conversion system fully operational

HOLMES: detectors characterization with a fluorescence source







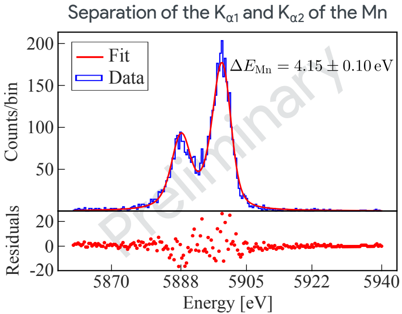
- non implanted detectors with KOH membrane release
- 13/16 working detectors (3 detectors with problematic resonators)
- Calibration run performed with a primary ^{55}Fe source faced to different targets
- Calibration lines:

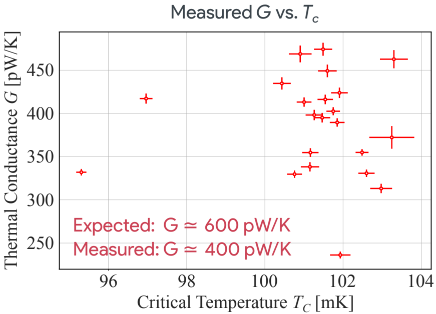
  ^{55}Mn (5.9 keV) ^{40}Ca (3.7 keV) ^{40}Cl (2.6 keV) ^{27}Al (1.5 keV)

Measured read out noise
$n_s \sim (19 - 33)\, pA/\sqrt{Hz}$

- Compatible with the previous prototypes Eur. Phys. J. C (2019) 79:304
- Two channels with higher noise due to not optimal rf-SQUID oscillations

HOLMES: detectors characterization results





For the best detector: $\Delta E_{Mn} = 4.15 \pm 0.10\,\text{eV} @ 5.9\,\text{keV}$

- Energy resolution in the (4 - 6) eV range @ 5.9 keV

  Large spread probably due to the large G dispersion
  different G $\Rightarrow$ different working point

- $\tau_{rise} \simeq 20\ \mu s$ and $\tau_{fall} \simeq 300\ \mu s$
  longer fall time due to lower thermal conductance G

KOH vs DRIE machining

- same energy resolution and rise time
- longer decay time and larger coupling dispersion

Background

The count rate at the ROI is very low (0.26 counts/eV/day/det @ [2650,2833]eV)
$\rightarrow$ the fraction of background signals must be kept as low as possible

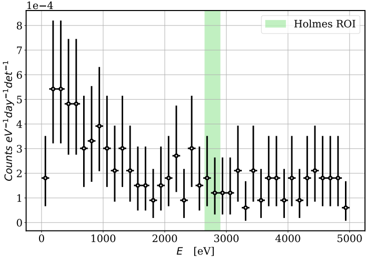
Background

1. **Pile-up**
$\rightarrow$ the main background source for pixel with A_{EC} ~300 Bq and τ_R ~1.5 µs. (0.8 counts/eV/day/det @ ROI)
2. **Internal radionoclides**
^{166m}Ho $\rightarrow$ expected count rate <0.01 counts/eV/day/det @ ROI
3. **Natural radioactivity**
Smooth and almost flat background @ ROI except for ^{40}K
4. **Cosmic rays**
GEANT 4 simulation 5x10^{-5} counts/eV/day/det @ [0,4000] eV

3. and 4. can be comparable or even overcome the pile-up rate if the ^{163}Ho activity per pixel is too low.

Background measurement

Single interaction in a pixel produces a background spectrum which seems to be monotonically decreasing.



0.0001 counts/eV/day/det @ HOLMES ROI
$\rightarrow$ lowering with a muon veto

Conclusion

- A powerful tool to determine the effective electron-neutrino mass is the calorimetric measurement of the energy released in ^{163}Ho electron capture (EC)
- The HOLMES experiment will performe a direct measurement of the neutrino mass by using TES microcalorimenters
- Ion implanter is working as expected. The production of a proper sputter target is almost ready!
- The software for analysis and signal processing of microcalorimeters events is up and running!
- For reading out the 1024 detectors, HOLMES will use the microwave multiplexing read-out
  - All the microresonator parameters match the HOLMES specification
- Transition edge sensors with Au absorber where the ^{163}Ho will be ion-implanted
  - Tested and tuned the final array fabrication processes
  - TES characterization with a fluorescence source without Ho
  - The performances (energy and time resolution) required by HOLMES are achieved
- The first phase of the HOLMES experiment is expected on the last quarter of 2022: a low dose implantation of a 2x32 pixel array