CALDER

Superconducting light detectors for neutrino and dark matter searches

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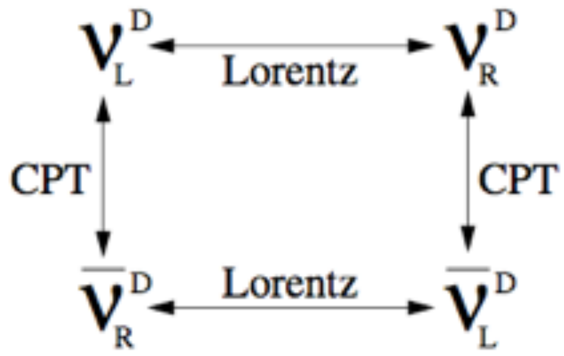
INFN Roma

Giornate di studio sul piano triennale, Trento, 8/11/2014.

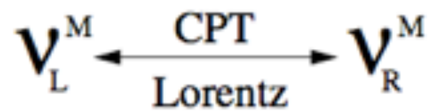
Majorana neutrinos

Is the total lepton number a conserved quantity?

If so, we could have that neutrinos are equal to anti-neutrinos: $\nu = \bar{\nu}$.



Dirac



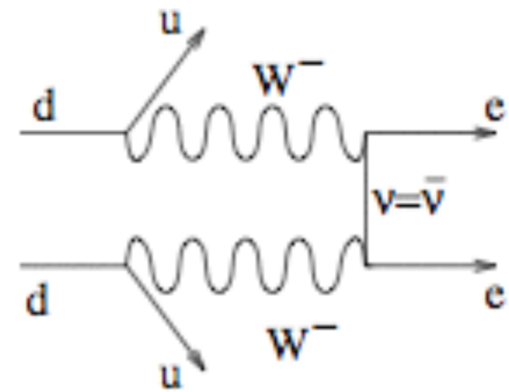
Majorana

It is still not clear today whether neutrinos are
Dirac or Majorana particles

The only way we know to answer this question is to observe a rare nuclear process, the neutrinoless double beta decay ($0\nu\beta\beta$)

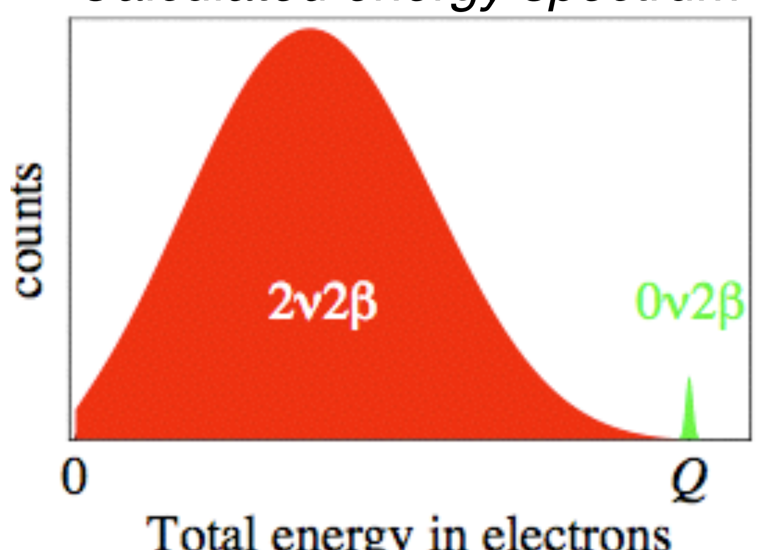
Neutrinoless double beta decay

Nuclear process: (A,Z) → (A,Z+2) + 2 e$^-$



- It happens only if $\nu = \bar{\nu}$ and in few natural isotopes: ^{130}Te, ^{76}Ge, ^{136}Xe, ^{100}Mo, ^{82}Se (and not many others).
- We measure the decay half-life: $\tau^{0\nu}_{1/2} \propto 1/m^2_\nu$
  Current limits are of the order of 10^{24} - 10^{25} years.
- Signature: peak at the sum-energy (*Q*) of the two electrons (2-3 MeV).

Calculated energy spectrum

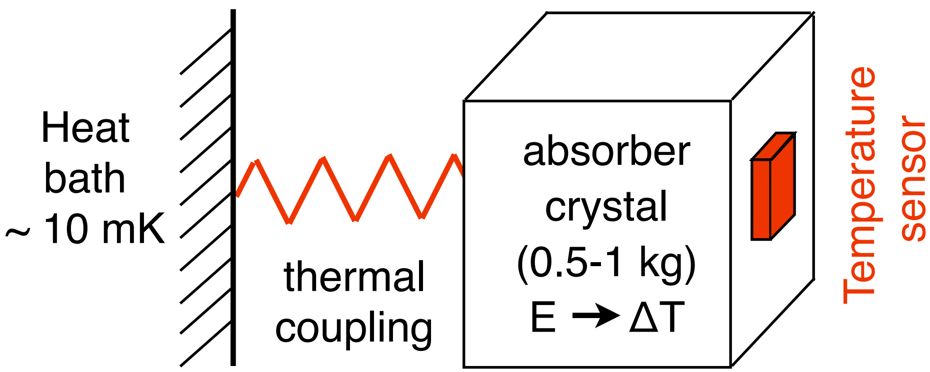


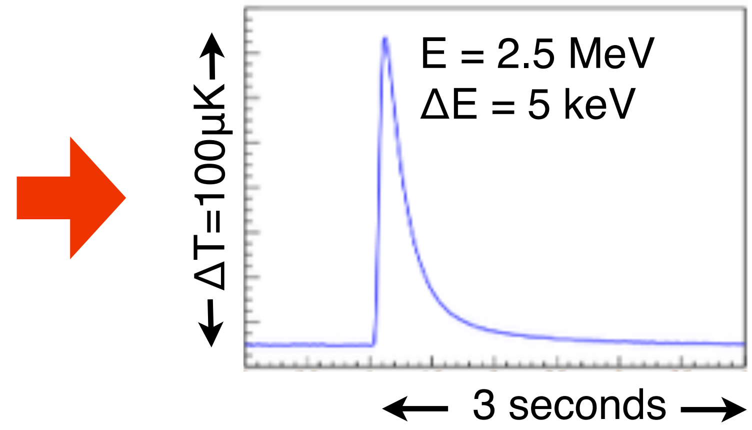
Ideal features of an experiment

Isotope Mass	> 100 kg
Background	close to zero counts/year
ΔE	O(keV)

Bolometers

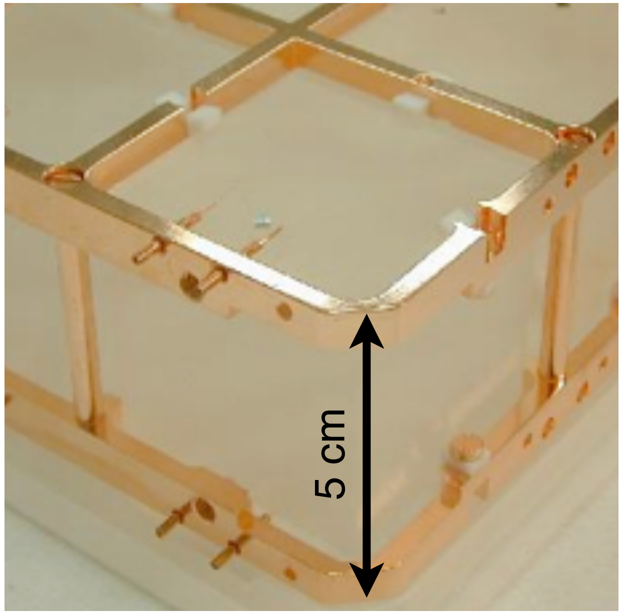
- Particle energy converted to temperature variation.
  - Cryogenic temperatures (< 20 mK).





- TeO_2 , ZnSe, $ZnMoO_4$ and other crystals: small heat capacitance.
- Source embedded in the detector,
  $0\nu\beta\beta$ emitters: **^{130}Te, ^{82}Se, ^{100}Mo, respectively.**
- Sensitive thermometers, NTD thermistors:

$$R(T) \simeq 1\,\Omega \cdot \exp\left(\frac{3\,\mathrm{K}}{T}\right)^{\frac{1}{2}}$$



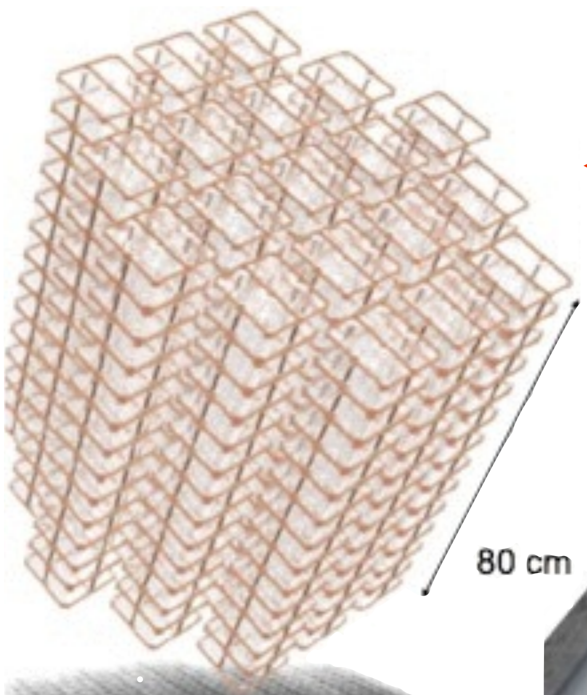
CUORE at Gran Sasso lab

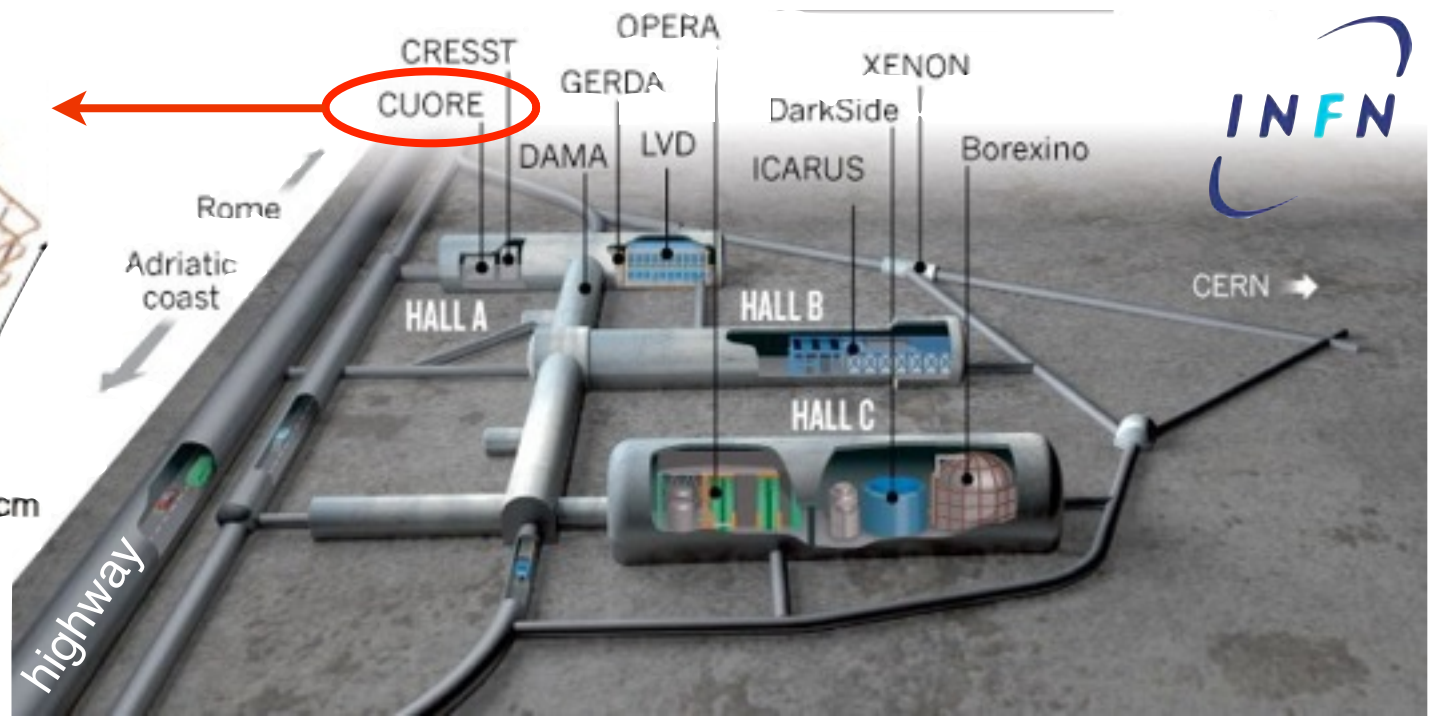
CUORE

988 $^{nat}TeO_2$ bolometers

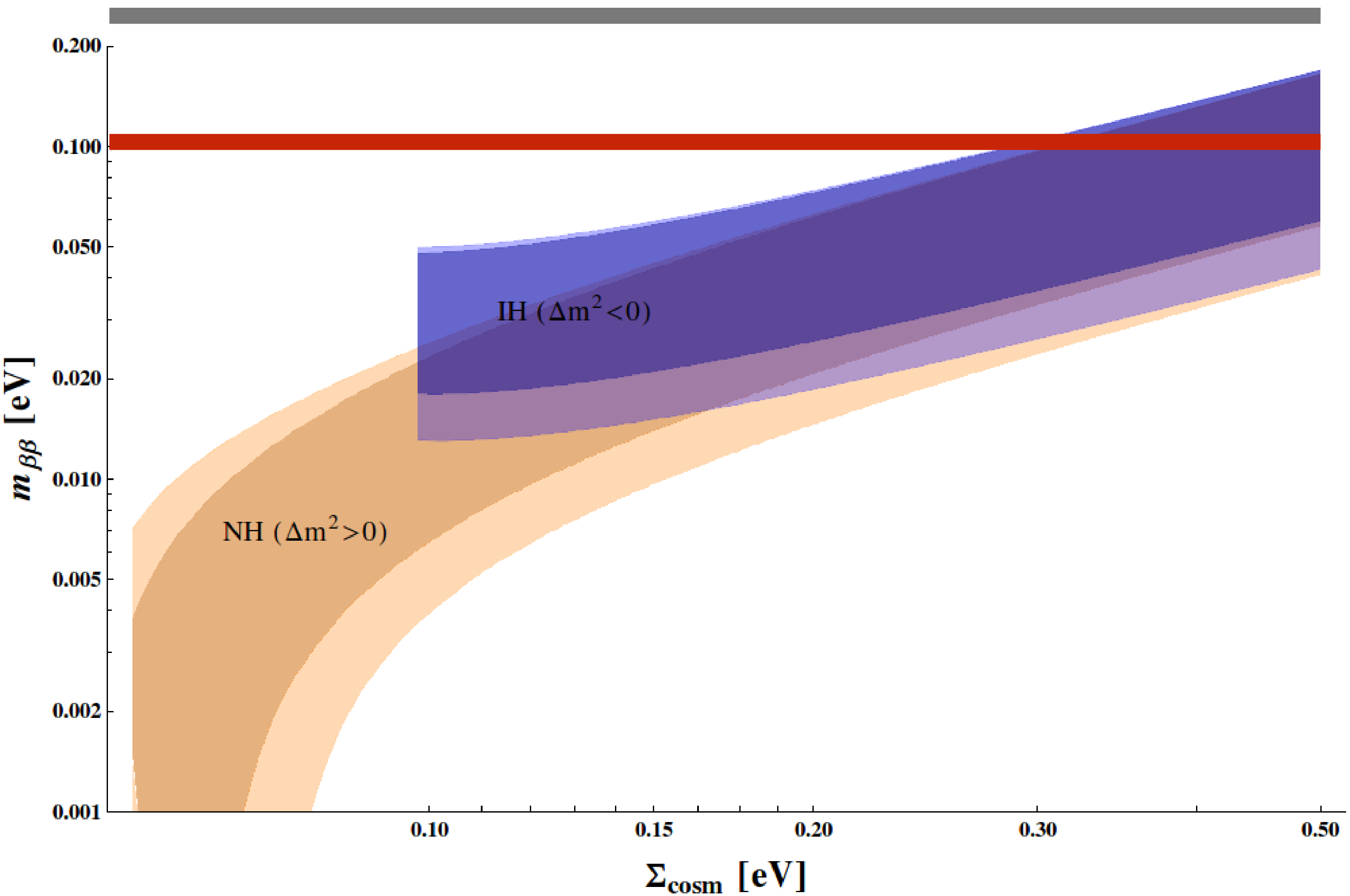
206 kg ^{130}Te
(34% abundance in Te)

Start data taking
at the end of 2015





Sensitivity to neutrino mass

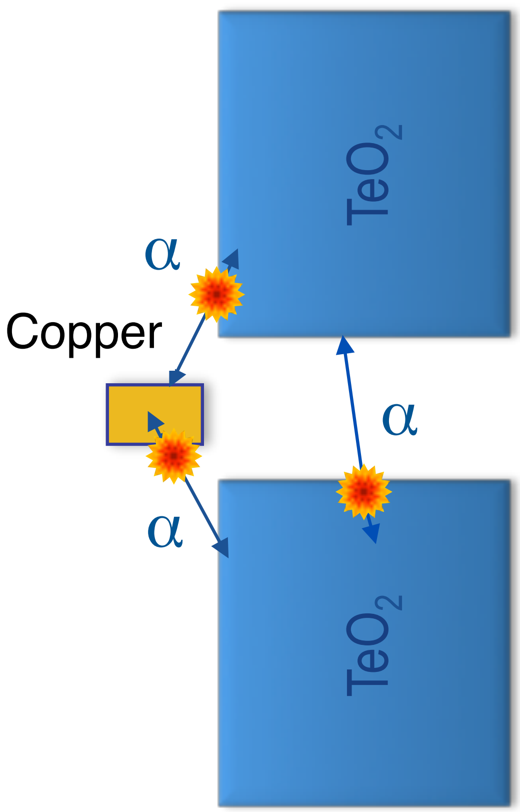


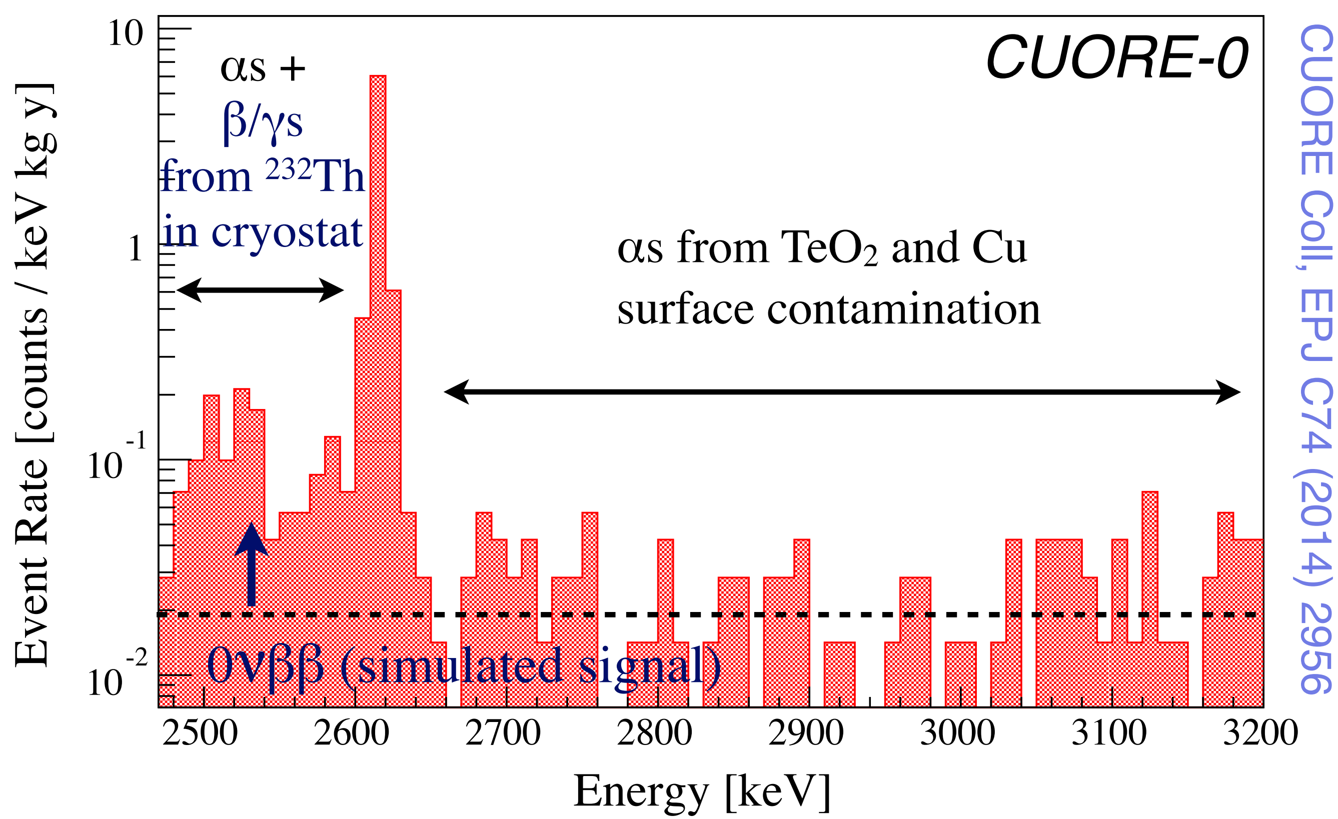
Current bound ($^{76}Ge+^{136}Xe$)

2015-2020: CUORE(^{130}Te)

Main challenge: α background

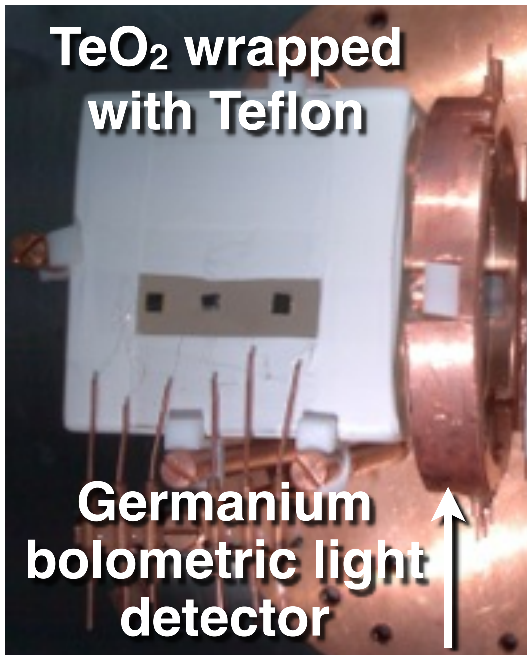
CUORE-0, the test of a single CUORE tower,
showed that most of the background in CUORE will be dominated by degraded α particles from natural radioactivity.

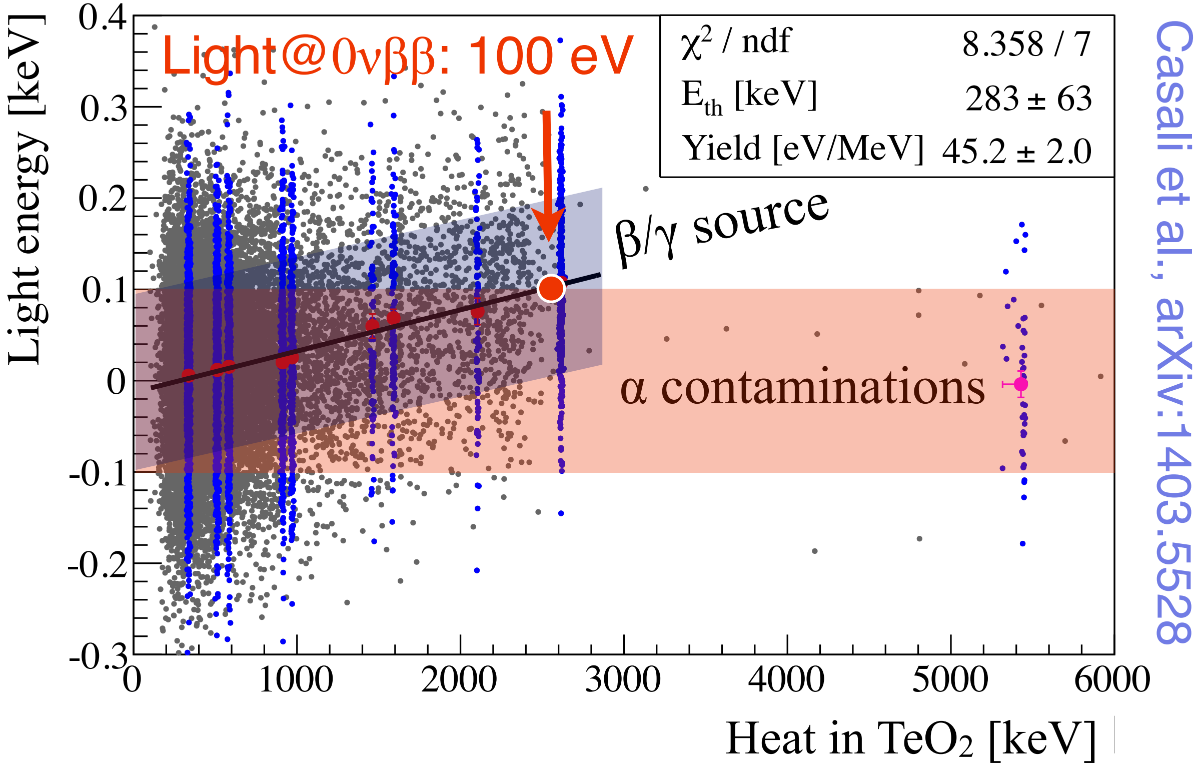




α removal in TeO_2: Cherenkov

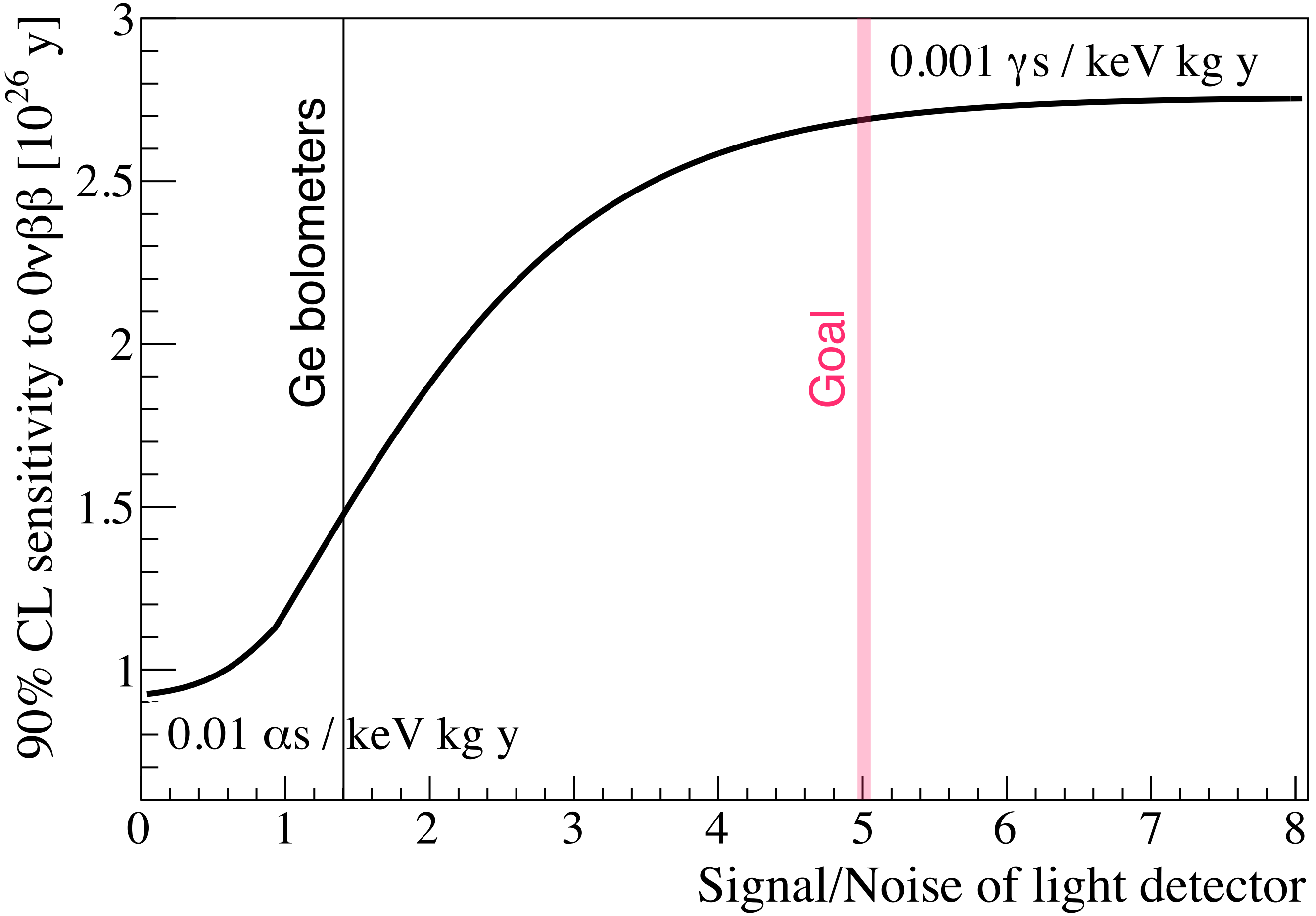
Rejection technique: detect the Čerenkov light emitted by βs (signal) and not by αs [T. Tabarelli de Fatis, EPJ C65 (2010) 359].





Noise of present light detectors is too high (70-100 eV RMS) compared to the signal (100 eV) ⟶ **need new light detectors.**

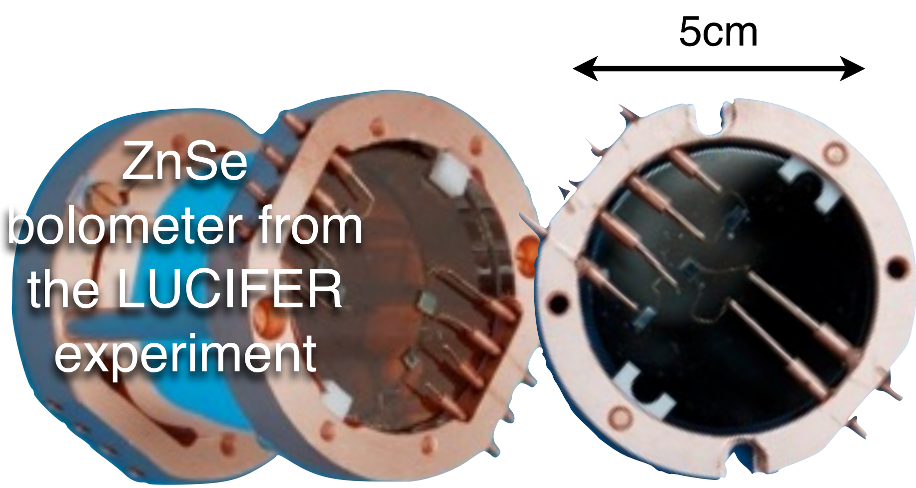
Sensitivity of the light detector



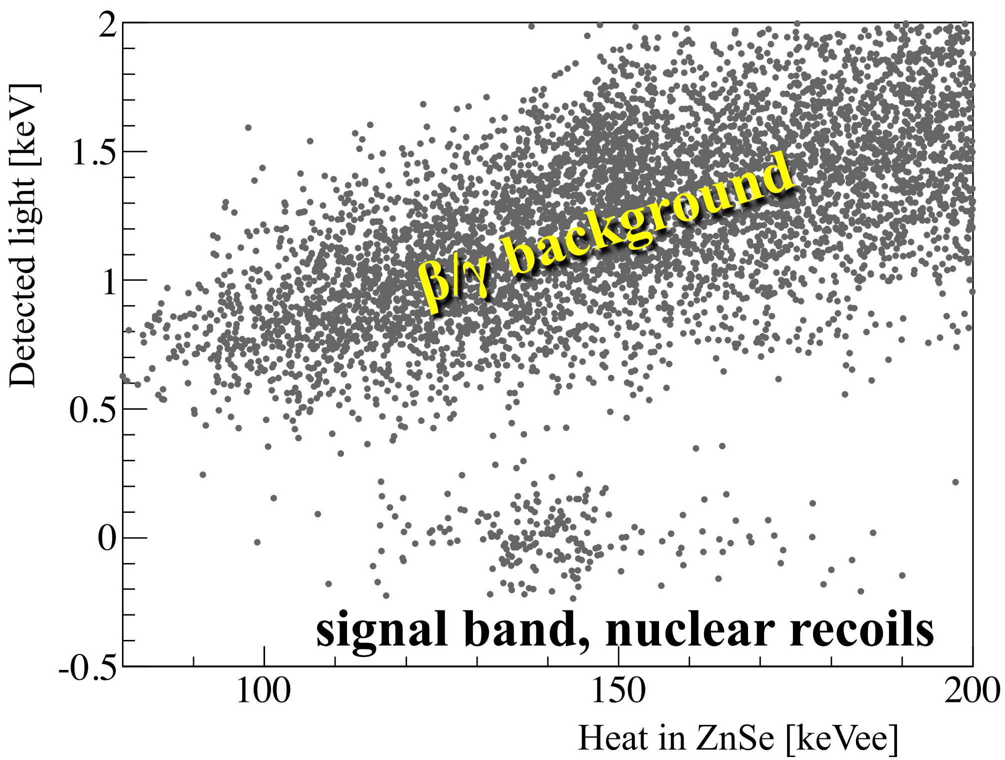
With a 100 eV signal, to obtain S/N > 5 we need a **noise < 20 eV RMS.**

Dark Matter with ZnSe

Identification of nuclear recoils in ZnSe scintillating bolometers:
nuclear recoils (signal) do not emit light , β/γs (background) emit a few light.
The discrimination is in principle possible at 10 keV (the DM search region).



J. W. Beeman et al., JINST 8 (2013) P05021



By using light detectors with noise below 20 eV RMS, **LUCIFER, a 0νββ experiment, could be extended to search also for Dark Matter**.

Which light detector technology?

? **Neutron Transmutation Doped** (**NTD**) **thermistors**, currently used in LUCIFER:

- Average ΔE ~ 100 eV**,** too large. Not reproducible.
- Could be improved using the Neganov-Luke effect.

? **Transition Edge Sensors (TES)**, à la CRESST Dark Matter experiment:

- ΔE < 20-30 eV, good!

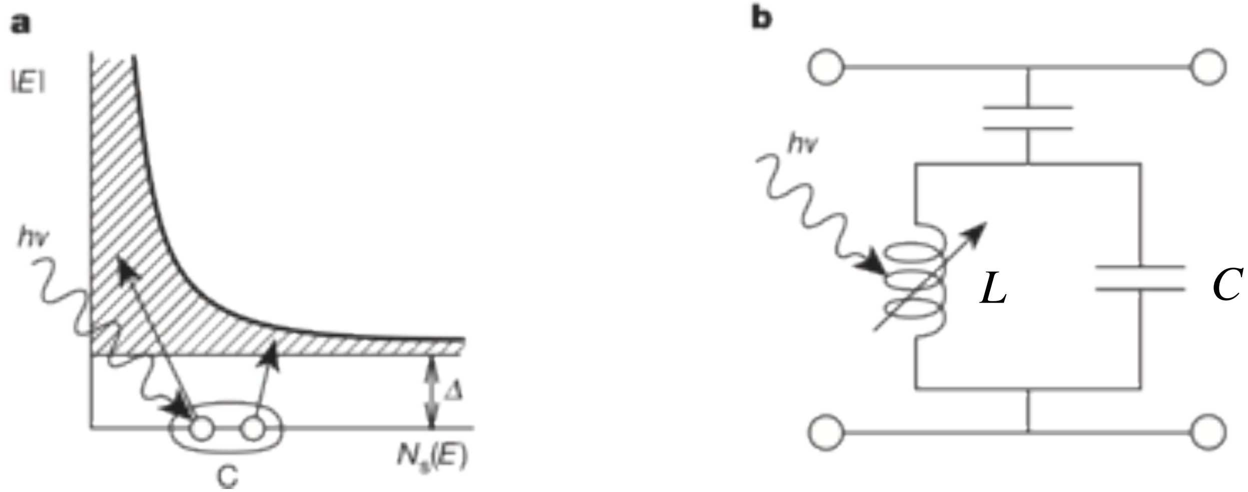
R&D needed in view of the scale up to 1000 detectors:

- Complicated readout: SQUID amplifiers, small multiplexing.

? **Kinetic Inductance Detectors (KID)**: new technology invented at Caltech and JPL, first paper: P. Day et al., Nature, 425 (2003) 817:

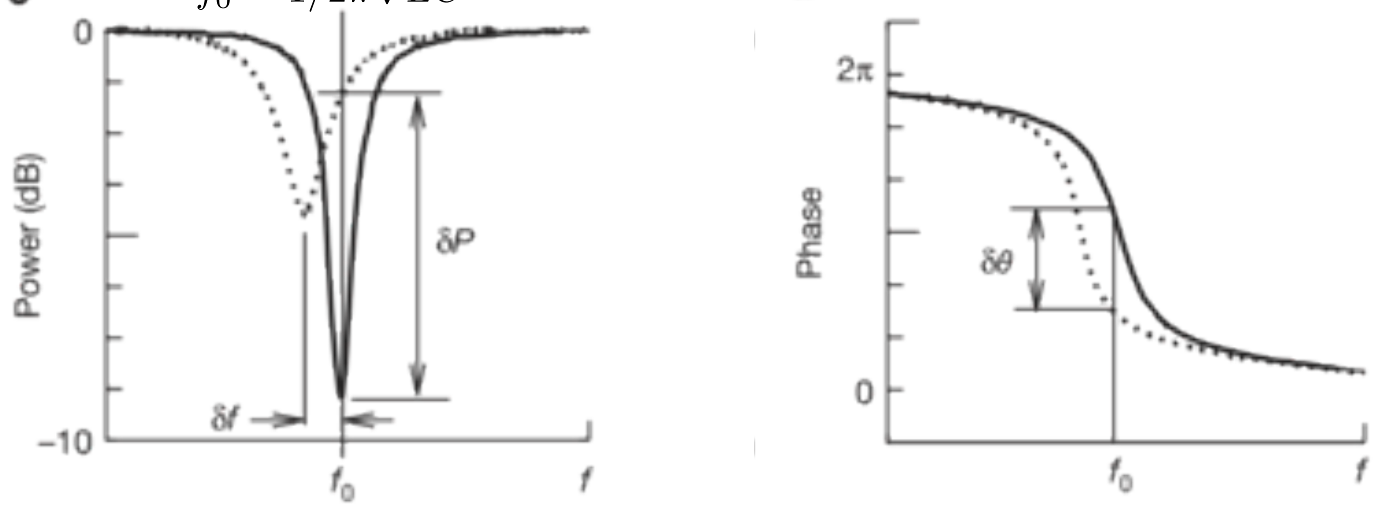
- Excellent reliability.
- Easy readout: FPGAs and 1 cold amplifier, high multiplexing.
- But, need to develop a large area light detector to monitor bolometers.

KID: Working principle



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

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

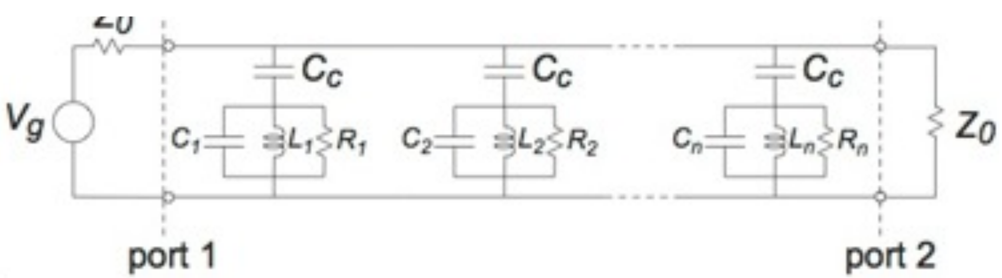


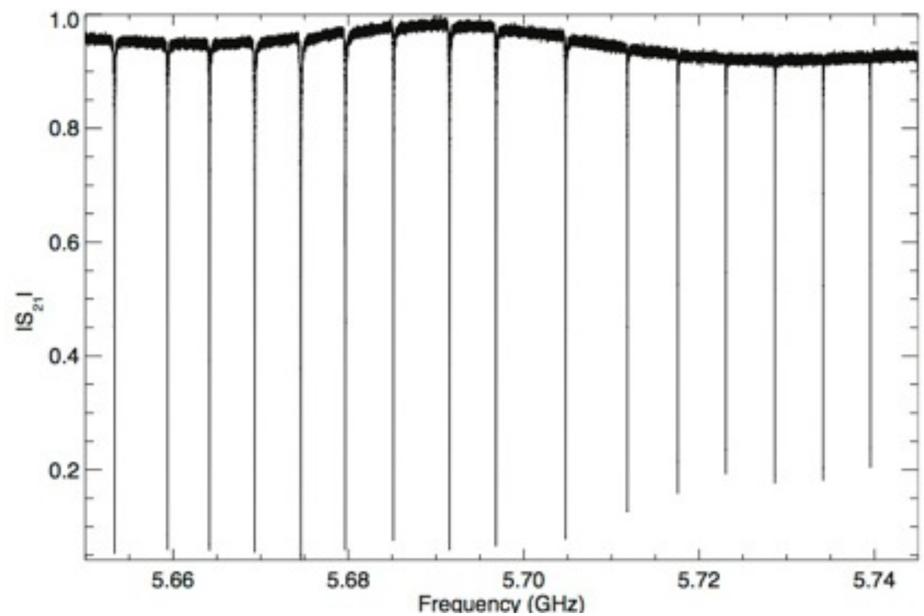
High quality factor (*Q*) resonating circuit biased with a microwave (GHz):
signal from amplitude and phase shift.

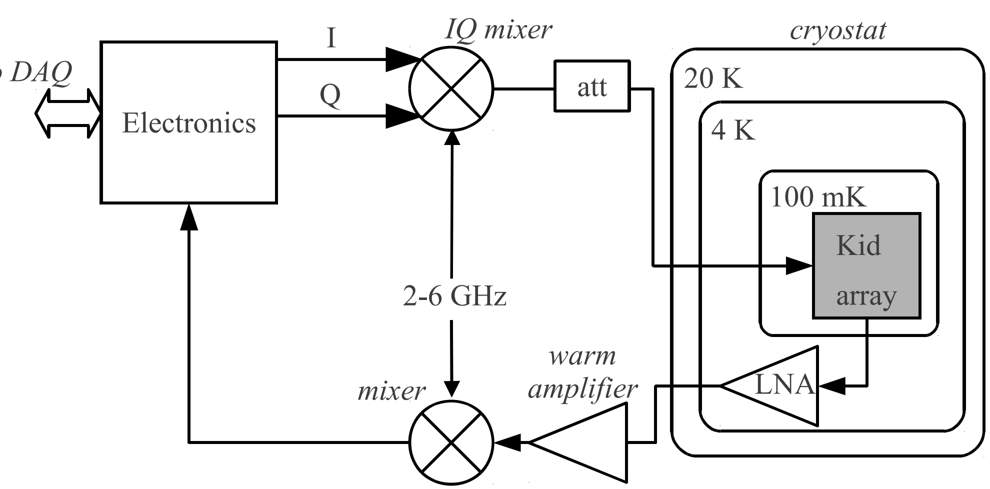
Day et al., Nature 425 (2003) 817

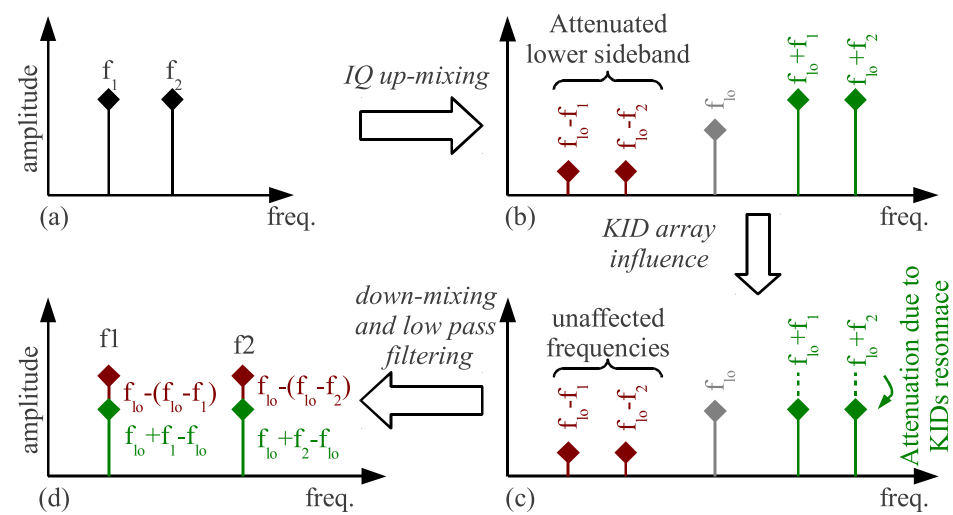
Multiplexed readout of a KID array

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





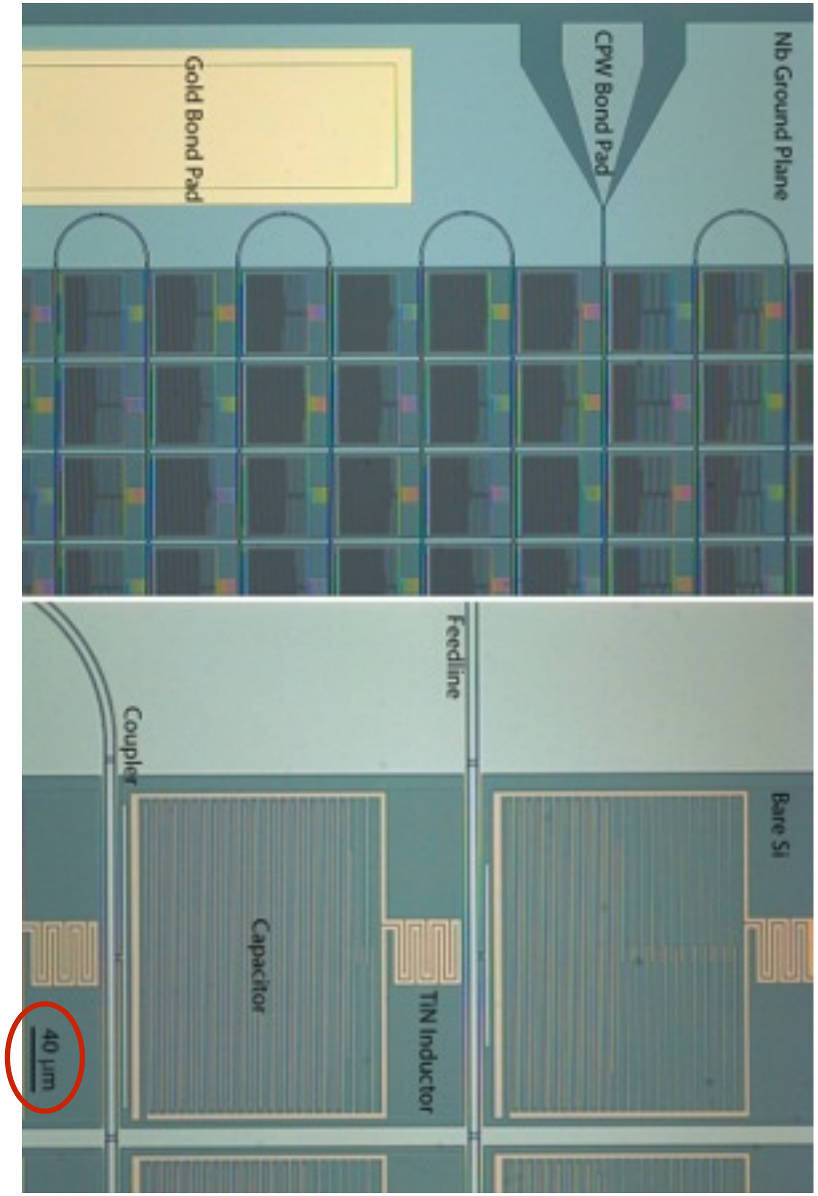


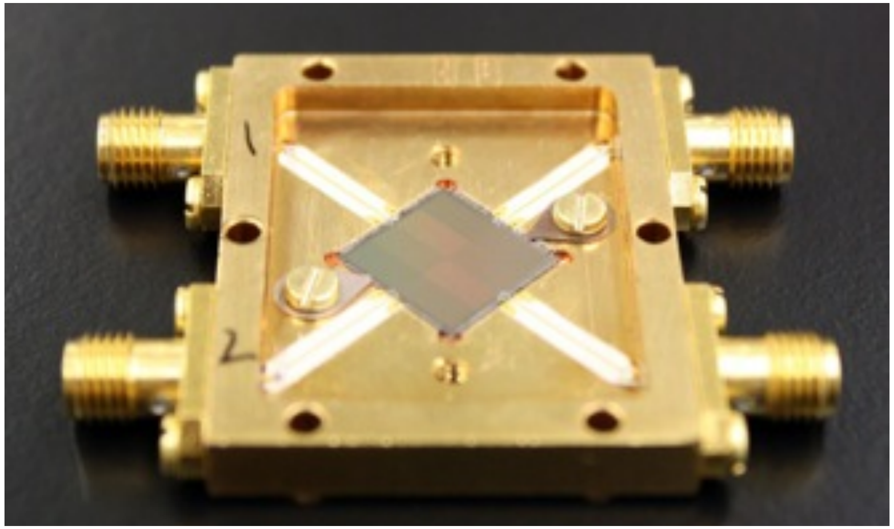


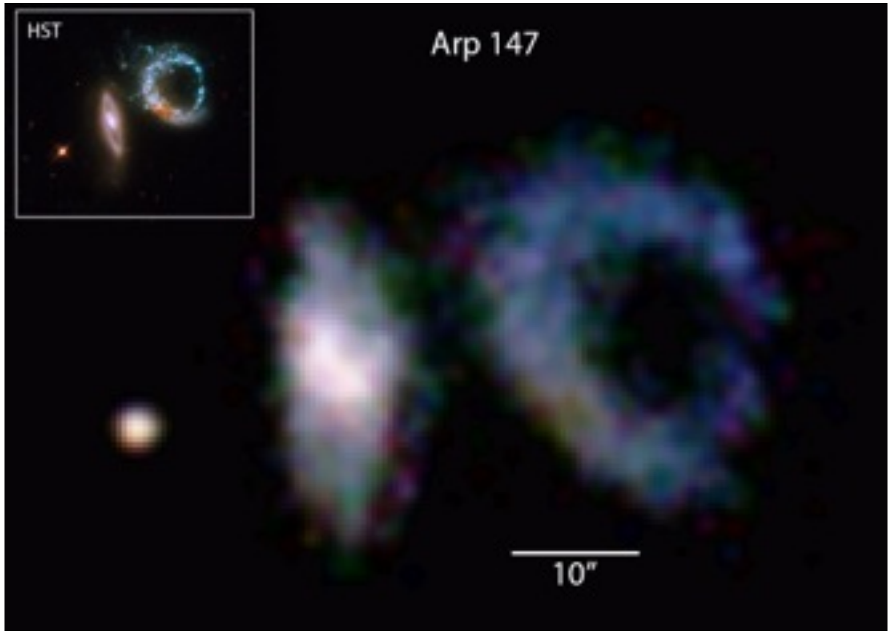
A successful implementation

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

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



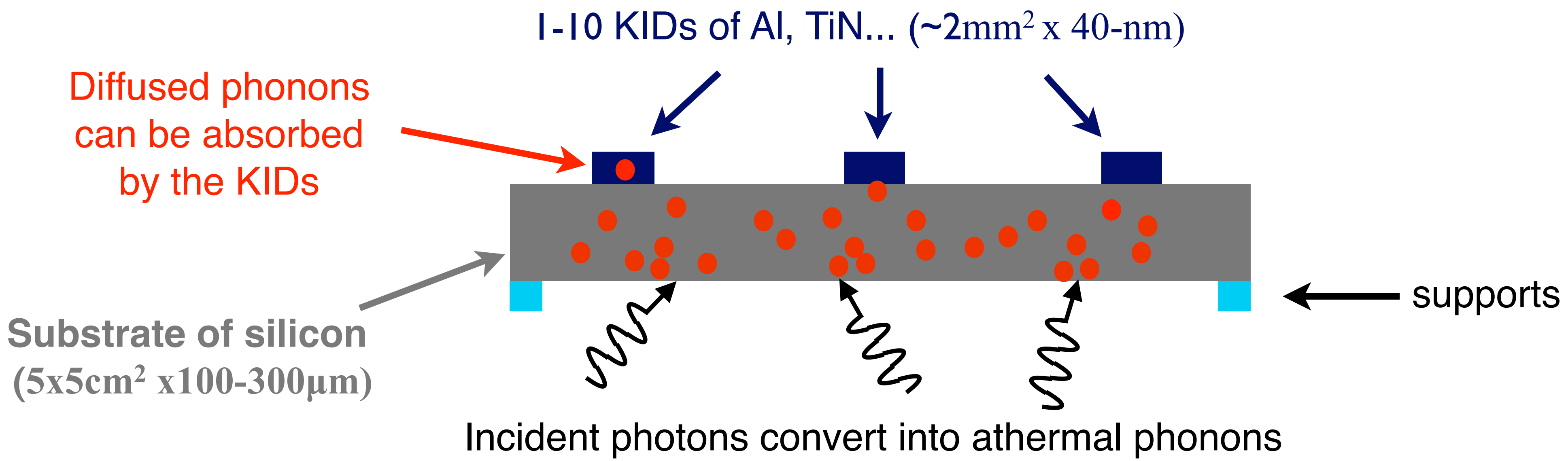




CALDER's implementation

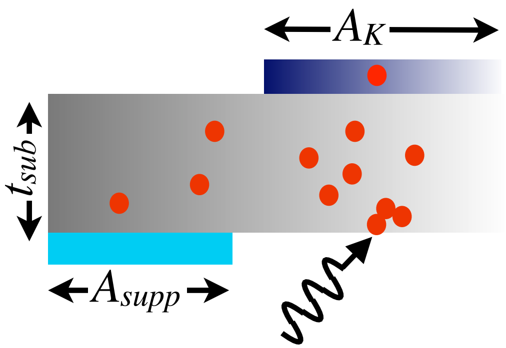
	State of the art	Goal	
Area	few mm	5x5 cm	difficult
ΔE [eV RMS]	< 1	< 20	achievable
T	80	10	pro

The maximum sensible area is fixed to few mm² (wavelength limited).
Proposed solution: indirect detection mediated by phonons



Scientific challenge: sensitivity

Problem: loss of phonon collection efficiency (ε) through the supports and via thermalization.



KID R&D: ε loss compensated by KID sensitivity:

$$\Delta E \propto \frac{1}{\epsilon} \cdot T_c \sqrt{\frac{N_K A_K}{Q\, L}}$$

1) Maximize film quality factor: $Q > 10^5$.

2) High inductivity (L) and low T_c superconductors

	Al	TiN (non stoich.)	Ti+TiN (stoich.)	Hf
T	1.2	0.9	>0.4	0.12
L [pH/square]	0.05	3	30	*3*

The CALDER research team

Istituto Nazionale di Fisica Nucleare:

C. Bucci, C. Tomei and M. Vignati.

Sapienza University of Rome:

E. Battistelli, F. Bellini, L. Cardani, C. Cosmelli, A. Cruciani, P. de Bernardis, S. Masi.

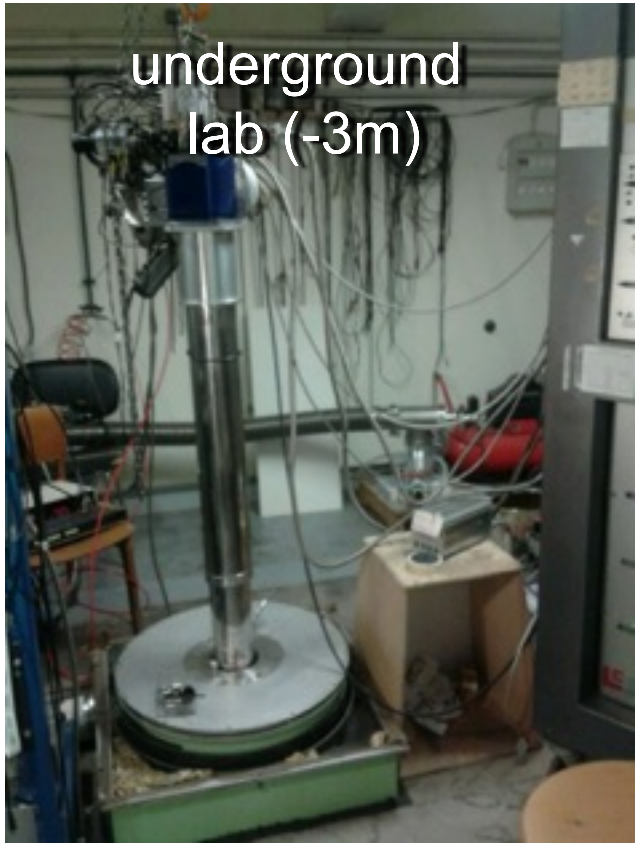
Consiglio Nazionale delle Ricerche:
Detector fabrication.

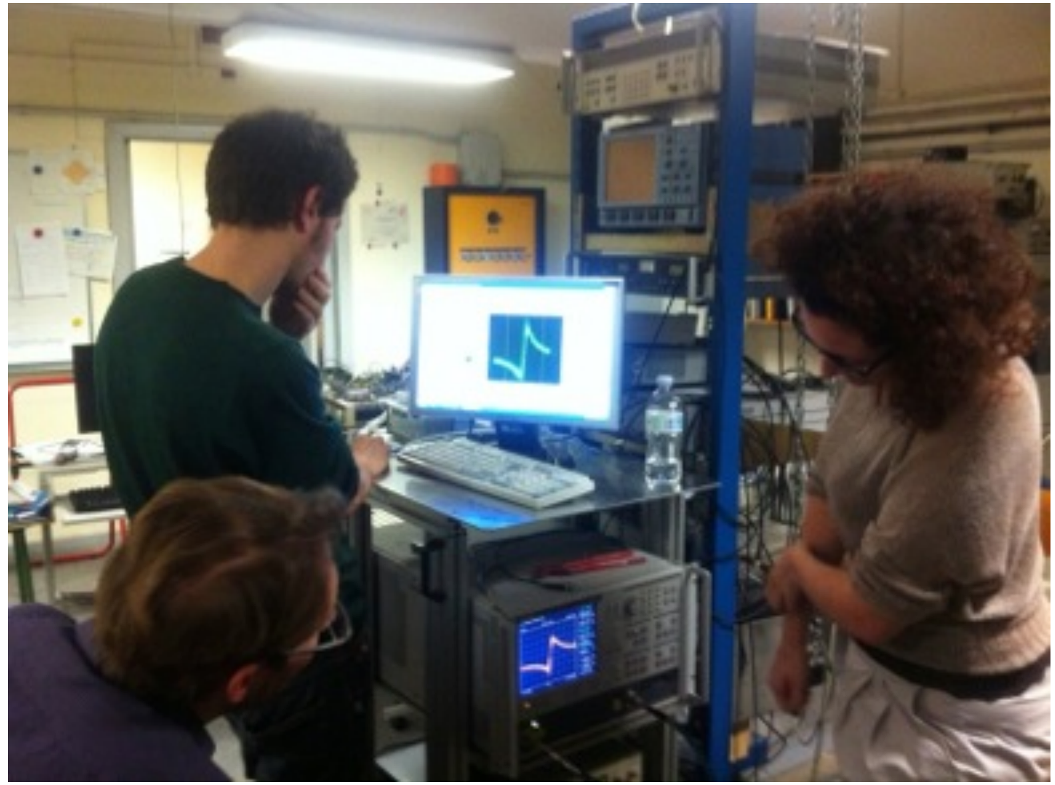
I. Colantoni and M.G. Castellano.

Università degli studi di Genova:
Electronics and DAQ.

S. Di Domizio.

Rome Lab



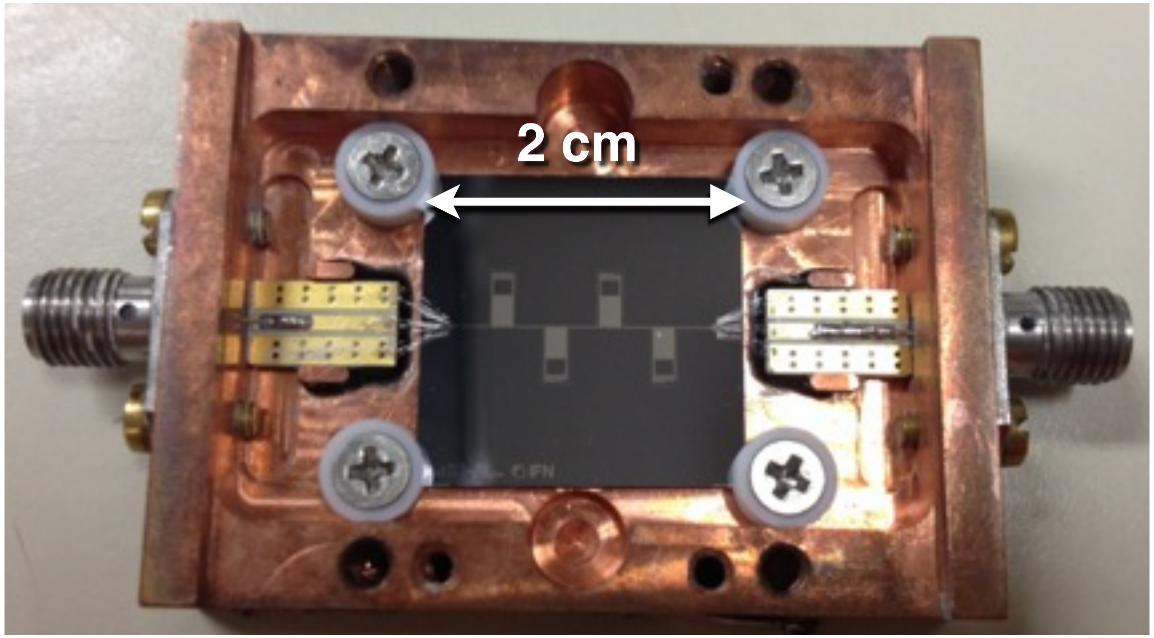


single
cryogenic
amplifier

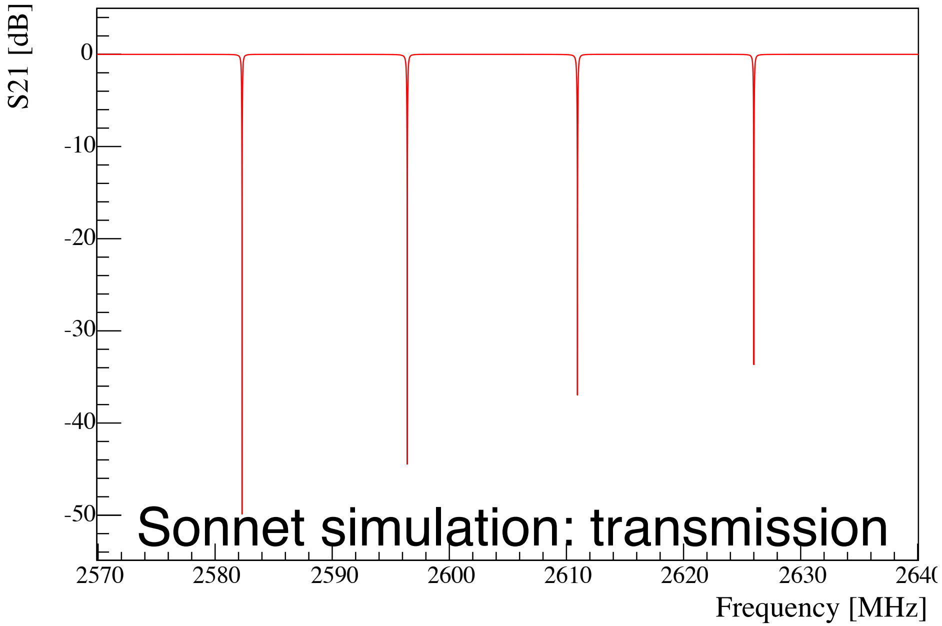
Nixa: electronics board developed at LPSC (Grenoble)

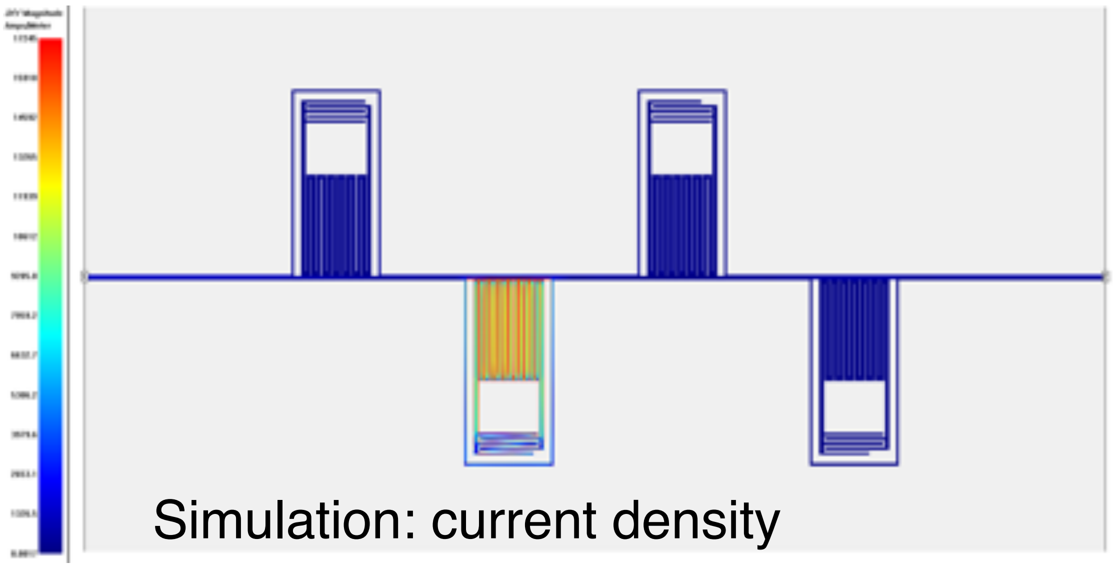
O. Bourrion et al., JINST 8 C12006 (2013)

2nd Prototype

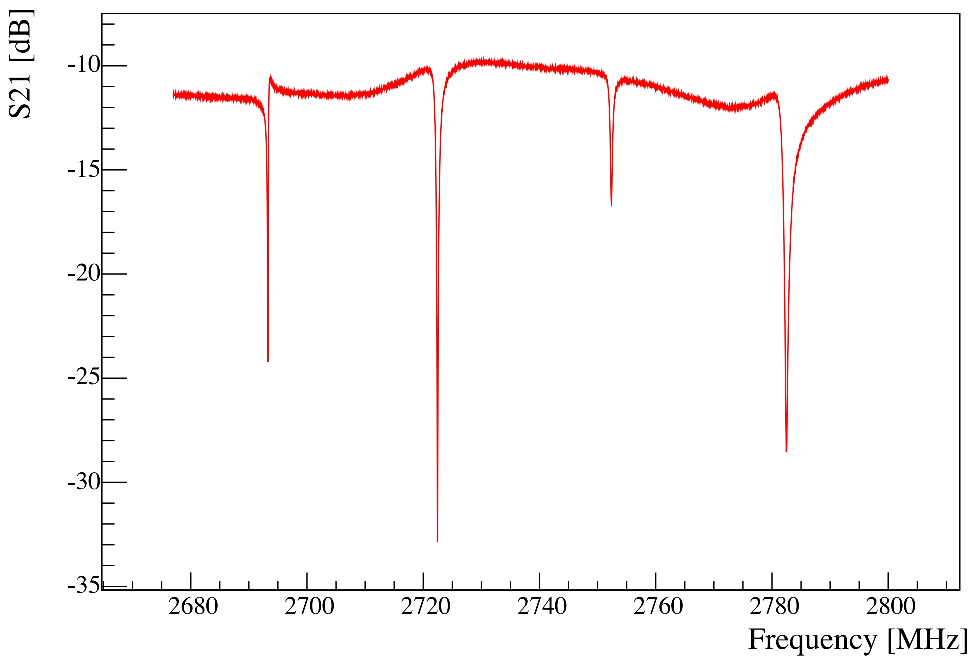


- Single pixel area: 2.4 mm².
- 4 pixels coupled to the same feed line.
- Frequency: 2.6 GHz (spacing 15 MHz).
- 40 nm Aluminum lithography on Silicon substrate

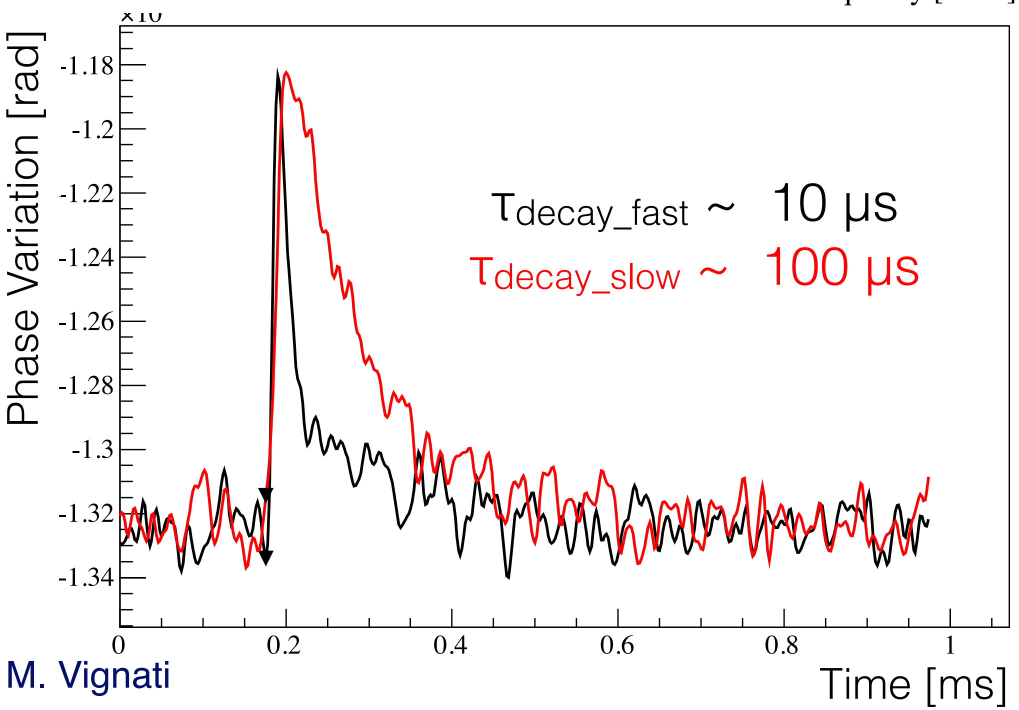




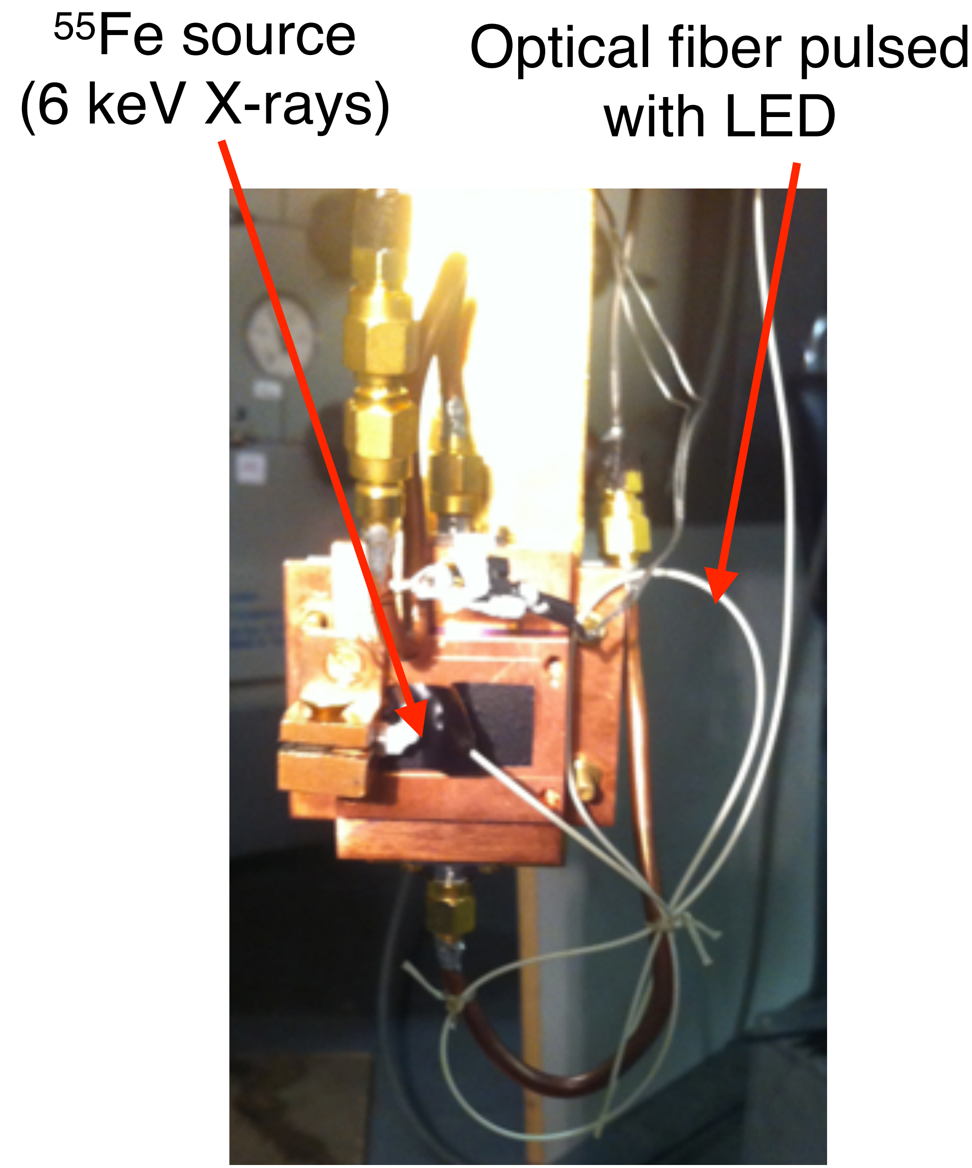
Data



S21 [dB]
-10
-15
-20
-25
-30
-35
2680
2700
2720
2740
2760
2780
2800
Frequency [MHz]



Phase Variation [rad]
-1.18
-1.2
-1.22
-1.24
-1.26
-1.28
-1.3
-1.32
-1.34
τdecay_fast ~ 10 μs
τdecay_slow ~ 100 μs
0
0.2
0.4
0.6
0.8
1
Time [ms]



55Fe source (6 keV X-rays)
Optical fiber pulsed with LED

Status and program

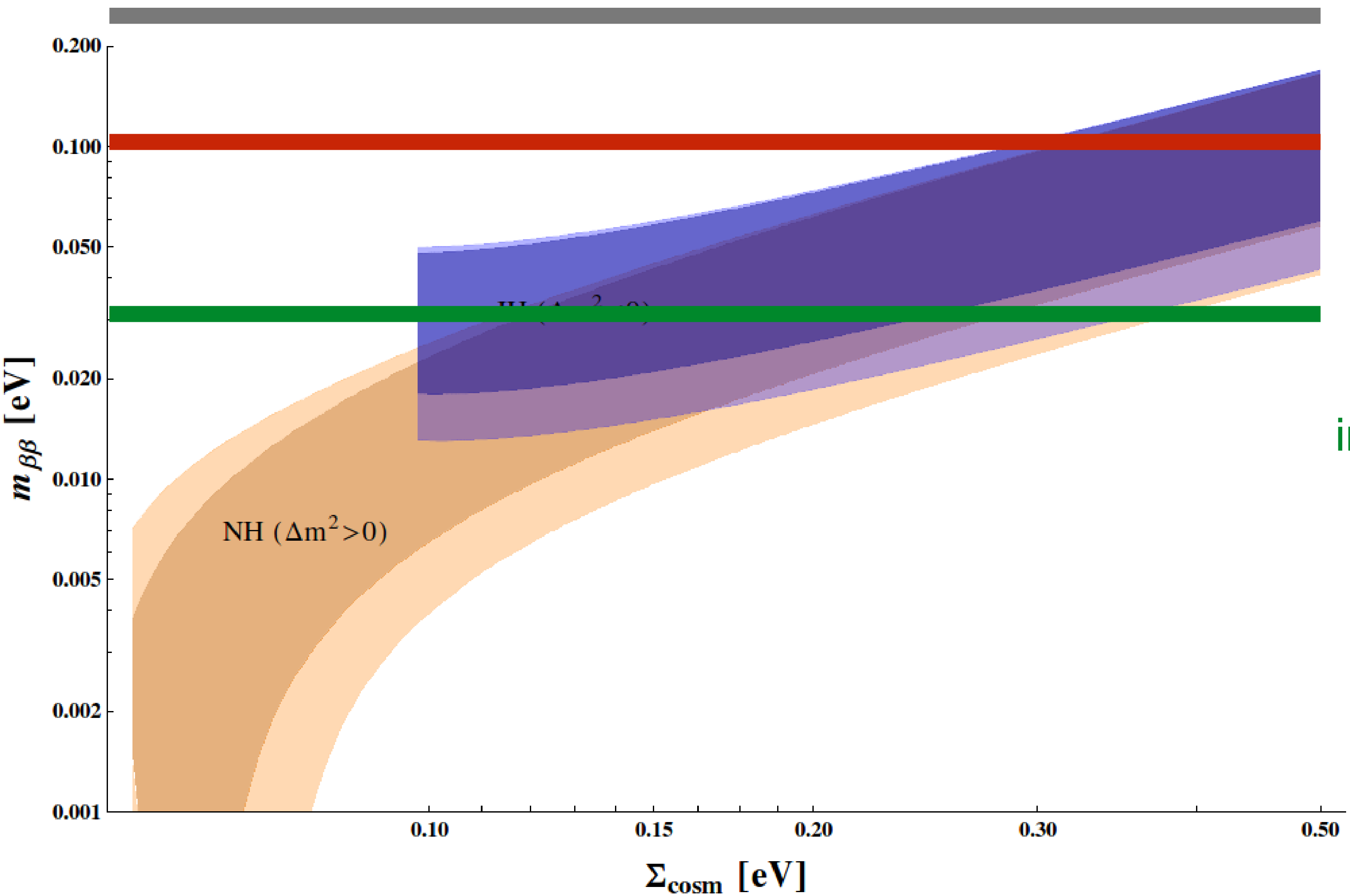
2013-2014 Cryostat setup (reached 10-15 mK), readout (12 pixels in parallel up to now), data analysis, and first prototypes (9 and 4 pixels) with low Q.

2014-2015 Finalize production and test of Aluminum sensors at high Q, reach 50-100 eV baseline noise.

2015-2016 Develop and test TiN - Ti/TiN sensors reach the goal of 20 eV RMS resolution.

2016-2017 Integration with the CUORE/LUCIFER setup at LNGS. Build a demonstrator with an array of TeO bolometers monitored by the new light detectors.

Sensitivity to neutrino mass



Current bound (^{76}Ge+^{136}Xe)

2015-2020: CUORE(^{130}Te)

2020-: CUORE enriched in ^{130}Te + CALDER?

A new proposed project

EPIC-MAPS

Low temperature detector technology for broad band high energy resolution spectroscopy

DETECTOR CONCEPT

Operate Kinetic Inductance Detectors as quasi-equilibrium thermal sensors

➔ Sensitivity limited by thermodynamic fluctuations

➔ Combine high efficiency, high resolution and high count rates

IMPLEMENTATION

➔ Exploit recent developments in superconducting materials with low, tunable T_c

➔ Simple readout thanks to the intrinsic frequency multiplexing of KIDs

DEMONSTRATOR

Realize a ready-to-use 1K-pixel X-ray detector to be deployed at a synchrotron facility

APPLICATIONS

Short pulse X-ray sources, nuclear safeguard, astrophysics, neutrino physics, etc

LONG TERM VISION

Build an scientific community of interdisciplinary nature and establish Europe as a leader in this field

A new proposed project

EPIC-MAPS

Project submitted for a H2020-FETOPEN-2014-2015-RIA grant

PI: A. Nucciotti (UniMiB)

Project duration: 4 years

INFN

People: S. Di Domizio (GE, INFN PI), V. Bocci and M. Vignati (ROMA1)

Tasks: electronics, signal processing, detector design and commissioning

10 Institutions involved

- Università di Milano-Bicocca
- Istituto Nazionale di Fisica Nucleare
- CNRS / Institut Néel and LPSC
- CEA/INAC/SBT
- Lund University
- Fondazione Bruno Kessler
- Consiglio Nazionale delle Ricerche
- Ruprecht-Karls-Universität Heidelberg
- Johann Wolfgang Goethe Universität
- MITO Technology