

Status and prospects of CDEX @CJPL

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On behalf of CDEX Collaboration

International joint workshop on the Standard Model and beyond,

14-17 October 2019, Beijing



PICTP program: New physics beyond the Standard Model

(2019.10.09-10.12)

International Joint Workshop on the Standard Model and beyond

(2019.10.13-10.17)



中国锦屏地下实验室

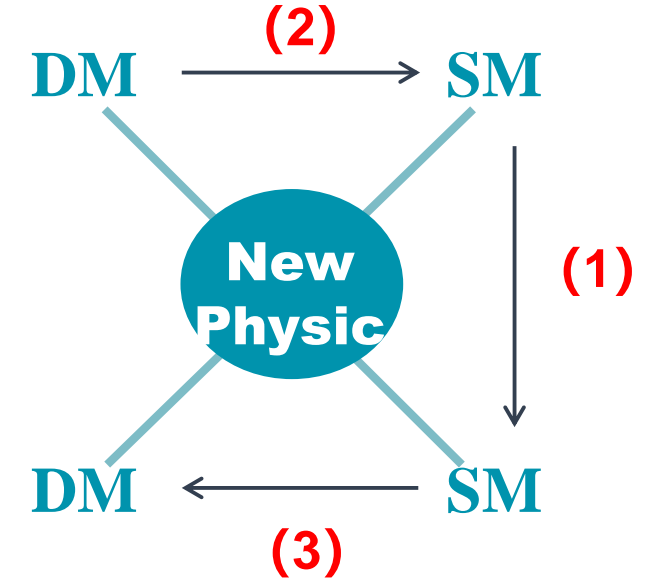
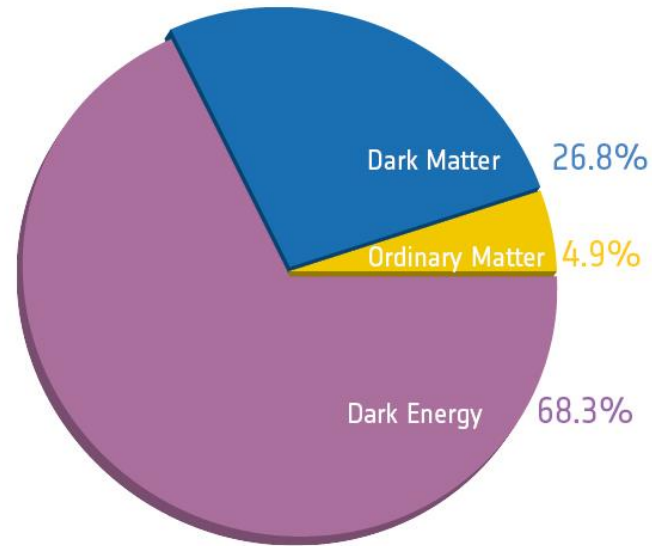
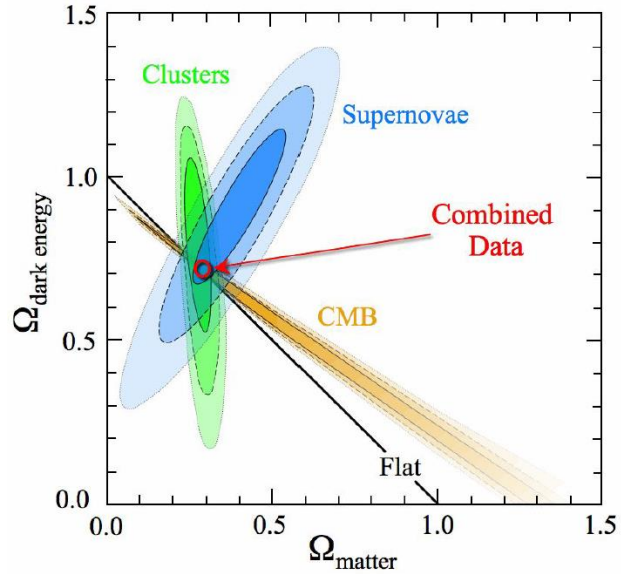
China Jinping Underground Laboratory

清华大学·雅砻江流域水电开发有限公司

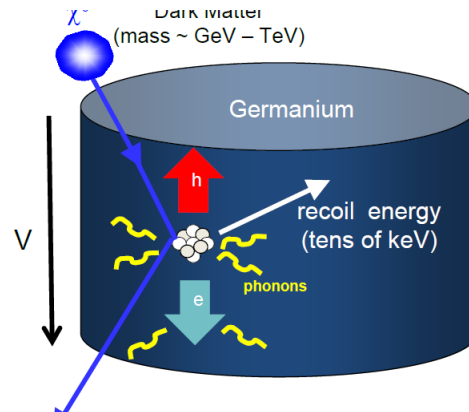
OUTLINE

- Dark Matter (DM) and its Direct detection
- Introduction to CDEX
- Recent status of CDEX-1 and CDEX-10
- R&D of key technologies
- Future plan of CDEX @CJPL-II
- Summary

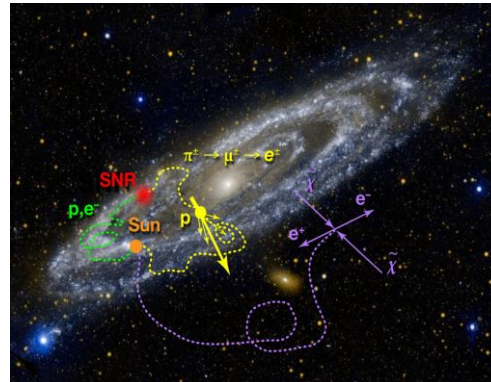
Dark Matter in Cosmology



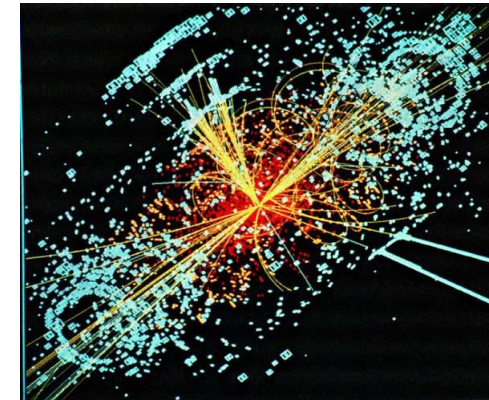
(1) Direct



(2) Indirect

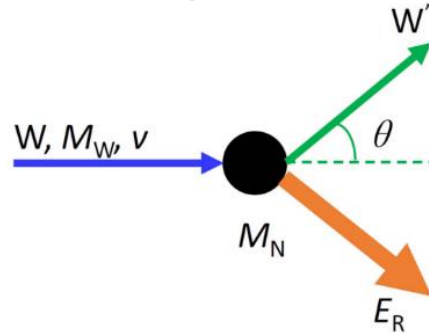


(3) Accelerator

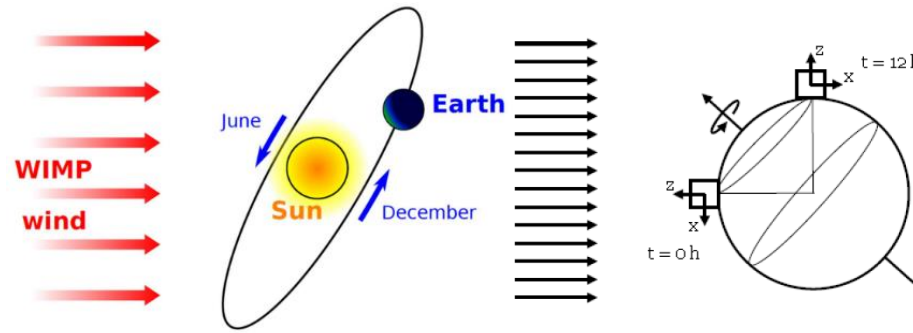


Direct detection of DM---Principle

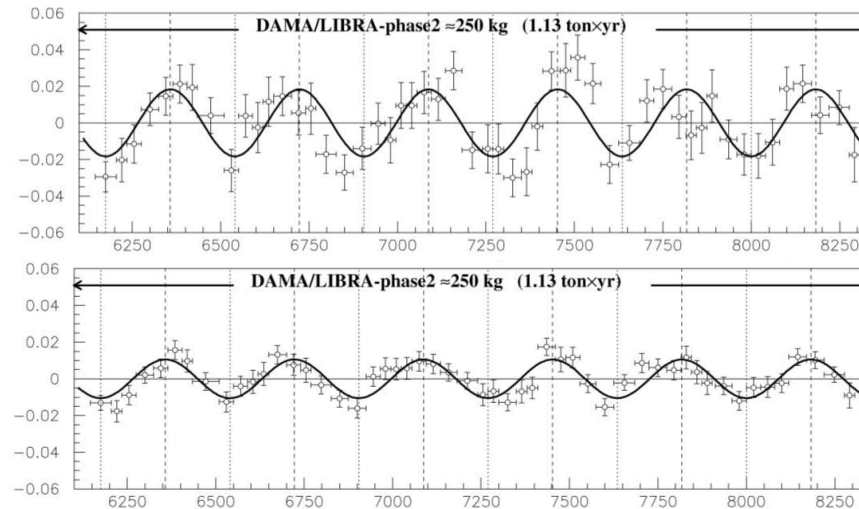
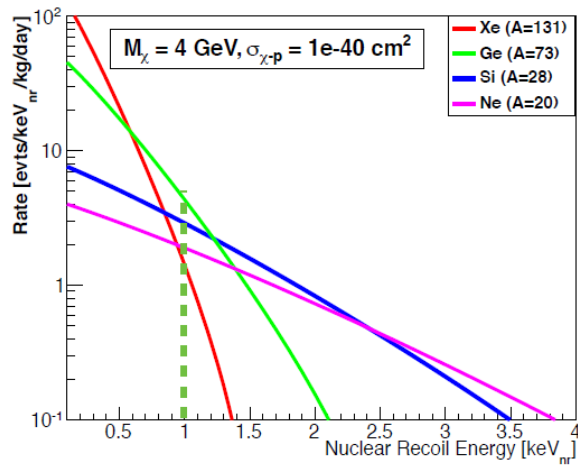
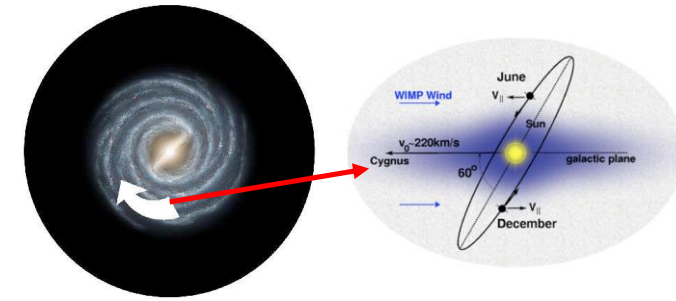
Elastic Scattering



Annual/ Diurnal Modulation

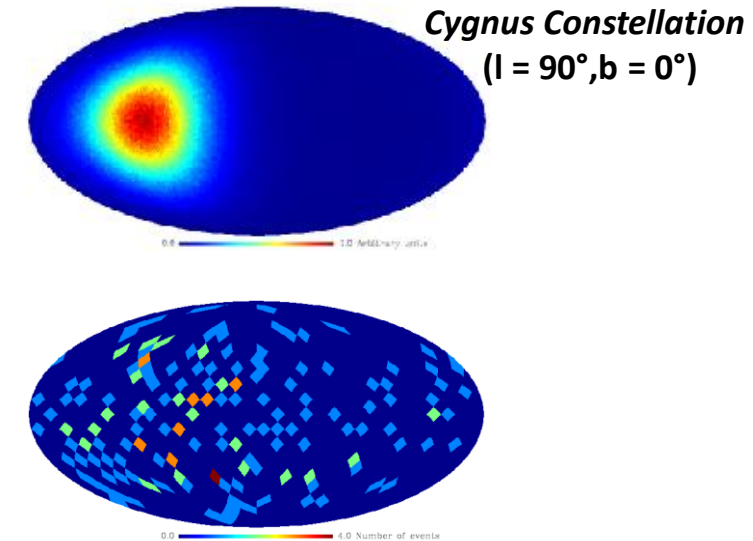


Direction Detection



- ☐ Lower Background
- ☐ Lower Energy threshold
- ☐ Long-time stability

- ☐ Lower Background
- ☐ Long-time stability



- ☐ Angular Resolution (<20°)

China Dark matter EXperiment

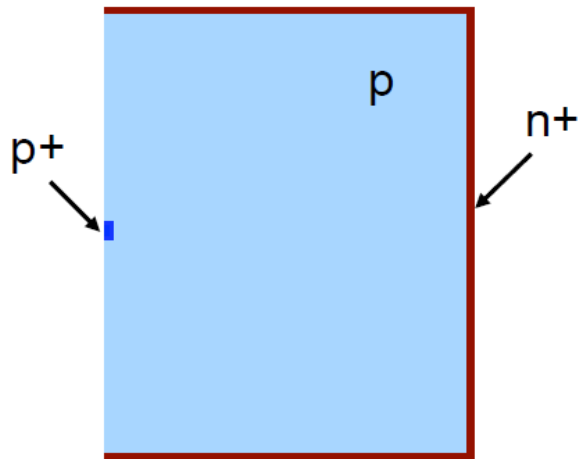
- Formed in 2009, now ~70 scientists and graduate students;
- Direct detection of light DM by P-type Point-Contact (PPC) Ge detectors.



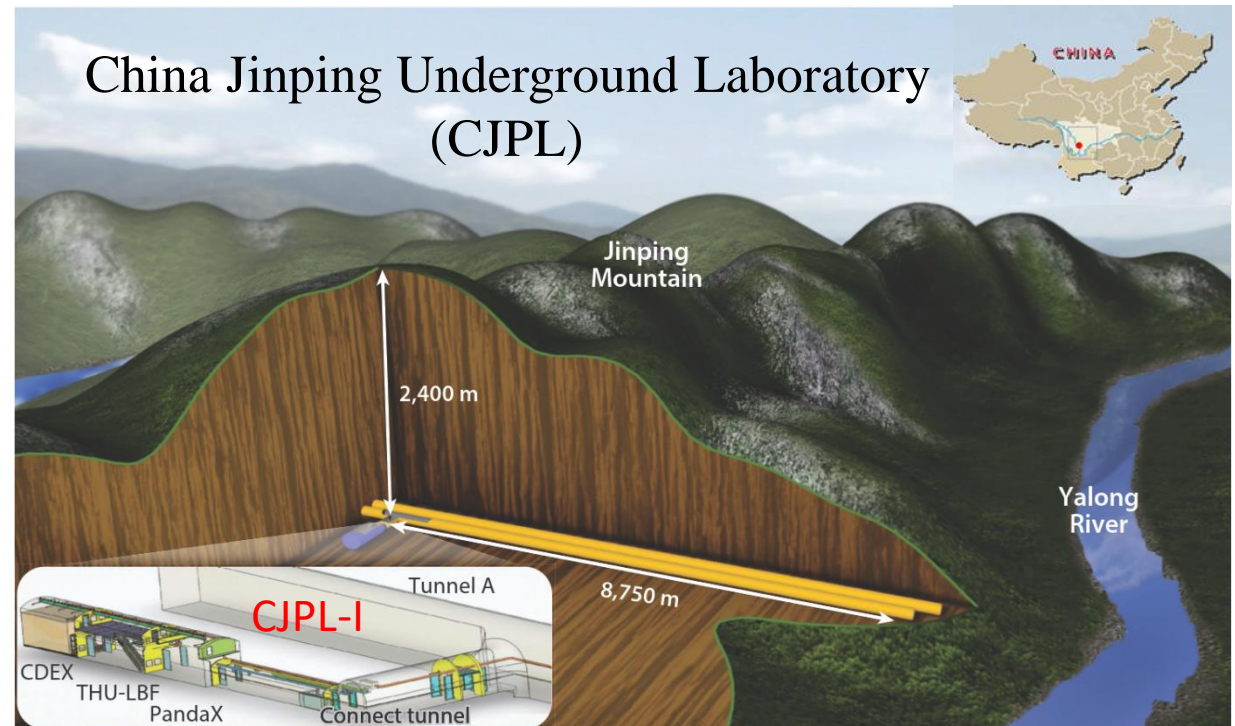
CDEX Stages

- DM detection w/ Ge prepared since 2003 and started in 2005 in Y2L (5g);
- **CDEX-1**: Development of **PPC Ge detector**, bkg understanding, since 2011;
- **CDEX-10**: Performances of **Ge array detector** immersed in LN_2 , since 2016;
- **CDEX-10X**: **Home-made Ge** detector and Ge crystal growth;

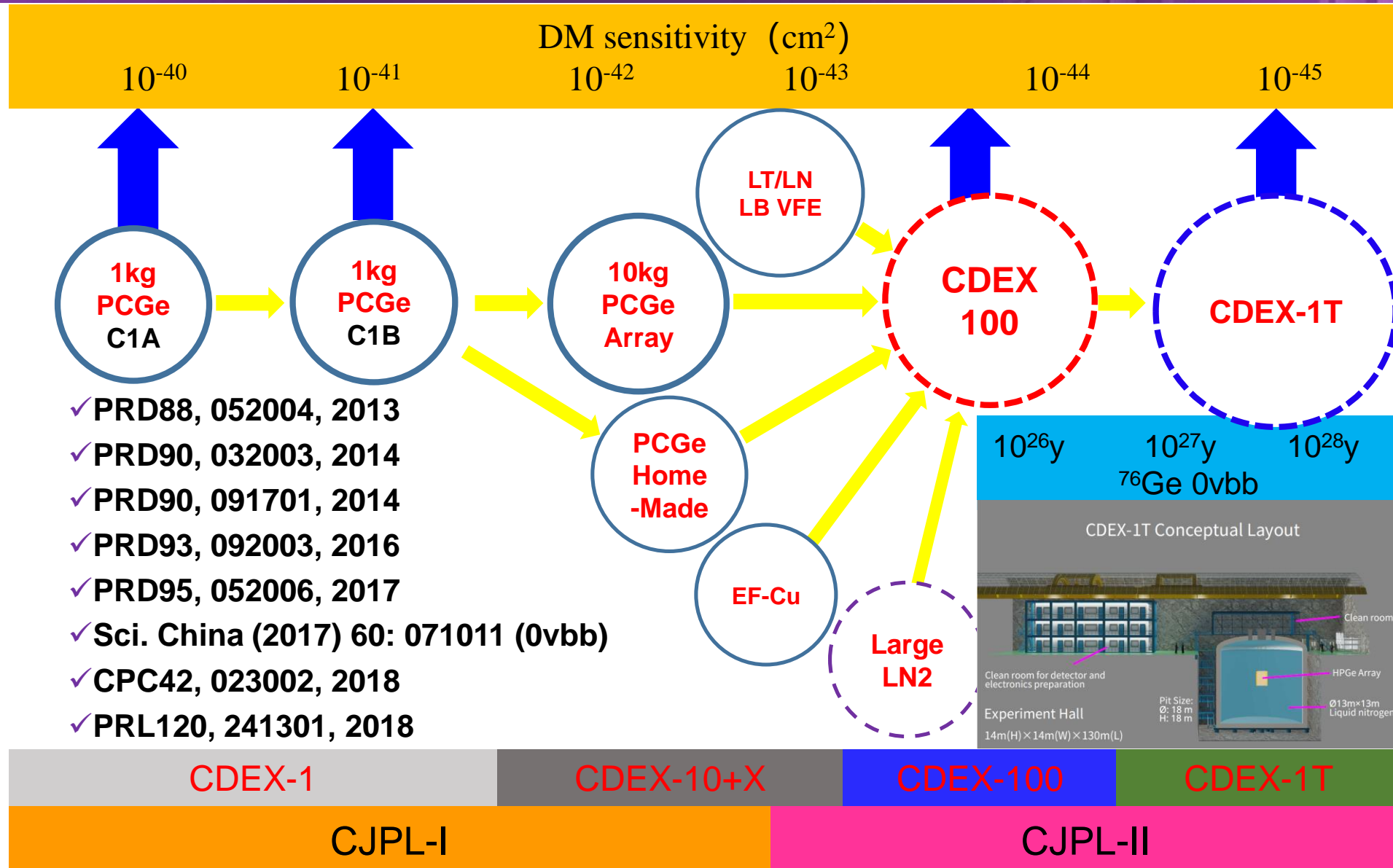
P-type Point-Contact(PPC)
Germanium detector



Direct detection of low-mass WIMPs w/ Ge
detector at CJPL.

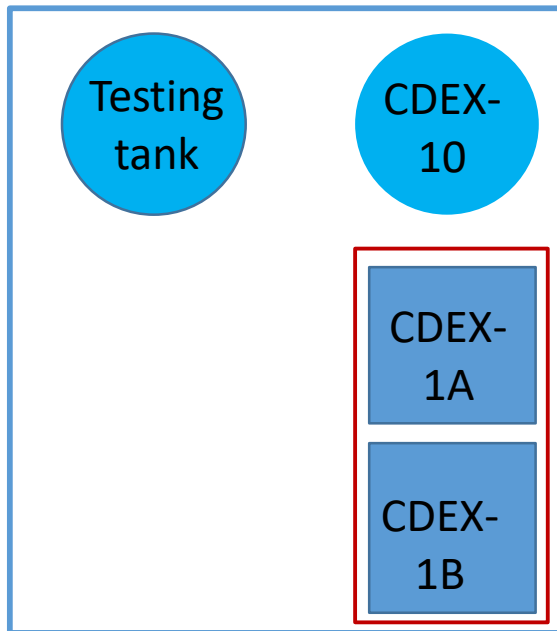


CDEX Roadmap



CDEX-1 stage

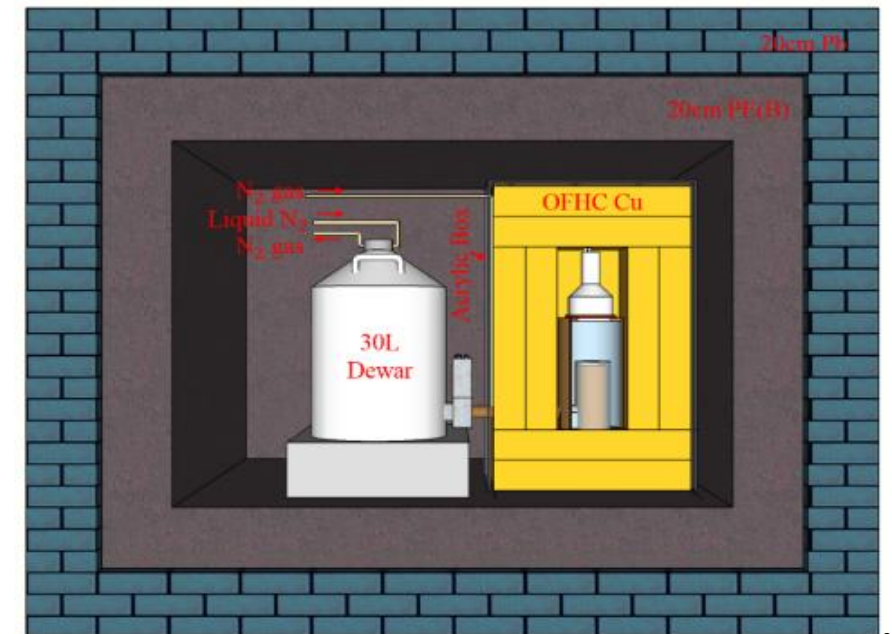
- 2 sub-stages: CDEX-1A(prototype, 2011)→1B(upgraded, 2013);
- Traditional single-element $\sim 1\text{kg}$ PPC Ge detector;
- Low-bkg Pb&Cu passive shield + NaI veto detector;
- Located in PE room at CJPL-I;



Layout of PE room, CJPL-I



CDEX-1 inside PE room



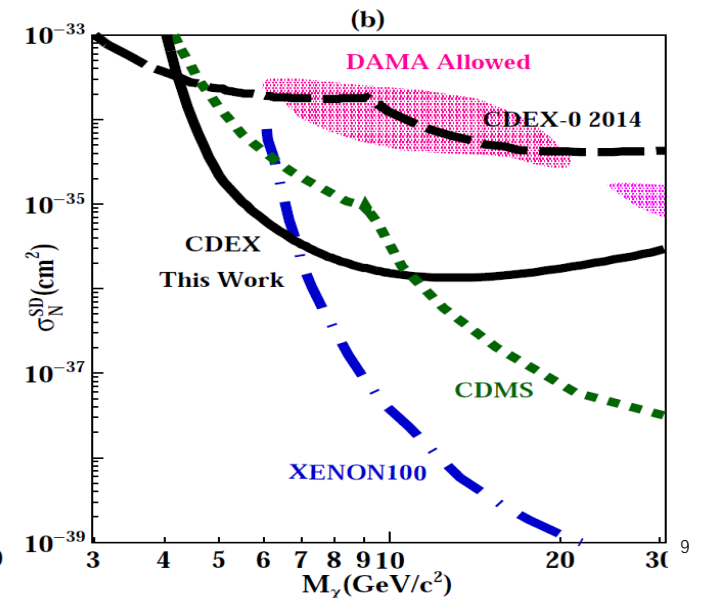
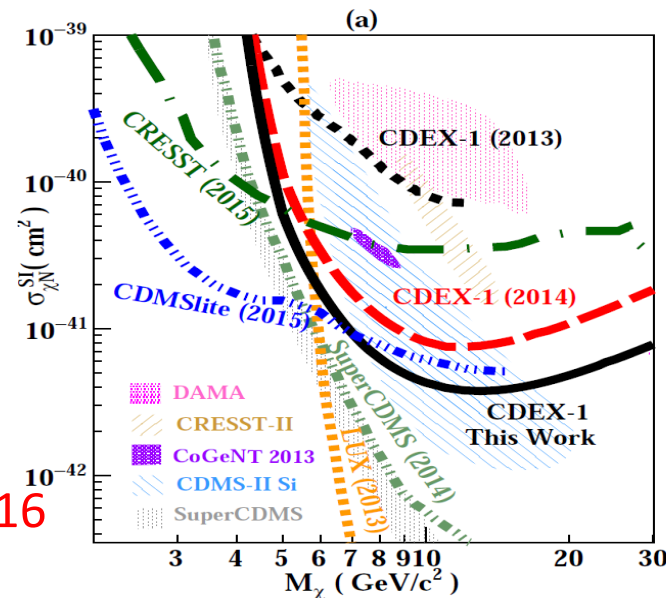
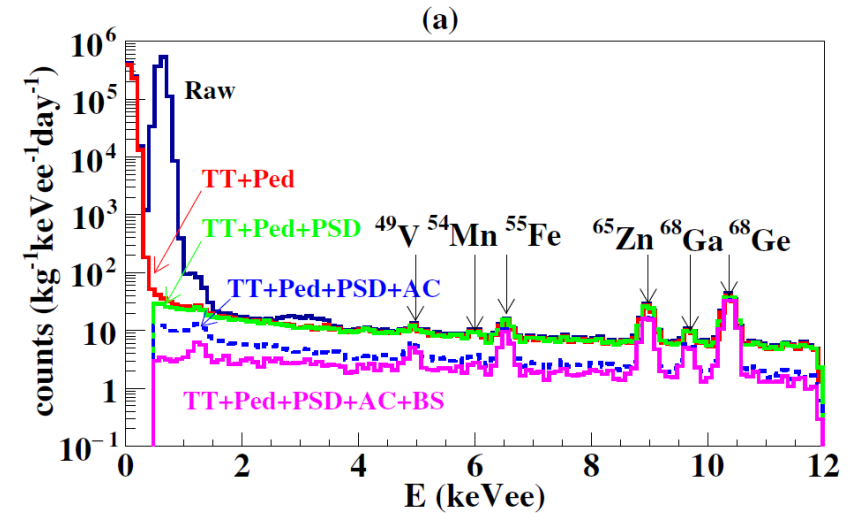
CDEX-1A&B: 1kg PPC Ge \times 2

CDEX-1A Results

- >500 days run, ~336 kg·day dataset;
- Energy threshold: 475 eVee;
- Bulk/Surface disc. to cut events with slow rise-time and partial charge collection;
- K/L X-rays from Cosmogenic nuclides to trace crystal history;

- SI sensitivity improved;
- SD best below 6 GeV then;

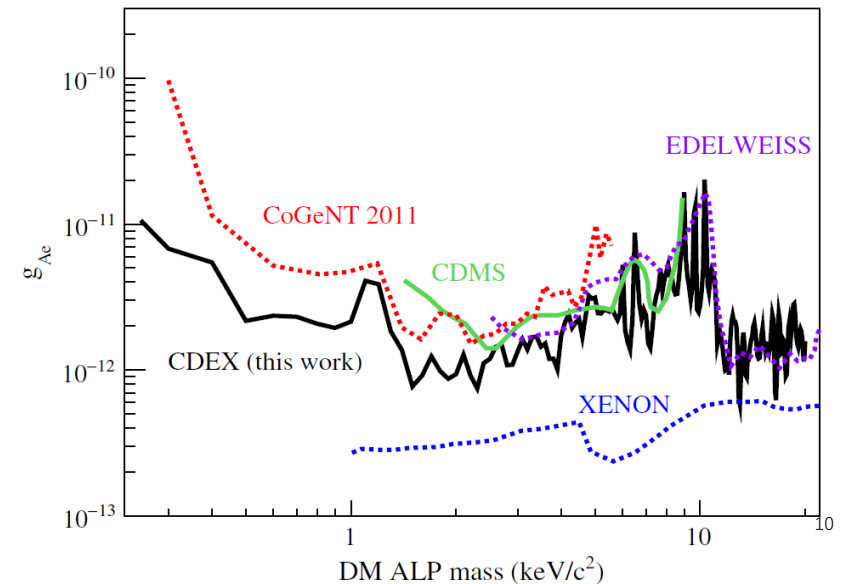
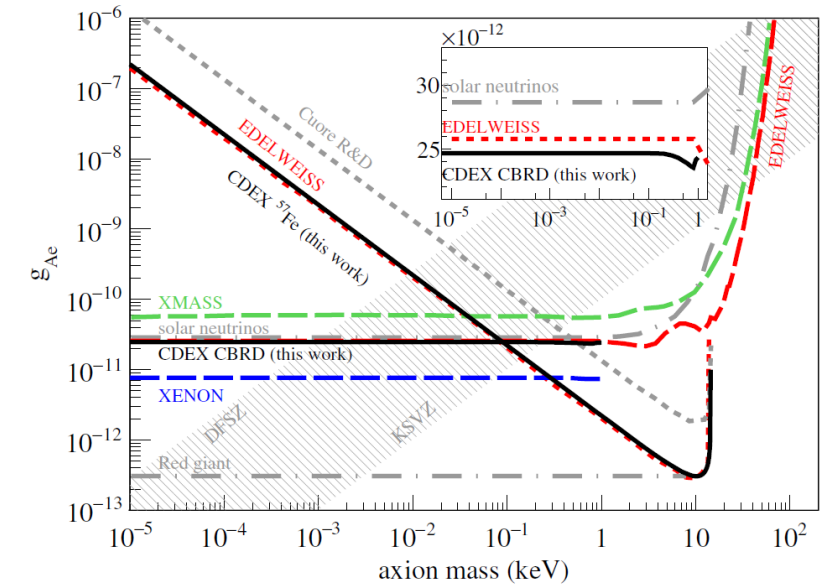
PRD93, 092003, 2016



CDEX-1A Results

PRD95, 052006, 2017

- Axion (335.6 kg·day data)
 - Solar axions: CBRD processes and ^{57}Fe M1 transition;
 - ALPs: more stringent constraint below 1 keV;

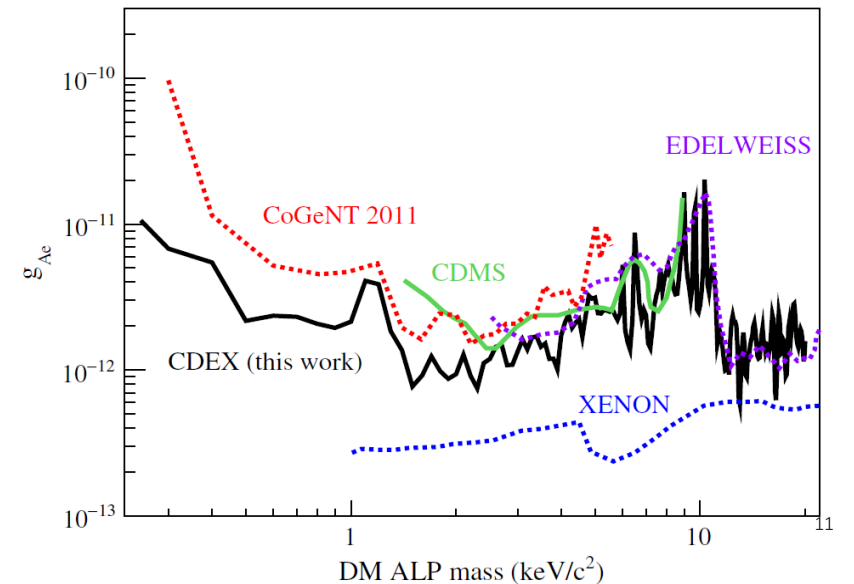
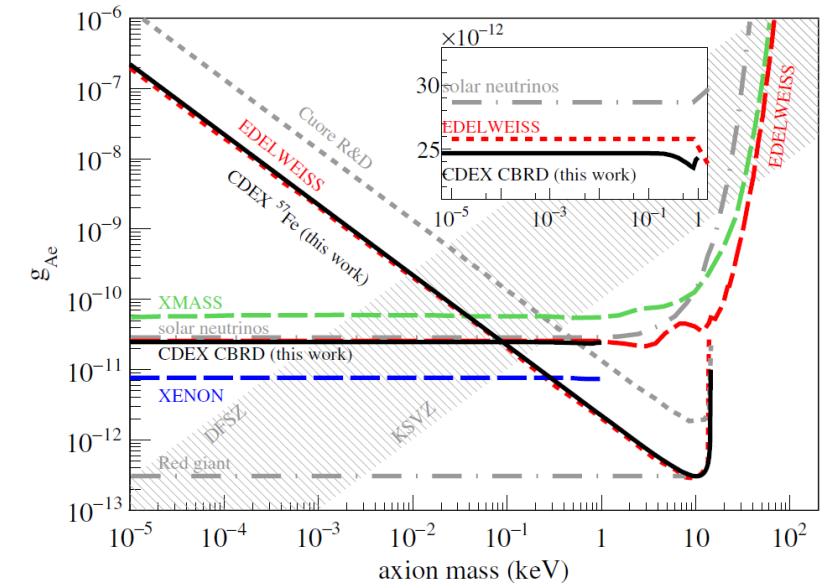
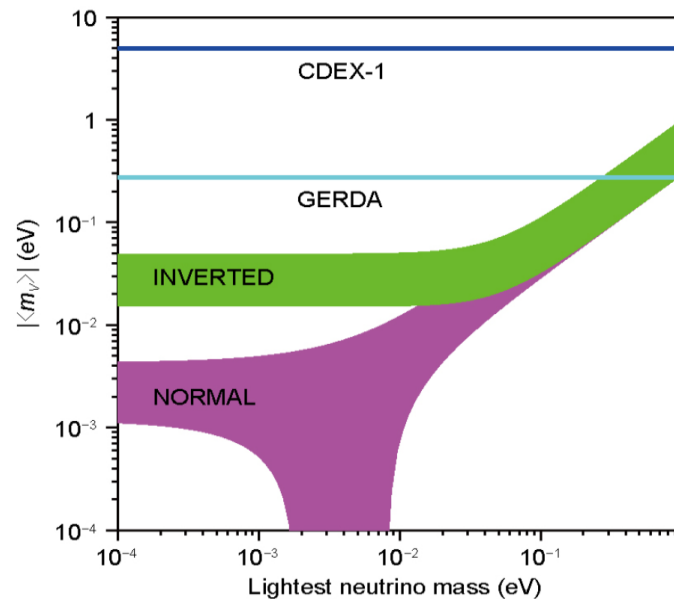
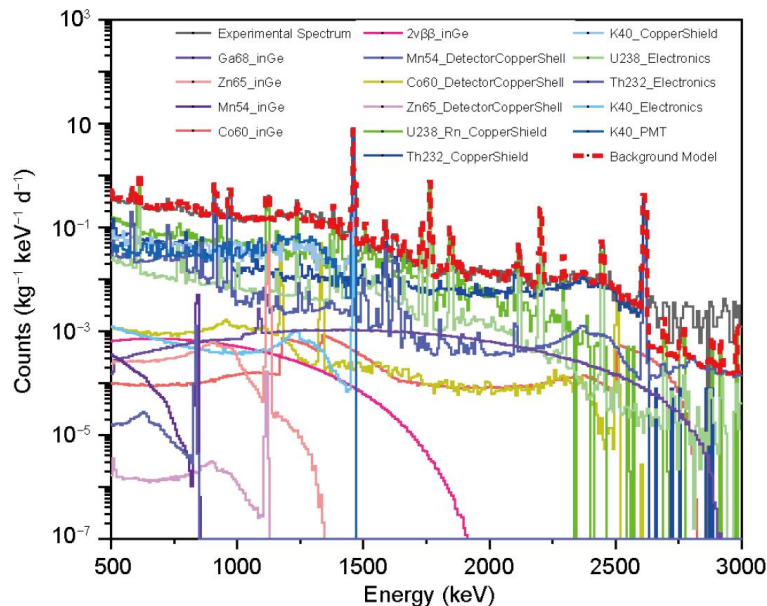


CDEX-1A Results

PRD95, 052006, 2017

- Axion (335.6 kg·day data)
 - Solar axions: CBRD processes and ^{57}Fe M1 transition;
 - ALPs: more stringent constraint below 1 keV;
- $0\nu\beta\beta$ (304 kg·day data)
 - Natural Ge crystal; $T_{1/2}^{0\nu} \geq 6.43 \times 10^{22} \text{ yr}$, 90% C.L.

Science China PMA (2017) 60: 071011



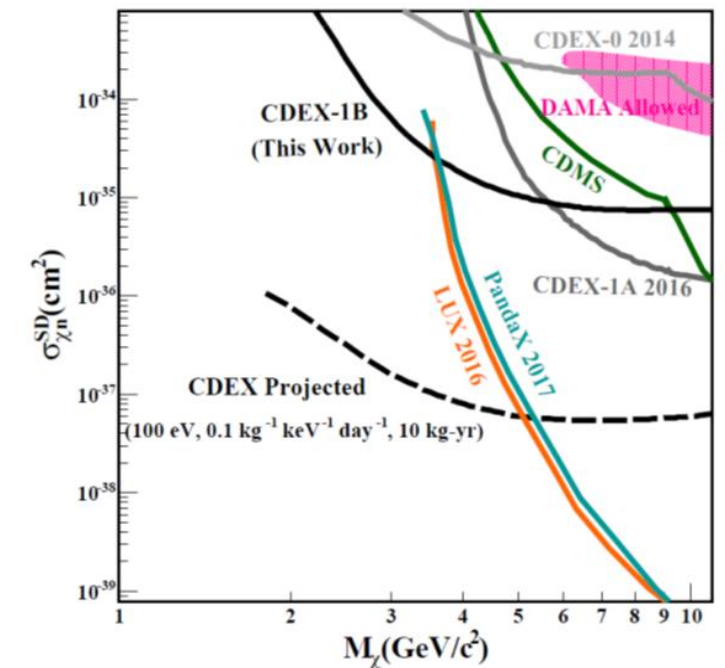
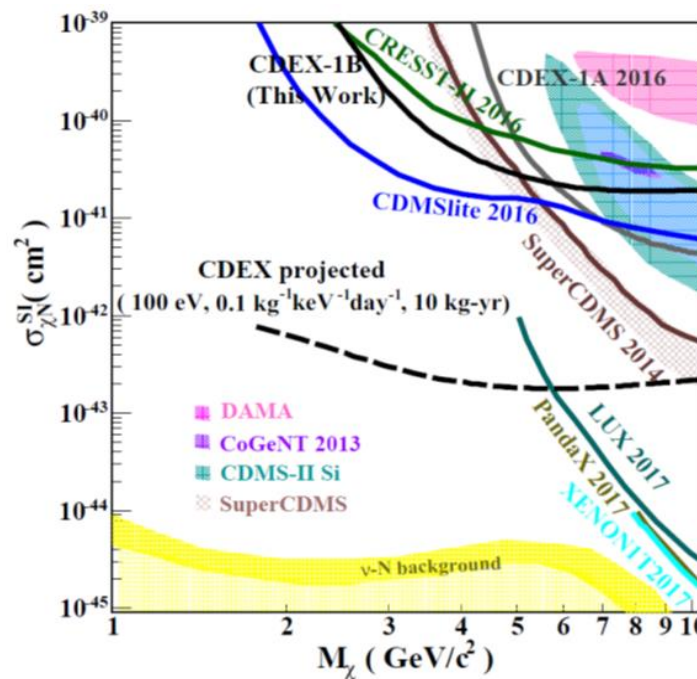
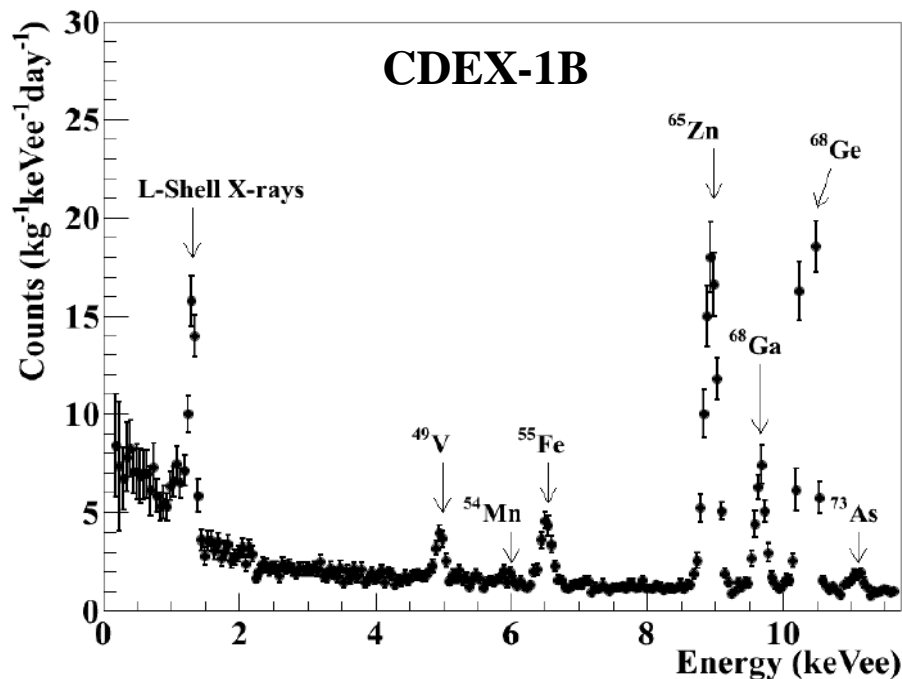
CDEX-1B Results

CPC 42, 023002, 2018

- Detector upgraded w/ lower JEFT noise and material bkg;
- >4 years run (Run-1&Run-2), >1200 kg·day exposure;
- Achieving 160 eVee energy threshold;
- Sensitivity improved and extending to 2 GeV/c².

Detector	FWHM of pulser
CDEX-1A	130 eVee
CDEX-1B	80 eVee

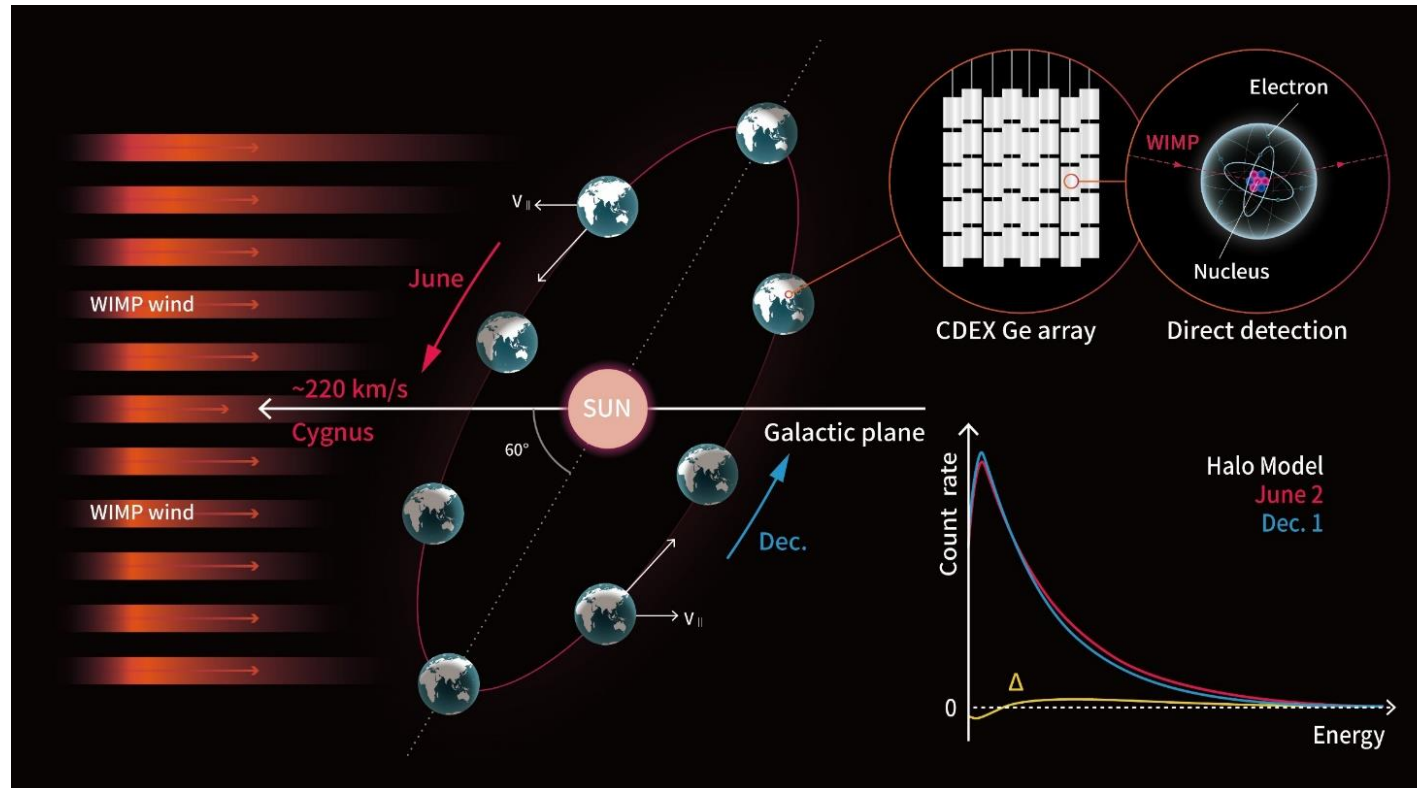
Run-1 Time-integrated (TI) analysis: CPC 42, 023002, 2018



WIMPs: Annual Modulation analysis from CDEX-1B

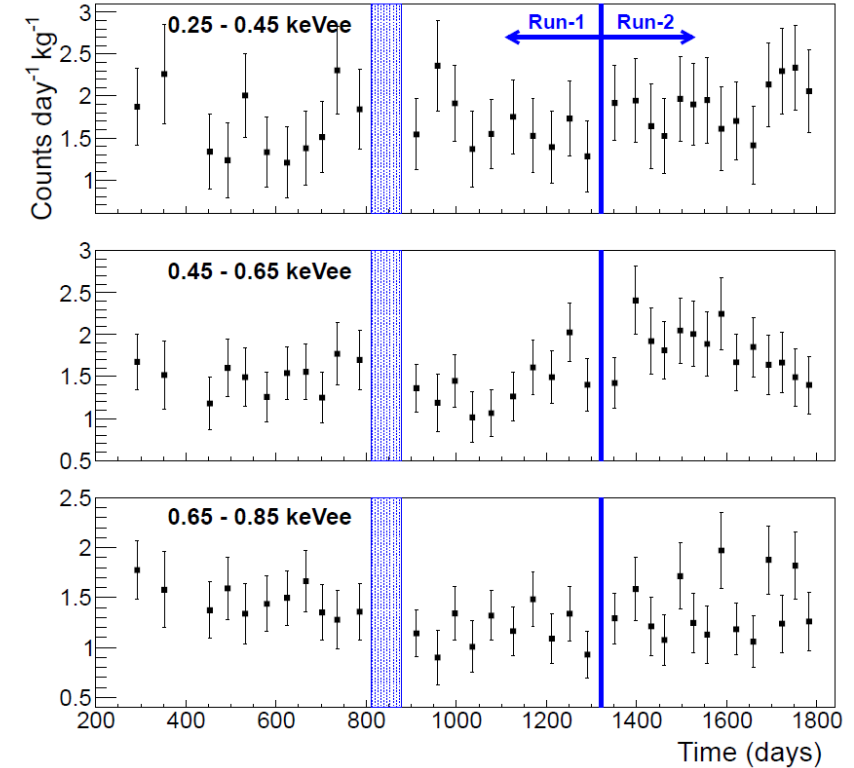
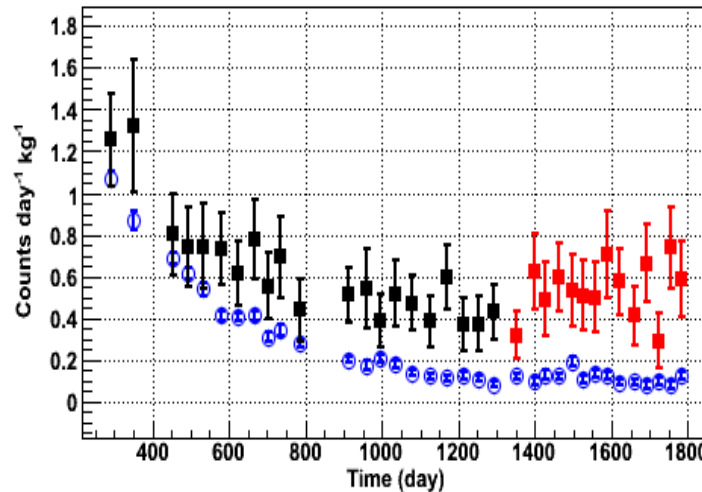
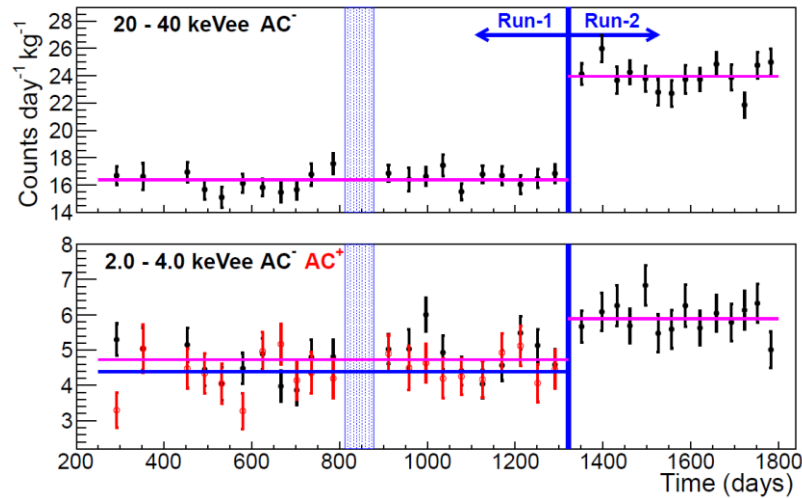
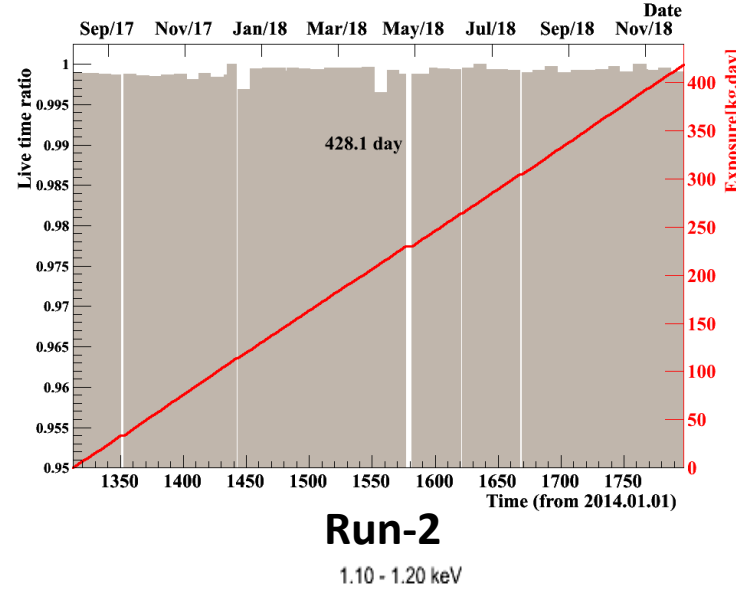
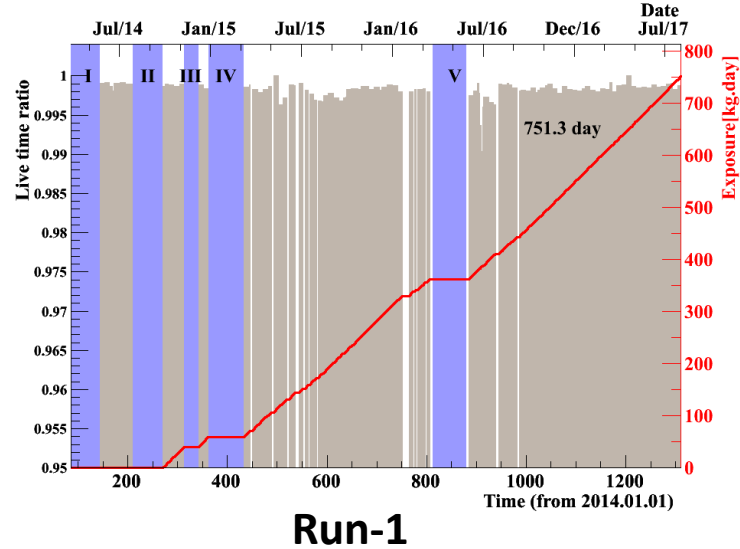
[arxiv: 1904.12889]

- AM provide smoking-gun signatures for WIMPs independent of background modeling, while only requires **background** at relevant energy range is **stable with time**;
- The expected χN rates have distinctive AM features with maximum intensity in June and a period of one year due to Earth's motion relative to the galactic WIMP-halo.



CDEX-1B Annual Modulation analysis

[arxiv: 1904.12889]

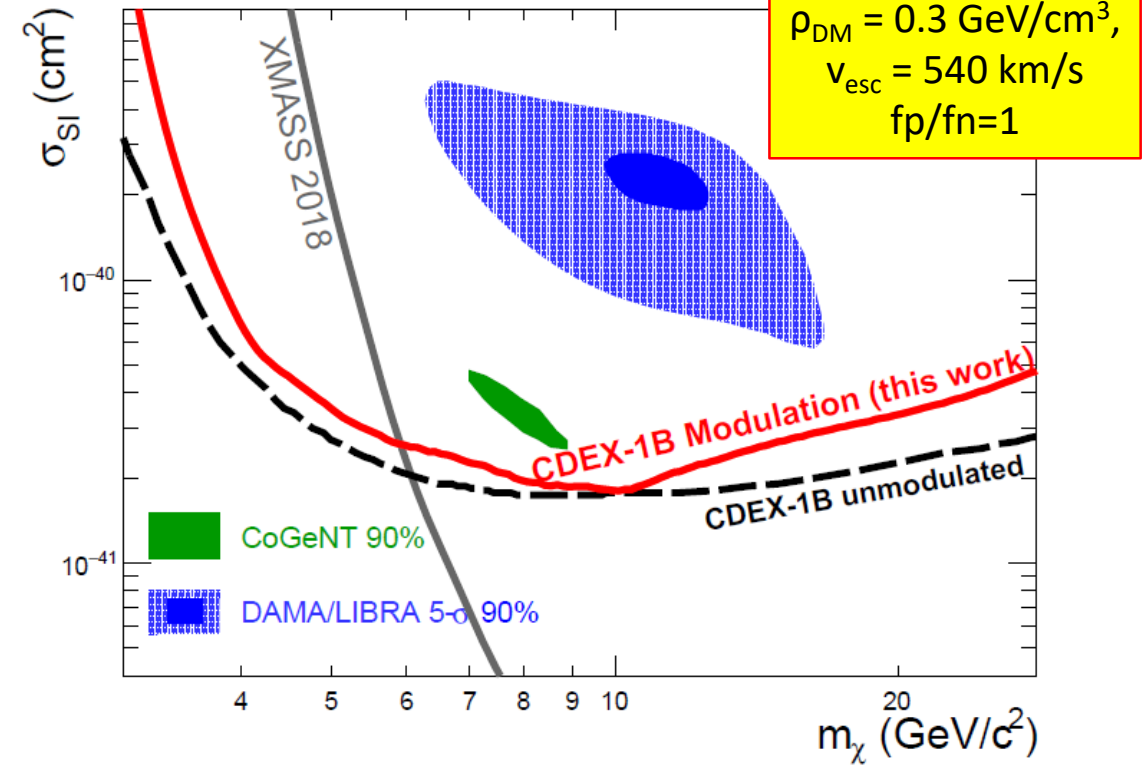
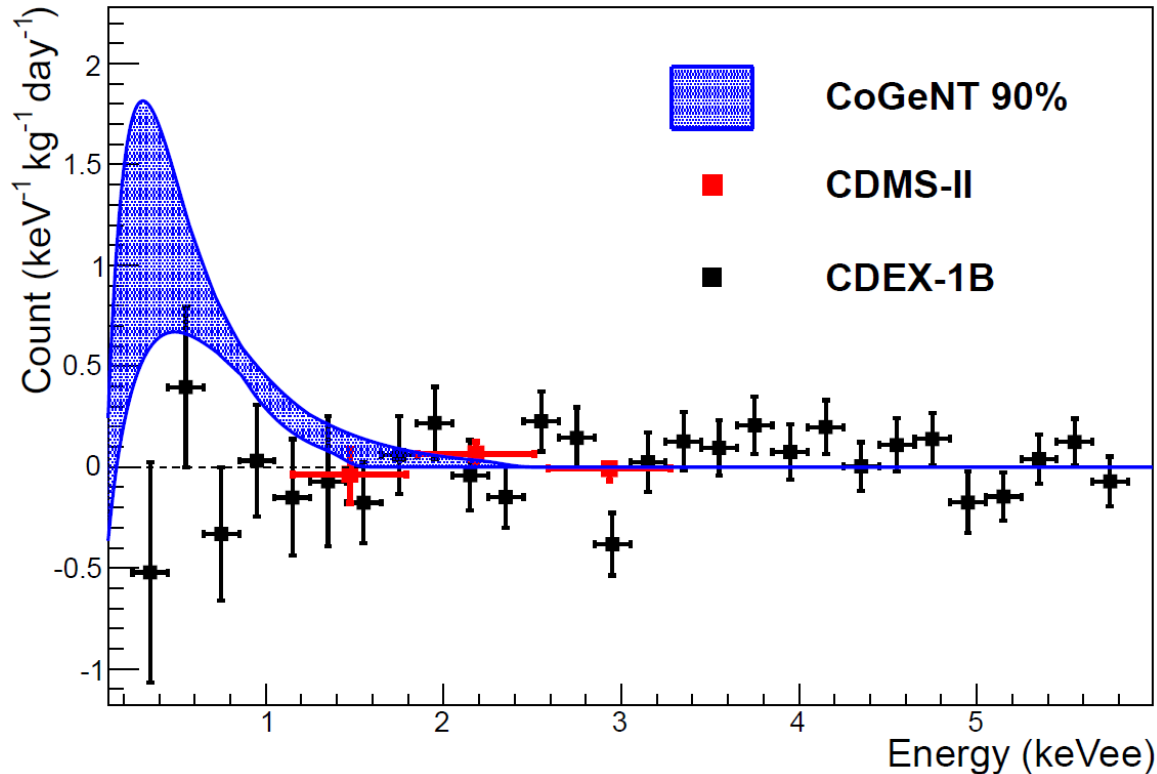


$$\chi^2_{ik} = \sum_{j \in \text{Time}} \frac{(n_{ijk} - P_{ijk} - B_{ik} - A_{ik} \cos(\frac{2\pi(t_j - \phi)}{T_{yr}}))^2}{\Delta_{ijk}^2}$$

Compton contribution from High-energy gammas L-Shell X-ray contribution – time varying

CDEX-1B Annual Modulation analysis

[arxiv: 1904.12889]

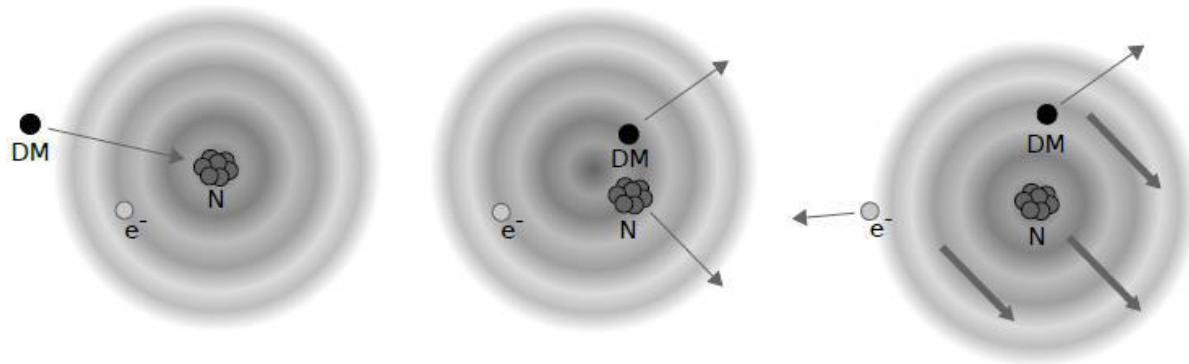


- ✓ CDEX-1B **excludes DAMA/LIBRA phase-1's** interpretation with the spin-independent WIMP interaction with **Standard Halo model in Germanium crystal.**

sub-GeV WIMPs: Migdal effect analysis

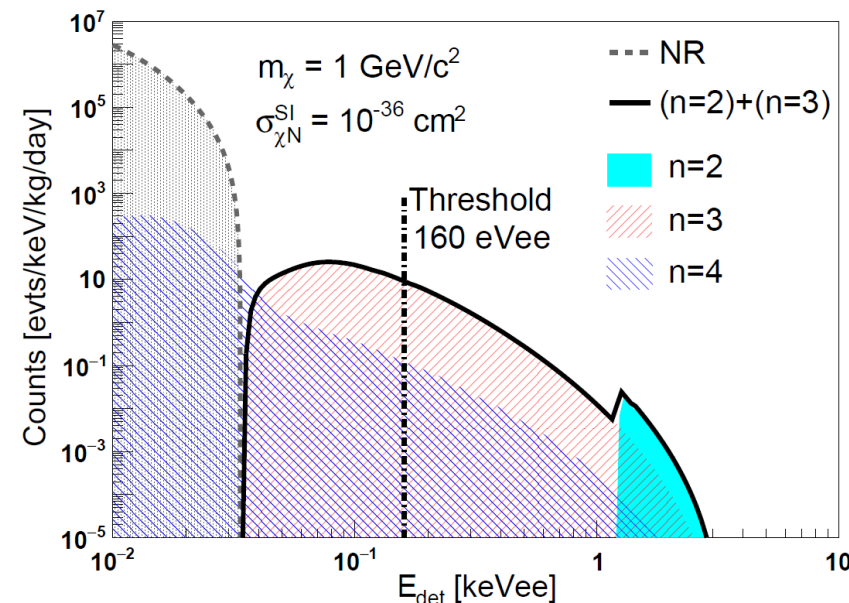
[arxiv: 1905.00354]

Migdal effect

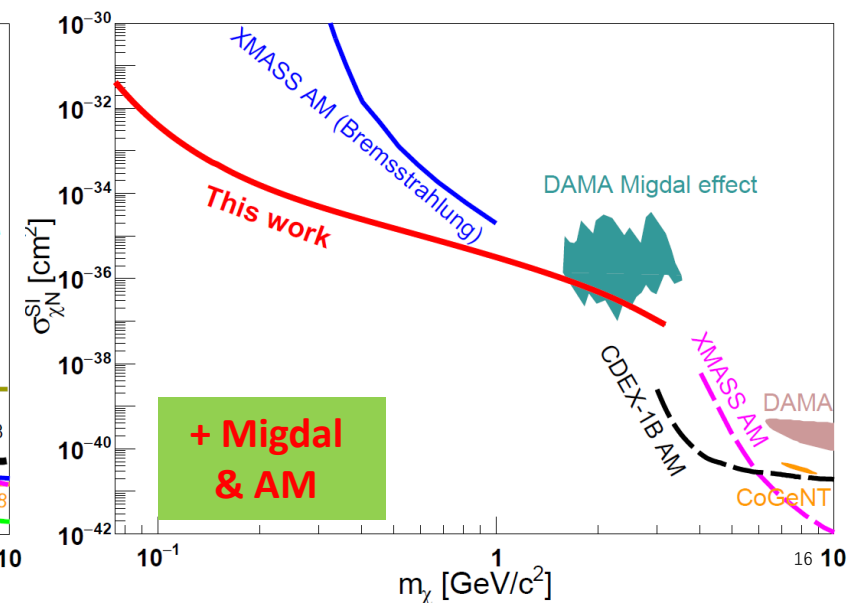
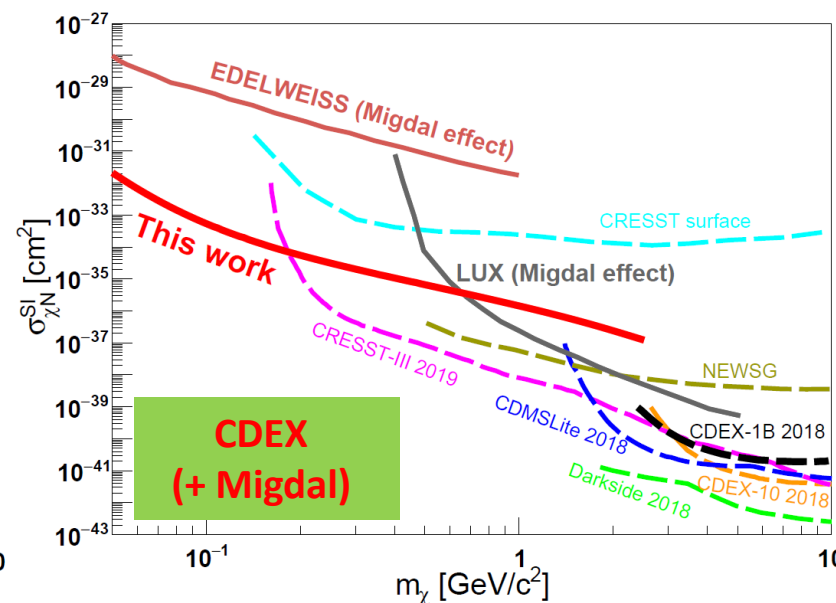


- Time-Integrated Analysis with Migdal: 737.1 kg-d ; 160 eVee threshold
- AM Analysis: 1107.5 kg-d ; 250 eVee threshold.
- Lead sensitivity in $m_{\text{DM}} \sim 50\text{-}180$ MeV

Expected measureable spectra

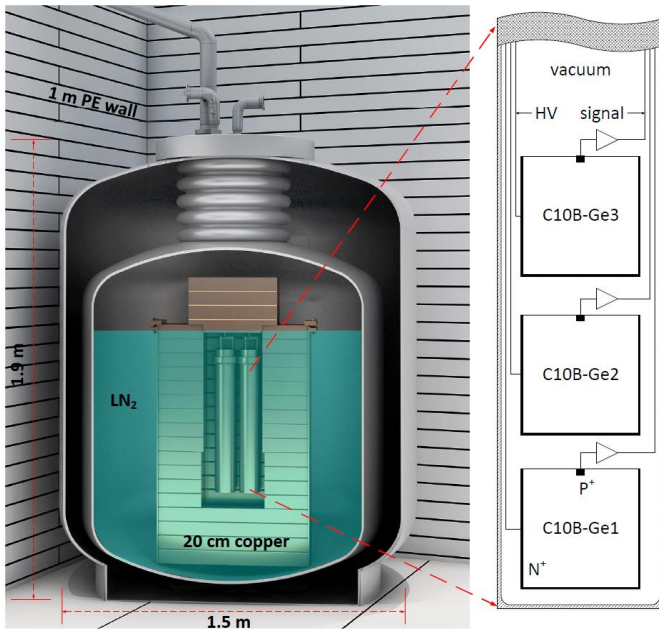


[arxiv: 1905.00354, PRL online soon]

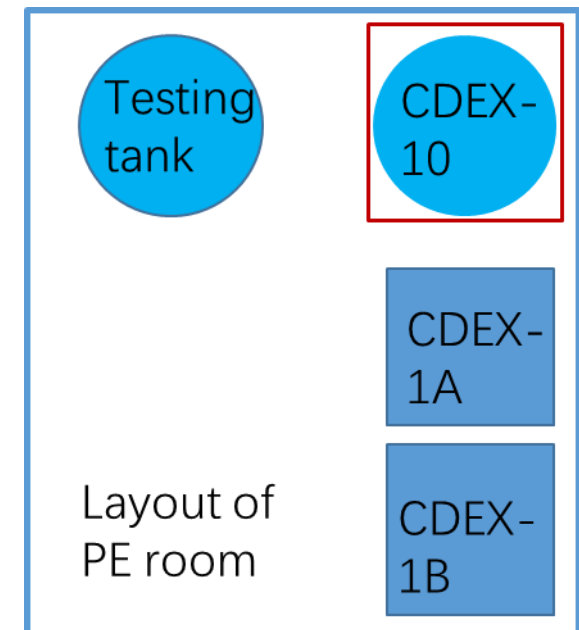


CDEX-10 stage

- Array detectors: 3 strings with 3 detectors each, ~10kg total;
- Direct immersion in LN_2 ;
- Prototype system for future hundred-kg to ton scale experiment
 - Light/radio-purer LN_2 replacing heavy shield i.e. Pb/Cu;
 - Arraying technology to scalable capability;

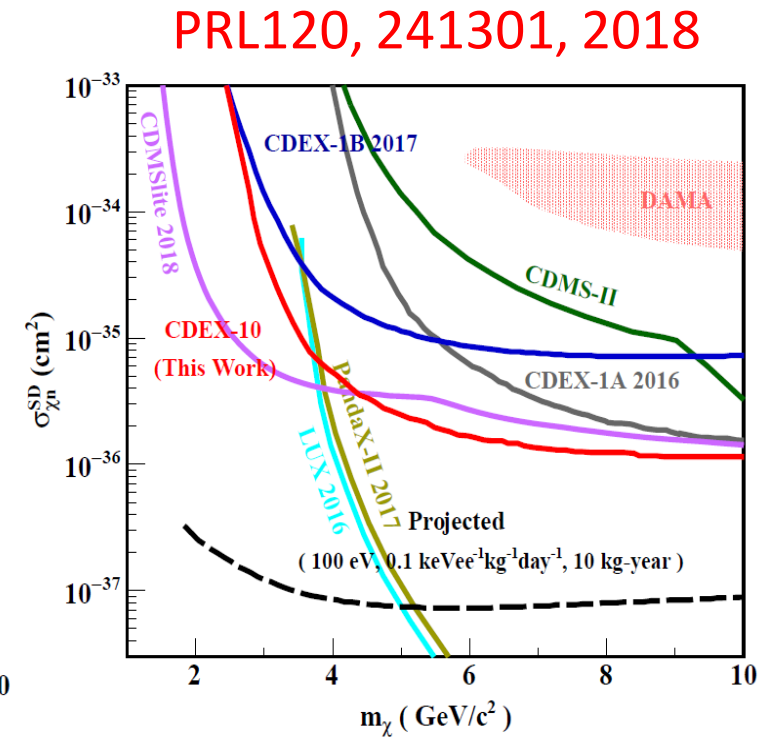
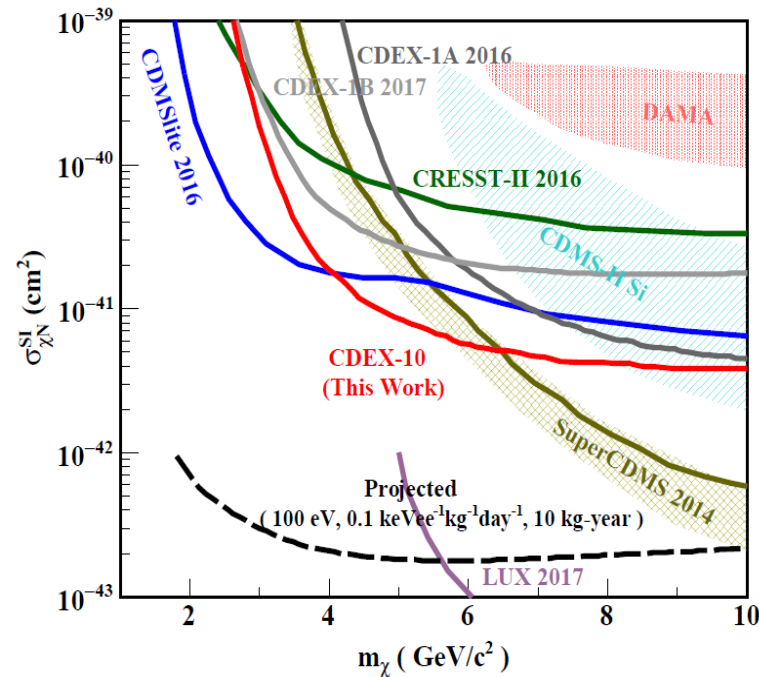
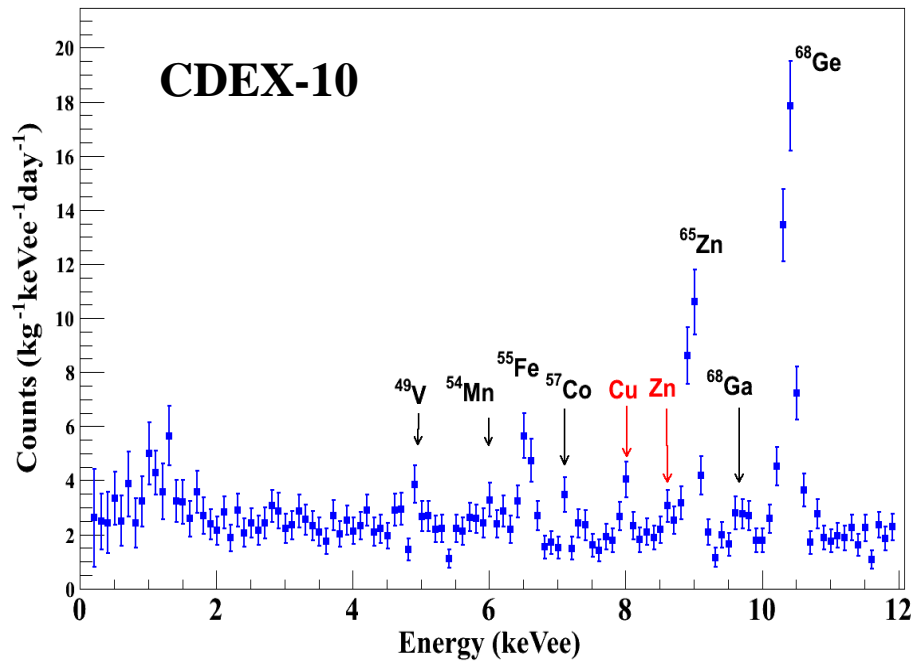


CDEX-10: ~10kg PPC Ge array



CDEX-10 First Results

- First results from 102.8 kg·day exposure w/ Eth 160eV;
- Bkg level: ~ 2 cpkkd @ 2-4 keV;
- New SI limit on 4-5 GeV/c²;

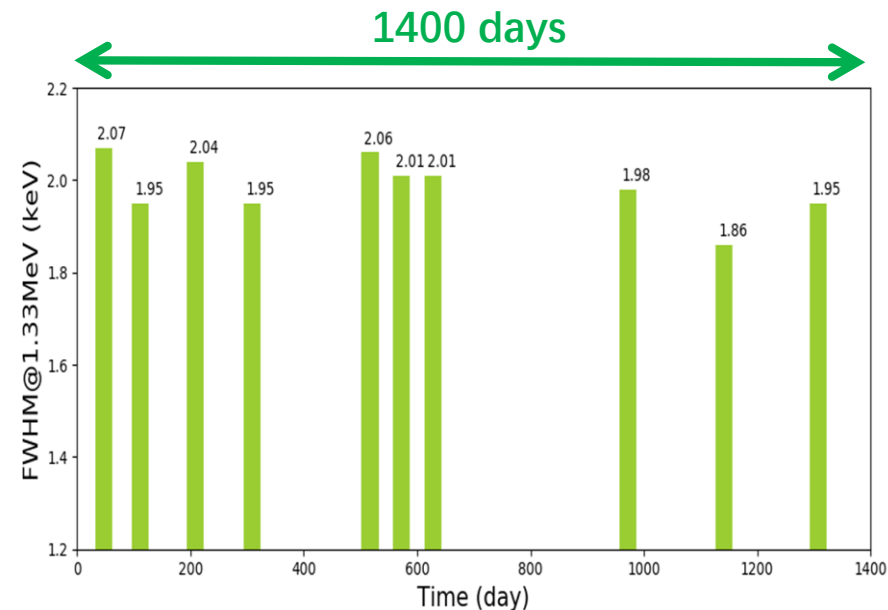


CDEX-10X: Ge detector fabrication

- CDEX10+**X** home-made Ge detectors;
- Understand & reduce detector intrinsic bkg;
- Various types, ~20 detectors
 - P-type planar/coaxial;
 - P-type point contact/ BEGe;
- Long time stability

- ✓ Commercial Ge crystal;
- ✓ Structure machining;
- ✓ Li-drift and B-implanted;
- ✓ Home-made ULB PreAmp;
- ✓ Underground EF-Cu;
- ✓ Underground assemble;
- ✓ Underground testing...

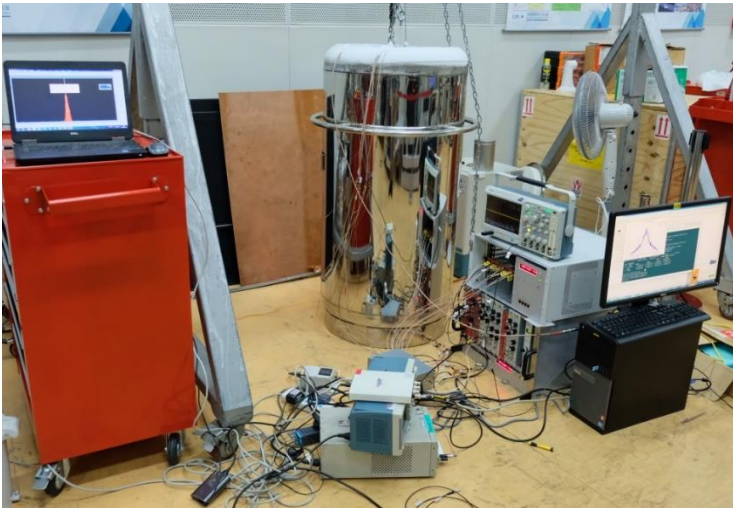
good performance keeping, >1400 days



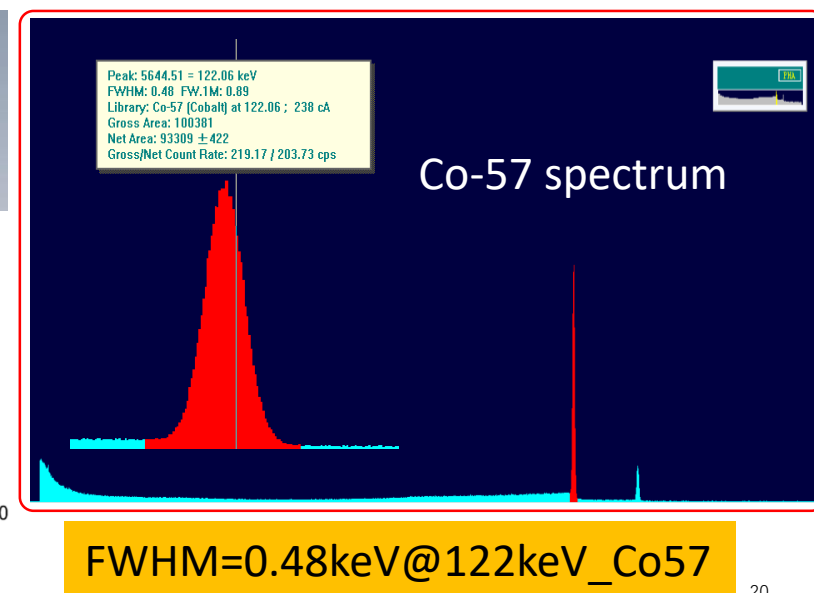
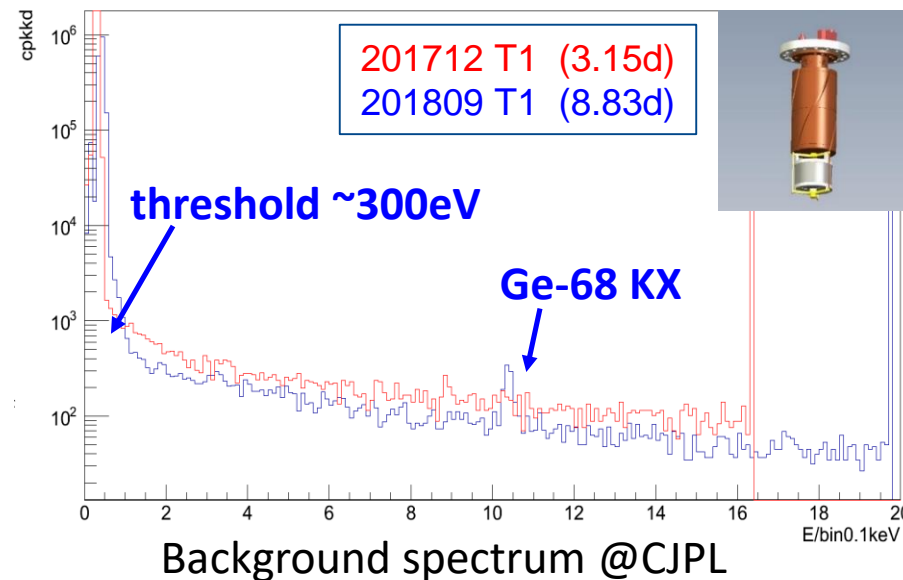
Vacuum systems

CDEX-10X Detector (T1)

- Commercial Ge crystal + stainless steel canister;
- T1 detector: 500g Ge($\phi 50 \times 50\text{mm}$) + CMOS ASIC preAmp;
- Works, and Performance expected;
- Going on to improve bkg, low-noise electronics...

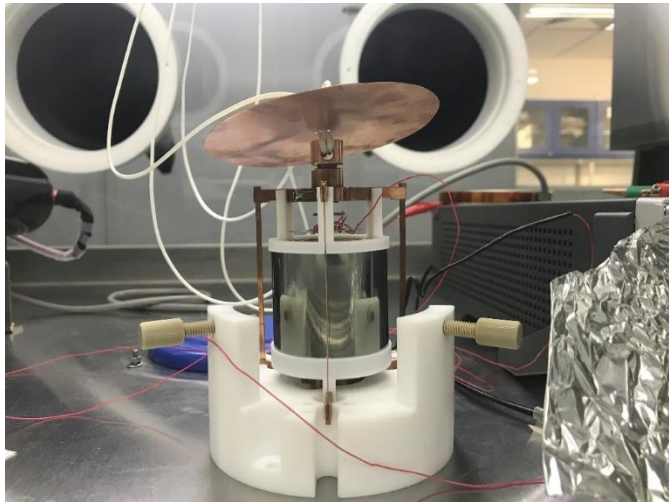
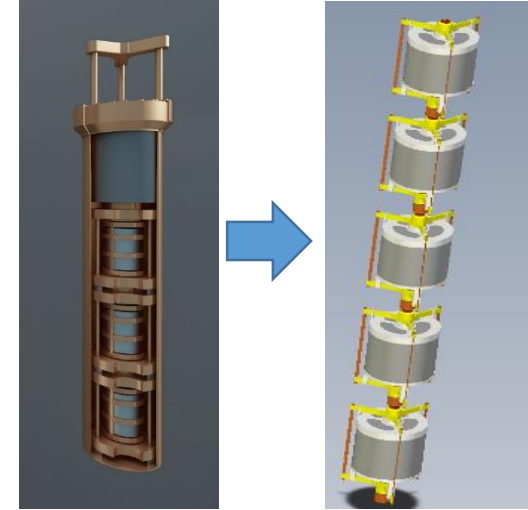


Tested in CJPL-I

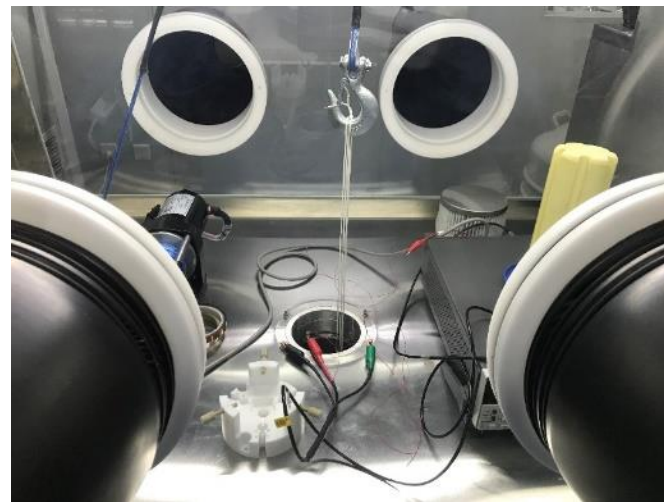


CDEX-10X Detector (Bare HPGe detectors in LN₂)

- Vacuum chamber, structure materials, not conducive to further reduce the radioactive background;
- ASIC-based preamplifiers can work well in liquid nitrogen;
- ✓ **Develop bare HPGe detectors immersed into LN₂!**
- ✓ Immerse the detector into liquid nitrogen for about 8 hours, we got a stable leakage current ~ 10 pA for 1000V bias voltage.

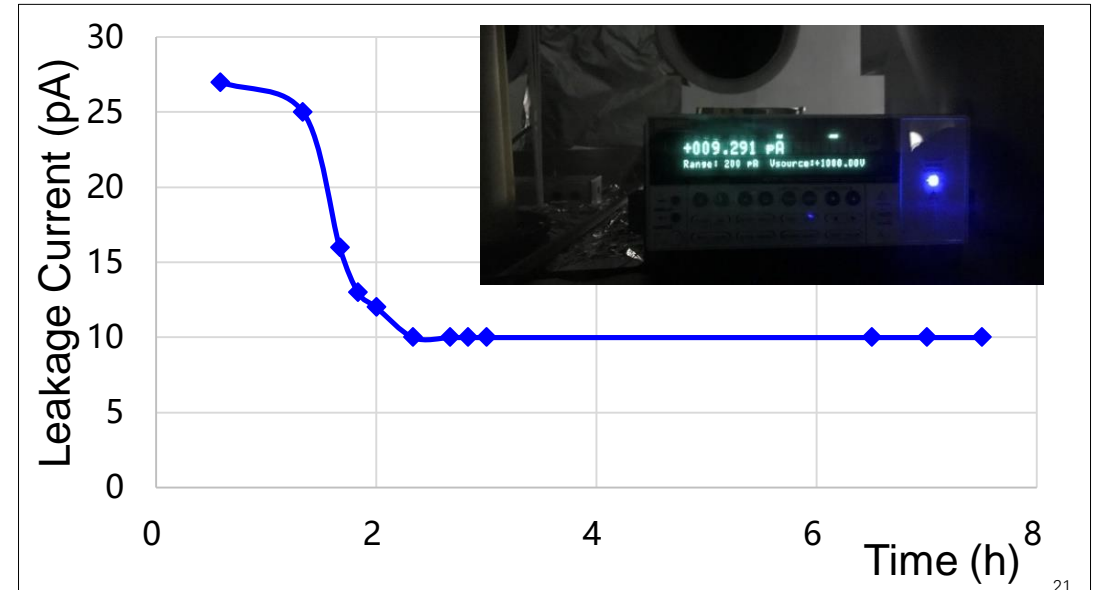


Bare HPGe detectors



Bare HPGe in LN₂

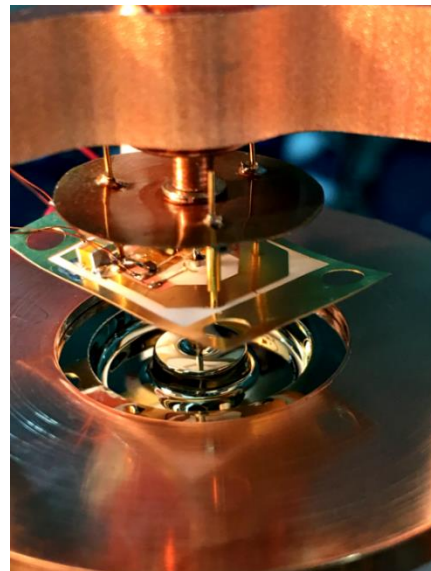
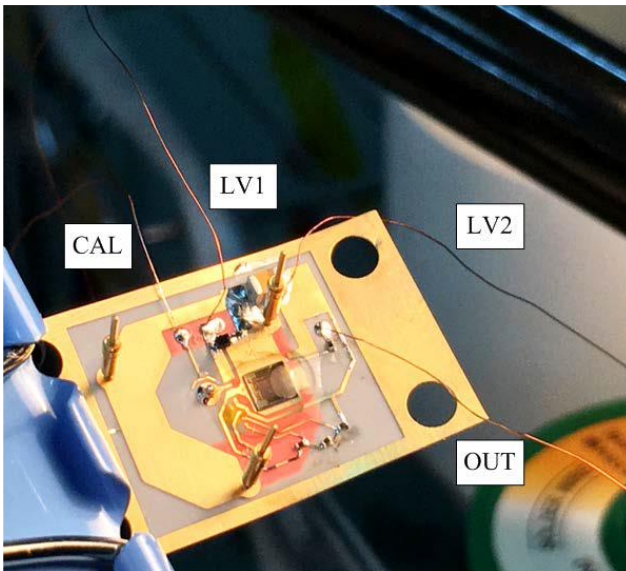
PPC: $\phi 50\text{mm} \times 50\text{mm}$, Depleted voltage: $\sim 800\text{V}$



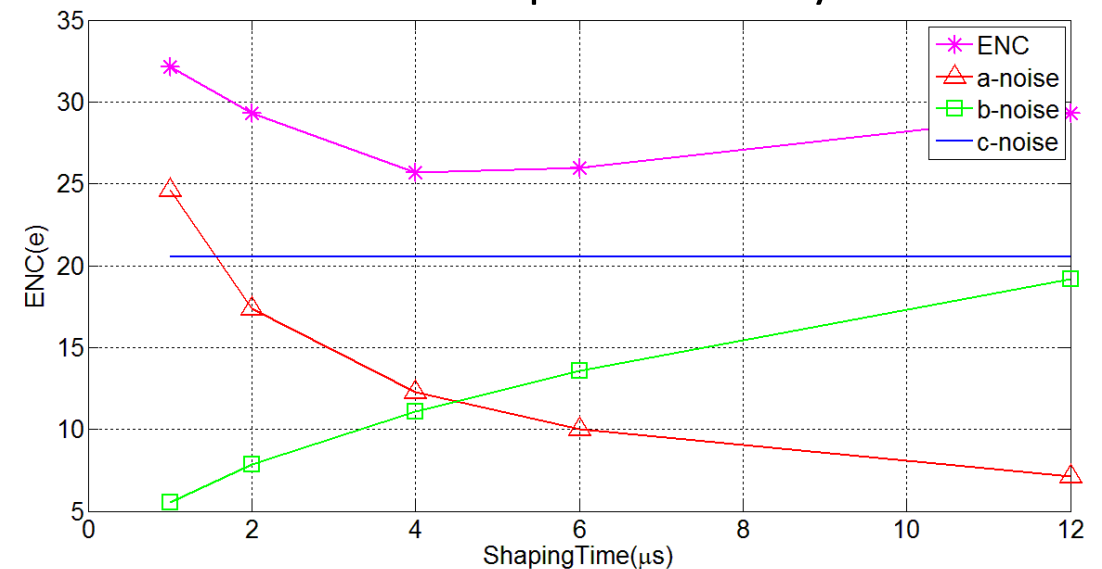
CMOS ASIC Front-end Electronics

- Light DM search \rightarrow low noise/threshold (low capacity, etc)
- Very close to Ge detectors \rightarrow low bkg (radiopure, low-mass, etc)
- ASIC preamplifier @ 77K
 - PCB material: PTFE(Rogers 4850);
 - ENC $\sim 26e(<200eV)$ w/ $4\mu s$ shaping time, mainly from $1/f$ noise ($\sim 21e$);

JINST (2018) 13: 8019



Noise components analysis

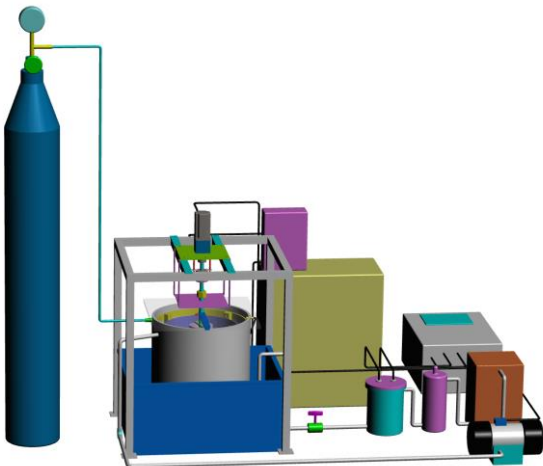


Underground E-forming copper and Assay

- Prototype setup for underground EF-Cu production
 - Cathode mandrel: 316L stainless steel, $\phi 95 \times 380 \text{ mm}$;
 - Plating bath: PE, $\phi 400 \times 500 \text{ mm}$;
 - Goal: Majorana copper, U/Th content $\sim O(0.1 \mu\text{Bq/kg})$;
- Test run in Tsinghua U. and moved to CJPL-I;
- U/Th Analysis by ICP-MS
 - Wet chemistry testing... , blank sensitivity $\sim 10^{-13} \text{ g/g}$



UG copper e-forming facilities@CJPL-I



E-forming setup



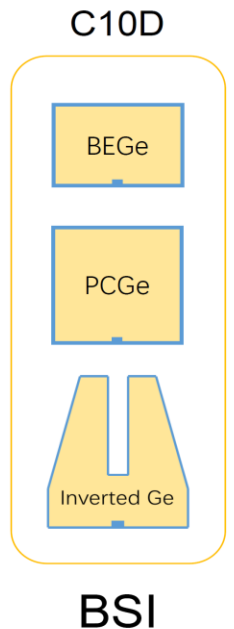
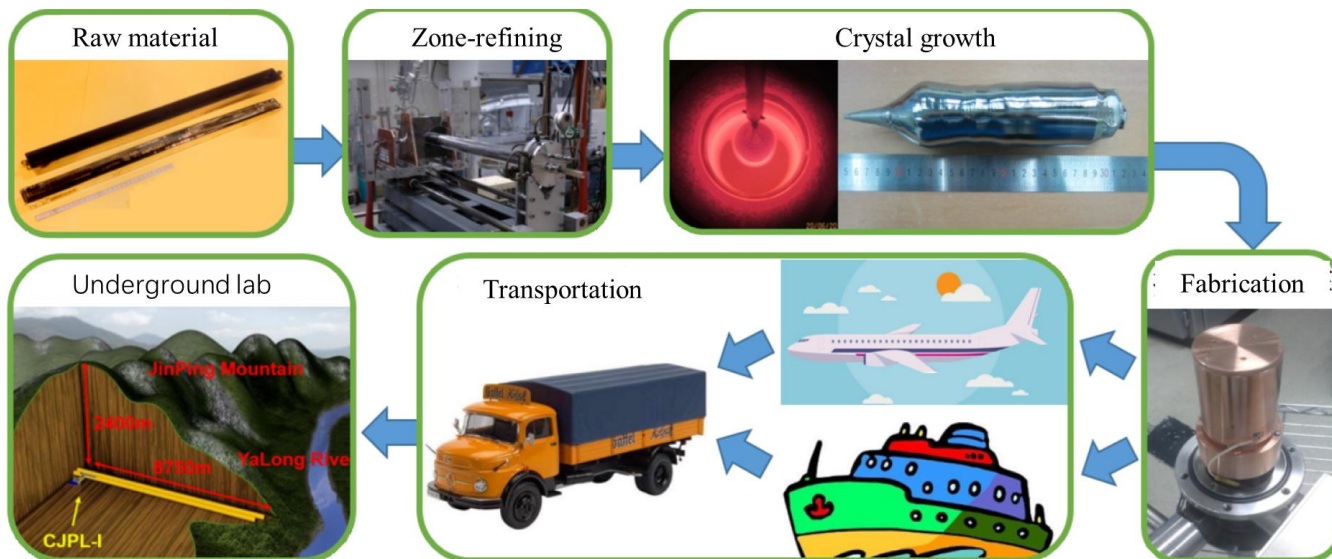
optimized electrical parameters



ICP-MS

Future Plan - Detector

- New detectors cooperated with commercial companies
 - 3kg from BSI, 2kg from ORTEC, planning 5kg from CANBERRA/ORTEC;
 - Particular control of detector fabrication process above ground;
- Home-made detectors
 - Improve T1 w/ low bkg material and low noise electronics;
 - Set up underground fabrication and testing facility;

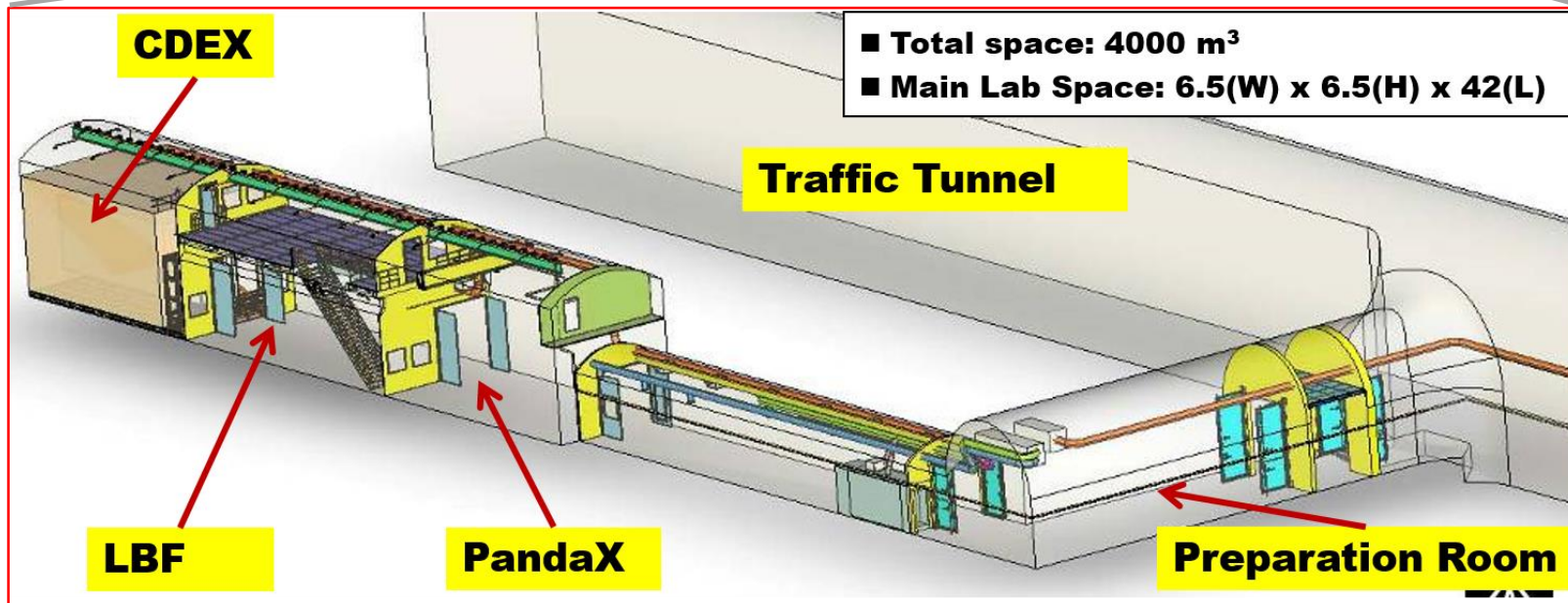
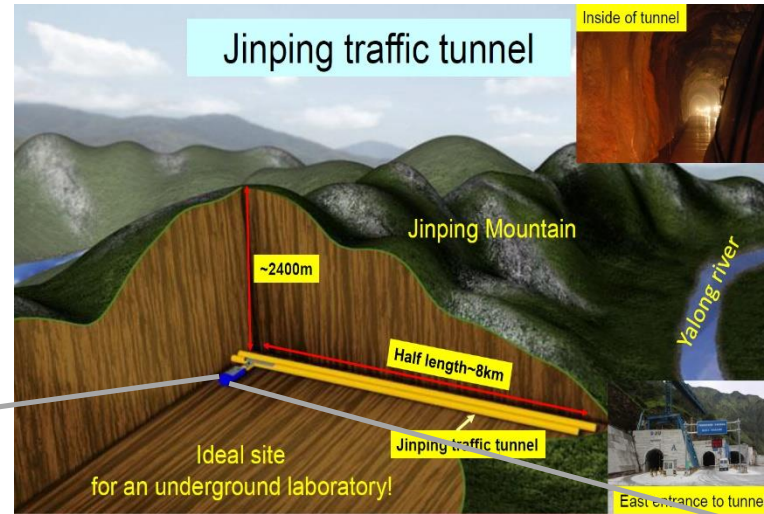


Detector production: 45days +
Ground transportation: 60 days +
Underground cooling: 180days →

Cosmogenic bkg: 0.03cpkcd(sim.)

Future Plan - Lab

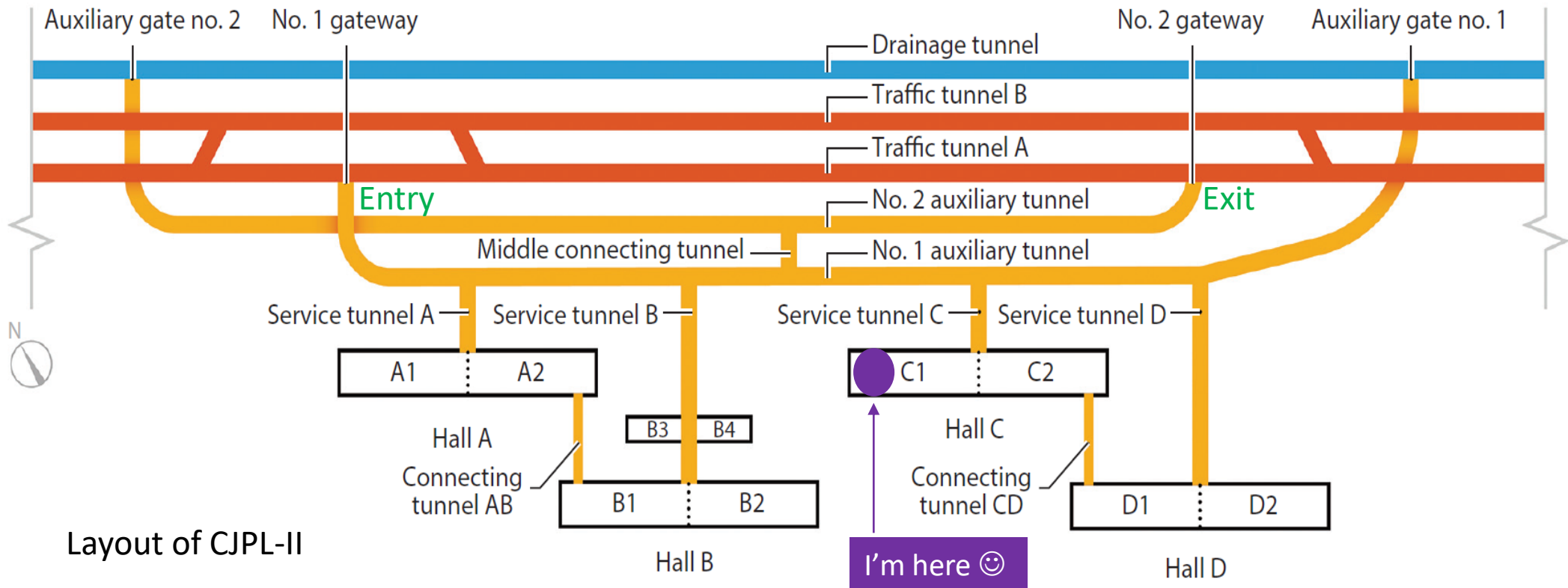
- CJPL-I
 - Volume: 4000 m³
 - 1 main hall (6.5x6.5x42m)



Future Plan - Lab

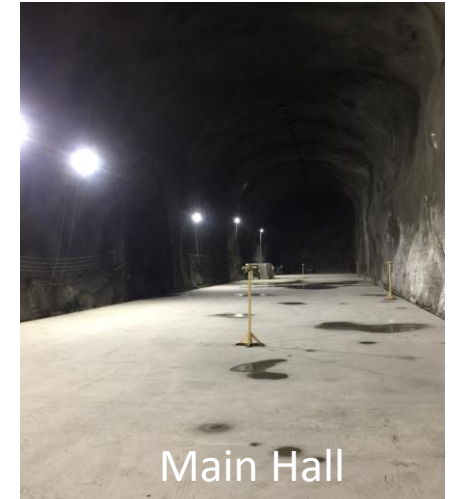
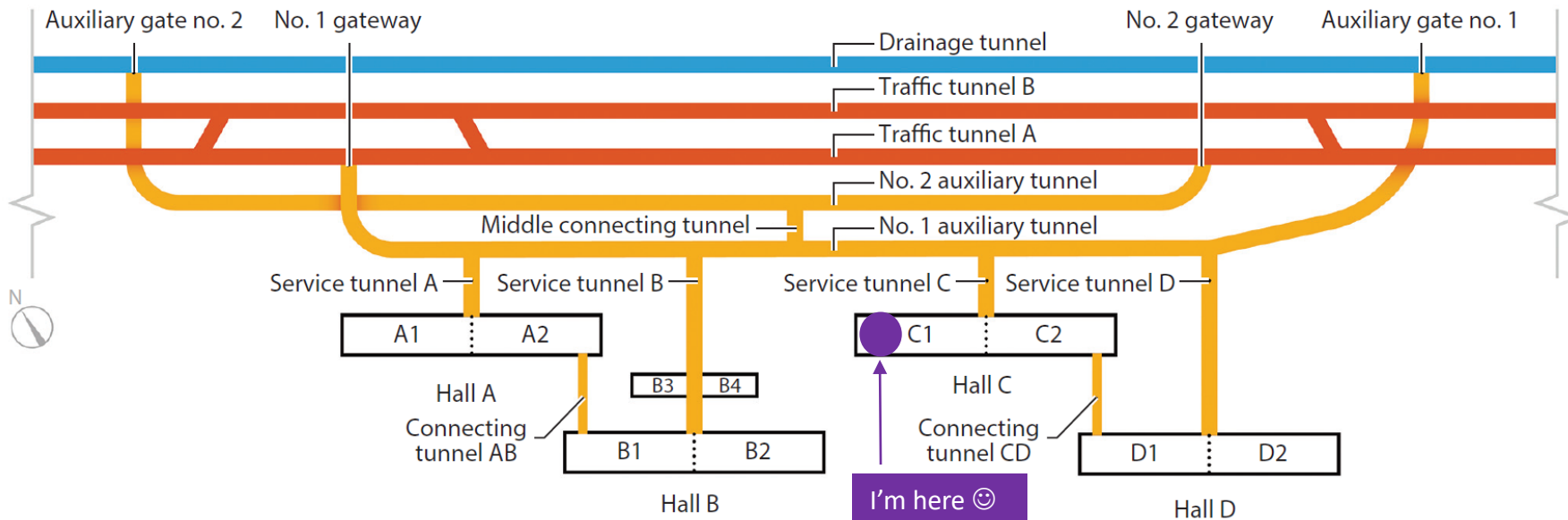
- CJPL-I to CJPL-II

- Volume: 4000 m³ to 300,000 m³;
- 1 main hall (6.5x6.5x42m) to 8 main halls (14x14x60m each);
- Additional pit for next-generation CDEX;



Future Plan - Lab

- CJPL-I to CJPL-II
 - Volume: 4000 m³ to 300,000 m³;
 - 1 main hall (6.5x6.5x42m) to 8 main halls (14x14x60m each);
 - Additional pit for next-generation CDEX;
- CJPL-II status
 - Civil engineering from Dec. 2014 to May 2016;
 - Ventilation system: 3 nine-km-long PE pipes till Jun. 2018;



CJPL-II construction next plan



Main Hall



Service tunnel

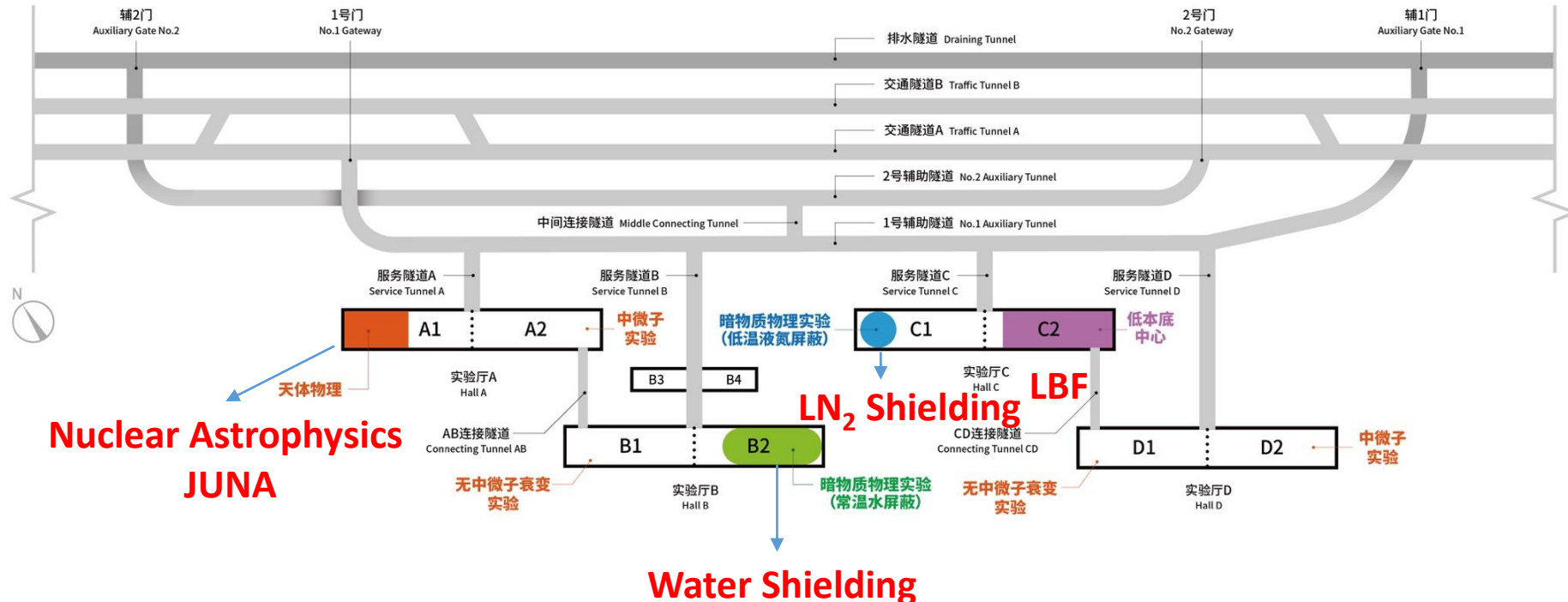
- CJPL was selected to be a candidate project of **National Major S&T infrastructure of China** in 2016.
- Proposal has been approved in Dec. 2018. The funding, **~\$180M**, just for the construction of the facility including the infrastructure, shielding, instrument and so on.
- Possible users:
 - CDEX-1T(DM, $0\nu\beta\beta$), PandaX-xT, LAr DM, CUPID-China
 - Nuclear astroparticle physics
 - Solar neutrino experiment
 - Rock mechanics experiment
 -
- Service
 - Low background counting
 - Ultra pure copper
 - popularization of science



Ground campus

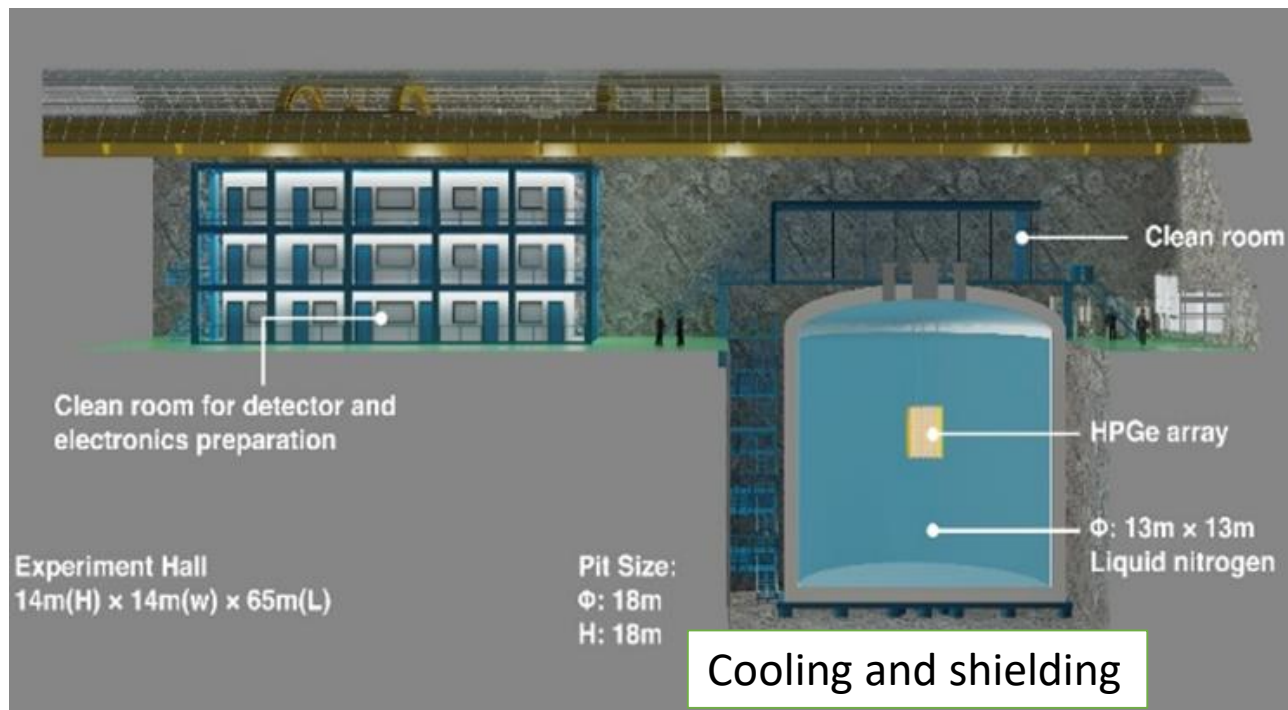
CJPL-II construction next plan

- CJPL will be an international platform for particle physics, nuclear physics, and so on.
- CJPL will aim to provide services to the researchers performing experiments there, and to develop it into an open and world-class research facility with first-rate working conditions used by internationally leading research teams.
- World-leading experiments will be highly encouraged to locate in CJPL-II.



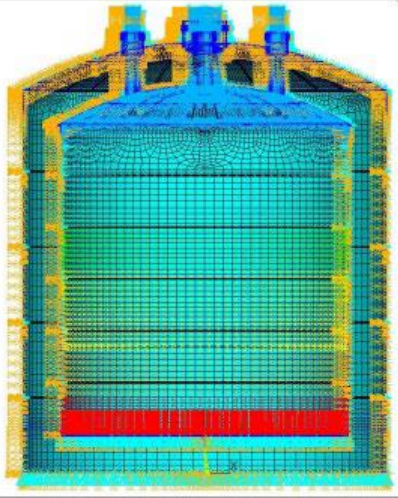
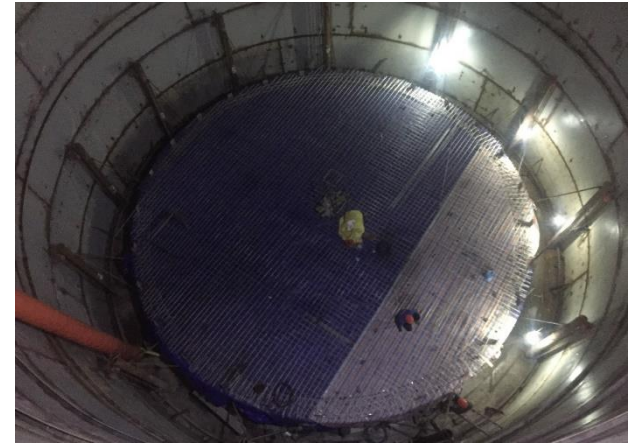
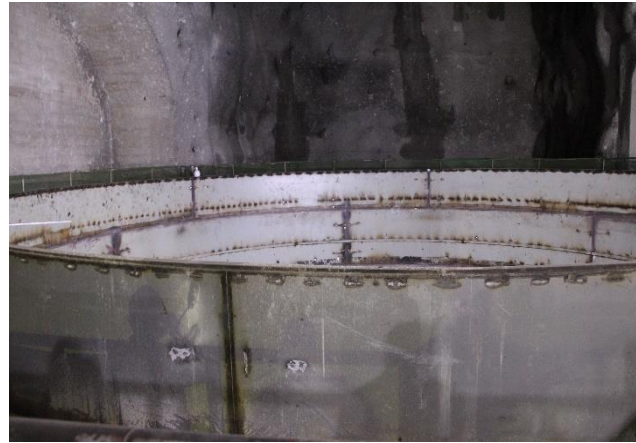
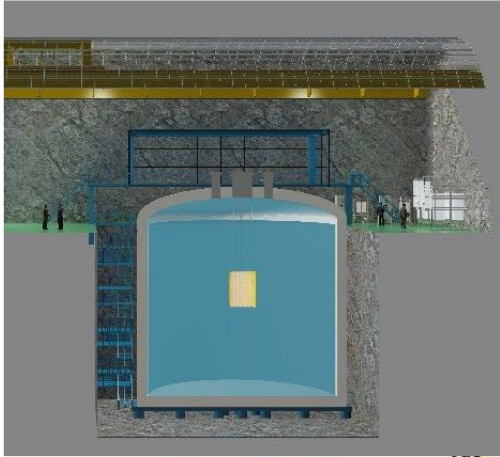
Future Plan - CDEX

- CDEX10X moving to a 1725m³ LN₂ tank (φ13x13m) located in the pit;
- Construction of LN₂ tank kicked off in Nov. 2018;
- 10+X kg detectors direct-immersion and then operation in LN₂ in 2019;
- CDEX-100 stage under technical design, report comes soon.



Future Plan - CDEX@CJPL-II

- Progress of the 1725m³ LN₂ tank (φ13x13m) @ CJPL-II C1;

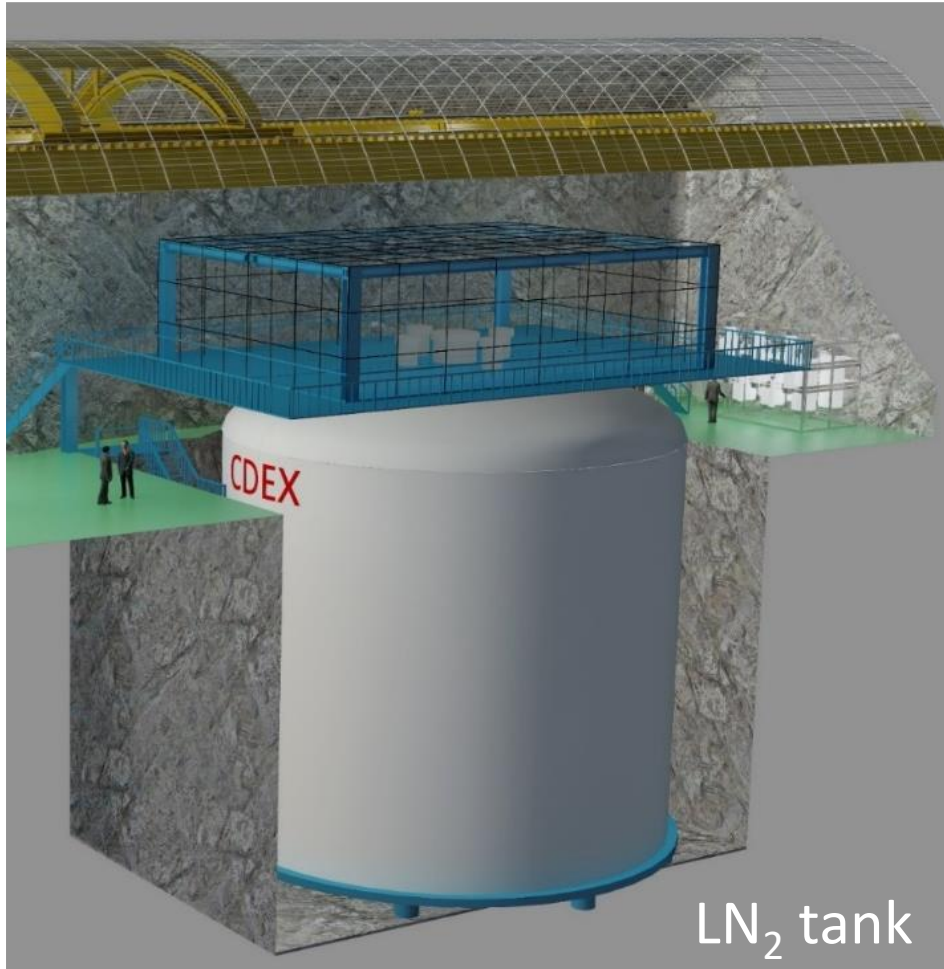


Future Plan - CDEX@CJPL-II

- Progress of the 1725m³ LN₂ tank (φ13x13m) @ CJPL-II C1;



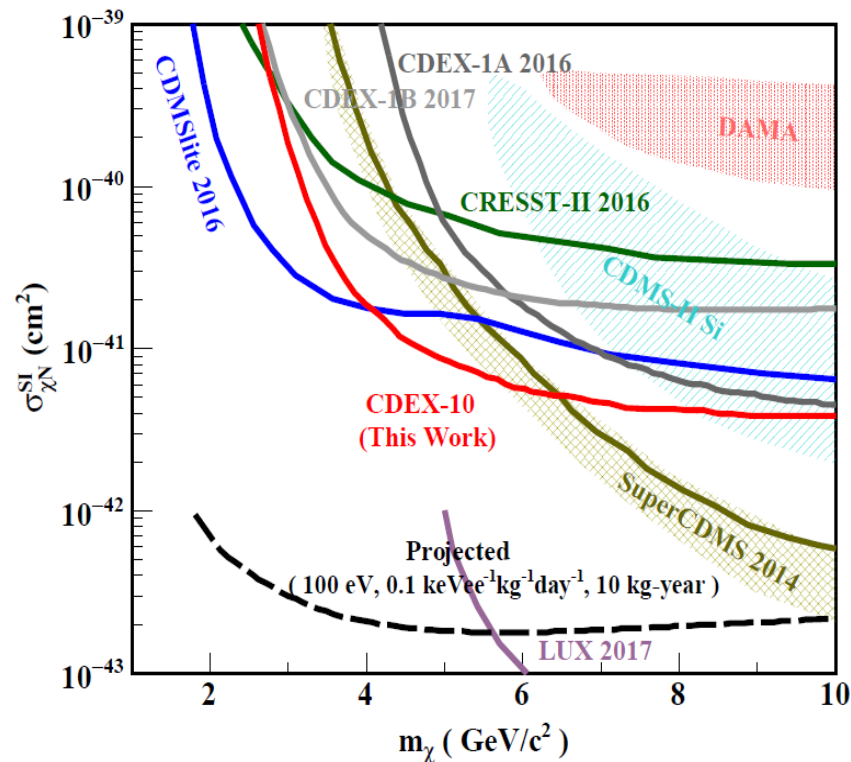
Future Plan - CDEX



Future Plan - CDEX

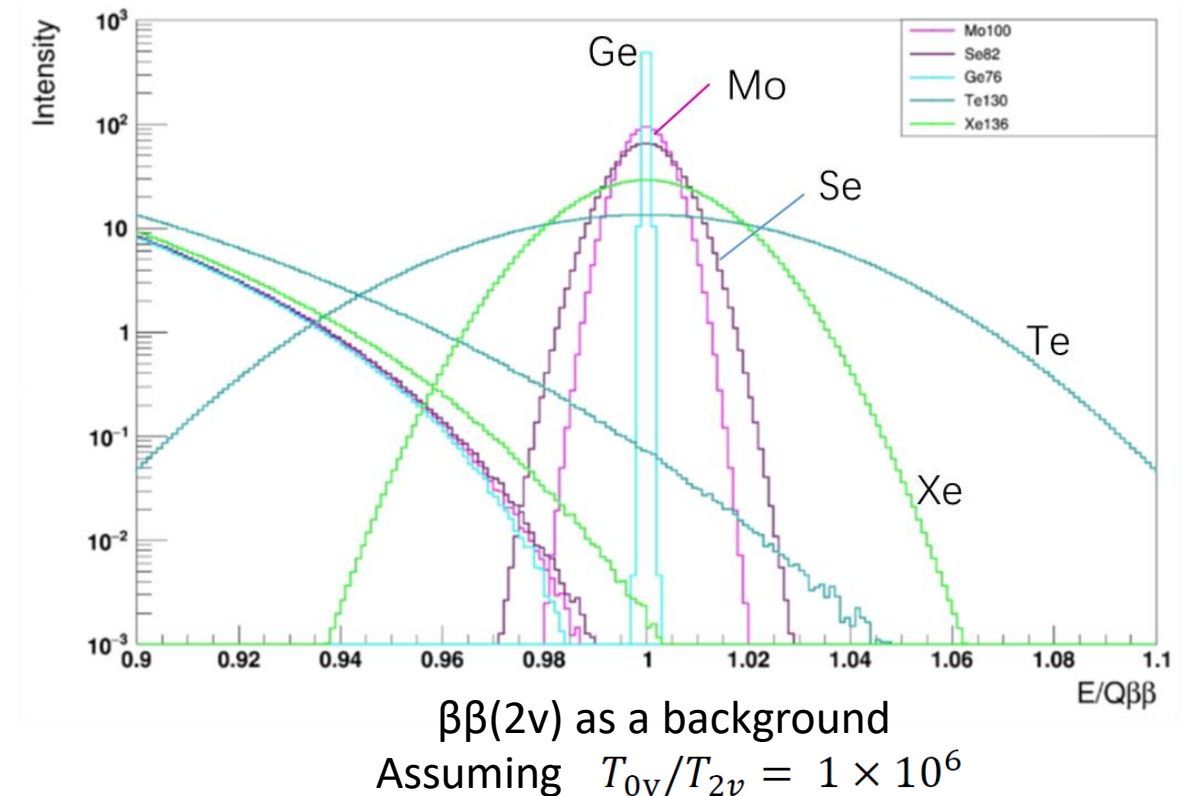
- DM

- WIMPs, include AM;
- Axion, Dark Photon...



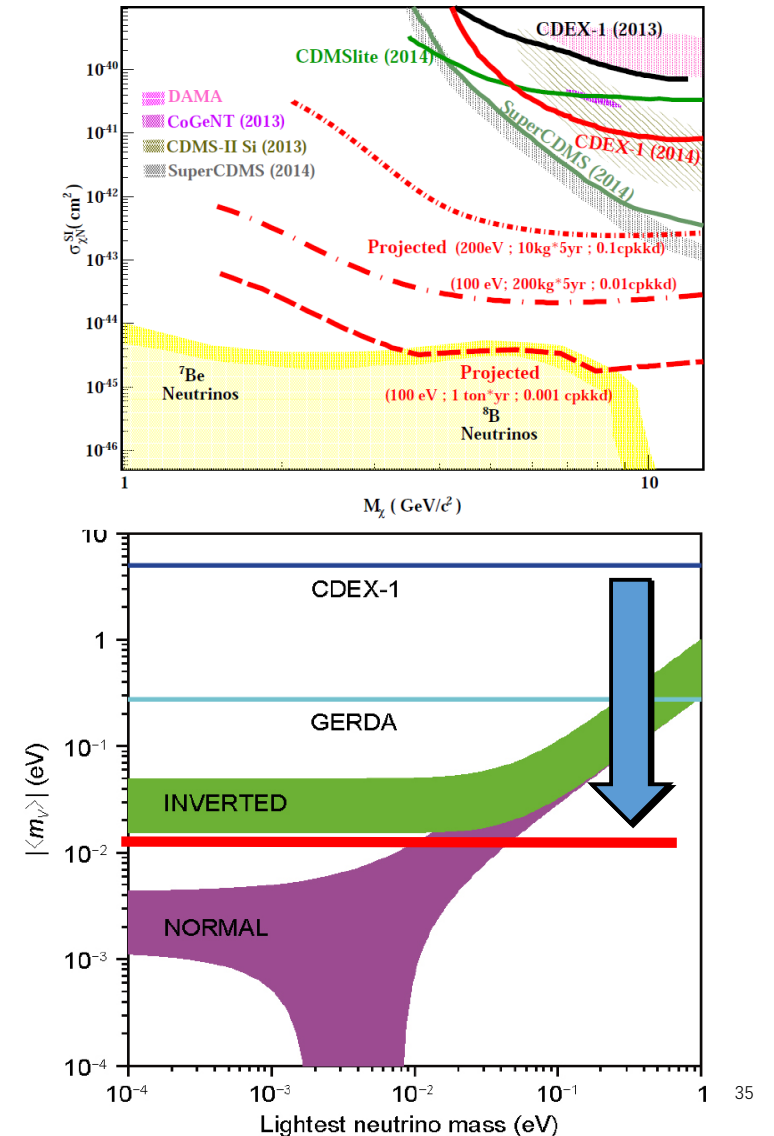
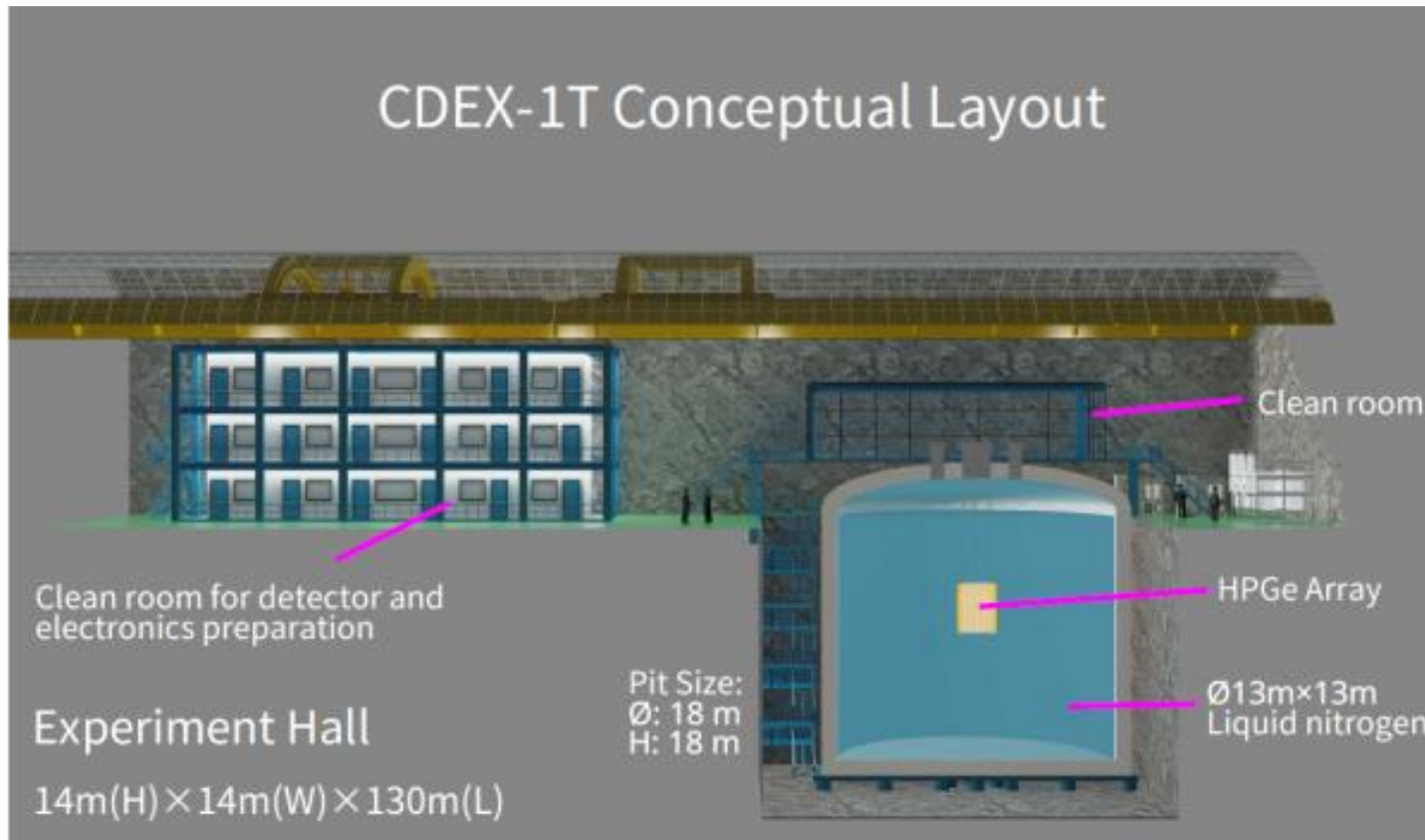
- $0\nu\beta\beta$

- Taking advantages of Ge detectors;
- Combined with Legend-1T
- Location Undetermined!



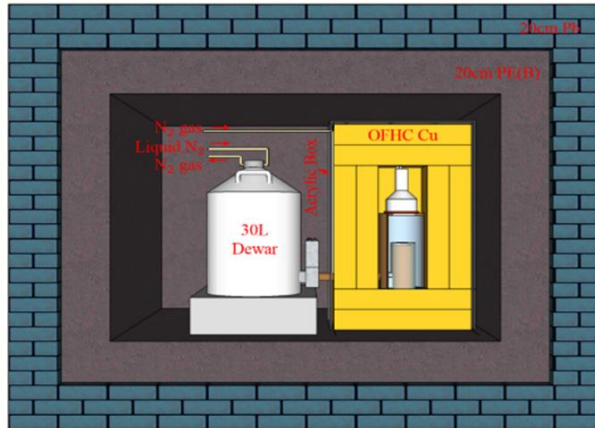
CDEX: China Dark Matter Experiment

- Based on Ge technologies, to directly detect DM;
- For $0\nu\beta\beta$, Combined with L1T.



CDEX Roadmap

CDEX-1A/B



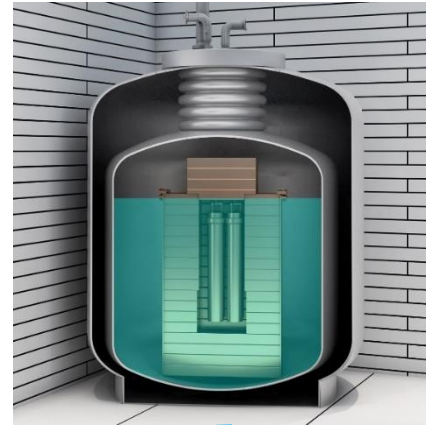
CJPL-I

2011

- ❑ PPC Ge detector with a mass of up to ~1 kg

- ✓ PRD88, 052004, 2013
- ✓ PRD90, 032003, 2014
- ✓ PRD90, 091701, 2014
- ✓ PRD93, 092003, 2016
- ✓ PRD95, 052006, 2017 (Axion)
- ✓ Sci. China (2017) ($0\nu\beta\beta$)
- ✓ CPC42, 023002, 2018

CDEX-10



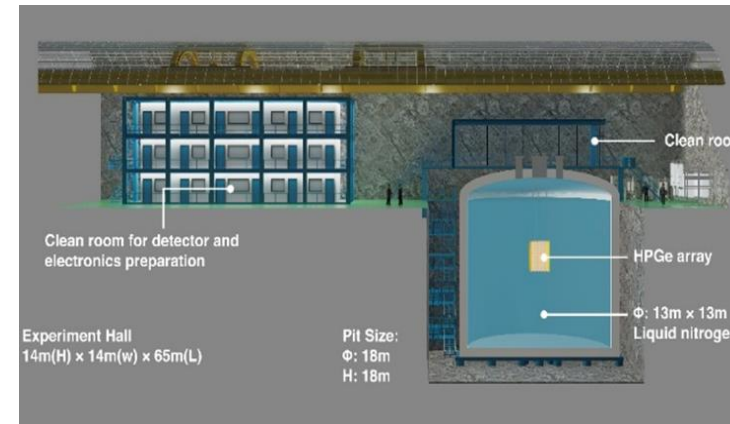
2016

- ❑ 10 kg PPC Ge detector array immersed into LN_2

- ✓ PRL120, 241301, 2018

Lower background
Lower threshold

CDEX-100 / CDEX-1T



CJPL-II

202X

- ❑ Ge array in large-volume LN_2
- ❑ multi-purpose: DM and $0\nu\beta\beta$

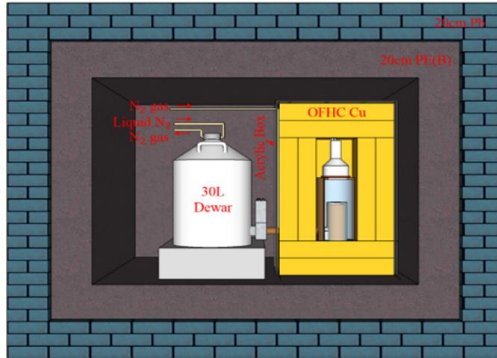
Key technologies:

- ✓ Ge crystal growth and ^{76}Ge enrichment
- ✓ Ge detector fabrication
- ✓ Ultra-low background VFE
- ✓ Ultra-pure copper for structure and cables
- ✓ Natural Ge detectors as veto
- ✓

Enriched Ge
Natural Ge

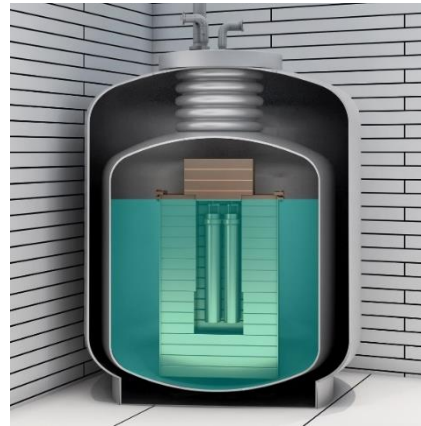
CDEX Roadmap

CDEX-1A/B



2011

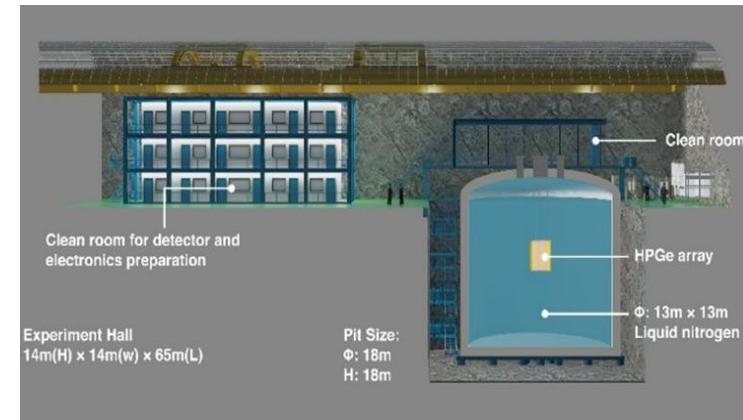
CDEX-10



2016

- Lower Background Level
- Lower Threshold
- Larger target mass

CDEX-100 / CDEX-1T

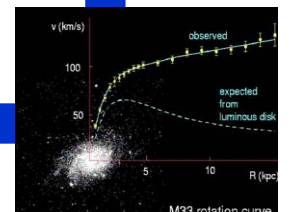


202X

- More key technologies in control
- More physics channels opened...
- More fun, more exciting...

Background Level

Threshold



Summary

- CDEX: unique advantages of PPC Ge detectors for light DM search at CJPL;
- New SI limit $8 \times 10^{-42} \text{cm}^2$ at 4-5 GeV by CDEX-10 first results;
- AM analysis based on CDEX-1B's 4-year data ruled out DAMA/LIBRA phase1 and CoGeNT, obtained the best sensitivity below 6 GeV;
- Via the Migdal effect, new m_χ windows are opened and extended down to 50 MeV, the best sensitivity in σ_{SI} is achieved for $m_\chi \sim 50\text{--}180$ MeV.
- New site in Hall C1 of CJPL-II project, lower bkg expected w/ new large cryo-tank;
- Home-made Ge detector, FE electronics, crystal, UG copper e-forming ongoing...
- More detectors coming w/ particular control of cosmogenic bkg;
- Other physics: Axion, dark photon, $0\nu\beta\beta$,...

Thanks for your attention!



锦屏一级水电站世界最高坝