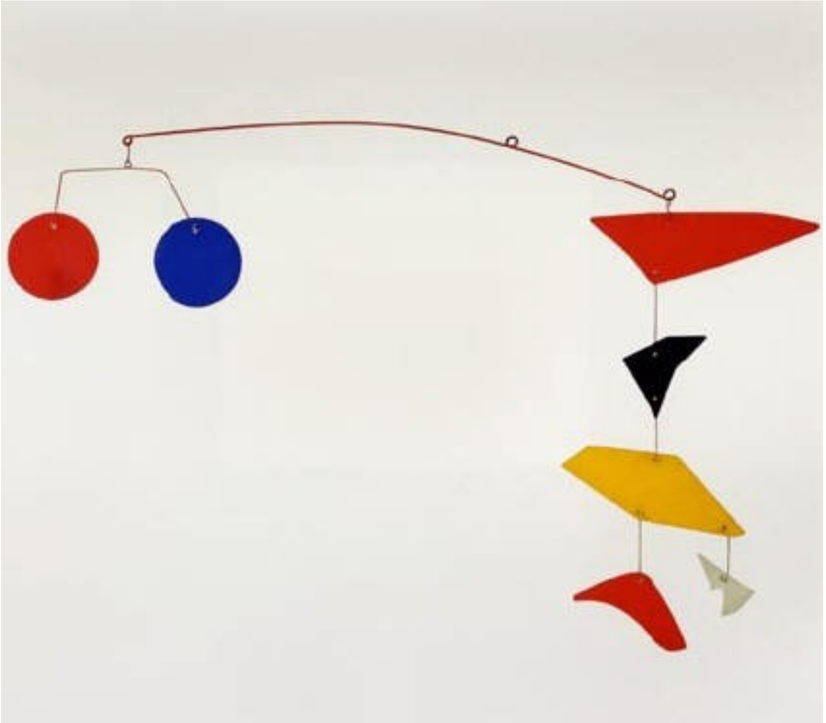
Istituto Nazionale di Fisica Nucleare
Sezione di Roma

Cryogenic light detectors for background suppression: the CALDER project

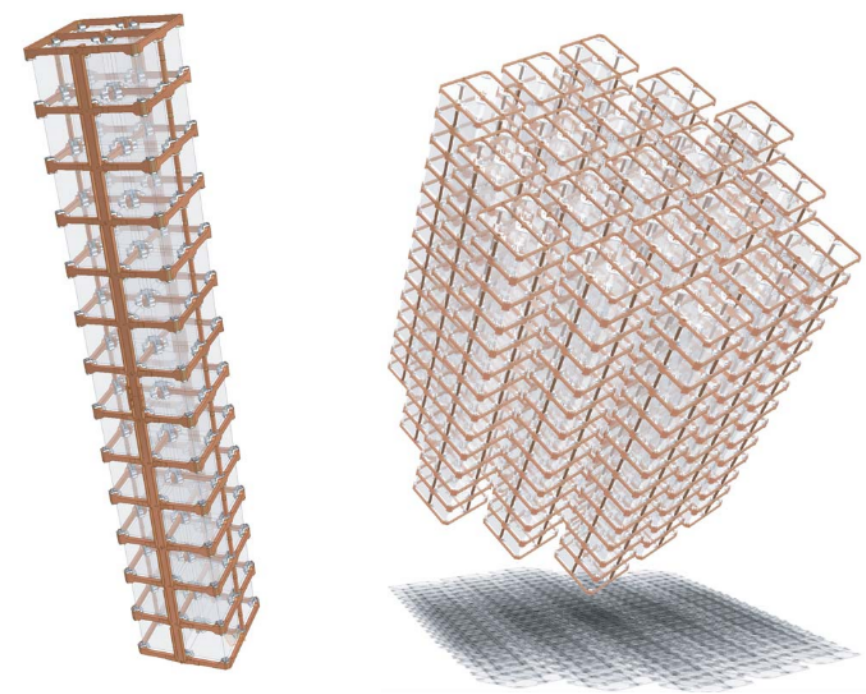


Nicola Casali on behalf of the CALDER collaboration -
TIPP, Beijing 22-26 May 2017

Why high sensitivity cryogenic light detectors?

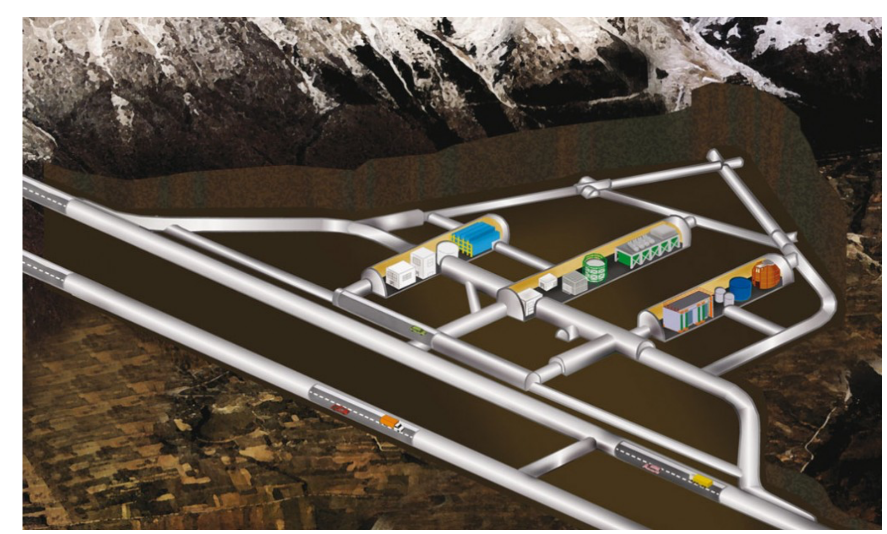
- Improve the sensitivity of the next generation experiments searching for rare events: **Neutrino-less double beta decay** and Dark Matter interactions.

- The CUORE experiment searches for neutrino-less double beta decay of ^{130}Te.
- The expected signal are two electrons with a total kinetic energy of ~ 2.5 MeV.



CUORE
988 TeO_2 bolometers;
now in data taking

Deep underground (3650 m.w.e.) in the INFN Laboratori Nazionali del Gran Sasso



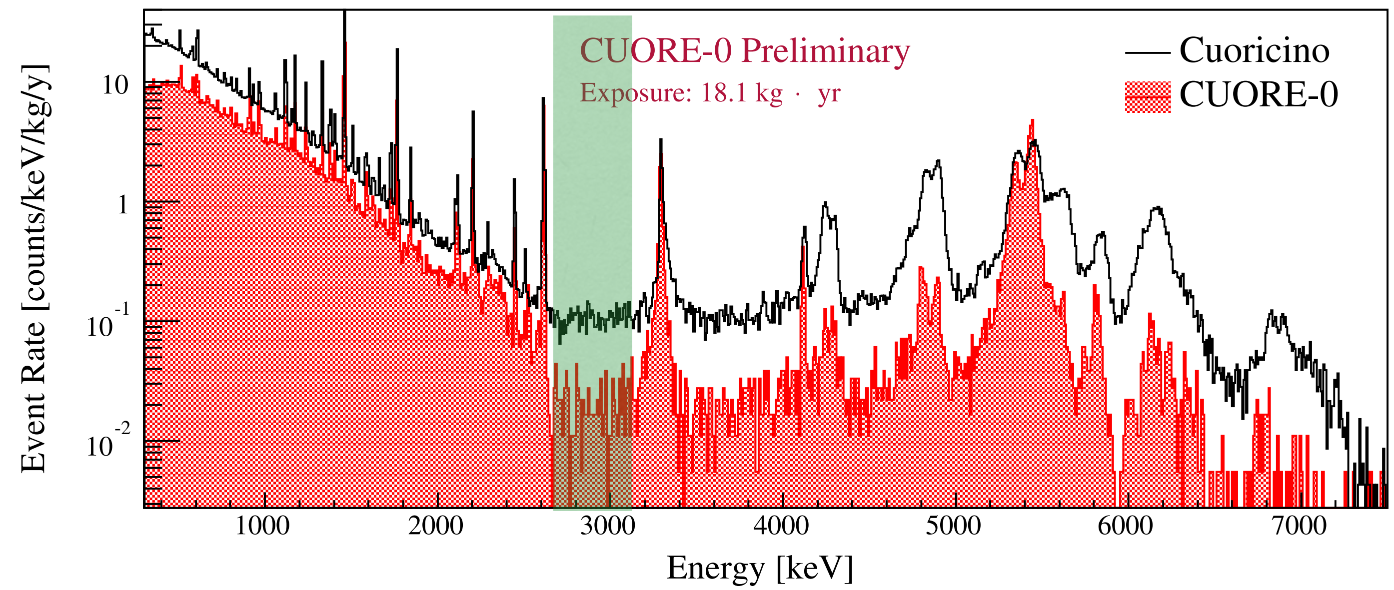
Why high sensitivity cryogenic light detectors?

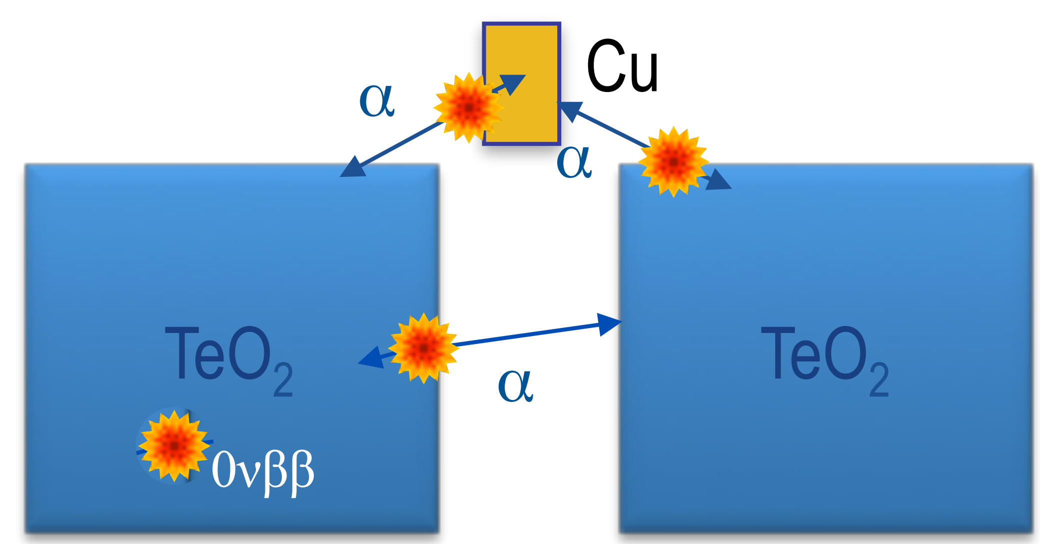
- Improve the sensitivity of the next generation experiments searching for rare events: **Neutrino-less double beta decay** and Dark Matter interactions.

- The CUORE experiment searches for neutrino-less double beta decay of ^{130}Te.

- The expected signal are two electrons with a total kinetic energy of ~ 2.5 MeV.

- The main background comes from α particles (residual radioactive contamination of the detector materials).



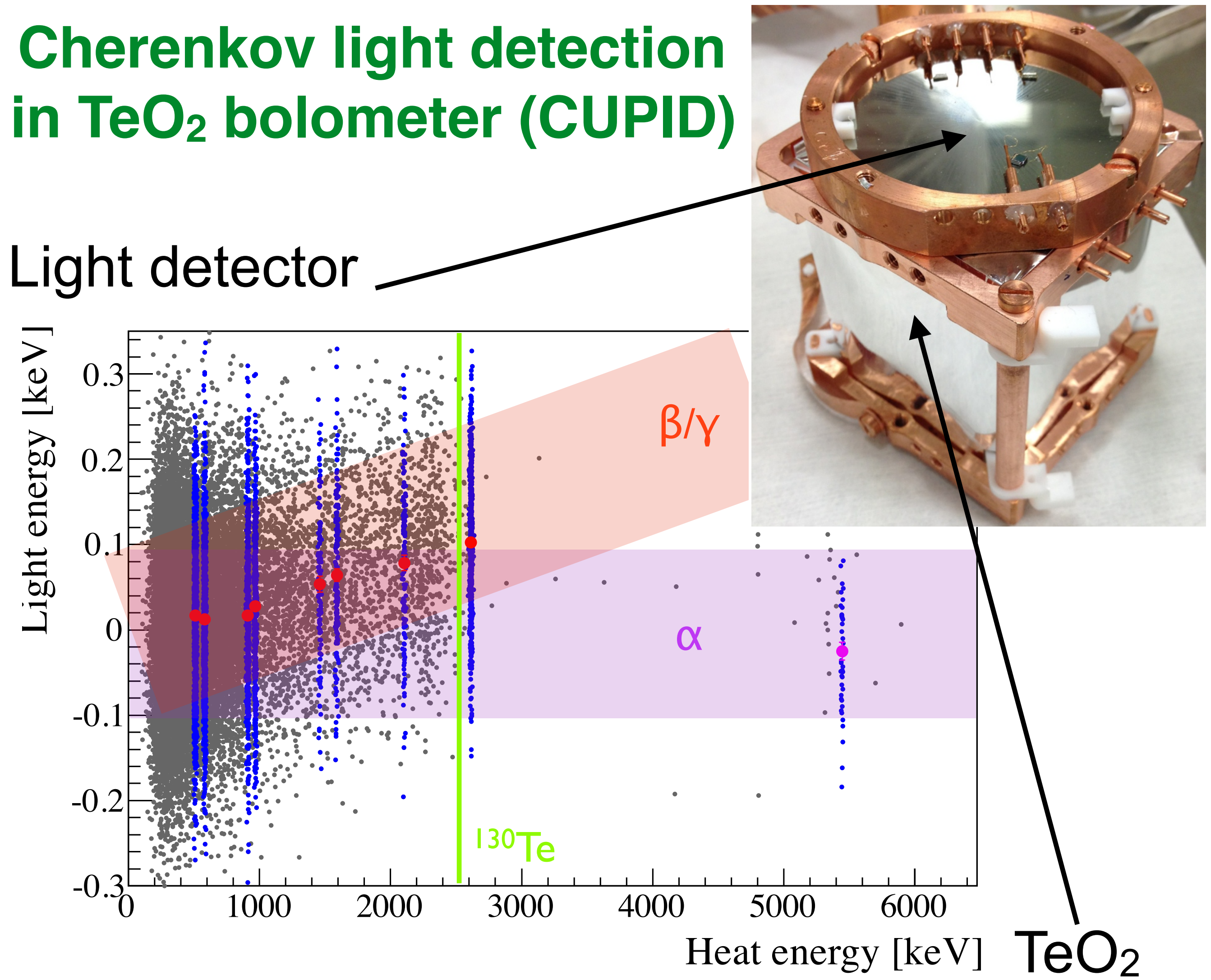


Why high sensitivity cryogenic light detectors?

- Improve the sensitivity of the next generation experiments searching for rare events: **Neutrino-less double beta decay** and Dark Matter interactions.

- The CUORE experiment searches for neutrino-less double beta decay of ^{130}Te.
- The expected signal are two electrons with a total kinetic energy of ~ 2.5 MeV.
- The main background comes from α particles (residual radioactive contamination of the detector materials).
- This background can be rejected detecting the **Cherenkov light** emitted only by β/γ interactions (the only ones above threshold).

Cherenkov light detection in TeO_2 bolometer (CUPID)



N. Casali et al., Eur.Phys.J. C **75** (2015) 1, 12

The next generation requirements

The light detectors for next generation bolometric experiments must satisfy these requirements:

1. High energy resolution < 20 eV RMS
2. Large active area ~25 cm^2
3. Ease in fabrication and operation
4. Scalability (~ 1000 channels size experiment)
5. High radio-purity level
6. Wide operation temperature range (5 - 20 mK)

Several works exploiting different technologies:

1) L.Pattavina et al., Journal of Low Temp Phys 1-6 (2015) -> Ge Naganov-Luke with NTD

2) M. Biassoni et al., Eur.Phys.J. C75 (2015) 10, 480 -> Si Naganov-Luke with NTD

3) K.Schaeffner et. al, Astropart.Phys. 69 (2015) 30-36 -> W-TES on SOS

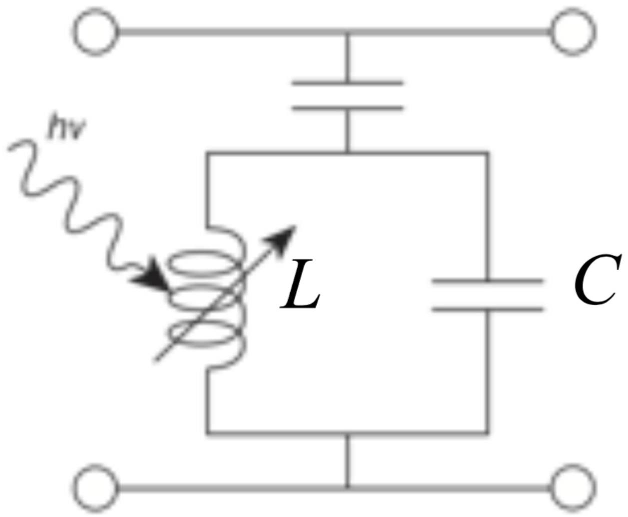
4) M. Willers et al., JINST 10 P03003 (2015) -> Si Naganov-Luke + TES

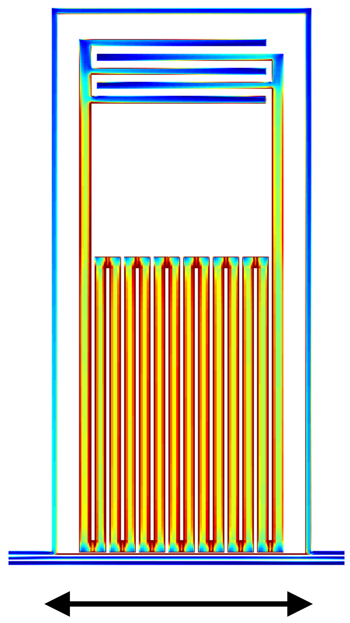
5) CALDER -> KID -> THIS TALK

Up to now none of these technologies demonstrated to satisfy all the requirements

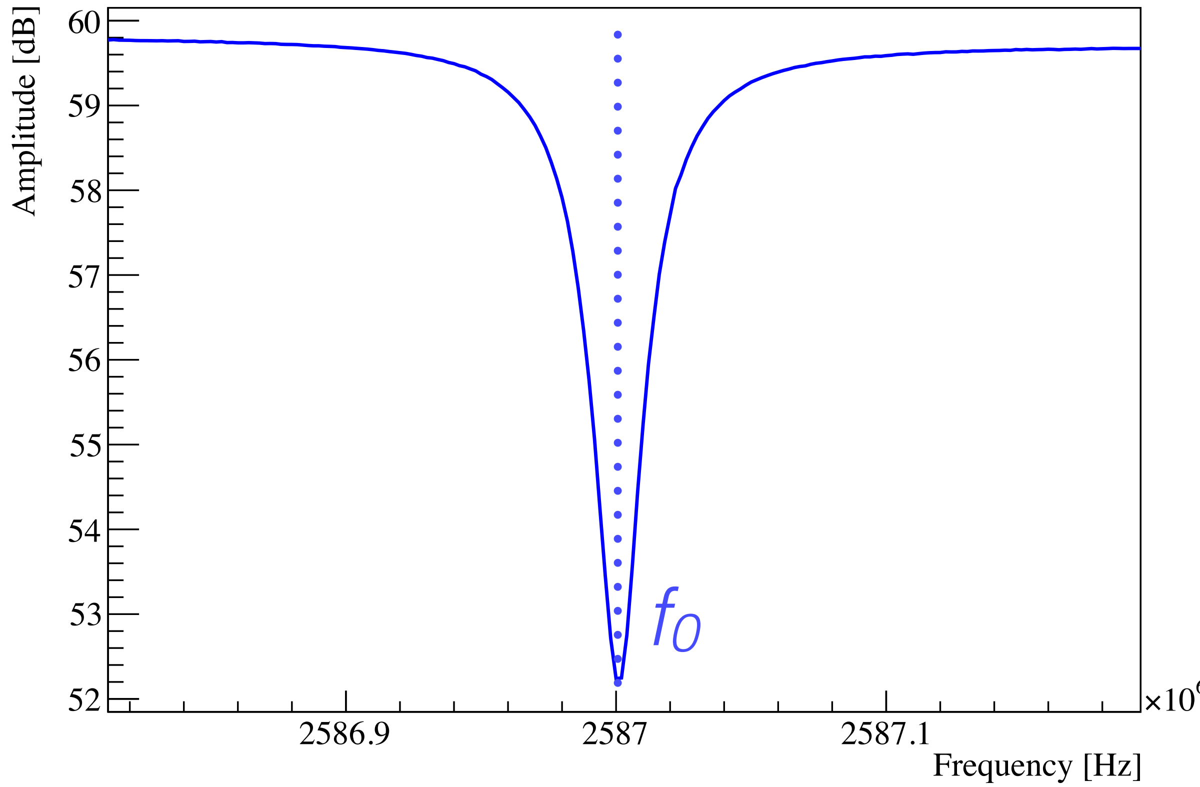
Kinetic Inductance Detector:KID

- Superconductors operated well below the critical temperature T_c
- Biasing with high frequency AC current (ν ~ GHz) they exhibit a kinetic inductance (L_k) -> caused by the inertia of the Cooper pairs
- By coupling the superconductor with a capacitor, a high quality factor RLC circuit can be realized ($Q \sim 10^4 - 10^5$)



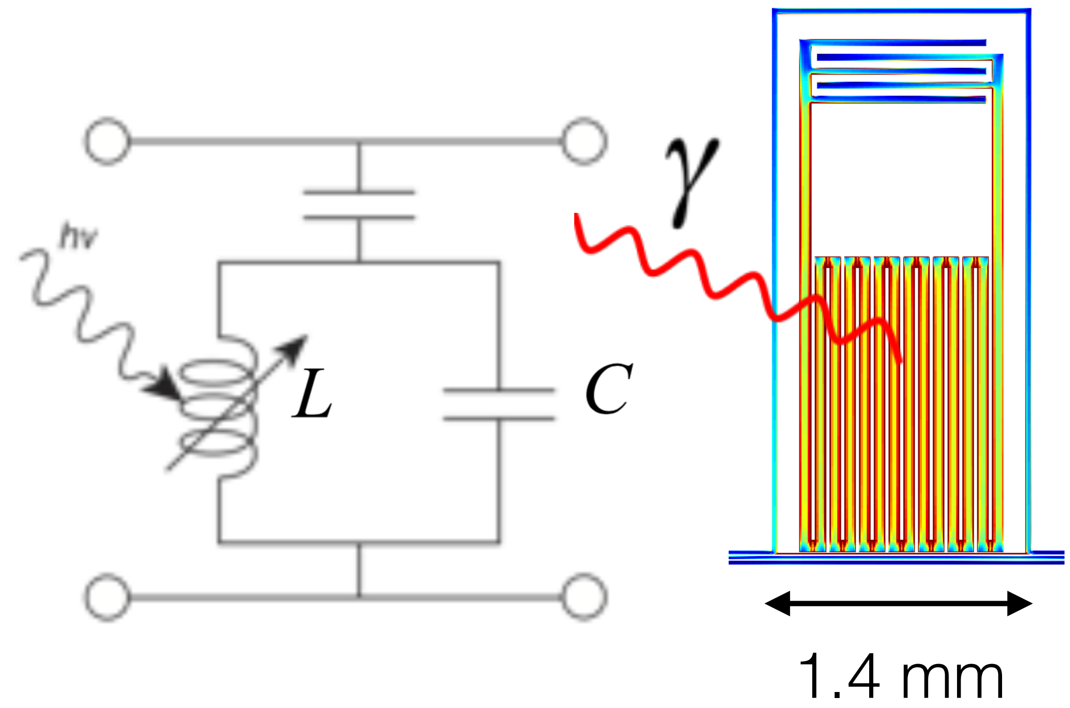


$$f_0 = \frac{1}{2\pi\sqrt{LC}}$$



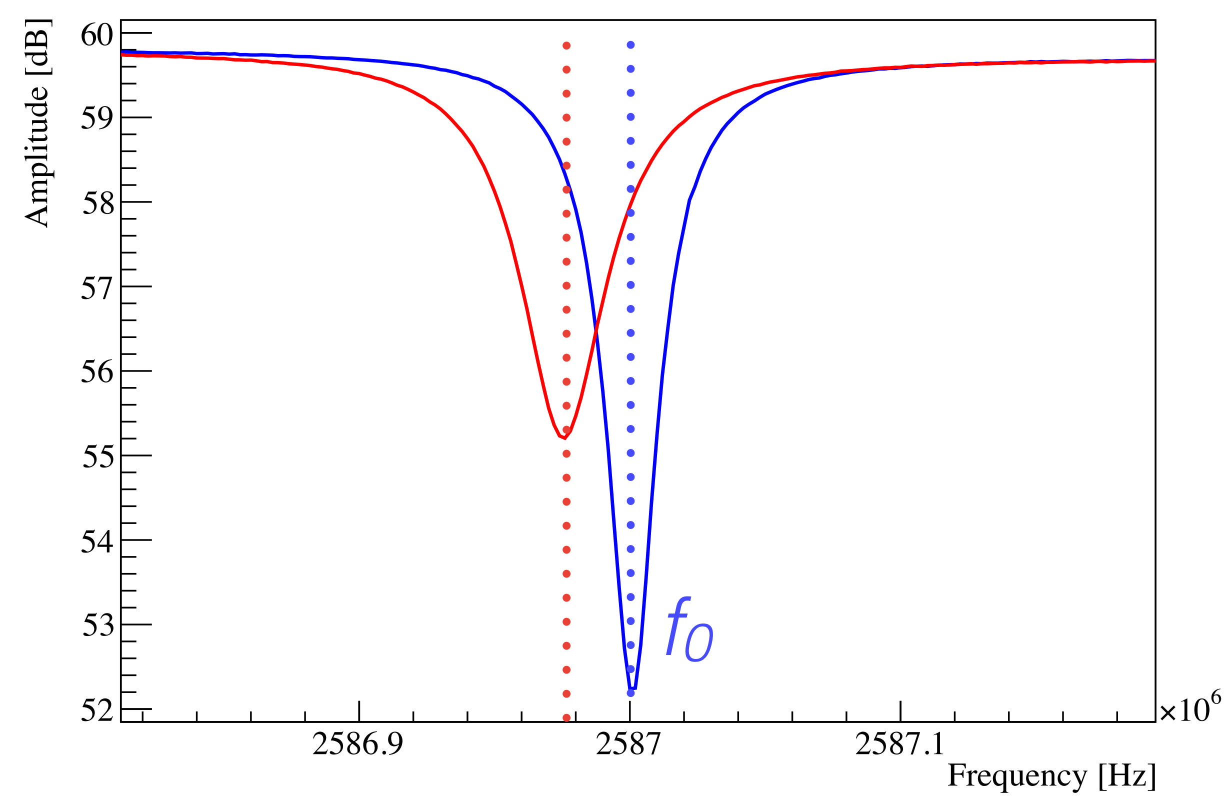
Kinetic Inductance Detector:KID

- Superconductors operated well below the critical temperature T_c
- Biasing with high frequency AC current (ν ~ GHz) they exhibit a kinetic inductance (L_k) -> caused by the inertia of the Cooper pairs
- By coupling the superconductor with a capacitor, a high merit factor RLC circuit can be realized ($Q \sim 10^4 - 10^5$)

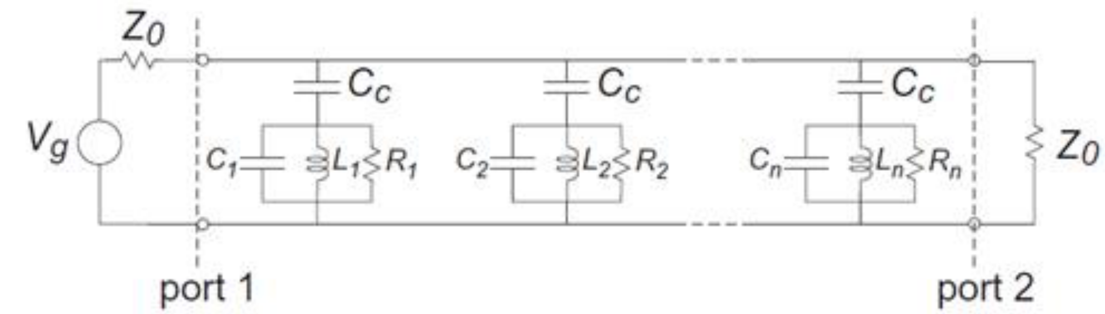


$$f_0 = \frac{1}{2\pi\sqrt{LC}}$$

- **A photon interaction breaks the Cooper pair -> the kinetic inductance changes -> the resonance shape and frequency change**

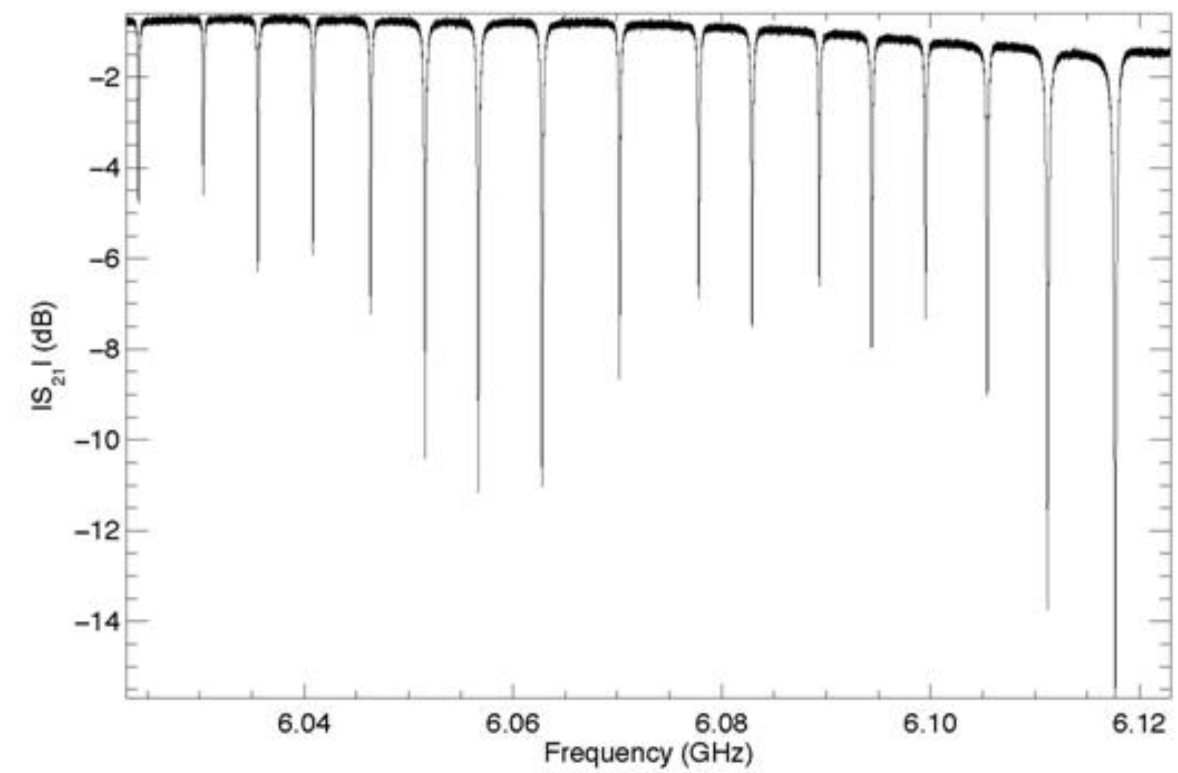


Kinetic Inductance Detector:KID



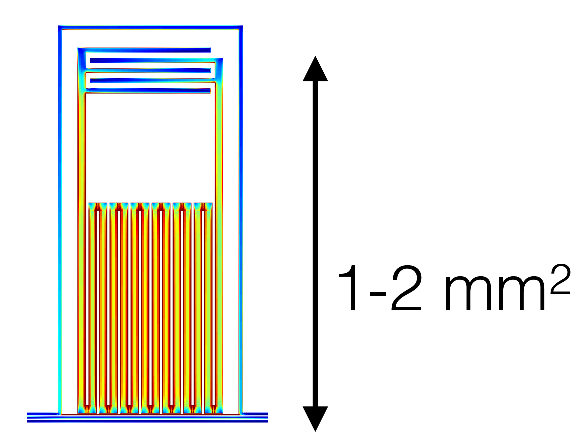
Advantages:

- Natural multiplexing in the frequency domain
- Excellent sensitivity -> baseline energy resolution ~eV
- Stable response and operation in a wide temperature range if $T << T_c$

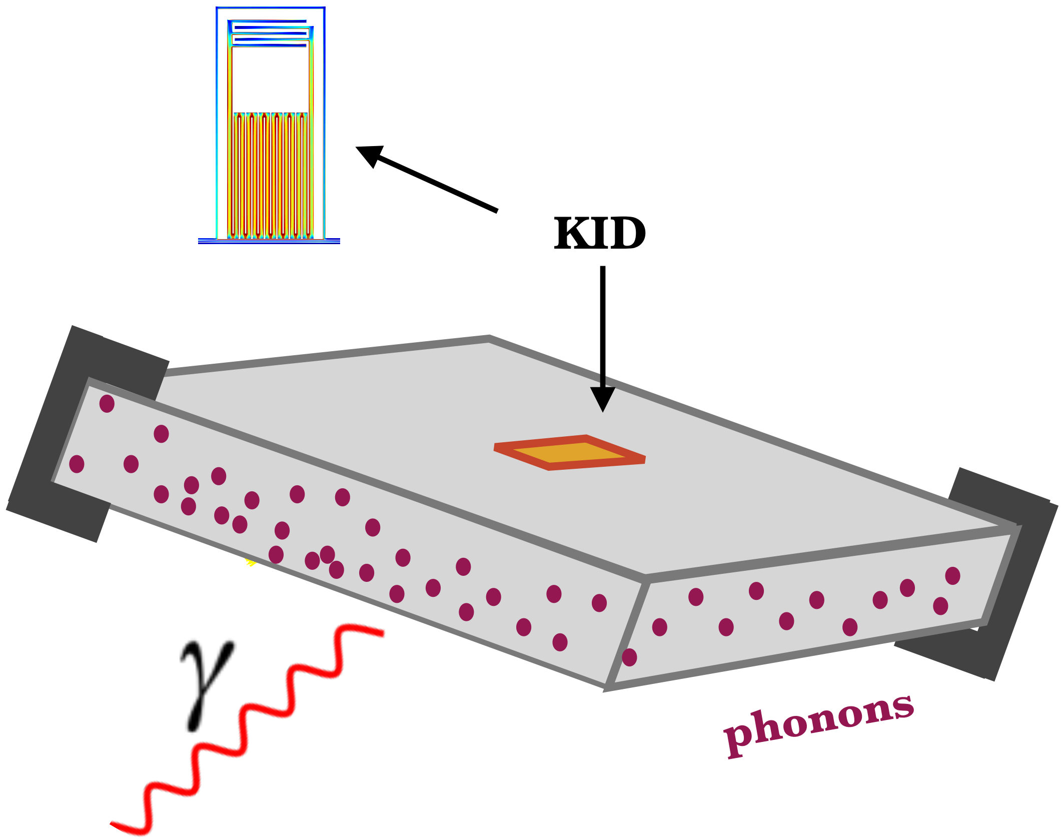


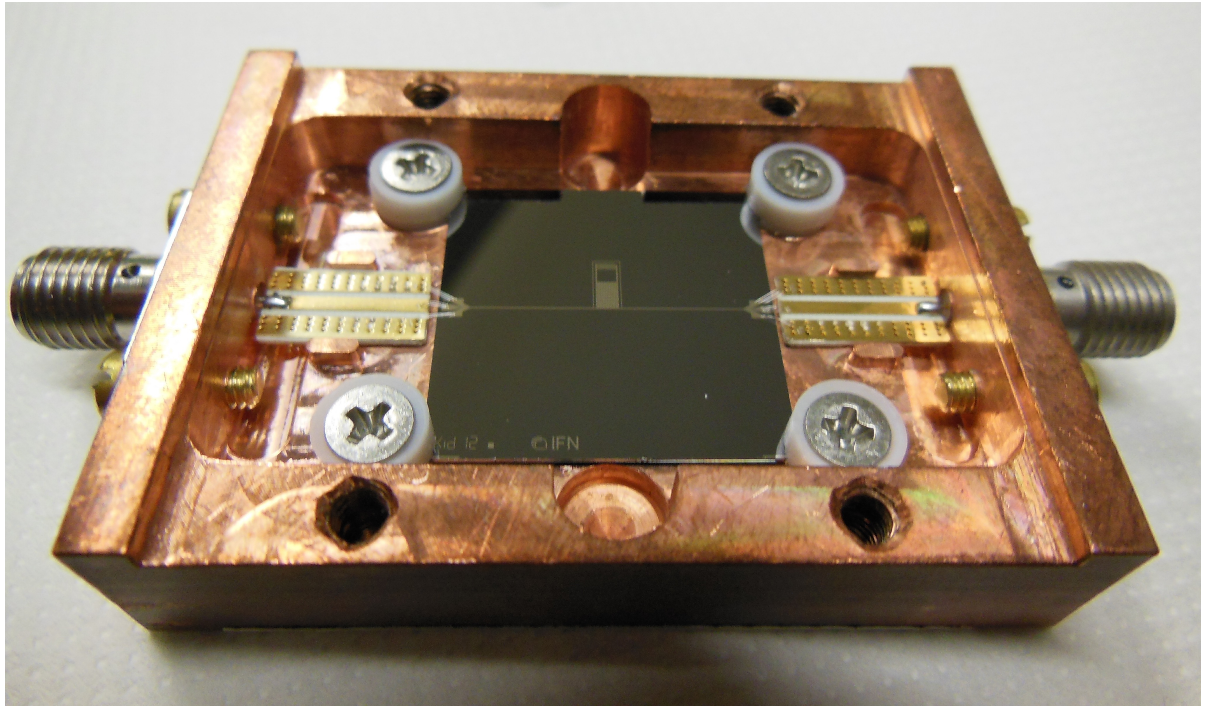
But..

- Poor active surface -> few mm^2

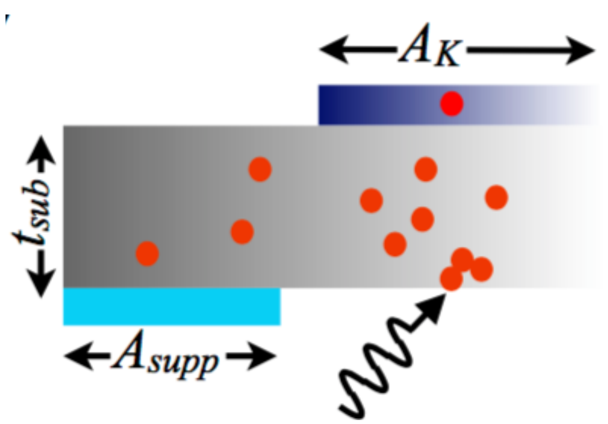


Phonon-mediated approach





- To get around the poor KID active surface an indirect detection of the photon interactions was proposed



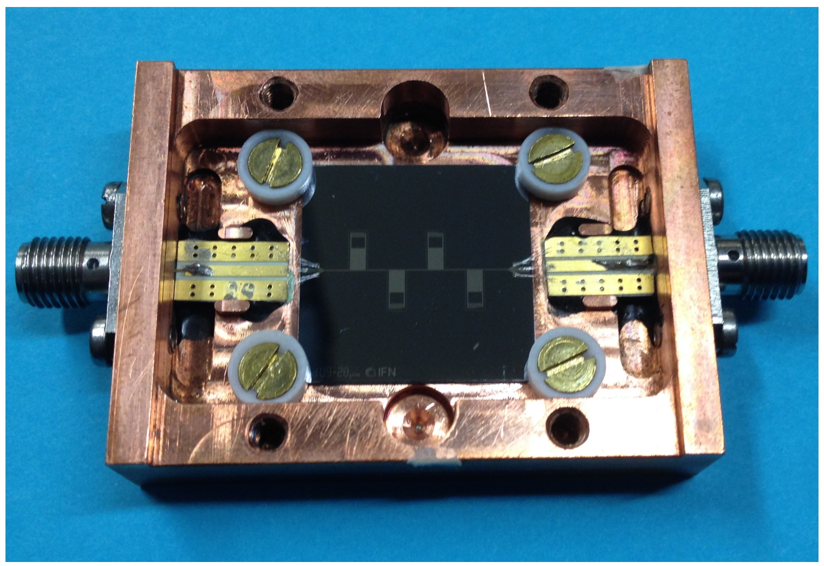
- KIDs are evaporated on a large (cm²) insulating substrate (Si or Ge) that mediates the photon interactions converting them into phonons

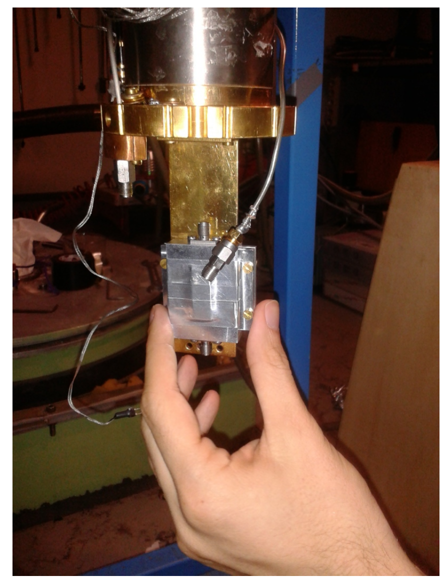
$$\frac{1}{\epsilon} = 1 + \frac{1}{N_K A_K p_K}\left(A_{supp}\, p_{supp} + A_{sub}\frac{t_{sub}/v_{sound}}{\tau_{thermal}}\right)$$

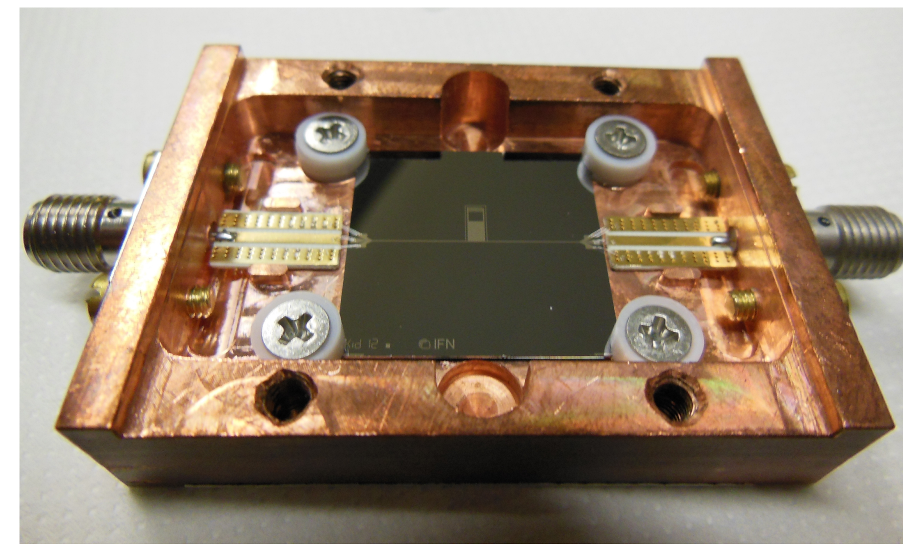
- ….. with a drawback: **phonons collection efficiency**

CALDER

Cryogenic Wide-**A**rea **L**ight **D**etector with **E**xcellent **R**esolution
ERC Starting Grant, from March 2014







3 main phases

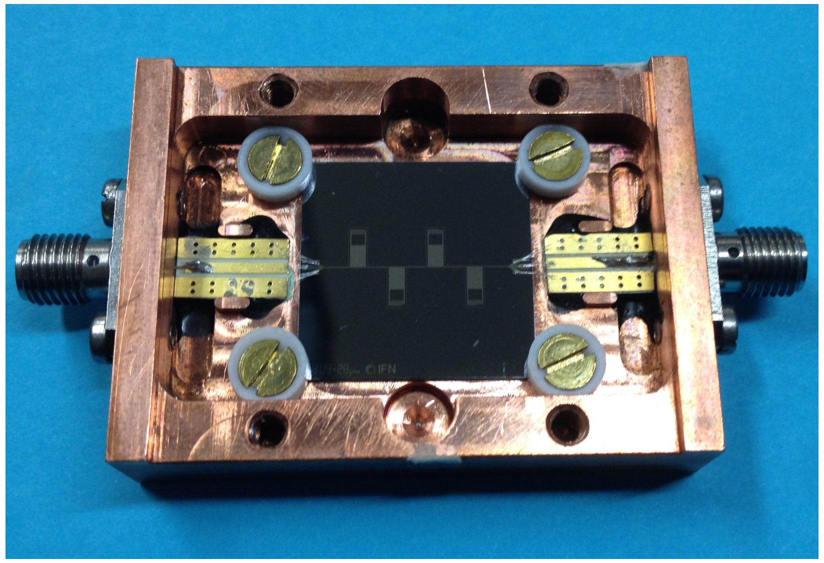
1. Read-out and analysis tools; optimization of the detector geometry using Al resonator -> 80 eV RMS

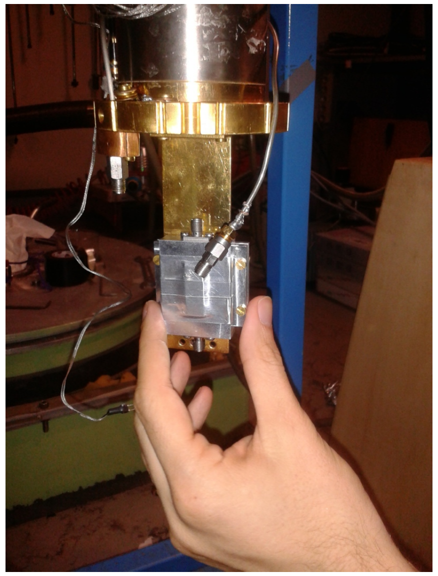
2. Test of more sensitive superconductors, such as TiN, Ti+TiN, or TiAl -> resolution < 20 eV

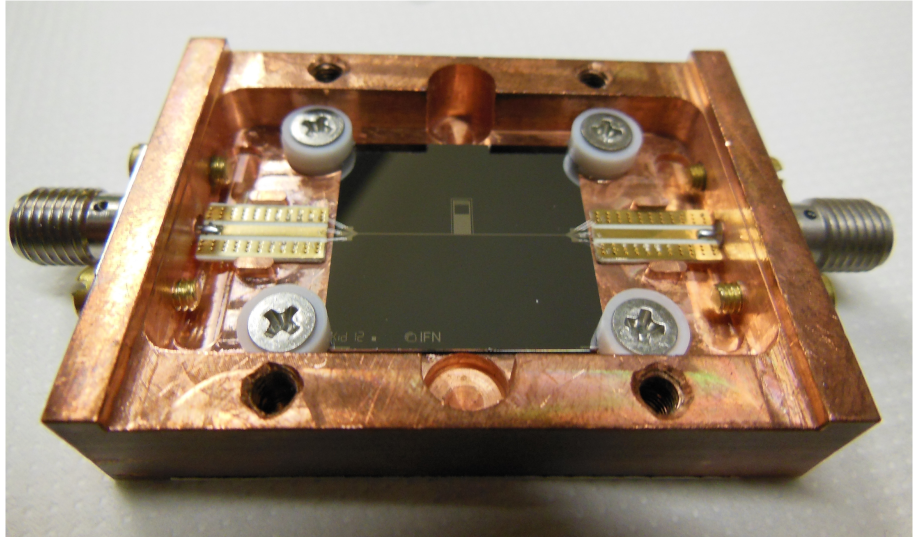
3. Large-scale test of the final detectors on TeO_2 array @ Laboratori Nazionali del Gran Sasso.

CALDER

Cryogenic Wide-**A**rea **L**ight **D**etector with **E**xcellent **R**esolution
ERC Starting Grant, from March 2014





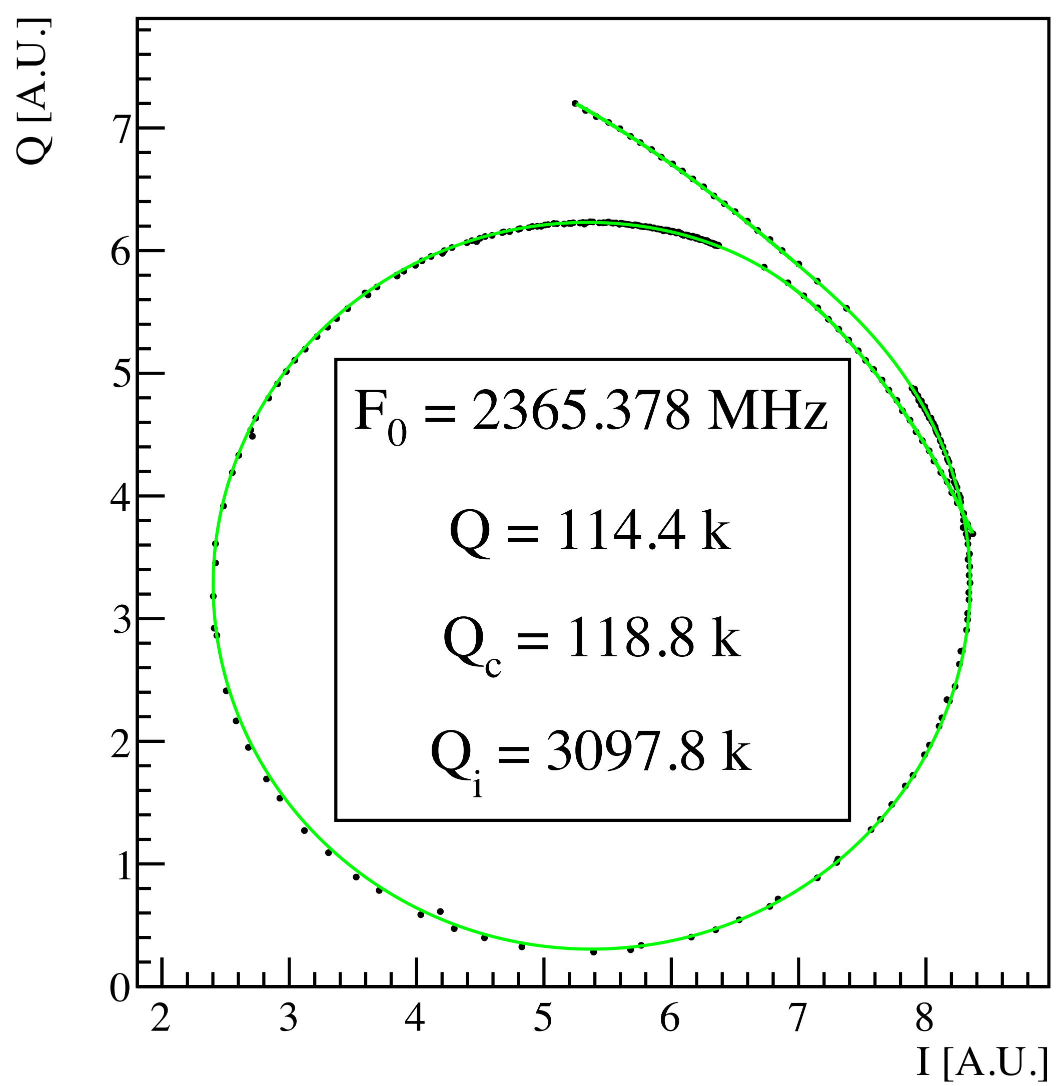


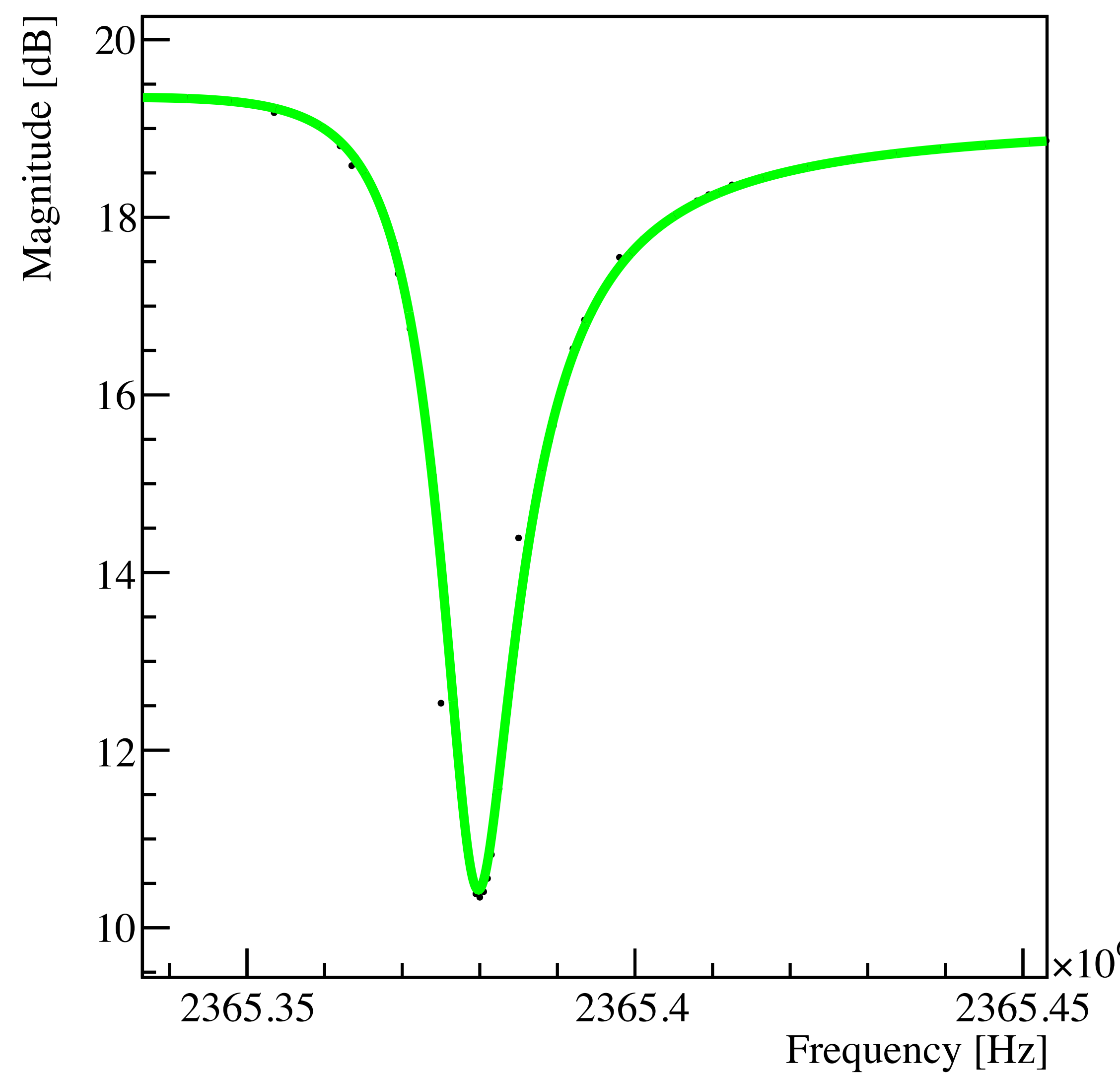
3 main phases

1. Read-out and analysis tools; optimization of the detector geometry using Al resonator -> 80 eV RMS
2. Test of more sensitive superconductors, such as TiN, Ti+TiN, or TiAl -> resolution < 20 eV
3. Large-scale test of the final detectors on TeO_2 array @ Laboratori Nazionali del Gran Sasso.

Resonators characterization

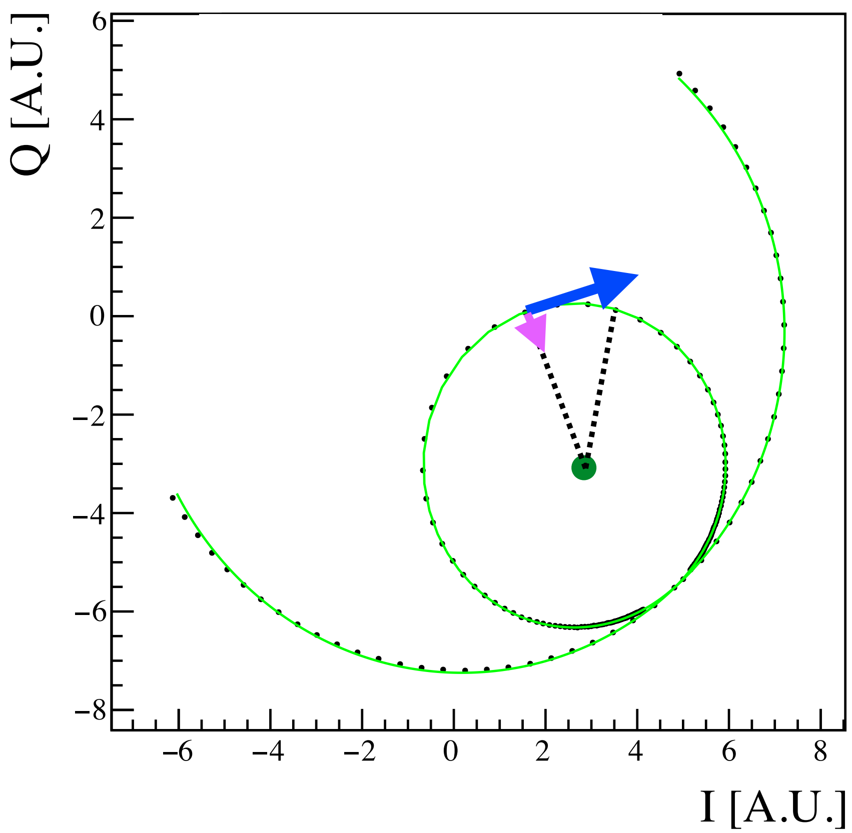
Basic resonance parameter evaluation with a fit of the frequency sweep of the transmitted signal



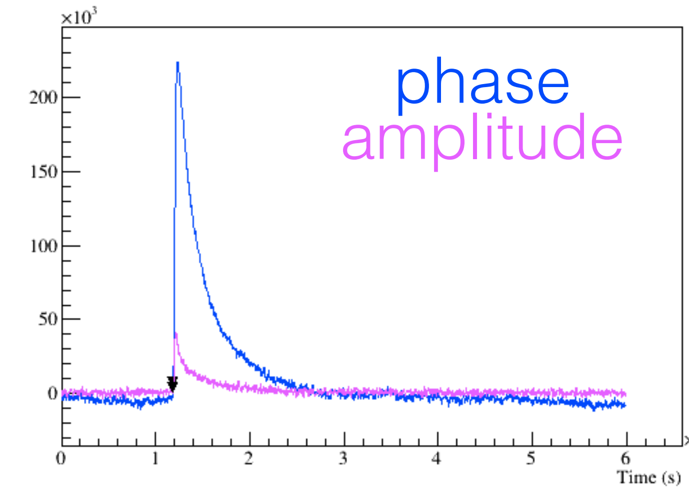


N. Casali et al., J.Low.Temp.Phys. **184** (2016)

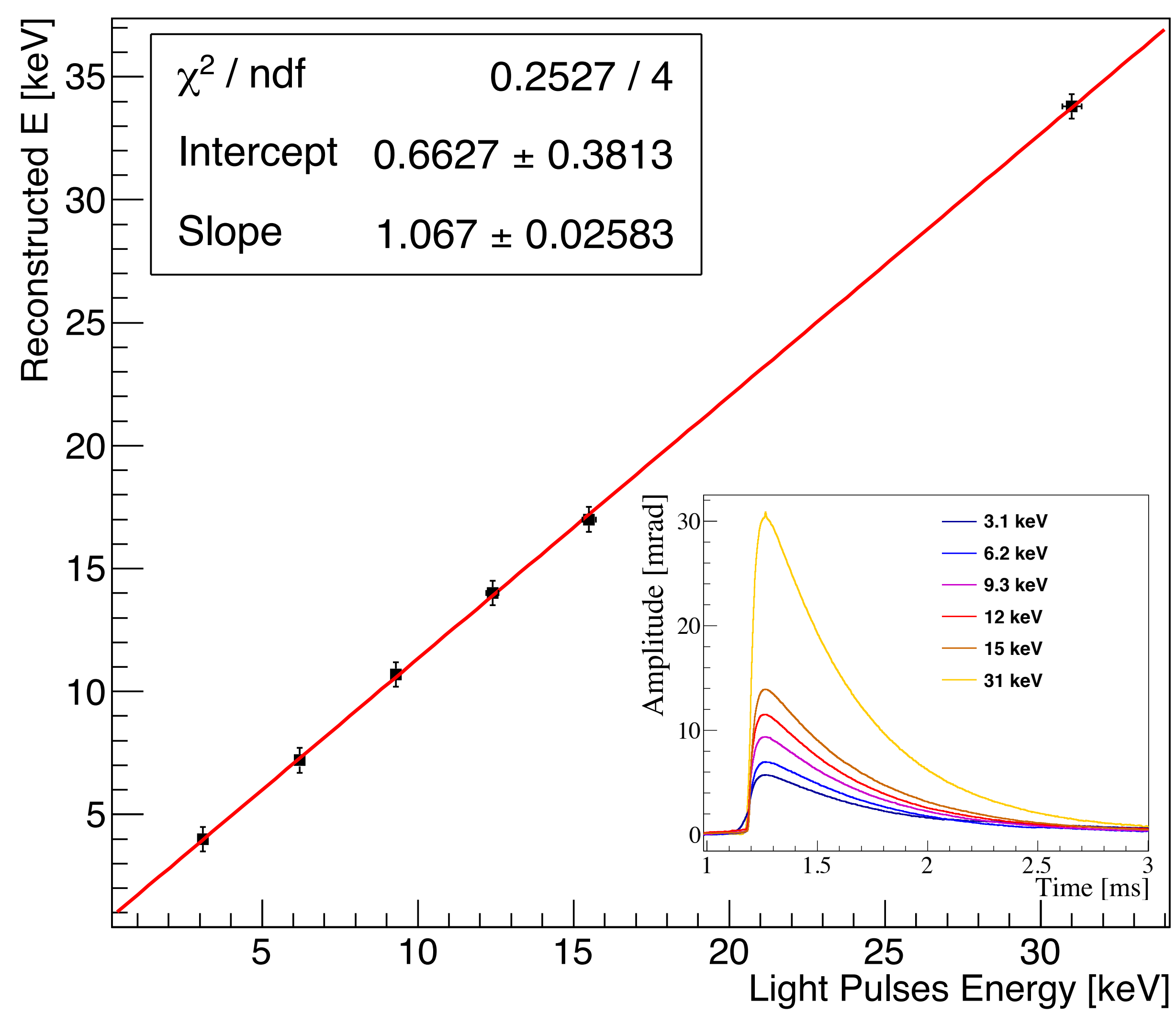
Detectors characterization



From the center of the resonance loop we monitor the amplitude and phase variations induced by energy depositions

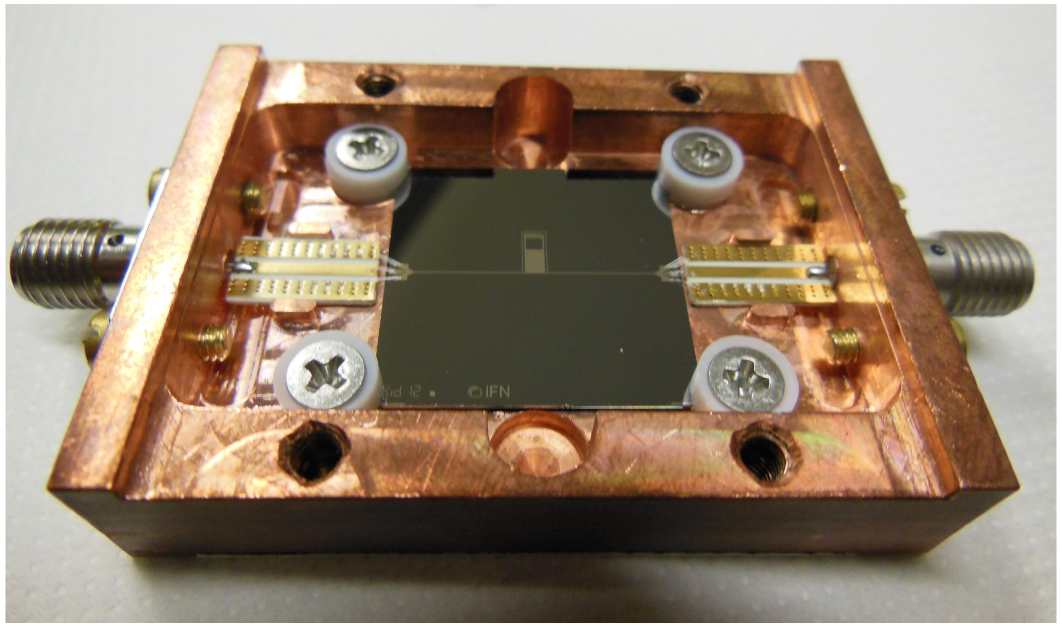


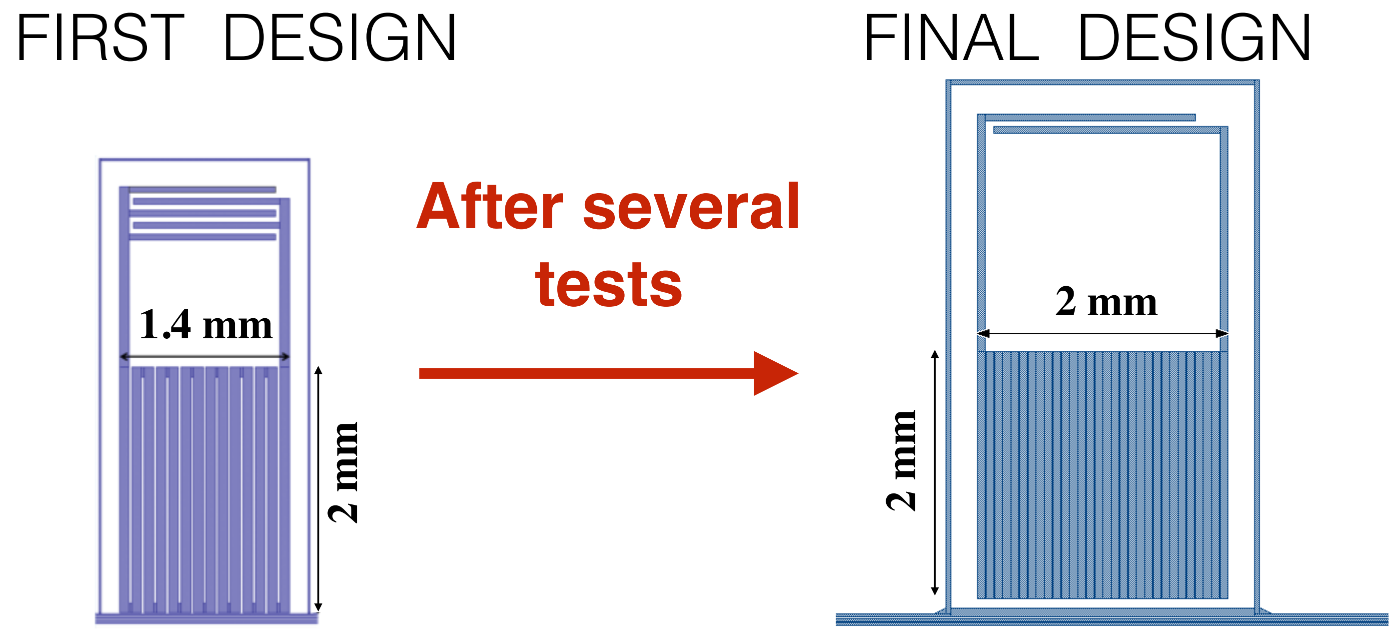
Detector response to optical pulses

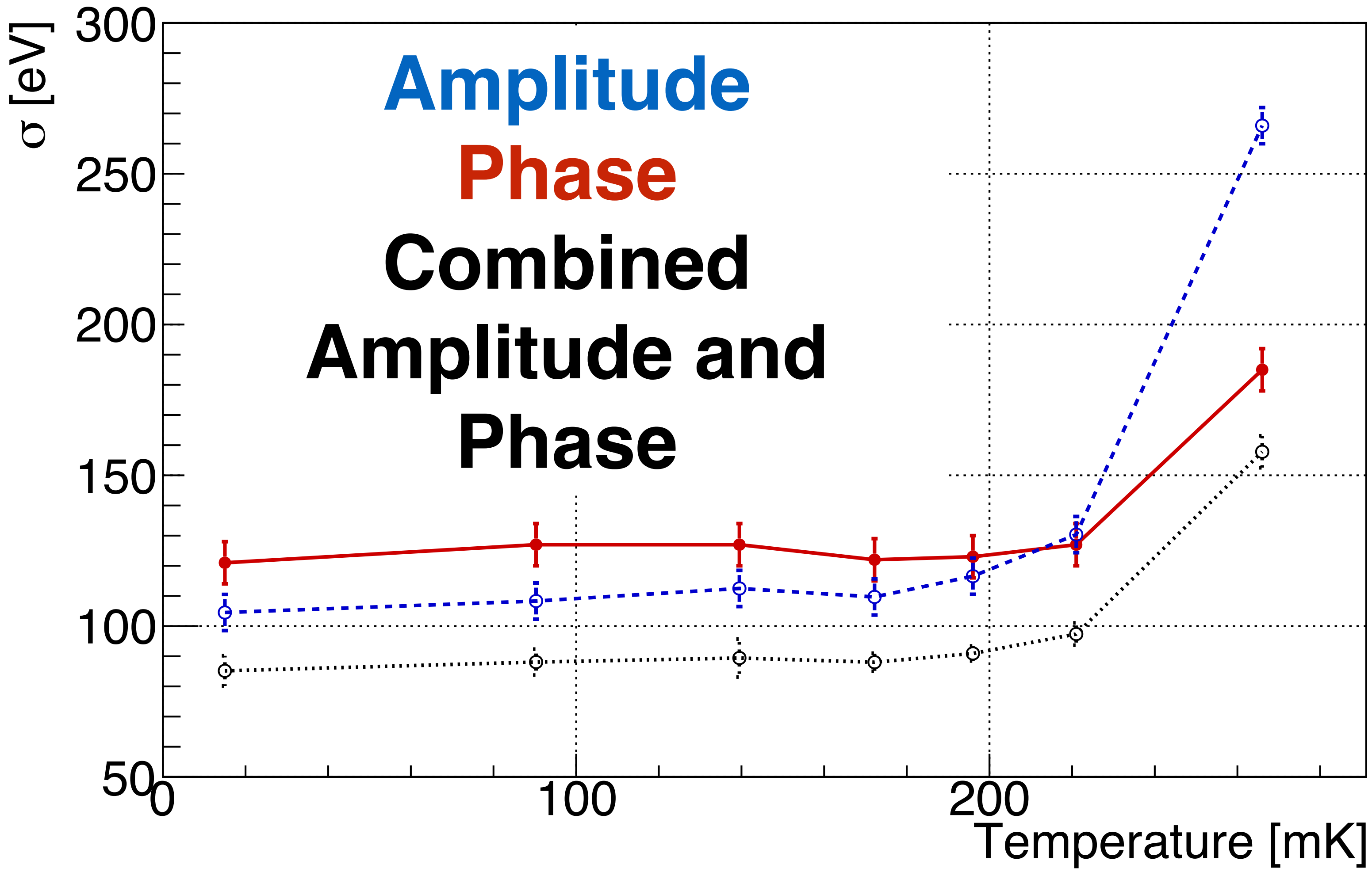


The energy depositions are originated by calibrated optical pulses (400 nm led bursts) in the range between 2 and 30 keV; and X-rays from $^{55}Fe/^{57}Co$ (as cross-check for the energy calibration)

Al detector optimization







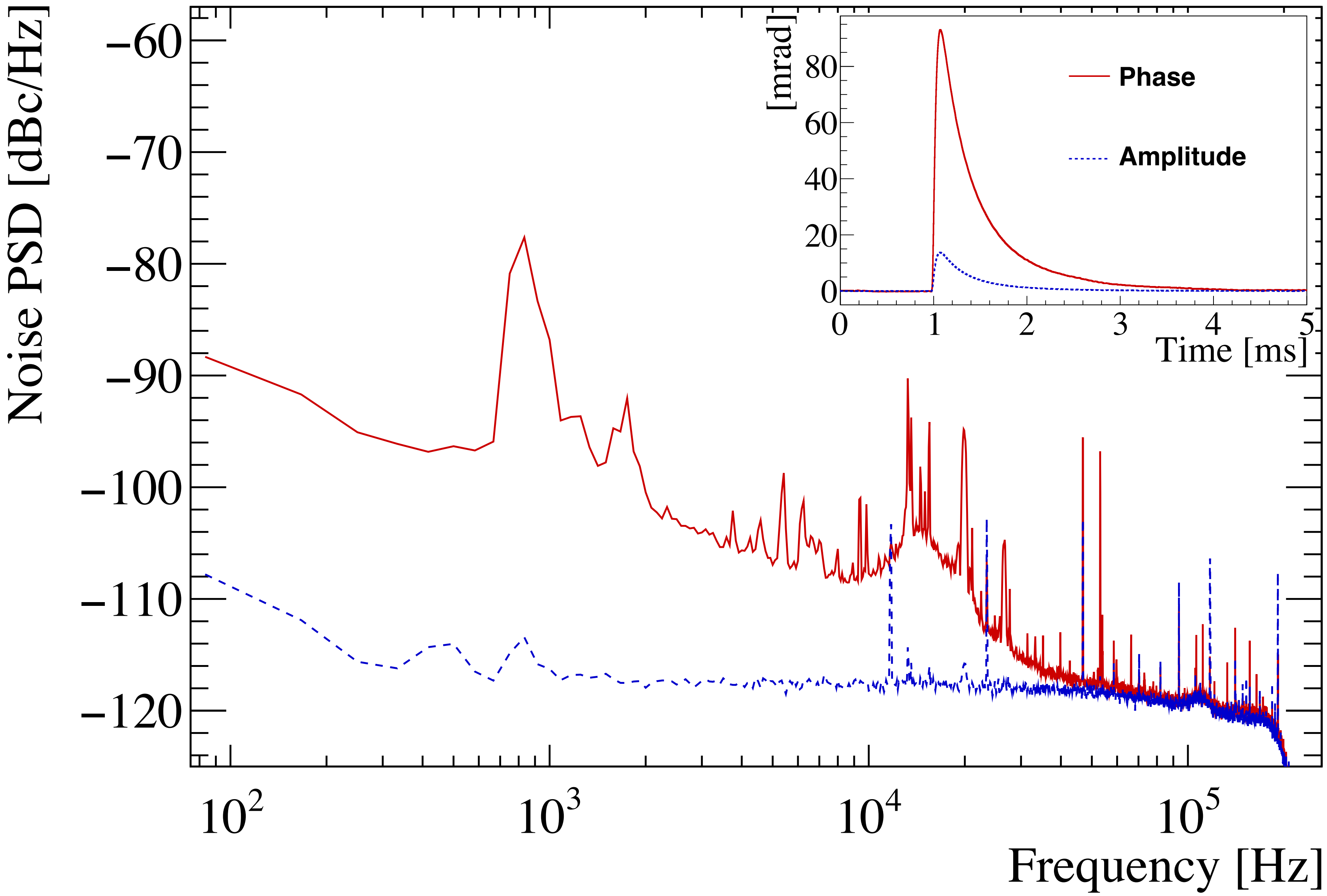
Resolution constant in a wide temperature range (10-200 mK)

Combining phase and amplitude we obtained 82±4 eV

L. Cardani et al, Appl.Phys.Lett. 107 (2015) 093508
L. Cardani et al, Appl.Phys.Lett. 110 (2017) 033504

Phase noise excess

Amplitude noise is consistent with the noise temperature of the cold amplifier (T_N ~ 7 K). The phase one is affected by an excess at low frequency.



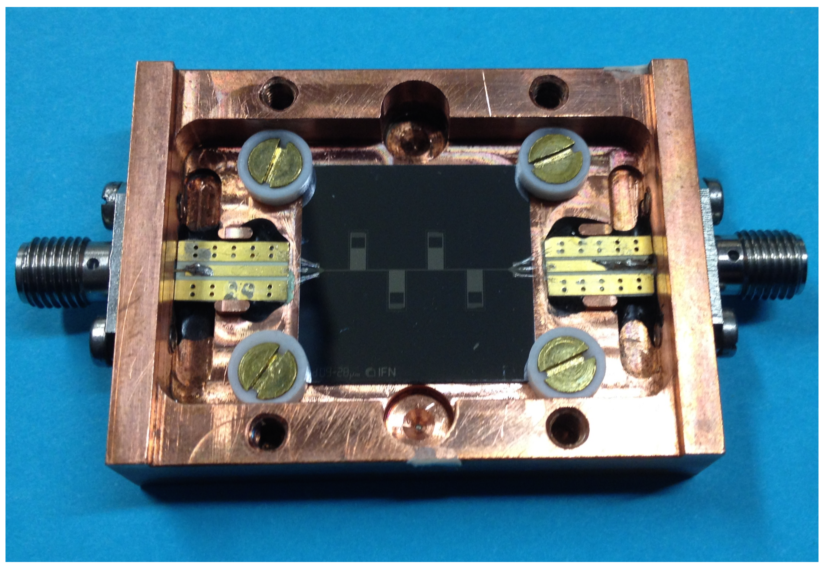
It is not generation-recombination or two level system noise (constant with temperature)

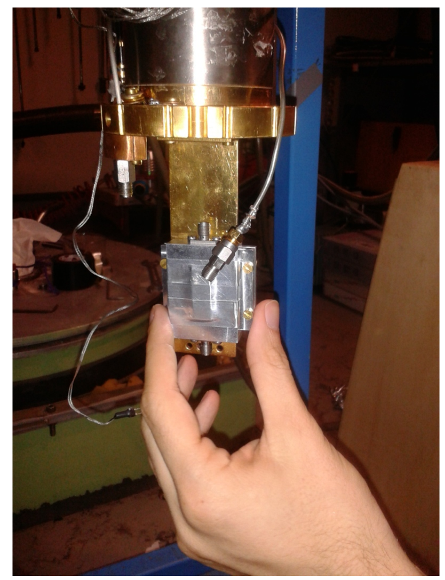
It seems not originated by electronic read-out chain

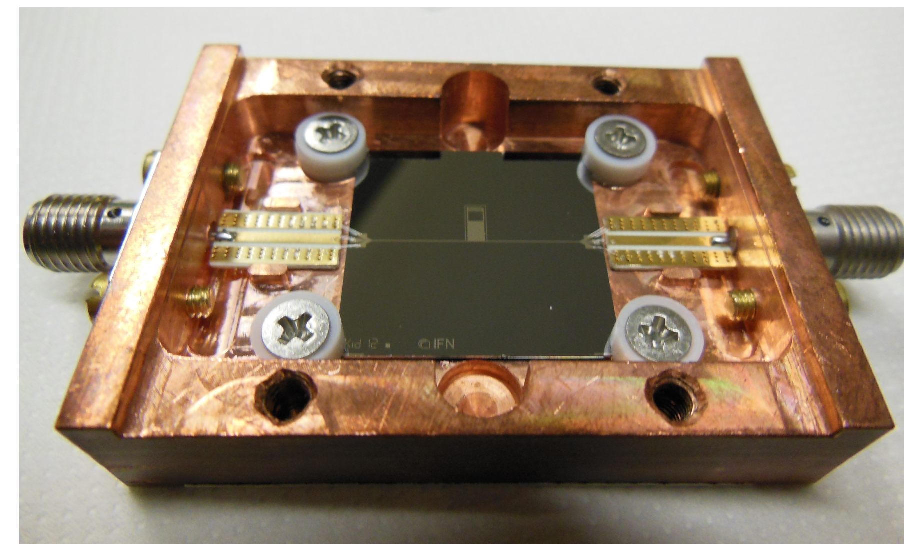
Its origin is still under investigation

CALDER

Cryogenic Wide-**A**rea **L**ight **D**etector with **E**xcellent **R**esolution
ERC Starting Grant, from March 2014







3 main phases

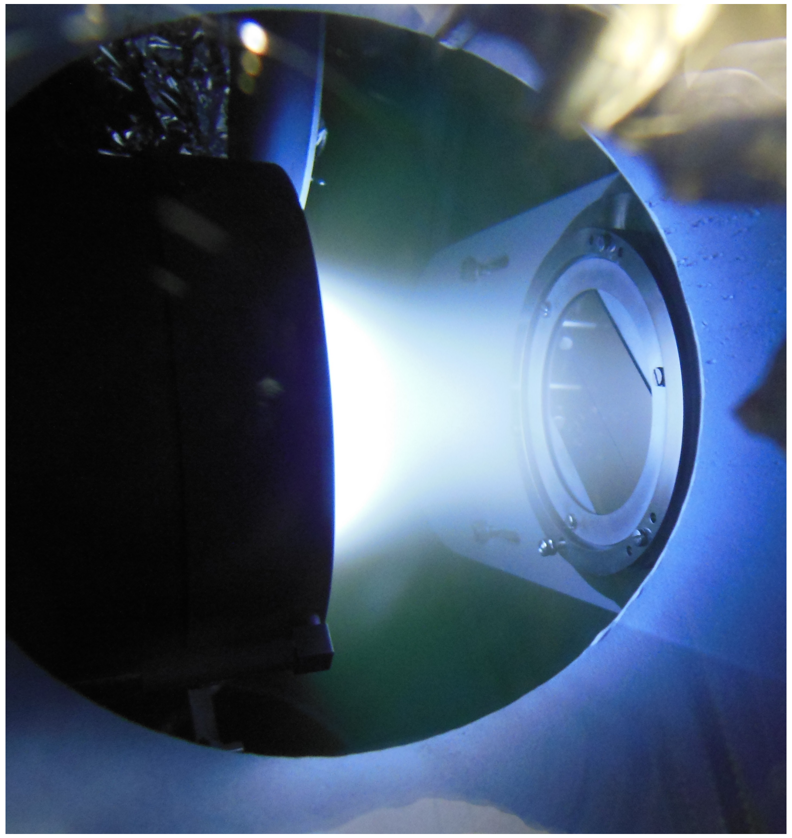
1. ✓ Development of the acquisition and analysis tools and optimization of the detector geometry -> Aluminum resonator; well known material, target resolution of about 80 eV RMS
2. Test of more sensitive superconductors, such as TiN, Ti+TiN, or TiAl, in order to lower the energy resolution < 20 eV
3. The optimized light detectors will be coupled to an array of TeO_2 bolometers to prove the potential of this technology @ Laboratori Nazionali del Gran Sasso.

CALDER phase2

- Testing more sensitive superconductors

$$\Delta E \propto \frac{T_C}{\epsilon\sqrt{QL}}$$

	Al	TiAl	Ti+TiN	TiN sub- stec.
Tc [K]	1,2	0.6-0.9	0.5-0.8	0,5
L [pH/ square]	0,5	1	6	up to 50

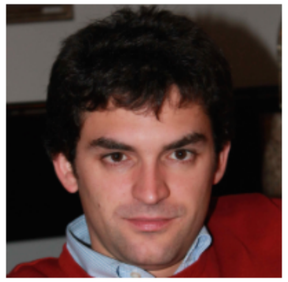


First test on TiAl and AlTiAl in collaboration with **Institut Neel Grenoble** (J. Goupy, M. Calvo and A. Monfardini) and **CSNSM-IN2P3 Paris** (H. Le Sueur)

Encouraging results: **30 eV RMS** reached (paper in preparation)

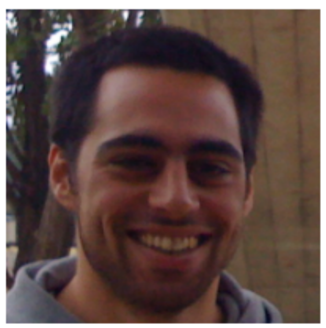
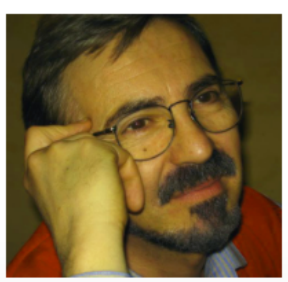
Conclusions

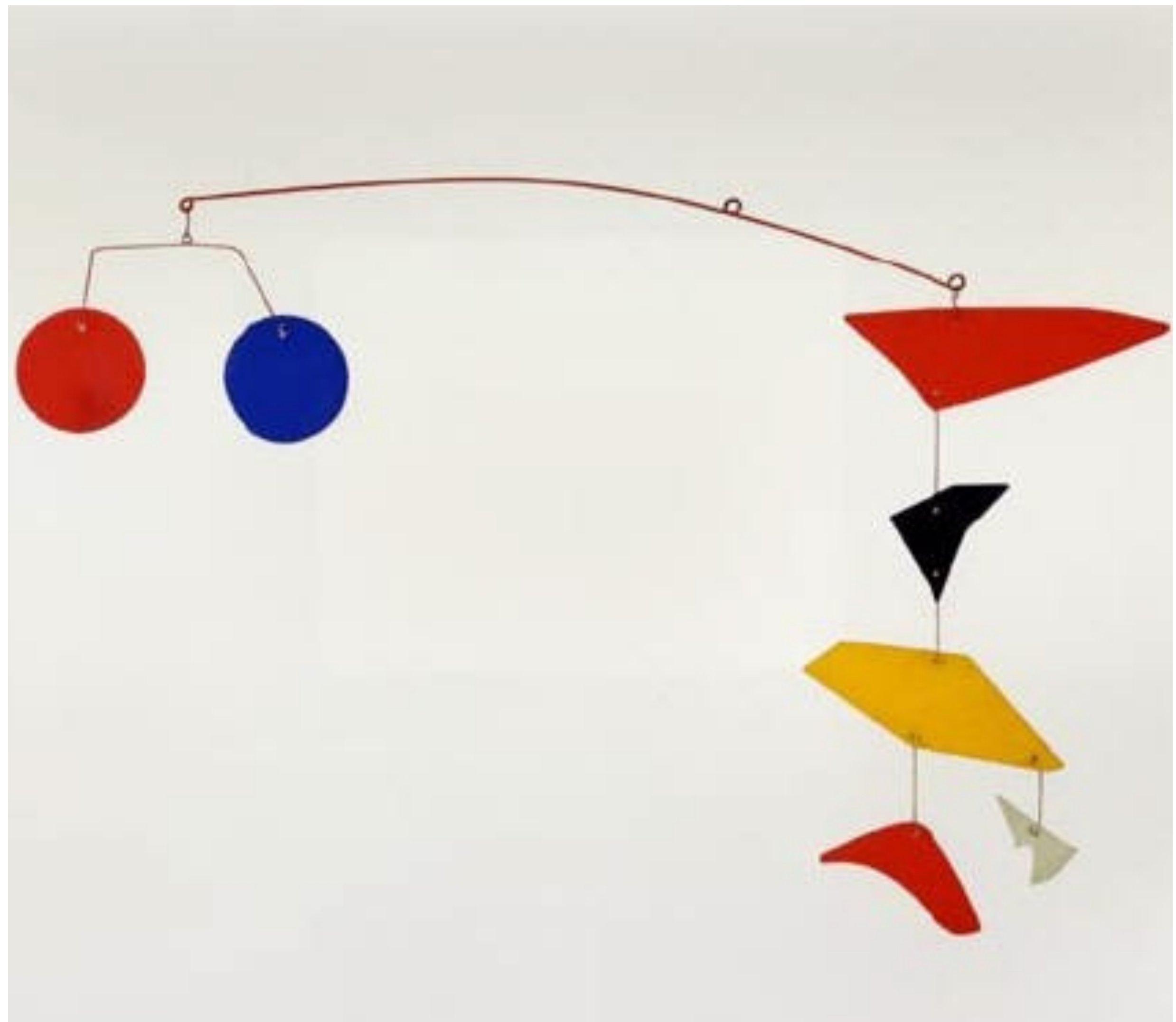
- The CALDER project aims to develop the light detector for the next generation bolometric experiments exploiting KIDs
- The phase1 of the project is accomplished: Al resonator with 80 eV baseline RMS
- An excess noise in phase direction is always present and its origin is still under investigation
- Encouraging results from the first AlTiAl resonator (30 eV RMS)



Thank you for the attention !



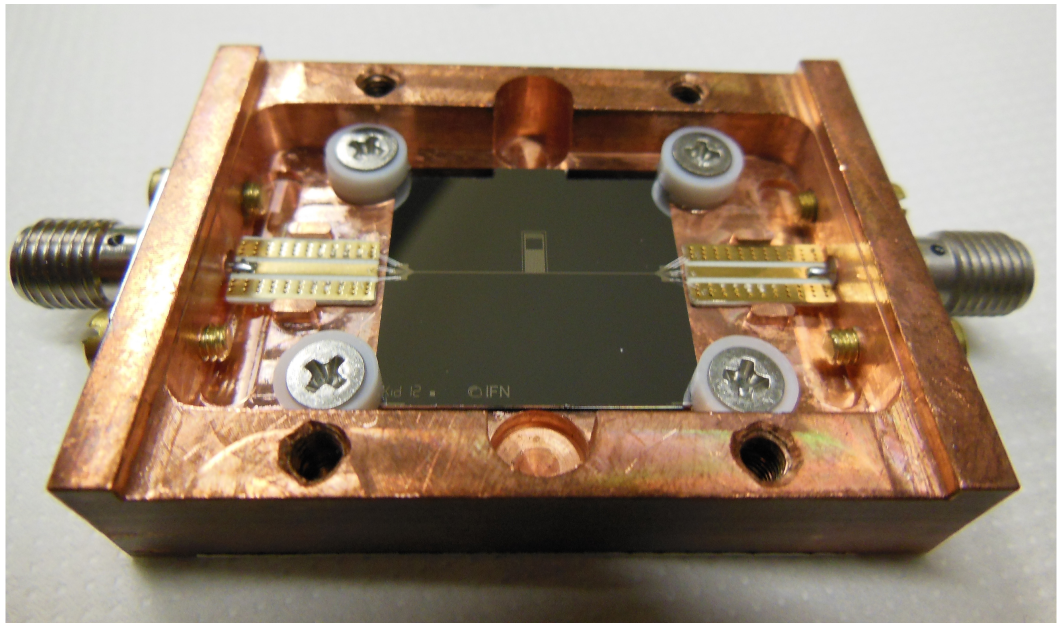


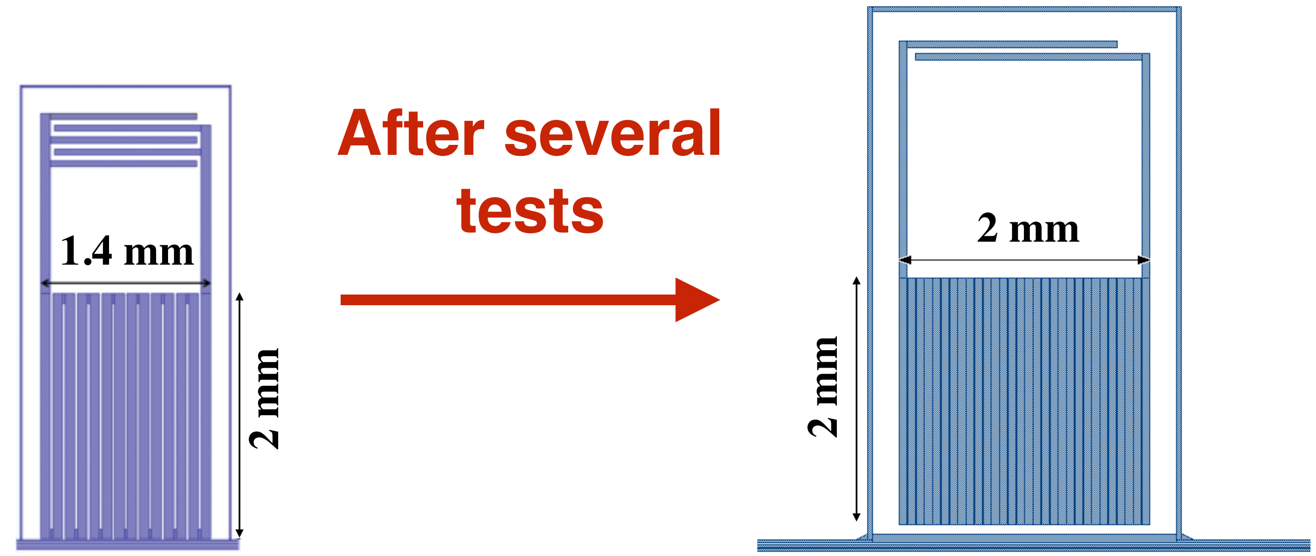



CALDER public webpage:
http://www.roma1.infn.it/exp/calder/new

BACKUP

Al detector optimization





1. **Single KID design** -> Absence of cross-talk and/or competition among pixels in the absorption of the propagating phonons.
2. **Increase active surface** -> higher phonons collection efficiency
3. **Increase the signal amplitude** -> Higher kinetic inductance fraction and higher Q
4. **Study several thickness Al films** -> 25, 40 and 60 nm

Resonance parameter evaluation

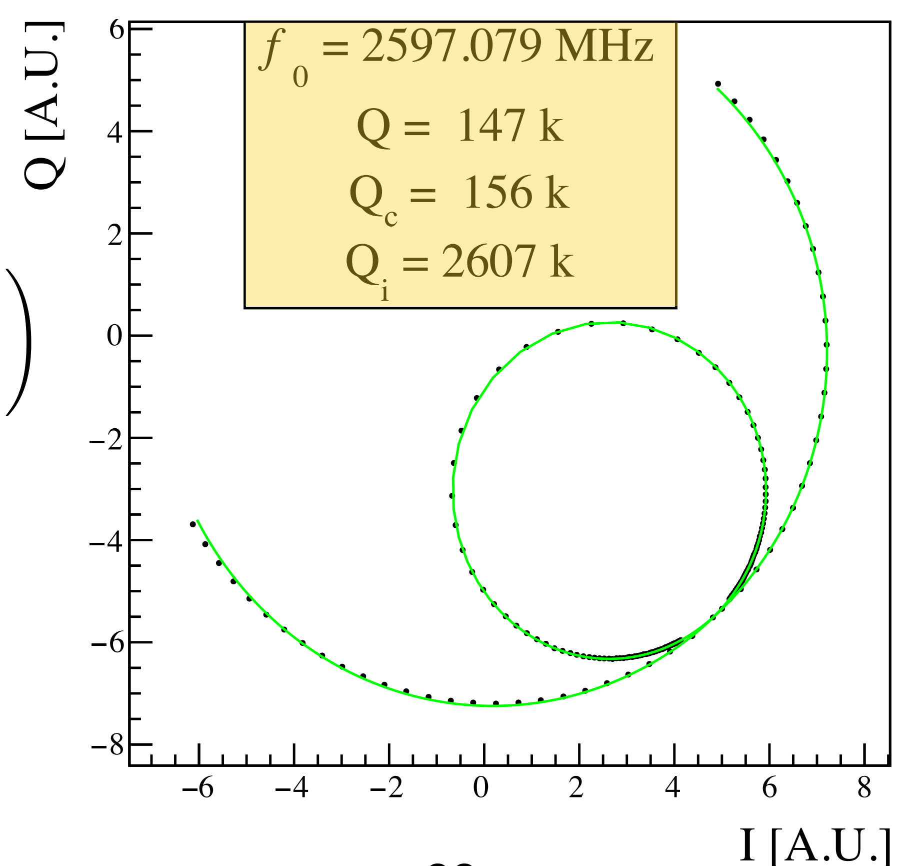
The transmitted microwave through feed-line (S_{21}) is affected not only by the resonator:

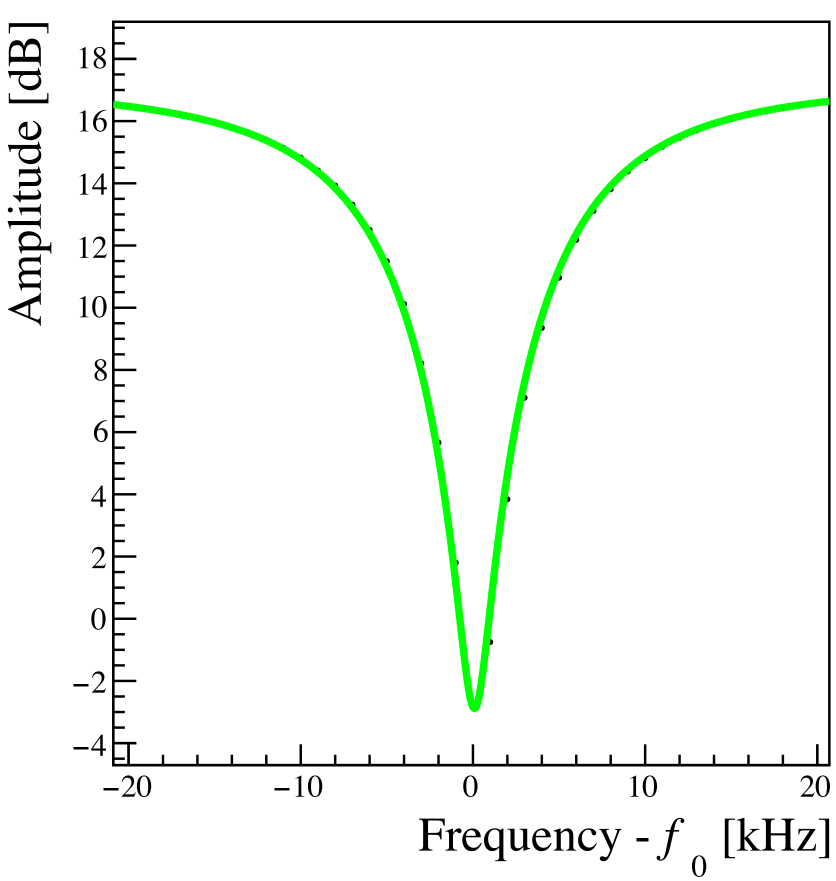
1) **read-out chain**
2) **impedance mismatches in proximity of the KID** [1]
3) **distortion of the resonance due to power absorbed by the resonator** [2]

$$S_{21}^{Tot} = Z_c + \left(A\cos\left(-2\pi f \tau\right) + j \cdot B\sin\left(-2\pi f \tau\right)\right) \cdot e^{-j\phi} \cdot \left(1 - \frac{\frac{Q}{Q_c} e^{j\theta}}{\frac{1+j2y}{\cos\theta}}\right)$$

S_{21} is fitted in the (I,Q, f) space with the frequency sweep:

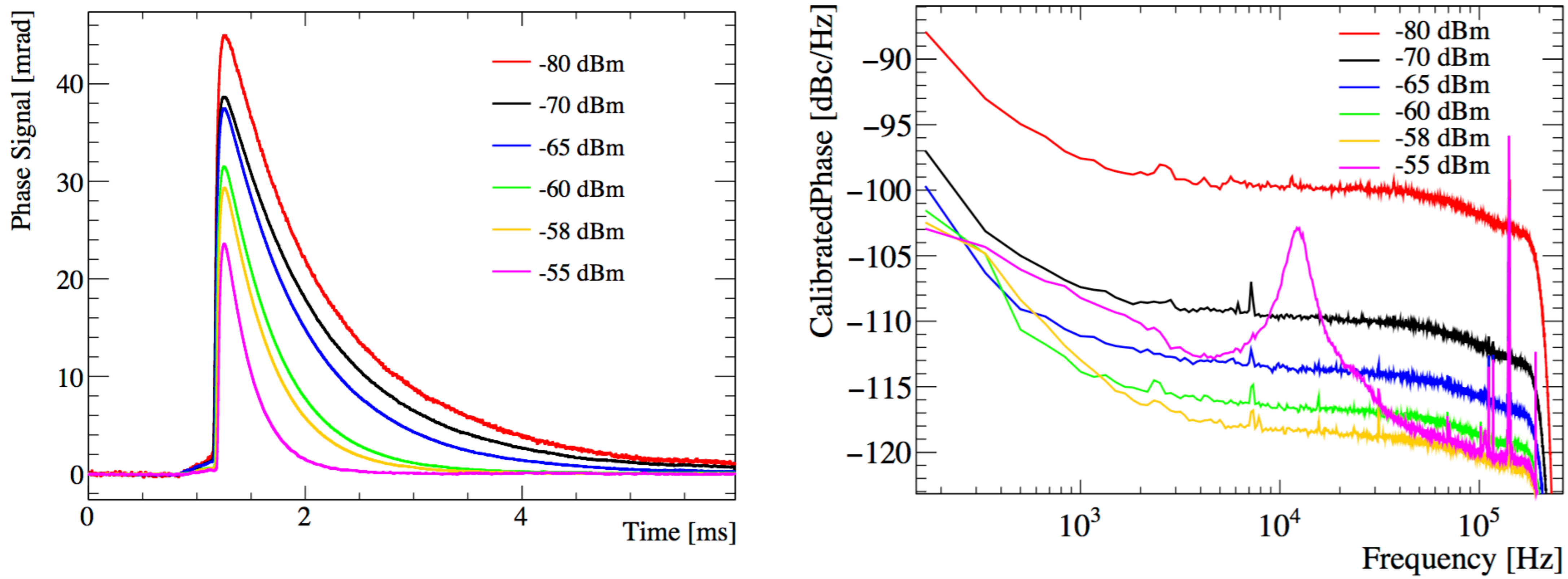
$$min\left(\sum_{n=0}^{N} \parallel S_{21}(f_n, 11par) - Data(f_n) \parallel^2\right)$$

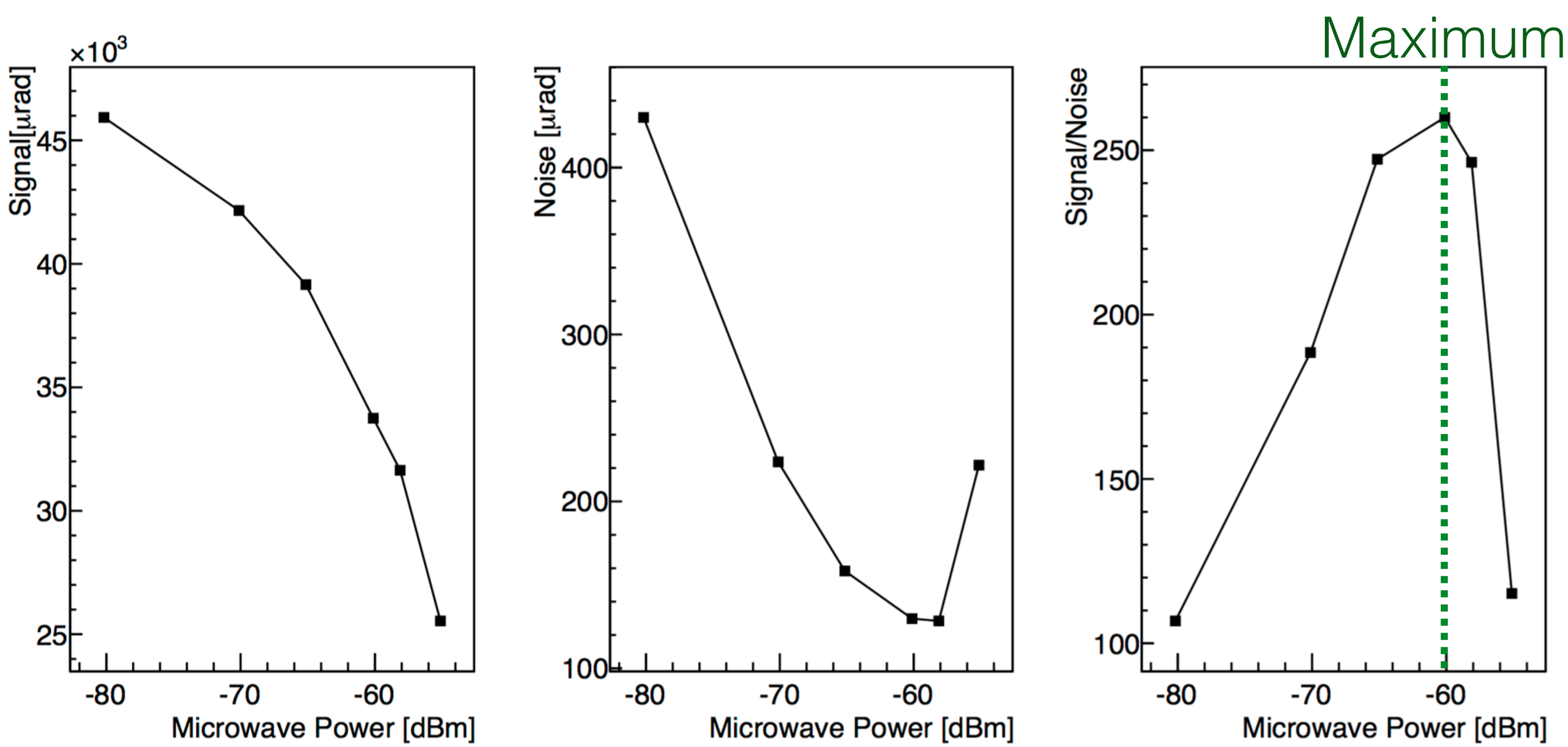




[1] M. S. Khalil et al., J. Appl. Phys. **111**, 054510 (2012)
[2] L. J. Swenson et al., J. Appl. Phys. **113**, 104501 (2013)
[3] N. Casali et al., J.Low.Temp.Phys. **184** (2016)

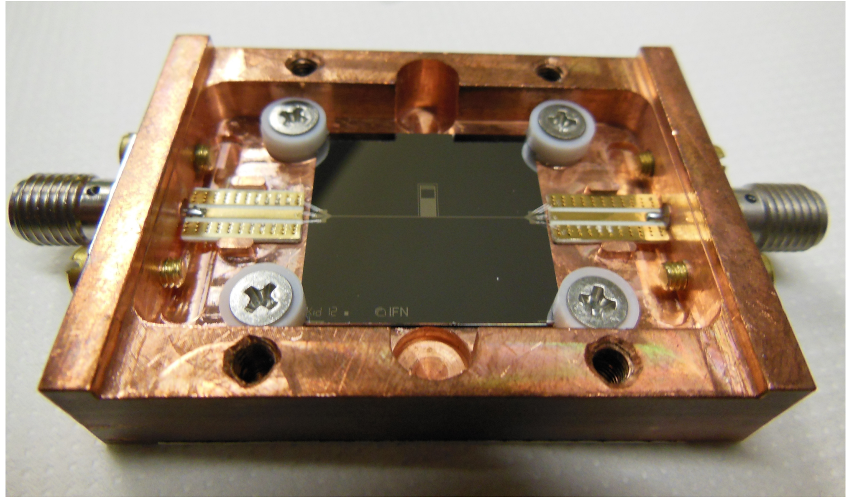
Detector operation: optimal microwave power

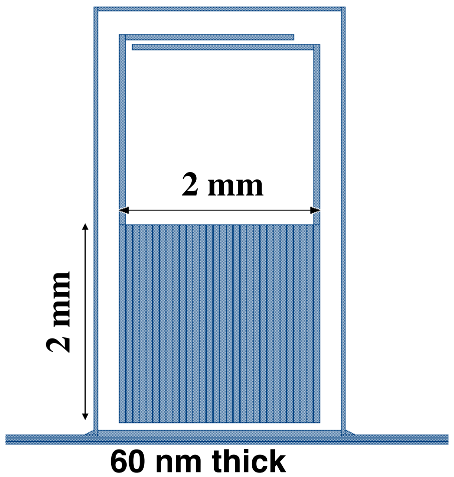




The detectors are operated in the most sensitive point, where the signal-to-noise ratio (S/N) is maximum

CALDER phase1: improved detector layout

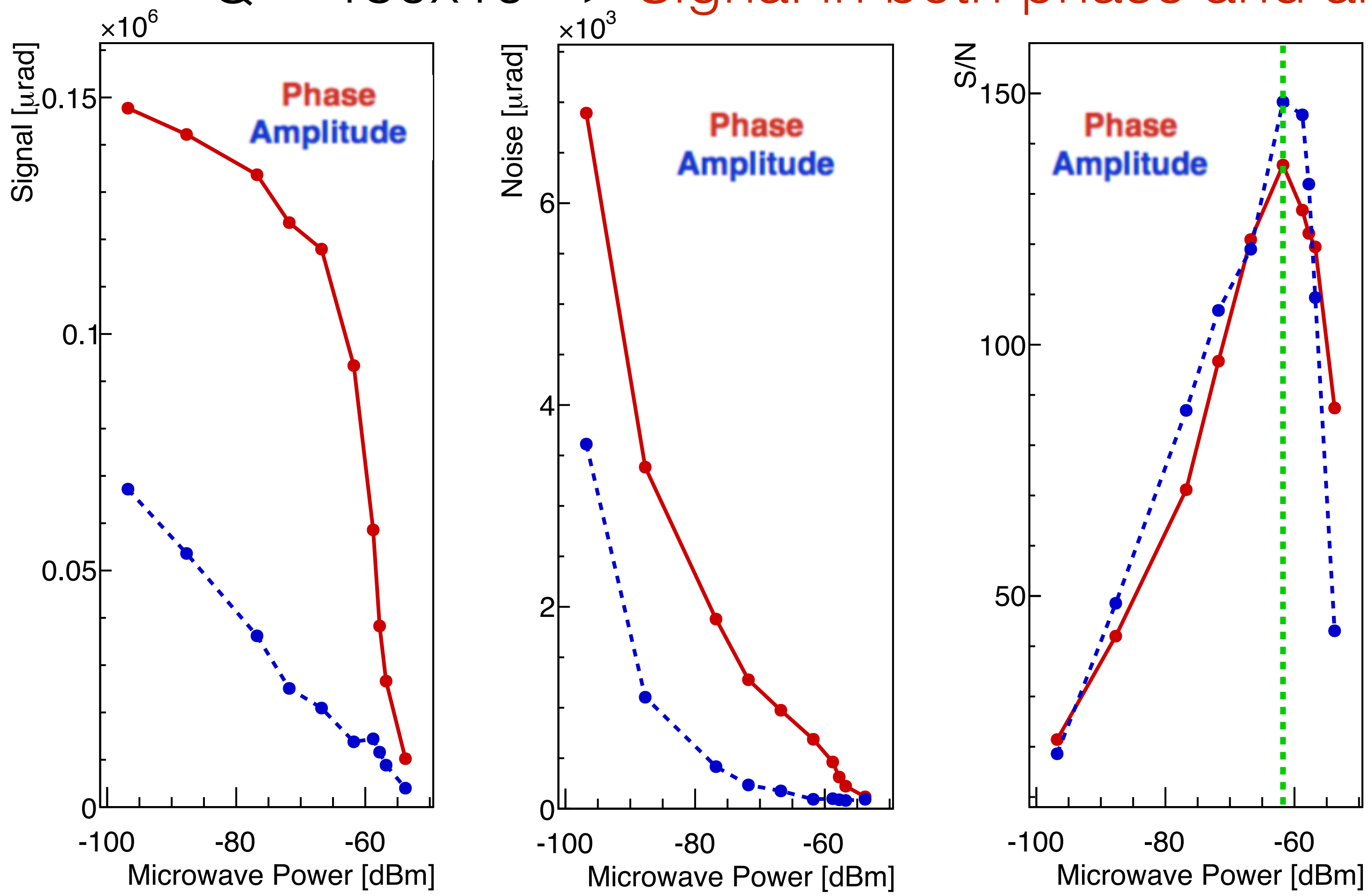




Active surface increase from 2.4 to 4 mm^2 -> Efficiency from 6.1 to 9.4%

Thickness 60 nm -> $Q_i > 2x10^6$

Q ~ $150x10^3$ -> Signal in both phase and amplitude increased by a factor 6



The signal to noise ratio in amplitude is competitive (better in the wp) with the phase one

We attribute this to the high values of Q and Q_i

Temperature scan: $\Delta f/f_0$

$$\frac{\delta f}{f_0} = -\frac{\alpha}{2} S_2(\omega, T) \frac{\delta n_{qp}}{2N_0\Delta}$$

$$\delta n_{pq} = 2N_0\sqrt{2\pi k_b T\Delta}\, e^{\left(\frac{-\Delta}{k_b T}\right)}$$