Future prospects for the CUPID Experiment

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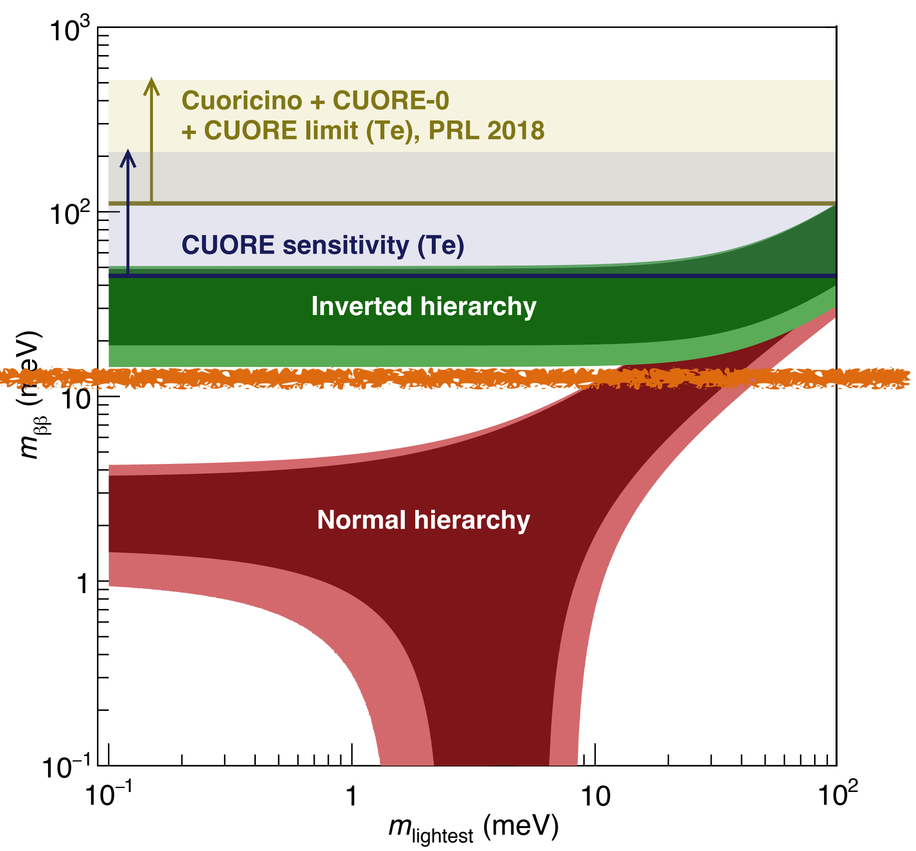
DBD 2018 - Oct 23 2018

Outline

- CUPID Goal: Probing the inverted hierarchy
- CUORE: Status for TeO_2 bolometers
- Progress of enriched ^{100}Mo bolometers
- Prospects for enriched ^{130}Te bolometers
- CUPID Collaboration forming

Goals for CUPID



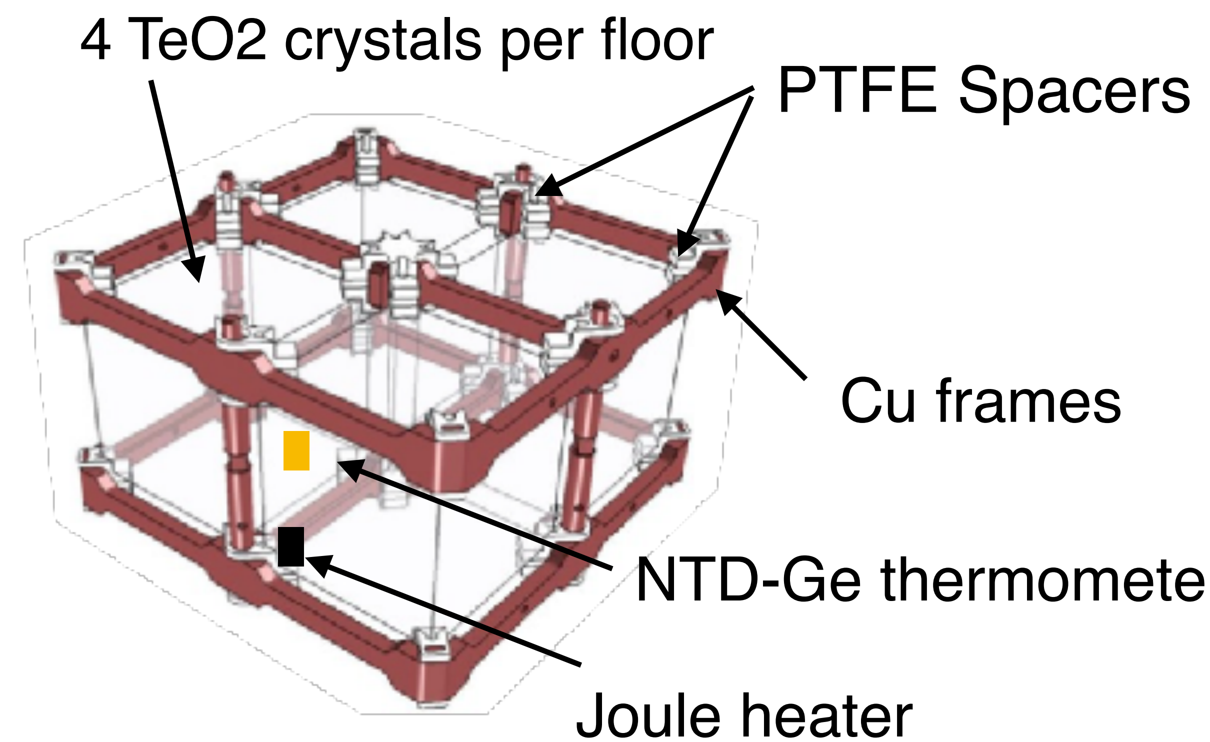
- CUPID:
  CUore Upgrade with Particle ID
- Fully probe the inverted hierarchy of neutrino masses
- Baseline target isotope is 100Mo embedded in LiMoO4 scintillating bolometers
- Viable alternative is 130Te embedded in TeO2 instrumented with advanced cryogenic light detectors

	BI (c/kev/kg/yr)	T1/2 sensitivity (90% C.L)	mbb (meV)
^{100} Mo	$<10^{-4}$	$2x10^{27}$	9-15
^{130}Te	$<10^{-4}$	$5x10^{27}$	6-28

At DNP see:
EN.00009:
Li2MoO4 for 0 decay search in CUPID - The Physics case and current status
B. Schmidt

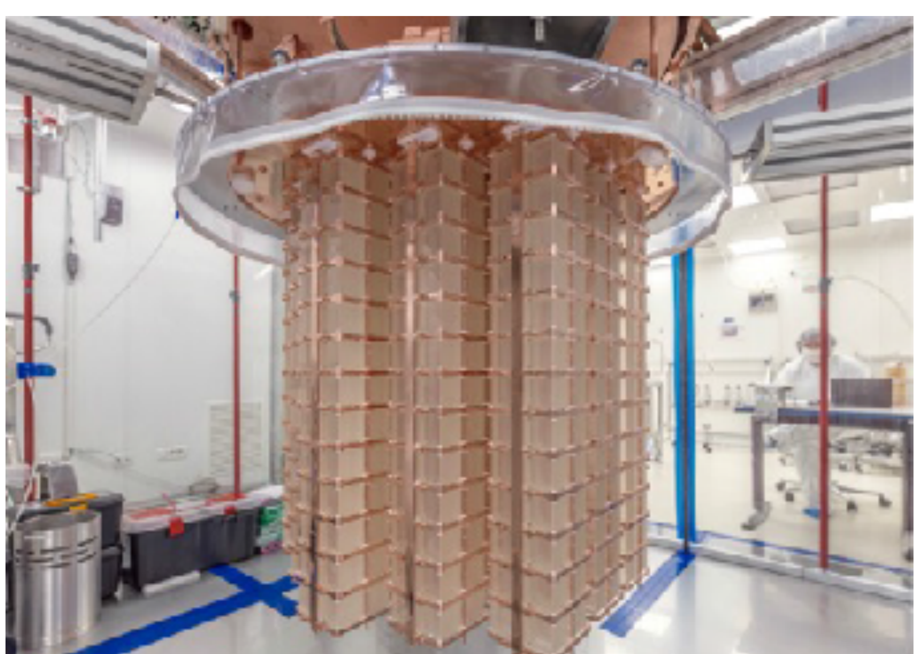
CUORE -reminder

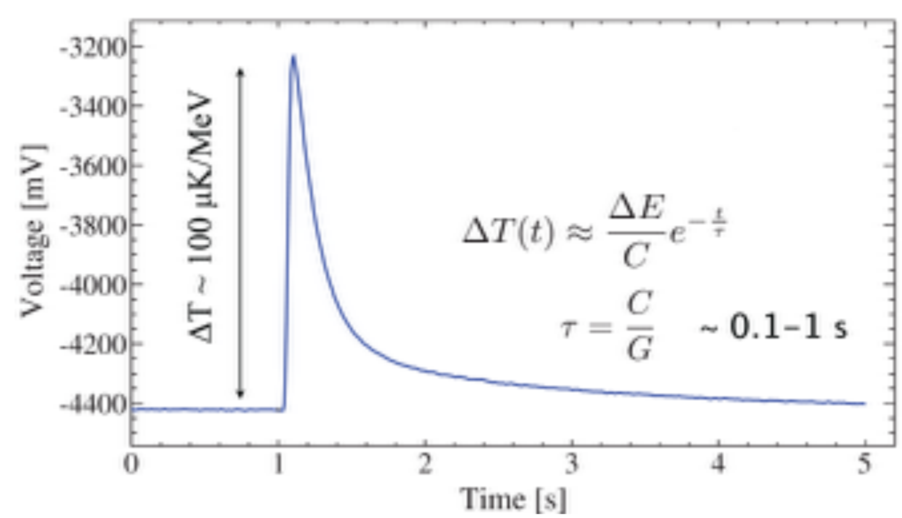
- Array of 988 $^{nat}TeO_2$ bolometers (750kg)
- Operated as thermal detectors (T~10mK)
- Target isotope ^{130}Te (206kg)
- Q-value: 2527.5 keV



13 floors per tower

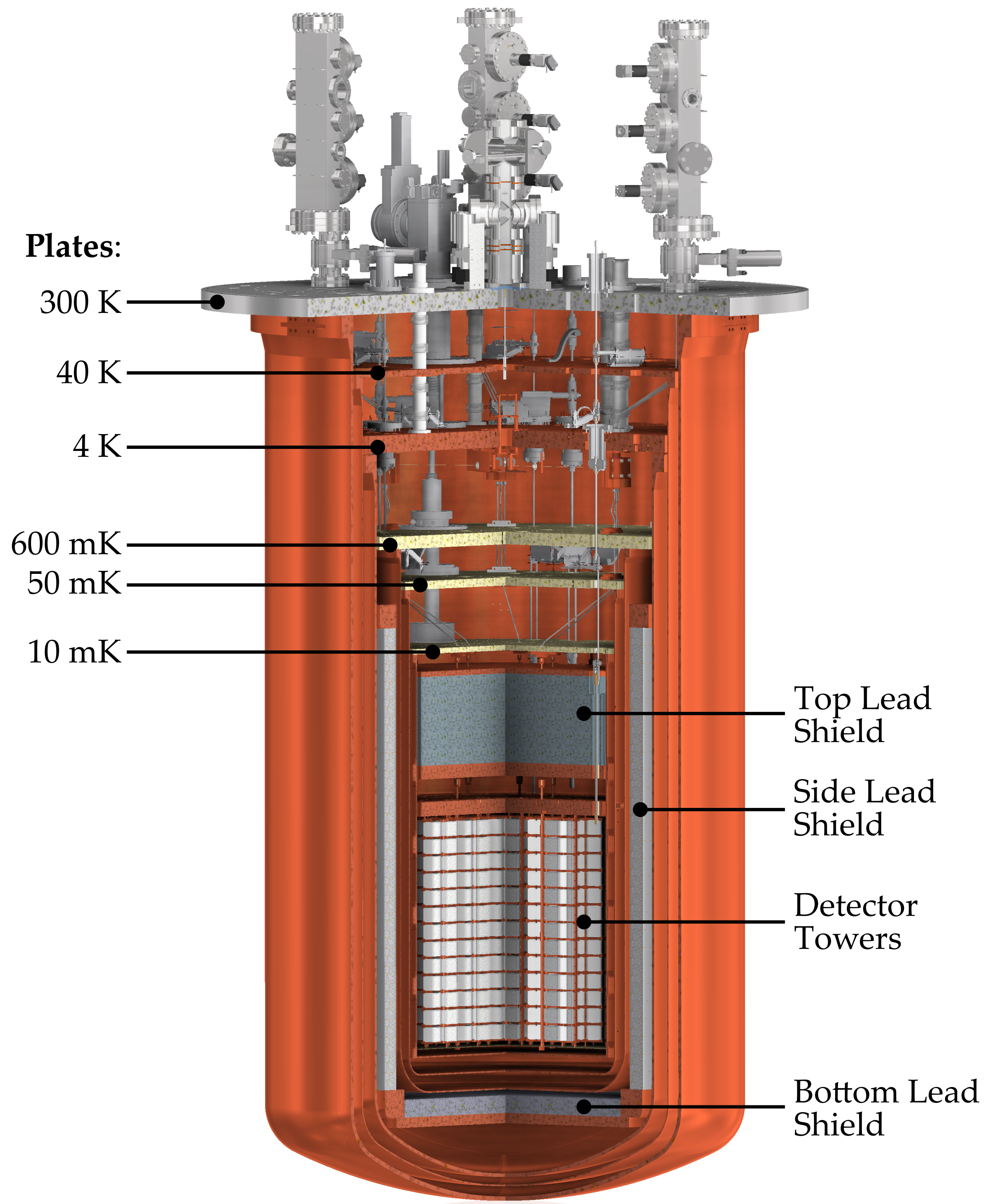
19 towers in total



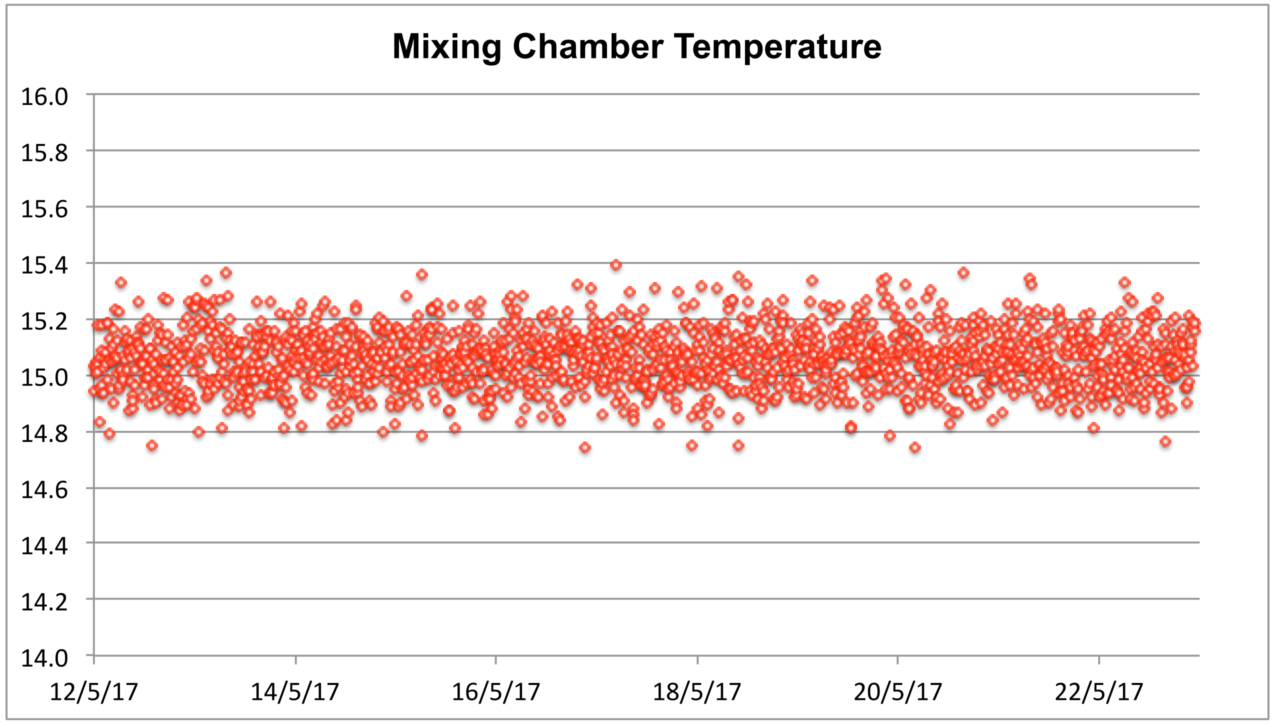


At DNP see DM.00007)
Ultralow-Radon Environment for the Installation of the CUORE 0νββ Decay Detector
A. Drobyzhev Oct 25 10.30 am

CUORE Cryogenics



Not shown:
Superinsulation (SI)

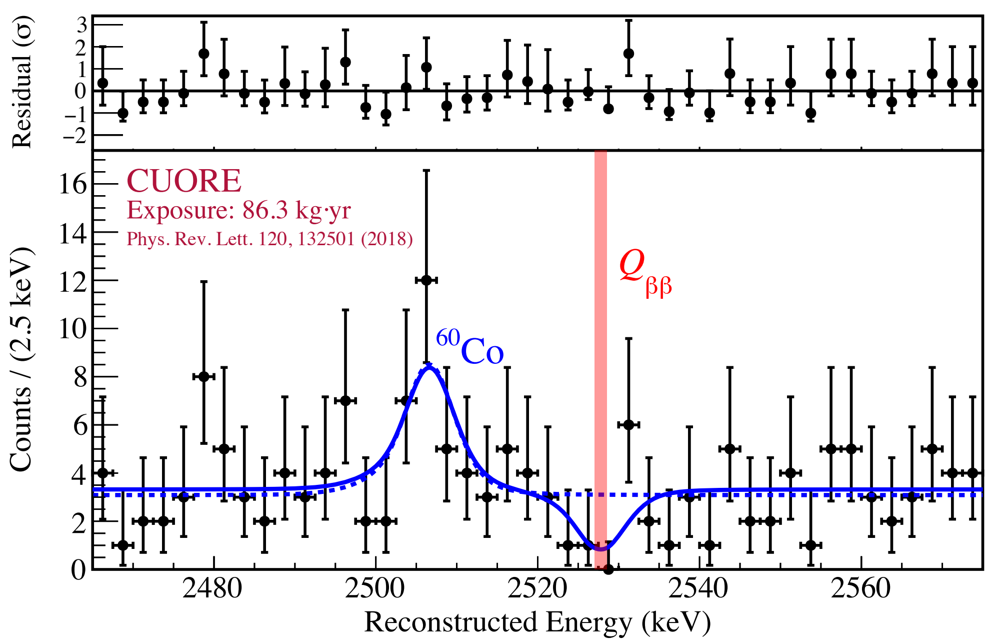


- Capable of cooling detector payload down to 7mK
- Demonstrates it is practical to operate tonne-scale detector at mK temperatures !

CUORE results

$0\nu\beta\beta$ search PRL **120** 132501 (2018)

See L.A. Winslow's talk



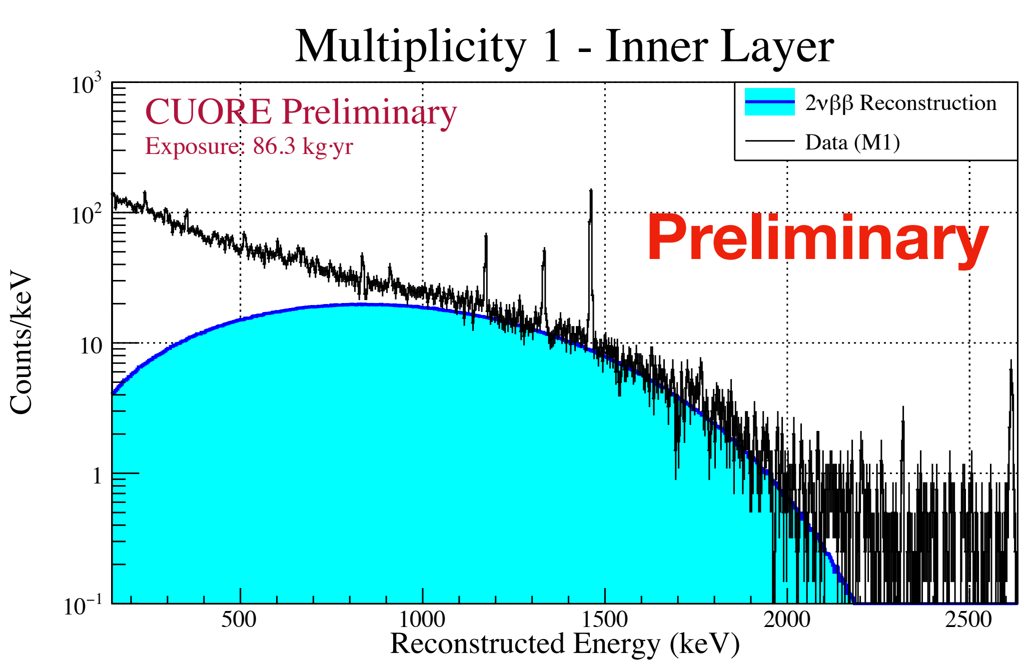
$$\mathrm{BI} = (1.4 \pm 0.2) \times 10^{-2} \mathrm{cnts/keV \cdot kg \cdot yr}$$

Effective resolution (FWHM) @Qbb: 7.7 keV

$$T^{0\nu}_{1/2} > 1.5 \times 10^{25} \mathrm{yr} \quad (90\%\mathrm{C.L.})$$

At DNP see EN.00007:
Neutrinoless Double Beta Decay And Other Rare Event Searches With CUORE
D. Speller , Oct 25

$2\nu\beta\beta$ measurement (in preparation)



- 2vbb decay signal in inner-most towers

Preliminary

$$T^{2\nu}_{1/2} = (7.9 \pm 0.1(\mathrm{stat}) \pm 0.2(\mathrm{syst.})) \times 10^{20} \mathrm{yr}$$

At DNP see MN.00007 :
CUORE Measurement of Two-Neutrino Double-Beta Decay
(C. Davis, Oct 27 3.30pm)

Interpretation of 0vbb search

- The combined 90% C.L. limit is

$$T_{1/2}^{0\nu\beta\beta} > 1.5 \times 10^{25}\ \mathrm{y}$$

$$\mathrm{m}_{\beta\beta} < 110 - 520\ \mathrm{meV}$$

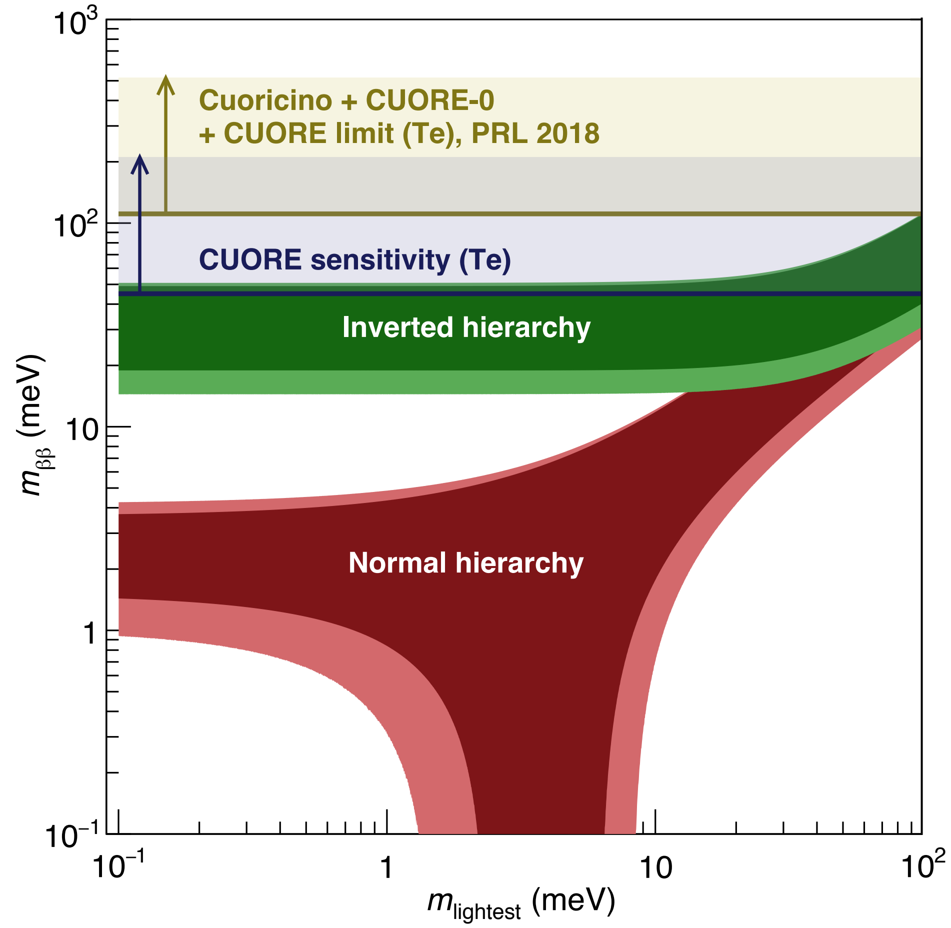
NME:
JHEP02 (2013) 025
Nucl. Phys. A 818, 139 (2009)
Phys. Rev. C 87, 045501 (2013)
Phys. Rev. C 87, 064302 (2014)
Phys. Rev. C 91, 034304 (2015)
Phys. Rev. C 91, 024613 (2015)
Phys. Rev. C 91, 024309 (2015)
Phys. Rev. C 91, 024316 (2015)
Phys. Rev. Lett. 105, 252503 (2010)
Phys. Rev. Lett. 111, 142501 (2013) (2010)

Projected CUORE Sensitivity

- CUORE sensitivity (5yrs livetime)

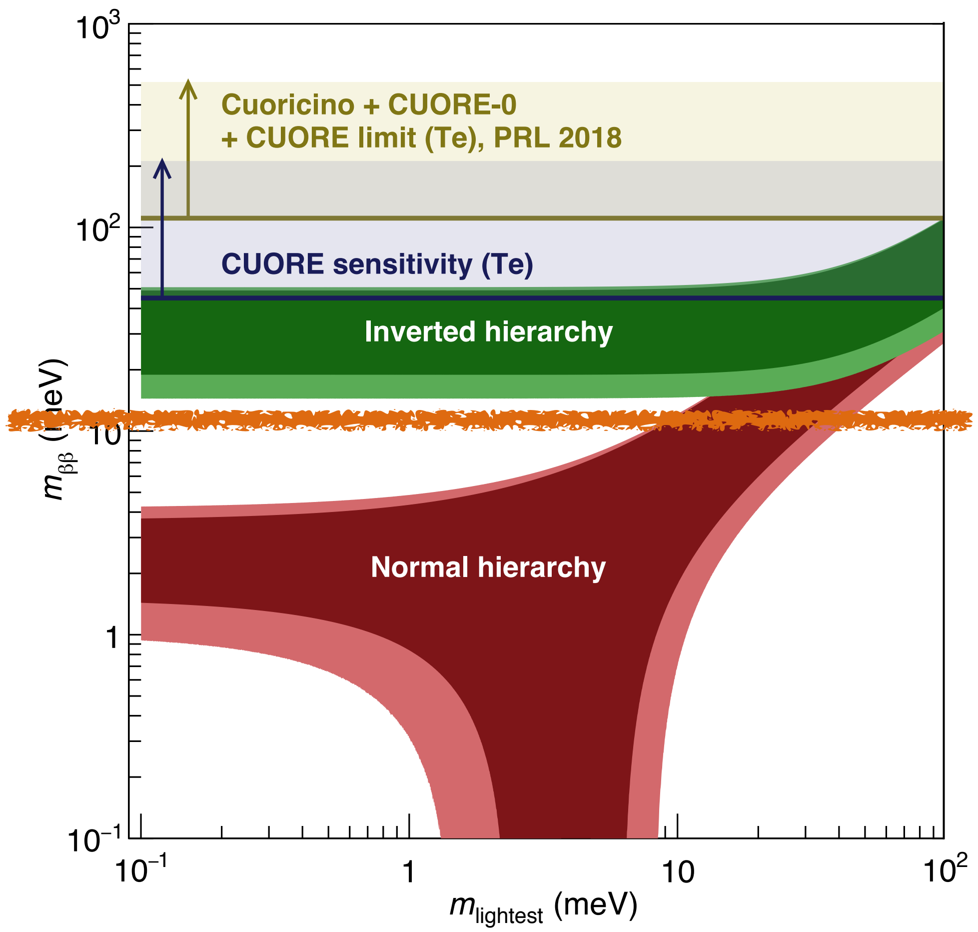
$$T_{1/2}^{0\nu\beta\beta} = 9.0 \times 10^{25}\mathrm{y}$$

$$\mathrm{m}_{\beta\beta} < 50 - 200\ \mathrm{meV}$$



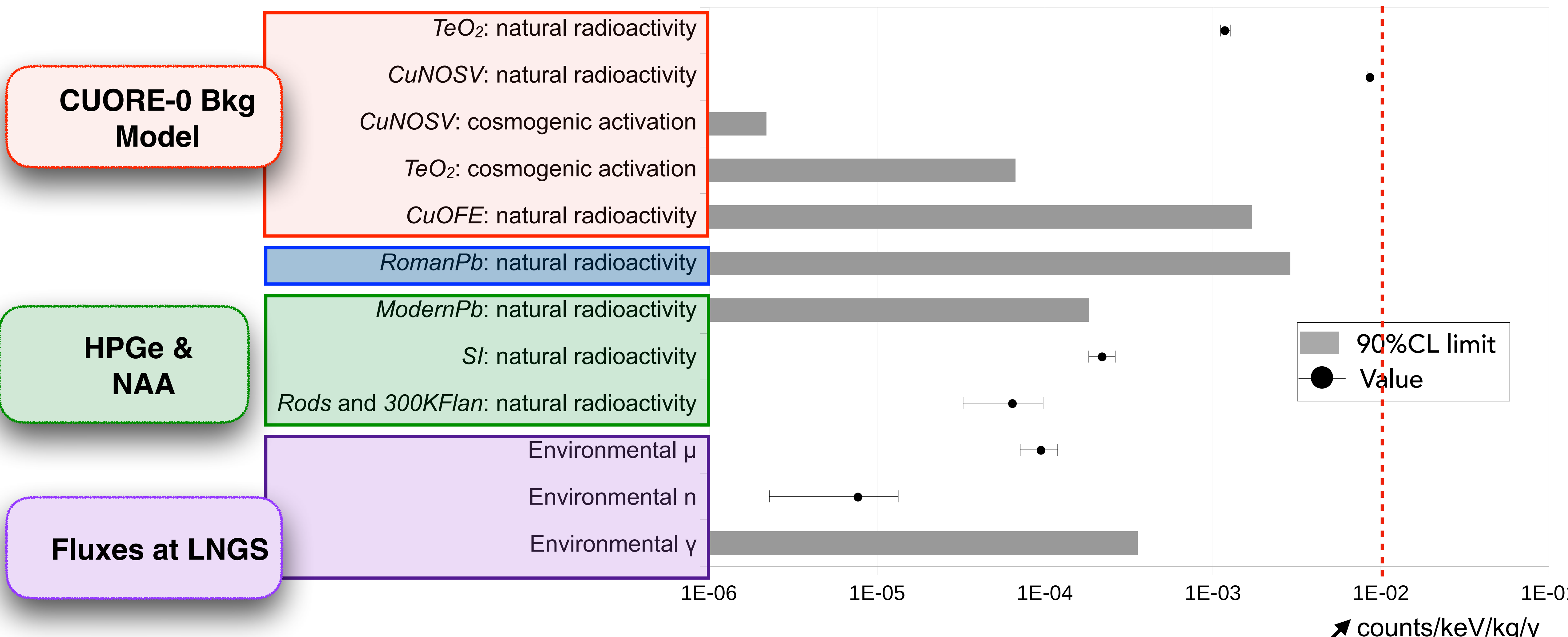
Eur. Phys. J. C (2017) 77:532

Prospects to explore the inverted hierarchy



- Requires half-life sensitivity on the order of 10^{27} years !
- To do this with 250~500 kg of isotope in a reasonable time (10 y) requires background free experiment (b < 10^{-4} c/kev/kg/y)

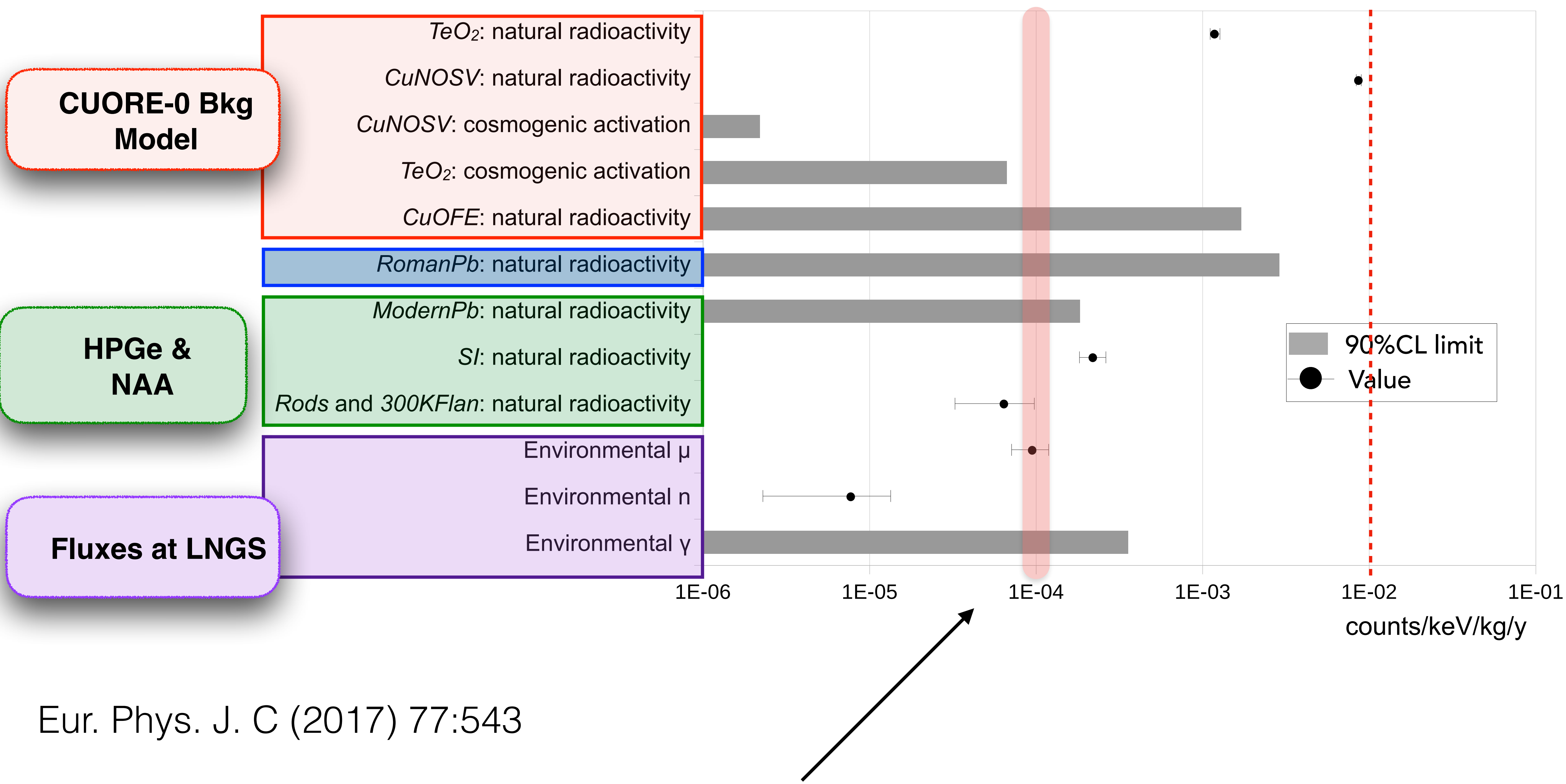
CUORE Background budget   ROI @ 2528 keV



Eur. Phys. J. C (2017) 77:543

Current CUORE Bkg ~0.01 c/keV/kg/y

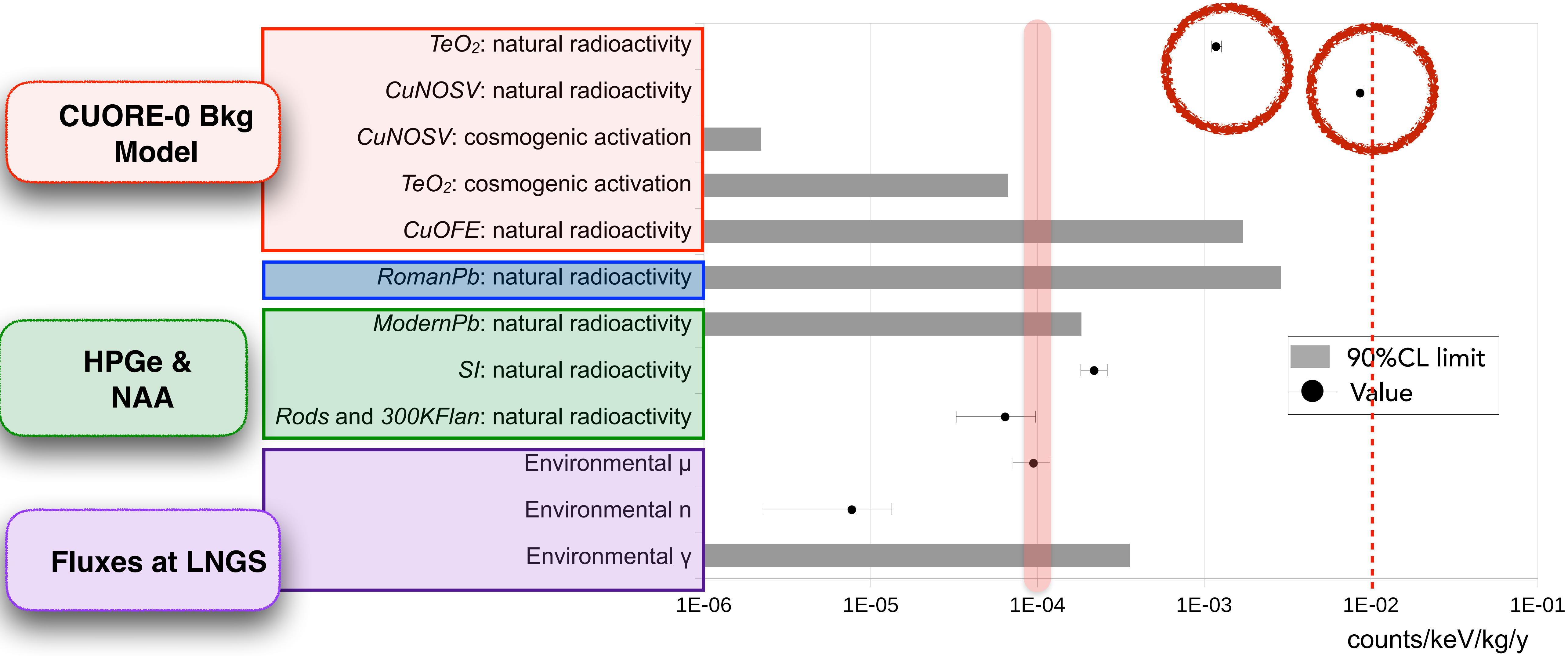
CUORE Background budget   ROI @ 2528 keV



Eur. Phys. J. C (2017) 77:543

Goal for CUPID ~ 10^{-4} c/keV/kg/yr

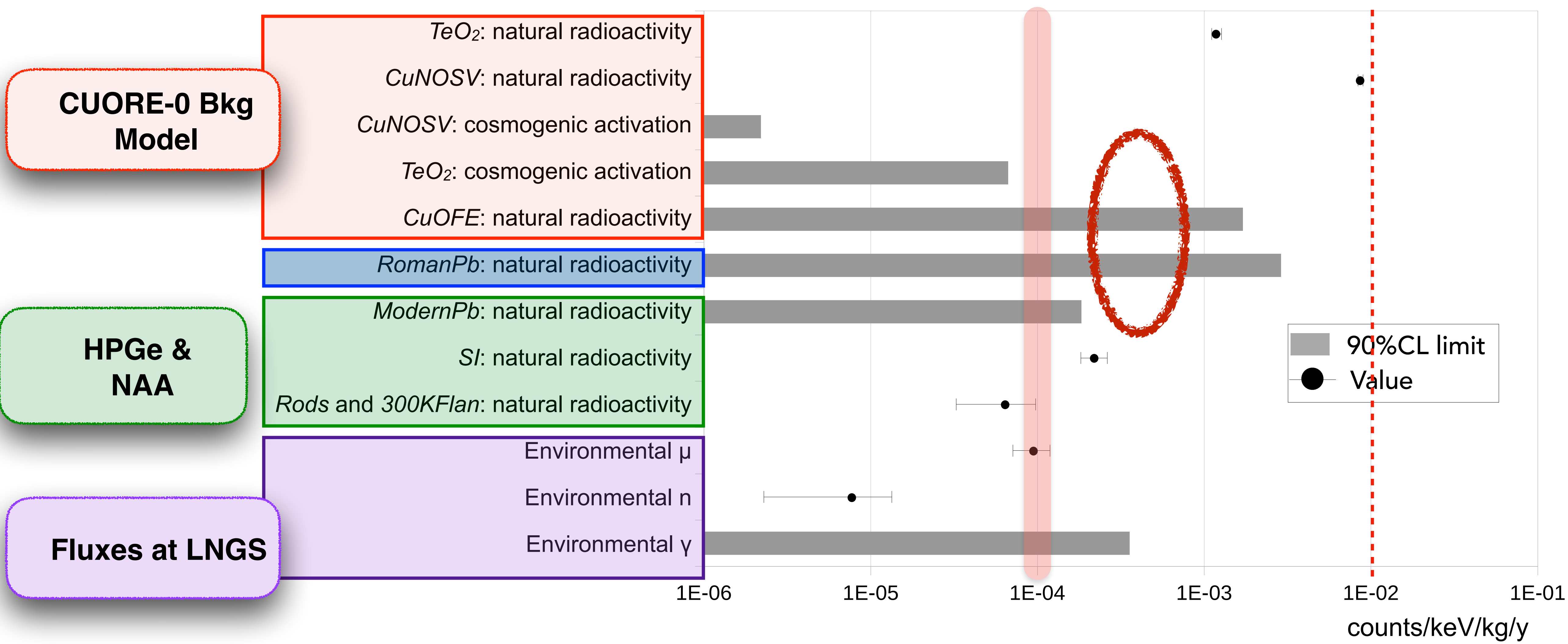
CUORE Background budget   ROI @ 2528 keV



Eur. Phys. J. C (2017) 77:543

Background from surface alphas are the dominant source

CUORE Background budget   ROI @ 2528 keV



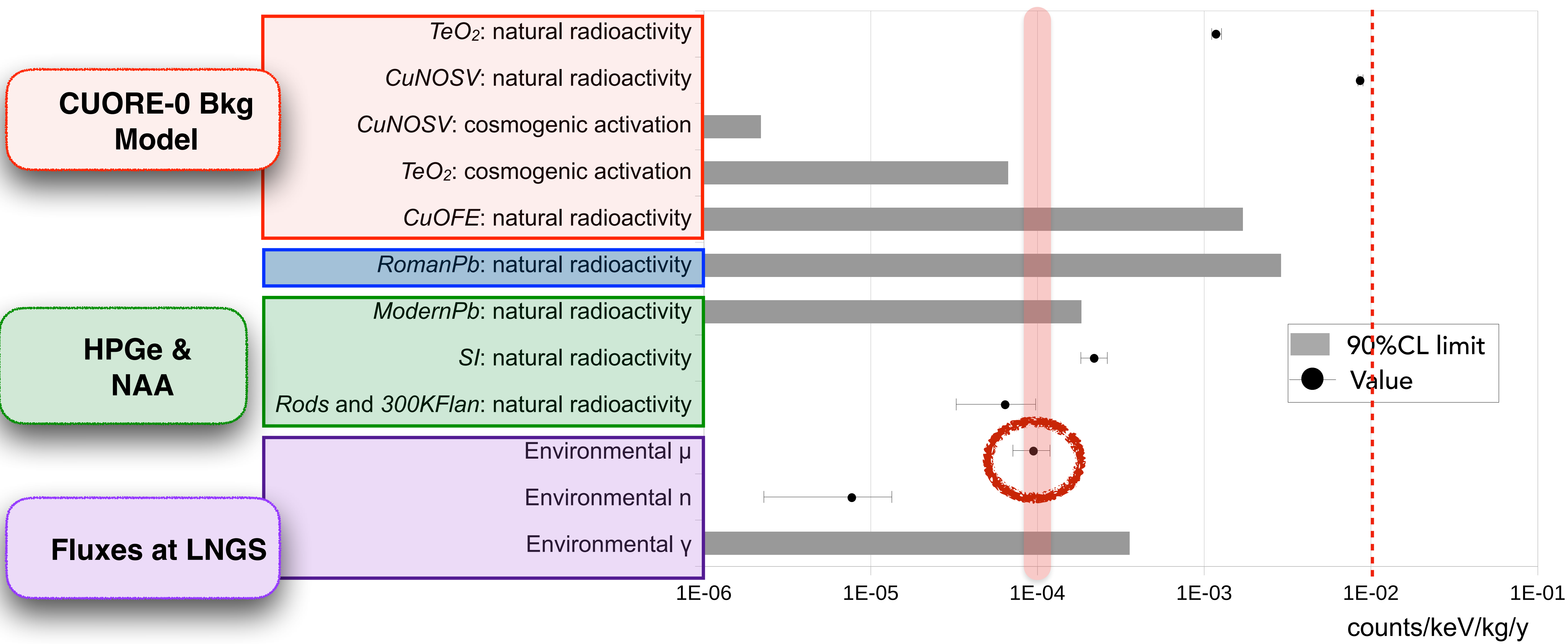
Eur. Phys. J. C (2017) 77:543

CUORE data will help quantify backgrounds that are poorly constrained by radio assay measurements

At DNP see
FN.00009
Background projections for CUPID
G. Benato

HA.00109 :
Tracking Crystal-Based Sources of CUORE Background
B. Daniel

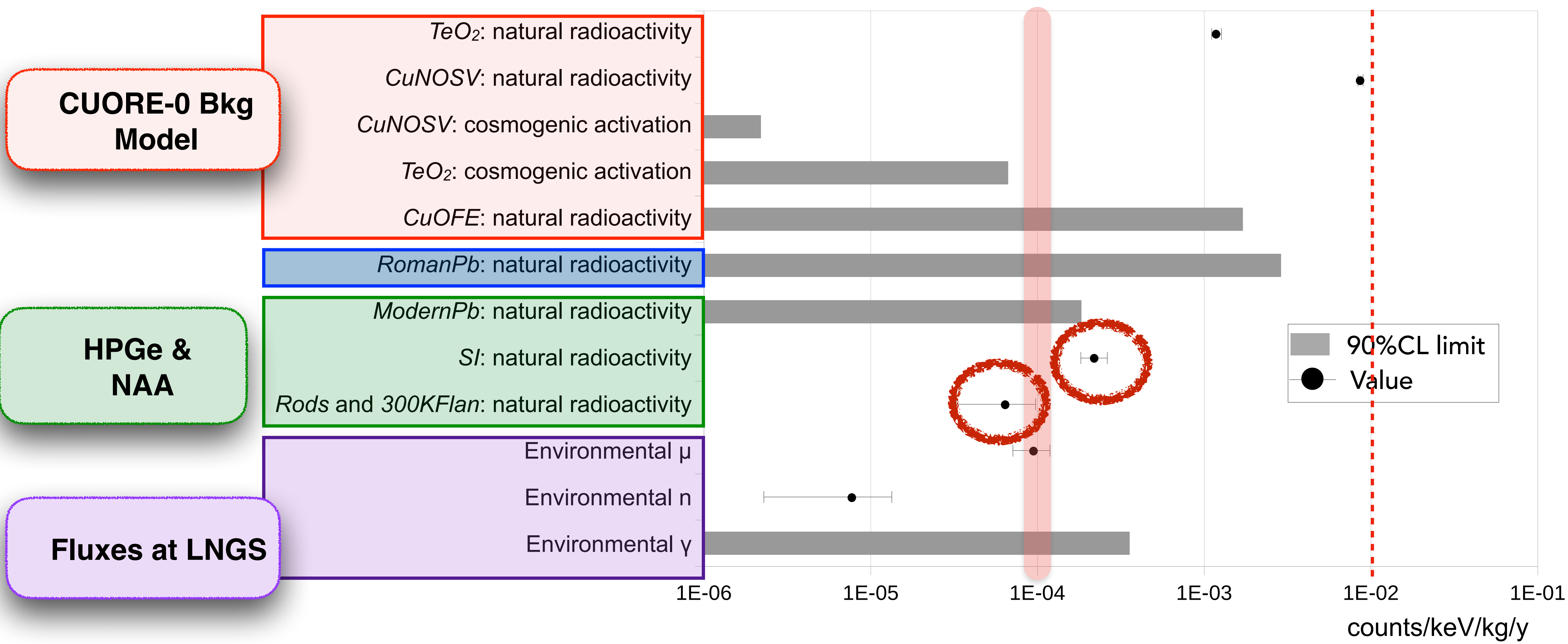
CUORE Background budget ROI @ 2528 keV



Eur. Phys. J. C (2017) 77:543

Active cosmic ray veto required (or a deeper site)

CUORE Background budget   ROI @ 2528 keV



Eur. Phys. J. C (2017) 77:543

Improved materials selection required for CUPID with 130Te

For higher Q-value isotope (e.g 100Mo @ 3034keV) β/γ background is decreased by ~20 fold

CUPID: CUORE Upgrade with Particle ID

- Dominant background is degraded alphas from surface contamination
- Leverage other energy loss mechanisms to tag particle type

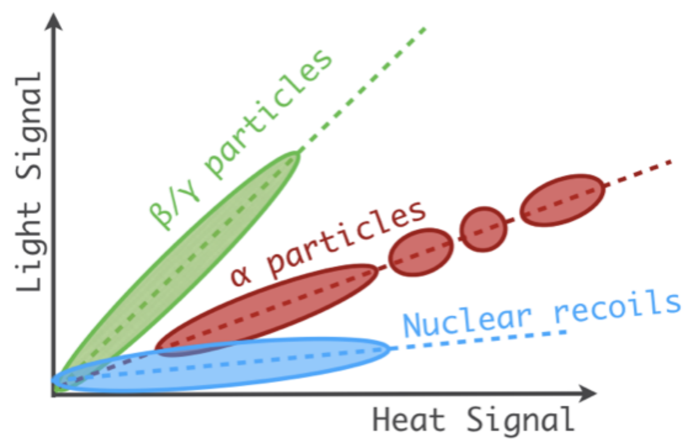
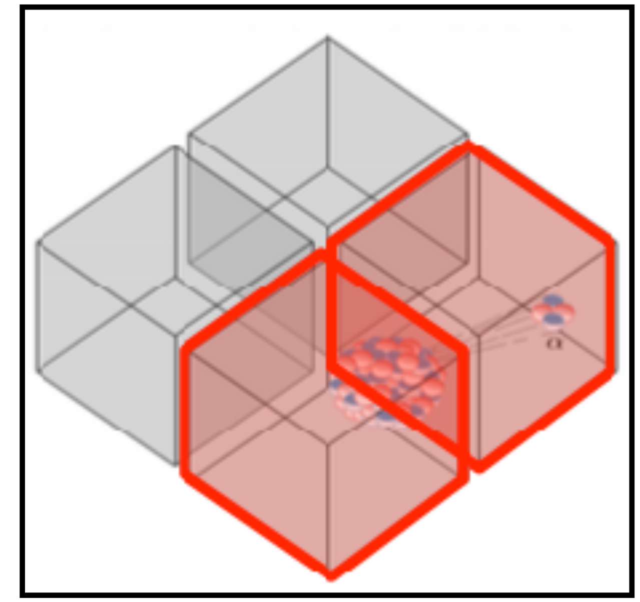
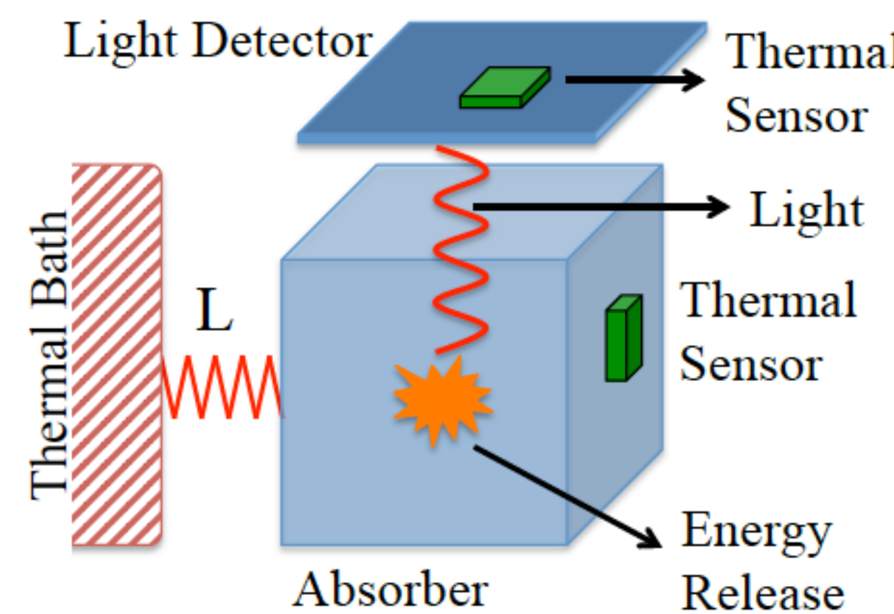


Fig. from L. Pattivina



- Maturing R&D and demonstrator efforts

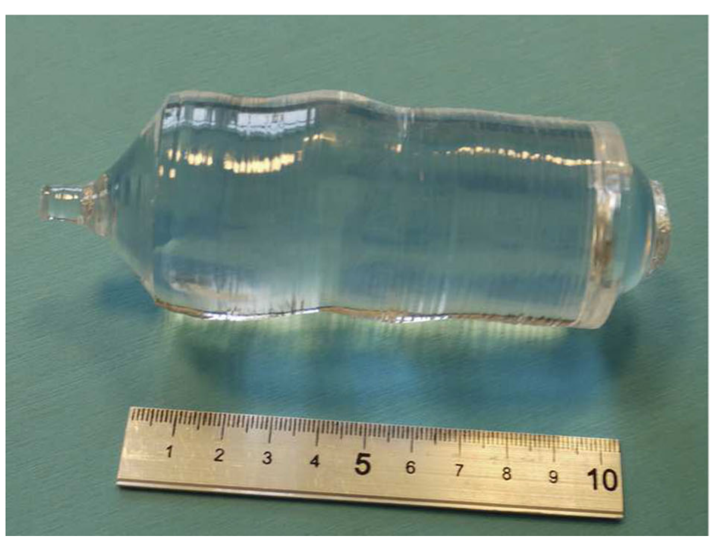
- [ ] Enriched $Li^{100}MoO_4$ scintillating bolometers
- [ ] Enriched $Zn^{82}Se$ scintillating bolometers
- [ ] Enriched $^{130}TeO_2$ bolometer with Cherenkov readout

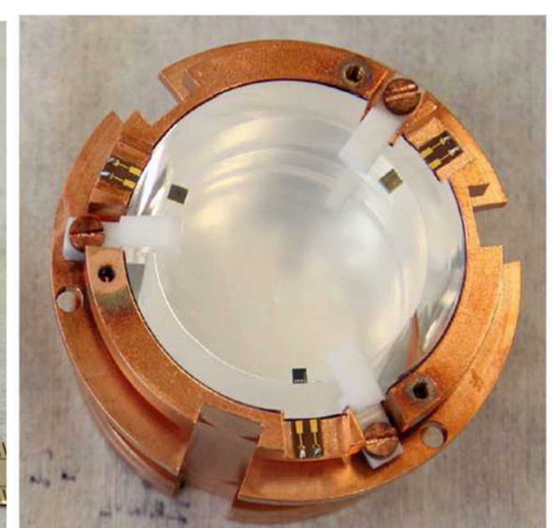
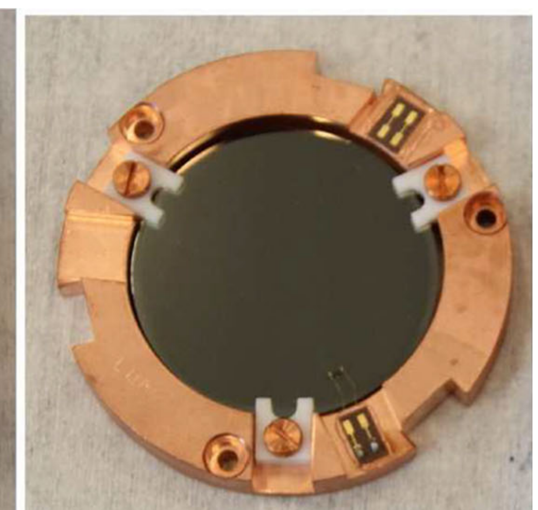


CUPID: $Li_2{}^{100}MoO_4$

- ^{100}Mo is an excellent choice for scintillating bolometer 0vbb search
- Q-value: 3034 keV
- Natural abundance: 9.7%, enrichment to ~97% is demonstrated
- Seminal R&D from Lumineu project
- Possible to grow large, high purity, high optical quality LMO crystals and operate as scintillating bolometers
- Vendors capable of growing high-quality LMO identified in Russia, US, China and France

Eur. Phys. J. C (2017) 77:785



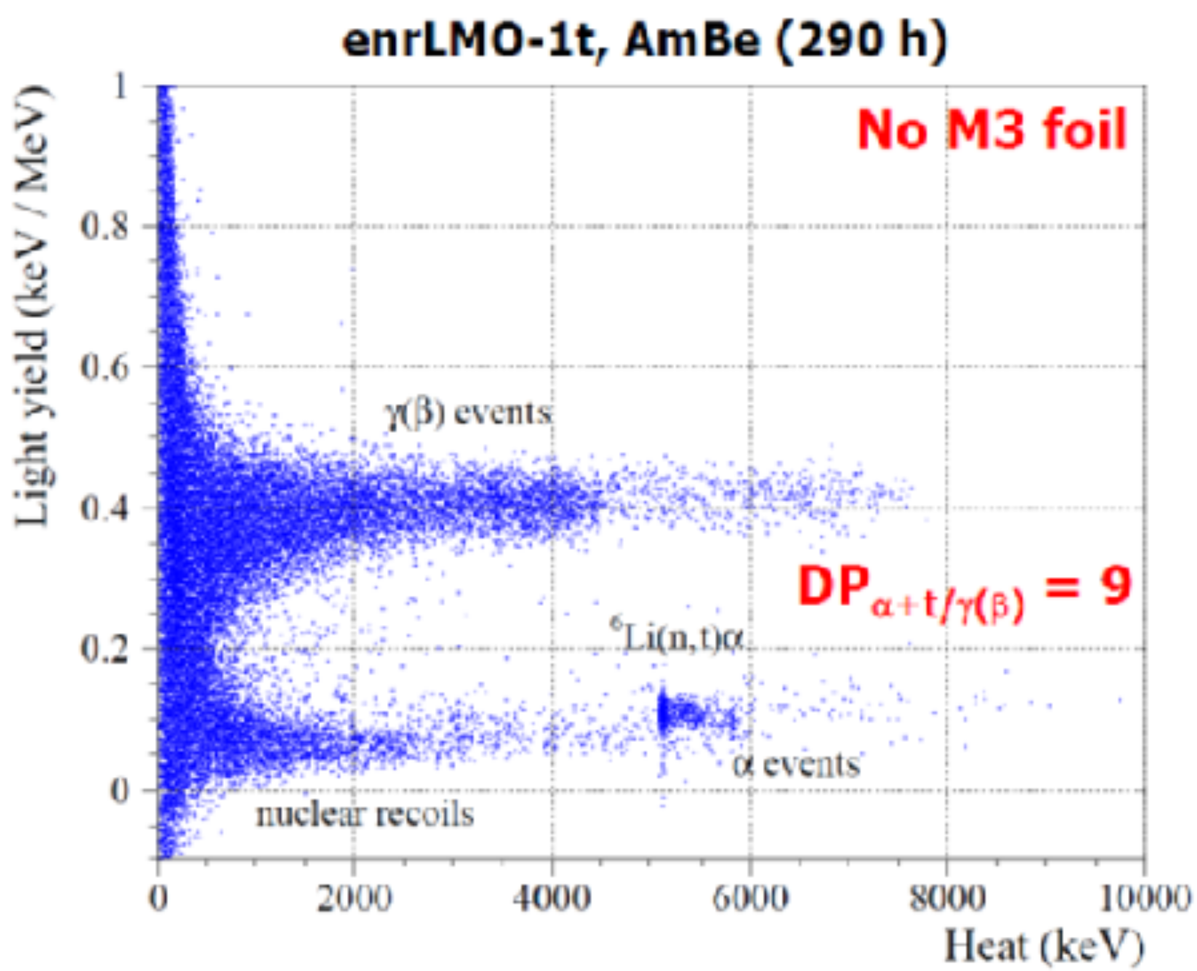



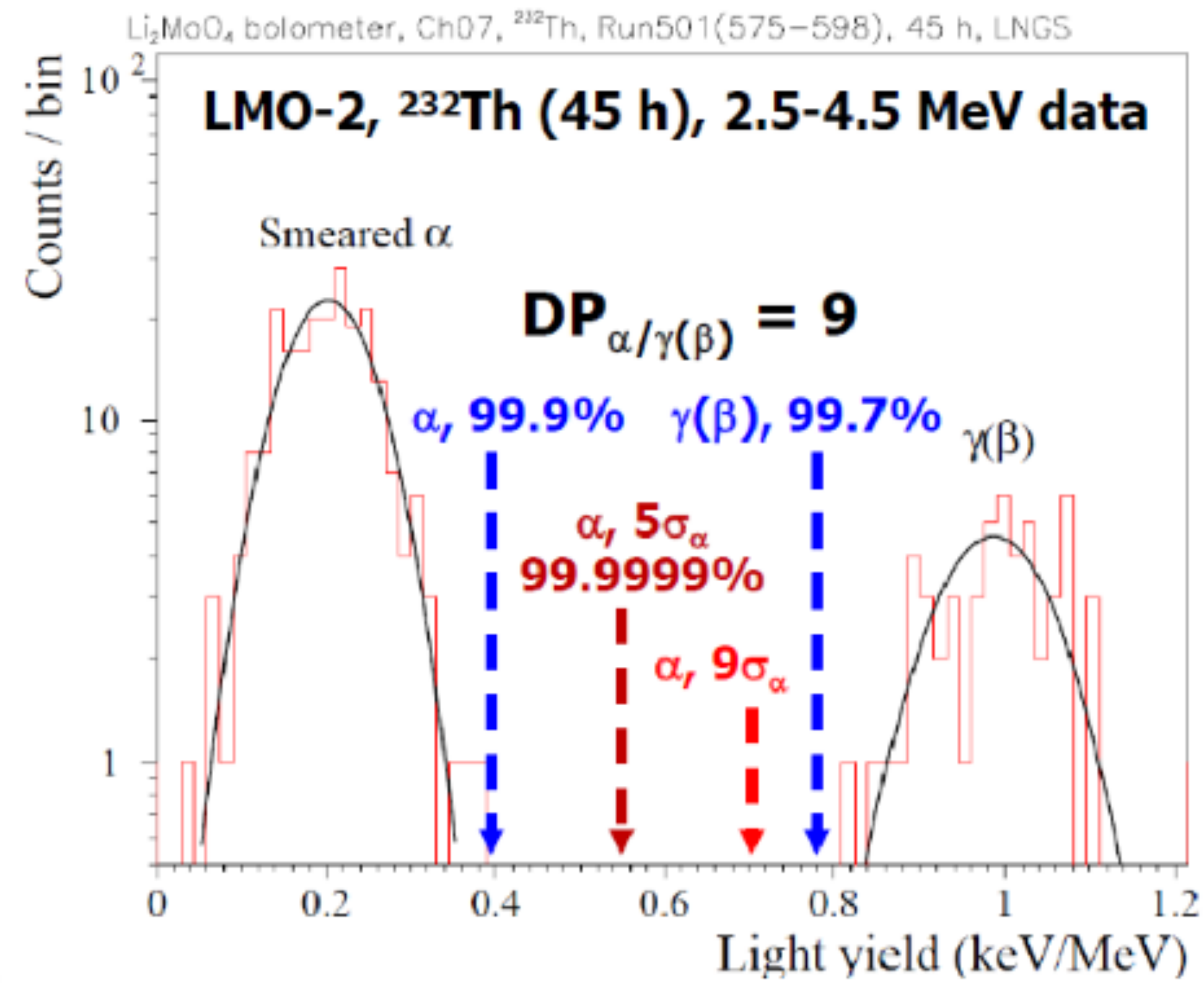

0.2 kg LMO scintillating bolometer

Main crystal, Ge wafer cryogenic light detector readout by NTDs

CUPID: $Li_2{}^{100}MoO_4$

- LMO alpha/beta discrimination using heat and light signals

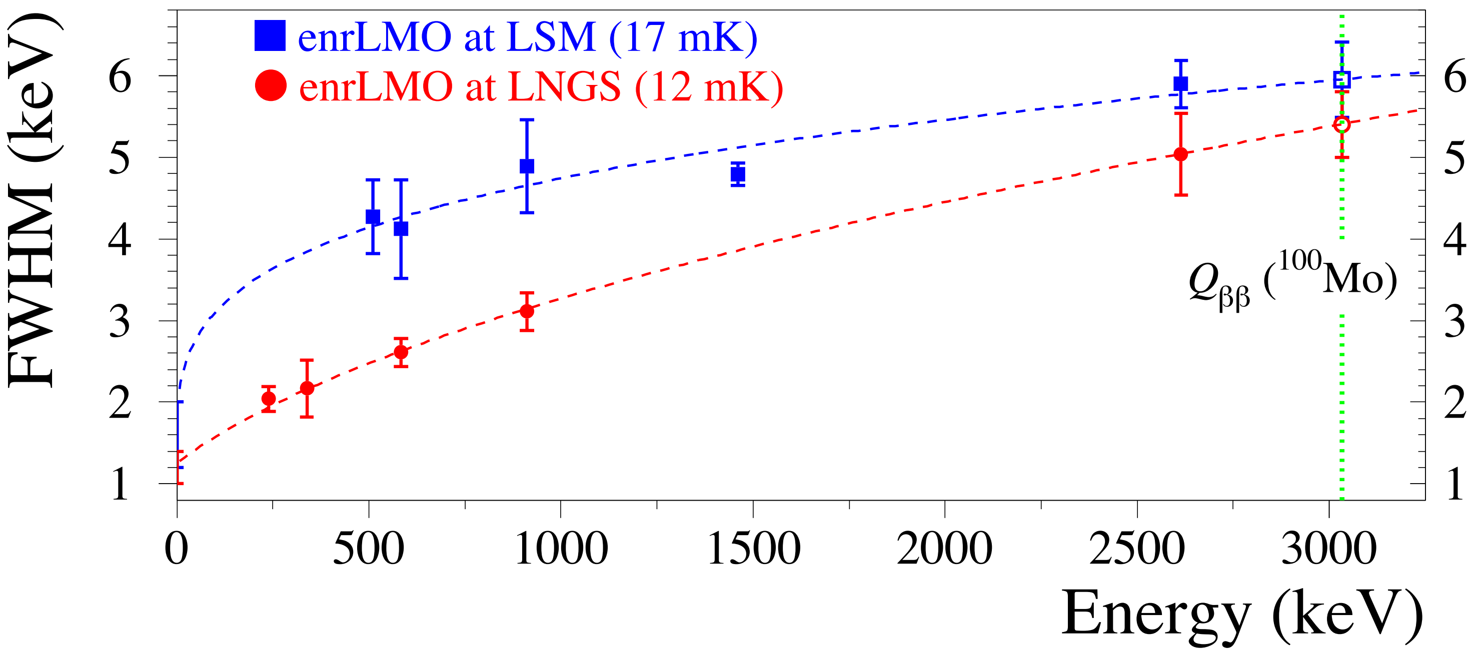




Figs. Courtesy of Andrea Giuliani, CSNSM, Saclay

CUPID: $Li_2{}^{100}MoO_4$

- Energy resolution demonstrated to be 5~6 keV FWHM
- Current limits on internal radio purity are compatible with requirements



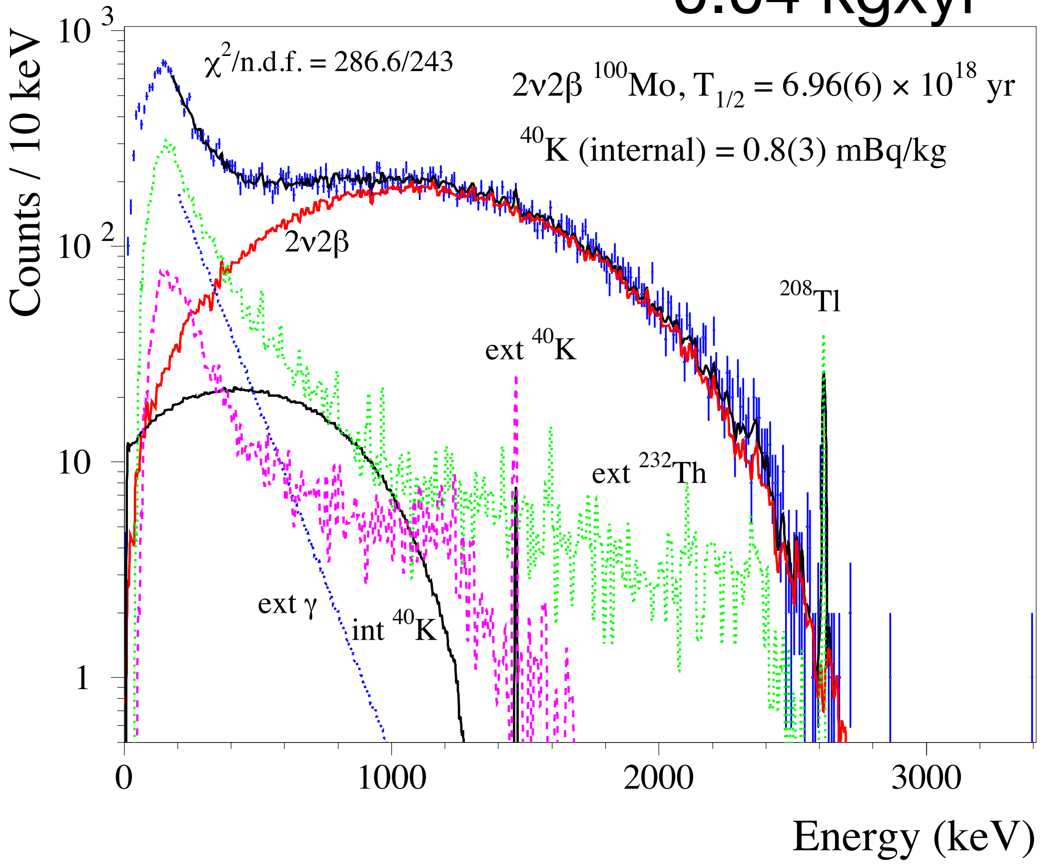
Detector's ID	Crystal's mass (g)	FWHM (keV) at 2615 keV	$LY_{\gamma(\beta)}$ (keV/MeV)	$\alpha/\gamma(\beta)$ Separation above 2.5 MeV	Activity (μBq/kg) ^{228}Th	^{226}Ra	^{210}Po
enrLMO-1	186	5.8(6)	0.41	9σ	≤4	≤6	450(30)
enrLMO-2	204	5.7(6)	0.38	9σ	≤6	≤11	200(20)
enrLMO-3	213	5.5(5)	0.73	14σ	≤3	≤3	76(10)
enrLMO-4	207	5.7(6)	0.74	14σ	≤5	≤9	20(6)

AIP Conf. Proc. 1894, 020017 (2017)

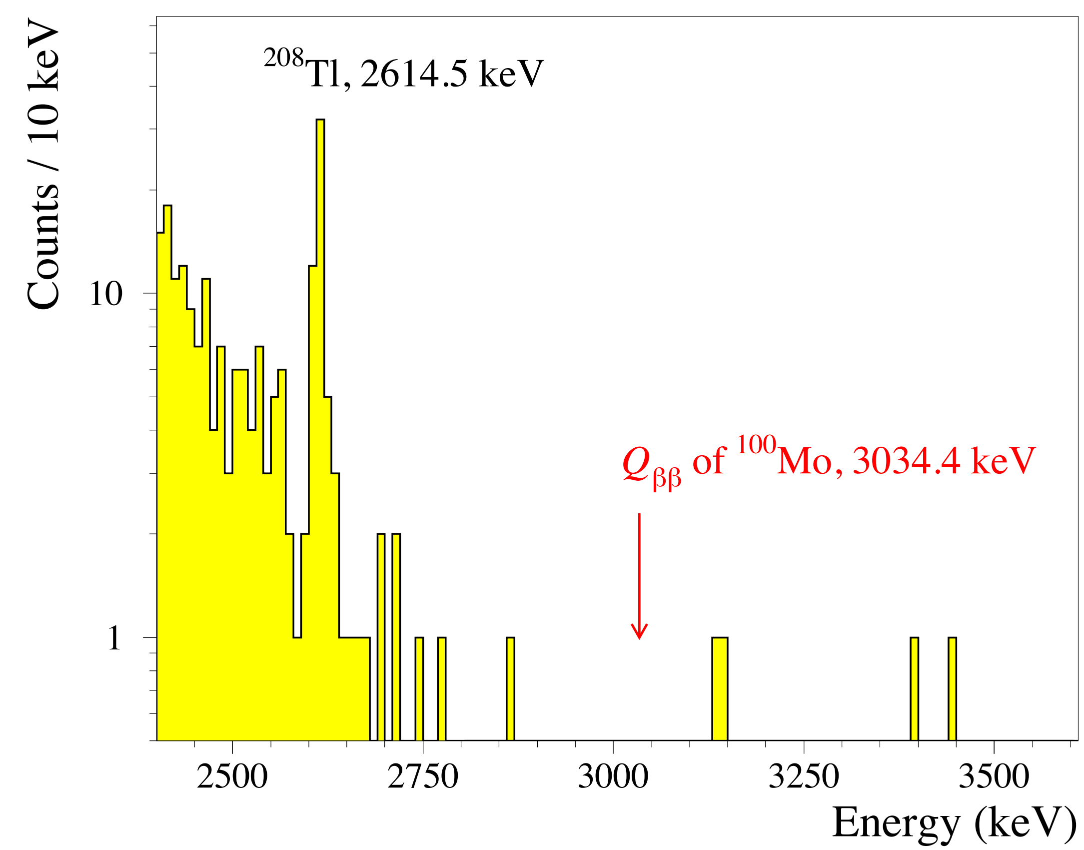
CUPID: $Li_2{}^{100}MoO_4$

- BB-decay results from Lumineu

0.04 kgxyr



0.06 kgxyr



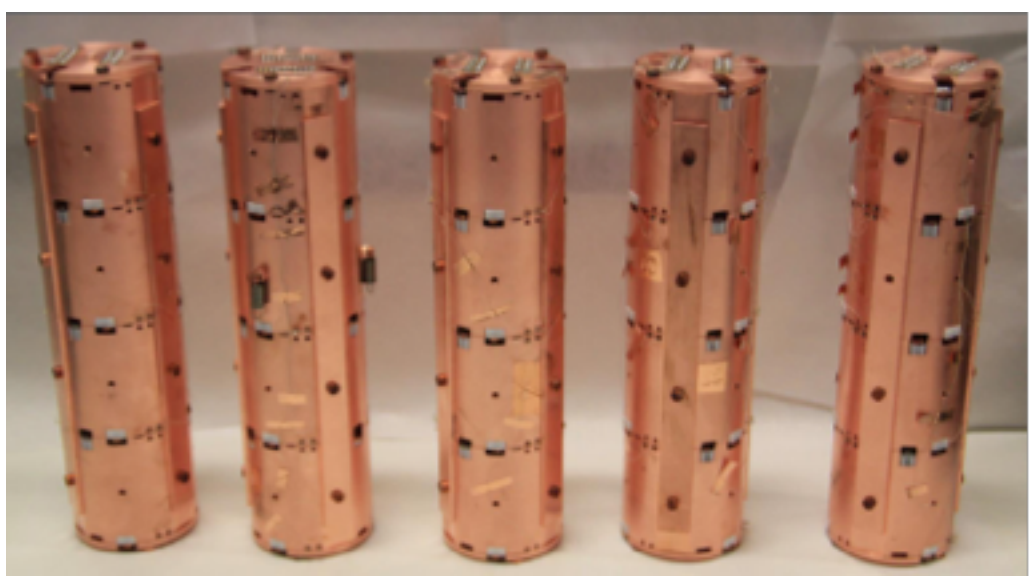
$$T_{1/2}^{2\nu} = (6.92 \pm 0.06(\mathrm{stat}) \pm 0.36(\mathrm{syst.})) \times 10^{18}\mathrm{yr}$$

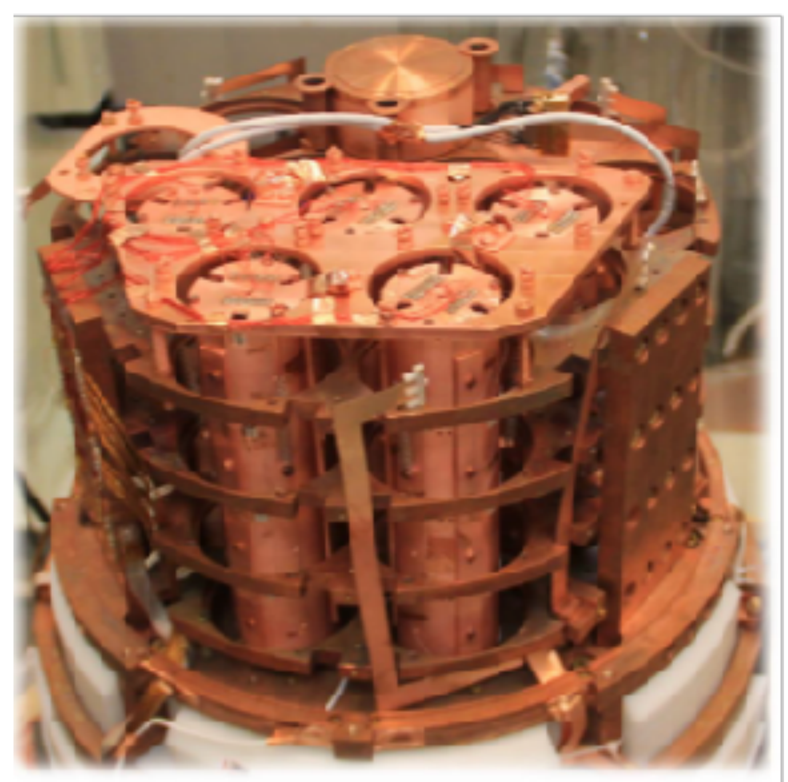
$$T_{1/2}^{0\nu 2\beta} \geq 0.7 \times 10^{23}\ \mathrm{yr}$$

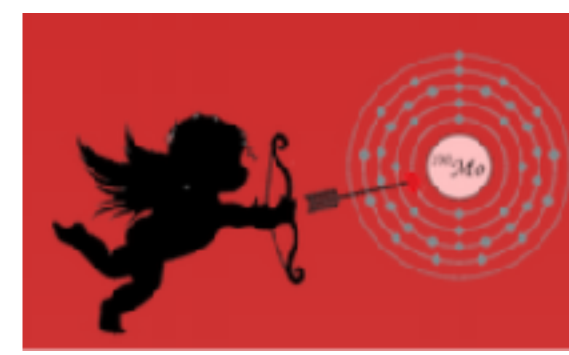
AIP Conf. Proc. 1894, 020017 (2017)

CUPID-Mo Demonstrators

- **Phase 1**: Array of 20 enriched 0.2 kg $Li_2{}^{100}MoO_4$ crystals operated a Lumineu-style scintillating bolometers (LMO)
- Deployed in the Edelweiss cryogenic setup at Modane lab
- Goal is an extended run to confirm LMO operation and reach higher-sensitivity on internal radio purity
- Currently running at Modane Underground lab
- **Phase 2:** Additional 20 modules to be deployed in the CUPID-0 R&D cryostat at LNGS







Figs courtesy of CUPID-Mo collaboration

CUPID-Mo Demonstrators

- Expected sensitivity of the CUPID-Mo program
- Assumptions
  - BI = 1 count/(keV/ton×yr) in 10 keV window around Q-value
  - J. Kotila and F. Iachello, Phys. Rev. C 85, p. 034316 (2012).
    S. Stoica and M. Mirea, Phys. Rev. C 88, p. 037303 (2013).
    J. Engel and J. Menendez, Rep. Prog. Phys. 80, p. 046301 (2017).
    L. S. Song, J. M. Yao, P. Ring, and J. Meng, Phys. Rev. C 95, p. 024305 (2017).

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CUPID-0/Mo configuration	Exposure (kg×yr of ^{100}Mo)	lim$T_{1/2}^{0\nu 2\beta}$ (yr)	lim$\langle m_{\beta\beta} \rangle$ (eV)
(1) 20×0.5 crystal×yr	1.2	1.3×10^{24}	0.33–0.56
(2) 20×1.5 crystal×yr	3.5	4.0×10^{24}	0.19–0.32
(3) 40×3.0 crystal×yr	14	1.5×10^{25}	0.10–0.17

At DNP see:
EN.00009:
Li2MoO4 for 0 decay search in CUPID - The Physics case and current status
B. Schmidt

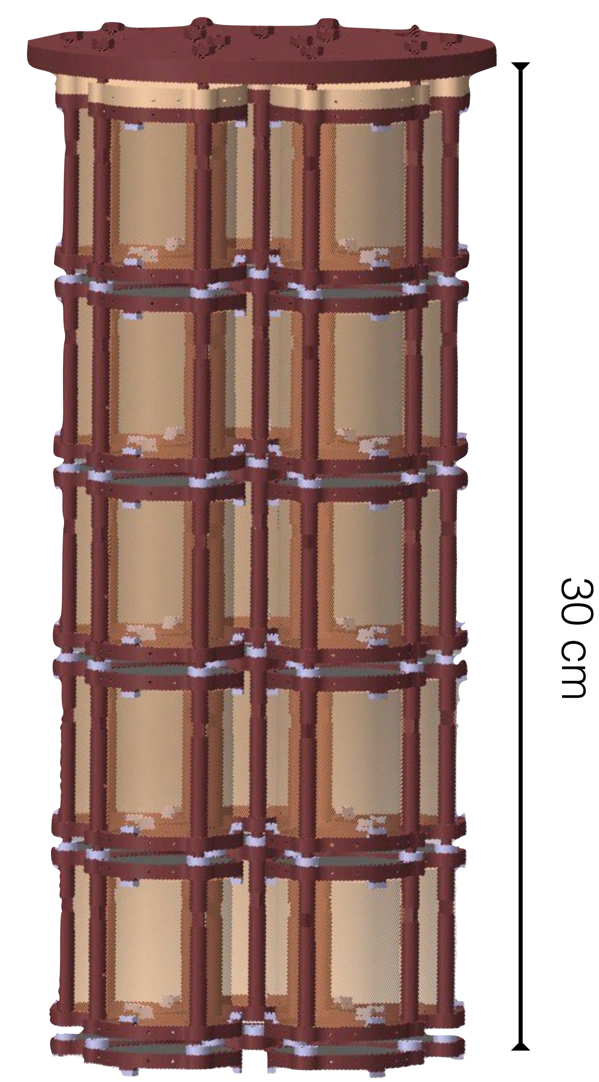
FN.00009
Background projections for CUPID
G. Benato

Courtesy of CUPID-Mo collaboration

CUPID: $Zn^{82}Se$

- ^{82}Se embedded in ZnSe scintillating bolometers
- Q-value: 2998 keV
- CUPID-0 Se demonstrator now operating at LNGS **See L. M. Pattivina's talk**

  - 95% 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 -> $N_{\beta\beta} = 3.8 \times 10^{25}$ ββ nuclei
  - LD: Ge wafer operated as bolometer



CUPID: $Zn^{82}Se$

- Light detector: Ge-wafer bolometer readout with NTDs

See L. M. Pattivina's talk

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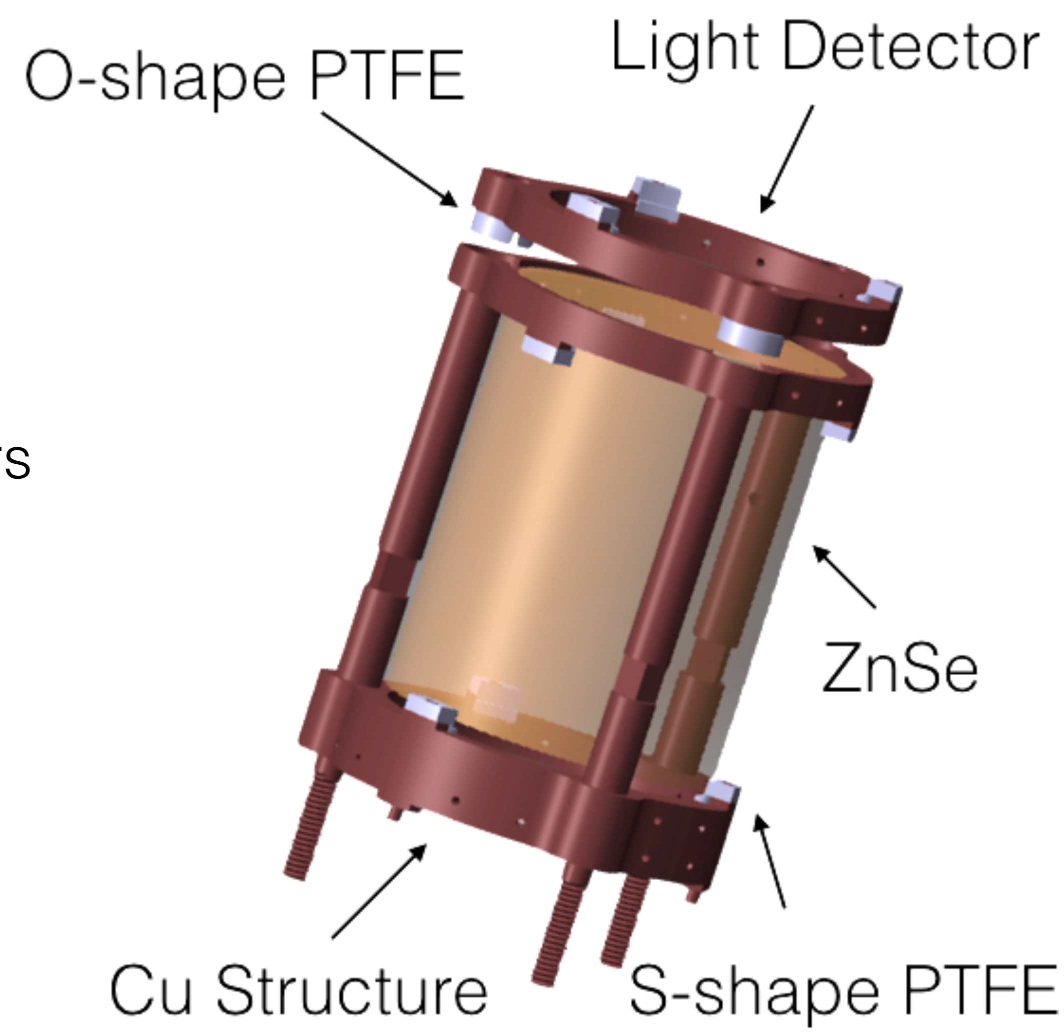
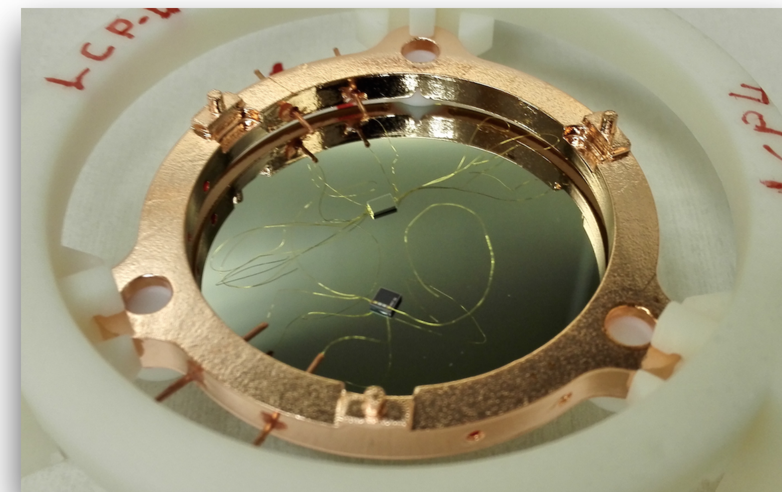
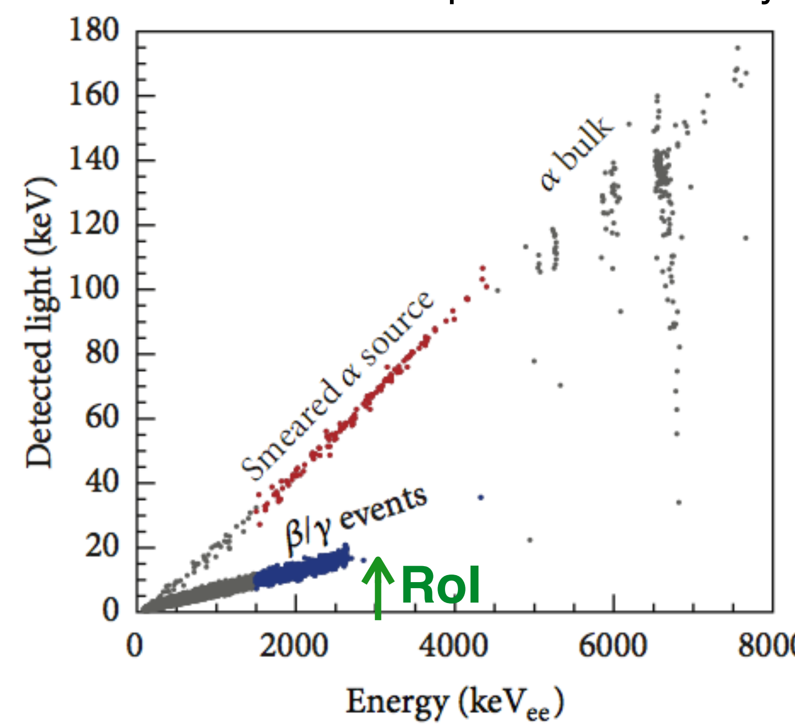




Calibration scatter plot of a ZnSe crystal

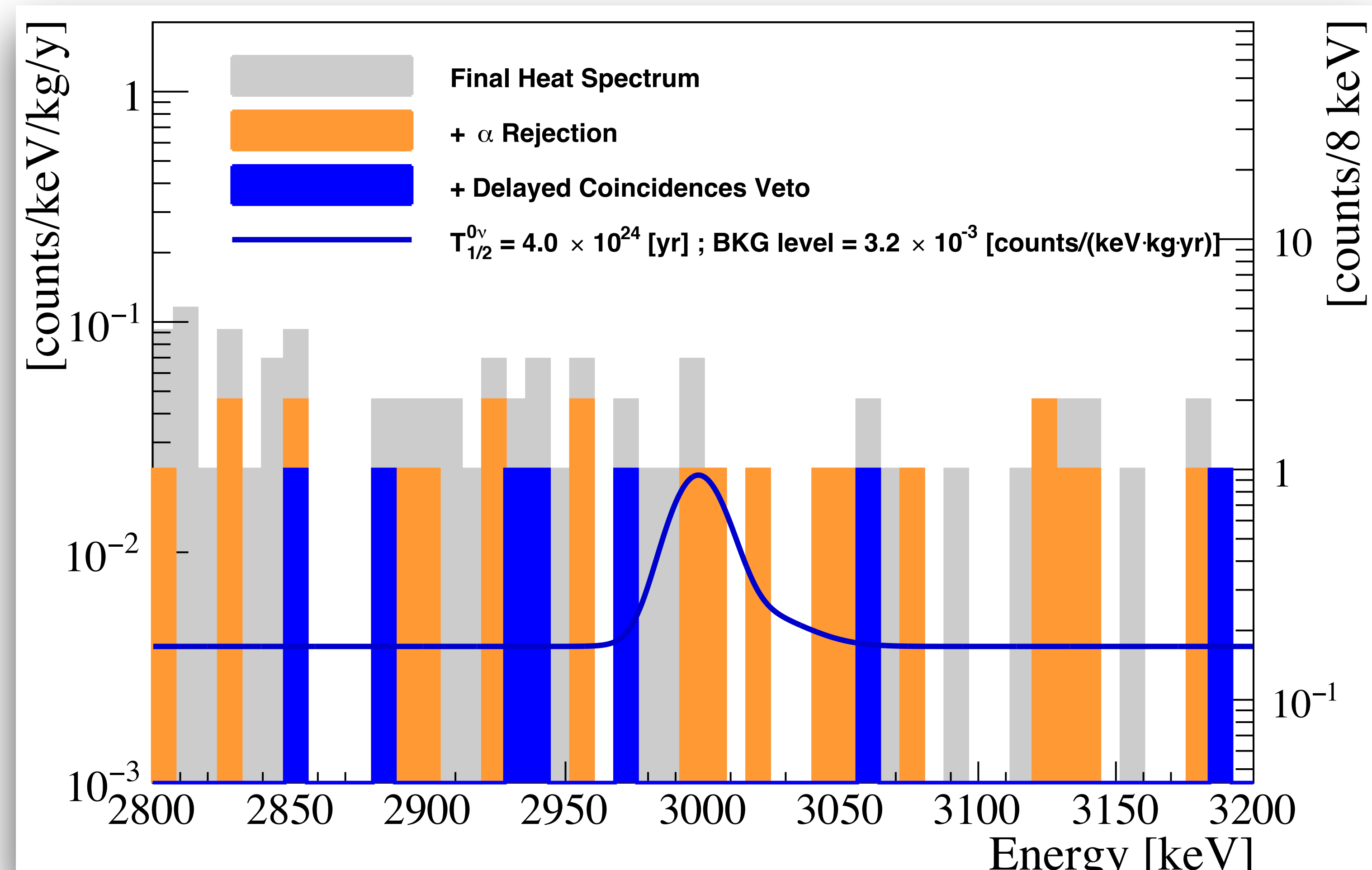


J.W. Beeman et al., J. Instrum. 8 (2013) P05021.

Background data selection

UEML Simultaneous fit over the datasets

Slide from L. M. Pattivina's talk



Exposure: **5.46 kg · y of ZnSe**

Energy resolution in ROI: **23.0±0.6 keV**

Total signal efficiency: **75±2%**

($\varepsilon_{ntrigger}$ + ε_{signal} + $\varepsilon_{\beta\beta}$)

$T_{1/2}(^{82}Se \rightarrow ^{82}Kr) > 4.0 \cdot 10^{24}$ yr @ 90C.L.

$m_{\beta\beta} <$ (290-596)[1] meV

NEMO3 measurement $3.6 \cdot 10^{23}$ yr @ 90C.L.

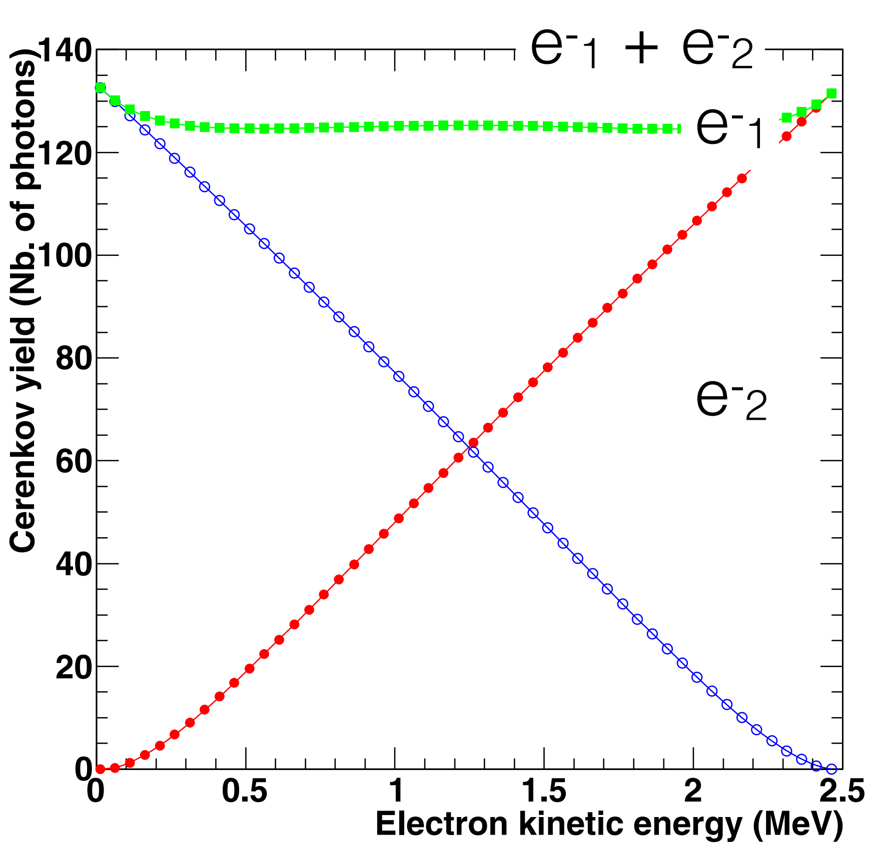
A. S. Barabash and V. B. Brudanin, NEMO, Phys.Atom.Nucl.74, 312 (2011).

CUPID: TeO2 prospects

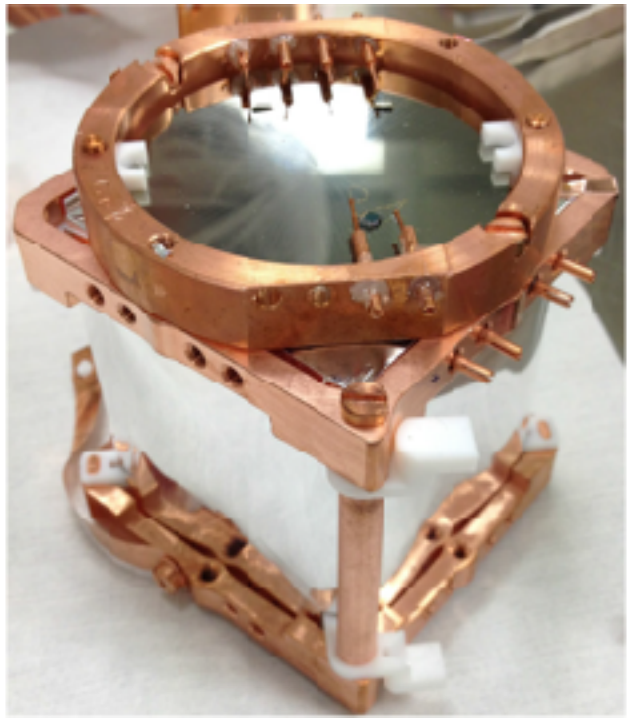
- As proposed in EPJC65 (2010) 359 exploit Cherenkov emission to tag beta/gamma events vs alpha events

- Challenge: very low light emission (~100 eV) vs a few keV of light in scintillating bolometers

Expected (theory) Cherenkov Yield



- EPJC **65** (2010) 359



- Ge cryogenic light detector

EPJC **75** 12 (2015)

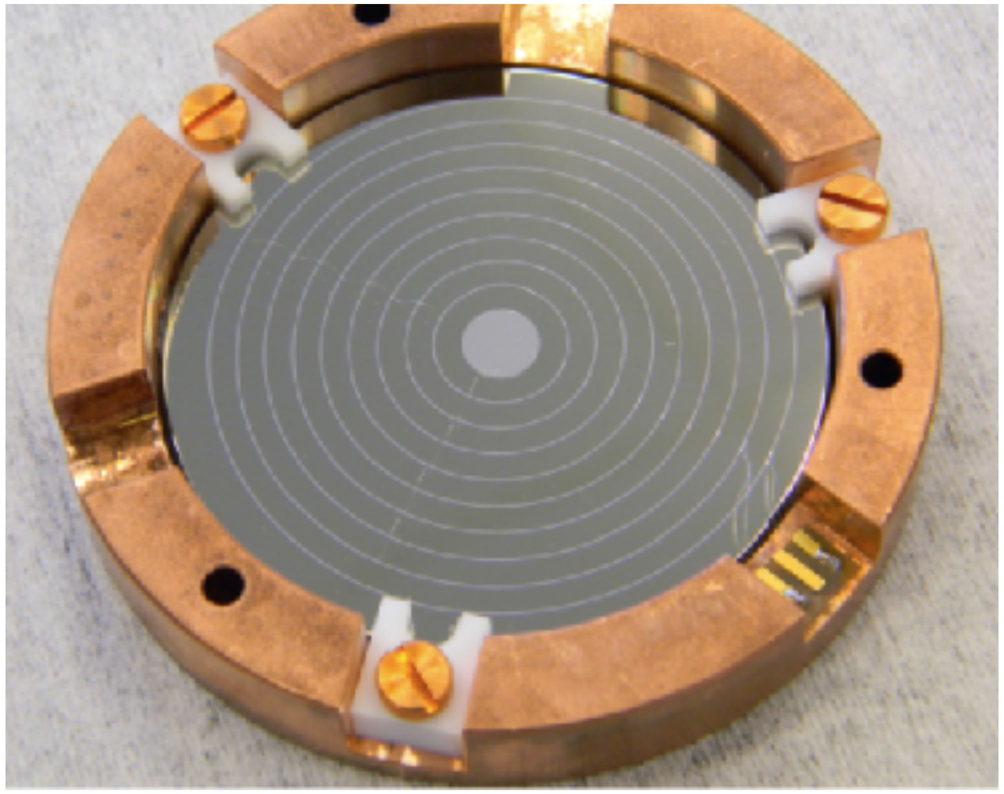
At DNP see DM.00009:
Measurements of Light Emissions in TeO2 Crystals
(R. Huang Oct 25 11.00 am)

CUPID: TeO2 prospects

- R&D to discriminate electron/alpha events based on Cherenkov light emission in TeO2 is yielding positive results

- Low threshold bolometric light detectors are steadily improving, exploiting Neganov-Luke amplification

L. Berge et al. Phys. Rev. C **97** 032501 2018



- Light detector thermometry can be done with standard NTD

- Other light detector readout schemes TES and KIDs are being investigated

Fig. Courtesy of Andrea Giuliani, CSNSM, Saclay

CUPID: TeO2 prospects

- R&D to discriminate electron/alpha events based on Cherenkov light emission in TeO2 is yielding positive results

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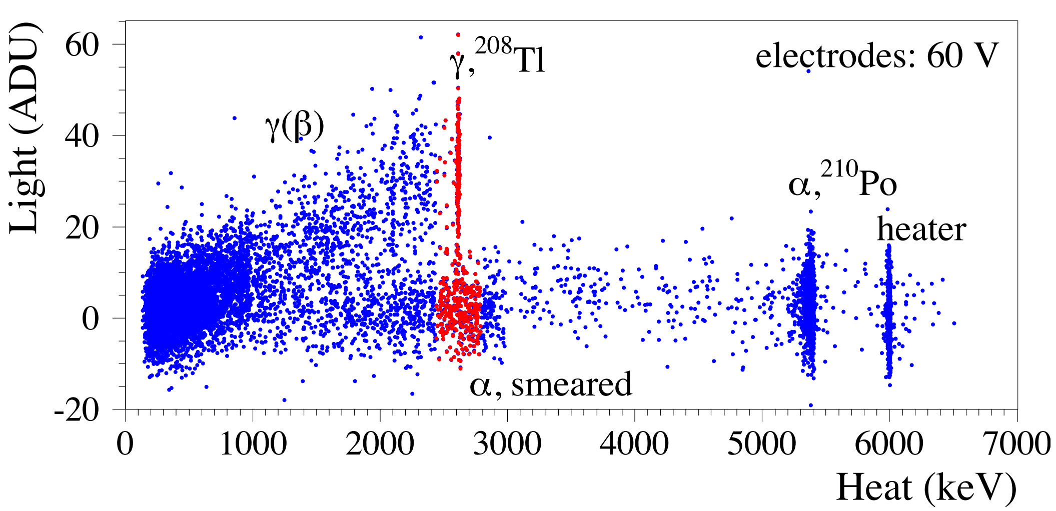
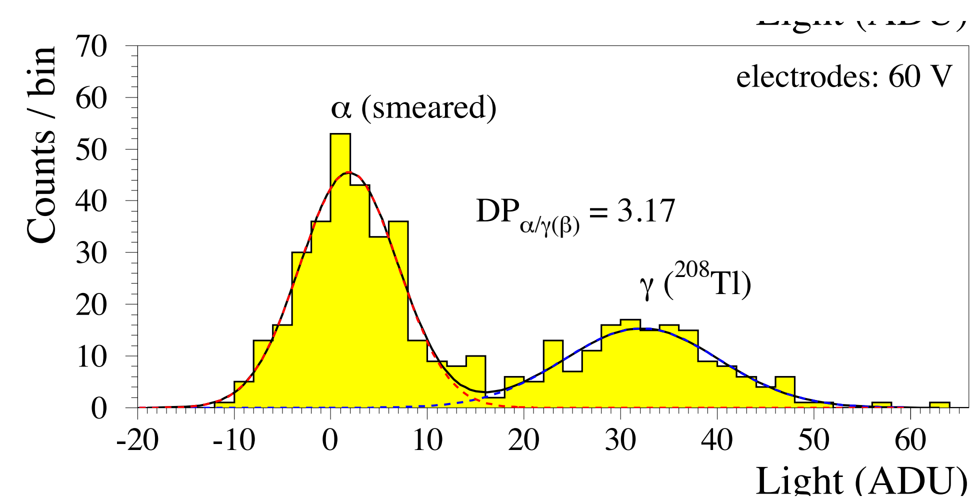
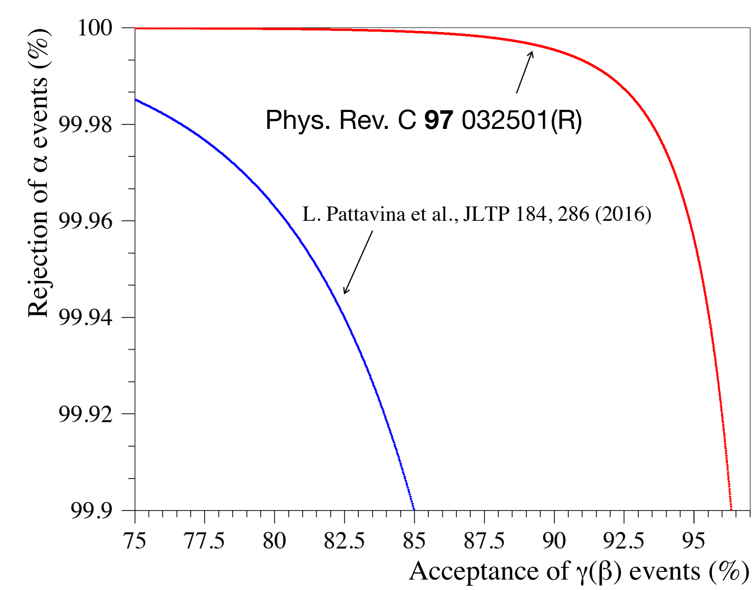
Phys. Rev. C **97** 032501 2018





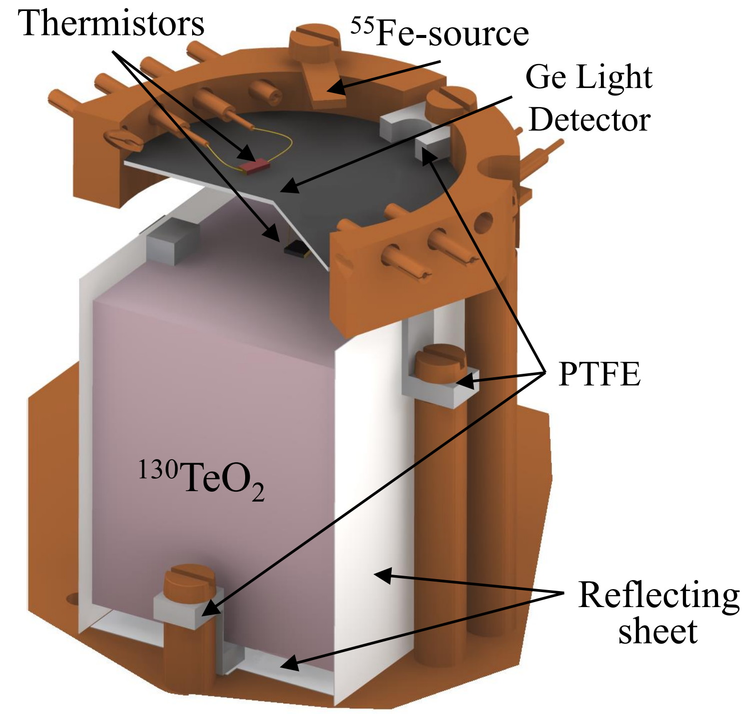


- 99.9% alpha rejection with >95% signal acceptance in CUORE-sized crystal

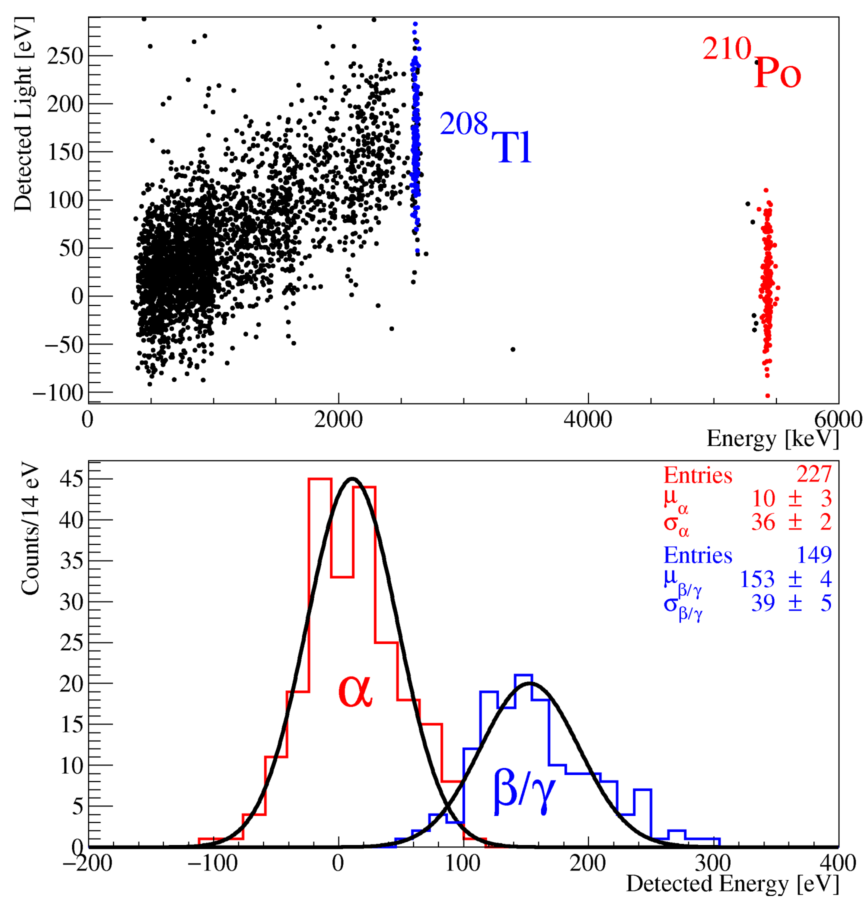
R&D on 130Te enrichment

- Test run at LNGS with 2x 435~g enriched 130TeO2 crystals

Isotope	ICP-MS [%]	Certification [%]	Natural [%]
^{130}Te	92.26	92.13	34.08
^{128}Te	7.71	7.28	31.74
^{126}Te	0.015	0.02	18.84
^{125}Te	0.006	0.01	7.07
^{124}Te	0.0005	$\leq$ 0.005	4.74



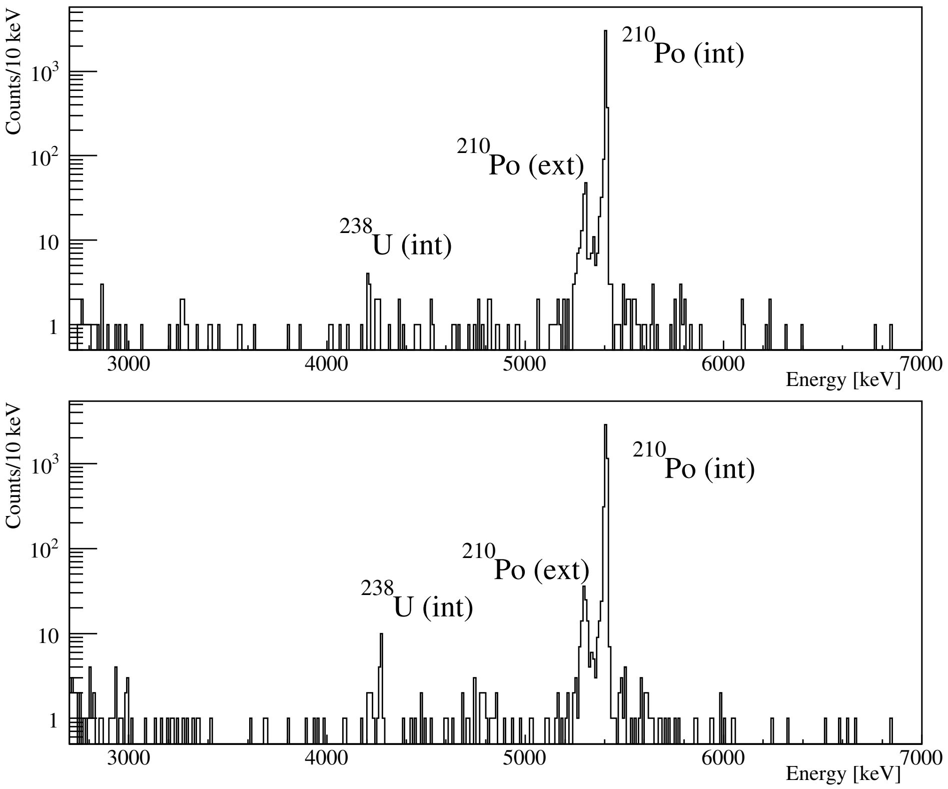
Physics Letters B **767**, 321-329 (2017)



bolometric performance	Det 1	Det 2
Energy res. (FWHM @2615 keV)	6.5 keV	4.3 keV
alpha rejection for 95% signal acceptance	98.21%	99.99%

R&D on 130Te enrichment

Alpha region of the spectrum



Physics Letters B **767**, 321-329 (2017)

	Det 1 uBq/kg	Det 2 uBq/kg	CUORE uBq/kg
232Th	<4.3	<4.8	<0.8
238U	8+/- 3	15 +/- 4	<0.6

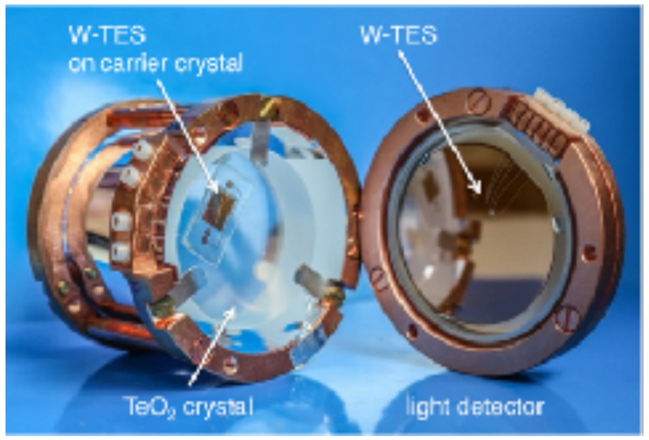
- Ongoing R&D item to purify crystal materials 130Te (zone refining)
- Larger exposure demonstrator under development

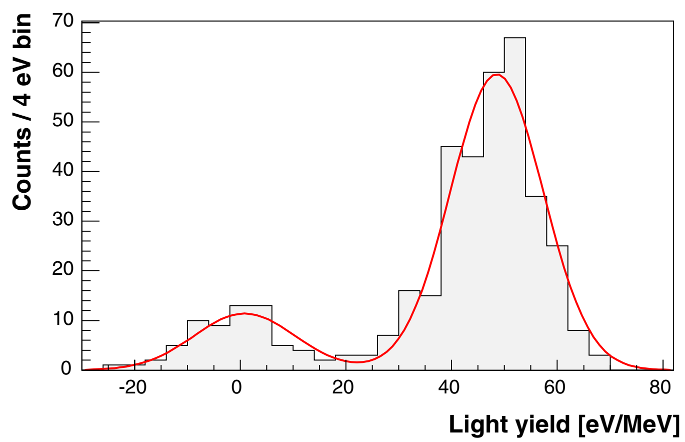
R&D on light detector readout schemes

- Bolometer readout based on NTD thermistors have been demonstrated to meet the technical requirements for alpha discrimination for CUPID
- There is active R&D to explore alternative temperature readout schemes
- CUPID-US group exploring Transition edge sensor (TES) readout
- CALDER project in Europe exploring kinetic inductance detectors (KIDS)
- Advanced light detector technologies benefit both the 100Mo and 130Te strategies

TES readout for CUPID

Astroparticle Physics 69 (2015) 30–36

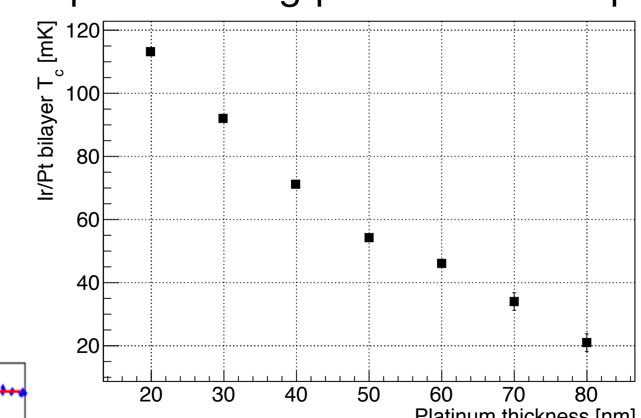




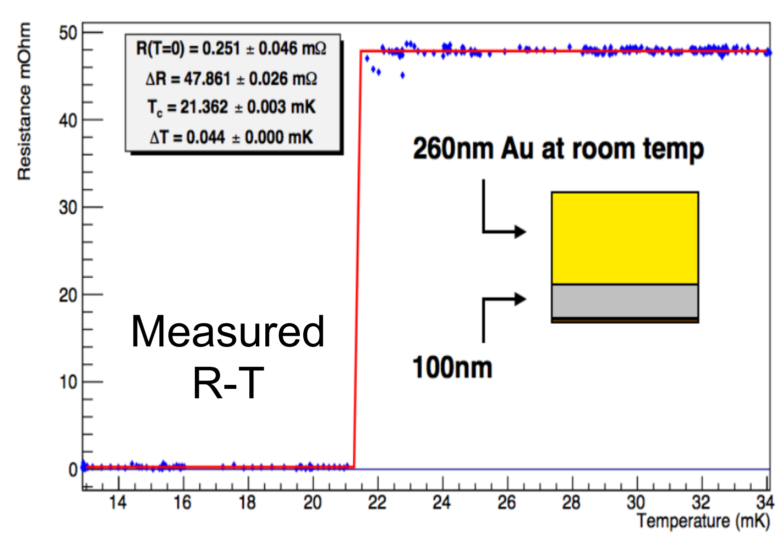
- Demonstration with tungsten TES (developed in CRESST)
- 3.7σ separation of α events from β/γ with 98% signal acceptance
- W-TES are difficult to produce reproducibly

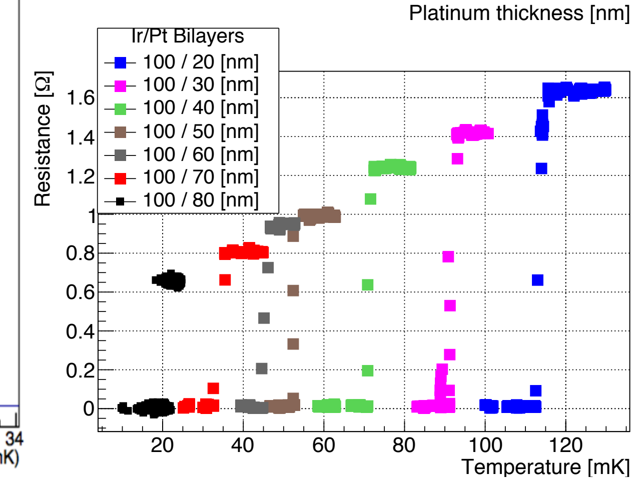
Superconducting bilayers

https://arxiv.org/pdf/1711.03648.pdf



- Ongoing R&D activity to use TES sensors fabricated from Ir/Au, Ir/Pt bilayers
- Bilayers with low Tc demonstrated



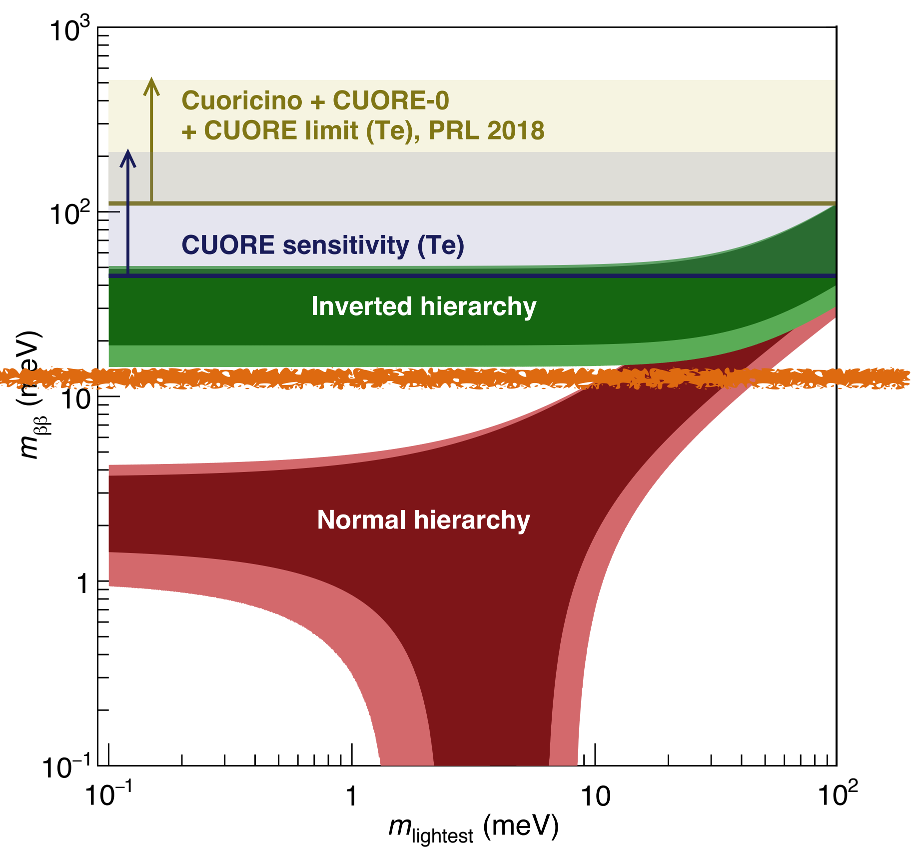


At DNP see

DM.00008:
Development of cryogenic optical-photon detectors with Ir/Pt-based transition edge sensors for CUPID
V. Singh (Oct 25 8.45 am)

EN.00008 :
Application of Cryogenic TES based Light Detectors for CUPID
B. Welliver (Oct 25 8.45pm)

Summary: CUPID Goals



- CUPID:
  CUore Upgrade with Particle ID
- Fully probe the inverted hierarchy of neutrino masses
- Baseline target isotope is 100Mo embedded in LiMoO4 scintillating bolometers
- Viable alternative is 130Te embedded in TeO2 instrumented with advanced cryogenic light detectors

	BI (c/kev/kg/yr)	T1/2 sensitivity (90% C.L)	mbb (meV)
^{100} Mo	$<10^{-4}$	2×10^{27}	9-15
^{130}Te	$<10^{-4}$	5×10^{27}	6-28

At DNP see:
EN.00009:
Li2MoO4 for 0 decay search in CUPID - The Physics case and current status
B. Schmidt

Conclusions

- CUORE (750kg TeO2 array) shows it is possible to operate a large array of macro bolometers at ultra-low cryogenic temperatures
- CUORE will continue to push sensitivity to 0vbb decay of 130Te and measure intrinsic background levels in the cryogenic system
- There is active R&D program in the US and Europe to realize a next generation experiment with the background, resolution and target mass required to probe the inverted hierarchy
- Small (~20 detector) scintillating bolometer arrays have made tremendous progress (CUPID-0 Se, Lumineu)
- Lithium molybdate scintillating bolometers enriched in 100Mo is the baseline choice for CUPID:
    - excellent alpha suppression
    - excellent energy resolution
    - high Q-value (above most environmental beta/gamma background)
    - good radio purity with improved limits expected from CUPID-Mo demonstrator
- Emergence of low noise cryogenic light detectors make enriched 130TeO2 bolometers a viable option for CUPID although lower Q-value requires additional care in materials selection for some cryogenic components

CUPID Working Meeting

- A CUPID interest group meeting is planned aimed at forming the CUPID collaboration and developing the conceptual design report
    - When: November 19 and 20 2018
    - Where: Gran Sasso Laboratory
    - Contacts: cupid_kickoff@mit.edu
    - More information: http://cupid.mit.edu/
- Open to any one interested in collaborating

Acknowledgements

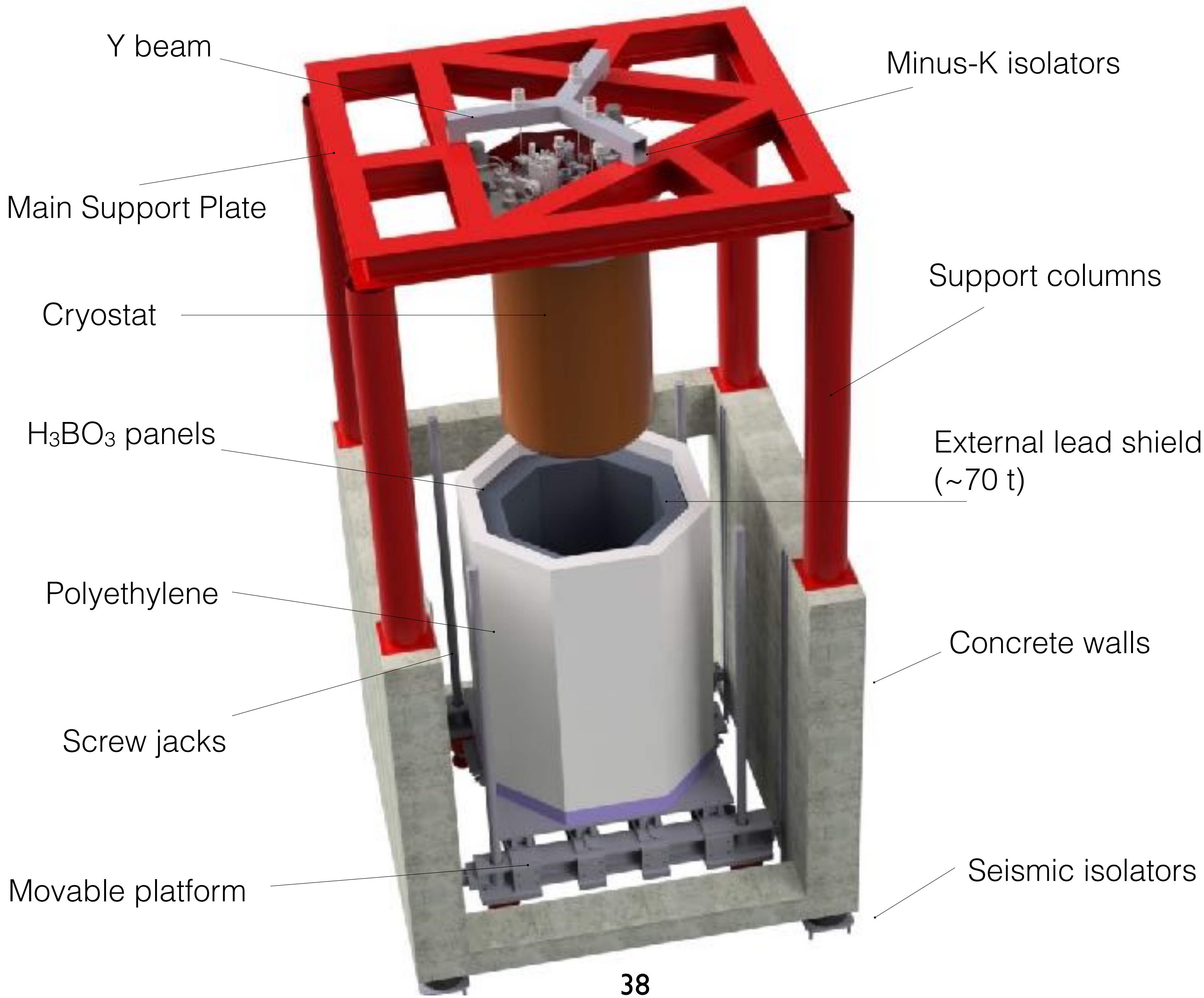
CUORE Funding Support

Acknowledgements

CUPID-Mo

CUORE Upgrade with Particle Identification in Molybdenum

Overview of experimental setup



The CUORE cryostat

- Cryogen-free cryostat
- Fast Cooling System (^4He gas) down to ~50K
- 5 pulse tubes down to ~4K
- Dilution refrigerator to operating temperature ~10 mK
- Nominal cooling power: 3 μW @ 10mK
- Cryostat total mass ~30 tons
- Mass to be cooled < 4K: ~15 tons
- Mass to be cooled < 50 mK: ~3 tons (Pb, Cu and TeO_2)