Status of CALDER: Kinetic Inductance light detectors for neutrinoless double beta decay

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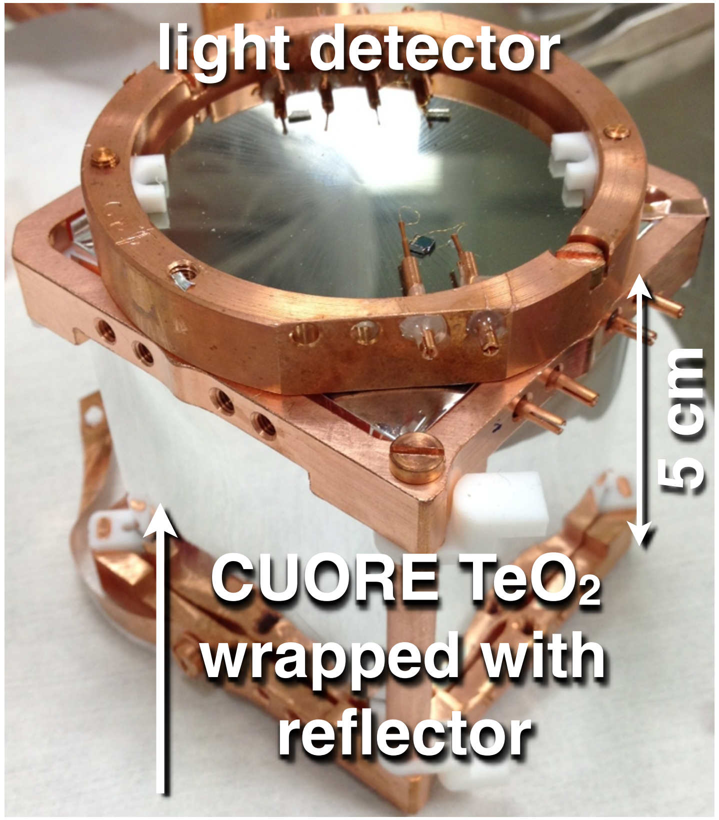
http://www.roma1.infn.it/exp/calder/

Istituto Nazionale di Fisica Nucleare

Motivation

Detect Cherenkov or scintillation light from large-mass bolometers to search for double beta decay with the CUORE successor.



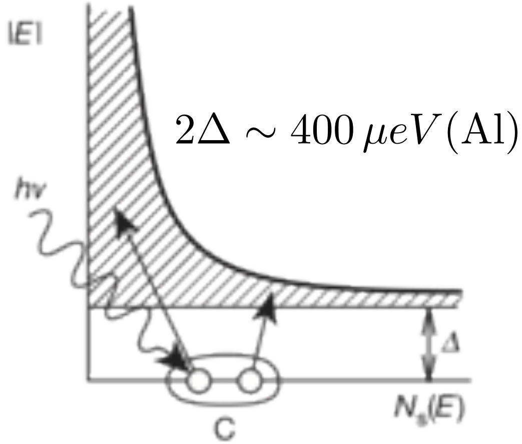
	CUPID ZnSe/LMO	CUPID TeO_2
Light signal [keV]	2 - 20	0.1
Area [cm²]	15	20 - 25
ΔE [eV RMS]	50-150	< 20
Temperature	8 - 20 mK	
# detectors	~1000	
Sensor	NTD	?

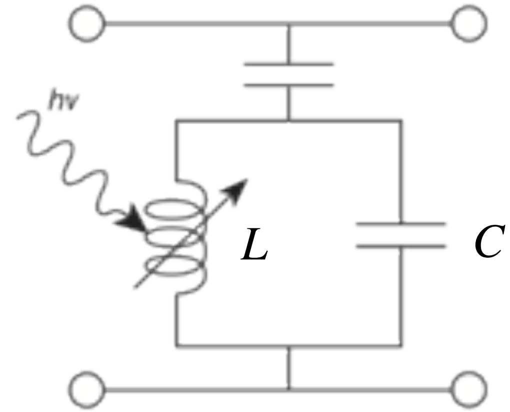
Sensor R&D by other groups: NTD or TES (w or w/o Luke amplification)

We investigate a new technology for this field: KIDs

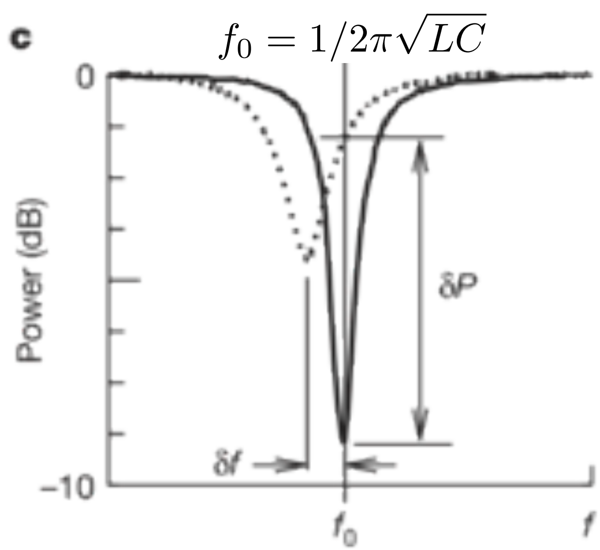
Kinetic Inductance Detectors (KIDs)

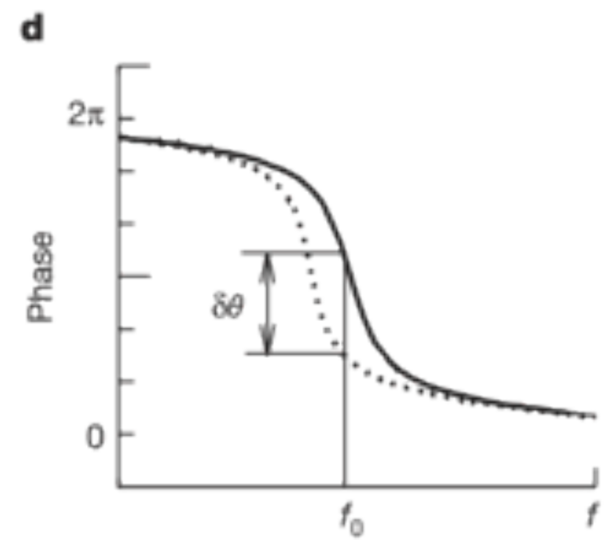
Day et al., Nature 425 (2003) 817





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

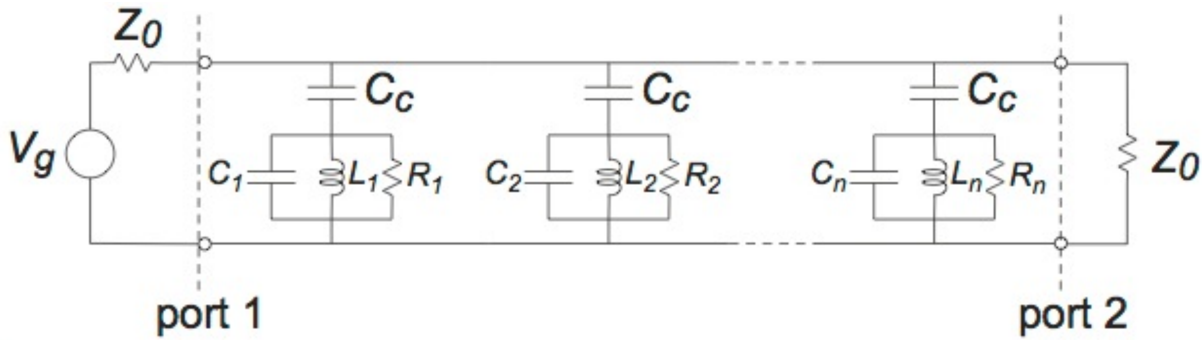


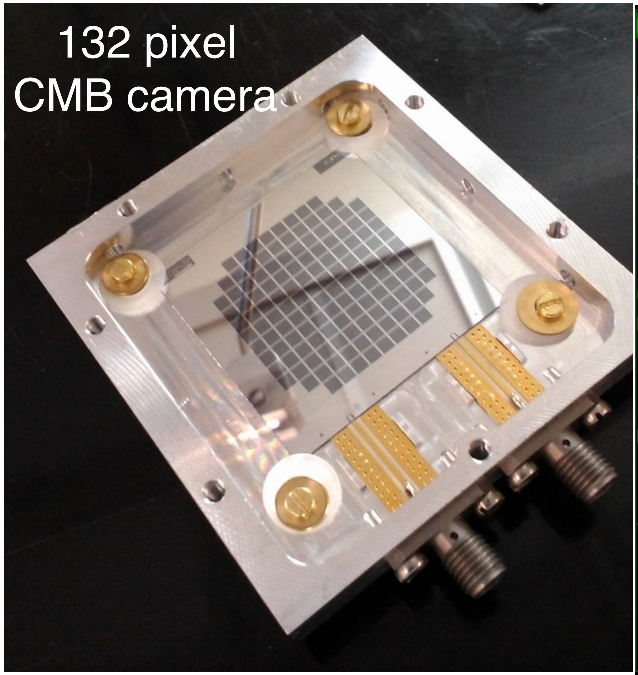


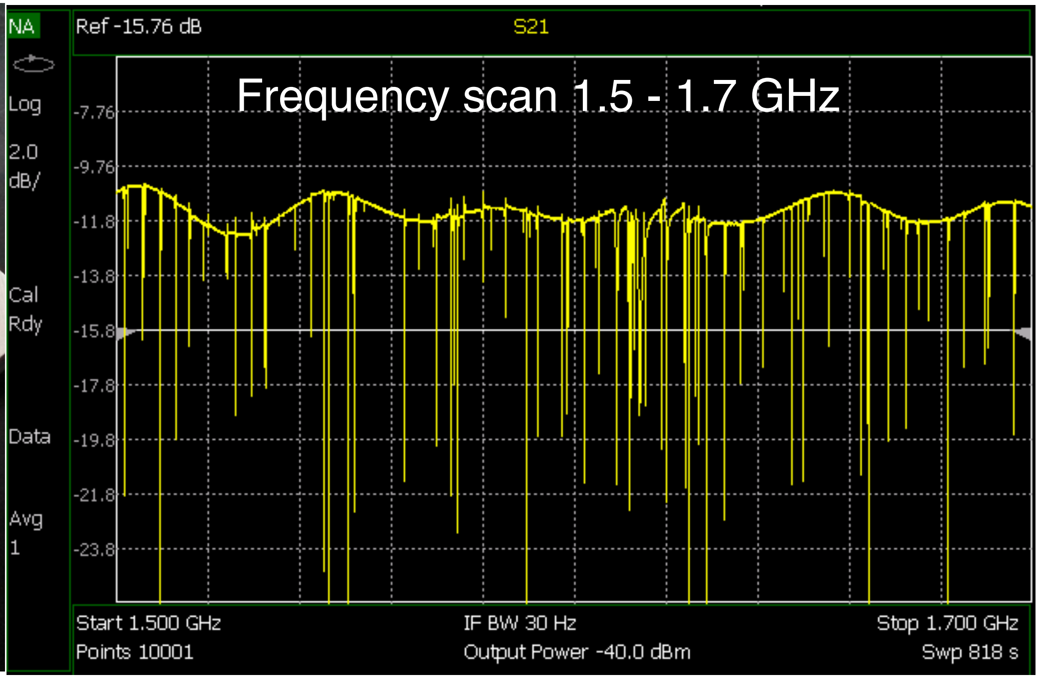
High quality factor (*Q*) resonating circuit biased with a microwave (GHz):
signal from amplitude and phase shift.

Multiplexed readout of a KID array

Different resonators can be coupled to the same feedline
with slightly different resonant frequencies.
Resonant frequency modified via the capacitor (C) pattern of the circuit.





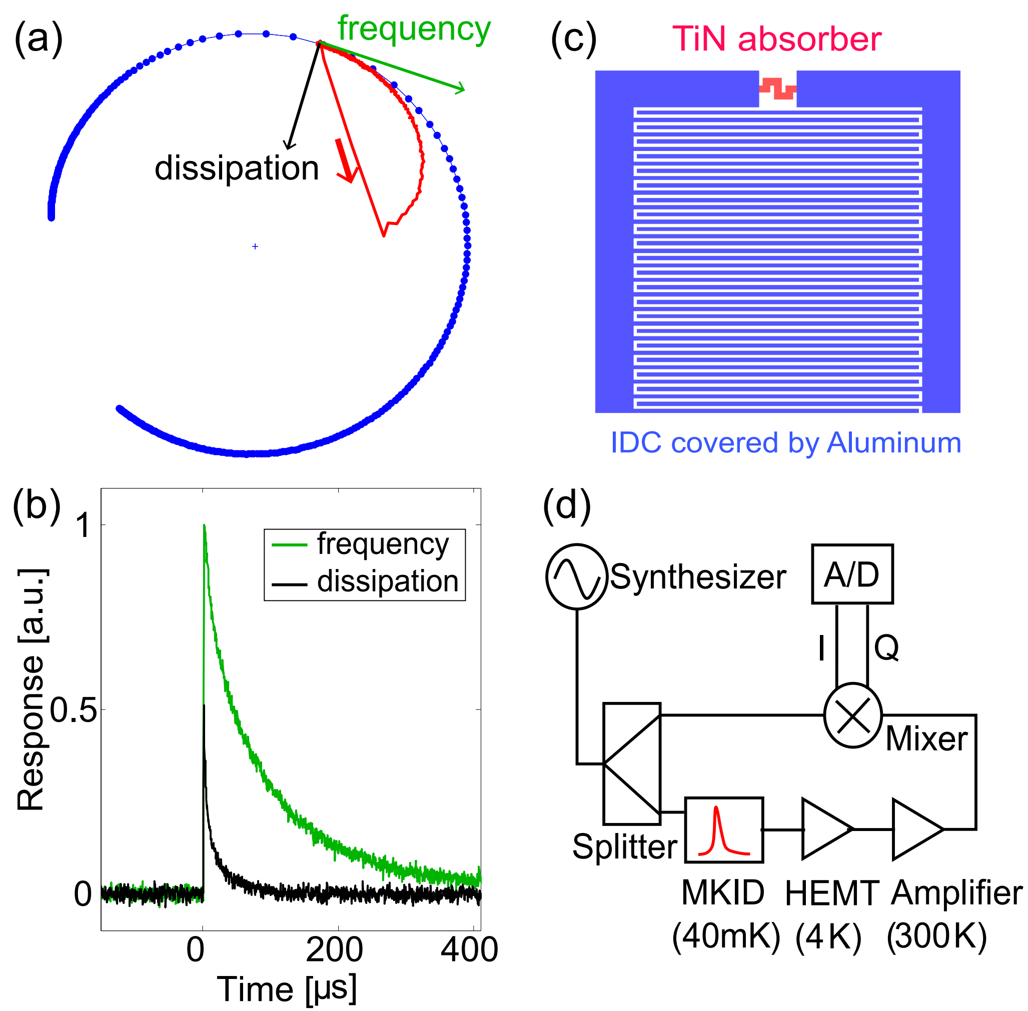


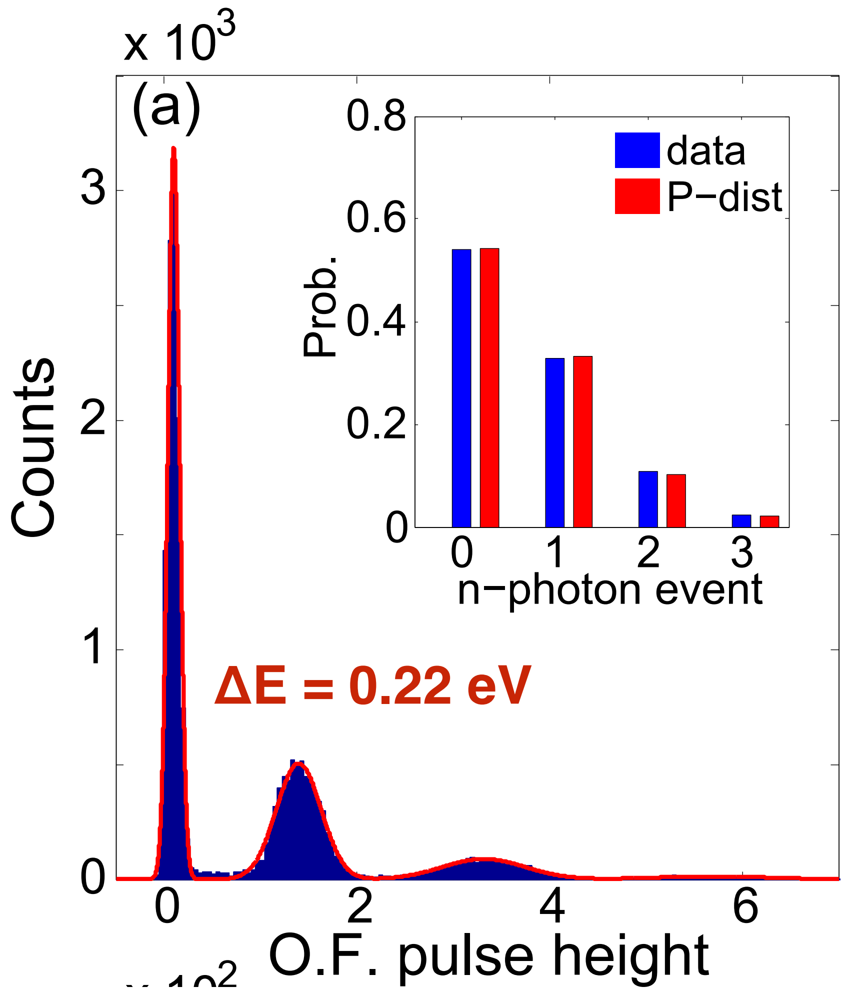
Multiplexing up to 100-1000 KIDs has been already demonstrated

Good energy resolution

Counting Near Infrared Photons with Microwave Kinetic Inductance Detectors

Guo, W. et al, Appl. Phys. Lett. 110, 212601 (2017)



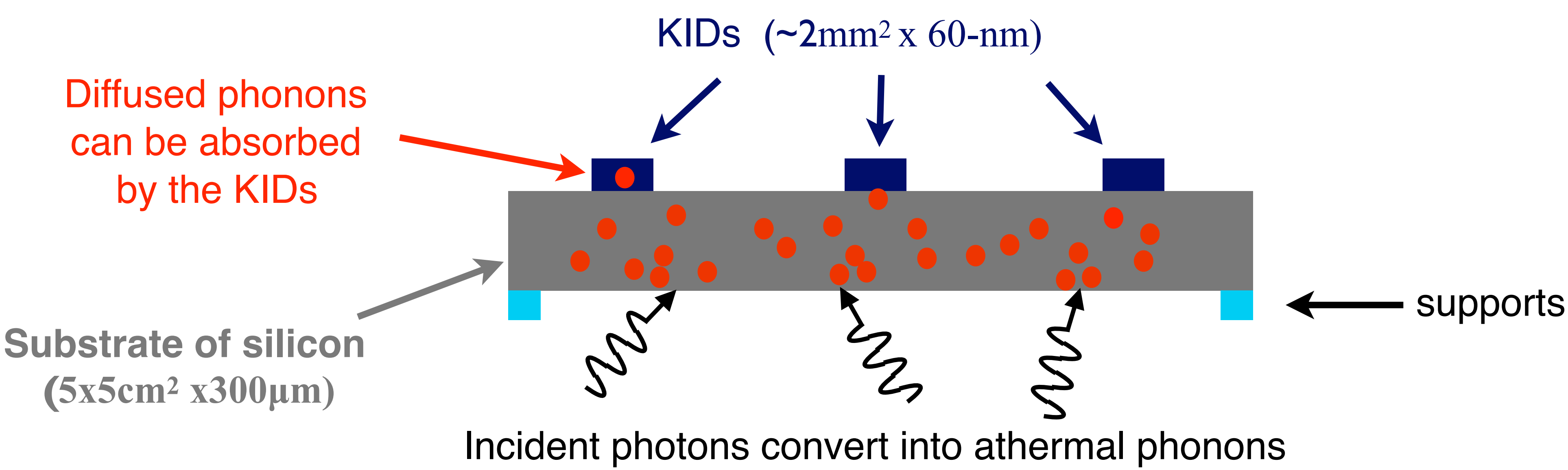


CALDER: light detectors with KIDs

GHz operation limits the maximum sensible area of KIDs to few mm^2

Scaling to several cm^2:

indirect detection mediated by phonons



Challenge: collect as many phonons as possible

The smaller the number of pixels the better!

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

CALDER collaboration

Istituto Nazionale di Fisica Nucleare:
L. Cardani, N. Casali, A. Cruciani, P. Fresch and M. Vignati.

Sapienza University of Rome:
F. Bellini, C. Cosmelli

Consiglio Nazionale delle Ricerche:
M.G. Castellano, G. Pettinari.

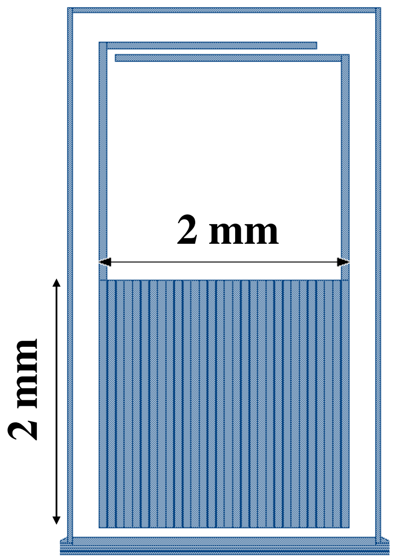
Università degli studi di Genova:
S. Di Domizio.

CSNSM - CNRS/IN2P3
H. Le Sueur

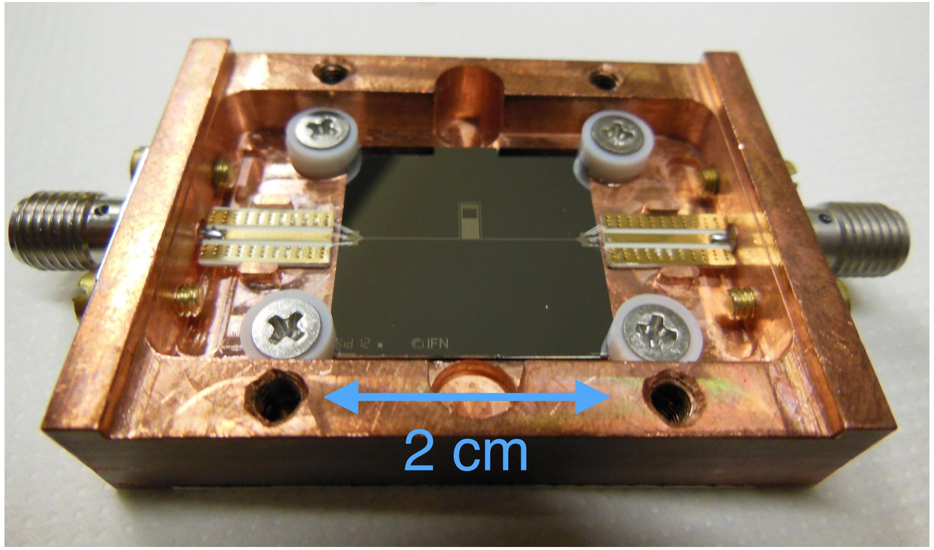
Universidad Zaragoza *M. Martinez*

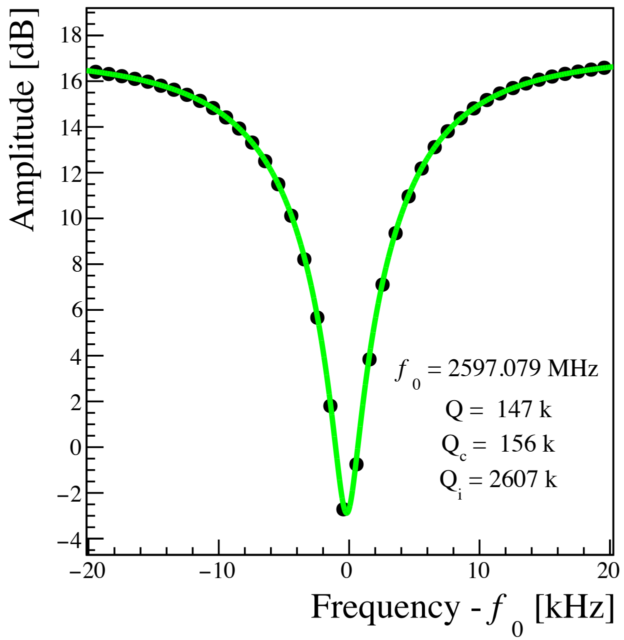
Institut Néel - CNRS
M. Calvo, J. Goupy, A. Monfardini

Aluminum detector (2016)



60 nm thick





Film thickness: provides better quality of the superconductor.

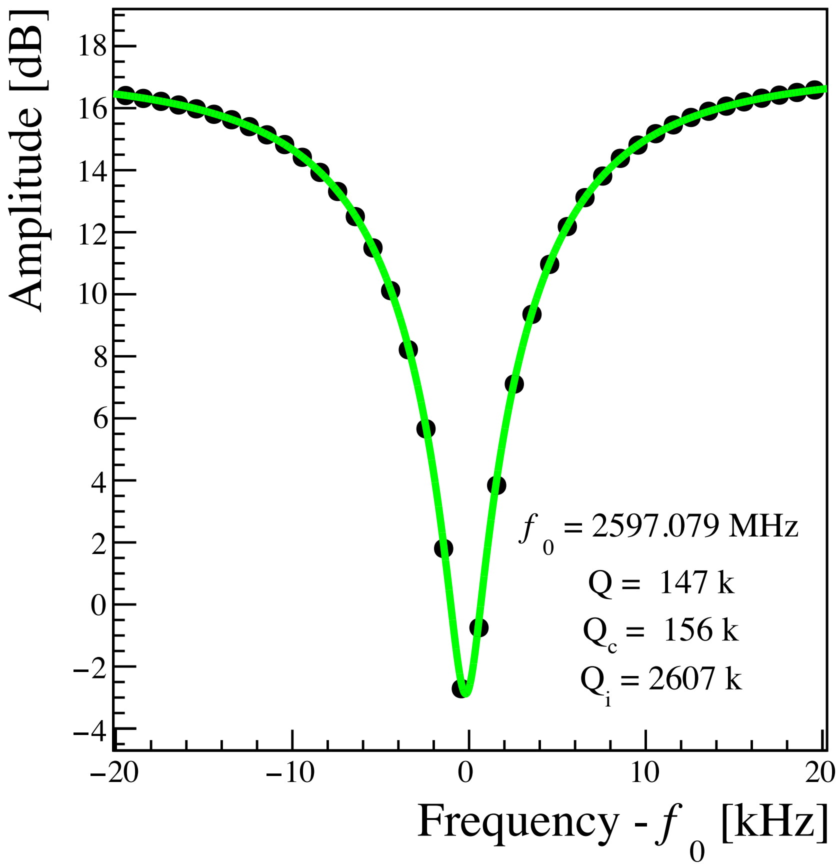
Large film area: increases the **phonon absorption efficiency.**

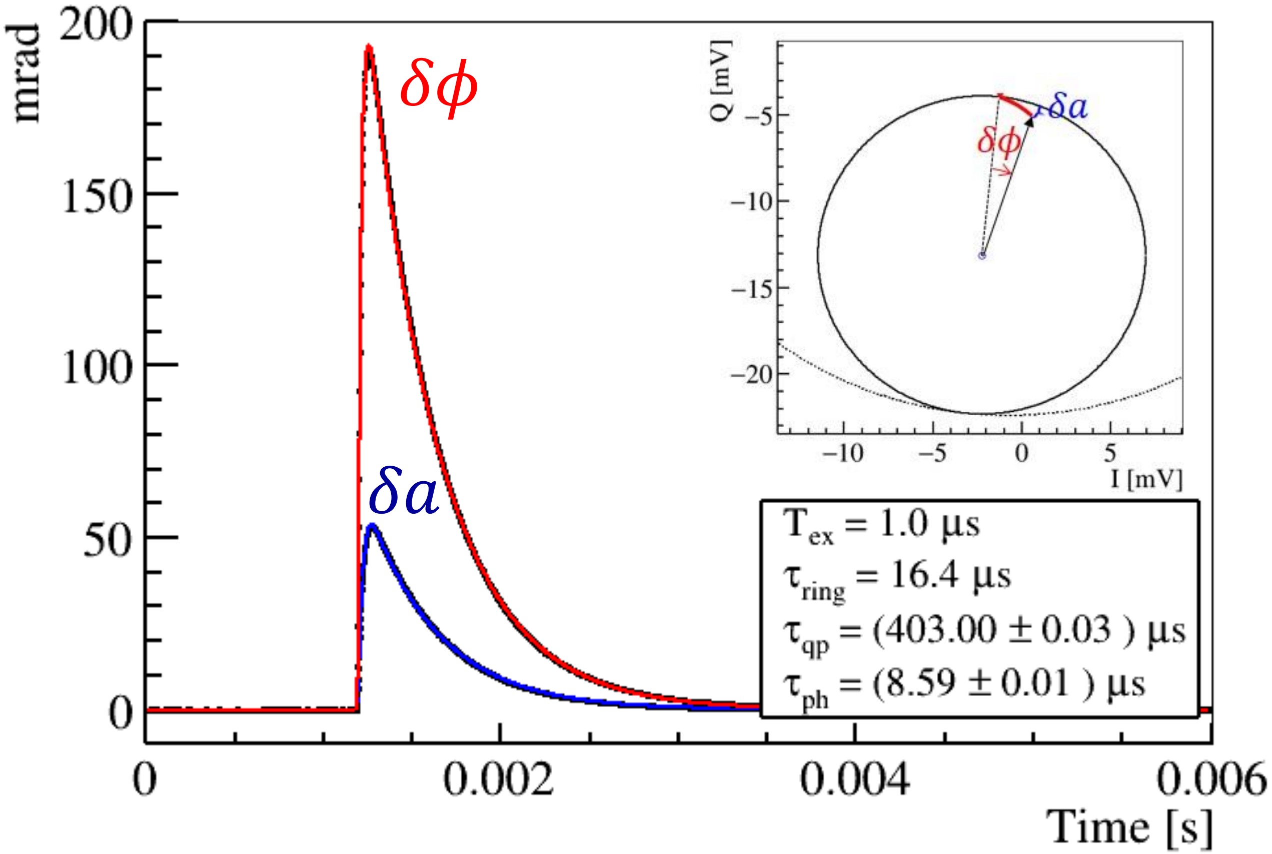
Resonant frequency ~ 2.5 GHz.

High resonator Q (~10^5): increases the signal height.

KID signal

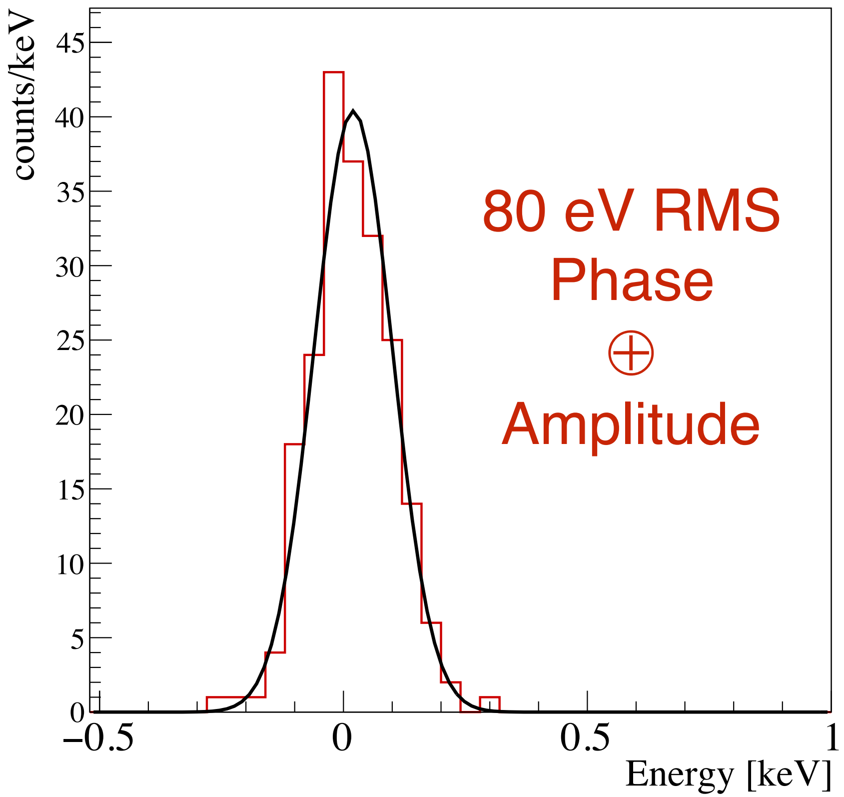
1. Frequency sweep to measure the transmission S_{21} past the resonator:
2. Determine the resonant frequency and bias the detector at that frequency.
3. Measure Phase and Amplitude Modulation of the wave transmitted past the resonator

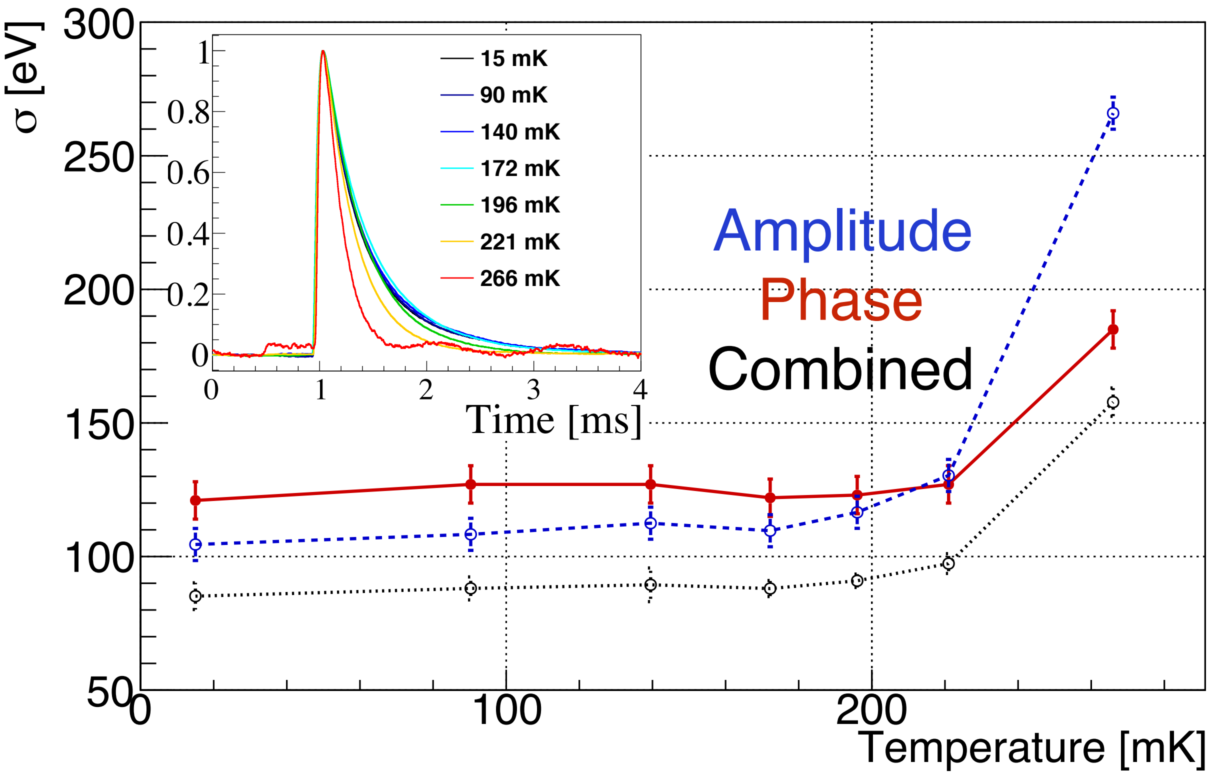




Results of the Aluminum detector

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





- Result obtained by combining phase and amplitude readout with a 2D optimal filter: $\vec{H}^T(\omega) = k\,\vec{S}^\dagger(\omega)N^{-1}(\omega)$
- Temperature independent up to 200 mK.
- Decay time identified as τ_{qp}, similar behavior with microwave power

Improving the energy resolution

Superconductor gap
[180 μeV for Aluminum]

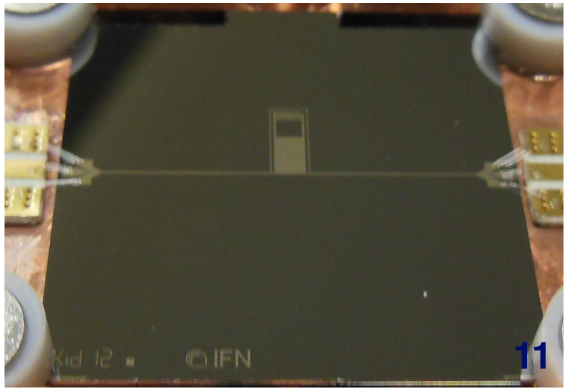
Amplifier noise
[2-6 K]

$$\Delta E \propto \Delta_0 \sqrt{\frac{T_N}{\alpha Q V}}$$

Superconductor Volume
[2x2mm^2 x 60nm]

Kinetic Inductance fraction
[3% for Al]

Resonator Q [10^5]



Superconductor R&D

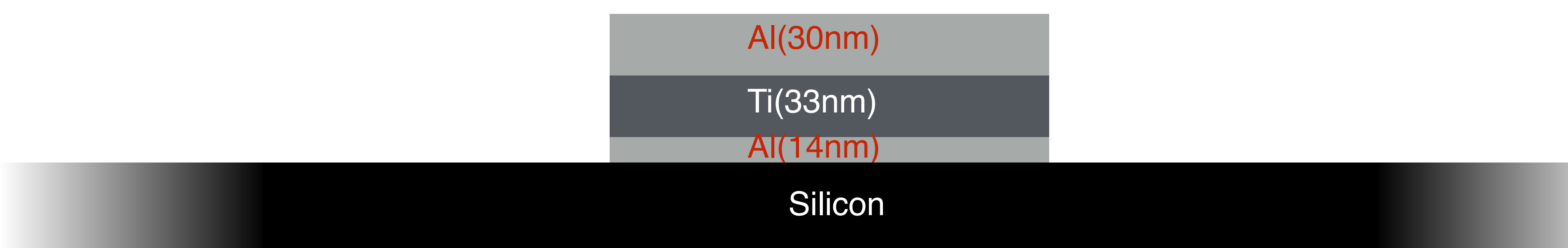
$$\Delta E \propto \frac{T_C}{\epsilon\sqrt{QL}}$$

	Al	Ti+Al	Ti+TiN	Granular Al
T_C [K]	1.2	0.6-0.9	0.5-0.8	1-2
L[pH/square]	0.35	1.2	6?	10-1000
Q_i max	$>10^6$	$10^{5\text{-}6}$	?	$>10^6$
Phonon ε	10%	10%	low?	10%
τ_{qp} [μs]	100-1000	100-1000	10-100	?
Fabrication	IFN-CNR	CSNSM Neel-CNRS	CNR/FBK	KIT
Status	Completed	Completed	Challenging	ongoing

Same design as Aluminum films.

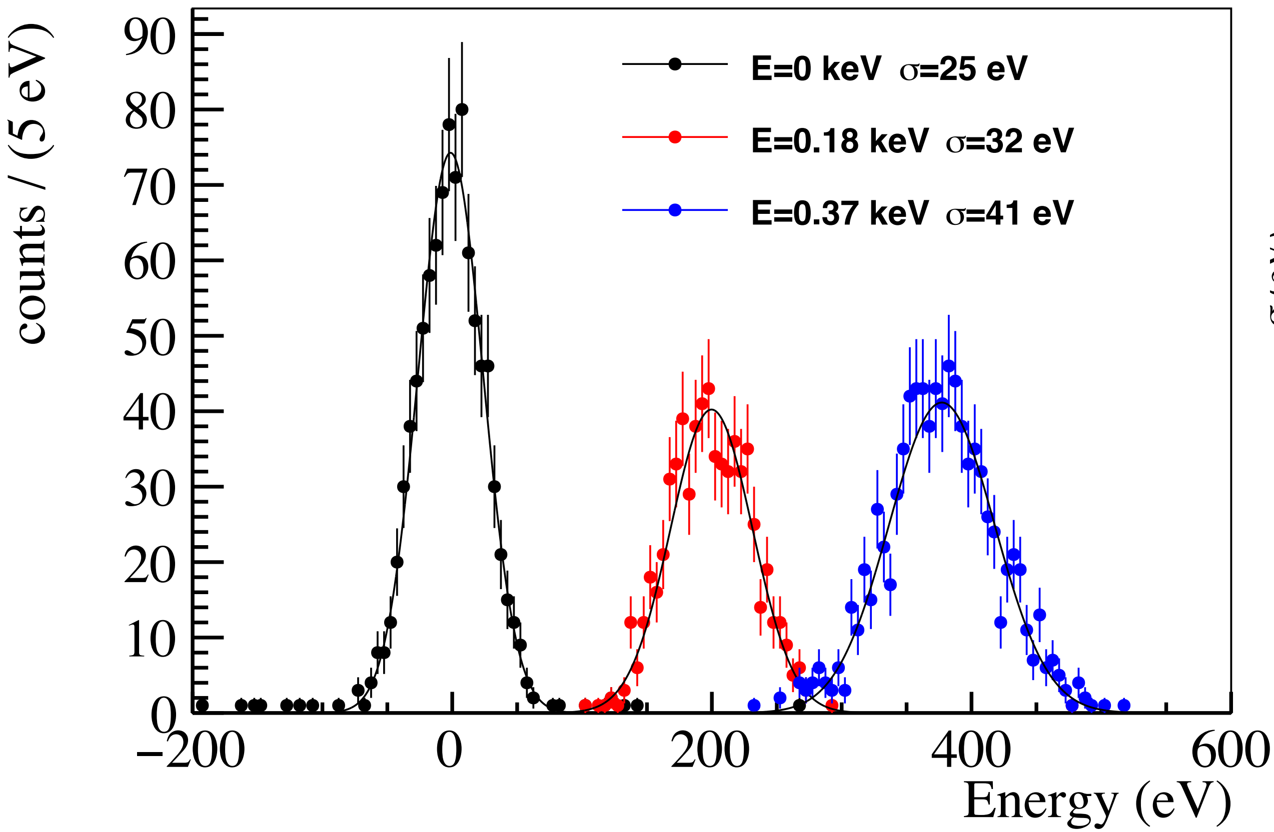
Titanium enhances Kinetic Inductance but lowers the internal *Q*.

Tested different TiAl and AlTiAl multilayers. Best results from:



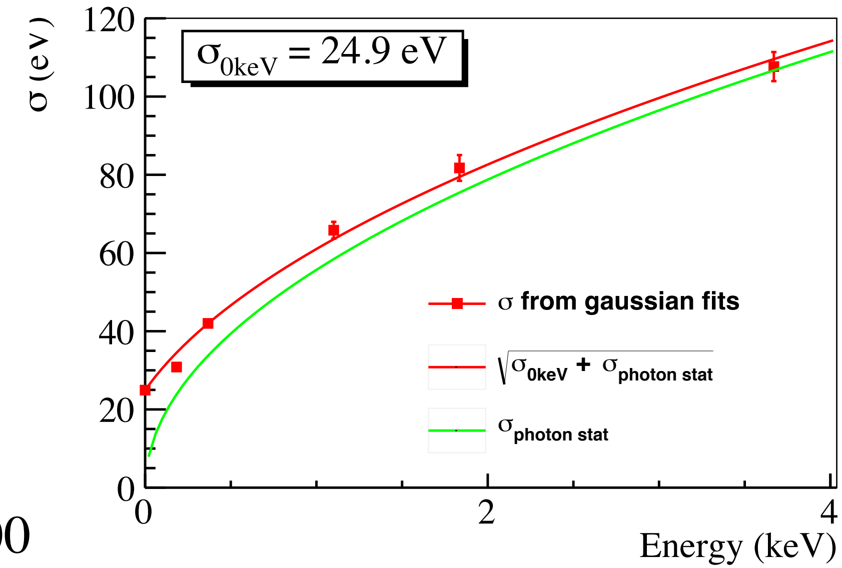
AlTiAl performance

Energy scan with optical fiber



L. Cardani, et al, SUST (2018)

Self-calibrated with photon statistics



- Phase signal 3x higher than Aluminum only
- Phase RMS = 25 eV @0 eV (4x better than Al)
- Amplitude RMS = 80 eV @0eV (similar to Al)

CALDER development

- 04/14 -
Aluminum KIDs
9 pixel
2x2 cm^2
2-8 keV

- 05/15 -
4 pixel
150 eV
APL107 093508

- 06/16 -
1 pixel
80 eV
APL110 033504

- 07/17 -
Ti/Al 1 pixel
25 eV
SUST31 075002

- Final goal -
Ti/Al 1-4 pixel
25 eV
5x5 cm^2

2013 2014 2015 2016 2017 2018

End of 2013
Lab refurbishment

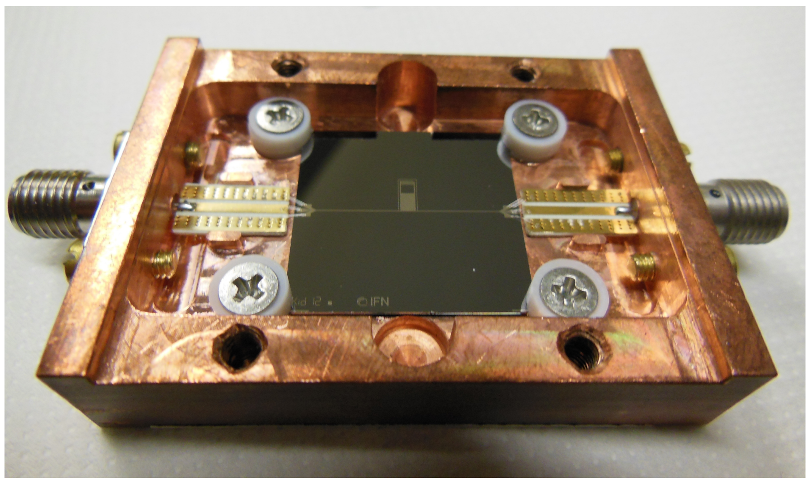
03/14
ERC start
EPJ C75 353

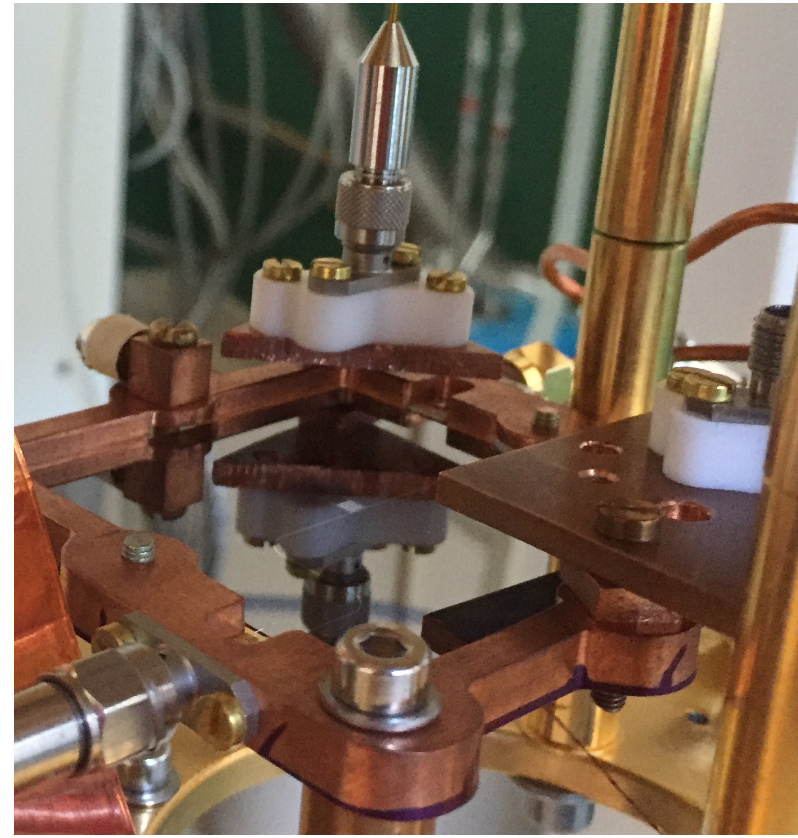
11/16
New lab
New cryostat

05/18
77th cool down

end/18
Final tests at Gran Sasso

Scaling the area to 5x5 cm^2

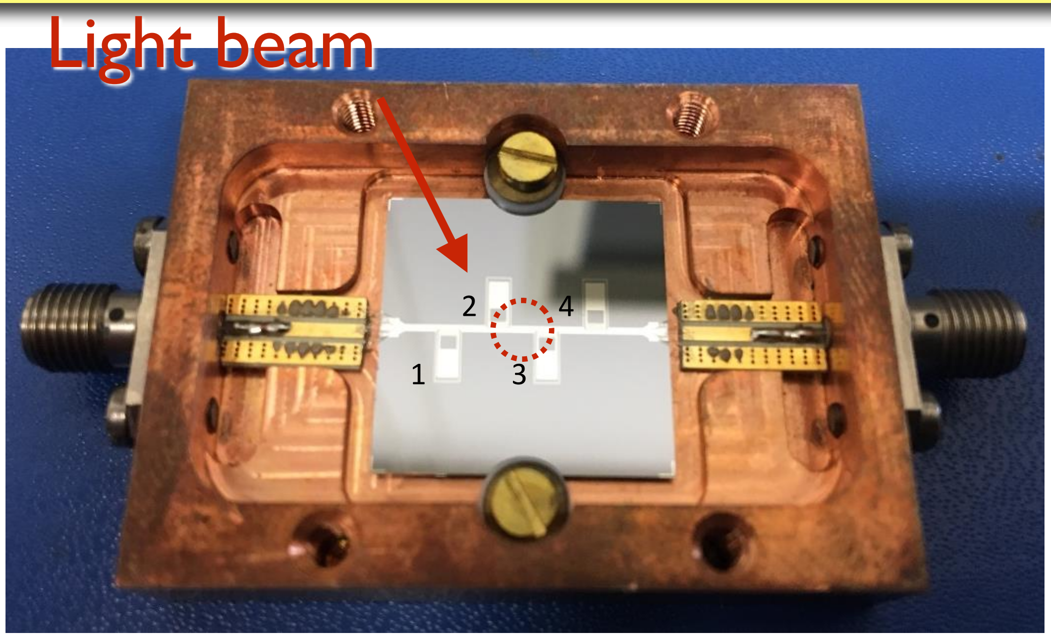


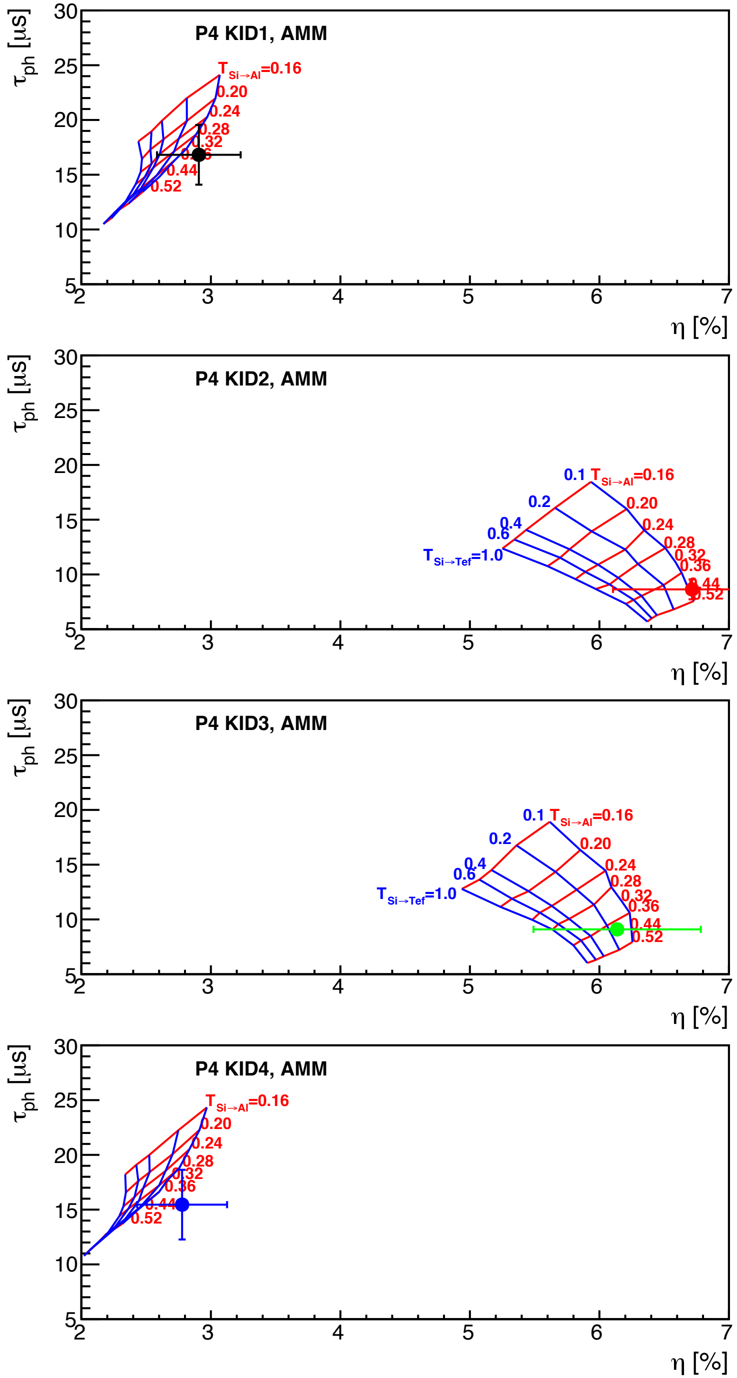


ISSUE: resonator quality factor deterioration, low SNR.

We are investigating on it, magnetic fields?
Stray radiation? Vibrations?

Athermal phonons characterization

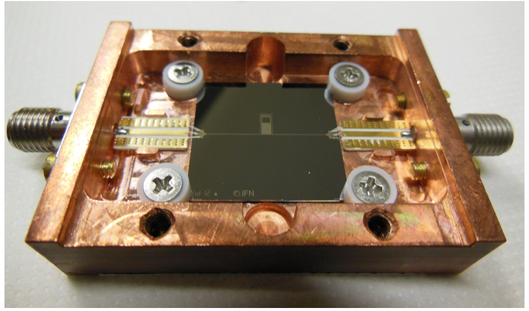




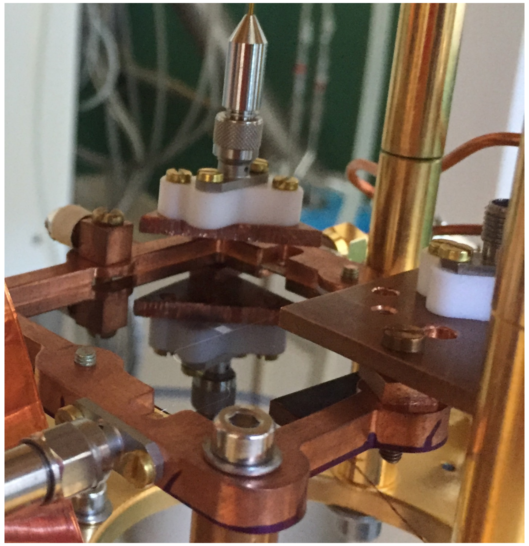
M. Martinez, et al 1805.02495

- Built a phonon simulation on top of the CDMS Geant4 Package
- We are able to simulate:
  - Phonon rise time
  - Collection efficiency
- We derived transmission coefficients: Si-Al and Si-Teflon.

Conclusion and outlook

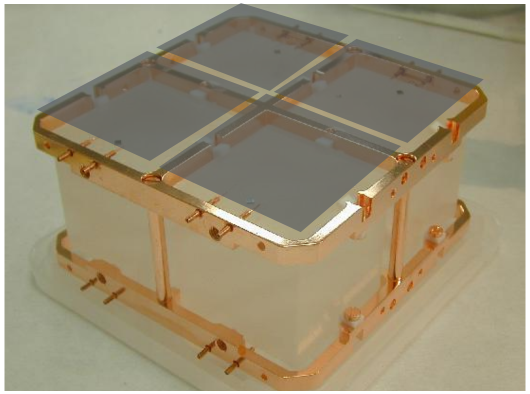


25 eV RMS have been reached by a large area light detector with KID, and we hope to further improve.



We are moving from 2x2 to 5x5 cm^2 .
Preliminary results indicate that the phonon loss with a single pixel is < 30%. Problems with quality factor.

➡ Determine whether 4 KID pixels are needed to compensate the loss and reach 25 eV RMS.



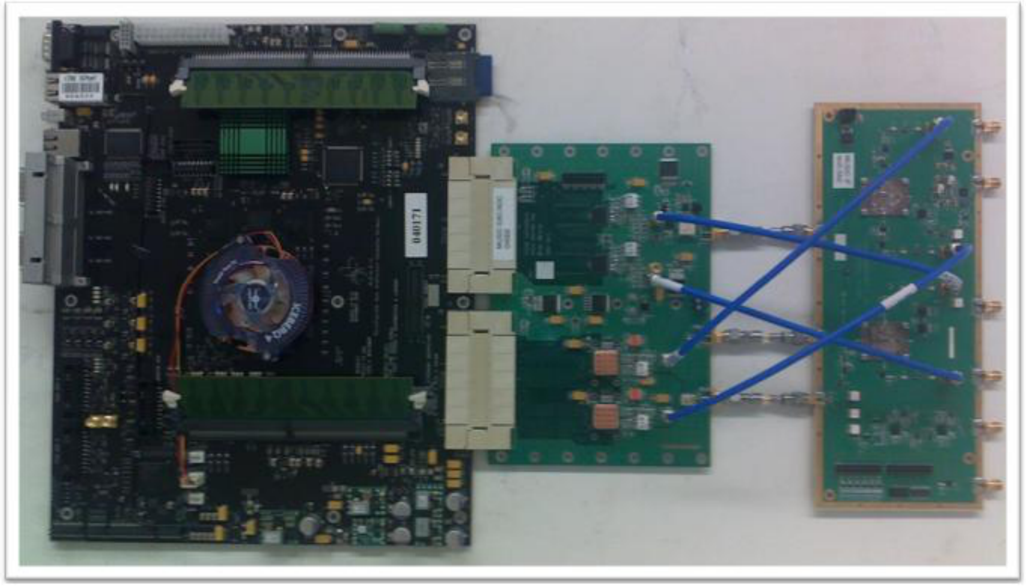
We are preparing the update of the LNGS test cryostat for the final test with TeO_2 bolometers.

CALDER

Backup

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 ROACH2 opensource hardware and software board.
  - Goal: 100 KIDs in parallel.
- Developed by a wide (mostly astro-) community.



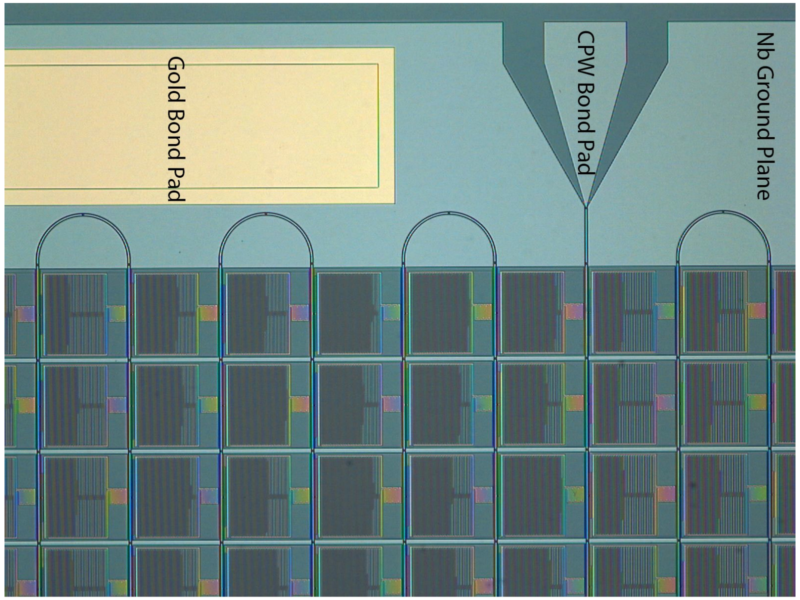
ROACH readout system

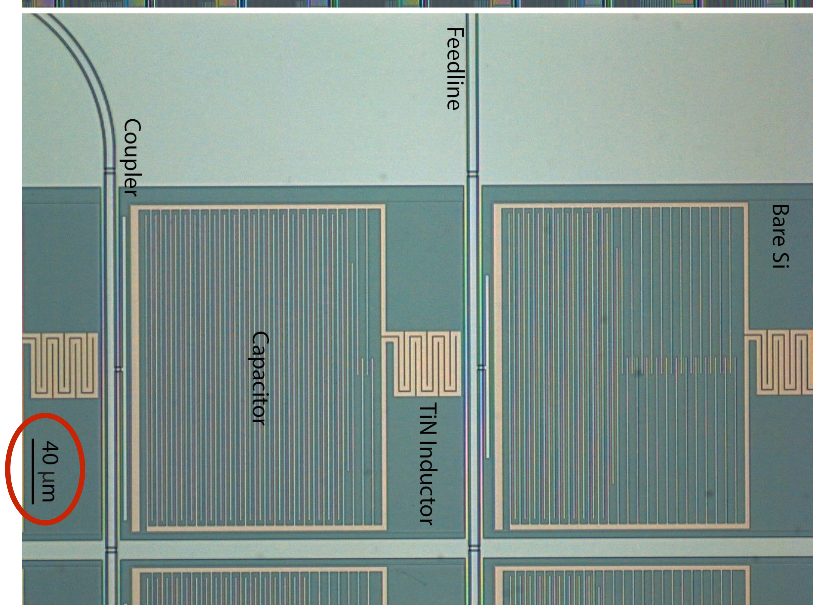
FPGA board (Virtex6) for signal processing
On-board PowerPc for FPGA control
16-bit 1000Msps dual DAC
14-bit 400Msps dual ADC
4x 10Gbe interfaces for data streaming
Up/down conversion w clock-distribution board

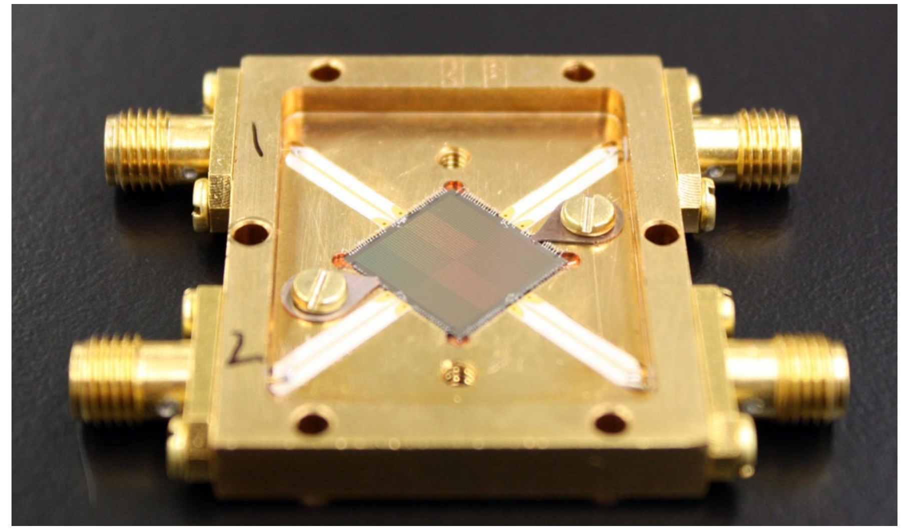
High scalability

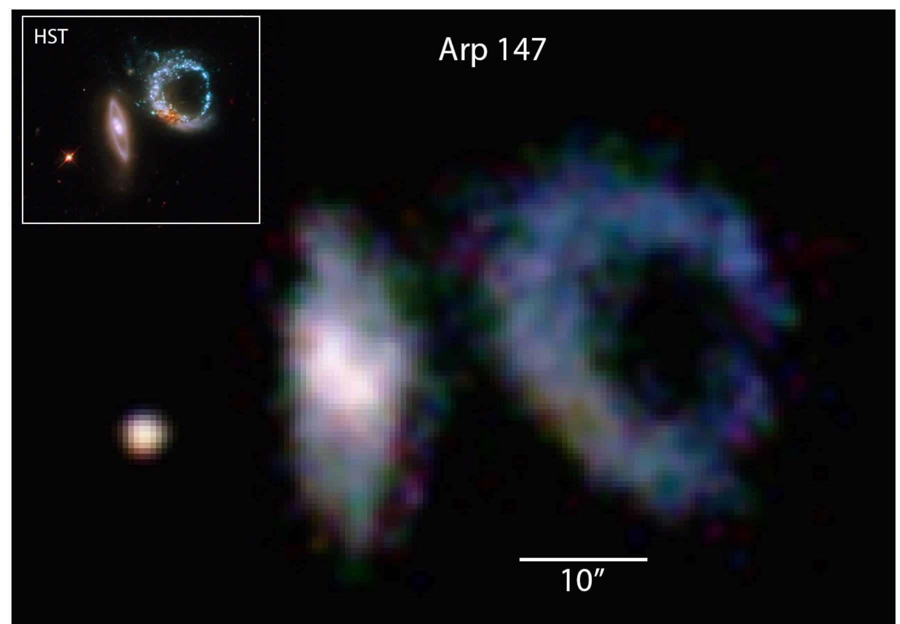
ARCONS: A 2024 Pixel Optical through Near-IR Cryogenic Imaging Spectrophotometer

Mazin, B.A. et al, PASP 125 (2013) , 1348.



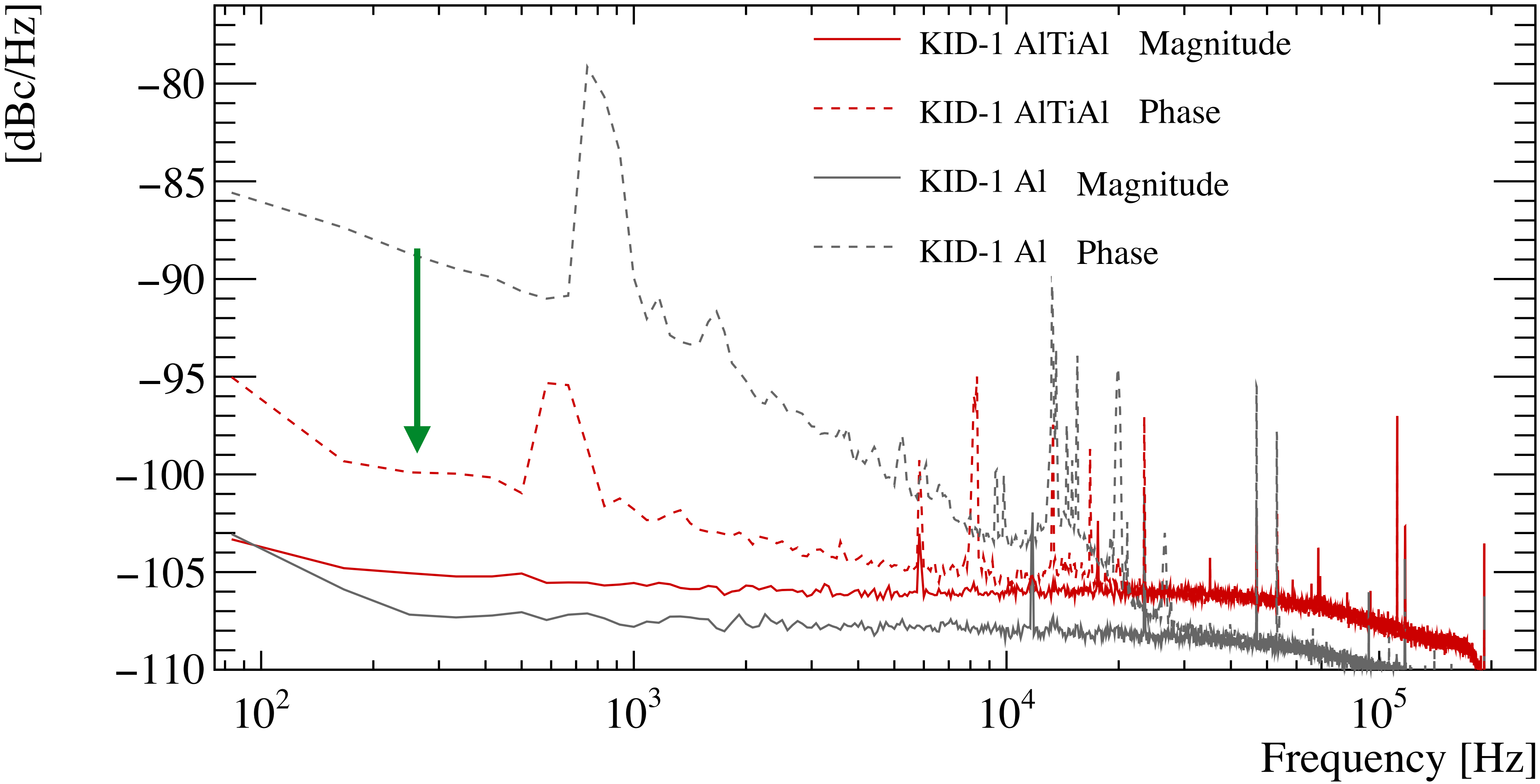






AlTiAl noise

noise comparison at similar readout power



The phase noise is substantially lower than Aluminum.

End of 2016: New cryostat, new lab