



# LUCIFER

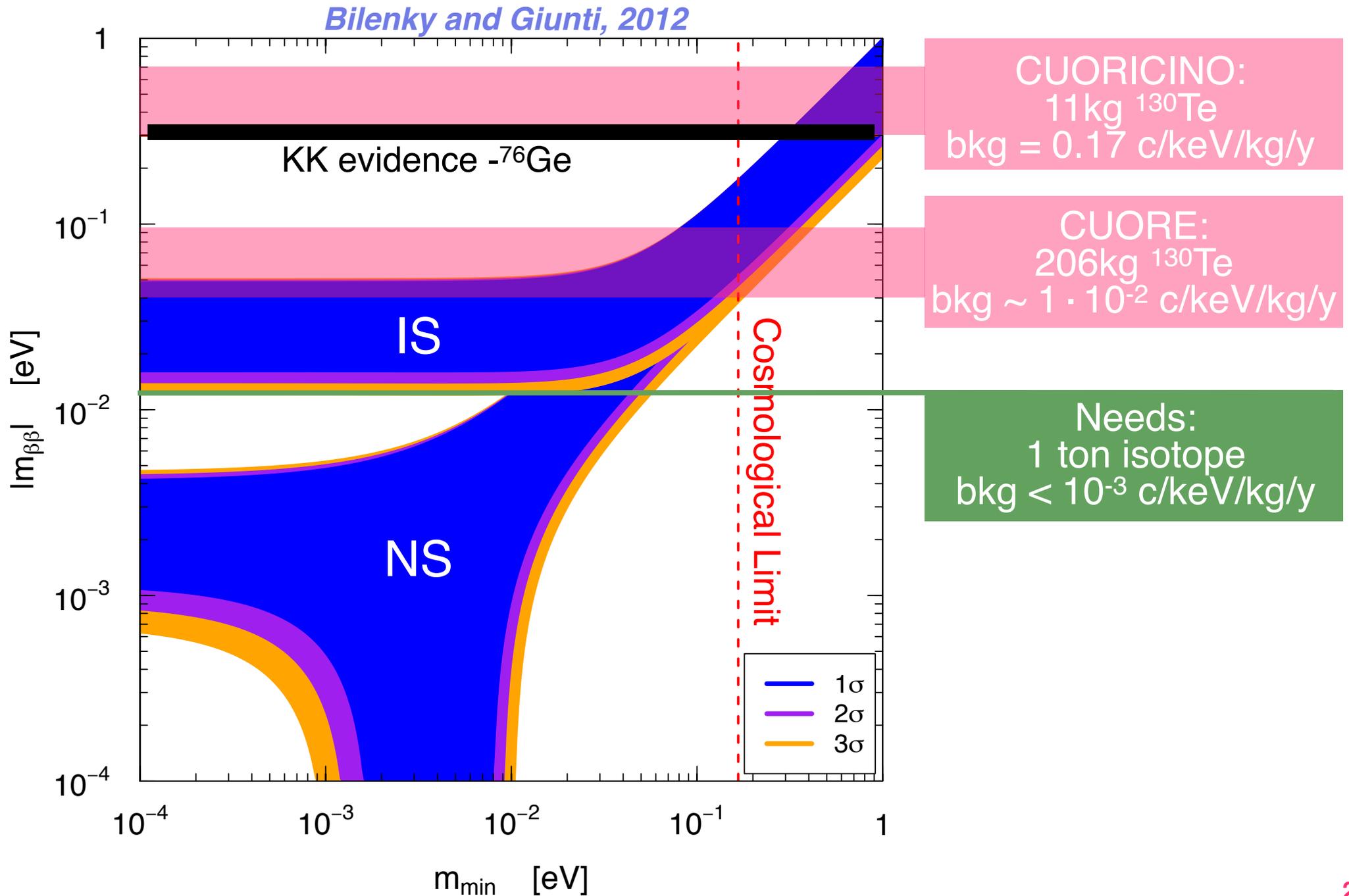
Low background Underground Cryogenic Installation For Elusive Rates

Marco Vignati

INFN Roma

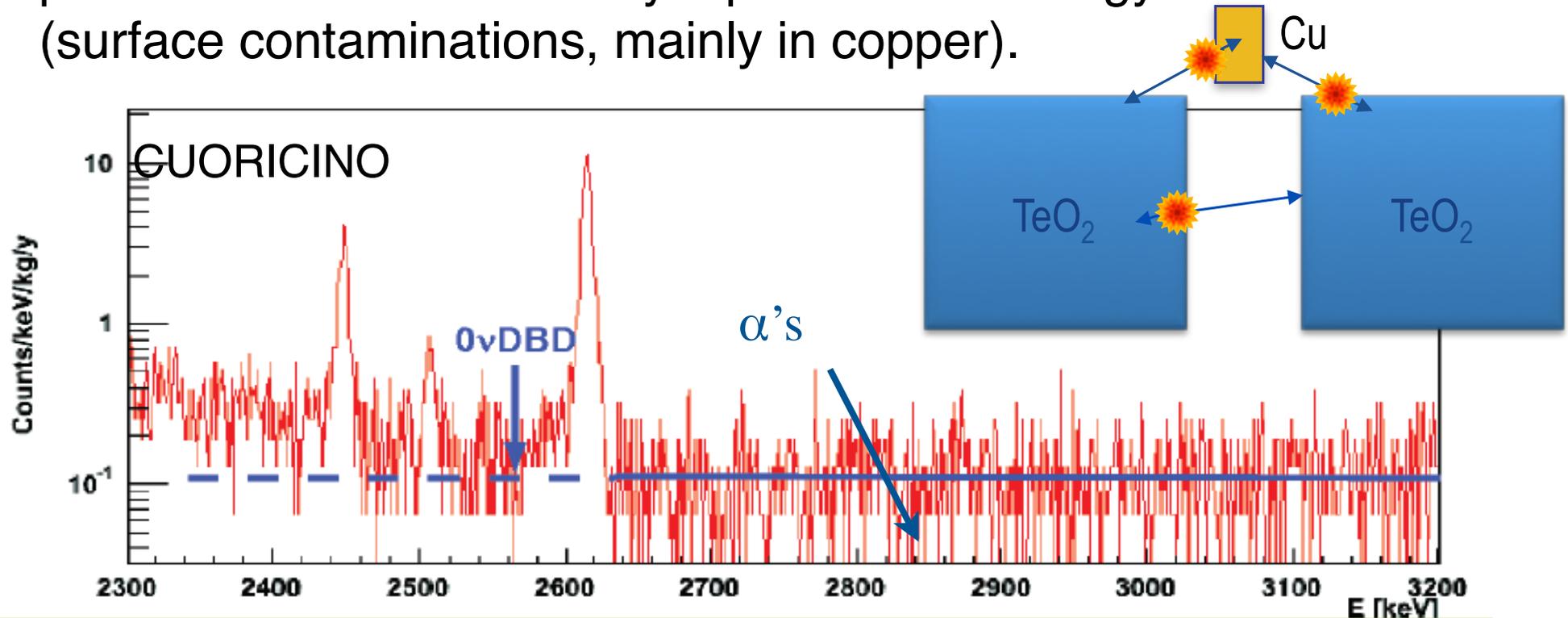
*NPB 2012, Shenzhen, 24 Sept. 2012*

# Bolometric searches of $0\nu\text{DBD}$



# CUORE: the $\alpha$ nightmare

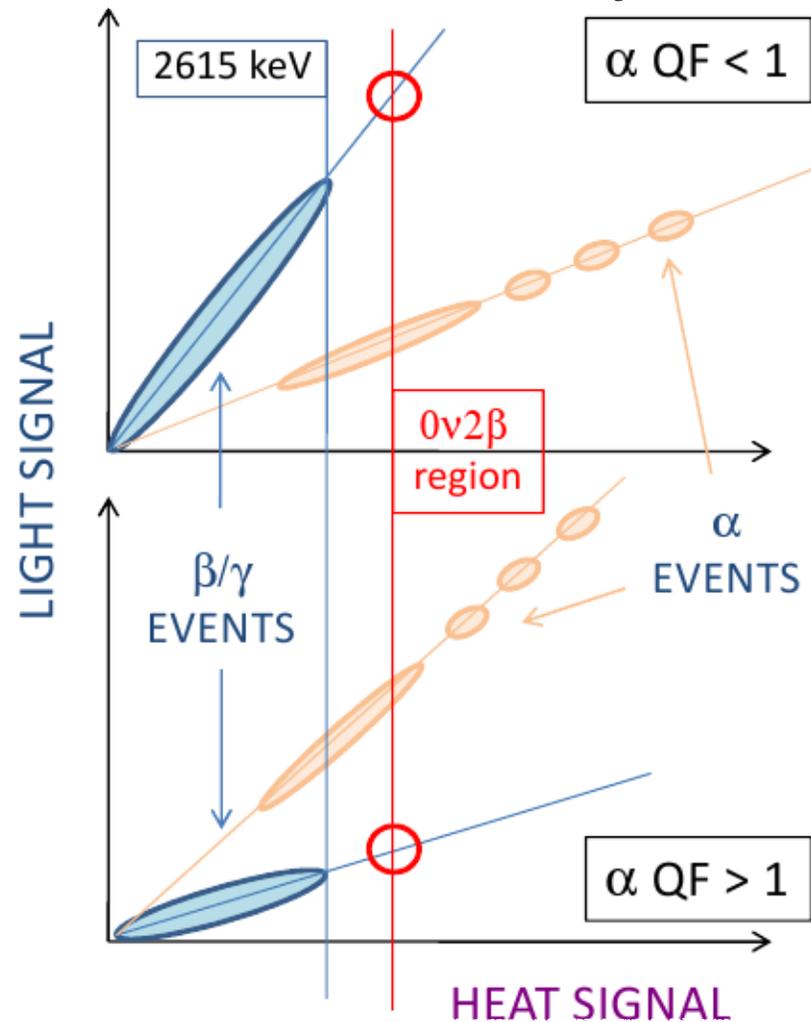
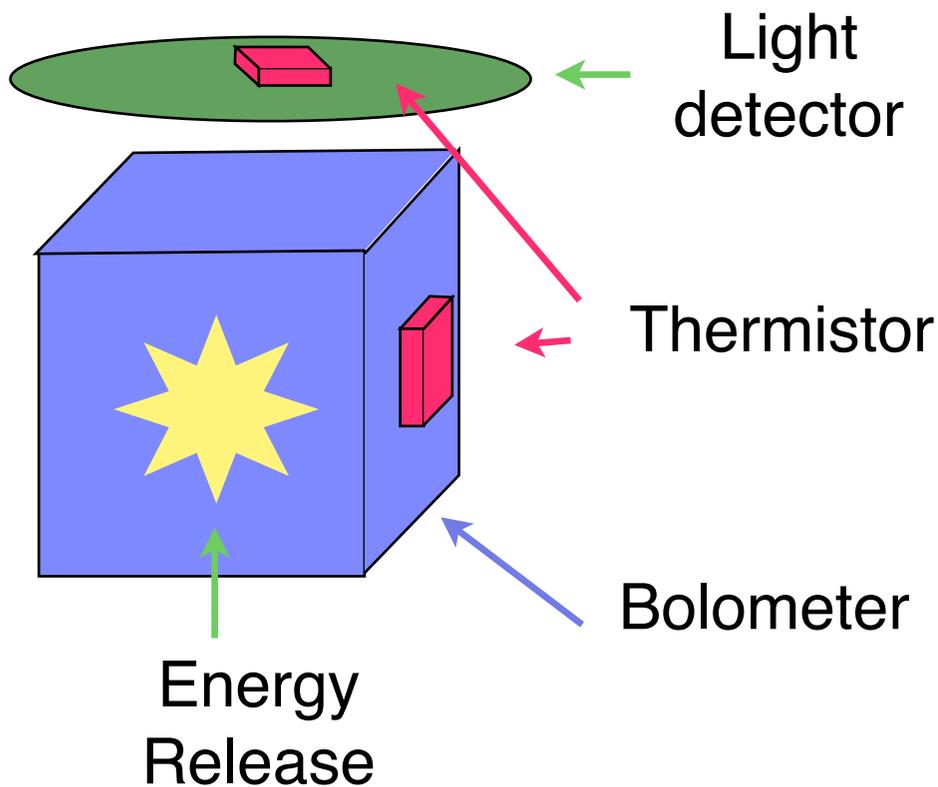
- MC: most of the background in CUORICINO is due to degraded  $\alpha$  particles which release only a part of their energy in the detector (surface contaminations, mainly in copper).



- TeO<sub>2</sub> bolometers, per se, do not allow to discriminate  $\beta$  and  $\alpha$  particles.
  - ▶  $\alpha$  bkg partially reduced by cleaning the detector parts.
  - ▶  $\beta/\gamma$  smaller in CUORE thanks also to the self-shielding geometry.

# Scintillating bolometers

- Scintillating crystals can be operated as bolometers. Unfortunately  $\text{TeO}_2$  does not scintillate, other compounds must be considered.
- The simultaneous read-out of light and thermal signals allows to discriminate the  $\alpha$  background thanks to the scintillation yield different from  $\beta$  particles.



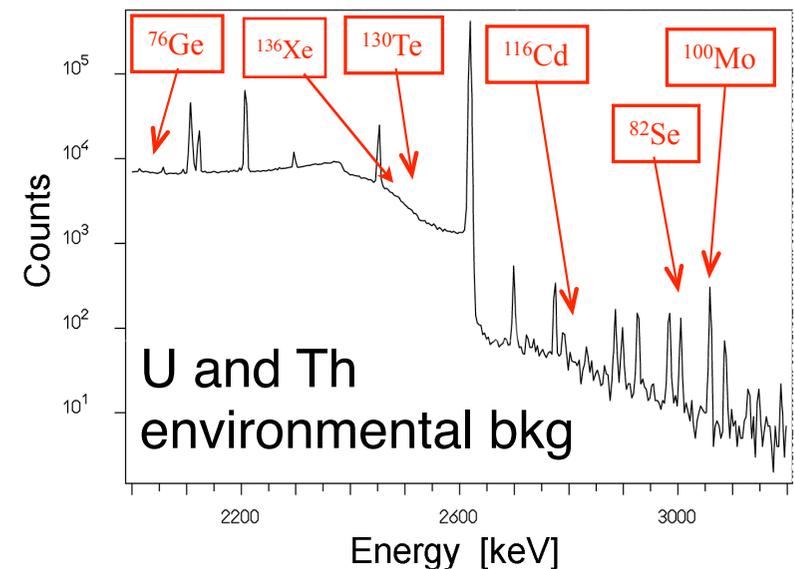
# Isotope choice

$$|m_{\beta\beta}|^2 = 1 / \left[ G(Q, Z) |M^{0\nu}|^2 \tau_{1/2}^{0\nu} \right]$$

- $0\nu$ DBD candidates of experimental interest: ([arXiv:1201.4916](https://arxiv.org/abs/1201.4916))

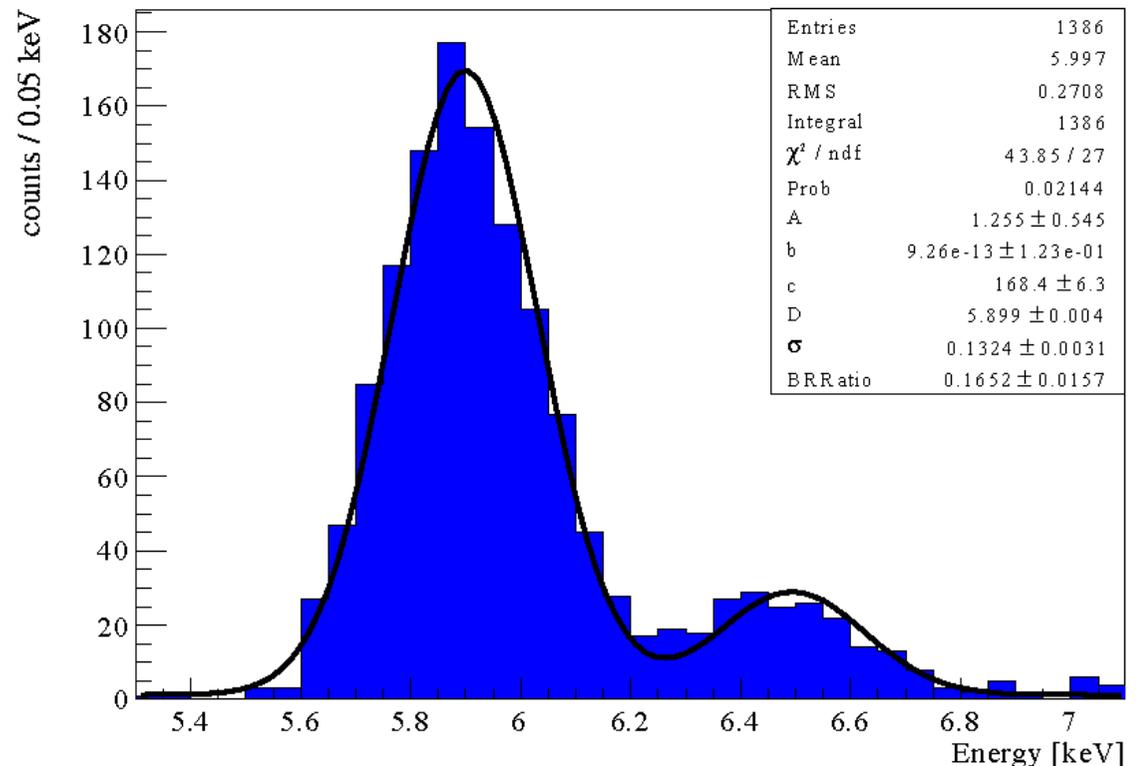
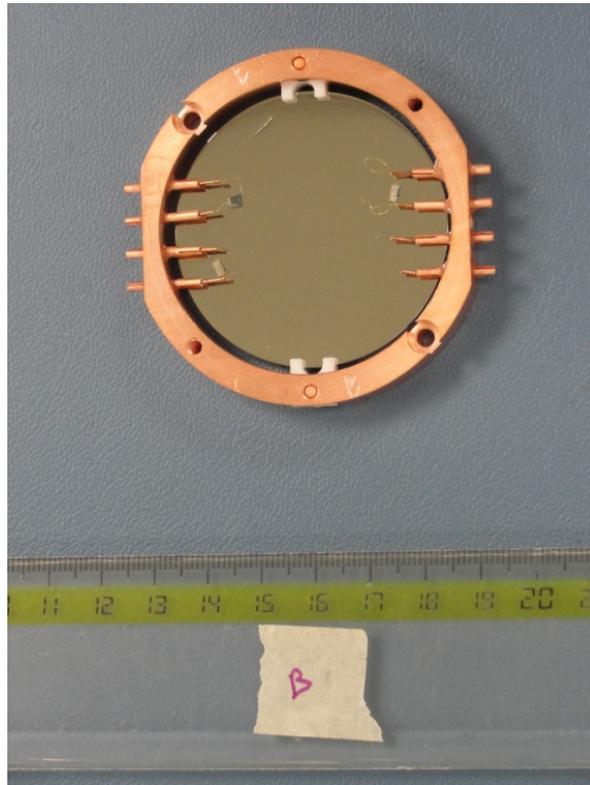
isotope	$G^{0\nu}$ [ $10^{-14}y^{-1}$ ]	$Q_{\beta\beta}$ [keV]	nat. abund. [%]	$T_{1/2}^{2\nu}$ [ $10^{20}y$ ]
$^{48}\text{Ca}$	6.3	4273.7	0.187	0.44
$^{76}\text{Ge}$	0.63	2039.1	7.8	15
$^{82}\text{Se}$	2.7	2995.5	9.2	0.92
$^{100}\text{Mo}$	4.4	3035.0	9.6	0.07
$^{116}\text{Cd}$	4.6	2809	7.6	0.29
$^{130}\text{Te}$	4.1	2528	34.2	9.1
$^{136}\text{Xe}$	4.3	2461.9	8.9	21
$^{150}\text{Nd}$	19.2	3367.3	5.6	0.08

- In general,  $Q > 2615$  keV isotopes are preferred because they lie above the natural radioactivity edge.
- However the choice has been dominated so far by technology compromises.



# Light detectors

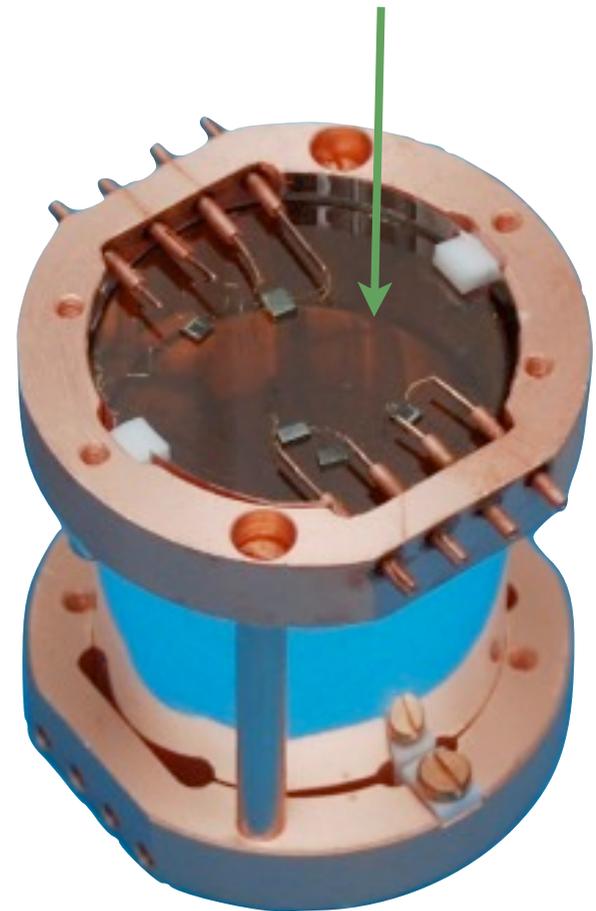
- Germanium disks (5 cm diameter, 0.1-1 mm thick).
- Calibration with a  $^{55}\text{Fe}$  source: 5.9 & 6.5 keV X-rays.
  - ▶  $\Delta E$  @ $^{55}\text{Fe}$ :  $\sim 130$  eV RMS
  - ▶  $\Delta E$  @baseline: 100 eV RMS



# Candidate #1: ZnSe

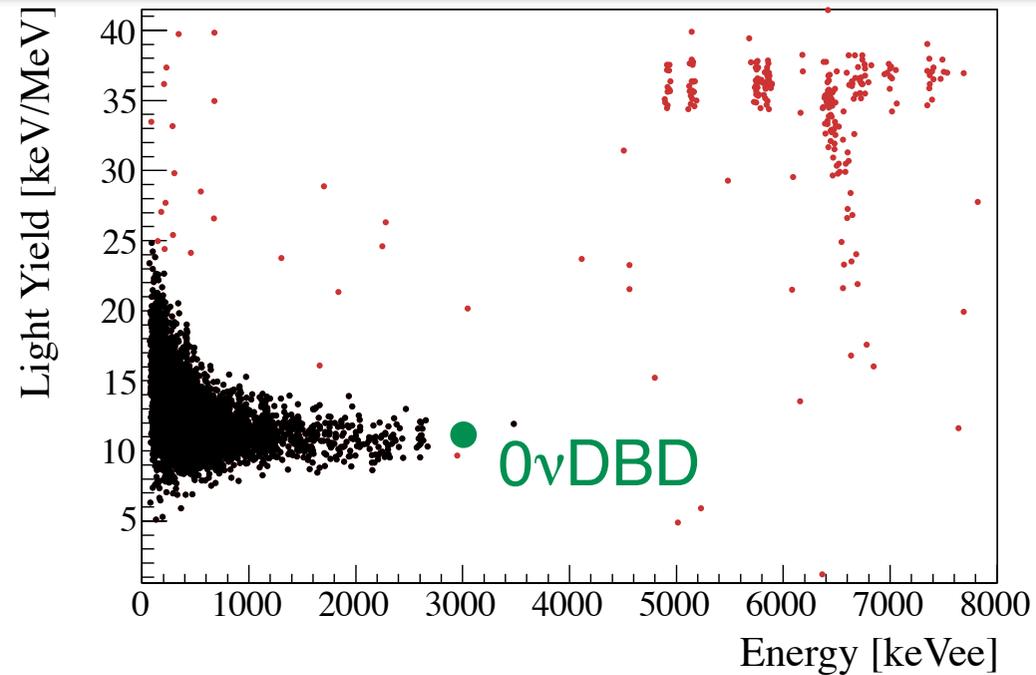
DBD Isotope:	$^{82}\text{Se}$
Q-value [keV]	2995
isotopic abundance	9%
Light Yield [keV/MeV]	7-11
QF	4

Largest crystal  
operated so far: 431g

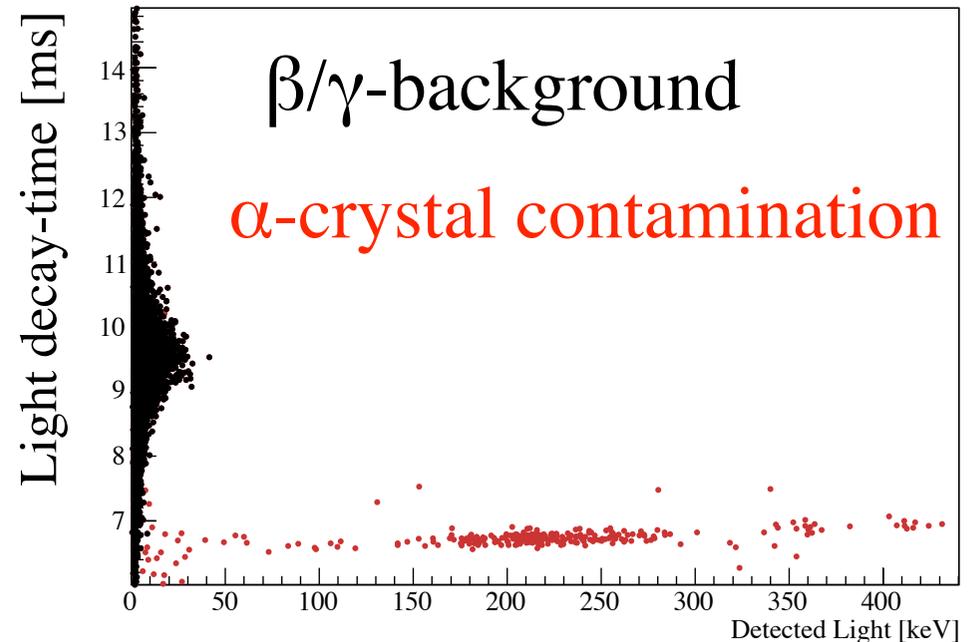


# ZnSe

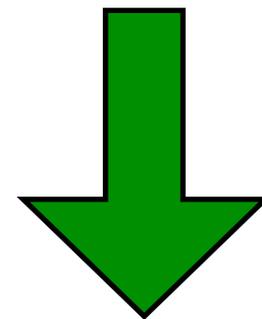
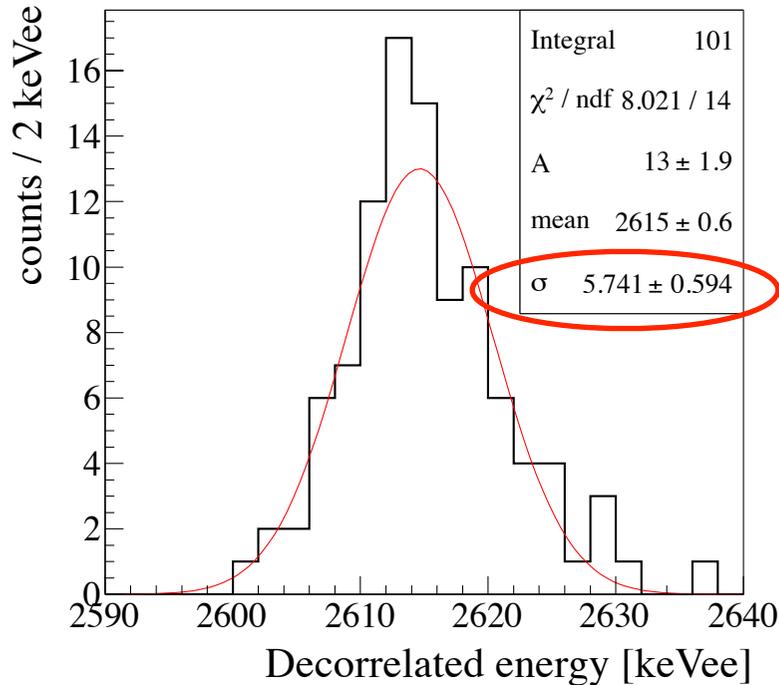
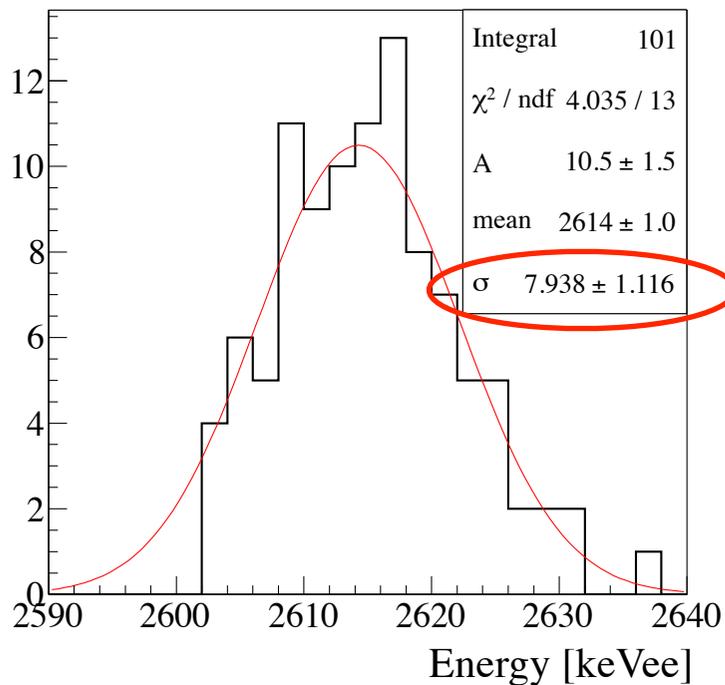
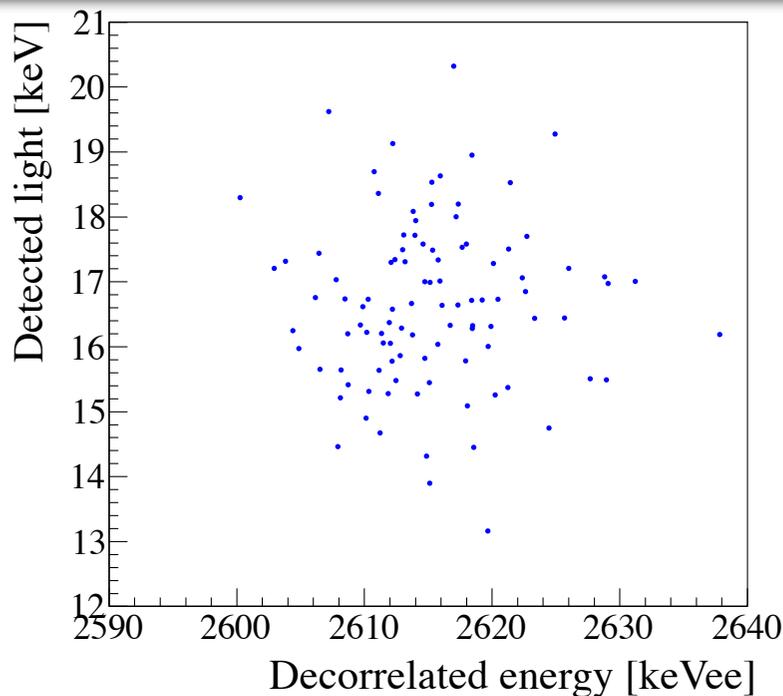
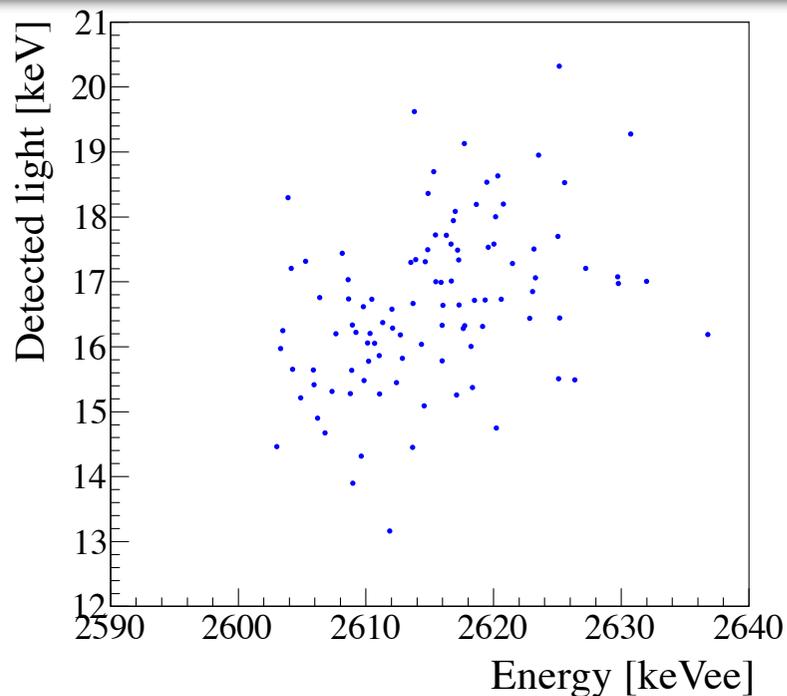
- $QF > 1$  is odd:
  - ▶ Observed only in this compound ( $\text{CdWO}_4$ ,  $\text{ZnMoO}_4$  and other crystals have  $QF < 1$ ).
  - ▶ not understood.



- Excellent separation using light energy and signal shape



# ZnSe: Light-Heat correlation

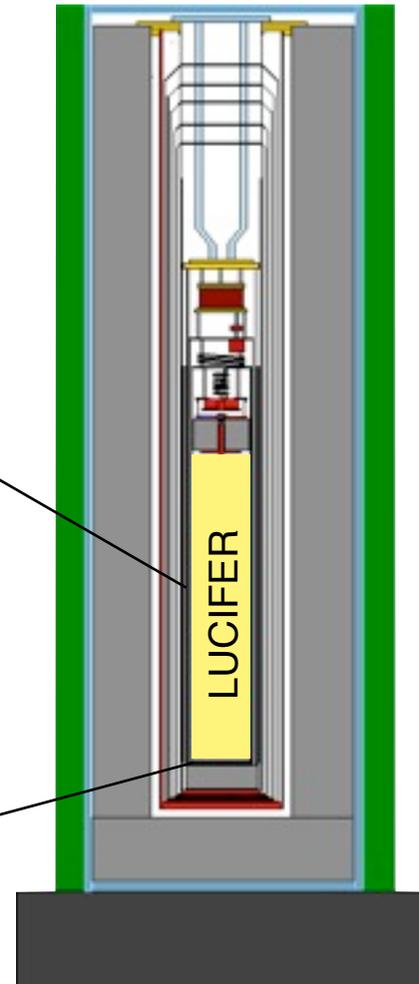
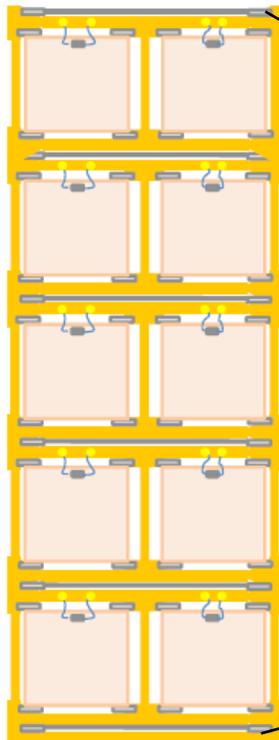


$\Delta E @ 2615 \text{ keV}: 13 \text{ keV FWHM}$

# Plan for a ZnSe array in 2015

- Operation of a tower of 32-40  $\text{Zn}^{82}\text{Se}$  crystals at LNGS.
  - ▶ Option1: use the Cuoricino cryostat in hallA (presently hosting CUORE-0), if CUORE-0 stops in 2015.
  - ▶ Option2: use the cryostat in hallC (presently running the CUORE-0 and LUCIFER R&Ds). Needs cryostat update.

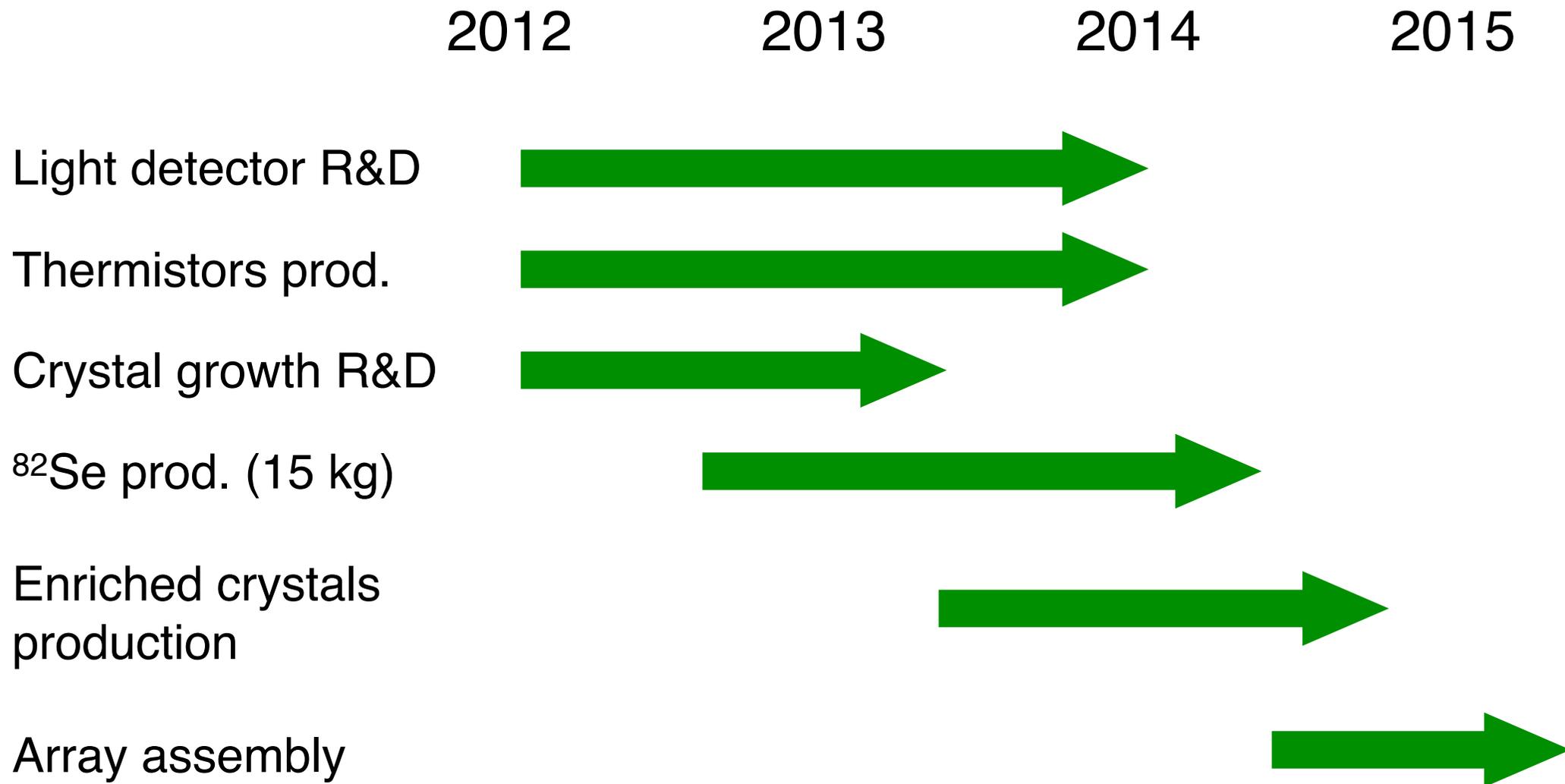
4 crystals  
per floor



*Cuoricino cryostat:*

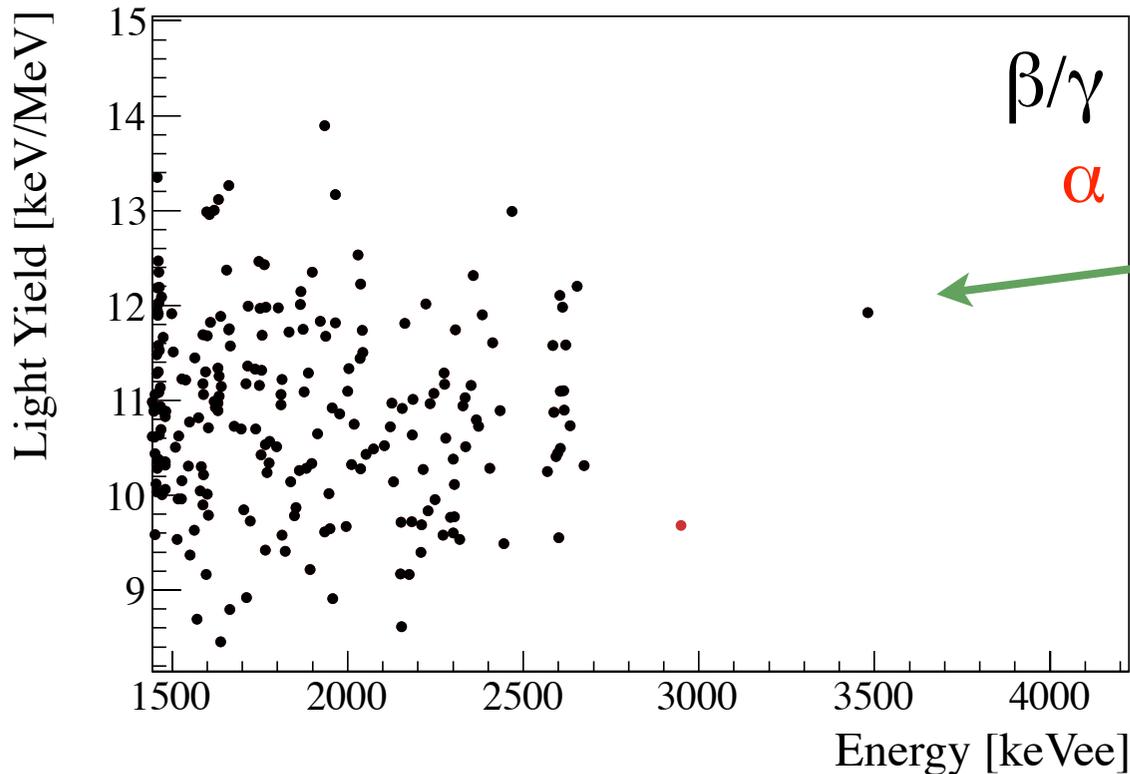
- Inner shield:
  - 1cm Roman Pb  
A ( $^{210}\text{Pb}$ ) < 4 mBq/Kg
- External shield:
  - 20 cm Pb
  - 10 cm Borated polyethylene
- Nitrogen flushing to avoid Rn contamination.

# ZnSe: schedule



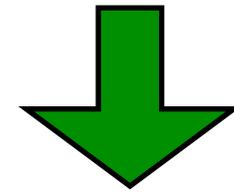
The most crucial part is represented by the crystal growth. The supplier (Ukraine) is presently fine-tuning the complicate procedure (that starts with metal Zn and metal Se). The request of minimizing the  $^{82}\text{Se}$  waste is a complicate issue. The target is to reach > 75 % efficiency.

# Do we need a $\mu$ -veto?



ZnSe data:

1  $\beta/\gamma$  event above  
the 2615 keV line  
in 580 hours



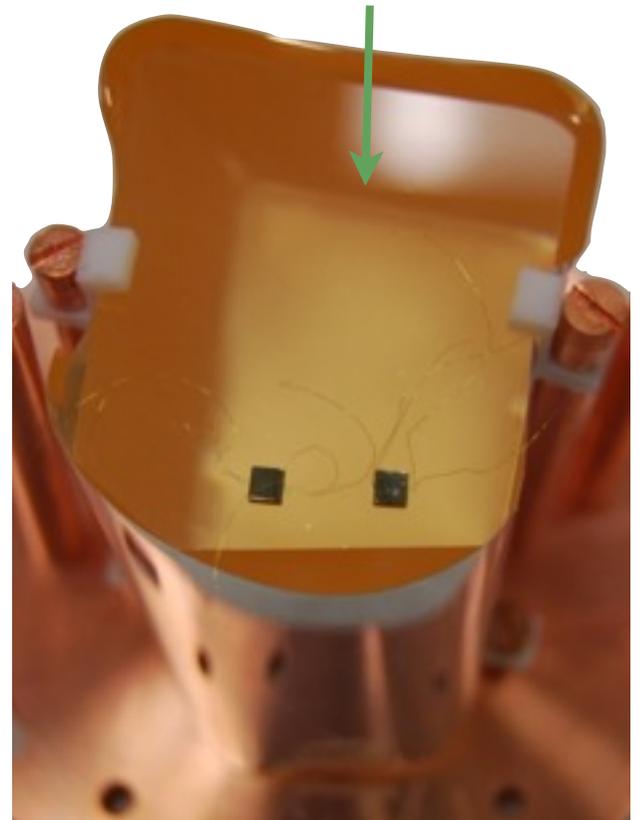
$\sim 5 \times 10^{-2}$  counts/keV/kg/y

- The event includes hits on close detectors (**multi-site** event)
  - ▶ Multiple  $\gamma$ 's produced by  $\mu$  interactions in the materials close to the detector.
- Easy to remove in this case, but what if one has one hit only?
  - ▶ Montecarlo simulation under development.

# Candidate #2: $\text{ZnMoO}_4$

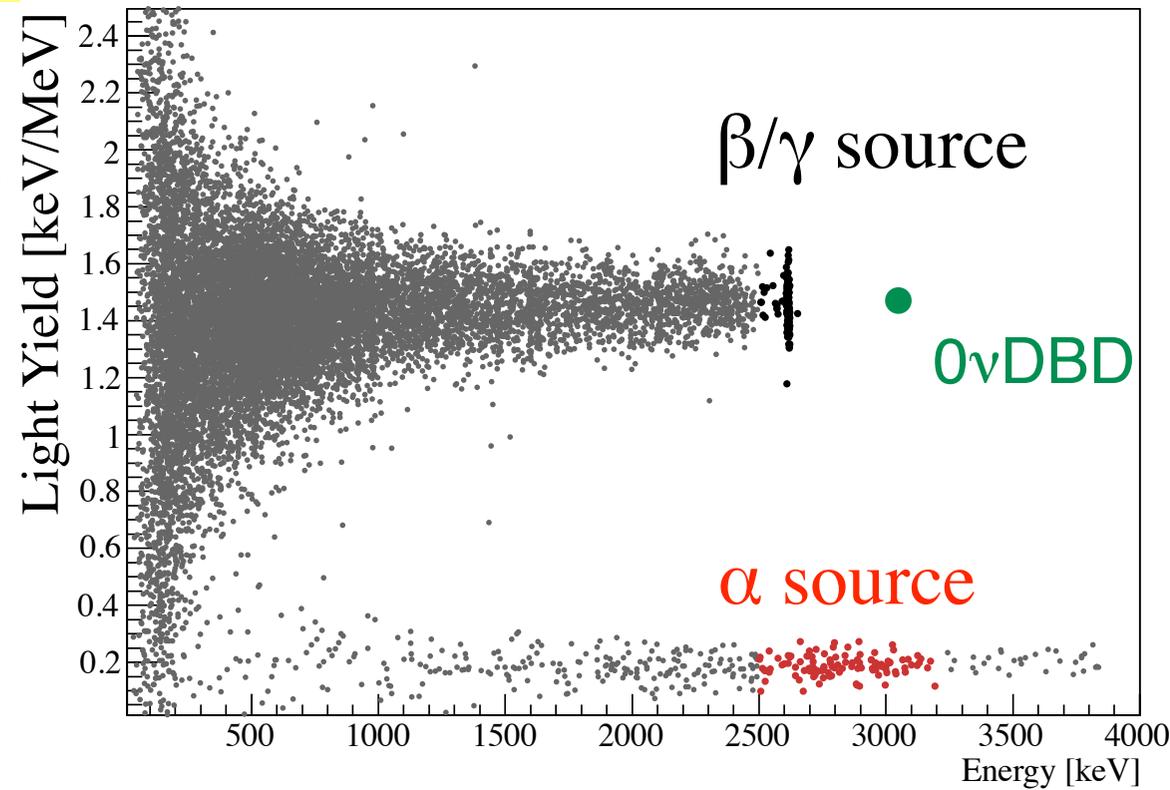
DBD Isotope:	$^{100}\text{Mo}$
Q-value [keV]	3034
isotopic abundance	10%
Light Yield [keV/MeV]	1.5
QF	0.2

Largest crystal  
operated so far: 330g

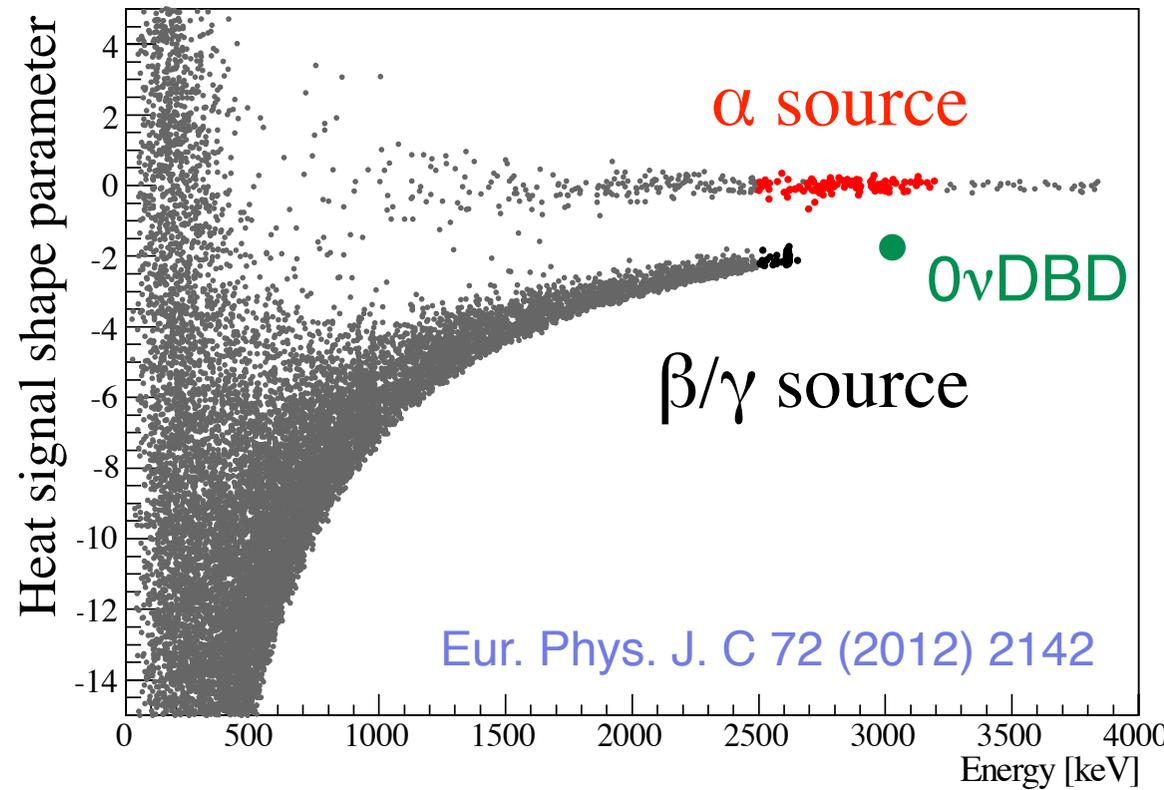


# ZnMoO<sub>4</sub>

Excellent discrimination  
using the light signal

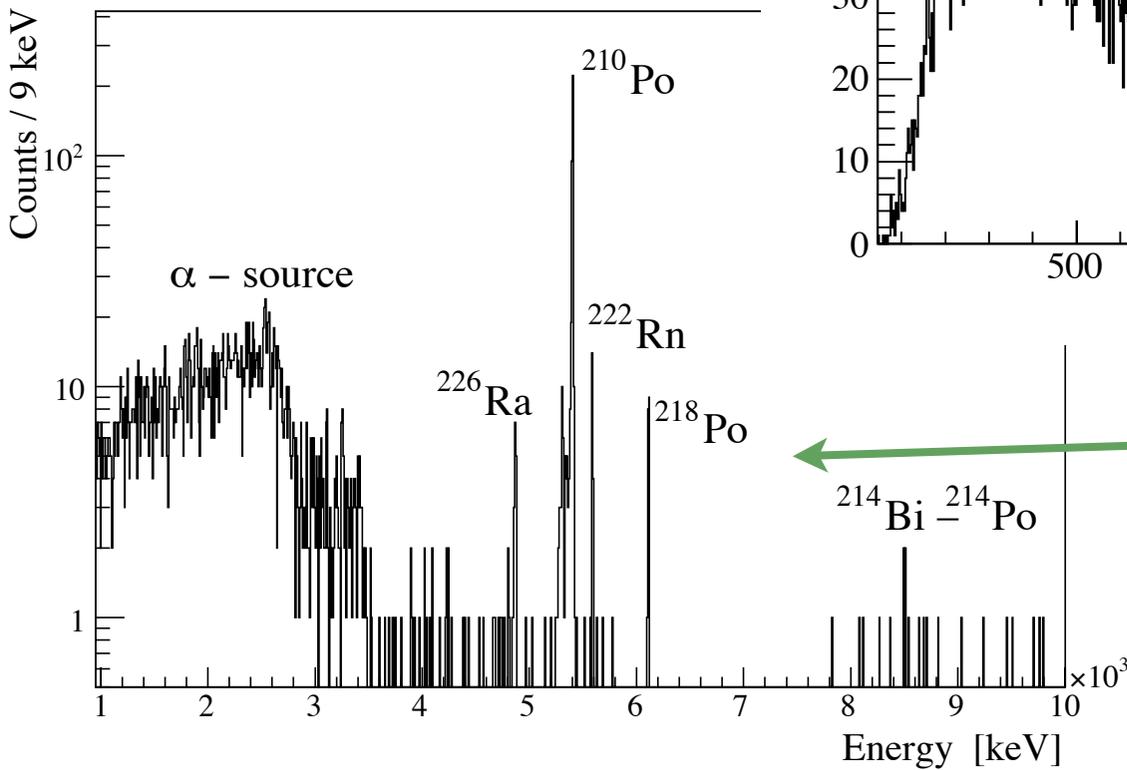
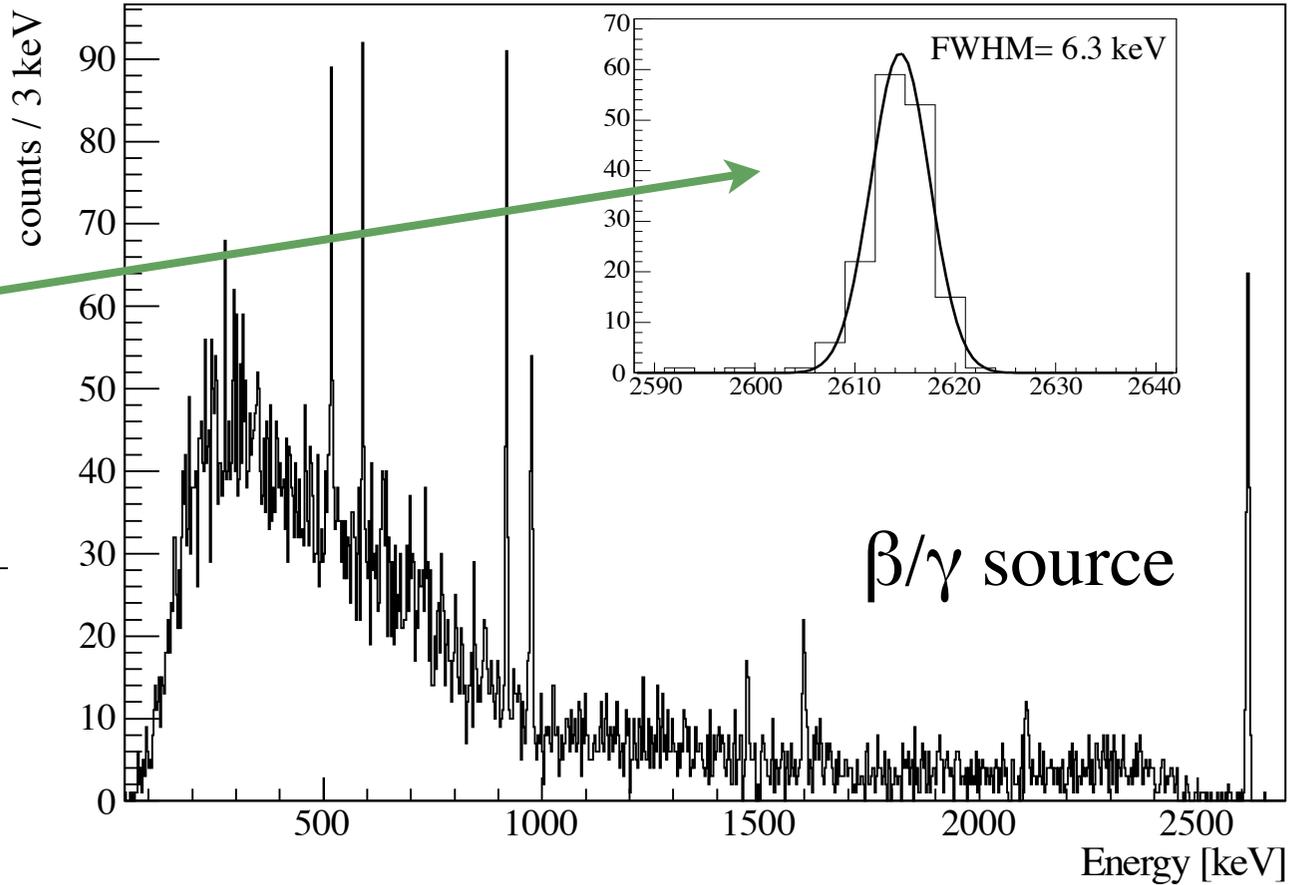


Discrimination using the  
shape of the *heat* signal!



# ZnMoO<sub>4</sub>

Energy resolution similar  
to CUORICINO  
(2x better than ZnSe)



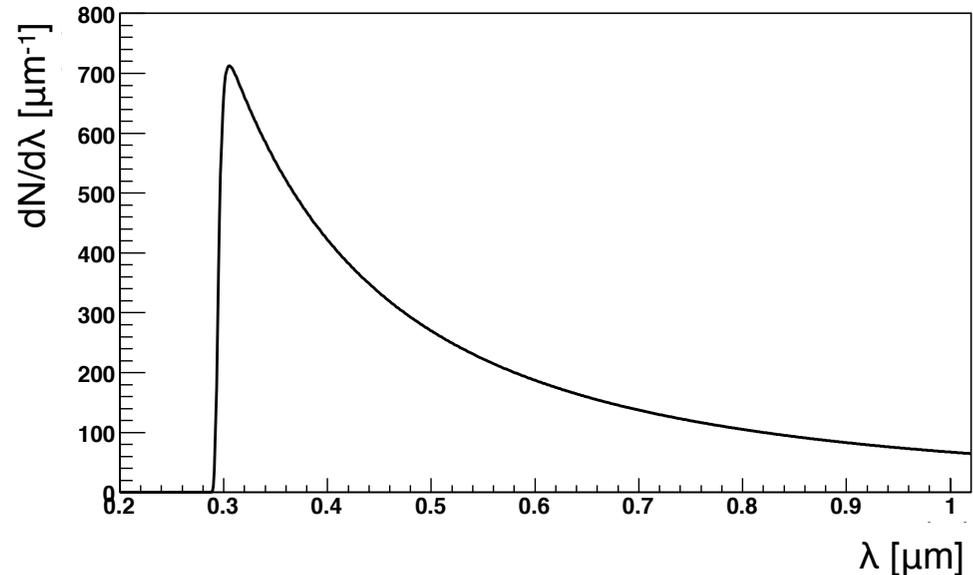
Internal contaminations:

<sup>232</sup>Th < 1.4 pg/g

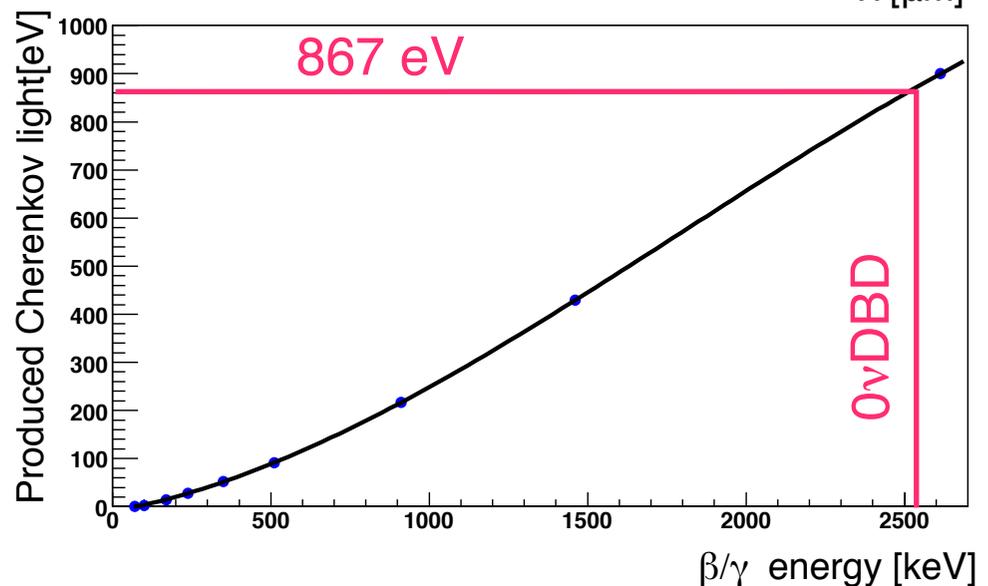
# Candidate #3: TeO<sub>2</sub>

TeO<sub>2</sub> does not scintillate, however MeV  $\beta$ 's emit Čerenkov light, unlike  $\alpha$ 's [ T. Tabarelli de Fatis, Eur. Phys. J. C 65 (2010) 359].

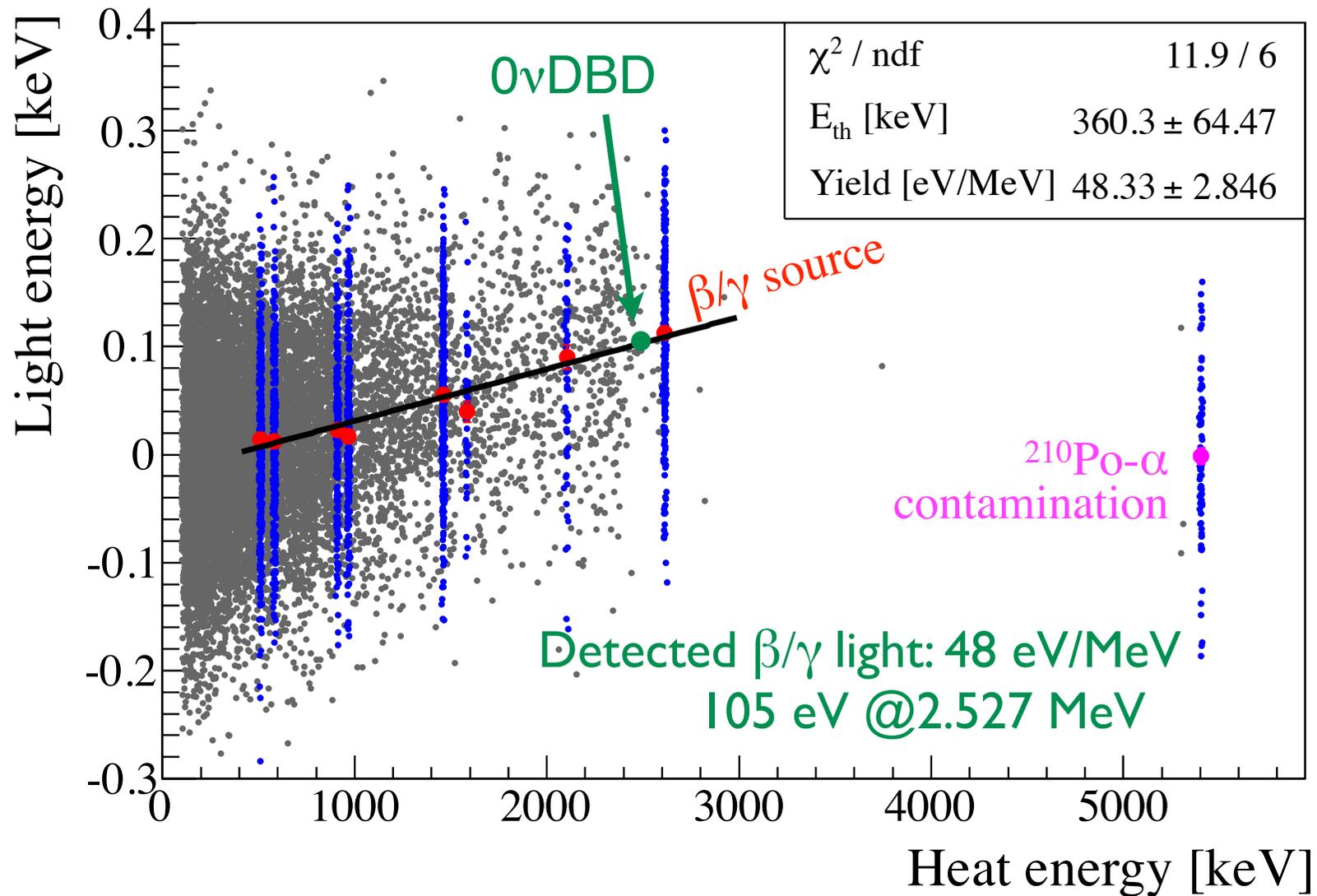
Simulated Čerenkov emission spectrum from 1.5 MeV  $\gamma$  in TeO<sub>2</sub> at low temperatures.



Simulated emitted Čerenkov light as a function of  $\beta/\gamma$  energy.

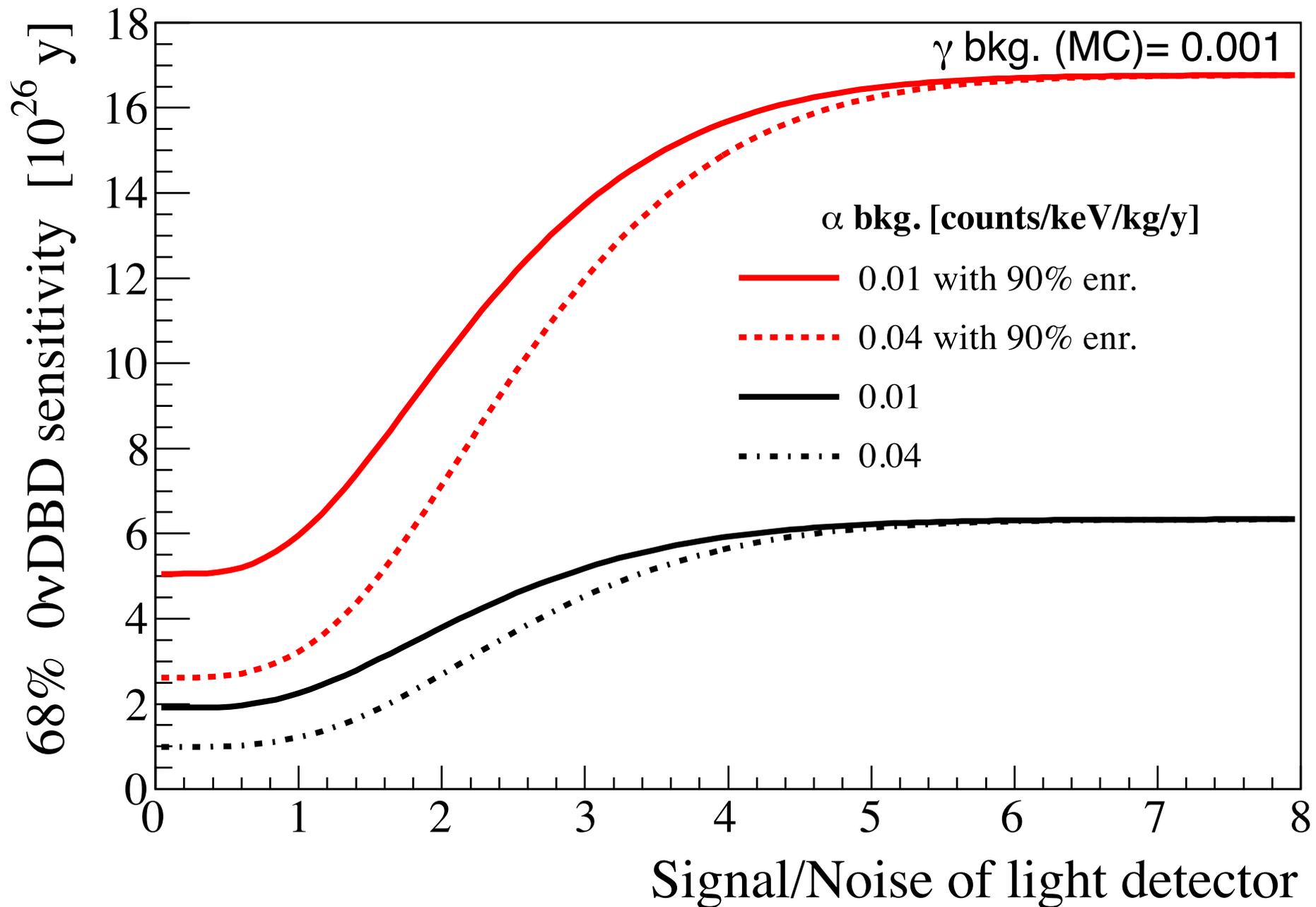


# Čerenkov from a CUORE crystal

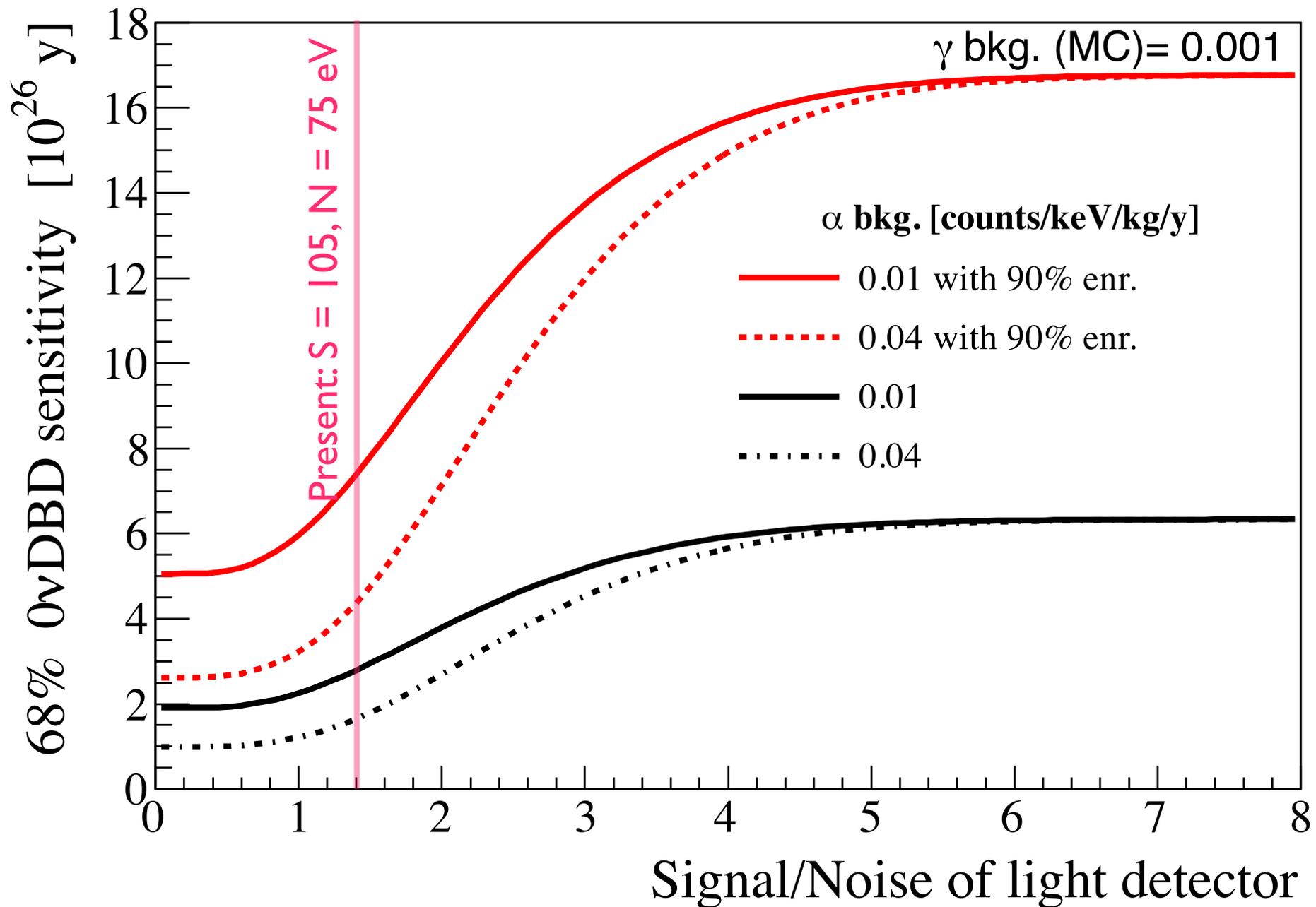


- Detected light not sufficient to discriminate  $\alpha$ 's event by event.
  - ▶ Needs light detector development: light collection, energy resolution.

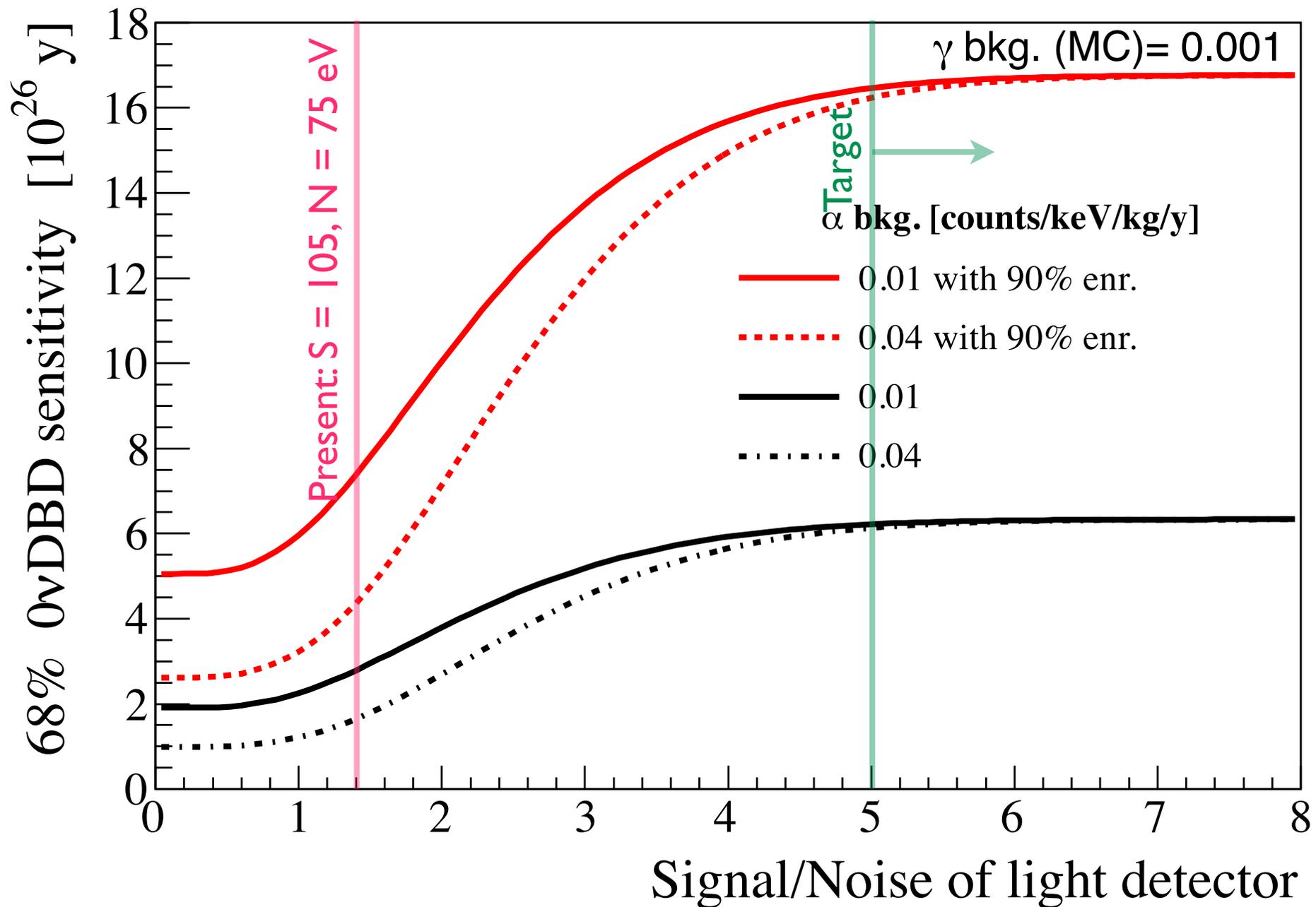
# CUORE + Čerenkov + enrichment



# CUORE + Čerenkov + enrichment



# CUORE + Čerenkov + enrichment



# Overview until 2015

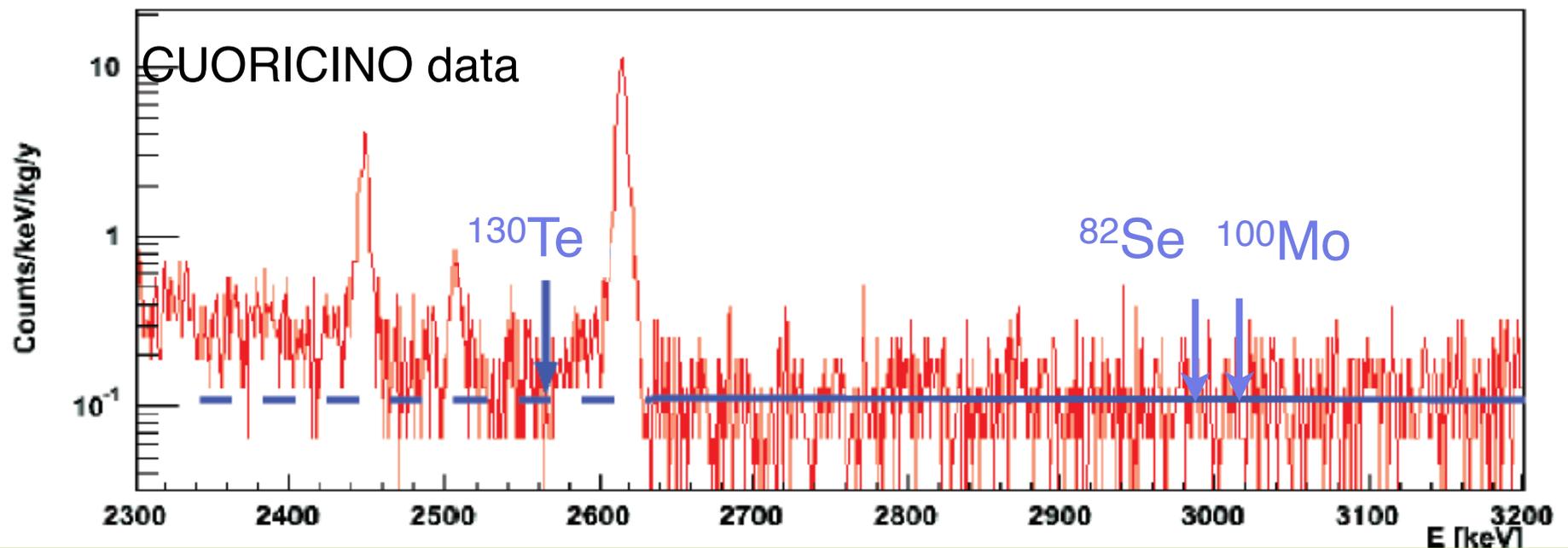
- ZnSe
  - ▶ Target: build a bolometric experiment of  $\sim 10$  kg of  $^{82}\text{Se}$
  - ▶ Status: Isotope in production, crystal growth under optimization.
- ZnMoO<sub>4</sub>
  - ▶ Target: build a bolometric experiment of  $\sim 10$  kg of  $^{100}\text{Mo}$
  - ▶ Status: MoU with IN2P3 and ITEP in consideration.
- TeO<sub>2</sub>
  - ▶ Target: develop light detectors with S/N improved by a factor 4.
  - ▶ Status: KIDs and Neganov-Luke detectors under development.

# Overview until 2015

- ZnSe *baseline*
  - ▶ Target: build a bolometric experiment of  $\sim 10$  kg of  $^{82}\text{Se}$
  - ▶ Status: Isotope in production, crystal growth under optimization.
- ZnMoO<sub>4</sub>
  - ▶ Target: build a bolometric experiment of  $\sim 10$  kg of  $^{100}\text{Mo}$
  - ▶ Status: MoU with IN2P3 and ITEP in consideration.
- TeO<sub>2</sub>
  - ▶ Target: develop light detectors with S/N improved by a factor 4.
  - ▶ Status: KIDs and Neganov-Luke detectors under development.

# Ultimate background: $\beta/\gamma$

- So far, we do not have a measure of the  $\beta/\gamma$  background above 2615 keV with bolometric arrays à la CUORICINO, and of the CUORE  $\beta/\gamma$  background at the  $^{130}\text{Te}$  Q-value.



so far:  $\alpha$ 's +  $\beta/\gamma$ 's  $\longleftrightarrow$   $\alpha$ 's (+  $\beta/\gamma$ 's?)

CUORE ( $^{130}\text{Te}$ ) will measure the reduction

$^{82}\text{Se}$  and  $^{100}\text{Mo}$  arrays will answer

# Conclusion: which one after CUORE?

- To cover the entire inverted hierarchy of neutrino masses a bolometric experiment operated in the CUORE cryostat will require:

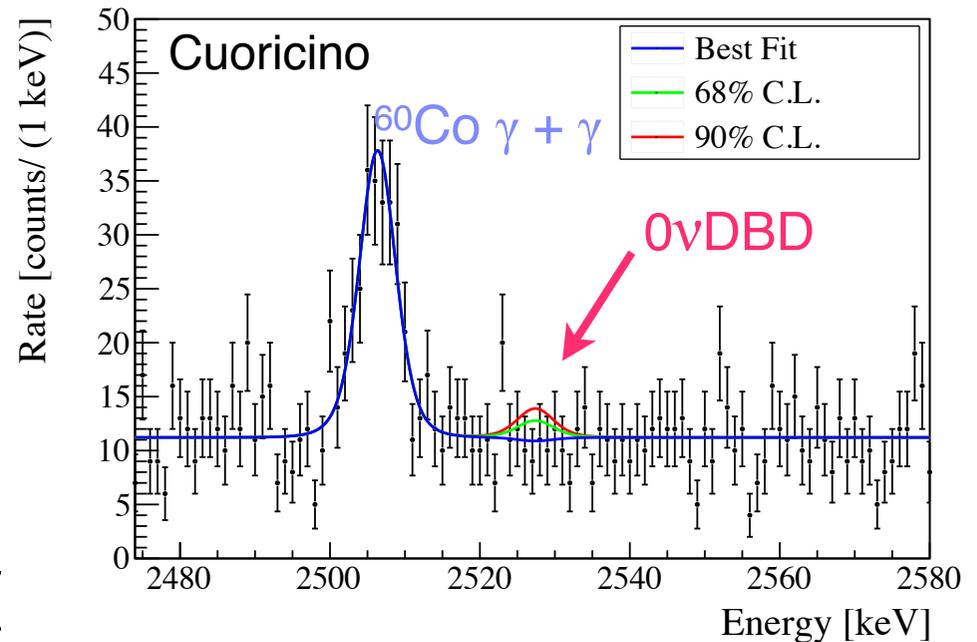
✓  $\Delta E \sim 5$  keV FWHM    ✓ Bkg < 1 count/keV/ton/y    ✓ 1 ton isotope

Crystal	R&D Status	$\Delta E$ (keV)	Bkg. reach	Enrichment cost (€/g)
Zn <sup>82</sup> Se	Isotope/crystals in preparation	13	likely	75 <i>(contract)</i>
Zn <sup>100</sup> MoO <sub>4</sub>	MoU to be signed	6	likely	100-130 <i>(estimate)</i>
<sup>130</sup> TeO <sub>2</sub> (Čerenkov)	CUORE experience Light Detectors	5	to be proved	10-20 <i>(estimate)</i>

Backup

# CUORE - @ LNGS

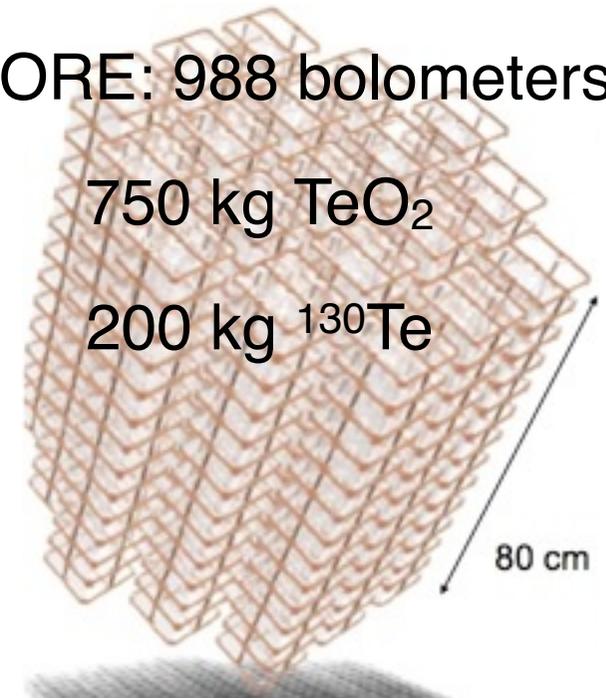
- $\text{natTeO}_2$  bolometers (34%  $^{130}\text{Te}$ ), 750g each ( $\Delta E = 5$  keV FWHM)
- Past: **Cuoricino**
  - ▶ 62 bolometers
  - ▶ 11 kg ( $^{130}\text{Te}$ ) $\times 2$ y,
  - ▶ Bkg: 0.16 cpy/keV/kg
  - ▶  $T^{0\nu}_{1/2} > 2.8 \times 10^{24}$  years (90% CL)
  - ▶  $\langle m_{\beta\beta} \rangle < 300 \sim 700$  meV
- Future: **Cuore** (data taking in 2015)
  - ▶ Expected bkg: 0.01~0.04 cpy/keV/kg
  - ▶ Exp.  $T^{0\nu}_{1/2} > 1.6 \times 10^{26}$  years
  - ▶  $\langle m_{\beta\beta} \rangle < 40 \sim 94$  meV
- Present: **Cuore-0**, a CUORE-like tower.
  - ▶ same mass of Cuoricino, 0.05 cpy/keV/kg.



CUORE: 988 bolometers

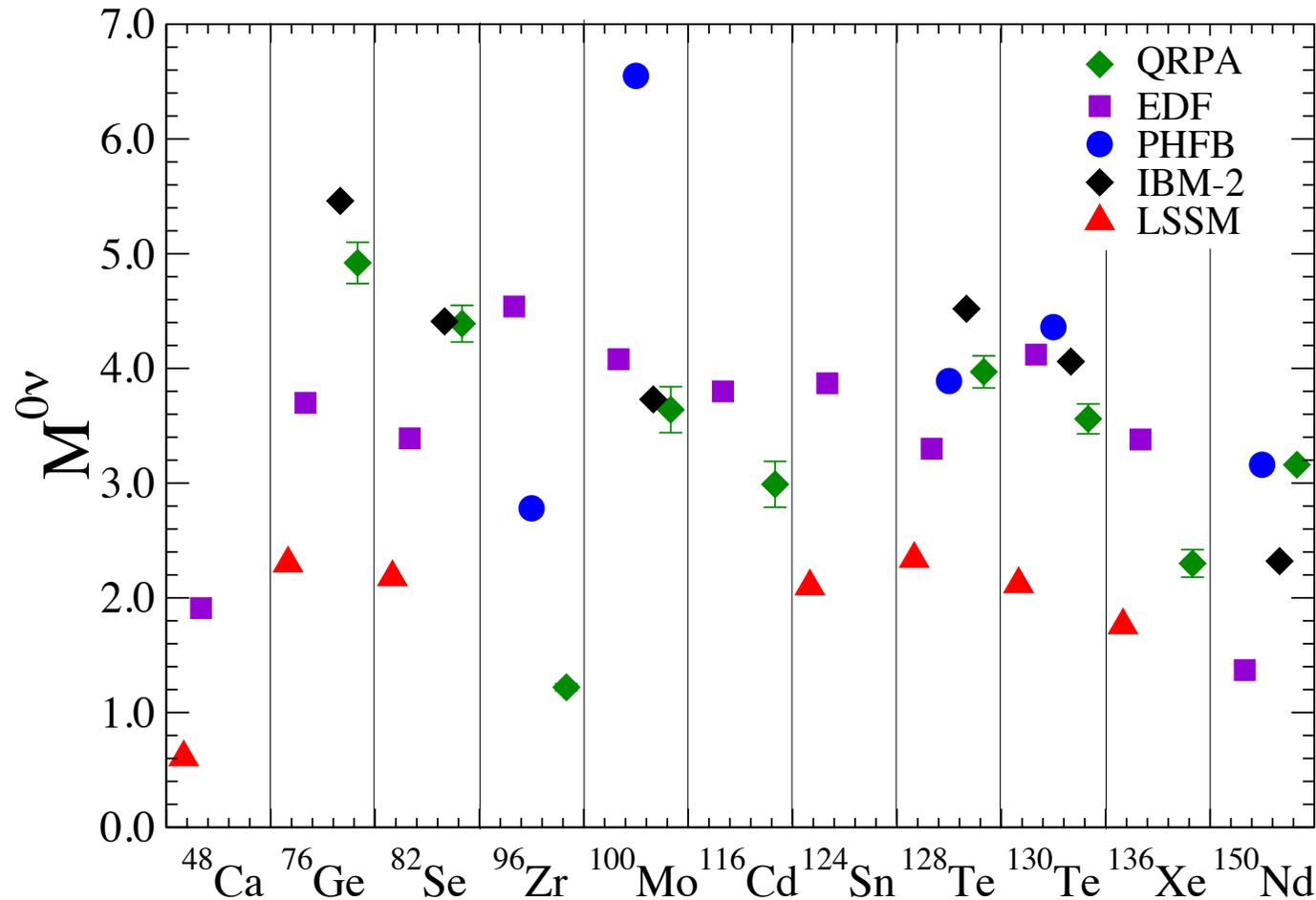
750 kg  $\text{TeO}_2$

200 kg  $^{130}\text{Te}$



# NME

$$|m_{\beta\beta}|^2 = 1 / \left[ G(Q, Z) |M^{0\nu}|^2 \tau_{1/2}^{0\nu} \right]$$



- The spread in the values does not influence the isotope choice.
- Generates problems when comparing exclusions and evidences from experiments running different isotopes.