Background-free ββ decay investigation with CUPID-0

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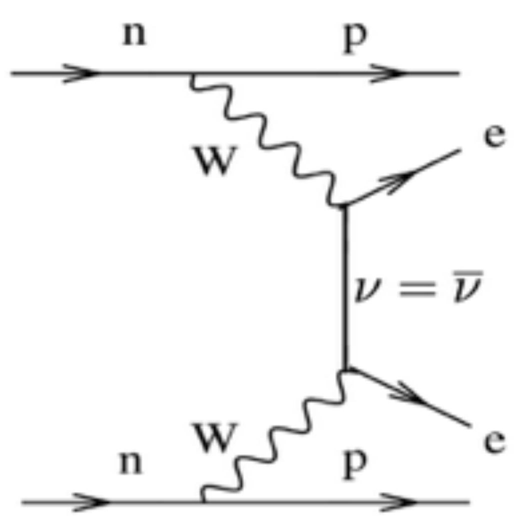
Outline

- Scintillating bolometer for 0νββ
- CUPID-0 detector design
  - $Zn^{82}Se$ absorber
  - Light detectors
- Detector performance
- Conclusion

Neutrinoless ββ decay

- Rare nuclear process: $\mathbf{(A, Z) \to (A, Z+2) + 2e^-}$



If observed:
- Lepton number violation ΔL=2
- Majorana Nature of neutrinos

- It occurs only in few natural isotopes: ^{76}Ge, ^{82}Se, ^{100}Mo, ^{130}Te, ^{136}Xe (and not many others).

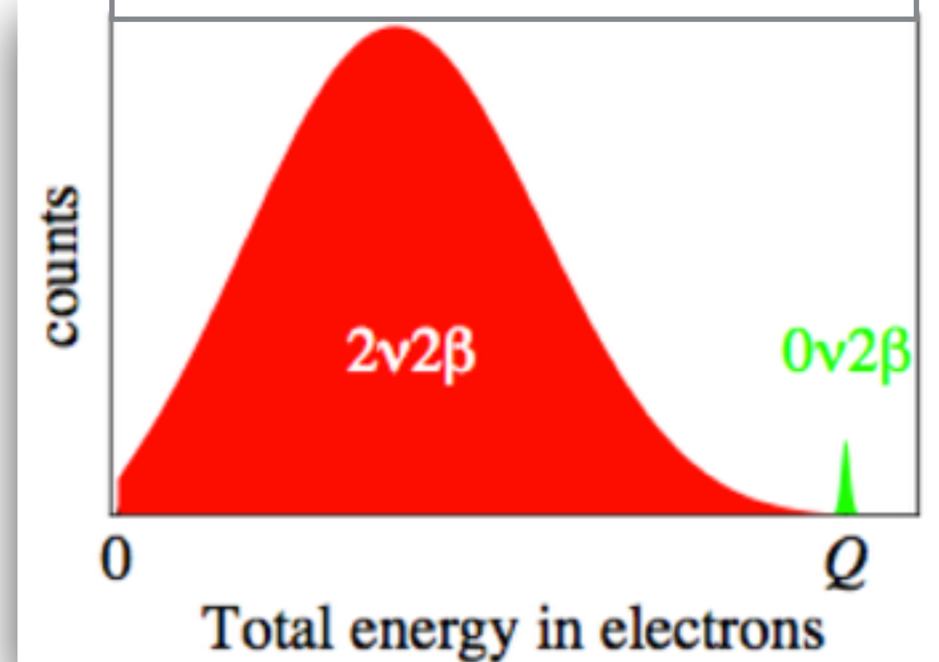
$$m_{\beta\beta} = \sum_{i=1}^{3} |U_{ei}^2| m_i$$

- We measure the decay half-life: $\tau_{1/2}^{0\nu} \propto 1/m_{\beta\beta}^2$

Current limits are of the order of 10^{24}-10^{25} years.

- Signature: peak at the sum-energy (Q) of the two electrons (2-3 MeV).

Calculated energy spectrum

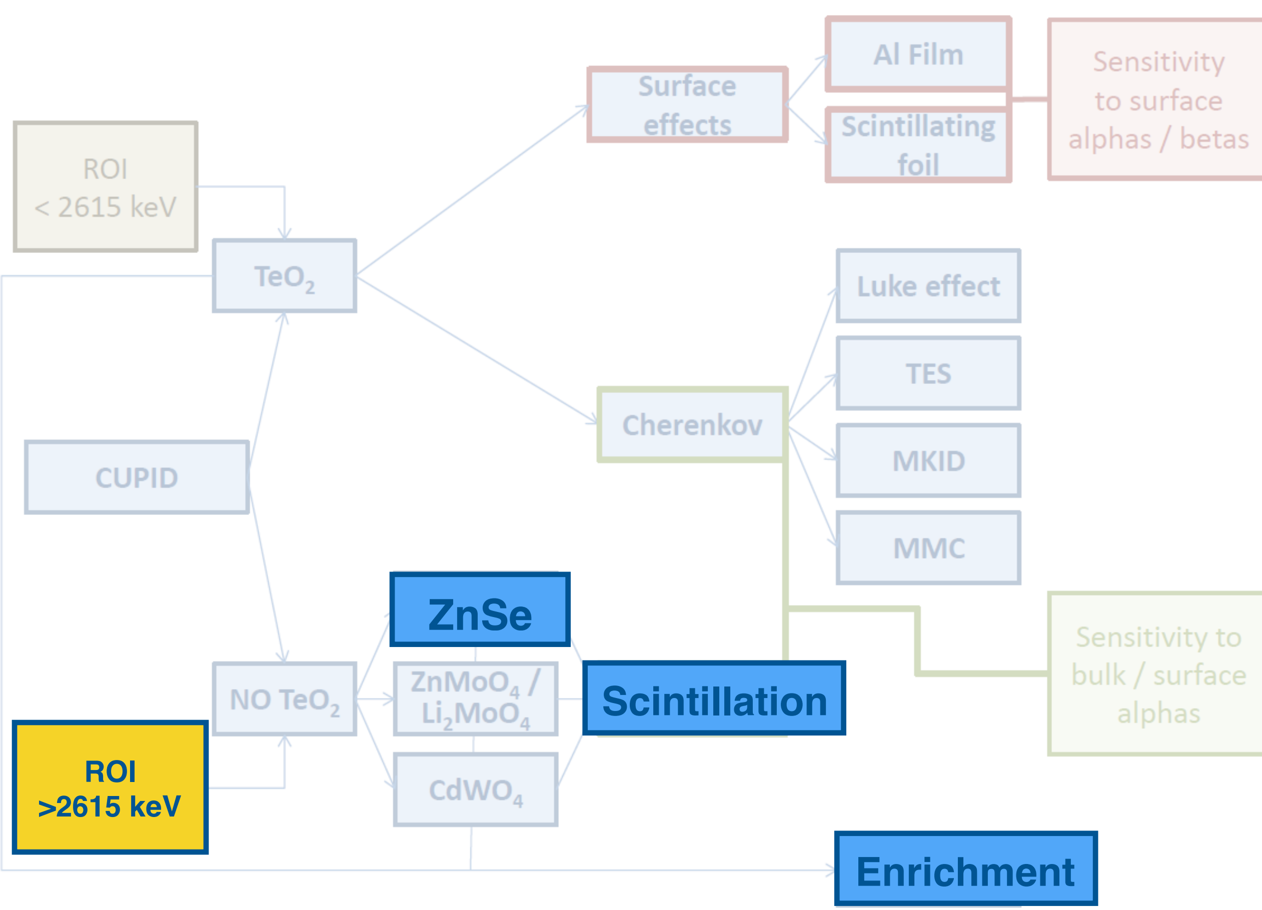


CUPID-0 for CUPID

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:

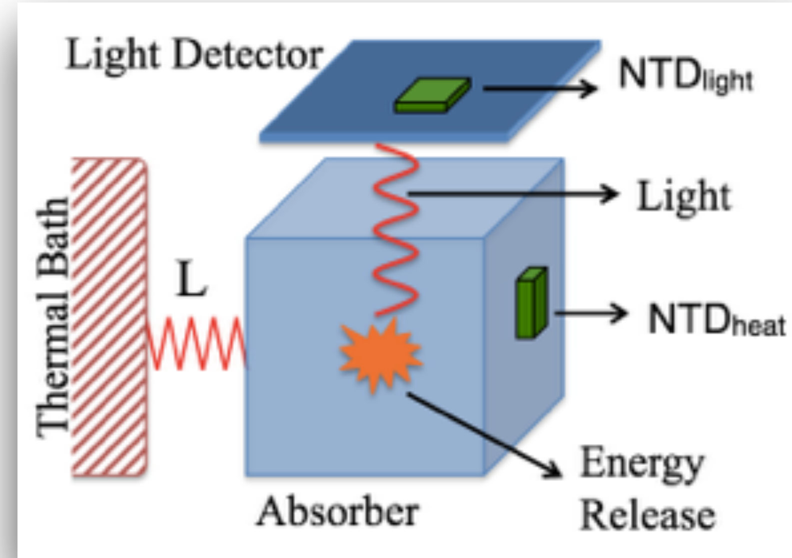
- Isotopic enrichment
- Active alpha rejection
- Improved material selection
- Better energy resolution
- Reduced cosmo-activation

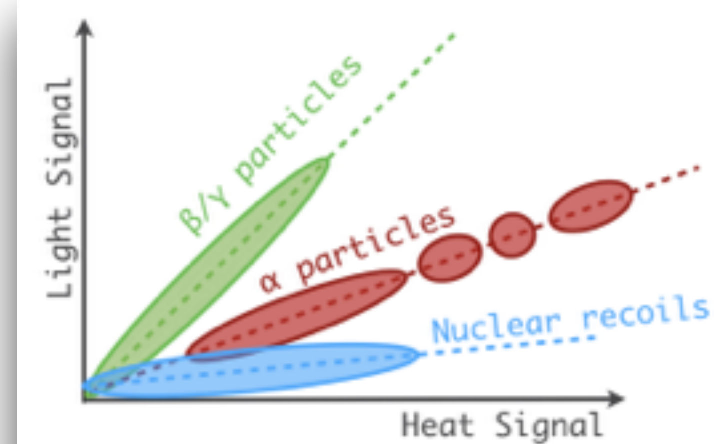
Scintillating bolometers

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

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

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





The simultaneous read-out of **HEAT** and **LIGHT** allows particle identification

Bolometer features:

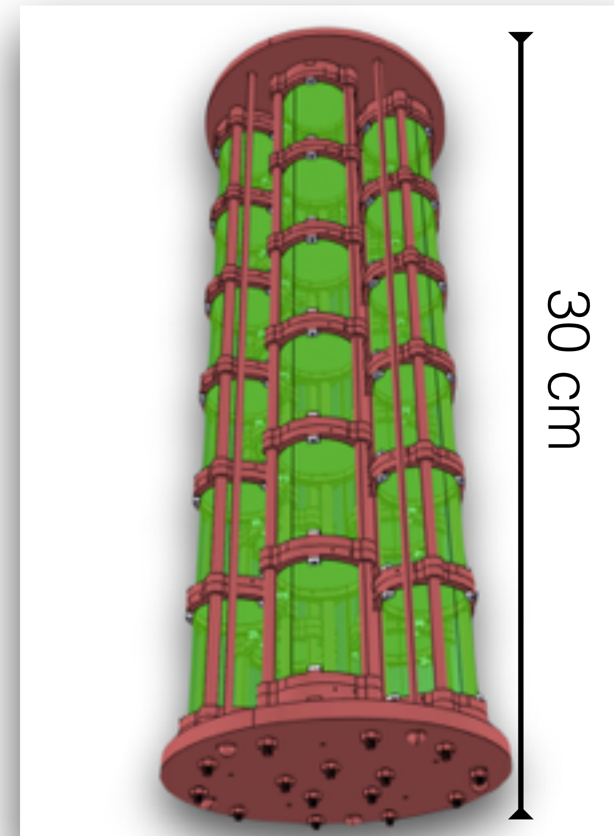
- high energy resolution O(1/1000)
- wide choice of compound ^{130}TeO$_2$, Li$_2$^{100}MoO$_4$, Zn^{82}Se
- high detection efficiency (source = detector)
- scalable to large masses
- **particle ID**

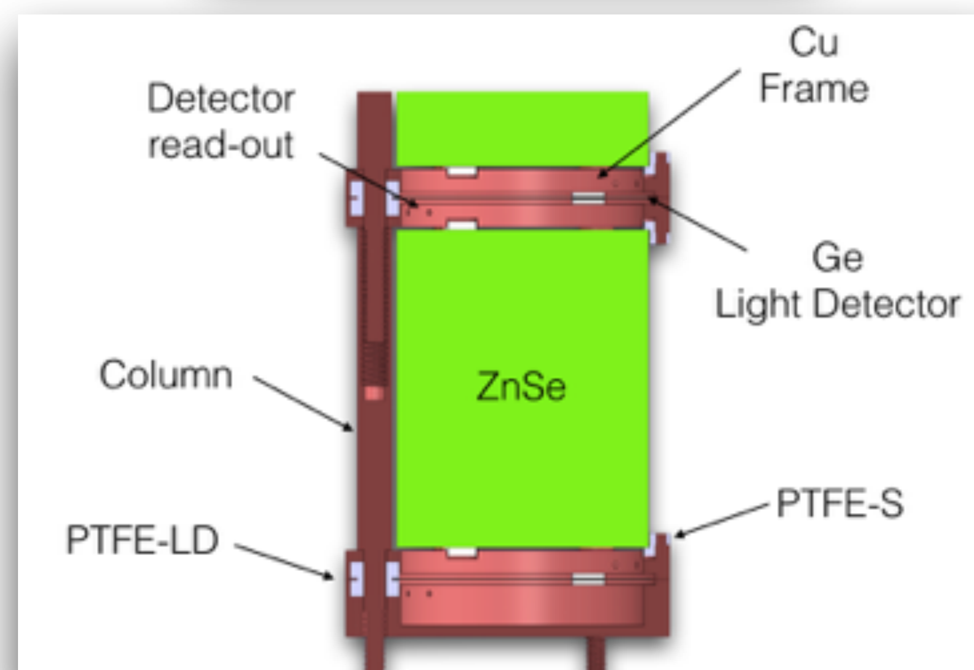
A **background-free experiment** is possible:
α-background: identification and rejection
β-background: ββ isotope with large Q-value

CUPID-0

CUPID-0 is the first array of scintillating bolometers for the investigation of ^{82}Se $0\nu\beta\beta$

- ^{82}Se Q-value 2998 keV
- 96% enriched $Zn^{82}Se$ bolometers
- 26 bolometers (24 enr + 2 nat) arranged in 5 towers
    - 10.5 kg of ZnSe
    - 5.17 kg of ^{82}Se -> 3.8×10^{25} ββ nuclei
- LD: Ge wafer operated as bolometer
- Simplest modular detector -> scale up
    - Copper structure (ElectroToughPitch)
    - PTFE holders
    - Reflecting foil (VIKUITI 3M)





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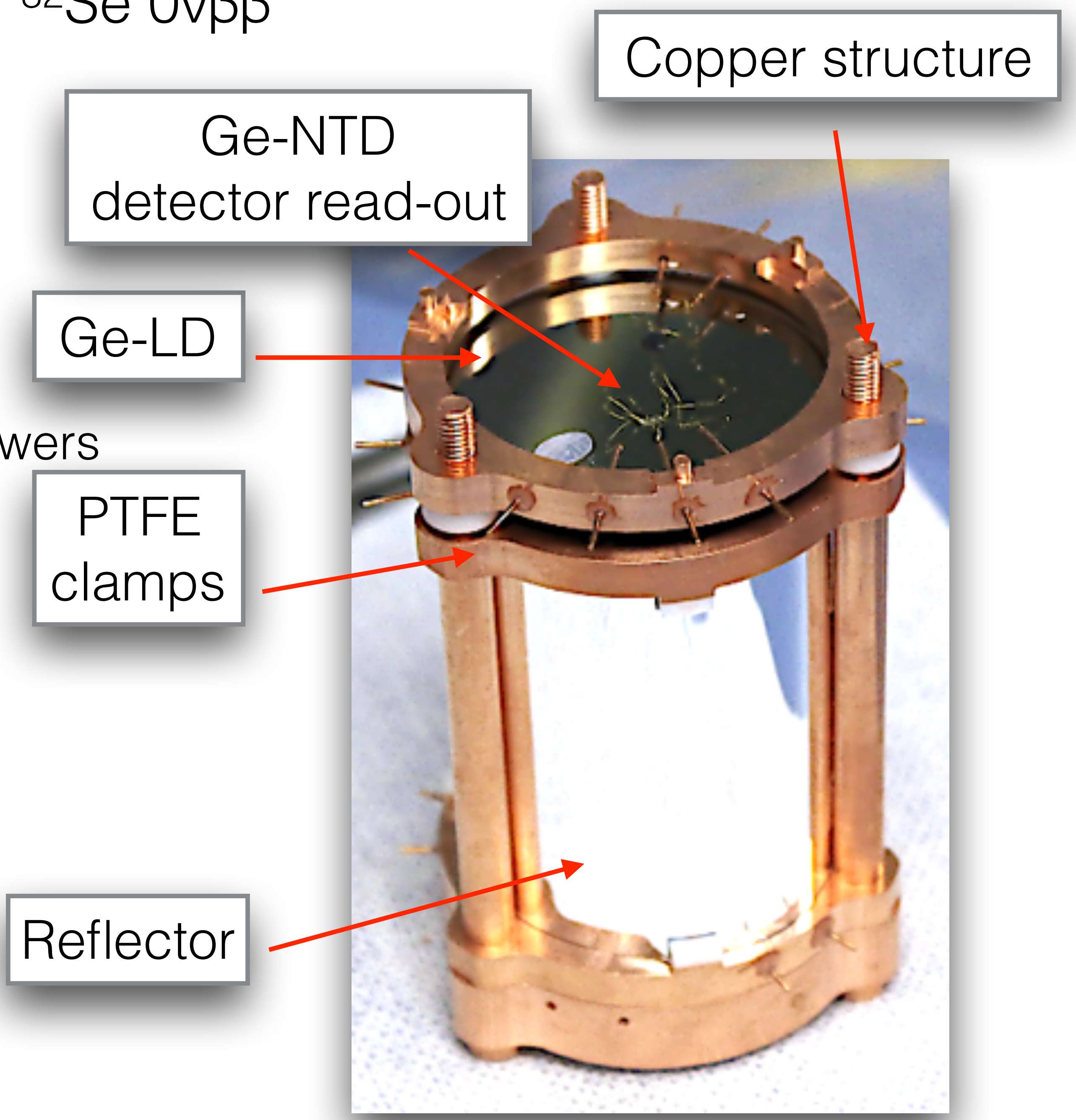


Main goal :
Minimize mass of passive materials next to the detector

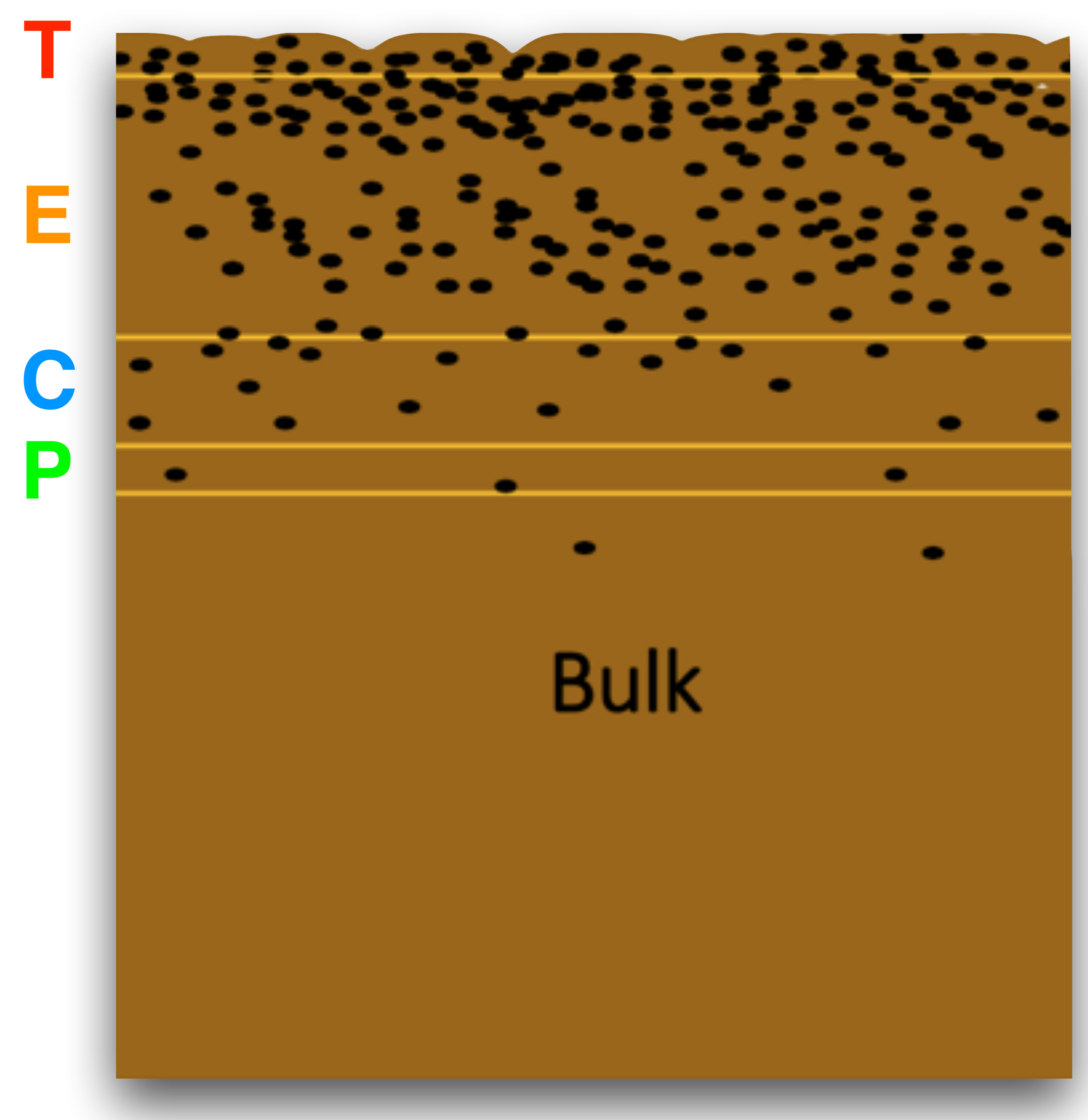
COPPER CLEANING

Copper cleaning procedure for mitigating surface contaminations

- Bolometers are fully-active detectors and are slow (~2 sec)
  - Reduce detector counting rate (pile-up)
- Reduce possible near ^{232}Th background source (2615 keV+583 keV)

- **Pre-cleaning**: lubricant removal from machining
- **Tumbling**: abrasion + smoothening
  - removal 1.2 um (0.06 um/h)
- **Electropolishing**: smoothening+contaminants dissolution
  - removal 100 um (12 um/h)
- **Chemical etching**: SUBU+passivation
  - removal 10 um (120 um/h)
- **Plasma etching**: desorption
  - 0.2 um (1um/h)

Copper surface



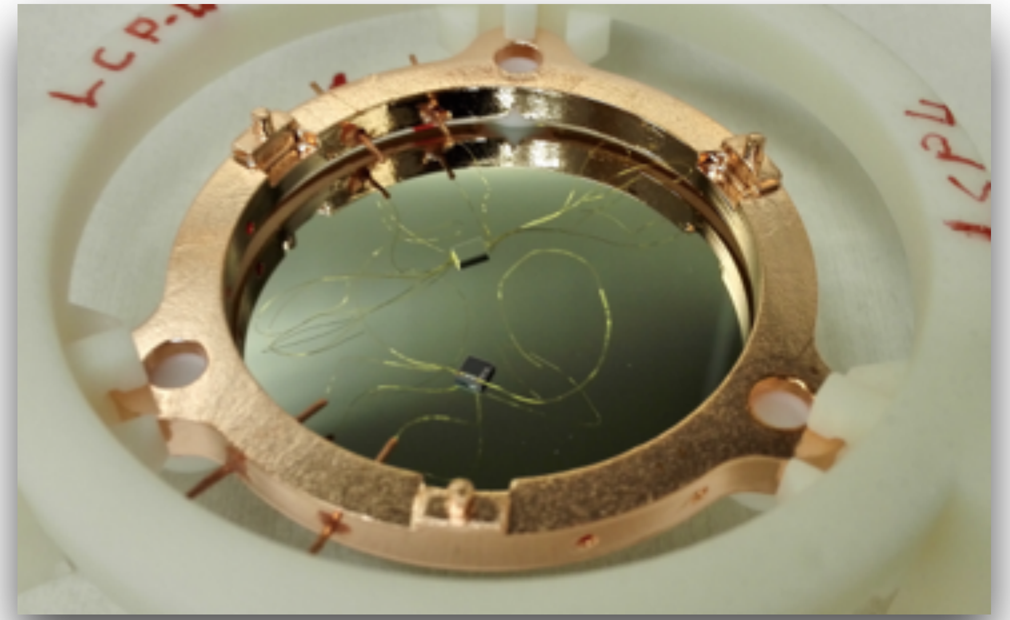
CUPID-0 LD

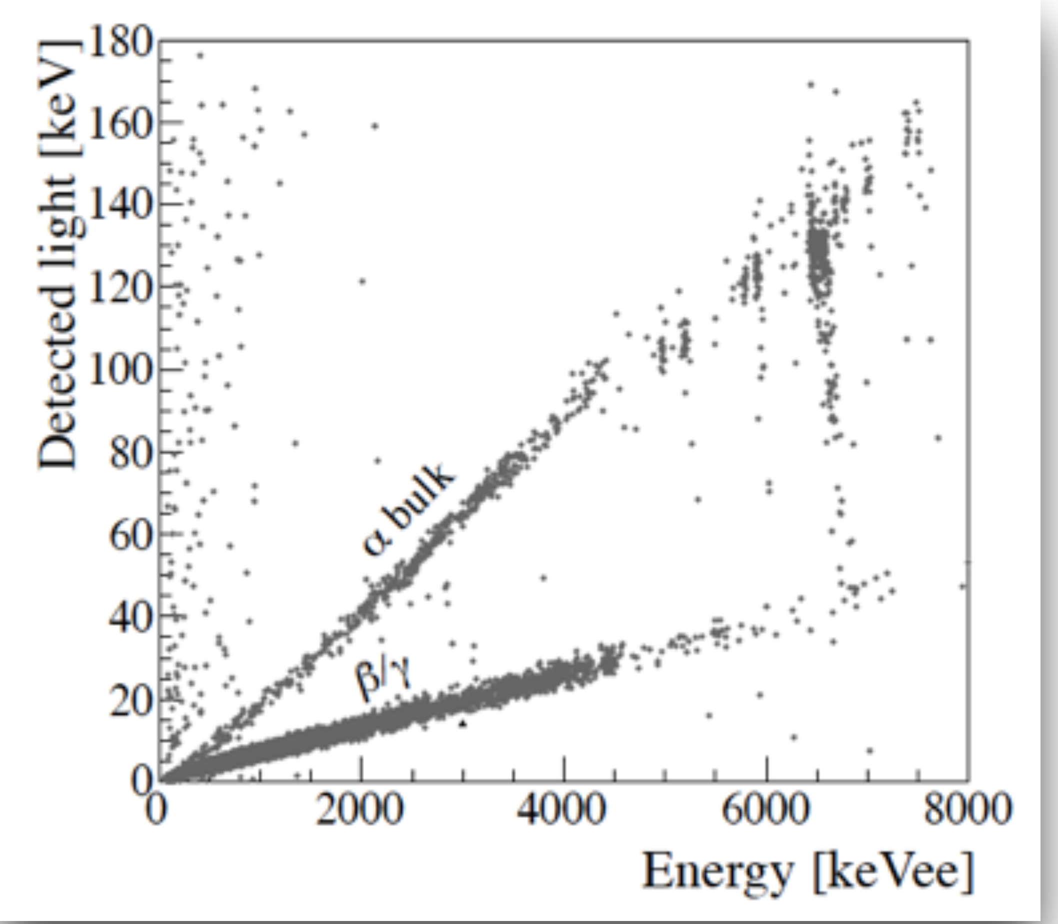
- Well established technology for bolometric LDs
  - Ge disk 44.5 x 0.17 mm
  - Ge-NTD thermal sensor 2x1.5x3 mm^3
  - Si-heater for gain drift corrections

- One face coated with 60 nm SiO_2
  - Light collection enhancement ~50%

- Performance are crucial for background suppression
  - Light vs Heat: α leakage in β/γ ROI band
  - PSA of Light: highly efficient PID

CUPID-0 has 31 LDs





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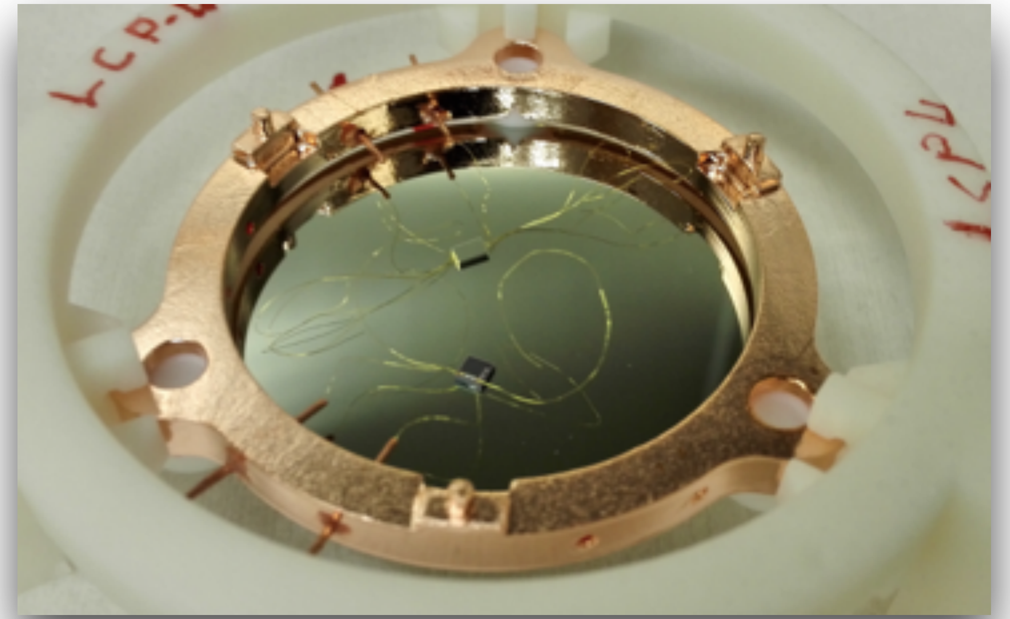
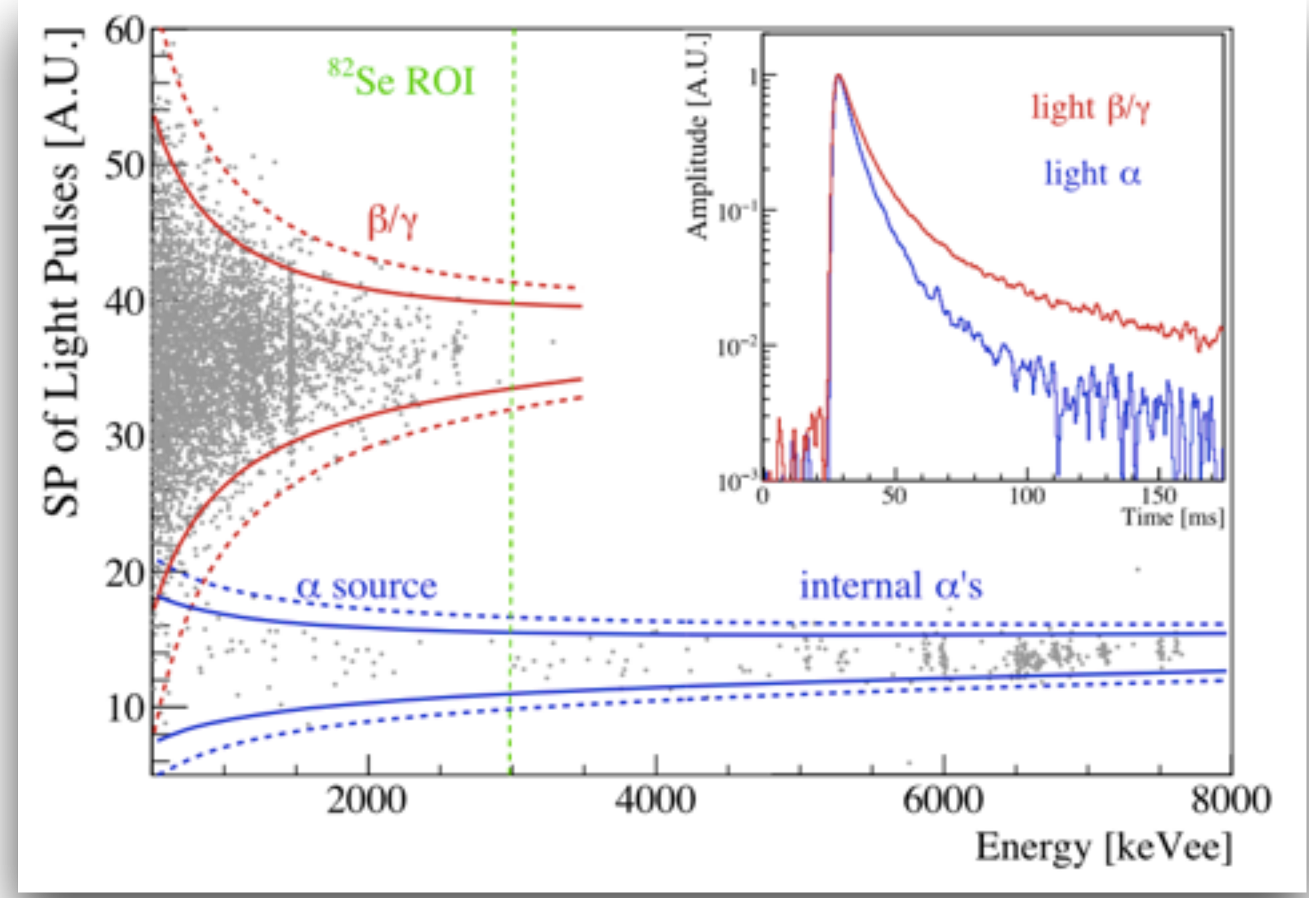


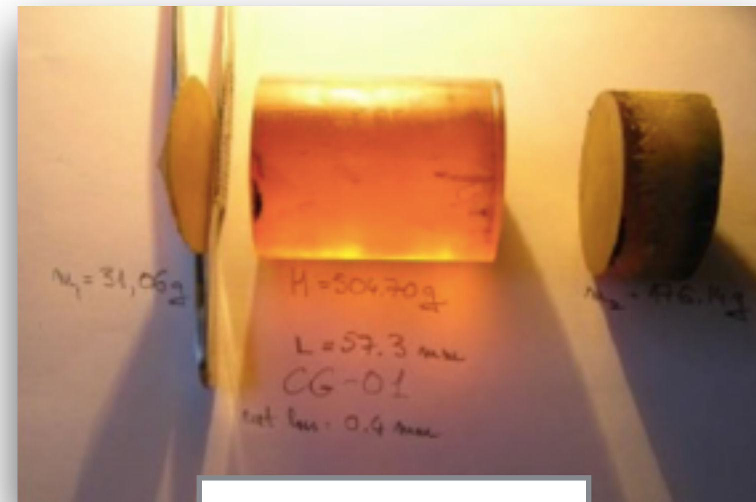


CUPID-0 - ZnSe

Crystal production

- Complex production process in extreme conditions (20 bar Ar & T ~1500C)
  - Synthesis+growth yield 85%
  - Manufacturing yield 60%

J Crys. Growth 393 (2014) 13-17



Crystal as grown

Crystal ready to be used

- Radio-pure material selection: HP-Zn and ^{82}Se

metal Zn

Chain	Nuclide	Activity [μBq/kg]
^{232}Th	^{228}Ra	< 61
	^{228}Th	< 110
^{238}U	^{226}Ra	< 110
	^{234}Th	< 6200
	^{234m}Pa	< 3400

metal ^{82}Se

Chain	Nuclide	Activity [μBq/kg]
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^{238}U	^{226}Ra	< 66
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	^{234m}Pa	< 4700

Eur. Phys. J. C (2015) 75:591

Zn^{82}Se test run *Eur. Phys. J. C76 (2016) 7, 364*

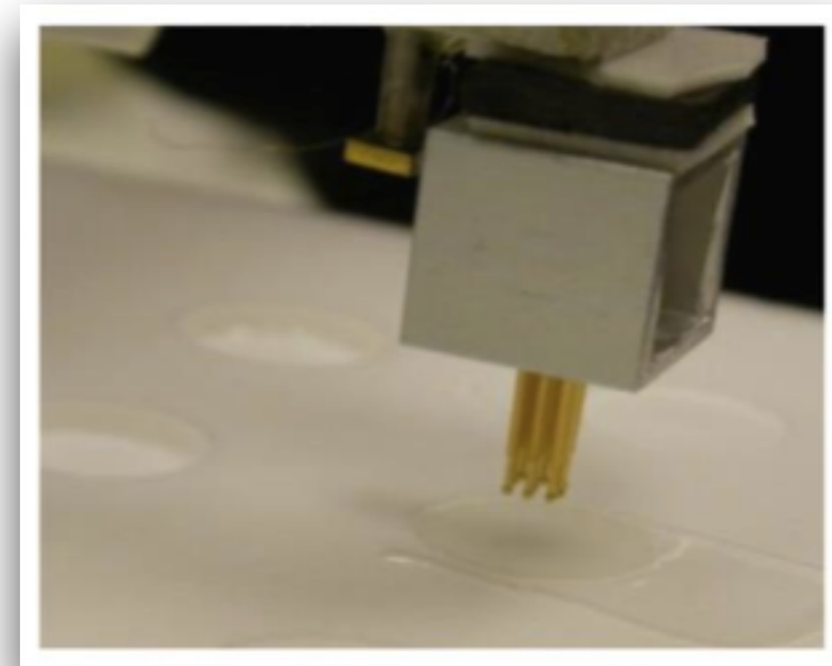
	Zn^{82}Se-1 (μBq/kg)	Zn^{82}Se-2 (μBq/kg)	Zn^{82}Se-3 (μBq/kg)	Array (μBq/kg)
^{232}Th	13 ± 4	13 ± 4	<5	7 ± 2
^{228}Th	32 ± 7	30 ± 6	22 ± 4	26 ± 2
^{224}Ra	29 ± 6	26 ± 5	23 ± 5	27 ± 3
^{212}Bi	31 ± 6	31 ± 6	23 ± 5	29 ± 3
^{238}U	17 ± 4	20 ± 5	<10	10 ± 2
^{234}U+^{226}Ra	42 ± 7	30 ± 6	23 ± 5	33 ± 4
^{230}Th	18 ± 5	19 ± 5	17 ± 4	18 ± 3
^{218}Po	20 ± 5	24 ± 5	21 ± 5	21 ± 2
^{210}Pb	100 ± 11	250 ± 17	100 ± 12	150 ± 8

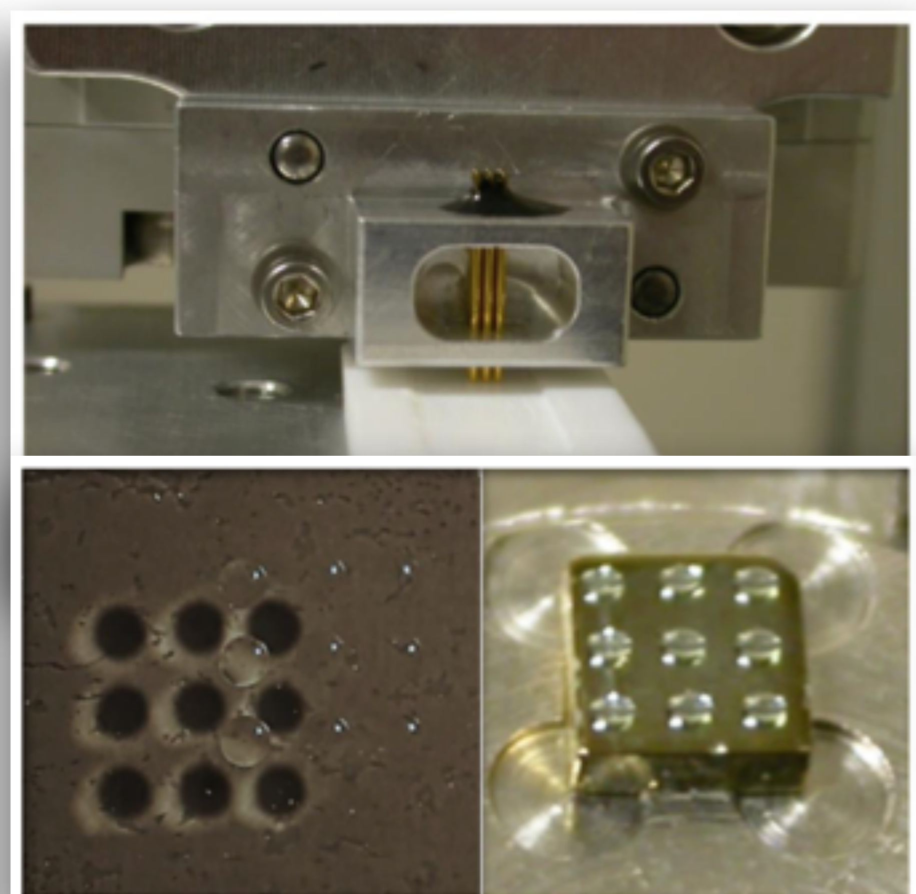
CUPID-0 has 24 Zn^{enr}Se and 2 Zn^{nat}Se

Detector assembly (1)

- Detectors are equipped with a Ge-NTD and a Si-heater glued with high radio-purity epoxy-resin
  - on $Zn^{82}Se$ 2.8x1x3 mm^3
  - on LD 2x1.5x3 mm^3

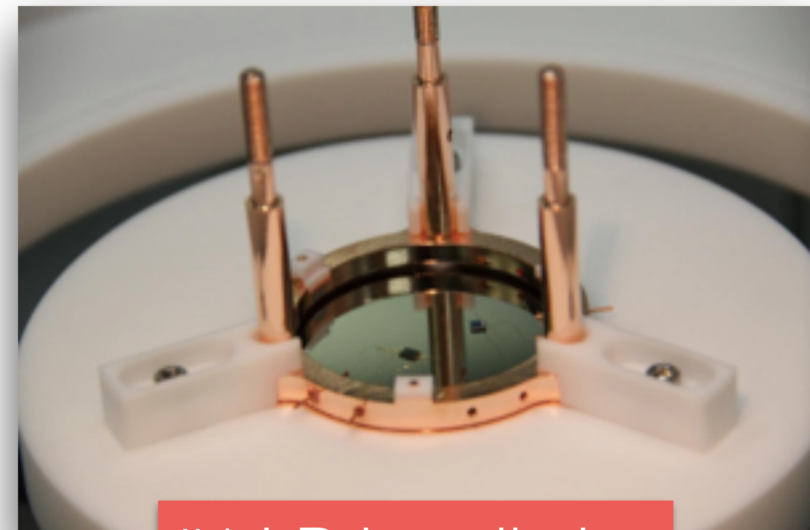
- A semi-automatic system was developed
  - flexible: handle **ZnSe crystals of 450 g** and **LD of 2 g**
  - reliable: uniform detector performance at mK temperature



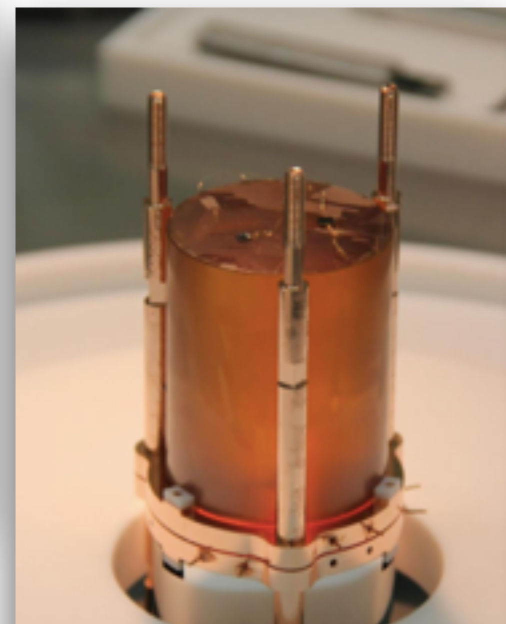


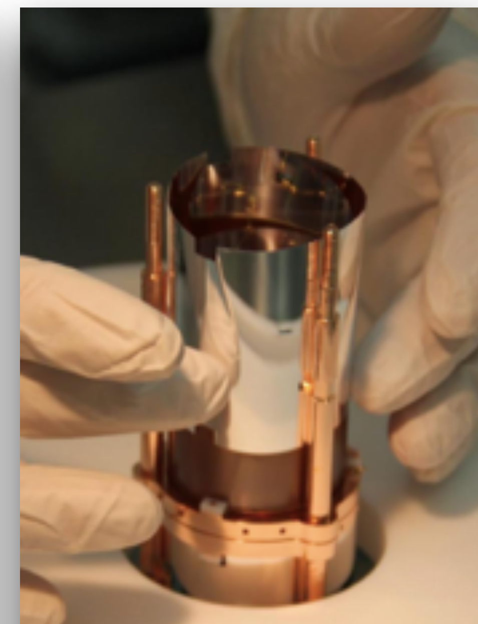
Detector assembly (2)

Detector assembly performed in ~2 weeks inside a low-Rn underground clean room at LNGS

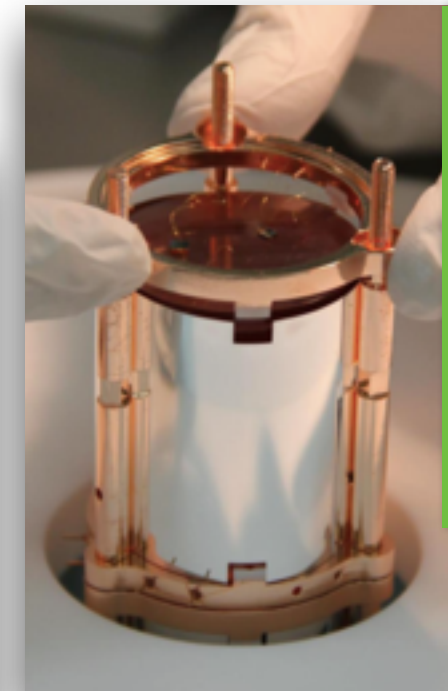


#1 LD installation

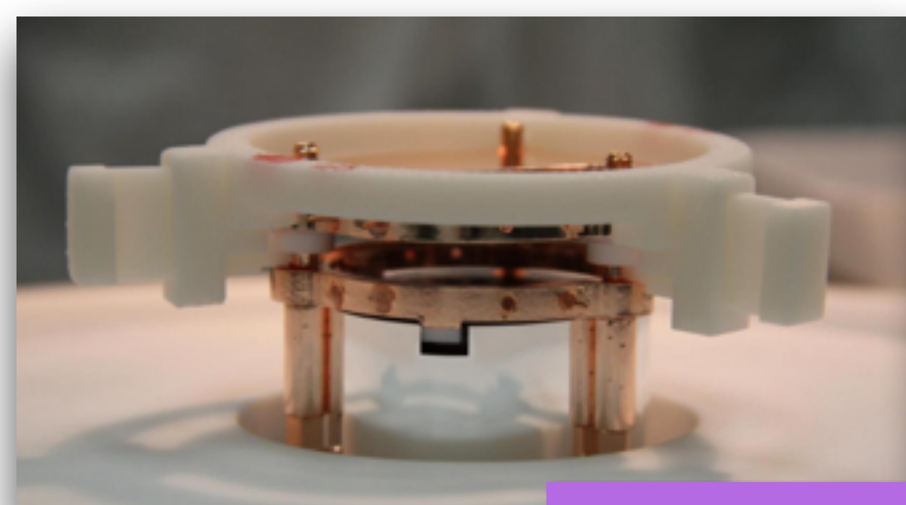




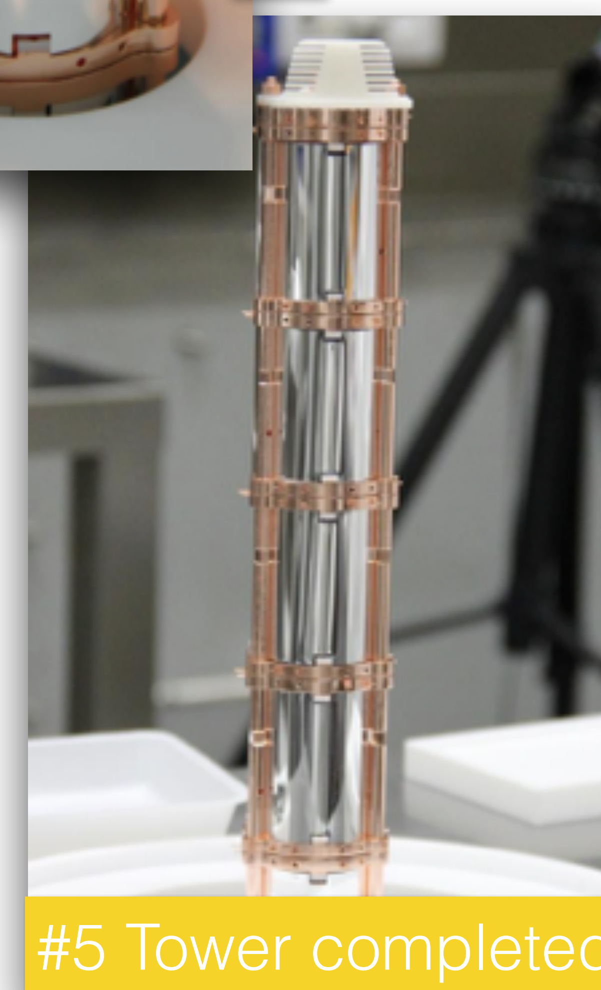
#2 ZnSe and light reflector installation



#3 Fixing of ZnSe

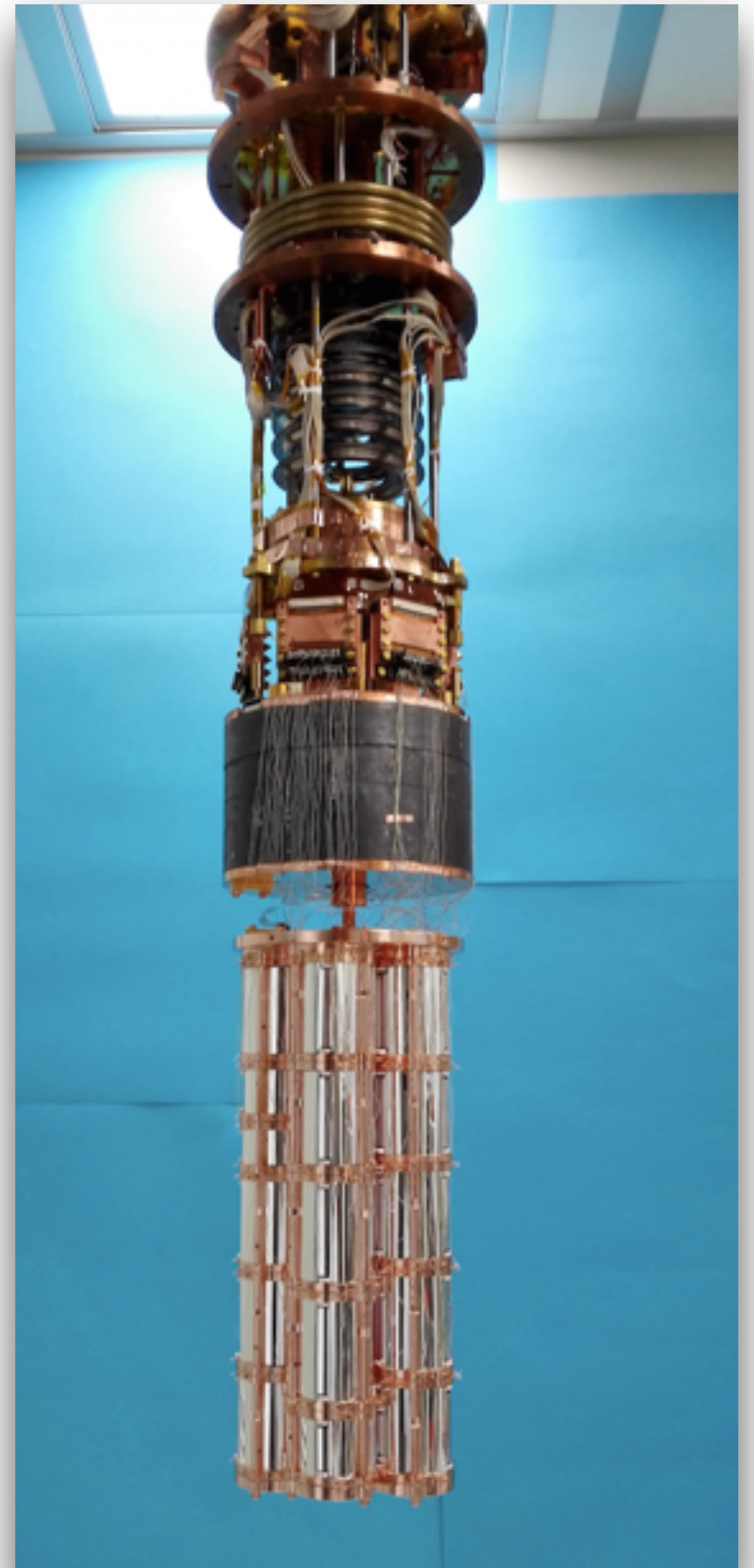


#4 LD installation



#5 Tower completed

Detector installation

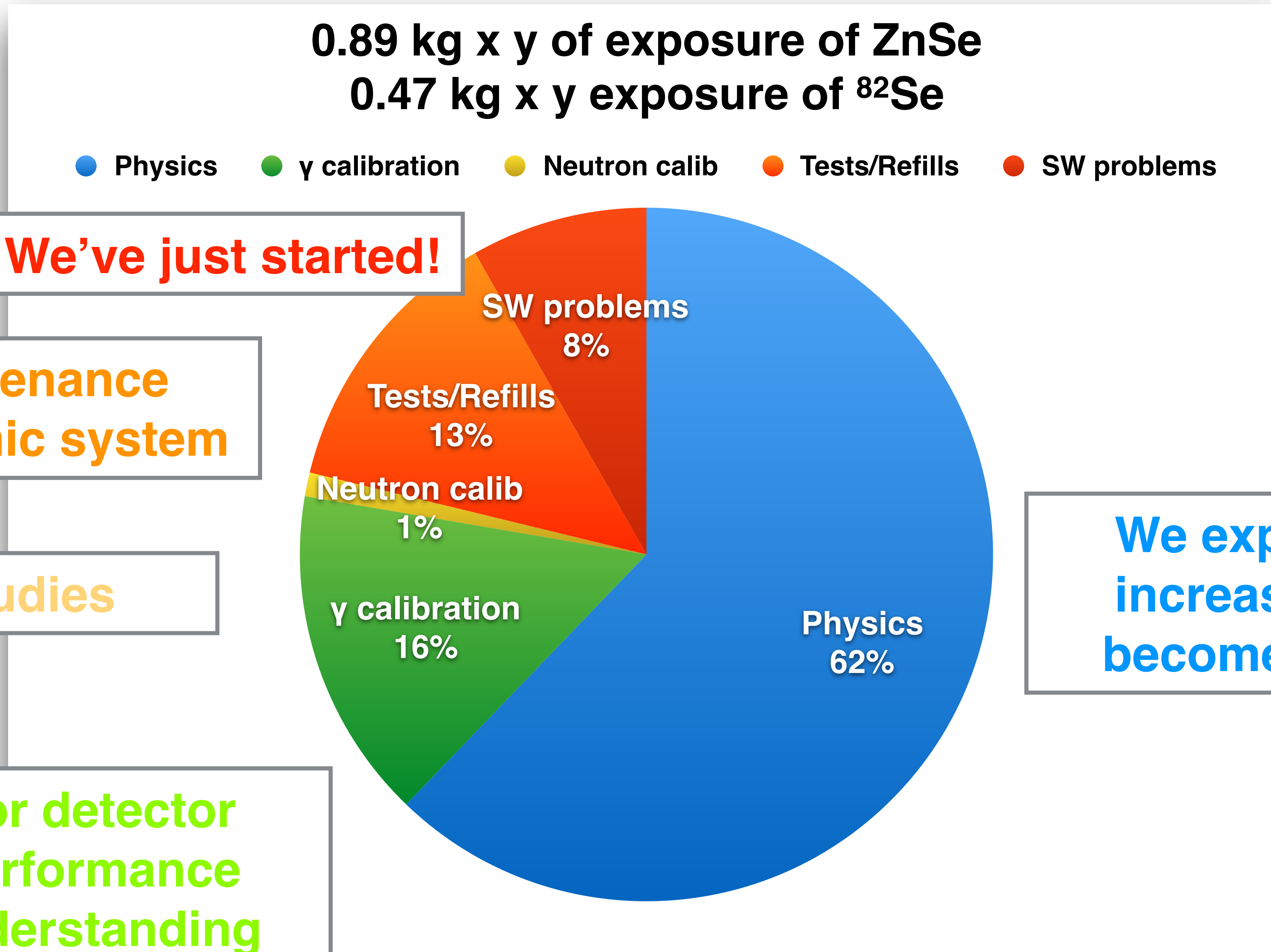


Detector installed in the former Qino/C0 cryostat with major upgrades:

- Rn-abatement system next to the cryostat
  - Reduction and Control of ^{214}Bi
- Double stage pendulum for low vibrational noise
  - LD performance
- Cryostat wiring: can host up to 120 detectors

In March 2017 the commissioning was finalized and the data taking has started

Data taking



We've just started!

Maintenance cryogenic system

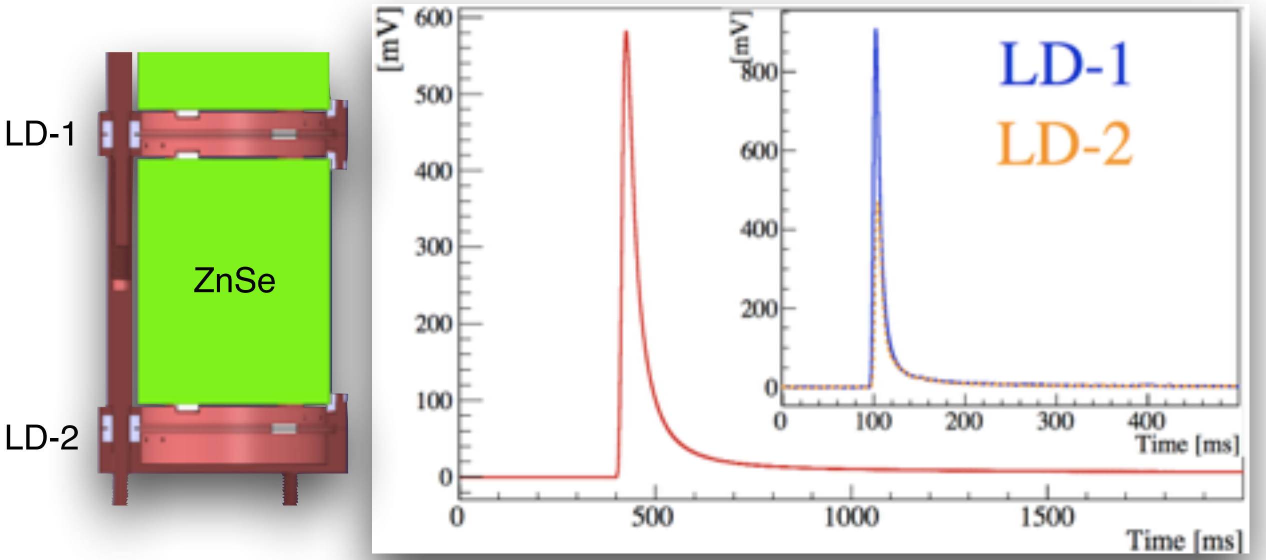
ROI studies

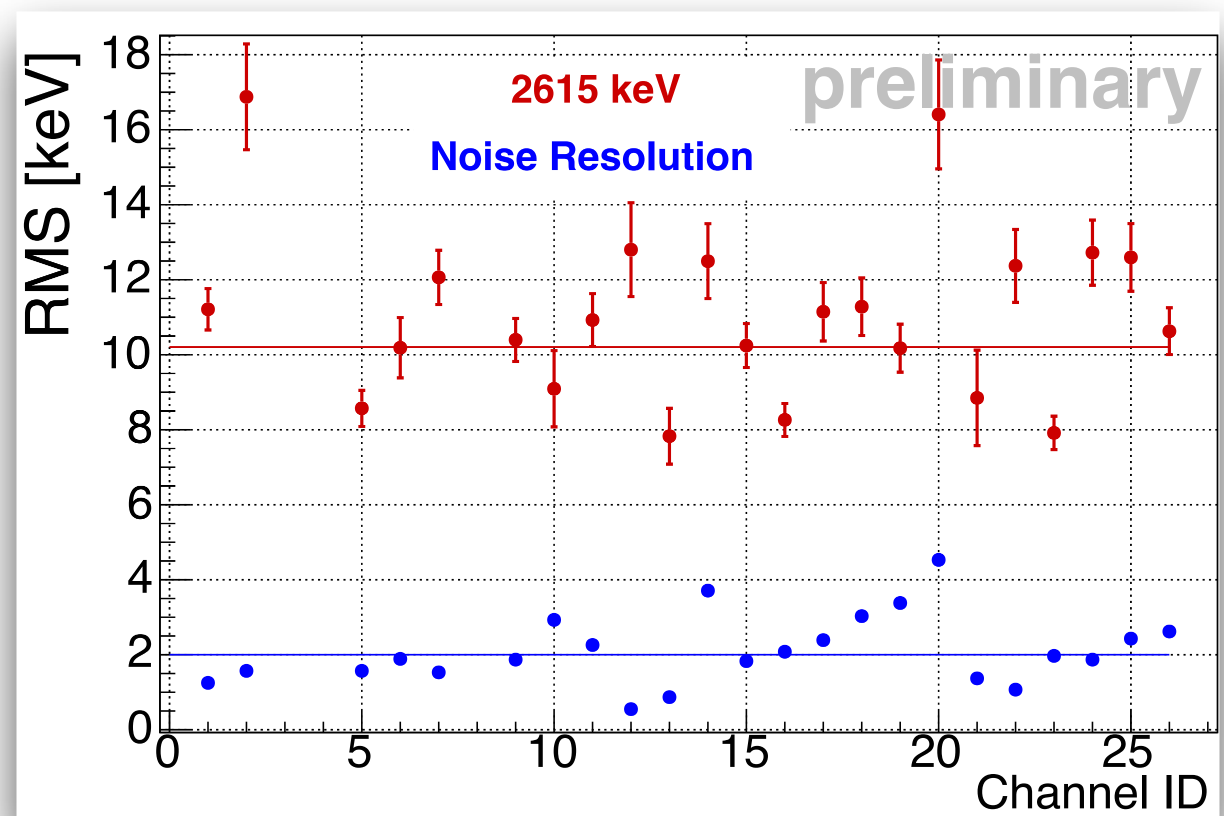
For detector performance understanding

We expect to increase it to become >70%

Detector performance

The detector performance were investigated using a ^{232}Th source





- Excellent scintillating performance
- The heat channel is within the expectation
  - average FWHM @2615keV= 25.5keV
- Major contribution to the energy resolution is the crystal quality
  - average FWHM @0keV= 4.5keV
  - <u>Still room for improvements</u>

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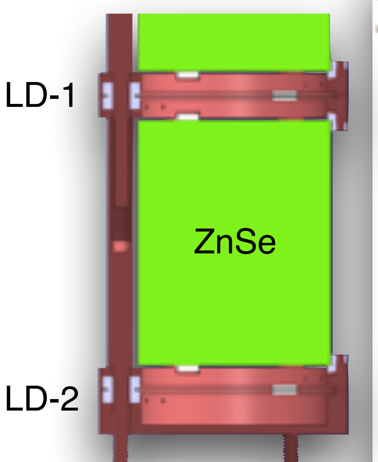

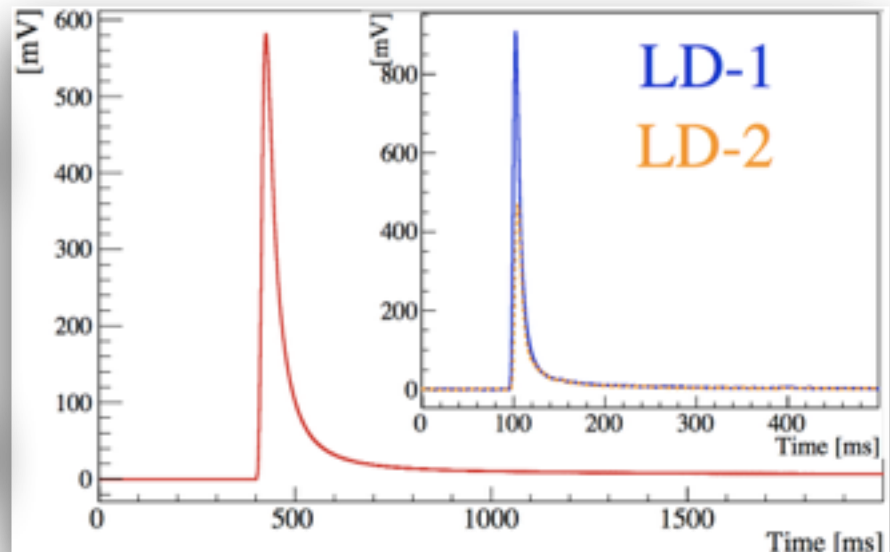

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  - average FWHM @2615keV= 25.5keV
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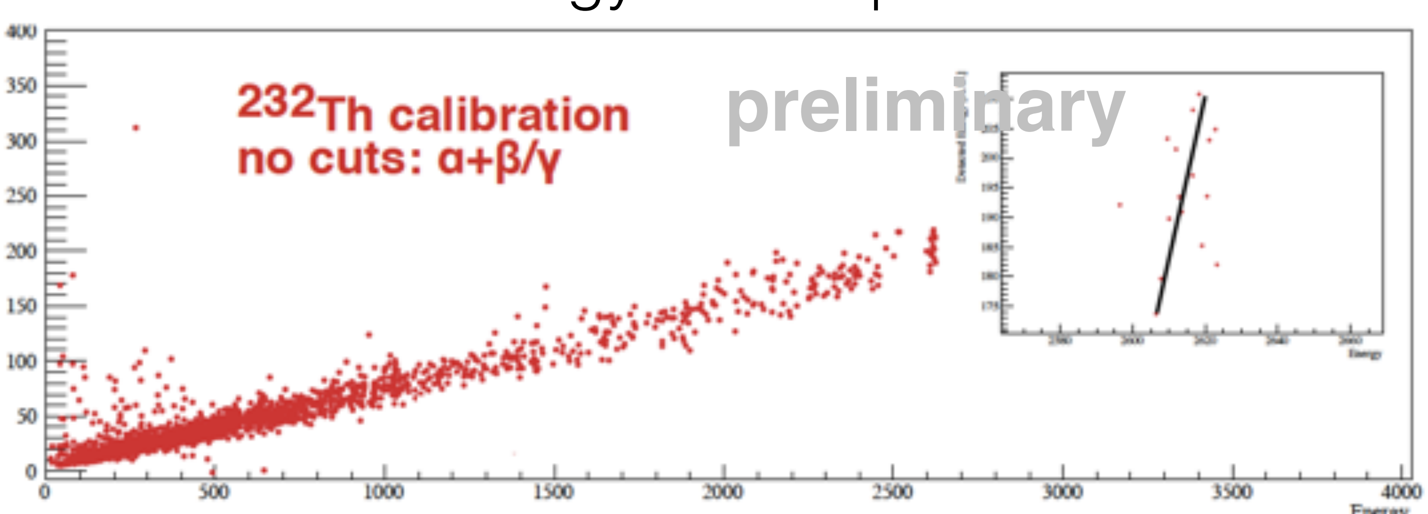
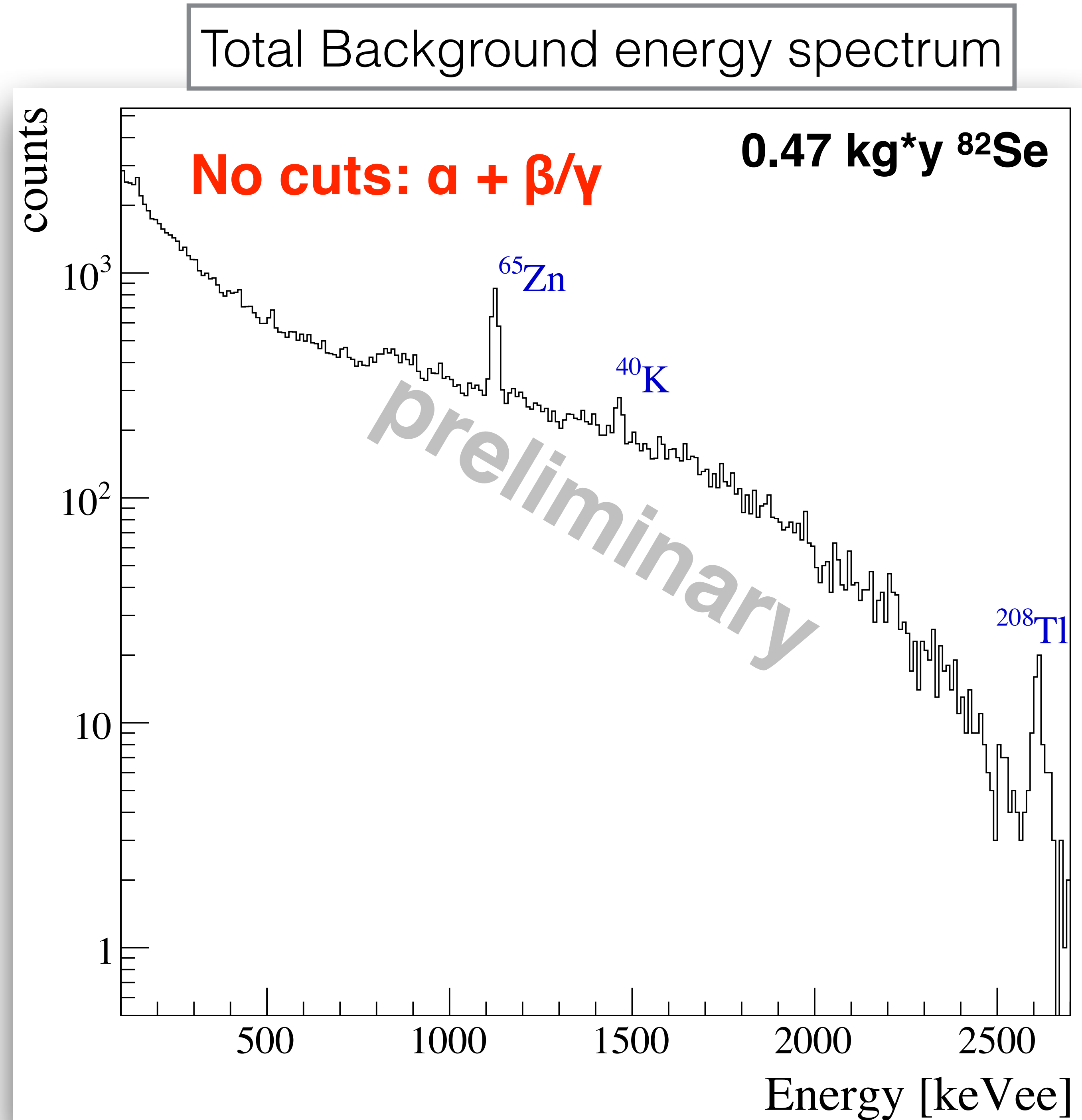
  - Still room for improvements

Calibration energy scatter plot of a Zn^{82}Se



Heat-Light correlation

Energy spectrum



The most relevant contribution to the β/γ region are

- ^{65}Zn (t~244d)
    - cosmogenic activation of ^{64}Zn
- ^{40}K experimental set-up
- 2νββ ^{82}Se ~18 c/h
    - enriched crystals!
- ^{208}Tl: external ^{232}Th in the experimental set-up

Conclusions

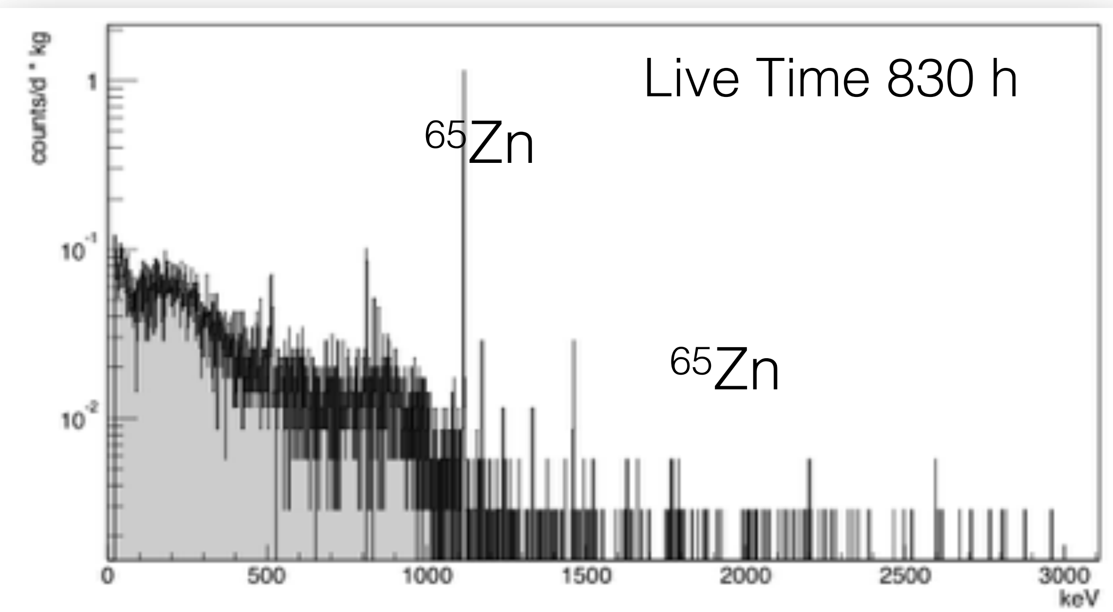
- The scintillating bolometer technique has the discovery potential for 0νββ (high resolution & low background)
- CUPID-0 is the the first large array of enriched scintillating bolometers for the study of ^{82}Se 0νββ
- CUPID-0 is not only a technology demonstrator, but despite the small mass has sensitivity comparable to other 0νββ experiments
- Data taking has just started
- We expect to release the first data in Summer 2017

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

Limits @ 90%CL

Chain	Nuclide	Activity [μBq/kg]
^{232}Th		
	^{228}Ra	< 95
	^{228}Th	< 36
^{238}U		
	^{226}Ra	< 66
	^{234}Th	< 6200
	^{234m}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

@ 25 OCT 2014

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

with ICP-MS

Cd < 2.3 ppm
others < 0.2 ppm

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

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

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	^{234m}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

$^{76}Se(n,2n)^{75}Se$ has a rather large neutron interaction cross section: 979 ± 90 mb for 16 MeV neutrons

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

High energy β/γs background

Background can be induced by contaminations
of ^{238}U & ^{232}Th decay products.
Elements with Q_{value} ~ 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 => 214Bi from 222Rn