Status of the HOLMES experiment to directly measure the electron neutrino mass with a calorimetric approach

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On behalf of the HOLMES collaboration

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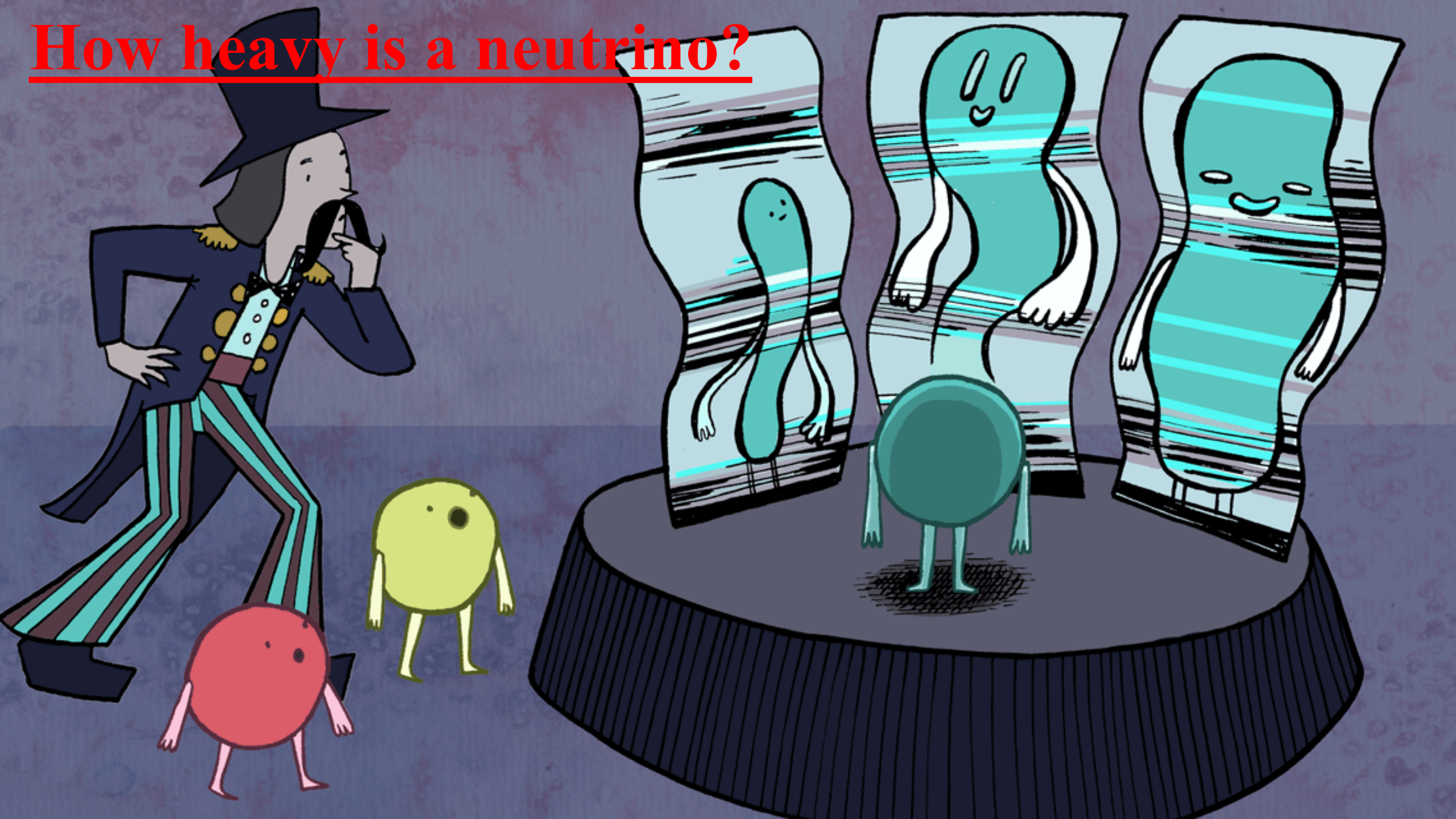
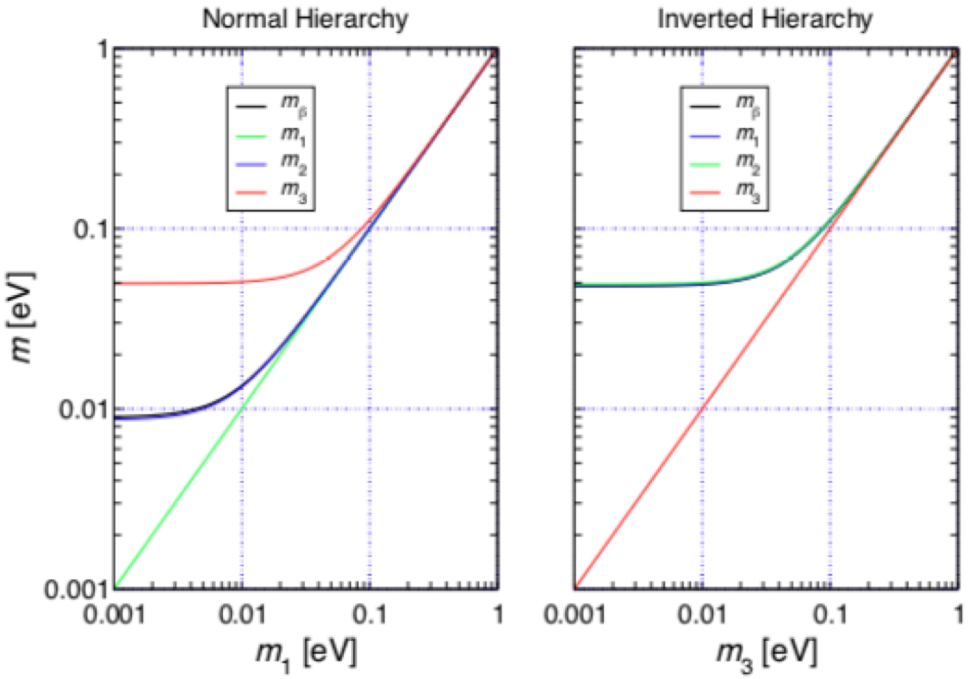
How heavy is a neutrino?



ν-mass

- Better understand the origin of fermion masses
- Extend the Standard Model
- Improve cosmological models (ν-mass affects the large-scale structure and dynamics of the universe)
- Neutrino mass hierarchy
- etc…



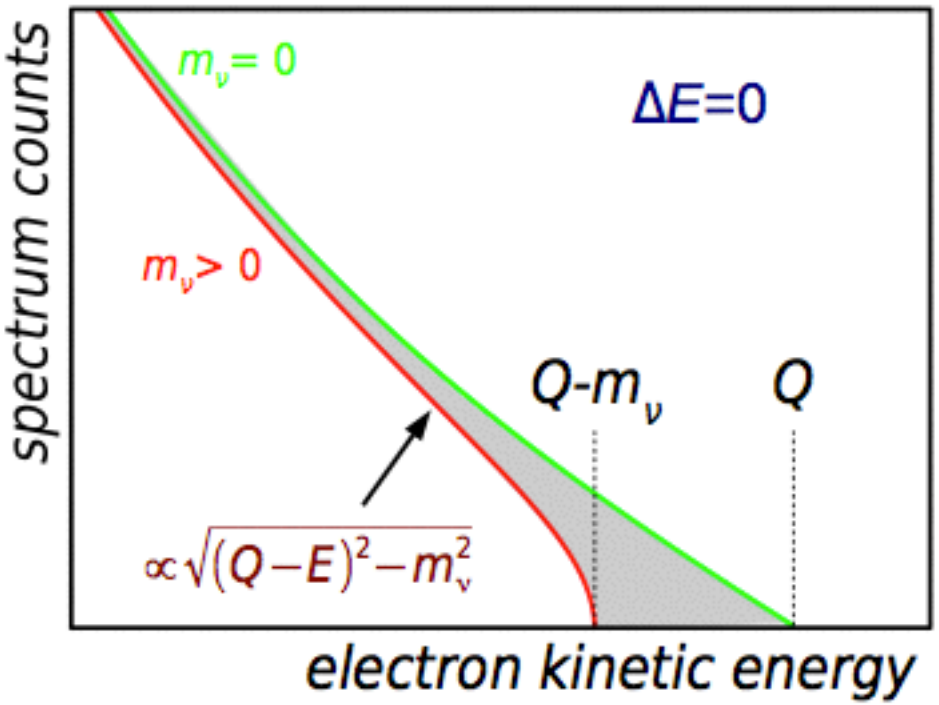
From direct measurement :$\lesssim 2\ eV$ (Mainz and Troitsk experiments)
From Double beta decay: $\lesssim 0.5\ eV$ (only Majorana neutrino)
From cosmological and astrophysical data : $\lesssim 0.2 - 1.3\ eV$ (model dependent)

Direct measurement (1)

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

$(A,Z) \rightarrow (A,Z+1) + e^{-} + \nu_e$

$$N(E_\beta) \propto p\beta\, E\beta\, (Q - E\beta)\sqrt{((Q - E_\beta) - m_\nu)}\, F(z,E_\beta) S(E\beta)$$



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/Q3)
- high activity/efficiency of the source
- Energy resolution order ~eV or below (comparable with m_ν)
- small systematic effects

Spectroscopy: external source
- high statistics
- high energy resolution (below eV)
- systematics due to the source (energy loss)
- systematics due to decay to excited states
- background

Calorimetry: embedded source
- 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

Electron capture (EC) in Holmium 163

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

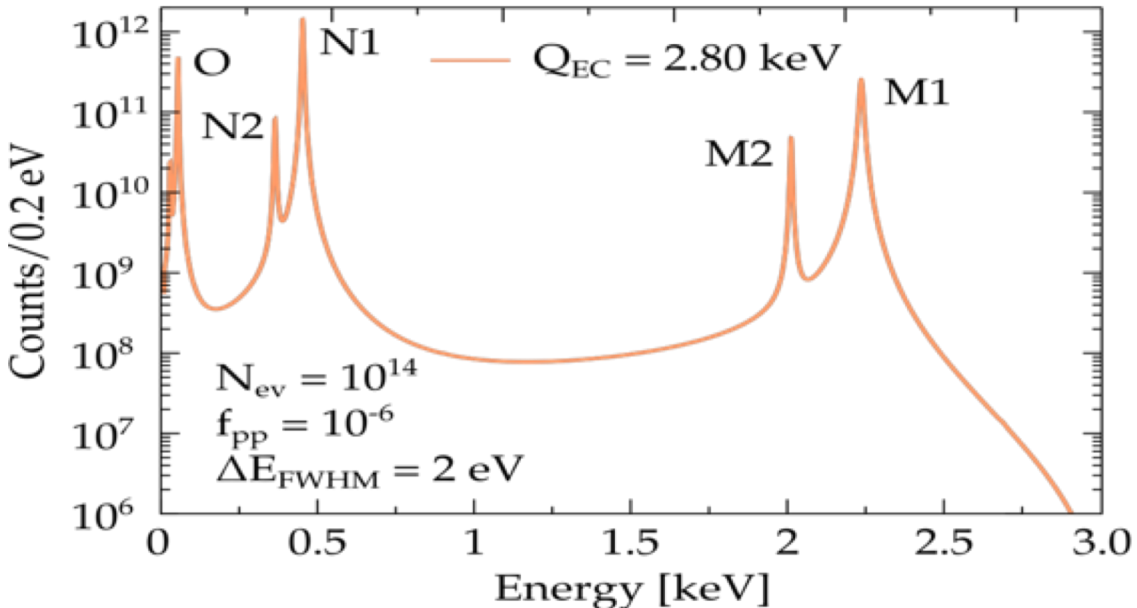
^{163}Ho decay via EC from shell ≥ M1
Proposed by A. De Rújula and M. Lusignoli, Phys. Lett. B 118 (1982) 429

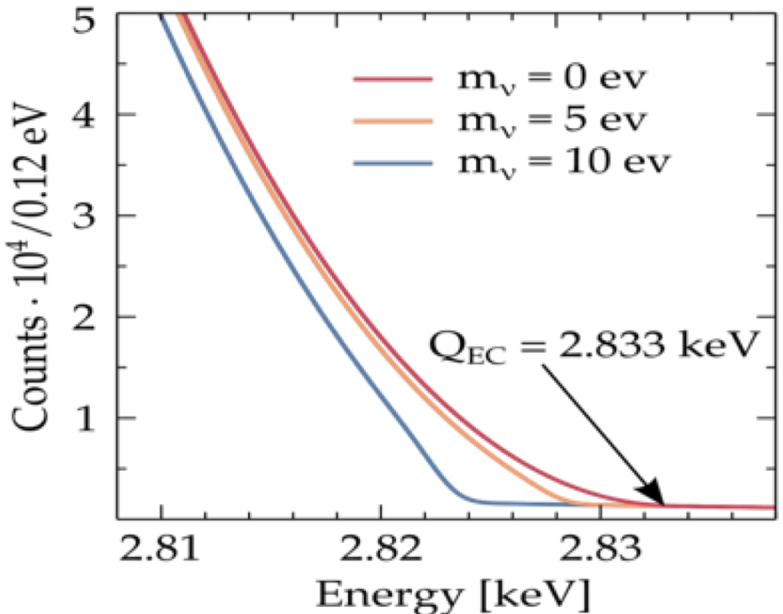
Calorimetric measurement of Dy atomic de-excitations

***Q* ≈ 2.83 keV** (recently measured with Penning trap)

Rate on the end point dependes on (Q-M1): the proximity to M1 resonance peak enhances the statistics at the end point

τ ≈ 4570years → 2x10 Ho nuclei↔1Bq



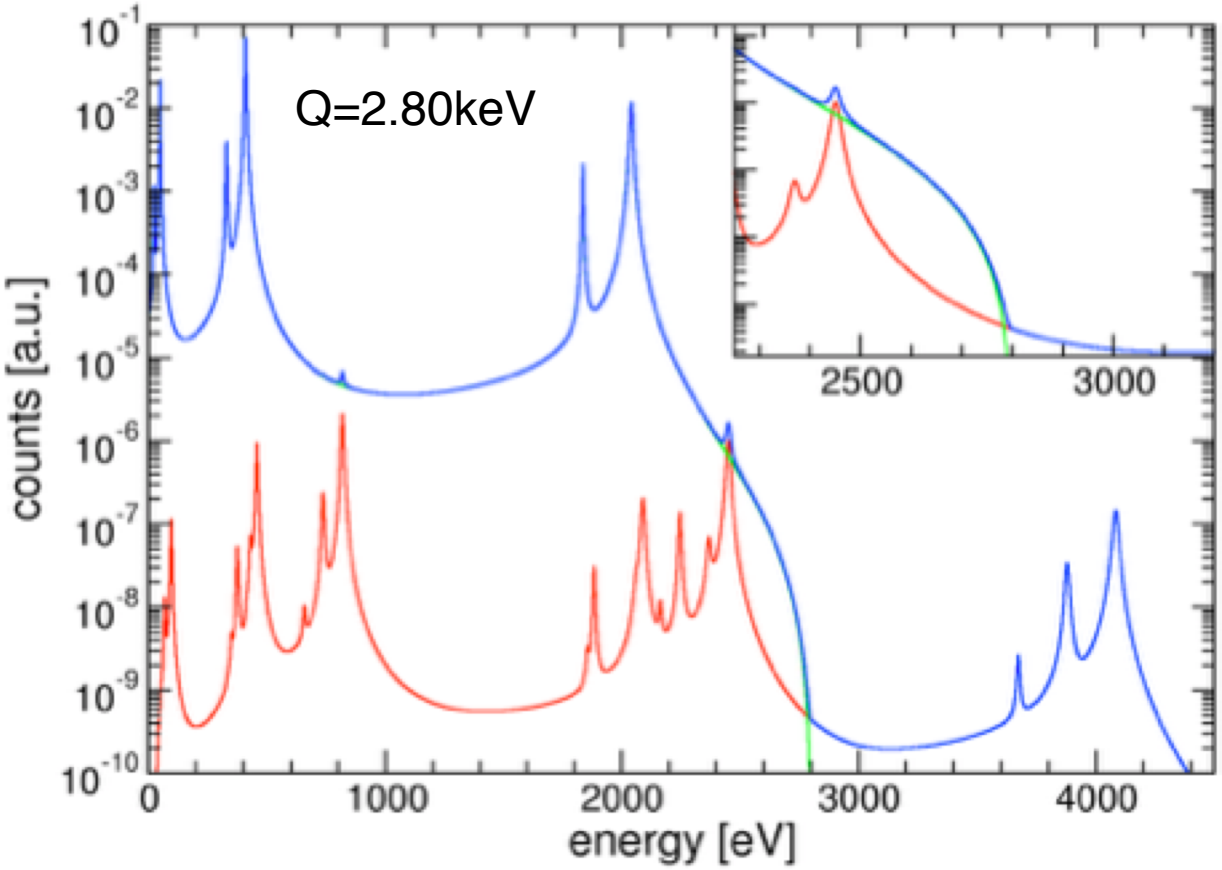


Electron capture (EC) in Holmium 163 (2)

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

In calorimetric measurement detector speed is critical

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



In order to reduce pile-up:

- trade-off between activity and statistic
- detector with fast signal rise time τ_r
- pile-up resolving algorithm

Holmes experiment in a nutshell

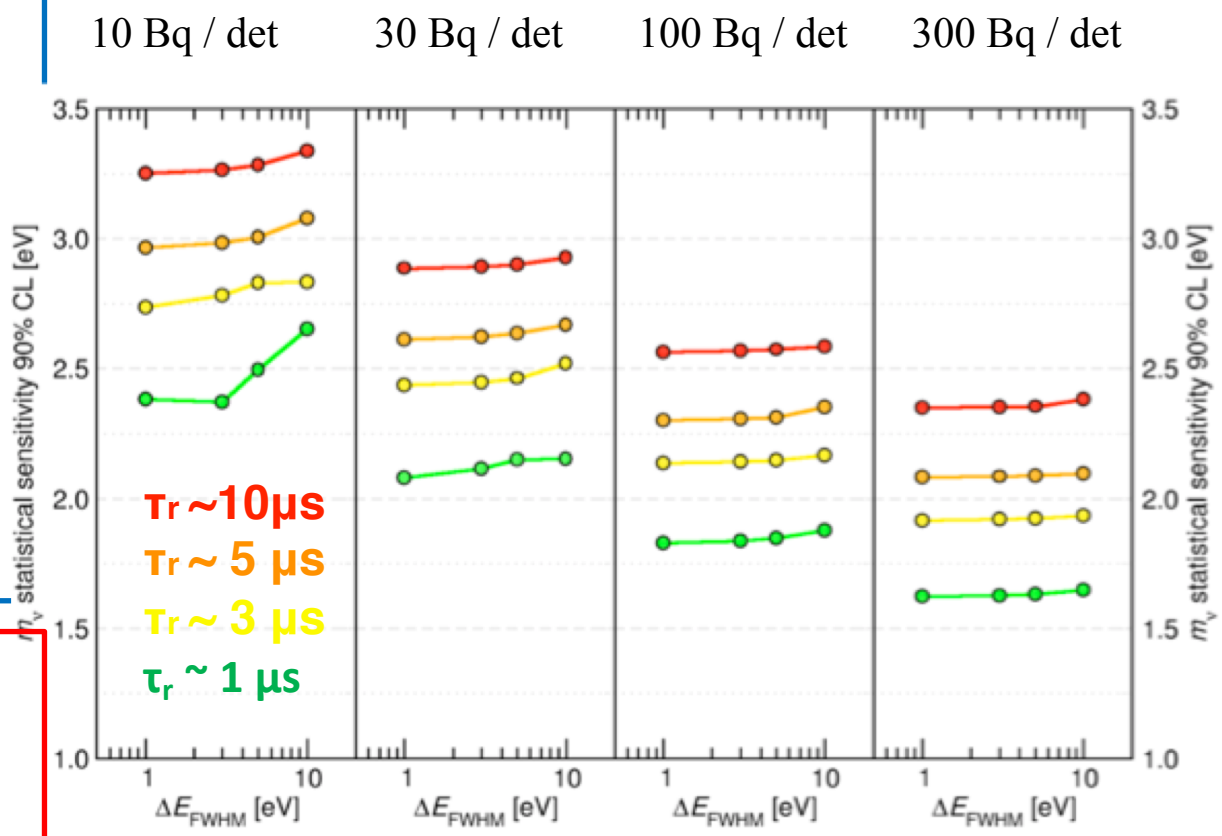
Direct neutrino mass measurement with statistical sensitivity around 1 eV.

Usage of Transition edge sensor (TES) based micro-calorimeters with ^{163}Ho implanted and Au absorber:

- Energy resolution ΔE~ 1eV, time Δt~ 1μs
- 6.5 x 10^{13} nuclei/det, A(EC) ~ 300 Bq/det
- 1000 channels array: 6.5 x 10^{16} total nuclei (≈18μg)
- O(10^{13}) events / year, data taking ~ 3 years
- Pile up fraction $f_{pp} \approx A \times \Delta t = 3 \times 10^{-4}$

Should prove the technique potential and scalability by:

- assessing EC spectral shape
- assessing systematic errors
- sensitivity on m_ν ~ eV



exposure: 1000 det x 3 years

BACKGROUND

HOLMES baseline: ^{163}Ho pile-up rate

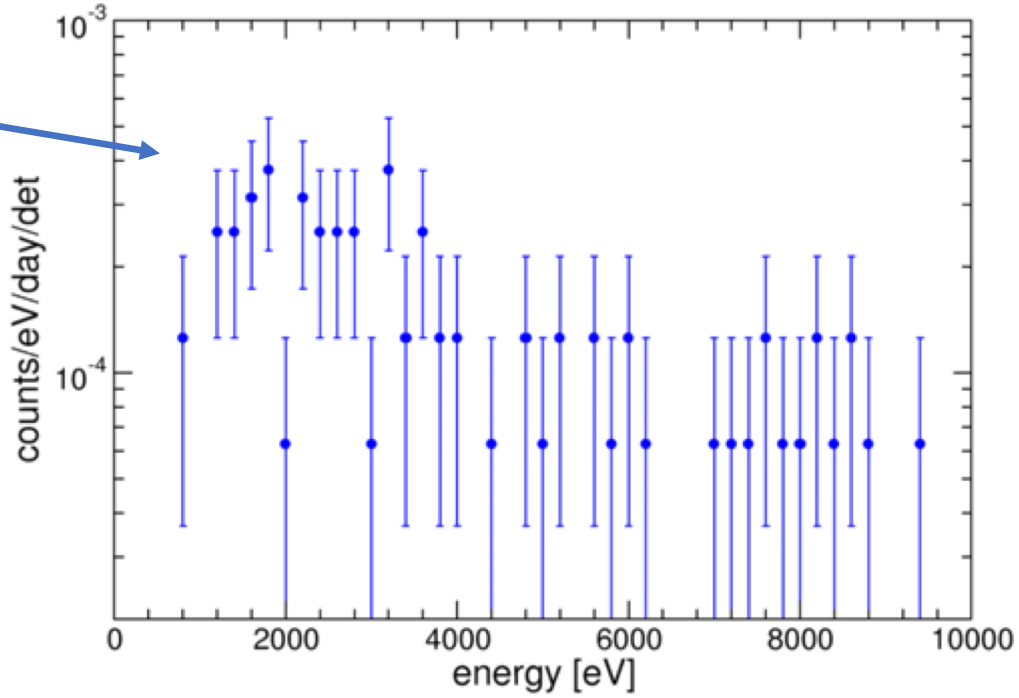
$\langle rpp \rangle = A \cdot fpp/2Q = 300$ Bq x $3 \cdot 10^{-4}/2Q =$ 1.5 count/eV/day/det

External sources

- Environmental γ radiation
- γ, X and β from close surroundings
- cosmic rays

Measured 200x200x2 μm^3 Au absorber (Holmes-like)

→ bkg(1-10 KeV) ≈ 5x10^{-3} count/eV/day/det



Internal source

radionuclides (byproduct of Ho production)

^{166m}Ho, (β^-, Q = 5970 keV, $t_{1/2}$ = 1200 y)

GEANT4 simulation for 200x200x2 mm3 Au absorber produce

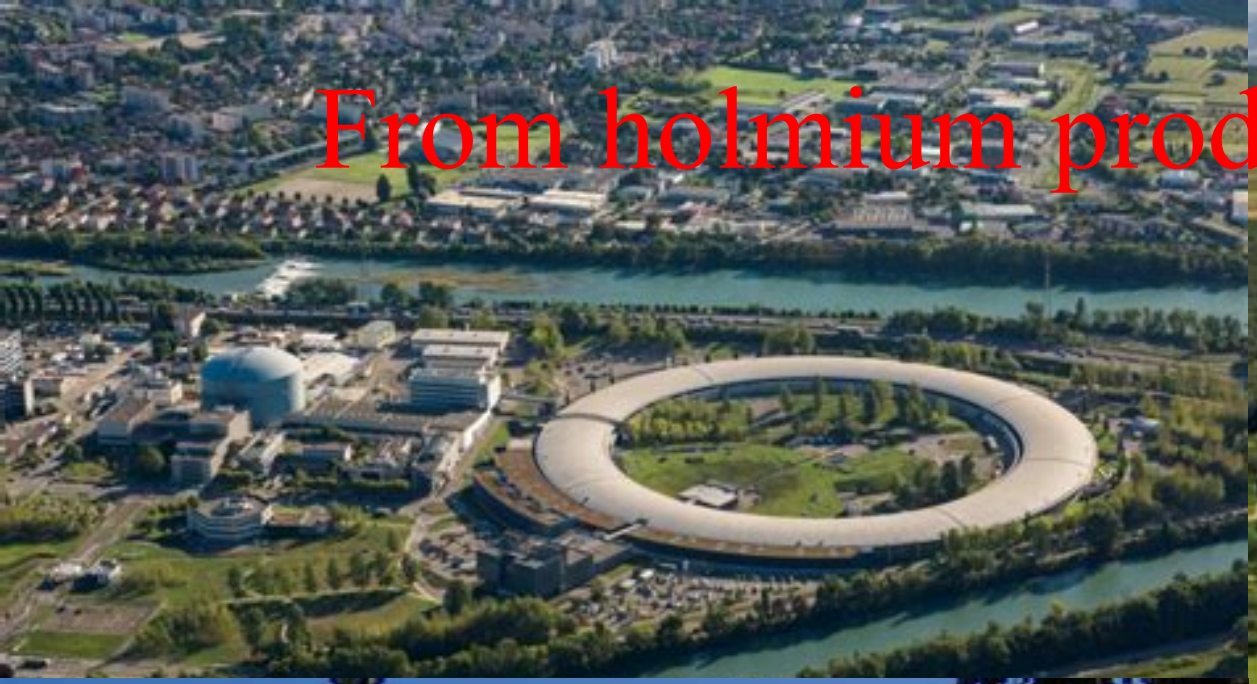
bkg 10^{-11} c/eV/day/det /^{166}HoNucleus

If A(300Bq) and requiring bkg <0.1 count/eV/day/det

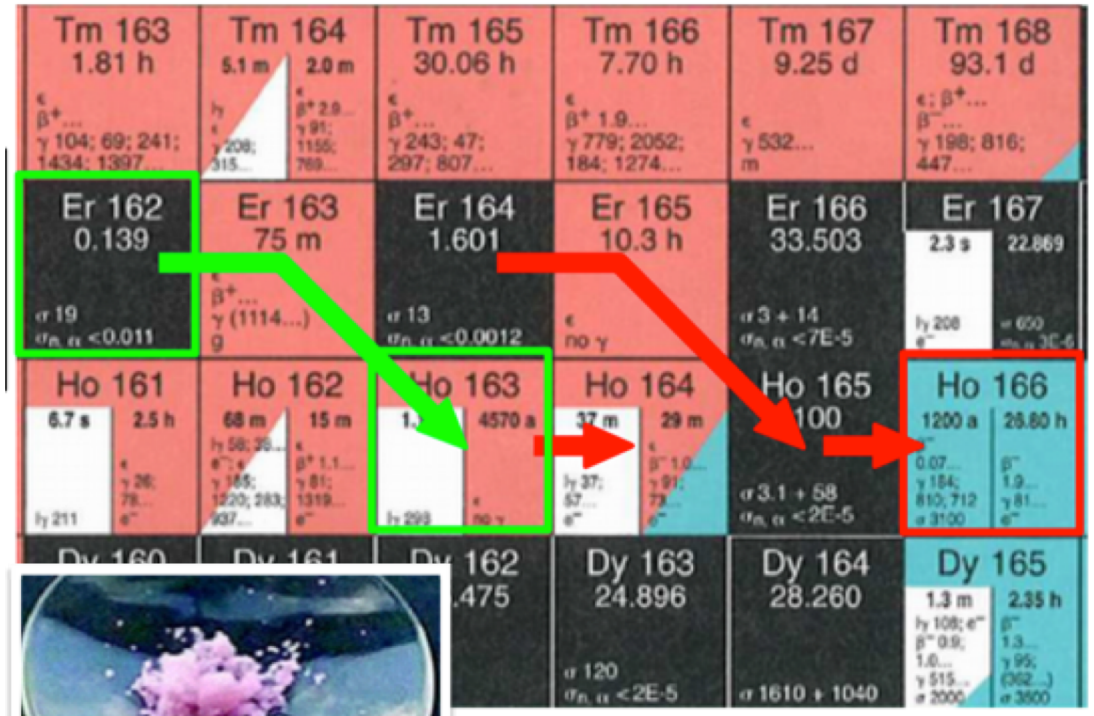
N(163)/N(166) >6000

A(163)/A(166)>1500

From holmium production to sputter target



163-Holmium production



^{163}Ho produced by neutron irradiation of Er_2O_3 enriched (30%) in ^{162}Er at the Institut Laue-Langevin (ILL, Grenoble, France).
Thermal neutron flux at ILL: 1.3×10^{15} n/cm2/s

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

$$^{163}\mathrm{Er} \rightarrow {}^{163}\mathrm{Ho} + \nu_e \qquad \tau_{1/2}^{EC} \approx 75\,\mathrm{min}$$

high yield (but not all cross sections are well known)

Contaminants:

1. Other elements (residual Er, rare earth contaminants, decay product, etc…)
2. Holmium isotopes, in particular ^{166m}Ho

$A(^{163}\mathrm{Ho})/A(^{166m}\mathrm{Ho}) = 100\text{-}1000$

1) Chemical purification at PSI;
2) Isotopic separation using an implanter.

Holmium chemical purification

Three different batches are produced:
1) 25 mg irradiated for 55 days (2014), A(163Ho) ≈ 5MBq(A(166mHo)≈10kBq)
2) 150 mg irradiated for 50 days (2015), A(163Ho) ≈38MBq(A(166mHo)≈37kBq)
3) 540 mg irradiated 50 days(2017),A(163Ho)≈130MBq(A(166mHo)≈180kBq) (~500 detectors)

The Er/Ho mixture is subjected to a radiochemical separation with ion-exchange resins in hot-cell at PSI.

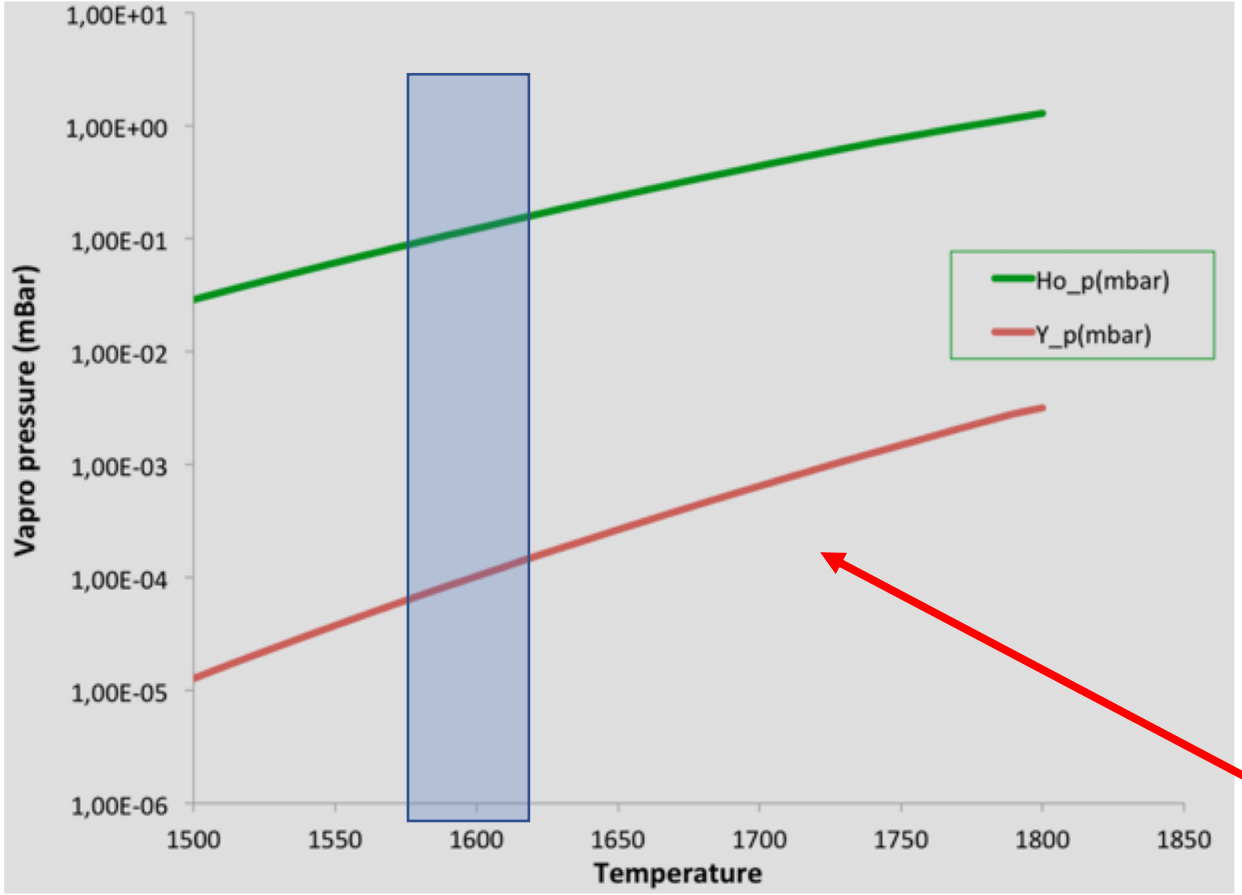
Efficiency > 80%

S. Heinitz *et al.*. PLoS One 13 (2018) no.8, e0200910

Reduction and distillation process (1)

Only holmium in the metallic chemical form must be introduced:
Increase ionization efficiency in metallic form;
Metallic form for sputter ion target .

Metal	Melting Point (°C)	Oxyde	ΔG (kJ/mol)
Holmium	1460	Ho_2O_3	-1791.1
Yttrium	1526	Y_2O_3	-1816.2

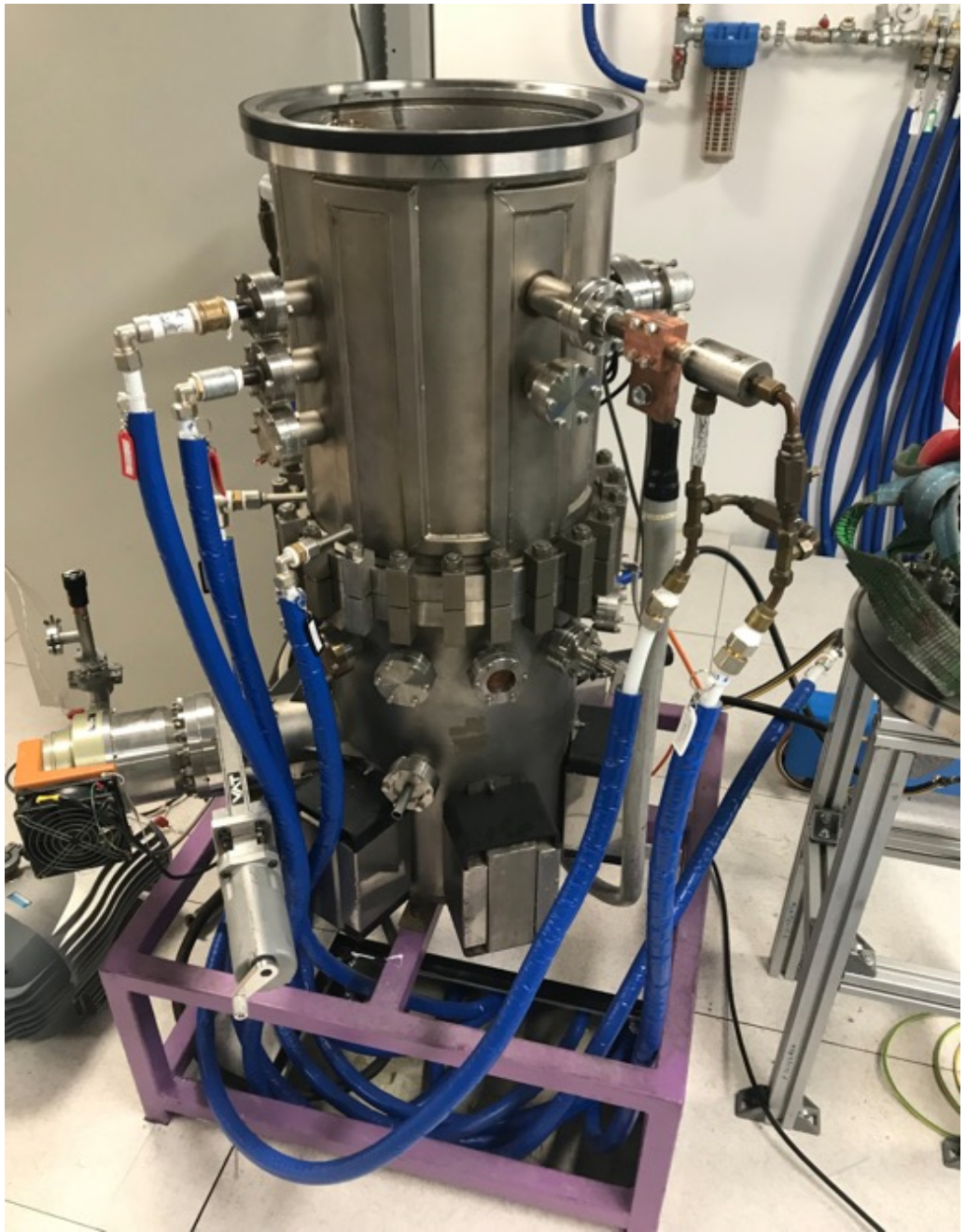


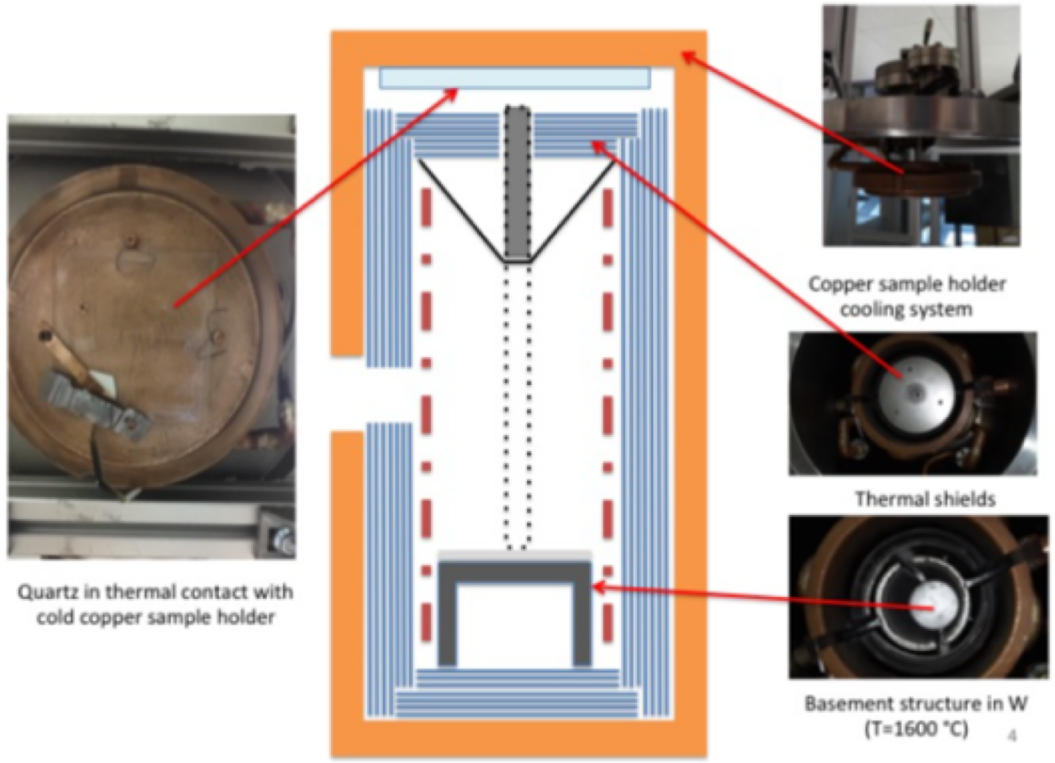
- Holmium Oxide powder is mixed with metallic Yttrium (lump).
- The mixture is heat up to about 1600 °C (Y melting point).
- When the Y wets the oxide the reaction starts.
- Metallic Ho has a high vapor pressure at this temperature and evaporated.
- Ho condensates on a cold substrate.

Oxide (Y and residual Ho) have a negligible vapor pressure.
The Y vapor pressure is three order of magnitude lower than Ho one at working point.

We use a dedicated evaporation chamber to the whole process.

Reduction and distillation process (2)

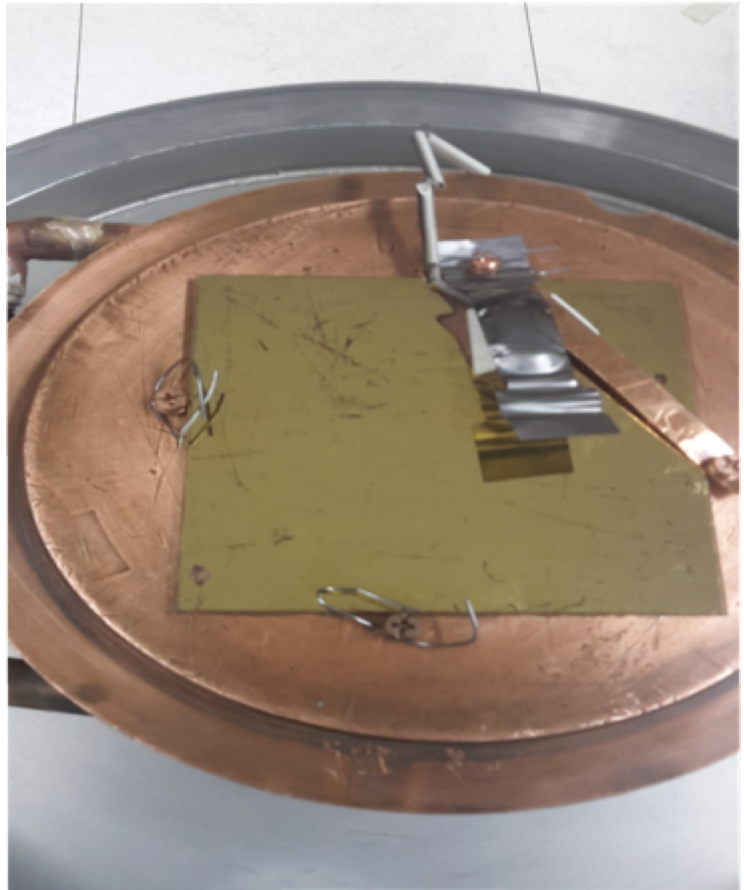


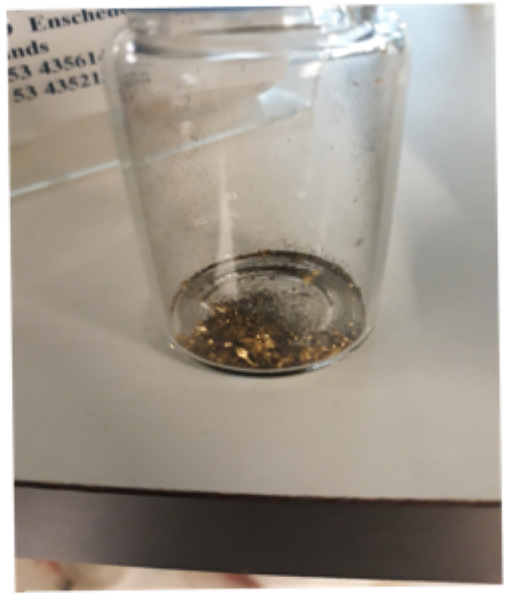


The hot zone is thermally isolated by nine tungsten layer.
The external copper box is water cooled.
The upper part of the shield is holed allowing the evaporated Ho flows from the crucible to a substrate fixed on the top of the copper box.
The whole system is set in a vacuum chamber which could reach pressures as low as 10^{-8} mBar.

Reduction/Distillation Process (3)

- The substrate used for the collection of the distilled Ho is made of quartz because of its high resistivity to thermal deformation.
- A thin layer of a low degassing thermal conducting paste is used to improve the thermal conductance between the quartz substrate and the cooled copper cap.
- A gold thin film has been deposited on quartz by thermal evaporation to easy remove Ho film from substrate. The high reflectivity of gold help to avoid excessive heating of substrate too.





Ho + Au powder

Efficiency ≥ 70%.

Next steps

Increase the collection efficiency

Sputter target

The sputter ion source of the implanter needs a metallic cathode.
We need turn the holmium powder into a metallic disk.

In collaboration with prof. Manfrinetti (from Chemistry Department of Genova University) we decide to realize a sintered sputter target.

- Natural ^{165}Ho(5%) is included in a metallic mixture of Ti(36%), Ni(41%), Sn(18%) fine grained powder (< 40 μm) in a copper support;
- Pressed at 350 bar/cm^2 and heated at 950 °C pressure 10^{-4} mbar for 2 days to improve the mechanical proprieties of the sintered.

Next steps
Produce more test targets
Produce a target with ^{163}Ho

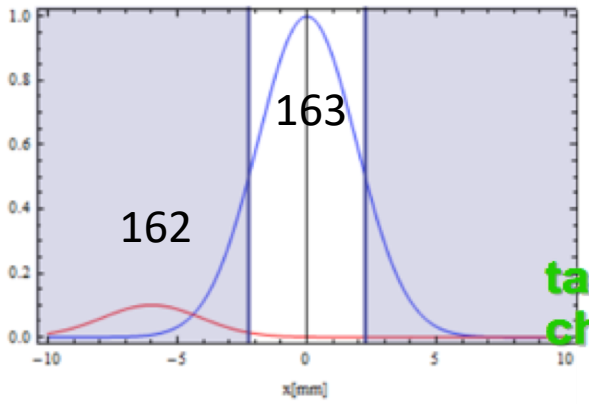
Mass separation and ion implantation

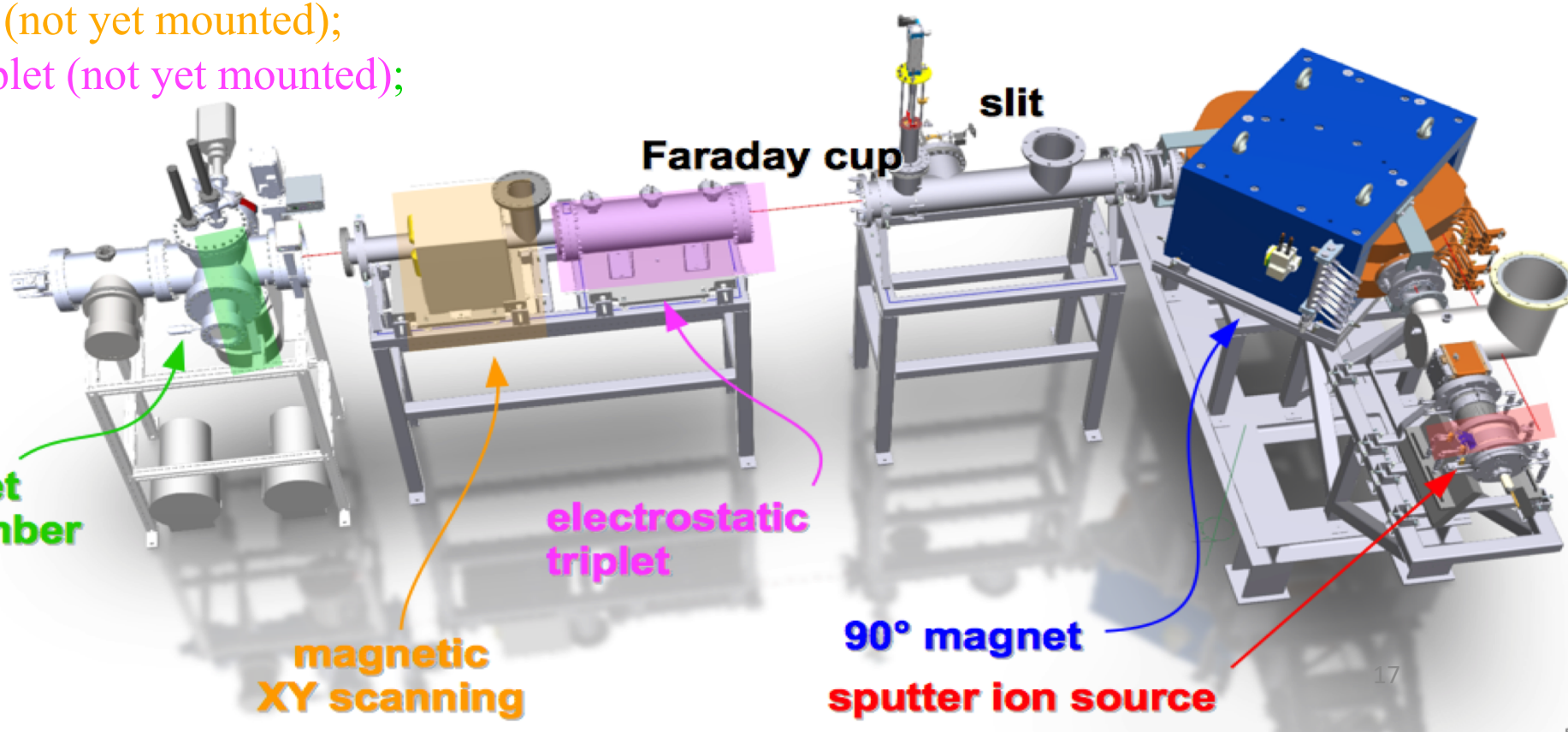
A dedicated ion implanter will be used to remove contamination of holmium isotopes different from ^{163}Ho as well as other impurities.

The ion implanter consists of six main components:

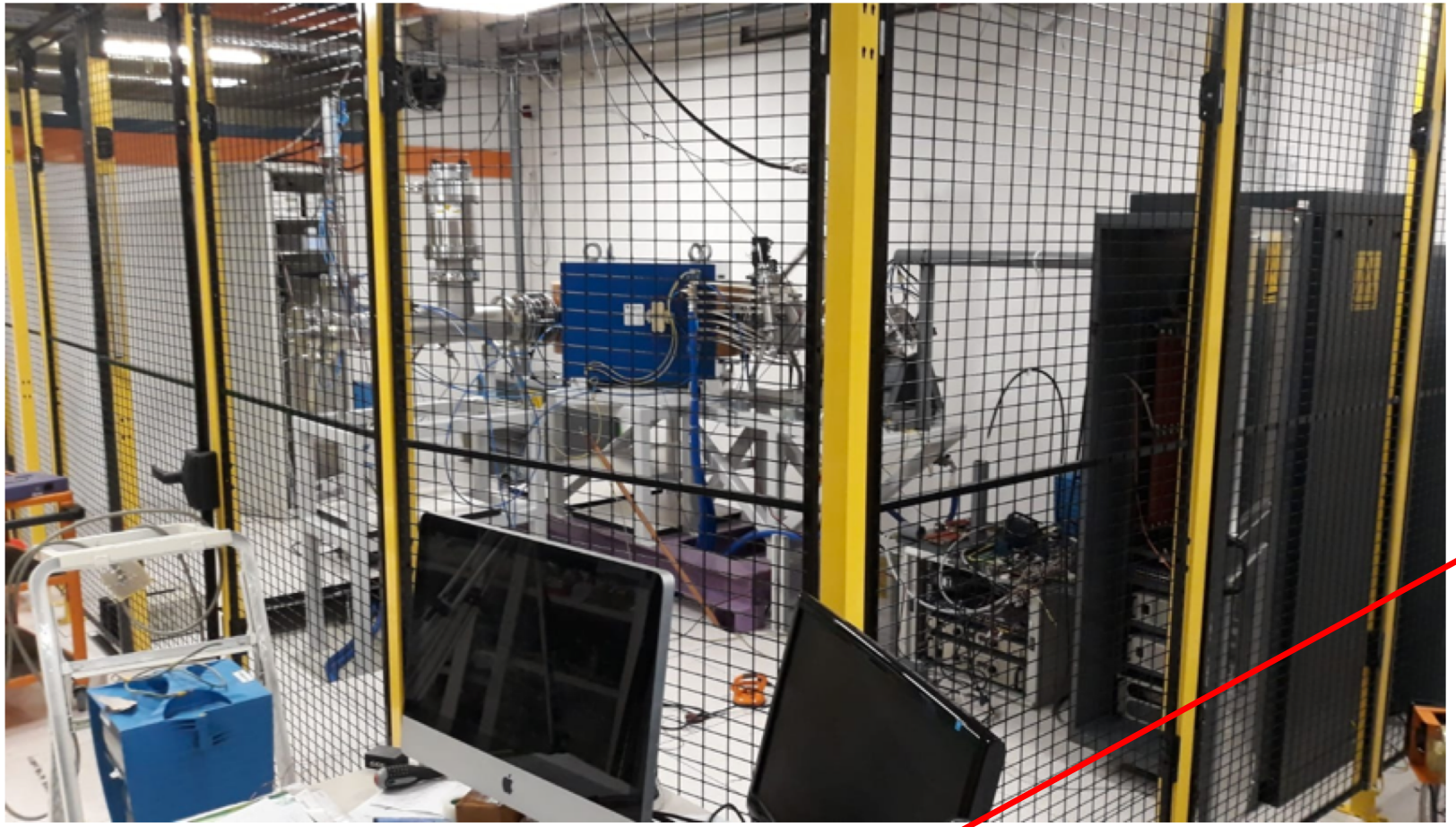
1. an argon sputter ion source;
2. an acceleration section to reach the beam energy of 50 KeV (~50 nm implantation depth)
3. a magnetic/electrostatic mass analyzer with magnetic field until 1.1 Tesla ^{163}Ho/^{166m}Ho separation better than 10^5
4. a magnetic scanning stage (not yet mounted);
5. a focusing electrostatic triplet (not yet mounted);
6. a target chamber.

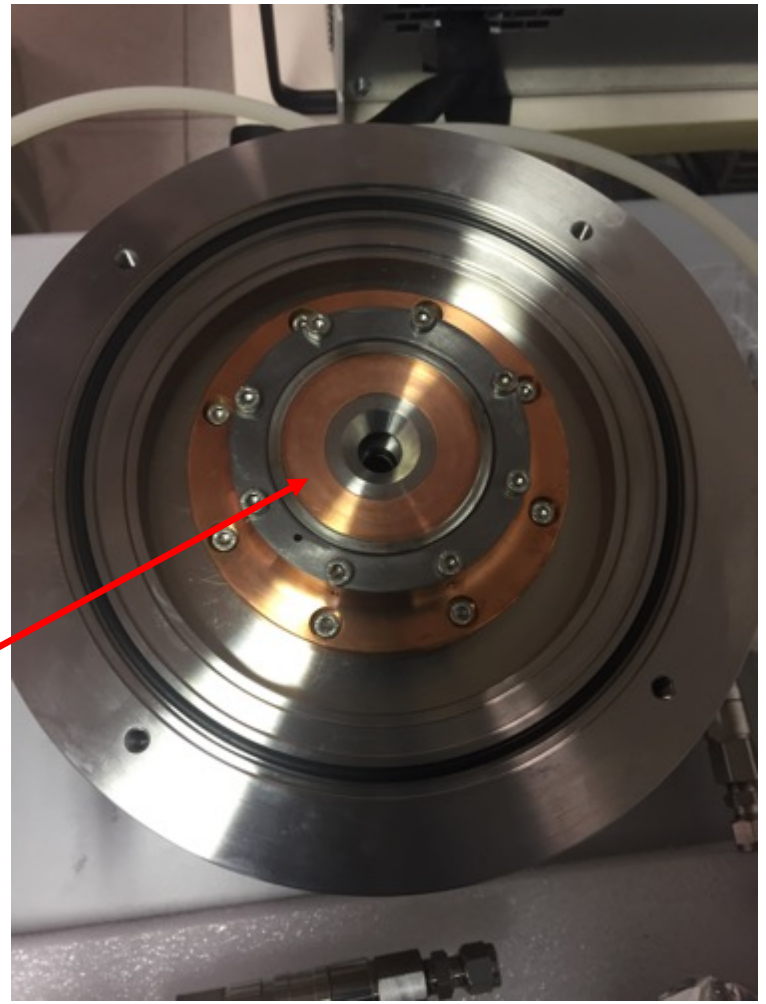
4mm FWHM at the slits





First implantation test

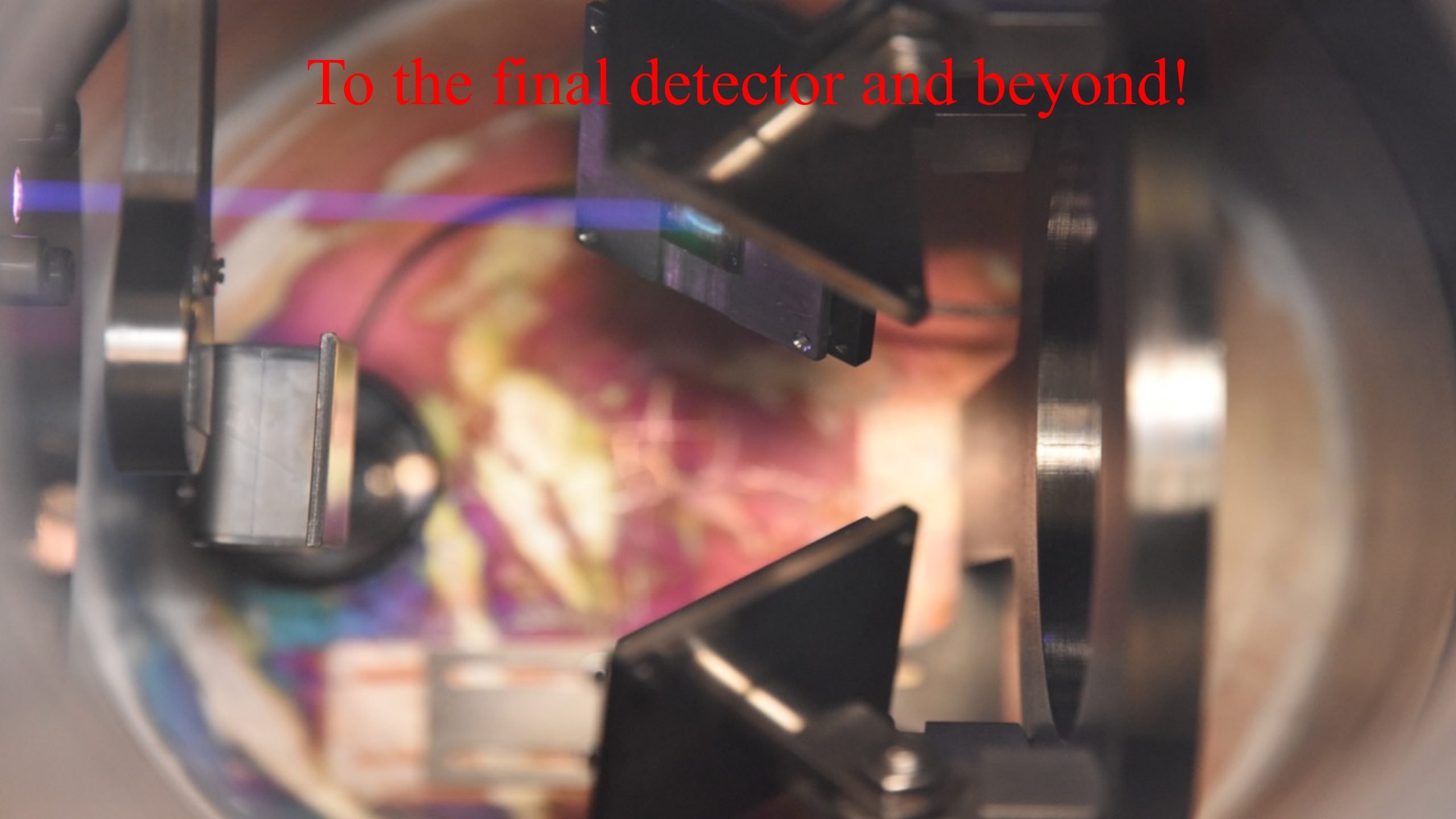




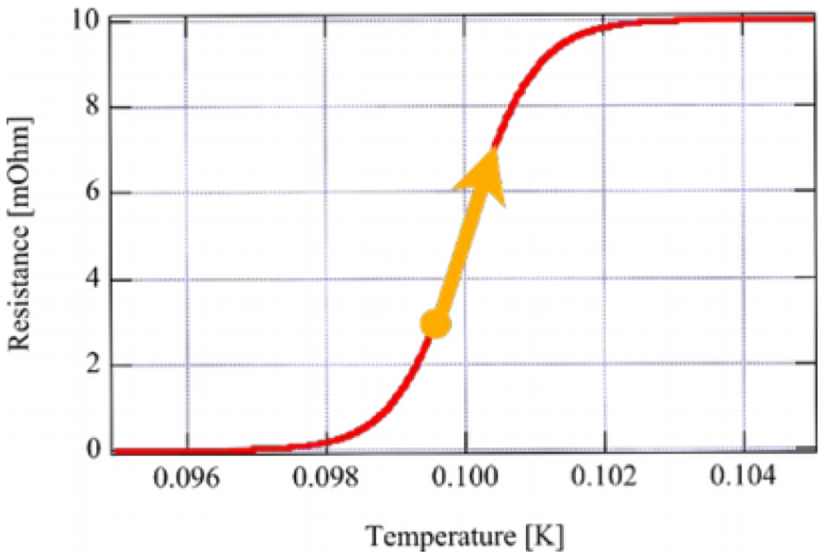
test in progress at INFN Genova
- no focusing
- sputter target made in Cu

measured current of 100 μA (preliminary)

Next steps
- Natural holmium (^{165}Ho)
- Test with ^{163}Ho


To the final detector and beyond!

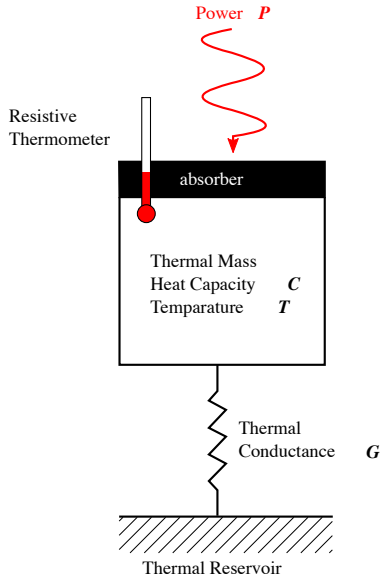
Detector design and test (1)

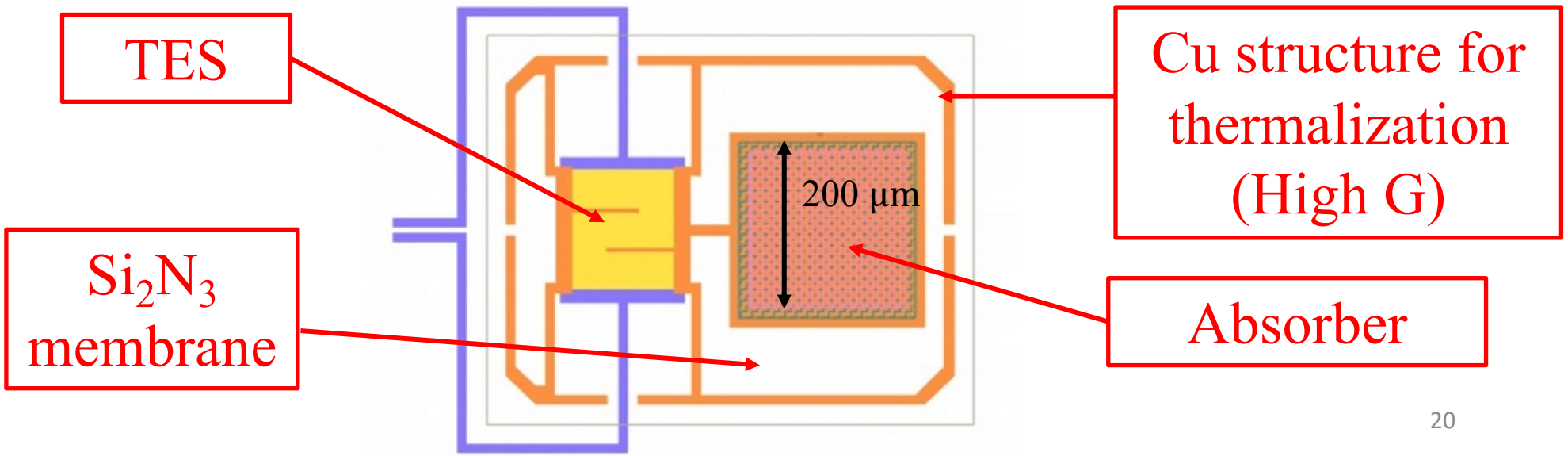


Transition Edge Sensors Superconductive Detectors (TES)

- Molybdenum/copper (T_c ~ 100 mK)
- Very steep R vs T dependency in transition region;
- Gold absorber with ^{163}Ho inside coupled to TES thermometer ;
- Ho sandwiched between two 1 mm thick gold layers for a total electron containment
- Fast detectors to reduce pile-up
  - tunable rise time ~ L/R
  - decay time dependent on detector characteristics C/G

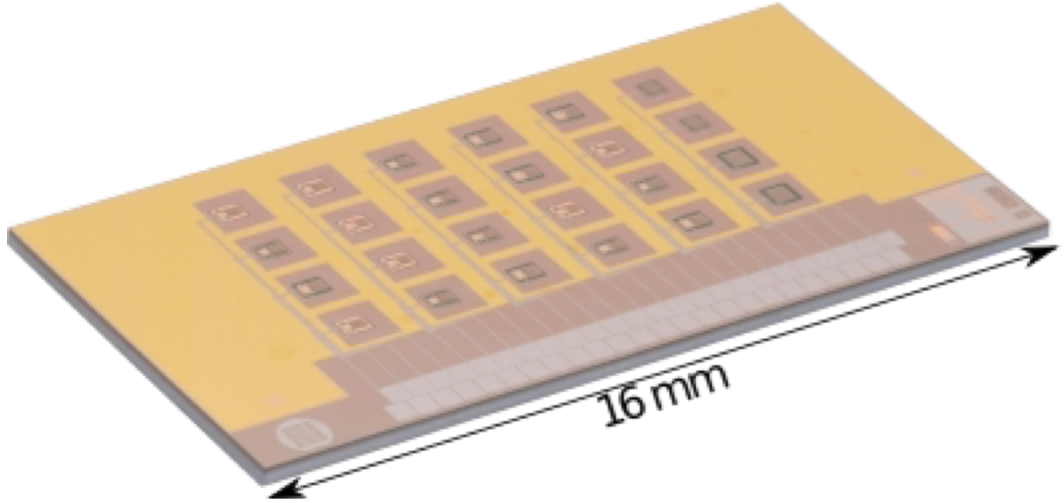
TES design, production and preliminary test is done @NIST



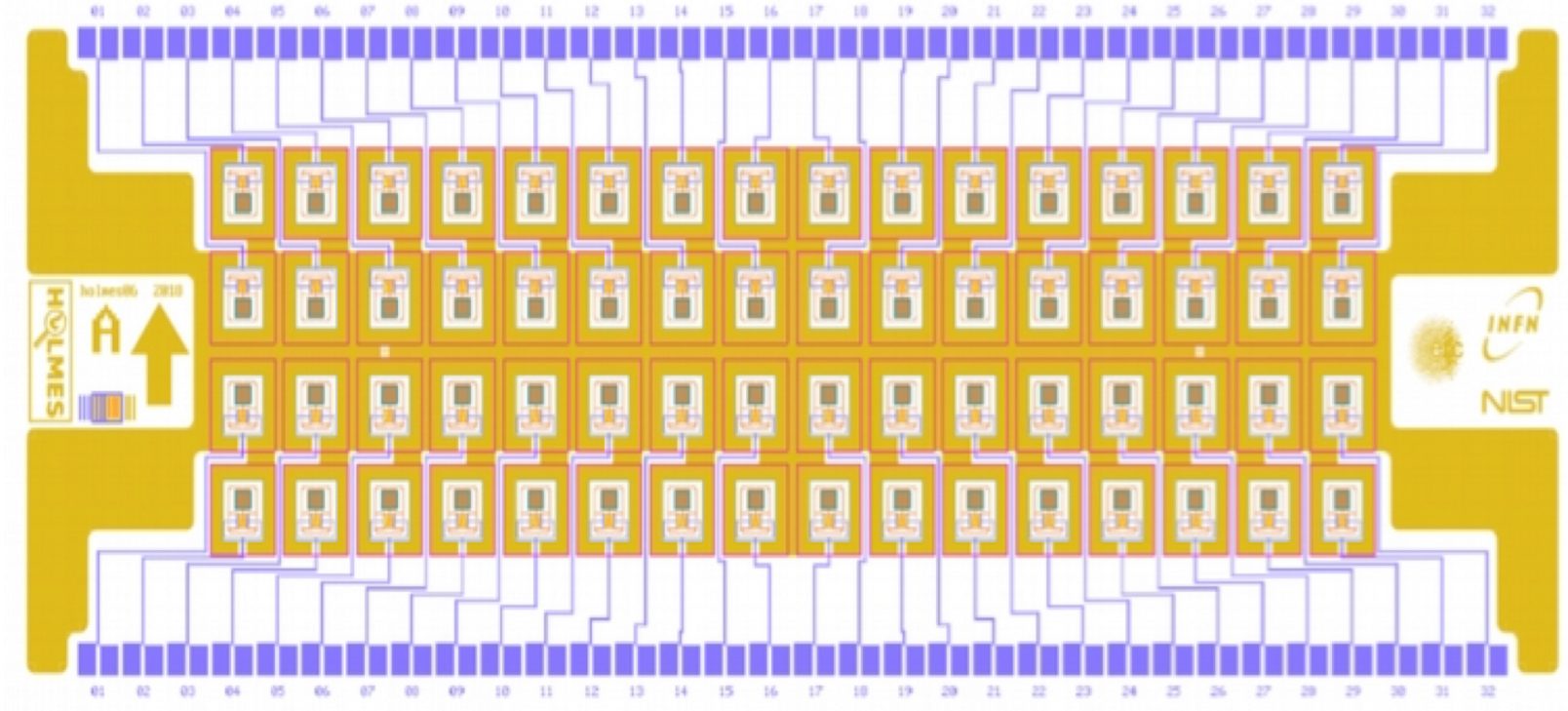


Detector design and test (2)

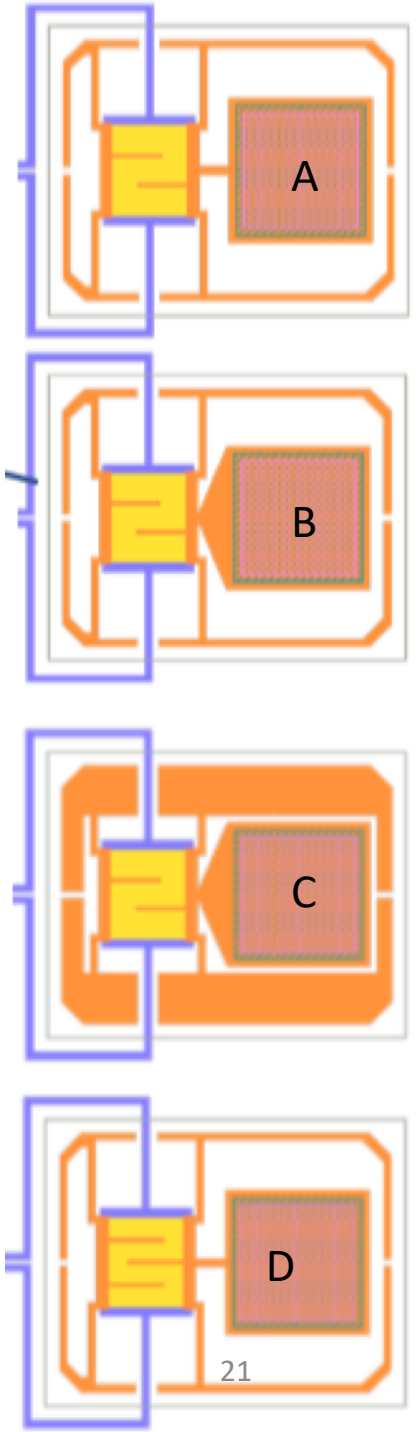
Four different designs to be tested
Different thermal conductance G
Different TES intrinsic parameters



4 x 16 linear array



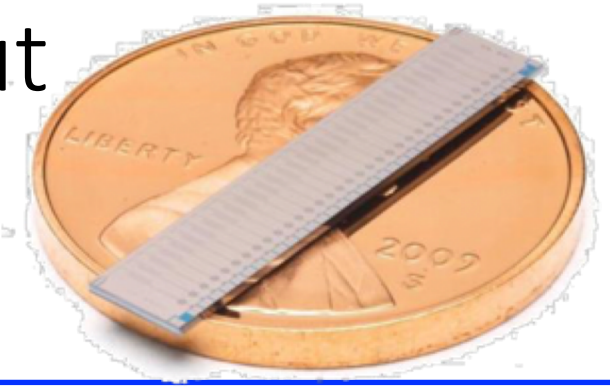
calculated ^{163}Ho beam FWHM



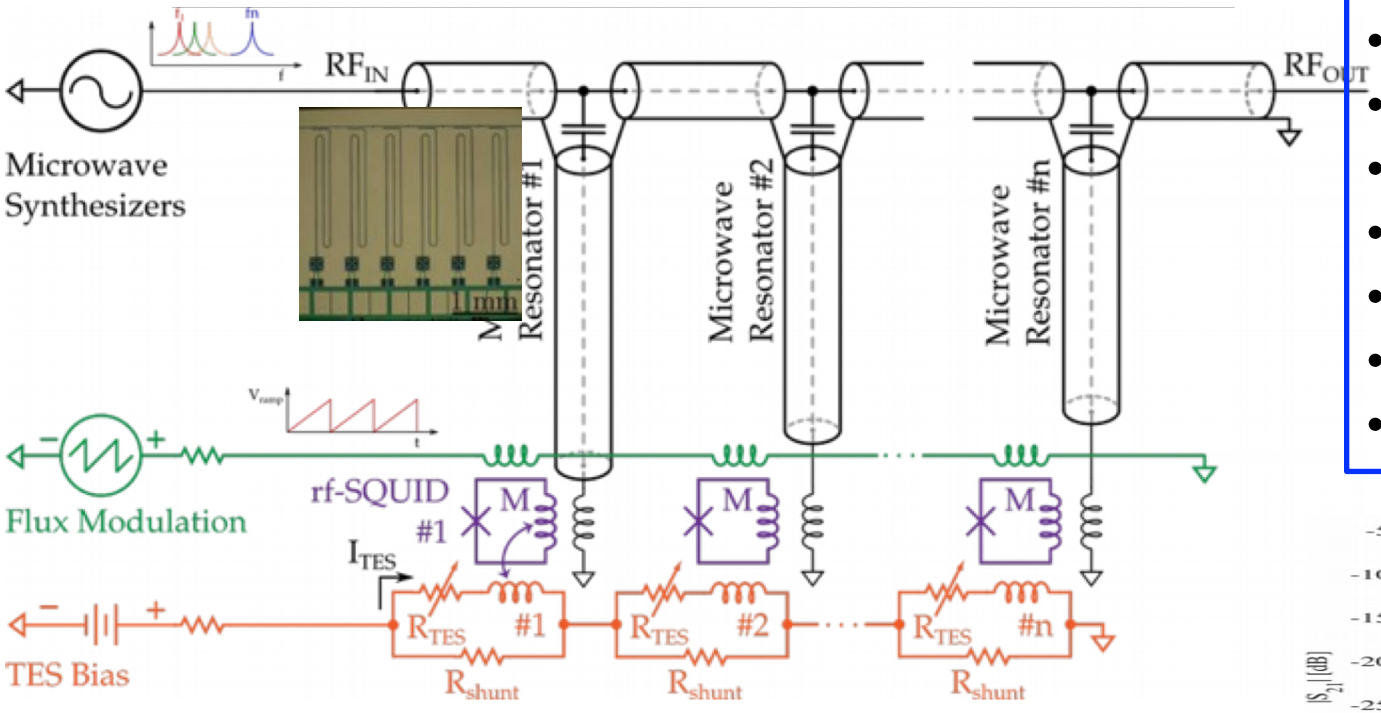
Microwave multiplexing readout

- Each TES is coupled to a RF-Squid
- Each RF-Squid is coupled to a common ramp
- Each RF-Squid is coupled to a resonant circuit (frequency multiplexing)

<u>A comb of signals probe the resonators at their characteristic resonant frequency</u>



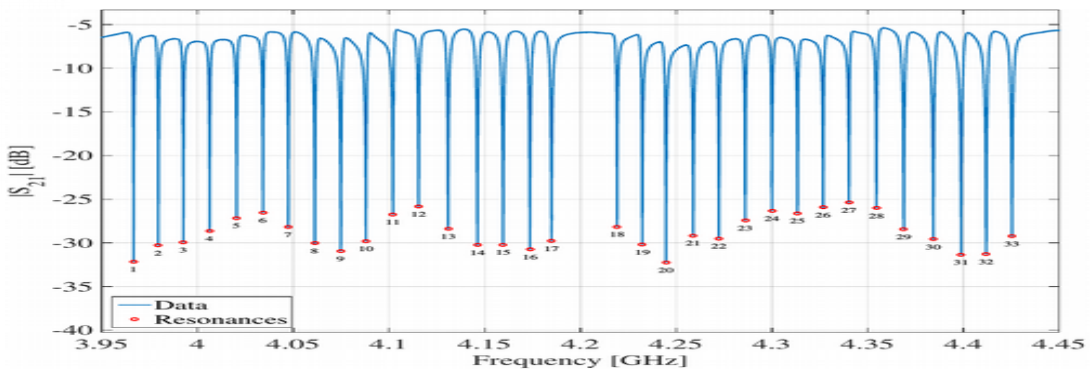
$$E \rightarrow \delta T_{TES} \rightarrow \delta I_{TES} \rightarrow \delta \phi_{squid} \rightarrow \delta f_{resonator}$$



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

Software Defined Radio with the open system ROACH2 (Casper collaboration)

- ADC BW 550 MHz
- real time pulse reconstruction
- Multiplexing factor proportional to the target ris
- time: $n_{TES} = 3.4 \times 10^{-6} \times \tau_{rise}$
- 33 resonances in 500 MHz
- width 2 MHz
- separation 14 MHz



Detector design and test (3)

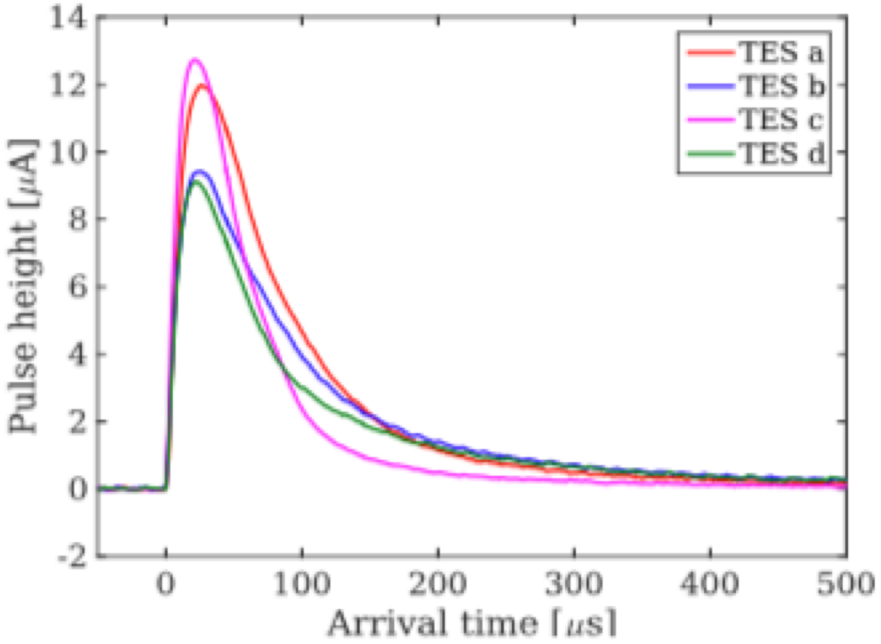
We tested the four different designs (non implanted detectors) to define heat capacity, thermal link geometry and TES design with:

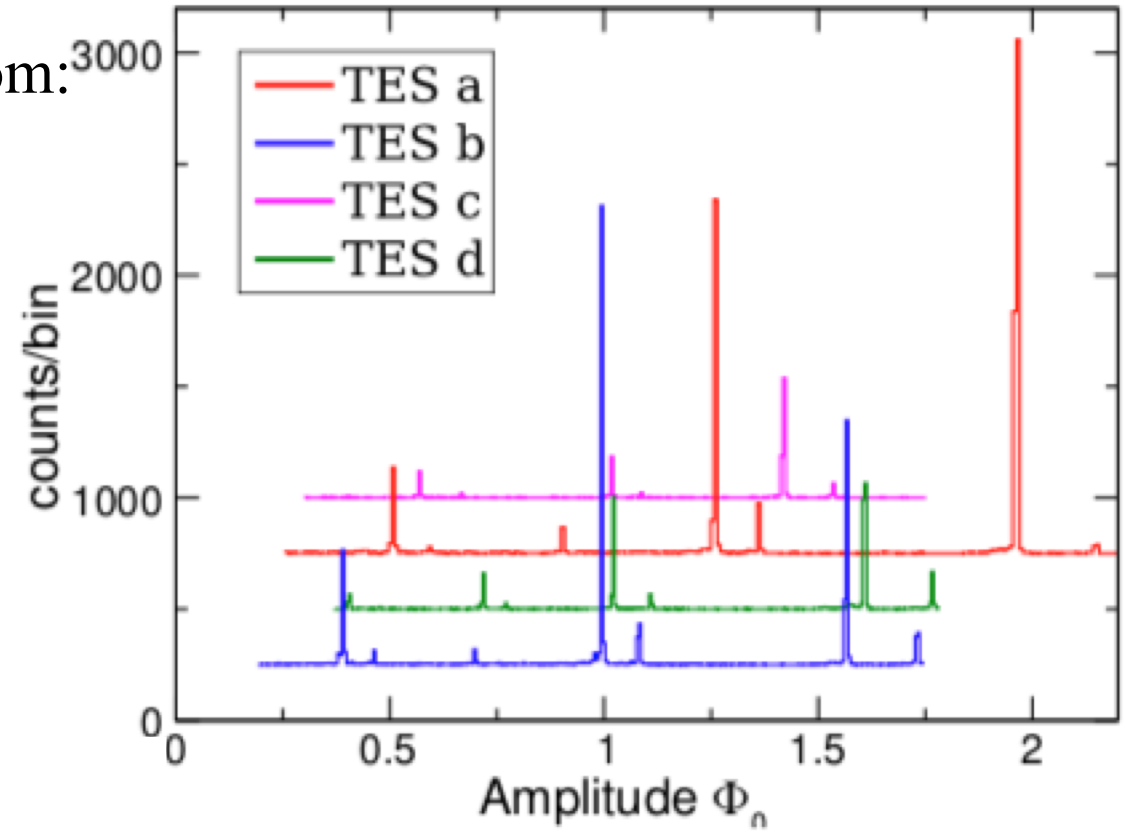
^{55}Fe (5.9 keV) + fluorescence from:

Ca – 3.7 keV

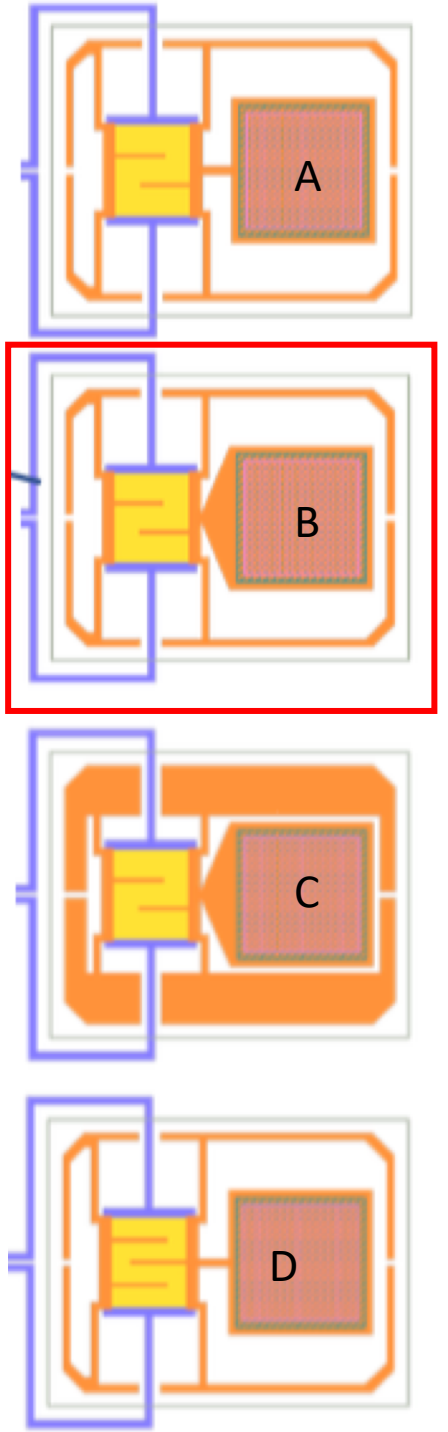
Cl – 2.6 keV

Al – 1.5 keV





Design B has the best performances



Detector design and test (4)

We tested also the linearity.
Detectors have good linearity over a wide (0 keV to 6 keV) energy range.

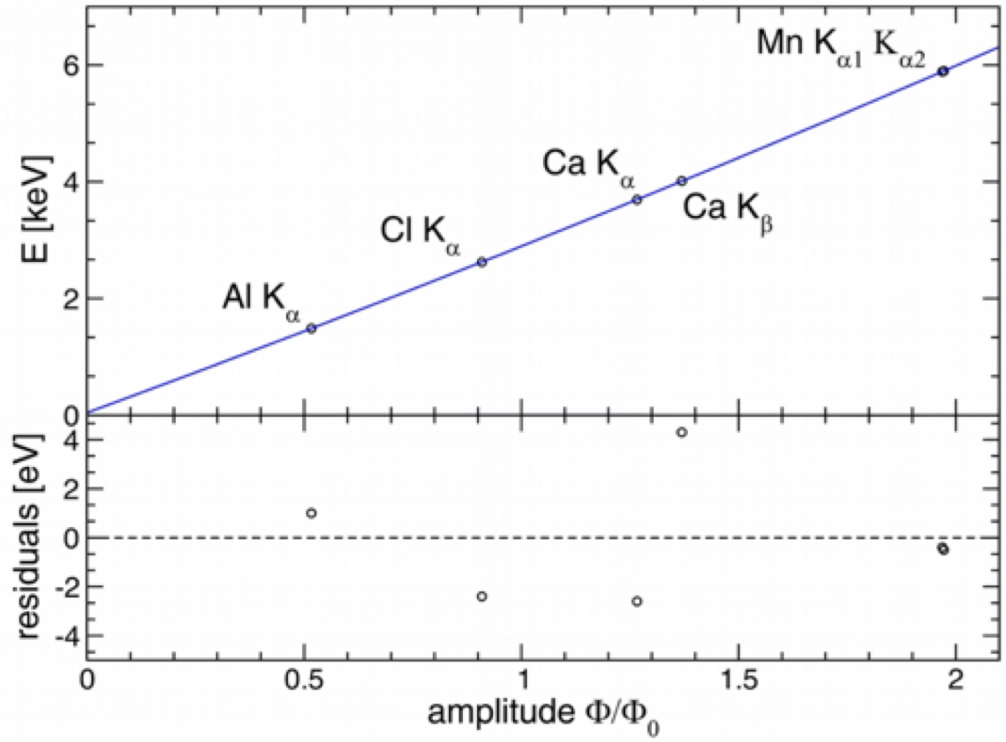
ΔE = 4.7 eV

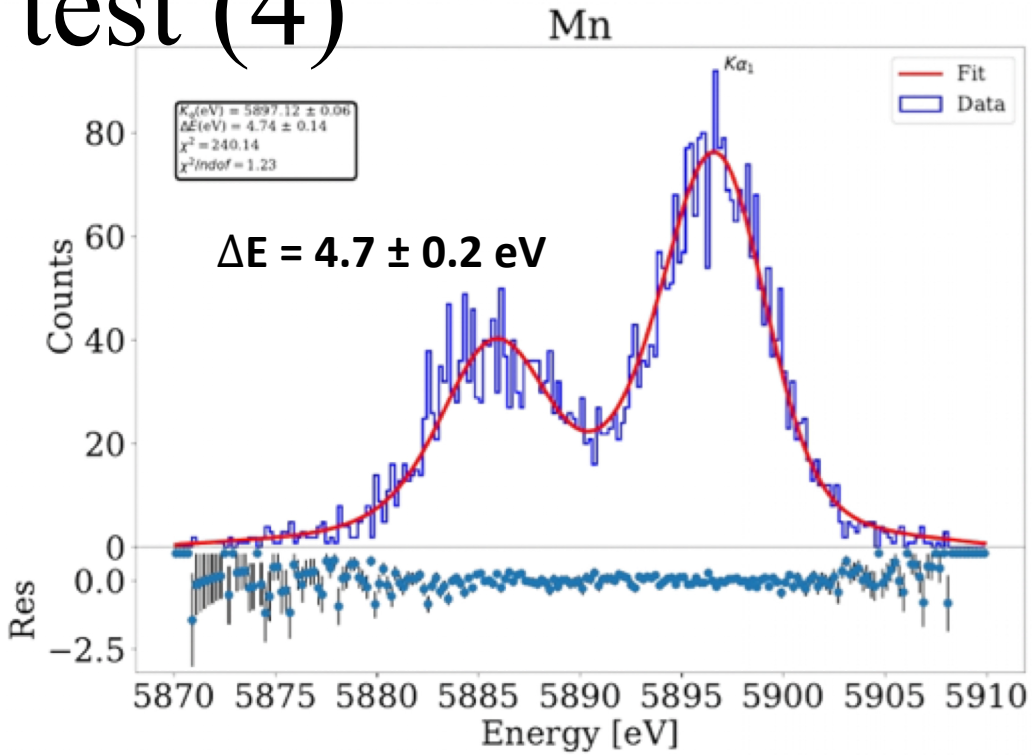
$\tau_{\mathrm{rise}} \sim 10\ \mu s$

$\tau_{\mathrm{decay}} \sim 190\ \mu s$

Calibration function:

$$E\ [\mathrm{keV}] = 0.11927\phi_0^2 + 2.7345\ \phi_0 + 0.041166$$

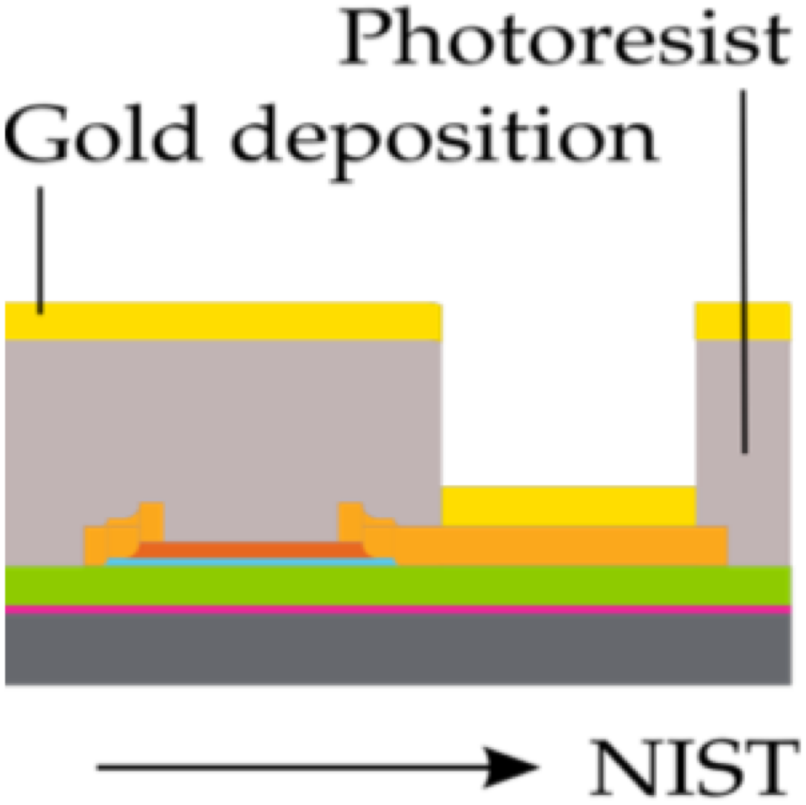


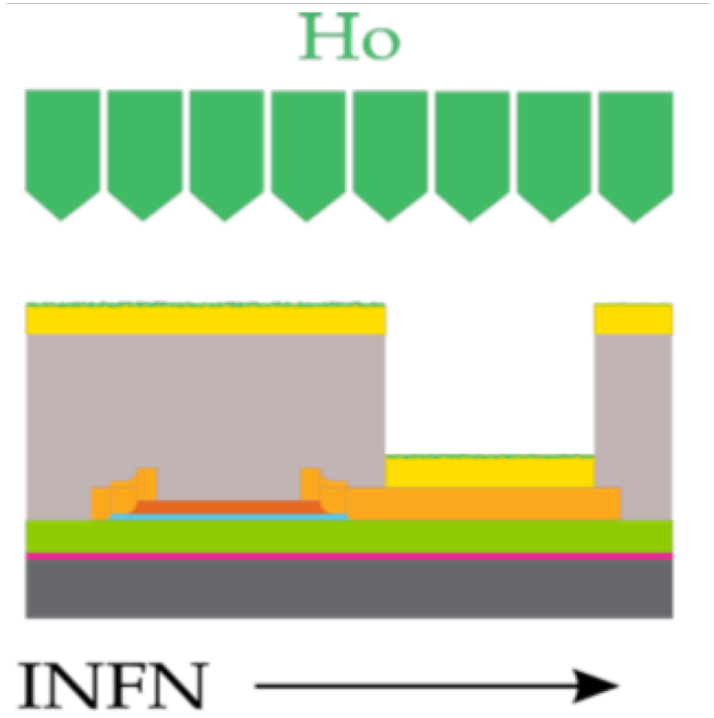


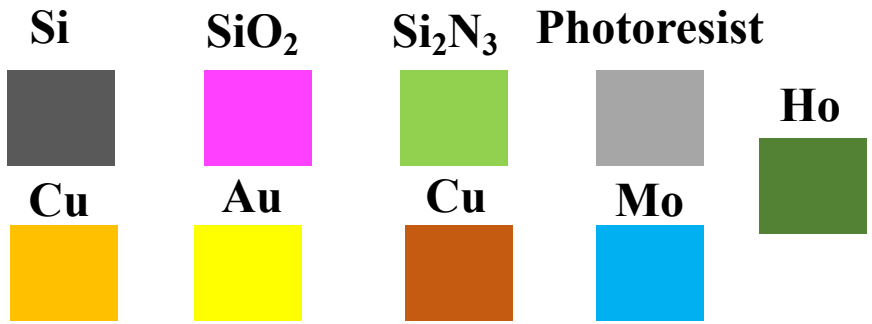
E [keV]	ΔE [eV]
1.49	4.3±0.3
2.62	4.5±0.3
3.69	4.6±0.3

Published in Eur. Phys. J. C (2019) 79: 304

Detector fabrication (1)







^{163}Ho concentration in absorbers saturate because ^{163}Ho sputters off Au from absorber. Maximum implantable activity ~ 3-4 Bq!!!

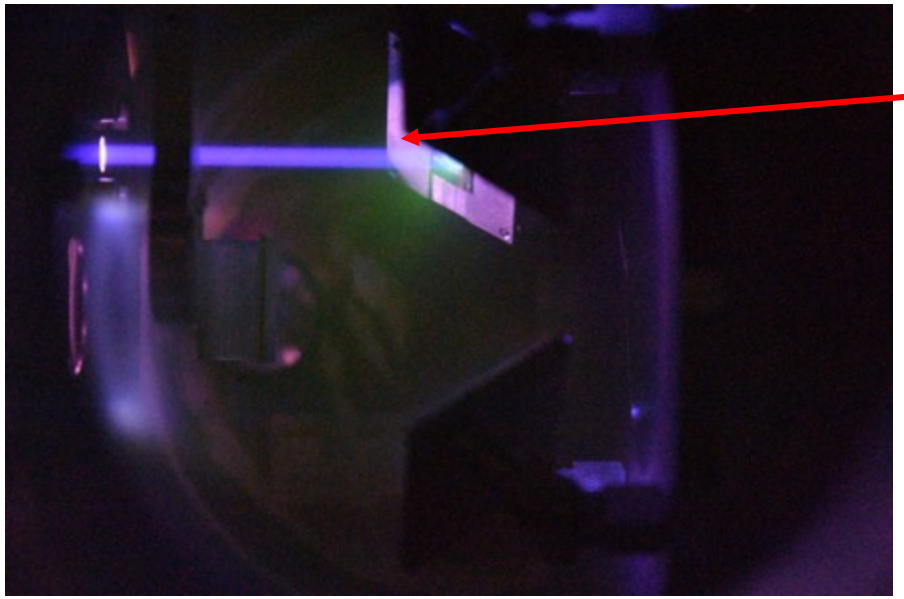
Detector fabrication (2)

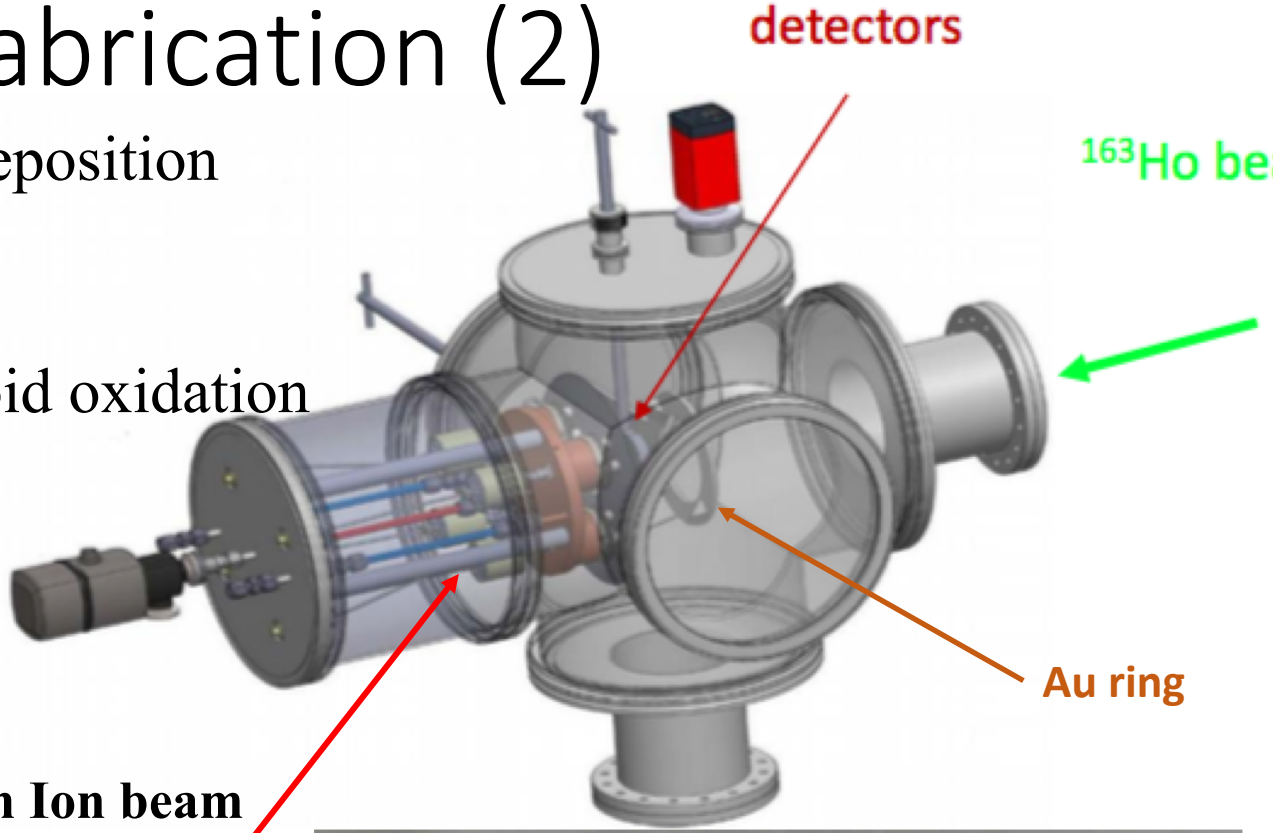
Four sputter ion sources coupled with the deposition chamber.

Effect compensated by Au co-evaporation.

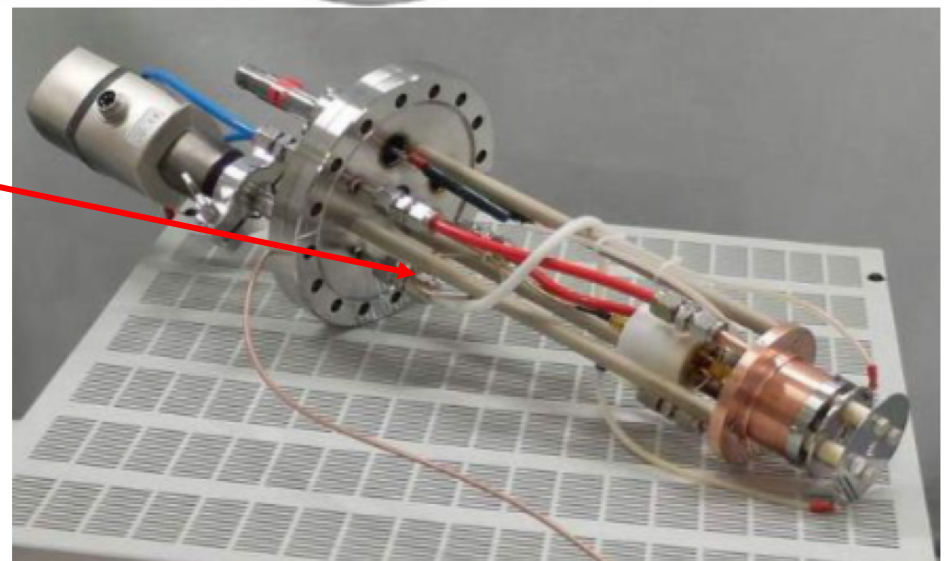
Final 1 μm Au layer deposited in situ to avoid oxidation

deposition rate (with 4 sputter sources)
≈ 50nm/hour
≈ 20 hours to deposit 1 μm
High Uniformity





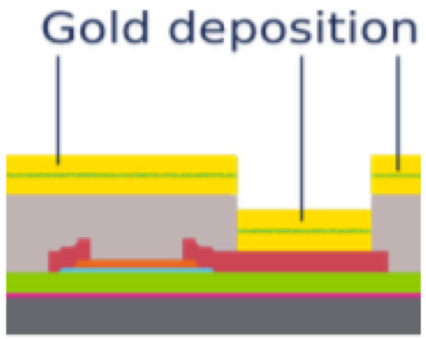
Argon Ion beam
microwave sources
for sputtering



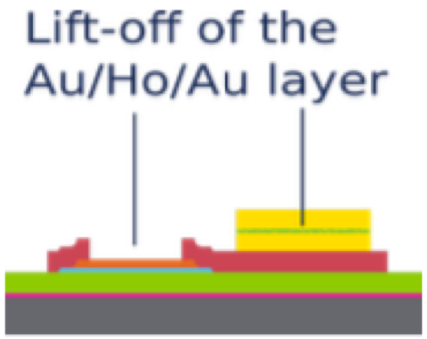
Next step
Try to improve the deposition rate

Detector fabrication (3)

1)

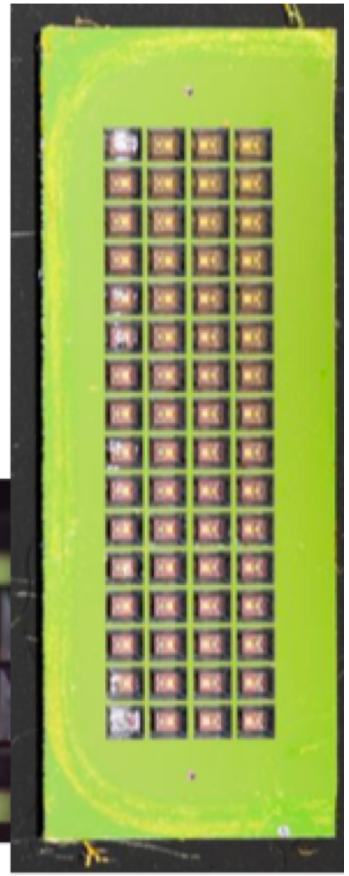


2)

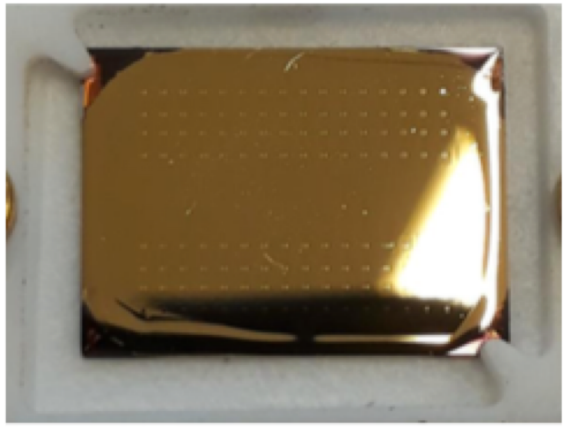


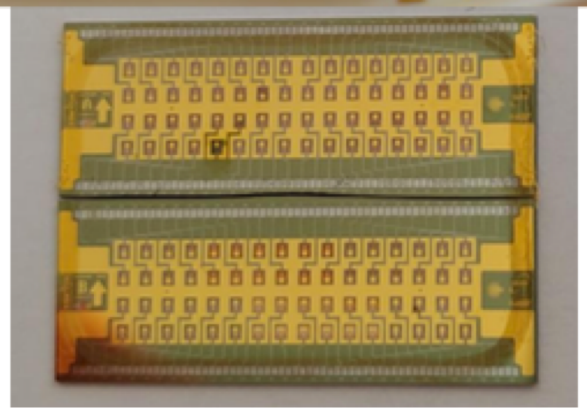
3)

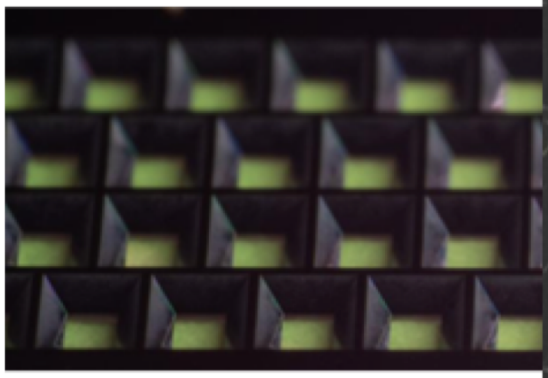
KOH...



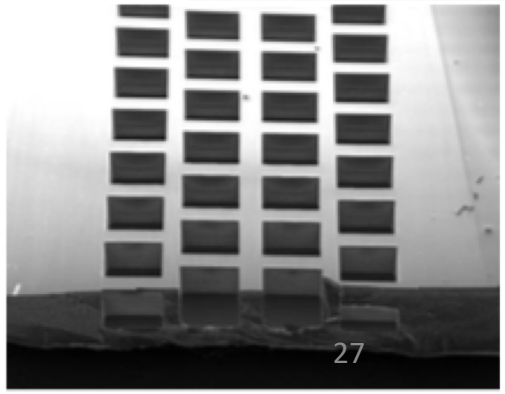
Using Acetone







... vs DRIE



Summary

The measurement of neutrino mass is still one of the most compelling issues in modern particle physics. Both calorimetric and spectrometric experiments are on going and could give a final answer.

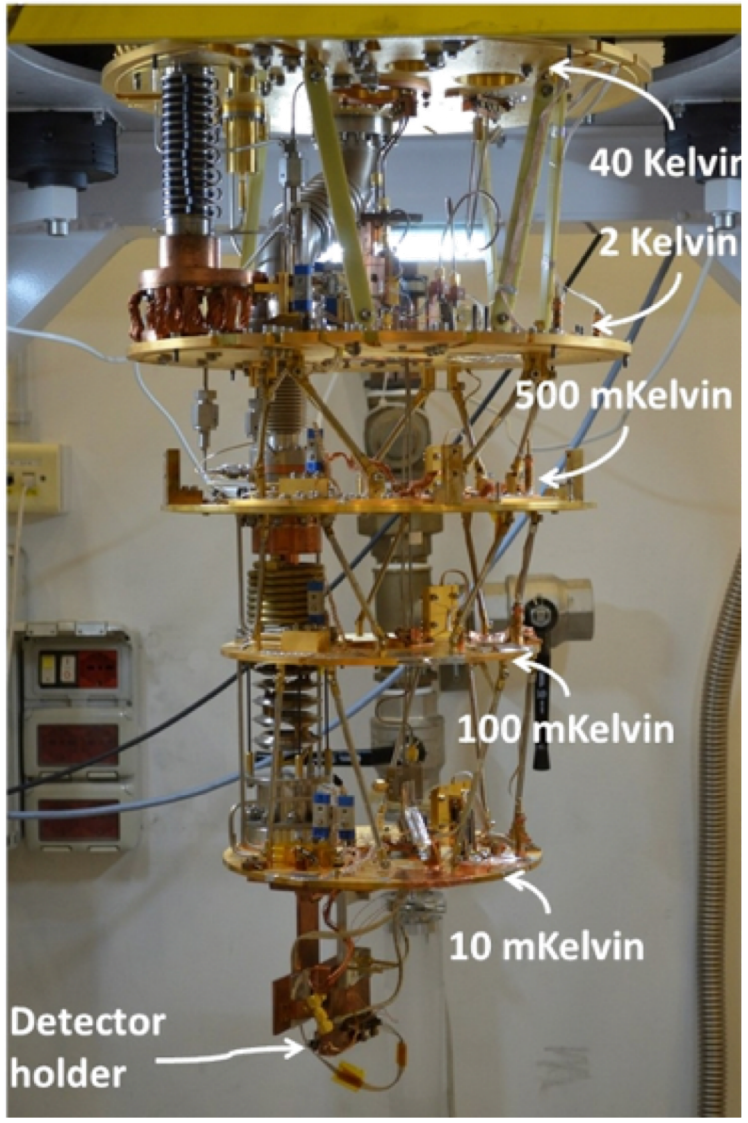
HOLMES is a calorimetric experiment with ^{163}Ho that aims to reach the statistical sensitivity around 1 eV.

Three batches of ^{163}Ho are purified and ready to be moved in Genova.
The procedure to distillate holmium is tested. Some refinements are needed.
The procedure to fabricate sputter target is tested.
The installation of the implanter for isotopic separation is mainly finished
Every part has been individually tested. Integration and first tests in progress.
HOLMES detector production procedure is defined and the firsts (not implanted) detectors are being characterized.
Readout is on test and is almost ready.

With 32 pixels for 1 month → m sensitivity ≈10 eV

BACKUP

Cryostat



Detctor box is coupled to the Mixing Chamber of a 3He/4He dilution refrigerator