Phonon-mediated KIDs as light detectors for rare event search: the CALDER project

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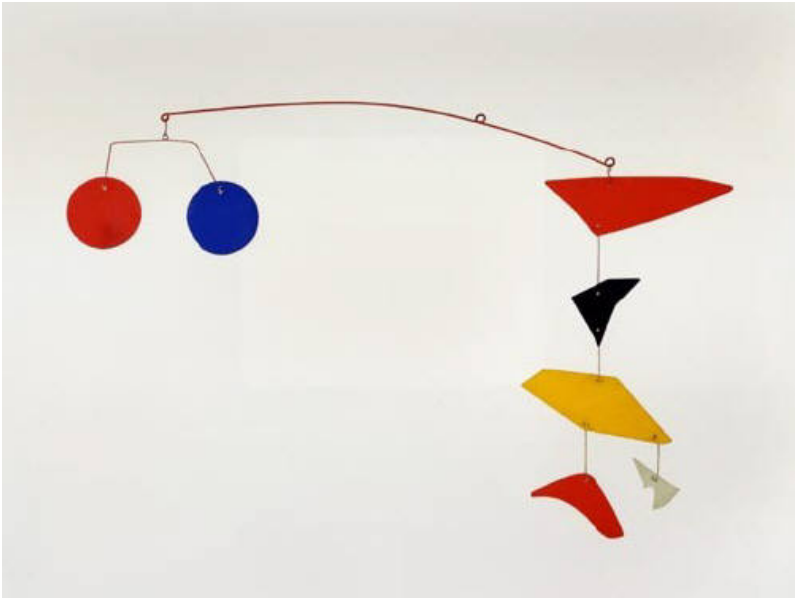
DIAS

for the CALDER collaboration

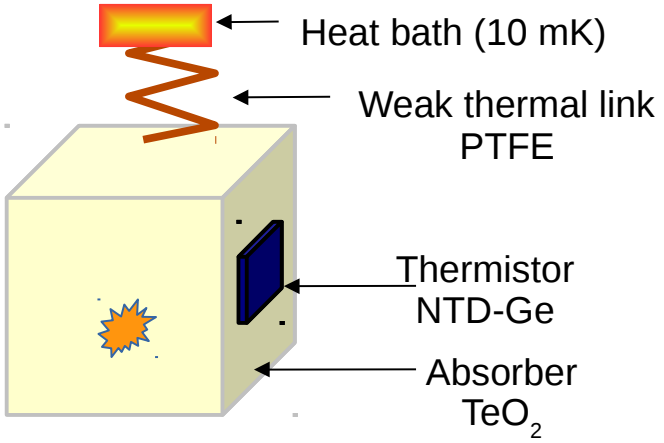


KIDs: The Next Generation
Dublin – 7th - 8th September 2017

Physics motivation

Next generation experiment in rare event search
very low background levels

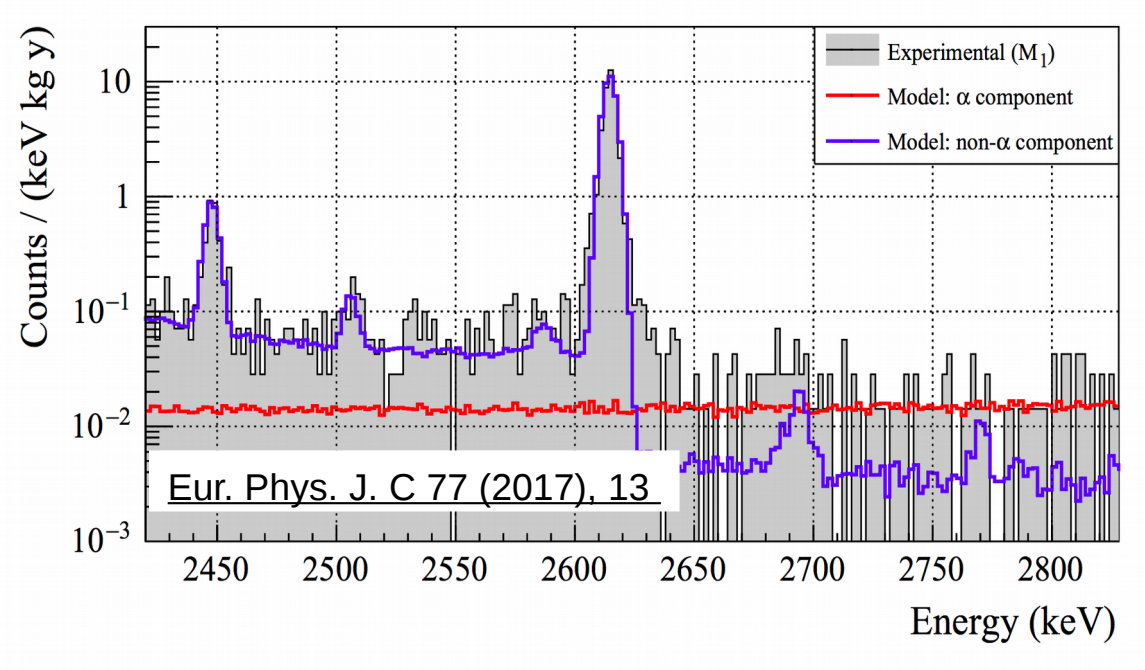
- Cryogenic bolometers are excellent detectors for rare events searches
- They feature large masses and excellent energy resolution
- Employed in many 0νββ and dark matter experiments
- Active background suppression can be obtained with particle discrimination



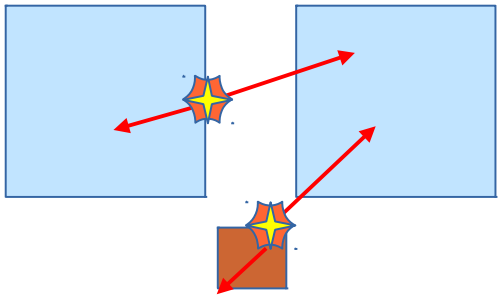
CUORE: 1 Ton tellurium dioxide + copper + ... @ 10 mK

CUORE

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



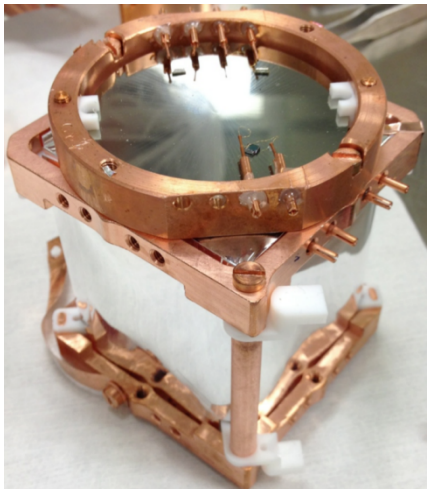
Main bkg in CUORE
alpha particles from surfaces



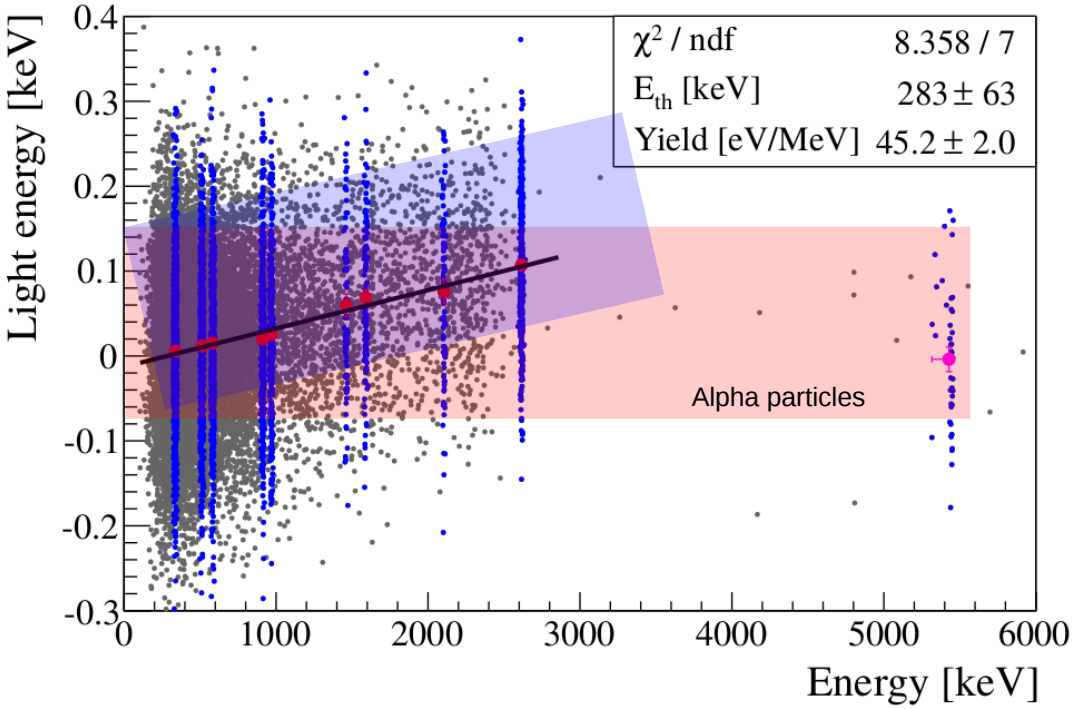
The CUORE collaboration performed an extensive R&D activity devoted to the suppression of this contribution of about one order of magnitude

Detecting Cerenkov light in TeO_2

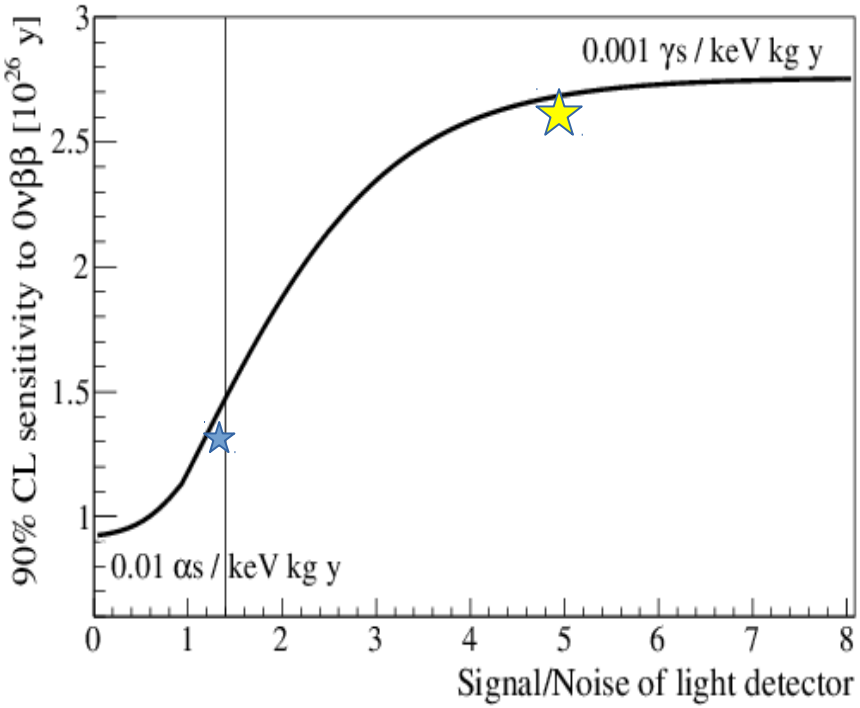
- TeO_2 crystals do not scintillate, but Cerenkov light from electrons can be detected
- Particle discrimination demonstrated on a CUORE-size bolometer
- Measurement performed with a 80eV RMS resolution light detector
- A more performing light detector would allow event-by-event particle discrimination



Eur. Phys. J. C 75 (2015), 12

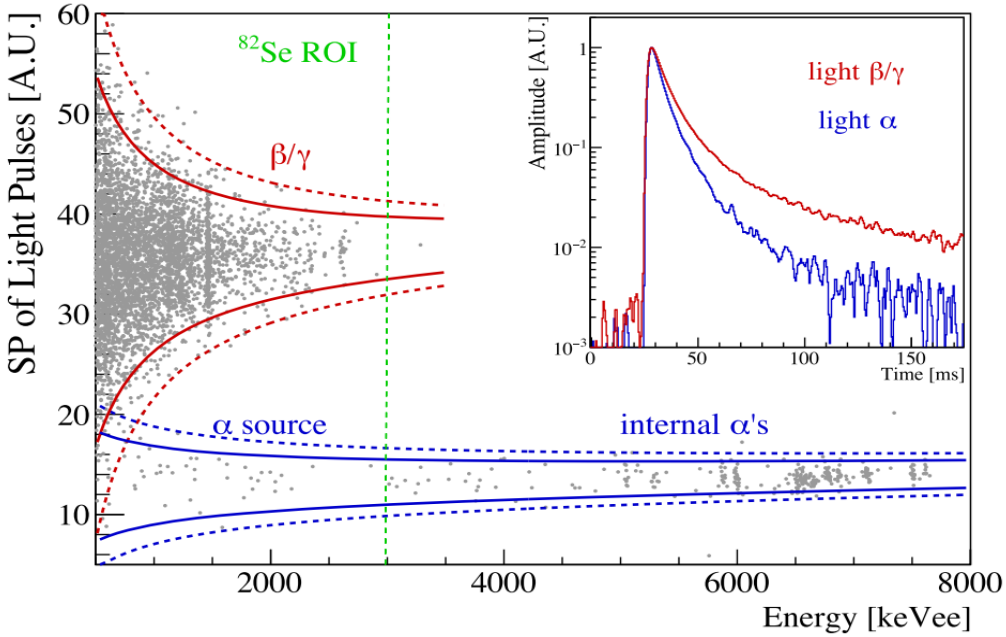


Eur. Phys. J. C 65 (2010), 359

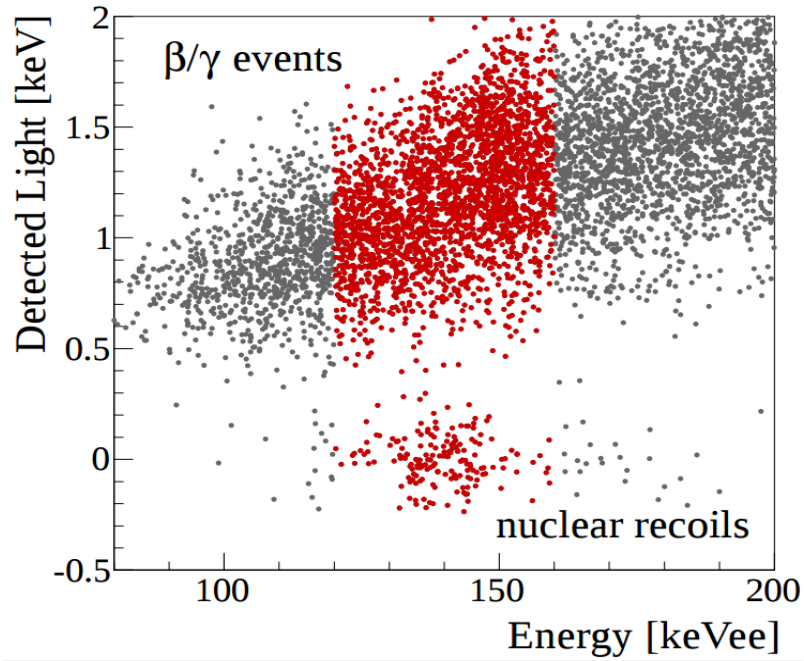


Discriminating nuclear recoils in ZnSe

- CUPID-0 uses scintillating ZnSe crystals for 0νββ 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

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

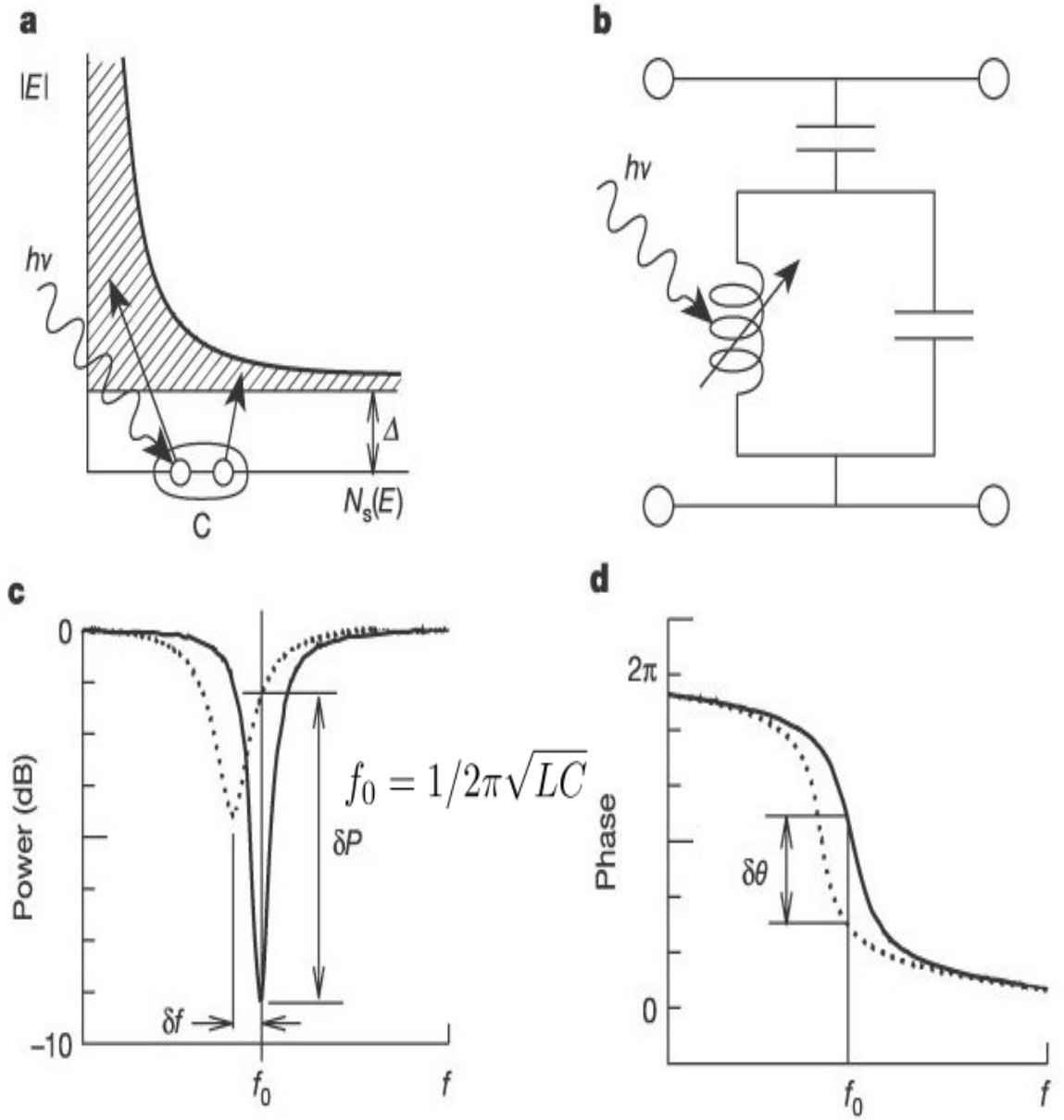
Astropart. Phys 69 (2015), 30-36

JINST 10 (2015) no.03, P03003

and many others

Kinetic inductance detectors

Day et al., Nature 425 (2003) 817

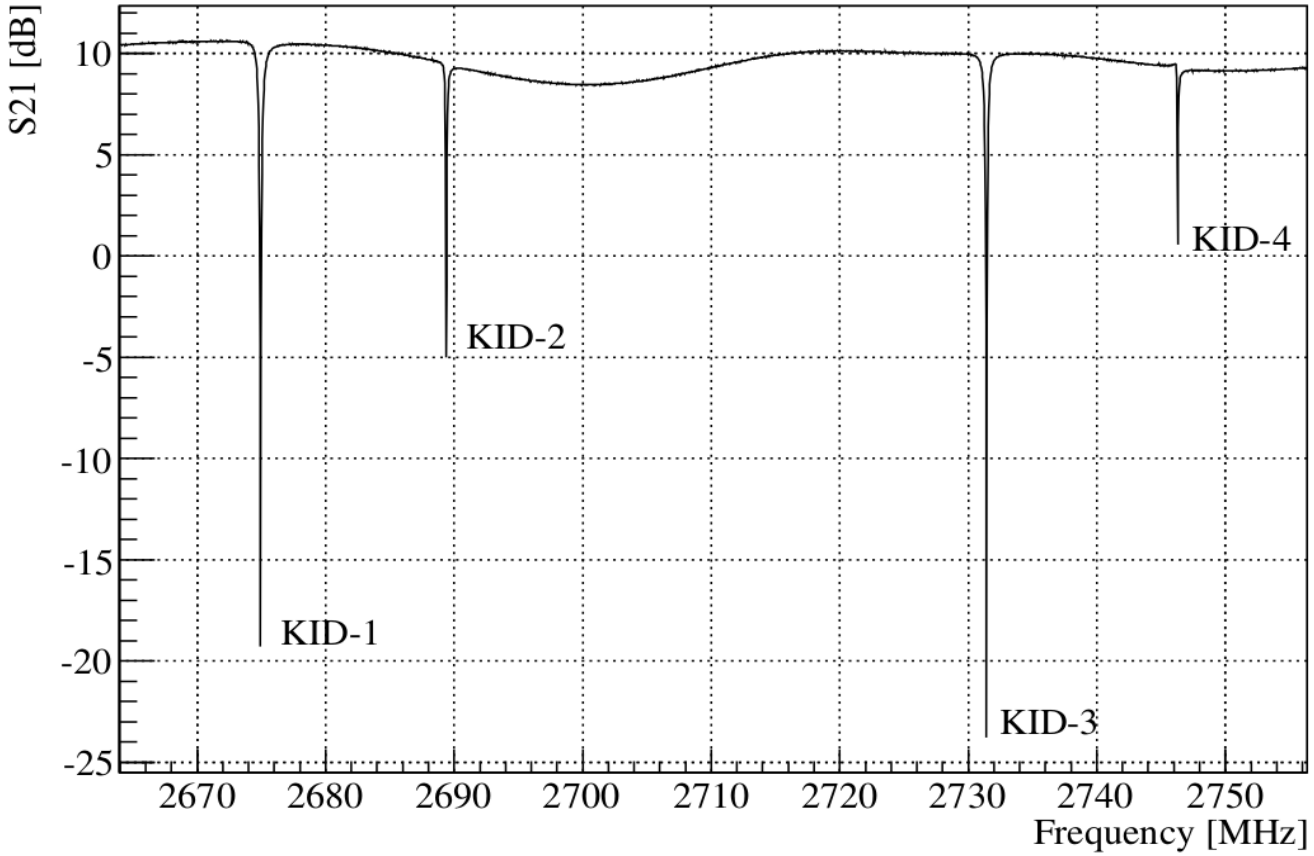


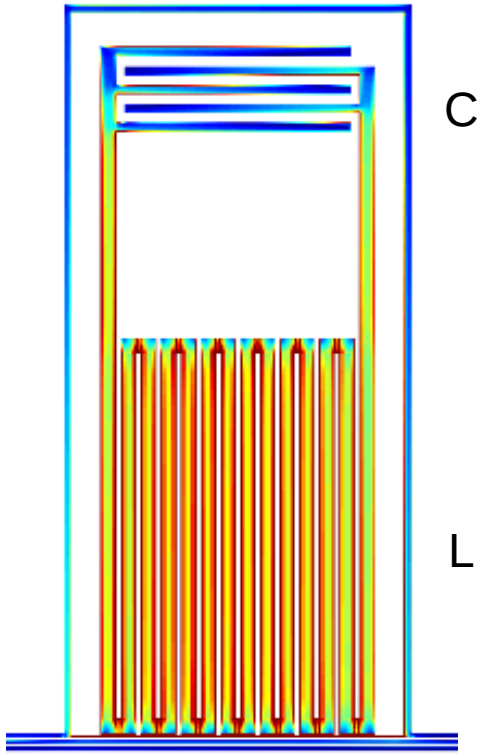
Cooper pairs (CP) in a superconductor act as an inductance (*L*).
Absorbed photons change cp density and *L*.

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

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_x

Target resolution
20 eV RMS

2016-2017

3. DEMONSTRATOR

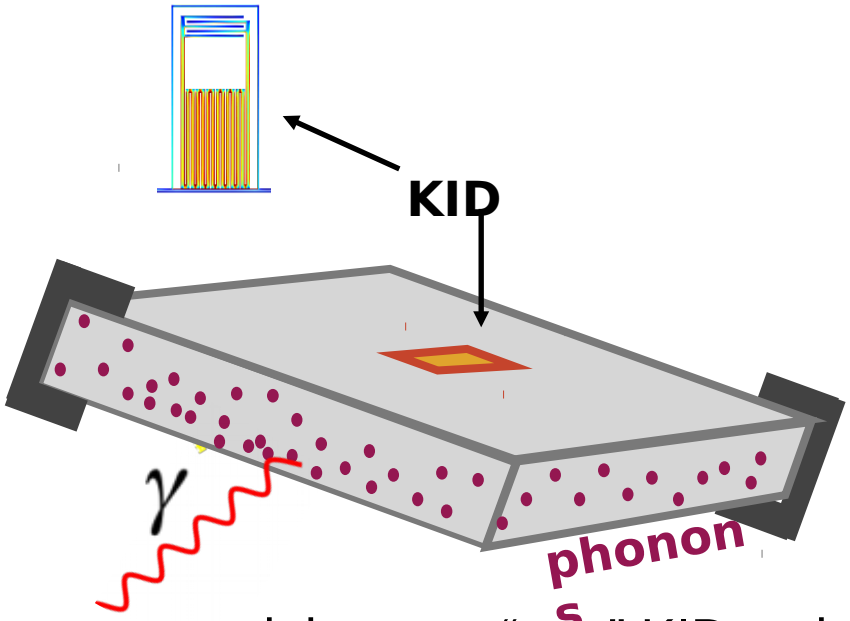
Demonstrate background suppression with real detectors

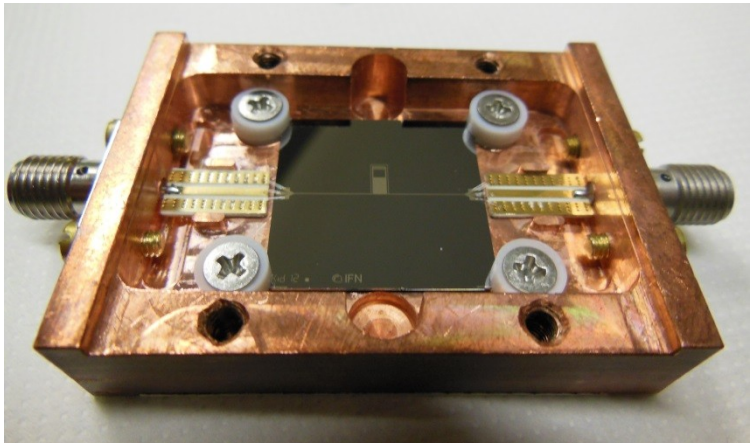
Run a small TeO_2 bolometer array at LNGS

2017-2018

CALDER is funded by an ERC Starting Grant

Phonon-mediated approach

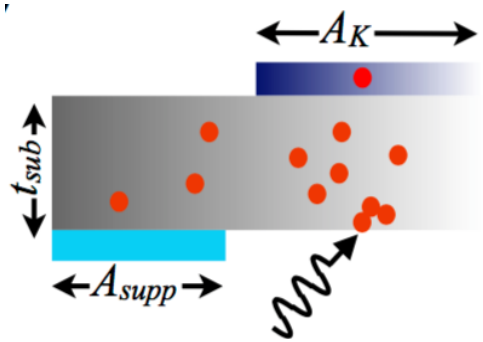




- To get around the poor “one” KID active surface an indirect detection of the photon interactions was proposed

- KIDs are evaporated on a large (cm^2) insulating substrate (Si or Ge) that mediates the photon interactions converting them into phonons

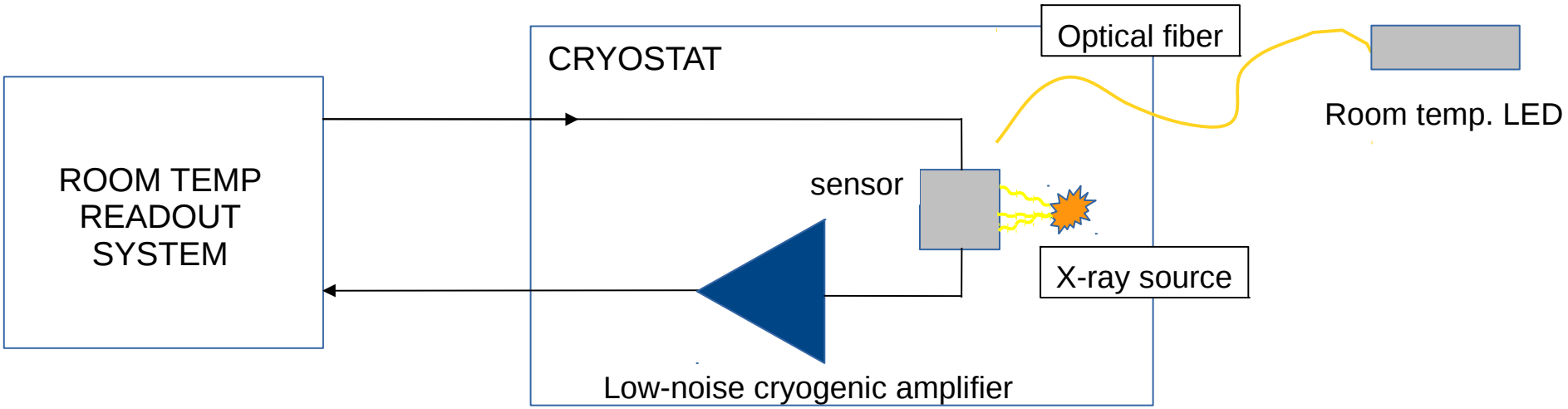
- ….. with a drawback: **phonons collection efficiency**



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

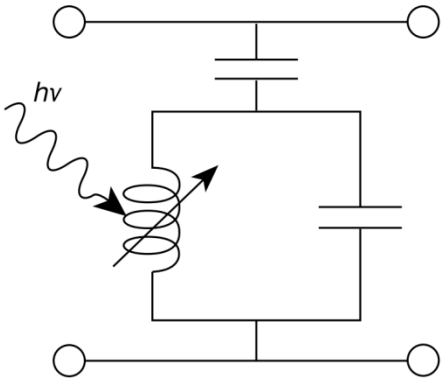
Experimental setup

- 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 (T_n=2 K)
- Calibration: sensor illuminated with a pulsed 400nm LED and with ^{55}Fe or ^{57}Co X-ray source

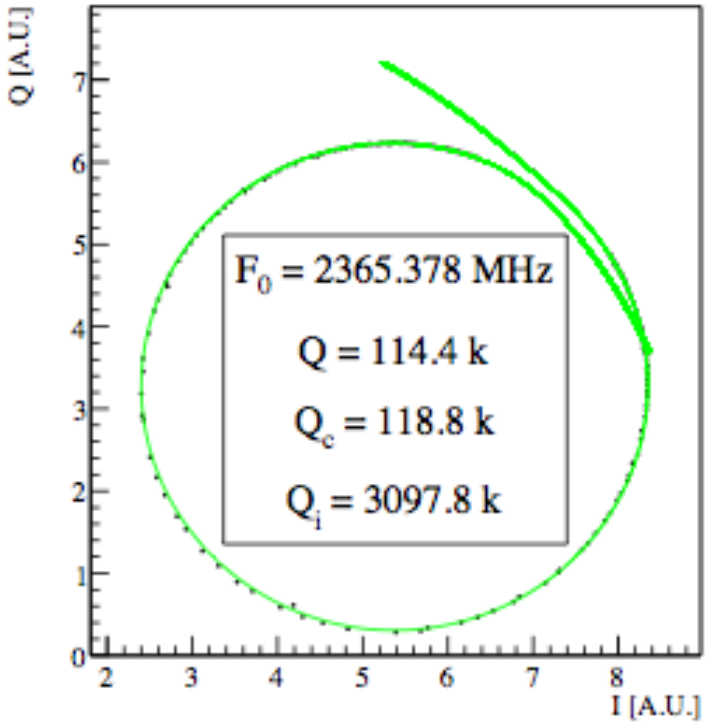


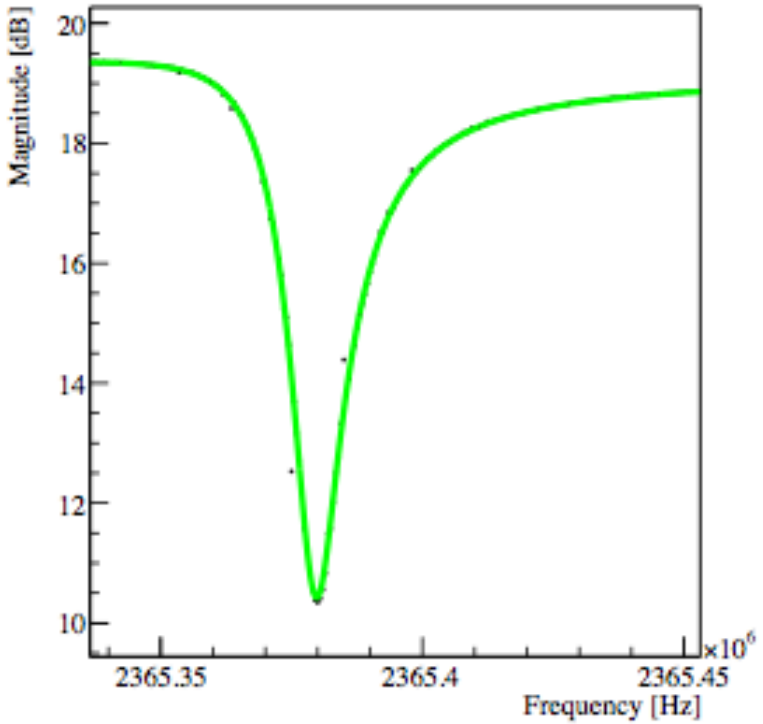
Sensor operation

Perform a frequency scan to determine the most sensitive operating frequency



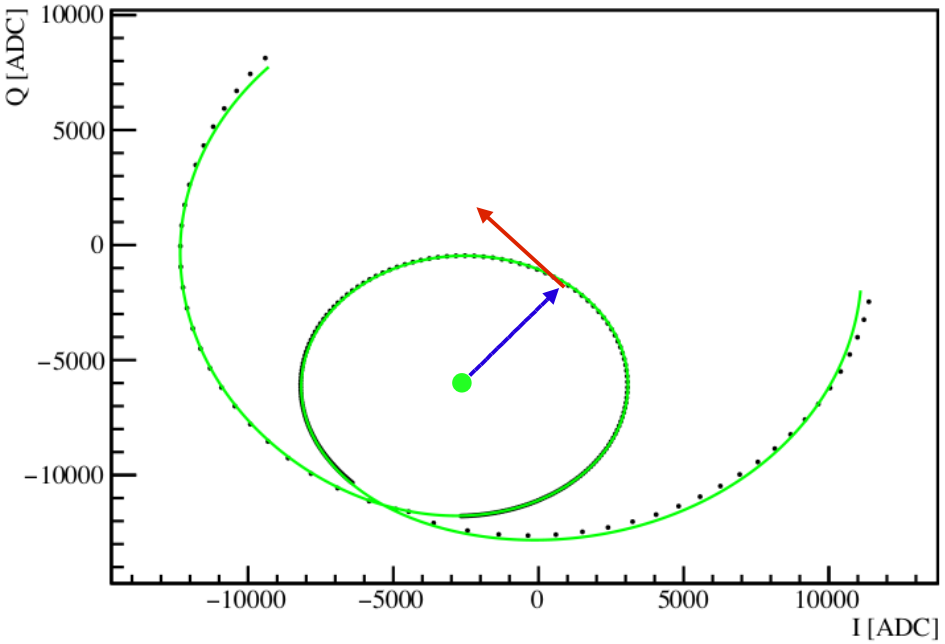
$$S_{21} = 1 - \frac{Q/Q_c}{1 + 2j\frac{f - f_0}{f_0}}$$

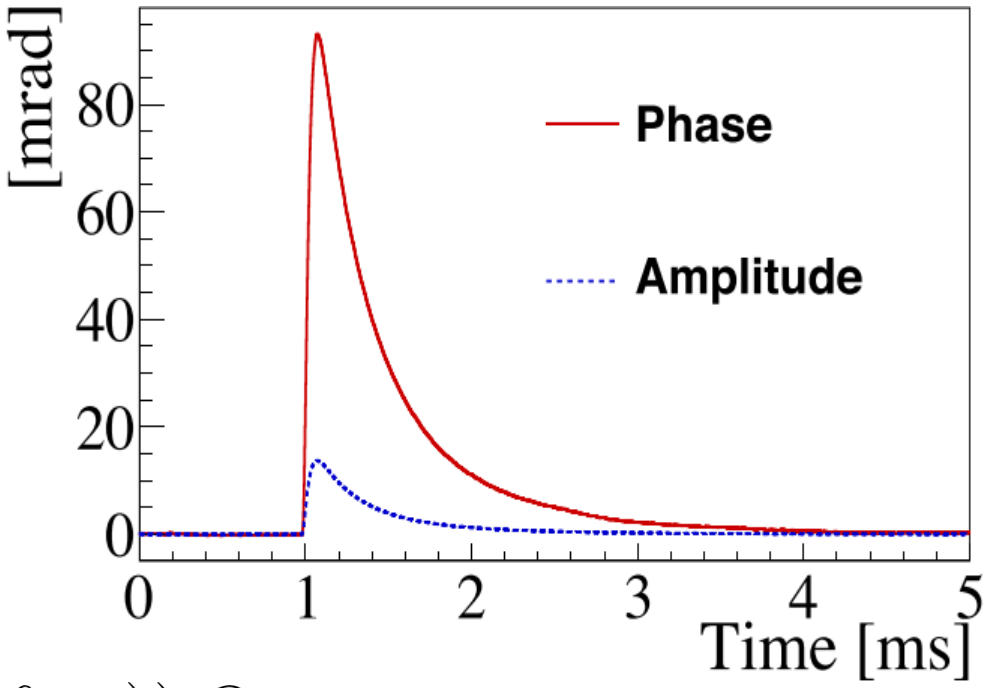




Amplitude and phase signal

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





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

1st phase: results

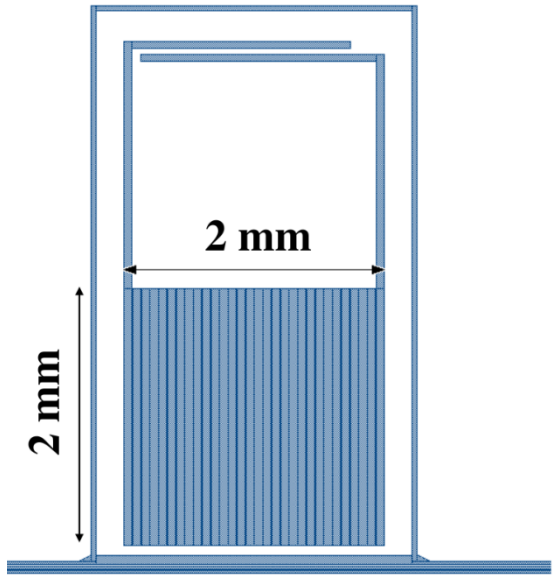
Q-value: **150k**

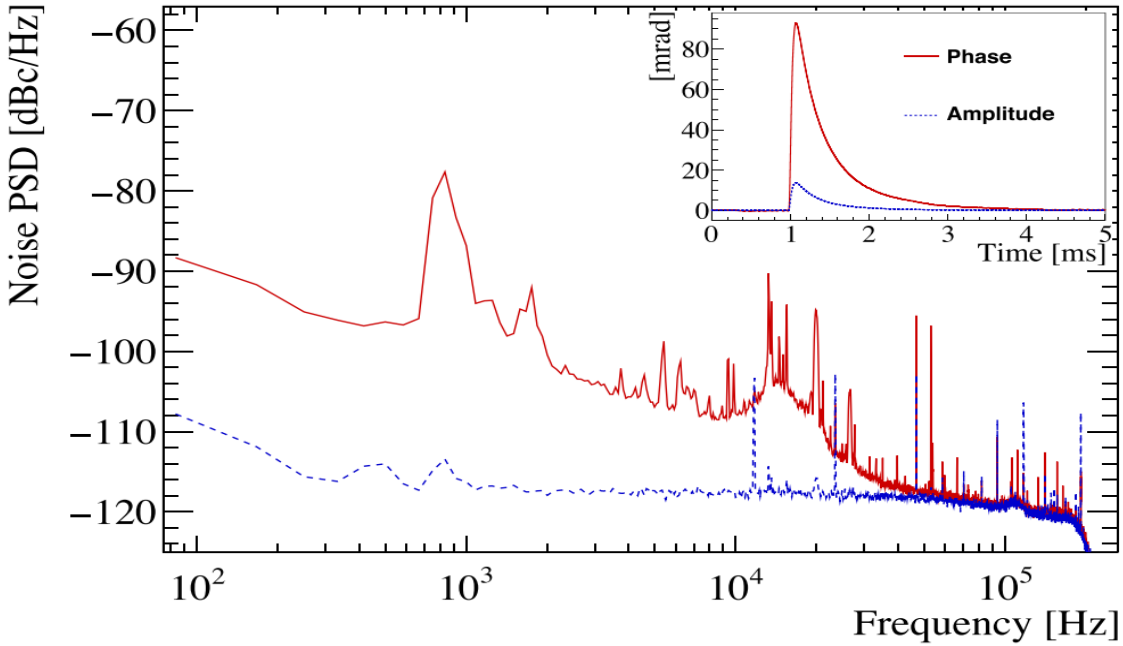
High low-f phase noise

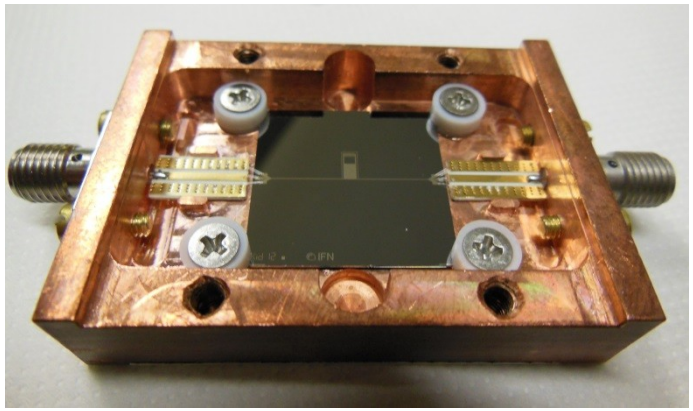
Combined amplitude and phase readout

Single-KID energy collection efficiency: **9.4%**

Baseline energy resolution: **82 eV RMS**







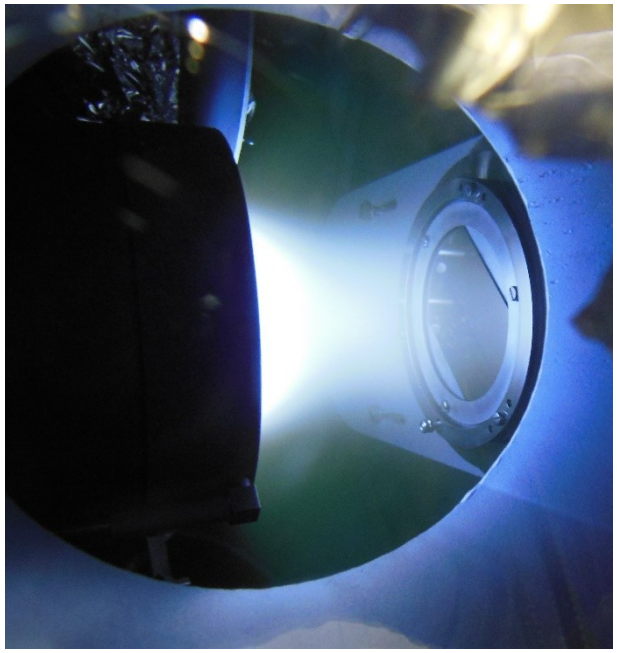
Appl. Phys. Lett. 110 (2017), 033504

2nd phase: in progress

Testing more sensitive superconductors

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

	Al	AlTiAl	Ti+TiN
TC [K]	1.2	0.6 – 0.9	0.5 – 0.8
L [pH/square]	0.5	1	6



First tests on TiAl and AlTiAl in collaboration with **Institut Neel Grenoble** (J. Goupy, M. Calvo and A. Monfardini) and **CSNSM-IN2P3 Paris** (H. Le Sueur)

Encouraging results: **30 eV RMS** reached (paper in preparation)

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 AlTiAl!

Thank you for your attention