# CDEX-300ν Program Searching for $^{76}$Ge 0νββ decay

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CJPL

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WIN2023

ZHUHAI CHINA

# Outlines

I. Neutrinoless double beta decay ($0\nu\beta\beta$)

II. Introduction to CDEX and CDEX-300$\nu$

III. $0\nu\beta\beta$ results from CDEX

IV. Pre-Conceptual design of CDEX-300$\nu$

V. Future plan of CDEX-300$\nu$

# Motivation from Neutrino Physics

## Questions for neutrino physics:

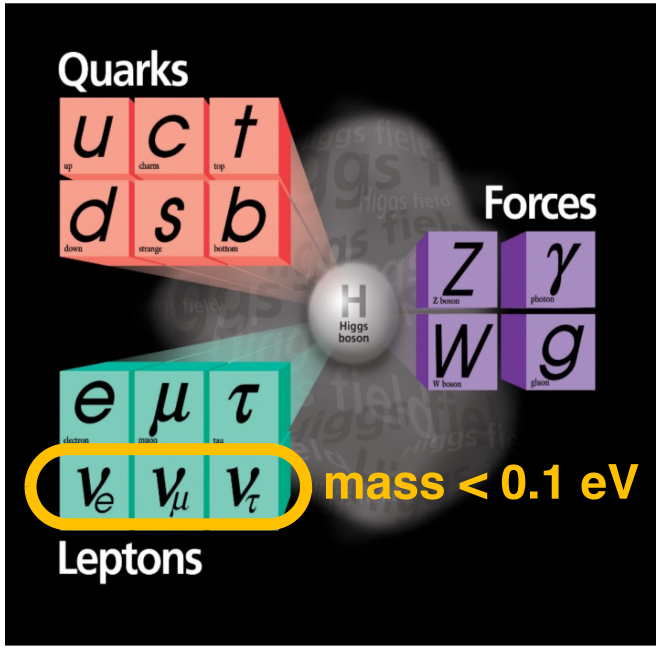
Oscillation experiments → non-zero neutrino mass

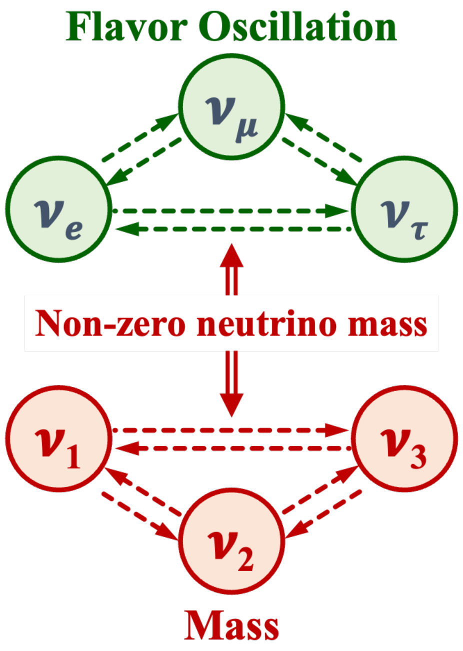
- How do neutrinos acquire their mass?
  - If $\nu \neq \bar{\nu}$ (Dirac fermion)

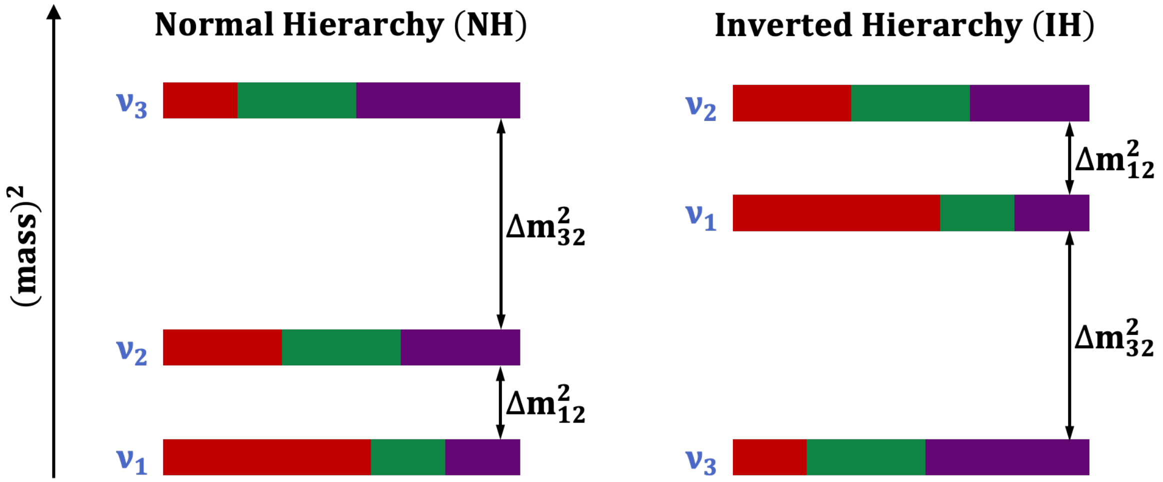
    get mass by the Higgs mechanism
  - If $\nu = \bar{\nu}$ (Majorana fermion)

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

…



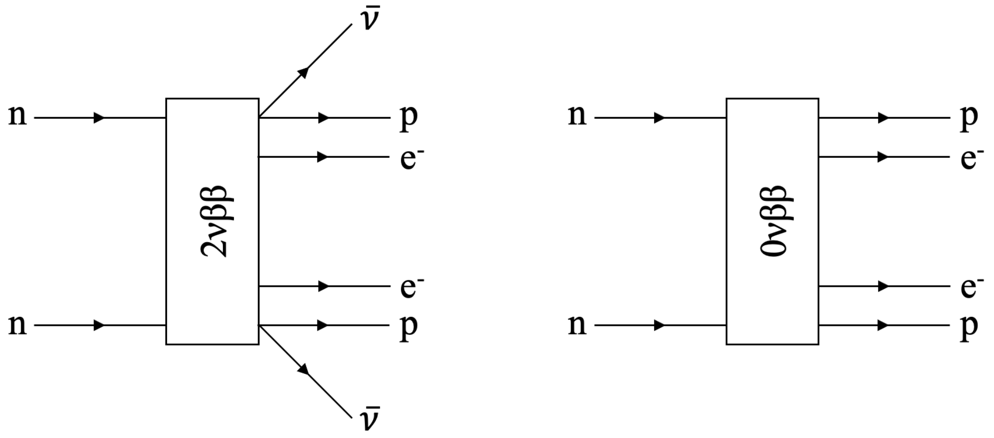



# Neutrinoless double beta decay

## ☐ Probe neutrino by 0νββ decay:

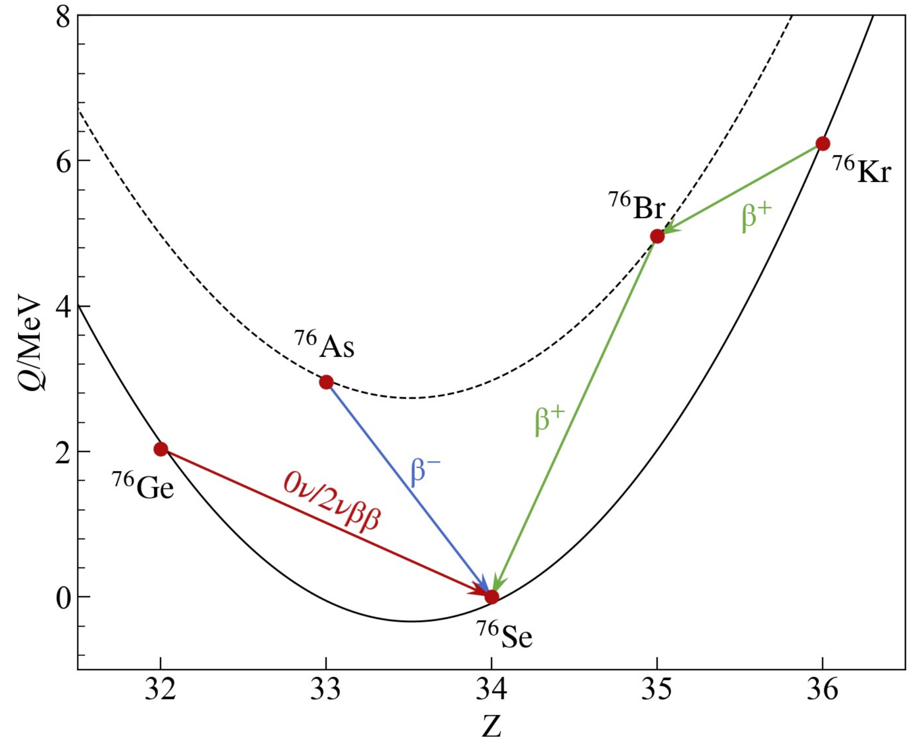
$$(A, Z) \rightarrow (A, Z+2) + 2e^-$$

- Occurred in 2νββ isotope if $\nu = \bar{\nu}$
- Lepton number violation process
- Search for a monoenergetic signal from the two e-




## ☐ If 0νββ decay is observed:

- ✓ **Neutrino is Majorana fermion ($\nu = \bar{\nu}$)**
- ✓ **Absolute mass scale given by 0νββ decay rate**
- ✓ **Key to understand matter anti-matter unbalance**
- ✓ **Beacon for many BSM theories**



# Neutrinoless double beta decay experiment

## ☐ Experimental search for 0νββ decay:

Build detector and wait for signal

Key to success:

- **More signal:**
  - Enrichment (A)
  - Larger exposure (M·T)
  - Higher efficiency ($\varepsilon$)
- **Less background (γ, 2νββ…)**
  - BG from 2νββ of Ge-76
  - BG from other materials

Enrichment — Exposure — BG counts in ROI for projected exposure

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

Efficiency — Background — Energy Resolution

**Benefits of extremely low background:**

- **Better use of the precious exposure**

**Energy resolution is important:**

- **crucial for reducing 2νββ background**

# Neutrinoless double beta decay experiment

## ☐ Germanium as 0νββ detector:

- Source = detector (high $\varepsilon$)
- Industrial enrichment for $^{76}$Ge to ≥86% ($A$)
- Intrinsic high-purity crystal: ~13N (Low $BI$)
- Background rejection (Low $BI$): PSD, LAr veto…
- Excellent E resolution ($\sigma$) ~0.05% @ 2MeV

➢ **Current best BI & $\sigma$ achieved by Ge detector**

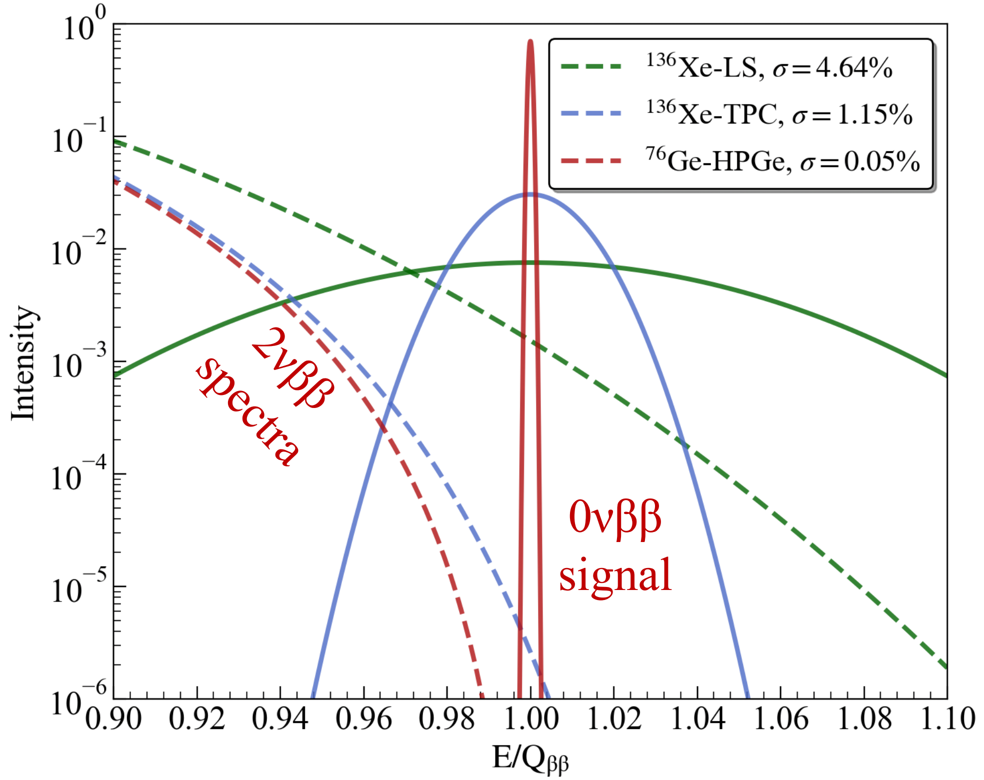
➢ **Energy resolution crucial for reducing 2νββ background**

| Iso | Experiment | Exposure [kg·yr] | $\sigma/Q_{\beta\beta}$ [%] | Background [cpROI·t·yr] | $T^{0\nu}_{1/2}$ [yr] | <$m_{\beta\beta}$> [meV] |
|---|---|---|---|---|---|---|
| **$^{76}$Ge** | **GERDA** | **127.2** | **0.05%** | **2.1** | **> 1.8E+26** | **< 79~180** |
| $^{130}$Te | CUORE | 288.8 | 0.31% | 568.3 | > 2.2E+25 | < 90~305 |
| $^{136}$Xe | KamLAND-Zen | 970 | 4.64% | 147.6 | > 2.3E+26 | < 36~160 |

Enrichment — Exposure — BG counts in ROI for projected exposure

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

Efficiency — Background — Energy Resolution



# CDEX Collaboration

- Founded in 2009, 11 institutions, more than 100 people now
- Persistently focused on Dark Matter direct detection, extended to Ge-76 0νββ search

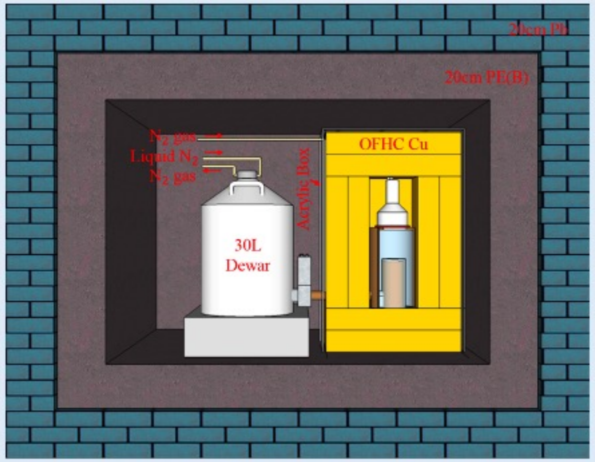
# CDEX Roadmap

| 2009-2016 | 2016-2020 | 2021- | Planed |
|---|---|---|---|

## CDEX-1

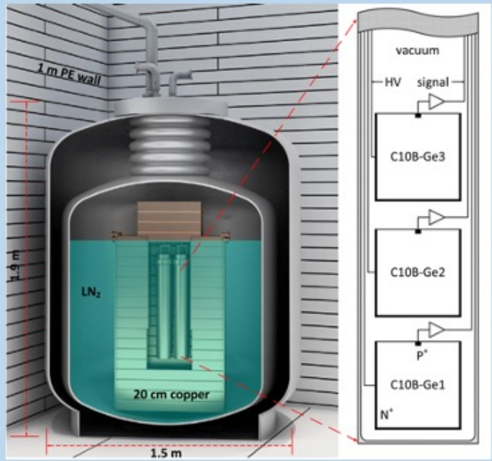
**CDEX-1A**
- DM: χ-N (SI/SD)
- Axion & Axion-like DM
- CDEX first 0νββ result

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




## CDEX-10

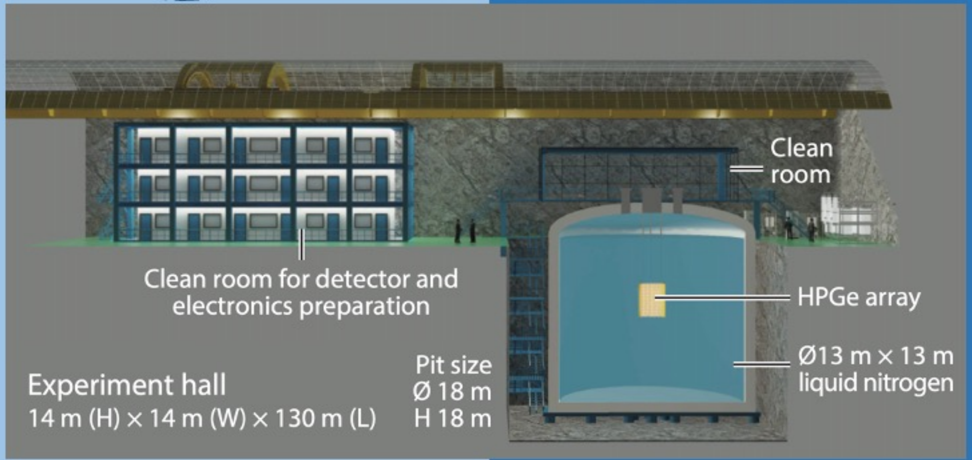
- DM: χ-N (SI/SD)
- DM: χ-N (EFT)
- Solar dark photon
- Dark photon DM
- DM: CR boosted DM
- DM: Exotic DM
- DM: χ-e
- DM: Evaporating PBHs




CDEX-50
(DM)

CDEX-300
(0νββ)

CDEX-1T
(0νββ, DM...)



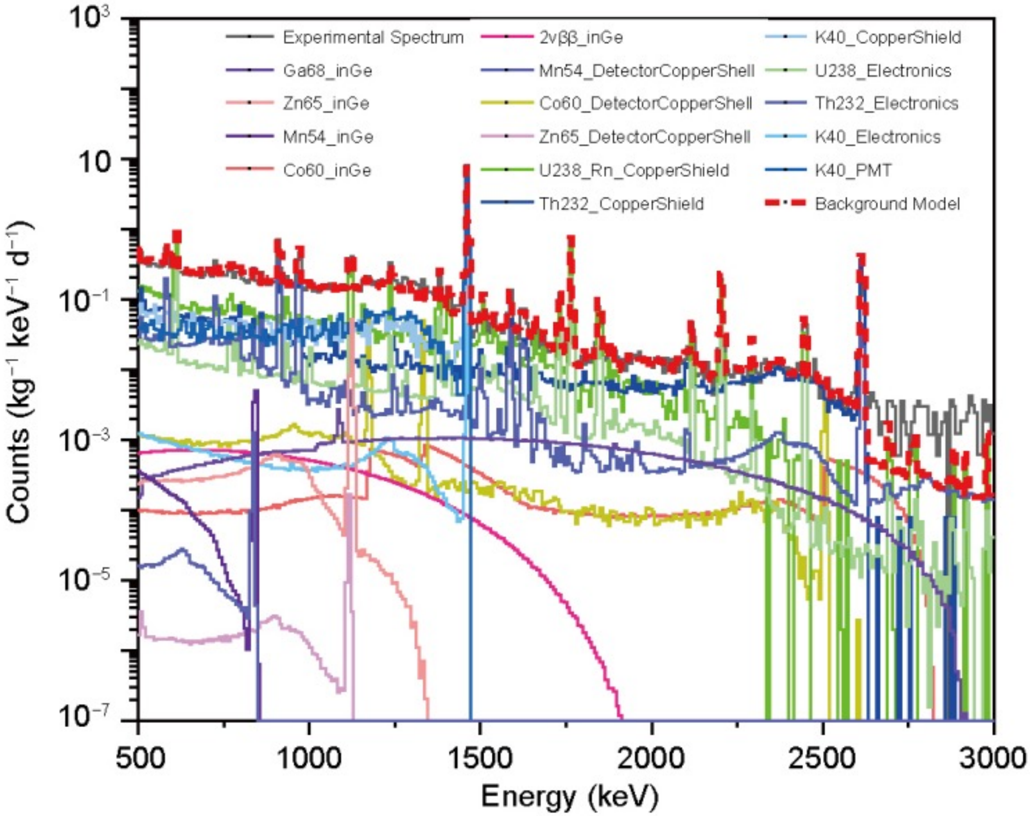

CJPL-I | CJPL-II

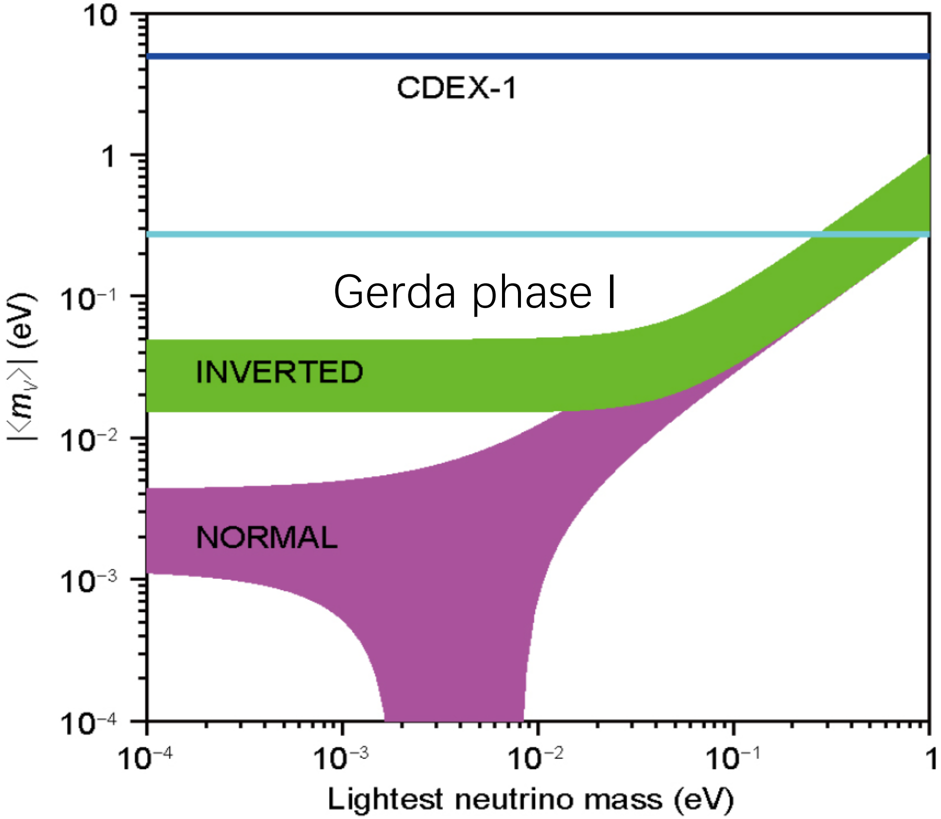
# 0νββ Results from CDEX

## First 0νββ result from CDEX:

- Also the first $^{76}$Ge 0νββ result in China
- CDEX-1A PPCGe (natural crystal), Exposure: 304 kg·day
- $T_{1/2}^{0\nu} \geq 6.4\times10^{22}$ yr, 90% C. L

*L. Wang et al, Science China P.M.A. 071011 (2017)*



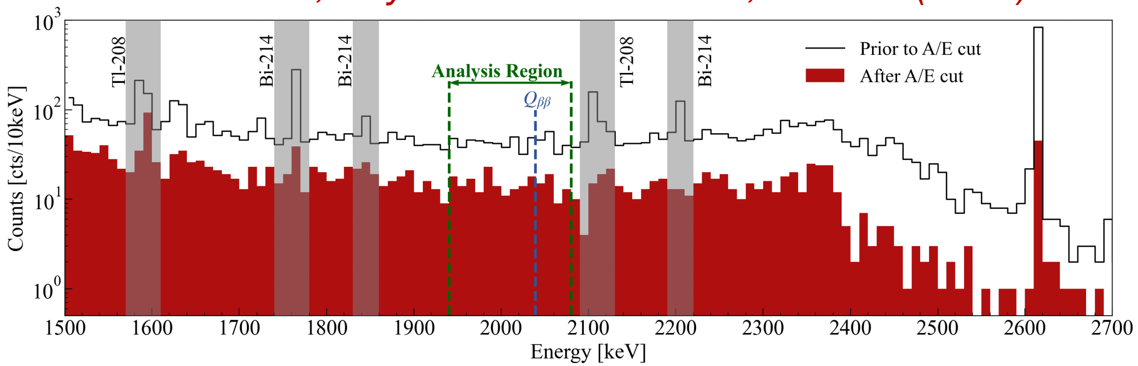



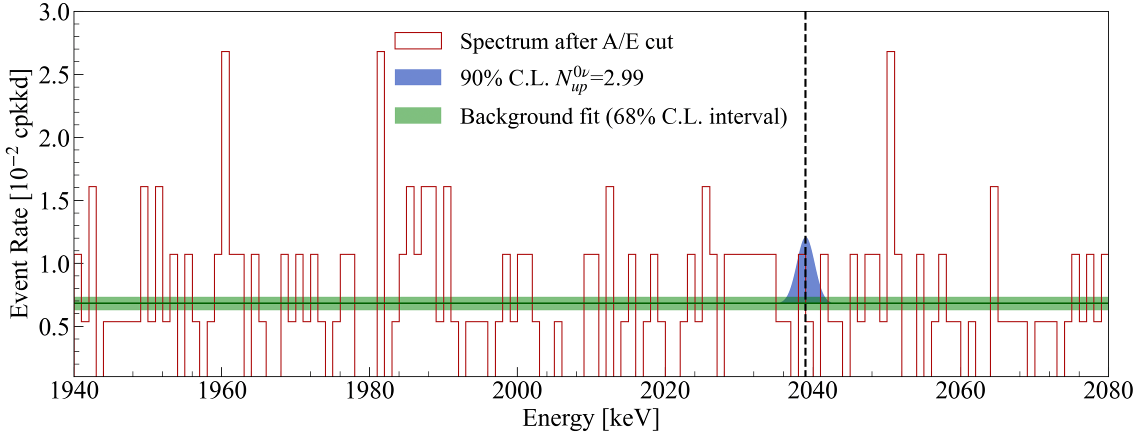
# 0νββ Results from CDEX

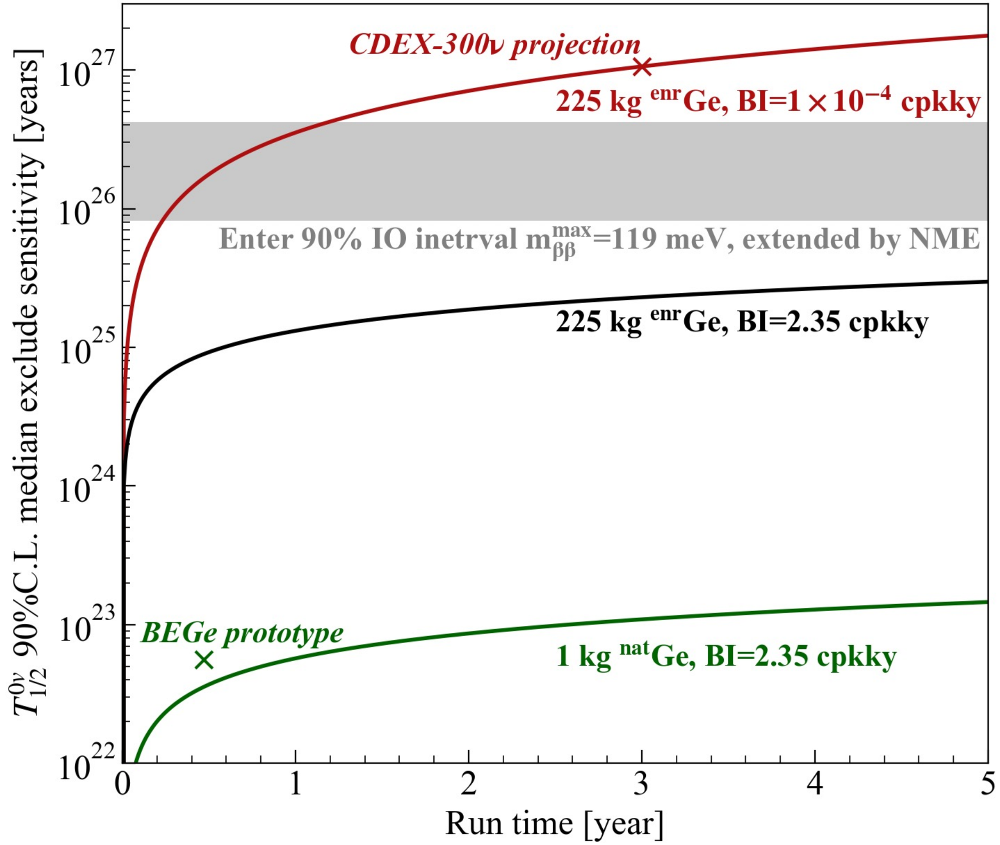
## New 0νββ result from CDEX (BEGe detector):

- 1.1 kg Natural BEGe detector; Exposure: 186.4 kg·day
- Apply PSD method for background reduction, background in ROI is two times lower than CDEX-1A
- First CDEX result from BEGe: $T_{1/2}^{0\nu} \geq 5.6\times10^{22}$ yr, 90% C. L

*W. Dai et al, Physical Review D 106, 032012 (2022)*



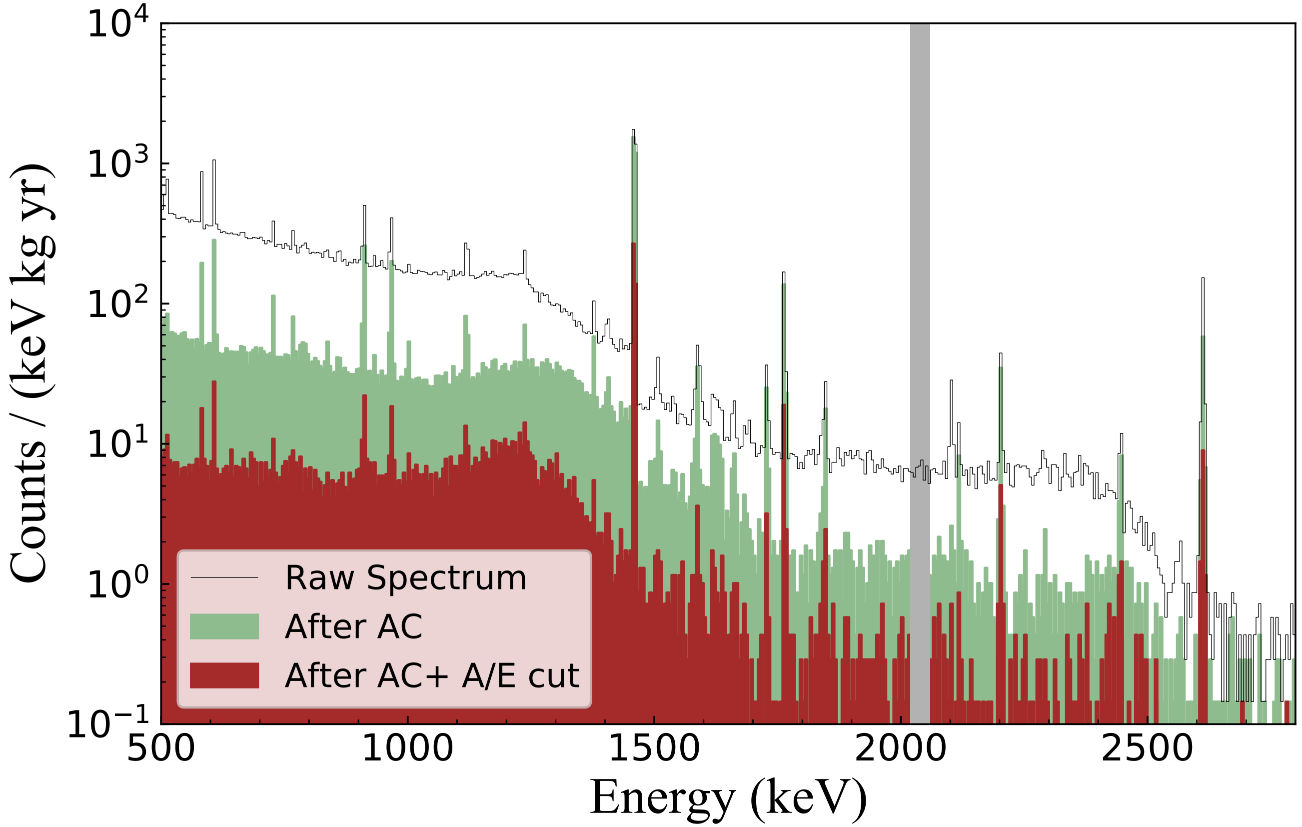



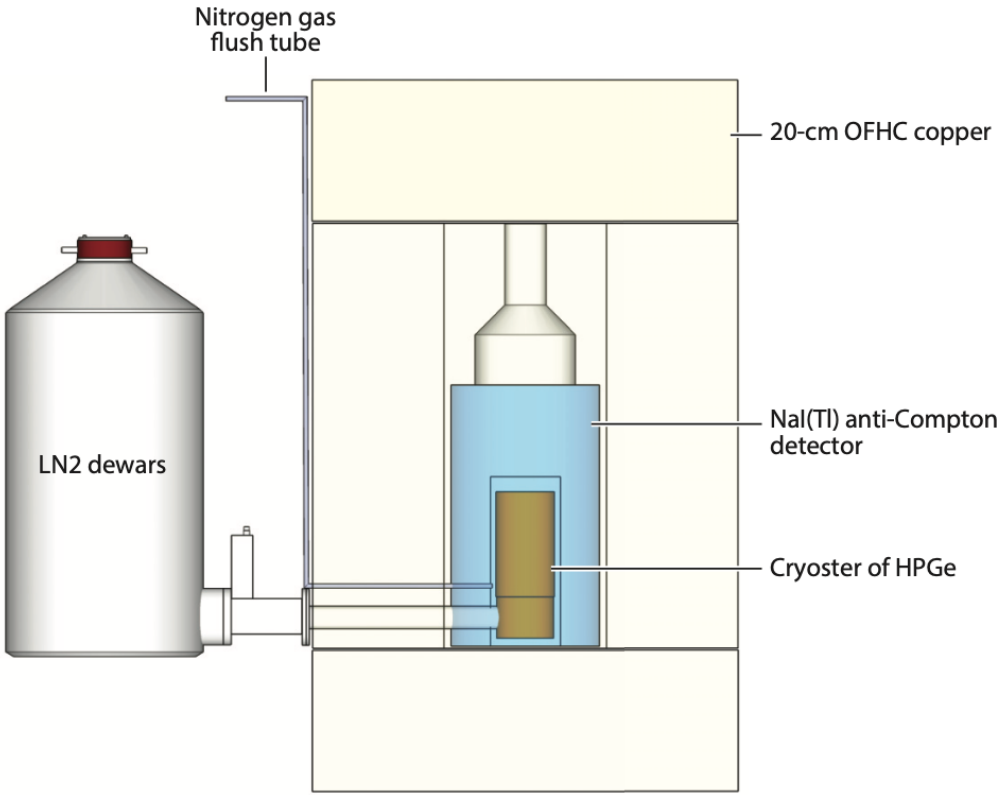
# 0νββ Results from CDEX

## New 0νββ result from CDEX (PPCGe detector):

- CDEX-1B PPCGe (natural crystal), Exposure: 504.3 kg·day
- Apply PSD and NaI AC-veto for background reduction, achieves 23 times BG reduction in ROI
- Best CDEX 0νββ result: $T_{1/2}^{0\nu} \geq 2.2\times10^{23}$ yr, 90% C. L

*B.T. Zhang et al, arXiv:2305.00894v2 (2023)*



# CDEX-300ν Program

## CDEX-300ν: the first stage of CDEX $^{76}$Ge 0νββ search project

| | | |
|---|---|---|
| **Physics goal:** | $T_{1/2} > 10^{27}$ yr | $<m_{\beta\beta}>$: 30-70 meV |
| **Key parameters:** | 0.5~1 ton-yr exposure | 1E-4 cpkky BG in ROI |

*cpkky: counts/keV/kg/yr*

- **Technical route:**

*Increasing exposure*

**Enriched Ge Array**

- ✓ Enriched $^{76}$Ge
- ✓ ~ 225 kg Ge
- ✓ Energy resolution

\+

*Controlling Background*

**LAr veto & $LN_2$ Shield**

- ✓ $LN_2$ as passive shield
- ✓ LAr as active shield
- ✓ Work with HPGe PSD

\+

*Controlling Background*

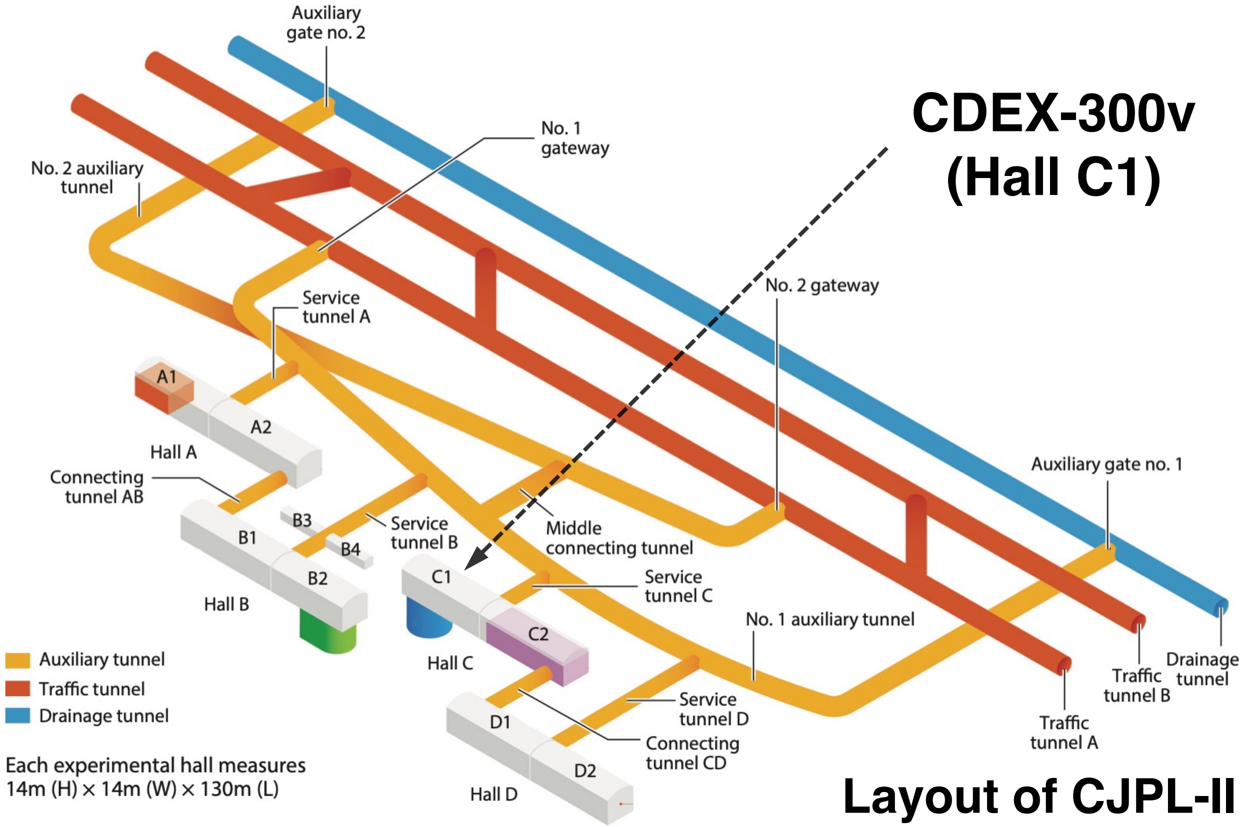
**Material background control**

- ✓ Cosmogenic radioactivity in Ge
- ✓ Materials near Ge crystal
- ✓ Radon in LAr & $LN_2$…

# CDEX-300ν pre-Conceptual Design

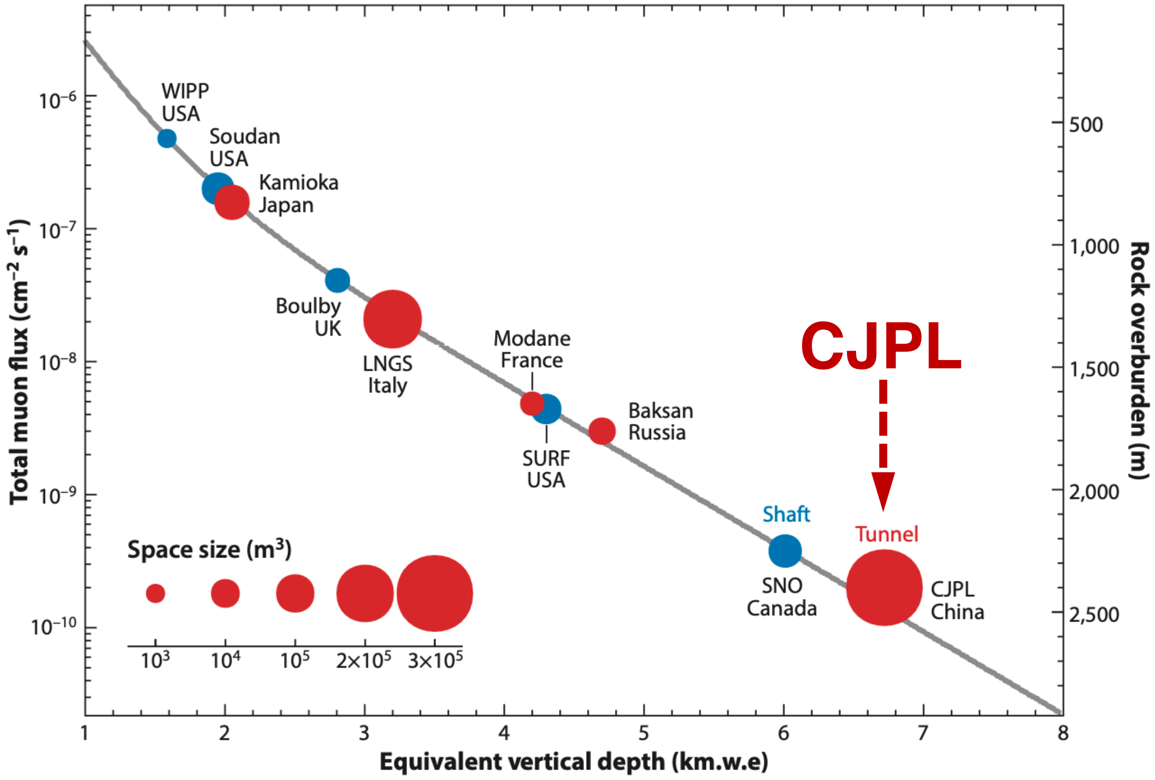
## Experiment at CJPL-II:

- Sufficient experiment space: ~25,000 $m^3$ in each hall, Total space of CJPL >300,000 $m^3$
- Low cosmic-ray background: Muon flux ~$10^{-10}$ $cm^{-2}\cdot s^{-1}$ (background negligible for CDEX-300ν)




Layout of CJPL-II

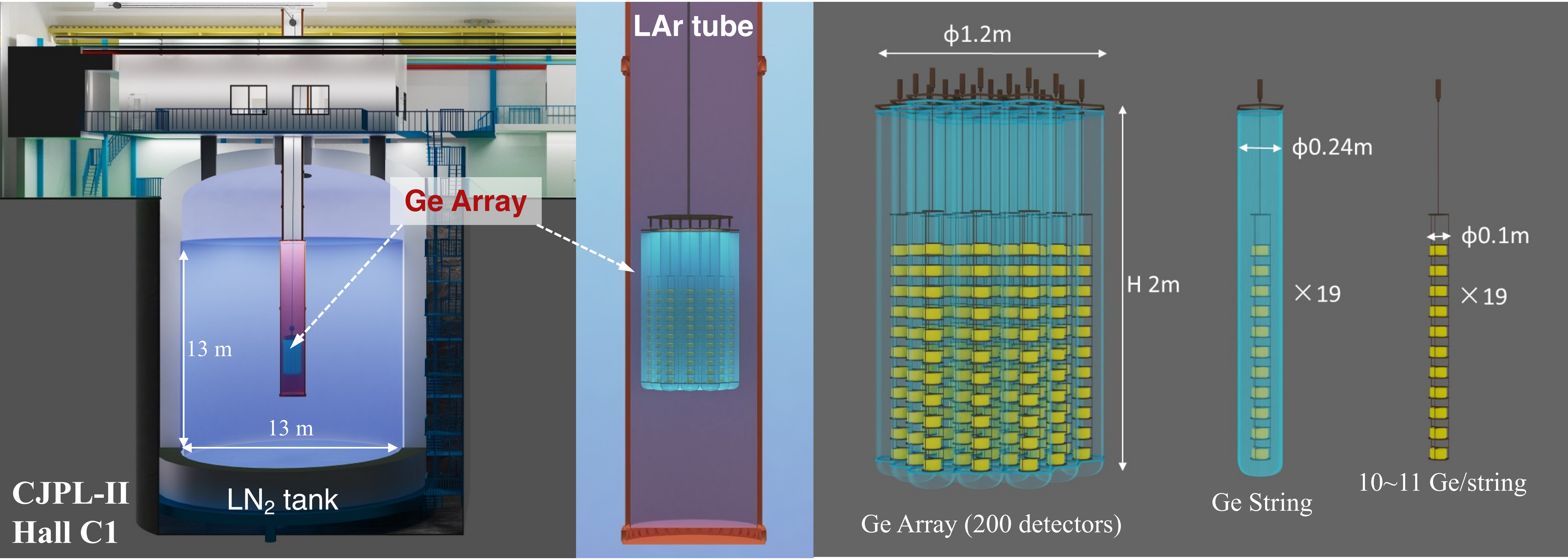
*Annu. Rev. Nucl. Part. Sci. 2017.67:231-251*



# CDEX-300ν pre-Conceptual Design

## Overview of the Experiment setup

- $LN_2$ tank shared with CDEX-50
- Reentrant tube containing LAr submerged in $LN_2$
- Ge detector array immersed in LAr (veto) tube
- Ge detectors divided into ~19 strings (200 in total)



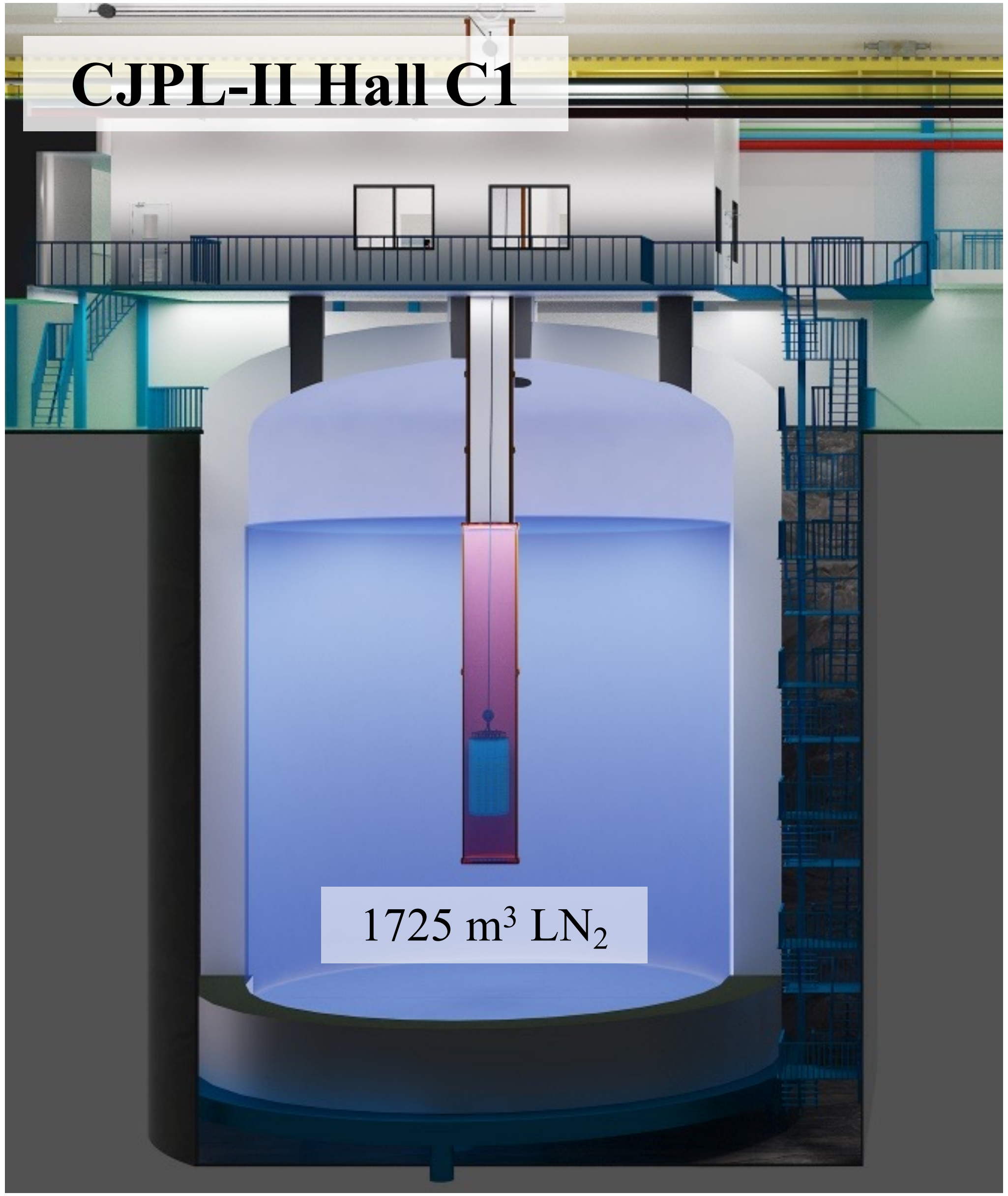
# CDEX-300ν pre-Conceptual Design

## ☐ 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

## ☐ Background:

- ➢ > 4 m $LN_2$ shields most backgrounds from surroundings
- ➢ Radon in $LN_2$ controlled by purification



# CDEX-300ν pre-Conceptual Design

## ☐ The LAr System

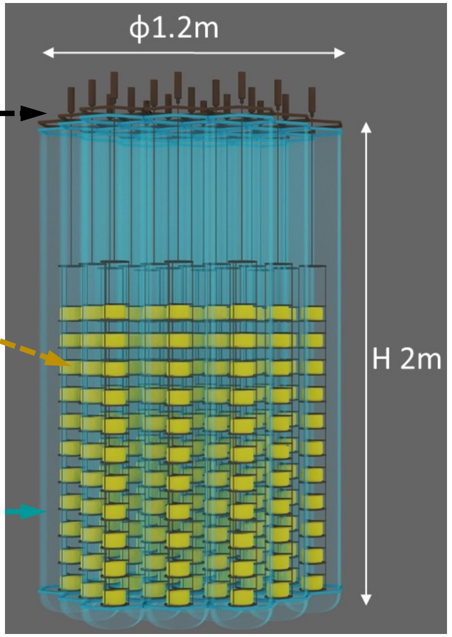
Baseline design:

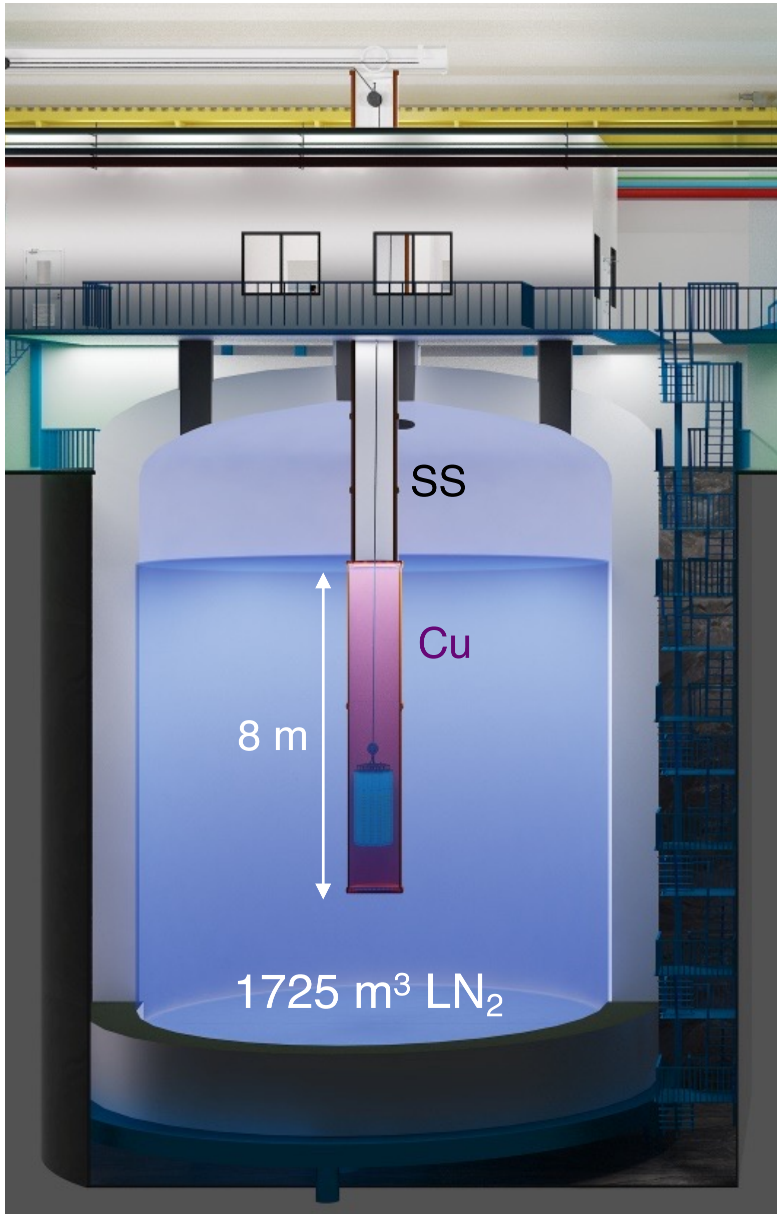
- ~20 t LAr held by **Cu** / SS cryostat
- LAr constantly purified
- LAr cryostat immersed in $LN_2$
- LAr light read out by WLS Fiber + SiPM

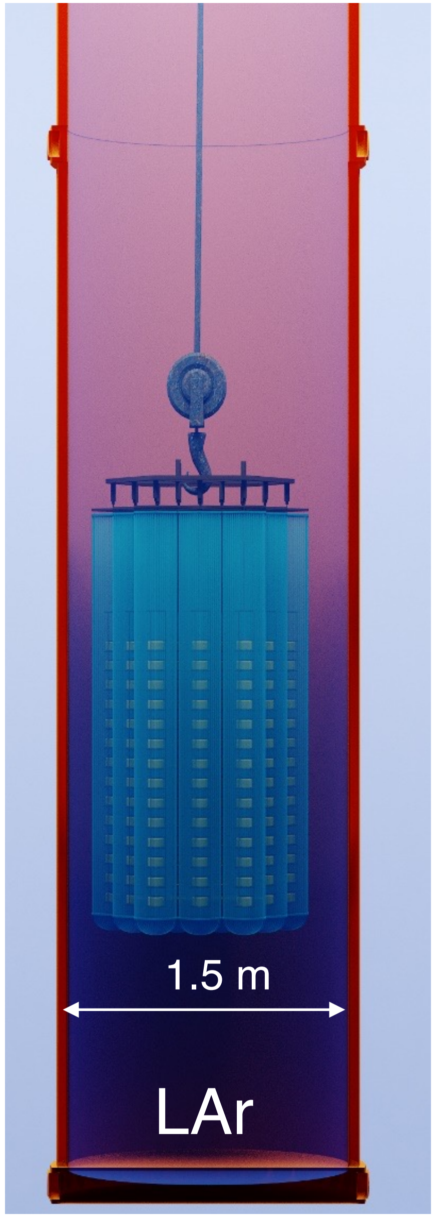
**SiPM at top**

**BEGe detectors**

**WLS Fiber curtain**



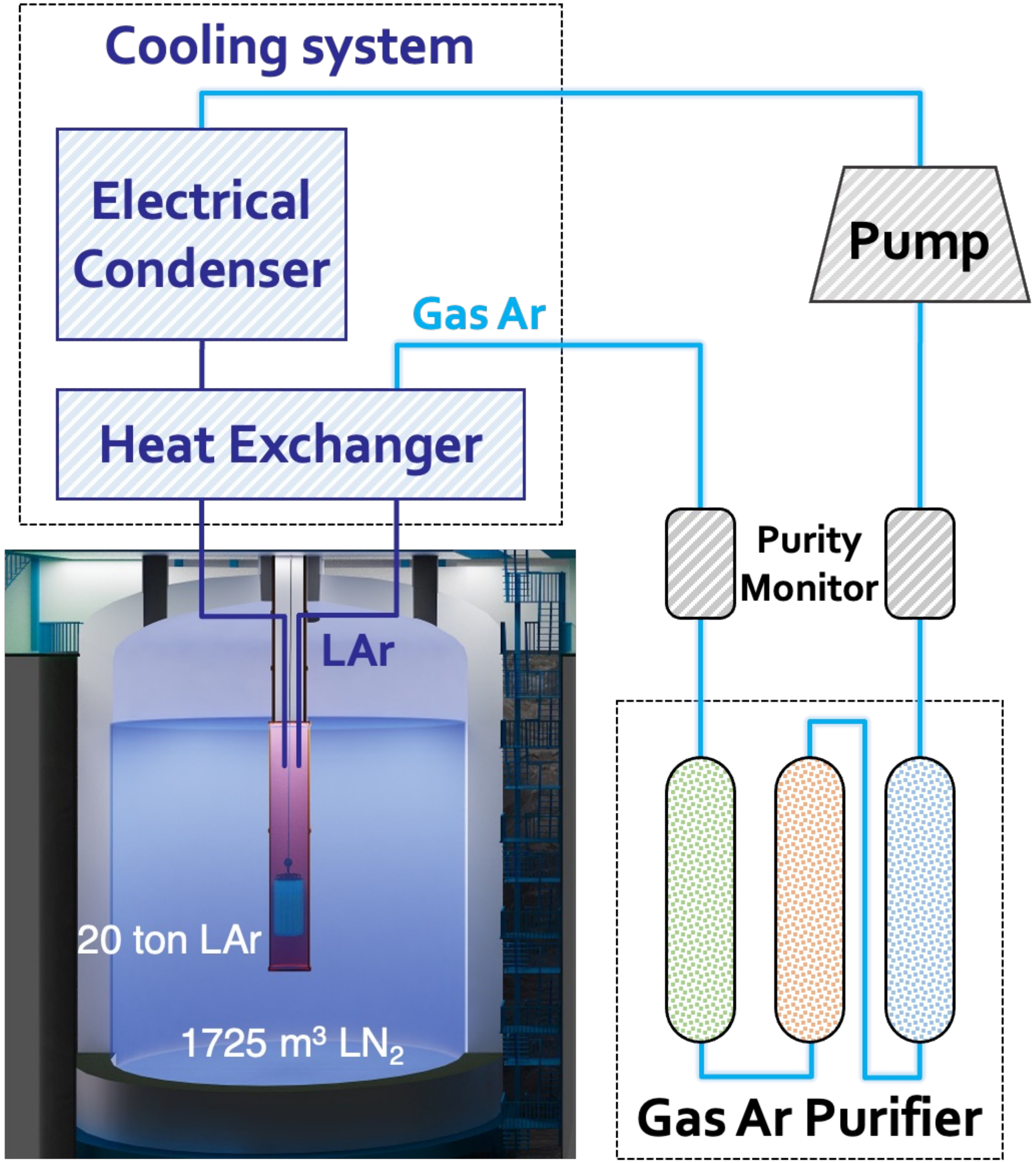
# CDEX-300ν pre-Conceptual Design

## ◻ 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/m³)
- ➢ Possible underground Argon (Ar-42 depleted)

## ◻ LAr Cooling:

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

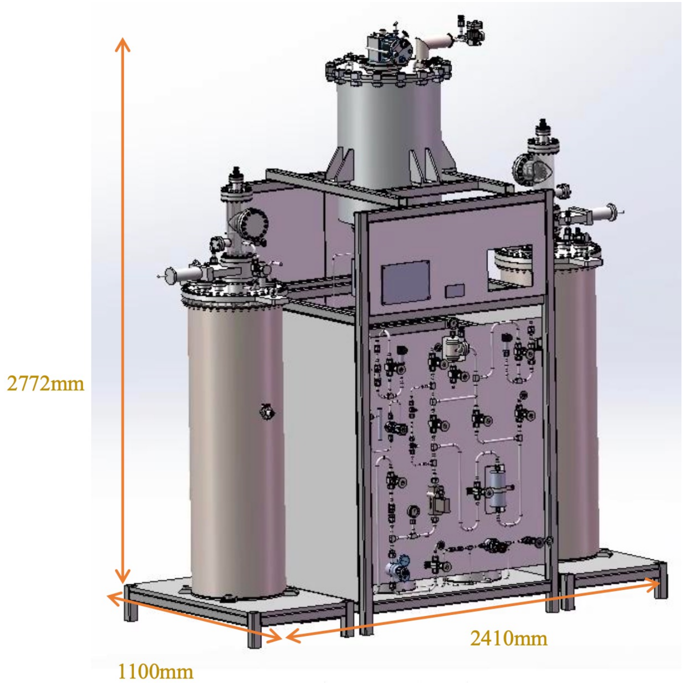


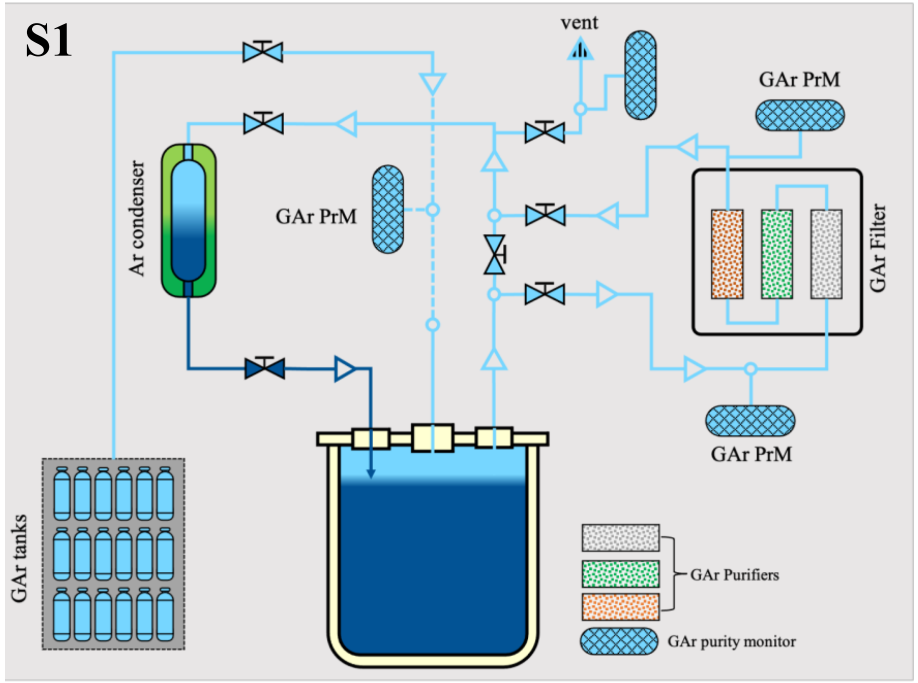
# CDEX-300ν pre-Conceptual Design

## LAr Test Facility:

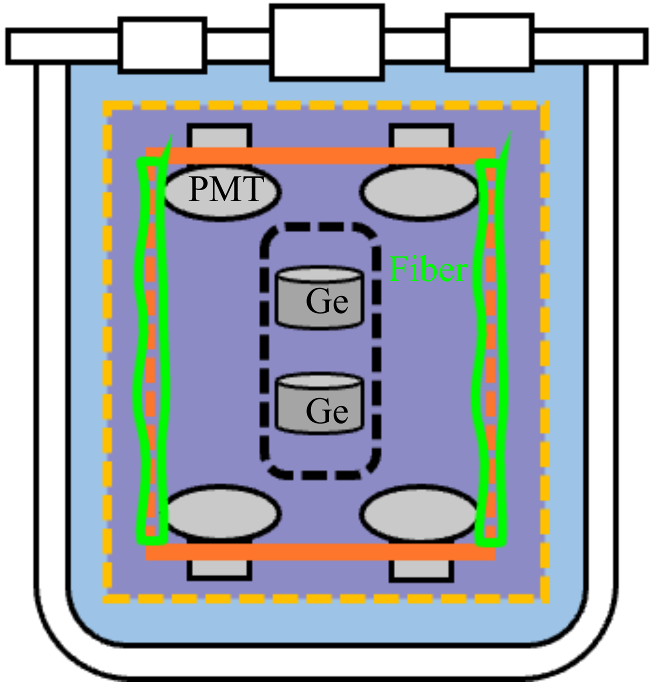
Currently under construction, plan to start testing in December 2023.

- **Stage-1:** Operating & Purifying 200 L LAr in a closed cycle
- **Stage-2:** Deploying light readout to study light yield / transmission of LAr in different impurity levels
- **Stage-3:** Deploying Ge detectors to test veto performance



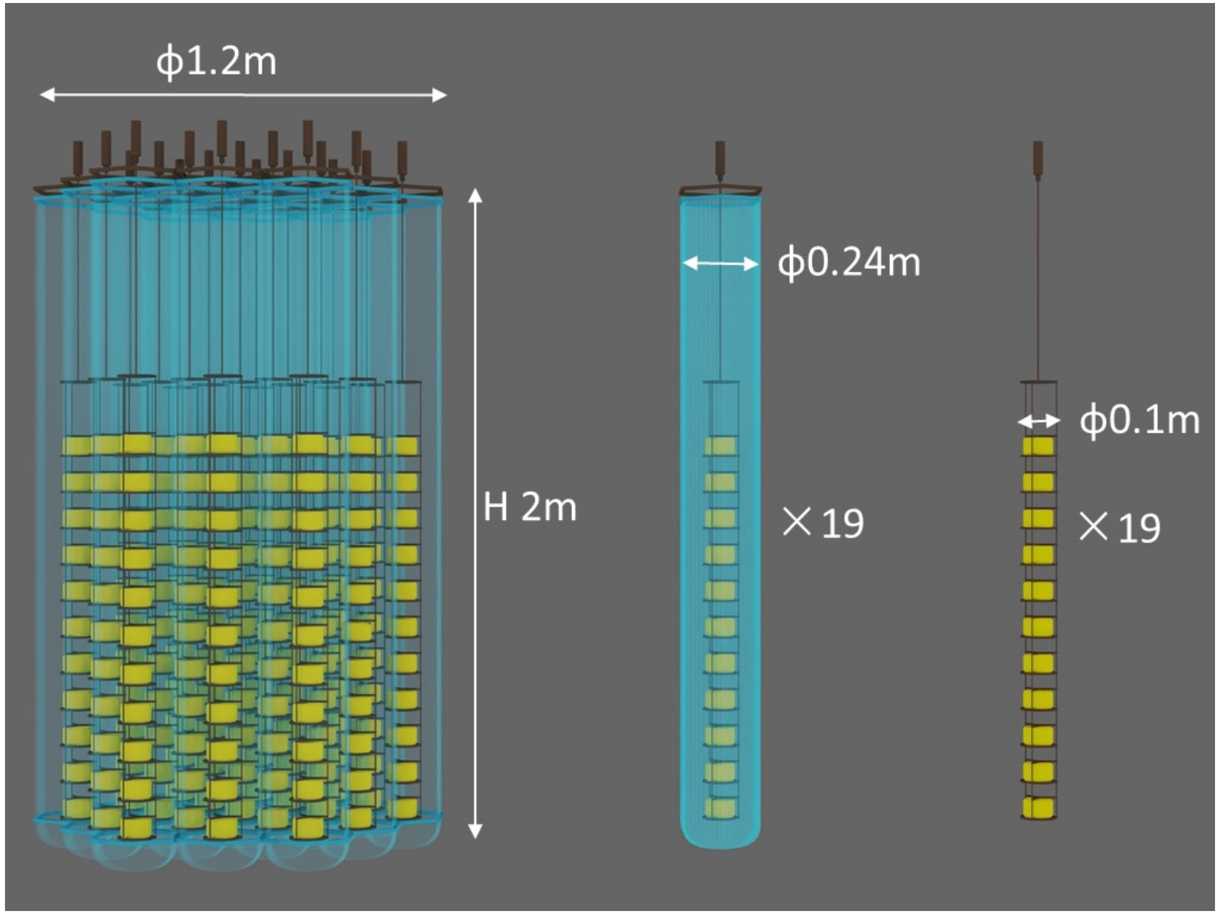

S2/S3

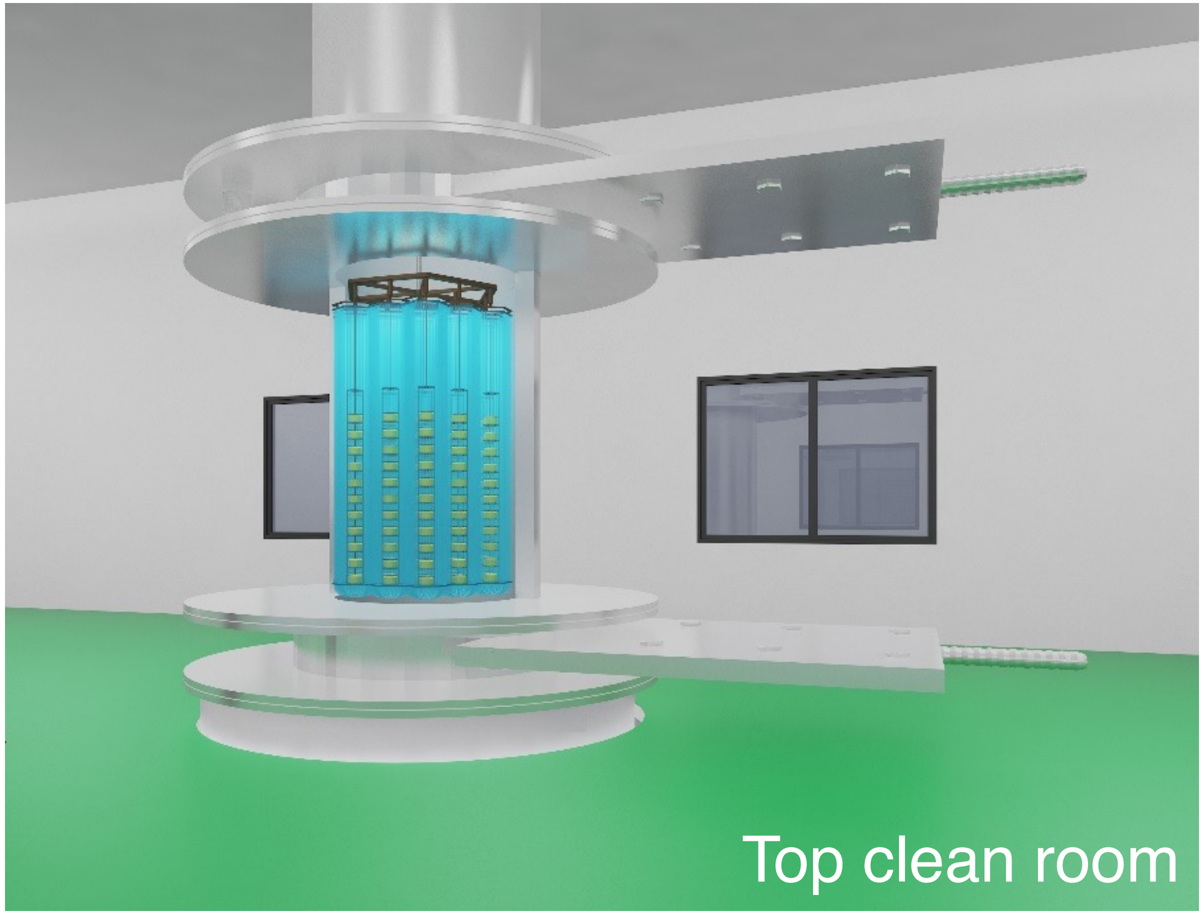


# CDEX-300ν pre-Conceptual Design

## Baseline design of Ge detector array

- 200 Ge-76 enriched detectors: 19 strings, 10~11 det/string, Total mass ~225kg
- Top clean room for Ge detector and fiber installation



# CDEX-300ν pre-Conceptual Design

## ☐ Procurement of Enriched Ge detector

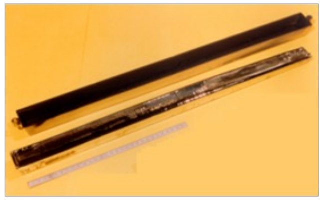
- Technical chain established: Ge-76 enrichment → Ge metal → Crystal growth → Detector fabrication

✓ 90 kg enriched $GeO_2$ from Russia

$^{76}GeO_2$ Power (Storage)

Enrichment ($GeF_4$ Gas)

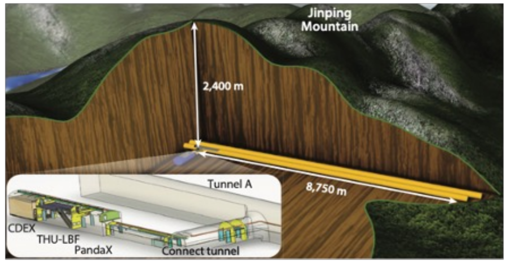
Ge Metal



Zone Refining

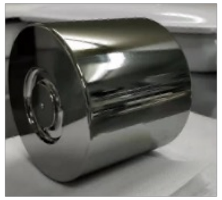
Crystal Growth

CJPL




Transport (w. steel shields)

Detector Fabrication



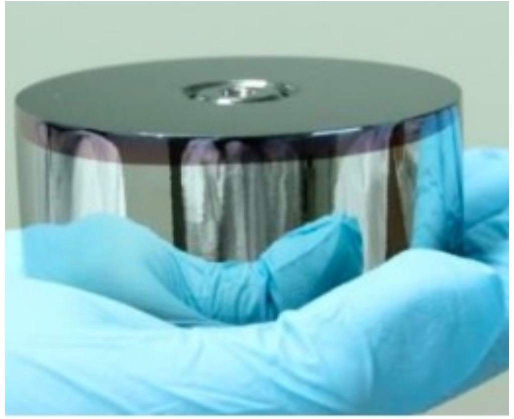
# CDEX-300ν pre-Conceptual Design

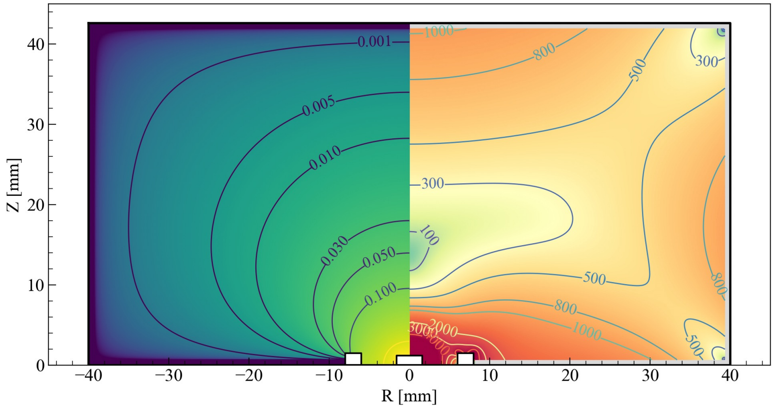
## ☐ Ge Detectors:

- **Enriched BEGe (Baseline)**
  - Mass: 1~1.2 kg (Ge-76 > 86%)
  - Size: φ80×40 mm
  - Dead layer: 0.6 mm
  - FWHM : <0.15% @2MeV (~2.5keV)
  - Commercial / Home-made

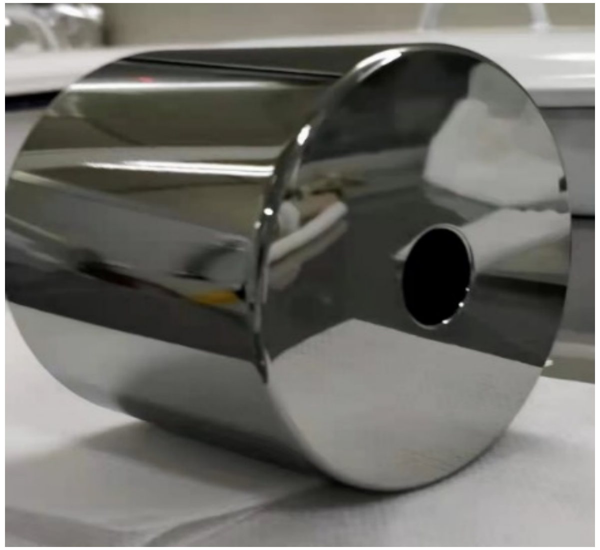
- **ICPC (Optional)**
  - Mass: ~2 kg
  - Size: φ80×80 mm
  - Dead layer: 0.6 mm
  - Bigger Detector → Less Electronics (BG)
  - Home-made

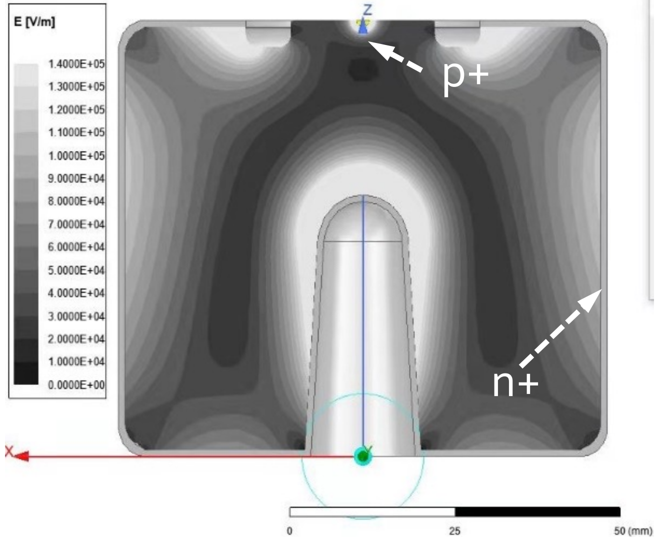
**BEGe: Broad Energy Germanium**





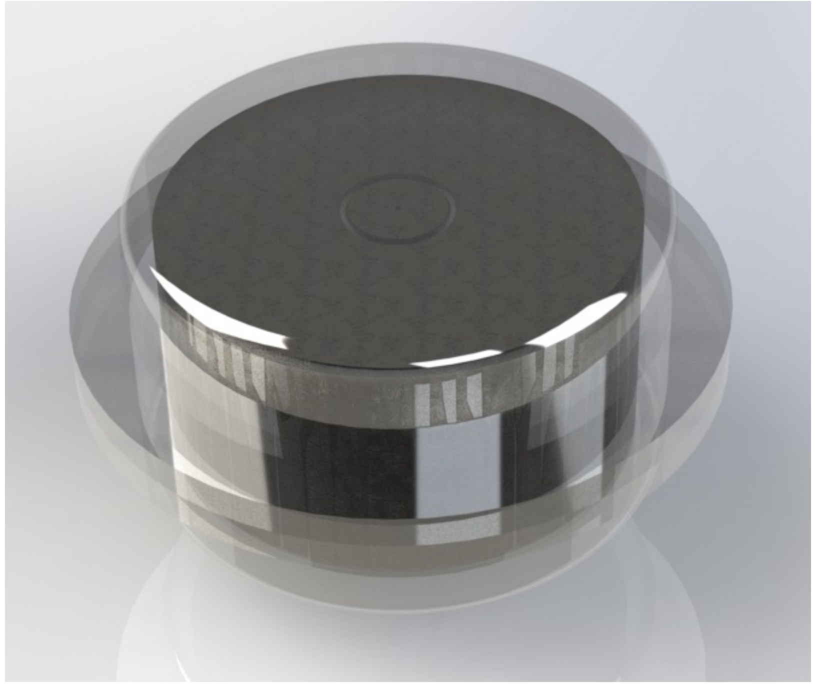

**ICPC: Inverted Coaxial Point Contact**

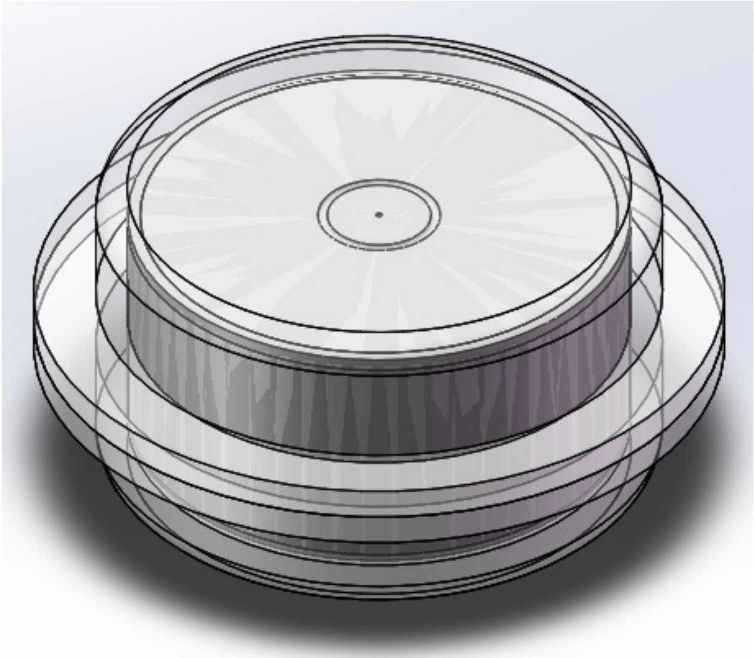


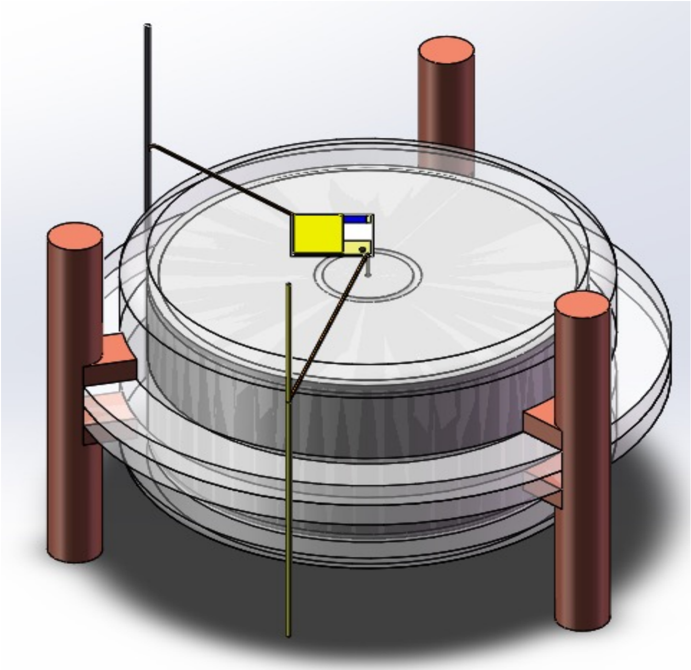


# CDEX-300ν pre-Conceptual Design

- **Detector operation (Baseline design):**
  - Naked enriched BEGe detector immersed in LAr
  - Free of traditional vacuum-related structure
- **R&D (reduce background from $^{42}Ar/^{42}K$):**
  - Ge crystal sealed in Low-Background acrylic capsule and isolated from LAr
  - Front Electronics on the outer surface of the acrylic shell







# CDEX-300ν pre-Conceptual Design

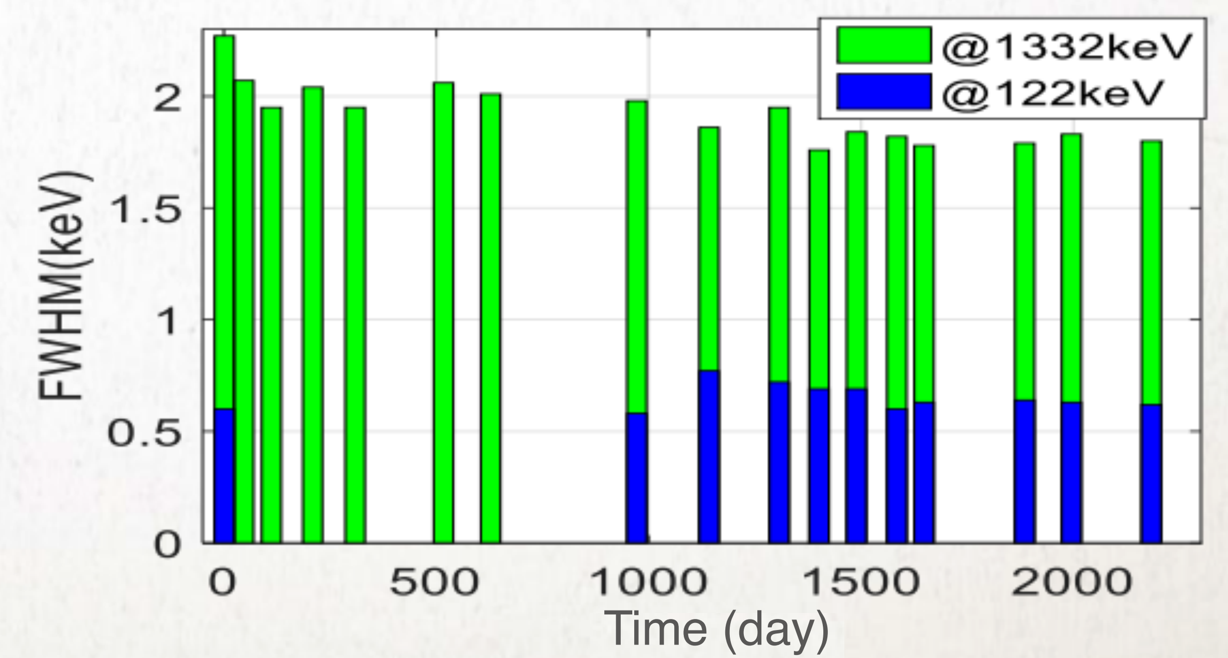
## ☐ Detector R&D:

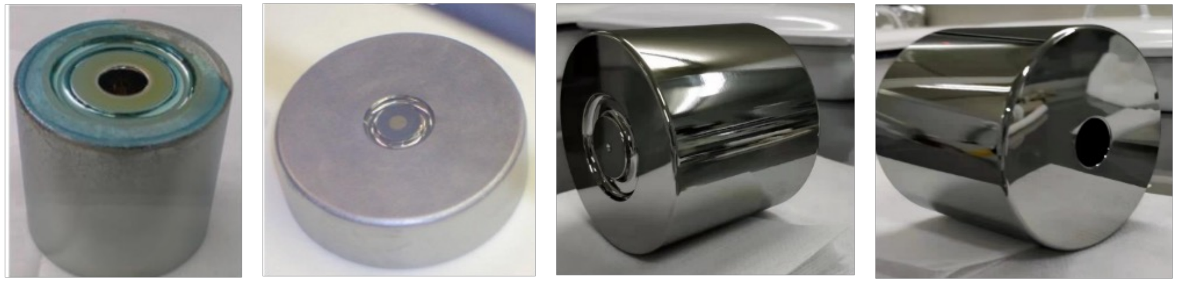
Home-made Ge detectors:

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

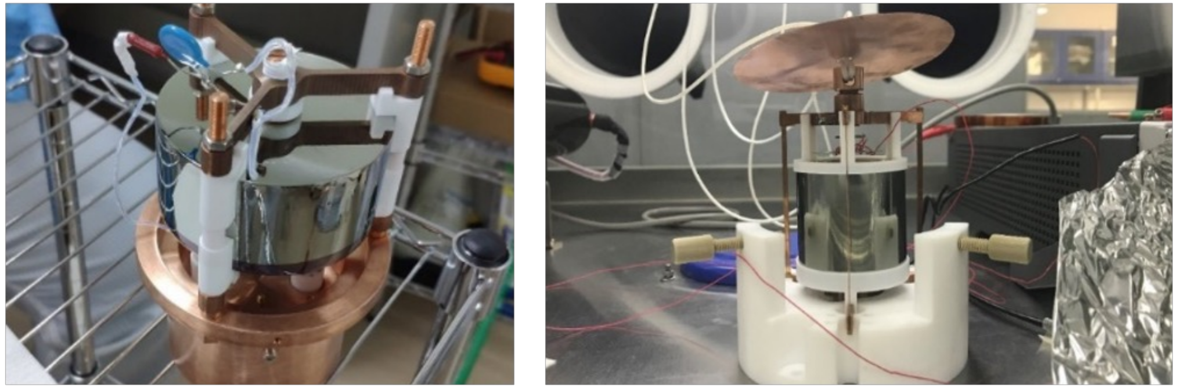
R&D on underground fabrication ongoing…

**Long-term stability: energy resolution**



Co-axial BEGe PPC ICPC



Cold finger cooling    Naked crystal to $LN_2$

# CDEX-300ν pre-Conceptual Design

## ☐ Material Background Control:

ALL materials to be screened and selected

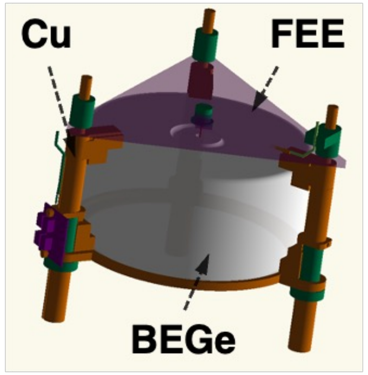
### ➢ Ge detector & FEE:

- 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





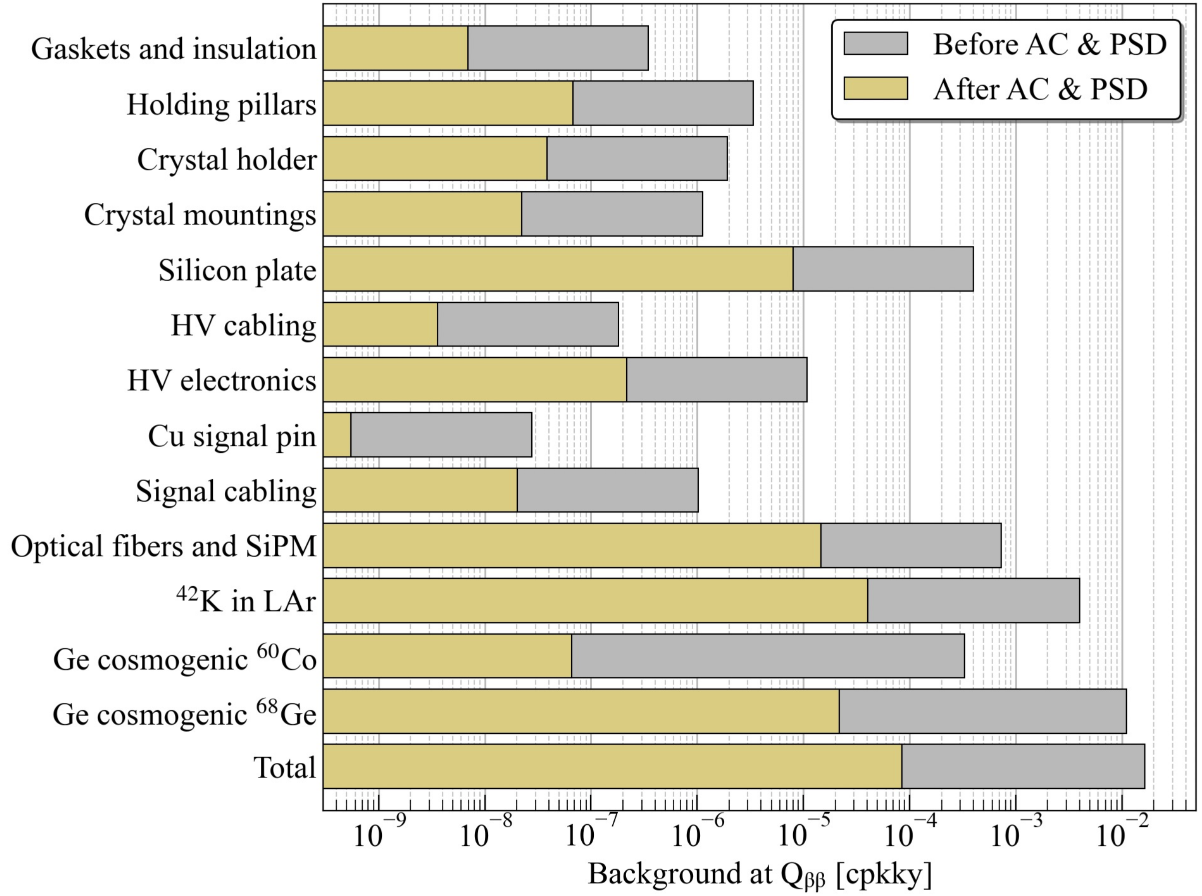



# CDEX-300ν pre-Conceptual Design

## Background Estimation:

We have estimated the background in ROI based on the pre-Conceptual design

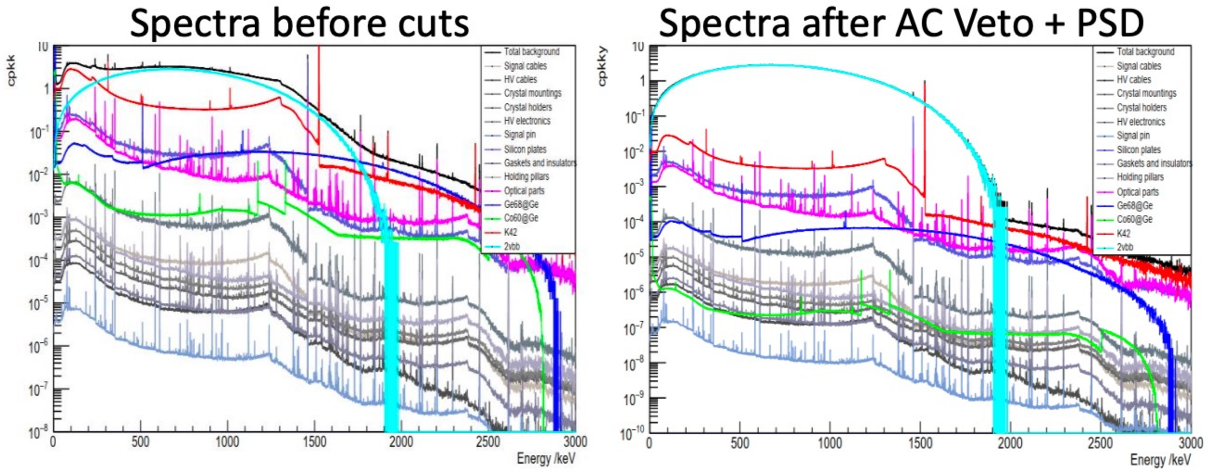
After active BG suppressions (LAr AC-veto & PSD), **BG in ROI < 1E-4 cpkky**




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

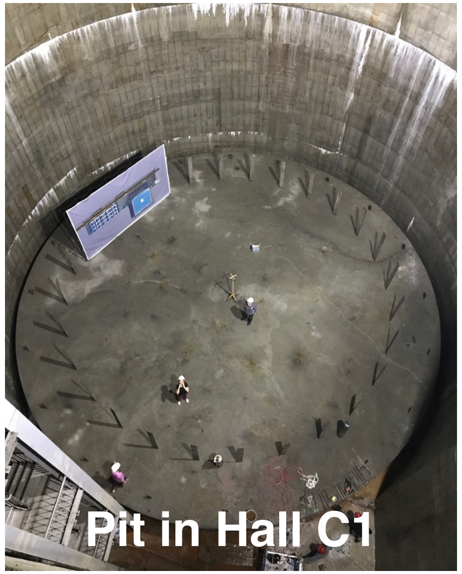
Further BG reduction may be achieved by:

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



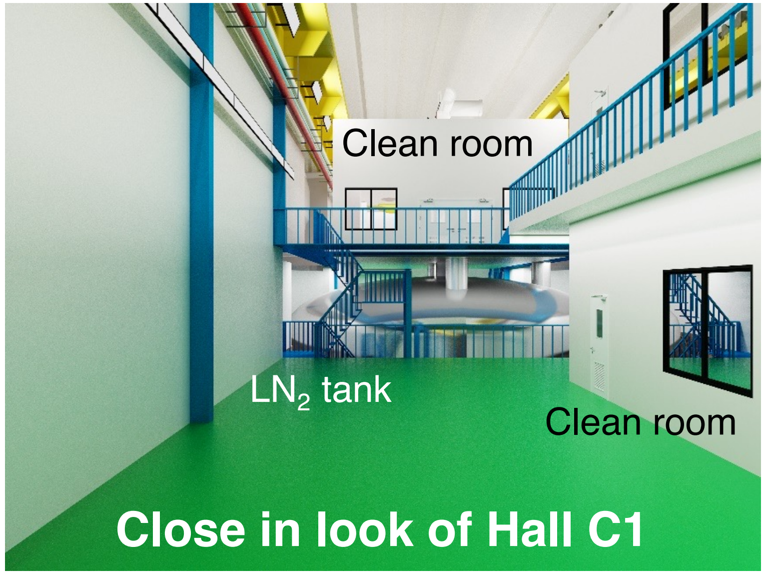
# CDEX-300ν Plans

- BEGe detectors test started in 2022 @ CJPL-I
- Test and operate LAr test facility at the end of 2023
- Hall C1 expected to be ready for experiment this fall
- Experimental setup in 2024
- First batch of Ge detector installation and test in 2024



Pit in Hall C1

1725 m$^3$ LN$_2$ tank in Hall C1



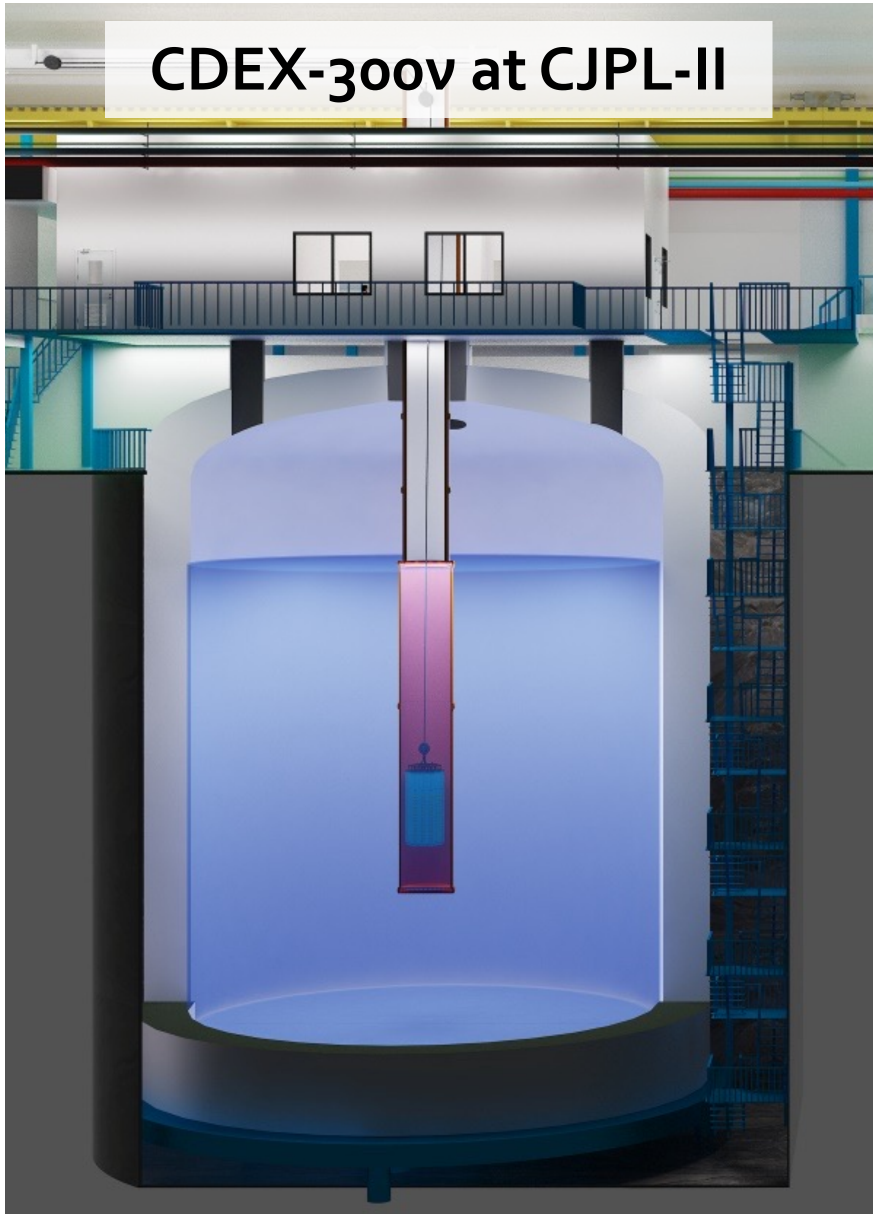

Close in look of Hall C1

# Summary

- **$0\nu\beta\beta$ decay is important for understanding the nature of neutrinos**

- **CDEX-300ν for $^{76}$Ge $0\nu\beta\beta$**
  - 225 kg enriched Ge detector system at CJPL-II
  - physics goal: $T_{1/2}>10^{27}$ yr, 90% C.L.
  - first batch of detectors deployed in 2024

- **R&D in progress**
  - Detector and electronics
  - LAr purification and scintillation light readout
  - Material screening and selection
  - ……




# Thanks for your attention!

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中国暗物质实验
China Dark matter EXperiment

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

# Neutrinoless double beta decay experiment

## ☐ Probe neutrino mass hierarchy:

$$\left(T^{0\nu}_{1/2}\right)^{-1} = G^{0\nu} \cdot \left|g_A^2\,\mathcal{M}^{0\nu}\right|^2 \cdot \left(\frac{m_{\beta\beta}}{m_e}\right)^2$$

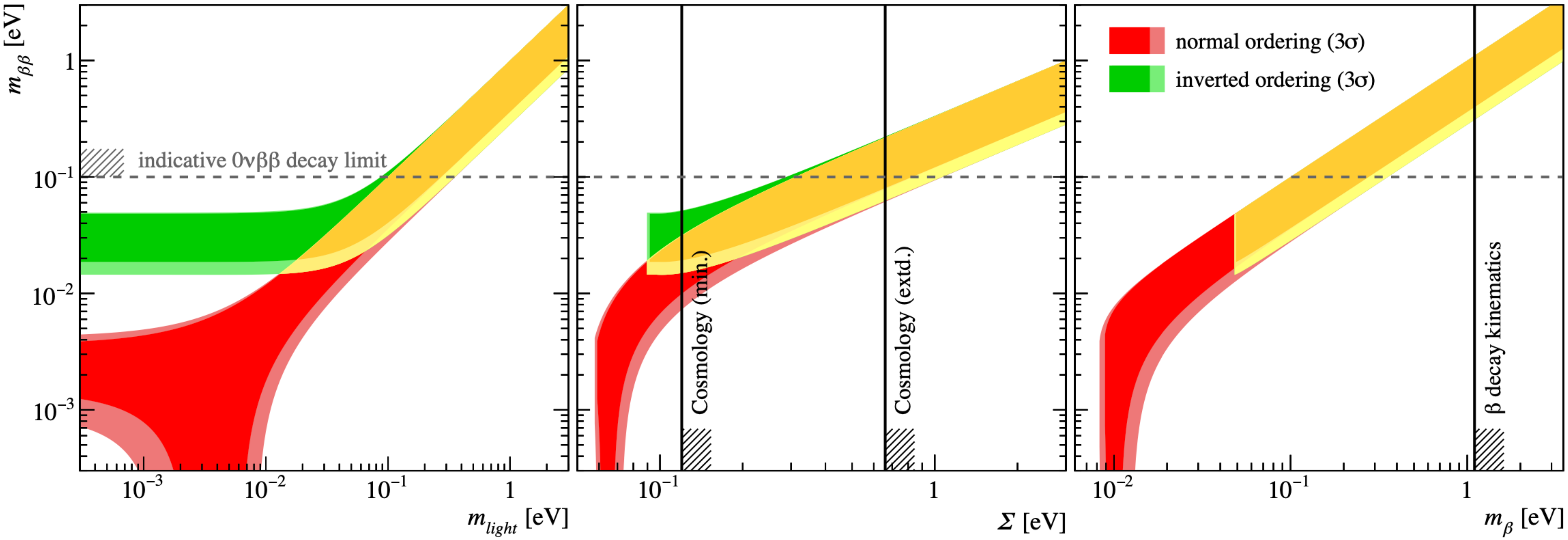
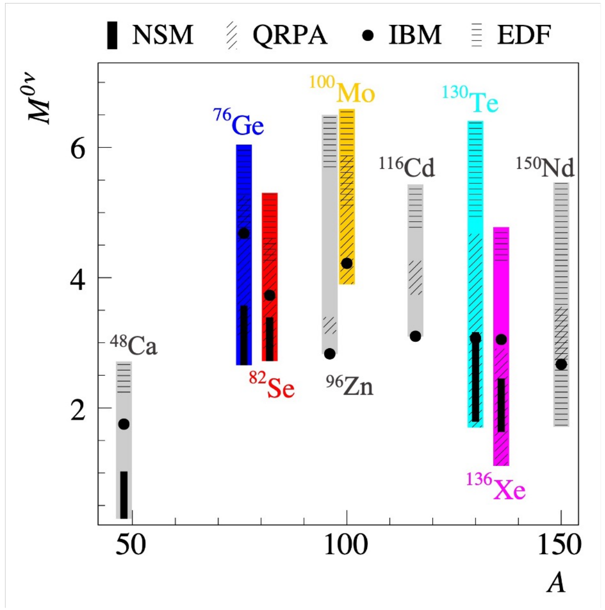



Fig from: C. Wiesinger (PhD Thiese). TECHNISCHE UNIVERSITÄT MÜNCHEN, 2020.

C. Wiesinger (PhD Thiese). TUM, 2020.




## ☐ Experimental search for 0νββ decay:

A great lot of experiment effects have been put into searching for 0νββ decay

$$\underbrace{\left(T_{1/2}^{0\nu}\right)^{-1}}_{\text{0νββ half life}} = \underbrace{G^{0\nu} \cdot \left|g_A^2\,\mathcal{M}^{0\nu}\right|^2}_{\text{Isotope related}} \cdot \left(\underbrace{m_{\beta\beta}}_{\text{Effective neutrino mass}}/m_e\right)^2$$

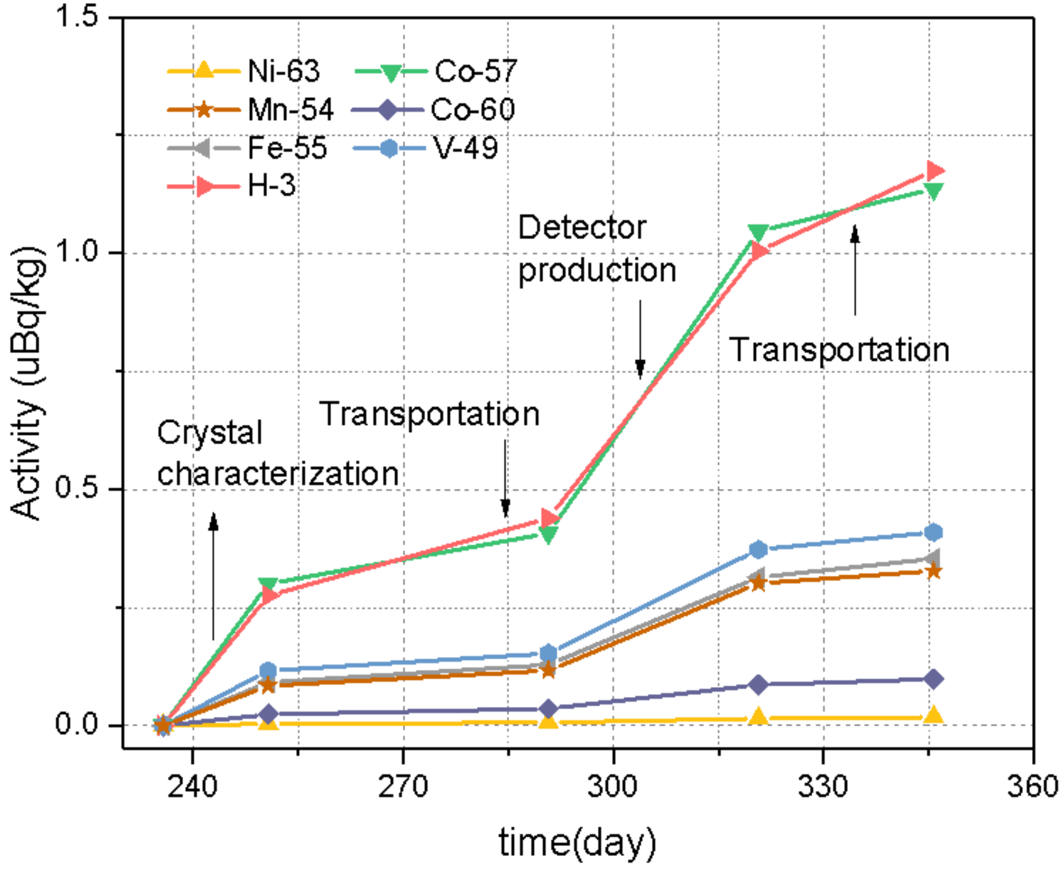
| iso | Experiment | Technology | Enrichment | Exposure [kg·yr] | Energy resolution at $Q_{\beta\beta}$ | Background [cpROI·ton·yr] | $T_{1/2}^{0\nu}$ [yr] | $<m_{\beta\beta}>$ [meV] |
|---|---|---|---|---|---|---|---|---|
| $^{76}$Ge | GERDA | HPGe | 86% | 127.2 | 0.05% | 2.1 | > 1.8E+26 | < 79~180 |
| $^{82}$Se | CUPID-0 | ZnSe Calorimeters | 96% | 5.29 | 0.28% | 141.4 | > 3.5E+24 | < 310~640 |
| $^{100}$Mo | CUPID-Mo | $Li_2MoO_4$ Calorimeters | 97% | 1.17 | 0.11% | 82.8 | > 1.5E+24 | < 310~540 |
| $^{130}$Te | CUORE | $TeO_2$ Calorimeters | 35% | 288.8 | 0.31% | 568.3 | > 2.2E+25 | < 90~305 |
| $^{136}$Xe | KamLAND-Zen | Xe-LS | 90% | 970 | 4.64% | 147.6 | > 2.3E+26 | < 36~160 |
| $^{136}$Xe | EXO-200 | Xe-TPC | 81% | 234.1 | 1.15% | 270.0 | > 3.5E+25 | < 93~286 |

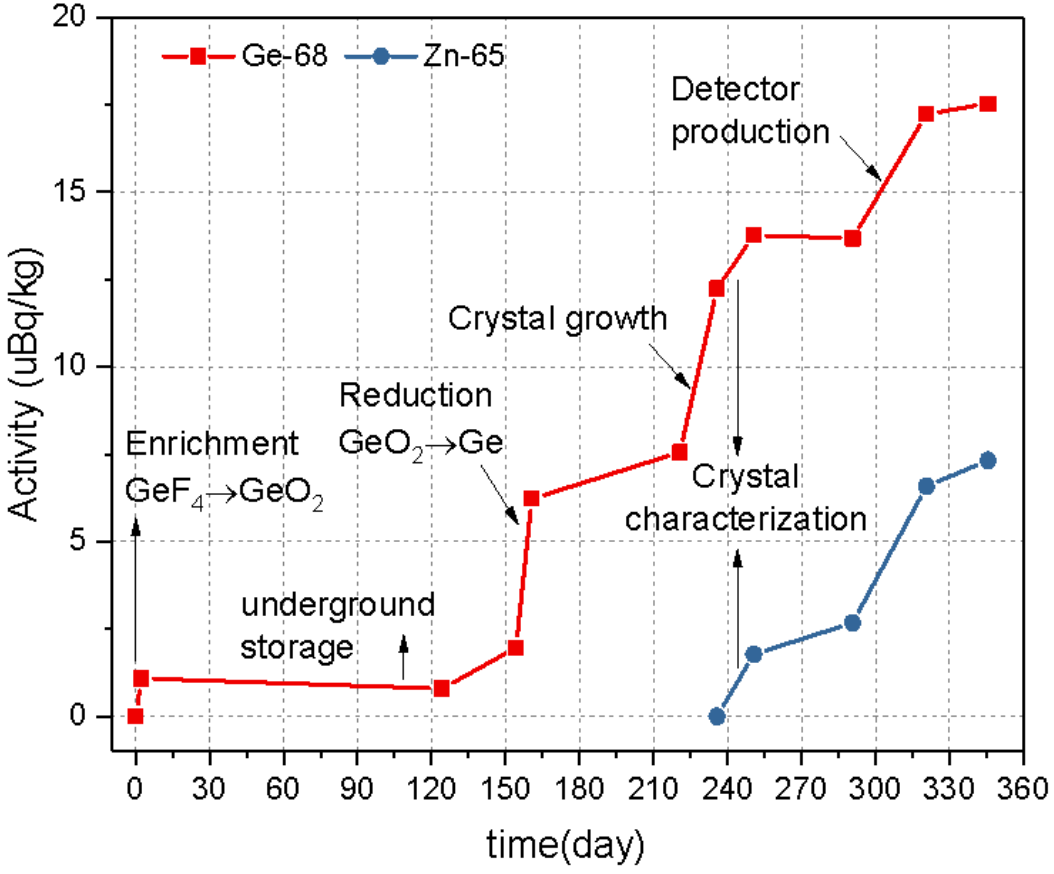
# CDEX-300v pre-Conceptual Design

## ❑ Ge cosmogenic background: Ge-68 & Co-60

| Co-60 (μBq/kg) | Initial | After 2 yr | After 5 yr |
|---|---|---|---|
| | 0.10 | 0.08 | 0.05 |

| Ge-68 (μBq/kg) | Initial | After 2 yr | After 5 yr |
|---|---|---|---|
| | 17.50 | 2.70 | 0.16 |

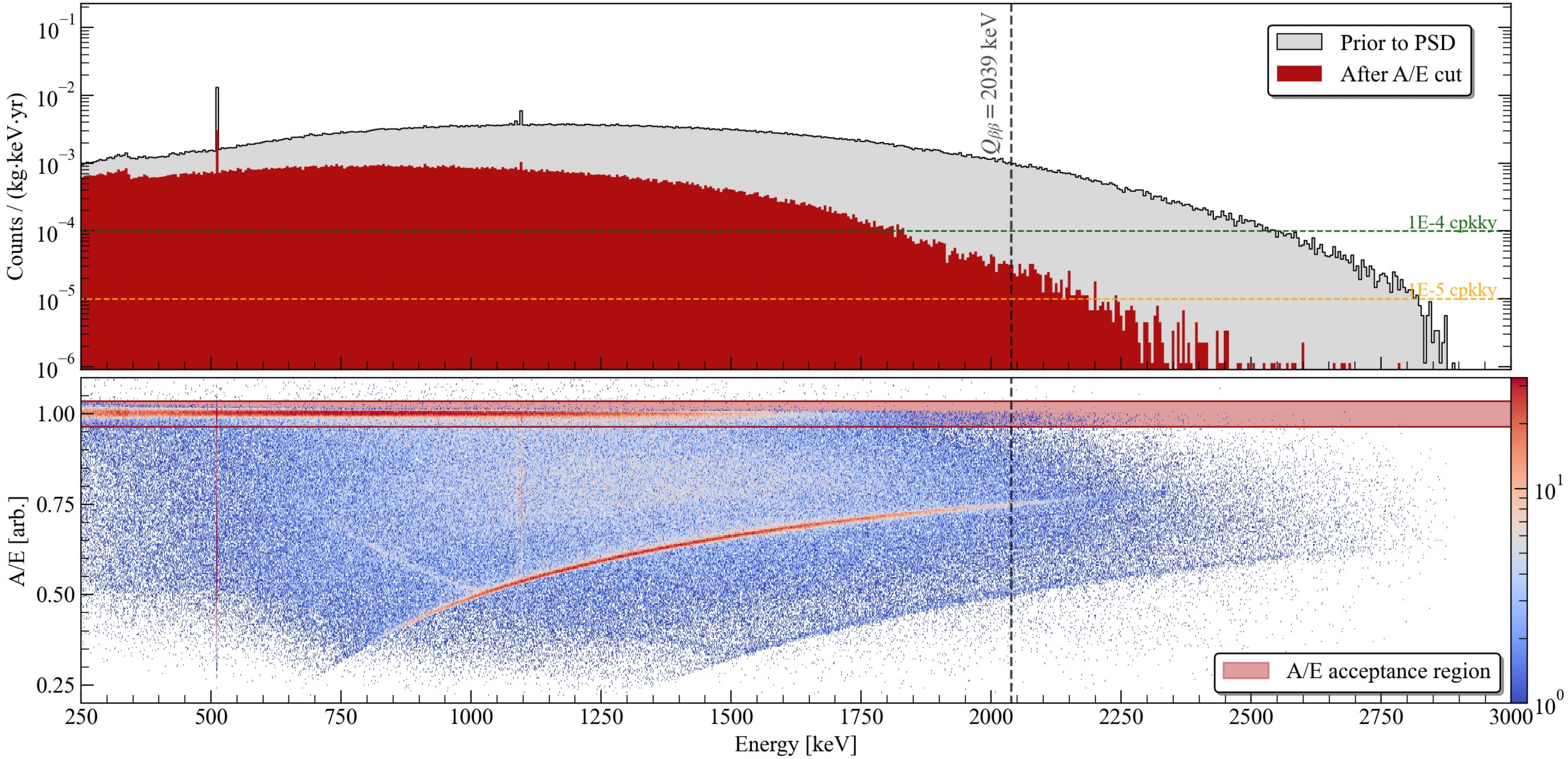


# CDEX-300ν pre-Conceptual Design

## Ge cosmogenic background from Ge-68:

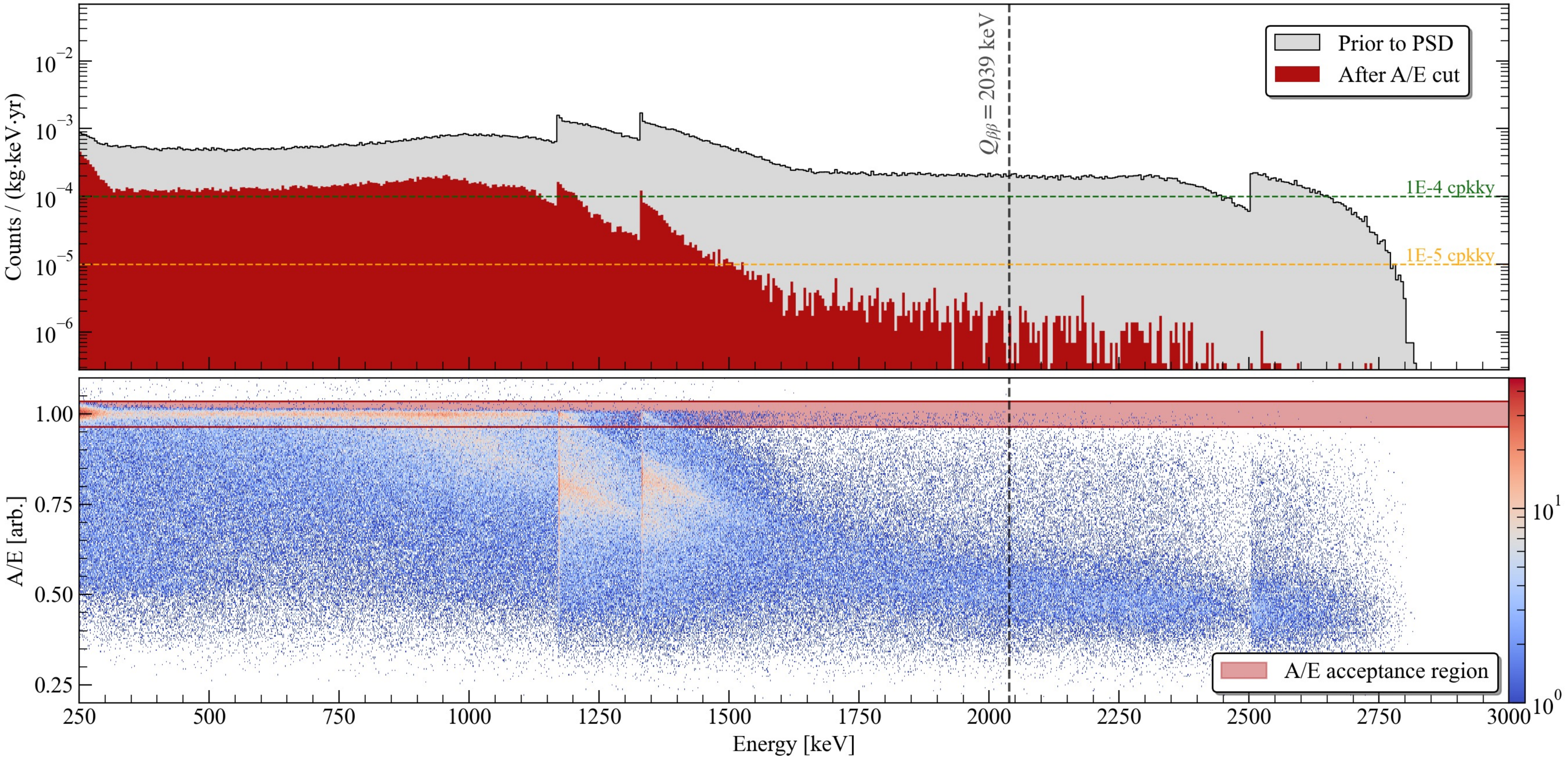
Suppression by PSD in 2039±3σ: ~30 times



# CDEX-300ν pre-Conceptual Design

## ☐ Ge cosmogenic background from Go-60:

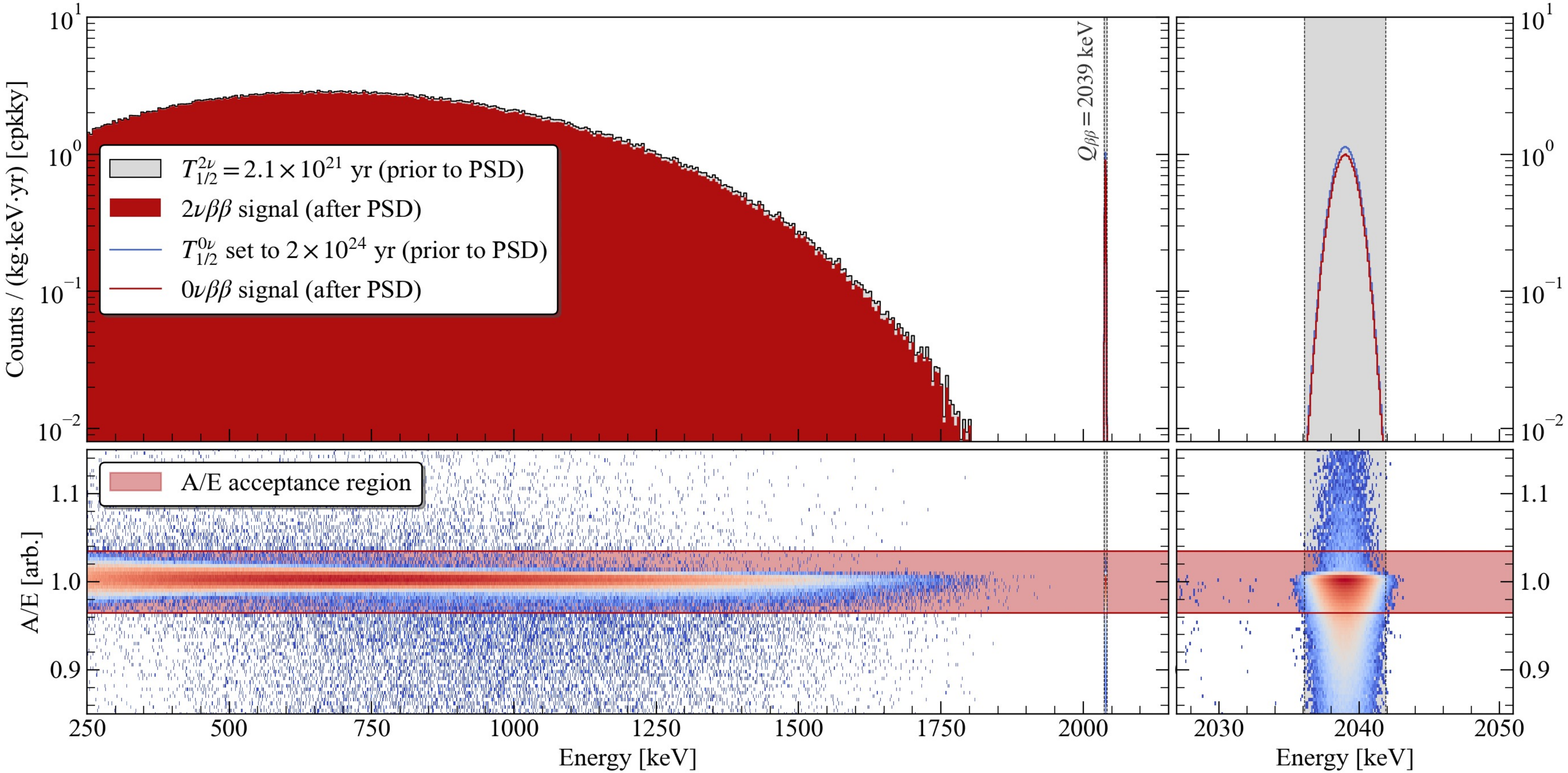
Suppression by PSD in 2039±3σ: ~140 times



# CDEX-300ν pre-Conceptual Design

## Signal efficiency (PSD):

Efficiency for 0νββ: (87.8±0.14)%



# CDEX-300ν pre-Conceptual Design

## Experiment Key Parameters:

| Experiment | CDEX-300ν |
|---|---|
| Detector mass | 225 kg |
| Ge-76 enrichment | ≥ 86% |
| Signal efficiency | 76% |
| Background level | 1E-4 cpkky |
| Energy resolution | 2.5 keV FWHM |
| **Sensitivity goal** | **$T \geq 10^{27}$ yr** |

# CDEX-300ν pre-Conceptual Design

## "0" Background scenarios:

- For 1E-4 cpkky + 2.5 keV FWHM + 1000 kg·yr: Expect background ($\lambda_b$) = 0.42 counts

### "0" Background

Exclusion:

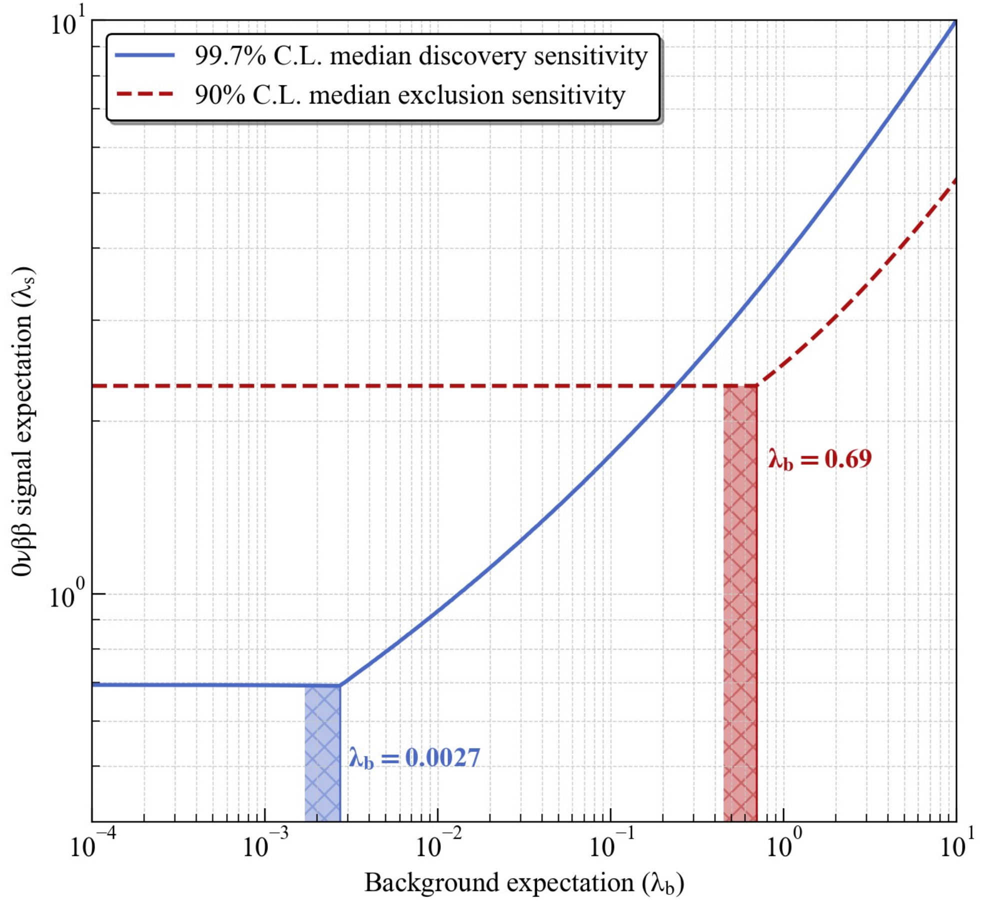
$$P(X = 0 \mid \lambda_b \leq 0.69) \geq 50\%$$

$$P(X \geq 1 \mid \lambda_b \leq 0.69, \lambda_s = 2.3) \geq 90\%$$

Discovery:

$$P(X = 0 \mid \lambda_b \leq 0.0027) \geq 99.73\%$$

$$P(X \geq 1 \mid \lambda_b \leq 0.0027, \lambda_s = 0.69) \geq 50\%$$

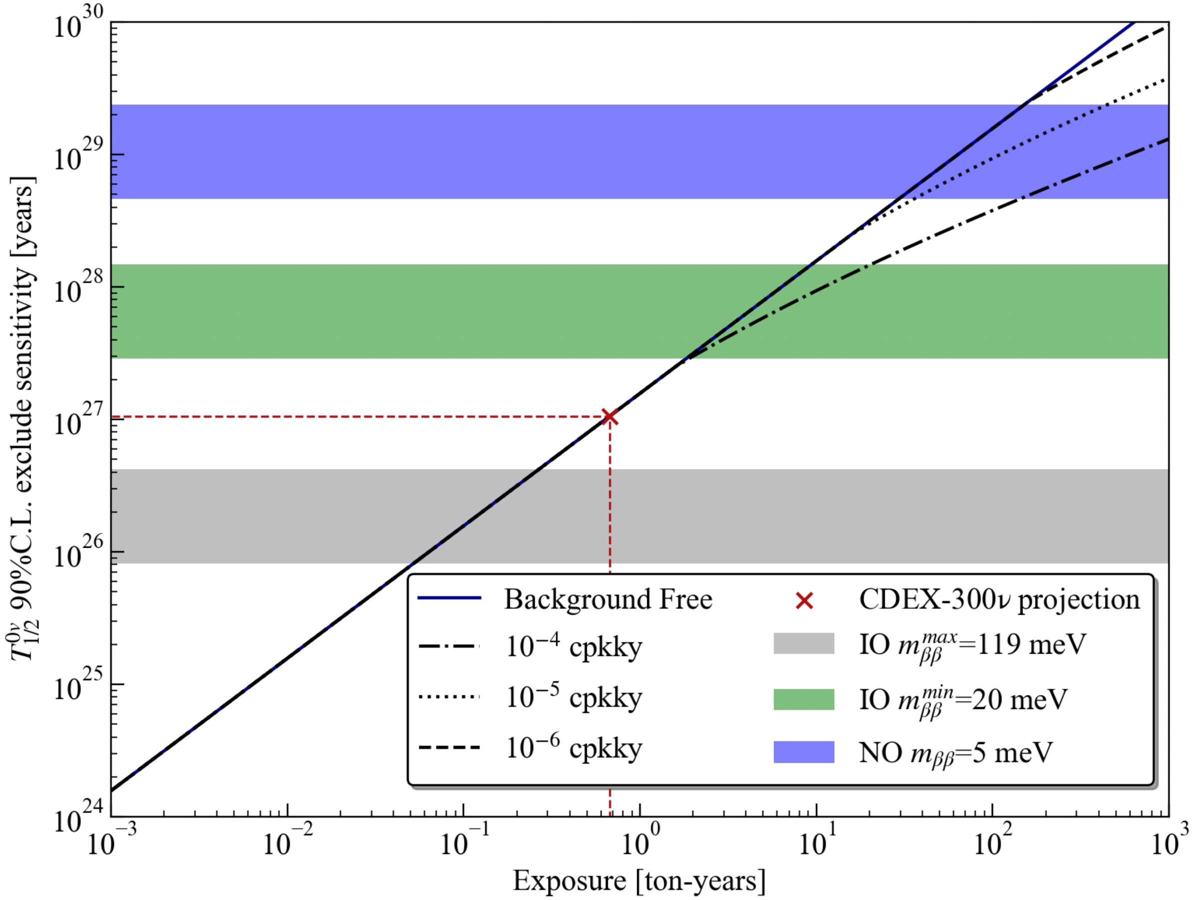


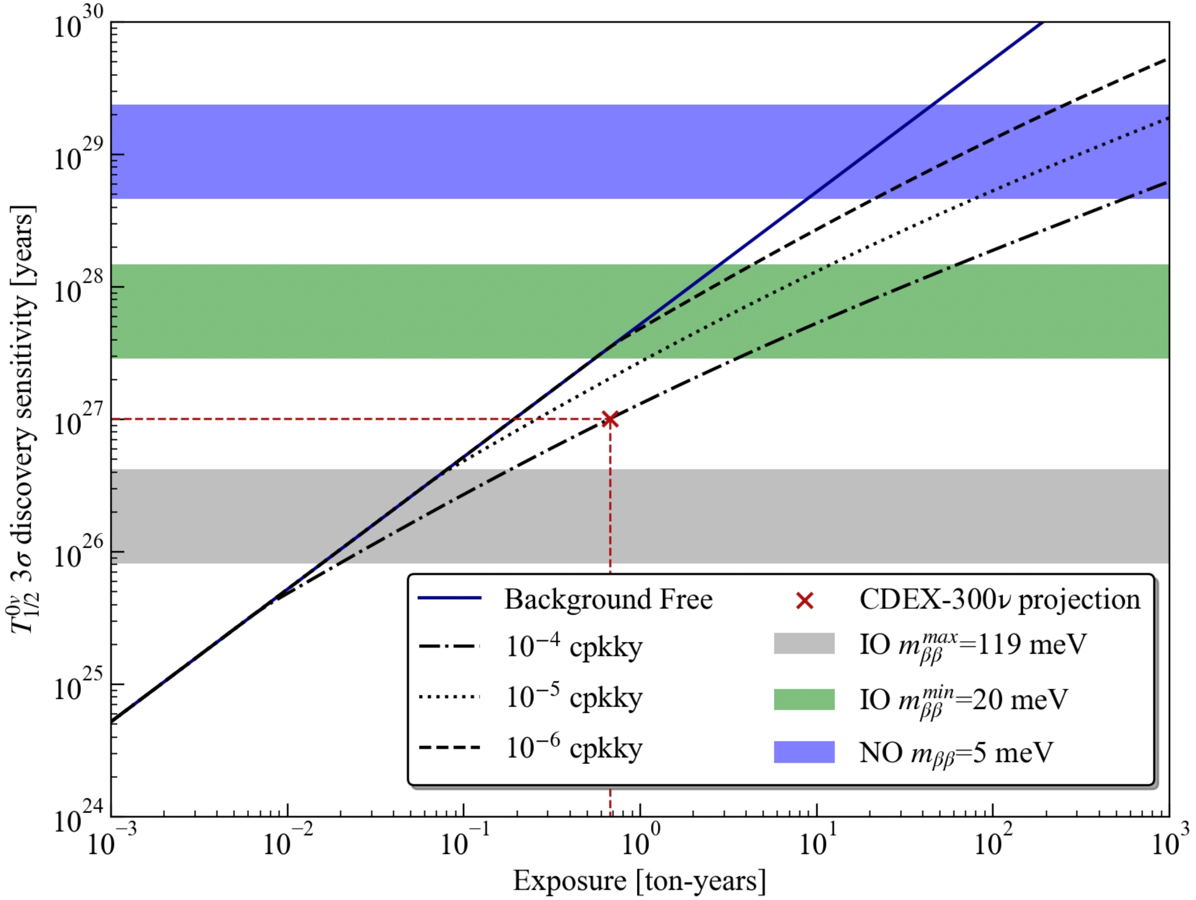

*Calculate method: M. Agostini, et al. Phys. Rev. D 96, 053001, 2017*

## ☐ Projected sensitivity for CDEX-300:

BI = 1E-4 cpkky; Exposure = 225 kg × 3 yr

| Parameters | | |
|---|---|---|
| | Efficiency | 76% |
| | FWHM | 2.5 keV |



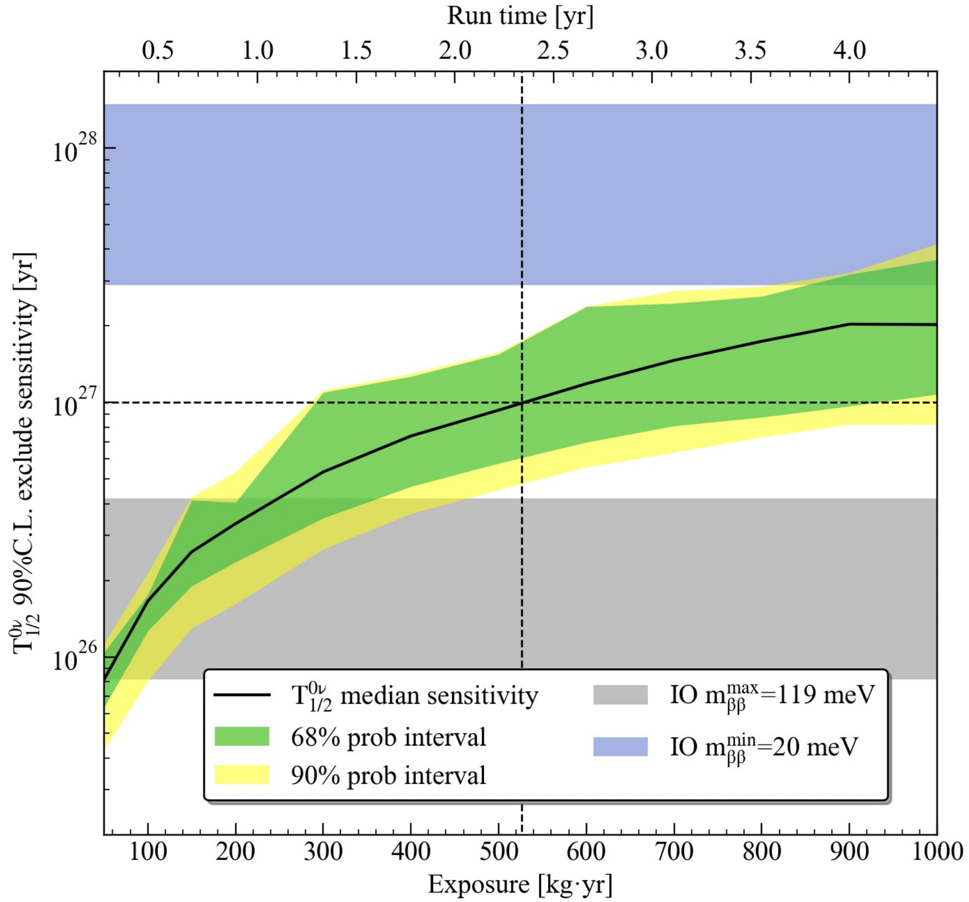




*Calculate method: M. Agostini, et al. Phys. Rev. D 96, 053001, 2017*

# CDEX-300ν pre-Conceptual Design

## ☐ Projected sensitivity for CDEX-300: Unbinned Profile likelihood ratio method

| CDEX-300ν Exclusion $T > 10^{27}$ yr | BI | 1E-4 cpkky |
|---|---|---|
| | M·T | 225 kg × 2.3 yr |




| CDEX-300ν Discovery $T > 10^{27}$ yr | BI | 1E-4 cpkky |
|---|---|---|
| | M·T | 225 kg × 3.2 yr |