LUCIFER: Low background Underground Cryogenic Installation For Elusive Rates

Luca Pattavina
INFN-LNGS

April 15th 2014,
LNGS Scientific Committee

OUTLINE

- Double-beta decay signal and sensitivity

- Scintillating bolometer investigation

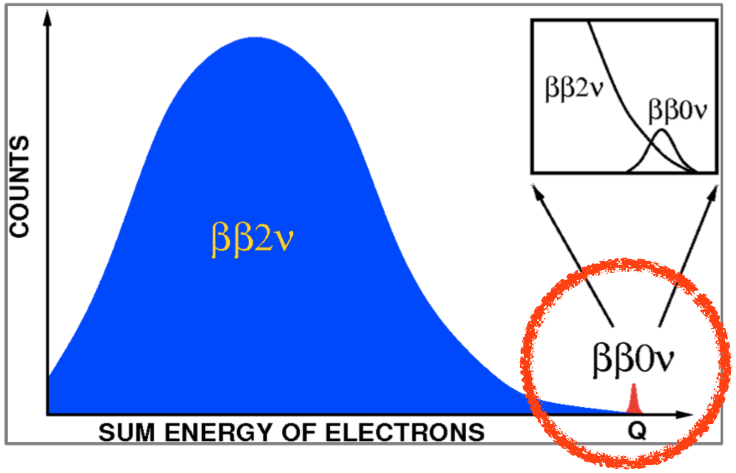
- LUCIFER project:

  - candidate crystals $ZnMoO_4$ & ZnSe
  - detector performance
  - sensitivity

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.



zero-background approximation

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

i.a.: isotopic abundance

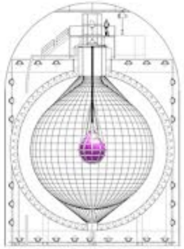
M: detector mass

t: measuring time

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

ε: detection efficiency

ΔE: energy resolution



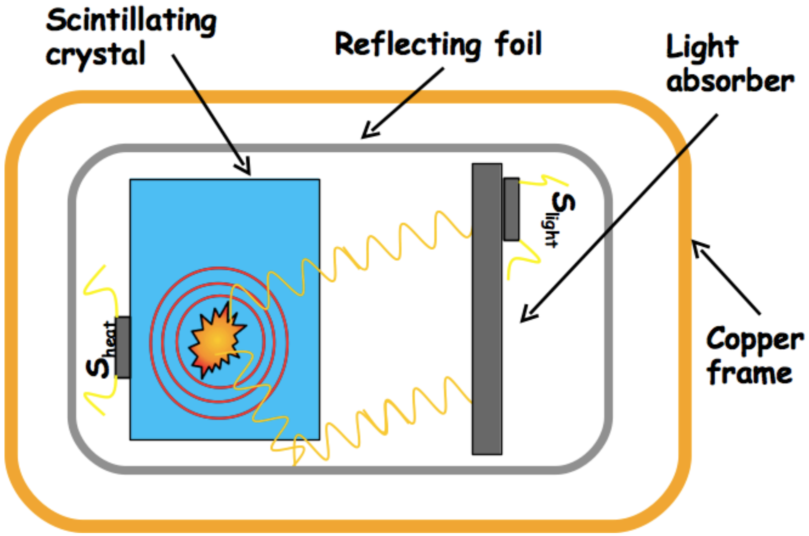
Scintillating bolometers

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.

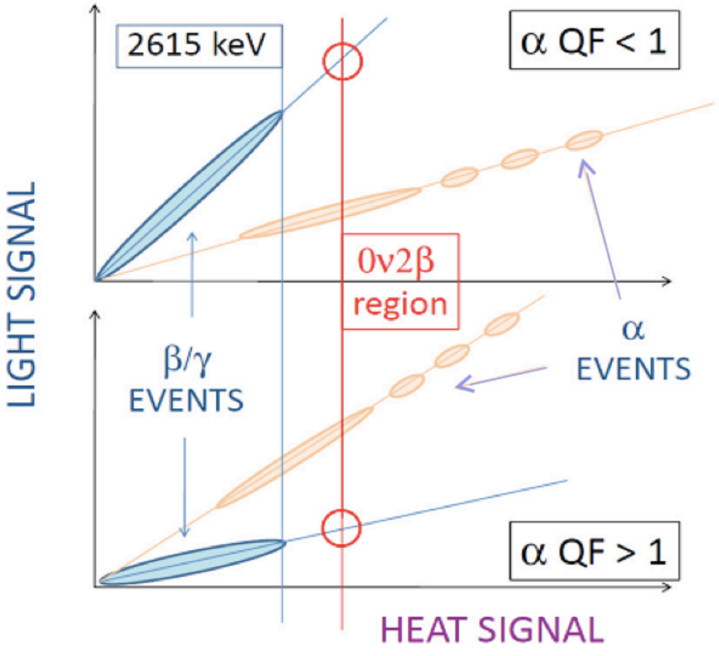
Double signal read-out:

Heat: absorber+thermometer

Light: PM / SiPM / bolometer



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

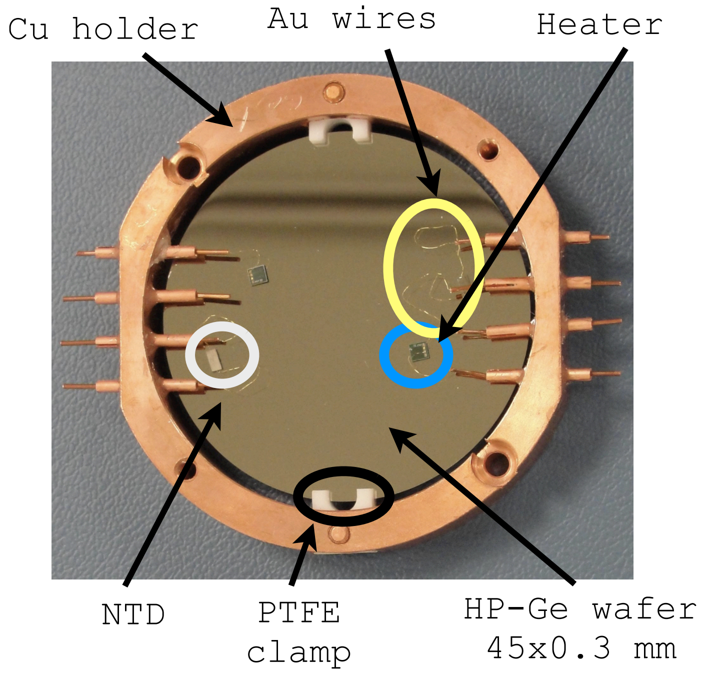


QF: ratio of the light signal amplitudes induced by α and an β/γ particles of the same energy.

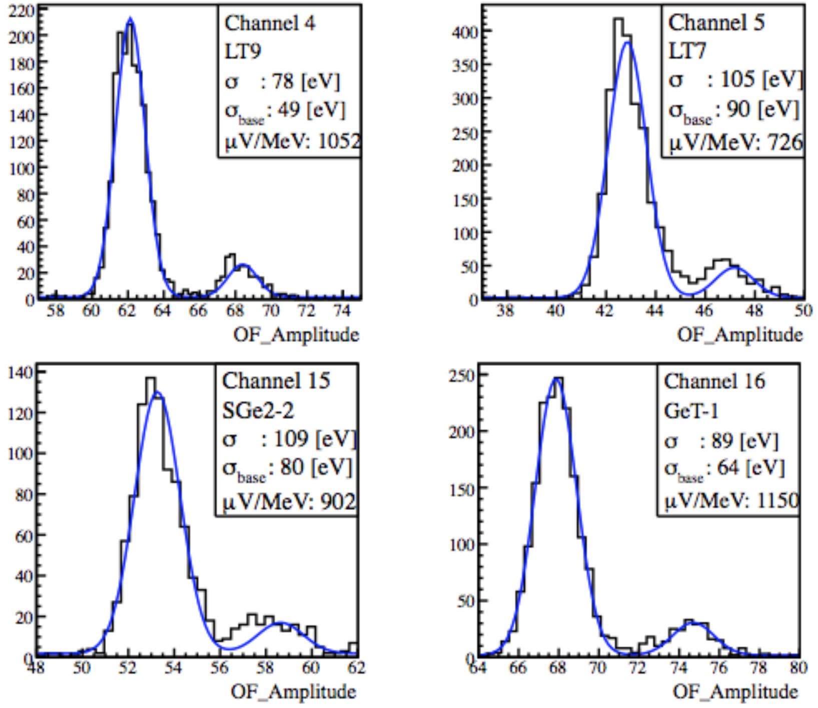
Light detectors (LD)

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

Light detector:	PMT	Bolometer
=> quantum efficiency	✗	✓
=> energy resolution	✗	✓
=> intrinsic radio-purity	✗	✓
=> must work @ low T	✗	✓
=> energy threshold	✓	✗



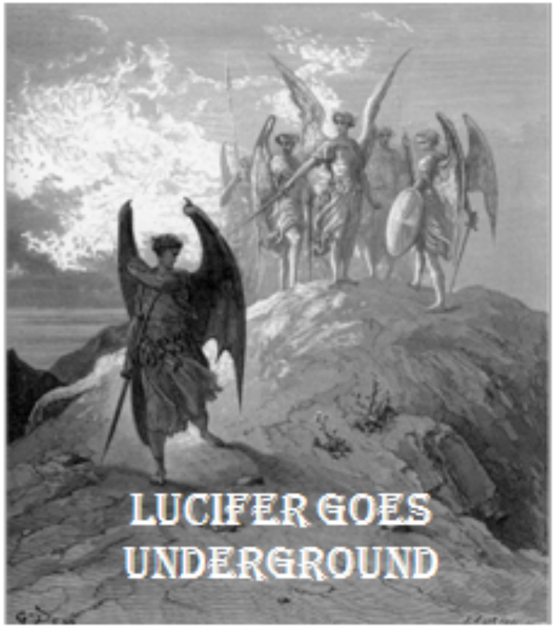
^{55}**Fe X-ray calibration (5.9 keV and 6.5 keV)**



LUCIFER

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

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

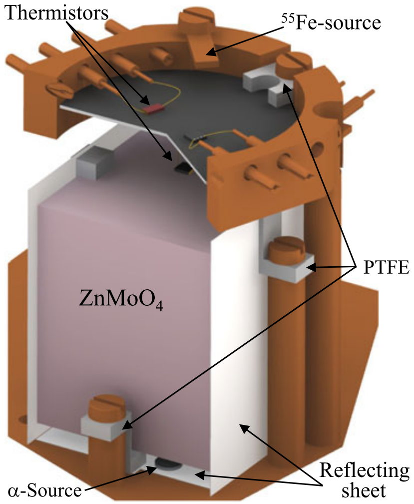


- Demonstrator array of enriched scintillating bolometers
- LUCIFER will search DBD0ν in: $Zn^{82}Se$ / $Zn^{100}MoO_4$ crystals
- Total isotope mass: ~15 kg
- Background index @ ROI ≤ 10^{-3} c/keV/kg/y

	Q-value [keV]	**Useful material**	**$LY_{\beta/\gamma}$ [keV/MeV]**	**QF_α**
ZnSe	2995	56%	6.5	4.2
$ZnMoO_4$	3034	44%	1.5	0.2

$ZnMoO_4$

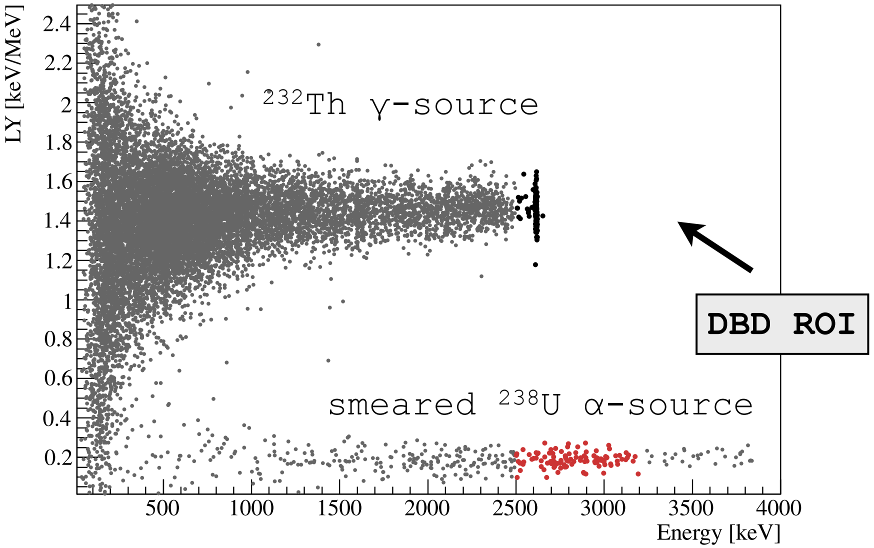
Candidate: ^{100}Mo



m=330 g
Calibrations α & γ
Background 520 h

	Q-value [keV]	**Useful material**	**$LY_{\beta/\gamma}$ [keV/MeV]**	**QF_α**
$ZnMoO_4$	3034	44%	1,5	0,2

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

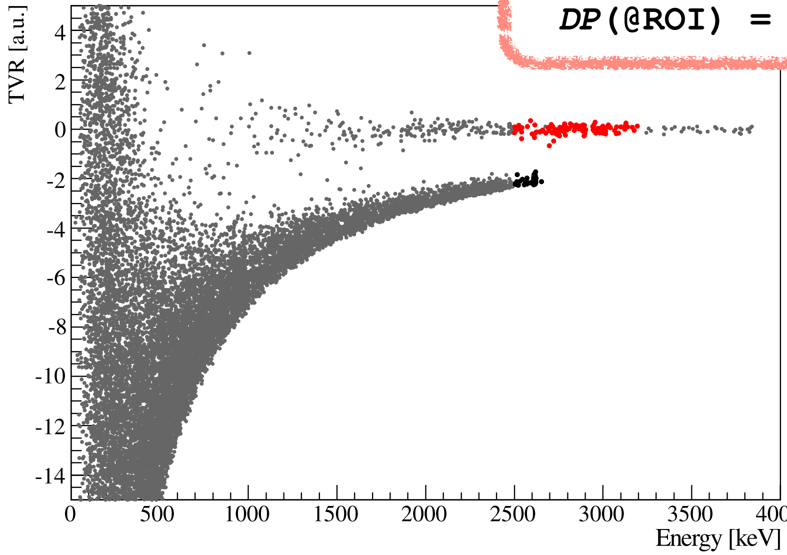


Impressive particle discrimination using **just Heat**

Discrimination potential:

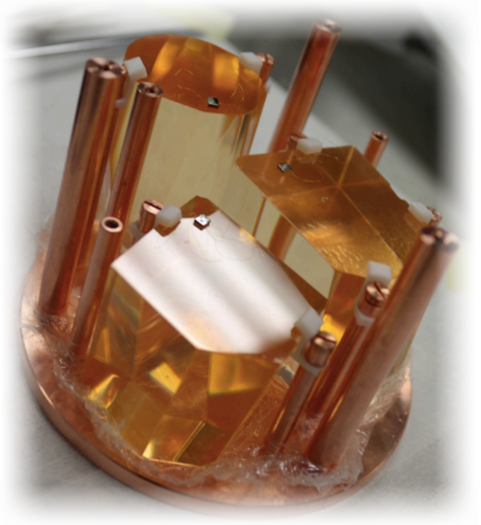
$$DP(E) = \frac{|\mu_\alpha(E) - \mu_{\beta\gamma}(E)|}{\sqrt{\sigma_\alpha^2(E) + \sigma_{\beta\gamma}^2(E)}}$$

***DP*(@ROI) = 20**



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

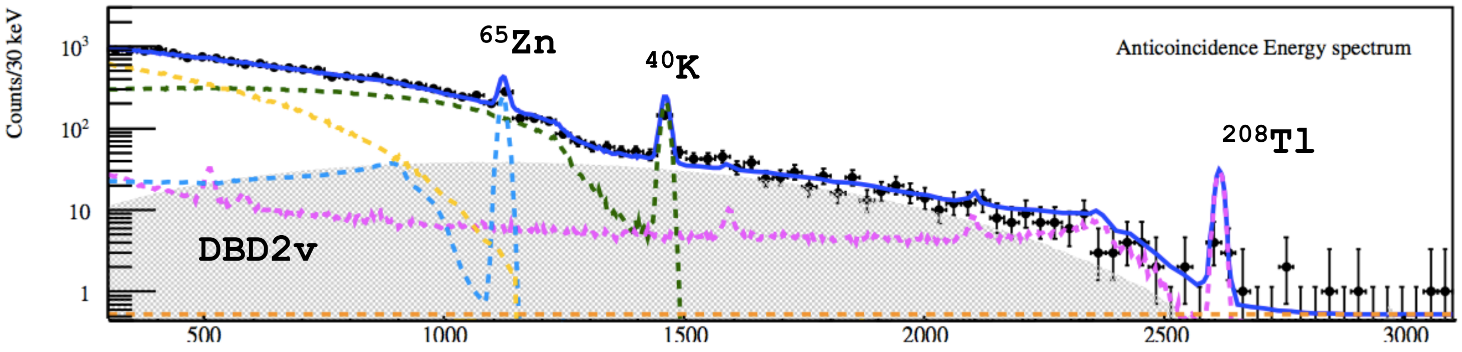
Array of $ZnMoO_4$



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

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

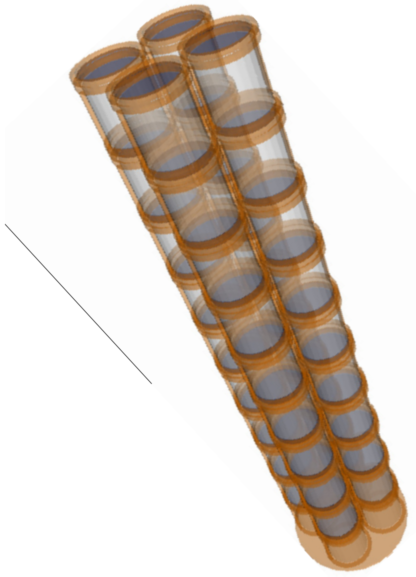
ArXiv:1312.4680



$$T^{DBD2v}_{1/2}=[7.15\pm0.37(stat)\pm0.66(syst)]10^{18}\ y$$

in agreement with NEMO3 measurement:
$T_{1/2}=[7.11\pm0.02(stat)\pm0.54(syst)]10^{18}$ 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)

→

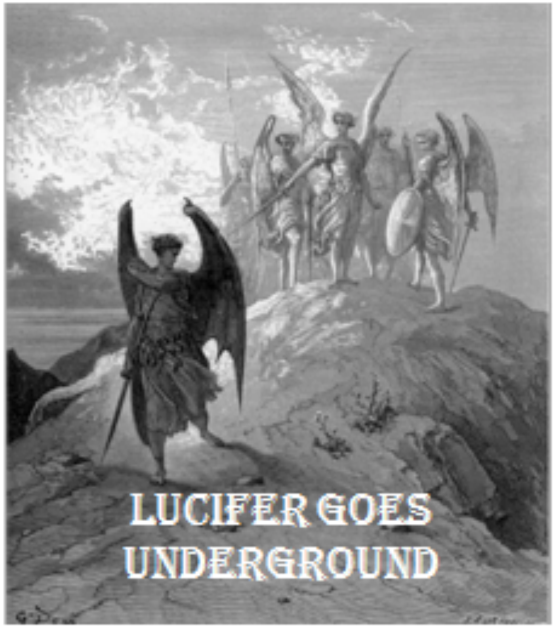
Faster thermal sensors must be developed

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

LUCIFER

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

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



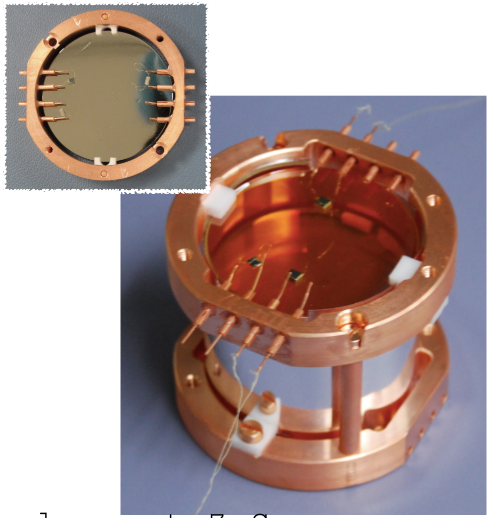
- Demonstrator array of enriched scintillating bolometers
- LUCIFER will search DBD0ν in: $Zn^{82}Se$ / $Zn^{100}MoO_4$ crystals
- Total isotope mass: ~15 kg
- Background index @ ROI ≤ 10^{-3} c/keV/kg/y

	Q-value [keV]	**Useful material**	**$LY_{\beta/\gamma}$ [keV/MeV]**	**QF_α**
ZnSe	2995	56%	6.5	4.2
$ZnMoO_4$	3034	44%	1.5	0.2

back-up solution → $ZnMoO_4$

ZnSe

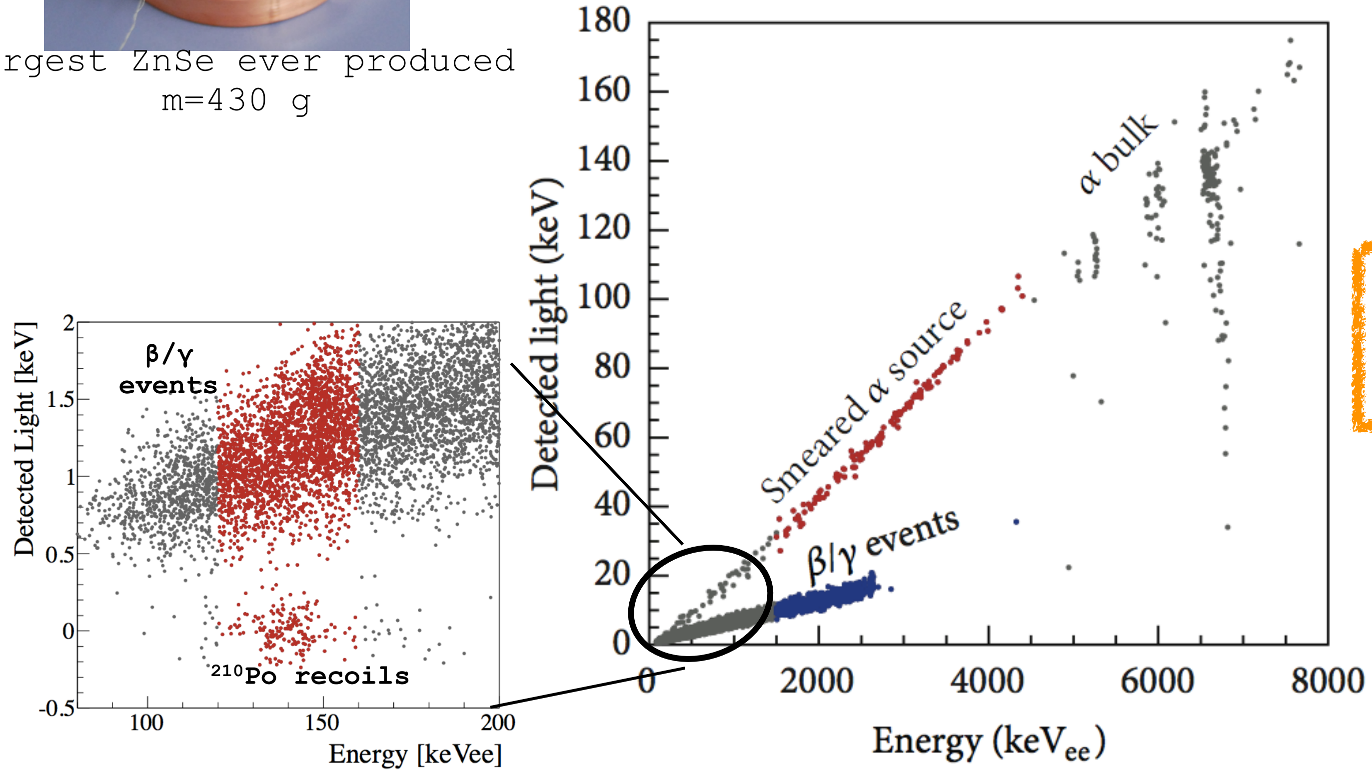
Candidate: ^{82}Se



largest ZnSe ever produced
m=430 g

	Q-value [keV]	**Useful material**	**$LY_{\beta/\gamma}$ [keV/MeV]**	**QF_α**
ZnSe	**2995**	**56%**	**6,4**	**4,2**

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

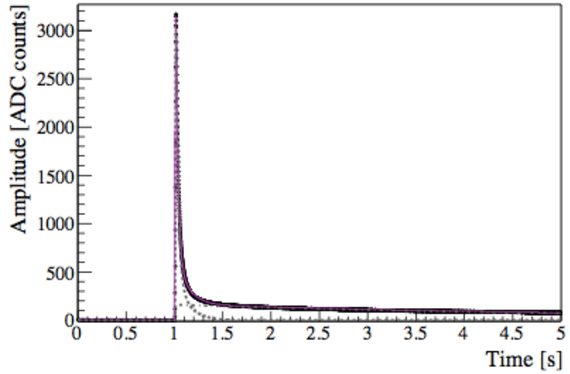


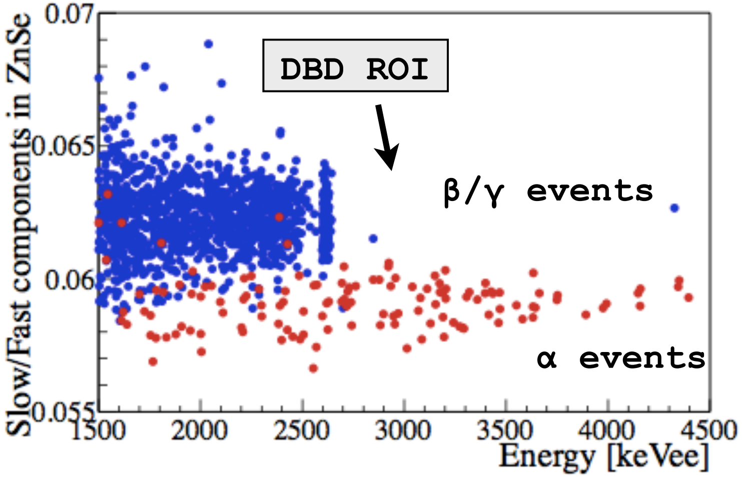
Excellent particle discrimination using **Light vs. Heat**

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

ZnSe Particle discrimination

Heat signal shape



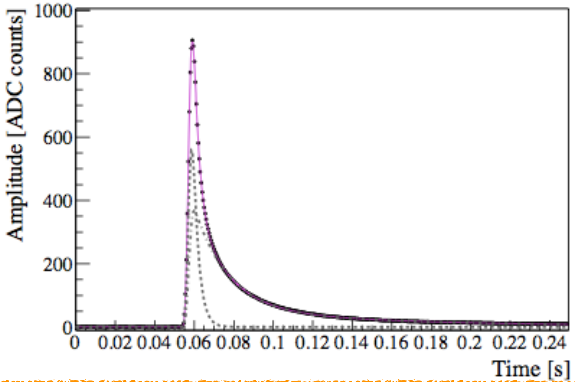


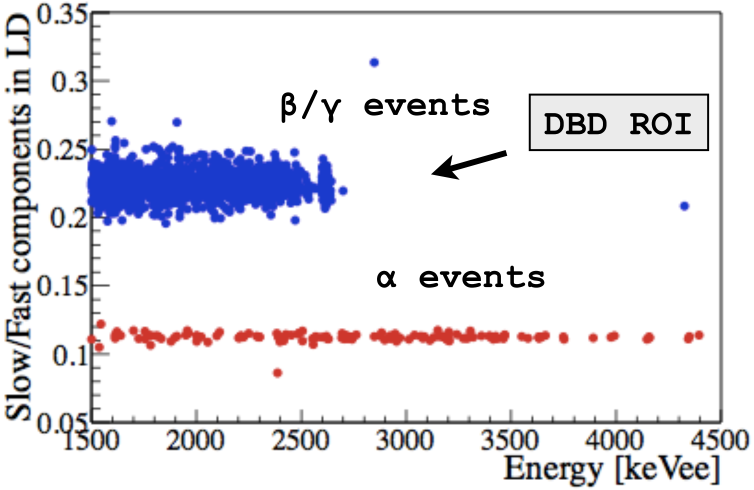
Discrimination potential:

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

***DP* (@ROI) = 2**

Light signal shape





Discrimination potential:

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

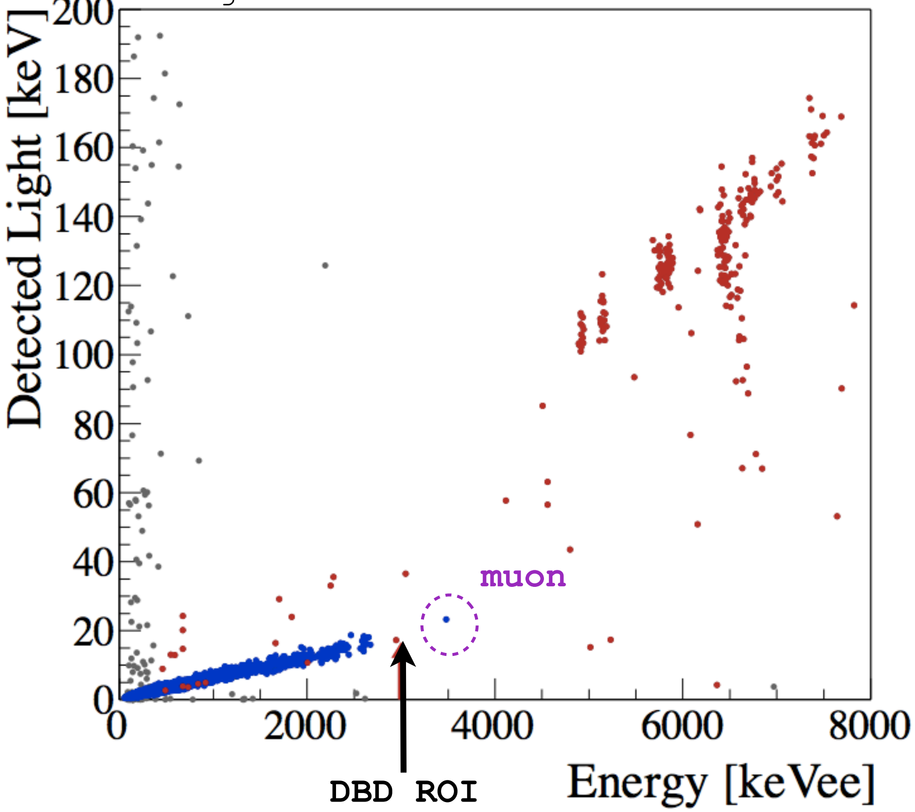
***DP* (@ROI) = 11**

highly performing LD are needed for bkg suppression

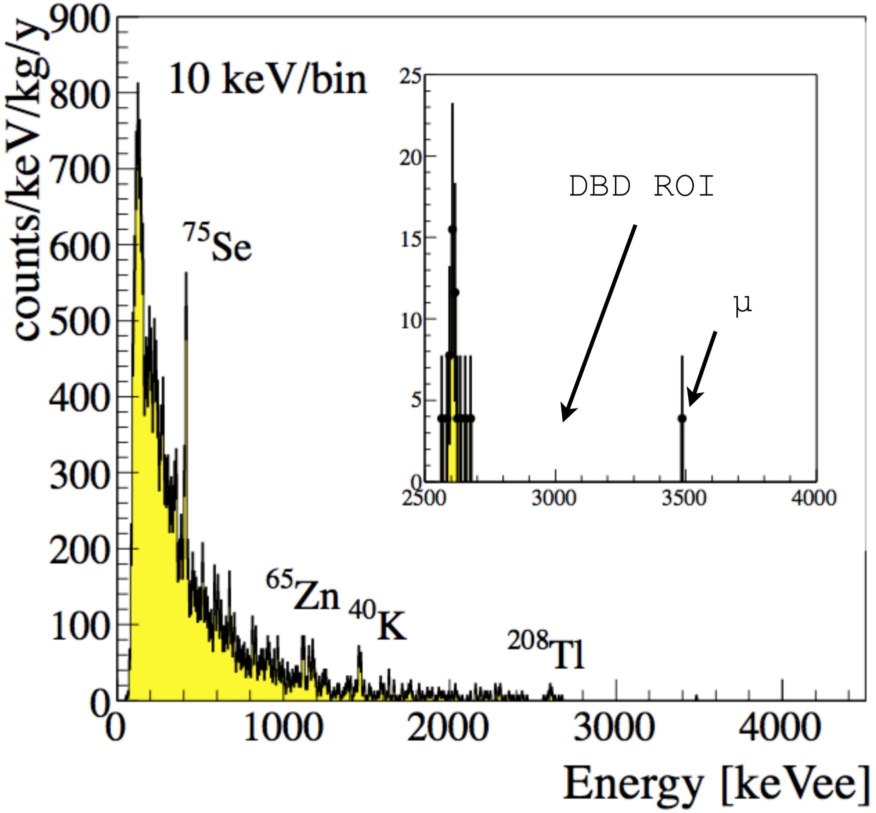
ZnSe background

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 processing

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

already delivered 4 kg @ LNGS

HP-Ge screening

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

^{232}Th:
^{224}Ra < 1.2 E-9 gTh/g
^{228}Th (4.3±0.8) E-10 gTh/g

^{40}K (1.3±0.6) E-7 gK/g

ICPMS screening

element dangerous for scintillation

Na	<	6711	ppb
Cr	<	11	ppb
Fe	<	45	ppb
V	<	22	ppb
S	<	201330	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 Scintillation Materials
(Kharkov, UA):

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

→

ICPMS screening
Natural powder
U < 1 ppb
Th < 1 ppb
K < 1000 ppb
V < 15 ppb
Fe < 50 ppb
Cr < 15 ppb

Criticalities:
- high chemical and radiopurity level

good radiopurity level,
not yet optimized

Crystal growth

ZnSe is a well known compound

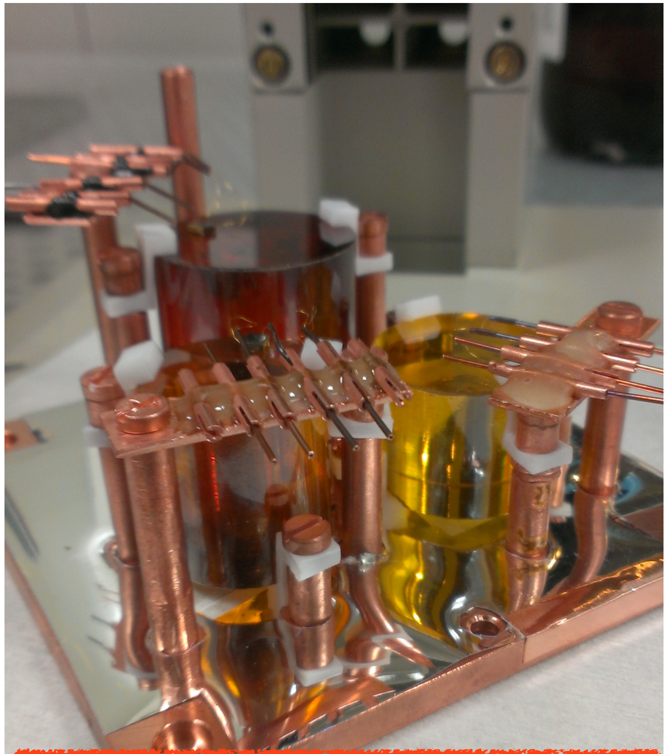
=> extended IR transmission (0.5um-20um)

=> 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



first crystals from controlled powders now under testing

Criticalities:
- production of crystals with good bolometric and scintillating performance
- large mass crystals
- high production yield

Crystal growth

ZnSe is a well known compound

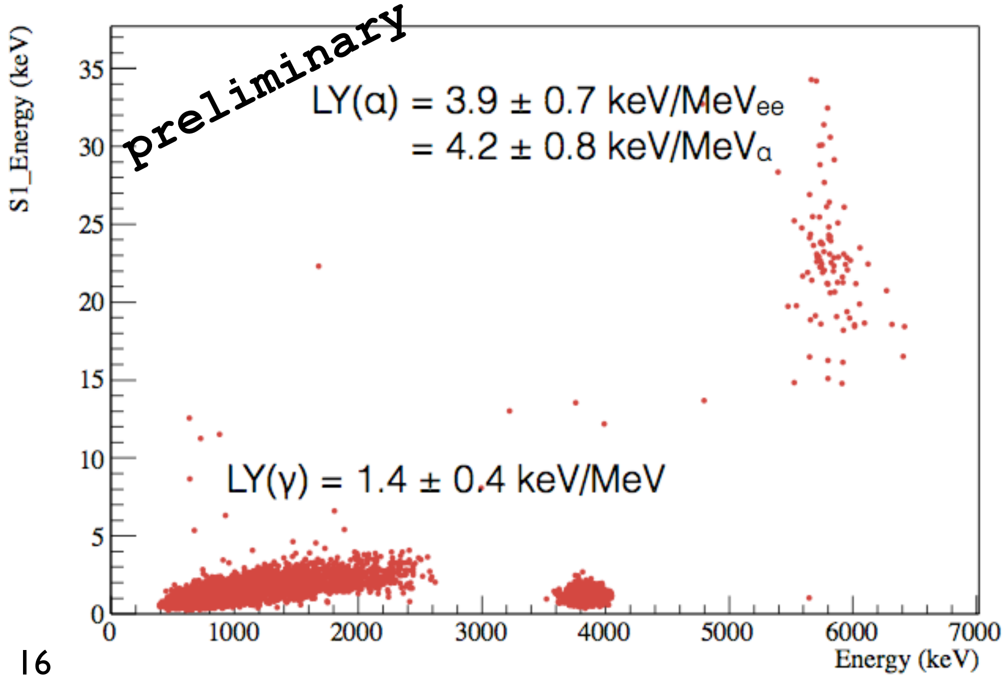
=> extended IR transmission (0.5um-20um)

=> 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



Crystal growth

ZnSe is a well known compound

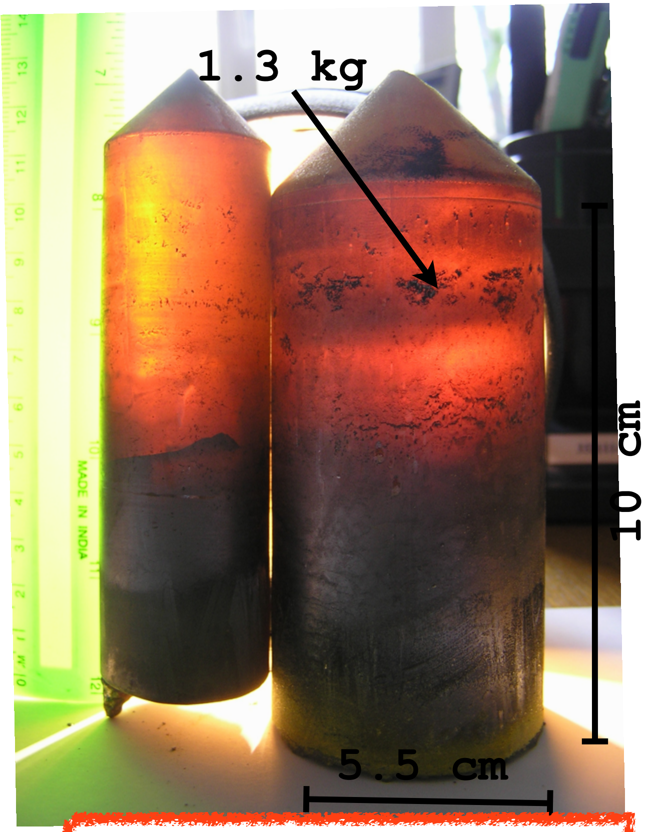
=> extended IR transmission (0.5um-20um)

=> 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

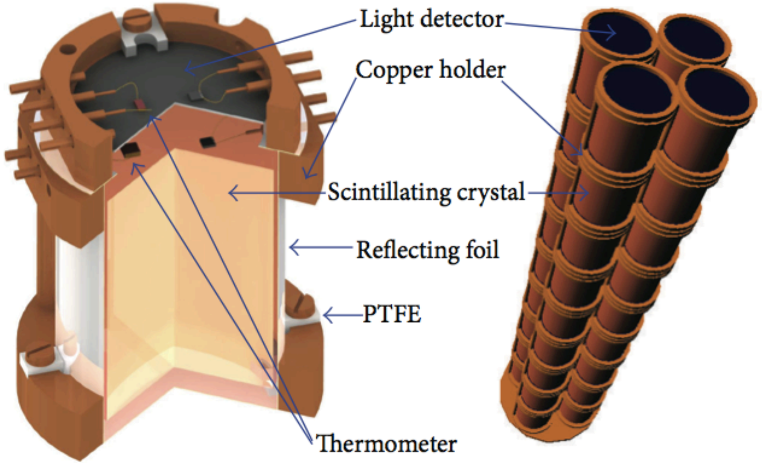


final candidates

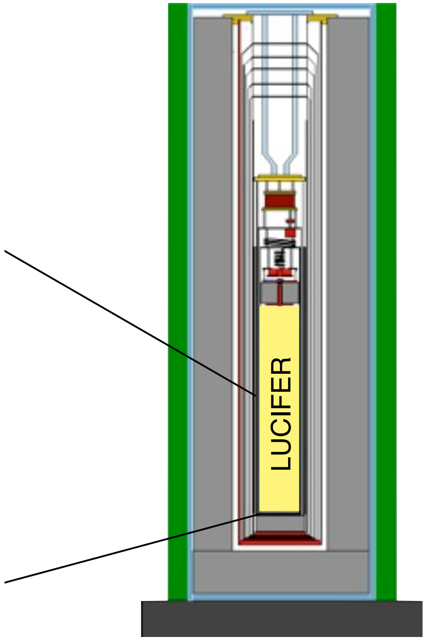
Criticalities:
- production of crystals with good bolometric and scintillating performance
- large mass crystals
- high production yield

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 ^{82}Se (14 kg of ^{100}Mo)
- 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

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

*
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

Conclusions

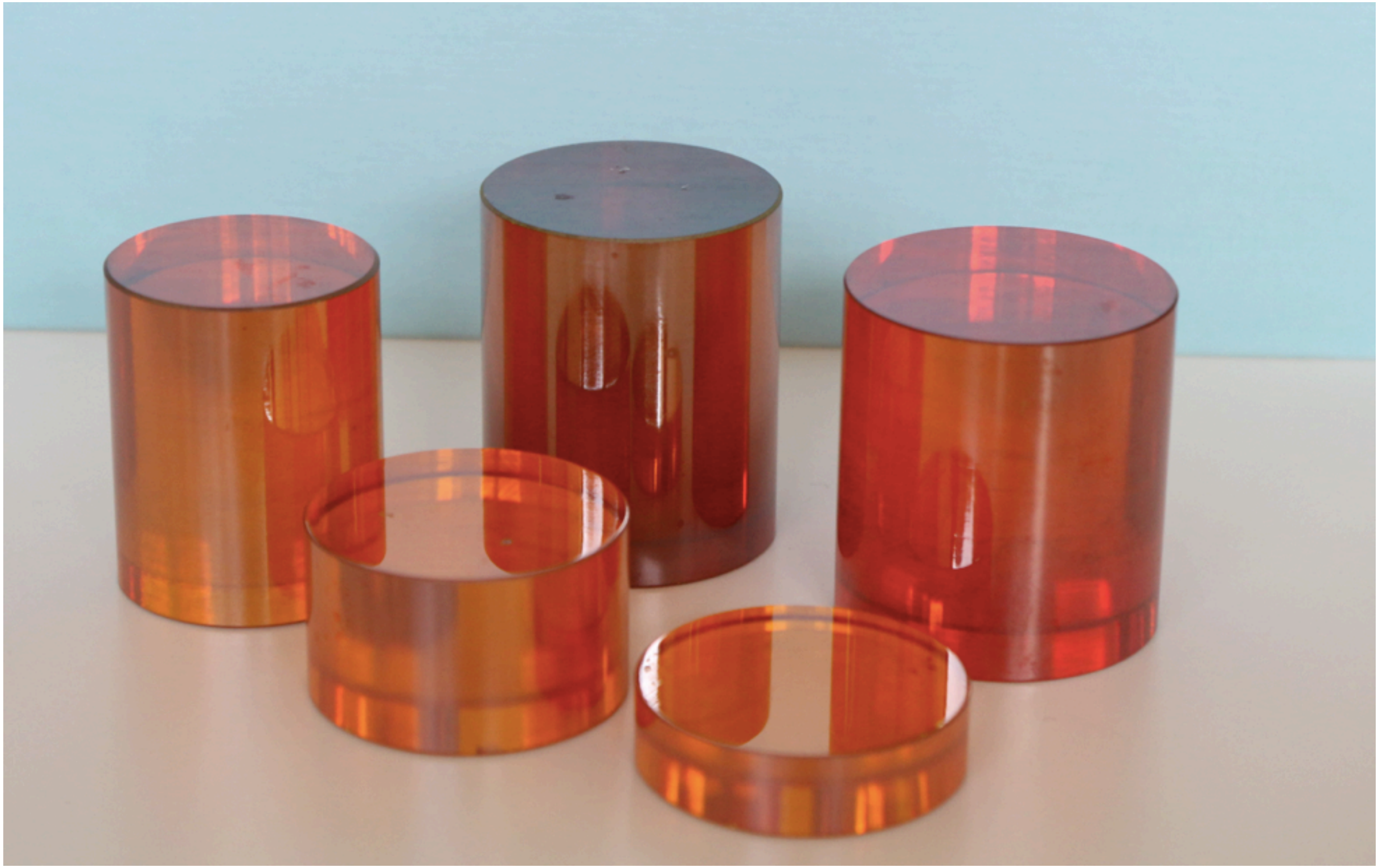
* Scintillating bolometers ensure excellent particle identification and energy resolution
=> they can be the next generation detector for rare process investigations (DBD, DM, rare decays, ...)

* Scintillation light is not the only channel for particle discrimination
=> PSA on 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 having a background level of ~10^{-3} c/keV/kg/y

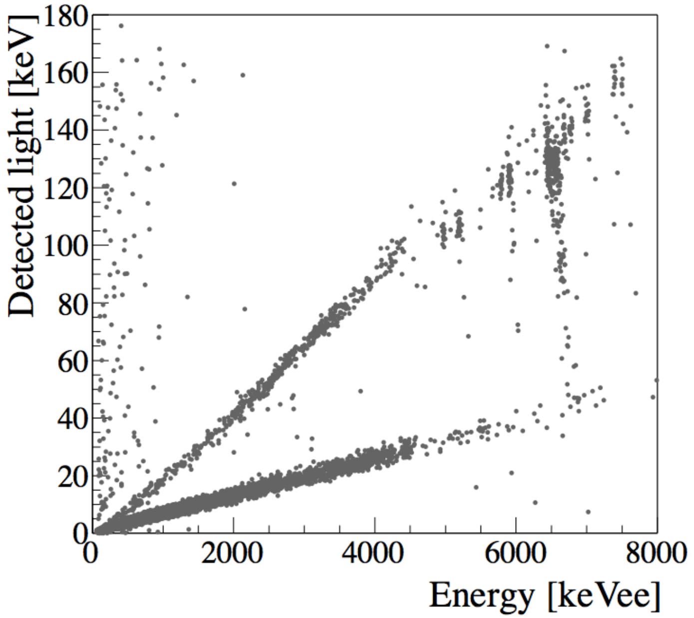
* LUCIFER will start in 2015



ZnSe α discrimination

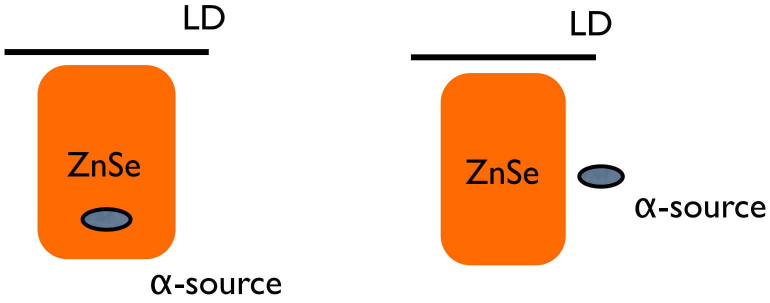
discrimination
surface αs - bulk αs

$$LY_{\alpha}^{bulk} = 26.6 \pm 0.9$$
$$LY_{\alpha}^{smeared} = 29.7 \pm 0.2$$



- Energy-dependence?

No: $LY^{bulk}(E_{\alpha}) < LY^{external}(E_{\alpha})$



- Self-absorption?

No: $LY^{lateral}(E_{\alpha}) = LY^{bottom}(E_{\alpha})$