Luminescent bolometers for the study of double beta decay

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Neutrinos

2017

Outline

Neutrinoless double beta decay: experimental challenges

Merits and limits of the pure bolometric technique

Advantages offered by luminescent bolometers

Present scenario of luminescent bolometers for double beta decay

Detection of Cherenkov light in TeO_2 bolometers

$^{116}CdWO_4$ program in France

Study of ^{100}Mo in the AMoRE project

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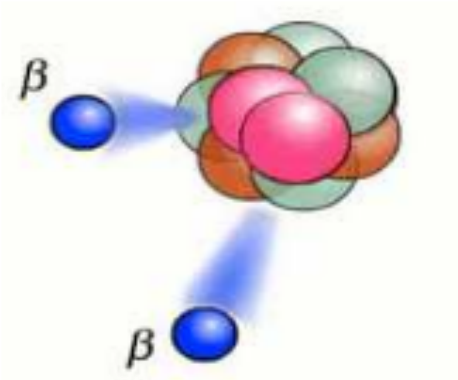
Neutrinoless double beta decay (0ν2β): standard and non-standard mechanisms

0ν2β is a test for « creation of leptons »: **$2n \rightarrow 2p + 2e^-$ ⇒ LNV**

This test is implemented in the nuclear matter:
$(A,Z) \rightarrow (A,Z+2) + 2e^-$



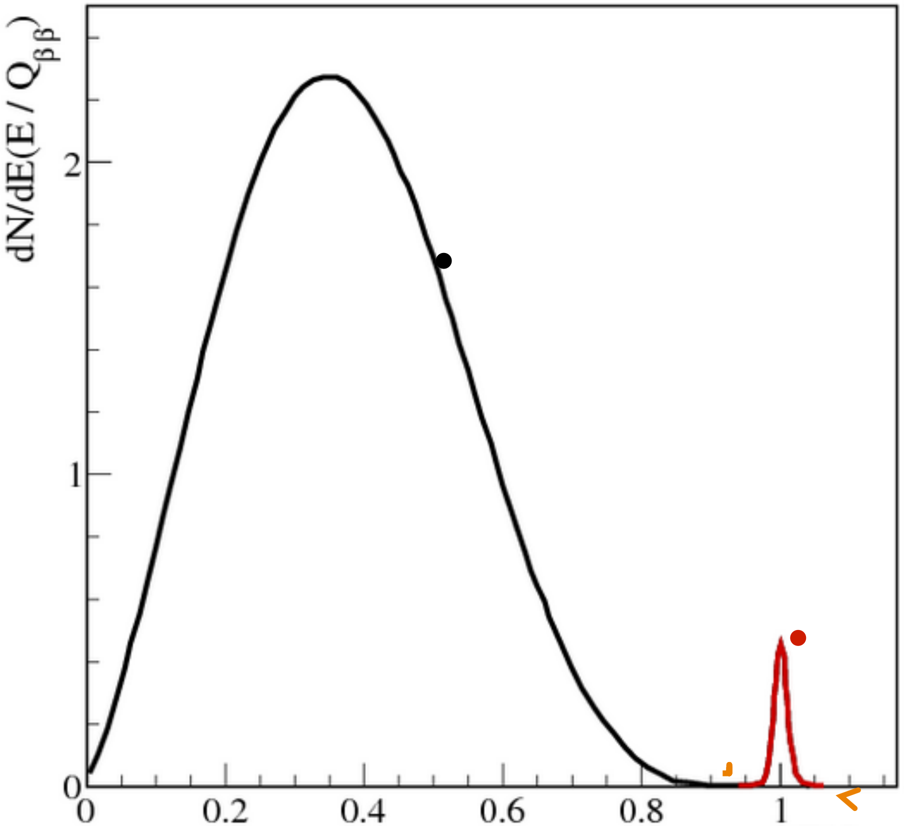
Energetically possible for **35 nuclei**
Only a few are experimentally relevant

0ν2β:

- Standard mechanism: **neutrino physics**
  0ν2β is mediated by **light massive Majorana neutrinos** (exactly those which oscillate)
- Non-standard mechanism: **BSM, LNV**
  Not necessarily neutrino physics

What we are looking for…

The shape of the two-electron sum-energy spectrum enables to distinguish between the **0ν** (new physics) and the **2ν** decay modes



Electron sum energy / Q

2ν DBD: (A,Z)→(A,Z+2)+2e+2ν

continuum with maximum at ~1/3 Q

$T_{1/2} \sim 10^{18} - 10^{21}$ y

0ν DBD: (A,Z)→(A,Z+2)+2e

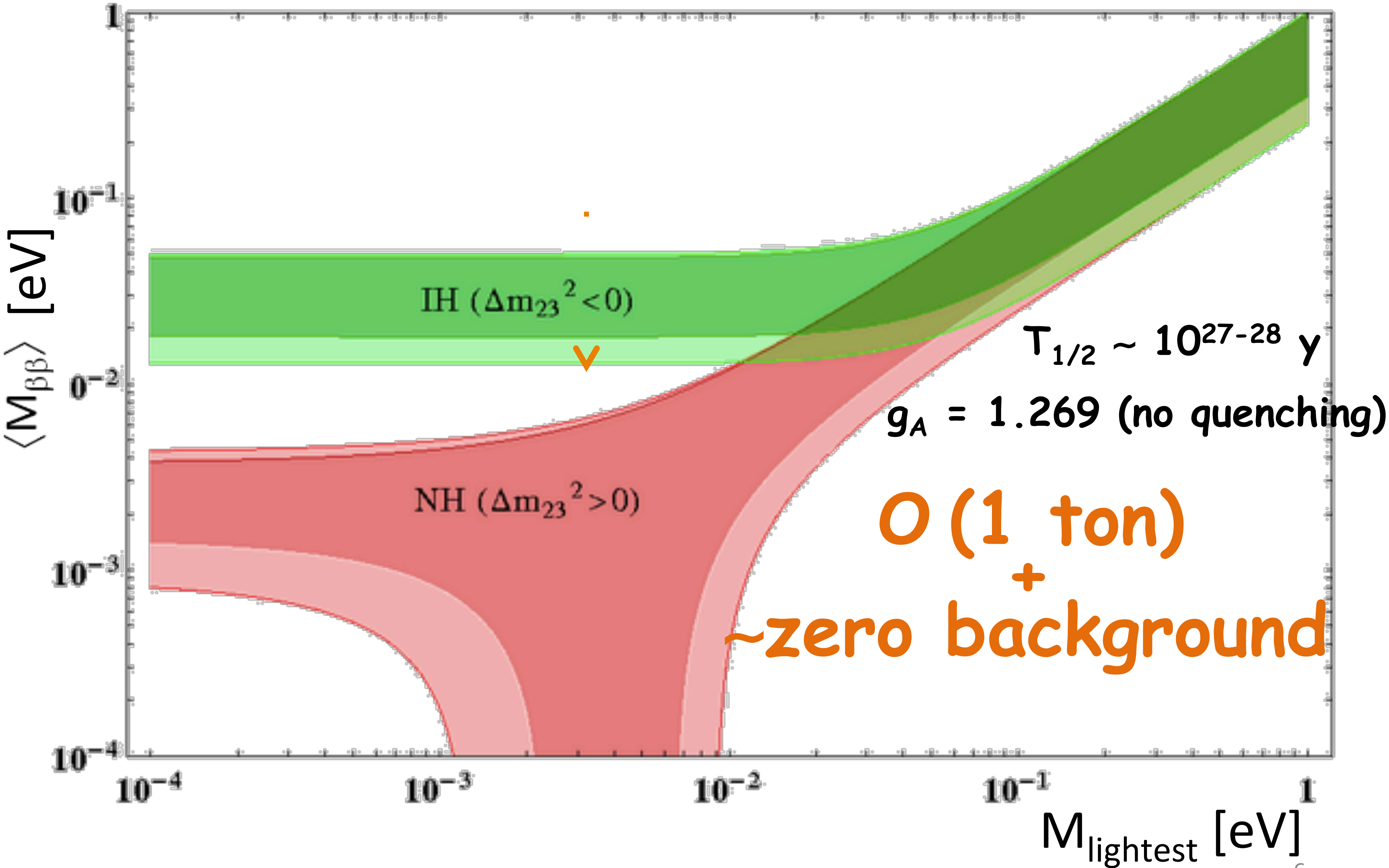
peak enlarged only by the detector energy resolution

$T_{1/2} > 10^{24} - 10^{26}$ y

Q ~ 2-3 MeV for the most promising candidates

The signal is a **peak (at the Q-value)** over an almost **flat background**

Goal of next-generation searches



Request for the background index

Background index

***b* [counts/(keV kg y)]**

number of background counts

detector (isotope) mass X live time X energy interval

around the Region of Interest

In the **source=detector approach**
with high energy resolution technique (ΔE_{FWHM} < 10 keV)
zero background at the tonne scale means

$b \leq 10^{-4}$ [counts/(keV kg y)]

Present record: GERDA (^{76}Ge) <
$b \sim 7 \times 10^{-4}$ counts/(keV kg y) – $\Delta E_{FWHM} \sim 3$ keV

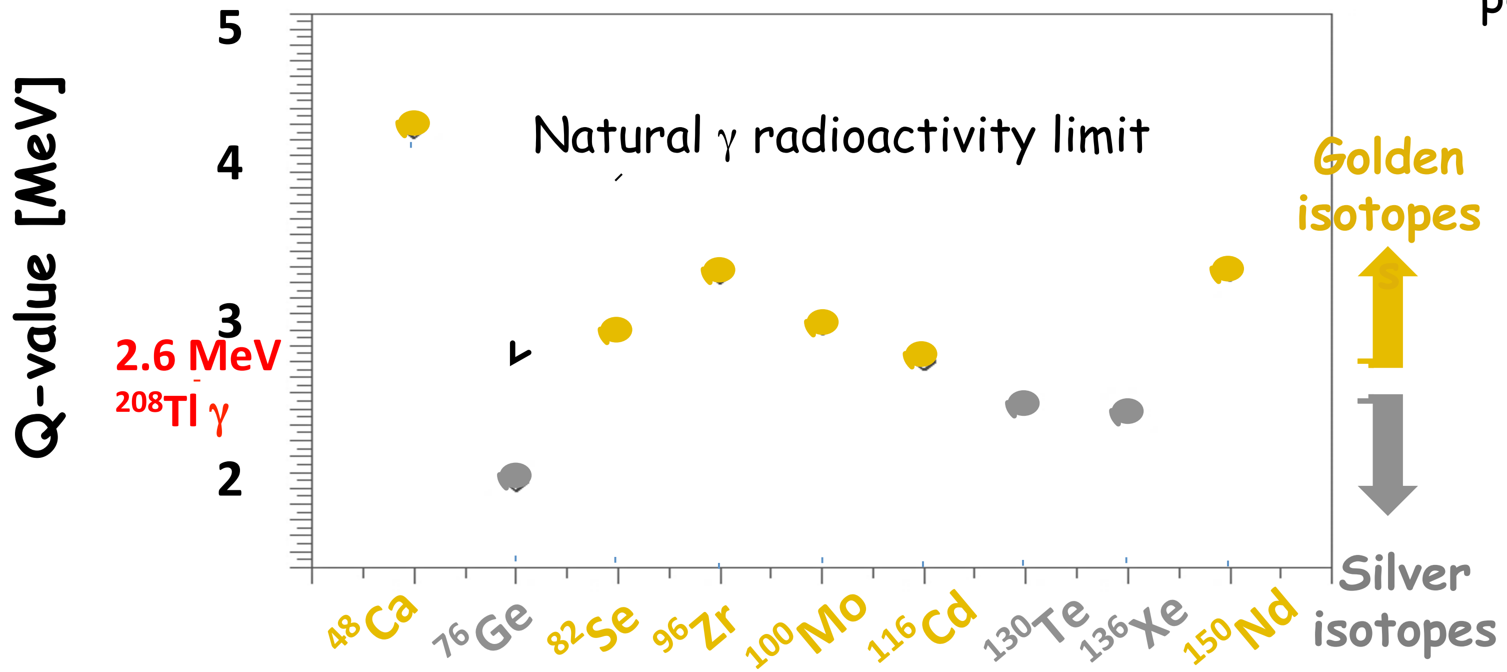
Talk of Ann-Kathrin Schuetz

Silver and golden isotopes

Q is the crucial factor
- Phase space: $G(Q,Z) \propto Q^5$ ➡ Magnificent Nine candidates
- Background

Golden isotopes: ^{48}Ca – ^{150}Nd – ^{96}Zr – ^{100}Mo – ^{82}Se – ^{116}Cd
Silver isotopes: ^{76}Ge – ^{130}Te – ^{136}Xe

Large-scale enrichment is possible



^{130}Te is almost golden: Q-value (**2527 keV**) in a clean window between **2615 keV** γ peak and its Compton edge (**2382 keV**)

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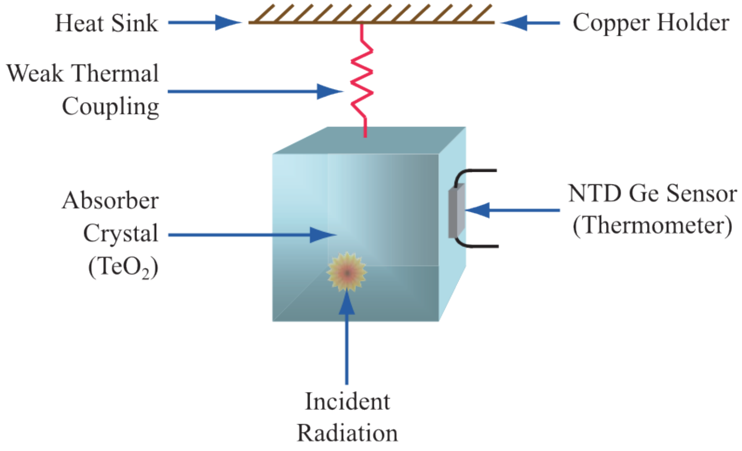
Bolometers: ideal detectors for $0\nu2\beta$

Bolometric approach: the source is embedded in a crystal, which is cooled down to **10-20 mK** and works as a **perfect calorimeter**

$$\Delta T = E/C$$



Attractive features of bolometers for $0\nu2\beta$ decay

- High energy resolution (~ **down to 4 keV FWHM** in the ROI)
- ~ **0.1-0.5 kg** source in each crystal → **large masses achievable** through arrays
- Crystals can achieve **very high radiopurity**
- High efficiency **(~ 80 – 90 %)**
- **Experience: Cuoricino/CUORE** experiments → crystals of **TeO_2** (isotope **^{130}Te**)
- **Large flexibility in the detector material choice:**
  ^{130}Te, and **three golden isotopes** (^{82}Se, ^{100}Mo, ^{116}Cd) **can be studied**

Talk of Brian Fujikawa

Are pure bolometers enough to fully explore the IH region?

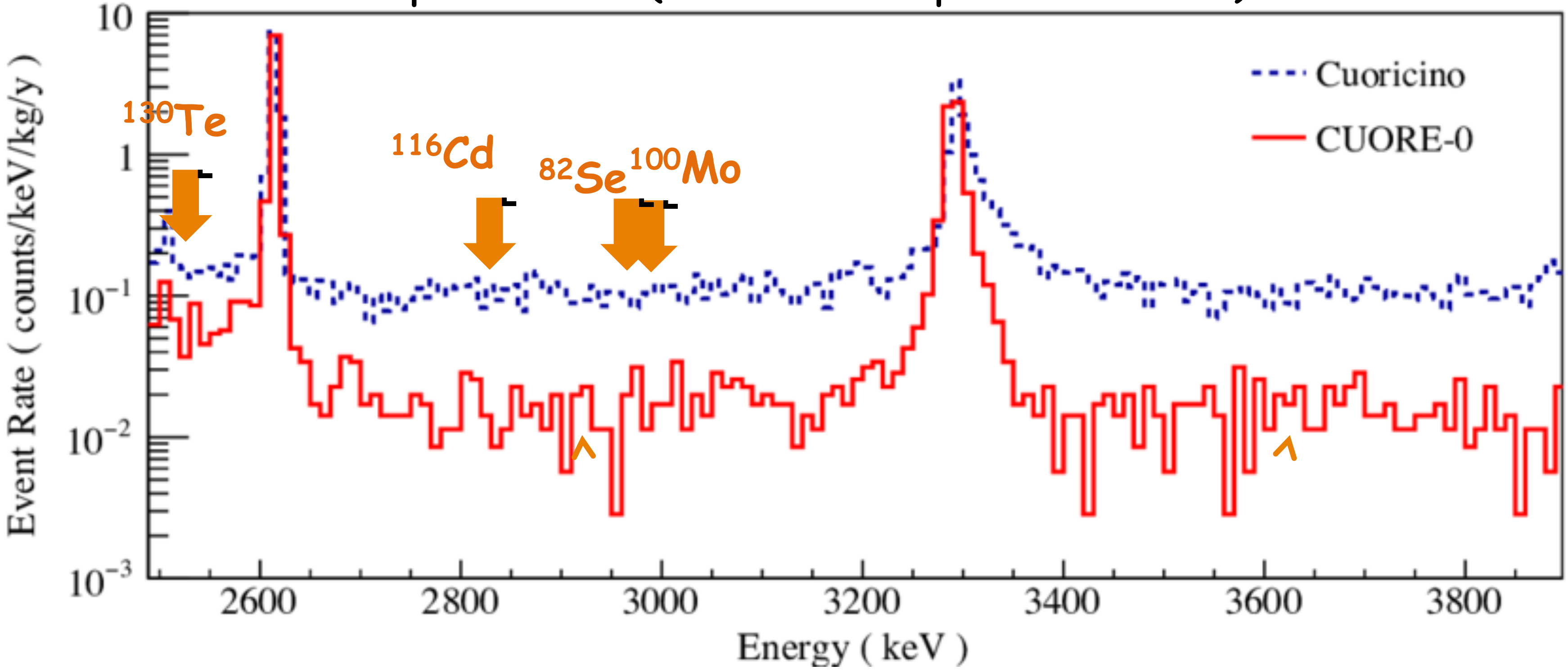
NO !!

CUORE will not be a zero-background search (~50 counts/y expected in the ROI)

WHY ??

Residual surface α background

Lessons learned from TeO_2 bolometric experiments (CUORE and predecessors)



Irreducible background due to **alpha particles**, emitted at the **surfaces** and energy-degraded

***b* ~ 10^{-2} [counts/(keV kg y)]**

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Luminescent bolometers: the solution!

> Scintillation
> Cherenkov light

Bolometric technique (**CUORE, EDELWEISS…**) + Simultaneous detection of heat and light (**CRESST**)

Choice of the candidate: **Golden or almost golden isotope**

"zero" **gamma** background

Full α/β separation

"zero" **alpha** background

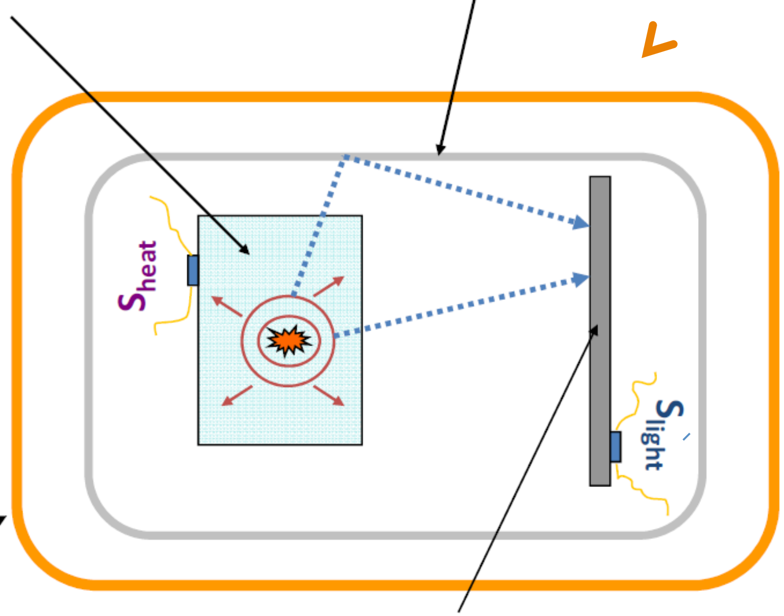
= **zero background** at the ≈ **1 ton x year scale**

- First proposal (scintillation): **L. Gonzalez-Mestres and D. Perret Gallix** (1988)
- First demonstration (in the 0ν2β context): **E. Fiorini's group (Milano) in 1992**
- First optical bolometer: **N. Coron's group (IAS, Orsay) in 1995**
- **Extensive application in Dark Matter** for electron/nuclear recoil separation (CRESST)
- First proposal (Cherenkov): **T. Tabarelli de Fatis** (2010)

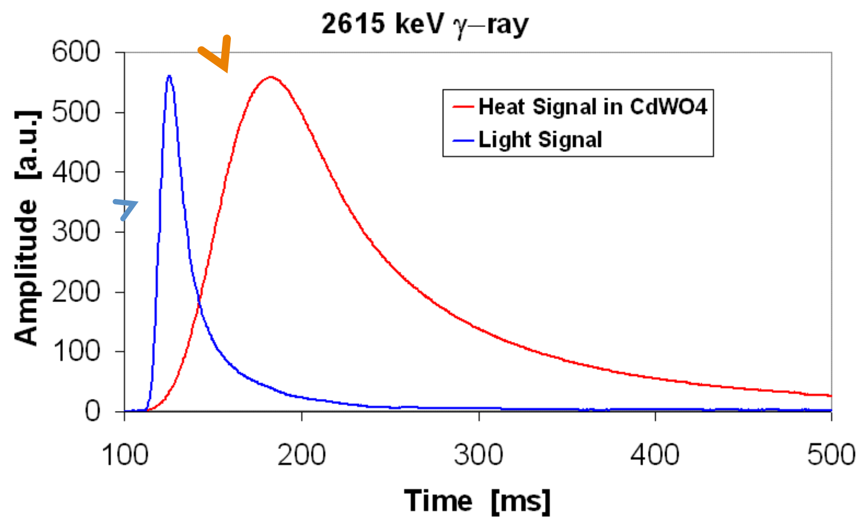
Double bolometer for heat and light

The most convenient method to realize a light detector at low temperatures is the development of an **auxiliary bolometer**, made with a thin absorber opaque to the light emitted by the **main bolometer**, and facing one polished side of it.

Luminescent bolometer



Actual light and heat signals acquired with a **$CdWO_4$** scintillating bolometer

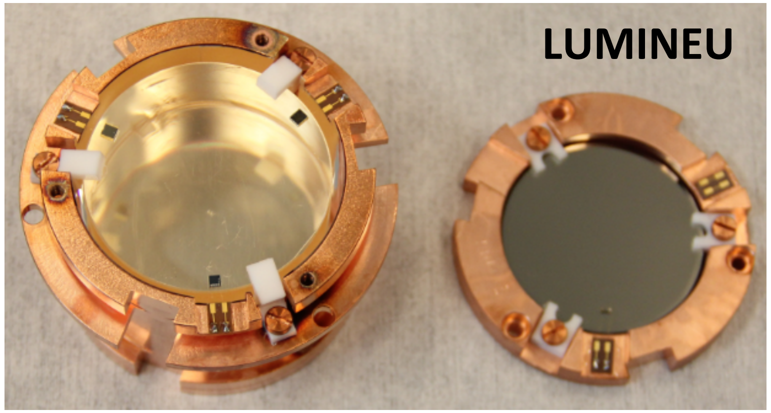


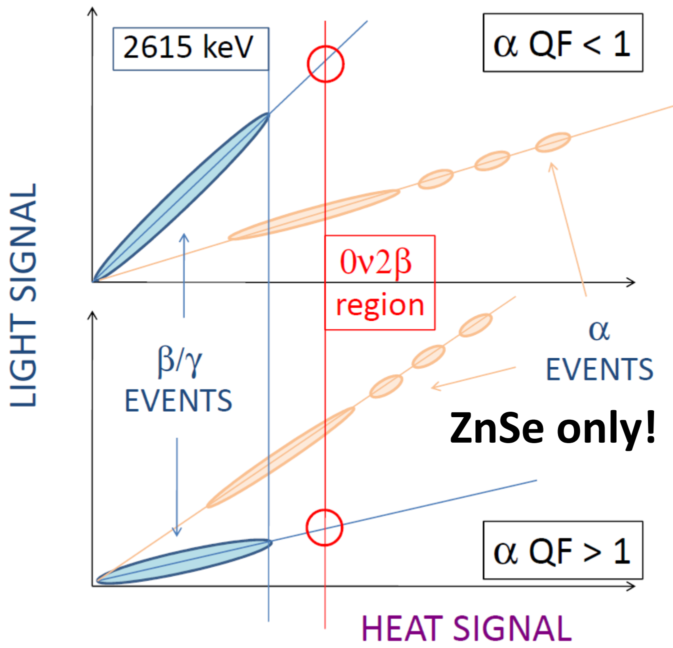
α / β separation

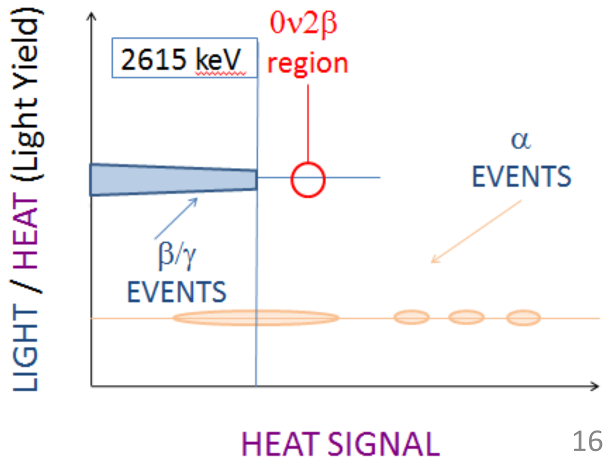
α's emit a different amount of light with respect to β/γ of the same energy
Separation can be achieved also with **pulse shape discrimination** in the light signal (ex. **ZnSe**)

A **scatter plot light vs. heat** or **plot light-yield vs. heat** separates α's from β's / γ's

Example of a luminescent bolometer with bolometric light detector







Extensive bolometric test of $0\nu2\beta$ candidates

Nucleus	I. A. [%]	Q-value [keV]	Materials successfully tested as bolometers in crystalline form (**underlined compounds: scintillators**)
^{76}Ge	7.8	2039	Ge
^{136}Xe	8.9	2479	NONE
^{130}Te	33.8	2527	TeO_2 ← Cherenkov + scintillation; **TeO_2 is a very weak scintillator**
^{116}Cd	7.5	2802	$CdWO_4$, $CdMoO_4$
^{82}Se	9.2	2995	ZnSe, $LiInSe_2$
^{100}Mo	9.6	3034	$PbMoO_4$, $CaMoO_4$, $SrMoO_4$, $CdMoO_4$, $SrMoO_4$,, $ZnMoO_4$,Li_2MoO_4, $MgMoO_4$
^{96}Zr	2.8	3350	ZrO_2
^{150}Nd	5.6	3367	NONE → many attempts
^{48}Ca	0.187	4270	CaF_2, $CaMoO_4$

Most of the compounds have been studied also as **luminescent bolometers**

- Pioneering work of S. Pirro and his group at LNGS
- LUCIFER group
- LUMINEU group
- AMoRE group

Luminescent bolometers are excellent candidates for the technology of CUPID, proposed follow-up of the CUORE experiment

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Current scenario

Increasing Q-value

^{130}Te →

Detection of Cherenkov light
Light detector technology

- TES-based
- NTD-Ge-thermistor based
- MKIDs based
- Neganov-Luke-effect assisted

^{116}Cd →

- Tests with natural crystals (Milano/LNGS group)
- First enriched crystal test (CSNSM-IRFU)

^{82}Se →

- LUCIFER program

↓

CUPID-0 experiment

^{100}Mo →

- **AMoRE experiment**
- LUMINEU / LUCIFER

↓

CUPID-Mo experiment

Current scenario

Covered in this conference

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CUPID-0 experiment < · *Talk of Nicola Casali*

^{100}Mo →

- **AMoRE experiment**
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CUPID-Mo experiment < ·*Talk of Andrea Giuliani*

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Covered in this conference

Covered in this talk

^{130}Te →

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CUPID-0 experiment < · *Talk of Nicola Casali*

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The case of ^{130}Te

Cherenkov light emission induced by $\gamma(\beta)$ interactions in TeO_2 is expected

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

Cherenkov thresholds:

$E_e > 50$ keV

$E_\alpha > 400$ MeV

@ ^{130}Te $Q_{\beta\beta}$ (~2.5 MeV)

~ 220 Cherenkov photons (300-900 nm) → **~600 eV**

No Cherenkov photons from natural α radioactivity

In real life, for TeO_2 CUORE-size crystals (5x5x5 cm^3), collected light corresponds to a total energy of **~100 eV**

Discrimination Power (DP) (to quantify α/β separation) ➡

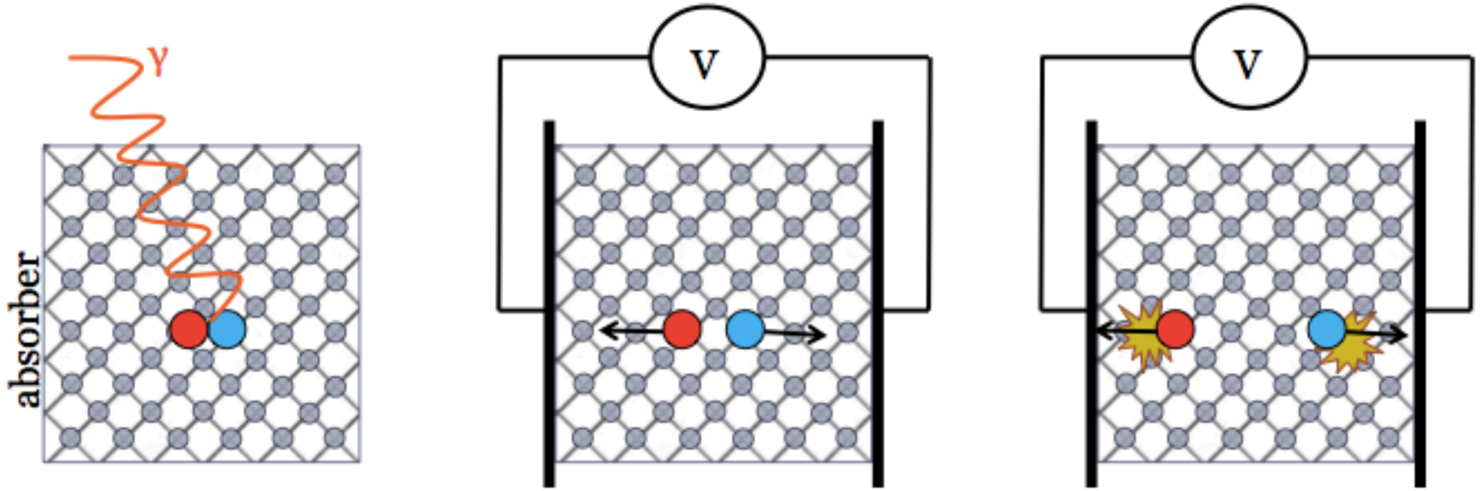
$$DP = \frac{|\mu_{\beta/\gamma} - \mu_\alpha|}{\sqrt{\sigma^2_{\beta/\gamma} + \sigma^2_\alpha}}$$

Vibrant R&D activities (variegate technologies)

Crystal	LD sensor	LD RMS [eV]	DP	
TeO_2, 6 g	NTD Ge	n.a.	4.70	*Phys. Rev. C 94 (2016) 054608*
TeO_2, 23 g	TES IrAu	8	3.59	*J. Instrum. 10 (2015) P03003*
TeO_2, 117 g	NTD Ge*	97	1.37	*Astropart. Phys. 35 (2012) 558*
TeO_2, 285 g	TES W*	23	3.69	*Astropart. Phys. 69 (2015) 30*
TeO_2, 750 g	NTD Ge	19	2.70	*J. Low Temp. Phys. 184 (2016) 286*
$^{130}TeO_2$, 435 g	NTD Ge	35	2.65	*Phys. Lett. B 767 (2017) 321-329*
$^{130}TeO_2$, 435 g	NTD Ge	25	3.50	

Neganov-Luke effect + NTD Ge thermistor readout

Goal : get full event-by-event α/β separation with the same read-out as in CUORE and the same crystal size presently adopted in CUORE



The absorption of photons produces *electron-hole pairs*

The electric field *drifts the charges and it prevents their recombination*

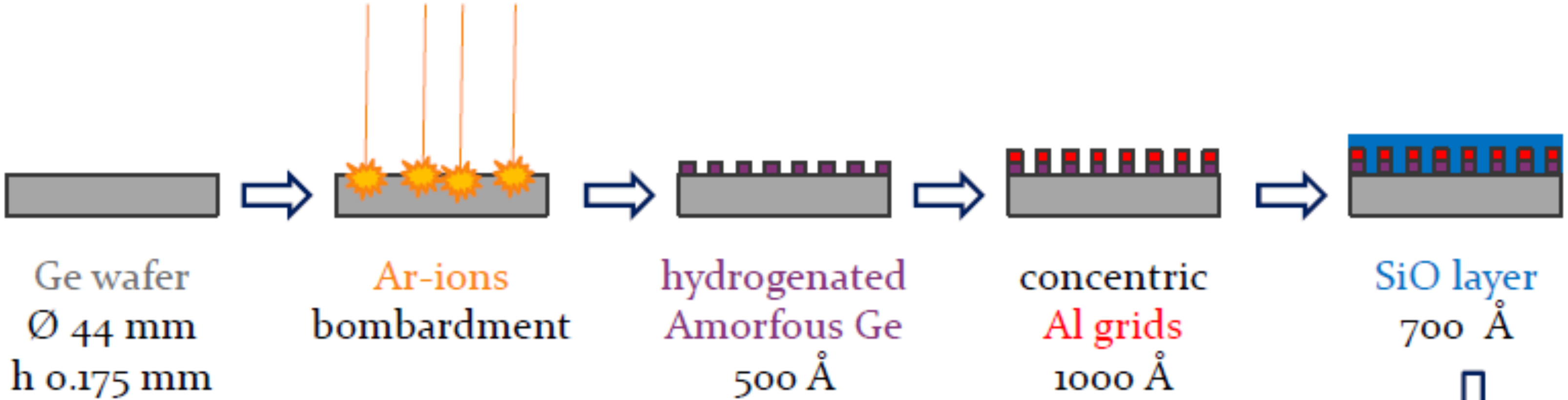
Carriers *collide with the lattice during the drift, increasing the temperature*

$$E = E_0 \cdot \left(1 + \frac{q \cdot V}{\varepsilon}\right)$$

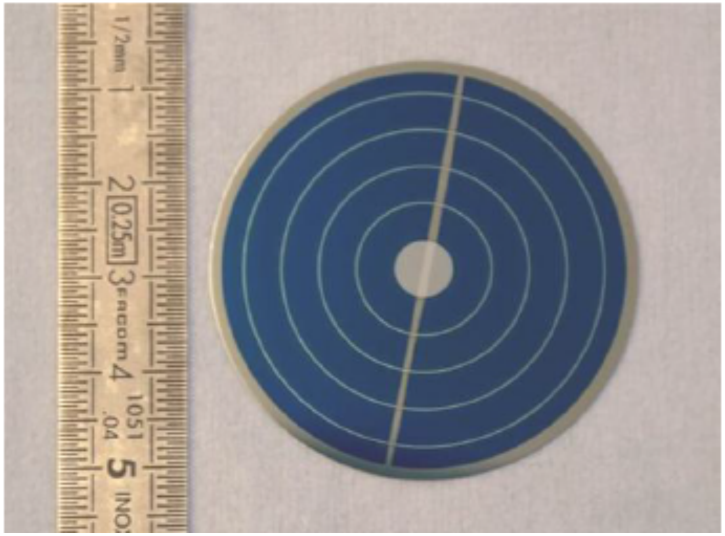
q electron charge
V voltage applied
ε energy used to produce an electron-hole pair

Light detector fabrication

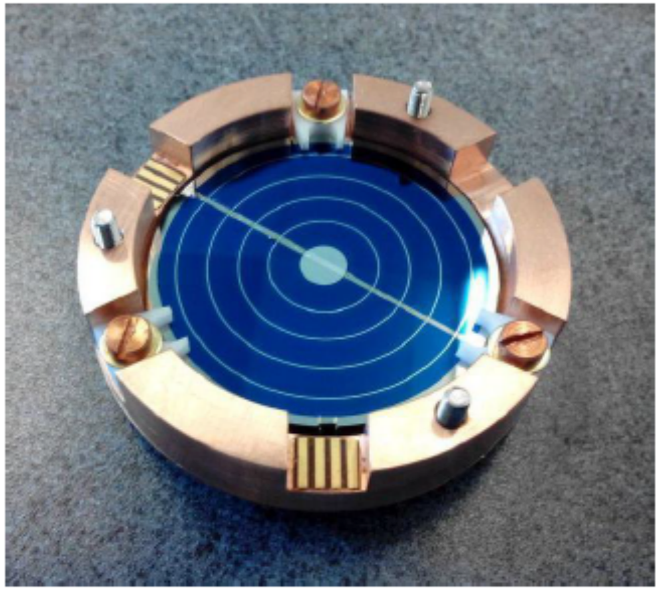
Development of Neganov-Luke light detectors at **CSNSM** using **EDELWEISS electrode technology** → Dedicated evaporators for Al and SiO films

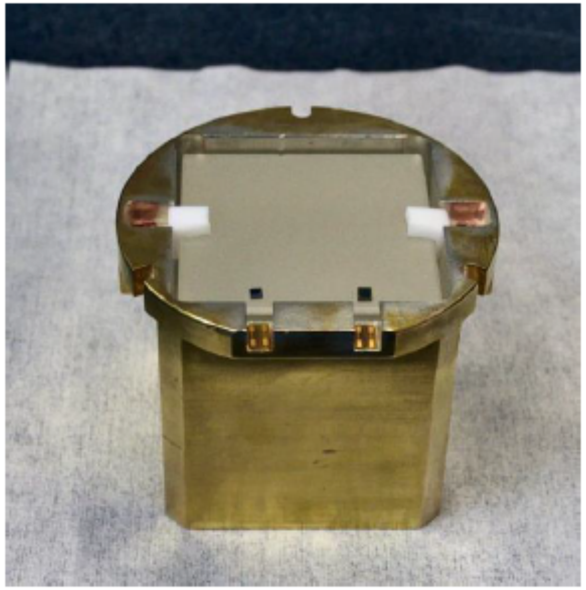


GeCo1
(**Germanium Coated**)



Test with a CUORE-size crystal at Modane underground laboratory





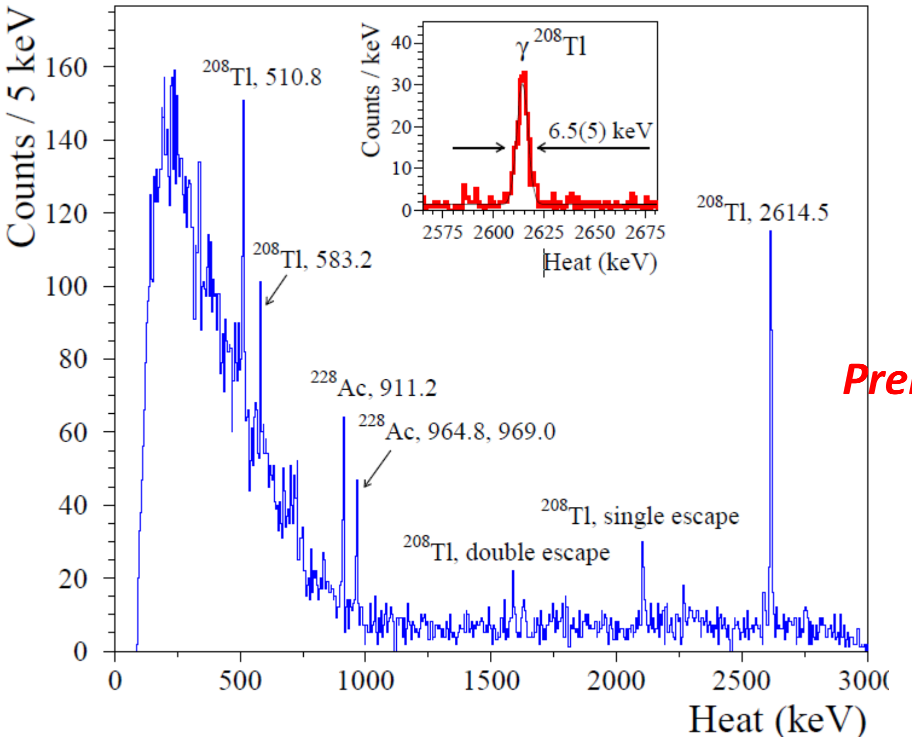
GeCo1 has also been tested coupled to a natural TeO_2 crystal (784 g) at a working temperature of 17 mK

This test has been performed in Laboratoire Souterrain de Modane (LSM, France)

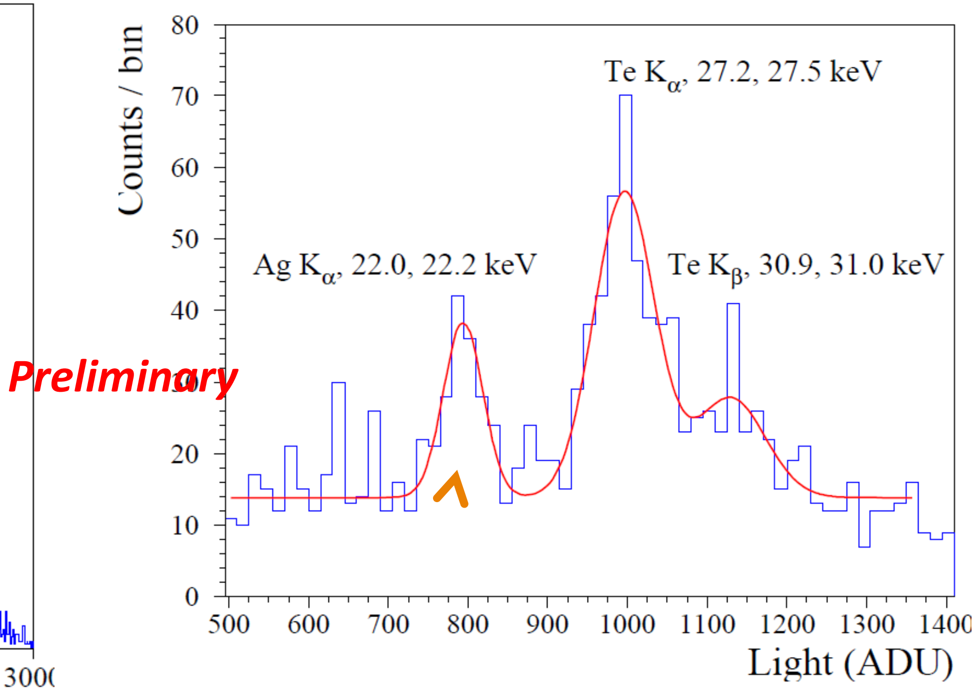
EDELWEISS set-up

Separated heat/light calibrations

Heat channel – ^{232}Th calibration



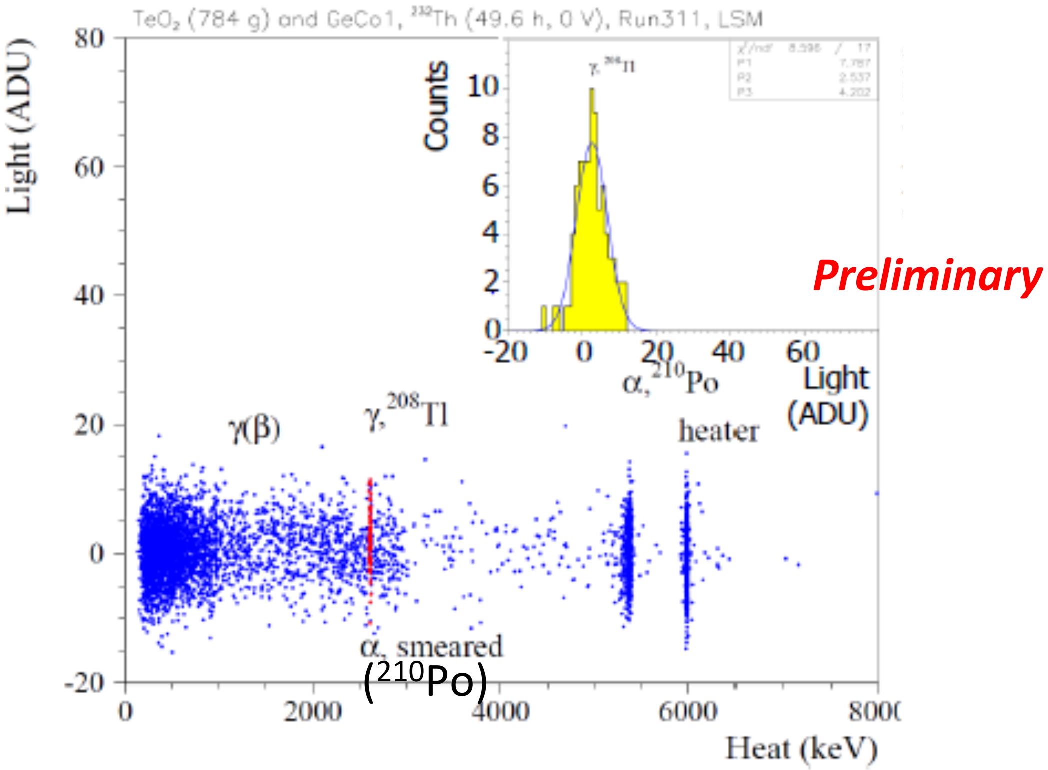
Light channel – X-ray fluorescence calibration (Zero bias on Neganov-Luke electrodes)



Detector holder internally coated with silver

α/β separation

Neganov-Luke voltage = 0 V



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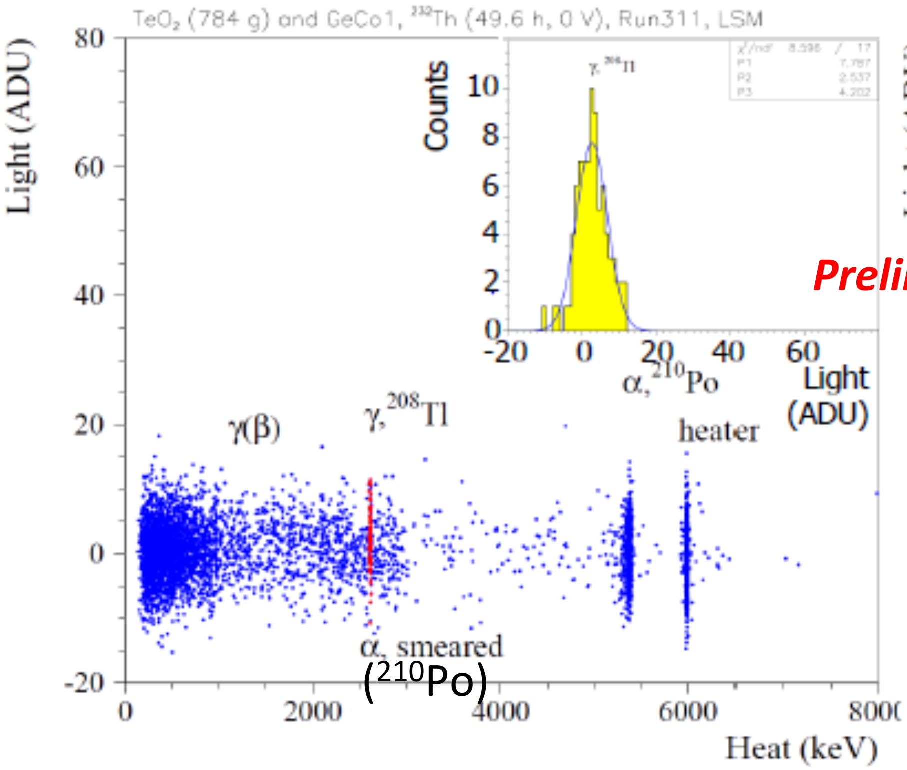
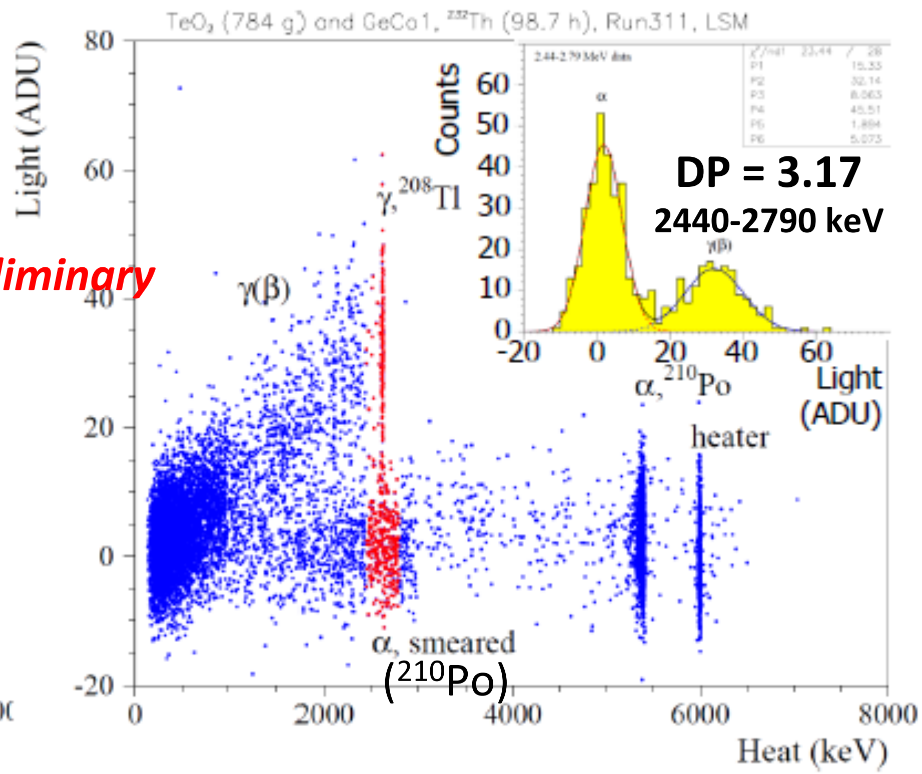


Neganov-Luke voltage = 60 V
(optimum performance)

Preliminary



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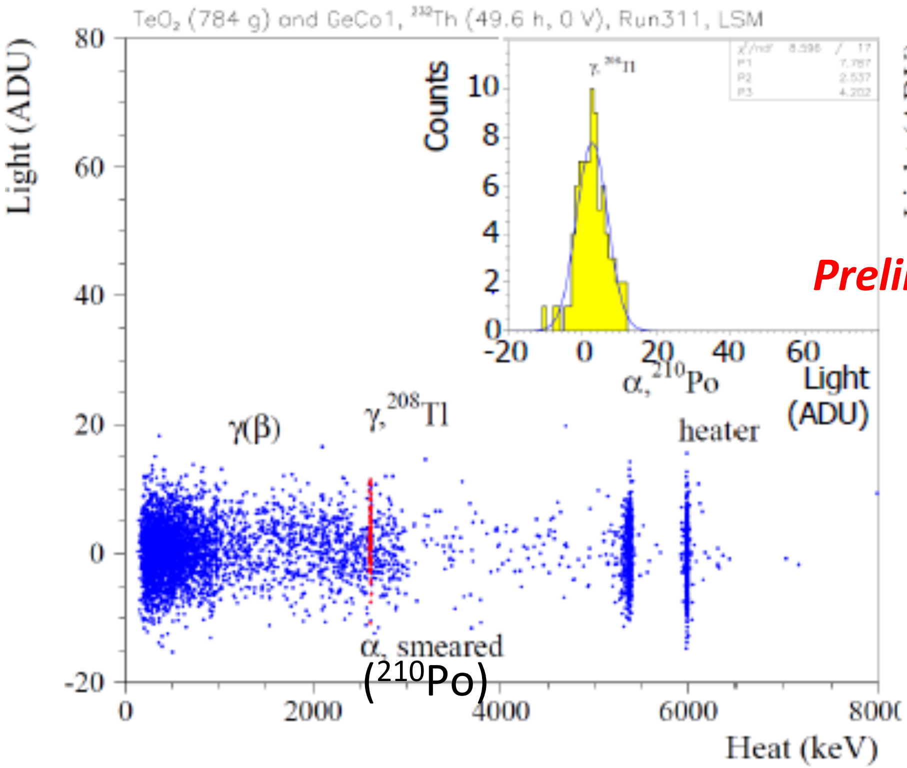
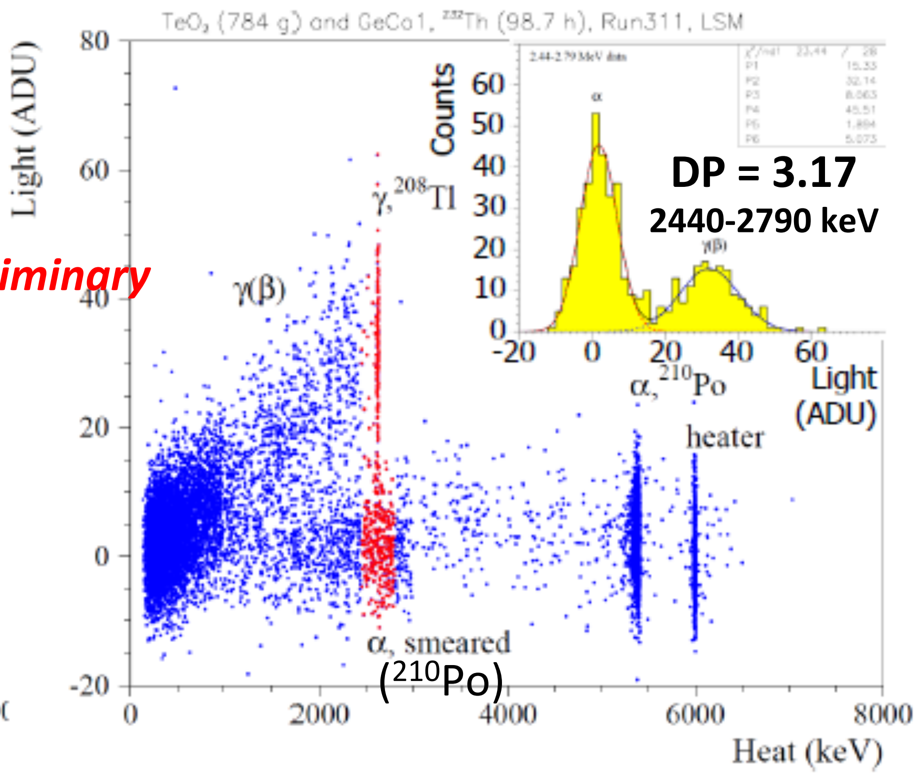


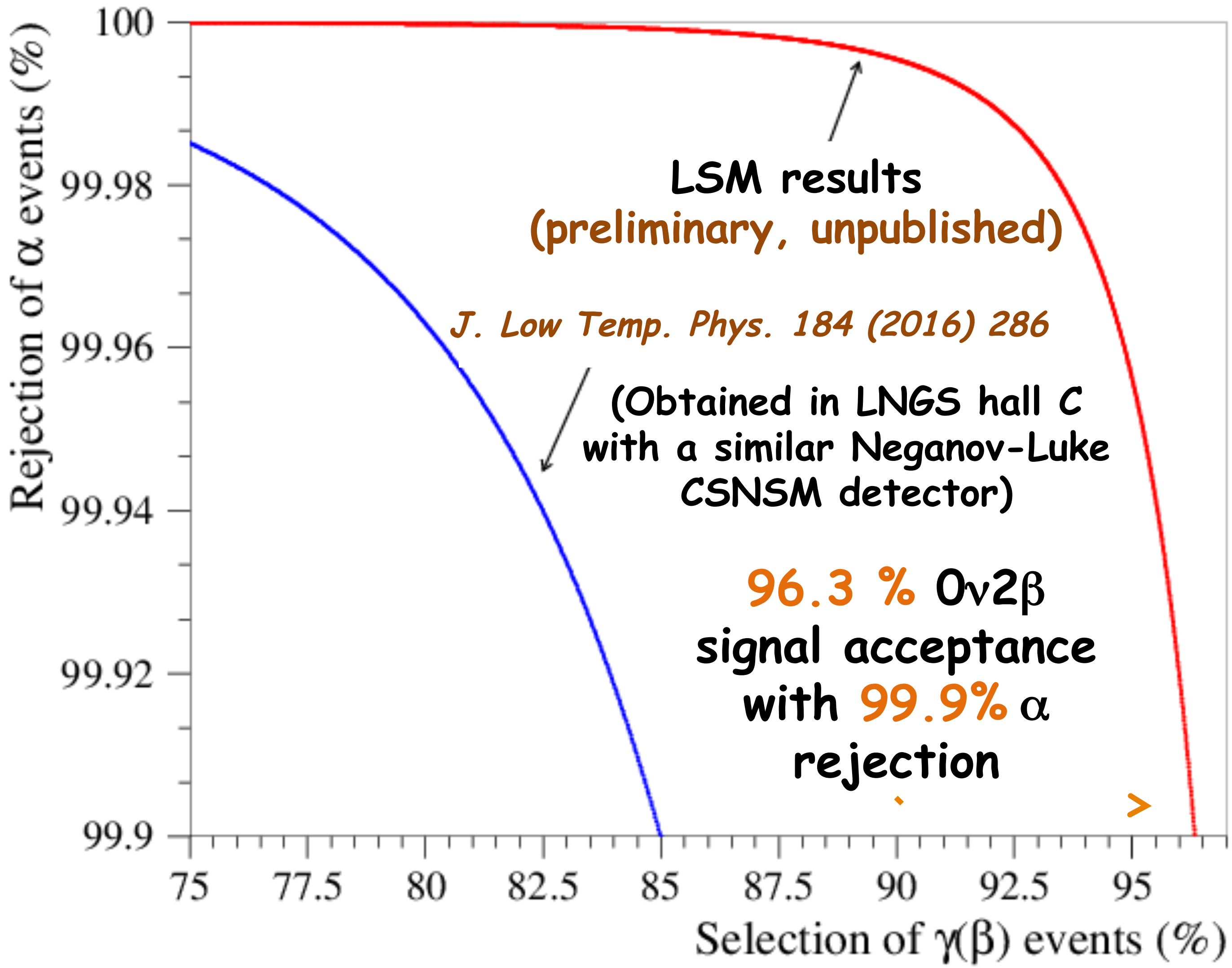


Preliminary

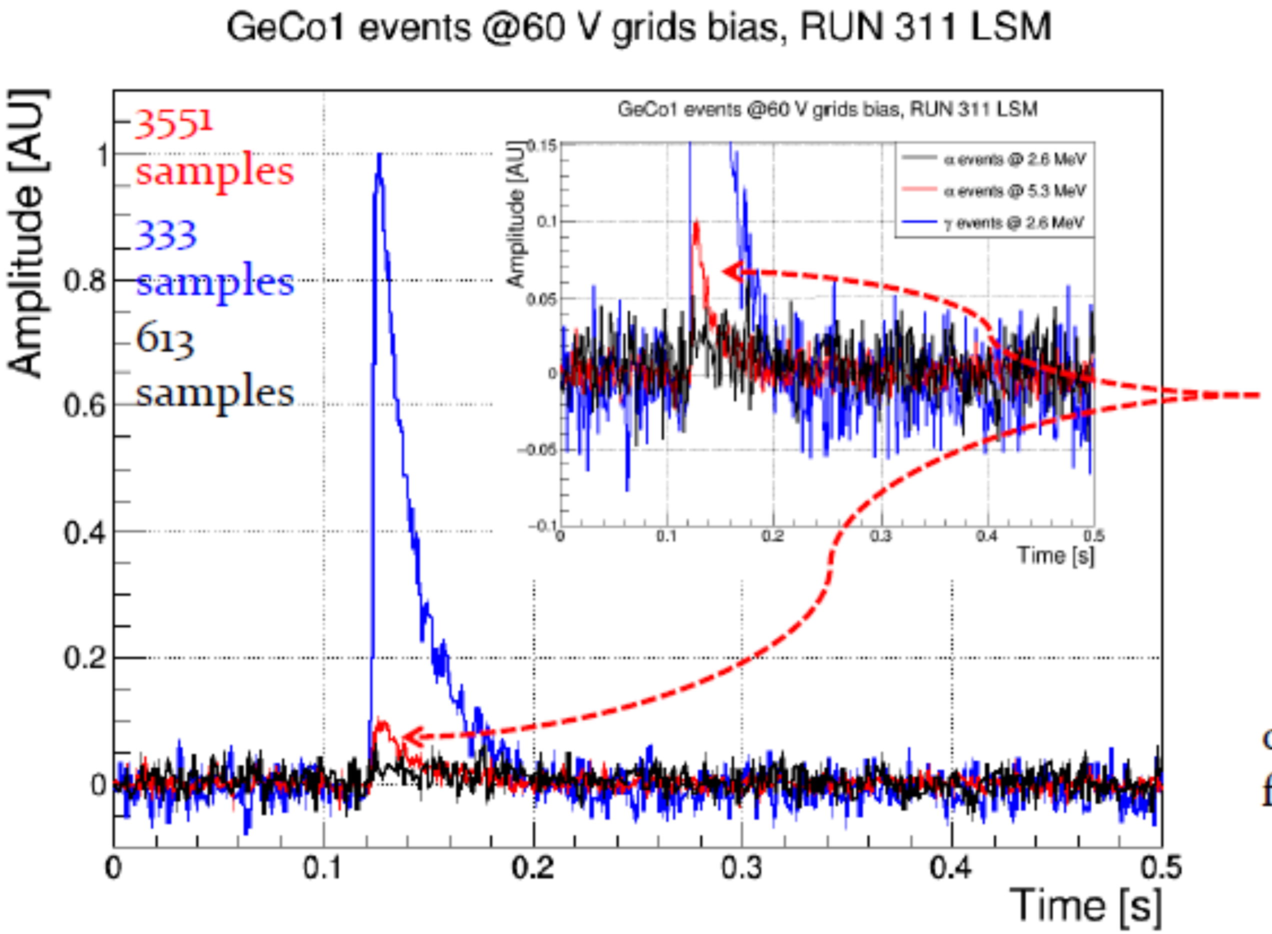
Grids bias	Baseline RMS	Signal/Noise
0 V	108 eV	0.6
60 V	10 eV	7

α/β separation

The best result ever obtained with a CUORE-size TeO_2 crystal



Not only Cherenkov light...



Averaging many events to reduce the baseline noise...

Scintillation light of αs emitted by ^{210}Po

If we consider a quenching factor of 0.2 for α-induced light, the ~20% of light is due to the scintillation

First hint of TeO_2 scintillation: ***Nucl. Instrum. Meth. A 520(1–3) (2004) 159–162***

(N. Coron's group (IAS, Orsay))

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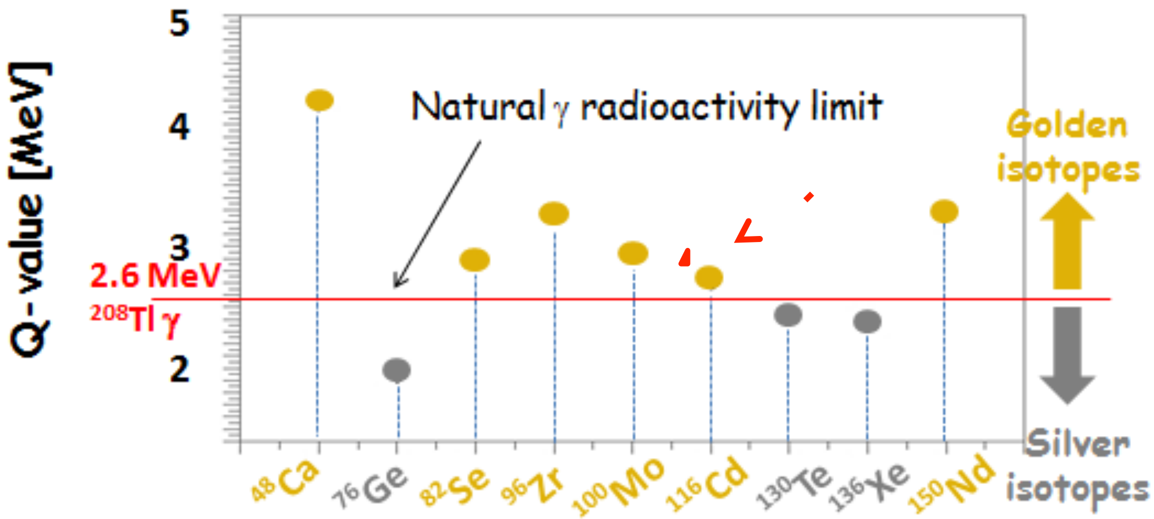
The case of ^{116}Cd



- $^{116}Cd \rightarrow {}^{116}Sn + 2e^-$
- Q_{bb} = **2814 keV**
- I.A.(100) = 7.5 %
- enrichable by gas centrifugation
- $CdWO_4$ crystals routinely produced on an industrial basis

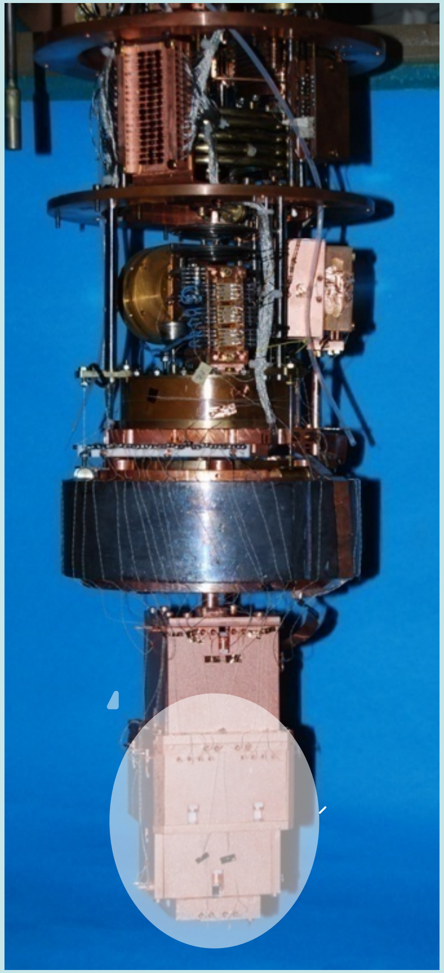
Caveats ^{113}Cd

- Enrichment cost at least a factor 2 higher than ^{100}Mo, ^{82}Se, ^{130}Te
- ^{214}Bi line at 3054 keV – B.R. 0.021 % - Compton edge 2818 keV

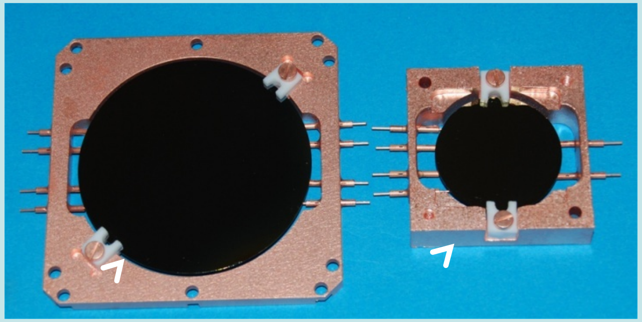
Historical results on $CdWO_4$ scintillating bolometers

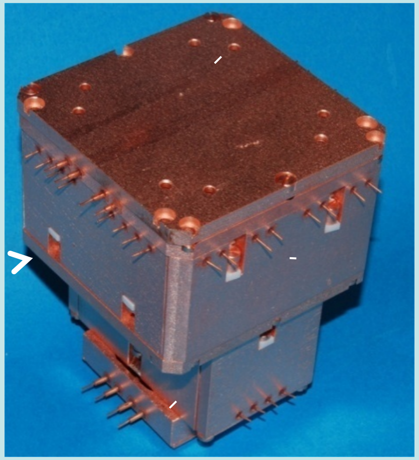
Tests performed in LNGS

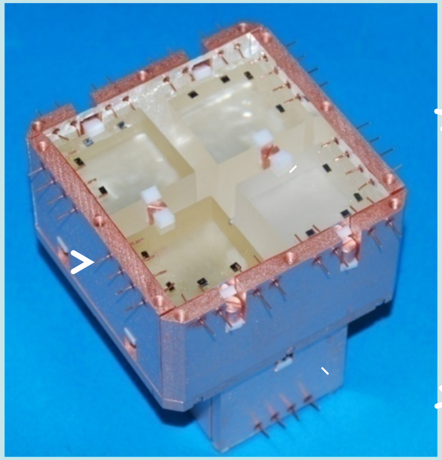
Astropart. Phys. 34 (2010) 143



Light Detector



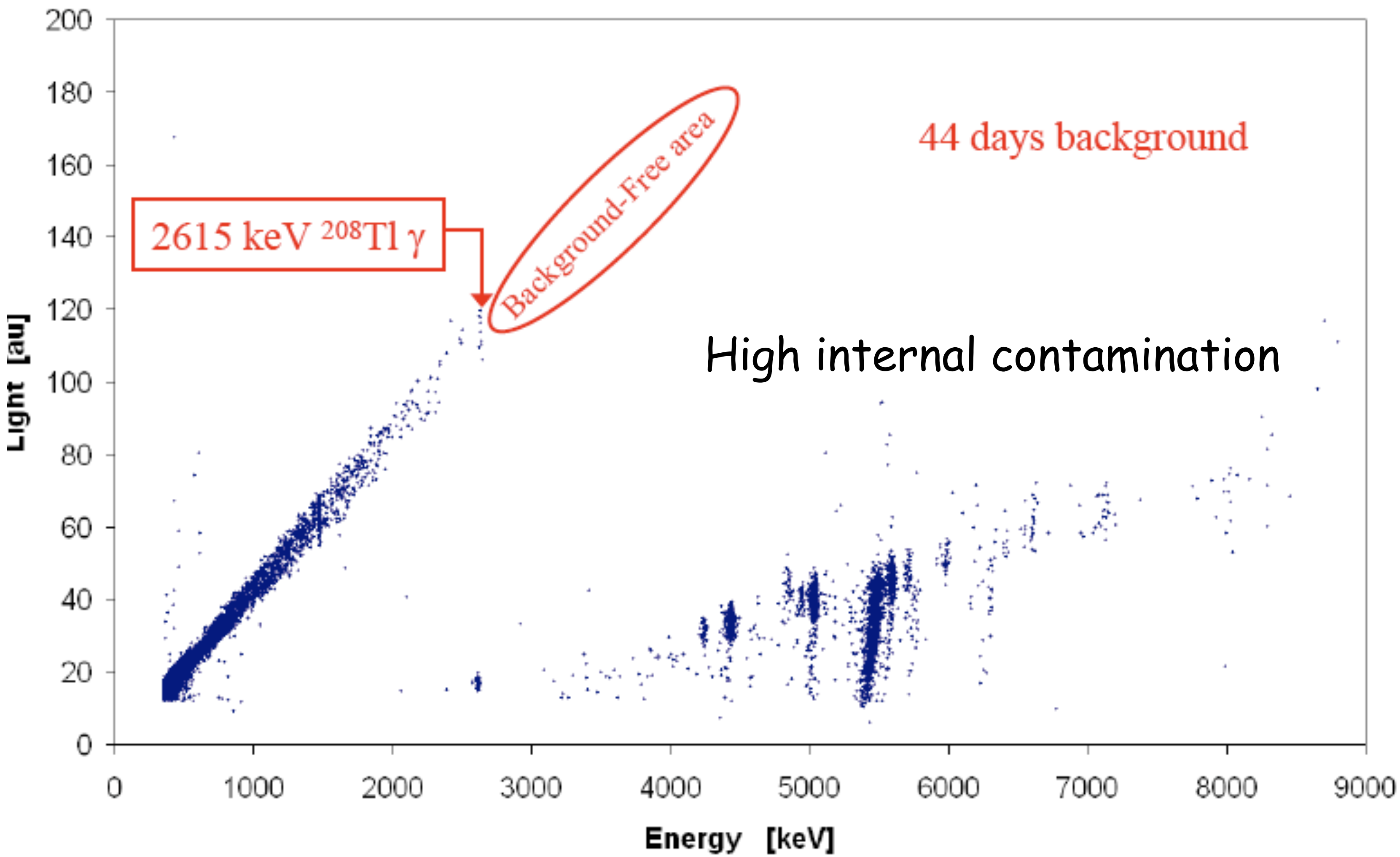




3x3x3 cm $CdWO_4$

3x3x6 cm $CdWO_4$

Historical results on $CdWO_4$ scintillating bolometers

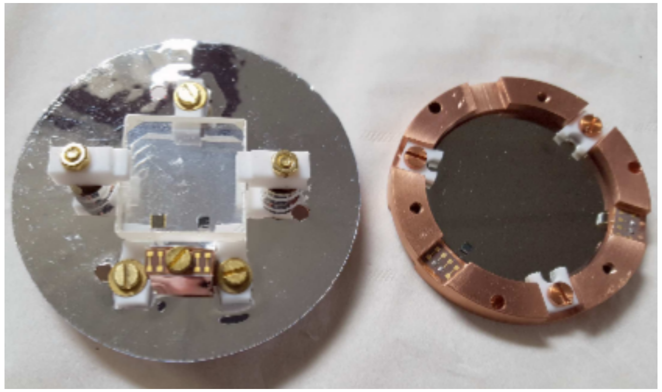


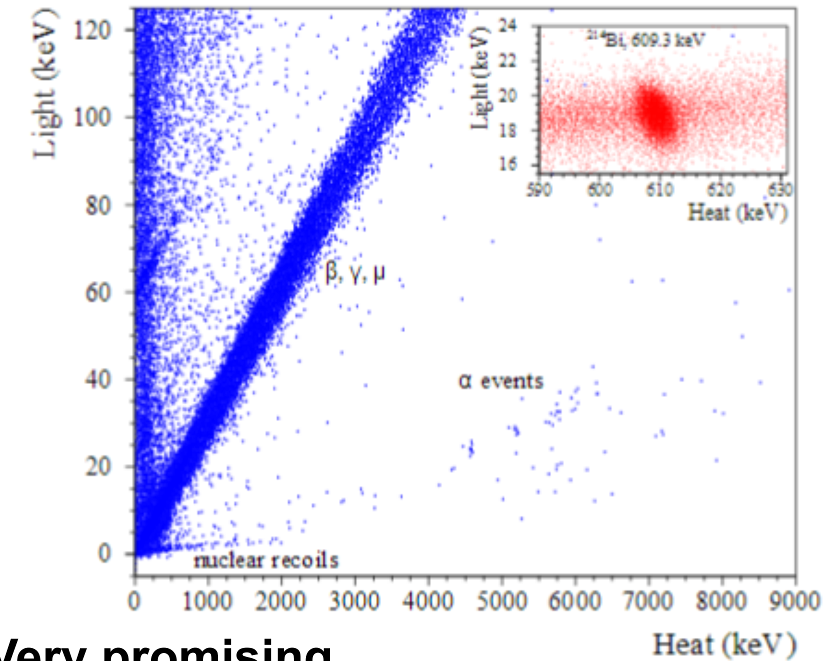
First results on an enriched $^{116}CdWO_4$ scintillating bolometer

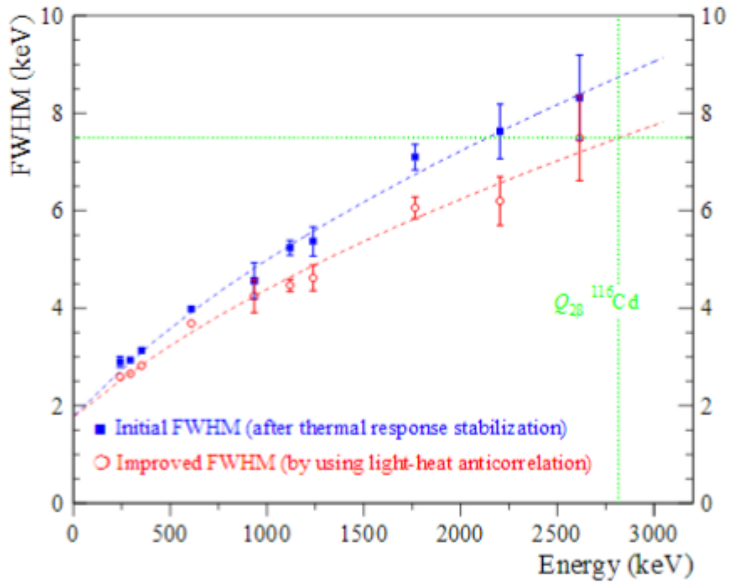
Aboveground test (CSNSM) of a 32 g enriched $CdWO_4$ detector

Very good energy resolution: **7.5 keV FWHM**
Excellent α/β separation

Double crystallization by low-thermal gradient Czochralski technique → excellent radiopurity







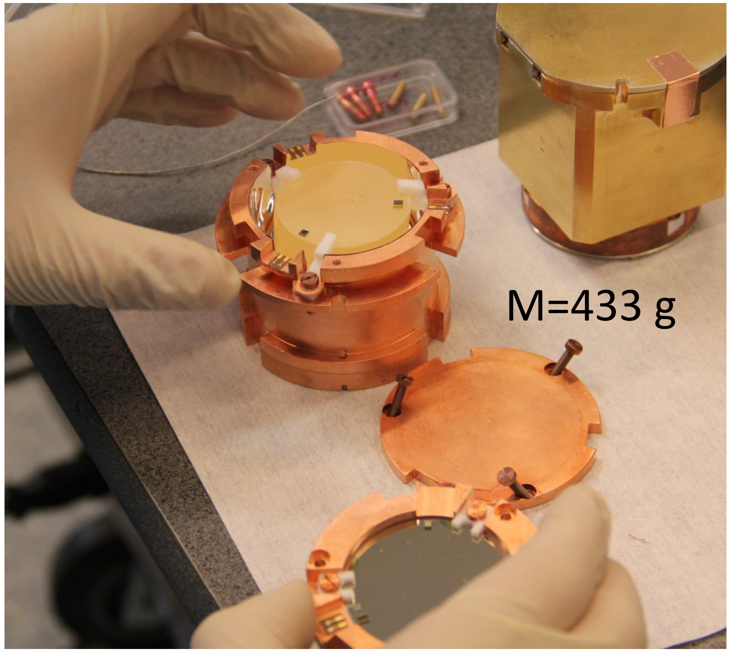
Very promising

Eur. Phys. J. C 76, 487 (2016)

Pilot experiment with $^{116}CdWO_4$ scintillating bolometers

CYGNUS project

- Use existing **radiopure $^{116}CdWO_4$ enriched crystals** (ITEP Moscow, KINR Kiev)
- Total mass **1.16 kg**
- Array of two or four elements to be installed in LSM (together with CUPID-Mo)



From the total background budget (Monte Carlo simulation of the EDELWEISS set-up):

$b = 2.4 \times 10^{-3}$ counts/(keV kg y)

dominated by **cosmogenic ^{110m}Ag**

3 y data taking: $T_{1/2}$ **> 8.2x10^{23} yr** at 90% C.L. The half-life limit corresponds to the effective neutrino mass limit $m_{\beta\beta}$ **< 0.6 - 0.9 eV**

Outline

Neutrinoless double beta decay: experimental challenges

Merits and limits of the pure bolometric technique

Advantages offered by luminescent bolometers

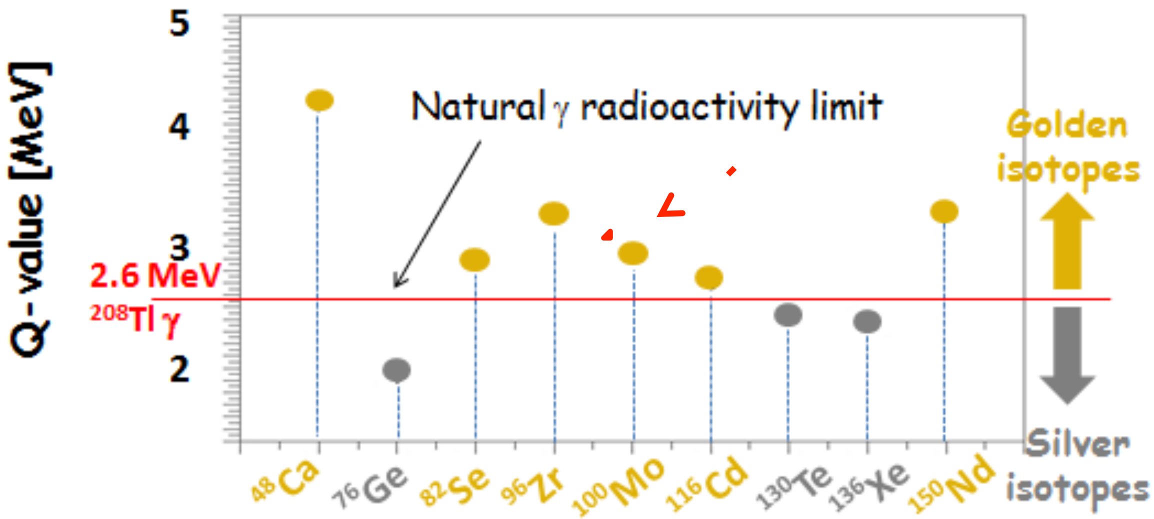
Present scenario of luminescent bolometers for double beta decay

Detection of Cherenkov light in TeO_2 bolometers

$^{116}CdWO_4$ program in France

Study of ^{100}Mo in the AMoRE project

The case of ^{100}Mo



- $^{100}Mo \rightarrow {}^{100}Ru + 2e^-$
- Q_{bb} = **3034 keV**
- I.A.(100) = 9.7 %
- enrichable by gas centrifugation

Caveats ^{100}Mo

- $T_{1/2}(2\nu) = 7.1 \times 10^{18}$ y – the fastest one in all $0\nu2\beta$ candidates
- ^{214}Bi line at 3054 keV – B.R. 0.021 % - Compton edge 2818 keV (less critical than for ^{116}Cd)

Useful Mo-based crystals

Crystals succesfully tested so far as scintillating bolometers:

$CdMoO_4$

$PbMoO_4$

$SrMoO_4$

$ZnMoO_4$

Li_2MoO_4

$CaMoO_4$

LUMINEU – CUPID-Mo
Initial choice (2012): $ZnMoO_4$
First tests on large Li_2MoO_4 crystals: spring 2014
Choice in favour of Li_2MoO_4

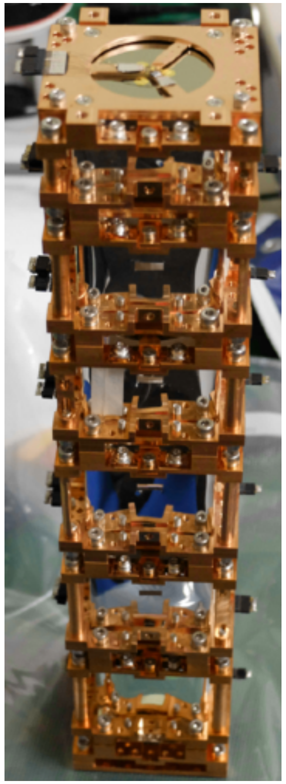
AMoRE

Advanced Mo-based Rare process Experiment

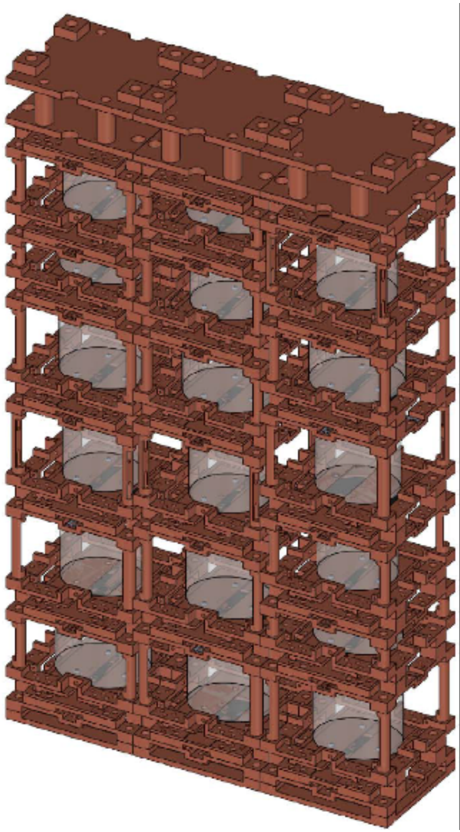
Drawbacks of $CaMoO_4$:
- ✓ Necessity of ^{48}Ca depletion
- ✓ Radiopurity (difficult to purify Ca from U, Th, Ra)

New crystals will be studied

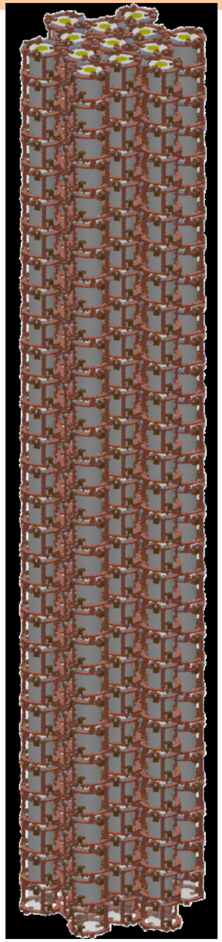
AMoRE-phased approach



AMoRE pilot
1.8 kg
now



AMoRE-I
5 kg
2018



AMoRE-II
200 kg
2020

From Yong-Hamb Kim's talk
Shanghai double beta decay workshop – June 2017

AMoRE-phased approach

- MMC technology for heat and light measurement
- Crystal: $^{40}Ca^{100}MoO_4$, doubly enriched scintillating crystals (Pilot & I)

  For Phase II: $X^{100}MoO_4$ (X: Li, Na, ^{40}Ca, Zn or Pb)
- Zero background condition in ROI
- Shield: Lead (Pilot, I), Water (II)
- Location: Y2L (Pilot, I) and a new deeper place (ARF at Handuk)

	Pilot	Phase I	Phase II
Mass	1.8 kg	~5 kg	~200 kg
MMC Channel	12	28-36	1000
Required background (ckky)	0.01	0.001	0.0001
Sensitivity($T_{1/2}$) (year)	$\sim10^{24}$	$\sim10^{25}$	$\sim5\times10^{26}$
Sensitivity(m_{ee}) (meV)	380-720	120-230	17-32
Location	Y2L	Y2L	ARF
Schedule	2017	2018-2019	2020-2022

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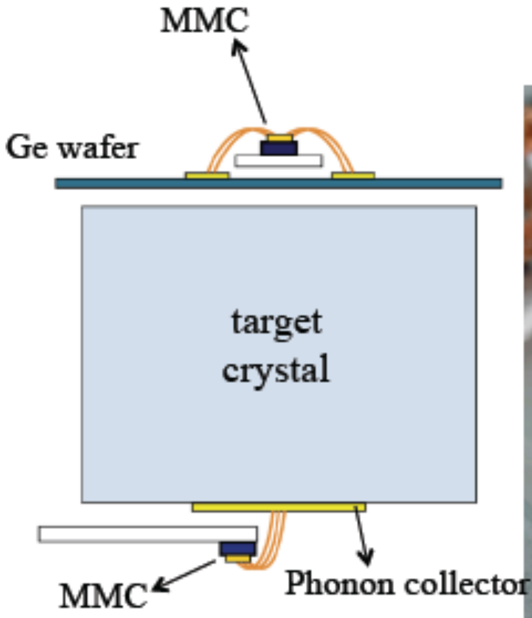
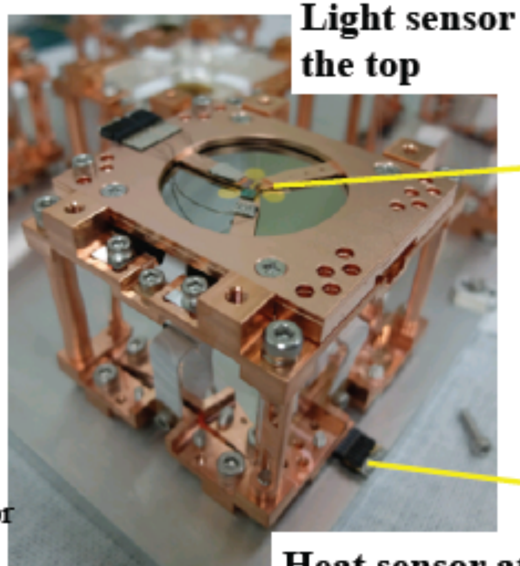
AMoRE-single module

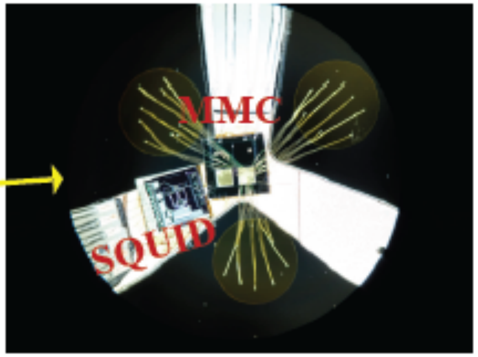
$^{40}Ca^{100}MoO_4$ + MMC

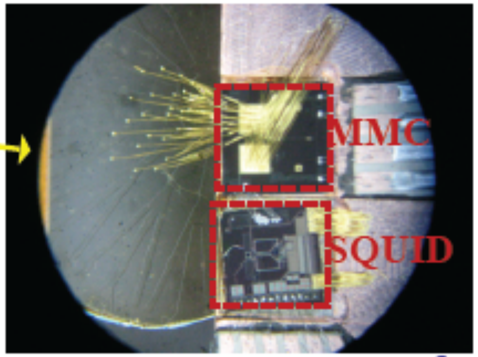
Phonon-Scintillation detection at mK





Light sensor at the top





Heat sensor at the bottom

Sensor technology Metallic Magnetic Calorimeter
SQUID readout

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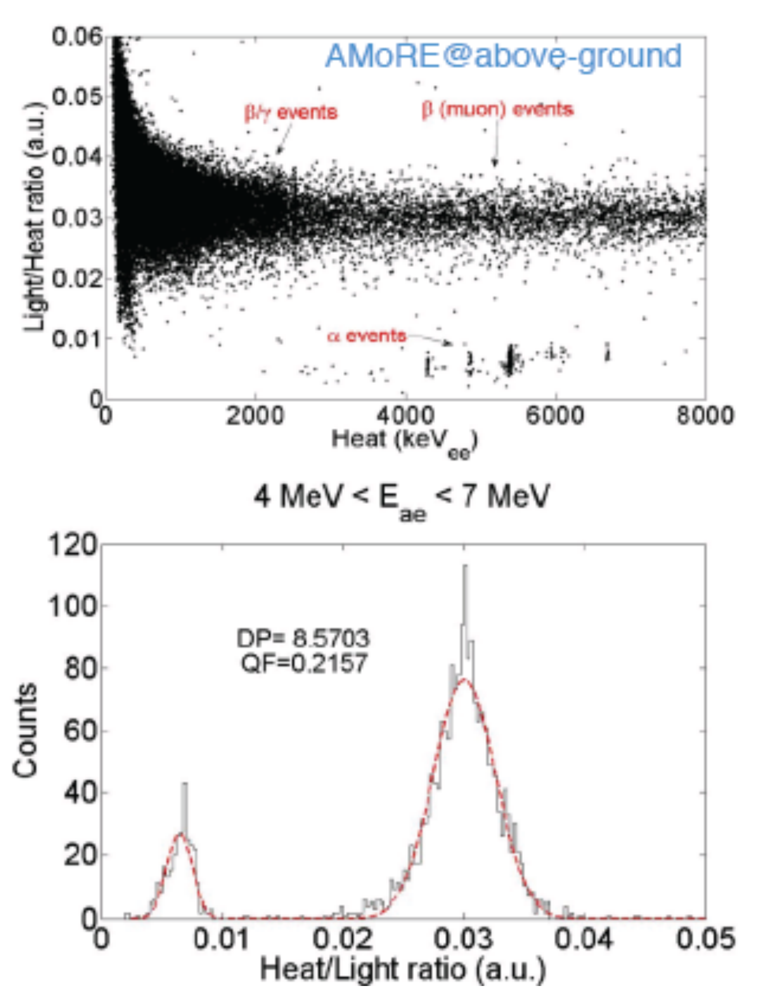
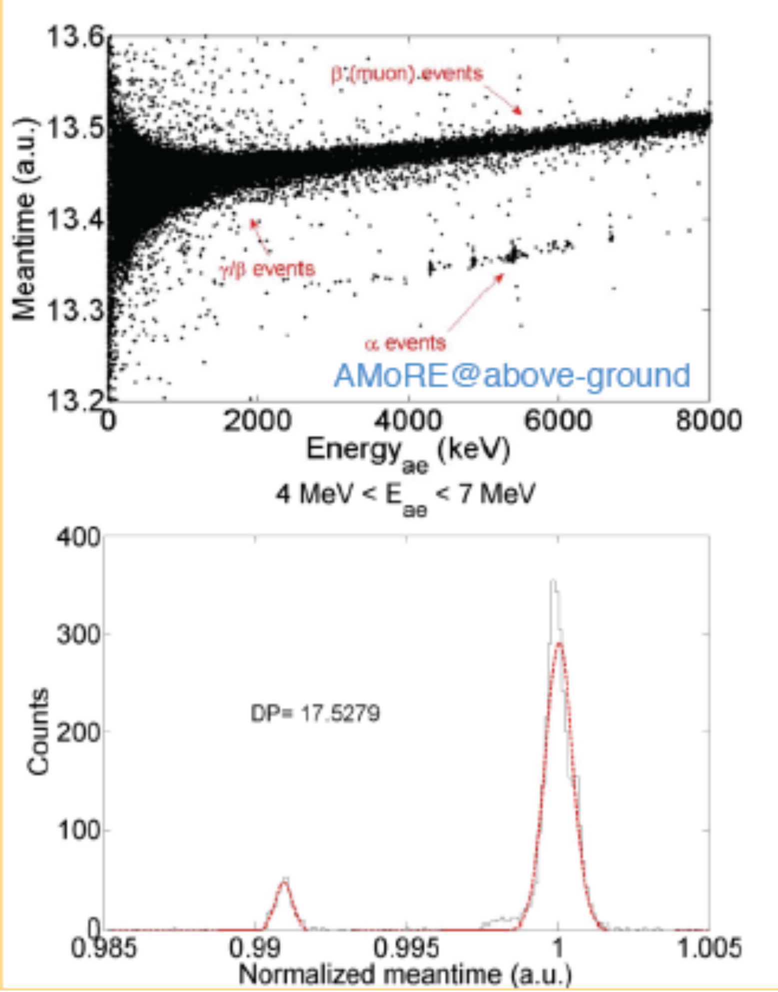
AMoRE-particle discrimination

Particle discrimination by light heat ratio



Phonon pulse shape discrimination (PSD)



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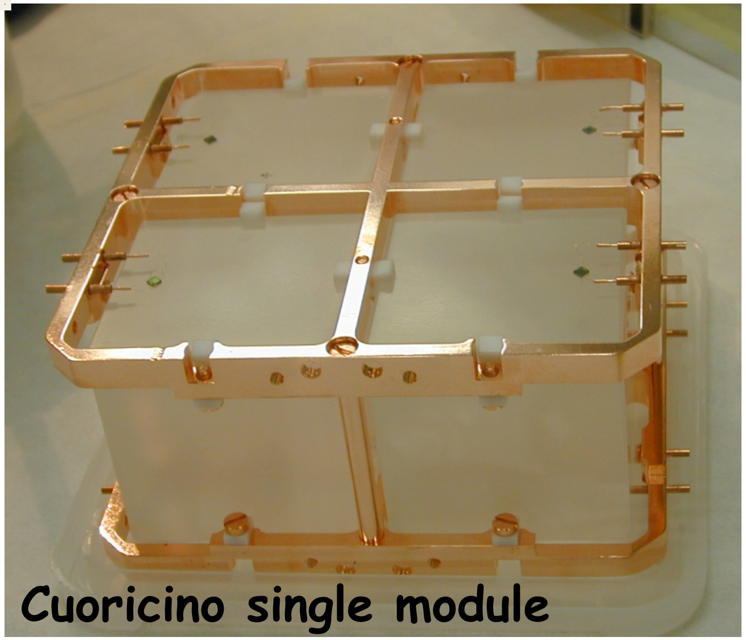
Conclusions

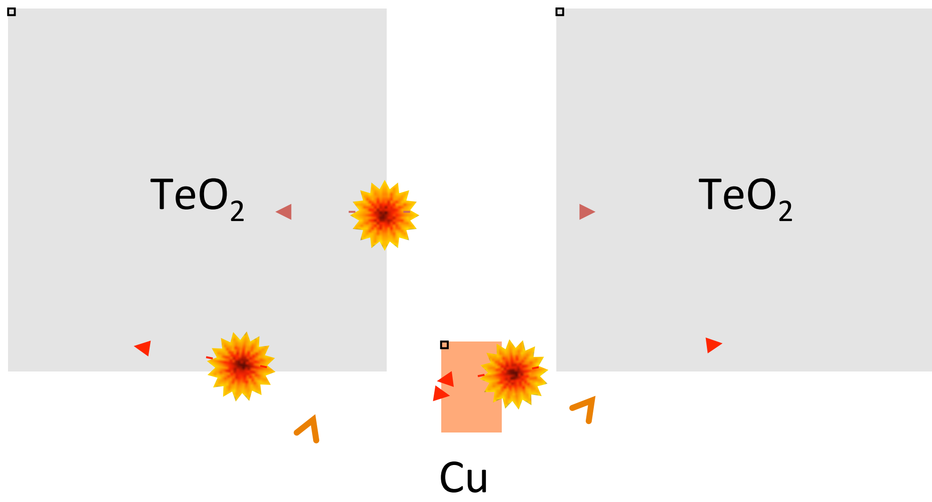
- α background is presently the limiting factor in bolometers for $0\nu2\beta$
- Luminescent bolometers have the potential to fully reject α events
- Luminescent bolometers are a mature technology: pilot experiments
  - **CUPID-0 (ZnSe)** → presently in data taking
  - **CUPID-Mo (Li_2MoO_4)** → data taking in 2018
  - **AMoRE-I ($CaMoO_4$ + $XMoO_4$)** → data taking in 2018
- Encouraging R&D results on $^{116}CdWO_4$ and TeO_2
- Large-scale projects are envisaged: **CUPID** and **AMoRE-II**

Mechanism of surface α background

Bolometers are fully sensitive, up to the detector surface → **no dead layer**

Shallow (up to **10 μm deep**) **surface contamination** (for example ^{210}**Po**) of the bolometers themselves or of the materials surrounding them emit **alpha particles**





Challenging events

They release in the detector only **a part of the α energy** and populate also the region above 2615 keV with a continuum