# Probing the absolute neutrino mass scale with $^{163}$Ho: the HOLMES project

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on behalf of the HOLMES collaboration

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# $^{163}$Ho electron capture

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

$$\frac{d\lambda_{EC}}{dE_c} = \frac{G_\beta^2}{4\pi^2}(Q-E_c)\sqrt{(Q-E_c)^2-m_\nu^2}\times\sum n_i C_i \beta_i^2 B_i \frac{\Gamma_i}{2\pi}\frac{1}{(E_c-E_i)^2+\Gamma_i^2/4}$$

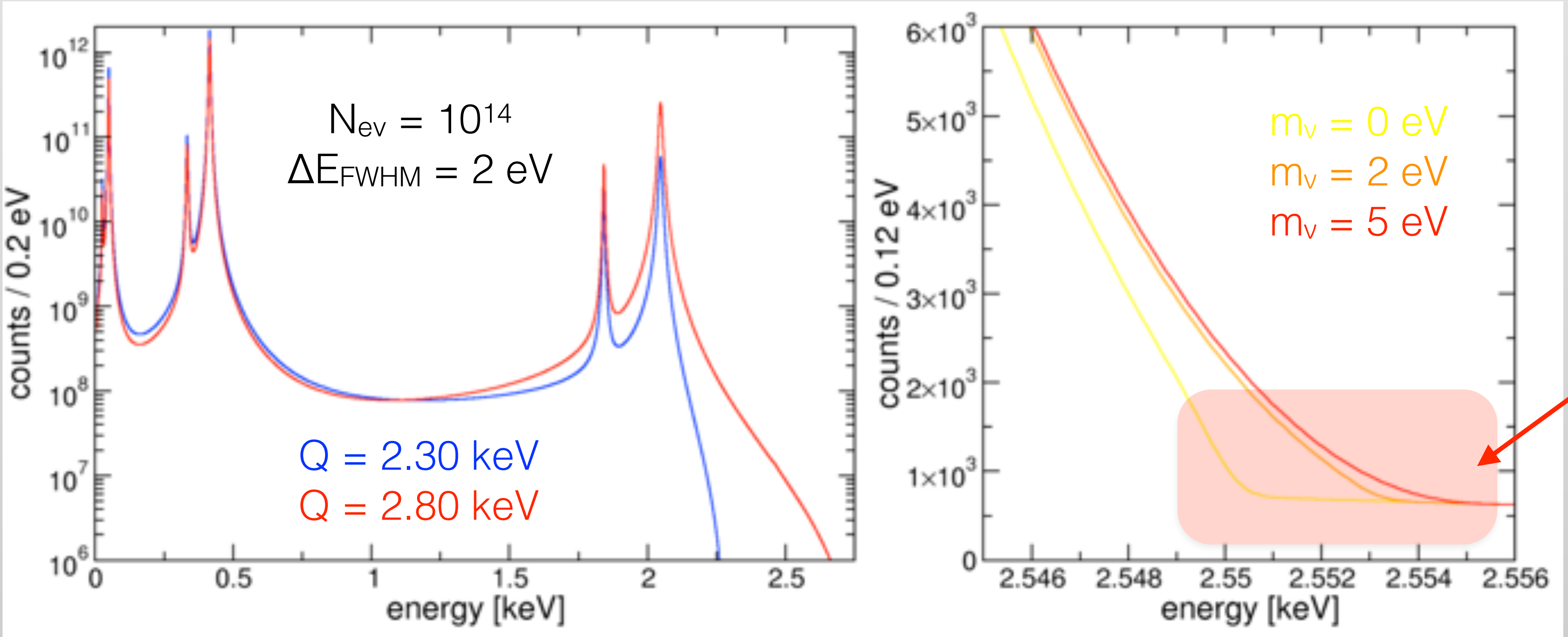
**Q~2.8keV,** capture only from shell ≥ M1
De Rujula & Lusignoli, Phys. Lett. B 118 (1982) 429

**same factor as β decay**
(total de-excitation energy $E_c$ instead of $E_e$)

Breit-Wigner shapes

- calorimetric measurement of Dy* de-excitation
- “good” event rate and ν mass sensitivity depends on Q-value and capture peak position (roughly ~$1/(Q-E_{M1})^3$)
- $\tau_{1/2}$ ~ 4570 years → few active nuclei needed

simulated spectra with different Q-value



expected ν mass effect

# $^{163}$Ho electron capture

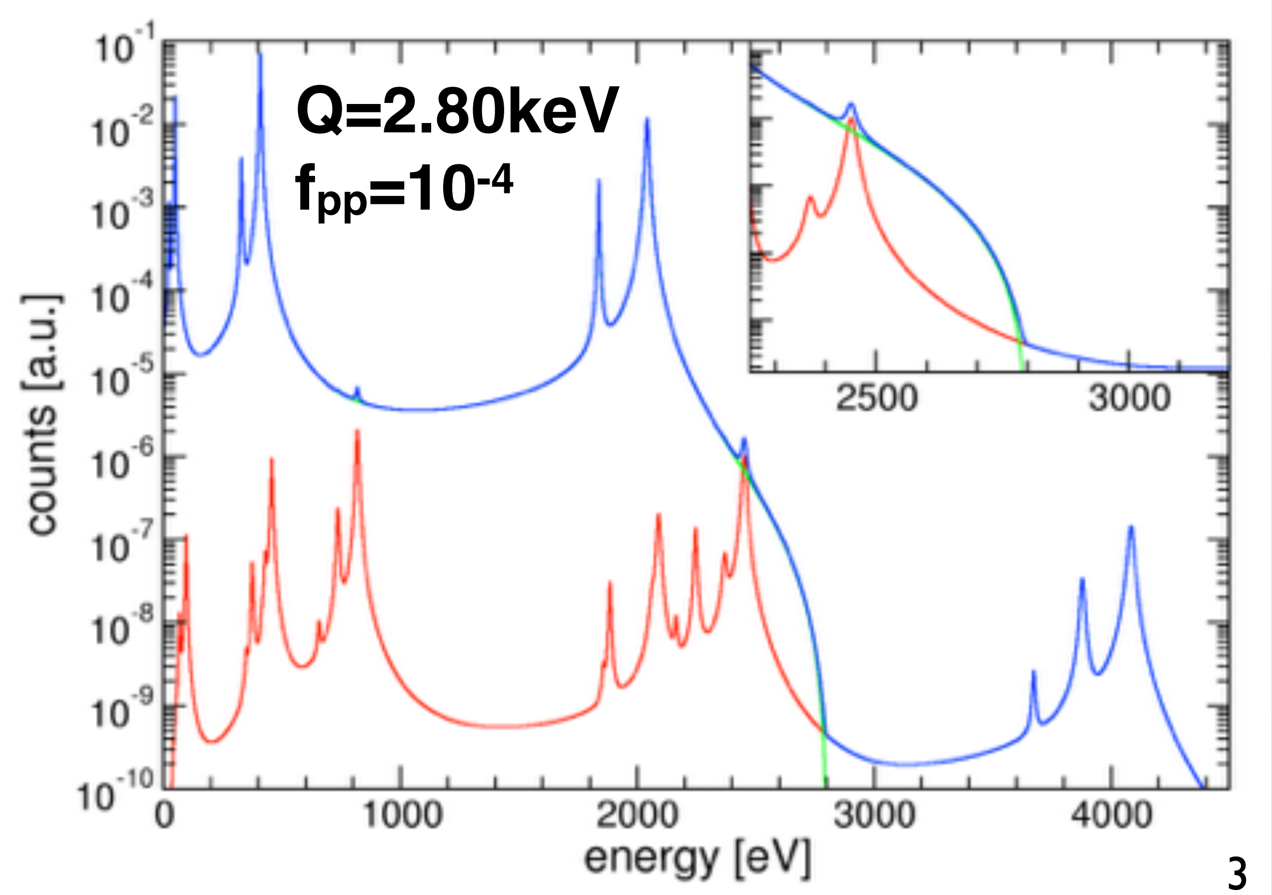
**Complex pile-up spectrum:** end-point is dominated by $((Q-E_C)^2 - m_\nu^2)^{1/2}$ but expected distortions due to pile-up:

$$N_{pp}(E) = f_{pp} N_{EC}(E) \otimes N_{EC}(E)$$

Pile-up occurs when multiple events arrive within the resolving time of the detector. In a first approximation, fraction of unresolved pile up is given by **$f_{pp} = \tau \times A_{EC}$.**

In order to reduce pile-up:

- **trade-off** between **activity and statistic;**
- detector with **fast signal rise time** $\tau_r$ ;
- pile-up **resolving algorithm.**



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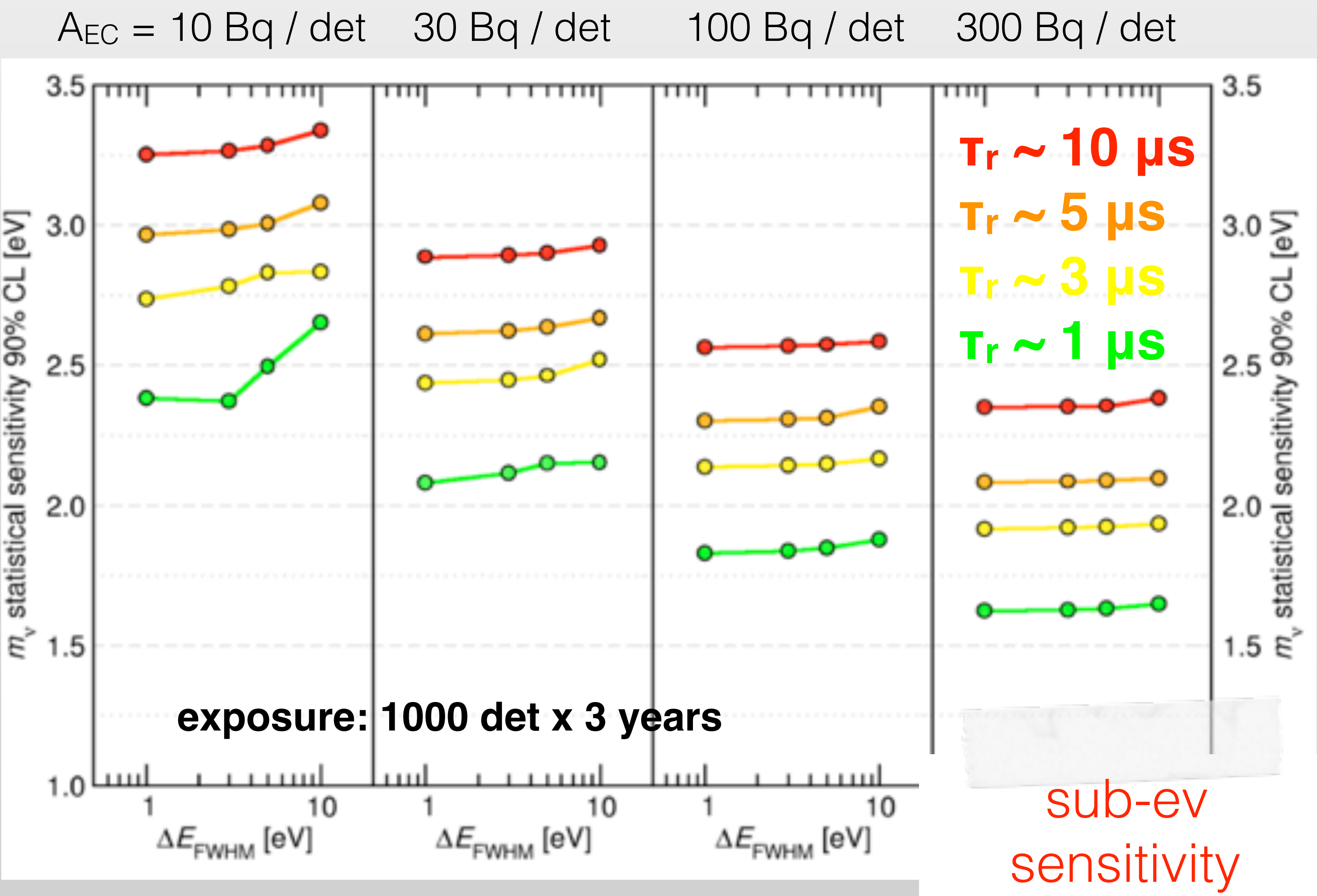
# The HOLMES project in a nutshell

- **Direct neutrino mass measurement** with statistical sensitivity around 1 eV

- **Usage of Transition Edge Sensor (TES) based micro-calorimeters** with $^{163}$Ho implanted Au absorber:
  - 6.5 x $10^{13}$ nuclei / det
  - $A_{EC}$ ~ 300 Bq / det
  - ΔE ~ 1eV, τ ~ 1μs

- **1000 channels array**:
  - 6.5 x $10^{16}$ total nuclei
  - O($10^{13}$) events / year

- **Should prove the technique potential and scalability** by:
  - assessing EC spectral shape
  - assessing systematic errors



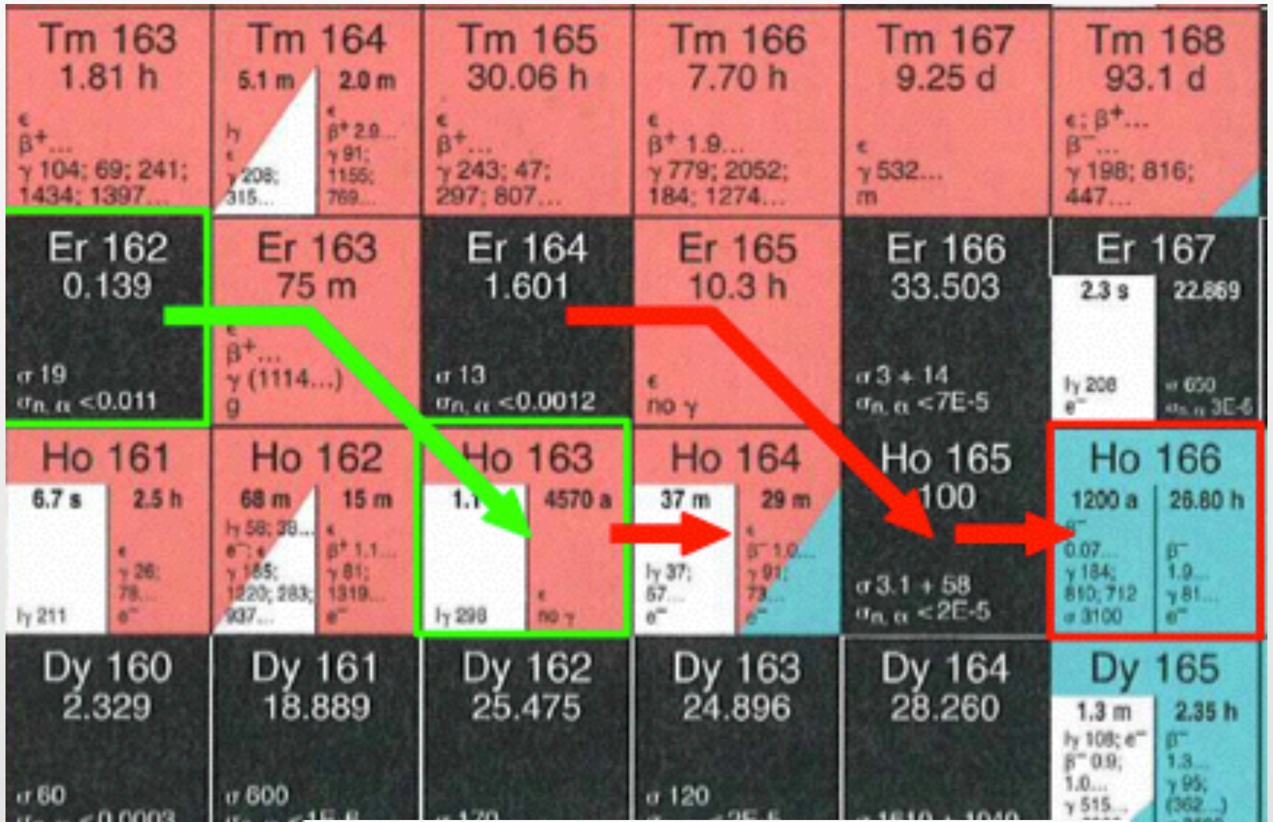
**exposure: 1000 det x 3 years**

sub-ev sensitivity region: $N_{ev} >> 10^{13}$

# $^{163}$Ho production

**$^{163}$Ho does not exist in nature: it is produced from $^{162}$Er neutron activation at nuclear reactor:**

- **$^{162}$Er (n,γ) $^{163}$Er, $\sigma_{therm}$ ~ 20 b**
- **$^{163}$Er + $e^-$ → $^{163}$Ho + $\nu_e$ ($\tau_{1/2}$ ~ 75 m)**
- high yield
  - ~3x$10^{12}$ $^{163}$Ho nuclei/mg$^{162}$Er/h
- requires $^{162}$Er enrichment and oxide chemical form ($Er_2O_3$)



But contaminations from other isotopic species. Main one:

- **$^{165}$Ho (n,γ) $^{166m}$Ho (β, $\tau_{1/2}$~ 1200 years)**
- from Ho contamination or $^{164}$Er (n,γ)
- **need high purification of sample:**
  - **radiochemical separation**
  - **mass separation with magnetic dipole**

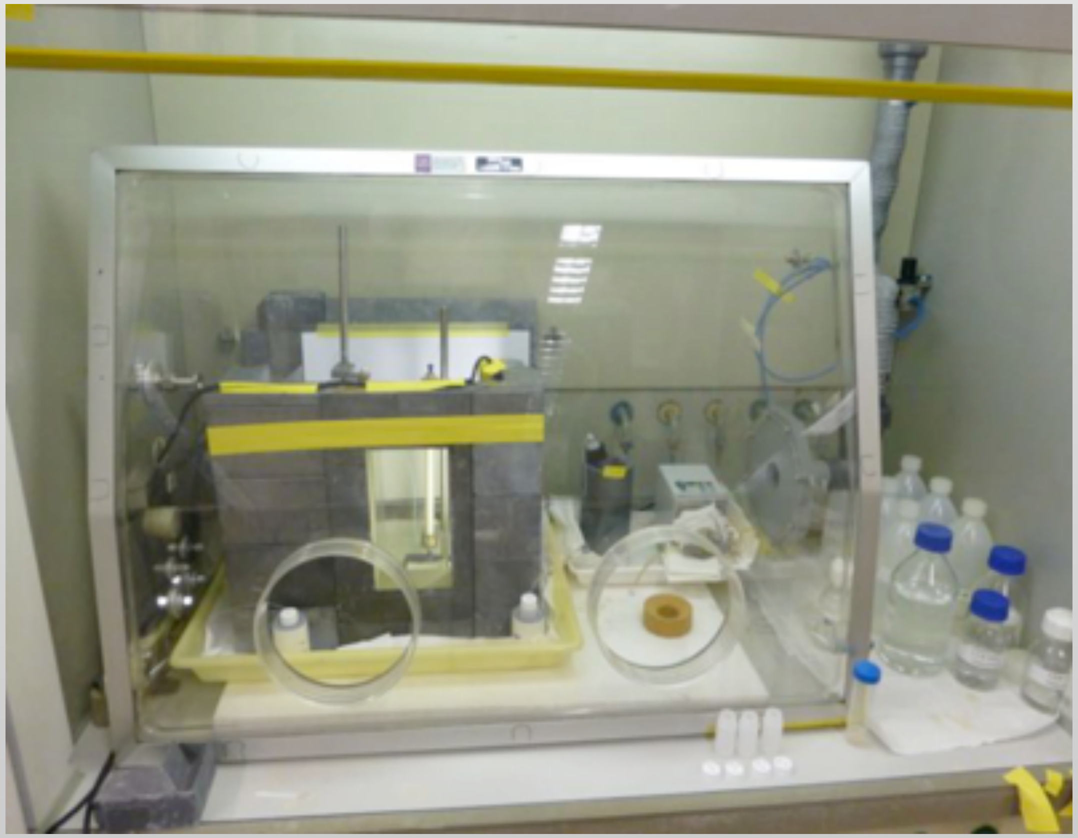
Collaboration with
ILL (Grenoble)
ITN (Lisboa)
Paul Scherrer Institute

# $^{163}$Ho purification

- Enriched $Er_2O_3$ samples irradiated at ILL (Grenoble) and post-processed at PSI
  - 25mg, 55 days irradiation → A($^{163}$Ho) ~ 5 MBq
  - 150mg, 50 days irradiation → A($^{163}$Ho) ~ 38 MBq

- **Ho radiochemical separation is performed via ion-exchange resins in hot-cell at PSI**
  - efficiency > 80% (provisional estimation)

- 540mg irradiated for 50 days at ILL in early 2017 are ready for purification
  - expected overall activity: ~130 MBq (enough for R&D and half pixels)



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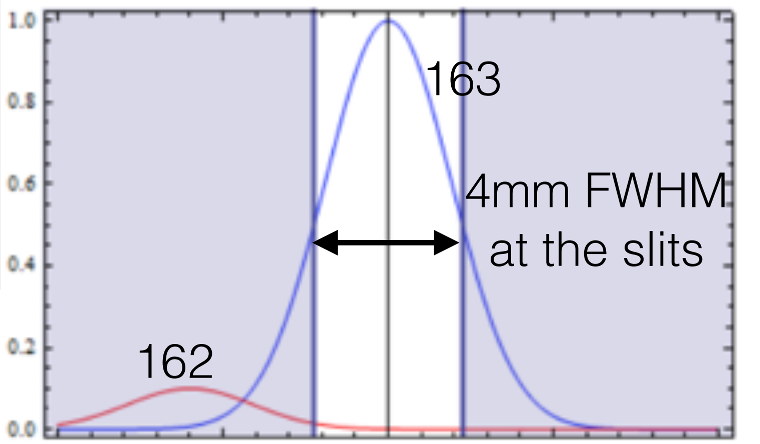
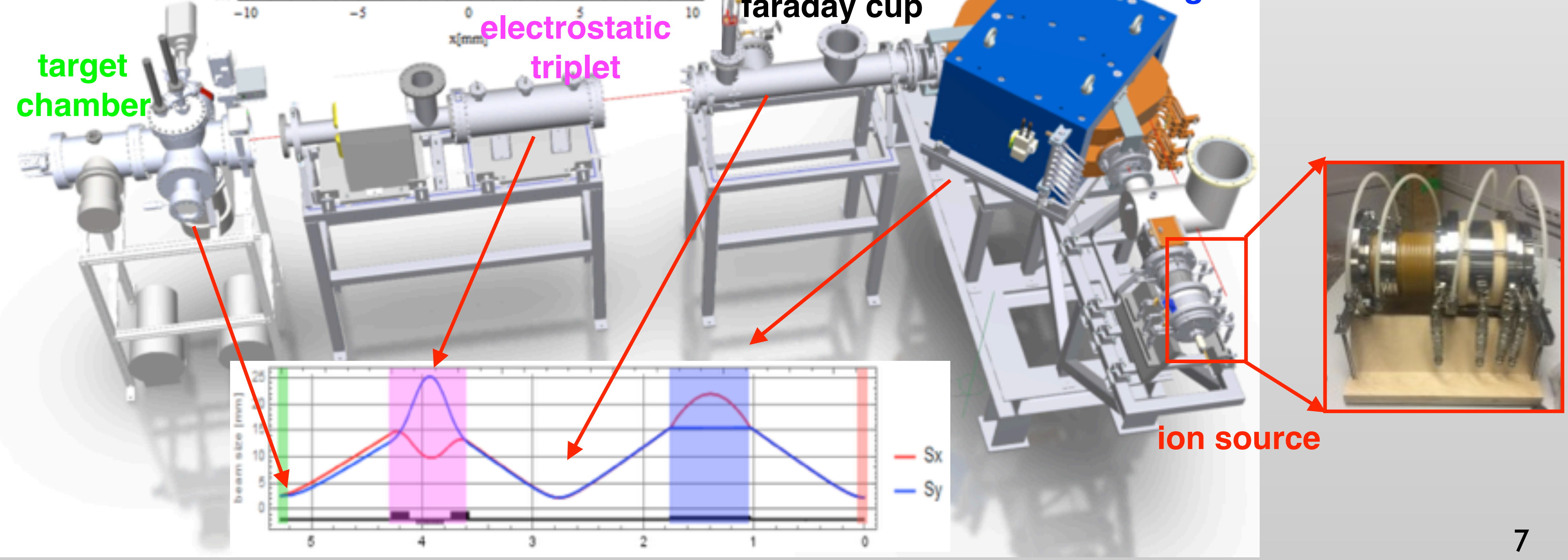
# $^{163}$Ho mass separation and implantation

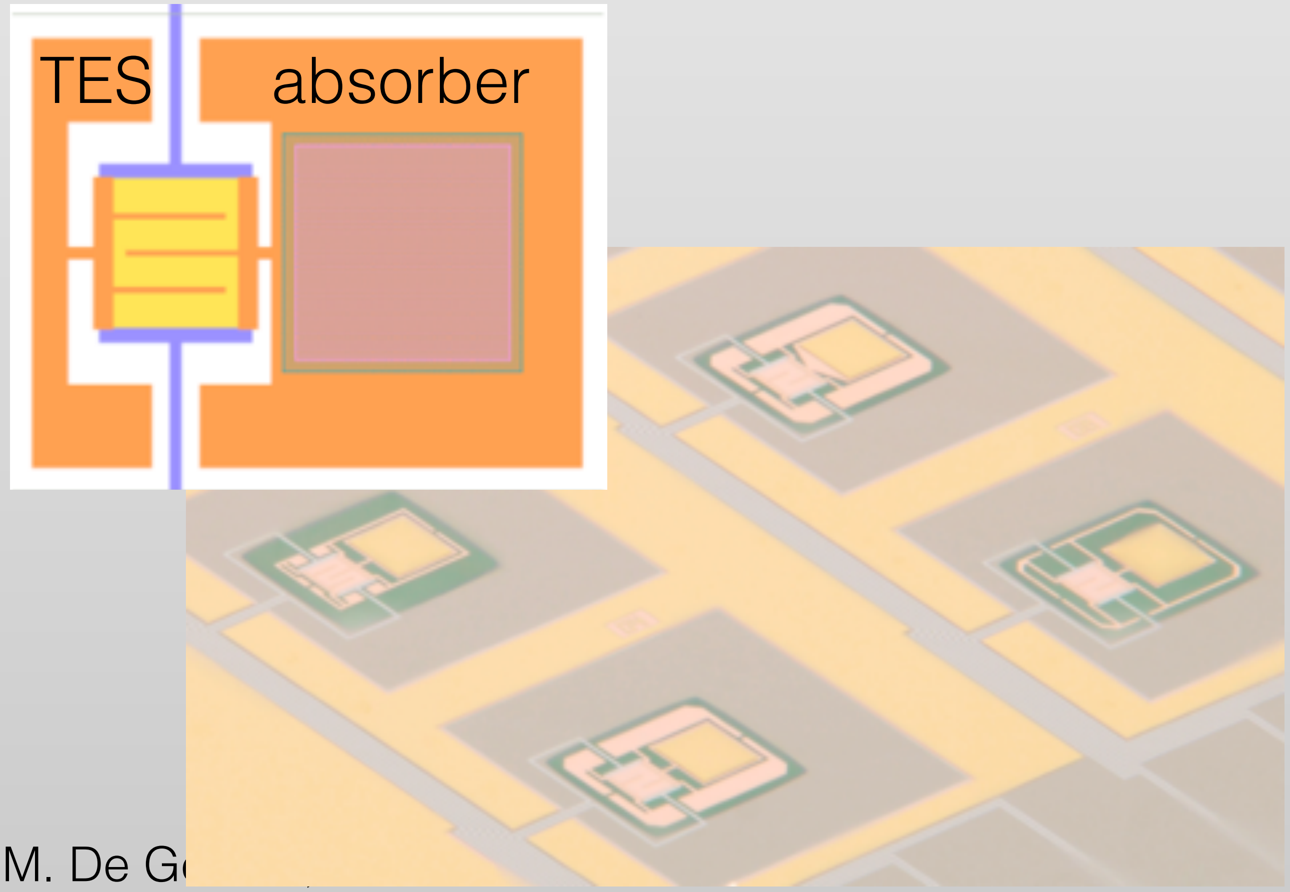
- **Implanter machine with 30/50 kV acceleration (10-50nm implantation depth) and magnetic dipole:**
  - $^{163}$Ho/$^{166m}$Ho separation better than $10^5$
  - first components delivered in Genova at beg. 2017, now under test (magnet, source, vacuum OK - full system test coming soon)
  - upgrade with focusing triplet and magnetic xy scanning expected for late 2017 / beg. 2018

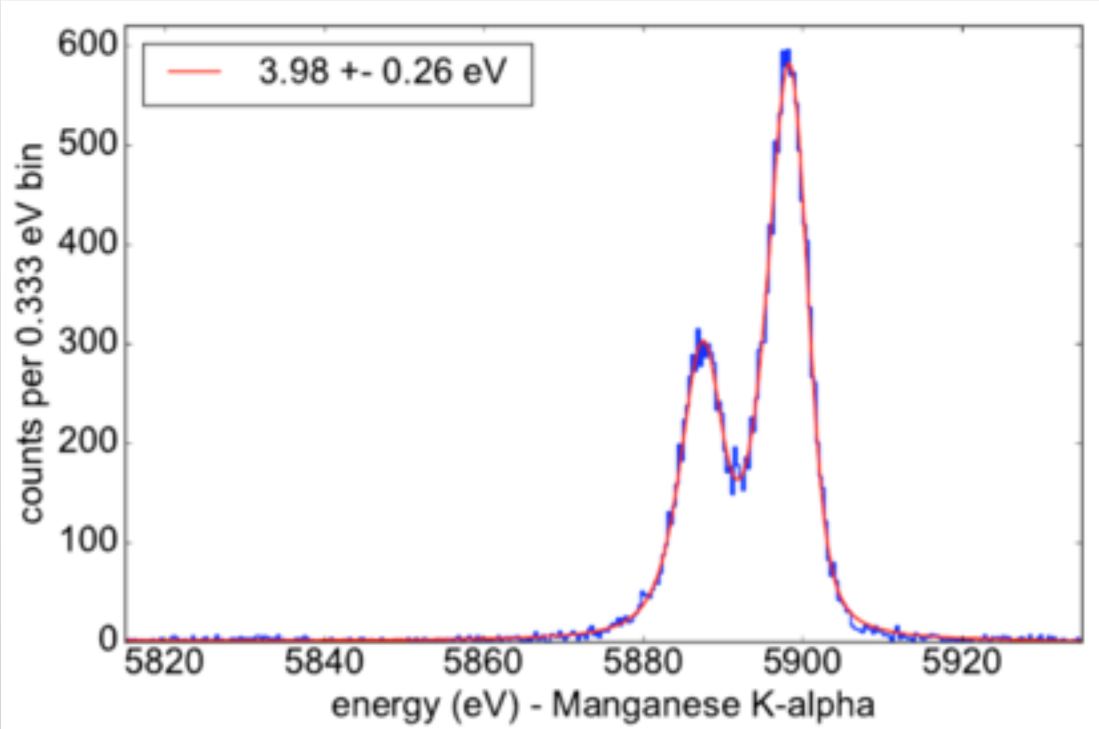




# Detector design and test

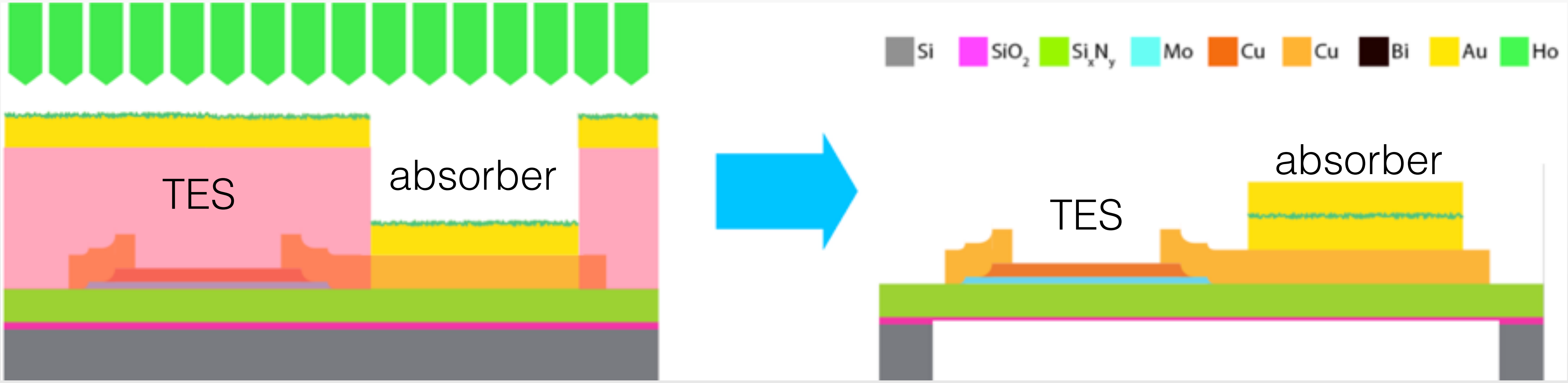
- TES design, production and preliminary test is done @NIST
- **2 μm gold thickness for full absorption** of electrons and photons
- **“side car” configuration** to avoid TES proximization and allow G engineering for τ control
- Design optimized to obtain **best compromise between resolution and time response**.
  Target (@3keV):
  - **$\Delta E_{FWHM}$ ~ 1eV**
  - **$\tau_{rise}$ ~ 1 μs**
  - **$\tau_{decay}$ ~ 100 μs**
- RF-SQUID readout with microwave MUX





- $\Delta E_{FWHM}$ ~ 4eV @6keV (~3eV @ $Q_{EC}$)
- $\tau_{rise}$ ~ 3μs
- $\tau_{decay}$ ~ 130μs

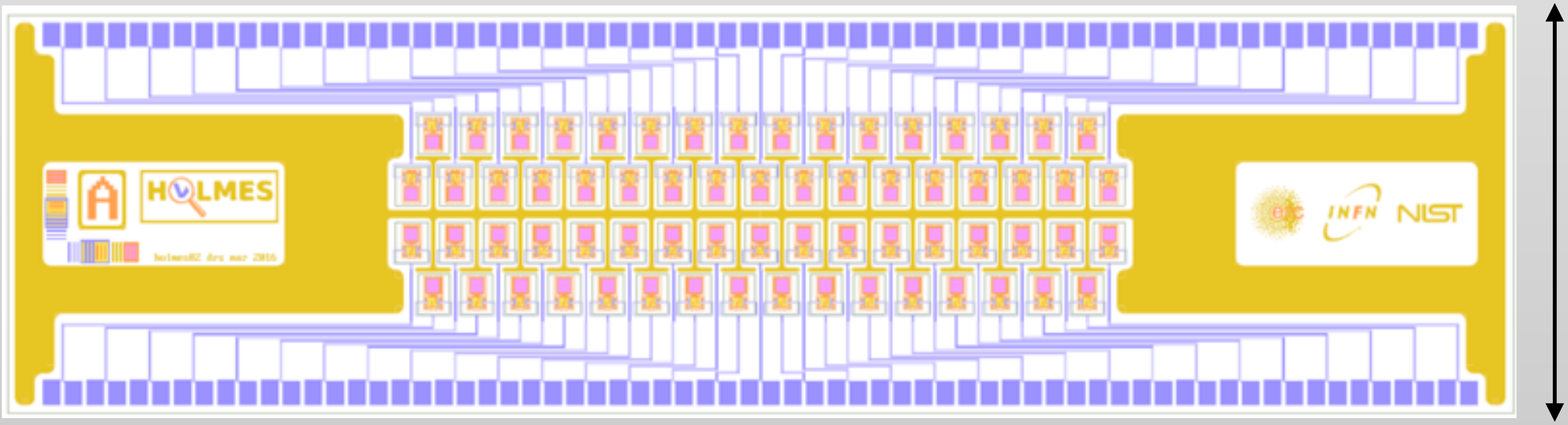
# Detector fabrication



Detector fabrication is done with a **multi-step procedure**:

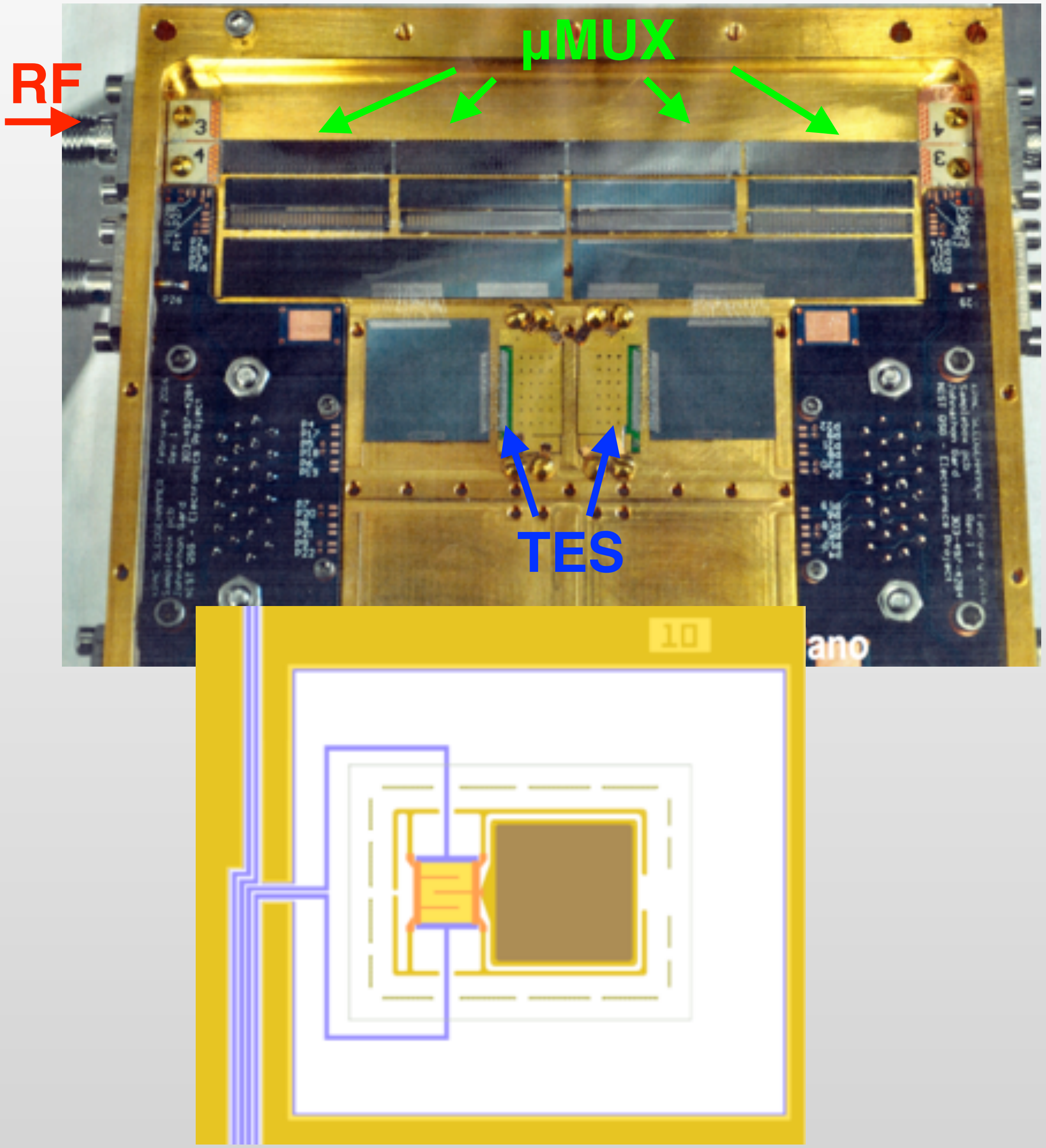
1) TES array is **produced @NIST**
2) 163Ho is **implanted @Genova**
3) 1 μm **Au final layer is deposited over Ho implantation** (“complete” the absorber)
4) final fabrication processes definition is on-going

4 x 16 linear array for implantation optimisation

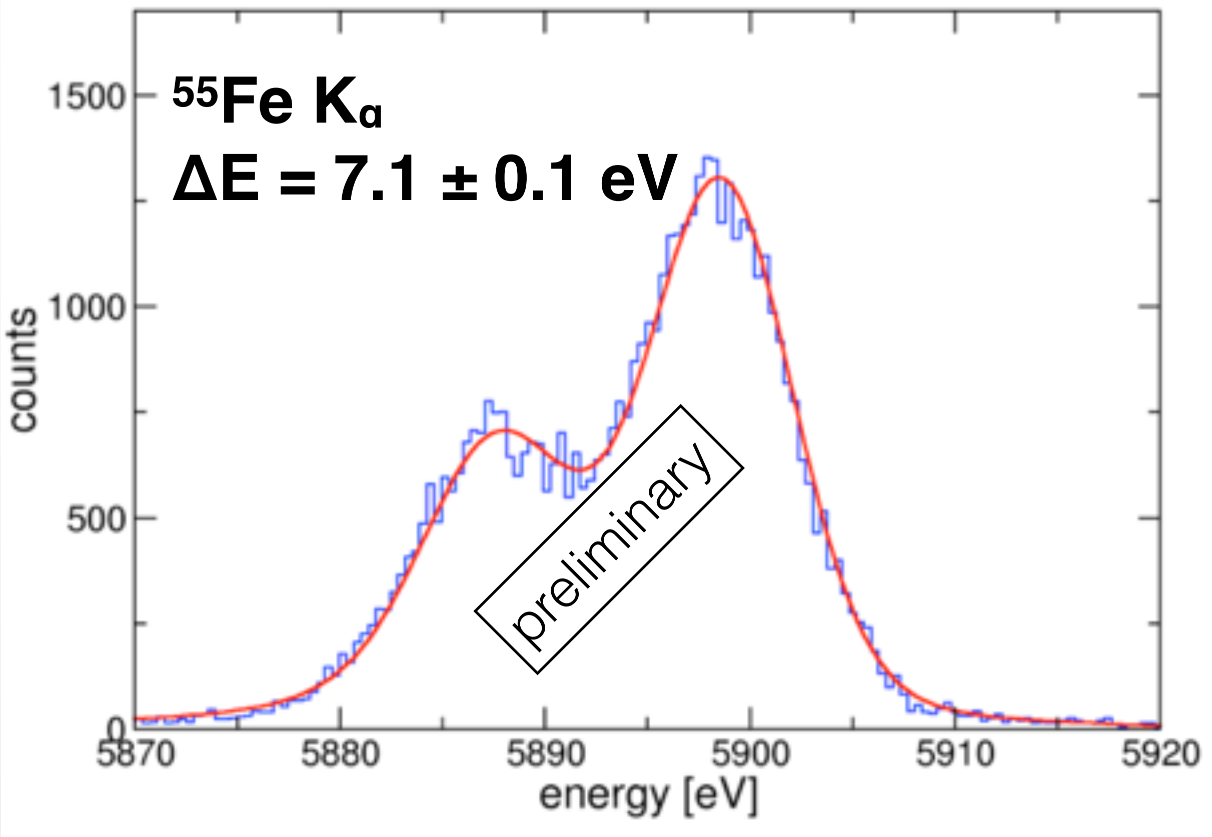


chip width: 5mm

# Pixel testing with HOLMES DAQ



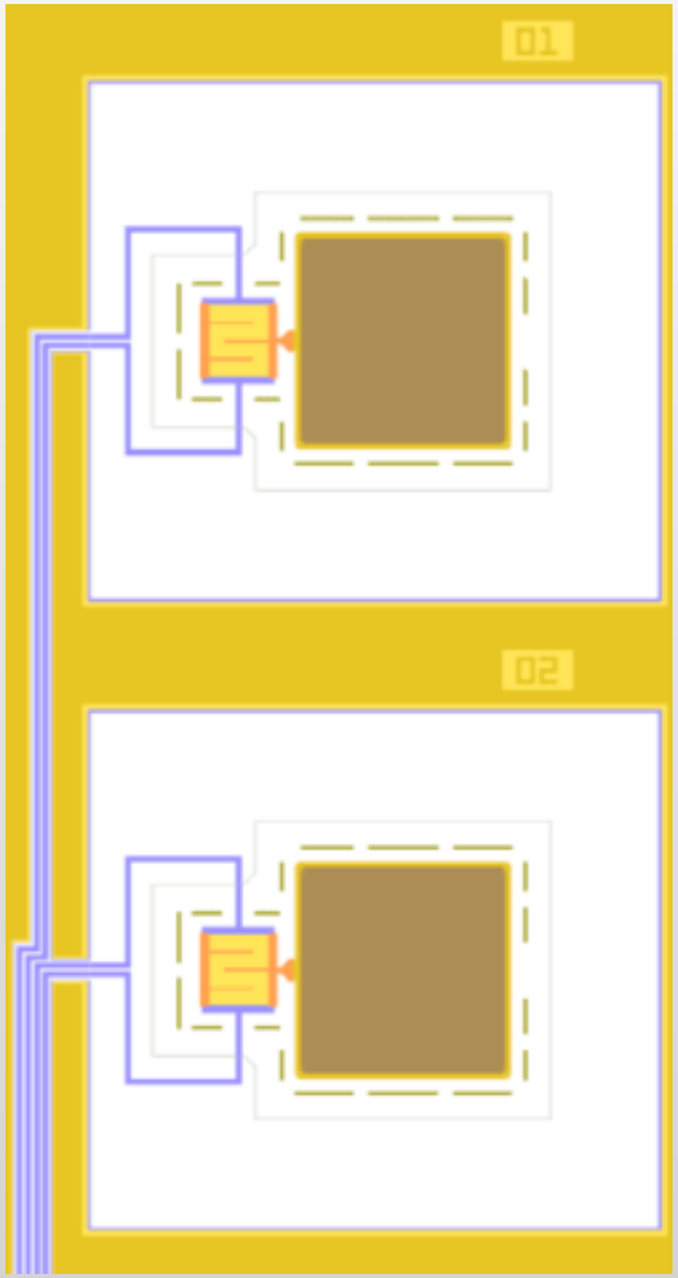
280 x 280 μm² absorber
C = 0.75 pJ/K
G = 330 pW/K



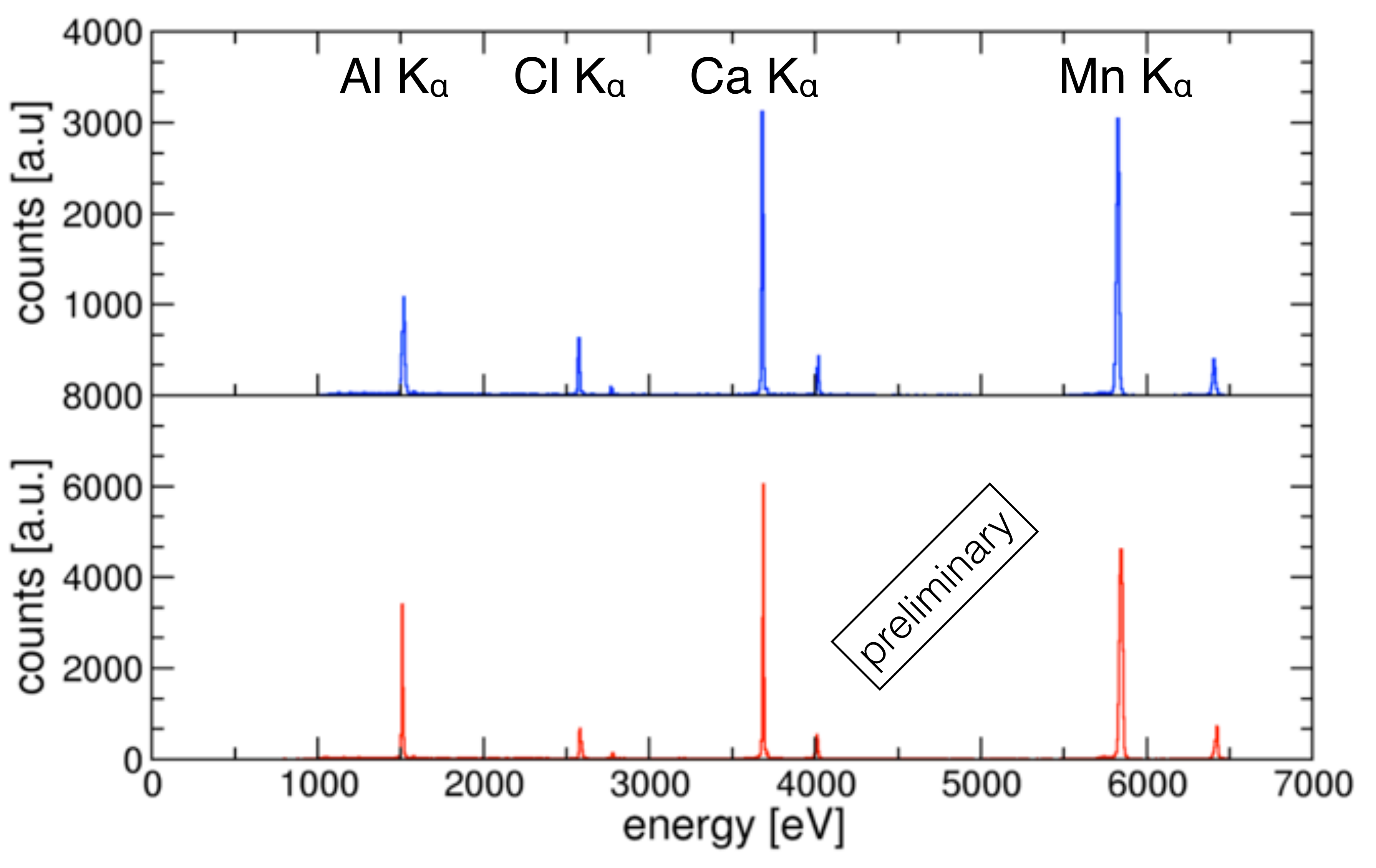
$f_{samp}$ = 500 kS/s
$\tau_{rise}$ = 6.5 μs
$\tau_{decay}$ = 67 μs

# Pixel testing with HOLMES DAQ

**HOLMES-like pixels without collimator**

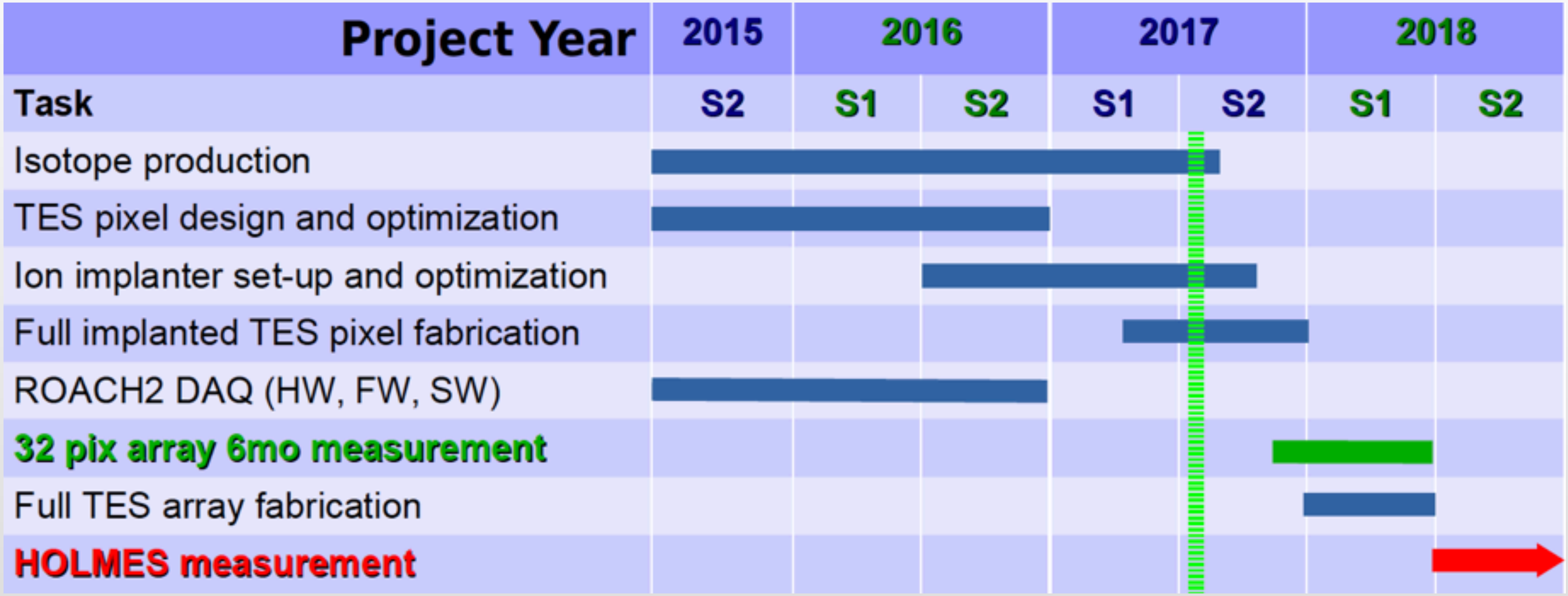


**380 x 380 μm² absorber**
**C = 0.9 pJ/K**
**G = 480 pW/K**



**$\Delta E \sim 9$ eV @2.6keV**
**$\tau_{rise} = 20$ μs**
**$\tau_{decay} = 140$ μs**

# Current status and schedule



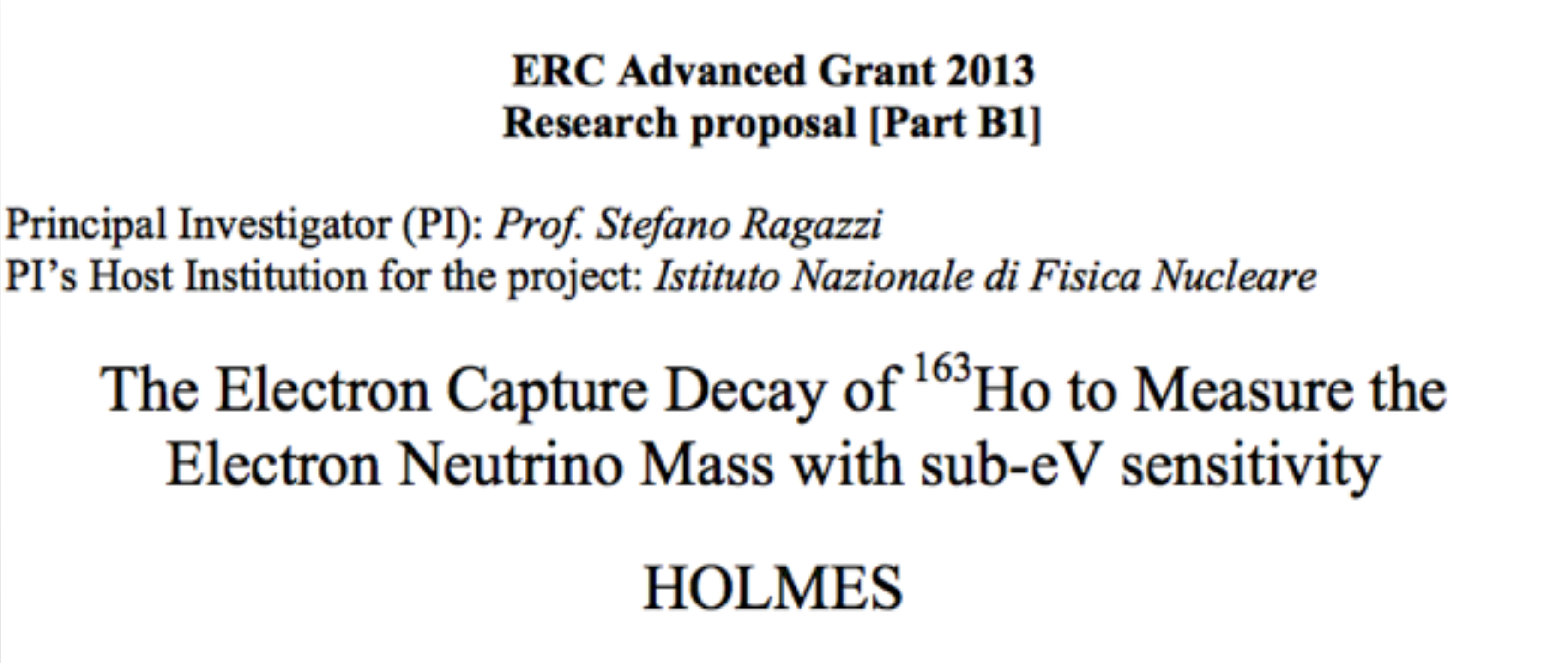
| Project Year | 2015 | 2016 | | 2017 | | 2018 | |
|---|---|---|---|---|---|---|---|
| **Task** | **S2** | **S1** | **S2** | **S1** | **S2** | **S1** | **S2** |
| Isotope production | █ | █ | █ | █ | █ | | |
| TES pixel design and optimization | █ | █ | █ | | | | |
| Ion implanter set-up and optimization | | | █ | █ | █ | | |
| Full implanted TES pixel fabrication | | | | █ | █ | | |
| ROACH2 DAQ (HW, FW, SW) | █ | █ | █ | | | | |
| **32 pix array 6mo measurement** | | | | | 🟩 | 🟩 | |
| Full TES array fabrication | | | | | | █ | |
| **HOLMES measurement** | | | | | | | 🟥→ |

**HOLMES project status:**

- TES array and DAQ ready
- Ion implanter setting up is in progress
- First $^{163}$Ho implantation coming shortly
- Spectrum measurements will begin late in 2017
- **32 pixels for 1 month → $m_\nu$ sensitivity ~10 eV**

# Back up slides

# The HOLMES collaboration



**ERC Advanced Grant 2013**
**Research proposal [Part B1]**

Principal Investigator (PI): *Prof. Stefano Ragazzi*
PI's Host Institution for the project: *Istituto Nazionale di Fisica Nucleare*

The Electron Capture Decay of $^{163}$Ho to Measure the Electron Neutrino Mass with sub-eV sensitivity

HOLMES

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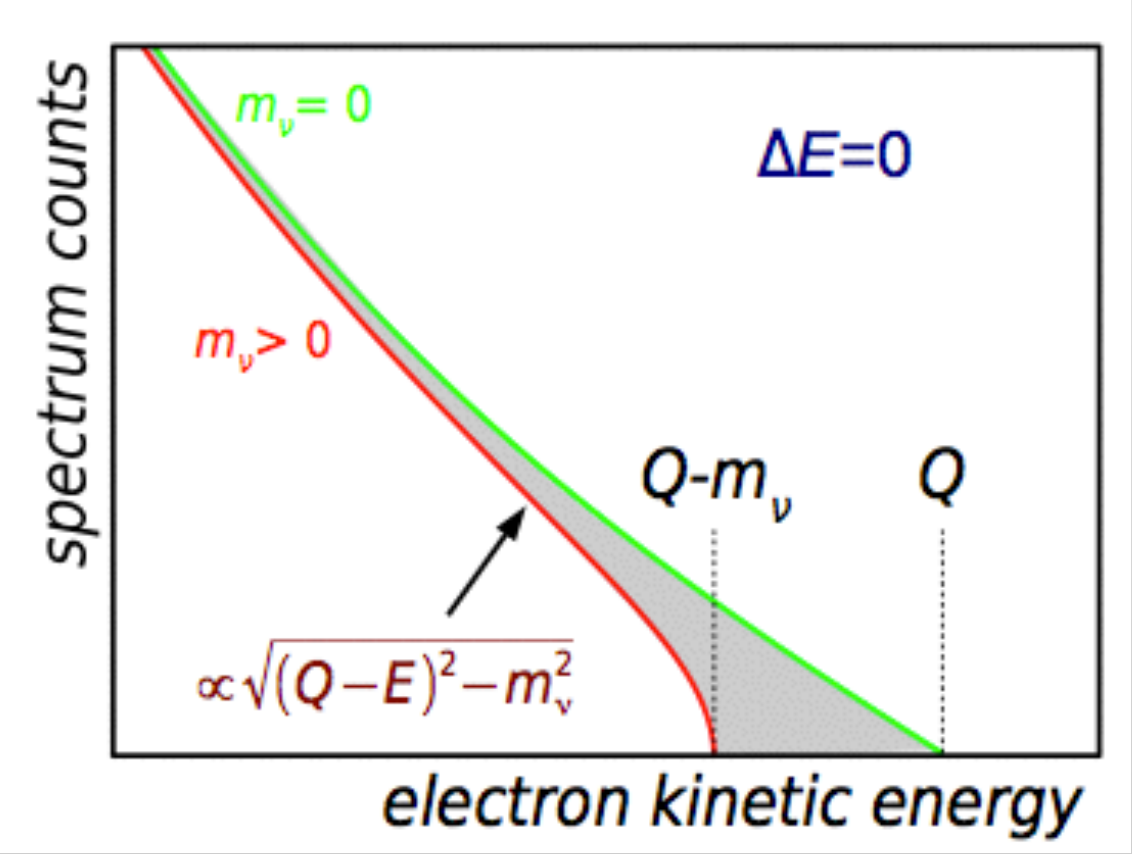
# Direct ν mass measurement

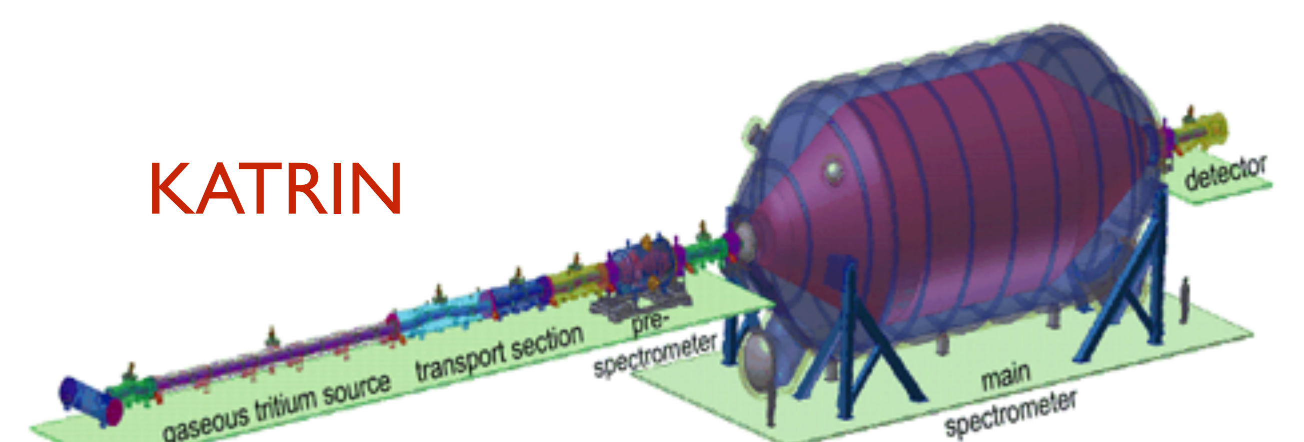
Kinematics of weak decay with ν emission:

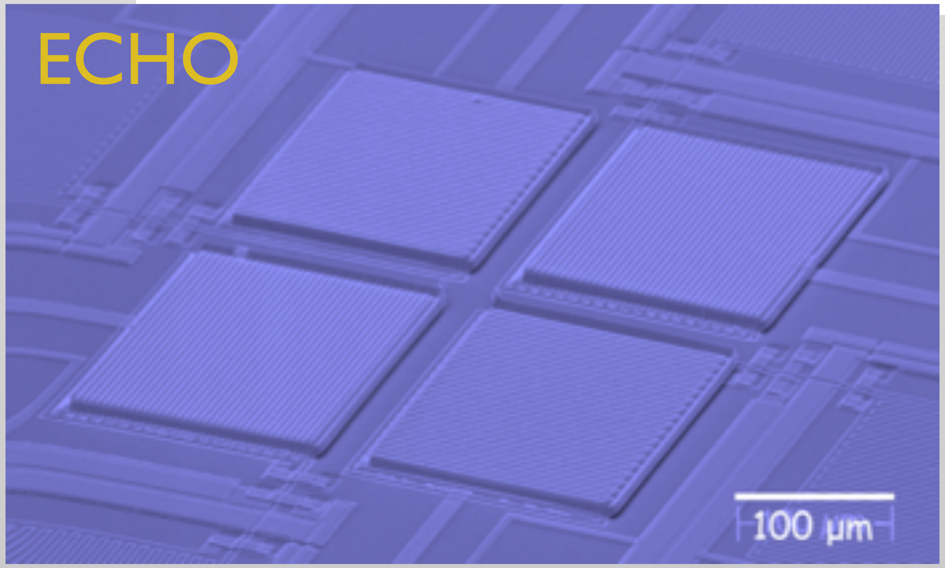
- low Q nuclear β decays ($^{3}$H, $^{187}$Re, $^{163}$Ho…)
- model independent: only E, p conservation
- **ν mass appears as a distortion in the Kurie plot**

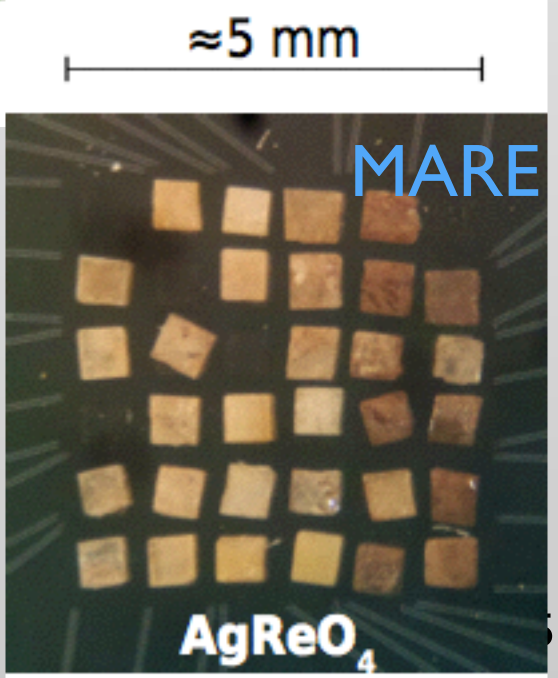
2 different approaches:

- **spectrometry**: source placed outside the detector (KATRIN approach)
- **calorimetry**: source embedded inside the detector (ECHO, MARE, HOLMES approach) ⇒ low T μ-calorimeters









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# Spectrometry vs calorimetry

General requirements for a $\nu$ mass experiment:

- High statistics near the end point
  - low Q-value (stat ~1/$Q^3$)
  - high activity/efficiency of the source
- Energy reso order ~eV or below (comparable with $m_\nu$)
- S/N ratio
- small systematic effects

Spectroscopy: source $\not\subset$ detector

- high statistics
- high energy resolution (below eV)

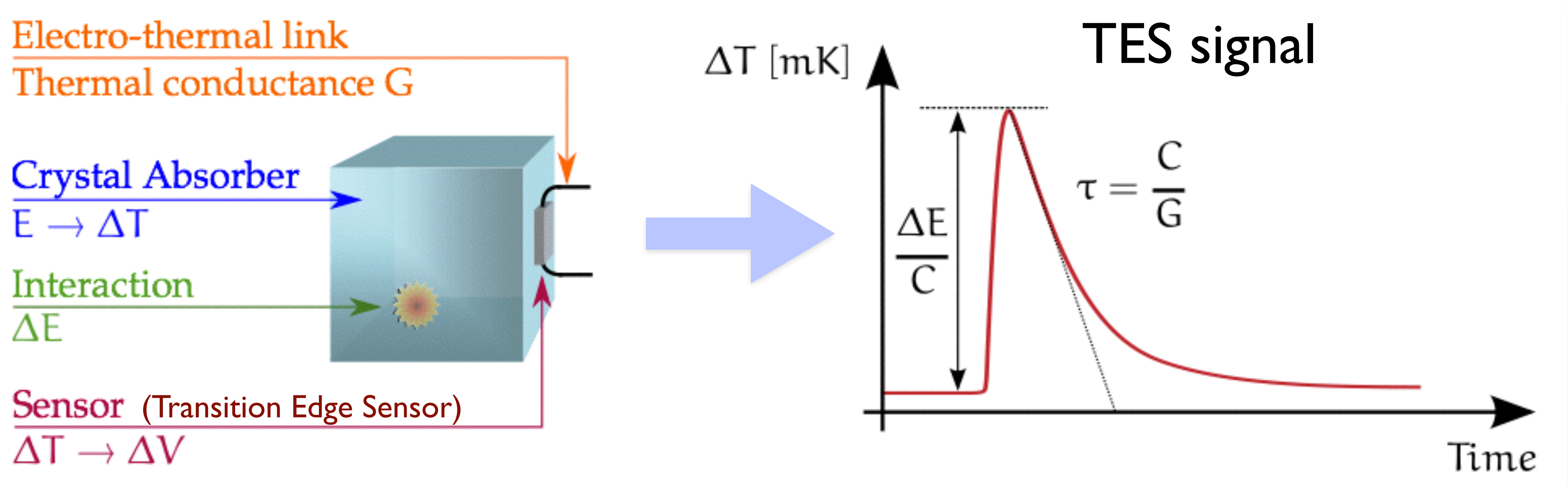
- systematics due to the source (energy loss)
- systematics due to decay to excited states
- background

Calorimetry: source $\subset$ detector

- no backscattering
- no energy loss in source
- no solid state excitation
- no atomic/molecular final state effects
- good energy resolution (~eV)

- limited statistics
- systematics due to pile-up
- background

# Low T calorimetry in a nutshell



- Complete energy thermalization (ionization, excitation → heat → calorimetry)
- $\Delta T_{max} = E/C$, C is the total thermal capacity
  - absorber with low thermal capacity
  - for superconductors below $T_C$ and dielectric: $C \sim (T/\theta_D)^3$ (Debye law)
  - very low T is needed (10÷100mK)
- $\Delta E_{rms} = (k_b T^2 C)^{1/2}$ due to statistical fluctuations of internal energy
- $\Delta T(t) = E/C\ e^{-t/\tau}$, $\tau = C/G$ and G is the thermal conductance

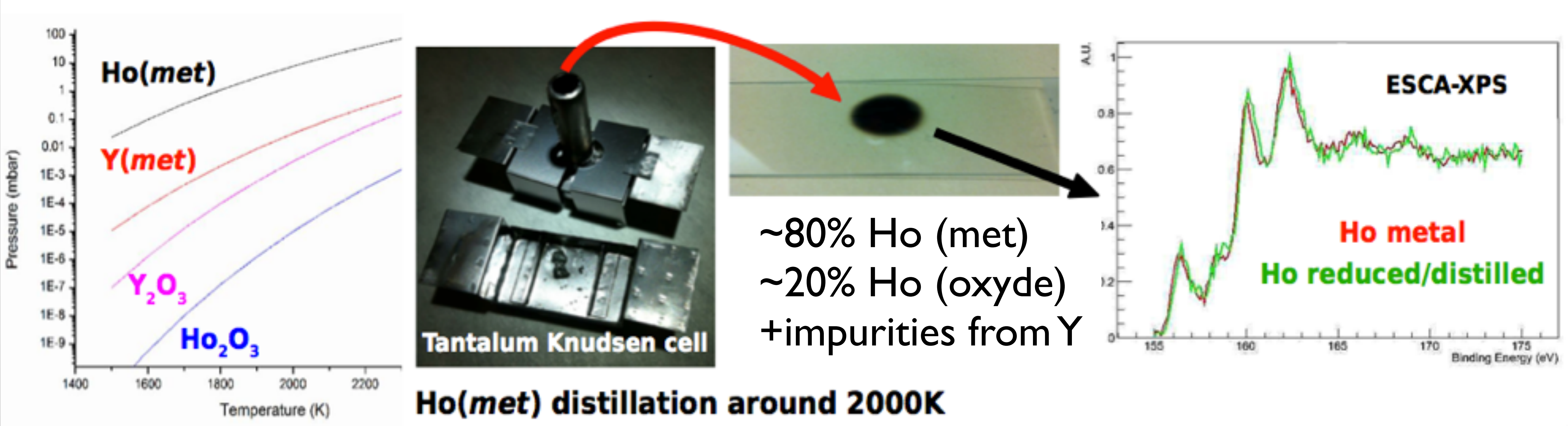
# Ho production and purification

$^{163}$Ho separation from Dy, Er and others…

- radiochemistry (before/after activation process)
- magnetic mass separation

$Ho_2O_3$ thermoreduction in Knudsen cell provides a metallic sample for the implantation:

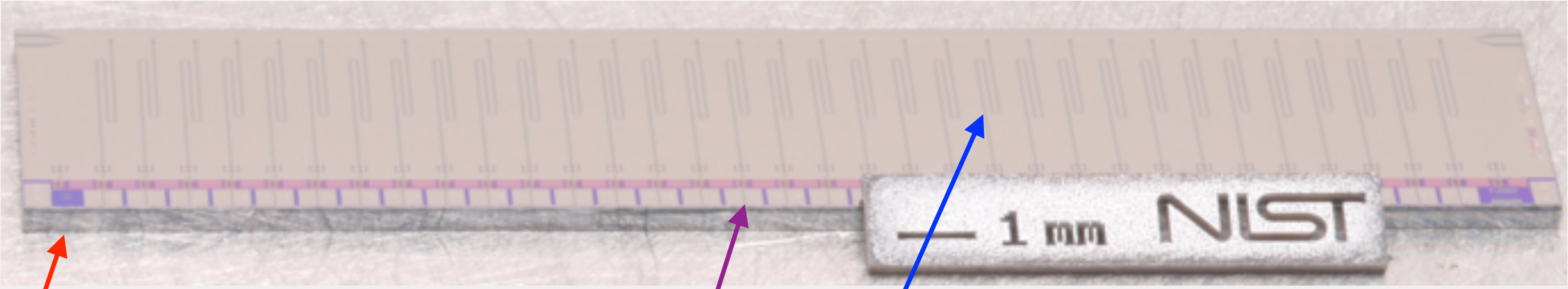
- $Ho_2O_3 + Y(met) \rightarrow Ho(met) + Y_2O_3$ @2000K
- First test already performed in Genova



~80% Ho (met)
~20% Ho (oxyde)
+impurities from Y

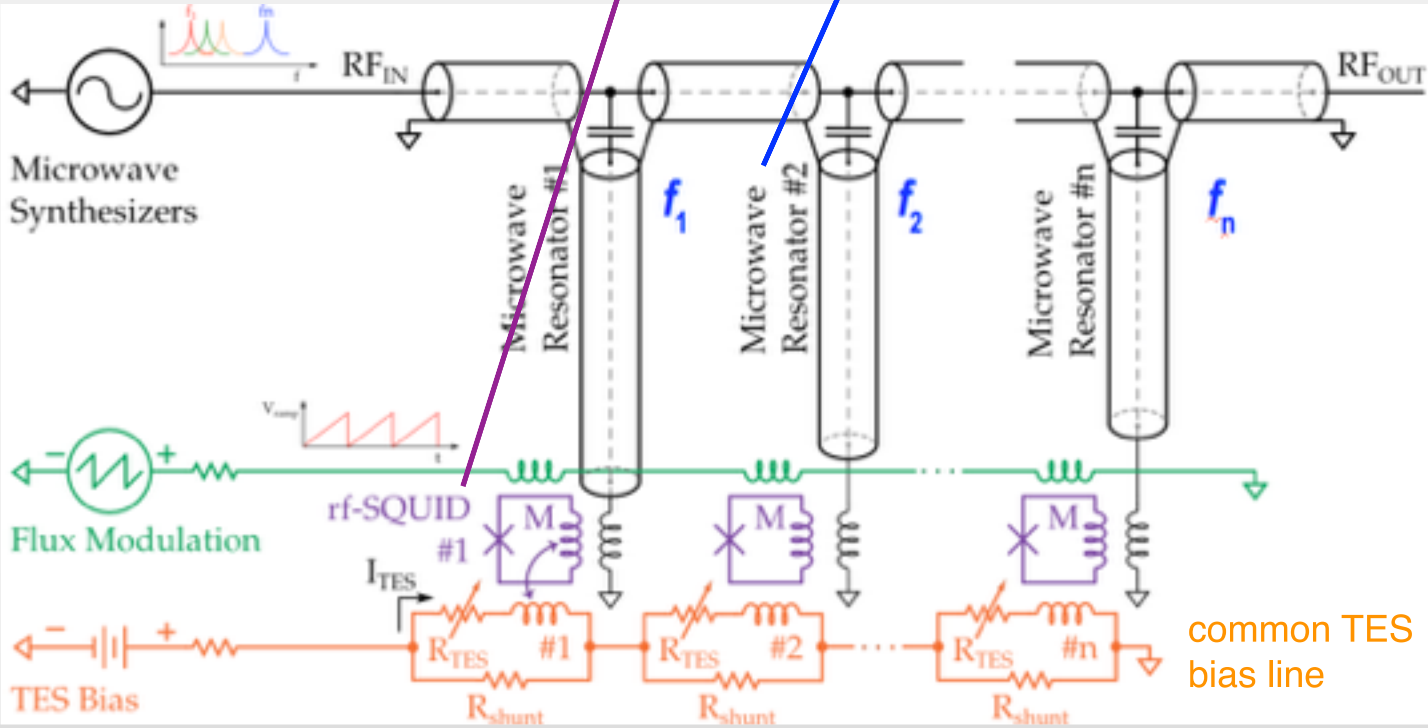
**Ho(*met*) distillation around 2000K**

# Array readout: rf-SQUID μwave mix

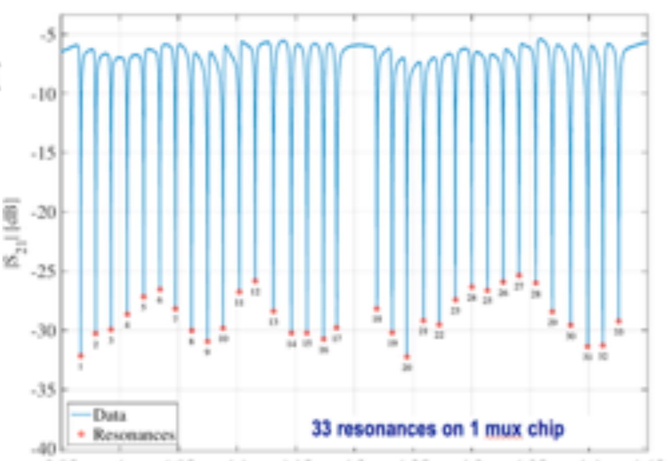


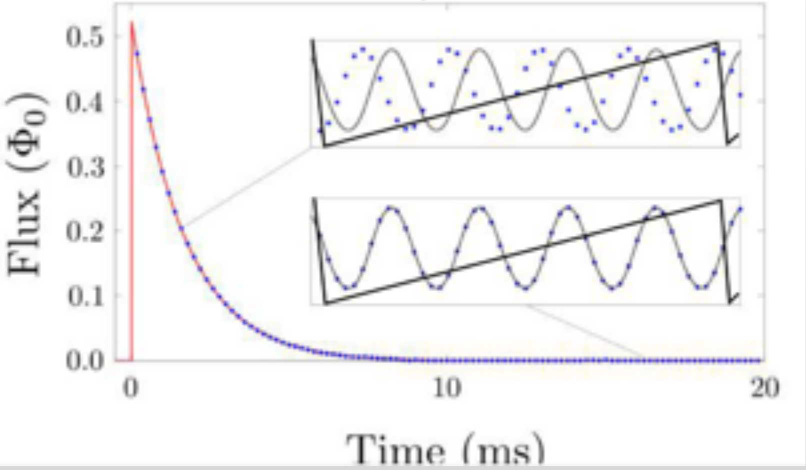
λ/4 resonators coupled to common feedline tuned at different frequencies for multiplexing

common SQUID modulation line



common TES bias line



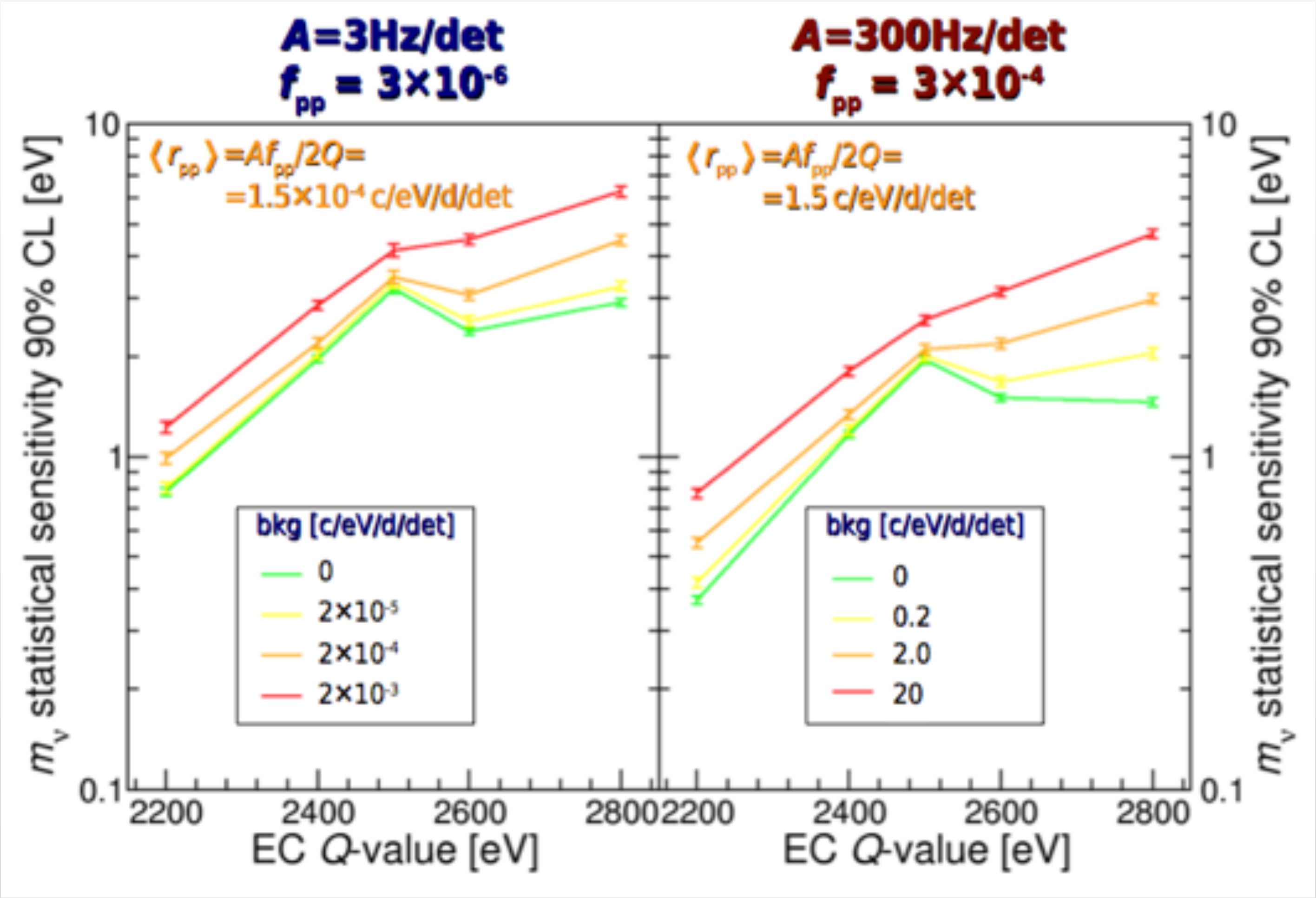


To linearize the SQUID response, a voltage ramp is constantly applied to every SQUID trough a common line.
The signal is reconstructed from the phase shift of the SQUID oscillation (solid line), with respect to a reference sine function (dotted line).
The ramp frequency is the effective pulse sampling

Each rf-SQUID is coupled to a GHz range resonator
- resonance bandwidth has to match the SQUID oscillation frequency i.e. 2 MHz
- resonance spacing has to be tuned to maximise multiplexing factor avoiding crosstalk i.e. 14 MHz

# Source of background

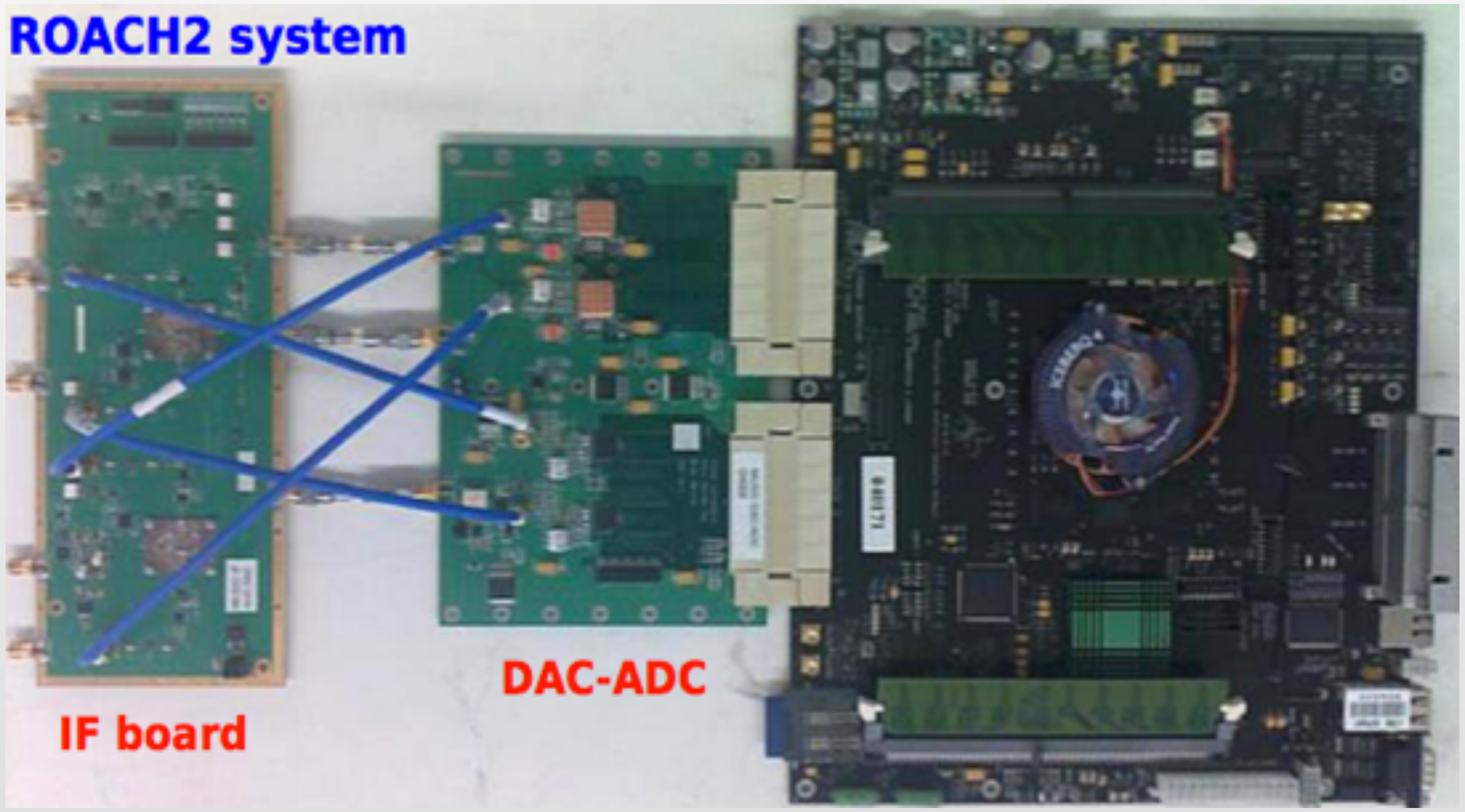
- Environmental γ radiation
  - Compton interactions, photoeletric interactions with p.e. escape
  - Fluorescent X-rays and X-ray escape line
  - Cosmic rays
    - GEANT4 simulation for CR at sea level (only muons)
    - Au pixel 200 x 200 x 2 $\mu m^3$ → bkg ~ 5 $\times 10^{-5}$ c/eV/day/det (0 - 4 keV)



- Internal radionuclides
  - $^{166m}$Ho ($\beta^-$, $\tau_{1/2}$ = 1200 y, produced along with $^{163}$Ho)
  - Au pixel 200 x 200 x 2 $\mu m^3$ → bkg ~ 0.5 c/eV/day/det/Bq($^{166m}$Ho)
  - A($^{163}$Ho) = 300Bq/det (~ $6.5\times10^{13}$ nuclei/det)
  - if bkg($^{166m}$Ho) < 0.1 c/eV/day/det
    - → A($^{163}$Ho)/A($^{166m}$Ho) > 1500
    - → N($^{163}$Ho)/N($^{166m}$Ho) > 6000

# ROACH2-based multiplexing

- Reconfigurable Open Architecture Computing Hardware (ROACH) designed by the Collaboration For Astronomy Signal Processing and Electronics Research (CASPER);
- Xilinx Virtex FPGA based digital data processing;
- Frequency comb generation (≃ 60 tones in the 0 ÷ 550 MHz range);
- Quadrature frequency upmixing (500 MHz → 5 GHz) and down- mixing (5 GHz → 500 MHz);
- Signal channelizing and rf-SQUID signal de-modulation
- Real time signal processing;
- Strongly tested for MKIDs read- out (ARCONS, 2048 pixels)



Holmes design:

- 4 × 256 = 1024 pixels;
- Target: 64 resonace per ROACH-module;
- Complete system composed by 16 module.