Rivelatori di Luce criogenici (Bolometrici)

Rivelatori per Materia Oscura
Rivelatori per Decadimento Doppio Beta

Stefano Pirro- INFN-LNGS

What Next, LNGS 15 Ottobre 2014

Rivelatori di luce bolometrici…Istruzioni per l'uso

- ✓ I rivelatori di luce bolometrici sono bolometri prima di tutto, quindi rivelatori di fononi
- ✓ Sono rivelatori "lenti" O(ms)
- ✓ Sono rivelatori che vengono "cihusi" in un criostato a diluizione per essere testati
- ✓ Non sono, decisamente, rivelatori "quantici"
- ✓ La loro QE non è semplice da calcolare
- ✓ Vengono –solitamente- calibrati *in energia* , tramite sorgenti radioattive di ^{55}Fe (6 keV)
- ✓ Non si comprano ma vengono –fino ad ora- assemblati da mani sapienti e certosine

Perché misurare la luce emessa da un bolometro

Un rivelatore Bolometrico (cristallo) misura, con ottima approssimazione, tutta l'energia rilasciata da una Particella nell'assorbitore, senza distinzione sul tipo di particella.
L'emissione di luce (come la ionizzazione indotta in un semiconduttore) dipende, invece, dal tipo di particella che interagisce (β/γ, α, n , rinculi).
Quindi la misura (simultanea) di calore e luce di scintillazione -in un bolometro costituito da un cristallo scintillante-permette di discriminare il tipo di particella incidente, chiave di volta per gli esperimenti di eventi rari

Quale è la differenza sostanziale tra un rivelatore di luce per DDB e per DM ?

DDB

Q-Value $\approx$ 2÷3 MeV

Rivelatori di luce "poco sensibili"

DM

$E_{recoil} \approx 0 \div 50$ keV

Rivelatori di luce "MOLTO sensibili"

Un po' di storia

382 Nuclear Instruments and Methods in Physics Research A279 (1989) 382–387
North-Holland, Amsterdam

DETECTION OF LOW ENERGY SOLAR NEUTRINOS AND GALACTIC DARK MATTER WITH CRYSTAL SCINTILLATORS

L. GONZALEZ-MESTRES and D. PERRET-GALLIX

LAPP, Annecy-le-Vieux, France

We suggest that dedicated scintillating crystals (DSC) may provide a way to detect low energy solar neutrinos and, possibly, galactic dark matter. DSC are scintillating monocrystals grown from a compound containing a large relative amount of the target material. The target element (or isotope) is chosen for its larger interaction cross-section and/or the specific signature it may provide, easing background rejection. A ^{115}In target appears to be the natural choice for solar neutrinos, and we propose to grow high quality scintillating crystals made of a suitable indium compound. Several targets can be considered for the detection of galactic dark matter, depending on WIMP interaction properties. We mainly focus on the detection of Majorana fermions through inelastic scattering. We finally propose to investigate the feasibility of composite cryogenic devices based on scintillating crystals at low temperature. A good time resolution would be obtained through the detection of the light pulse even on large crystals, whereas the energy resolution would be provided by bolometric readout (sensitive to thermal phonons) and low temperature photosensitive devices.

La prima misura sperimentale

Nuclear Physics B (Proc. Suppl.) 28A (1992) 233–235
North-Holland

NUCLEAR PHYSICS B
PROCEEDINGS SUPPLEMENTS

DEVELOPMENT OF A THERMAL SCINTILLATING DETECTOR FOR DOUBLE BETA DECAY OF ^{48}Ca

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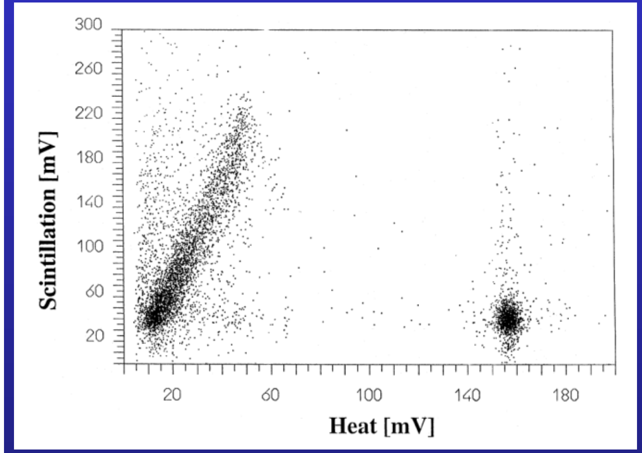
Among double beta candidates ^{48}Ca stands out for its 4.271 MeV transition energy, well above most of the contribution of natural γ and β radioactivity, but extremely near to the energy released in the α decay of ^{238}U (4.274 MeV including nucleus recoil). A CaF_2(Eu) detector with both thermal pulse and scintillation light readout would give very good discrimination against this very dangerous source of background.
We tested CaF_2 crystals with 0.01 to 0.07% Eu doping, in the range of temperature between 300 K and 20 mK. The result shows that detection of the scintillation light from alpha particles of 5.4 MeV with a silicon photodiode is possible down to 20 mK with high signal/noise ratio, and that such doping levels do not affect the performance of CaF_2 as a thermal detector

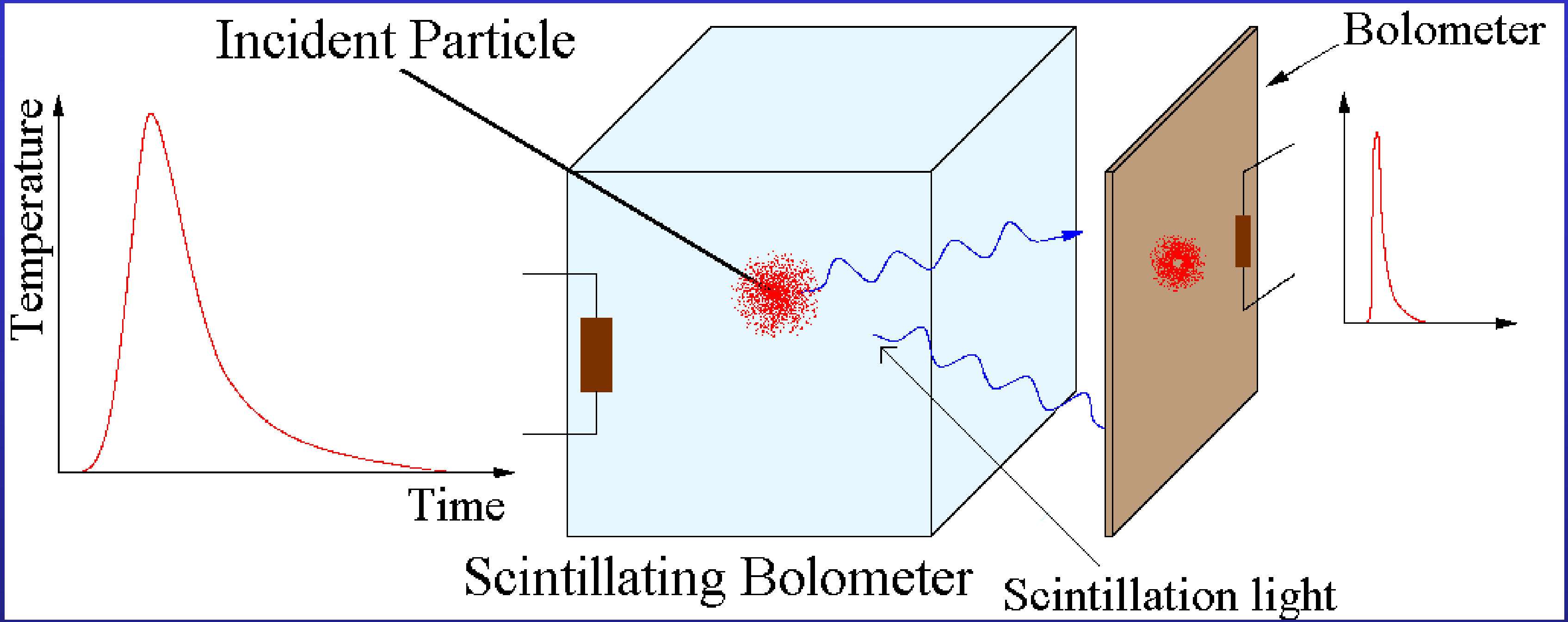


But this technique, using a silicon PD at low temperatures showed several difficulties

- Cold stage charge preamplifier inside the cryostat
- Relatively small surface area of the PD
- Resistivity of the Semiconductor (➔Photoresistence)

Misurare i fotoni con un bolometro

Sul finire degli anni 90 si fece strada la (semplice…) idea di misurare la luce di scintillazione tramite un secondo bolometro, un cristallo "opaco" di piccola massa



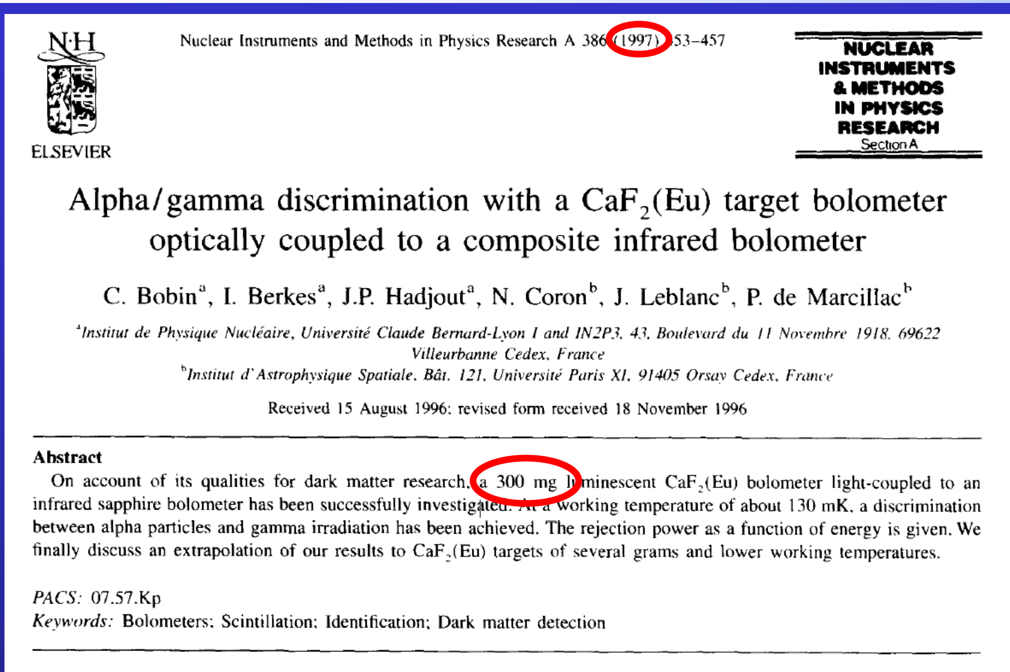
A Bolometric Light Detector (BLD) is fully active a particle detector

The time response of a BLD is the same of a standard bolometer O (ms)

The QE of a BLD is, probably, comparable with that one of PD's but it is not easy to measure it

Normally PURE (undoped) Ge or Si crystal are used as absorbers (or "coated" crystals)

La prima misura di luce bolometrica



Nuclear Instruments and Methods in Physics Research A 386 (1997) 453–457

ELSEVIER

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

Alpha/gamma discrimination with a CaF_2(Eu) target bolometer optically coupled to a composite infrared bolometer

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Abstract

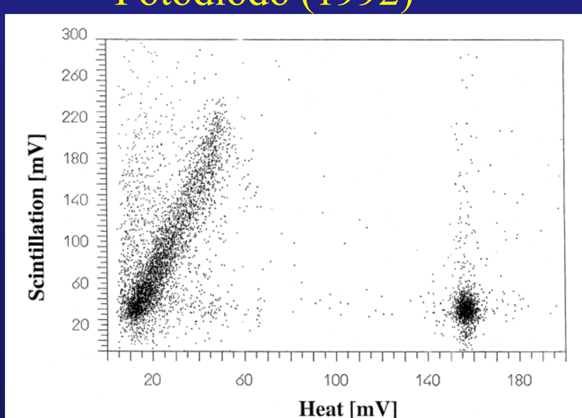
On account of its qualities for dark matter research, a 300 mg luminescent CaF_2(Eu) bolometer light-coupled to an infrared sapphire bolometer has been successfully investigated. At a working temperature of about 130 mK, a discrimination between alpha particles and gamma irradiation has been achieved. The rejection power as a function of energy is given. We finally discuss an extrapolation of our results to CaF_2(Eu) targets of several grams and lower working temperatures.

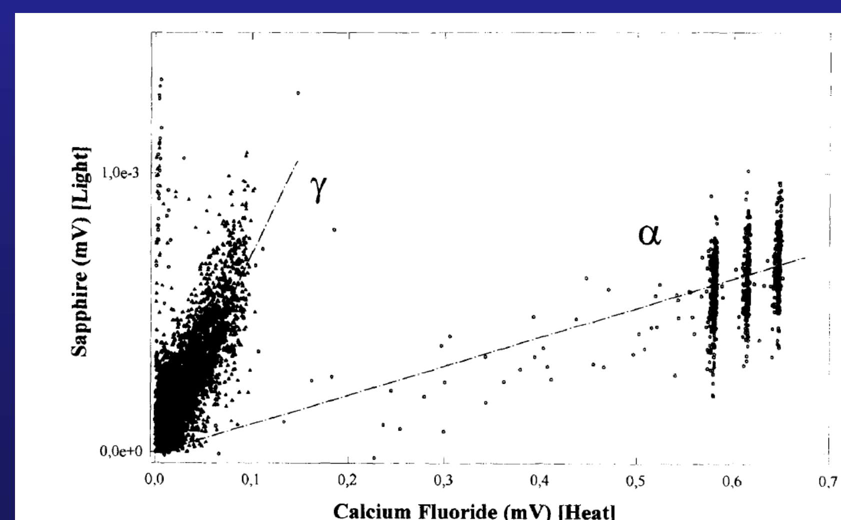
PACS: 07.57.Kp

Keywords: Bolometers; Scintillation; Identification; Dark matter detection

Bolometro 1997 (Al_2O_3 Bi coated)

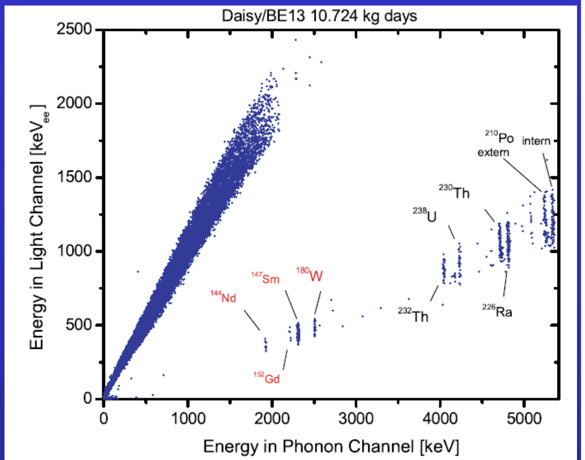
Fotodiodo (1992)

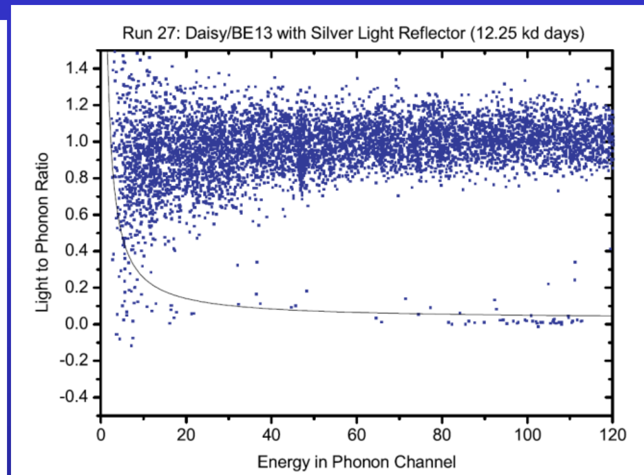




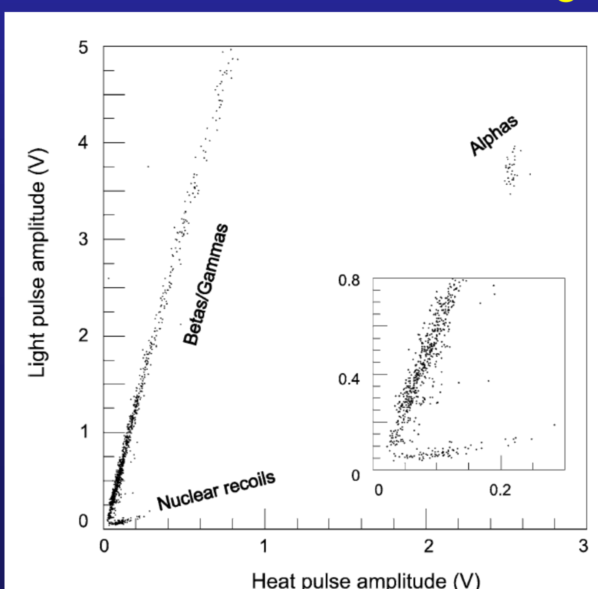
Alcuni anni dopo…

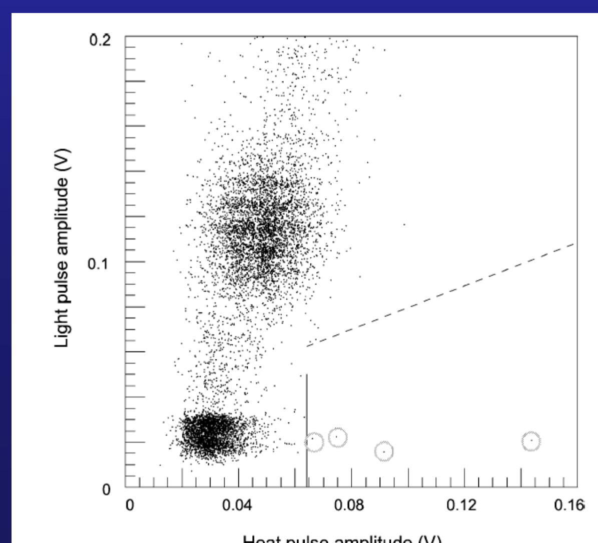
CRESST – 2004- 300 g $CaWO_4 + Al_2O_3$ (Si coated) Light Detector





ROSEBUD – 2003 54 g $CaWO_4$ + Ge Light detector



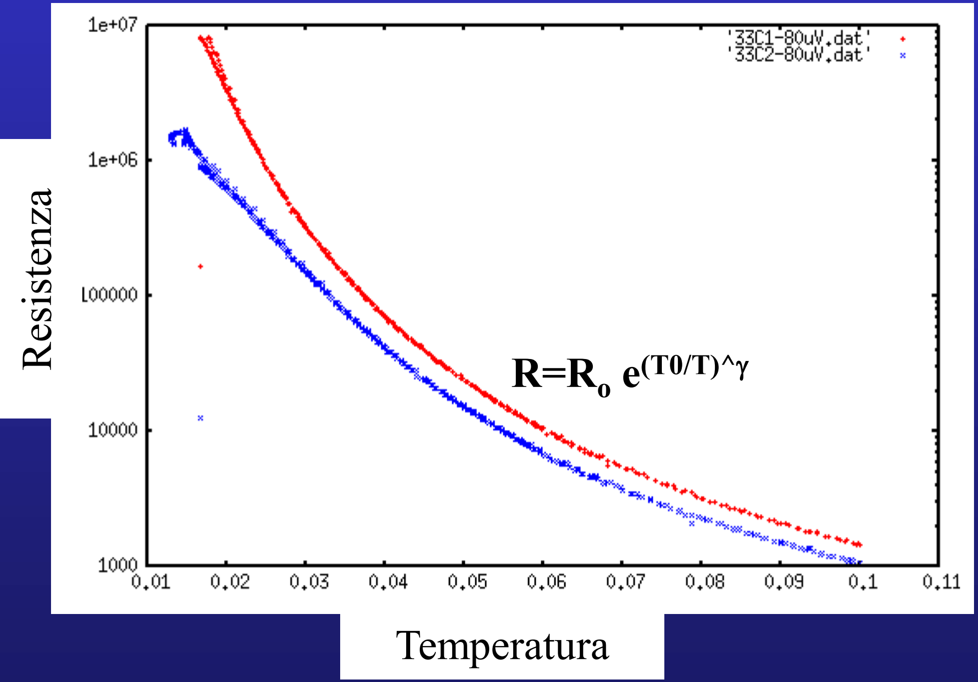


Diversi tipi di termometri per Rivelatori di Luce

In realtà la sola differenza è il "termometro" (sensore di fononi) dell'assorbitore di luce

Esiste una grande varietà di rivelatori di fononi: **Termistori NTD, Transition Edge Sensors, Metallic Magnetic Calorimeters, Anderson TES, Kinetic Inductance Detector** (vedi Vignati)

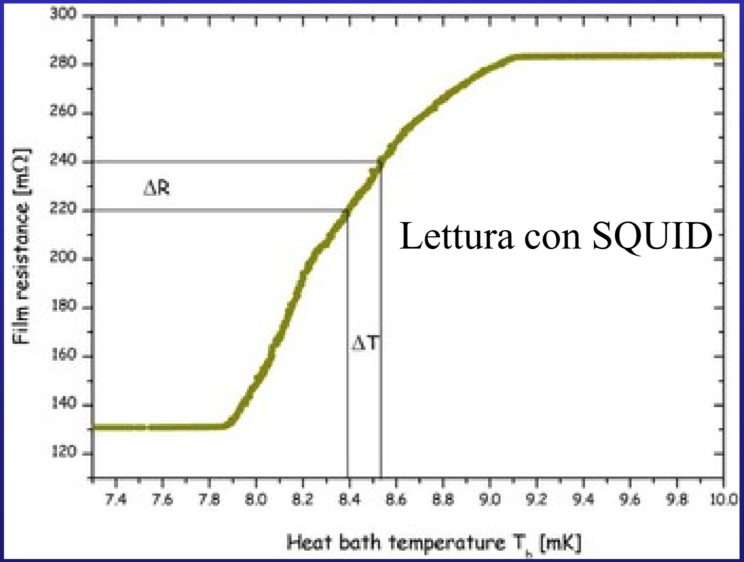
I rivelatori più semplici sono sicuramente quelli basati su termistori NTD



$R=R_o\, e^{(T0/T)^\wedge\gamma}$

(CUORE, EDELWEISS)

I rivelatori più sensibili sono sicuramente quelli basati su TES



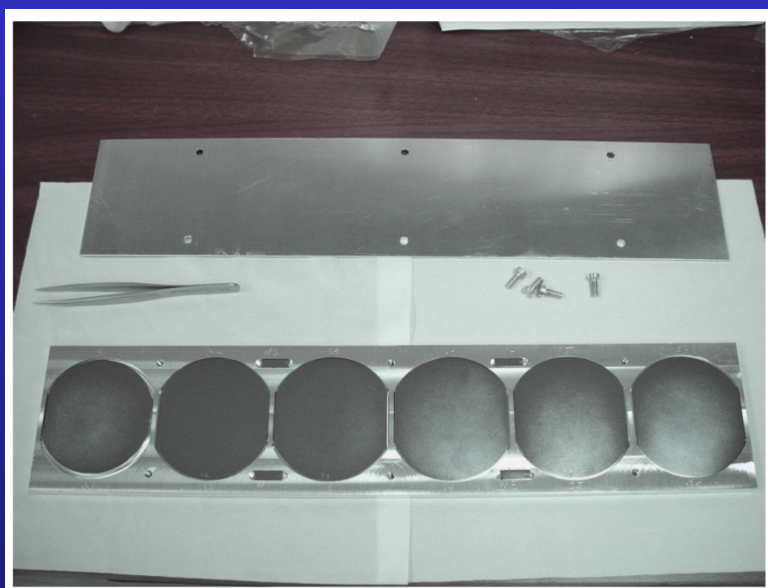
CDMS, CRESST

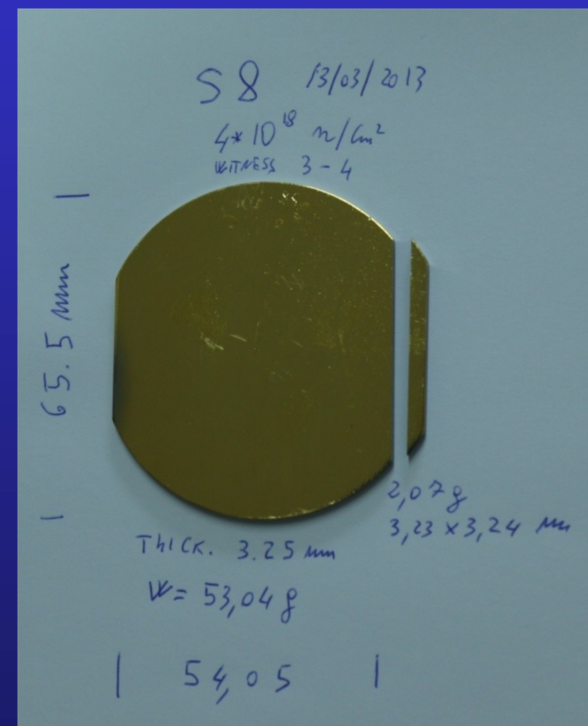
La sensibilità del rivelatore è direttamente proporzionale alla complessità del rivelatore

Termistori NTD

I termistori NTD sono semiconduttori fortemente drogati (~10^{17} atomi/cm^3)con una densità di drogante leggermente al di sotto della transizione metallo-isolante

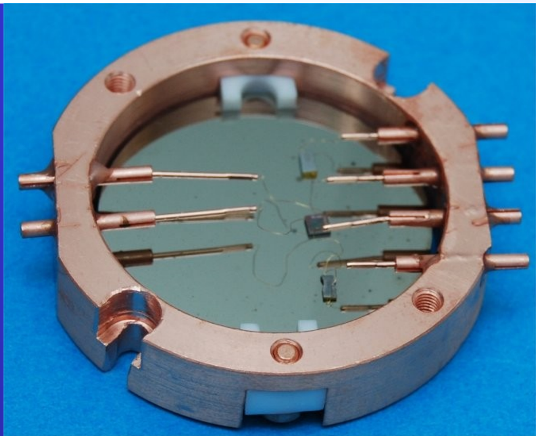
Si parte da cialde di Germanio che vengono irraggiate a reattore e, tramite reazioni di trasmutazione nucleare indotte da neutroni termici, si “autodrogano” in maniera estremamente omogenea

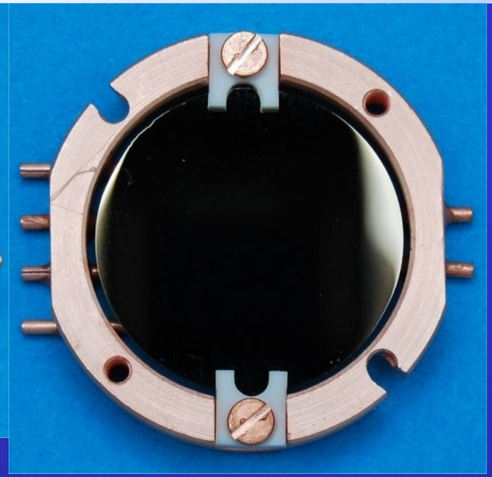




La difficoltà maggiore è quella di avere un livello di dose di neutroni precisa all’ordine di massimo l’1 % e la tempistica dovuta all’irraggiamento….. Ma una volta finito si hanno termistori “a volontà”

Thermistors: Lucifer light Detectors for DBD



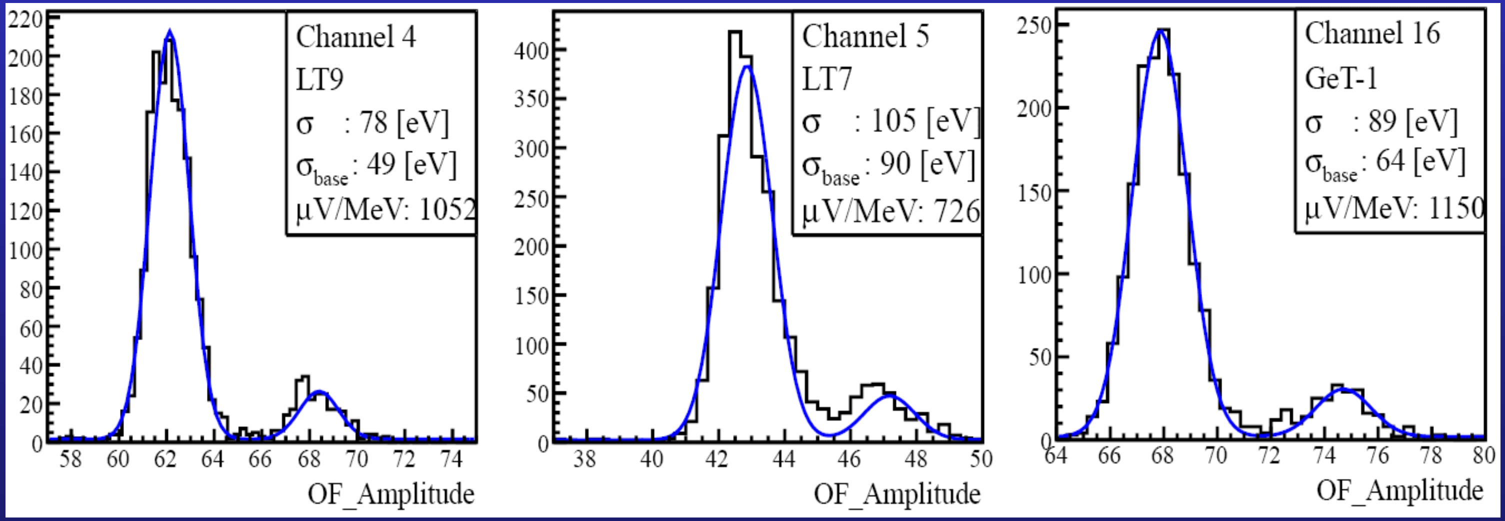


The light detector is a Ge thin crystal

Ø=44.5 mm, h=0.175 mm

1 face is coated with 60 nm layer of SiO_2 to increase light absorption

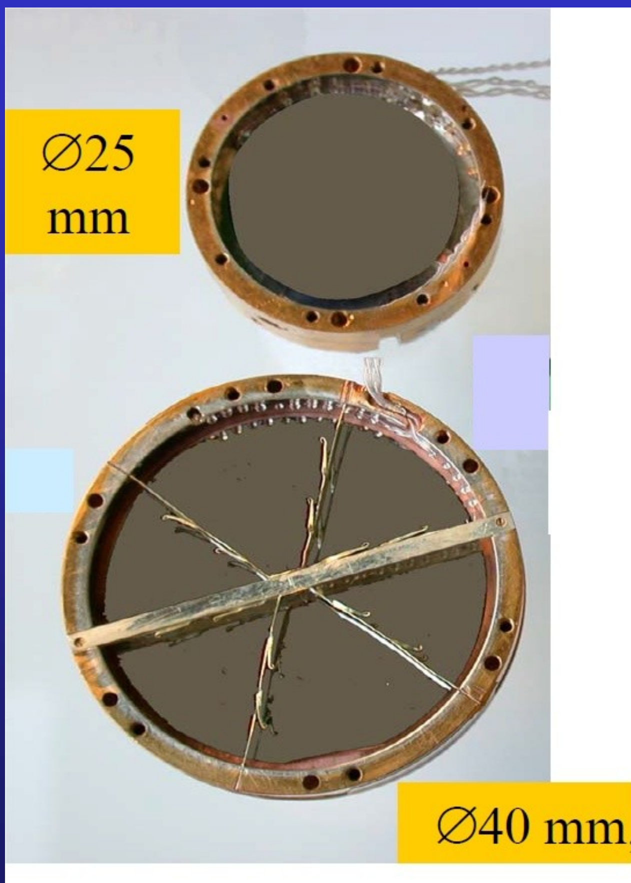
These devices are calibrated through an Ionizing ^{55}Fe source placed close to them; ^{55}Fe shows two X-lines at 5.9 and 6.5 keV

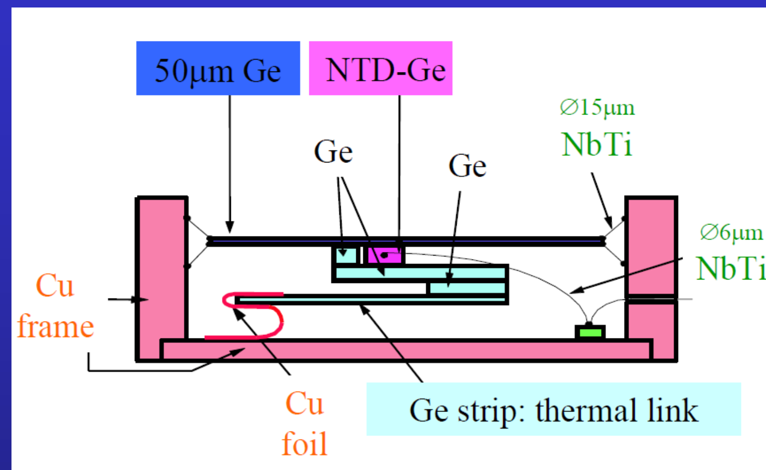


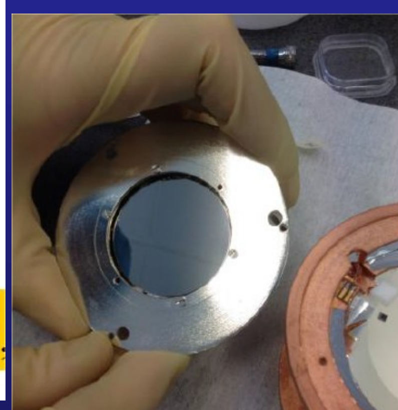
The ^{55}Fe energy spectra evaluated on three different UMICORE Ge-crystals. σ represents the evaluated energy resolution on the peaks, while σ_{base} represents the baseline resolution.

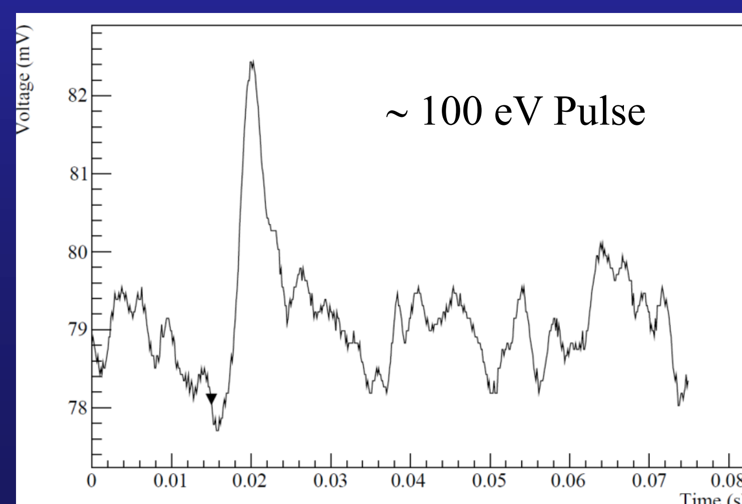
Thermistors: Rosebud Experiment for DM searches

I primi rivelatori di luce bolometrici sono stati sviluppati dal gruppo di N. Coron (Institue d'Astrophysique Spatiale d'Orsay). Essi sono basati su assorbitori di Ge e termistori NTD.
Una cura meticolosa è usata per massimizzare il segnale termico per raggiungere la soglia più bassa possibile









Questi rivelatori riescono ad arrivare ad una risoluzione σ di circa 15 eV (@ LNGS)

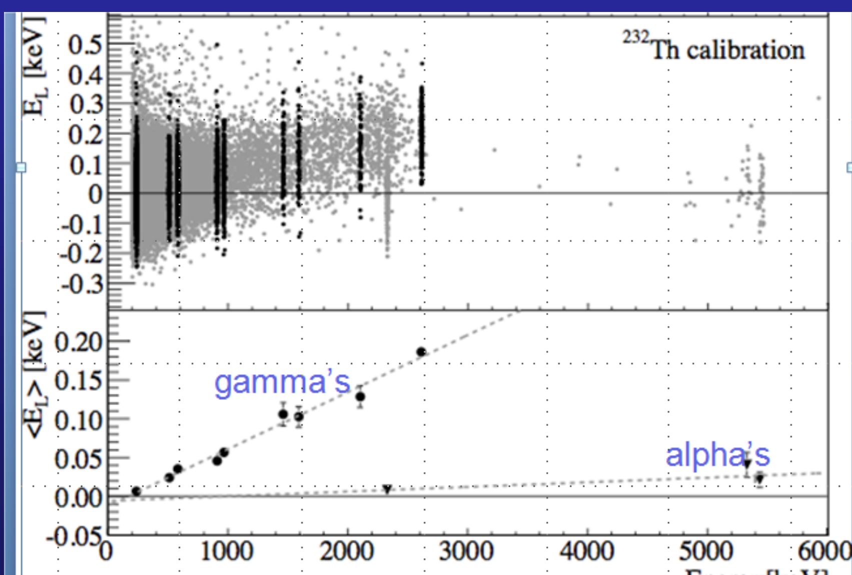
La luce Cherenkov nel TeO_2

La emissione di luce "di scintillazione" su un cristallo di TeO2 fu osservata relativamente tanto tempo fa (Coron-De Marcillac)

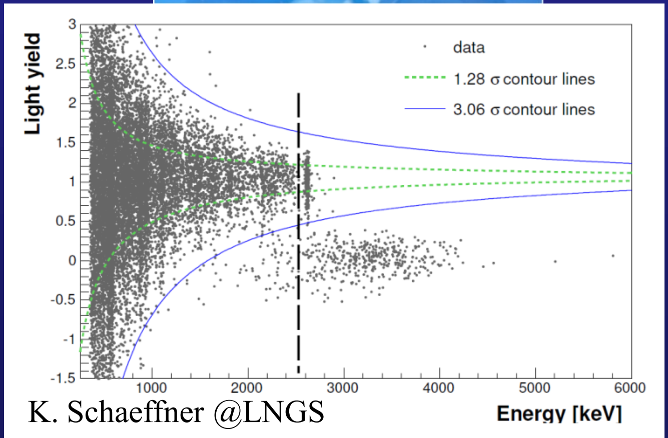
In realtà, come suggerito da De Fatis e poi misurato –all'interno della collaborazione LUCIFER - la "scintillazione" altri non era che l'emissione di luce Cherenkov O(100 eV)

Questo ha portato negli ultimi 2 anni ad iniziare R&D su rivelatori di luce per il DDB cercando, però, di ottenere (a "basso costo") caratteristiche simili a quelle dei rivelatori per la DM (Effetto Neganov-Luke).

Germani-Termistori- DBD Light detectors σ= 80 eV



TES-MAX PLANK INSTITUTE- Munich
TES LD for DM, σ= 20 eV



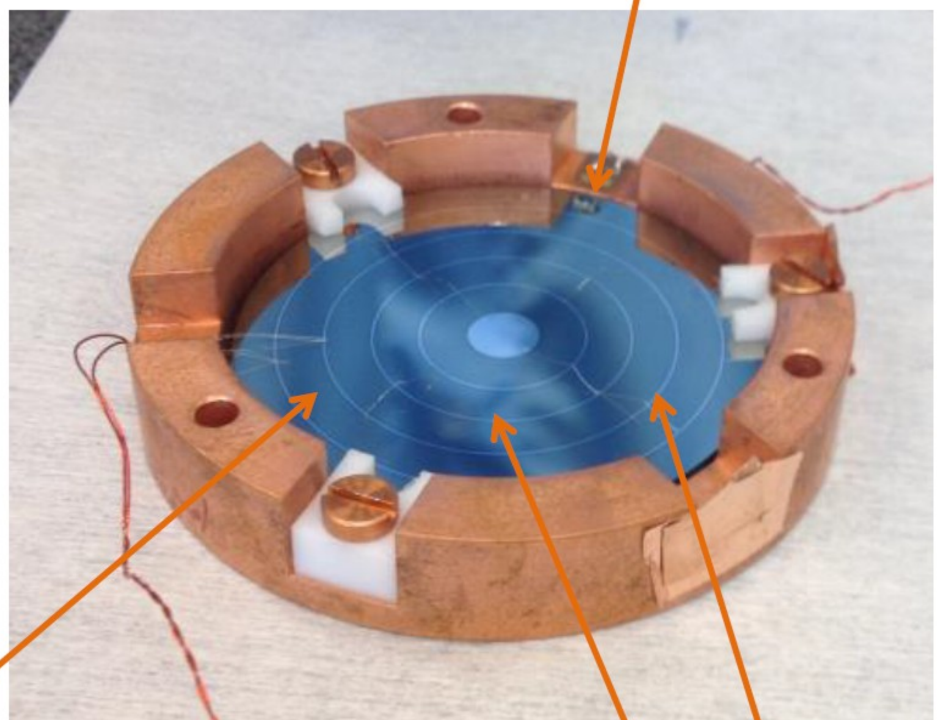
Luke effect detectors at CSNSM

Light detector → auxiliary bolometer with a **temperature sensor** and a **set of electrodes**

The ionization charges induced by the impinging photons are transported by the electric field produced by the voltage applied to the electrodes.

The **work done by the field** on the charges is detected as **additional heat** → **amplification**

Temperature sensor (NTD Ge thermistor)

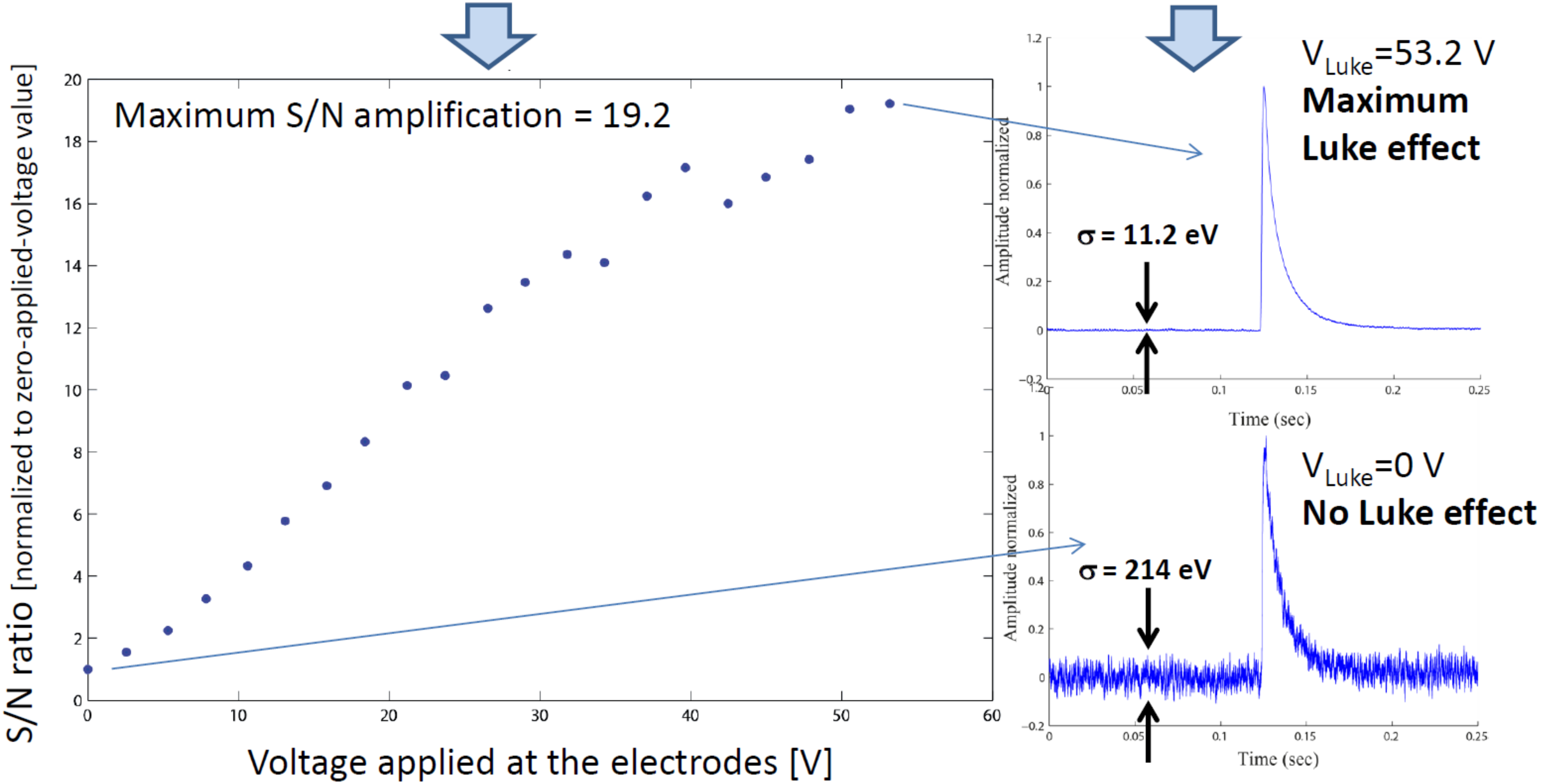


Ge wafer (photon absorber)
Ø = 44 mm

Concentric Al electrodes
(EDELWEISS-like configuration)

Luke-effect amplification tested with pulses delivered by an infrared LED

The same amount of energy delivered with and without Luke effect



^{55}Fe calibration with **no Luke effect** → $\sigma_{baseline}$ **= 214 eV** – pulse amplitude = 0.71 μV/keV

Baseline width with **maximum Luke effect** → $\sigma_{baseline}$ **= 11.2 eV** = (214/19.2) eV

Caveats:
- energy scale fixed by X-rays and not by low energy photons
- excess noise associated to Luke amplification is not known for low energy photons

Si Light detectors with Luke Effect (MiB – FBK)

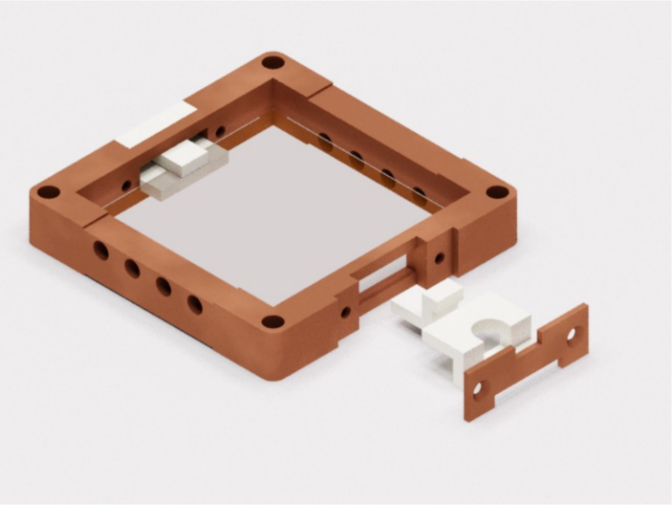
- **Development of Si light detectors with very low energy thresholds to detect very small release of energy (e.g. Cherenkov radiation)**

- **Si bolometers with Neganov-Luke effect (heating of the detector due to carrier drift)**

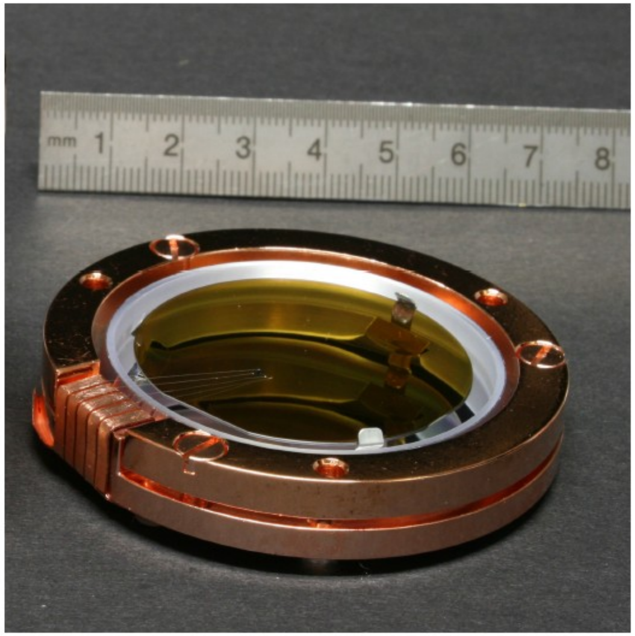
Si vs Ge:

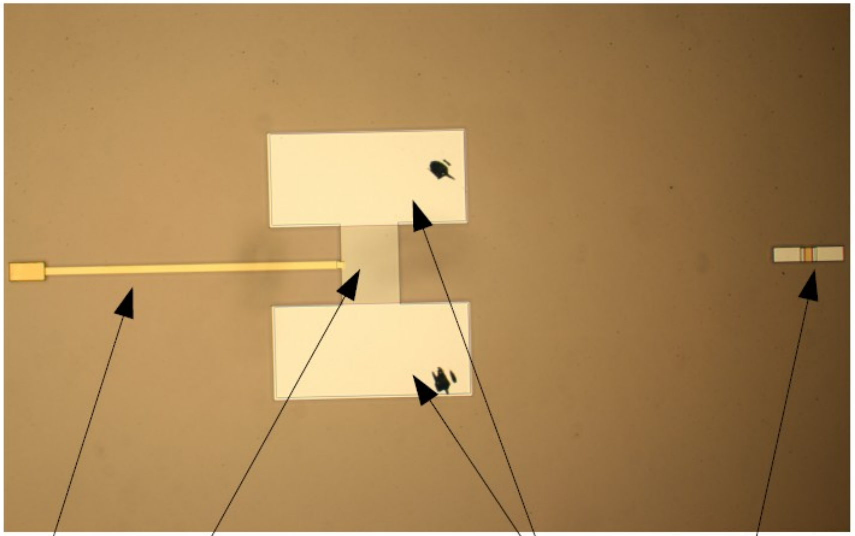
"Since the specific heat capacity of Silicon at low temperature is eight times smaller than that of Germanium, Silicon has a faster response" and higher pulses…...
In the past, Si slabs have been tested but the obtained results were not encouraging since it didn't cool down properly….
FBK develop Si devices for different purposes, can take care of the design and realization of electrodes and coating starting from high resistivity Si wafers (>5 kΩ/cm)

- Tests on different coating
- Tests with detectors with electrodes for the Neganov-Luke effect (different electrodes geometries to create electric fields of different intensity and uniformity)
- Tests with Si slab with higher resistivity
- Optimization of the light detectors holder
- Realization of a system for the production of calibrated light to compare different coating



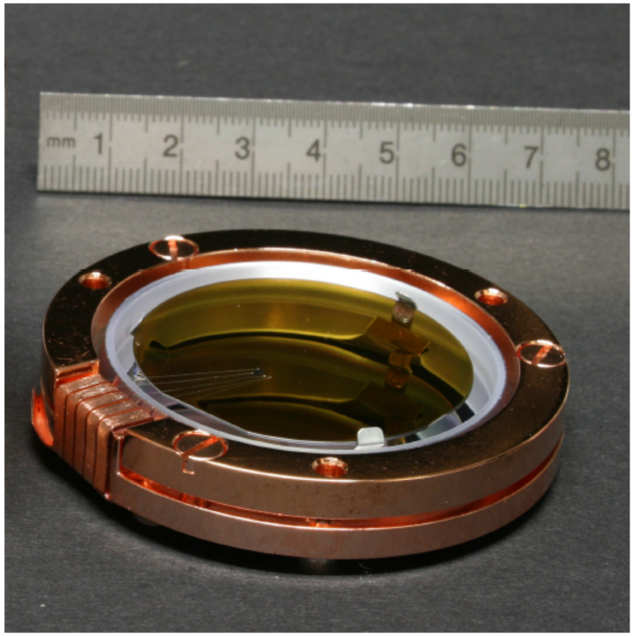
CRESST light detectors

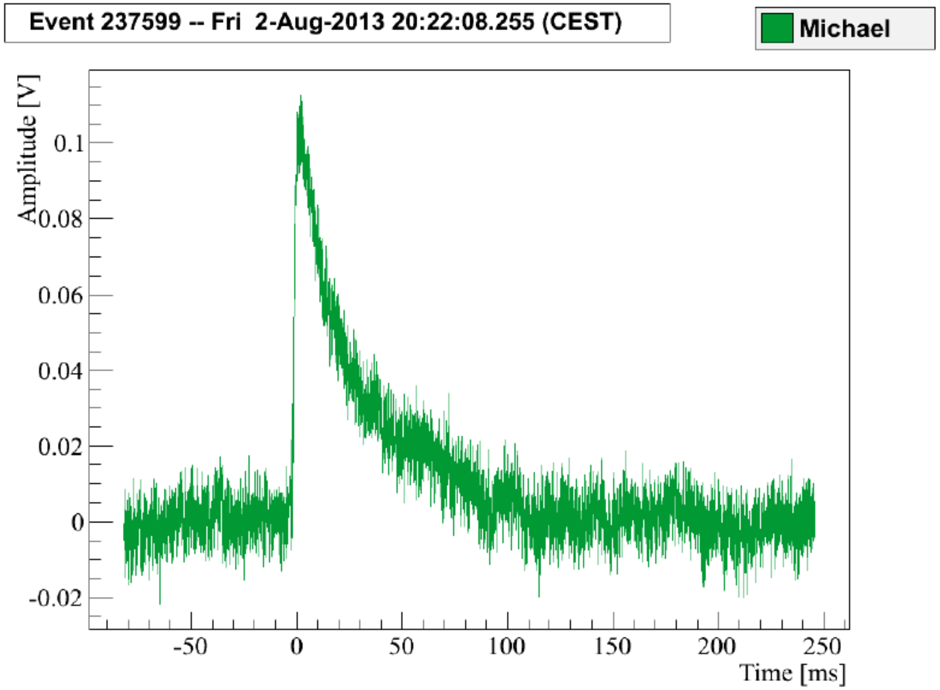




Silicon on Sapphire or Si disk
∅: 40mm; thickness: 0.4mm
Sensor: W-TES with
Al phonon collectors
Read-out: SQUID
Transition temperature : ~15mK

CRESST light detectors





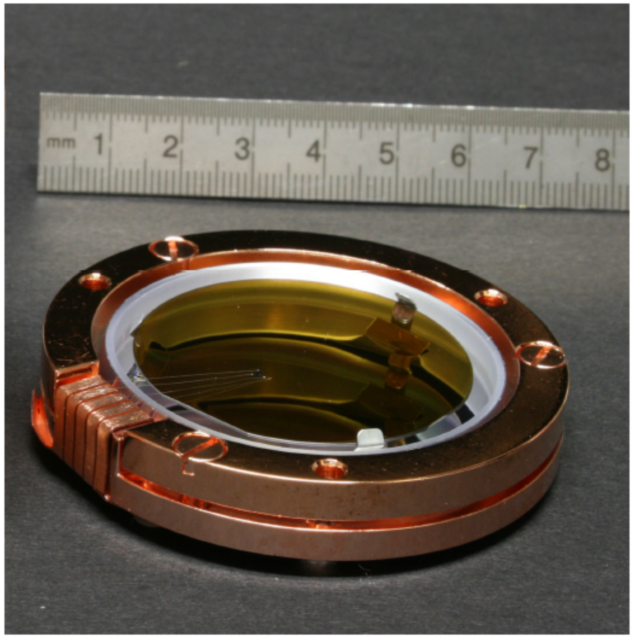
Silicon on Sapphire or Si disk
∅: 40mm; thickness: 0.4mm
Sensor: W-TES with
Al phonon collectors
Read-out: SQUID
Transition temperature : ~15mK

~ 100eV light signal from crystal TUM45

No direct light detector calibration available
Energy calculated from:

- calibration of phonon detector
- measured light yield of the crystal
- measured non proportionality of the crystal

CRESST light detectors



Silicon on Sapphire or Si disk
∅: 40mm; thickness: 0.4mm
Sensor: W-TES with
Al phonon collectors
Read-out: SQUID
Transition temperature : ~15mK

Pro
+ ~5eV σ noise of base line on average detector
+ (relatively) fast signals*:
rise time O(1ms)
decay time O(10 ms)

Contra
- complete in-house production
- still require individual characterization

➡ mass production not yet feasible

* rise: slow scintillation process
decay: weak thermal link by design

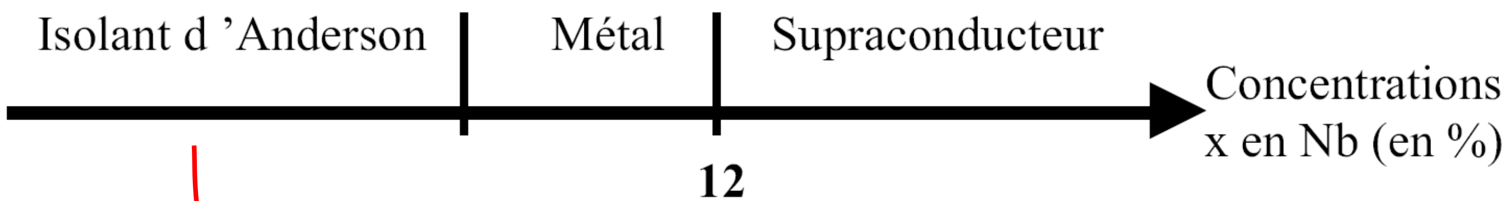
A new proposal: NbSi films (CEA, CSNSM -Orsay)

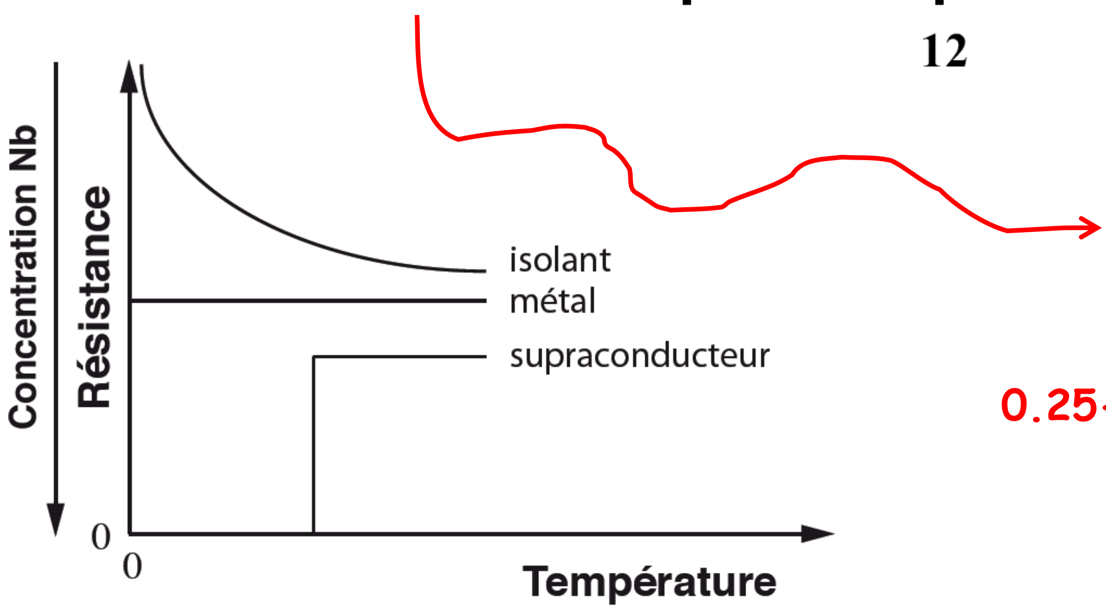
Nb_xSi_{1-x}

Physics properties depend on the x concentration

Very interesting alternative to NTD sensors for bolometers operated at 20mK.

- High sensitivity ΔR/ΔT, low noise
- Adapted to JFET electronics
- Well controlled and fast fabrication process (CSNSM-MINERVE)
- The design can be easily adapted and fine-tuned to a given absorber
- Can be glued onto any absorber
- Compatible with very low background experiments





$$R = R_0 \exp\left(\frac{T_0}{T}\right)^{\gamma}$$

$\gamma = 0.25$ for T>150 mK (Mott)

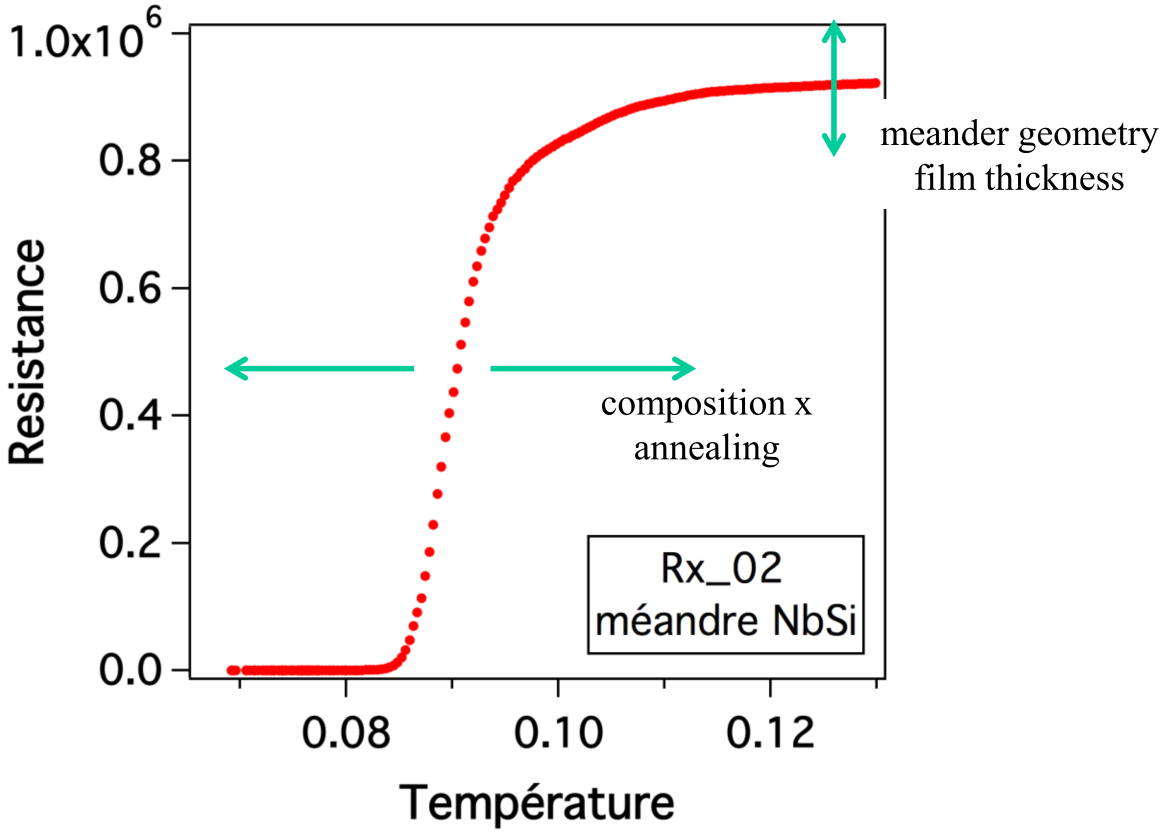
$0.25<\gamma<1$ for T<150 mK (Efros-Shklovski

$\Delta V/\Delta T \approx 1$ V/K @ 30mK-45mK

NbSi meander TES

Nb_xSi_{1-x} TES meanders :

- Hi sensitivity (ΔR/ΔT)
  - control of R_N, Tc
- R_N few MΩ -> optimized for JFET or HEMT electronics



NbSi heat sensor

Development of NbSi heat sensors for macro-bolometers?

Is it possible to easily replace NTDs by more efficient sensors?

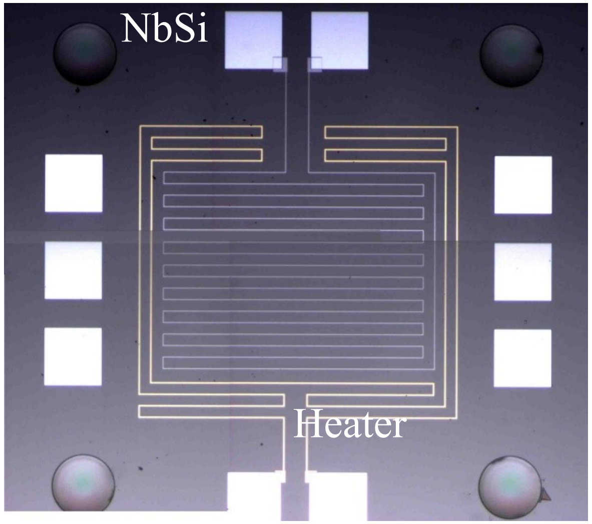
(lower threshold, less microphonics, heat only event study…)

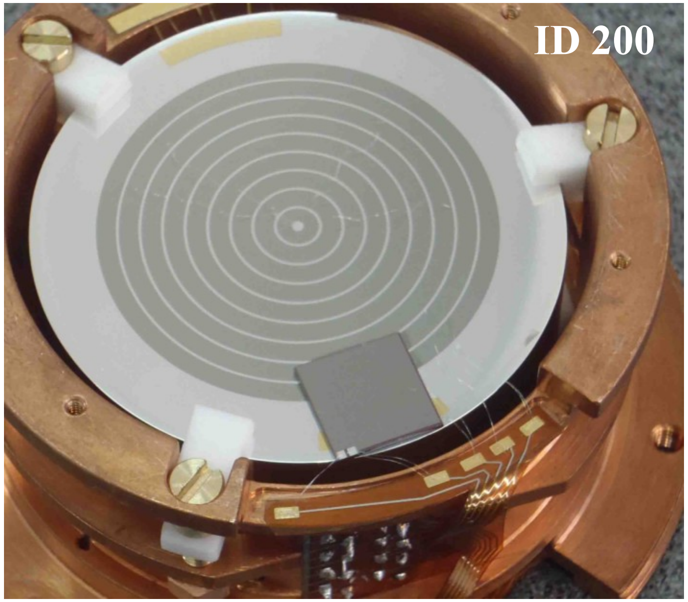
Nb_xSi_{1-x} meander shape TES :

- Thin film technology, Nb-Si co-evaporation:

a-Nb_xSi_{1-x} can be deposited onto any substrate (crystal, Ge or Si wafers…)

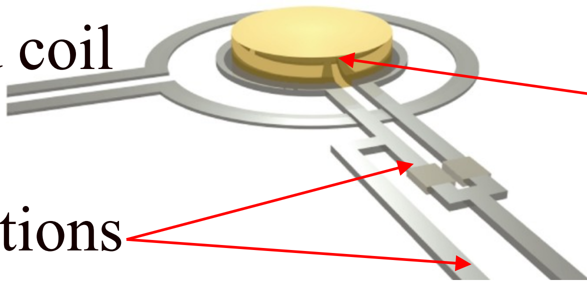
lithography or shadow masks : meander geometry (1µm-30µm line resolution)





First test of MMC-based photon sensors (Amore Project)

Field coil

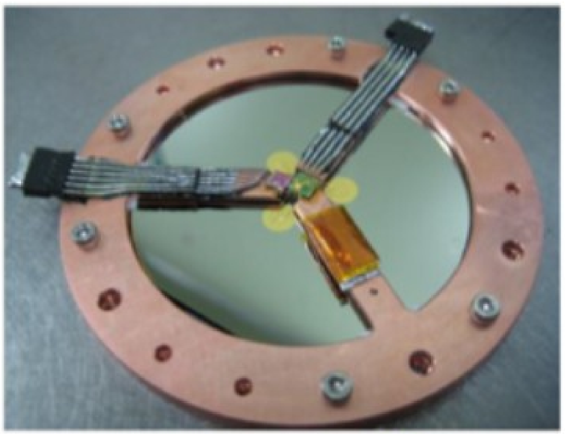


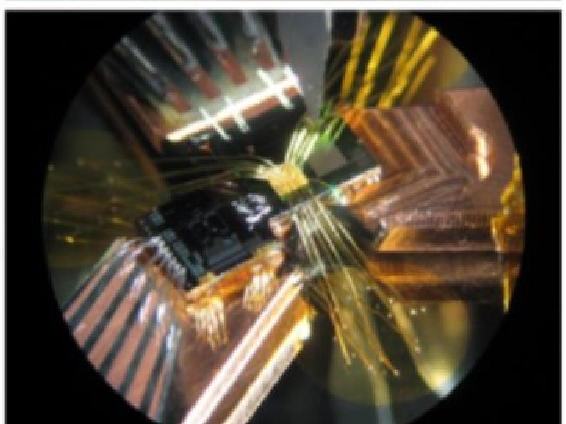
junctions

Magnetic material (Au:Er) in dc SQUID
Au:Er(10~1000ppm)

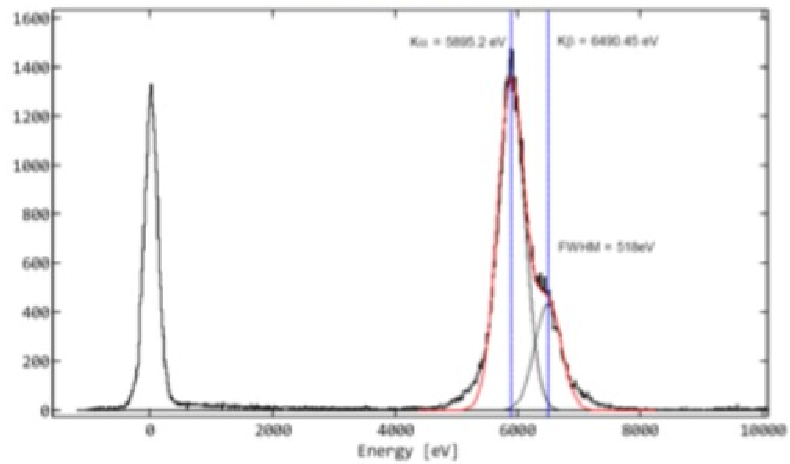
weakly-interacting paramagnetic system

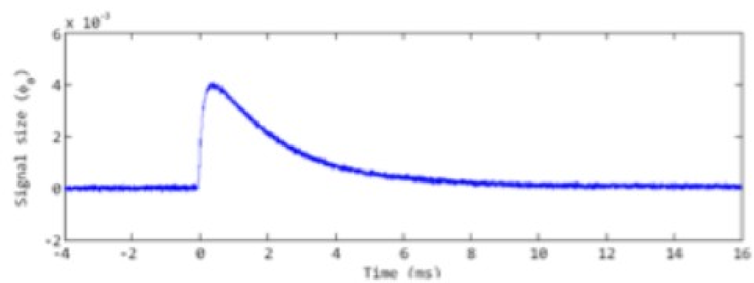
0.5mm x 2 inch Ge wafer





~500eV FWHM





6keV signal
0.2 ms rise time

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Conclusioni

- ✓ I rivelatori di luce bolometrici hanno delle potenzialità sulla carta ancora molto migliorabili
- ✓ Ovviamente sono vincolati a misure bolometriche (DM e DDB)
- ✓ Fino ad ora ogni gruppo ha sviluppato e costruito i propri devices
- ✓ I rivelatori di luce non rappresentano il vero problema di un esperimento “next”