Development of microwave superconducting microresonators for neutrino mass measurement in the HOLMES framework

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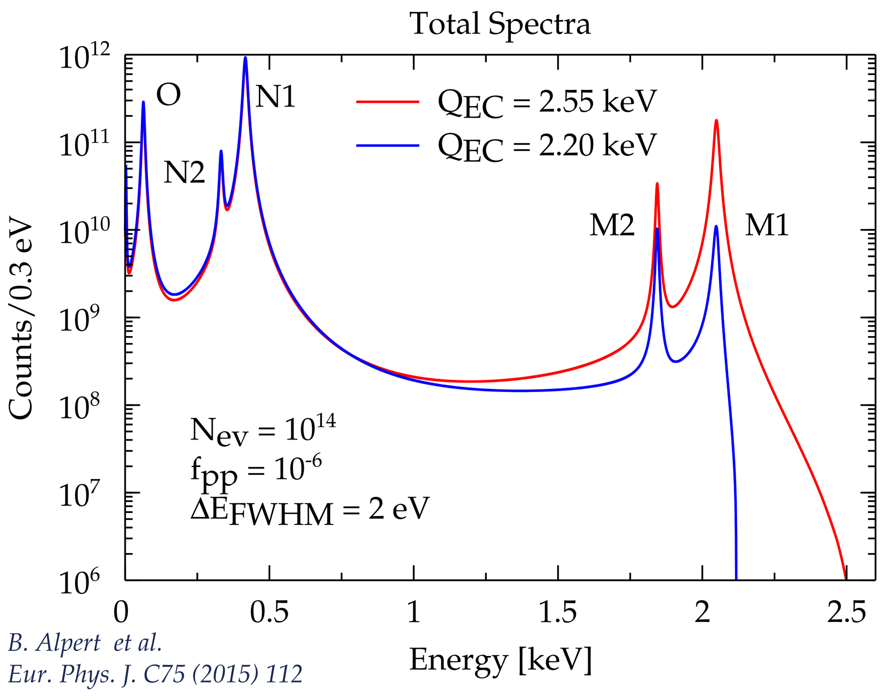
ERC-ADG-2013
no. 340321

1. Overview

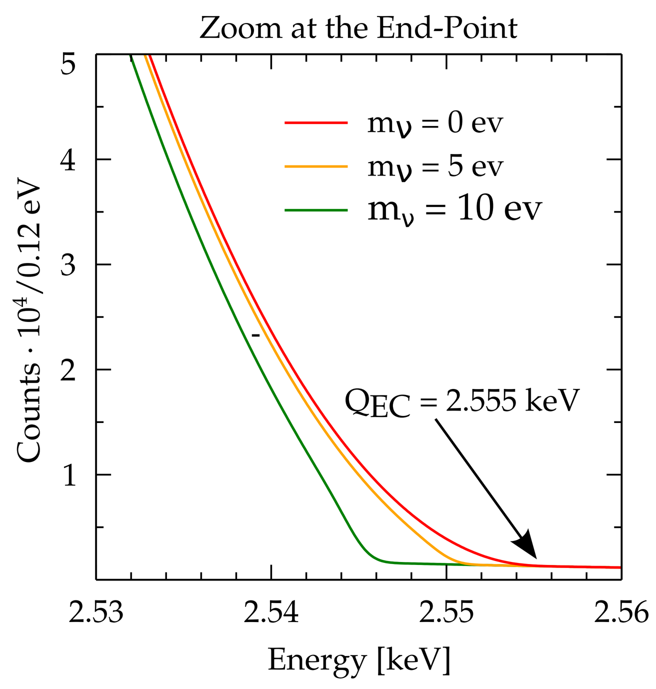
HOLMES is a new experiment to directly measure the neutrino mass with a sensitivity as low as **0.4 eV**. HOLMES will perform a calorimetric measurement of the energy released in the electron capture (EC) decay of ^{163}Ho. The baseline for HOLMES is microcalorimeters coupled to a **Transition Edge Sensor (TES)** read out with a **rf-SQUID**, for microwave multiplexing purposes. A promising alternative solution is based on **superconducting microwave resonators** (MKID, Microwave Kinetic Inductance Detectors), that have undergone rapid development in the last decade. The natural multiplexing capability, simple fabrication process, the high performances and the reduction in complexity at the cryogenic level makes the **MKIDs** increasingly relevant to the future development of multipixel detector arrays.

2. Experimetal Sensitivity

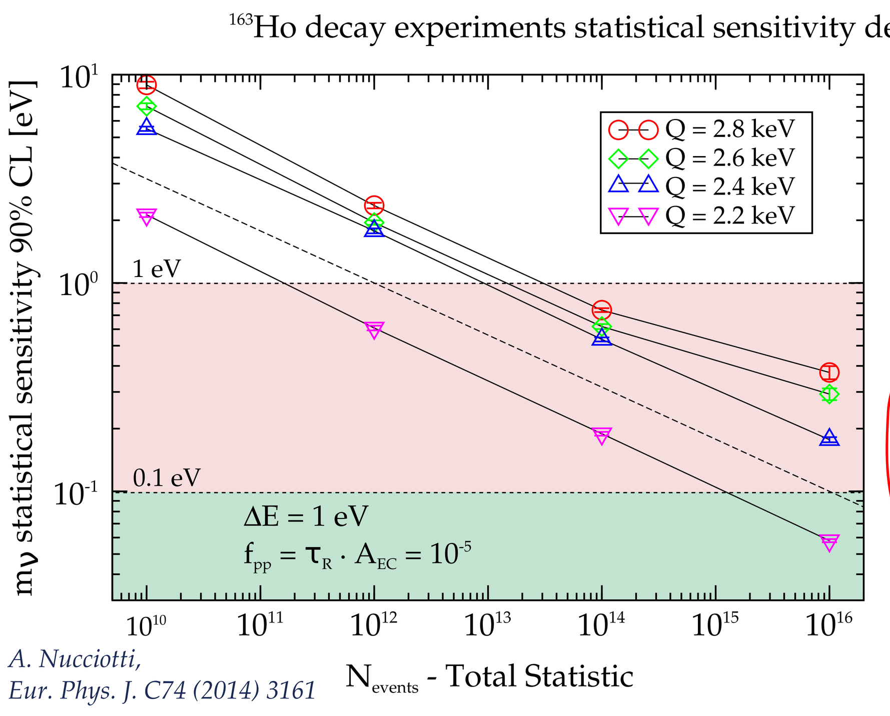
The method consists in searching for a tiny deformation caused by a non-zero neutrino mass to the ^{163}Ho EC spectrum near its end point (Q_{EC}).



B. Alpert et al.
Eur. Phys. J. C75 (2015) 112



In order to reach the sensitivity of **0.4 eV** HOLMES will deploy **1000 detectors** of low temperature microcalorimeters with implanted ^{163}Ho nuclei. The baseline sensors for HOLMES are Mo:Cu TESs (Transition Edge Sensors) on SiNx membrane with bismuth absorbers.



A. Nucciotti,
Eur. Phys. J. C74 (2014) 3161

Exposure required for $m_\nu = 0.1$ eV sensitivity and $Q_{EC} = 2800$ eV

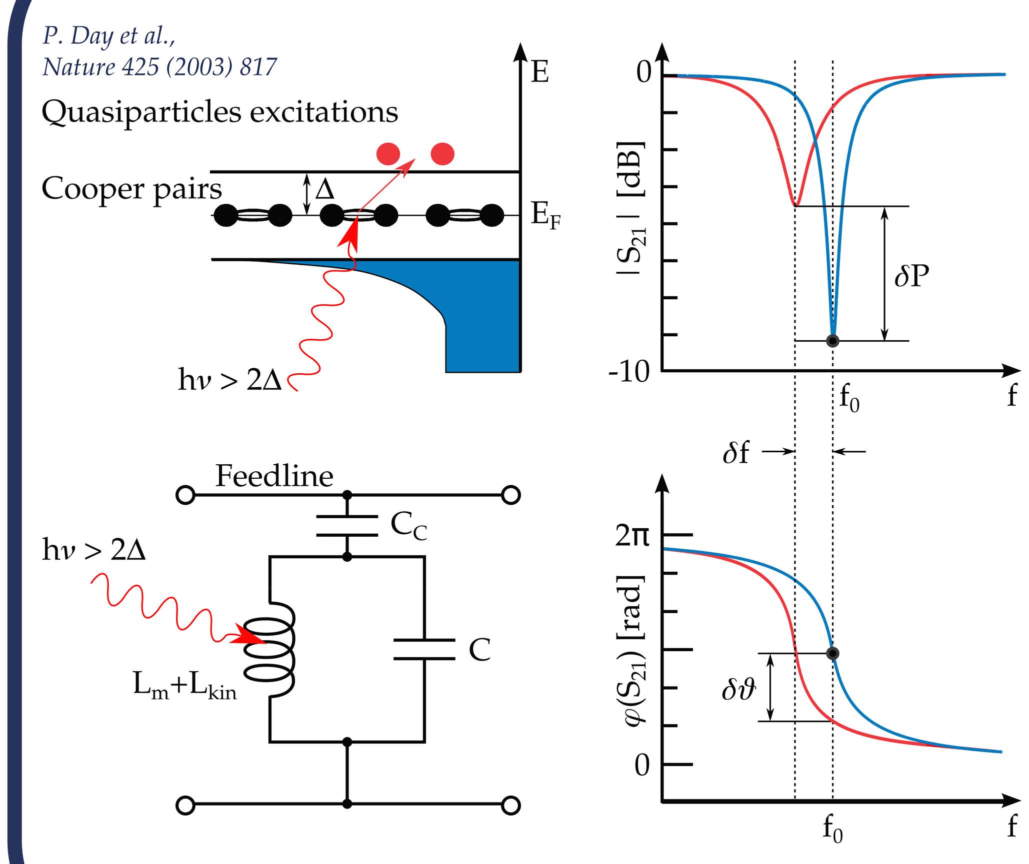
A_β [Hz]	τ_{rise} [μs]	ΔE [eV]	N_{ev} [counts]	Exposure [det·year]
1	0.1	0.3	$1.2 \cdot 10^{14}$	$3.9 \cdot 10^6$
100	0.1	0.3	$6.4 \cdot 10^{14}$	$2.0 \cdot 10^5$
100	0.1	1	$7.4 \cdot 10^{14}$	$2.4 \cdot 10^5$
10	0.1	1	$4.5 \cdot 10^{14}$	$1.5 \cdot 10^6$
10	1	1	$7.4 \cdot 10^{14}$	$2.4 \cdot 10^6$

- 10^6 pixels/array;
- 6 arrays;
- 10 years of live-time;
- $8 \cdot 10^{19}$ nuclei of 163 Ho

The HOLMES technologies are not readily scalable to Mega-pixel arrays needed for a high neutrino mass sensitivity measurement ($m < 0.1$ eV). An alternative solution is based on MKIDs detectors that have recently demonstrated the feasibility to build 100kpixel arrays with promising performances.

3. MKIDs

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



The **inductor** is the **active part** of the detector

- An interaction with energy larger than the superconducting energy gap Δ can break Cooper pairs increasing the quasiparticles density (N_{qp});
- To sensitively measure these n_{qp} density change, the film is placed in a high frequency planar resonant circuit
- The increase in the kinetic inductance and surface resistance of the film pushes the resonance to lower frequency and changes its quality factor.
- If the detector (resonator) is excited with a constant on-resonance microwave signal, the energy of the absorbed radiation can be determined by measuring the degree of phase and amplitude shift.

4. MKIDs for X-rays

The responsivity of a MKID is related to the $d\sigma/dN_{qp}$, where σ is the complex conductivity;

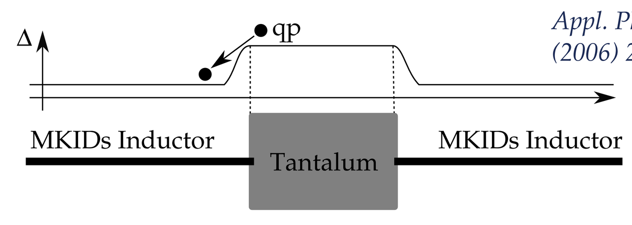
Two possible ways:
- In non-equilibrium mode (**athermal mode**) the excess quasiparticles $d\sigma/dn_{qp}$ is due to an external pair breaking;
- In thermal equilibrium mode (**thermal mode**) an identical increase of quasiparticle population can be generated by a temperature change

J. Gao et al.,
J. Low Temp. Phys. 151 (2008) 557

Athermal Mode

X-ray detection is possible by coupling the MKIDs inductor with a tantalum absorber.

B. A. Mazin et al.
Appl. Phys. Lett. 89 (2006) 2222507



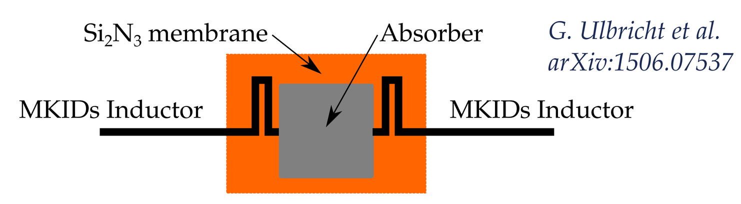
Energy resolution: limited by the statistical fluctuation of the number of the created qp

$$\Delta E = E \cdot \xi \sqrt{(F\Delta)/(\eta h\nu)}$$

Thermal mode

X-ray detection is possible by using a metal absorber thermally coupled with the inductive part and suspended by Si_3N_3 membrane

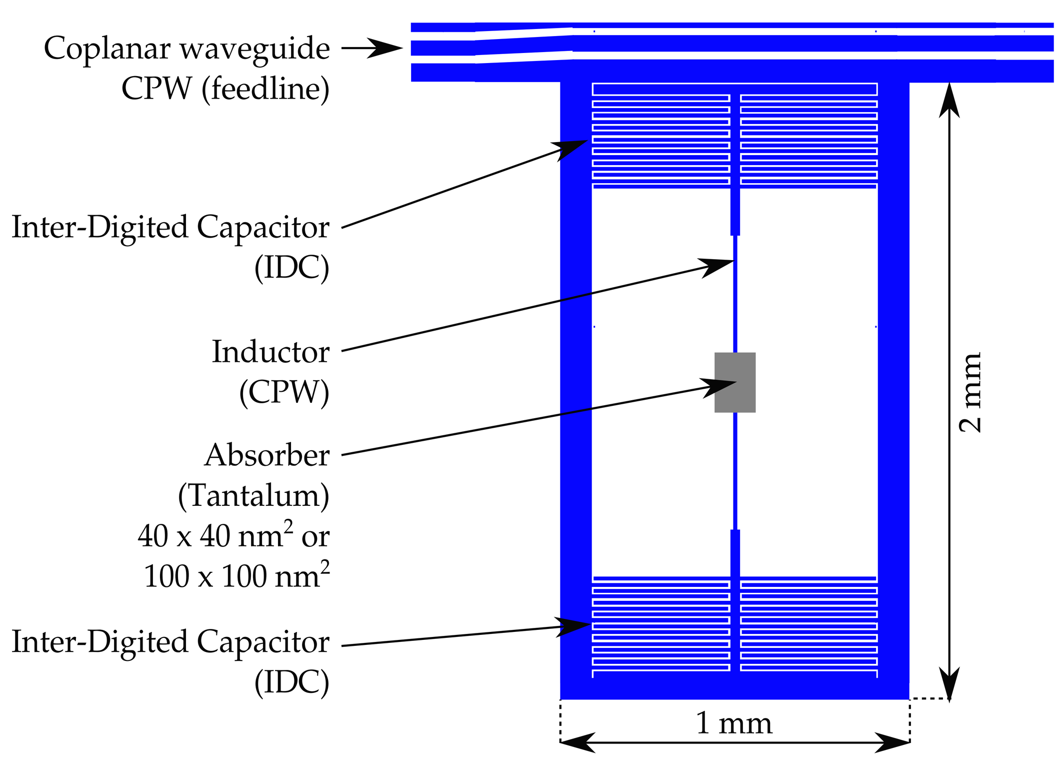
G. Ulbricht et al.
arXiv:1506.07537



Energy resolution: theoretically limited only by thermodynamic fluctuations across the thermal weak link:

$$\Delta E \simeq \xi \sqrt{k_B T^2 C}$$

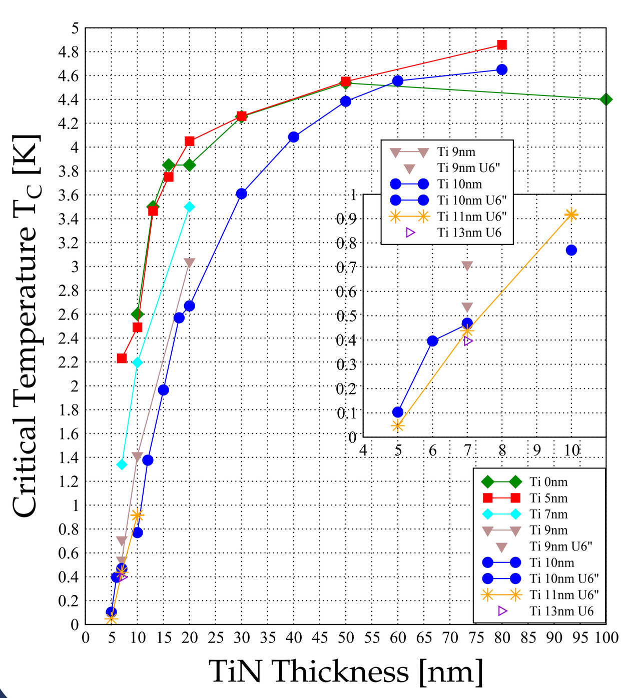
5. Design and Production

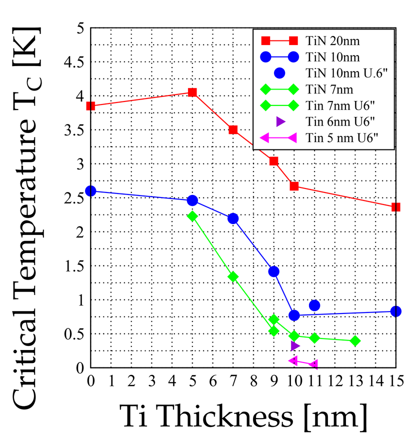


- Geometry in the lumped element form with two interdigitated capacitors (IDC) connected with a CPW that works as inductor;
- Resonator capacitively coupled to a coplanar waveguide (CPW) used as feedline and for the readout;
- The spacing and width of the conductors of the IDC optimized to minimize the TLS noise;
- Two versions, with and without Tantalum absorber;

Superconduction films made by using **multilayer Ti/TiN** films composed by a **superposition of bilayers Ti/TiN** (proximity effect). This approach allows to achive the target critical temperature T_C with a good reproducibility and uniformity in the range (0.1 - 4.5) K.

A Giachero et al.
J. Low Temp. Phys. 176 (2014) 155



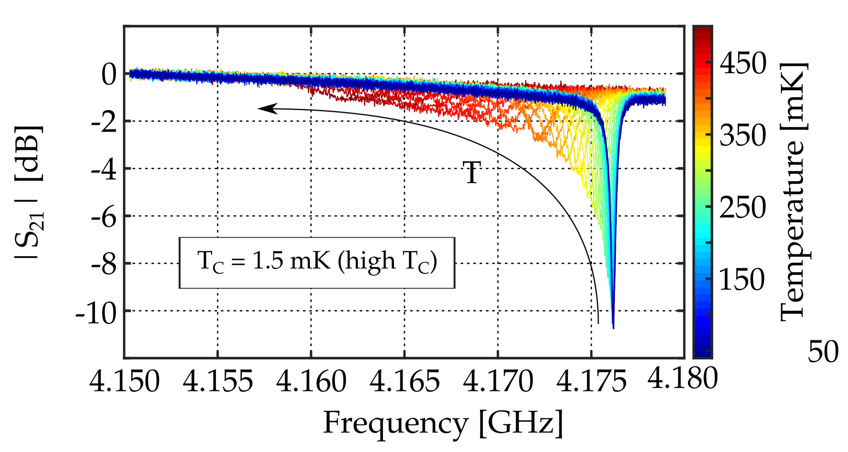


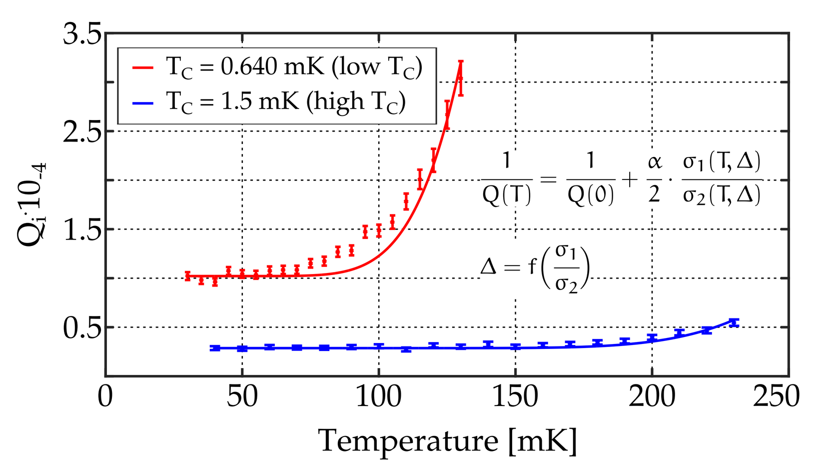
Final production with two different families of chips with **two different critical temperatures.**

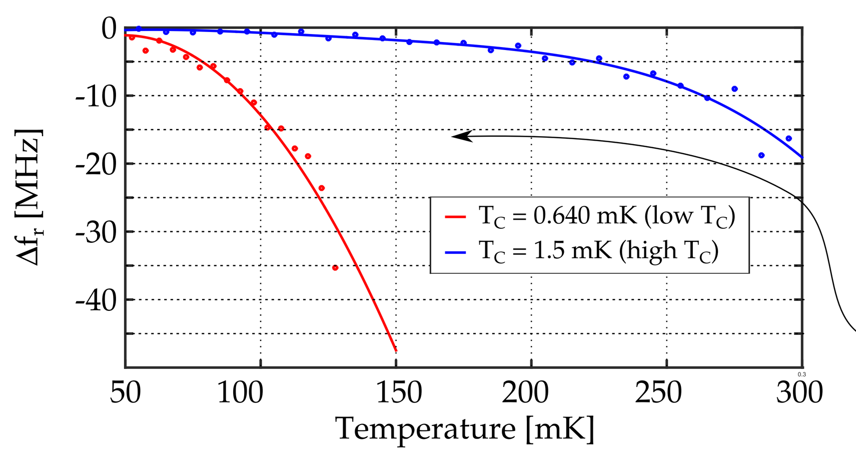
Ti [nm]	TiN [nm]	N layers	T_C [K]
10	12	9	1.5
10	7	12	0.6

- Devices with **high** T_C to study the athermal mode with Tantalum absorber;
- Devices with **low** T_C to study the thermal mode (absorber not yet implemented);

6. First Characterizations

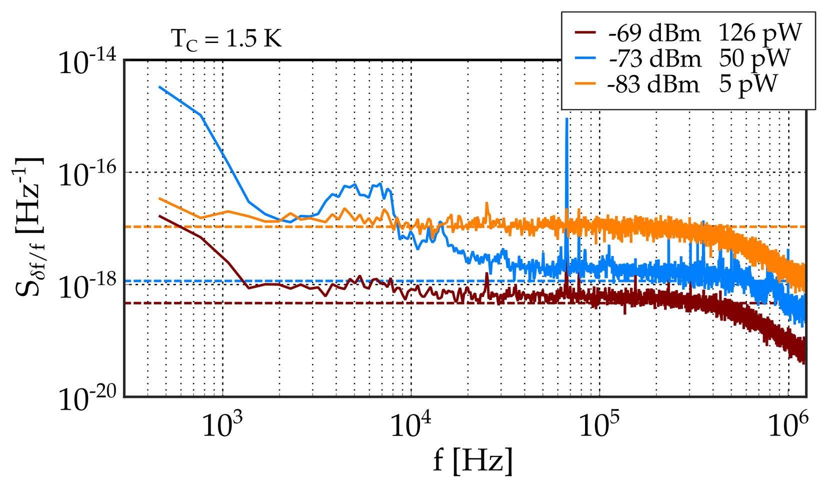


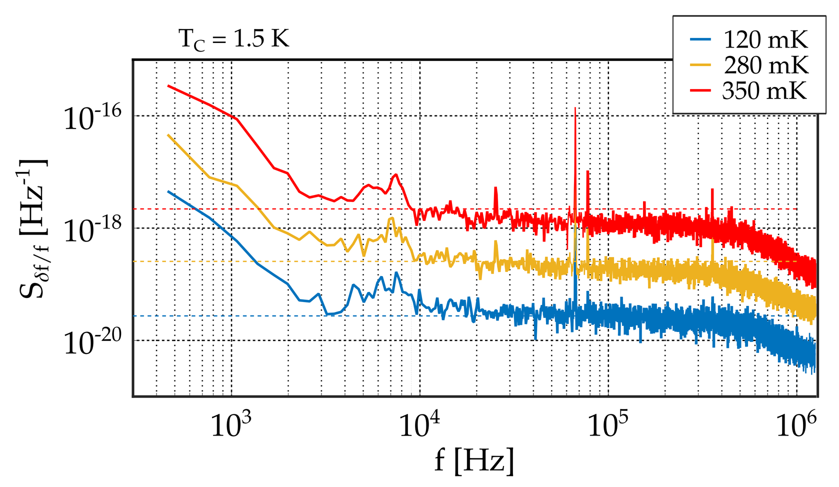




T_C [K]	Δ [meV]	α	L_S [pH/sq]	Q_i
1.5	0.200 ± 0.004	0.26 ± 0.01	13.1	$< 10^5$
0.640	0.091 ± 0.001	0.95 ± 0.01	36.9	$< 10^4$

The variation of the resonant frequency as a function of the temperature is steeper with lower critical temperatures.





The amplifier noise (dotted lines) is the dominant noise source

Conclusion

- We developed MKIDs detectors with Low (0.6 K) and High (1.5 K) T_C made by using multilayer of Ti/TiN;
- We characterized the produced detectors measuring all the relevant parameters;
- Tests with absorbers for X-ray detection are on the way;