A direct neutrino mass measurement with ^{163}Ho: the HOLMES experiment

M. De Gerone
INFN Genova
on behalf of the HOLMES collaboration

XX Lomonosov Conference on elementary particle physics

Moscow State University, August 19-25 2021

^{163}Ho electron capture

^{163}Ho + e$^-$ → Dy* + ν_e

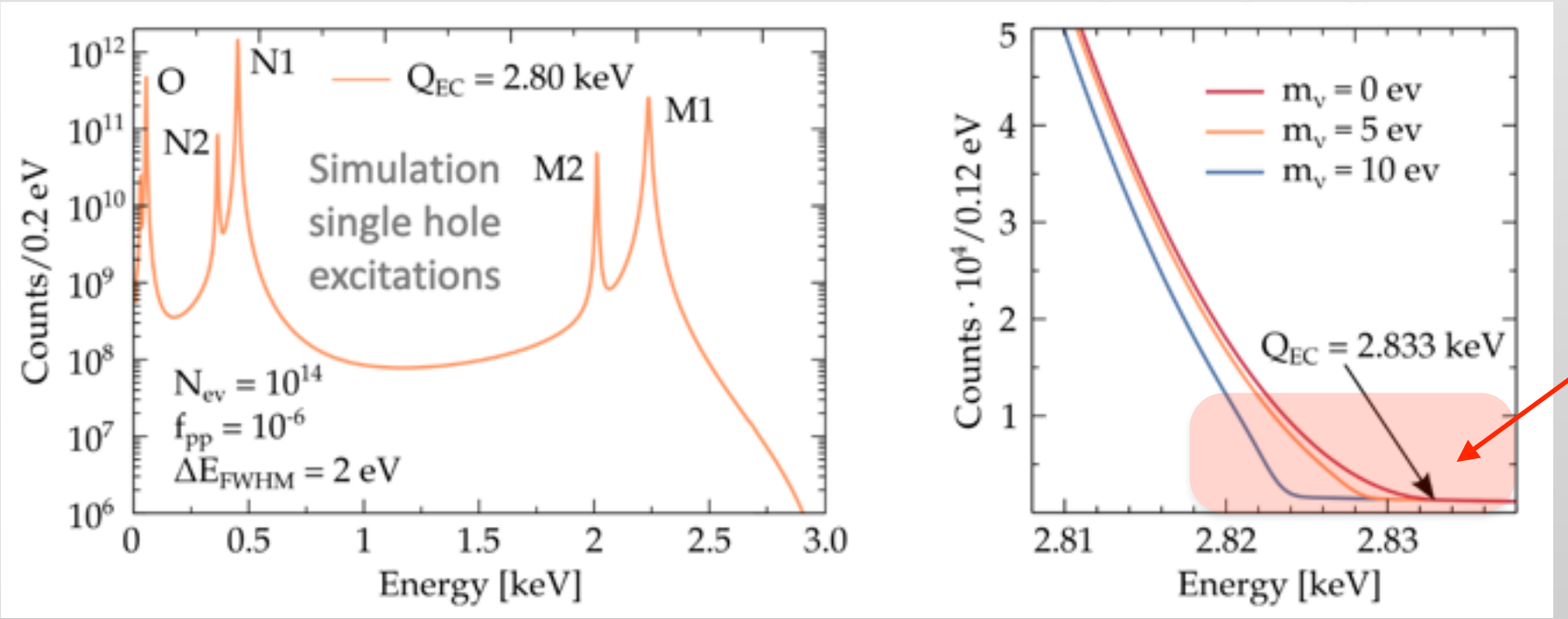
$$\frac{d\lambda_{EC}}{dE_c} = \frac{G_\beta^2}{4\pi^2}(Q-E_c)\sqrt{(Q-E_c)^2-m_\nu^2} \times \sum n_i C_i \beta_i^2 B_i \frac{\Gamma_i}{2\pi} \frac{1}{(E_c-E_i)^2+\Gamma_i^2/4}$$

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 shape

- 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



expected ν mass effect

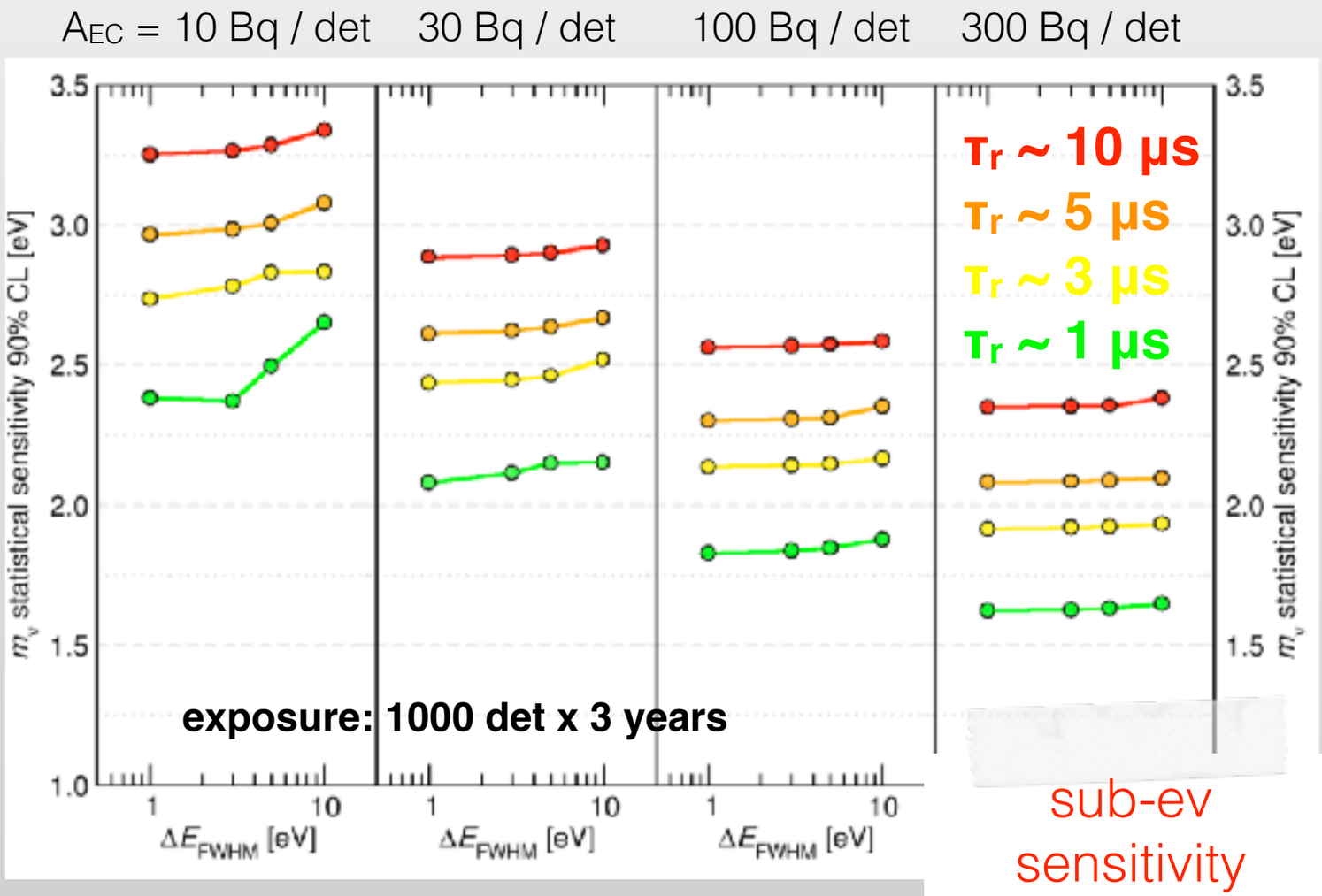
The HOLMES project in a nutshell

- 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 ~ 1 eV, τ ~ 1-10 μs

- 2 steps approach:
  - 64 channels prototype,
    - t_m = 1 month, m_ν < 10 eV
  - 1000 channels array:
    - 6.5 x 10^{16} total nuclei
    - O(10^{13}) events / year
    - m_ν ~1 eV

- Should prove the technique potential and scalability by evaluating EC spectral shape and systematic errors



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

^{163}Ho electron capture

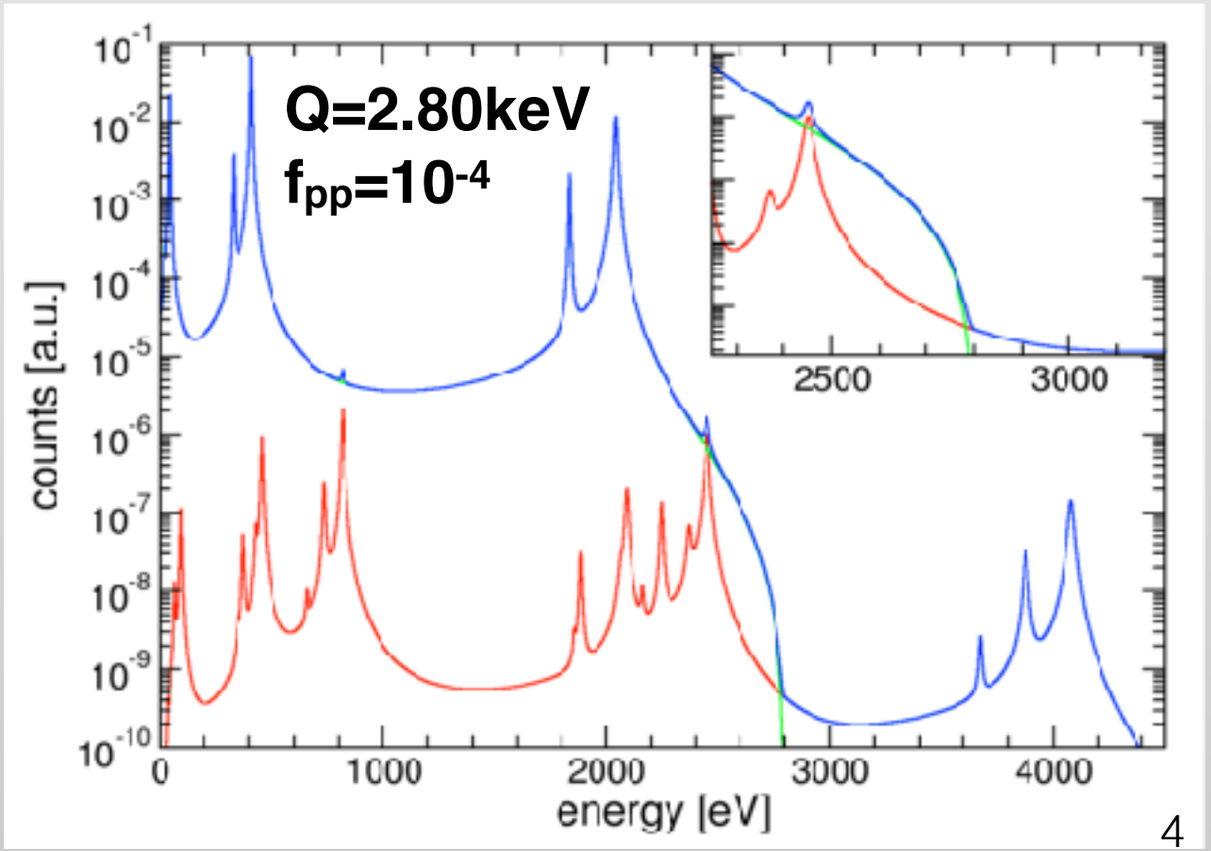
Complex pile-up spectrum: end-point is dominated by $((Q-E_C)^2 - m_\nu^2)^{1/2}$ but expected distortions due to pile-up:

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

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 τ_r ;
- pile-up resolving algorithm.



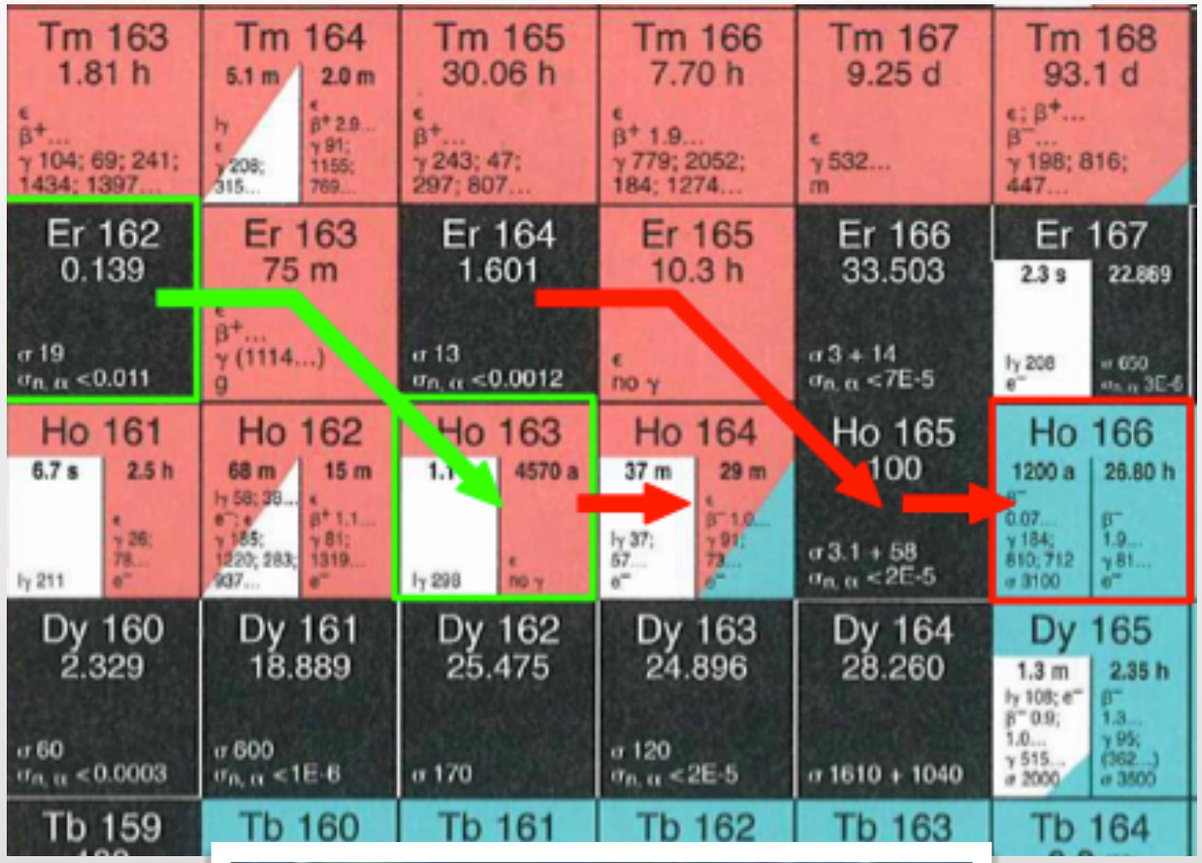
^{163}Ho production

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

- ^{162}Er (n,γ) ^{163}Er, σ_{therm} ~ 20 b
- ^{163}Er + e^- → ^{163}Ho + ν_e ($\tau_{1/2}$ ~ 75 m)
- high yield
  - ~3x10^{12} ^{163}Ho nuclei/mg^{162}Er/h
- requires ^{162}Er enrichment and oxide chemical form (Er_2O_3)

It is a "dirty" process: many other isotopic species are created together with ^{163}Ho. Worst one:

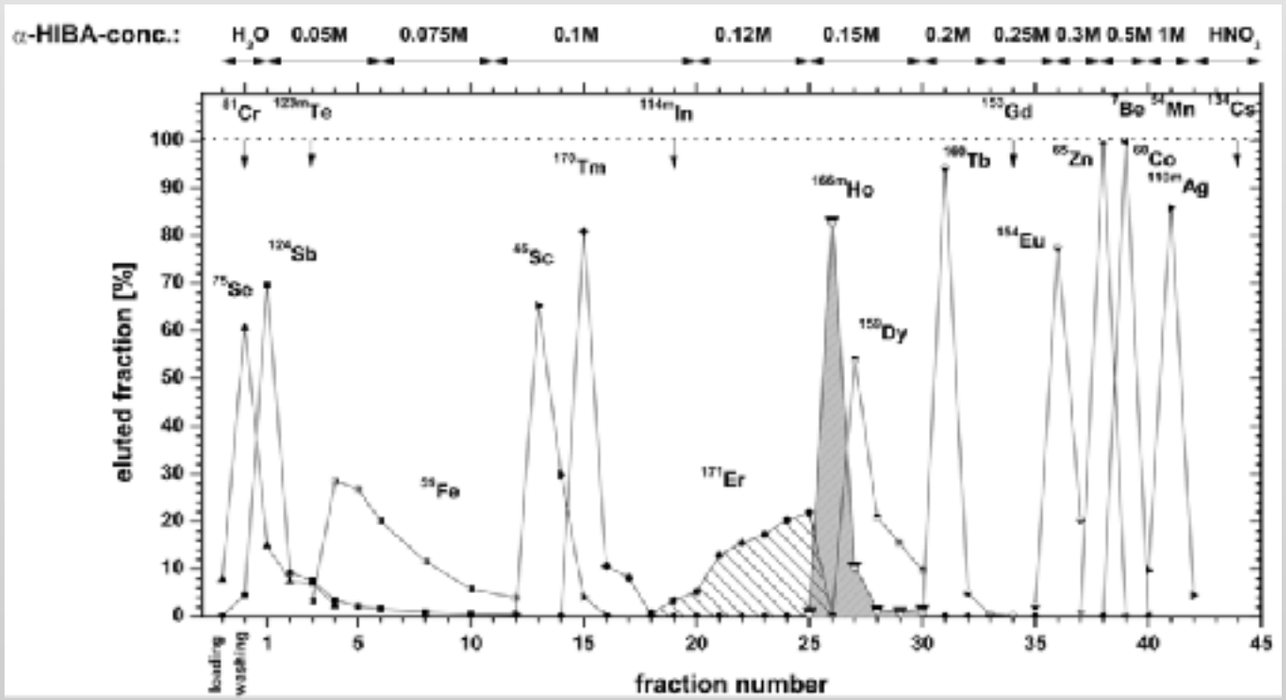
- ^{165}Ho (n,γ) ^{166m}Ho (β, $\tau_{1/2}$~ 1200 years)
- from Ho contamination or ^{164}Er (n,γ)
- need high purification of sample:
  - radiochemical separation:
    - removes everything but Ho;
  - mass separation with magnetic dipole.

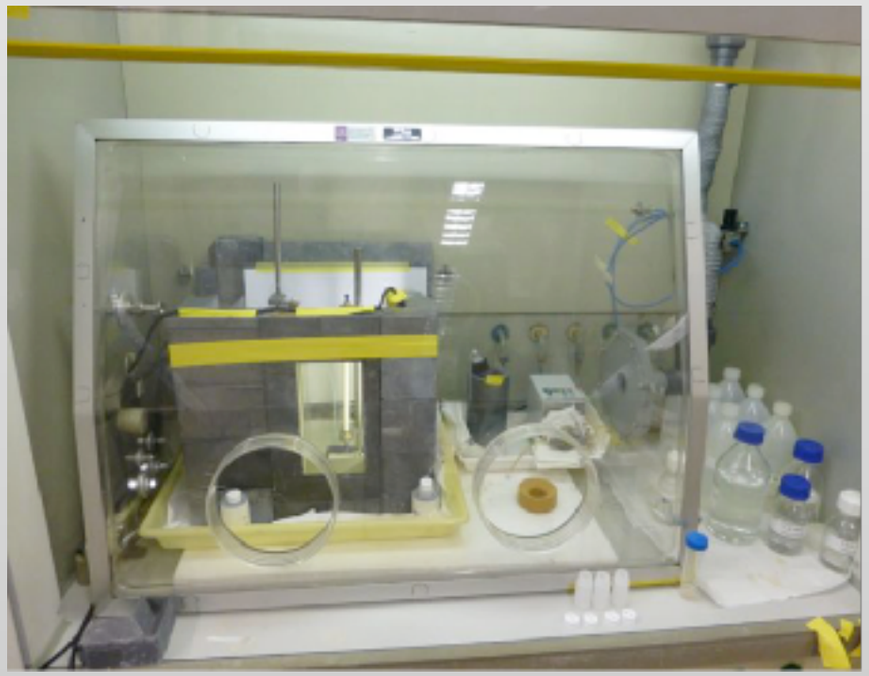


In collaboration with
ILL (Grenoble, FR)
Paul Scherrer Institute (Villigen, CH)

^{163}Ho purification

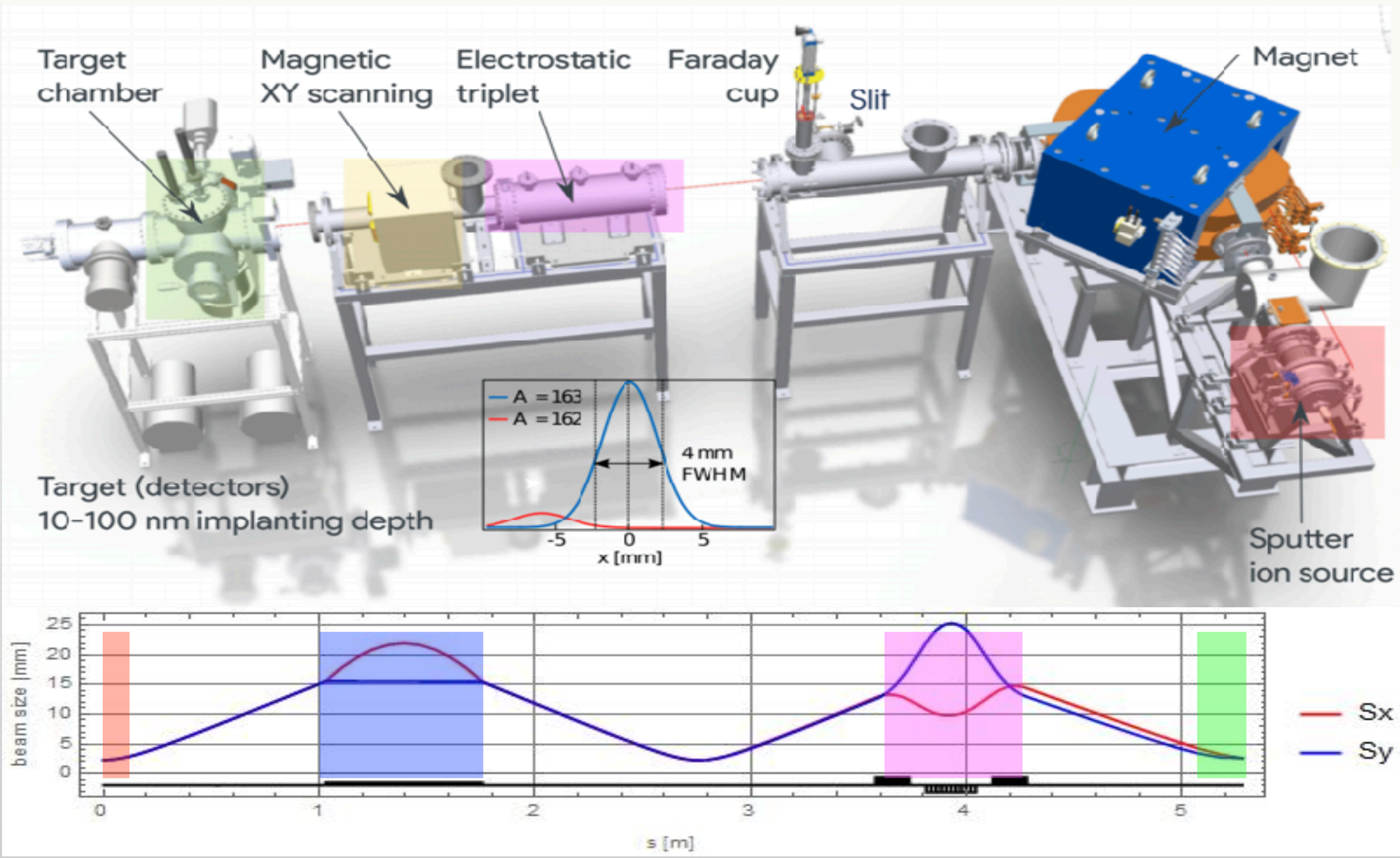
- Enriched Er_2O_3 samples irradiated at ILL (Grenoble) and post-processed at PSI:
  - 25 mg, 55 days irradiation → A(^{163}Ho) ~ 5 MBq
  - 150 mg, 50 days irradiation → A(^{163}Ho) ~ 38 MBq
  - 540 mg, 50 days irradiation → A(^{163}Ho) ~ 120 MBq
- Ho radiochemical separation is performed via ion-exchange chromatography at PSI.
  - Expected ^{166m}Ho contamination fraction: ~10^{-3}
  - Currently available activity is already enough for HOLMES purposes.





S. Heinitz et al. PLOS ONE 13(8):e0200910

^{163}Ho mass separation



^{163}Ho mass separation

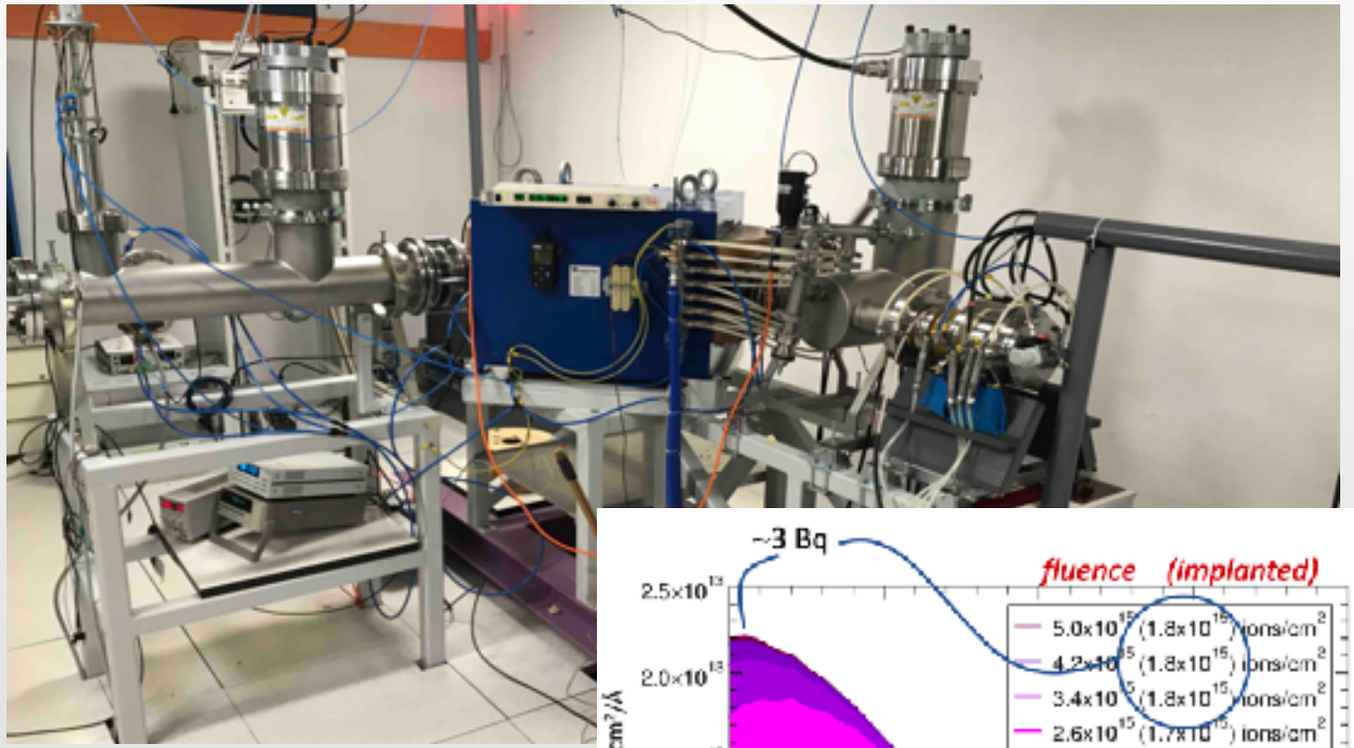
The layout currently installed in Genova's lab includes:

- an argon Penning sputter ion source with a 50kV acceleration section, corresponding to O(10 nm) implantation depth;
- a magnetic dipole mass analyzer, field up to 1.1 T; expected 163/166 a.m.u. separation > 5 σ;
- a Faraday cup and a slit.

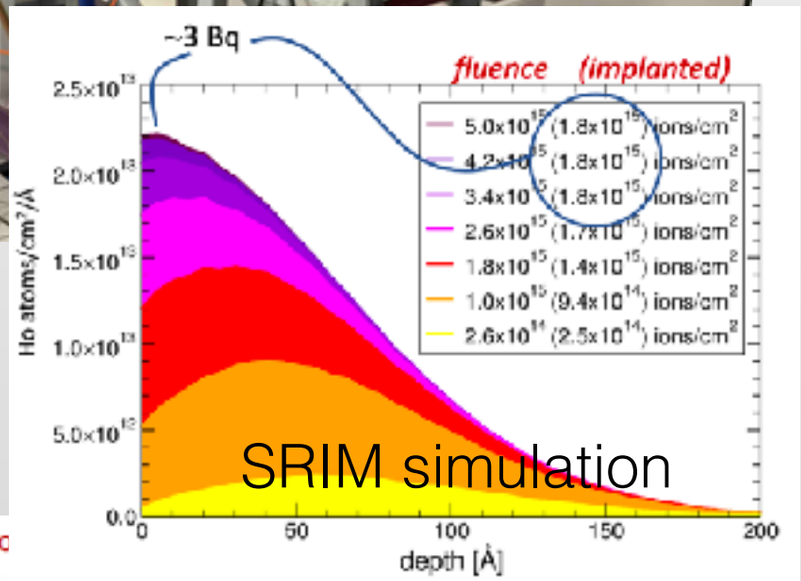
The target chamber, which allows simultaneous co-evaporation of Au will be installed soon. Co-evaporation is needed:

- to fully encapsulate the source in the absorber and
- because after a while ^{163}Ho concentration in the absorber saturates.

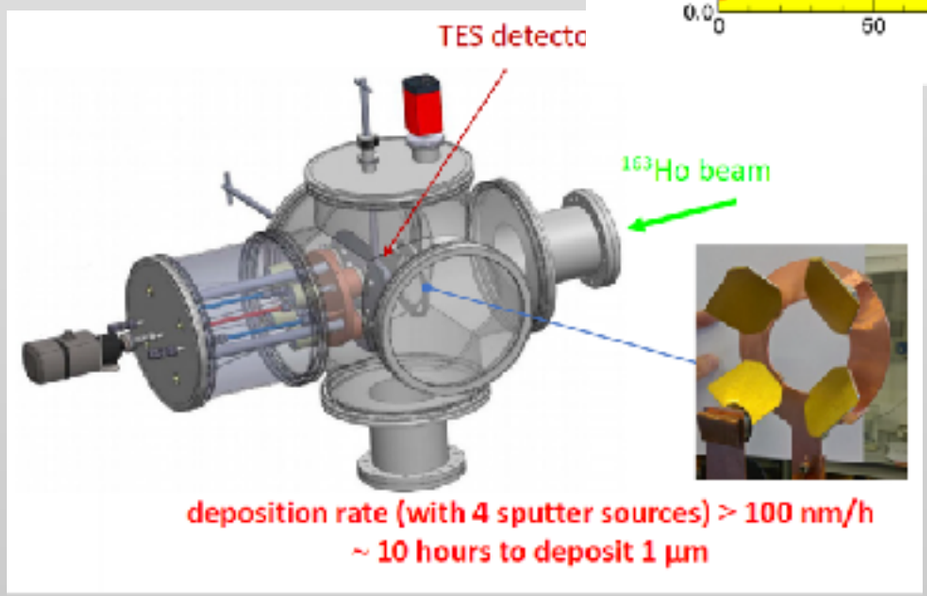
The machine will be upgraded after first 64 detector arrays production.



Target chamber



SRIM simulation

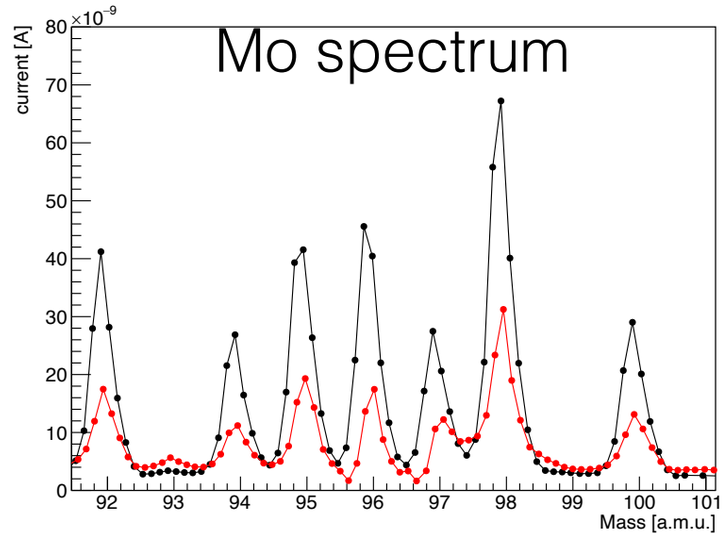


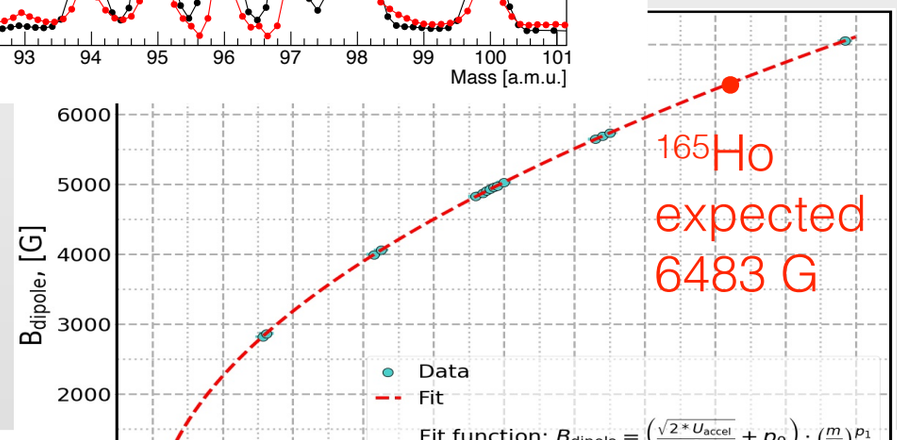
Ion implanter calibration and test

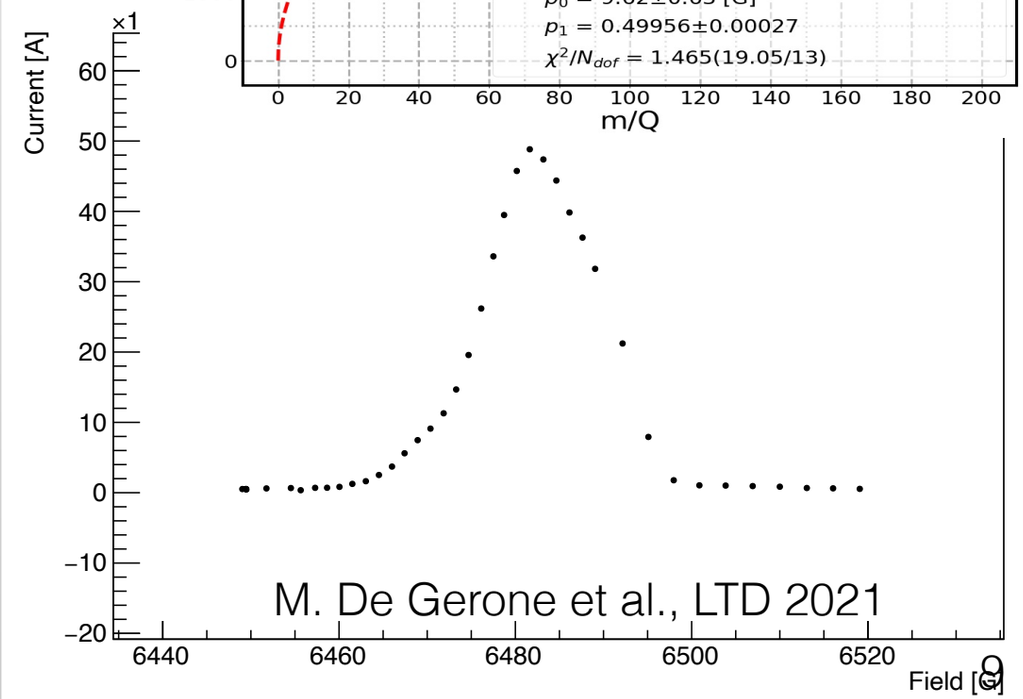
The machine is calibrated using peaks from Cu, Au and Mo (from sputter target and anode). A small misalignment has been measured and taken into account. Mass resolving power has been evaluated from Cu and Mo peaks and extrapolate to be 18 mm at 163/166 a.m.u.

First tests performed with sputter target made with bulk Cu disk with a thin layer of $^{165}Ho(OH)_3$ deposited via molecular plating:

- clear peak at 165 a.m.u. BUT source efficiency is still quite low:
  - current O(50nA) sustained for few minutes…
  - Maybe $^{165}Ho(OH)_3$ dissociates in different compound? (HoO, Ho(OH)…)
- Now testing:
  - Different Ho compounds to be included in sputter target:
    - $Ho(CH_3COOH)$, $HoPO_4$, $Ho(NO_3)_3$
  - Different techniques for sputter target production:
    - Sintered target (mixture of Ho/Ti/Ni/Sn)



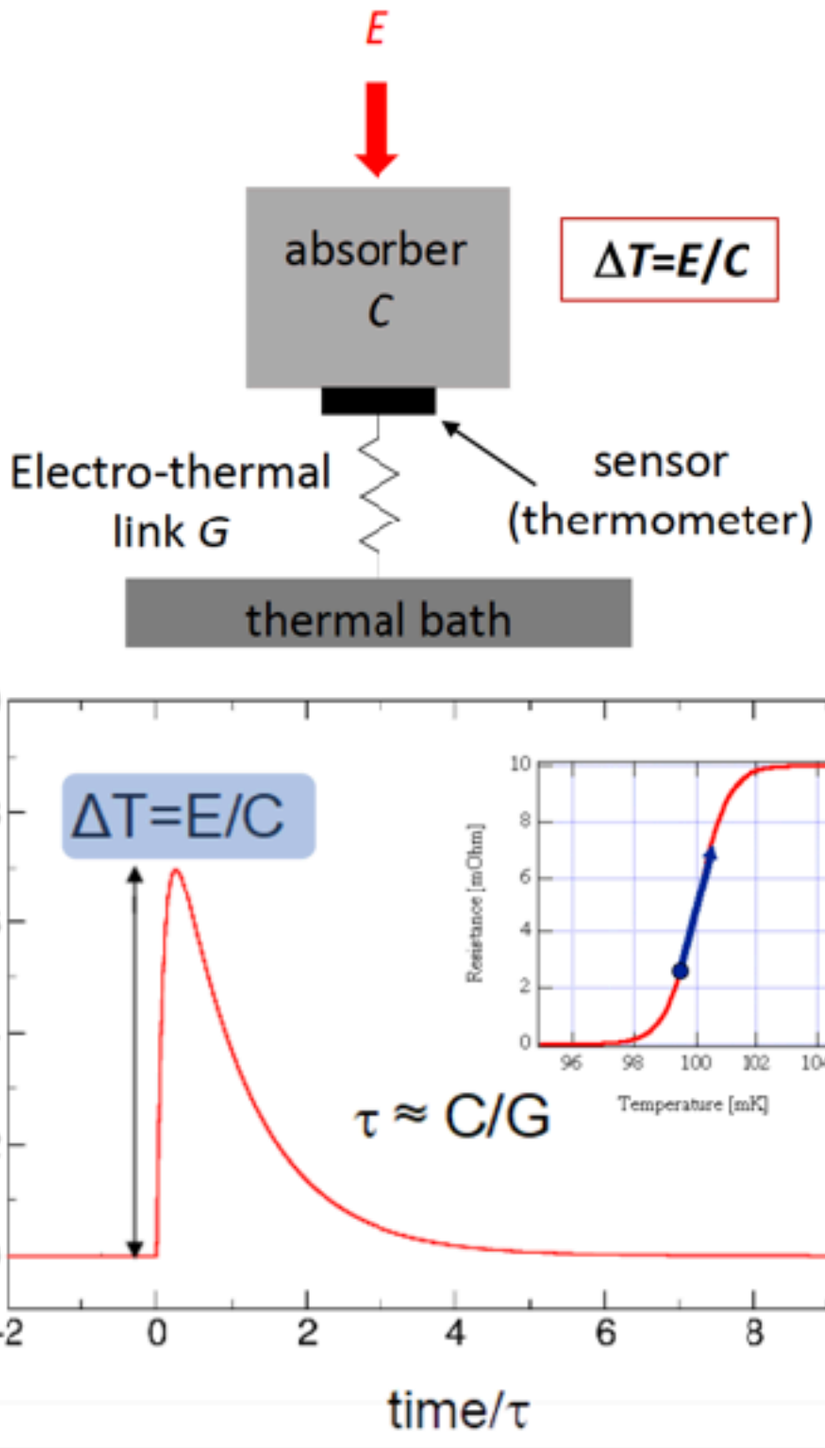




TES based μ-calorimeters

Transition edge sensors based μ-calorimeters:

- absorber coupled to a superconductive sensor (thermometer) kept in the transition region;
- energy release in the absorber produces a temperature increase in thermometer and then a change in TES resistance;
- Exploit the steepness of R(T) of a superconductor kept in its transition to measure ΔE:
  - state of art energy resolution (O(eV));
  - multiplexing readout scheme available;
  - limited dynamics: design has to be optimized for a specific application.
  - $\Delta T_{max} = E/C$, C = thermal capacity
  - $\Delta T(t) = E/C\ e^{-t/\tau}$, $\tau = C/G$, G is the thermal conductance

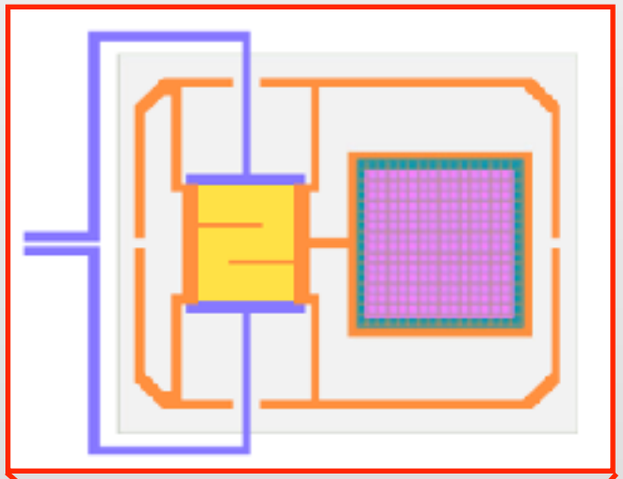


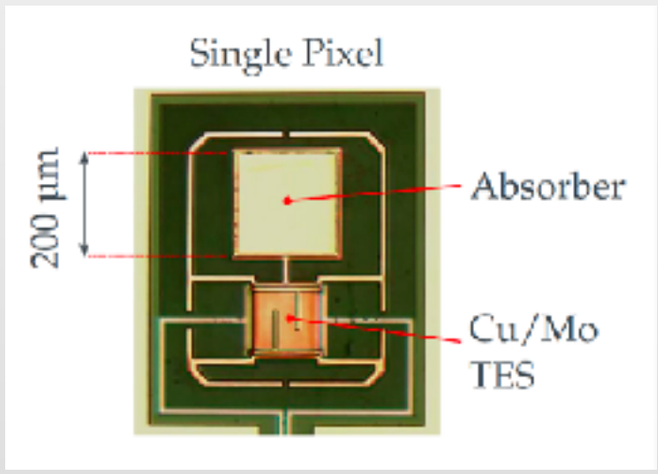
Holmes detector design

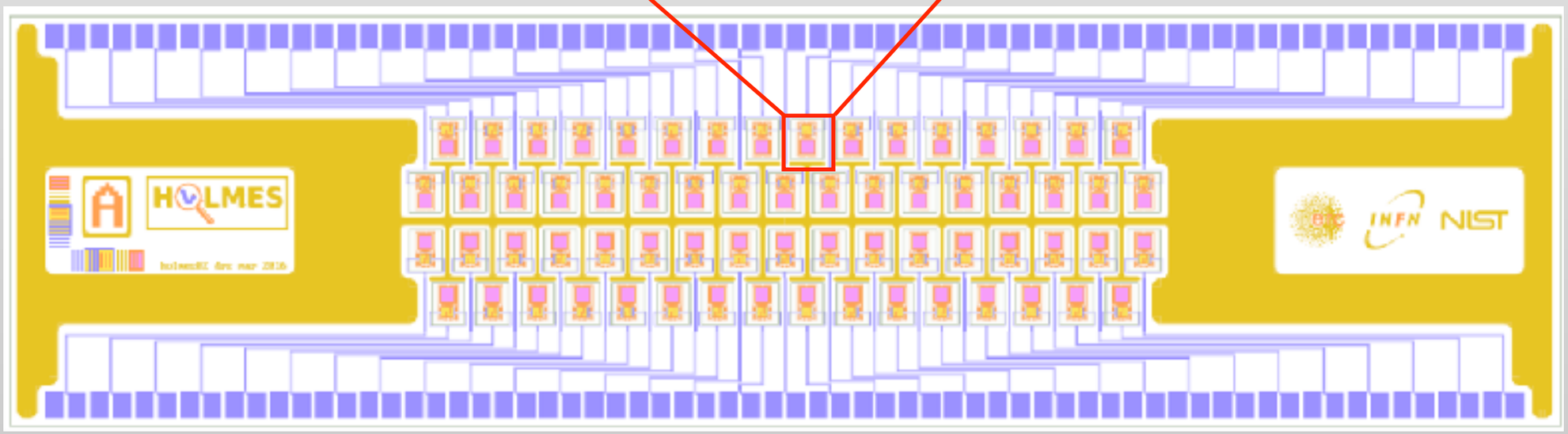
- TES design, production and preliminary test is done @NIST
- 2 μm Au thickness for full absorption of electrons and photons
- "side car" configuration to avoid TES proximization and allow G engineering for a better τ control
- Design optimized to obtain best compromise between resolutions and time response.

Target performances (@ 3 keV):

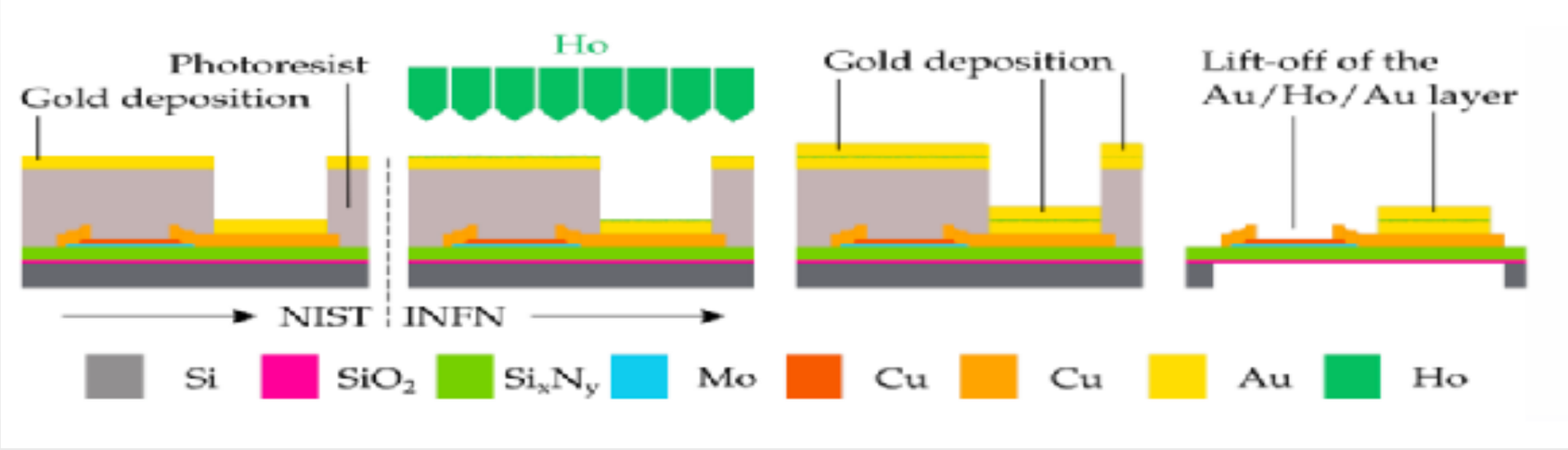
- ΔE_{FWHM} O(eV)
- τ_{rise} ~ 10 μs
- τ_{decay} ~ 100 μs







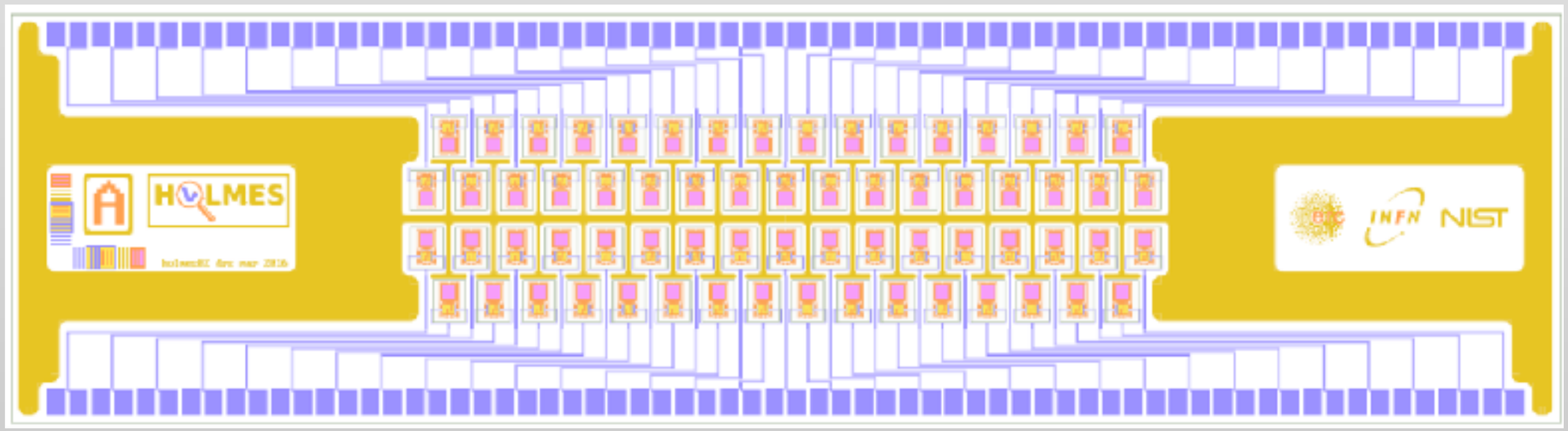
Holmes Detector production



Detector fabrication is done with a multi-step procedure:

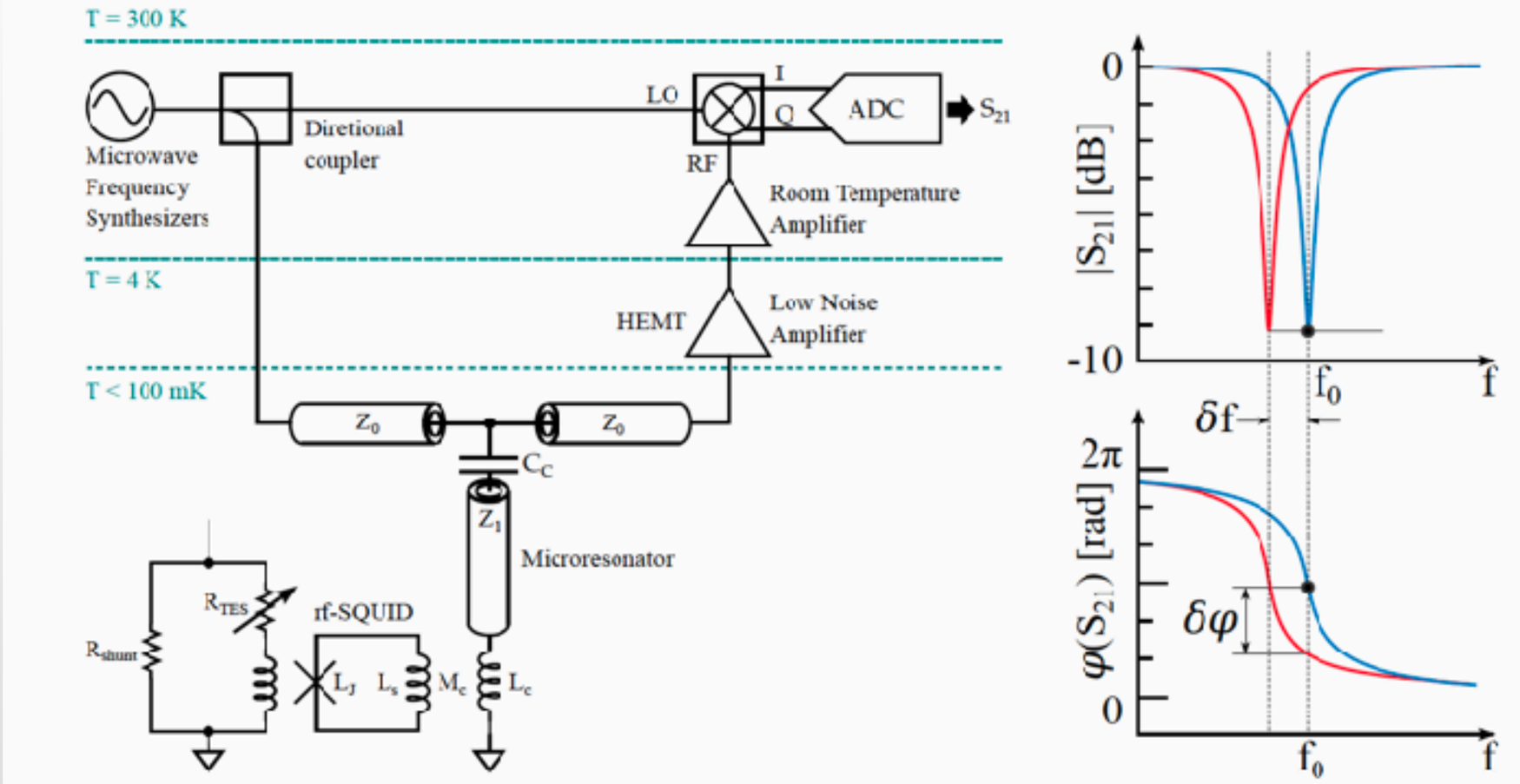
1) TES array is produced @NIST up to first 1 μm Au layer;
2) ^{163}Ho implantation and Au co-evaporation;
3) 1 μm Au final layer is deposited over Ho implantation ("complete" the absorber)
4) membrane release with KOH or DRIE process

4 x 16 linear array for implantation optimization and low parasitic L



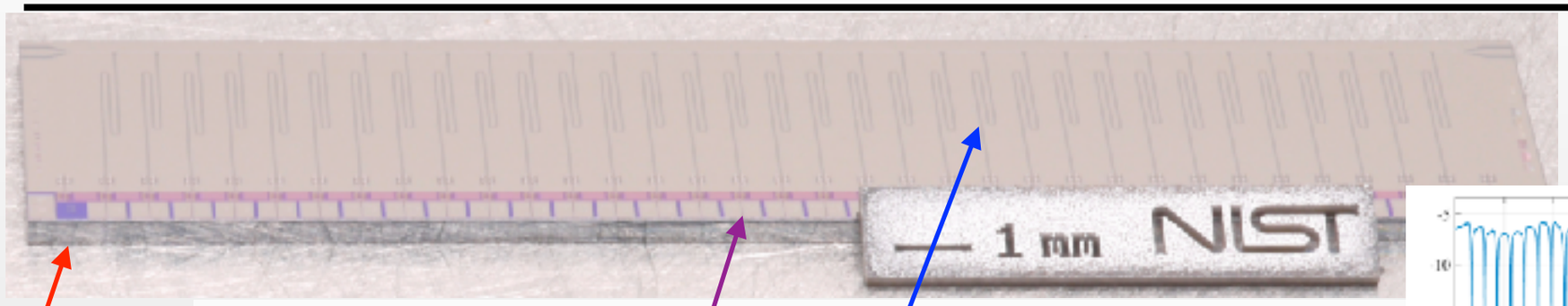
chip width: 5mm

Multiplexed readout



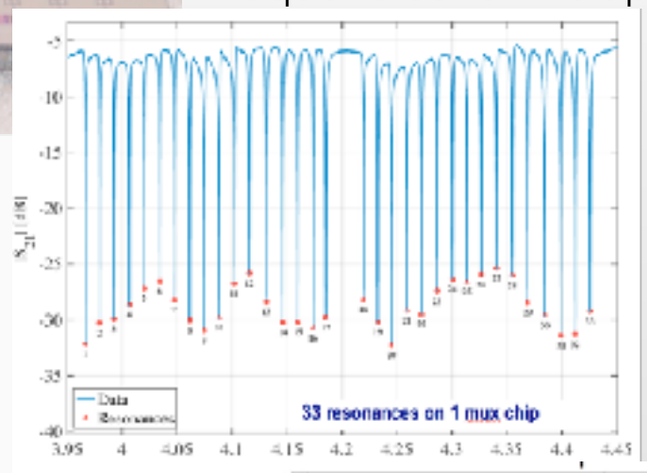
- DC-biased TES inductively coupled to a dissipation less RF-SQUID
- RF-SQUID inductively coupled to a high-Q superconducting λ/4 resonator
- Change in TES current ⇒ change in the input flux to the SQUID
- Change in the flux to the SQUID ⇒ change of resonance frequency and phase
- Each micro-resonator can be continuously monitored by a probe tone

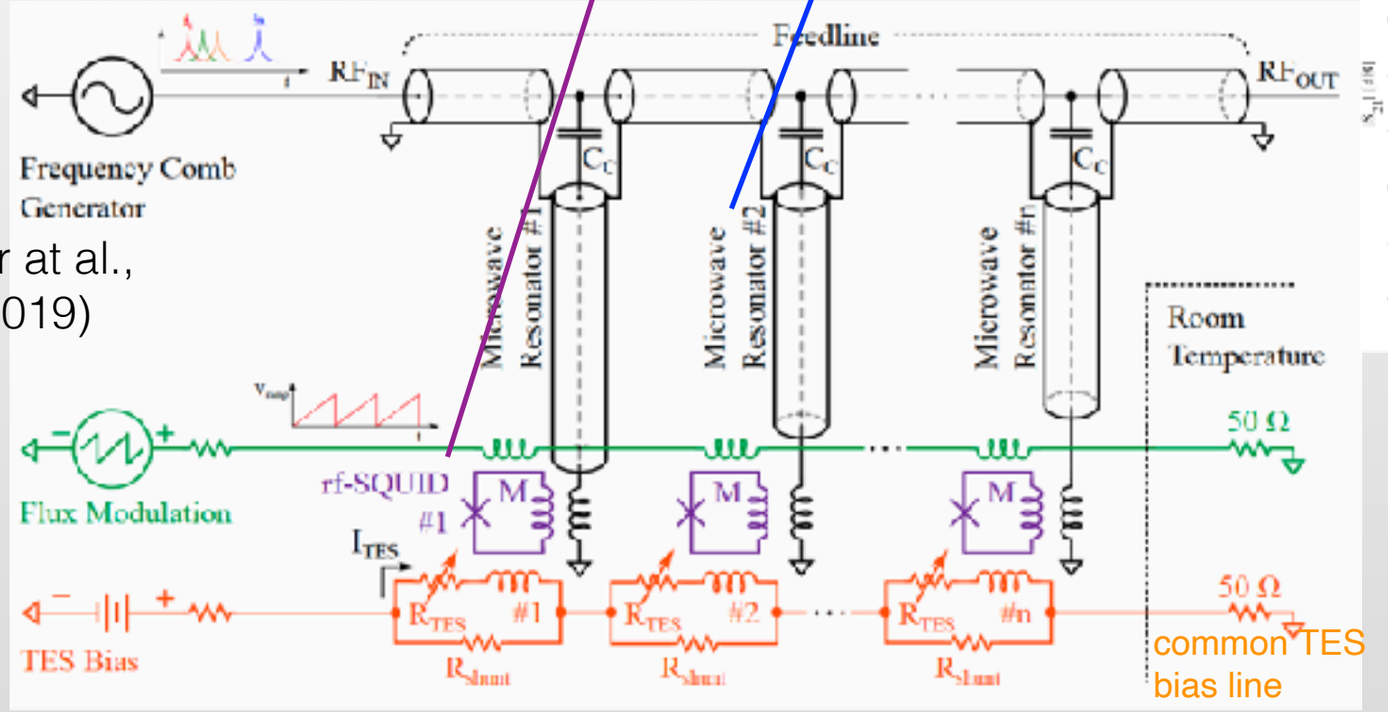
Array readout: rf-SQUID μwave mix



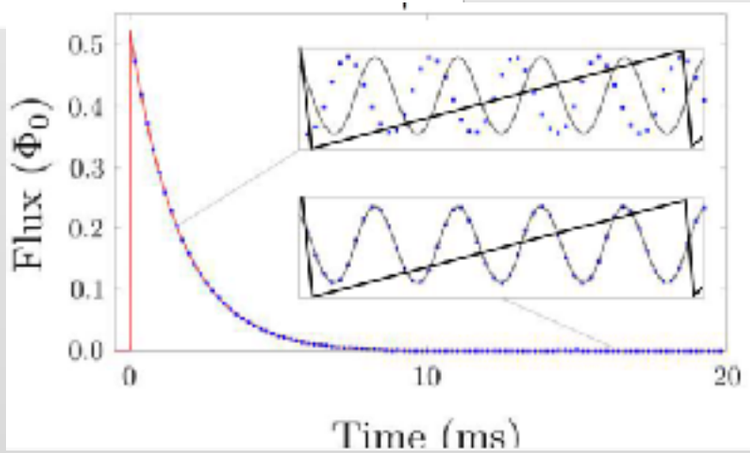
common SQUID modulation line

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



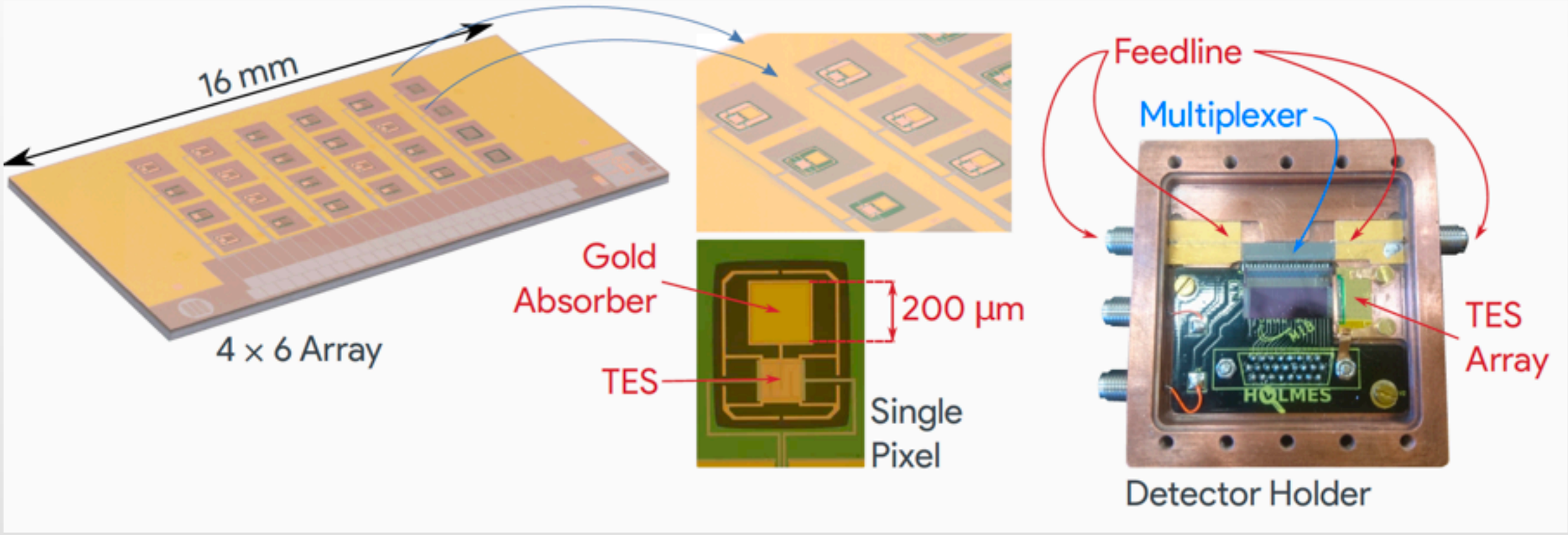


D. T. Becker at al., JINST 14 (2019) 10, P10035

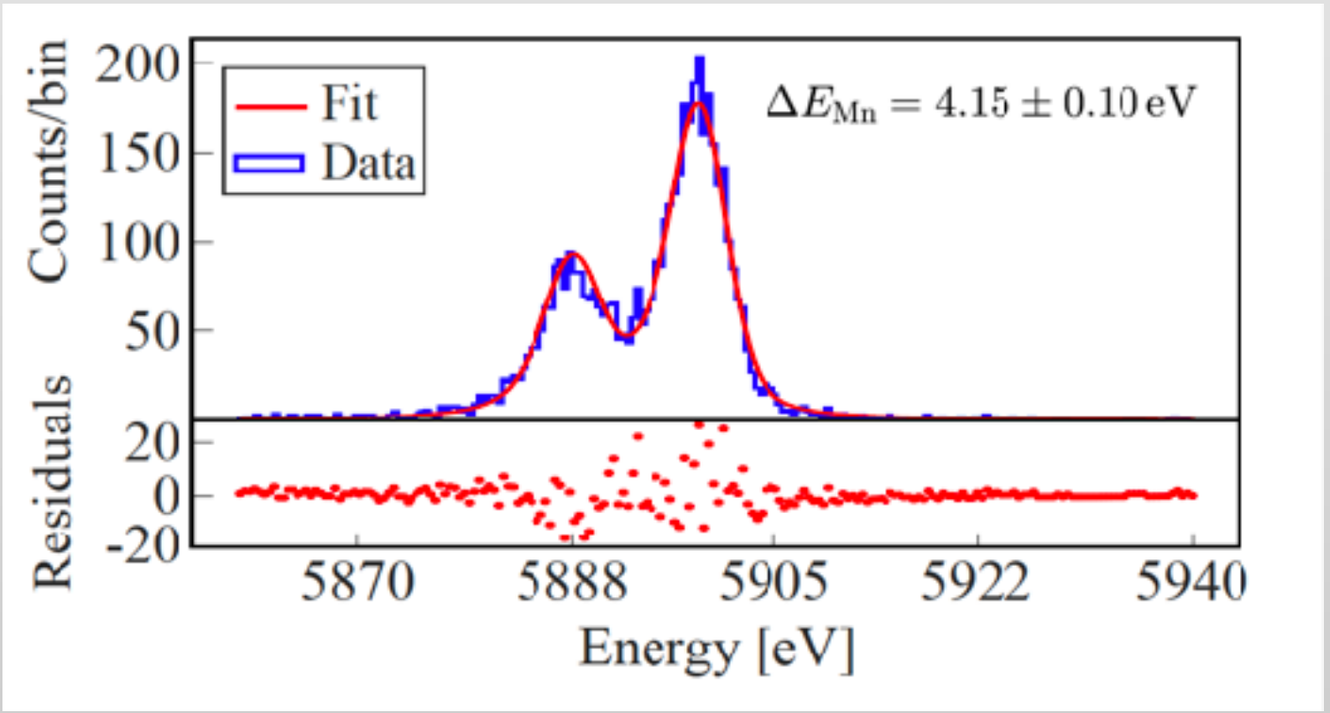


- By coupling many resonators to a single microwave feedline it is possible to perform the readout of multiple detectors
- Sensors are monitored by a set of sinusoidal probe tones (frequency comb)
- The signal is reconstructed from the phase shift of the SQUID oscillation (solid line), with respect to a reference sine function (dotted line).
- The ramp induced a controlled flux variation in the rf-SQUID, crucial to linearize the response
- Large multiplexing factor (>100), limited by digitizer bandwidth

Pixel testing with HOLMES DAQ



- Tested different u-calorimeter geometries
- Produced at NIST
- Not yet implanted with Ho
- Sources: ^{55}Fe + fluorescence sources (range 1.6 - 6 keV)
- Energy resolution ~ (4.5 ± 0.3) eV
- Best performing detector: (4.15 ± 0.10) eV @Mn K_α



A. Giachero et al., IEEE Trans.Appl.Supercond. 31 (2021) 5, 2100205

Conclusion and prospects

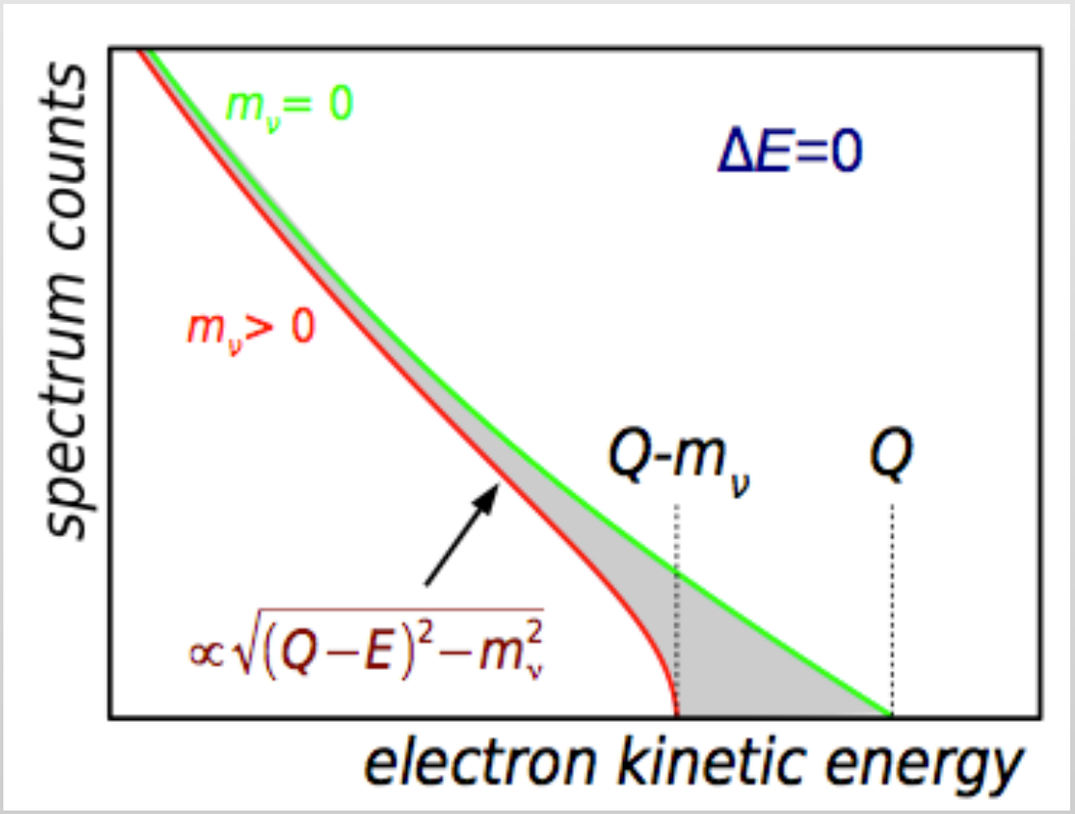
- The HOLMES experiment aims to perform a direct neutrino mass measurement with calorimetric technique exploiting the ^{163}Ho EC decay.
- Thanks to its low Q-value this isotope seems to be a good candidate for such a measurement.
- Some experimental challenges:
  - Embedding high activity into detectors arrays, managing possibile pile-up issues;
  - Design and produce detectors arrays with suitable resolutions;
  - Implement a multiplexing readout scheme.
  - Optimization studies are ongoing.
- We expect to have the first data from implanted detectors by fall 2021.

Back up slides

Direct ν mass measurement

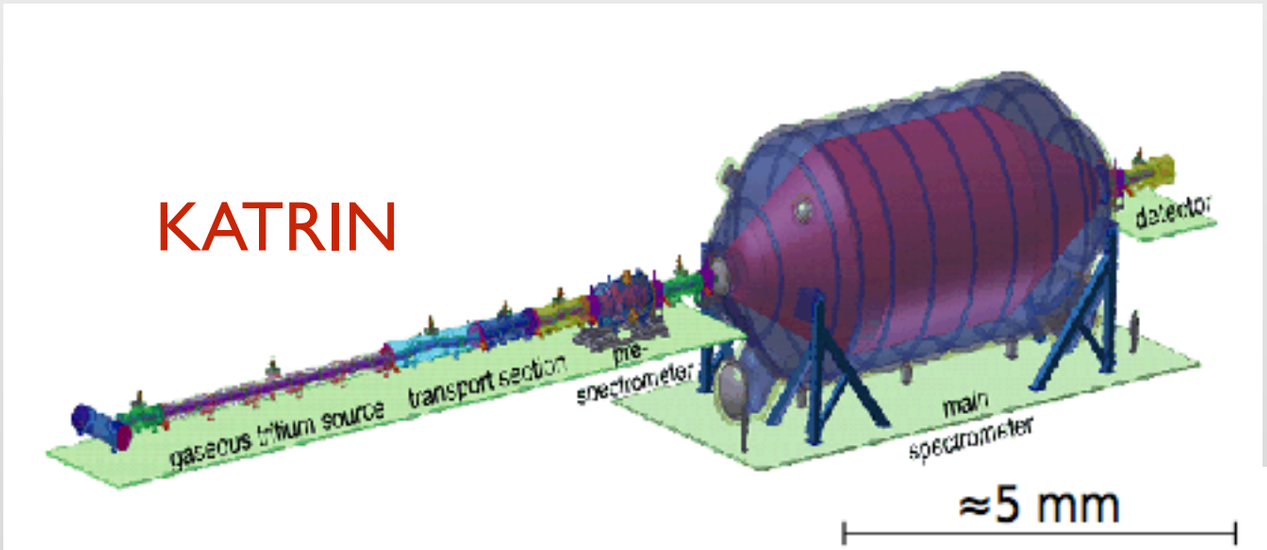
Kinematics of weak decay with ν emission:

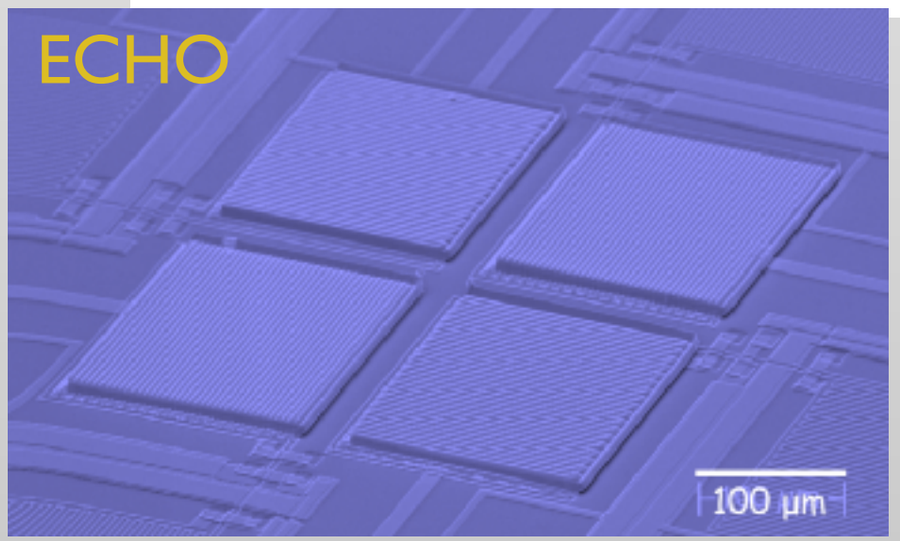
- low Q nuclear β decays (^{3}H, ^{187}Re, ^{163}Ho…)
- model independent: only E, p conservation
- **ν mass appears as a distortion in the Kurie plot**



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





Spectrometry vs calorimetry

General requirements for a ν 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_ν)
- S/N ratio
- small systematic effects

Spectroscopy: source ⊄ 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 ⊂ 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

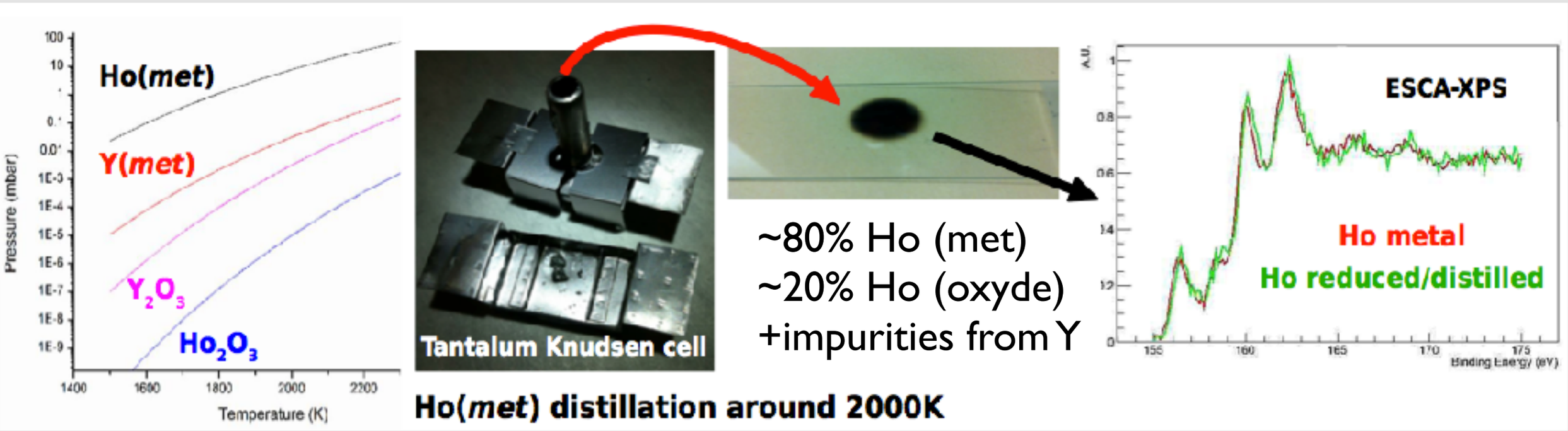
Ho production and purification

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

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

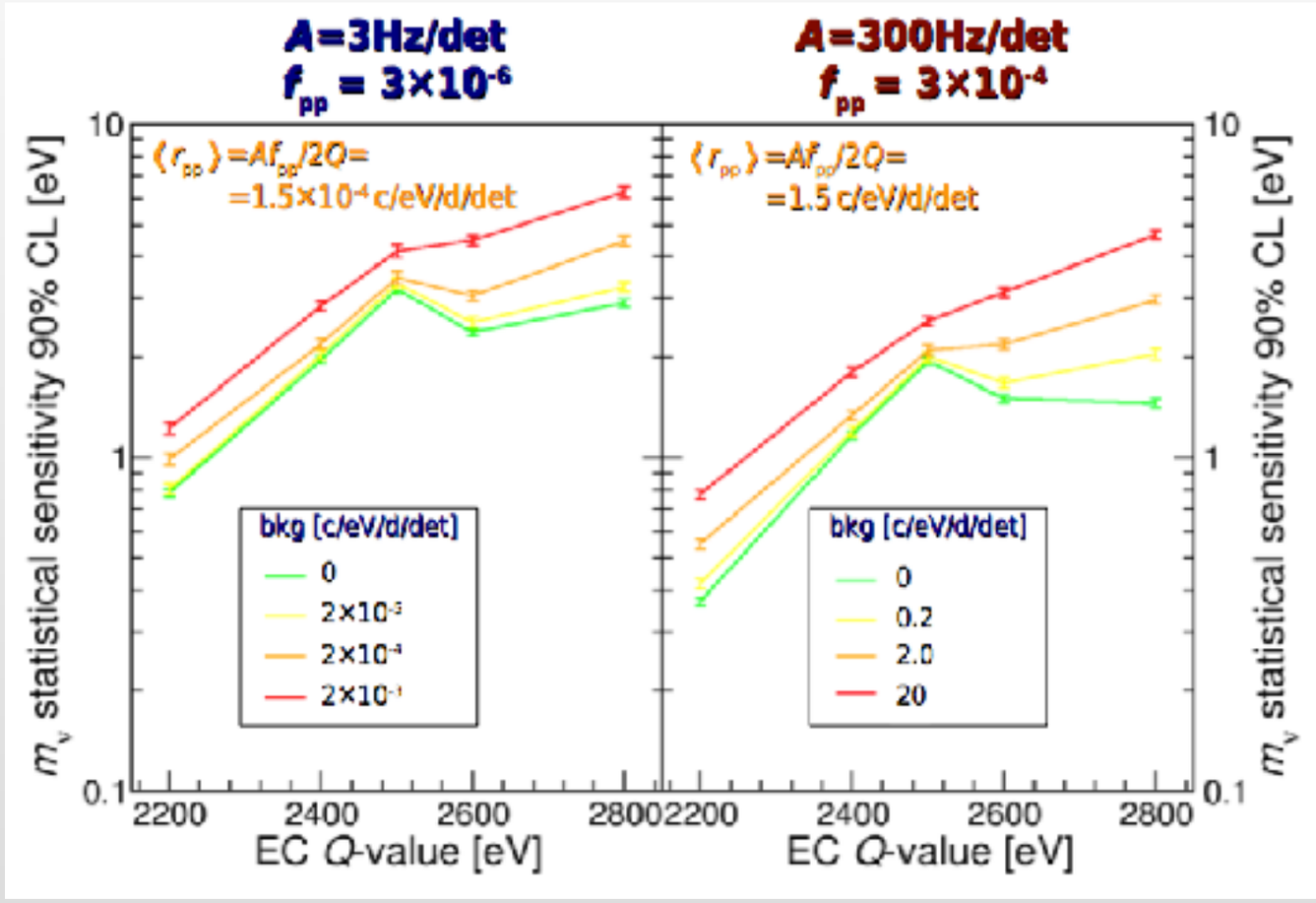
Ho_2O_3 thermoreduction in Knudsen cell provides a metallic sample for the implantation:

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



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 μm^3 → bkg ~ 5 x10^{-5} c/eV/day/det (0 - 4 keV)



- Internal radionuclides
  - ^{166m}Ho (β$^-$, τ½ = 1200 y, produced along with ^{163}Ho)
  - Au pixel 200 x 200 x 2 μm^3 → bkg ~ 0.5 c/eV/day/det/Bq(^{166m}Ho)
  - A(^{163}Ho) = 300Bq/det (~ 6.5×10^{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