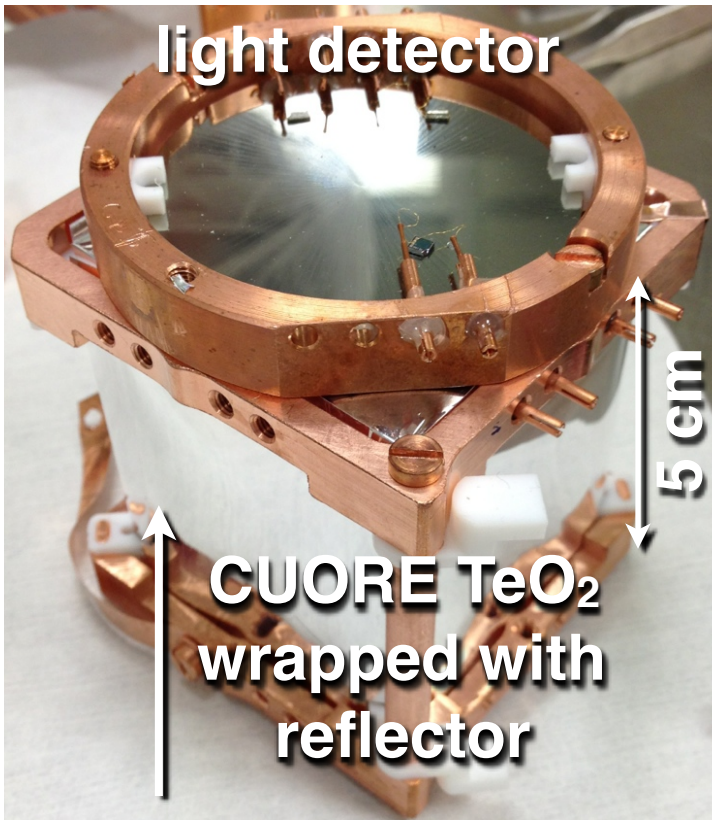
# Phonon-mediated Kinetic Inductance Detectors

Marco Vignati
INFN Sezione di Roma
*Frascati, 28 Marzo 2017*

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

# Motivation

**Detect Cherenkov or scintillation light from large-mass bolometers to search for double beta decay or dark matter.**

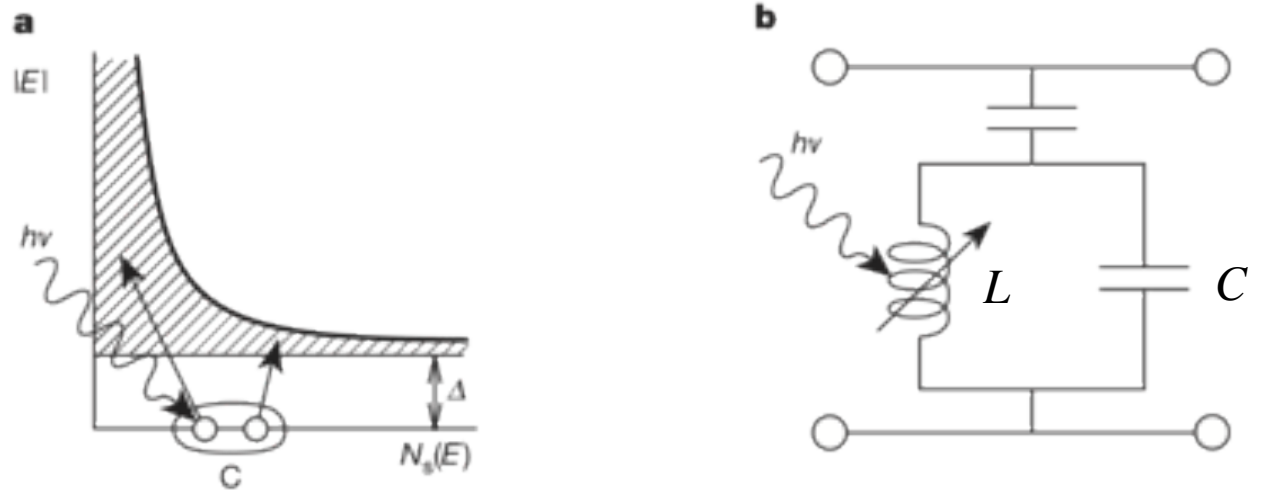



Light detector Requirements:

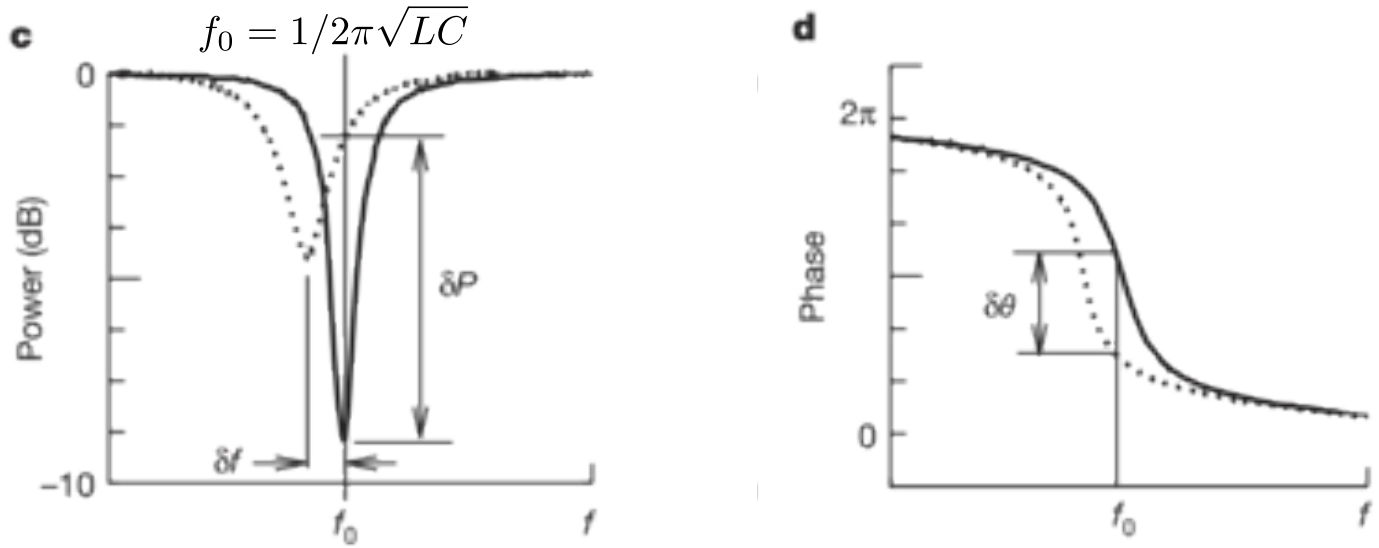
- ✓ Active area = 5x5 $cm^2$
- ✓ $\Delta E < 20$ eV RMS
- ✓ $10 < T_{work} < 20$ mK
- ✓ Scalable to ~1000 detectors

$\Delta E$ of present NTD-based light detectors is too high (100 eV RMS)
**need a new technology.**

# Kinetic Inductance Detectors (KIDs)




Cooper pairs (cp) in a superconductor act as an inductance (*L*).
Absorbed photons change cp density and *L*.

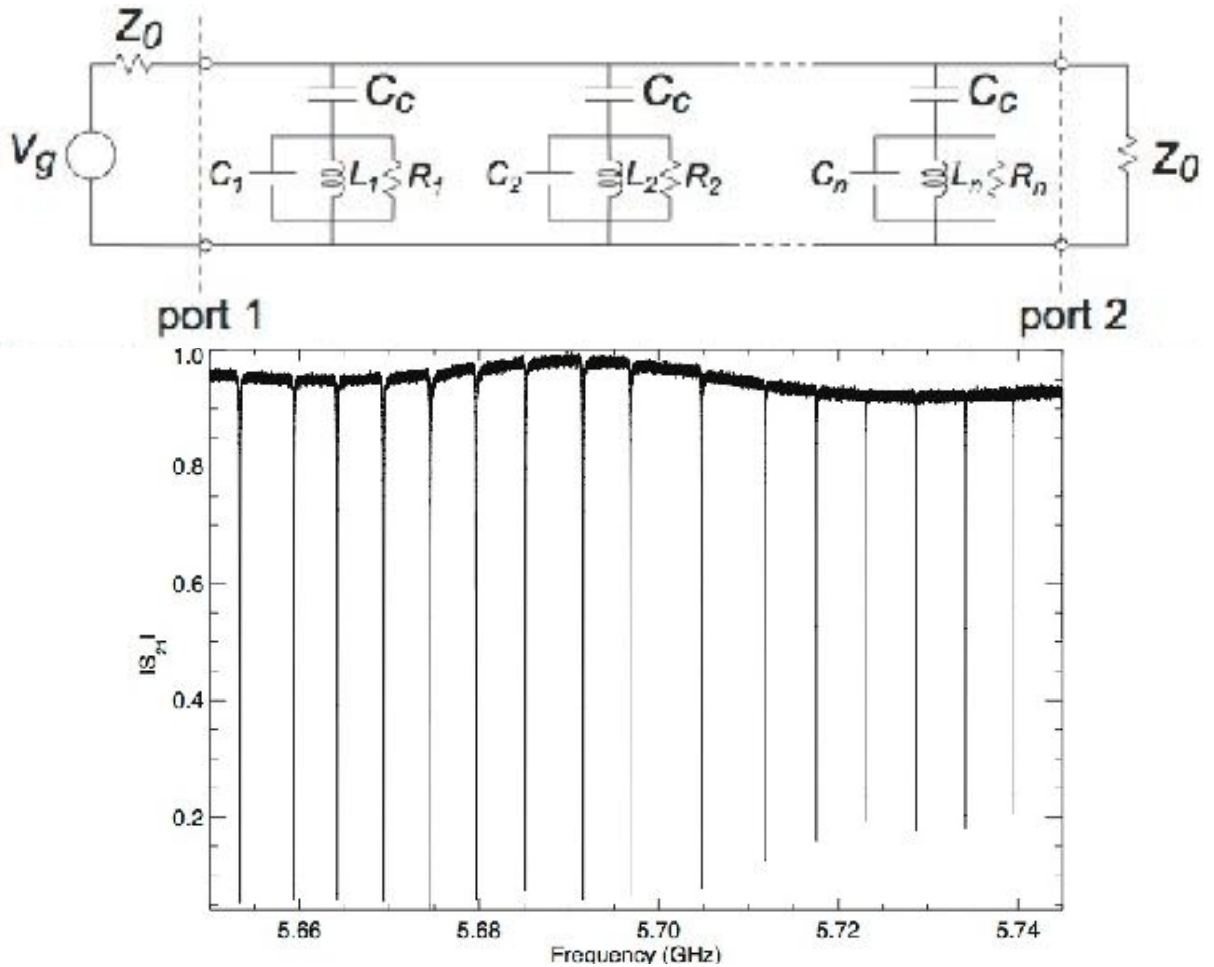



High quality factor (*Q*) resonating circuit biased with a microwave (GHz): signal from amplitude and phase shift.

Day et al., Nature 425 (2003) 817

# Multiplexed readout of a KID array

- Different resonators can be coupled to the same feedline by making them resonate at slightly different frequencies.
- The resonant frequency can be changed by modifying the capacitor (C) or the inductor (L) pattern of the circuit.



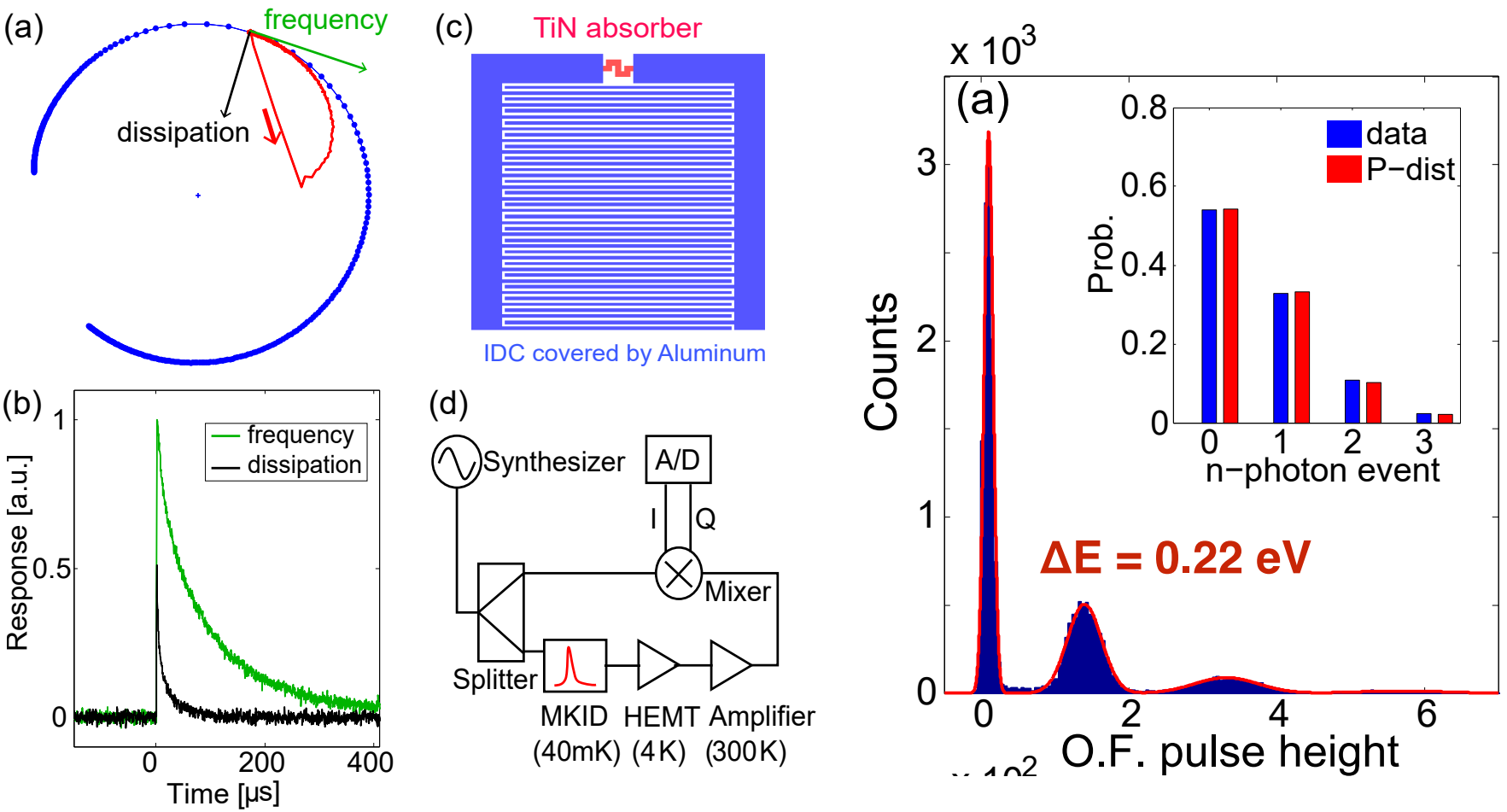

O. Bourrion et al, JINST 6 P06012 (2011)

- A single cryogenic amplifier can be used to read up to 1000 detectors.

# Good energy resolution

**Counting Near Infrared Photons with Microwave Kinetic Inductance Detectors**

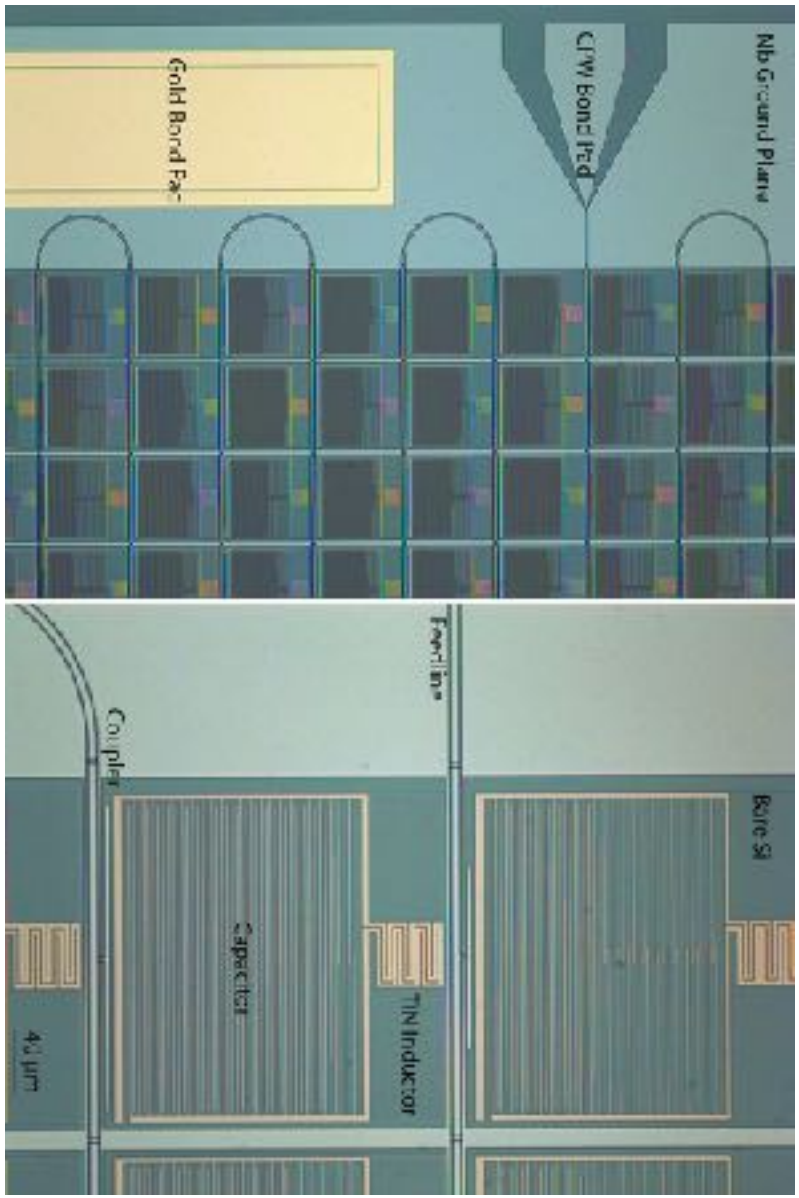
Guo, W. et al, arXiv:1702.07993

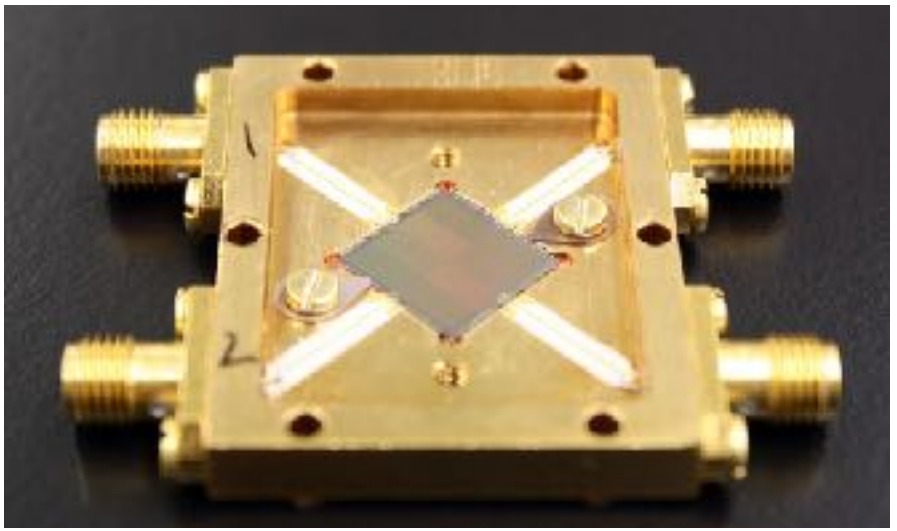


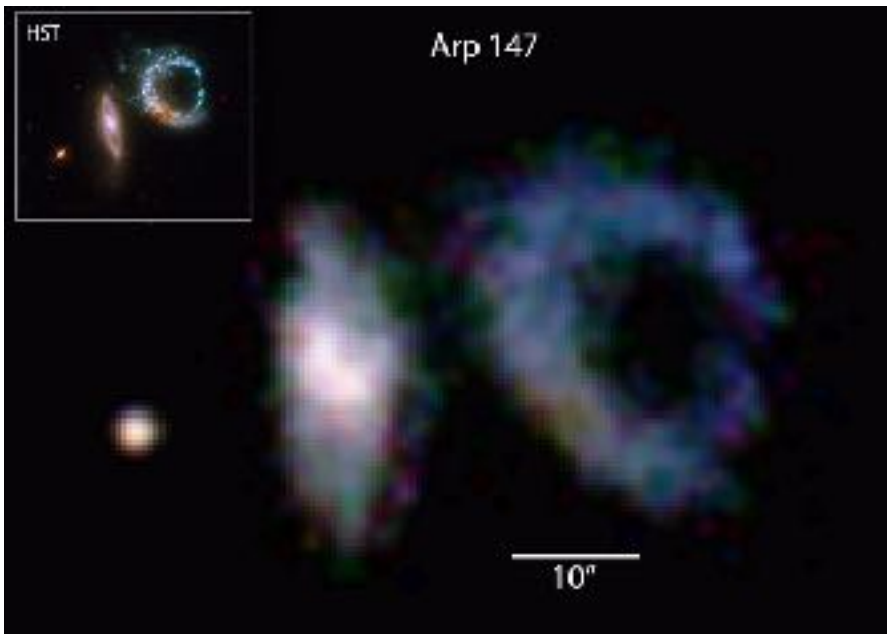
# High scalability

**ARCONS: A 2024 Pixel Optical through Near-IR Cryogenic Imaging Spectrophotometer**

Mazin, B.A. et al, PASP, 123, 933, 2013.



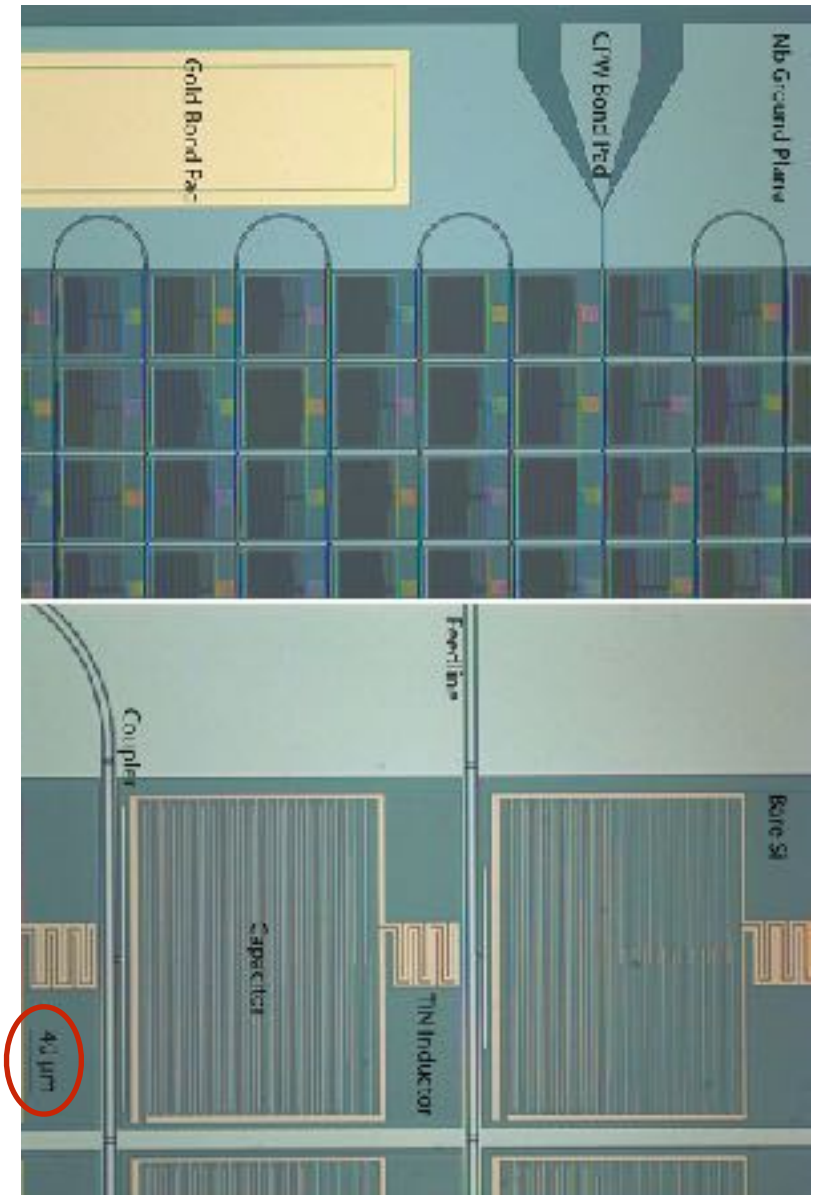



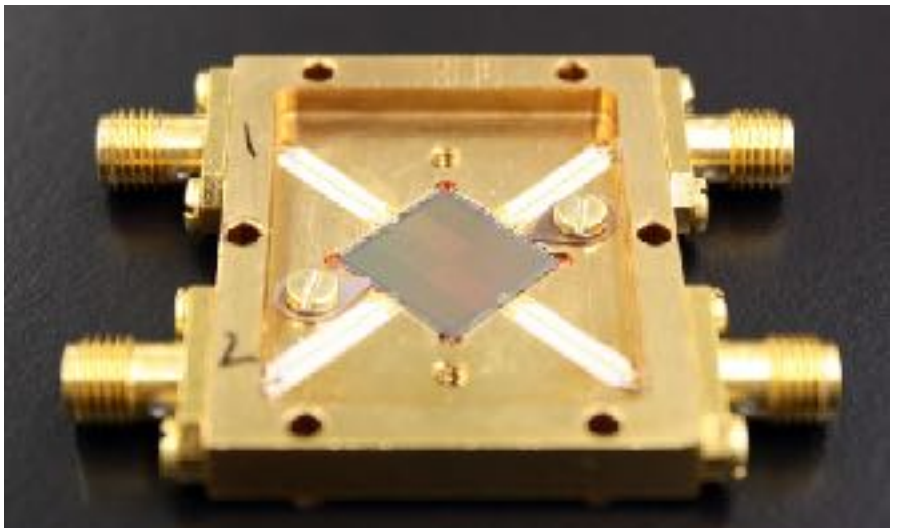


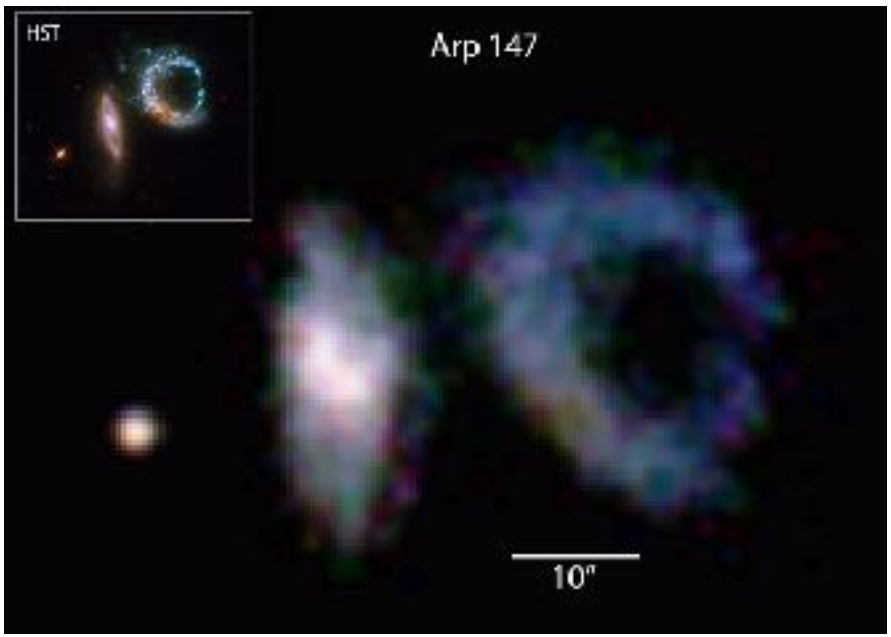
# High scalability

**ARCONS: A 2024 Pixel Optical through Near-IR Cryogenic Imaging Spectrophotometer**

Mazin, B.A. et al, PASP, 123, 933, 2013.



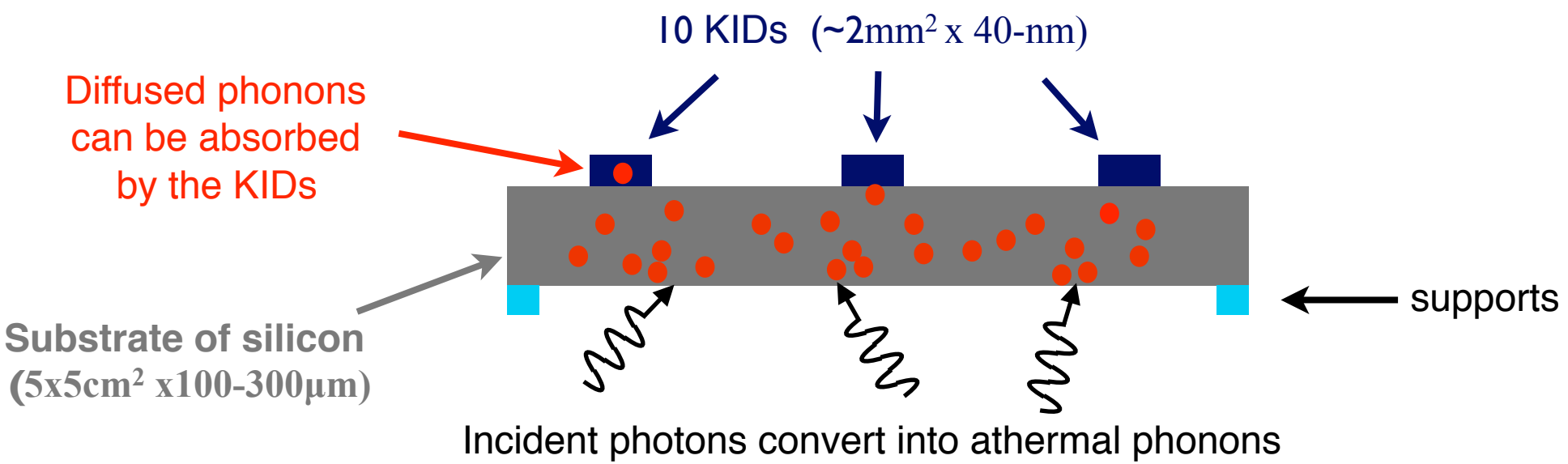





# CALDER: light detectors with KIDs

| | State of the art | Goal | |
|---|---|---|---|
| **Area** | few $mm^2$ | 5x5 $cm^2$ | difficult |
| **ΔE [eV RMS]** | < 1 | < 20 | achievable |
| **$T_{work}$ [mK]** | 80 | 10 | pro |

The maximum sensible area is of few $mm^2$ (wavelength limited).
Scaling to several $cm^2$: indirect detection mediated by phonons




E.S. Battistelli, et al, EPJ C75 (2015) 353

# The CALDER research team

**Istituto Nazionale di Fisica Nucleare:**
*L. Cardani, N. Casali, A. Cruciani,*
*A. D'Addabbo, C. Tomei and M. Vignati.*

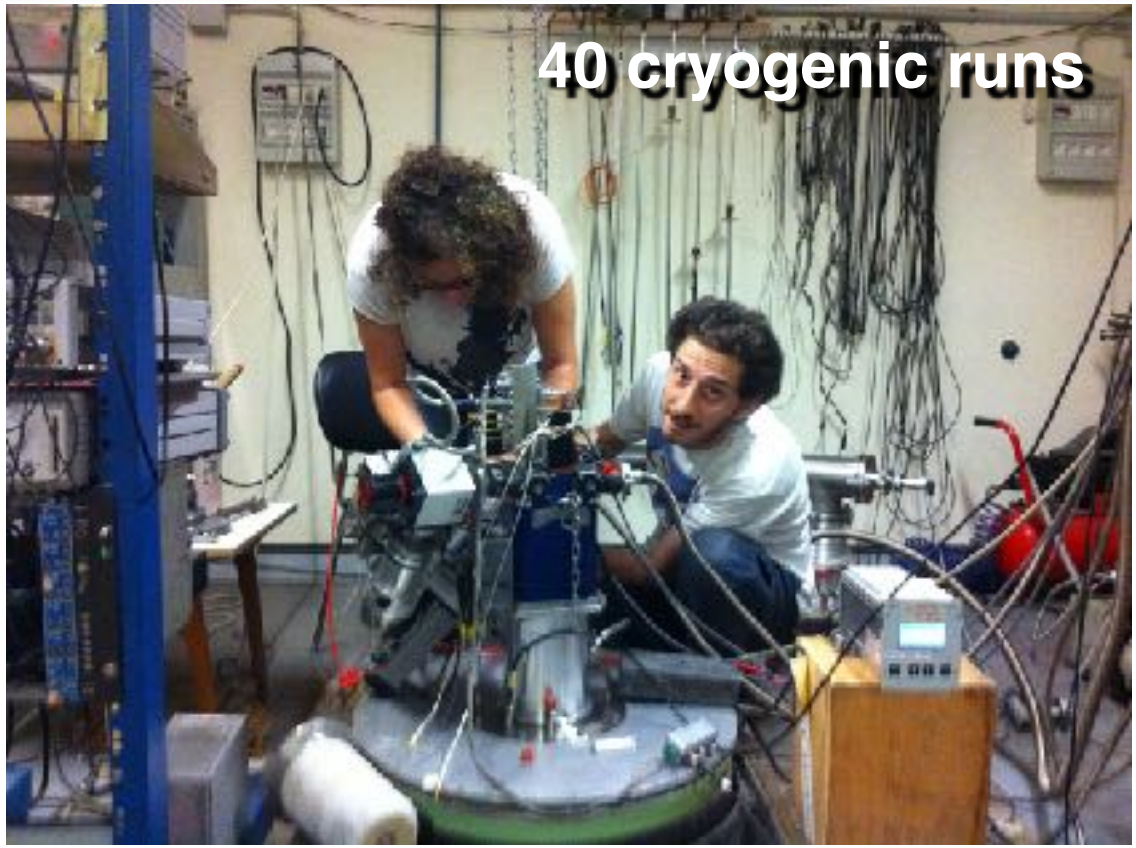
**Sapienza University of Rome:**
*F. Bellini, C. Cosmelli, L. Minutolo, M. Martinez.*

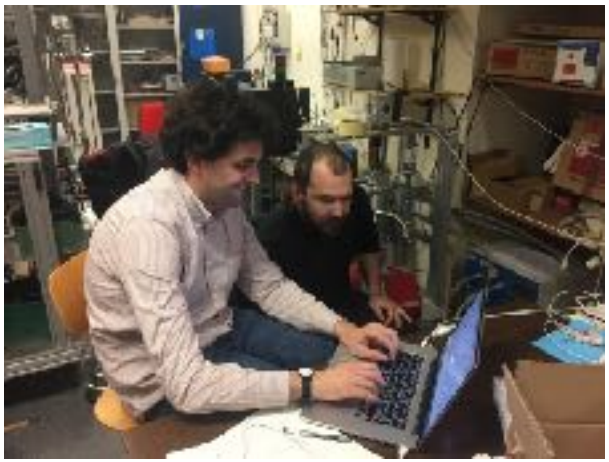
**Consiglio Nazionale delle Ricerche:**
Detector fabrication.
*I. Colantoni and M.G. Castellano.*

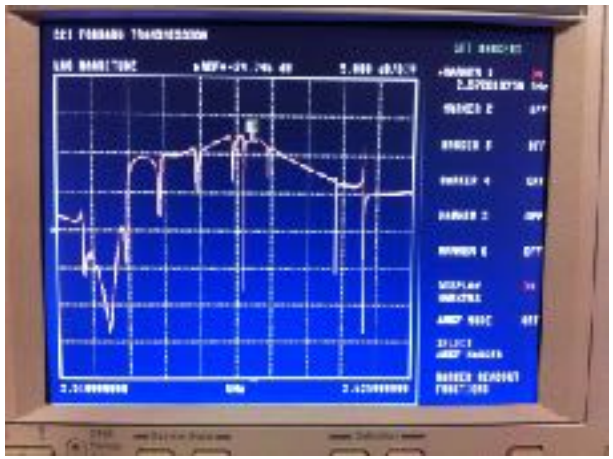
**Università degli studi di Genova:**
Electronics and DAQ.
*S. Di Domizio.*

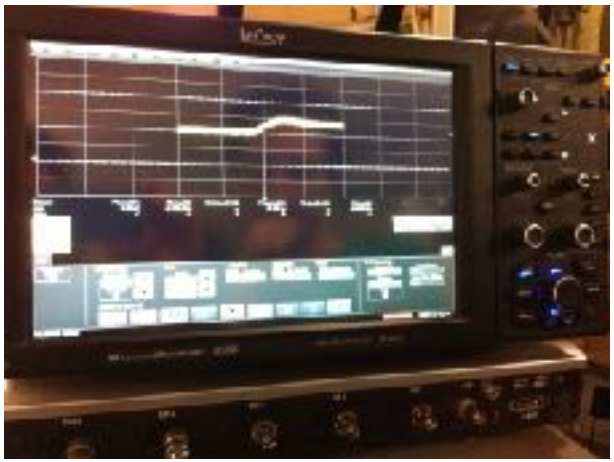
Grants
2014 - 2018

# First phase 2013-2016

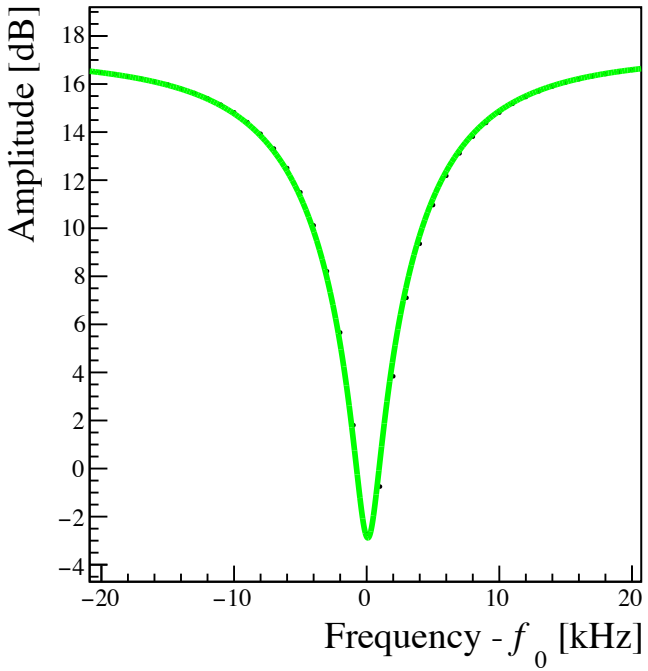



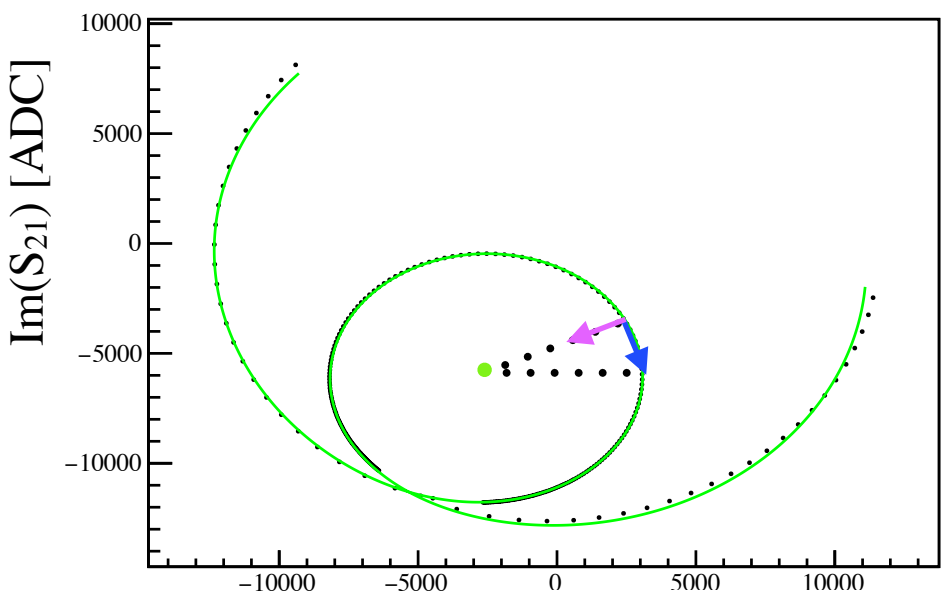


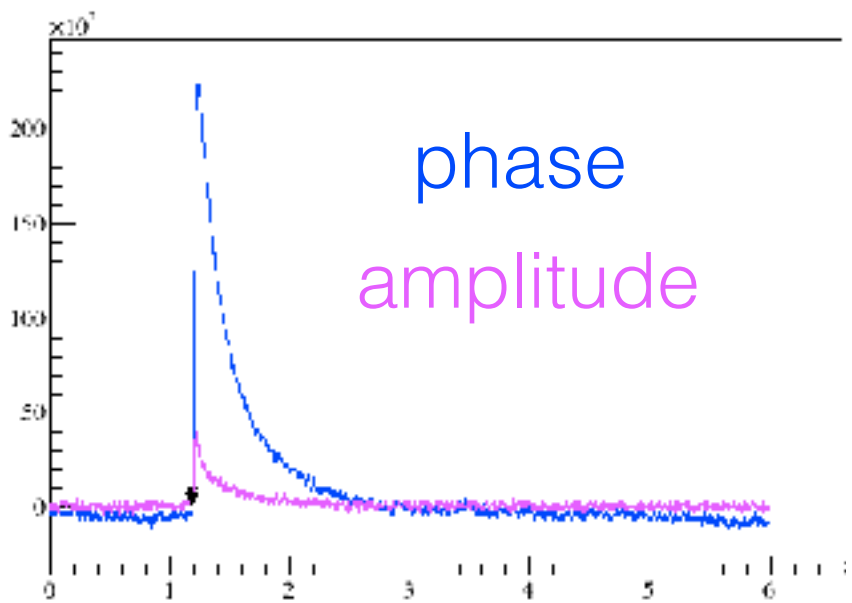


# The KID signal

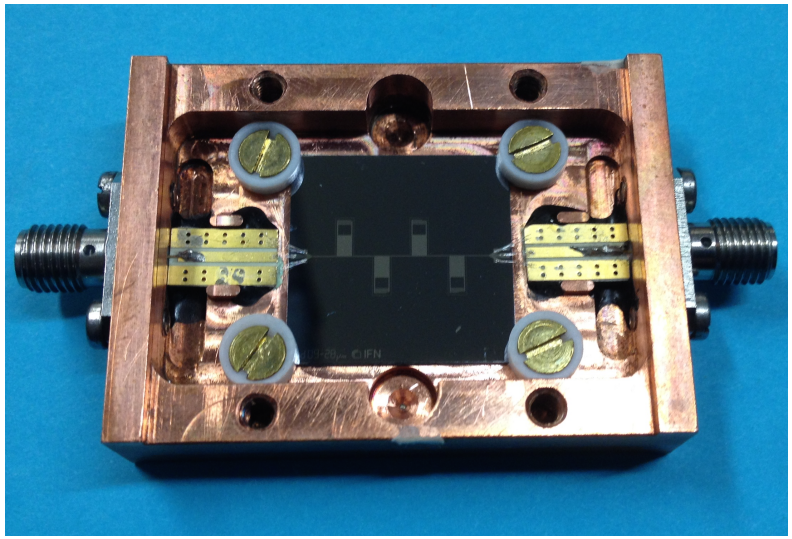



1. Frequency sweep to measure the transmission $S_{21}$ past the resonator:
2. Determine the resonant frequency and bias the detector at that frequency.
3. Measure Phase and Amplitude Modulation of the wave transmitted past the resonator



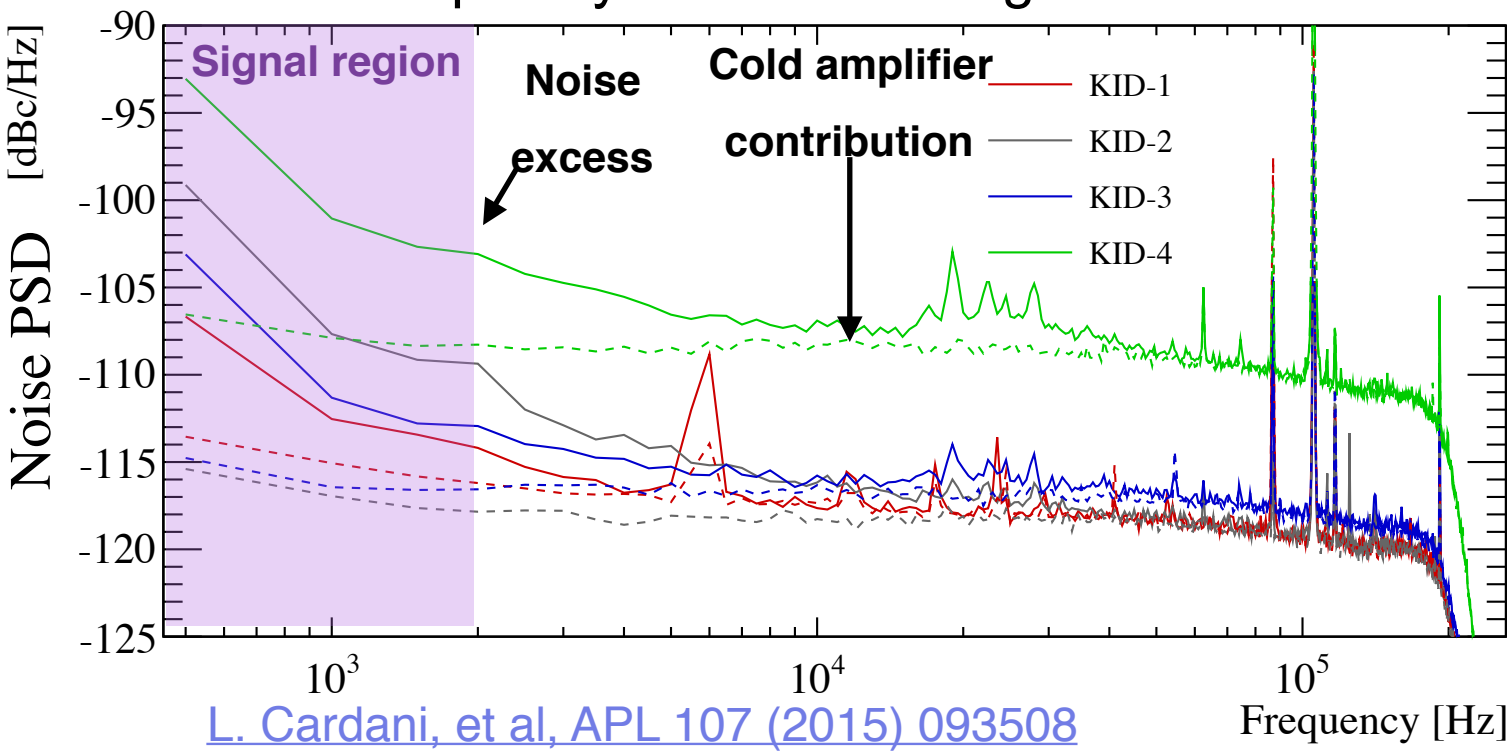



# First results



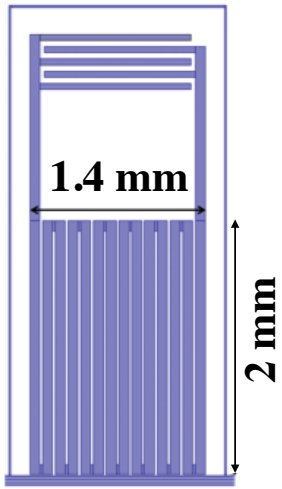
- Prototype with 4 Aluminum resonators on silicon substrate (2x2 cm²)
- Total phonon efficiency ~ 18%
- Combined Baseline resolution ~150 eV

a low frequency noise is limiting the resolution:

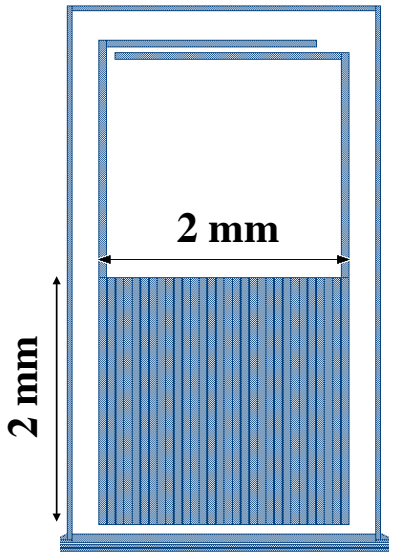



L. Cardani, et al, APL 107 (2015) 093508

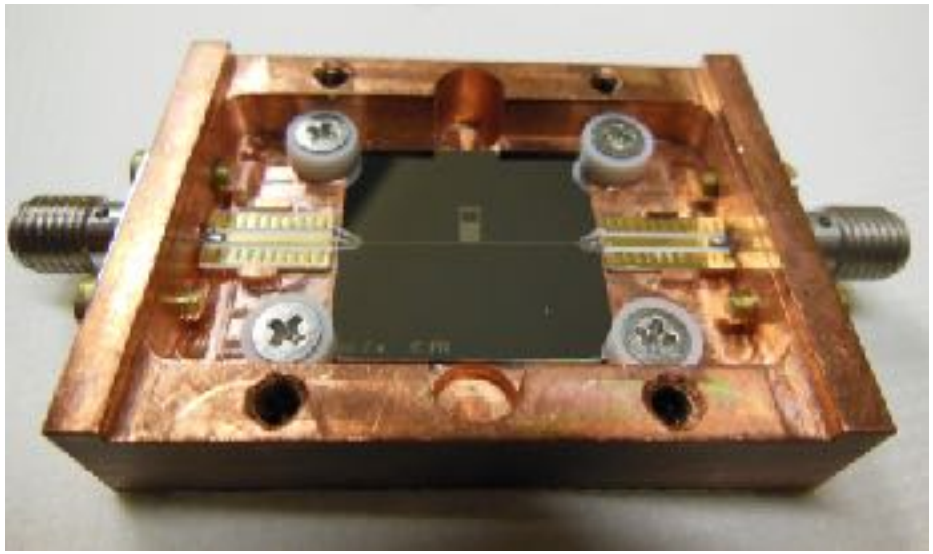
# Detector improvement




40 nm thick



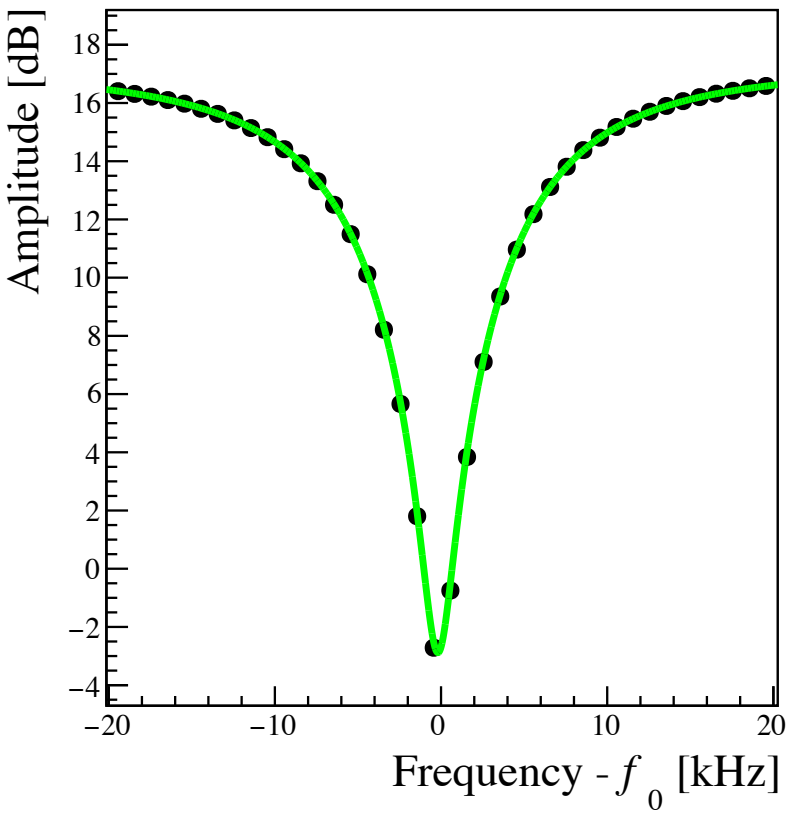

60 nm thick



- Keep resonant frequency above 2 GHz (electronics constraint).
- Higher thickness: provides better quality of the superconductor.
- Higher resonator Q (from $10^4$ to $10^5$): increases the sensitivity.
- Wider area: increases the **phonon absorption efficiency.**

# 80 eV: First milestone achieved

factor ~4 improvement on a single KID

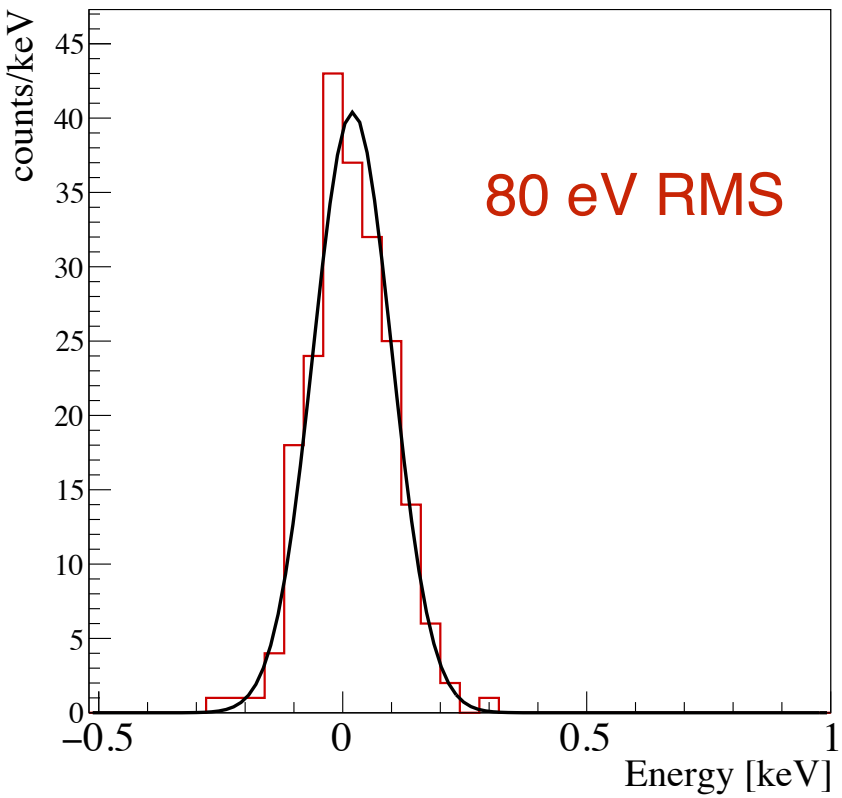



$f_0 = 2597.079$ MHz

$Q = 147$ k

$Q_c = 156$ k

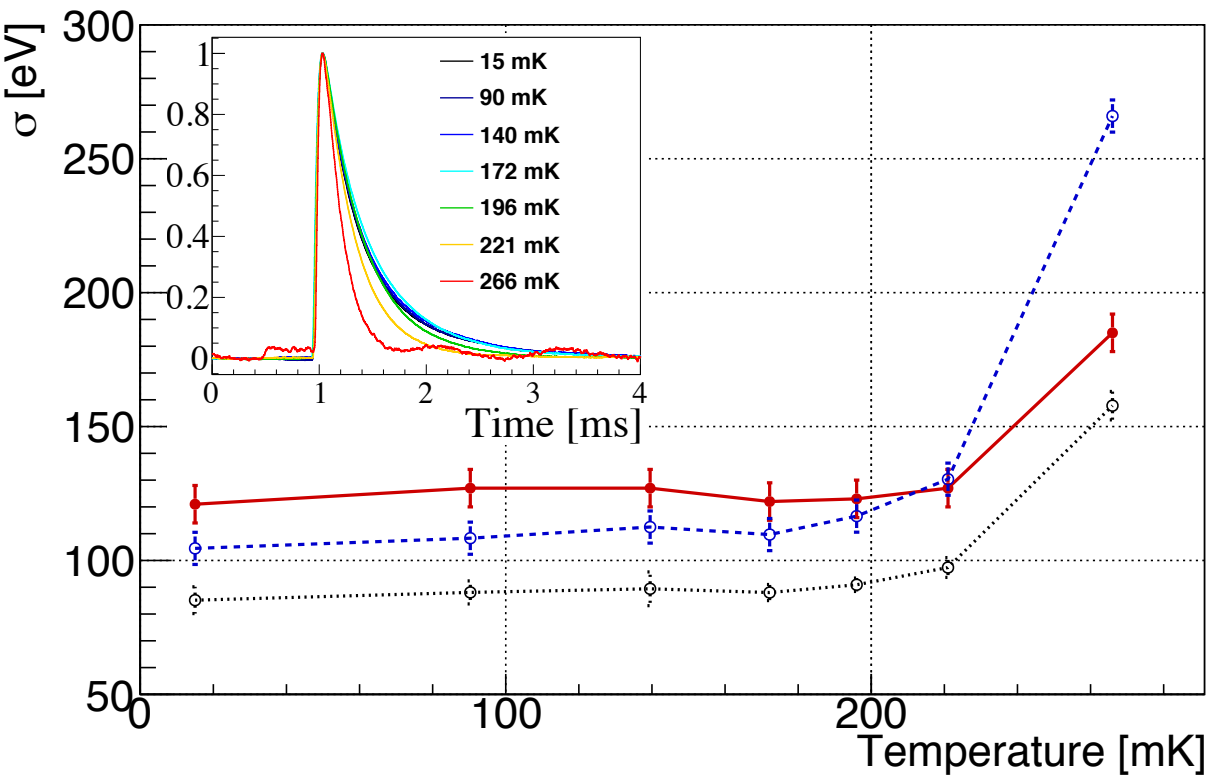
$Q_i = 2607$ k



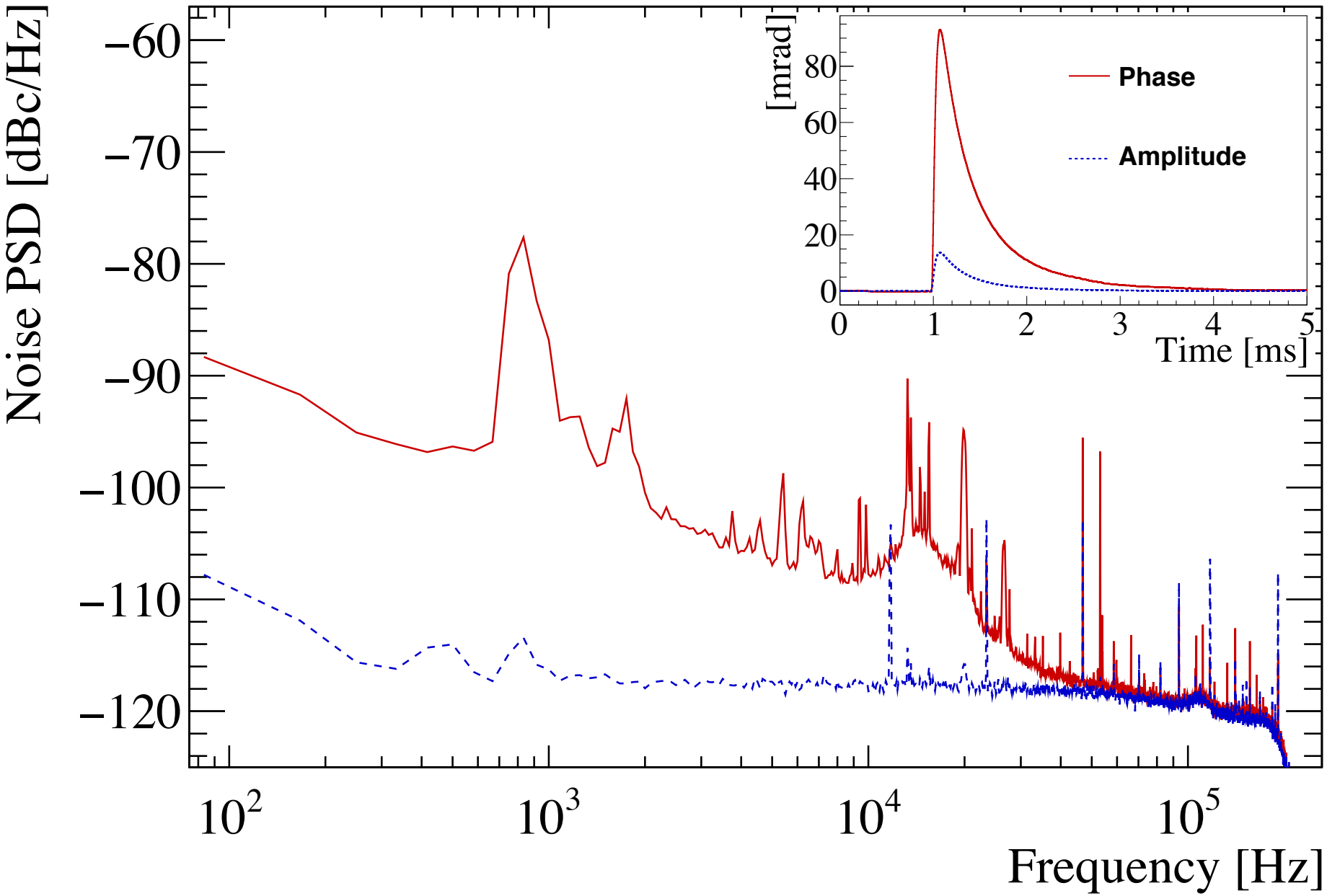

L. Cardani, et al, APL 110 (2017) 033504

# 80 eV: First milestone achieved

- Result obtained by combining the phase and amplitude signals
- Resolution independent from temperature up to 200 mK.
- Amplitude resolution better than the phase one.

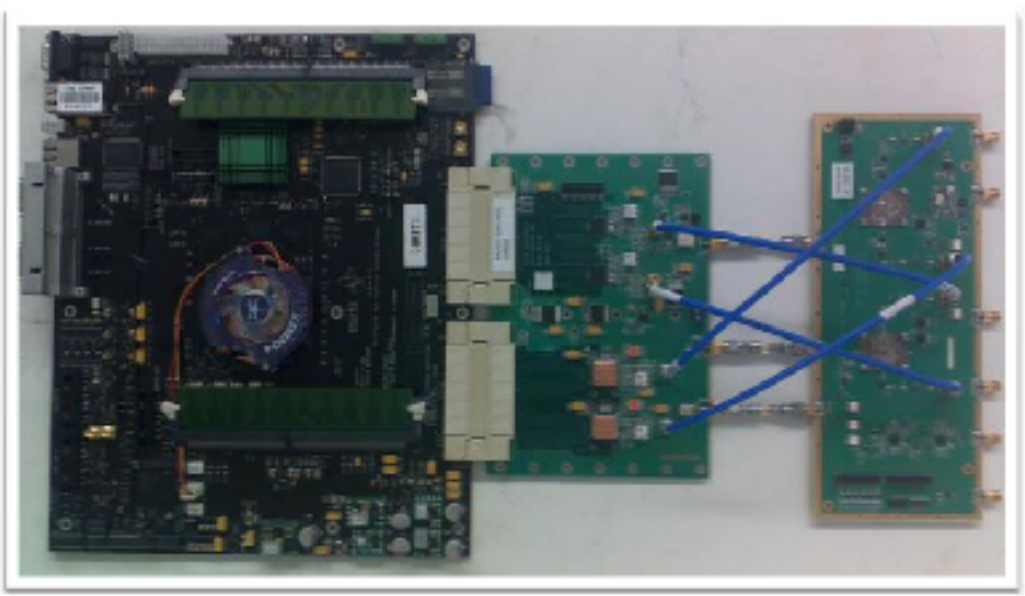


# Phase noise still there



# Heterodyne readout development

- So far using an electronics able to handle up to 12 KIDs in parallel.
- We are developing a custom FPGA firmware on top of the ROACH opensource hardware and software board.
  - Goal: 100 KIDs in parallel.
- Developed by a wide (mostly astro-) community.



ROACH readout system

FPGA board (Virtex6) for signal processing
On-board PowerPc for FPGA control
16-bit 500Msps dual DAC
14-bit 400Msps dual ADC
4x 10Gbe interfaces for data streaming
Up/down conversion w clock-distribution board

# End of 2016: New cryostat, new lab

| | |
|---|---|
| ***Base temperature*** | < 10 mK |
| ***Cooling Power*** | 400 uW @100 mK |
| ***Experimental Volume*** | 44h x 24⌀ $cm^3$ |
| ***Bath Cooling*** | Pulse tube |
| ***Dilution unit*** | $^3$He - $^4$He (50 L) |
| ***Model*** | Oxford Triton 200 |
| ***Run mode*** | Automatic |

# Test of new superconductors

If we do not find the noise origin, we have to increase the response in the superconductor.

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

| | Al | TiAl AlTiAl | Ti+TiN | TiN sub- stoic. |
|---|---|---|---|---|
| $T_C$ [K] | 1.2 | 0.6-0.9 | 0.5-0.8 | 0.5 |
| $L$ [pH/square] | 0.5 | 1 | 6 | up to 50 |
| $Q$ max | $10^{5\text{-}6}$ | $10^{5\text{-}6}$ | ? | ? |
| phonon collection ε | 10% | 5-10% | low? | low? |
| Producer | IFN CNR | CSNSM Neel-CNRS | FBK | IFN CNR |
| Status | Completed | First results | Production | Material R&D |

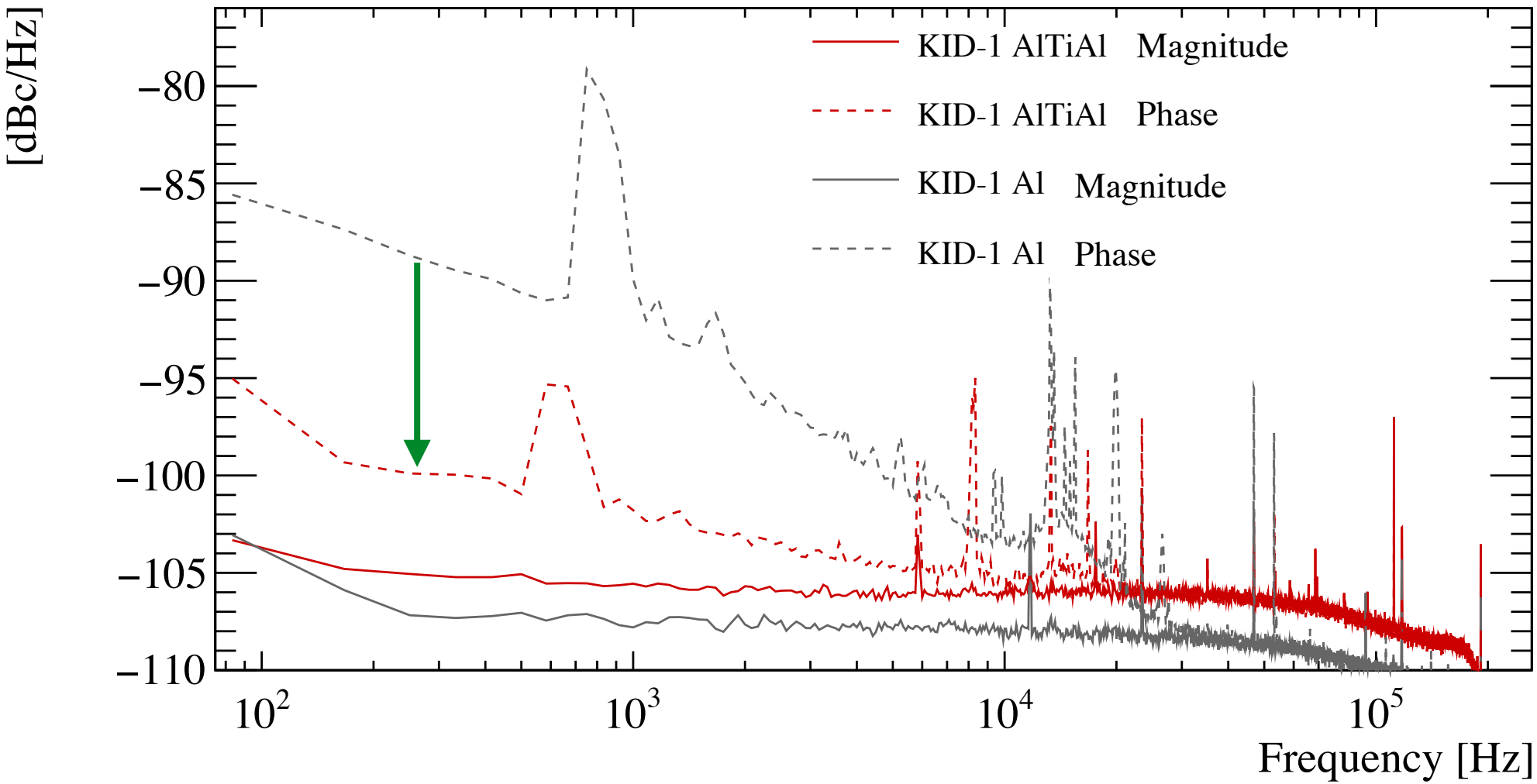
# Test of new superconductors

If we do not find the noise origin, we have to increase the response in the superconductor.

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

| | Al | TiAl AlTiAl | Ti+TiN | TiN sub- stoic. |
|---|---|---|---|---|
| $T_C$ [K] | 1.2 | 0.6-0.9 | 0.5-0.8 | 0.5 |
| $L$ [pH/square] | 0.5 | 1 | 6 | up to 50 |
| $Q$ max | $10^{5\text{-}6}$ | $10^{5\text{-}6}$ | ? | ? |
| phonon collection ε | 10% | 5-10% | low? | low? |
| Producer | IFN CNR | CSNSM Neel-CNRS | FBK | IFN CNR |
| Status | Completed | First results | Production | Material R&D |

# Al-Ti-Al

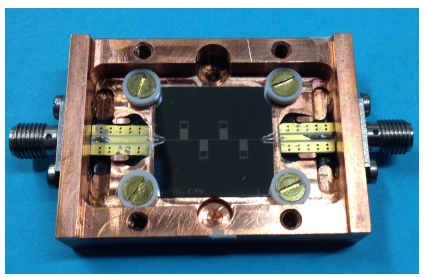



The phase noise is substantially lowered

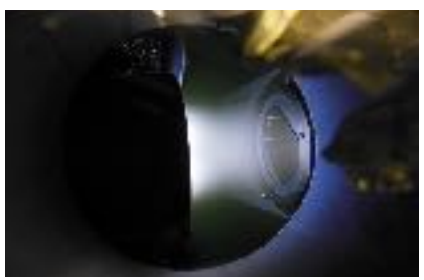
This pushes the sensitivity close to our 2nd milestone of 20 eV

# Summary and program

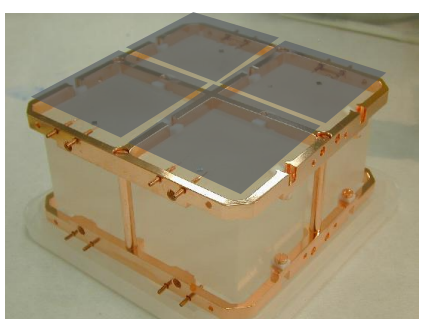
**2013-2014**
Started activity from scratch.
First aluminum prototypes with low Q.



**2014-2016**
Aluminum: Q up to 300k, resolution from 150 to 80 eV.



**2016-2017**
New lab.
Compounds with Titanium: about to reach the goal of 20 eV.



**2017-2018** Build a demonstrator at LNGS: an array of $TeO_2$/ZnSe bolometers monitored by the new light detectors.