Direct neutrino mass measurement by the HOLMES experiment

Andrei Puiu on behalf of the HOLMES collaboration

The collaboration

HOLMES

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European Research Council

Established by the European Commission

PAUL SCHERRER INSTITUT

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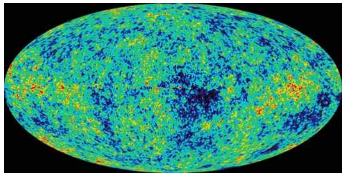
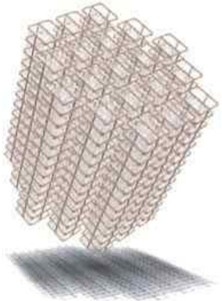
UNIVERSITÀ DEGLI STUDI DI MILANO BICOCCA

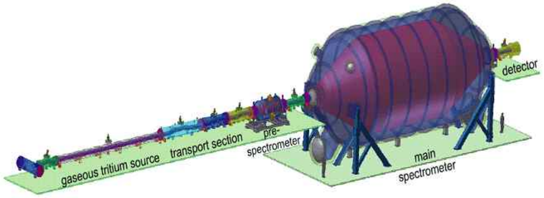
INFN

Istituto Nazionale di Fisica Nucleare

Mass measurements





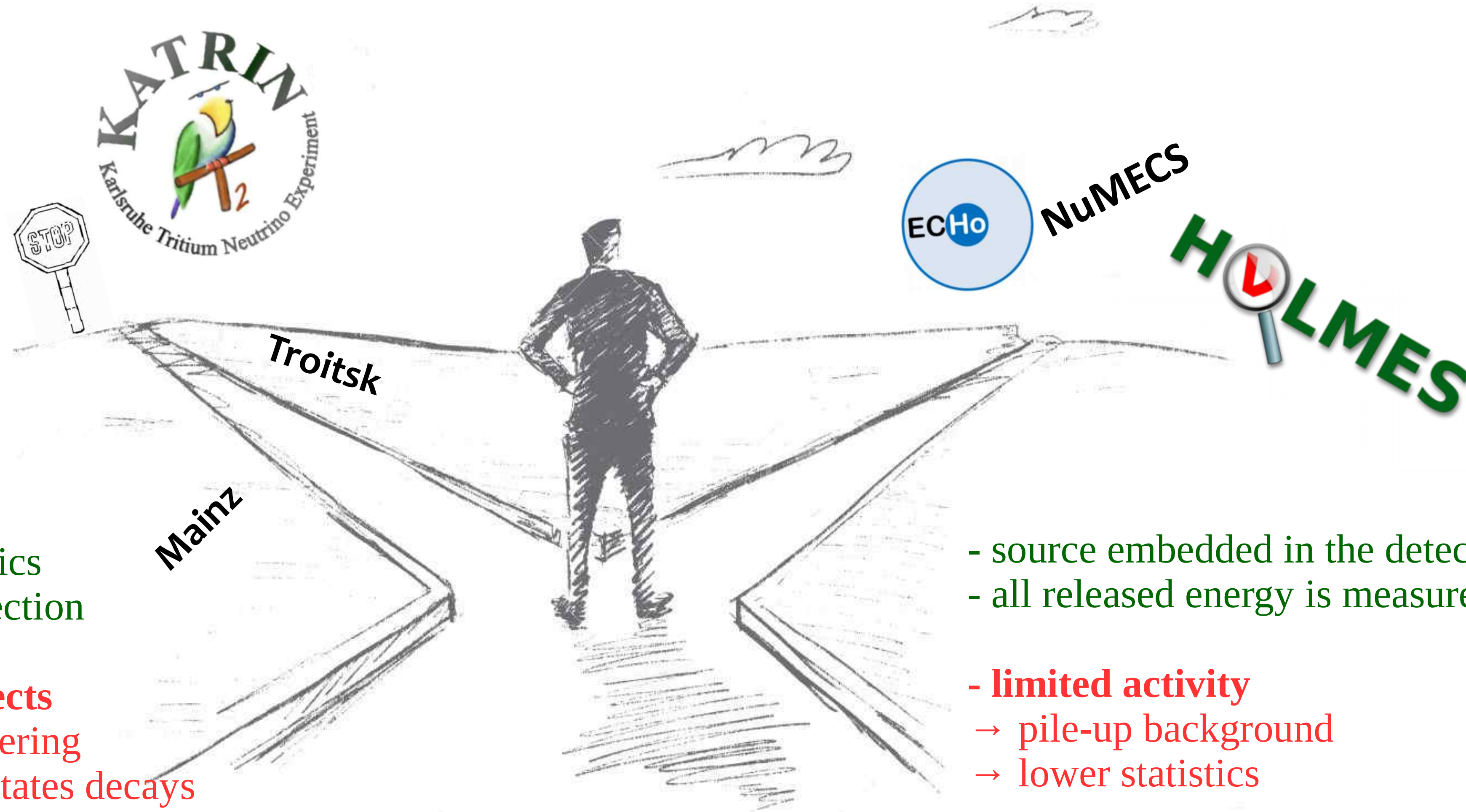


Method	Cosmology	0νββ decay	β spectrum endpoint
Observable	$m_\Sigma = \Sigma_i m_{\nu i}$	$m_{\beta\beta} = \left\| \Sigma_i m_{\nu i} U_{ei}^2 \right\|$	$m_\beta = \left(\Sigma_i m_{\nu i}^2 U_{ei}^2 \right)^{1/2}$
Status quo	~0.1 eV	~0.1 eV	2 eV
Next generation	0.01 eV	0.01 eV	0.2 eV
Systematics	large	good	large
Model	dependent	dependent	independent

- m_Σ is strongly dependent on cosmological assumptions
- The evaluation of nuclear matrix elements involved in 0νββ decay is a major challenge (IMB, QRPA)
- Direct measurement of beta or Electron Capture (EC) spectrum is not model dependent. Energy conservation.

HOLMES

Direct neutrino mass measurement



- high statistics
- energy selection

- source effects
→ backscattering
→ excited states decays

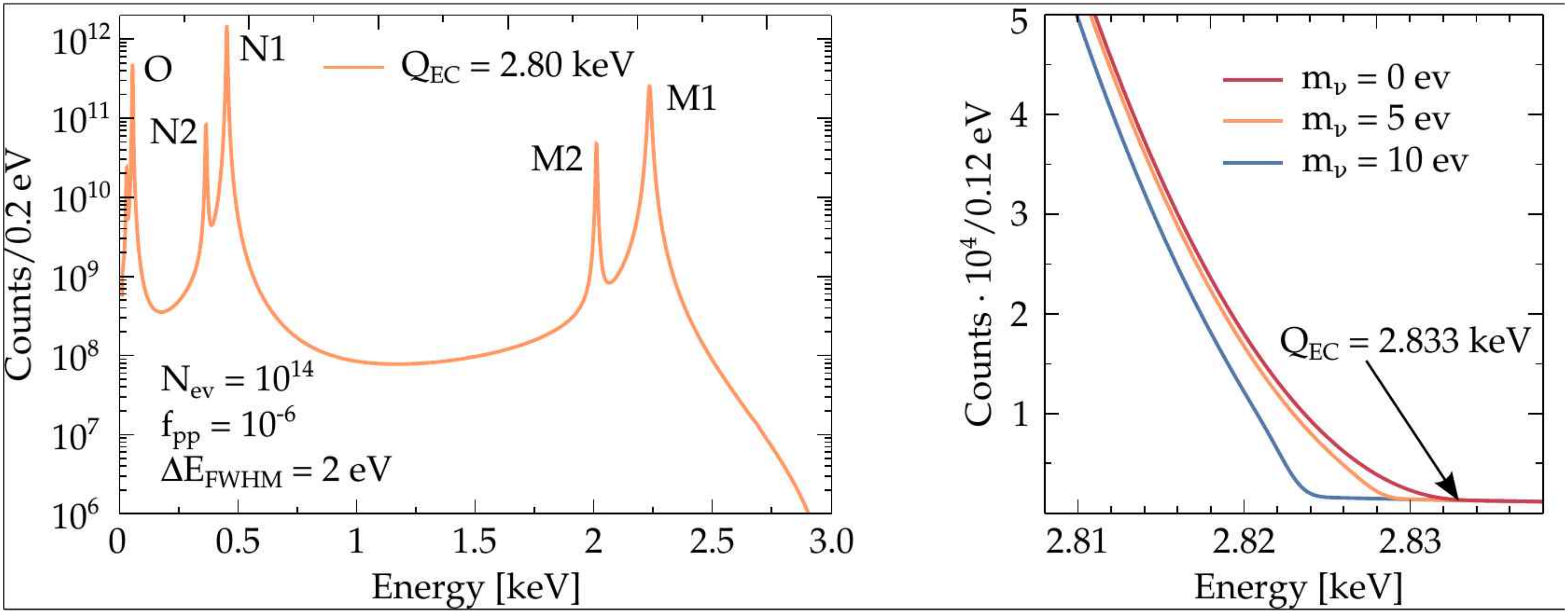
- source embedded in the detector
- all released energy is measured

- limited activity
→ pile-up background
→ lower statistics

End point measurement

- The end point si the region of spectrum where the effect of the non vanishing neutrino mass is measureable
- The vicinity to the M1 resonance enhances the number of events at the end point
- Second order effects i.e. shake-up and shake-off need to be taken into account

$$\frac{dW}{dE_C} = N(Q - E_C)\sqrt{[(Q - E_C)^2 - m_\nu{}^2]} \propto \sum_H \frac{\varphi_H^2(0)(\Gamma_H/2\pi)}{[(E_C - E_H)^2 + \Gamma_H{}^2/4]}$$



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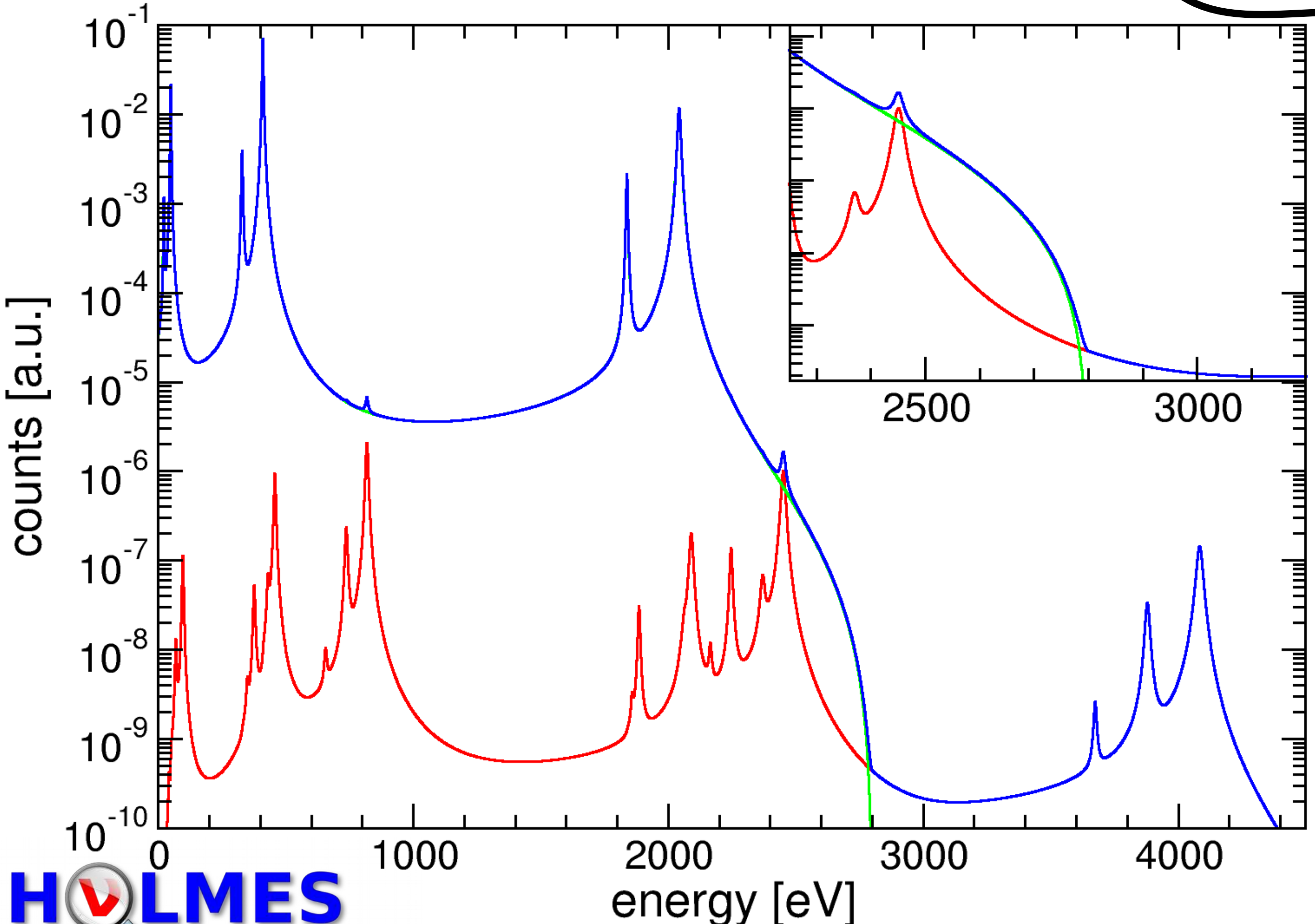
$$^{163}\mathrm{Ho} + e^- \rightarrow {}^{163}\mathrm{Dy}^* + \nu_e$$
$$^{163}\mathrm{Dy}^* \rightarrow {}^{163}\mathrm{Dy} + E_C$$

Pile-up

- no direct calorimetric measurement of Q (end-point) so far
- complex pile-up spectrum
  - $N_{pp}(E)=f_{pp}N_{EC}(E)\otimes N_{EC}(E)$ with $f_{pp}\approx A_{EC}\tau_R$

Maximizing the detector activity pays in terms of overall sensitivity

Pile up is an important factor for the sensitivity of HOLMES



→ **Crucial to have fast detectors**

$Q = 2800$ eV

$f_{pp} = 10^{-4}$

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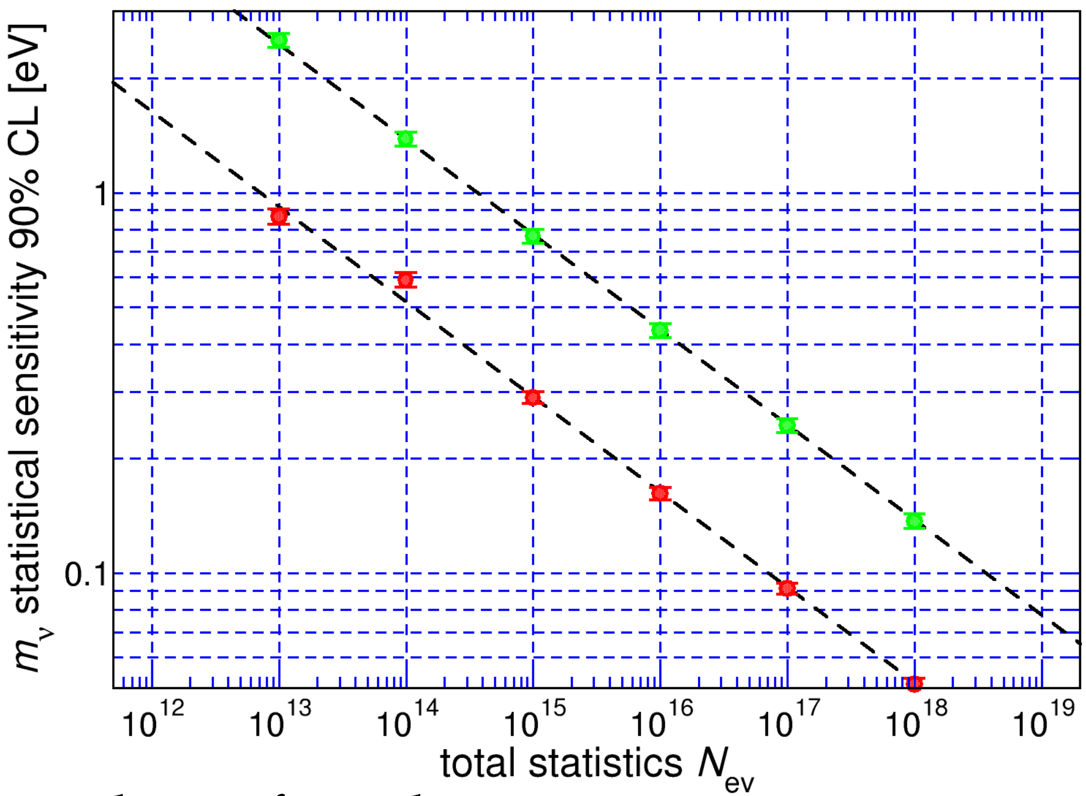
Sensitivity on m_ν

f_{pp} = 10^{-6}, 10^{-3}



Experimental requirements to gather high statistics

10^{13} events in 3 years time for ~1 eV sensitivity on m_ν

Detectors:

- Energy resolution 1 eV @ 2 keV
- Time resolution 1 μs to discriminate pile up
- Very large detector array (1000 detectors)

Best choice for calorimetric measurement:

LOW TEMPERATURE DETECTORS

Calorimeters coupled to Transition Edge Sensors with RF multiplexed readout

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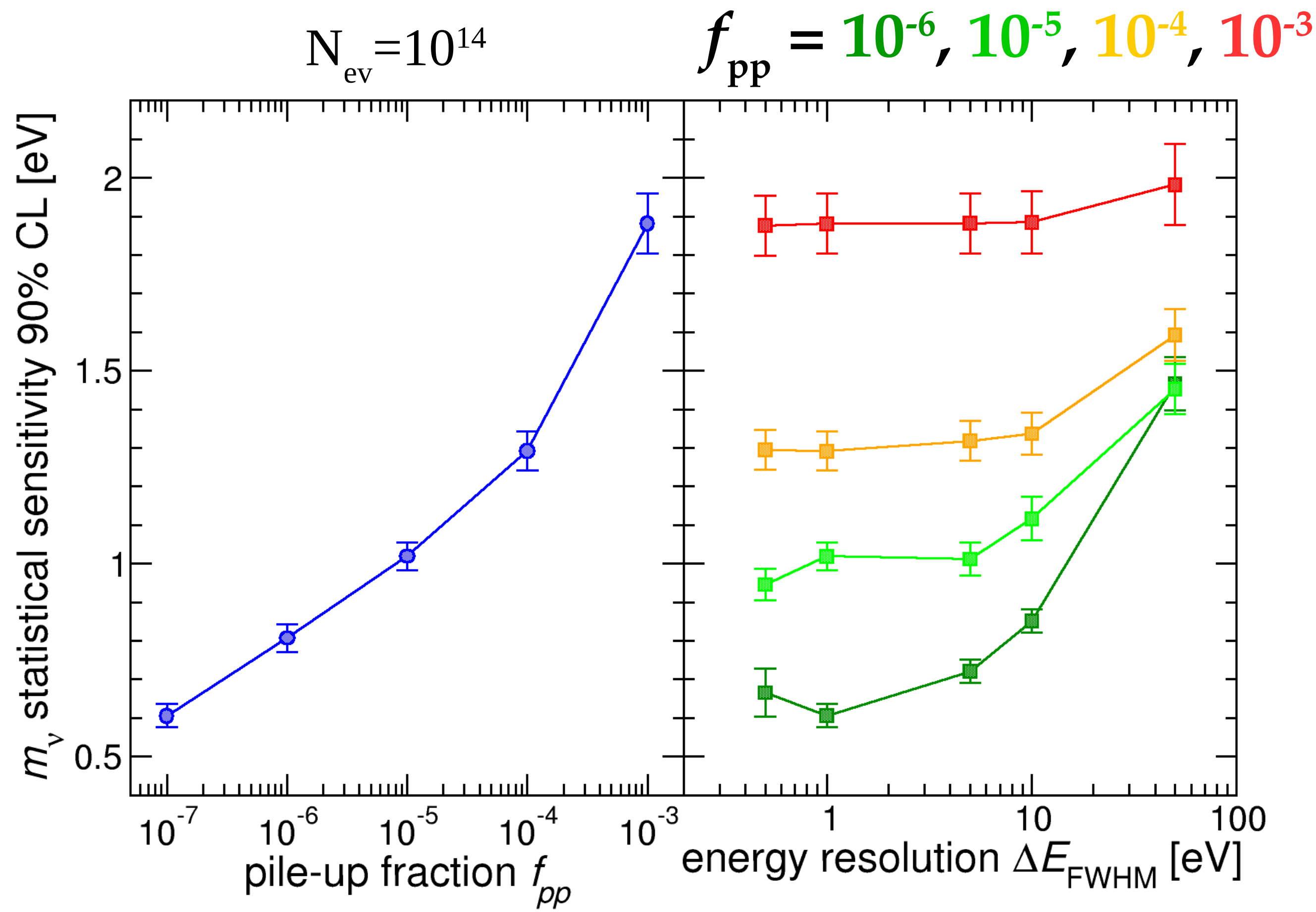
Requirements for sub-eV sensitivity



Q = 2.8 keV
ΔE = 1 eV
τ_R = 1 μs

Sub eV

$A = 1000\text{Bq}$

$N_{det} t_M \approx 3\times10^9$ det × y

1 μs time resolution and 1 eV energy resolution

1000 Bq activity → pile up background of 3×10^{-4}

... to reach a 0.1 eV sensitivity on neutrino mass 3×10^9 detectors × year are necessary

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HOLMES milestones

Goal:

neutrino mass measurement: m_ν statistical sensitivity as low as 1 eV

→ prove technique potential and scalability: assess EC Q-value and systematic errors

European Research Council

European Research Council (FP7/2007–2013) under Grant Agreement HOLMES no. 340321.

Baseline

TES with implanted ^{163}Ho

→ 6.5×10^{13} nuclei per pixel (300 dec/sec)

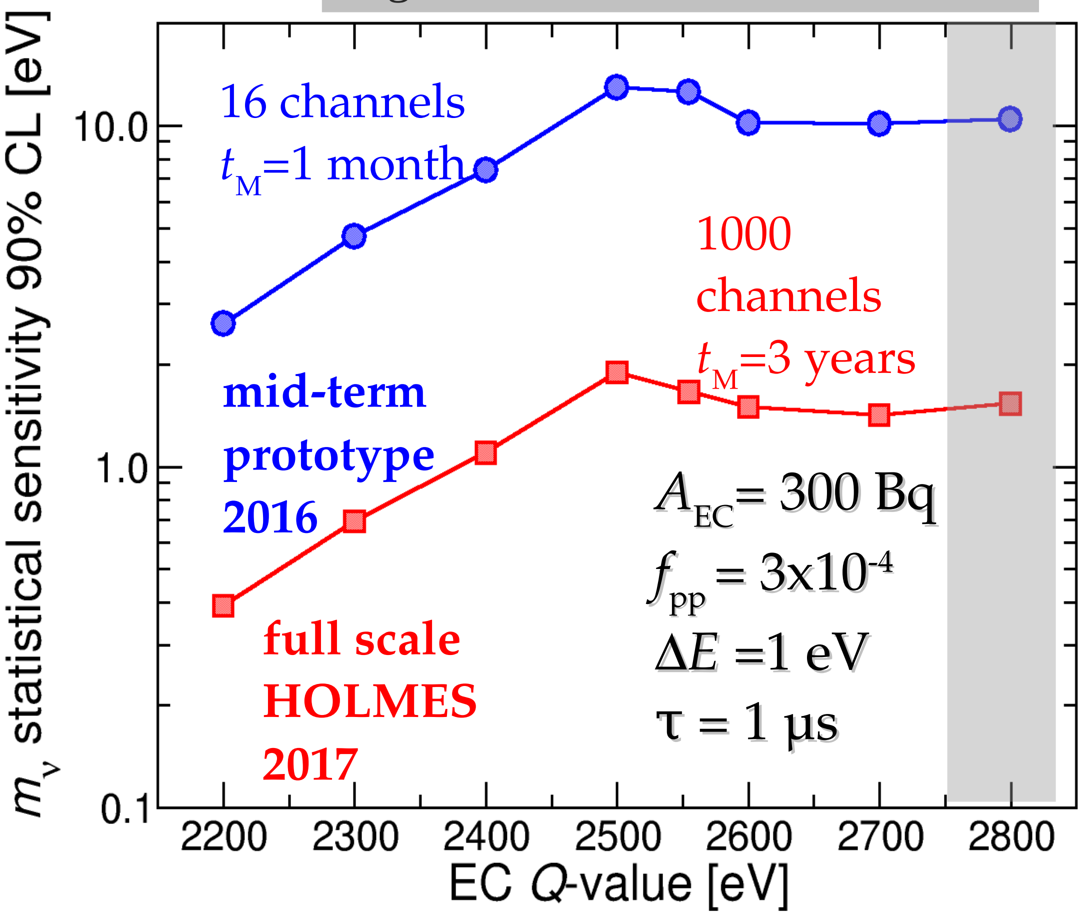
→ $\Delta E \approx 1 eV$ and $\tau_R \approx 1 \mu s$

→ 1000 channel array

→ 6.5×10^{16} ^{163}Ho nuclei (≈18μg)

→ 3×10^{13} events in 3 years

HOLMES



Ho production

$$^{162}\mathrm{Er}(n,\gamma)^{163}\mathrm{Er} \longrightarrow ^{163}\mathrm{Ho} + \nu_e$$

- Ho production at the high flux neutron reactor of Istitute Laue Langevin (Grenoble) from enriched Er powder
- Purification at the Paul Scherrer Institute (Villigen) before and after irradiation
- ^{163}Ho Oxide shipped to Genova for subsequent processing

$$\mathrm{Ho_2O_3} + 2\mathrm{Y(met)} \longrightarrow 2\mathrm{Ho(met)} + \mathrm{Y_2O_3}$$

- ^{163}Ho reduced to metal in Genova labs
- ^{163}Ho powder mixed with Ti for avoiding oxidation and with Sn for mechanical properties
- Target produced by pressing the compound
- Ready to be placed in the ion sputtering source of the implanter

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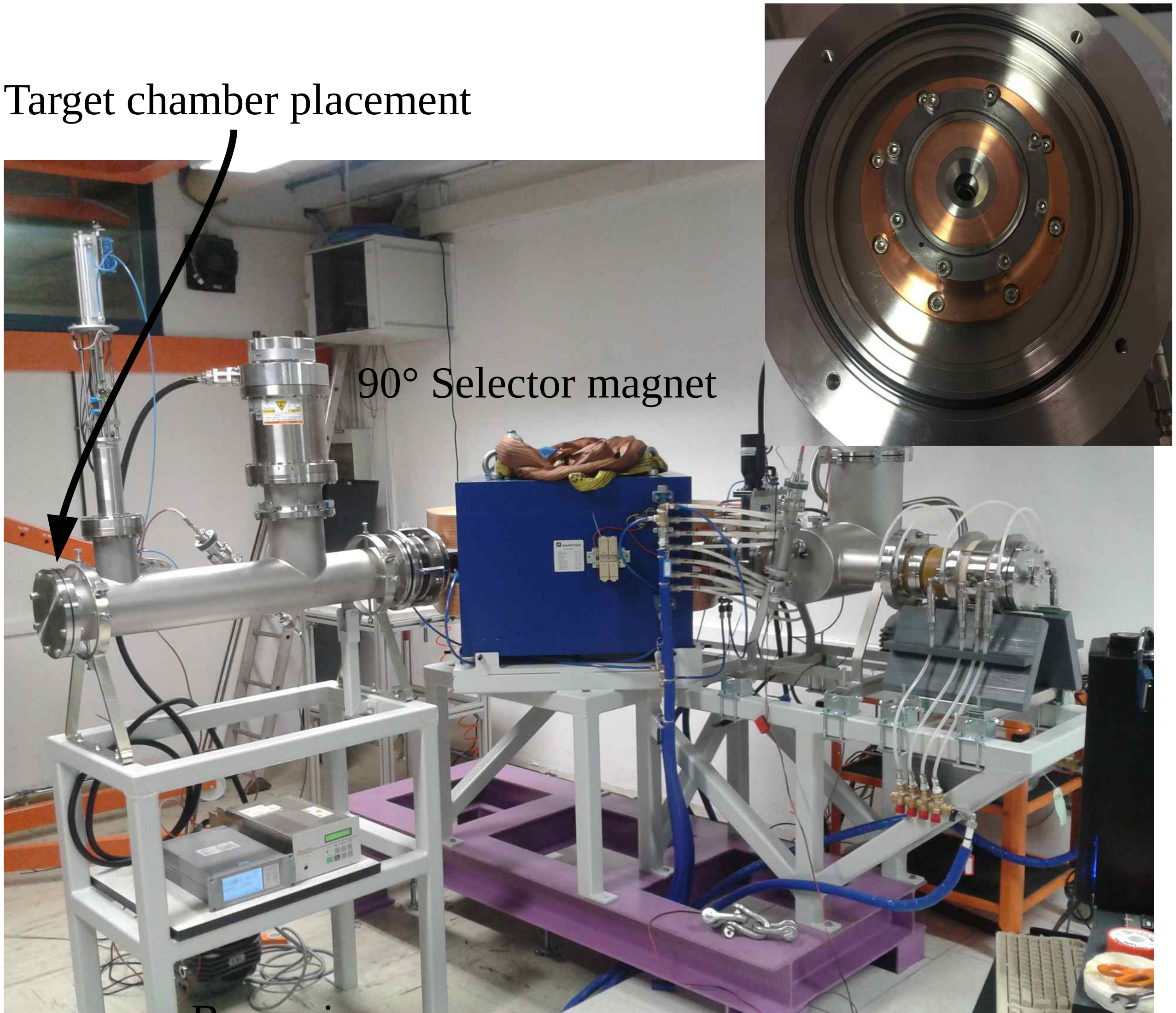
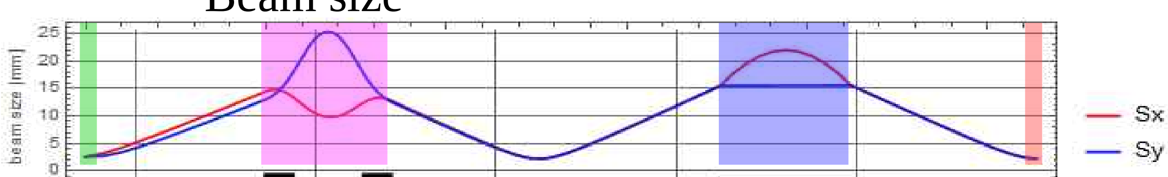
Holmium implantation

Sputter ion source

Target chamber placement



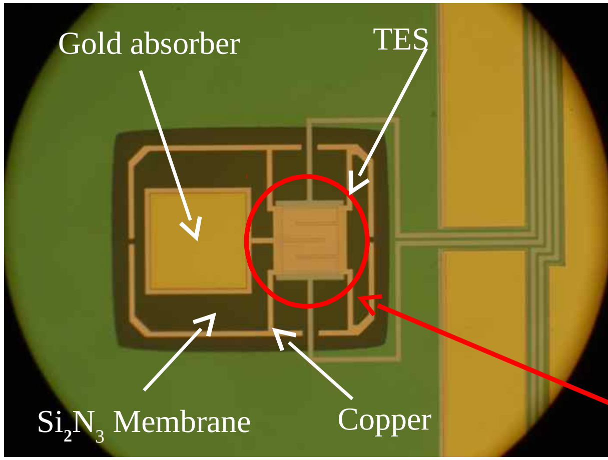
Beam size

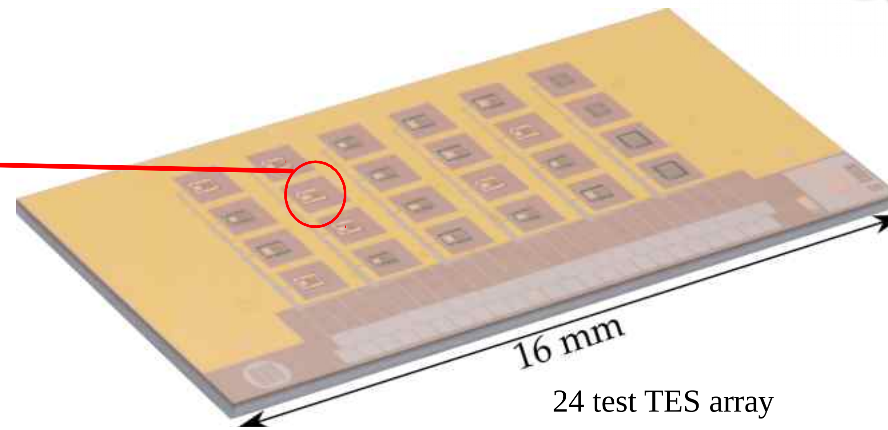


- 163Ho needs to be implanted in the gold absorbers of the detectors
- Crucial to avoid Ho oxidation → chemical shift of the end point
- Separation from neighbouring isotopes
- Gold sputtering on detectors during implantation
- Final 1μm Gold deposition for complete absorption of the decay electrons

Transition Edge Sensors

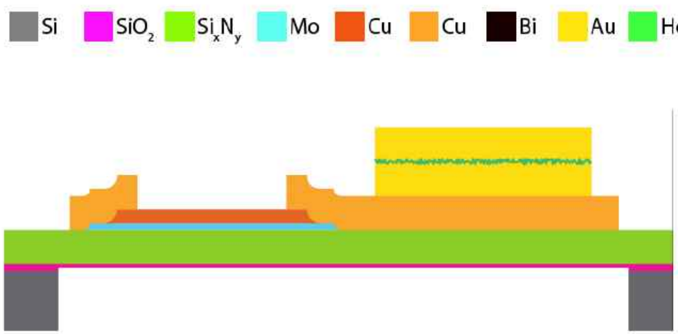
TES under microscope

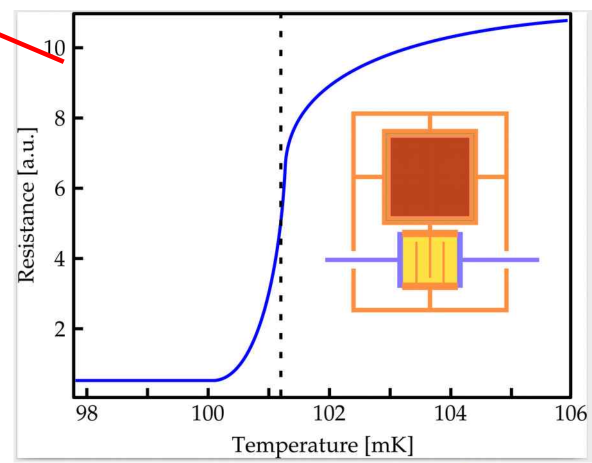




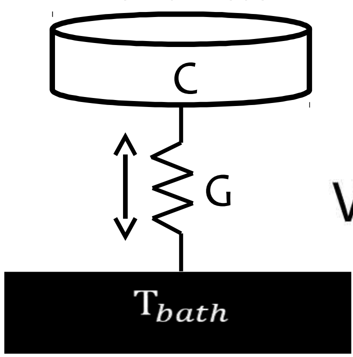
24 test TES array

TES, side view

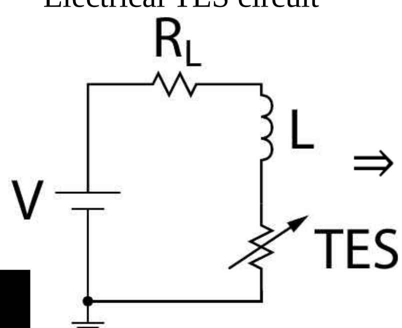




Thermal model



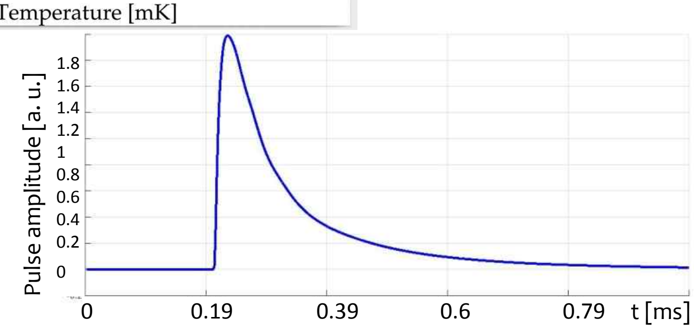
Electrical TES circuit



$\Rightarrow$

$$\begin{cases} C\dfrac{dT}{dt} = -P_{bath} + P_J + P \\ L\dfrac{dI}{dt} = V - IR_L - IR_{TES}(T,I) \end{cases}$$

$\Rightarrow$

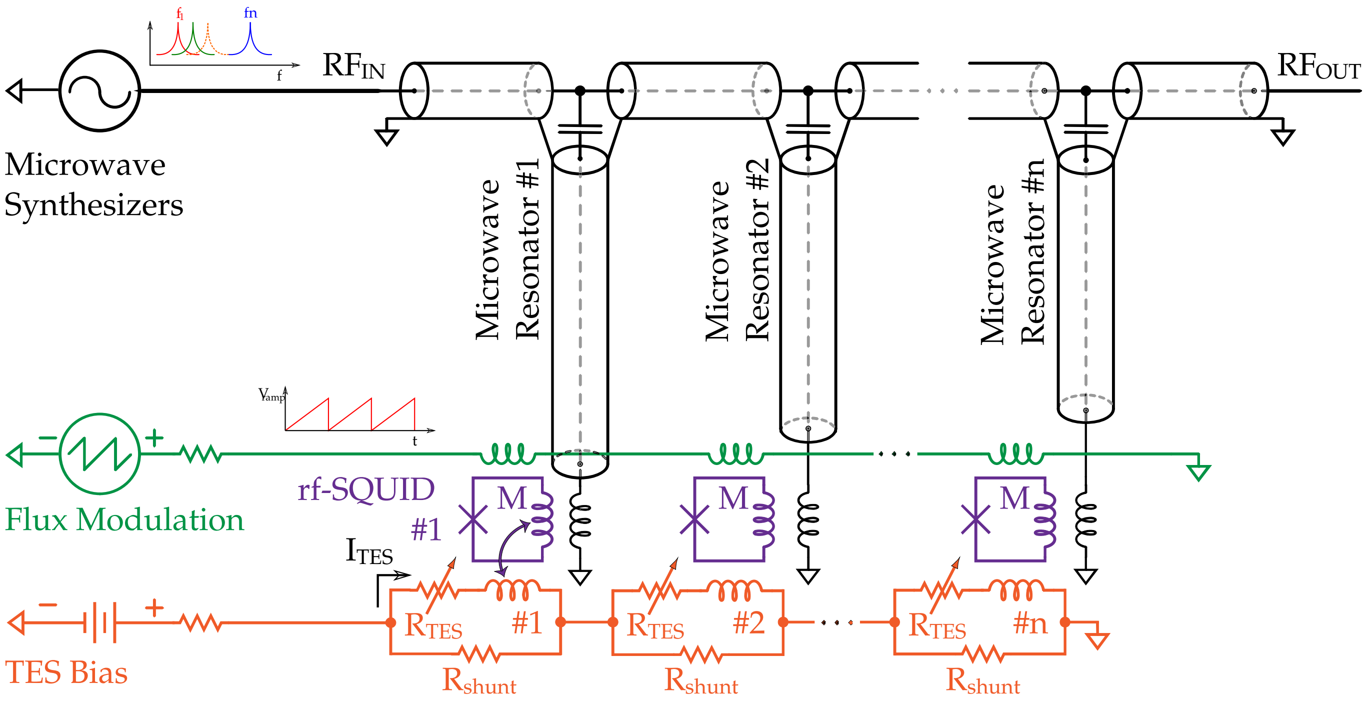


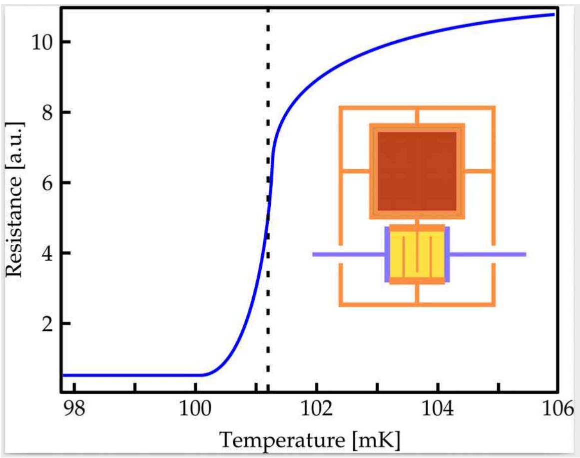
Multiplexed readout

Each TES is coupled to a RF-Squid coupled again to a quarter wavelength resonator.
Each resonator is tuned at a different frequency in the 4-8 GHz range

- Energy released in the absorber
- TES temperature increase and resistance decrease
- Current variation in the bias circuit

$$E \rightarrow \delta T_{TES} \rightarrow \delta I_{TES}$$





Multiplexed readout

Each TES is coupled to a RF-Squid coupled again to a quarter wavelength resonator.
Each resonator is tuned at a different frequency in the 4-8 GHz range

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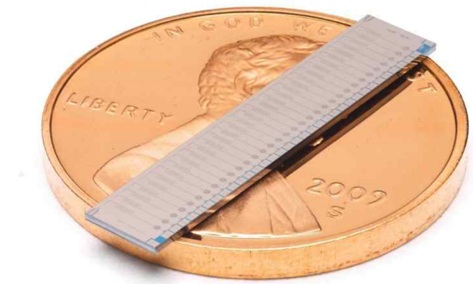
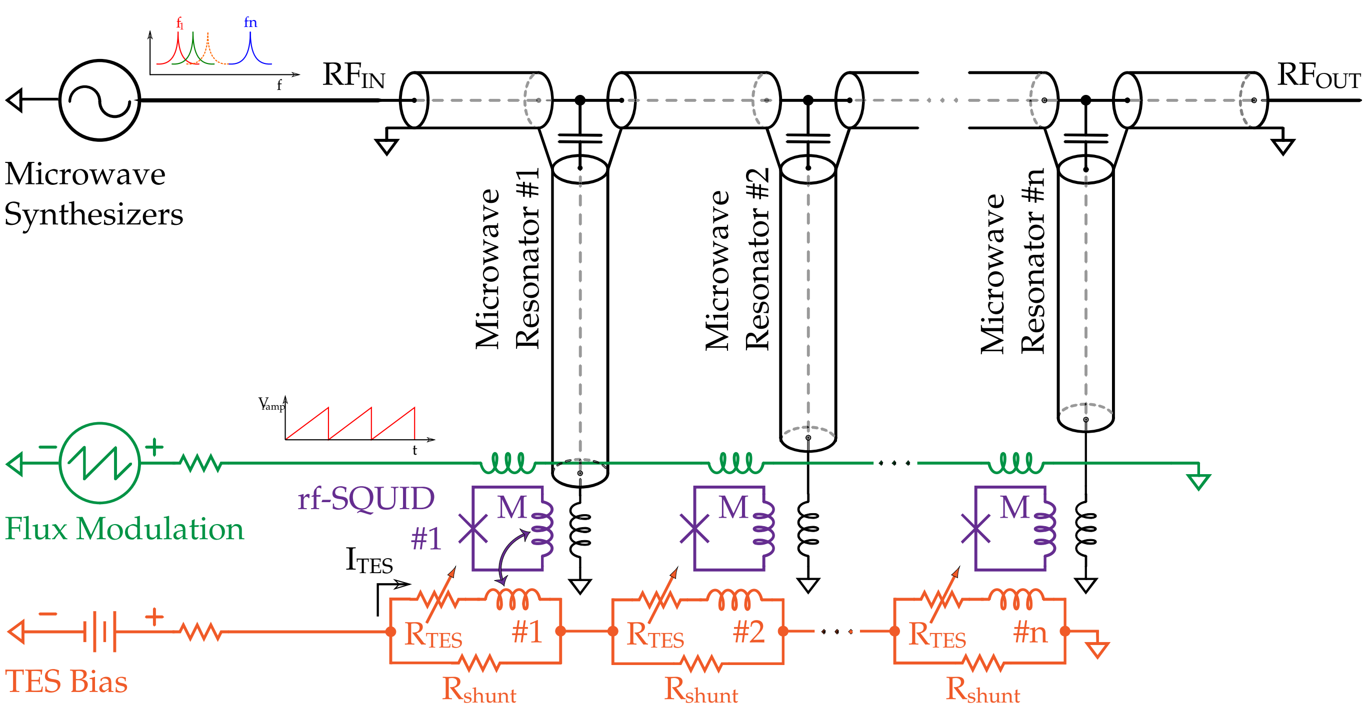
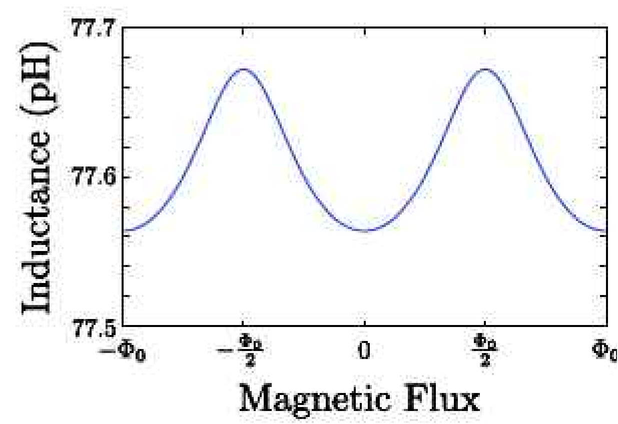
- Energy released in the absorber
- TES temperature increase and resistance decrease
- Current variation in the bias circuit
- Extra magnetic flux in the SQUID



$$E \rightarrow \delta T_{TES} \rightarrow \delta I_{TES} \rightarrow \delta \Phi_{squid}$$

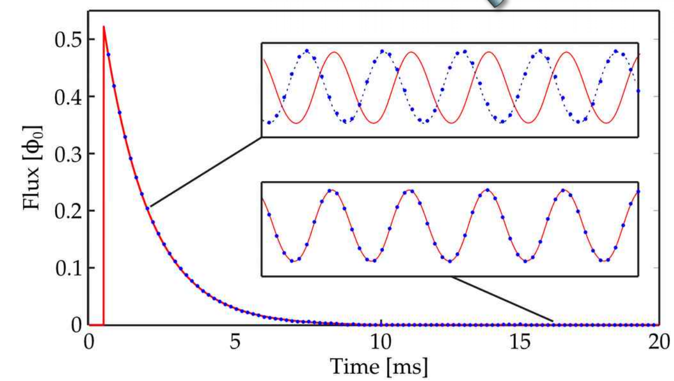




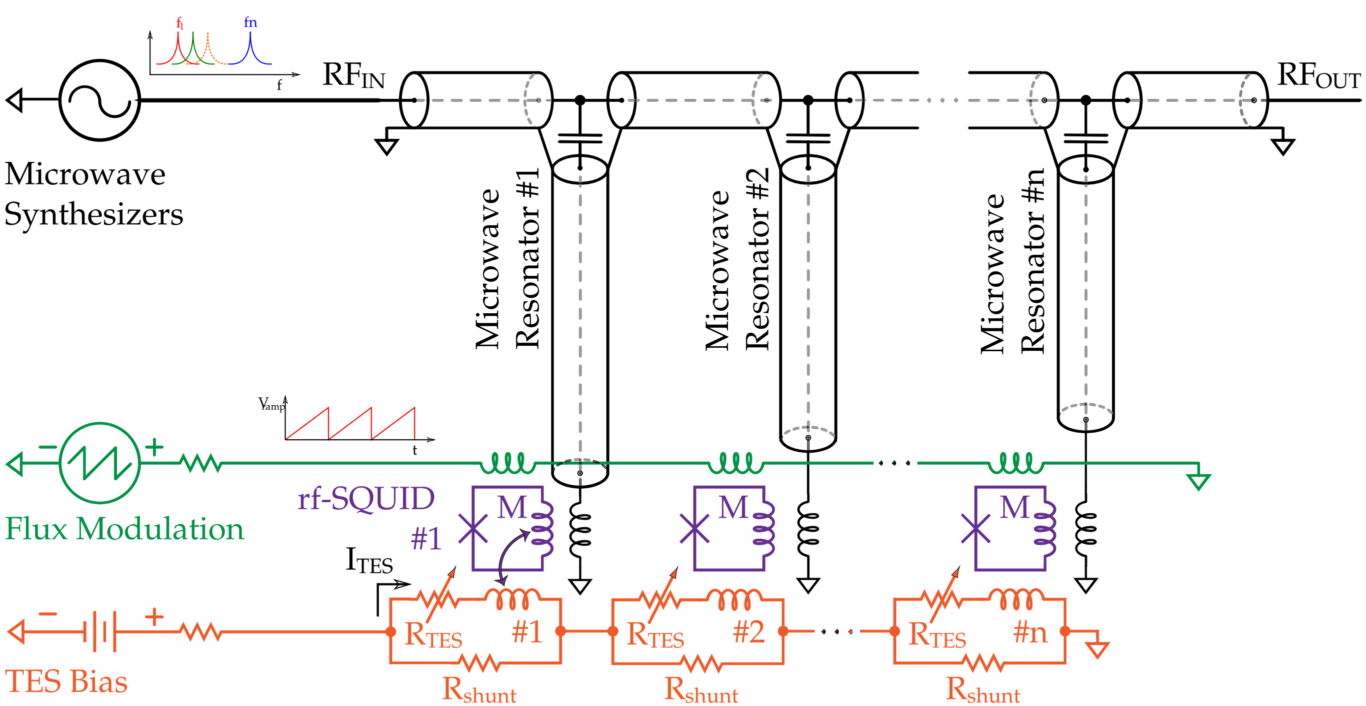
Multiplexed readout

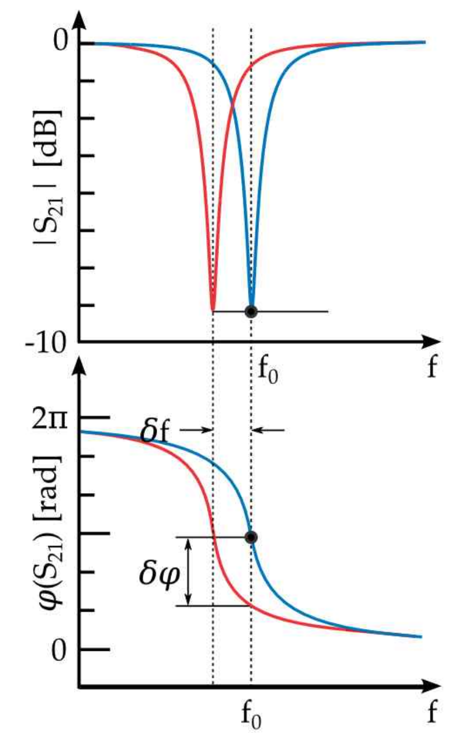
Each TES is coupled to a RF-Squid coupled again to a quarter wavelength resonator.
Each resonator is tuned at a different frequency in the 4-8 GHz range

- Energy released in the absorber
- TES temperature increase and resistance decrease
- Current variation in the bias circuit
- Extra magnetic flux in the linearised SQUID
- RF resonator phase shift

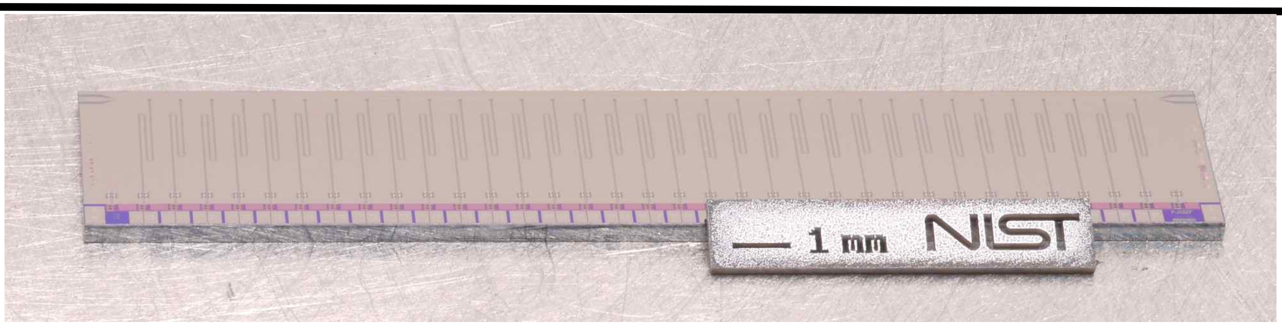


$$E \rightarrow \delta T_{TES} \rightarrow \delta I_{TES} \rightarrow \delta \Phi_{squid} \rightarrow \delta f_{risonatore}$$



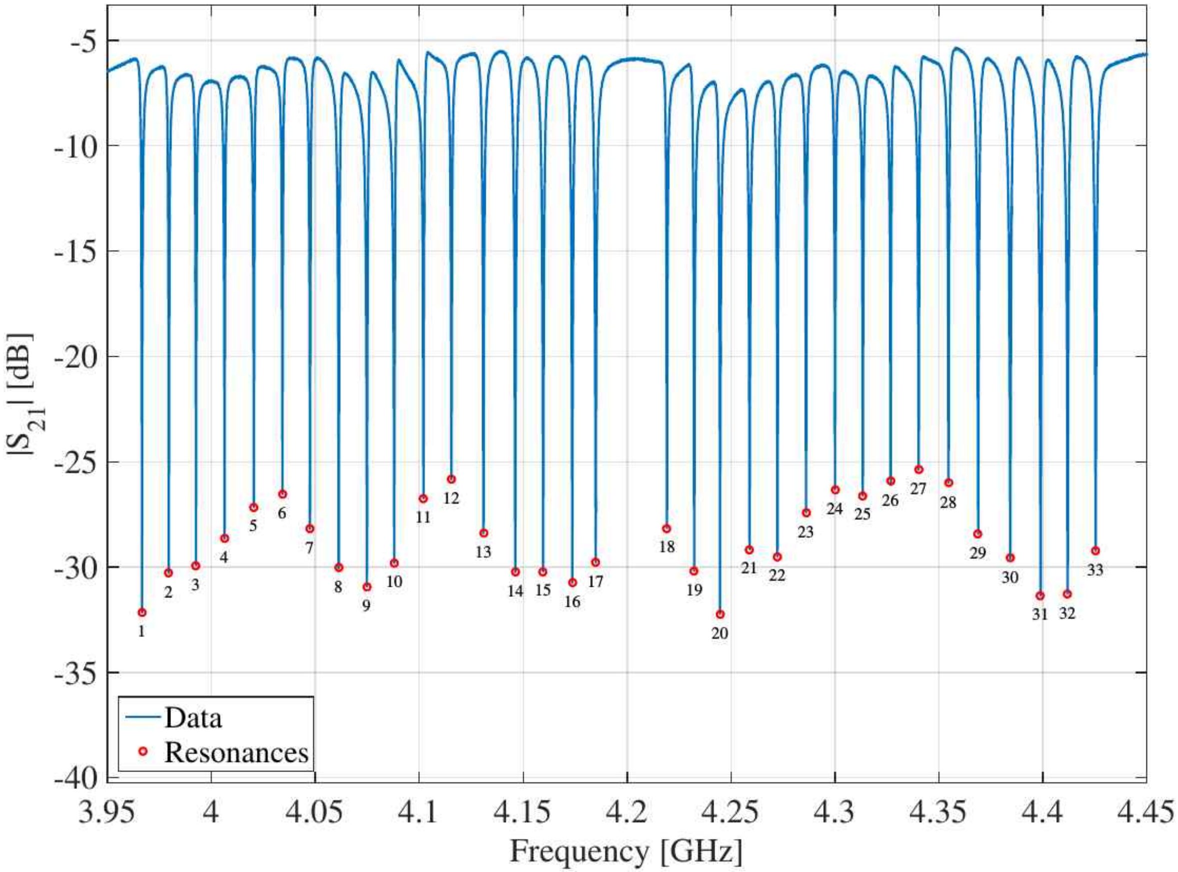


Multiplexing



33 resonances on each chip (500 MHz wide)
- resonances: 2 MHz bandwidth
- 14 MHz separation

- SQUID noise <= 2 $\mu\Phi_0/\sqrt{Hz}$

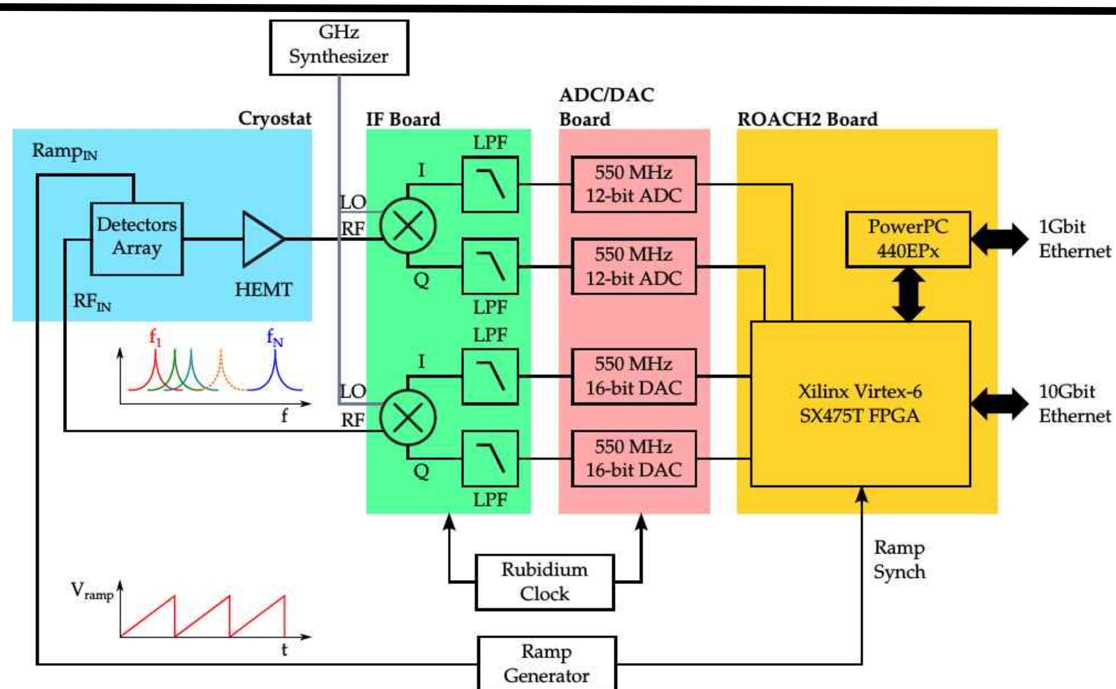


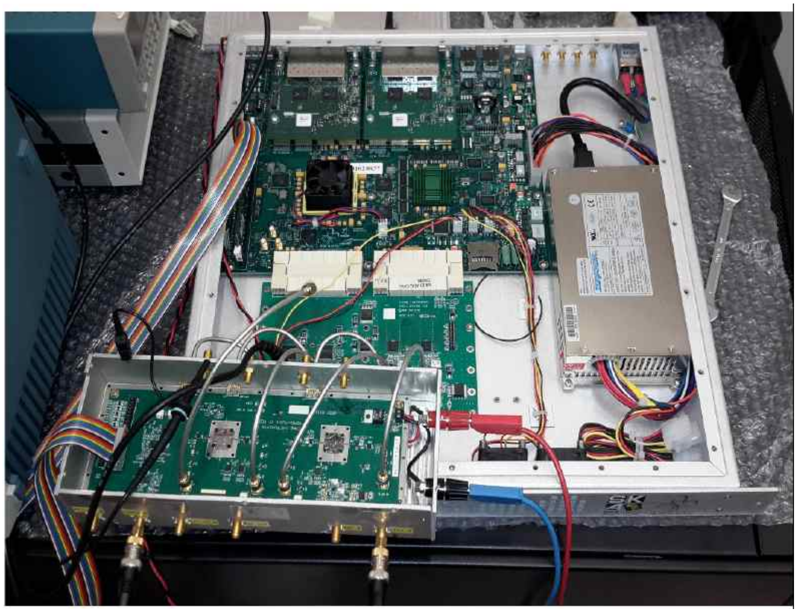
ROACH-2 readout

ROACH2

- *FPGA (Virtex6 Xilinx)* for data processing
- 550 MHz ADC

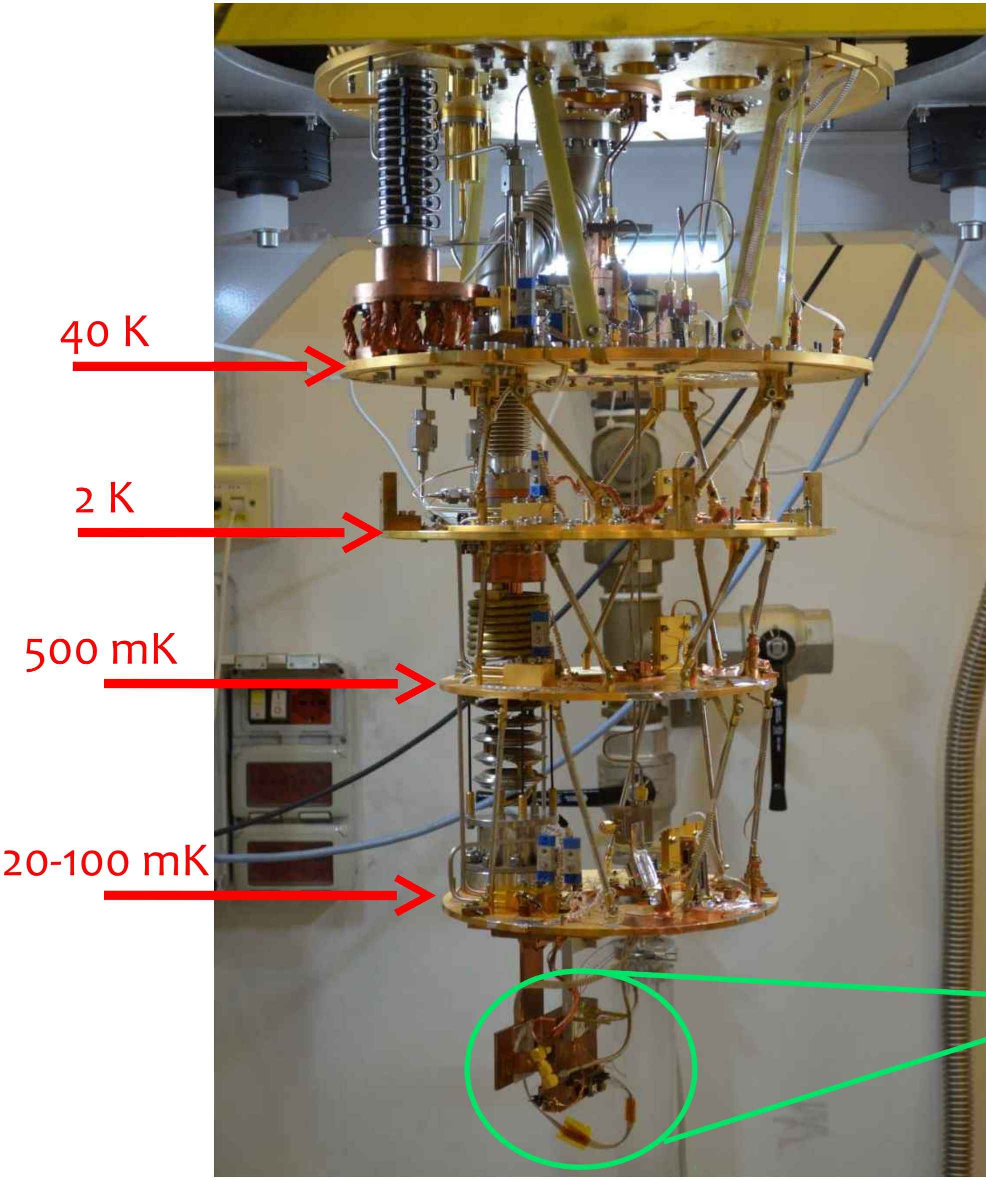
- ROACH2 (real time)
  - Pulse reconstruction
  - Trigger
- Server (almost real time)
  - Optimum Filter and Pile-up rejection

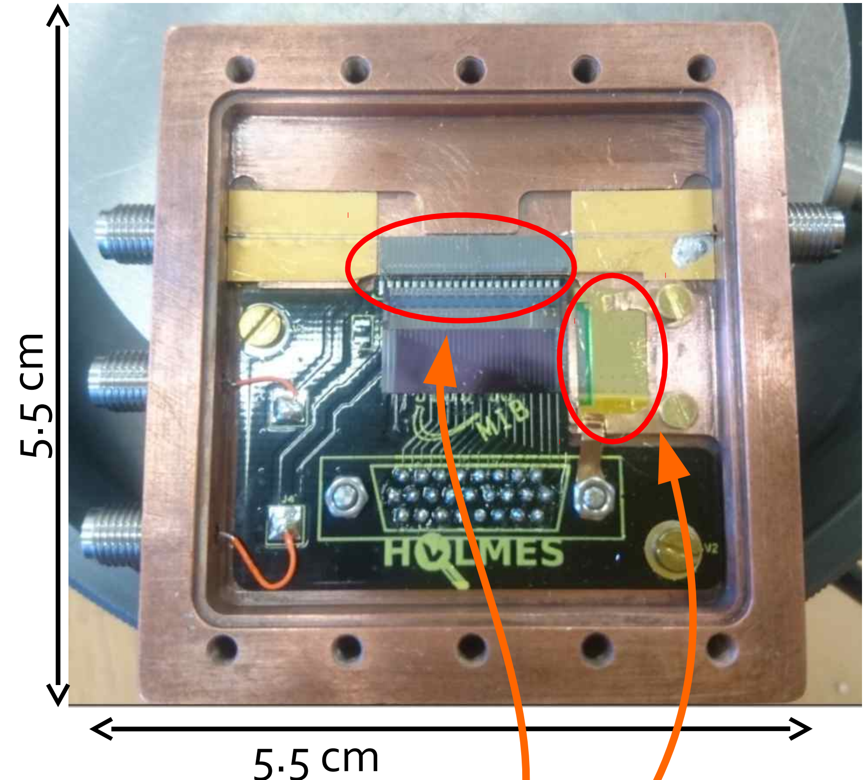




HOLMES
final specifications
- 32 Channels / ROACH-2 board
- 500 kHz sampling
- 20 μs RT pulses

HOLMES setup



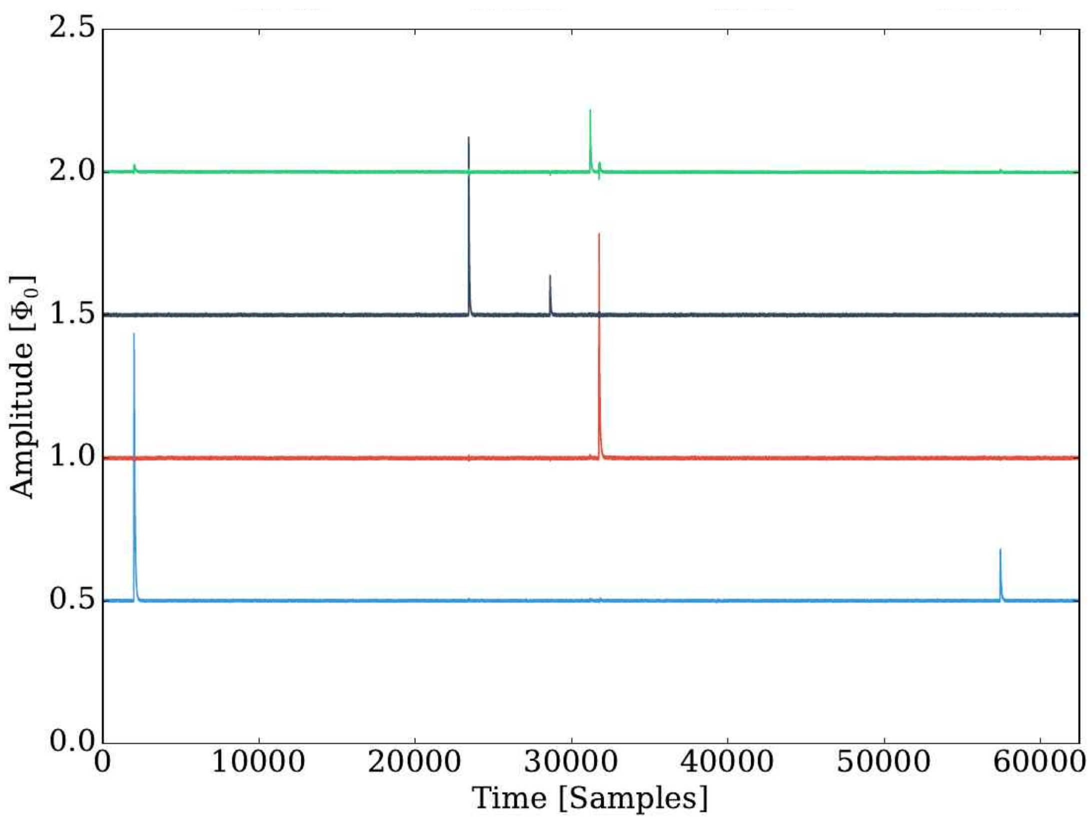


- μMux chip
- TES chip
- Fe, Ca, Cl, Al source

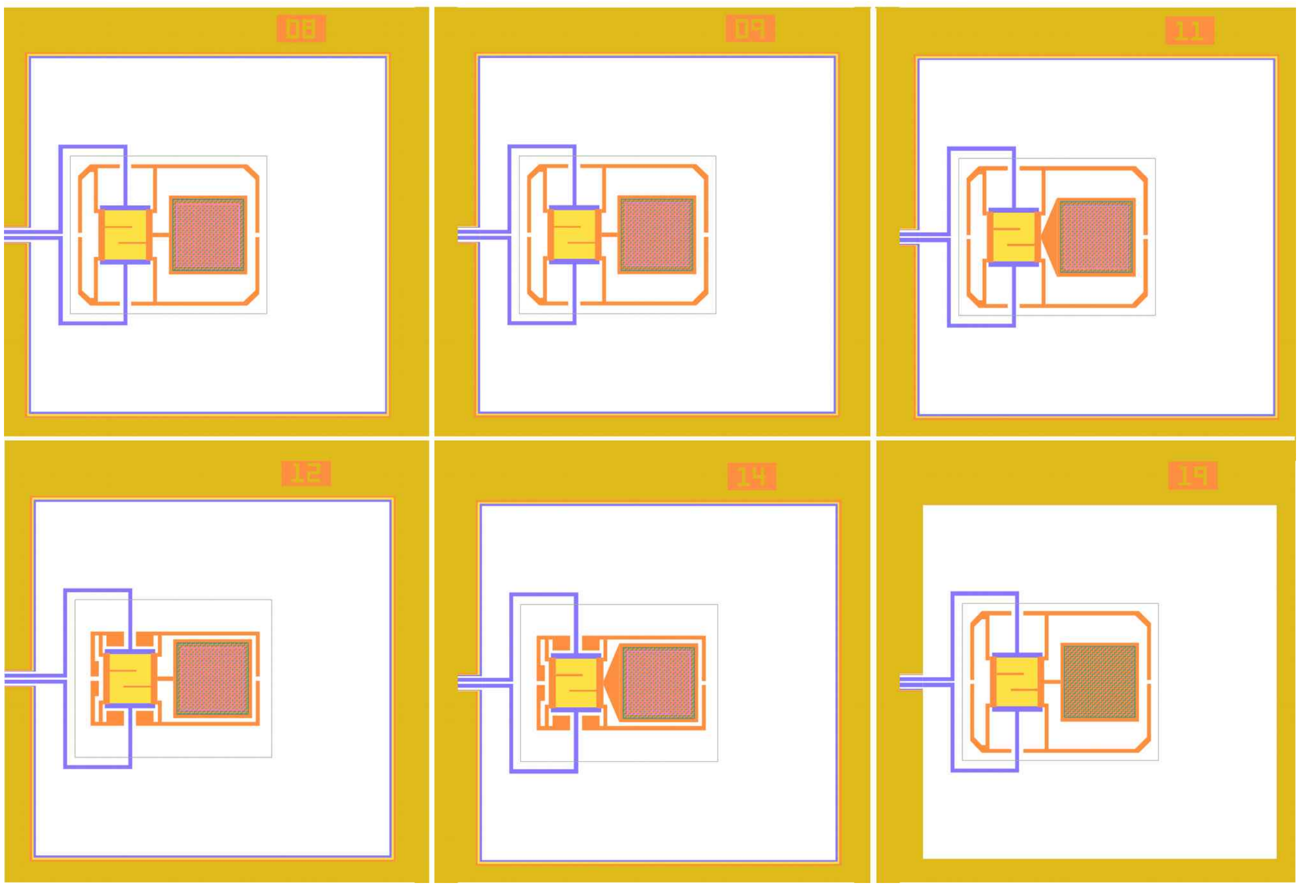
First Roach-2 run

First Roach-2 readout

- 16 Channel multiplexing
- 32 Channel under development
- Successfully generated and demodulated 16 tones used to read 16 rf-SQUIDs
- Sampling rate up to 500 kHz

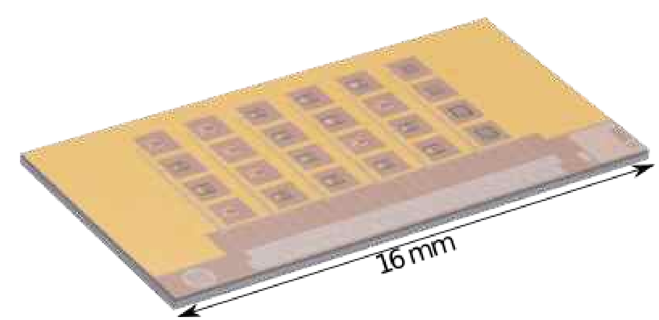


Prototype detectors

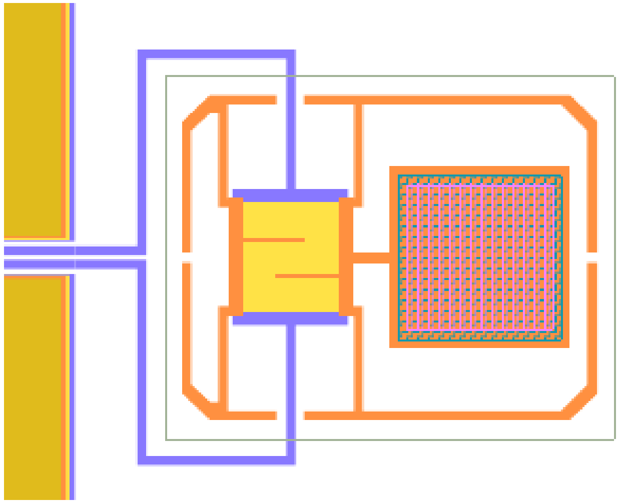


- Detectors produced and tested at NIST, Boulder, Co.
- NIST acquisition with Time Domain Multiplexing
- Tested in Milano-Bicocca with microwave Multiplexing
- First uMux tests with HOLMES-like TES

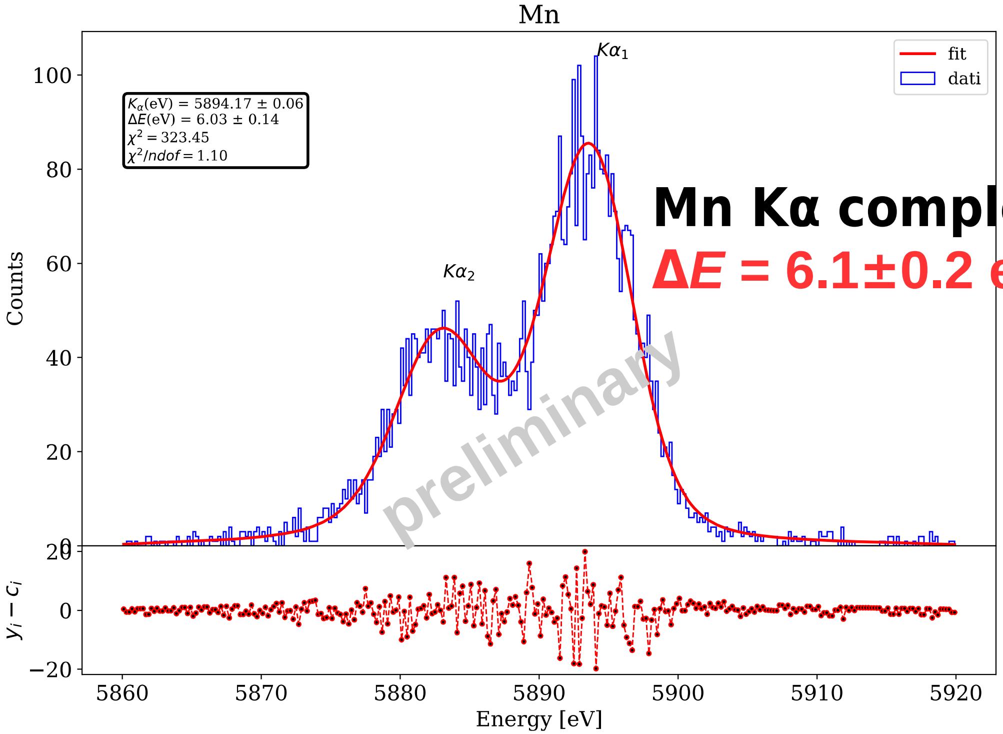
- Different absorber-TES link geometry
- Different Thermal conductance



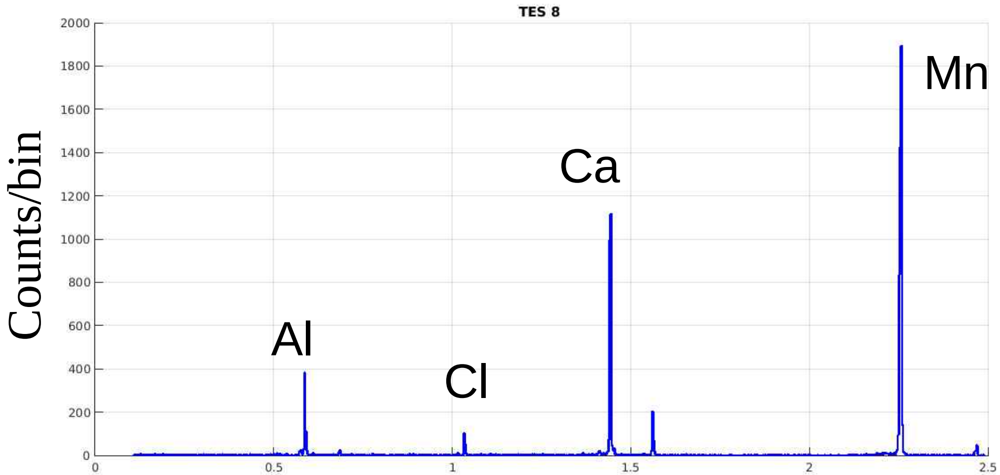
HOLMES detectors



200✕200 μm² absorber
C = 0.9 pJ/K
G = 570 pW/K



Mn Kα complex
ΔE = 6.1±0.2 eV



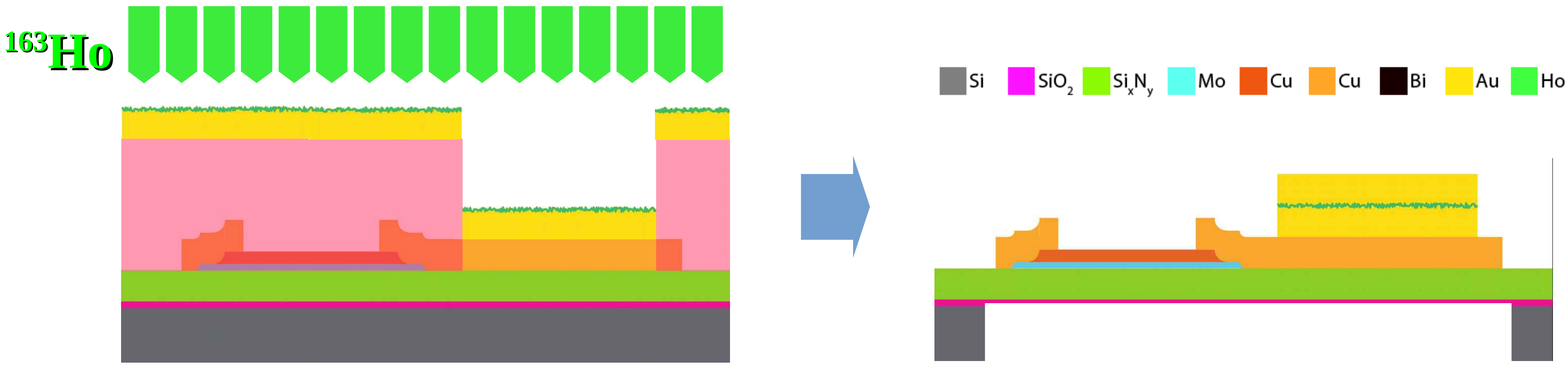
f_{samp} = 500 kS/s

ΔE_0 = 4.0 eV

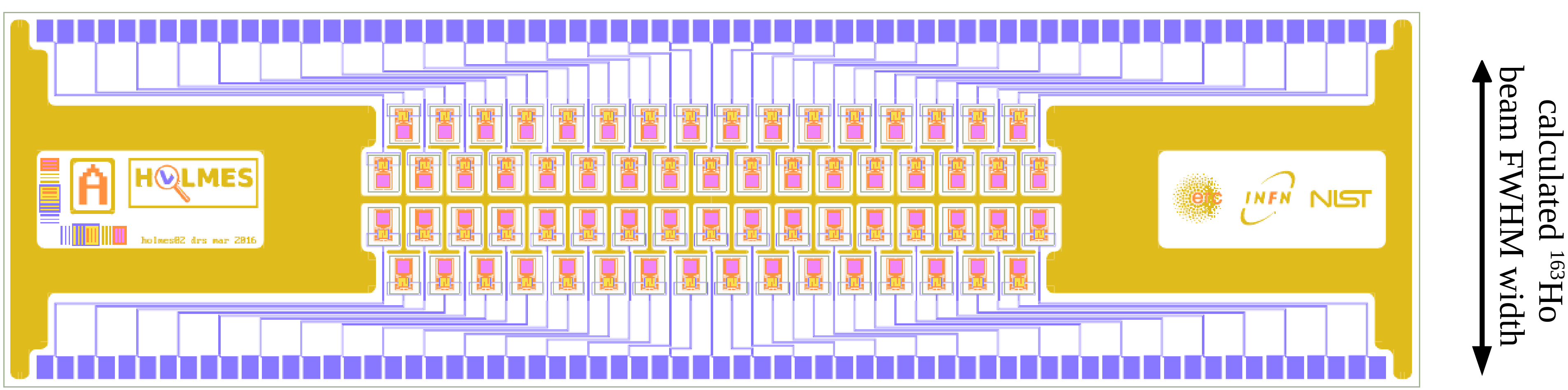
τ_{rise} = 12 μs

τ_{decay} = 80 μs

Detector production



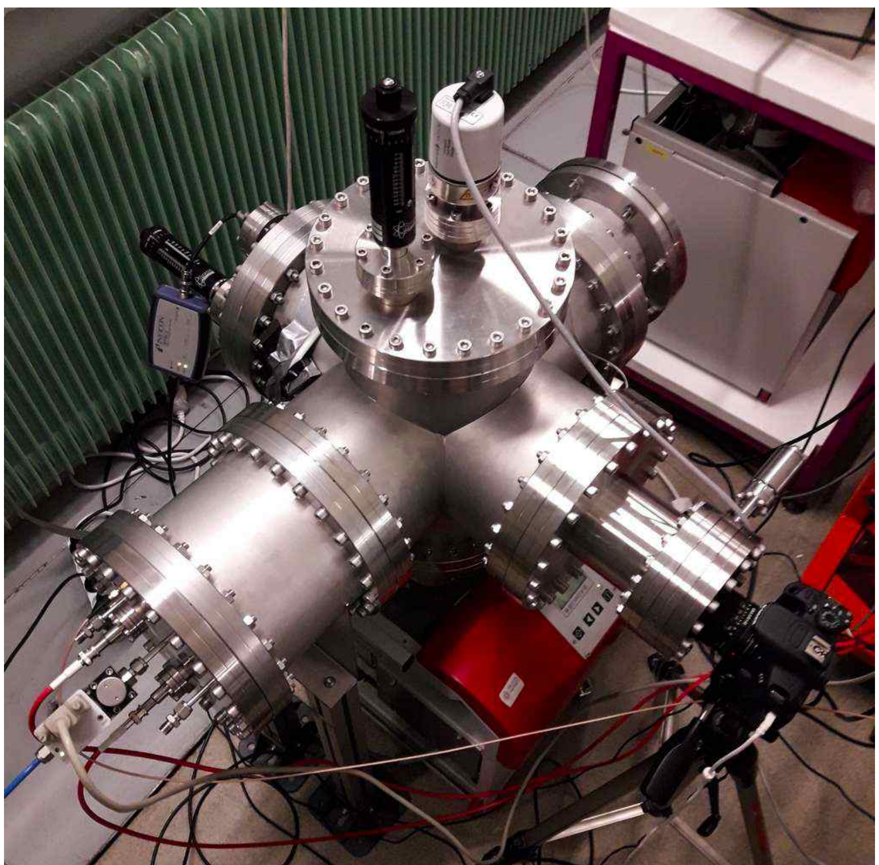
- TES array fabricated at NIST, Boulder, CO, USA
- ^{163}Ho implantation at INFN, Genova, Italy
- 1 μm Au final layer deposited at INFN Genova
- final fabrication process definition in progress
- HOLMES 4×16 linear sub-array for low parasitic *L* and high implant efficiency

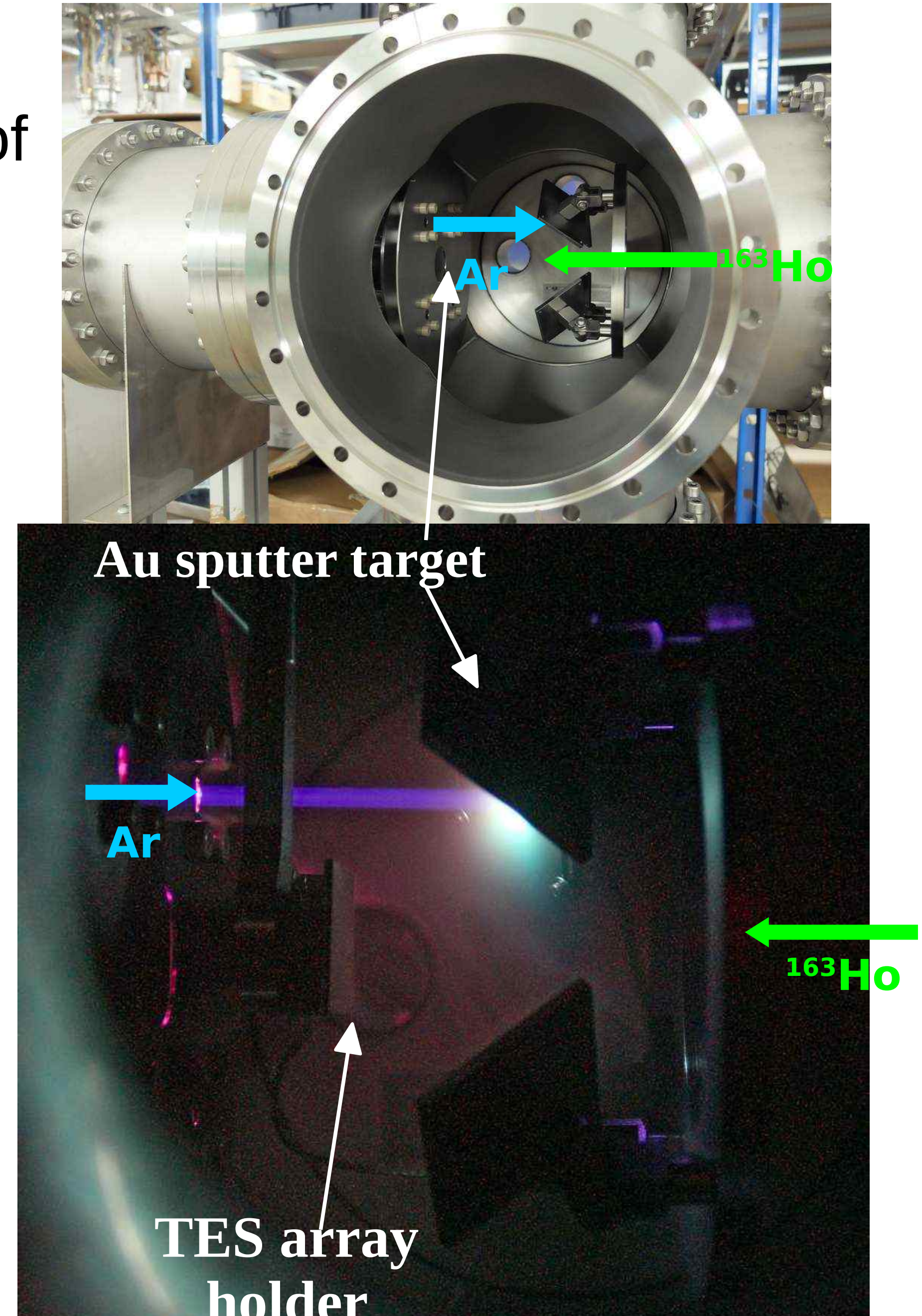


Target chamber almost ready

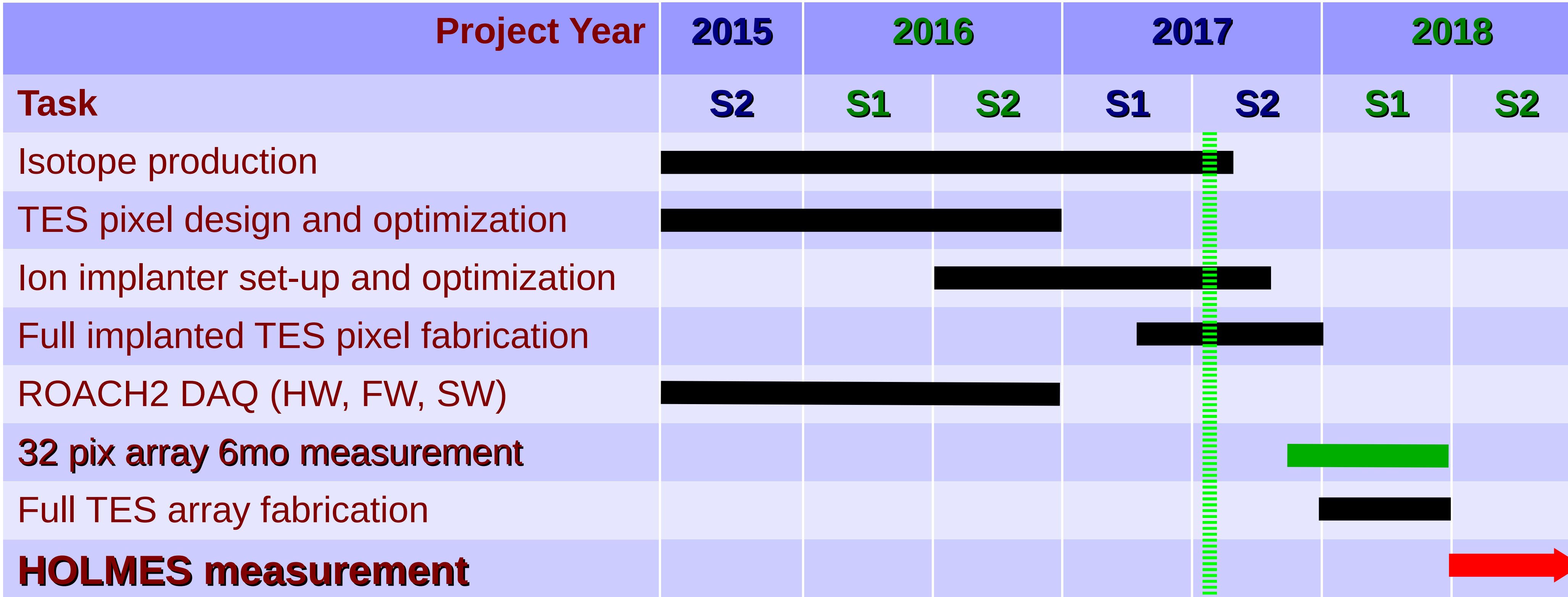
-System being mounted at Milano

-First Au sputtering tests by the end of 2017





Next steps



- 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_ν **sensitivity ≈10 eV**

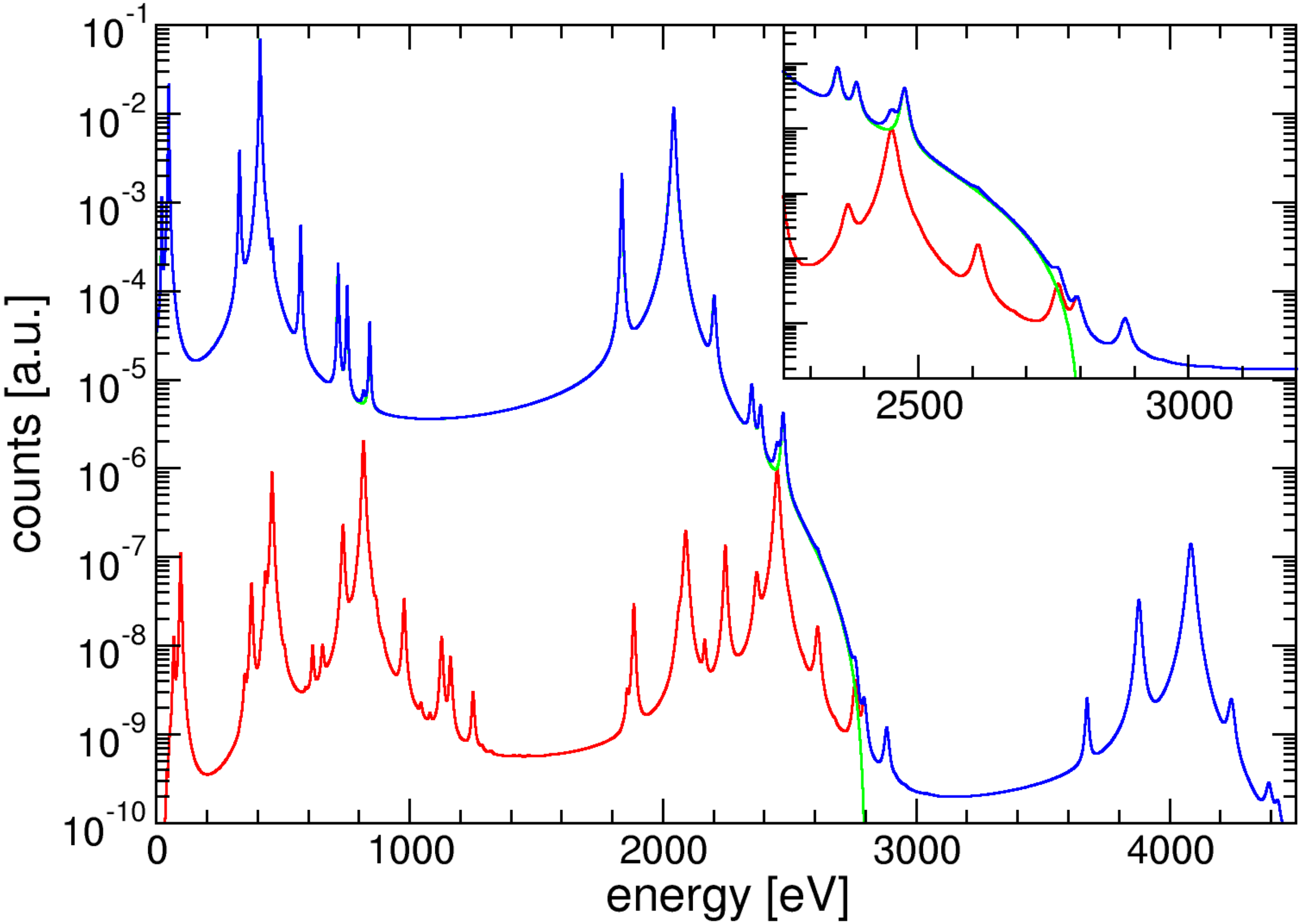
Thank you for your patience and attention

Back-up

Pile-up/2

- shake-up/shake-off → double hole excitations
- even more complex pile-up spectrum
- it may be worth keeping f_{pp} smaller than 10^{-4}

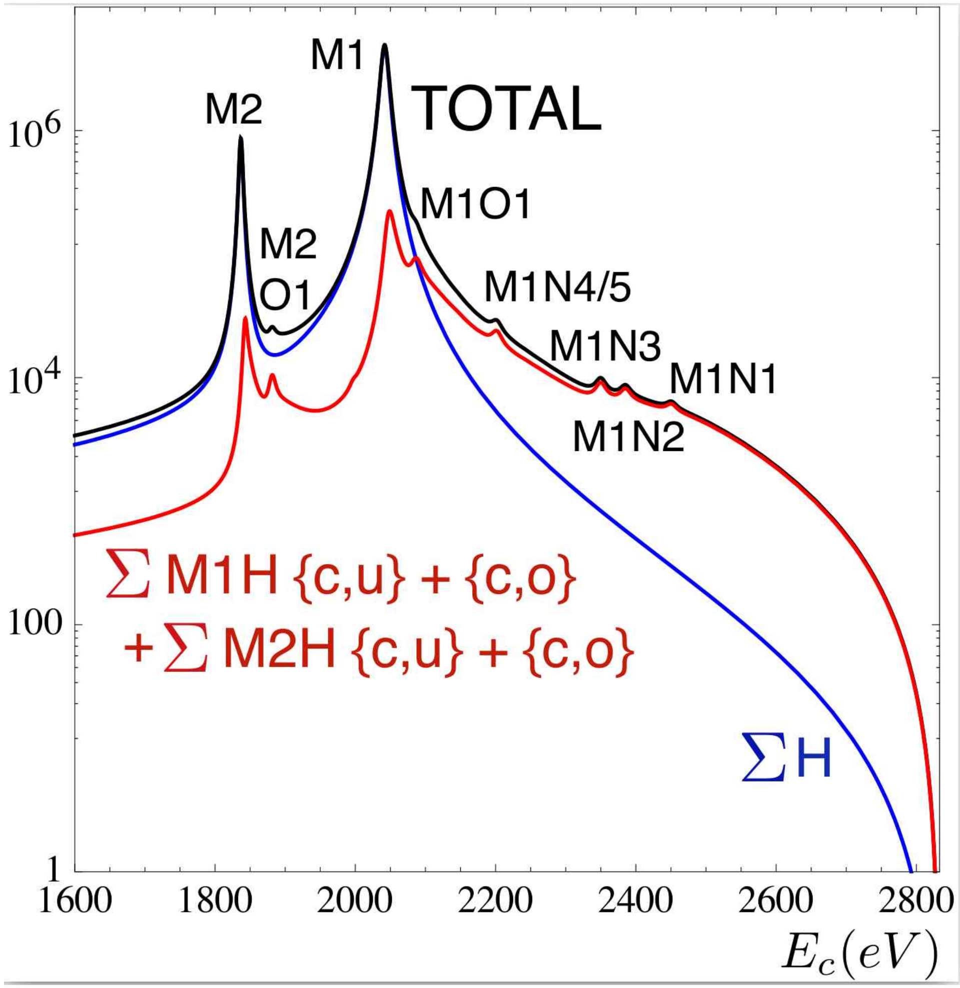
Calculations made by:
A.De Rujula, arXiv:1305.4857
R.G.H.Robertson, arXiv:1411.2906
A.Faessler et al., PRC 91 (2015) 45505
do not fully agree



Q = 2800 eV

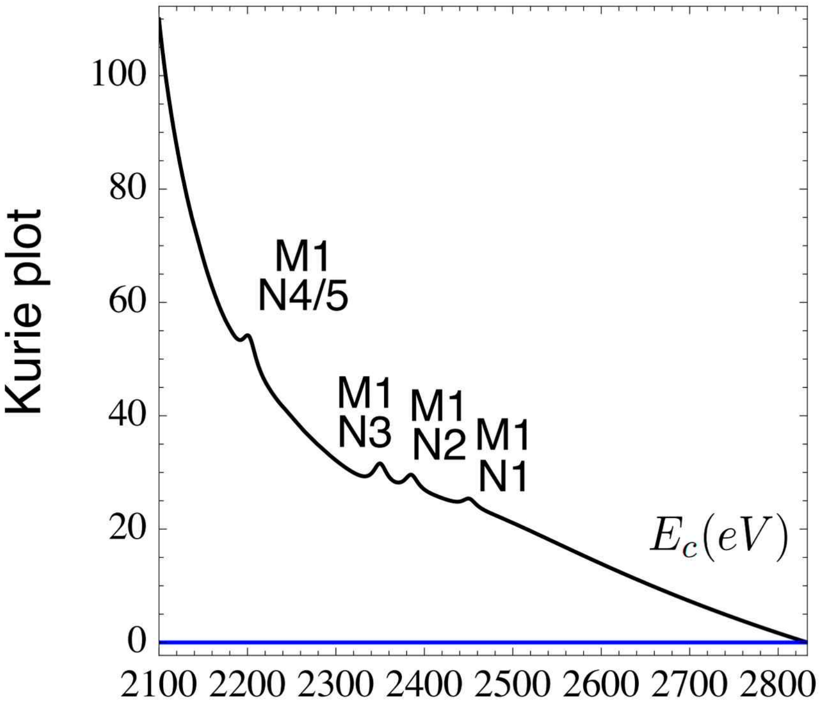
$f_{pp} = 10^{-4}$

II-order processes/2

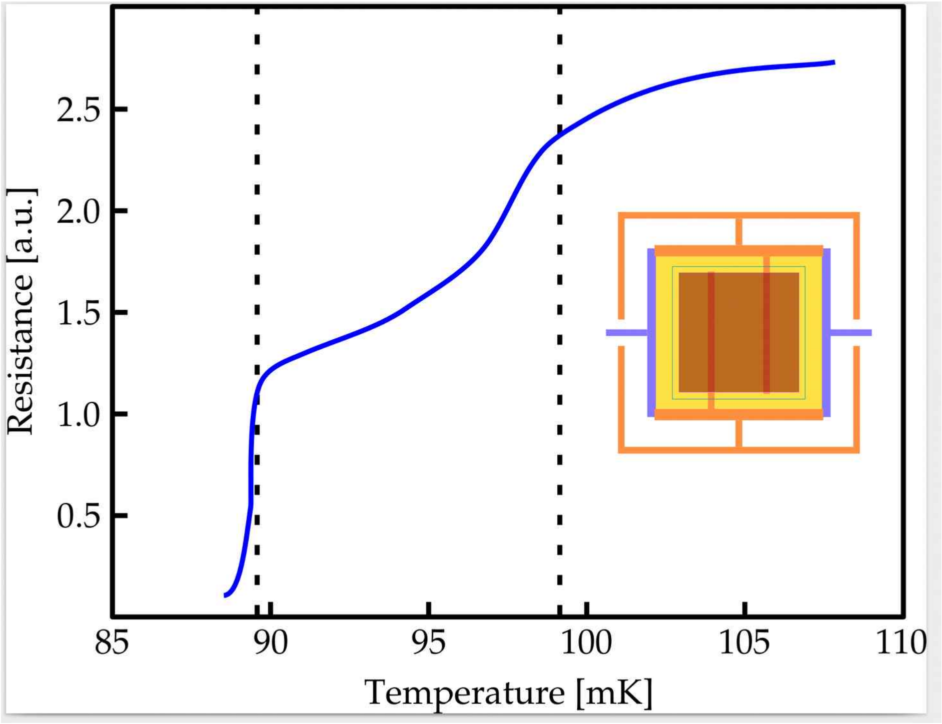


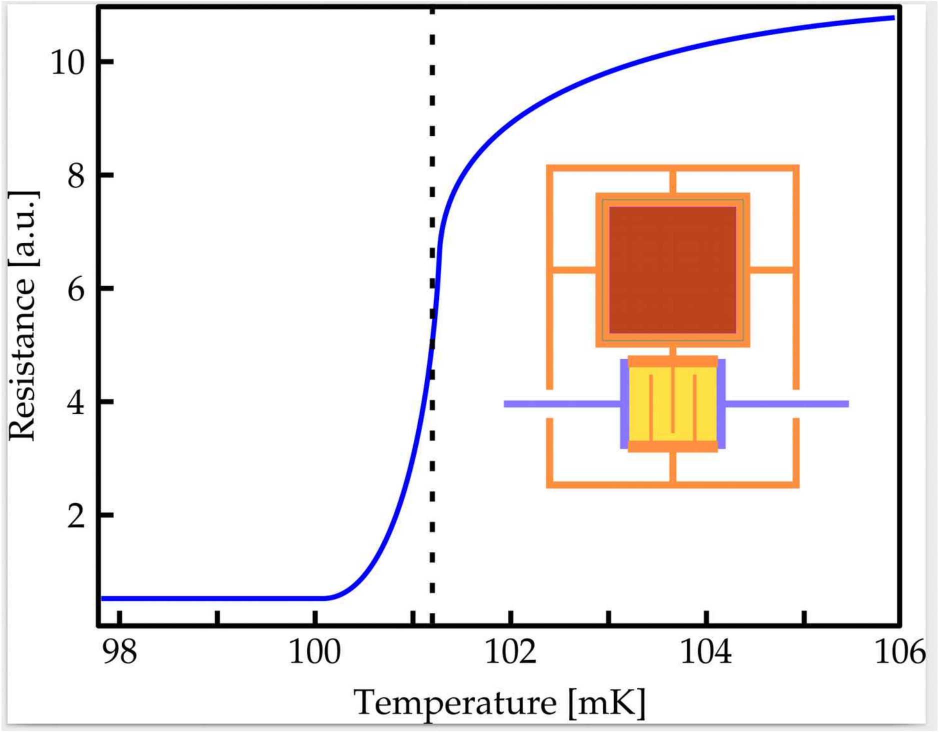
Shake up and shake off are second order process that can significantly enhance the rate at the end point

During the first measurement HOLMES will assess important parameters for studying these second order processes



Sidecar design





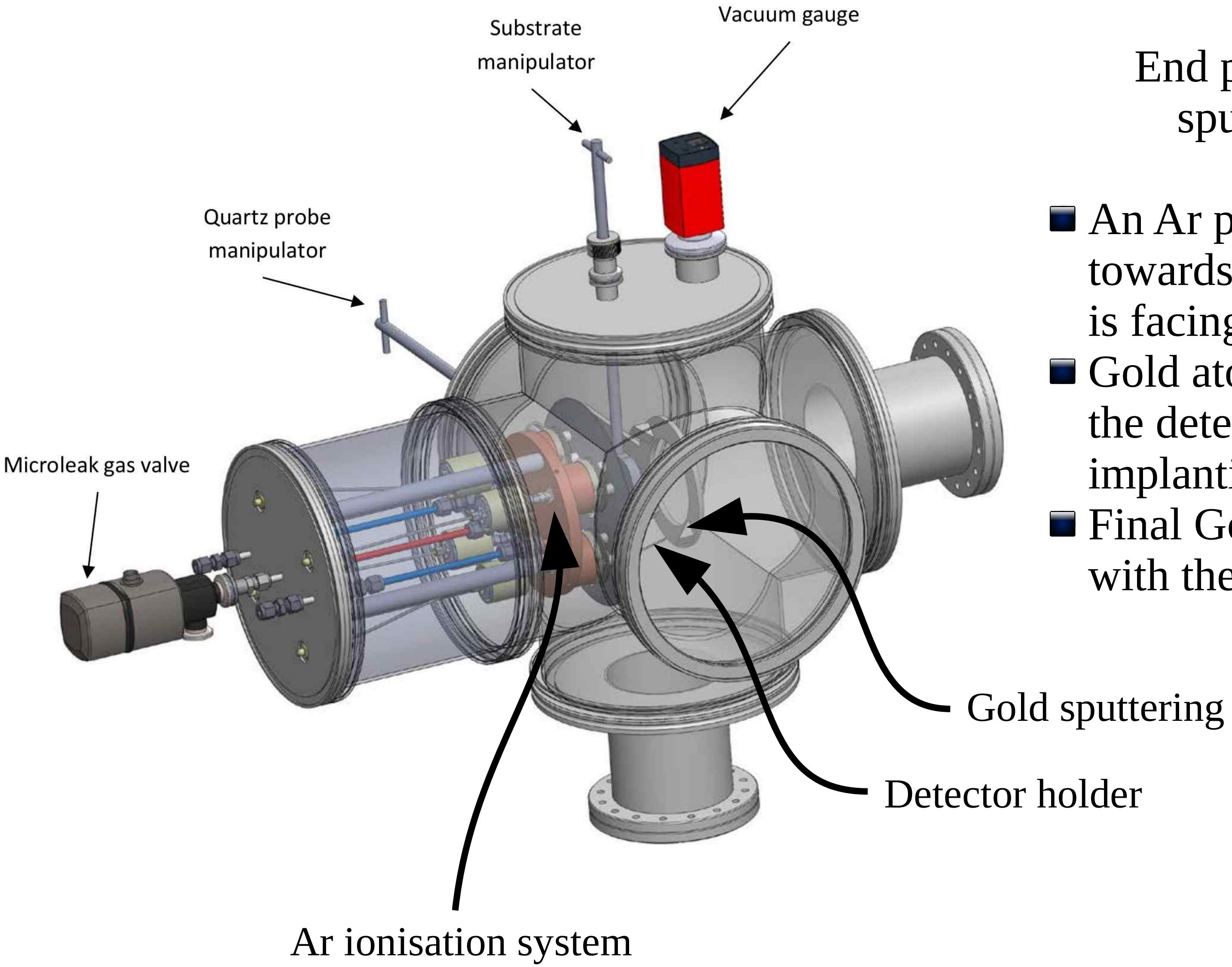
First HOLMES design

- Absorber on top of the TES
- Proximity effect of Au and TES
- Degradation of the transition shape

Second HOLMES design

- Absorber placed aside of the TES on the same membrane
- Strong thermal conductance between TES and absorber provided by copper link
- Single transition shape

Implanter end station



End point station with sputtering system

- An Ar plasma is accelerated towards a gold target which is facing the detectors
- Gold atoms are sputtered on the detectors while implanting
- Final Gold layer is deposed with the same system