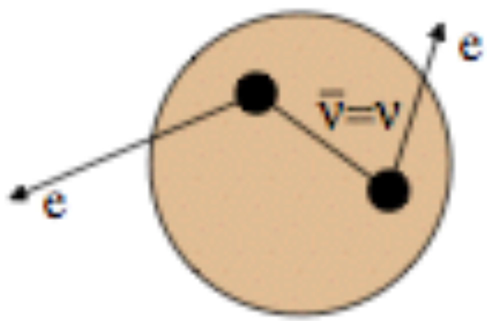
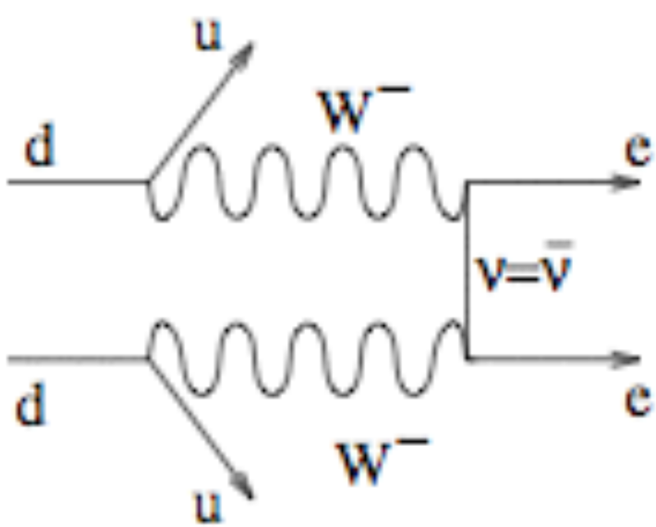
The Present Generation of Bolometers for DBD Searches





C.Brofferio
University of Milano Bicocca and INFN

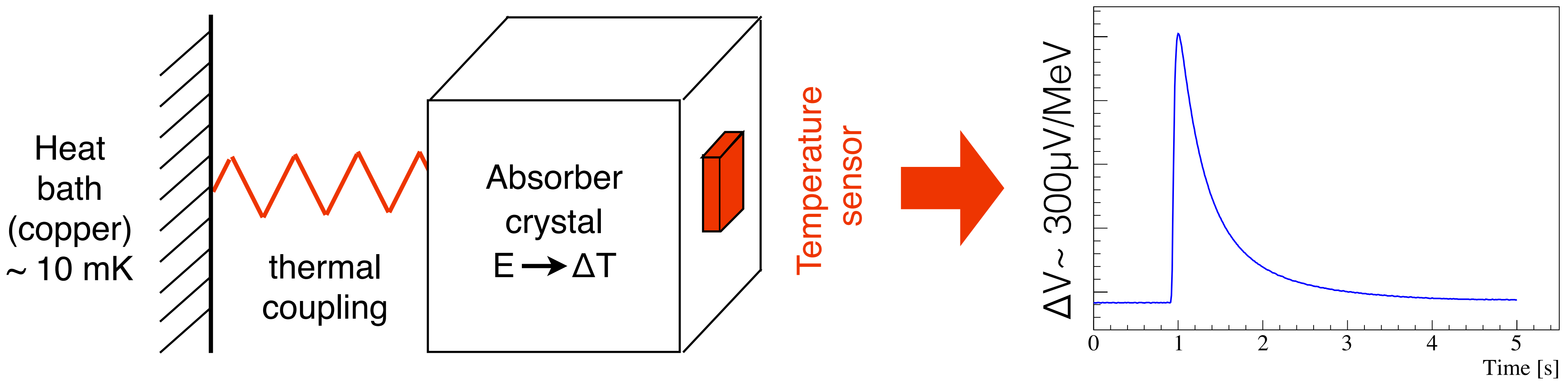
NDM15,
Jyvaskyla June 1-5, 2015

Why Bolometers ?

- Excellent energy resolution (better than 0.2 % FWHM possible)
- Excellent high efficiency (typically more than 80%)
- Can study many candidates (even at the same time)
- Scalable up to 1000 detectors (CUORE as demonstrator)
- Effective anti-coincidence technique (eliminate multi-site events)
- **Possible particle identification with same readout technique**

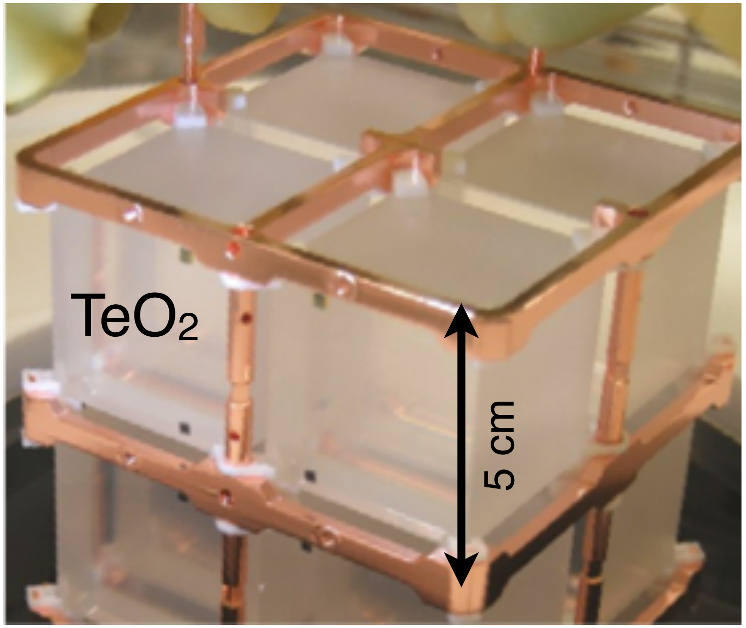
The bolometric way to DBD

- Source embedded in the detector, $0\nu\beta\beta$ emitters: **^{130}Te, ^{82}Se, ^{100}Mo, ^{124}Sn**

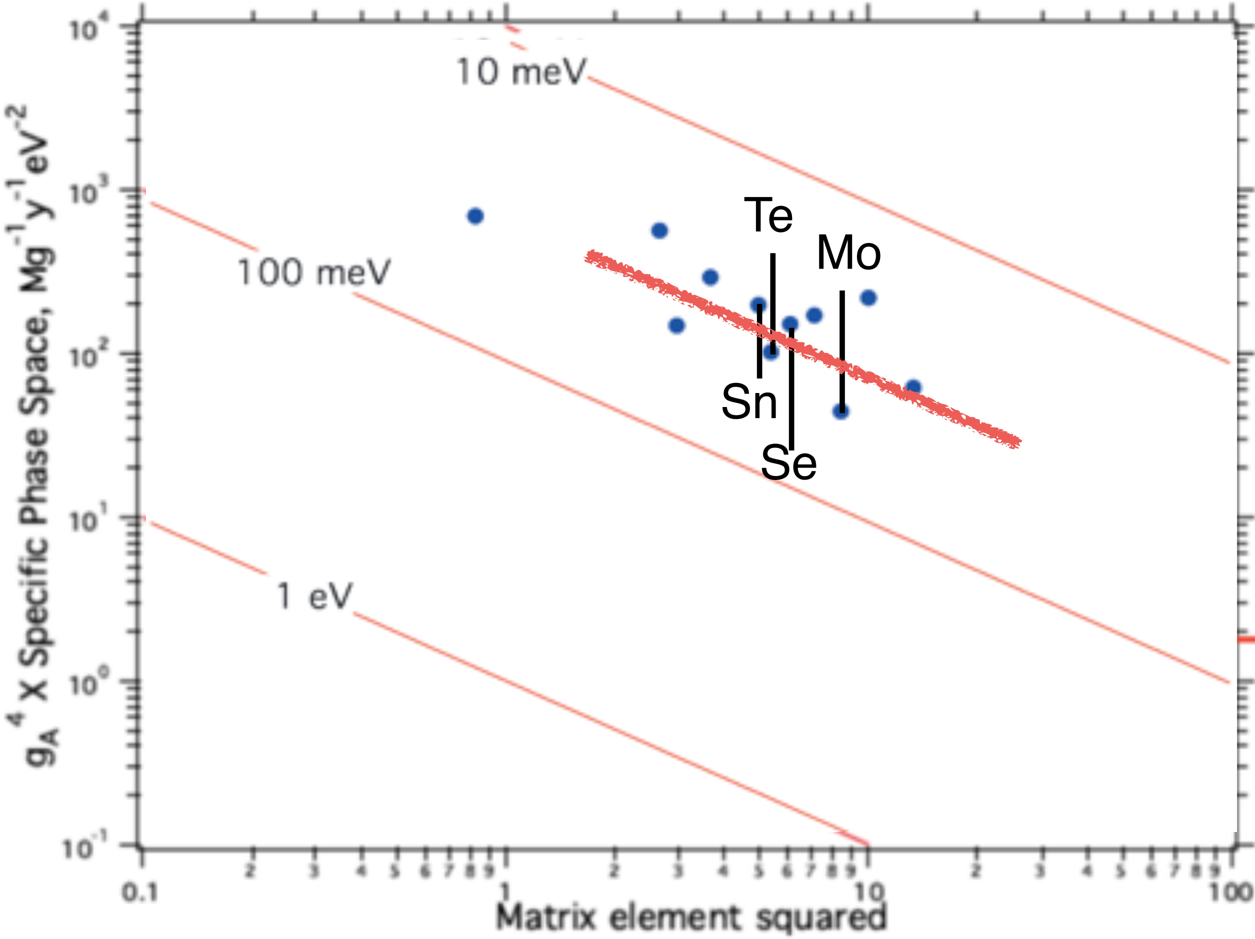


- Material: TeO_2 , ZnSe, $ZnMoO_4$, $CaMoO_4$, Sn…

  All with small enough specific heat at low temp.
- Temperature sensors:
  - NTD thermistors (G ~ 10, easy)
  - TES (G ~ 100-1000, difficult but well settled)
  - MMC (G ~ 100, R&D level)
- Excellent resolution @$0\nu\beta\beta$ energy: ΔE_{FWHM} ~5 keV



Best isotope?



$$\left[T_{1/2}^{0\nu}\right]^{-1} = G_{0\nu} g_A^4 \left|M_{0\nu}\right|^2 \left|\frac{\langle m_{\beta\beta}\rangle}{m_e}\right|^2$$

uncertainty on value of g_A^4

Signal of 1 cnt/t-y for corresponding values of NME and g_A

$$g_A^4 H_{0\nu} = g_A^4 \ln(2) \frac{N_A}{A m_e^2} G_{0\nu}^{(0)}$$

Isotopes have comparable sensitivities in terms of rate per unit mass

Ref: Robertson
MPL A28, 2013, 1350021
arXiv:1301.1323

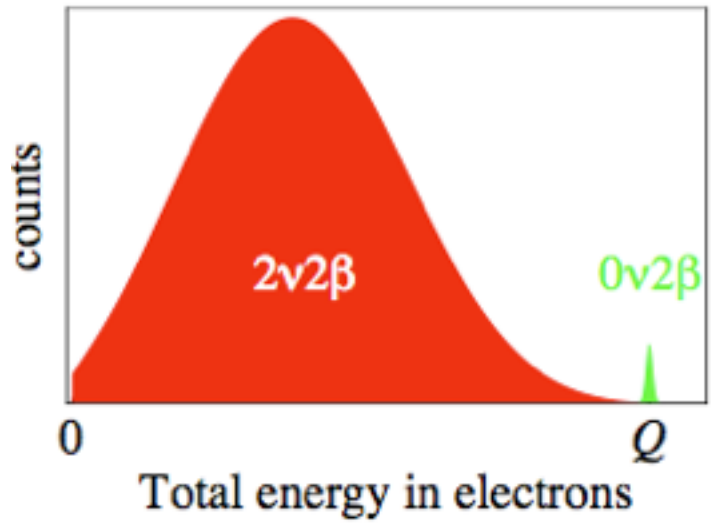
Best isotope?

On the large scale, all isotopes are NOT the same owing to backgrounds, natural and enriched material cost, challenging technologies, logistics of implementation…

Isotope	Q (MeV)	percent natural abund.	element cost [5] ($/kg)	$G^{0\nu}$ (10^{-14}/yr) [6]	$M^{0\nu}$ (avg) [7]	$T^{0\nu}_{1/2}$ for 2.5meV (10^{29}yrs)	tons of isotope for 1 ev/yr	equivalent natural tons	annual world production [5] (tons/yr)	natural elem. cost ($M)	enriched at $20/g ($M)	$0\nu/2\nu$ rate [2][8] (10^{-8})
^{48}Ca	4.27	0.19	0.16	6.06	1.6	2.70	31.1	16380	2.4×10^8	2.6	622	0.016
^{76}Ge	2.04	7.8	1650	0.57	4.8	3.18	58.2	746	118	1221	1164	0.55
^{82}Se	3.00	9.2	174	2.48	4.0	1.05	20.8	225	2000	39	416	0.092
^{96}Zr	3.35	2.8	36	5.02	3.0	0.93	21.4	763	1.4×10^6	27	427	0.025
^{100}Mo	3.04	9.6	35	3.89	4.6	0.51	12.2	127	2.5×10^5	4.4	244	0.014
^{110}Pd	2.00	11.8	23000	1.18	6.0	0.98	26.0	221	207	5078	521	0.16
^{116}Cd	2.81	7.6	2.8	4.08	3.6	0.79	22.1	290	2.2×10^4	0.81	441	0.035
^{124}Sn	2.29	5.6	30	2.21	3.7	1.38	41.2	736	2.5×10^5	22	825	0.072
^{130}Te	2.53	34.5	360	3.47	4.0	0.75	23.6	68	$\sim$150	24	471	0.92
^{136}Xe	2.46	8.9	1000	3.56	2.9	1.40	45.7	513	50	513	914	1.51
^{150}Nd	3.37	5.6	42	15.4	2.7	0.37	13.4	240	$\sim 10^4$	11	269	0.024

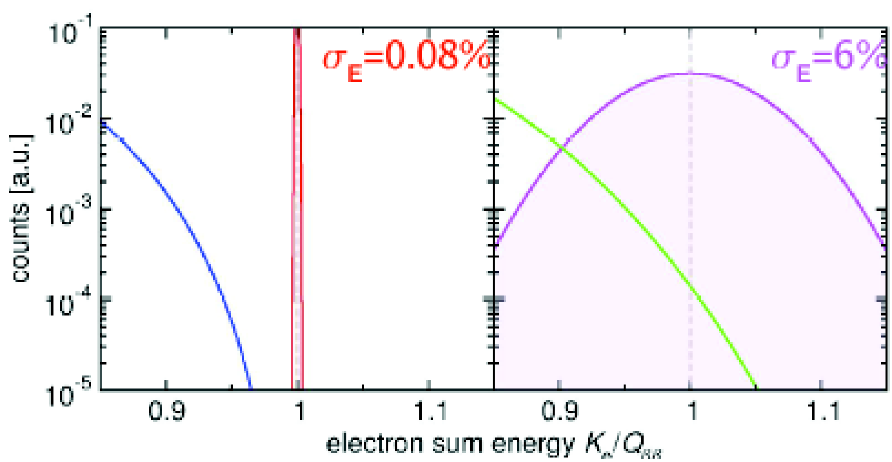
Courtesy of S. Biller, ICTP October 2013

Importance of energy resolution



$$\frac{S}{B} = \frac{Q^5}{\Delta E^6} \cdot \frac{\tau^{2\nu}}{\tau^{0\nu}}$$

Only energy resolution help



Experiments measure the sum of the kinetic energies of the two emitted βs.

Signature: monochromatic line at the Q-value of the decay.

2νββ irreducible background

negligible if ΔE<10 keV

BUT don't forget pile-up!!

Eur.Phys.J. C74 (2014) 10, 3096

Isotope	Crystal	$N_{\beta\beta}$ [n/crystal]	$T^{2\nu}_{1/2}$ [y]	Bkg in ROI [5 keV] [cnts/ton/y]
^{82}Se	ZnSe	2.5×10^{24}	9.2×10^{19}	2.7×10^{-2}
^{116}Cd	$CdWO_4$	1.5×10^{24}	2.8×10^{19}	0.07
^{100}Mo	$ZnMoO_4$	1.3×10^{24}	0.7×10^{19}	1.5
^{130}Te	TeO_2	2.5×10^{24}	68×10^{19}	0.5×10^{-3}

^{100}Mo needs <1msec time res.

Excellent ΔE extra-bonus:

- narrower ROI = better sensitivity
- better identification of background components
- handle against any peaking background

Experimental issues

Half-life sensitivity

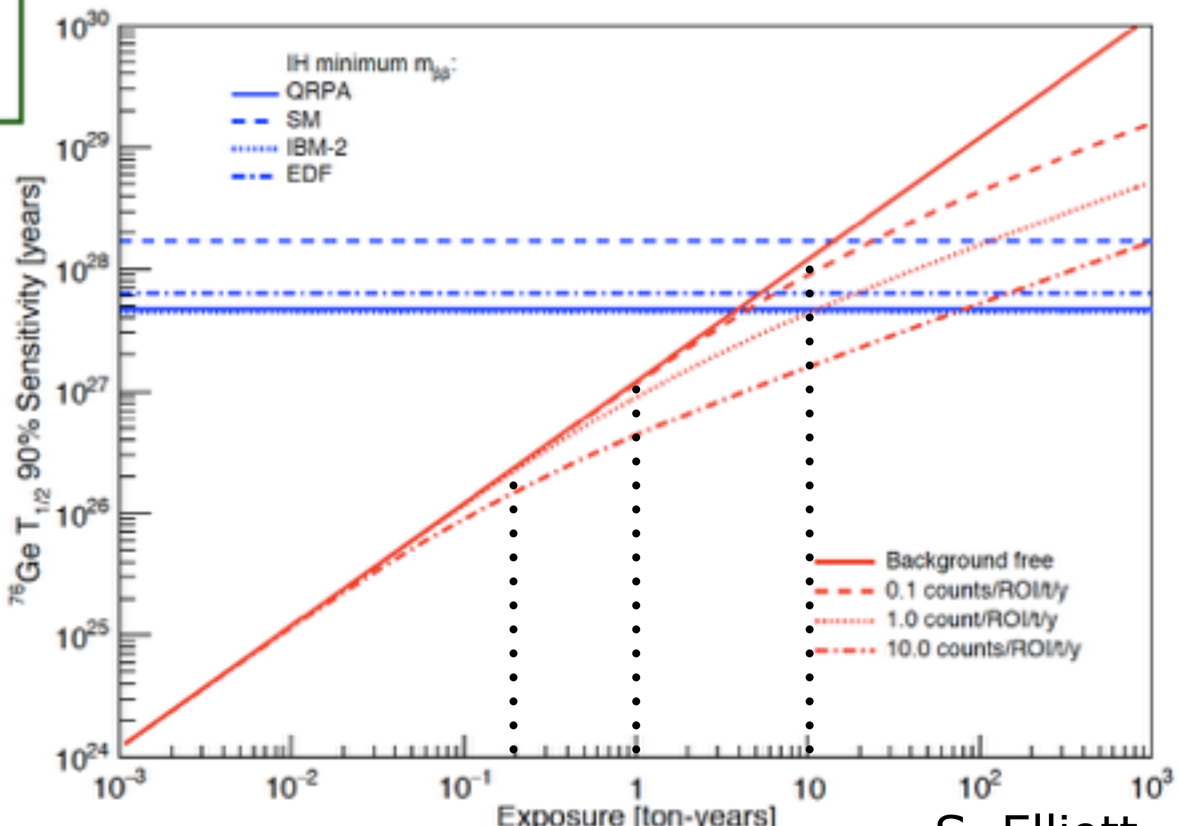
Std case: Signal in competition with bkg

$$F_{0\nu} = \tau_{1/2}^{Back.Fluct.} = \ln 2 \; N_{\beta\beta}\epsilon \frac{T}{n_B} =$$
$$= \ln 2 \times \frac{x \; \eta \; \epsilon \; N_A}{A} \sqrt{\frac{M \; T}{B \; \Delta}} \; (68\% CL)$$

Extreme case: Zero-background

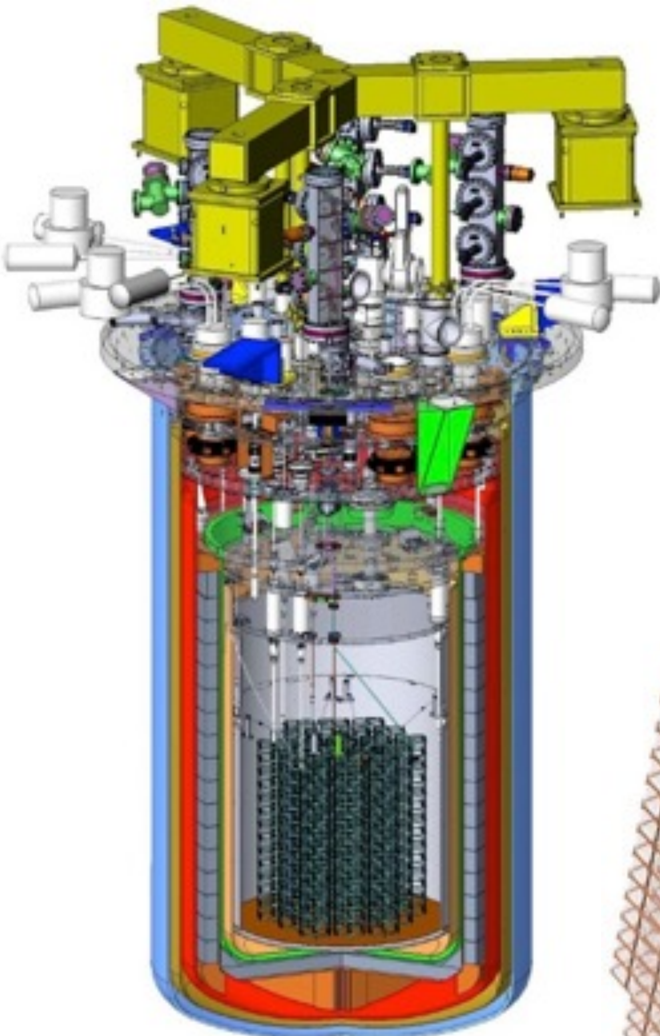
$$F_{0\nu}^{ZB} = \ln 2 \; N_{\beta\beta}\epsilon \frac{T}{n_{CL}} =$$
$$= \ln 2 \times \frac{x \; \eta \; \epsilon \; N_A}{A} \frac{M \; T}{n_{CL}}$$

Example: ^{76}Ge, similar sensitivities for other isotopes



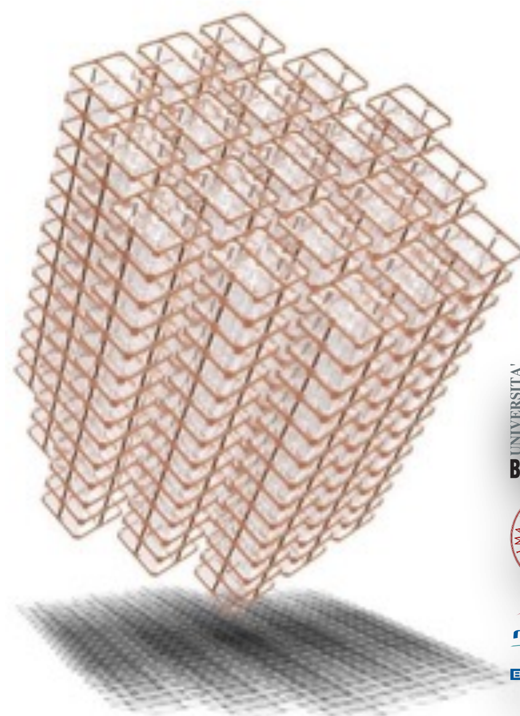
S. Elliott

CUORE



Cryogenic Underground Observatory for Rare Events

- 988 TeO_2 crystals run as a bolometer array
  - 5x5x5 cm^3 crystal, 750 g each
  - 19 Towers; 13 floors; 4 modules per floor
  - 741 kg total; 206 kg ^{130}Te
  - 10^{27} ^{130}Te nuclei



Fiorini's and Avignone's
big dream was born in 1997…

Goal and Status of CUORE

Energy resolution @ ROI: 5 keV

Background goal: 0.01 c/(keV kg y)

Sensitivity 90% C.L. (5 y):

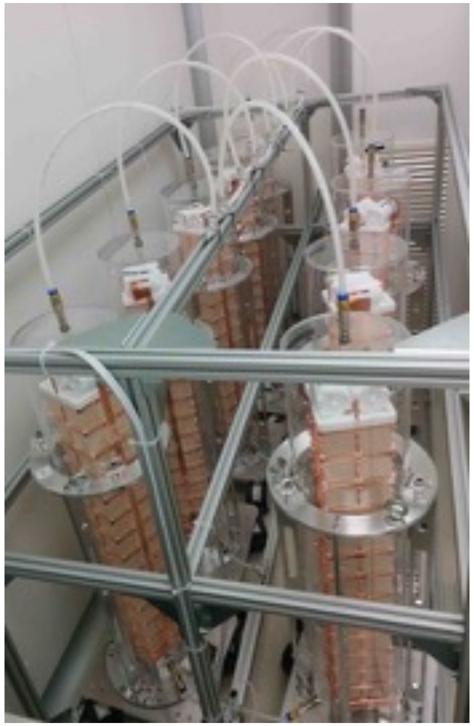
$T_{1/2} = 9.5 \times 10^{25}$ y $m_{\beta\beta} = 50\text{-}130$ meV

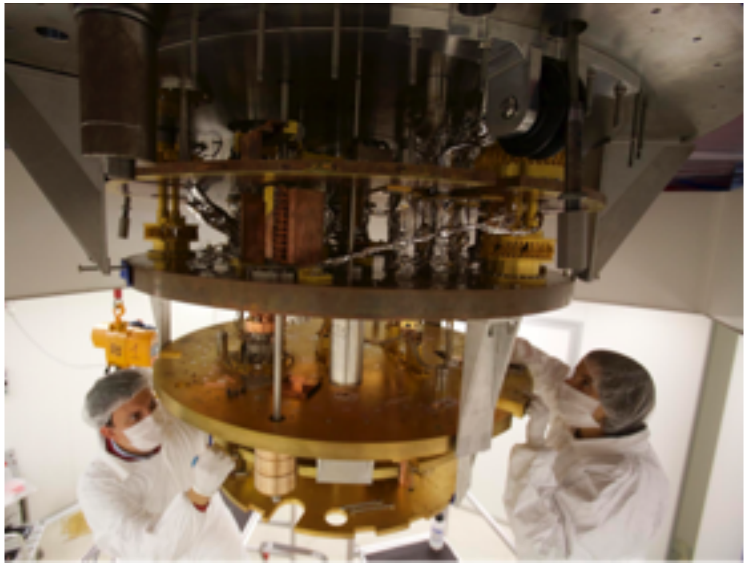
Assembly of the 19 CUORE towers is complete.

Commissioning of the cryogenic system and experimental infrastructure is in progress

6mK stable base temperature achieved in October 2014

Plan to start operations by end of 2015.

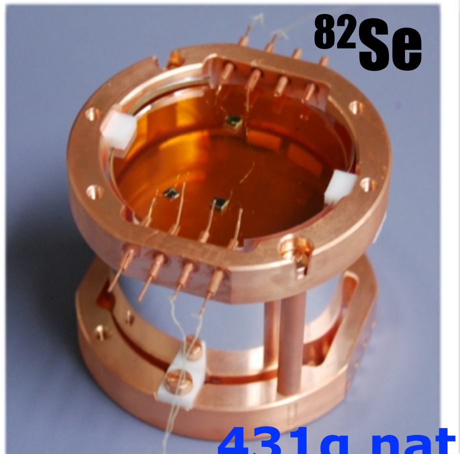




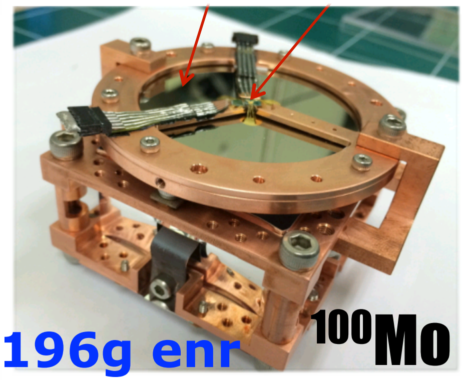
DBD with bolometers: status

The Family Album June 2015

Lucifer : ZnSe

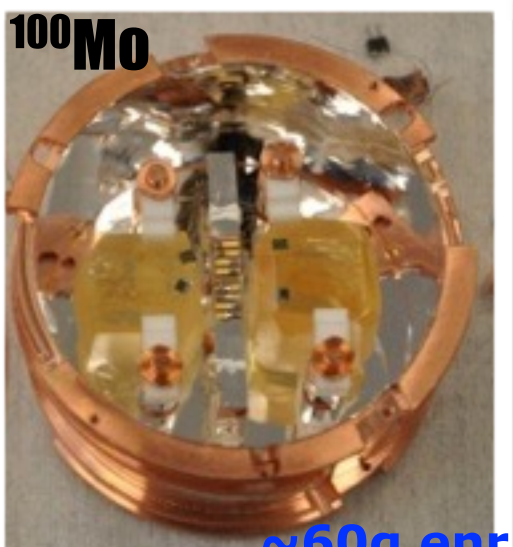


AMoRE: $CaMoO_4$

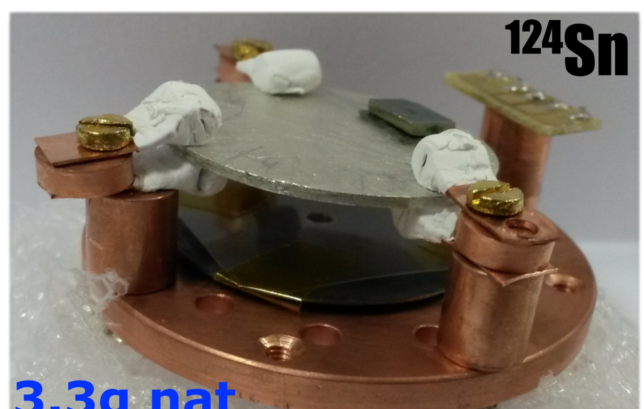


Cuore-0

Lumineu : $ZnMoO_4$



TIN.TIN: pure Sn



DBD with bolometers: status

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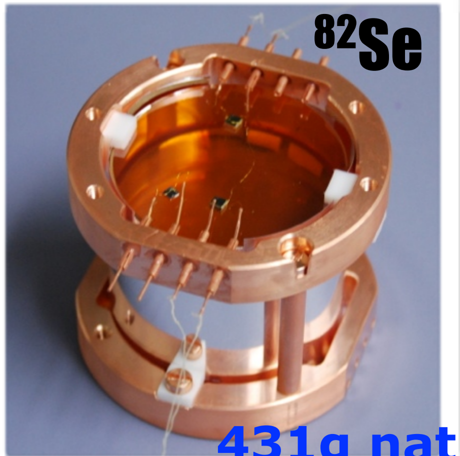
Talks from: P.K. Rath, A. Giuliani, M. Mancuso, K. Schaffner, J. So, M. Biassoni

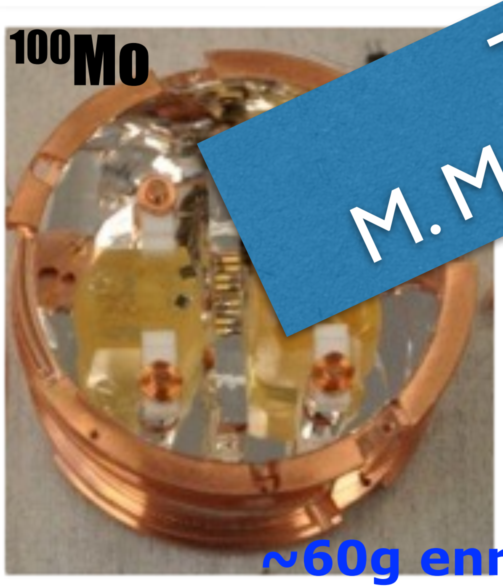
Lucifer : ZnSe



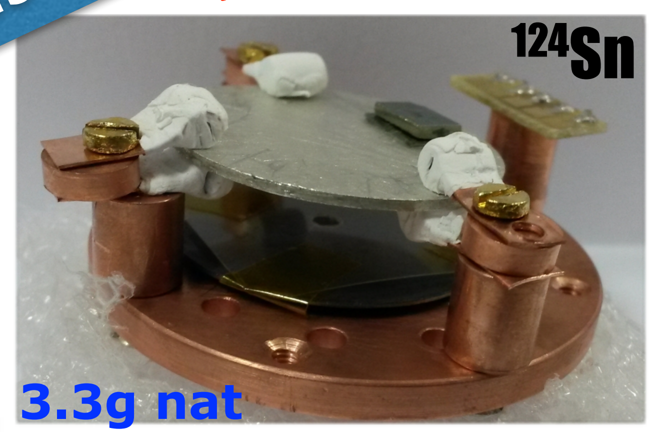
AMoRE: $CaMoO_4$

…e-0

Lumineu : $ZnMoO_4$



…N: pure Sn



DBD with bolometers: ΔE

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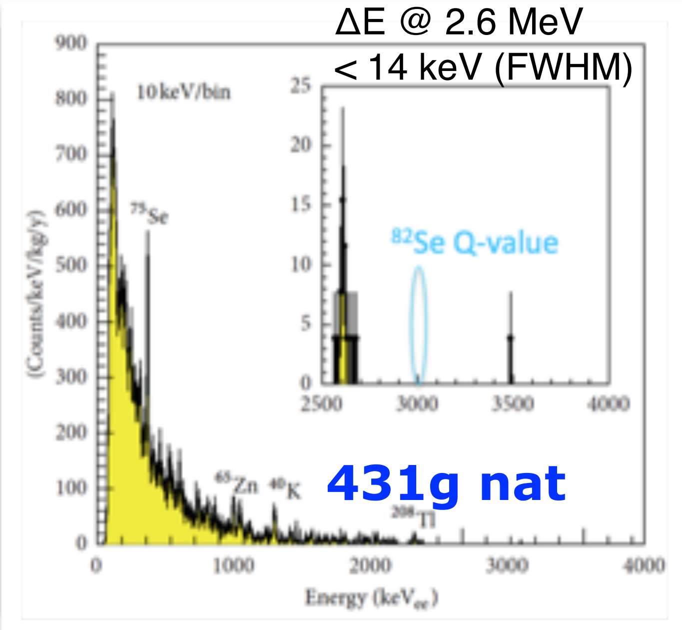
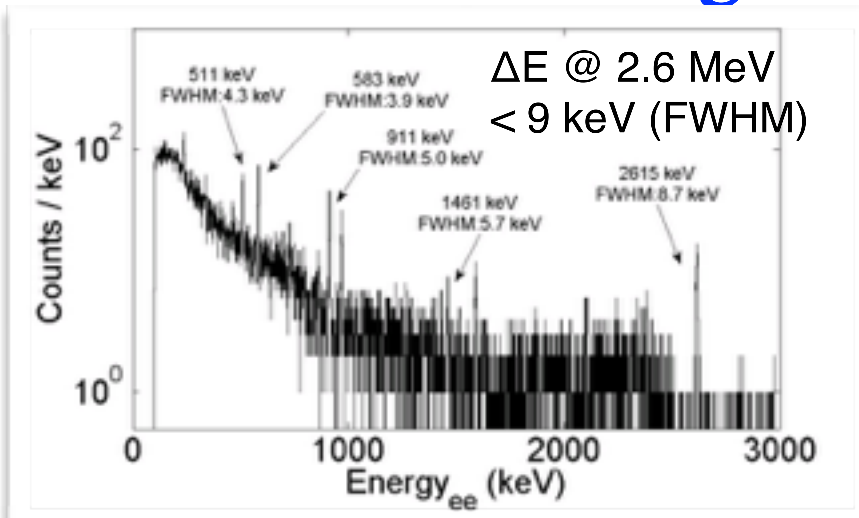
June 2015

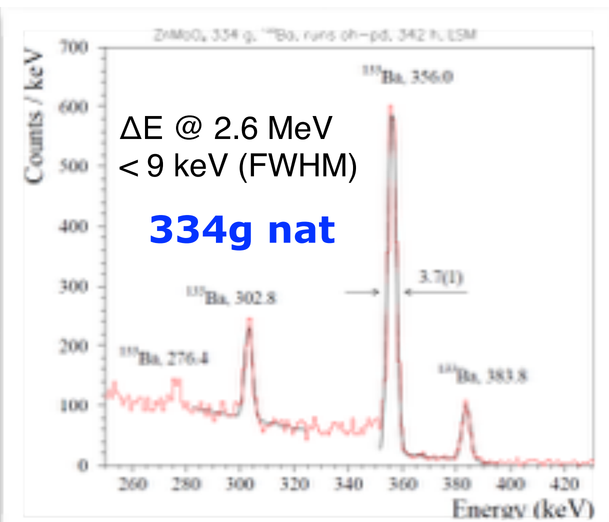
Lucifer



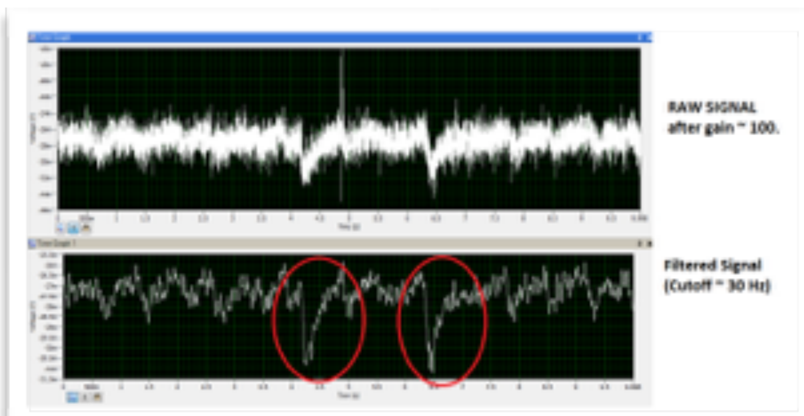
AMoRE **196g enr**



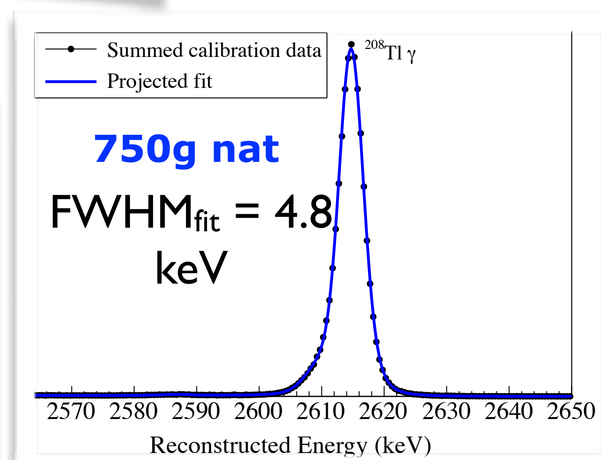
Lumineu



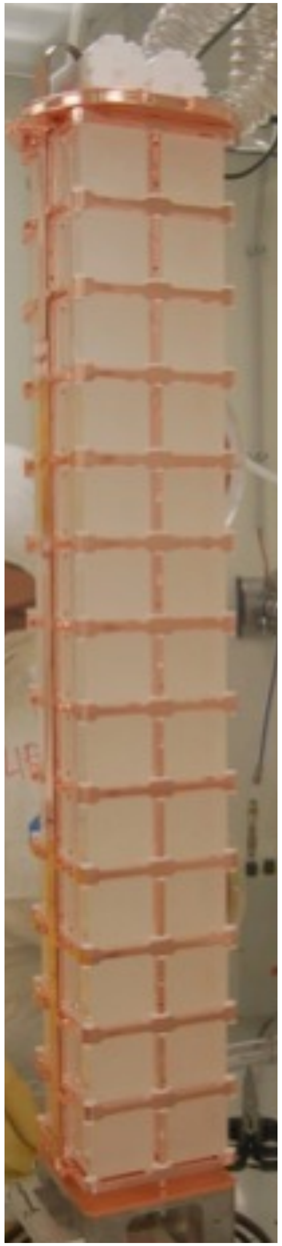
TIN.TIN

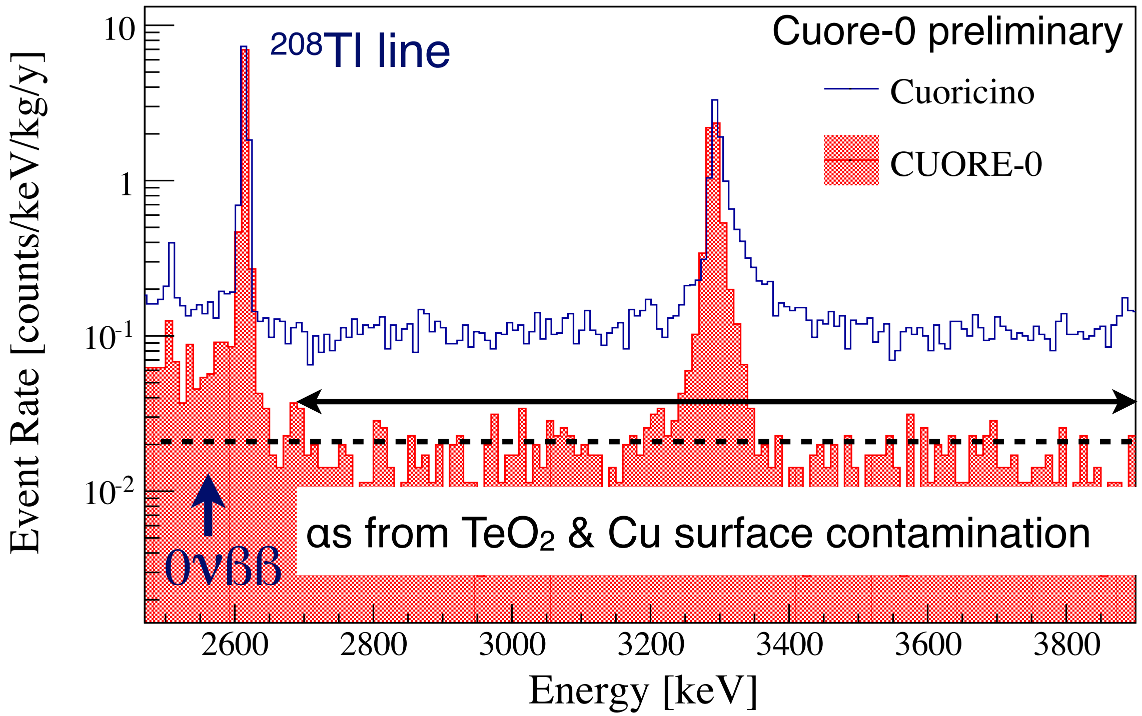


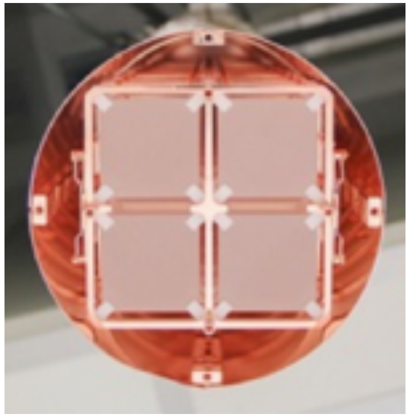
Cuore-0



CUORE-0: the present





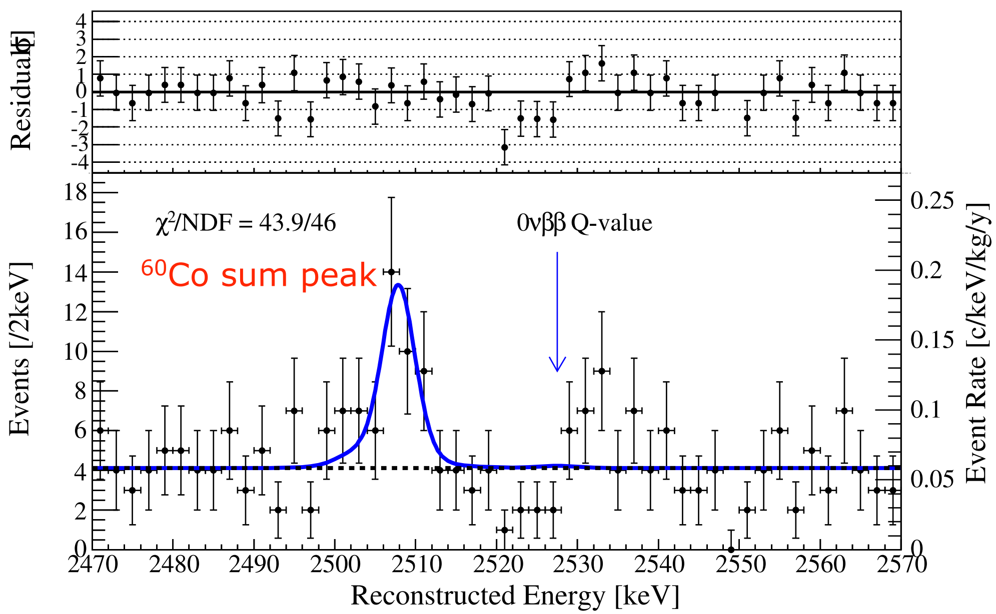


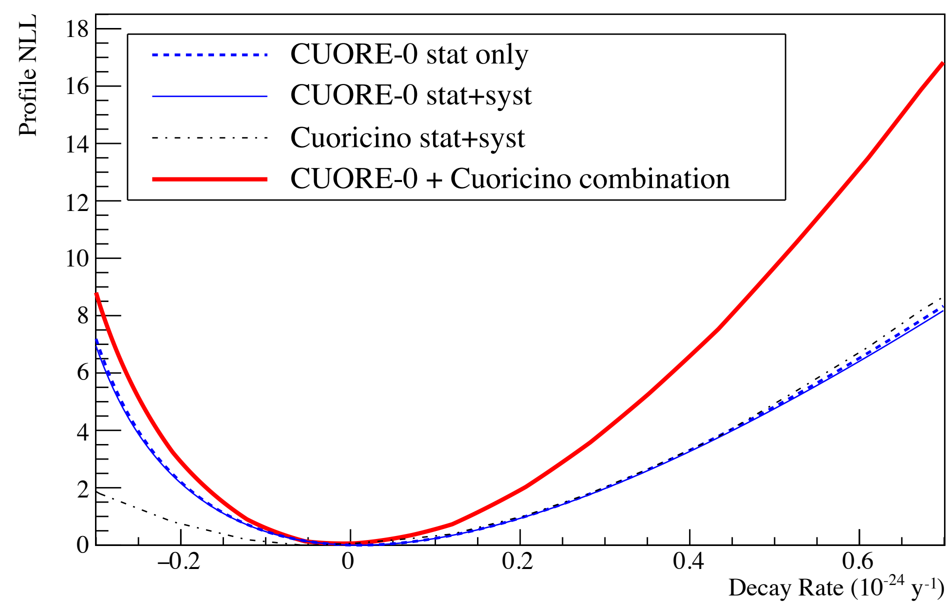
	Background rate [counts/keV/kg/y]		signal eff. [%] (detector+cuts)
	0νββ region	α region (excl. peak)	
Cuoricino	0.169 ± 0.006	0.110 ± 0.001	82.8±1.1
CUORE-0	0.058 ± 0.011	**0.016 ± 0.001**	81.3±0.6

CUORE-0 0νDBD results

A real benchmark for many key items on the path to CUORE

BUT also a good experiment for 0νDBD





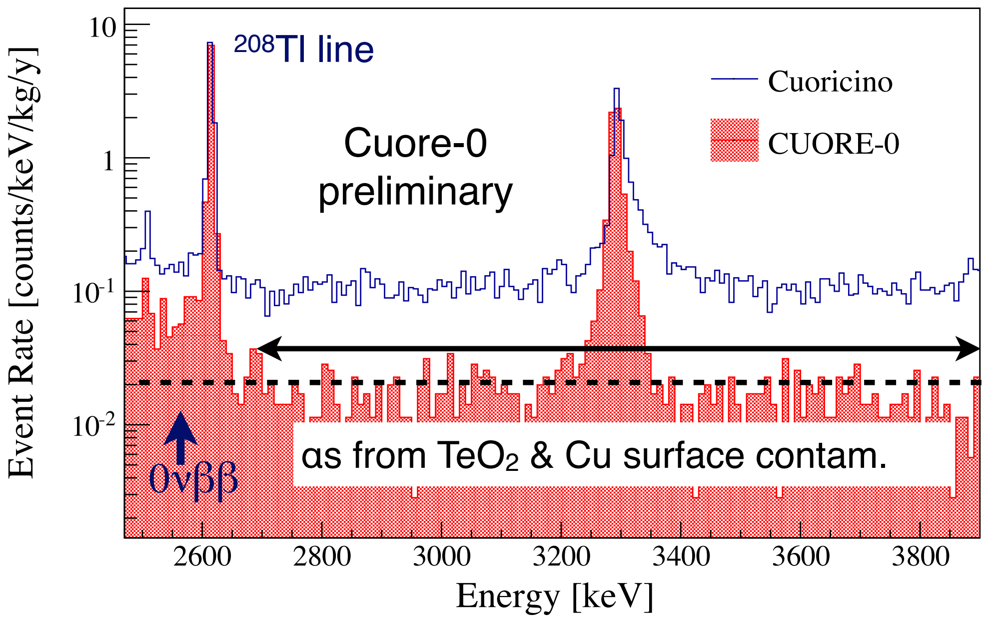
$\Gamma_{0\nu}$	$0\nu\beta\beta$ decay rate	$0.01 \pm 0.12\,(\text{stat.}) \pm 0.01\,(\text{syst.}) \times 10^{-24}\ \text{yr}^{-1}$
Γ_B	Background rate	$0.058 \pm 0.004\,(\text{stat.}) \pm 0.002\,(\text{syst.})$ counts/(keV · kg · yr)

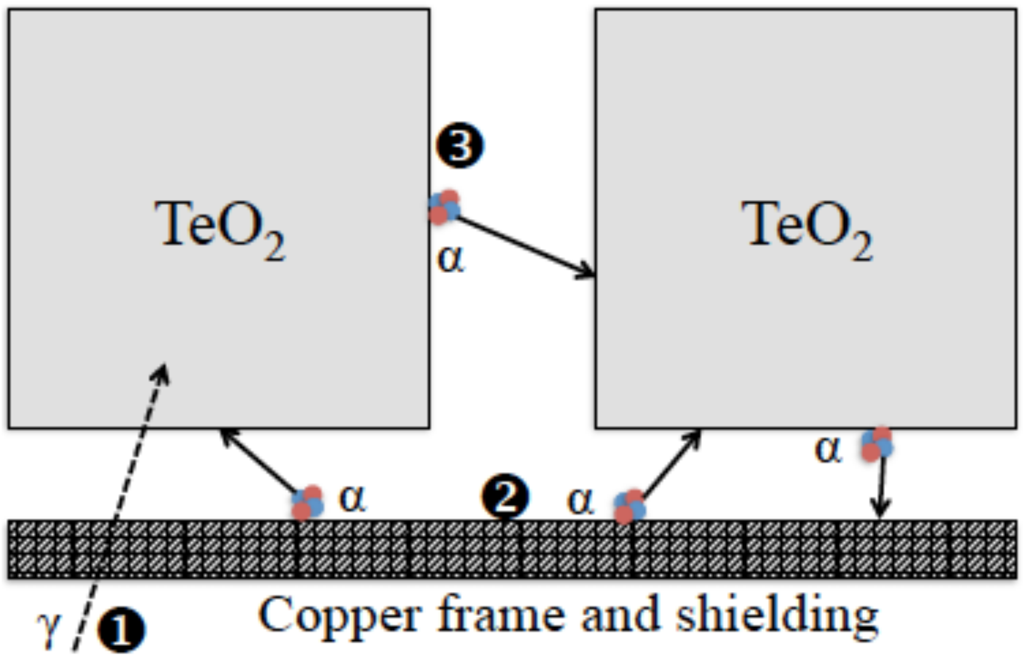
$$T^{0\nu}_{1/2} > 2.7 \times 10^{24}\ \text{yr} \qquad 90\%\ \text{C.L.}$$

CUORICINO: 19,75 kg(^{130}Te)y
CUORE-0: 9,8 kg(^{130}Te)y

The combined 90% C.L. limit is
$T_{0\nu} > 4.0 \times 10^{24}$ yr

CUORE-0 lesson: the bkg





CUORICINO bkg in the ROI :
0.169 ± 0.006 c/keV kg y

CUORE-0 bkg in the ROI :
0.058 ± 0.011 c/keV kg y

1. 0.05 ~ 0.06 from γ peak of ^{208}Tl and old small crystals bkg

Same Cryostat →

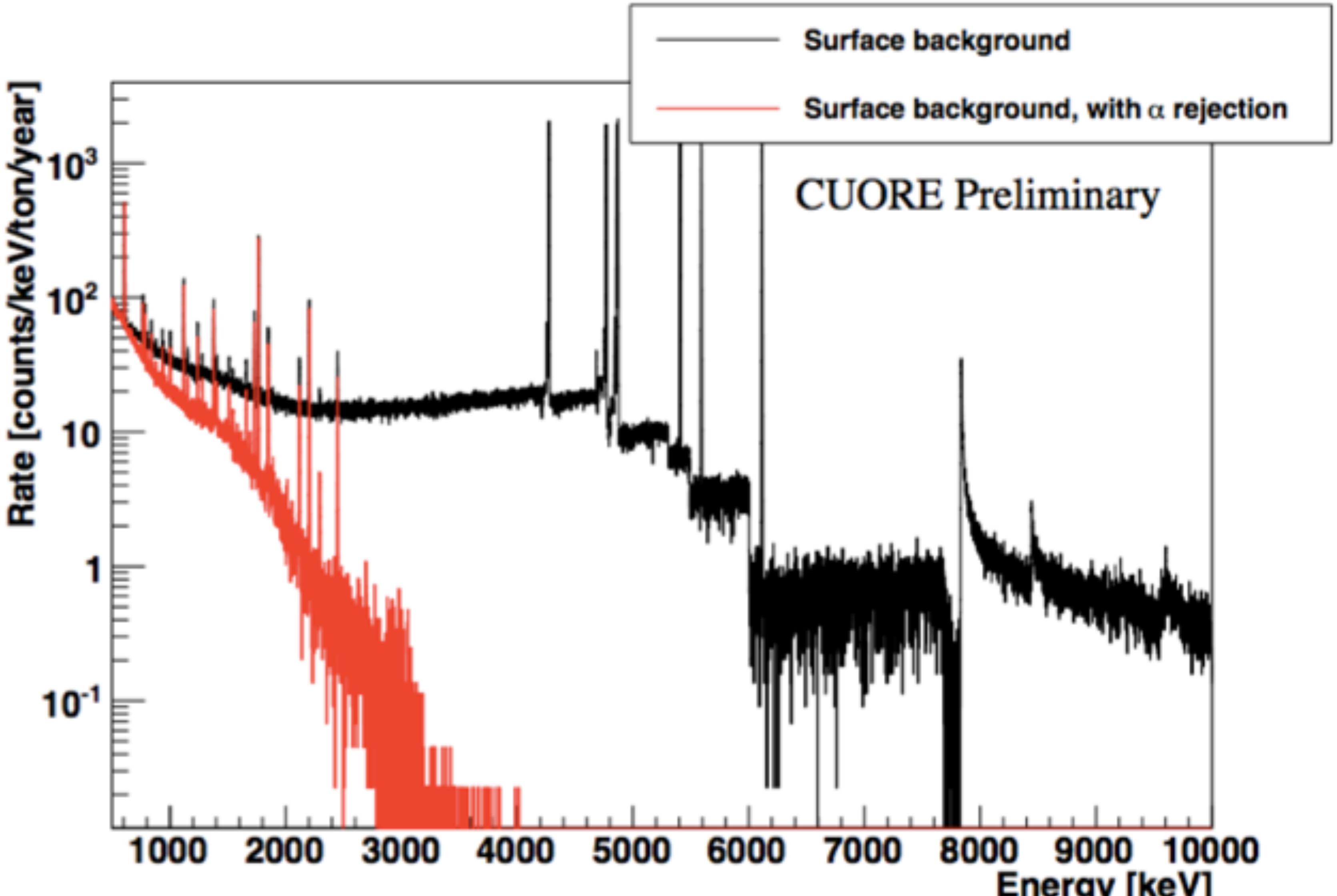
1. γ peak of ^{208}Tl: the same

2. ~0.1 from copper surface contamination
3. ~0.01 from crystal surface contamination

Copper cleaning
Clean assembly
Better surface treatment →

2. 0.016 ± 0.001: Cu and crystal surface contam.

Power of Particle Identification

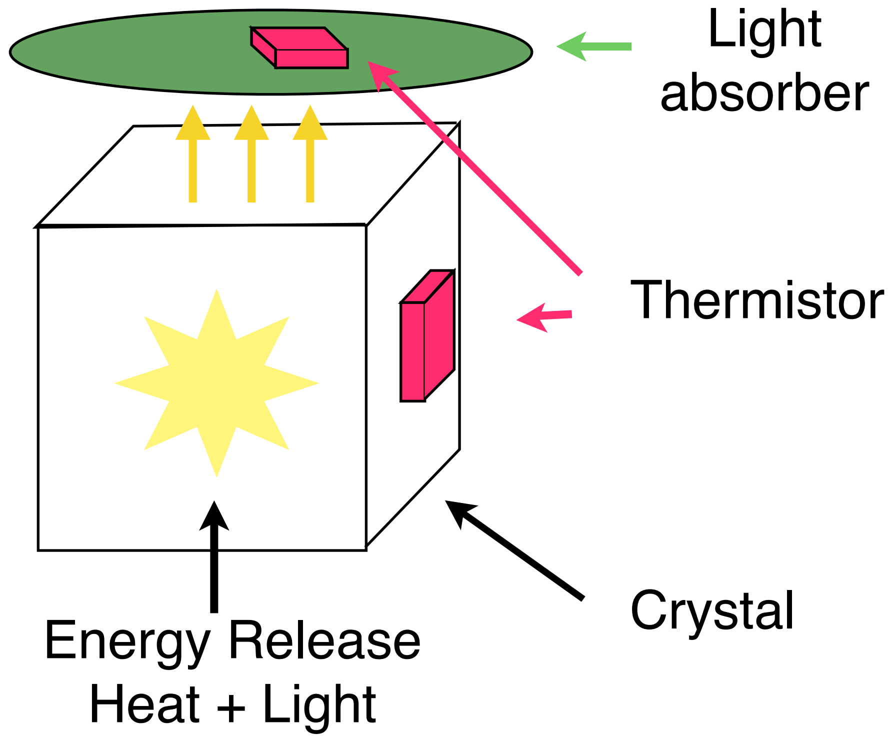


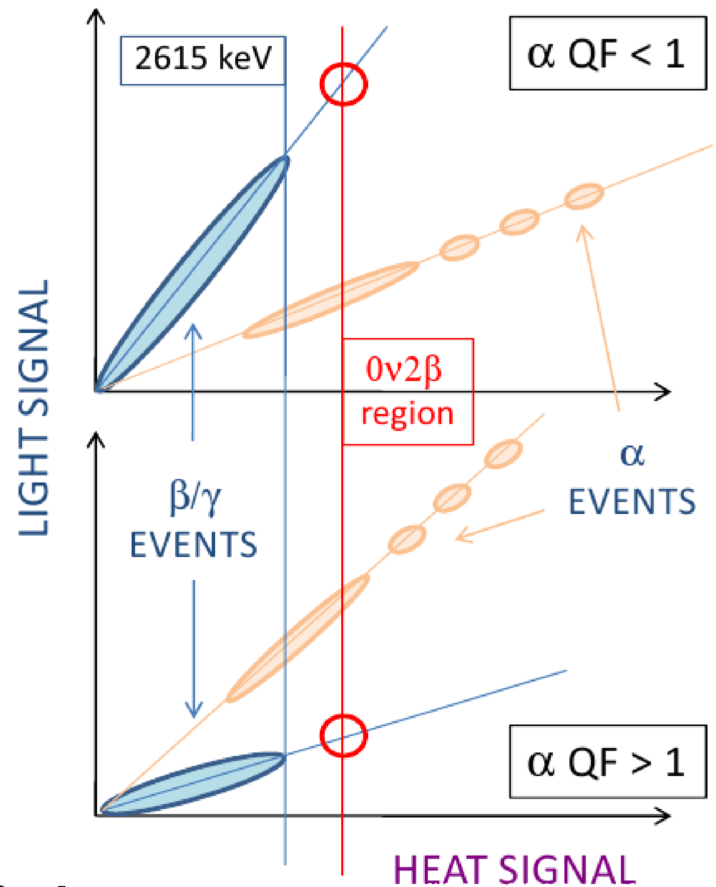
^{238}U with 5μm depth profile on TeO_2 and detector copper surfaces

Assume 5σ α-β separation

α identification in scintillating bol.

Scintillating crystals can be operated as bolometers. The simultaneous read-out of light and thermal signals allows to discriminate the α background thanks to the scintillation yield different from β particles.



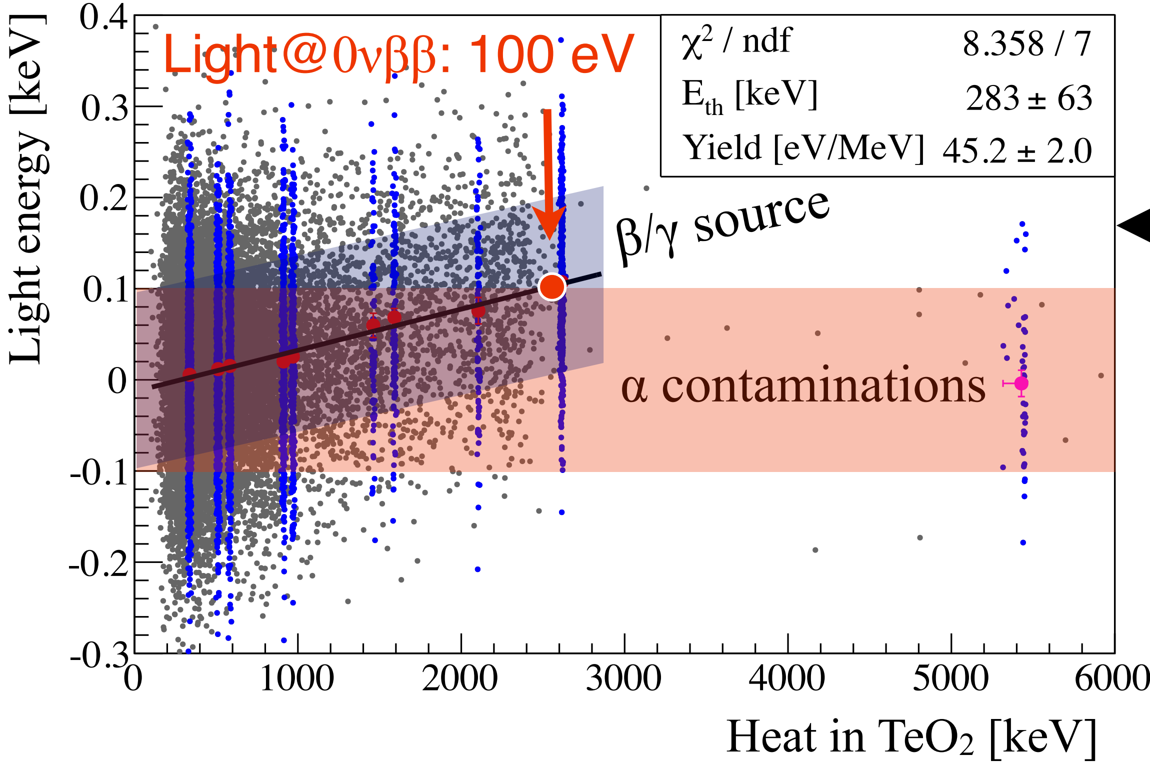


$ZnSe$, $ZnMoO_4$, $CaMoO_4$ ...

NOT TeO_2!

α identification in TeO_2: Cherenkov

Rejection technique: detect the Cherenkov light emitted by βs (signal) and not by αs.

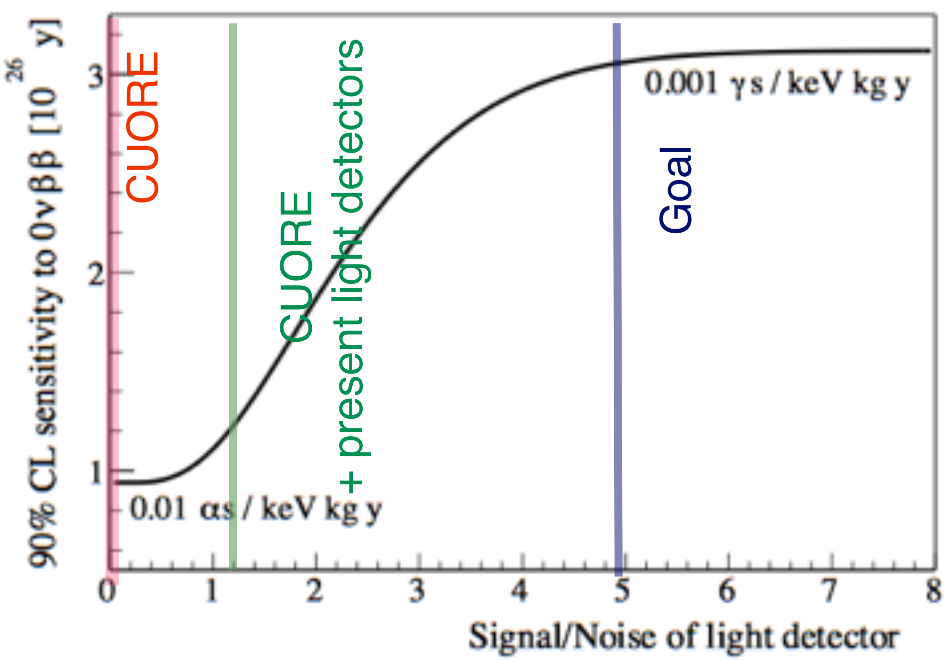


Eur. Phys. J. C65 (2010) 359

Eur. Phys. J. C75 (2015) 1

signal/noise ~1

To obtain S/N > 5 need **noise < 20 eV RMS.**



technology must be scalable to 1000 light detectors.

α identification: LY

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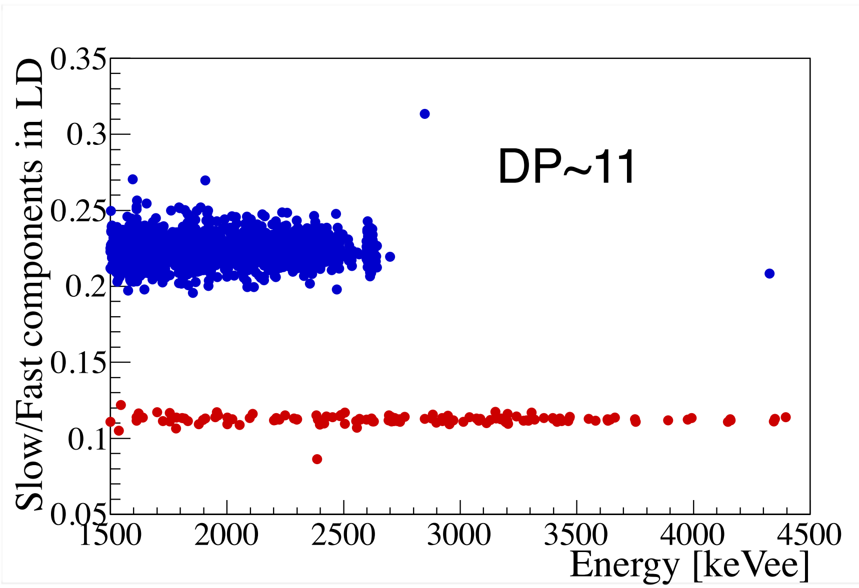
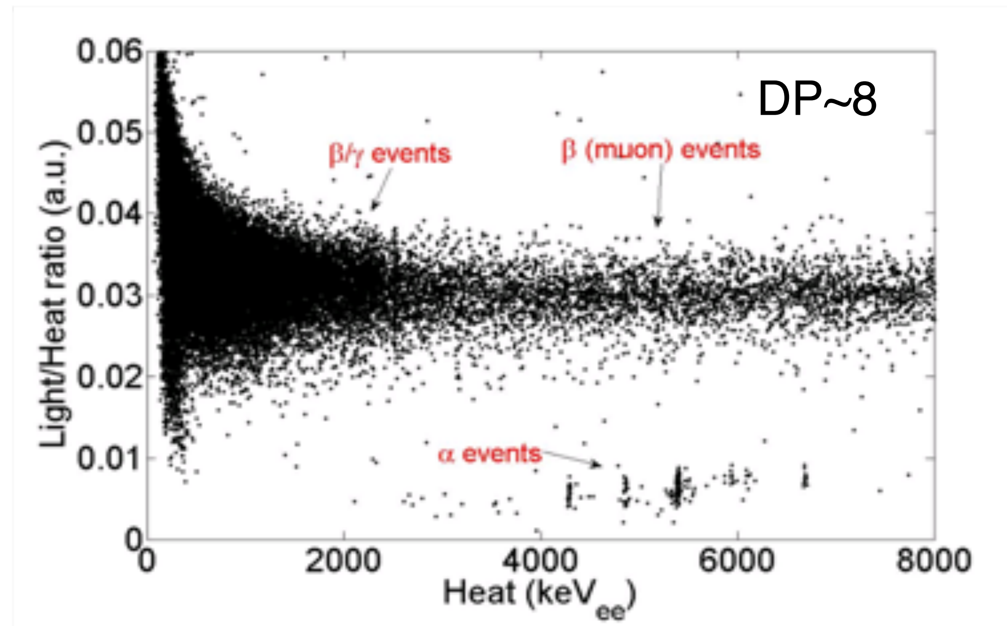
$$DP(E) = \frac{|\mu_\alpha(E) - \mu_{\beta/\gamma}(E)|}{\sqrt{\sigma_\alpha^2(E) + \sigma_{\beta/\gamma}^2(E)}}$$

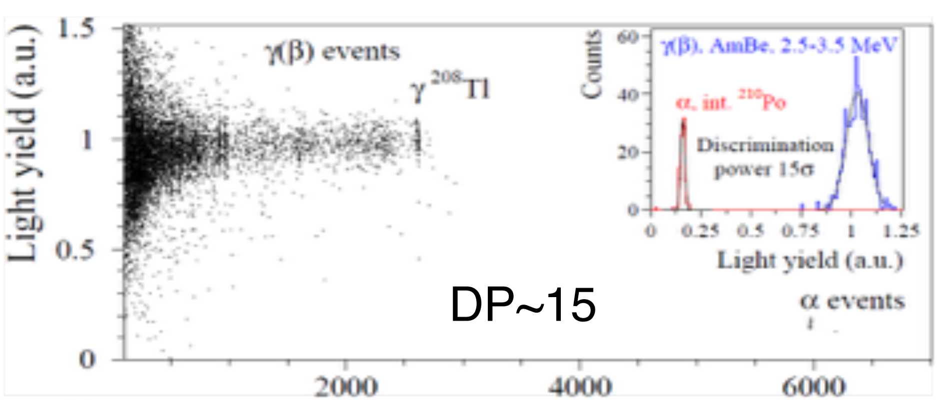
Lucifer Se nat.



AMoRE Mo enr.

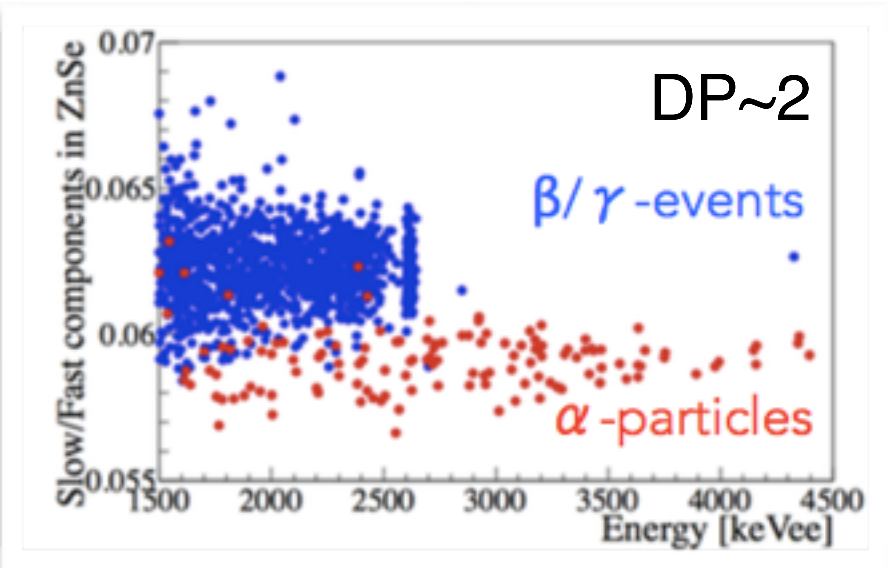


Lumineu Mo nat.



α identification: PSD

Lucifer Se



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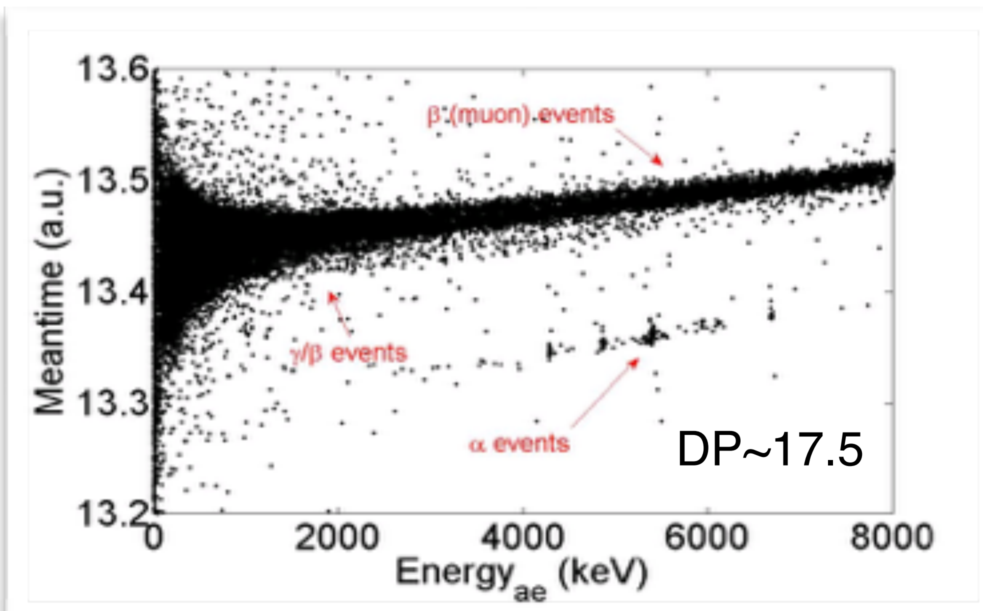
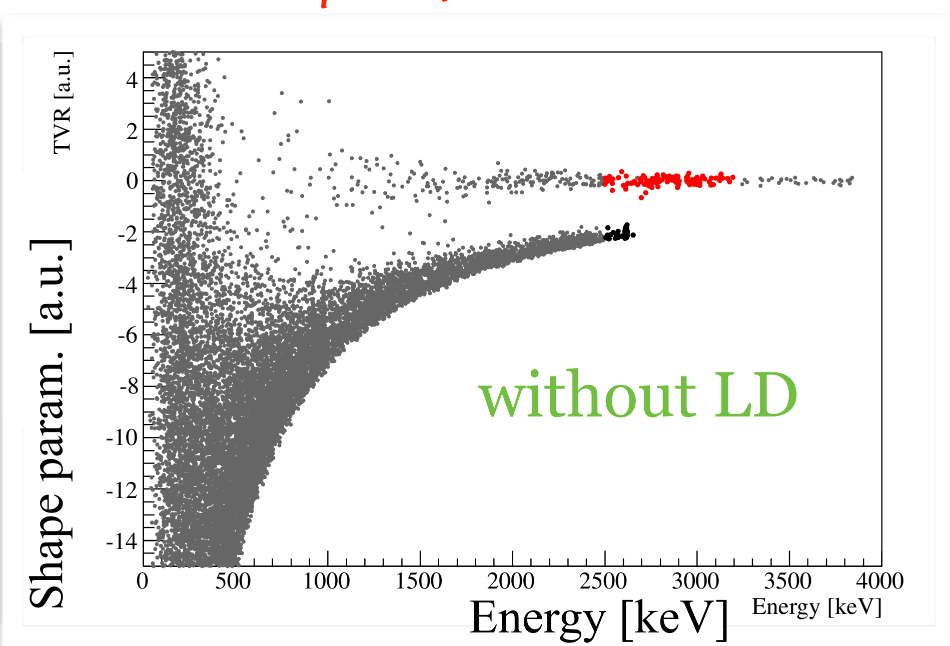
AMoRE Mo enr.



Lucifer Mo



α identification: light detectors

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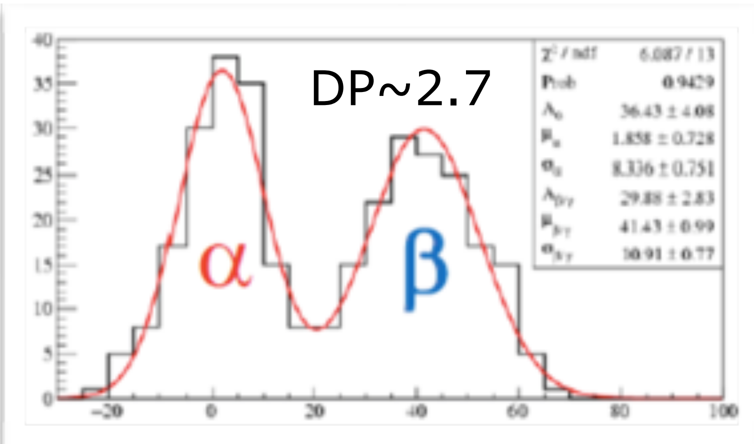
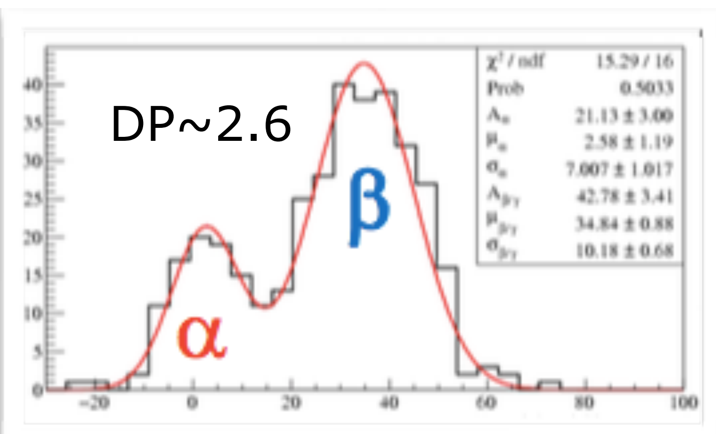
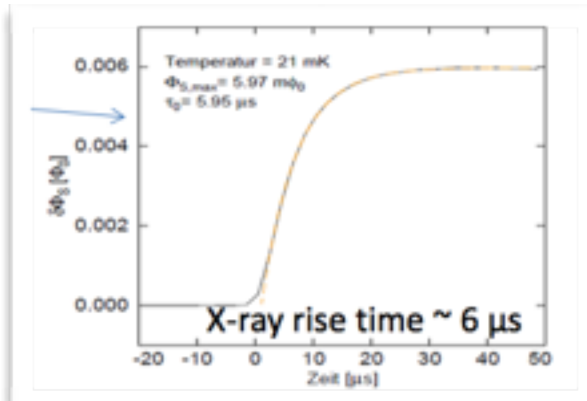
NTD+NTD+TeO_2



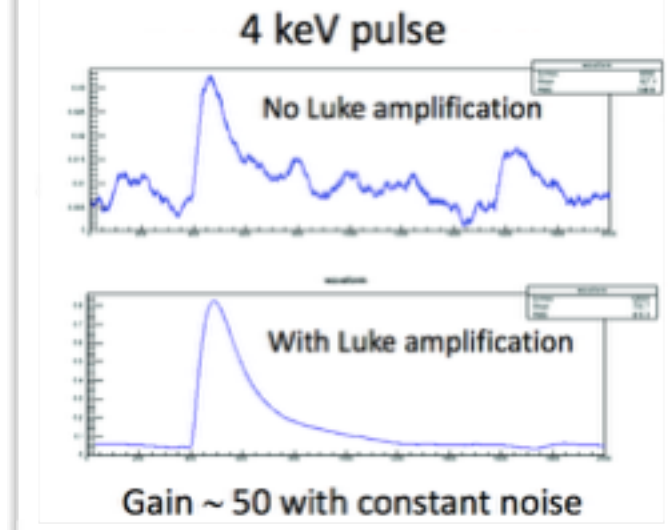
NTD+GeNL+TeO_2



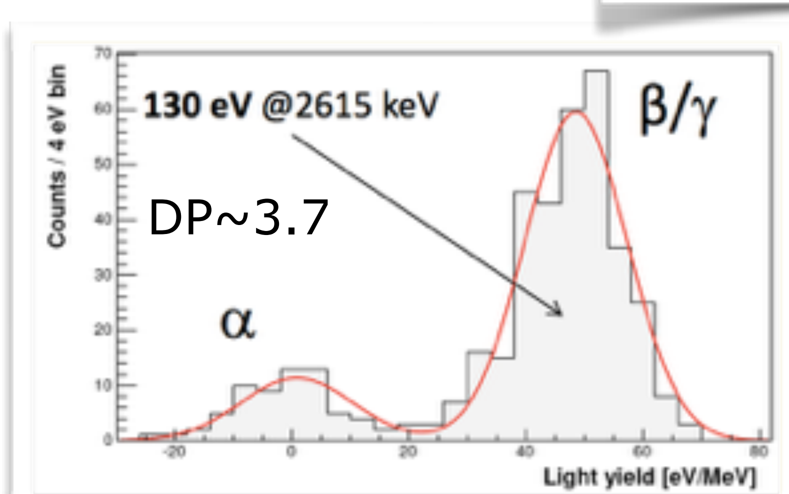
MMC



NTD+SiNL



TES+TES+TeO_2



see A. Giuliani's talk on CUPID

DBD with bolometers: crystals

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Lumineu : $ZnMoO_4$

previous test

Enriched ~1.4 kg boule

Crystallization and enr.:

- specific for each crystal
- can increase bkg
- losses

Best crystal bkg (TeO2 nat, μBq/kg):

^{238}U: < 0.7
^{232}Th: < 0.8
^{210}Po: < 3.3
^{60}Co: < 8 e-4
^{110m}Ag: ~ 0.06

AMoRE: $CaMoO_4$

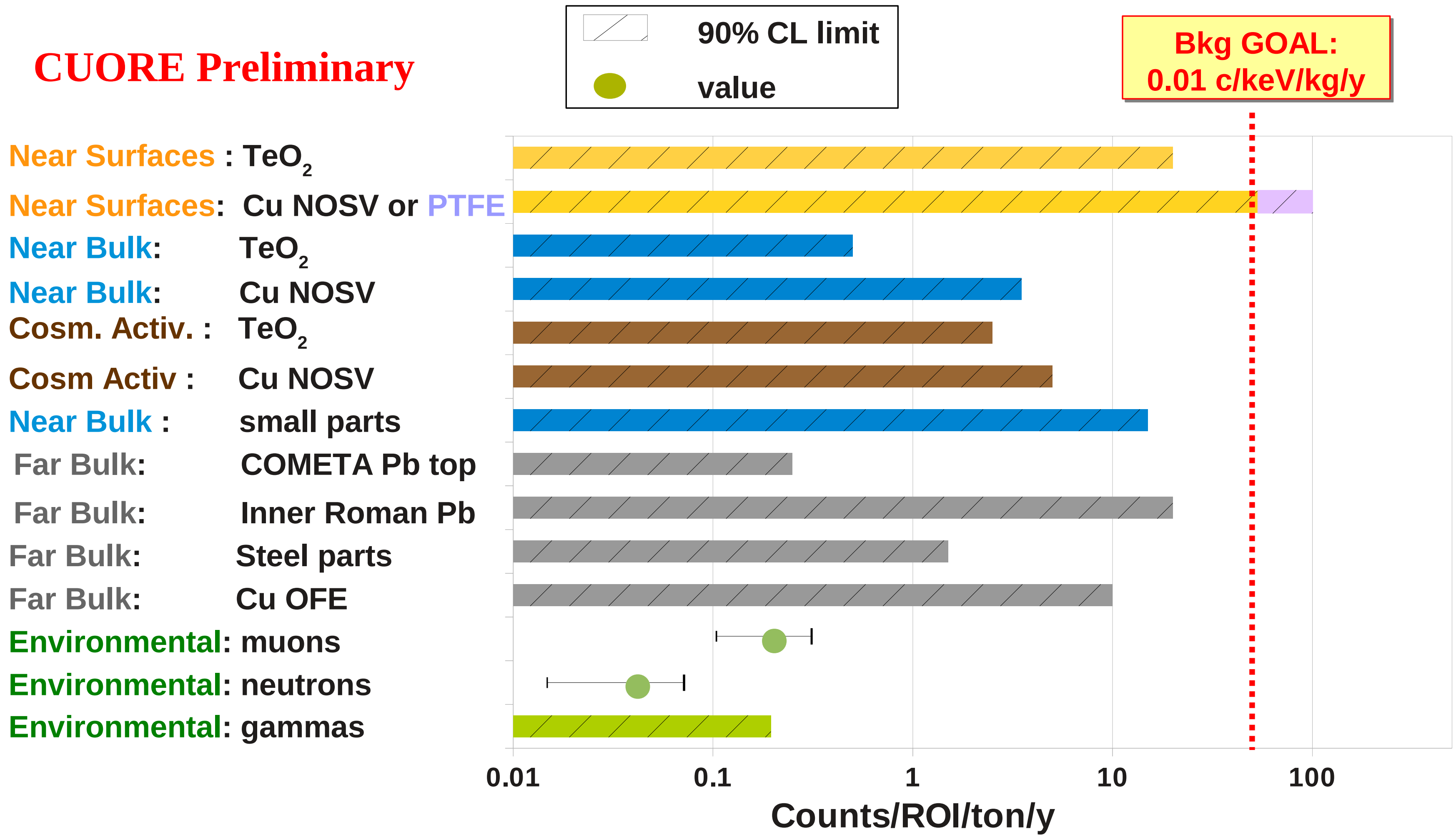
Enrichment: 17 \$/g Te
100 \$/g Se, Mo

Present expected characteristics

	CUORE	LUCIFER	LUCINEU	AMoRE
Crystal	TeO_2	ZnSe	$ZnMoO_4$	$ZnMoO_4$
$0\nu\beta\beta$ isotope	^{130}Te	^{82}Se	^{100}Mo	^{100}Mo
Enrichment	natural	96%	95%	90%
Det. mass	741 kg	13 kg	10 kg	10 kg
Isotope mass	206 kg	~7 kg	~7 kg	~7 kg
Laboratory	LNGS	LNGS	Modane+LNGS	Y2L
$\tau_{1/2}$	~10^{26} y	~4.5 x10^{25} y	~5x10^{25} y	~3x10^{25} y
Sensitivity	50-130 meV	~100-300 meV	90-300 meV	~60-180 meV

CUORE Bkg Budget

Conservative upper limits: NEED CUORE MEASURE



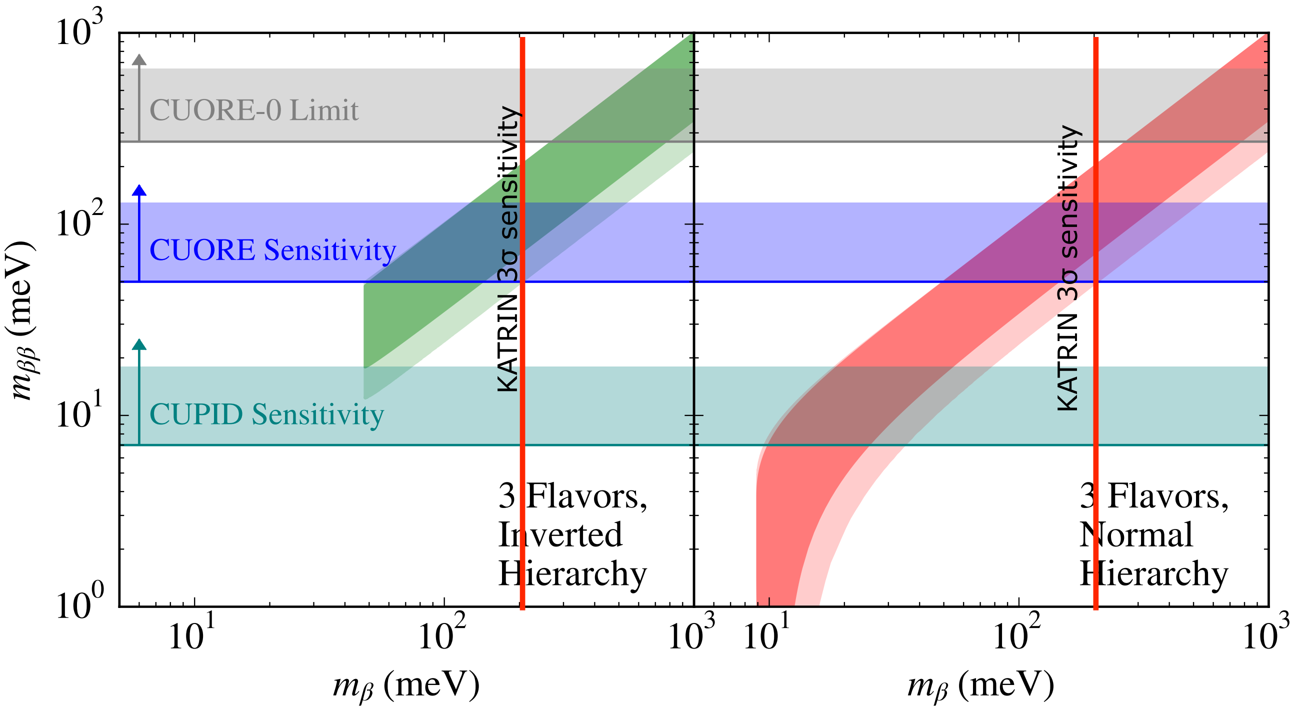
Only after ~1 y of CUORE data we will be able to know how all these contribute

Future for bolometers in DBD?

- Successful operation (cryogenics) of a ton-scale bolometric exp.
  - ☛ CUORE
- In-situ background measurements in a ton-scale detector
  - ☛ For CUPID, see CUORE by ~2016
- Demonstration of a technology for ~0 bkg ton-scale experiment
  - ☛ Already done with scintillating bolometers
  - ☛ Additional R&D activities on going (e.g. Cherenkov for TeO_2)
- Demonstration of scalability of technology choice
  - ☛ AMoRE phase 1 in 2016 @Y2L
  - ☛ LUCIFER/LUCINEU in 2016 @LNGS
  - ☛ Additional multi-channel R&D runs @LNGS
- R&D on industrialization of crystal production, enrichment

BACK-UP

CUORE and CUPID Sensitivity

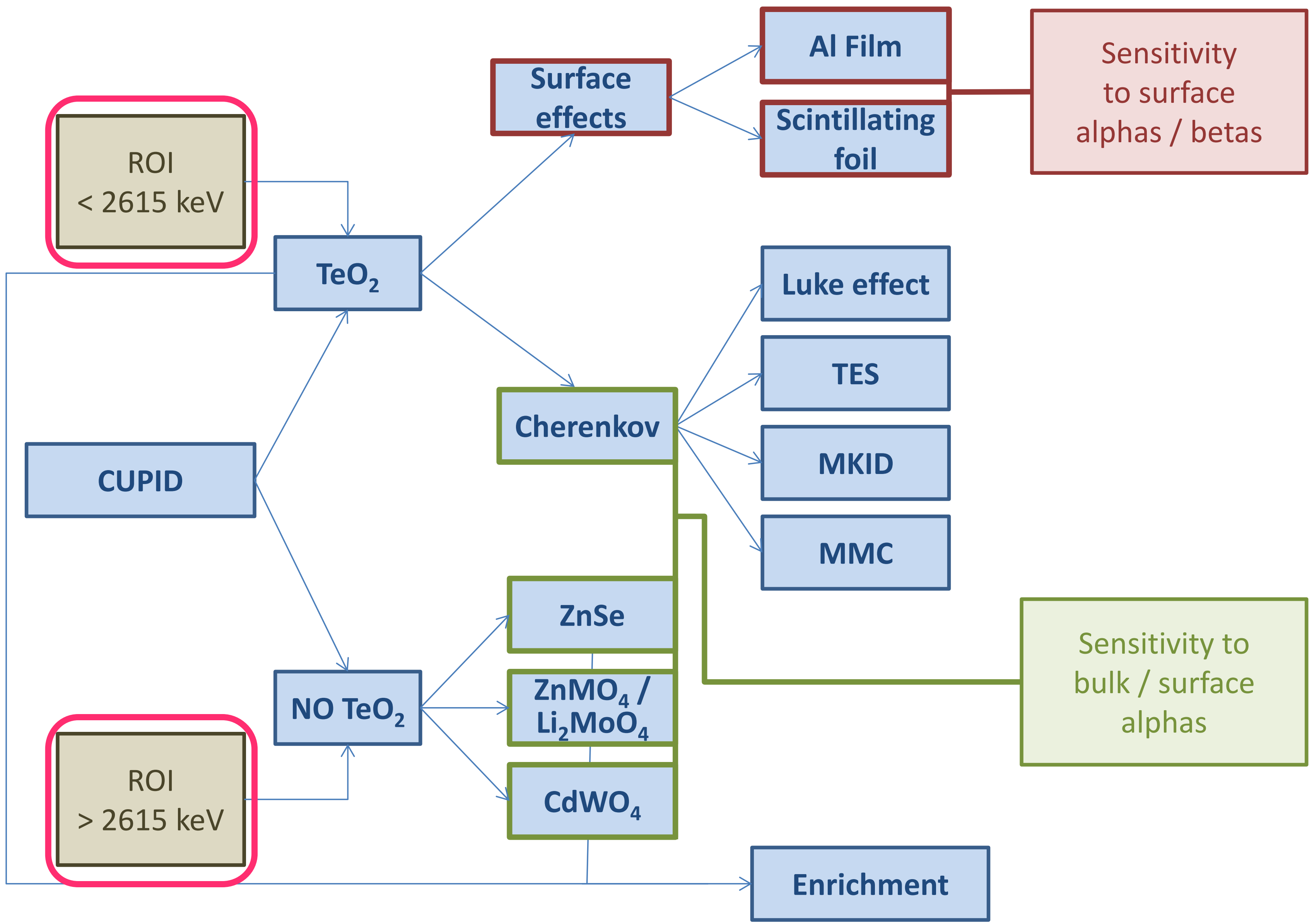


Plot against m_β for a change…

CUORE will cover a good part of the IHR

Strange enough, Katrin and CUORE sensitivities match at the border line of both HR

Cuore Upgrade with Particle Identification



Cosmic and Cosmogenic Backgrounds

Cosmic ray-induced backgrounds within ±20 keV of $Q_{\beta\beta}(^{130}Te)$

CUORE ROI - BULK CONTRIBUTIONS FROM EXTERNAL SOURCES

Source	Total	Anti-coinc. (Global)	Anti-coinc. (Near neighbor)
Gamma	<0.390	<0.390	<0.390
Neutron	0.270 ± 0.022	$(8.56 \pm 6.06)\times10^{-3}$	0.0642 ± 0.0442
Muon	17.3 ± 0.3	0.104 ± 0.022	1.850 ± 0.049

counts/(ton keV year)

γ rate estimates limited by available data and MC statistics: will measure in CUORE

μ rate may need to be reduced (by ~1/10): μ veto at LNGS or deeper site

Cosmogenic activation of near detector elements (Te and Cu): minimize by storing both underground as soon as possible. Most dominant backgrounds from

- ^{60}Co in Cu structures: <50 μBq/kg → $<5\times10^{-1}$ counts/(ton keV year) in ROI
- Other contributions negligible → will measure Cu activation in CUORE and reassess

Sensitivity

Crystal	IHE mass [ton]	Exposure [ton·y]	$T^{0\nu}_{1/2\,D}$ [10^{27}y]	$\|m_{ee}\|_D$ [meV]	$T^{0\nu}_{1/2\,S}$ [10^{27}y]	$\|m_{ee}\|_S$ [meV]
ZnSe	0.664	3.3	0.81	18–52	2.2	9–27
$CdWO_4$	0.985	4.9	0.49	24–45	1.5	12–22
$ZnMoO_4$	0.540	2.7	0.19	24–69	0.65	11–31
TeO_2	0.751	3.7	0.90	17–43	2.6	8–21

- Assumptions:
  - 988 125 cm^3 crystals
  - 90% enrichment
  - 5 years & 5 keV resolution
  - background ~0.1cpy/ton

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Crystal	^{238}U [Bq/kg]	^{232}Th [Bq/kg]	^{238}U rate in ROI [cnts/ton/y]	^{232}Th rate in ROI [cnts/ton/y]	Ref.
TeO_2	$< 7 \times 10^{-7}$	$< 8 \times 10^{-7}$	$< 2 \times 10^{-2}$	$< 5 \times 10^{-1}$	[62]
ZnSe	$< 4 \times 10^{-7}$	$< 4 \times 10^{-7}$	$< 3 \times 10^{-2}$	$< 3 \times 10^{-1}$	[50]
$CdWO_4$	$< 4 \times 10^{-5}$	$< 4 \times 10^{-6}$	< 1	< 5	[51]
$ZnMoO_4$	$(27 \pm 6) \times 10^{-6}$	$< 8 \times 10^{-6}$	$(5.5 \pm 1.0) \times 10^{-1}$	< 5	[55]

Element	Contamination [Bq/cm^2]	Te [cnts/ton/y]	Se/Cd/Mo [cnts/ton/y]
^{238}U on crystal surface	$< 2 \times 10^{-9}$	< 2	$< 4 \times 10^{-1}$
^{232}Th on crystal surface	$< 1 \times 10^{-9}$	$< 5 \times 10^{-1}$	$< 3 \times 10^{-1}$
^{210}Pb on crystal surface	$< 6 \times 10^{-9}$	$< 2 \times 10^{-3}$	$< 2 \times 10^{-3}$
^{238}U on copper surface	$< 7 \times 10^{-8}$	< 15	< 5
^{232}Th on copper surface	$< 7 \times 10^{-8}$	< 4	< 5
^{210}Pb on copper surface	$< 9 \times 10^{-7}$	$< 2 \times 10^{-1}$	$< 2 \times 10^{-1}$

Isotope	Crystal	$N_{\beta\beta}$ [n/crystal]	$T^{2\nu}_{1/2}$ [y]	Bkg in ROI [5 keV] [cnts/ton/y]
^{82}Se	ZnSe	2.5×10^{24}	9.2×10^{19}	2.7×10^{-2}
^{116}Cd	$CdWO_4$	1.5×10^{24}	2.8×10^{19}	0.07
^{100}Mo	$ZnMoO_4$	1.3×10^{24}	0.7×10^{19}	1.5
^{130}Te	TeO_2	2.5×10^{24}	68×10^{19}	0.5×10^{-3}