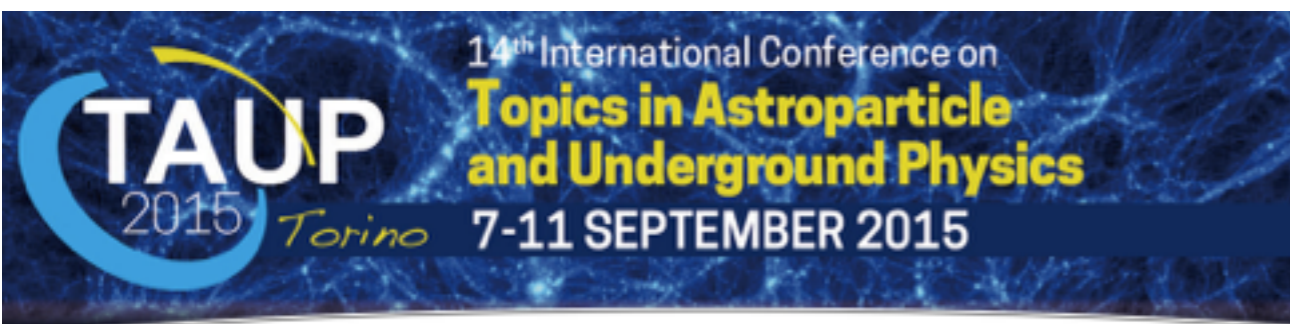


Scintillating bolometers for the LUCIFER project



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Outline

- Scintillating bolometers
 - basics
 - potential
- The LUCIFER R&D activity:
 - ^{100}Mo $0\nu\beta\beta$ in $\text{Zn}^{100}\text{MoO}_4$ & ^{82}Se $0\nu\beta\beta$ in Zn^{82}Se
 - characterization
 - projected sensitivity
- Conclusions

Scintillating bolometers

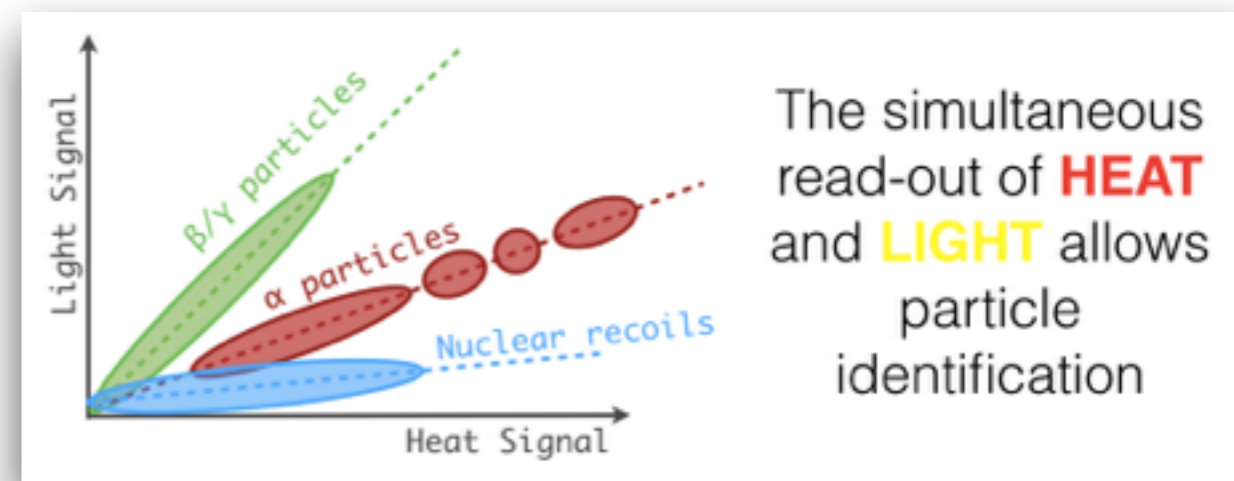
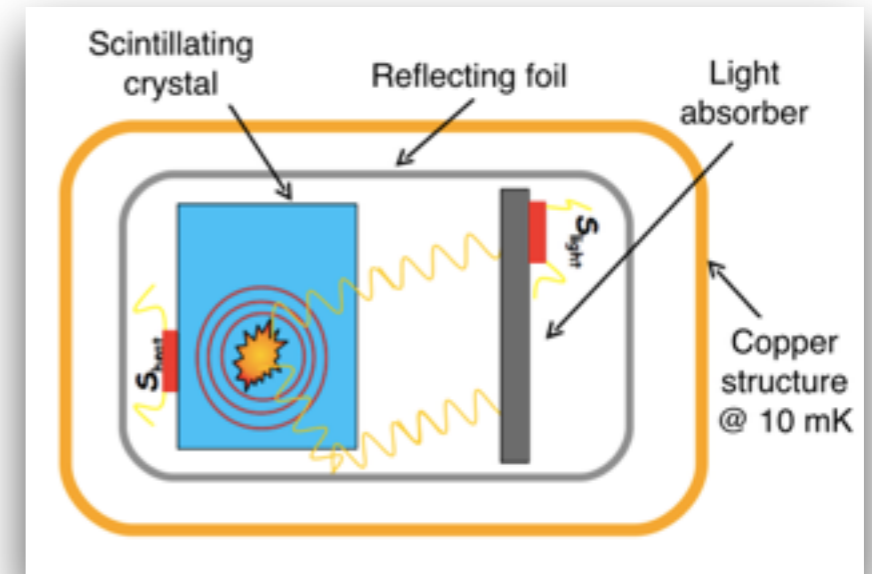
A bolometer is a highly sensitive **calorimeter** operated @ cryogenic temperature (~ 10 mK).

Energy deposits are measured as **temperature** variations of the absorber.

- Bolometer features:

- ▶ high energy resolution $O(1/1000)$
- ▶ wide choice of compound TeO_2 , ZnMoO_4 , ZnSe
- ▶ high detection efficiency (source = detector)
- ▶ scalable to large masses
- ▶ **particle ID**

If the absorber is also an **efficient scintillator** the energy is converted into **heat + light**



A **background-free experiment** is possible:

α -background: identification and rejection

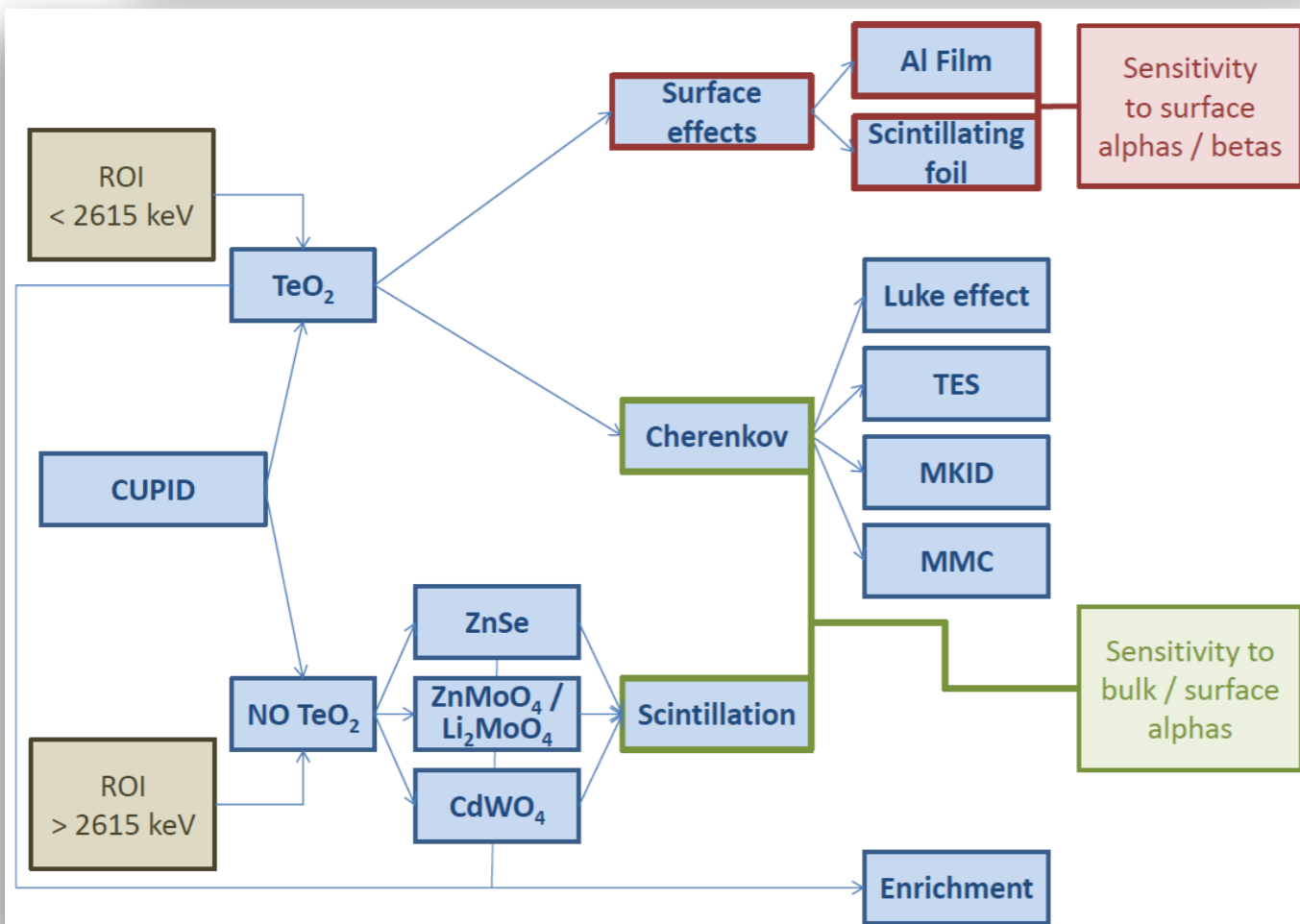
β -background: $\beta\beta$ isotope with large Q-value

CUPID

Cuore Upgrade with Particle ID

III. SCIENTIFIC OBJECTIVE

CUPID is a proposed bolometric $0\nu\beta\beta$ experiment which aims at a sensitivity to the effective Majorana neutrino mass on the order of 10 meV, covering entirely the so-called inverted hierarchy region of the neutrino mass pattern. CUPID will be designed in such a way that, if the neutrino is a Majorana particle with an effective mass in or above the inverted hierarchy region ($\sim 15 - 50$ meV), then CUPID will observe $0\nu\beta\beta$ with a sufficiently high confidence (significance of at least 3σ). This level of sensitivity corresponds to a $0\nu\beta\beta$ lifetime of $10^{27} - 10^{28}$ 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, and the background must be close to zero at the ton \times year exposure scale in the ROI of a few keV around $0\nu\beta\beta$ transition energy. <http://arxiv.org/abs/1504.03599>



Five steps beyond the present technology are required:

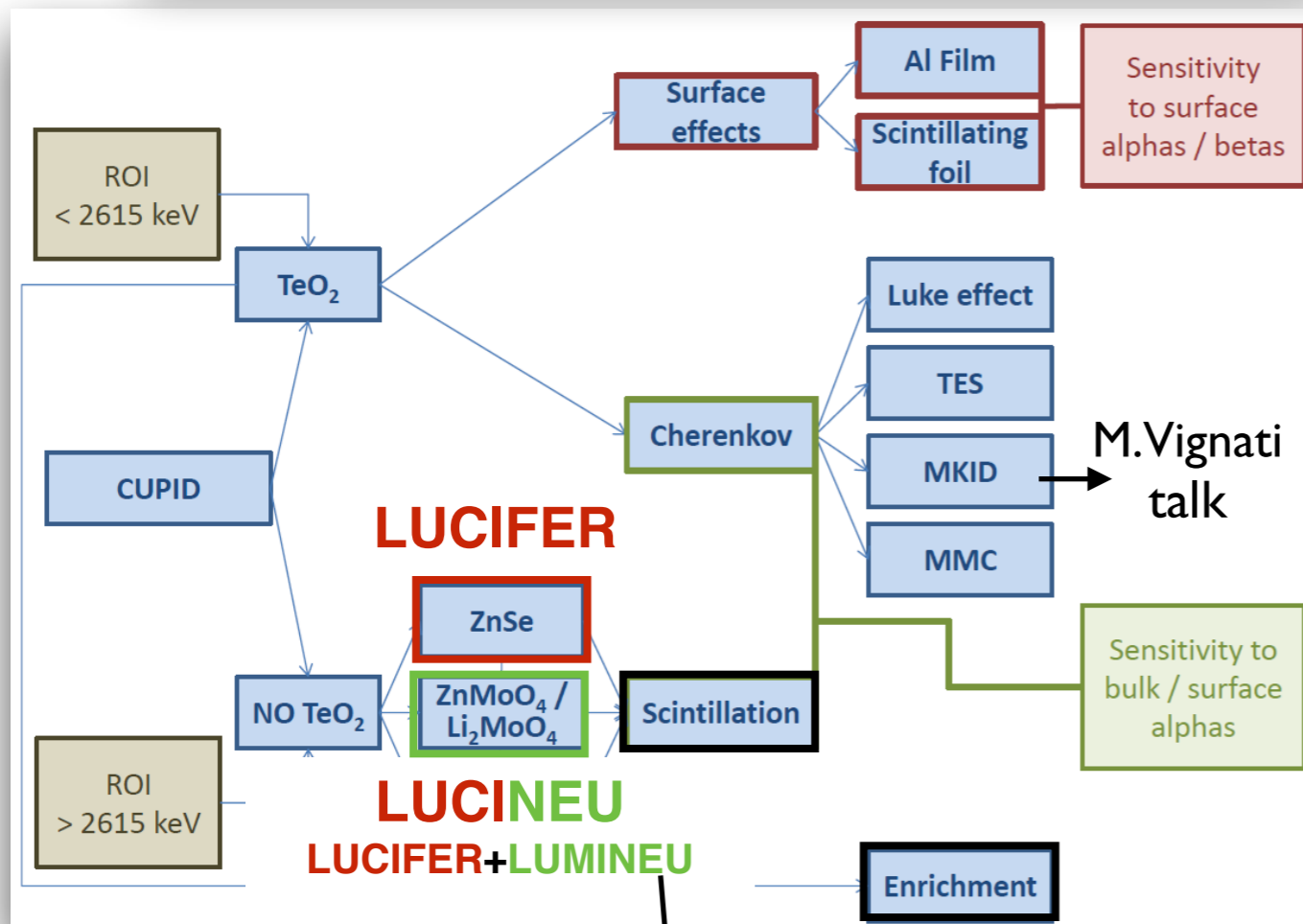
- Isotopic enrichment
- Active alpha rejection
- Improved material selection
- Better energy resolution
- Reduced cosmo-activation

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See F.Danevich poster

Five steps beyond the present technology are required:

- Isotopic enrichment
- Active alpha rejection
- Improved material selection
- Better energy resolution
- Reduced cosmo-activation

LUCIFER = CUPID-0 demonstrator for Zn⁸²Se (and Li/Zn¹⁰⁰MoO₄)

LUCIFER demonstrator

Low-background Underground Cryogenics Installation For Elusive Rates

Laboratori Nazionali
del Gran Sasso
INFN, Italy



- LUCIFER is funded by a ERC Advanced Grant (3.3M€) for 6 years, March 2010 - March 2016
- R&D on enriched scintillating bolometers
- LUCIFER investigates $0\nu\beta\beta$ of ^{82}Se (^{100}Mo) in Zn^{82}Se ($\text{Li}_2^{100}\text{MoO}_4/\text{Zn}^{100}\text{MoO}_4$) crystals
- Total isotope mass: ~ 15 kg
- Background index @ ROI $\leq 10^{-3}$ c/keV/kg/y

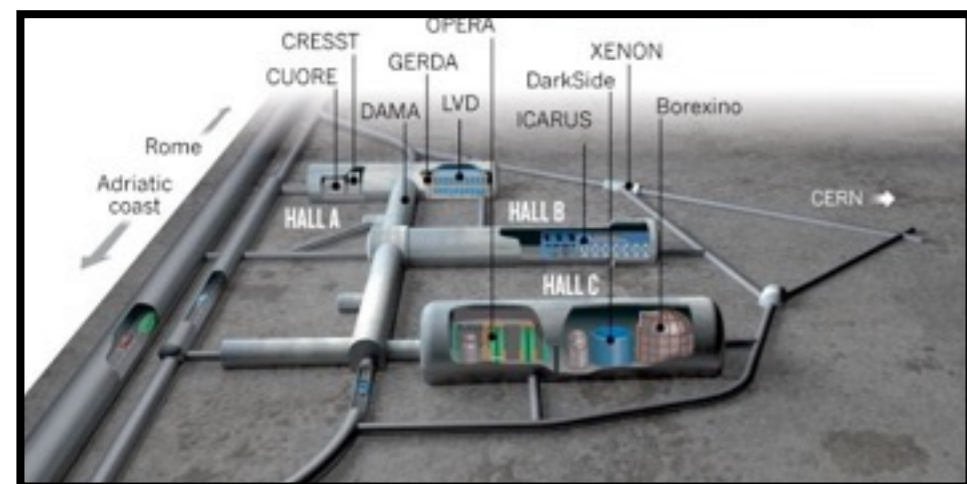
baseline compound
this talk

	Q-value [keV]
ZnSe	2997
$\text{Li}_2\text{MoO}_4/\text{ZnMoO}_4$	3034

See publications

J. Instrum. 8 (2013) P10002.
Astropart.Phys. 72 (2015) 38-45

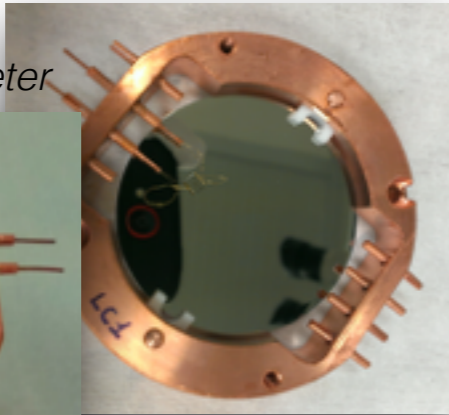
Q-value above most of β/γ
natural radioactivity



Bolometric Light Detector

ZnSe Scintillating bolometer

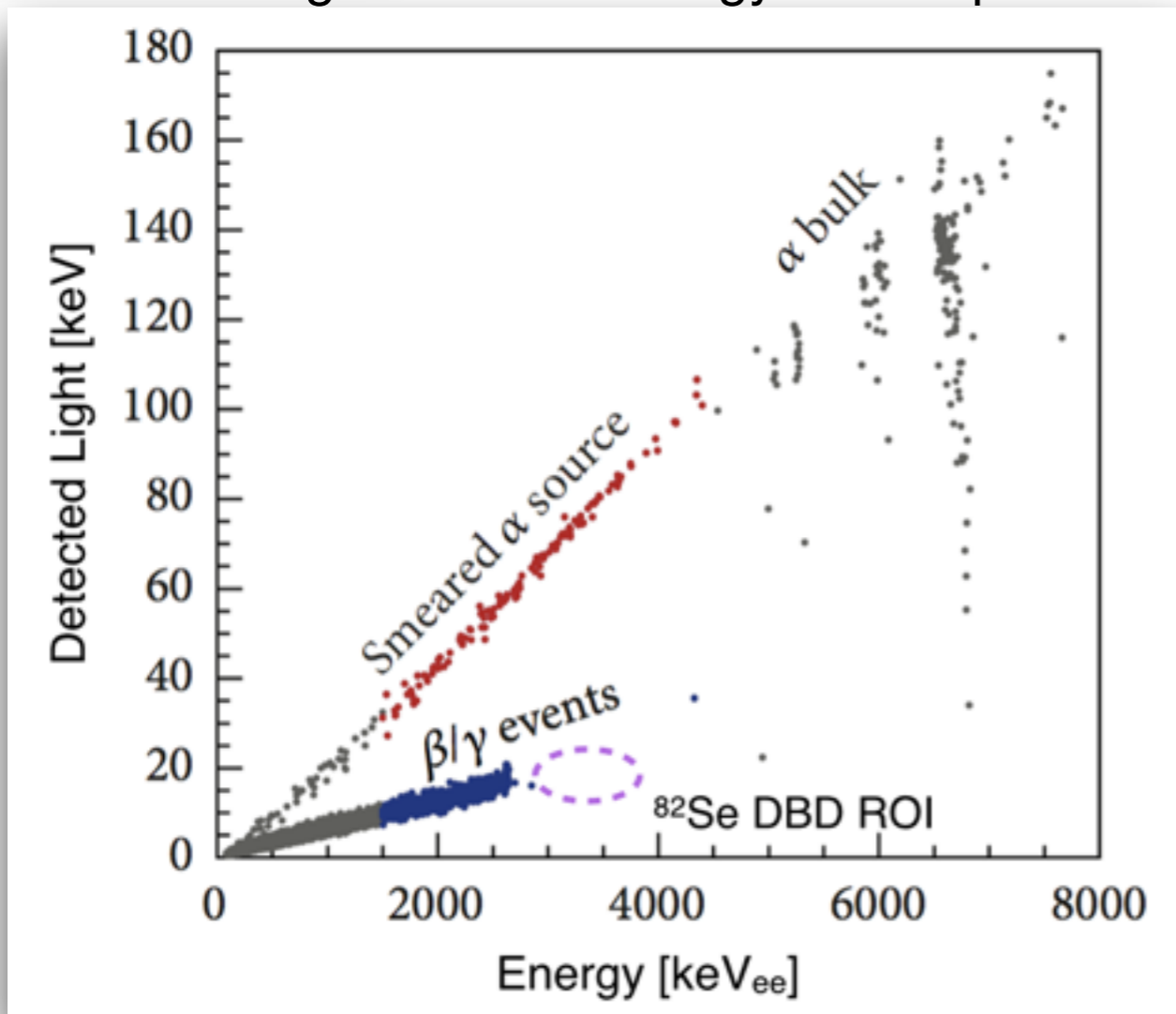
Zn^{nat}Se



430 g crystal

	Q-value [keV]	LY _{β/γ} [keV/MeV]	QF _α
ZnSe	2997	6.4	>1

ZnSe light VS heat energy scatter plot



Inverse Quenching Factor for α particles!

QF >1

Might be a problem for the bkg in the ROI

→ Leaking events in the ROI

- Large LY
- Excellent particle discrimination

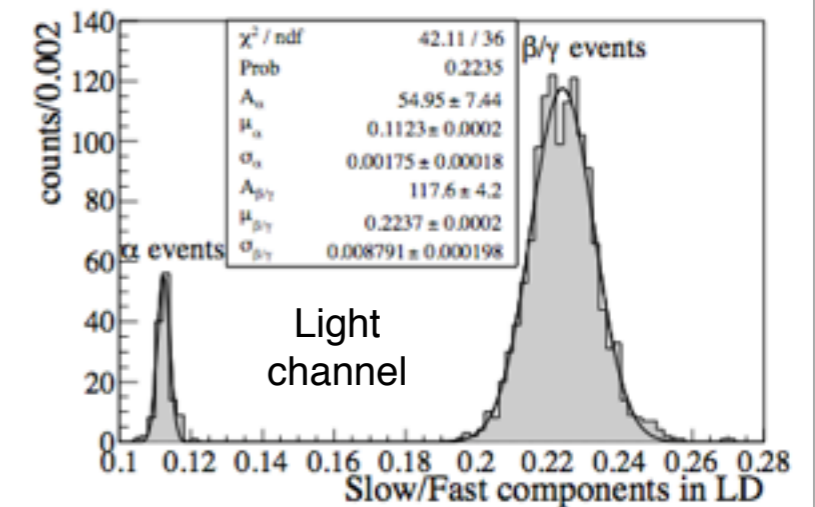
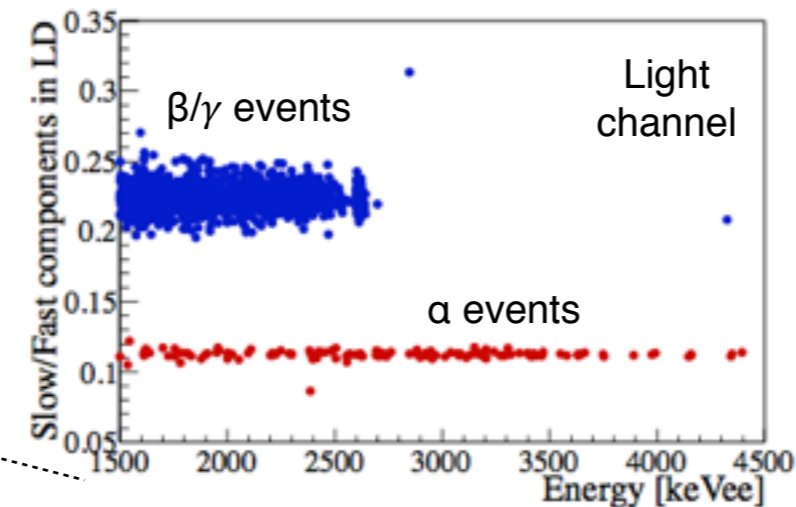
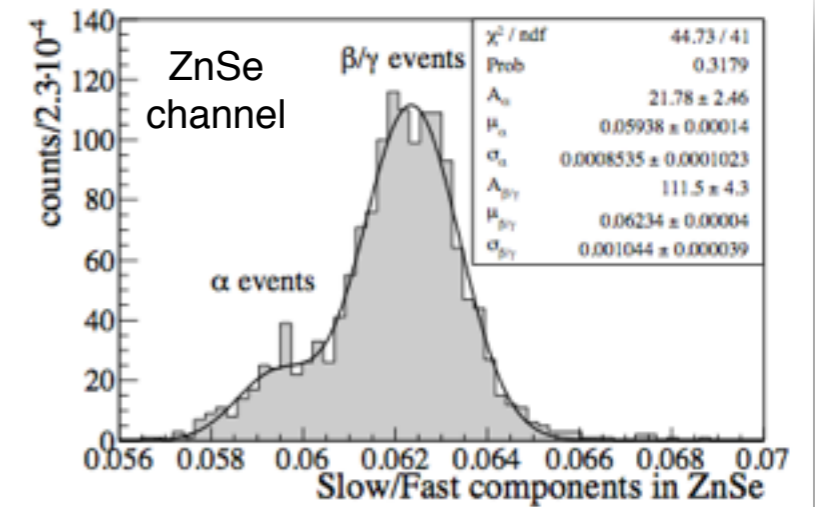
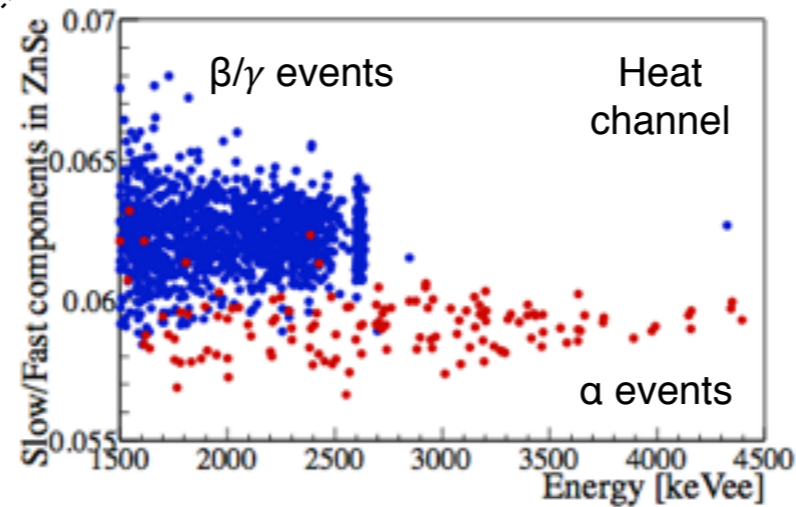
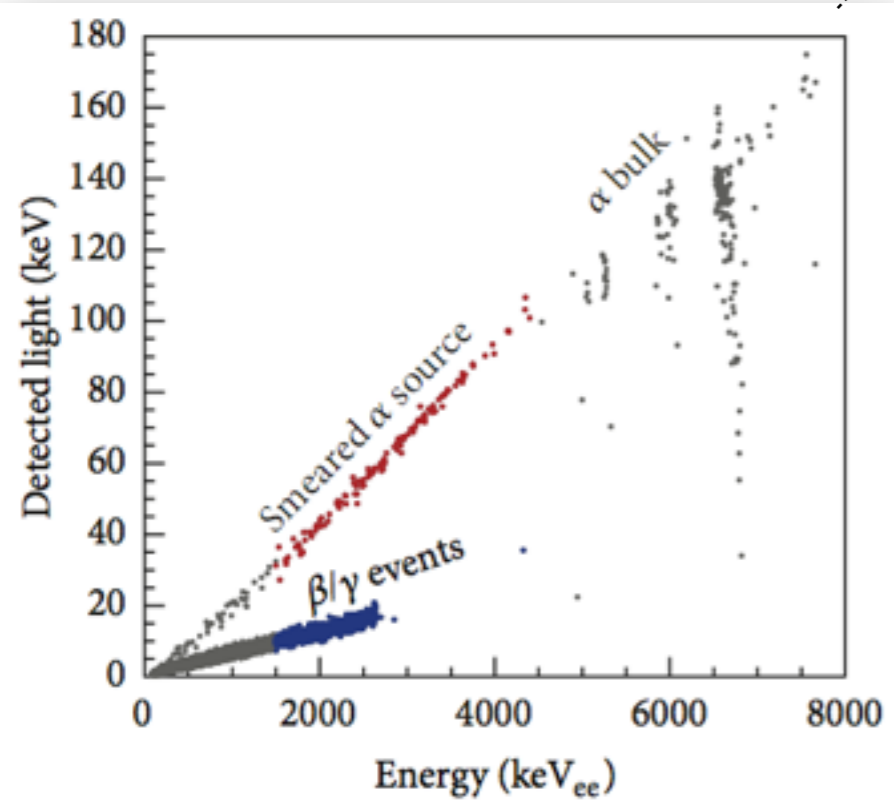
$$LY_{\alpha} = 27-30 \text{ keV/MeV}$$

$$LY_{\beta/\gamma} = 6.4 \text{ keV/MeV}$$

ZnSe

Particle identification using Pulse Shape Parameters (decay time)

Calibration Light VS Heat scatter plot of a ZnSe crystal



Discrimination potential @ ROI:

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

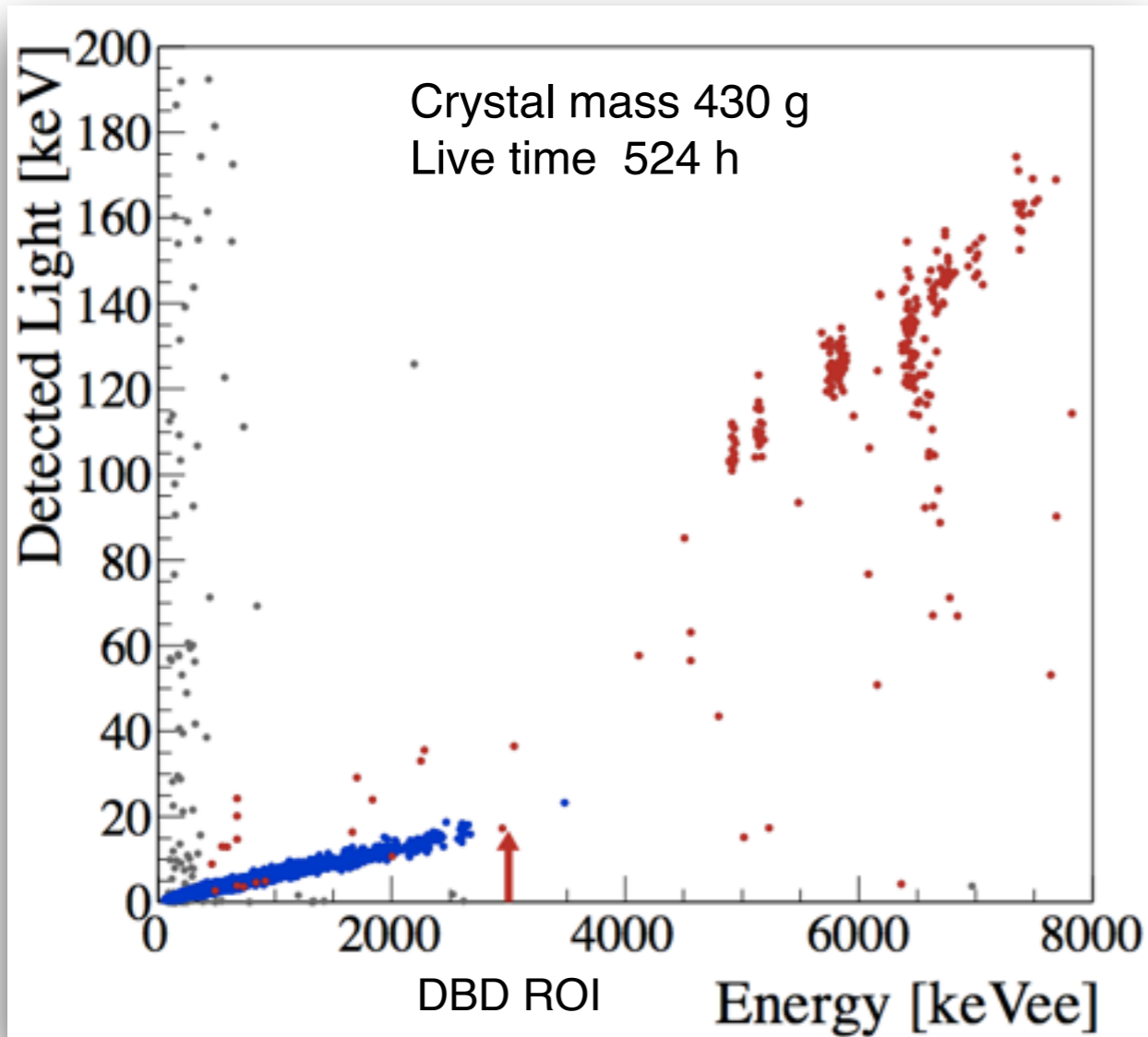
Heat channel
DP@ROI = 2

Light channel
DP@ROI = 11

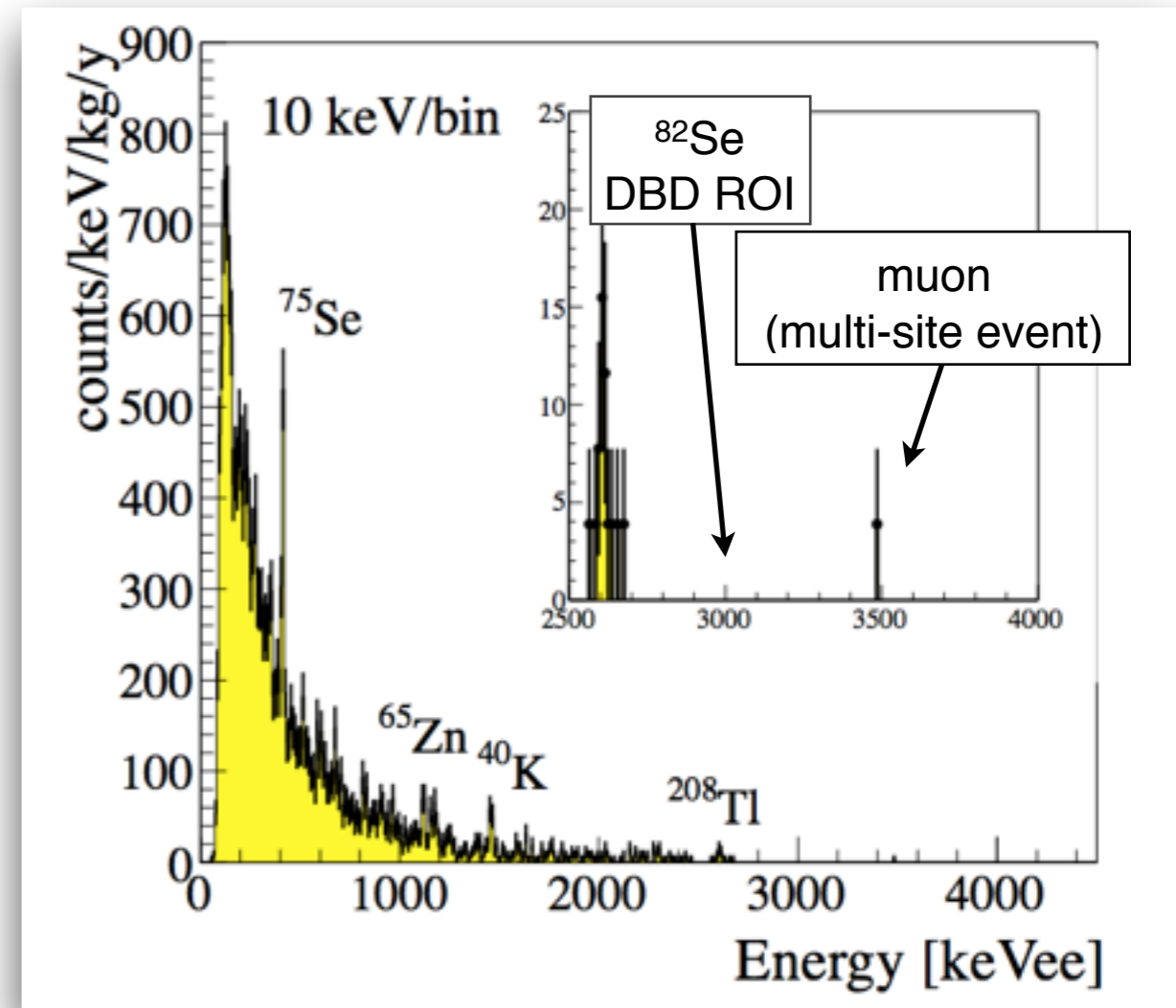
**Full rejection of alpha events
shapeHEAT+shapeLIGHT+light**

ZnSe background

Low Background measurement



β/γ events selection



- Cosmogenic activation ^{75}Se and ^{65}Zn
- Natural radioactivity: ^{40}K , ^{232}Th & ^{238}U
- No β/γ events in the ROI!!

running 1 crystal for 0.06 y:
BI $\sim 10^{-2}$ c/keV/kg/y

10^{-3} c/keV/kg/y seems to be achievable with a large mass array

Zn⁸²Se crystal production

3 main STEPS

1. Procurement of high-purity zinc metal and enriched ⁸²Se metal
2. Synthesis of metal zinc and selenium to form Zn⁸²Se powder
3. Growth of Zn⁸²Se crystals

**They are key for the final crystal quality
→ background & energy resolution**

Zinc



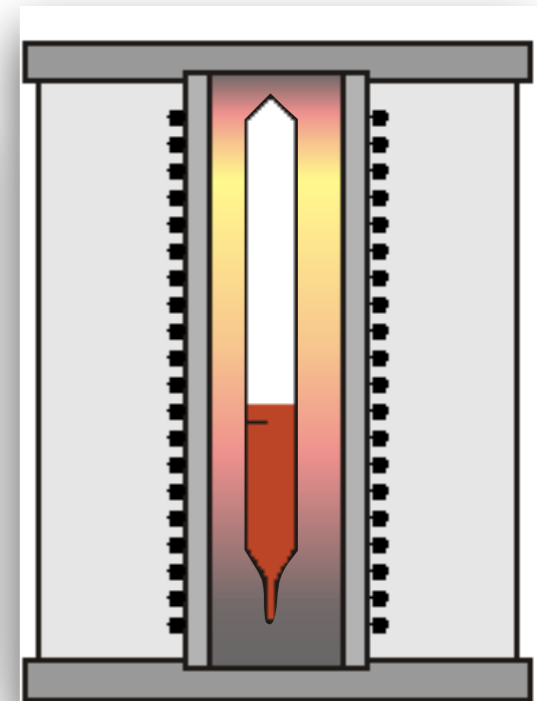
Enriched ⁸²Se



Synthesised ZnSe



Growth

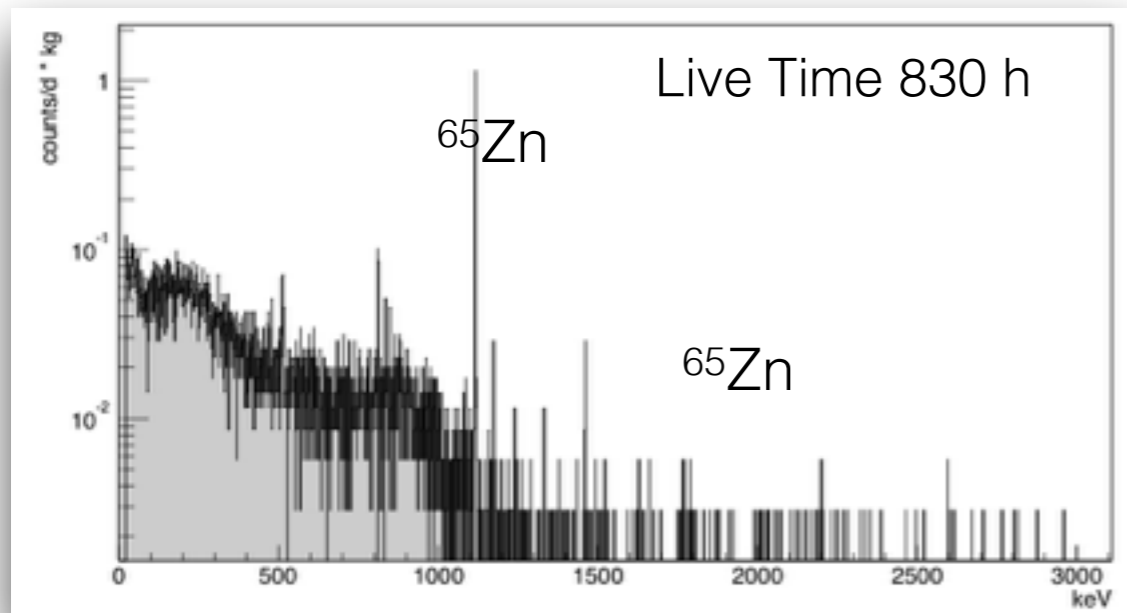


Starting materials: HP-zinc

Producer:
National Science Center KITP (Ukraine)

Internal radioactive and chemical contaminations measured @ LNGS

Energy spectrum of 10 kg of zinc on a HP-Ge detector



^{238}U and ^{232}Th contaminations are below the detector sensitivity. No lines over 1 month of measurement

with HP-Ge GeMPI4

Chain	Nuclide	Activity [$\mu\text{Bq/kg}$]
^{232}Th	^{228}Ra	< 95
	^{228}Th	< 36
^{238}U	^{226}Ra	< 66
	^{234}Th	< 6200
	$^{234\text{m}}\text{Pa}$	< 4700
^{235}U	^{235}U	< 91
	^{40}K	< 380
	^{60}Co	< 36
	^{65}Zn	5200 ± 600
	^{56}Co	80 ± 20
	^{57}Co	200 ± 90
	^{58}Co	220 ± 40
	^{54}Mn	110 ± 20

Limits @ 90%CL

with ICP-MS

Cd	< 2.3 ppm
others	< 0.2 ppm

Not dangerous for bkg
low Q-value
and/or short half-life

^{56}Co :
 β^- Q:4566 keV
but $T_{1/2}=77$ days

@ 25 OCT 2014

Starting materials: ^{82}Se

Internal radioactive and chemical contaminations measured @ LNGS

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

Natural SeF_6

centrifuge cascade (dedicated line)

chemical conversion: SeF_6 gas to ^{82}Se metal

^{82}Se metal:

→ @ 95% enrichment

→ @ 99.5% chemical purity

with HP-Ge GeMPI4

Limits @ 90%CL

Chain	Nuclide	Activity [$\mu\text{Bq/kg}$]
^{232}Th	^{228}Ra	< 61
	^{228}Th	< 110
^{238}U	^{226}Ra	< 110
	^{234}Th	< 6200
	$^{234\text{m}}\text{Pa}$	< 3400
^{235}U	^{235}U	< 74
^{40}K	^{40}K	< 990
^{60}Co	^{60}Co	< 65
^{75}Se	^{75}Se	110 ± 40

@ 8 OCT 2014

with ICP-MS

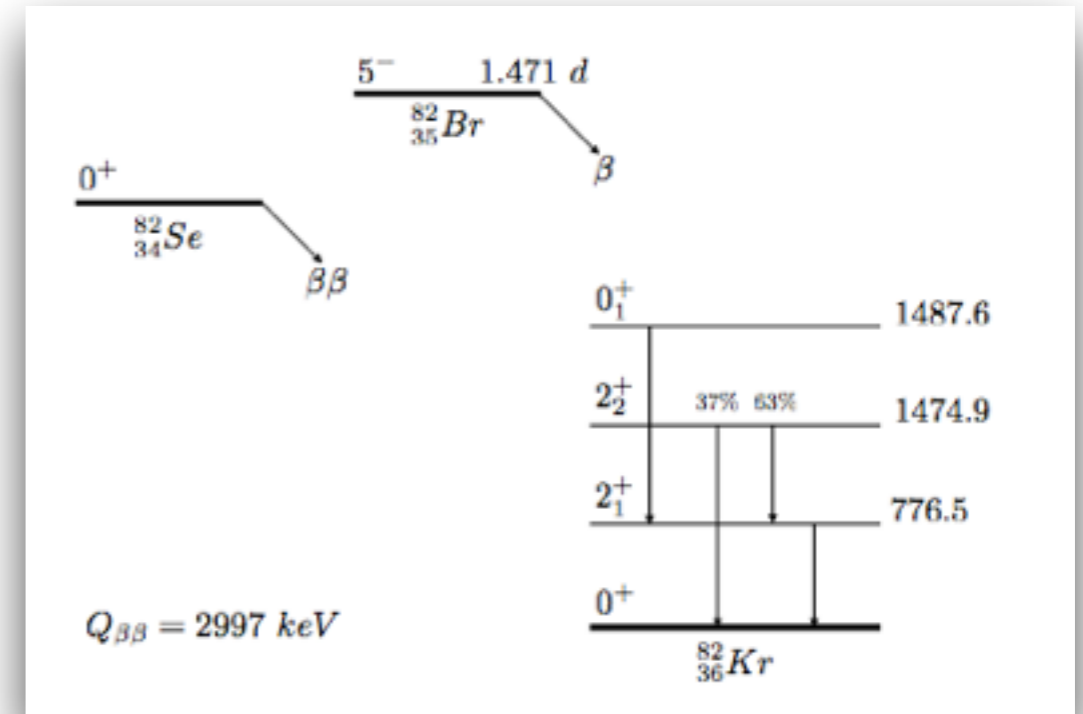
S 130÷250 ppm
others <0.5 ppm

Selenium isotopic abundance

	^{74}Se	^{76}Se	^{77}Se	^{78}Se	^{80}Se	^{82}Se
Nat. Se [%]	0.87	9.36	7.63	23.78	49.61	8.73
Enr. Se [%]	<0.01	<0.01	<0.01	<0.01	3.67 ± 0.14	96.33 ± 0.31

^{82}Se $\beta\beta$ on excited levels

The high purity of ^{82}Se metal and the HP-Ge low-background detector gave opportunity for $\beta\beta$ investigation on excited levels of daughter nuclei of ^{82}Kr

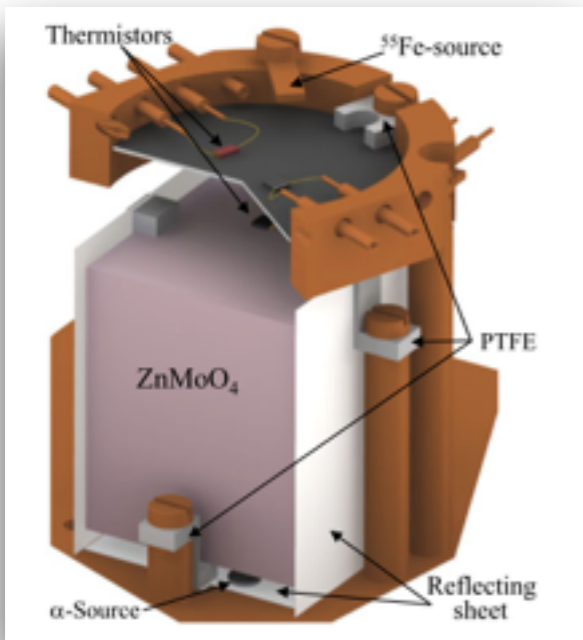


J.W. Beeman et al., ArXiv:1508.01709

Transition	Decay channel	Level of daughter nucleus	E_γ [keV]	Experimental limit $T_{1/2}$ [y] @ 90% C.L.	
				^{82}Se	Previous results
$^{82}\text{Se} \rightarrow ^{82}\text{Kr}$	$(0\nu+2\nu)\beta\beta^-$	2_1^+	776	1.0×10^{22}	2.8×10^{21} [1]
		2_2^+	1475	1.3×10^{22}	1.6×10^{21} [2]
		0_1^+	1488	3.4×10^{22}	3.0×10^{21} [2]

ZnMoO₄ at a glance

Crystal bought *off the shelf*
(no optimization in crystal growth or radiopurity)



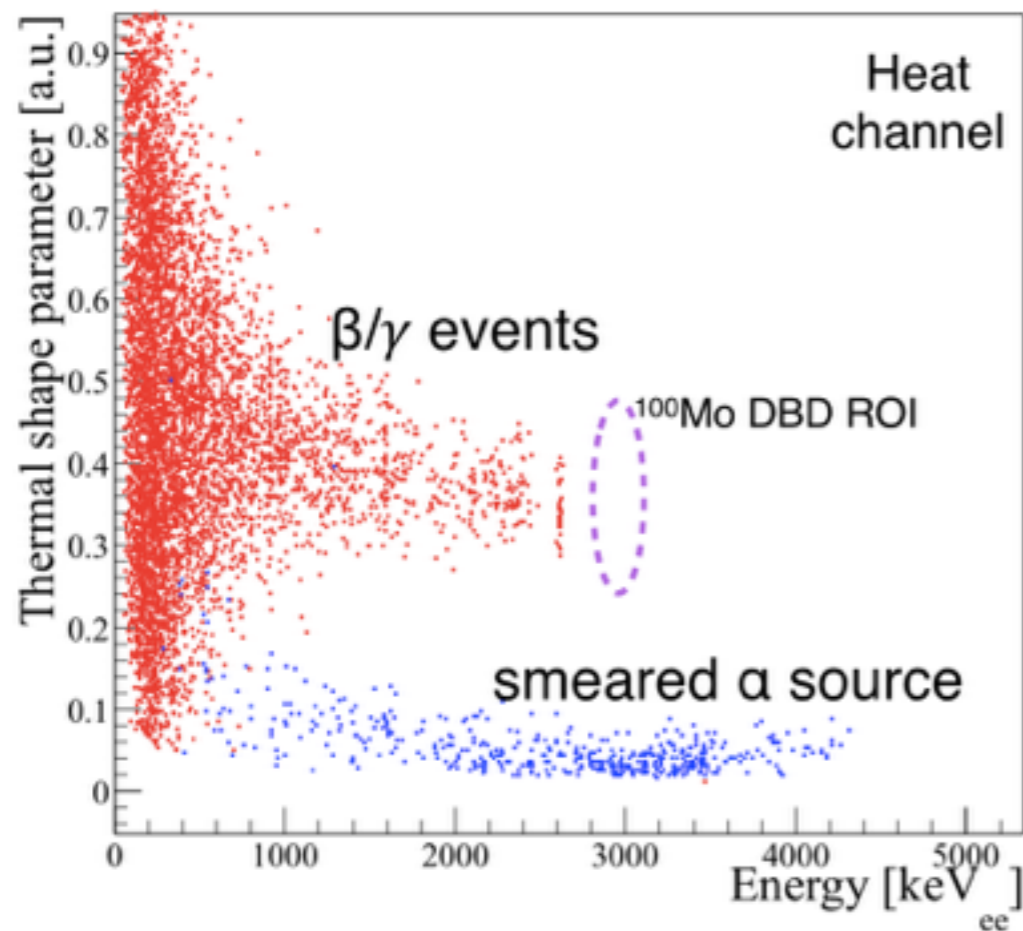
Excellent energy resolution

FWHM @ 2615 keV: 6.3 keV
FWHM @ 1460 keV: 4.9 keV

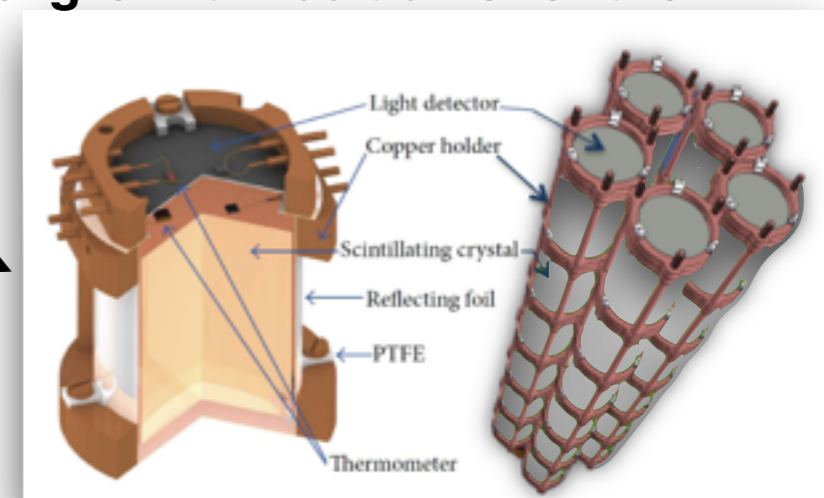
Excellent intrinsic radiopurity

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

Particle ID using only
PulseShapeAnalysis of the HEAT

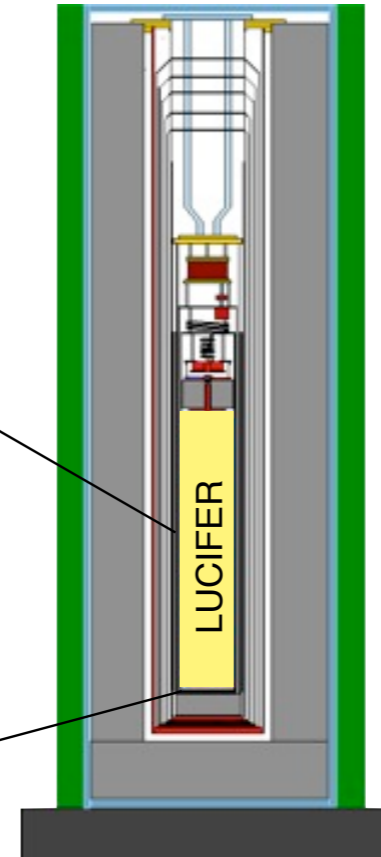
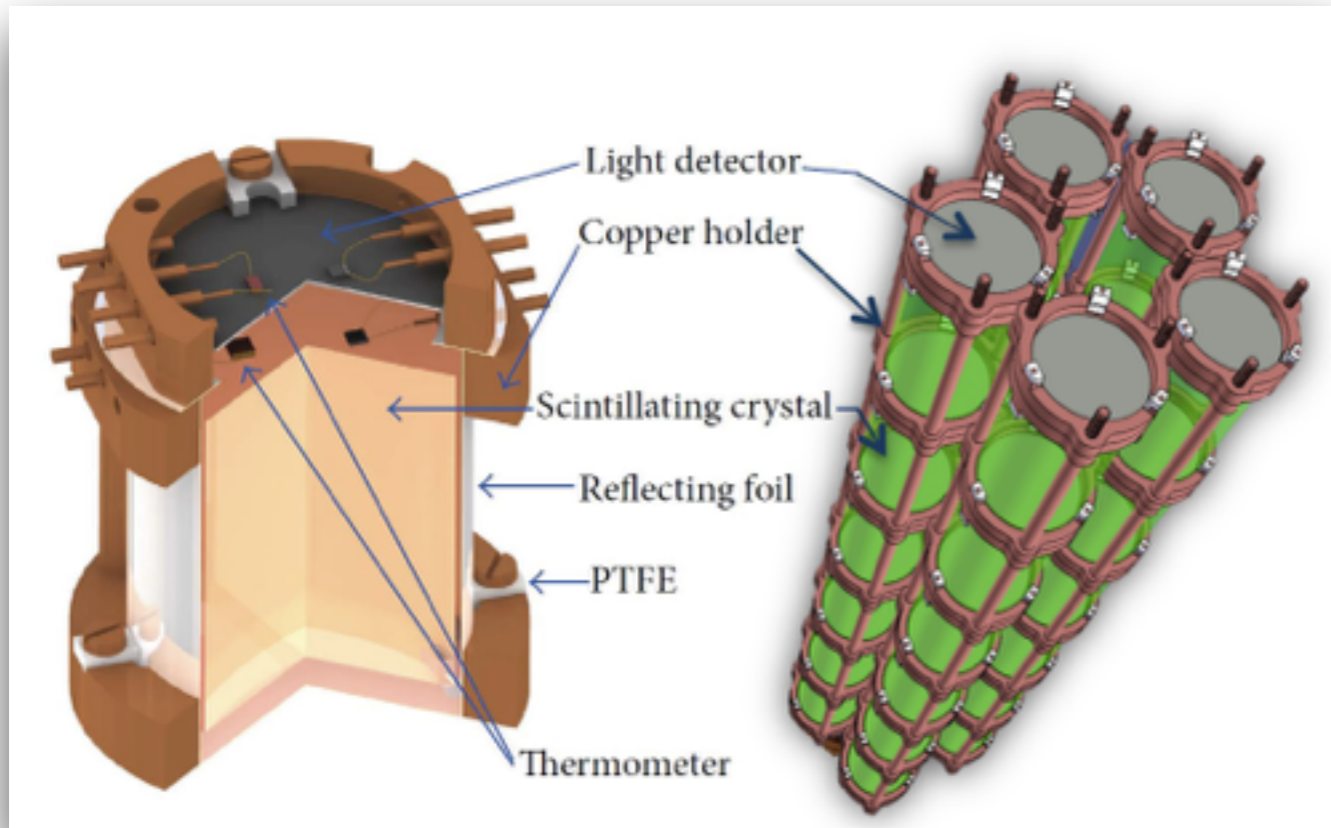


Excellent compound for a
background-free demonstrator detector



event by event discrimination: **shape**

LUCIFER (CUPID-0) demonstrator



CUORE-0 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.

(new shields, new wiring read-out, ...)

- 30 (20) enriched detectors @ 95% level enrich.
- detector mass 17 kg of Zn^{82}Se (14 kg of $\text{Zn}^{100}\text{MoO}_4$)
- expected bkg @ ROI 10^{-3} c/keV/kg/y
- FWHM @ ROI: 10 keV (5 keV)

Sensitivity projection:
 1.8×10^{25} y @ 90% C.L. for ^{82}Se
 6.2×10^{24} y @ 90% C.L. for ^{100}Mo
after 2 y of data taking

Conclusion

- Scintillating bolometers have a huge potential for the observation of $0\nu\beta\beta$:
 - **Excellent energy resolution and zero-background** are key for the investigation
- Scintillating bolometers allow for highly efficient particle discrimination (even without light detection)
- The LUCIFER experiment, as a small scale project, has a great potential
 - Particle discrimination, material selection and isotope enrichment are key for the investigation
- In 2016 LUCIFER will start its operation