LUCIFER: scintillating bolometers for DBD0v decay

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DBD14
International workshop on "Double beta decay and Underground science"

Outline

- Double-beta decay sensitivity

- Scintillating bolometer

- LUCIFER project using $Zn^{100}MoO_4$ & $Zn^{82}Se$:
  - particle discrimination
  - detector performance
  - sensitivity

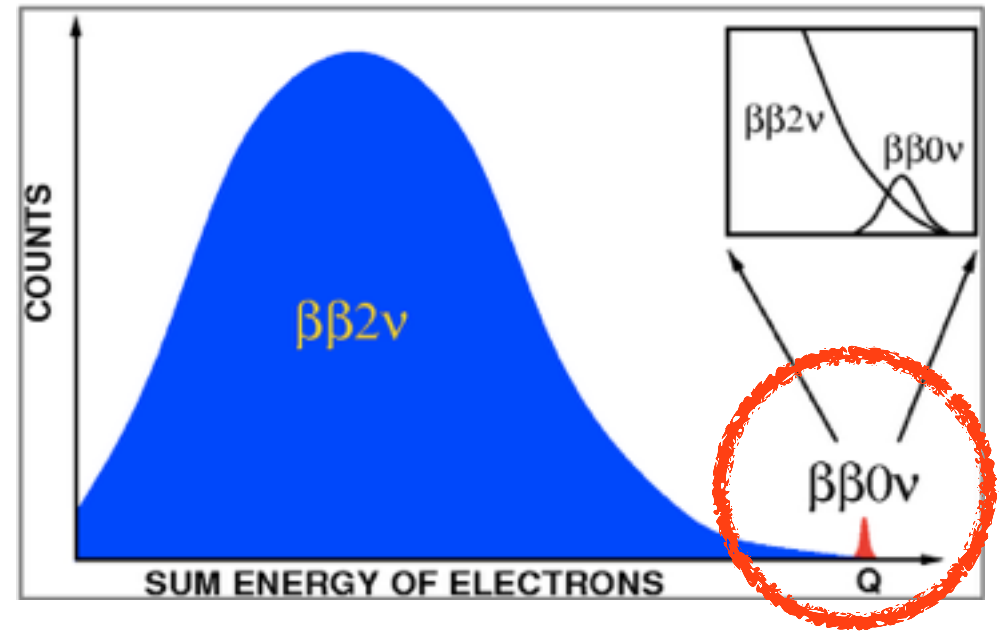
- An interesting application of sci-bolo

- Conclusions

$0\nu\beta\beta$ Sensitivity

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

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



$S_{0\nu}$: half-life corresponding to the signal that could be emulated by a background fluctuation 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 $0\nu\beta\beta$ candidates or enrichment

M: detector mass

Large mass array

t: measuring time

Stable over long time (~y)

B: background

- **Deep undergound location**
- **Material selection**
- **High granularity**

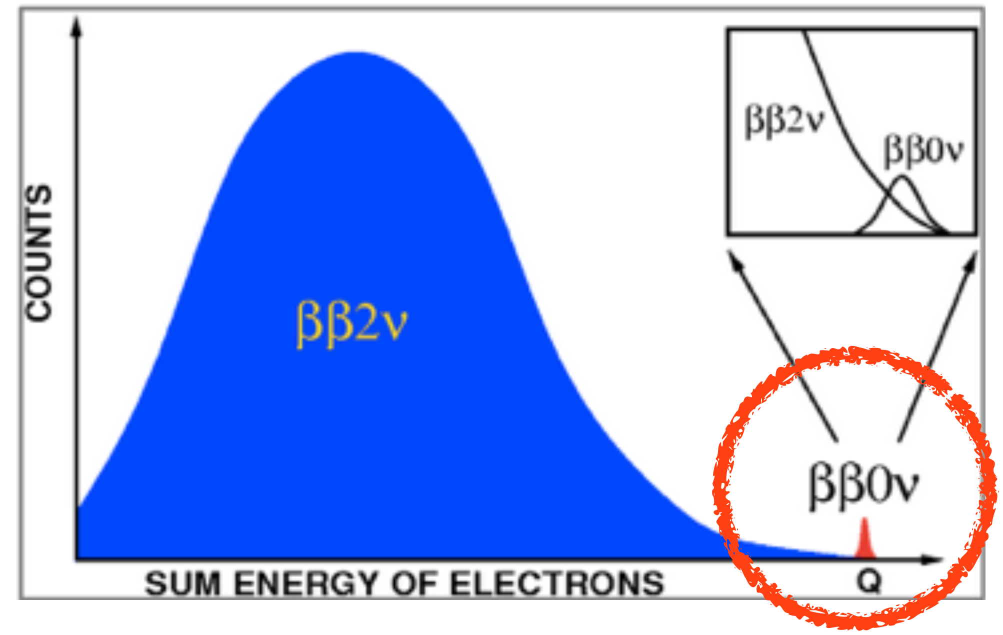
ΔE: energy resolution

Bolometric approach

0νββ Sensitivity

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

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



$S_{0\nu}$: half-life corresponding to the signal that could be emulated by a background fluctuation at a given c.l.

zero-background approximation: B*M*t*ΔE <<1

i.a.: isotopic abundance

M: detector mass

t: measuring time

$$S_{0\nu} \propto i.a. \cdot \epsilon \cdot M \cdot t$$

ε: detection efficiency

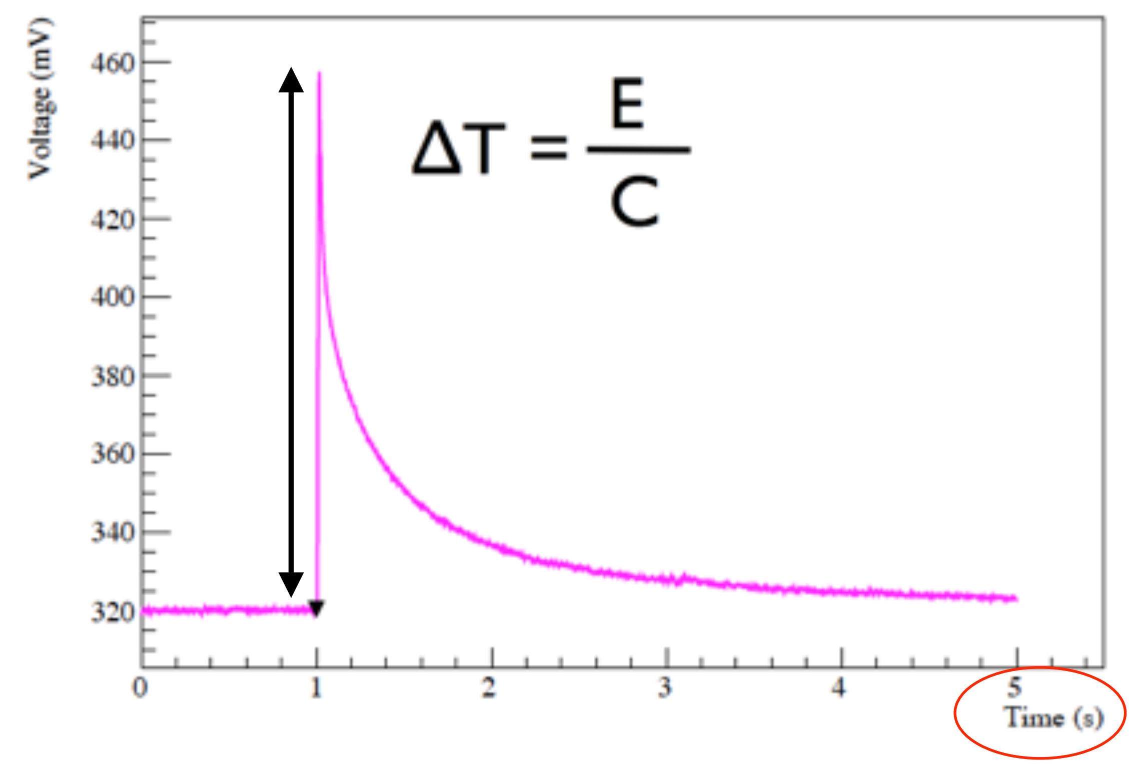
Sensitivity scales linearly with exposure!

The bolometric technique

fully-active detector

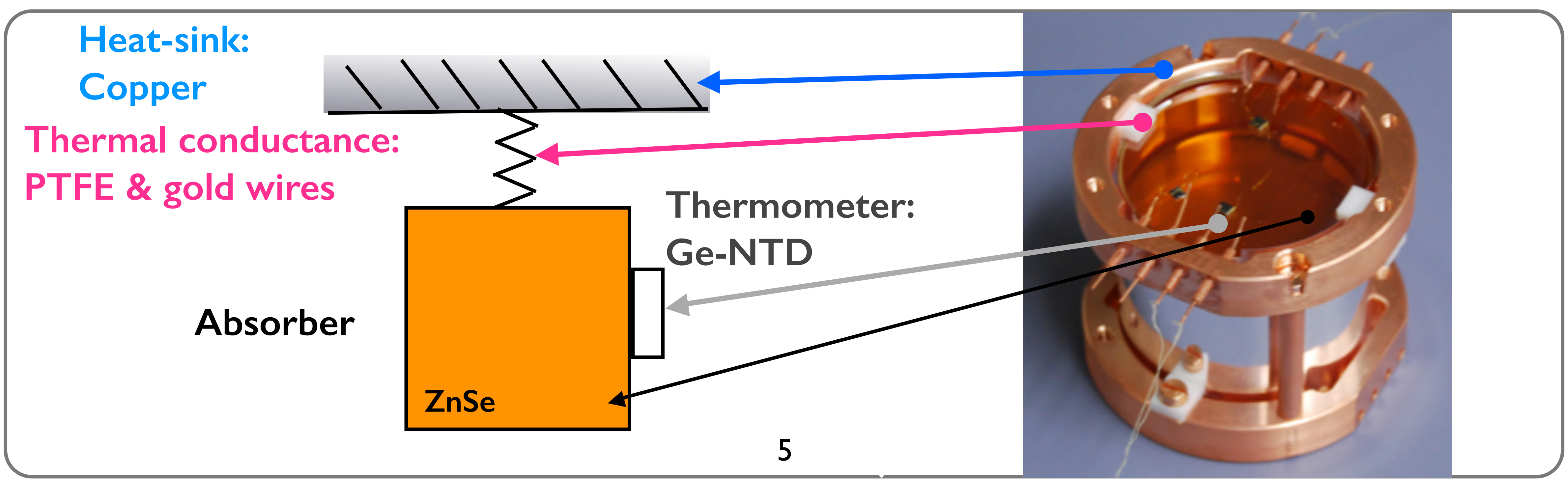
Almost all the deposited energy is converted into phonons which induce a measurable temperature rise

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



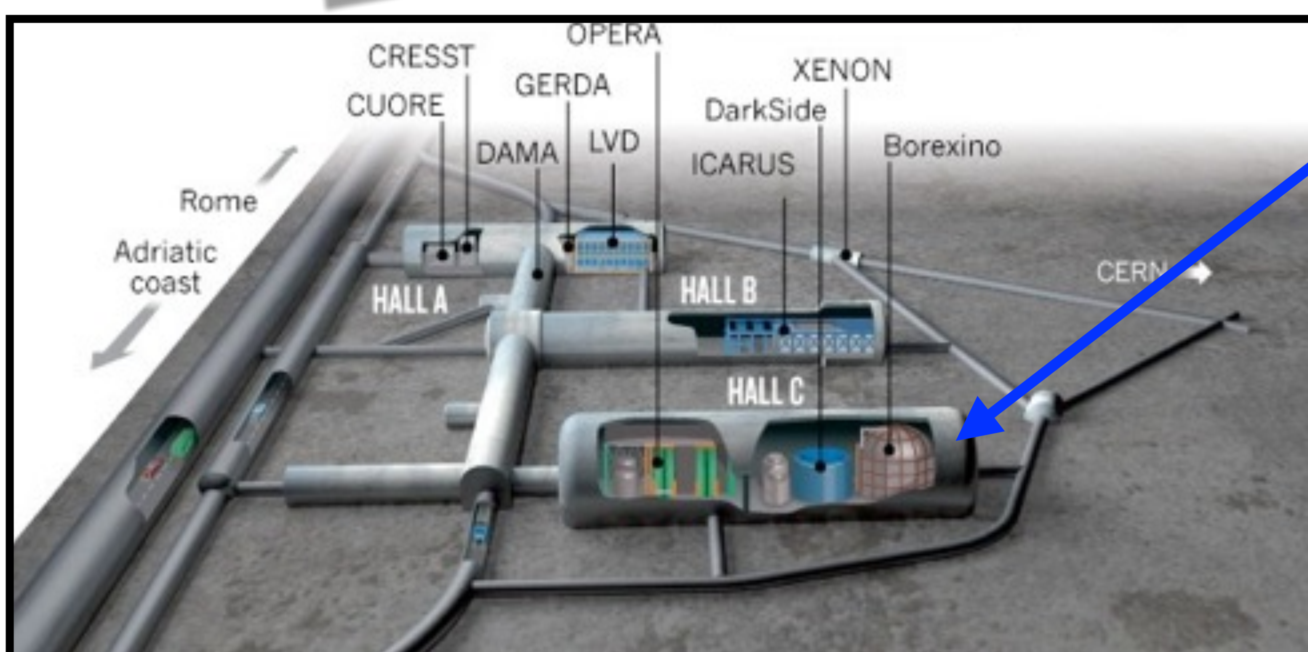
Absorber
- M ~ 0.45 kg
- C ~ 10^{-10} J/K
- ΔT/ΔE ~ 500μK/MeV

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



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 $\gamma/s/cm^2$

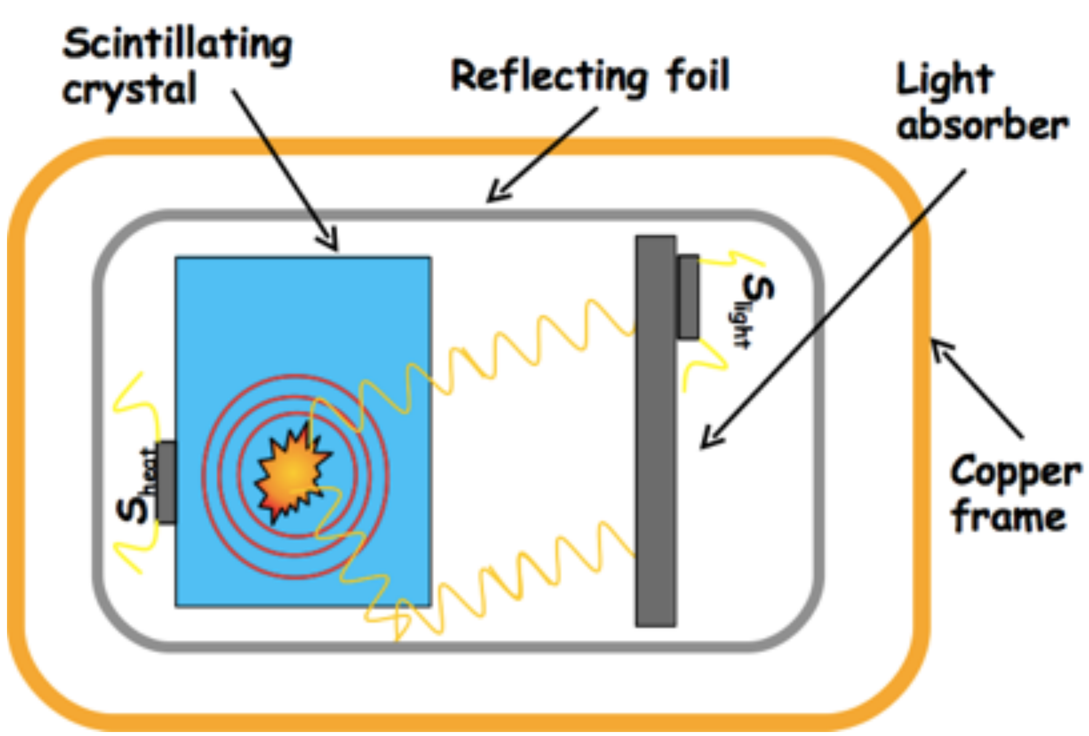
Scintillating bolometers

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.

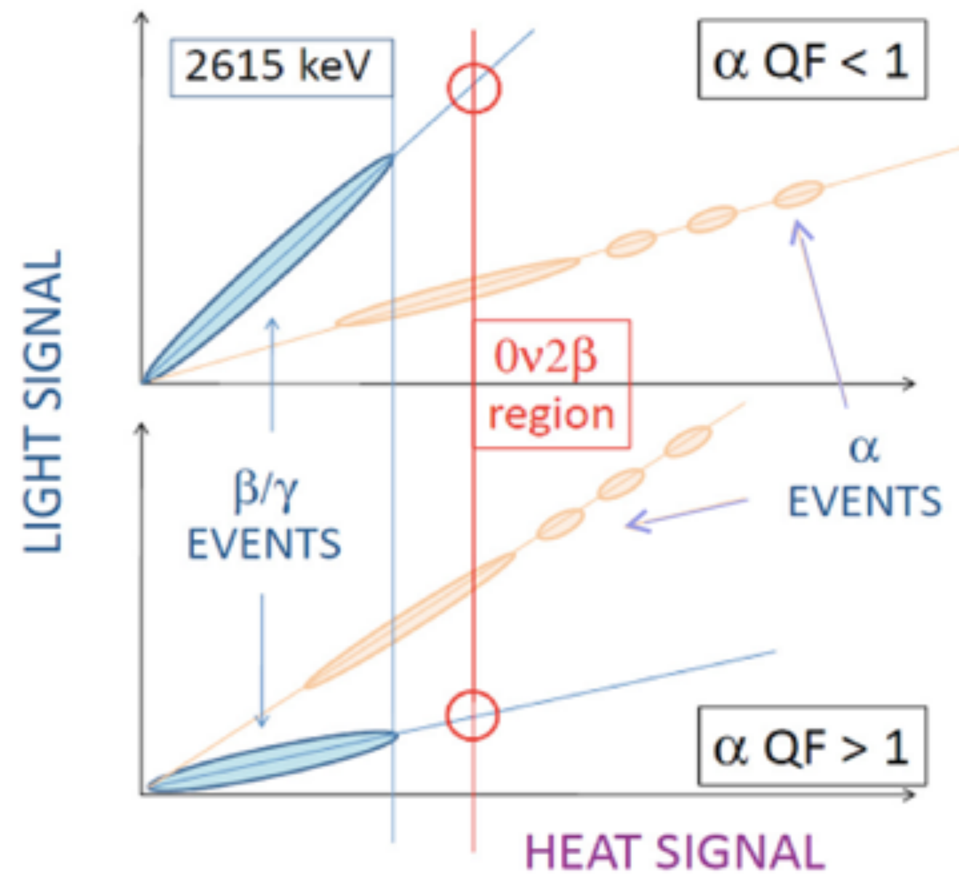
Double signal read-out:

Heat: absorber+thermometer

Light: PM / SiPM / bolometer



A. Alessandrello et al., Nucl. Phys. B ***28*** *(1992) 233-235*



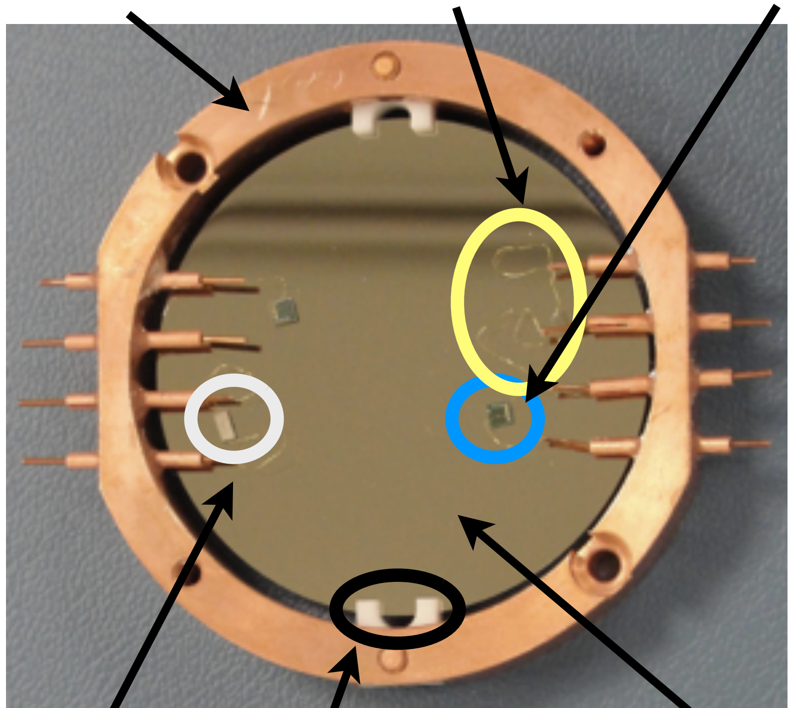
Particle discrimination!
alpha, beta/gamma and neutrons

Light detectors (LD)

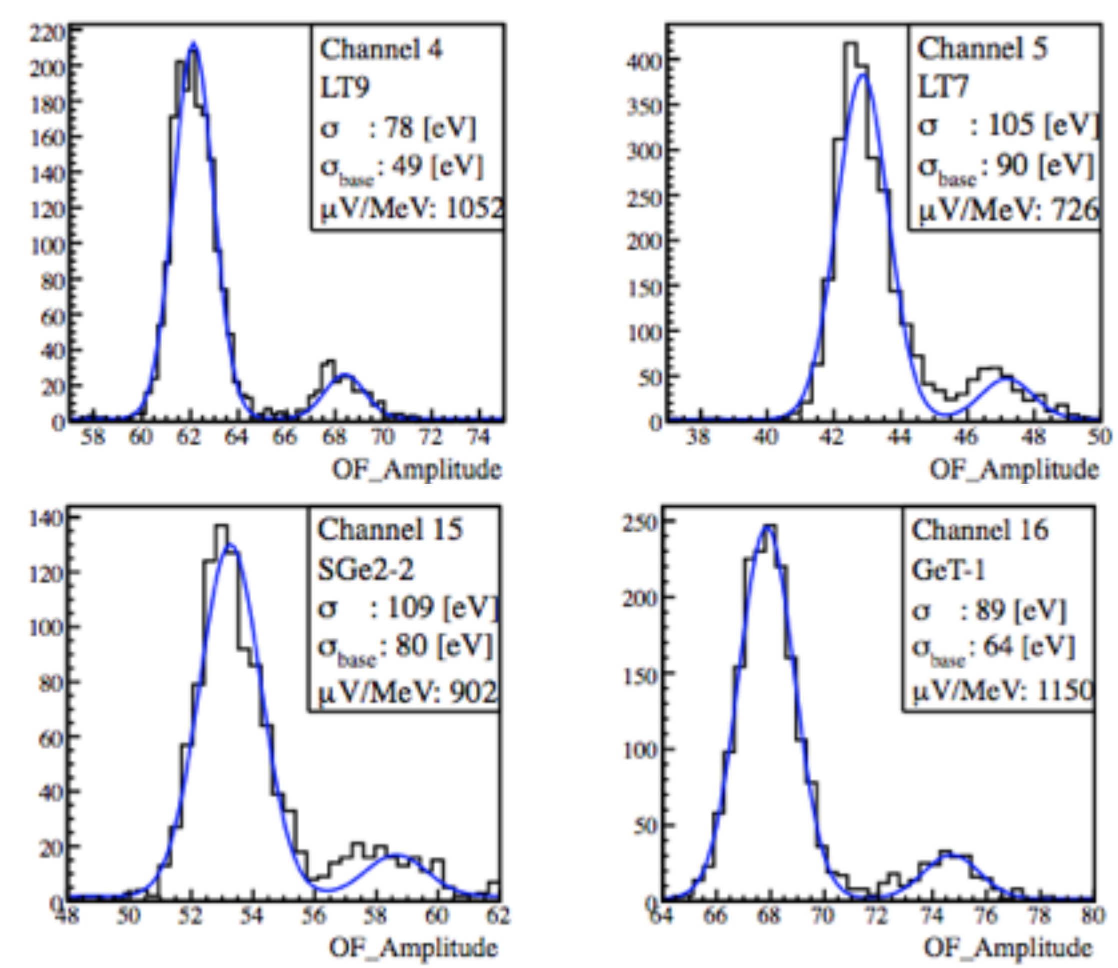
Light signal: => few keV/MeV
=> is isotropic

Light detector:

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



^{55}Fe X-ray calibration
(5.9 keV and 6.5 keV)



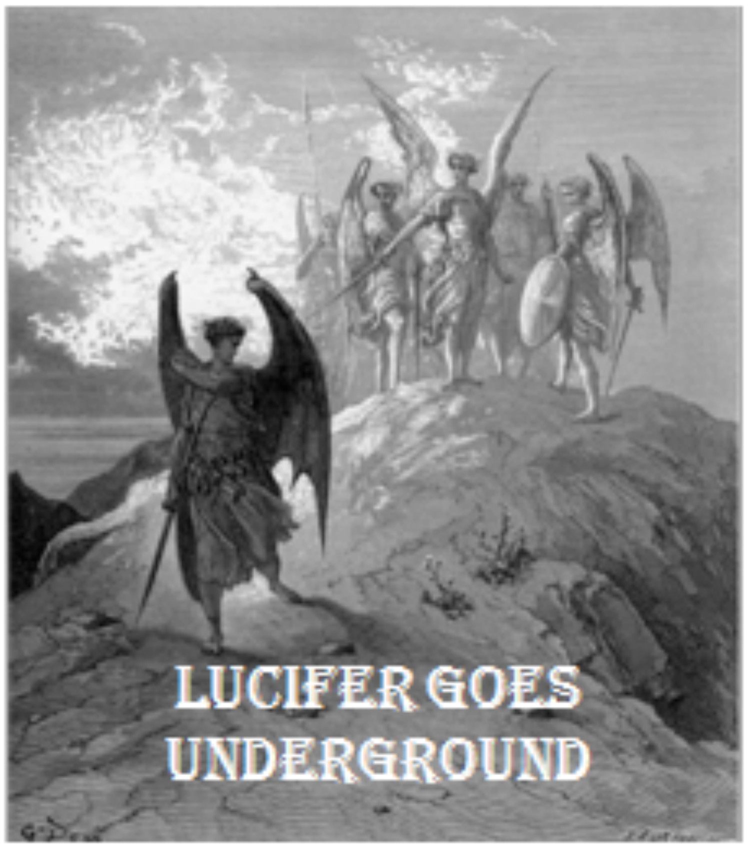
J.W. Beeman et al., *JINST*, **8** P07021 (2013)

INFN Istituto Nazionale di Fisica Nucleare

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€



- Demonstrator array of enriched scintillating bolometers

- LUCIFER investigates the “best” compound for DBD0ν searches among:
 $Zn^{82}Se$ / $Zn^{100}MoO_4$ / $^{116}CdWO_4$ crystals

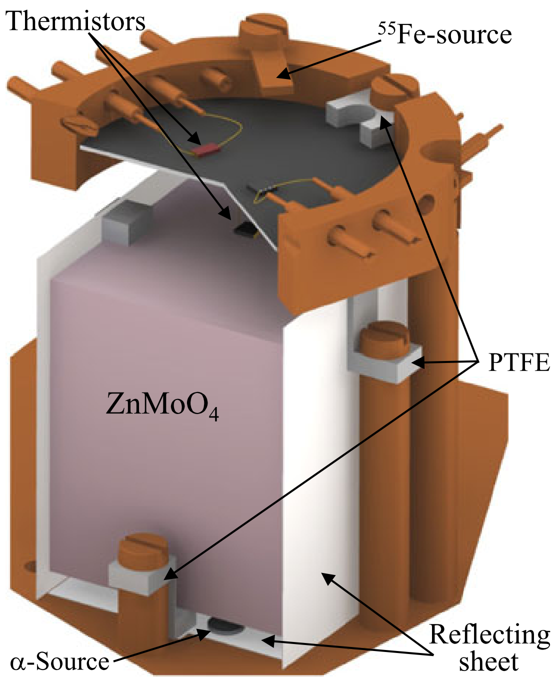
- Total isotope mass: ~15 kg

- Background index @ ROI ≤ 10^{-3} c/keV/kg/y

	Q-value [keV]	Useful material	$LY_{\beta/\gamma}$ [keV/MeV]	QF_α
$Zn^{100}MoO_4$	3034	44%	1.5	0.2
$^{116}CdWO_4$	2814	32%	17.6	0.2
$Zn^{82}Se$	2996	56%	6.5	4.2

$ZnMoO_4$

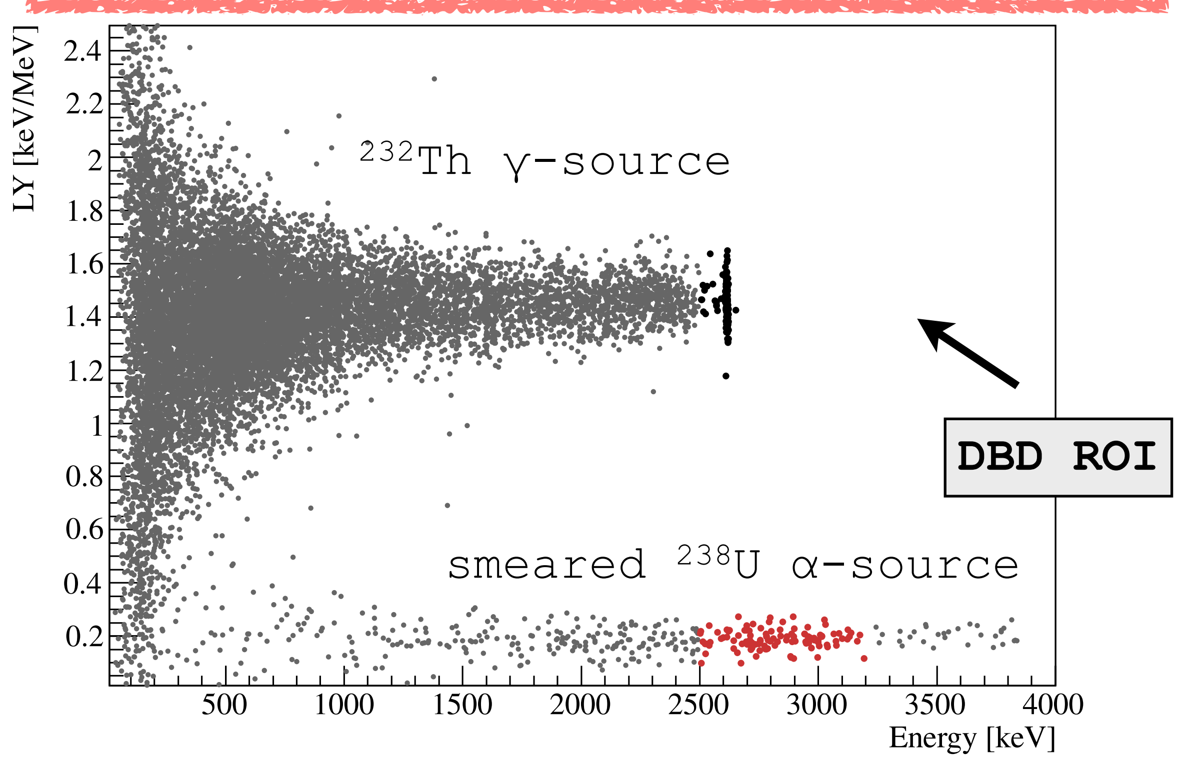
Candidate: ^{100}Mo



m=330 g
natural crystal
large mass

	Q-value [keV]	Useful material	LY [keV/MeV]	QF
ZnMoO	3034	44%	1,5	0,2

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

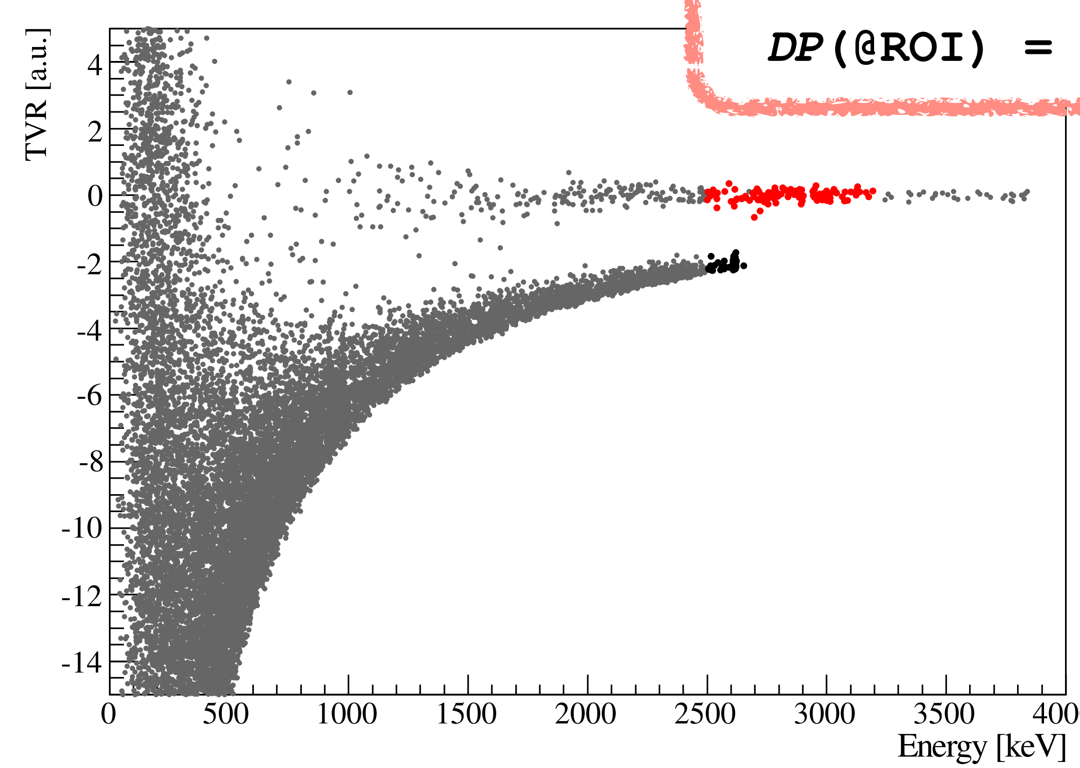


Impressive particle discrimination using **just Heat**

Discrimination potential:

$$DP(E) = \frac{|\mu_\alpha(E) - \mu_{\beta\gamma}(E)|}{\sqrt{\sigma_\alpha^2(E) + \sigma_{\beta\gamma}^2(E)}}$$

DP **(@ROI) = 20**

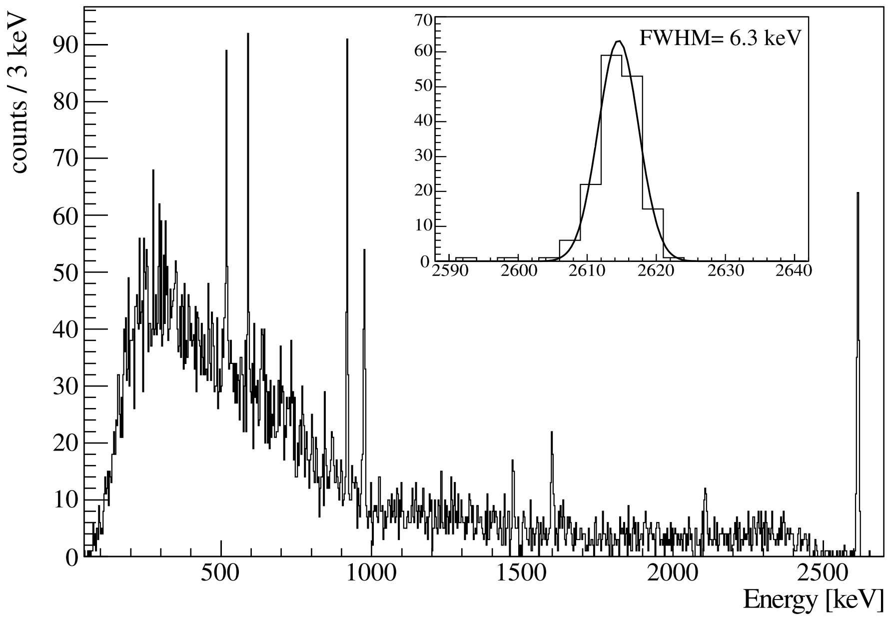


J.W. Beeman *et al.*, *Eur. Phys. J. C* (2012) **72**:2142

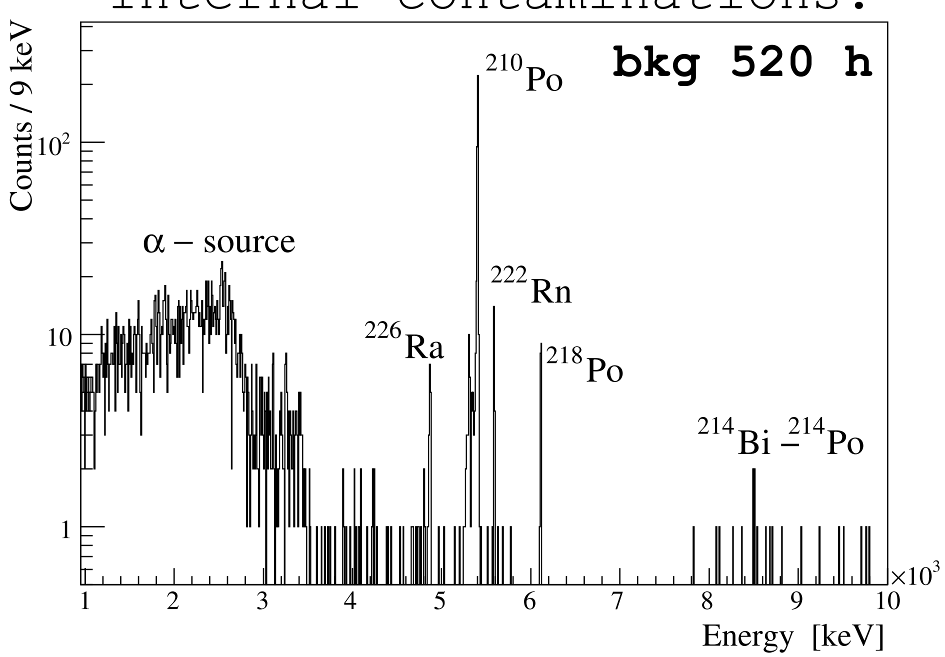
$ZnMoO_4$ performance

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±0.5 keV
FWHM @ 1460 keV: 4.9±1.0 keV



Internal contaminations:



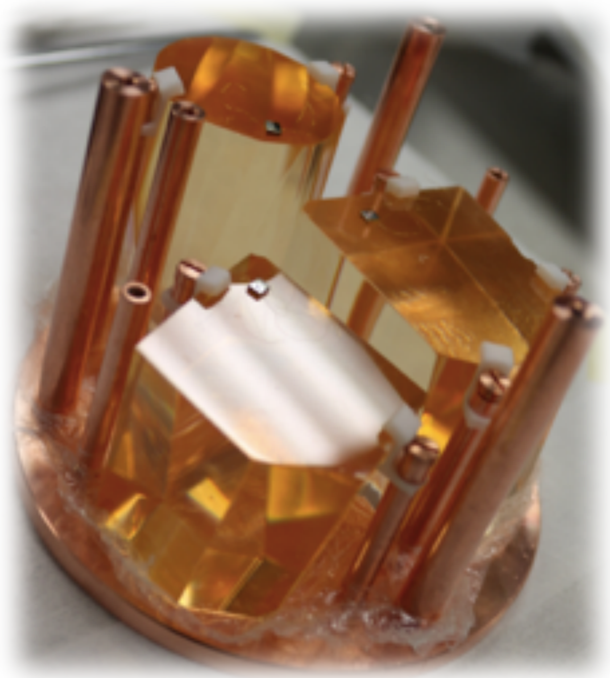
Chain	Nuclide	Activity [μBq/kg]
^{232}Th	^{232}Th	<8
	^{228}Th	<6
^{238}U	^{238}U	<6
	^{234}U	<11
	^{230}Th	<6
	^{226}Ra	27 ± 6
	^{210}Po	700 ± 30

Reference:
CUORE TeO_2 crystals ready-to-use:

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

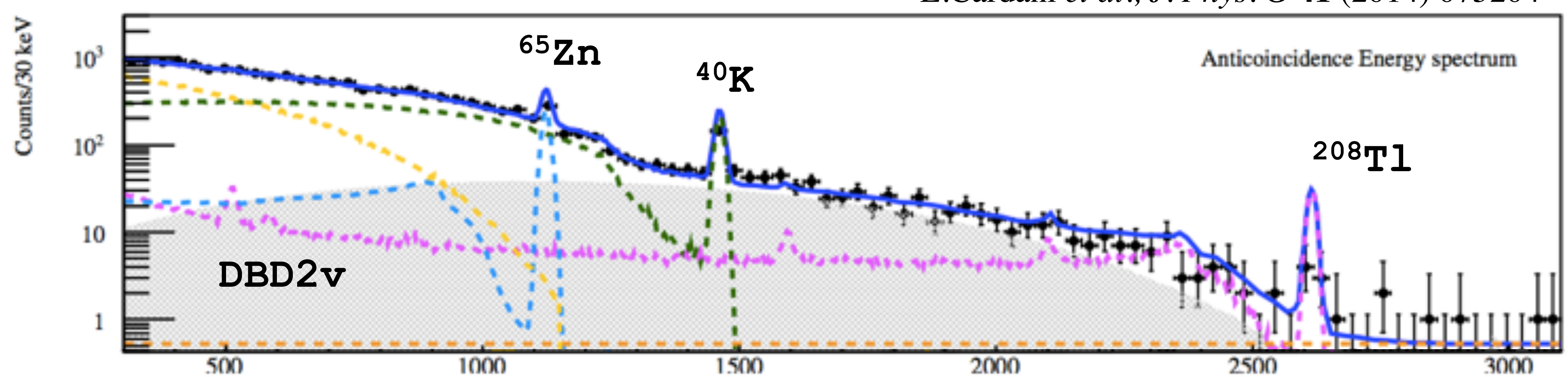
C. Arnaboldi *et al.*, *J. Cryst. Growth* **312** (2010) 2999

Array of $ZnMoO_4$



First bolometric measurement of DBD2v with a $ZnMoO_4$ crystal array

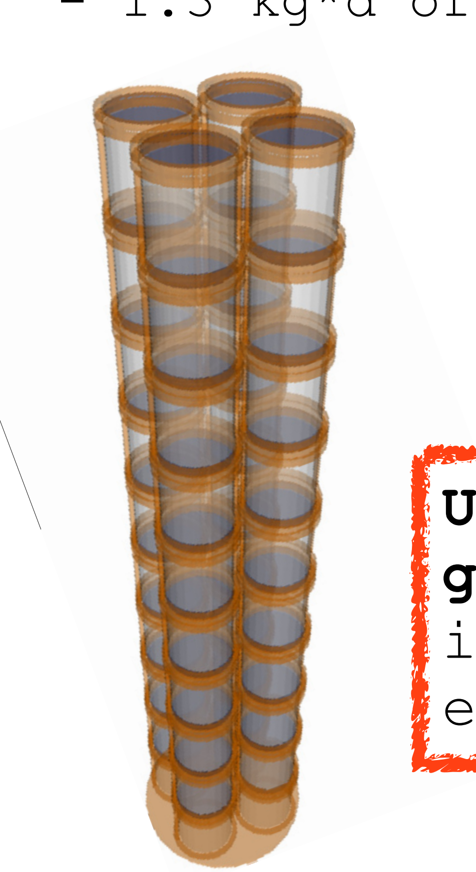
L.Cardani *et al*., *J. Phys. G* **41** (2014) 075204



- 3 natural $ZnMoO_4$
- 1.3 kg*d of ^{100}Mo

$T^{DBD2v}_{1/2}$=[7.15±0.37(stat)±0.66(syst)]10^{18} y

in agreement with NEMO3 measurement:
$T_{1/2}$=[7.11±0.02(stat)±0.54(syst)]10^{18} y



Given the short half-life of ^{100}Mo and the slow signal development of bolometers

Ultimate background for next generation bolometric experiment is induced by ^{100}Mo DBD2v pile-up events O(>10^{-3} c/keV/kg/y)

-Faster thermal sensors
-New trigger algorithms must be developed (see **LUMINEU** project)

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

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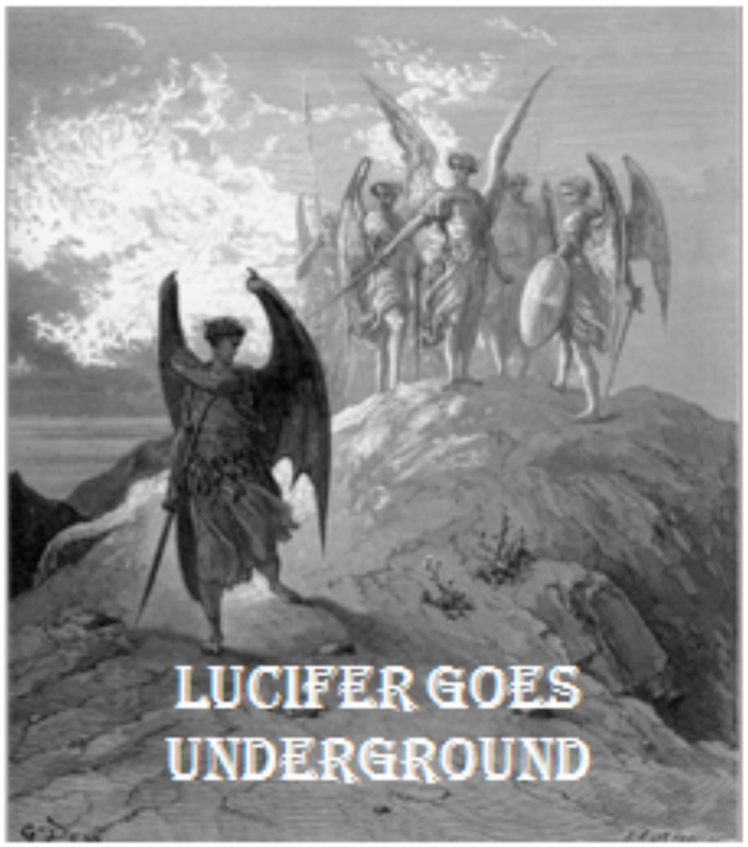

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back-up solution: collaboration with LUMINEU project → $Zn^{100}MoO_4$

still under investigation → $^{116}CdWO_4$

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

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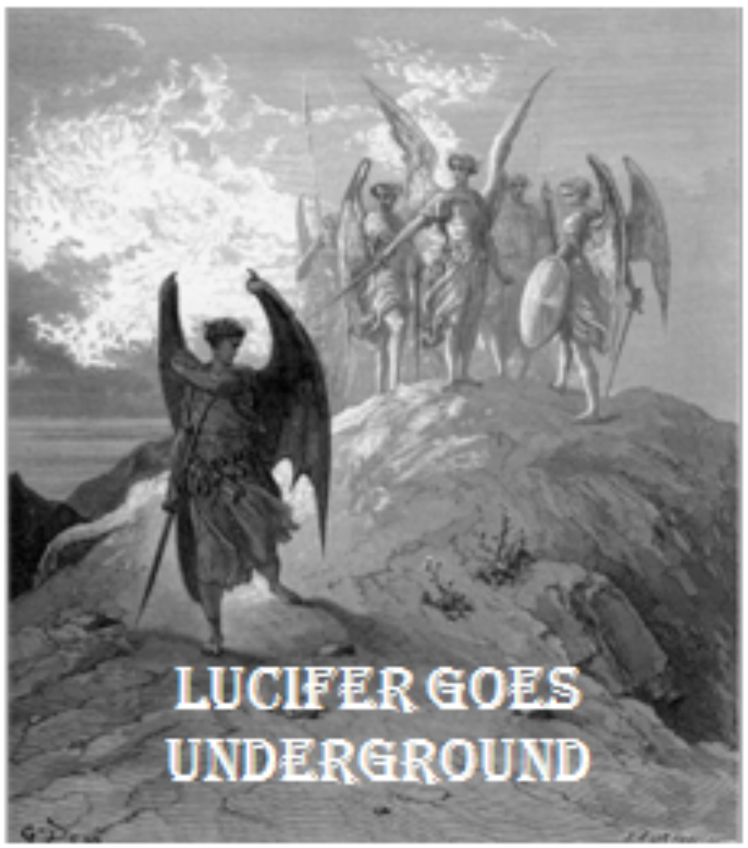

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- Background index @ ROI ≤ 10^{-3} c/keV/kg/y

primary solution driven by various factors:
- enrichment (price,...)
- bkg discrimination
- ...

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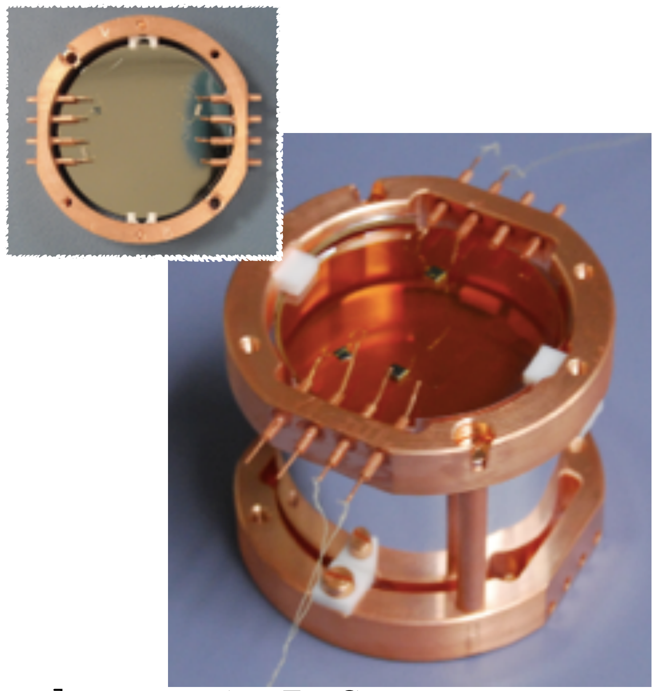
→ $Zn^{82}Se$	2996	56%	6.5	4.2

ZnSe

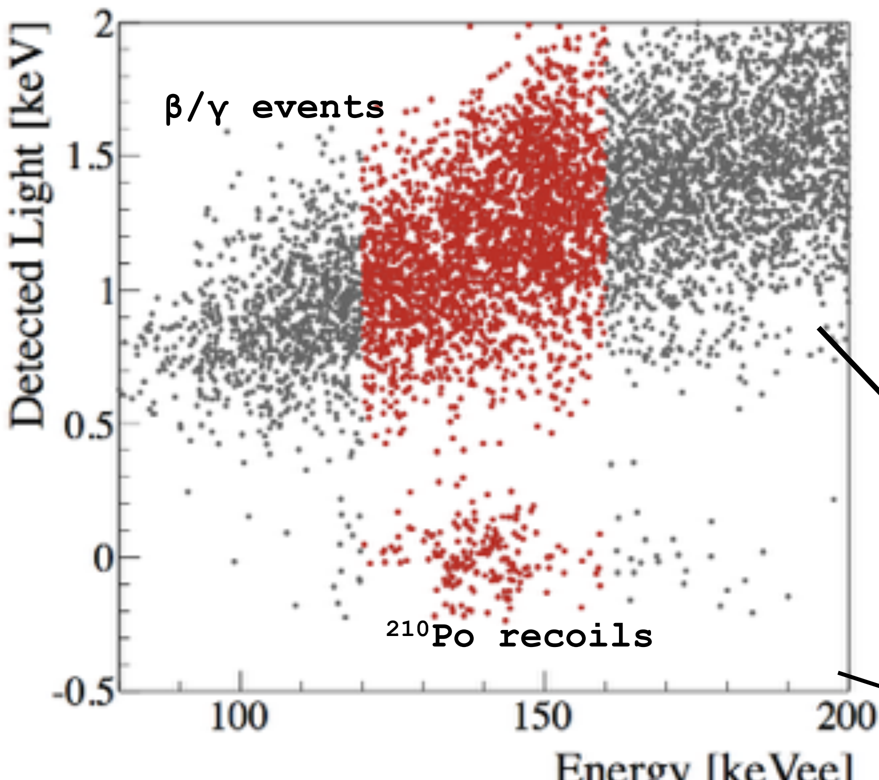
Candidate: ^{82}Se

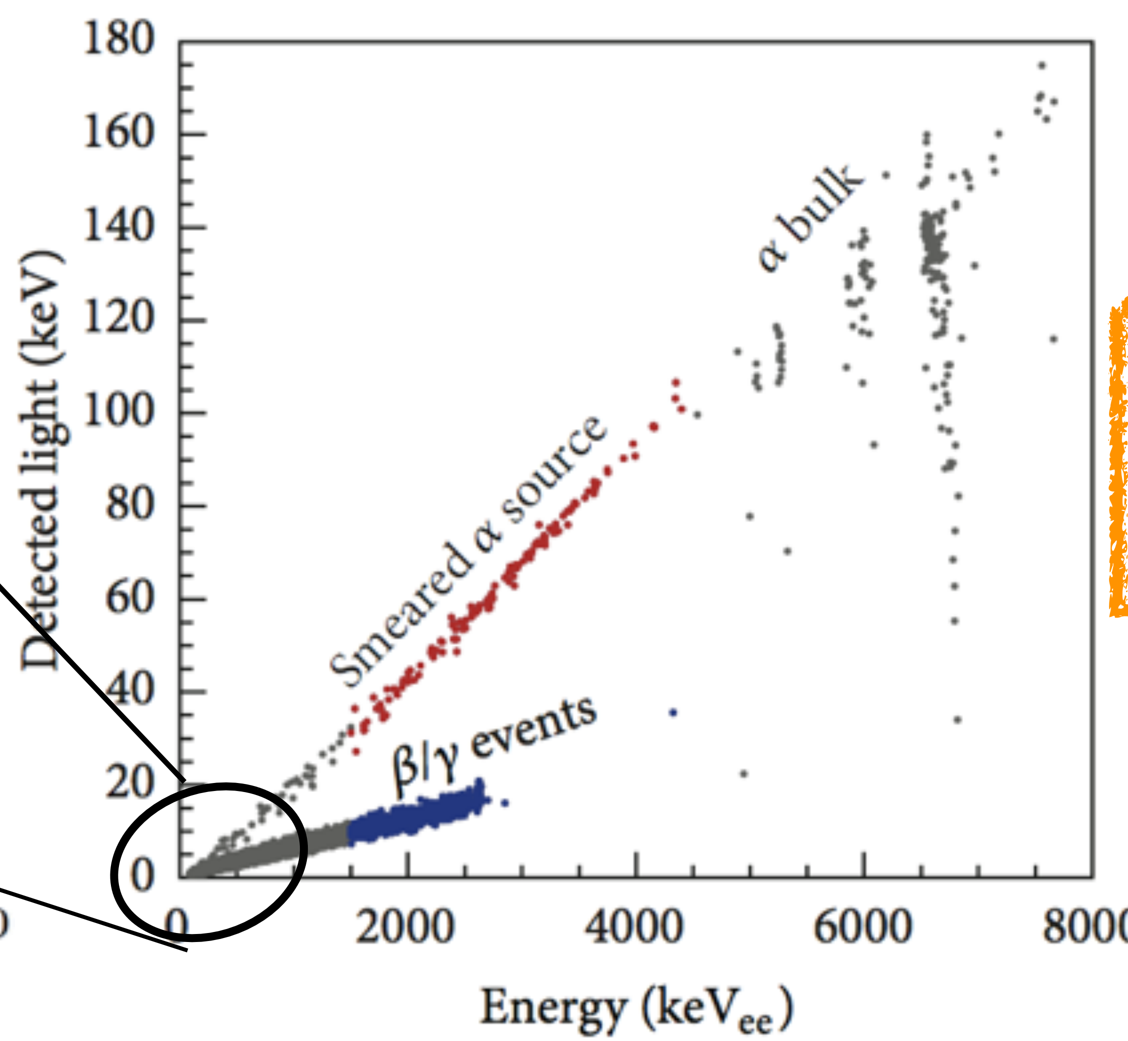


largest ZnSe ever produced
m=430 g

	Q-value [keV]	Useful material	LY [keV/MeV]	QF
ZnSe	2996	56%	6,4	4,2

Odd QF_α for ZnSe: αs produce more light than β/γs





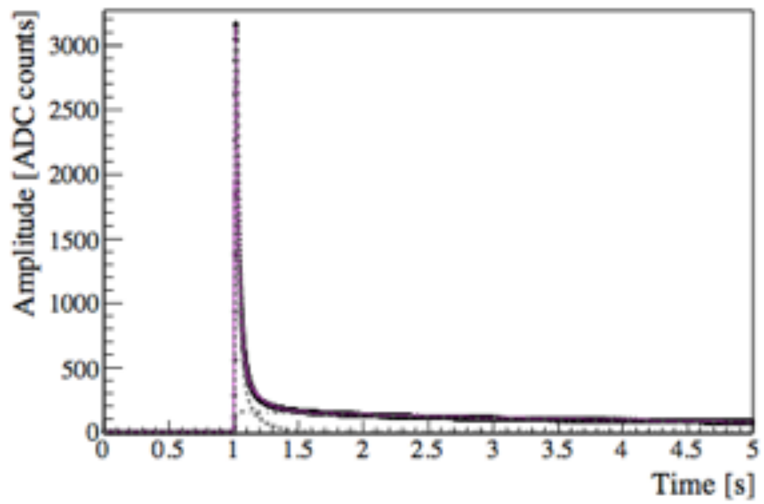
Excellent particle discrimination on the **Light vs. Heat** plane

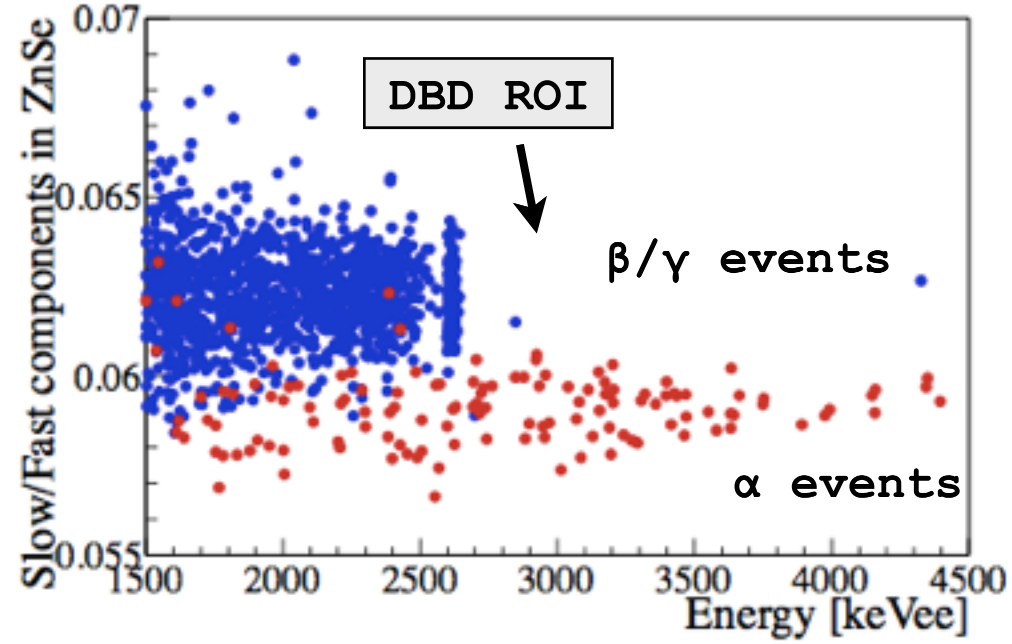
nuclear recoils are in the "right" position!

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

ZnSe Particle discrimination

Heat signal shape



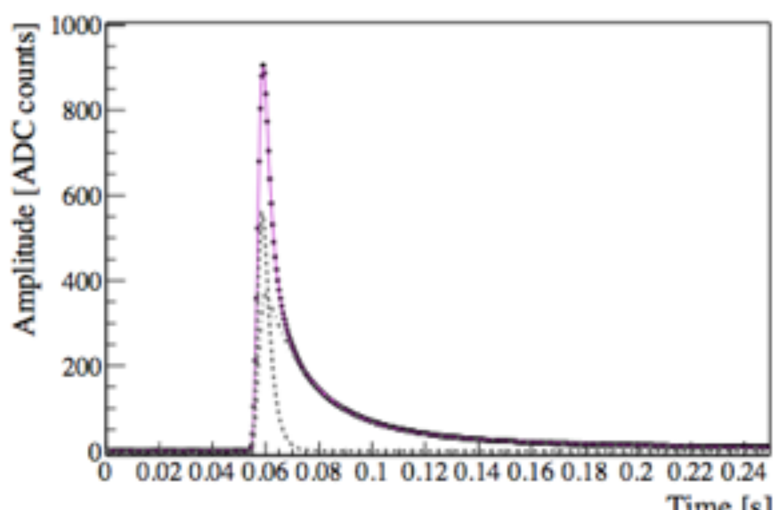


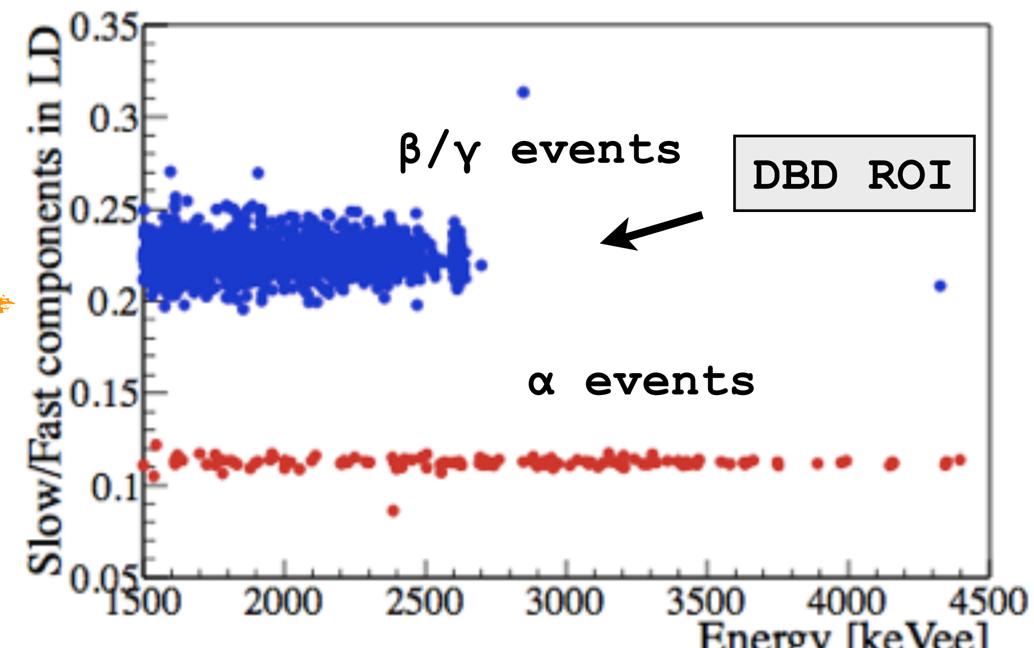
Discrimination potential:

$$DP(E) = \frac{|\mu_\alpha(E) - \mu_{\beta\gamma}(E)|}{\sqrt{\sigma_\alpha^2(E) + \sigma_{\beta\gamma}^2(E)}}$$

DP(@ROI) = 2

Light signal shape





Discrimination potential:

$$DP(E) = \frac{|\mu_\alpha(E) - \mu_{\beta\gamma}(E)|}{\sqrt{\sigma_\alpha^2(E) + \sigma_{\beta\gamma}^2(E)}}$$

DP(@ROI) = 11

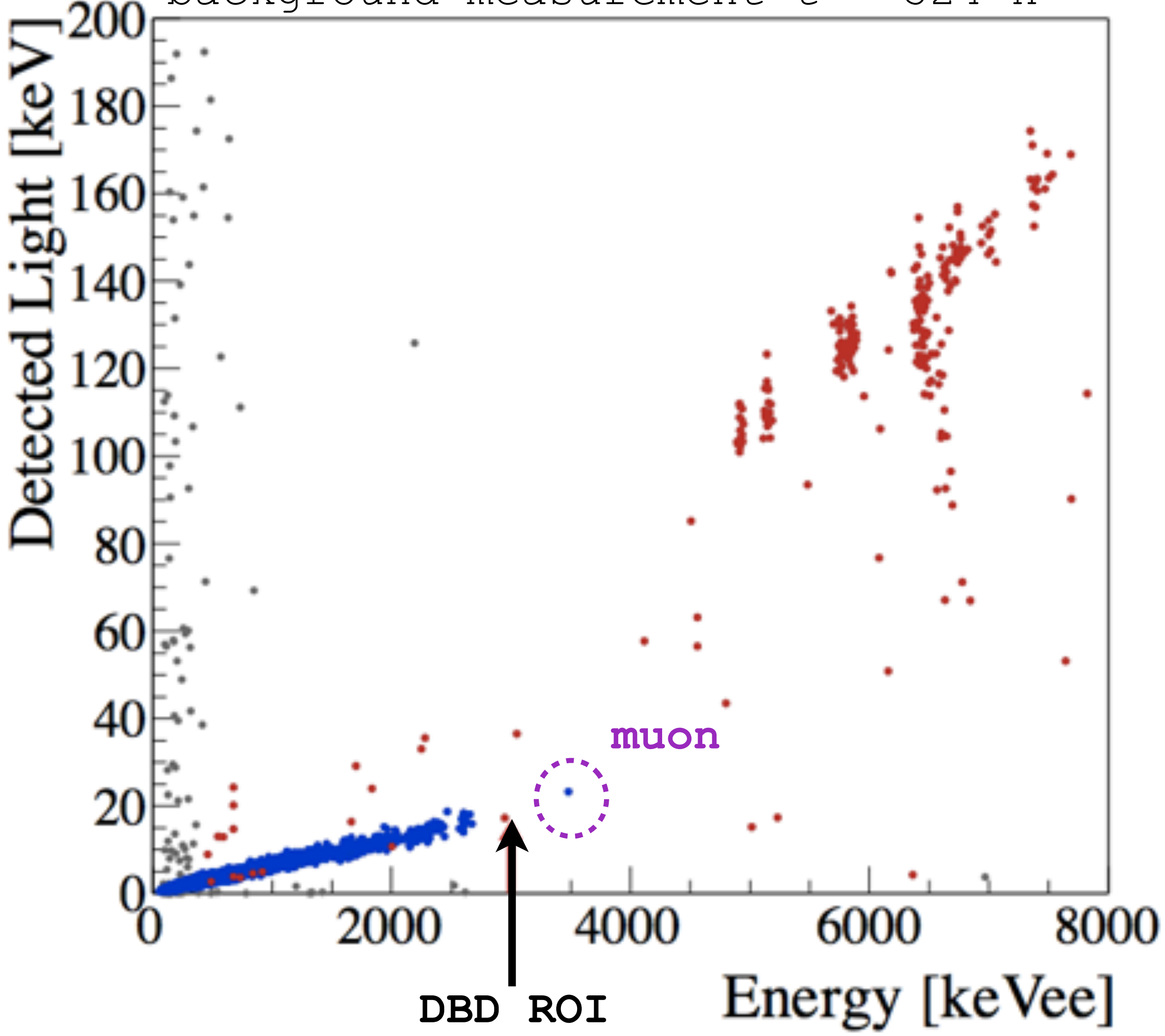
highly performing LD are needed for bkg suppression

J.W. Beeman et al., Adv. High Energy Phys. **2013**, 237973

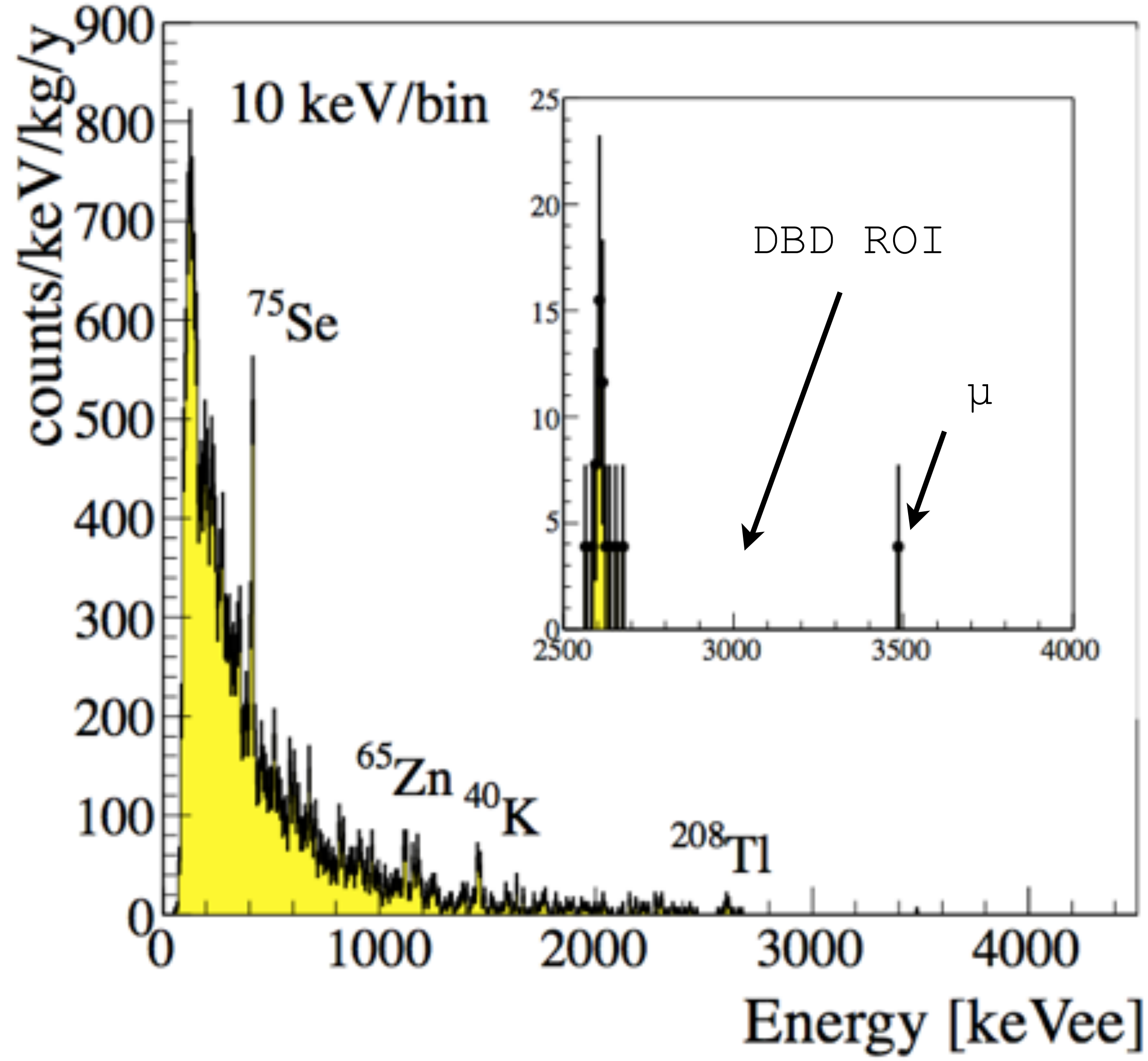
ZnSe background

Low Background measurement

crystal m = 430 g
background measurement t = 524 h



β/γ events selection



- Cosmogenic activation ^{75}Se and ^{65}Zn
- Natural radioactivity: ^{40}K, ^{232}Th & ^{238}U @ ~ μBq/kg

Energy resolution

	ZnSe [keV FWHM]	ZnSe and Light [keV FWHM]
1461 keV	13.4 ± 1.0	12.2 ± 0.8
2615 keV	16.3 ± 1.5	13.4 ± 1.3

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

^{82}Se: enrichment

Natural ^{82}Se => isotopic abundance 8.7%
LUCIFER ^{82}Se => enrichment @ 95% => higher sensitivity

15 kg of ^{82}Se from URENCO (Netherlands)

Natural SeF_6

centrifuge cascade (dedicated line)

chemical conversion

^{82}Se metal:
=> @ 95% enrichment
=> @ 99.5% chemical purity

re-distillation

already delivered ~10 kg @ LNGS

element dangerous for scintillation

ICPMS screening
Before => After re-dist.

	Before		After	
Na	1860000	=>	<6711	ppb
Cr	<110	=>	<11	ppb
Fe	<300	=>	<45	ppb
V	<20	=>	<22	ppb
S	1140000	=>	<201330	ppb

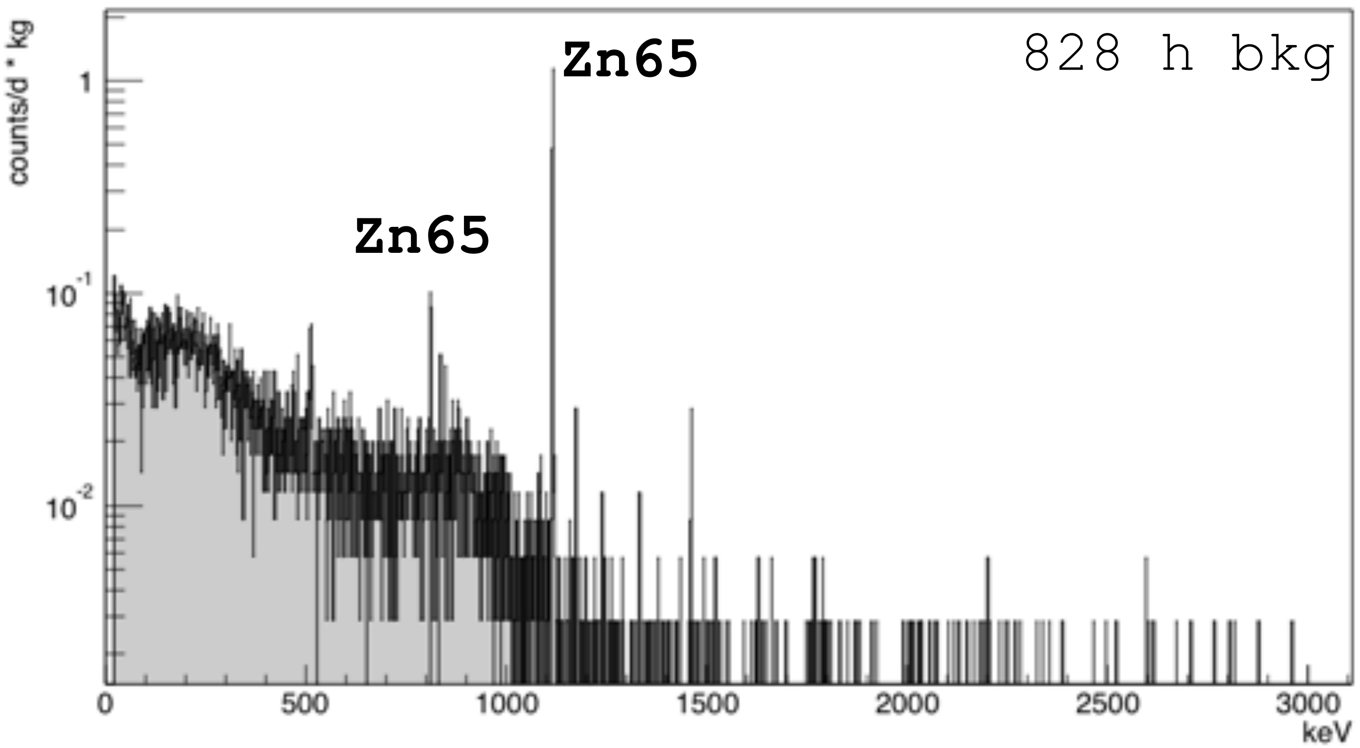
HP-Ge screening <u>before</u> re-distillation

^{238}U:
^{234}Th < 1.4 E-9 gU/g
^{226}Ra < 1.4 E-10 gU/g

^{232}Th:
^{228}Th (4.3±0.8) E-10 gTh/g
^{224}Ra < 1.2 E-9 gTh/g
^{40}K (1.3±0.6) E-7 gK/g

HP-zinc

Producer:
National Science Center KITP (UA)



There are only short-living cosmogenic activation products
+
Zn-65

No U/Th lines over 34 days!

γ spectroscopy on GEMPI4@LNGS:

Th-232:
Ra-228: < 2.4 E-11 g/g
Th-228: < 8.9 E-12 g/g

U-238:
Ra-226 < 5.4 E-12 g/g
Th-234 < 5.0 E-10 g/g
Pa-234m < 3.8 E-10 g/g

U-235:
U-235: < 1.6 E-10 g/g

K-40: < 1.2 E-8 g/g

Zn-65: (5.2 +- 0.6)mBq/kg

element dangerous for scintillation

ICPMS screening

Cr	<85	ppb
Fe	<170	ppb
V	<9	ppb
S	<8530	ppb

Crystal growth

ZnSe is a well known compound

=> extended IR transmission (0.5um-20um)

=> production of glass / small crystals

No commercial use of large size - high quality crystals
=> **few people** are able to grow ZnSe crystals for our purpose

LUCIFER crystal production
@ Institute for Single Crystals
(Kharkov, UA):

1) ZnSe powder synthesis
2) Bridgman growth
3) mechanical processing

→

ICPMS screening
ZnSe Natural powder

U < 1 ppb
Th < 1 ppb
K < 1000 ppb
V < 15 ppb
Fe < 50 ppb
Cr < 15 ppb

good radiopurity level,
not yet optimized

Criticalities:

- volatility of Zn and Se => change of stoichiometry

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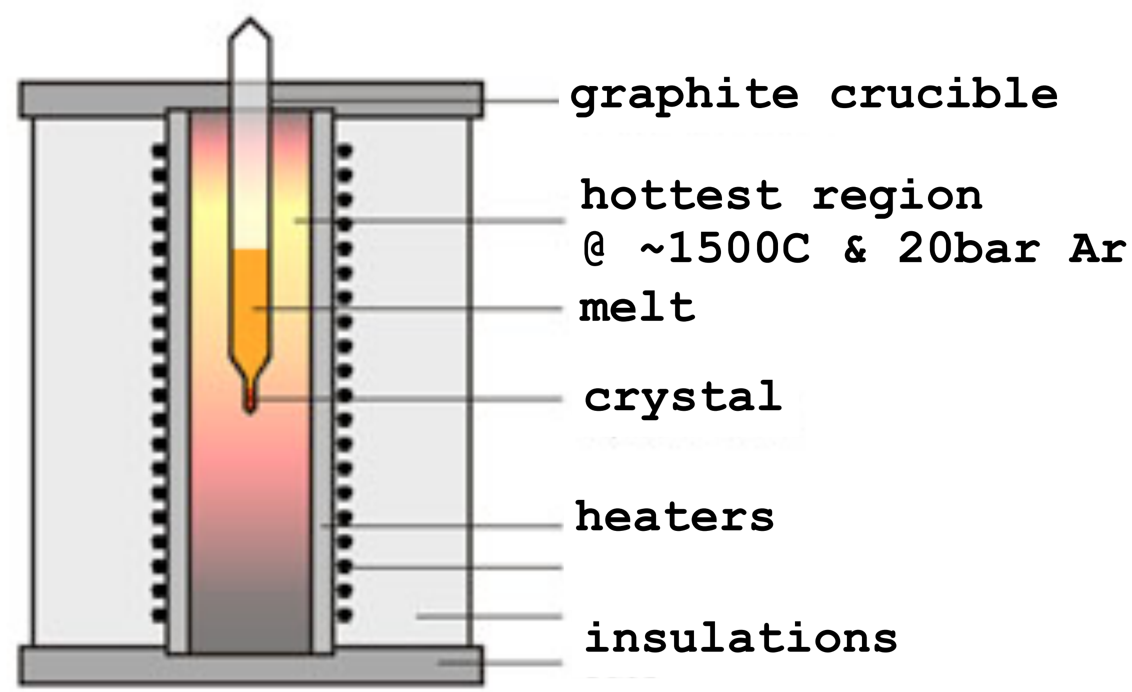
Bridgman technique



Criticalities:
- production of crystals with good bolometric and scintillating performance
- low production yield => loss of material

Crystal growth

ZnSe is a well known compound

=> extended IR transmission (0.5um-20um)

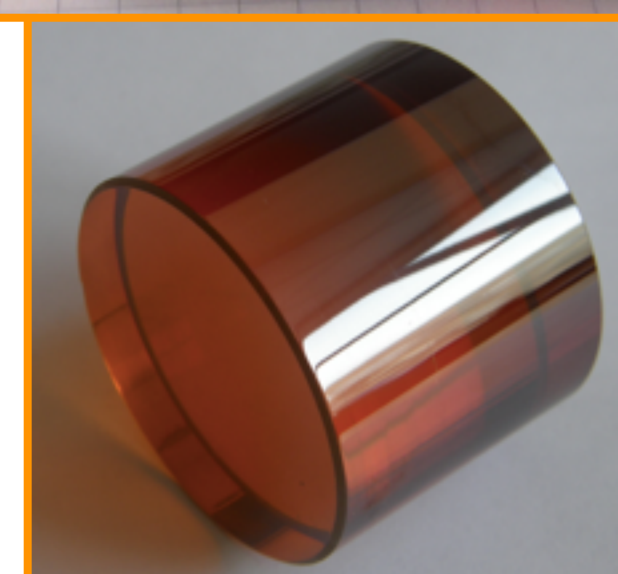
=> production of glass / small crystals

No commercial use of large size - high quality crystals
=> **few people** are able to grow ZnSe crystals for our purpose

LUCIFER crystal production
@ Institute for Scintillation Materials
(Kharkov, UA):

1) ZnSe powder synthesis
2) Bridgman growth
3) mechanical processing

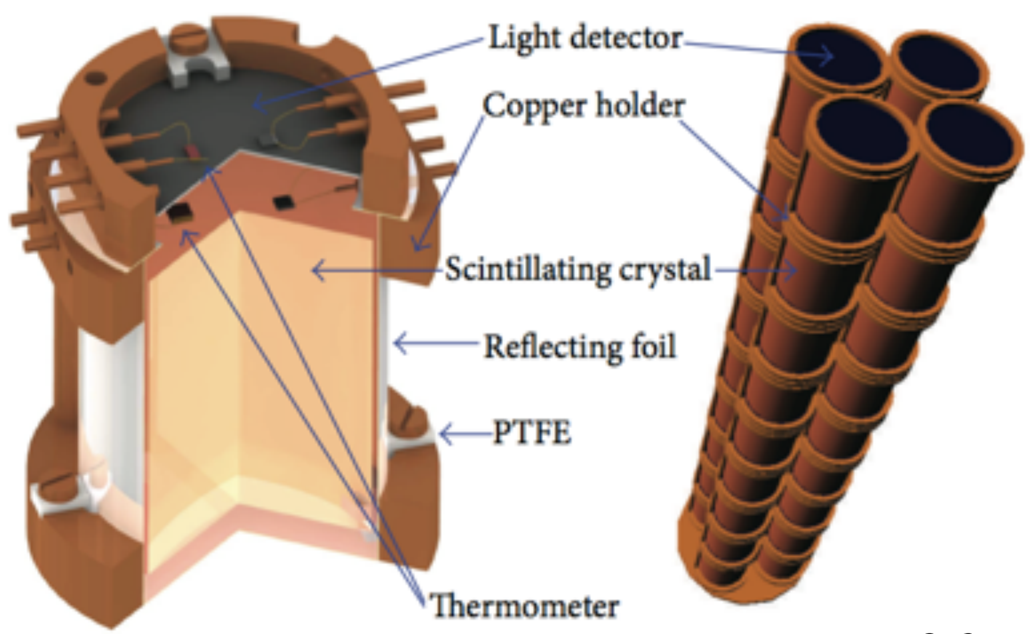
ZnSe as grown



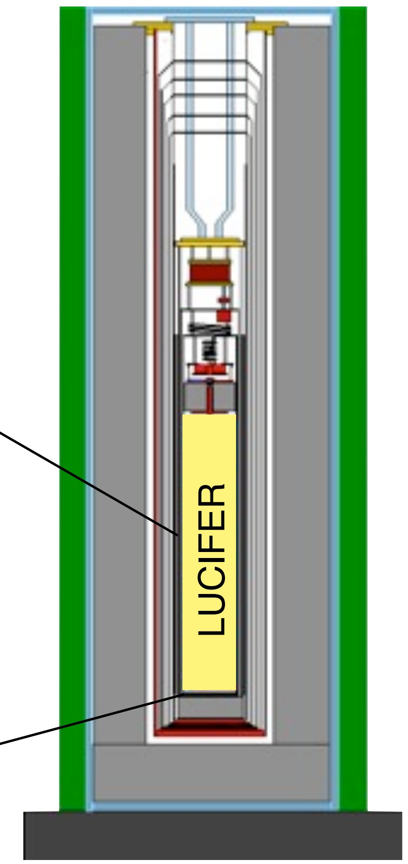
Criticalities:
- loss of enriched material
- recycling of the crystal scraps
  => radio/chemical purity

LUCIFER sensitivity

LCF single module



LCF tower ~36 modules



Cuoricino cryostat:

- 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.

+ some upgrades (new shields, new wiring read-out, ...)

- 36 enriched detectors @ 95% level
- detector mass 17 kg of $Zn^{82}Se$ (14 kg of $Zn^{100}MoO_4$)
- expected bkg @ ROI 10^{-3} c/keV/kg/y
- FWHM @ ROI: 10 keV (5 keV)

Crystal	Live time (y)	Half-life sensitivity (10^{26} y)	$\langle m_\nu \rangle^*$ (meV)
ZnSe	5	0.6	65–194
	10	1.2	46–138
$ZnMoO_4$	5	0.3	60–170
	10	0.6	42–120

*
Nucl. Phys A, 818 (2009) 139
J. Phys G, 39 (2012) 124006
Phys. Rev. C, 83 (2011) 034320
J. Phys G, 39 (2012) 124005
Phys. Rev. C, 87 (2013) 014315
Phys. Rev. C, 82 (2010) 064310
Phys. Rev. Lett., 105 (2010) 252503
Phys. Rev. Lett., 85 (2012) 034316

LCF coll., Adv. High Energy Phys., (2013) 237973

not just scintillation

According to:
T. Tabarelli de Fatis,
Eur. Phys. J. C, 65, 359 (2010)

in TeO_2 crystals, interacting particles can produce Cherenkov light, having different energy thresholds:

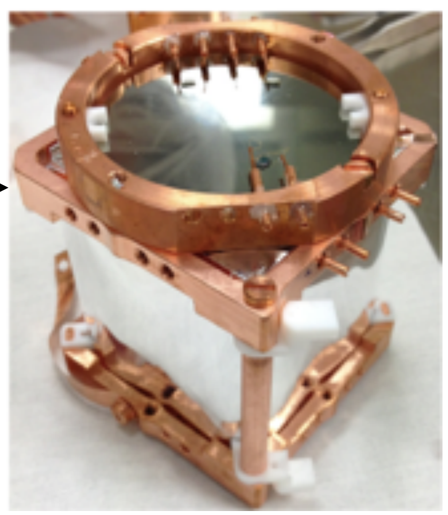
Alpha 400 MeV
Beta 50 keV

→ β/γ tagging with a light detector faced to a TeO_2

Theoretical value 740 eV @ DBD0v

Thermal sensors: NTD
LD: Ge+SiO_2 disk

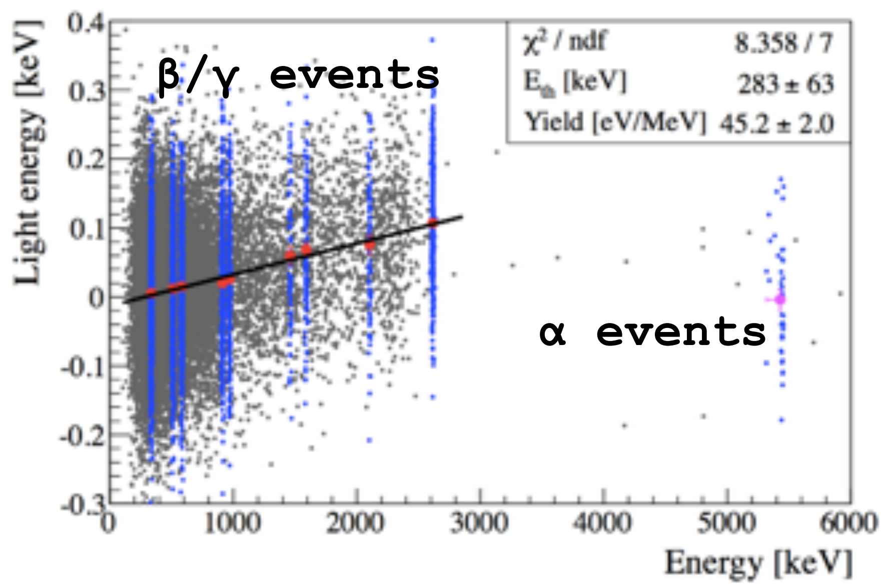
TeO_2 750g



TeO_2 300g

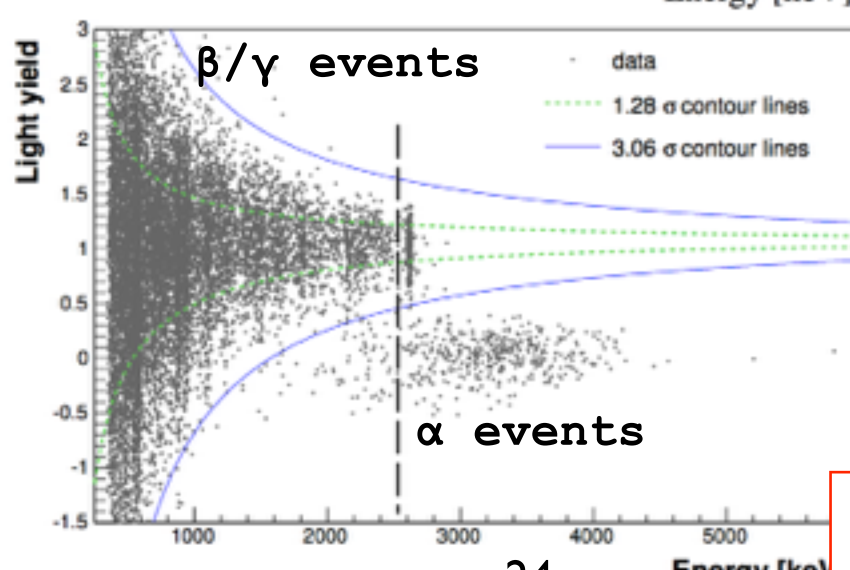
Thermal sensors: TES
LD: Al_2O_3+Si disk

N. Casali *et al.*, ArXiv:1403.5528



LY [eV/MeV] = 45

Light measured
@ 2.6MeV DBD0v:
101 eV
=> low DP



LY [eV/MeV] = ~48

Light measured
@ 2.6MeV DBD0v:
~128 eV
=> large DP

in collaboration with the Max Planck Institute of Munich

soon on ArXiv!

Conclusions

* Scintillating bolometers ensure **excellent** particle **identification** and **energy resolution**
=> they can be the next generation detector for rare process investigations (DBD, DM, rare decays, ...)

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

* ZnSe is a promising compound for DBD, nevertheless a **huge effort** is needed for R&D on **crystal production**

* LUCIFER aims at reaching a background level of **$\leq 10^{-3}$ c/keV/kg/y**

* LUCIFER is a **demonstrator** for next generation ton-scale DBD experiment

ZnSe samples