CALDER

Cryogenic light detectors for background-free searches

Sergio Di Domizio
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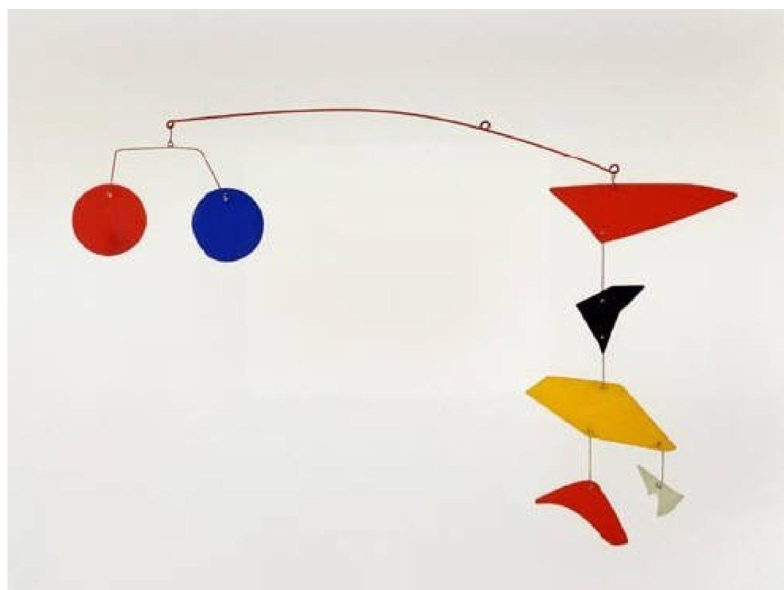
for the CALDER collaboration



LOW RADIOACTIVITY TECHNIQUES 2017
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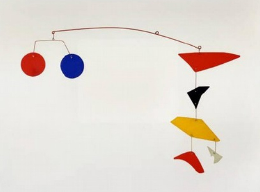


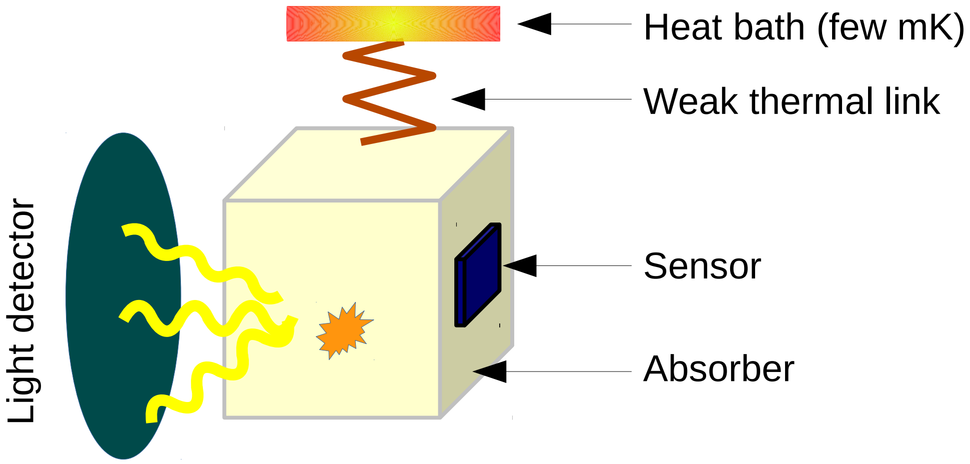
Physics motivation

- Cryogenic calorimeters are excellent detectors for rare events searches
- They feature large masses and excellent energy resolution
- Employed in many $0\nu\beta\beta$ and dark matter experiments
- Active background suppression can be obtained with particle discrimiation

REPRESENTED IN THIS WORKSHOP

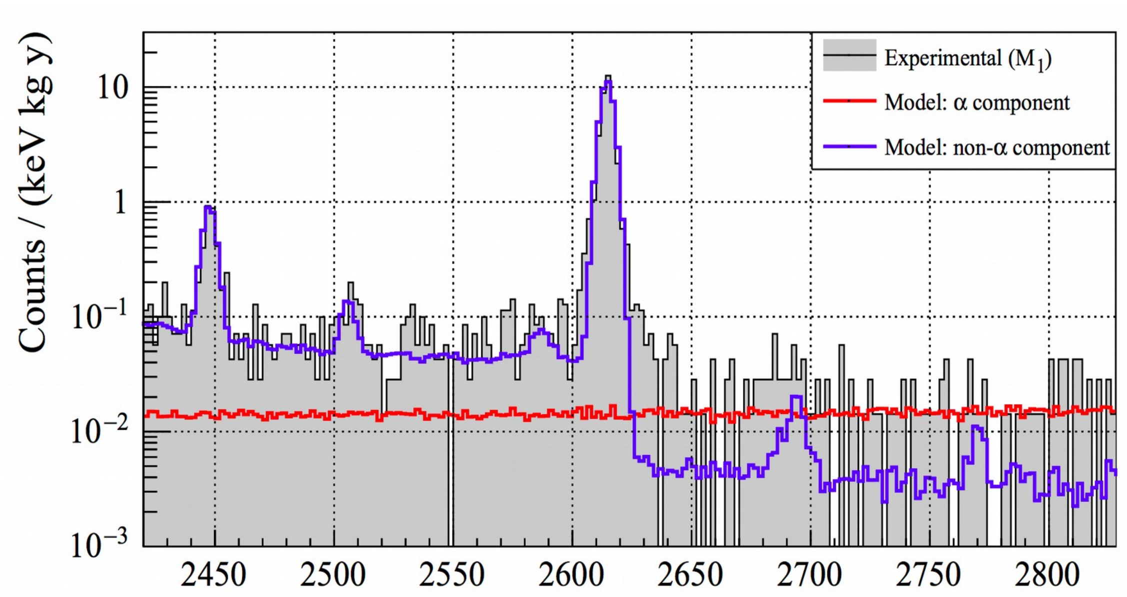
- AMoRE: O. Gileva
- CRESST: R. Strauss
- CUORE: G. Benato
- CUPID-0: L. Pattavina

and there are others



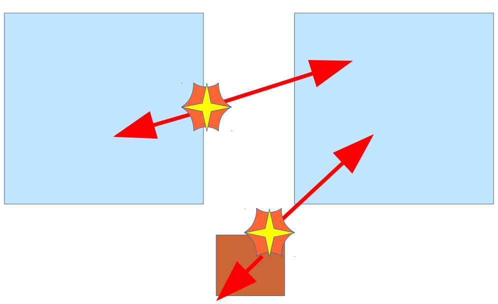
CUORE

- Uses TeO_2 bolometers to search for $0\nu\beta\beta$
- Search for a peak at 2.528 MeV
- Background dominated by α decays from surface radioactive contaminations



Eur. Phys. J. C 77 (2017), 13

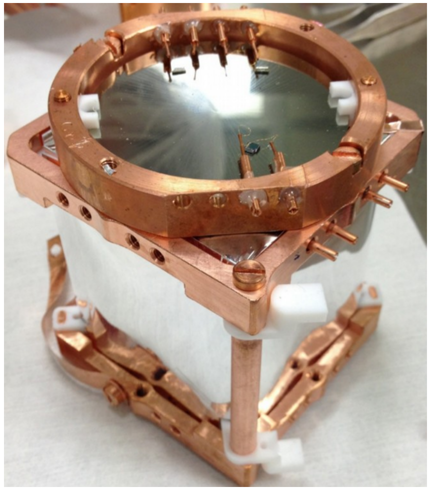
Main bkg expected in CUORE
degraded alpha particles from materials facing the detectors

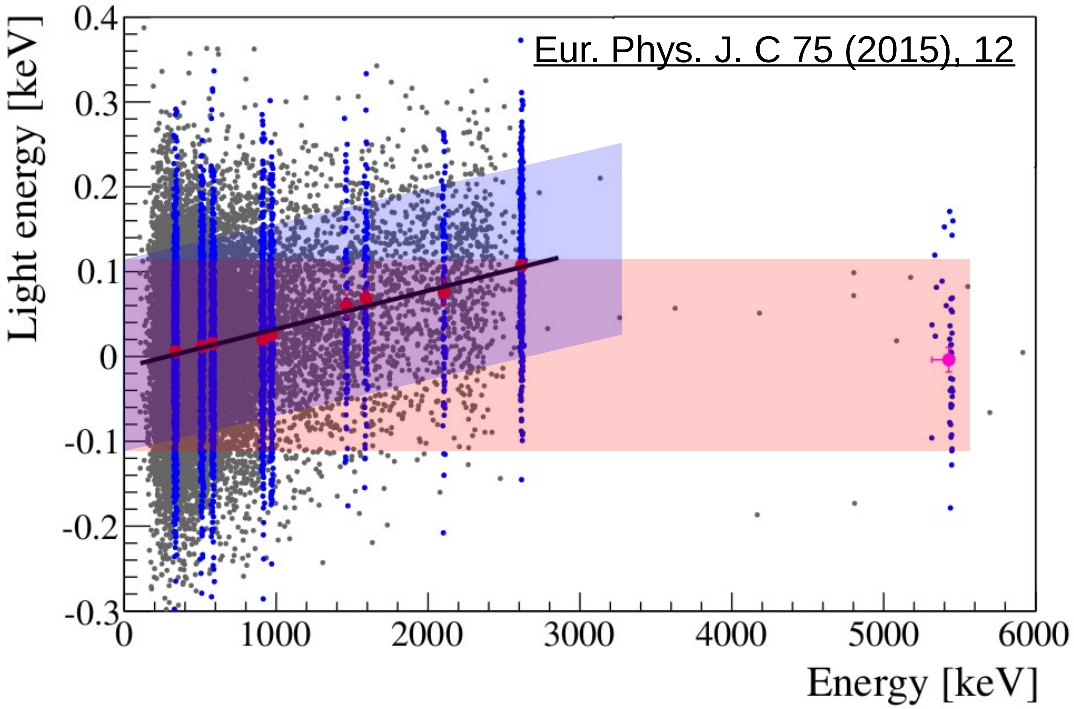


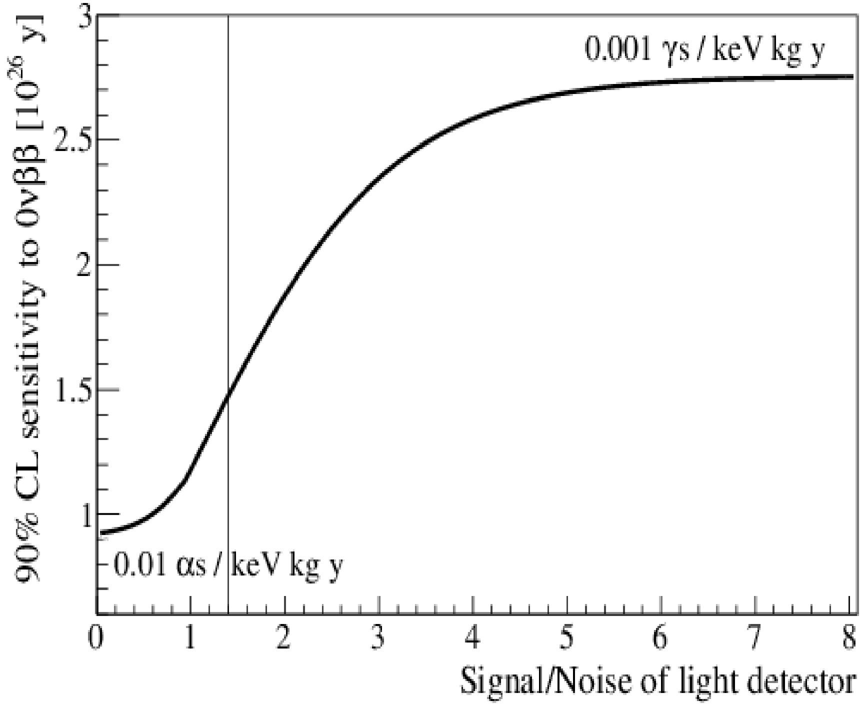
More on CUORE in G. Benato's talk

Detecting Cerenkov light in TeO_2

- TeO_2 crystals do not scintillate, but Cerenkov light from electrons can be detected   Eur. Phys. J. C 65 (2010), 359
- Particle discrimination demonstrated on a CUORE-size bolometer
- Measurement performed with a 80eV RMS resolution light detector
- A more performing light detector would allow event-by-event particle discrimination

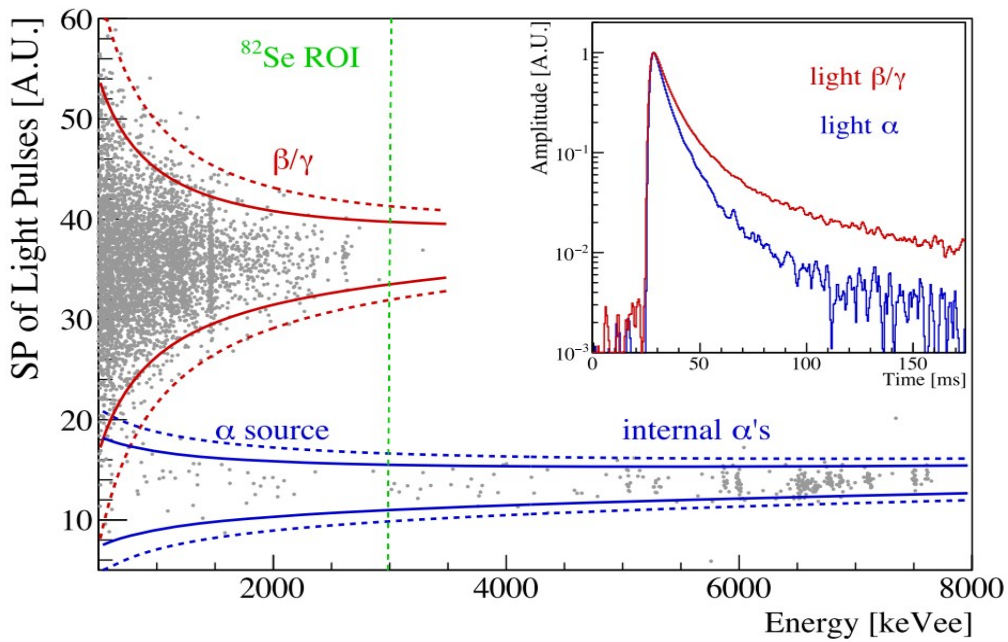




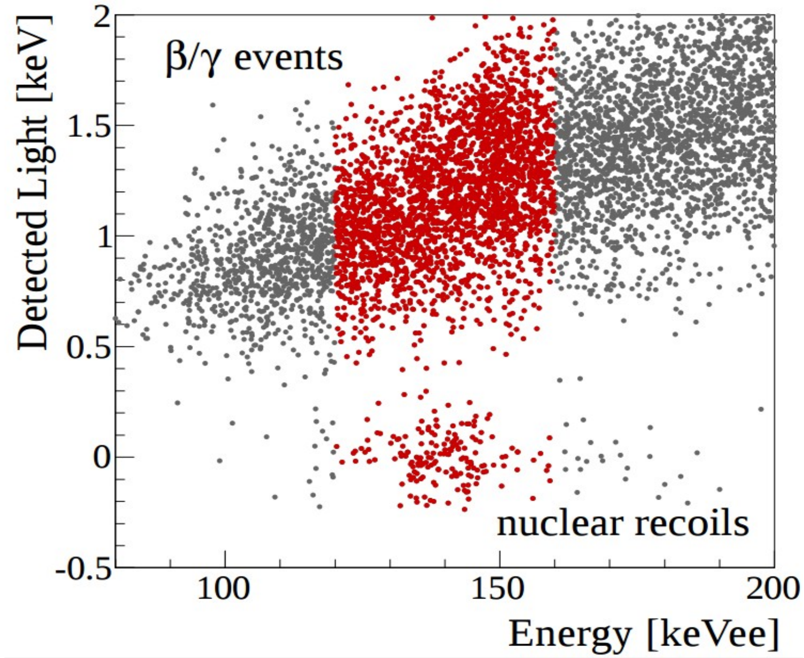


Discriminating nuclear recoils in ZnSe

- CUPID-0 uses scintillating ZnSe crystals for $0\nu\beta\beta$ search in ^{82}Se
- NTD-based light detectors allow for particle discrimination in the MeV region
- A more performing light detector would also provide particle identification at low energy → also sensitive to dark matter

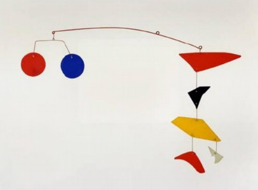


Eur. Phys. J. C 76 (2016), 364



JINST 8 (2013) P05021

More on CUPID-0 in L. Pattavina's talk



A more performing light detector

A light detector for a next generation bolometric experiment should satisfy several requirements

Light detector requirements

- Baseline resolution < 20 eV RMS
- Large active area: 5x5 cm^2
- Low radioactivity
- Capable of working in a relatively wide temperature range: 5-20 mK
- Scalable to ~1k detectors
  - Easy fabrication and operation
  - Introduce an affordable heat load in the cryogenic system

From the CUPID interest group:
arXiv:1504.03612, arXiv:1504.03599

Lots of R&D activities, but none of them currently meets all the requirements

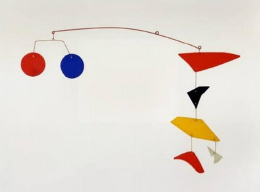
Phys. Rev. C 94 (2016), 054608

J.Low.Temp.Phys. 184 (2016), 286-291

Astropart. Phys 69 (2015), 30-36

JINST 10 (2015) no.03, P03003

and many others



Kinetic inductance detectors

- Superconductor operated below T_C
- Exhibit an impedance when driven by an AC current: kinetic inductance L_K
- Interacting photons break Cooper pairs and L_K changes: measure energy
- L_K inserted in high-Q resonant circuit: monitor amplitude and phase changes

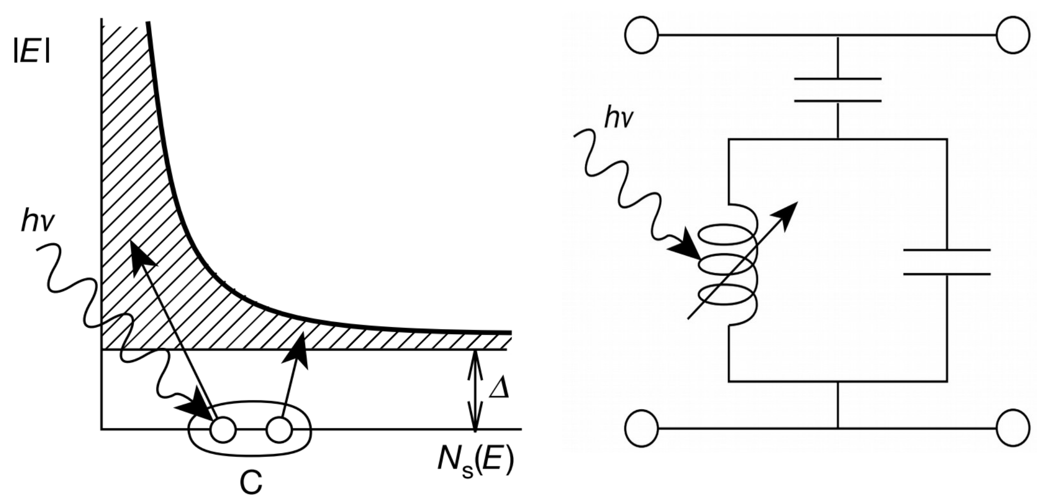
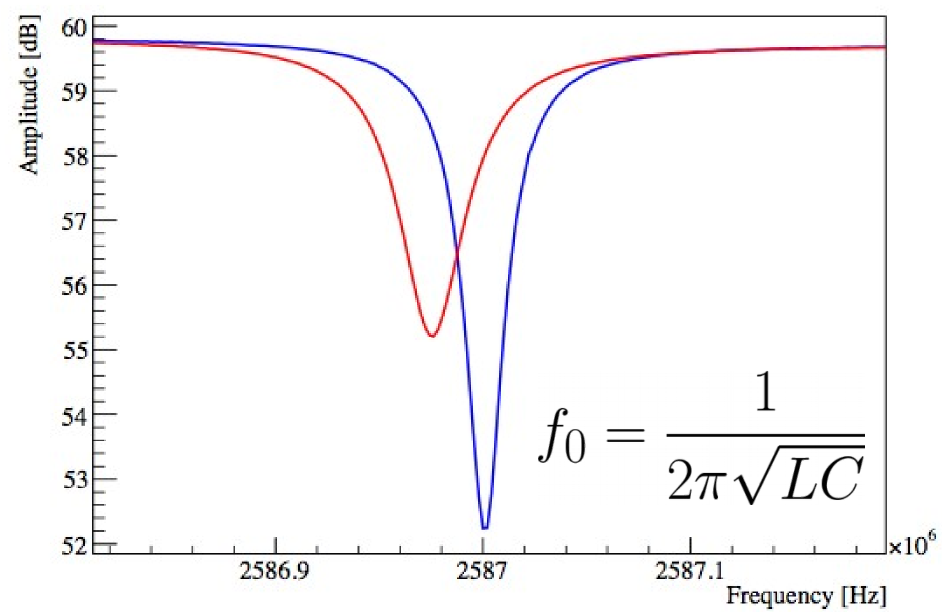
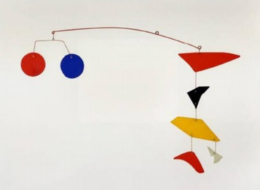


Figure from P. K. Day et al., Nature 425 (425), 817-821

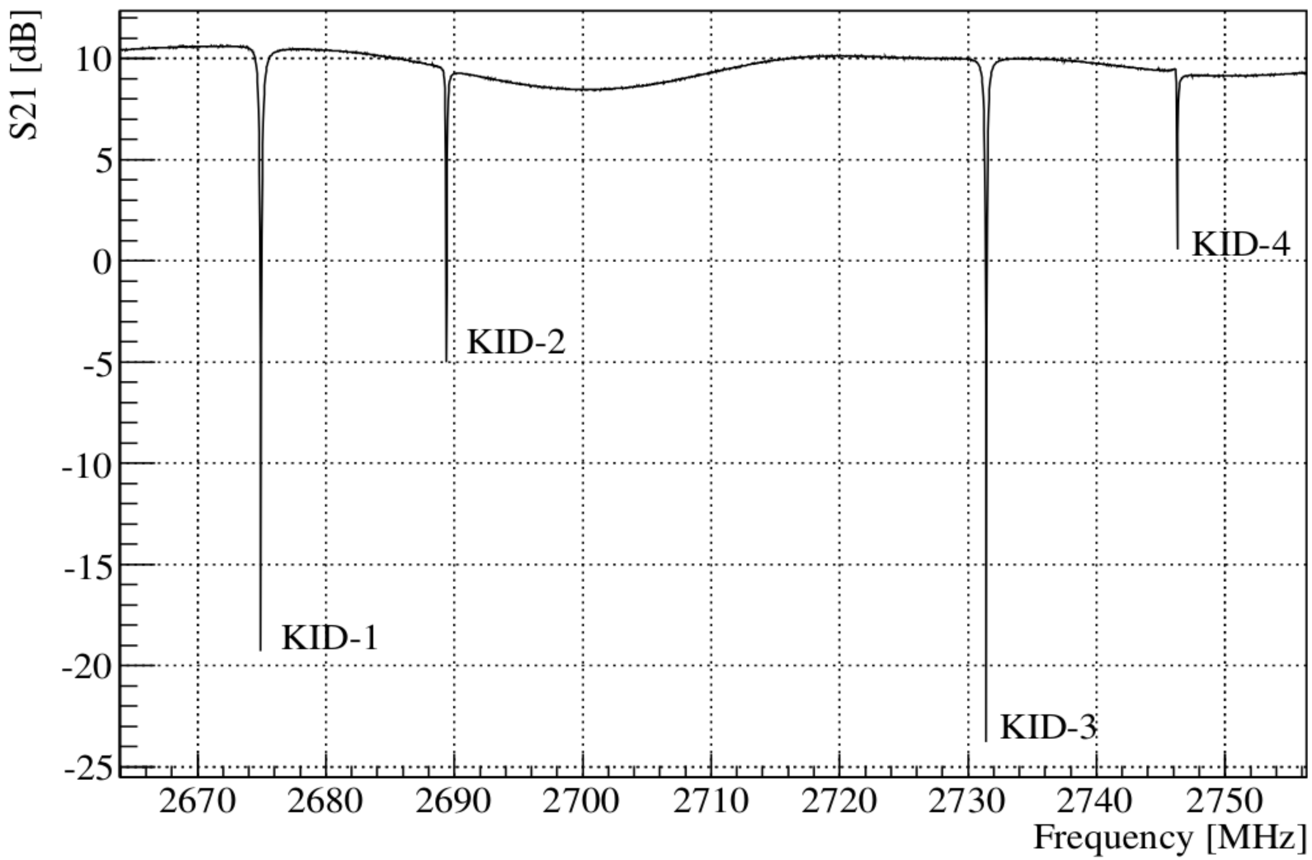


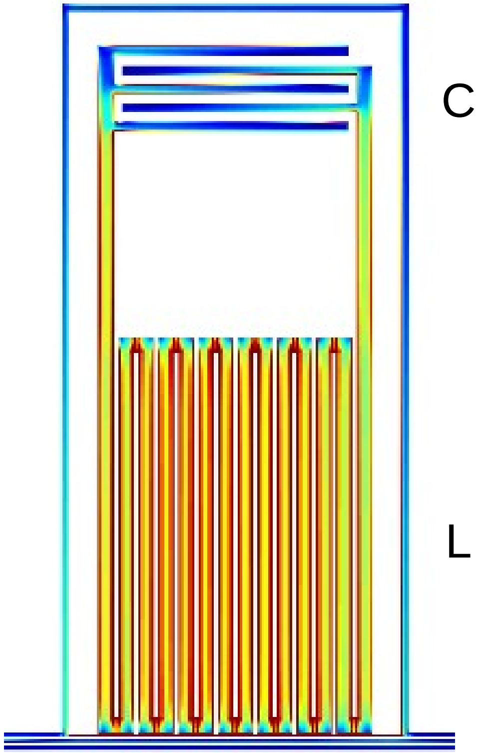
A novel an promising technique initially exploited in astrophysics applications



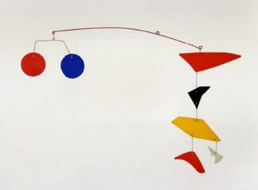
Frequency-domain multiplexing

- Multiple resonators can be operated on the same feed line
- Intrinsic attitude to frequency-multiplexing
- Resonance frequency tuned by adjusting the sensor capacitance





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



The CALDER project

Demonstrate the potential of KID-based detectors for particle identification in a next generation bolometric experiment

A 4-years project, 3 main steps

Eur. Phys. J. C 75 (2015), 353

1. DETECTOR DESIGN

Optimize detector geometry

Readout and analysis

Standard superconductor: Al

Target resolution
80 eV RMS

2014-2016

2: OTHER MATERIALS

Test alternative materials to improve resolution

TiAl, Ti-TiN, TiN

Target resolution
20 eV RMS

2016-2017

3. DEMONSTRATOR

Demonstrate background suppression with real detectors

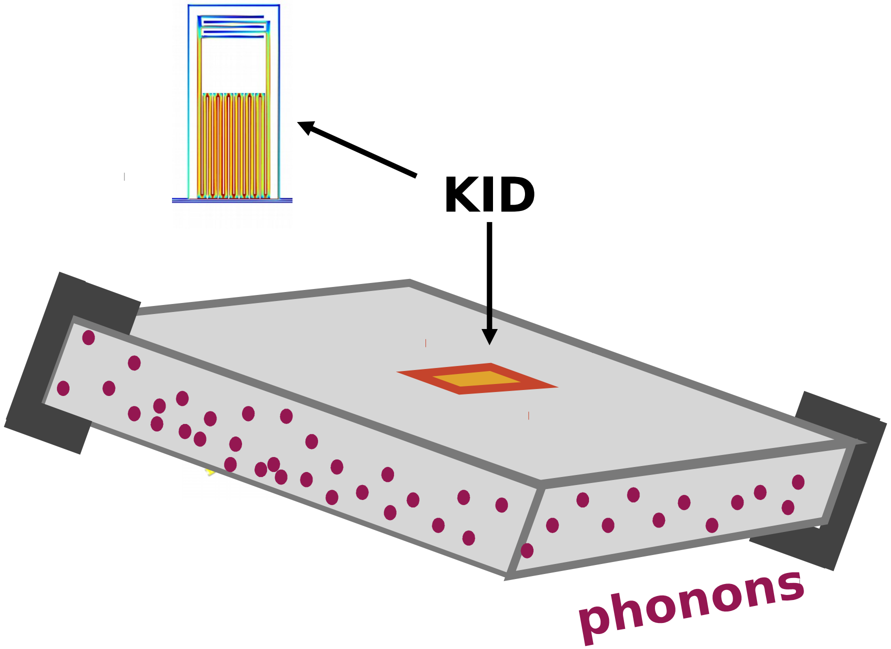
Run a small TeO_2 bolometer array at LNGS

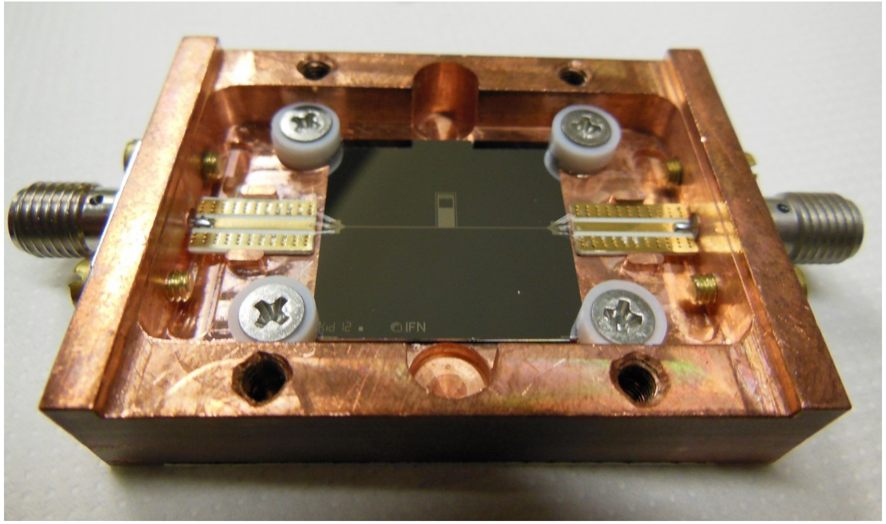
2017-2018

CALDER is funded by an ERC Starting Grant

Phonon-mediated approach

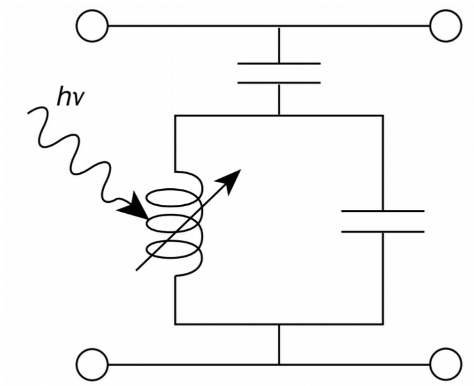
- KIDs have a sensitive area of few mm^2, but we need 5x5cm^2
- Phonon-mediated approach
  - Photons to phonons conversion in a large area substrate
  - KID deposited on the substrate samples the phonon signal



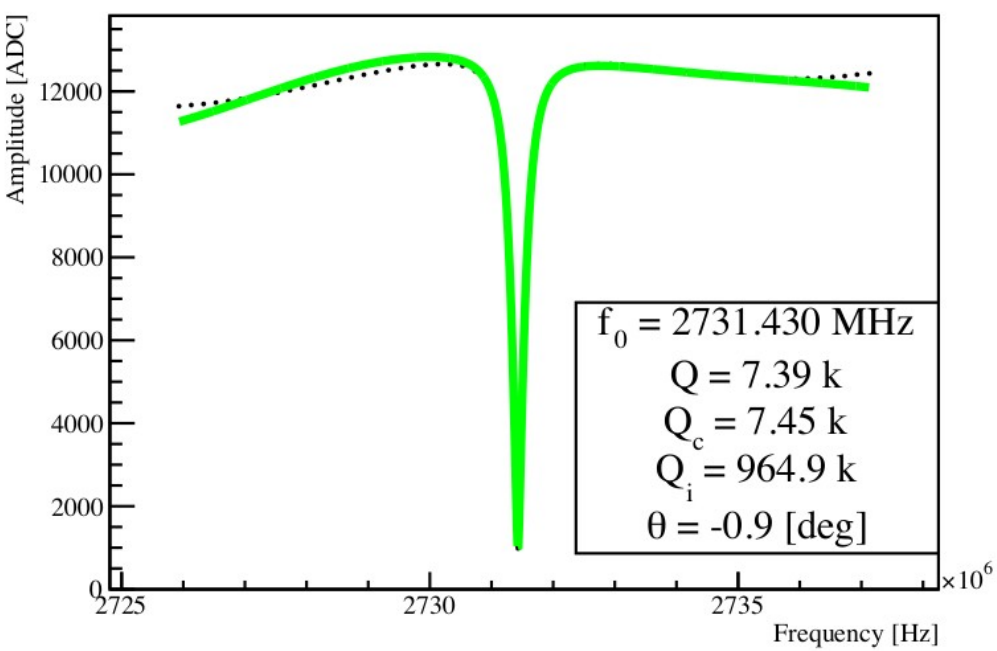


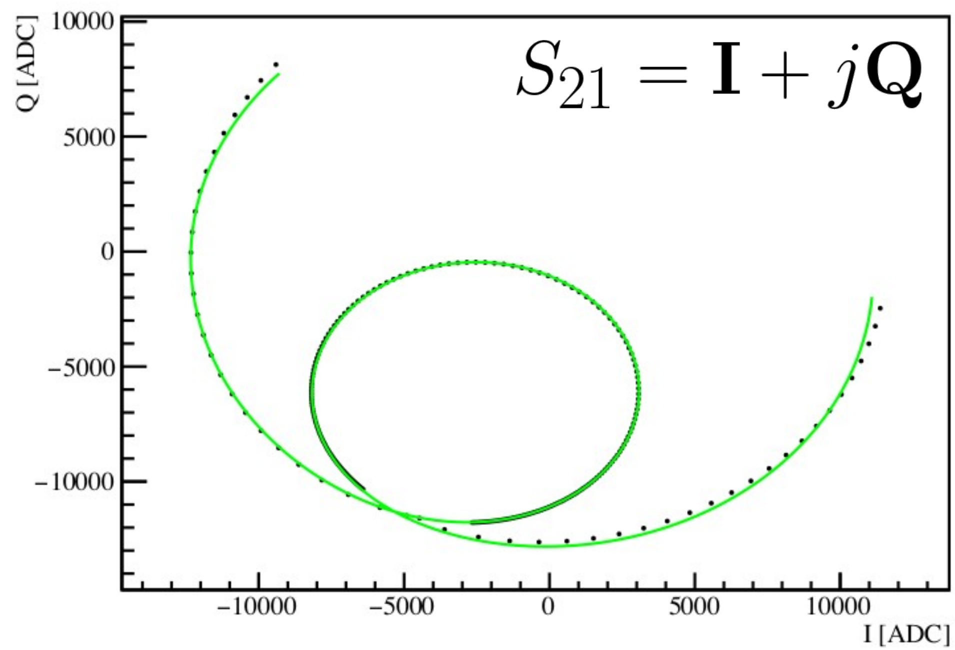
Sensor operation

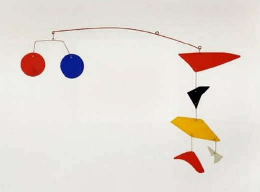
Perform a frequency scan to determine the most sensitive operating frequency



$$S_{21} = 1 - \frac{Q/Q_c}{1 + 2j\frac{f - f_0}{f_0}}$$

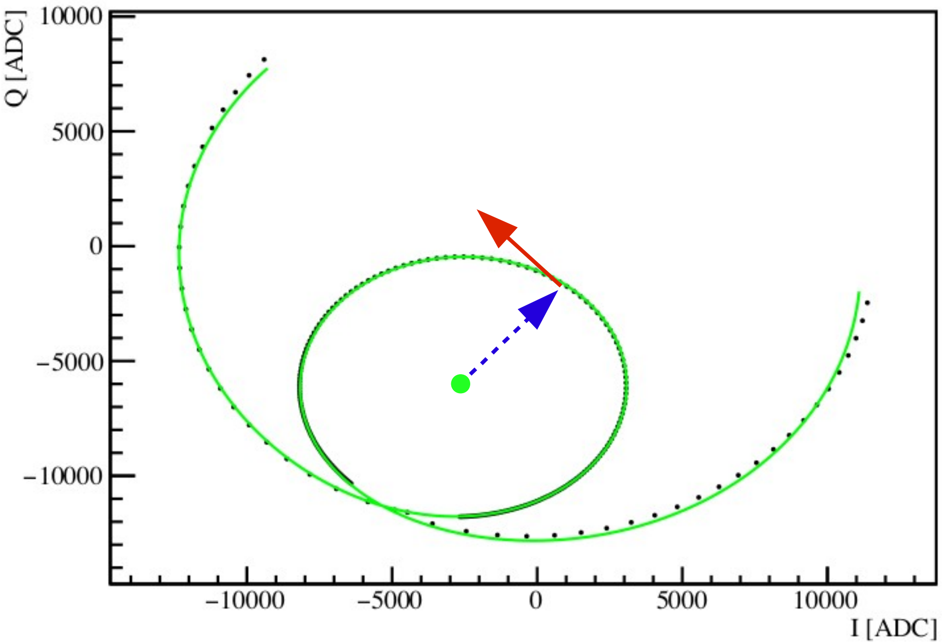


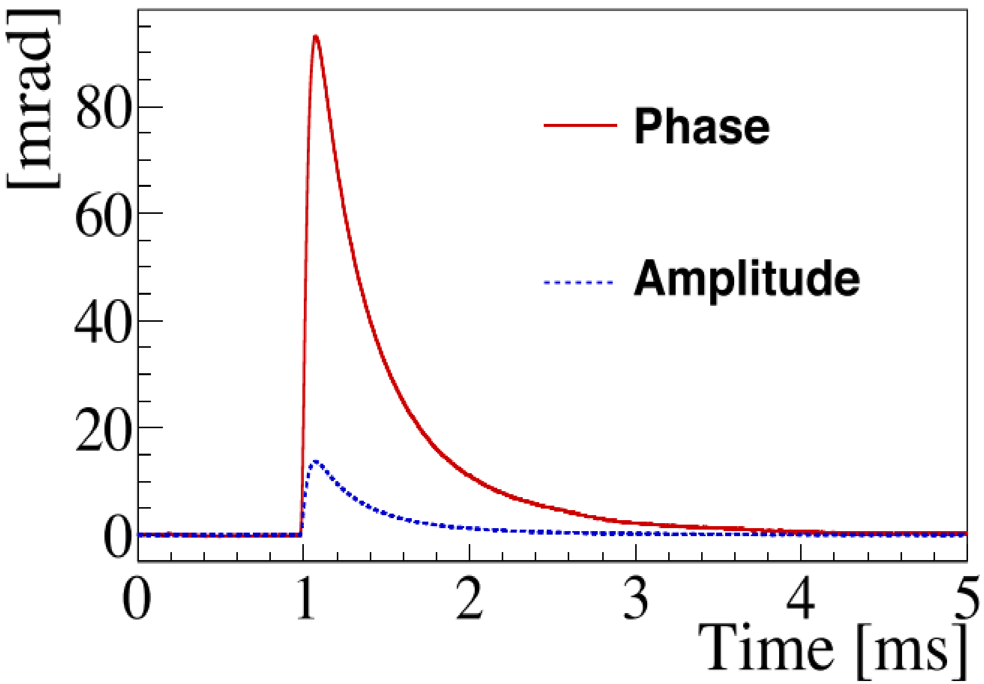




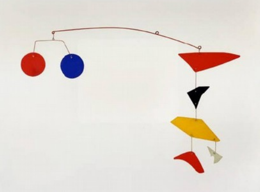
Amplitude and phase signal

- Perform detector response calibration
- Measure amplitude and phase variations relative to the center of the resonance circle



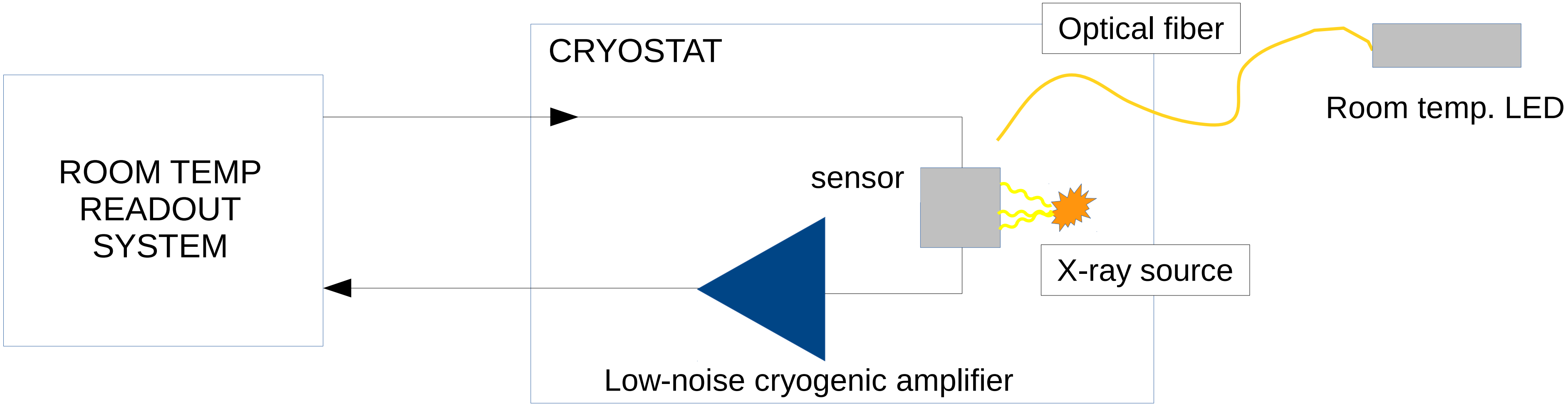


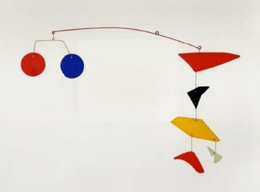
$$\delta\phi = \frac{\alpha S_2(f,T))}{N_0\Delta^2}\frac{Q}{V}\varepsilon E$$



Experimental setup

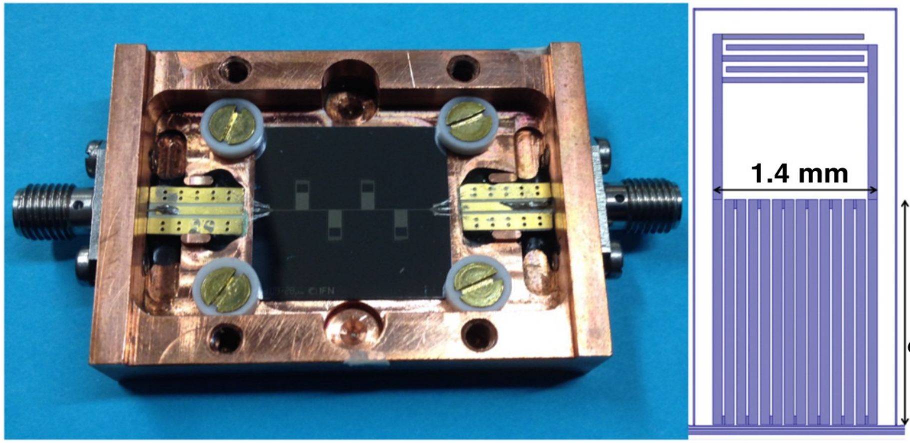
- Test facility based on a cryogen-free dilution refrigerator
- All the readout system is at room temperature, the only exception is a low noise cryogenic amplifier
- Calibration: sensor illuminated with a pulsed 400nm LED and with ^{55}Fe or ^{57}Co X-ray source





First results

- Four Al KIDs on a 2x2cm^2 x 300µm Si substrate
- Single-KID: 2.4 mm^2 x 40nm
- Q in the range 6K – 35K
- Analysis based on pahse signal only

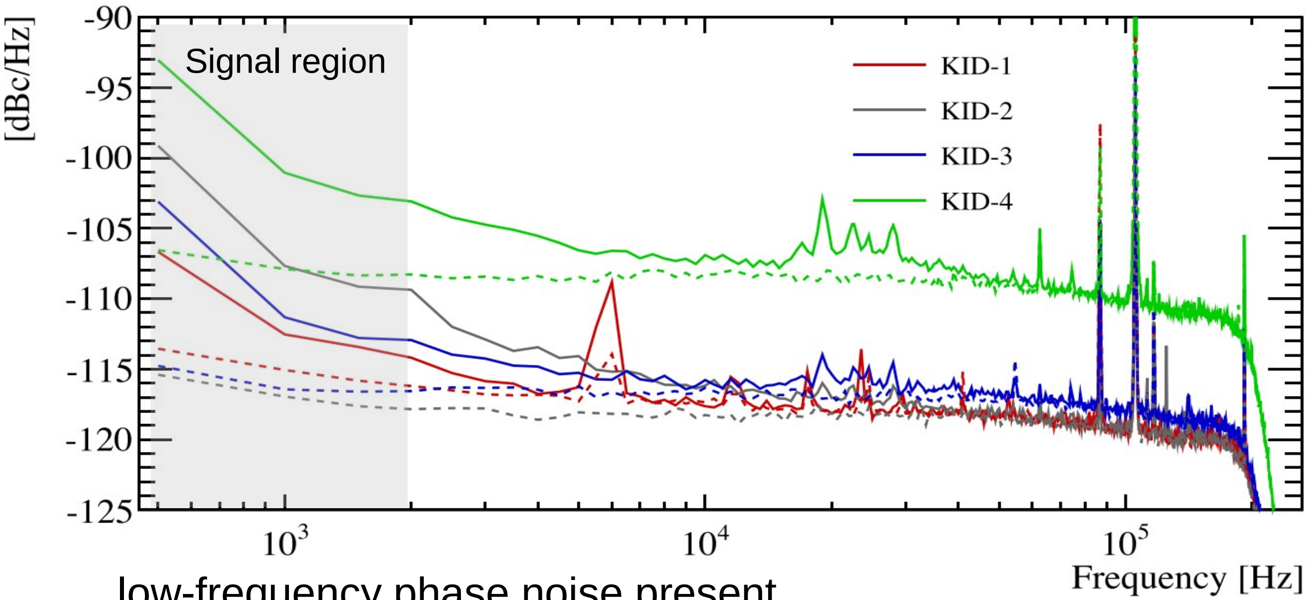


Total energy collection efficiency: 18%

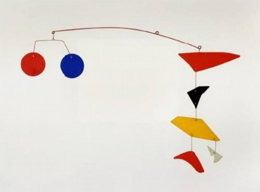
Single KID collection efficiency: (3 – 6)%

Baseline resoliution: 154 keV RMS

Appl. Phys. Lett. 107 (2015), 093508



low-frequency phase noise present

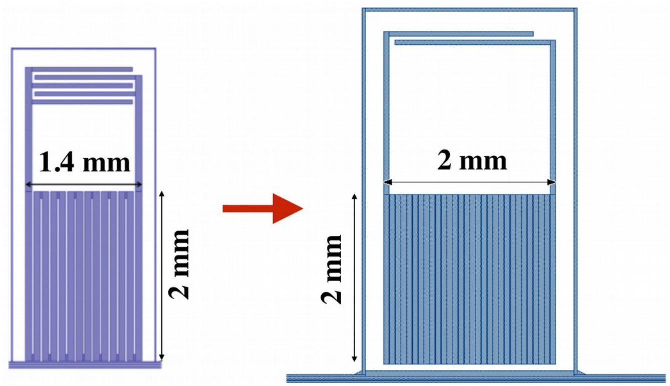


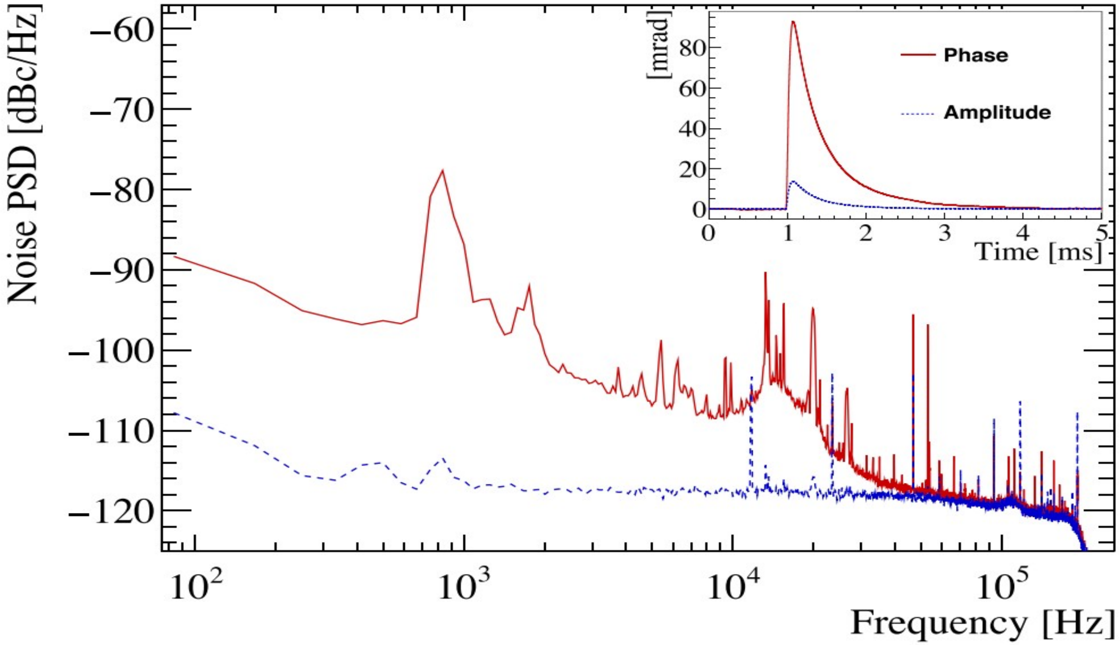
Sensor optimization

- Single-KID: simpler and no cross-talk
- Sensitive area and thickness increased: 4mm^2 x 60nm
- Q increased: 150k
- Combined amplitude and phase readout

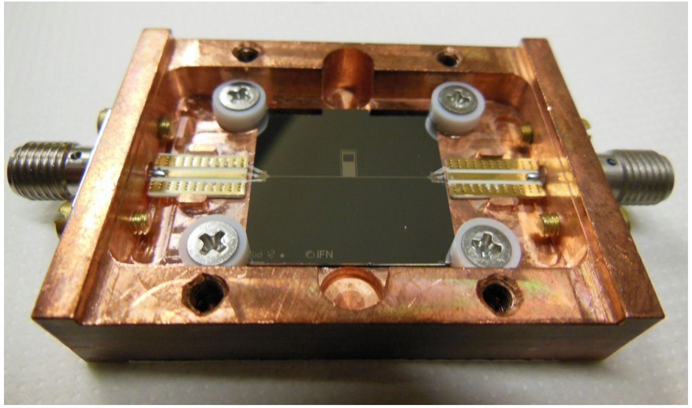
Baseline energy resolution: 82 eV RMS

Single-KID energy collection efficiency: 9.4%





low-frequency phase noise still present



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

Sensor optimization

- Single-KID: simpler and no cross-talk
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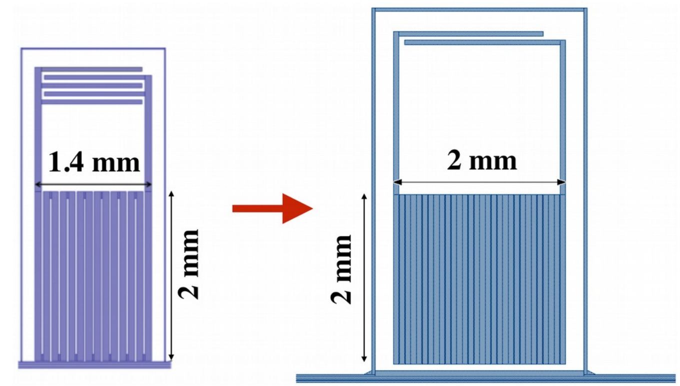
- Q increased: 150k
- Combined amplitude and phase readout



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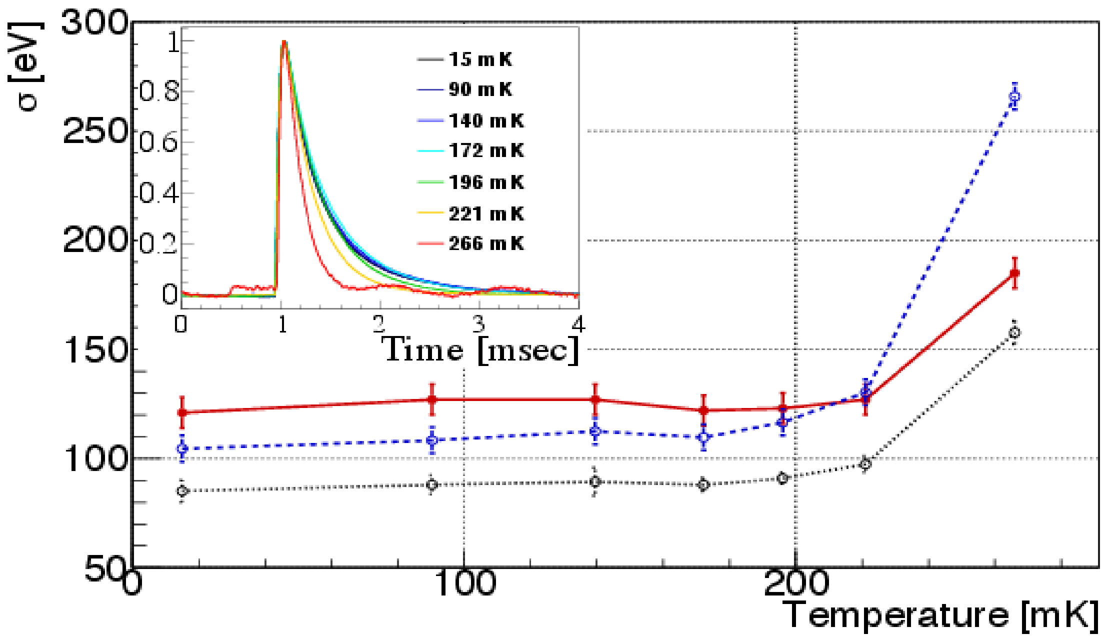
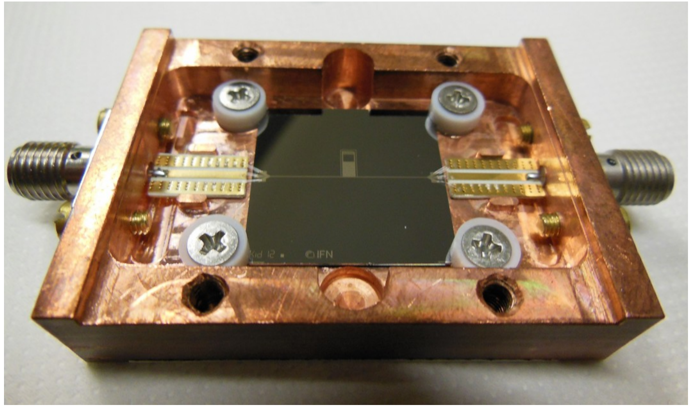


Baseline resolution remains constant below 200 mK



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

Testing other superconducting materials

Target sensitivity with aluminum KIDs reached: 82 eV RMS

Test other materias to improve the detector sensitivity

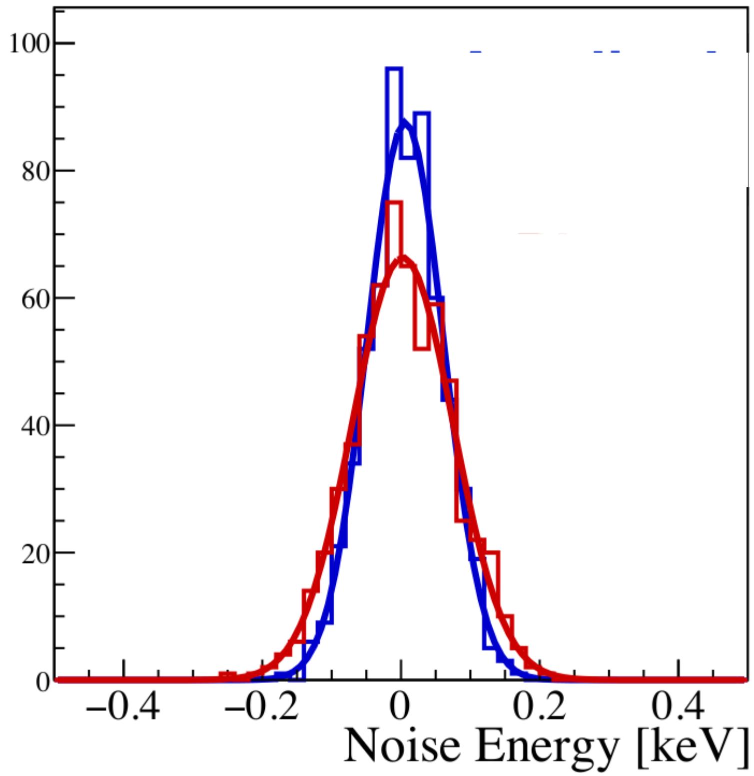
$$\Delta E \propto \frac{T_C}{\varepsilon\sqrt{QL}}$$

	Al	TiN sub-stoich.	Ti+TiN	TiAl
TC [K]	1.2	0.5	0.5 – 0.8	0.6 – 0.9
L [pH/square]	0.5	up to 50	6	1

Testing TiAl and Ti+TiN prototypes

Preliminary tests with TiAl KIDs

First tests with same geometry, just change the superconductor material



amplitude: 52 eV RMS
phase: 66 eV RMS
combined ~ 50 eV RMS

Energy collection efficiency slightly lower than Al prototypes with the same geometry

Tests on TiAl performed in collaboration with

CSNSM (Orsay, France) and Institut Neel, CNRS (Grenoble, France)

Preliminary tests on other prototypes show baseline resolutions as good as 30 eV RMS

Conclusion

- High resolution light detectors can make the difference in future large mass bolometric experiments
- The CALDER project is developing cryogenic light detectors based on KIDs
- Target resolution of 80 eV obtained with Al KIDs
- Promising results are being obtained with other superconductors: 30 eV with TiAl!