Development of low-background scintillator for rare event searches

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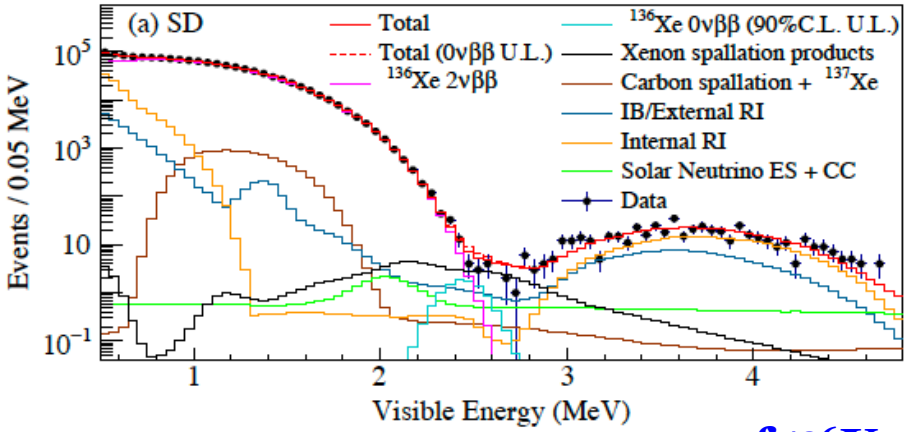
Center for Underground Physics (CUP)

Institute for Basic Science (IBS)

Particle Detector Workshop 2026

What are we looking for?

- Kamland-ZEN ($0\nu\beta\beta$)



2.1 ton yr of ^{136}Xe

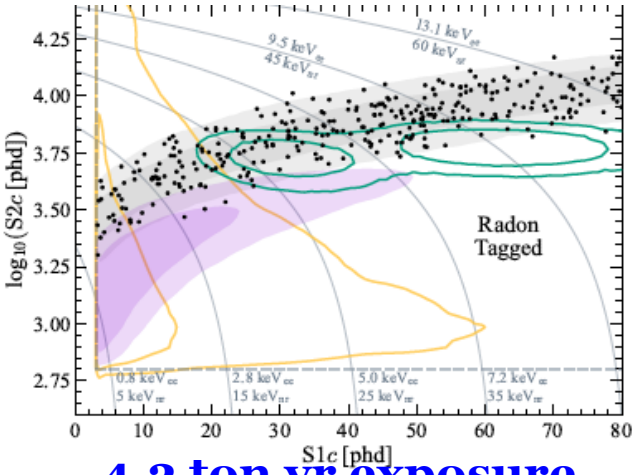
$$T_{1/2}^{0\nu\beta\beta} > 3.8 \times 10^{26}\ \text{yr} \quad (90\%\ \text{C.L.})$$

PRL 135, 262501 (2025)

i.e.) 136 kg of ^{136}Xe = 1000 mol × 6.02×10^{23} atom/mol = 6.02×10^{26} atom

Challenge : We need to observe 1 event signal from 100 kg detector of 1 year operation

- LZ (Dark matter)



4.2 ton yr exposure

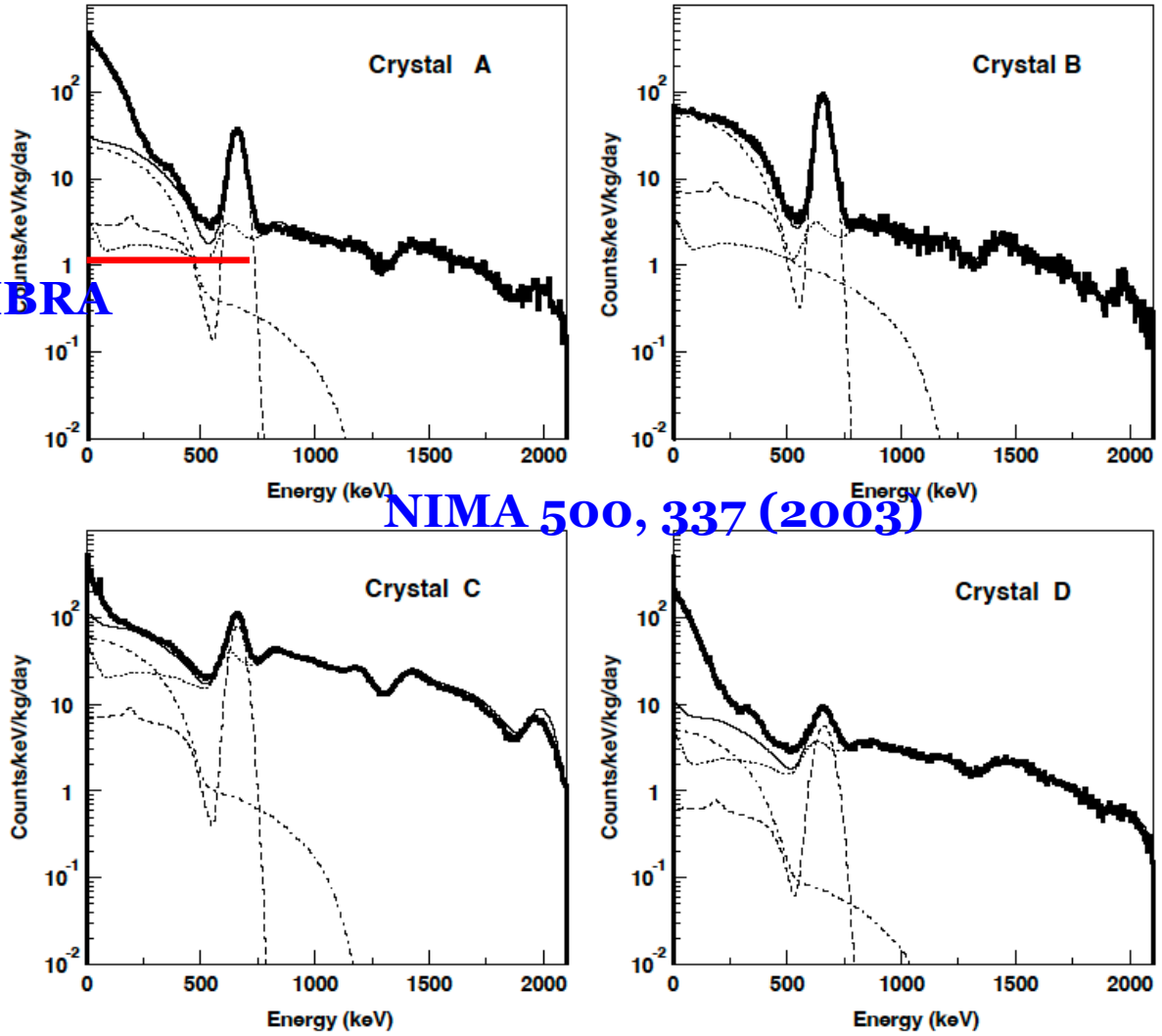
PRL 135, 011802 (2025)

Challenge : We need to observe 1 event signal from 1000 kg detector of 1 year operation

Common Challenge : Ultimate Radio-purity

When we start experiments about 28 years ago

- CsI(Tl) crystals used for Belle experiment (KIMS experiment)



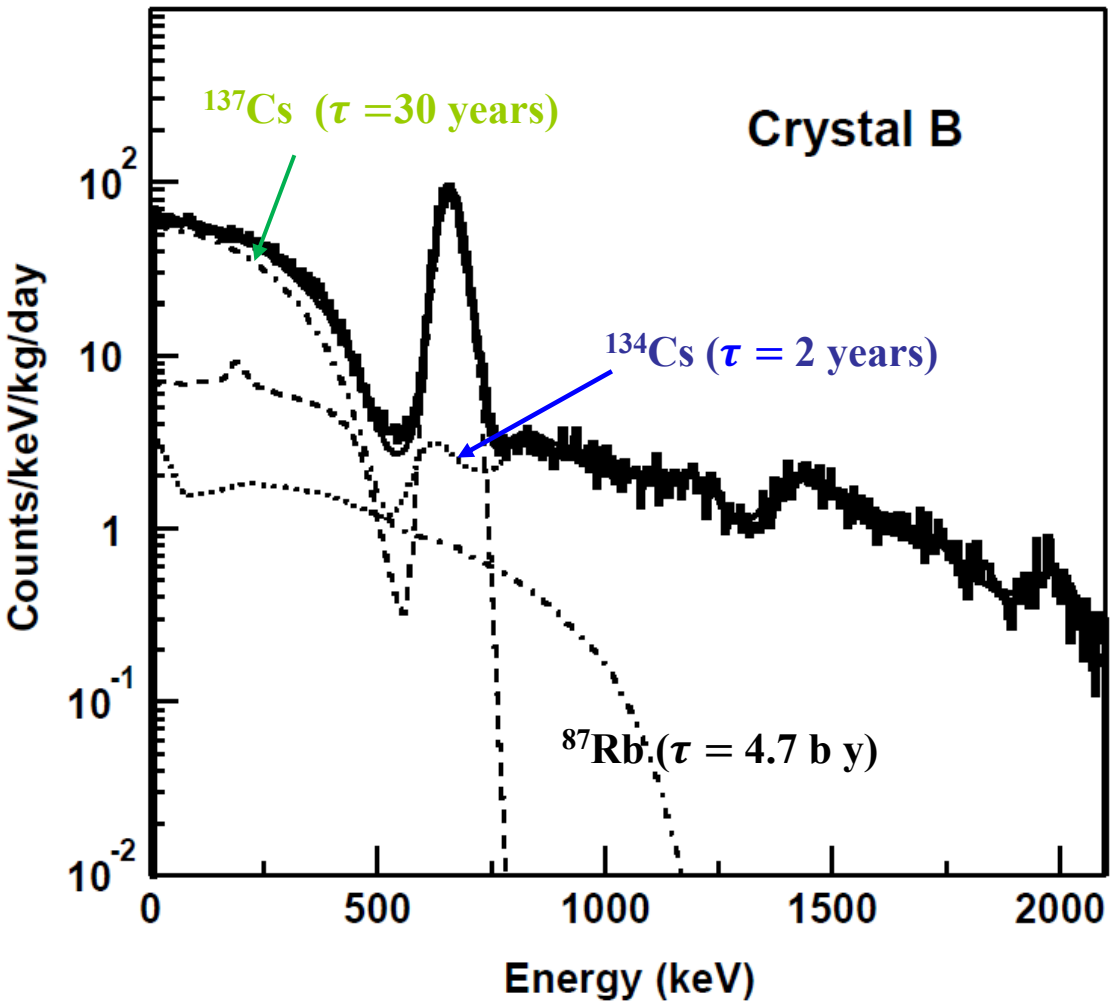
DAMA/LIBRA

NIMA 500, 337 (2003)

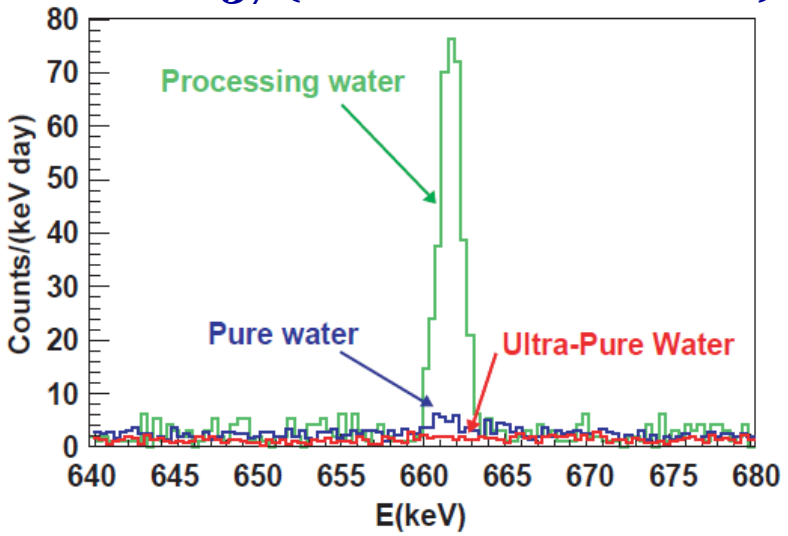
1-6 keV : ~ 20,000 events/kg/year

Initial goal ~ O(1) counts/keV/kg/day (similar to DAMA/LIBRA)

Background understanding and reduction



Cesium-137 (water is main source)



NIMA 552 (2005) 456

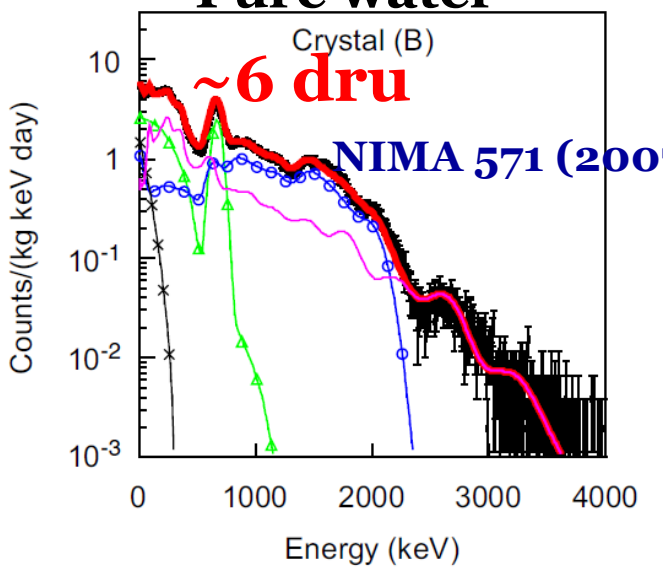
Rb-87 : Recrystallization

Cs-134 : Cosmogenic but can tagged by surrounding crystals

- Low background CsI powder from Chemetall (Germany)
- Crystal growing from SICASS and Beijing Hamamatsu

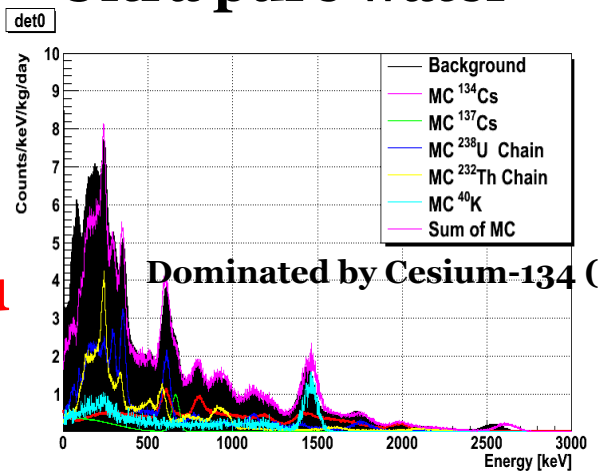
Success of KIMS experiment

Pure water



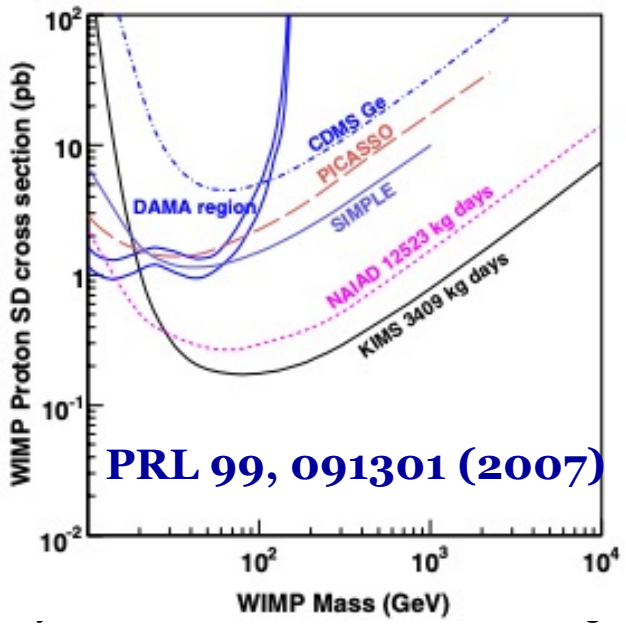
~2.5 dru

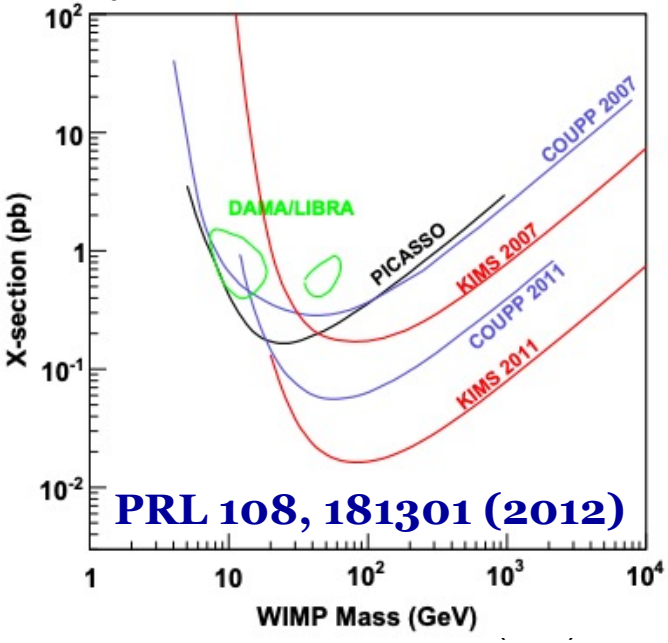
Ultra pure water



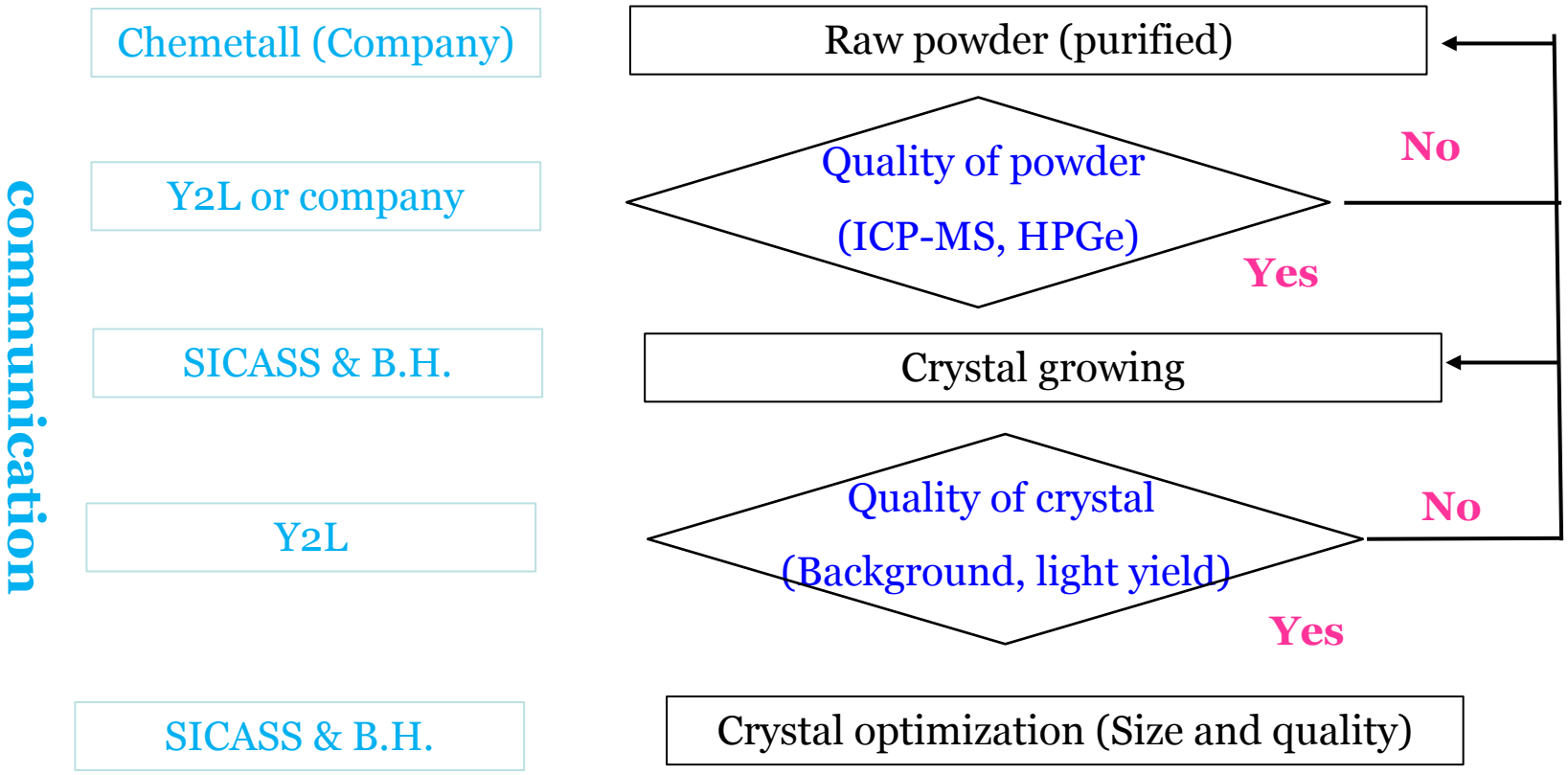
Dominated by Cesium-134 (2 year half life)

Best quality CsI crystals in the world



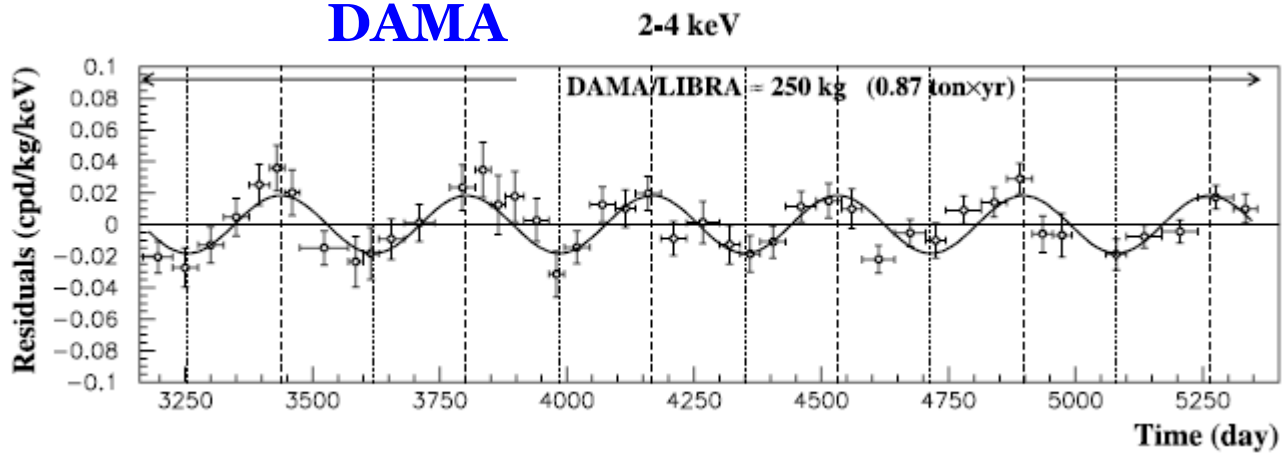


Protocol to develop low-background crystals



- This model works for KIMS experiment ~ 5 years journey
- This model highly rely on the company's activities

Low-background NaI(Tl) development



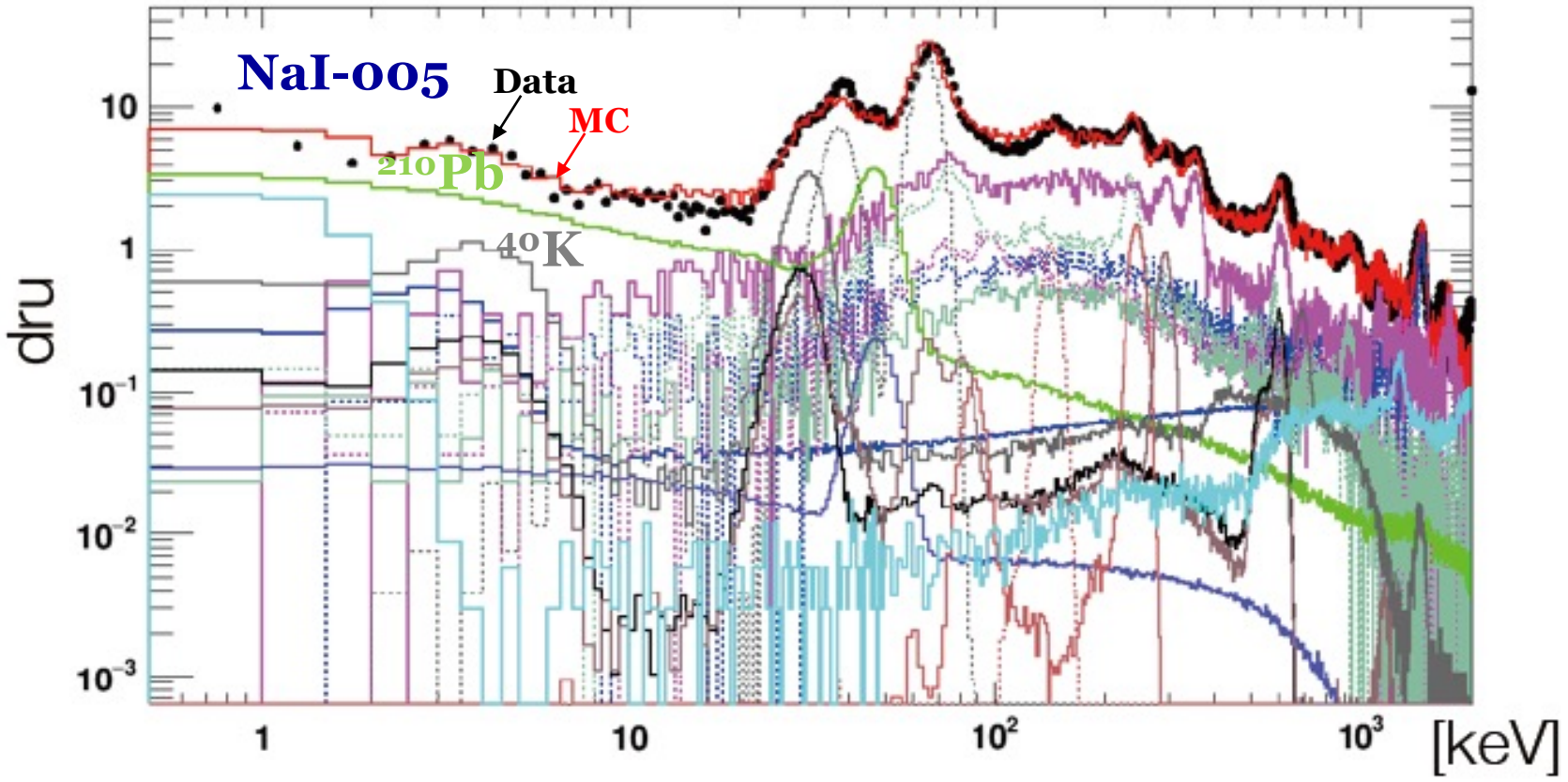
Since 2013

- To confirm DAMA annual modulation signature
  - ❖ CsI is not enough for WIMP-Na interaction
  - ❖ Same NaI crystal for the same annual modulation signature

- Need to develop ultra-pure NaI(Tl) crystals
  - ❖ Goal is less than DAMA background (~1 dru = 1 counts/keV/kg/day)
  - ❖ 200 kg×3 years data will prove DAMA signature without any ambiguity

Main background of NaI(Tl)

- Internal ^{40}K and ^{210}Pb are main backgrounds



- Goal : K < 20 ppb, ^{210}Pb < 0.5 mBq/kg

Similar approach to make good NaI(Tl)

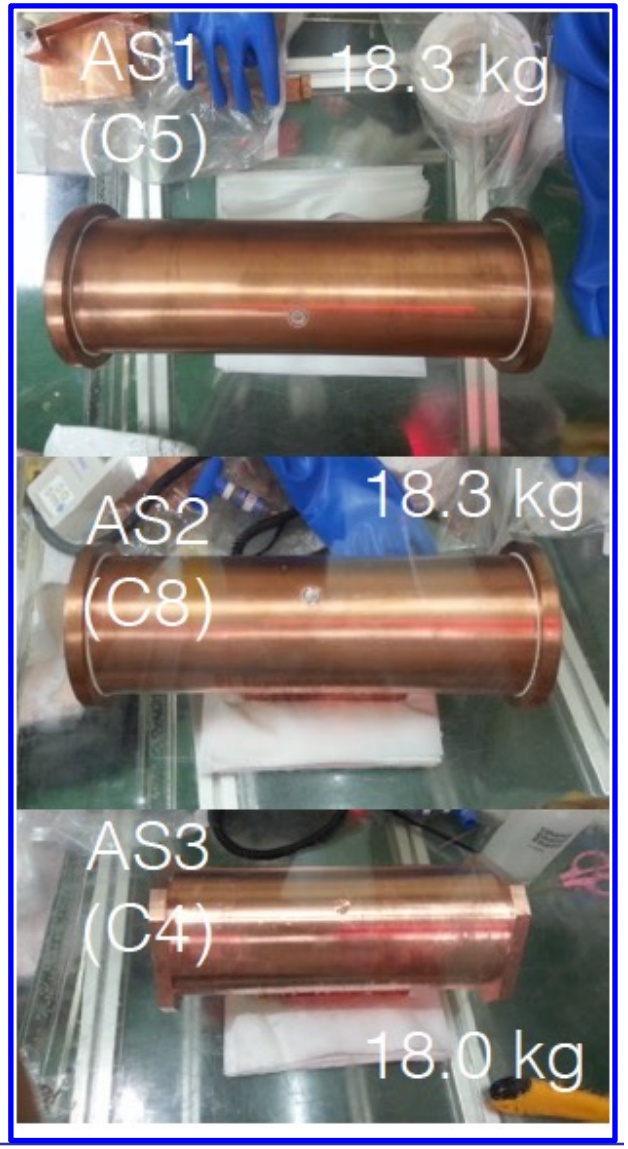
- Identify **good quality powder** and **grow crystal** from various companies
  - ❖ SA-AG : Sigma Adrich Astro-Grade Powder (with SABRE)
  - ❖ AS-WS : Alpha-Spectra WIMPScint Powder (with KIMS+ANAIS+DM-Ice)
  - ❖ AS : Alpha Spectra (crystal growing @ US)
  - ❖ BH : Beijing Hamamatsu, SC : SICCAS

	NaI-003	**NaI-005**	**NaI-008**	**NaI-011**	**NaI-015**
K (ppb)	$\mathbf{25.3 \pm 2.4}$	40.1 ± 4.2	–	16.8 ± 2.5	19.1 ± 8.3
^{210}Pb(mBq/kg)	2.4 ± 0.1	0.5 ± 0.1	21.4 ± 0.7	1.5 ± 0.1	0.5 ± 0.1
Mass (kg)	3.3	9.2	1.8	12.5	1.8
K (powder)	25	?	25	?	25
Powder	SA-AG	AS-WS-II	SA-AG	AS-WS-III	SA-AG
Crystal	AS	AS	BH	AS	SICCAS

- **SICCAS : Can not grow large size crystals**
- **AS: R&Ds with commercial company are extremely difficult**

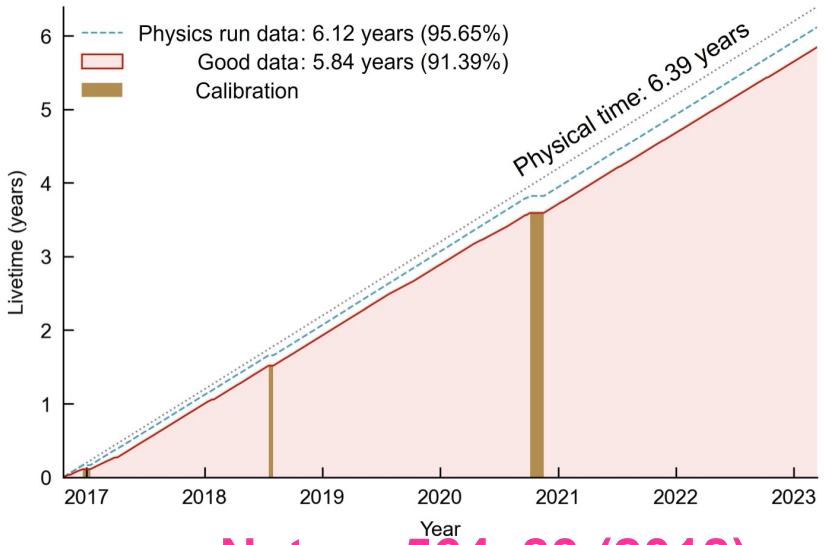
COSINE-100 detectors

- ~106 kg crystals running since Sept/2016



DAMA/LIBRA exclusion from COSINE-100 (3σ)

~ 6.5 years operation at Y2L

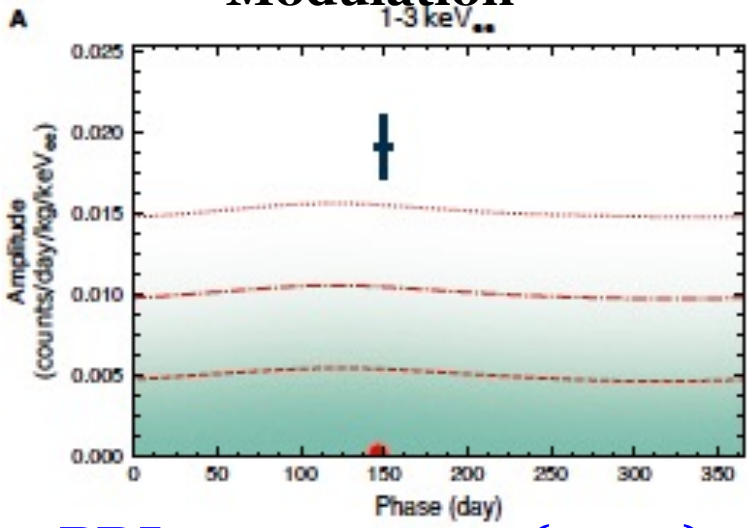


Nature 564, 83 (2018)

Sci. Adv. 7, eabk2699 (2021)

PRL 135, 231001 (2025)

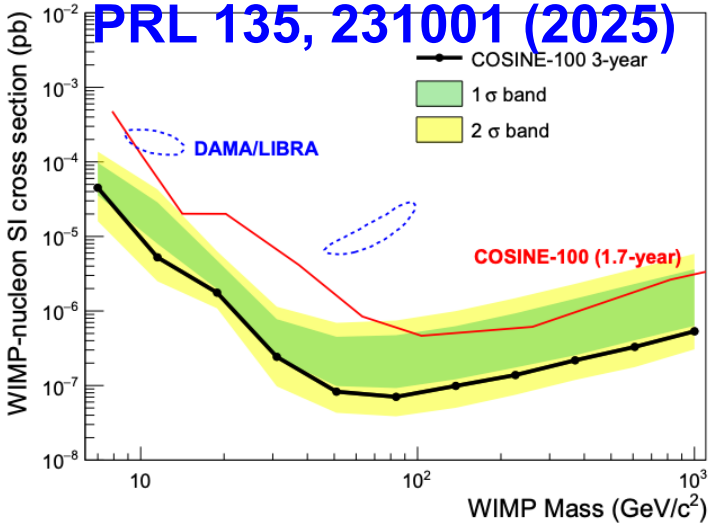
Modulation

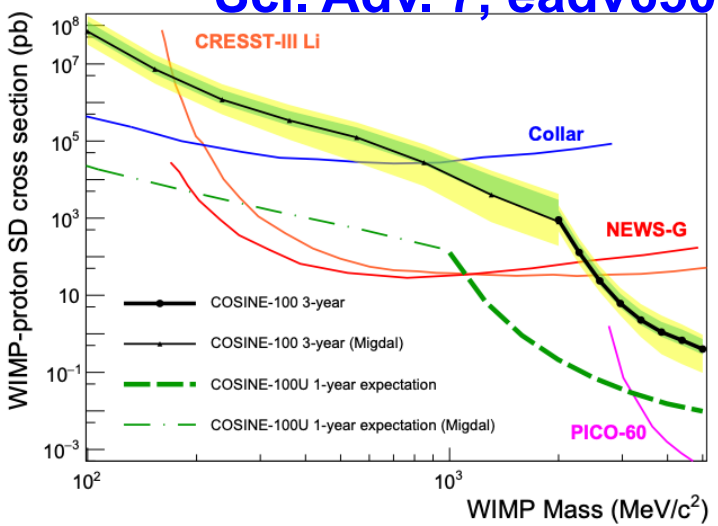


PRL 123, 031302 (2019)

PRL 135, 121002 (2025)

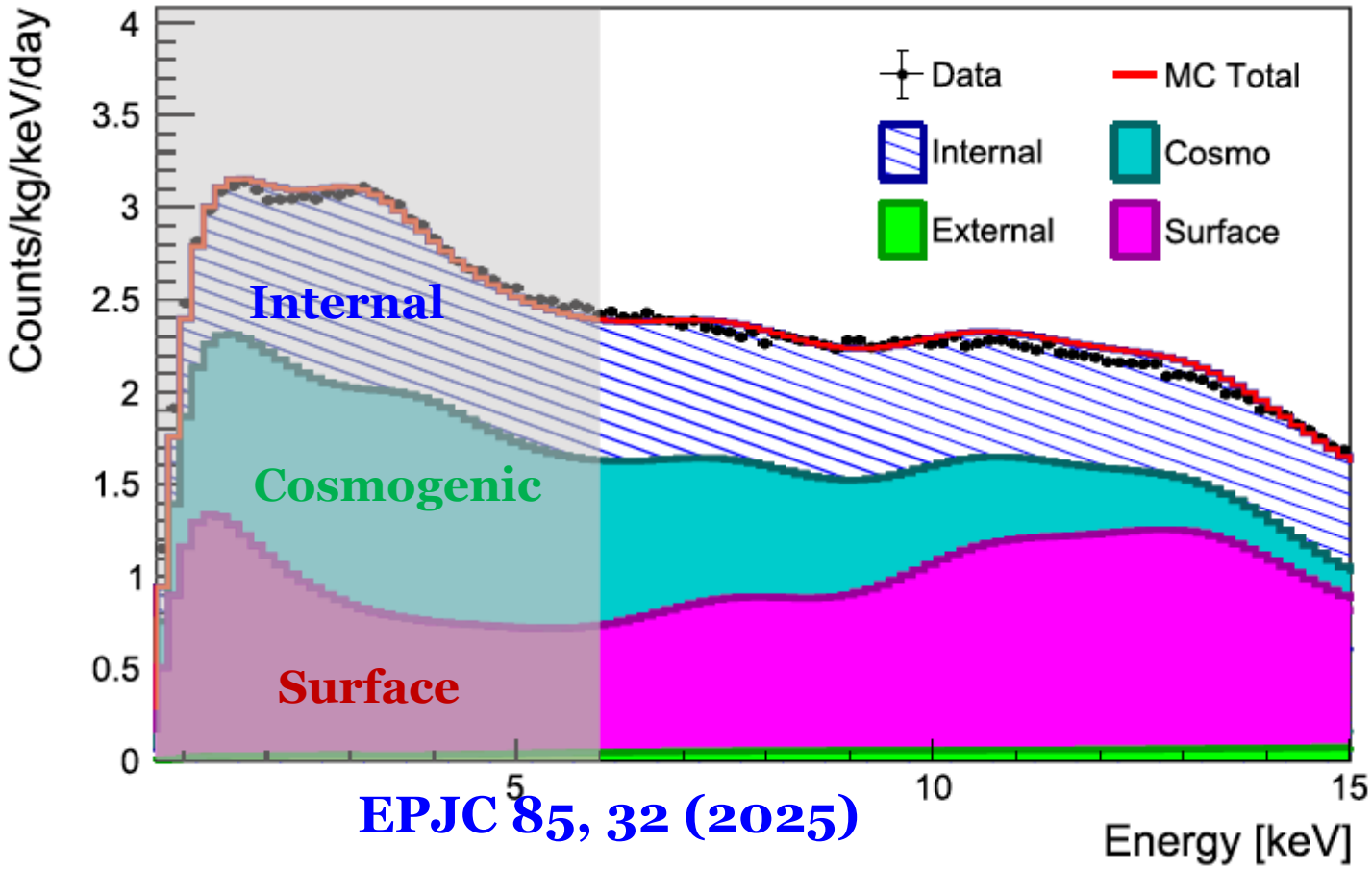
Sci. Adv. 7, eadv6503 (2025)





COSINE-100 Background

- Internal ~ 0.8 dru, Cosmogenic ~ 1.2 dru, Surface ~ 1 dru



- Alpha Spectra (Grand Junction ~ 1000 m height)
- Daejeon 70 m (much smaller cosmogenic)

Powder

- Powder purification
  - SA-AG was available: The cost of powder doubled within two years (~1M KRW/kg –> 2M KRW/kg) before being discontinued
  - In-house purification facility is required in IBS-CUP
- Recrystallization of powder

K.A. Shin et al., J. Rad. Nucl. Chem. 317, 1329 (2018)

K.A. Shin et al., JINST 15, C07031 (2020)

K.A. Shin et al., Front. Phys. 11, 1142849 (2023)

	K (ppb)	Pb (ppb)	U (ppb)	Th (ppb)
Initial NaI	248	19.0	<0.01	<0.01
Purified NaI	11.1	0.4	<0.01	<0.01

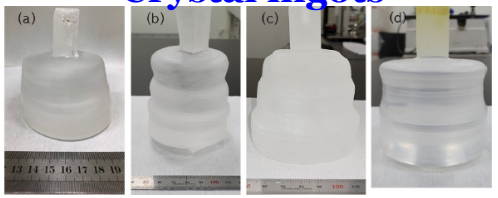
Mass production of powder ~ 35 kg/2 weeks

400 kg low background powder is available

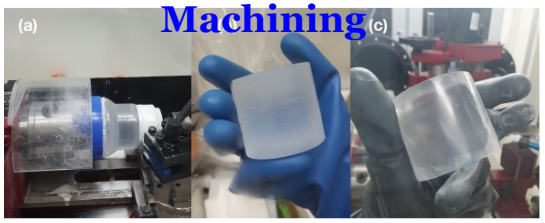
NaI(Tl) crystal growing

- A Proof of low-background NaI(Tl) principle (Kyropoulos)

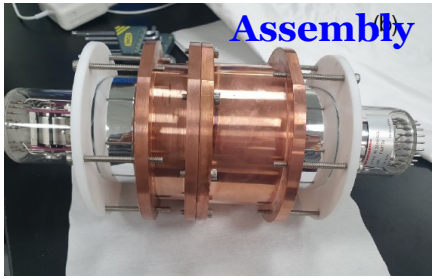
Crystal ingots



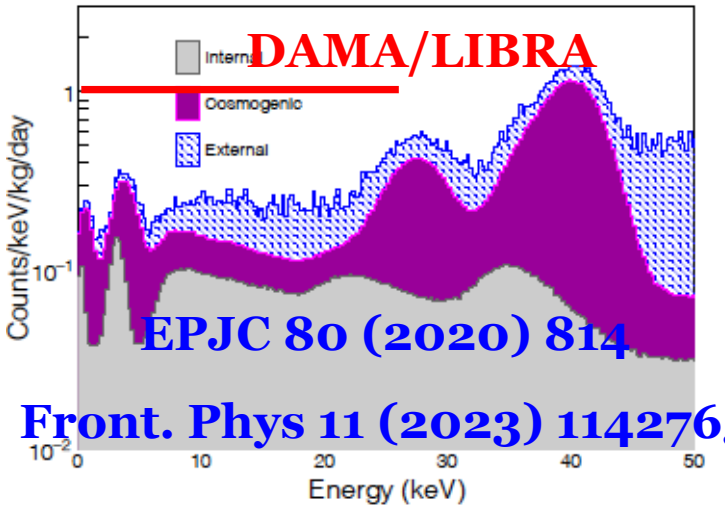
Machining



Assembly



K : ~13 ppb, ^{210}Pb: 0.1 mBq/kg



EPJC 80 (2020) 814

Front. Phys 11 (2023) 1142765

A proof of principle for low background NaI

Large crystal growing is going on

- Challenges in Large-Scale Crystal Growth with Kyropoulos
  - ❖ Safe management of the high toxicity of Thallium
  - ❖ High powder consumption per growth cycle
  - ❖ Ongoing refinement of growth conditions to obtain optimal parameter

NaI(Tl) crystal growing

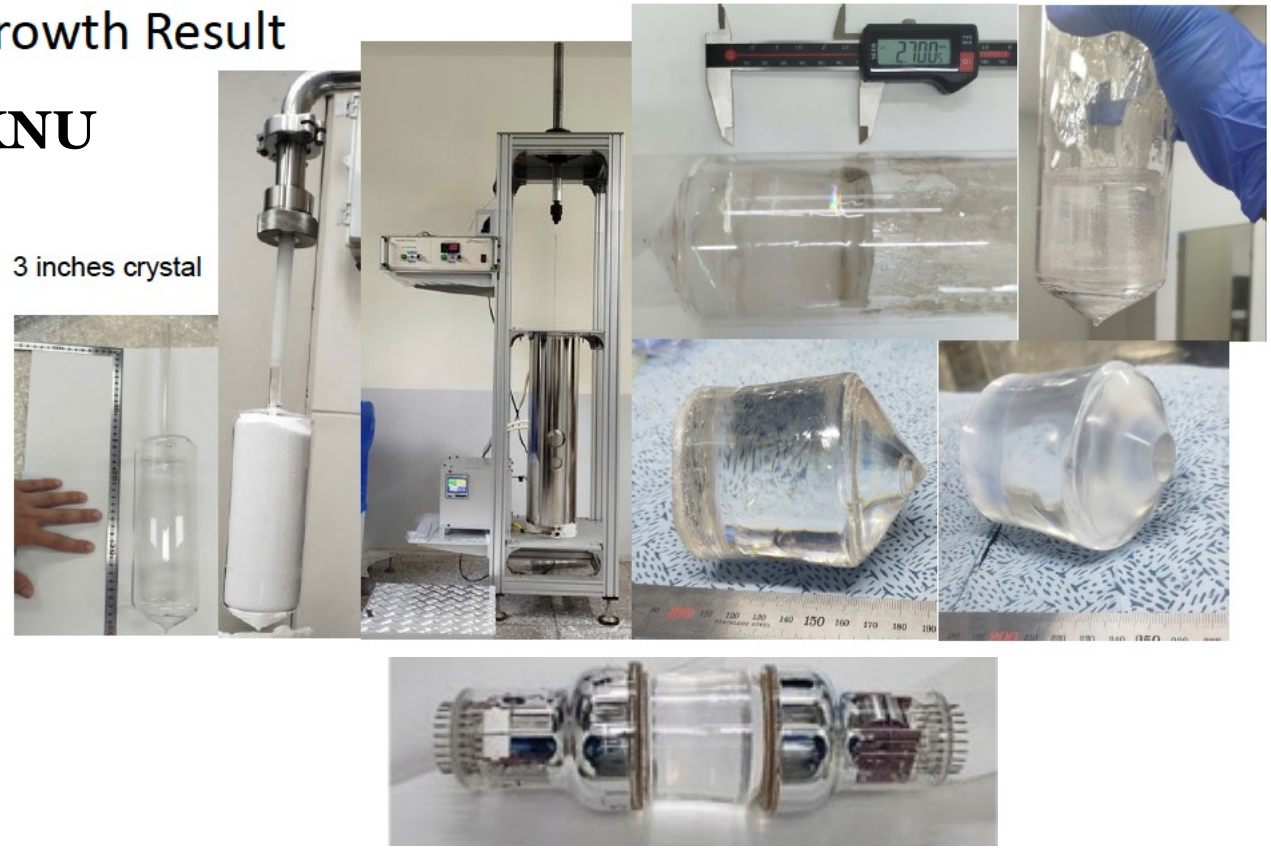
- 3-inch **Bridgman** (vacuum sealed)

4.5-inch is under construction

Growth Result

KNU

3 inches crystal



New furnace design

- High light yield (27 NPE/keV)
- Low ^{210}Pb (0.21 mBq/kg)
- ^{40}K measurement is ongoing (Powder ~ 7 ppb)

Updated protocol

communication

IBS HQ

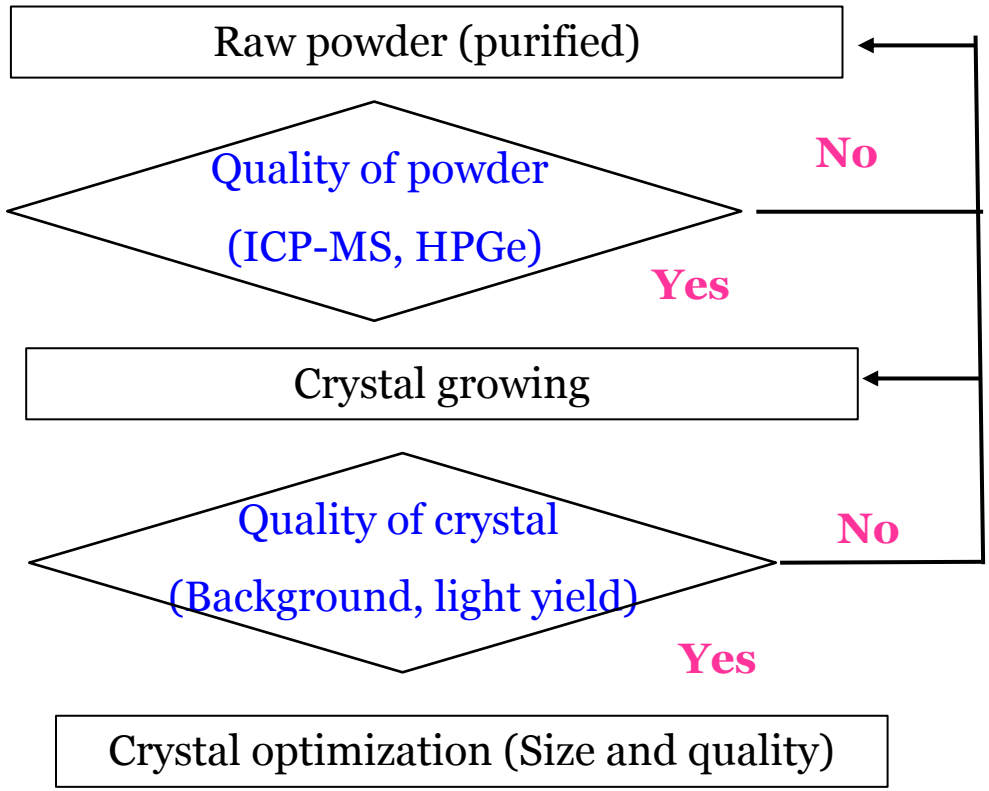
IBS and Yemilab

IBS or Yemilab

company

IBS and Yemilab

IBS and Yemilab



Updated protocol

communication

IBS HQ

Raw powder (purified)

IBS and Yemilab

IBS or Yemilab

IBS and Yemilab

IBS and Yemilab

IBS-CUP is currently the only facility worldwide capable of producing low-background NaI powder (K<20 ppb)

Updated protocol

IBS HQ

IBS and Yemilab

communication

Raw powder (purified)

Quality of powder (ICP-MS, HPGe)

No

Yes

Crystal growing

Updated protocol

communication

IBS HQ

IBS and Yemilab

IBS or Yemilab

Raw powder (purified)

Quality of powder (ICP-MS, HPGe)

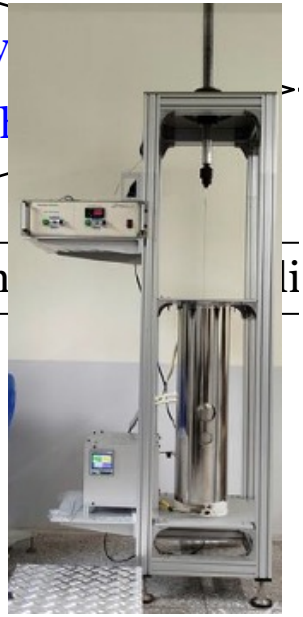
No

Yes

Crystal growing

Kyropoulos

Bridgman



New furnace design

Updated protocol

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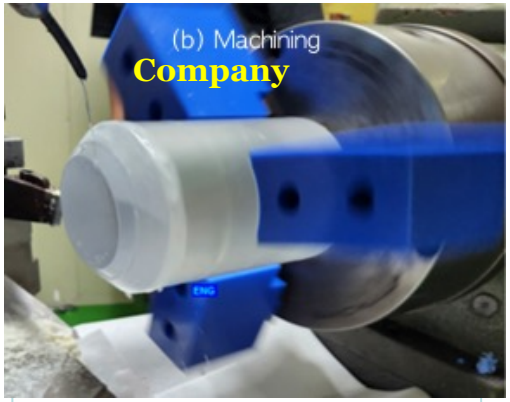
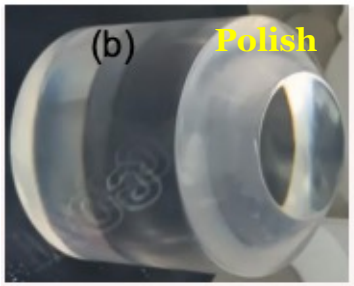
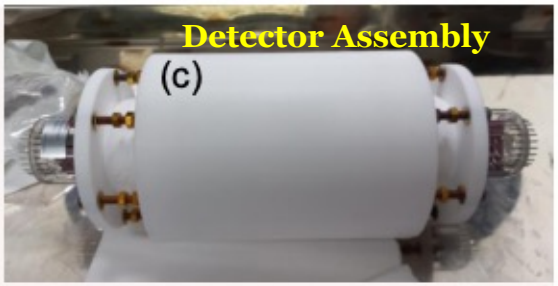
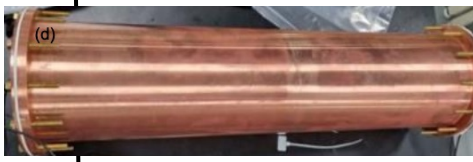








Crystal growing

company

IBS and Yemilab

Quality of crystal
(Background, light yield)

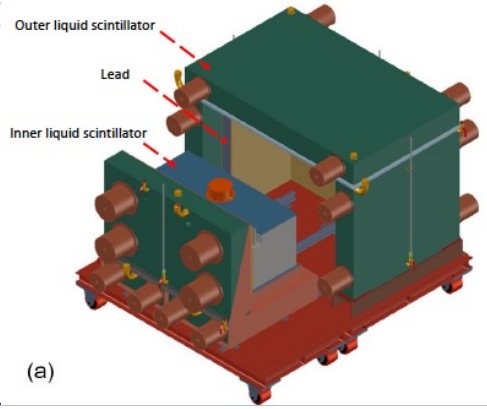
No

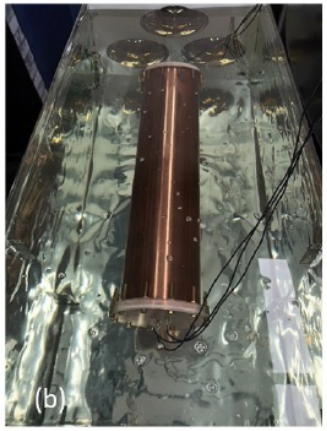
Yes

IBS a

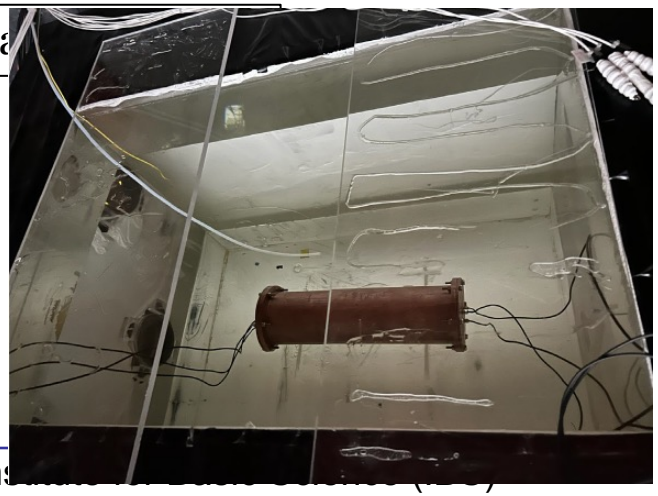
Size a

IBS HQ Test bench

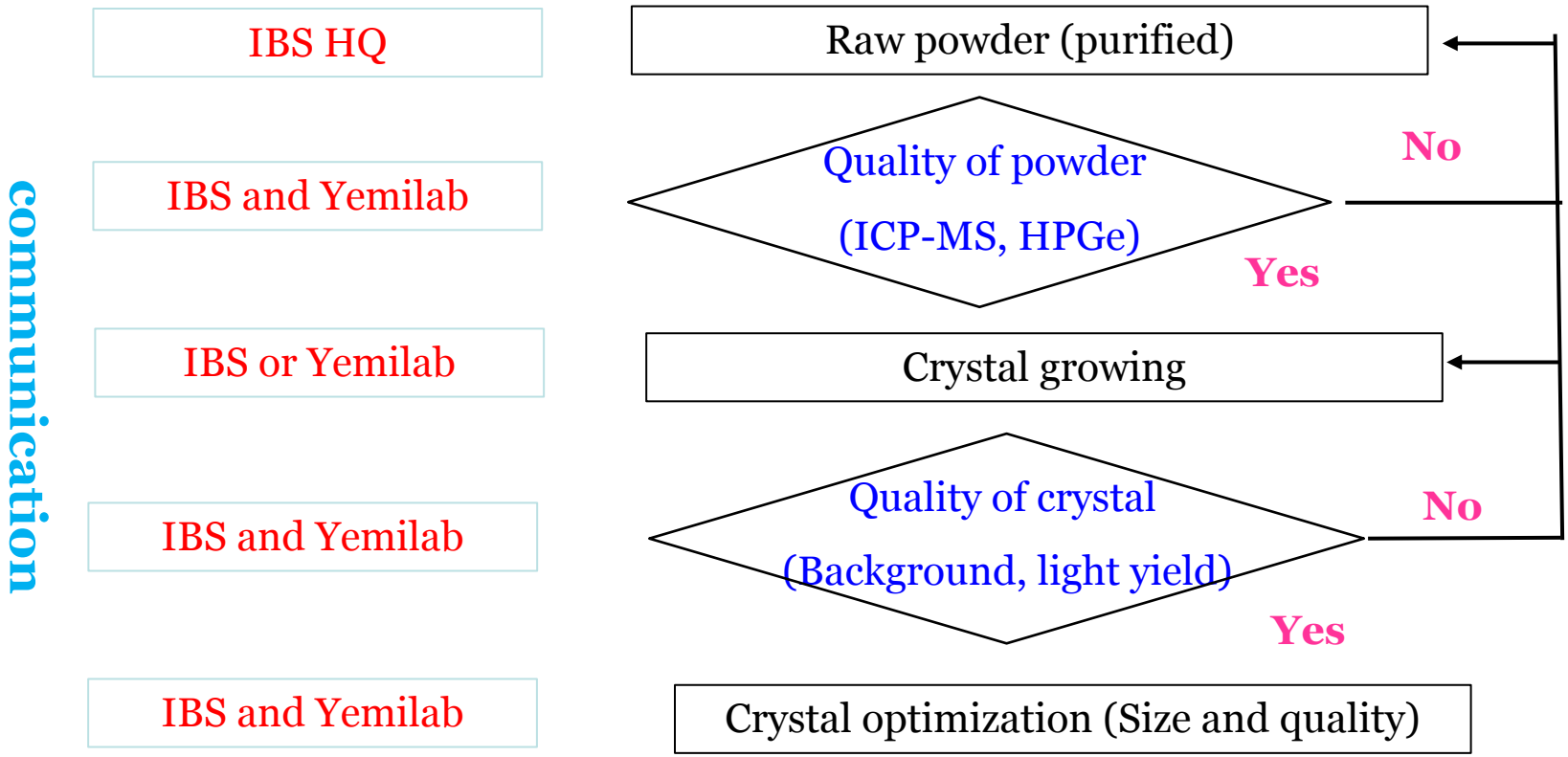




Yemilab Test bench



Updated protocol



- Established end-to-end NaI(Tl) crystal growth at IBS-CUP
  - ❖ This allow for rapid testing and optimization for COSINE-200
- Easily scalable and adaptable for other halide crystals
  - ❖ Recently grow 1-inch updoed CsI, NaI, NaI+LiI (mixed), CsI+RbI (mixed)

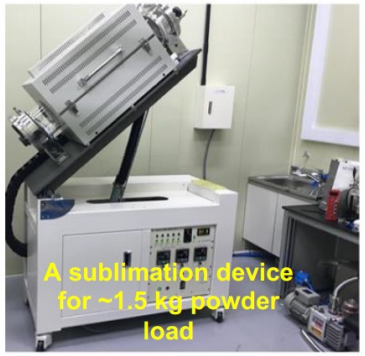
World-wide interest on low-background halide crystals

- NaI(Tl)
  - COSINE-200
  - **SABRE**-North (LNGS), SABRE-South (Stawell), ANAIS (Canfranc), PICO (Kamioka)
- CsI(Tl) and undoped CsI
  - COHERENT experiment (Oak Bridge)
  - **J-PARC Coherent** proposal by Juan Collar
- Undoped NaI
  - COSINUS (LNGS)

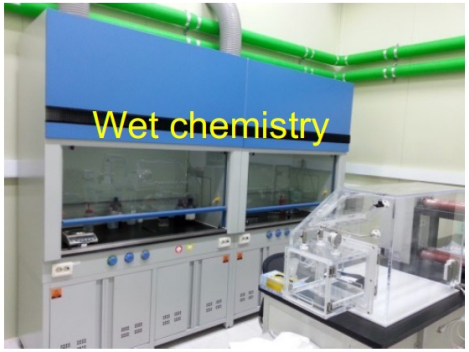
- We are the only group worldwide providing a complete lifecycle for ultra-low-background halide crystals, from raw material purification to final detector assembly

AMoRE crystals for $0\nu\beta\beta$

Purification facility @ IBS HQ



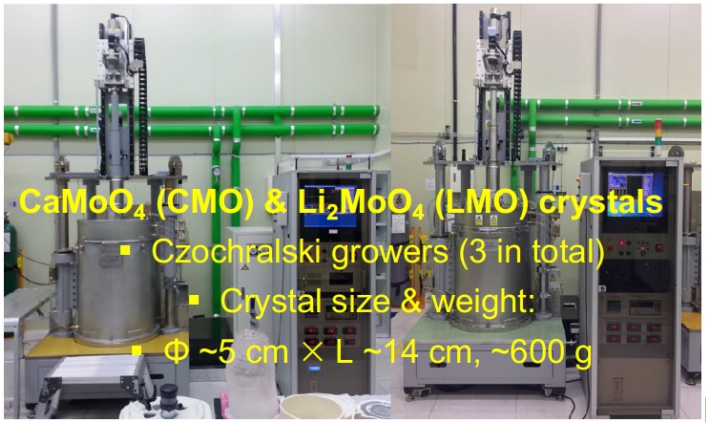
Purified powder after sublimation



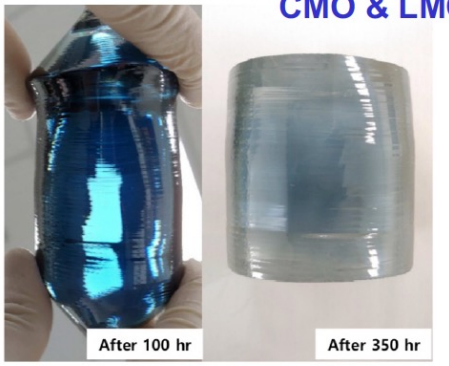
Purified $^{100}MoO_3$ powder (examples)

S/N	Amount (kg)	Al (ppb)	K (ppb)	Cr (ppb)	Mn (ppb)	Fe (ppb)	Ni (ppb)	Cu (ppb)	W (ppb)	Sr (ppb)	Ba (ppb)	Pb (ppb)	Th ppt	U ppt
1	1.1	585	409	<200	<30	39	<20	<200	33	<0.15	3.9	0.3	<10	<7
31	1.2	<30	153	<200	<30	136	<20	<200	711	<0.15	<3.0	<0.5	<10	<7
32	1.3	<30	150	<200	<30	26	<20	<200	648	<0.15	<3.0	<0.5	<10	<7

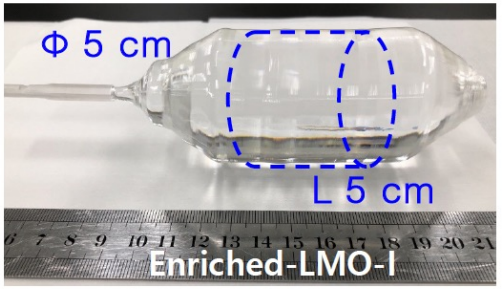
Czochralski growers @ IBS HQ and Russia



CMO & LMO crystals by CUP



Purified CMO (Ir, Annealed)

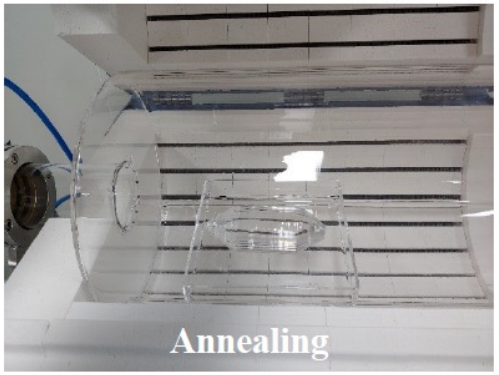


$^{48depl}Ca^{100}MoO_4$ (AMoRE-Pilot/I): Excellent but $^{48depl}Ca$ & Ca deep purification necessary .

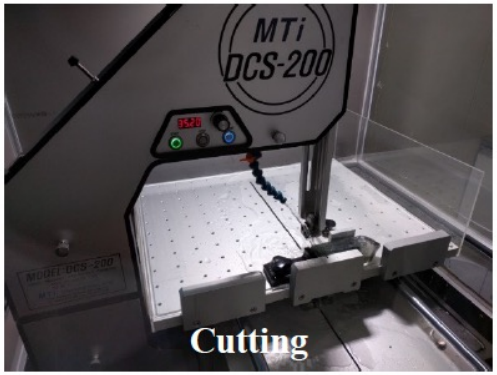
AMoRE crystals for $0\nu\beta\beta$

Full-Cycle Vertical Integration for AMoRE

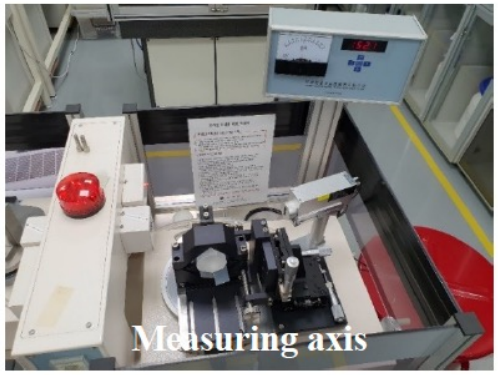
- Czochralski grower 3 ea (2014 ~)
- Fused alumina refractory (less impurities)
- Platinum crucible (99.95 %) 1600 °C
- High purity (99.999 %) Air



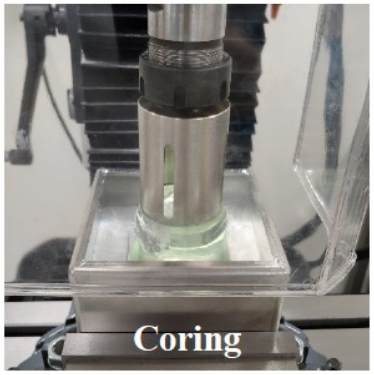
- Annealing furnace (2019)
- Quartz tube
- High purity (99.999 %) Air
- Temperature : 500 °C



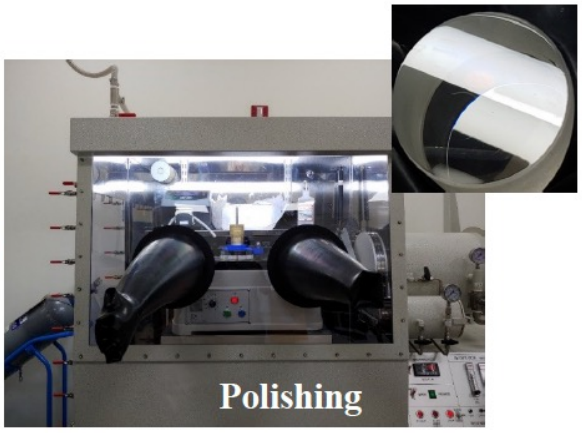
- Cutting machine (2017)
- Diamond band saw
- Mineral oil (for hygroscopic crystal)



- Crystal orientation unit (2019)
- X-ray goniometer



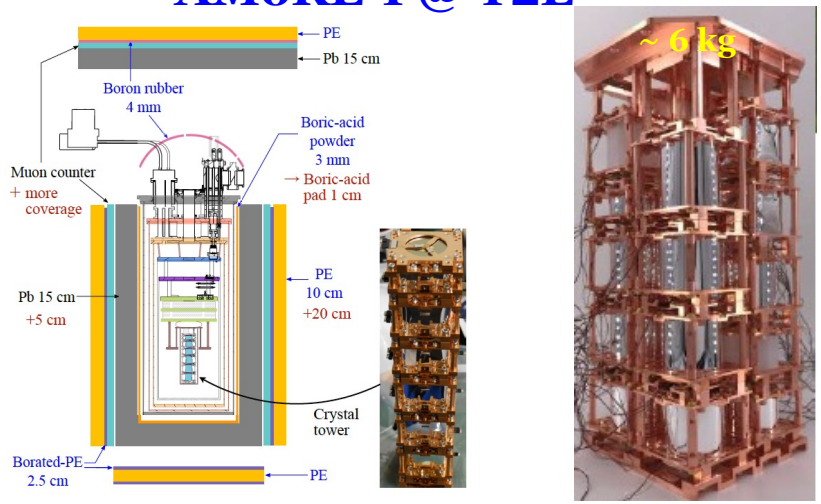
- Milling machine (2020)
- Diamond core drill bit
- Mineral oil (for hygroscopic crystal)



- Polishing machine in a glove box (2019)
- SiC + oleic acid and colloidal silica
- Polytex pad

AMoRE-I and AMoRE-II

AMoRE-I @ Y2L



AMoRE-II @ Yemilab

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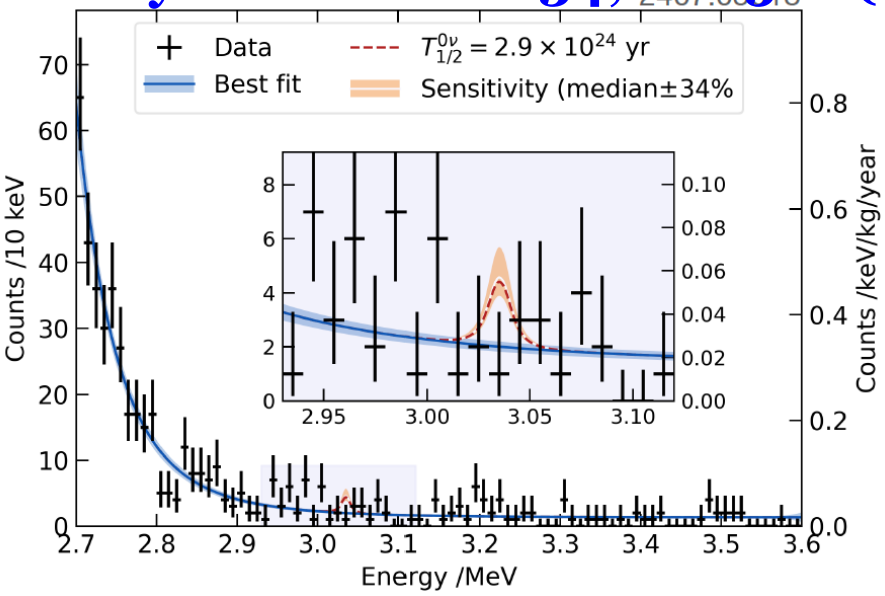
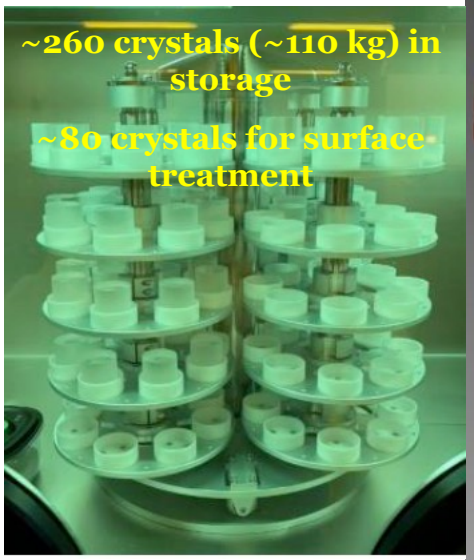
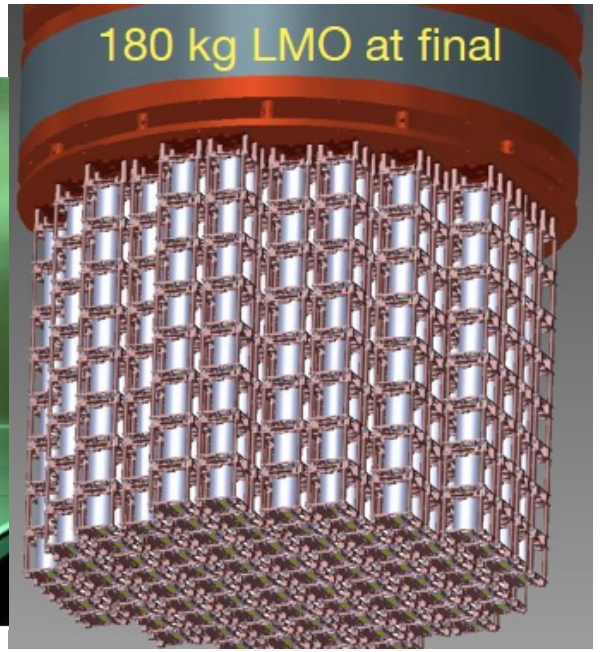






Summary

- **Reducing** internal and surface **radio-impurities** are the primary challenge for rare event searches.

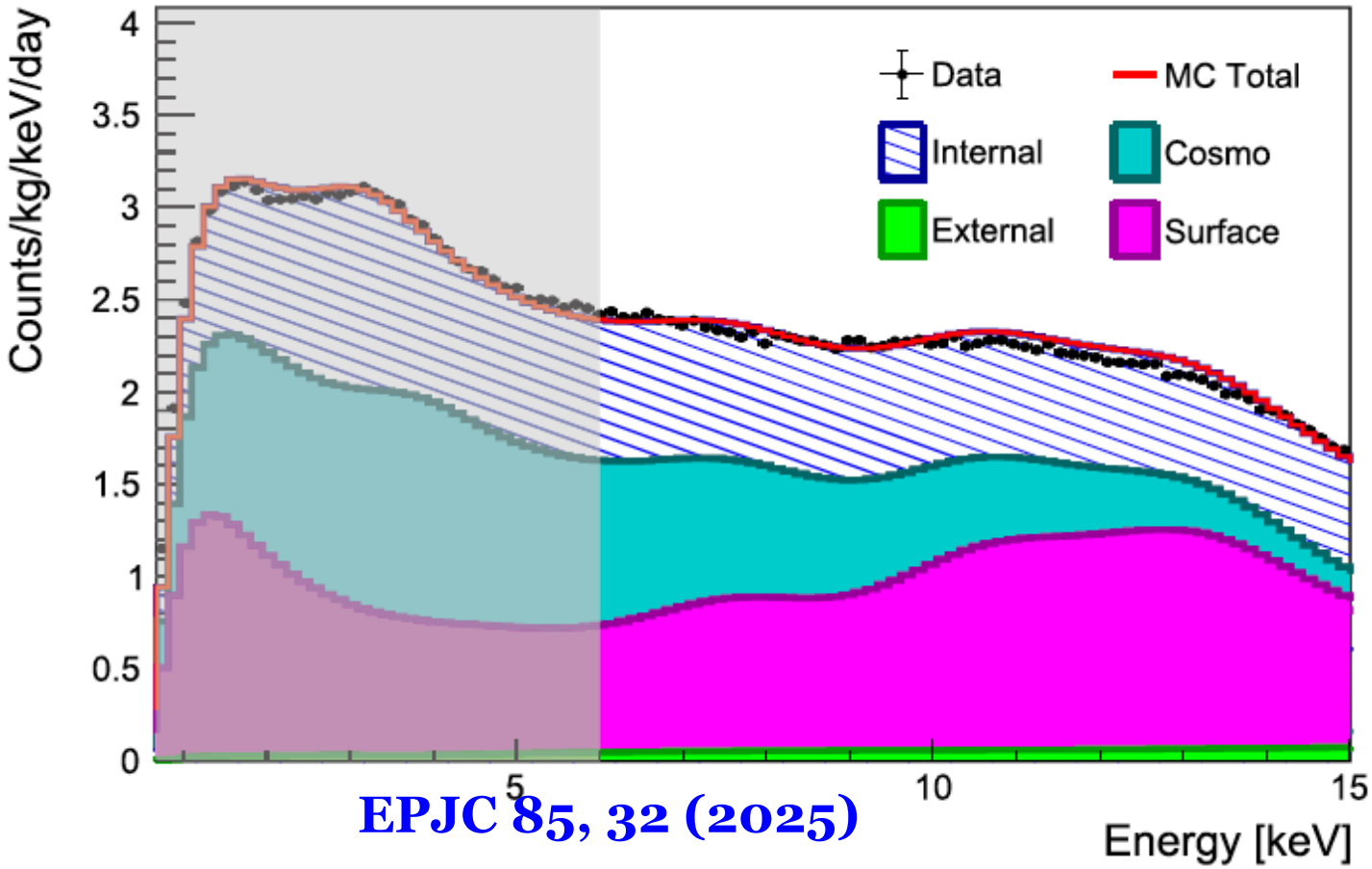
- IBS/CUP has successfully established a full-chain facility for ultra-pure crystal production, from powder purification to ingot growth.

- Recent results demonstrate that our crystals now meet or exceed world-leading standards.

- Open to collaborative opportunities leveraging our unique purification and growth infrastructure.

COSINE-100 Background

- Internal ~ 0.8 dru, Cosmogenic ~ 1.2 dru, Surface ~ 1 dru



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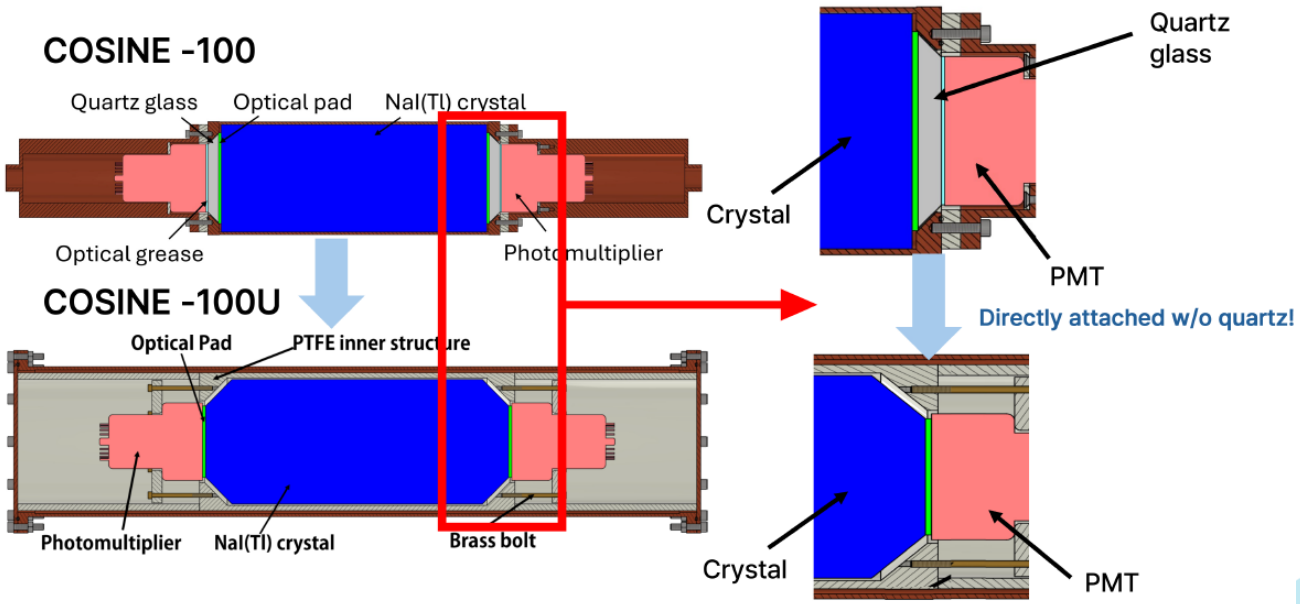
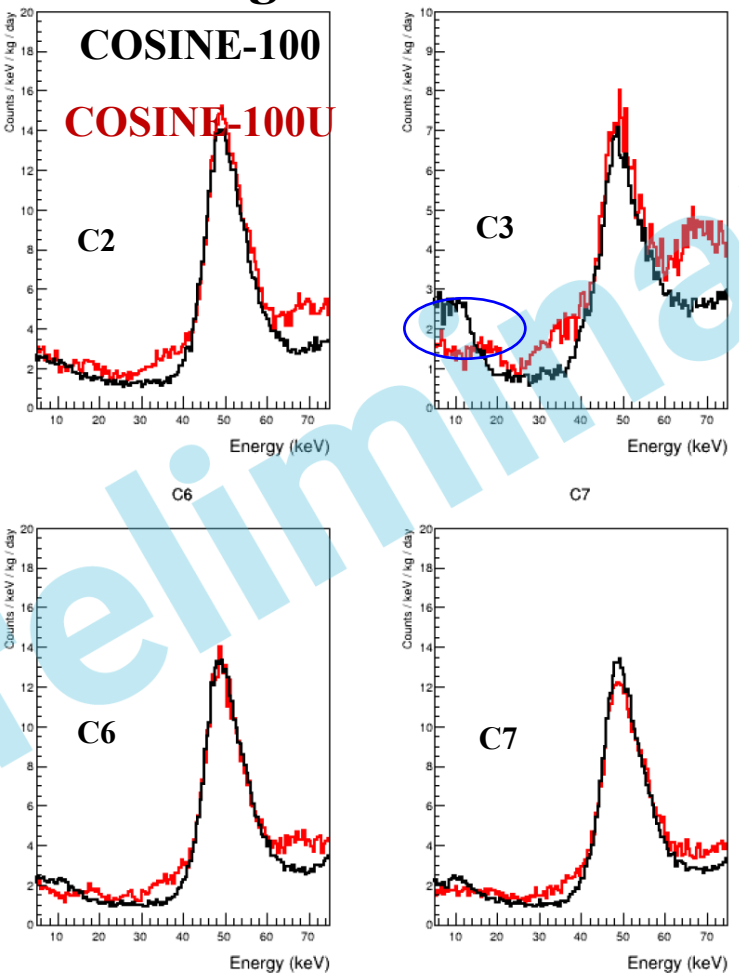
- We can reduce surface background by careful treatment of crystal surface (Machining & polishing)

COSINE-100U : Assembly of crystal by ourself

- Enhance light collection : 15 NPE/keV –> 23 NPE/keV
- Reduced surface contamination (~1 dru @ COSINE-100)



Background Level



- Reduced surface alpha
- Reduced low-energy background