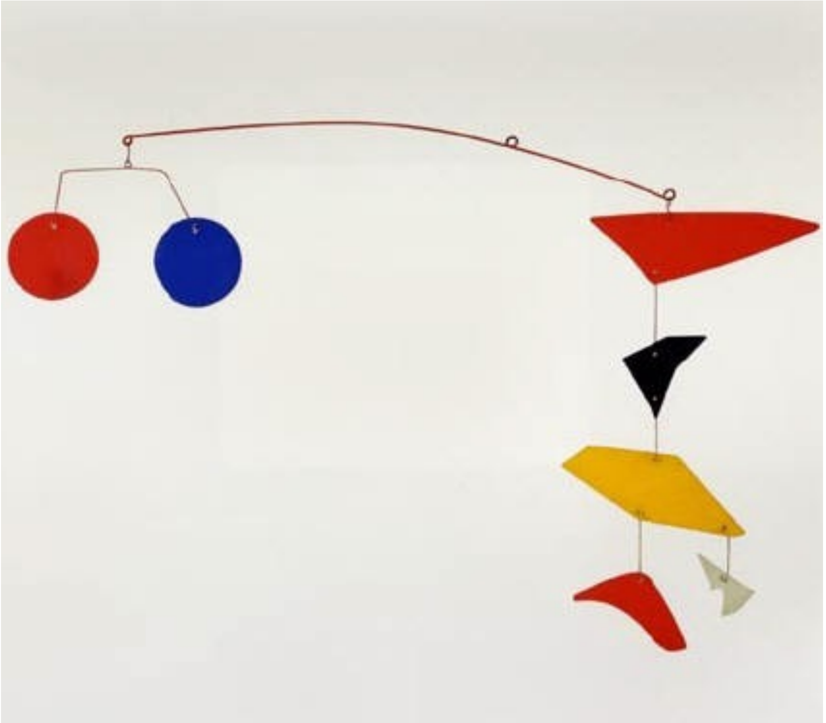
European Research Council

Istituto Nazionale di Fisica Nucleare
Sezione di Roma

INFN Istituto Nazionale di Fisica Nucleare

Cryogenic light detectors for background suppression: the CALDER project



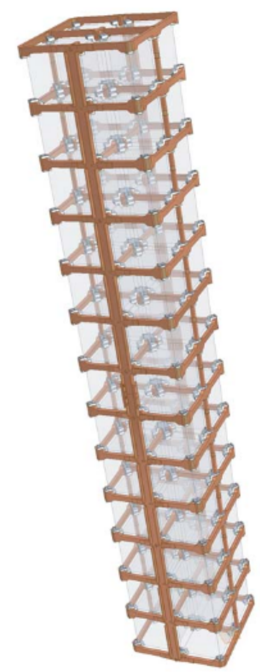
Nicola Casali on behalf of the CALDER collaboration - 14th Pisa Meeting on Advanced Detectors, La Biodola, Isola d'Elba (Italy) May 27 - June 2, 2018

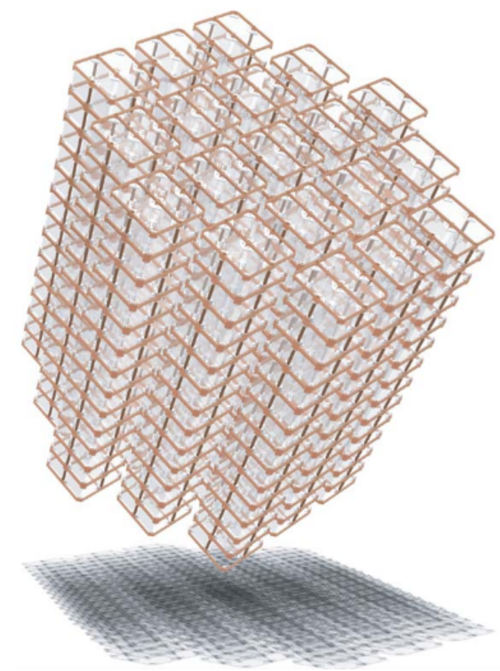
Why high sensitivity cryogenic light detectors?

- Improve the sensitivity of the next generation experiments searching for **Neutrino-less double beta decay**.

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

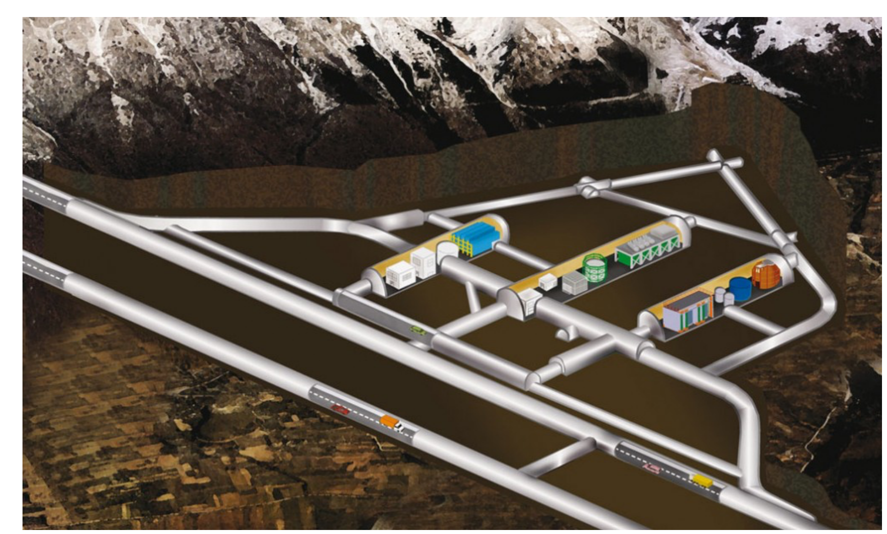
- The expected signal are two electrons with a total kinetic energy of ~ 2.5 MeV.





CUORE
988 TeO_2
bolometers;
now in data taking

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



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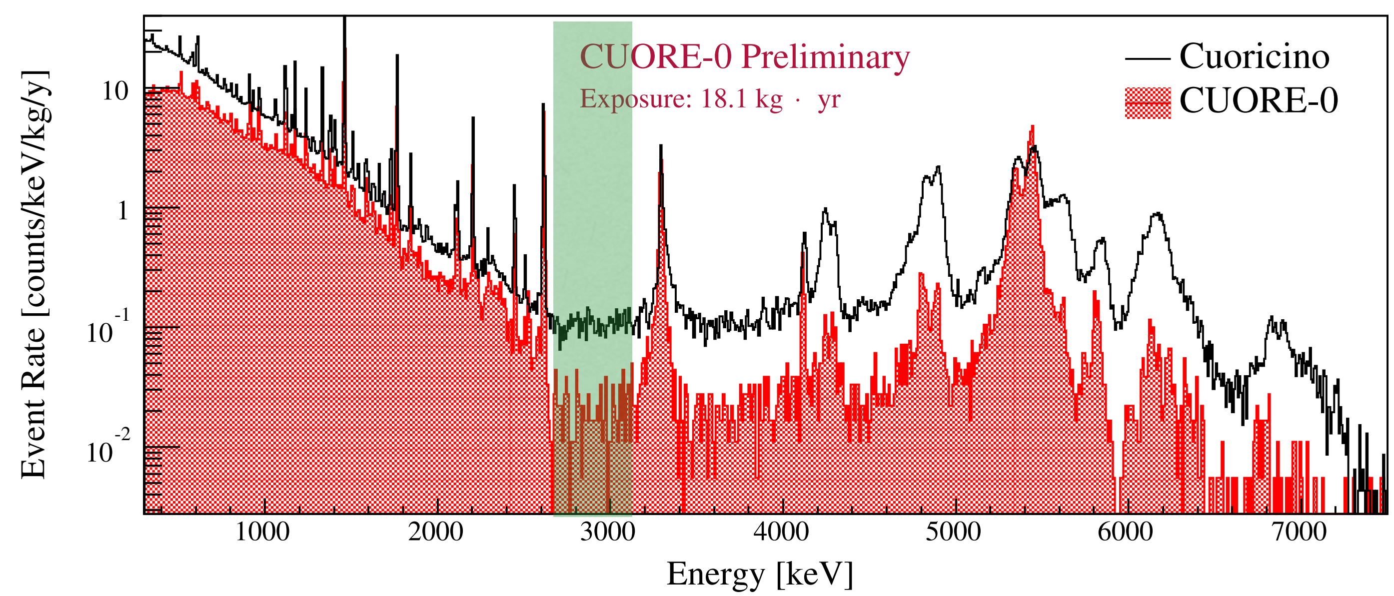
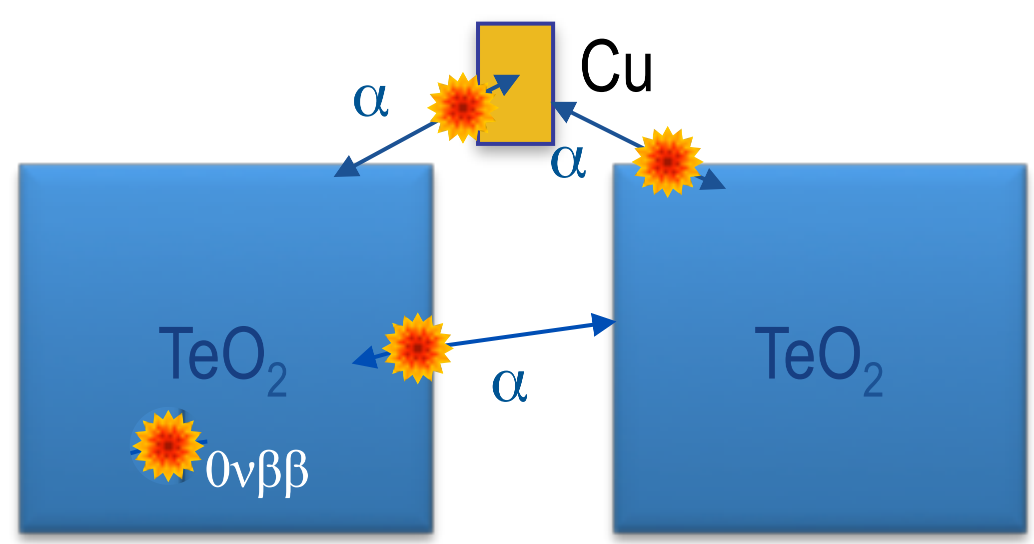
- The main background comes from α particles (residual radioactive contamination of the detector materials).





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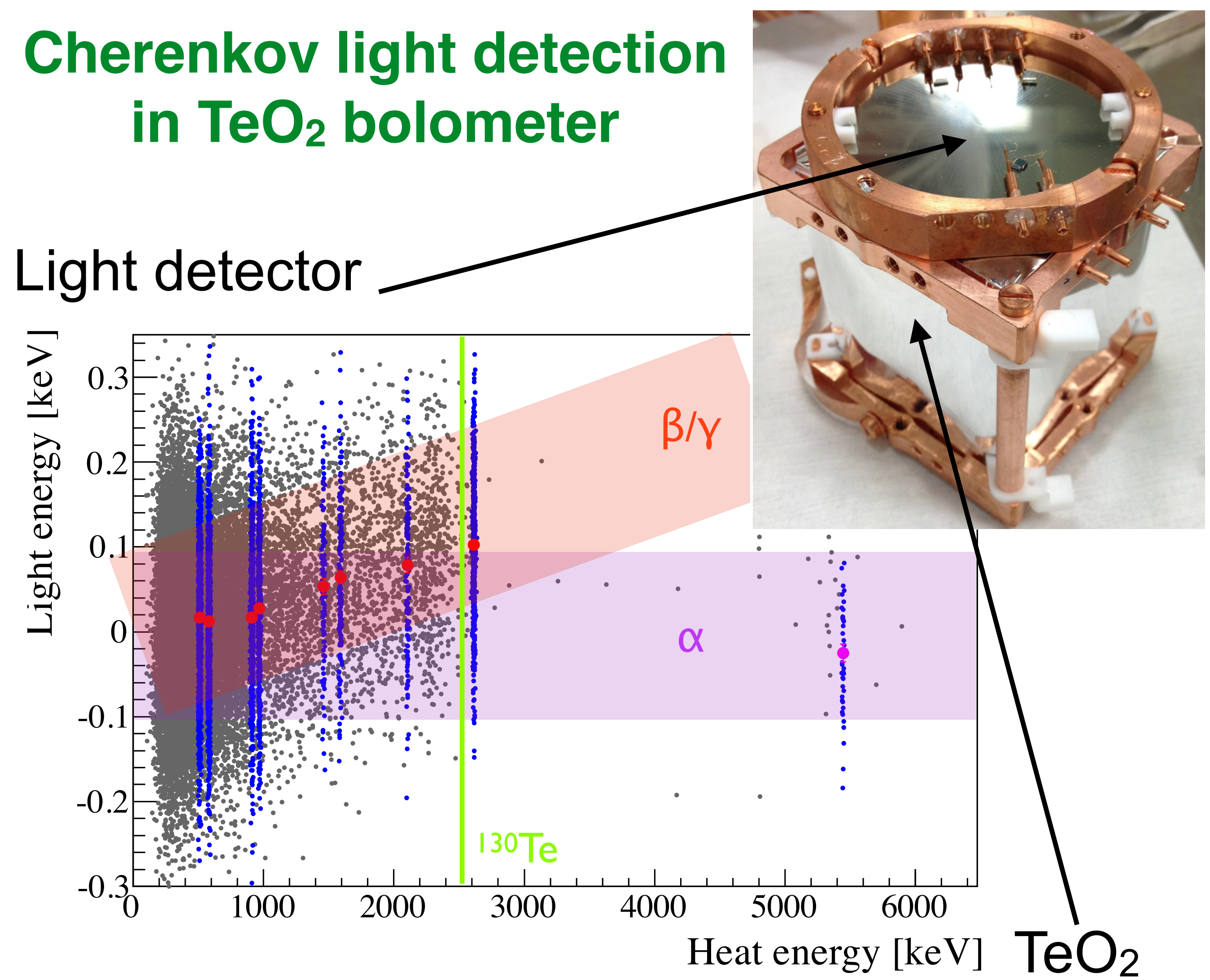
- The CUORE experiment searches for neutrino-less double beta decay of ^{130}Te.
- The expected signal are two electrons with a total kinetic energy of ~ 2.5 MeV.
- The main background comes from α particles (residual radioactive contamination of the detector materials).
- This background can be rejected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

Cherenkov light detection in TeO_2 bolometer



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. Bergé et al., Phys. Rev. C 97 (2018) -> 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

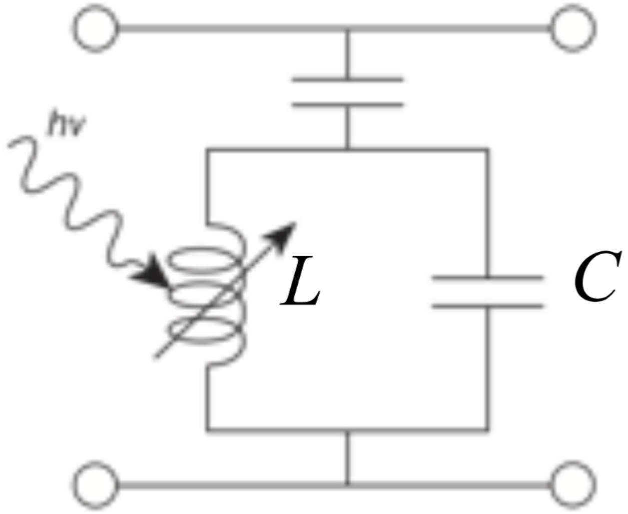
5) CALDER -> KID -> THIS TALK

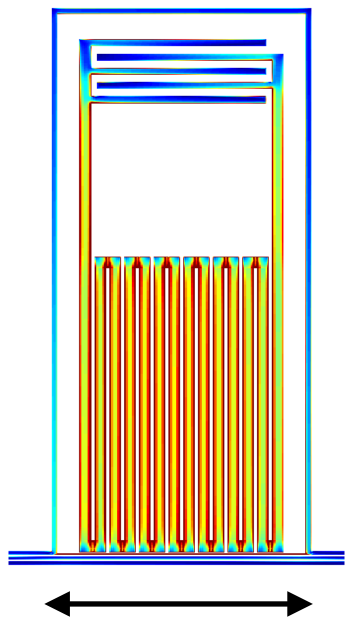
Up to now none of these technologies demonstrated to satisfy all the requirements

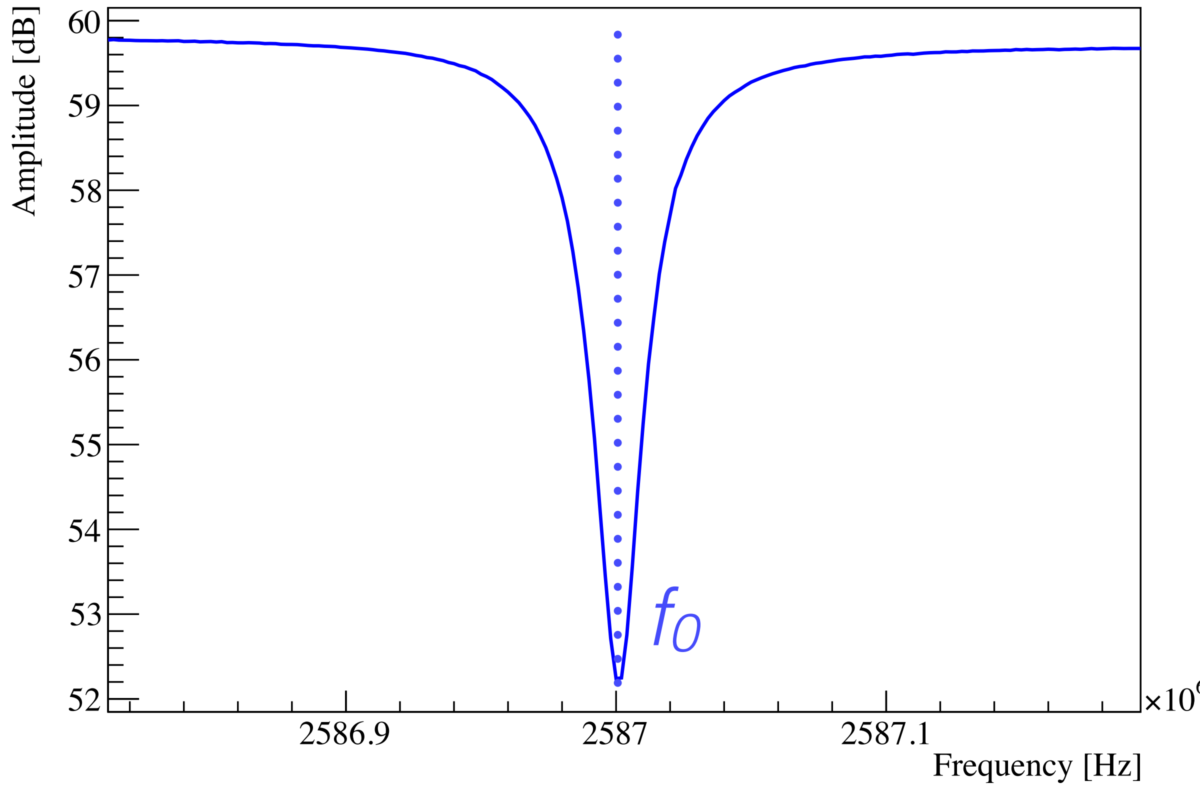
Kinetic Inductance Detector:KID

- 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 merit factor RLC circuit can be realized ($Q \sim 10^4 - 10^5$)

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







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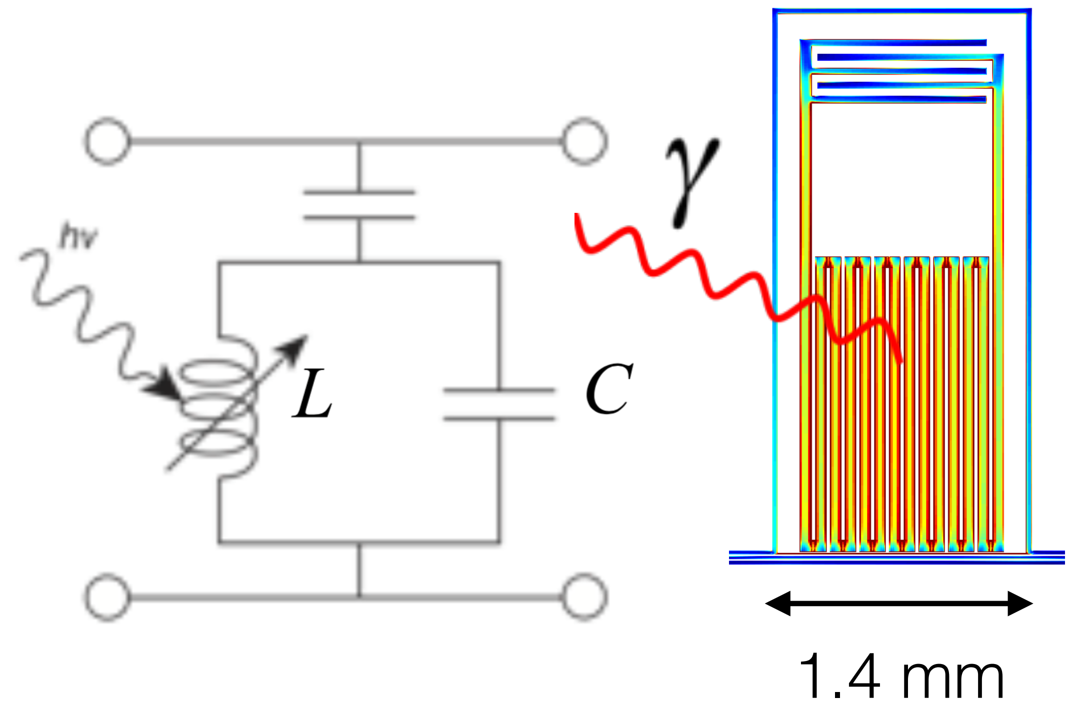
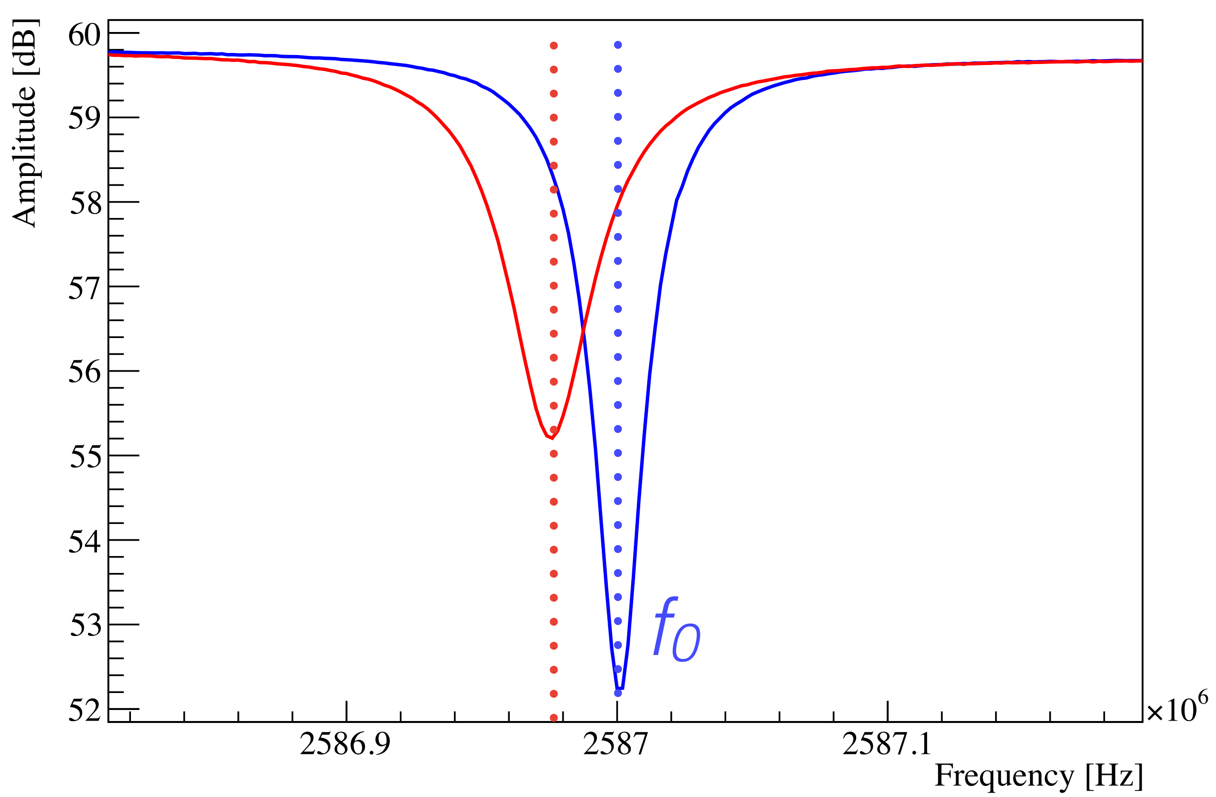


$$f_0 = \frac{1}{2\pi\sqrt{LC}}$$

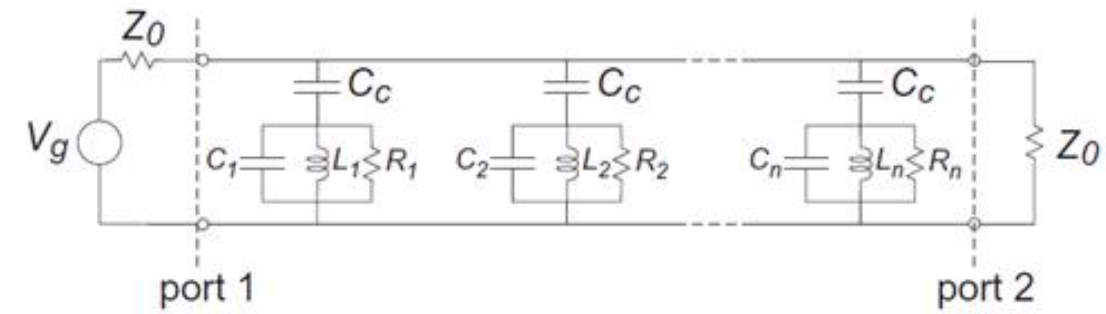
- **A photon interaction breaks the Cooper pair -> the kinetic inductance changes -> the resonance shape and frequency change**

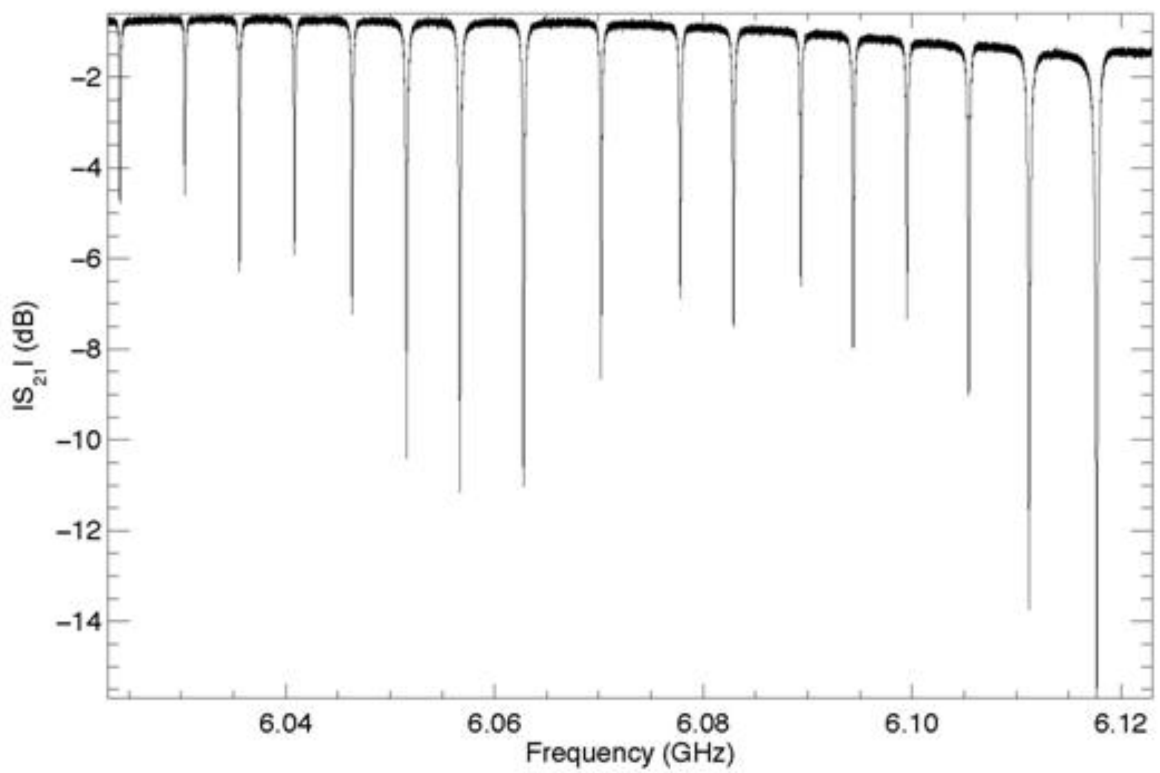


Kinetic Inductance Detector:KID

Advantages:

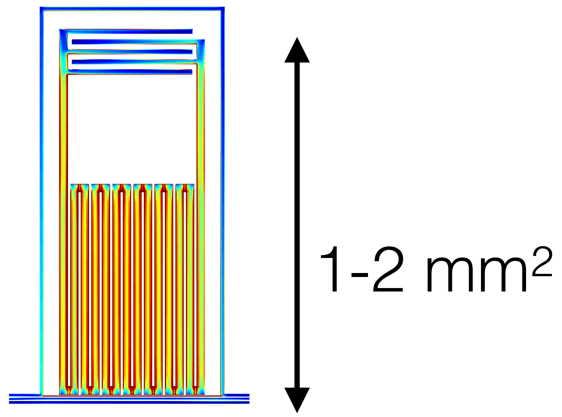
- Natural multiplexing in the frequency domain
- Excellent sensitivity -> baseline energy resolution ~eV
- Stable response and operation in a wide temperature range if $T << T_c$



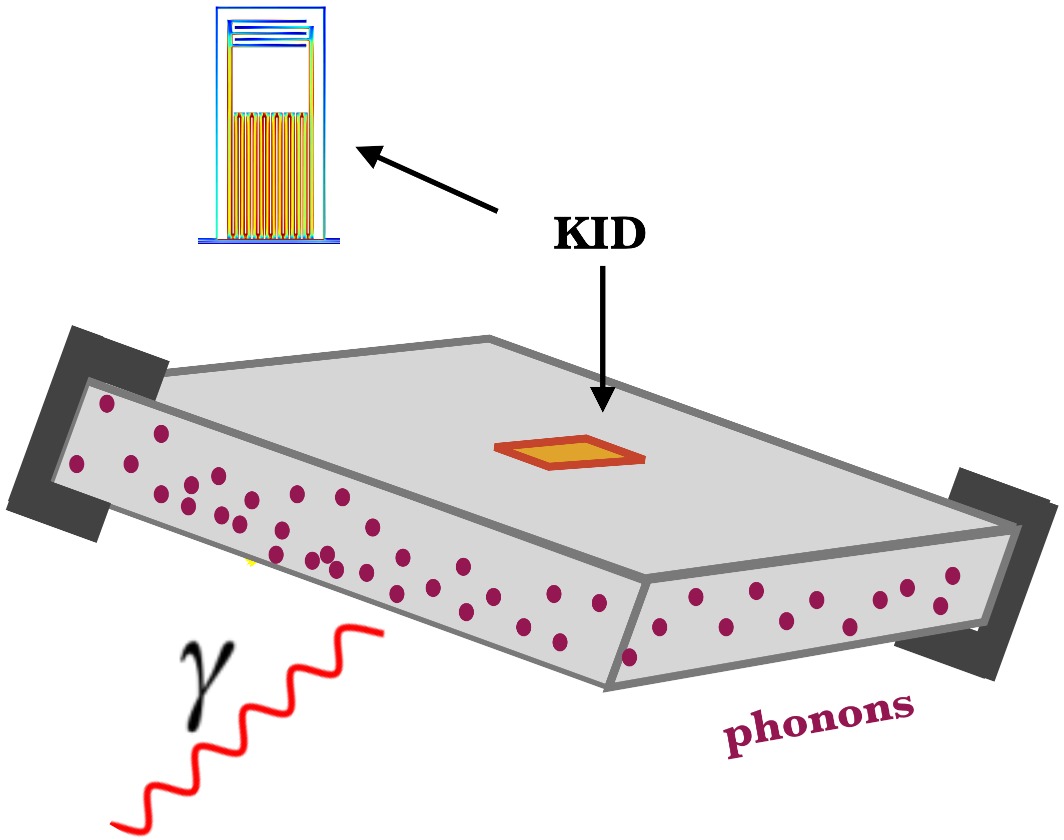


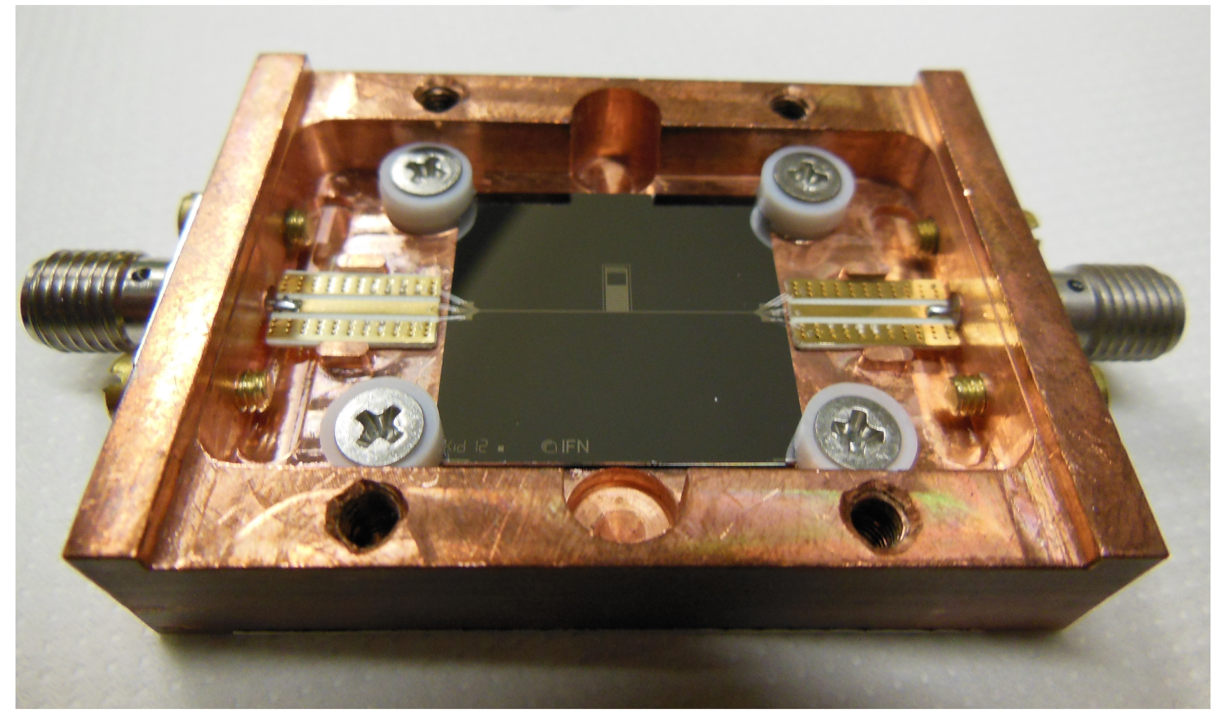
But..

- Poor active surface -> few mm²

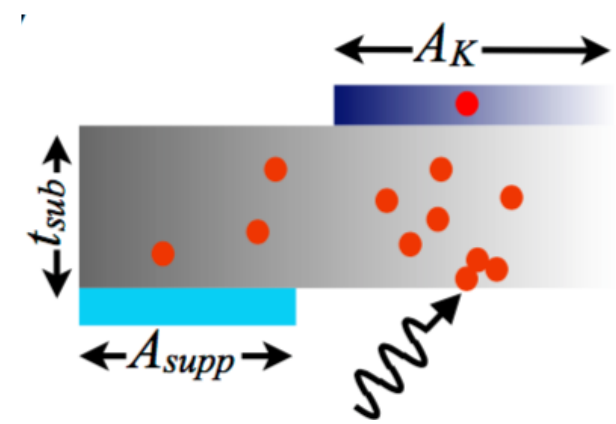


Phonon-mediated approach





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

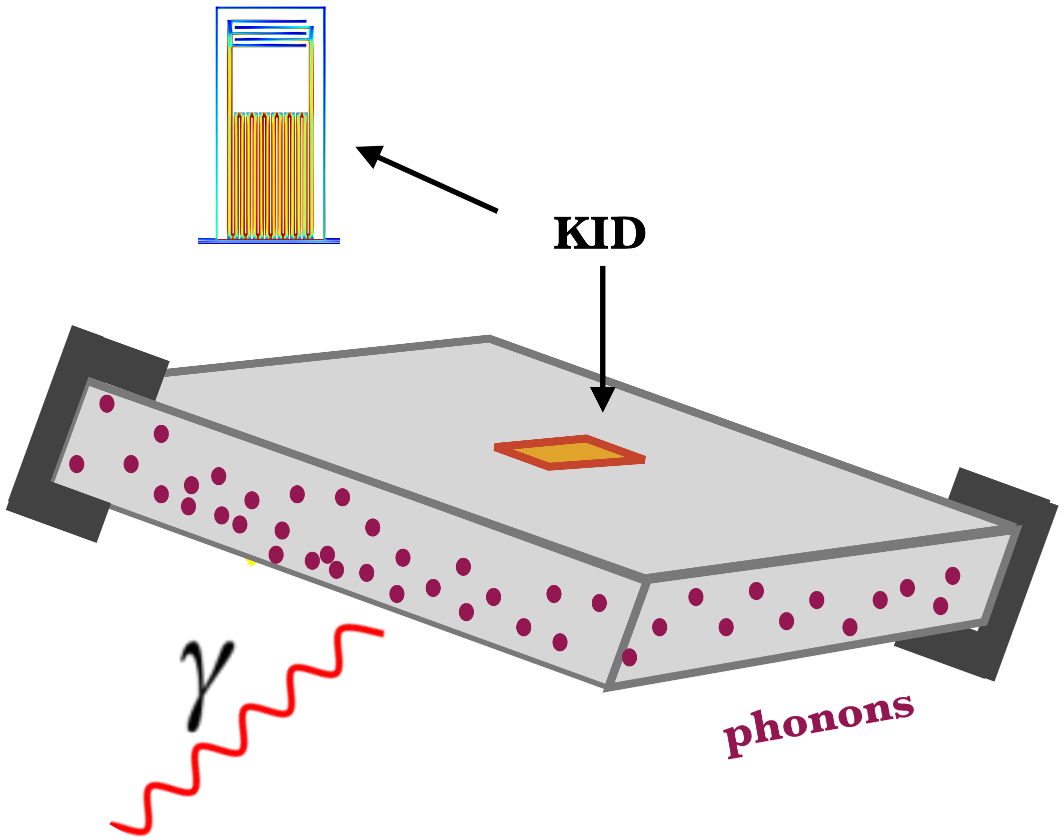


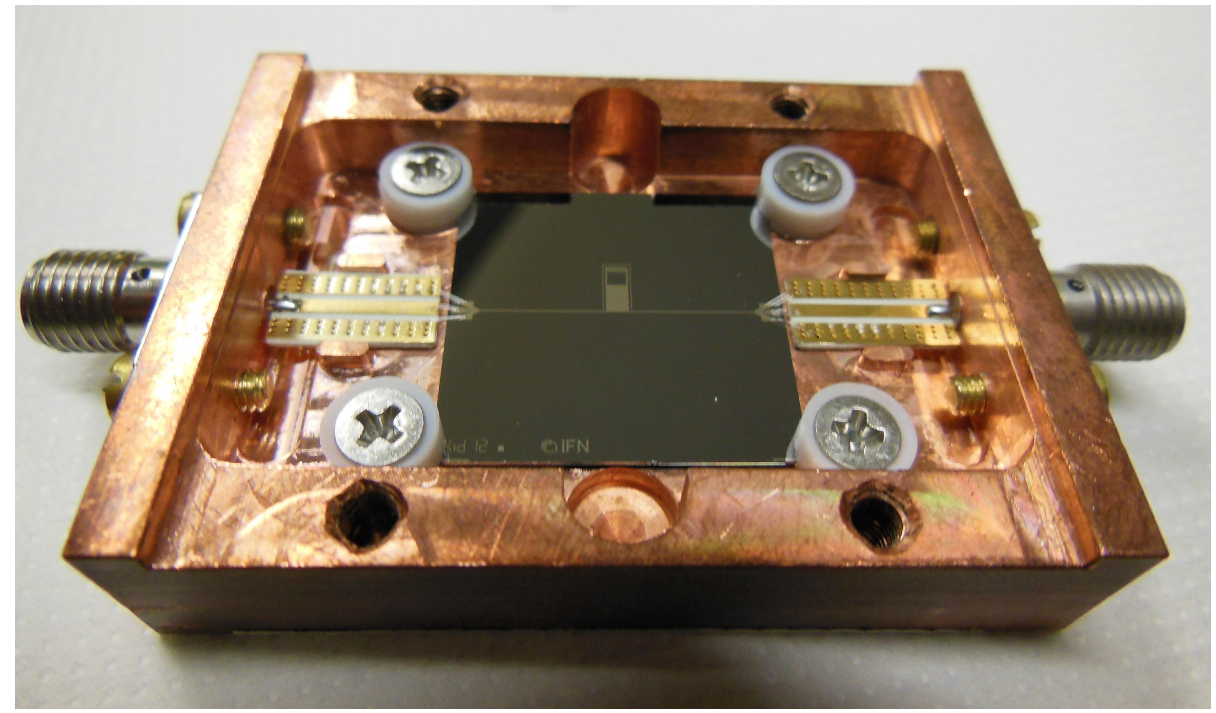
- KIDs are evaporated on a large (cm²) insulating substrate (Si or Ge) that mediates the photon interactions converting them into phonons

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

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

Phonon-mediated approach

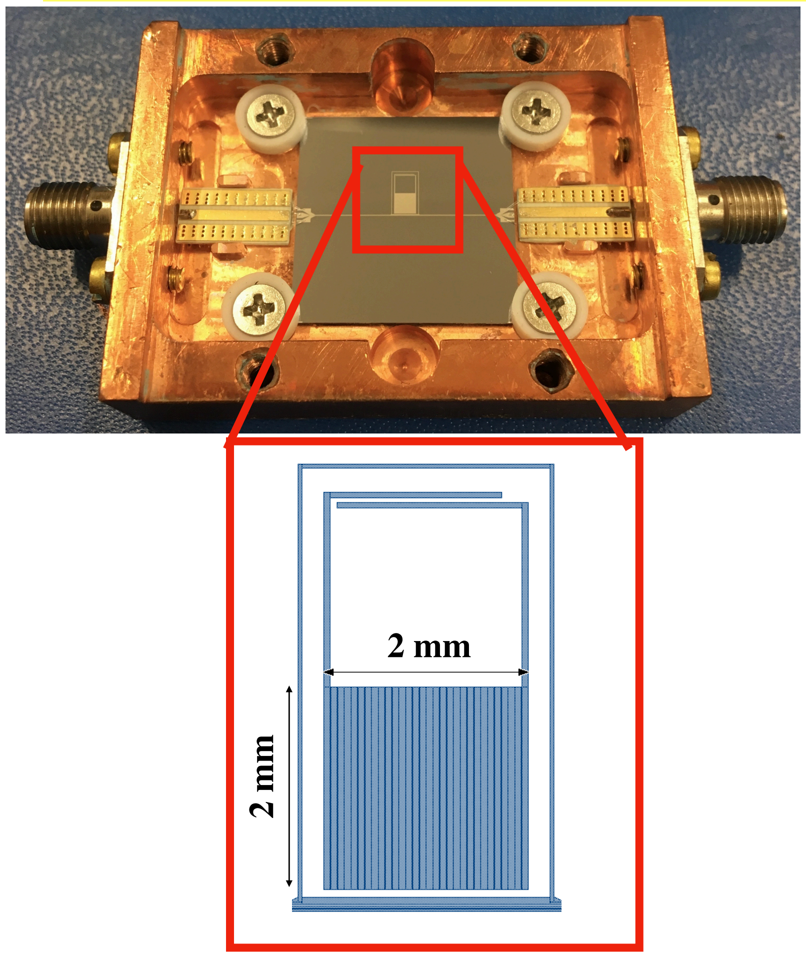


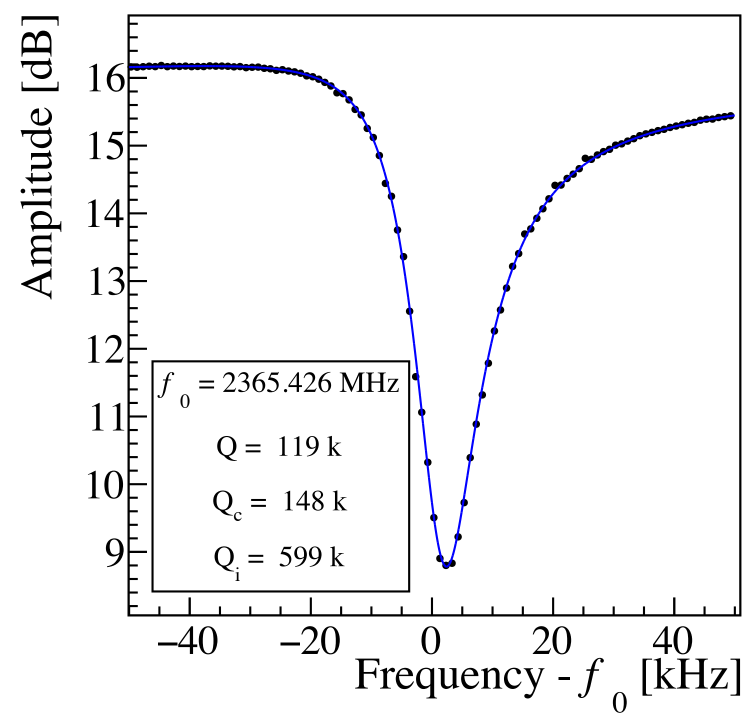


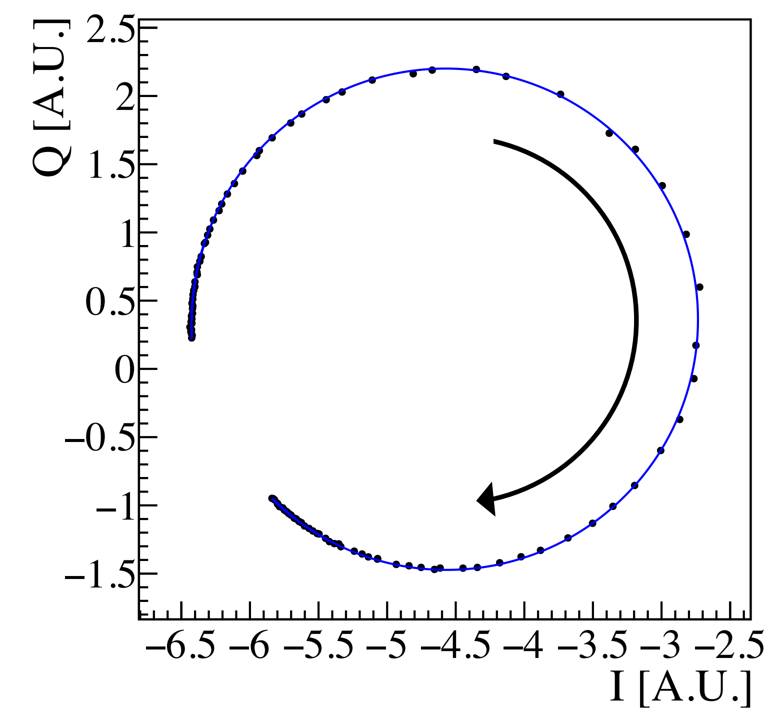
Cryogenic Wide-**A**rea **L**ight **D**etector with **E**xcellent **R**esolution
ERC Starting Grant, from March 2014

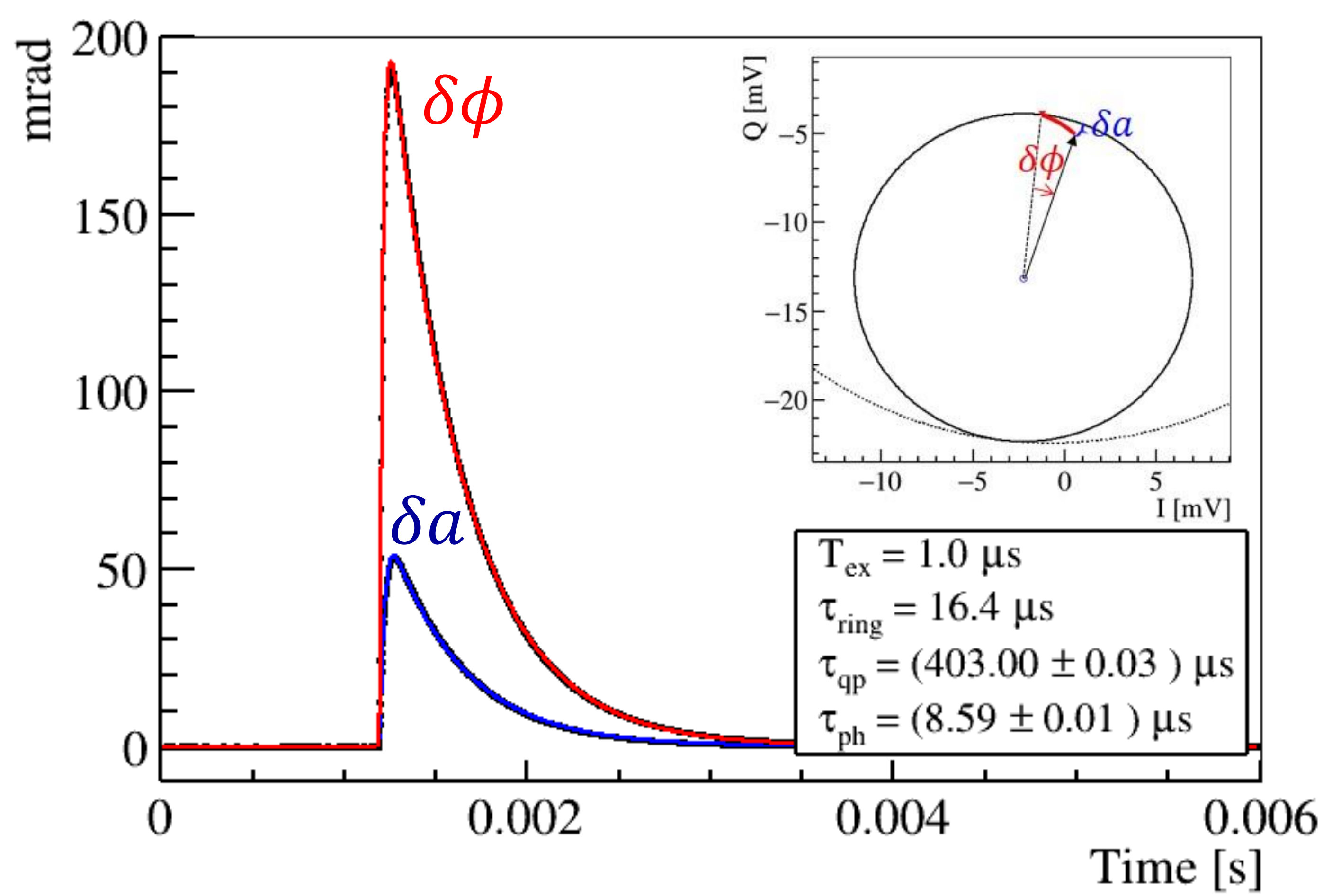
1. Read-out and analysis tools; optimization of the detector geometry using Al resonator and 2x2 cm^2 Si substrate -> 80 eV RMS
2. Test of more sensitive superconductors, such as Ti+TiN, or TiAl -> resolution < 20 eV
3. Large-scale test of the final detectors 5x5 cm^2 on TeO_2 array @ Underground Laboratory of Gran Sasso.

Detectors characterisation



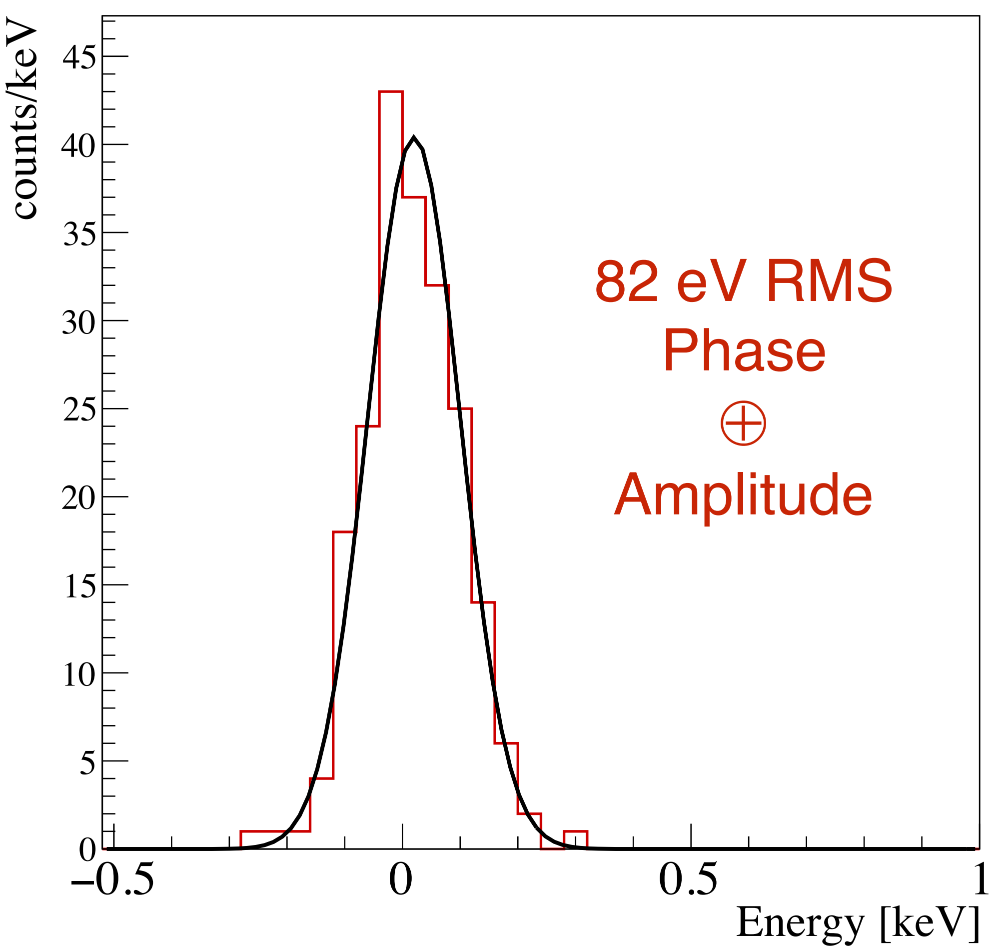


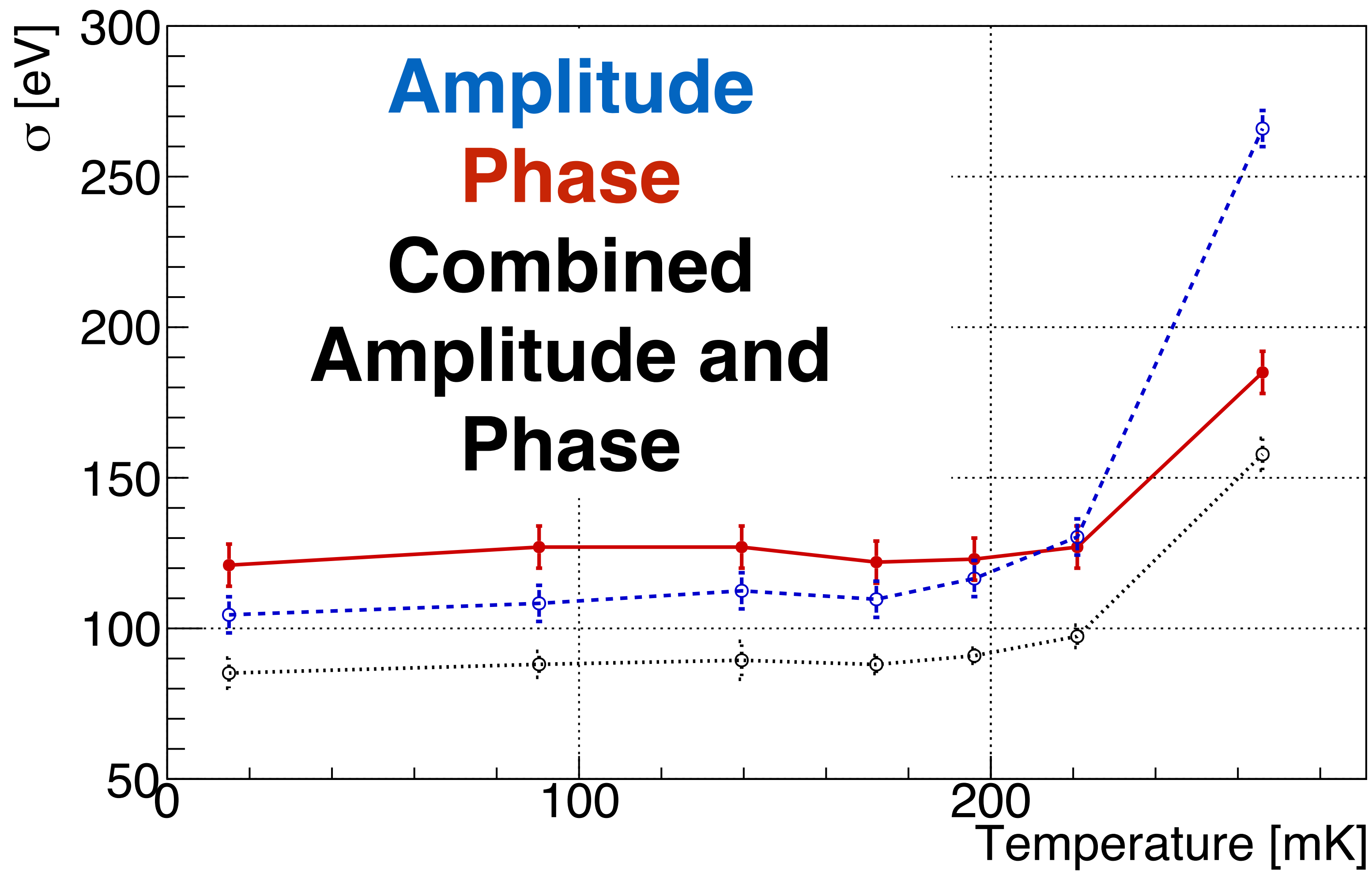




- **Basic resonance parameter evaluation with a fit of the frequency sweep of the transmitted signal**
- **From the center of the resonance loop we monitor the amplitude and phase variations induced by energy depositions**
- **Calibrated optical pulses (400 nm led bursts) in the range between 0.1 and 30 keV; and X-rays from 55Fe/57Co (as cross-check for the energy calibration)**

Al prototype: final results





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

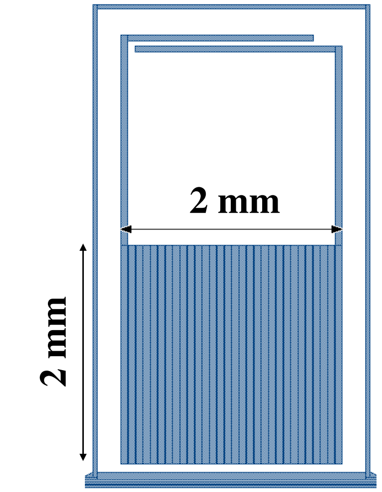
Combining phase and amplitude we obtained 82±4 eV

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

More sensitive superconductor: AlTiAl

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

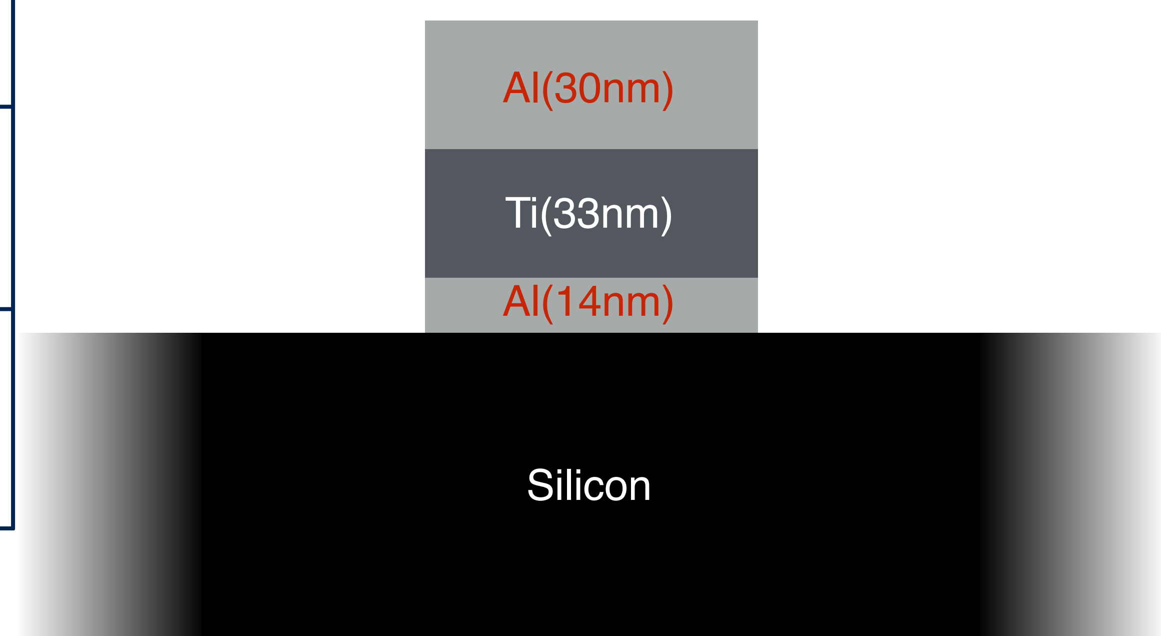
	Al	Ti+Al	Ti+TiN
T_C [K]	1,2	0.6-0.9	0.5-0.8
L[pH/square]	0,35	1,2	6?
Q_i max	>10^6	$10^{5\text{-}6}$	?
Phonon ε	10%	10%	low?
Producer	IFN-CNR	CSNSM Neel-CNRS	CNR/FBK
Status	Completed	Completed	Aborted



Same design as Aluminum films.

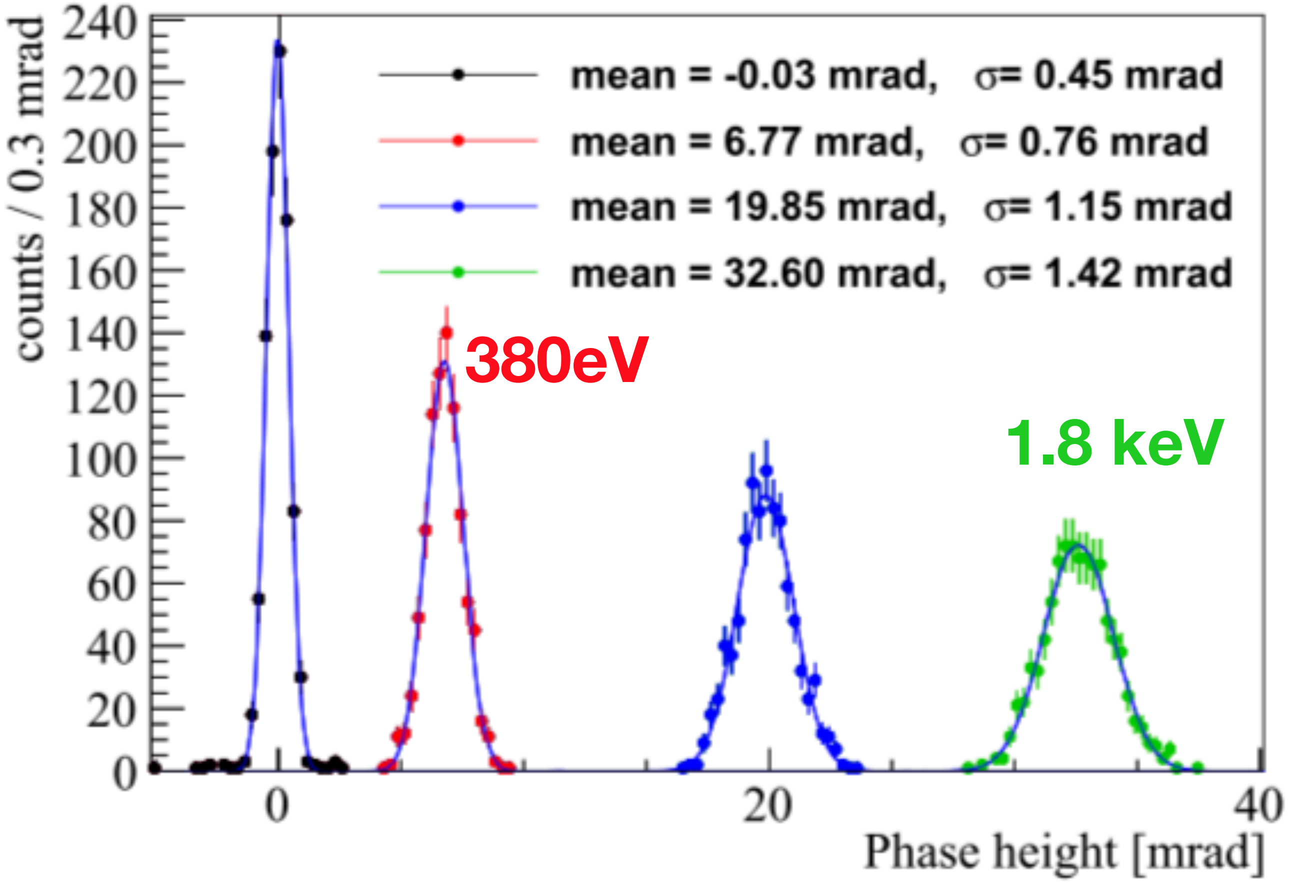
Titanium enhances Kinetic Inductance but lowers the internal *Q*.

Tested different TiAl and AlTiAl multilayers. Best results from:

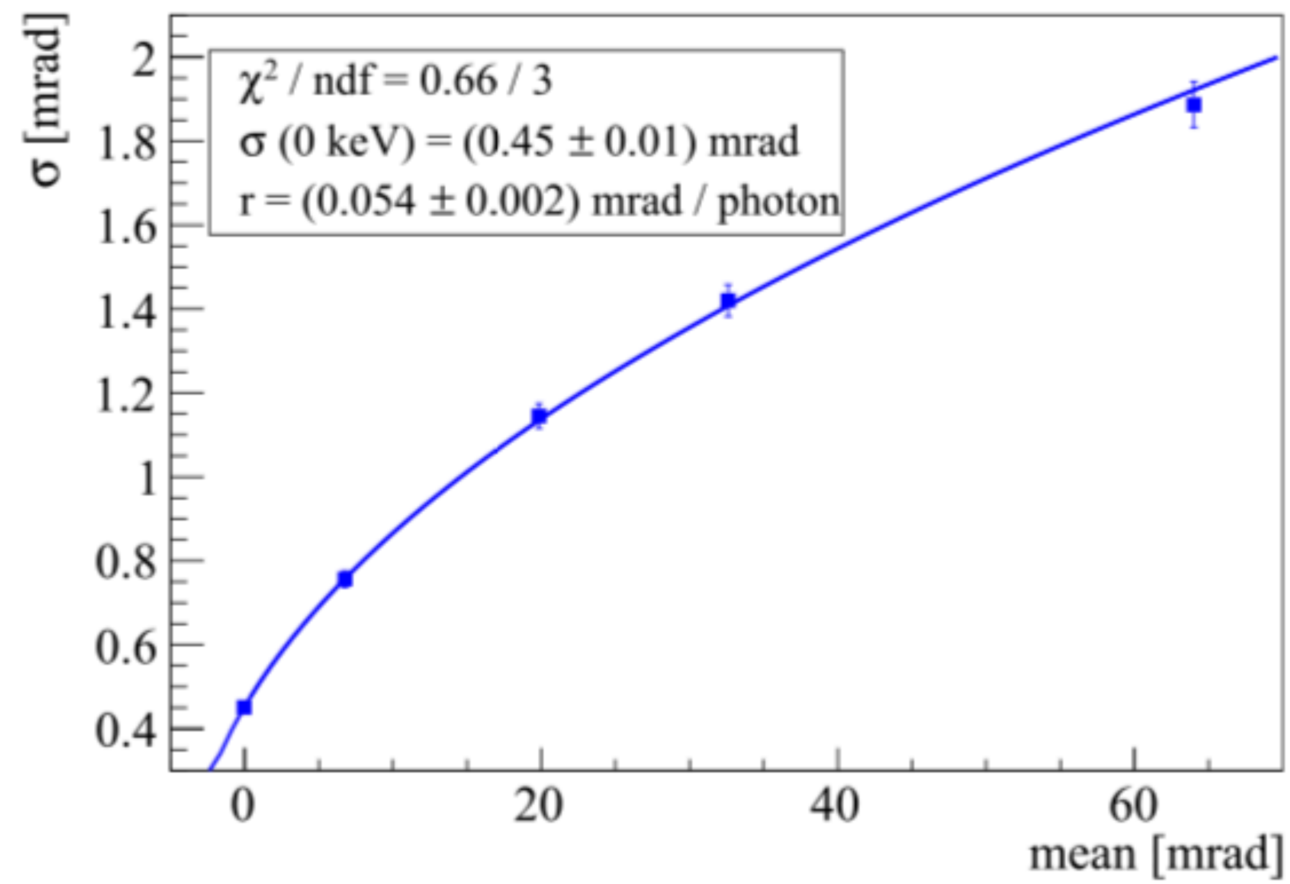


AlTiAl prototype: final results

Energy scan with optical pulses



Absolute energy calibration with poisson



$$\sigma_{\rm ph} = \sqrt{N_{\rm ph}} \times r = \sqrt{m/r} \times r = \sqrt{m \times r}$$

$$\sigma = \sqrt{\sigma_0^2 + m \cdot r}$$

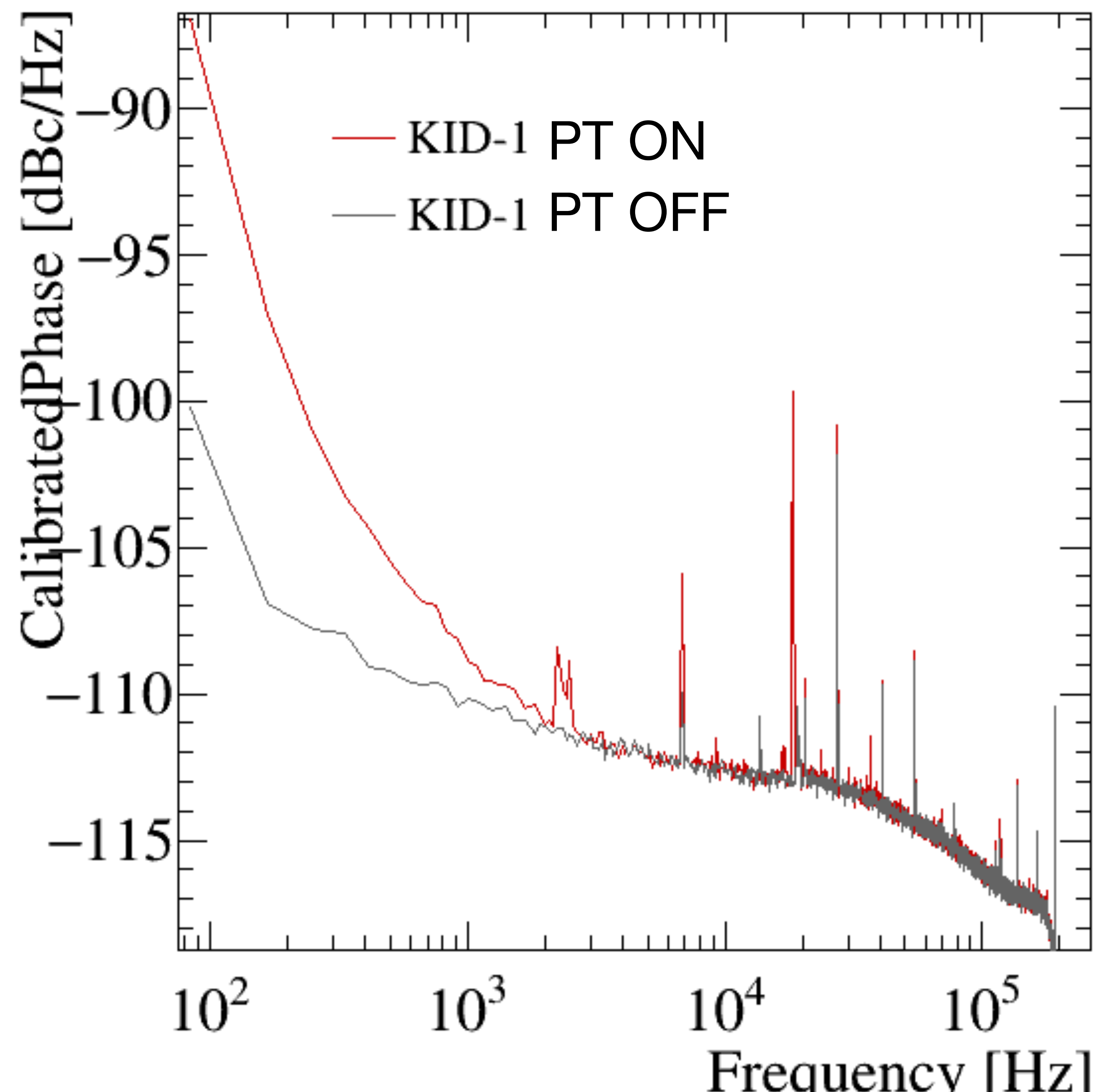
Phase Signal enhanced respect to Al prototypes -> Phase RMS ~ 25 eV

Amplitude Signal is the same -> 80 eV RMS

L. Cardani et al, SU.S.T. 31 7 (2018)

Pulse tube induced noise

A dry dilution refrigerator is precooled by a two-stage pulse tube refrigerator

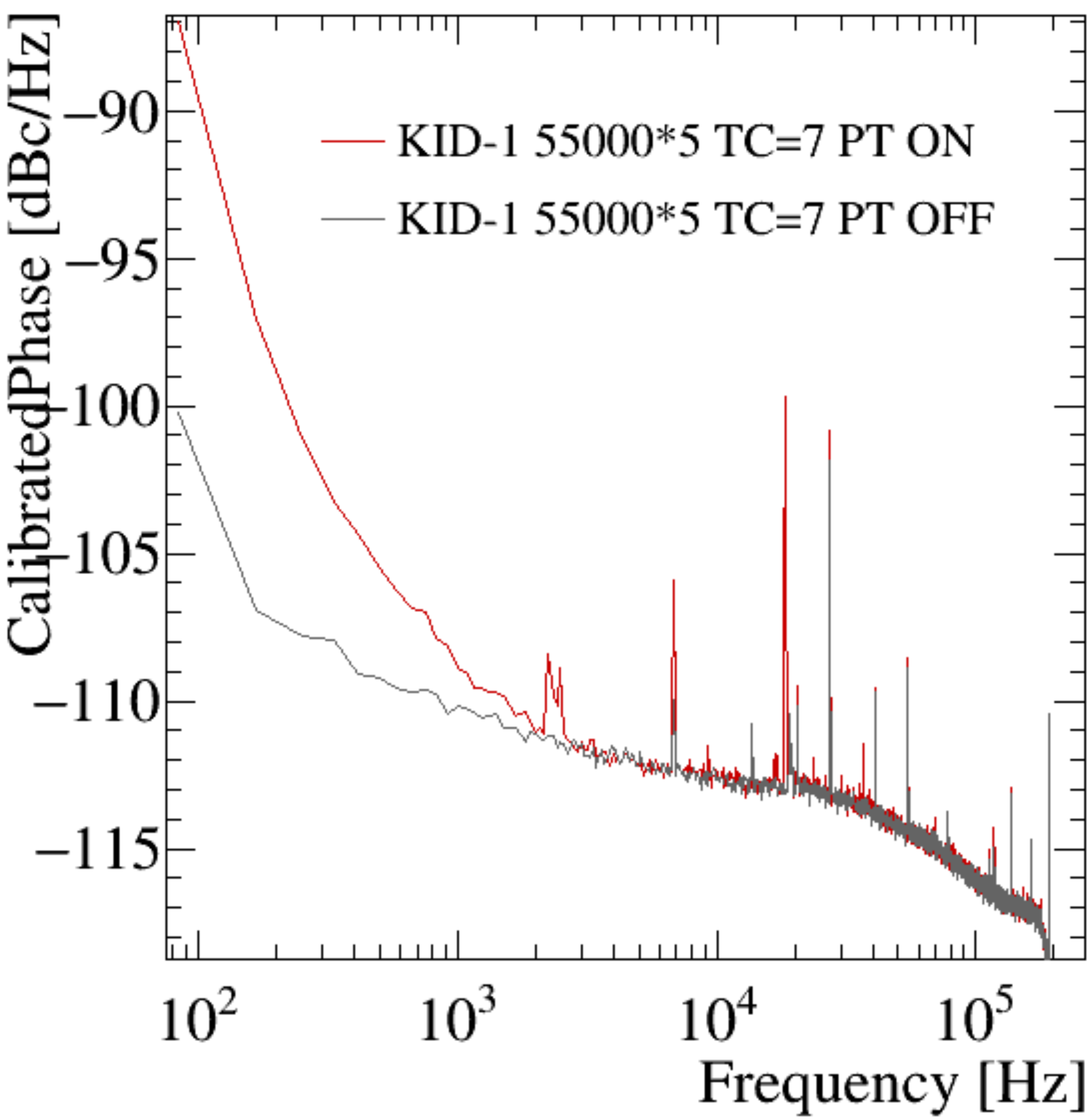


The vibrations are induced in all the refrigerator structure, as a result also on the detector

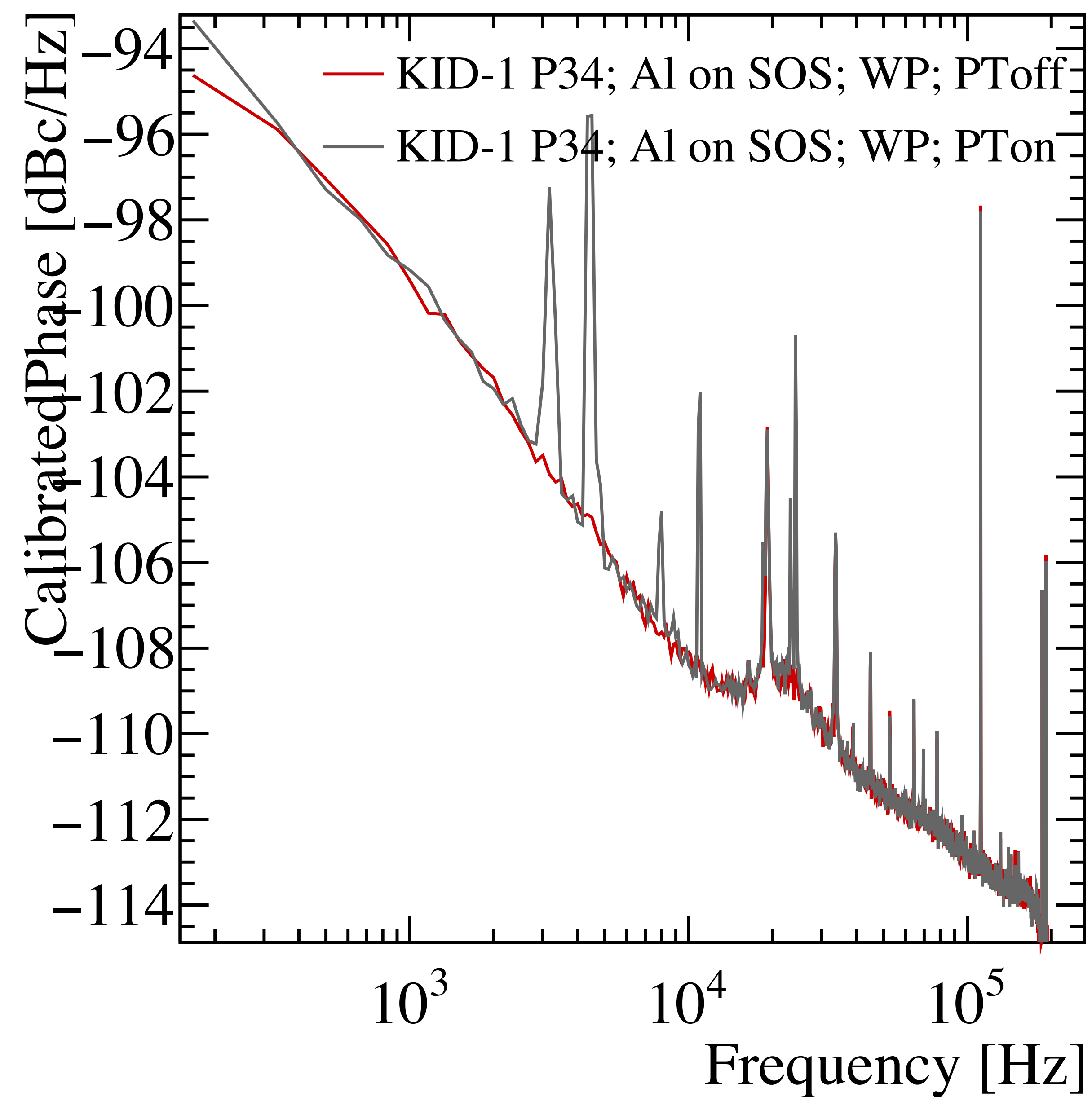
Worsening of the energy resolution

Silicon on Saphire substrate: SOS

Silicon



SOS



KIDs on (SOS) are barely affected by the Pulse Tube induced noise

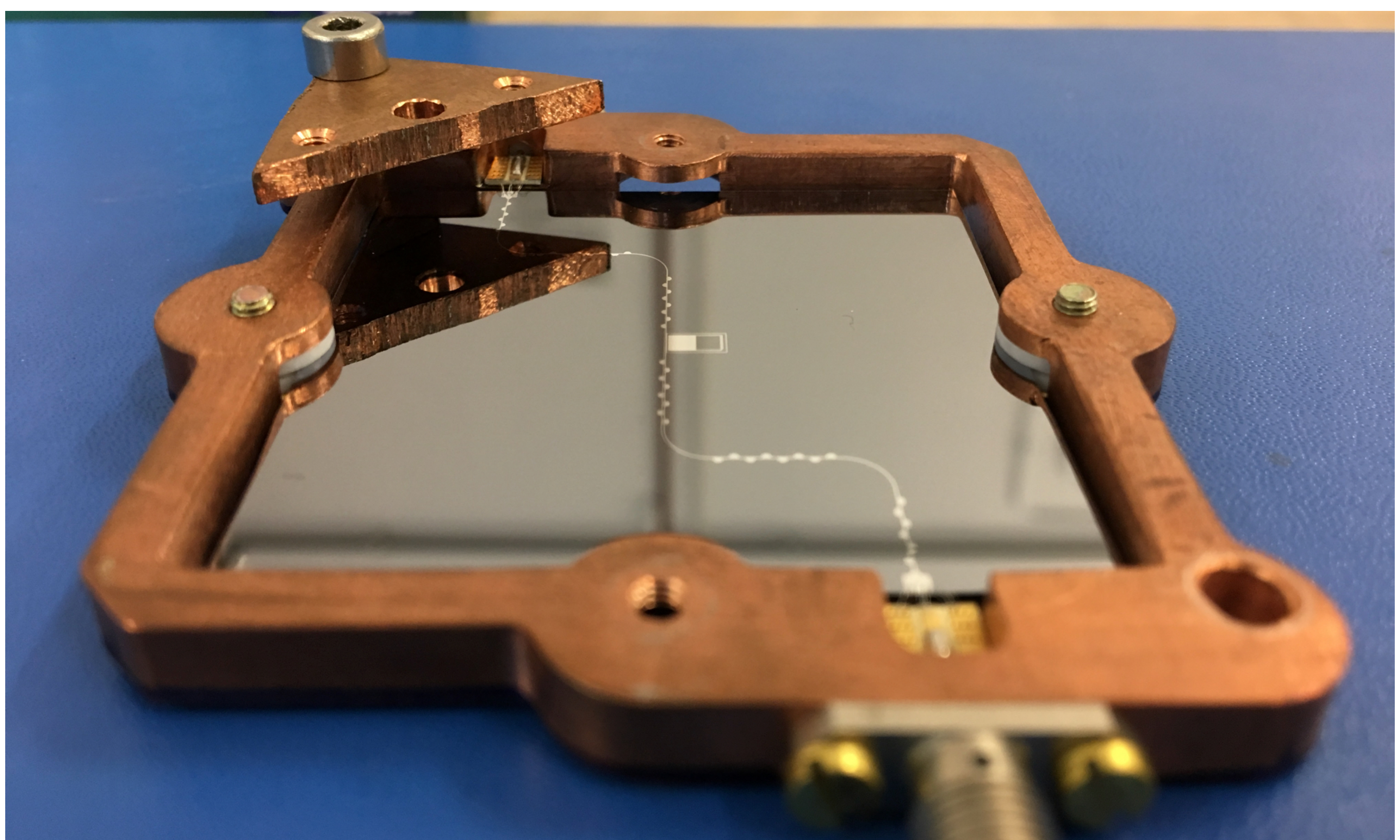
Fundamental requirement for an application in the CUORE cryogenic facility

Last CALDER phase: the 5x5 cm^2 detector

1. ~~Read-out and analysis tools; optimization of the detector geometry using Al resonator and 2x2 Si substrate -> 80 eV RMS~~

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

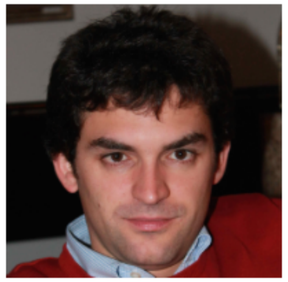
3. Large-scale test of the final detectors 5x5 cm^2 on TeO_2 array @ Underground Laboratory of Gran Sasso.



Result are still preliminary; several aspects are still under investigation

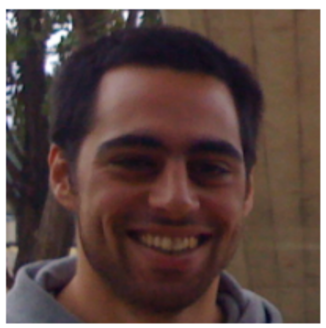
Conclusions

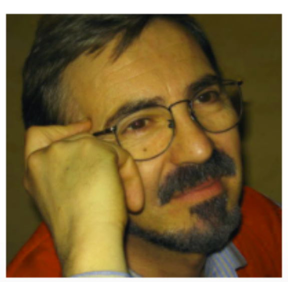
- The CALDER project aims to develop the light detector for the next generation bolometric experiments exploiting KIDs
- The phase 1 and 2 of the project are accomplished: AlTiAl resonator with 25 eV baseline RMS
- Using the SOS substrate the PT vibrations worsen the energy resolution just of few percent (5-10%)
- The test and optimisation of the final 5x5 cm^2 light detector are in progress.

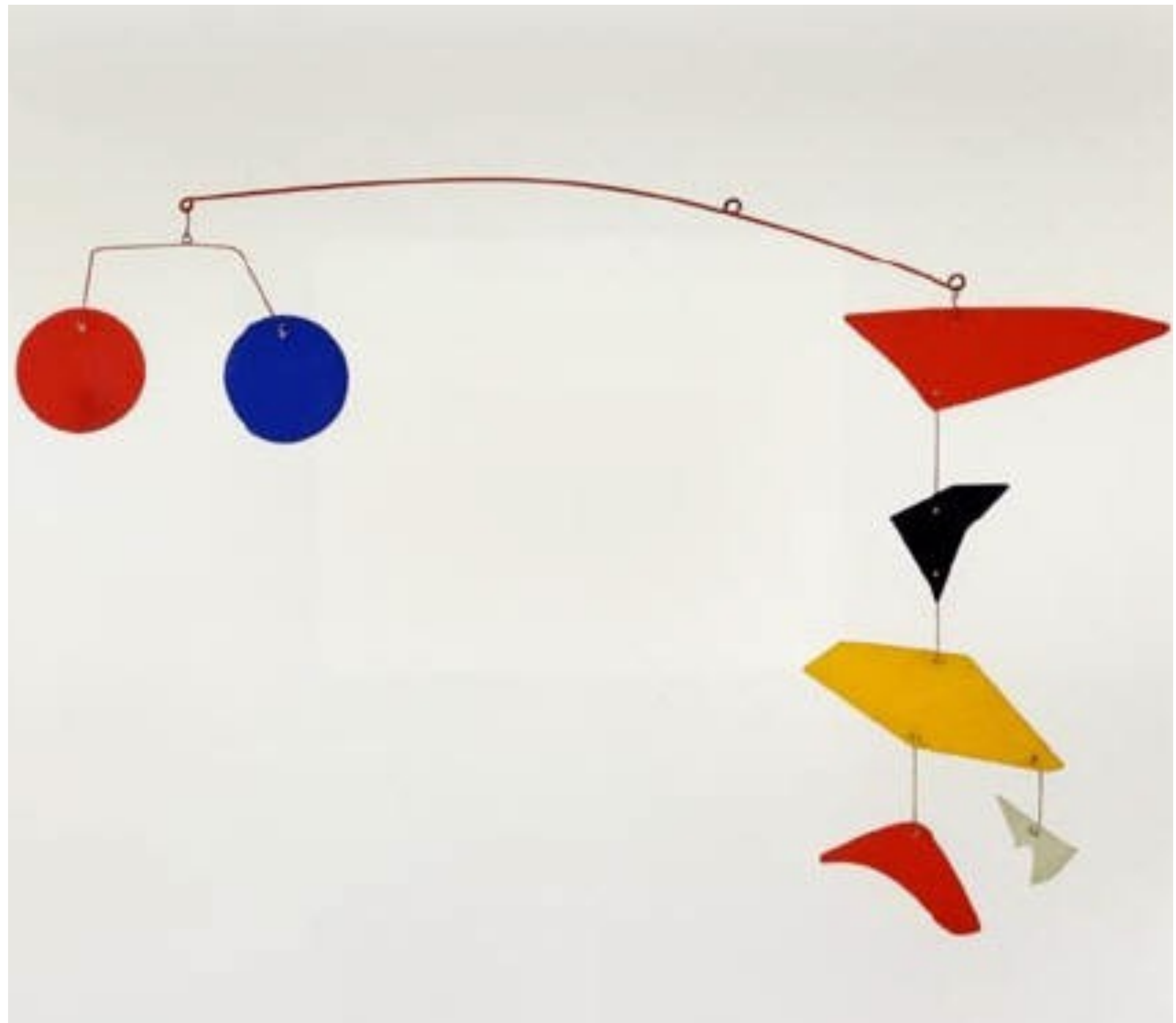



Thank you for the attention !









CALDER public webpage:

http://www.roma1.infn.it/exp/calder/new

BACKUP

Resonance parameter evaluation

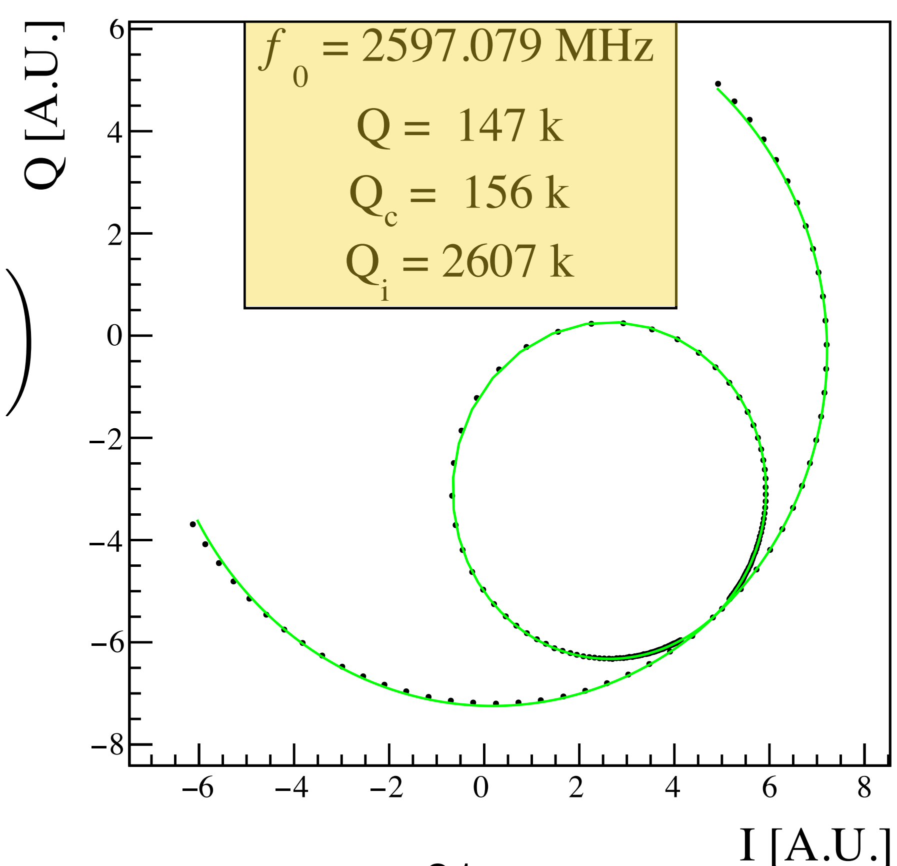
The transmitted microwave through feed-line (S_{21}) is affected not only by the resonator:

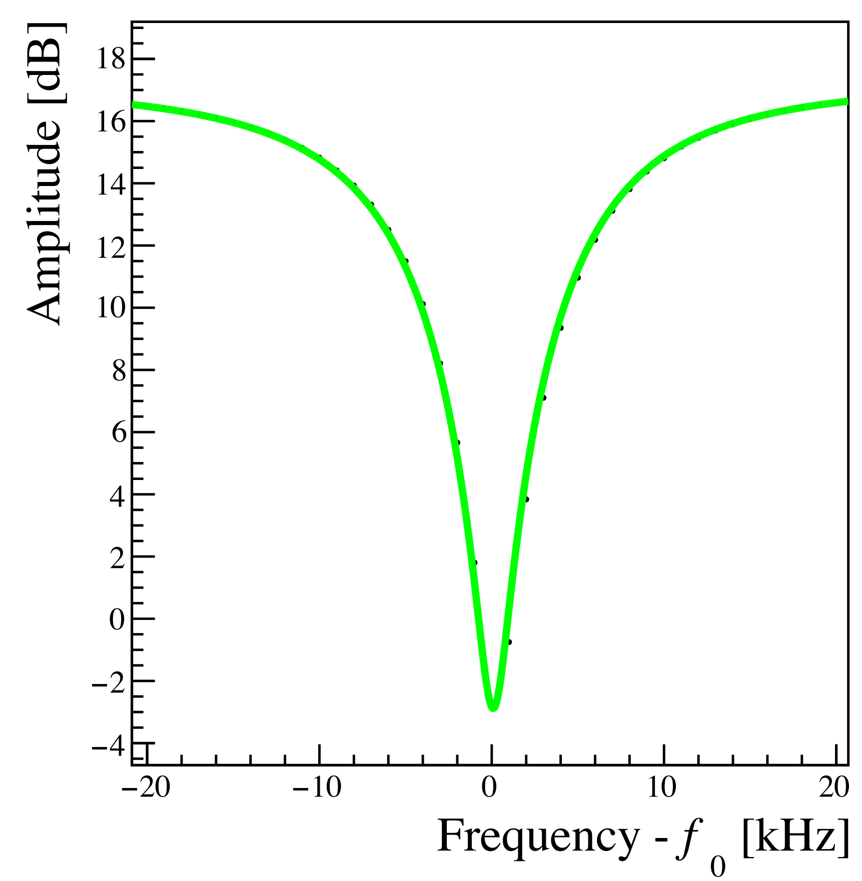
1) **read-out chain**
2) **impedance mismatches in proximity of the KID** [1]
3) **distortion of the resonance due to power absorbed by the resonator** [2]

$$S_{21}^{Tot} = \boxed{Z_c + \left(A cos\left(-2\pi f\tau\right) + j\cdot B sin\left(-2\pi f\tau\right)\right)\cdot e^{-j\phi}}\cdot\left(1-\frac{\frac{\frac{Q}{Q_c}\boxed{e^{j\theta}}}{1+j2\boxed{y}}}{\boxed{\cos\theta}}\right)$$

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

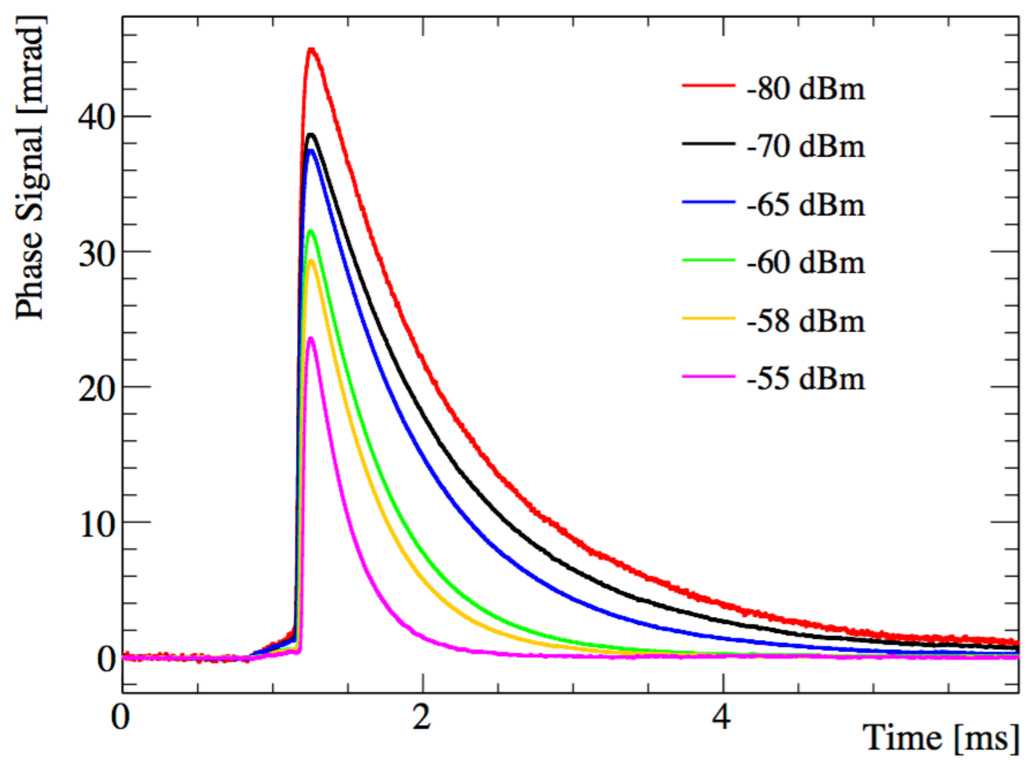
$$min\left(\sum_{n=0}^{N}\parallel S_{21}(f_n, 11par) - Data(f_n)\parallel^2\right)$$

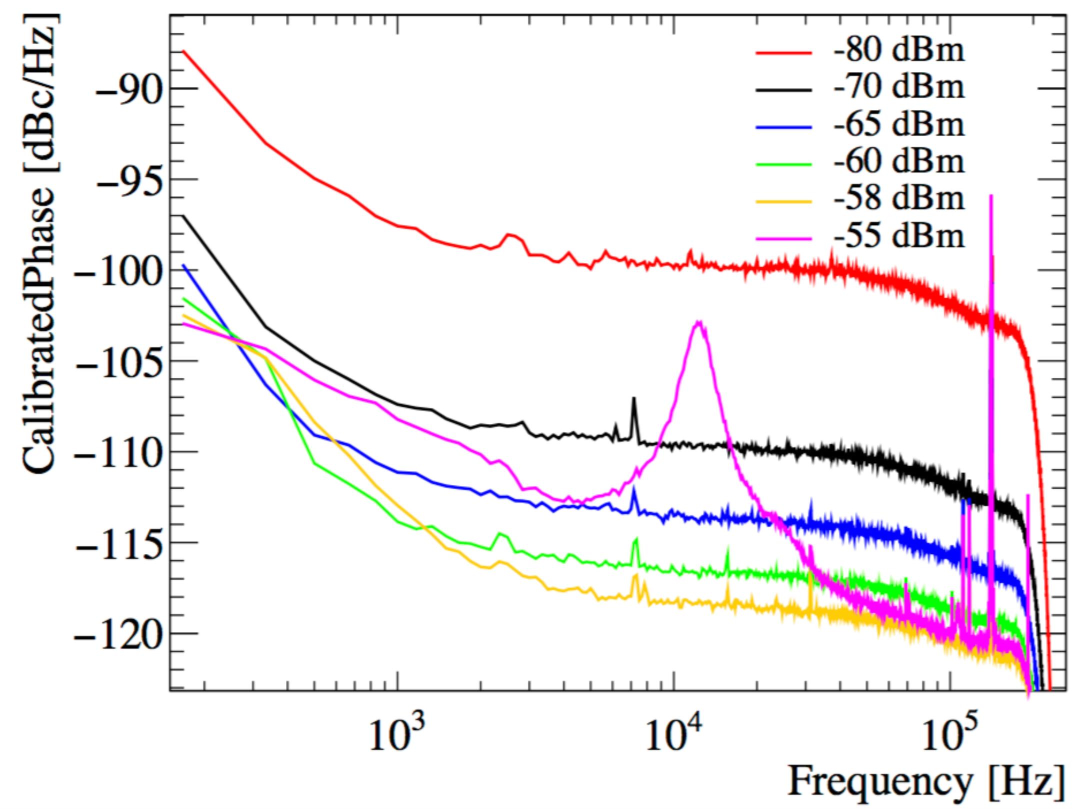


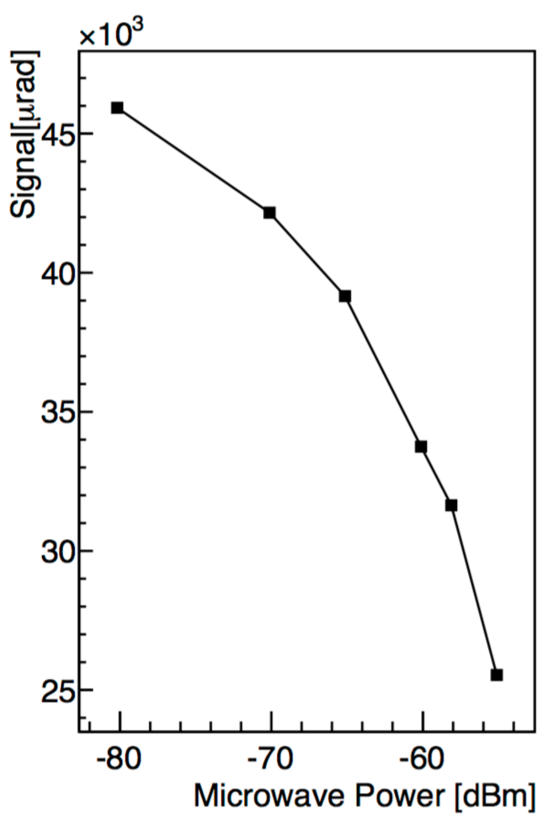


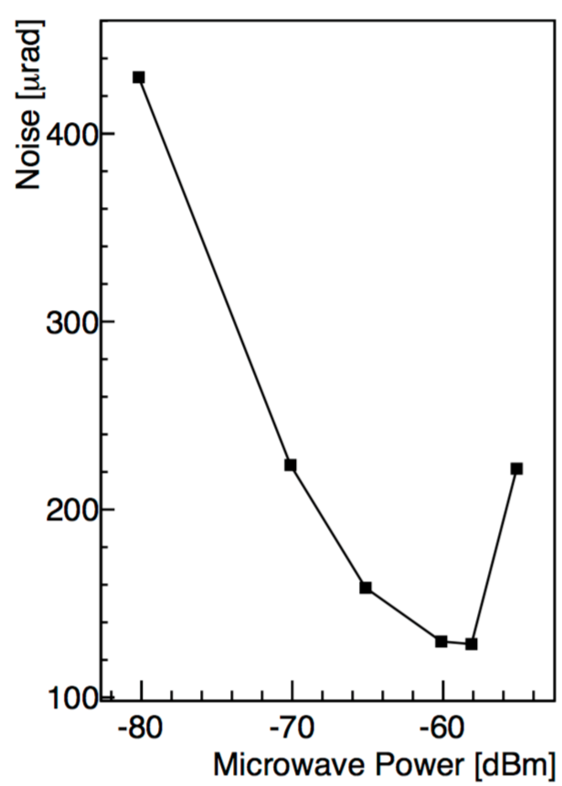
[1] M. S. Khalil et al., J. Appl. Phys. **111**, 054510 (2012)
[2] L. J. Swenson et al., J. Appl. Phys. **113**, 104501 (2013)
[3] N. Casali et al., J.Low.Temp.Phys. **184** (2016)

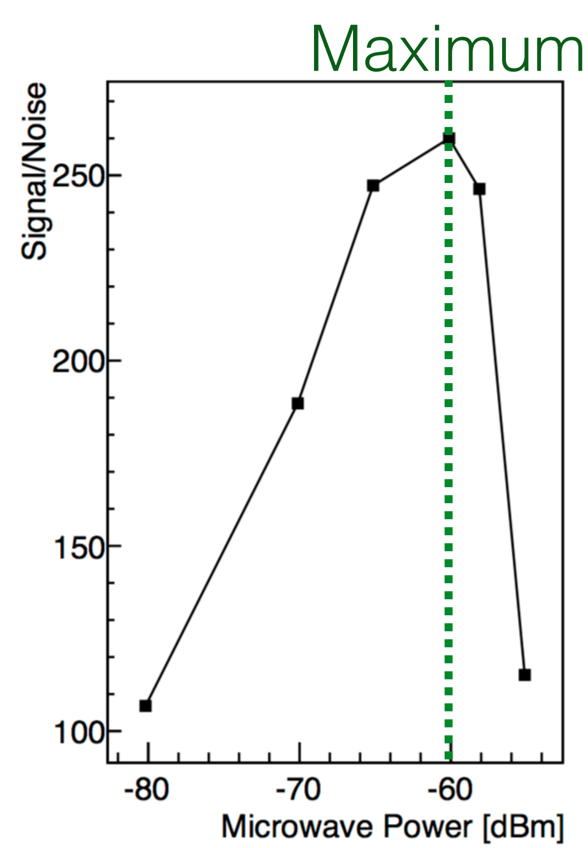
Detector operation: optimal microwave power











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