CDEX-300v program for ^{76}Ge 0νββ search

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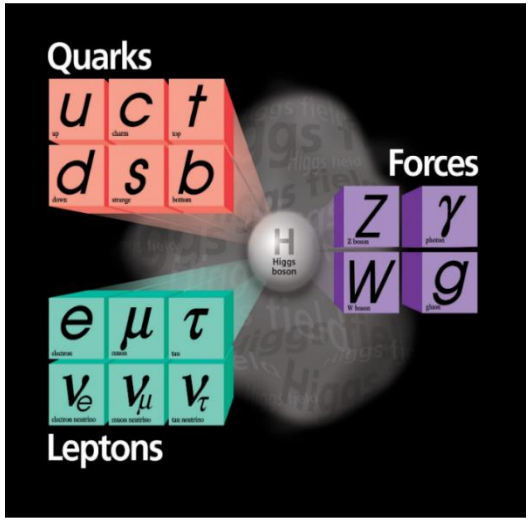
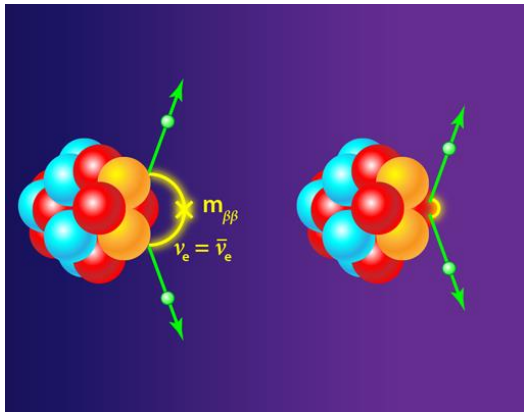
Outline

- Introduction to CDEX
- $0\nu\beta\beta$ results from CDEX
- CDEX-300v design and status
- Future plan of CDEX-300v

Neutrinoless Double Beta Decay

- **Questions for neutrino physics:**
  - Neutrino mass and mass hierarchy
  - Dirac or Majorana nature of neutrino
  - Neutrino species
  - …
- **If 0νββ decay observed:**
  - Neutrino behaves as a Majorana particle
  - Lepton number conservation violated
  - Neutrino absolute mass
  - …

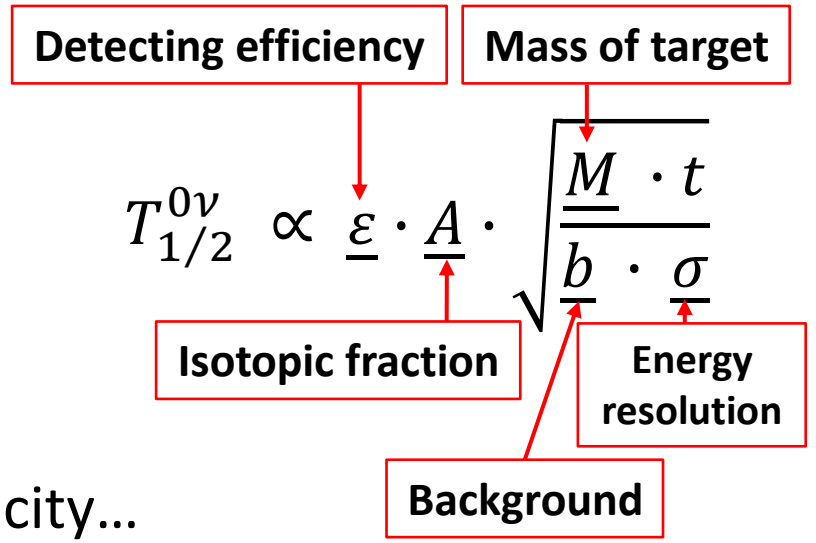




$$(A, Z) \rightarrow (A, Z+2) + 2\,e^- + Q_{\beta\beta}$$

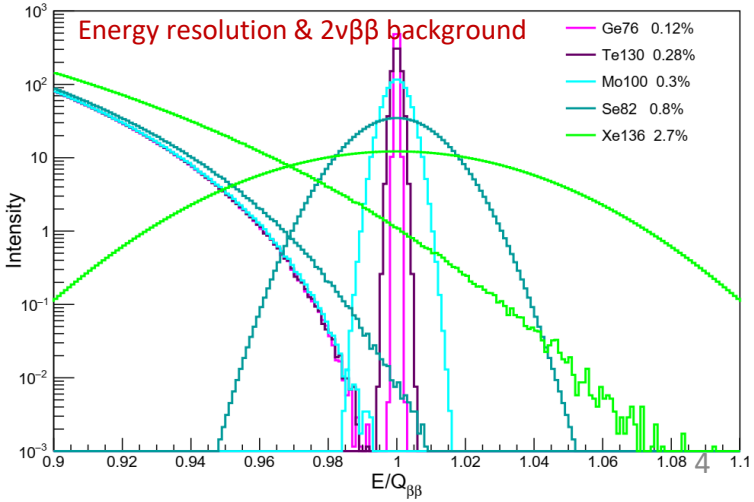
Neutrinoless Double Beta Decay Exp.

- **Germanium as 0νββ detector**
  - Intrinsic high-purity crystal ~13N
  - Source = detector (high ε)
  - Industrial enrichment to ≥86% (A)
  - Excellent E resolution (σ) ~0.1% @ 2MeV
  - Background rejection (b): PSD, LAr veto, multiplicity…



- **Current best BI & σ achieved by HPGe detector @GERDA**

Iso	Experiment	Exposure [kg·yr]	$\sigma/Q_{\beta\beta}$ [%]	Background [cpROI·t·yr]	$T_{1/2}^{0\nu}$ [yr]	$\langle m_{\beta\beta} \rangle$ [meV]
^{76}Ge	**GERDA**	**127.2**	**0.05%**	**2.1**	**> 1.8E+26**	**< 79~180**
^{130}Te	CUORE	288.8	0.31%	470.0	> 2.2E+25	< 90~305
^{136}Xe	KamLAND-Zen	970	4.64%	23.8	> 2.3E+26	< 36~160

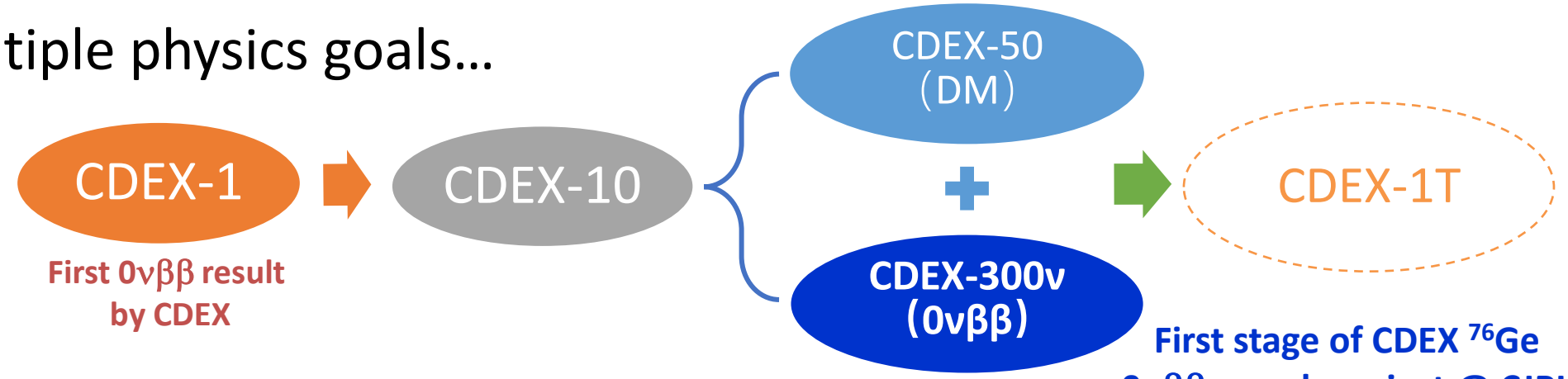


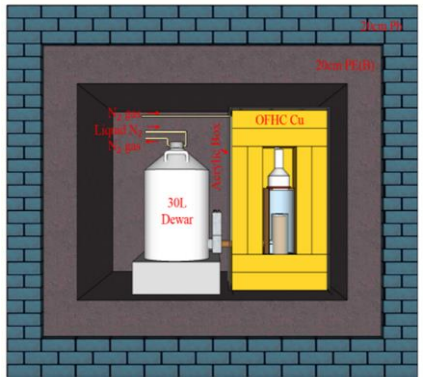
China Dark matter EXperiment

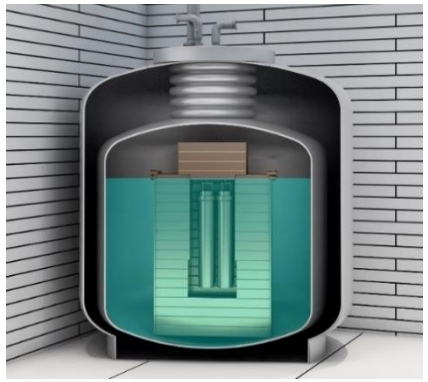
- Formed in 2009, 11 institutions and ~100 people now
- **Key technology:** P-type Point-Contact (PPC) Ge detectors

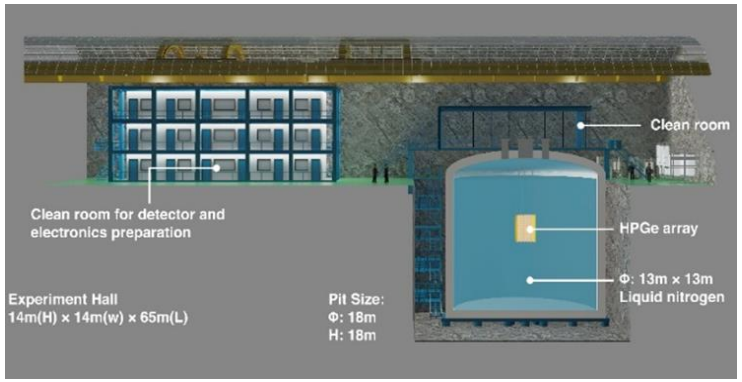
CDEX Roadmap

- Persistently focused on DM direct detection
- Extended to ^{76}Ge 0νββ search
- Multiple physics goals…









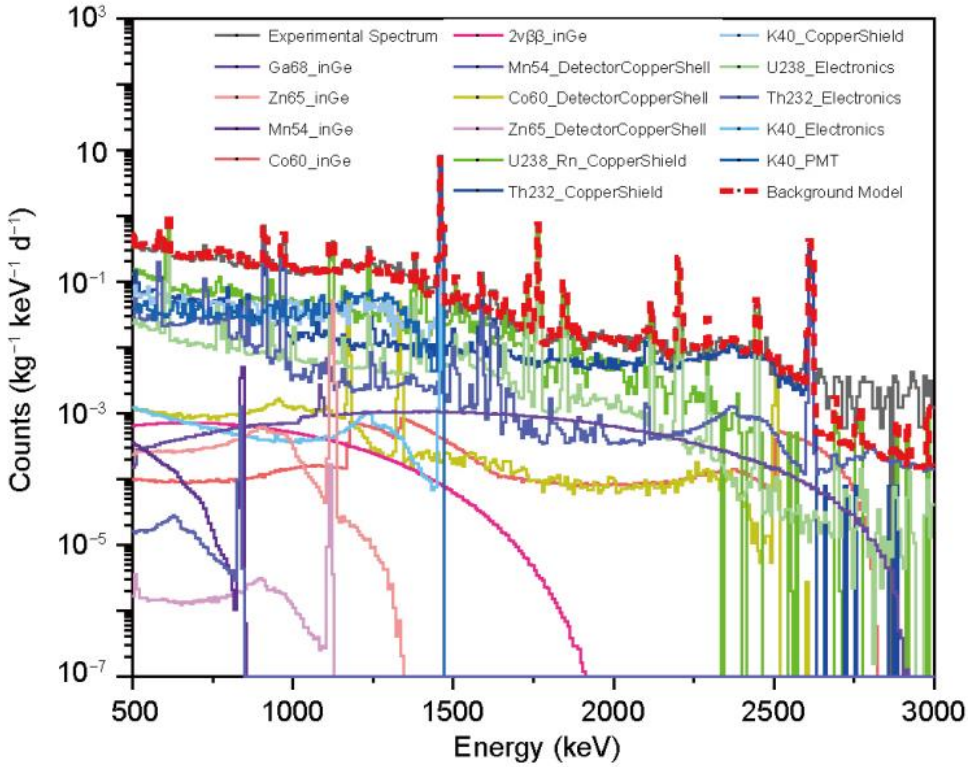
CJPL-I

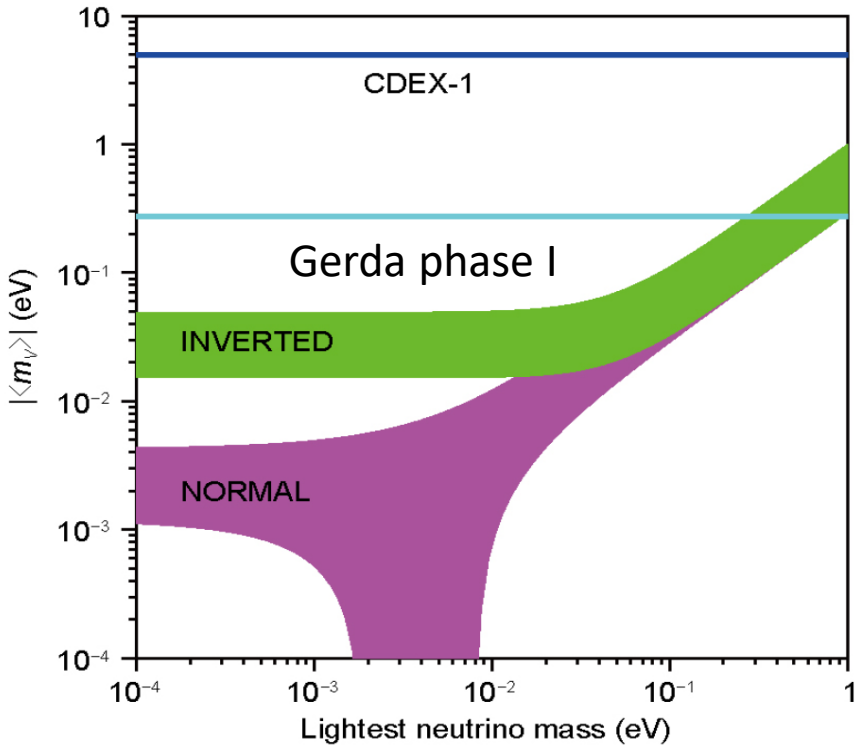
CJPL-II

First 0νββ result from CDEX @2017

- First ^{76}Ge 0νββ result in China
- Exposure: 304 kg·day, CDEX-1A PPC (natural crystal)
- $T_{1/2}^{0\nu} \geq 6.4 \times 10^{22}$ yr, 90% C. L.

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

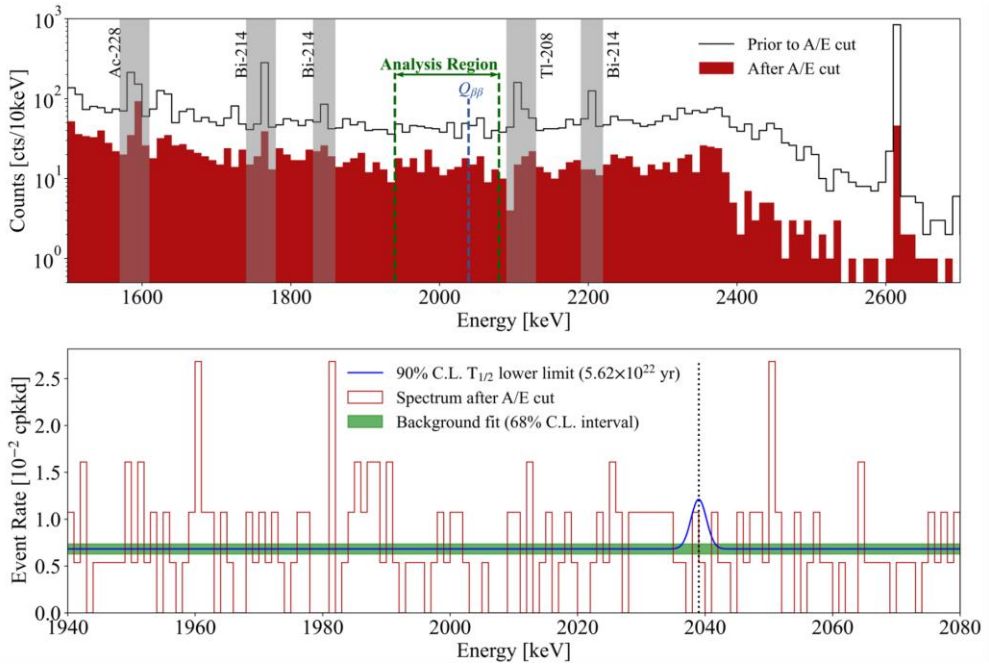


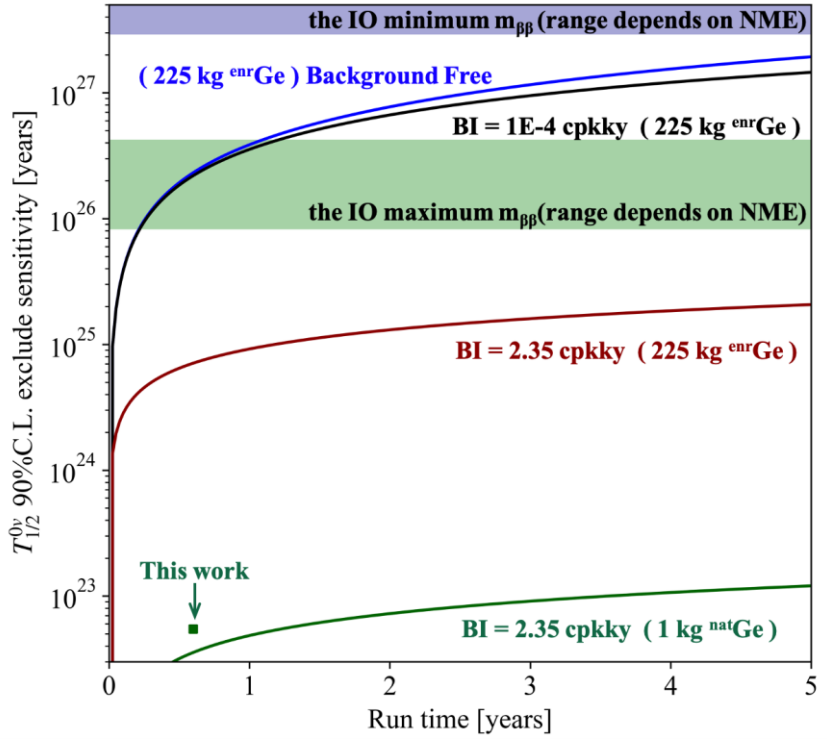


Study PSD in BEGe @2022

- 1.1kg Natural BEGe, 186.4 kg·day exposure
- Apply PSD, 50% reduction of background in ROI than CDEX-1A
- First CDEX result from BEGe, $T_{1/2}^{0\nu} \geq 5.6 \times 10^{22}$ yr,90% C. L.

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

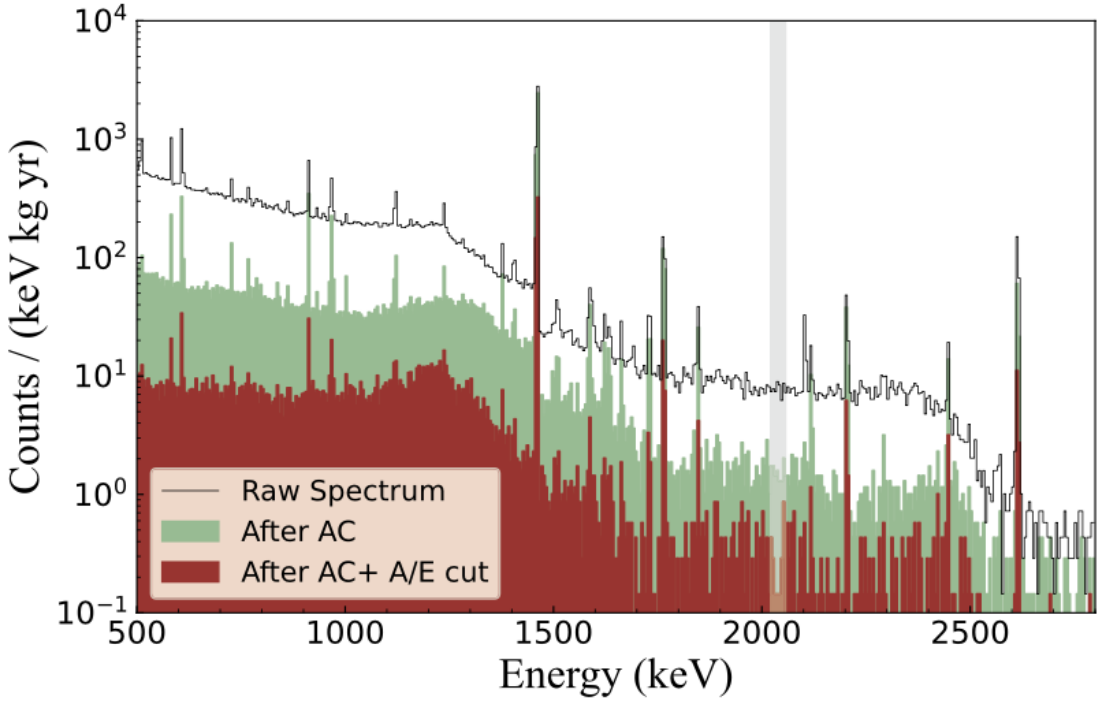


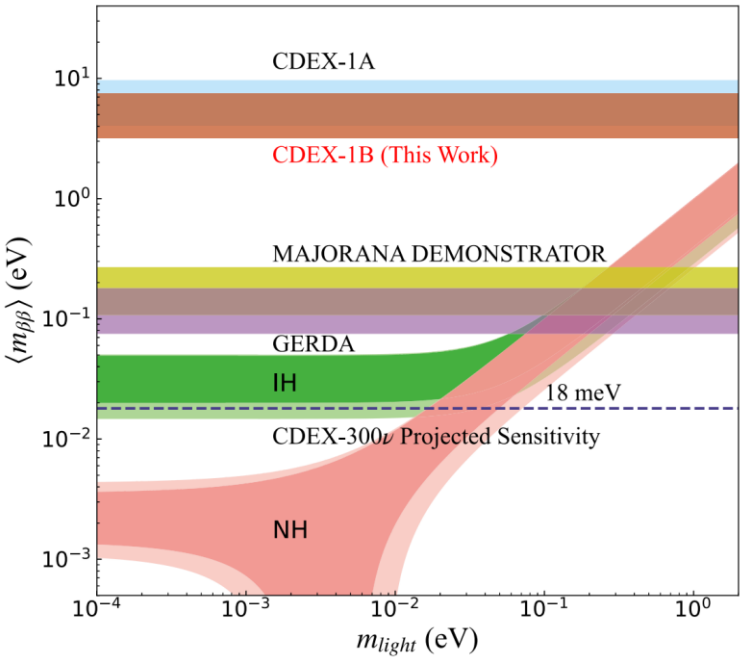


Study PSD & AC-Veto in PPCGe @2024

- CDEX-1B PPCGe (natural crystal), 500.3 kg·day exposure
- Apply PSD and NaI AC-veto, 23 times background reduction in ROI
- Best CDEX 0νββ result: $T_{1/2}^{0\nu} \geq 1.0 \times 10^{23}$ yr @90% C.L.

B.T. Zhang et al. Chinese Physics C. 48, 10, 101001, 2024





Pulse Shape simulation toolkit: SAGE

SAGE

Simulation and Analysis framework for Germanium Experiment

Analysis

Data process
- Event selection
- Energy calibration
- Efficiency correction
- …

B/S discrimination
- Ratio method
- Machine learning method

Spectra Matching
- Background model
- Sample spectrum analysis

Data process for GeTHU
- Energy calibration
- Spectra analysis
- MDA analysis
- …

Other applications
- …

Simulation

Geant4 simulation
- Based on Geant4

SAGE-PSS
- Pulse shape simulation
- Inactive layer model

Optical simulation
- Based on Geant4

SAGE for CDEX
- Build-in geometry
- Two bias methods

Pulse simulation
- Based on C++

Mini-SAGE
- Build-in GeTHU
- One bias method

Language

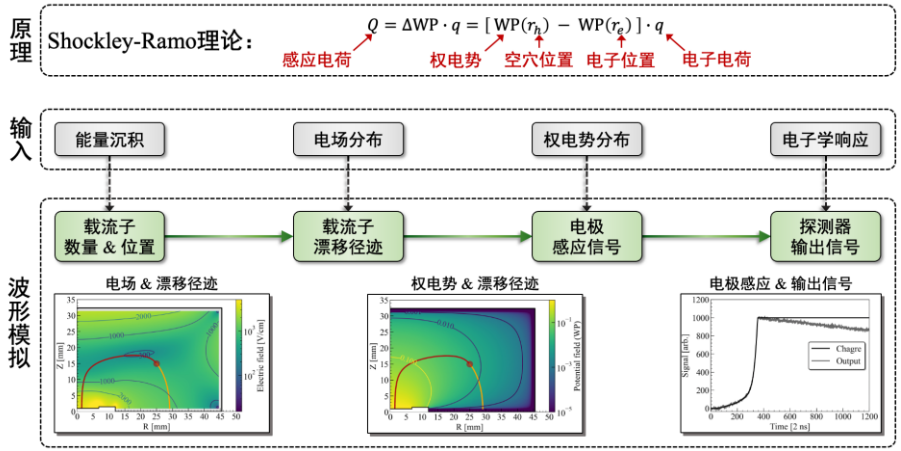
GEANT4 A SIMULATION TOOLKIT

ROOT Data Analysis Framework

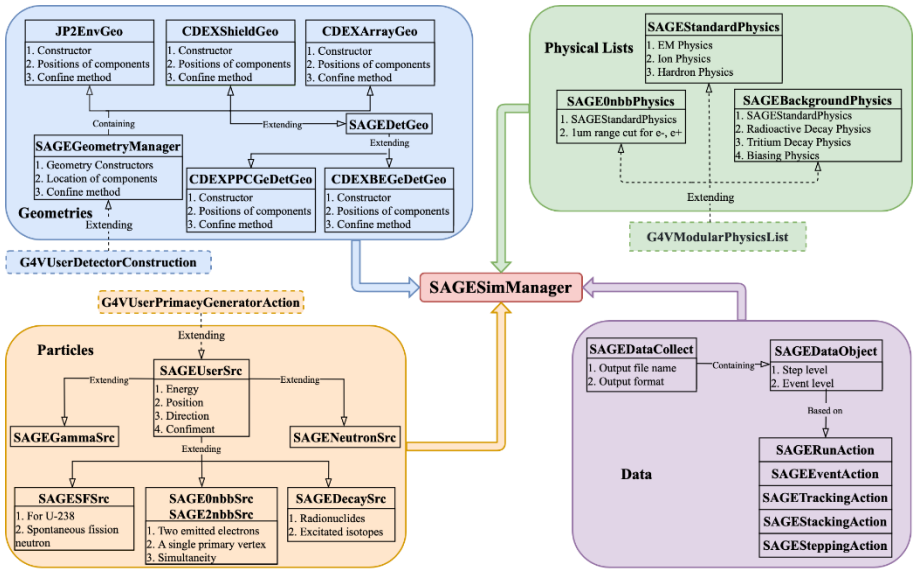
python

C++

Pulse shape simulation for HPGe



Particle simulation for HPGe experiment



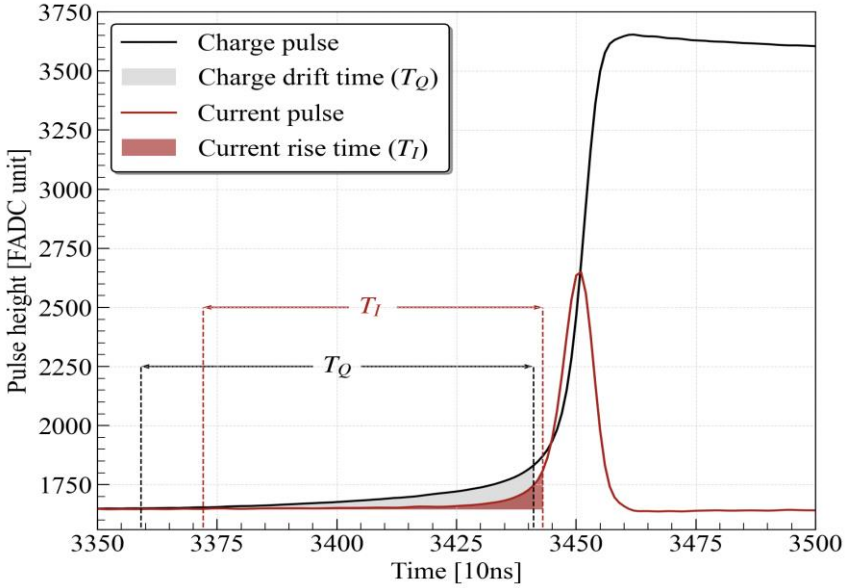
New PSD method for Background suppression

- **Virtual Segmentation of a single-readout PCGe**

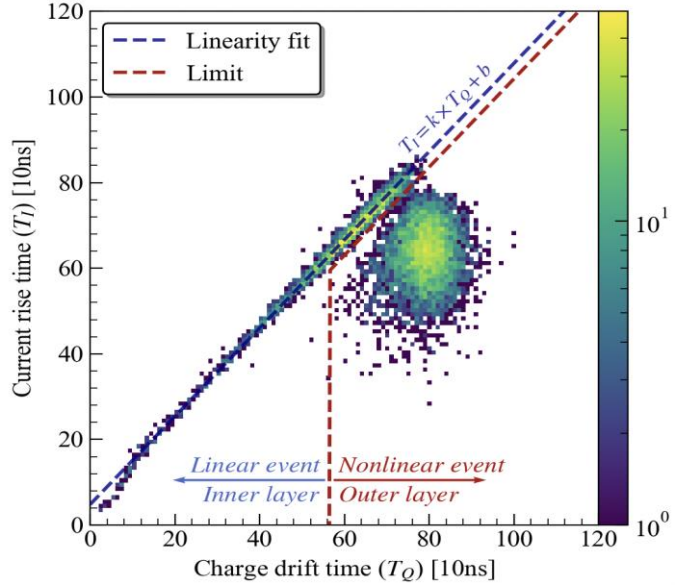
Eur. Phys. J. C (2024) 84:294

- ✓ Infer single-site events (SSEs) position by rise time analysis
- ✓ Determine inner layers volume by Th-228 scanning
- ✓ **Suppress surface background in the search for Ge-76 0νββ decay**

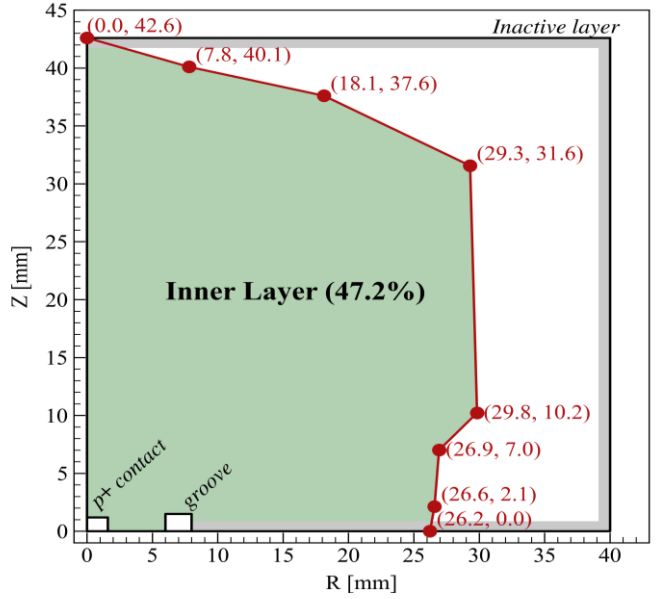
Rise time of charge and current pulse



Identify inner and outer Layer SSE



Virtual Segmentation of a PCGe



CDEX-300v Design

- First stage of CDEX ^{76}Ge 0νββ search project
- Physics goal: **$T_{1/2} > 10^{27}$ yr, $\langle m_{\beta\beta} \rangle$: 28.5-68.0 meV**

$$T_{1/2}^{0\nu} \propto \underline{\varepsilon} \cdot \underline{A} \cdot \sqrt{\frac{\underline{M} \cdot t}{\underline{b} \cdot \underline{\sigma}}}$$

- Technical route:

Enriched Ge Array

- ✓ Enriched ^{76}Ge (A)
- ✓ ~ 225kg Ge (M)
- ✓ Energy resolution (σ)

+

LAr veto + LN_2 shield

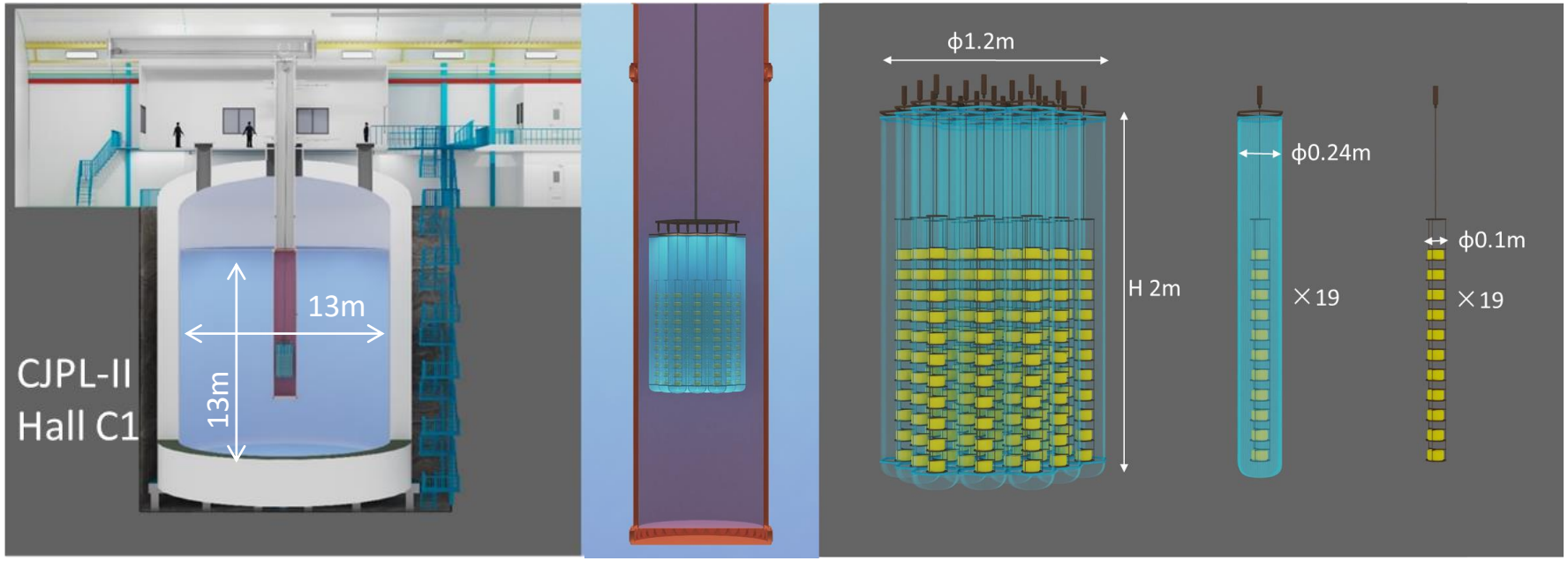
- ✓ LAr as active shield
- ✓ LN_2 as passive shield

+ **Material bkg control**

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

CDEX-300v Design

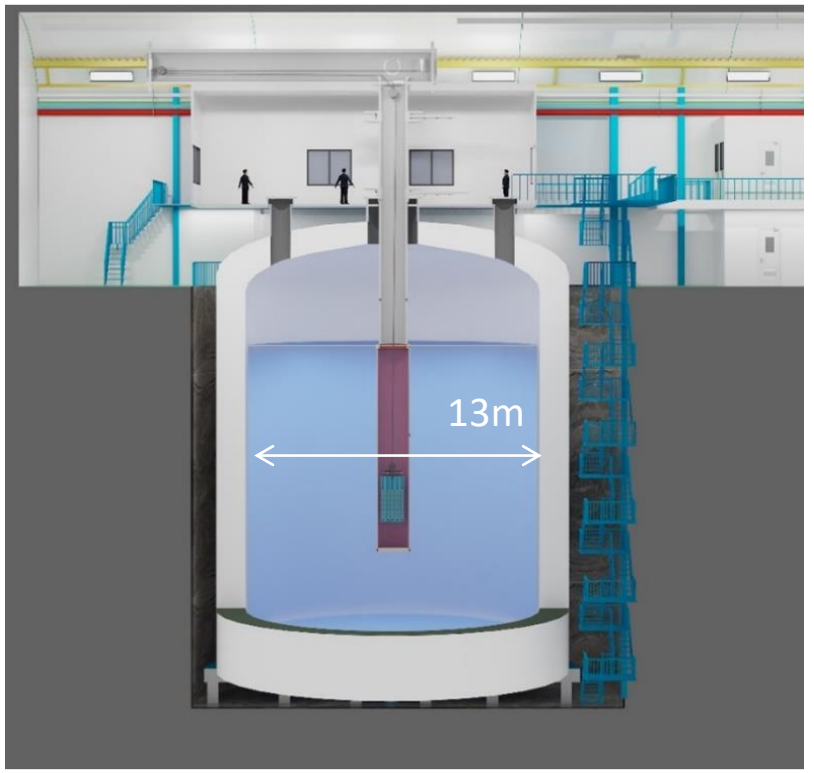
- LN_2 tank in Hall C @ CJPL-II
- Reentrant tube containing LAr submerged in LN_2
- Ge detector array immersed in LAr (veto) tube
- Ge detectors divided into 19 strings (10-11 det/string, 200 in total)



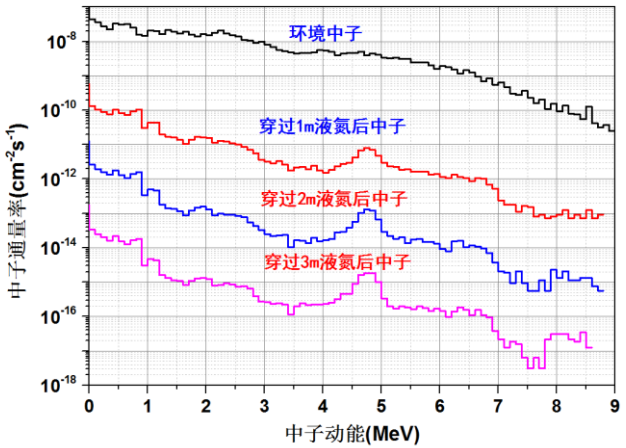
1725 m^3 Liquid Nitrogen | LAr tube | Enriched Ge array

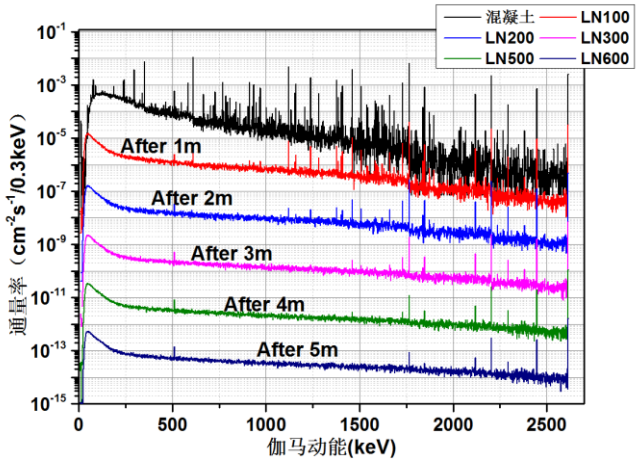
The large LN_2 tank

- Total volume: 1976m^3
- LN_2 volume: ϕ13m×H13m, **~1725 m^3**
- LN_2 as Passive Shield & Cryogen
- Five top flanges for detector deployment
  - 1×ϕ1.5m, centrally (CDEX-300v)
  - 4×ϕ750mm, on a 6m-diameter circle
- >4m LN_2 shields most bkg from surroundings



1725 m^3 Liquid Nitrogen

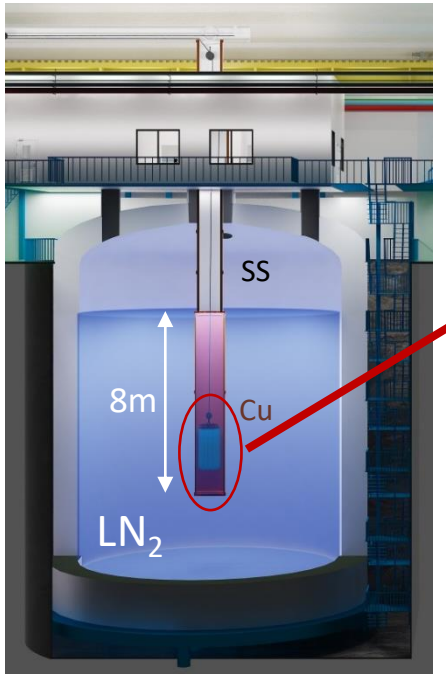




CDEX-300v LAr System (1)

Baseline Design:

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



- ✓ purification system
- ✓ circulation system
- ✓ readout system

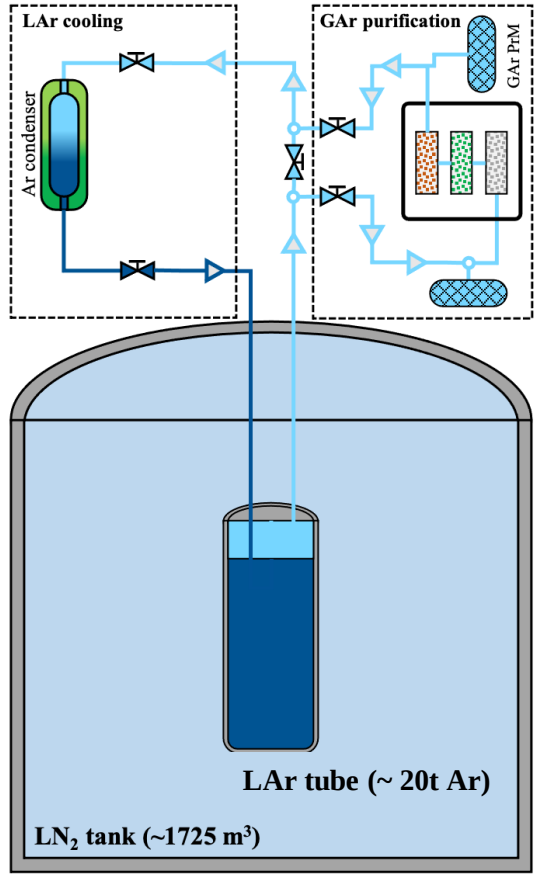
CDEX-300v LAr System (2)

LAr Purification:

- Removing O_2 / H_2O / N_2 from GAr (~10ppb impurity)
- Maintaining high light yield & transmission length
- Removing Rn by active carbon (~μBq/m^3)
- Possible underground Argon (Ar-42 depleted)

LAr Cooling:

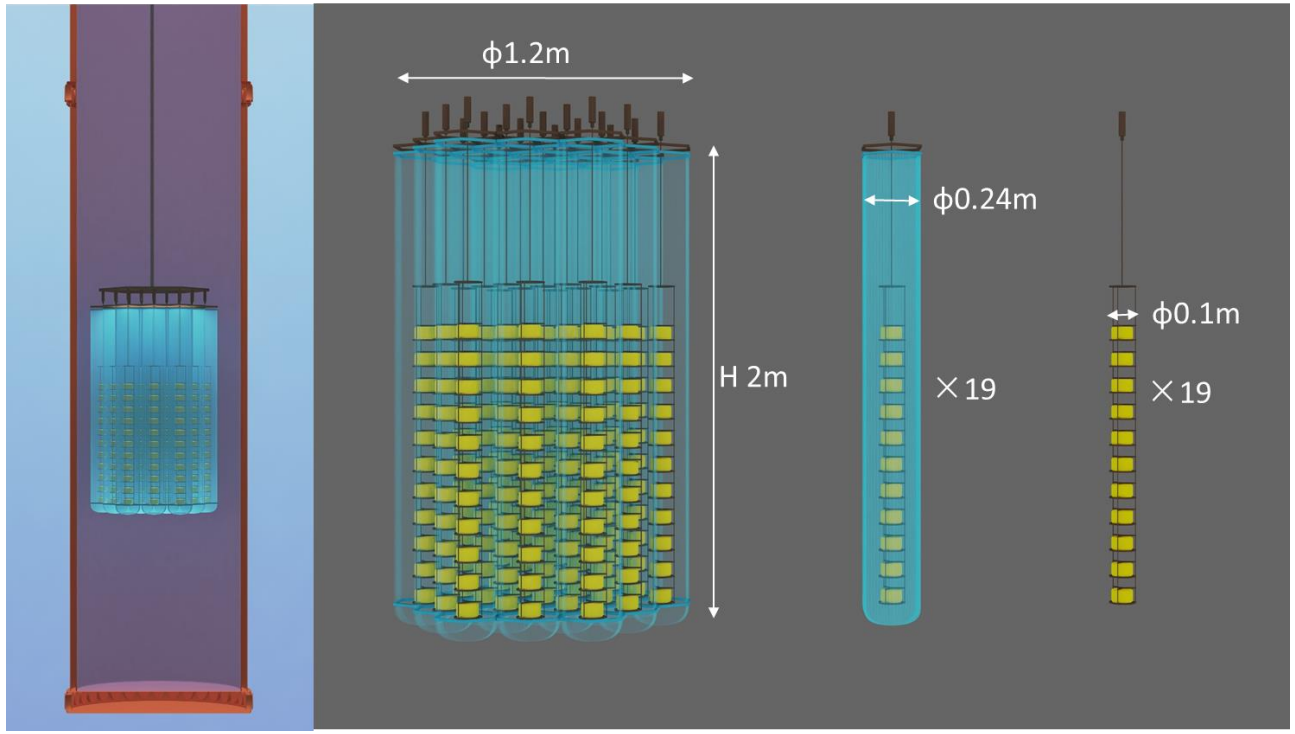
- Cooling purified GAr to LAr
- Heat exchanger + electrical condenser
- Backup LN_2 cooling module



CDEX-300v LAr System (3)

LAr Scintillation Light Readout

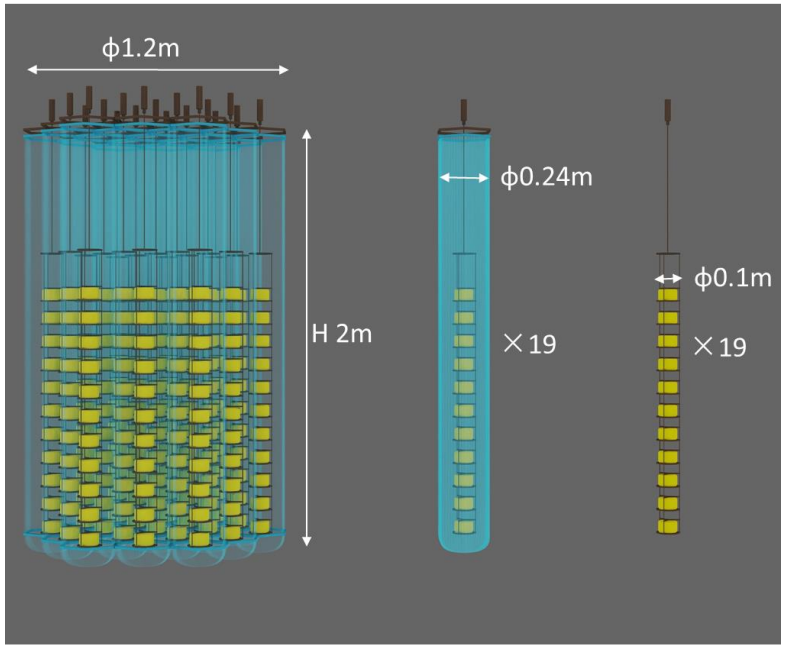
- Detector strings surrounded by fiber curtains to collect light
- Read out via top SiPM/PMT

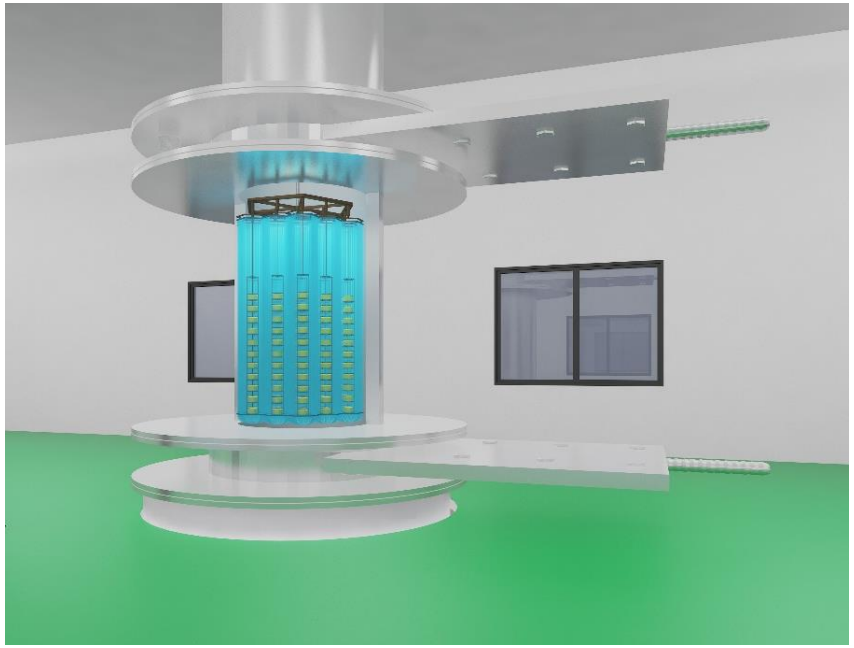


Ge detector Array

Baseline Design:

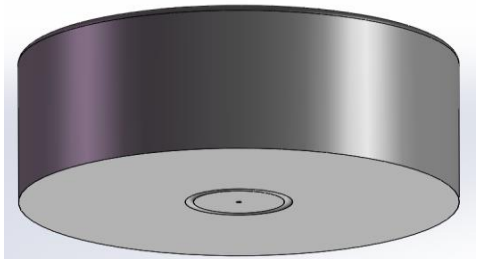
- 200 Ge detectors, 19 strings, 10-11 det/string
- Total mass of Ge detectors: **~225kg**
- Top clean room for Ge detector and fiber installation



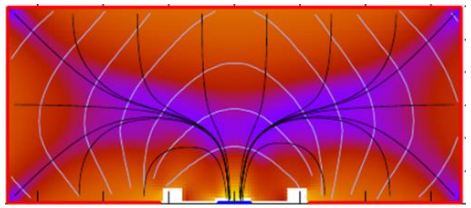


Ge Detectors

- **Enriched BEGe (Baseline)**
  - Mass: ~1.12 kg； Ge-76 > 86%
  - Size: ϕ80×40 mm
  - Dead layer: 0.6 mm
  - FWHM : <0.15% @2MeV (~2.5keV)
  - Commercial / Home-made

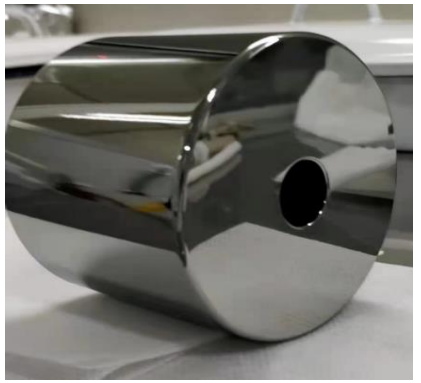


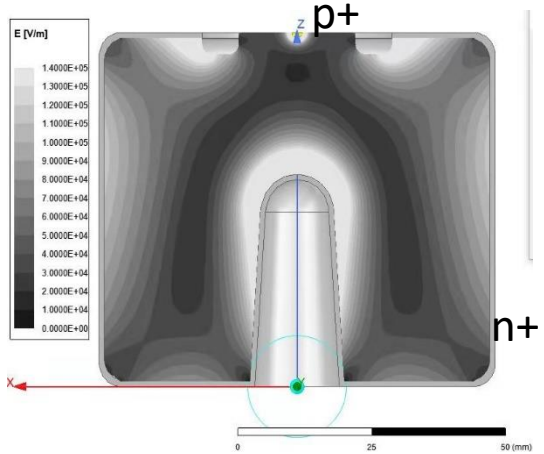
BEGe: Broad Energy Germanium



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

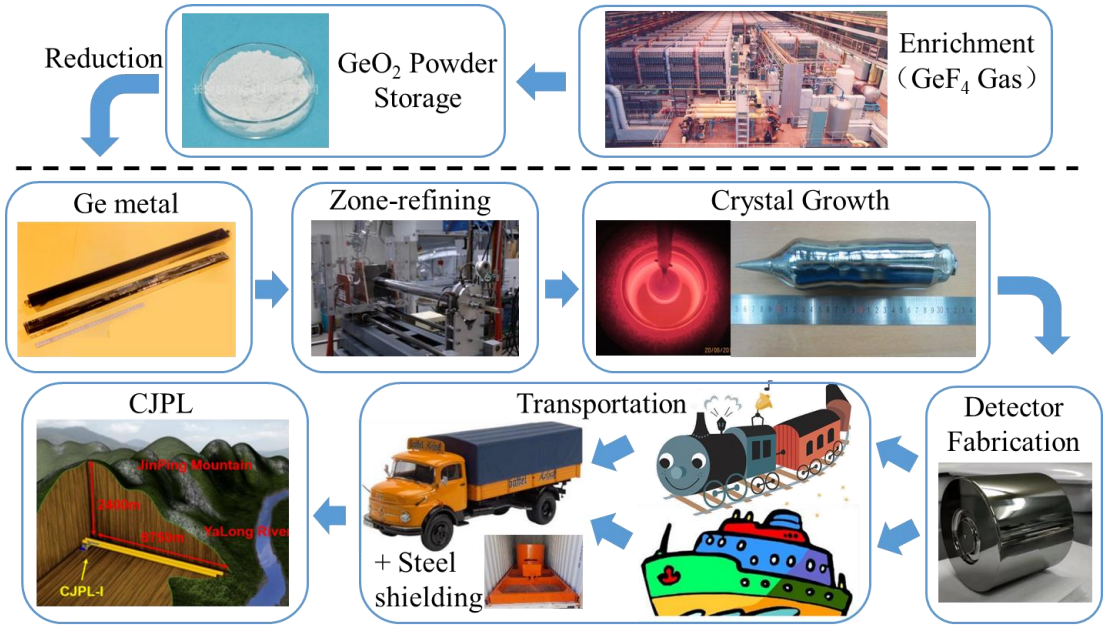
ICPC: Inverted Coaxial Point Contact





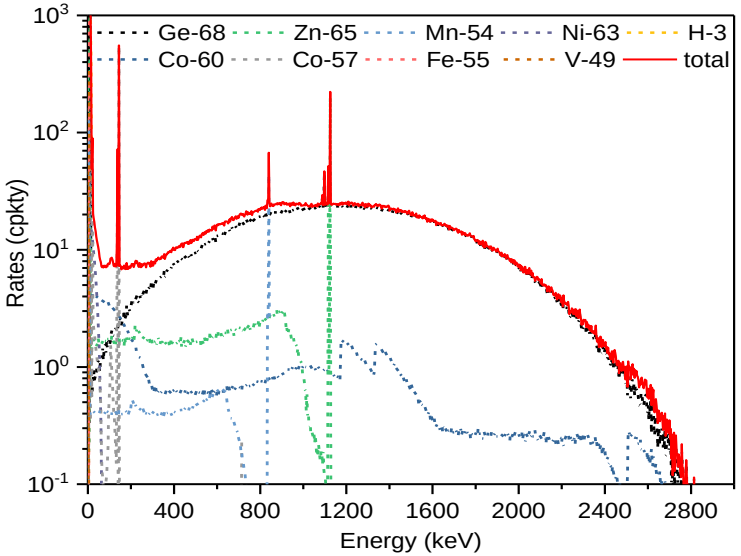
Enriched Ge material

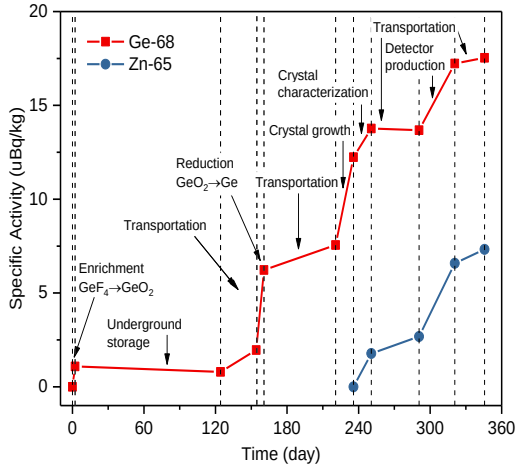
- 200kg ^{76}Ge (>86%) arrived, half from Russia and half from China
- Whole technical chain established
- The mass production power (hundreds of kg per year) of enriched ^{76}Ge material has been setup in China and it is an important contribution to international ^{76}Ge 0νββ experiment community

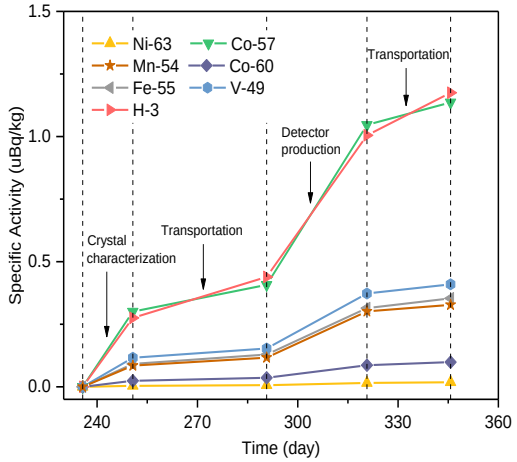


Cosmogenic Background Control

- **Main BG in 0νββ ROI:**
  - Ge-68 (T=270.9 d) & Co-60 (T=1925.5 d)
- **After 3 years of cooling in CJPL:**
  - Cosmogenic BG: 6.1E-3 cpkky @2 MeV ROI
  - 96% from Ge-68







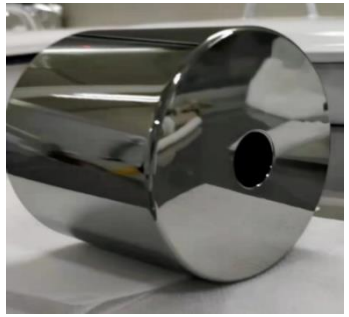
JINST 19:P03002, 2024

Detector R&D

- **Home-made Ge detector**
  - Co-axial/BEGe/PPC/ICPC
  - Cold finger/Naked immersion

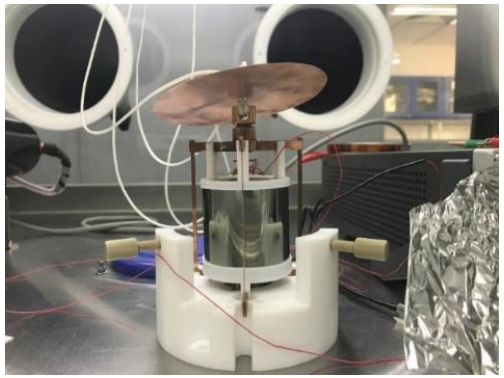
BEGe

PPC

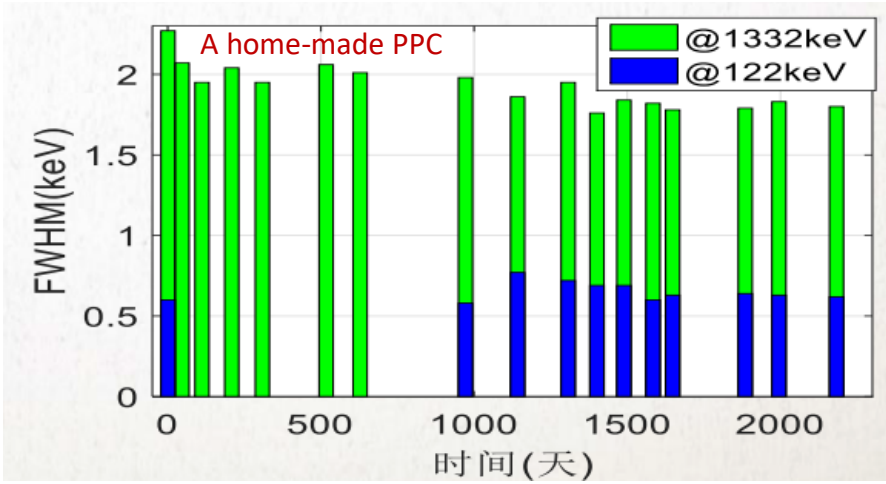


ICPC

Cold finger cooling



Naked crystal to LN_2

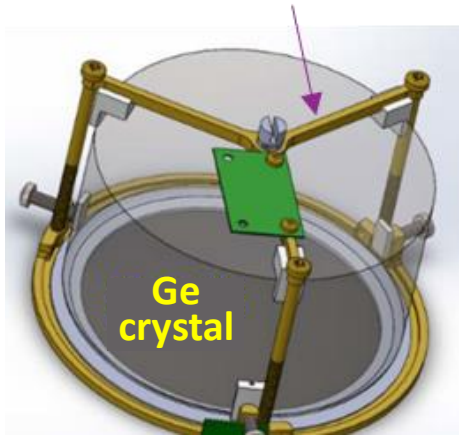


Long-term stability: energy resolution

Material Background Control

All materials to be screened and selected

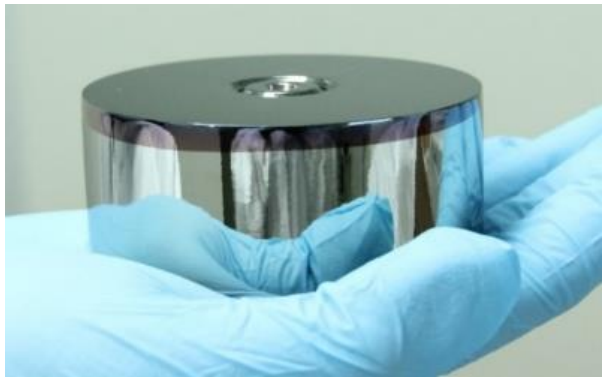
- **Ge detector & FEE:**
  - Mitigation of cosmic activation on the ground
  - Low mass & pure detector structures
  - Low background cables or flexible PCB
  - CMOS ASIC Front-end Electronics
  - Underground fabrication of Ge detectors
- **Underground Electro-forming copper**
  - U/Th activity <10 μBq/kg
  - Free of cosmogenic radioactivity



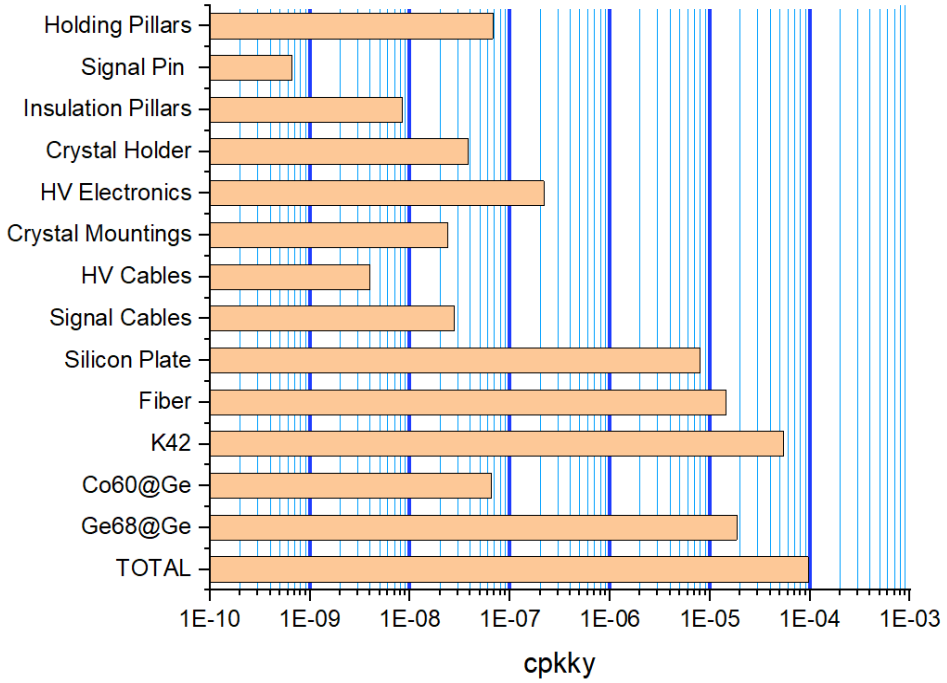
Th/U: ~1.6/10.7 μBq/kg

CDEX-300v Background Model and Simulation

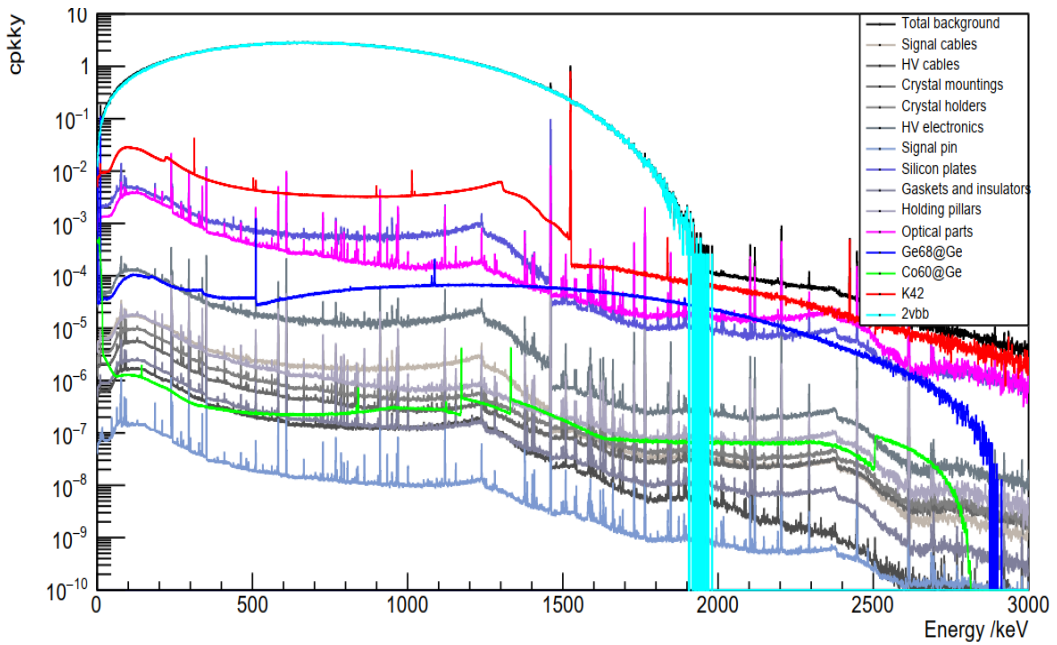
- Detector prototype: BEGe / ICPC
- Energy resolution: 0.12% FWHM@2.039MeV
- Background Index: 1×10^{-4} cts/(keV·kg·year)@$Q_{\beta\beta}$



CDEX-300v background model



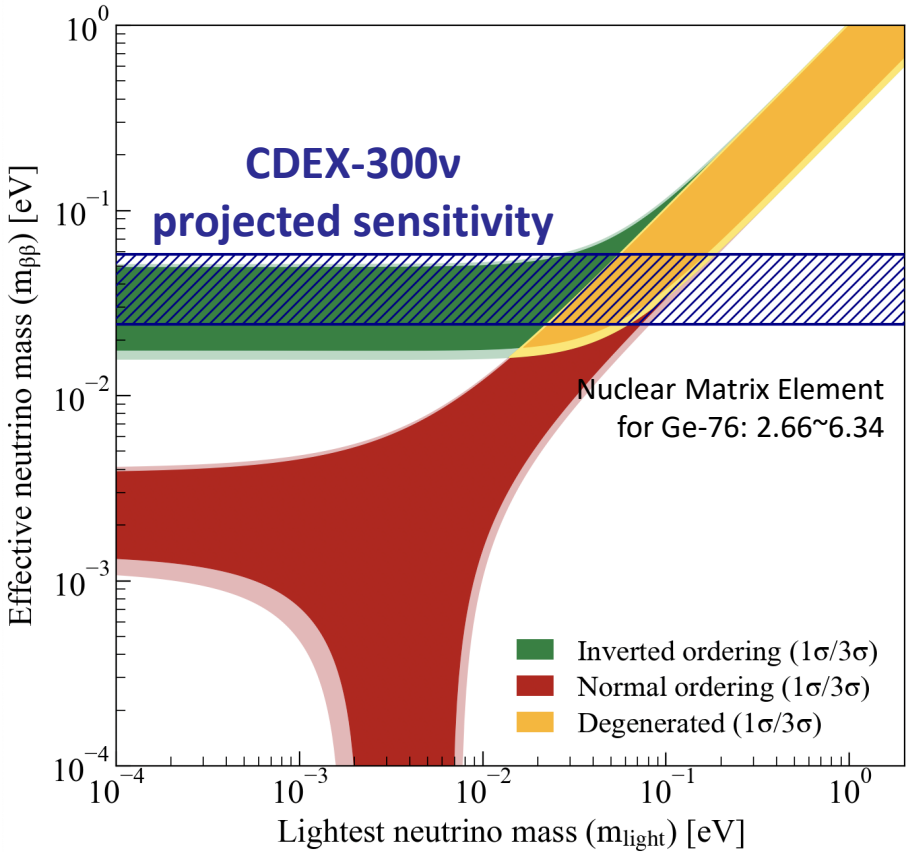
CDEX-300v background model



CDEX-300v projected results

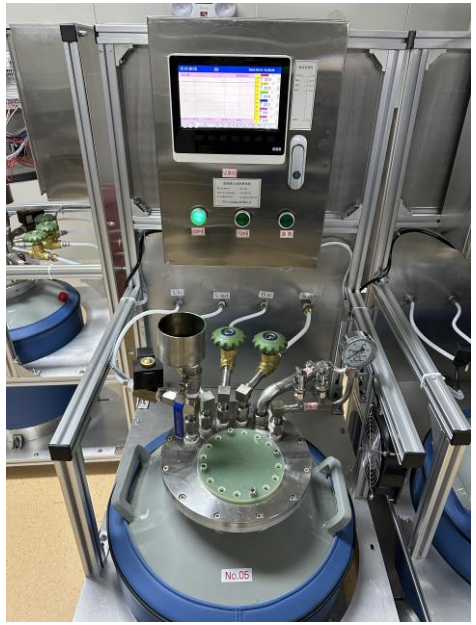
- Construction time: 2021-2027, Run time: 2028-2032 (5 years)
- An exposure for ^{76}Ge 0νββ: >1t·y, $T_{1/2} > 10^{27}$y

Parameter	CDEX-300
detector mass	225 kg
Ge-76 enrichment	>86%
BI@2039keV	10^{-4} cpkky
E_R@2039keV	2.5 keV (FWHM)
Run time	5 yr
Exposure	1.125 t·y
$T_{1/2}$	>1×10^{27}y
$m_{\beta\beta}$	28.5~68.0 meV



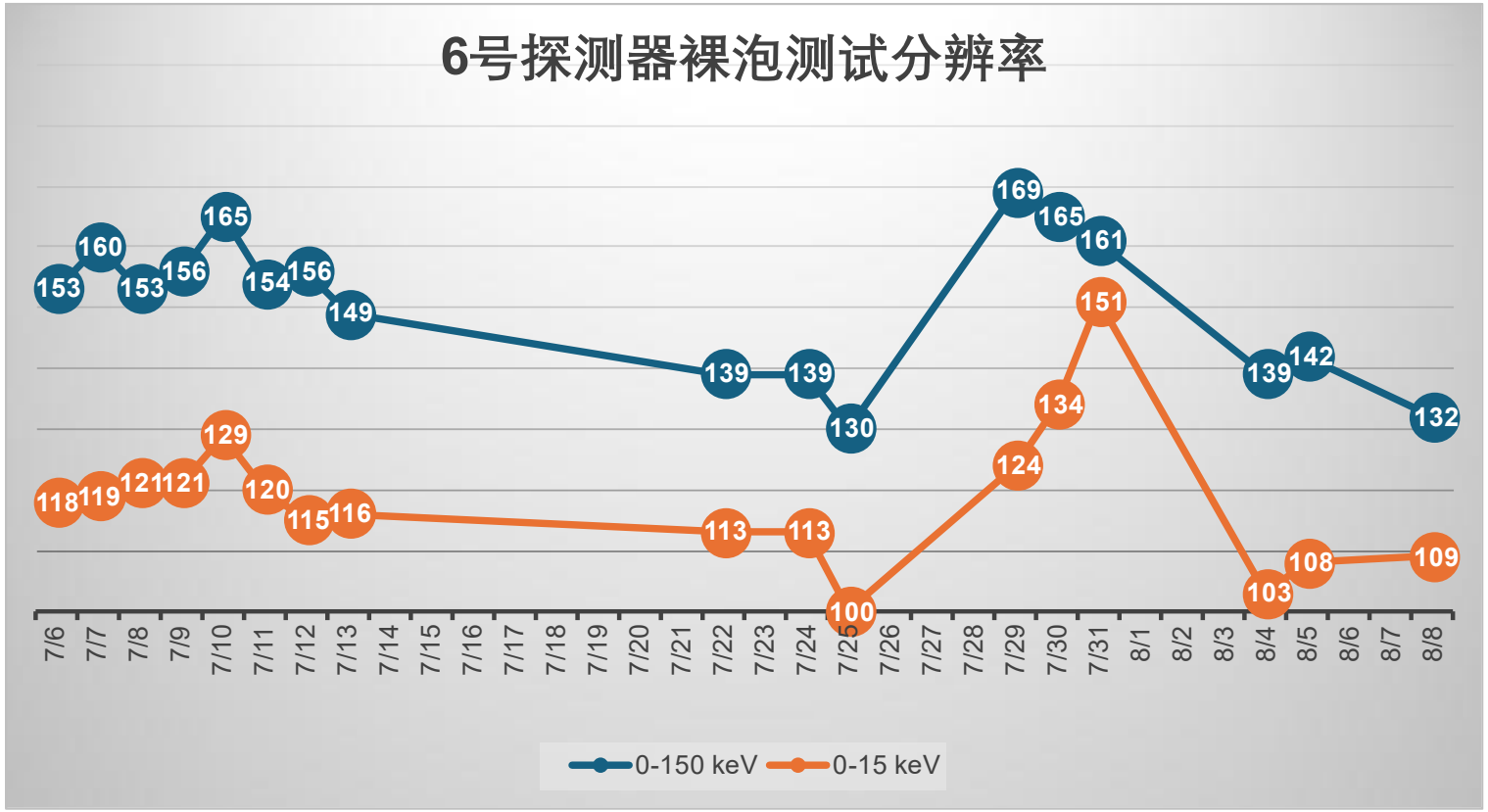
CDEX-300v status

- Hall C1 is ready for experiment this June
- First batch of Enriched Ge detector test in 2024
- Second batch of Enriched Ge detector test is ongoing
- Ge det. array structure being assembled and tested



CDEX-300v status

- Energy resolution meets the design criteria
- Achieve long-term steady operation in LN2



Detector	FWHM with pulser	
	@0-15 keV	@0-150keV
00	94 eV	116 eV
01	104 eV	145 eV
02	108 eV	120 eV
03	119 eV	138 eV
04	107 eV	135 eV
05	104 eV	139 eV
06	119 eV	141 eV
07	113 eV	149 eV
08	111 eV	146 eV
09	112 eV	136 eV
10	117 eV	140 eV

CDEX-300v status

- Construction of LN2 tank completed at end of 2019
- 3 copper tube inside LN2 tank constructed in November, 2024
- 1725 m^3 Liquid nitrogen filling complete this June

CJPL-II C1 hall

LIN tank

Clean room above LIN tank

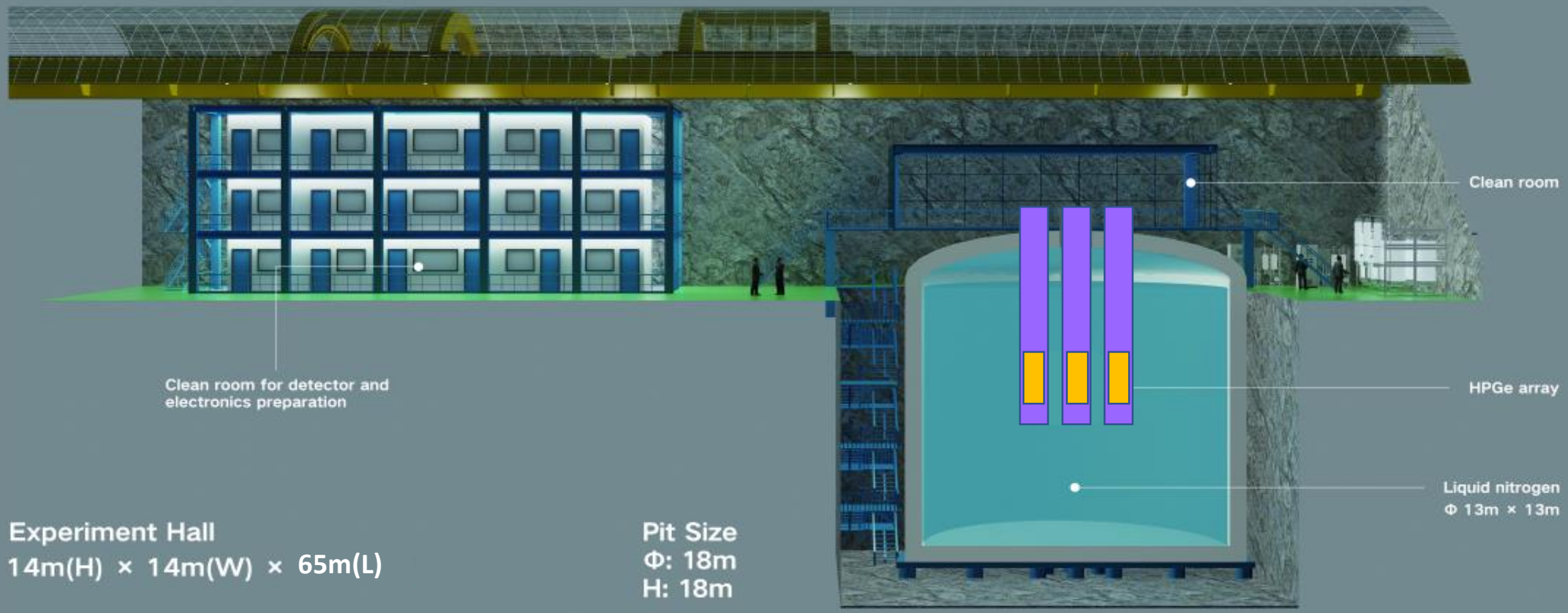
CDEX-300v status

- Construction of LN2 tank completed at end of 2019
- 3 copper tube inside LN2 tank constructed in November, 2024
- 1725 m^3 Liquid nitrogen filling complete this June

CDEX-1T and CDEX-10T Conceptual Layout

中国暗物质实验
China Dark matter EXperiment

中国锦屏地下实验室
China Jinping Underground Laboratory
CJPL
清华大学 · 雅砻江流域水电开发有限公司



Experiment Hall
14m(H) × 14m(W) × 65m(L)

Pit Size
Φ: 18m
H: 18m

The physical goals of CDEX-1T and CDEX-10T

- **CDEX-300 → CDEX-1T:**

  ULAr/pure materials/Short-time Ground crystal handling…
- **CDEX-1T → CDEX-10T:**

  Sealed Ge crystal or Solid Ar/**Crystal and detector at CJPL**…

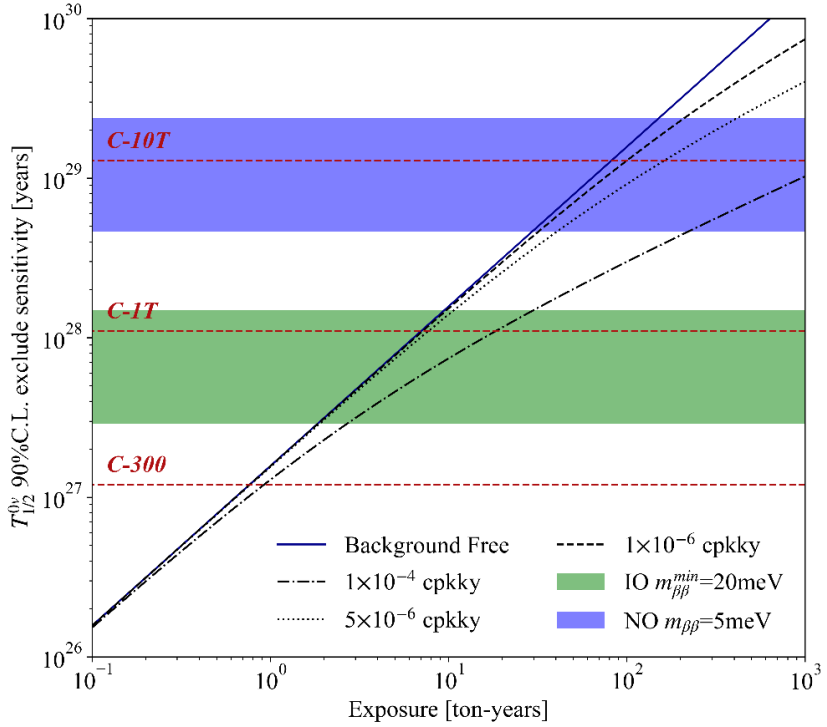
Parameter	CDEX-300	CDEX-1T	CDEX-10T
Detector mass	225 kg	1000 kg	10000 kg
BI@2039keV	1×10^{-4} cpkky	5×10^{-6} cpkky (**20 times lower**)	1×10^{-6} cpkky (**5 times lower**)
Run time	Construction 5yr Run 5yr	Construction 5yr Run 5yr	Construction 5yr Run 10yr
Exposure	>1 t·y	5 t·y	100 t·y
$T_{1/2}$	$>1.0\times10^{27}$y	$>1.0\times10^{28}$y	$>1.0\times10^{29}$y
$m_{\beta\beta}$	<[28.5~68.0] meV	<[11.6~26.4] meV	<[2.9~6.7] meV

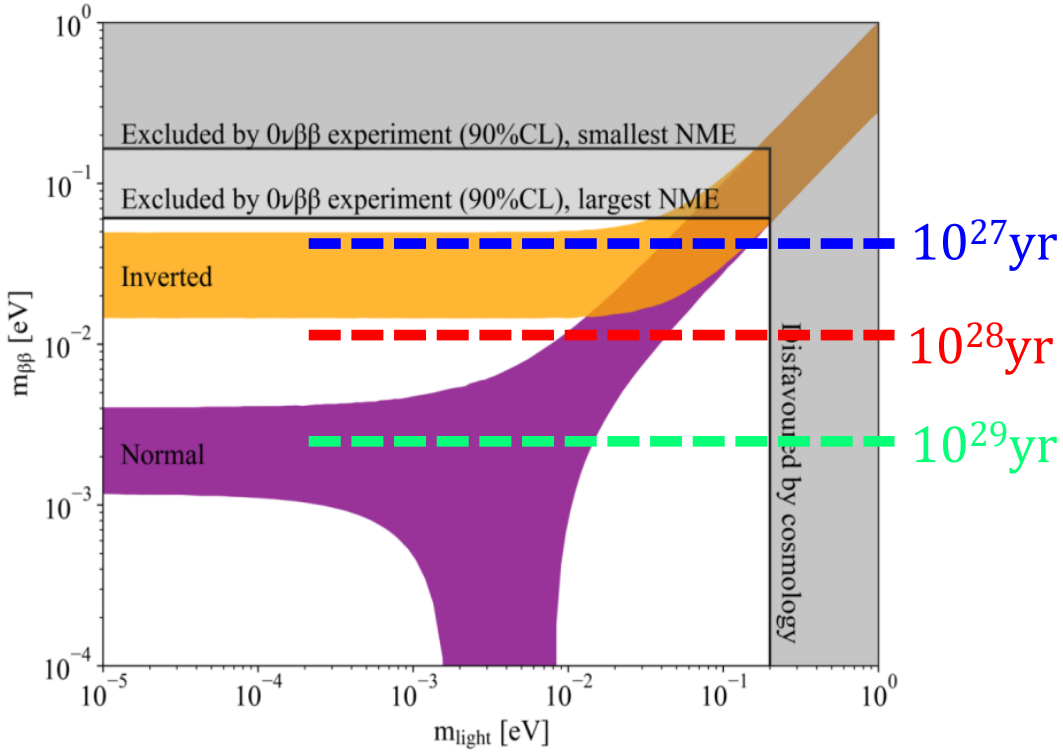
The physical goals of CDEX-1T and CDEX-10T

- **CDEX-300 → CDEX-1T:**

  ULAr/pure materials/Short-time Ground crystal handling…
- **CDEX-1T → CDEX-10T:**

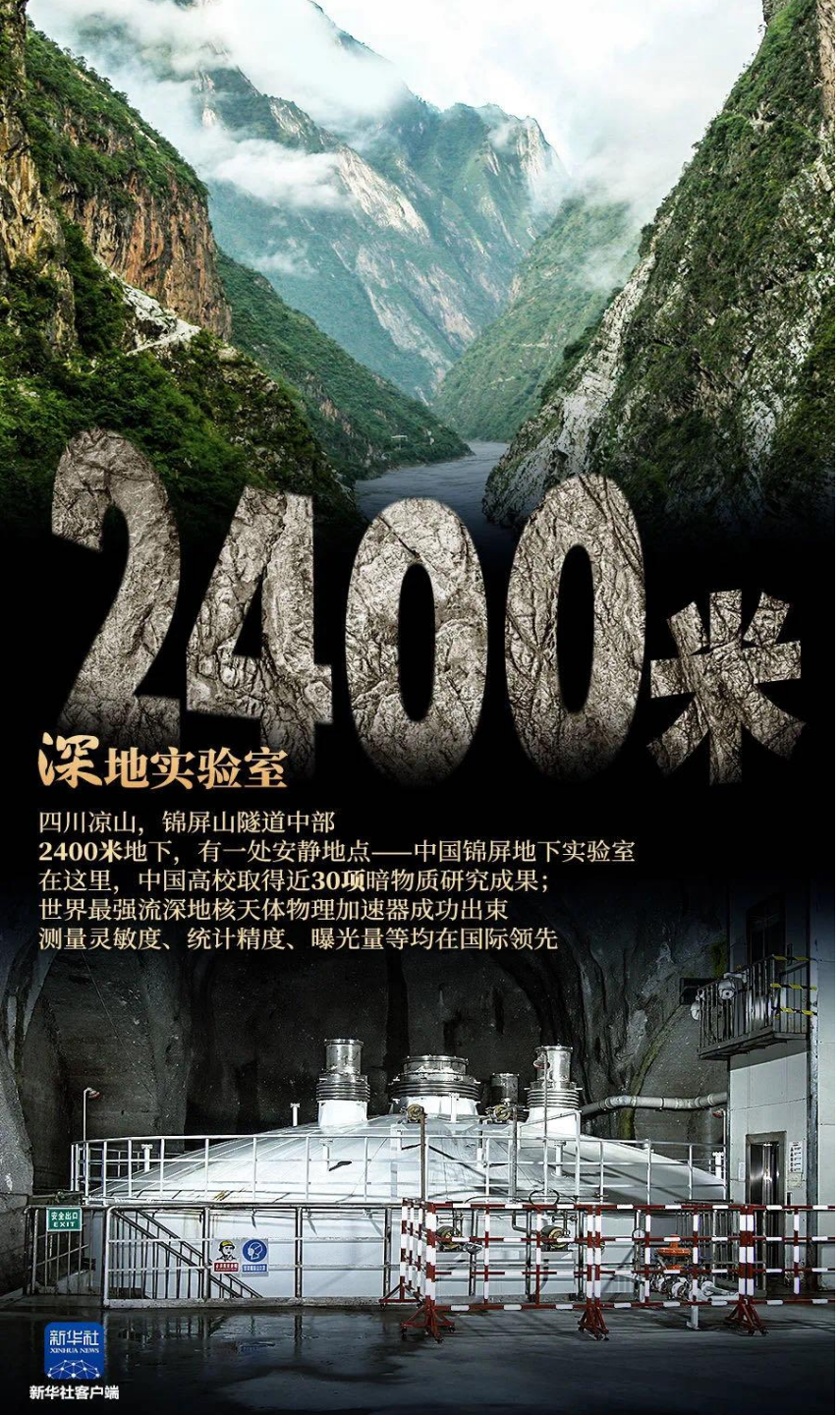
  Sealed Ge crystal or Solid Ar/**Crystal and detector at CJPL**…





Summary

- Searching for $0\nu\beta\beta$ decay plays an essential role in understanding the nature of neutrinos
- CDEX-300v for ^{76}Ge $0\nu\beta\beta$
  - 225kg enriched Ge detector system at CJPL-II
  - physics goal : $T_{1/2}>10^{27}$ yr; $m_{\beta\beta}$: 28.5-68.0 meV
  - first enriched Ge detectors array assembled in 2025
- 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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