

A neutrinoless double beta decay investigation with ^{100}Mo in AMoRE

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On Behalf of the AMoRE Collaboration

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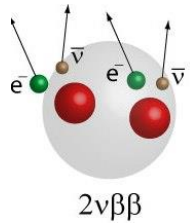
Neutrinoless double beta decay

AMoRE:

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

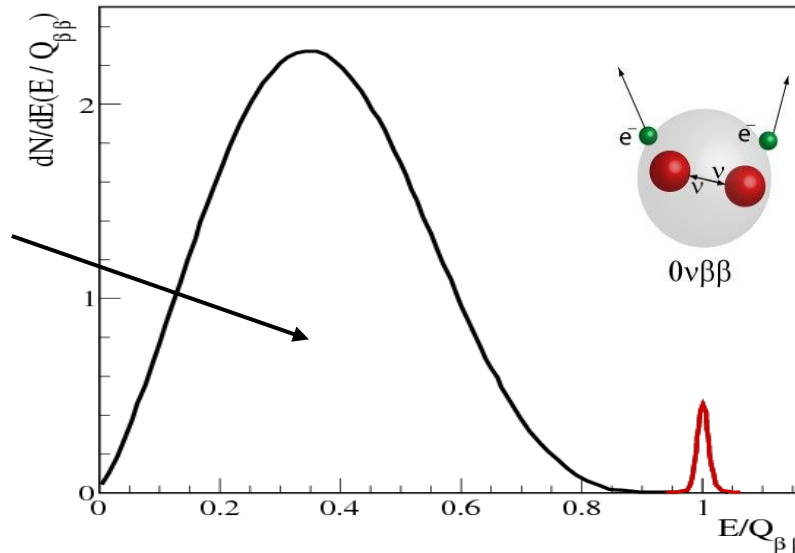
$2\nu\beta\beta$ decay

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



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

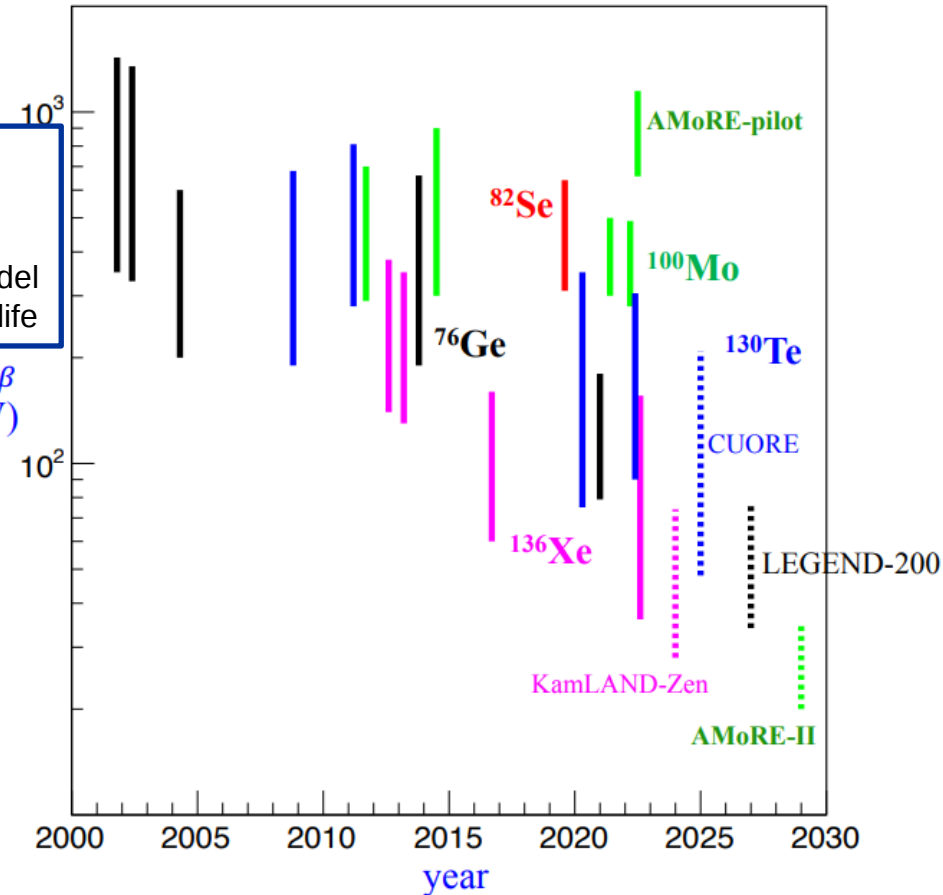
$$(Z, A) \rightarrow (Z + 2, A) + 2e^-$$



$0\nu\beta\beta$ decay

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

$m_{\beta\beta}$
(meV)

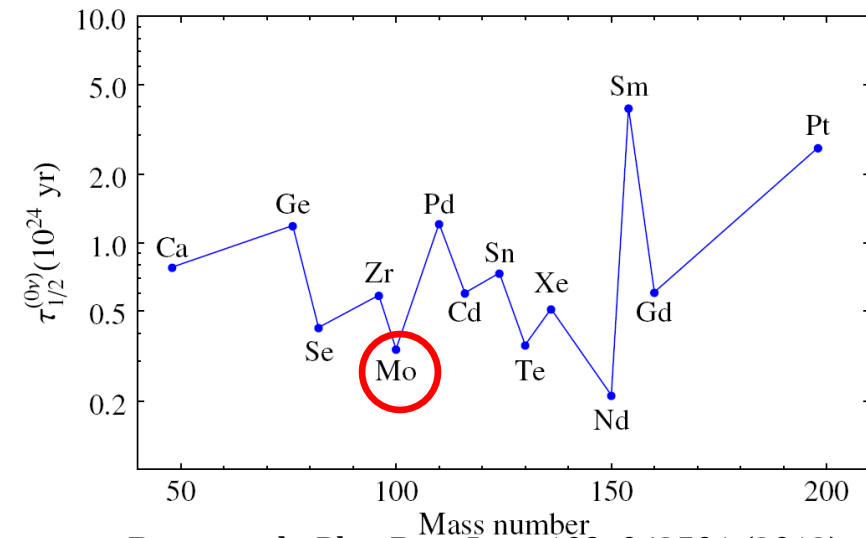


- Neutrinoless double beta decay:
 - Direct measure of Majorana nature of neutrino.
 - Lepton number violation process.
 - Effective neutrino mass.

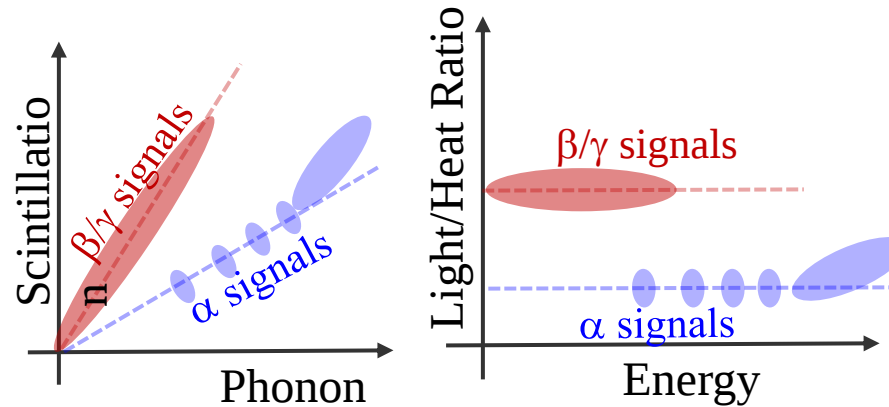
$0\nu\beta\beta$ search using ^{100}Mo

^{100}Mo :

- High $Q_{\beta\beta} = 3034$ keV
- High natural abundance: 9.7 %
- Scintillation crystals with ^{100}Mo enrichment > 95% — XMo_aO_b (XMO):
 - $\text{X}=\text{Ca}, \text{Li}_2, \text{Na}_2, \text{Zn}, \text{Sr}, \text{Pb}, \dots$
 - Detection of light/heat signal $\rightarrow$ rejection of surface- α background.
- Relatively short half life ($0\nu\beta\beta$) in theoretical expectation



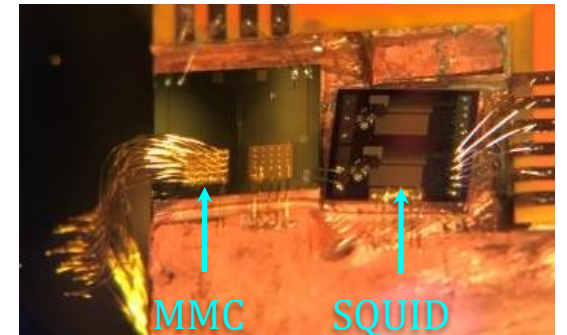
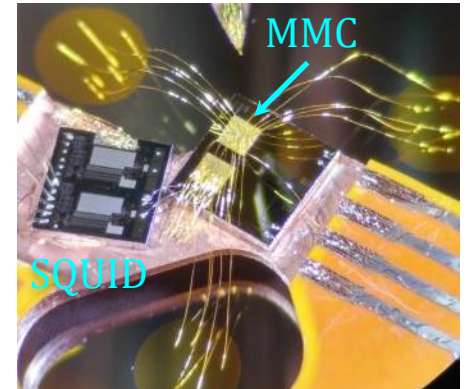
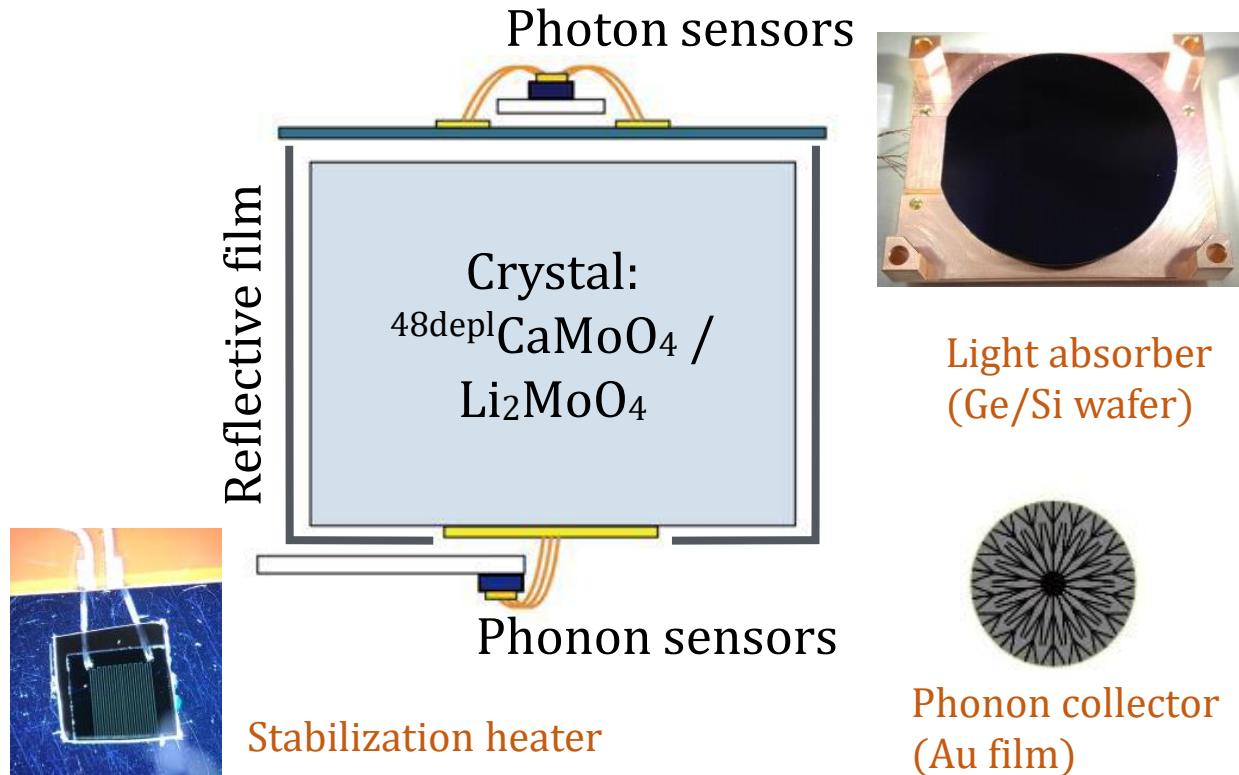
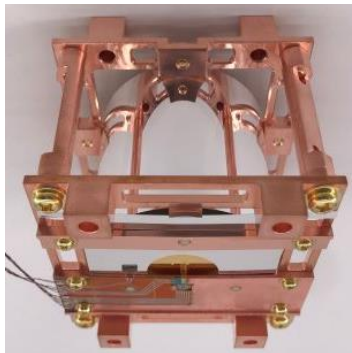
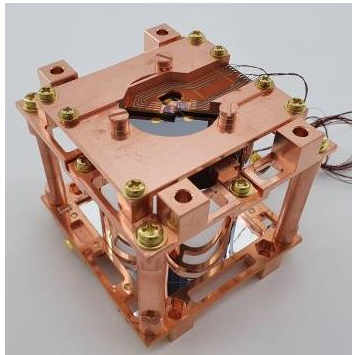
Barea et al., Phy. Rev. Lett. 109, 042501 (2012)



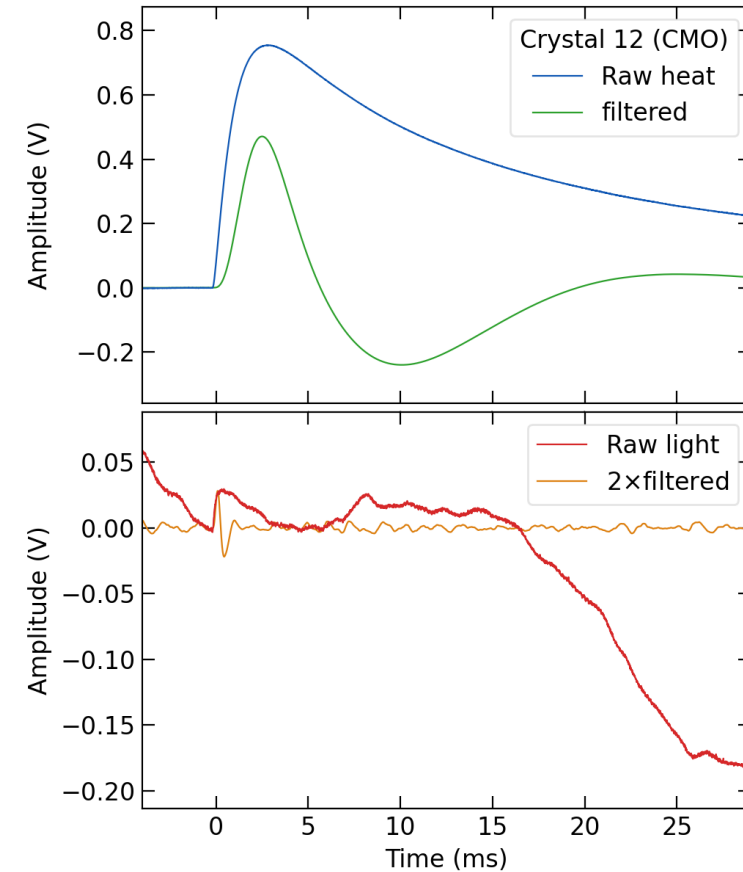
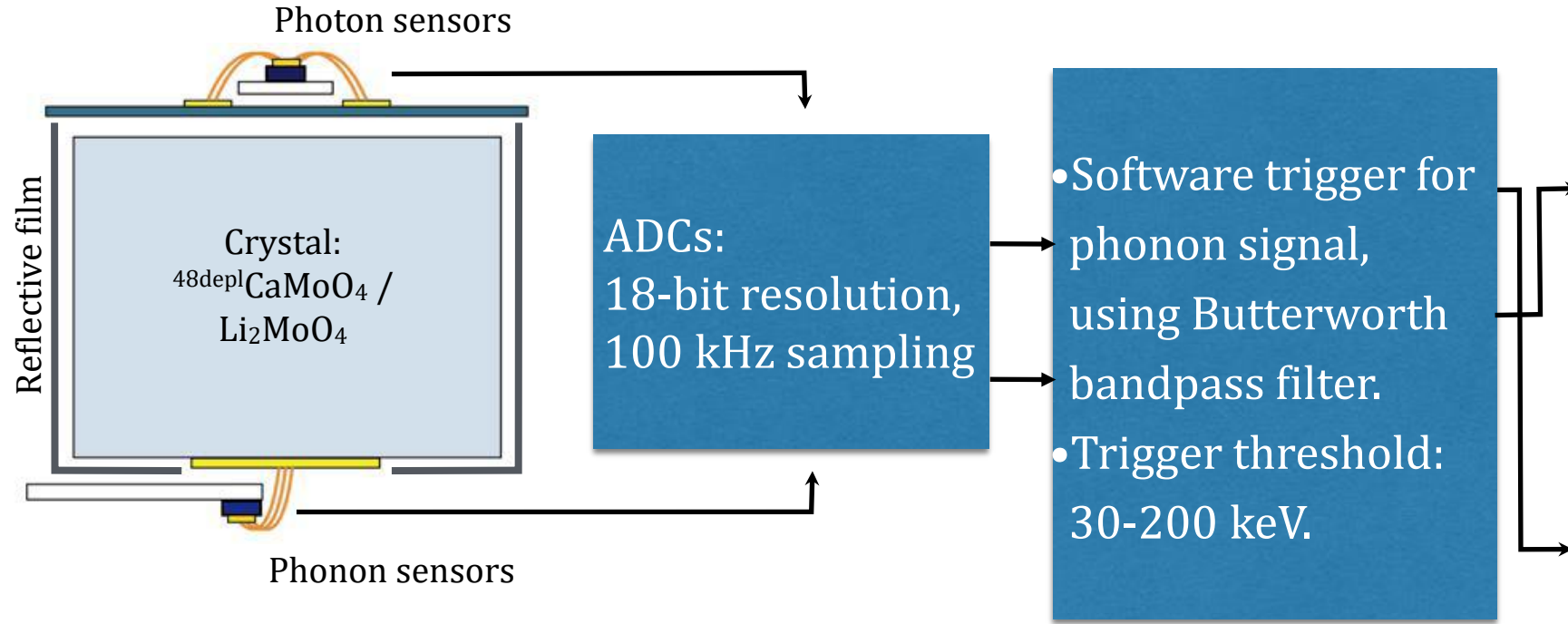
$\beta\beta$ -decay nuclei with $Q > 2$ MeV	Q (MeV)	Abund. (%)
$^{48}\text{Ca} \rightarrow ^{48}\text{Ti}$	4.271	0.187
$^{76}\text{Ge} \rightarrow ^{76}\text{Se}$	2.040	7.8
$^{82}\text{Se} \rightarrow ^{82}\text{Kr}$	2.995	9.2
$^{96}\text{Zr} \rightarrow ^{96}\text{Ru}$	3.350	2.8
$^{100}\text{Mo} \rightarrow ^{100}\text{Ru}$	3.034	9.7
$^{110}\text{Pd} \rightarrow ^{110}\text{Cd}$	2.013	11.8
$^{116}\text{Cd} \rightarrow ^{116}\text{Sn}$	2.802	7.5
$^{124}\text{Sn} \rightarrow ^{124}\text{Ge}$	2.228	5.8
$^{130}\text{Te} \rightarrow ^{130}\text{Xe}$	2.528	34.2
$^{136}\text{Xe} \rightarrow ^{136}\text{Ba}$	2.479	8.9
$^{150}\text{Nd} \rightarrow ^{150}\text{Sm}$	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, $Q_{\beta\beta}(^{48}\text{Ca}) = 4271$ 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

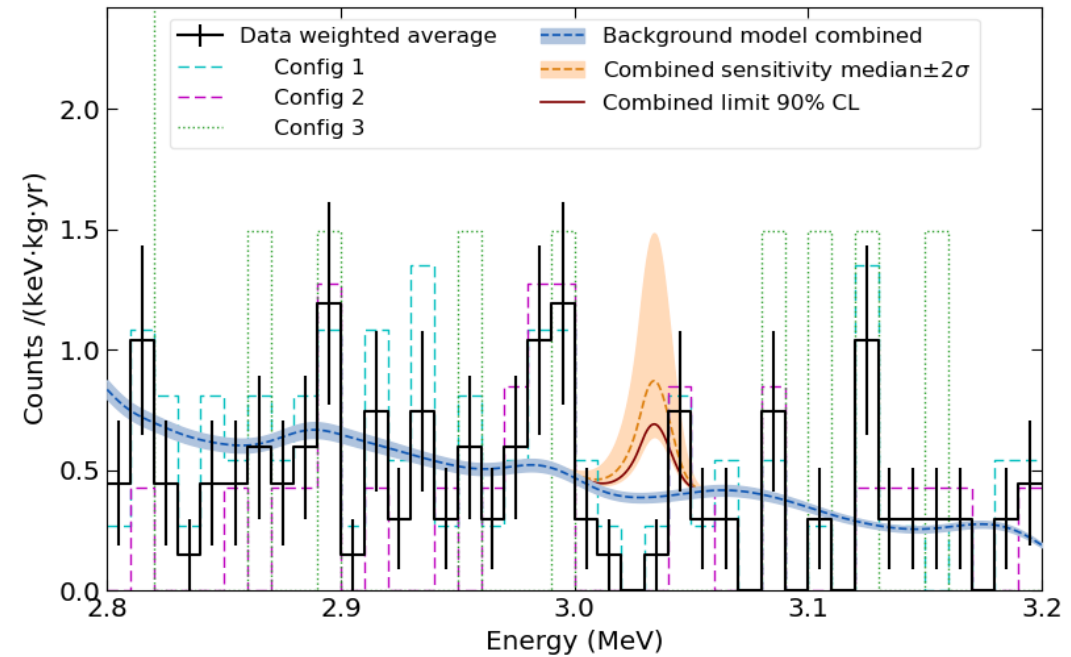
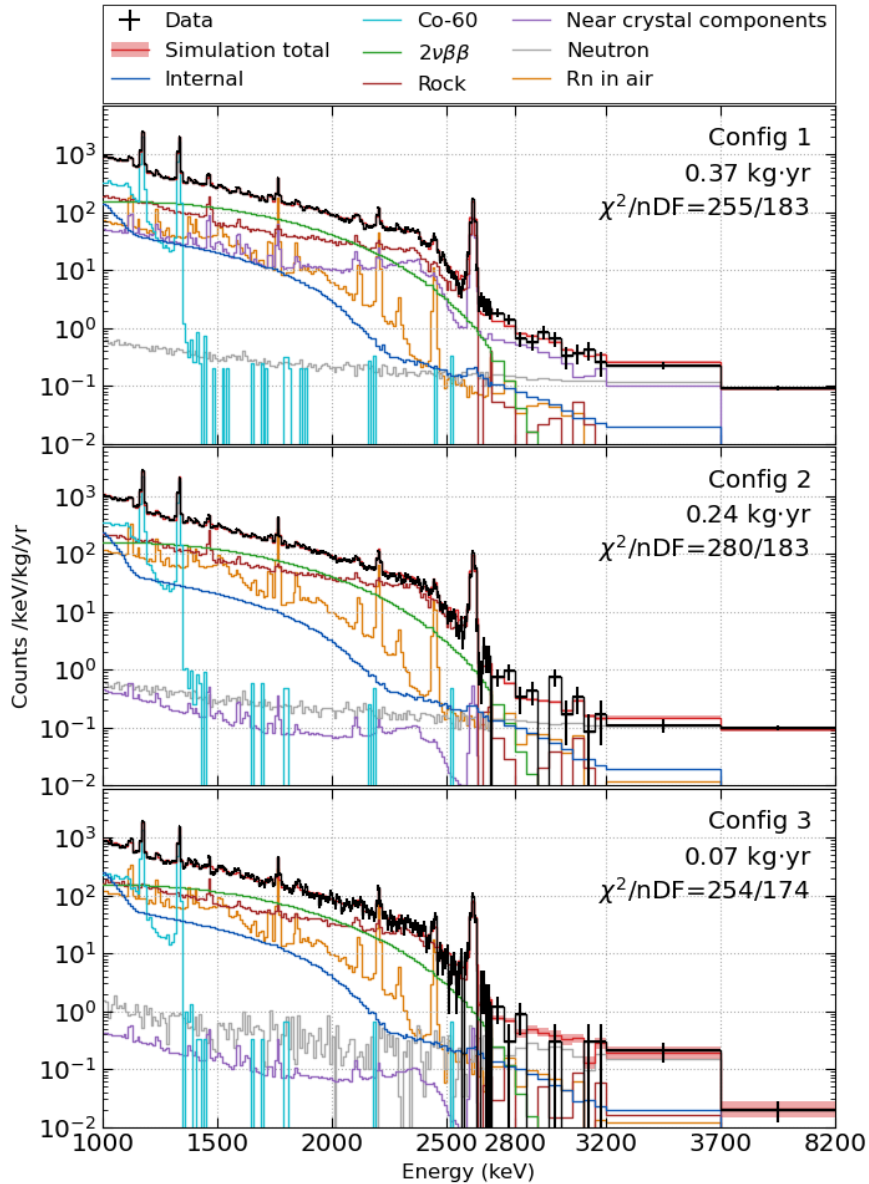


Signal Processing & Analysis



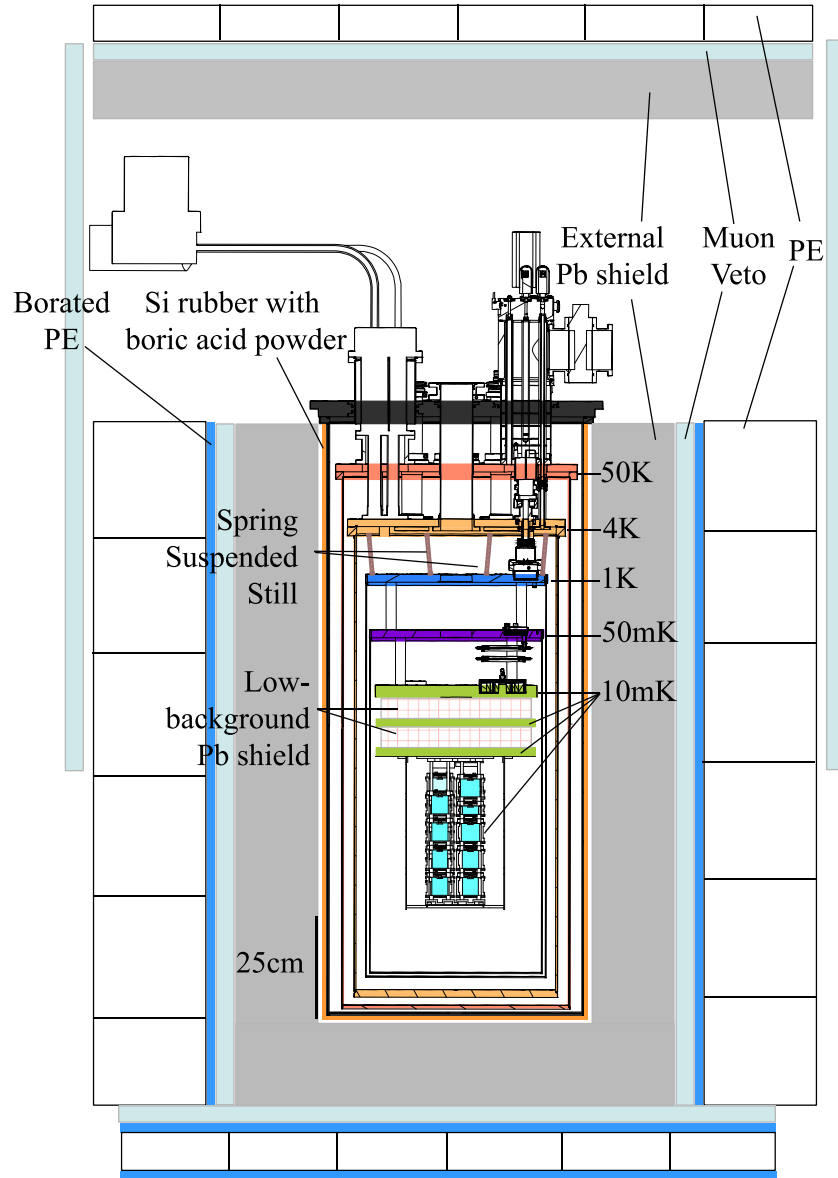
- Raw waveform:
 - baseline/noise informations.
 - timings (rise/fall): pulse shape discrimination (PSD).
- Reconstruction for improving energy resolution and β/α discrimination power (DP):
 - Butterworth bandpass filter— mainly for noise suppression:
 - pulse amplitude: pulse height or a least square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

AMoRE-pilot final result

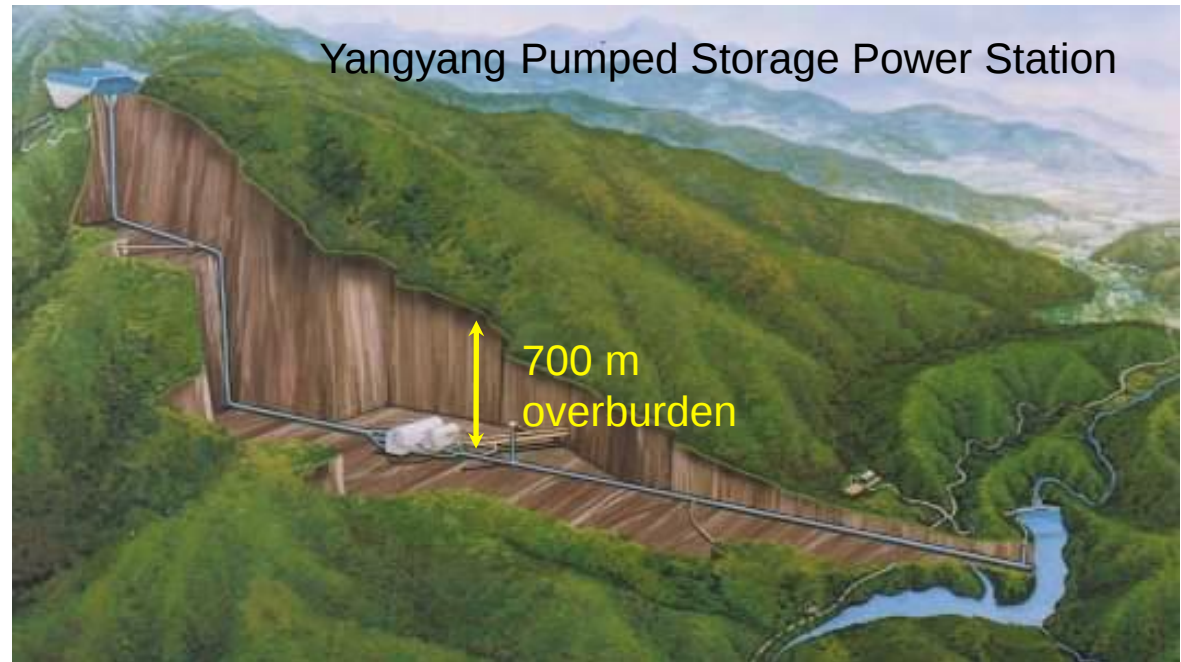


- Experiment between 2016-2018
- Understanding of the background components and reduction of them.
- Background level of ~ 0.5 counts/keV/kg/yr at 2.8-3.2 MeV.
- neutron-induced γ , crystals' internal contamination, rock/air-radon γ .
- Internal background— arXiv:2107.07704
- $T_{1/2}^{0\nu} > 3.2 \times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

Cryostat & Shielding

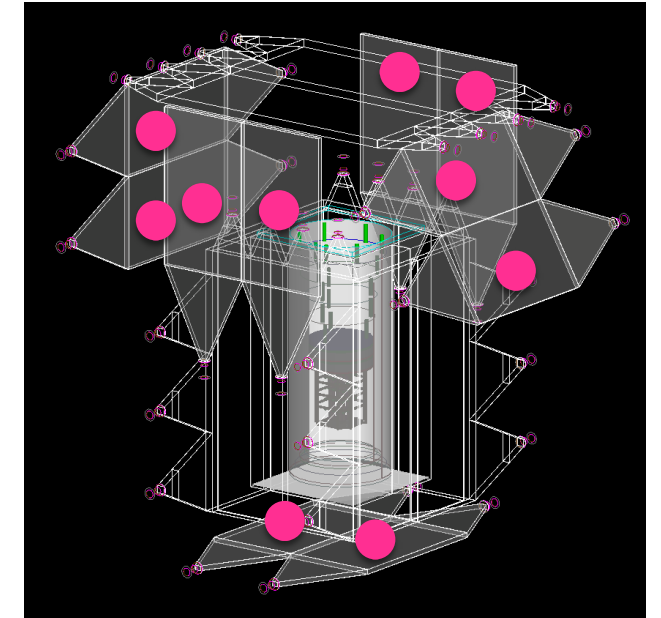
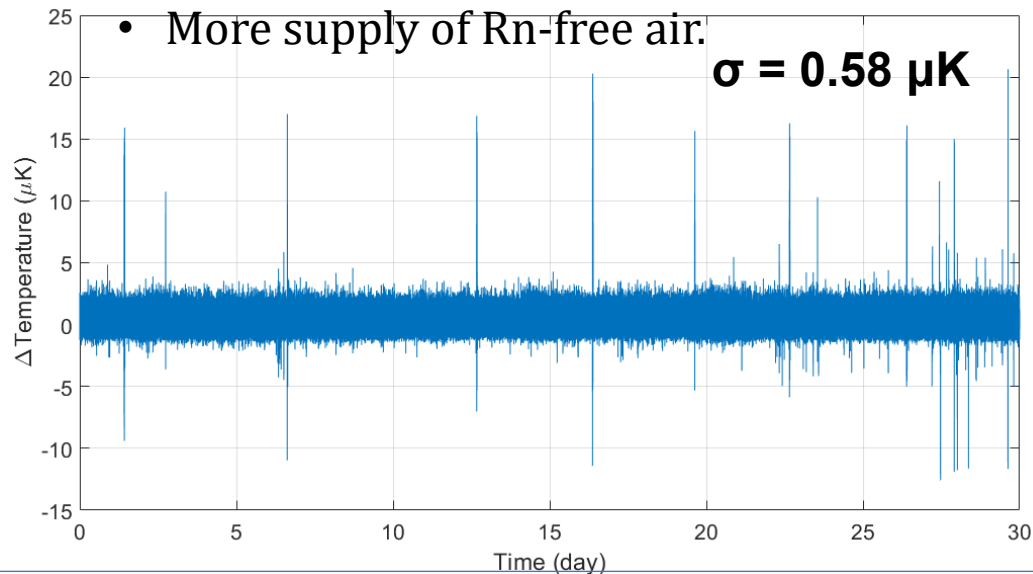


- Cryogen-free dilution refrigerator.
- For AMoRE-pilot and AMoRE-I.
- Now operating at 12 mK with $\sim 1 \mu\text{W}$ cooling power.
- Pb (γ), boron, and polyethylene (n).
- Plastic scintillator muon counter.
- Yangyang Underground Laboratory (Y2L) at 700 m depth.

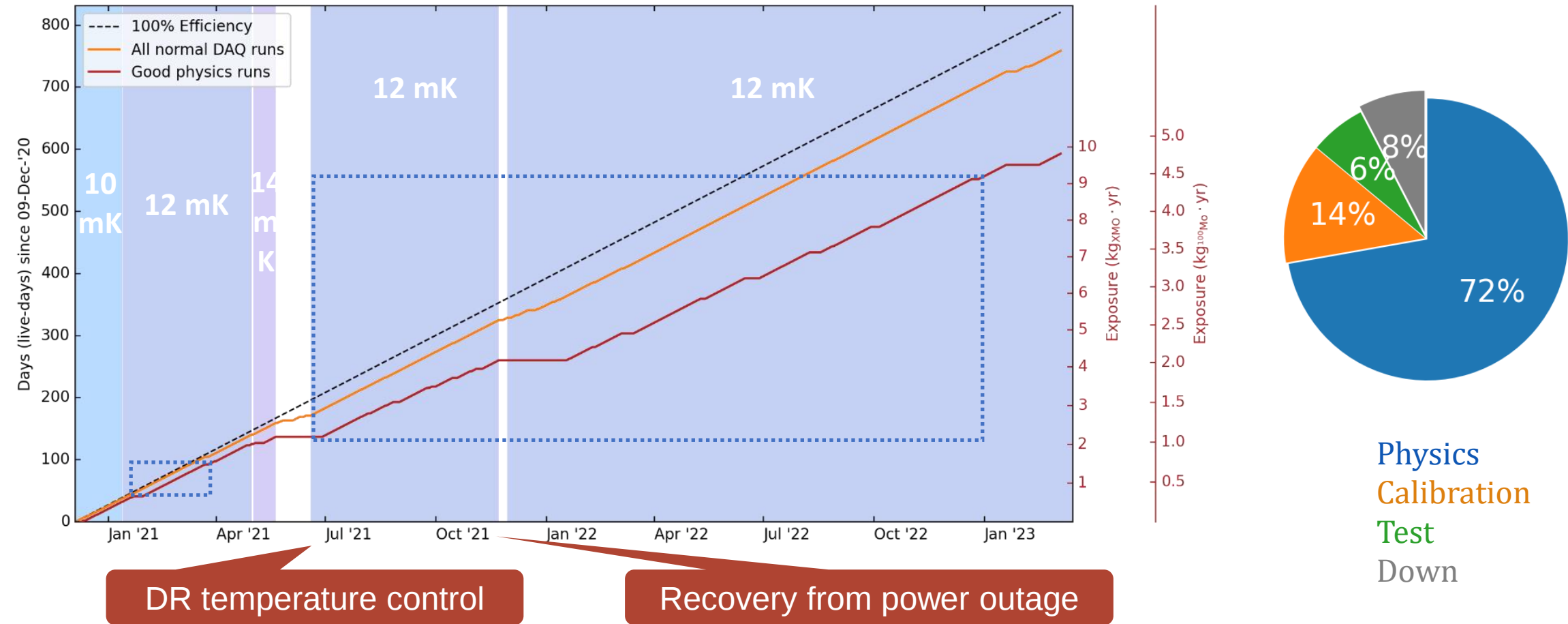


AMoRE-pilot → AMoRE-I

- 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. ($\sim 1/T^2$ heat capacity component associated with nuclear quadrupole moments removed)
- Using same cryostat + two stage temperature control: $\langle \Delta T \rangle < 1 \mu\text{K}$.
- Shielding enhancements:
 - Outer Pb: 15 → 20 cm; neutron shields: boric acid silicon + more PE / B-PE.
 - More muon counter coverage. ($\sim 4\pi$)

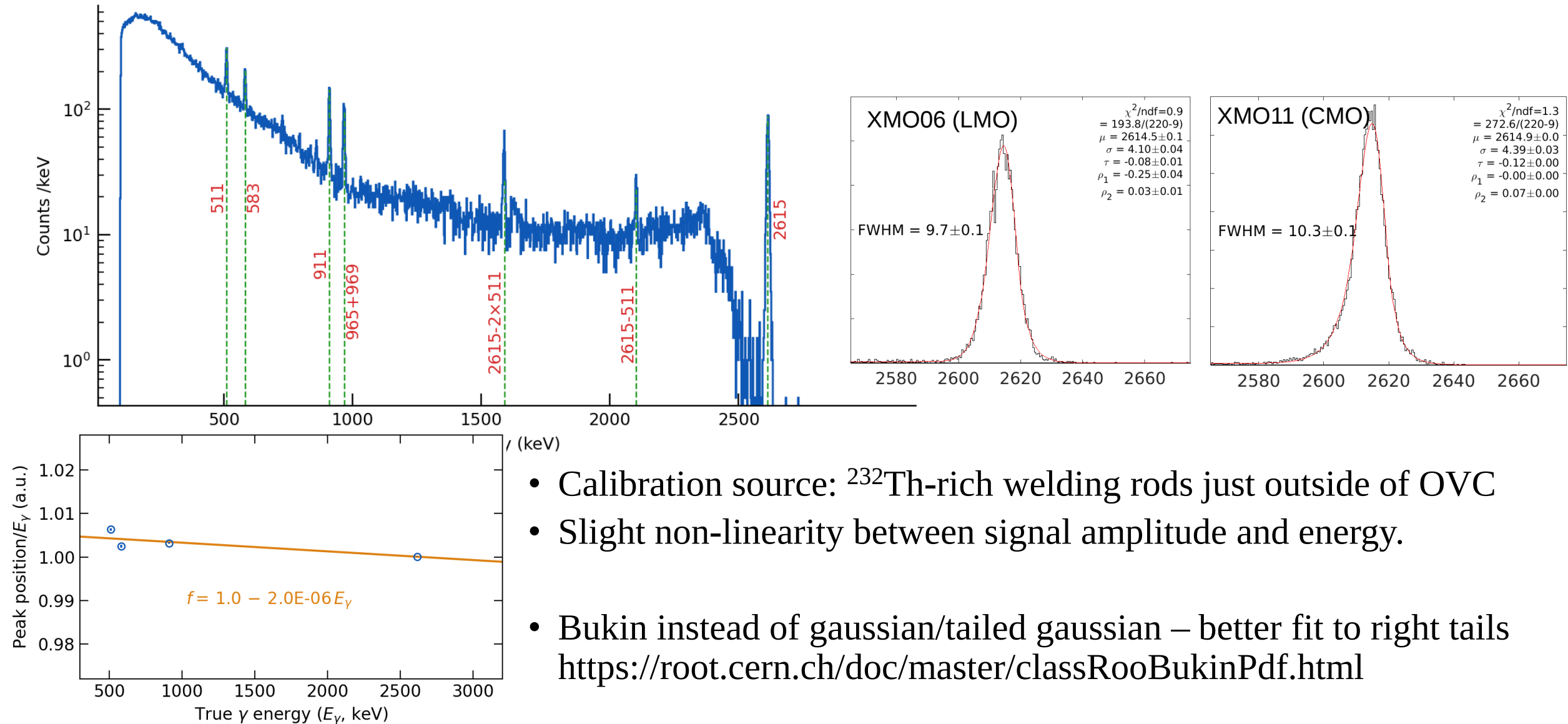


AMoRE-I data taking



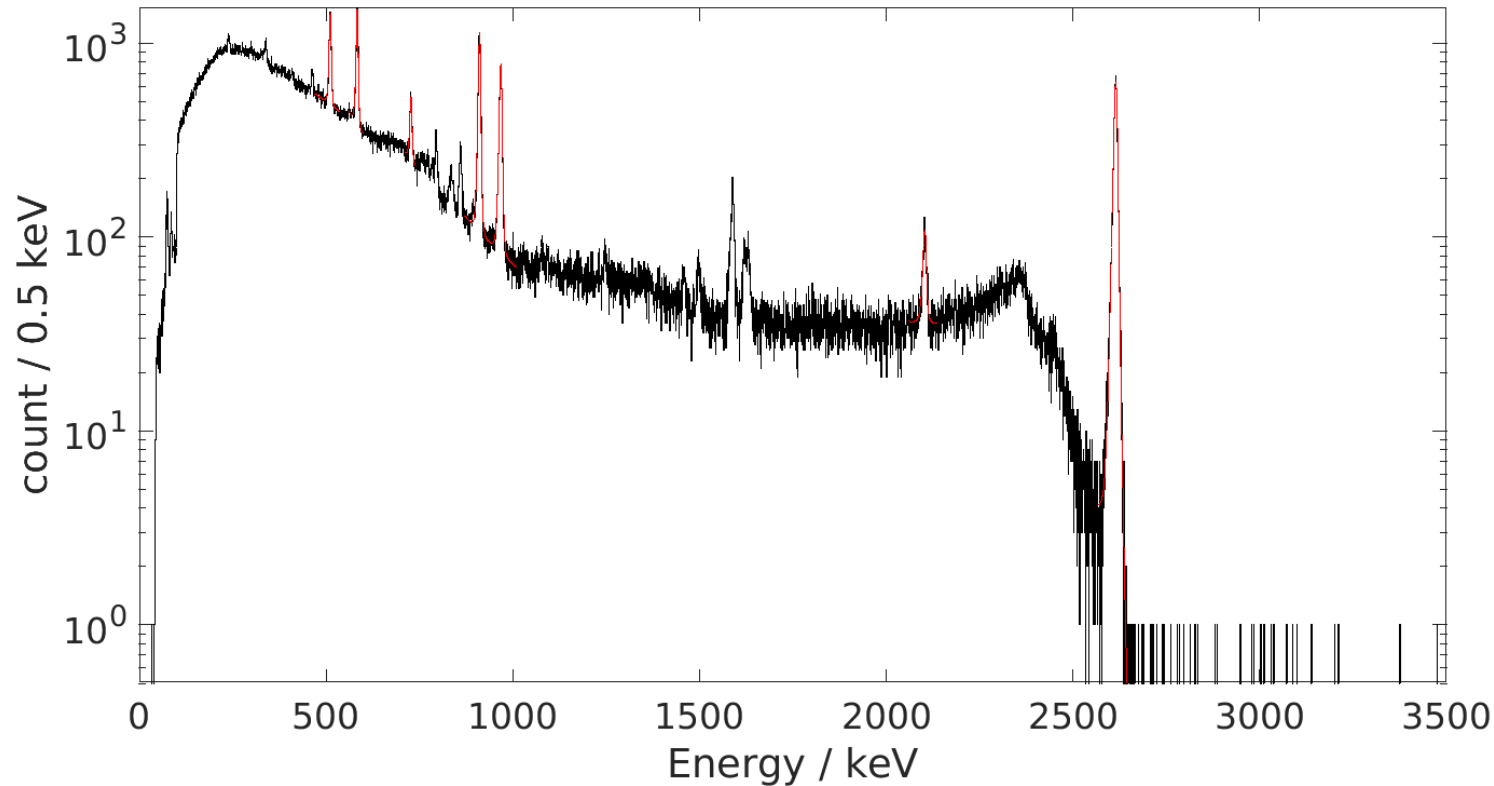
- Data taking is still ongoing
- 7.59 kg · year crystal (3.66 kg · year ^{100}Mo) exposure is presented here

Energy Calibration

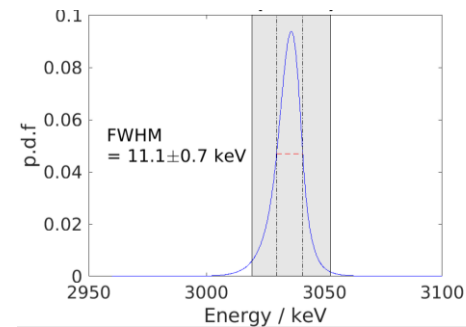


- Calibration source: ^{232}Th -rich welding rods just outside of OVC
- Slight non-linearity between signal amplitude and energy.
- Bukin instead of gaussian/tailed gaussian – better fit to right tails
<https://root.cern.ch/doc/master/classRooBukinPdf.html>

ROI estimation

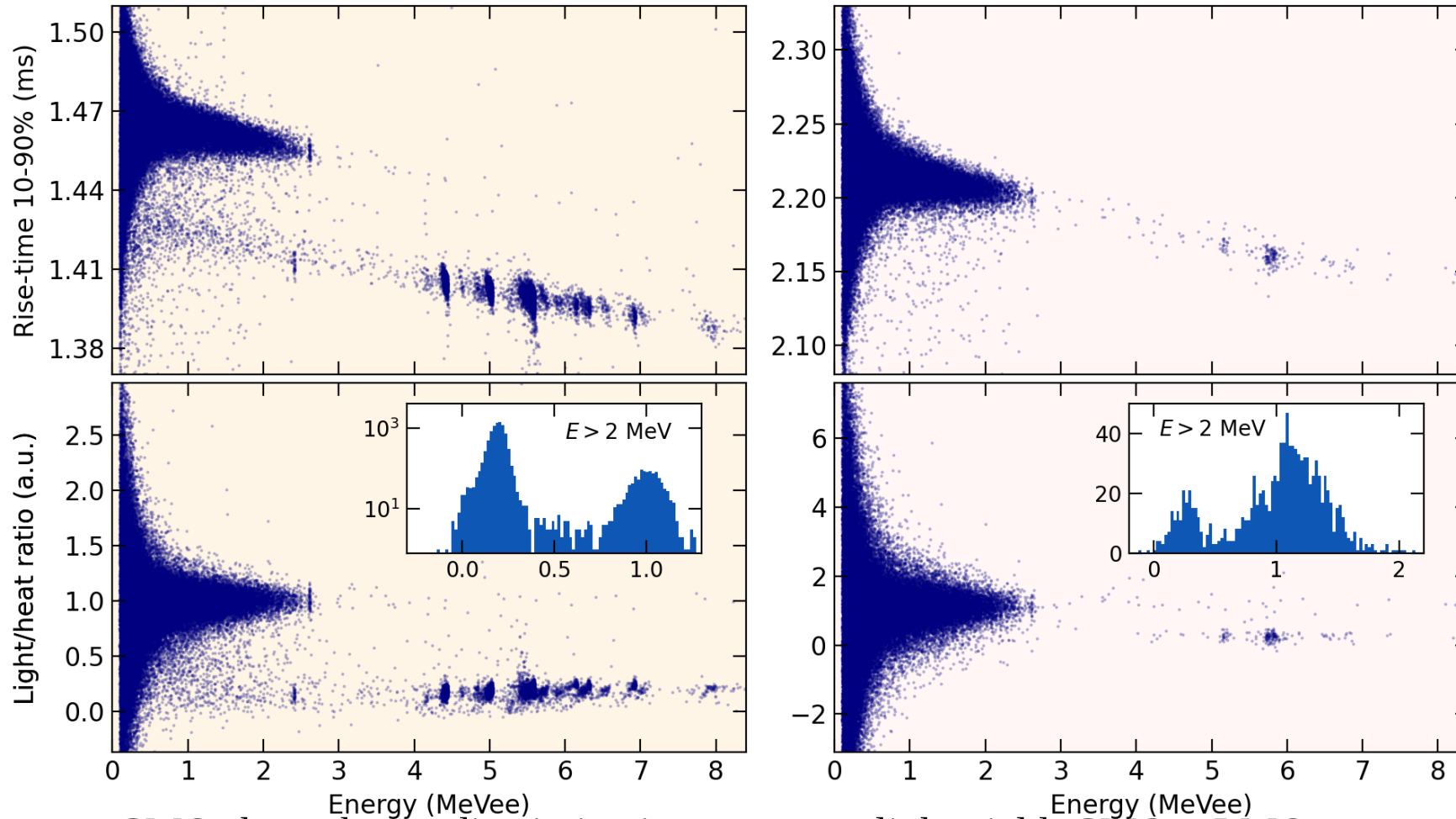


- $E_{\text{bias}} \sim 2^{\text{nd}}$ polynomial of energy
- $\sigma(E) = \sqrt{b_1 + b_2E + b_3E^2}$
- Other parameters of bukin (τ, ρ_1, ρ_2) are assumed to be the same



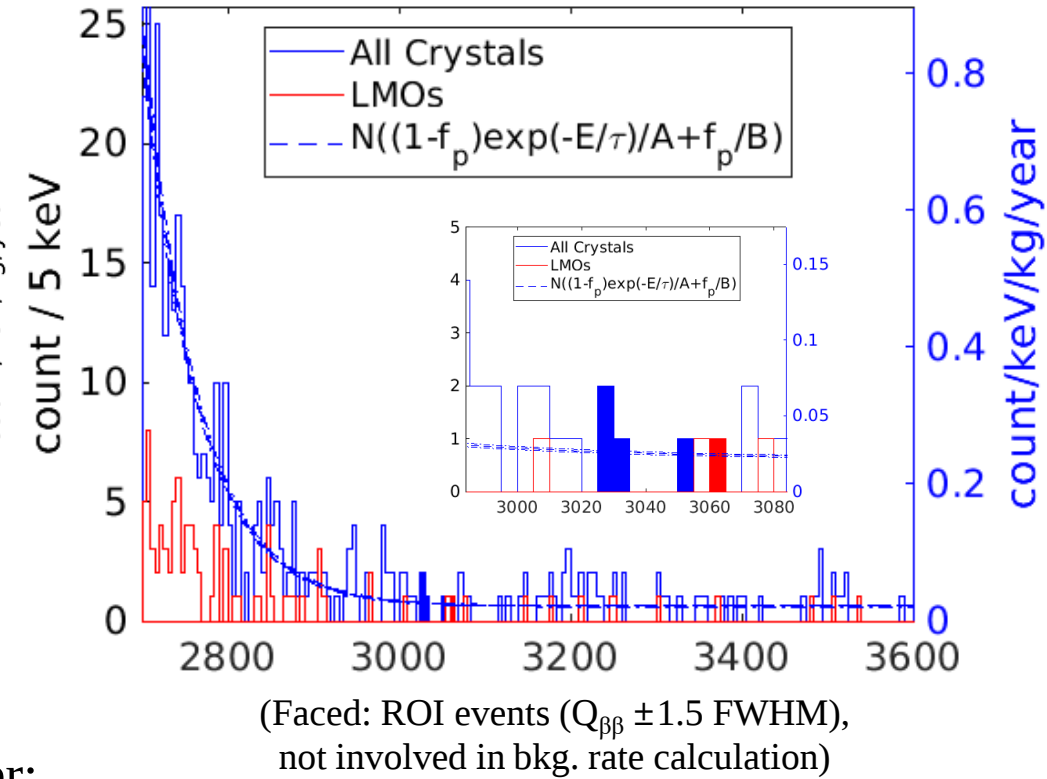
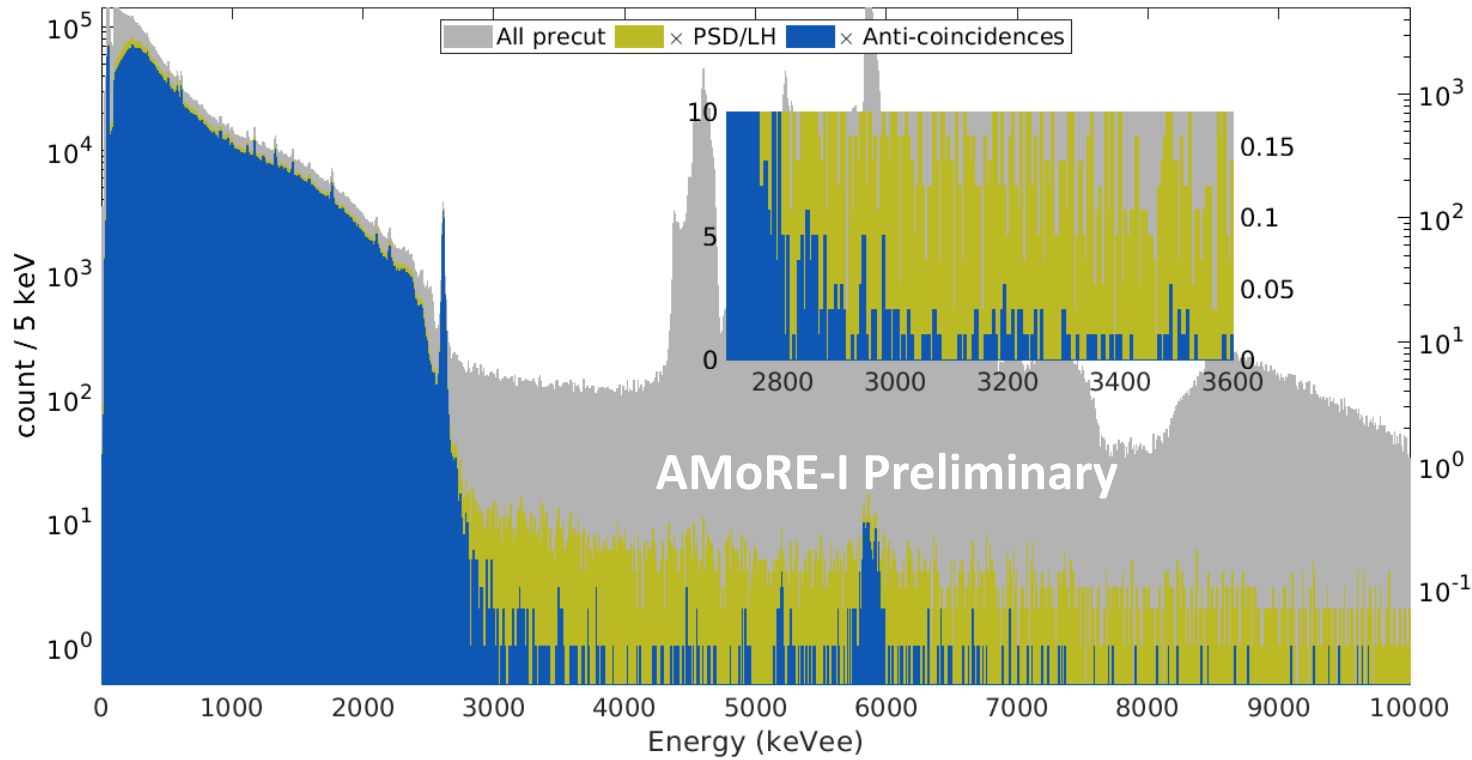
#	Name	FWHM@Q _{ββ} (keV)
1	SB29	13.7±1.0
2	SE01	11.9±0.8
3	SE02	16.5±0.9
4	SE08	12.2±0.8
5	LMO2	27.5±2.3
6	LMO4	10.2±0.8
7	LMO3	11.3±1.1
8	S35	15.7±0.7
9	SS68	14.4±0.6
10	LMOCUP	19.3±0.5
11	SE03	11.1±0.7
12	SE07	14.1±1.0
13	SE09	14.9±0.7
15	SB28	22.9±1.1
16	SE04	19.3±0.8
17	SE05	16.3±0.7
18	SE06	11.4±0.6

Particle Identifications, CMO and LMO



- CMO shows better discrimination power — light yield: CMO > LMO.
- LMO has much less α contamination.
- $\epsilon_{\text{PaID}} \sim 91.6 \%$ (± 3 median absolute deviations ($\sim \pm 2\sigma$) gives 95.70 % C.L.)

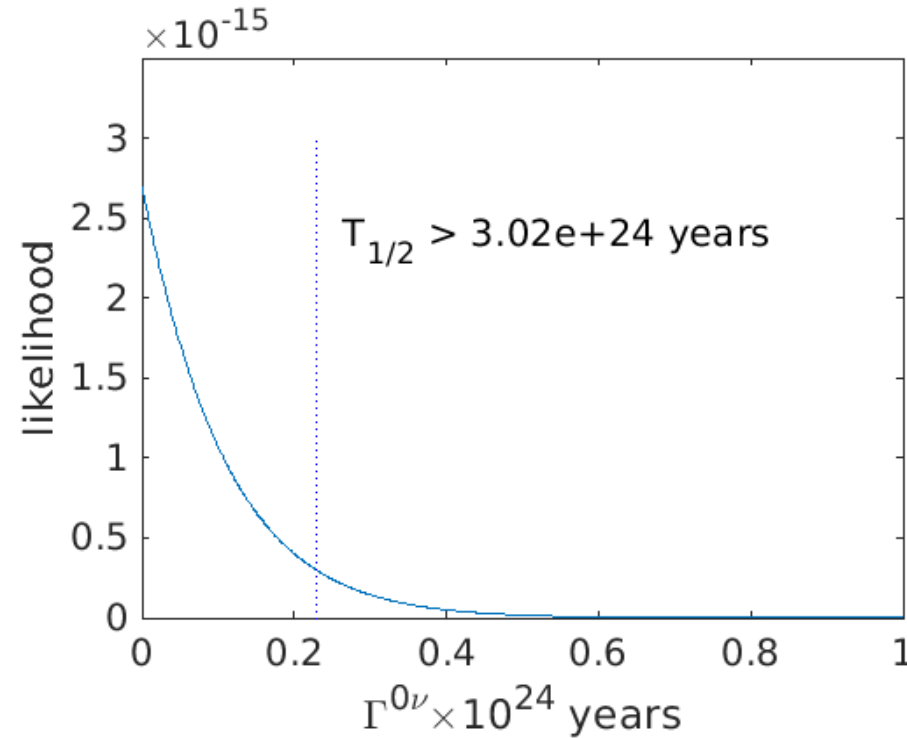
Background Spectrum



- All crystal excluding 1 LMO for very poor β/α discrimination power:
 - 13 CMO + 4 LMO: exposure = $7.59 \text{ kg}_{\text{XMO}} \cdot \text{yr} = 3.66 \text{ kg}_{\text{ISO}} \cdot \text{yr}$. (^{100}Mo live exposure: $2.96 \text{ kg} \cdot \text{yr}$)
- Anti-coincidence cuts reject events:
 - coincident at multiple crystals within 2 ms ($\varepsilon \sim 99.8\%$),
 - within 10 ms after a muon counter event ($\varepsilon \sim 99.8\%$),
 - within 20 minutes after a ^{212}Bi α -decay event candidate ($\varepsilon \sim 98\%$).

Live exposure	@ $Q_{\beta\beta}$
Total (6.12 kg y)	$0.024 \pm 0.001 \text{ ckky}$
CMO (4.70 kg y)	$0.025 \pm 0.001 \text{ ckky}$
LMO (1.43 kg y)	$0.020 \pm 0.002 \text{ ckky}$

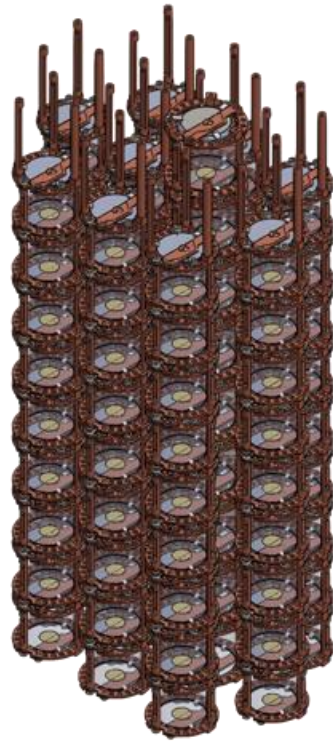
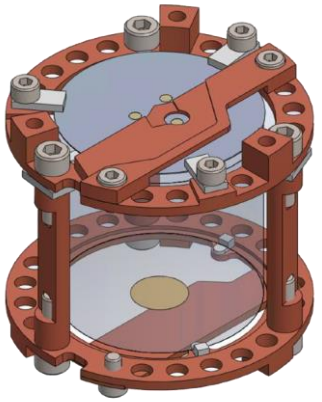
Preliminary ^{100}Mo $0\nu\beta\beta$ limit from AMoRE-I



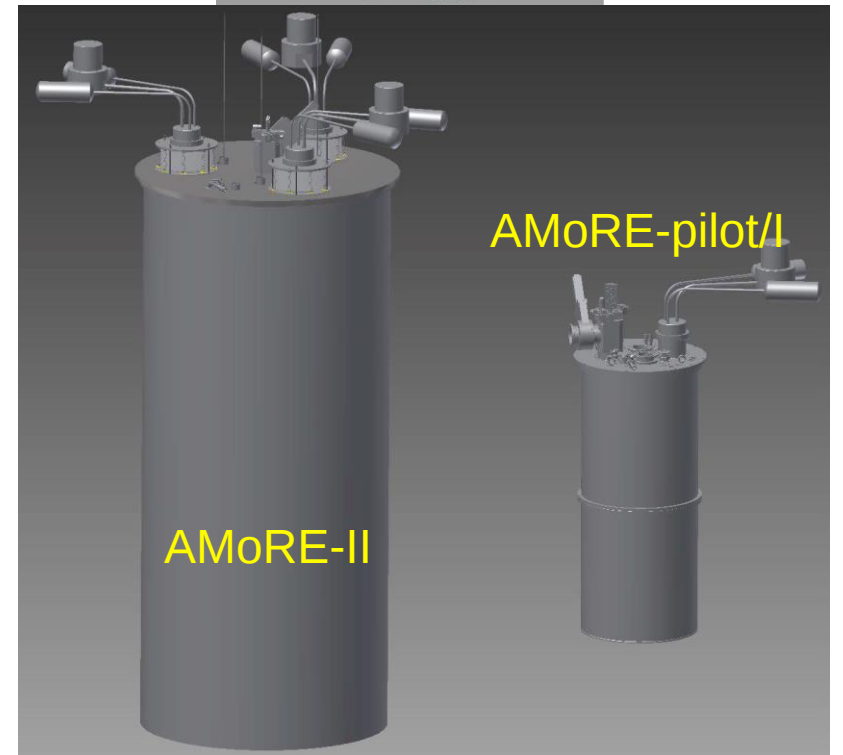
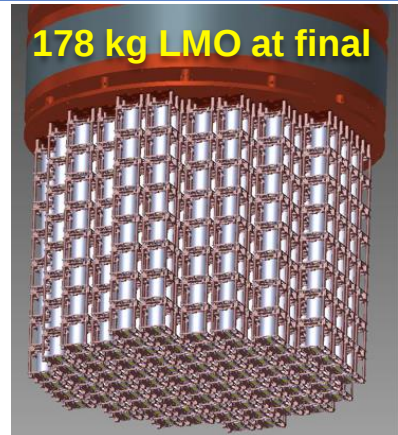
- ROI to contain most ($> 99\%$) of the $0\nu\beta\beta$ signal peak, $\varepsilon_{\text{containment}} \sim 81\%$.
- Background = 0.024 ± 0.001 counts/keV/kg/year, from ROI side-band.
- Combining the result of shape analysis at ROI, with a flat & exponential background constraint from the side-band events for each crystal.
- $T_{1/2}^{0\nu} > 3.02 \times 10^{24}$ years at 90% C.L. (Current best limit: 1.8×10^{24} of CUPID-Mo)

AMoRE-II in preparation

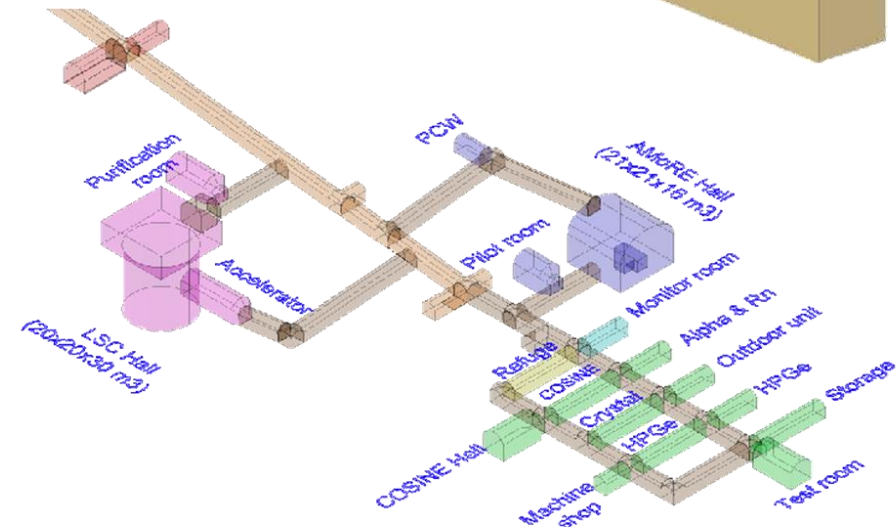
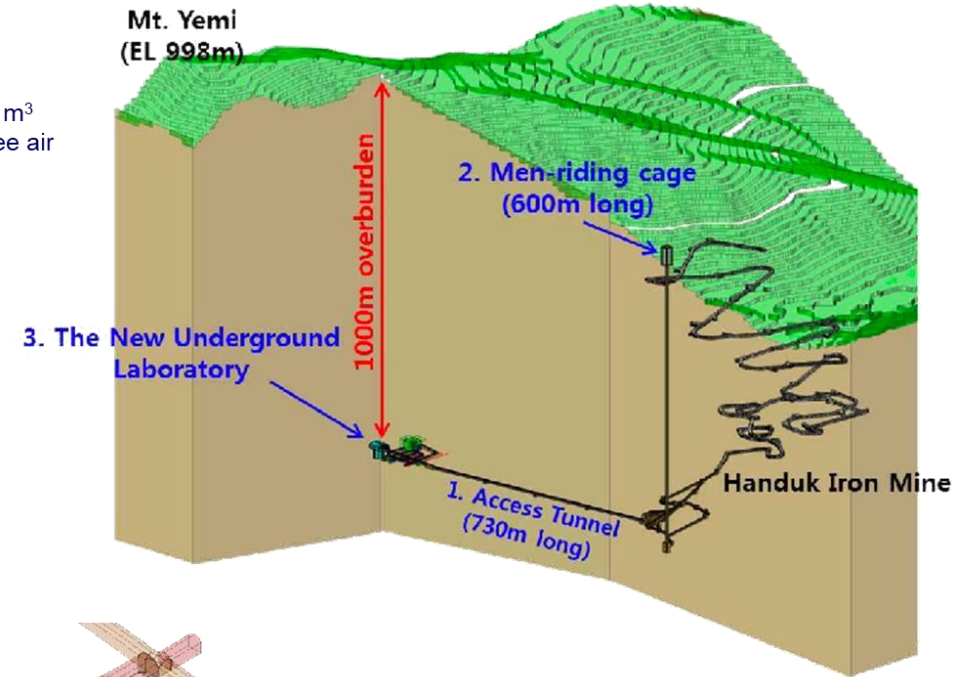
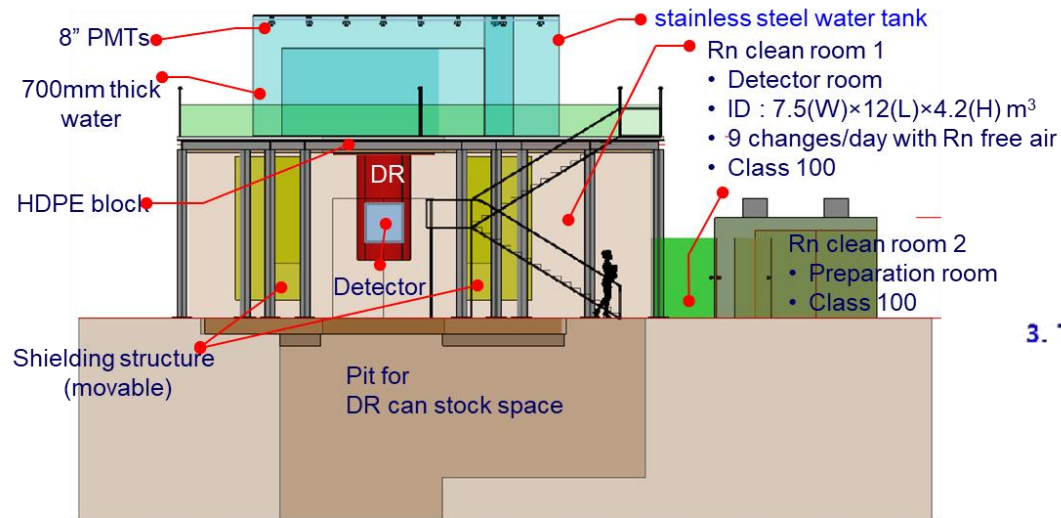
AMoRE-II Detector module

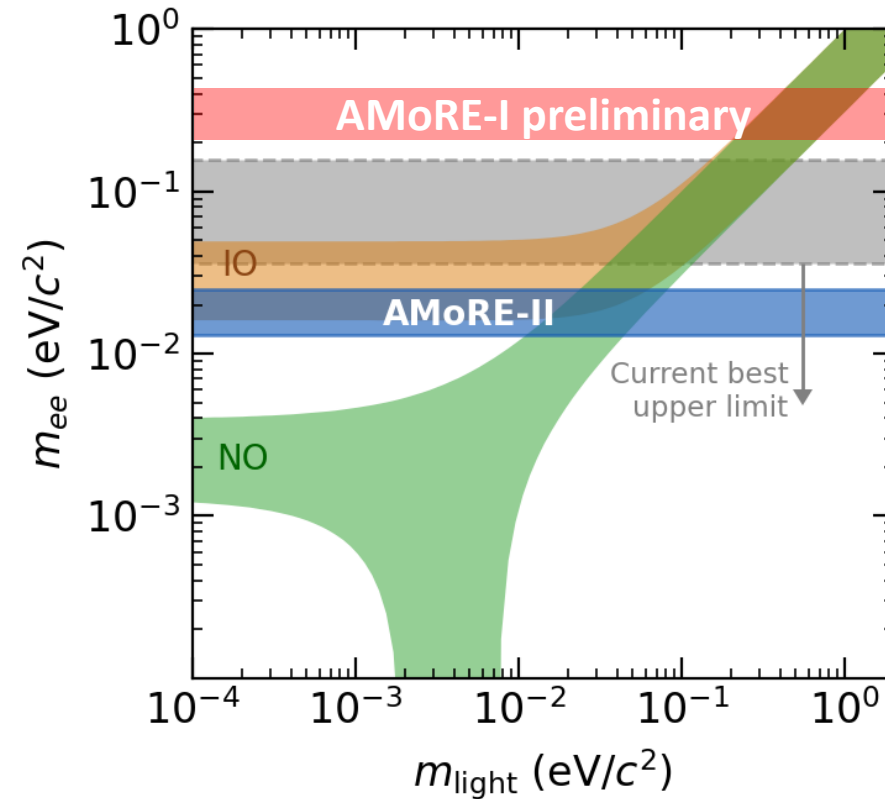
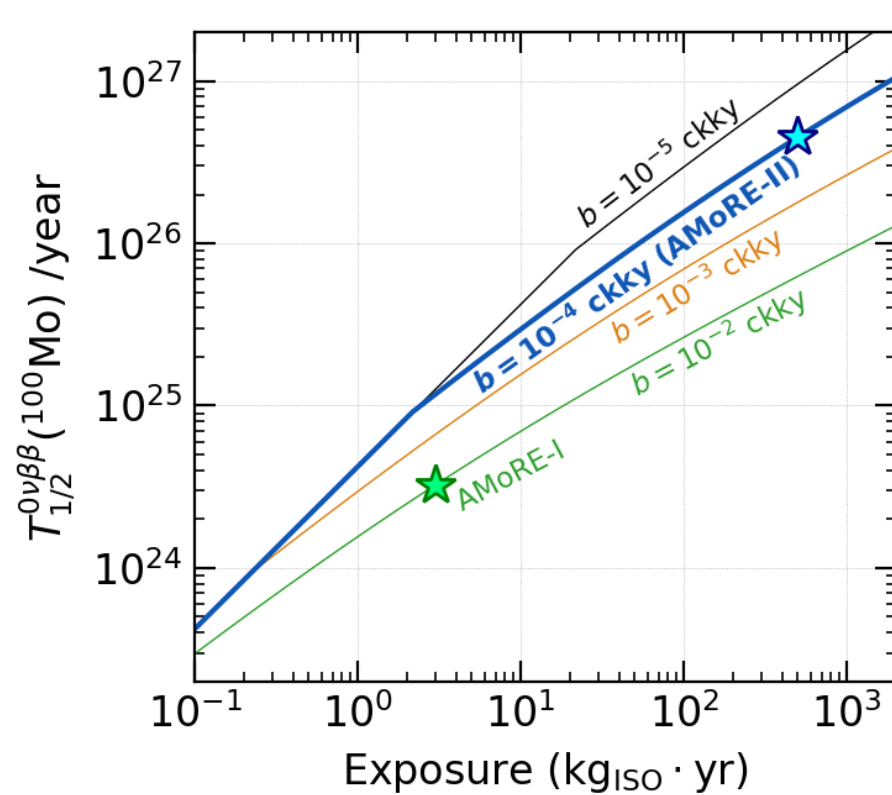


90 modules (~27 kg LMO)
for the first stage



AMoRE-II in YemiLab





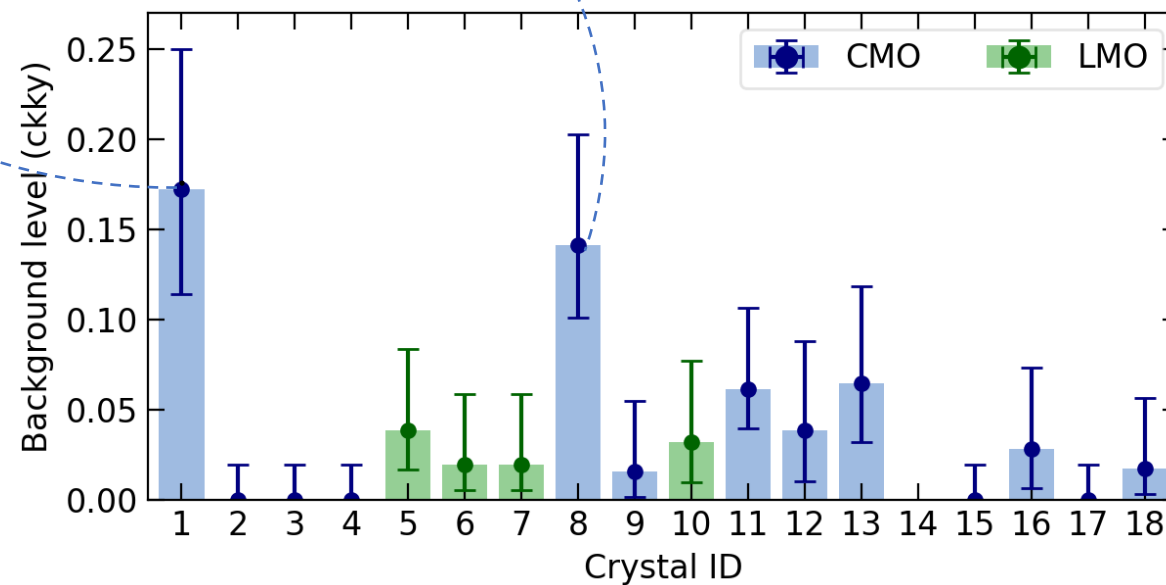
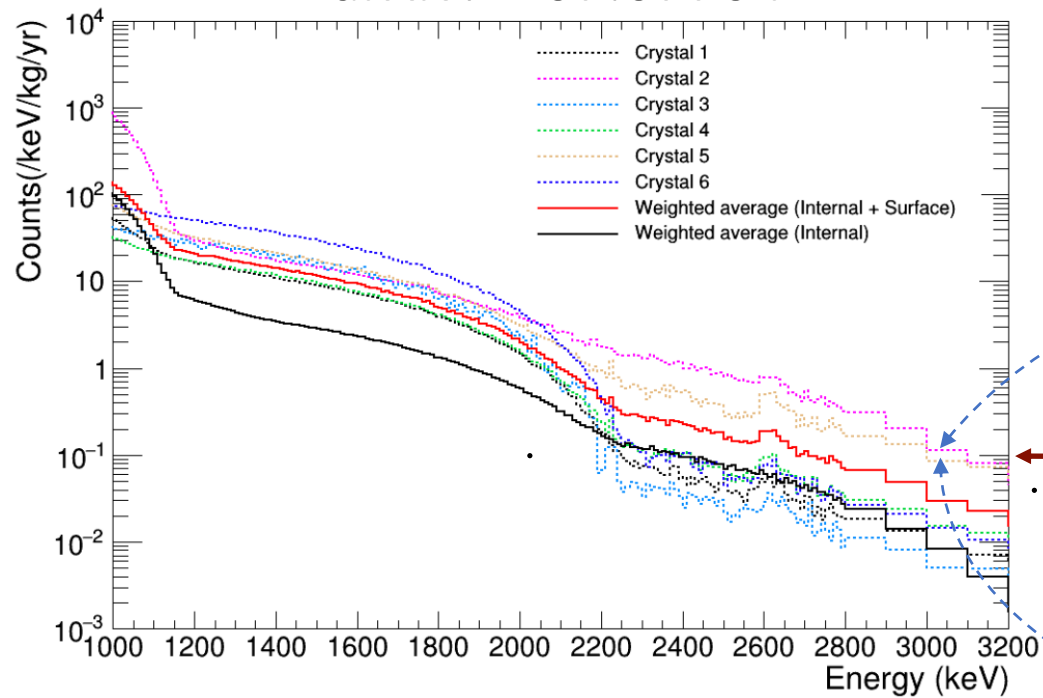
- Final results of AMoRE-I with more data and further improved analysis.
- AMoRE-II for $T_{1/2}^{0\nu} > 5 \times 10^{26}$ years by 100 kg of $^{100}\text{Mo} \times 5$ years running.
- Reduction of background level down below 10^{-4} ckky.

- 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: 7.59 (3.66) kg · yr XMO (^{100}Mo).
 - Background level ~ 0.024 counts/keV/kg/year at $Q_{\beta\beta}$.
 - Resolution: 10.2 – 27.5 keV around $Q_{\beta\beta}$
 - Preliminary limit: $T_{1/2}^{0\nu} > 3.02 \times 10^{24}$ years
 - 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.

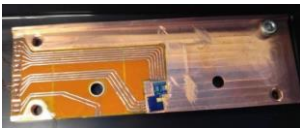
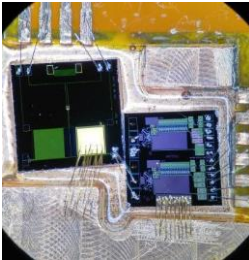
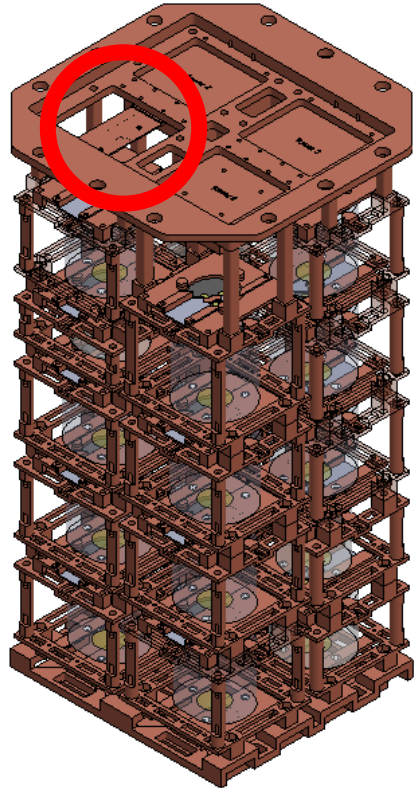
Thank you!

backup

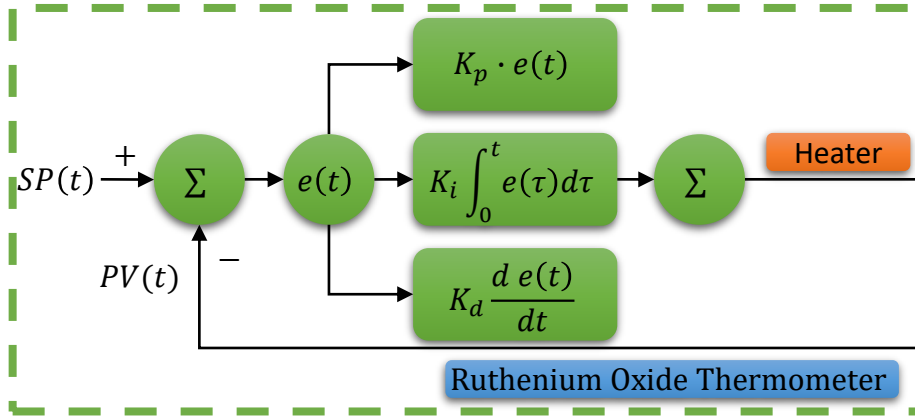
arXiv:2107.07704



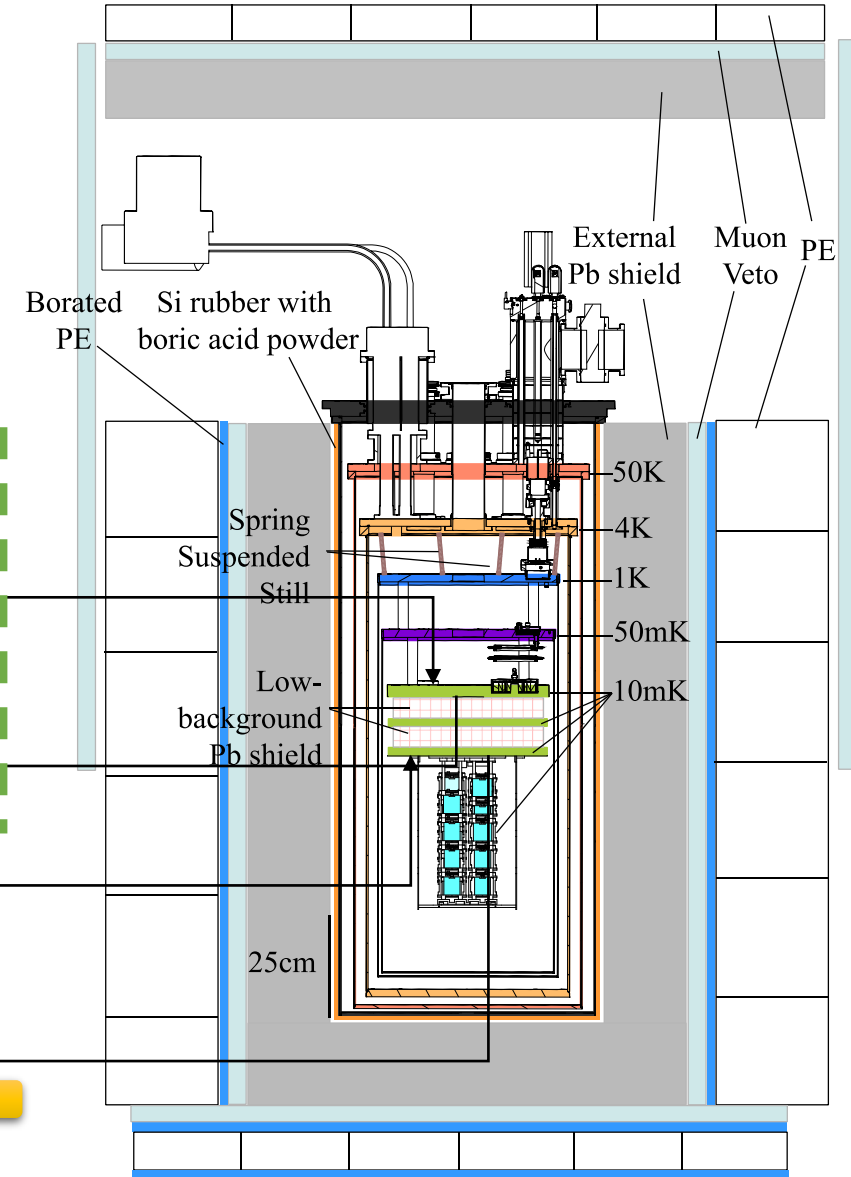
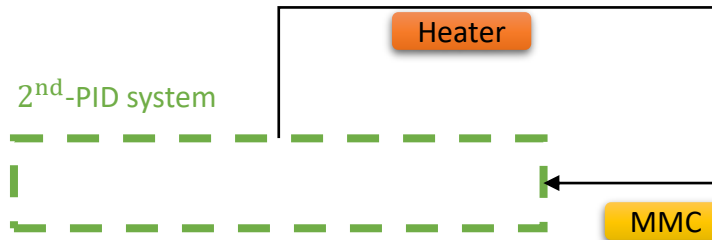
Two stage temperature control



1st-PID system



2nd-PID system

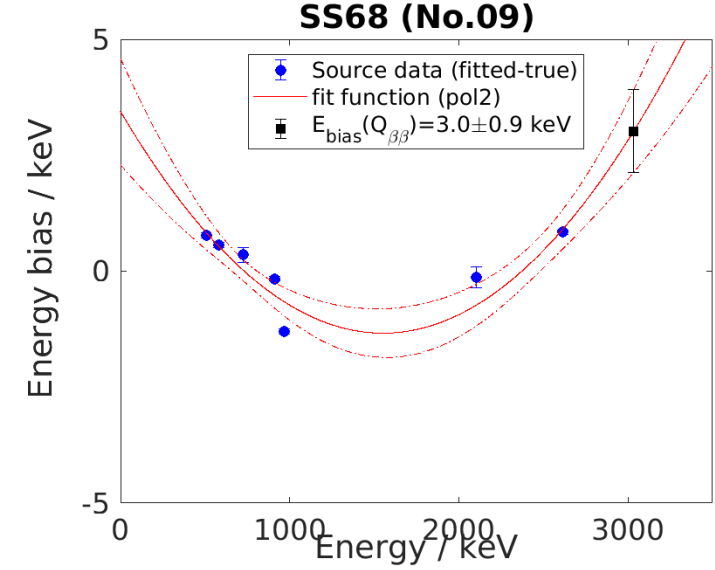
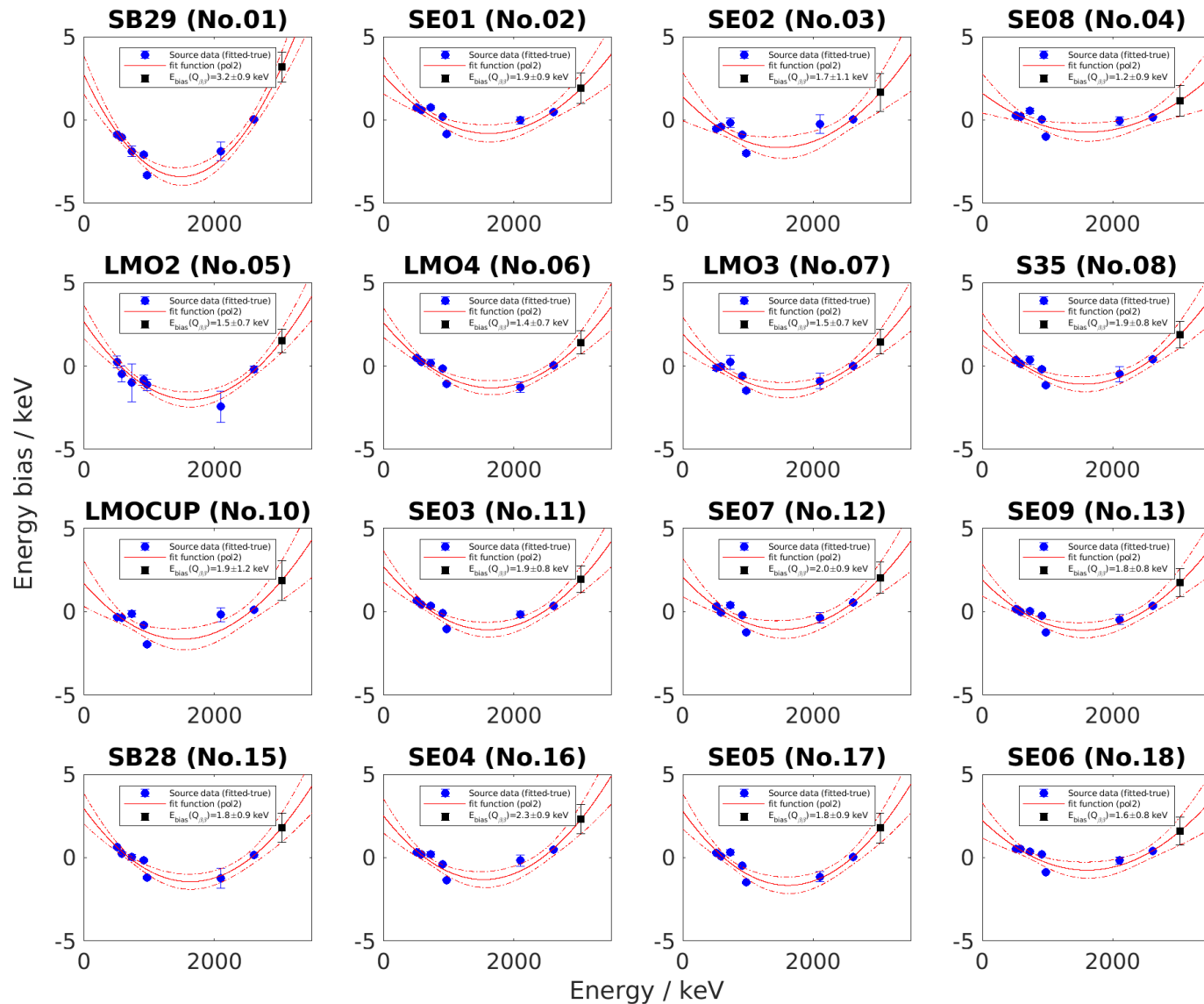


Live time

#	1	2	3	4	5	6	7	8
Name	SB29	SE01	SE02	SE08	LMO2	LMO4	LMO3	S35
Total Time	21205887	40364490	14650585	40364490	40364490	40364490	40364490	40364490
DFT loss time	0	5977	1211.8	5977	5977	5977	5977	5977
Alpha rejection time	4949195.5	1609920.8	410809.7	307480.9	109200	81600	102000	1497216.8
Muon veto time	20885.8	95455.6	36939.6	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
Trigger dead time	386708.8	369980.3	127836.7	380845.7	1612835.4	358898.7	361941.2	898951.4
PaID efficiency (%)	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
Efficiency (%)	69.61	86.96	88.17	89.86	87.58	90.48	90.42	86.12

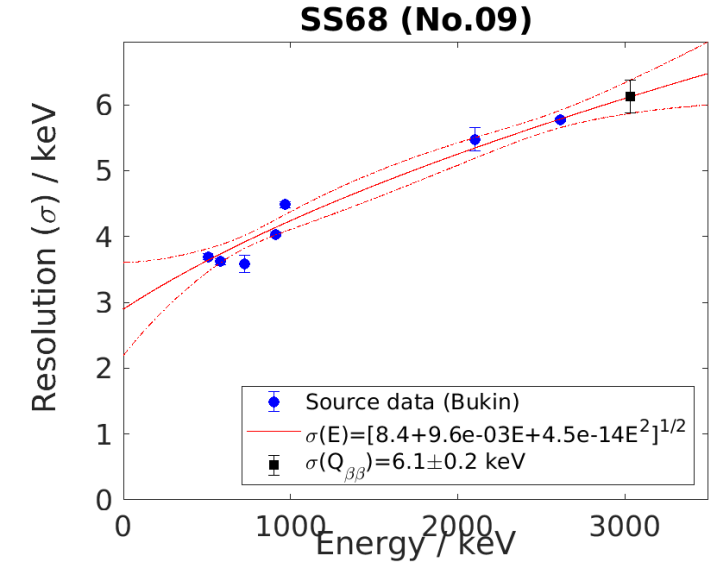
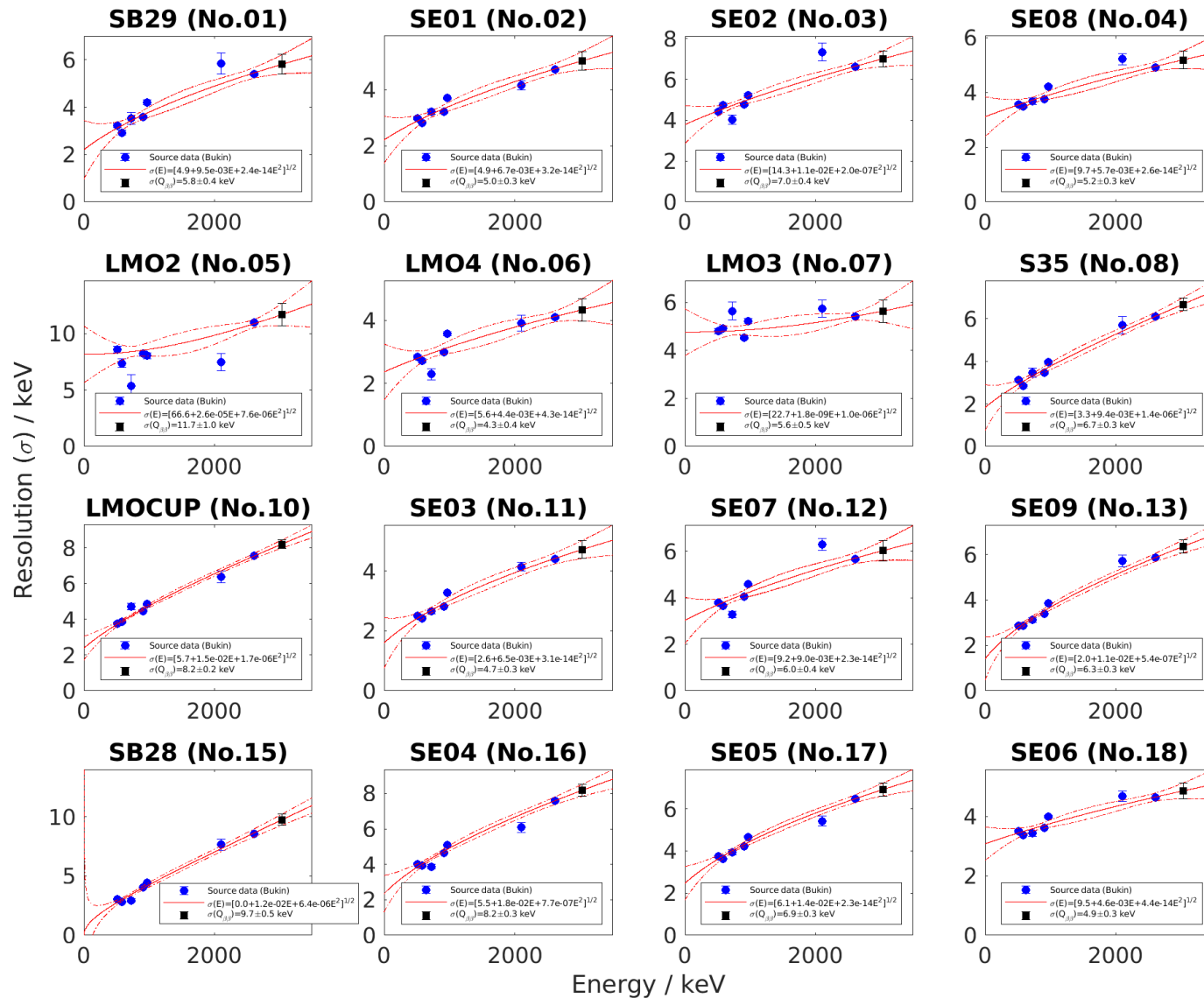
10	11	12	13	15	16	17	18
LMOCUP	SE03	SE07	SE09	SB28	SE04	SE05	SE06
33714497	40364490	40364490	40364490	40364490	40364490	40364490	40364490
5977	5977	5977	5977	5977	5977	5977	5977
96000	590485	356390.1	183578	2851350.5	335013.6	237714.6	269451.3
83384.7	95455.6	95455.6	95455.6	95455.6	95455.6	95455.6	95455.6
53022.5	63066.3	63098.5	63115	63086.5	62748.5	63081.2	63093.7
329982.6	454299.9	375145	378863.2	357261.5	392521.9	400338.4	379229.3
91.6	91.6	91.6	91.6	91.6	91.6	91.6	91.6
30377546	35950682	36234260	36391495	33985035	36237042	36324056	36314086
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:

$$\sigma(E) = \sqrt{b_1 + b_2E + b_3E^2}$$

ROI estimation

#	Name	$E_{bias}(Q_{\beta\beta})$ (keV)	$\sigma(Q_{\beta\beta})$ (keV)	$\tau \times 100$	$\rho_1 \times 100$	$\rho_2 \times 100$	FWHM (keV)
1	SB29	3.2 ± 0.9	5.8 ± 0.4	7.0 ± 0.7	-0.0 ± 1.9	5.9 ± 0.9	13.7 ± 1.0
2	SE01	1.9 ± 0.9	5.0 ± 0.3	-15.3 ± 0.4	-0.0 ± 0.2	8.1 ± 0.4	11.9 ± 0.8
3	SE02	1.7 ± 1.1	7.0 ± 0.4	9.4 ± 0.6	-0.0 ± 1.4	2.4 ± 1.0	16.5 ± 0.9
4	SE08	1.2 ± 0.9	5.2 ± 0.3	-7.2 ± 0.4	-0.0 ± 0.2	8.4 ± 0.3	12.2 ± 0.8
5	LMO2	1.5 ± 0.7	11.7 ± 1.0	1.8 ± 0.7	-12.7 ± 4.8	5.9 ± 0.9	27.5 ± 2.3
6	LMO4	1.4 ± 0.7	4.3 ± 0.4	-7.7 ± 0.7	-25.5 ± 4.2	3.3 ± 1.4	10.2 ± 0.8
7	LMO3	1.5 ± 0.7	5.6 ± 0.5	1.8 ± 0.6	-0.0 ± 1.7	3.2 ± 1.0	11.3 ± 1.1
8	S35	1.9 ± 0.8	6.7 ± 0.3	0.2 ± 0.6	-0.1 ± 0.6	7.6 ± 0.6	15.7 ± 0.7
9	SS68	3.0 ± 0.9	6.1 ± 0.2	-12.4 ± 0.3	-0.0 ± 0.6	0.0 ± 0.2	14.4 ± 0.6
10	LMOCUP	1.9 ± 1.2	8.2 ± 0.2	14.5 ± 0.5	-0.0 ± 1.1	0.0 ± 0.3	19.3 ± 0.5
11	SE03	1.9 ± 0.8	4.7 ± 0.3	-12.0 ± 0.4	-0.0 ± 0.1	7.4 ± 0.4	11.1 ± 0.7
12	SE07	2.0 ± 0.9	6.0 ± 0.4	-0.7 ± 0.4	-0.0 ± 0.4	8.2 ± 0.3	14.1 ± 1.0
13	SE09	1.8 ± 0.8	6.3 ± 0.3	-4.3 ± 0.4	-0.0 ± 0.1	9.7 ± 0.3	14.9 ± 0.7
15	SB28	1.8 ± 0.9	9.7 ± 0.5	-16.1 ± 0.5	-7.7 ± 1.7	8.2 ± 1.0	22.9 ± 1.1
16	SE04	2.3 ± 0.9	8.2 ± 0.3	-1.0 ± 0.4	-0.0 ± 0.3	11.4 ± 0.5	19.3 ± 0.8
17	SE05	1.8 ± 0.9	6.9 ± 0.3	-5.0 ± 0.4	-0.0 ± 0.2	10.3 ± 0.4	16.3 ± 0.7
18	SE06	1.6 ± 0.8	4.9 ± 0.3	-7.6 ± 0.4	-0.0 ± 0.4	0.0 ± 0.4	11.4 ± 0.6

Likelihood calculation

P model construction

Likelihood function can be calculated with Bayes Theorem

$$P(\text{model}|\text{data}) = \frac{P(\text{data}|\text{model}) * \pi(\text{model})}{\int P(\text{data}|\text{model}') * \pi(\text{model}') d \text{model}'}$$

Hence, the total extended model at the ROI is given as the following;

$$P(\text{data}|\text{model}) = h_1(x; \mu, \sigma, \alpha, s, b) = \frac{(s+b)^n}{n!} * \exp(-(s+b)) * \prod_i \left(\frac{s}{s+b} f(x_i; \mu, \sigma, \alpha) + \frac{b}{s+b} g(x_i) \right)$$

where s = signal strength, b = background strength, which are 'expected number of events', and n is the total number of events in the ROI.

Marginalization

We have a prior knowledge on n_b, from counting events outside the ROI.

For m = number of events outside the ROI, assuming $P(m|b) \sim \text{Poisson}(\tau b)$, (τ = scale factor)

$$\pi(b) = \pi(b|m) \propto P(m|b) * \pi(b) \propto \frac{(\tau b)^m}{m!} * \exp(-\tau b) * \pi_0(b)$$

Here, $\tau = \text{BackgroundWindow} / \text{ROIWindow}$.

Assuming flat prior for b, we get

$$\pi(b|m) \propto \frac{(\tau b)^m}{m!} * \exp(-\tau b)$$

Hence, b follows gamma distribution,

$$\pi(b|m) = f(b; m+1, \tau) = \tau * \frac{(\tau b)^m}{\Gamma(m+1)} * \exp(-\tau b)$$

where tau and m are known.

We marginalize out b,

$$\begin{aligned} h_2(x; \mu, \sigma, \alpha, s, m) &= \int h_1(x; \mu, \sigma, \alpha, s, b) * \pi(b|m) db \\ &= \int \frac{(s+b)^n}{n!} * \exp(-(s+b)) * \prod_i \left(\frac{s}{s+b} f(x_i; \mu, \sigma, \alpha) + \frac{b}{s+b} g(x_i) \right) * \tau * \frac{(\tau b)^m}{\Gamma(m+1)} * \exp(-\tau b) db \end{aligned}$$

Since m is a known constant,

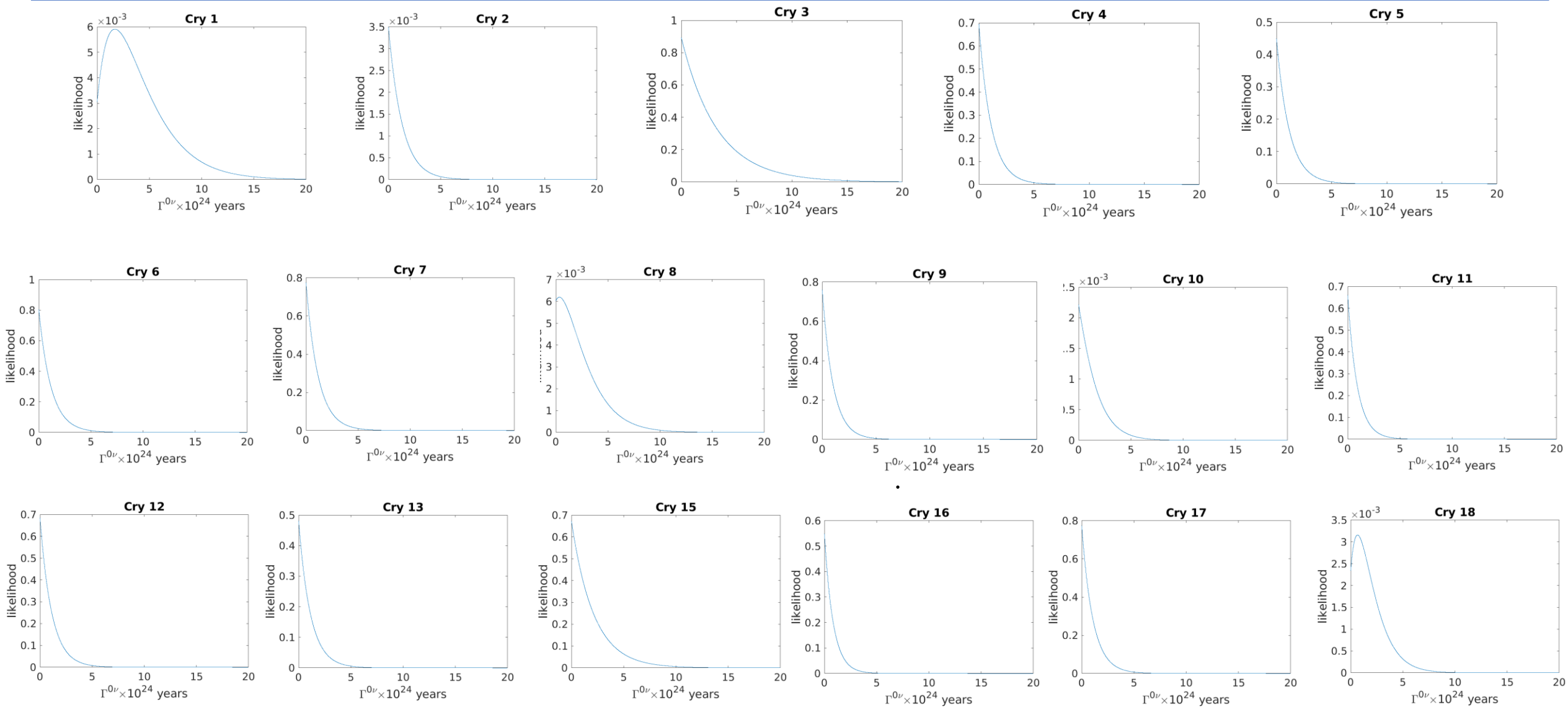
$$h_2(x; \mu, \sigma, \alpha, s, m) = h_2(x; \mu, \sigma, \alpha, s)$$

We also marginalize out mu, sigma and alpha assuming they are normally distributed.

$$h_3(x; s) = \int \int \int h_2(x; \mu, \sigma, \alpha, s) * \text{gauss}(\mu; \mu_\mu, \sigma_\mu) * \dots * \text{gauss}(\sigma; \mu_\sigma, \sigma_\sigma) * \text{gauss}(\alpha; \mu_\alpha, \sigma_\alpha) d\mu d\sigma d\alpha$$

Nuisance parameters are obtained from calibration curves. (mean = Prediction line, sigma = RMS error)

Likelihood calculation



Total Likelihood Function

The total likelihood function, assuming flat prior on s , is given by

$$L(s; \text{data}) = \prod_j^6 [h_j(x_j; s)]^{n_j}$$

where n_j = number of events @ ROI in each crystal and j is the crystal index.

We then plot $L(s; \text{data})$ against s , to reject 10 % model s , i.e. we find s_0 such that

$$\frac{\int_0^{s_0} L(s; \text{data}) ds}{\int_0^{\infty} L(s; \text{data}) ds} = 0.9$$

Then, for R_u = upper limit of rate at 90% confidence level,

$$R_u = \frac{s_0}{T_{\text{live}} * n_{100\text{Mo}} * R_{\text{eff}}}$$

where T_{live} = live time, $n_{100\text{Mo}}$ = number of Mo-100 nucleus, R_{eff} = efficiency

Background budget for AMoRE-II

