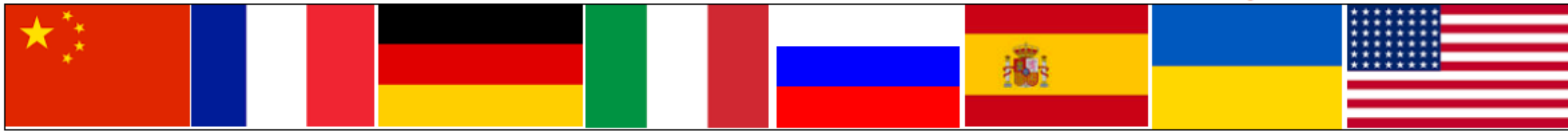
Cuore Upgrade with Particle IDentification

Toward a bolometric Inverted Hierarchy Explorer

Stefano Pirro
on behalf of the CUPID interest group

R&D towards CUPID: arXiv:1504.03612 CUPID : arXiv:1504.03599

The CUPID Interest Group



High Energy Physics Division, Argonne National Laboratory, Argonne, IL, USA
Materials Science Division, Argonne National Laboratory, Argonne, IL, USA
INFN - Laboratori Nazionali del Gran Sasso, Assergi (AQ), Italy
Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA, USA
Department of Nuclear Engineering, University of California, Berkeley, CA, USA
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Università di Bologna and INFN Bologna, Bologna, Italy
Massachusetts Institute of Technology, Cambridge, MA, USA
Department of Physics and Astronomy, University of South Carolina, Columbia, SC, USA
Technische Universität München, Physik-Department E15, Garching, Germany
Dipartimento di Fisica, Università di Genova and INFN - Sezione di Genova, Genova, Italy
Institute for Nuclear Research, Kyiv, Ukraine
INFN - Laboratori Nazionali di Legnaro, Legnaro, Italy
Lawrence Livermore National Laboratory, Livermore, CA, USA
Department of Physics and Astronomy, University of California, Los Angeles, CA, USA
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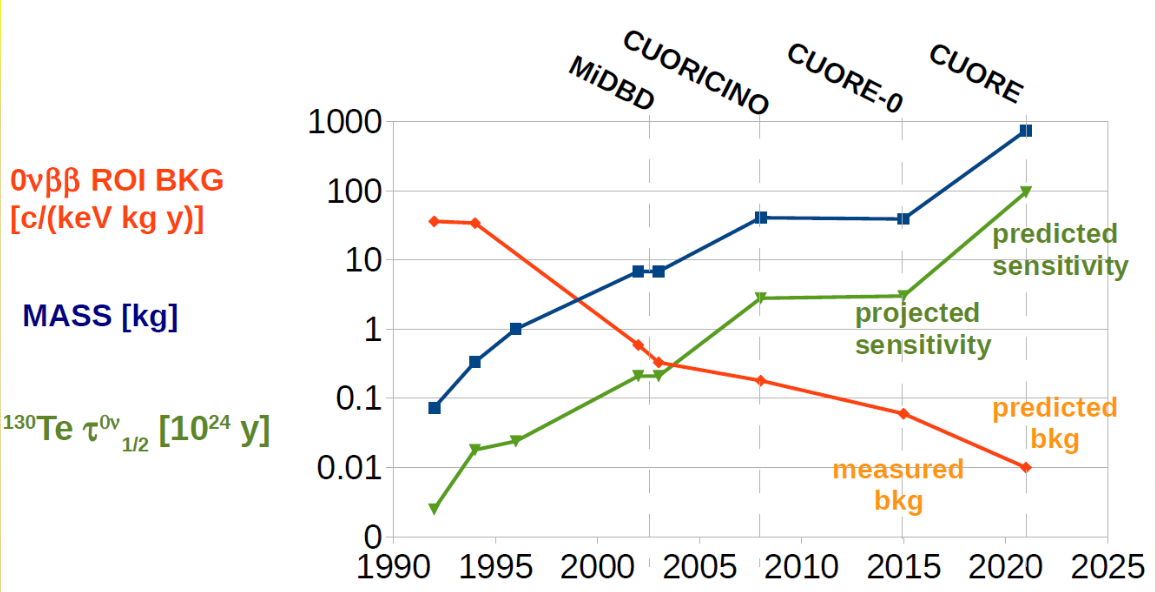
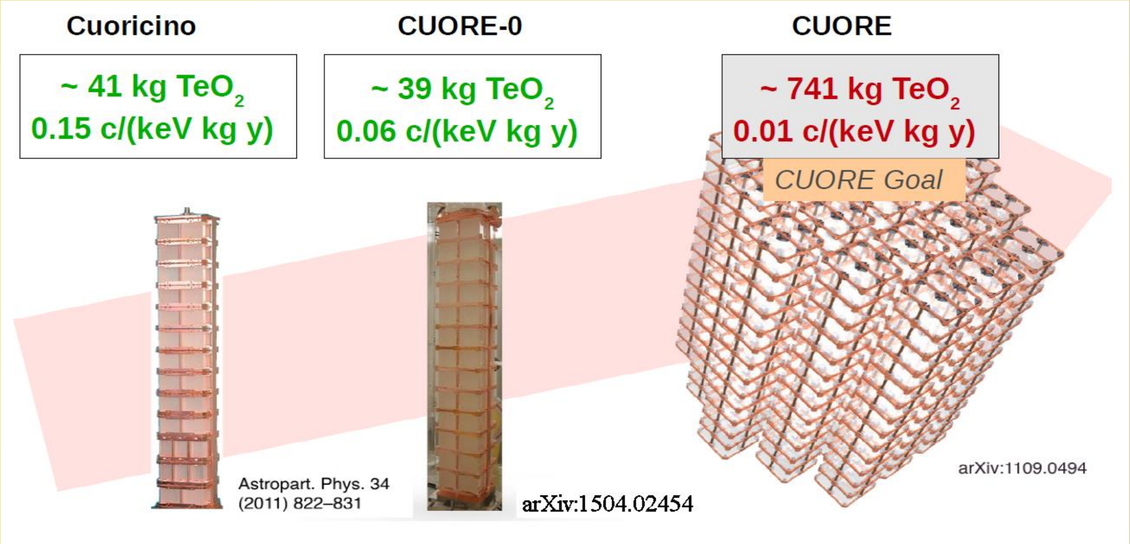
TeO_2 Bolometers: a story of successes





Bolometers as (almost) ideal DBD-detectors

$$S_{0\nu} = ln(2) N_A \frac{\eta \cdot \epsilon}{W} \sqrt{\frac{M \cdot T}{\Delta E \cdot B}}$$

"large" Background : $M \cdot T \cdot B \cdot \Delta E >> 1$

$$S_{0\nu} = ln(2) N_A \frac{\eta \cdot \epsilon}{W} M \cdot T$$

"0 Background" : $M \cdot T \cdot B \cdot \Delta E \leq 1$

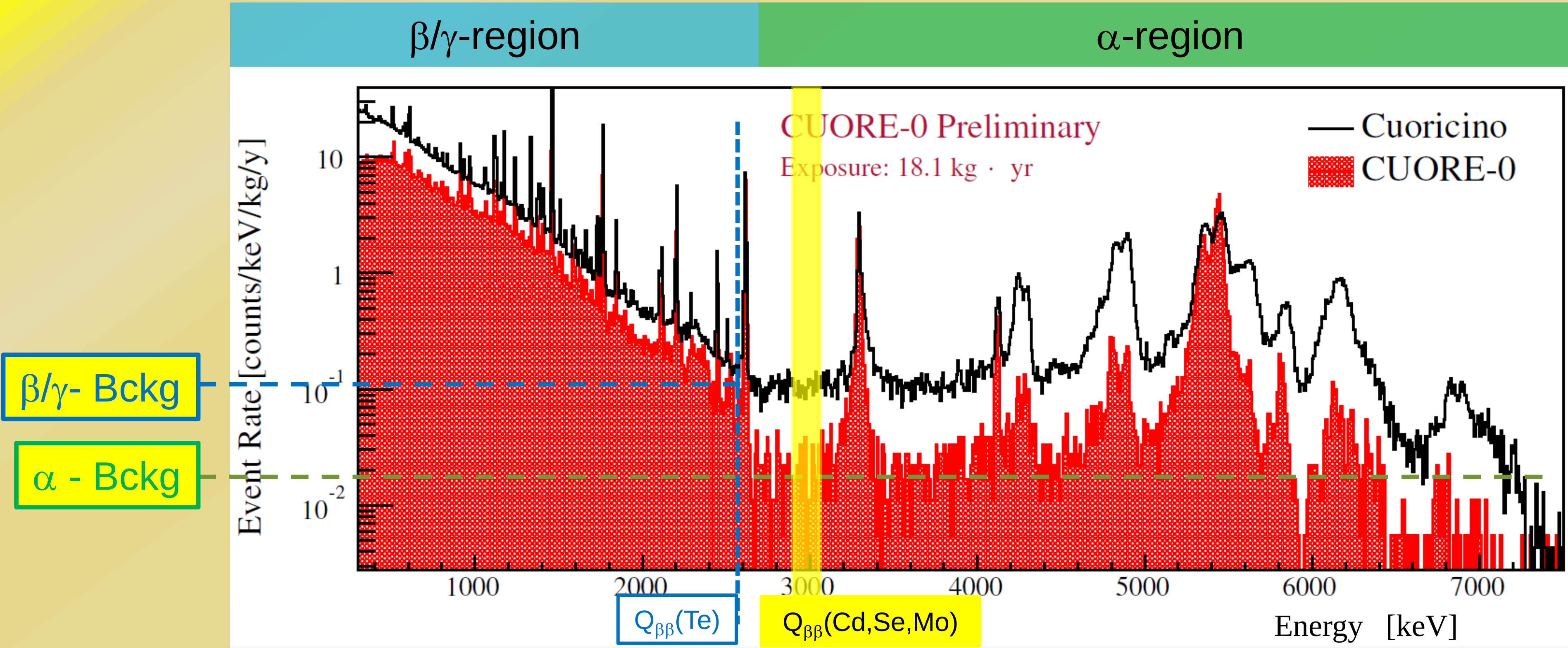
High Energy Resolution
- Smaller ROI better Sensitivity
- Better identification of bkg contributions
- Smaller probability to be close to natural peaks
- Negligible 2-ν DBD bkg

Scalability — CUORE-0 operated 52 crystals, CUORE will operate 988 crystals

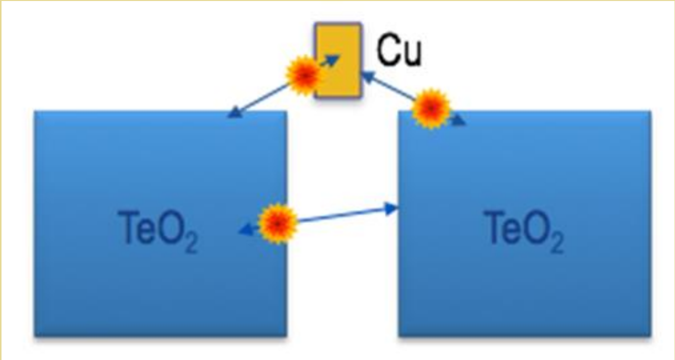
Efficiency — > 80 % calorimeter approach

Versatility — Te (CUORE isotope) - high i.a. but Q below the 2.6 MeV
Cd, Se and Mo = "new" isotopes low i.a. but Q>2.6 MeV

α-background: the bottleneck for DBD with bolometers



α-induced background reduced by a factor 6 with respect to CUORICINO, but still dominant for CUORE)



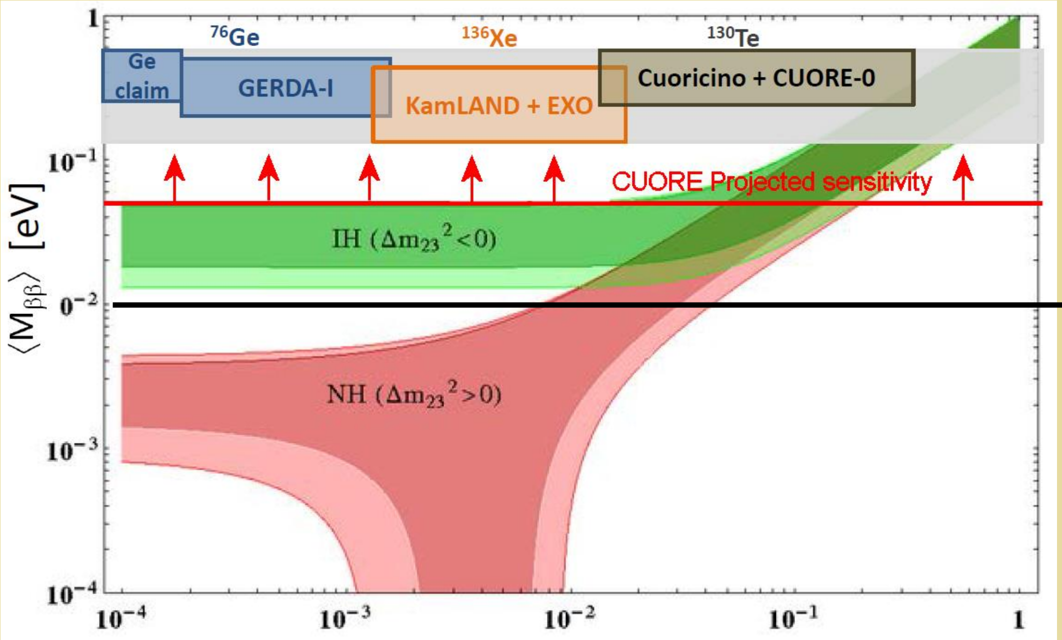
Fully sensitive up to the surface, no α vs β/γ discrimination in the TeO_2 heat channel

Dominant Background :
energy-degraded αs from surfaces

Scientific Objective

CUPID is a proposed bolometric 0ν-DBD experiment which aims at a sensitivity to the effective Majorana neutrino mass of the order of 10 meV. This level of sensitivity corresponds to the a lifetime of few $\sim 10^{27}$ years, depending on the isotope.
This primary objective poses a set of technical challenges:

- *the sensitive detector mass must be in the range of several hundred kg to a ton of the isotope*
- *the background must be close to zero at the ton x year exposure scale.*



CUPID GOAL

CUPID Background Target
≈ 0.05÷0.1 cpy/ton

CUPID

CUORE **U**pgrade with **P**article **ID**entification represents a new world-wide interest group (133 Signers) aiming at constructing a future ton-scale bolometric neutrinoless double beta decay experiment, based on the experience, expertise and lessons learned in CUORE.

The CUPID goal is the use of the ***unique*** CUORE infrastructure @ LNGS, once CUORE completes operation

This requires major upgrades focused on the detector technology :

- ***New detector technologies (α-background or surface event ID)***
- ***Isotopic enrichment***
- ***New purification and crystallization procedures***

As well as stricter material selection, and possibly new shielding concepts with respect to the state of the art deployed in CUORE.

✓ select technology & produce Conceptual Design Report for discovery $0\nu\beta\beta$ in IH
✓ define common framework to exploit synergies, science goals & near-term R&D

R&D towards CUPID: arXiv:1504.03612 CUPID : arXiv:1504.03599

CUPID Program

The target background rate for CUPID can't be verified on small scale detectors.

• We have to prove that this target is achievable ➔ Phased approach

✓ step 1 - proof of concept: alpha rejection is achievable at the desired level (small bolometric arrays used to study and compare different technologies)

✓ step 2 - scalability: proven with an intermediate scale array ("demonstrator")

by-product: results of demonstrators will be better than existing bolometric limits

- Next Year

  - ✓ Operations of ton-scale bolometric experiment with CUORE
  - ✓ First demonstrator of the attainability of large scale **enriched** arrays (LUCIFER/LUCINEU) with crystals different from TeO_2

- CUPID Goal : select the best technology within 2017-2018

Background reduction

In order to achieve the scientific goals a significant improvement of the current CUORE background figure is mandatory.

CUORE
10 C/(keV ton y)

100 reduction →

CUPID
0.1 C/(keV ton y)

The expected dominant component of the background in CUORE is due to **energy-degraded alpha particles** emitted from the surfaces of the materials surrounding the detector or of the detector itself. Active background suppression promises the required levels, either with TeO_2 as sensitive material, or with other isotopes.

It is important to stress that improvement in the detector technology, even if mandatory, may not be not sufficient. Background coming from residual environmental radioactivity and that induced by sporadic muon interactions in the current CUORE configuration could produce backgrounds .

Background budget

- Bkgd model: uncertainties from limited CUORE-0 statistics, large γ bkgd from CUORICINO cryostat, upper limits on actual contaminations

- Environmental μ's, neutrons, γ's
- Far sources: γ's from contaminations in cryogenic set-up

- Near sources: close to detector or crystals
  - Cu bulk:
  - Crystal bulk:
  - Surface: energy degraded α interactions, dominant background accordingly to CUORE model

Background budget

- Bkgd model: uncertainties from limited CUORE-0 statistics, large γ bkgd from CUORICINO cryostat, upper limits on actual contaminations
  - ➢ Fundamental input from CUORE

- Environmental μ's, neutrons, γ's $\longrightarrow$active muon veto and thicker shields

- Far sources: γ's from contaminations in cryogenic set-up

  <1 cpy/ton 90%CL for Te, <0.1 cpy/ton 90%CL for Mo,Se

- Near sources: close to detector or crystals

  – Cu bulk: <2 cpy/ton 90%CL for Te, <1 cpy/ton 90%CL for Mo,Se

  – Crystal bulk: one order of magnitude less compared to Cu

  – Surface: energy degraded α interactions, dominant background accordingly to CUORE model: <2 cpy/ton 90% CL if we assume 99.9% α rejection

D.R. Artusa *et al.*, Eur. Phys. J. **C 74** (2014) 3096

The CUPID R&D

CUPID

TeO_2

Pros

- ✓Well defined and known compound
- ✓ large commercial crystal production
- ✓ high reproducibility

Cons

- ✓$Q_{\beta\beta}$ **below** 2516 keV
- ✓ α and srface Id needs extremely performing technologies
- ✓Crystals yield is presently low (30%)

Non TeO_2

Pros

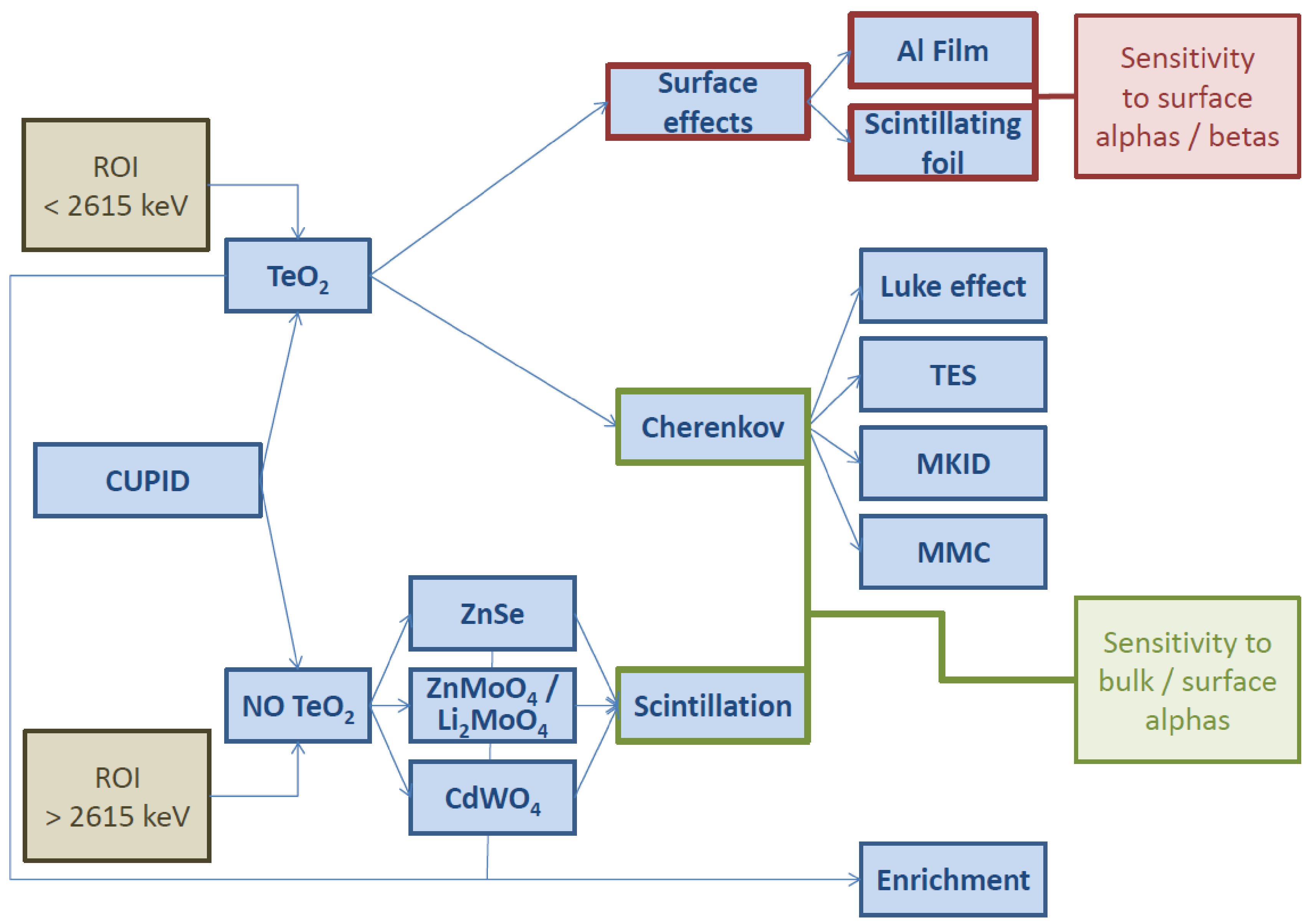
- ✓$Q_{\beta\beta}$ **above** 2516 keV
- ✓ α Id is straightforward
- ✓ enriched material already pure
- ✓ crystal growth yield can reach 85 %

Cons

- ✓Not commercial crystals
- ✓ larger enrichment price
- ✓ not yet proved crystal growth reproducibility

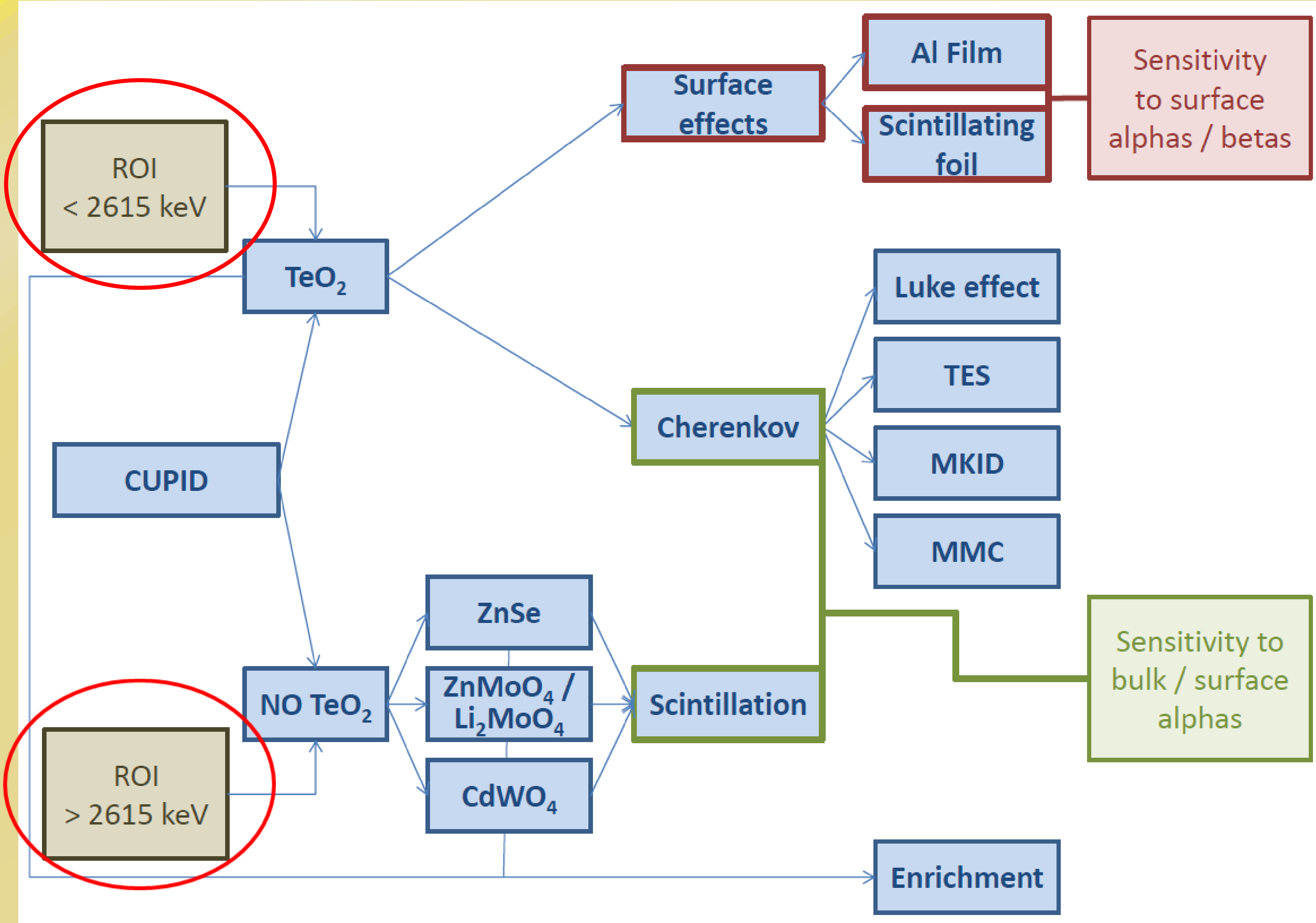
The advantage of the large group of interest grown around CUPID is that it was possible to gather together groups with different expertise, from crystal grow to sensor development. This will allow us to pursue a large number of R&D in parallel....

The CUPID R&D



ROI
< 2615 keV
TeO$_2$
CUPID
NO TeO$_2$
ROI
> 2615 keV
Surface effects
Al Film
Scintillating foil
Sensitivity to surface alphas / betas
Cherenkov
Luke effect
TES
MKID
MMC
ZnSe
ZnMoO$_4$ / Li$_2$MoO$_4$
CdWO$_4$
Scintillation
Sensitivity to bulk / surface alphas
Enrichment

The CUPID R&D



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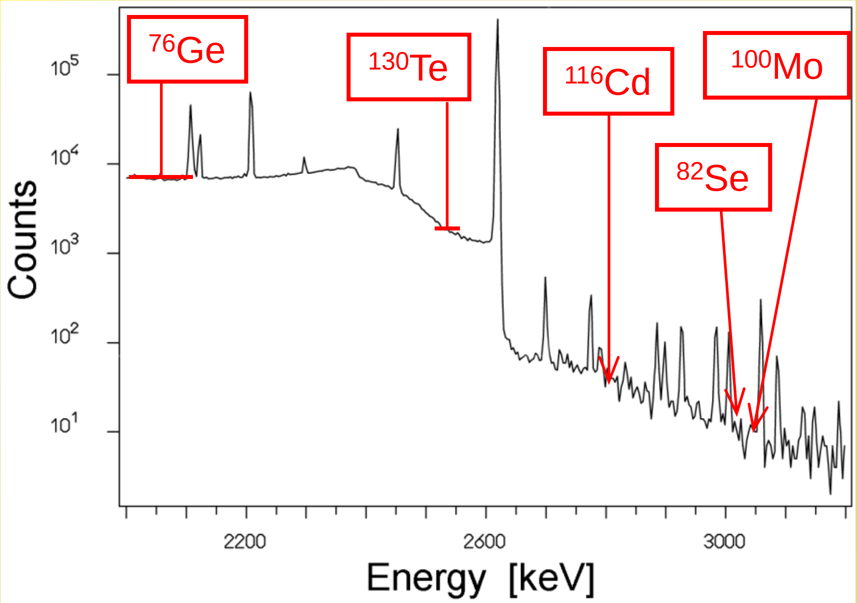
Q-value and Background: Isotope Choice

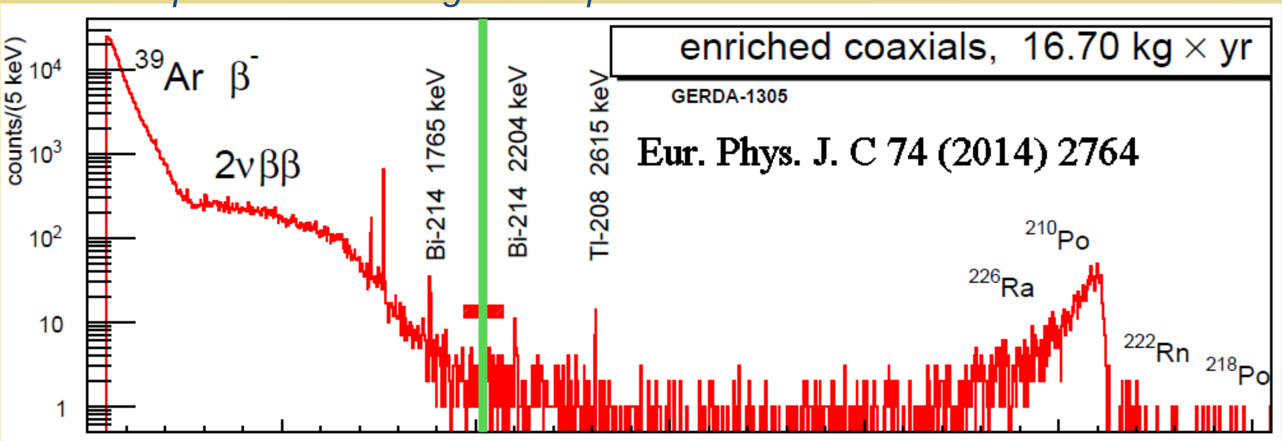


Environmental "underground" HPGE Background: ^{238}U and ^{232}Th trace contaminations

isotope	$G^{0\nu}$ $[10^{-14} y^{-1}]$	$Q_{\beta\beta}$ [keV]	nat. abund. [%]	$T_{1/2}^{2\nu}$ $[10^{20}$ y]
^{48}Ca	6.3	4273.7	0.187	0.44
^{76}Ge	0.63	2039.1	7.8	15
^{82}Se	2.7	2995.5	9.2	0.92
^{100}Mo	4.4	3035.0	9.6	0.07
^{116}Cd	4.6	2809	7.6	0.29
^{130}Te	4.1	2528	34.2	9.1
^{136}Xe	4.3	2461.9	8.9	21
^{150}Nd	19.2	3367.3	5.6	0.08

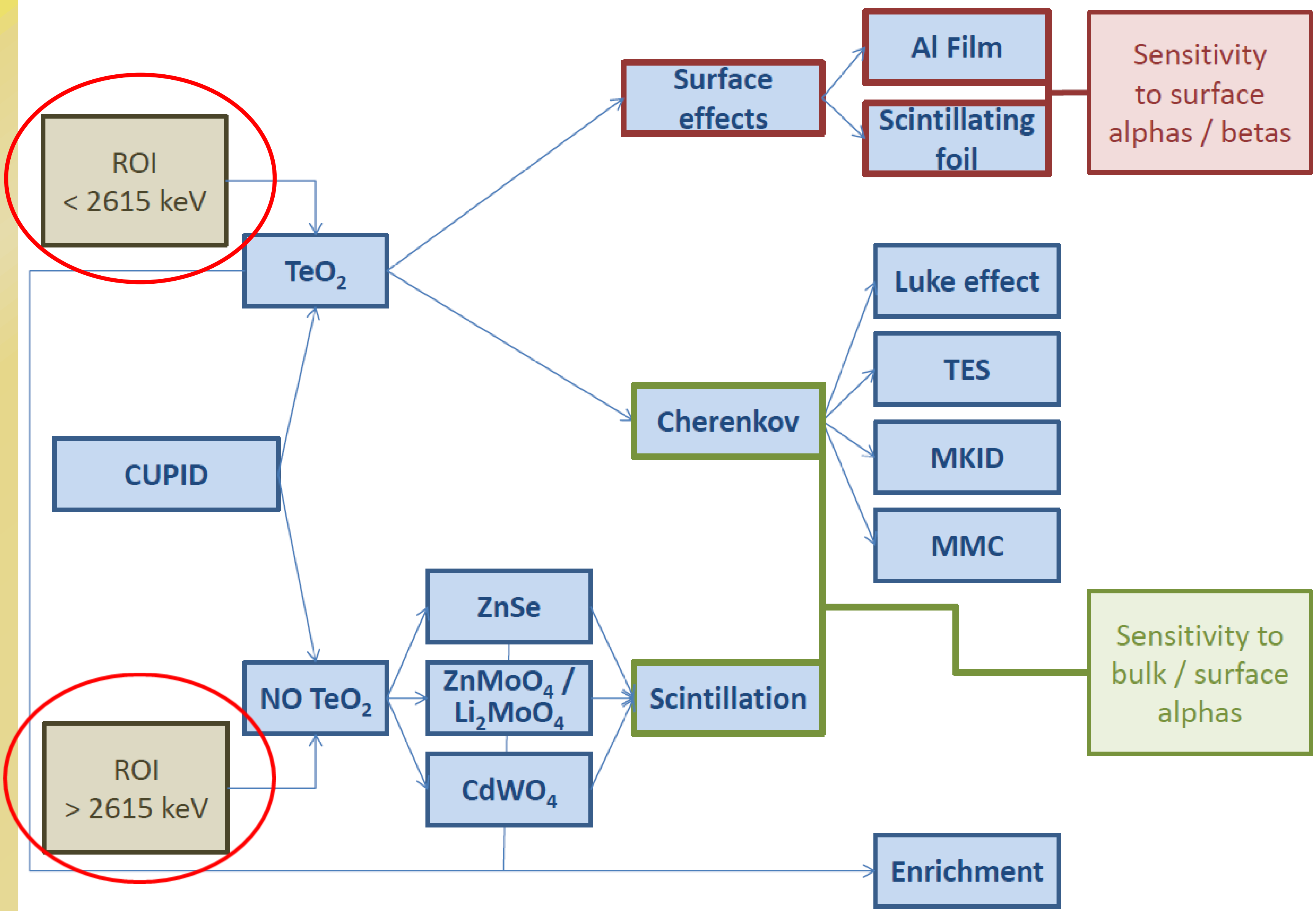
Bolometers already successfully tested

Gerda Experiment – Background spectrum



Isotopes with $Q_{\beta\beta}$ > 2615 keV *would be preferred* because they lie above the most intense natural γ radioactivity edge

The CUPID R&D



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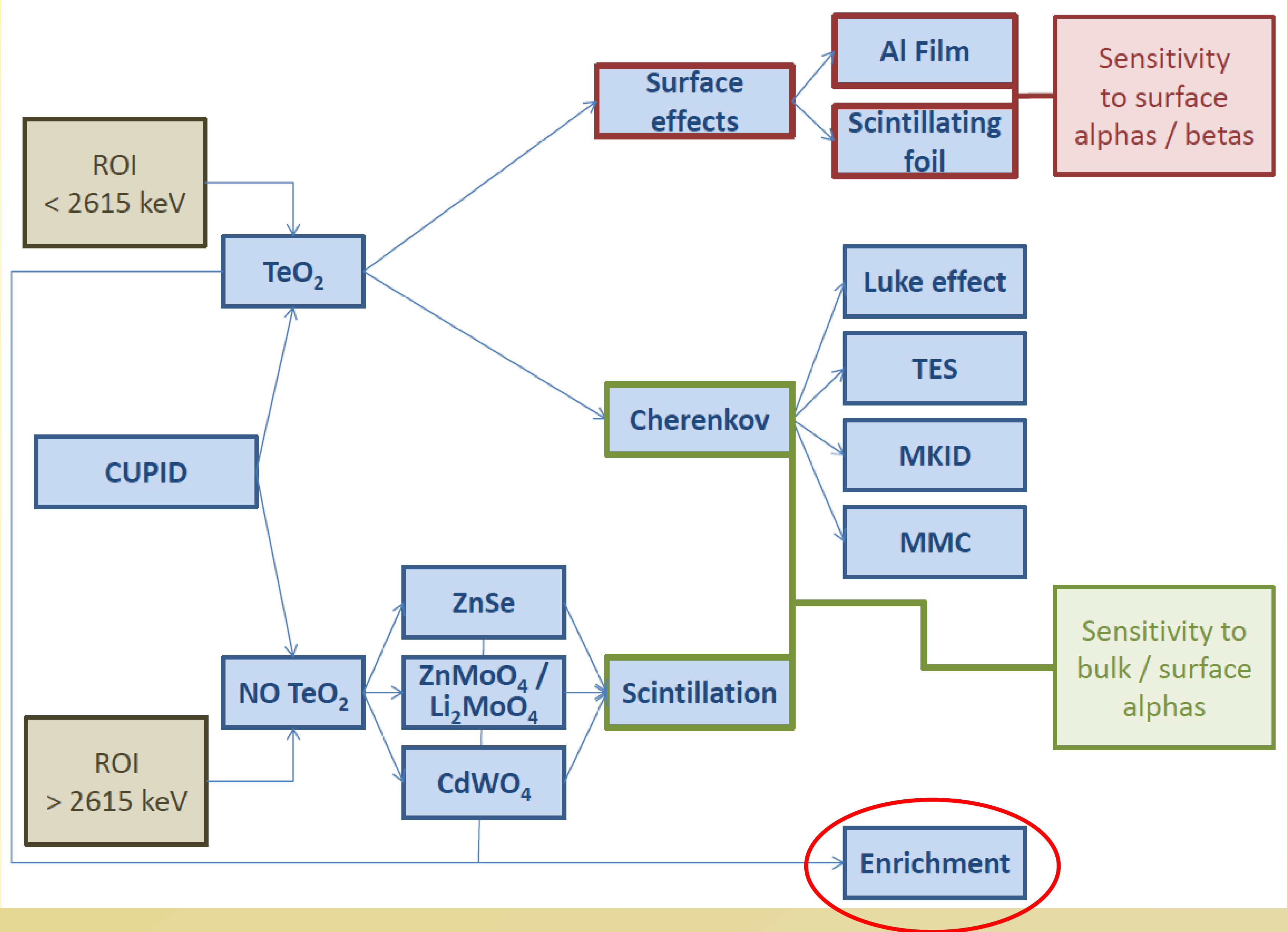

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Enrichment

CUPID will require isotopic enrichment *for any isotope* under consideration. All of the isotopes under investigation in the following, **^{130}Te**, **^{100}Mo**, **^{82}Se** and **^{116}Cd** can be enriched by centrifugation. This implies that they are all viable for a next-generation experiment in terms of cost and production rate. However, technical reasons determine differences in the enrichment cost which may impact the final choice. Very approximately *at the* **few kg scale**, the enrichment cost are the following:

^{130}Te	^{100}Mo	^{82}Se	^{116}Cd
17 k$/kg	90 k$/kg	80 k$/kg	200 k$/kg

These costs derives from small productions (few kg, 15 kg for ^{82}Se, 10 kg of ^{130}Te).
It has to be pointed out, however, that the use of isotopically enriched material changes remarkably the purification / crystallization issues, for two main reasons:

- ✓ first, the enriched material could have residual chemical impurities which may demand additional purification stages to get high-quality crystals;

- ✓ the enriched material is costly, and therefore the growth procedure needs to be adapted in order to reduce as much as possible the irrecoverable losses of the initial charge.

Enrichment – achievable nuclei

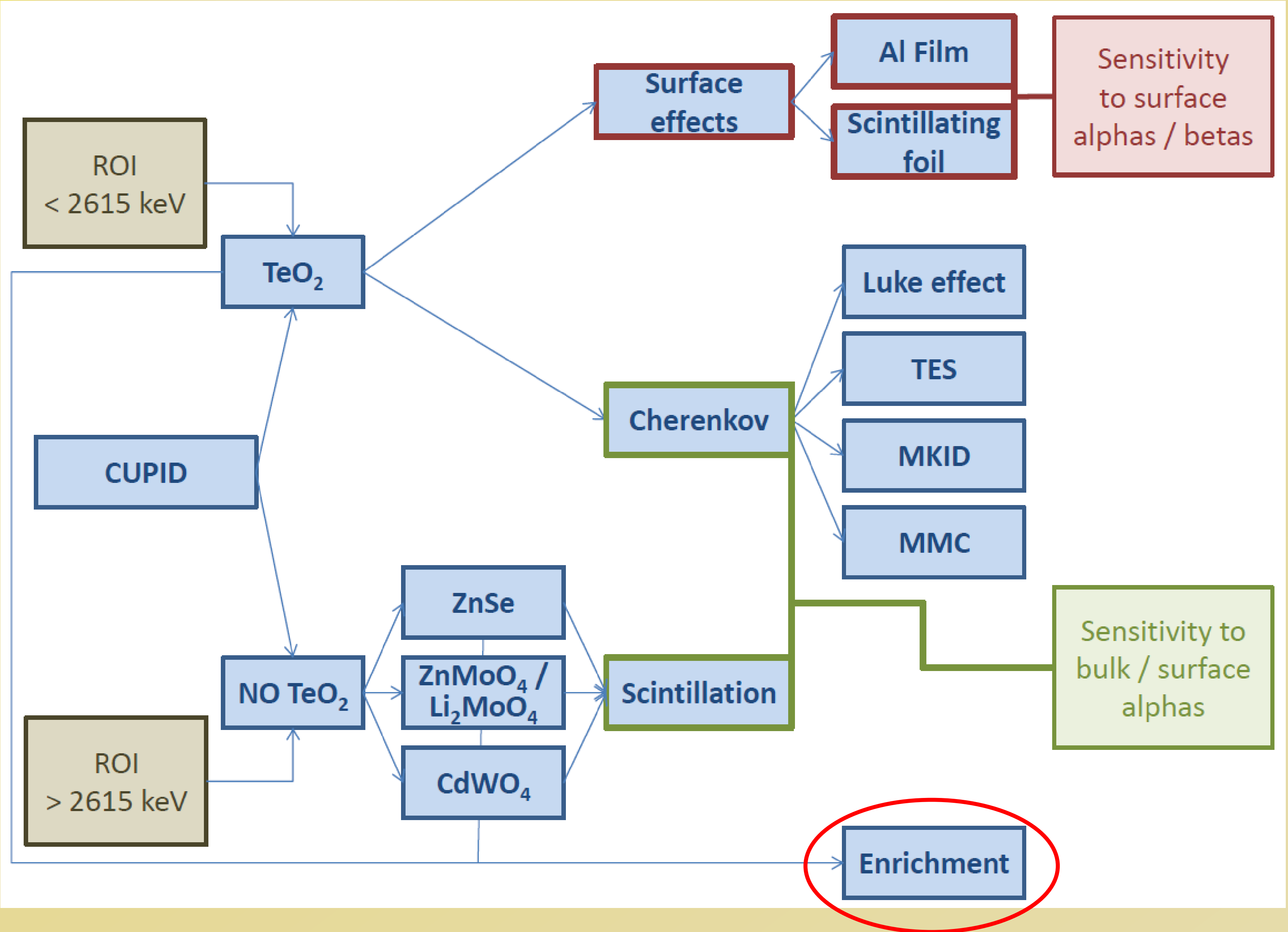
CUORE-like experimental setup ===> **Volume=988 bolometers x 125 cm^3 each**

Enrichment mandatory: assume **90 %**

	Detector Mass [kg]	Total Isotope Mass (kg)	Enrichment cost ($/g)	$N_{\beta\beta}$ [10^{27}]	$N_{\beta\beta}$ cost [M$]
$Zn^{82}Se$	664	369	~70	2.4	26
$Zn^{100}MoO_4$	545	237	~90	1.3	21
$^{116}CdWO_4$	986	314	~200	1.5	63
$^{130}TeO_2$	755	606	~17	2.5	10

- New purification methods :
  - ✓ residual chemical impurity after gas→elementary powder conversion
- New powder synthesis and crystallisation method to limit losses of initial charges
  - ✓ amount of enriched material needed scales as (Isotope Mass)/eff$_{pur+synt+growth}$

The CUPID R&D



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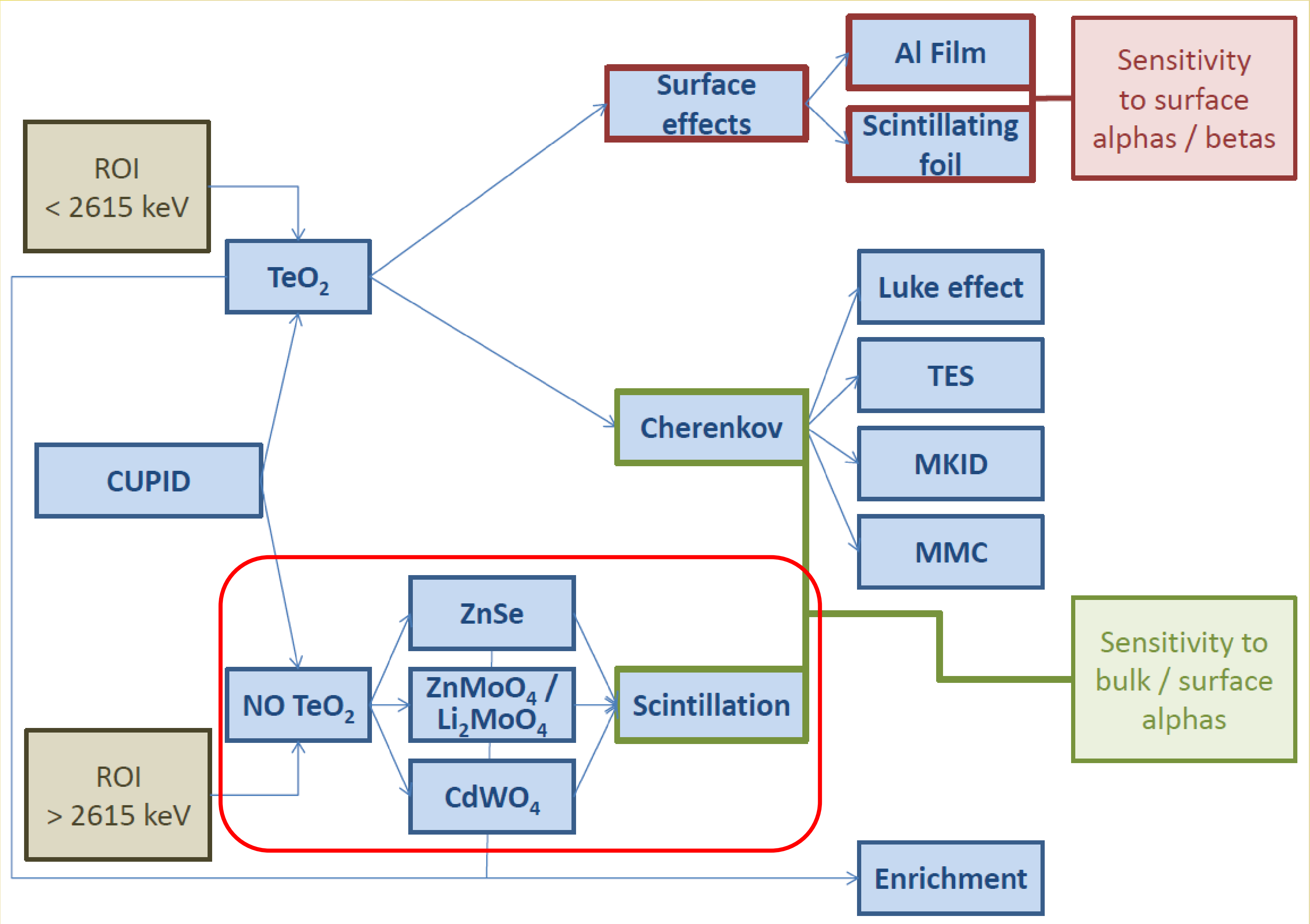
The CUPID R&D



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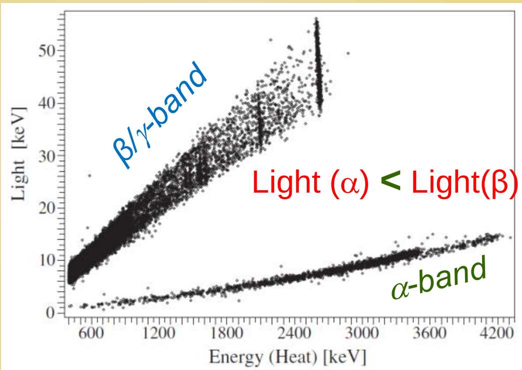
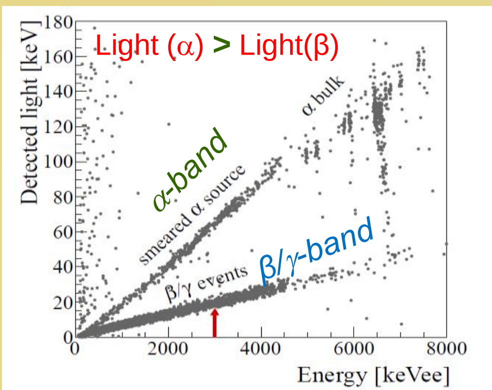
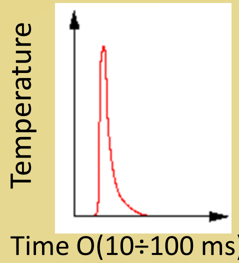
ROI > 2615 keV
Enrichment

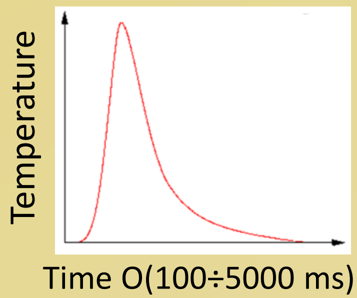
Scintillating bolometers

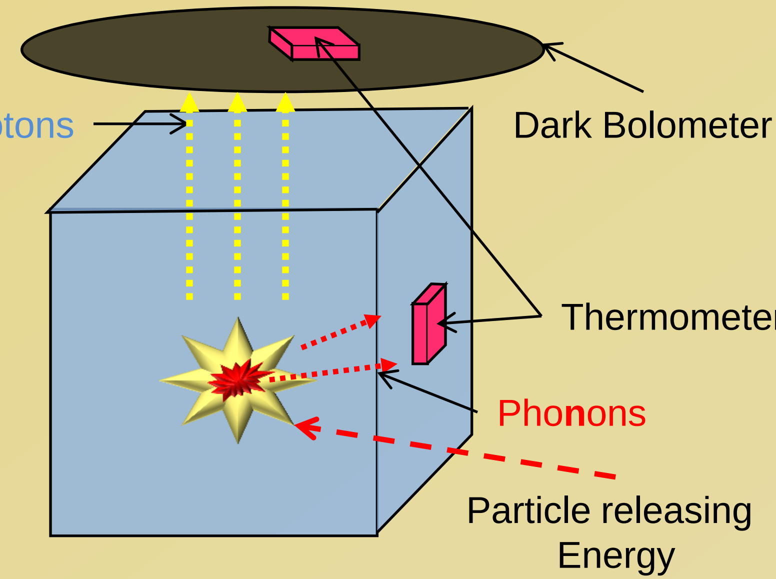
The development of this technique started in 2005 (SP *et al.*, Phys.Atom.Nucl.69 (2006) 2109) after the first results of CUORICINO that show the hard core of α-induced background

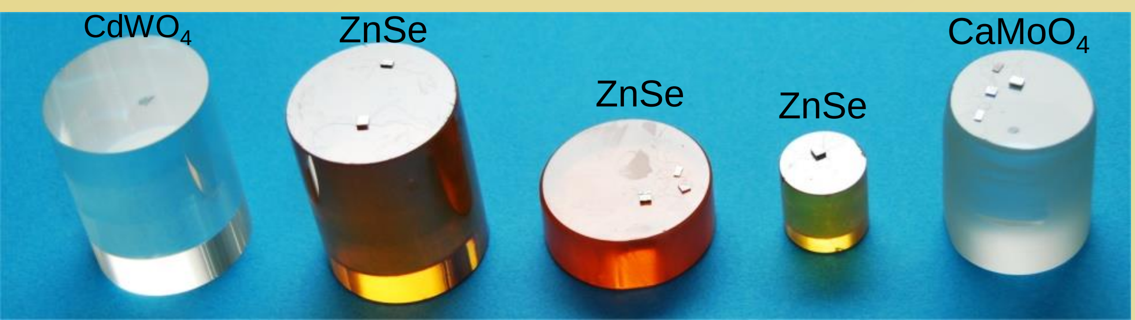


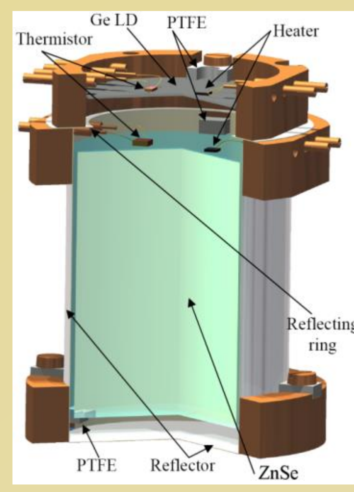


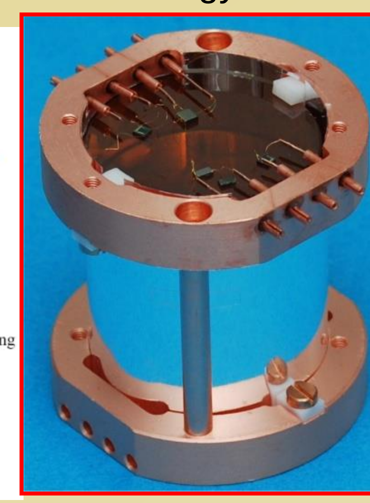












Bolometric Light Detectors – simple readout

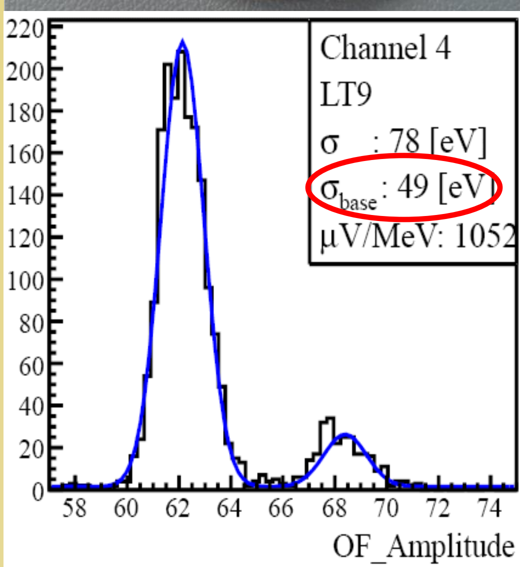
In case of *scintillating crystals even in case of very "bad" scintillators (Light Yield ≈ 0.05 %)*, the scintillation light at $Q_{\beta\beta}$ results of the order O(1 keV). This amount of energy release can be "easily" readout by standard thermistor-based bolometers.

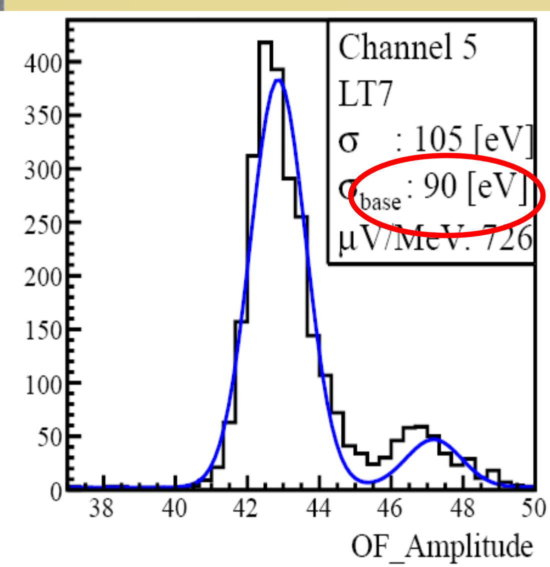
Ø=44.5 mm, h=0.175 mm

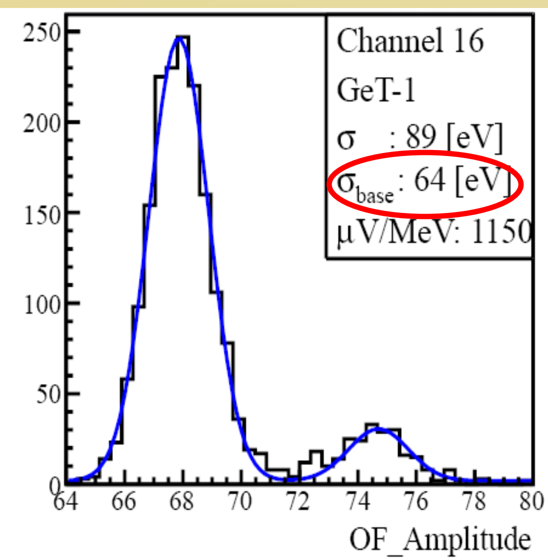
The light detector is a Ge thin crystal (LUCIFER)

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 LUCIFER Ge-crystals. σ represents the evaluated energy resolution on the peaks, while $\boldsymbol{\sigma_{base}}$ represents the baseline resolution.





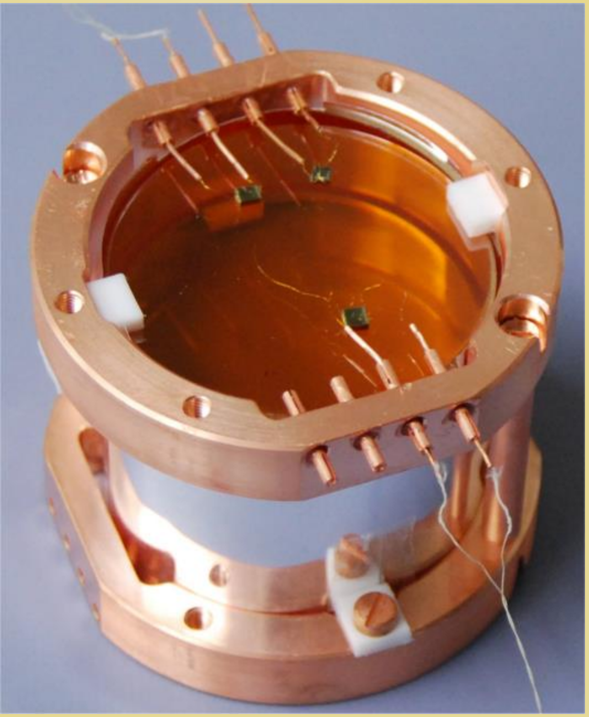


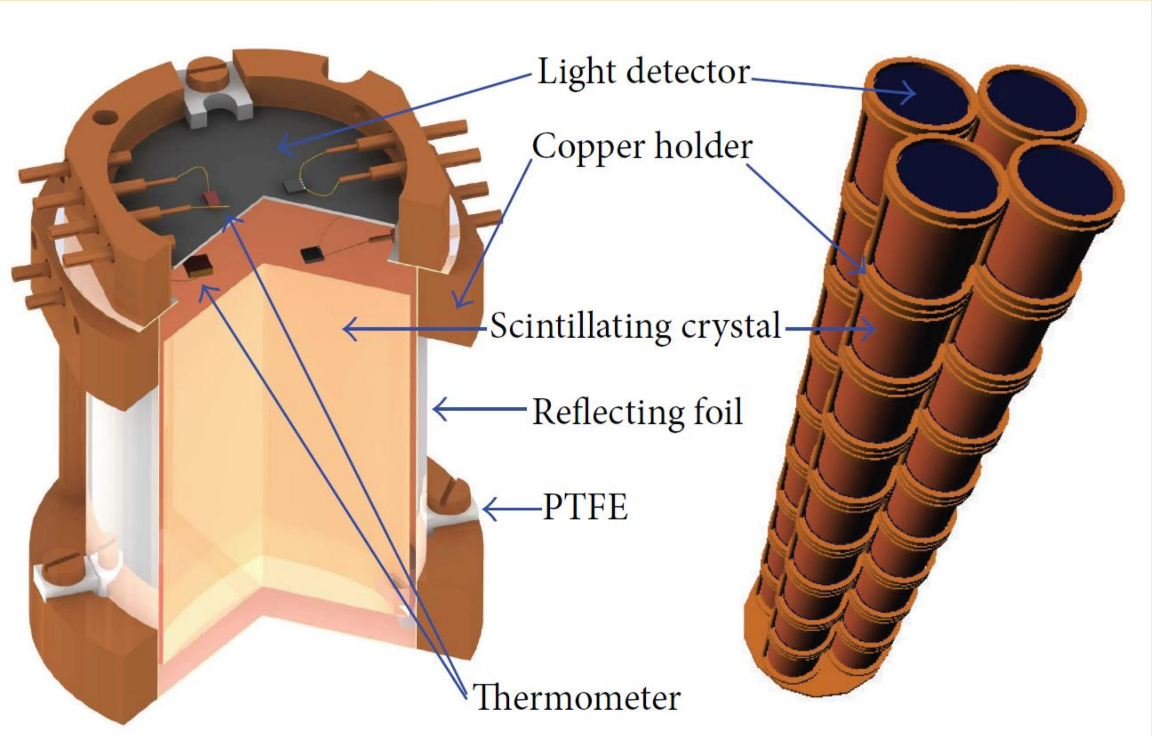
<σ> ≈100 eV

$Zn^{82}Se$: Lucifer (first CUPID demonstrator)

Low-background **U**nderground **C**ryogenics **I**nstallation **F**or **E**lusive **R**ates

Goal: to reach a decay of few 10^{25} y and demonstrator for a background free experiment





Lucifer will be composed by an array of 32 enriched (95%) $Zn^{82}Se$ crystals. Total ^{82}Se nuclei will be $\approx$4.3)10^{25}

The expected background in the ROI (2995 keV) is of the order of $1 \div 2\ 10^{-3}$ c/keV/kg/y

The energy resolution of the single detector is expected to be $\sim 10 \div 20$ keV FWHM

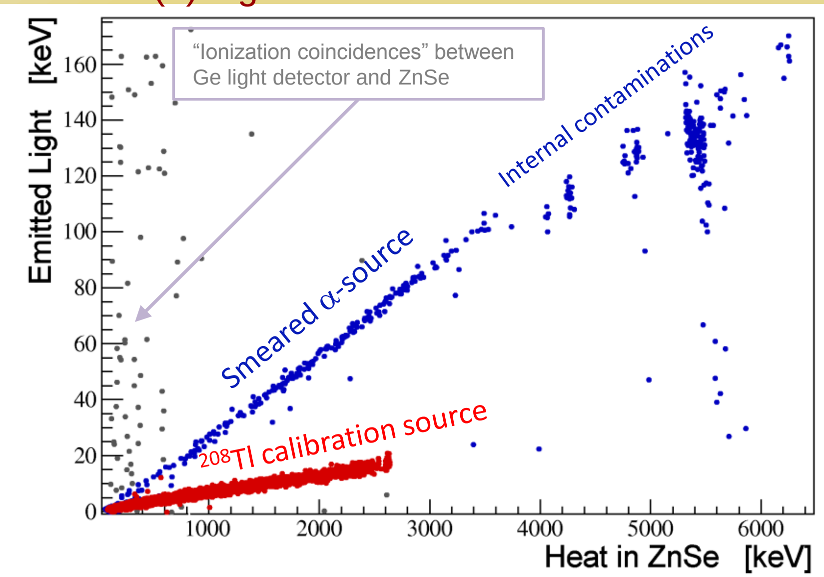
JW Beeman *et al*., Advan. in High Energy Phys 2013, 237973

ZnSe crystals α discrimination

The α-induced background is recognized through two independent measurements: 1) the decay time of the scintillating signal 2) the different scintillation yield between α and γ/β particles (the "usual" light Vs Heat scatter plot)

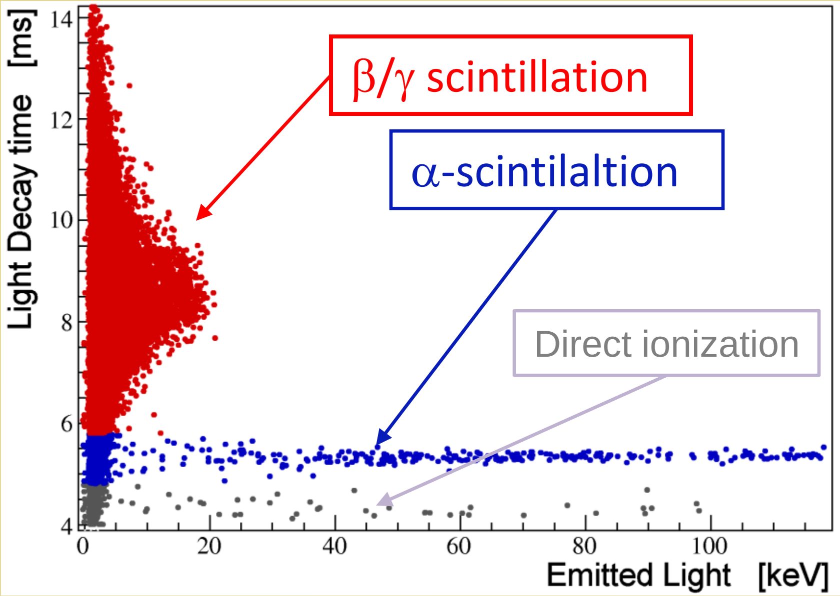
ZnSe crystals shows an "inverse" QF, i.e. α-particles scintillate more than β/γ's (C. Arnaboldi *et al.*, Astrop. Phys. **34**(2011)

(2) Light Vs Heat scatter Plot



JW Beeman *et al.*, JINST **8** (2013) P05021

(1) Decay time of the scintillation light



^{82}Se :Enrichment

The use of isotopically enriched material changes remarkably the purification / crystallization issues for all kind of crystal being studied in CUPID.

A) Enriched material could have residual chemical impurities which may demand additional purification stages

B) The enriched material **is costly**, and therefore the overall growth procedure needs to have a high yield

The procurement of a considerable amount of ultra-pure ^{82}Se by a **European company** (URENCO) represented a major achievement in this field.

LUCIFER faced both the abovementioned problems, in particular **(A)**

	Se(nat) [mBq/kg]	Se(Enr.) [mBq/kg]	Se(enr-Dist.) [mBq/kg]
^{238}U / ^{226}Ra	<1.7	<0.41	< 0.11
^{238}U / ^{234}Th	<17	<27	< 6.2
^{232}Th / ^{228}Th	1.7±0.3	1.4 ± 0.2	< 0.11
^{232}Th / ^{228}Ra	<0.7	<0.37	< 0.061
^{40}K	4 ± 2	3 ± 1	< 0.99
^{60}Co	<0.3	<0.17	< 0.065
^{235}U	<0.7	<0.30	< 0.074
^{137}Cs	<0.14	<0.076	< 0.012

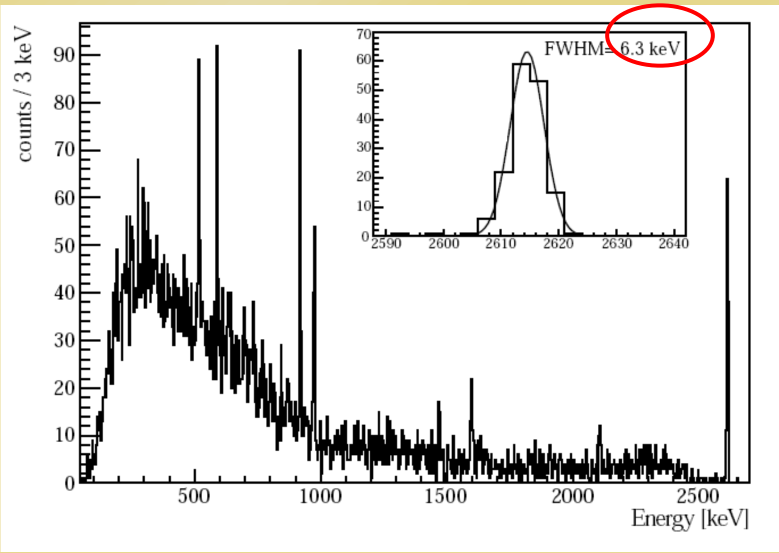
The enriched ^{82}Se did show a lot of contaminants that were not compatible with a “good” bolometer: Iron, Chromium and other metal contaminants. Moreover a huge (≈0.1%) contamination of chemical reagents used for the conversion from Hexafluoride to Isotope will be present in the final metal (Na and S in case of Se)

→ Two years of R&D in order to provide a reliable -high yield- purification

Mo-Based compounds- $ZnMoO_4$

Successful R&D pursued within **LUCIFER** before choosing ZnSe.

Energy resolution compatible with CUORE detectors



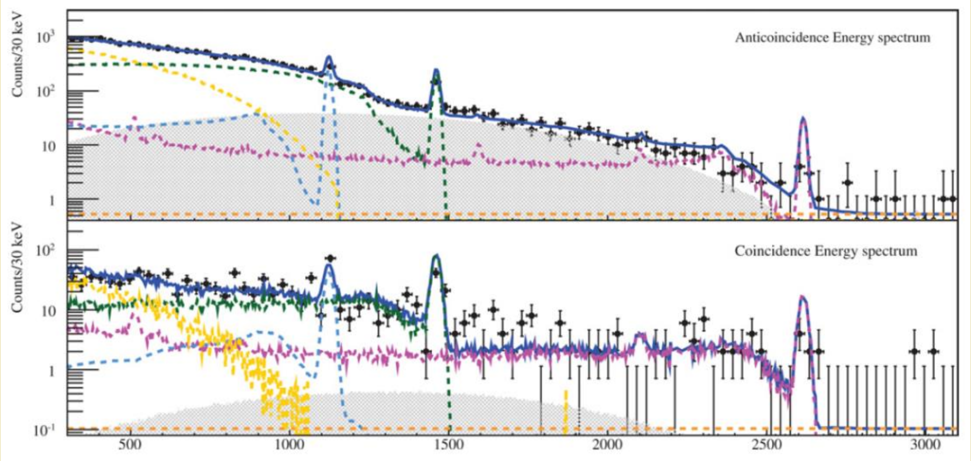
L. Gironi *et al*., JINST **5** (2013) P P11007

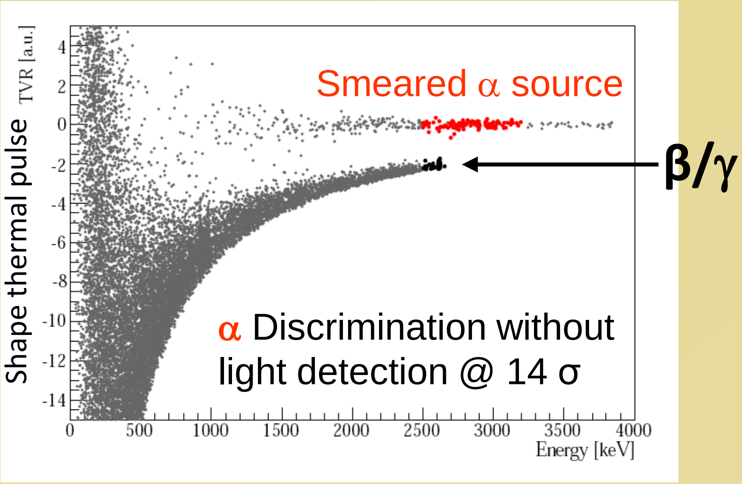
JW Beeman *et al*., Astrop. Phys., 3**5** 813

JW Beeman *et al*., Eur. Phys. J. C **72** (2012) 1

L. Cardani *et al.,* J. of Phys. G: **41** (2104) 075204

Extreme radiopure: 2 ν decay mode
Measured in a R&D Run





The fast 2 ν decay mode implies to increase the time response of detector in order to get rid of the random coincidences

^{100}Mo-Based compounds- LUMINEU

L*uminescent* **U***nderground* **M***olybdenum* **I***nvestigation* for **NEU***trino mass and nature*

LUMINEU is an *ANR* funded pilot experiment to demonstrate the feasibility of **$Zn^{100}MoO_4$** scintillating bolometers using 1 kg of ^{100}Mo.

Crystals grown in NIIC(Russia) using Low Thermal Gradient CZochralski technique (LTGCz)

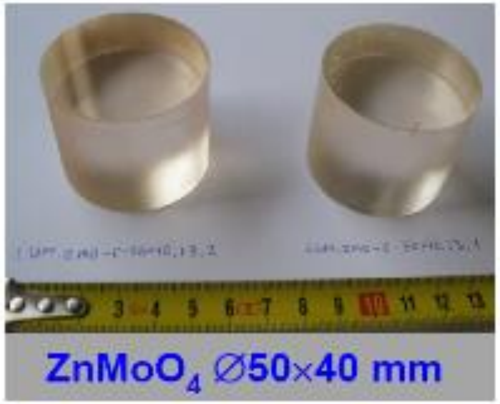
Two ~340g $Zn^{(nat)}MoO_4$ tested underground

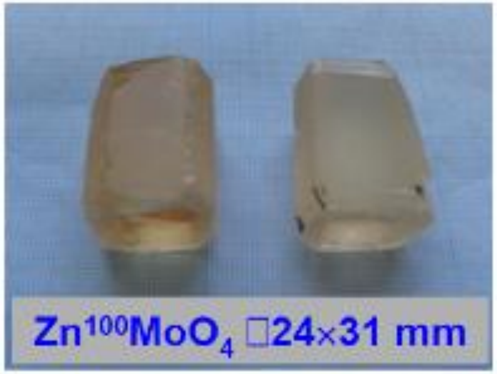
Two ~60g $Zn^{(100)}MoO_4$ (99% enriched) tested above ground

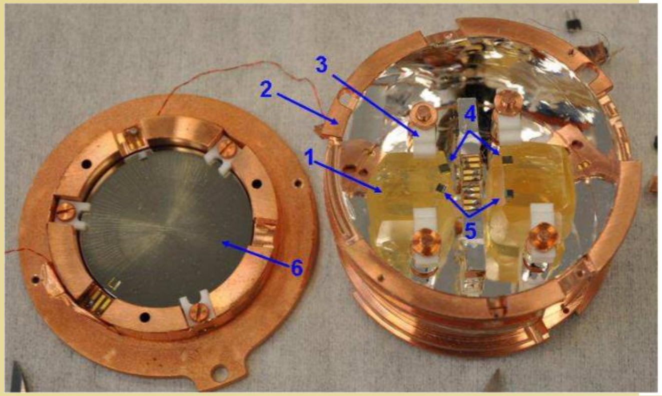
- ✓ Mo purified by double sublimation & recrystallization from solution (arXiv:1312.3515)
- ✓ Excellent radiopurity, U, Th < 4μBq/kg
- ✓ Crystal growth yield **85 %**
- ✓ Irrecoverable losses **< 4 %**

J.W. Beeman *et al.*, Phys Lett **B** 710 (2012)

A. S. Barabash *et al.*, Eur. Phys. J. **C** **74** (2014) 3133







^{100}Mo-Based compounds- LUCINEU

MOU signed by ITEP, IN2P3, INFN makes ~9 kg of ^{100}Mo (95-99%) belonging to ITEP available (formerly measured in NEMO)

LUCIFER + LUMINEU ➔ LUCINEU

LUCIFER and LUMINEU use the same technology, same light detectors. The experimental volume of the CUORE-0 cryostat permits to mount other detectors, below the LUCIFER tower

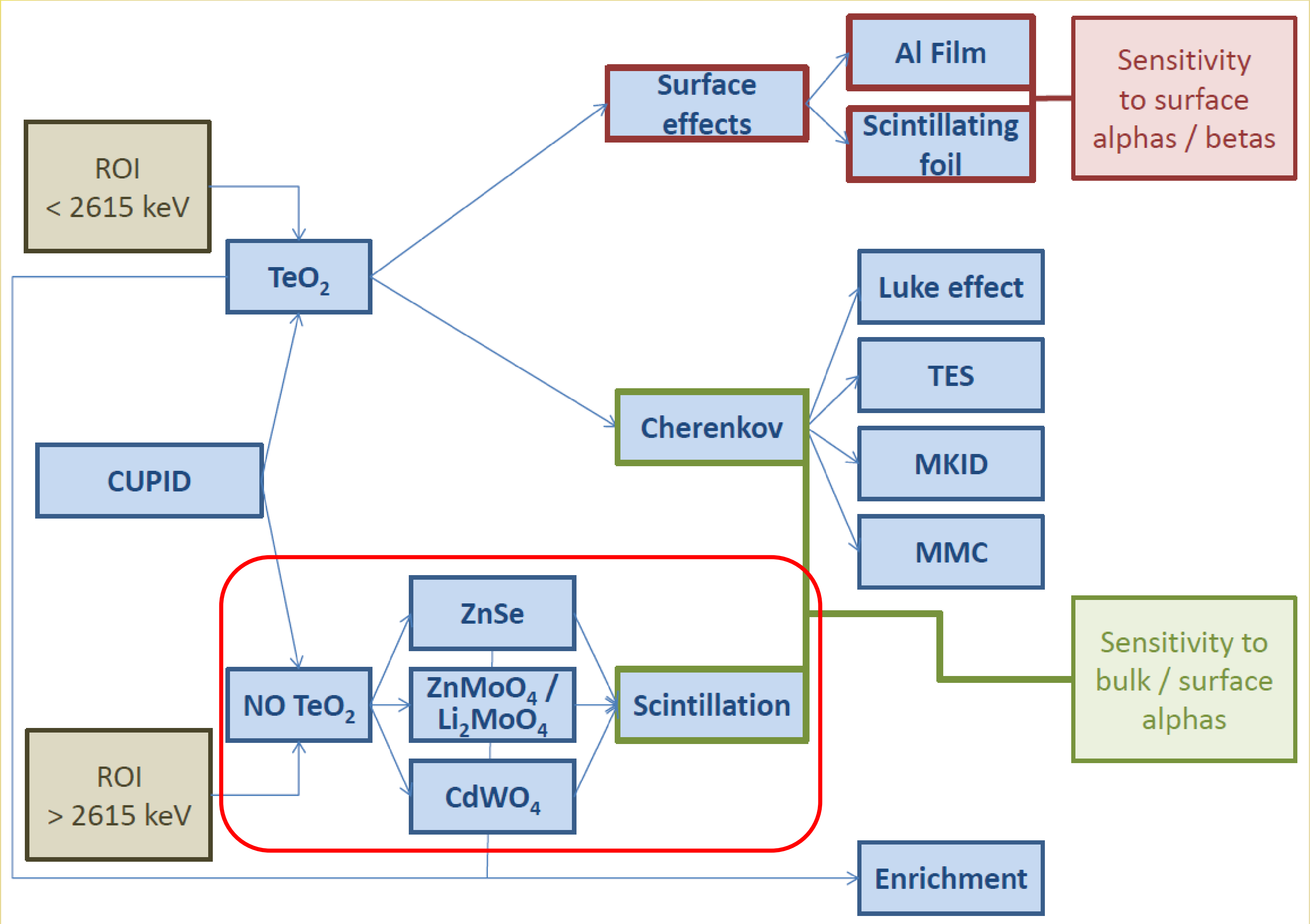
LUCINEU: LoI in preparation

- ✓ Run Background free demonstrator with ~8 kg of ^{100}Mo
- ✓ 1st 20 crystals at LNGS, 2nd 20 crystals in Modane
- ✓ thermistors/light detectors/Cu-supports available within LUCIFER
- ✓ same electronic read-out/DAQ/data-analysis tools

1.45 kg 99% $Zn^{100}MoO_4$ (Lumineu)

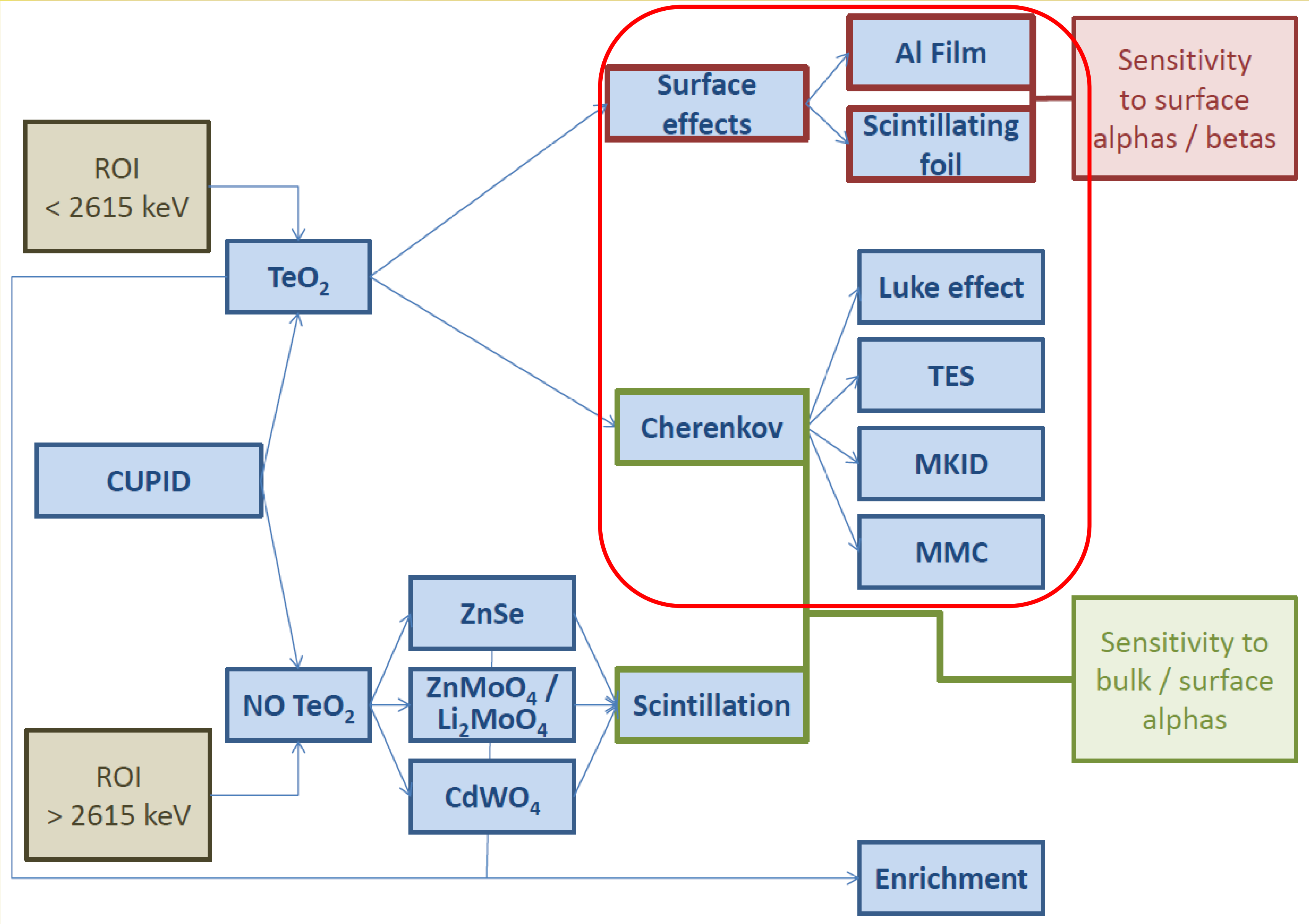
LUCINEU could be the second CUPID Demonstrator starting data taking in 2016

The CUPID R&D



ROI
< 2615 keV
TeO$_2$
Surface effects
Al Film
Scintillating foil
Sensitivity to surface alphas / betas
Luke effect
TES
Cherenkov
MKID
MMC
CUPID
ZnSe
NO TeO$_2$
ZnMoO$_4$ / Li$_2$MoO$_4$
Scintillation
CdWO$_4$
Sensitivity to bulk / surface alphas
ROI
> 2615 keV
Enrichment

The CUPID R&D



ROI
< 2615 keV
TeO$_2$
CUPID
NO TeO$_2$
ROI
> 2615 keV
Surface effects
Al Film
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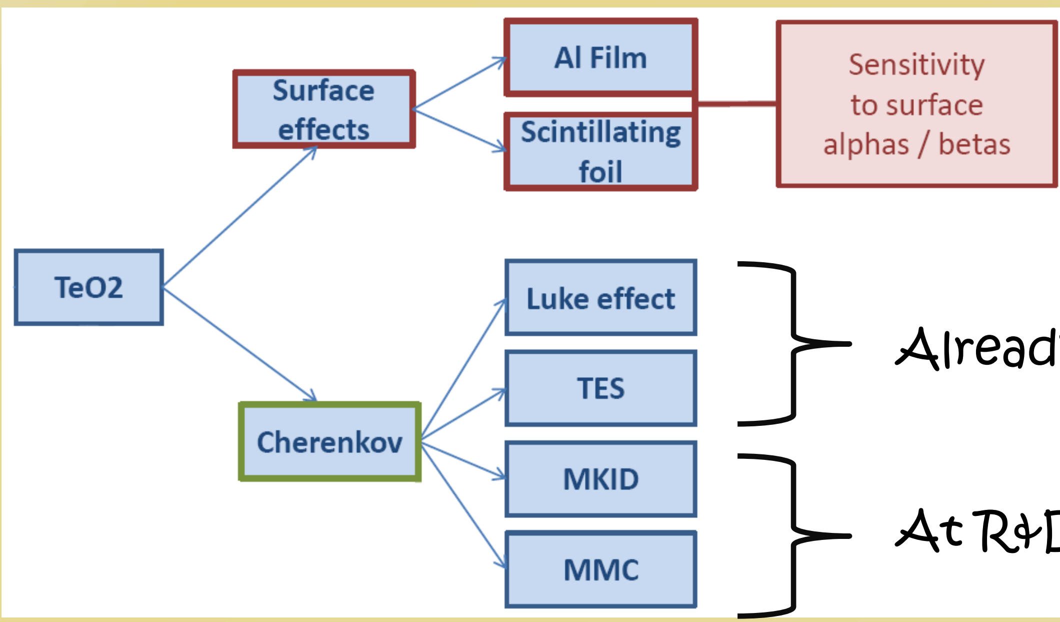
Sensitivity to surface alphas / betas
Luke effect
TES
Cherenkov
MKID
MMC
ZnSe
ZnMoO$_4$ / Li$_2$MoO$_4$
CdWO$_4$
Scintillation
Sensitivity to bulk / surface alphas
Enrichment

α-discrimination in TeO_2 Bolometers

There are two strategies:

- identify events taking place close the surfaces (α and β, being β identification more complicated)
- identifying α-interaction through the Cherenkov light emission (not emitted by α)



At R&D phase

Already proved on large TeO_2 bolometers

At R&D phase, not yet enough sensitivity

The Cherenkov light detection

The threshold for Cherenkov emission in TeO_2 is around 50 keV for electrons, and around 400 MeV for α's

The issue is to be able to detect a light signal, together with the Heat from TeO_2 , of the order of O(100 eV). This implies a light detector with a RMS baseline of the order of 20 eV.

Tabarelli de Fatis, Eur. Phys. J.C **65** (2010) 359. — First Idea of detecting Cherenkov light

J.W. Beeman *et al., Astrop. Phys.* **35** (2012) 558–562 — First detection of Cherenkov light with **LUCIFER** light detectors

F. Bellini *et al*., JINST **9 (2014)** P10014 — Cherenkov light yield simulation and optimization In TeO_2 at room temperature

N. Casali *et al*., Eur. Phys. J. C **(2015),** 75:12 — Cherenkov light emission in CUORE-like crystals Bolometers with **LUCIFER** light detectors

M. Willers *et al*., JINST **10 (2015)** P03003 — First event-by-event discrimination on small TeO_2 Bolometer with TES and LUKE-amplification

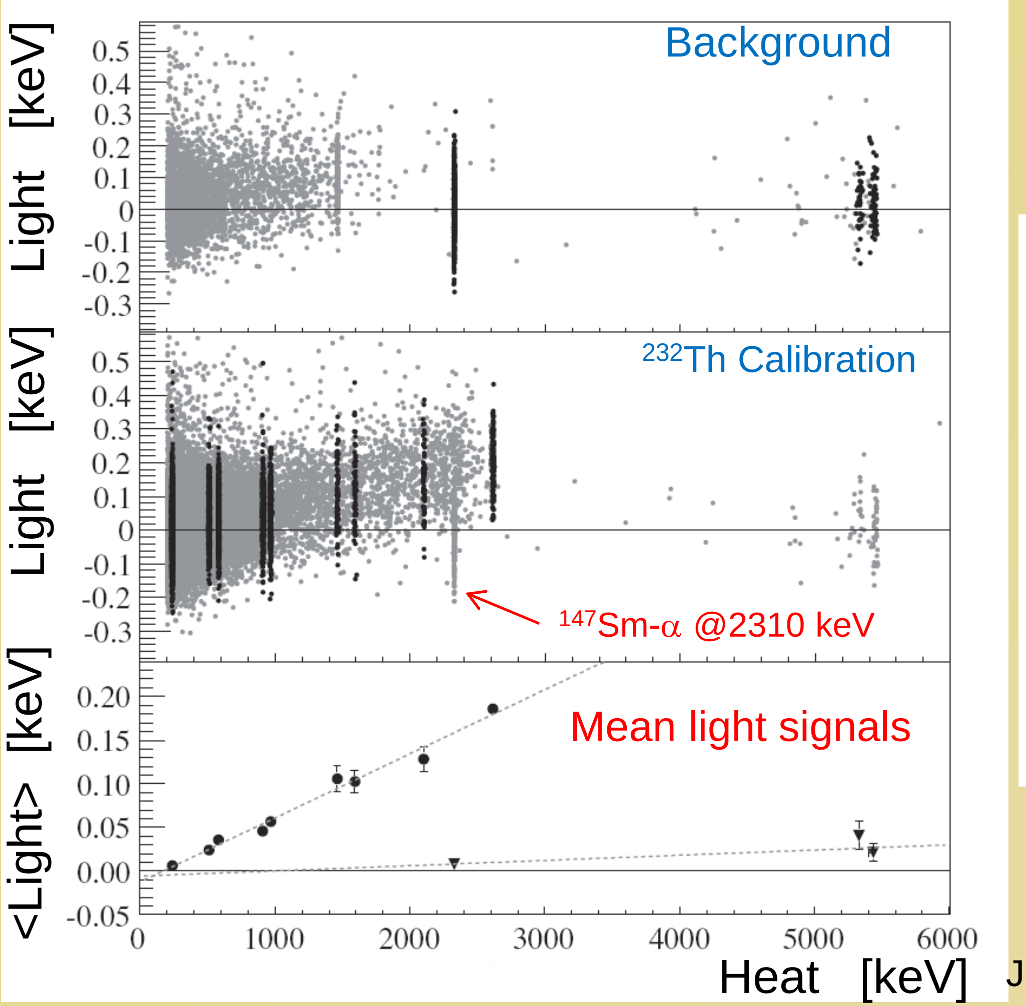
K. Schäffner et al**.,**Astrop. Phys. **69** (2015) 30-36 — First event-by-event discrimination in large (285 g) crystal bolometer with *CRESST* TES

F. Bellini *et al*., in preparation — First event-by-event discrimination in CUORE-like (790 g) crystal with improved NTD based LD @**LUCIFER**@**Lumineu**

The Cherenkov light detection NTD-detectors -1

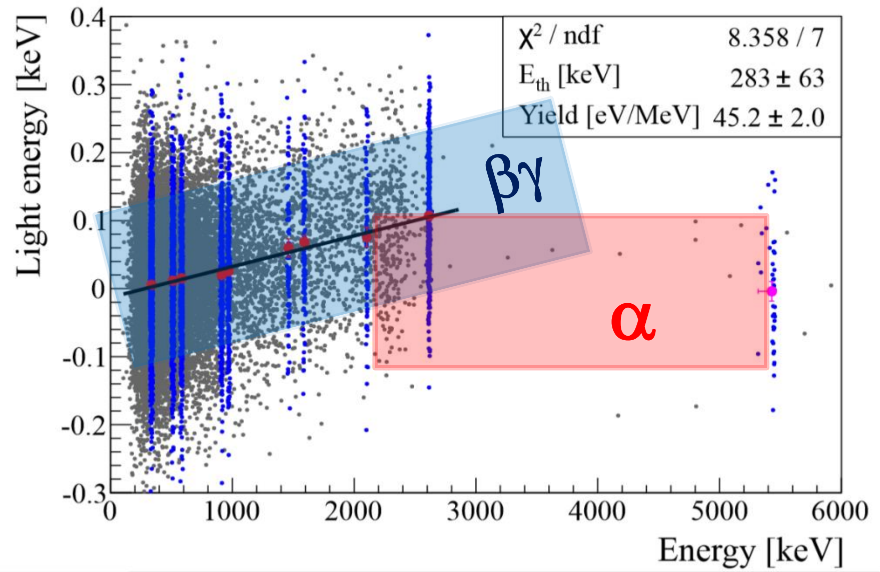
The first Cherenkov light detection were made within LUCIFER R&D using thermistor-based light detectors.
After several tests we obtained that the light escapng from a CUORE-Like crystal lies between **90 and 110 eV**.
Due to this small amount it is clear that standard thermistors light detector are not able to perform an event-by-event-discrimination

116 g TeO_2 crystal: 195 eV @2615 keV



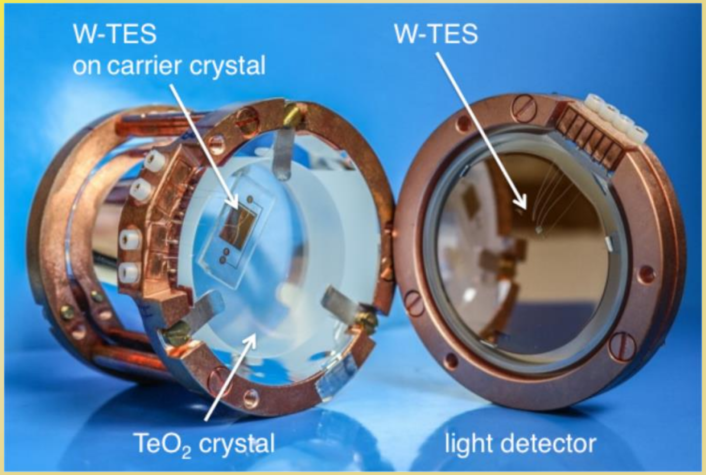
J.W. Beeman *et al.*, Astrop. Phys. 35 (2012) 558

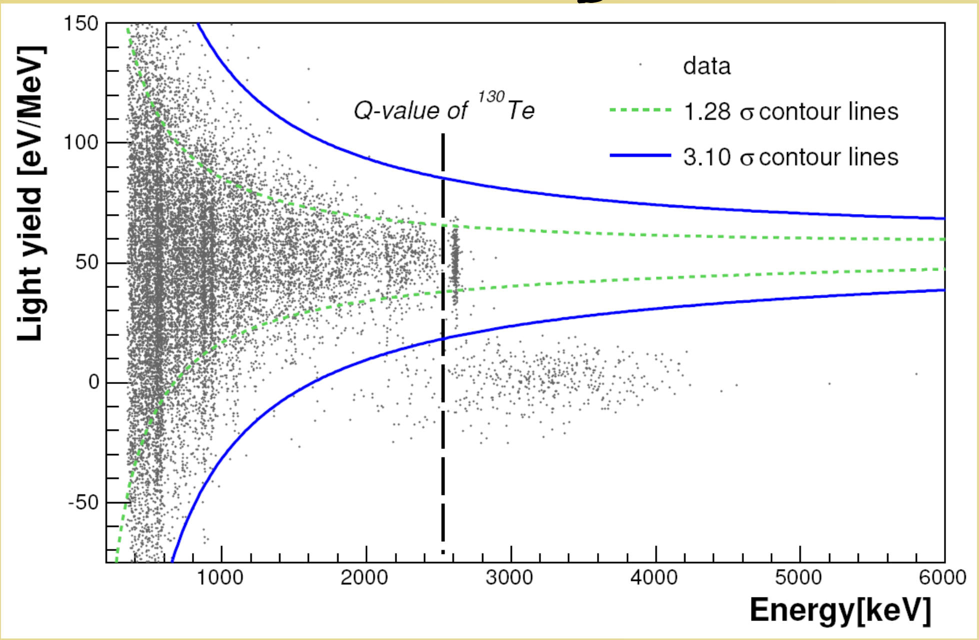
CUORE-LikeTeO_2 crystal: 110 eV @2615 keV

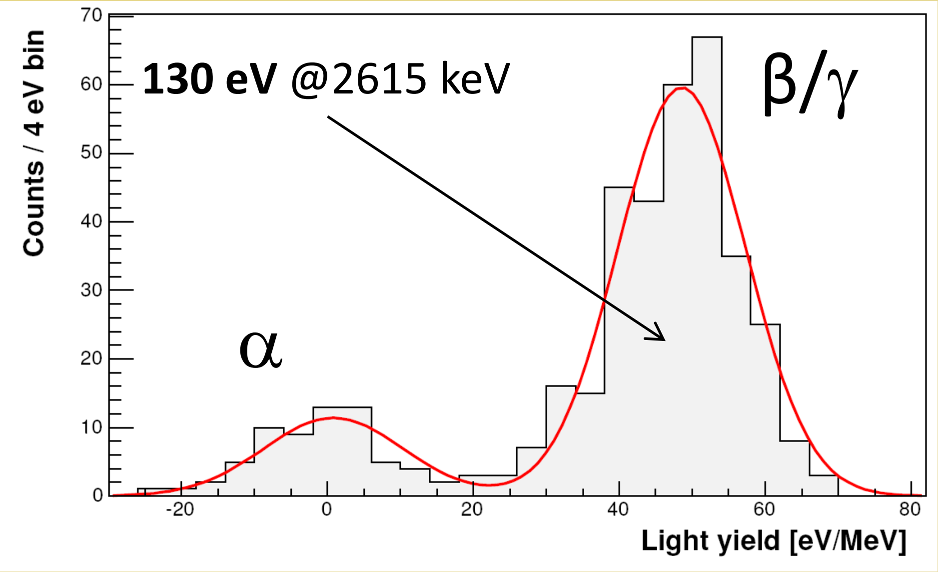


N. Casali *et al.*, Eur. Phys. J. C **(2015),** 75:12

The Cherenkov light detection TES-Light detector







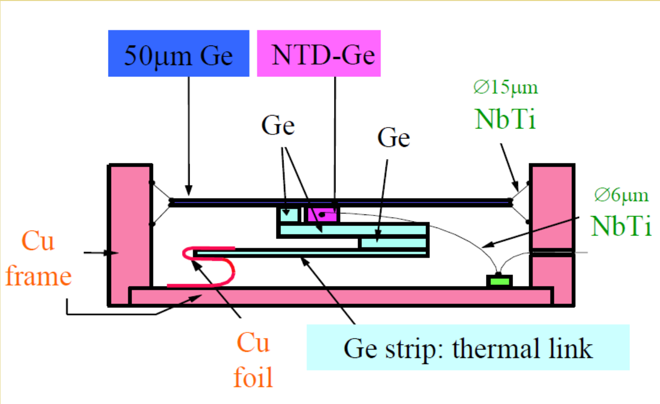
Results obtained with collaboration of Max-Plank Munich and LUCIFER, using a 4 cm dia, 4 cm height 285 g TeO_2 crystals

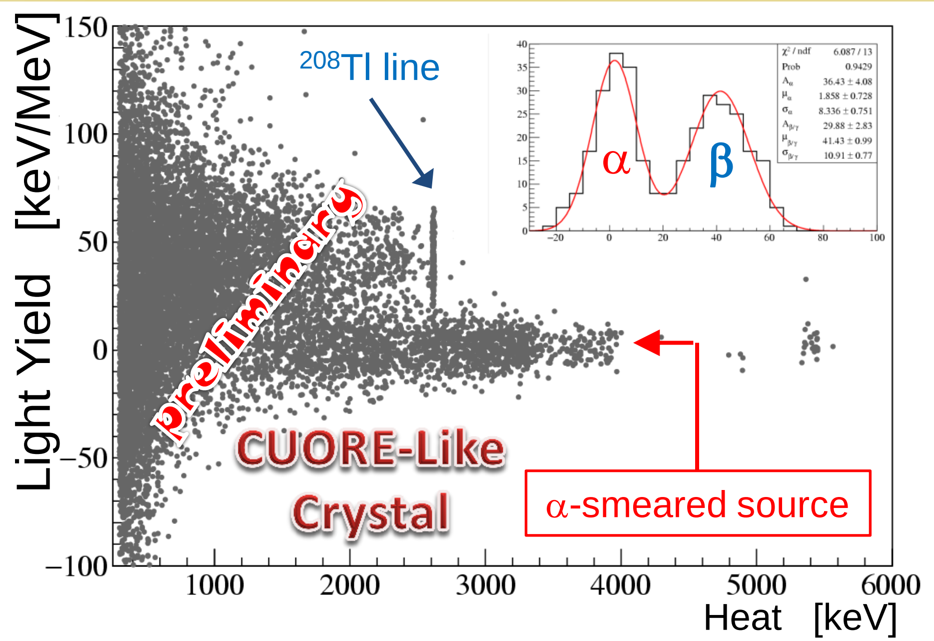
- **Transition Edge Sensors (TES)** (CRESST)
  - $\Delta E < 20$ eV
  - Complicated readout:
    - SQUID amplifiers.
    - scaling needs R&D

K. Schäffner *et al.*, Astrop. Phys. **69** (2015) 30

The Cherenkov light detection NTD-detectors -2

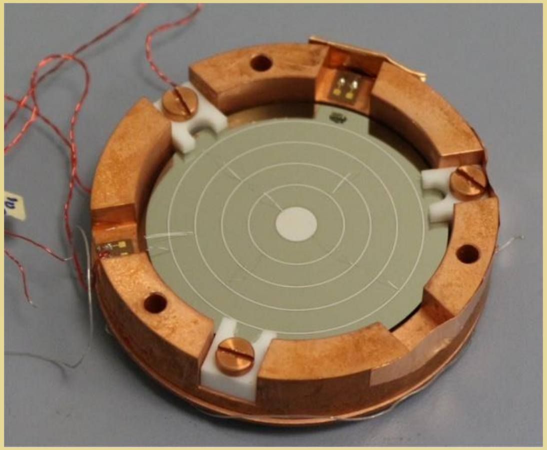
With optimised thermal coupling **@IAS-Orsay**

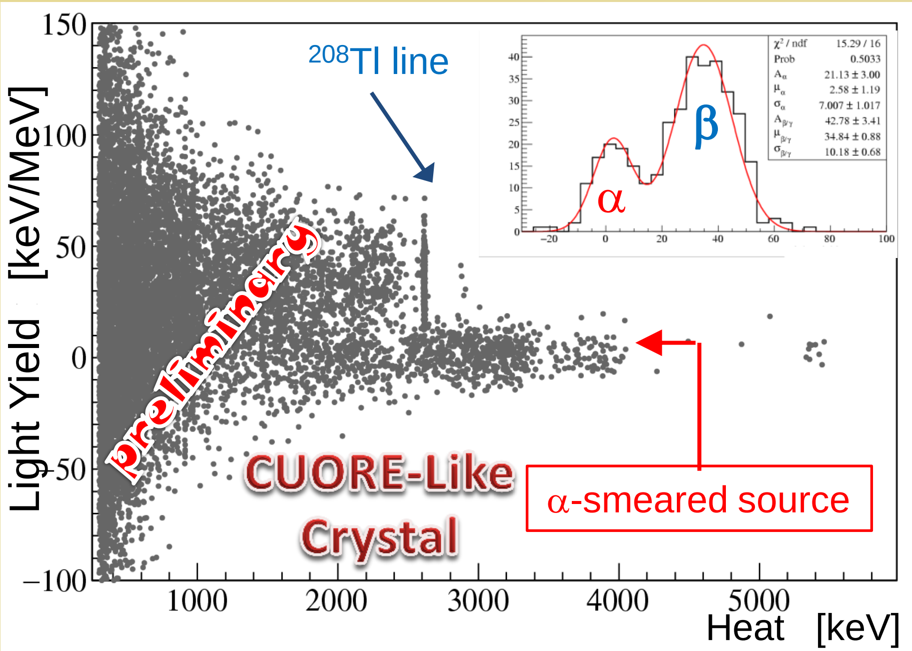




ΔE~18 eV with standard read-out
reproducibility must be investigated

With Neganov-Luke enhancement **@CSNSM-Orsay**

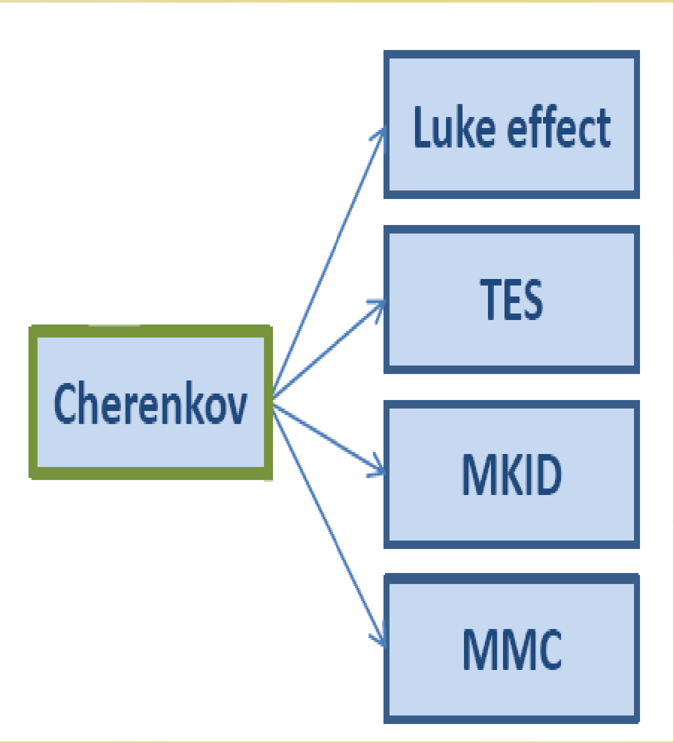




ΔE~20 eV with standard read-out
reproducibility must be investigated

Status on Light detectors

The amount of Cherenkov light signal escaping a large TeO_2 crystals requires LDs with ΔE_{RMS} **≤ 20 eV** in order to achieve 99.5 % α-rejection



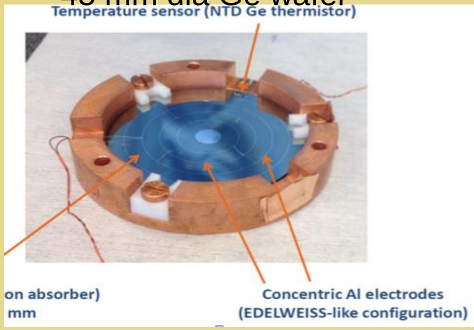
Pro	Con	Light detection on Bolometers $<\Delta E_{RMS}>$
Standard readout easy assembly	detector reproducibility to be established	Fully tested ≈20 eV
Best resolution Established reproducibility Possible multiplexing	Squid electronics	Fully tested <10 eV
High multiplexing and reproducibility. Theoretical high resolution	Resolution not yet demonstrated	Not yet tested 100 eV
Theoretical high resolution and fast response	Squid electronics	tested ≈100 eV

R&D on Light detectors

Neganov Luke

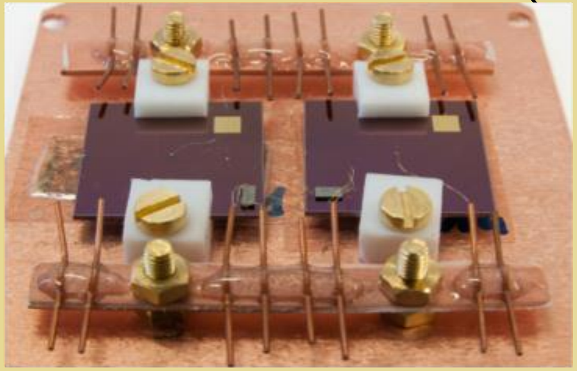
CSNSM, France

45 mm dia Ge wafer

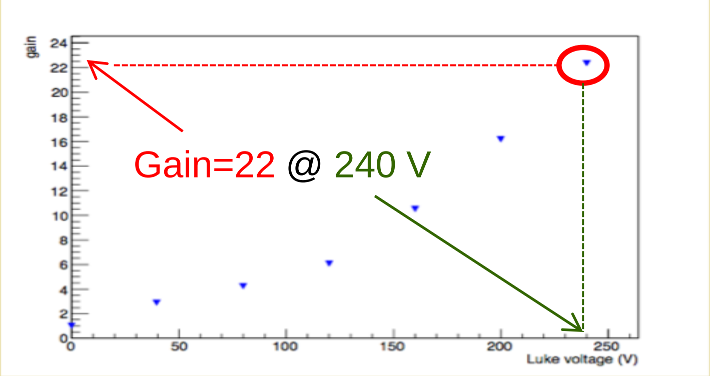


Best projected resolution ≈5 eV
Intense R&D on electrodes
deposition reproducibility

R&D in Milano-Bicocca (in coll. with **FBK**):



2x2 cm Si wafers



No leakage current observed in any sample

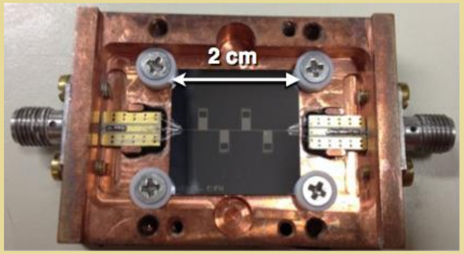
TES

R&D (Berkeley/Argonne on low-Tc TES) to increase the surface
of the single light detectorin order to use it for several
bolometers (MPI-Munich) – work for possible multiplexing

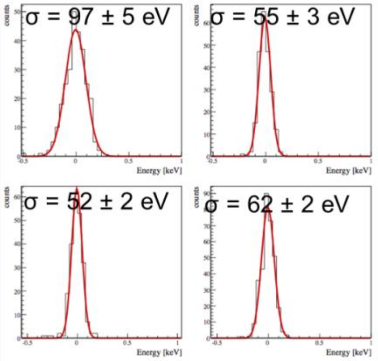
Kid

Calder n. 335359

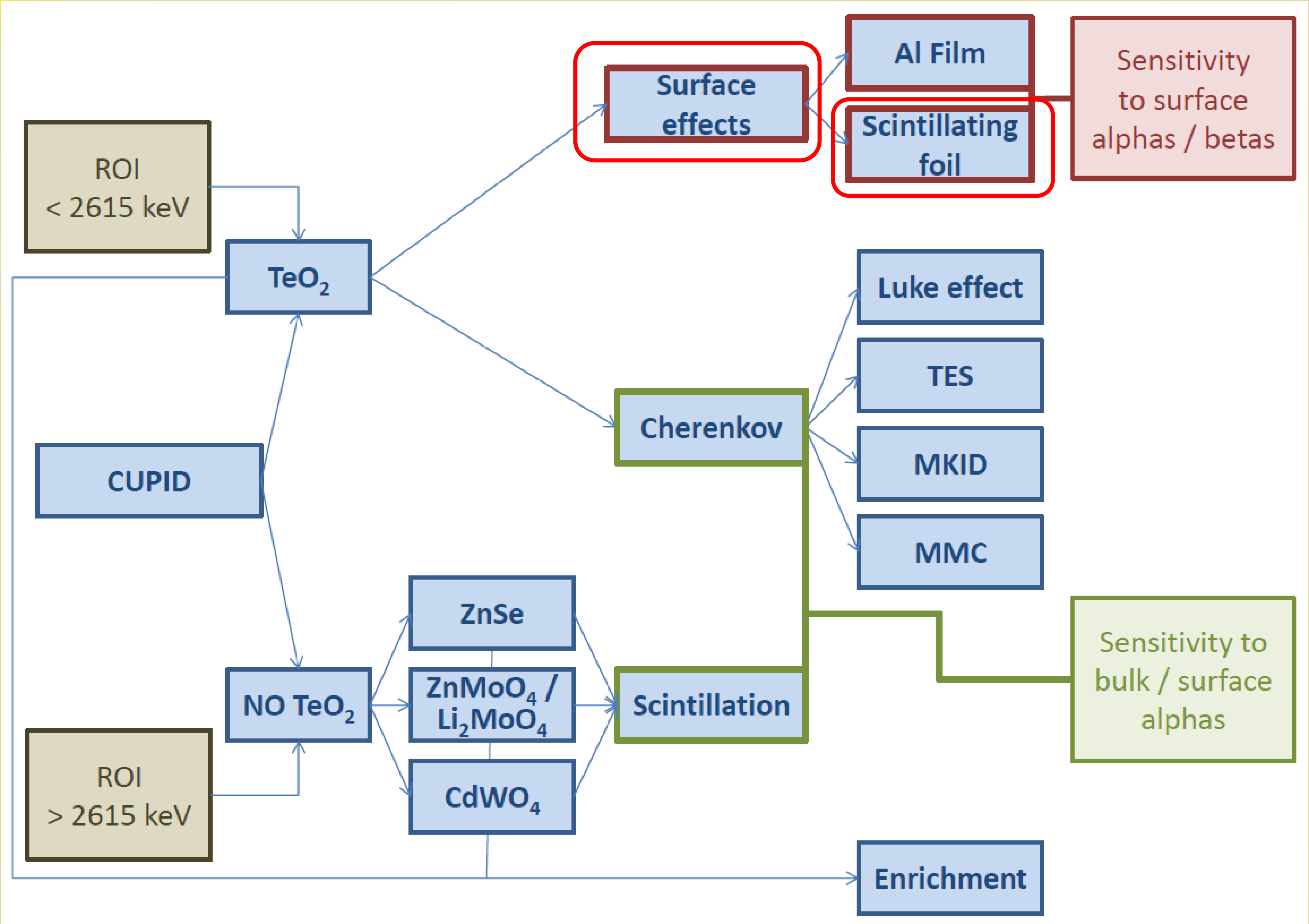
erc
European Research Council
Established by the European Commission



Need to develop larger
area detectors and to
Increase energy resolution

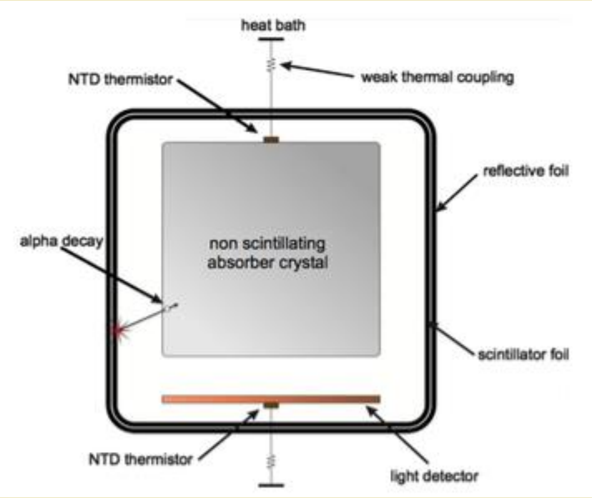


R&D on Light detectors



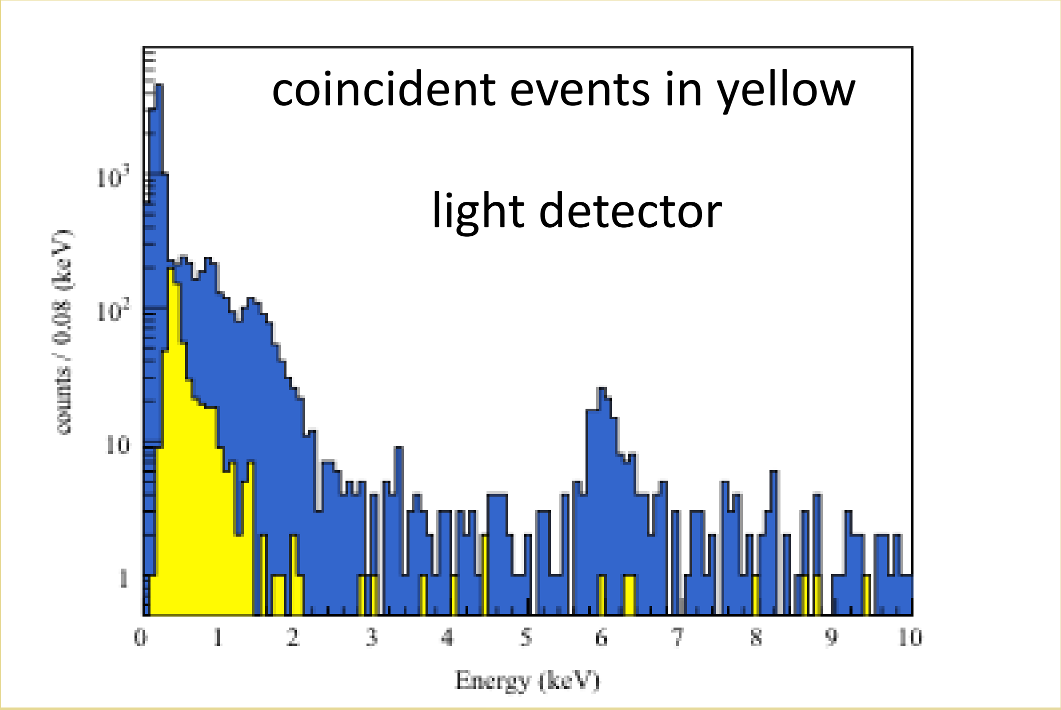
Surface- Effects- ABSURD

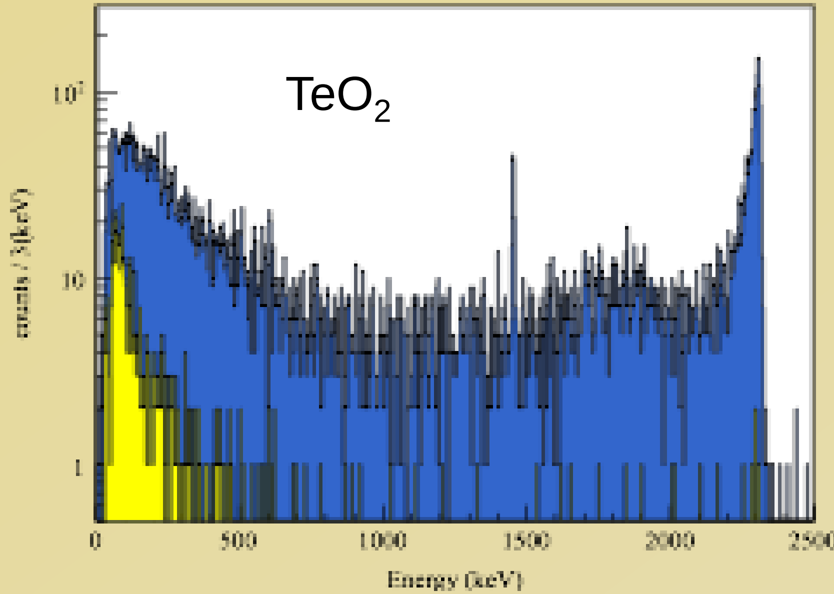
- A Background Surface Rejection Detector
- TeO_2 + NTD light detector encapsulated in a scintillating foil
  - degraded αs release energy both in TeO_2 and scintillating foil: heat/light coincidence tag
  - ^{147}Sm α source (Q=2.3MeV) on crystal surface



heat detector

doi:10.1016/j.nima.2013.05.114





^{130}Te Enrichment

In the CUORICINO experiment enriched ^{130}Te and ^{128}Te crystals were used in order to measure the 2-neutrino decay mode of ^{130}Te. Unfortunately these crystals did show a very bad energy resolution O(20 keV) and internal contaminations a factor 10 larger than the natural ones.

10 kg of 92% enriched ^{130}Te were recently purchased (NSF Grant) . Two 40% enriched 750 g $^{130}TeO_2$ crystals were grown and bolometrically tested. First results are encouraging but they show internal contamination larger than the one observed in CUORE

- ✓ Chemical impurities (Fe, Ni, Cu) deteriorate the energy resolution
- ✓ Enriched material shows trace of radioactive contaminants

40% Enriched TeO_2

	Energy Range [keV]	Anti-coincident Event Rate [$keV^{-1}kg^{-1}y^{-1}$]		
		Typical CUORE Crystal	08X002	08X003
Continuum	2700 - 3200	0.23 ± 0.03	0.96 ± 0.30	1.15 ± 0.33
Pt-190	3200 - 3400	0.39 ± 0.07	3.11 ± 0.86	1.91 ± 0.67
Continuum	3400 - 3900	0.11 ± 0.02	1.34 ± 0.36	1.34 ± 0.36
U/Th Peaks	4000 - 5000	0.14 ± 0.02	2.63 ± 0.35	3.20 ± 0.39
Po-210 Peak	5000 - 6000	---	47.56 ± 1.50	75.73 ± 1.90
U/Th Peaks	6000 - 8000	0.06 ± 0.01	0.21 ± 0.07	0.22 ± 0.07

B. Wang APS/DNP/JPS meeting Waikaloa, HI, US, Oct 2014

Different R&D started in order to purify the enriched material

- Zone refinement (@USC)
- Wet chemistry @SICCAS
- Vacuum distillation (@Lucifer)

R&D @SICCAS in order to increase crystal growth yield

CUPID & Environmental Radioactivity

The active background rejection techniques, on which detector developments are focused, aim at reducing to negligible levels the effect of surface contaminations of detector materials. This background source is identified as the dominant contributor to CUORE-0 counting rates and as the most likely limiting factor for CUORE sensitivity. However, the reduction of surface contamination effects ***can't by itself ensure the achievement of a background level two orders of magnitude lower than CUORE***.
For this reason there is the need to increase the sensitivity of radioactive screening methods

- Pre-concentration of radio-contaminants through chemical treatment of materials. This technique already developed by other collaboration allows increasing the sensitivities of NAA ICPMS as well as of HPGE measurements.

- Development of a bolometric detector for the measurement of surface/bulk contamination of small samples and foils.

Moreover, according to the simulations based on CUORE and the measured muon flux at LNGS, the event rate induced by the cosmic ray muons or μ-showers in the ROI is expected to be on the order of 0.5 counts/(ton y). For a 5-10 year exposure, a reduction in this rate of about a factor of 10 or more would be required for a zero-background experiment.

- R&D on active muon veto

CUPID Sensitivity

	Detector Mass [kg]	Isotope Fiducial Mass [kg]	$T^{1/2}$(90%) [10^{27} y] (@10 years)	$m_{\beta\beta}$ (90%) [meV] (@10 years)
$Zn^{82}Se$	664	335	4.2	6-19
$Zn^{100}MoO_4$	545	212	2.2	6-17
$^{116}CdWO_4$	986	283	3.0	8-15
$^{130}TeO_2$	755	543	5.1	6-15

Energy resolution < 5 keV

Event selection efficiency in fiducial volume 75-90%

Background within FWHM of endpoint <0.02 counts/(ton· year)

Conclusions

CUPID technology should be as compatible as possible with the existing CUORE infrastructure, in terms of cryogenics, readout, and DAQ features

The primary goal of CUPID is sensitivity of 10–15 meV to the effective neutrino mass. This requires a detector with an active isotope mass of order ton and a background level of $\leq$ 0.1 counts/(ton·y)

The chosen technology should prove convincingly that this target can be achieved, by means of dedicated experimental tests and verifiable simulations.

A tonne-scale bolometric detector will imply O (1000) single detectors. An appealing feature of the bolometric technology is its scalability:

A chosen technology must demonstrate reproducibility in terms of technical performance (energy resolution, pulse shape, noise features). The detector behavior should therefore be tested with an array of at least 8 modules and, if possible, larger, operated underground

The cost and schedule of the enrichment process and of the crystal production must be compatible with a timely realization of the experiment

The first two **CUPID** demonstrator (**LUCIFER** and **LUCINEU**) could probably start together, in CUORE-0 cryostat in 2016.

Backup

R&D Table

TABLE I: Status of the R&D's on the various Particle Identification (PID) options explored in CUPID (see text for acronyms)

Isotope	Compound	Crystals	Enriched crystals	PID technique		PID status
^{130}Te	TeO_2	125 cm^3 radio-pure natural crystals available from CUORE experience. Even larger natural crystals (216 cm^3) successfully grown.	54 cm^3 (125 cm^3) enriched crystals with a.i.=75% (40%) available and tested. R&D in progress.	Surface effects	Al films	Bulk/surface rejection demonstrated with a 2 cm^3 crystal and a fast sensor
					Scintillating foil with conventional NTD light detector	Bulk/surface rejection partially achieved with a 125 cm^3 crystal
				Cherenkov light detection	Optimized NTD light detector	α/β rejection demonstrated with a 125 cm^3 crystal.
					NL-effect light detector	α/β rejection demonstrated with a 125 cm^3 crystal.
					TES light detector	α/β rejection demonstrated with a 48 cm^3 crystal.
					MKID	Prototype light detectors demonstrated. R&D in progress.
					MMC	Technology used in AMoRE. No test done on TeO_2.
^{100}Mo	$ZnMoO_4$	78 cm^3 radio-pure natural crystals available.	14 cm^3 enriched crystals with a.i.=99% available and tested. 325 cm^3 crystalline boule with a.i.=99% grown. R&D in progress.	Scintillation light detection	Conventional NTD light detector	α/β rejection demonstrated with 78 cm^3 natural crystals and 14 cm^3 enriched crystals.
	Li_2MoO_4	78 cm^3 natural crystals available.	No test yet.			α/β rejection demonstrated with a 50 cm^3 natural crystal.
^{82}Se	ZnSe	73 cm^3 radio-pure natural crystals available, but reproducibility problems.	No test yet.			α/β rejection demonstrated with a 73 cm^3 crystal but reproducibility problems.
^{116}Cd	$CdWO_4$	Large (> 100 cm^3) natural crystals available.	75 cm^3 enriched crystals available.			α/β rejection demonstrated with a 63 cm^3 natural crystal.

Near-Far Background sources

Element	material	contamination [Bq/kg]	Te [cnts/ton/y]	Se/Cd/Mo
Far Sources				
^{238}U external shield	lead	$< 1 \times 10^{-5}$	$< 7 \times 10^{-3}$	$< 4 \times 10^{-3}$
^{232}Th external shield	lead	$< 7 \times 10^{-5}$	< 1	$< 1 \times 10^{-2}$
^{238}U 300 K top plate	stainless steel	$< 2 \times 10^{-4}$	$< 5 \times 10^{-4}$	$< 3 \times 10^{-4}$
^{232}Th 300 K top plate	stainless steel	$< 1 \times 10^{-4}$	$< 3 \times 10^{-2}$	$< 3 \times 10^{-4}$
^{238}U cryostat elements	copper	$< 7 \times 10^{-5}$	$< 4 \times 10^{-1}$	$< 3 \times 10^{-1}$
^{232}Th cryostat elements	copper	$< 2 \times 10^{-6}$	$< 3 \times 10^{-1}$	$< 1 \times 10^{-2}$
^{238}U internal shield	copper	$< 7 \times 10^{-5}$	< 1	$< 6 \times 10^{-1}$
^{232}Th internal shield	copper	$< 2 \times 10^{-6}$	$< 8 \times 10^{-1}$	$< 8 \times 10^{-3}$
^{238}U 30 cm disk	lead	$< 1 \times 10^{-5}$	$< 1 \times 10^{-3}$	$< 7 \times 10^{-4}$
^{232}Th 30 cm disk	lead	$< 7 \times 10^{-5}$	$< 2 \times 10^{-1}$	$< 2 \times 10^{-3}$
Near Sources				
^{238}U detector holders	copper	$< 7 \times 10^{-5}$	< 2	< 1
^{232}Th detector holders	copper	$< 2 \times 10^{-6}$	$< 1 \times 10^{-1}$	$< 2 \times 10^{-1}$

Cupid sensitivity goals

TABLE I: CUPID sensitivity goals

Parameter	Projected value and/or range	
Readiness for construction	2018 (technical limit)	
Construction time	5 years	
Total fiducial mass (kg)	TeO_2	750
	$ZnMoO_4$	540
	ZnSe	670
	$CdWO_4$	980
Isotope fiducial mass (kg)	^{130}Te	543
	^{100}Mo	212
	^{82}Se	335
	^{116}Cd	283
Energy resolution at endpoint (FWHM)	< 5 keV	
Event selection efficiency in fiducial volume	75-90%	
Background within FWHM of endpoint	< 0.02 counts/(ton·year)	
90% C.L. $0\nu\beta\beta$ lifetime limit for 10 year run (10^{27} years)	^{130}Te	5.1
	^{100}Mo	2.2
	^{82}Se	4.2
	^{116}Cd	3.0
90% C.L. $m_{\beta\beta}$ limit for 10 year run (90% C.L.) (meV)	^{130}Te	6–15
	^{100}Mo	6–17
	^{82}Se	6–19
	^{116}Cd	8–15
$0\nu\beta\beta$ lifetime discovery sensitivity (3σ) in 10 years	^{130}Te	4.9
	^{100}Mo	2.1
	^{82}Se	4.0
	^{116}Cd	2.9
$m_{\beta\beta}$ discovery sensitivity (3σ) in 10 years	^{130}Te	6–15
	^{100}Mo	7–17
	^{82}Se	6–19
	^{116}Cd	8–15

Cupid-$Q_{\beta\beta}$ – counts in ROI

Table 1: Properties of the most commonly studied $0\nu\beta\beta$ candidates: Q-value, isotopic abundance, and $T^{2\nu}_{1/2}$ half-life (average values from [41]). $R^{|m_{ee}|=10\mathrm{meV}}_{0\nu}$ is the range of $0\nu\beta\beta$ count rates expected in an energy window of a FHWM around the Q-value, for a Majorana mass of 10 meV, corresponding to the largest and smallest NME values among those of Fig. 2. The ratio of signal counts in an energy window of a FHWM around the Q-value for a Gaussian distributed-signal is $f(\Delta E = \mathrm{FWHM}) = 0.76$. In the last column we report the $2\nu\beta\beta$ event rate around the Q-value, calculated by integrating the last 10 keV below the end point of the $2\nu\beta\beta$ spectrum. All rates are expressed in counts per year per ton of $0\nu\beta\beta$ emitting isotope.

Isotope	Q [keV]	a [%]	$T^{2\nu}_{1/2}$ 10^{19} [y]	$R^{\|m_{ee}\|=10\mathrm{meV}}_{0\nu}$ [cnts/y/ton$_{iso}$]	$R^{10\mathrm{keV}}_{2\nu}$ [cnts/y/ton$_{iso}$]
^{48}Ca	4274	0.2	$4.4^{+0.5}_{-0.4}$	0.06 - 0.9	5×10^{-6}
^{76}Ge	2039	7.6	160^{+13}_{-10}	0.05 - 0.5	4×10^{-6}
^{82}Se	2996	8.7	9.2±0.7	0.17 - 1.5	8×10^{-6}
^{96}Zr	3348	2.8	2.3±0.2	0.16 - 2.0	2×10^{-5}
^{100}Mo	3034	9.6	0.71±0.04	0.35 - 2.9	8×10^{-5}
^{116}Cd	2814	7.5	2.85±0.15	0.27 - 0.9	2×10^{-5}
^{130}Te	2528	34.2	69±13	0.15 - 1.0	2×10^{-6}
^{136}Xe	2458	8.9	220±6	0.1 - 0.6	6×10^{-7}
^{150}Nd	3368	5.6	0.82±0.9	0.36 - 1.7	3×10^{-5}

Cupid-$N_{\beta\beta}$ – Sensitivity

Table 4: IHE characteristics for the different $\beta\beta$ candidates. For each isotope we quote the type of scintillating crystal, the total mass of a 988 $5\times5\times5$ cm^3 crystal array, the number of $\beta\beta$ candidates, the number of decays in 5 years ($N_{0\nu\beta\beta}$) for the most and the least favourable values of F_N among those discussed in Section 2.2 for $|m_{ee}|$ = 50 meV and $|m_{ee}|$ = 10 meV. We assume a 90% isotopic enrichment in the $\beta\beta$ emitting isotope. In the last column we list the 5 year sensitivity at 90% CL under the zero background hypothesis (see Eq. (7)).

Isotope	Crystal	Mass [kg]	$N_{\beta\beta}$	$N^{50meV}_{0\nu\beta\beta}$ [cnts]	$N^{10meV}_{0\nu\beta\beta}$ [cnts]	5 y sensitivity [y]
^{82}Se	ZnSe	664	2.4×10^{27}	10 - 85	0.4 - 3.4	2.1×10^{27}
^{116}Cd	$CdWO_4$	985	1.5×10^{27}	13 - 44	0.5 - 1.8	1.5×10^{27}
^{100}Mo	$ZnMoO_4$	540	1.3×10^{27}	12 - 99	0.5 - 4	1.1×10^{27}
^{130}Te	TeO_2	751	2.4×10^{27}	13 - 89	0.5 - 3.6	2.5×10^{27}

Cupid-2ν- pileup

Table 8: $2\nu\beta\beta$ pile-up induced background in a 5 keV ROI for experiments based on the four $\beta\beta$ candidates discussed in this work. The pile-up rate is evaluated for a 90% enrichment, a $5\times5\times5$ cm^3 crystal and for a minimum pulse separation time $\Delta T = 1$ ms.

Isotope	Crystal	$N_{\beta\beta}$ [n/crystal]	$T^{2\nu}_{1/2}$ [y]	Bkg in ROI [5 keV] [cnts/ton/y]
^{82}Se	ZnSe	2.5×10^{24}	9.2×10^{19}	2.7×10^{-2}
^{116}Cd	$CdWO_4$	1.5×10^{24}	2.8×10^{19}	0.07
^{100}Mo	$ZnMoO_4$	1.3×10^{24}	0.7×10^{19}	1.5
^{130}Te	TeO_2	2.5×10^{24}	68×10^{19}	0.5×10^{-3}

NSAC guidelines

The Subcommittee recommends the following guidelines be used in the development and consideration of future proposals for the next generation experiments:

1.) Discovery potential: Favor approaches that have a credible path toward reaching 3σ sensitivity to the effective Majorana neutrino mass parameter $m_{\beta\beta}$=15 meV within 10 years of counting, assuming the lower matrix element values among viable nuclear structure model calculations.

2.) Staging: Given the risks and level of resources required, support for one or more intermediate stages along the maximum discovery potential path may be the optimal approach.

3.) Standard of proof: Each next-generation experiment worldwide must be capable of providing, on its own, compelling evidence of the validity of a possible non-null signal.

4.) Continuing R&D: The demands on background reduction are so stringent that modest scope demonstration projects for promising new approaches to background suppression or sensitivity enhancement should be pursued with high priority, in parallel with or in combination with ongoing NLDBD searches.

5.) International Collaboration: Given the desirability of establishing a signal in multiple isotopes and the likely cost of these experiments, it is important to coordinate with other countries and funding agencies to develop an international approach.

6.) Timeliness: It is desirable to push for results from at least the first stage of a next-generation effort on time scales competitive with other international double beta decay efforts and with independent experiments aiming to pin down the neutrino mass hierarchy.

NSAC desired features

- Very low, and preferably flat, background within the spectral region of interest, relative to the signal size anticipated at the half-life sensitivity goal;
- Good energy resolution with excellent energy calibration, to enhance a potential signal above backgrounds and to minimize the $2\nu\beta\beta$ tail underneath the $0\nu\beta\beta$ peak;
- Ability to scale the experimental approach to larger masses at realizable cost, as needed to maximize the discovery potential within the inverted hierarchy region;
- Tracking capability to enhance identification of $0\nu\beta\beta$ decay event topology;
- A favorable $0\nu\beta\beta$ Q-value to enhance the phase space factor and provide a region of interest above many of the gamma ray lines from U- and Th-chain contaminants;
- Ability to remove or replace the enriched isotope without affecting detector performance, in order to verify the reality of a possible non-null signal.

However, it is unlikely that any one approach will achieve all of these desirable features. It is best to support the approach that provides the combination of these features most likely to reach the desired sensitivity at a cost that can be funded on a competitive time schedule.

http://science.energy.gov/~/media/np/nsac/pdf/docs/2014/NLDBD_Report_2014_Final.pdf