Innovative light detectors for background rejection in CUORE and CUPID

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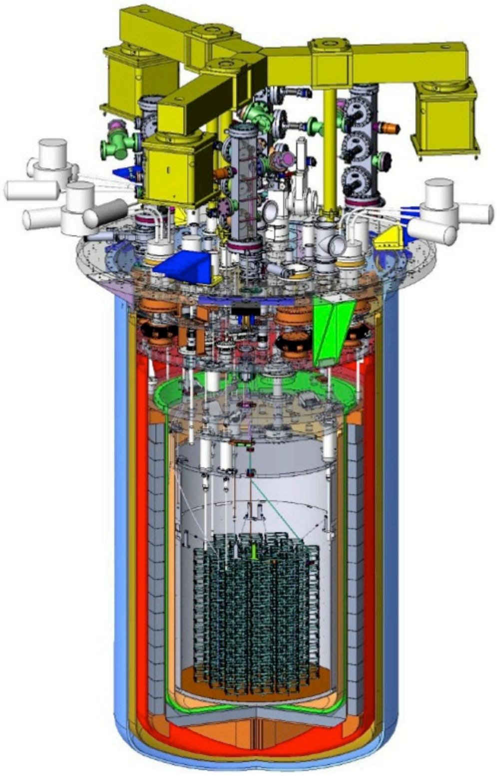
Istituto Nazionale di Fisica Nucleare

Rencontres du Vietnam
July 19 2017, ICISE, Qui Nhon

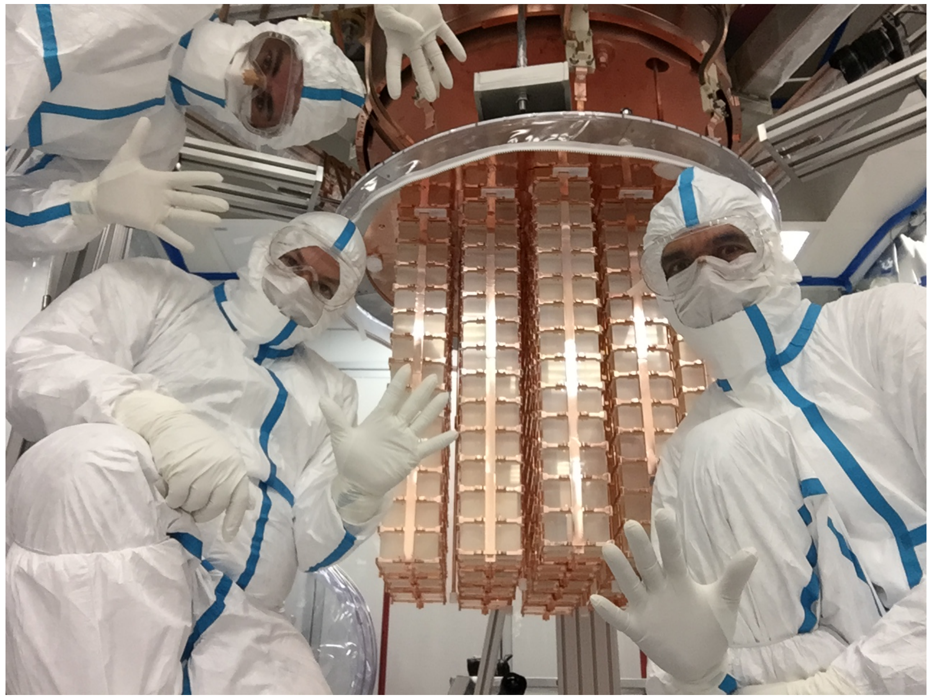
Calorimeters for 0nDBD

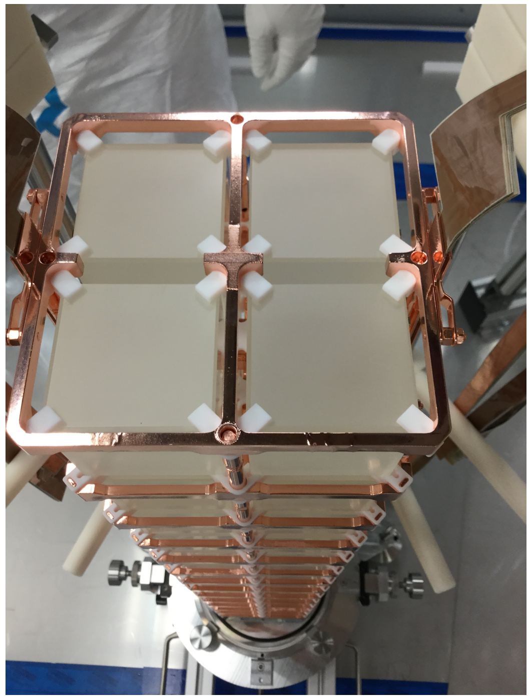
CUORE

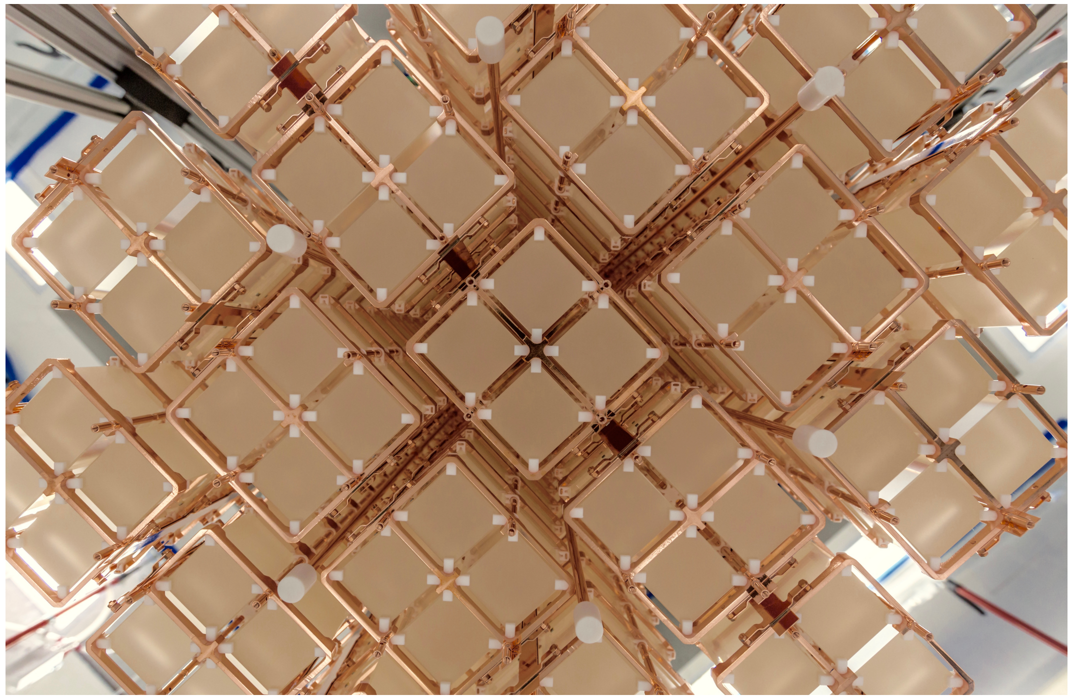


sets the standard for next generation experiments exploiting calorimeters:

- Hundreds of kg of source ➪ **Proved**
- Good Energy Resolution ➪ **~0.1% for CUORE-like detectors**
- Goal: **background of *o*(100) events** in the ROI —>$T_{1/2}(\beta\beta)$~10^{26} y







B.Fujikawa: “The CUORE experiment at LNGS”, 20th July

https://cuore.lngs.infn.it

CUPID

CUPID: **C**uore **U**pgrade with **P**article **ID**entification

arXiv:1504.03612, arXiv:1504.03599

Goal: increase sensitivity on 0nDBD from 9×10^{25} y to $>10^{27}$ y

- **CUORE cryostat** ➪ useful also for CUPID (ultimate limit in mass)
- Calorimeters: **energy resolution 0.1%** ➪ ideal also for CUPID
- But reduce **background** from ***o*(100) events** in the ROI ➪ **~0 in CUPID!**

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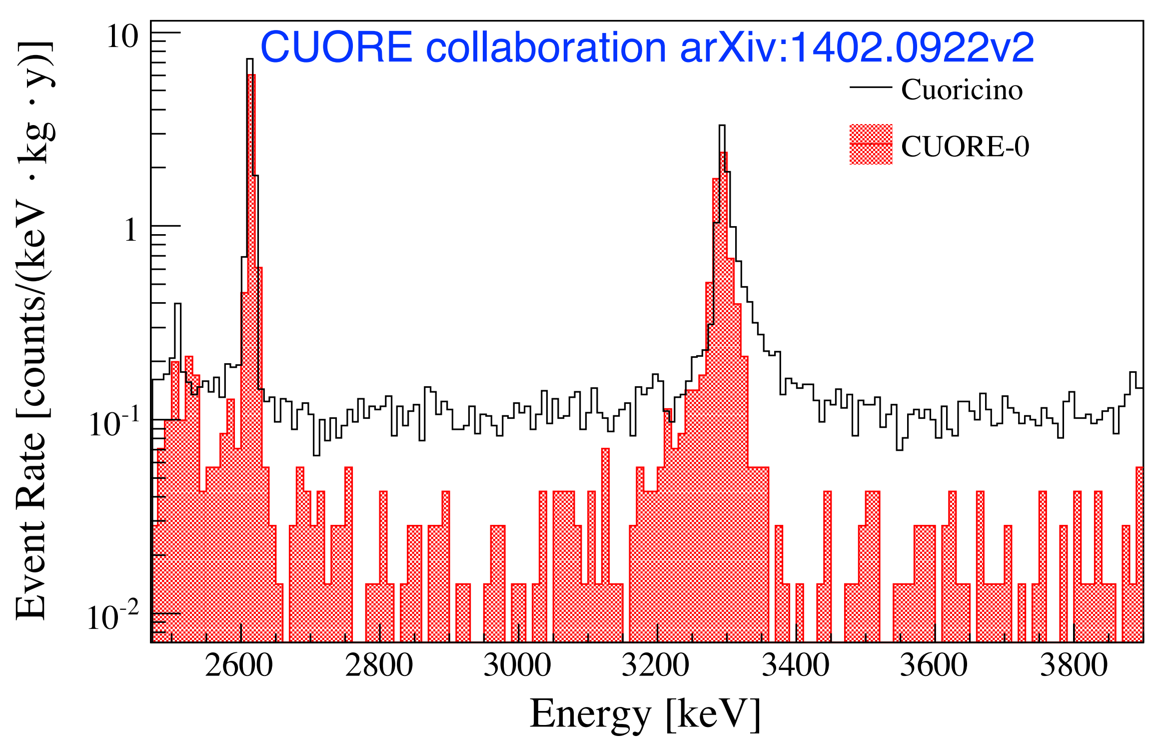


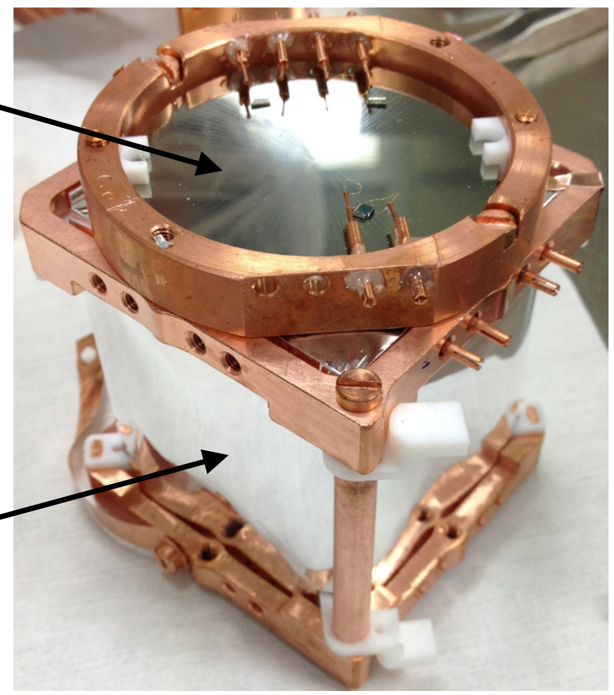
- Main background: **alpha particles from detector materials**
- Exploit **light output** for particle ID (alpha rejection)

Particle Identification in TeO_2

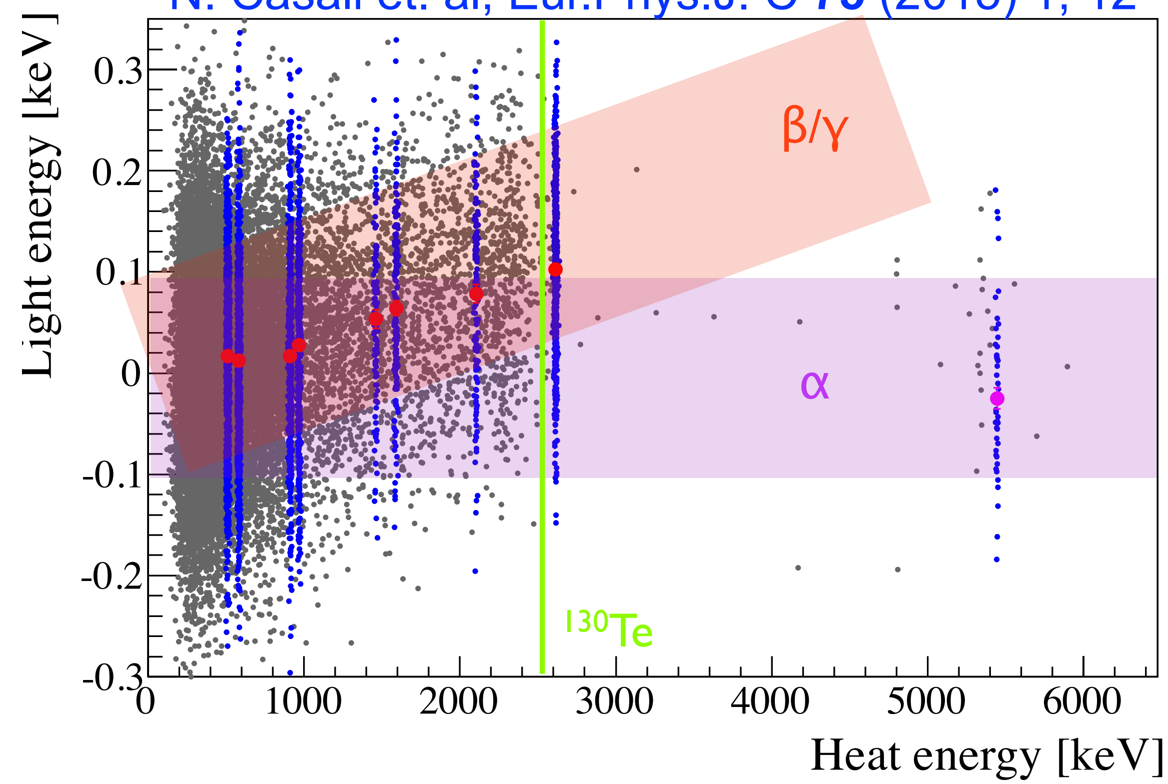
Couple a light detector to TeO_2 to measure the Cherenkov light emitted by e- (not by α's)

Light Detector

TeO_2



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



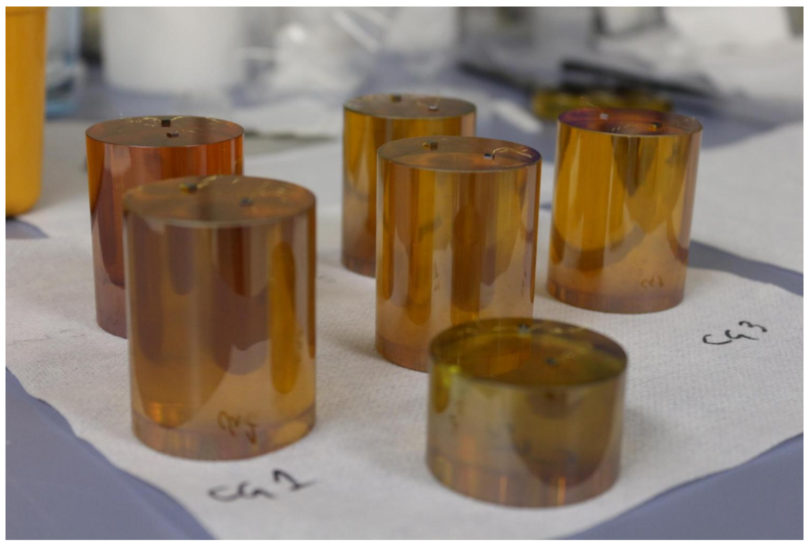
CUORE TeO_2 : low light output (~100 eV at 0νββ from Cherenkov emission)

Using a “standard" LD with noise of 80 eV RMS does not permit particle ID

A LD with **noise RMS < 20 eV** would allow to reject the dominant background (α)

Particle Identification: alternative

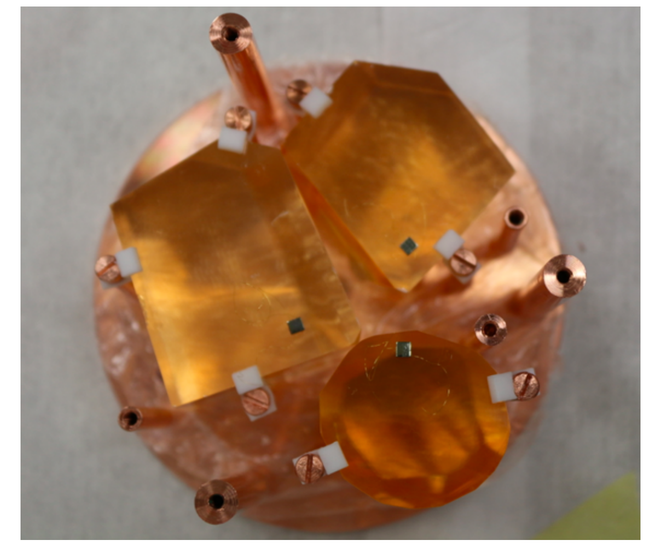
Use compounds that, in contrast to TeO_2, emit scintillation light at 10 mK



$ZnSe$
(^{82}Se)

$ZnMoO_4$
Li_2MoO_4
(^{100}Mo)

$CdWO_4$
(^{116}Cd)



Suggested talks (all the 20th):

- C. Nones: “Scintillating bolometers for the study of double beta decay”
- N. Casali: “CUPID-0 cryogenic calorimeters with particle ID for double beta decay”
- A. Giuliani: “A 100Mo pilot experiment with scintillating bolometers (CUPID activities)

Particle Identification in TeO_2

Requirements for a light detector suitable for CUPID:

- Baseline resolution <20 eV RMS
- Large active area (5x5 cm^2)
- High radio-purity
- Ease in fabrication/operation (~1000 channels)
    - Reproducible behavior in a rather wide temperature range (5-20 mK)
    - Low heat load for cryogenic system

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L.Pattavina et al., Journal of Low Temp Phys 1-6 (2015)
M. Biassoni et al., Eur.Phys.J. C75 (2015) 10, 480
K.Schaeffner et. al, Astropart.Phys. 69 (2015) 30-36
M. Willers et al., JINST 10 P03003 (2015)
L.Gironi et al. Phys. Rev. C 94, 054608 (2016)
D.R. Artusa et al Phys Lett B 2017 (2017)
…and many others

But none of the existing technologies fulfills **all** these requirements (yet)

↓

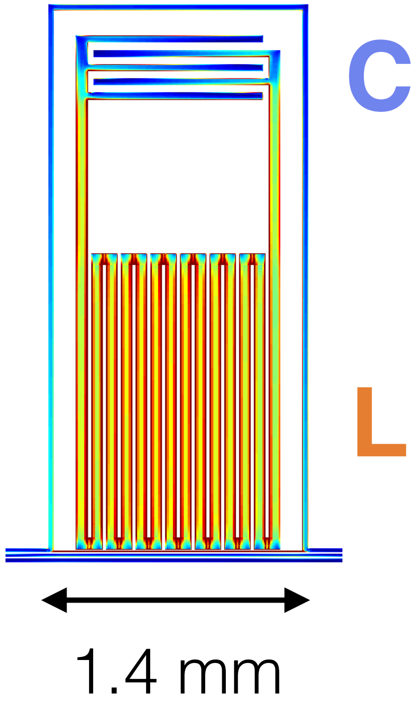
We propose a new technology

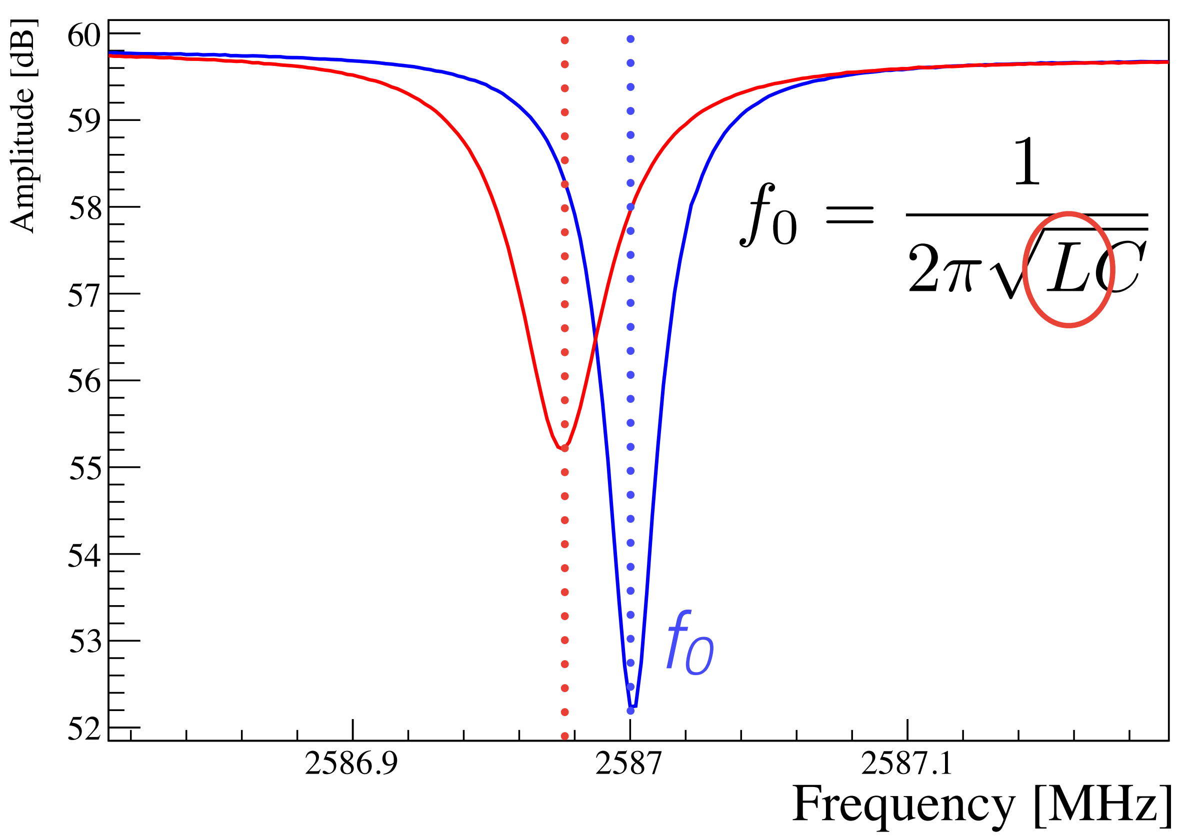
Kinetic Inductance Detectors

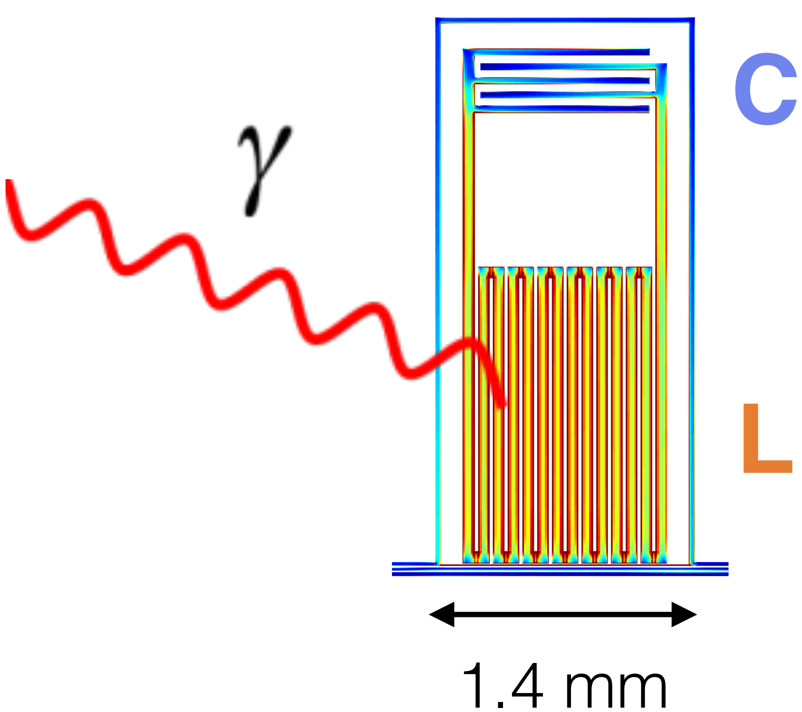
- Superconductors operated in AC

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

- Cooper Pairs acquire **kinetic inductance** L
- It act as a **resonator**
- **Photons** break Cooper pairs —> change L —> change resonance







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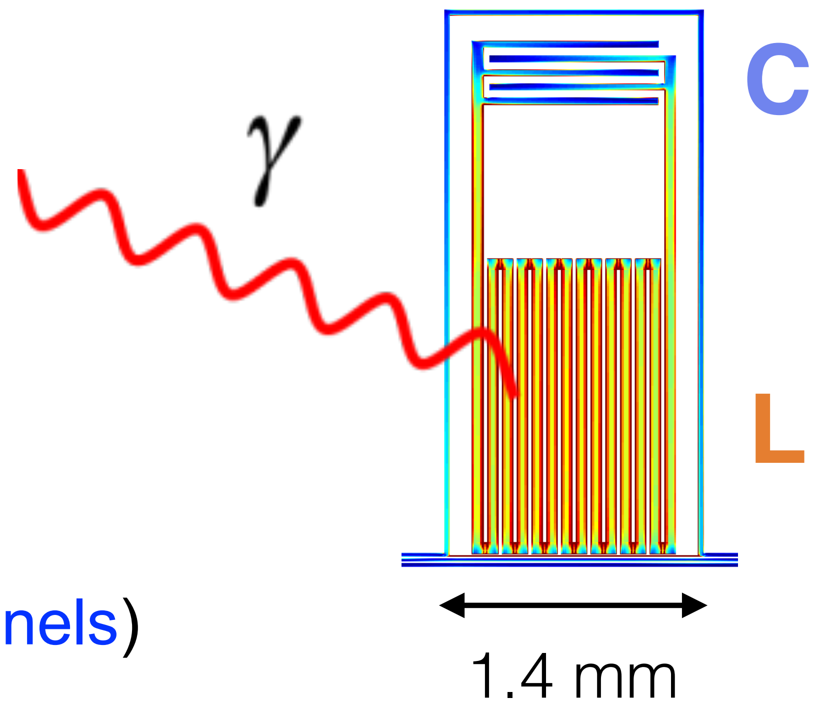
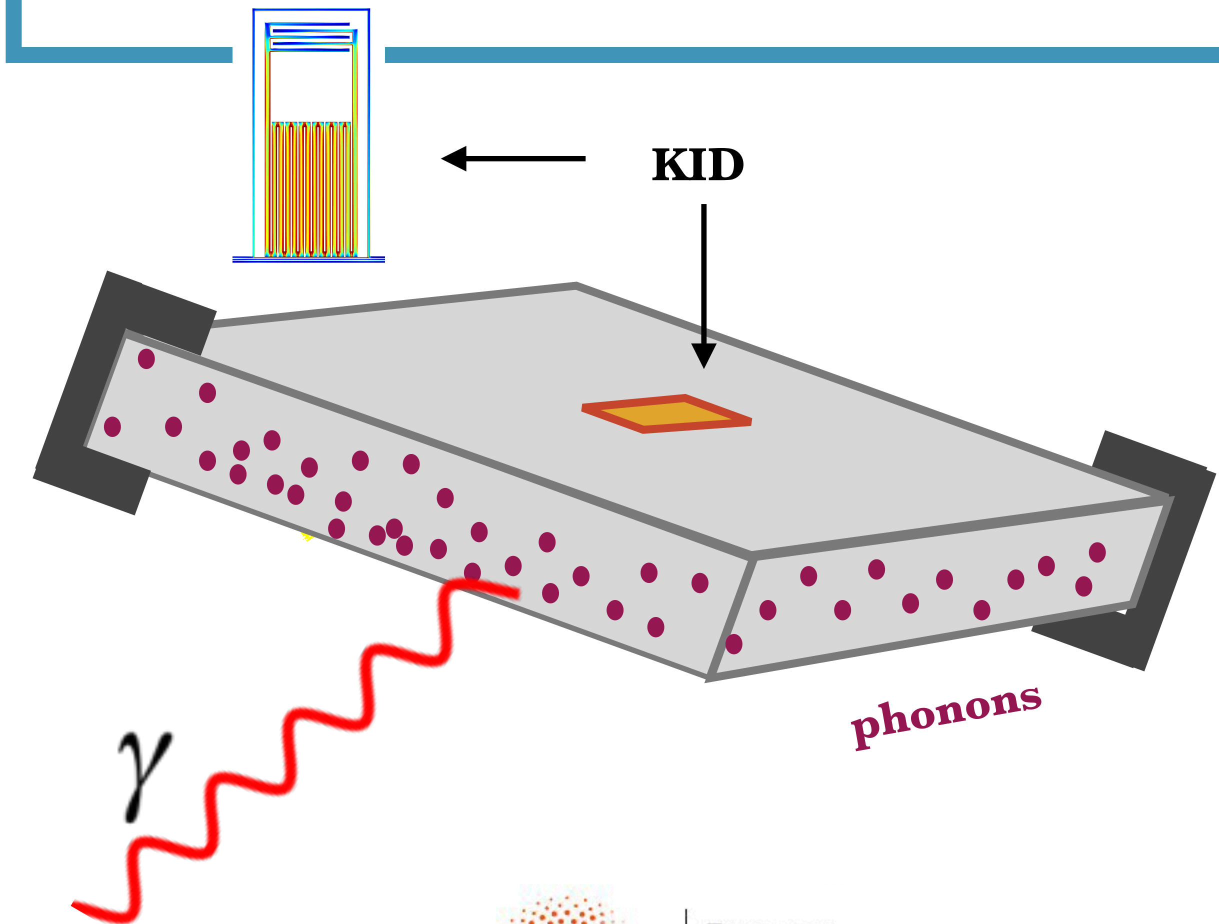
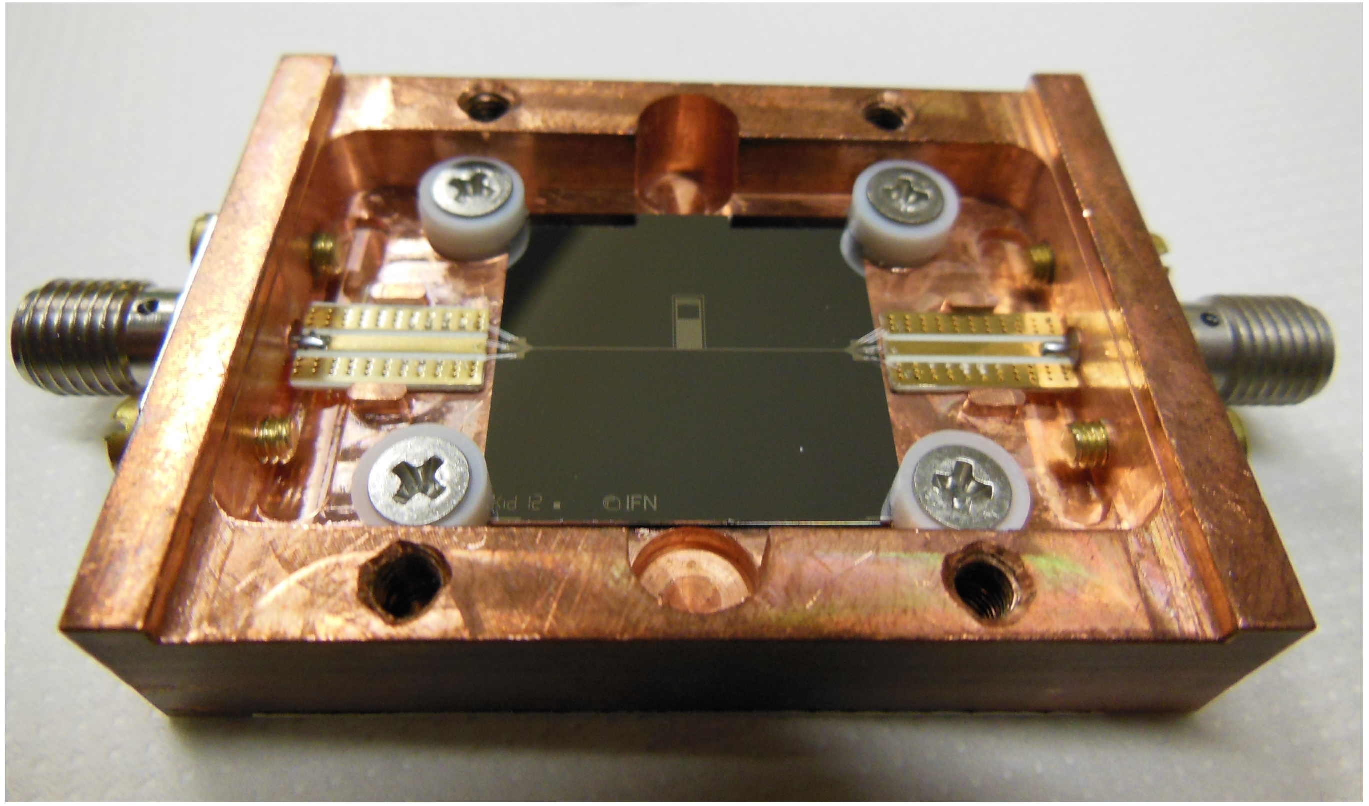


Phonon mediated approach





European Research Council

Goal of the CALDER project

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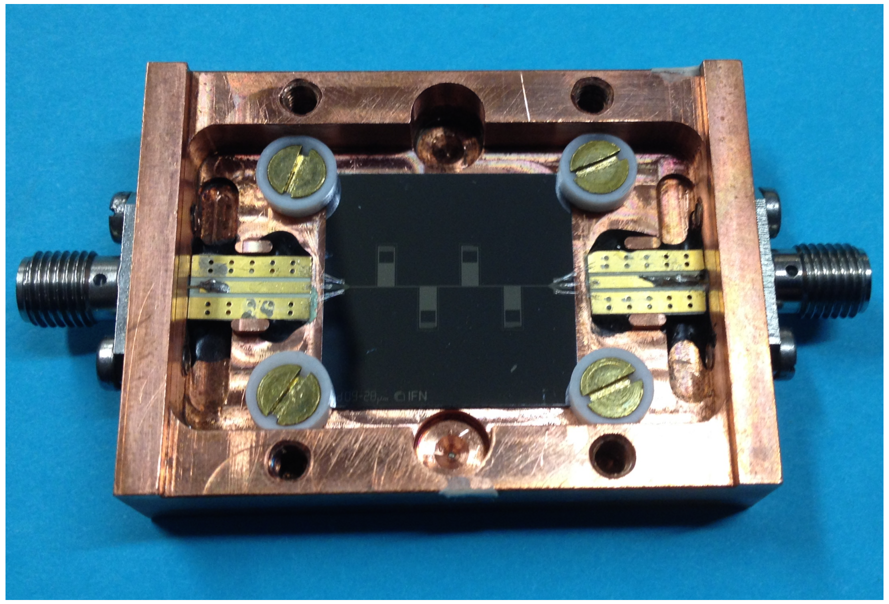
1) Optimize detector geometry, read-out and analysis using Aluminum → 80 eV

2) Move to more sensitive superconductors (TiAl, TiN..) and increase surface → <20 eV

3) Large-scale test of our light detectors on TeO_2 array at LNGS (Italy)

[E.S Battistelli et. al, Eur.Phys.J. C75 (2015) 8, 353]

Phase1



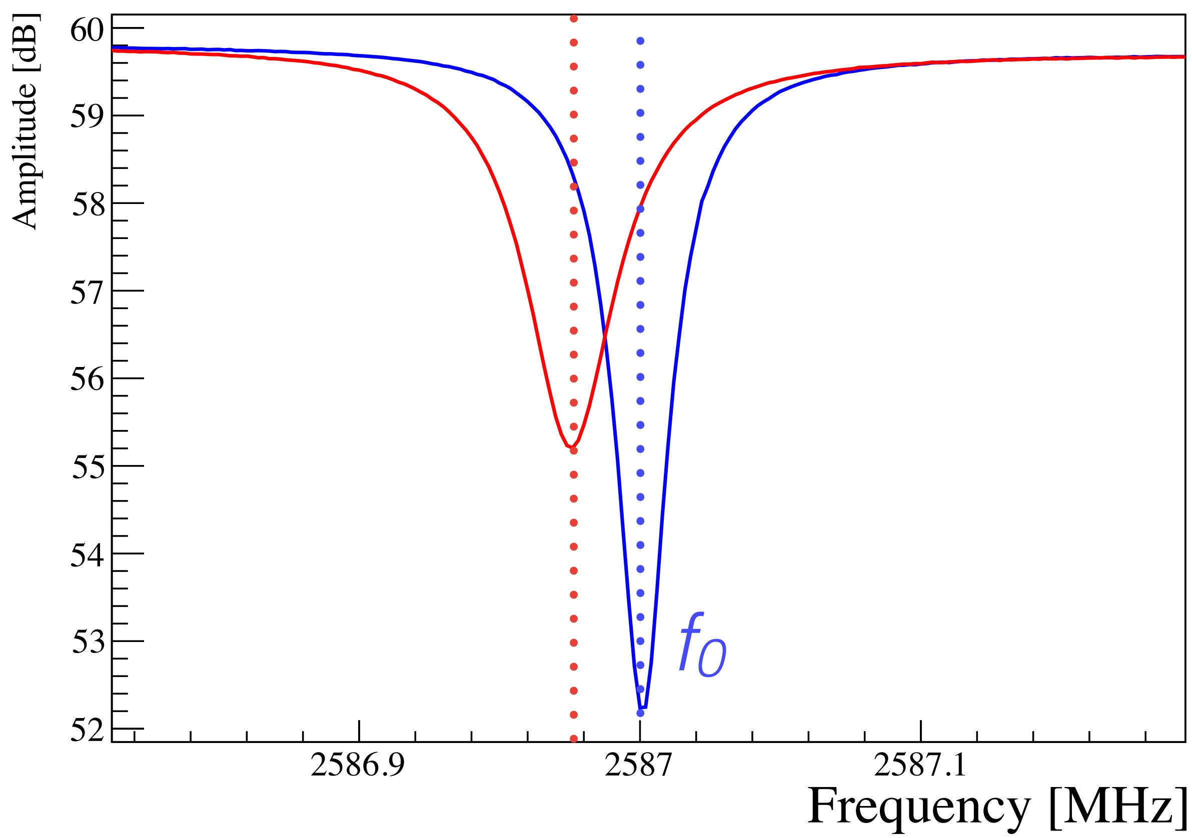
Al KIDs on 2x2 cm^2 Si substrate (goal: 5x5 cm^2)

First test (with 4 KIDs): 150 eV RMS (goal: 80 eV)

Appl.Phys.Lett. 107 (2015) 093508

Optimize the design of the resonator and our analysis tools to improve the RMS

Analysis Optimization



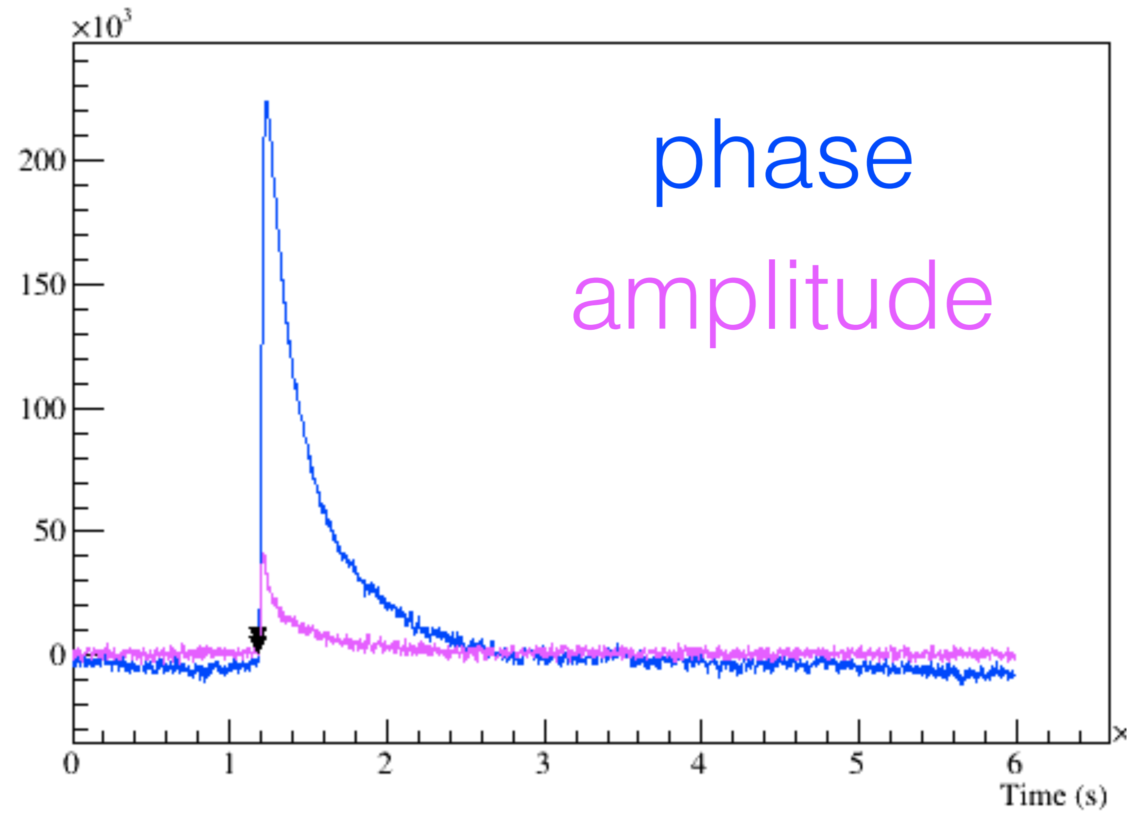
Frequency and width —> 2 informations

KIDs are characterized by dual-readout

Two energy estimators: phase/amplitude

Usually phase has better signal-to-noise ratio

We developed tools to combine them accounting for noise correlations



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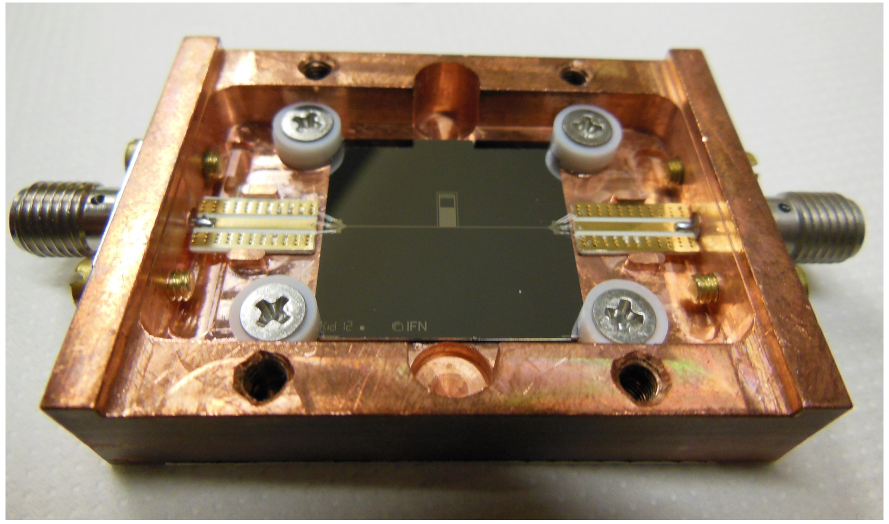

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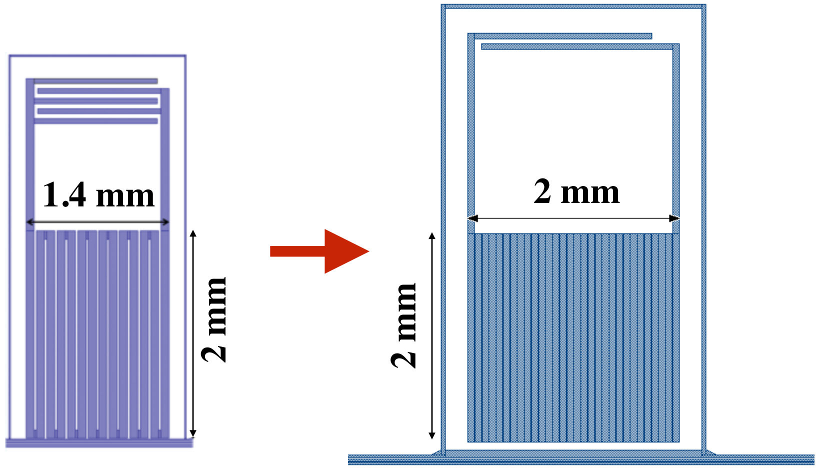
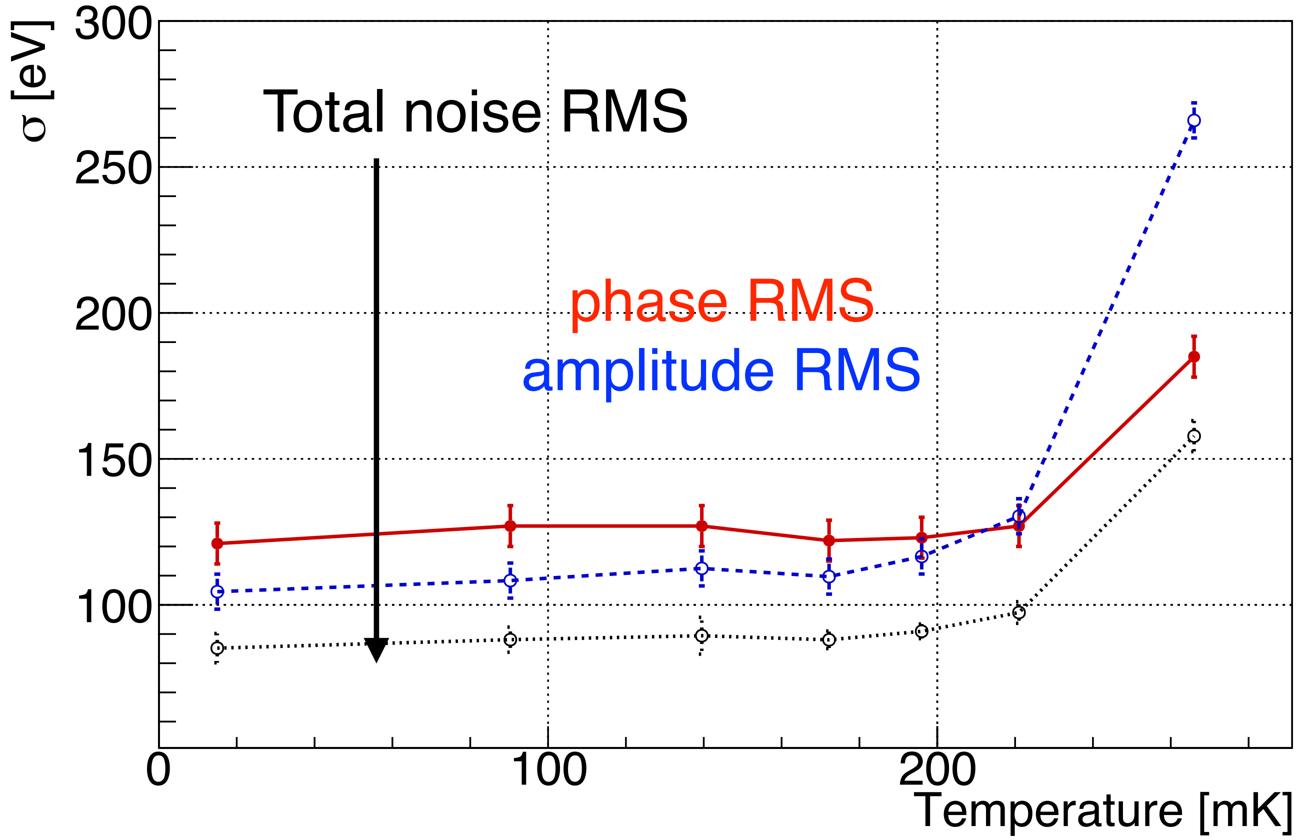


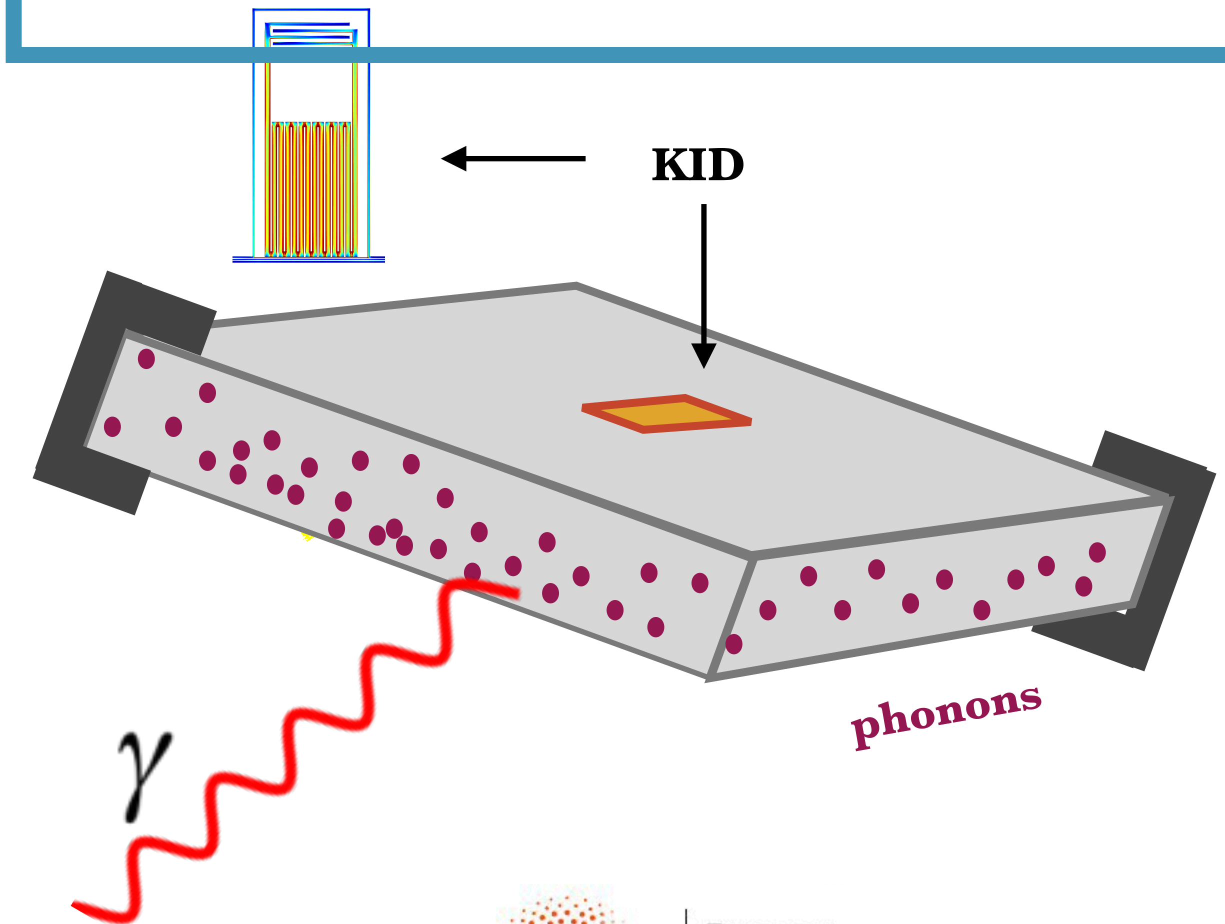


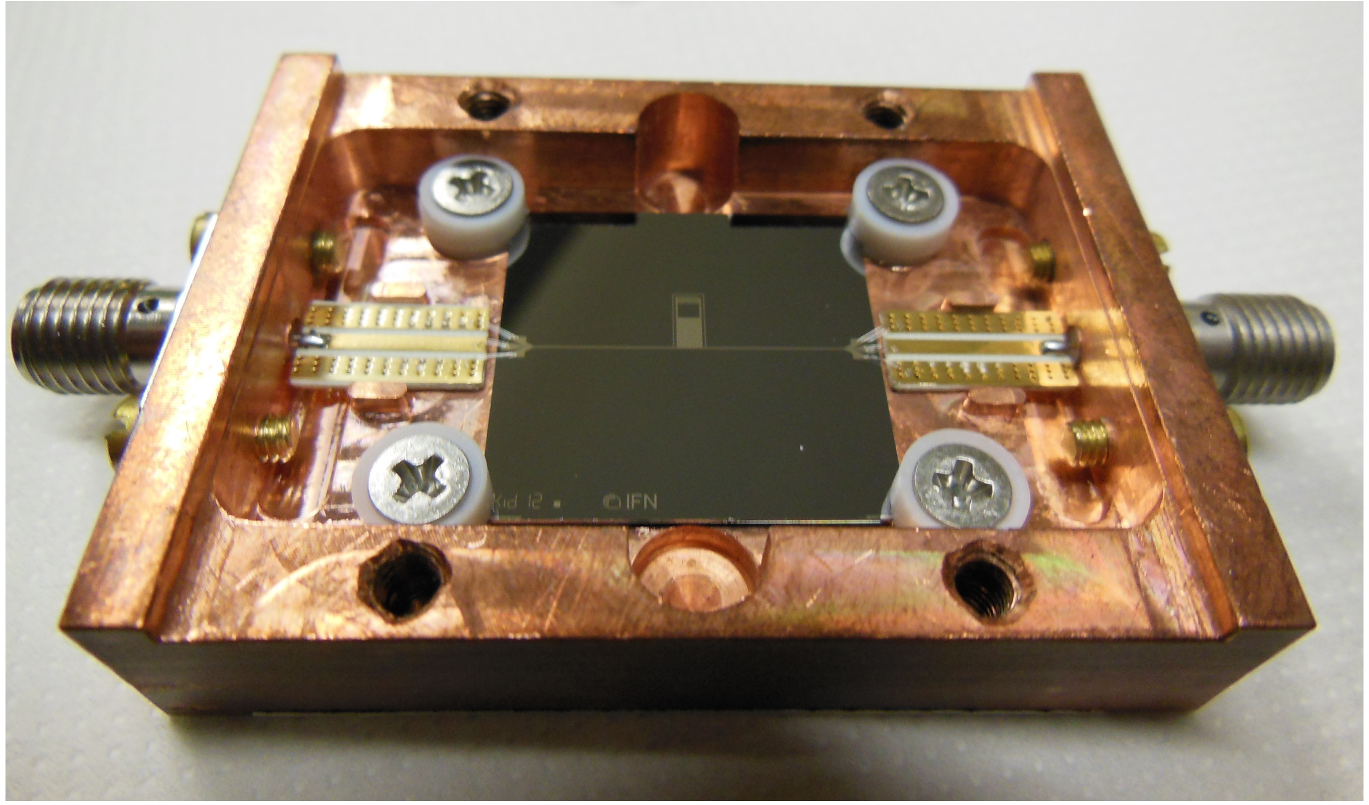
Reached noise 82 eV RMS

Resolution constant up to 200 mK

Appl. Phys. Lett. 110, 033504 (2017)

Phonon mediated approach





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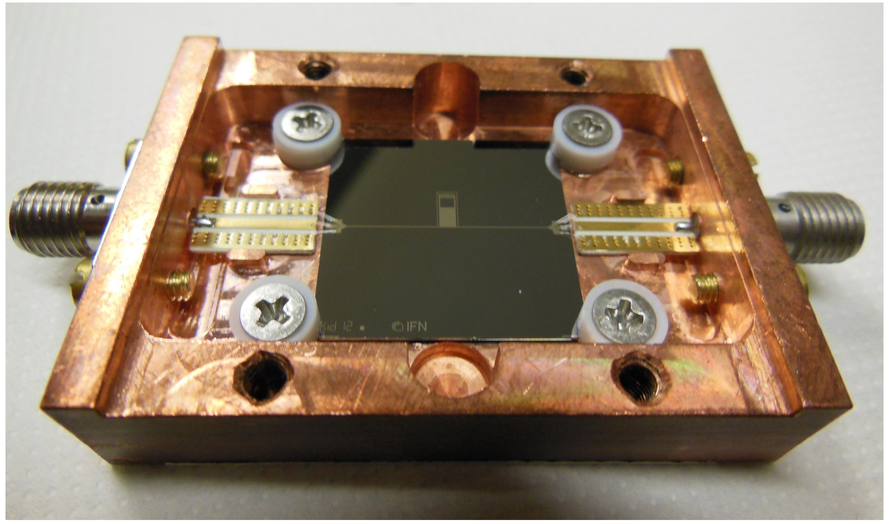
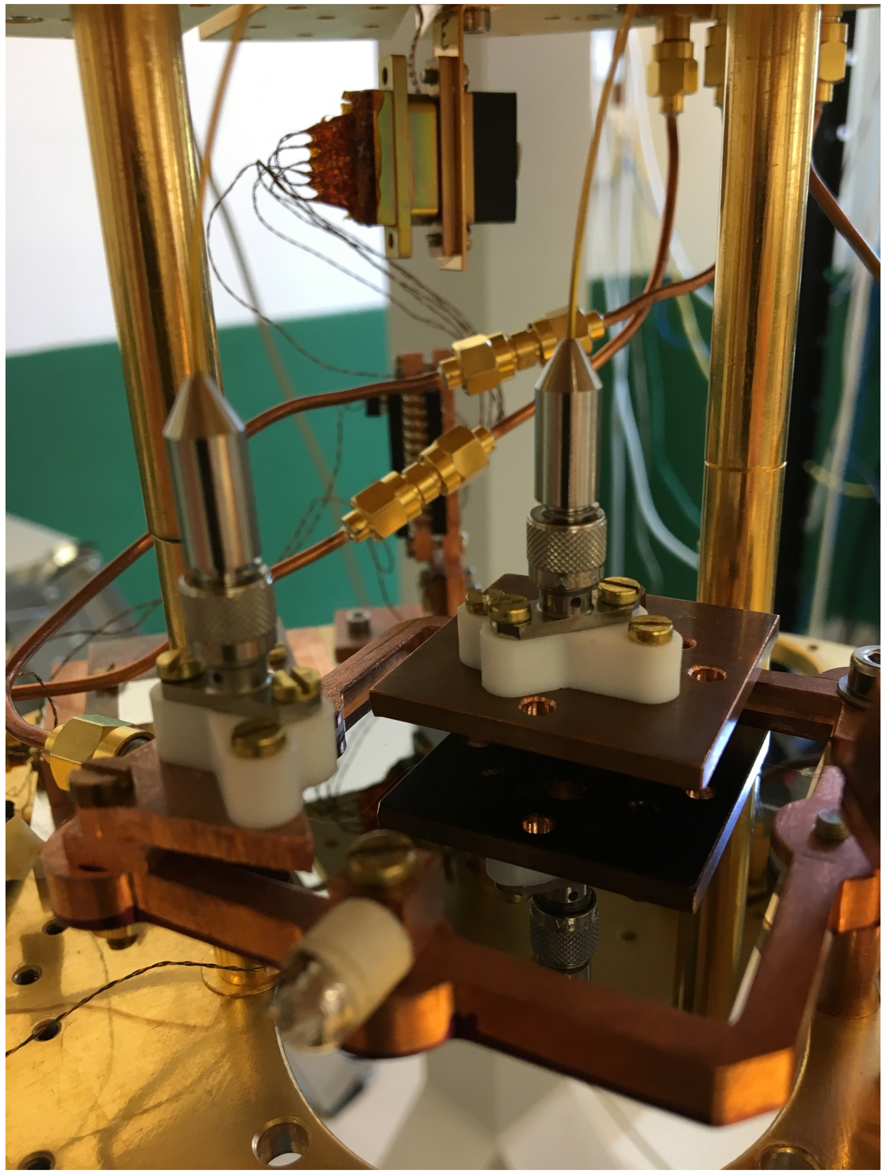
E.S Battistelli et. al, Eur.Phys.J. C75 (2015) 8, 353

Phase2: surface

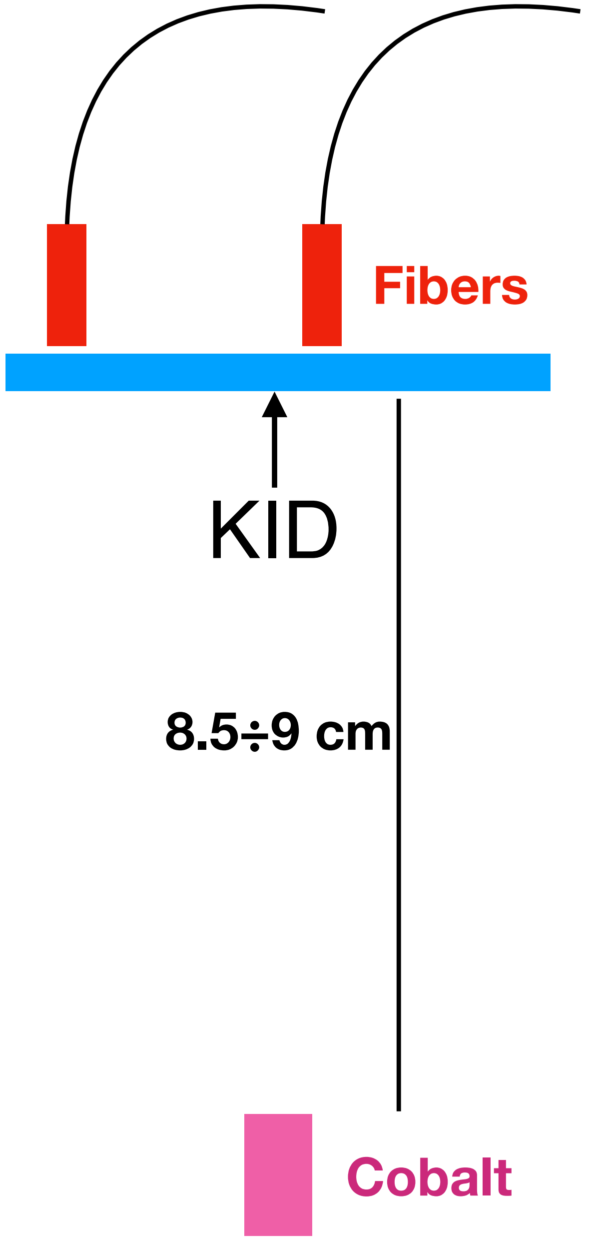
Preliminary

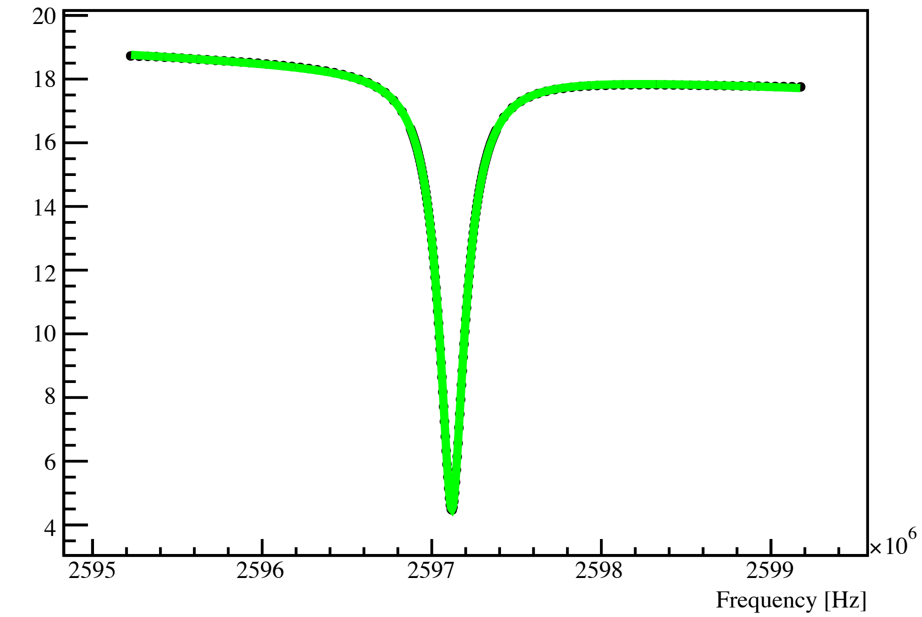


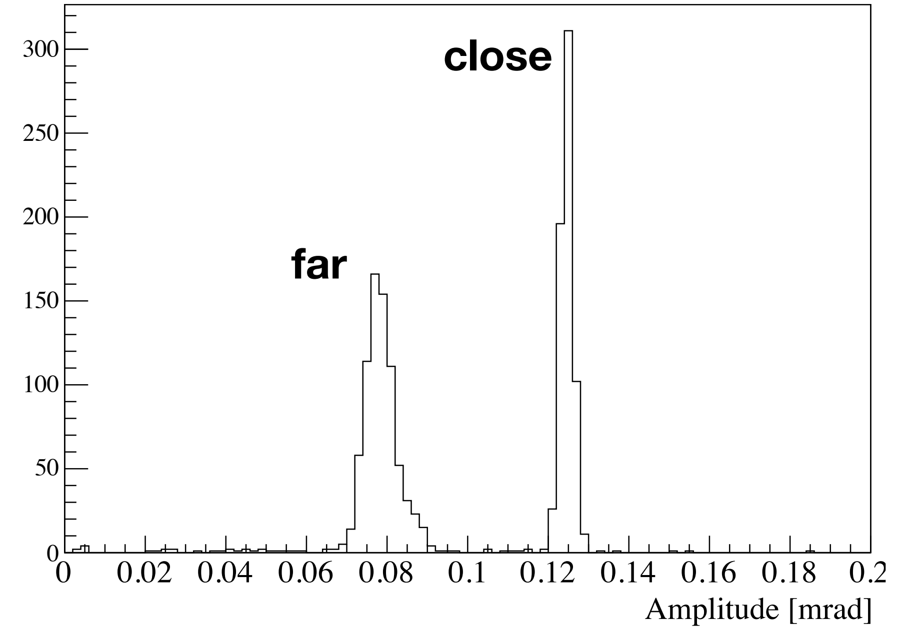


Al KIDs on 2x2 cm² Si substrate (goal: 5x5 cm²)

1st test with a KID on a 5x5 cm² substrate (last week)





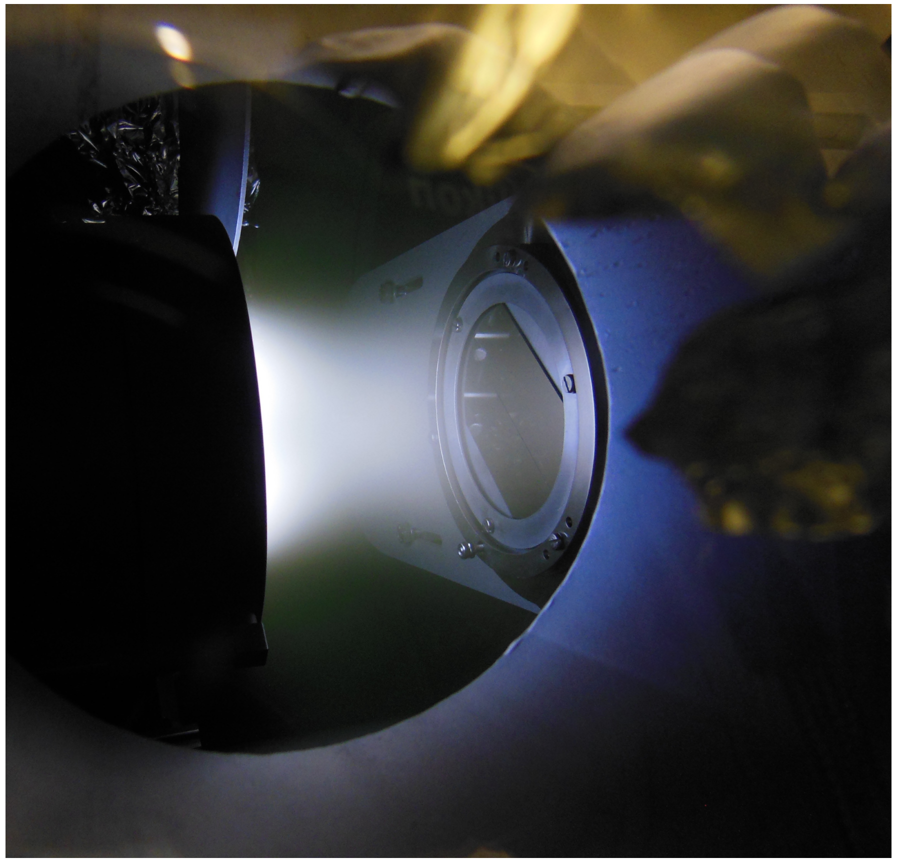


Phase2: new materials

Al does not allow to achieve the necessary sensitivity → other superconductors

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

	Al	Ti-Al Al-Ti-Al	Ti+TiN
Tc [K]	1.2	0.6 - 0.9	0.5 - 0.8
L [pH/square]	0.5	1	6
producer	INF-CNR	CSNSM-Néel, CNRS	FBK
status	completed	this result	in production

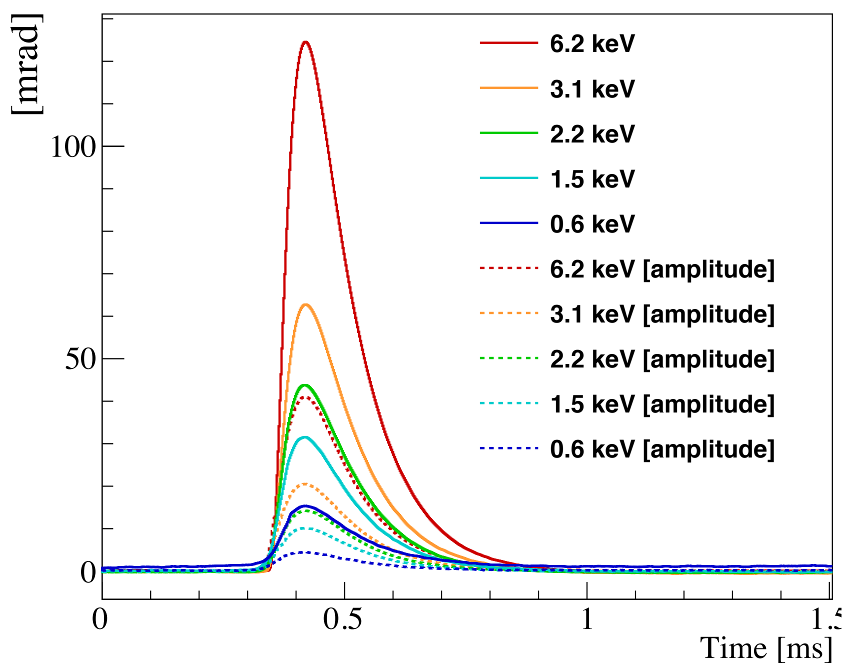


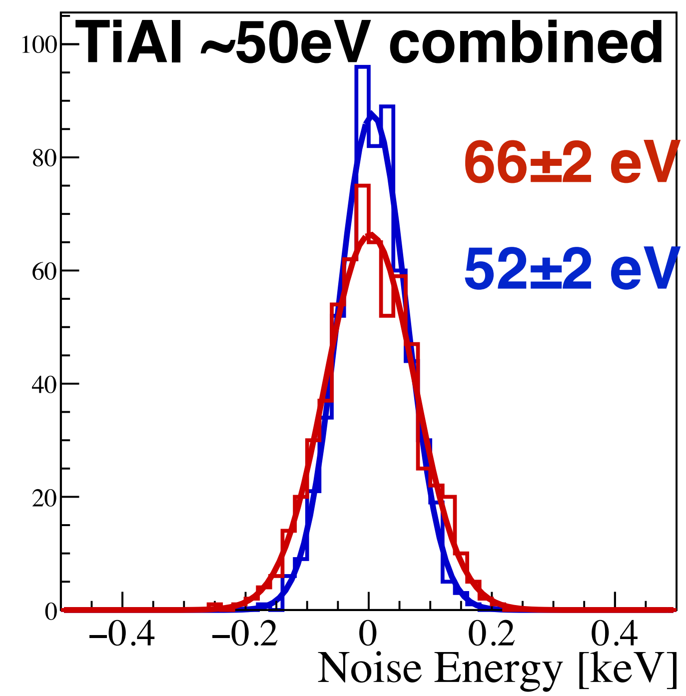
First tests on Ti-Al and Al-Ti-Al prototypes

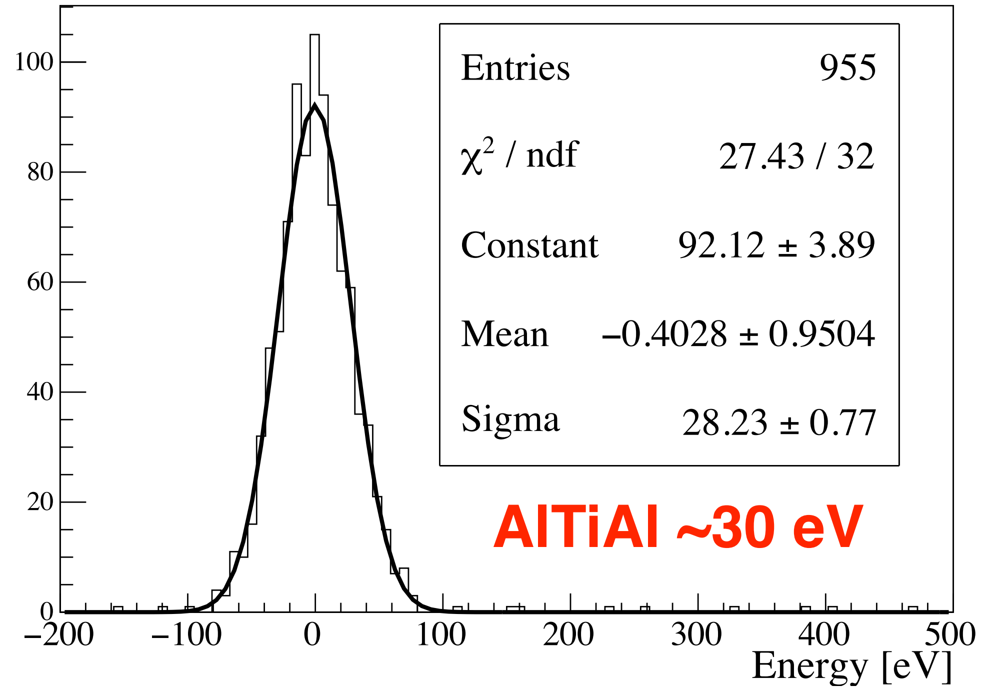
Phase2: new materials

Preliminary

Again a 2x2 cm^2 Si substrate sampled by KIDs made of different materials
Goal: from 80 eV to <20 eV







Conclusion

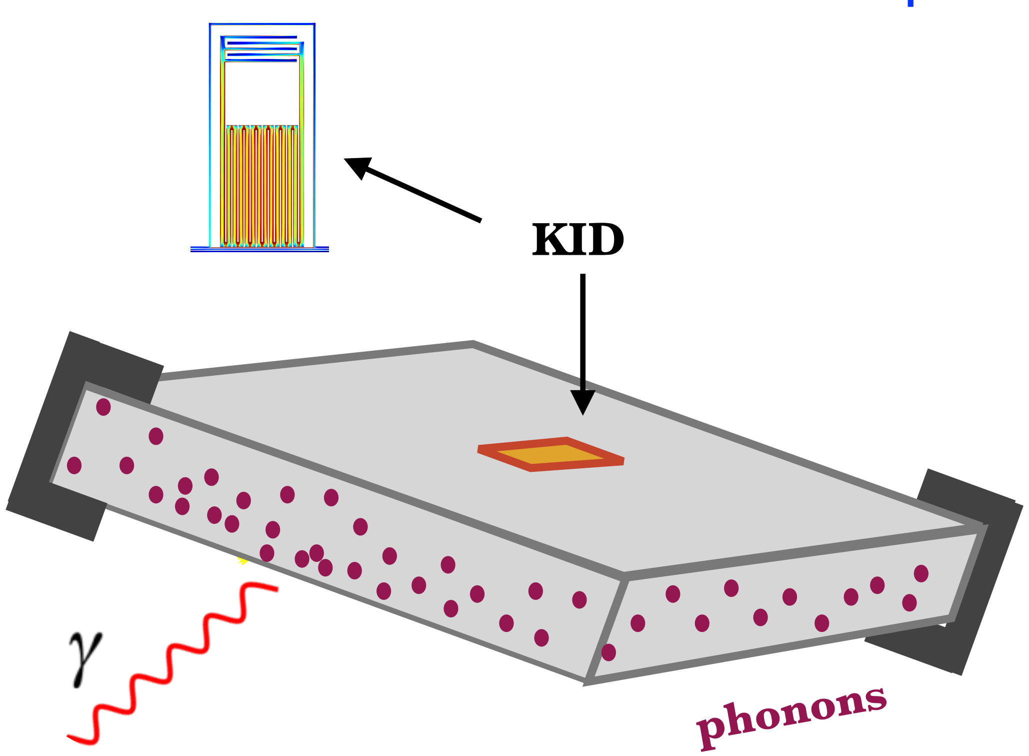
Development of sensitive cryogenic LD is fundamental for CUPID

Phonon-mediated KIDs is a viable technology

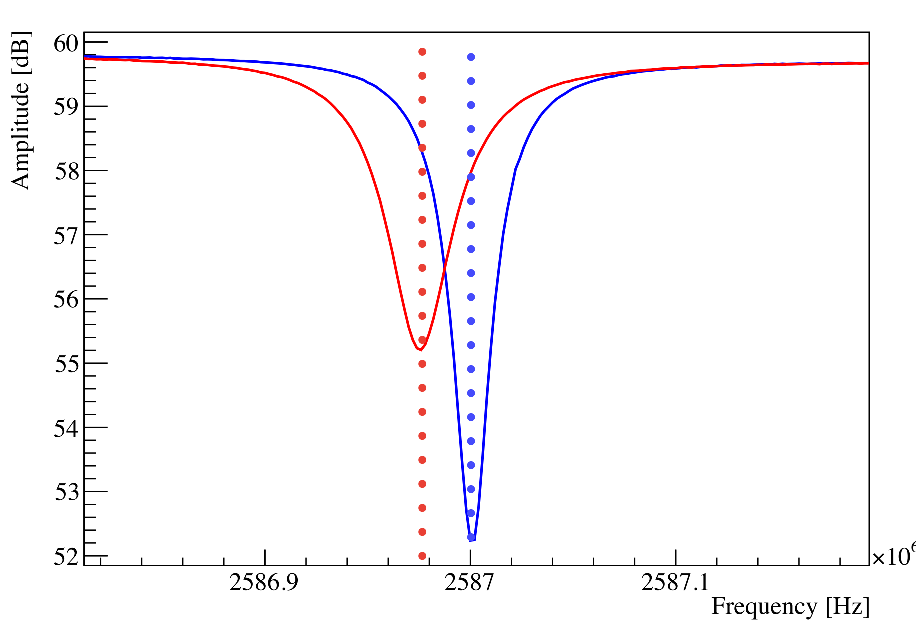
CALDER Phase-I reached 80 eV with Aluminum KIDs, now in Phase-II (20 eV) with more sensitive superconductors

Preliminary tests already hit 30 eV

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



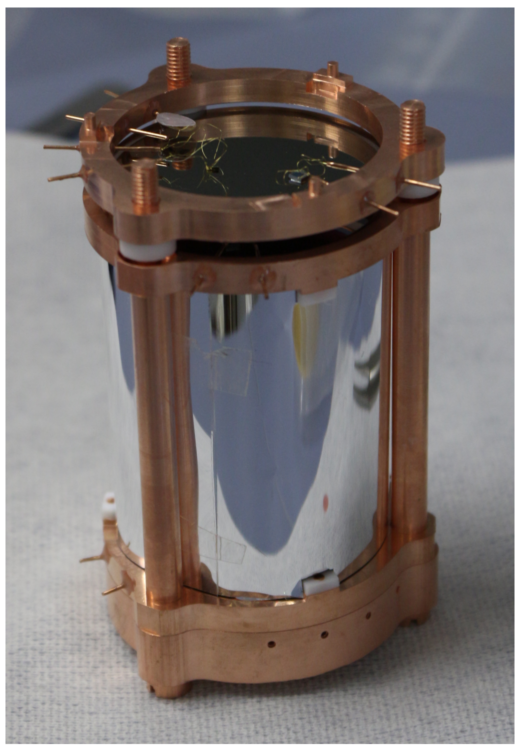
Thank you for the attention

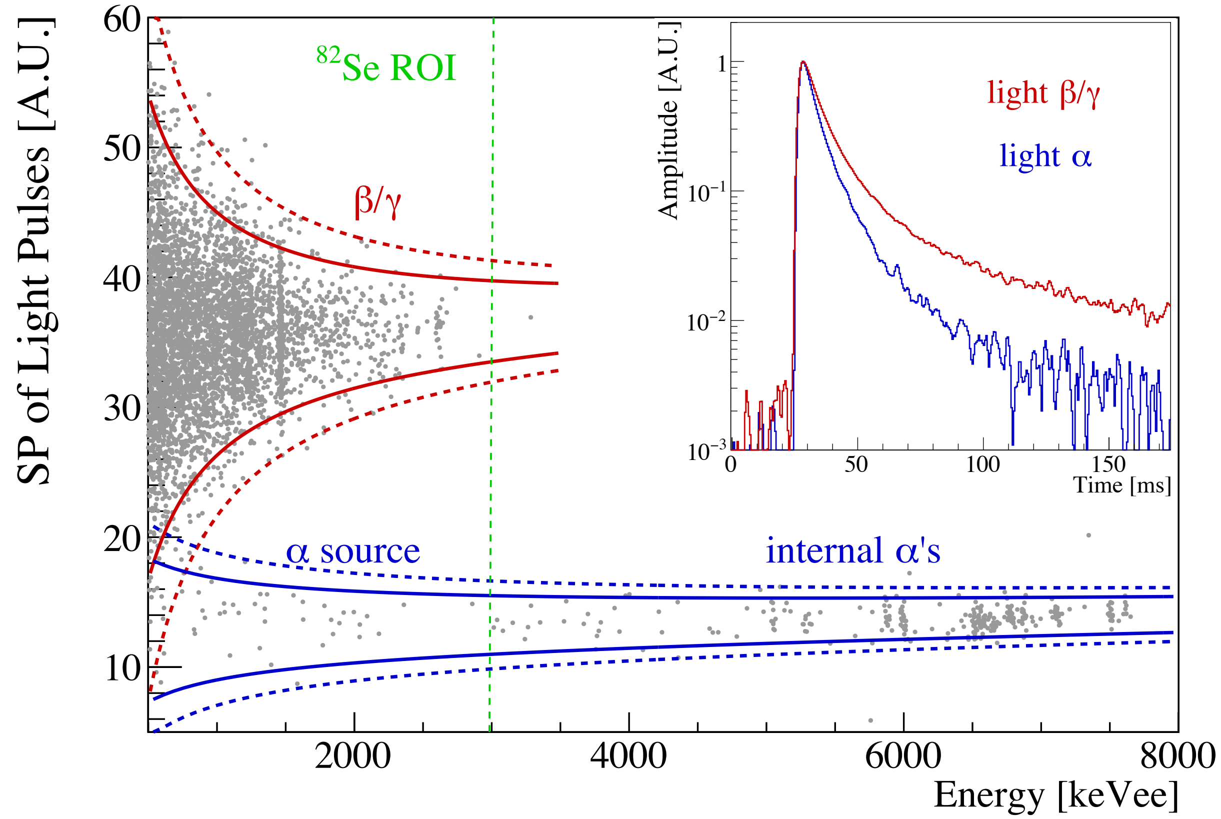


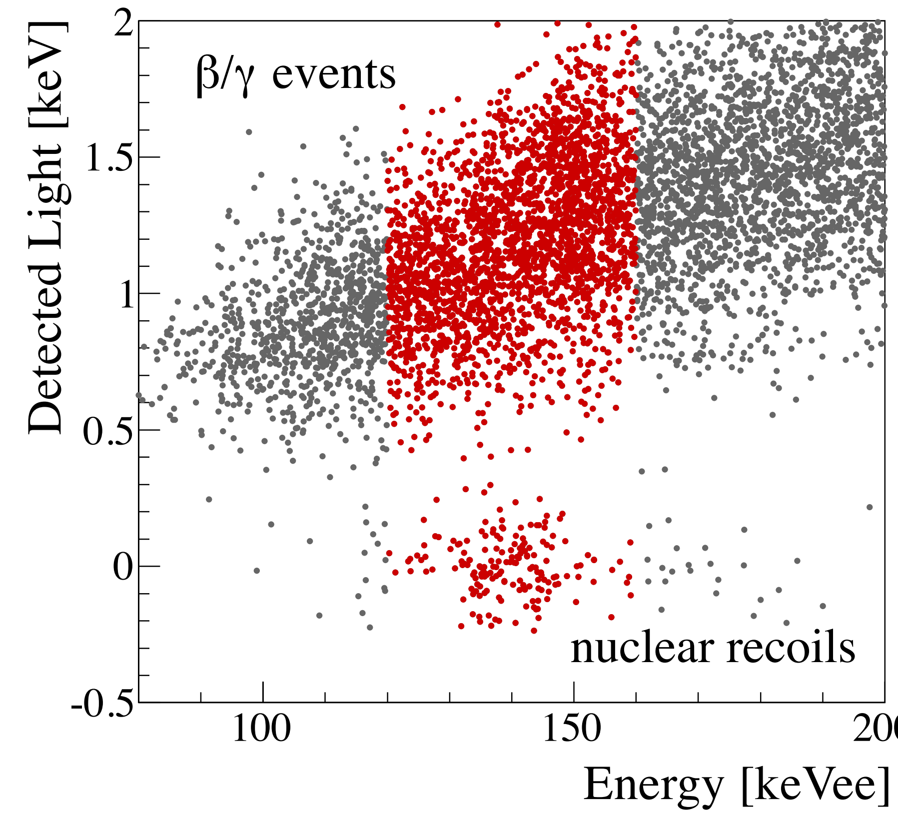
Dark Matter Searches with KIDs LD

Most of cryogenic calorimeters suffer from the lack of active background rejection

Solution: measure not only energy but also **light**







Images from CUPID-0 (E. Previtali's talk and EPJ C 76 (2016) no.7, 364)

JINST 8 P05021 (2013)

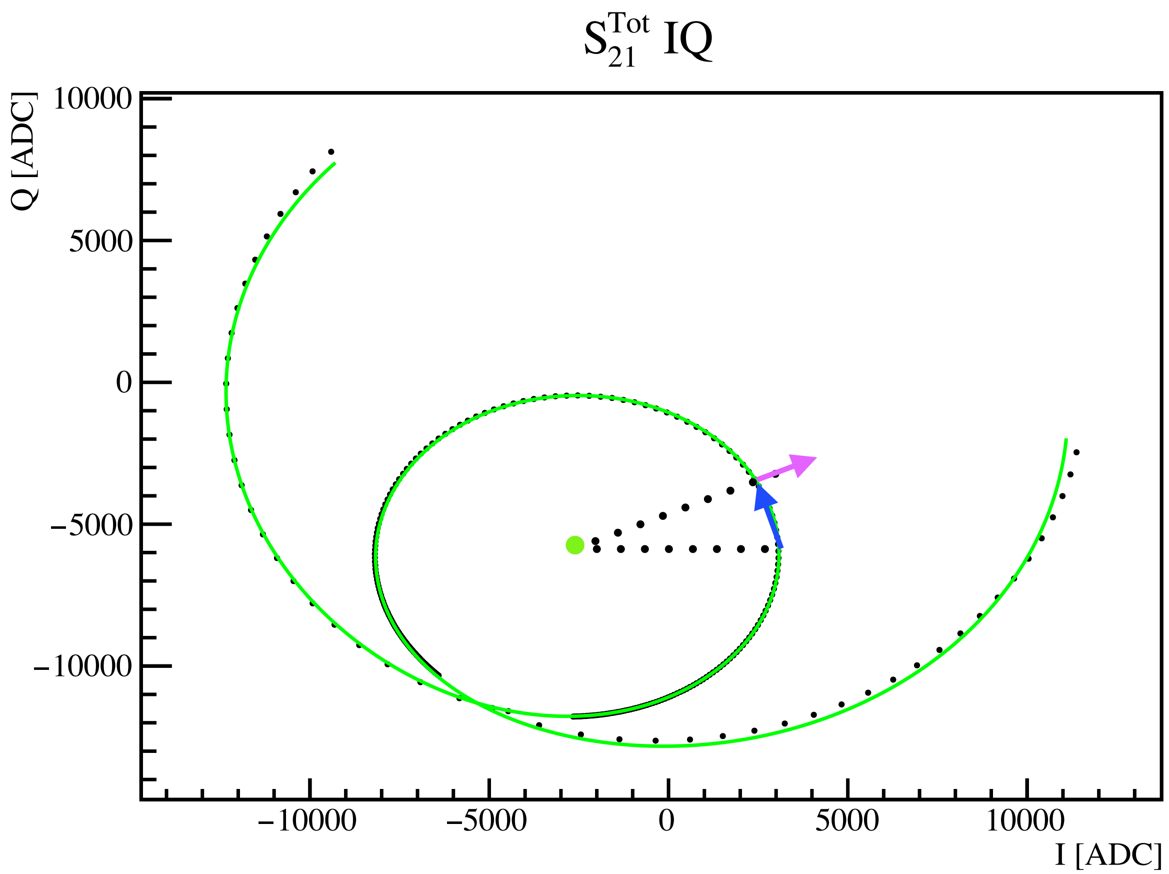
Good discrimination power >1 MeV, spoiled at low E because of LD resolution ~80 eV RMS

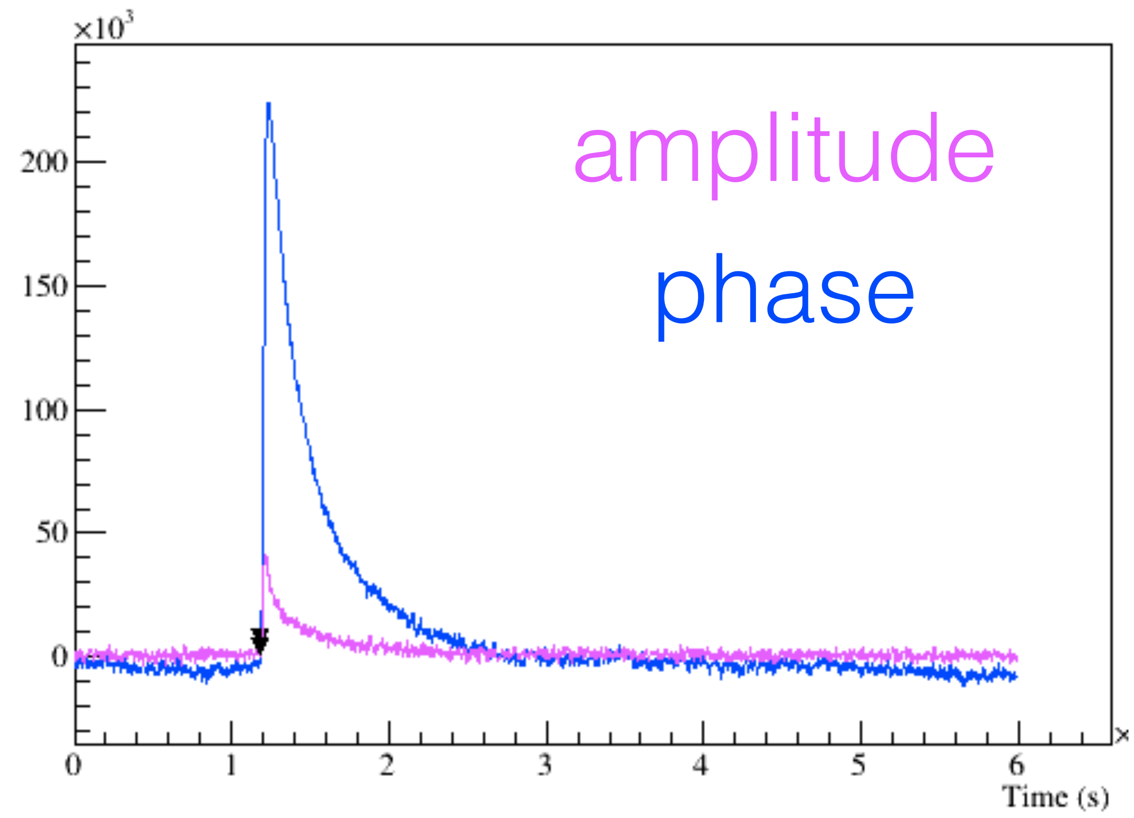
Not a problem for 0νββ, but a better LD (**RMS < 20eV**) would provide particle ID also at low energy (below 30 keV) —> dark matter searches "for free"

KIDs Read-Out

Sitting in the center of the resonance loop, we can monitor variations in I and Q (or, changing coordinates, in amplitude/phase) produced by interactions

Since phase is more sensitive, we use this estimator to reconstruct the pulse energy





KIDs efficiency

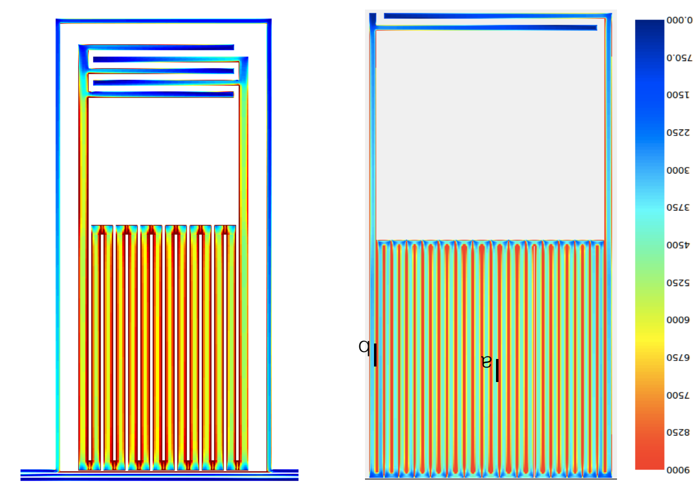
$$\delta\phi = \frac{\alpha S_2(\omega, T)}{N_0 \Delta_0^2} \cdot \frac{Q}{V} \cdot \epsilon E$$

More or less material dependent

Geometry

Efficiency

We tested different detector configurations:
Al on a 2x2 cm^2, 300 μm thick Si substrate:

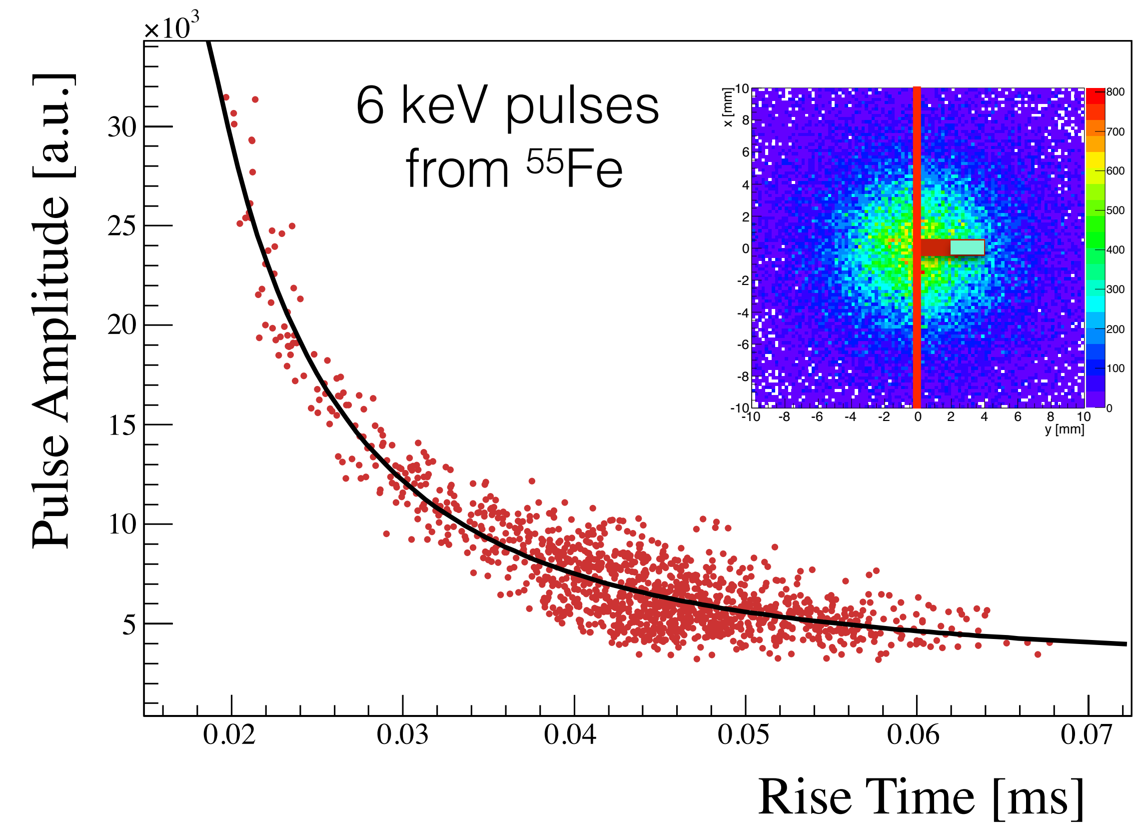


Test with LED [400 nm] + optical fiber, but also with ^{55}Fe/^{57}Co X-rays (calibration systematics)

We varied thickness (t) and active area (A), as we expect ε to scale as (tA)

1. Single pixel t: 25 nm, A: 2.4 mm^2 → ε ~ 2%
2. Single pixel t: 40 nm, A: 2.4 mm^2 → ε ~ 7%
3. Single pixel t: 40 nm, A: 4.0 mm^2 → ε ~11%

The efficiency is position dependent, but we can correct this effect exploiting pulses time development



Resolution

If we are dominated by the amplifier noise (ideal case), we expect the resolution to scale as:

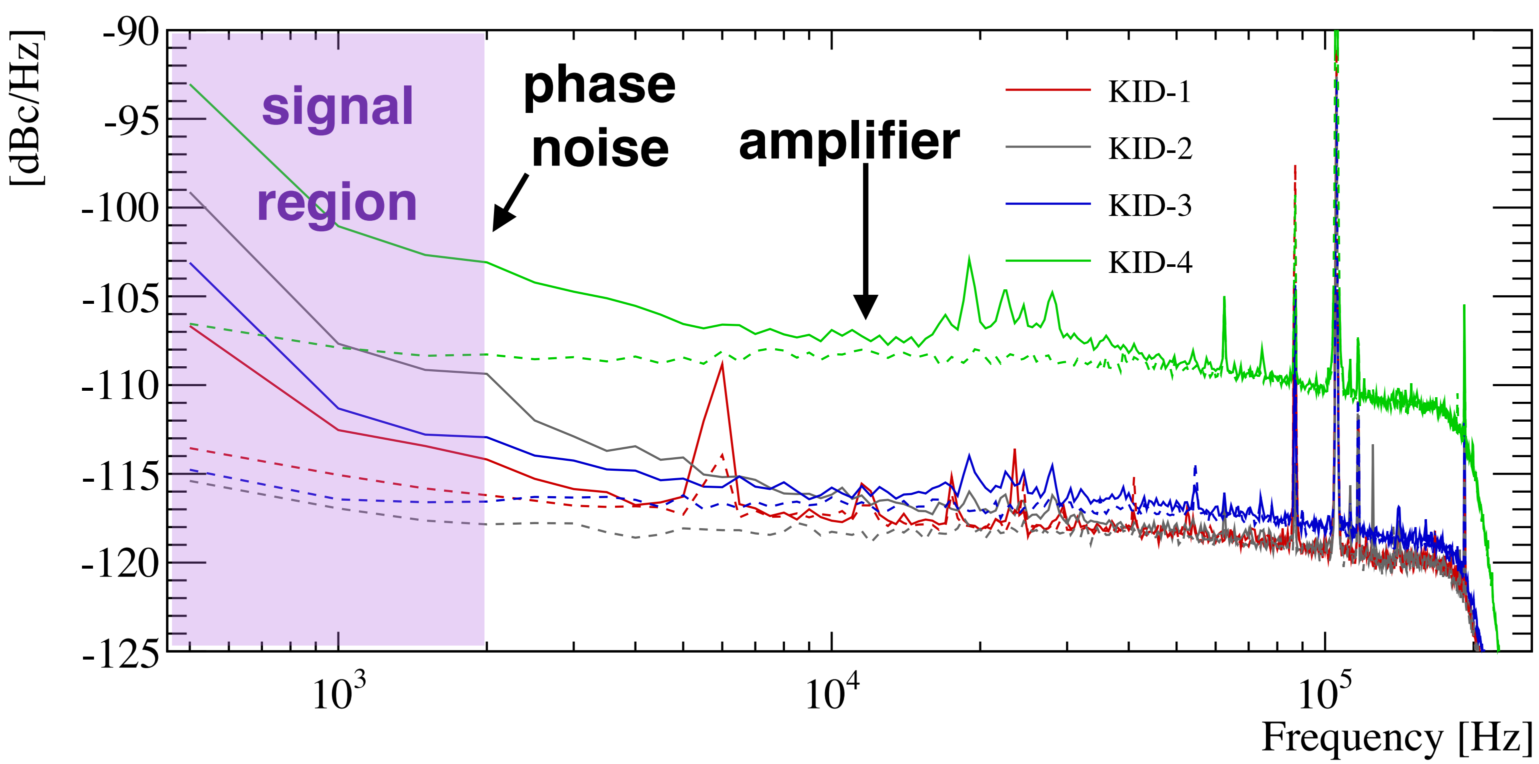
$$\sigma_E = \frac{2N_0\Delta_0^2}{\alpha S_2(\omega,T)} \frac{V}{Q\epsilon} \sqrt{\frac{kT_N}{P_f \tau_{qp}}}$$

More or less material dependent

Geometry

In the 4-pixel configuration, we measured samples with noise from 150 eV to 90 eV.
We changed V, α, Q and ε of the single KID. The resolution changed from 160 to 90 eV.

Target of phase-I (80 eV) within reach



Low frequency noise, probably ascribable to electronics, always present in our KIDs.

It limits the energy resolution, that could better also with Al films.

Now under investigation.