Contents

For CUORE and CUPID, I referred

Stefano Pirro and Andrea Giuliani's presentation at NDM2018

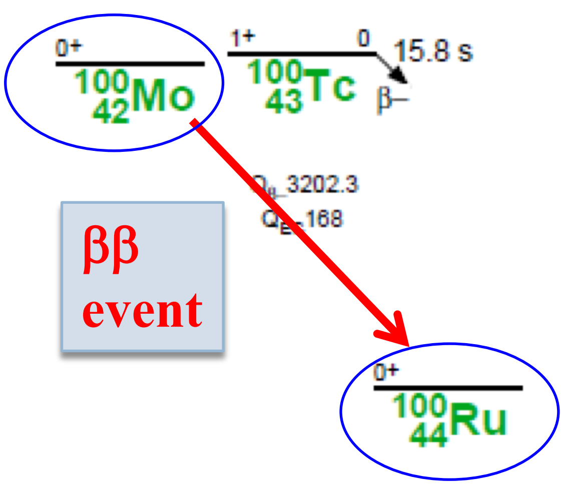
CUORE collaboration, EPJC 77, 543 (2017)

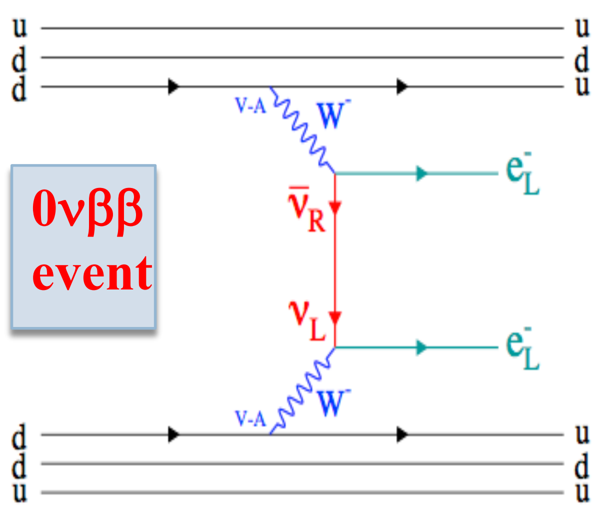
Search for Neutrinoless double beta decay (0νββ)

Observation of 0νββ

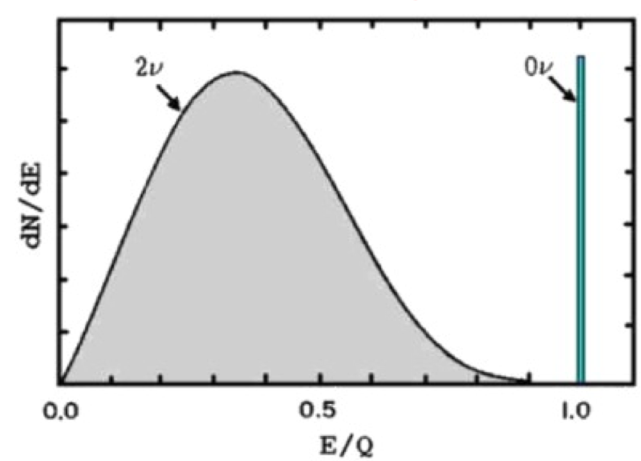
- **will confirm**
  - Neutrinos are Majorana particles and have Majorana masses.
  - Lepton number non-conservation.
- **will support on**
  - See-Saw model of the neutrino mass.
  - Leptogenesis to account for the baryon asymmetry of the universe.

$$m_\nu \approx \frac{m_D^2}{m_N}$$





Signal : sharp peak @ Q-value



Neutrino mass from 0νββ experiment

- **Half-lives of 0νββ inversely proportional to (effective neutrino mass)^2 by theory.**
- **To discover a sharp peak @ Q-value, we need a good energy resolution and extremely low background at that energy.**

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

Phase factor

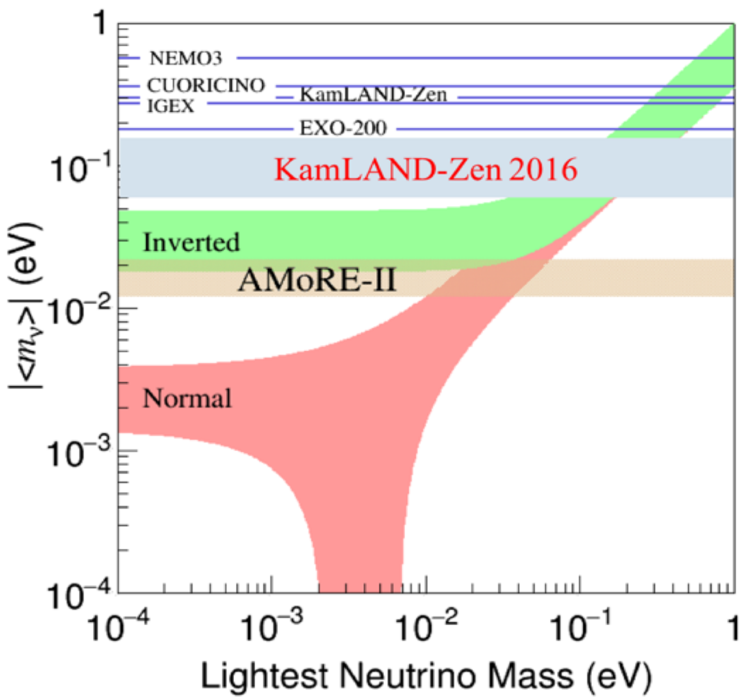
Half-life Measured

Nuclear Matrix Element

Neutrino Mass

$$T_{1/2}^{0\nu} \rightarrow m_{\beta\beta}$$

for light neutrino exchange model.



Current best results for 0νββ

Nucl.	Q (keV)	Abun. (%)	$T^{2\nu}_{1/2}$ (10^{20} Y)	Exp	$T_{1/2}$ (10^{24} Y)	M (eV)	Ref.
^{48}Ca	4270.0	0.187	0.44	CANDLES	> 0.058	<3.1-15.4	PRC 78 058501 (2008)
^{76}Ge	2039.1	7.8	15	GERDA-II	>53	<0.15-0.33	Nature 544, 47 (2017)
^{82}Se	2997.9	9.2	0.92	CUPID-0	> 2.4	<0.38-0.77	PRL120, 232502 (2018)
^{100}Mo	3034.4	9.6	0.07	NEMO-3	>1.1	<0.33-0.62	PRD89, 111101 (2014)
^{116}Cd	2813.4	7.6	0.29	AURORA	> 0.19	<1-1.8	nulc-ex/1601.05578.
^{130}Te	2527.5	34.5	9.1	CUORE	> 15	<0.11-0.52	PRL120, 132501 (2018)
^{136}Xe	2458.0	8.9	21	KamLAND -Zen	> 107	<0.06-0.16	PRL117, 082503 (2016)
^{150}Nd	3371.4	5.6	0.08	NEMO-3	> 0.02	<1.6-5.3	PRD 94 072003 (2016)

Cryogenic experiments

Backgrounds are most critical !

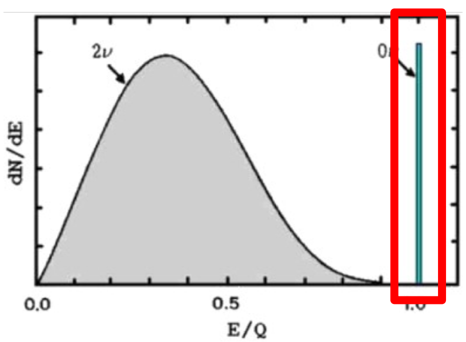
- If "zero" backgrounds in ROI(Region of Interests), the half-life limits are proportional to the detector mass and DAQ time. If finite backgrounds, sqrt (MT).

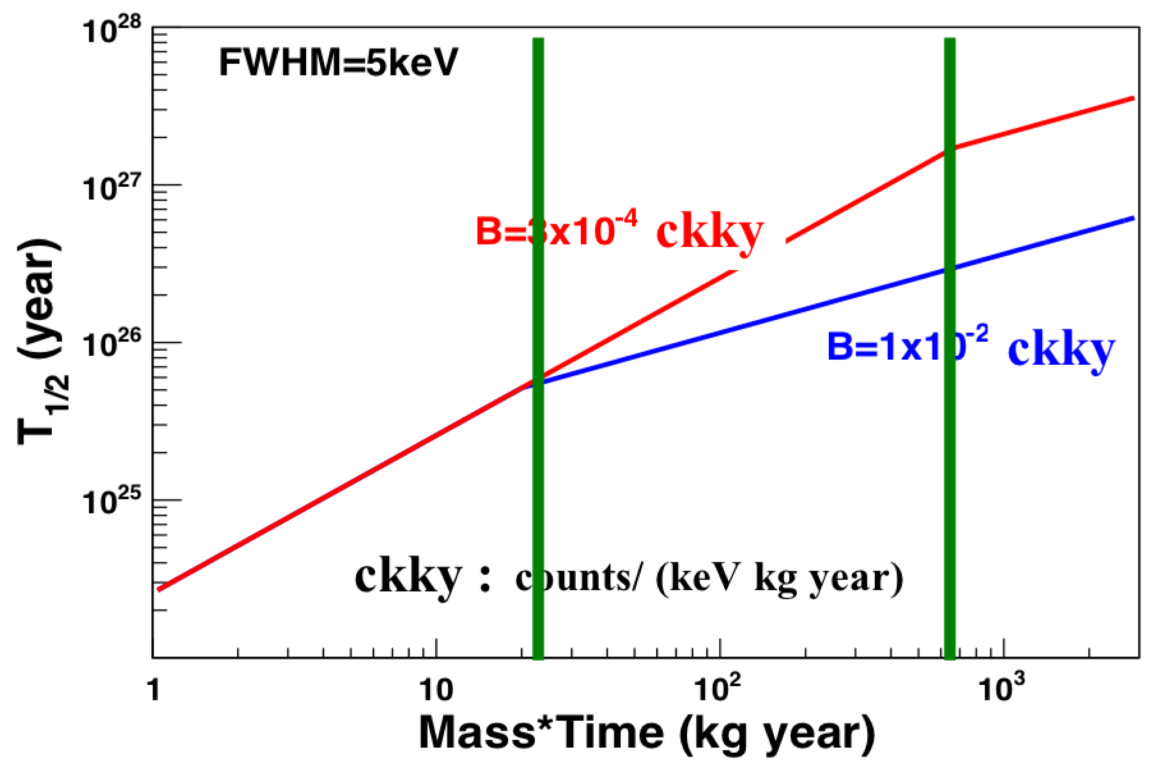
$T_{1/2}^{0\nu} \propto MT\ (for\ zero\ backgronds)$

$T_{1/2}^{0\nu} \propto \sqrt{\frac{MT}{b\Delta E}}$(for finite backgrounds)

Background Unit : ckky : counts/ (keV kg year)

ROI(Region of Interests





Identify critical radioactivity

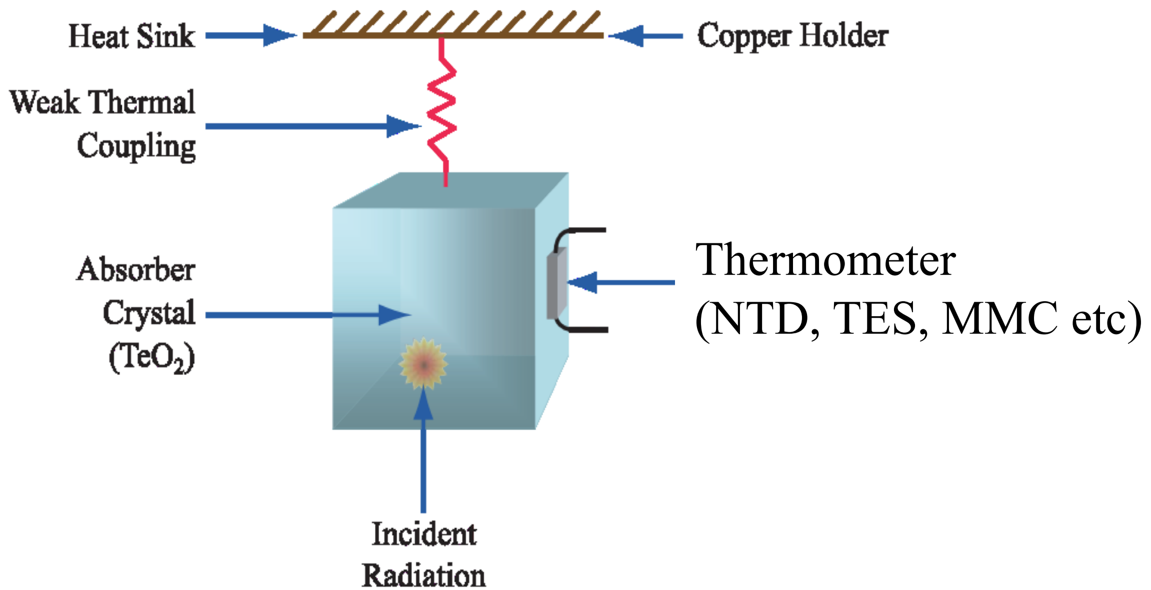
- Go through all known nuclei decaying β $with$ Q > 3.02MeV in NNDC database.
- ^{110m}Ag(3010.5 keV) doesn't contribute for Mo experiment.
- Cosmogenic excitation is negligible after 1 year at underground.
- Only Thorium and Uranium natural radioactivity are critical for Q> 3.02MeV. → Great advantage to run high Q-value nuclei !

El	Decay	$T_{1/2}$	Q	Mother	Chain	Comment
			MeV	N/A		
^{26}Al	EC	7.4×10^5y	4.004	N/A		Long lifetime
^{56}Co	EC	0.21y	4.567	N/A		Short lifetime
^{88}Y	EC	0.29y	3.623	^{88}Zr (0.23 y)		Short lifetime
^{106}Rh	B-	30s	4.004	^{106}Ru(1.02y)		
^{126}Sb	B-	12.5d	3.670	^{126}Sn(2.3×10^5y)		Long lifetime
^{146}Eu	EC	4.61d	3.878	^{146}Gd (0.13 y)		Short lifetime
^{208}Tl	B-	3.05m	4.999	^{228}Th (1.91 y)	Th232	Main
^{209}Tl	B-	2.16m	3.970	^{233}U(159200y)	U233	2.1% branching
^{210}Tl	B-	1.3m	5.482	^{226}Ra(1600y)	U238	0.02% branching
^{214}Bi	B-	19.9m	3.269	^{226}Ra(1600y)	U238	Main

+ high energy gammas from (n,g) and muon induced high energy gammas

Principle of low temp detector

Bolometric approach : the source is embedded in a crystal, which is cooled down to 10-20 mK and works as a perfect calorimeter.

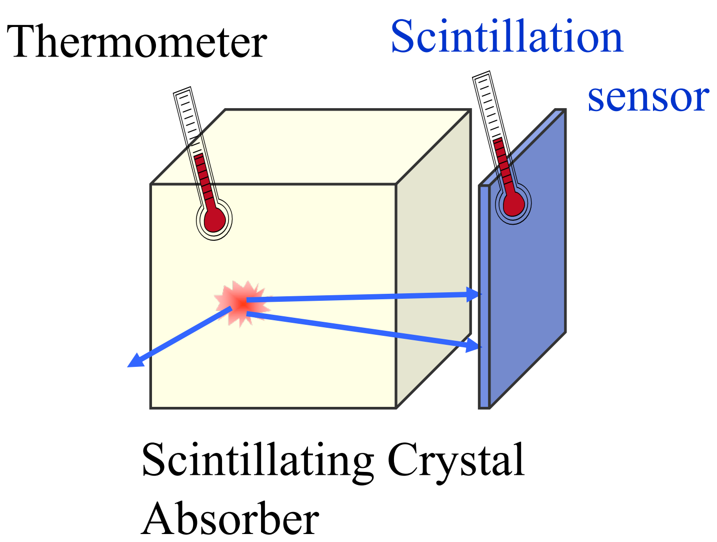


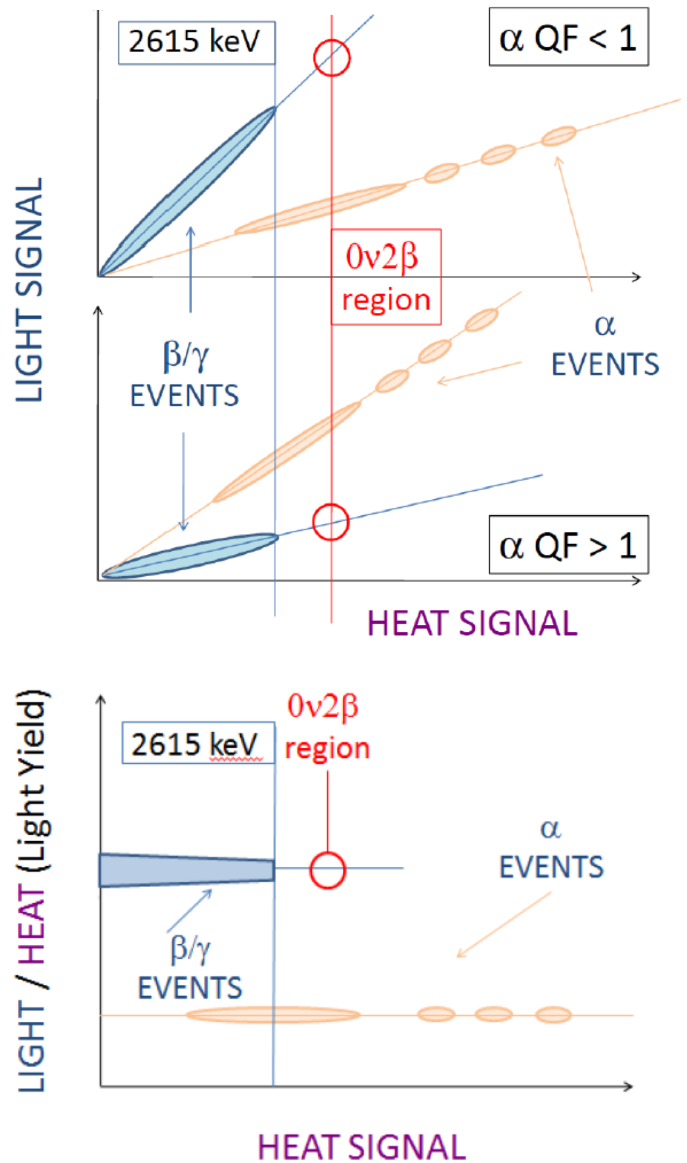
Advantages :

- High energy resolution (~5 keV FWHM)
- High efficiency (~70 – 90 %)
- Large flexibility in the isotope choice: ^{130}Te, ^{82}Se, ^{100}Mo, ^{116}Cd

Alpha background rejection

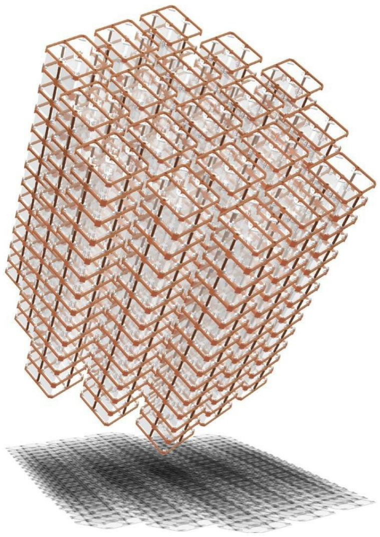
Scintillating Bolometric approach : Both heat and scintillation are measured and alphas are separated.

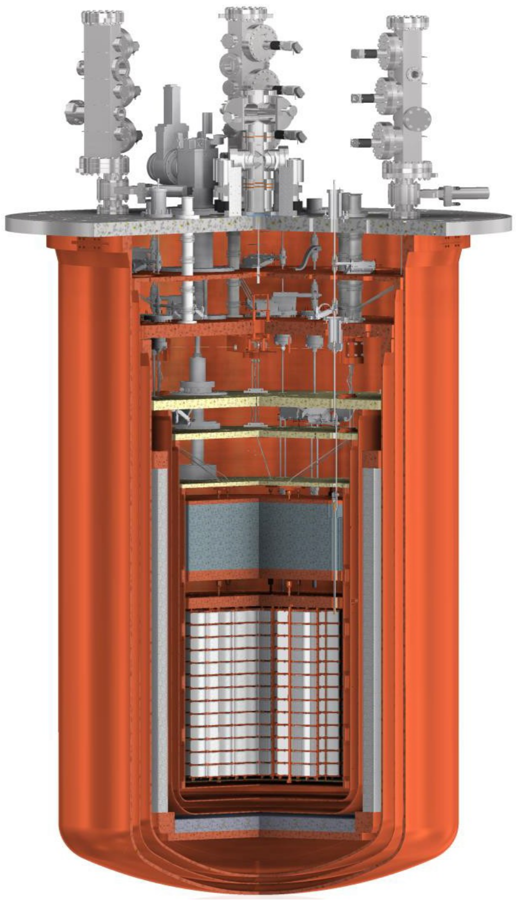




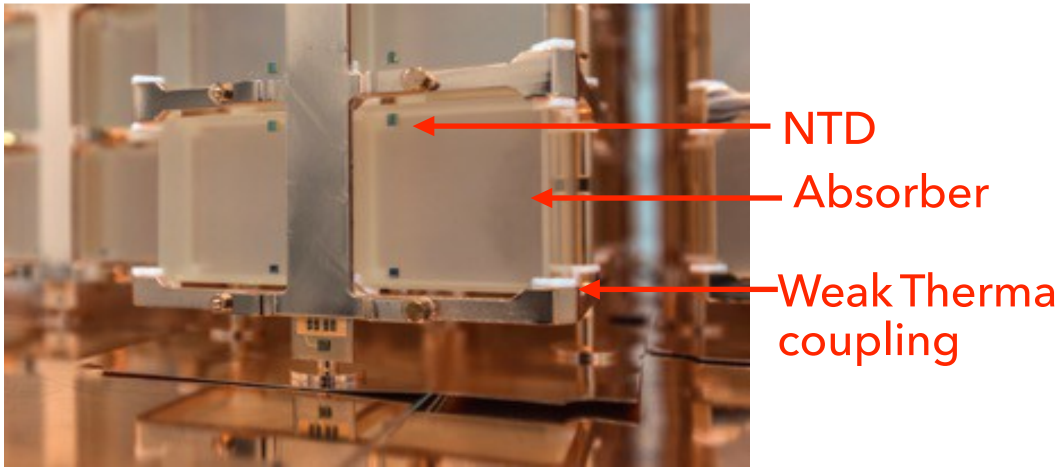
CUORE (Cryogenic Underground Observatory for Rare Events)

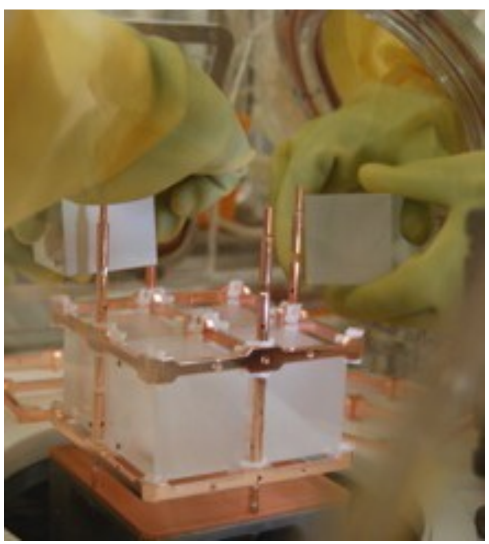
- Search for $0\nu\beta\beta$ of ^{130}Te and other rare events
- 988 TeO_2 crystals run as a bolometer array
  - 19 Towers, 13 floors
  - 4 modules per container
  - 741 kg total mass ; 206 kg ^{130}Te
  - 10^{27} ^{130}Te nuclei
- 10 mK base temperature in a custom dilution refrigerator
- Gran Sasso underground lab (LNGS), Italy

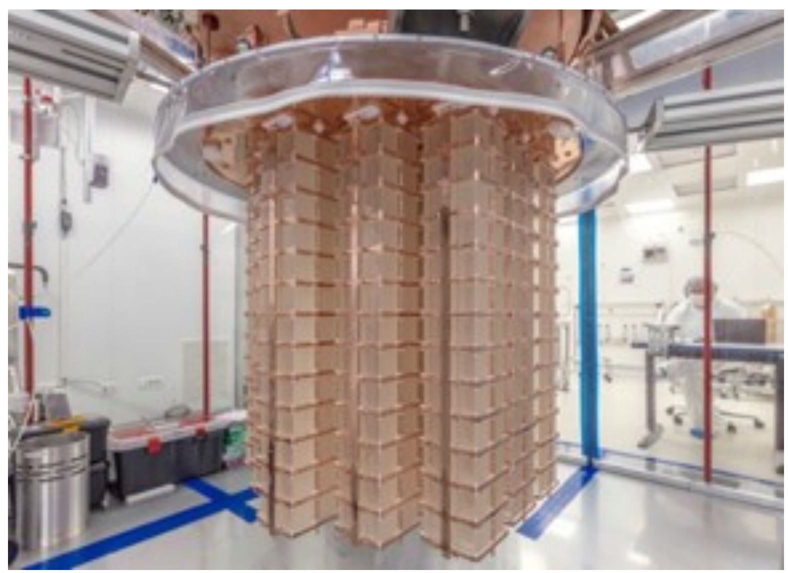




Setup

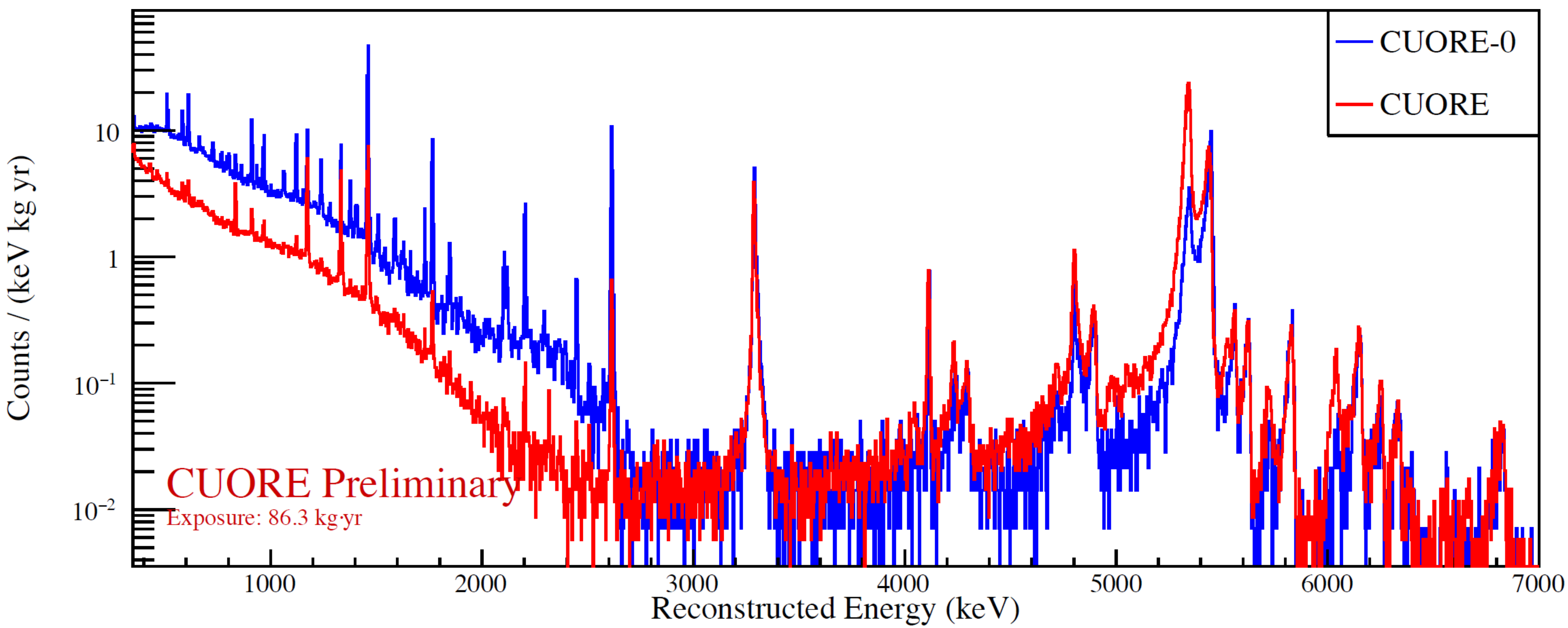






CUORE Backgrounds

- Significant reduction in the gamma region with respect to CUORE-0 (earlier version)
- ^{210}Po excess appears to be from shallow contamination in copper around the detectors.

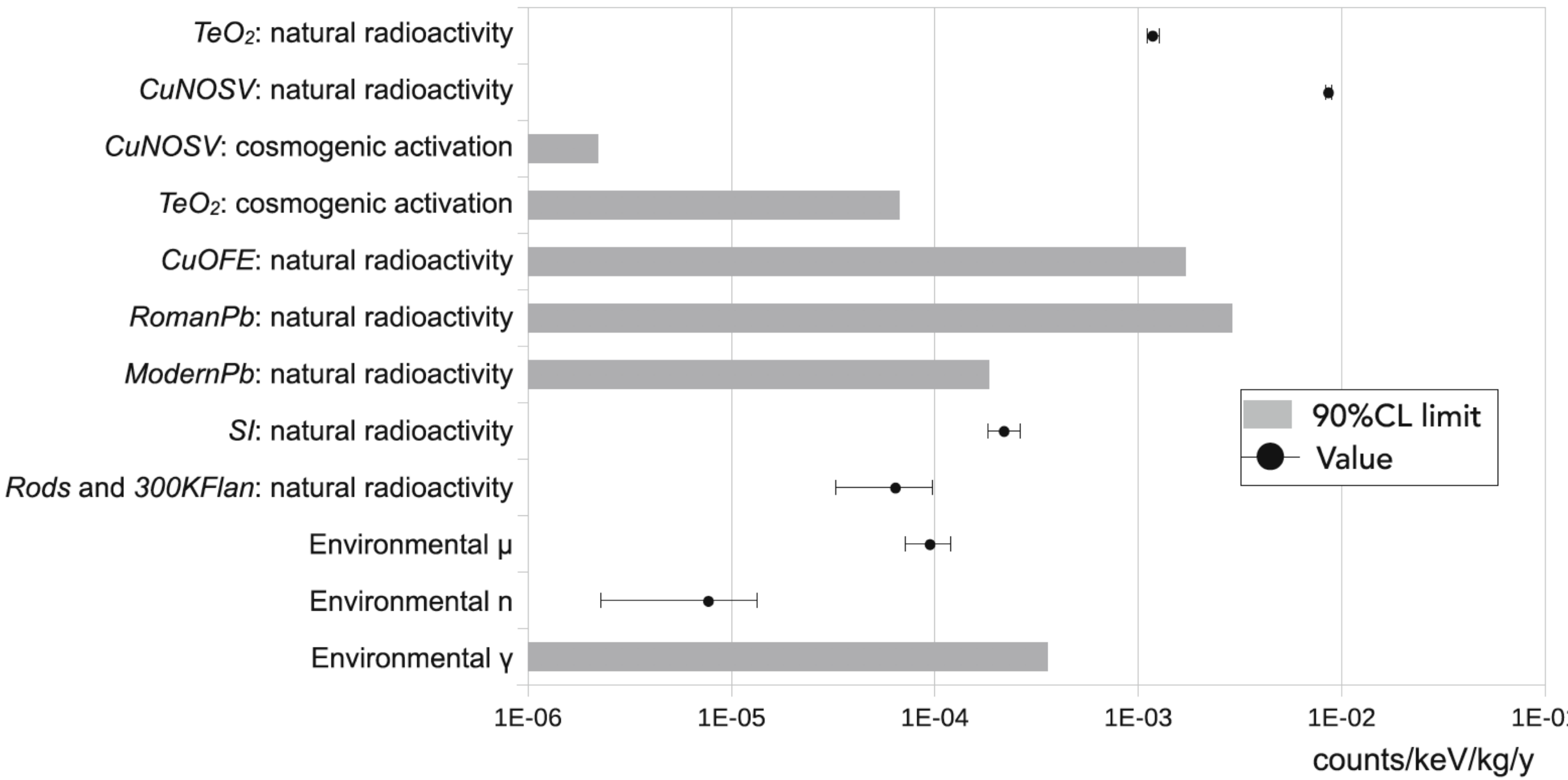


Background Index of CUORE

For CUORE, by far the most dominant backgrounds are

1. **CuNOSV copper holder** ~10^{-2}
2. **TeO2 crystal** ~10^{-3}
3. **SI & Rods & Muons** ~10^{-4}

Surface > Bulk (items 1–2)

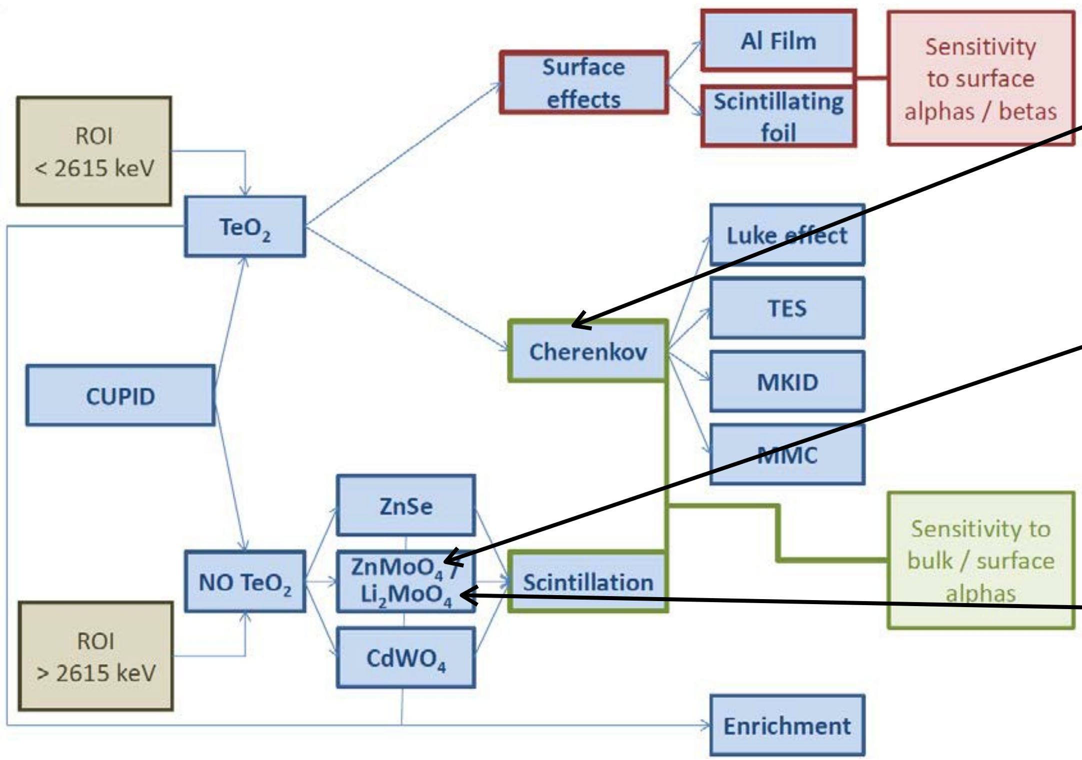


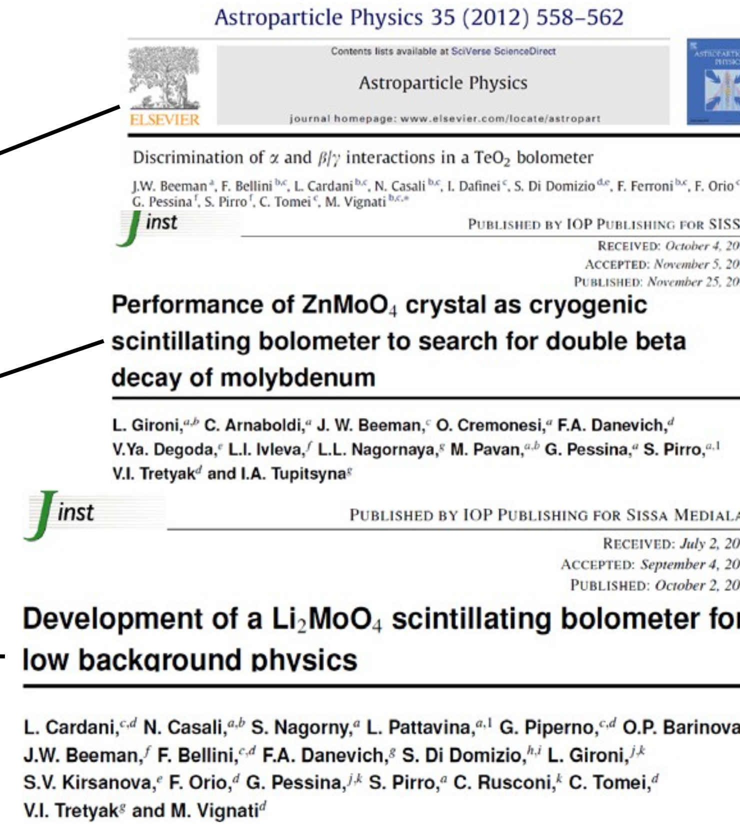
CUPID

CUORE Upgrade with Particle IDentification

R&D towards CUPID: arXiv:1504.03612 **CUPID : arXiv:1504.03599**

It is clear from CUORE that we need alpha background rejection.




Astroparticle Physics 35 (2012) 558–562
Contents lists available at SciVerse ScienceDirect
Astroparticle Physics
journal homepage: www.elsevier.com/locate/astropart

Discrimination of α and β/γ interactions in a TeO_2 bolometer

J.W. Beeman[a], F. Bellini[b,c], L. Cardani[b,c], N. Casali[b,c], I. Dafinei[c], S. Di Domizio[d,e], F. Ferroni[b,c], F. Orio[c], G. Pessina[f], S. Pirro[f], C. Tomei[c], M. Vignati[b,c,*]

JINST
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Published: November 25, 2010

Performance of $ZnMoO_4$ crystal as cryogenic scintillating bolometer to search for double beta decay of molybdenum

L. Gironi,[a,b] C. Arnaboldi,[a] J. W. Beeman,[c] O. Cremonesi,[a] F.A. Danevich,[d] V.Ya. Degoda,[e] L.I. Ivleva,[f] L.L. Nagornaya,[g] M. Pavan,[a,b] G. Pessina,[a] S. Pirro,[a,1] V.I. Tretyak[d] and I.A. Tupitsyna[g]

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Published: October 2, 2013

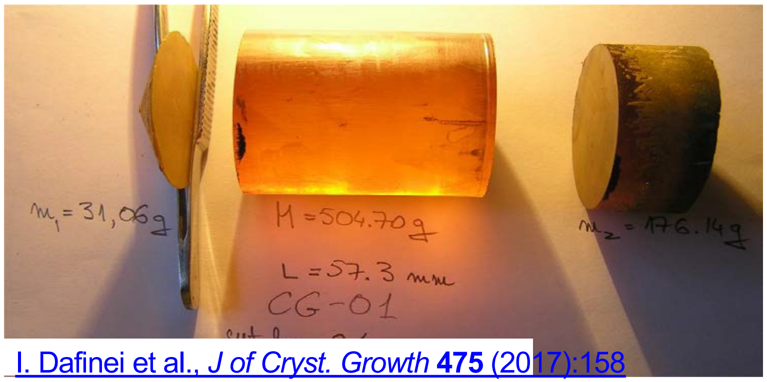
Development of a Li_2MoO_4 scintillating bolometer for low background physics

L. Cardani,[c,d] N. Casali,[a,b] S. Nagorny,[a] L. Pattavina,[a,1] G. Piperno,[c,d] O.P. Barinova,[e] J.W. Beeman,[f] F. Bellini,[c,d] F.A. Danevich,[g] S. Di Domizio,[h,i] L. Gironi,[j,k] S.V. Kirsanova,[e] F. Orio,[d] G. Pessina,[j,k] S. Pirro,[a] C. Rusconi,[k] C. Tomei,[d] V.I. Tretyak[g] and M. Vignati[d]

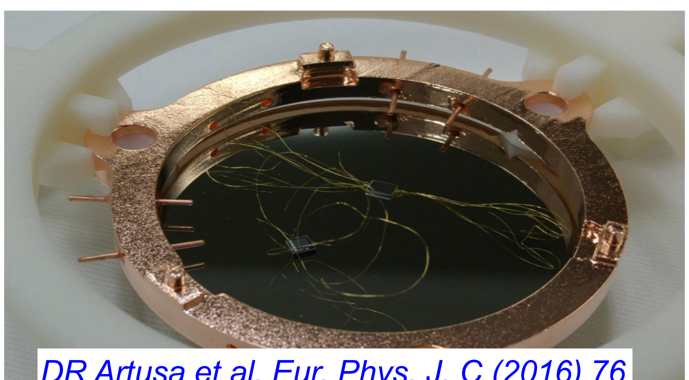
CUPID-0 : ZnSe crystals (Lucifer)

CUPID-0 represent the first enriched bolometer ββ-experiment that is demonstrating the background rejection achievable for hybrid ββ scintillating bolometers

Cuoricino/CUORE-0 cryostat

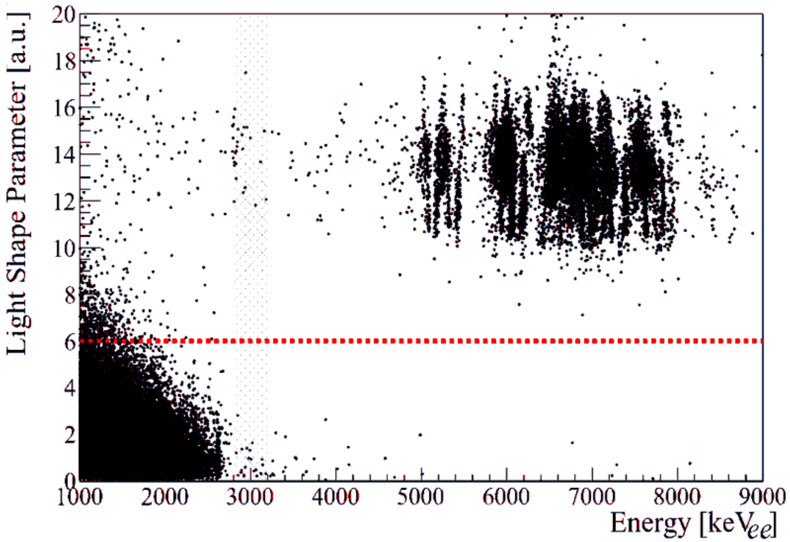


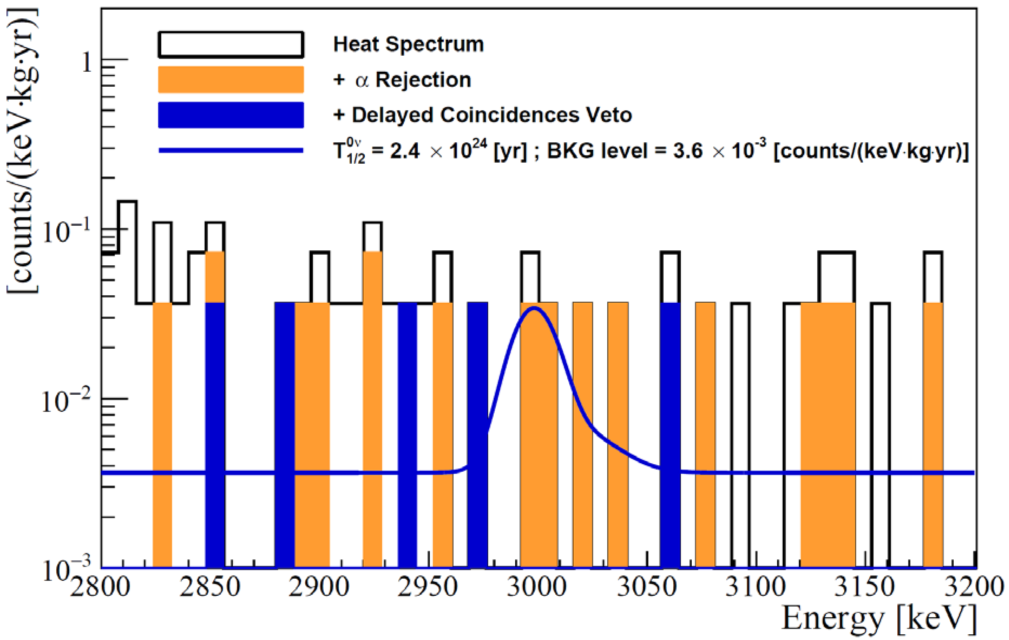
I. Dafinei et al., *J of Cryst. Growth* **475** (2017):158


DR Artusa et al. Eur. Phys. J. C (2016) 76

ββ-0ν Results

alpha vs beta separation





Background Level: 3.6×10^{-3} ckky

$T_{1/2}(^{82}Se \rightarrow ^{82}Kr) > 2.4 \times 10^{24}$ y (90%C.I.). → 4.0×10^{24} y (2018)

This results overcomes by 1 order of magnitude the results of Nemo recently republished (https://arxiv.org/abs/1806.05553)

EDELWEISS-III cryogenic facility at LSM (France)

Laboratoire Souterrain de Modane
1.7 km rock overburden (~4.8 km w.e.)
5 μ/day/m²; 10^{-6} n/day/cm² (>1 MeV)
Deradonized air flow (~30 mBq/m³)

EDELWEISS set-up

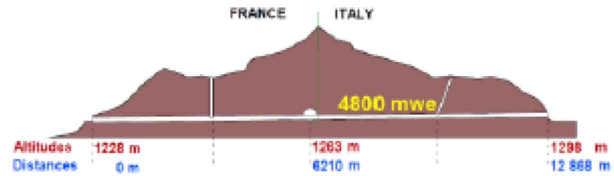
Clean room (ISO Class 4)

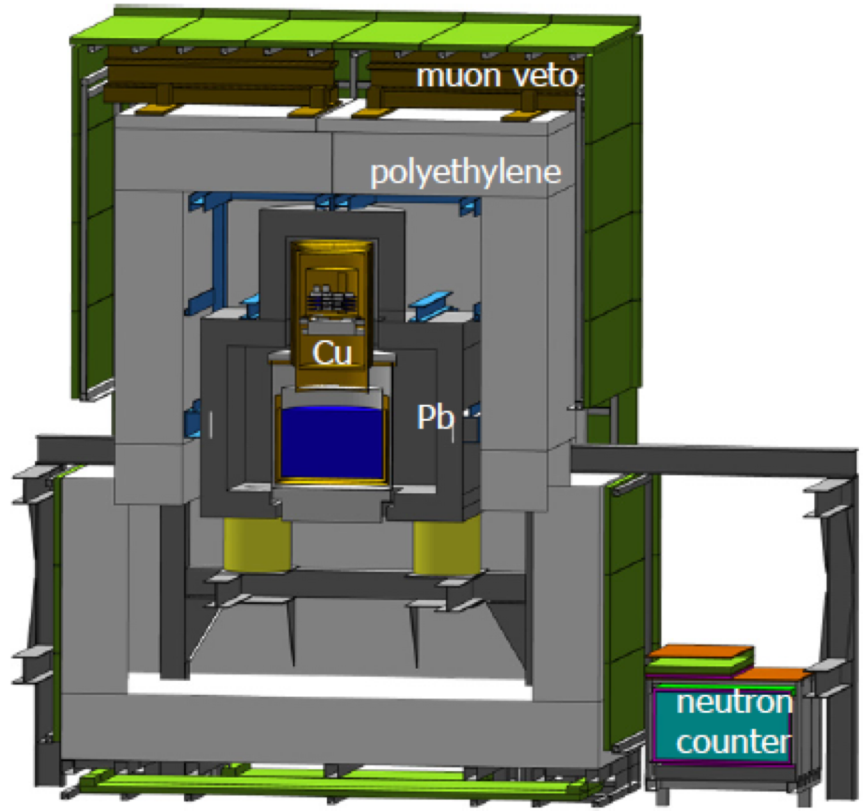
^{3}He/^{4}He inverted wet cryostat

Passive shield
Modern lead (18 cm)
Roman lead (2 cm; 14 cm at 1 K plate)
Polyethylene (external ~ 50+5 cm and 10 cm at 1 K plate)

Background monitors
Muon veto (98.5% covering)
Neutron counter
Radon counter

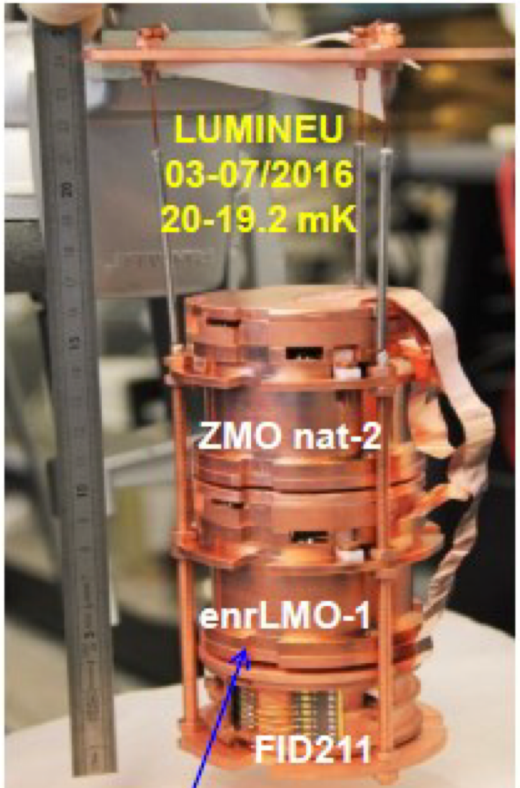
Electronics, DAQ (Samba)
Low noise cold electronics
AC bias, modulation (100 kHz)
→ demodulation (up to 1 kHz)
16-bit or 14-bit ADC
Trigger and/or Stream data



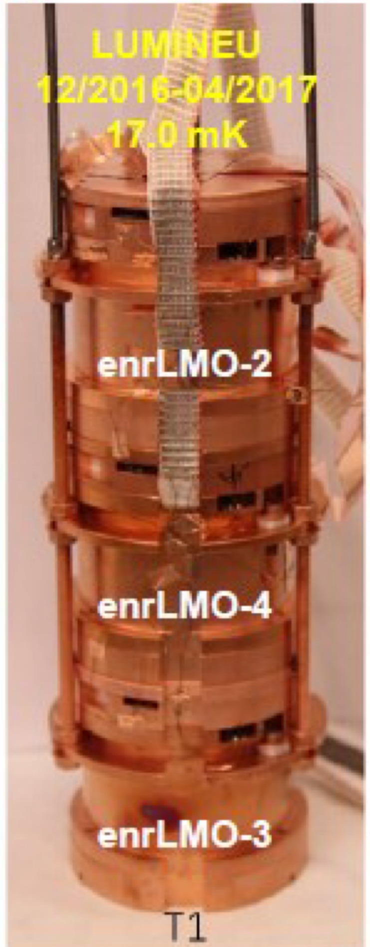


PLB 702 (2011) 329; JINST 12 (2017) P08010; EPJC 77 (2017) 785

Tests of $Li_2{}^{100}MoO_4$ scintillating bolometers

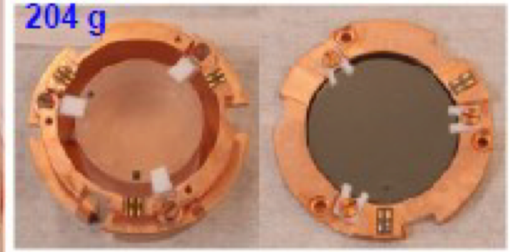


+ enrLMO-2
was tested at LNGS
05/2016, 12 mK



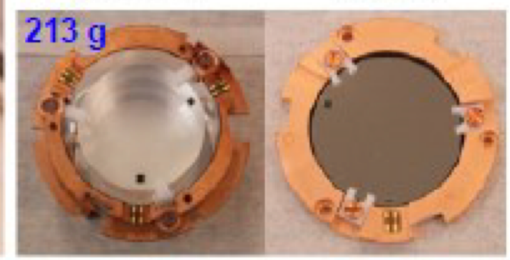
+ a tower T2
with enrLMO-1

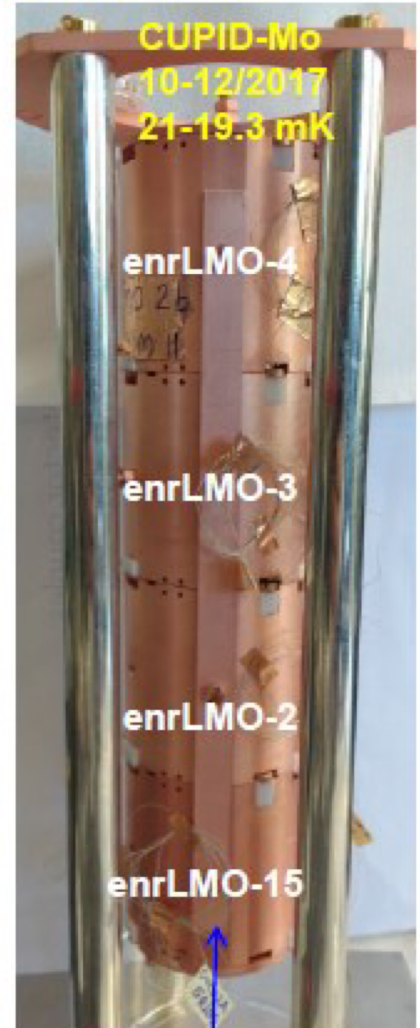
LMO1b Ge LD



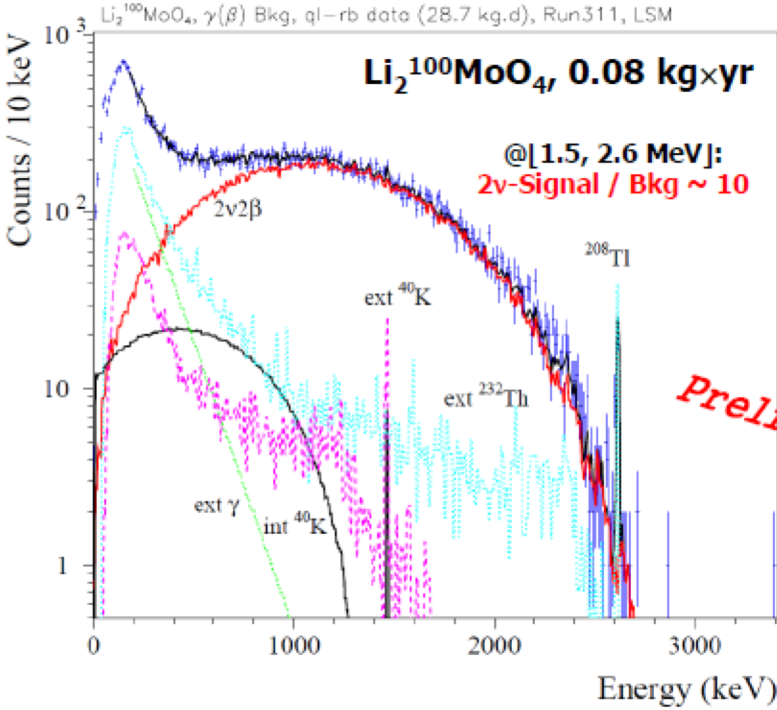
LMO2b Ge LD

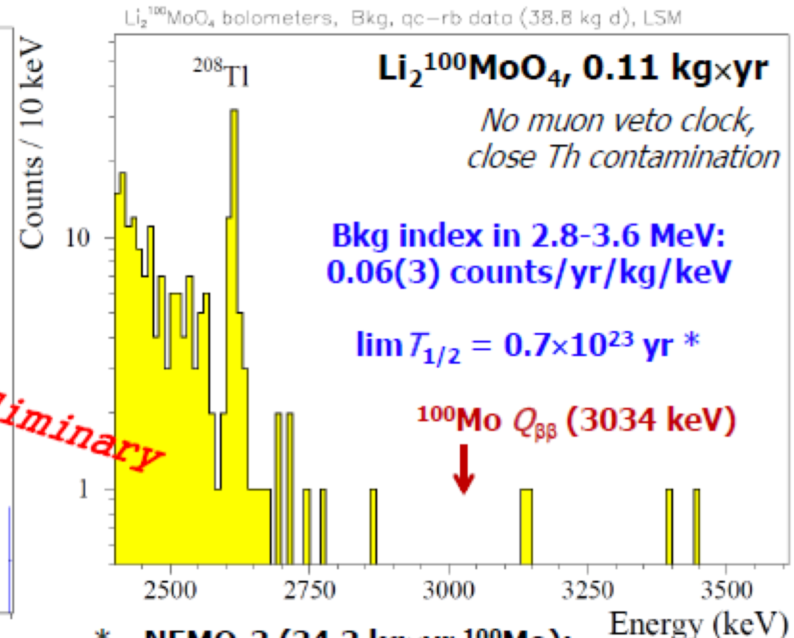
LMO2t Ge LD



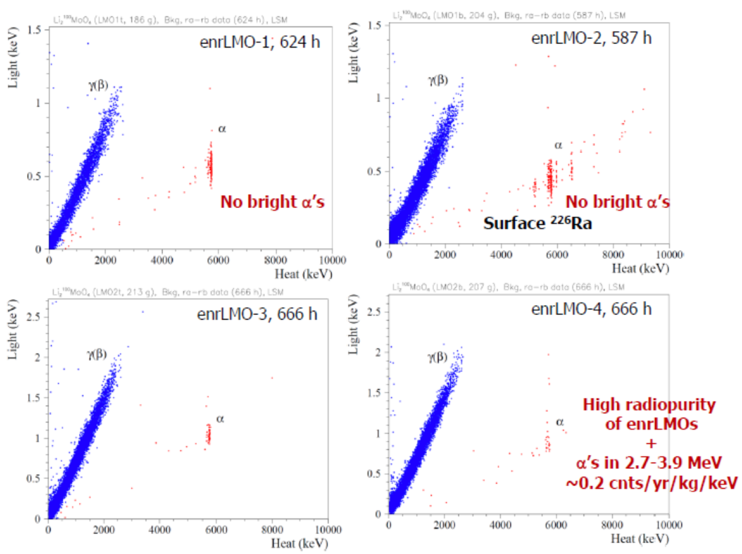


LUMINEU: search for 2β decay of ^{100}Mo





* - NEMO-3 (34.3 kg×yr ^{100}Mo):
$T_{1/2} \geq 1.1\times10^{24}$ yr, PRD 92, 072011 (2015)

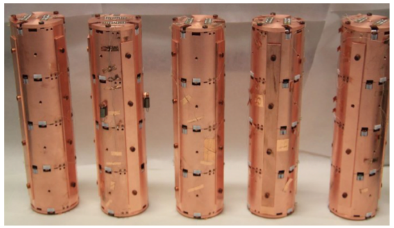


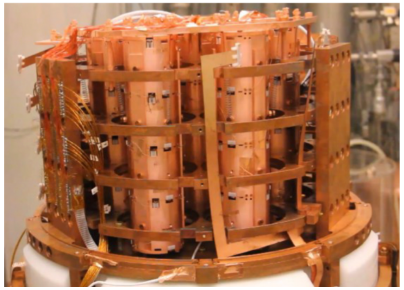
Background index in the CUPID-Mo precursor → b = 0.06(3) ckky

This value is due to ^{232}Th-contaminated connectors close to the detectors.

Full estimation of the background is in progress Reasonable expectation: b ~ 10^{-2} – 10^{-3} ckky

CUPID-Mo





CUPID-Mo Phase I (20 crystals):

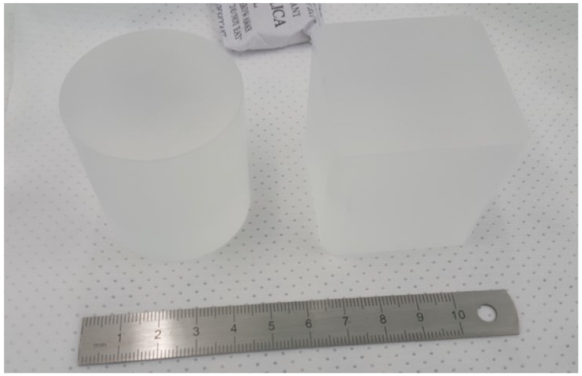
- **20 ^{100}Mo-enriched (97%) Li2MoO4**
  (Ø44X45 mm, 0.21 kg each; 4.18 kg total)
  → **2.5 kg of 100Mo**
- **20 Ge light detectors** (Ø 44X0.175 mm)+SiO
- **EDELWEISS set-up** @ LSM (France)

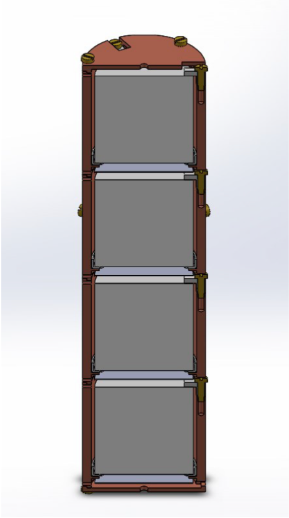
START DATA TAKING: in the next weeks

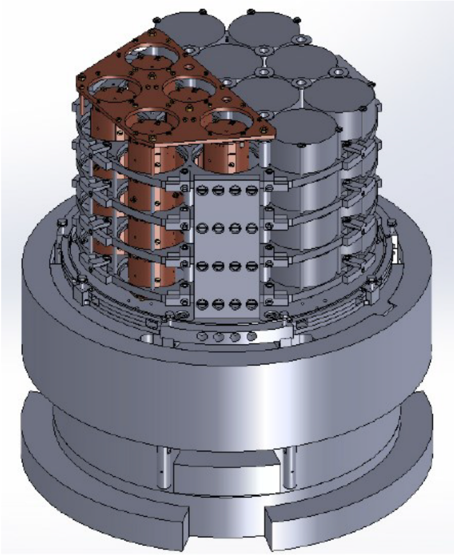
CUPID-Mo Phase II (20+26 crystals):

- Additional **26 cubic Li2100MoO4**
  (45x45x45 mm, 0.28 g each)
  → **5 kg of 100Mo**
- **CUPID-0 set-up** @ LNGS (Italy)

PLANNED START DATA TAKING: June 2019

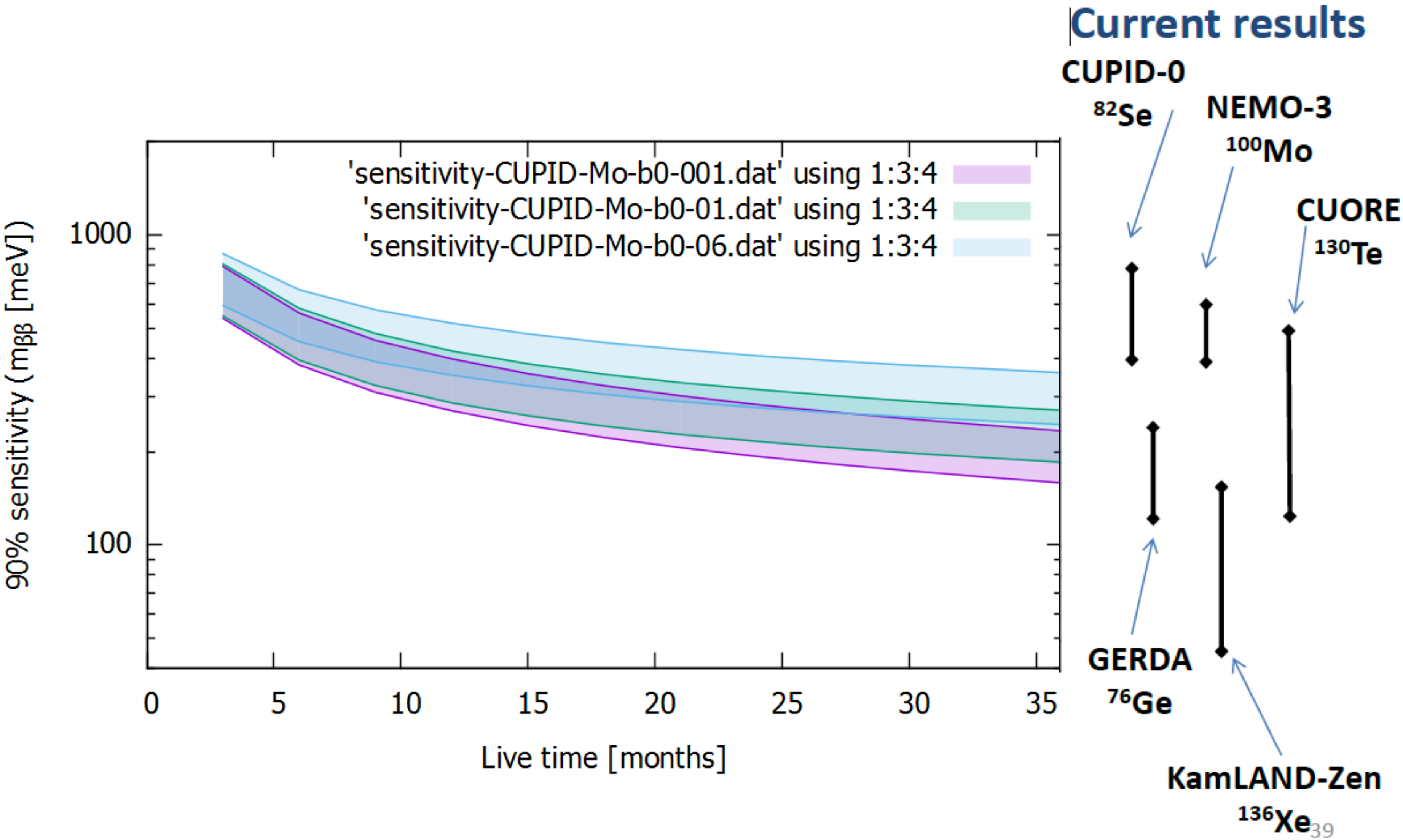






CUPID-Mo Modane (Phase I)

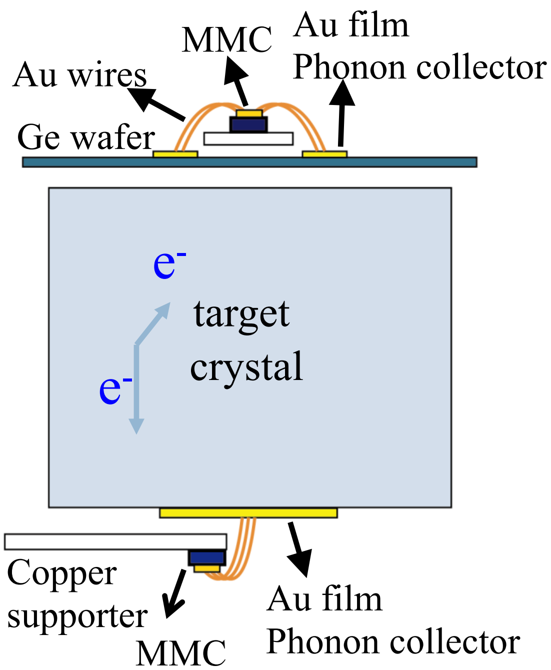
Evolution of the Majorana mass sensitivity

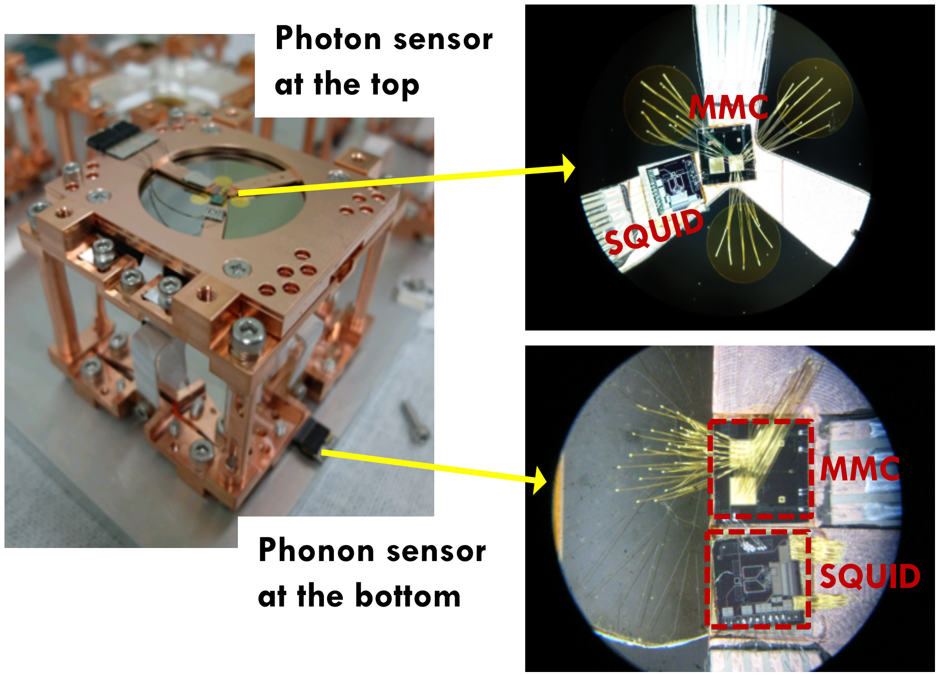


Overview of AMoRE Project

Detector schematics of AMoRE

- Use Mo containing Scintillating Bolometer : $(^{40}Ca,X)^{100}MoO_4$ + MMC
- For Each crystal, phonon and photon sensors made of MMCs, SQUIDs to separate alphas (background) and betas. -- Fully covered by Yong-Hamb's presentation.





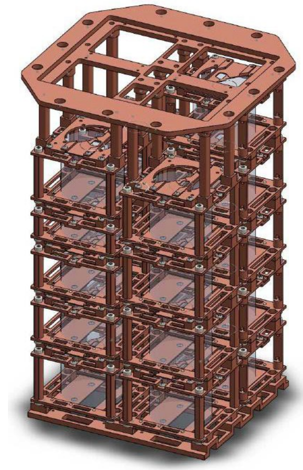
Plan of AMoRE Project

- 100 kg ^{100}Mo double beta decay experiment, largest experiment Q> 2614 keV
- One of two ^{100}Mo DBD projects.

$^{40}Ca^{100}MoO_4$

~ 1.9 kg

AMoRE Pilot



$(^{40}Ca,X)^{100}MoO_4$

~ 6 kg

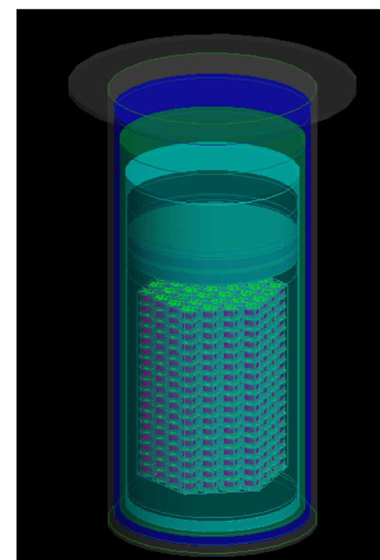
AMoRE-I

X = Li, Na, Pb…

$(^{40}Ca,X)^{100}MoO_4$

200 kg

AMoRE-II



	Pilot	AMoRE-I	AMoRE-II
Crystal Mass (kg)	1.9	6	200
Background Goal(**ckky**)	$<10^{-2}$	$<10^{-3}$	$<10^{-4}$
$T_{1/2}$(year)	1.0×10^{24}	8.2×10^{24}	8.2×10^{26}
m_{bb} (meV)	380-719	130-250	13-25
Schedule	2015-2018	2018-2020	2021-2025

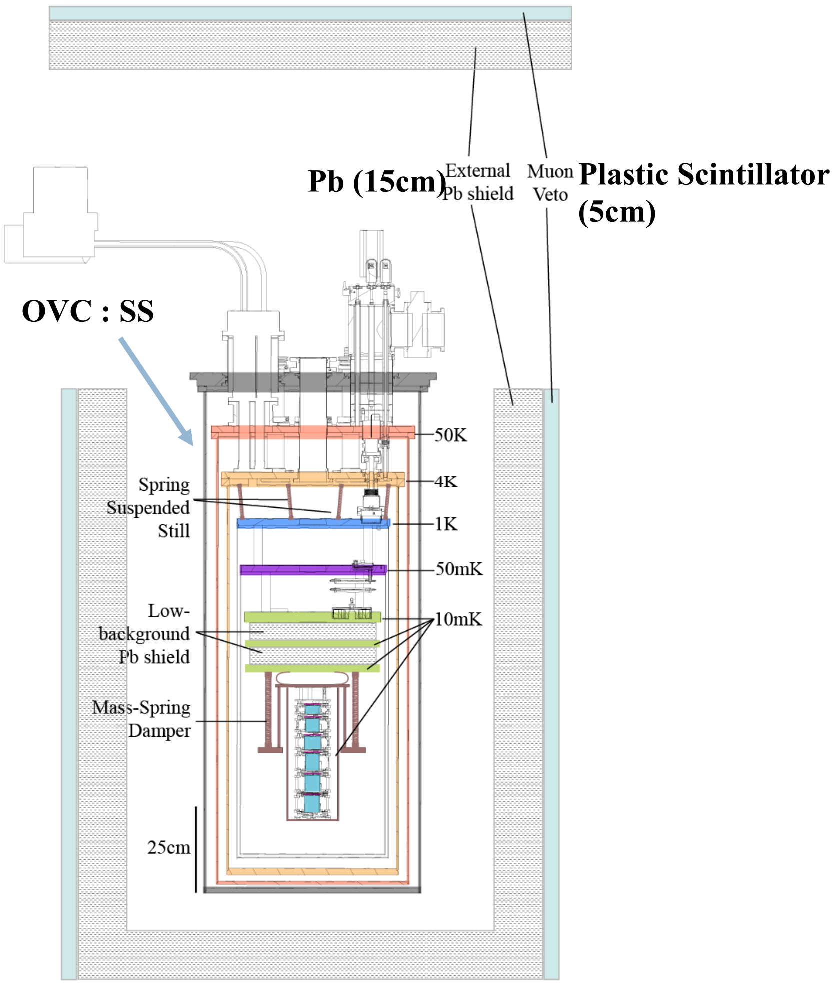
AMoRE Collaboration

- **Total 105 members from 23 institutes at 8 countries.**

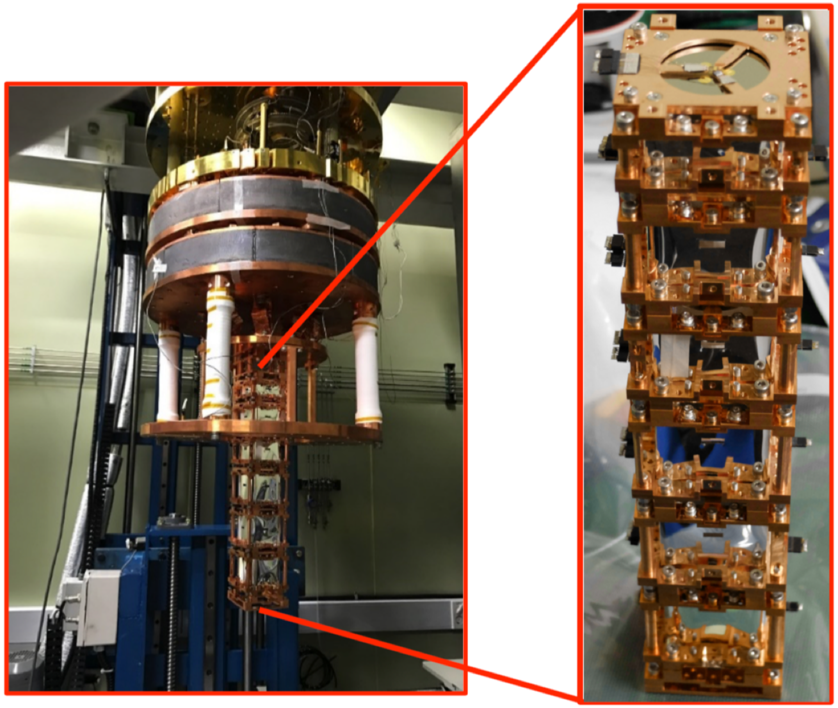
Korea	CUP, Institute of Basic Science (CUP)		
	Kyungpook National University (KNU)	11	Simulation, Crystal Tests
	Soongsil University (SSU)	3	Theory
	Seoul National University (SNU)	4	Low Temp., Data Analysis
	Ehwa Womans University (EWU)	3	HPGe
	Semyung University (SMU)	1	
	KRISS	3	DR, Cryostat
	Sejong University (SJU)	3	Data Analysis, Muon
	Chung-Ang University (CAU)	3	Theory
Russia	JSC FOMOS-Materials (FOMOS)	2	CMO crystals
	Baksan Neutrino Observatory of INR RAS (BNO)	8	HPGe, Simulation
	National Research Nuclear University (NRNU)	1	Backgrounds, Crystals
	Nikolaev Institute of Inorganic Chemistry (NIIC)	3	Enriched Crystal
Germany	Physikalisch-Technische Bundesanstalt (PTB)	2	SQUID
	Kirchhoff-Institute for Physics (KIP)	3	MMC, Photon Detector
Ukraine	Institute for Nuclear Research (INR)	7	Simulation, Background
China	Tsinghua University (THU)	3	
Thailand	Nakhon Pathom Rajabhat University (NPRU)	6	
Indonesia	Institut Teknologi Bandung (ITB)	2	Muon Veto
	University of Mataram (UM)	1	
Pakistan	Abdul Wali Khan University (AWKUM)	1	
	Kohat University of Science and Technology (KUST)	2	

AMoRE-Pilot Setup

- 6 crystals making total mass 1.89 kg.
- Two vibration reduction systems are installed.

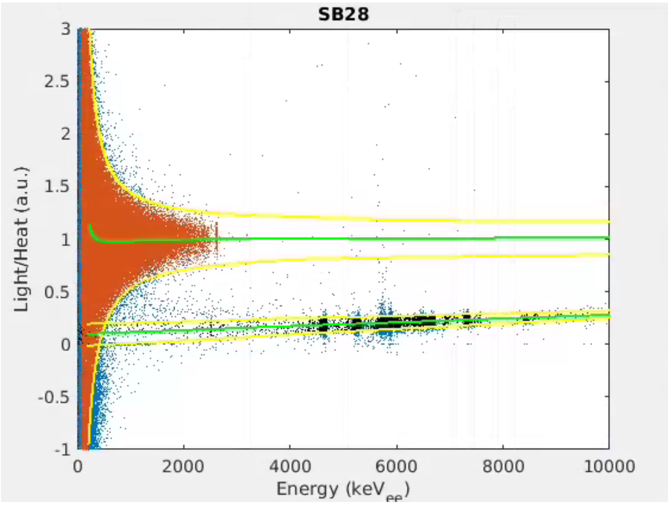


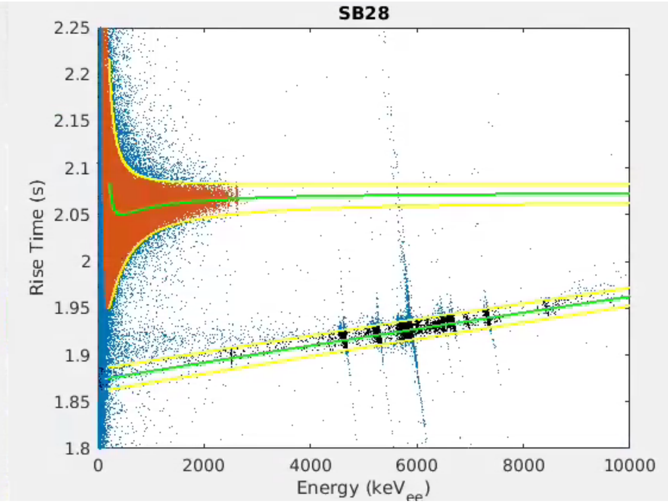
12 detector channels
(6 heat detectors + 6 light detectors)

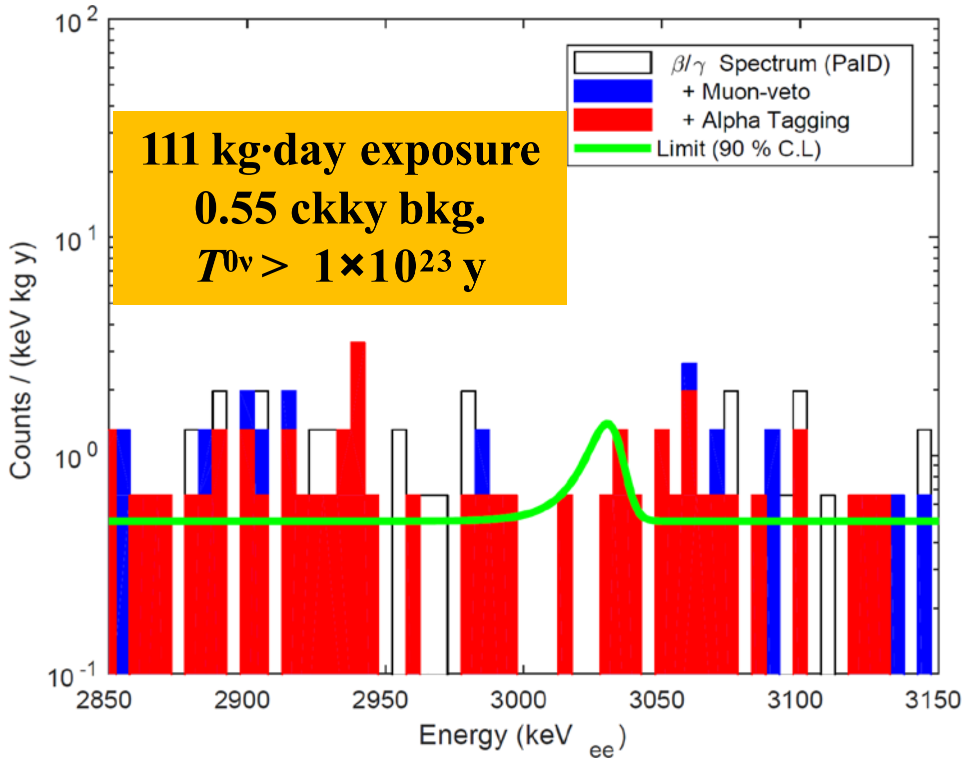


Preliminary results

- **Both photon/phonon ratio and rise time used to remove alpha background.**
- **Internal radioactivity is measured by alphas.**

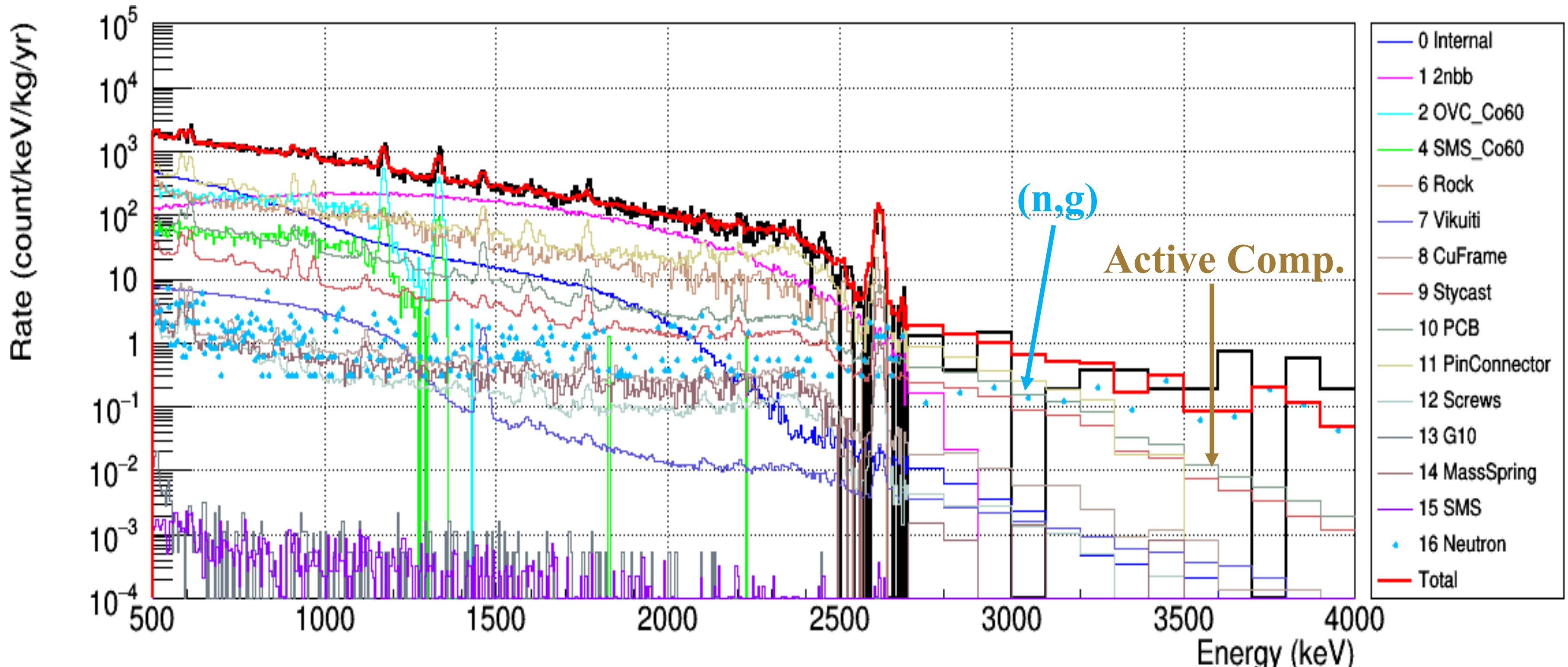


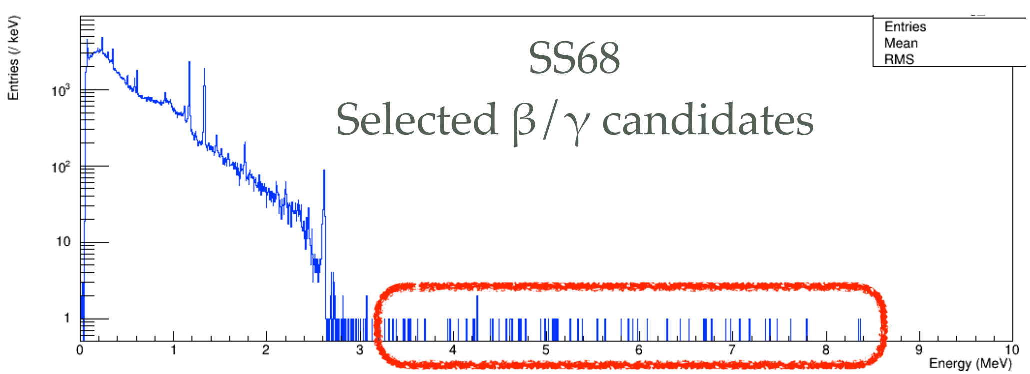




Comparison of Data with MC simulation

Simulated spectra from the radioactivity measurements vs data.

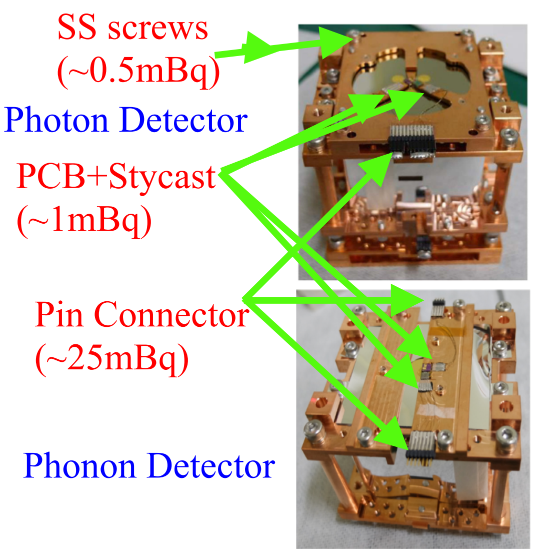


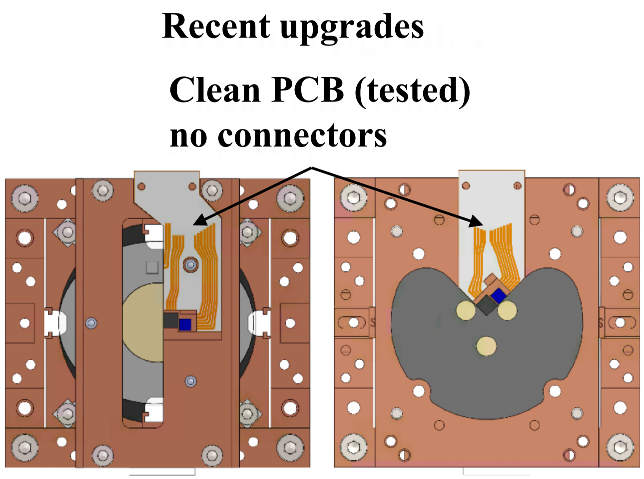


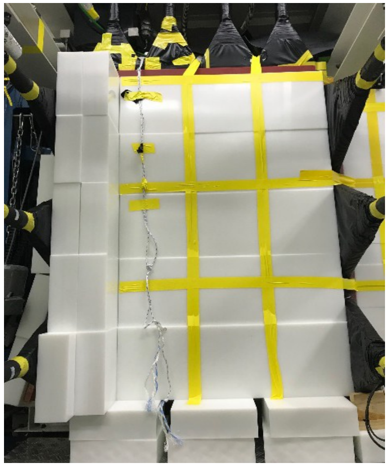
Flux(thermal neutron)
~ 2x10^{-5} /cm2/sec
Active components &
neutron capture dominant

Background reduction in AMoRE-Pilot Exp.

- Connectors, glue, and PCB boards were found highly radioactive and are removed for next runs in Pilot setup.



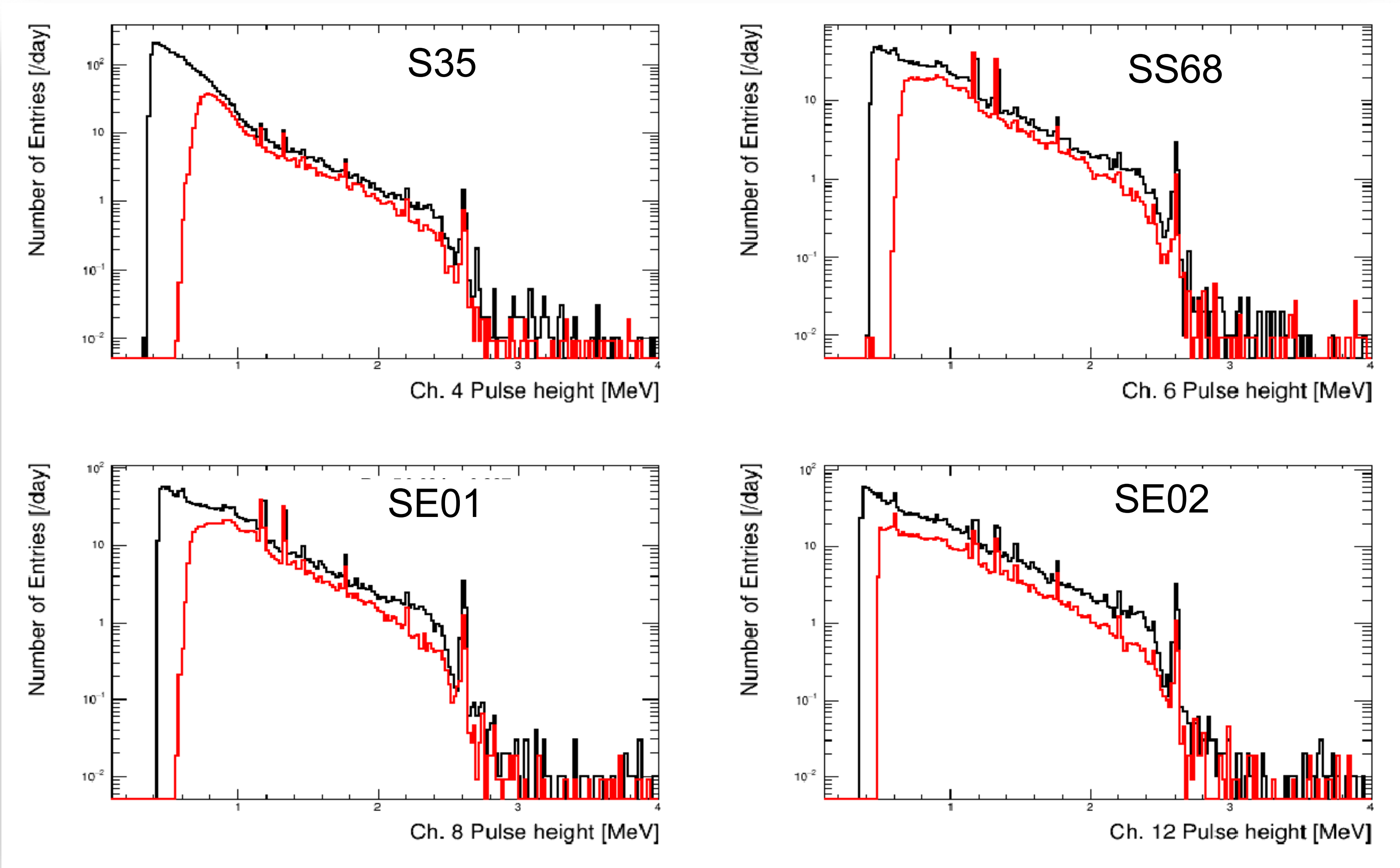




Also installed neutron shielding inside and outside of Pb shielding with Borated PE, PE blocks, and Boric Acids.

Preliminary Results

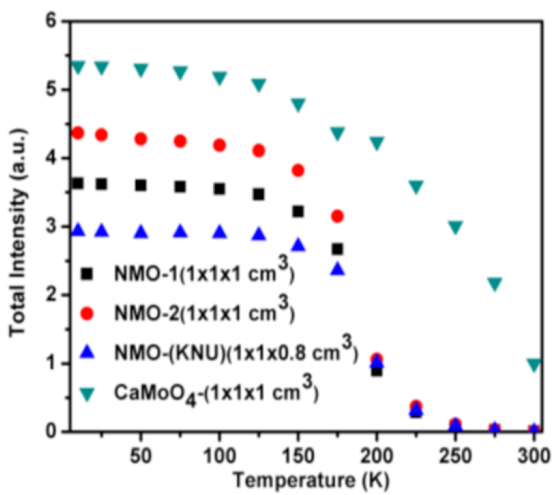
- Black (Red) : Before (After) replacing high activity materials.
- Currently we are getting data after installing neutron shielding.

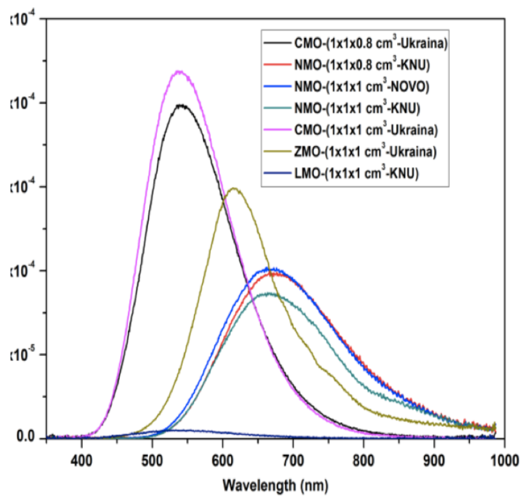


Decision on crystals for AMoRE-II

- CMO ($CaMoO_4$) is a very good crystal with the largest light output, but CMO has a disadvantage that we need ^{48}Ca depleted isotopes, expensive.
- LUMINEU group decided to use LMO (Li_2MoO_4), and we are working on LMO, PMO ($PbMoO_4$), & NMO ($Na_2Mo_2O_7$), crystals.

Crystal	Emission (nm)	LightYield(10K)		Decay time (μs)	density	Mo Fraction
		280nm	X-ray			
CMO(Ukra)	540	100	100	240	4.34	0.49
ZMO(NIIC)	614	63	35		4.37	0.436
LMO(KTI)	535	1	5	23	3.03	0.562
PMO(NIIC)	592	11	105	20	6.95	0.269
NMO(NIIC)	663	75	9	750	3.62	0.558





CMO ($CaMoO_4$)
LMO (Li_2MoO_4)
NMO ($Na_2Mo_2O_7$)
PMO ($PbMoO_4$)

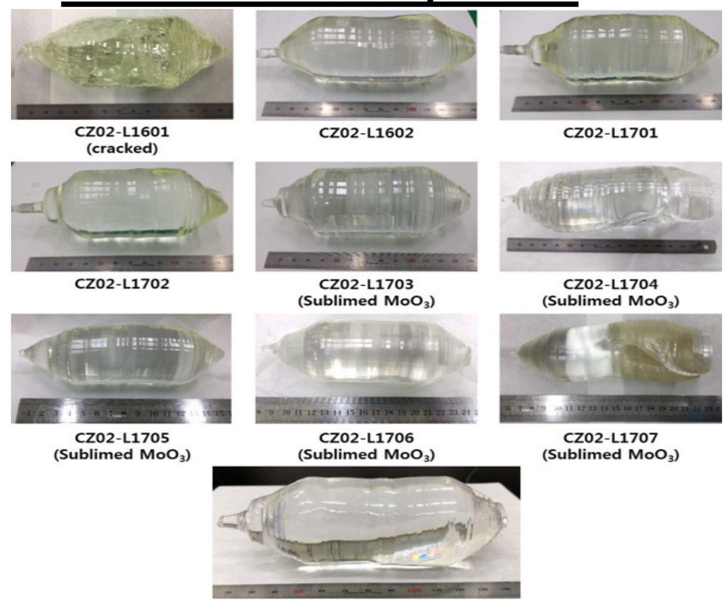
Publications :

Pandey et al., IEEE Trans. Nucl. Sci. (2018)
Pandey et al., Journal of Crystal Growth 480 (2017) 62-66
J.Y. Lee et al., IEEE Trans. Nucl. Sci. (2018)

CUP and NIIC grow enriched molybdate crystals at CUP.

- Crystal group has been successful in growing molybdate crystals. Growing time ~ 1 week.
- The purity of the grown crystals are measured by ICP-MS → Promising results
- We have a campaign to grow an enriched LMO crystal in this summer at NIIC and CUP.

Purified Mo and Li powders



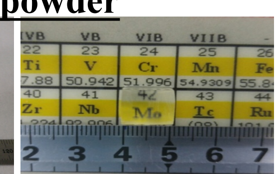
CZ02-L1601 (cracked) | CZ02-L1602 | CZ02-L1701
CZ02-L1702 | CZ02-L1703 (Sublimed MoO_3) | CZ02-L1704 (Sublimed MoO_3)
CZ02-L1705 (Sublimed MoO_3) | CZ02-L1706 (Sublimed MoO_3) | CZ02-L1707 (Sublimed MoO_3)
CZ02-L1801 (Double crystallization)

Unpurified Mo and Ca powders

CZ01_1501 | CZ01_1502 | CZ01_1601 | CZ01_1502 annealing
CZ01_1602 | CZ01_1603 | CZ01_1604 | CZ01_1604 annealing

Purified Mo and Na powder

Weight : 255.6 g, Height : 100 mm

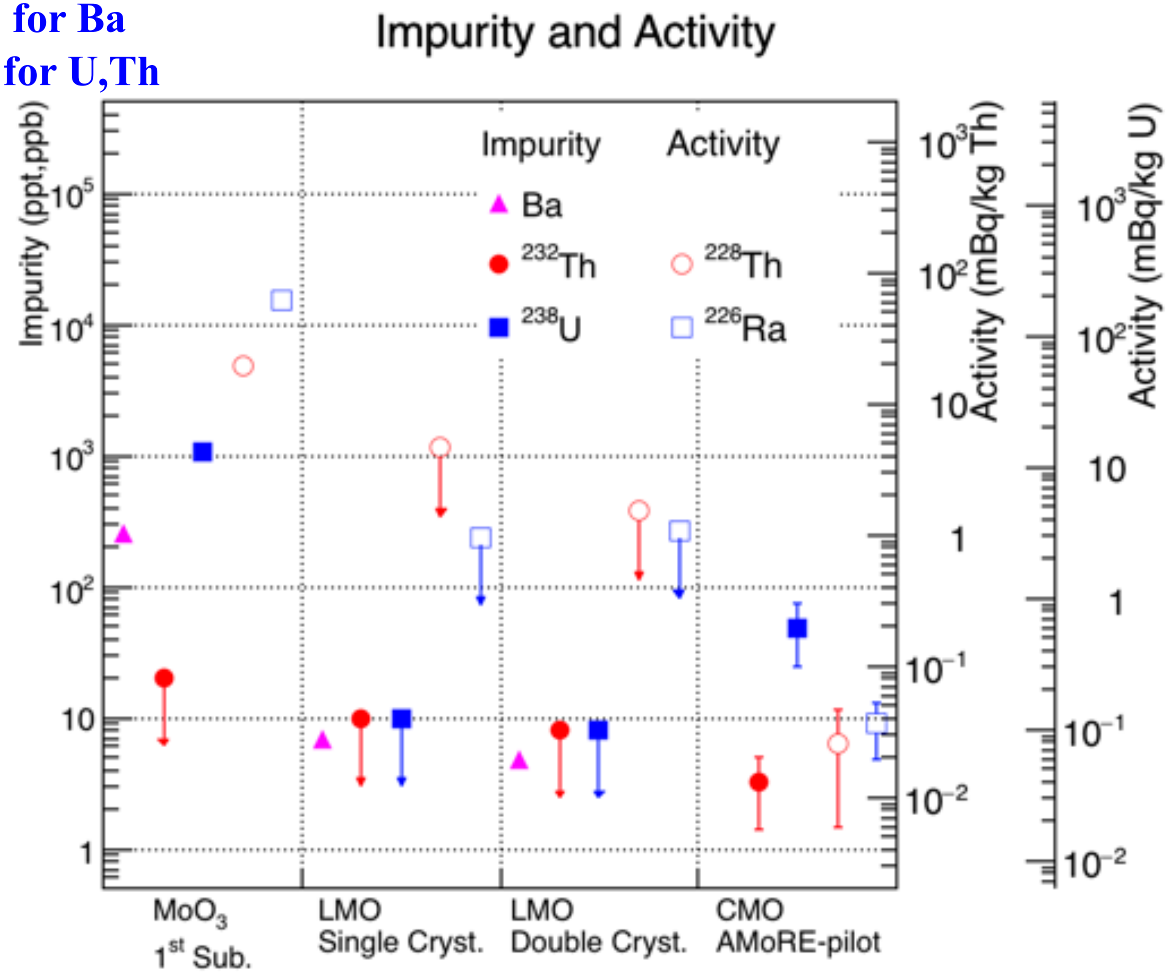


After cut and polished

Impurity summary of molybdate crystals

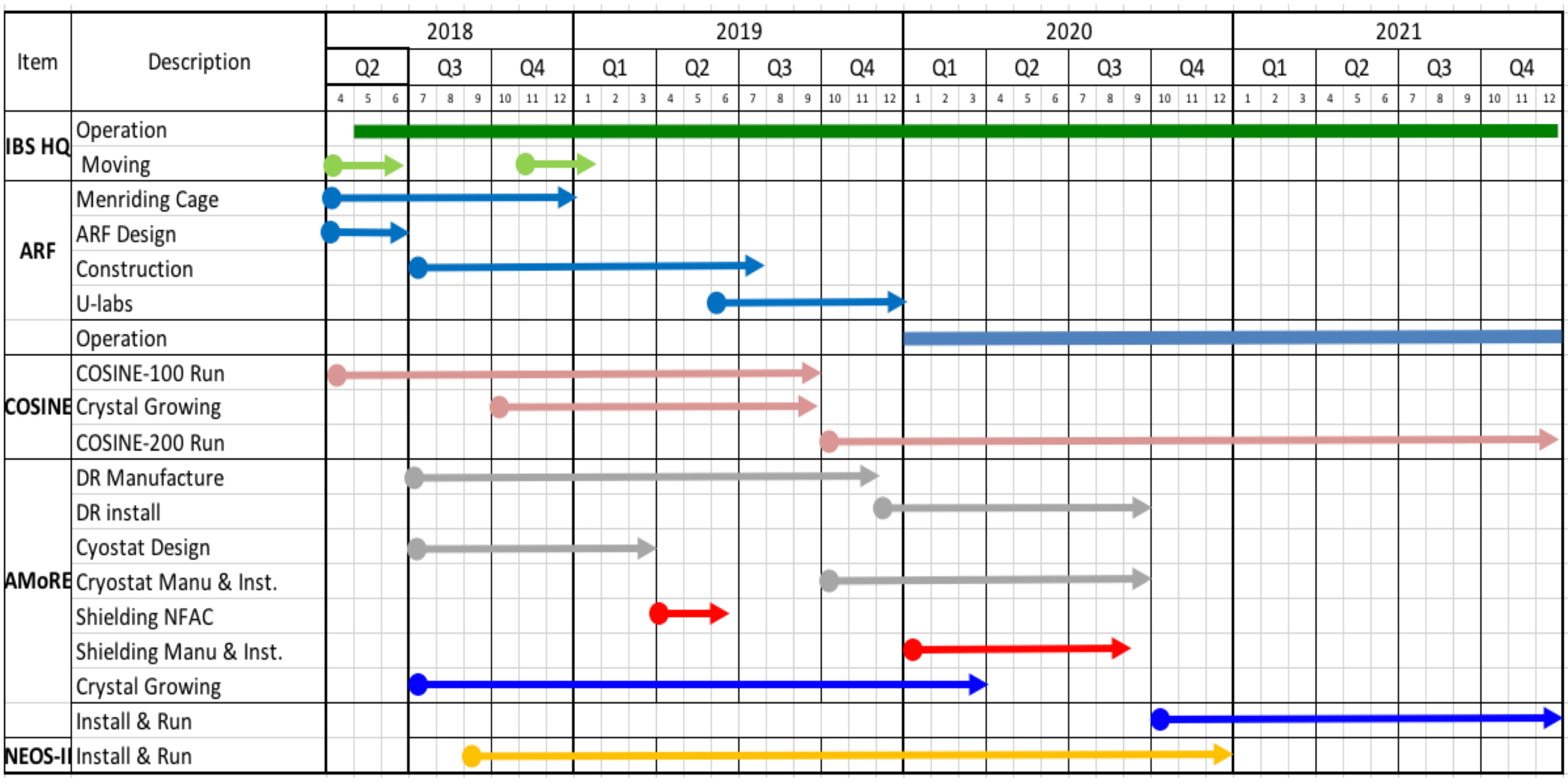
- Low temperature crystal tests are critical and under preparation.
- We have a good progress toward AMoRE-II crystals.
- Enriched LMO crystals will be grown at CUP and NIIC (Russia) in this summer.

ppb for Ba
ppt for U,Th



Final decision of crystal will depend on background and particle identification power.

Schedule


Item
Description
2018
2019
2020
2021
Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4
4 5 6 7 8 9 10 11 12 1 2 3 4 5 6 7 8 9 10 11 12 1 2 3 4 5 6 7 8 9 10 11 12 1 2 3 4 5 6 7 8 9 10 11 12
IBS HQ
Operation
Moving
ARF
Menriding Cage
ARF Design
Construction
U-labs
Operation
COSINE
COSINE-100 Run
Crystal Growing
COSINE-200 Run
AMoRE
DR Manufacture
DR install
Cyostat Design
Cryostat Manu & Inst.
Shielding NFAC
Shielding Manu & Inst.
Crystal Growing
Install & Run
NEOS-II
Install & Run

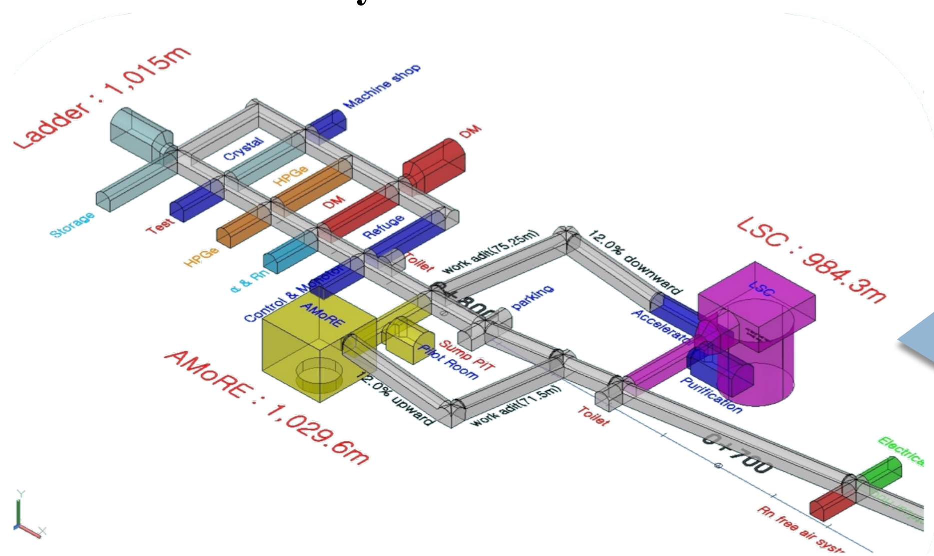
IBS is building a new underground lab.

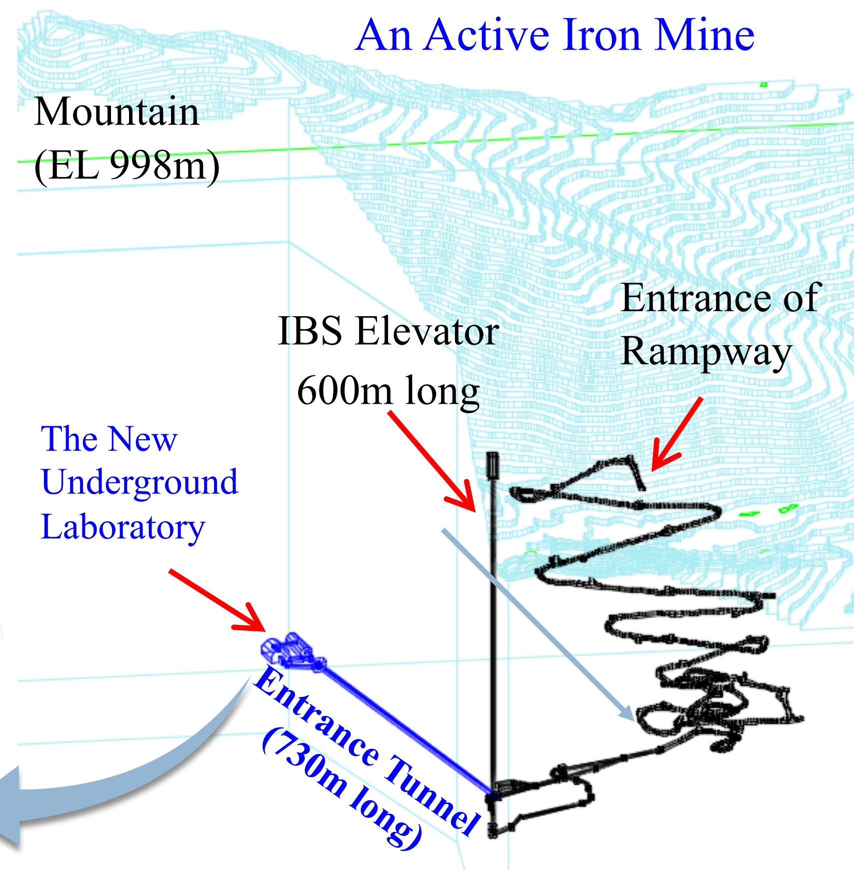
- **Will have an independent entrance (human vertical elevator) from mine activity.**
- **The construction starts this year and completed early of 2020.**

Center for Underground Physics

Bird view of Handuk Iron Mine

Handuk mine, ~ 0.7milion tons iron ore a year





Large (>2000m²), deeper (1100m depth)

Comparison of cryogenic experiments

Exp	Q (keV)	ΔE (keV)	Background ROI (ckky)	Comment (Mass of isotope)
CUORE (^{130}Te)	2527.5	~5	0.01	Copper holder surface
CUPID-0 (^{82}Se)	2997.9	~23	0.0032	muons, neutron capture(?)
CUPID-Mo (^{100}Mo)	3034.4	~6	0.06	Active components 5kg (2019)
AMoRE (^{100}Mo)	3034.4	~15	~0.5	Neutron capture, improving 35 kg (2021) 100kg(2023)

Summary

- Cryogenic double beta decay experiments demonstrates the competence.
- Backgrounds can be reduced to confirm "zero background" reaching down to 10 meV scale.
- CUPIDs experiments are in progress towards next phases.
- AMoRE-Pilot & AMoRE-I is making progress in detector performance and reducing backgrounds.
- AMoRE-II will begin in 2021 at a new underground laboratory.