Design and prospect of the CDEX-300 neutrinoless double beta decay experiment

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Outlines

I. Searching 0νββ with HPGe detectors

II. CDEX and its 0νββ studies

III. Design and status of CDEX-300ν

IV. Summary

I. Searching $0\nu\beta\beta$ with HPGe detectors

Motivation from Neutrino Physics

- **How do neutrinos get their mass?**
  - If $\nu \neq \bar{\nu}$ (Dirac fermion)

    get mass by the Higgs mechanism
  - If $\nu = \bar{\nu}$ (Majorana fermion)

    get mass by the Seesaw mechanism
- **What is the absolute mass scale?**
- **What is the mass hierarchy?**

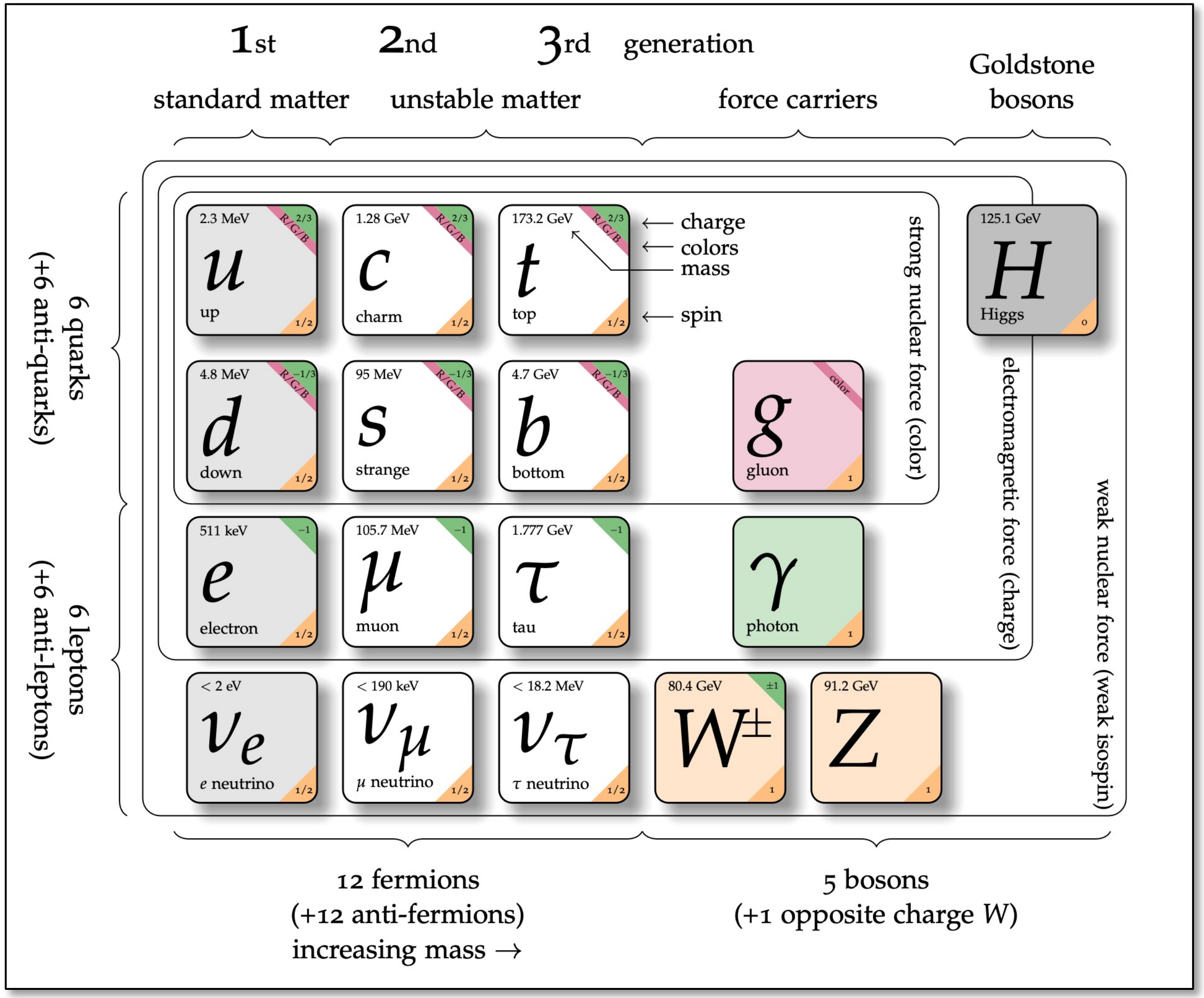
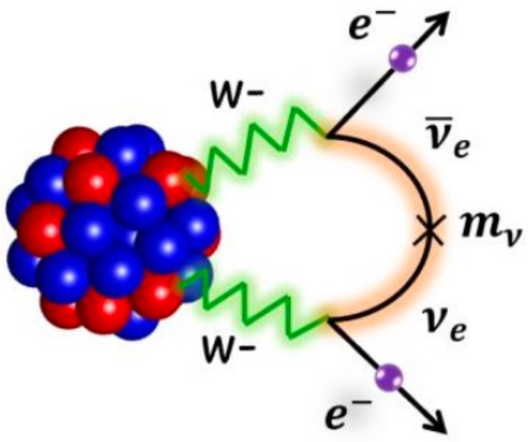
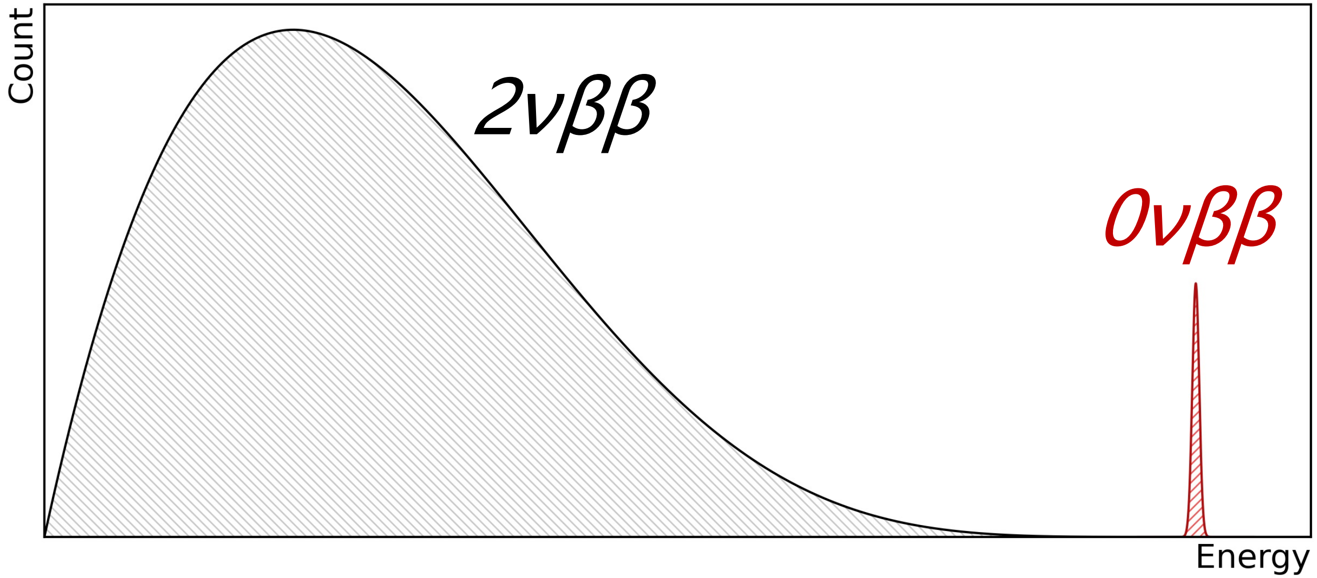


Fig from https://davidgalbraith.org/portfolio/ux-standard-model-of-the-standard-model/

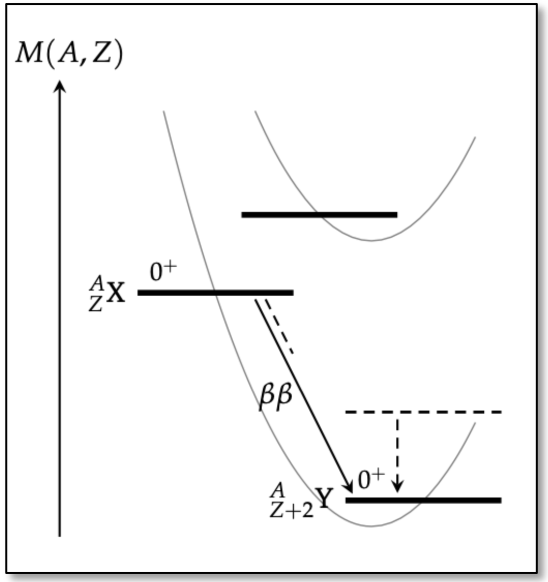
Neutrinoless Double Decay (0νββ)



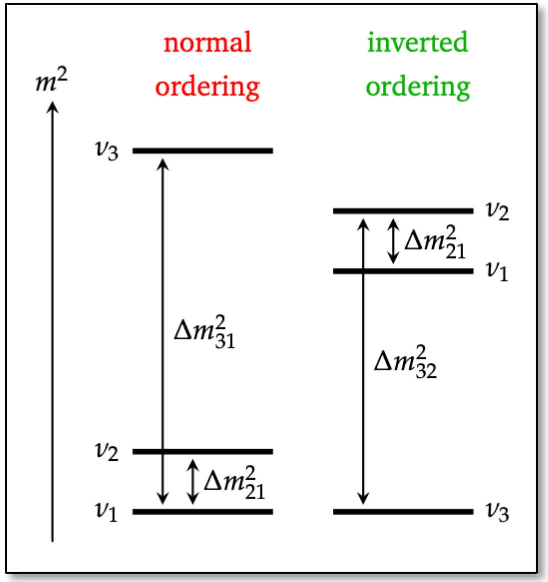
$(A,Z) \rightarrow (A,Z+2) + 2e^-$



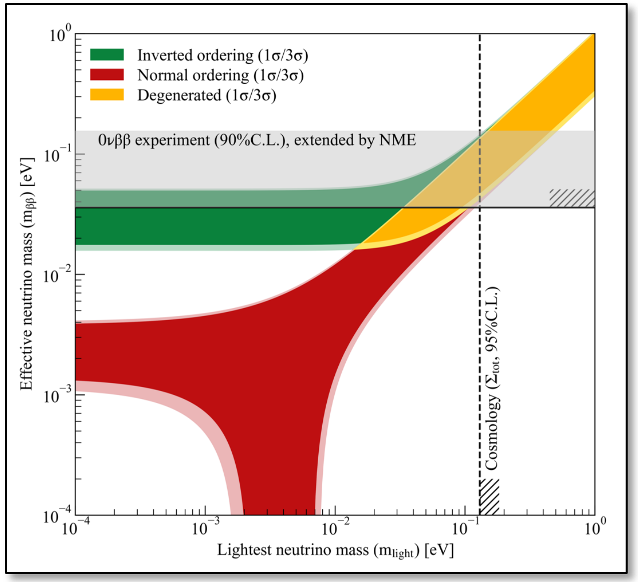
2β isotope



Mass hierarchy



Mass scale

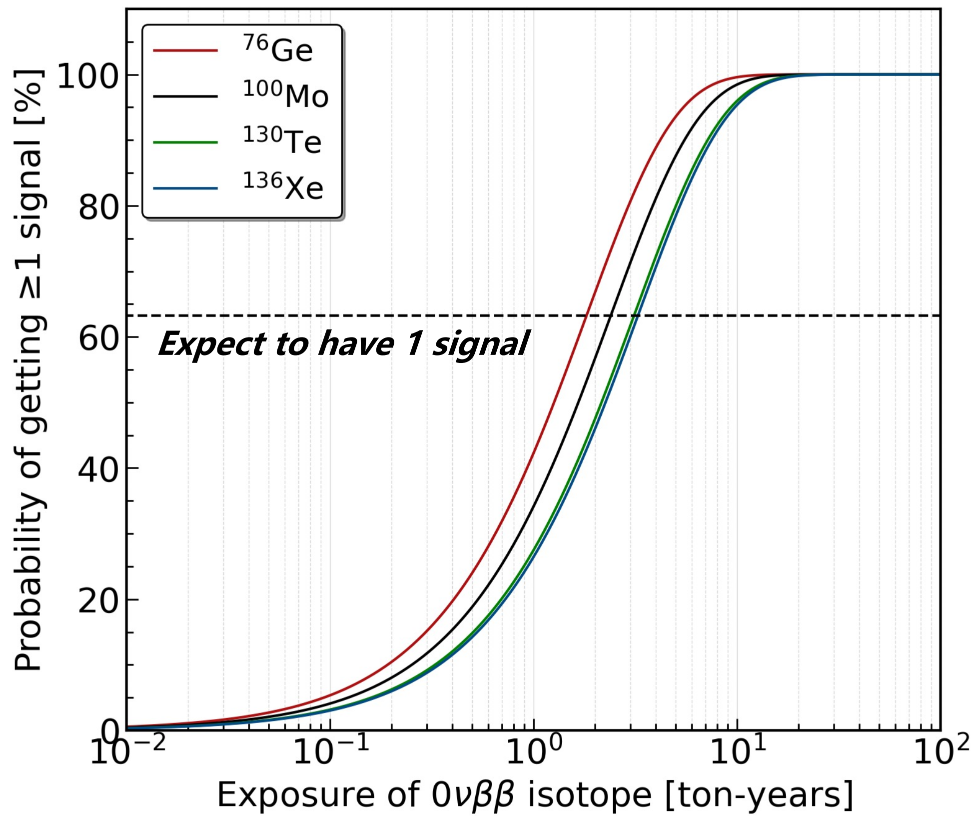


Experimental Search for 0νββ

Search Extremely Rare Signal Requiring Ultra Low Background

Run Big detector for Long time

(Ton•yr exposure for 1 signal @T=10^{28} yr)



Cut background to "0"

(<0.0027 for 3σ discovery sensitivity)

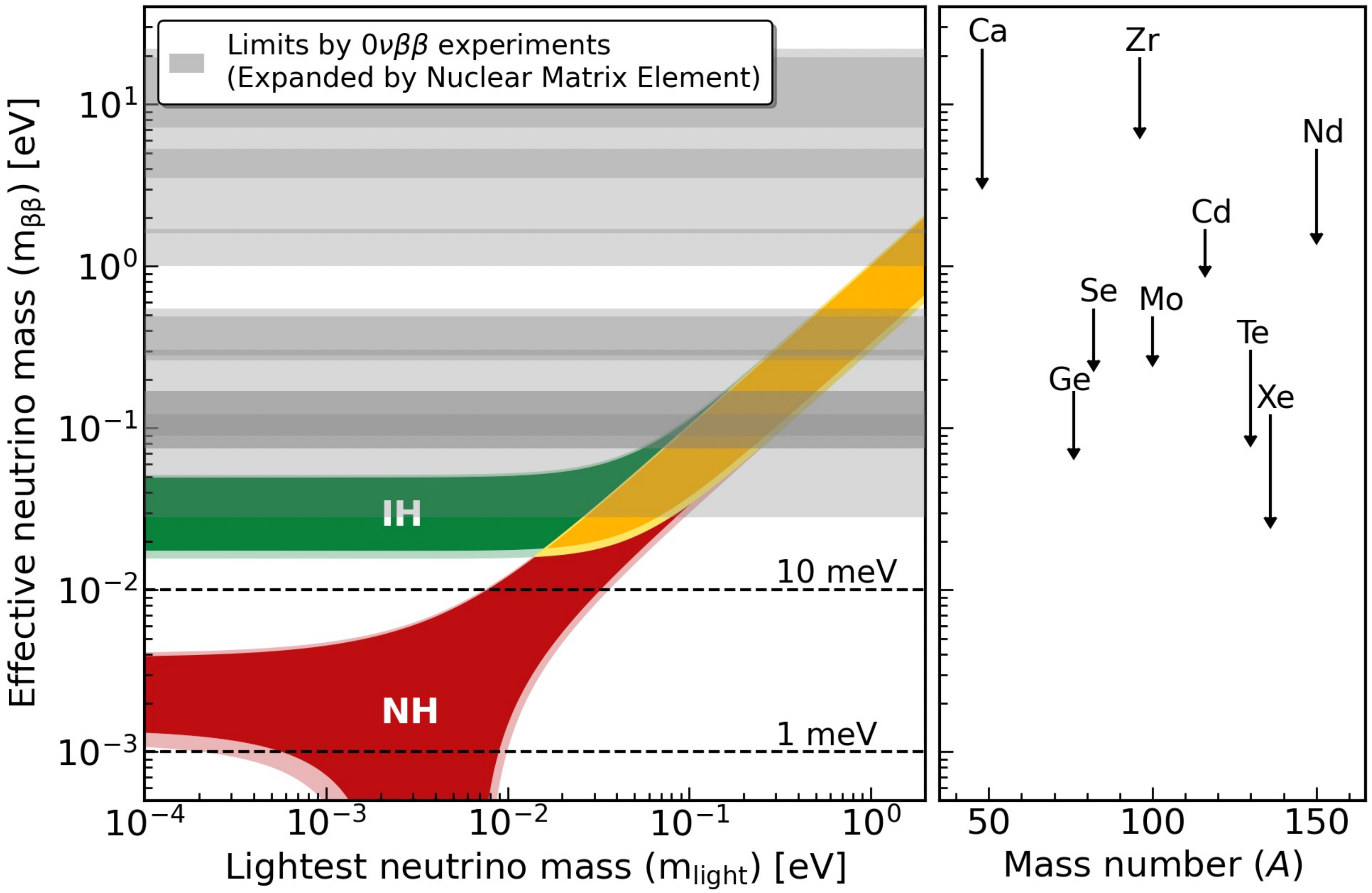
BG in ROI	P(observing ≥1 BG)
5	99.33%
1	63.21%
0.1	9.52%
0.01	1.00%
0.0027	**0.27% (3σ)**

When BG in ROI <0.0027, Observing 1 signal will be a >3σ discovery

Experimental Search for 0νββ

Multiple isotopes & Detector choices

Direction of efforts: Ton-scale & BG-free to 1~10 meV sensitivity



Phys. Rev. C 78, 058501 (2008)
Phys. Rev. Lett. 125, 252502 (2020)
ArXiv:2501.10046, (2025)
Phys. Rev. Lett 129, 111801 (2022)
Nucl. Phys. A 847, 168–179 (2010)
Eur. Phys. J. C, 82:1033, (2022)
Phys. Rev. D 98, 092007 (2018)
NATURE 604, 7 (2022)
Phys. Rev. Lett. 130, 051801 (2023)
ArXiv:2406.11438, (2024)
Phys. Rev. D 94, 072003 (2016)

Advantages of HPGe Technology

Enrichment, Exposure, BG counts in ROI

$$T_{1/2}^{0\nu} \propto \begin{cases} \varepsilon \cdot A \cdot \underline{M \cdot T} & \boxed{(BI \cdot \Delta E \cdot M \cdot T)} \ll 1 \\ \varepsilon \cdot A \cdot \sqrt{\dfrac{M \cdot T}{BI \cdot \Delta E}} & (BI \cdot \Delta E \cdot M \cdot T) \gg 1 \end{cases}$$

Efficiency, Background, Energy Resolution

① **High efficiency (ε): Source = detector**

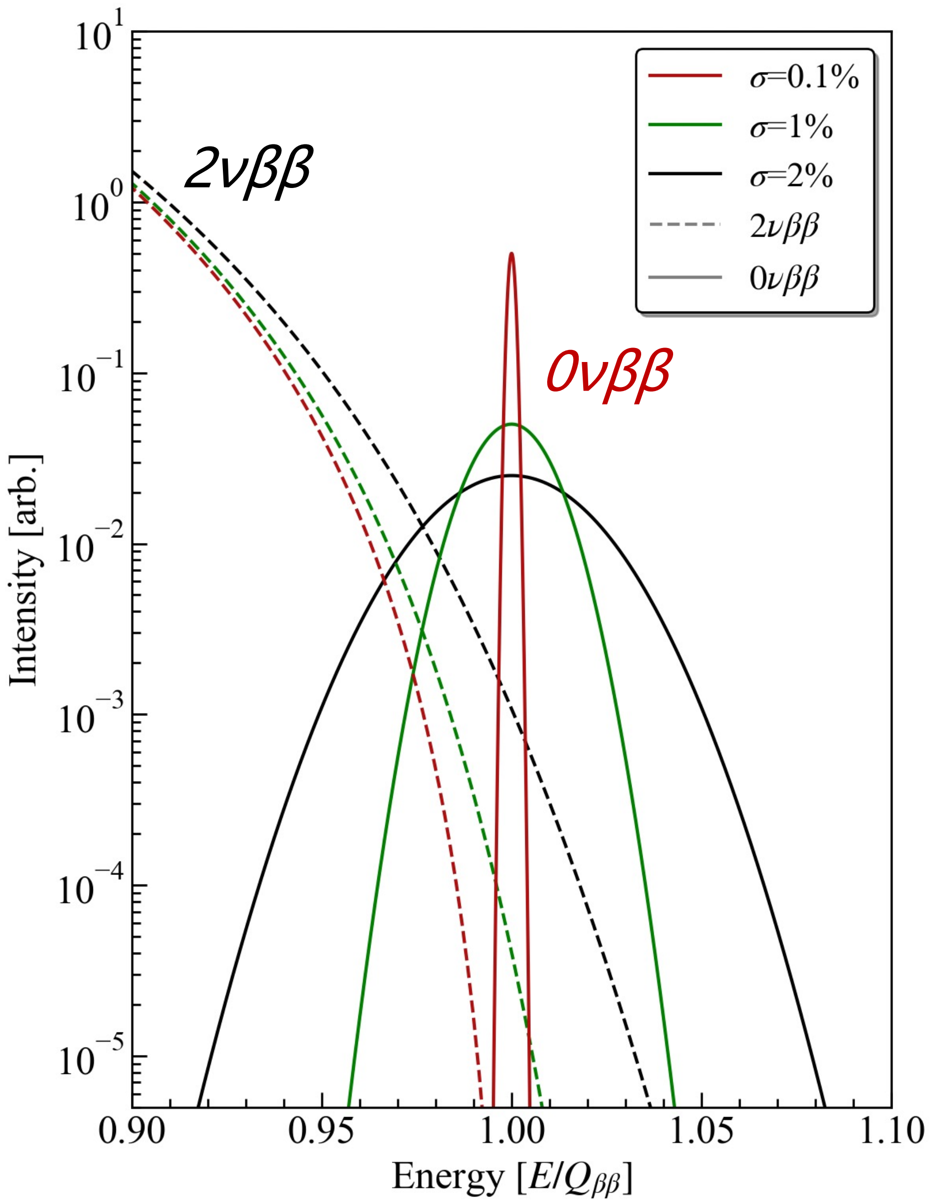
② **Industrial enrichment for ^{76}Ge: ≥86% (A)**

③ **Intrinsic high-purity crystal: ~13N (Low BI)**

④ **Background rejection: PSD, LAr veto…**

⑤ **Energy resolution (σ) ~0.05% @ 2MeV**

HPGe can be free from 2νββ background!

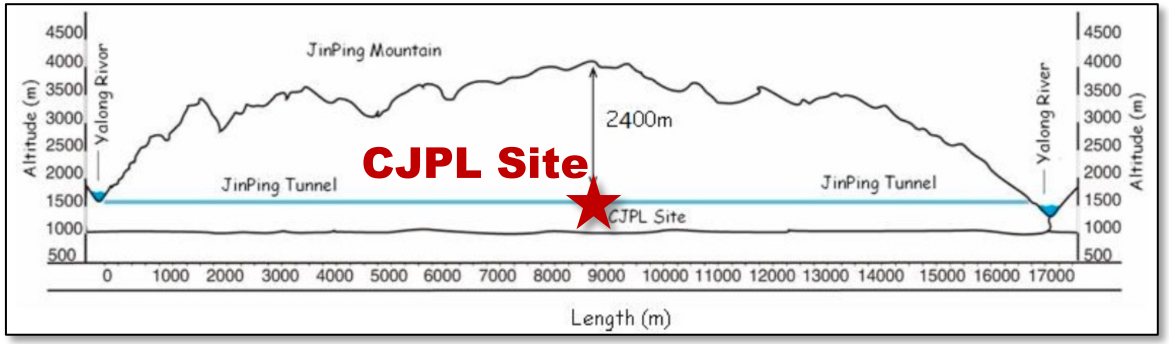


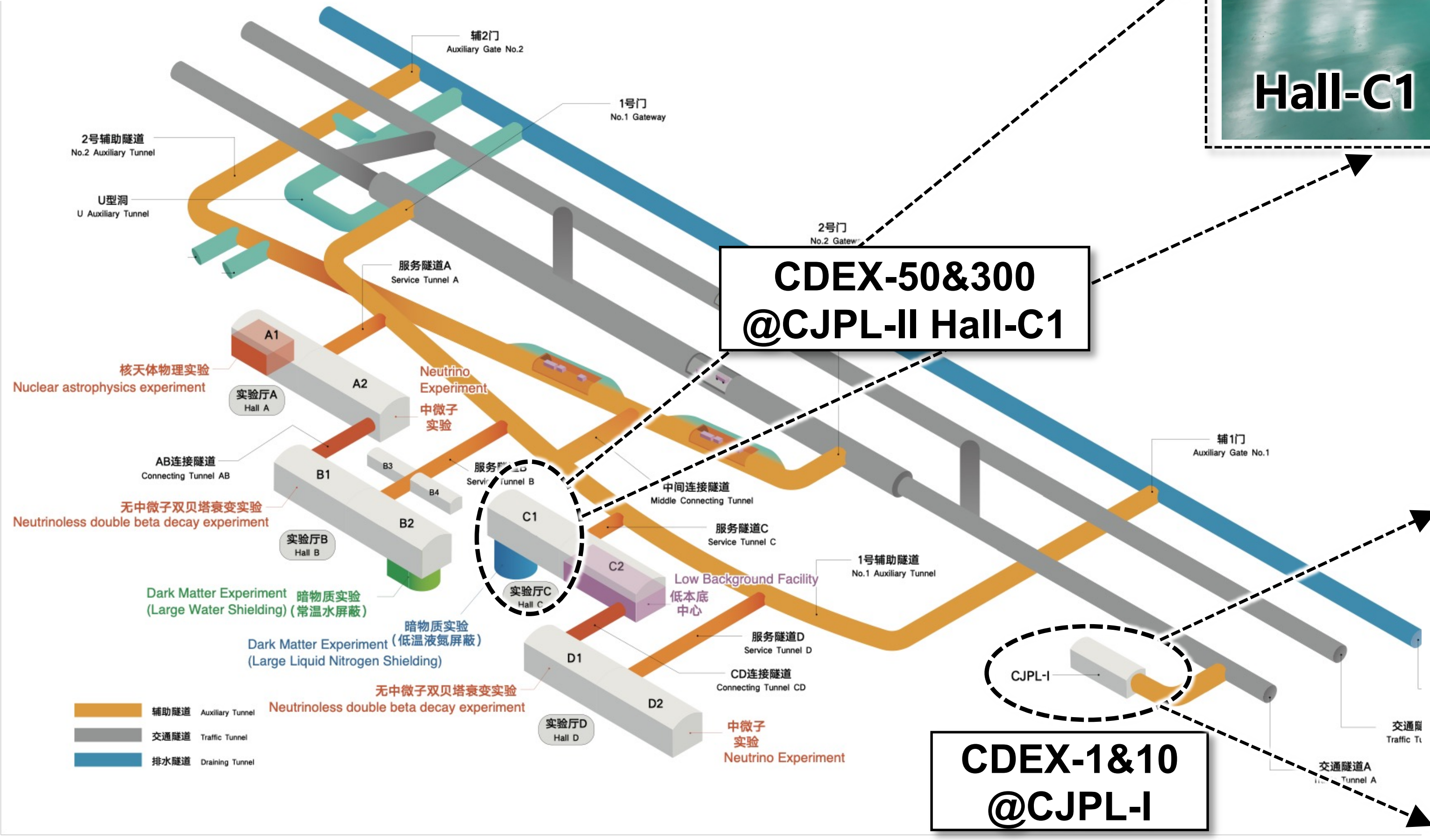
II. CDEX and its $0\nu\beta\beta$ studies

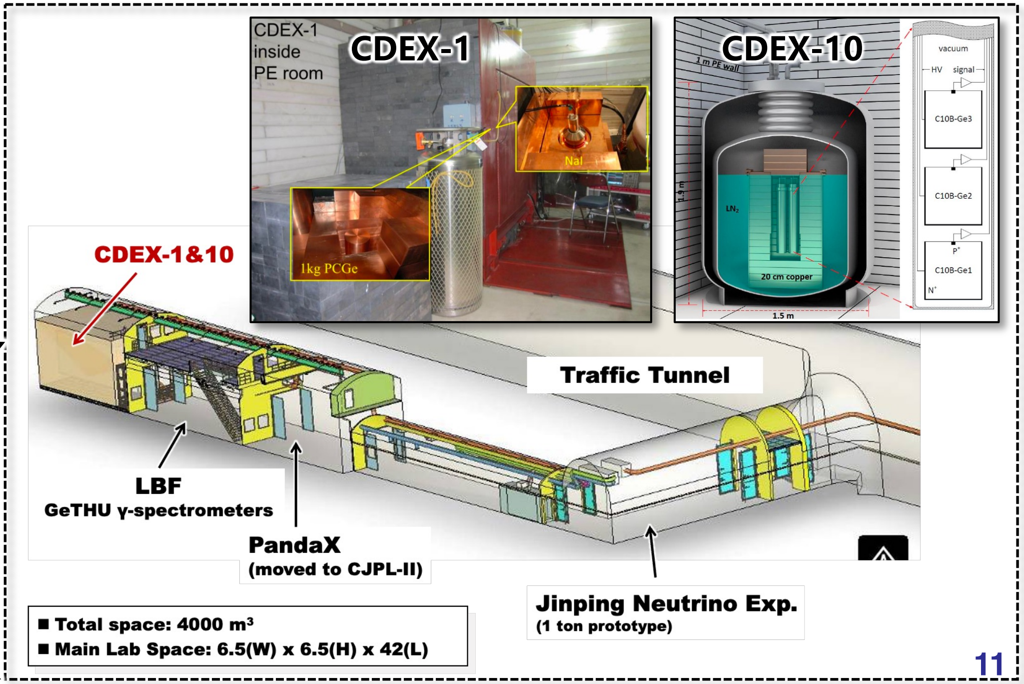
China Dark matter EXperiment (CDEX)

- Founded in 2009, 10 institutions, more than 100 people now
- Search for Dark Matter and Ge-76 0νββ via HPGe detectors

China Jinping Underground Laboratory (CJPL)







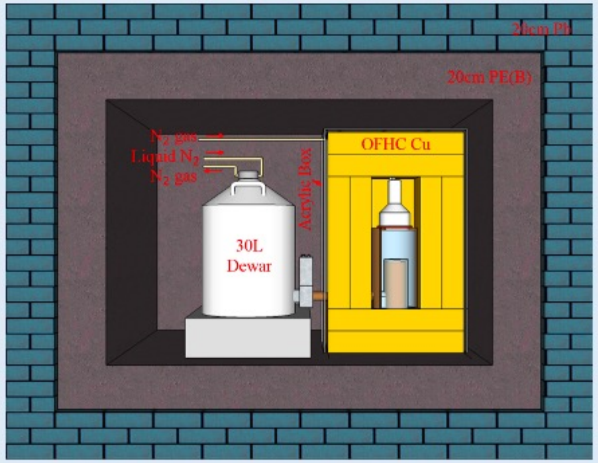
CDEX Roadmap

2009-2016	2016-2022	2021-	Planed

CDEX-1

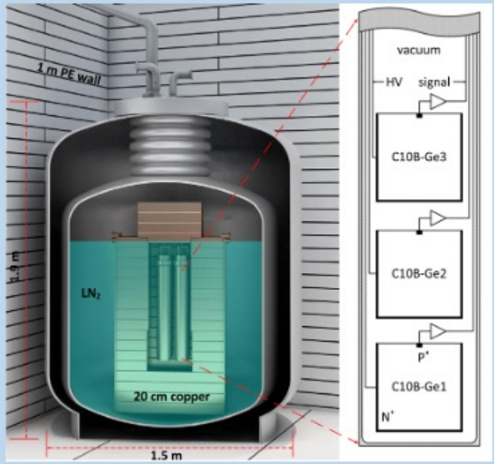
CDEX-1A
- DM: χ-N (SI/SD)
- Axion & Axion-like DM
- CDEX first 0νββ result

CDEX-1B
- DM: χ-N (SI/SD)
- DM: χ-N (Migdal Effect)
- DM: χ-N (AM)
- Axion & Axion-like DM



CDEX-10

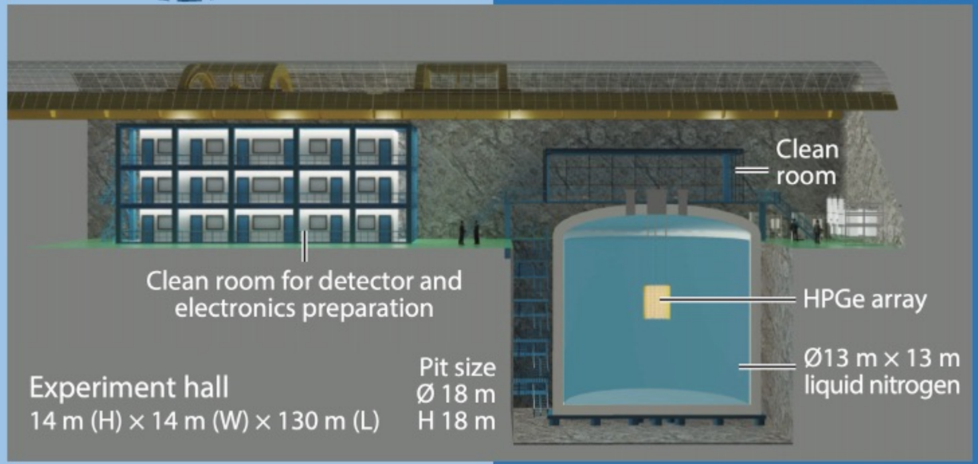
- DM: χ-N (SI/SD)
- DM: χ-N (EFT)
- Solar dark photon
- Dark photon DM
- DM: CR boosted DM
- DM: Exotic DM
- DM: χ-e
- DM: Evaporating PBHs



CDEX-50 (DM)

CDEX-300 (0νββ)

CDEX-1T (0νββ, DM…)



CJPL-I

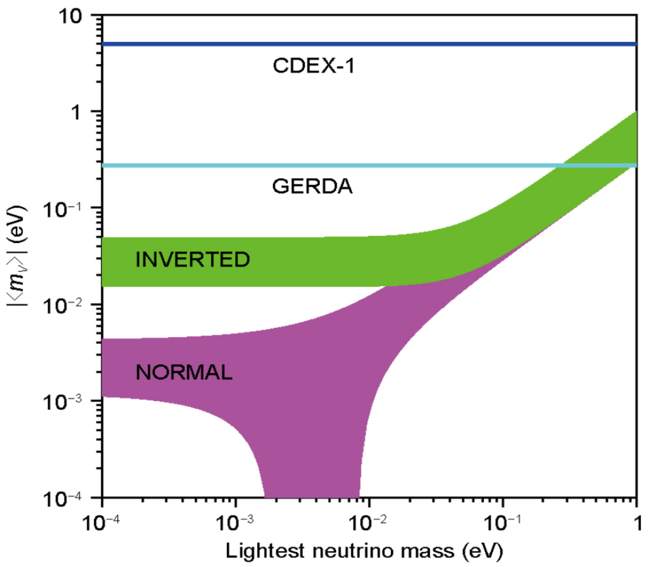
CJPL-II

0νββ Study in CDEX-1

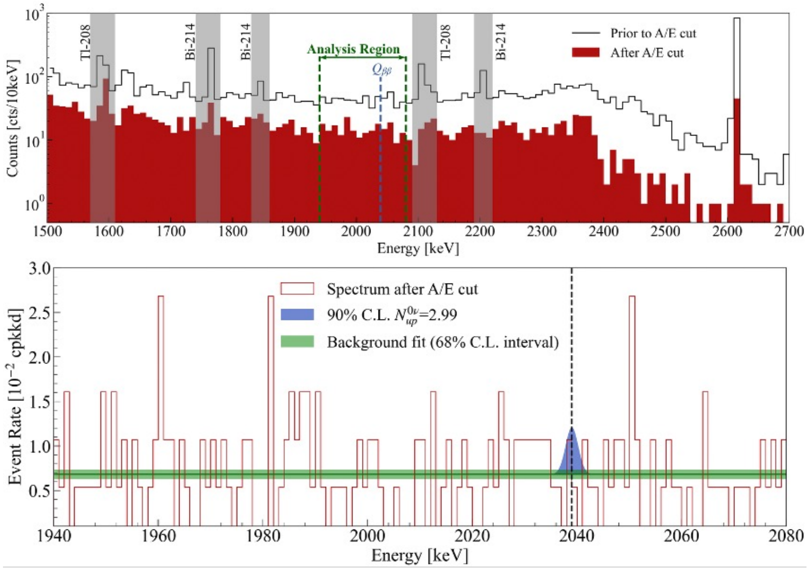
Pre-study for future large scale 0νββ experiment (CDEX-300)

- 2017, First 0νββ result using CDEX-1A data
- 2022, Study Pulse shape discrimination using a BEGe detector
- 2024, Improved 0νββ result using CDEX-1B with PSD & veto

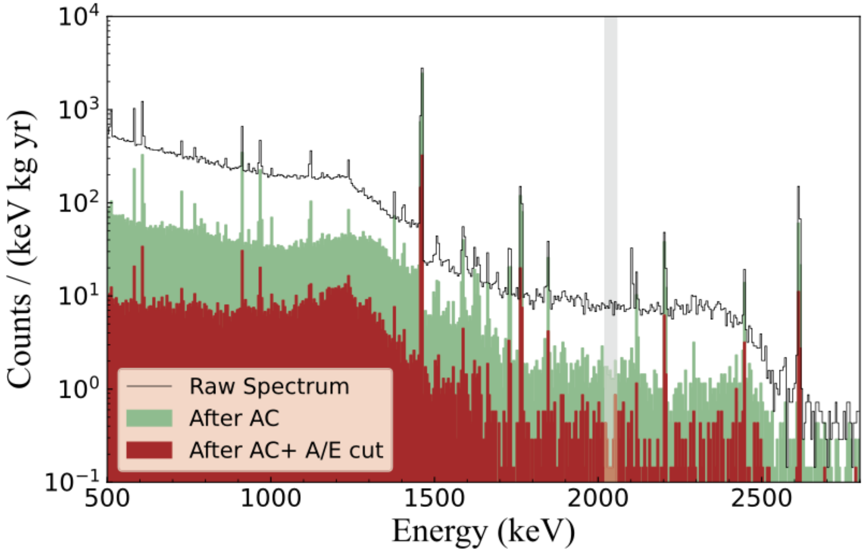
Sci. China PMA. 60, 071011, 2017



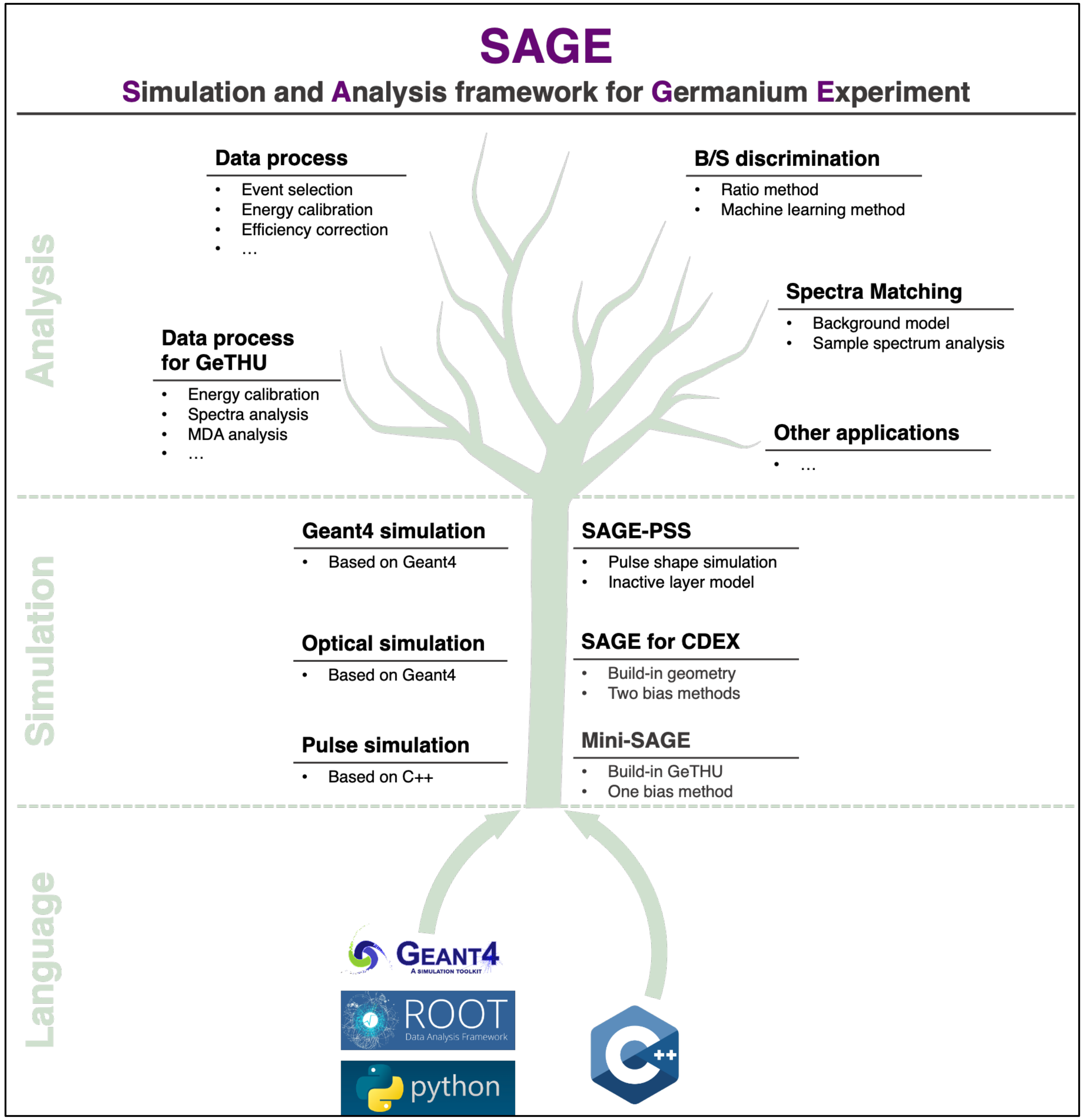
PRD 106, 032012, 2022



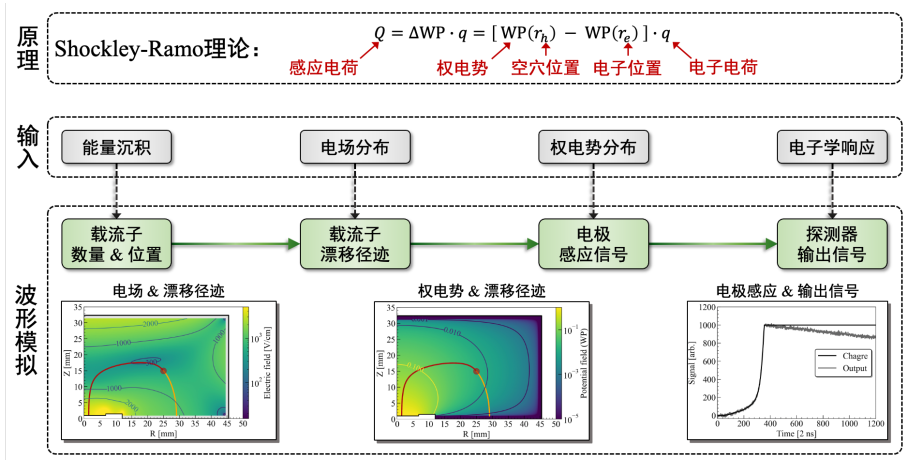
CPC 48, 101001, 2024



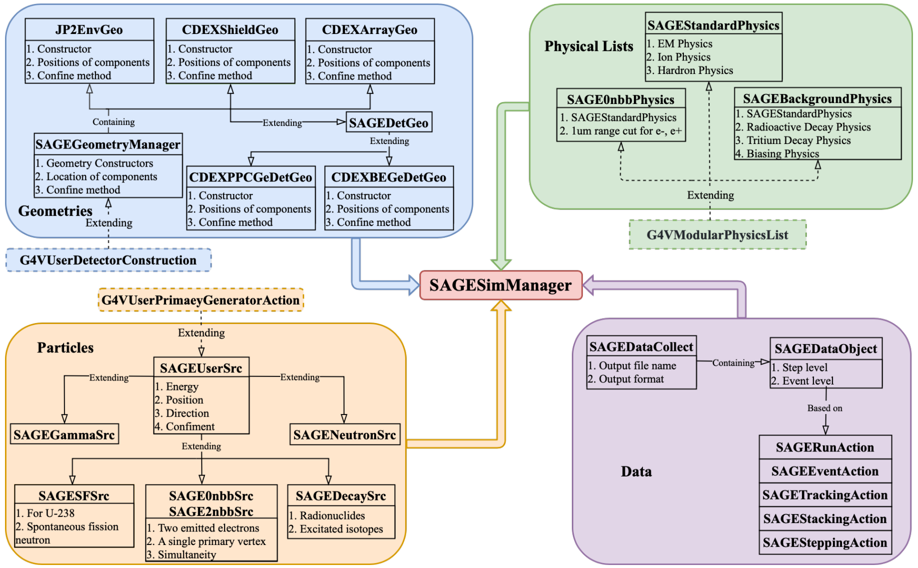
Simulation toolkit for CDEX: SAGE



Pulse shape simulation for HPGe



Particle simulation for HPGe experiment

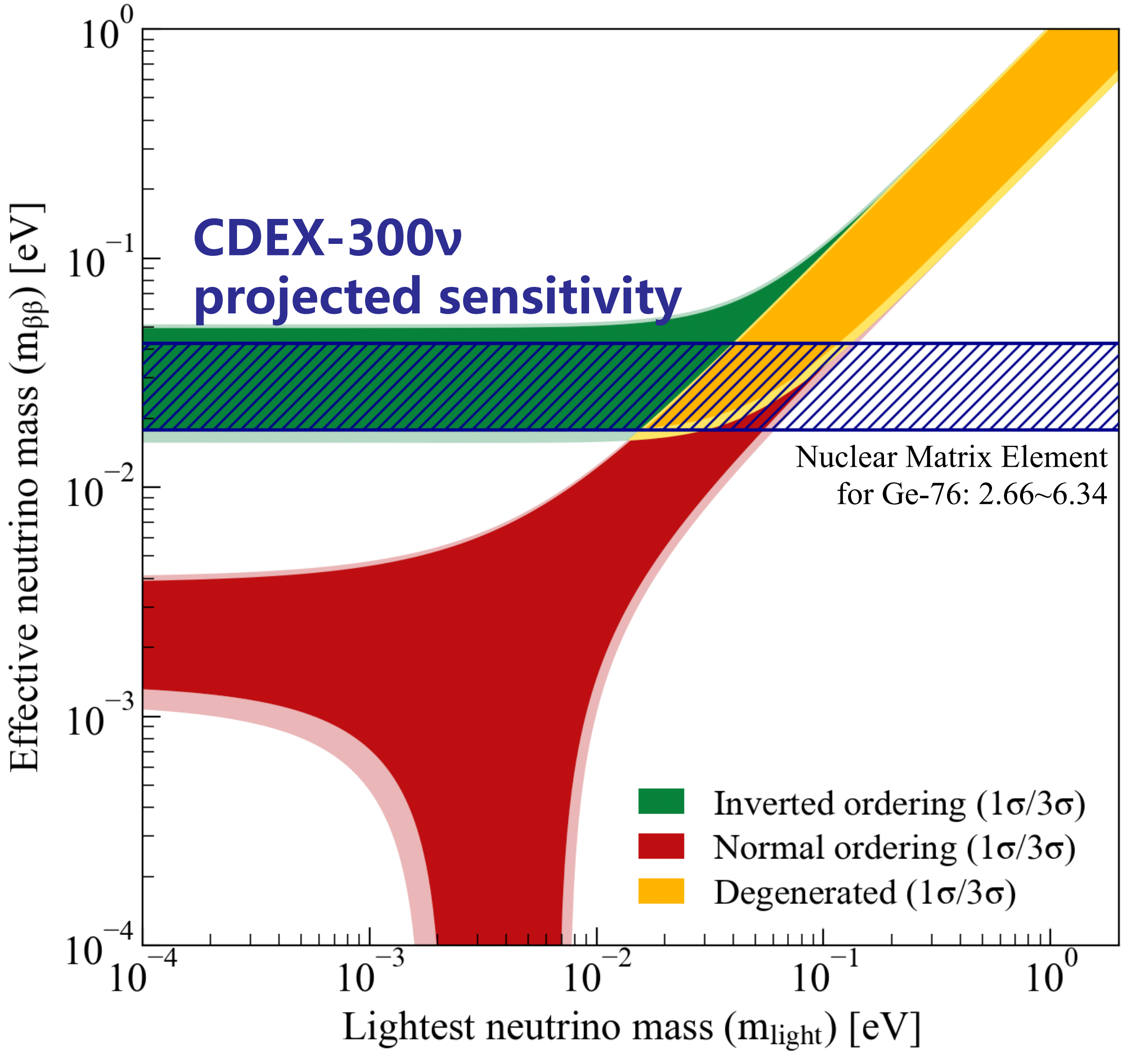


III. Design and status of CDEX-300ν

Physics Goal of CDEX-300

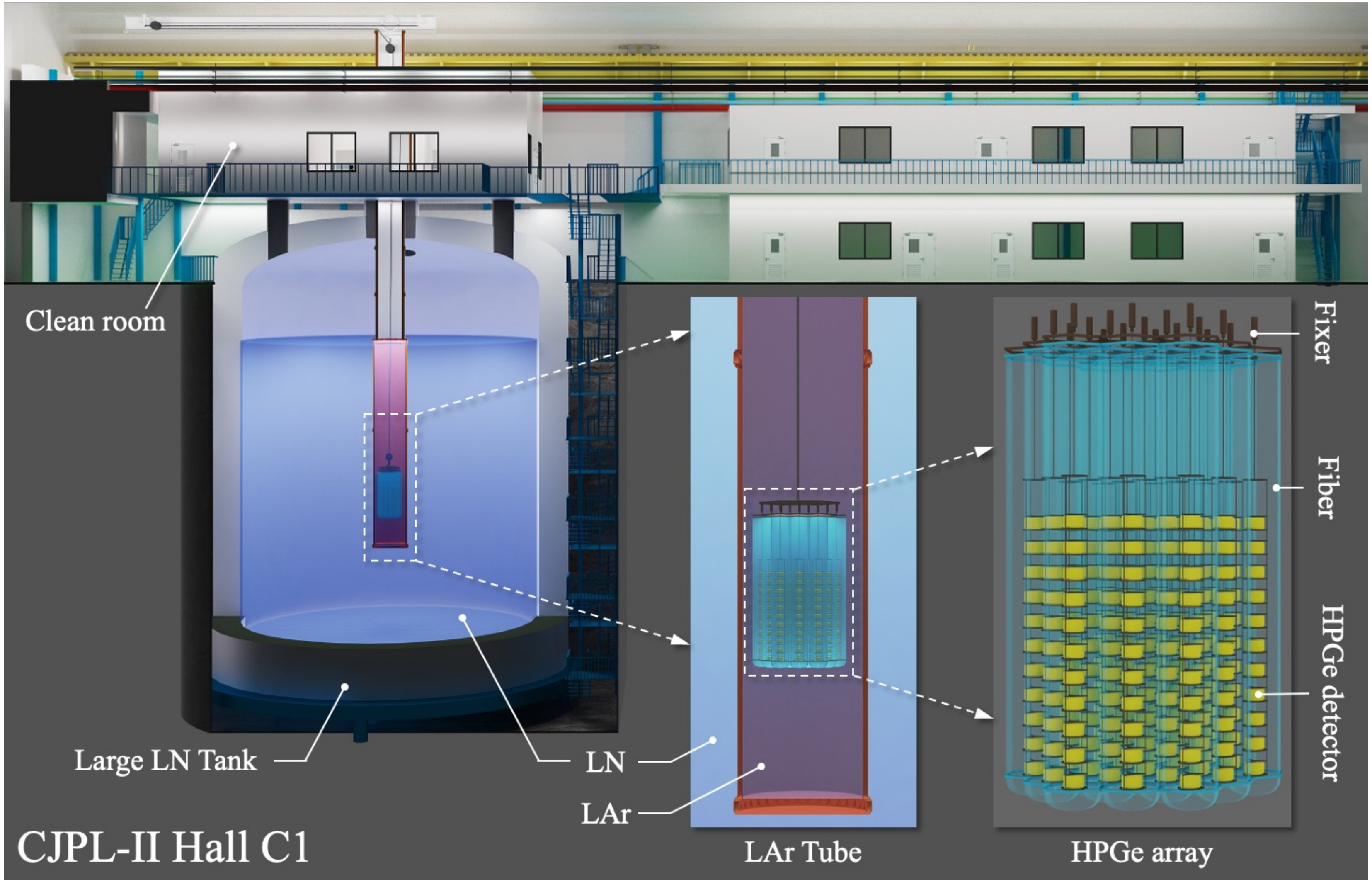
Physics Goal	
0νββ half-life	3.06×10^{27} yr (exc) 1.91×10^{27} yr (dis)
Effective mass	18.5 ~ 44.2 meV (exc) 23.4 ~ 55.8 meV (dis)
Detector Parameter	
Detector mass	225 kg
Operation time	10 yr
Ge-76 enrichment	≥ 86%
Signal efficiency	76%
Background level	1E-4 cpkky
Energy resolution	2.5 keV FWHM

Search Ge-76 0νββ decay at Inverted Ordering (IO) region

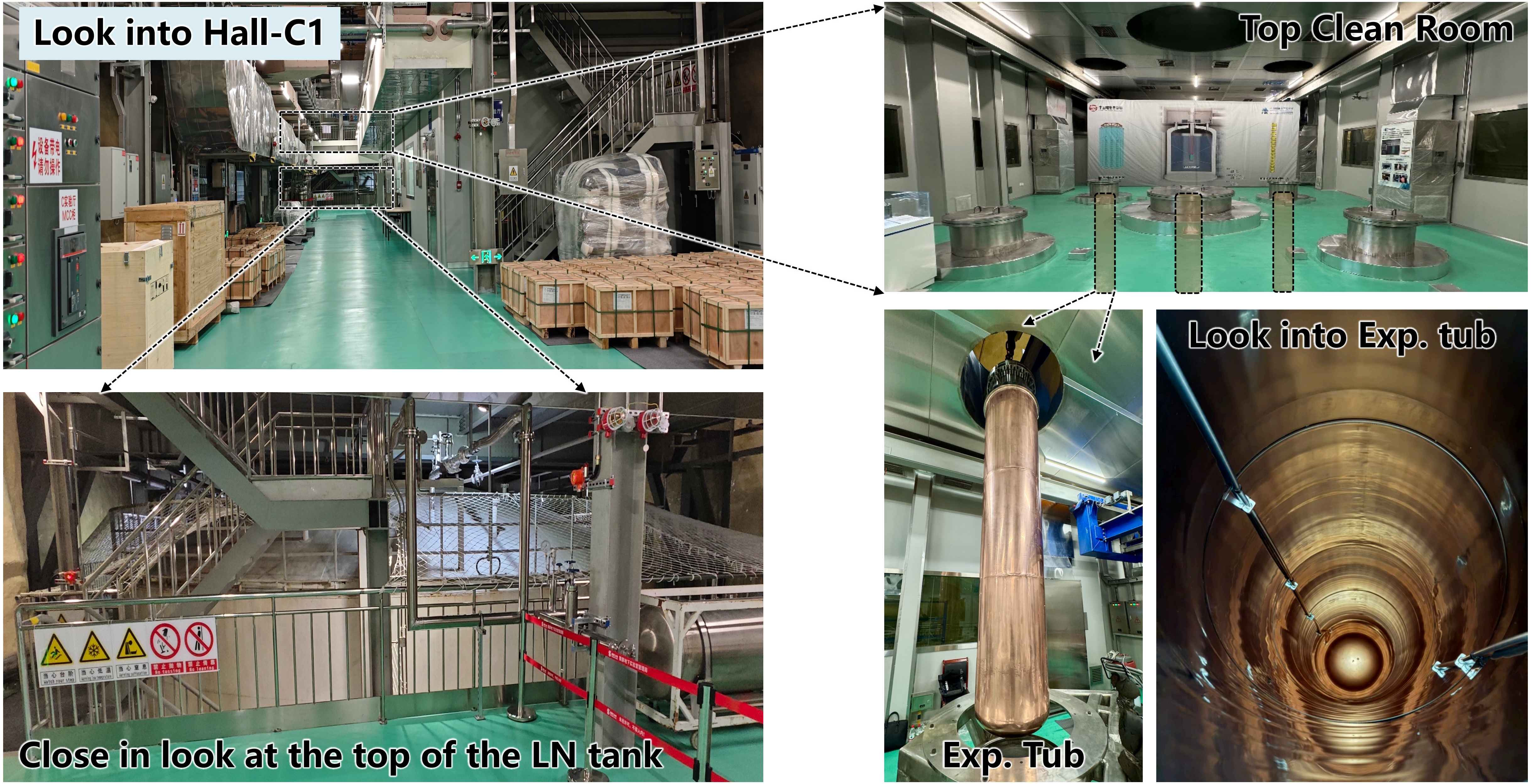


CDEX-300 Overview

- Hall-C1 at CJPL-II
- LN_2 tank shared with CDEX-50
- LAr tube containing LAr submerged in LN_2
- Ge detector array immersed in LAr
- 200 enriched HPGe detectors divided into ~19 strings

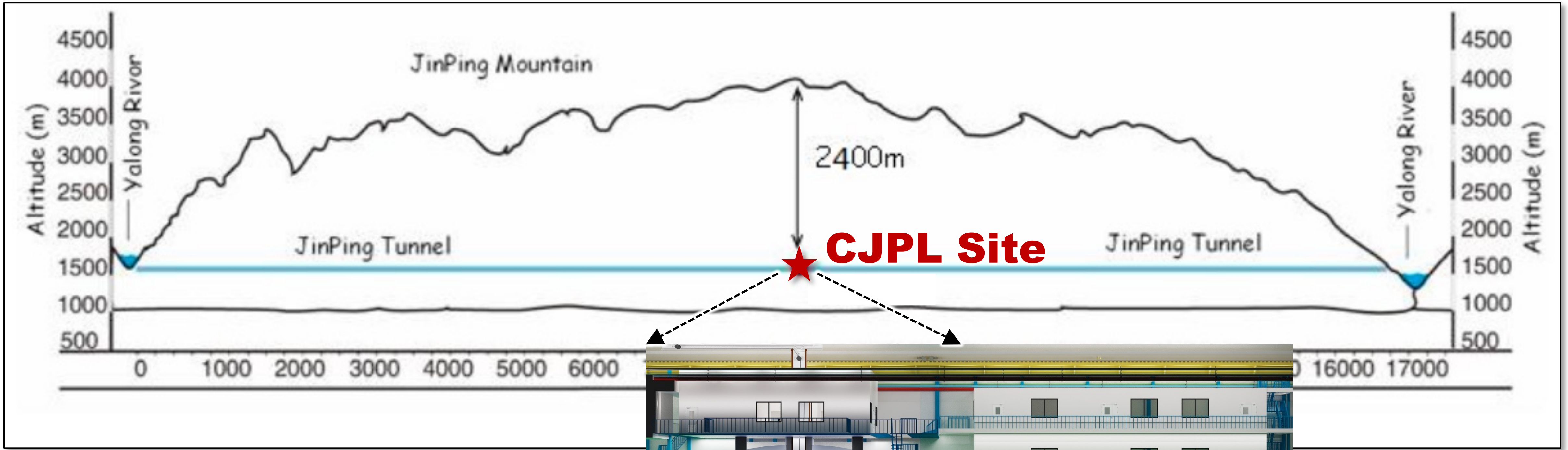


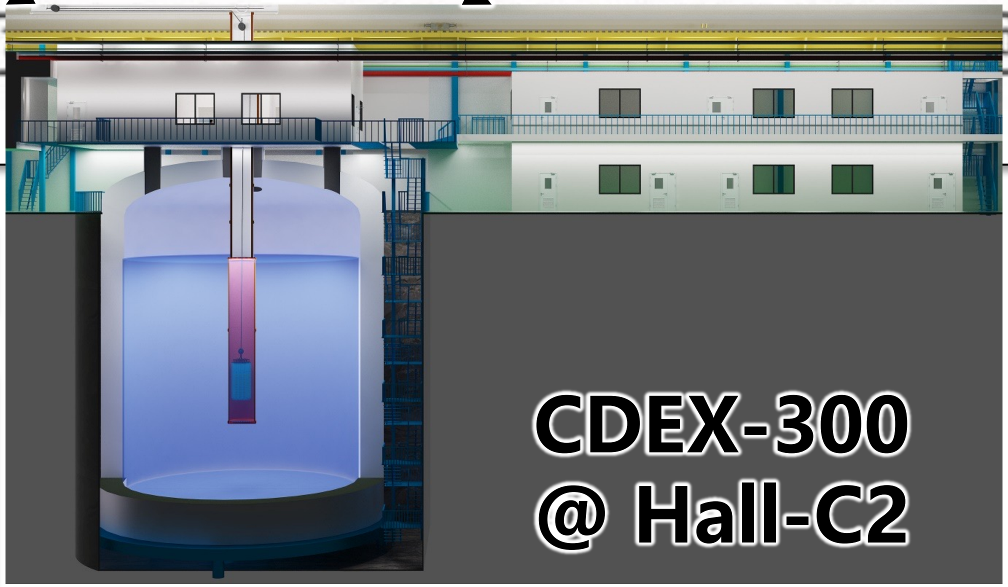
Current Status of Hall-C1



2400 m Rock Shielding against Cosmic-ray

Muon & Muon-induced background is negligible for CDEX-300





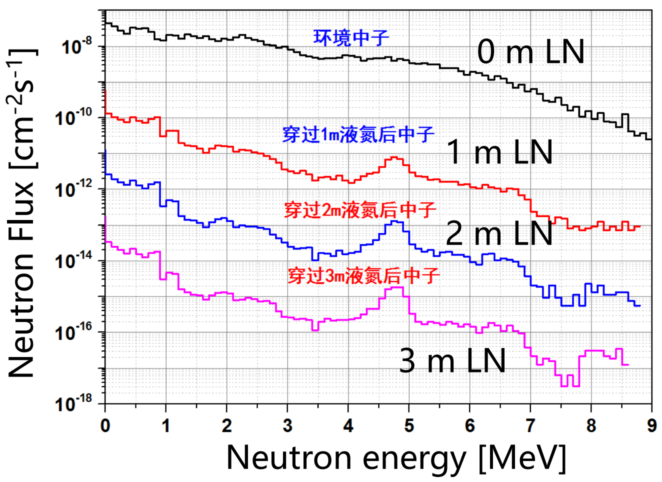
- □ **Muon flux 3.03×10^{-10} cm^{-2}s^{-1}**

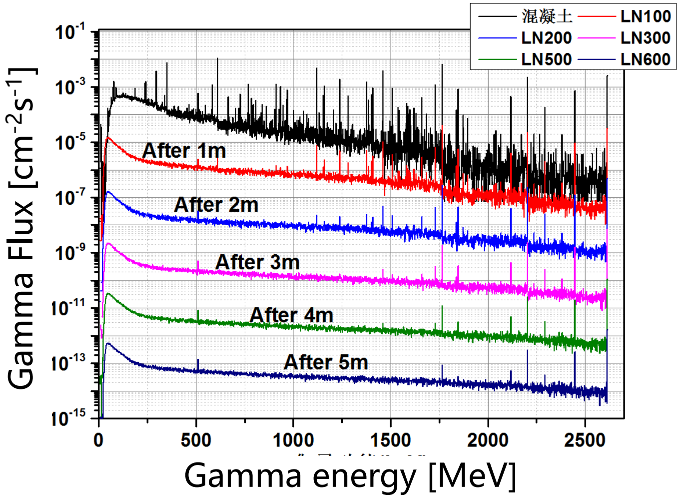
Muon-induce background
- □ **~1E-7 cpkky @ 2MeV ROI**
- □ **Negligible for CDEX-300**

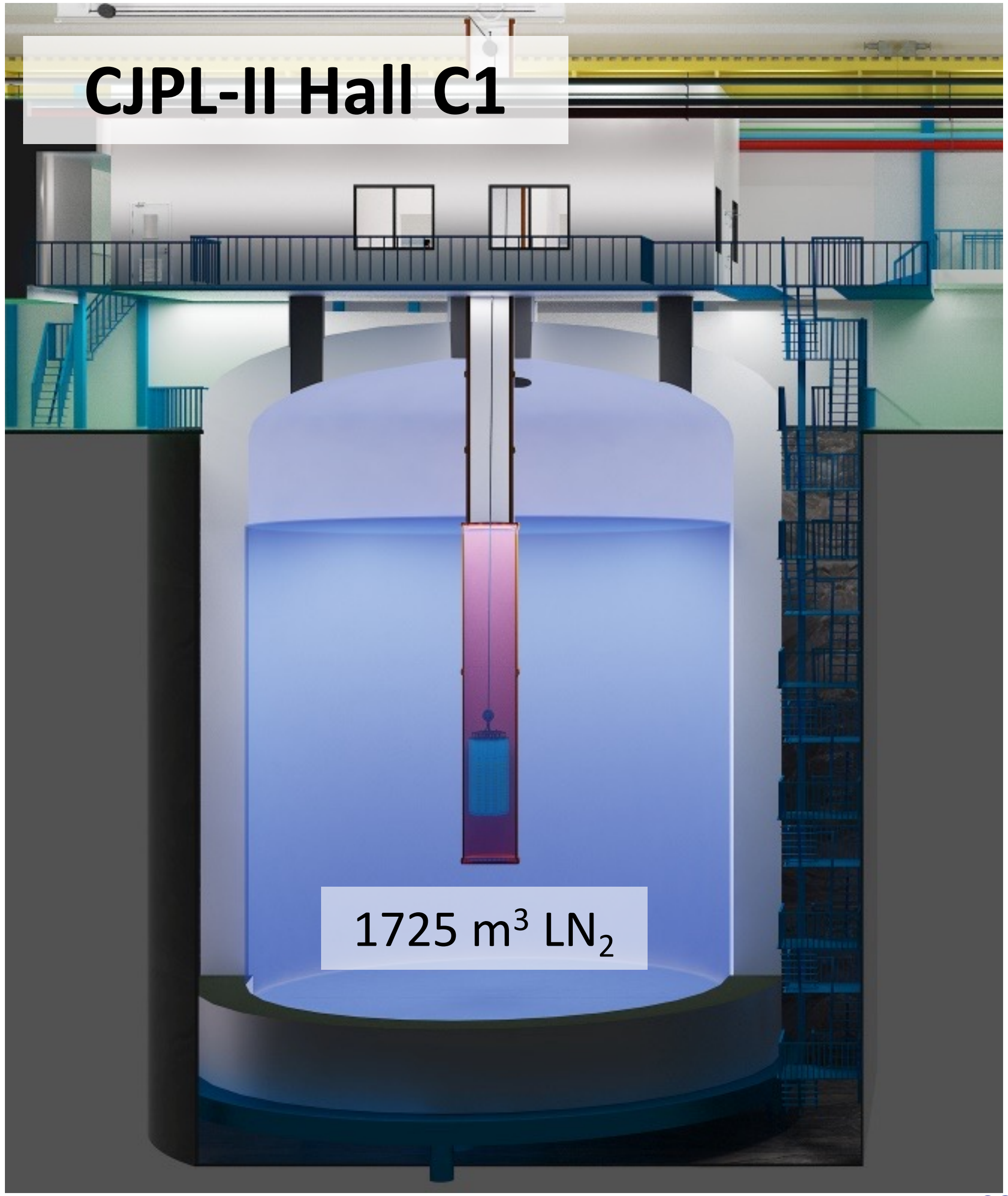
The LN_2 tank

- Total volume: 1976 m^3
- LN_2 volume: Φ13m×H13m, ~1725 m^3
- LN_2 as Passive Shield / cold source for LAr
- Five top flanges for detector deployment
  - 1×φ1.5m, centrally (CDEX-300ν)
  - 4×φ750mm, on a 6 m diameter circle

LN_2 as Effect Shielding against neutron & gamma



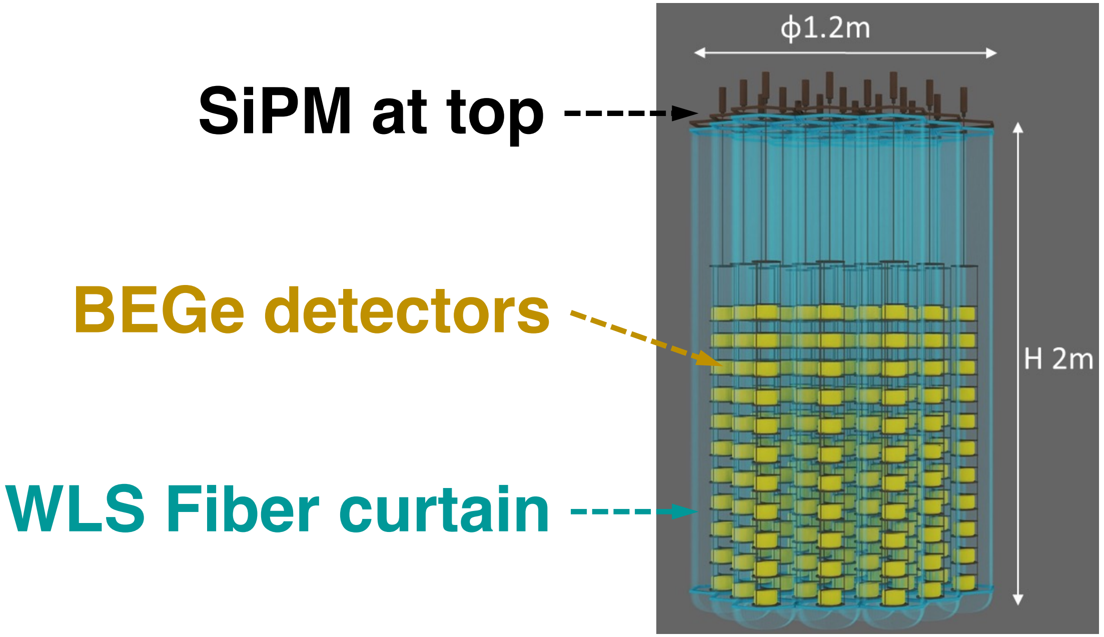


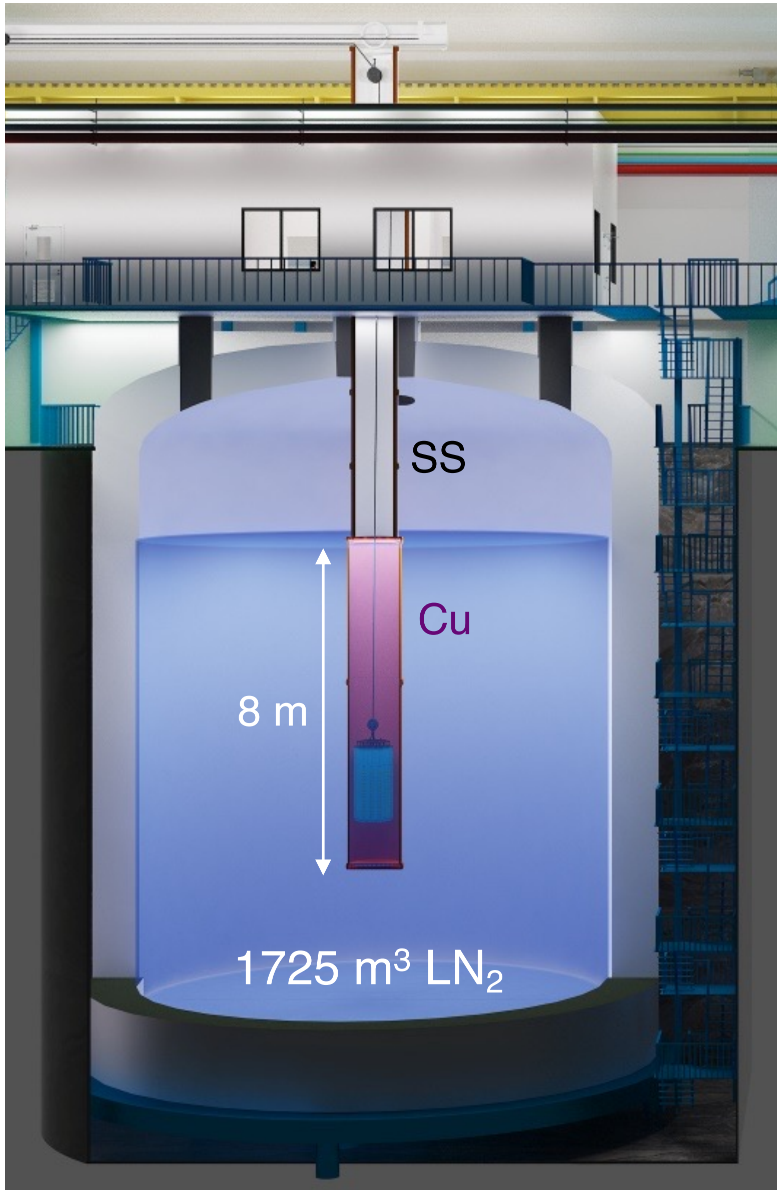


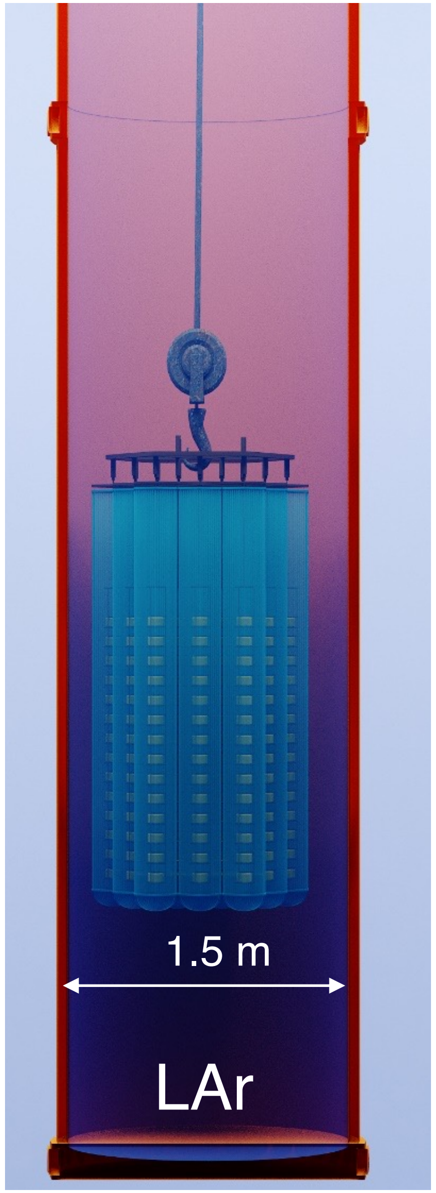
The LAr Veto System

Baseline design:

- ~20 t LAr held by Cu / SS cryostat
- LAr constantly purified
- LAr cryostat immersed in LN_2
- LAr light read out by WLS Fiber + SiPM







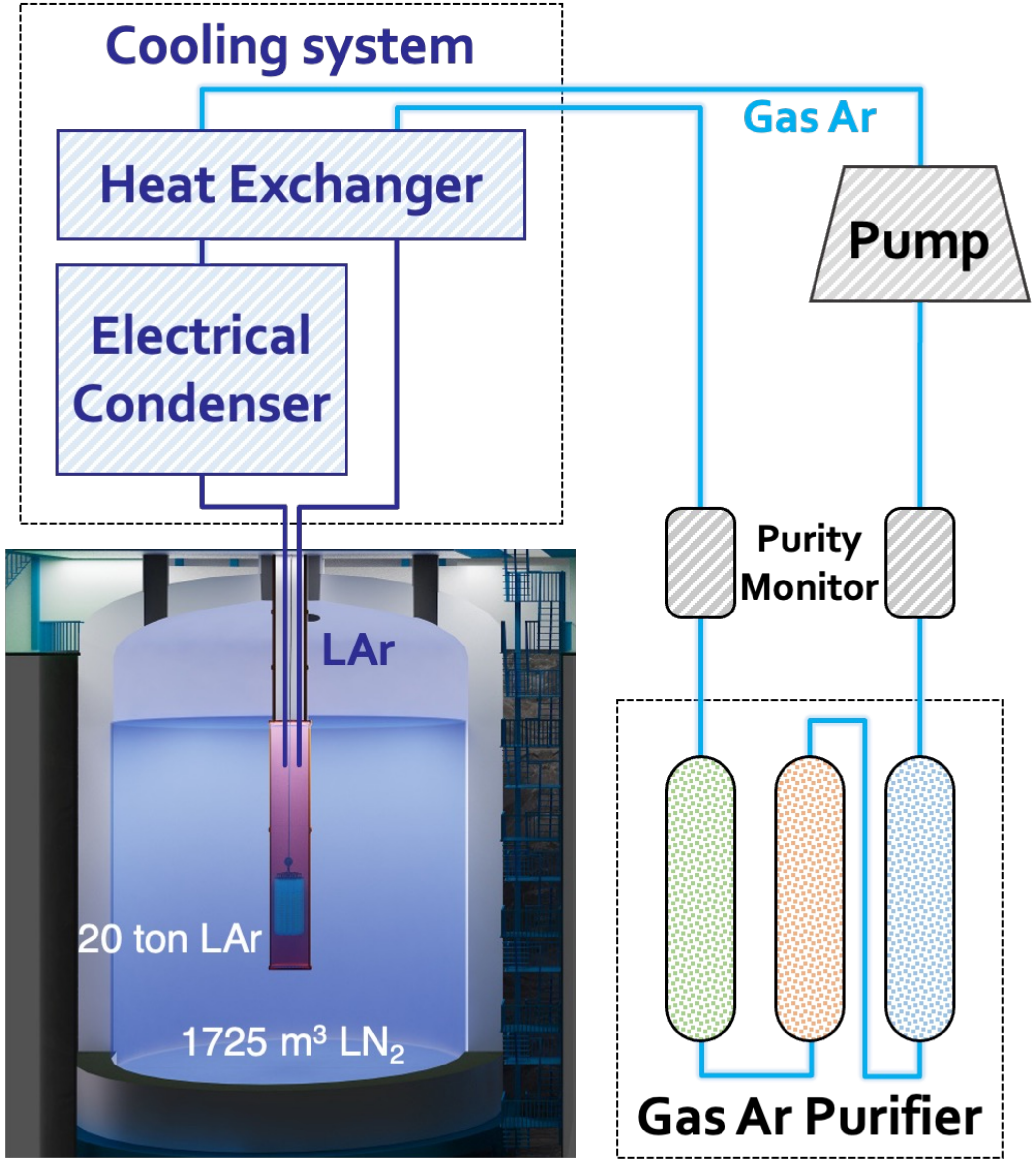
The LAr Veto System

The LAr Purification

- Removing O_2, H_2O… from GAr (≤10 ppb)
  - Maintaining light yield of LAr
  - Reducing light absorption in LAr
- Removing Rn by active carbon (~μBq/m^3)
- Possible underground Argon (Ar-42 depleted)

LAr Cooling

- Cooling purified GAr to LAr
- Heat exchanger + electrical condenser
- Backup LN_2 cooling module



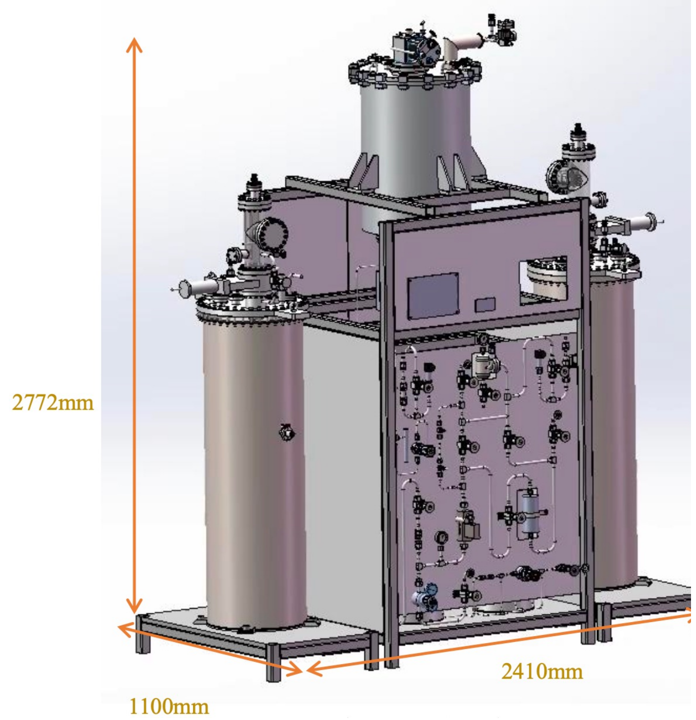
Prototype LAr system at Xichang ground Lab

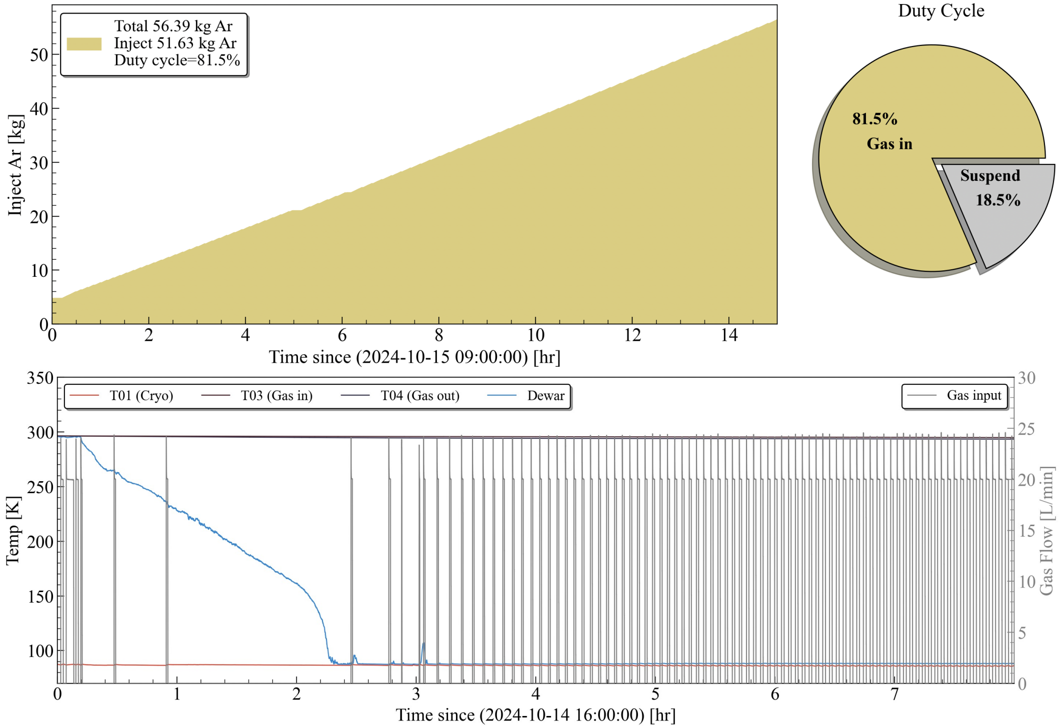
Construction finished and started testing in December 2024

① **Stage-1:** Operating & Purifying 200 L LAr in a closed cycle

② **Stage-2:** Deploying light readout to study light yield / transmission of LAr in different impurity levels

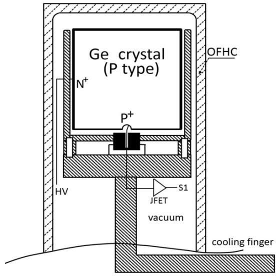
③ **Stage-3:** Deploying Ge detectors to test veto performance



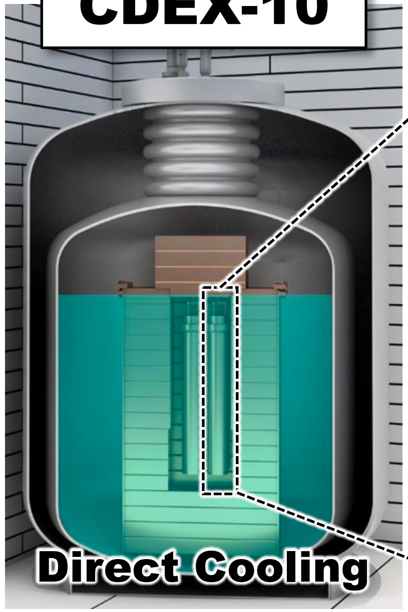


Detector Module: Reducing Structure Mass

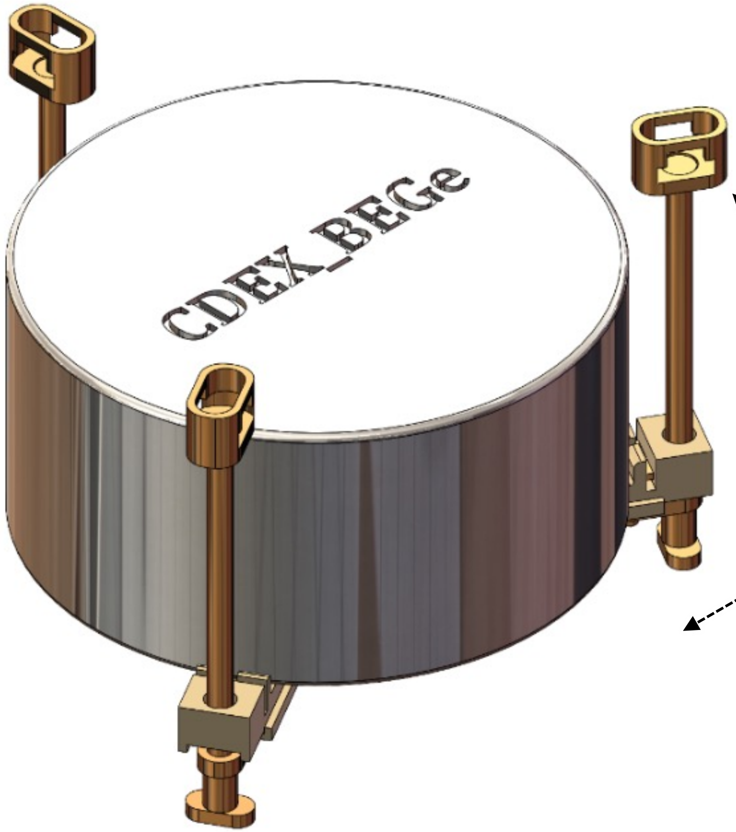
CDEX-1



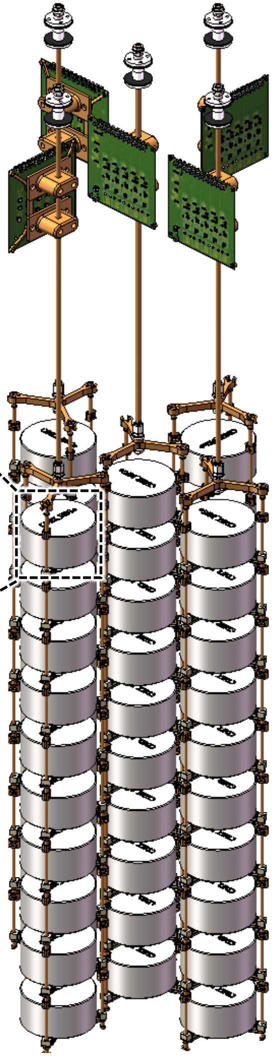
CDEX-10



CDEX-300



Detector string
Total 200 dets.

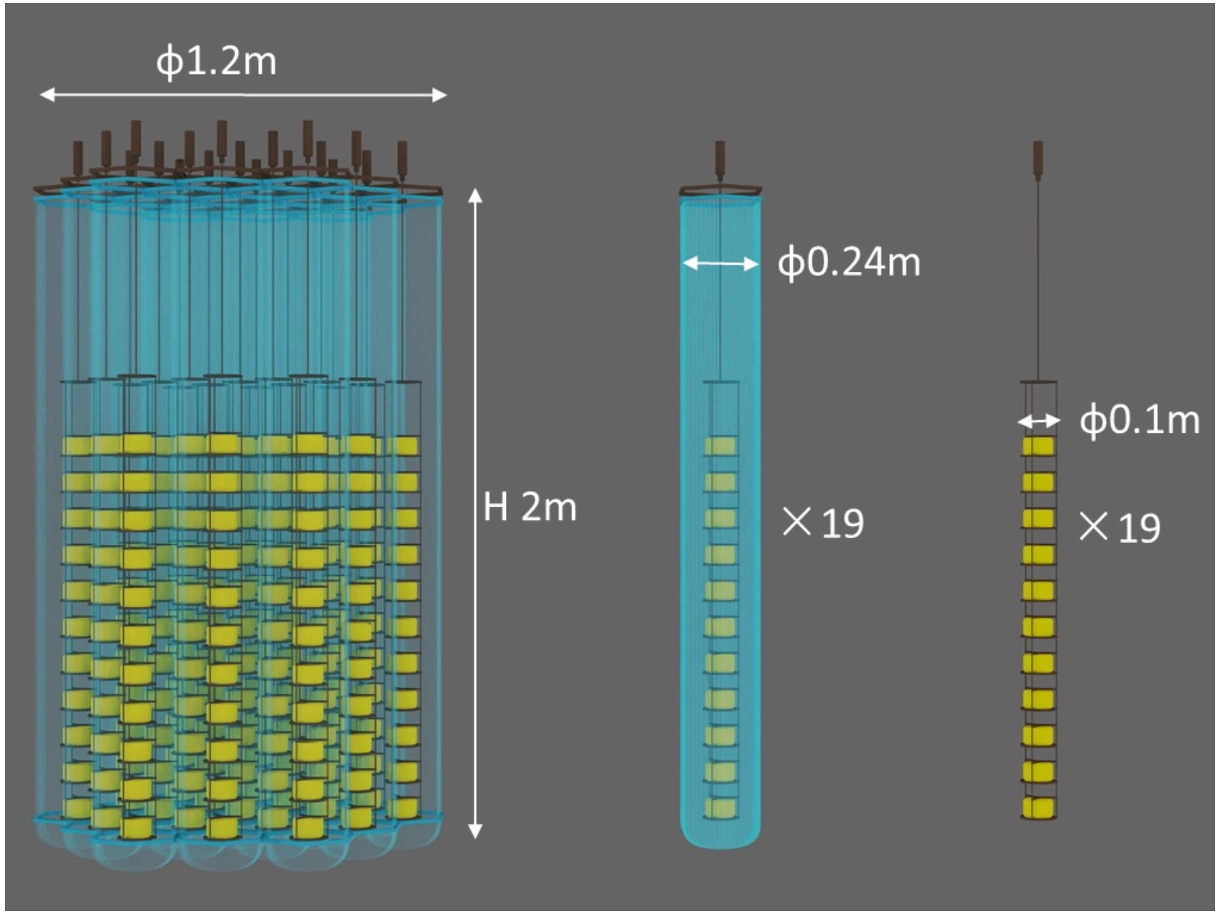


Detector module

Directly immersed in LAr

Ge Detector Array

- 200 Ge-76 enriched detectors: 19 strings, 10~11 det/string
- Top clean room for Ge detector and fiber installation

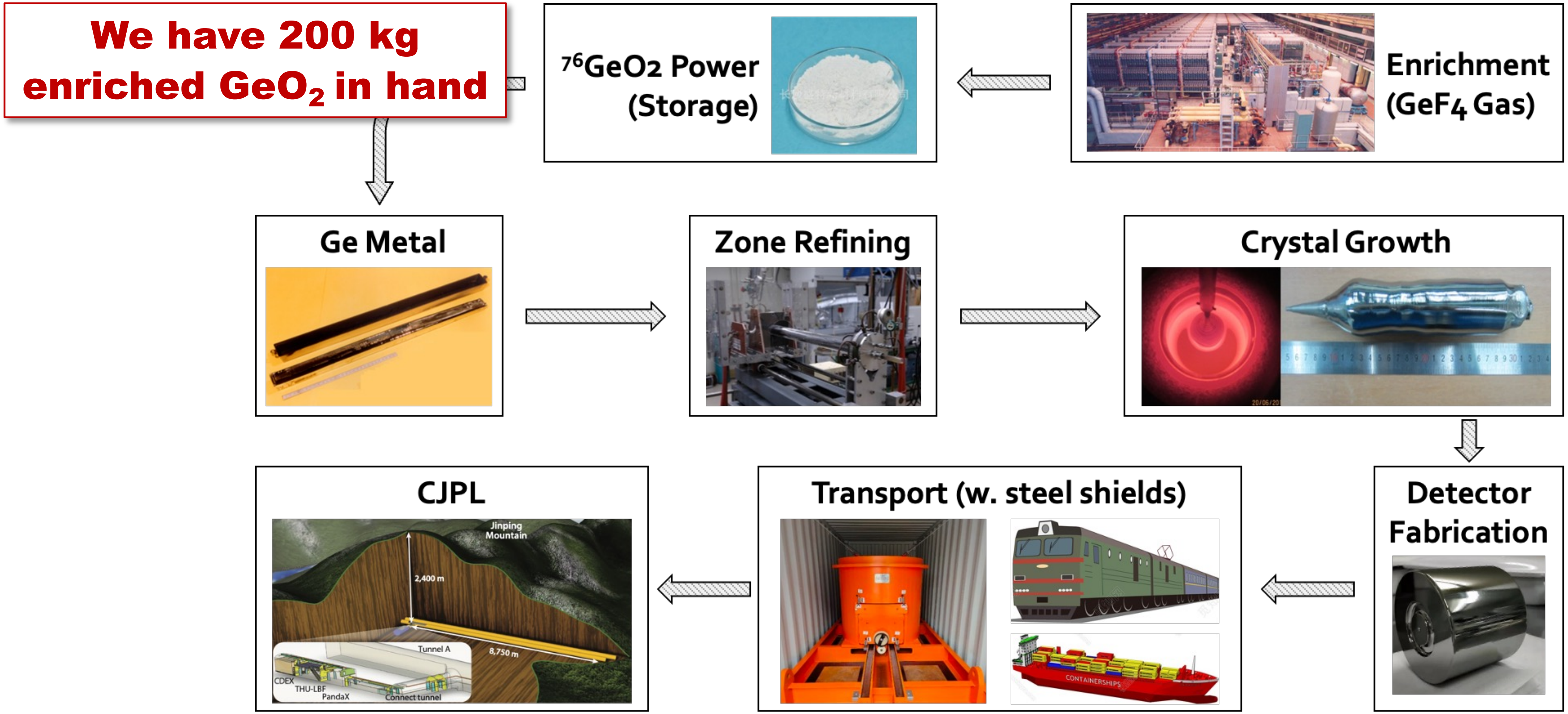


Status of the Top Clean Room

Enriched HPGe detector

Procurement of Enriched Ge detector

(Technical chain established: Ge-76 enrichment → Ge metal → Crystal growth → Detector fabrication)



Cosmogenic Background Control

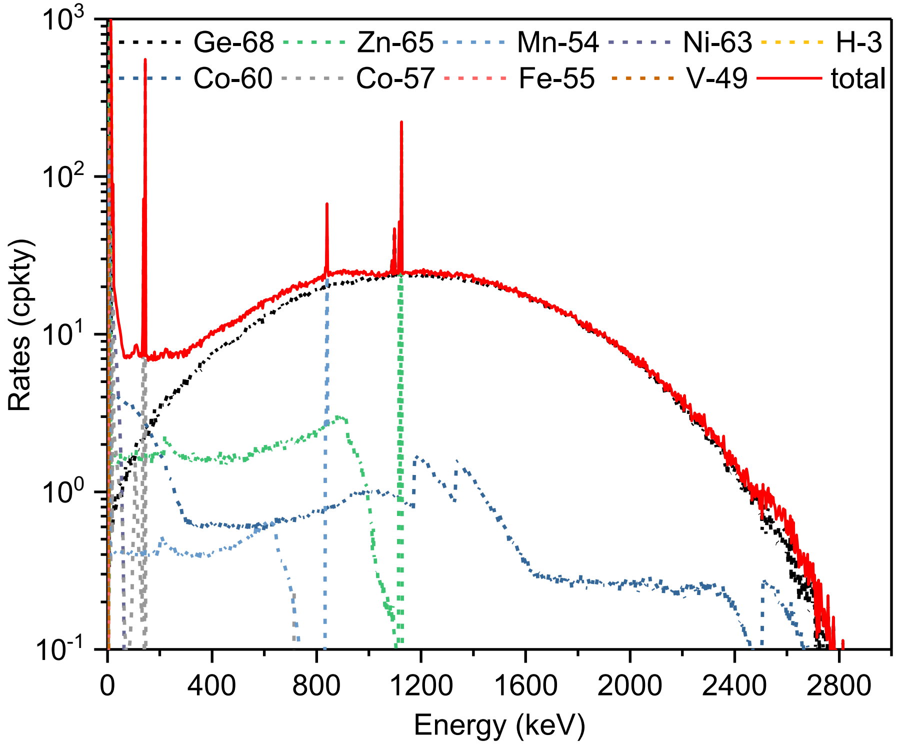
Cosmogenic isotopes produced during above-ground fabrication & transportation

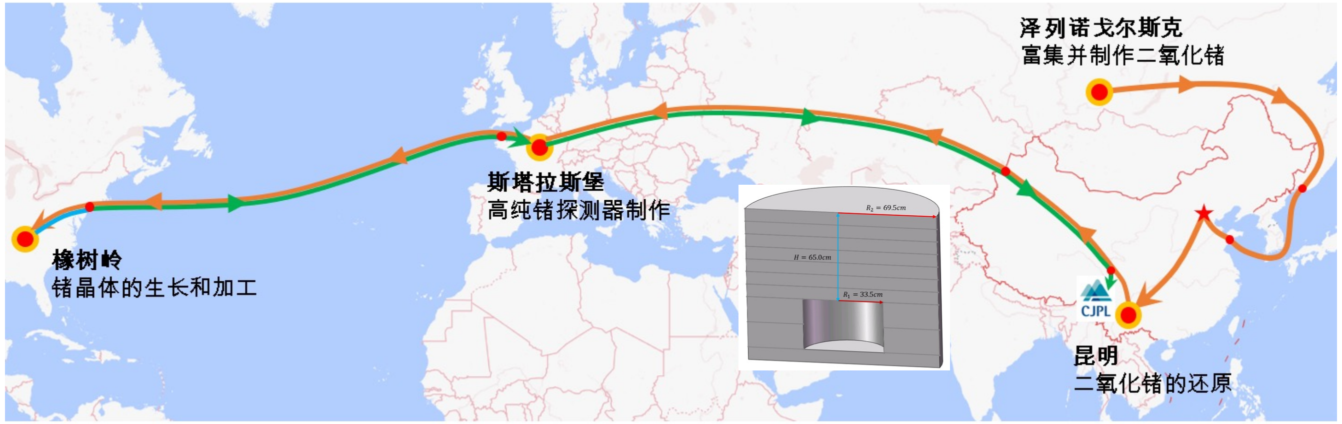
When detector arrives CJPL:

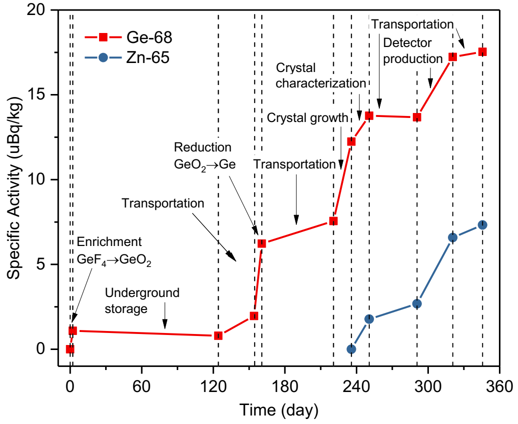
- **Ge-68 = 17.5 μBq/kg** (~100 μBq/kg w.o. control)
- **Co-60 = 0.1 μBq/kg** (~10 μBq/kg w.o. control)

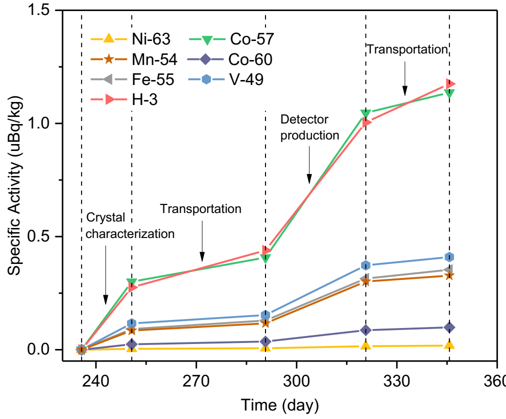
For 87% enrichment HPGe:

- **Ge-76 2νββ ~ 70 μBq/kg**







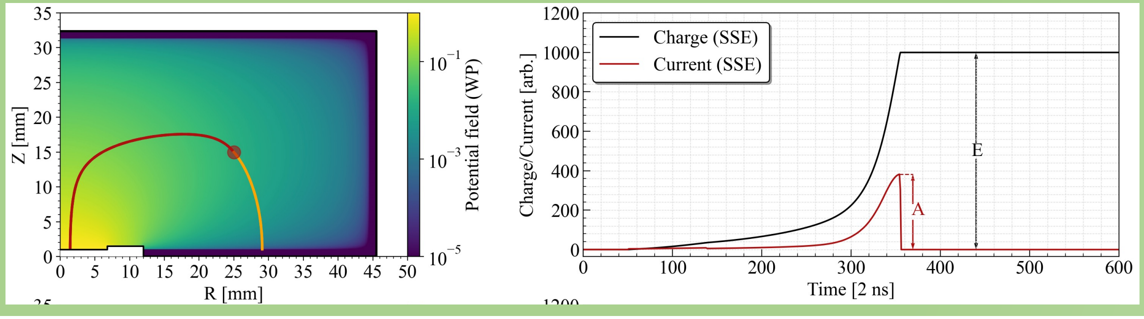


JINST 19:P03002, 2024

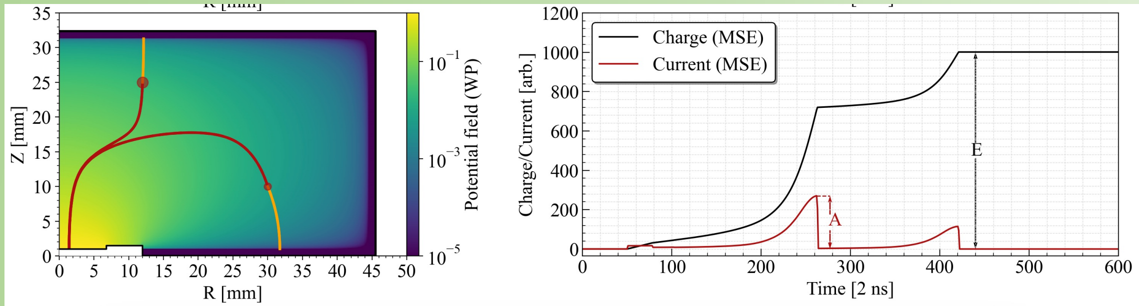
Cosmogenic Background Control

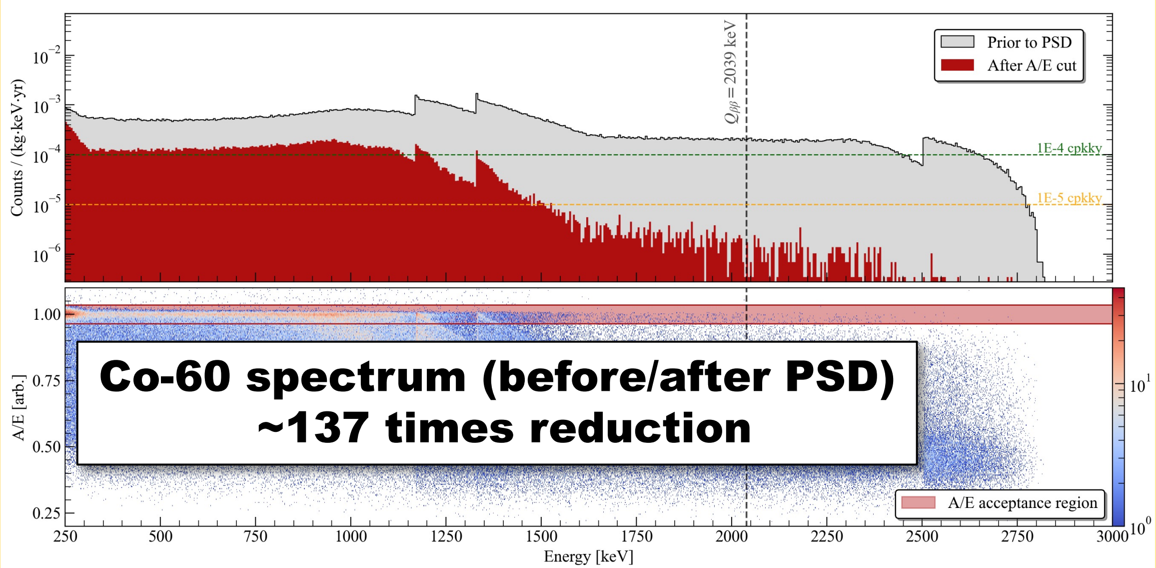
**Ge-68 (Ga-68) & Co-60 produce typical Multi-site hits in Ge det.
and can be decimated by PSD as the A/E method**

Pulse shape of single-site event (Signal)

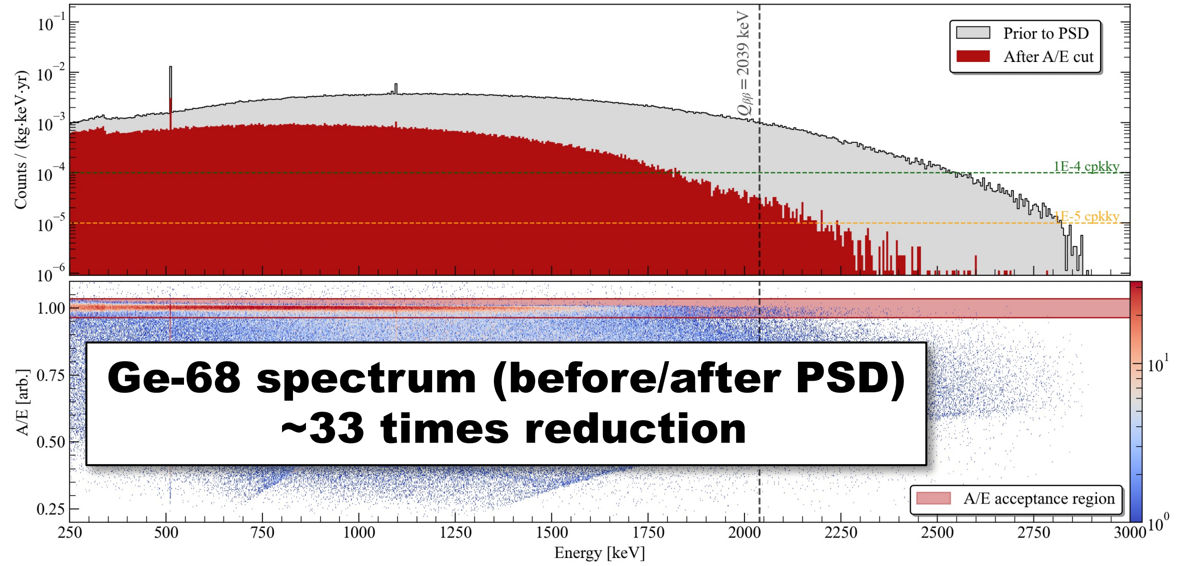


Pulse shape of single-site event (BG)





Co-60 spectrum (before/after PSD)
~137 times reduction

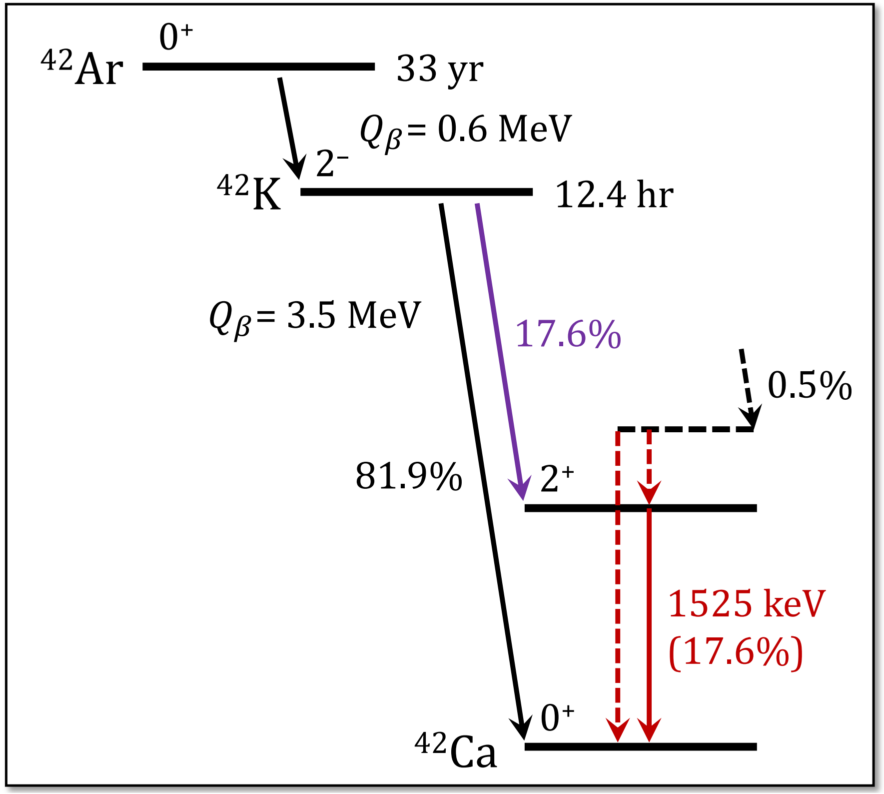


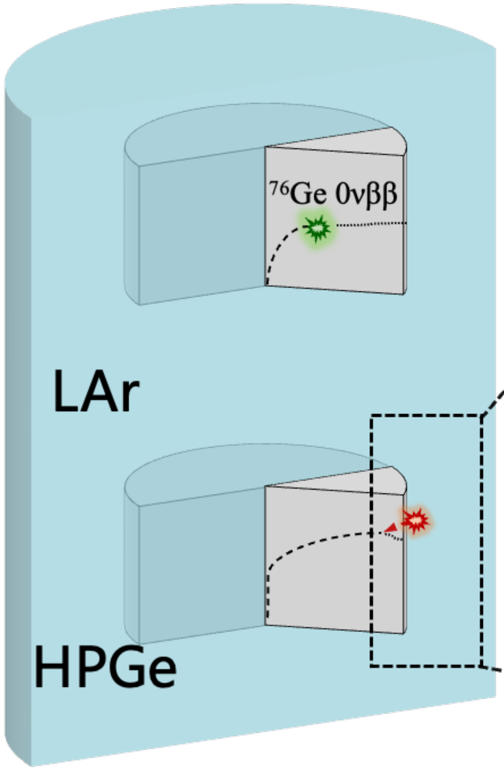
Ge-68 spectrum (before/after PSD)
~33 times reduction

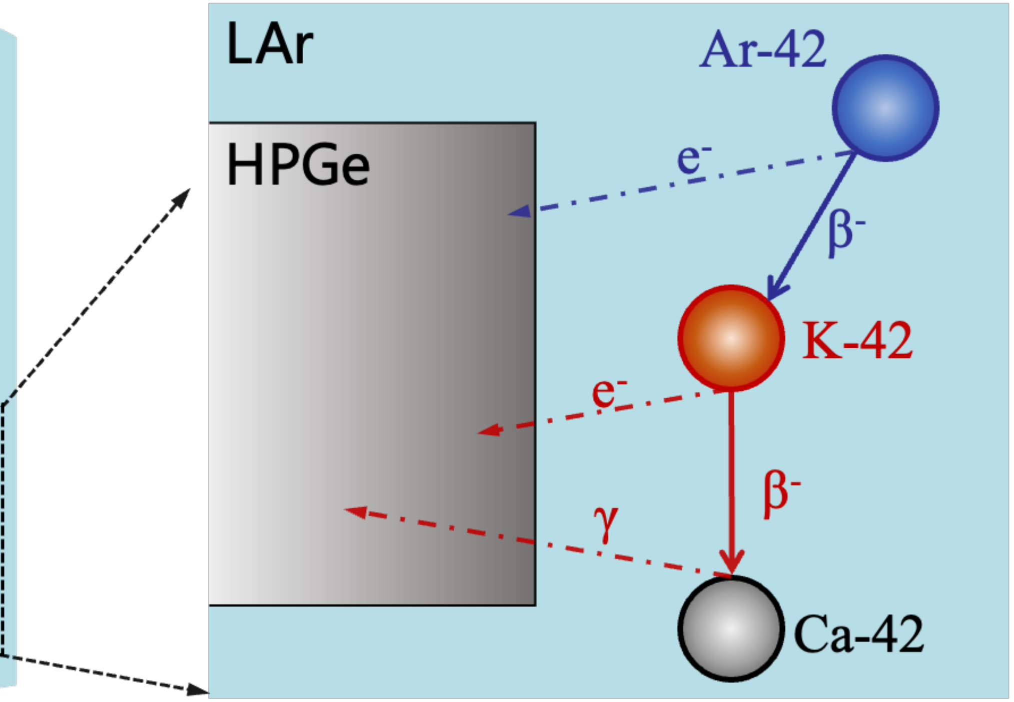
Cosmogenic Background from Ar-42 (K-42) in LAr

CDEX-300 will use atmosphere Ar (Ar-42 ~92 µBg/kg)

Ar-42 (K-42) contributes Surface Background in 2 MeV region

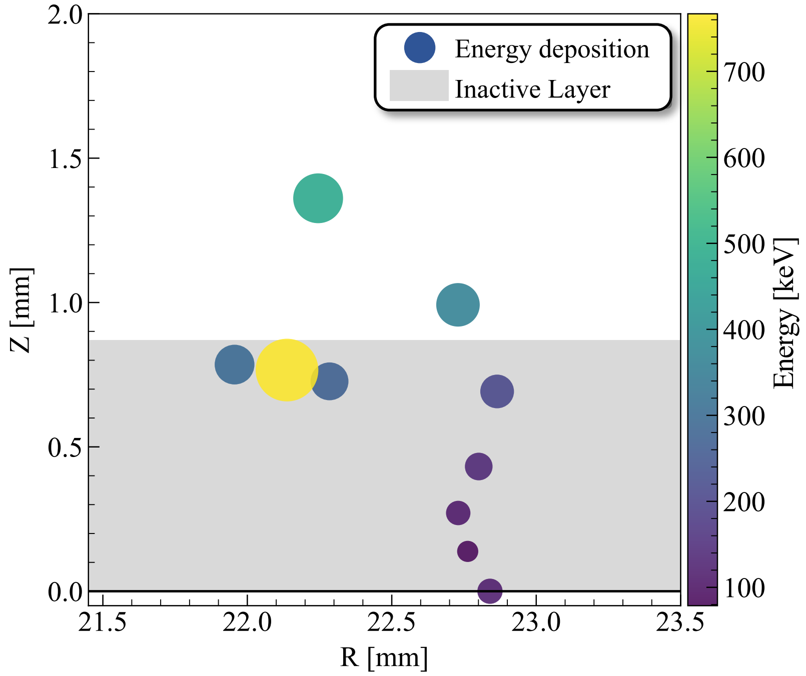




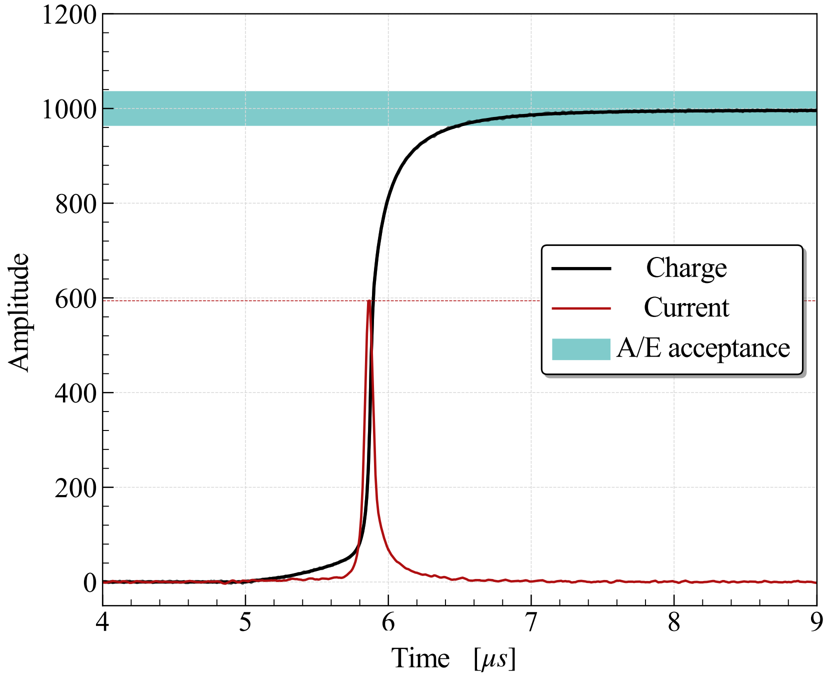


Cosmogenic Background from Ar-42 (K-42) in LAr

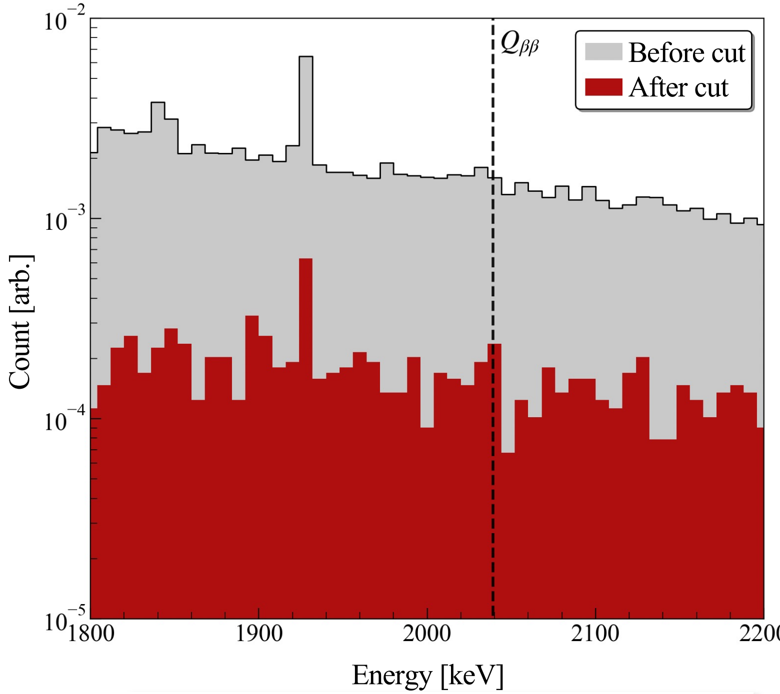
- **Ar-42 (K-42) surface background features a slow pulse shape**
- **A/E method could reduce BG by ~10 times**
- **Remaining BG clusters on the surface**



Simulated Energy deposition of Ar-42 (K-42)



Simulated Pulse shape of Ar-42 (K-42) background

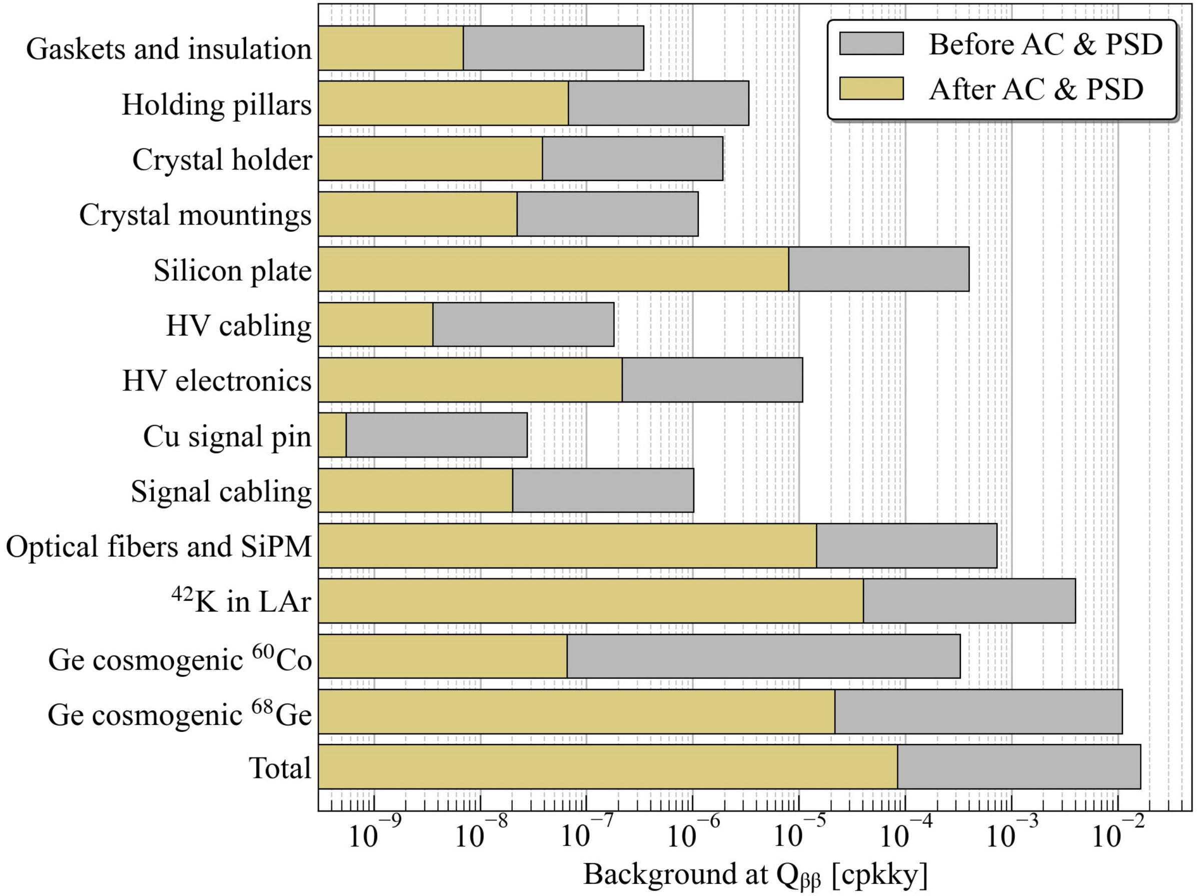


Simulated spectra of Ar-42 (K-42) background

Background Goal for CDEX-300

Estimation of background in ROI using the SAGE simulation toolkit

After active cuts (LAr veto & PSD), BG @2 MeV ~1E-4 cts/(keV•kg•yr)

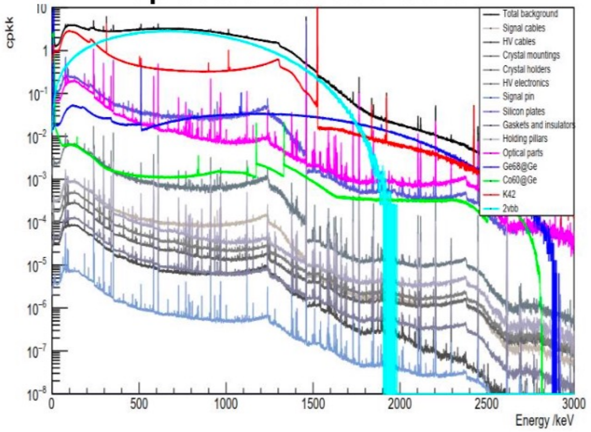


Cosmogenic ^{68}Ge in Det. and **^{42}K (^{42}Ar)** in LAr are two primary BG sources after all cuts

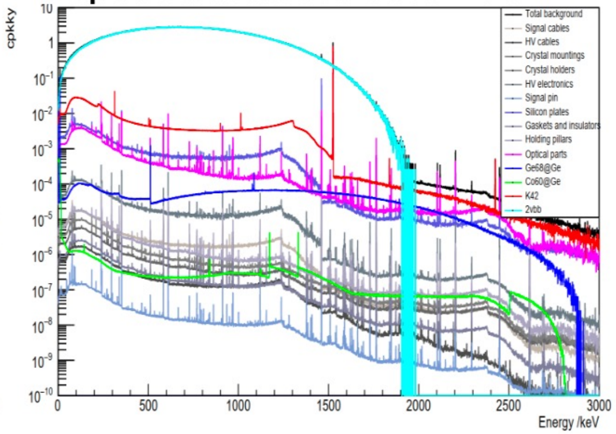
Further BG reduction may be achieved by:

- Underground fabrication of Ge crystal and Det.
- Underground Ar (^{42}Ar depleted)

Spectra before cuts



Spectra after AC Veto + PSD



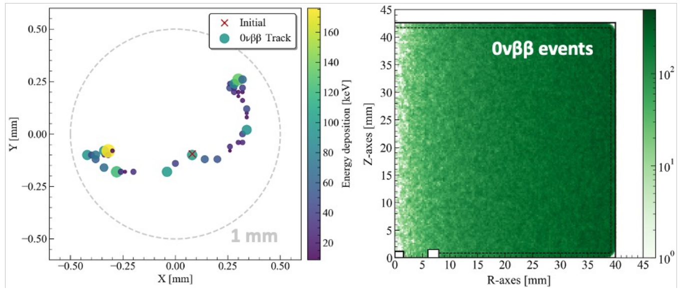
Virtual Segments

Virtual Segmentation of single-readout Point-contact HPGe

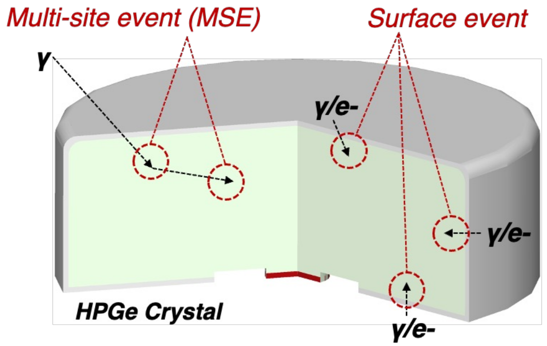
- Infer single-site events (SSEs) position by Pusle shape analysis
- Potential way to further suppress Ar-42 (K-42) surface background

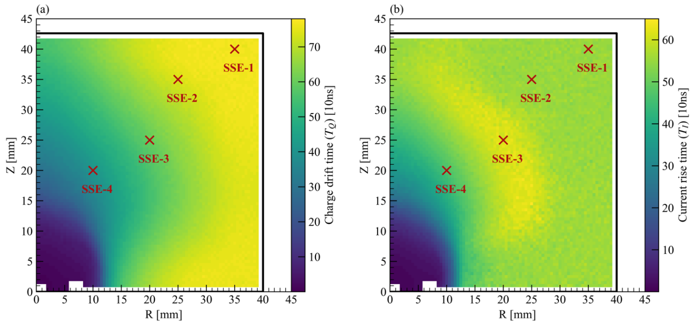
Signal (2e- from 0νββ)

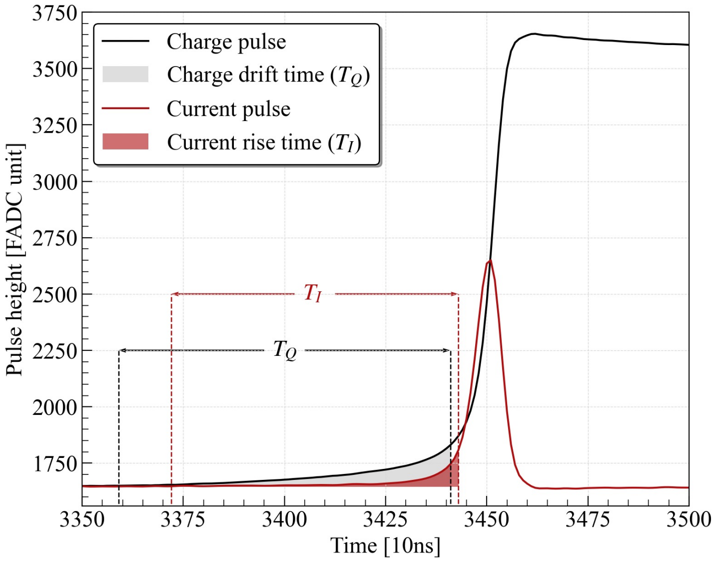
Single-site event (SSE) *Uniformly distributed*



Background (external e-, γ)







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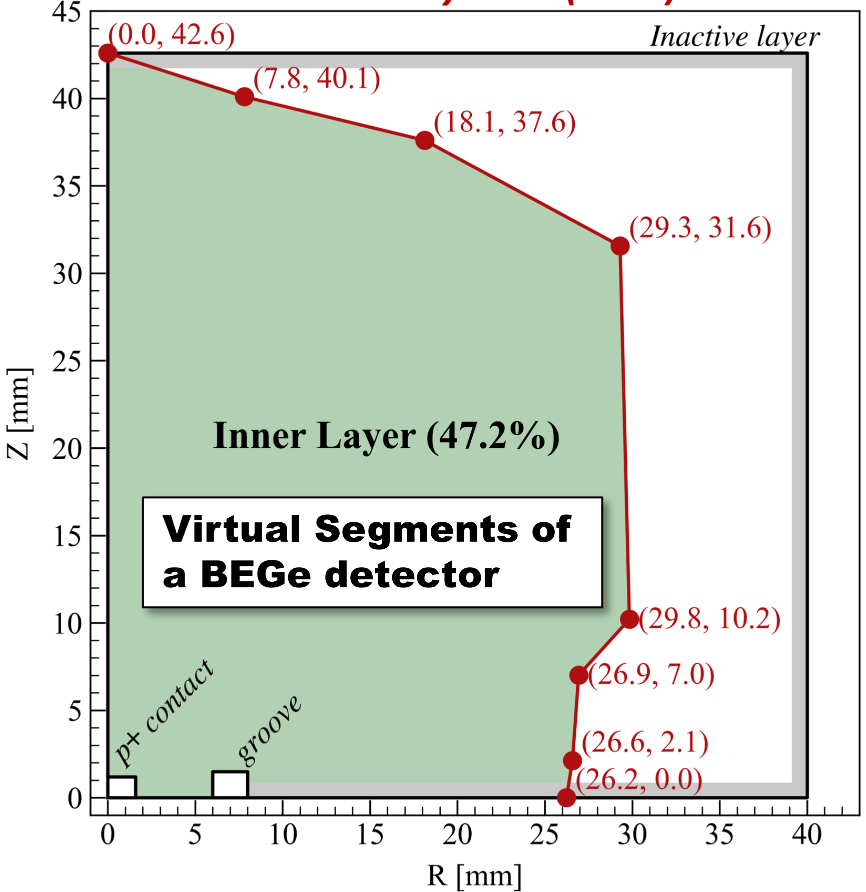


Other progresses

☐ Material Background Control

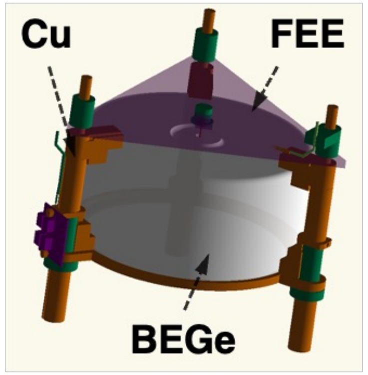
ALL materials to be screened and selected

☐ Ge detector & FEE

- Mitigation of cosmic activation on the ground
- Low-mass & pure detector structures
- Low background cables or flexible PCB
- CMOS ASIC Front-end Electronics
- Underground fabrication of Ge detectors

☐ Underground Electro-forming Cu

- U/Th activity <10 μBq/kg
- Free of cosmogenic radioactivity



Enriched HPGe detector test at CJPL

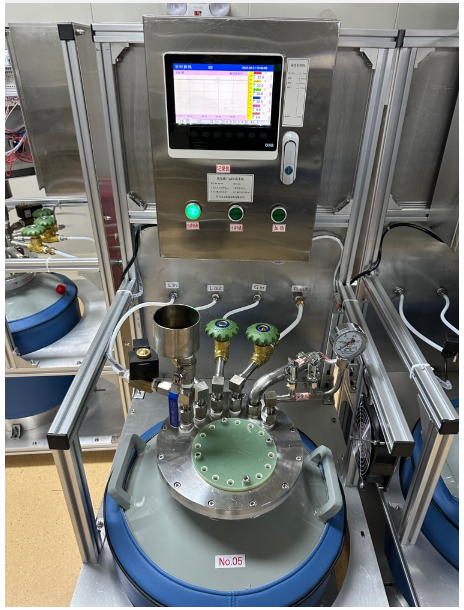
First 11 enriched HPGe detectors tested at CJPL

(Testing the energy resolution and long-term stability)

- **Design an auto LN filling system for the test facility**
- **Test HPGe detectors in steel vacuum isolators and directly immersed in LN**
- **The second batch (11 BEGe) has arrived at CJPL, testing is ongoing**

5 of the 11 HPGe at CJPL

Single HPGe Test Unit



Detector test facility at CJPL-II C1 Hall

Summary

- **CDEX: using Ge detectors search for light DM and Ge-76 0νββ at CJPL**
- **CDEX-50 (DM) has started in Hall C1 of CJPL-II**
- **CDEX-300 (0νββ) is on the pipe line**
- **Many key technologies R&D are ongoing**

Thanks for your attention!

http://cdex.ep.tsinghua.edu.cn

http://cjpl.tsinghua.edu.cn

Back up

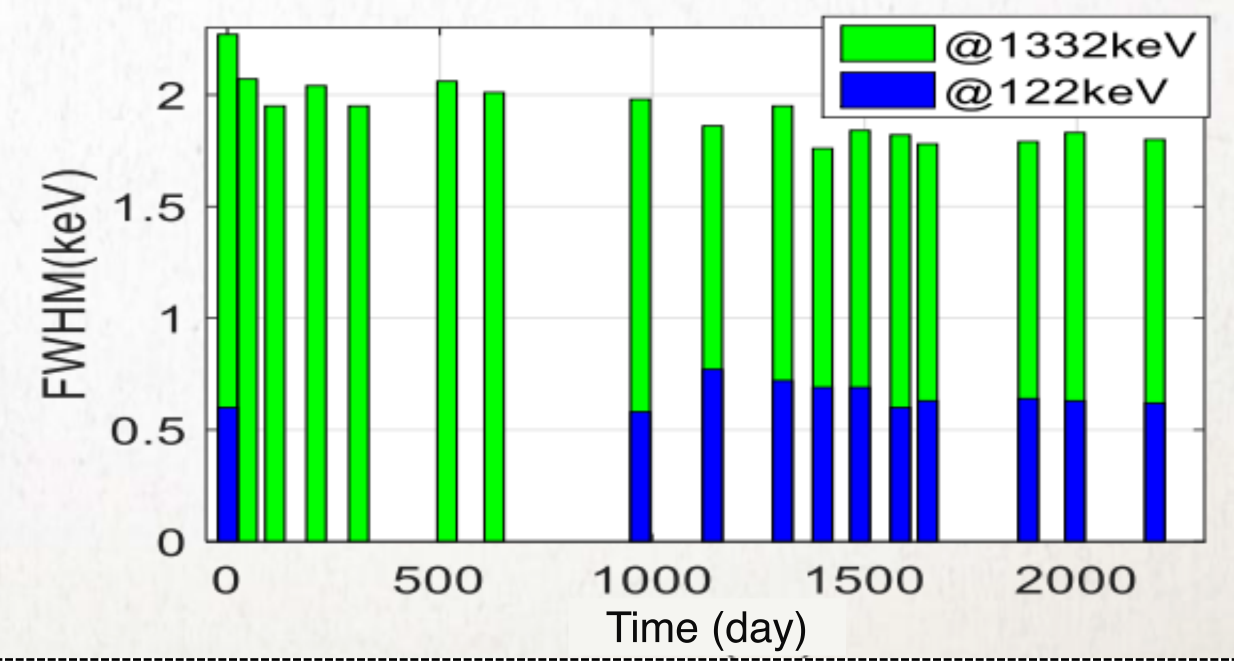
Research & Development on HPGe detector

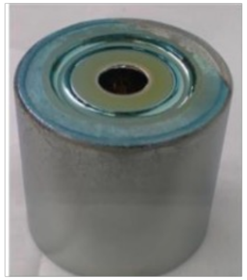
Home-made Ge detectors

- ✓ Co-axial/BEGe/PPC/ICPC
- ✓ Cold finger / Naked immersion

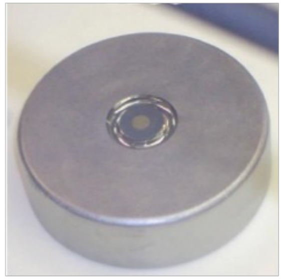
R&D on underground fabrication ongoing…

Long-term stability: energy resolution

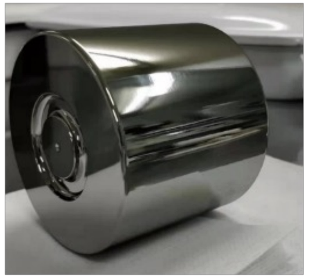




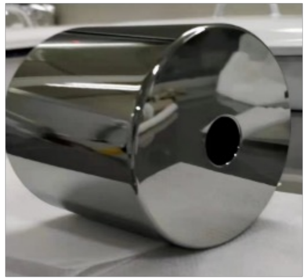
Co-axial



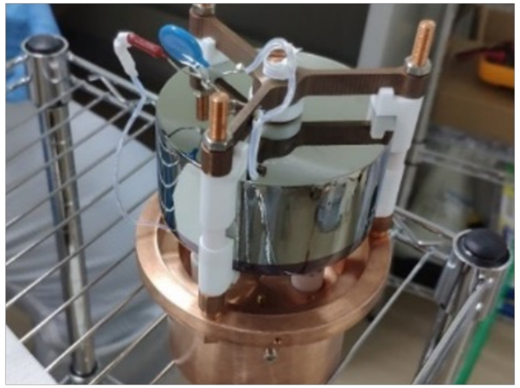
BEGe



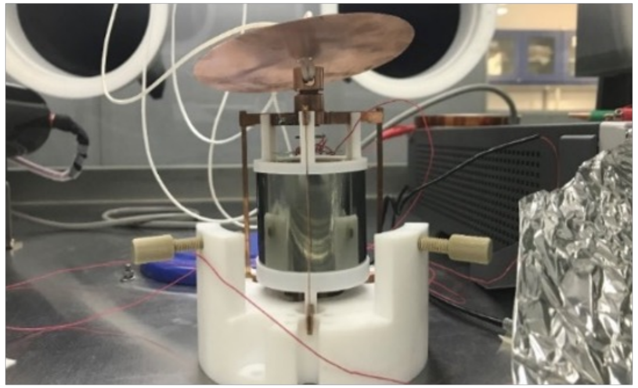
PPC



ICPC



Cold finger cooling



Naked crystal to LN_2

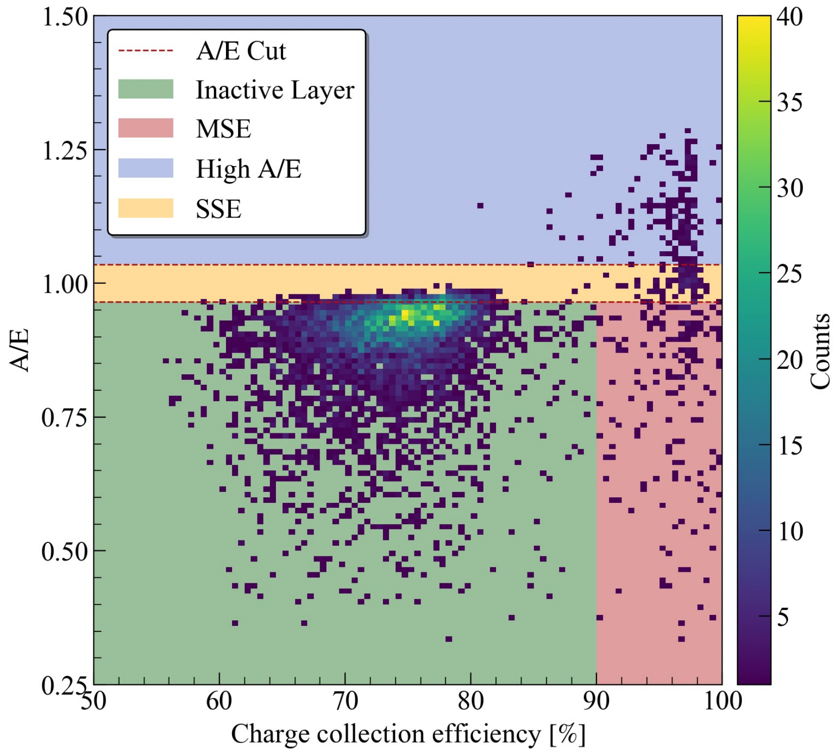
Background Suppression of A/E Method

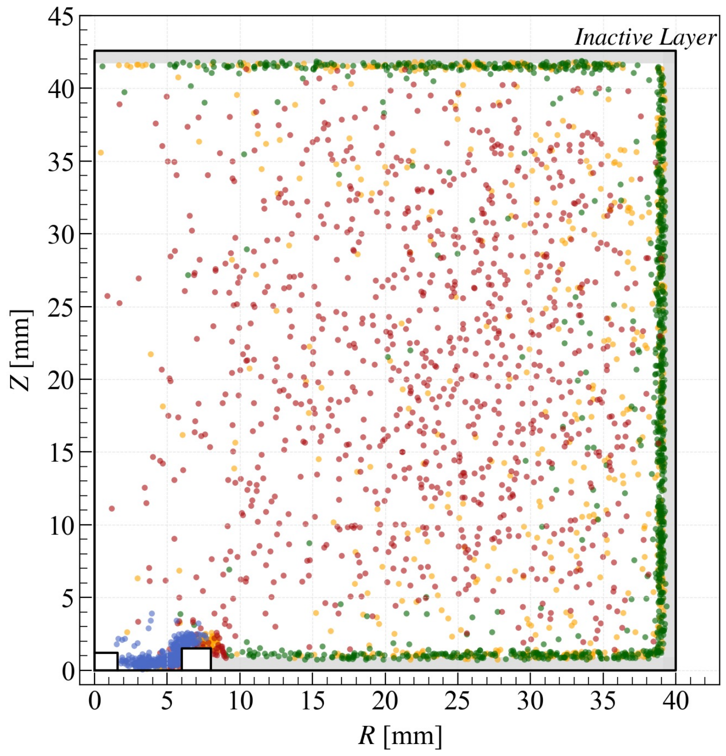
◻ A/E Cut for Ar-42 surface events:

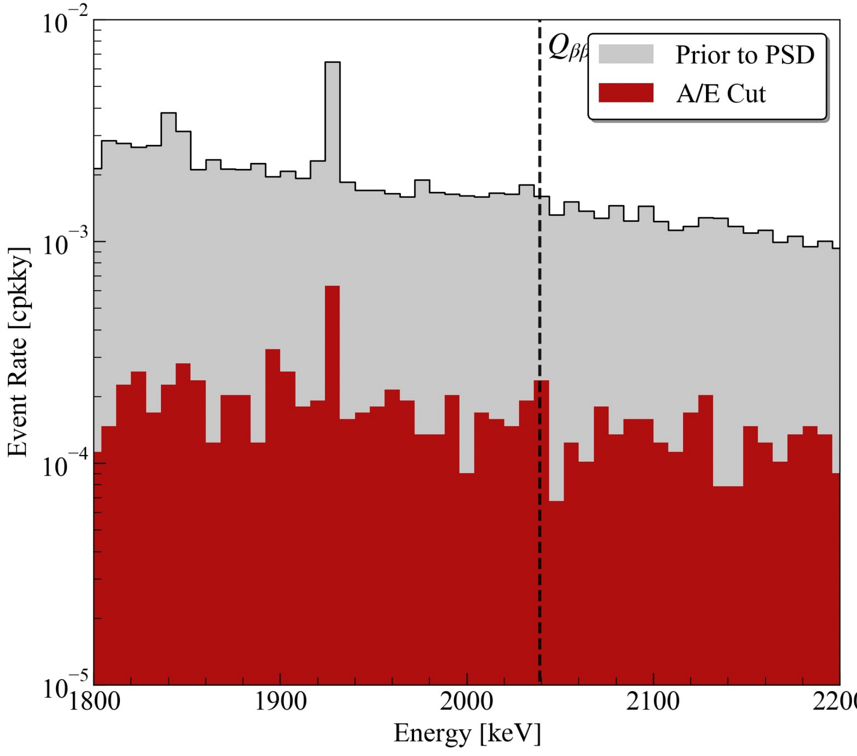
① *Most Ar-42 backgrounds are surface events and be removed by a low A/E cut*

② *When the background is near p+ contact, it can be removed by a high A/E cut*

A/E method could suppress Ar-42 background by ~~10 times~ in $Q_{\beta\beta}$ region







Simulation of Ar-42 (K-42) events

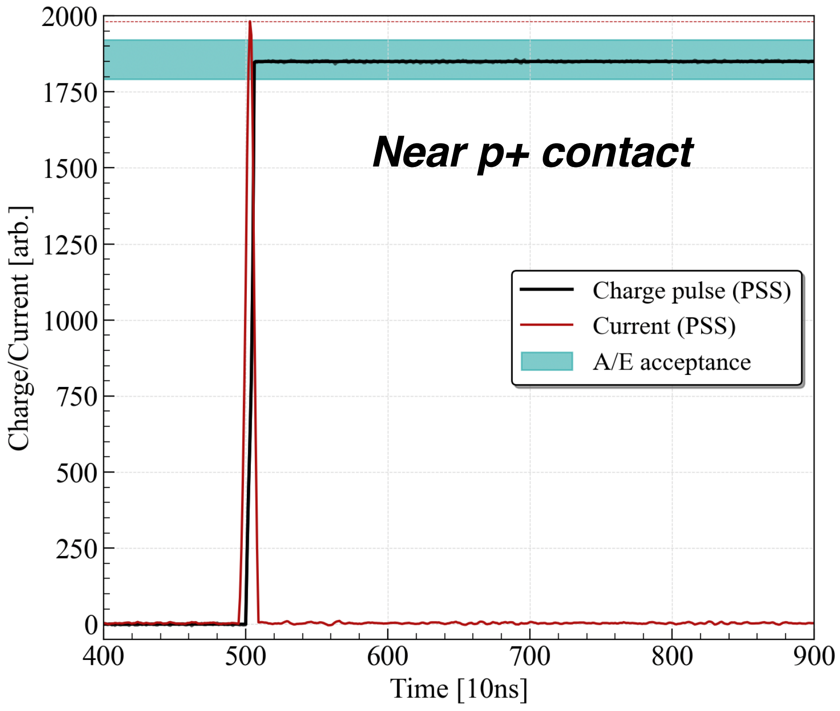
Pulse shape simulation for Ar-42 surface events:

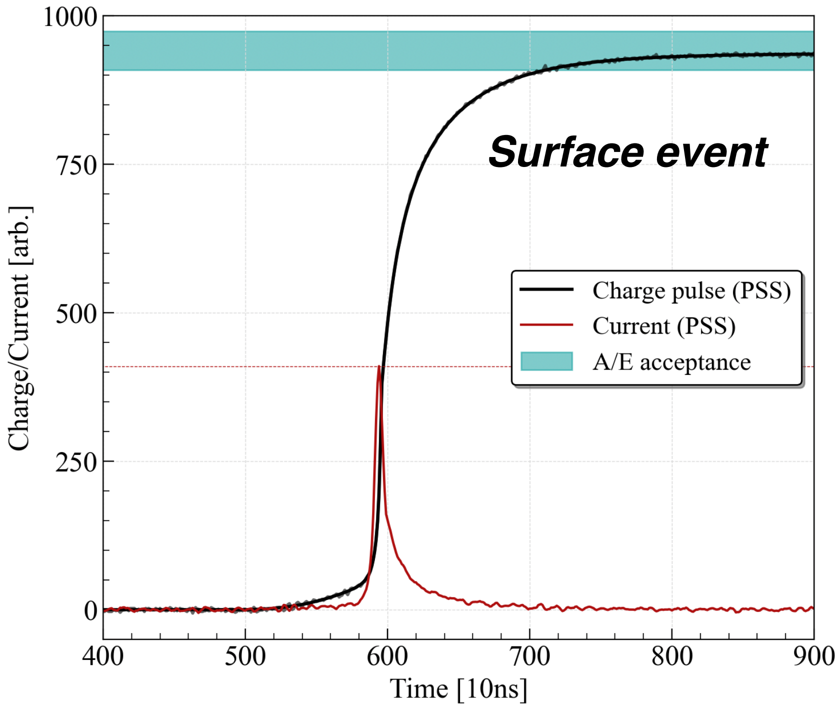
*Three types of Ar-42 events could be removed by **A/E cut**:*

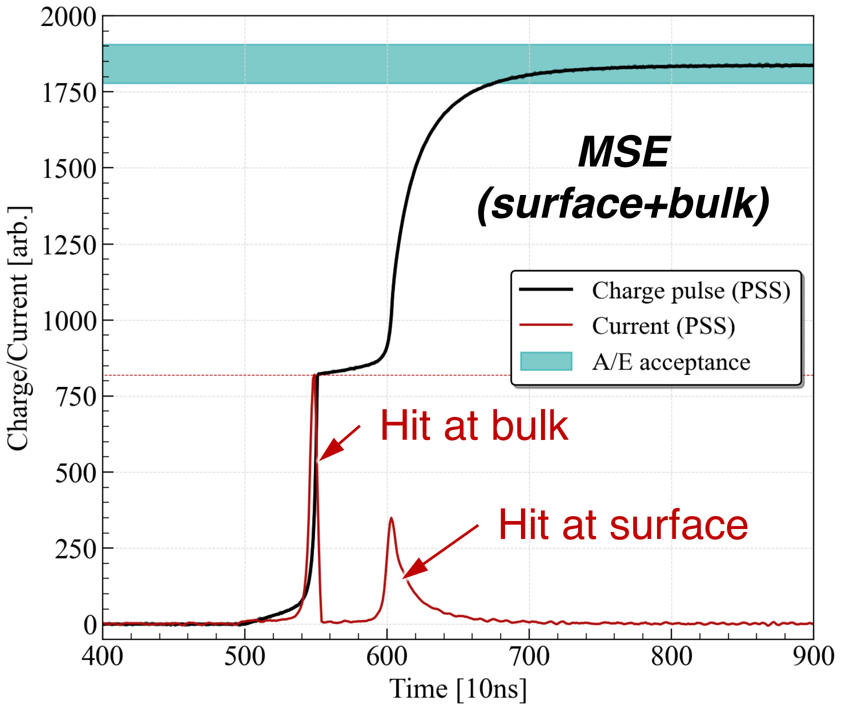
① ***Near p+ contact:*** *High A/E value than normal SSE*

② ***Surface events:*** *slow pulse and incomplete charge collection (lower A/E)*

③ ***Multi-site events:*** *a mixture of surface and surface/bulk hit position (lower A/E)*





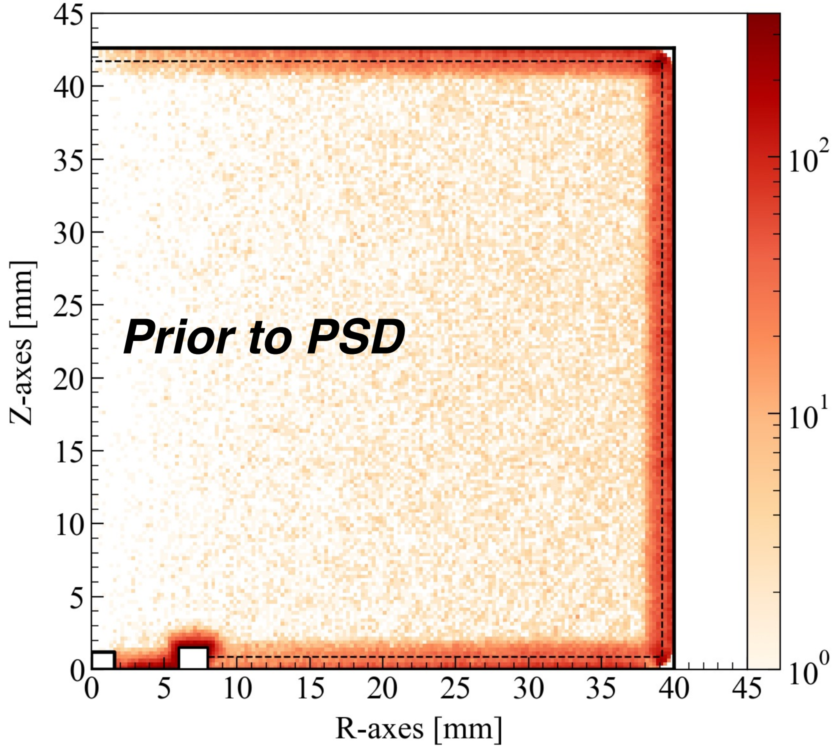


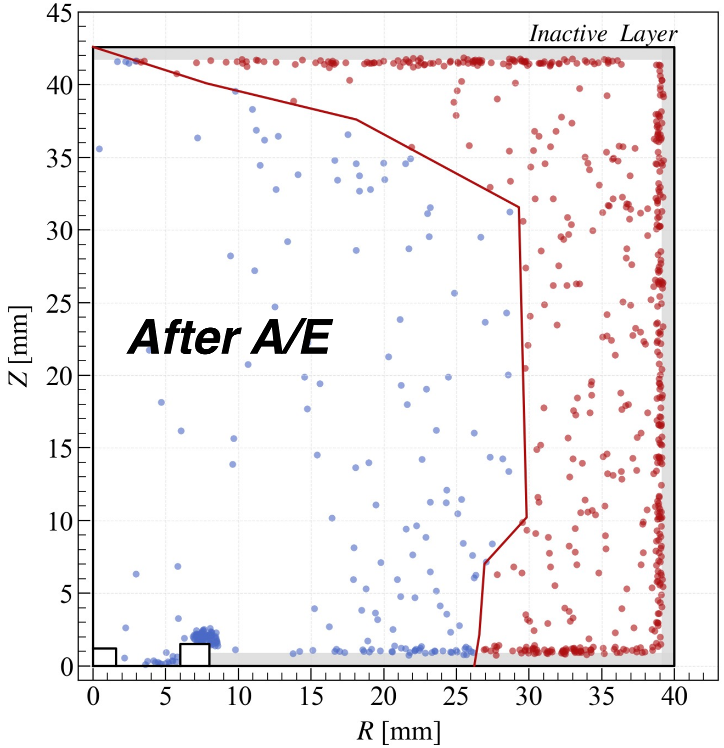
Background Suppression of Virtue Segments

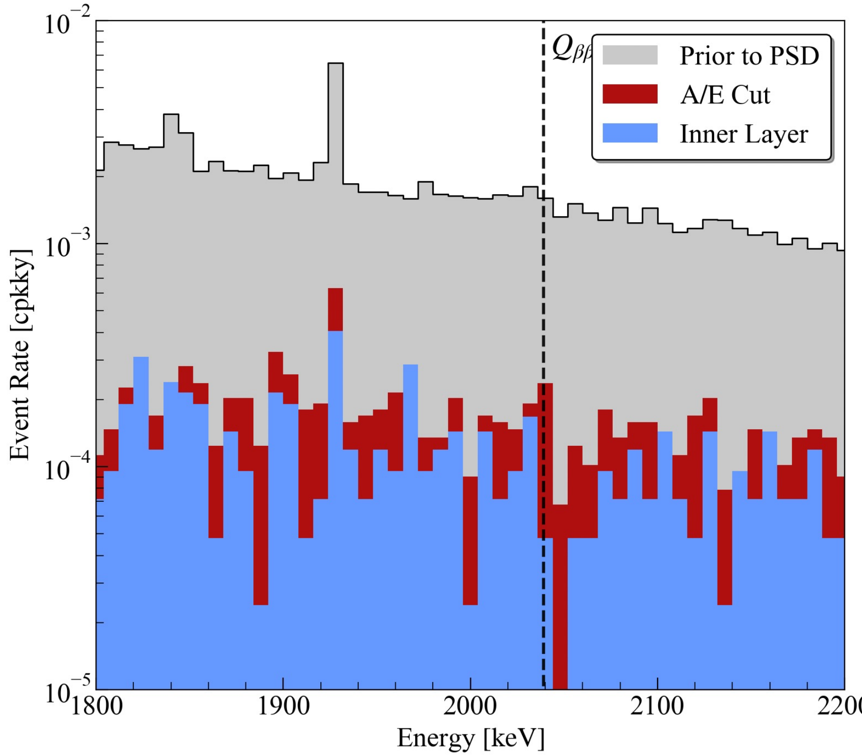
Surface background from Ar-42

Assess PSD background suppression power by Geant4 + Pulse Shape Simulation

PSD Method	Prior to PSD	A/E Cut	**Outer Layer**	**Inner Layer**
Background [10^{-4} cpkky]	16.8±0.90	1.61±0.11	**2.10±0.15**	**1.05±0.09**







Improve 0νββ Sensitivity by Virtual Segmentation

☐ Joint Analysis of Inner/Outer Layer Data

➢ Inner Layer has a ***lower Background*** while the Outer Layer ***shares ~1/2 sensitive mass***

Combine Inner/Outer Layer data to achieve better sensitivity

Joint Analysis

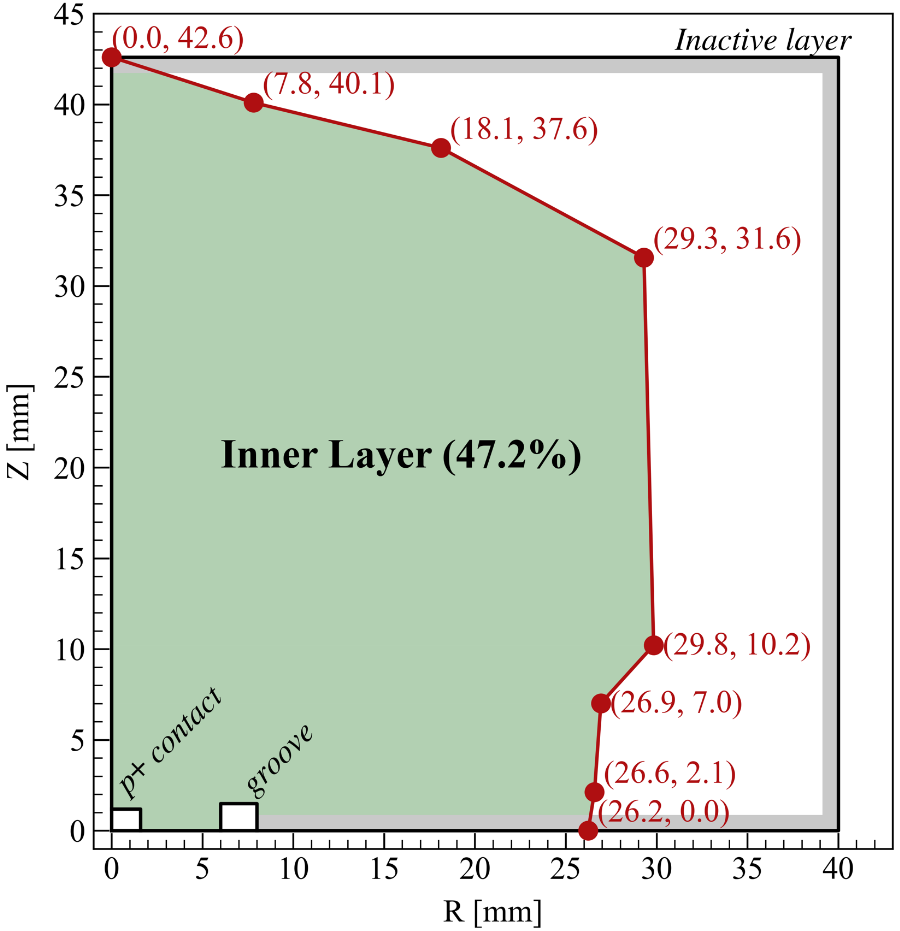
Likely hood Function for counts in 0νββ ROI：

$$L(N_{0\nu}) = \text{Poisson}(C_1|B_1 + S\cdot f_1\cdot\varepsilon_1)\times\text{Poisson}(C_2|B_2 + S\cdot f_2\cdot\varepsilon_2)$$

- **S is number of 0νββ signal**
- **C the counts、B the background,**
- **f the inner layer volume, ε the signal efficiency**
- **Index 1 (2) represents inner (outer) layer**

Estimate signal number ($\widehat{S}$) via Maximum likely hood:

$$\frac{\partial L(S)}{\partial S} = 0 \Longrightarrow \hat{S} = F(C, B, f, \varepsilon)$$



Improve 0νββ Sensitivity by Virtual Segmentation

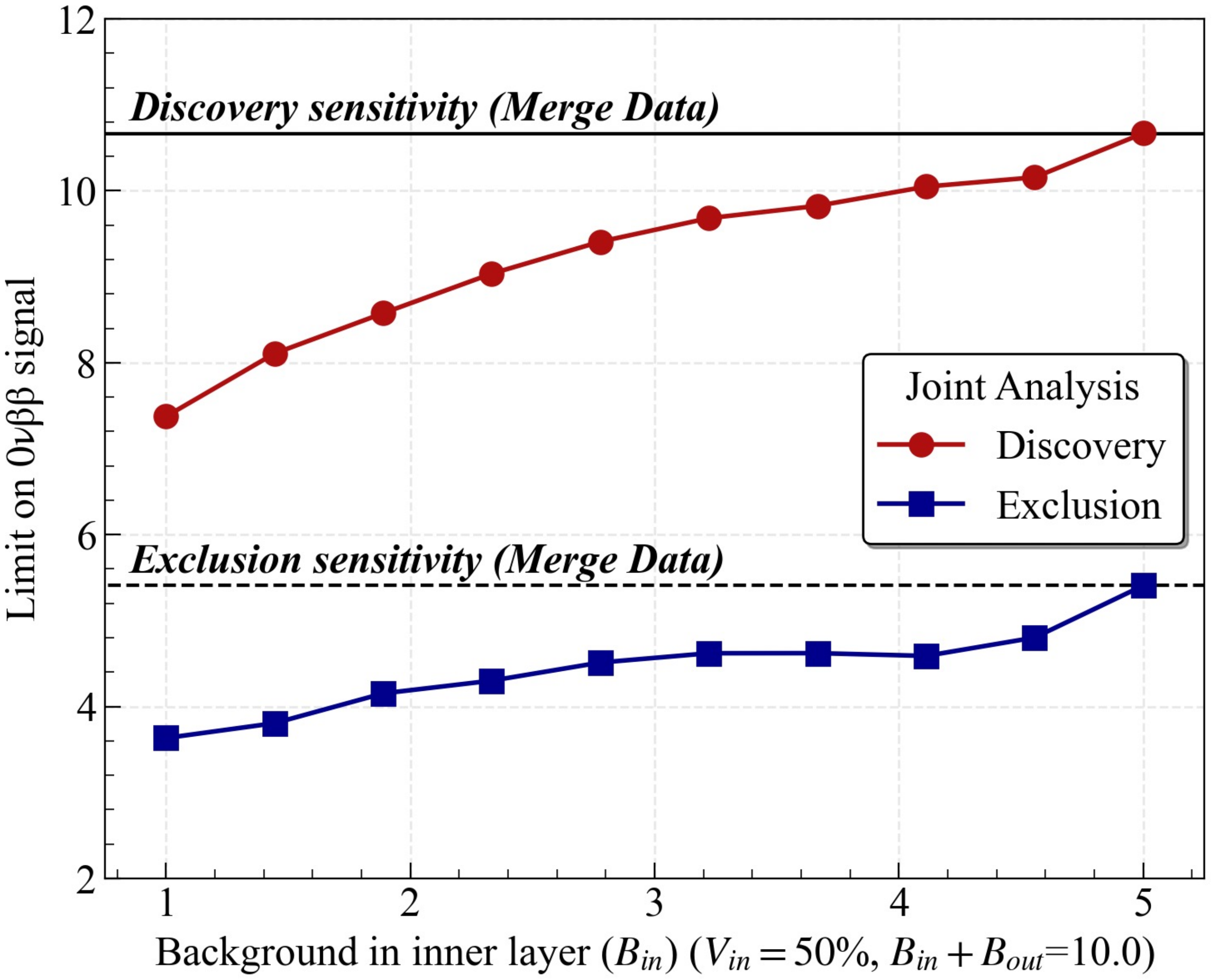
Discovery Sensitivity

$$\begin{cases} P(\hat{S}_{0\nu} \leqslant x \mid B_1, B_2, S_{0\nu} = 0) \geqslant 99.73\% \\ P(\hat{S}_{0\nu} \geqslant x \mid B_1, B_2, S_{0\nu} = S_{dis}) \geqslant 50\% \end{cases}$$

Exclusion Sensitivity

$$\begin{cases} P(\hat{S}_{0\nu} \leqslant x \mid B_1, B_2, S_{0\nu} = 0) \geqslant 50\% \\ P(\hat{S}_{0\nu} \geqslant x \mid B_1, B_2, S_{0\nu} = S_{exc}) \geqslant 90\% \end{cases}$$

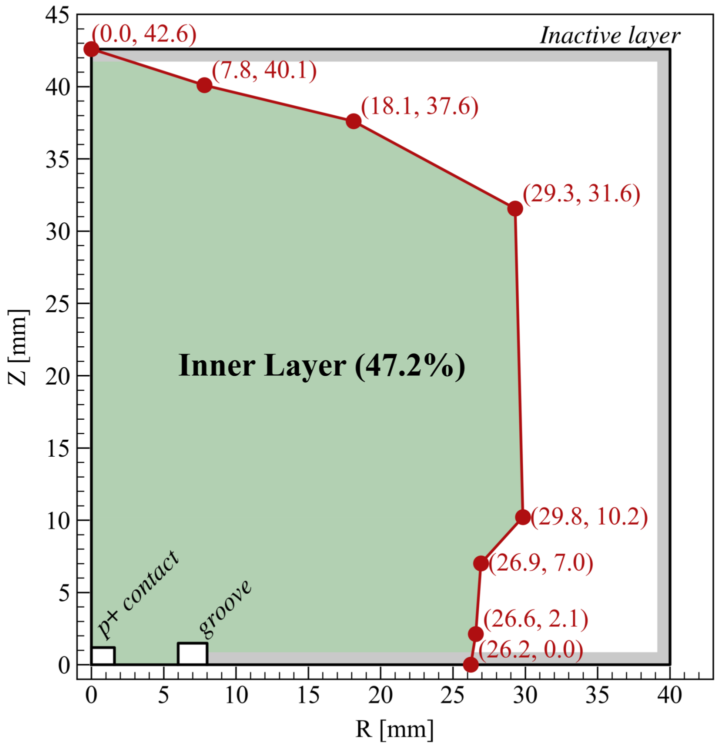
Joint analysis gives a **better sensitivity** for a **lower** inner layer background

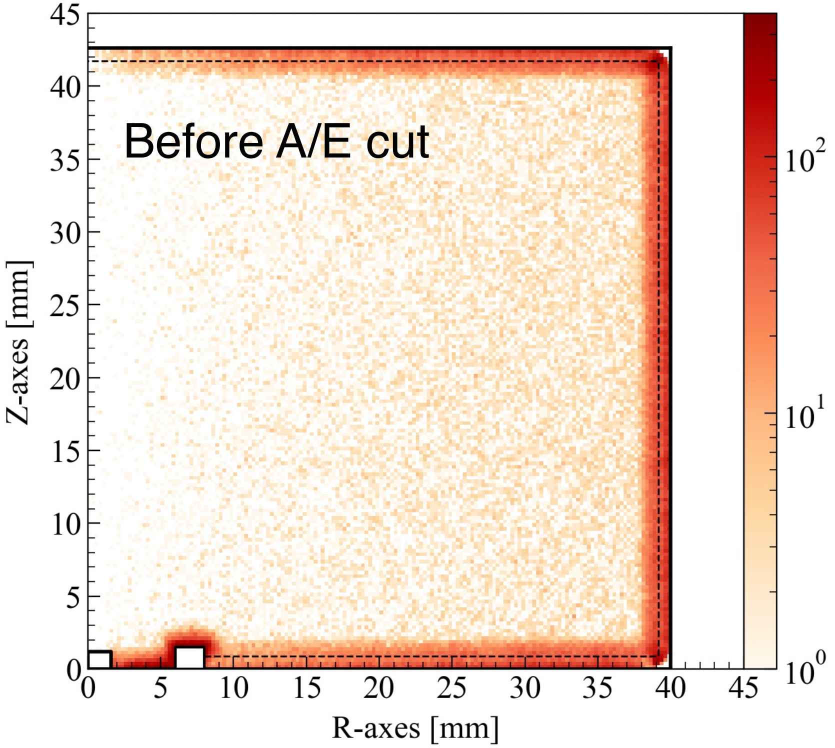


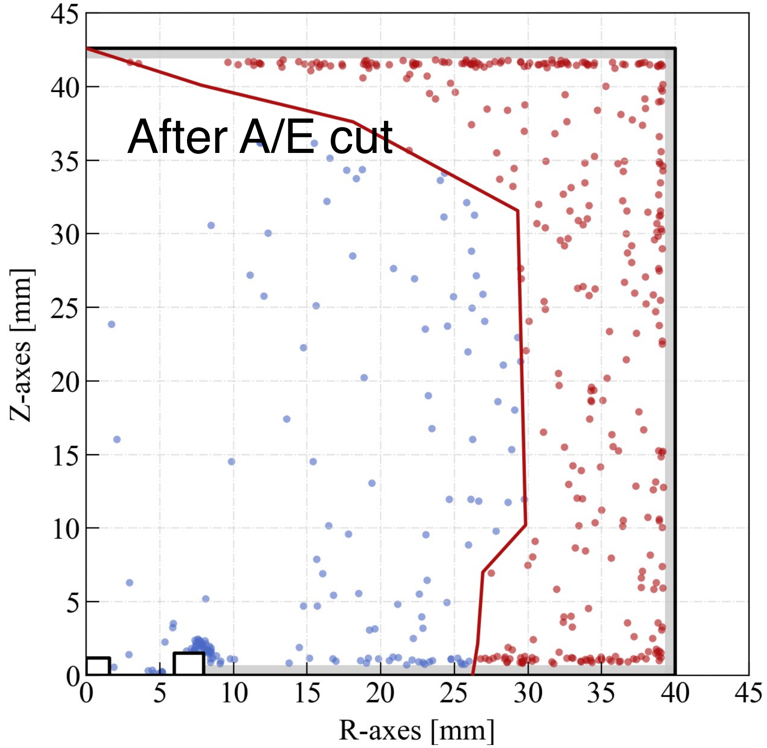
Improve 0νββ Sensitivity by Virtual Segmentation

Apply Method on Ar-42 Background in CDEX-300:

PSD cuts	Before cut	A/E Cut	Outer layer	Inner layer
BI/10^{-4} cpkky	16.8±0.89	1.61±0.11	**2.10±0.15**	**1.05±0.09**
Background in 1-ton·yr	10.7	1.03	**0.71**	**0.32**



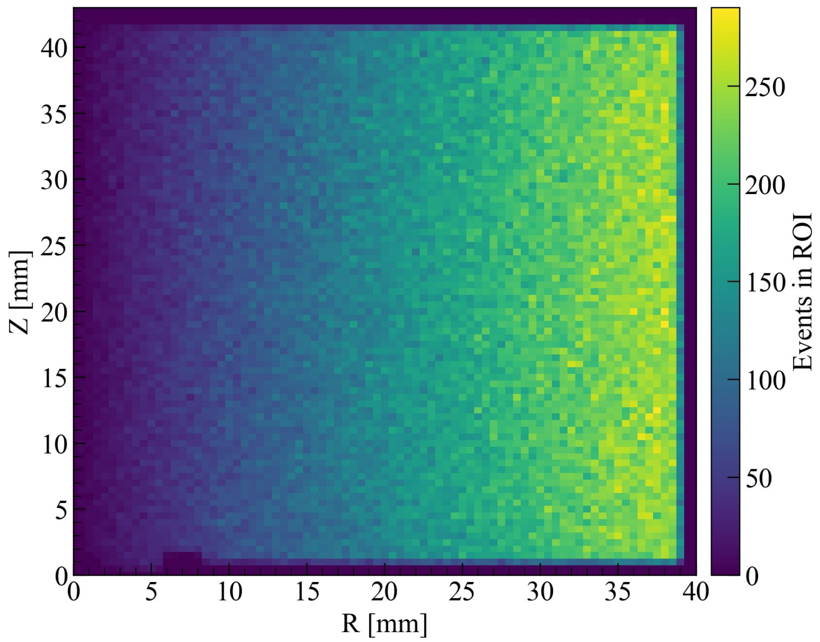




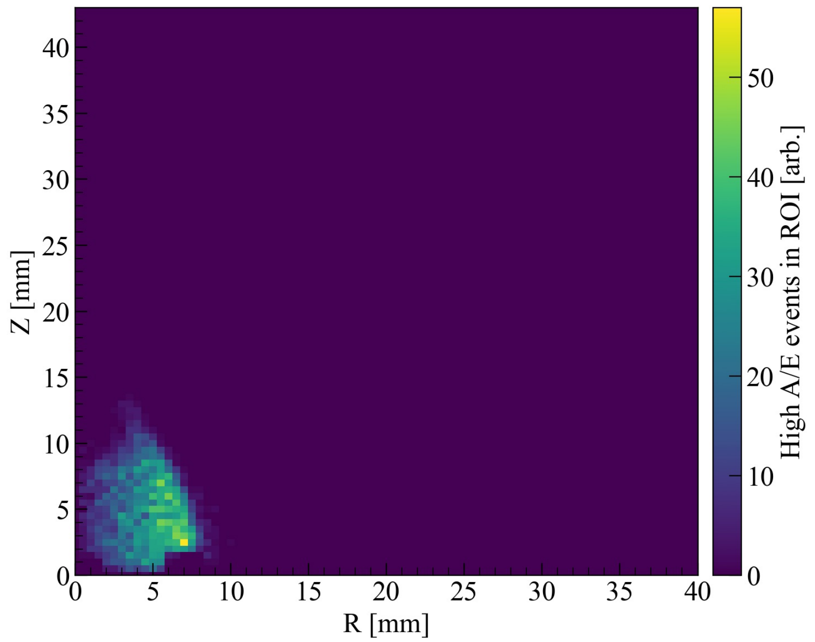
Improve 0νββ Sensitivity by Virtual Segmentation

Apply Method on Ar-42 Background in CDEX-300: Signal efficiency

PSD Cut	Sensitive Volume	0νββ Signal Loss			0νββ Signal Efficiency
		Energy Loss	Low A/E cut	High A/E cut	
Before cut	100.0%	16.6%	/	/	85.4%
A/E cut	100.0%	16.6%	10.67%	0.53%	72.2%
Inner layer	**47.2%**	**8.9%**	**16.50%**	**1.20%**	**73.4%**
Outer layer	**52.8%**	**22.8%**	**6.00%**	**0.00%**	**71.2%**



Events in Signal Region energy in ($Q_{\beta\beta}\pm3\sigma$)



Events rejected by High A/E cut

Improve 0νββ Sensitivity by Virtual Segmentation

- **Apply Method on Ar-42 Background in CDEX-300:**

PSD Cut	Sensitive Volume	0νββ Signal Efficiency	Background	Sensitivity (Exclusion)	Sensitivity (Discovery)
Before cut	100.0%	85.4%	10.7	6.91	12.84
A/E cut	**100.0%**	**72.2%**	**1.03**	**3.97**	**6.44**
Inner layer	47.2%	73.4%	0.32	5.74	9.69
Outer layer	52.8%	71.2%	0.71	8.46	10.54
Joint analysis	**100%**	**/**	**/**	**3.26**	**5.40**