Institute for Basic Science

CENTER FOR UNDERGROUND PHYSICS

AMoRE neutrinoless double beta decay experiment

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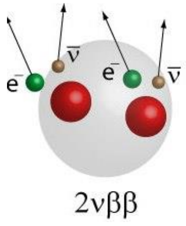
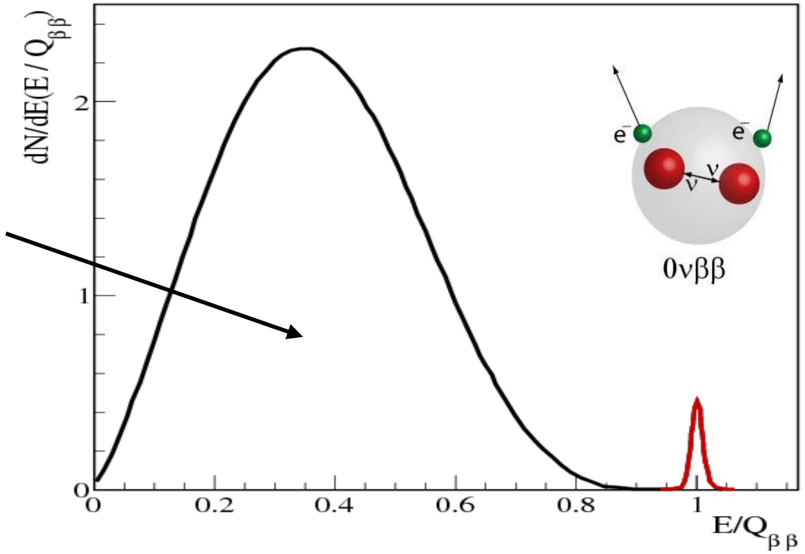
0νββ search using ^{100}Mo

AMoRE:

A search for neutrinoless double beta (0νββ) decay of ^{100}Mo using Mo-based scintillating crystals and low-temperature sensors.

2 ν $\beta\beta$ decay
- 2nd order beta decay
- Rare nuclear decay
- (>10^{18} years of half life)





0 ν $\beta\beta$ decay
- Massive neutrino
- Majorana particle
- Beyond the SM model
- >10^{25} years of half-life

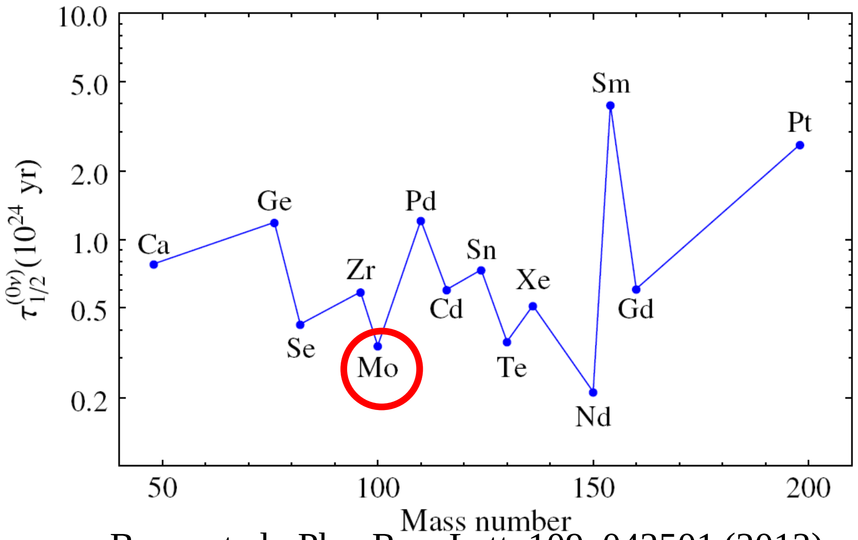
$$(Z, A) \rightarrow (Z+2, A) + 2e^- + 2\bar{\nu}_e$$
$$(Z, A) \rightarrow (Z+2, A) + 2e^-$$

- Neutrinoless double beta decay:
  - Direct measure of Majorana nature of neutrino.
  - Lepton number violation process.
  - Effective neutrino mass.

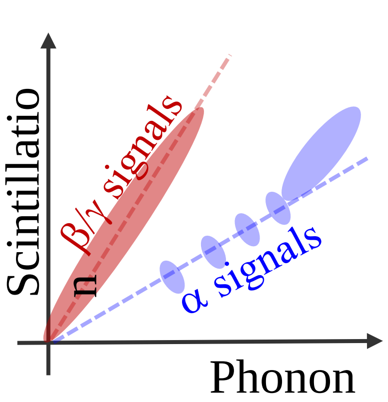
$0\nu\beta\beta$ search using ^{100}Mo

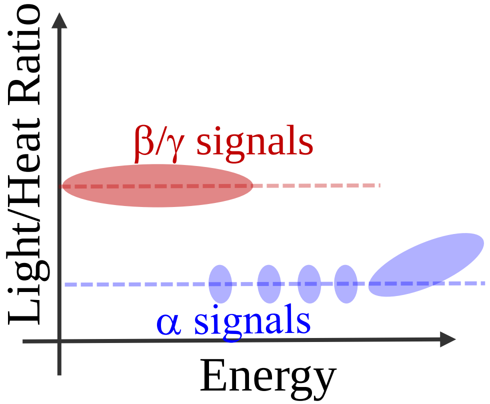
^{100}Mo:

- High $Q_{\beta\beta}$ = 3034 keV
- High natural abundance: 9.7 %
- Scintillation crystals with ^{100}Mo enrichment > 95% —XMo_aO_b (XMO):
  - X=Ca, Li_2, Na_2, Zn, Sr, Pb, …
  - Detection of light/heat signal ➔ rejection of surface-α background.
- Relatively short half life ($0\nu\beta\beta$) in theoretical expectation



Barea et al., Phy. Rev. Lett. 109, 042501 (2012)



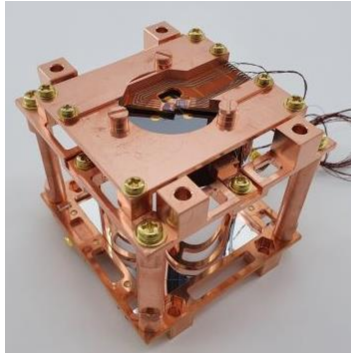


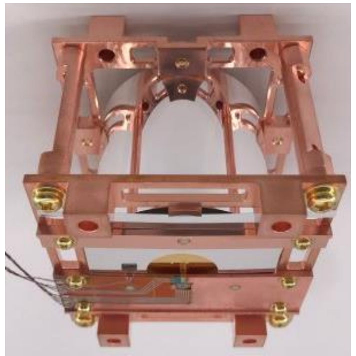
ββ-decay nuclei with Q > 2 MeV	Q (MeV)	Abund. (%)
$^{48}Ca \rightarrow ^{48}Ti$	4.271	0.187
$^{76}Ge \rightarrow ^{76}Se$	2.040	7.8
$^{82}Se \rightarrow ^{82}Kr$	2.995	9.2
$^{96}Zr \rightarrow ^{96}Ru$	3.350	2.8
$^{100}Mo \rightarrow ^{100}Ru$	3.034	9.7
$^{110}Pd \rightarrow ^{110}Cd$	2.013	11.8
$^{116}Cd \rightarrow ^{116}Sn$	2.802	7.5
$^{124}Sn \rightarrow ^{124}Ge$	2.228	5.8
$^{130}Te \rightarrow ^{130}Xe$	2.528	34.2
$^{136}Xe \rightarrow ^{136}Ba$	2.479	8.9
$^{150}Nd \rightarrow ^{150}Sm$	3.367	5.6

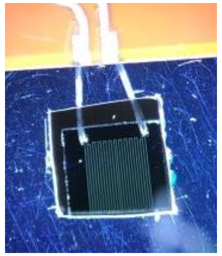
Detector Module

- Cylindrical CMO and LMO crystals, sizes vary $\Phi \geq 4$ cm / H $\lesssim 5$ cm.
    - CMO: ^{48}Ca depleted, $Q_{\beta\beta}$ (^{48}Ca) = 4271 keV.
- Metallic magnetic calorimeter (MMC) + SQUID:
    - Fast signal timing: a few millisecond rise-time for phonon signals at mK.
    - Low random coincidence background.
    - Energy resolution ~ 10 keV FWHM at 2.6 MeV.

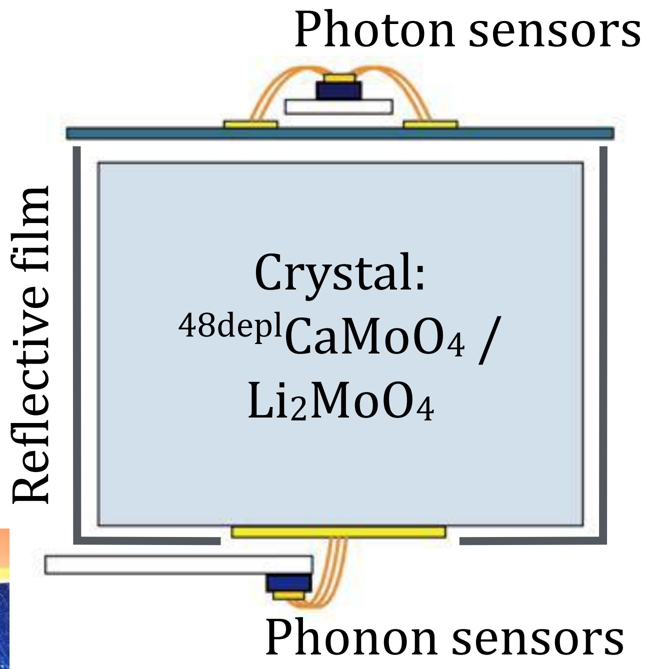
- Wide dynamic range
- High linearity





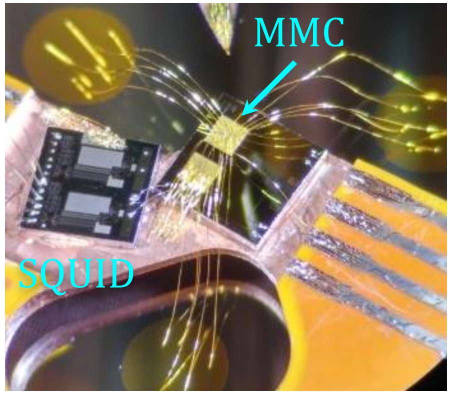


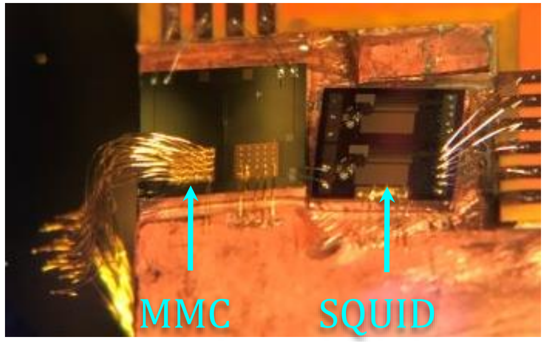
Stabilization heater



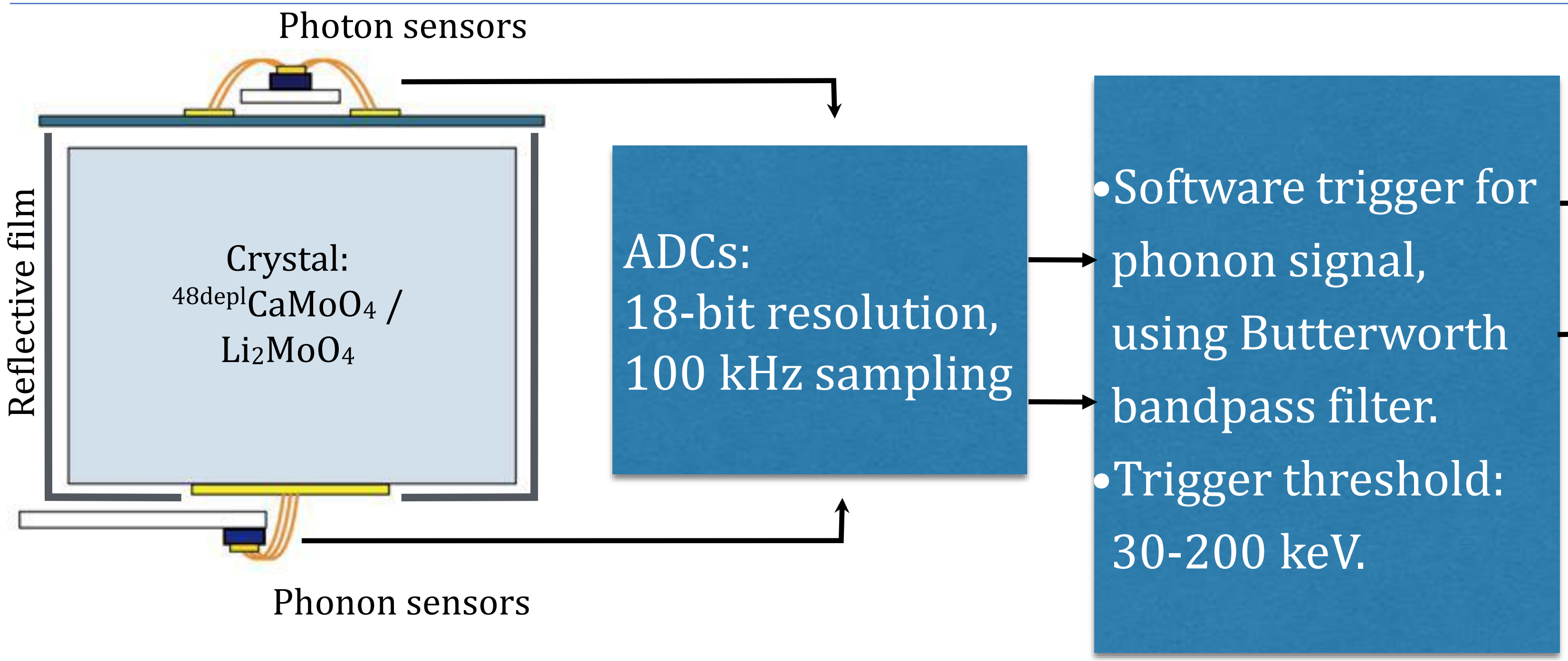
Light absorber (Ge/Si wafer)

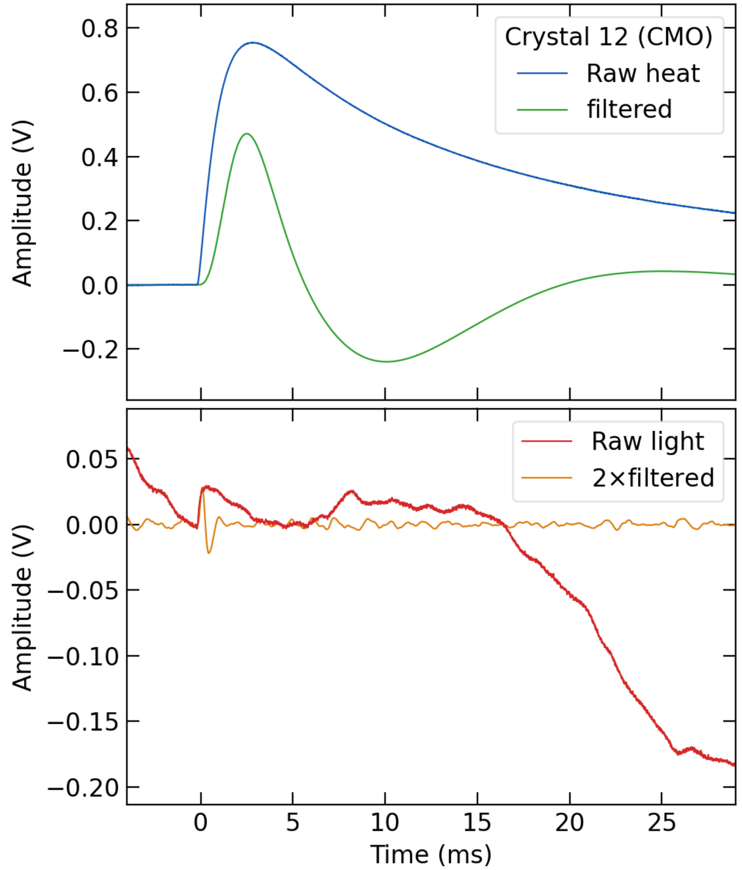
Phonon collector (Au film)





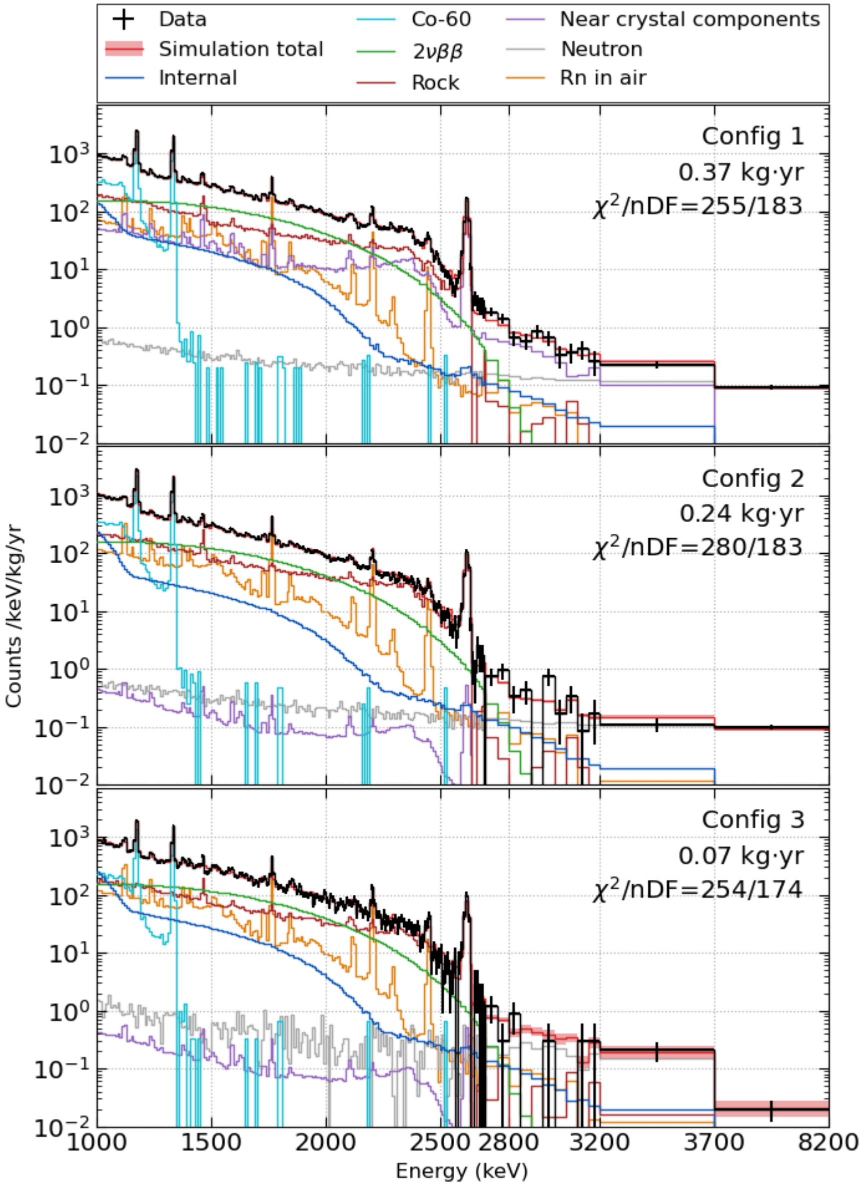
Signal Processing & Analysis

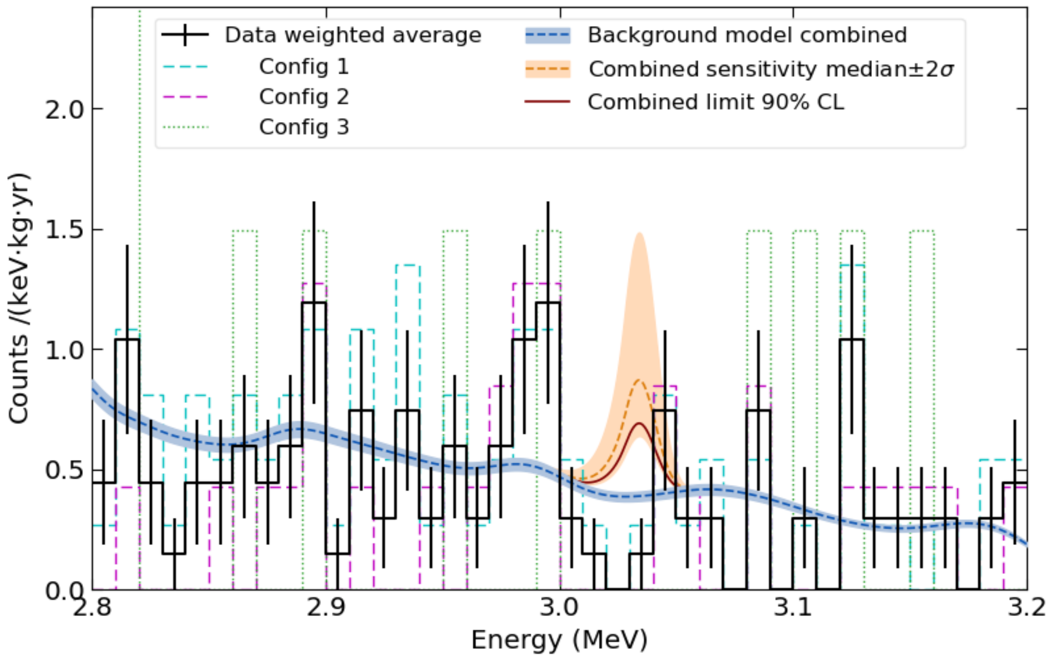




- Raw waveform:
  - baseline/noise informations.
  - timings (rise/fall): pulse shape discrimination (PSD).
- Reconstruction for improving energy resolution and β/α discrimination power (DP):
  - Butterworth bandpass filter— mainly for noise suppression:
    - pulse amplitude: pulse height or a least square fit to the template signal.
  - Stabilization heater signal every 10 seconds to gain drift corrections.

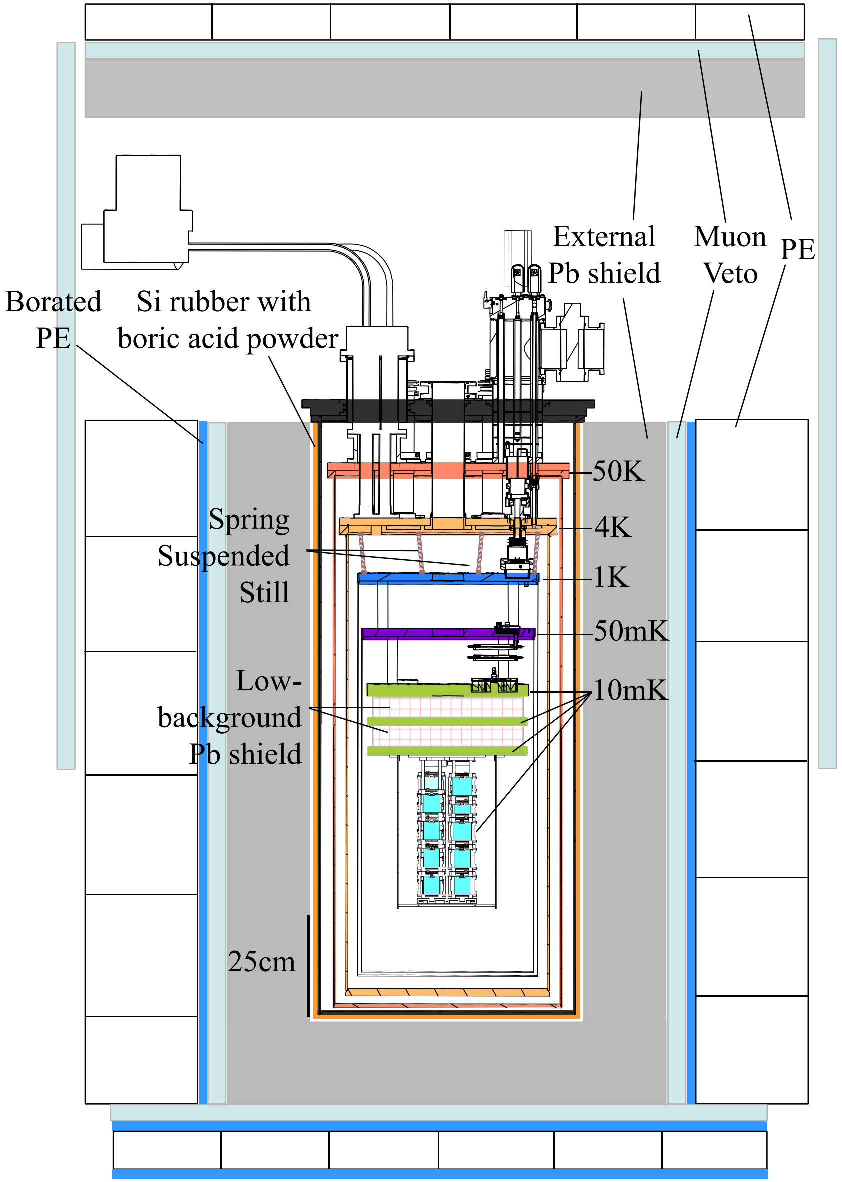
AMoRE-pilot final result



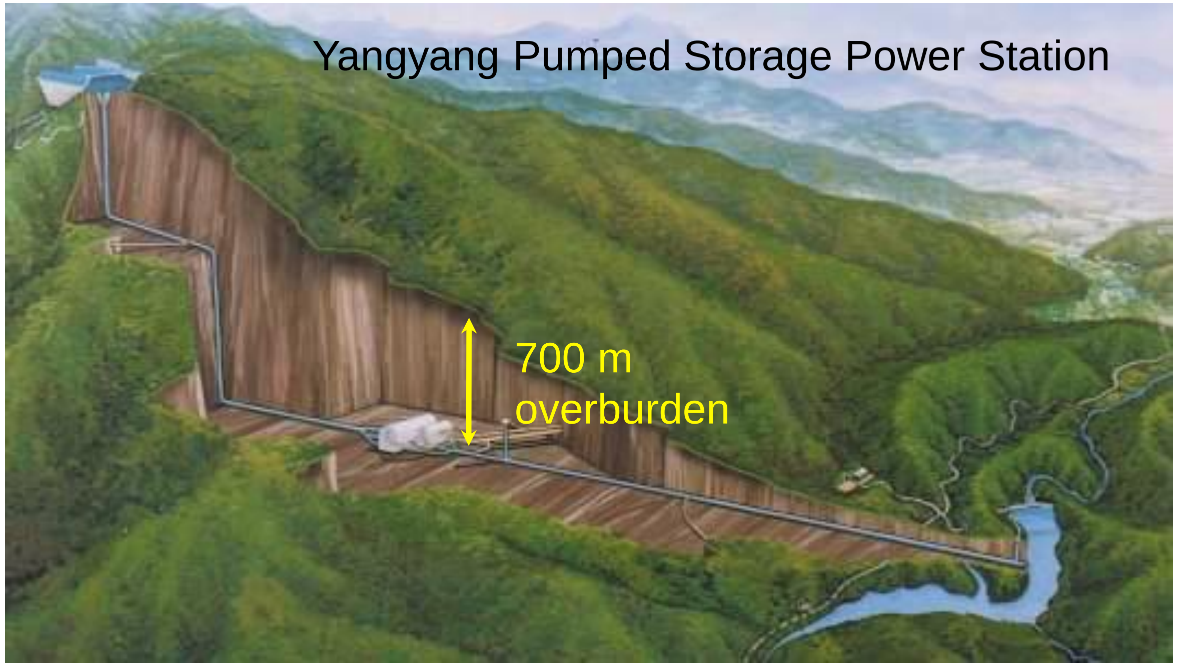


- Experiment between 2016-2018
- Understanding of the background components and reduction of them.
- Background level of ~0.5 counts/keV/kg/yr at 2.8-3.2 MeV.
- neutron-induced γ, crystals' internal contamination, rock/air-radon γ.
- Internal background— arXiv:2107.07704
- $T_{1/2}^{0\nu} > 3.2 \times 10^{23}$ years at 90% CL.

Cryostat & Shielding

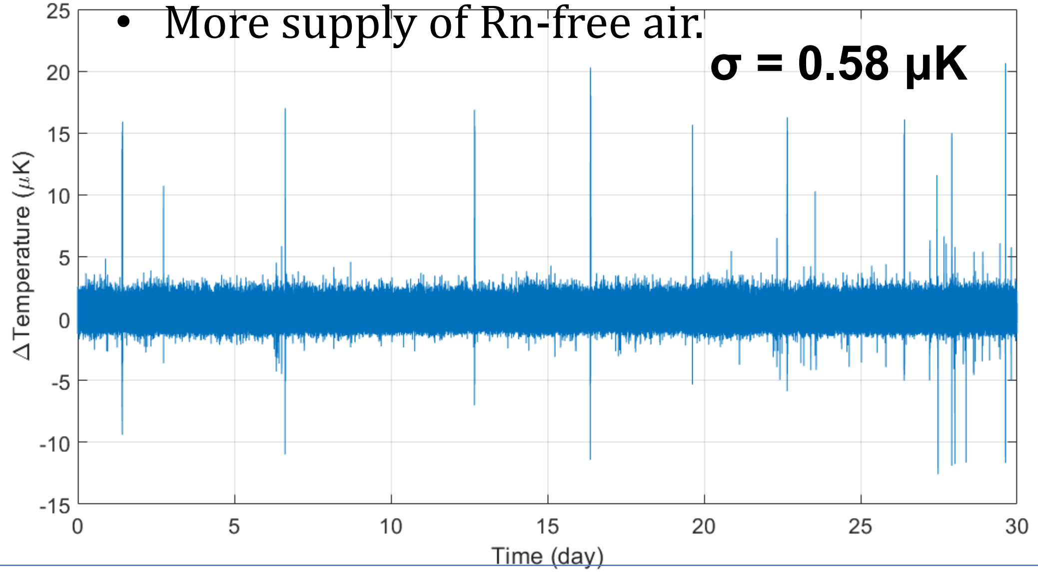


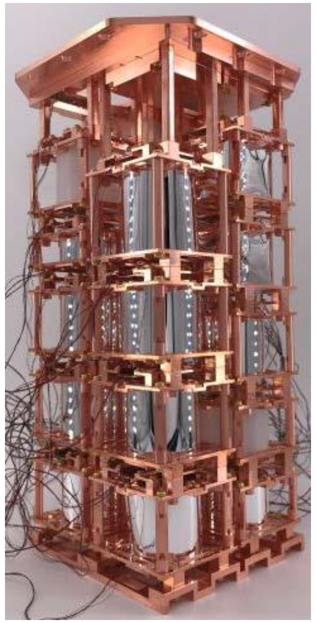
- Cryogen-free dilution refrigerator.
- For AMoRE-pilot and AMoRE-I.
- Now operating at 12 mK with ~1 μW cooling power.
- Pb (γ), boron, and polyethylene (n).
- Plastic scintillator muon counter.
- Yangyang Underground Laboratory (Y2L) at 700 m depth.

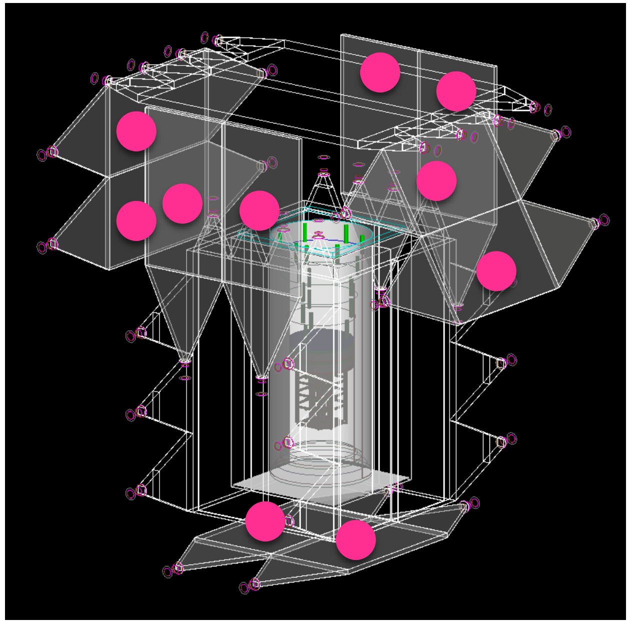


AMoRE-pilot → AMoRE-I

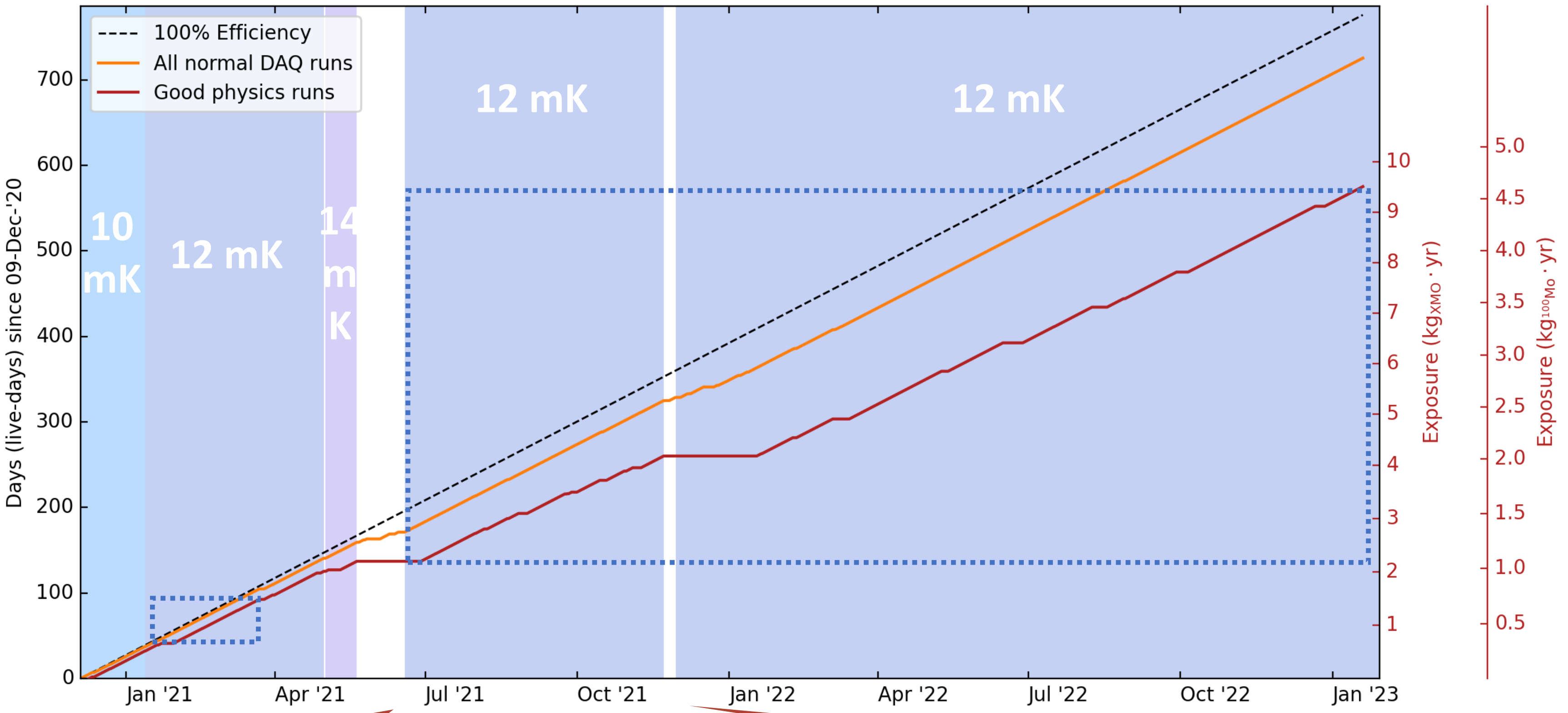
- 6 CMO (1.886 kg) ➔ 13 CMO (4.582 kg) + 5 LMO (1.609 kg)
  - Total crystal mass = 6.193 kg, ^{100}Mo mass = 3.0 kg
- Stabilization heater for all crystals. + 1 additional MMC for temperature regulation
- MMC sensor upgrade: Au:Er ➔ Ag:Er. (~$1/T^2$ heat capacity component associated with nuclear quadrupole moments removed)
- Using same cryostat + two stage temperature control: $\langle \Delta T \rangle < 1$ μK.
- Shielding enhancements:
  - Outer Pb: 15 ➔ 20 cm; neutron shields: boric acid silicon + more PE / B-PE.
  - More muon counter coverage. (~4π)
  - More supply of Rn-free air.





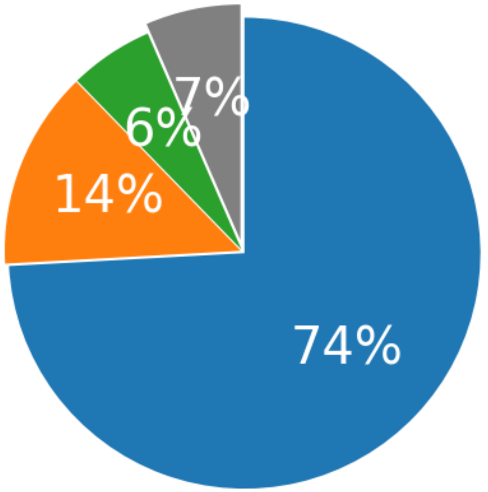


AMoRE-I data taking



DR temperature control

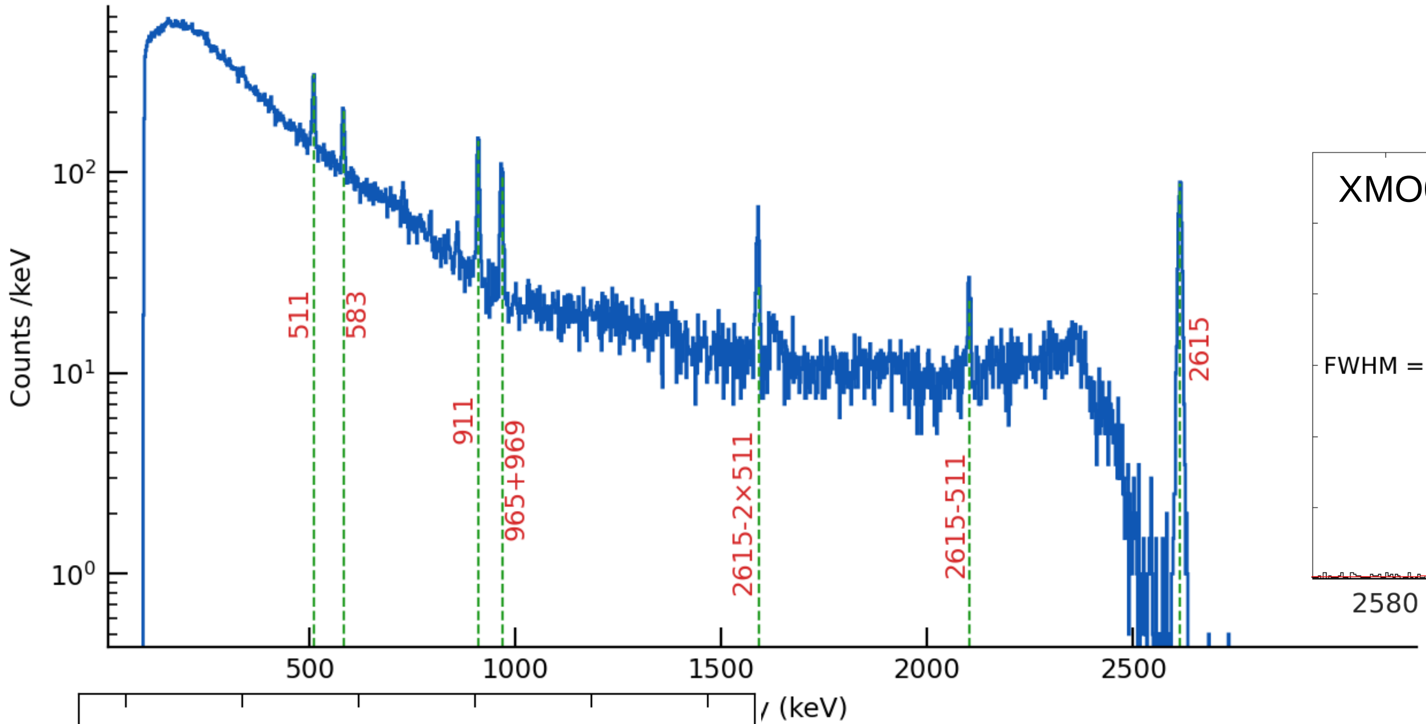
Recovery from power outage

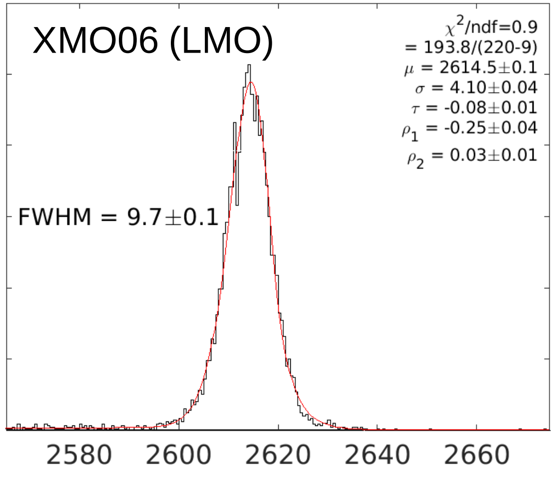


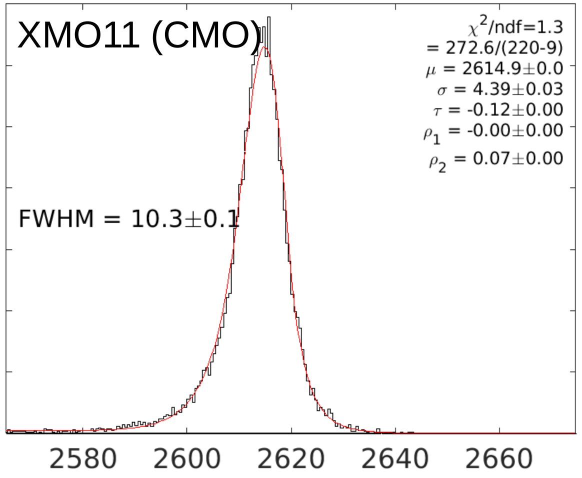
Physics
Calibration
Test
Down

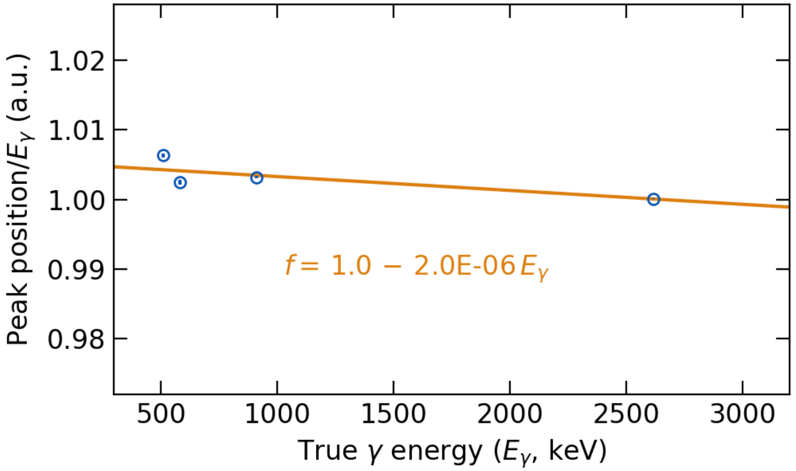
- Data taking is still ongoing
- 7.18 kg · year crystal (3.47 kg · year ^{100}Mo) exposure is presented here (selected data in blue dotted boxes, 467 d.).

Energy Calibration





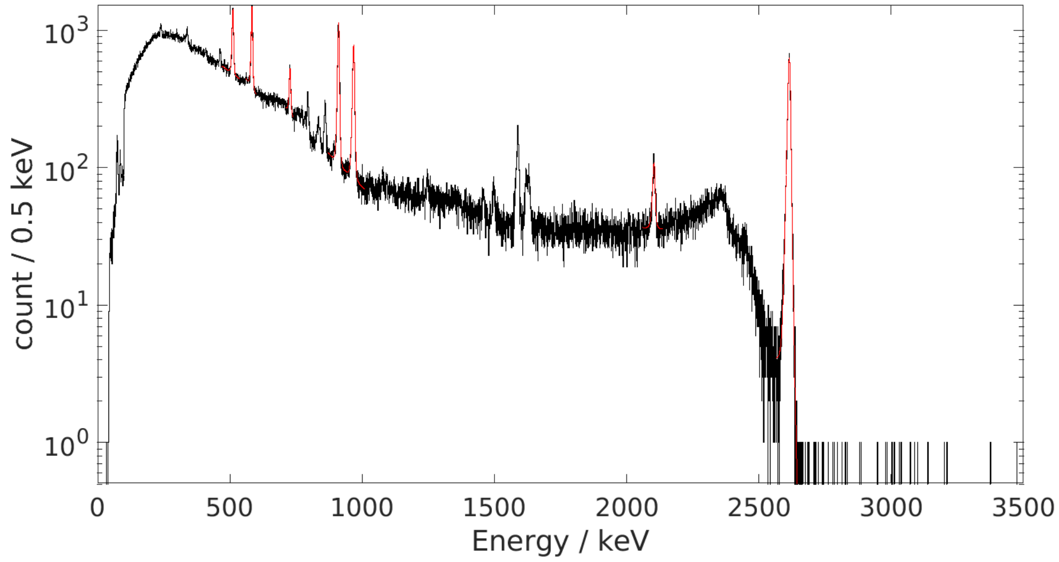


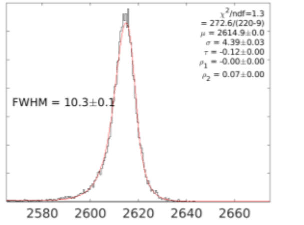


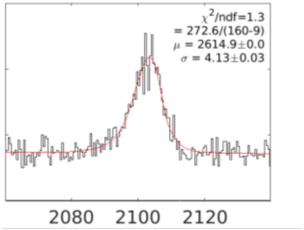
- Calibration source: ^{232}Th-rich welding rods just outside of OVC
- Slight non-linearity between signal amplitude and energy.

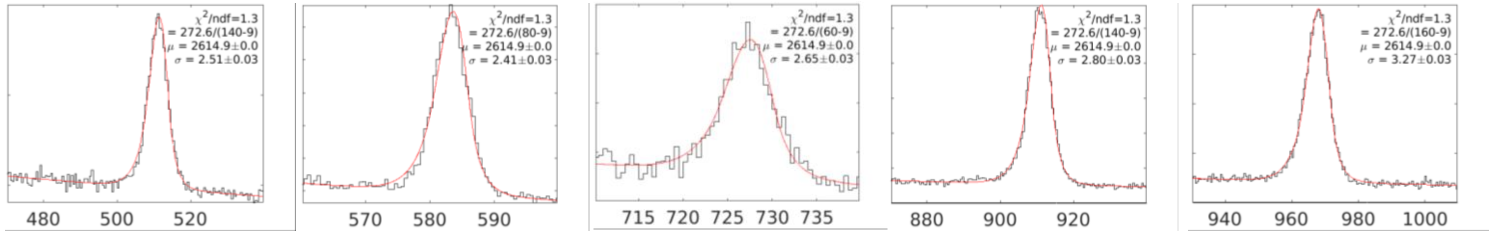
- Bukin instead of gaussian/tailed gaussian – better fit to right tails https://root.cern.ch/doc/master/classRooBukinPdf.html

ROI estimation

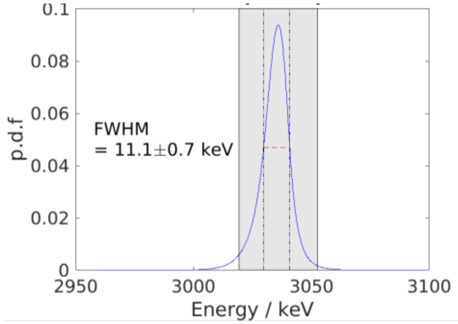






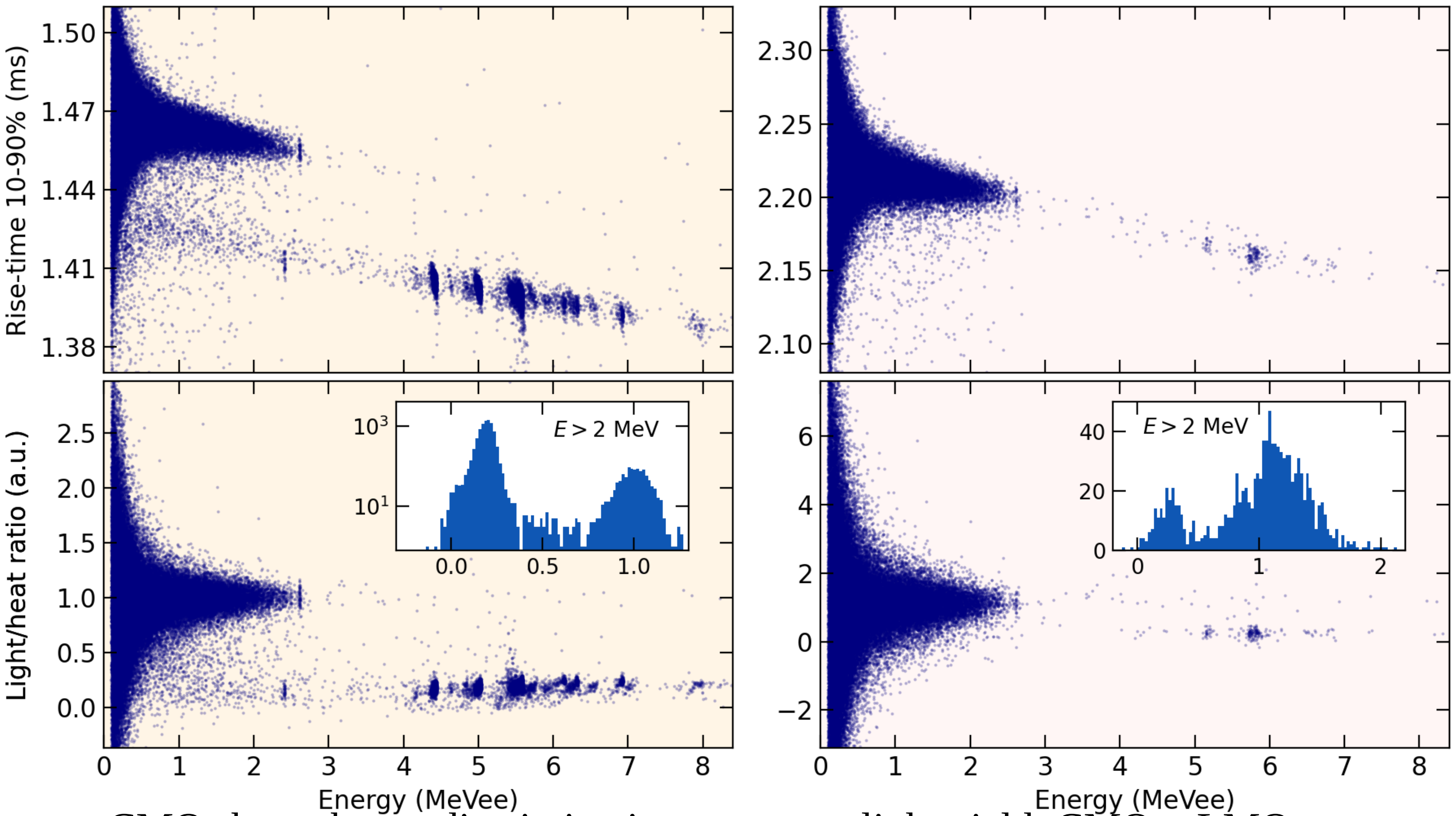


- E_{bias} ~ 2^{nd} polynomial of energy
- $\sigma(E) = \sqrt{b_1 + b_2 E + b_3 E^2}$
- Other parameters of bukin (τ, ρ_1, ρ_2) are assumed to be the same



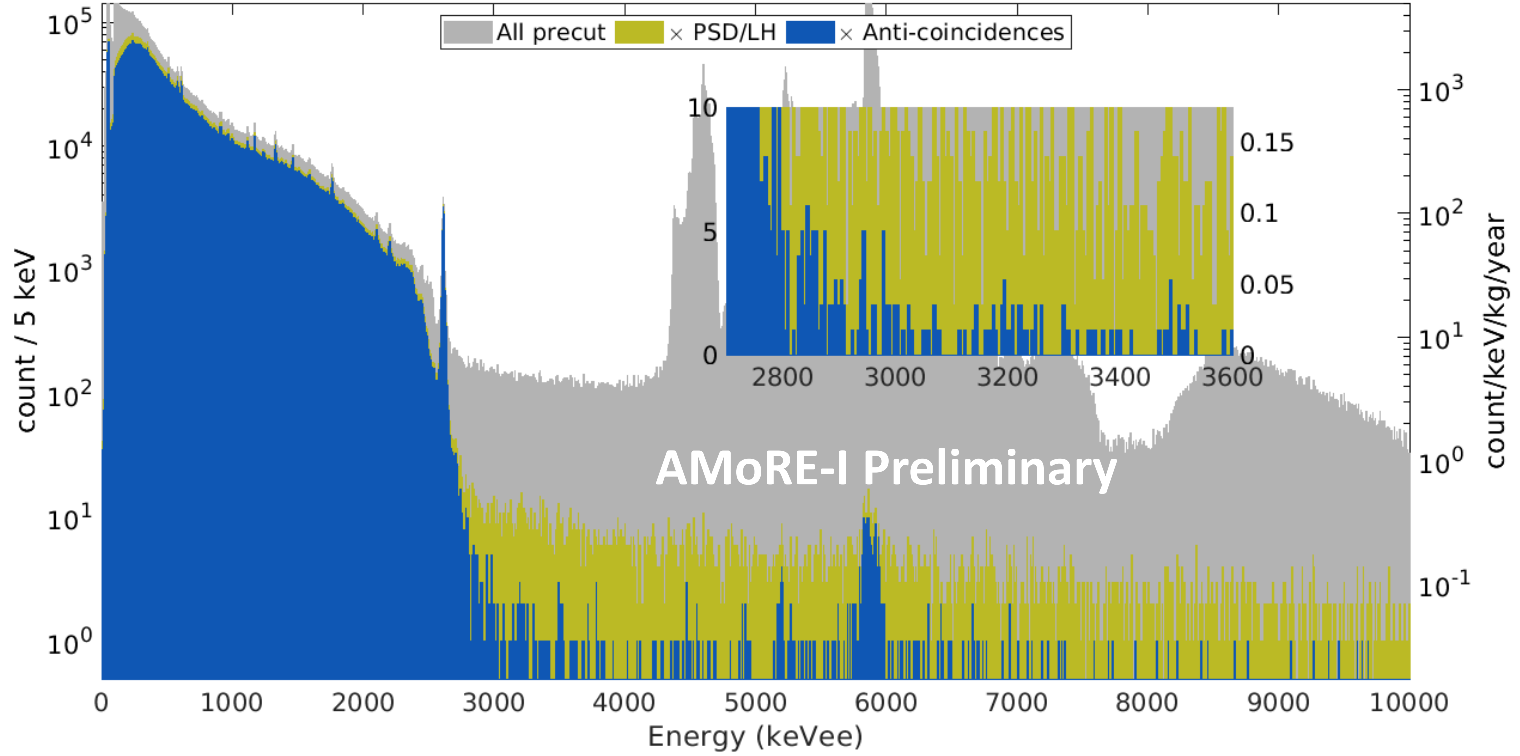
#	Name	FWHM@$Q_{\beta\beta}$ (keV)
1	SB29	13.7±1.0
2	SE01	11.9±0.8
3	SE02	16.5±0.9
4	SE08	12.2±0.8
5	LMO2	27.5±2.3
6	LMO4	10.2±0.8
7	LMO3	11.3±1.1
8	S35	15.7±0.7
9	SS68	14.4±0.6
10	LMOCUP	19.3±0.5
11	SE03	11.1±0.7
12	SE07	14.1±1.0
13	SE09	14.9±0.7
15	SB28	22.9±1.1
16	SE04	19.3±0.8
17	SE05	16.3±0.7
18	SE06	11.4±0.6

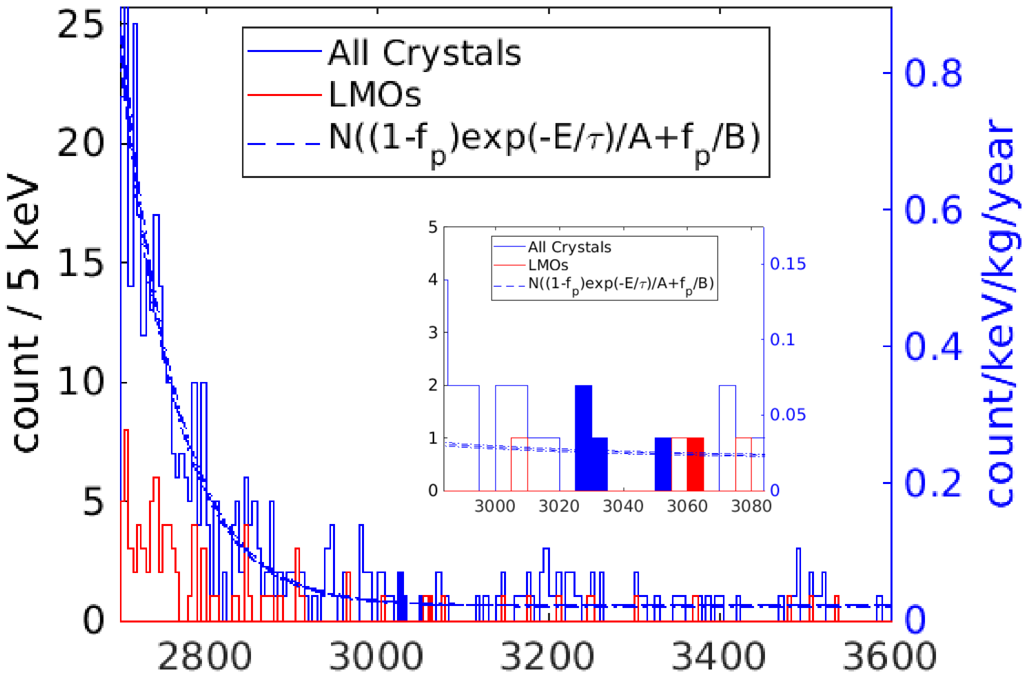
Particle Identifications, CMO and LMO



- CMO shows better discrimination power — light yield: CMO > LMO.
- LMO has much less α contamination.
- ε_{PaID} ~ 91.6 % (±3 median absolute deviations (~±2σ) gives 95.70 % C.L.)

Background Spectrum



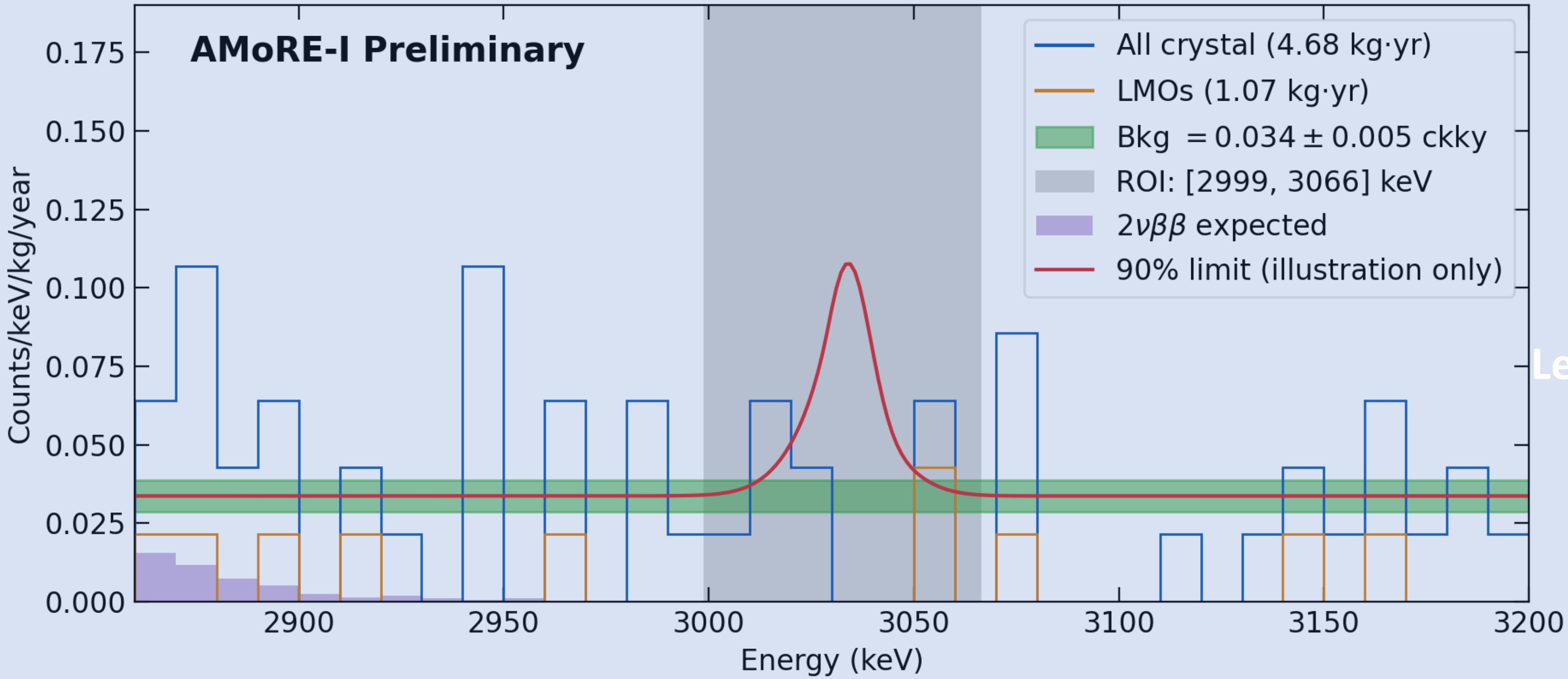


(Faced: ROI events ($Q_{\beta\beta}$ ±1.5 FWHM), not involved in bkg. rate calculation)

- All crystal excluding 1 LMO for very poor β/α discrimination power:
  - 13 CMO + 4 LMO: exposure = 7.18 kg_{XMO} ▪ yr = 3.47 kg_{ISO} ▪ yr. (^{100}Mo live exposure: 2.78 kg ▪ yr)
- Anti-coincidence cuts reject events:
  - coincident at multiple crystals within 2 ms (ε ~ 99.8%),
  - within 10 ms after a muon counter event (ε ~ 99.8%),
  - within 20 minutes after a ^{212}Bi α-decay event candidate (ε ~ 98%).

Live exposure	@ $Q_{\beta\beta}$
Total (5.74 kg y)	0.026±0.001 ckky
CMO (4.31 kg y)	0.028±0.001 ckky
LMO (1.43 kg y)	0.020±0.002 ckky

Preliminary 0νββ limit from AMoRE-I



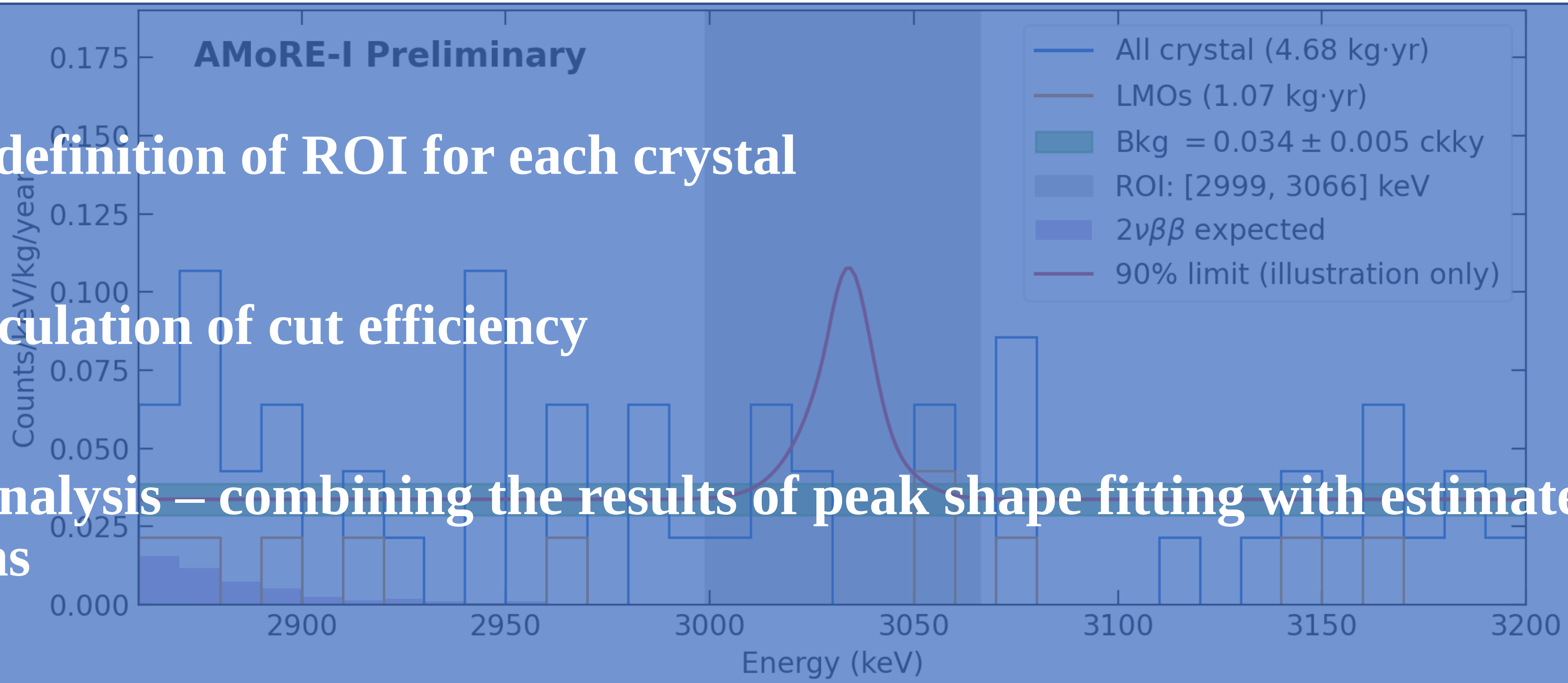
Previous result

Less accumulated data

- ROI to contain most (> 99%) of the $0\nu\beta\beta$ signal peak, $\varepsilon_{\text{containment}} \sim 81\%$.
- Background = 0.034 ± 0.005 counts/keV/kg/year, from ROI side-band.
- Combining the result of counting analysis at ROI, with a flat background constraint from the side-band events for each crystal.
- $T_{1/2}^{0\nu} > 1.05 \times 10^{24}$ years at 90% C.L.

Rough analysis with combined spectrum

Preliminary 0νββ limit from AMoRE-I



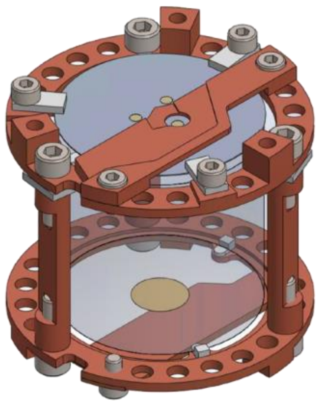
- **Precise definition of ROI for each crystal**
- **Fine calculation of cut efficiency**
- **Shape analysis – combining the results of peak shape fitting with estimated bukin functions**

➢ **We will have new limit in the near future.**

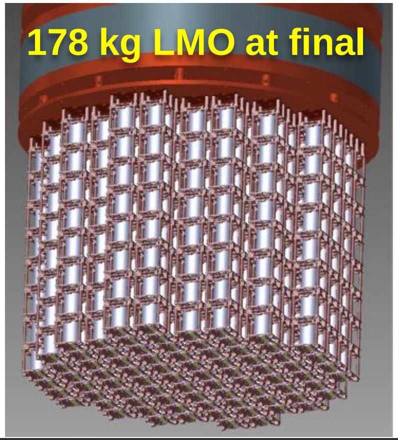
- ROI to contain most (~ 90%) of the 0νββ signal peak, $\varepsilon_{\text{containment}}$ ~ 81%.
- Background = 0.034 ± 0.005 counts/keV/kg/year, from ROI side-band.
- Combining the result of counting analysis at ROI, with a flat background constraint from the side-band events for each crystal.
- $T^{0\nu}_{1/2} > 1.05 \times 10^{24}$ years at 90% C.L.

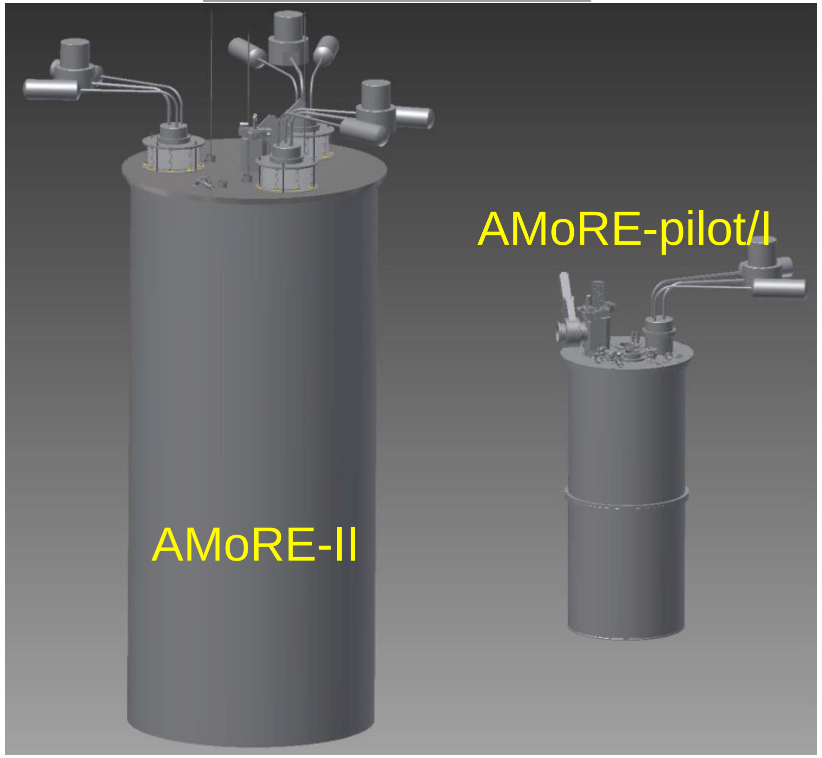
AMoRE-II in preparation

AMoRE-II
Detector module

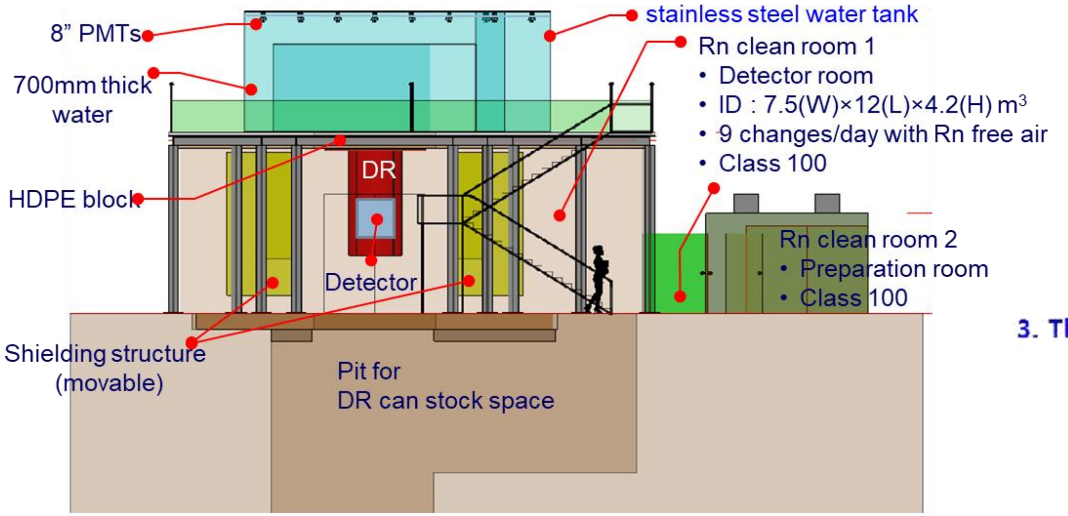


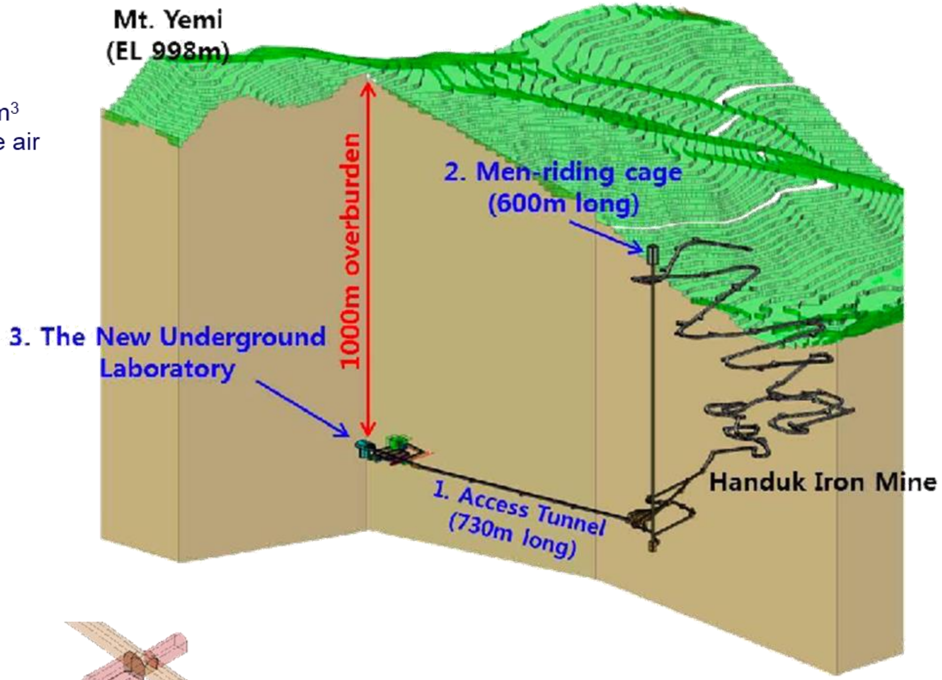
90 modules (~27 kg LMO)
for the first stage

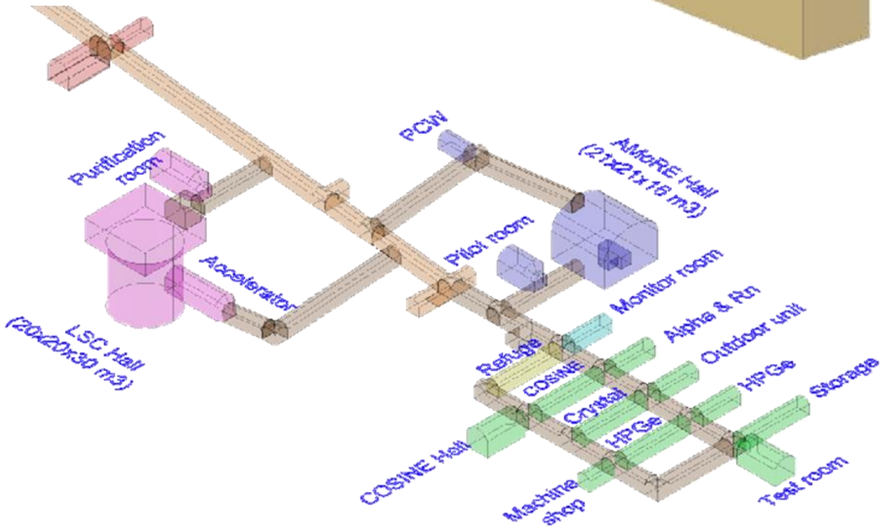




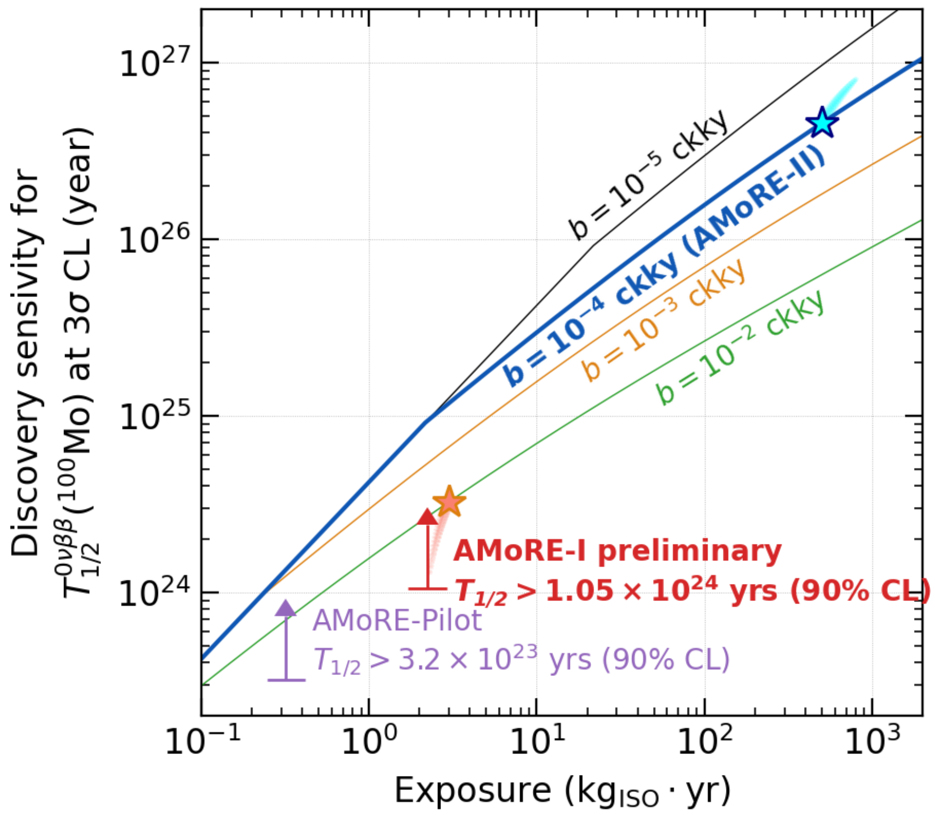
AMoRE-II in YemiLab

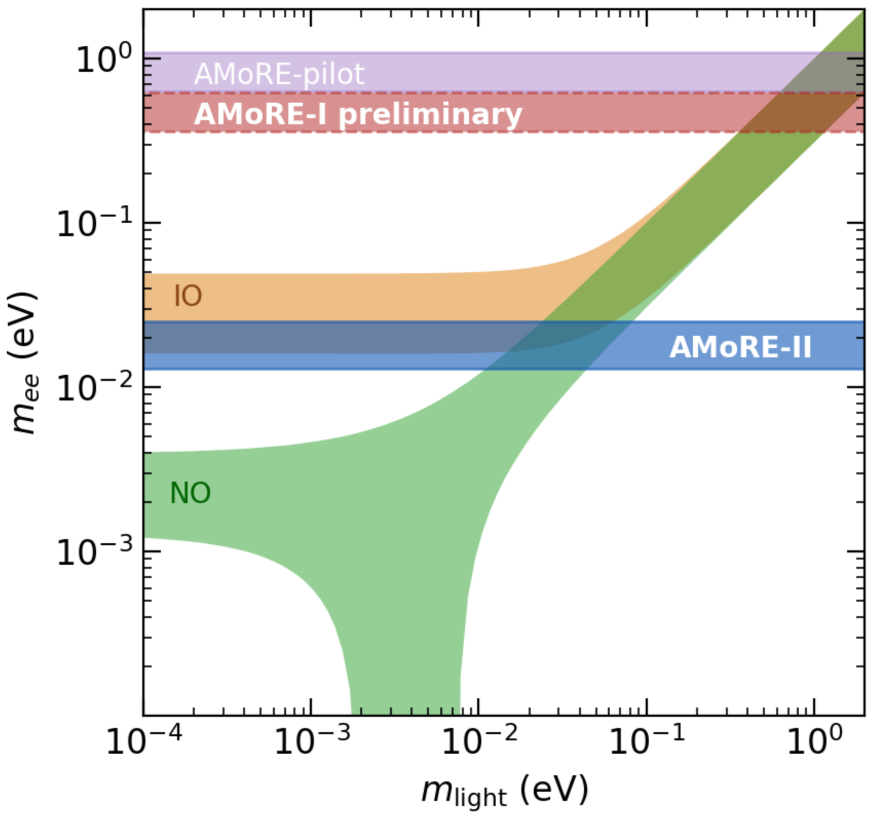






Limits & Sensitivities





- Final results of AMoRE-I with more data and further improved analysis.
- AMoRE-II for $T_{1/2}^{0\nu} > 5 \times 10^{26}$ years by 100 kg of ^{100}Mo × 5 years running.
- Reduction of background level down below 10^{-4} ckky.

Summary

- AMoRE searches for $0\nu\beta\beta$ using ^{100}Mo based scintillating crystals at the low temperature detector system.

- Preliminary result of AMoRE-I:
  - Mass×time exposure: 7.18 (3.47) kg · yr XMO (^{100}Mo).
  - Background level ~ 0.026 counts/keV/kg/year at $Q_{\beta\beta}$.
  - Resolution: 10.2 – 27.5 keV around $Q_{\beta\beta}$
  - Preliminary limit: $T_{1/2}^{0\nu} > 1.05 \times 10^{24}$ years – update required!
  - Further analysis still goes on; the final limit will be reported.

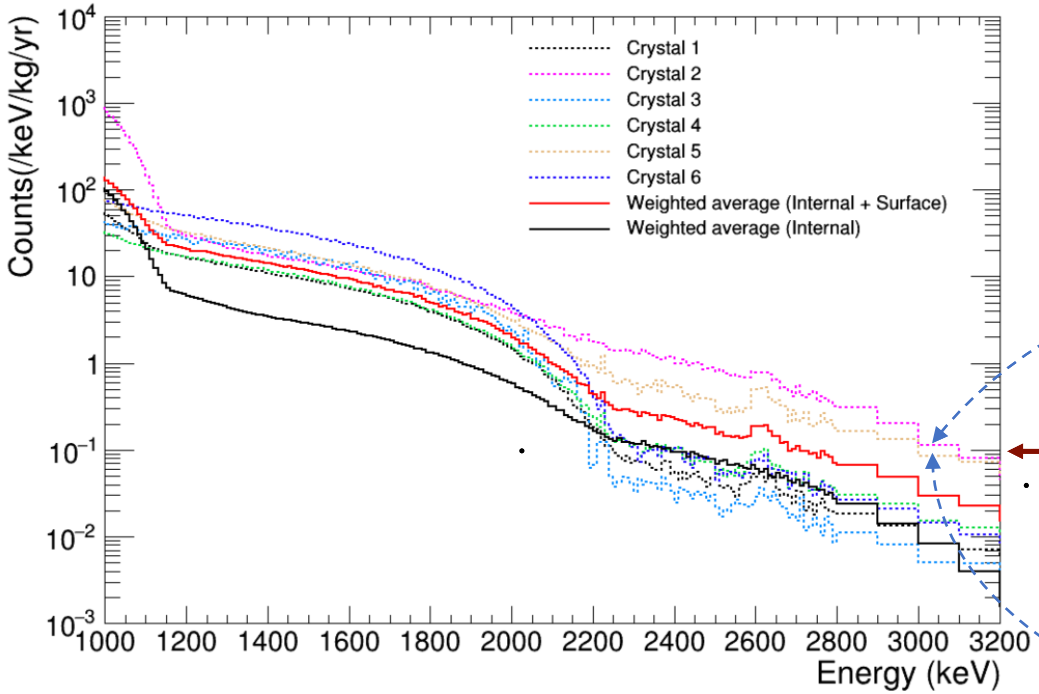
- AMoRE-II starts its data taking soon to head for $T_{1/2}^{0\nu} > 5 \times 10^{26}$ years.

Thank you!

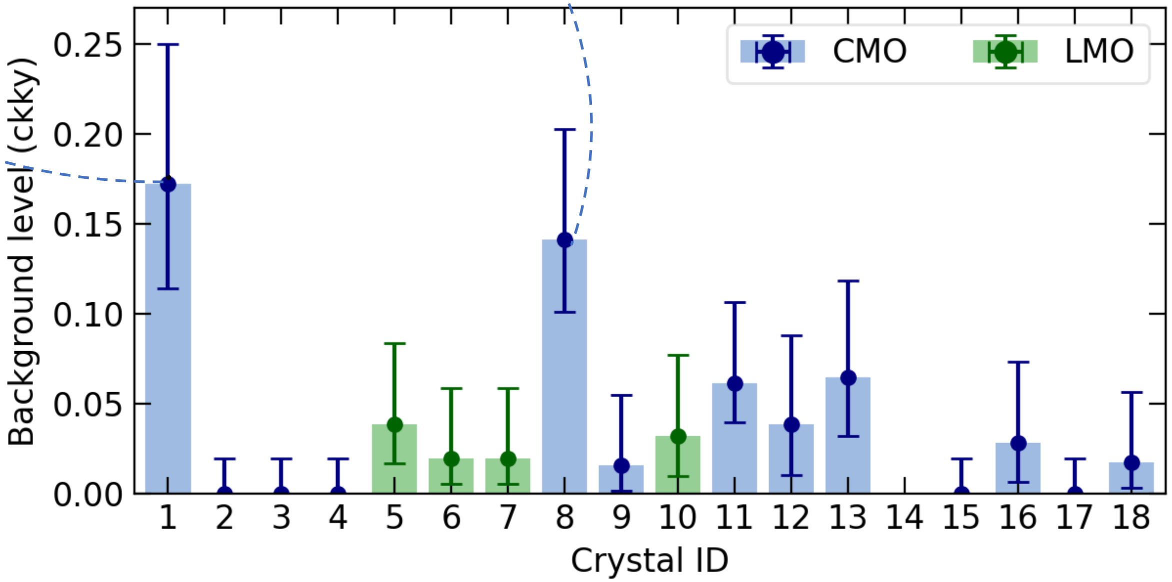
backup

CMO internal background

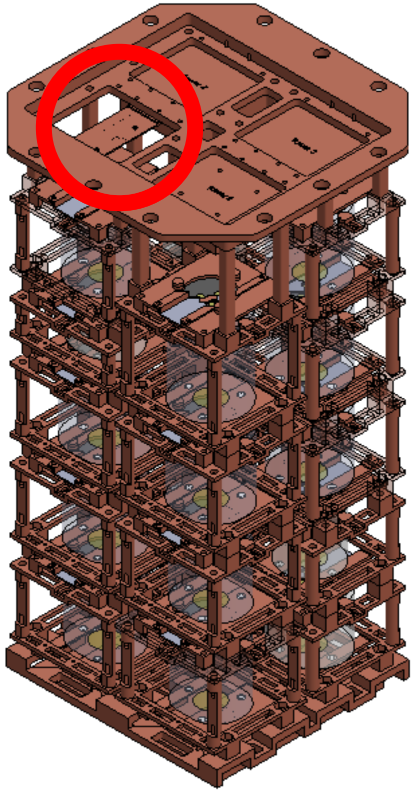
arXiv:2107.07704

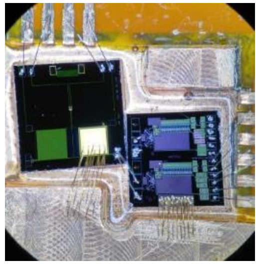


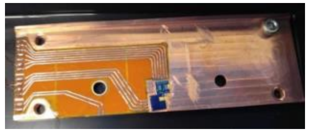
0.1 ckky!

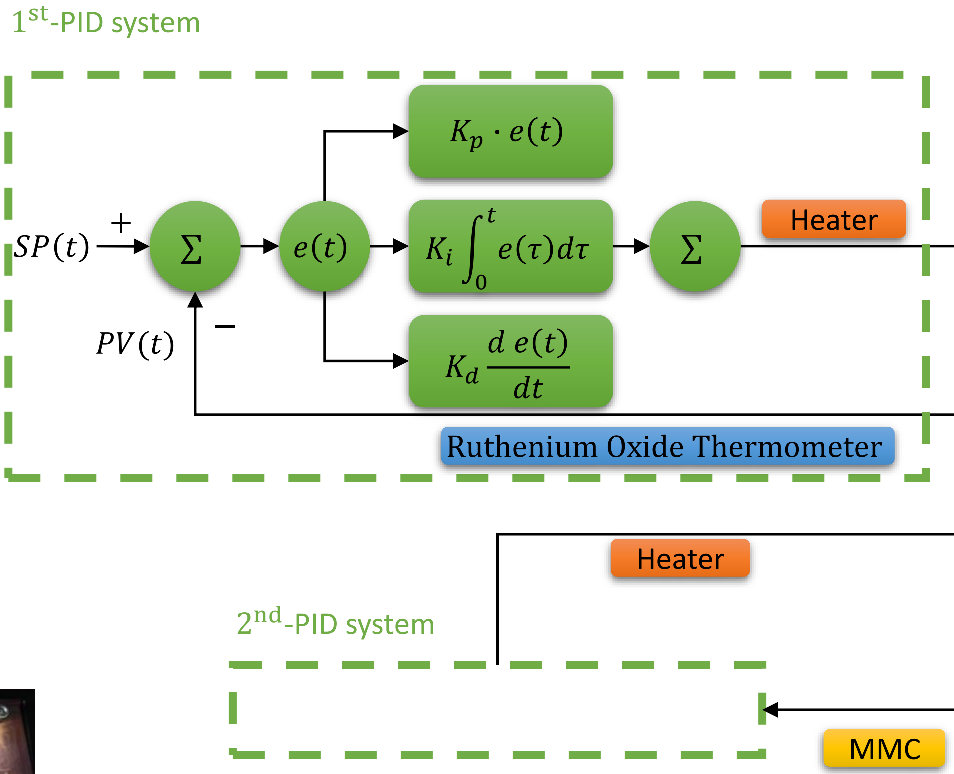


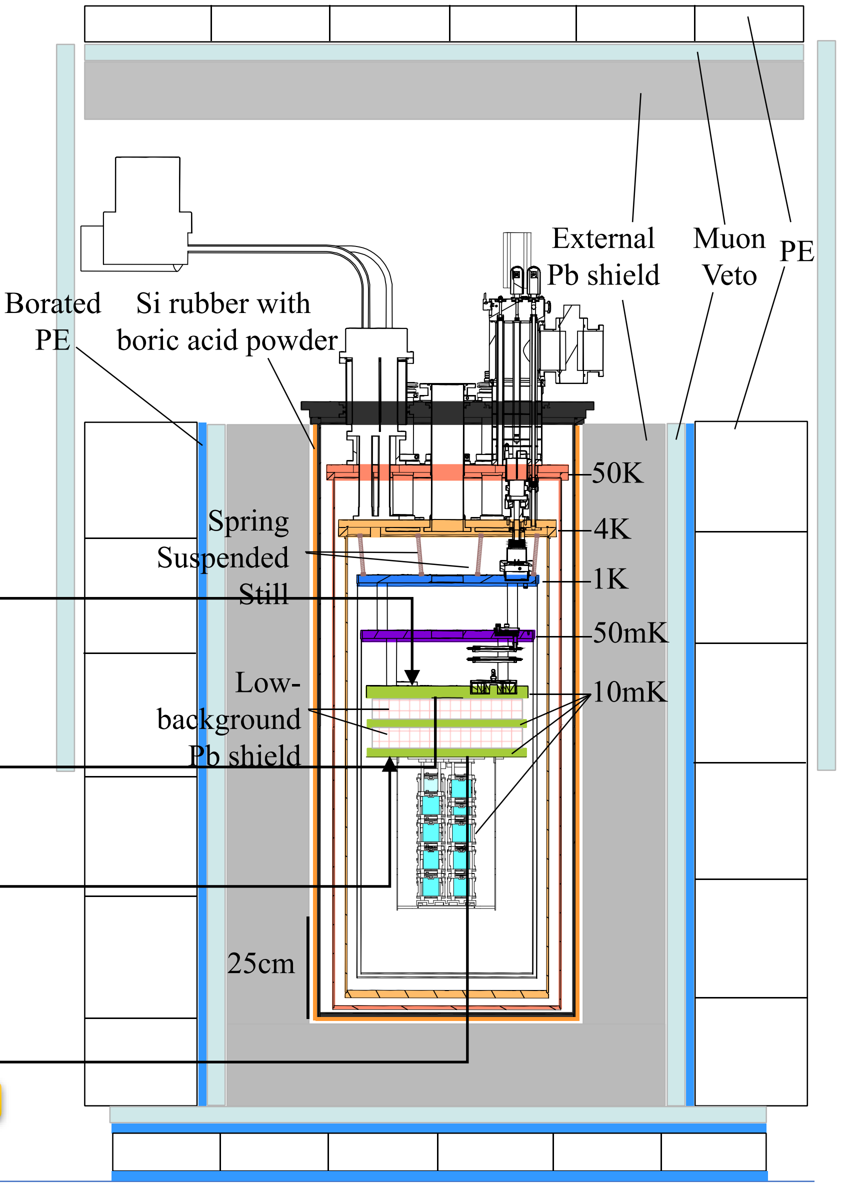
Two stage temperature control







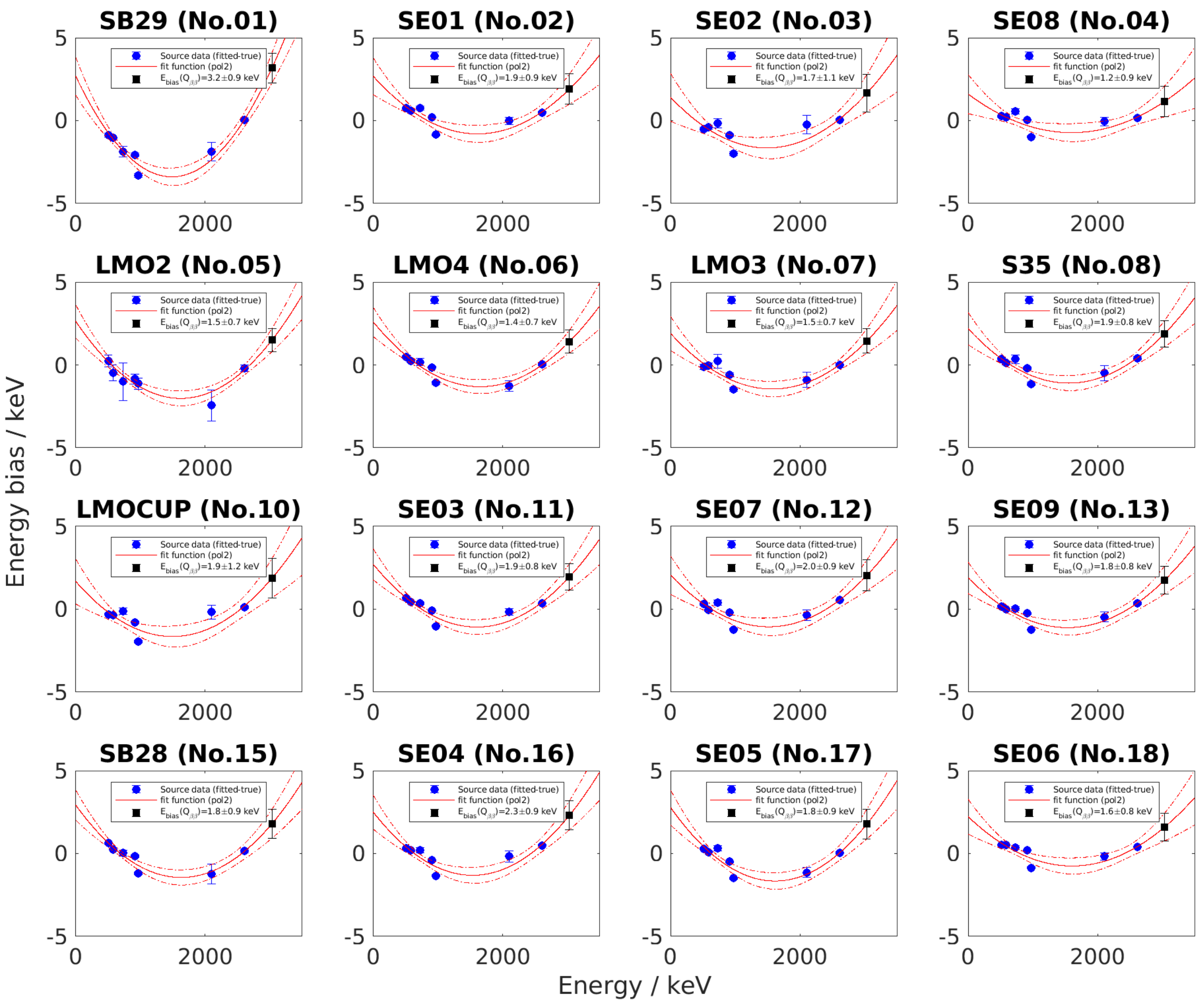


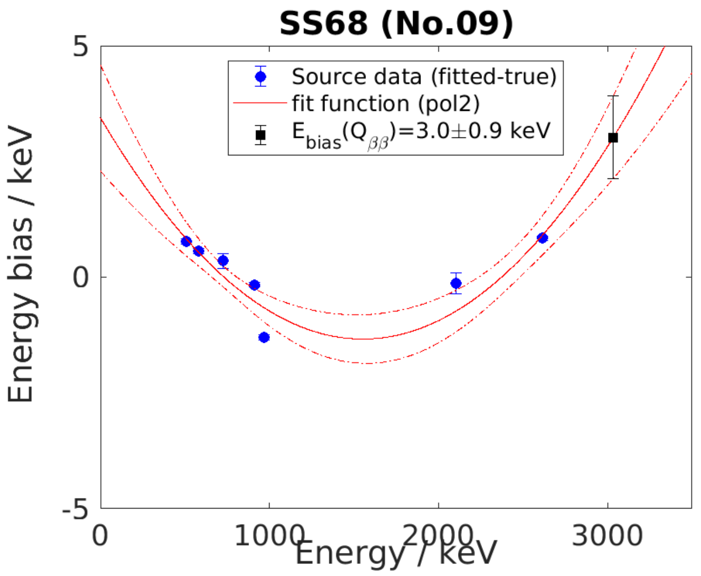


Live time

#	1	2	3	4	5	6	7	8	10	11	12	13	15	16	17	18
Name	SB29	SE01	SE02	SE08	LMO2	LMO4	LMO3	S35	LMOCUP	SE03	SE07	SE09	SB28	SE04	SE05	SE06
Total Time	21205887	40364490	14650585	40364490	40364490	40364490	40364490	40364490	33714497	40364490	40364490	40364490	40364490	40364490	40364490	40364490
DFT loss time	0	5977	1211.8	5977	5977	5977	5977	5977	5977	5977	5977	5977	5977	5977	5977	5977
Alpha rejection time	4949195.5	1609920.8	410809.7	307480.9	109200	81600	102000	1497216.8	96000	590485	356390.1	183578	2851350.5	335013.6	237714.6	269451.3
Muon veto time	20885.8	95455.6	36939.6	95455.6	95455.6	95455.6	95455.6	95455.6	83384.7	95455.6	95455.6	95455.6	95455.6	95455.6	95455.6	95455.6
Multiple hit veto time	35474.9	62360.9	25677.7	62699.4	63068.2	62074.1	62974	62087	53022.5	63066.3	63098.5	63115	63086.5	62748.5	63081.2	63093.7
Trigger dead time	386708.8	369980.3	127836.7	380845.7	1612835.4	358898.7	361941.2	898951.4	329982.6	454299.9	375145	378863.2	357261.5	392521.9	400338.4	379229.3
PaID efficiency (%)	91.6	91.6	91.6	91.6	91.6	91.6	91.6	91.6	91.6	91.6	91.6	91.6	91.6	91.6	91.6	91.6
Live Time	14761651	35100324	12917882	36272483	35350666	36523283	36496452	34763008	30377546	35950682	36234260	36391495	33985035	36237042	36324056	36314086
Efficiency (%)	69.61	86.96	88.17	89.86	87.58	90.48	90.42	86.12	90.1	89.07	89.77	90.16	84.2	89.77	89.99	89.97

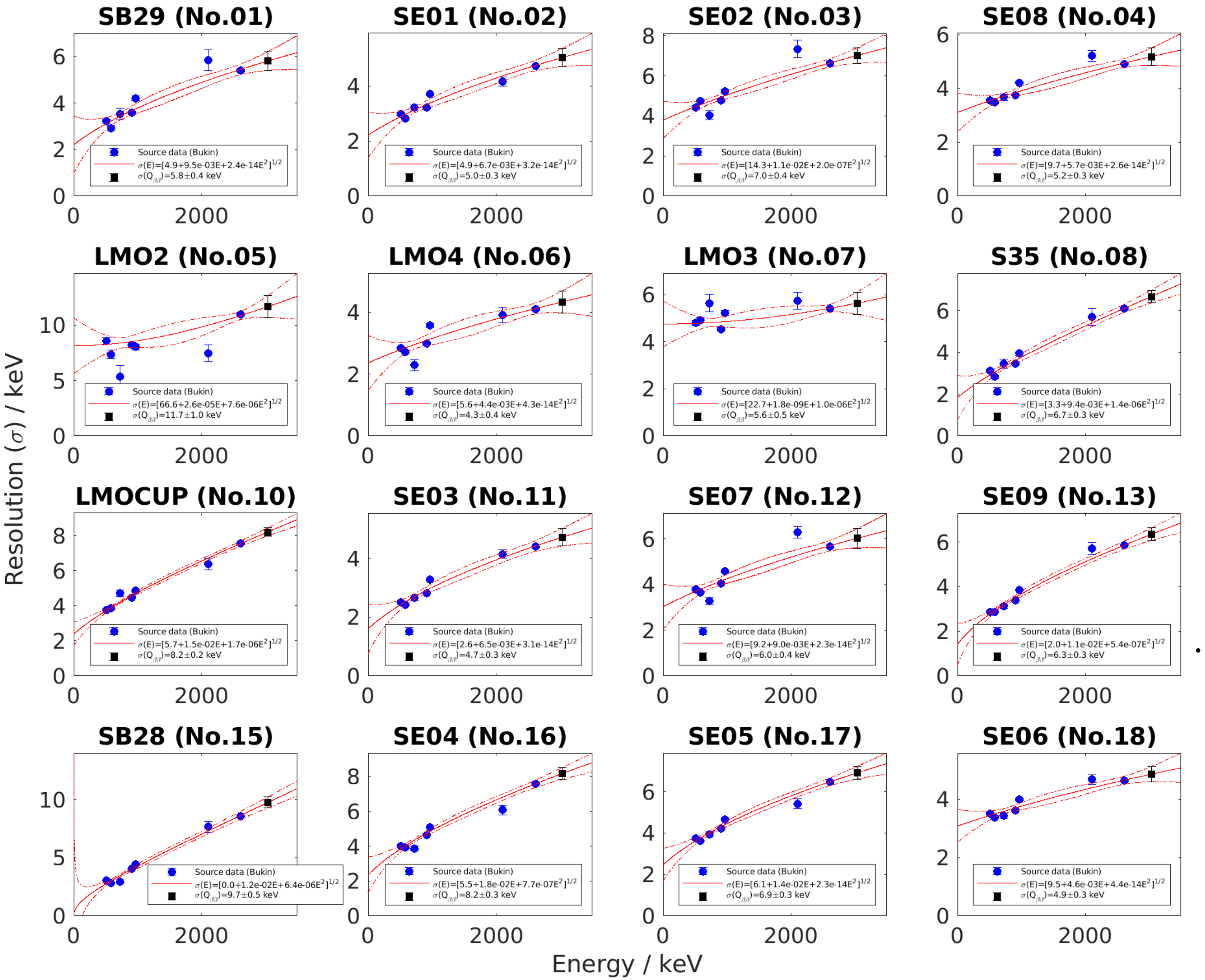
ROI estimation

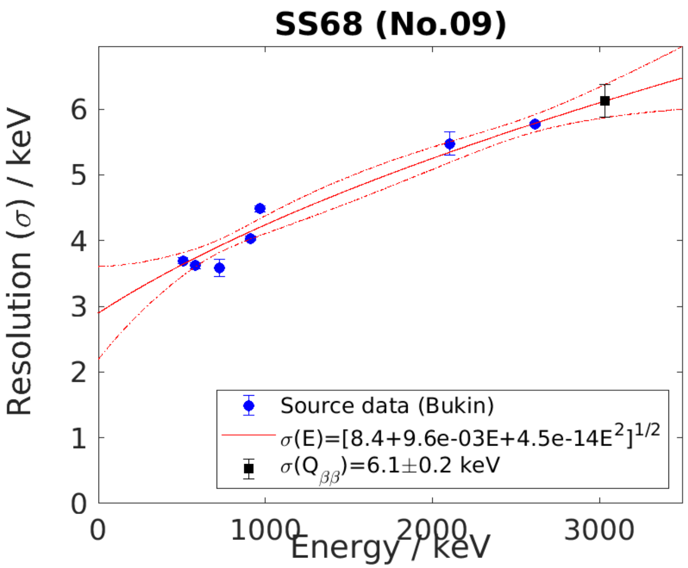




- Fitting function:
  2nd polynomial of energy
- The estimated energy biases at $Q_{\beta\beta}$ tend to be larger than zero.

ROI estimation





- Fitting function:

$$\sigma(E) = \sqrt{b_1 + b_2 E + b_3 E^2}$$

ROI estimation

#	Name	$E_{bias}(Q_{\beta\beta})$ (keV)	$\sigma(Q_{\beta\beta})$ (keV)	τ	ρ_1	ρ_2	FWHM (keV)
1	SB29	3.2±0.9	5.8±0.4	0.07±0.01	-0.00±0.01	0.00±0.06	13.7±1.0
2	SE01	1.9±0.9	5.0±0.3	-0.15±0.00	-0.00±0.00	0.08±0.00	11.9±0.8
3	SE02	1.7±1.1	7.0±0.4	0.09±0.01	-0.00±0.00	0.02±0.01	16.5±0.9
4	SE08	1.2±0.9	5.2±0.3	-0.07±0.00	-0.00±0.00	0.08±0.00	12.2±0.8
5	LMO2	1.5±0.7	11.7±1.0	0.02±0.01	-0.13±0.05	0.06±0.01	27.5±2.3
6	LMO4	1.4±0.7	4.3±0.4	-0.08±0.01	-0.25±0.04	0.03±0.01	10.2±0.8
7	LMO3	1.5±0.7	5.6±0.5	0.02±0.01	-0.00±0.02	0.03±0.01	11.3±1.1
8	S35	1.9±0.8	6.7±0.3	0.00±0.01	-0.00±0.01	0.08±0.01	15.7±0.7
9	SS68	3.0±0.9	6.1±0.2	-0.12±0.00	-0.00±0.01	0.00±0.00	14.4±0.6
10	LMOCUP	1.9±1.2	8.2±0.2	0.14±0.01	-0.00±0.01	0.00±0.00	19.3±0.5
11	SE03	1.9±0.8	4.7±0.3	-0.12±0.00	-0.00±0.00	0.07±0.00	11.1±0.7
12	SE07	2.0±0.9	6.0±0.4	-0.01±0.00	-0.00±0.00	0.08±0.00	14.1±1.0
13	SE09	1.8±0.8	6.3±0.3	-0.04±0.00	-0.00±0.00	0.10±0.00	14.9±0.7
15	SB28	1.8±0.9	9.7±0.5	-0.16±0.01	-0.08±0.02	0.08±0.01	22.9±1.1
16	SE04	2.3±0.9	8.2±0.3	-0.01±0.00	-0.00±0.00	0.11±0.00	19.3±0.8
17	SE05	1.8±0.9	6.9±0.3	-0.05±0.00	-0.00±0.00	0.10±0.00	16.3±0.7
18	SE06	1.6±0.8	4.9±0.3	-0.08±0.00	-0.00±0.00	0.00±0.00	11.4±0.6

Background budget for AMoRE-II