LUCIFER:
Low background Underground Cryogenic Installation For Elusive Rates

Luca Pattavina

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13th June 2013, LNGS

Outline

- Introduction on double-beta decay (DBD) physics

- Bolometers as a probe for DBD physics
  - the technique
  - the limitation (background sources)
  - the potential

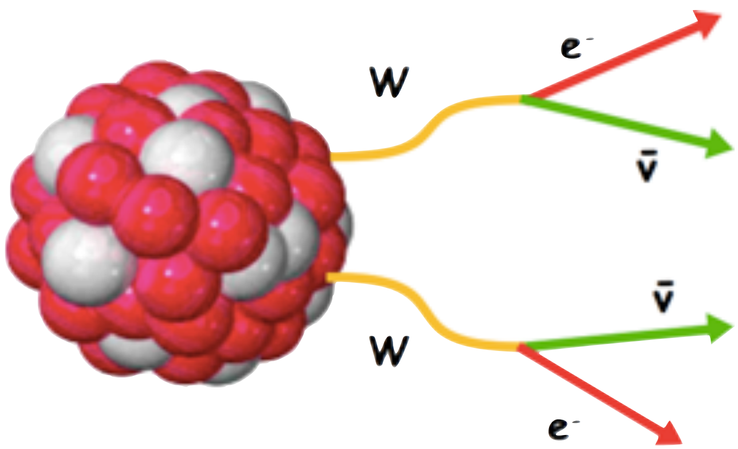
- Particle discrimination with scintillating bolometers

- The LUCIFER project:
  - $ZnMoO_4$
  - ZnSe
  - R&D prototypes

Double-Beta Decay

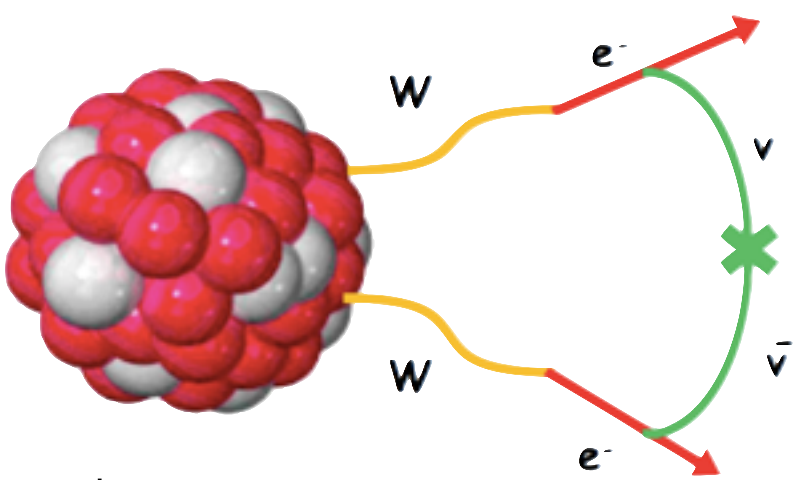
It is a very rare nuclear decay:
$(A,Z) \rightarrow (A, Z+2)+2e^{-}+(2\bar{\nu}_e)$

2νββ



- Second order SM weak process
- Rarest decay ever observed: $T_{1/2} \sim 10^{19} - 10^{21}$ y

0νββ



- Not allowed by the Standard Model ($\Delta L=2$)
- Decay never observed: $T_{1/2} > 10^{22} - 10^{25}$ y
- Possible only if neutrinos are Majorana particles

Indirect neutrino mass measurement

Decay rate:

$$\frac{1}{T^{0\nu}_{1/2}} \propto G(Q,Z)|M_{nucl}|^2|m_{\beta\beta}|^2$$

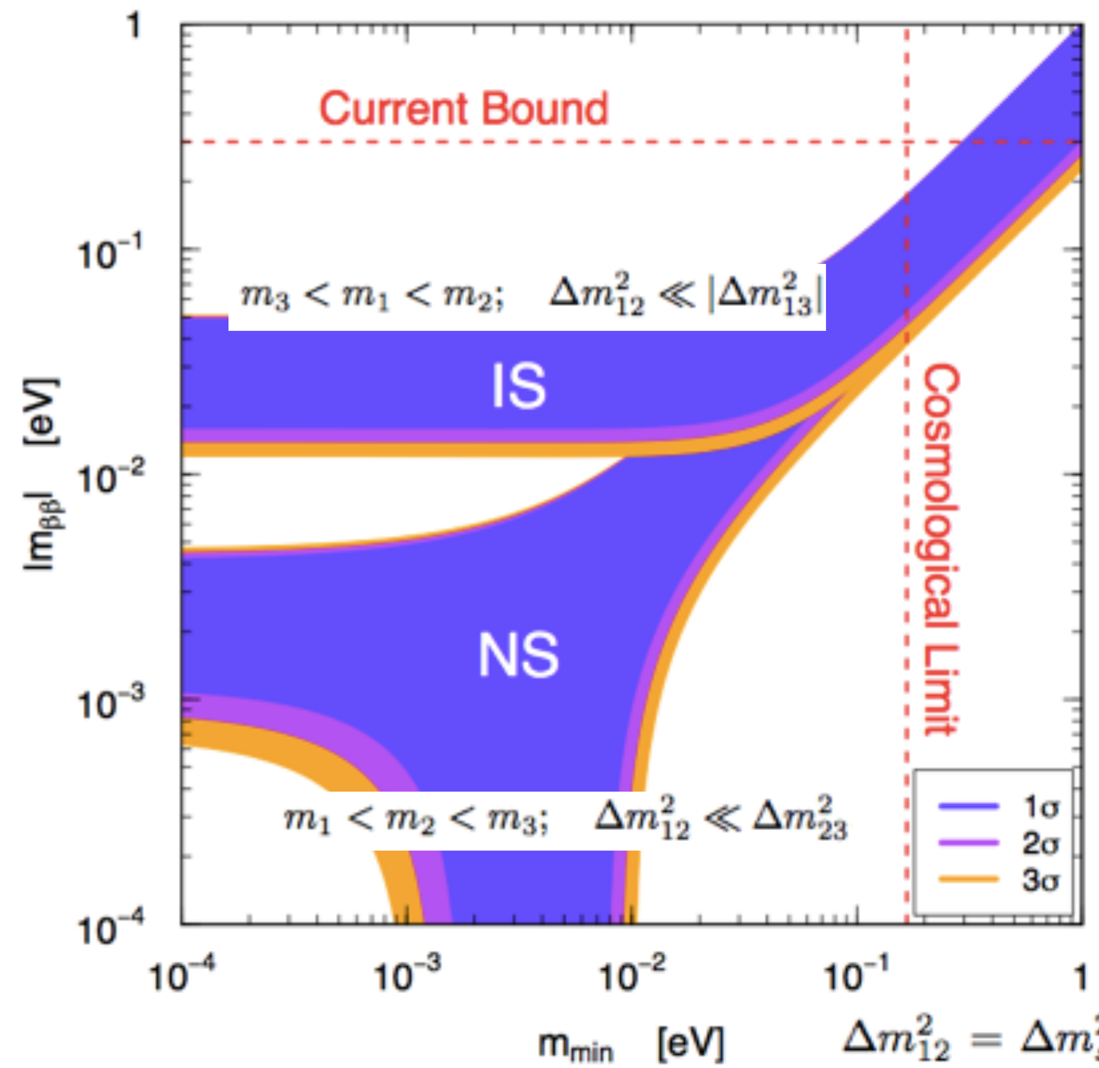
Phase space factor

Nuclear matrix element

Effective neutrino mass

$$m_{\beta\beta} = |\sum_i m_{\nu_i} U_{ei}^2|$$

$$m_{\beta\beta} = \cos^2\theta_{13}(m_1\cos^2\theta_{12} + m_2 e^{2i\alpha}\sin^2\theta_{12}) + m_3 e^{2i\beta}\sin^2\theta_{13}$$



$\Delta m^2_{12} = \Delta m^2_s$

IS: $|\Delta m^2_{13}| = \Delta m^2_a$

NS: $\Delta m^2_{23} = \Delta m^2_a$

Bilenky and Giunti
ArXiv.org:1203.5250

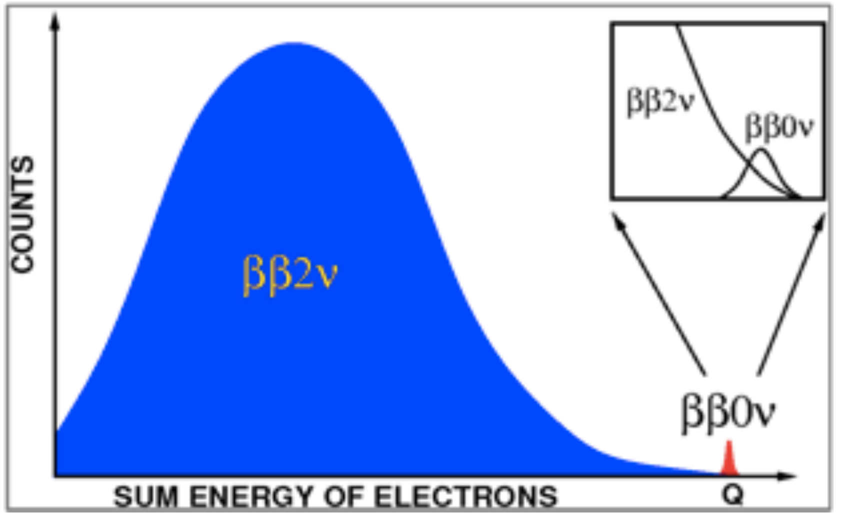
The observation of 0νββ:

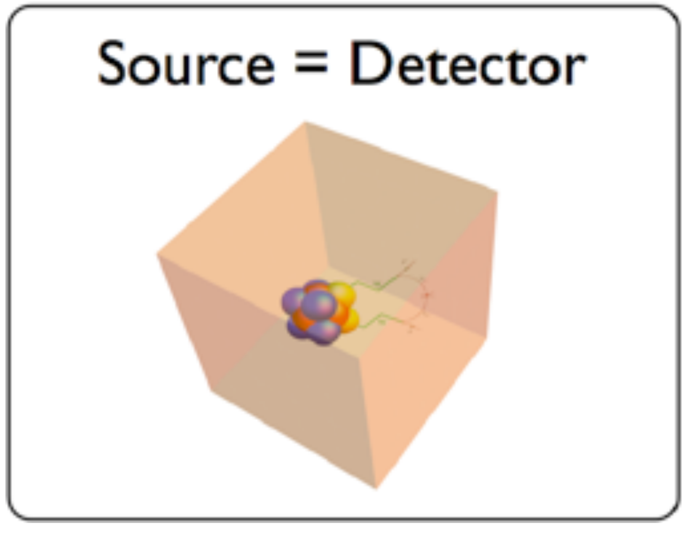
- proof of the Majorana nature of neutrinos
- constraints on neutrino mass hierarchy
- neutrino mass scale
- infer information about Majorana phases

Experimental signature

Measurement of the kinetic energy of the decay products (~MeV).

It is a monochromatic peak at the Q-value of the nuclear transition.

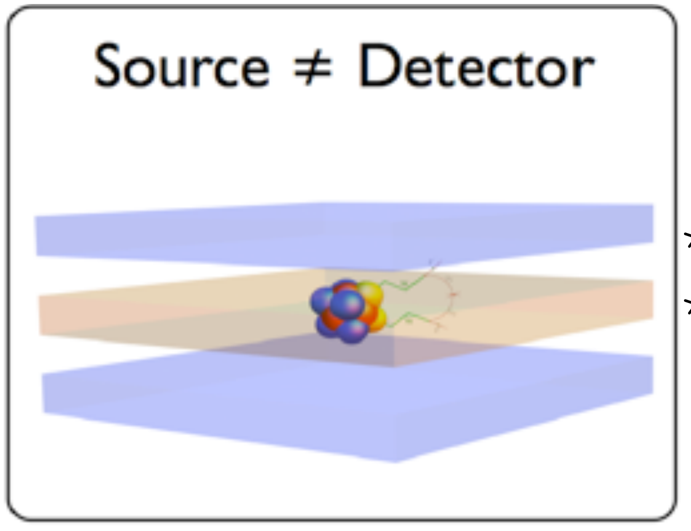




Calorimetry

Solid-state device **Bolometer** **Gas Detector**

* High efficiency
* Good energy resolution
* Large mass source



Scintillation & Tracking

Liquid scintillator **TPC**

* Large mass source
* Particle identification

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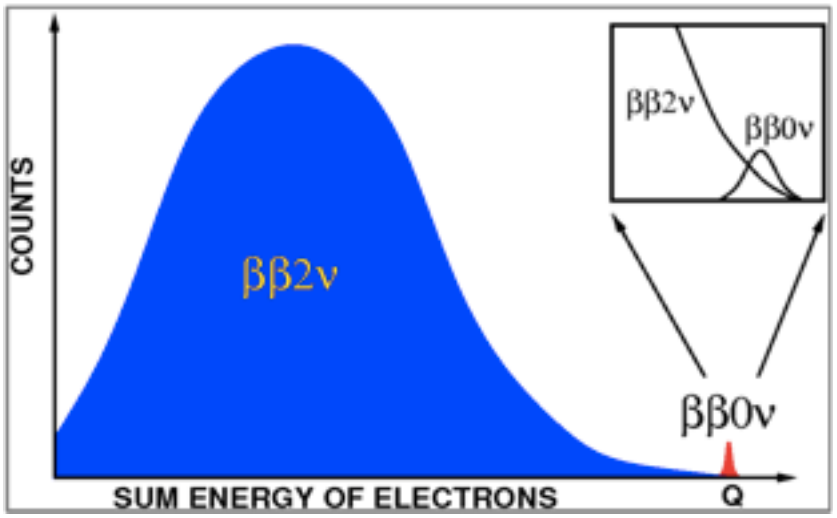
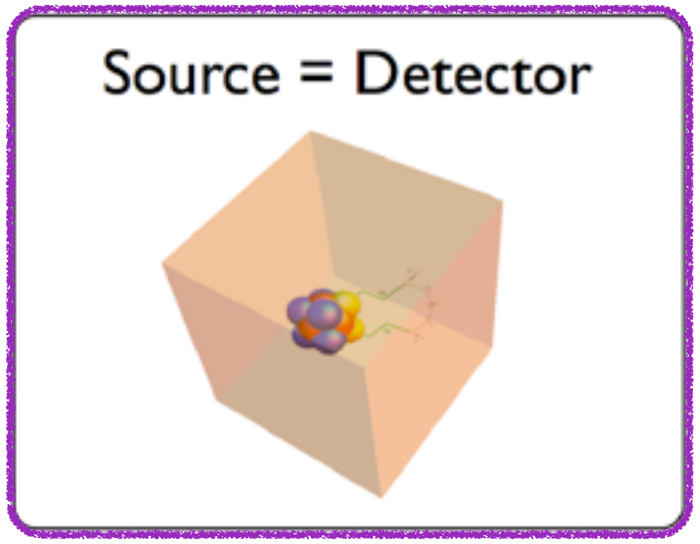
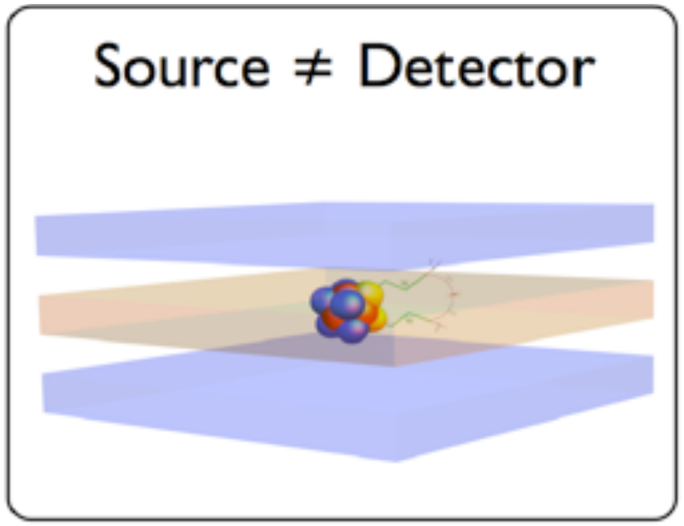




Calorimetry

Solid-state device **Bolometer** **Gas Detector**

* High efficiency
* Good energy resolution
* Large mass source
* Wide range of absorber materials



Scintillation & Tracking

Liquid scintillator **TPC**

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0νββ Sensitivity

$S_{0\nu}$: half-life corresponding to the minimum number of detectable signals above background at a given C.L.

$$S_{0\nu} \propto a.i.\sqrt{\frac{M\cdot t}{B\cdot \Delta E}}$$

- **i.a.: isotopic abundance**
  - high natural i.a. among 0νββ candidates or enrichment
- **M: detector mass**
  - Large mass array
- **t: measuring time**
  - Stable over long time (~y)
- **B: background**
  - Deep underground location
  - Material selection
  - High granularity
- **ΔE: energy resolution**
  - Bolometric approach

Q-value: 2995 keV
Material: ZnSe
Enriched a.i.: 95%
Source Mass: ~10 kg of Se-82
Projected Bkg: ~0.001 c/keV/kg/y
Resolution: ~ **10 keV** @ ROI
Sensitivity $T_{1/2}$: ~10^{26} **y** in **5 y**

Q-value: 2528 keV
Material: TeO_2
Natural a.i.: 34%
Source Mass: 206 kg Te-130
Projected Bkg: ~0.01 c/keV/kg/y
Resolution: ~ **5 keV** @ ROI
Sensitivity $T_{1/2}$: ~10^{26} **y** in **5 y**

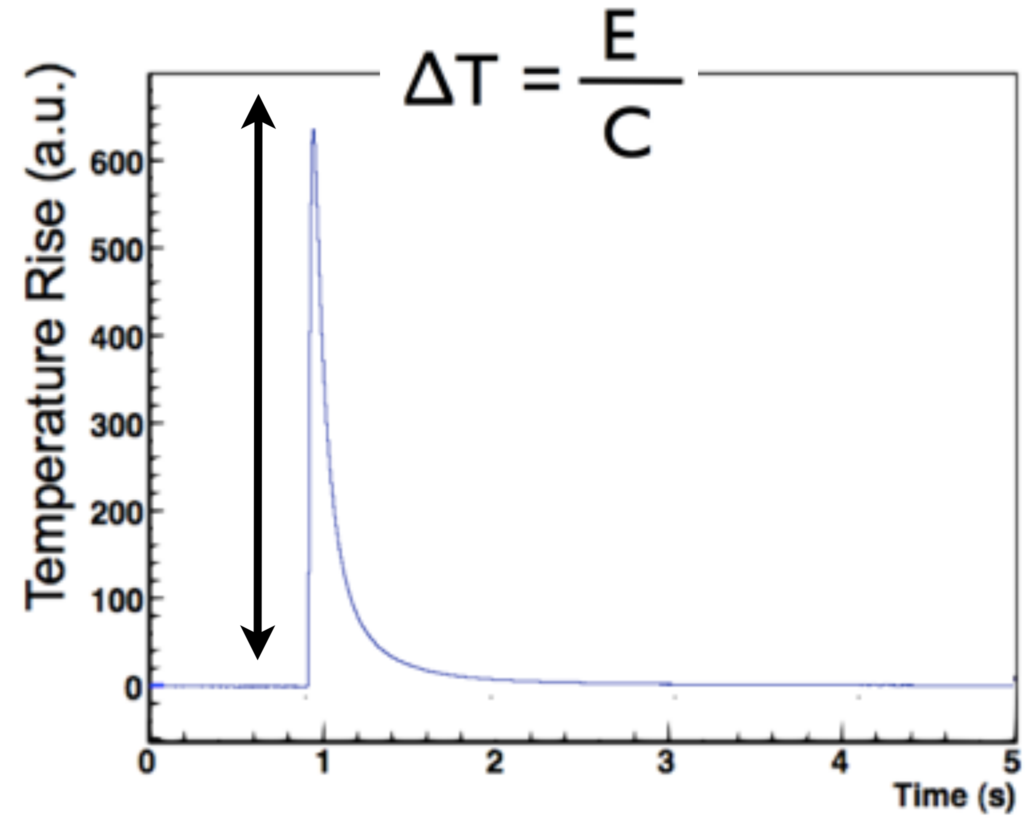
F.Alessandria et al., arXiv:1109.0494

The bolometric technique

Almost all the deposited energy is converted into phonons which induce a measurable temperature rise

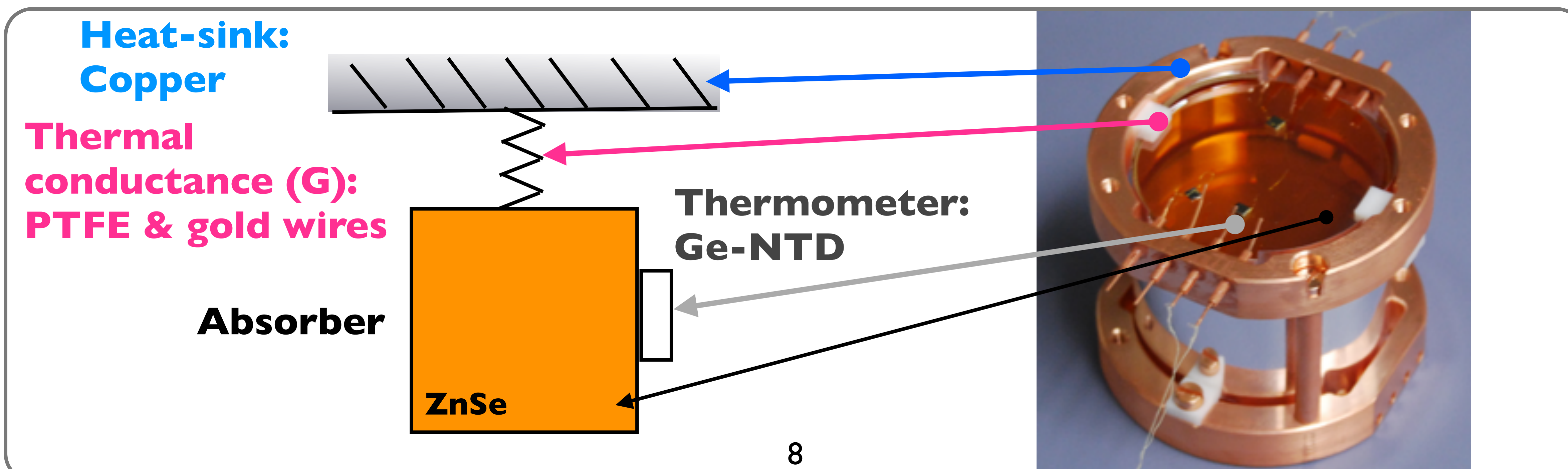
The heat capacity of the crystal must be very small
(-> **low Temperature ~10 mK**)

fully-active detector



Absorber
- M ~ 0.45 kg
- C ~ 10^{-10} J/K
- ΔT/ΔE ~ 500μK/MeV

Sensor
- $R = R_0 \exp[(T_0/T)^{1/2}]$
- R ~ 100 MΩ
- ΔR/ΔE ~ 3 MΩ/MeV



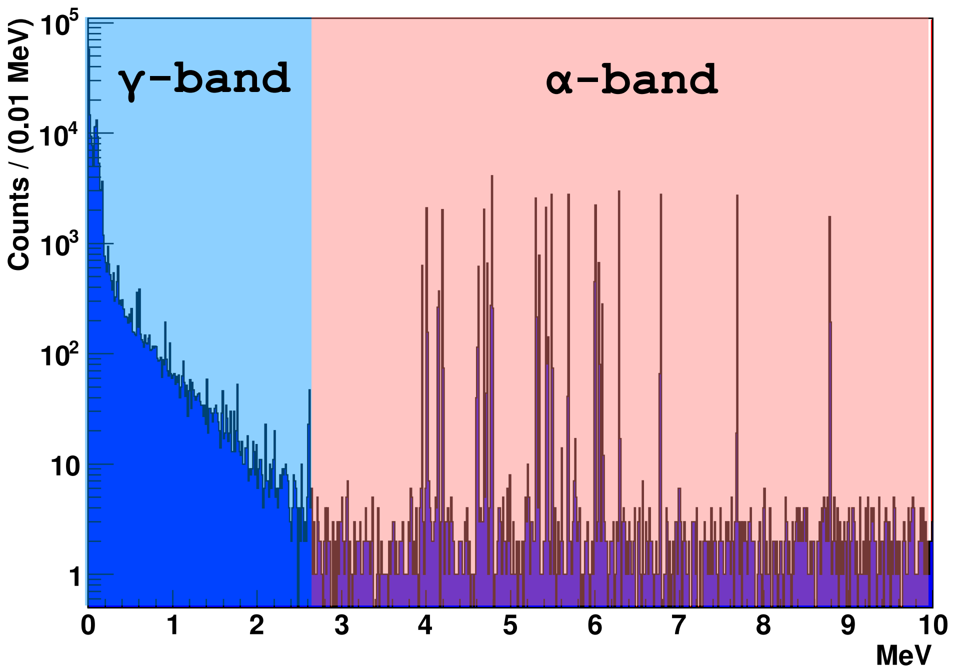
0νββ candidate isotopes

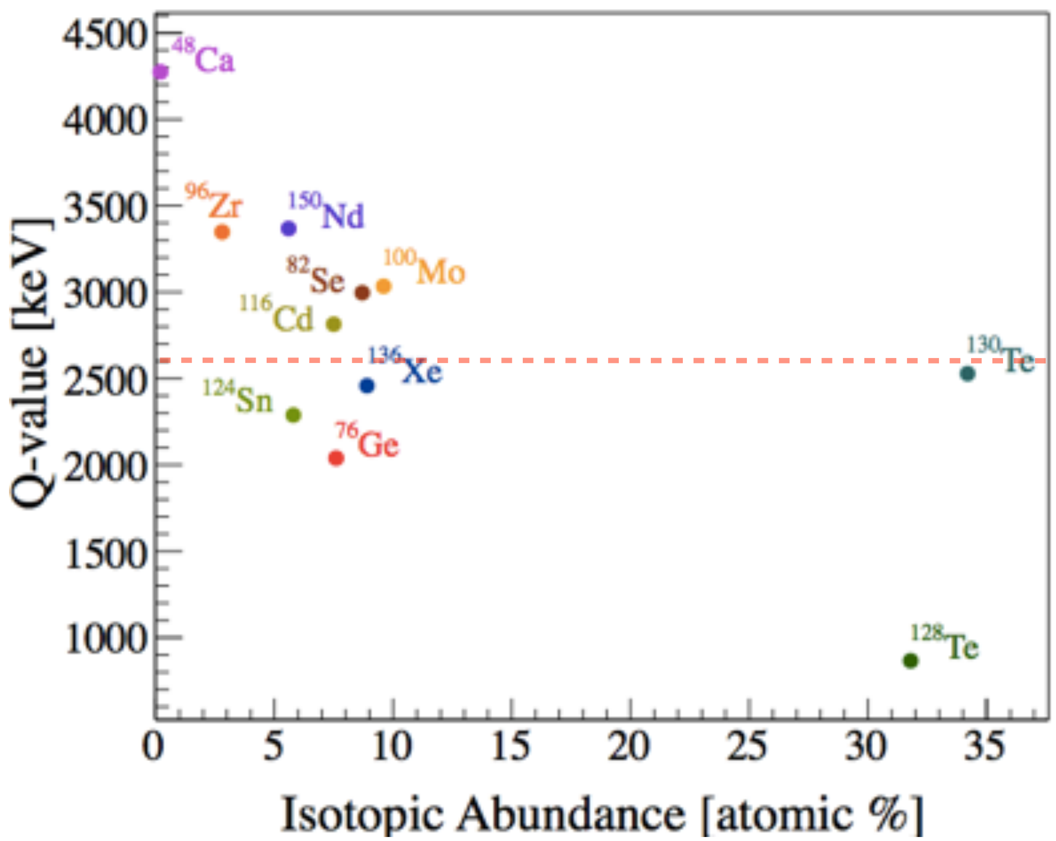
-> the "best-isotope" must have:

* high Q-value
* high a.i.

$$S_{0\nu} \propto a.i.\sqrt{\frac{M \cdot t}{B \cdot \Delta E}}$$

Environmental radioactivity energy spectrum (^{232}Th & ^{238}U)





requirements:

- high Q-value -> better if > 3 MeV
- high a.i. -> the highest possible but...
- easy/cheap enrichment -> reduce radioactive contaminations
- solid -> bolometers have crystal structures

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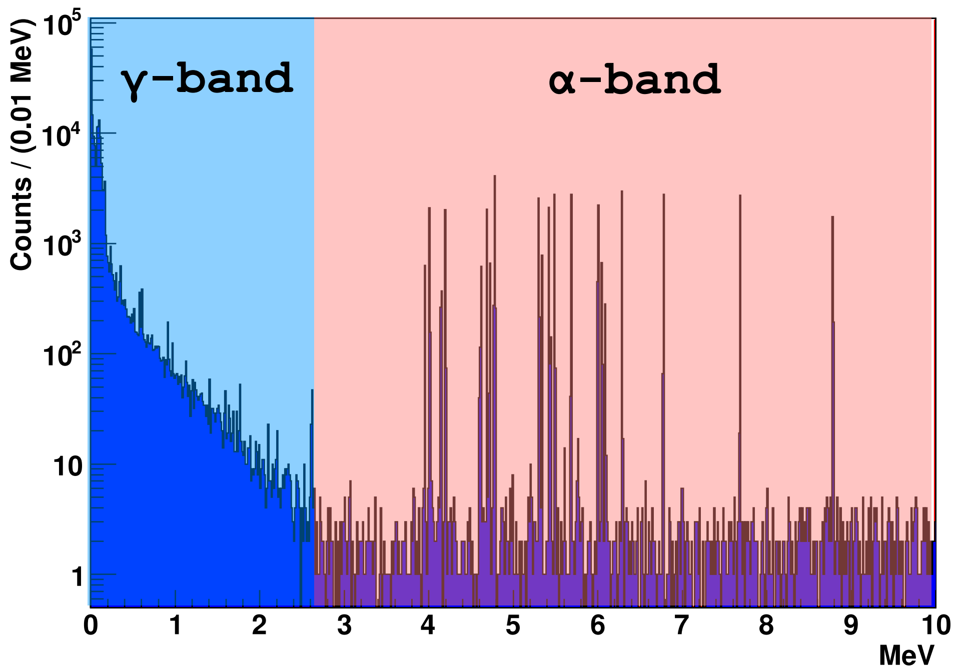

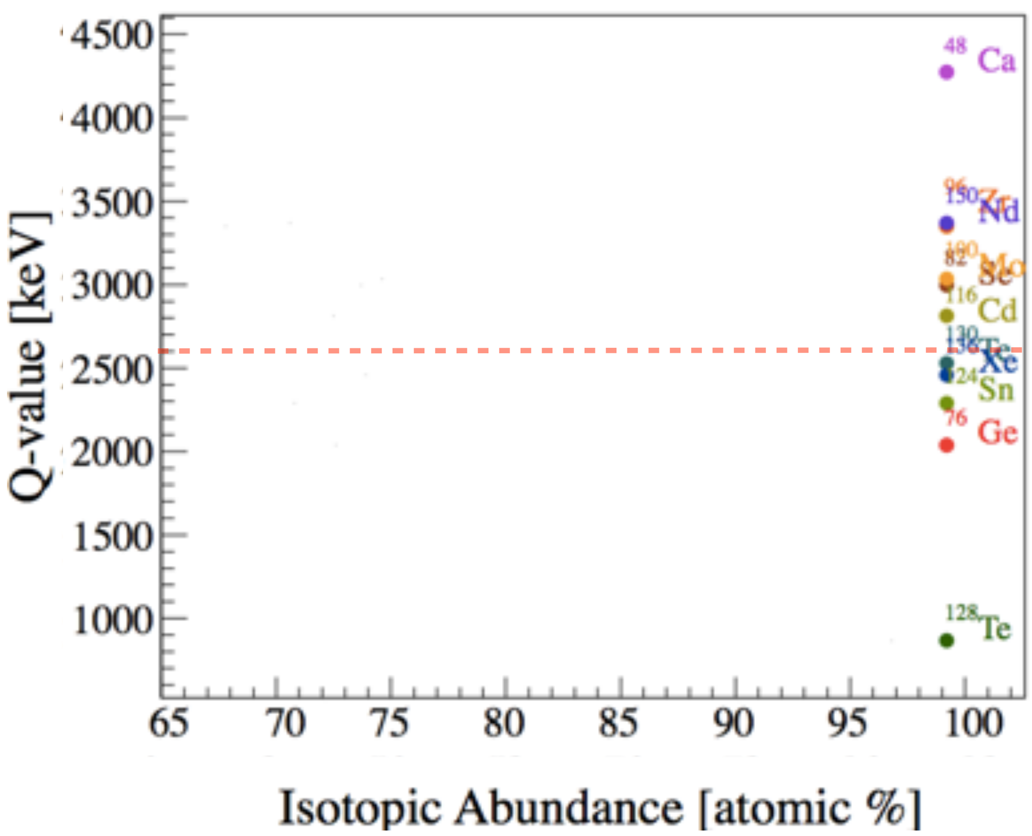

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Bkg sources in bolometric DBD experiments

Since bolometers are **fully-active detectors** and are sensitive to all radiation types, various sources can limit the experimental sensitivity

Neutrons => - neutron activation: (n,γ) reactions
* appropriate shields are needed

Muons => - energy deposit in the ROI
* underground installation & granularity & veto

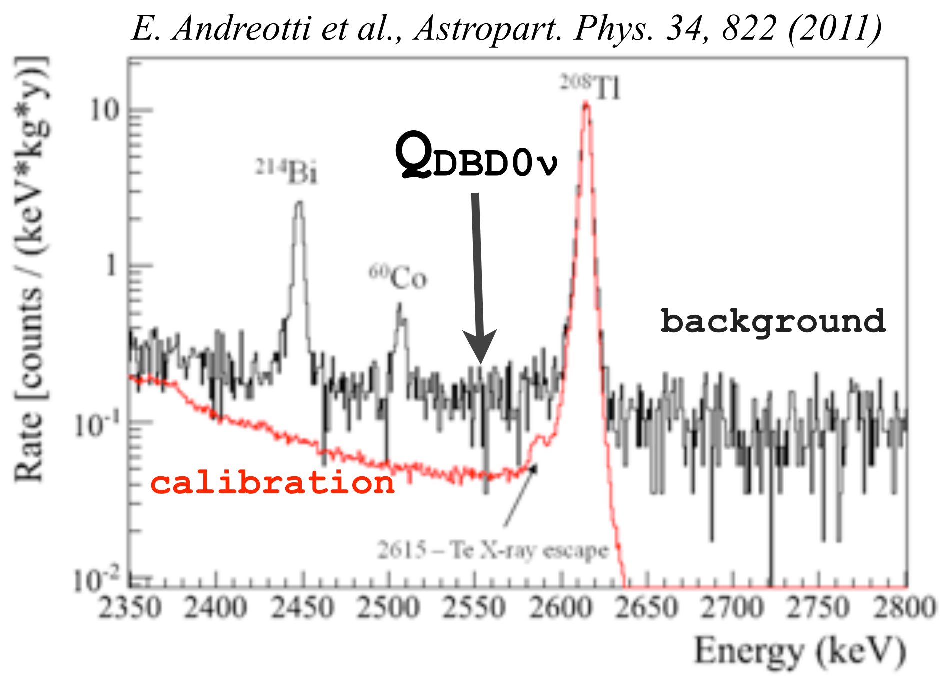
β/γs => - natural radioactivity (^{238}U & ^{232}Th)
* isotope choice and material selection

degraded αs => - αs coming out from detector surfaces
* surface cleaning and particle discrimination

CUORICINO experiment

Cuoricino:

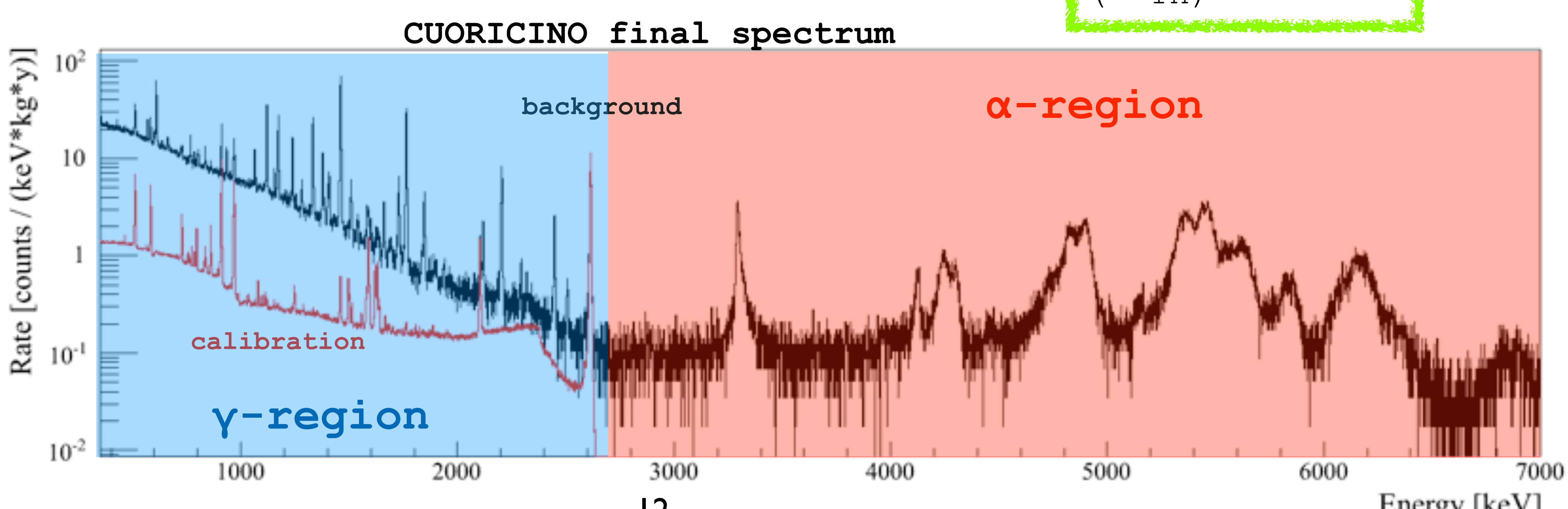
- first large array (62 bolometers = ~41 kg) for DBD
- high statistics (exposure: 19.75 kg(Te^{130})×y)
- energy resolution @ DBD0ν: 6.3±2.5 keV



background @ DBD0ν:
0.17 c/keV/kg/y

65% Degraded α struggling from TeO_2 and Cu surface contaminations (^{232}Th & ^{238}U)

External high energy γ (^{232}Th) **35%**



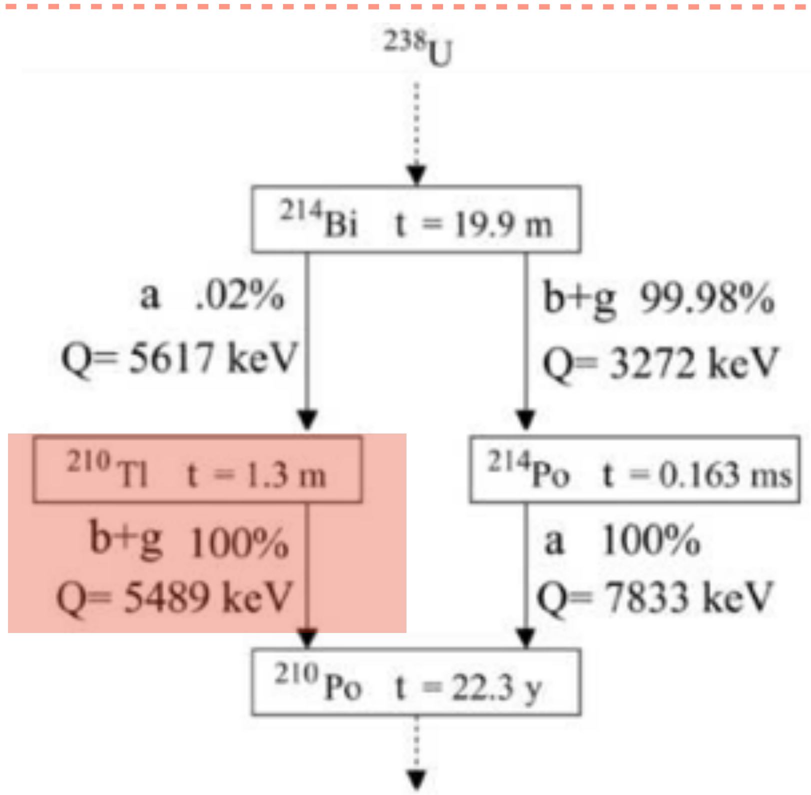
High energy β/γs background

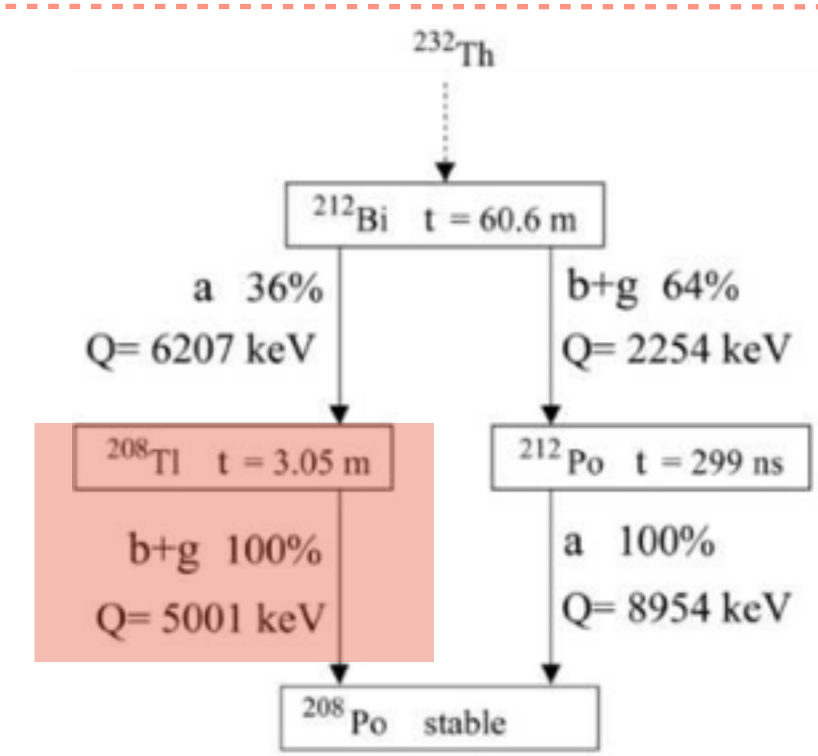
Background can be induced by contaminations
of ^{238}U & ^{232}Th decay products.
Elements with $Q_{value} \sim Q_{DBD}$:

Near contaminations (crystal or Cu structure):

- ^{214}Bi-^{214}Po : Q_{value} 3.27 MeV => rejection because of pile-up with ^{214}Po and slow thermal signal
- ^{210}Tl-^{210}Po : Q_{value} 5.49 MeV => delayed coincidence with ^{214}Bi α
- ^{208}Tl-^{208}Pb : Q_{value} 5.00 MeV => delayed coincidence with ^{212}Bi α

Far contaminations (external) are dangerous => proper shields & material selection





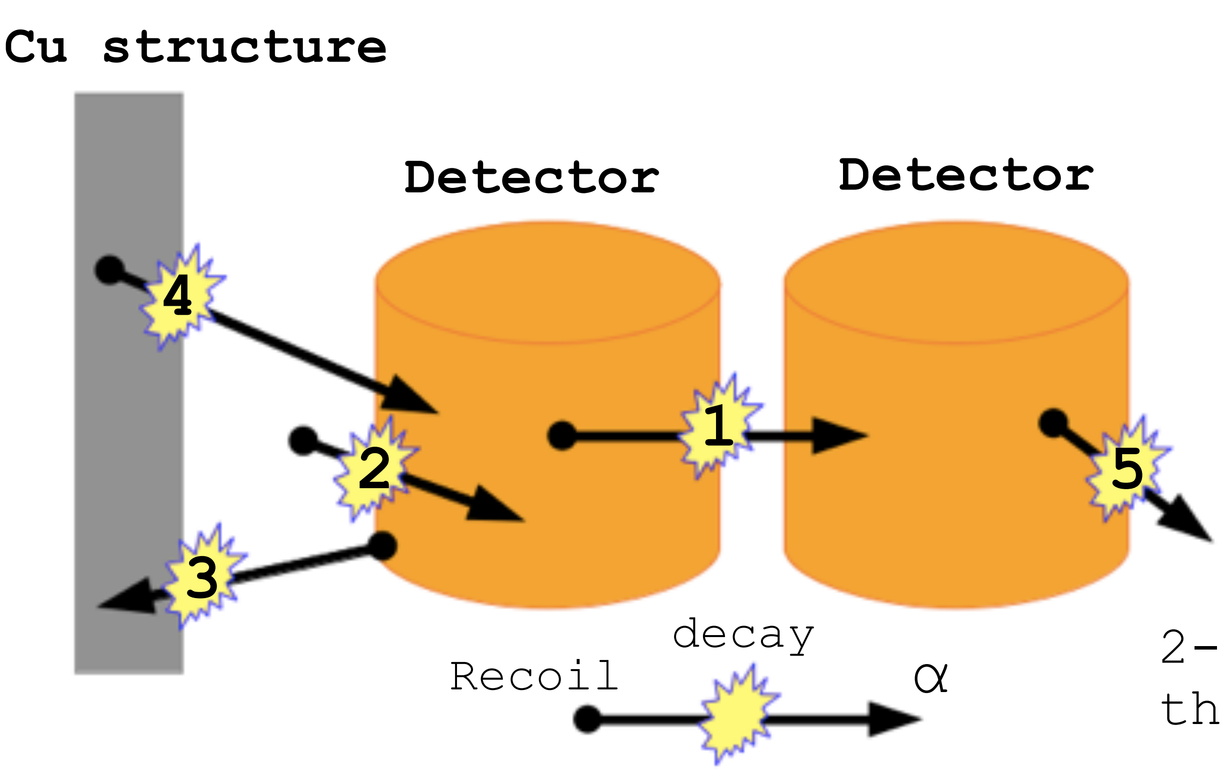
α surface contaminations

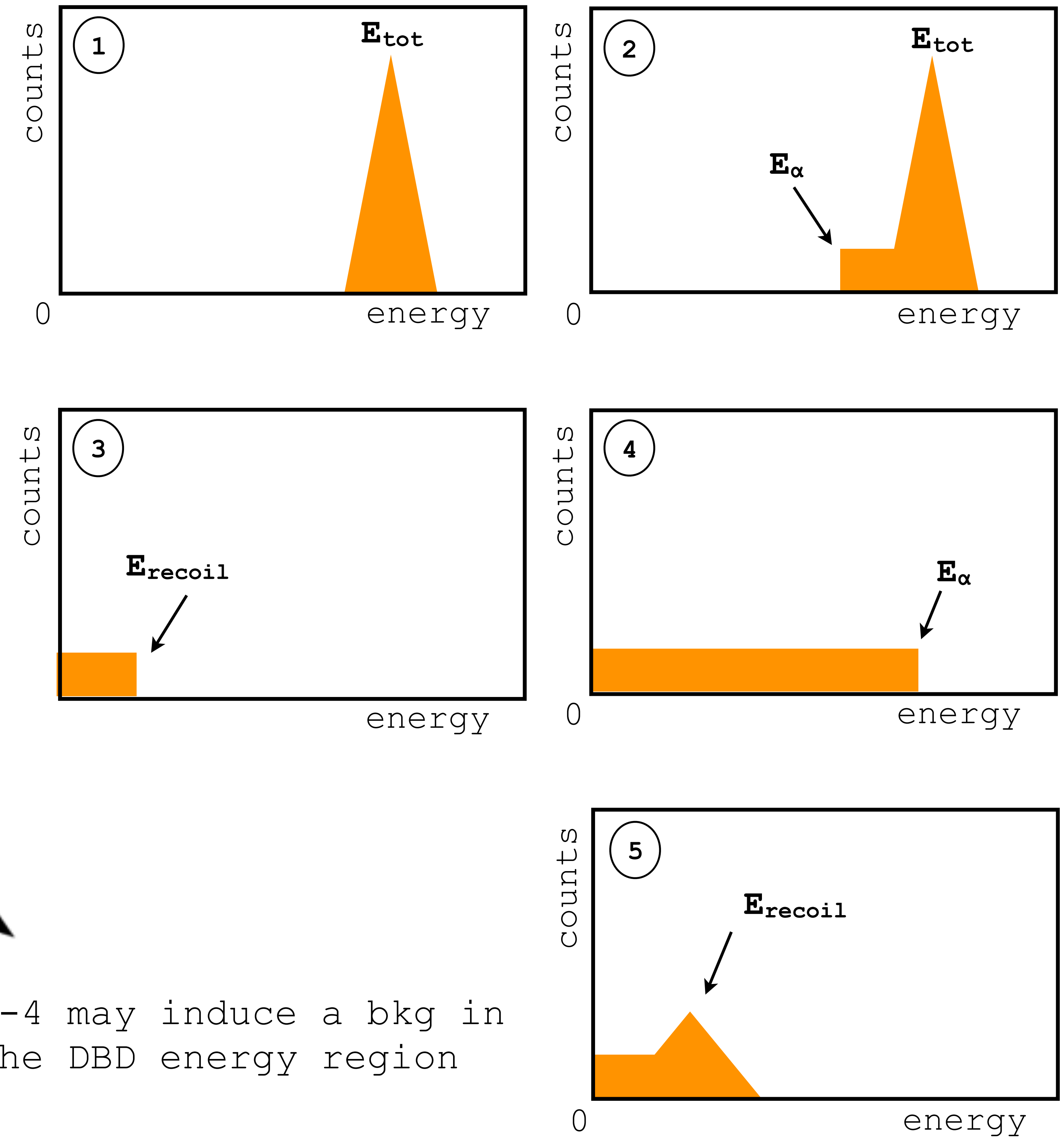
α decays may occur on surfaces of Cu structure or on the detectors due to possible re-contaminations of radio-pure materials.

N.B. bolometers are fully-active detectors

$$E_{tot} = E_{\alpha} + E_{recoil}$$

$$\sim\text{MeV} = \sim\text{MeV} + \sim 10\text{-}100 \text{ keV}$$





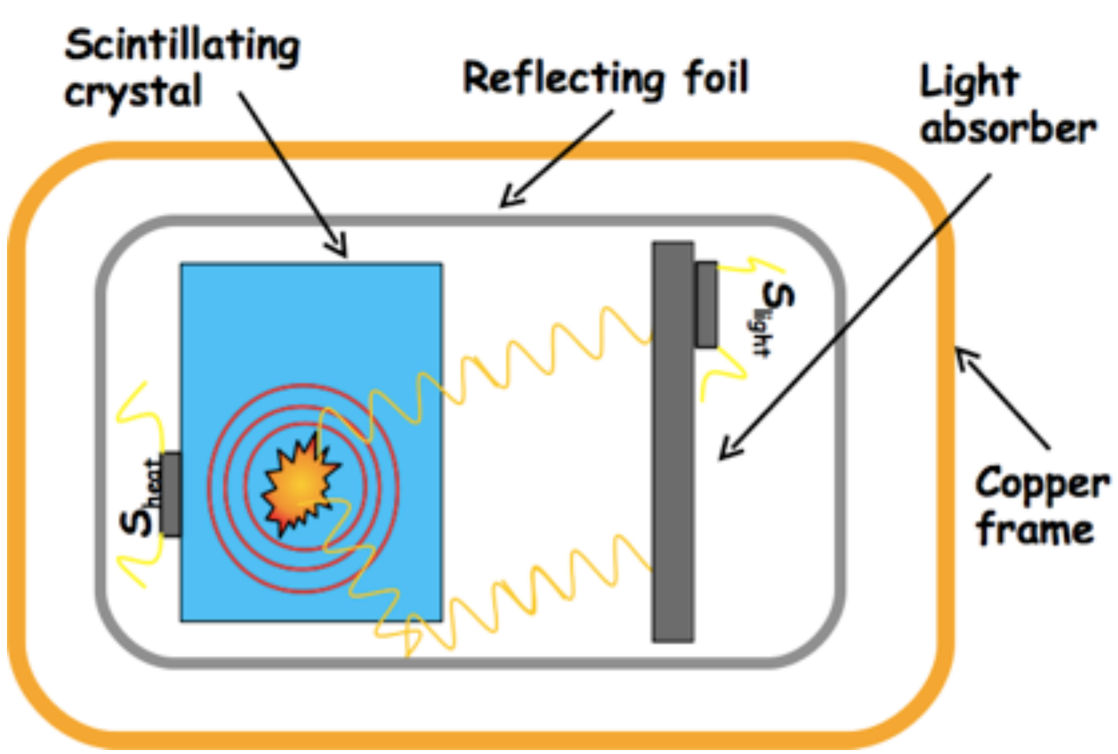
2-4 may induce a bkg in the DBD energy region

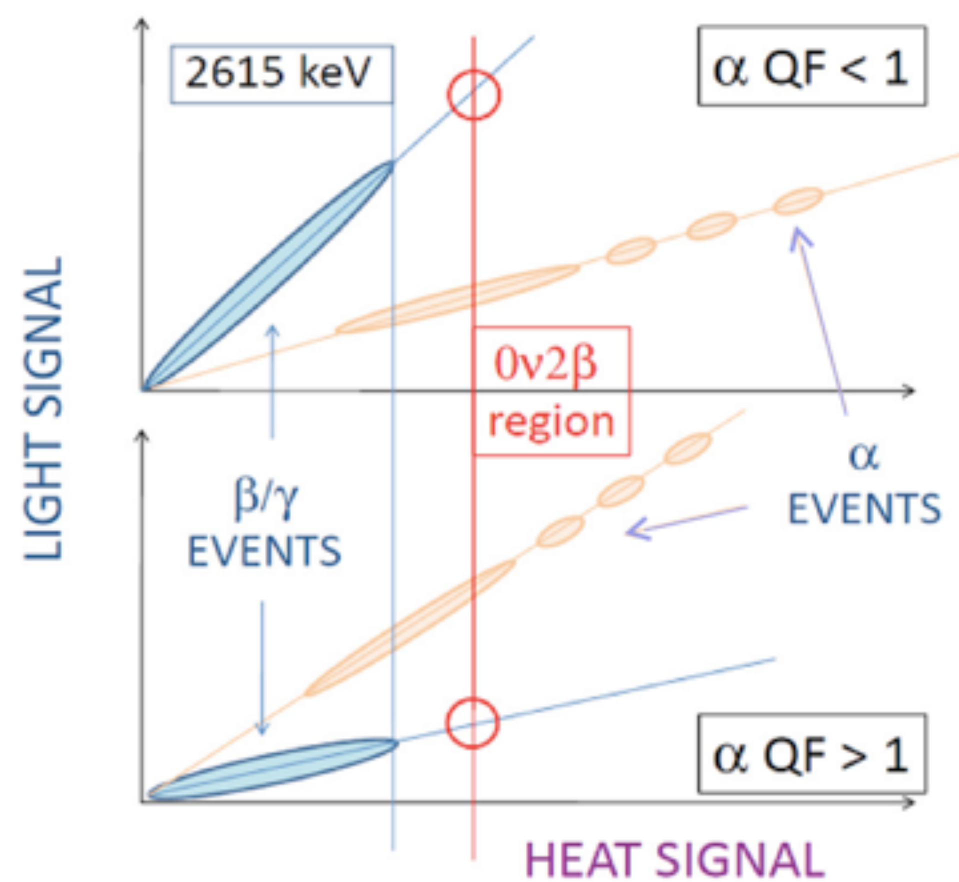
M. Clemenza et al., Eur. Phys. J. C **71**, 1805 (2011)

Scintillating bolometers

When a **bolometer is an efficient scintillator** at low temperature, a small but significant fraction of the deposited energy is converted into scintillation photons while the remaining dominant part is detected through the heat channel.

The simultaneous read-out of **light** and **thermal** signals allows to discriminate the α background thanks to the scintillation yield different from β particles.





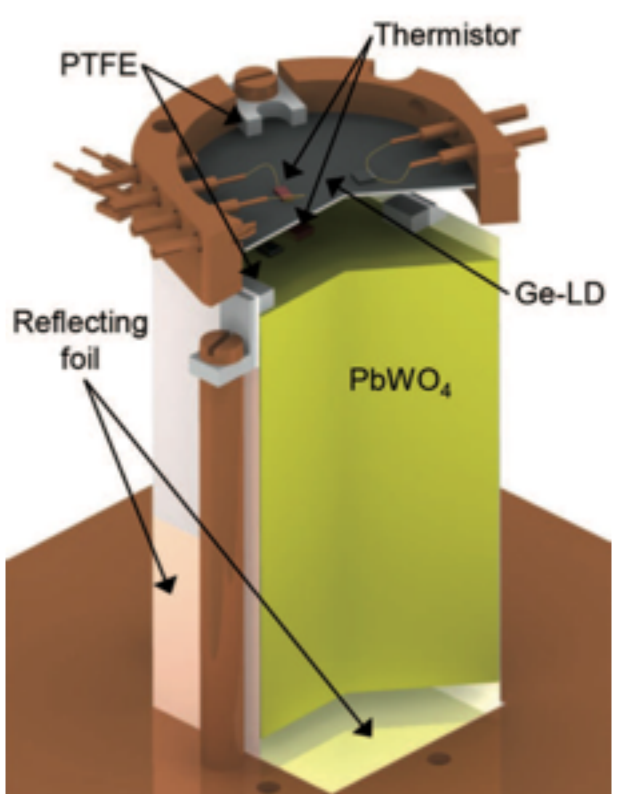
QF: is defined as the ratio of the signal amplitudes induced by an α and an β/γ of the same energy.

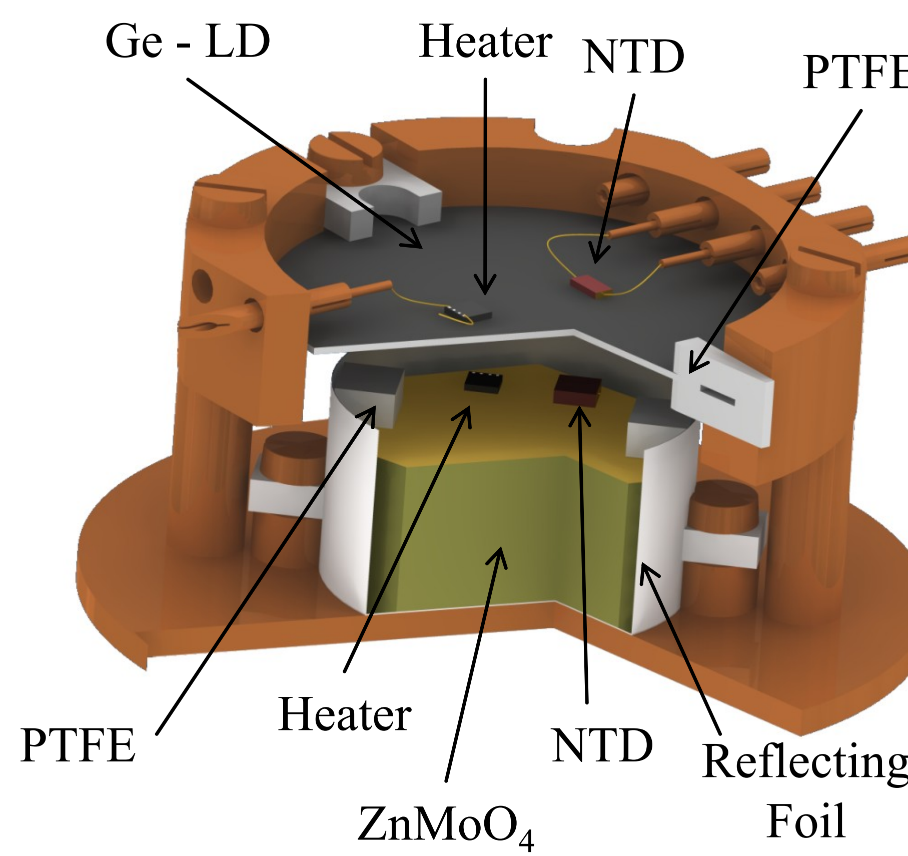
Light detectors (LD)

Light signal: => few keV/MeV (depending on the crystal)
=> is isotropic

Light detector:

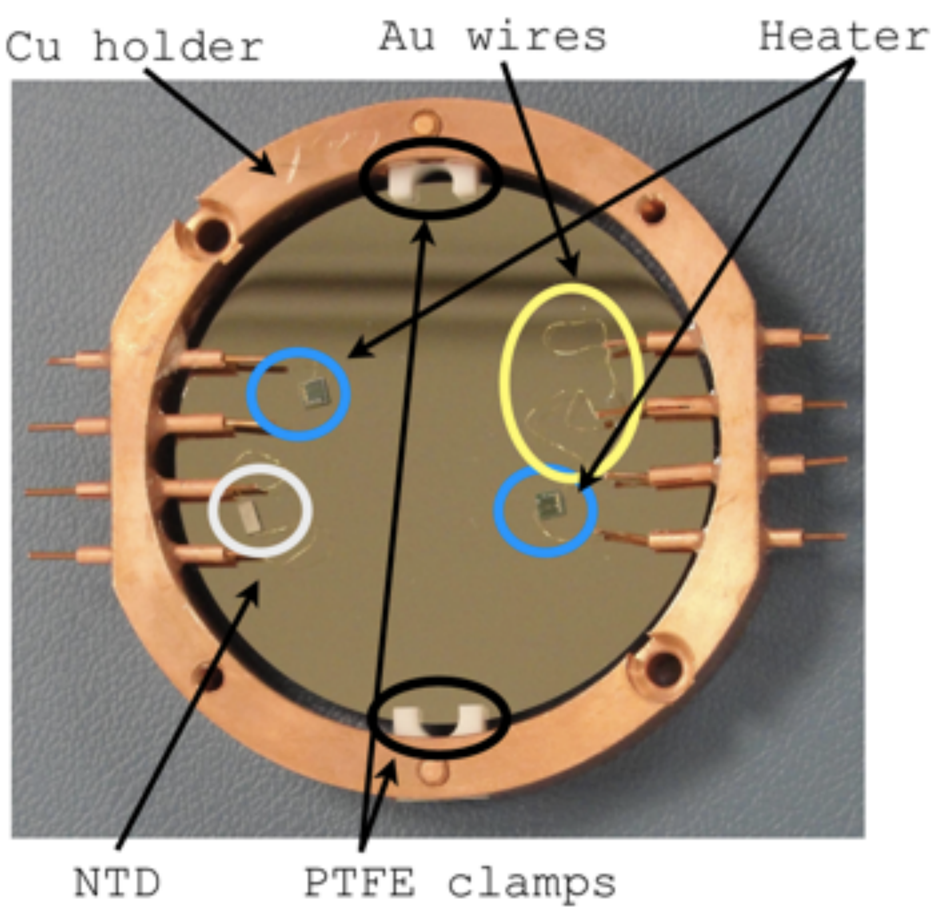
	PMT	Bolometer
=> quantum efficiency	✗	✔
=> extremely good energy resolution	✗	✔
=> intrinsic radio-purity	✗	✔
=> must work @ low T	✗	✔
=> energy threshold	✔	✗



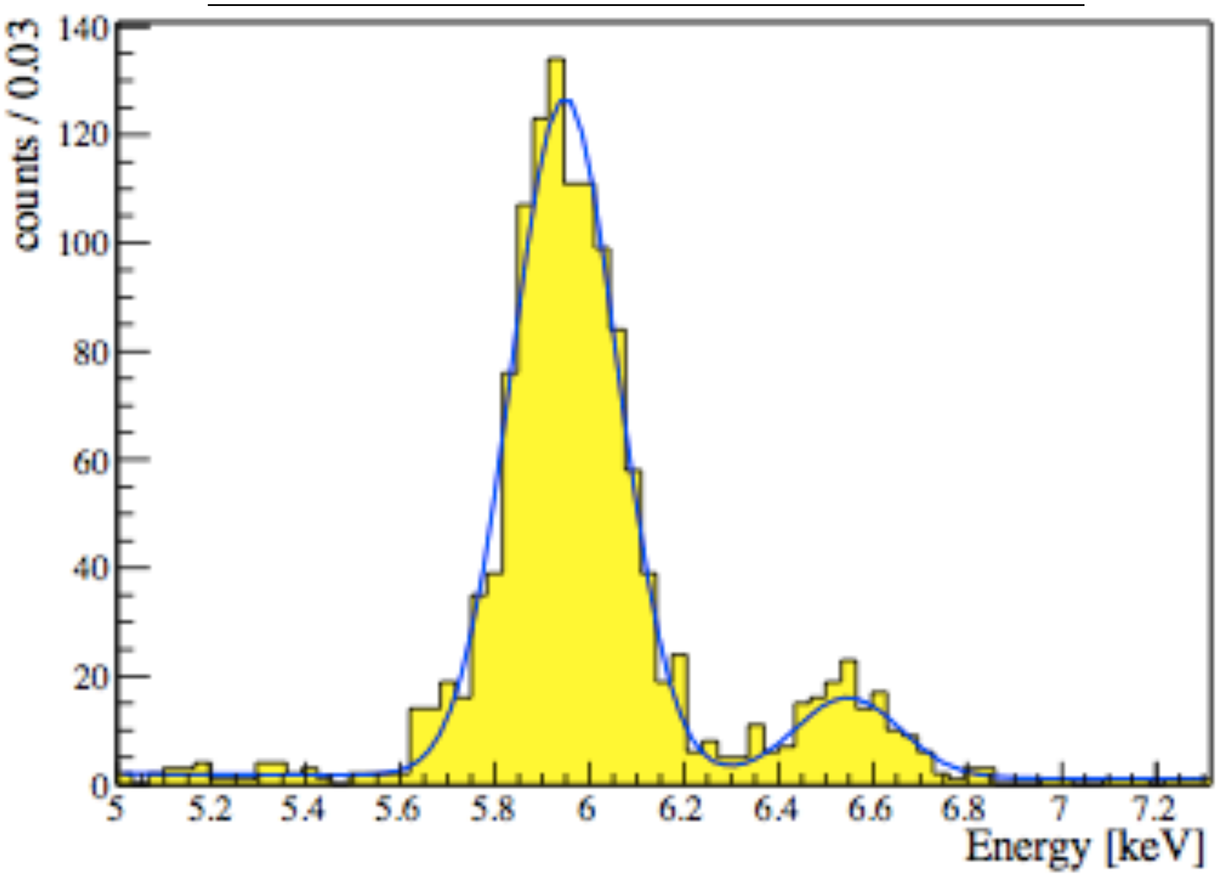


Bolometric LD

- HP-Ge disk (3-5 cm diameter, 0.1-1 mm thick)
- SiO_2 coating for darkening the surface => reduce light reflections
- Calibration with ^{55}Fe X-rays @ 5.9 keV and 6.5 keV
  - Energy resolution: ~100 eV
  - Energy threshold: ~10 eV



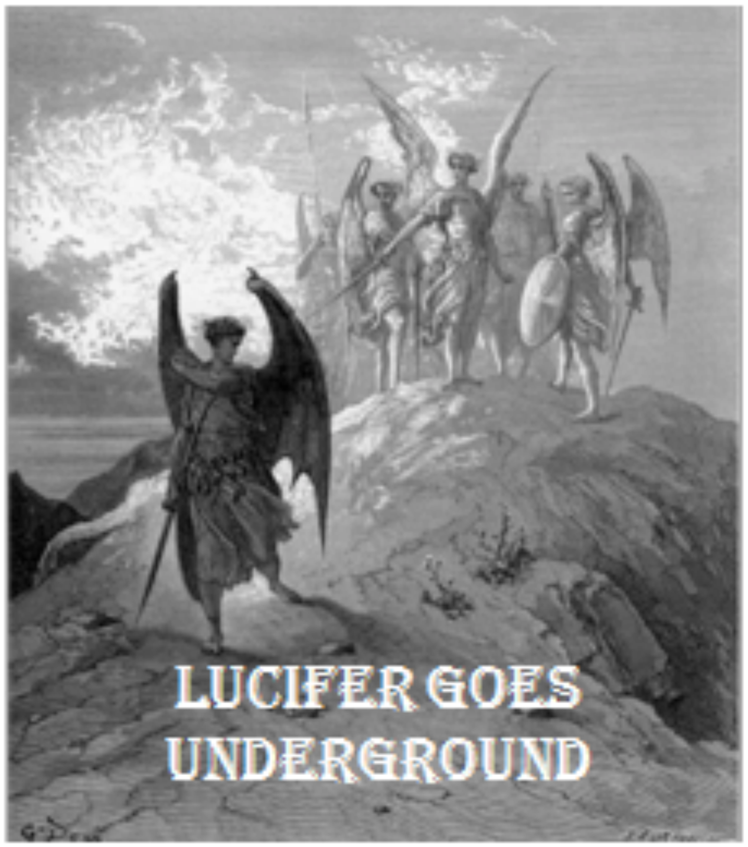
Detector	$FWHM_{baseline}$ [keV]	$FWHM_{^{55}Fe}$ [keV]
LD	0.068±0.001	0.262±0.002



LUCIFER

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

LUCIFER is funded by an Advanced Grant ERC: 3.3M€



- First prototype array of enriched scintillating bolometers

- LUCIFER will search DBD0ν in: $Zn^{82}Se$ or $Zn^{100}MoO_4$ or $^{116}CdWO_4$ crystals

- Total isotope mass: ~10 kg, ~36 detectors

- Light Detectors: HPGe bolometers

	Q-value [keV]	**Useful material**	**$LY_{\beta/\gamma}$ [keV/MeV]**	**QF_α**
ZnSe	**2995**	**56%**	**6.4**	**4.2**
$ZnMoO_4$	**3034**	**44%**	**1.5**	**0.2**
$CdWO_4$	**2809**	**32%**	**17.6**	**0.19**

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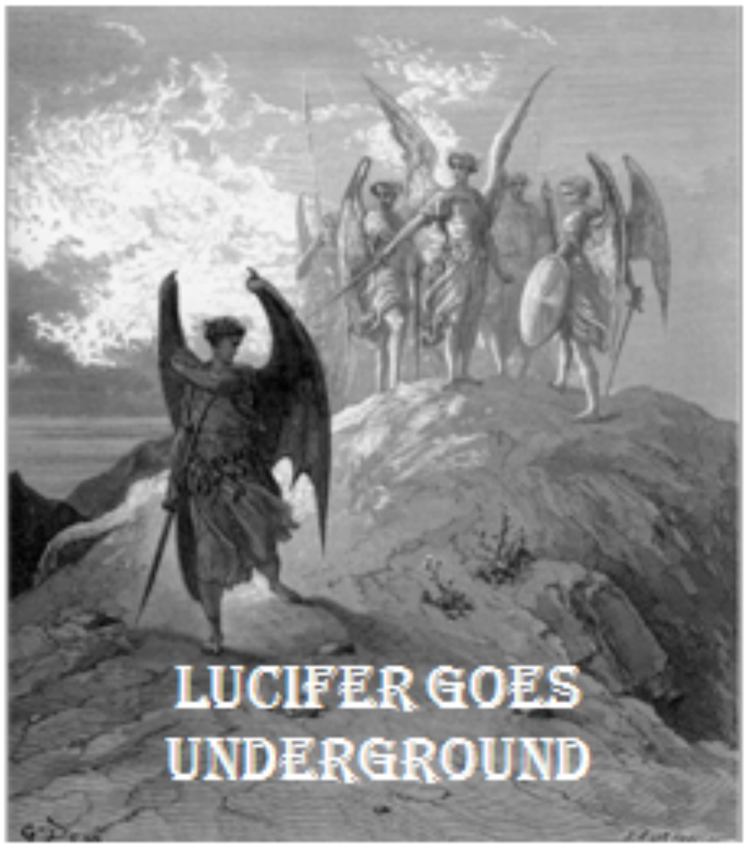

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~~$CdWO_4$~~	~~2809~~	~~32%~~	~~17.6~~	~~0.19~~

^{113}Cd:
- high neutron XS (n-inelastic scattering, $^{113}Cd(n,\gamma)$, ...)
- natural beta emitter (Q-value: 316 keV)

The underground facility

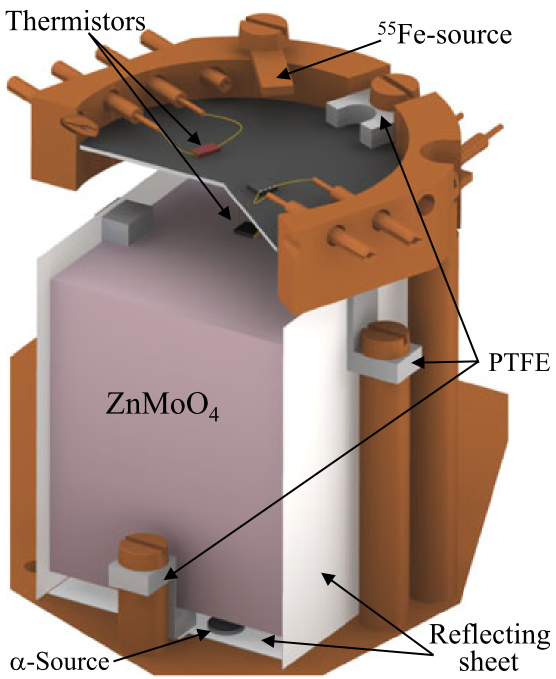
Laboratori Nazionali del Gran Sasso INFN, Italy

Experimental location:

- Average depth ~ 3650 m w.e.
- Muon flux ~ 2.6×10^{-8} $\mu/s/cm^2$
- Neutrons < 10 MeV: $4*10^{-6}$ $n/s/cm^2$
- Gamma < 3 MeV: 0.73 $\gamma/s/cm^2$

$ZnMoO_4$

Candidate: ^{100}Mo

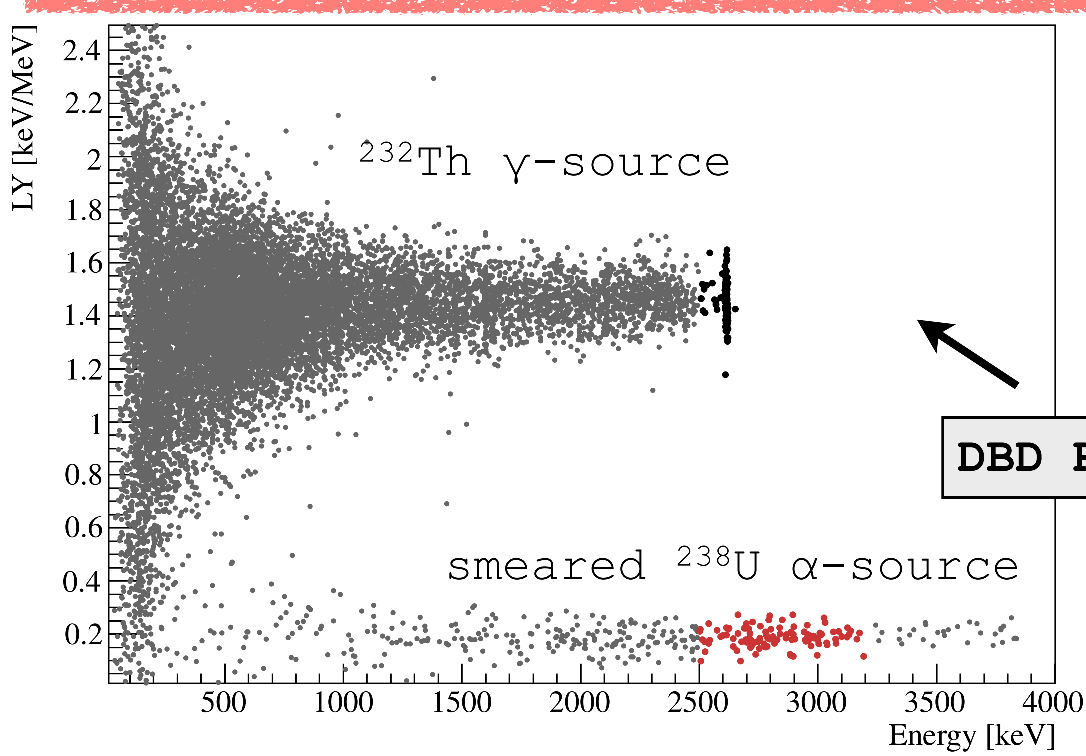


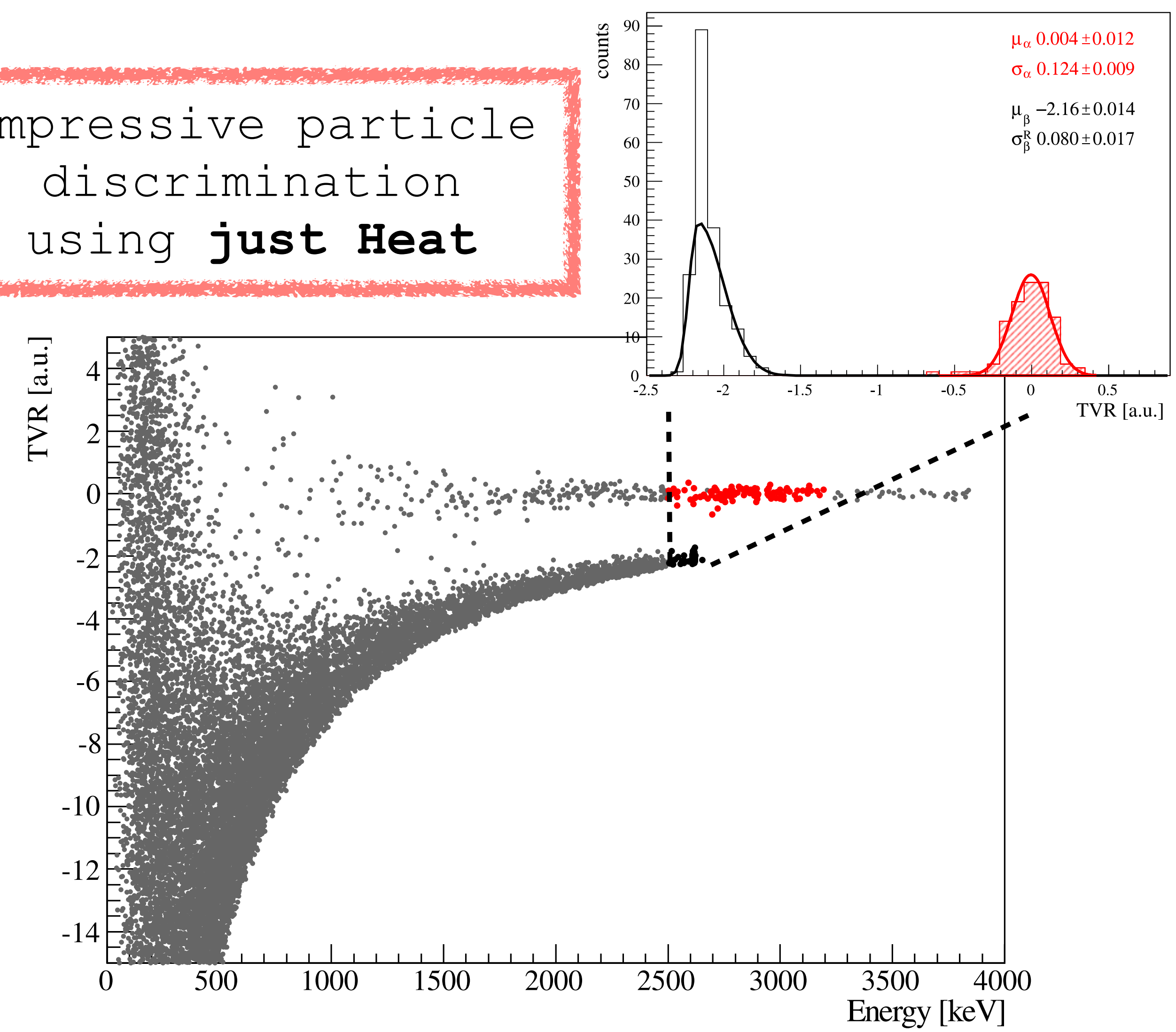
	Q-value [keV]	Useful material	$LY_{\beta/\gamma}$ [keV/MeV]	QF_α
$ZnMoO_4$	3034	44%	1.5	0.2

m=330 g
Calibrations α & γ
Background 520 h

Impressive particle discrimination using **just Heat**

Excellent particle discrimination using **Light vs. Heat**



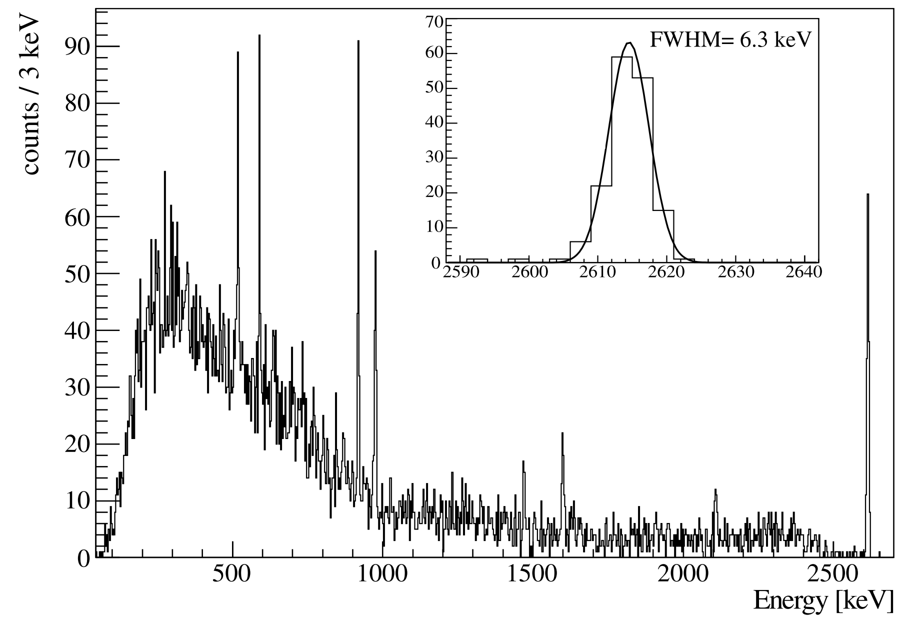


J. Beeman *et al*., *Eur. Phys. J. C* (2012) **72**:2142

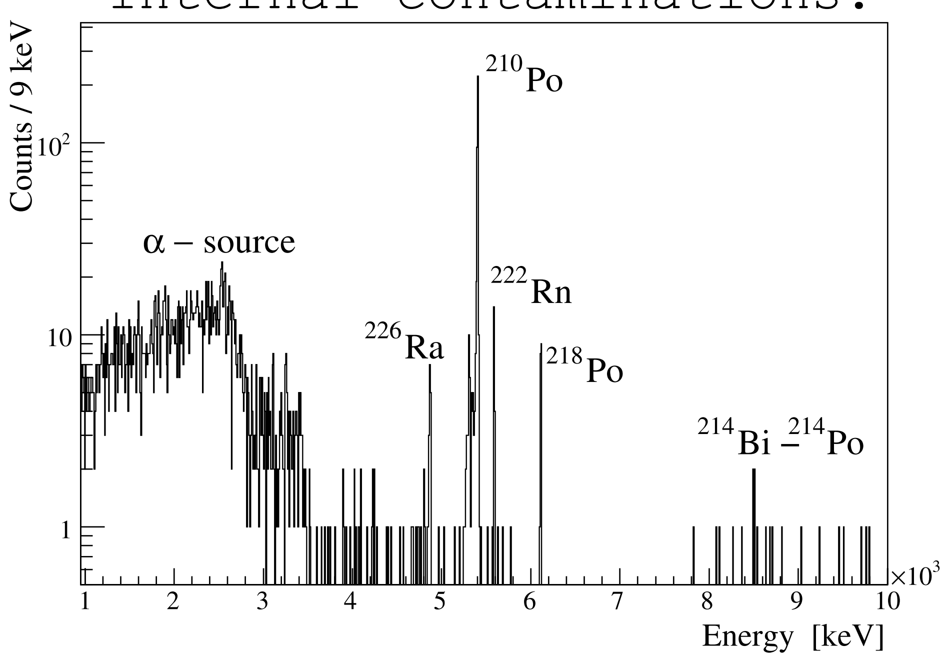
$ZnMoO_4$ performance

By means of the good energy resolution and the excellent background discrimination, $ZnMoO_4$ crystals are suited for DBD search

FWHM @ 2615 keV: 6.3 keV



Internal contaminations:



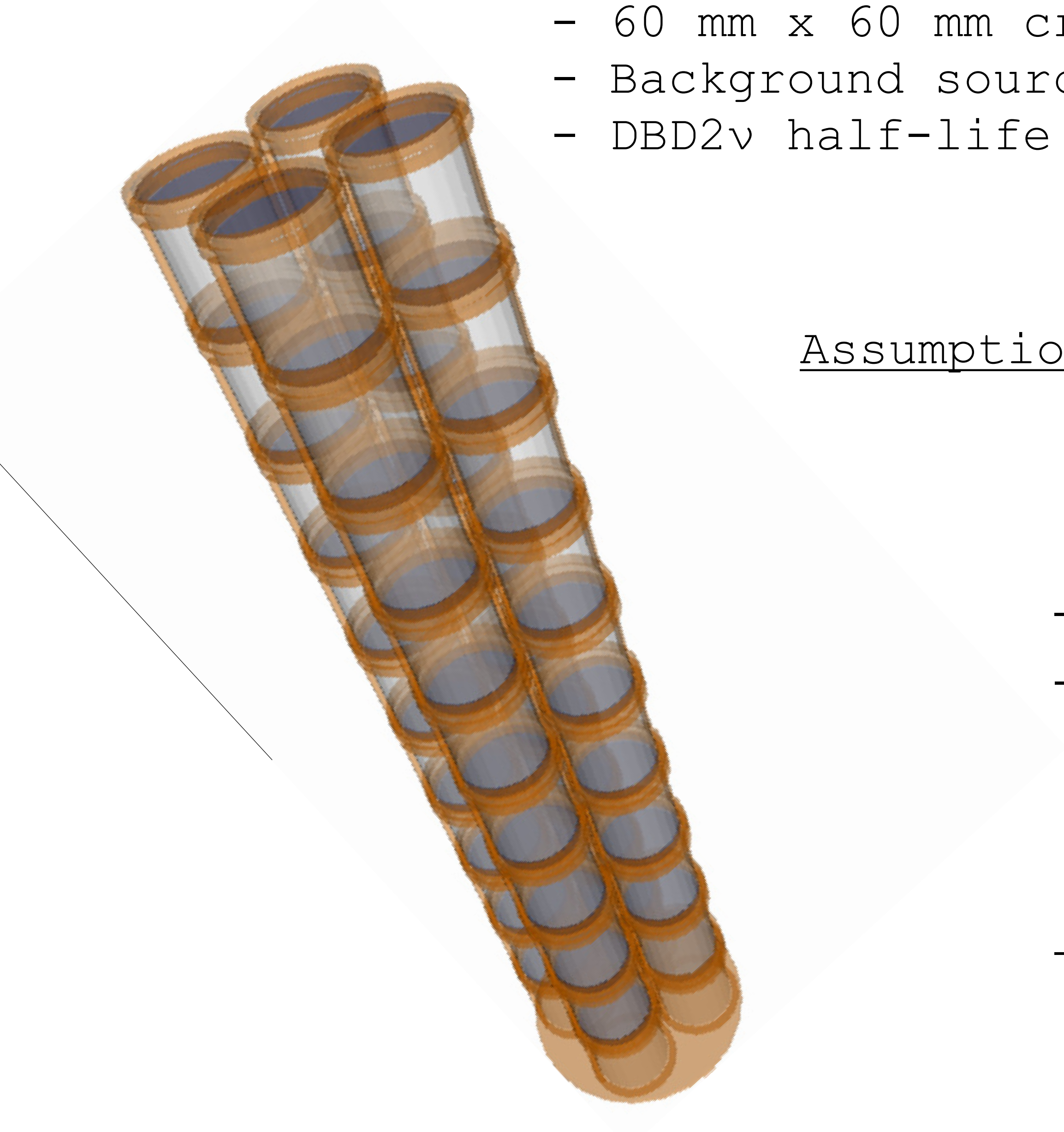
Chain	Nuclide	Activity [μBq/kg]
^{232}Th	^{232}Th	<8
	^{228}Th	<6
^{238}U	^{238}U	<6
	^{234}U	<11
	^{230}Th	<6
	^{226}Ra	27 ± 6
	^{210}Po	700 ± 30

CUORE TeO_2 crystals ready-to-use:

^{238}U < 3.7 μBq/kg
^{232}Th < 3.7 μBq/kg

C. Arnaboldi *et al.*, *J. Cryst. Growth* **312** (2010) 2999

$ZnMoO_4$: exercise



Exercise:
- Array of 40 $Zn^{100}MoO_4$ bolometers enriched @ 90% level
- 60 mm x 60 mm crystals
- Background source: U & Th in Cu structure and in crystals
- DBD2ν half-life of ^{100}Mo: 7.1×10^{18} y (~5 mHz per crystal)

A. Barabash *et al.*, *Phys. Rev. C* **81** (2011)

Assumptions:
- Neutrons in ROI < 10^{-5} c/keV/kg/y
- Muons (anti-coincidence) < 10^{-4} c/keV/kg/y
- Pile-up window: 5.5 ms (conservative)

Source	Position	Background [c/(keV kg y)]
U chain	Crystals bulk	$<1.16 \pm 0.1 \cdot 10^{-5}$
Th chain	Crystals bulk	$<2.18 \pm 0.04 \cdot 10^{-4}$
2νDBD pile-up	Crystals bulk	$1.96 \pm 0.36 \cdot 10^{-3}$
U + Th chains	Cu frame bulk*	$<2.40 \pm 0.04 \cdot 10^{-4}$
U + Th chains	Cu shield bulk*	$<1.40 \pm 0.05 \cdot 10^{-4}$

Ultimate background: pile-up with DBD2ν decay

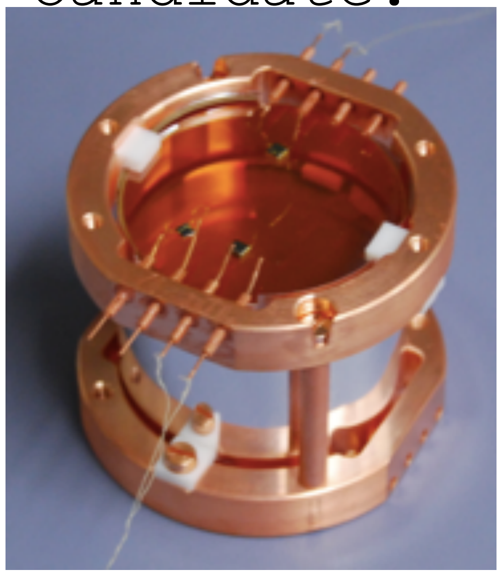
* G. Heusser et al., Radioactivity in the Environment, vol. 8, Elsevier, 2006, p. 495. → ^{232}Th: 19 μBq/kg, ^{238}U: 16 μBq/kg

For next generation experiments need faster signal development

J.W. Beeman *et al.*, *Astrop. Phys.* **35** (2012) 813

ZnSe

Candidate: ^{82}Se



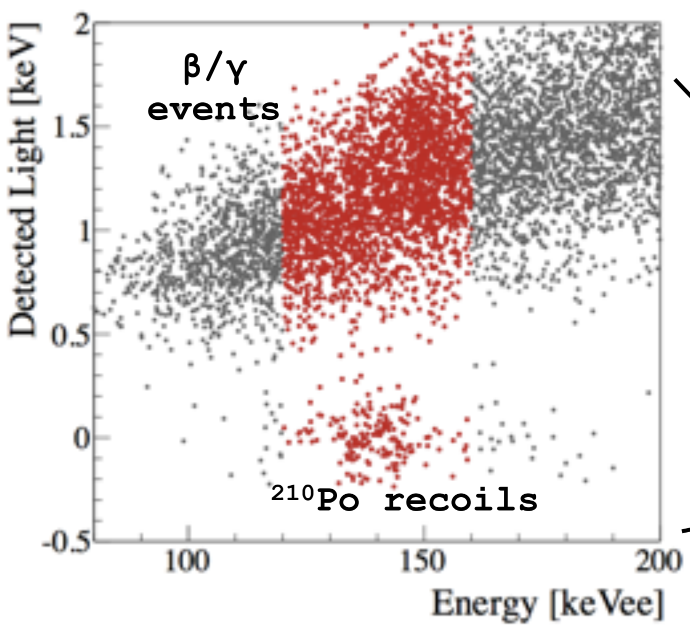
m=430 g
Calibrations α & n & γ
Background 524 h

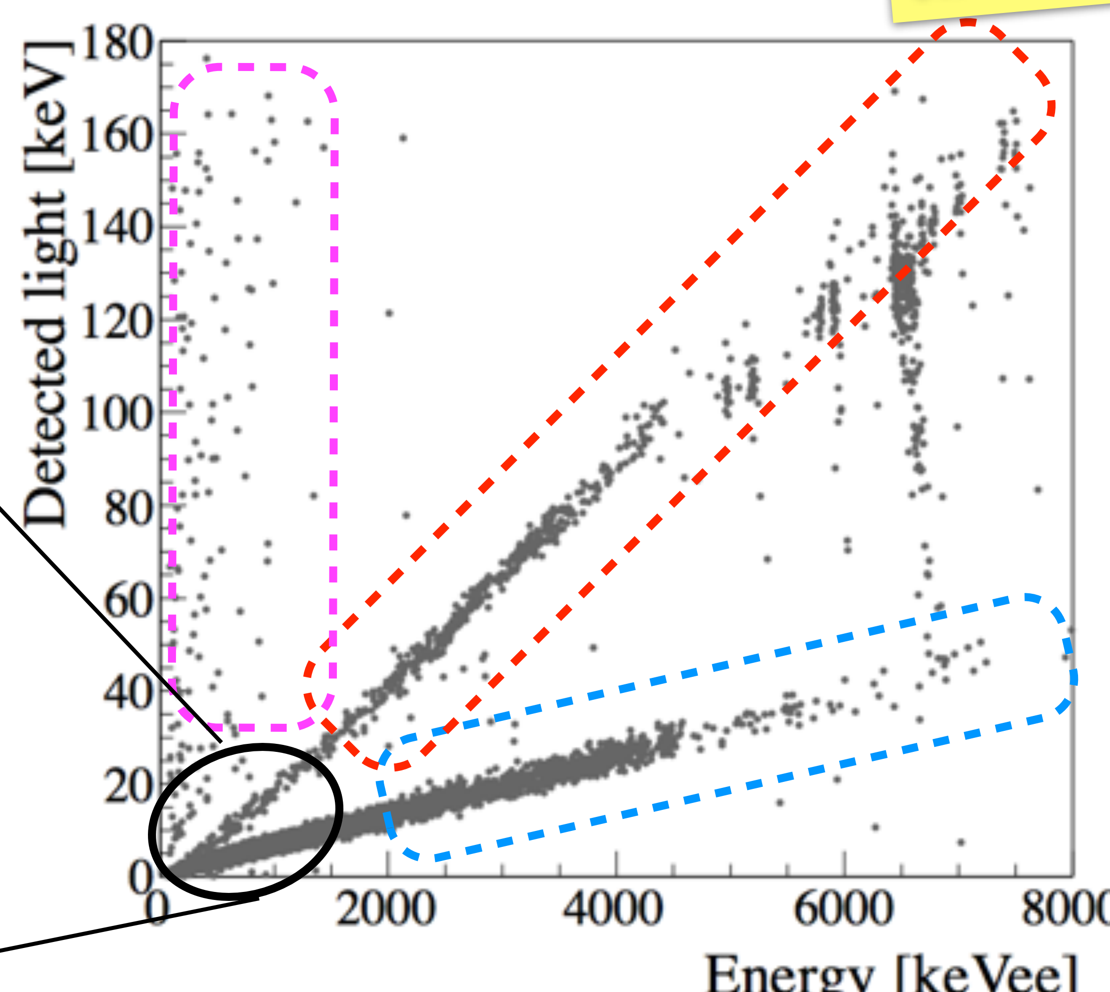
	Q-value [keV]	Useful material	$LY_{\beta/\gamma}$ [keV/MeV]	QF_{α}
ZnSe	2995	56%	6.4	4.2

Birks' law: αs have higher dE/dx than β/γs, thus saturation effects on the luminescence centers arise.

Odd QF_{α} for ZnSe: αs produce more light than β/γs

Excellent particle discrimination using **Light vs. Heat**





γs from n-source

surface and bulk αs

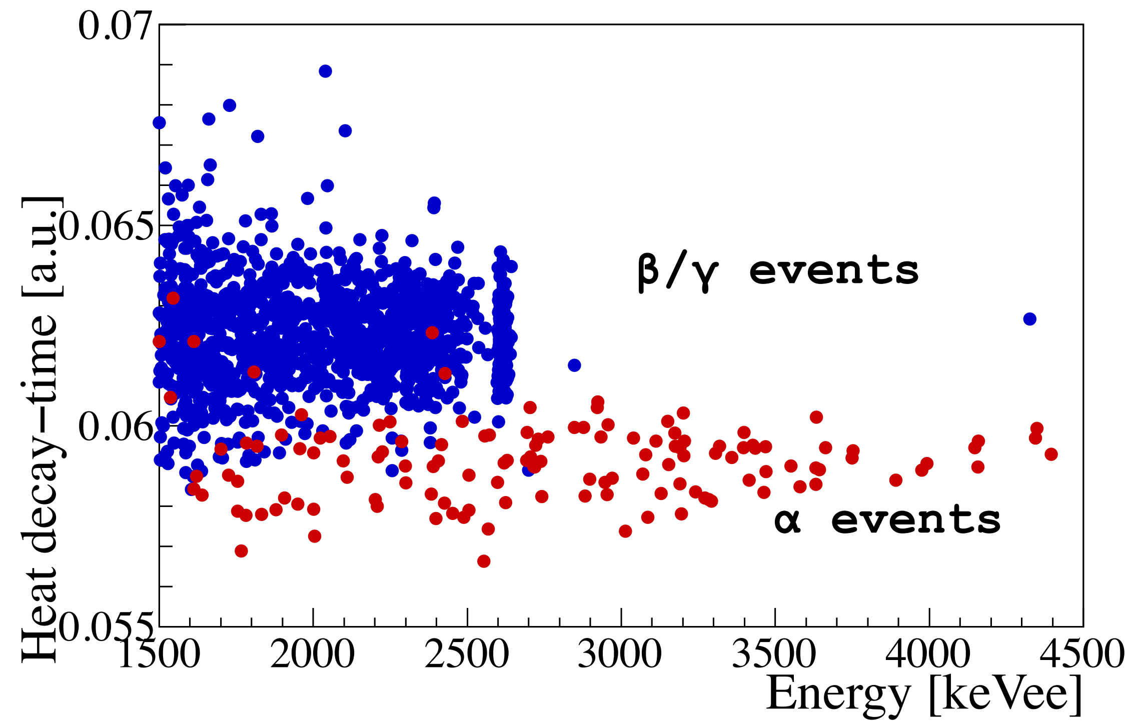
direct ionization in LD

Particle discrimination with ZnSe crystals

Excellent particle discrimination:

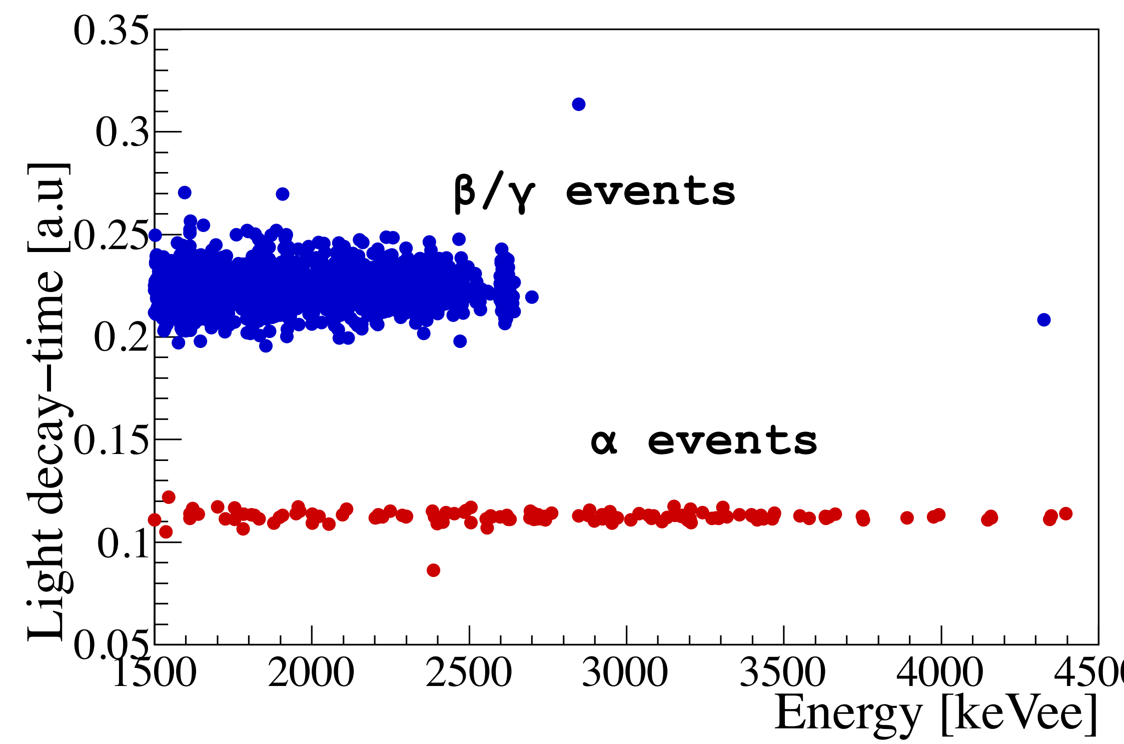
using **Heat signal shape**
even @ low energy

Calibration with α, β/γ sources



using **Light signal shape**

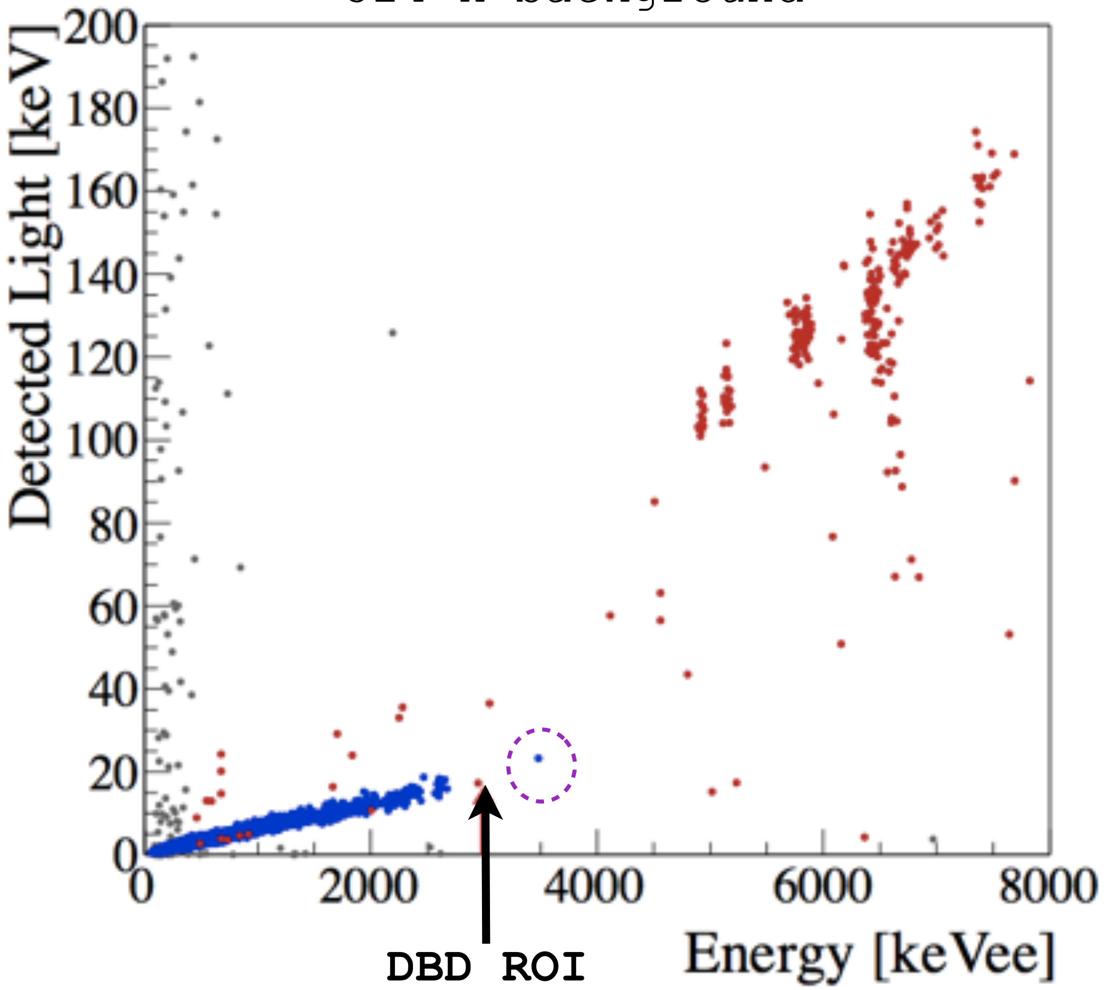
Calibration with α, β/γ sources



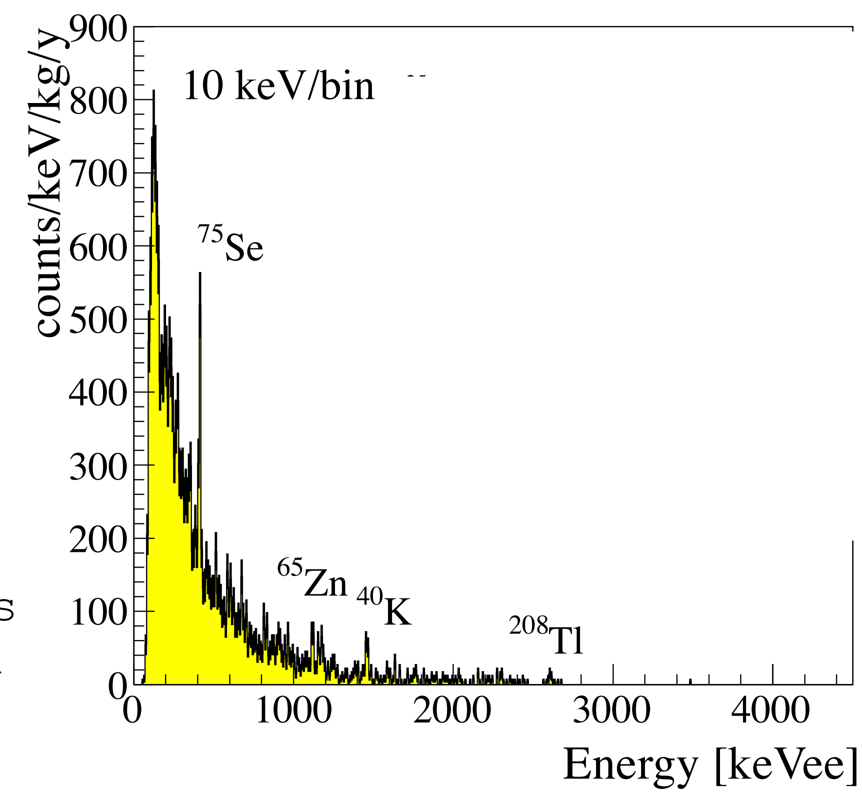
ZnSe background

Background measurement performed with Roman Lead shields inside the cryostat

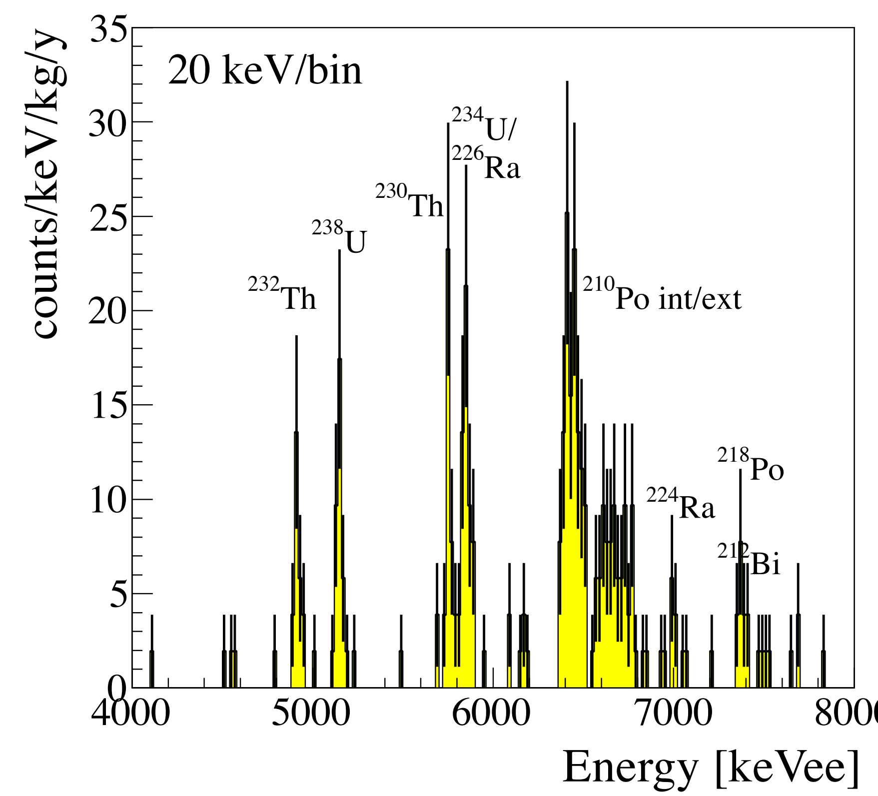
524 h background



β/γ events selection



α events selection



- Cosmogenic activation ^{75}Se and ^{65}Zn
- Natural radioactivity ^{40}K, ^{232}Th & ^{238}U (~20 μBq/kg)
 - 1 β/γ event @ ~3.5 MeV: coincidence with other detectors (**muon**)

J W Beeman *et al* 2013 *JINST* **8** P05021

ZnSe background

Internal contaminations

Chain	Nuclide	Activity [μBq/kg]
^{232}Th	^{232}Th	17.2 ± 4.6
	^{228}Th	11.1 ± 3.7
^{238}U	^{238}U	24.6 ± 5.5
	^{234}U	17.8 ± 3.3
	^{230}Th	24.6 ± 5.5
	^{226}Ra	17.8 ± 3.3
	^{210}Po	$< 90.9 \pm 10.6$

bkg in the ROI

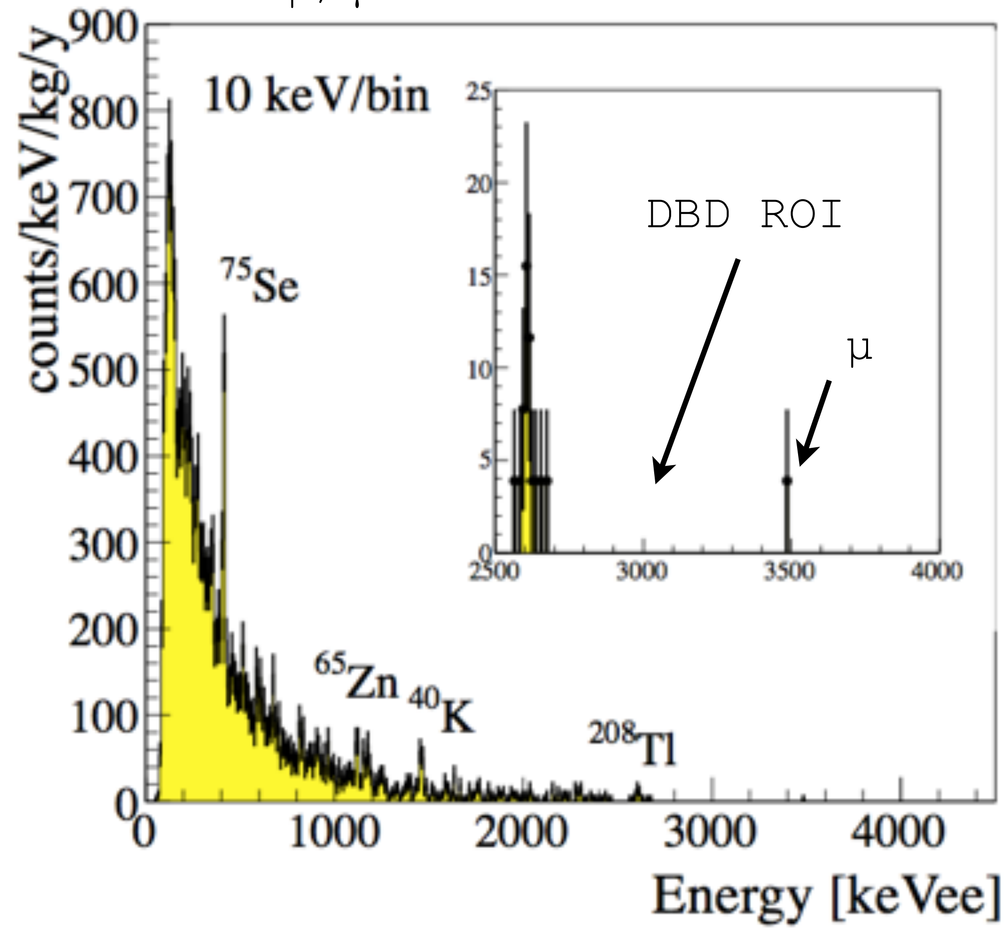
→ 2.5×10^{-3} c/keV/kg/y (^{212}Bi) ✘

if we use delayed coincidences we have:
- x3 less bkg
- 10% dead time

→ 3×10^{-4} c/keV/kg/y (^{210}Tl) ✔

Not a primary issue for a bkg level of ~10^{-3} c/keV/kg/y

β/γ events selection



Exercise:
- 0 counts in 1.3 MeV region [2.7,4.0] MeV
- mass = 0.43 kg
- t = 0.06 y

=> < 0.07 c/keV/kg/y

1 crystal, 3 weeks live time

LUCIFER

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

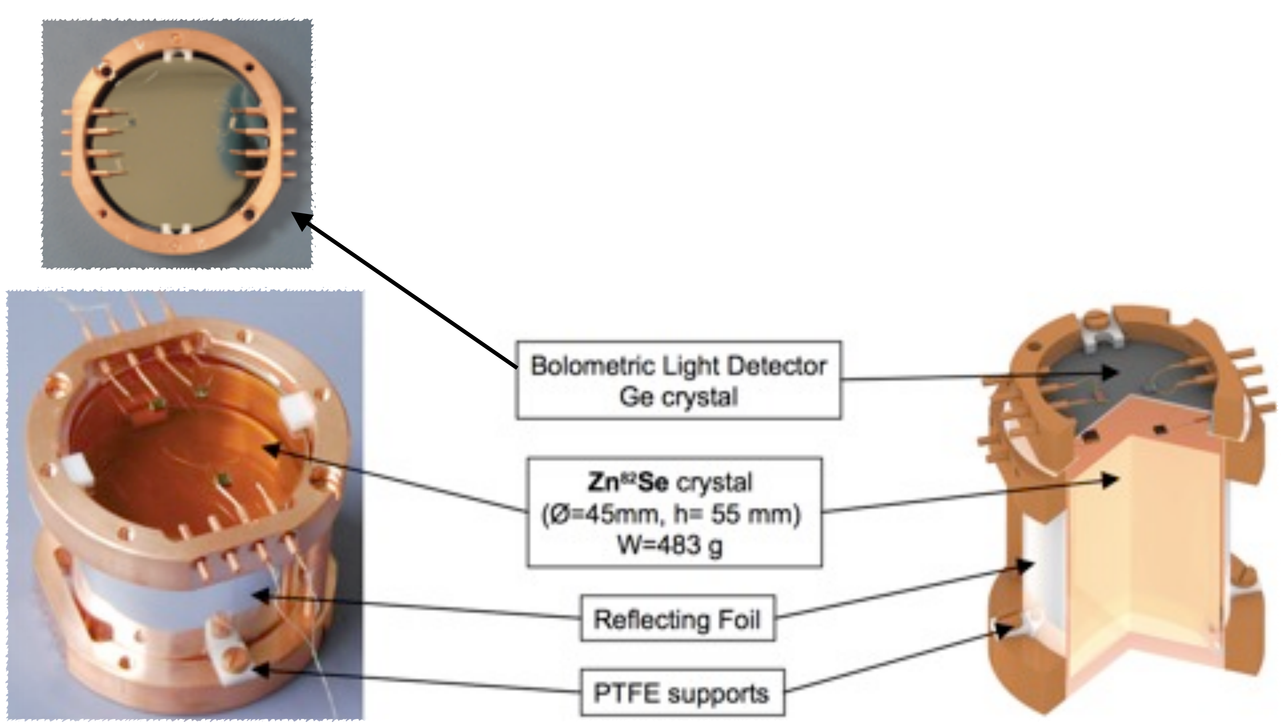
LUCIFER is funded by an Advanced Grant ERC: 3.3M€

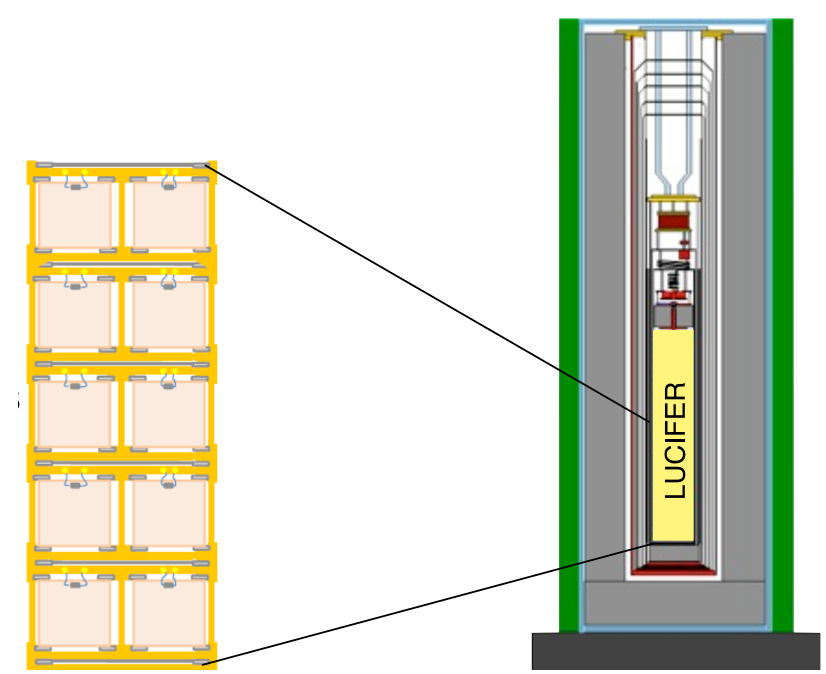
Winner:
- no DBD2ν bkg
- more useful material
- high LY

	Q-value [keV]	Useful material	$LY_{\beta/\gamma}$ [keV/MeV]	QF_{α}
ZnSe	2995	56%	6.4	4.2
$ZnMoO_4$	3034	44%	1.5	0.2
~~$CdWO_4$~~	~~2809~~	~~32%~~	~~17.6~~	~~0.19~~

^{82}Se (0.92±0.07)x10^{20} y
^{100}Mo (7.1±0.4)x10^{18} y

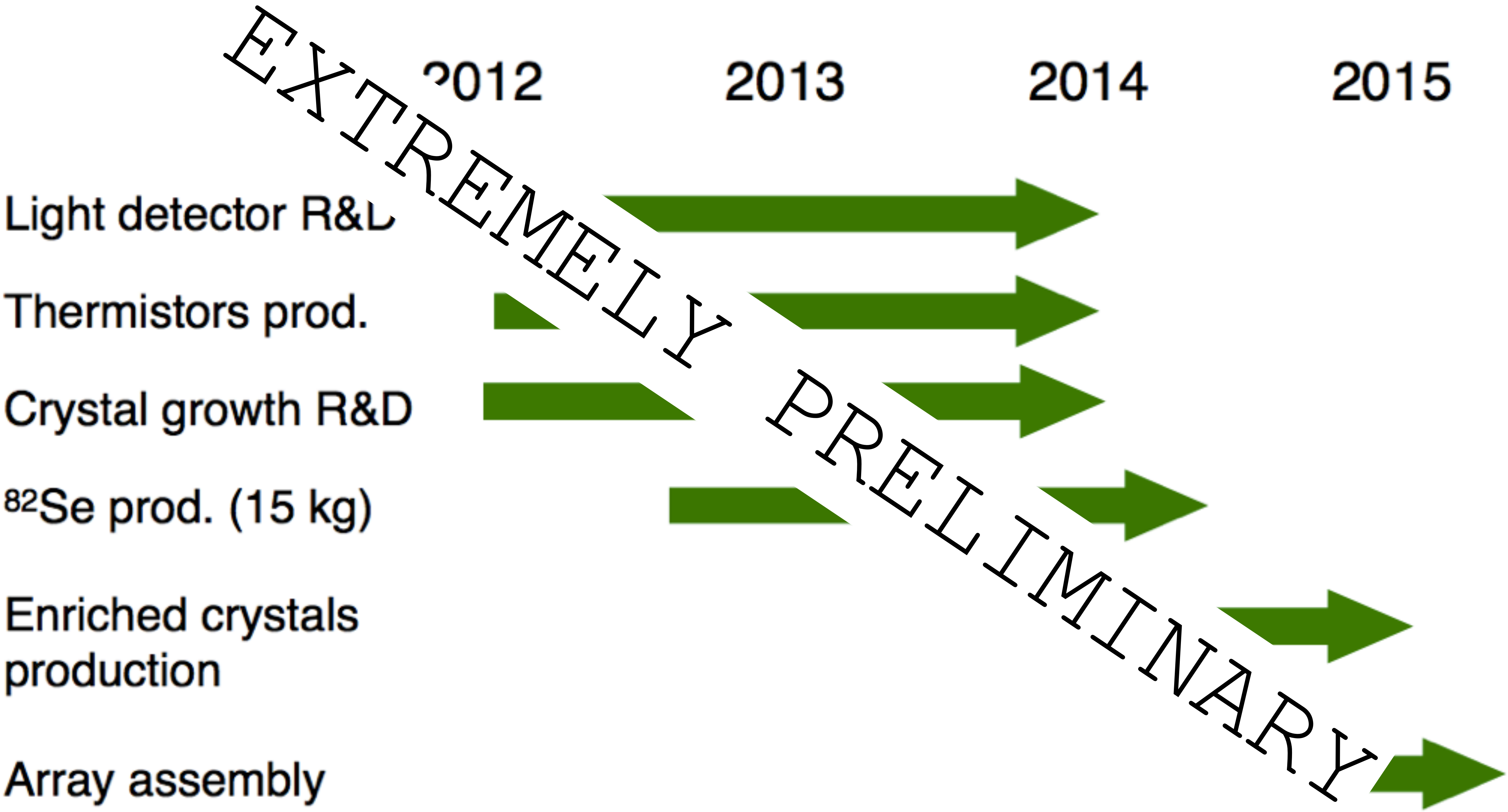
A. Barabash *et al.*, *Phys. Rev. C* **81** (2011)





- Inner shield:
  - 1cm Roman Pb A (^{210}Pb) < 4 mBq/Kg
- External shield:
  - 20 cm Pb
  - 10 cm Borated polyethylene
- Nitrogen flushing to avoid Rn contamination.

LUCIFER *rough* STATUS



LUCIFER R&D

We tested our LD with some interesting compounds:

- $PbWO_4$
- TeO_2
- Li_2MoO_4
- ...

PWO crystals

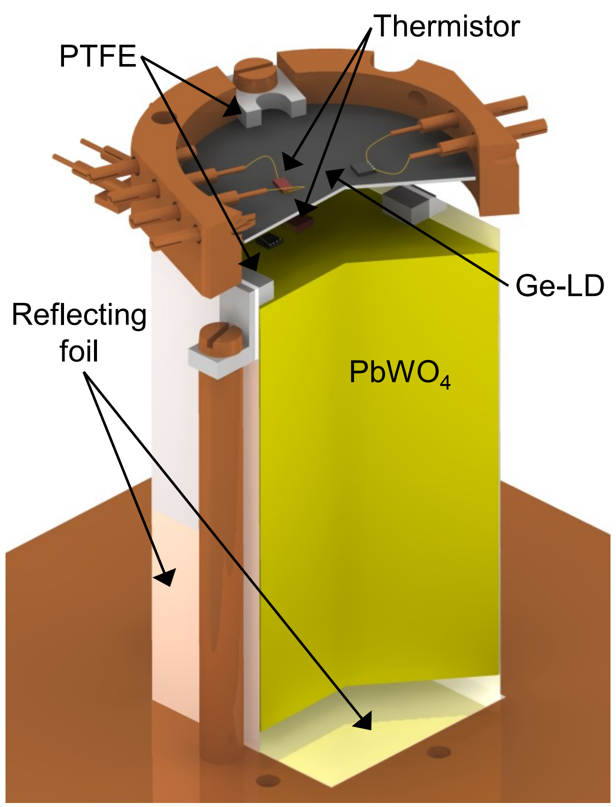
$PbWO_4$:

-> Small LY (~ 20 ph/MeV @ 300K)
-> Intrinsic radiopurity (low ^{238}U and ^{232}Th internal contaminations, but **high ^{210}Pb** and ^{180}W)
-> can be grown with large size

WHY :

-> ^{204}Pb is considered to be the heaviest stable isotope (study of Pb isotopes stability)
-> sci-bolo is the only possible way to study α decay of ^{204}Pb, which has a rather small Q-value (< 2.6 MeV)
-> previous measurement with nuclear emulsions (1958)
-> good target for Heavy WIMPS interaction (Pb and W)!

PWO measurement



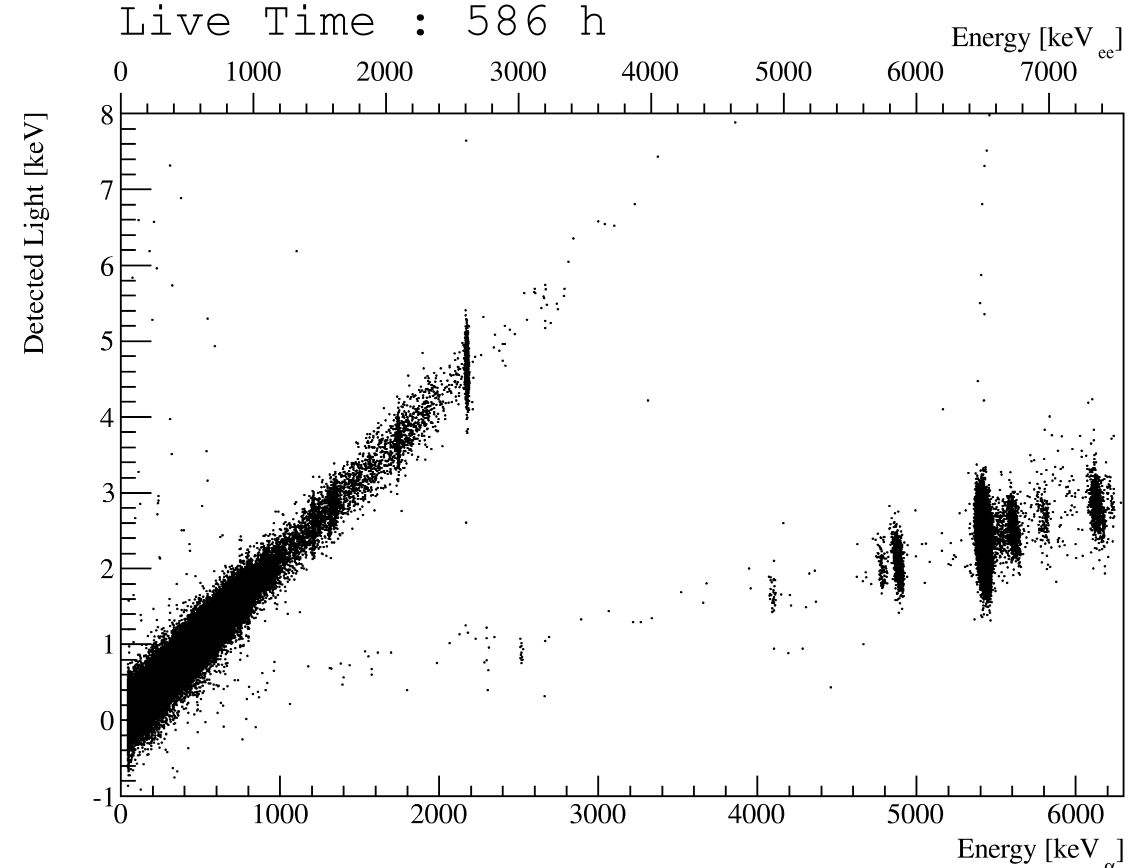
First $PbWO_4$ ever grown with **Ancient Roman Lead**

Highly pure Lead (^{210}Pb free)

Cooled down at ~15 mK:
- a 3x3x6 cm^3 PWO crystal (m= 454 g)
- a 36 mm x 1 mm HPGe LD
- PWO surrounded on 5 faces by reflecting foil (VM2002)

Isotope	δ [%]	Q_α [keV]	$T_{1/2}^{theor}$ [y]
^{204}Pb	1.4 (1)	1969.5 (12)	$2.3 \cdot 10^{35} \div 1.2 \cdot 10^{37}$
^{206}Pb	24.1 (1)	1135.5 (11)	$1.8 \cdot 10^{65} \div 6.7 \cdot 10^{68}$
^{207}Pb	22.1 (1)	392.3 (13)	$3.6 \cdot 10^{152} \div 3.4 \cdot 10^{189}$
^{208}Pb	52.4 (1)	516.9 (13)	$1.2 \cdot 10^{124} \div 7.4 \cdot 10^{132}$

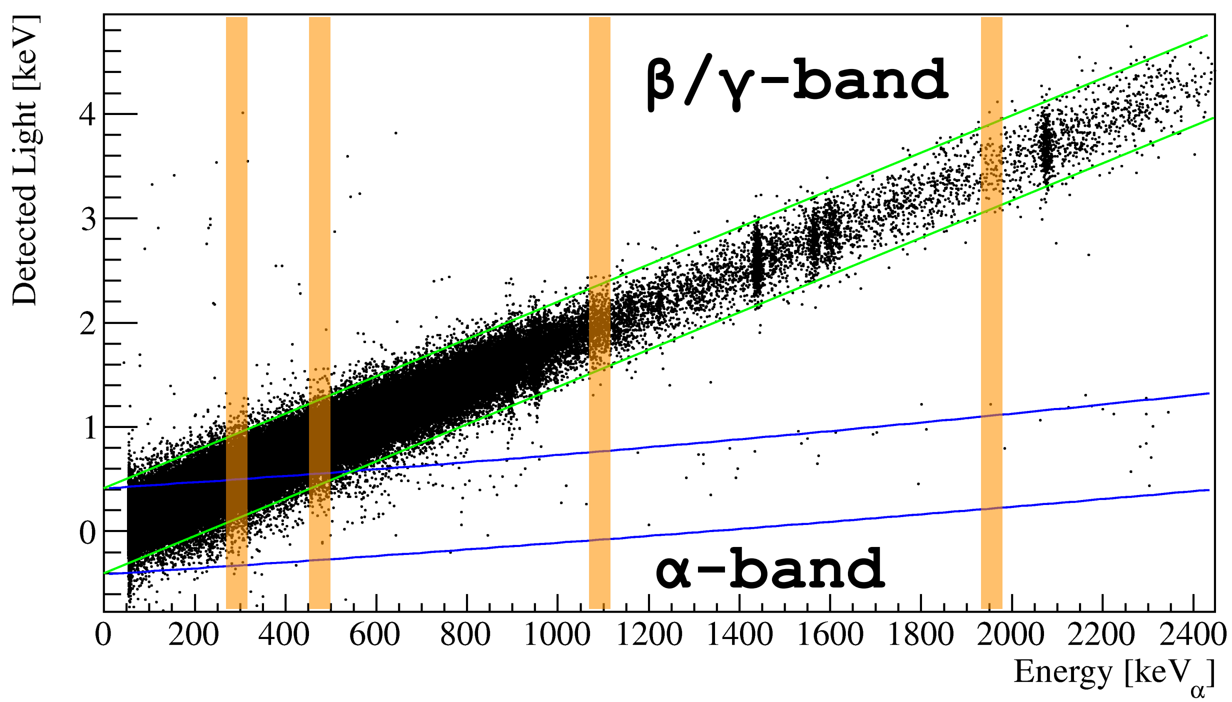
Live Time : 586 h

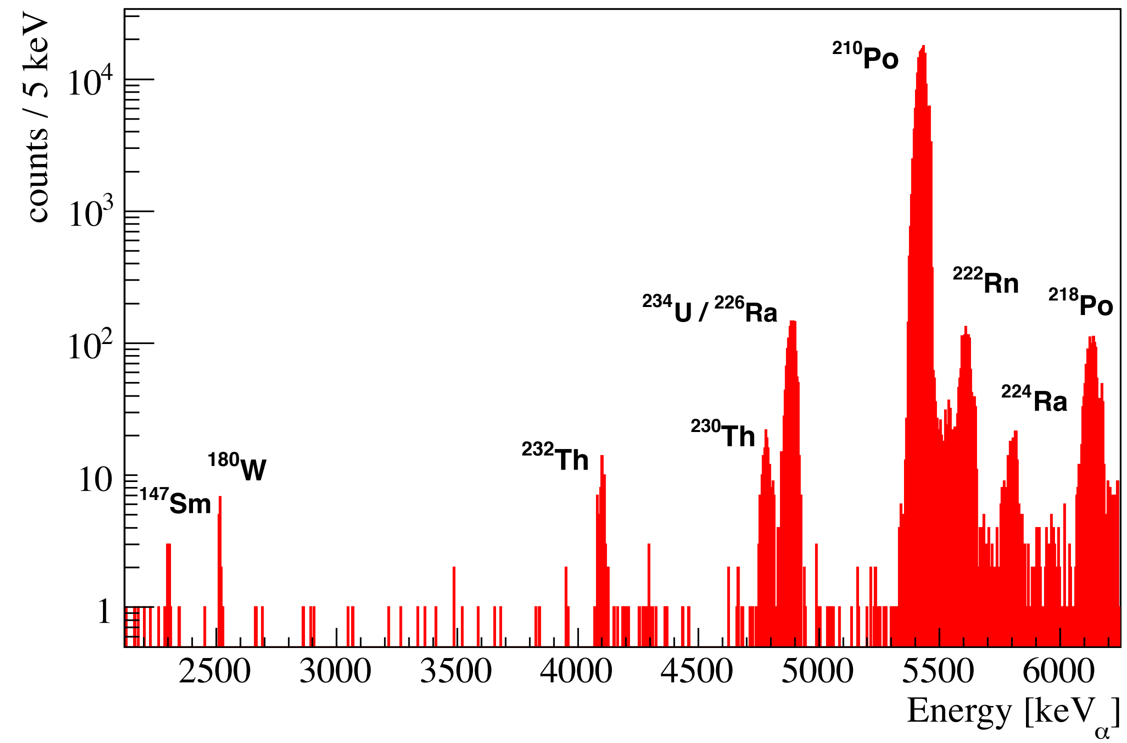


PWO results

- Highly contaminated (also in ^{210}Pb)

- FWHM heat channel 15 keV @ 2.6 MeV
- FWHM light channel 379 eV @ 6 keV





Improved the limit of 3 orders of magnitude!!!!

$$T^{\alpha}_{1/2}(^{204}Pb) > 1.4 \cdot 10^{20}\ y \quad \text{at} \quad 90\%\ \text{C.L.}$$

$$T^{\alpha}_{1/2}(^{206}Pb) > 2.5 \cdot 10^{21}\ y \quad \text{at} \quad 90\%\ \text{C.L.}$$

$$T^{\alpha}_{1/2}(^{207}Pb) > 1.9 \cdot 10^{21}\ y \quad \text{at} \quad 90\%\ \text{C.L.}$$

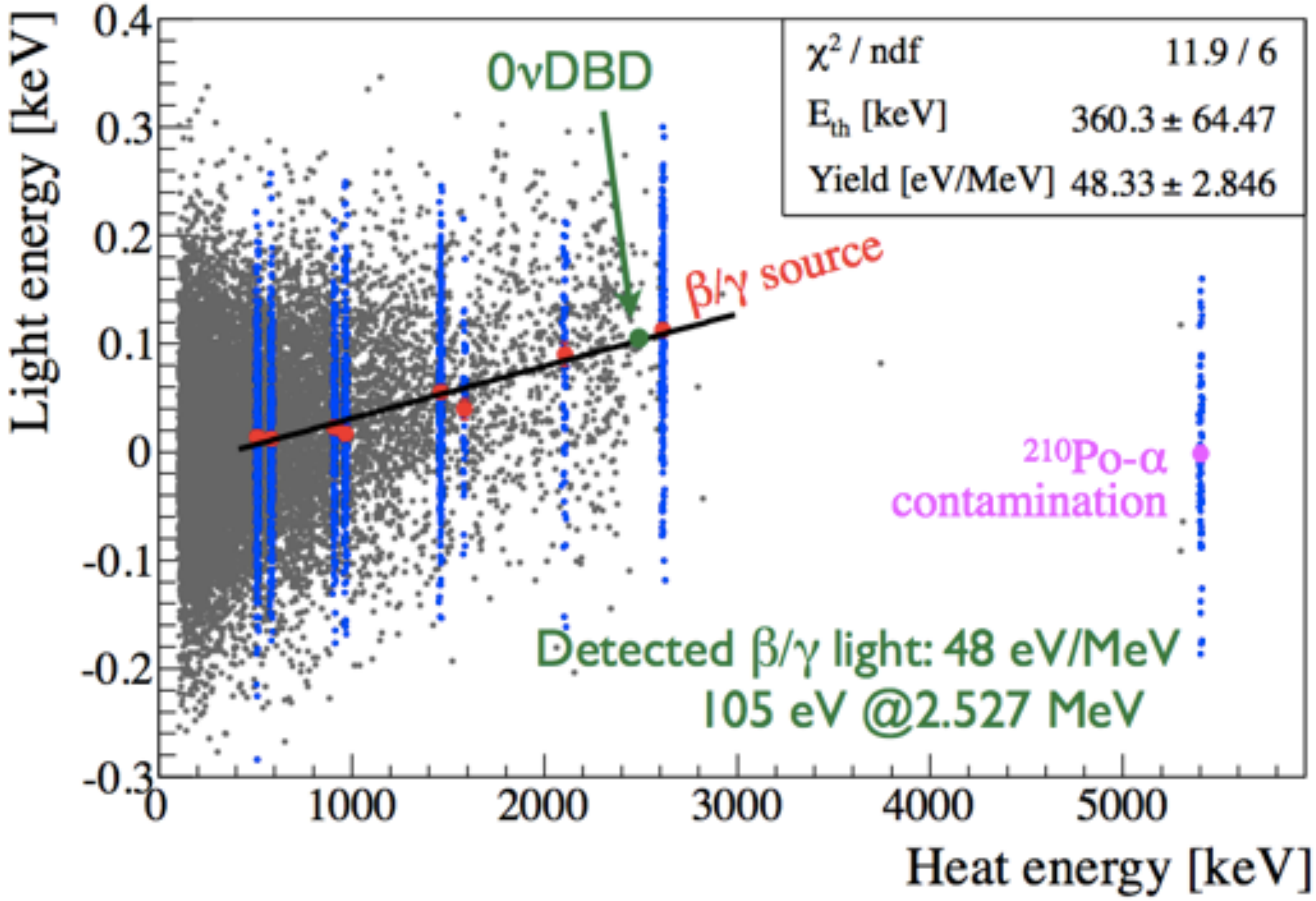
$$T^{\alpha}_{1/2}(^{208}Pb) > 2.6 \cdot 10^{21}\ y \quad \text{at} \quad 90\%\ \text{C.L.}$$

J. Beeman *et al*. *Eur. Phys. J. A* (2013) **49**: 50

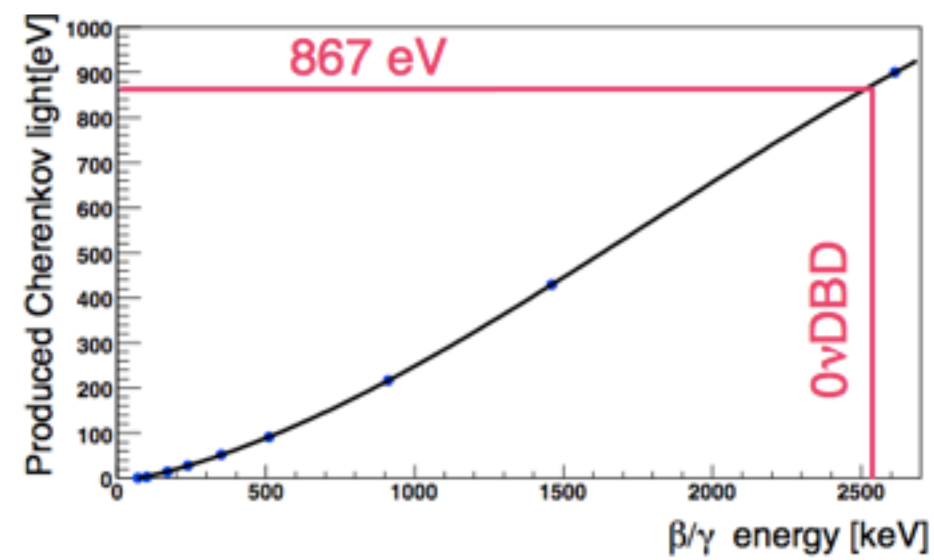
TeO_2 Čerenkov

TeO_2 CUORE crystals do not scintillate but:
βs with energy greater than 50 keV can produce Čerenkov light, unlike αs.

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



Courtesy of M.Vignati



- observed LY: 48 eV/MeV
- expected LY: 343 eV/MeV

- Better understanding of the light production/collection is needed
  - particle discrimination is not optimized (need more light)

- R&D on next generation LD is on going: KID and Neganov-Luke effect

J. Beeman et al., **Astropart.Phys. 35 (2012) 558-562**

Conclusions

* Scintillating bolometers are the next generation detectors for rare events searches (DBD, rare decays, ...)

* The scintillation light is not the only channel for particle discrimination
=> PSA on Heat channel allows us to reduce the background without increasing the # of detectors

* ZnSe is a promising compound for DBD and DM searches, nevertheless R&D of LDs is needed

* ZnSe (and ZnMoO4) allows to reach a background level of ~10^{-3} c/keV/kg/y (at least)

* A bright future is ahead...