Microscopi e telescopi neutrinici: HOLMES e PTOLEMY

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HOLMES

NEUTRONS FOR SCIENCE

NIST

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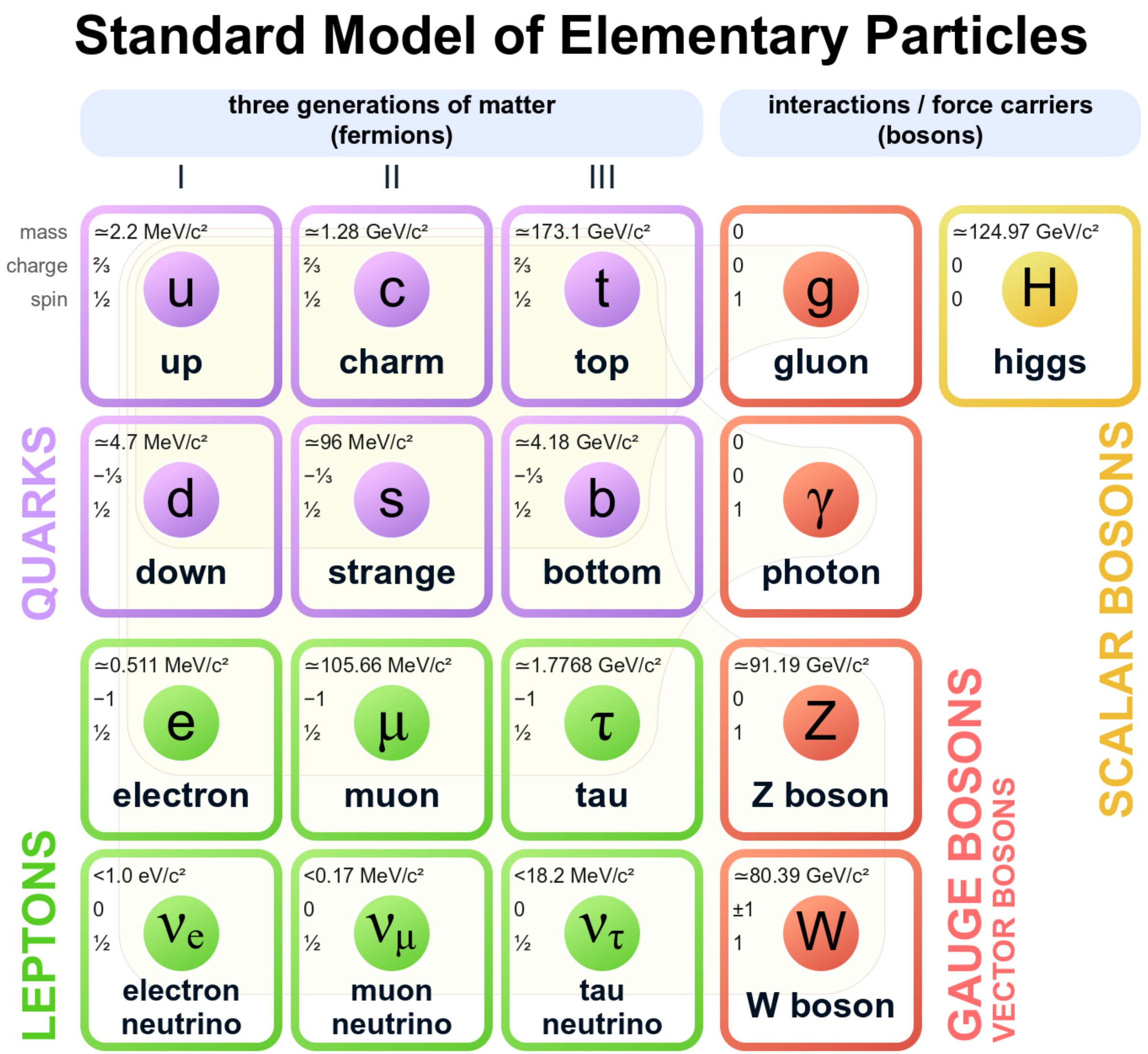
Neutrino: one of the most mysterious known particle



<u>What we do know…</u>

- ➢ at least three families
- ➢ extremely light **but not massless**
- ➢ interacts only via vector bosons (plus gravity)

<u>…and what we are still missing</u>

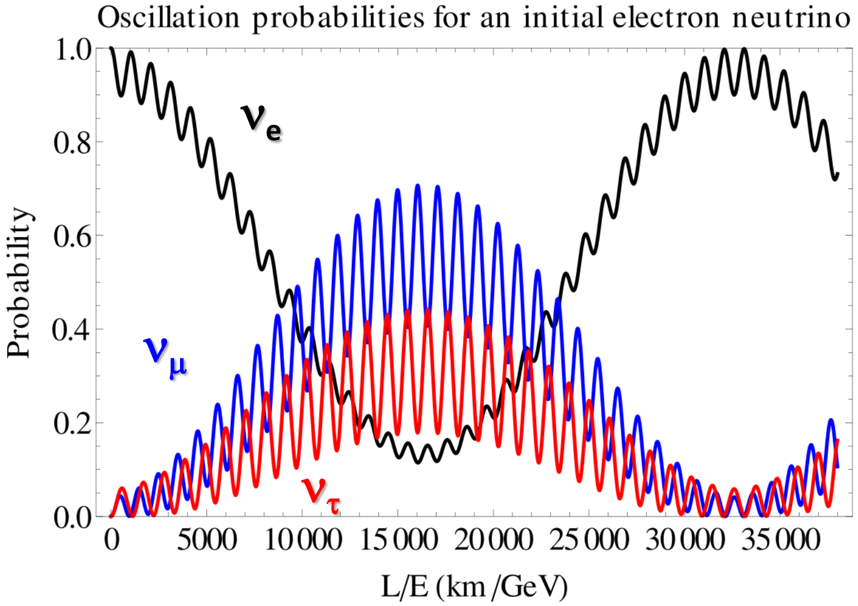
- ▪ absolute mass scale (and its origin)
- ▪ Majorana vs Dirac nature ($\nu \equiv \bar{\nu}$)
- ▪ other (sterile) families? → dark matter candidate
- ▪ mass ordering

Extremely elusive particles → difficult to detect

Neutrino mass measurement: an overview

Originally, in the SM neutrino is described as massless. Today it is an established fact that neutrinos have a (small) finite mass: the first evidence came from the observation of flavour oscillation at Super-Kamiokande (1998, Japan)

The probability of oscillation is ≠ 0 if each flavour neutrino is a mixing of three different masse eigenstates: m_1, m_2 and m_3, giving rise to an “interference” phenomenon during their propagation through space, as in the case of acoustic beat. From the oscillations it is possible to measure $m_i^2 - m_j^2$ **but not the absolute mass scale**.

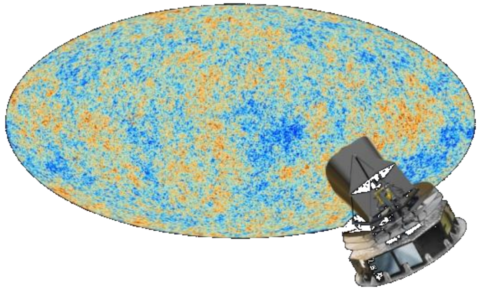


Given the faintness of the absolute value of the neutrino mass, in order to appreciate its effects one has to consider extremely large systems, such as the entire cosmos, or extremely high sensitivity apparatus.

Neutrino mass measurement: an overview (cont'd)

Cosmological

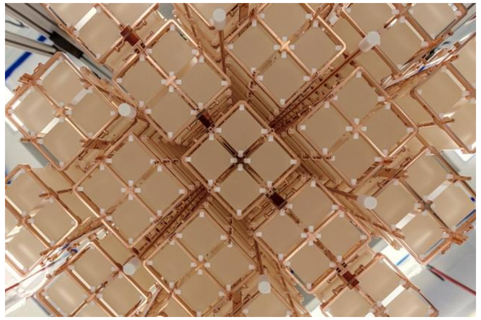
- ➢ high sensitivity
- ➢ observable $m_\Sigma = \sum m_i$
- ➢ model dependent (cosmological model)



WMAP, Plank, …

0νββ searches

- ➢ high sensitivity
- ➢ observable $m_{\beta\beta} = \left|\sum U_{i,j}^2\, m_j\right|$
- ➢ model dependent (nuclear matrix element, Majorana nature of neutrino?)



CUORE/CUPID, GERDA/LEGEND, KamLAND-Zen, NEMO-3, EXO, DAMA, …

β decay ("direct" measurement)

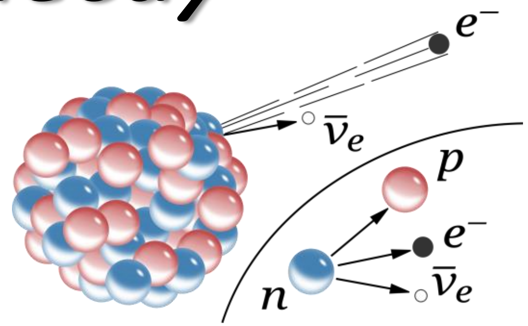
- ➢ model independent
- ➢ observable $m_\beta = \left(\sum \left|U_{i,j}\right|^2 m_j\right)^{1/2}$
- ➢ lower sensitivity (so far)

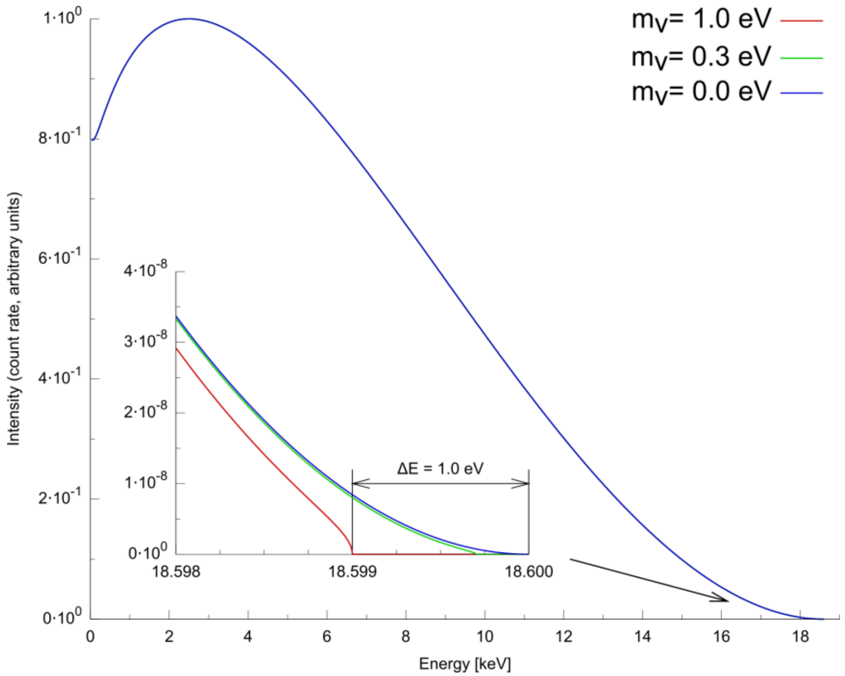
Troitsk, Mainz, Mibeta, Manu, MARE, HOLMES, ECHo, NuMECS, KATRIN, Project8, …

Measuring m_ν through beta decay

$$ {}^{A}_{Z}X \rightarrow {}^{A}_{Z+1}X' + e^- + \bar{\nu}_e $$

$$ Q = m_n\left({}^{A}_{Z}X\right) - m_n\left({}^{A}_{Z+1}X'\right) - m_e - m_{\bar{\nu}_e} $$





single beta decay spectrum of ^{3}H

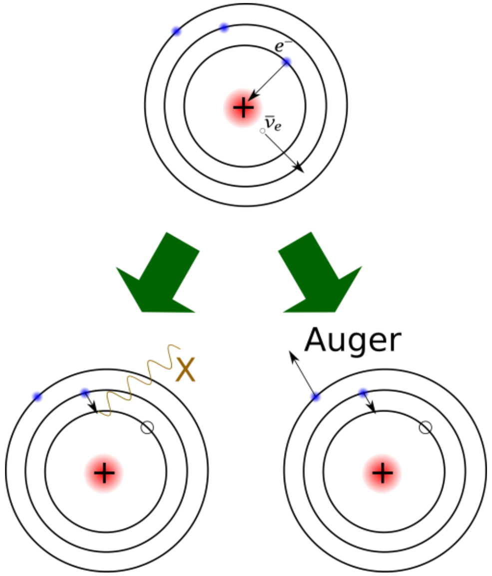
The decay energy Q is shared between the electron and the (anti)neutrino: only the electron energy is detected, displaying a continuum with $E_{max} = Q - m_\nu$

The region of interest is where the neutrino is notconsidered relativistic, which happens when all the energy is carried by the electron and the neutrino is emitted nearly at rest. Being the neutrino mass very small, this means studying the region of the spectrum with very low statistics!

Measuring m_ν through electron capture decay

$$ {}^{A}_{Z}X + e^- \rightarrow {}_{Z-1}^{\;\;\;A}X' + \nu_e $$

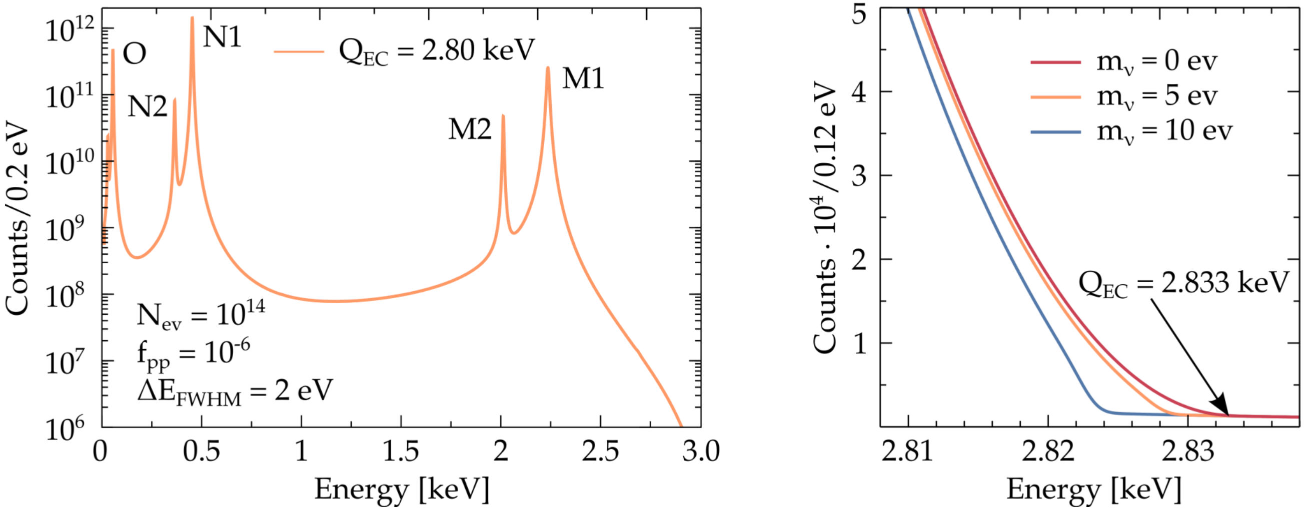
$$ Q = m_n\left({}^{A}_{Z}X\right) + m_e - m_n\left({}_{Z-1}^{\;\;\;A}X'\right) - m_{\nu_e} $$



Following the electron capture of an electron by the nucleus, the daughter atom is left with a vacancy in one of its inner shells: the de-excitation happens with emission of X-rays of Auger electrons, with a spectral distribution showing several Breit-Wigner distributions. The maximum energy achievable by the electron (or photon) is, again, $E_{max} = Q - m_\nu$

The signal due to the neutrino mass is stored, like in the single beta decay, at the end-point of the de-excitation spectrum, where the statistics is very poor.

electron capture decay spectrum of ^{163}Ho



Spectrometry vs calorimetry

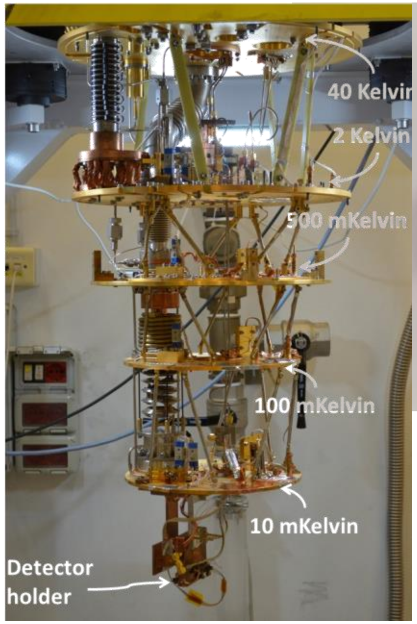
Spectrometers

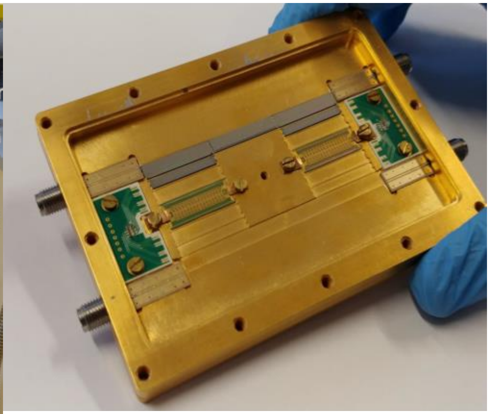
- only electrons around the end-point with EM filters
  - ➢ large statistics
- source-related systematics
- large volumes → background

to date the most sensitive approach (1 eV and on its way down to 0.2 eV), but complex to develop further

Calorimeters

- source ≡ detector
  - ➢ entire decay energy detected
- state of the art energy resolution
- pile-up
  - ➢ limits on the statistics
- spectrum-related systematics



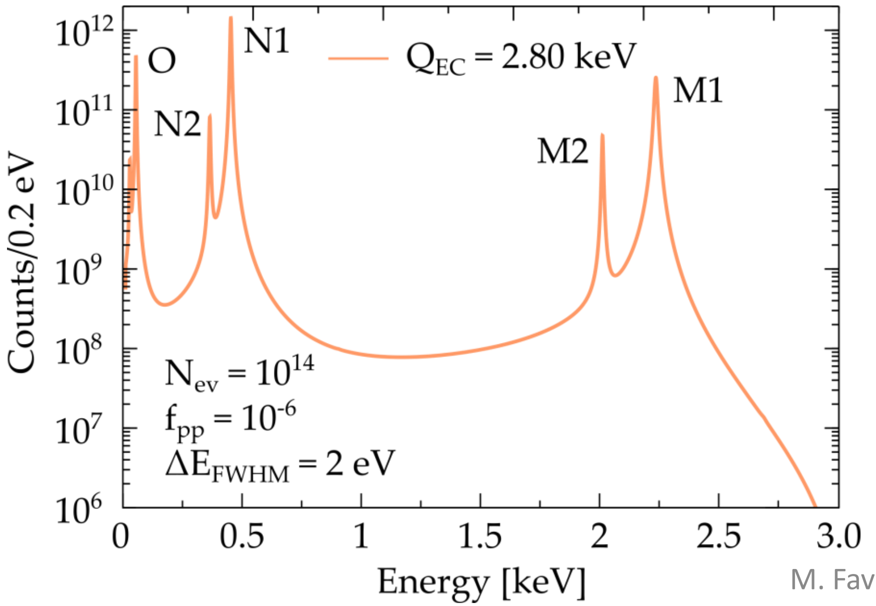


Aims at sensitivity around 1 eV, but scalable (?) to reach sub-eV

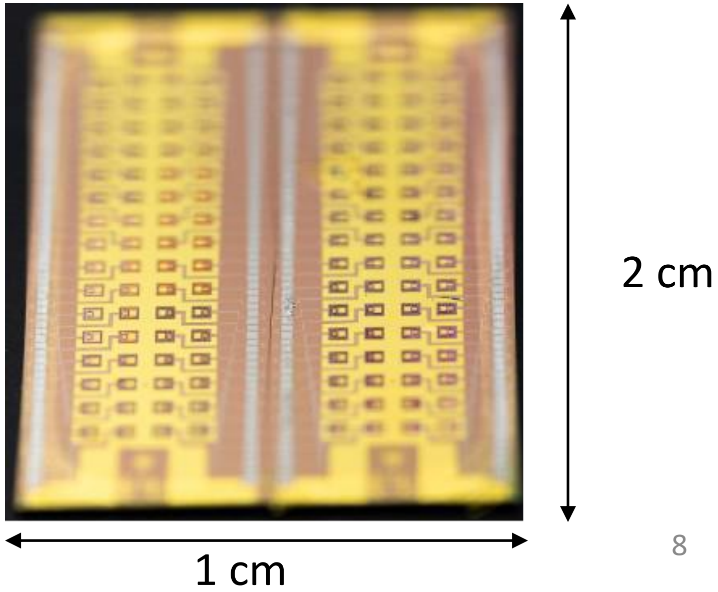
The “microscope” for neutrinos: HOLMES

HOLMES is an experiment aiming to perform a direct and calorimetric measurement of the neutrino mass with a sensitivity down to ≈ 1 eV. It studies the **electron capture decay of ^{163}Ho**:

- low decay energy 2.8 keV
    - ➢ important to increase the fraction of events at the end-point
- relatively short living 4570 y
    - ➢ few nuclei needed to achieve the target activity of 300 Bq per detector
- relative closeness between the end point and the M1 peak
    - enhancement of the statistics at the end-point. It would have been better if even closer, but that’s life…
- Transition Edge Sensors as detectors working at cryogenic temperatures (≈ 50 mK) with excellent energy resolution
- 1000 detectors working at the same time to collect as many events as possible

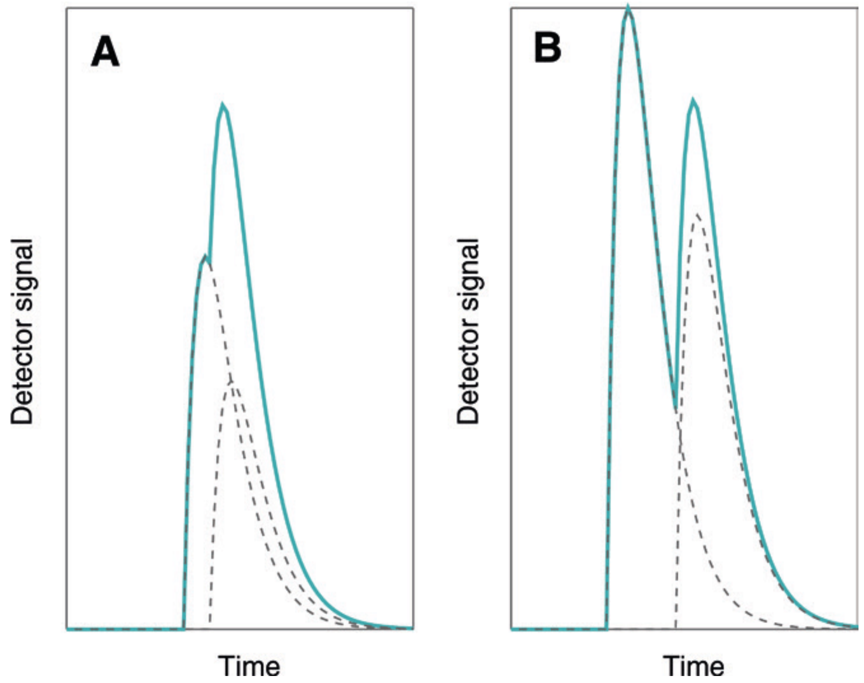


2 x 32
detectors



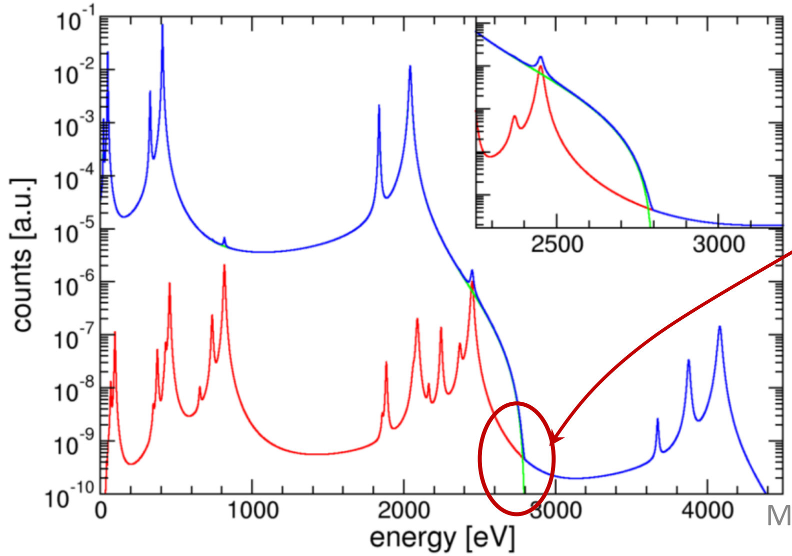
What's pile-up

A. if the two events with energies E_1 and E_2 are very close in time, they are mistaken for a single event having an energy equal to $E \approx E_1 + E_2$. The presence of these events is critical for measuring the neutrino mass!



B. events happening within a time window greater than the *time resolution* of the detector are labelled as pile-ups and discarded, increasing the *dead time* of the system. Their presence is not great (i.e. longer measuring time to get a certain amount of statistics), but not terrible

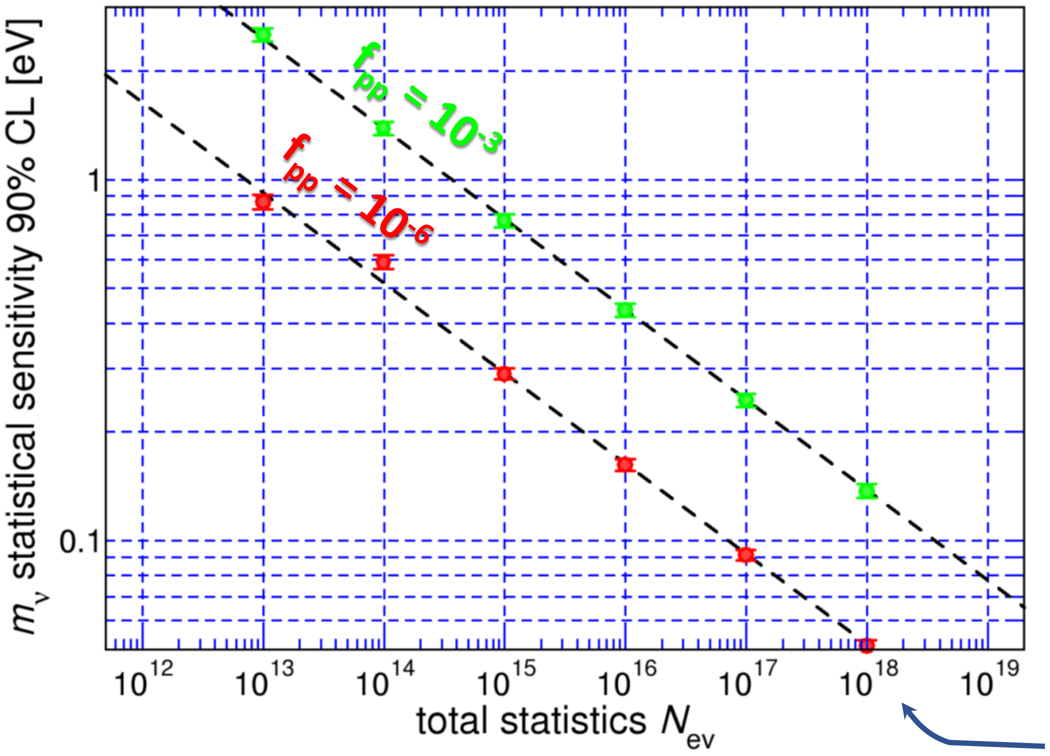
Pile-up happens whenever a signal arrives during a previous event. It can be recognised as such and eliminated, or it can remain undetected.



The presence of the undetected pile-ups impairs the signal due to the neutrino mass. It is important to divide the activity over several detectors and to speed up the detectors!

Statistical sensitivity

fraction of pup events: $f_{pp} = A_{EC}\tau_R$



$\propto \sqrt[4]{1/N_{ev}}$

to obtain sensitivity sub-eV (0.1 eV)

- A = 1 Bq, $f_{pp} = 10^{-6}$
  - low activity but small pup
- $N_{det}t_M \approx 2\text{x}10^9$ det · y

- A = 1000 Bq, $f_{pp} = 10^{-3}$
  - extremely high activity, but pup limits the advantages
- $N_{det}t_M \approx 10^8$ det · y

Detectors:

- **time resolution τ_R = 1μs**
- **ΔE = 1eV @ 2.8 keV**
- **Extremely large detector array!!**

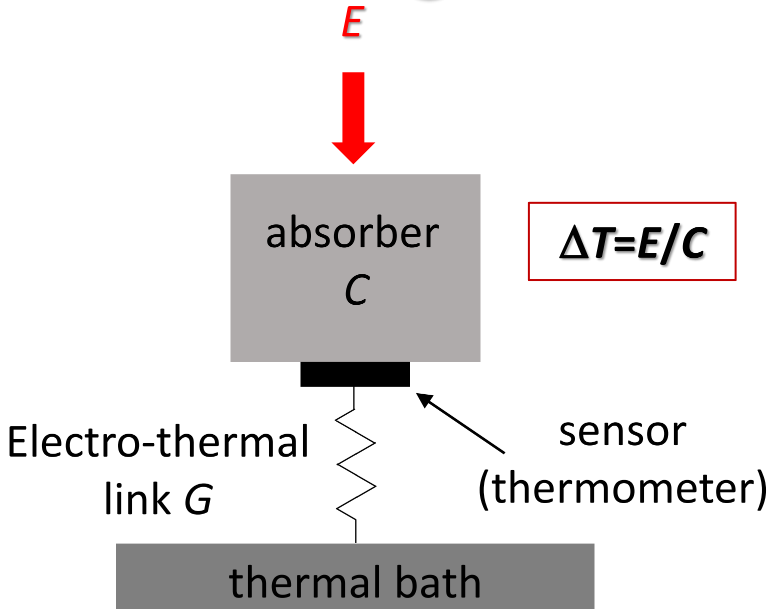
A sensitive thermometer: Transition Edge Sensor

Superconductors

- each conductor, even the best ones one can think of (copper, gold…), have a finite resistance
- some materials, below a certain temperature called *critical temperature*, behave like an ideal conductor with zero DC resistance
- across the critical temperature the resistance goes through a *transition* region: from the *normal conductivity*, where the transport of the electric charge is due to the electrons, and the *superconductivity*, where the electric charge is carried by *Cooper pairs* which do not scatter during their flow
- in the temperature range of the transition, the dependence of the resistance on the temperature is very strong

Transition Edge Sensors exploit this strong dependence to use a superconductor as a thermometer.

- ➢ state of the art energy resolution
- ➢ relatively slow → unrecognized pile-up and dead time



E

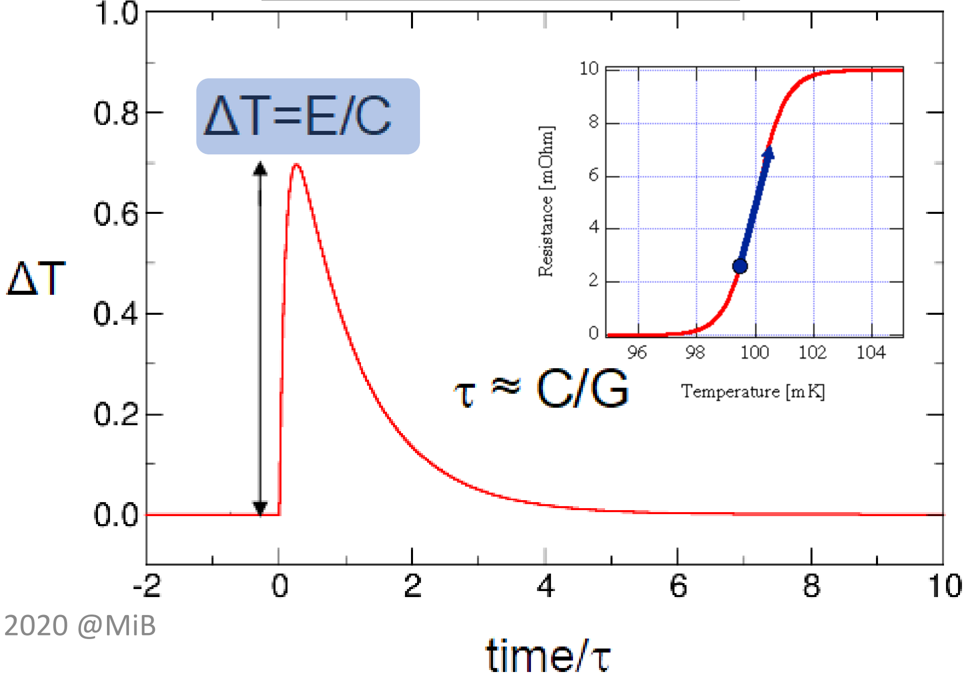
absorber
C

Δ*T*=*E*/*C*

Electro-thermal
link *G*

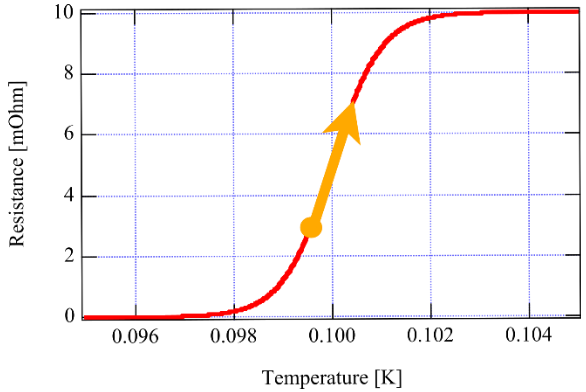
sensor
(thermometer)

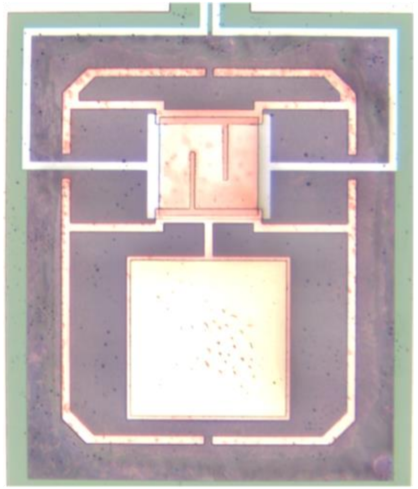
thermal bath

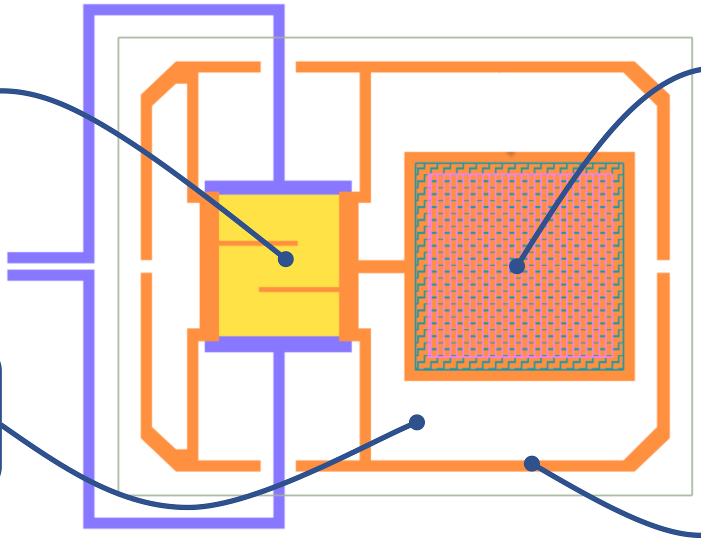


Detectors for HOLMES

- Transition Edge Sensors: high sensitivity thermometer which exploits the strong dependence of *R* vs *T* of a superconductor kept in its transition
- ^{163}Ho must be embedded inside the sensitive area of the detector (*absorber*)
- the detector needs a finite a precise thermal reference to the thermal bath (SiN membrane)
- absorber thickness determined by stopping power of electrons and photons
- fast detector response for high counting rate
  - ➢ signal rise time determined by electrical cut-off
  - ➢ signal decay time (at the first order) set by *C*/*G*: large *G* to reduce dead time







TES

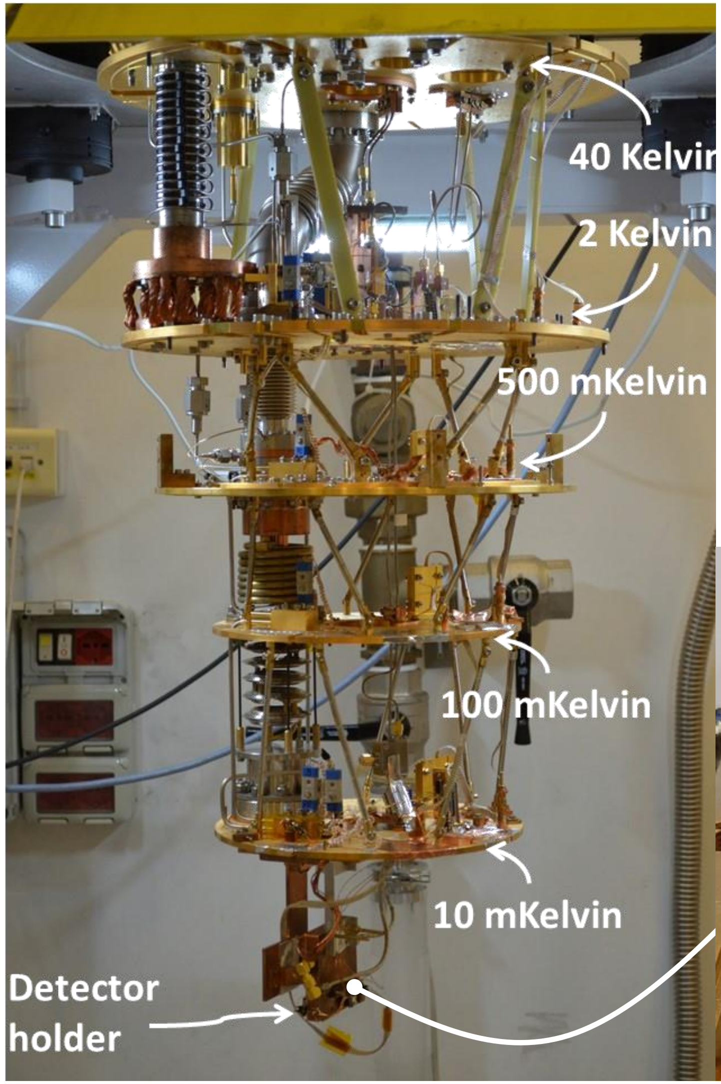
SiN$_x$ membrane

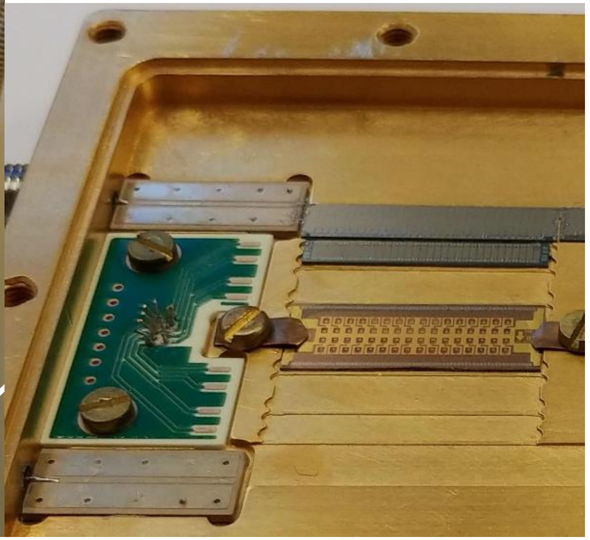
^{163}Ho ion-implanted gold absorber

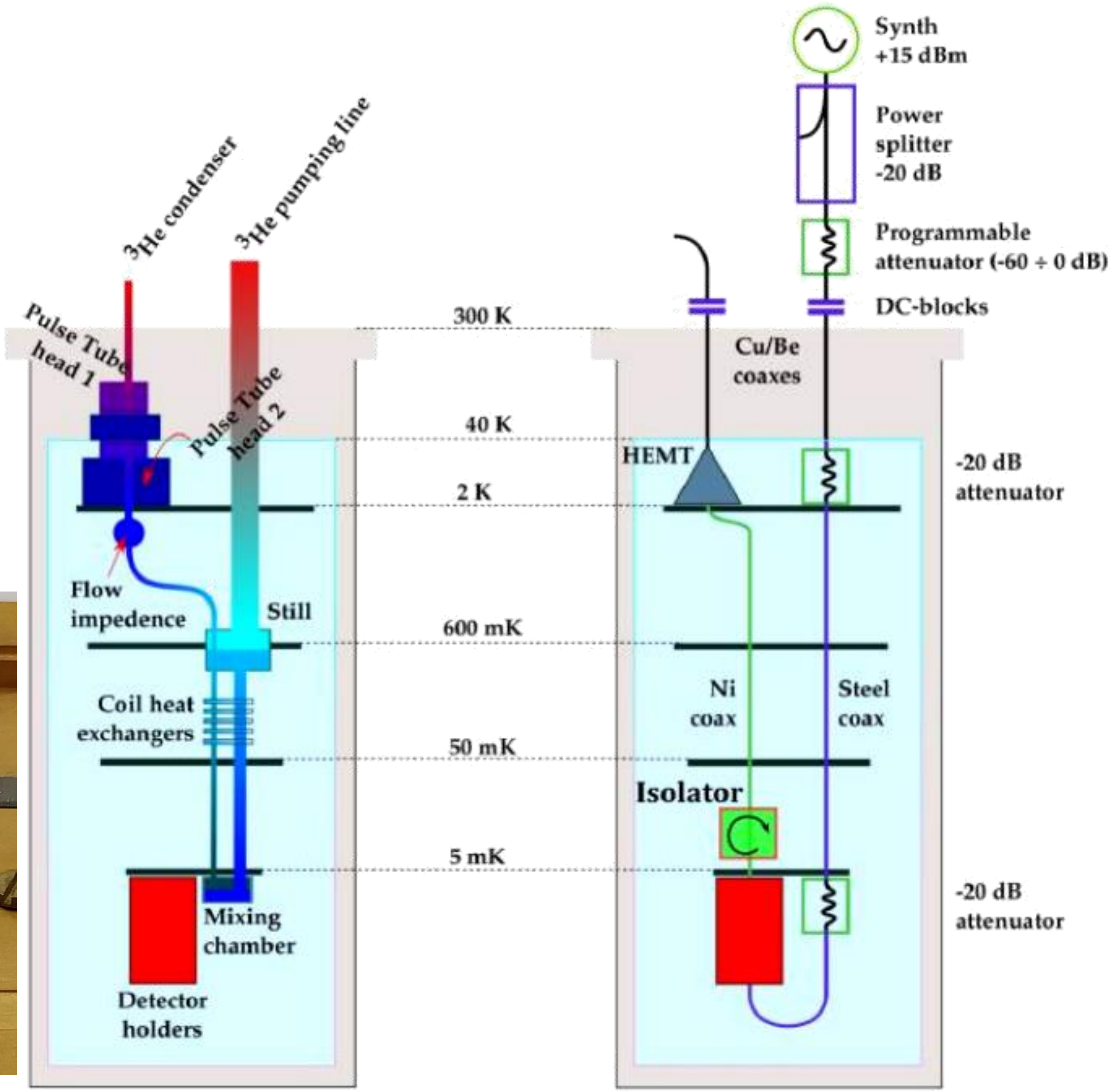
copper structure intended to increase the perimeter (and hence the *G*)

Cryogenic set-up

dry dilution refrigerator





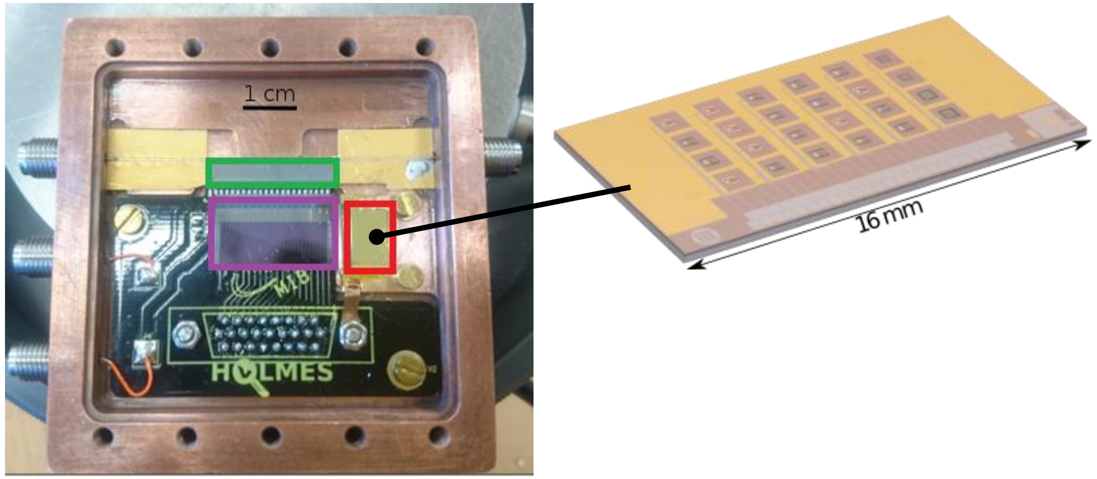


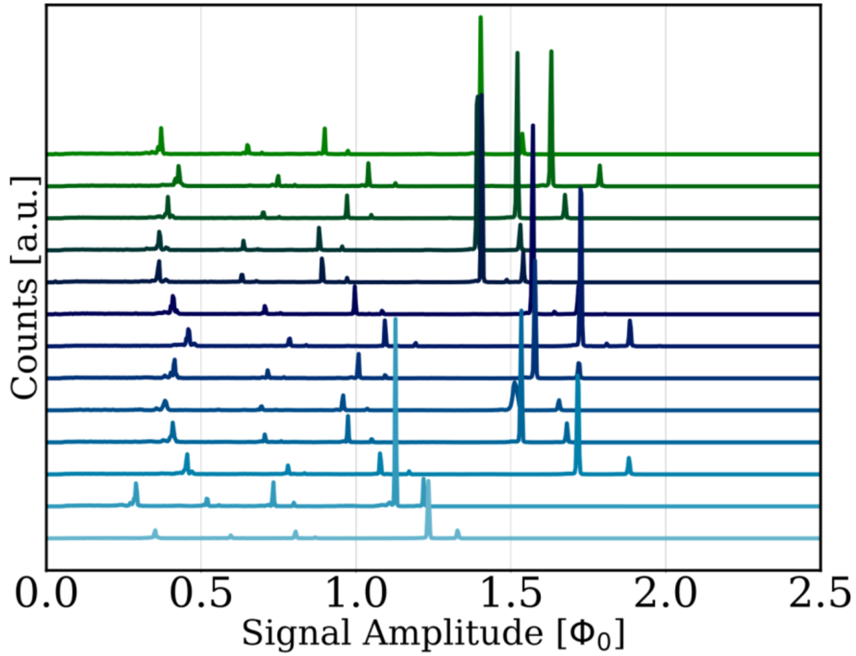
Detectors testing

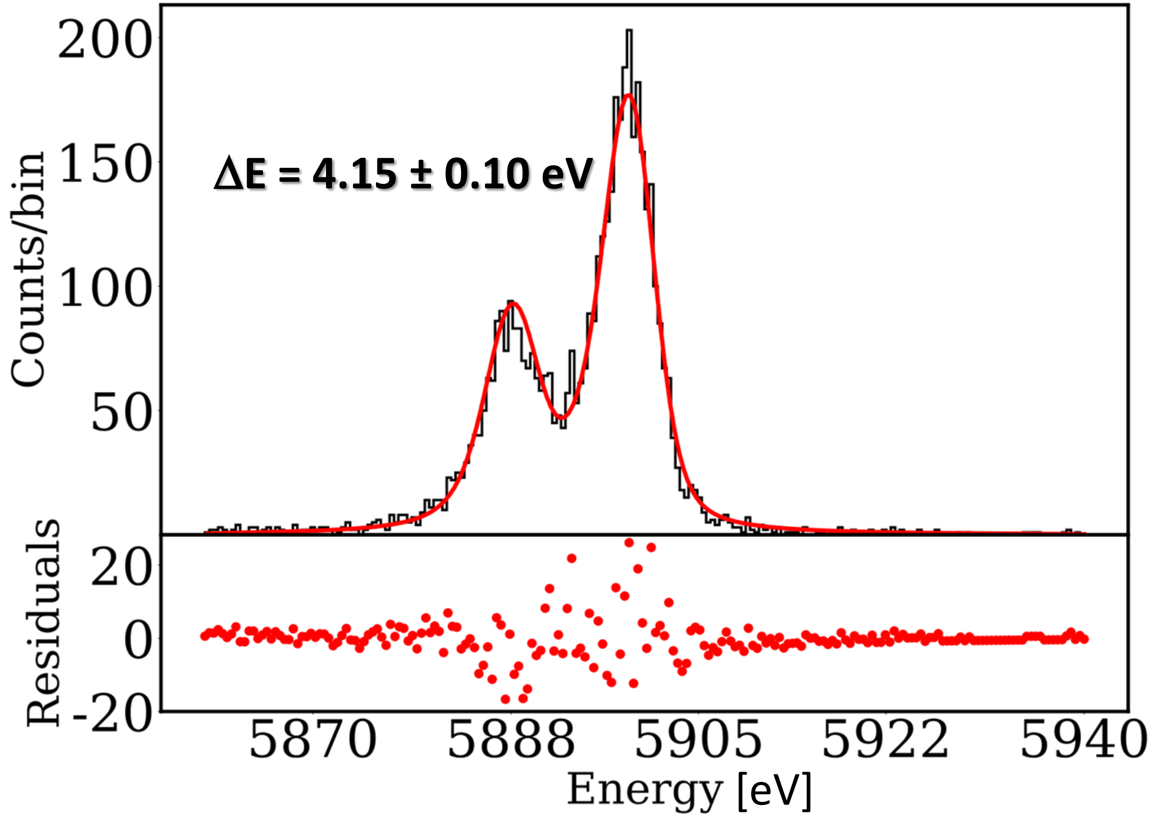
- detectors performance tested with X-rays test source
- ^{55}Fe (5.9 keV) + fluorescence source (Ca – 3.7 keV; **Cl – 2.6 keV**; Al – 1.5 keV)
- $\tau_{rise} \approx 13\ \mu$s

  test @Milano **with μ–wave multiplexing**

  f_{samp} = 500 kHz



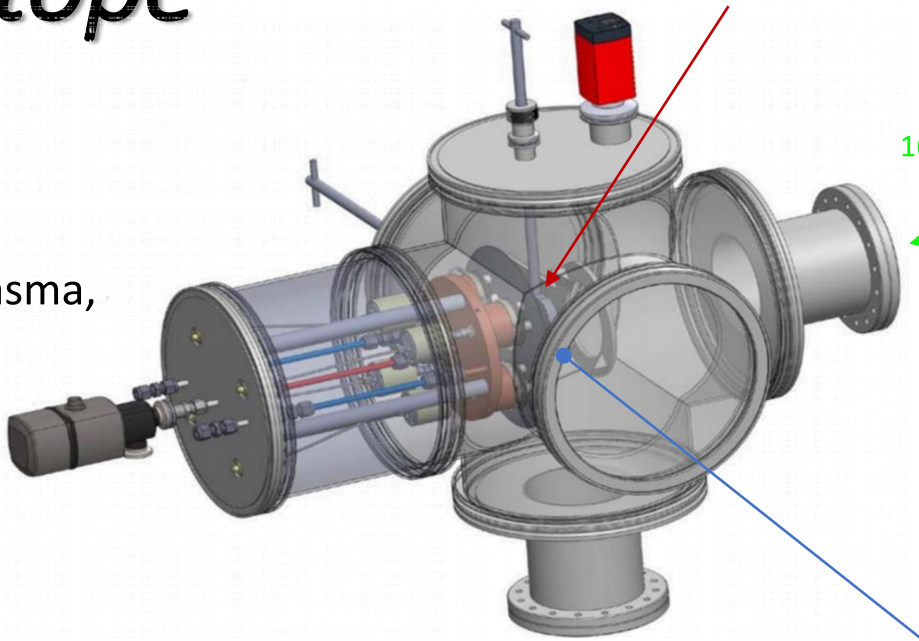


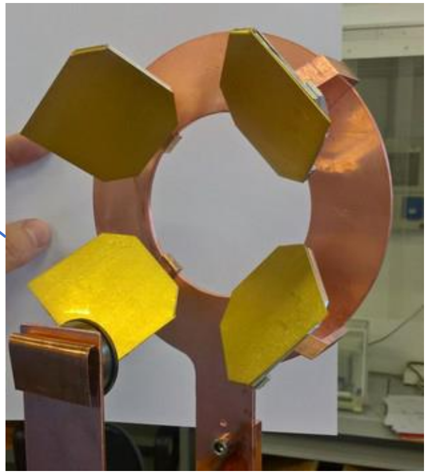

ΔE = 4.15 ± 0.10 eV

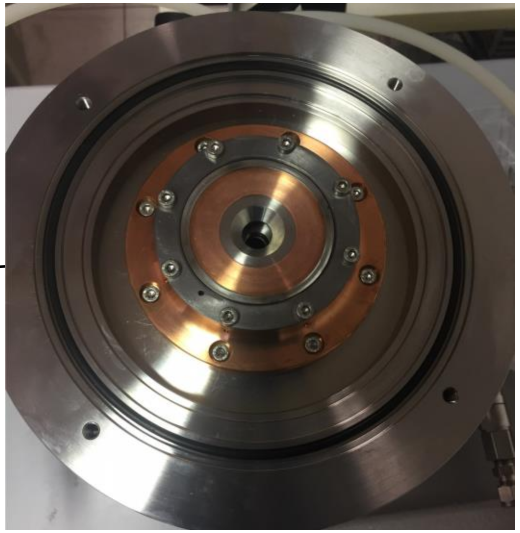
How to embed the isotope

Since only a few nuclei ($10^{11} \approx 1$ Bq) are needed in the detector, we can embed the isotope via ion implanting

- a “bulk” source is bombarded with accelerated Ar plasma, in order to create ions of holmium
- the ions are accelerated with a DV up to 50 kV
- a magnet selects only the mass of interest
- the ions get to destination hitting the absorber
- at the end, a final 1 μm Au layer is deposited on the absorbers to fully encapsulate the source



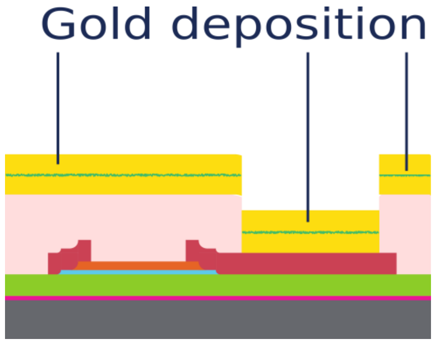




The gold deposition happens in the same setup where the holmium is implanted to avoid oxidation

Detectors fabrication @ Milano-Bicocca

1)



Gold deposition

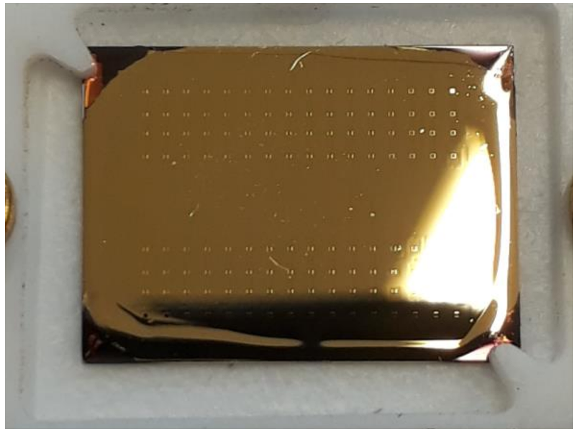
2)

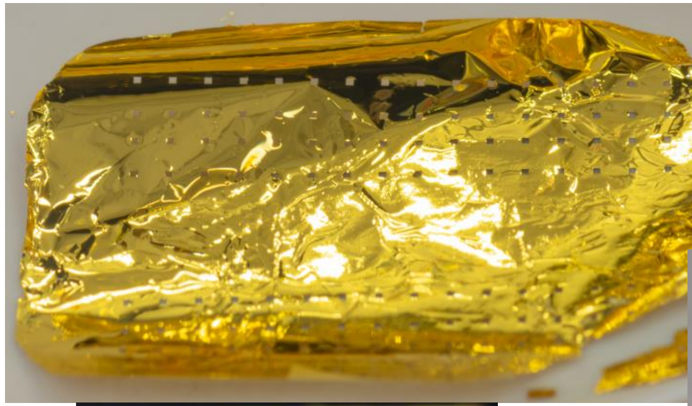
Lift-off of the Au/Ho/Au layer

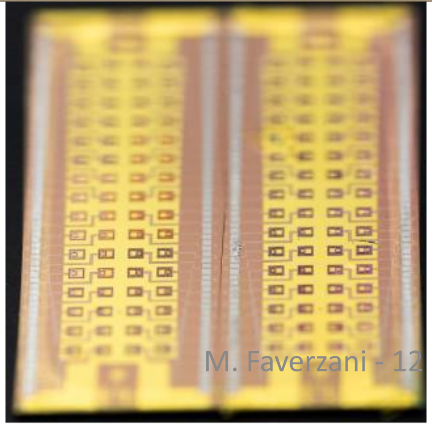
3)

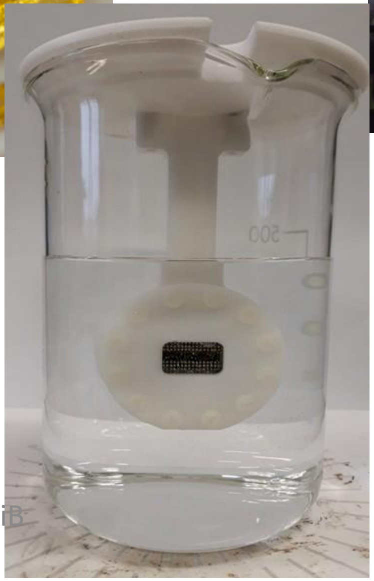
SiN membrane release

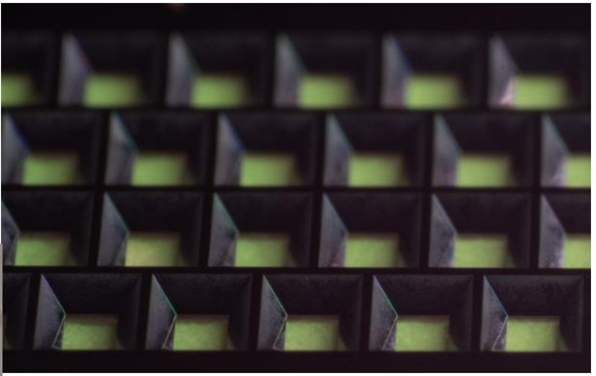
KOH…











- ✓ gold thickness uniformity measured: $^{\sigma_t}/_{t} \sim 4\ \%$
- ✓ full fab tested on 2 arrays

… vs DRIE

Background: how relevant is it?

HOLMES baseline: ^{163}Ho pile-up rate
$\langle r_{pp} \rangle = A \cdot f_{pp}/2Q = 300\ \mathrm{Bq} \times 3 \cdot 10^{-4}/2Q =$
1.5 c/eV/day/det

Each background source has to compared with the pup contribution

- environmental γ radiation
- γ, X and β from close surroundings
- cosmic rays
  - from simulations with the absorber of HOLMES detectors **bkg ≈ 10^{-4} c/eV/day/det** (0 – 10 keV)
  - measured: 200x200x2 $\mu\mathrm{m}^3$ Au absorber (HOLMES-like) **bkg ≈ 5×10^{-3} c/eV/day/det** (1 – 10 keV)
- internal radionuclides (^{166m}Ho, byproduct of ^{163}Ho production)
  - ^{166m}Ho (β^-, Q = 1856 keV, $\tau_{1/2}$ = 1200 y)
  - **bkg ≈ 10^{-11} c/eV/day/det/(^{166m}Ho nucleus)**

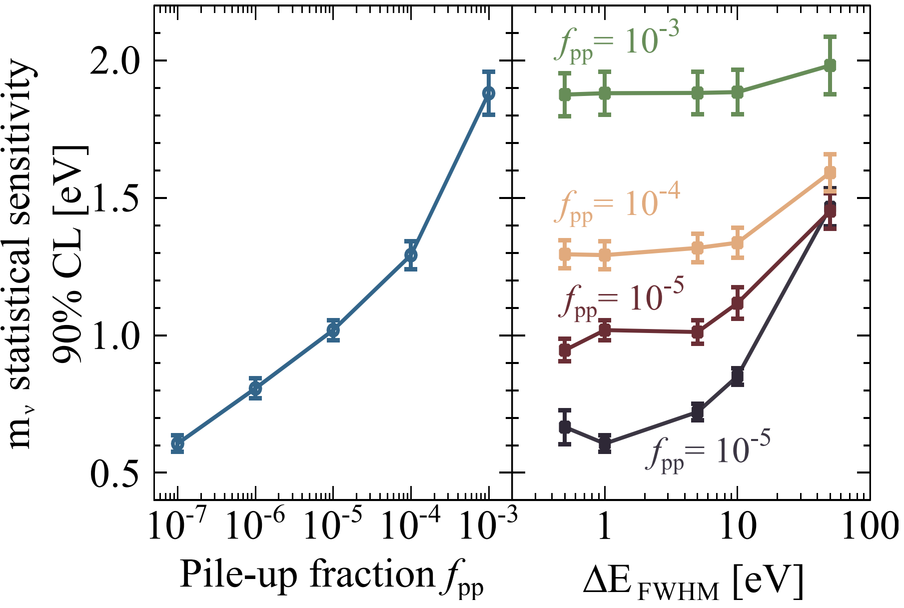
if ***A*** **(^{163}Ho) = 300 Bq** and requiring ***bkg*****(^{166m}Ho) < 0.1 c/eV/day/det**

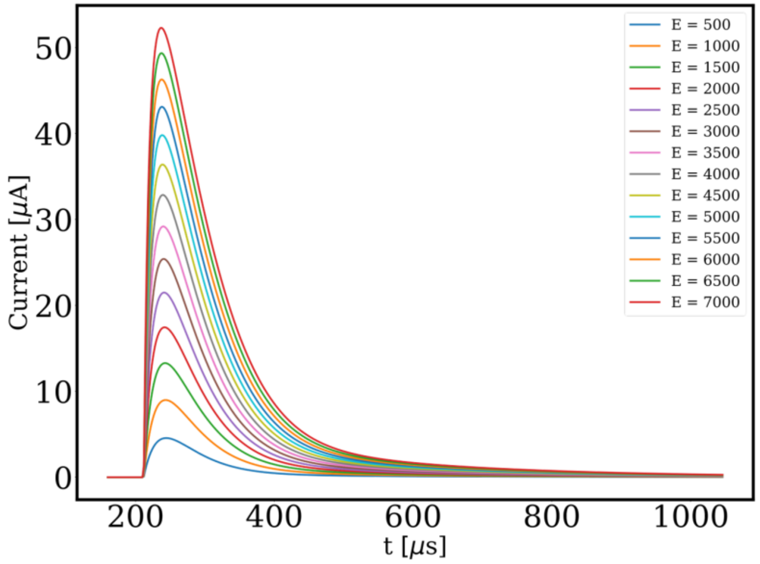
N**(^{163}Ho)/*****N*****(^{166m}Ho) > 6000**

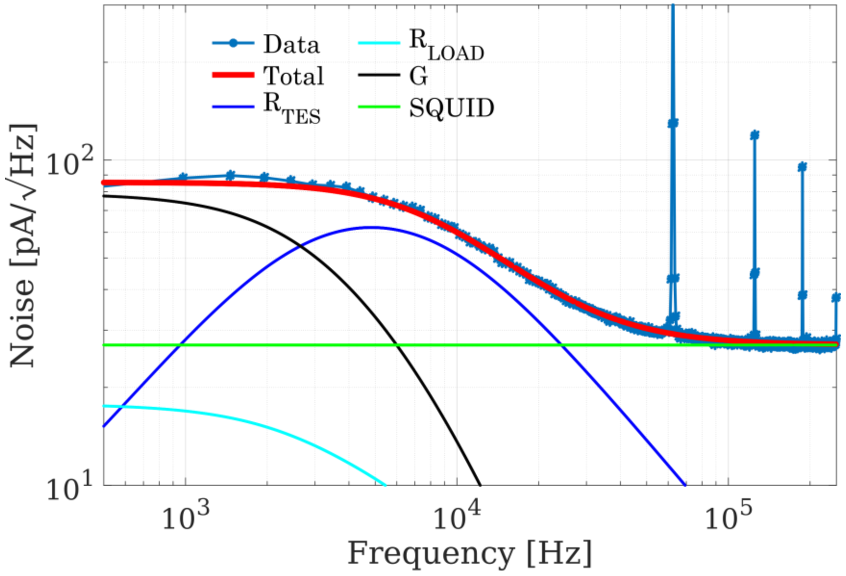
A**(^{163}Ho)/*****A*****(^{166m}Ho) > 1500**

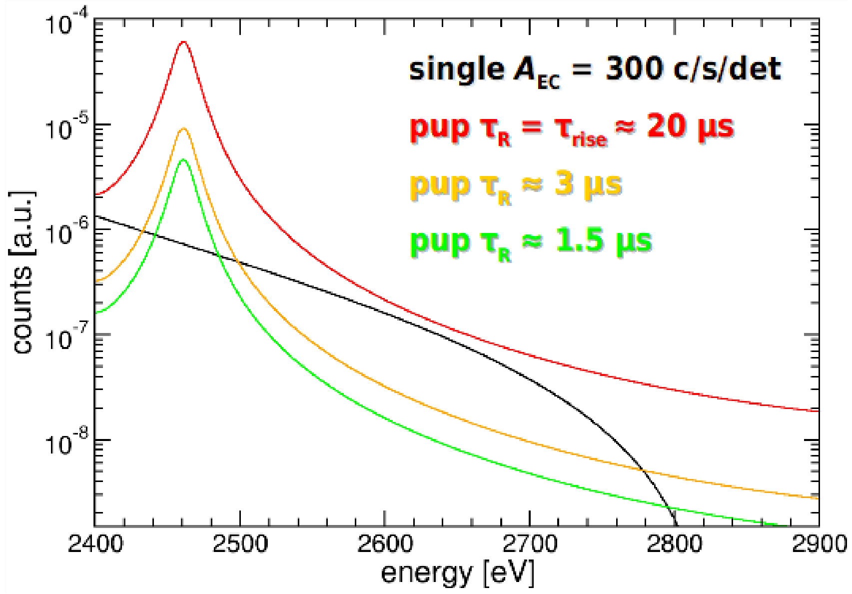
ensured by mass separation system

The importance of being time resolute









E1 + E2 ∈ (2.7 ÷ 2.9) keV (from ^{163}Ho spectrum), $\Delta t \in [0 \div 10]$ µs

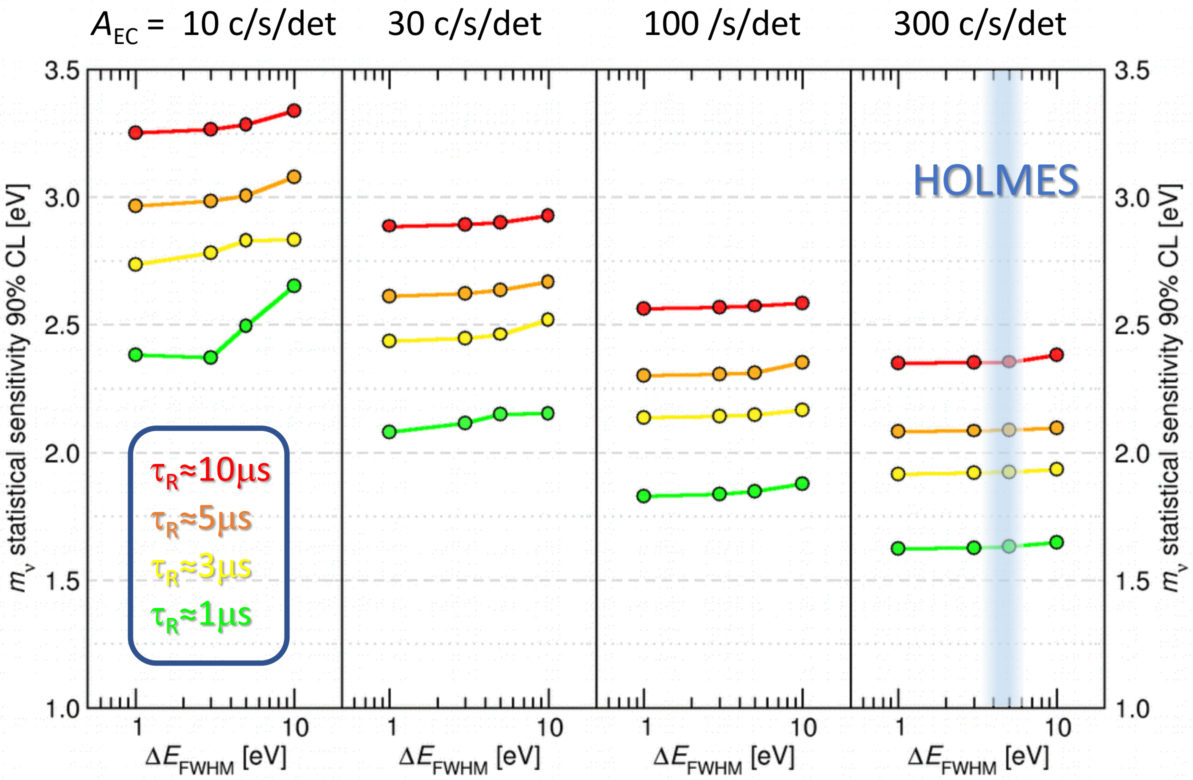
pile-up detection algorithms for f_{samp} = 0.5 MHz, $\tau_{rise} \approx 20$ µs:

- Wiener Filter → **$\tau_R \approx 3$ µs**
- Singular Value Decomposition → $\tau_R \approx$ **1.9 µs** (preliminary)

Backup

HOLMES

MonteCarlo with 1000 detectors x 3 years



B. Alpert et al., Eur. Phys. J. C, (2015) 75:112
http://artico.mib.infn.it/holmes

Goals:

- Neutrino mass determination with a sensitivity as low as ~ 1 eV
- proof potential and scalability of the approach
- precise calorimetric determination of *Q*
- systematic errors assessment

Two steps approach:

- 64 channels mid-term prototype, t_M = 1 month (m_ν < 10 eV)
- full scale: **1000 channels** (Transition Edge Sensors)
- 300 Hz/detector → 3×10^{13} events collected in 3 years
- 6.5×10^{16} ^{163}Ho nuclei (≈18 μg)

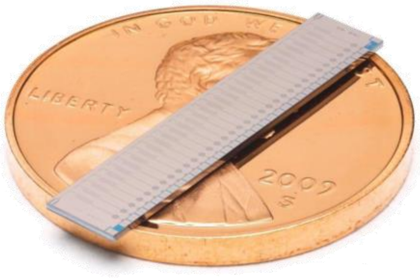
How to readout many detectors

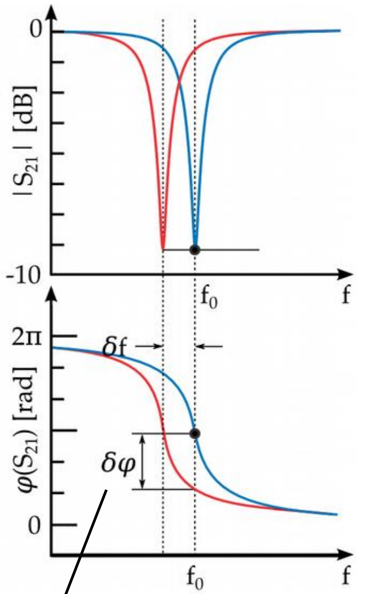
TESs readout with microwave multiplexing (produced by NIST)

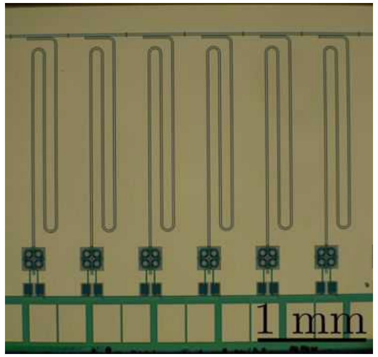
- each sensor inductively coupled to a RF-squid part of a $\lambda/4$ resonator
- a comb of signals probe the resonators at their characteristic resonant frequency

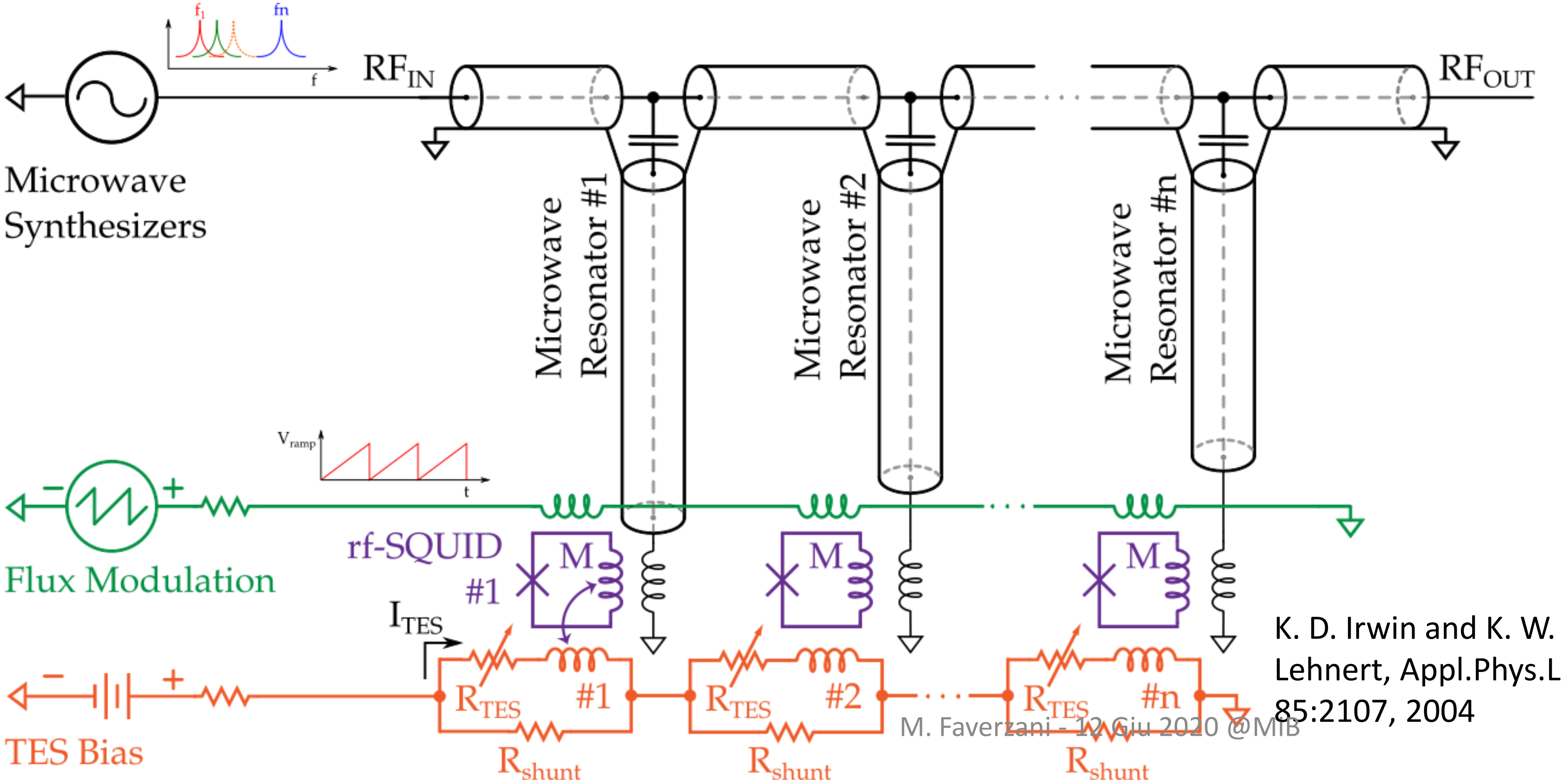
$$E \longrightarrow \delta T_{TES} \longrightarrow \delta I_{TES} \longrightarrow \delta\phi_{squid} \longrightarrow \delta f_{resonator}$$

- a ramp signal added to the squids in order to linearize the response

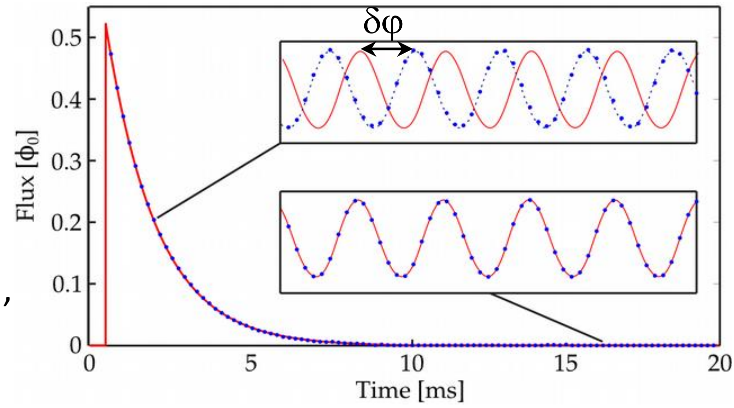




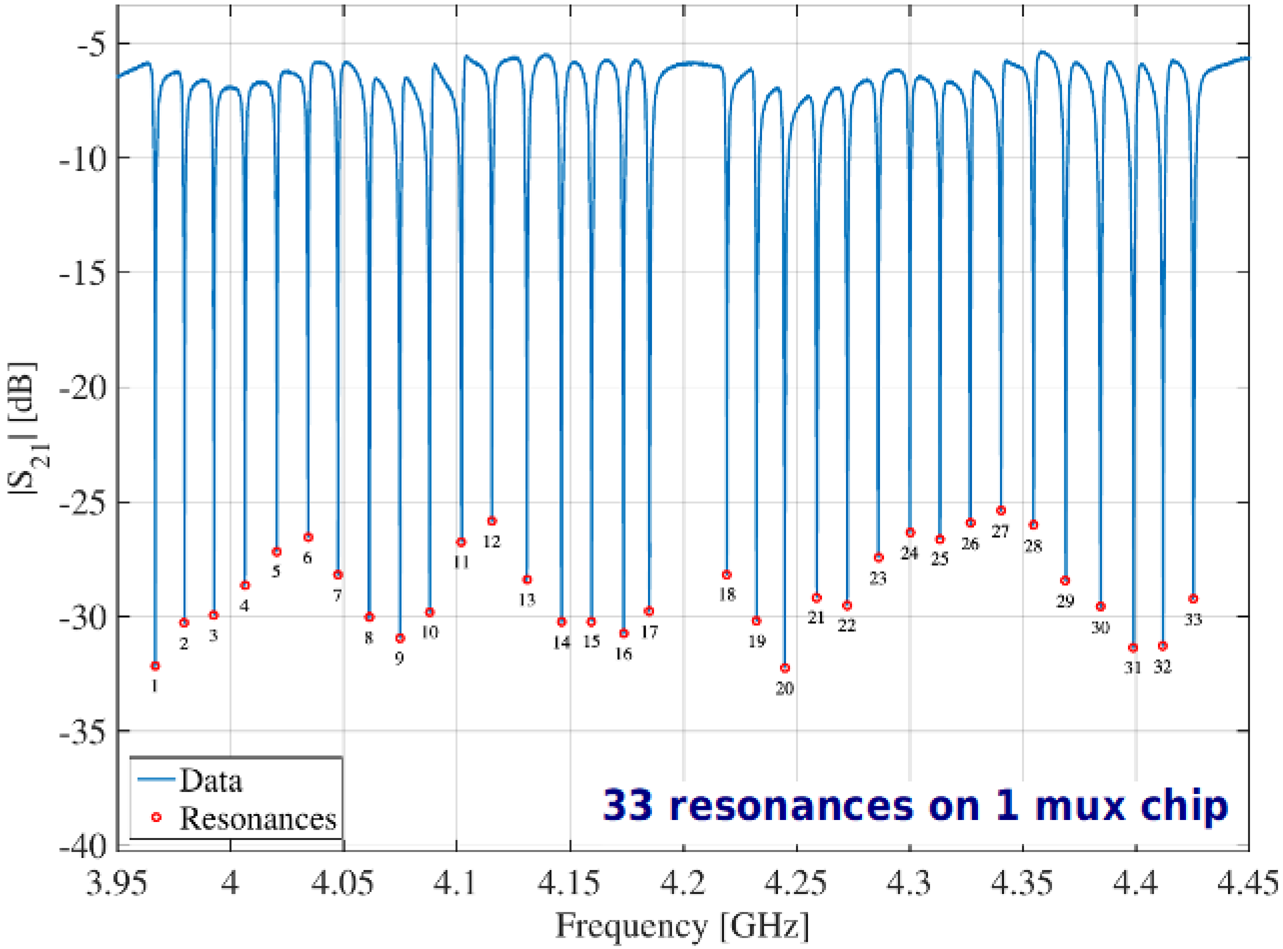


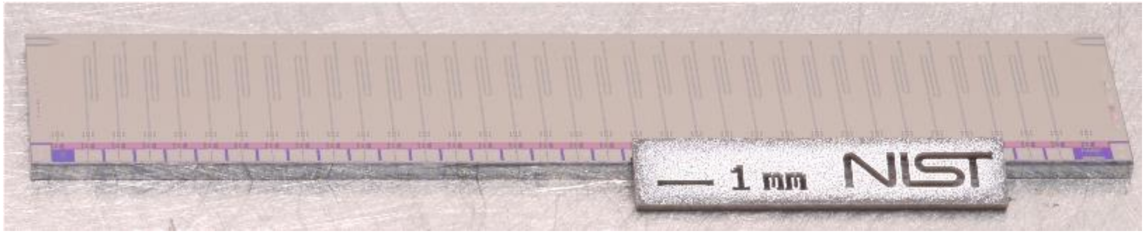


K. D. Irwin and K. W. Lehnert, Appl.Phys.Lett., 85:2107, 2004



Microwave multiplexing readout





- 33 resonances/chip over 500 MHz
- BW = 2 MHz per resonator
- separation between resonances 14 MHz (to prevent crosstalk)
- depth greater than 10 dB
- SQUID equivalent noise: ≤ 2 $\mu\phi_0/\sqrt{Hz}$