

Design and status of the CDEX-300 $0\nu\beta\beta$ experiment

Wenhan Dai, Hao Ma
(on behalf of the CDEX Collaboration)
Tsinghua University
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Outlines

- I. Searching $0\nu\beta\beta$ with HPGe detectors**
- II. CDEX and its $0\nu\beta\beta$ studies**
- III. Design and status of CDEX-300v**
- IV. Summary**

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

Motivations 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?

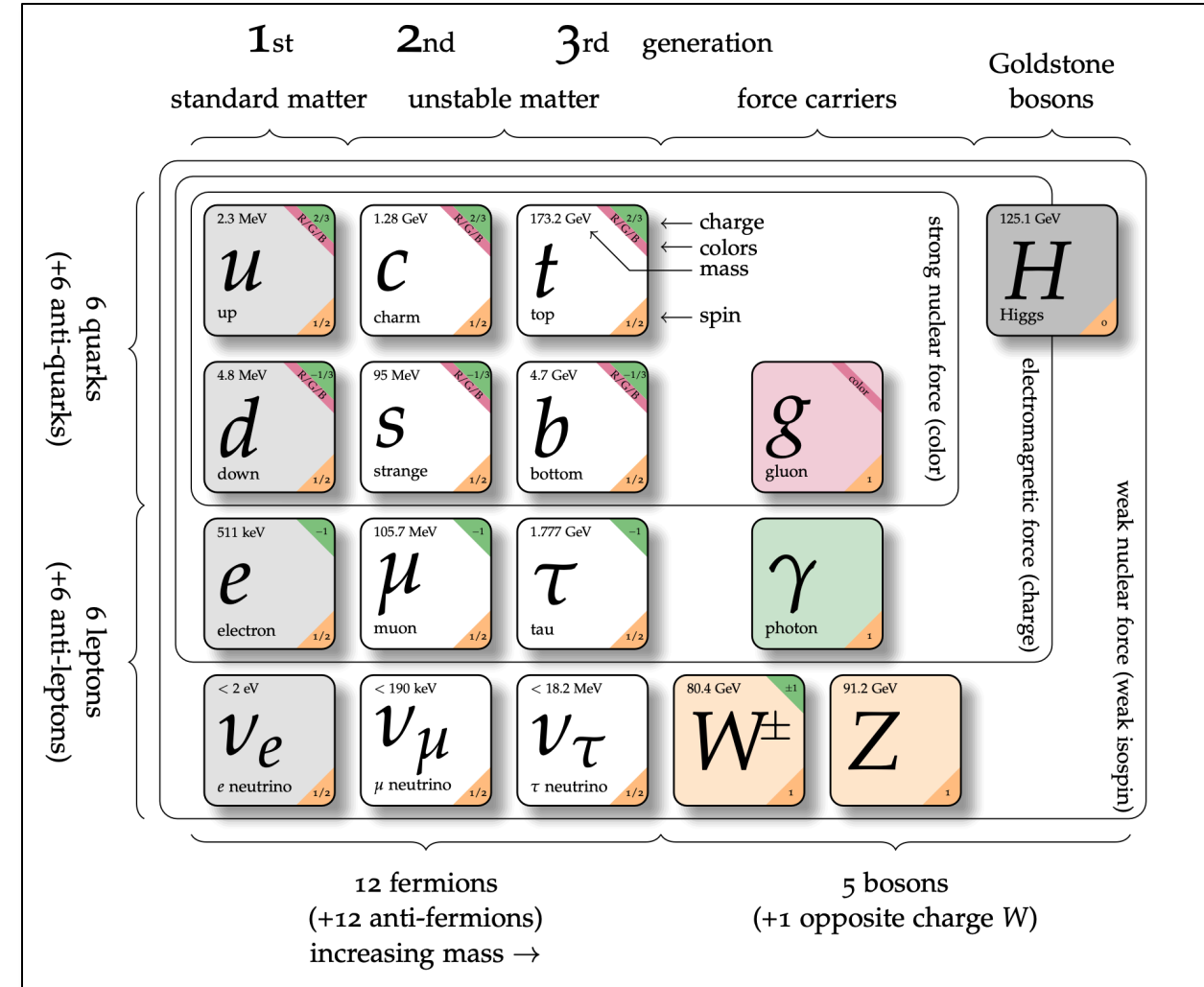
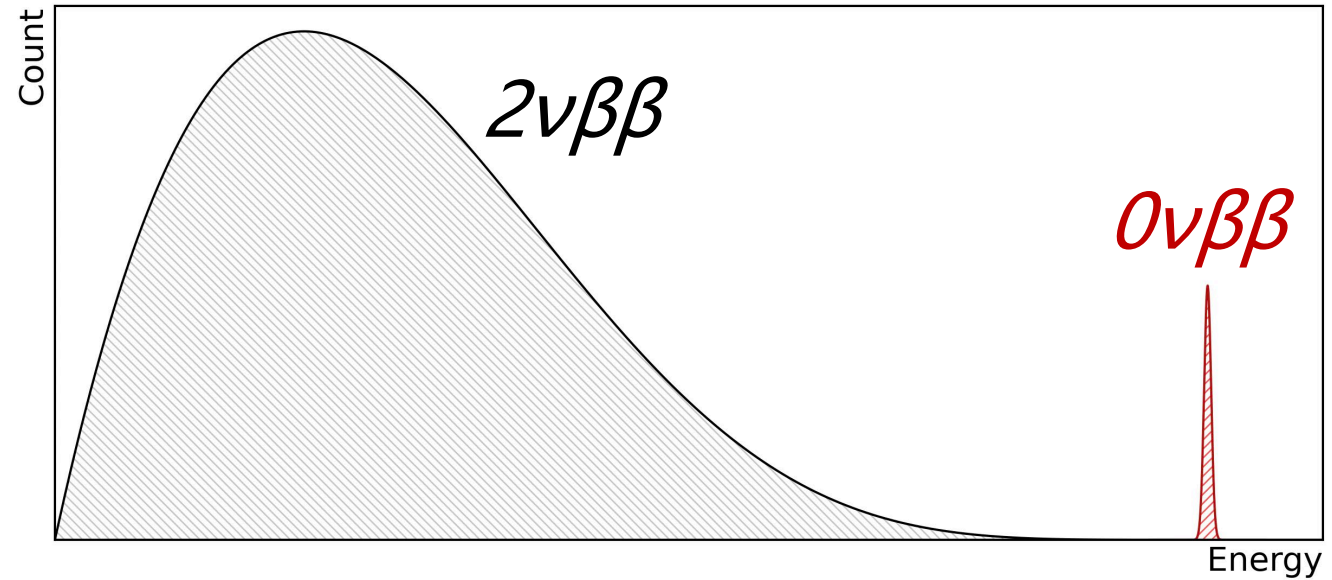
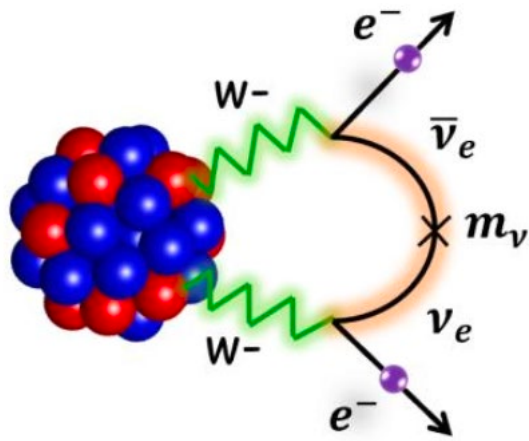
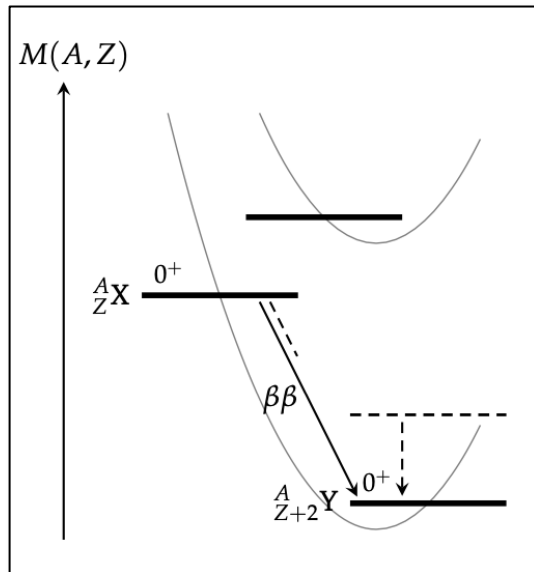


Fig from <https://davidgalbraith.org/portfolio/ux-standard-model-of-the-standard-model/>

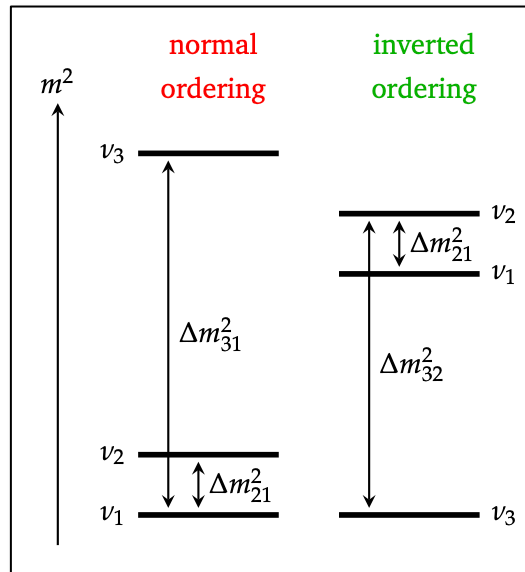
Neutrinoless Double Decay ($0\nu\beta\beta$)



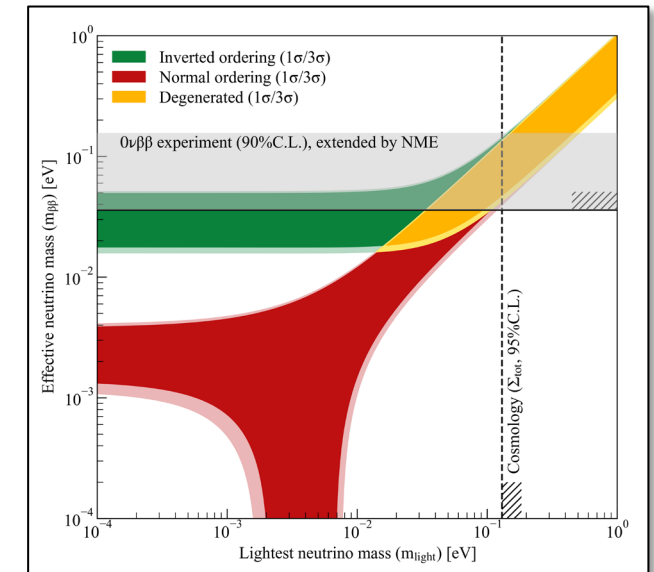
2β isotope



Mass hierarchy



Mass scale

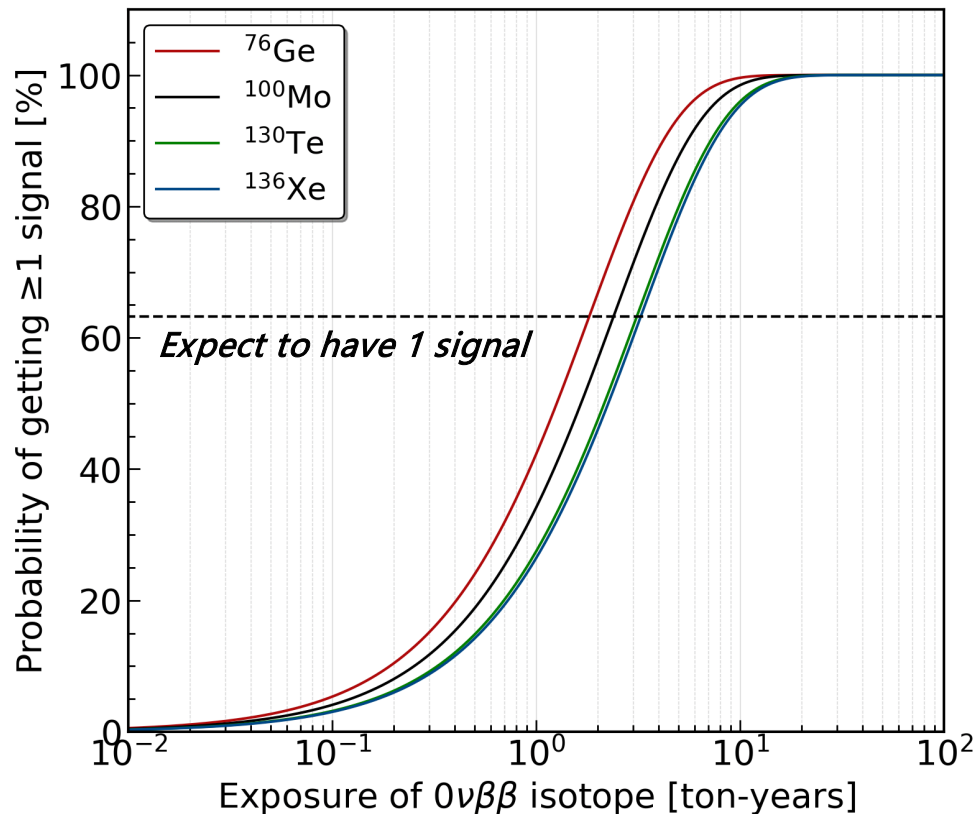


Experimental Search for $0\nu\beta\beta$

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)

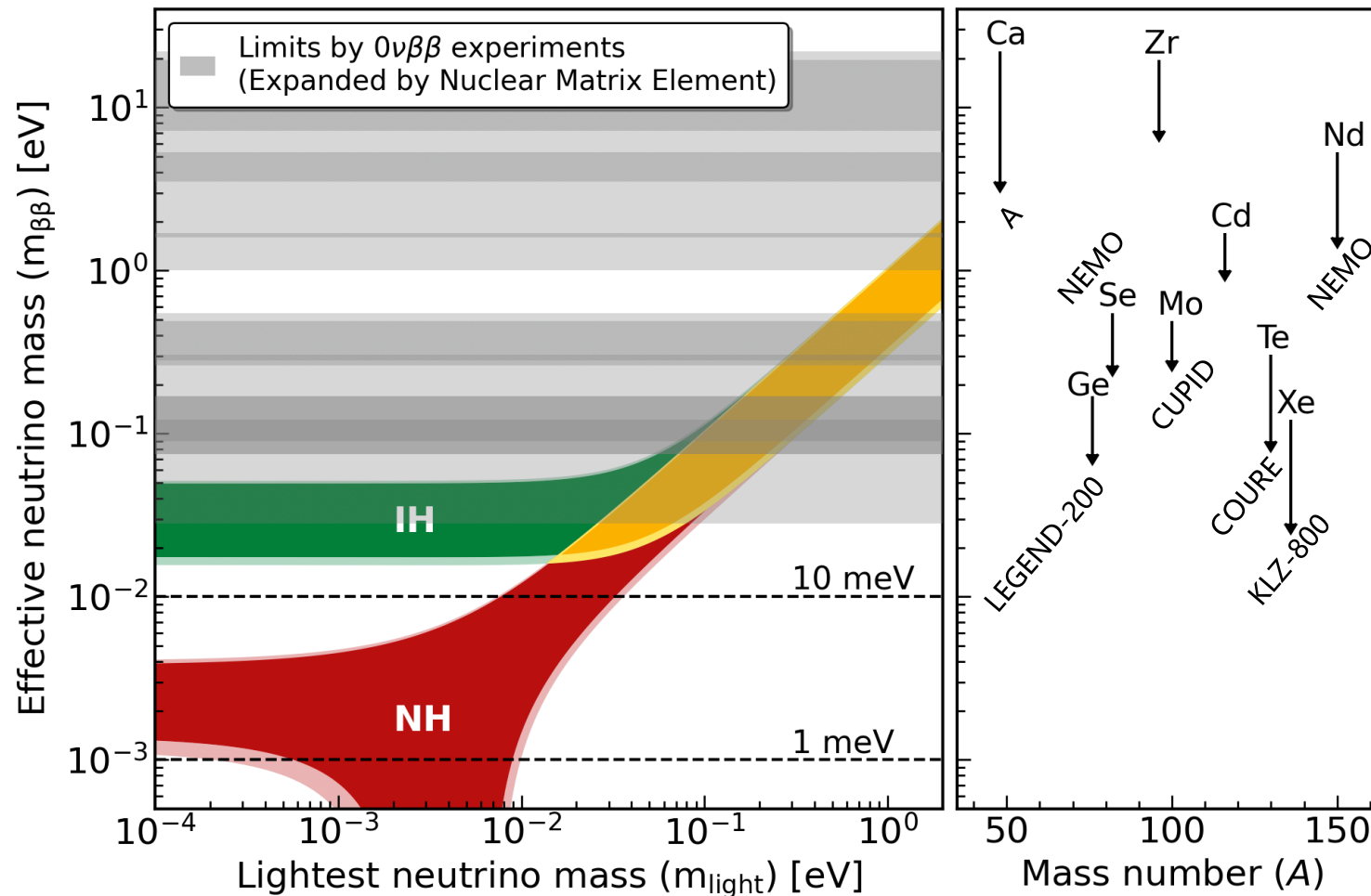
BG in ROI	P(observing ≥ 1 BG)
5	99.33%
1	63.21%
0.1	9.52%
0.01	1.00%
0.0027	0.27% (3σ)

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

Experimental Search for $0\nu\beta\beta$

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)

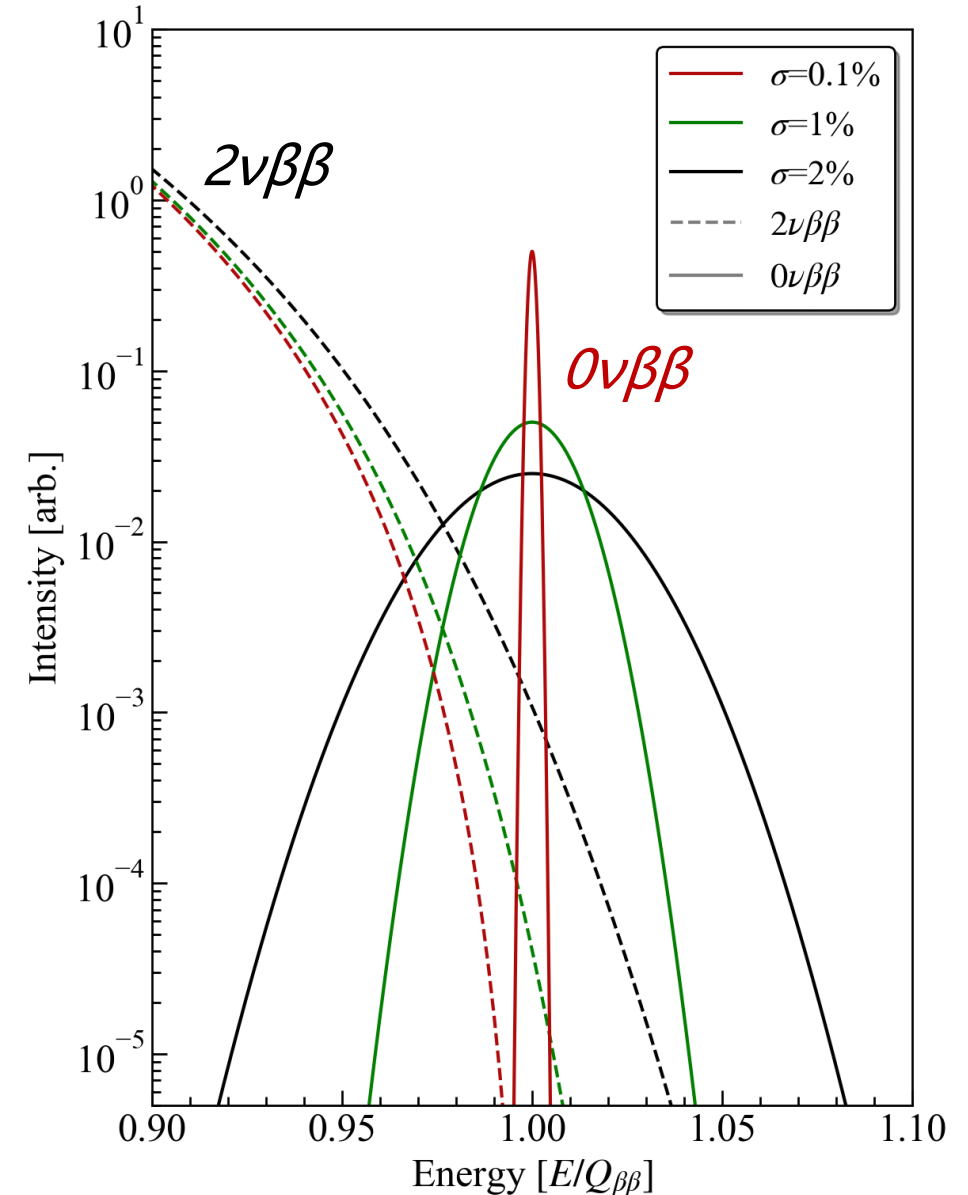
Advantages of HPGe Technology

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

Enrichment $\rightarrow \varepsilon$ **Exposure** $\rightarrow M \cdot T$ **BG counts in ROI** $\rightarrow (BI \cdot \Delta E \cdot M \cdot T)$
Efficiency $\rightarrow \varepsilon$ **Background** $\rightarrow BI$ **Energy Resolution** $\rightarrow \Delta E$

- ① High efficiency (ε): Source = detector
- ② Industrial enrichment for ^{76}Ge : $\geq 86\%$ (A)
- ③ Intrinsic high-purity crystal: $\sim 13\text{N}$ (Low BI)
- ④ Background rejection: PSD, LAr veto...
- ⑤ Energy resolution (σ) $\sim 0.05\%$ @ 2MeV

HPGe can be free from $2\nu\beta\beta$ background!



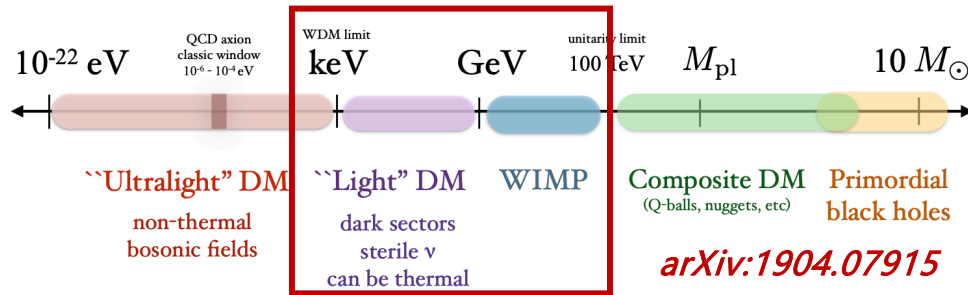
II. CDEX and its $0\nu\beta\beta$ studies

China Dark matter EXperiment (CDEX)

- ❑ Founded in 2009, 10 institutions, more than 100 people now
- ❑ Search for Dark Matter and Ge-76 $0\nu\beta\beta$ via HPGe detectors



CDEX Probes DM and $0\nu\beta\beta$ with HPGe Detectors

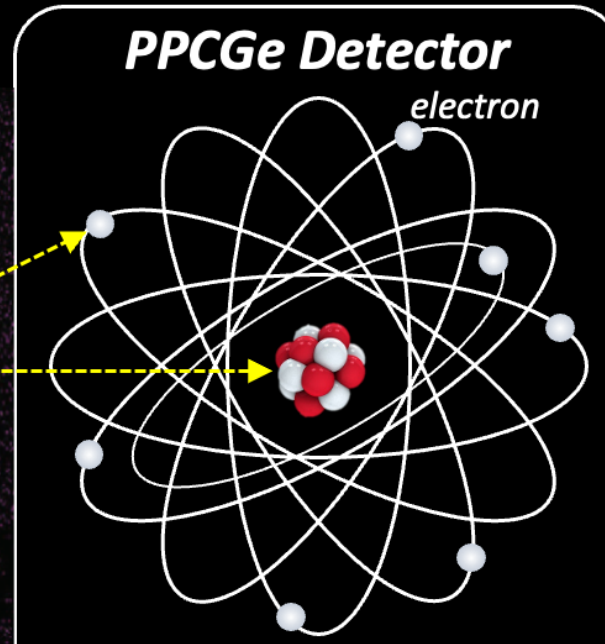


HPGe has

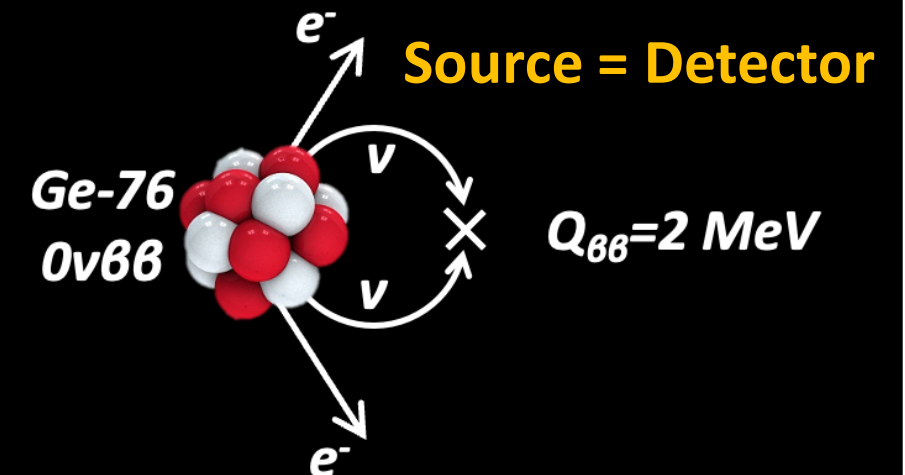
- Low E threshold for low mass DM
- Good E resolution for Ge-76 $0\nu\beta\beta$



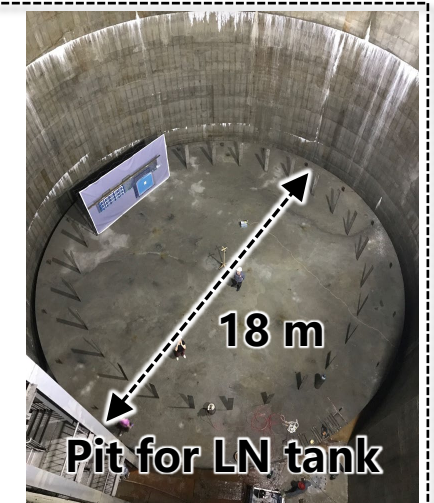
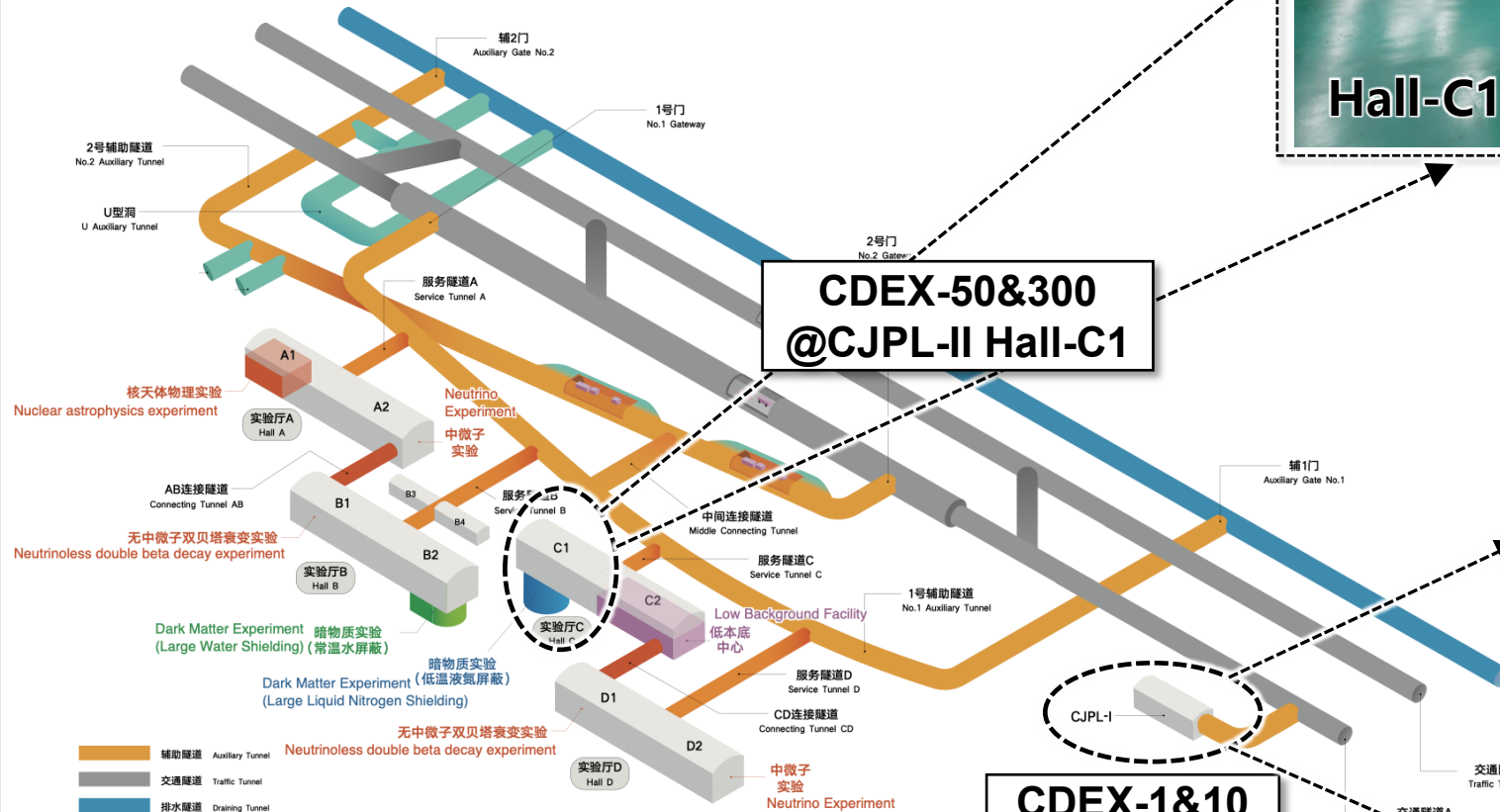
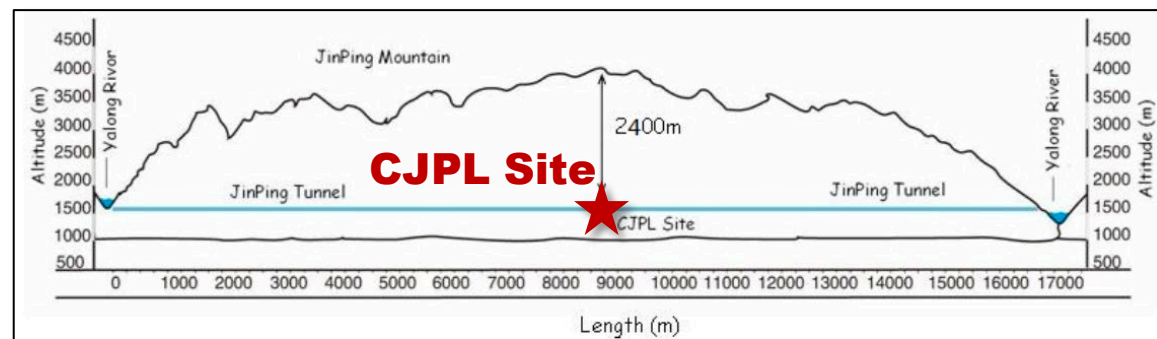
Dark Matter Direct Detection



Neutrinoless Double Beta Decay (Ge-76 $\rightarrow$ Se-76 + 2e⁻ + 2039 keV)

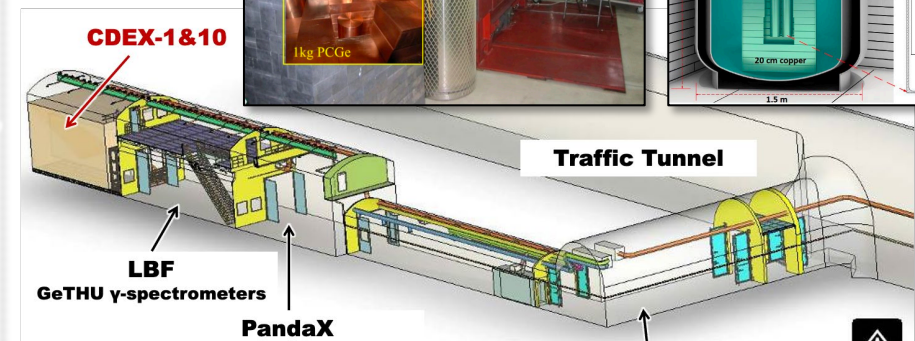
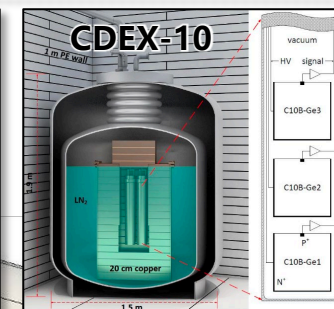
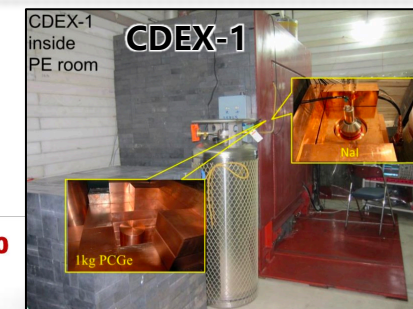
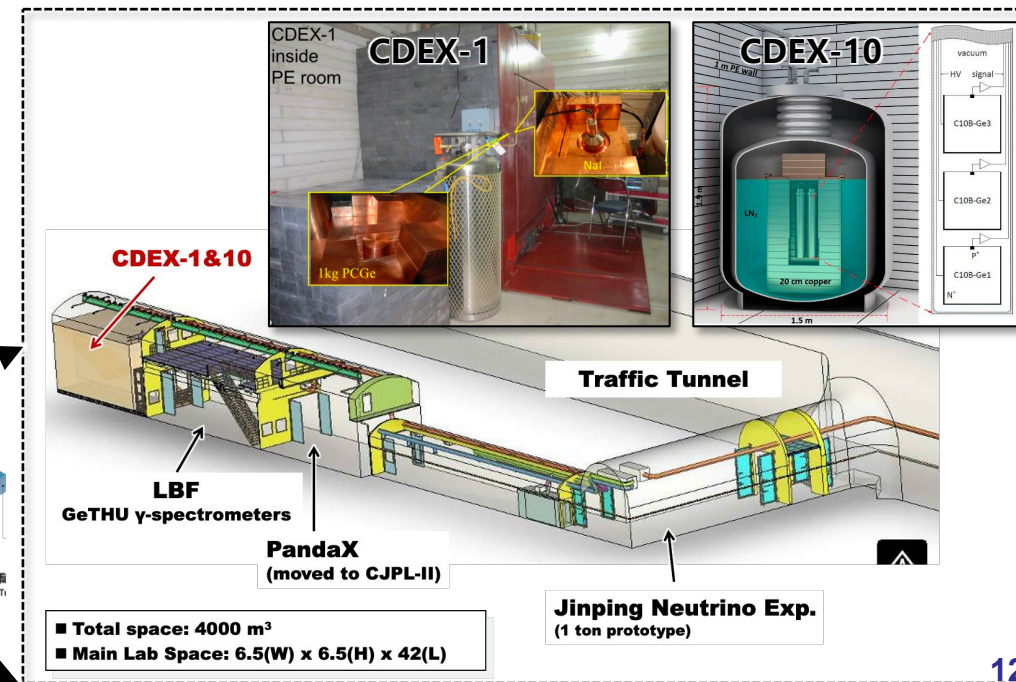


China Jinping Underground Laboratory (CJPL)



**CDEX-50&300
@CJPL-II Hall-C1**

**CDEX-1&10
@CJPL-I**



■ Total space: 4000 m³
■ Main Lab Space: 6.5(W) x 6.5(H) x 42(L)

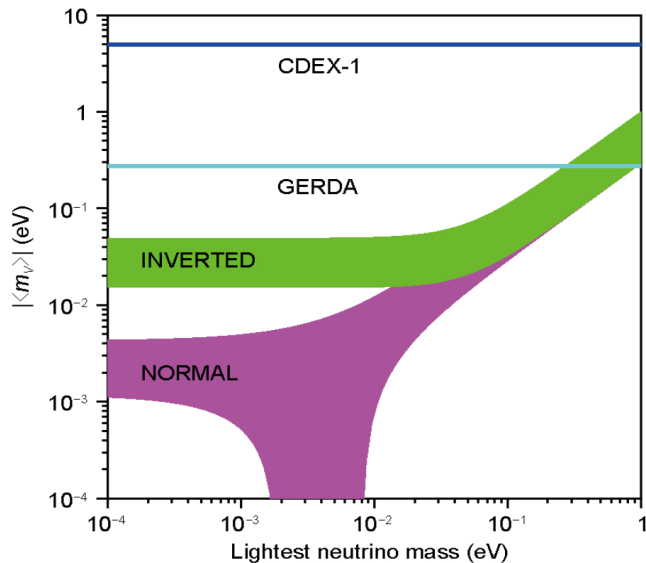
Jinping Neutrino Exp.
(1 ton prototype)

$0\nu\beta\beta$ Study using natural HPGe

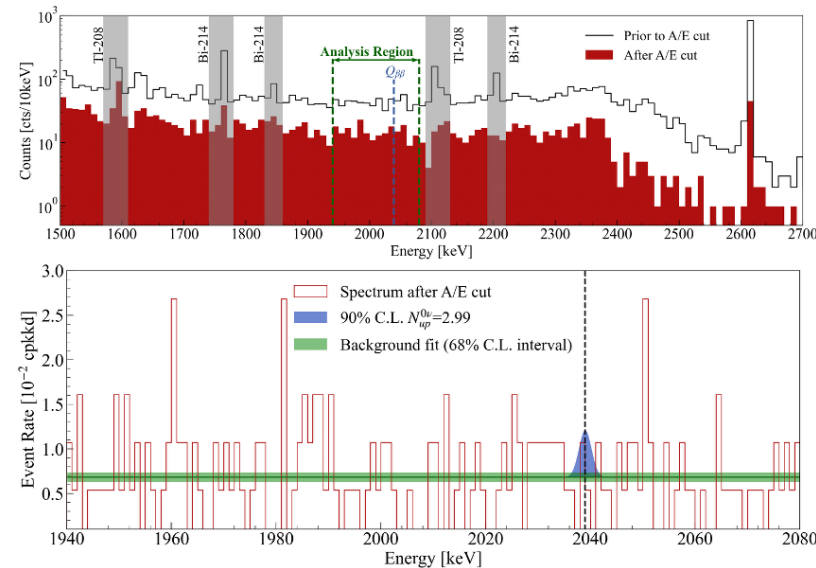
Pre-study for future large scale $0\nu\beta\beta$ experiment (CDEX-300)

- 2017, First $0\nu\beta\beta$ result using CDEX-1A PPC detector
- 2022, Study pulse shape discrimination (PSD) using a BEGe detector
- 2024, Improved $0\nu\beta\beta$ result using CDEX-1B with PSD & NaI veto

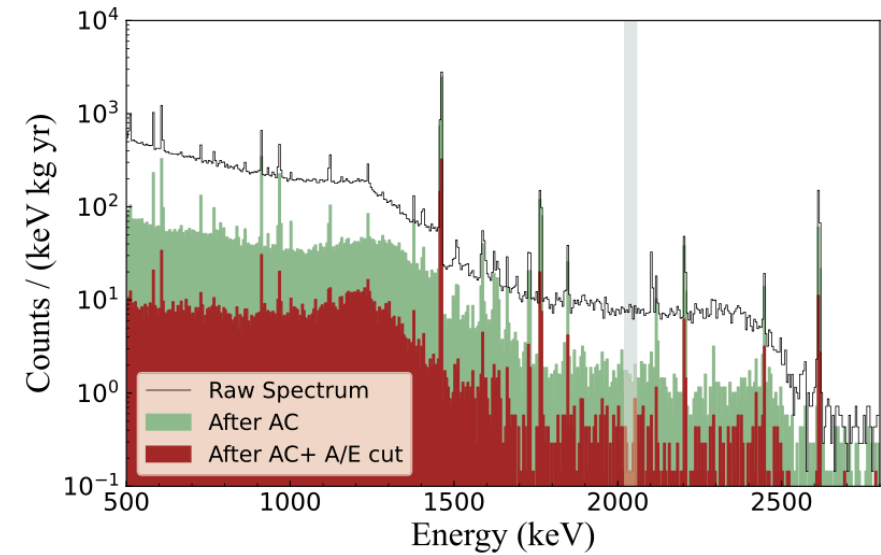
Sci. China PMA. 60, 071011, 2017



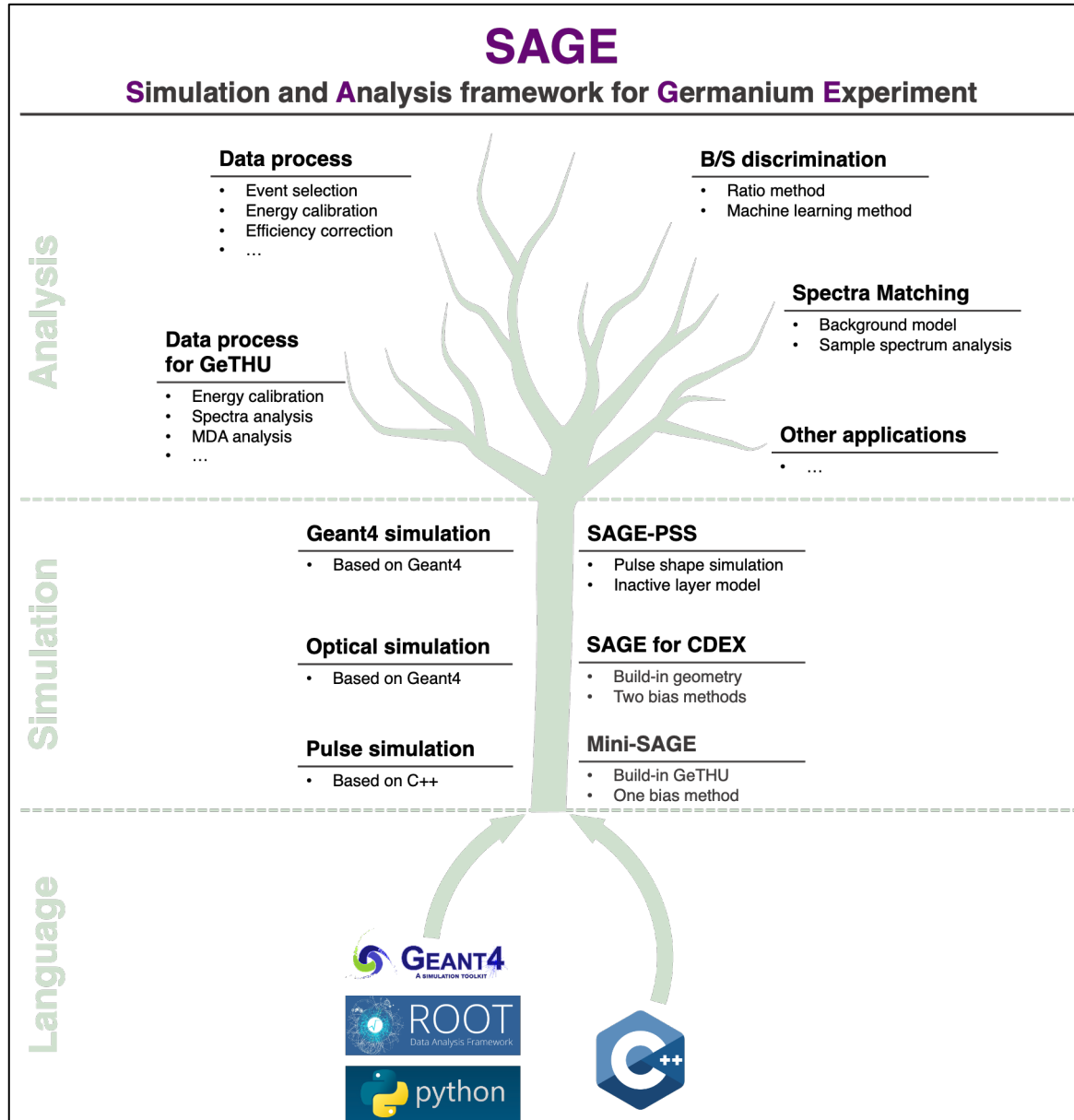
PRD 106, 032012, 2022



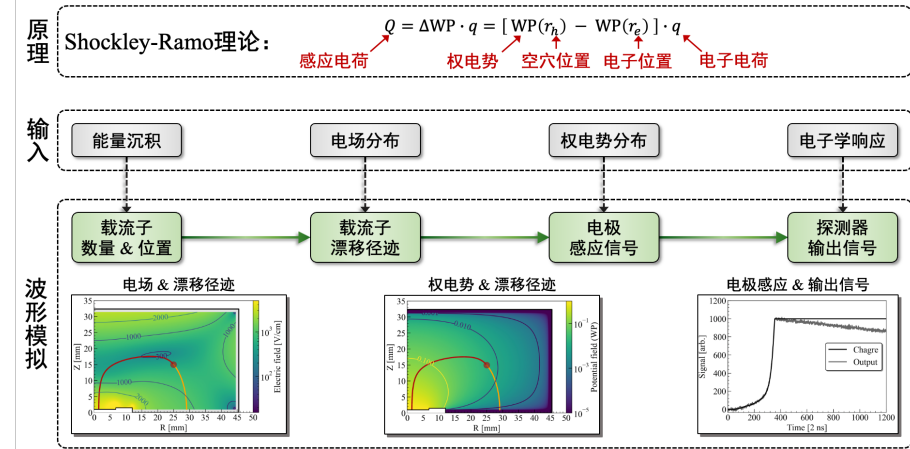
CPC 48, 101001, 2024



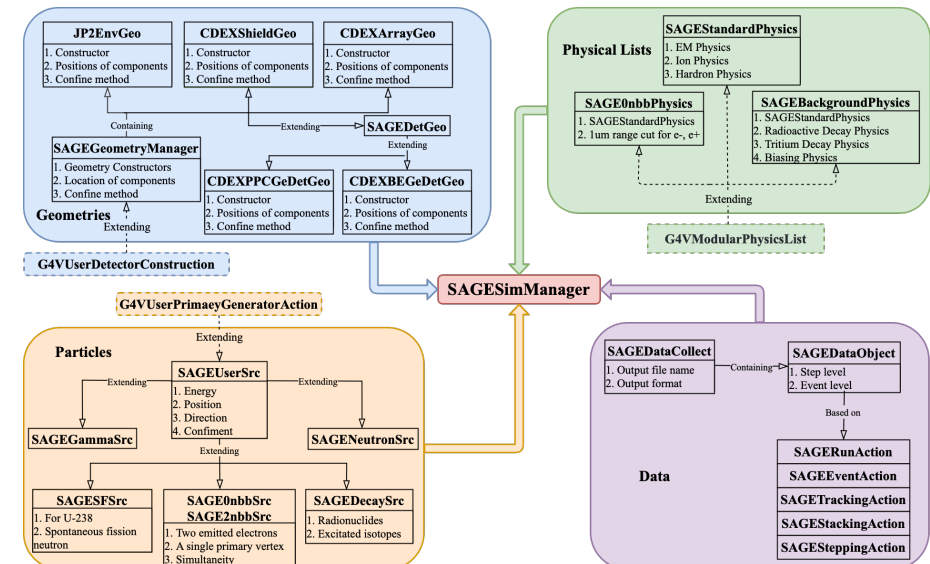
Simulation toolkit for CDEX: SAGE



Pulse shape simulation for HPGe



Particle simulation for HPGe experiment

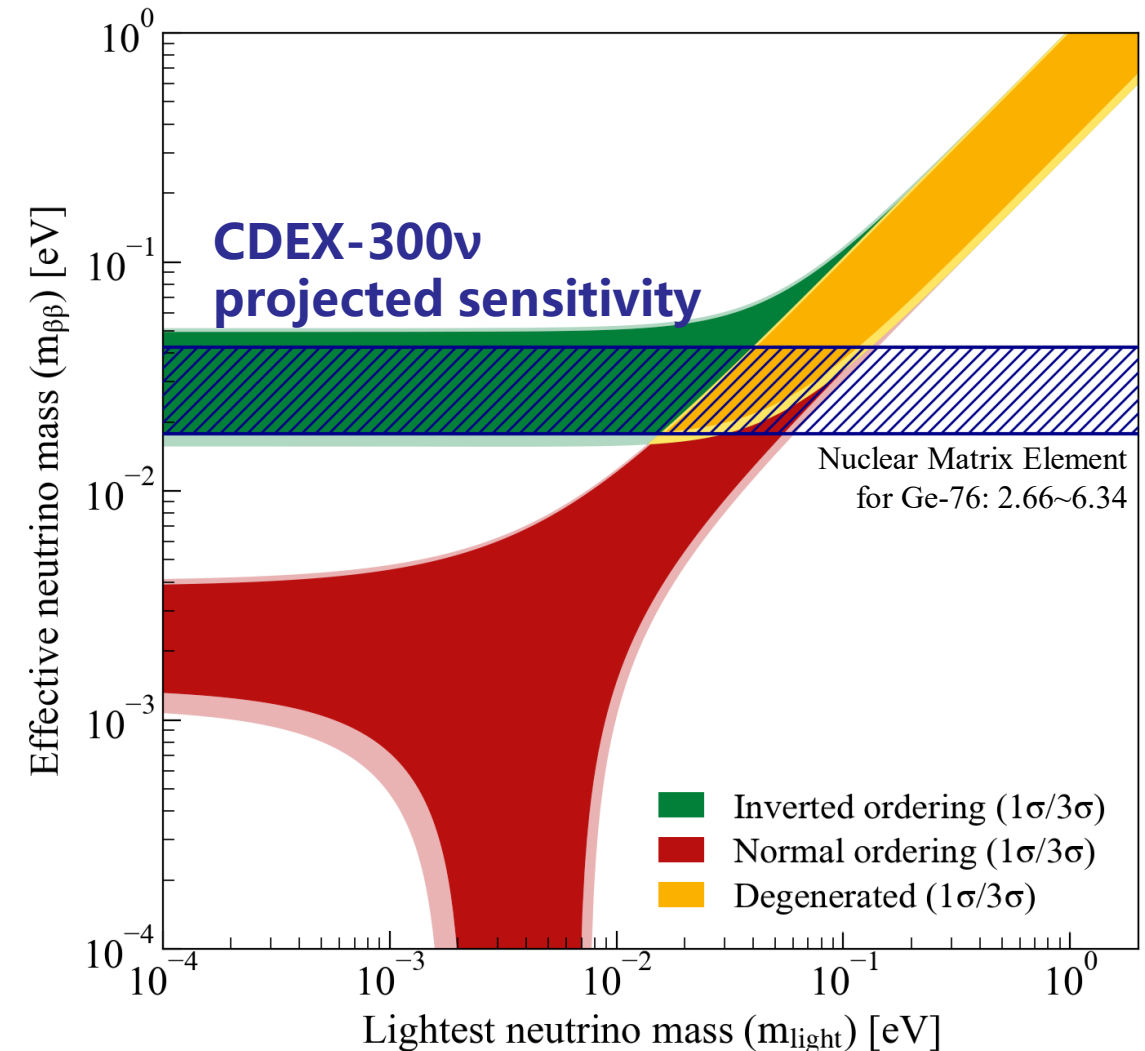


III. Design and status of CDEX-300v

Physics Goal of CDEX-300

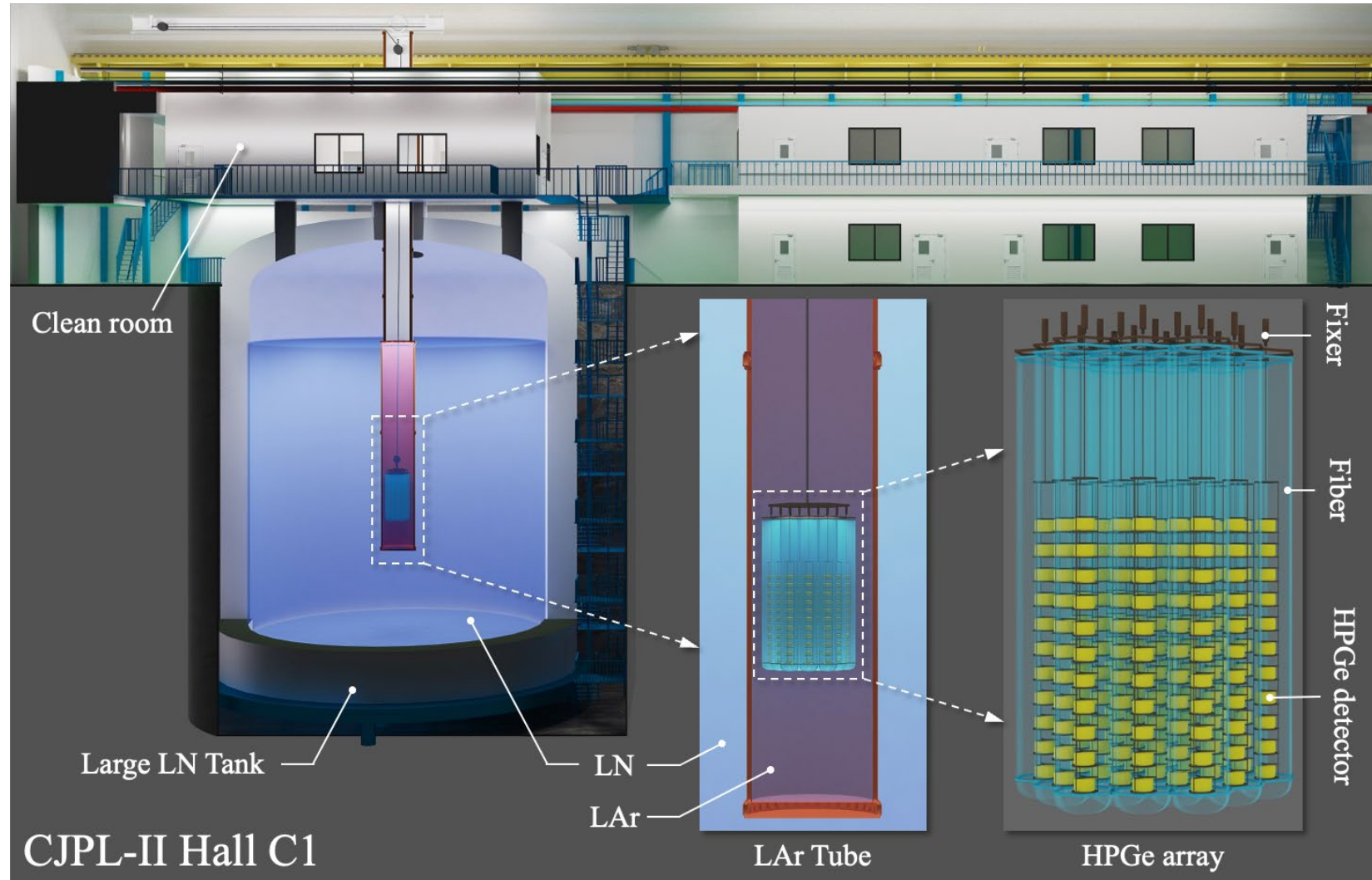
Physics Goal	
$0\nu\beta\beta$ half-life	3.06×10^{27} yr (exc)
	1.91×10^{27} yr (dis)
Effective mass	18.5 ~ 44.2 meV (exc)
	23.4 ~ 55.8 meV (dis)
Detector Parameter	
Detector mass	225 kg
Operation time	10 yr
Ge-76 enrichment	$\geq 86\%$
Signal efficiency	76%
Background level	1E-4 cpkky
Energy resolution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

Search Ge-76 $0\nu\beta\beta$ decay at Inverted Ordering (IO) region



CDEX-300 Overview

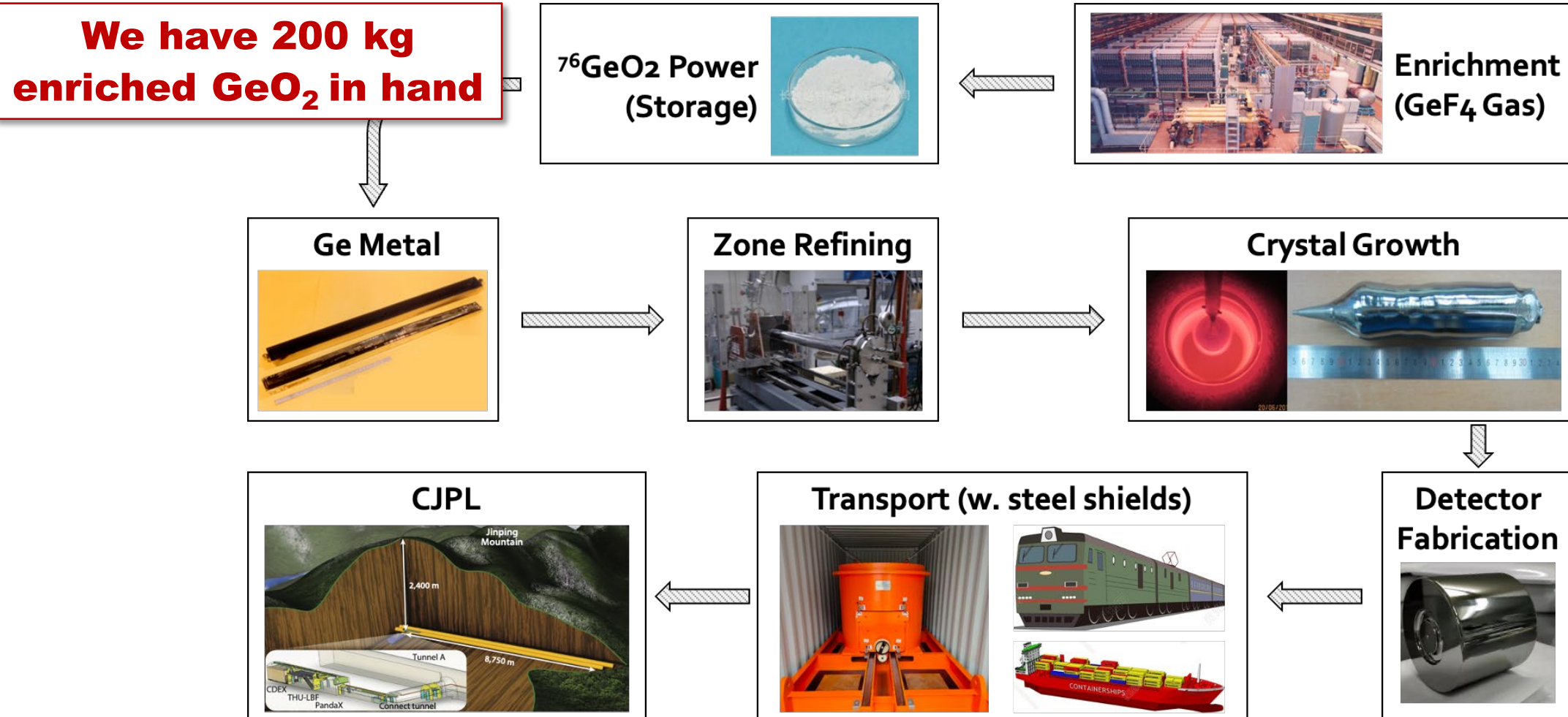
- Hall-C1 at CJPL-II
- LN_2 tank shared with CDEX-50
- LAr tube containing LAr submerged in LN_2
- Ge detector array immersed in LAr
- 200 enriched HPGe detectors divided into ~19 strings



Enriched HPGe detector

Procurement of Enriched Ge detector

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



Cosmogenic Background Control

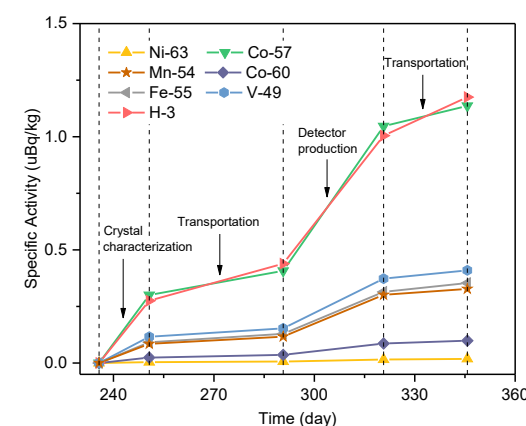
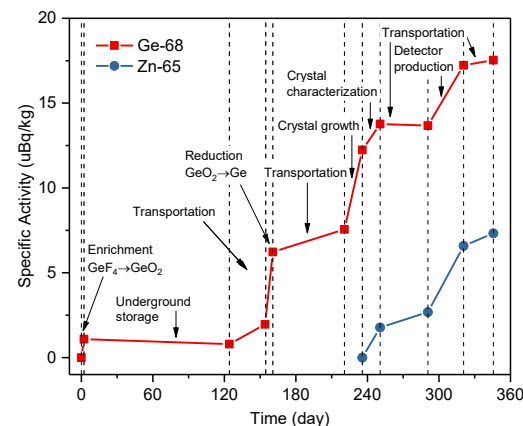
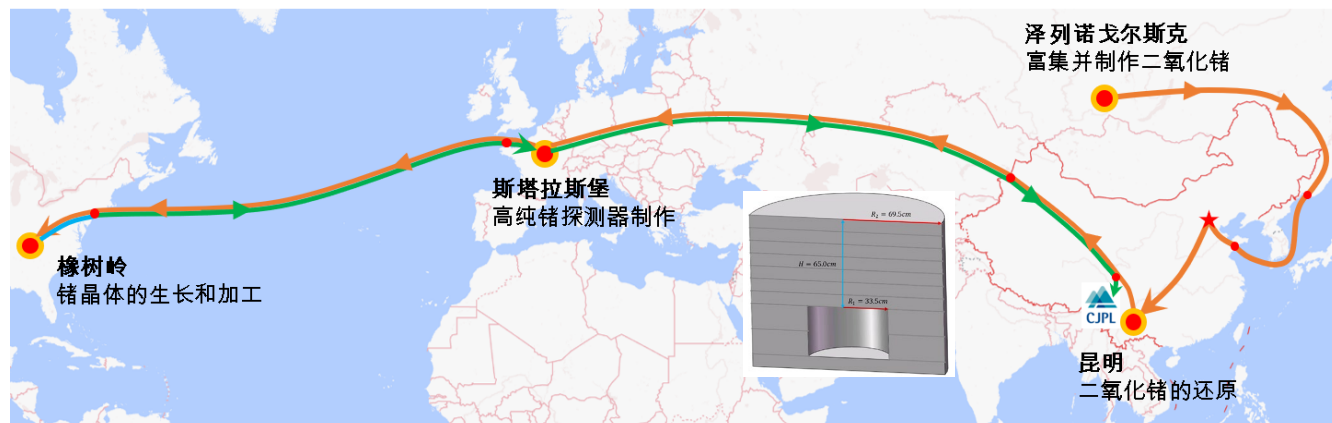
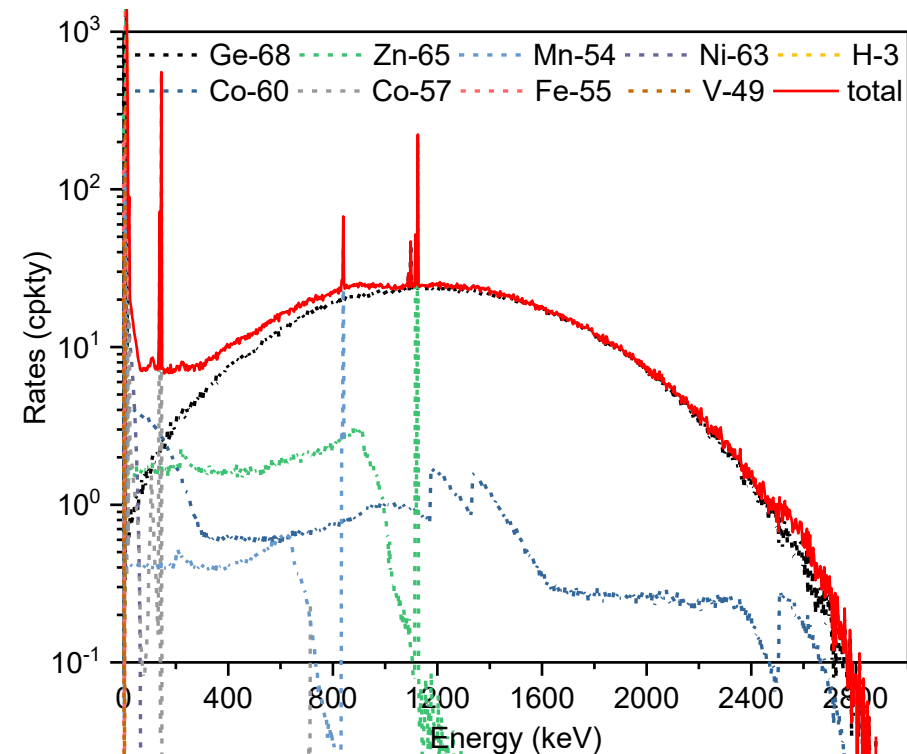
Cosmogenic isotopes produced during above-ground fabrication & transportation

Upon arrival at CJPL:

- **Ge-68: 17.5 $\mu\text{Bq/kg}$** (~100 $\mu\text{Bq/kg}$ w.o. control)
- **Co-60: 0.1 $\mu\text{Bq/kg}$** (~10 $\mu\text{Bq/kg}$ w.o. control)

For 87% enrichment HPGe:

□ **Ge-76 $2\nu\beta\beta$ ~ 70 $\mu\text{Bq/kg}$**



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 cryostat and then 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

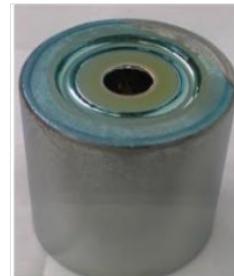
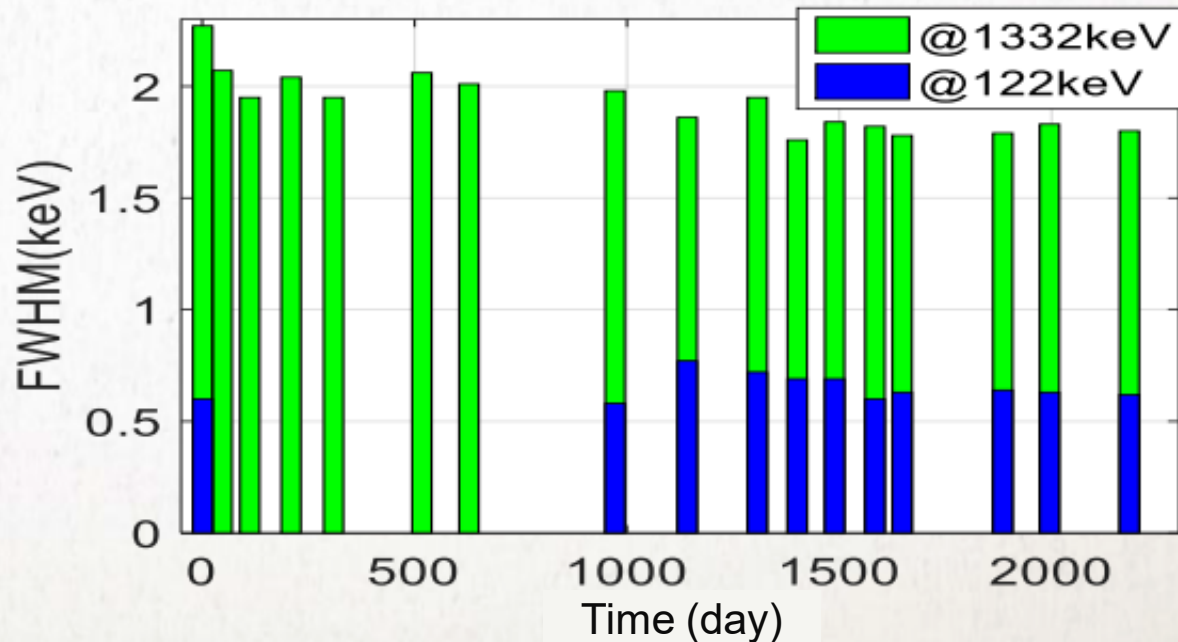
R&D on HPGe detector

Home-made Ge detectors

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

R&D on underground fabrication ongoing...

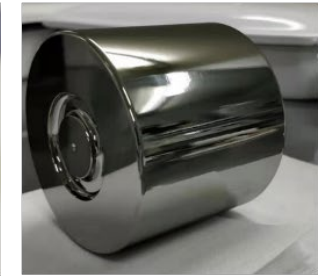
Long-term stability: energy resolution



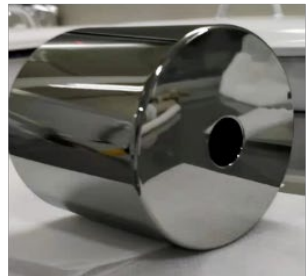
Co-axial



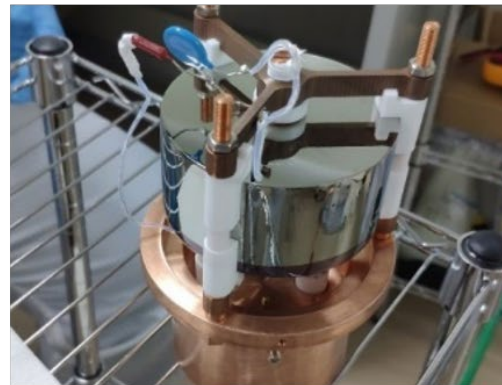
BEGe



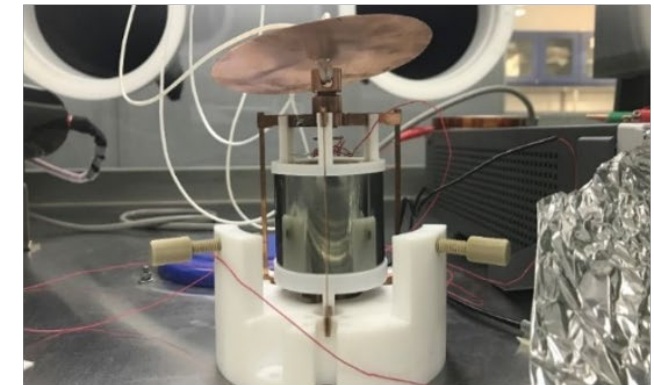
PPC



ICPC



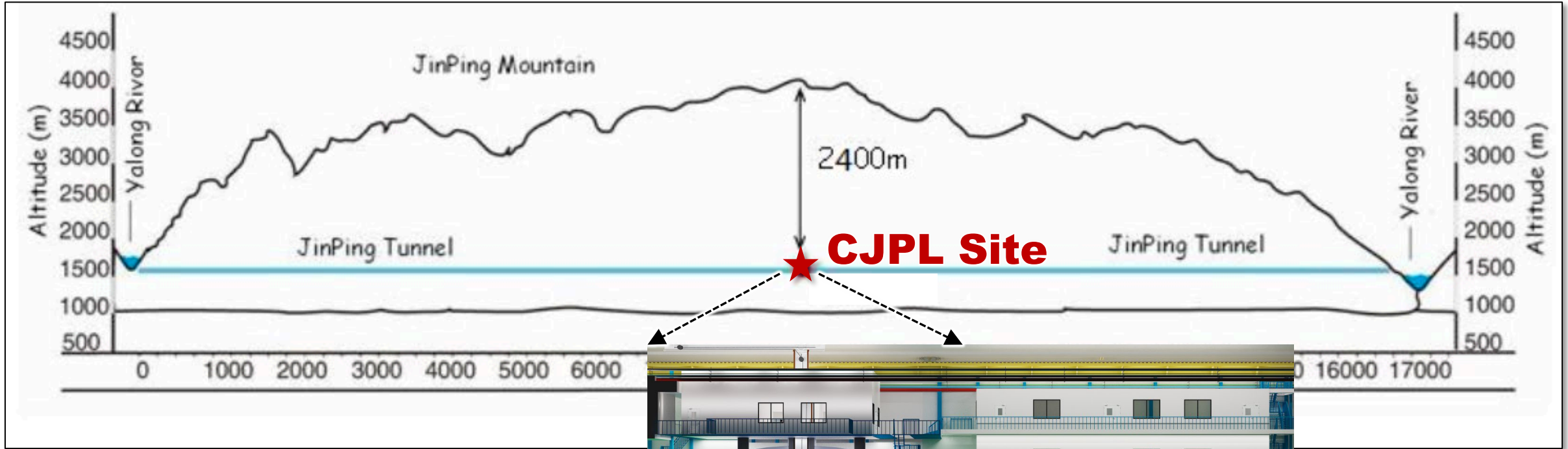
Cold finger cooling



Naked crystal to LN₂

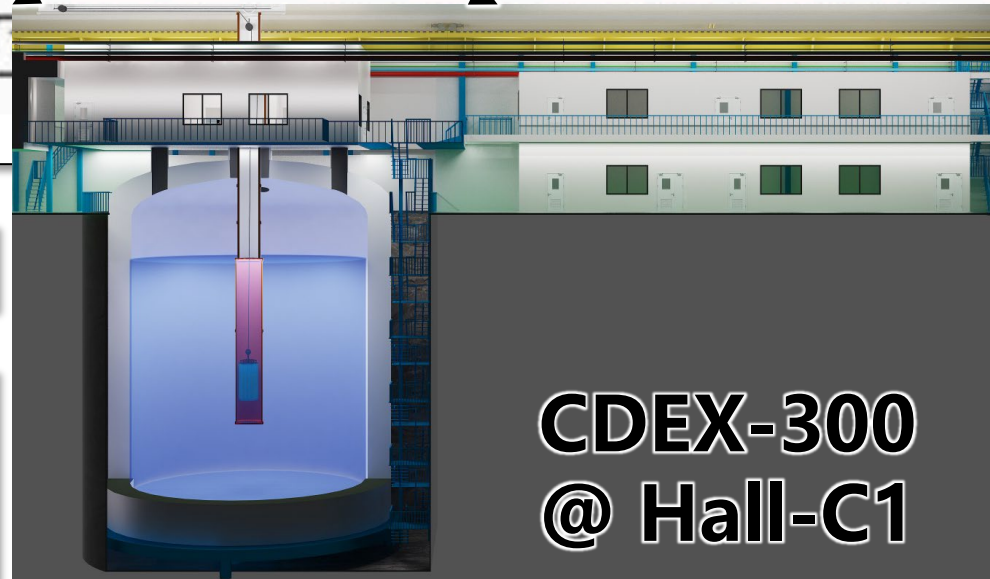
Infrastructure: 2400 m Rock Shielding

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



□ Muon flux $3.03 \times 10^{-10} \text{ cm}^{-2} \text{ s}^{-1}$

Muon-induced background
□ $\sim 1\text{E-}7 \text{ cpkky @ 2MeV ROI}$
□ **Negligible for CDEX-300**

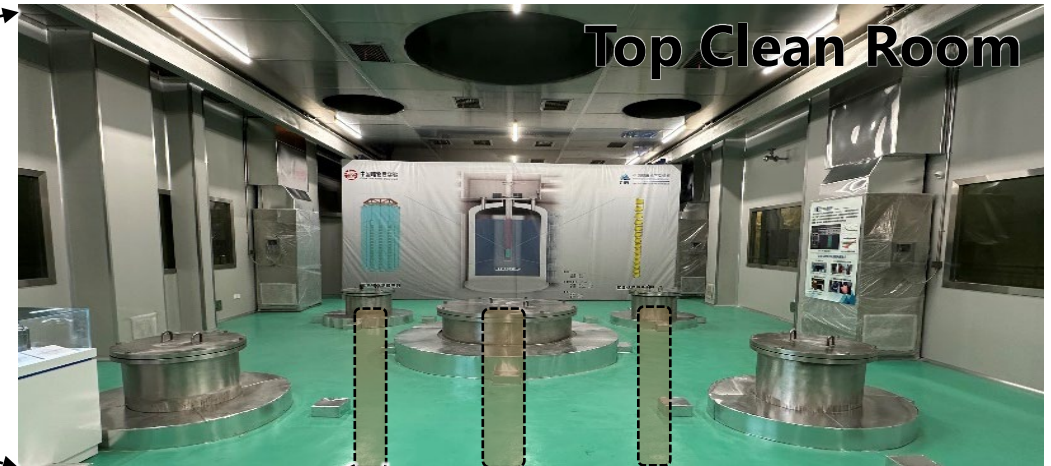


Infrastructure: Current Status of Hall-C1

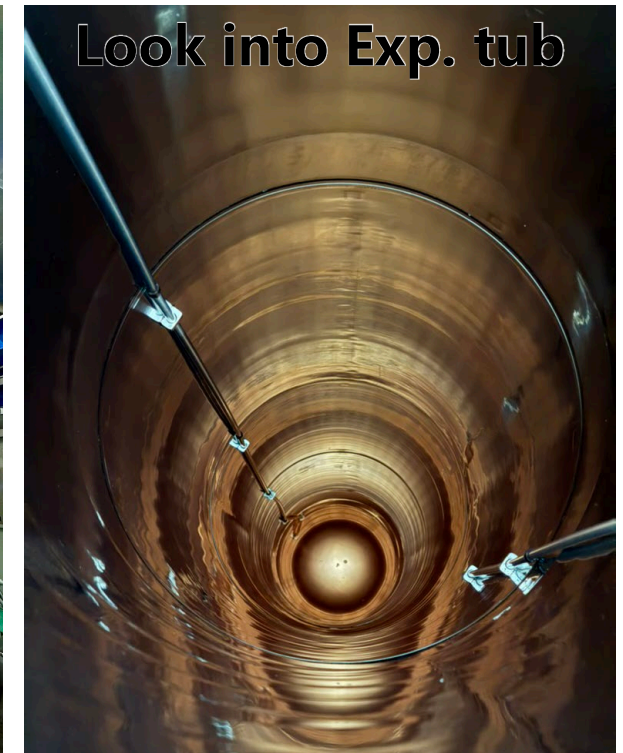
Look into Hall-C1



Top Clean Room



Look into Exp. tub



Exp. Tub



Look in-front of the LN tank

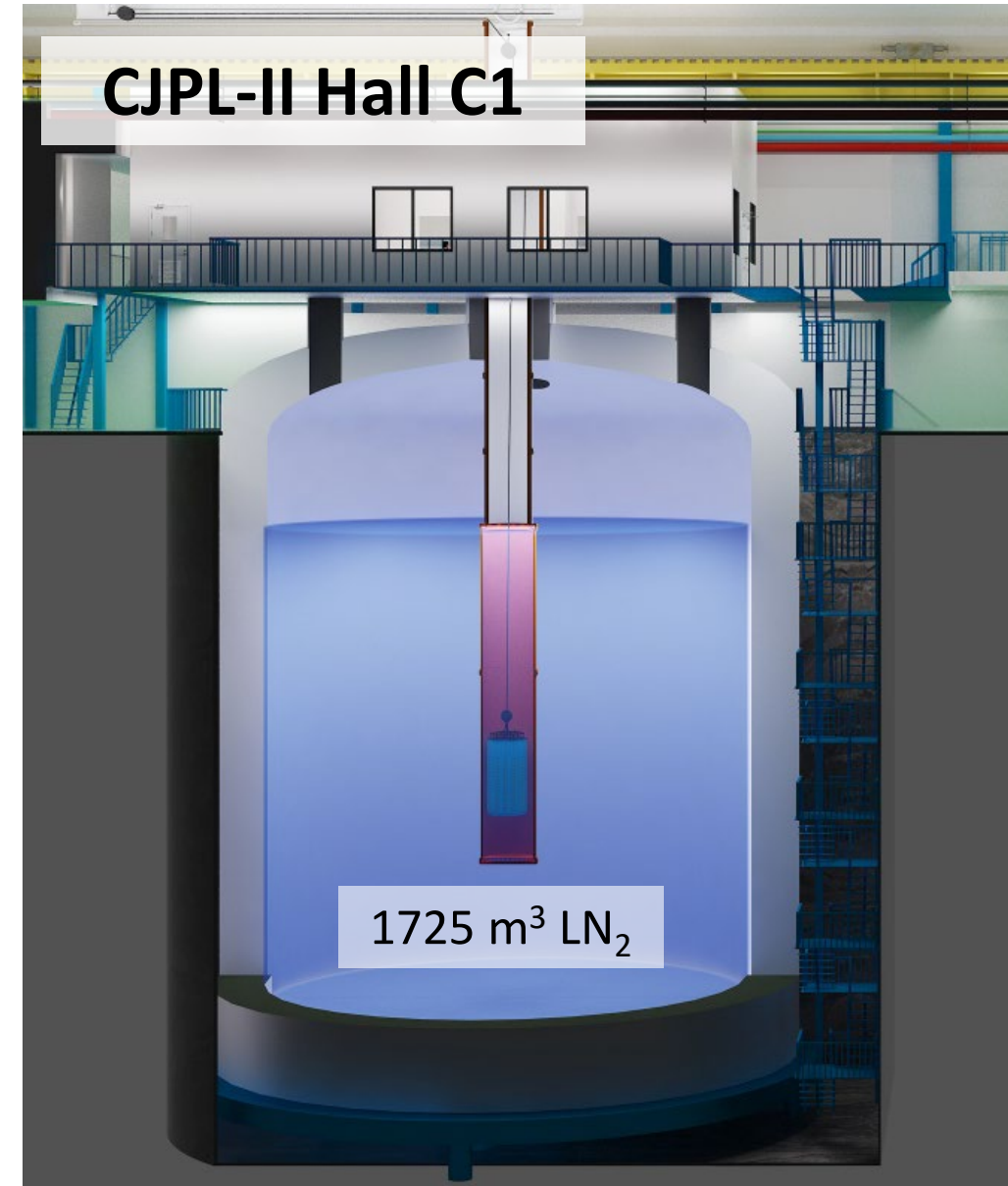
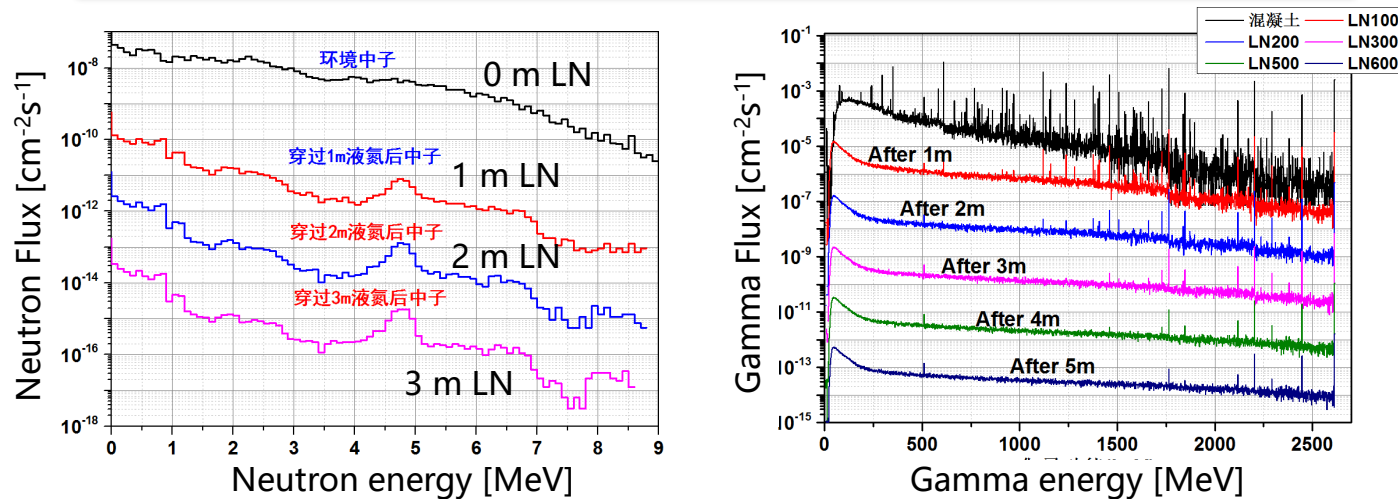


The Large LN Tank

The LN₂ tank

- Total volume: 1976 m³
- LN₂ volume: $\Phi 13\text{m} \times H 13\text{m}$, $\sim 1725\text{ m}^3$
- LN₂ as Passive Shield / cold source for LAr
- Five top flanges for detector deployment
 - 1 $\times \phi 1.5\text{m}$, centrally (CDEX-300v)
 - 4 $\times \phi 750\text{mm}$, on a 6 m diameter circle

LN₂ as Effect Shielding against neutron & gamma



The LAr Veto System

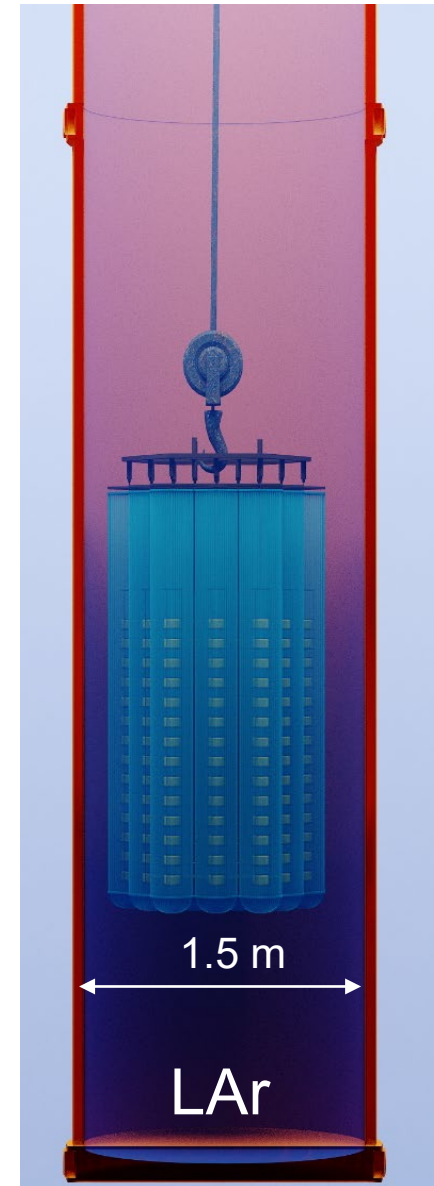
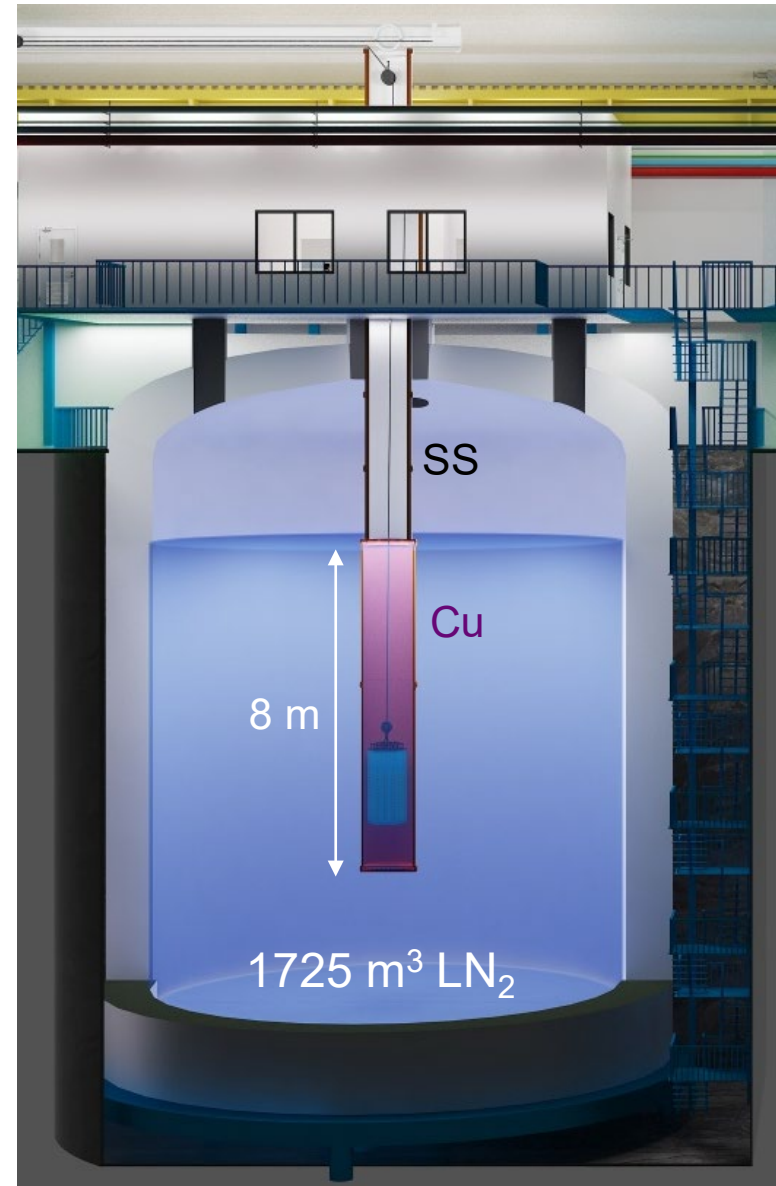
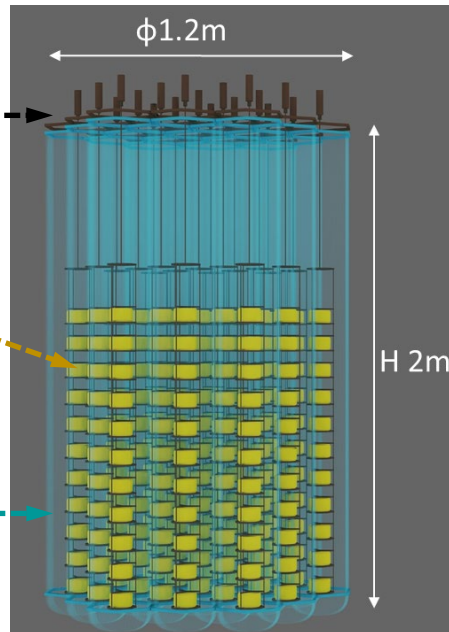
Baseline design:

- ~20 t LAr held by Cu / SS cryostat
- Atmosphere argon
- LAr constantly purified
- LAr cryostat immersed in LN₂
- LAr light read out by WLS Fiber + SiPM

SiPM at top

BEGe detectors

WLS Fiber curtain



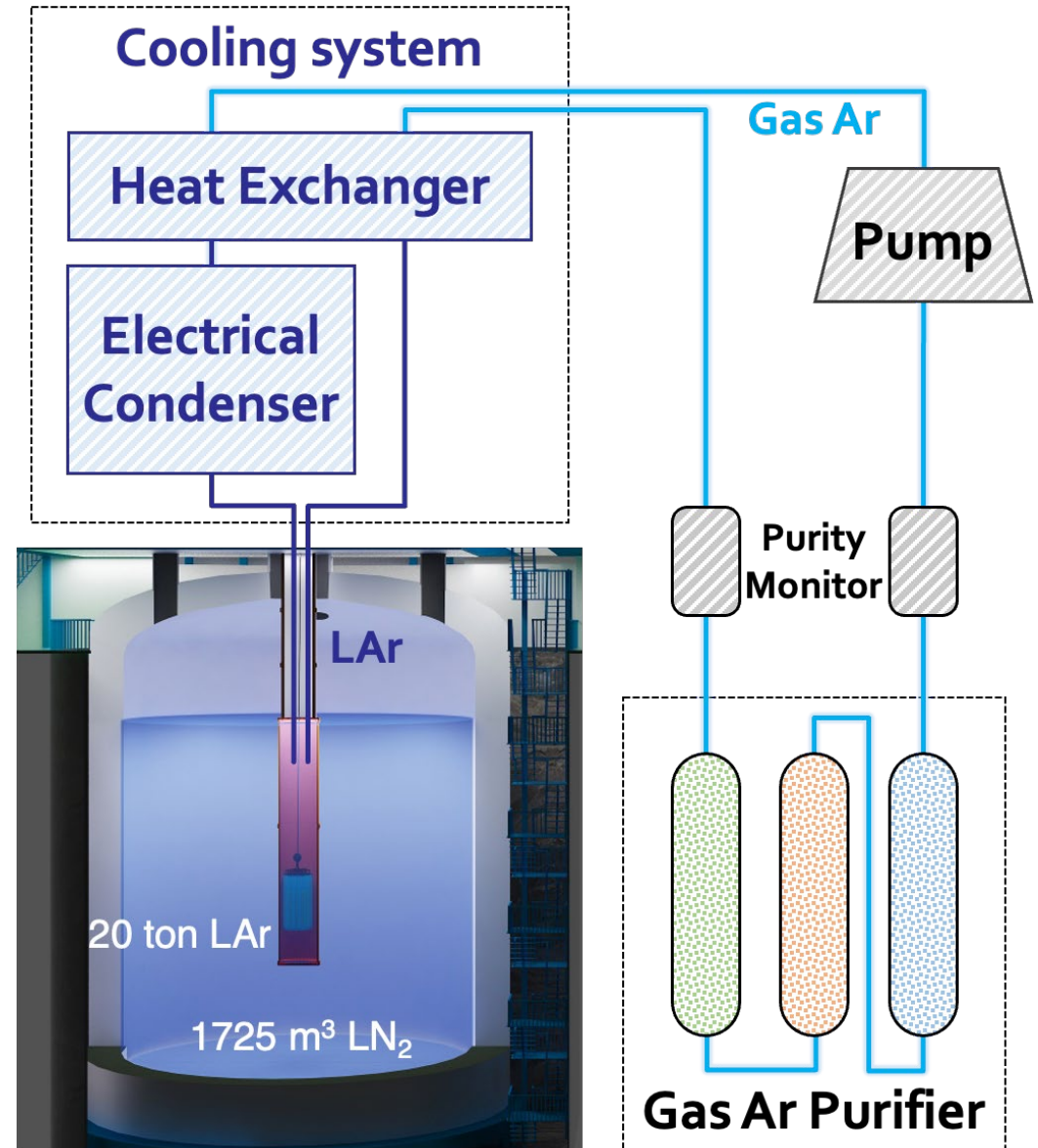
The LAr Veto System

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 ($\sim \mu\text{Bq}/\text{m}^3$)
- Possible underground Argon (Ar-42 depleted)

LAr Cooling

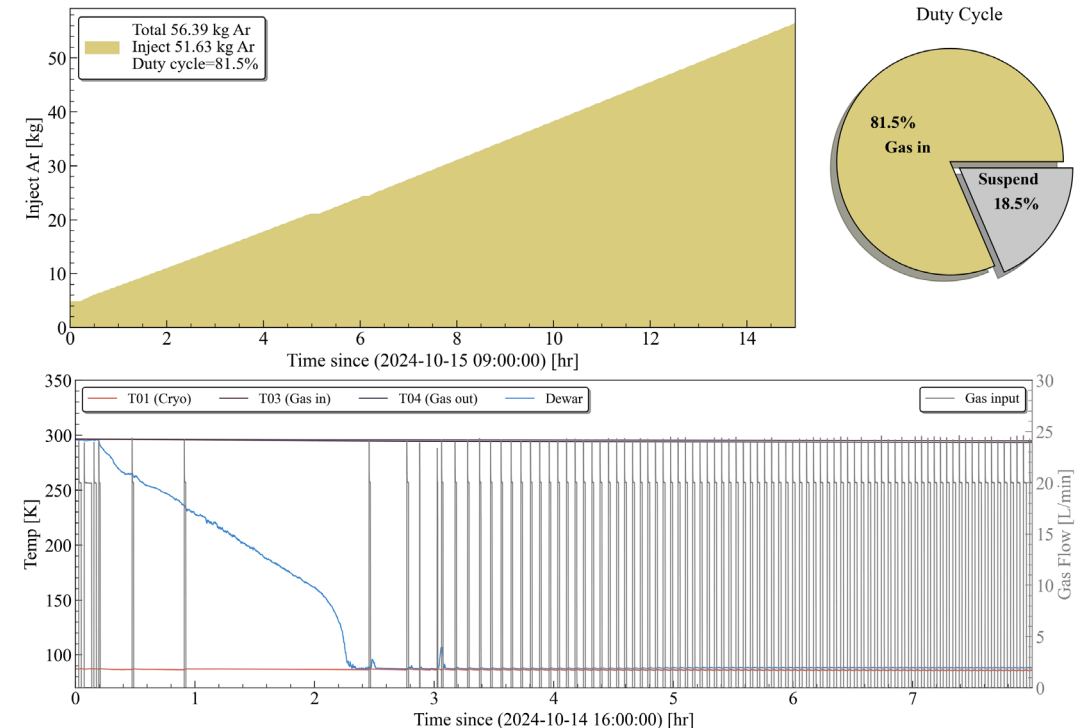
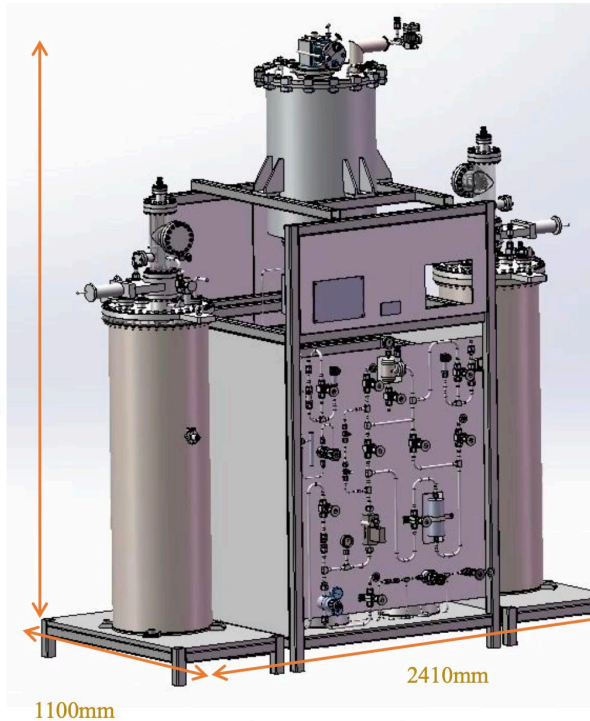
- Cooling purified GAr to LAr
- Heat exchanger + electrical condenser
- Backup LN_2 cooling module



Prototype LAr system at ground Lab in Xichang

Installed and started testing in December 2024

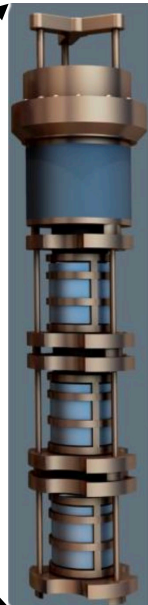
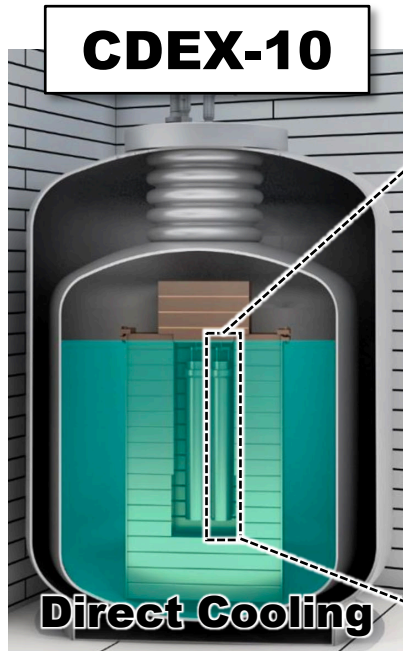
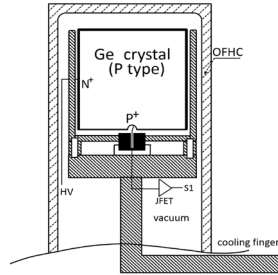
- ① **Stage-1:** Operating & Purifying LAr in a closed cycle (✓)
- ② **Stage-2:** Deploying light readout to study light yield / transmission of LAr in different impurity levels (Ongoing)
- ③ **Stage-3:** Deploying Ge detectors to test veto performance (Future)



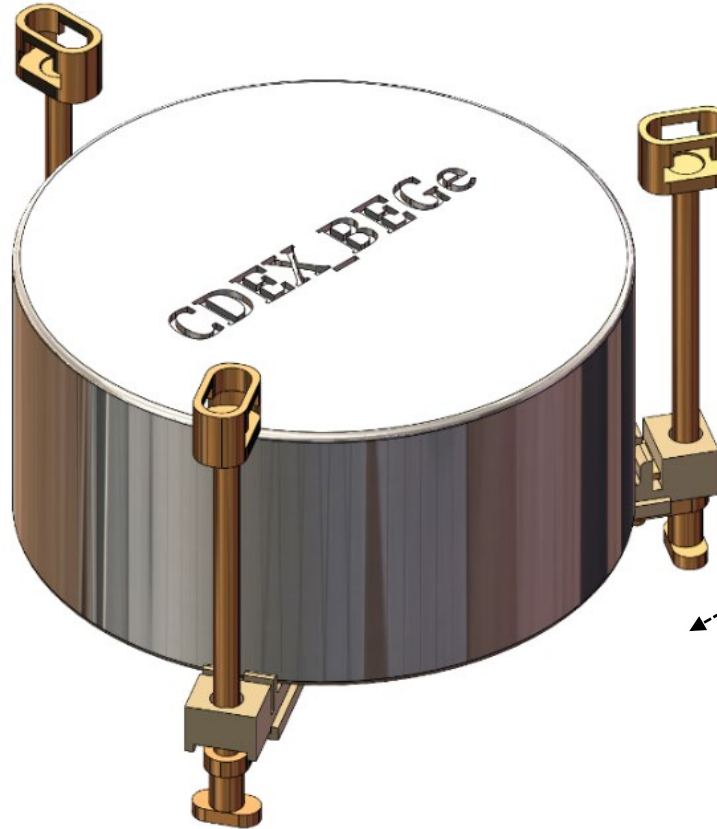
Detector Module: Reducing Structure Mass



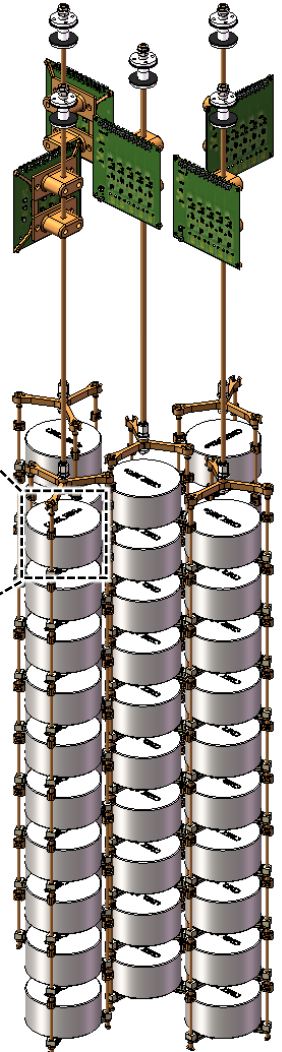
CDEX-1



CDEX-300



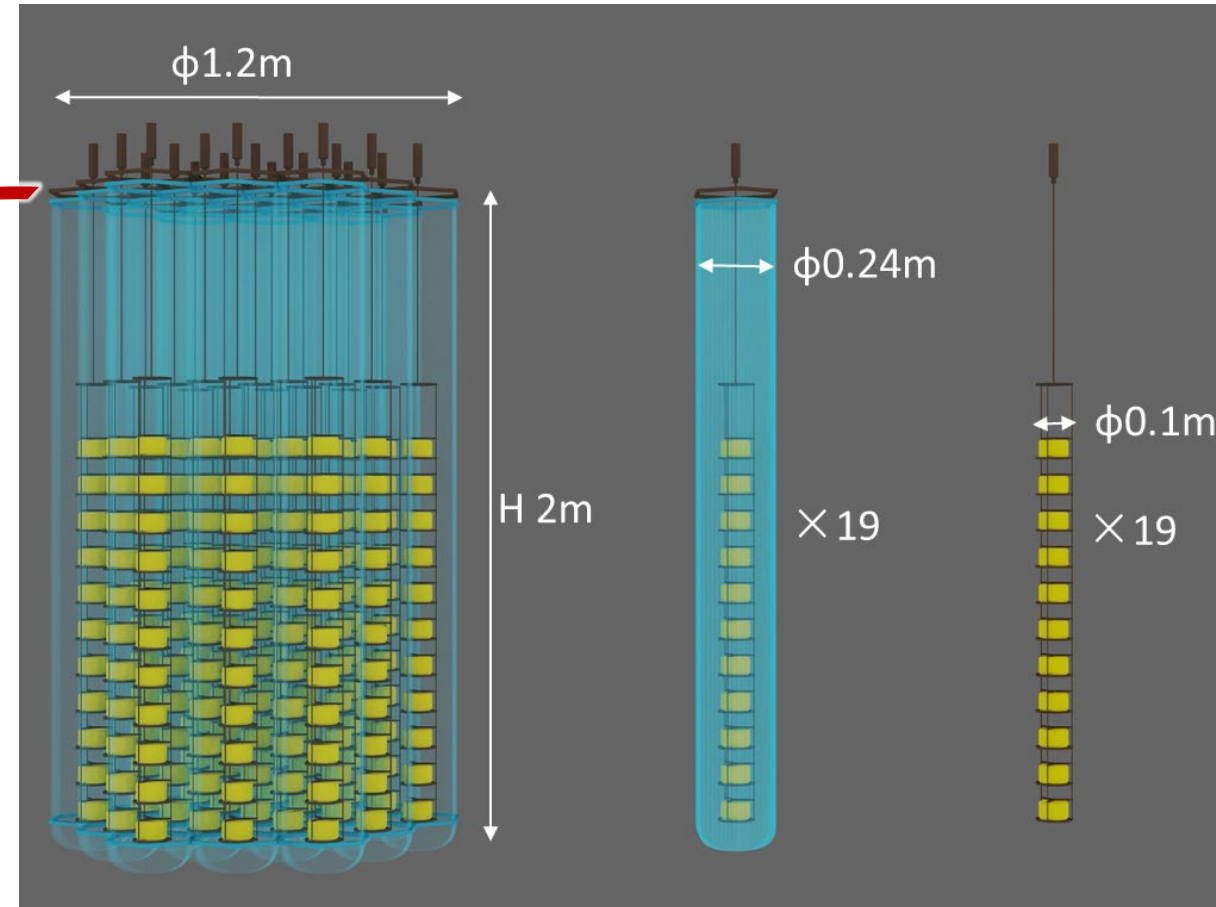
**Detector string
Total 200 dets.**



Ge Detector Array

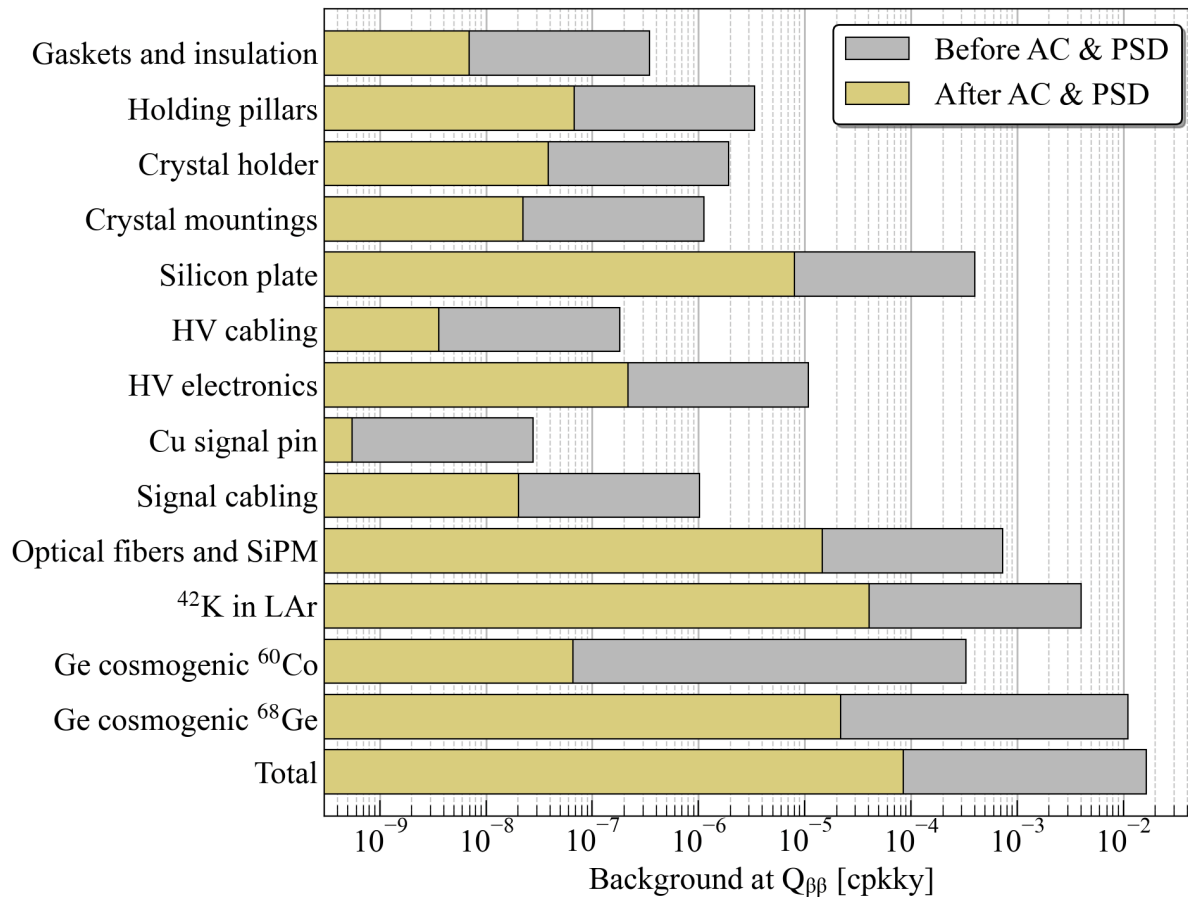
- 200 Ge-76 enriched detectors: 19 strings, 10~11 det/string
- Top clean room for Ge detector and fiber installation

Top Clean Room



Background Goal for CDEX-300

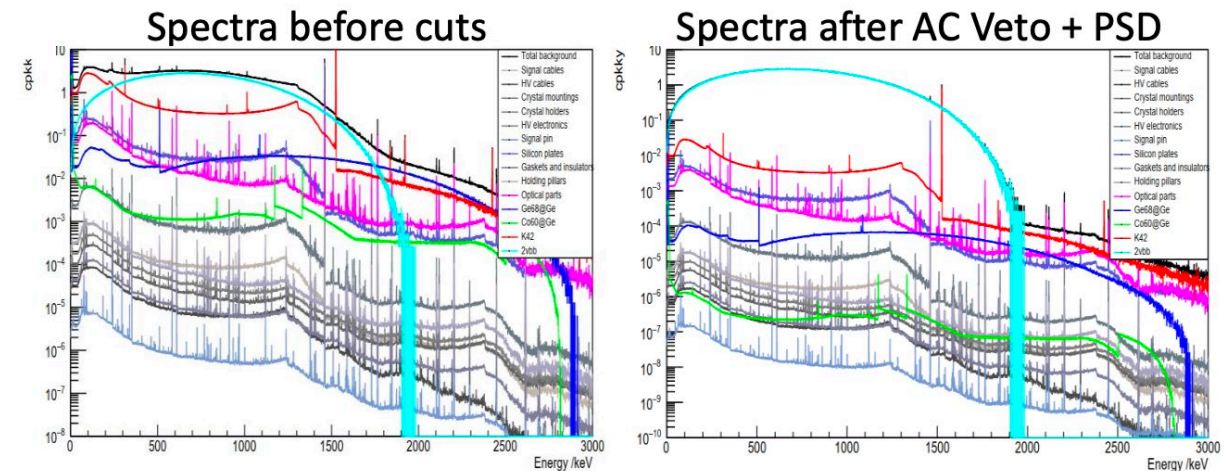
Estimation of background in ROI using the SAGE simulation toolkit
After active cuts (LAr veto & PSD), **BG @2 MeV $\sim 1\text{E-4 cts}/(\text{keV}\cdot\text{kg}\cdot\text{yr})$**



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

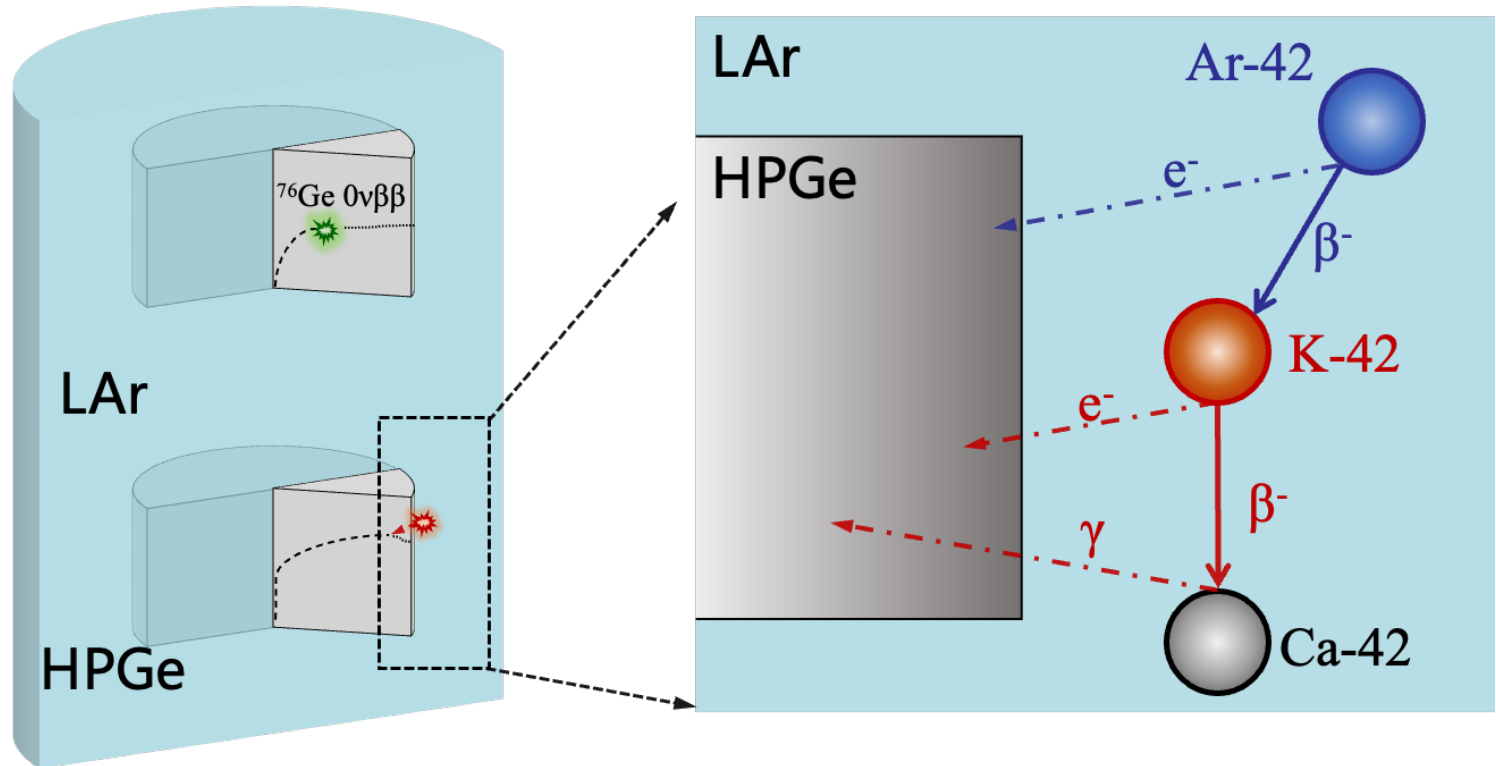
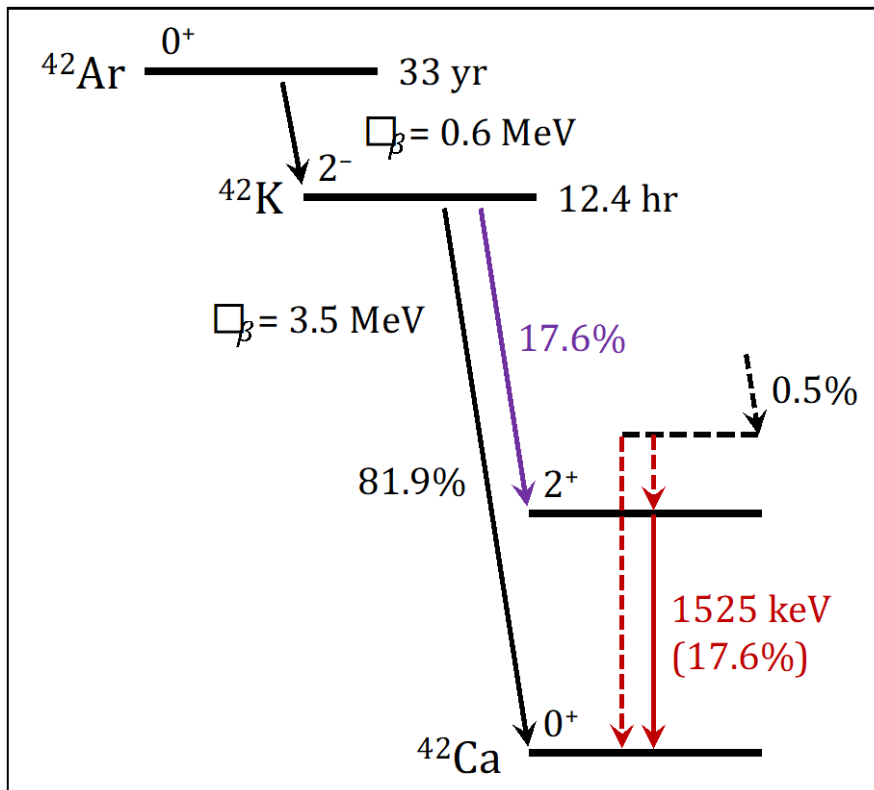
Further BG reduction may be achieved by:

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



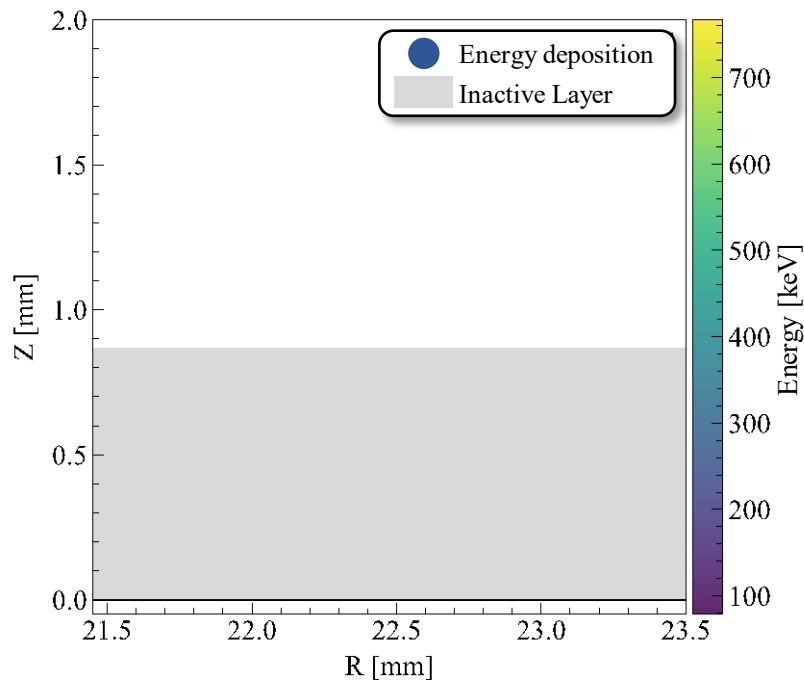
Surface Background from Ar-42 (K-42) in LAr

CDEX-300 will use atmosphere Ar (Ar-42 $\sim 100 \mu\text{Bg/kg}$)
Ar-42 (K-42) contributes Surface Background in 2 MeV region

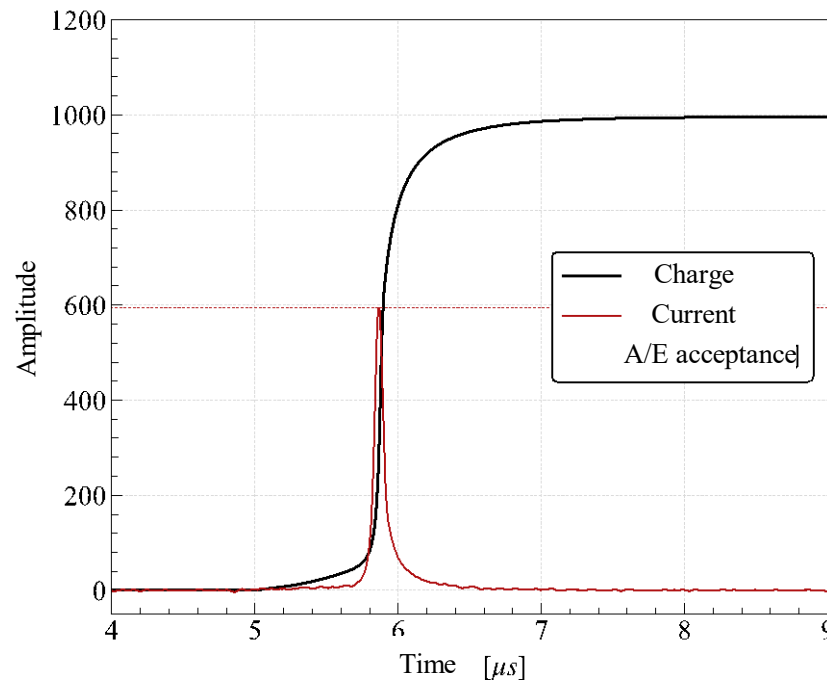


Surface Background from Ar-42 (K-42) in LAr

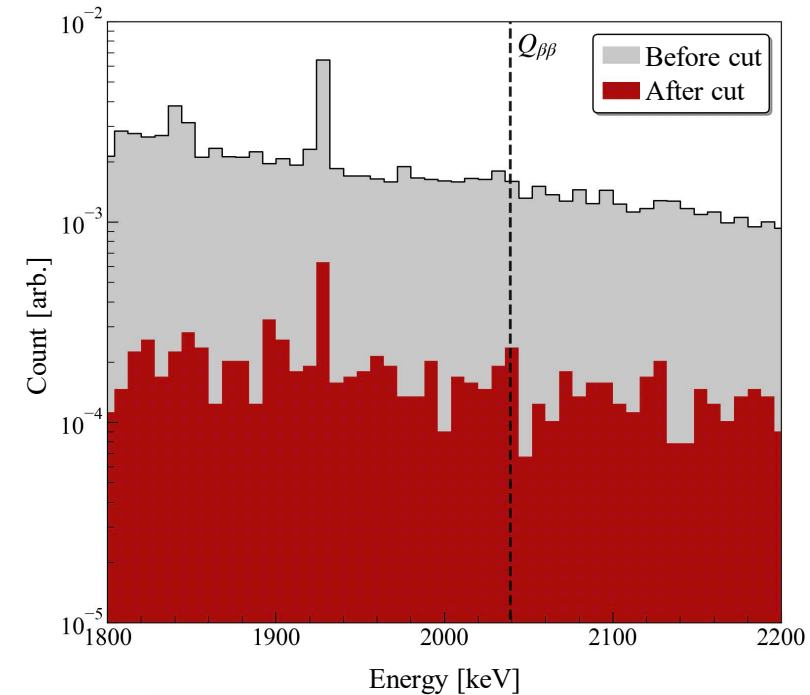
- ❑ Ar-42 (K-42) surface background features a slow pulse shape
- ❑ A/E method could reduce BG by ~ 10 times
- ❑ Remaining BG clusters on the surface



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



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

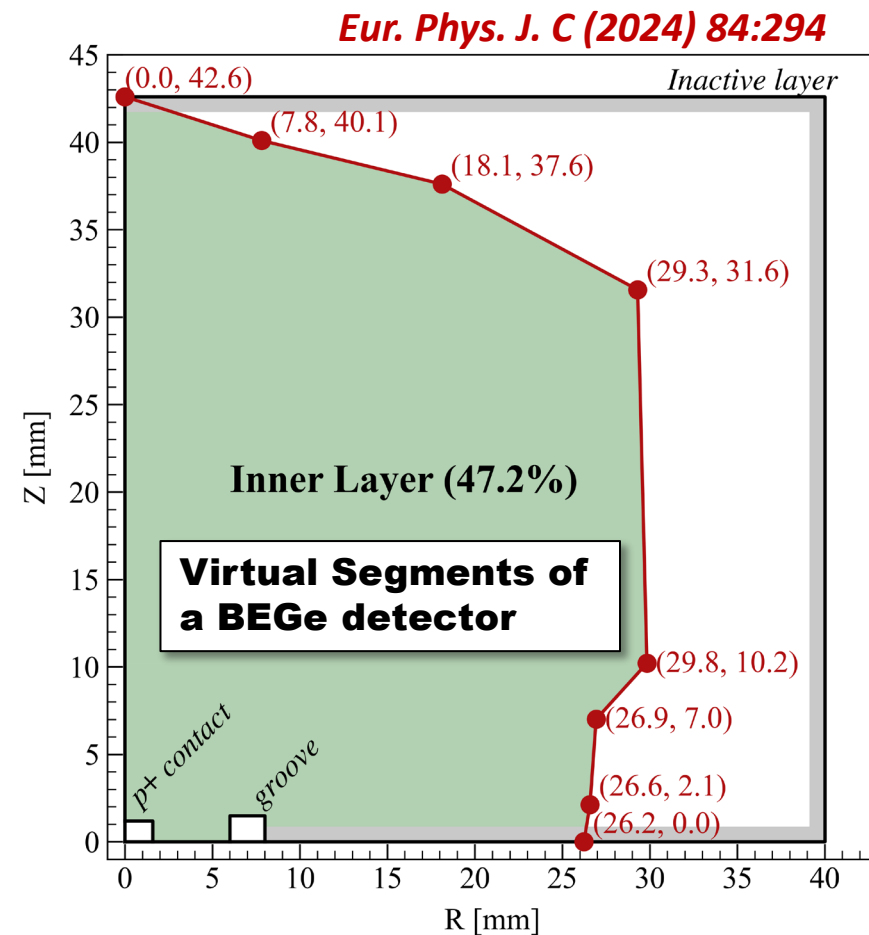
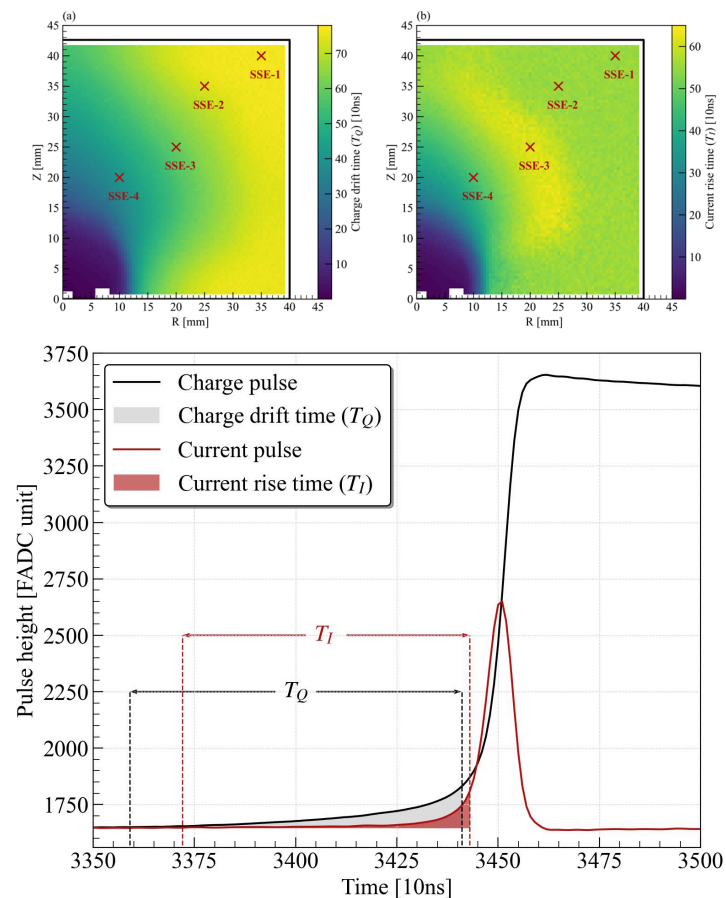
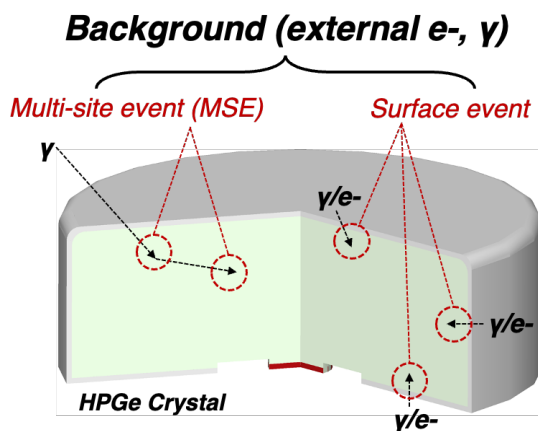
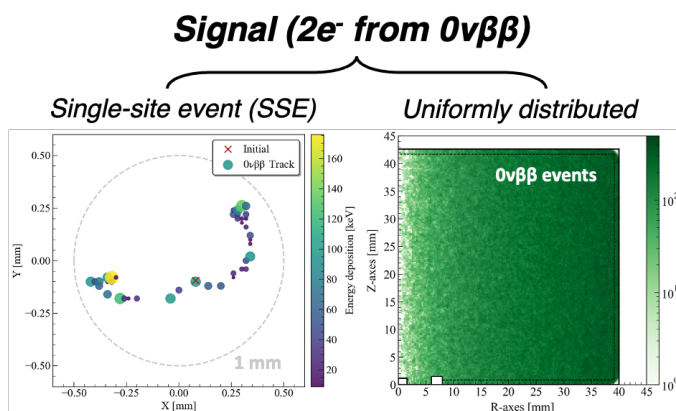


**Simulated spectra of
Ar-42 (K-42) background**

R&D on New PSD Method

Virtual Segmentation of single-readout Point-contact HPGe

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



Other progress

❑ Material Background Control

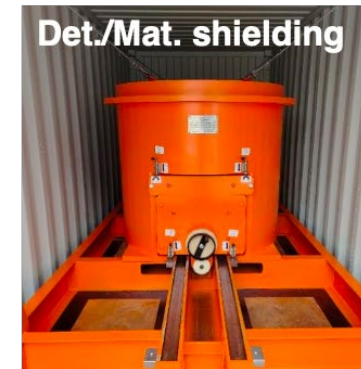
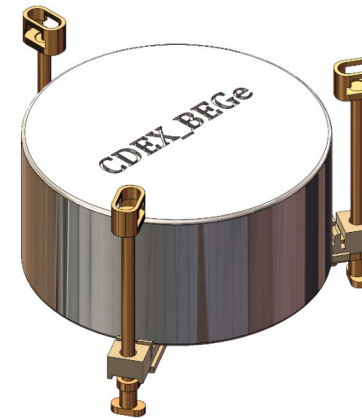
ALL materials to be screened and selected

❑ 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 $< 10 \mu\text{Bq/kg}$
- Free of cosmogenic radioactivity



Summary

- ❑ CDEX uses Ge detectors searching for light DM and Ge-76 $0\nu\beta\beta$ at CJPL
- ❑ CDEX-300 ($0\nu\beta\beta$) is in the pipe line
- ❑ LN tank filled and LAr tube installed inside
- ❑ Key technologies R&D are ongoing

Thanks for your attention!



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

CJPL 

中国锦屏地下实验室
China Jinping Underground Laboratory

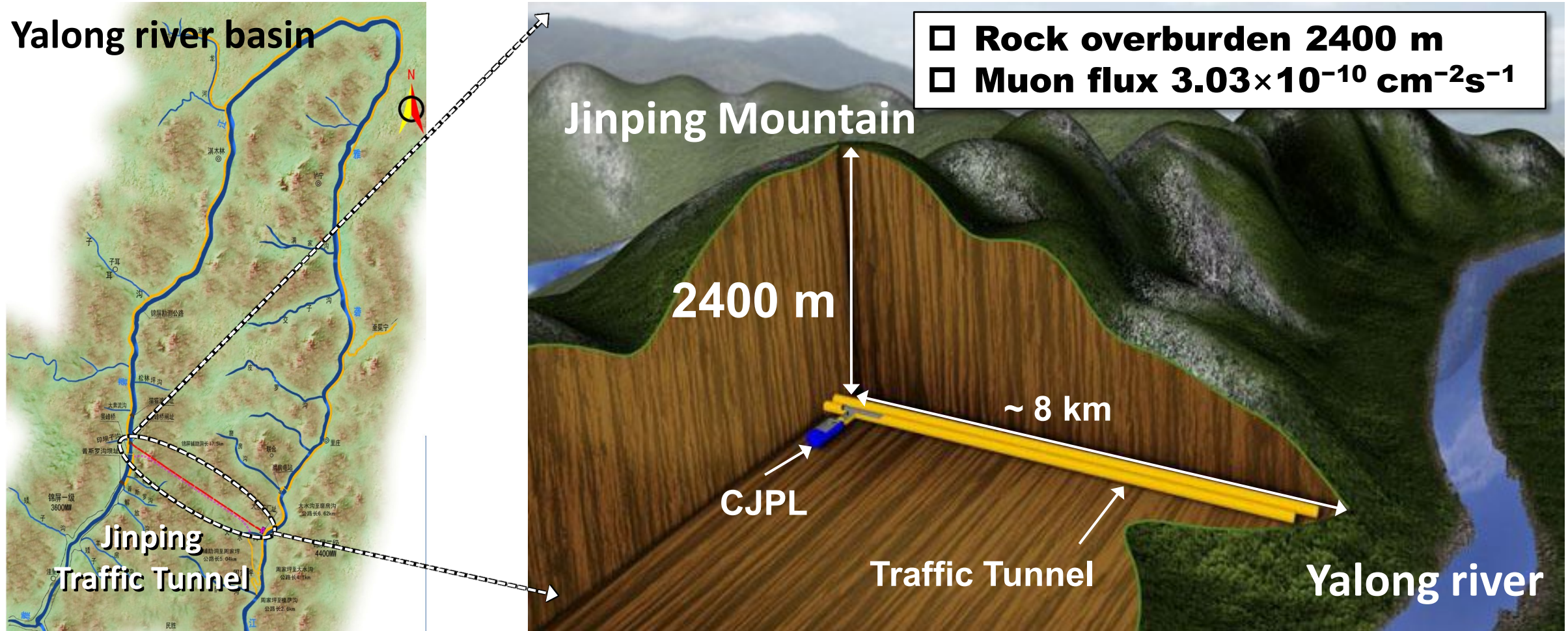
清华大学·雅砻江流域水电开发有限公司

<http://cjpl.tsinghua.edu.cn>



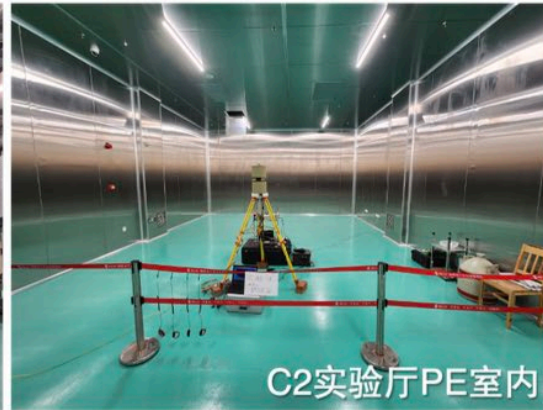
Back up

China Jinping Underground Laboratory (CJPL)



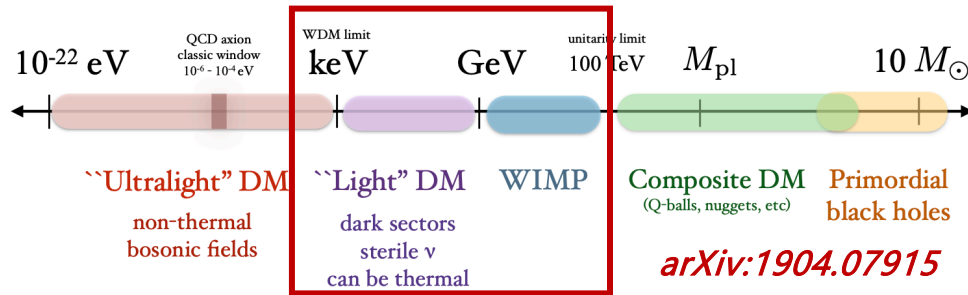
CDEX is operated at CJPL
The Deepest & Largest underground lab in the world

Radiation Environment in CJPL-II



Lab	In-situ meas. by detector	Energy Range[keV]	Integral counts [cps]	Environment Radio. in Lab[Bq/kg]		
				U-238	Th-232	K-40
Gran Sasso	NaI	35-3000	69.5	9.5 ± 0.3	3.7 ± 0.2	70 ± 2
Modane	HPGe	7-2734	79	22.8 ± 0.7	6.7 ± 0.2	91 ± 3
Boulby	HPGe	7-2734	24	7.1 ± 0.2	3.9 ± 0.1	120 ± 2
Sanford	NaI	0-3300	596~1335	29 ± 15	13 ± 3	220 ± 60
SNOLAB	NaI	0-3300	92.5	14.7 ± 0.4	9.7 ± 0.5	232.8 ± 15.8
CJPL-I	HPGe	60-2700	73.4	18.0	7.6	36.7
CJPL-II						
A1 Hall	HPGe	60-2700	77.4	5.8 ± 0.06	6.7 ± 0.03	148.9 ± 1.70
C2 Hall	HPGe	60-2700	69.9	4.7 ± 0.12	6.2 ± 0.04	149.4 ± 1.66
PE in C2 Hall	HPGe	60-2700	2.2	<1.24	<0.22	<2.38
CD tunnel	HPGe	60-2700	75.2	5.2 ± 0.04	5.6 ± 0.02	127 ± 0.78

CDEX Probes DM and $0\nu\beta\beta$ with HPGe Detectors

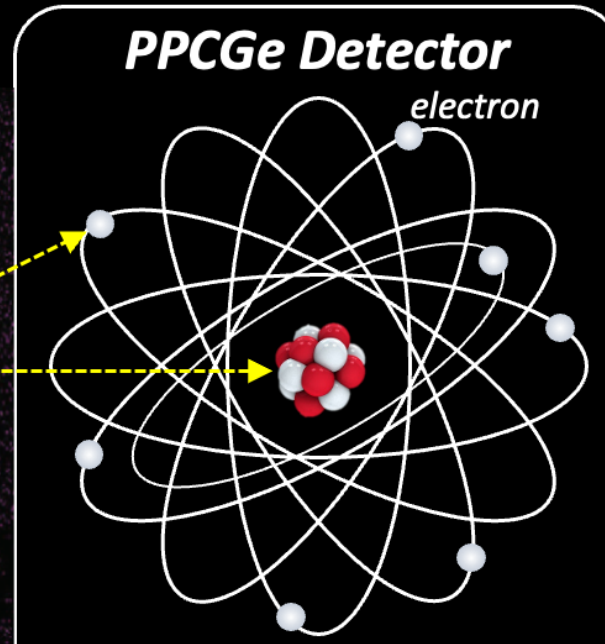


HPGe has

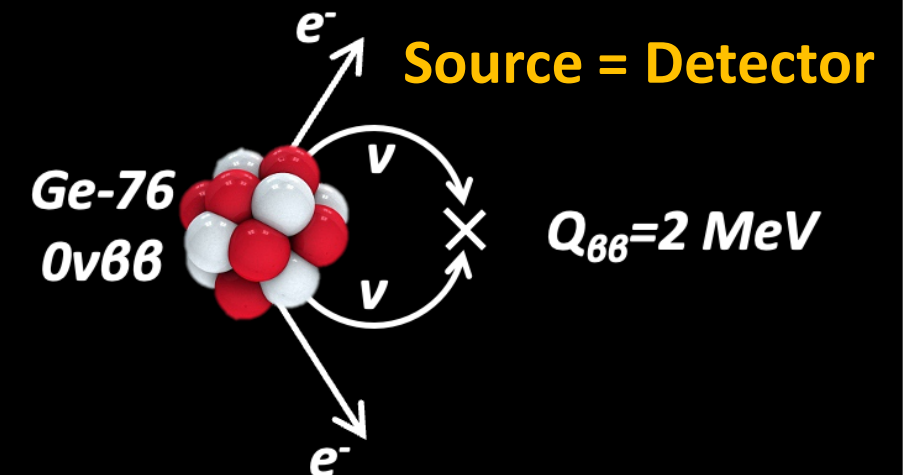
- Low E threshold for low mass DM
- Good E resolution for Ge-76 $0\nu\beta\beta$



Dark Matter Direct Detection



Neutrinoless Double Beta Decay (Ge-76 $\rightarrow$ Se-76 + 2e⁻ + 2039 keV)

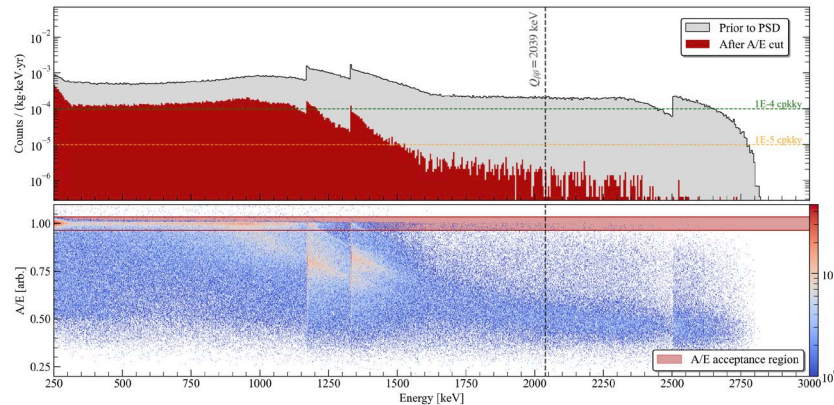


Enriched HPGe detector

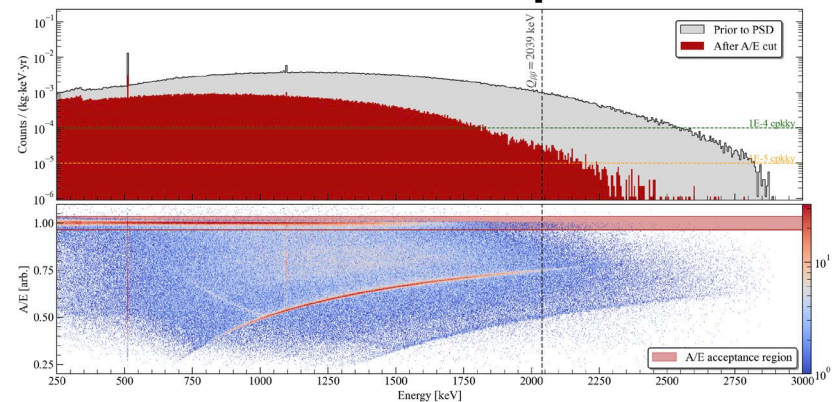
Ge-76 Enriched HPGe: enhance $0\nu\beta\beta$ signal & Reducing BG

(Cosmogenic BG in $0\nu\beta\beta$ ROI: Ge-68, Co-60)

Simulated Co-60 Spectrum

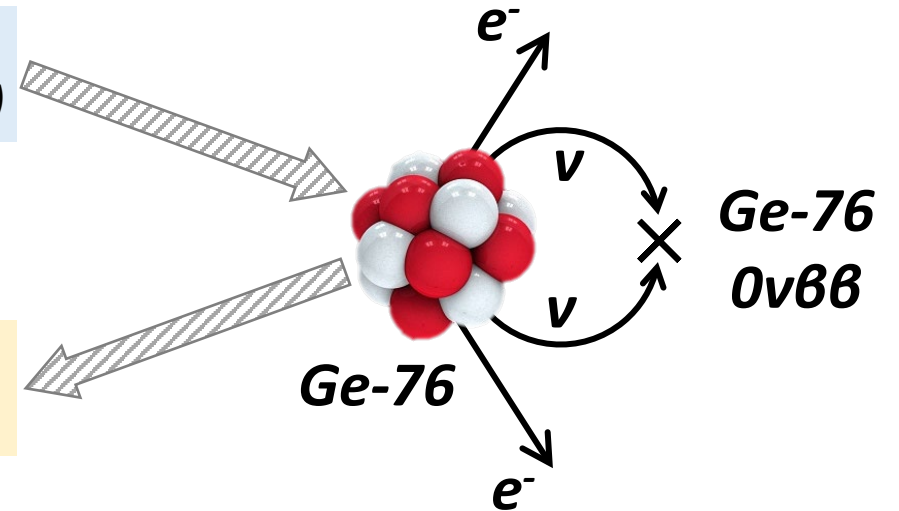


Simulated Ge-68 Spectrum

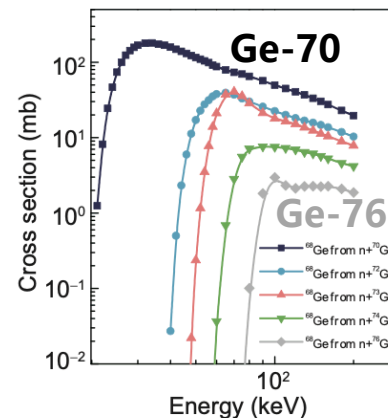


*Cosmic-ray
(cosmogenic most form neutron)*

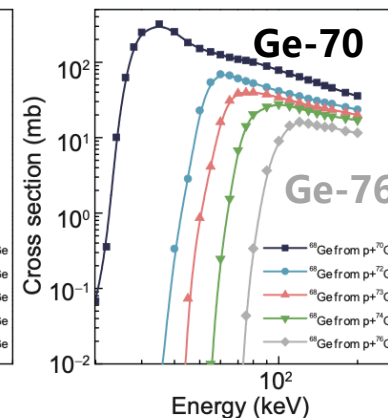
*Less Ge-68 produced in
Ge-76 than other Ge-iso*



Ge+n→Ge-68



Ge+p→Ge-68

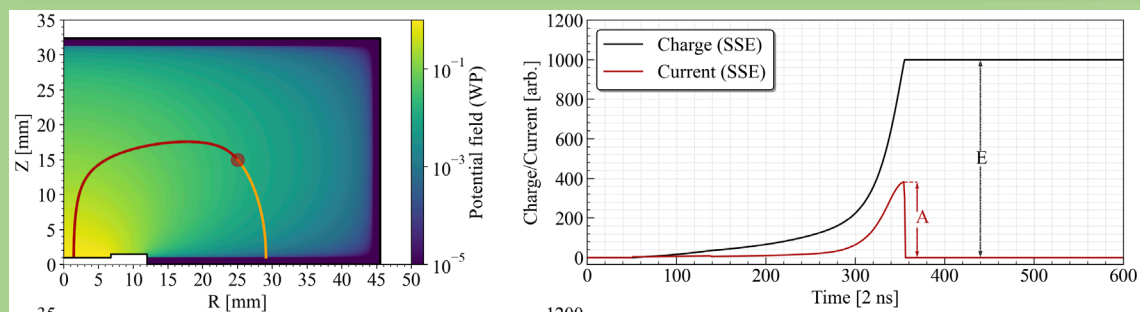


**Enrich to Ge-76 can
reduce cosmogenic
Ge-68 by 5~6 times**

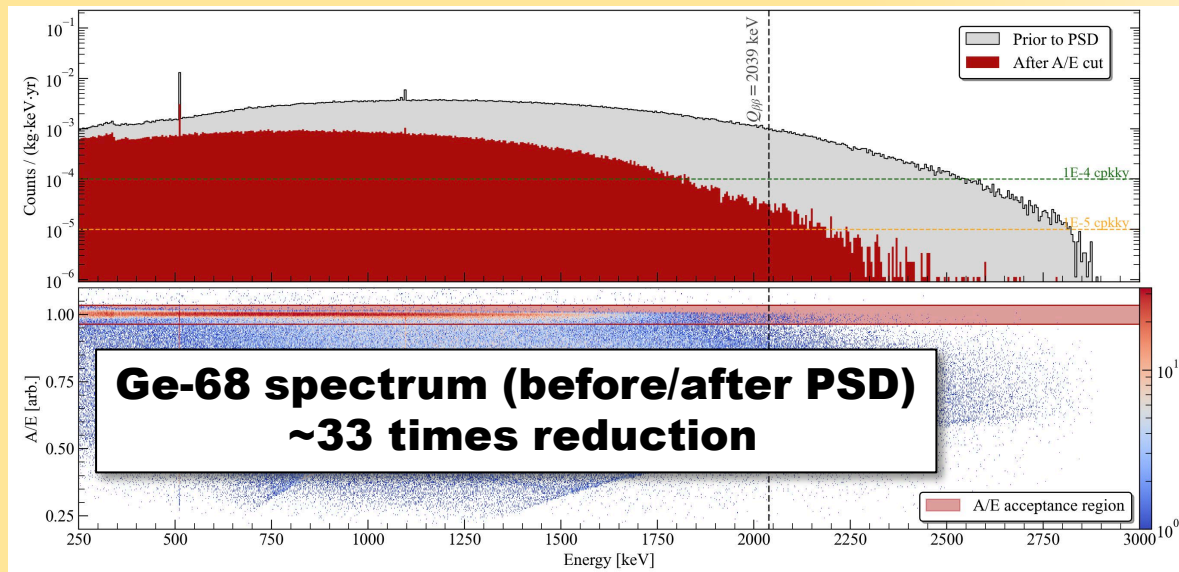
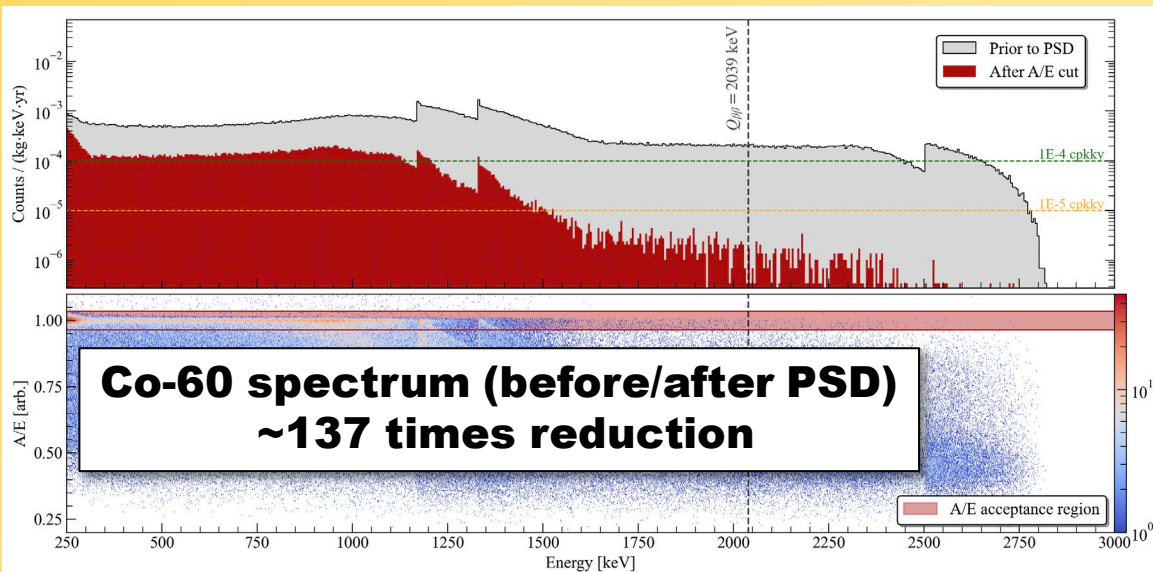
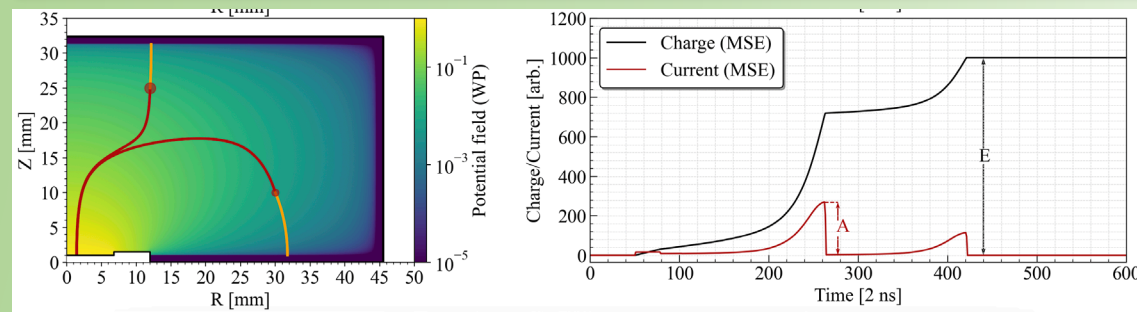
Cosmogenic Background Control

**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)

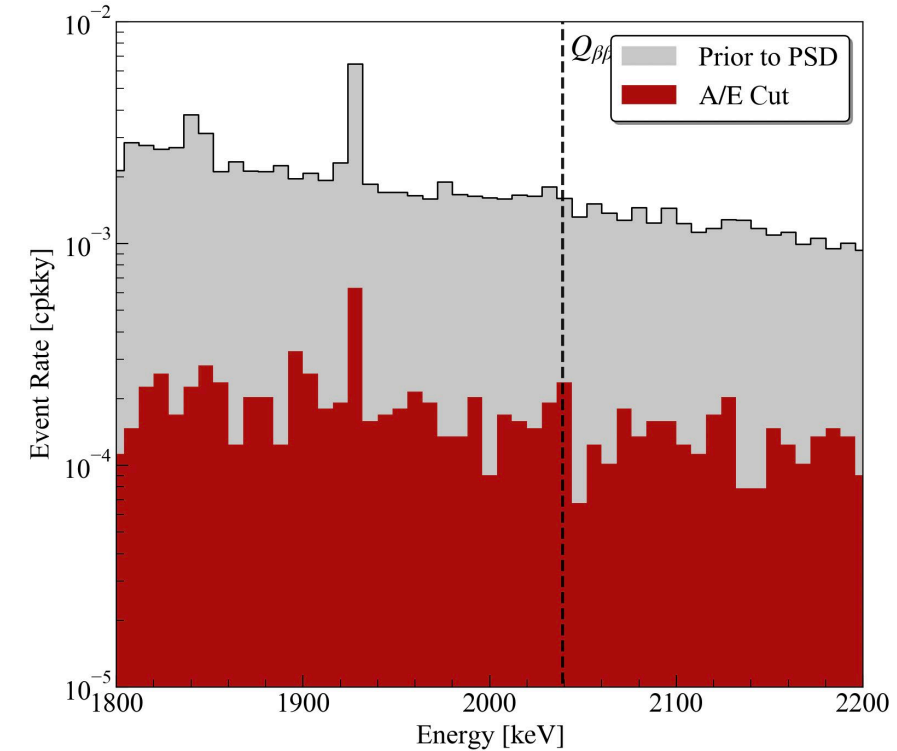
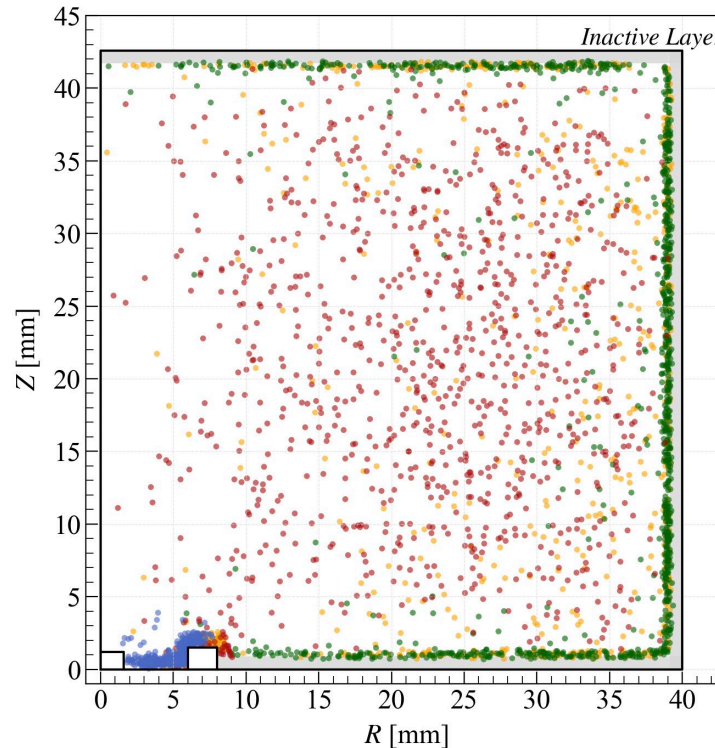
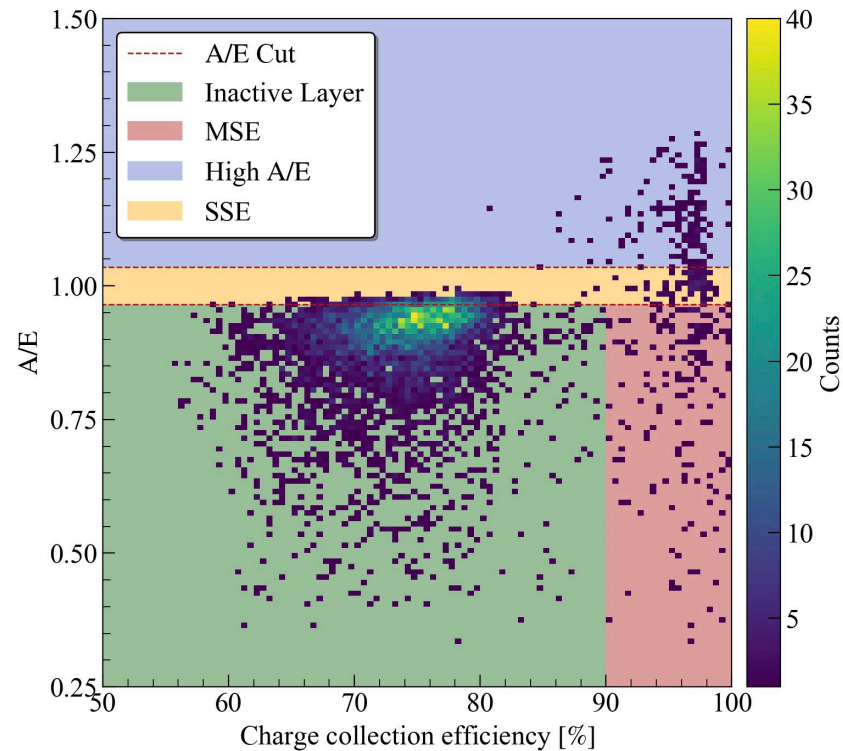


Background Suppression of A/E Method

■ 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

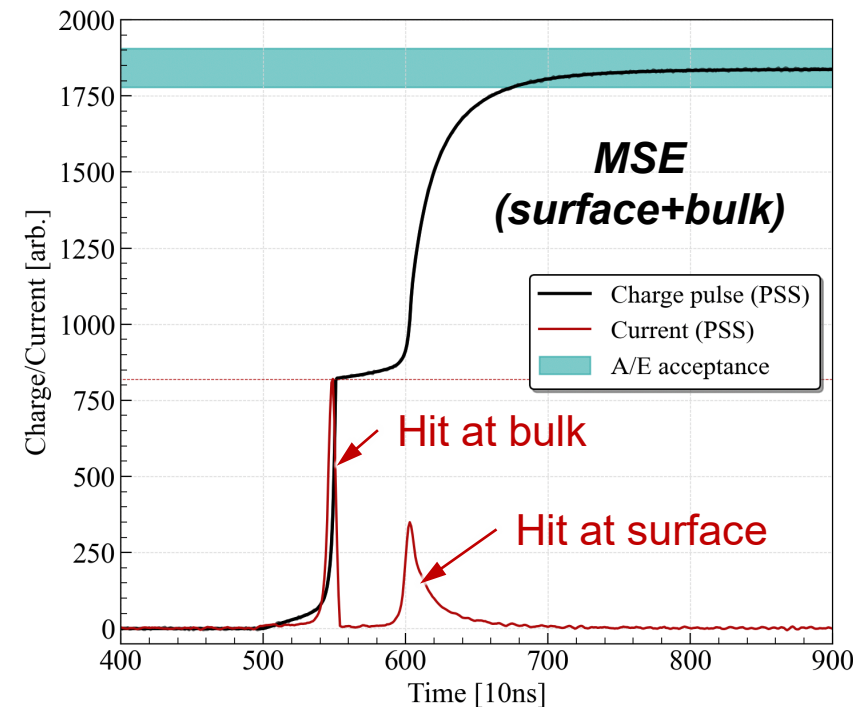
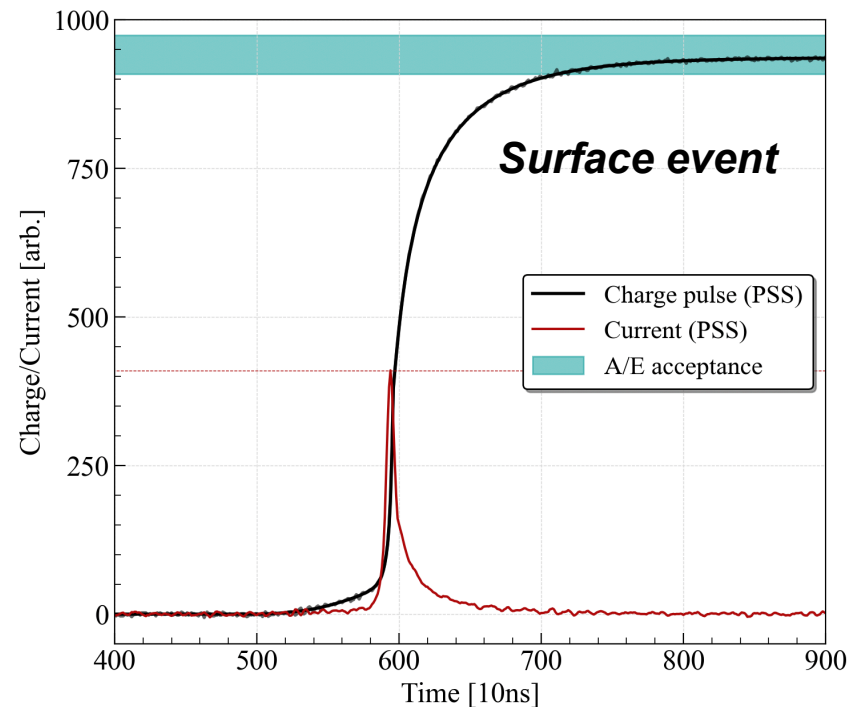
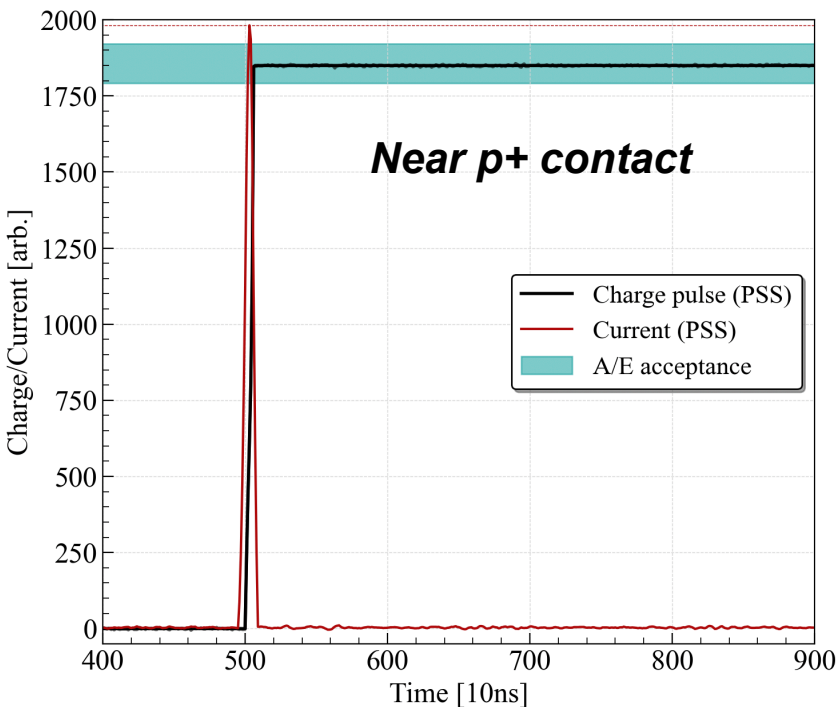


Simulation of Ar-42 (K-42) events

❑ 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)

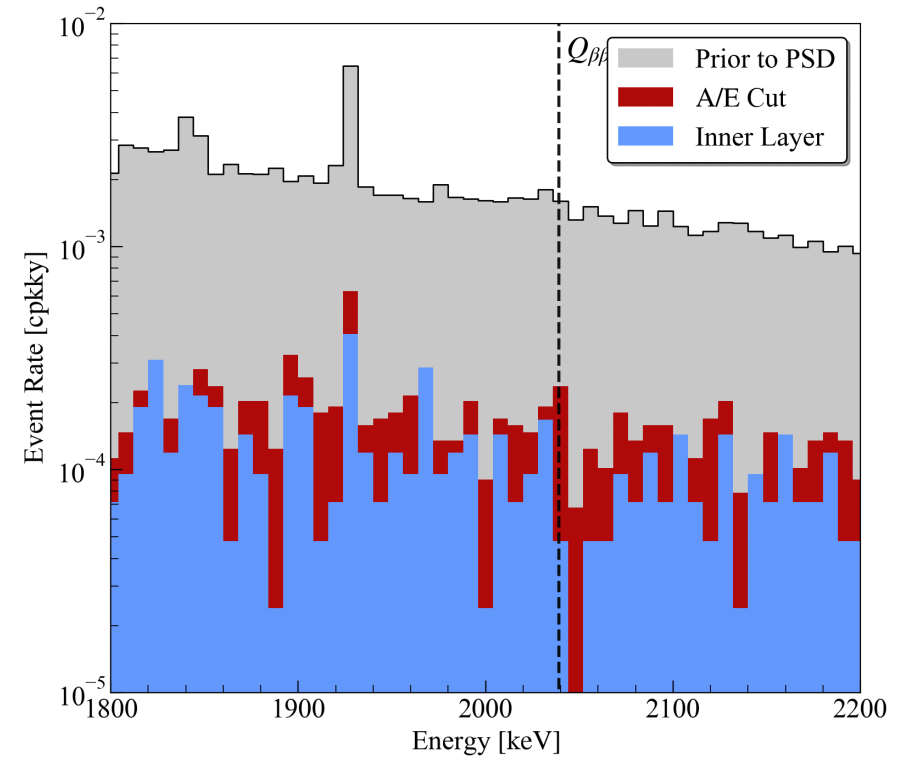
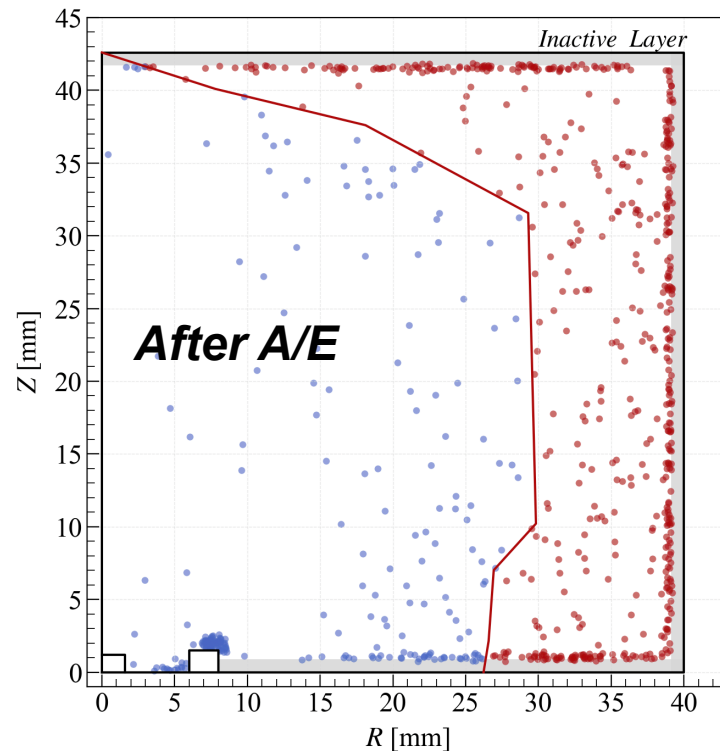
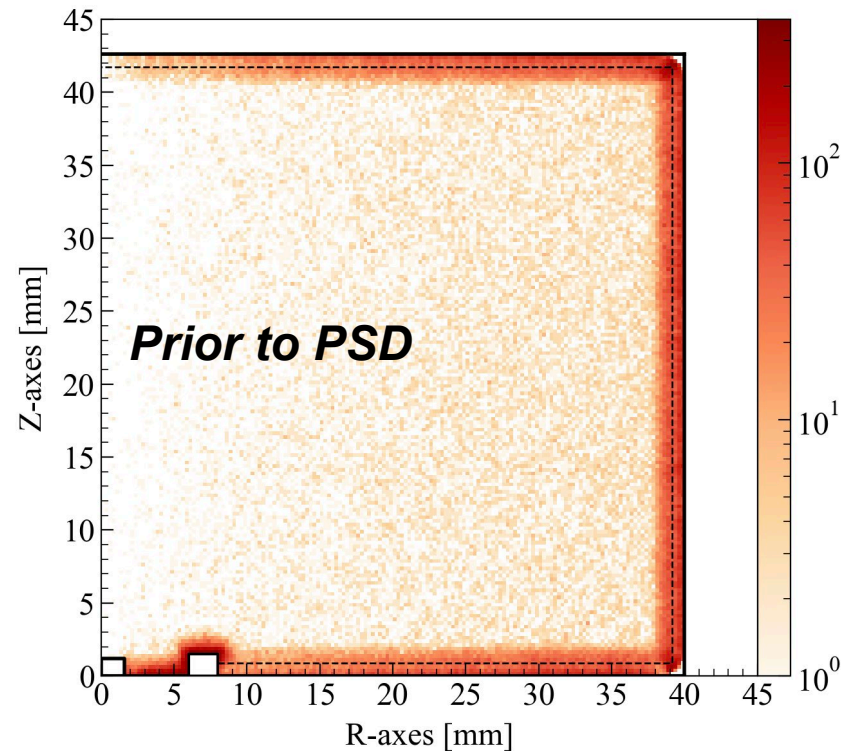


Background Suppression of Virtue Segments

■ 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 $0\nu\beta\beta$ 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

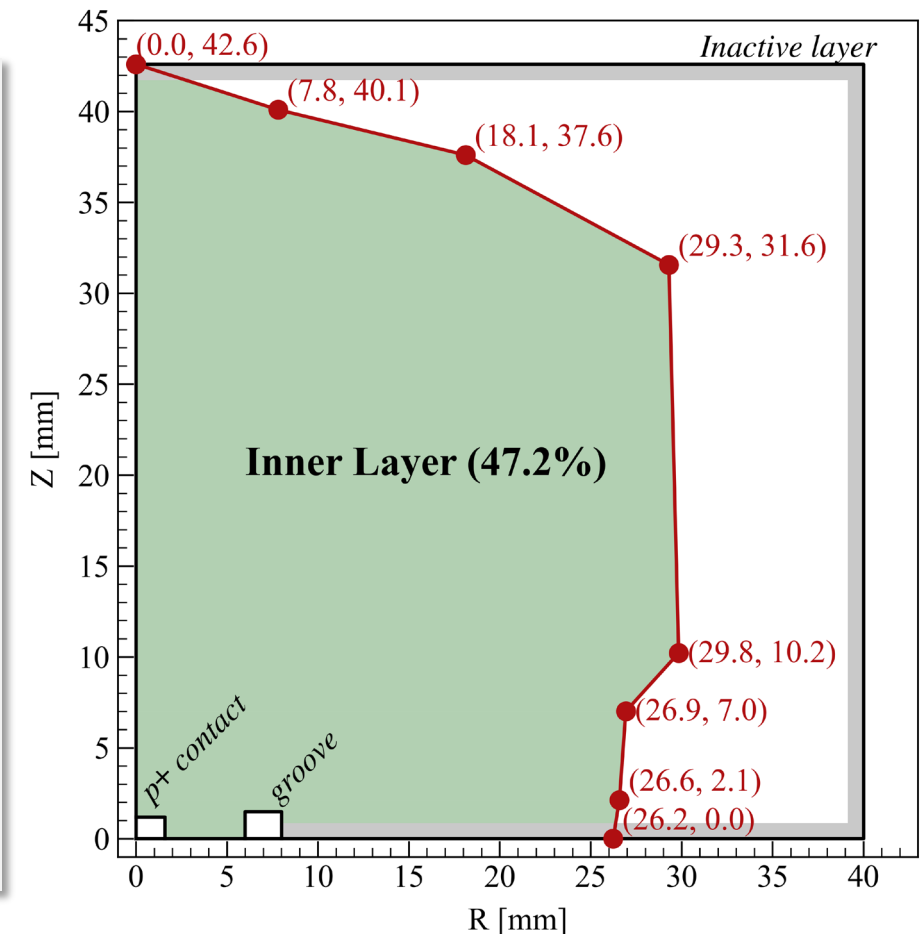
Likely hood Function for counts in $0\nu\beta\beta$ ROI:

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

- **S** is number of $0\nu\beta\beta$ 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 ($\hat{S}$) via Maximum likely hood:

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



Improve $0\nu\beta\beta$ Sensitivity by Virtual Segmentation

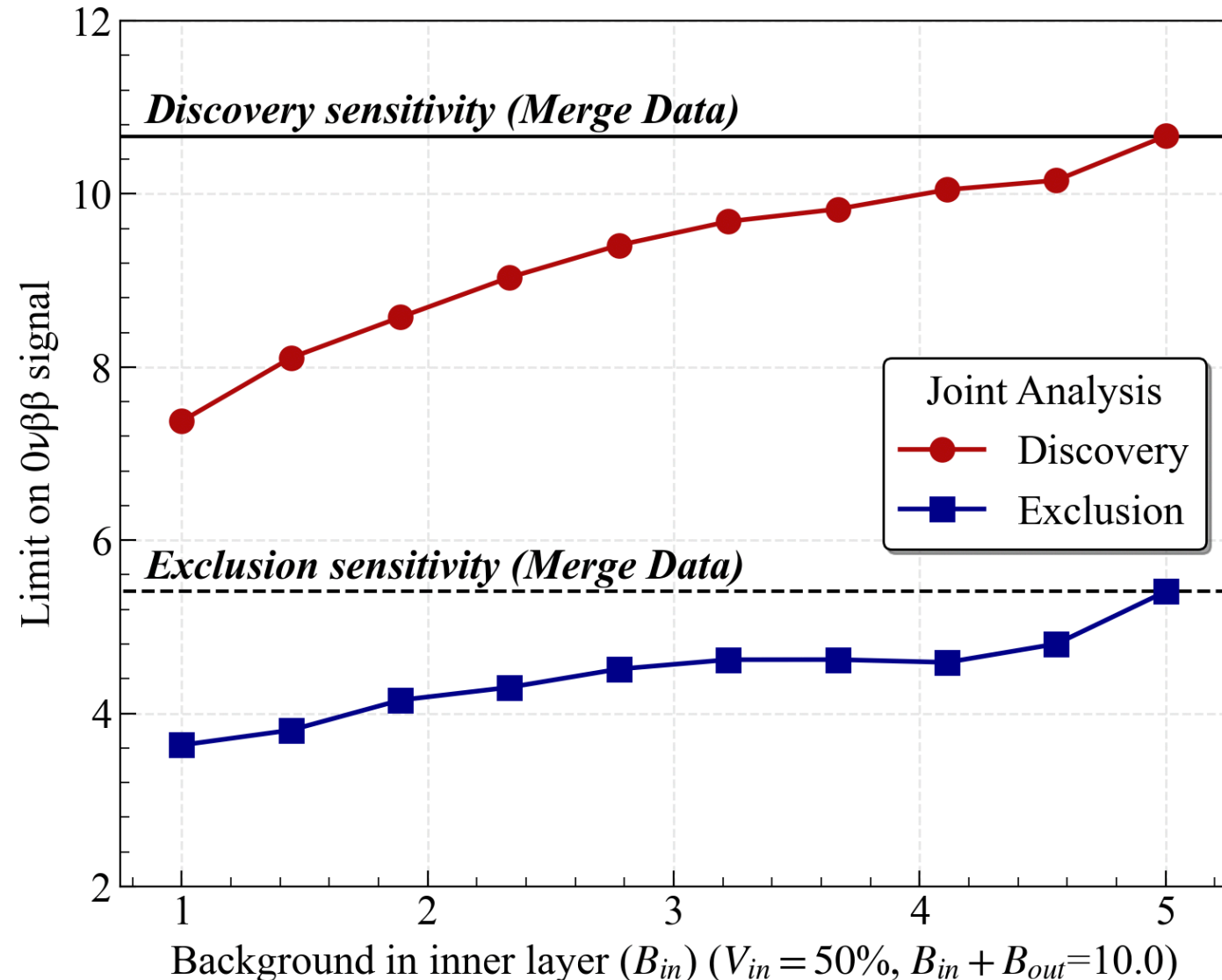
Discovery Sensitivity

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

Exclusion Sensitivity

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

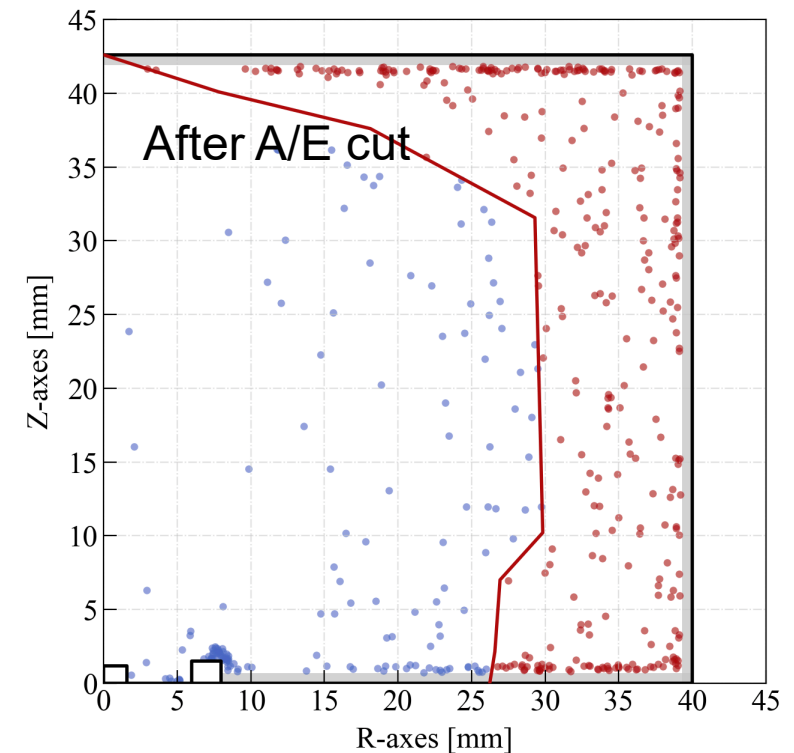
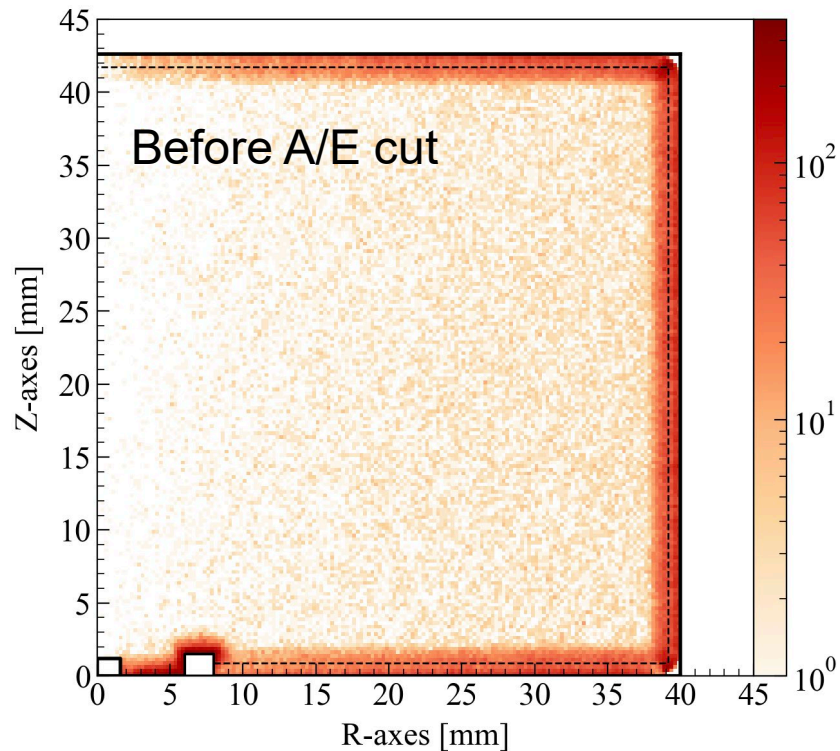
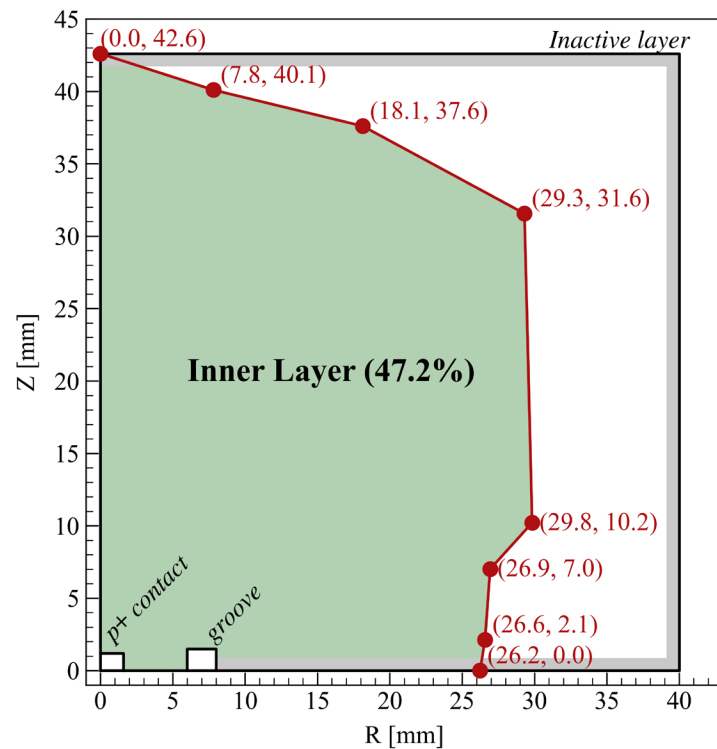
Joint analysis gives a **better sensitivity** for a **lower** inner layer background



Improve $0\nu\beta\beta$ Sensitivity by Virtual Segmentation

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

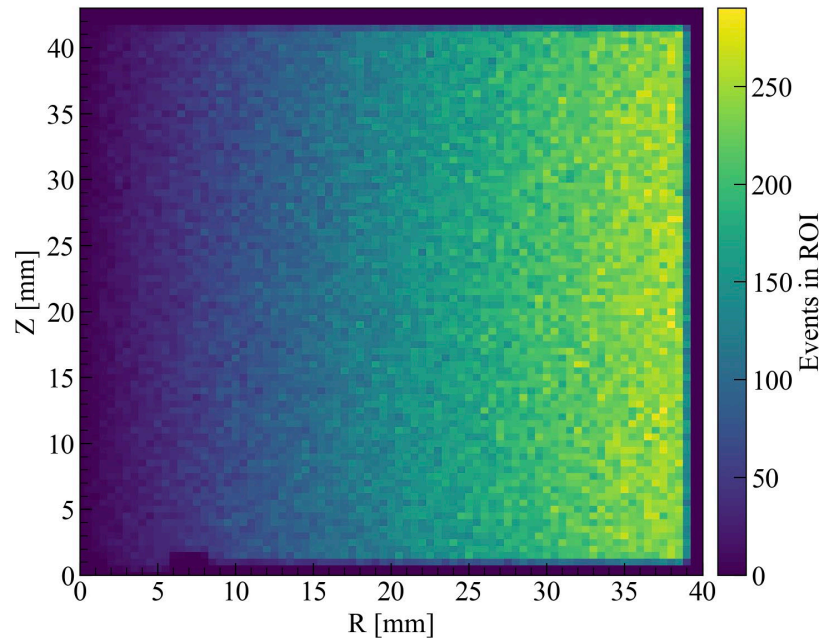
PSD cuts	Before cut	A/E Cut	Outer layer	Inner layer
BI/ 10^{-4} cpkky	16.8 ± 0.89	1.61 ± 0.11	2.10 ± 0.15	1.05 ± 0.09
Background in 1-ton·yr	10.7	1.03	0.71	0.32



Improve $0\nu\beta\beta$ Sensitivity by Virtual Segmentation

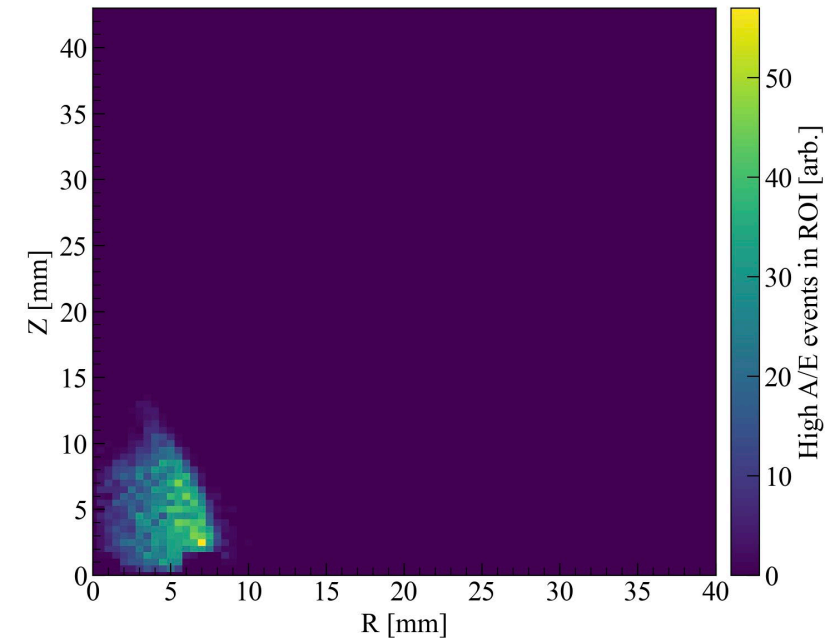
□ Apply Method on Ar-42 Background in CDEX-300: Signal efficiency

PSD Cut	Sensitive Volume	0 $\nu\beta\beta$ Signal Loss			0 $\nu\beta\beta$ 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 ($Q_{\beta\beta} \pm 3\sigma$)*

*Events rejected by
High A/E cut*



Improve $0\nu\beta\beta$ Sensitivity by Virtual Segmentation

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

PSD Cut	Sensitive Volume	$0\nu\beta\beta$ 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

