Superconducting detectors for neutrino mass measurement

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on behalf of the HOLMES collaboration

EUCAS 2015

12th EUropean Conference on Applied Superconductivity

6th - 10th September 2015 Lyon - France

ESAS The European Society for Applied Superconductivity

Direct calorimetric neutrino mass measurement

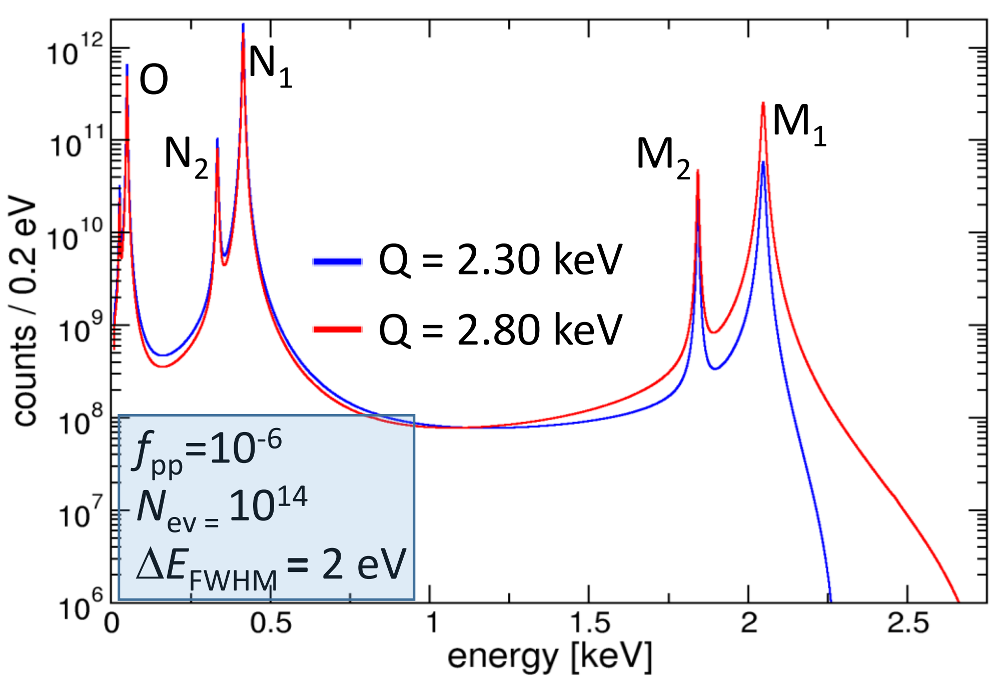
$$^{163}\mathrm{Ho} + e^- \longrightarrow {}^{163}\mathrm{Dy}^* + \nu_e$$

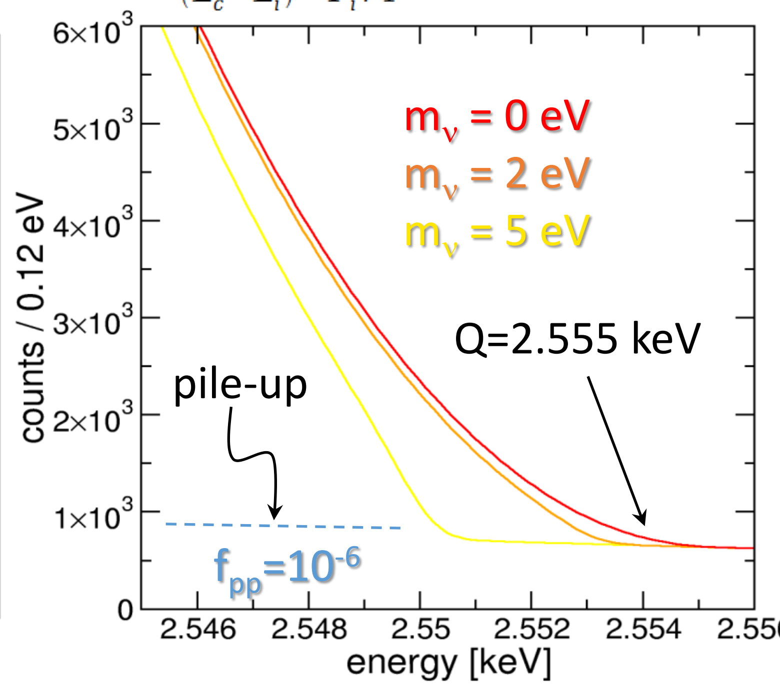
^{163}Ho decay via EC from shell ≥ M1, with $Q_{EC} \sim 2.8$keV

Proposed by *A. De Rujula and M. Lusignoli, Phys. Lett. B 118 (1982) 429*

- calorimetric measurement of the Dy atomic de-excitation (mostly non-radiative)
- rate at the end point depends on the Q value ($Q_{EC} \sim 2.8$ keV) and proximity to M1 resonance line enhances the statistics at the end point (i.e. sensitivity on m_ν)
- $\tau_{1/2} \sim 4570$ years: few nuclei are needed

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





The HOLMES collaboration

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	INFN LNGS		
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HOLMES (ERC-Advanced Grant n. 340321)

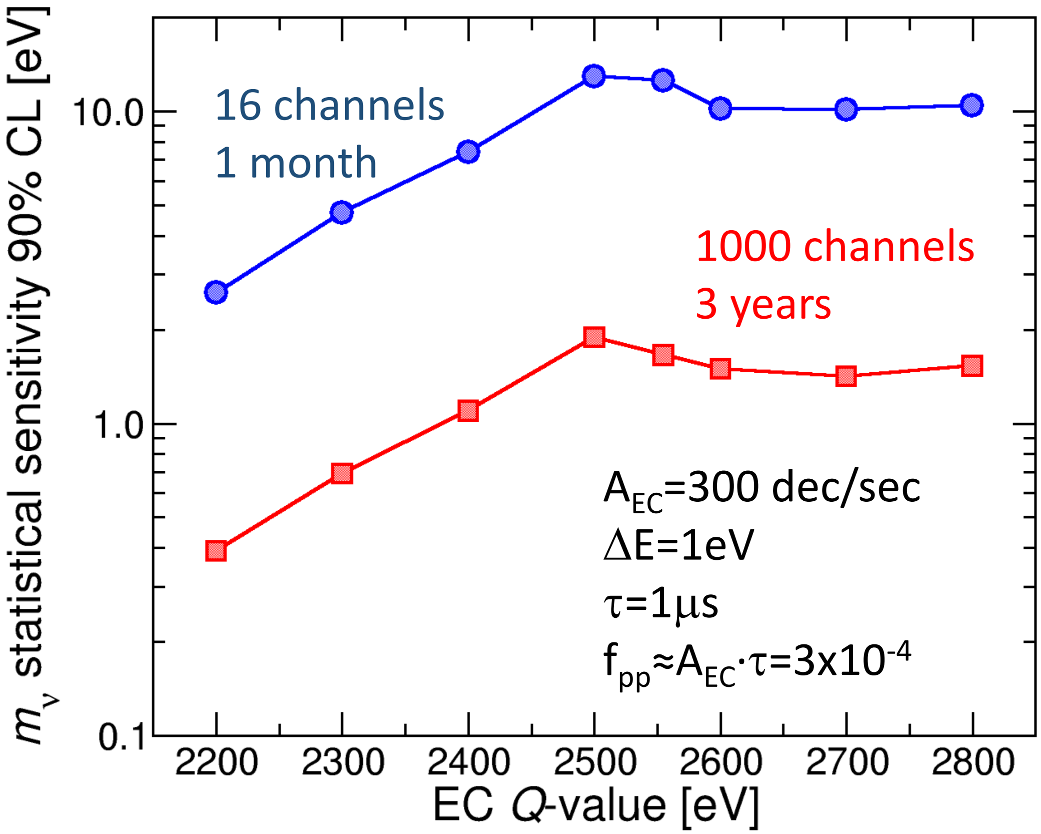
- Neutrino mass determination with a sensitivity as low as ~ 0.4 eV (baseline)
- calorimetric EC measurement
- assess of systematics

- Detectors: Mo/Cu bilayer Transition Edge Sensors (TES) with ^{163}Ho implanted absorbers
  - 6.5×10^{13} nuclei/pixel = 300 dec/sec
  - $\Delta E \approx 1$ eV, $\tau_R \approx 1\ \mu s$
- two steps:
  - 16 channels mid-term prototype, t_M=1 month
  - full scale: 1000 channels, t_M=3 years

6.5×10^{16} ^{163}Ho nuclei (≈**18μg**)

3×10^{13} events

B. Alpert et al., Eur. Phys. J. C, (2015) 75:112

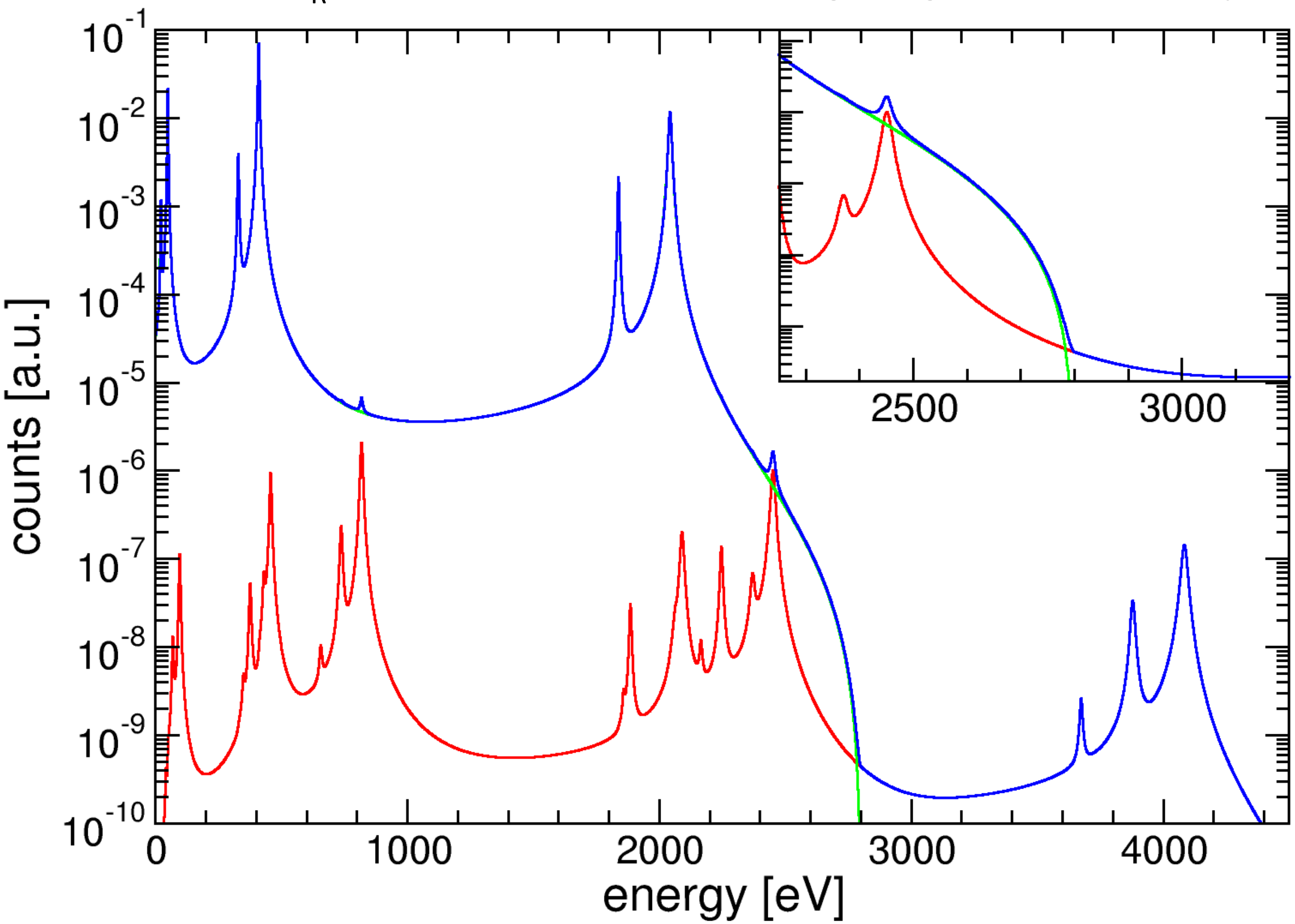


Ho calorimetric end-point measurement

complex pile up spectrum:

$N_{pp}=f_{pp}N_{EC}(E)\otimes N_{EC}(E)$, where $f_{pp}\approx A_{EC}\tau_R$

time resolution $\tau_R \leq$ rise time (Wiener filtering/Single value decomposition)



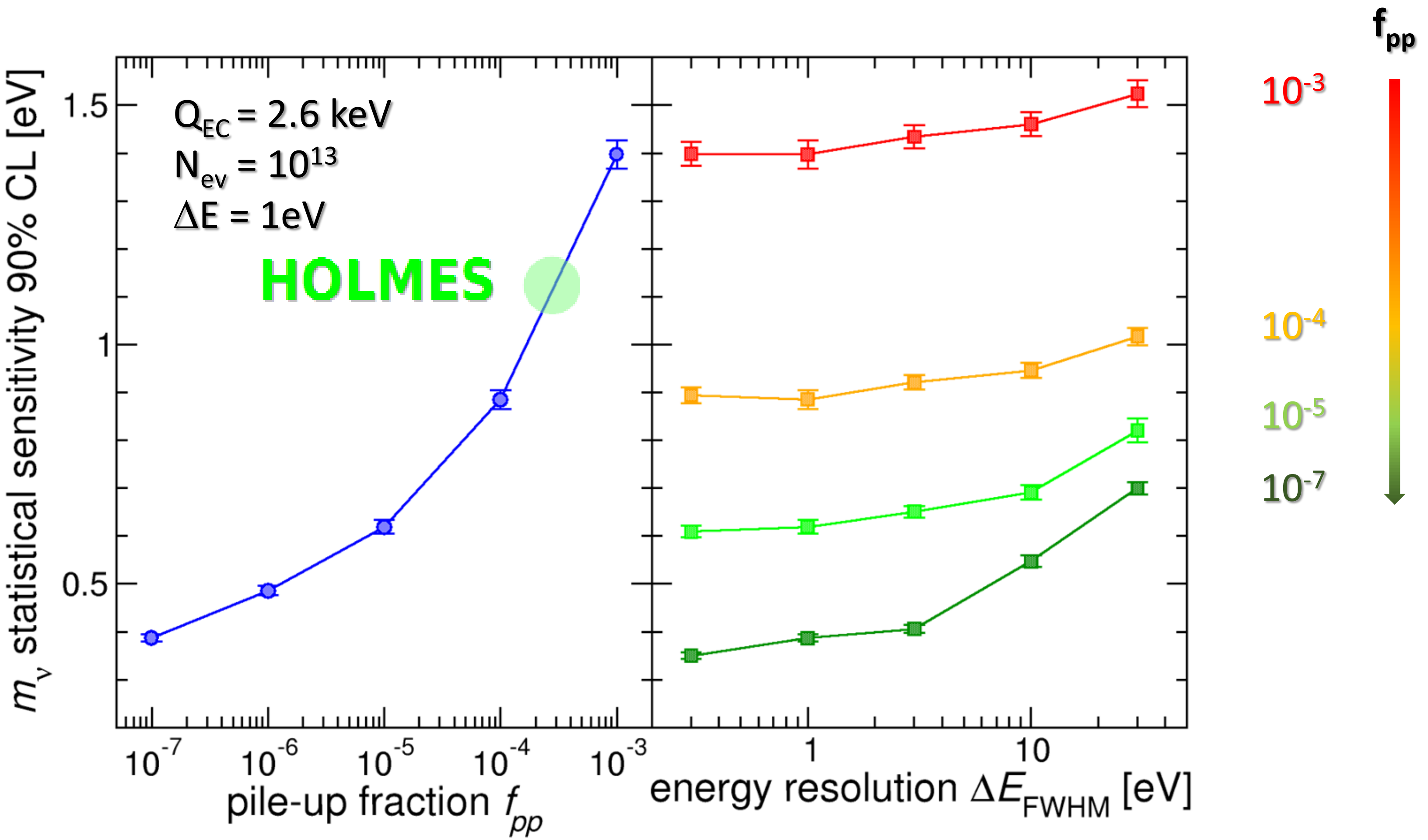
Q=2800 eV
$f_{pp}=10^{-4}$

Statistical sensitivity from MC simulations

Dependencies of the statistical sensitivity

1. very strong on statistics
2. strong on pile up
3. weak on energy resolution

- high mux factor
- fast detectors

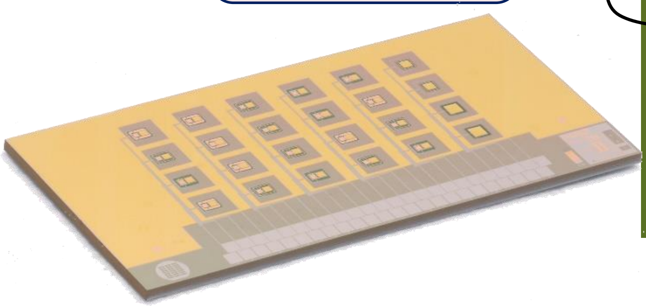


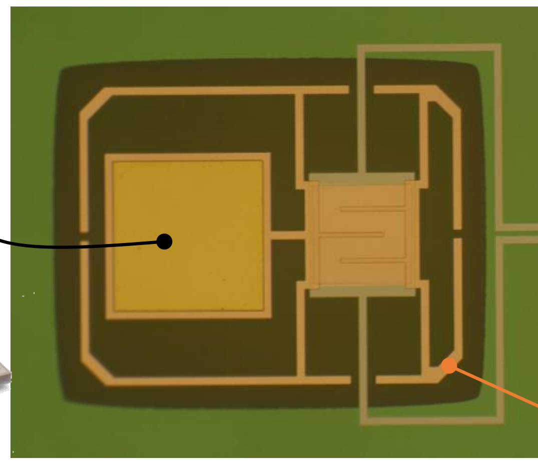
F. Gatti et al., arXiv:1202.4763

TESs for HOLMES (NIST @ Boulder, CO + Genova)

- **design compatible with ion implanting**
  - absorber made of gold and bismuth thermally coupled to the sensor
- **fast detectors**
  - rise time determined by electrical cut-off (L/R) ⟶ small L
  - decay time set by C/G. Constrains on C (the absorber must contain all the energy: 2 μm of gold stop 99.99998% of the electrons) ⟶ large G

Ho-implanted absorber (Au)





"side car" design, to avoid proximization between the gold and the TES

sensor + absorber suspended on a Si_2N_3 membrane

Cu structures to expand the perimeter (i.e. the G)

test @ NIST (in progress) demonstrated

$\Delta E_{FWHM} \approx 2.9$ eV @ 1.5 keV, $\tau_{rise} \approx 6$ μs (L=35nH), $\tau_{decay} \approx 130$μs

- **large number of detectors multiplexed**
  - microwave multiplexing

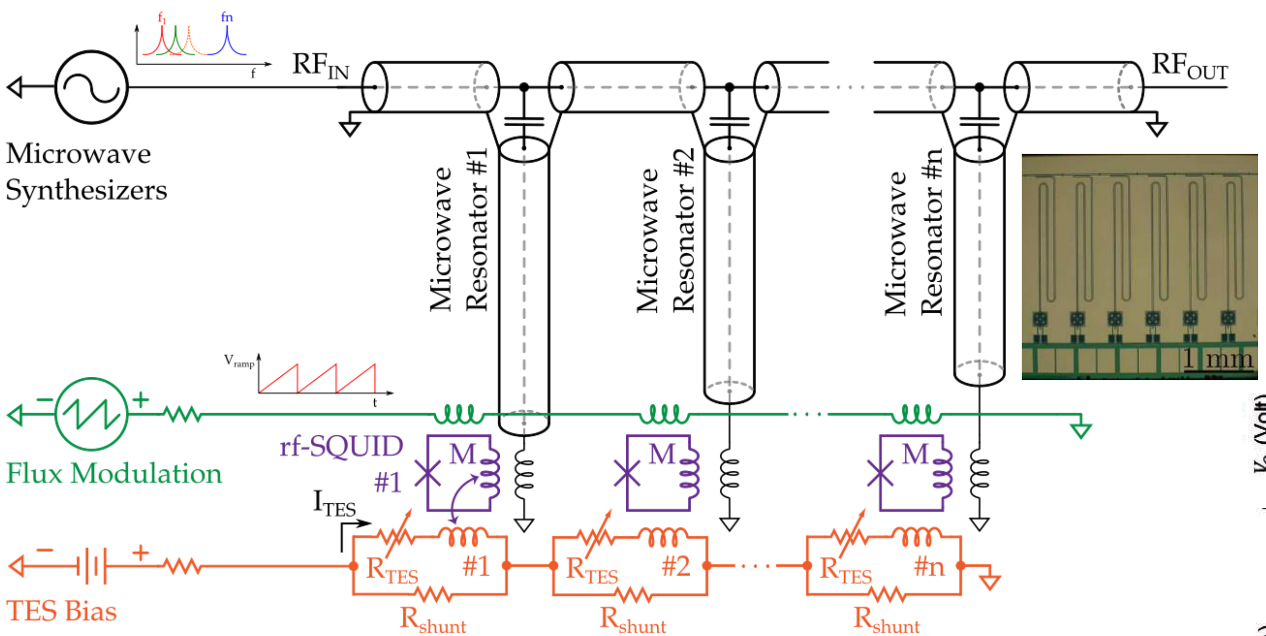
Microwave multiplexing

DC TESs read with microwave multiplexing technique

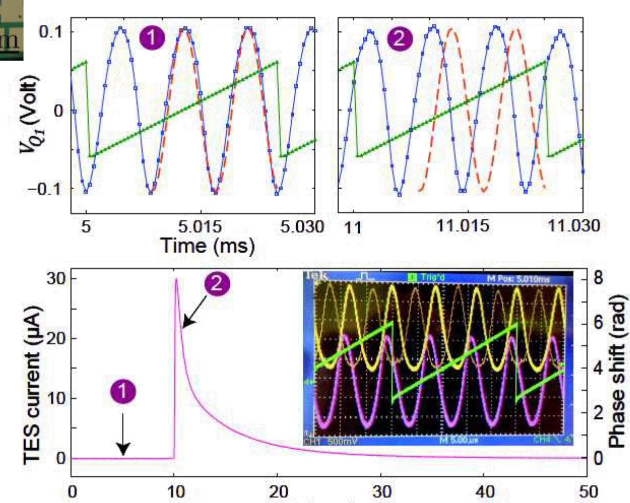
- each sensor inductively coupled to a RF-squid part of a *LC* resonant circuit
- a comb of signals probe the resonators at their characteristic resonant frequency

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

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



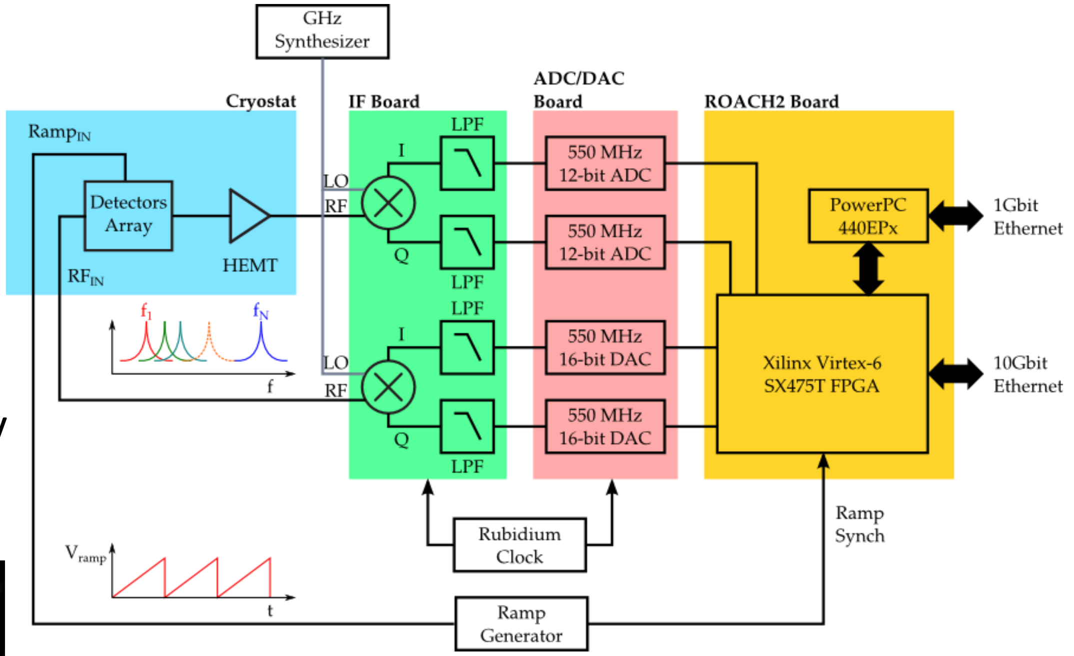
K. D. Irwin and K. W. Lehnert, Appl.Phys.Lett., 85:2107, 2004

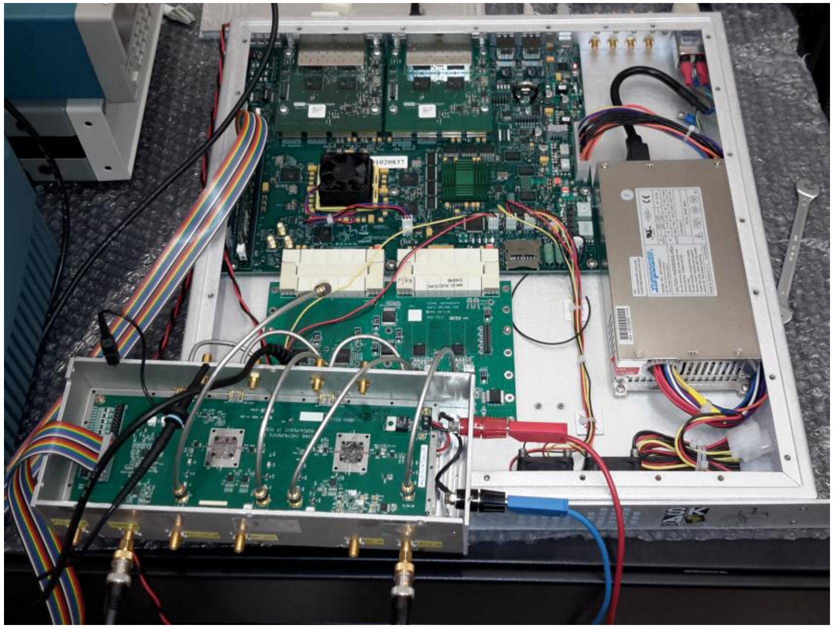


ROACH2 readout

Readout made with the open system ROACH2 (by Casper collaboration)

- data processed by Xilinx FPGA
- available bandwidth 550 MHz
- signals from detectors obtained with homodyne technique
- ~ 150 TB in 3 years
  (with threshold @ 2.022 keV; 20 TB/day without threshold)





- ROACH2 fw (real time)
  - pulse reconstruction
  - threshold cut
- Server (quasi-real time)
  - OF analysis (*n*-tuple)
  - pile-up detection

Bandwidth and mux factor

- effective sample rate f_s set by the frequency of the ramp signal f_r
- constrain on resonator bandwidth $\Delta f_{res} \geq 2 f_s n_{\phi_0}$
- constrain to avoid cross talk $f_n \geq 5 \Delta f_{res}$
- sampling faster than rise time $f_s \geq 5/\tau_r$
- multiplex factor $n_{mux} = f_{adc}/f_n \approx f_{adc}\tau_r/50 n_{\phi_0}$

n_{ϕ_0}=number of flux quanta/ramp

f_n=spacing between tones

τ_r=rise time of the pulses

f_{adc}=550MHz (ROACH2)

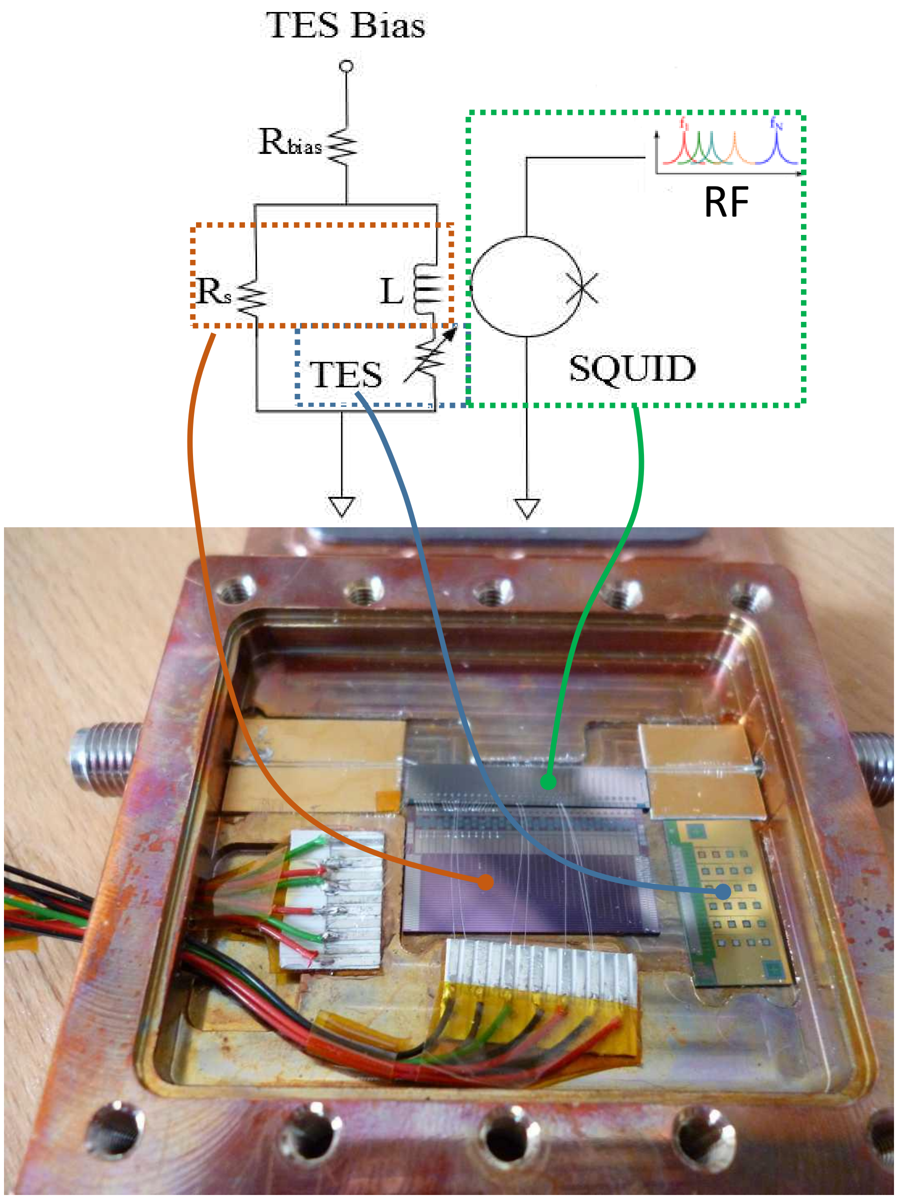
currently the number n_{ϕ_0} is 3 pushable to 2, feasible 1.1

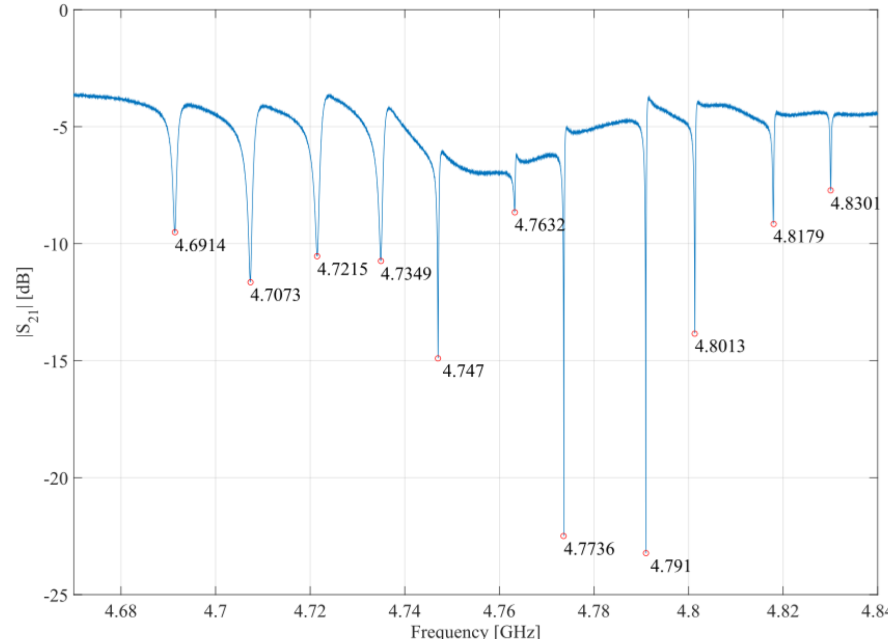
with a rise time of 5μs

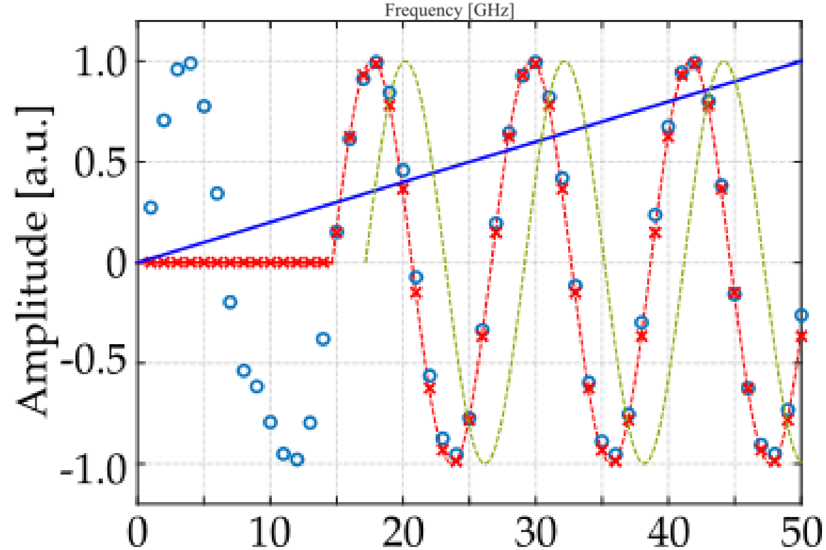
$n_{mux} \approx 30 \div 50$

20/30 ROACH2 boards needed for 1000 detectors

Single channel test @ Milano-Bicocca (not HOLMES TESs)







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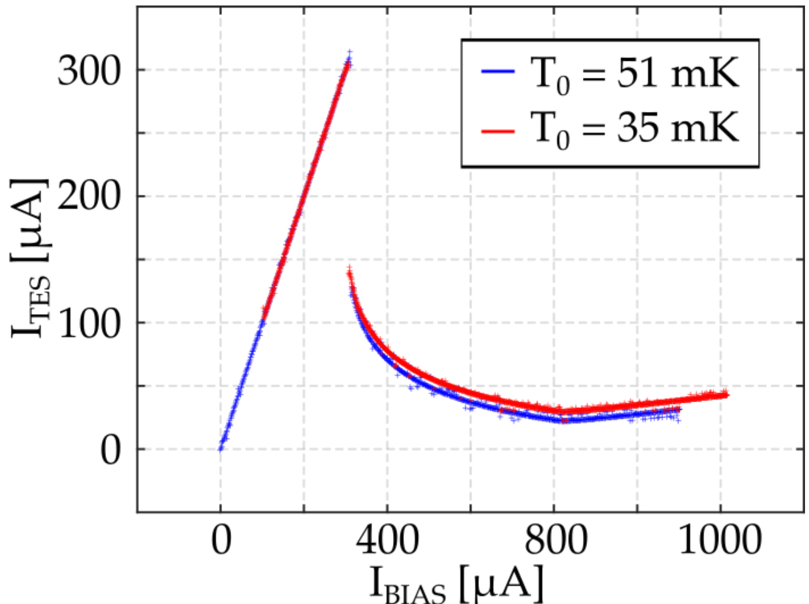
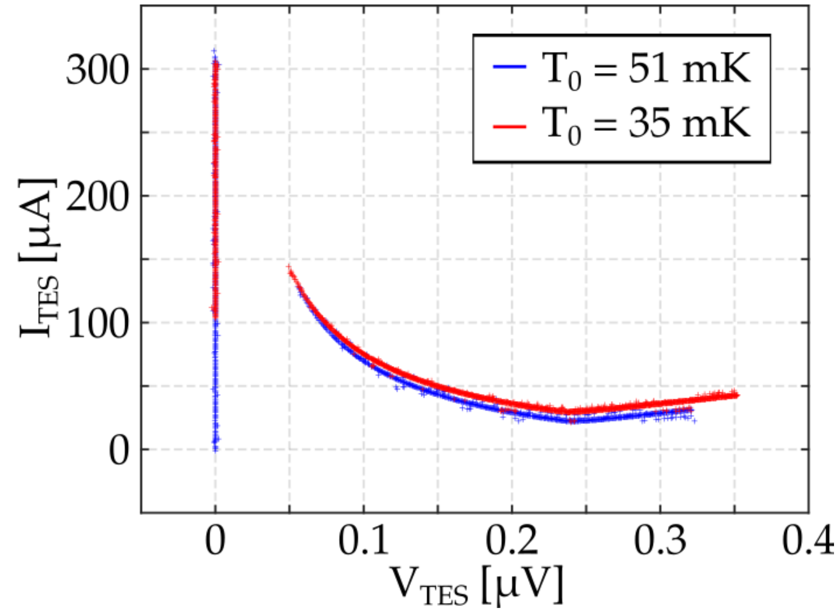
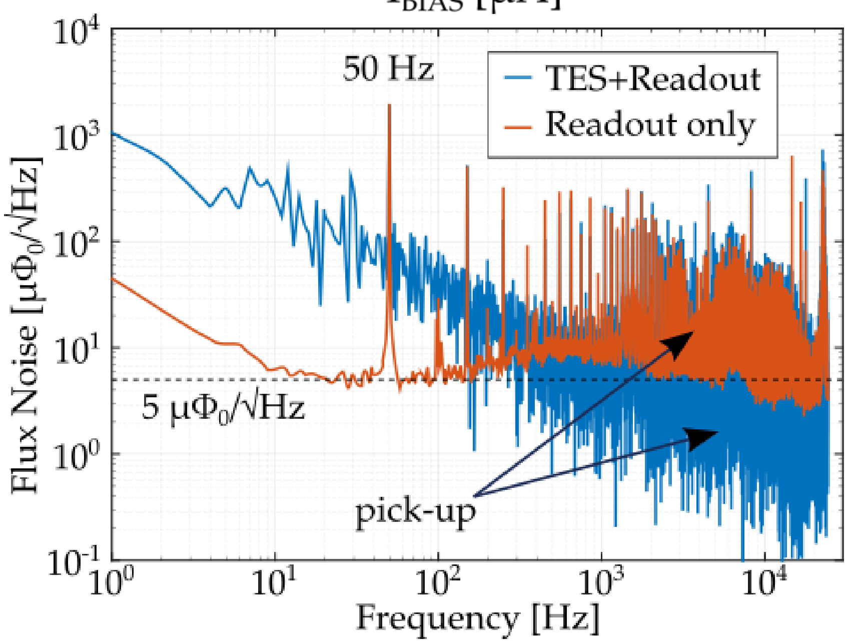
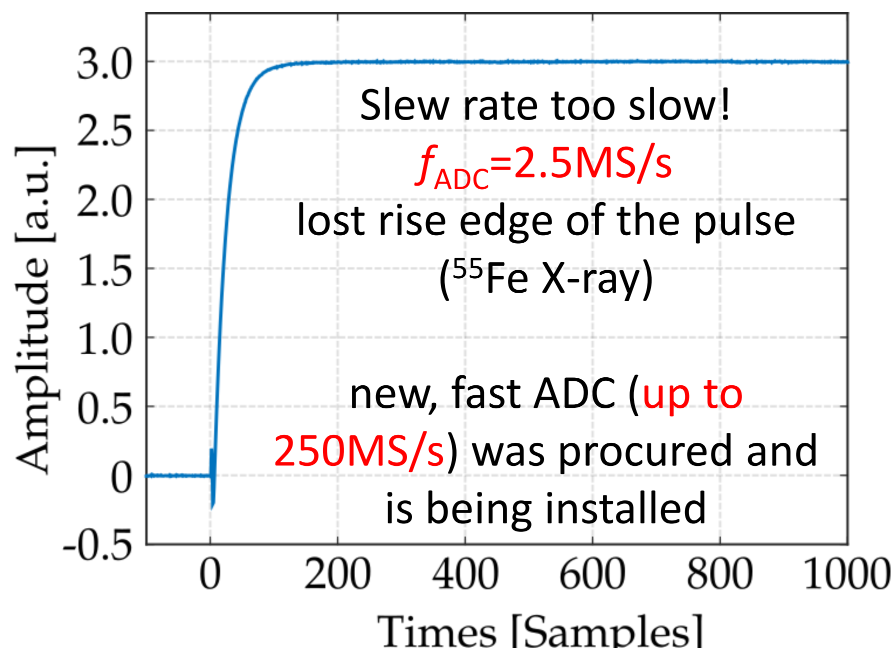








An alternative for the future: MKIDs

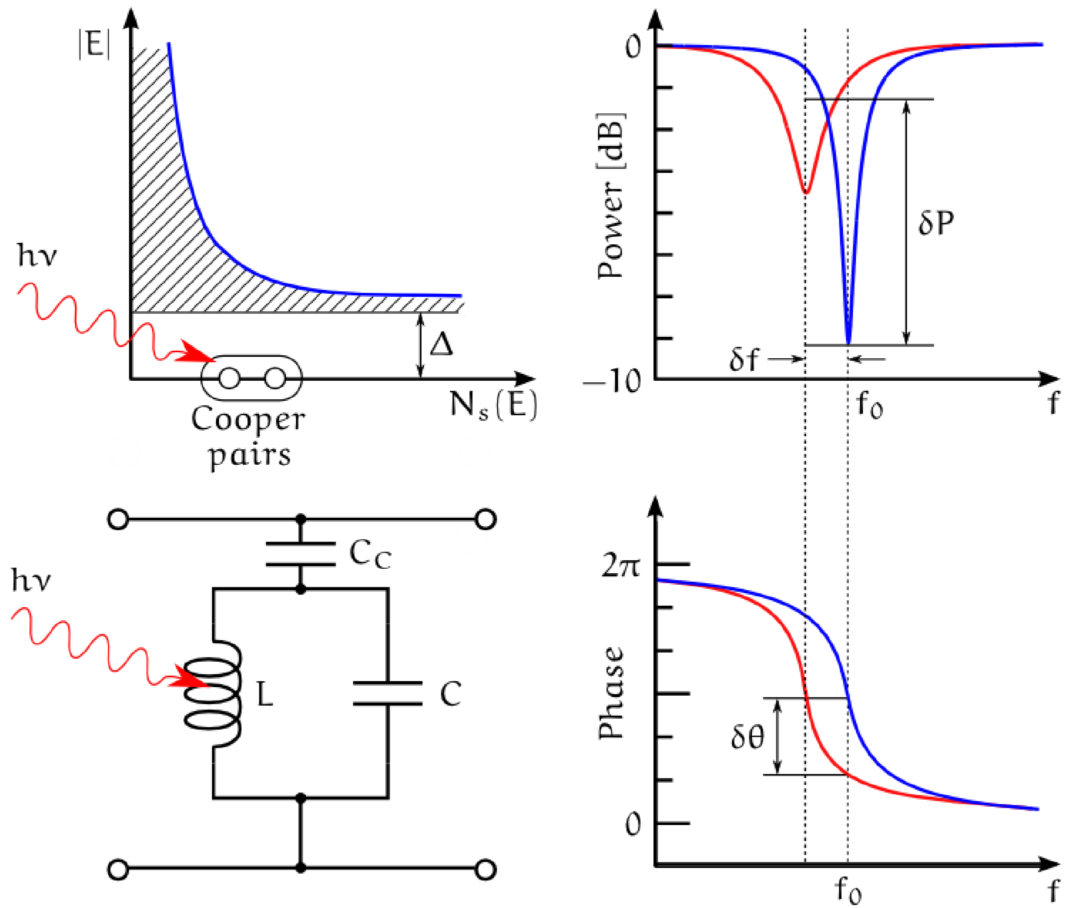
Pair breaking detector

$h\nu > 2\Delta$ (~meV)

- breaking of the Cooper pairs
- quasi-particle creation $N_{qp} \sim h\nu/\Delta$
- change in complex surface impedance $Z_s = R_s + j\omega L_s$ ($L_s = L_k + L_g$)

$$\frac{\delta f}{f_0} = -\frac{\alpha}{2}\frac{\delta L_s}{L_s} \qquad \delta Q^{-1} = \frac{\alpha \delta R_s}{\omega L_s}$$

recombination after τ_{qp}

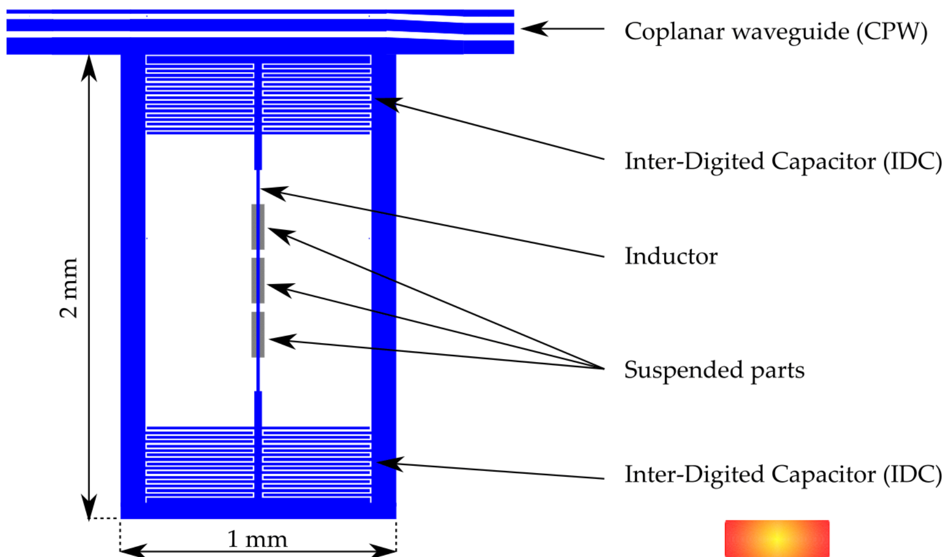


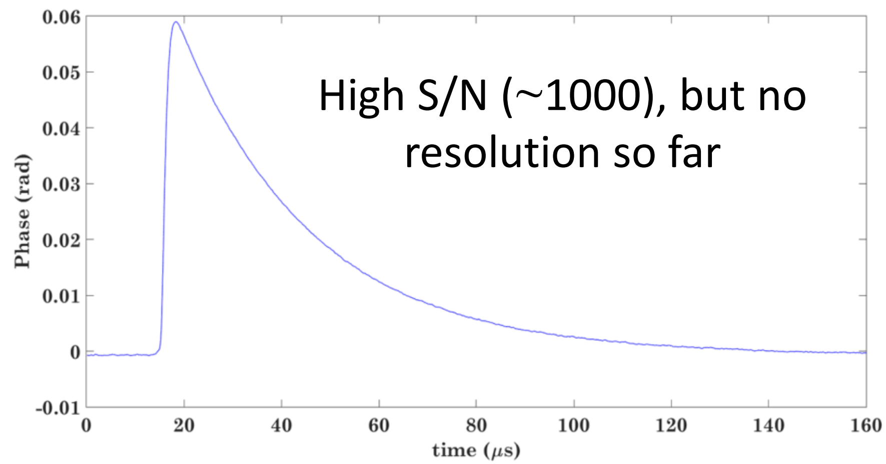
P. Day et al., Nature, 425 (2003) 817

- ➢ easy and large multiplex
- ➢ easy to fabricate (not expensive)
- ➢ technology not ready for Ho experiment

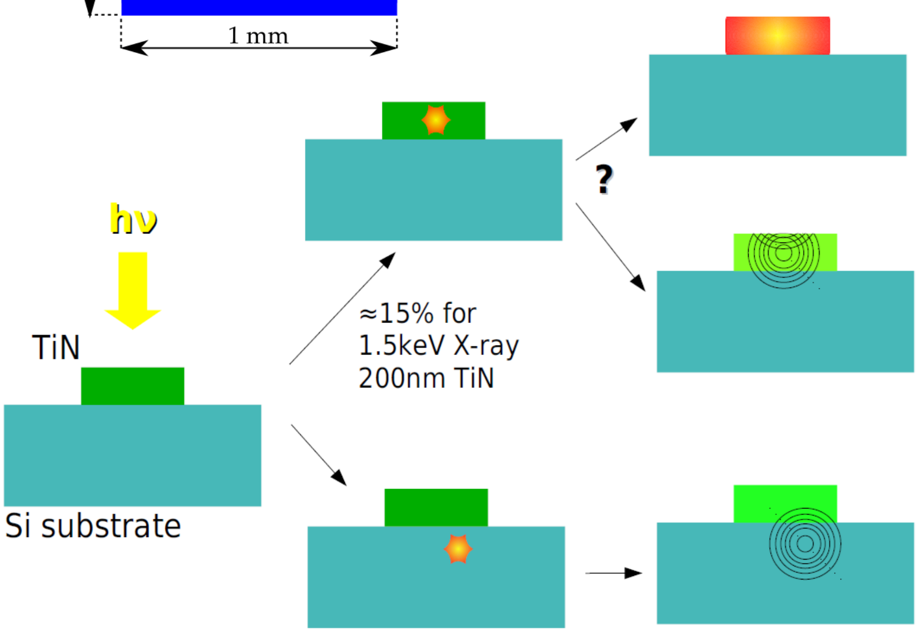
Measurements/problems

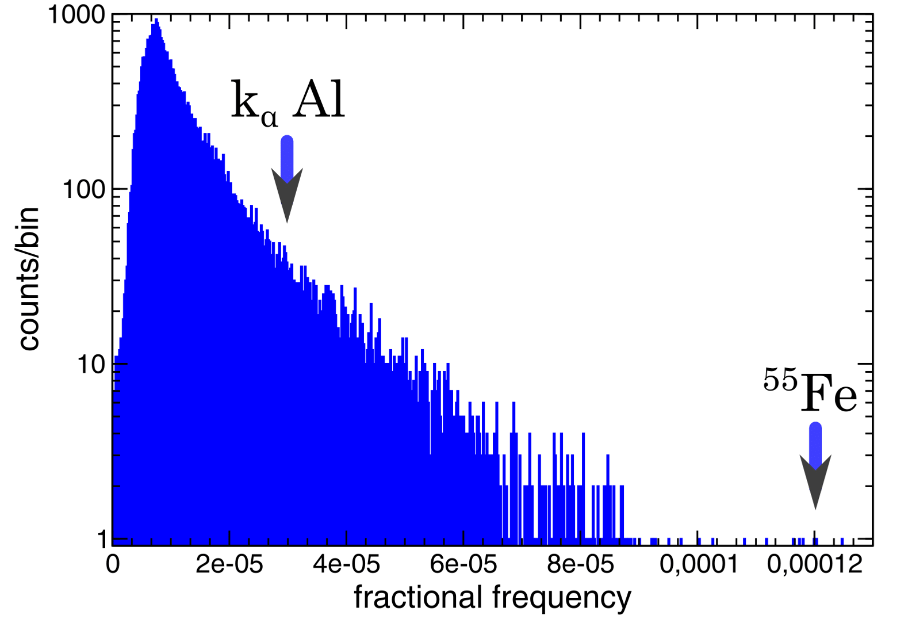
Ti/TiN multilayer produced at FBK → high sensitivity, “low” critical temperature (~ 1K)



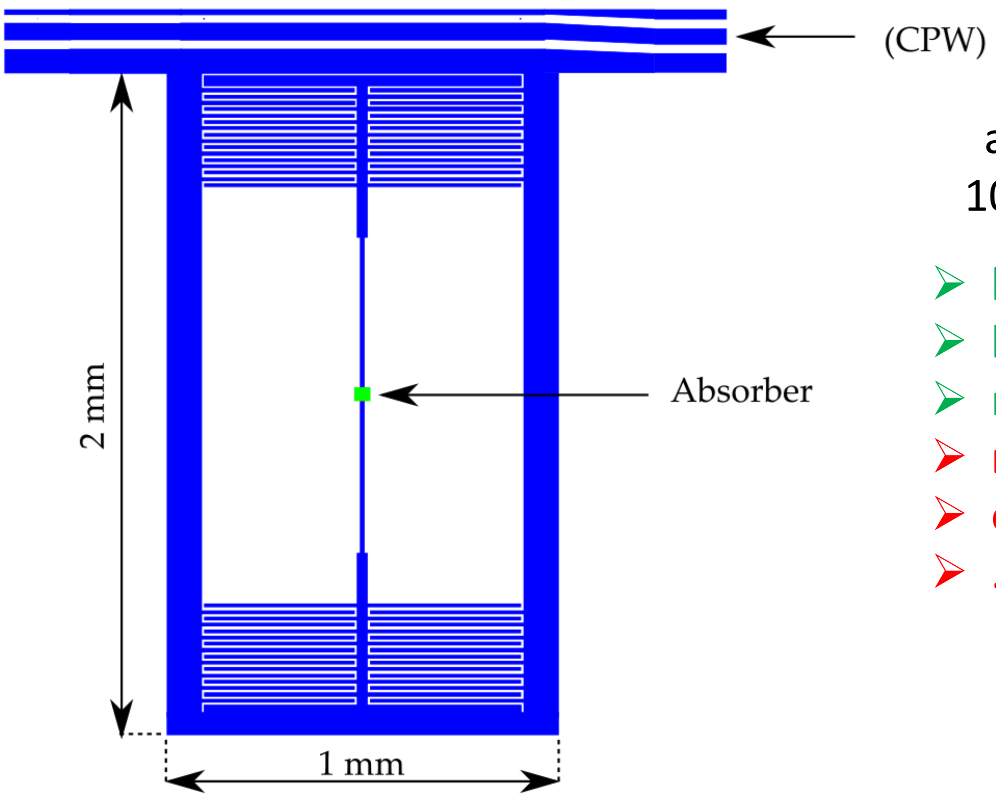


High S/N (~1000), but no resolution so far





Next devices



absorber in tantalum (40x40 μm^2 and 100x100 μm^2) coupled to the resonator

- higher stopping power
- better diffusion of qps before detection
- maintain good qualities of MKIDs
- not straightforward to deposit Ta
- efficiency of qp collection?
- …

devices to be completed and tested

Conclusions

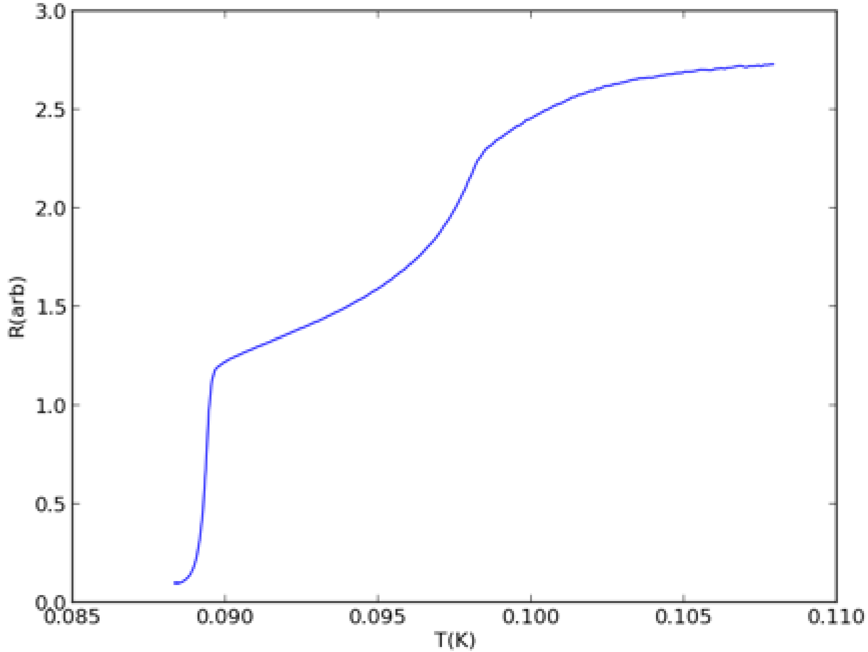
TESs:

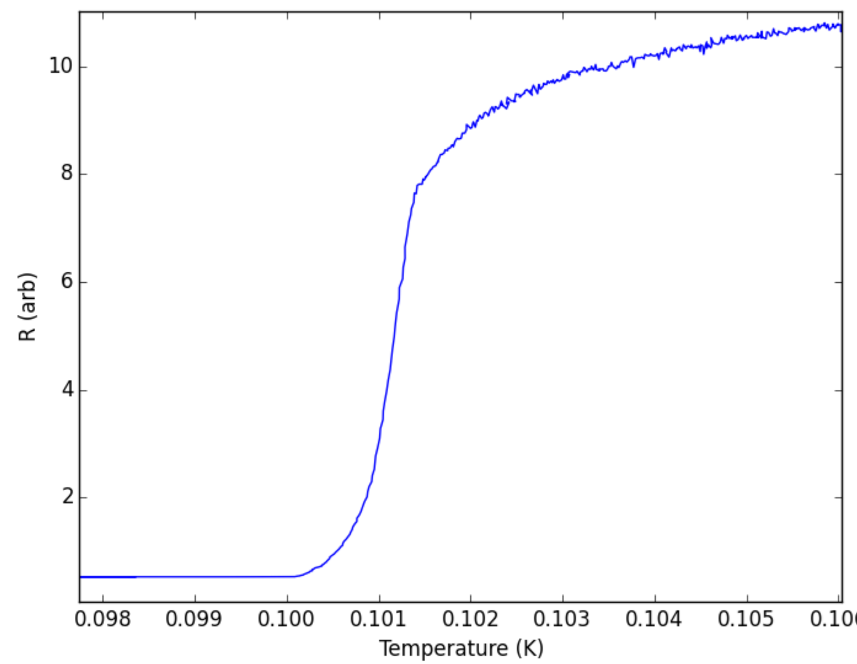
- ✓ identified pulses of the test source (^{55}Fe)
- ✓ load curves
- ✓ new, fast, ADC procured and being installed for the one channel setup
- ➢ test of the "side-car" geometry (two-body effects?)
- ➢ implantation of the Ho
- ➢ setting up of the ROACH2 firmware
- ➢ …

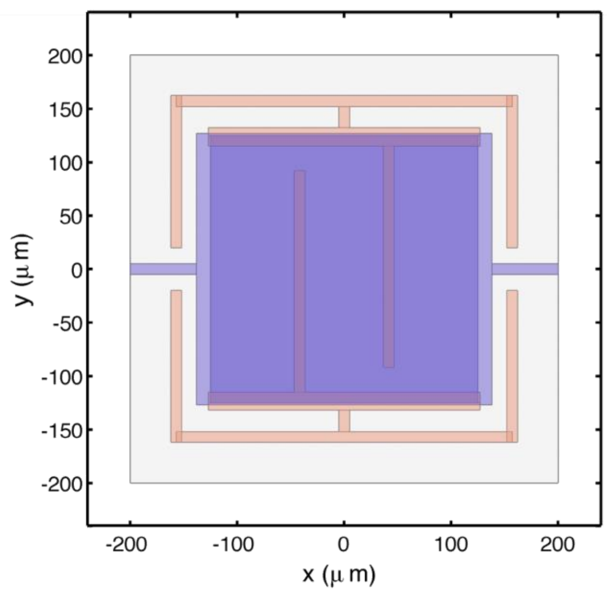
MKIDs:

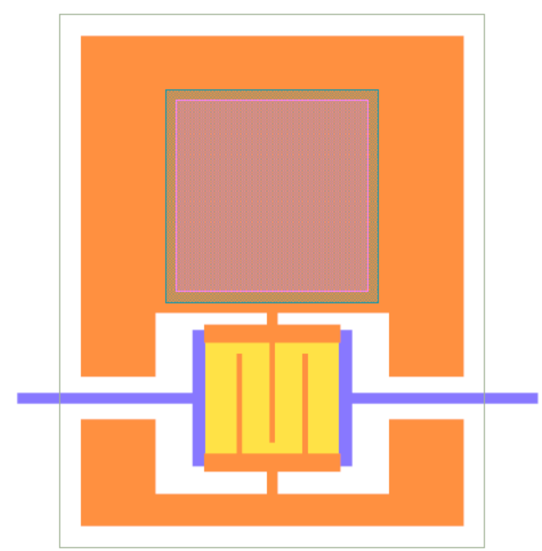
- ✓ observed pulses from the test sources (^{55}Fe + Al K_{α})
- ✓ great S/N
- ➢ not resolving detectors so far (direct absorption)
- ➢ possibly identified problems
- ➢ devices with Ta absorbers to complete and test

Backup – tests @ NIST

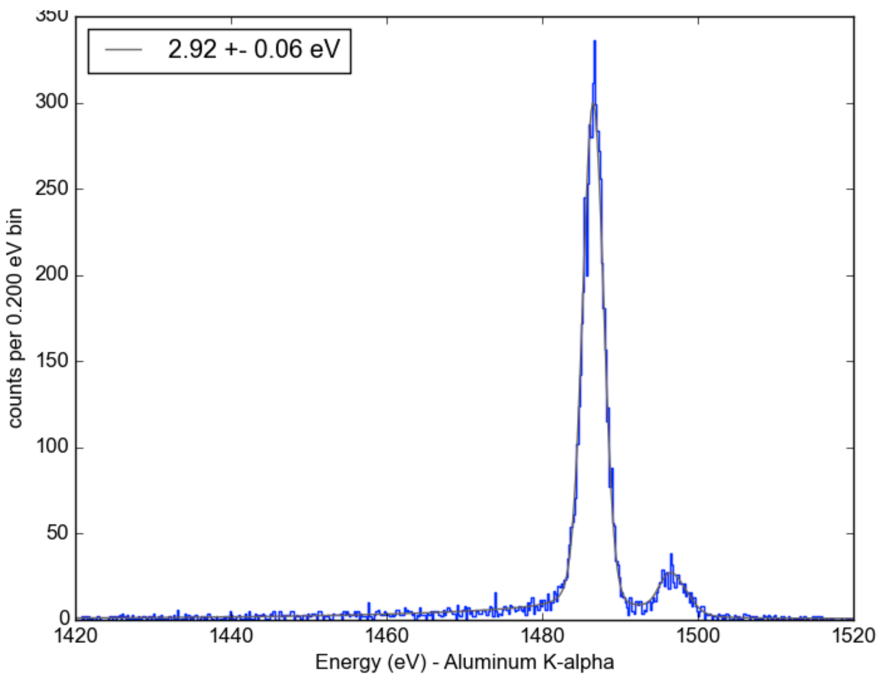


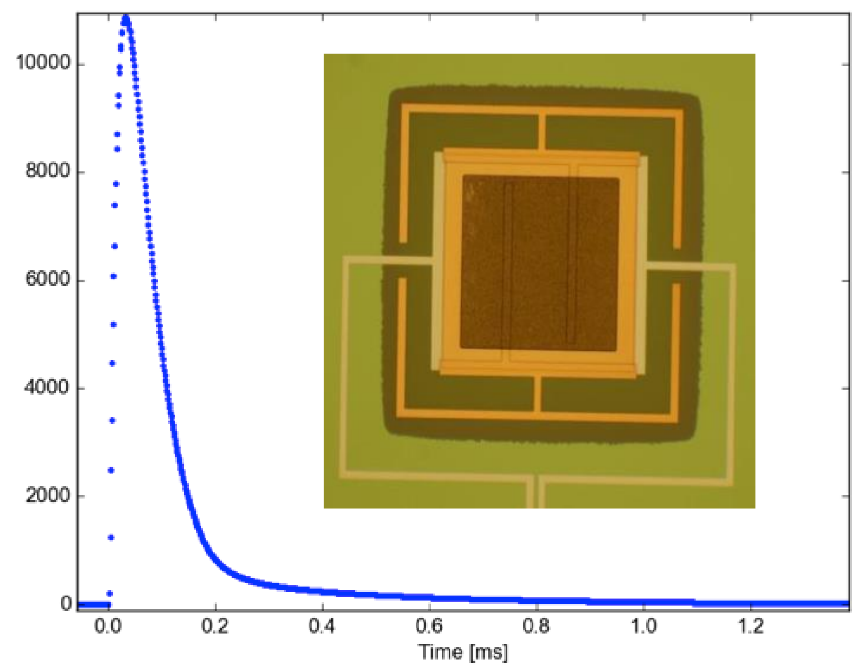






Backup – tests @ NIST

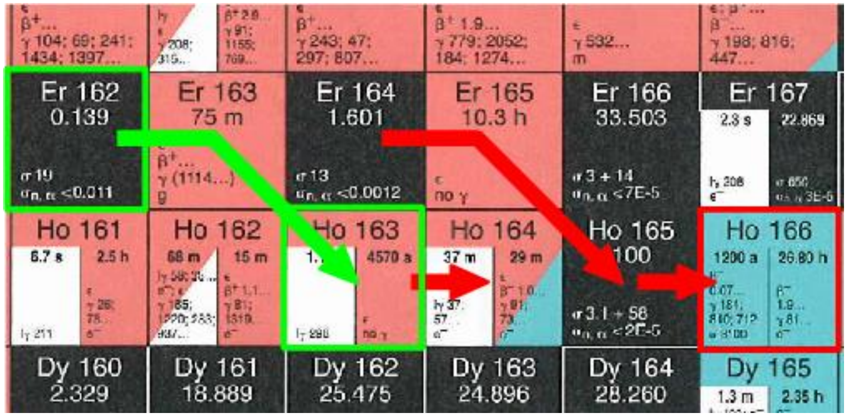




Backup – Ho production

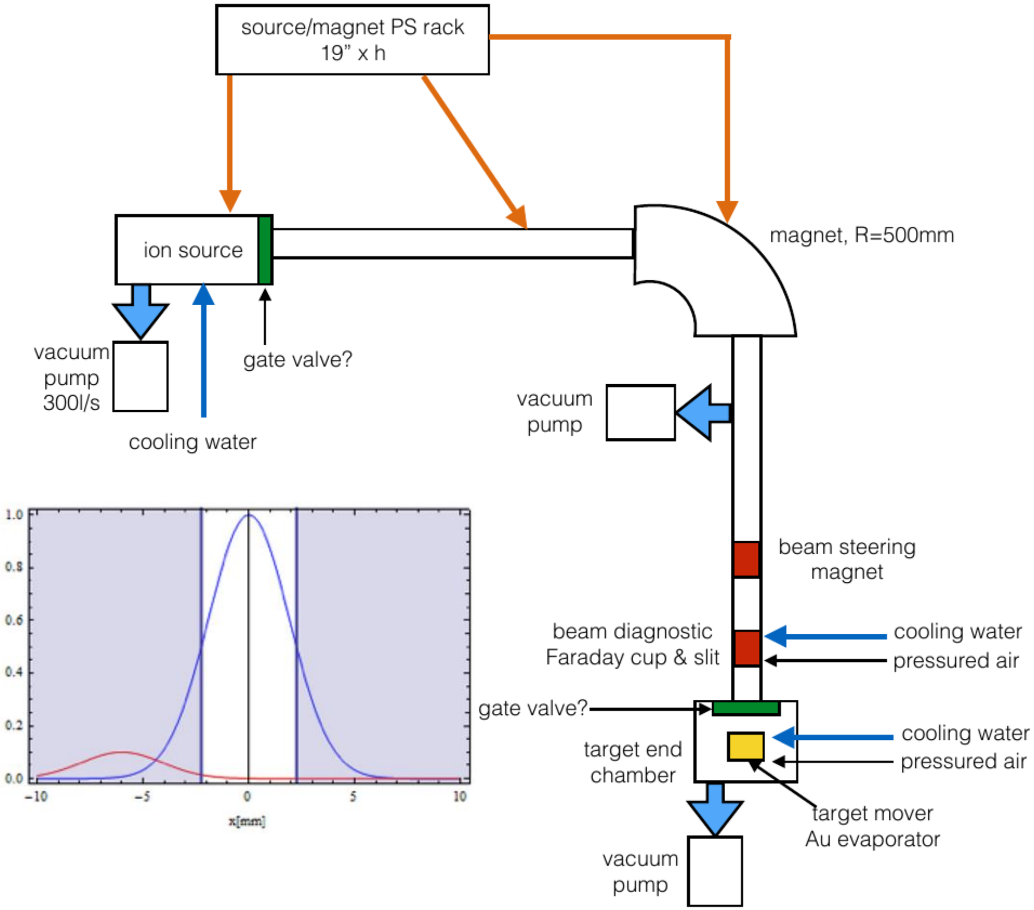
150MBq of ^{163}Ho required for HOLMES

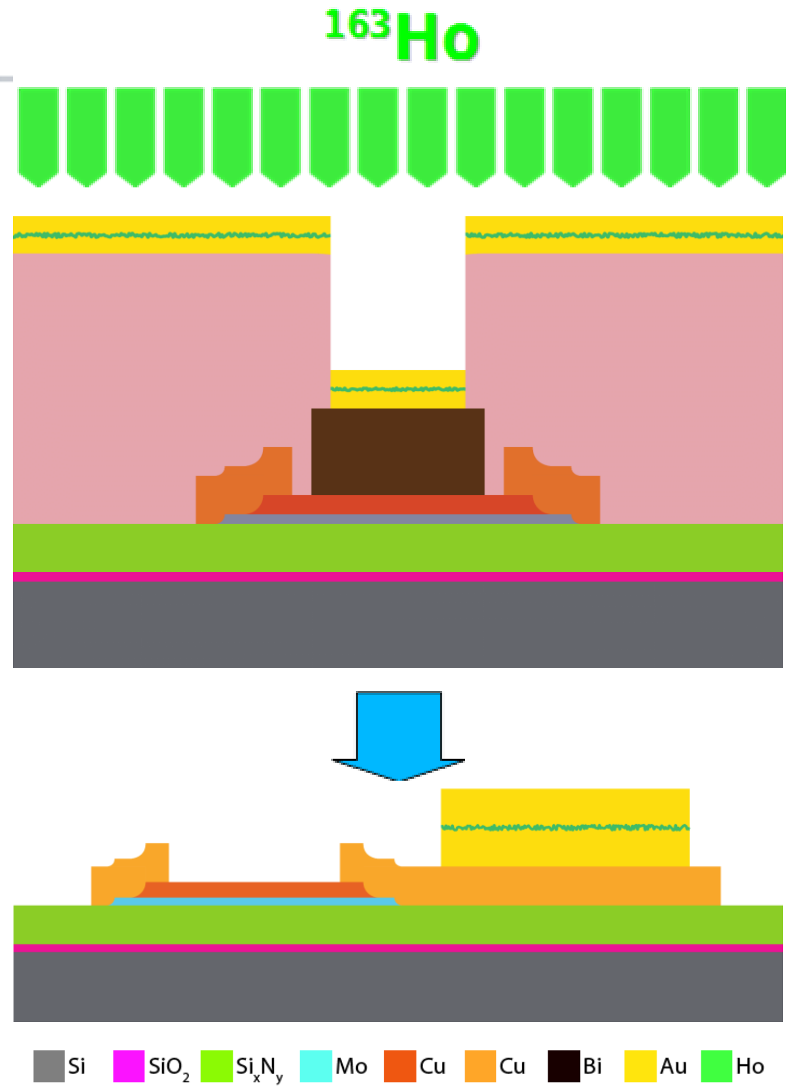
$^{162}Er(n,\gamma)^{163}Er$	$\sigma_{thermal} \approx 20b$
$^{163}Er \longrightarrow {}^{163}Ho + \nu_e$	$t_{½}^{EC} \approx 75min$

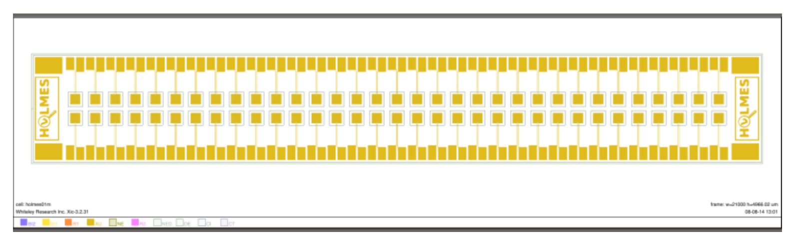


- uncertainty on σs
- ILL reactor @ Grenoble: thermal n flux 1.3×10^{15} n/cm^2/s
- ≈270 kBq(^{163}Ho)/mg(^{162}Er)/week @ ILL (→ 80mg(^{162}Er) for 7 weeks → ≈150MBq of ^{163}Ho)
- cross section burn up $^{163}Ho(n,\gamma)^{164}Ho$: not known. Possibility of degradation of yield
- $^{165}Ho(n,\gamma)$ (mostly from $^{164}Er(n,^{g})$) → ^{166m}Ho, β $\tau_{½}$=1200y
- chemical pre-purification and post-separation at PSI (Villigen, Switzerland)
- irradiated and processed samples are under investigation with ICP-MS
- 150mg of enriched Er_2O_3 are @ ILL since 2014 (56 days → **≈70-80MBq**)

Backup – Ho implantation







- 2 µm thick Au encapsulating implanted ^{163}Ho
- TES fabricated at NIST, Boulder, CO, USA
- ^{163}Ho implantation and Si_2N_3 membrane release at INFN Genova