Recent status and prospects of CDEX dark matter search at CJPL

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On behalf of the CDEX collaboration

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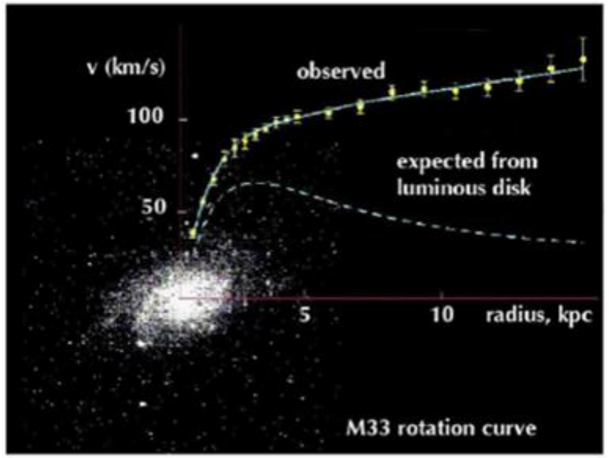
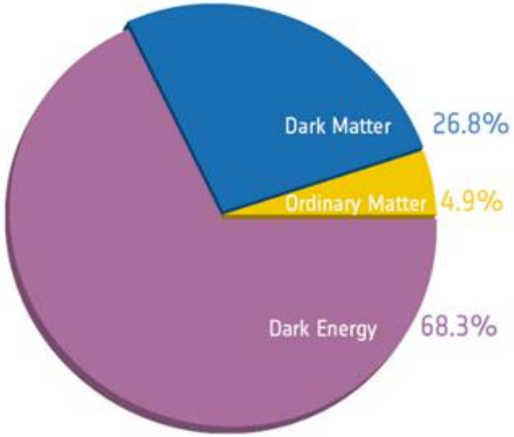
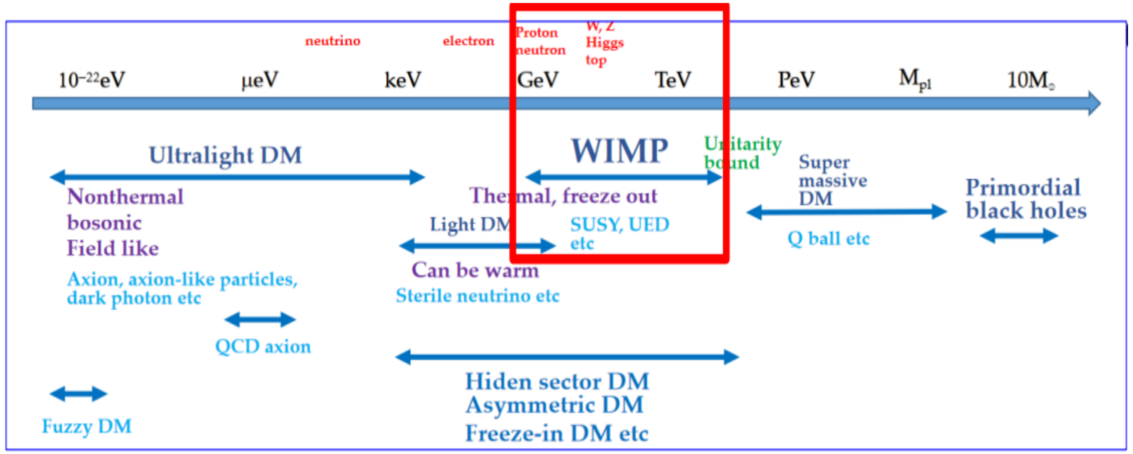
Outline

- Dark Matter (DM) and its Direct detection (DD)
- Introduction to CDEX and CJPL
- Recent status of CDEX
- Prospect of CDEX
- Summary

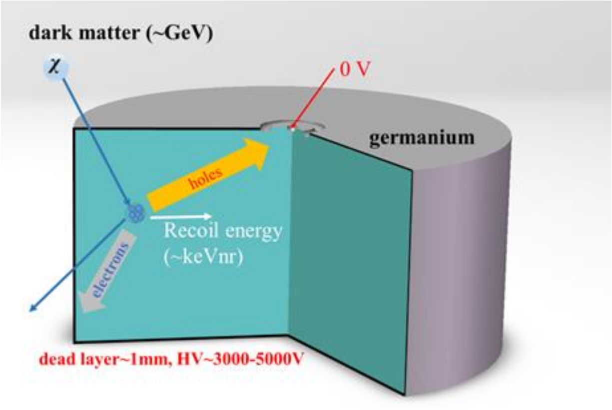
Dark Matter



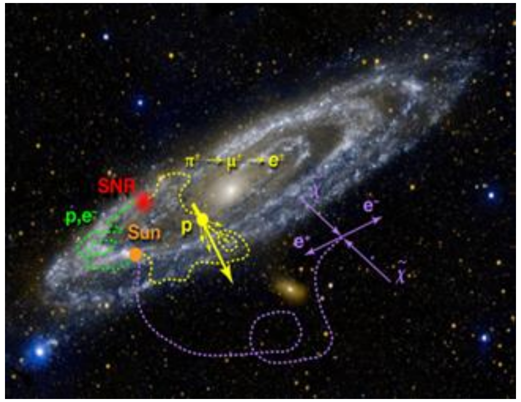




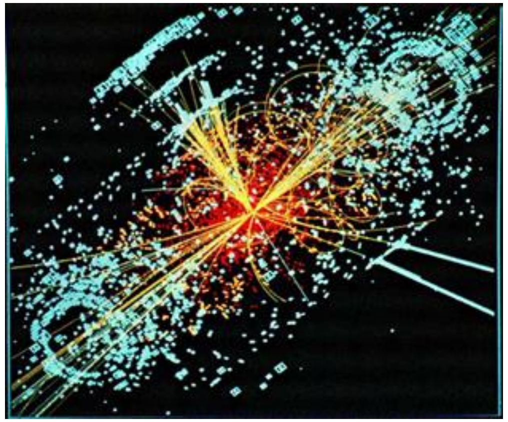
Direct



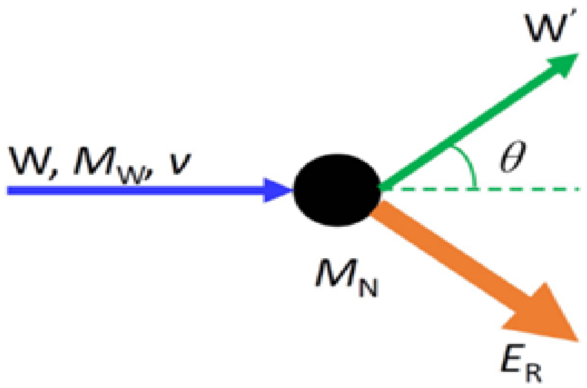
Indirect

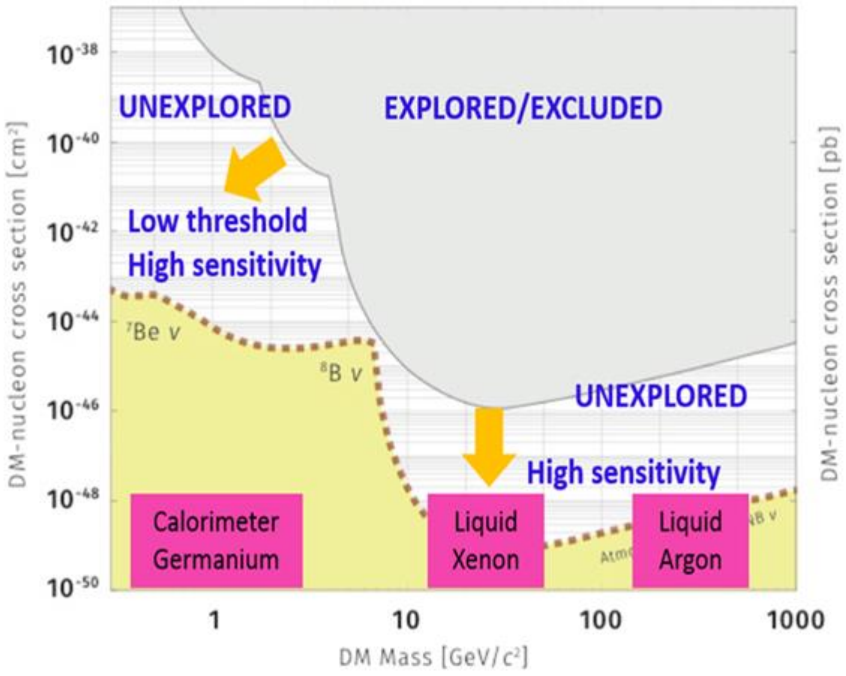


Accelerator



Dark Matter Direct Detection





Astrophysics Particle physics

$$\frac{dR}{dE_R} = N_T \frac{\rho_\chi}{m_\chi} \int d^3\vec{v} v f_v(\vec{v} + \vec{v_E}) \frac{d\sigma}{dE_R}$$

- **Advantage of Ge detector:**
  - ✓Lower Background
  - ✓Lower Energy threshold
  - ✓Better Energy Resolution
  - ✓Long-time stability

China Dark matter EXperiment

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

- Formed in 2009, 11 institutions and 100 persons now;
- Direct detection of light DM by High Purity Germanium detectors (HPGe);

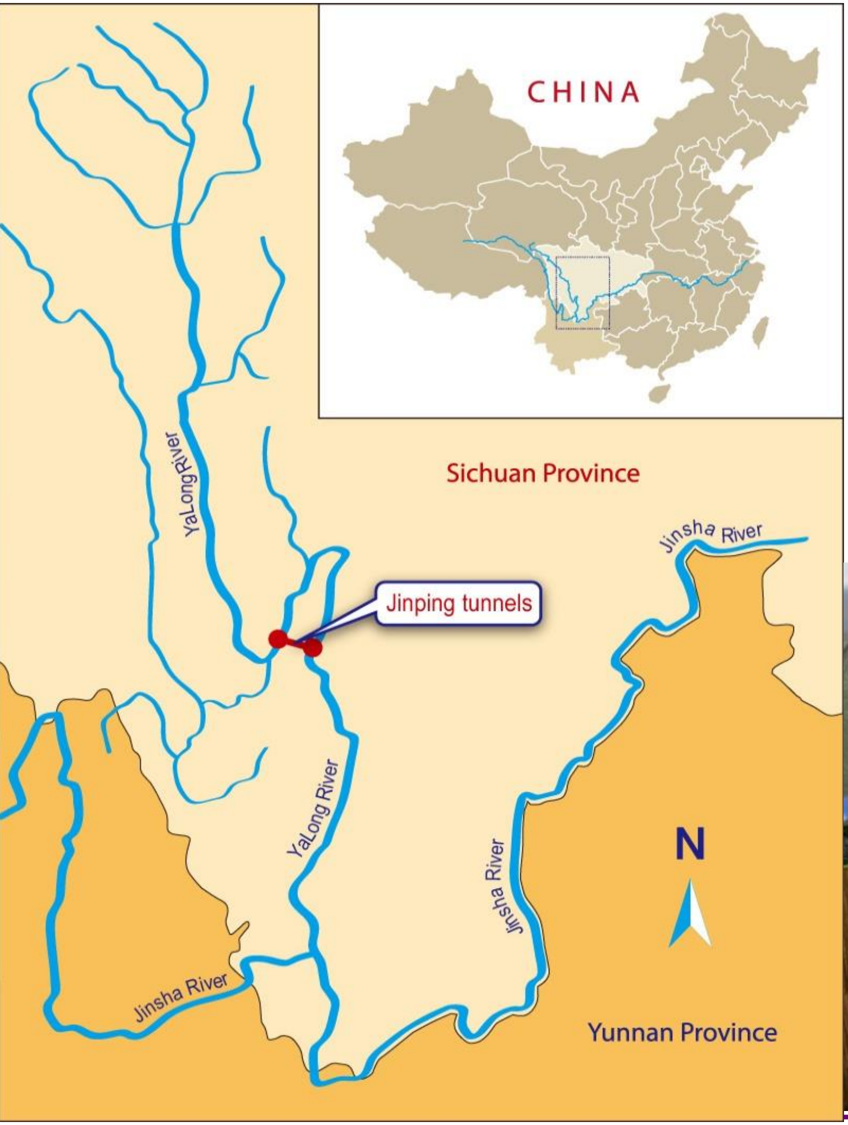
China JinPing underground Laboratory

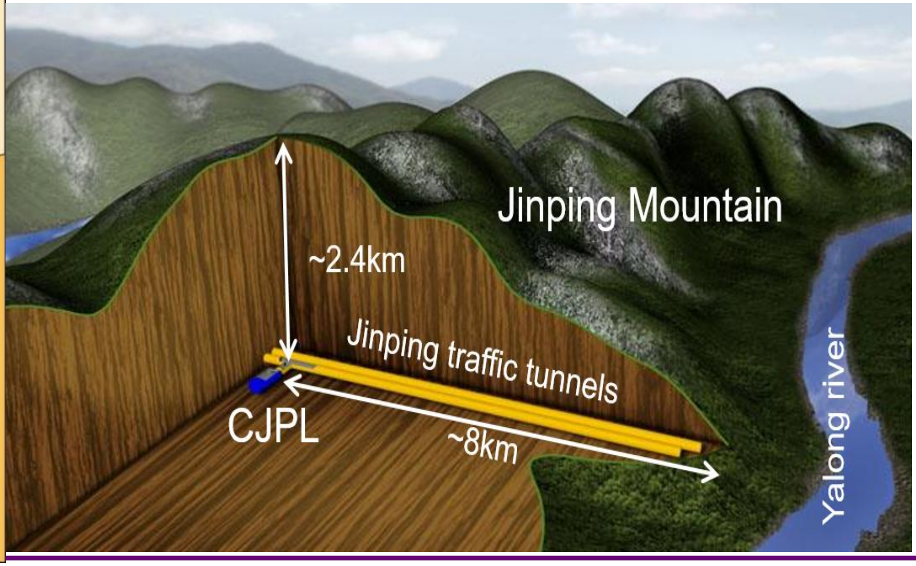
CJPL
中国锦屏地下实验室
China Jinping Underground Laboratory

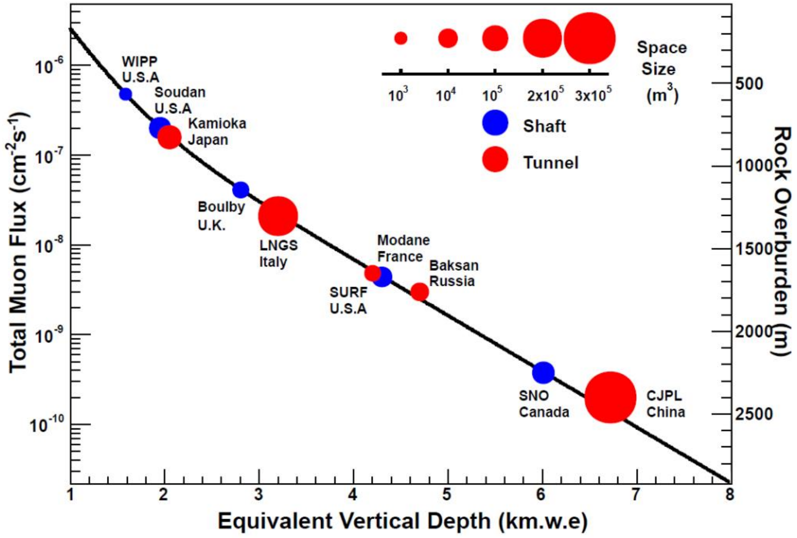
http://cjpl.tsinghua.edu.cn/

World's deepest underground lab, CJPL

- Constructed by Tsinghua U. and Yalong Hydropower Company in 2009-2010
- Extension project, CJPL-II, final exam and expected to be completed in 2024



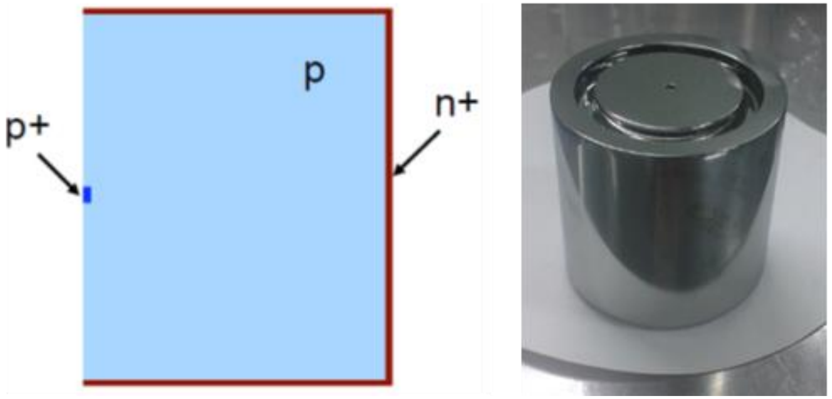


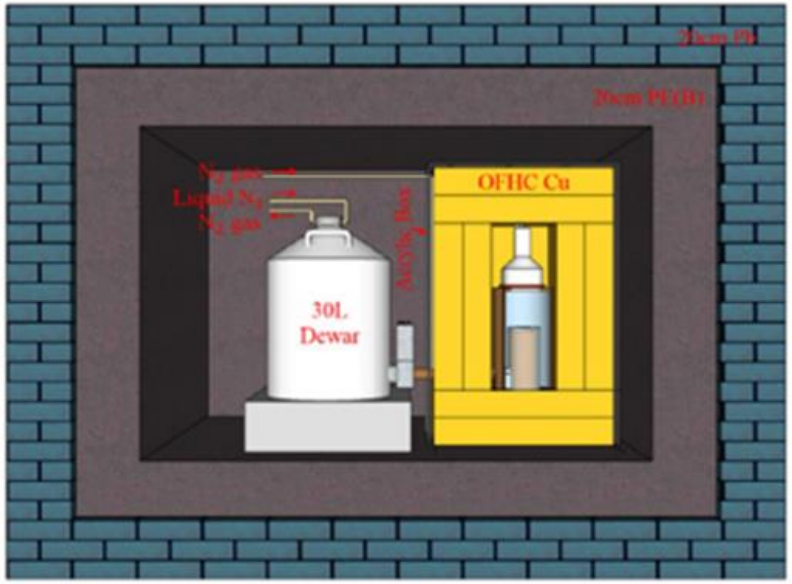


CDEX Experiment

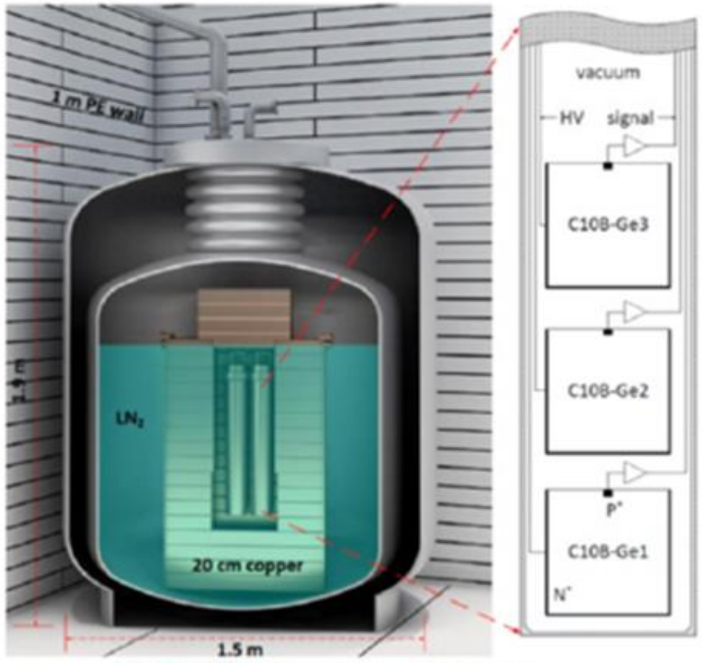
- DM detection with Ge prepared since 2003 and started in 2005 in Y2L (5g);
- **CDEX-1:** Development of PPC Ge detector, bkg understanding, since 2011;
- **CDEX-10:** Performances of Ge array detector immersed in LN_2, since 2016;

P-type Point-Contact(PPC) Germanium detector





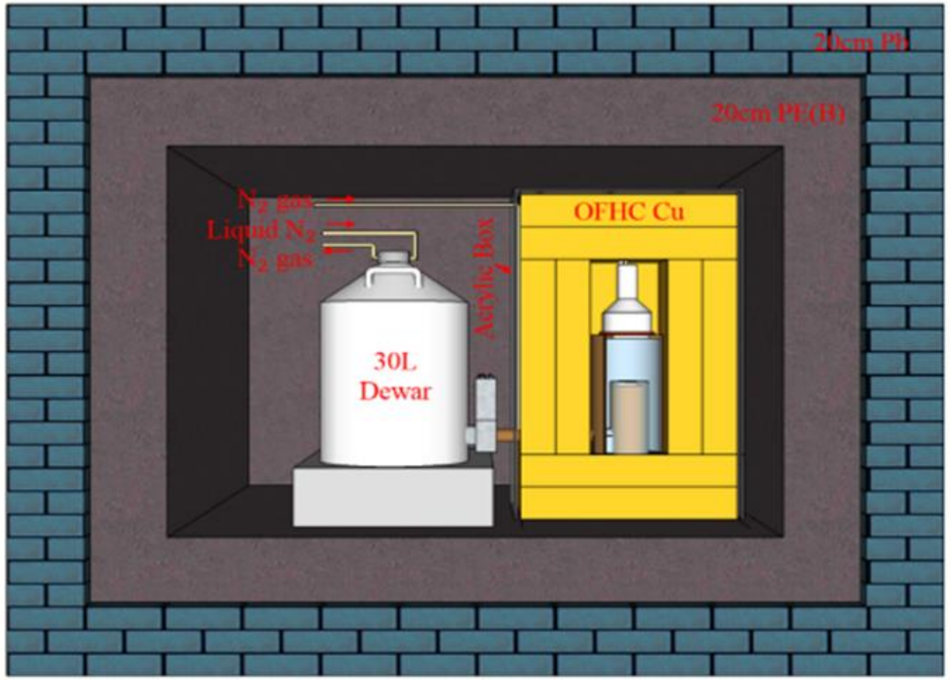
CDEX-1A&B: 1kg PPC Ge×2



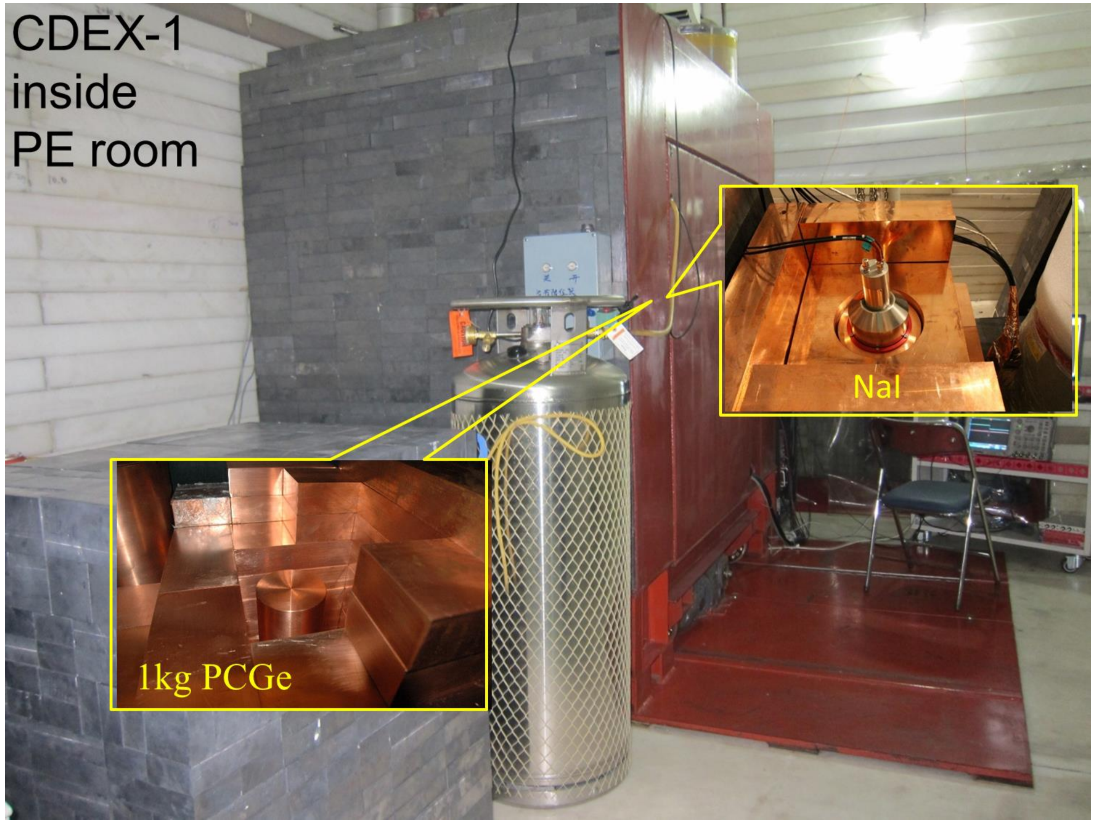
CDEX-10: ~10kg PPC Ge array

CDEX-1 Status

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

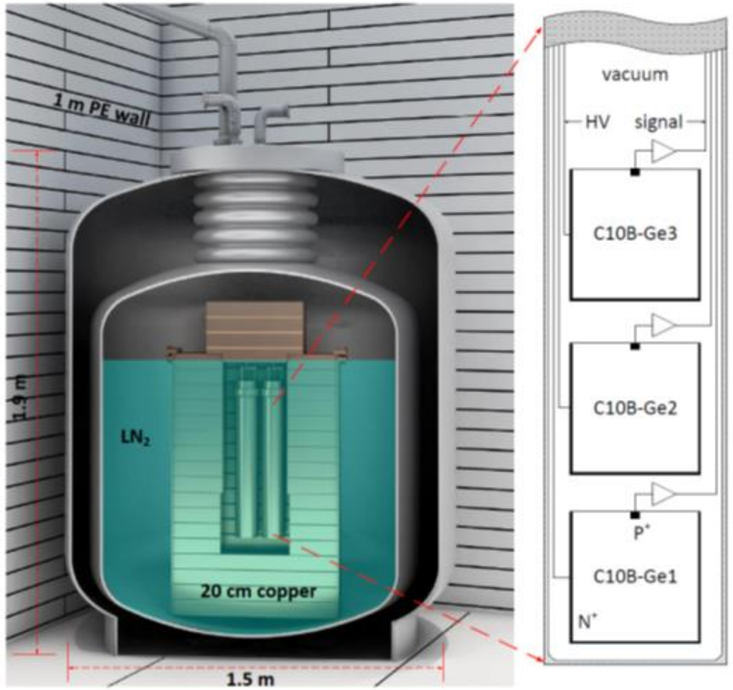


CDEX-1A&B: 1kg PPC Ge×2

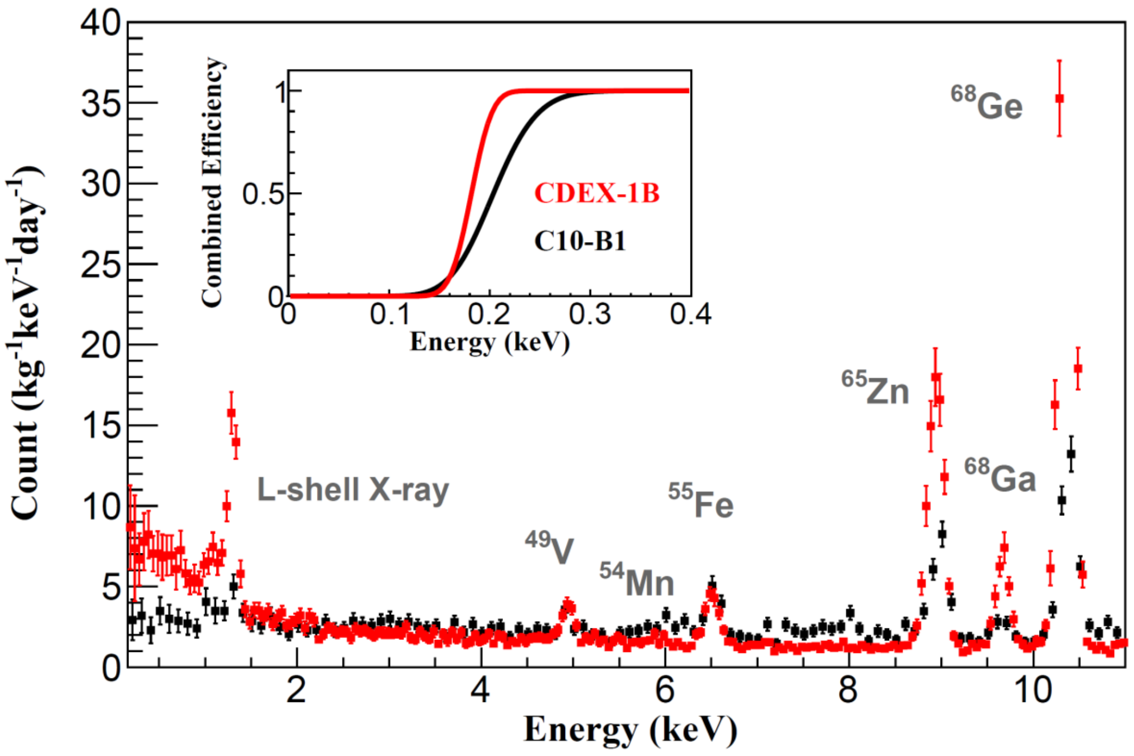


CDEX-10 Status

- Array detectors: 3 strings with 3 detectors each, ~10kg total;
- Direct immersion in LN2 for cooling and shielding;
- Prototype system for future hundred-kg to ton scale experiment
  - ✓ Light/radio-purer LN2 replacing heavy shield i.e. Pb/Cu;
  - ✓ Arraying technology to scalable capability;



Dataset of CDEX-1B&10B



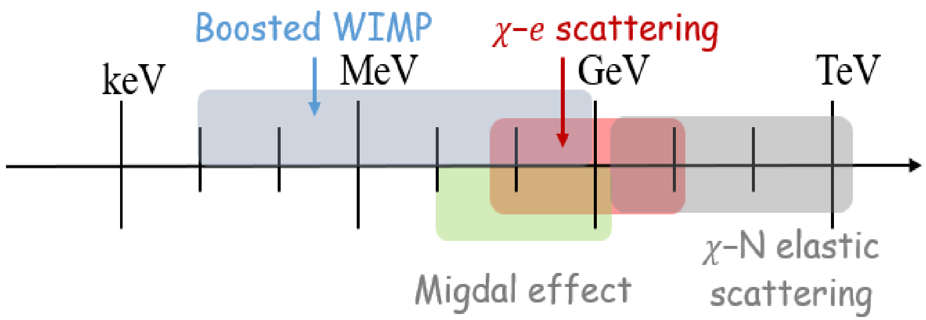
Measured C1B(red) and C10B1 spectrum.
The combined efficiency is shown in the inset.

- **Threshold：**
  - ✓ 160 eVee (electron equivalent energy)
- **Background level：**
  - ✓ 2.5 cpkkd@2-4 keVee (cts/(keV·kg·day))
- **Exposure:**
  - ✓ CDEX-1B： 1107.5 kg•day
  - ✓ C10-B1： 205.4 kg•day

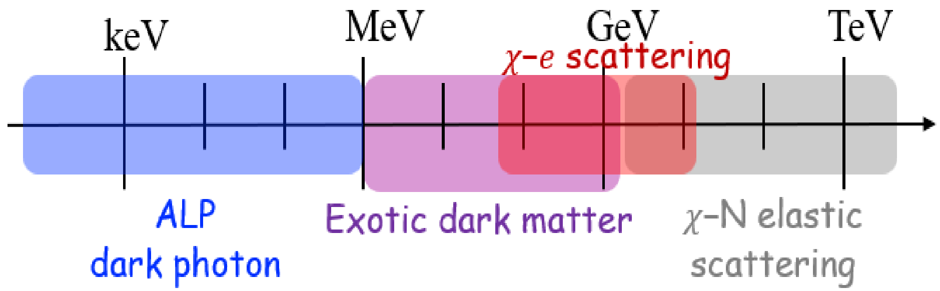
Chin. Phys. C 42, 023002 (2018); ***Phys. Rev. Lett.*** 120, 241301 (2018)

CDEX-1 & CDEX-10 Results

- **WIMP search**
  - ✓ $\chi - N$ elastic scattering
  - ✓ Annual modulation *PRL 123, 221301 (2019)*
  - ✓ Migdal effect *PRL 123, 161301 (2019)*
  - ✓ Boosted WIMP: down to $\mathcal{O}(10\ \mathrm{keV})$ *PRD 106, 052008 (2022)*
  - ✓ $\chi - e$ scattering down to $\mathcal{O}(10\ \mathrm{MeV})$ *PRL 129, 221301 (2022)*



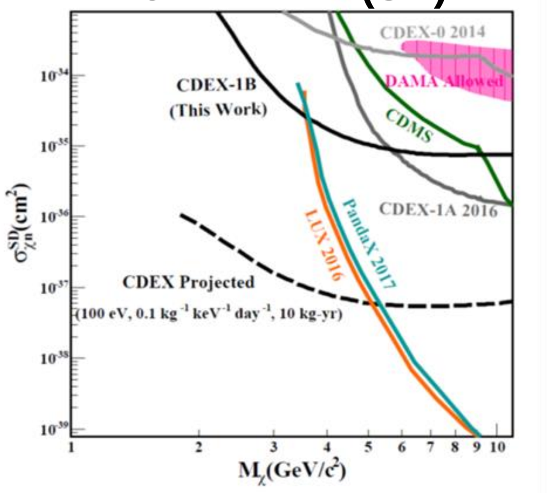
- **New physics beyond the WIMP**
  - ✓ Axion like particle: down to $\mathcal{O}(100\ \mathrm{eV})$ *PRD 101, 052003 (2020); PRD 95, 052006 (2017)*
  - ✓ Dark photon: down to $\mathcal{O}(100\ \mathrm{eV})$ *PRL 124, 111301, (2020)*
  - ✓ Exotic DM: down to $\mathcal{O}(1\ \mathrm{MeV})$ *PRL 129, 221802, (2022)*



$\chi - N$ elastic scattering from CDEX-1B&10

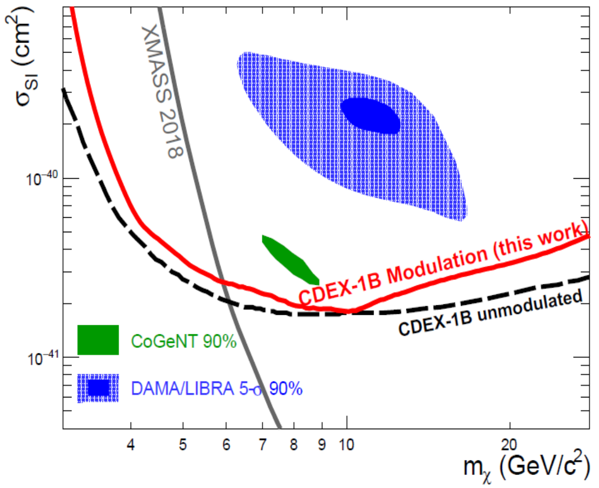
- **CDEX-1B**:
  - ✓ First extended the mass to 2 GeV among Ge experiments.
  - ✓ The most sensitive result on SD χ−N elastic scattering below 4 GeV.
  - ✓ The best result on the WIMP annual modulation below 6 GeV.
- **CDEX-10:**
  - ✓ The most sensitive result on SI χ−N elastic scattering at 4-5 GeV.

C1B WIMP (SD)



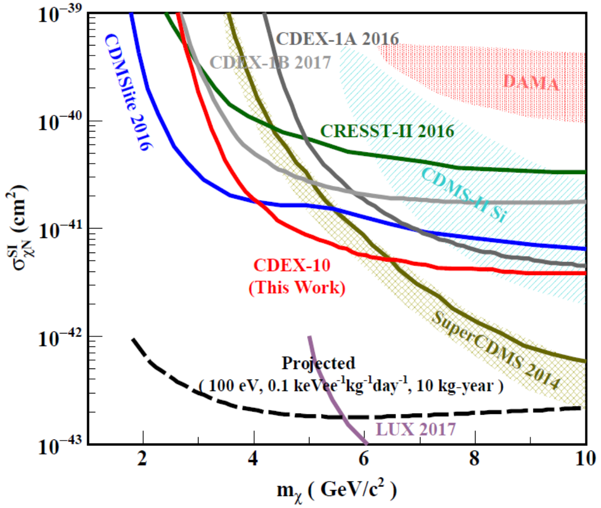
Chin. Phys. C 42, 023002 (2018)

C1B WIMP Annual Modulation



Phys. Rev. Lett. 123, 221301 (2019)

C10 WIMP

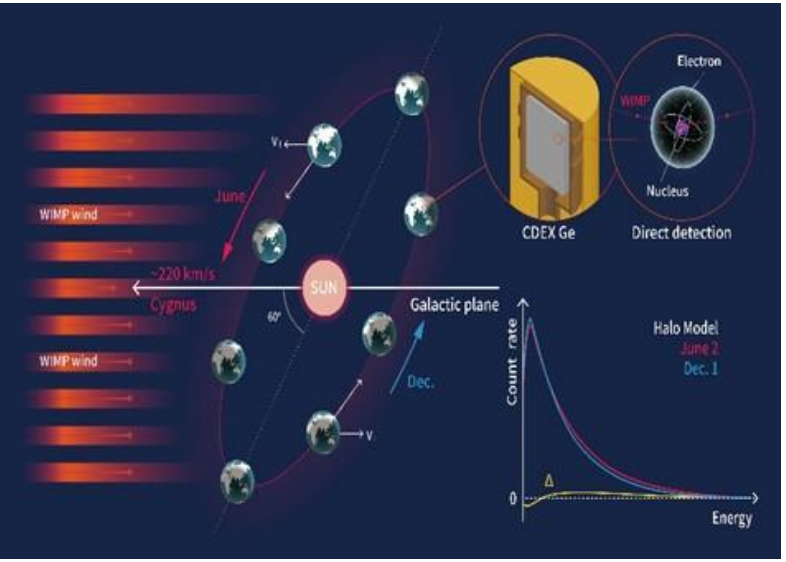


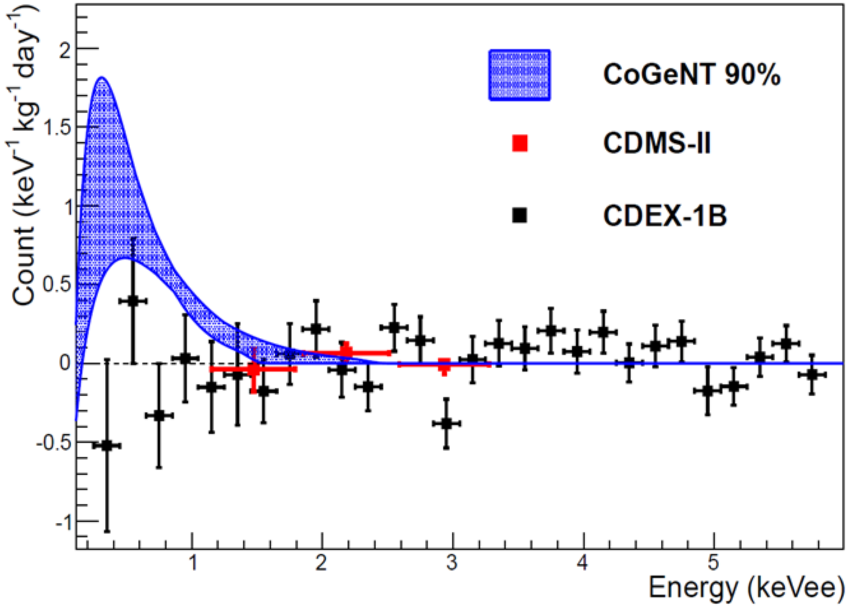
Phys. Rev. Lett. 120, 241301 (2018)

Annual Modulation analysis from CDEX-1B

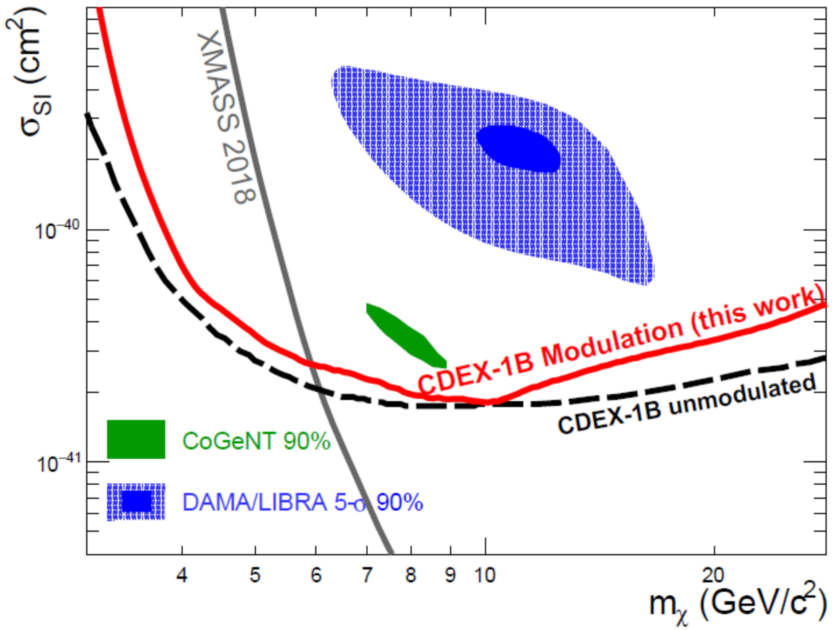
- AM provide smoking-gun signatures for WIMPs independent of background modeling, while only requires background is stable with time;
- CDEX-1B excludes CoGeNT's signal region, also DAMA/LIBRA phase-1's interpretation with the WIMP SI interaction under Standard Halo model in Germanium crystal.

Phys. Rev. Lett. 123:221301 (2019)





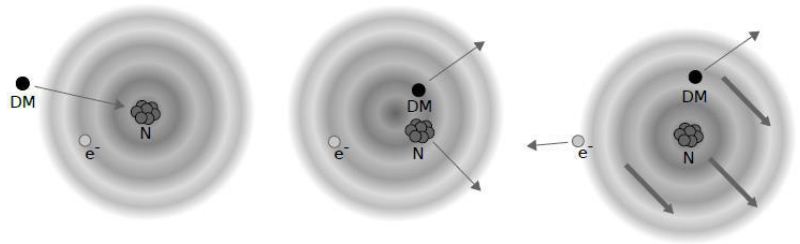
Best-fit of modulation amplitude w/ phase=152.5day



SI Limits from AM

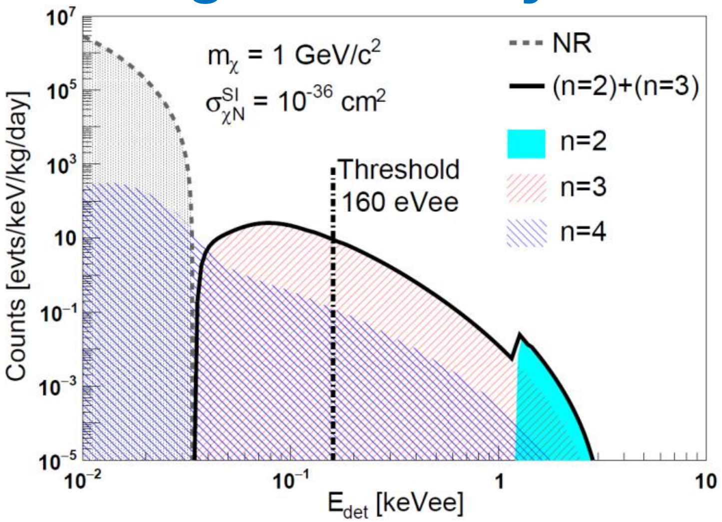
WIMP searches with Migdal effect

- **Migdal effect (ME)**：
  - ✓ Elastic scattering： $\chi+N\rightarrow\nu+N(E_R)$
  - ✓ Migdal effect： $\chi+A\rightarrow\chi+N(E_R)+e^-\ (E_{EM})$

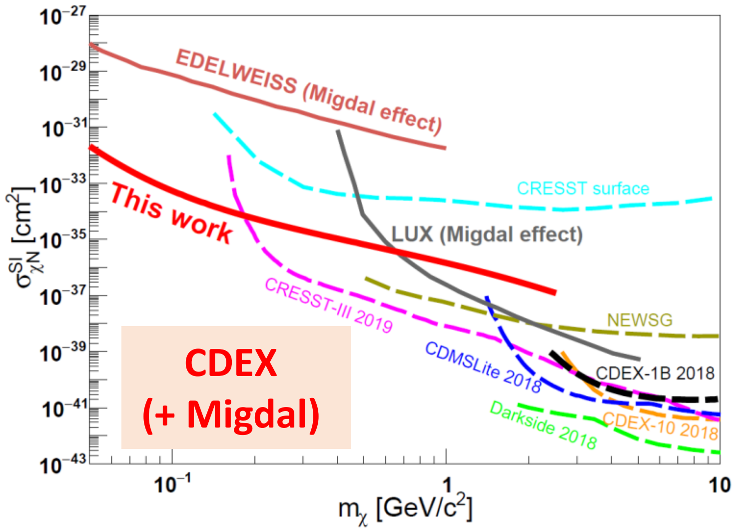


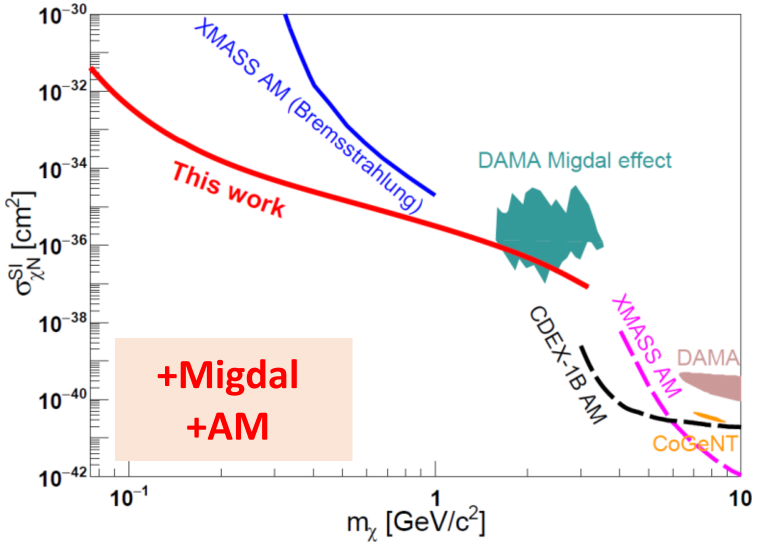
- Time-Integrated Analysis with Migdal: 737.1 kg-d, w/ Eth 160 eVee;
- AM Analysis: 1107.5 kg·day, w/ Eth 250 eVee;
- **Leading sensitivity in 50-180 MeV;**

Phys. Rev. Lett. 123:161301 (2019)



Expected Spectrum

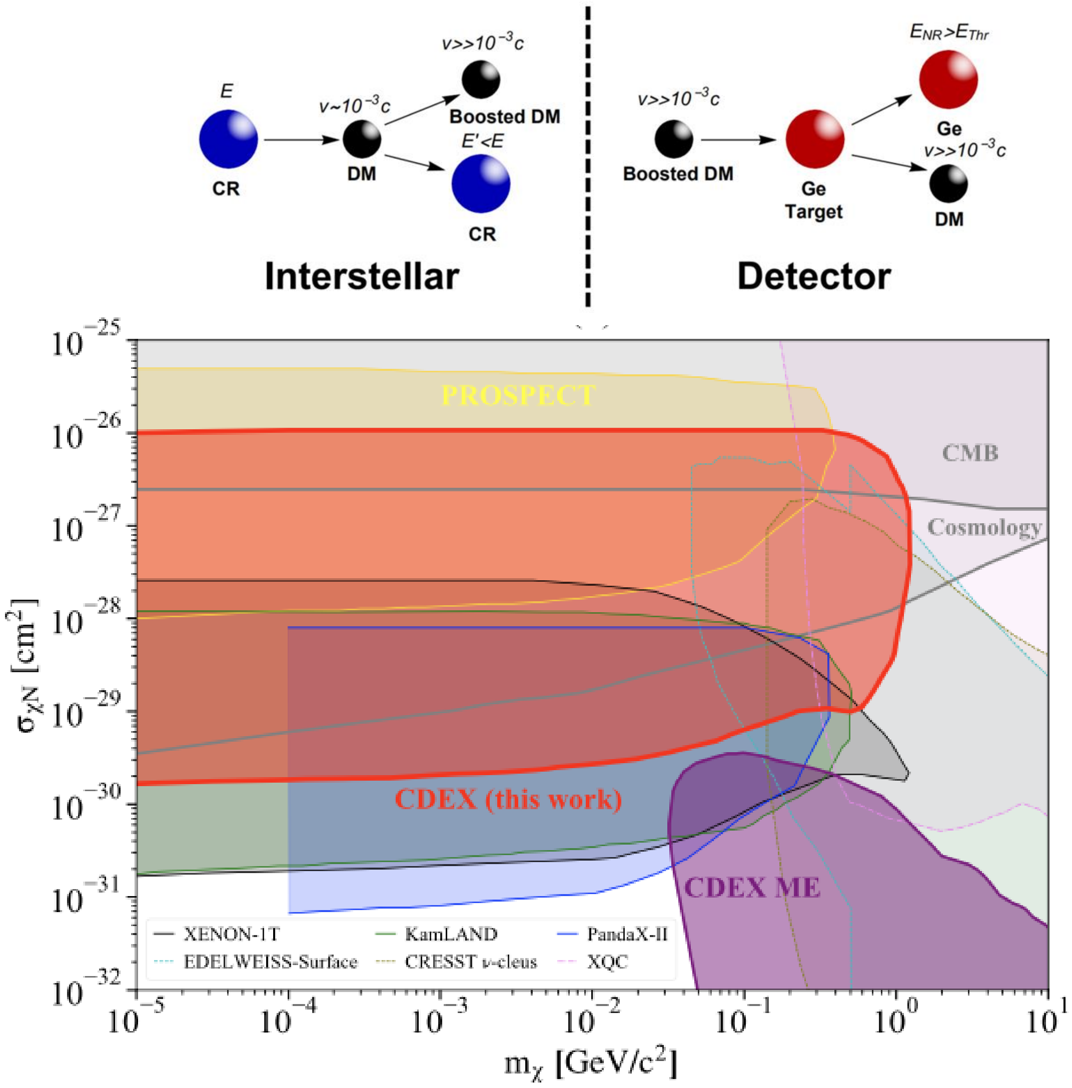




Cosmic Ray Boosted DM (CRDM)

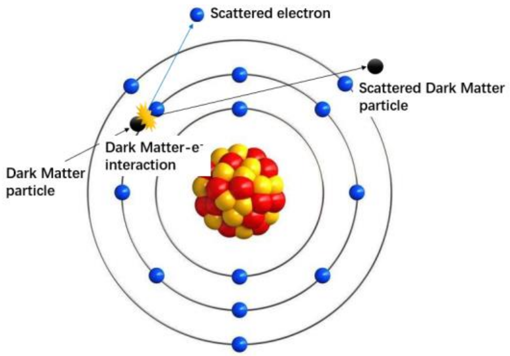
- DM particles can be boosted to relativistic momenta by elastic scattering with CR nucleus in the Galaxy;
- Using CDEX-10 205.4 kg·day data and the CRDM scenario to **exclude region from 1.7×10^{-30} to 10^{-26} cm^2**, most sensitive results from solid detector baed experiment;
- Earth shielding effect is evaluated by the Monte-Carlo sim package CJPL_ESS

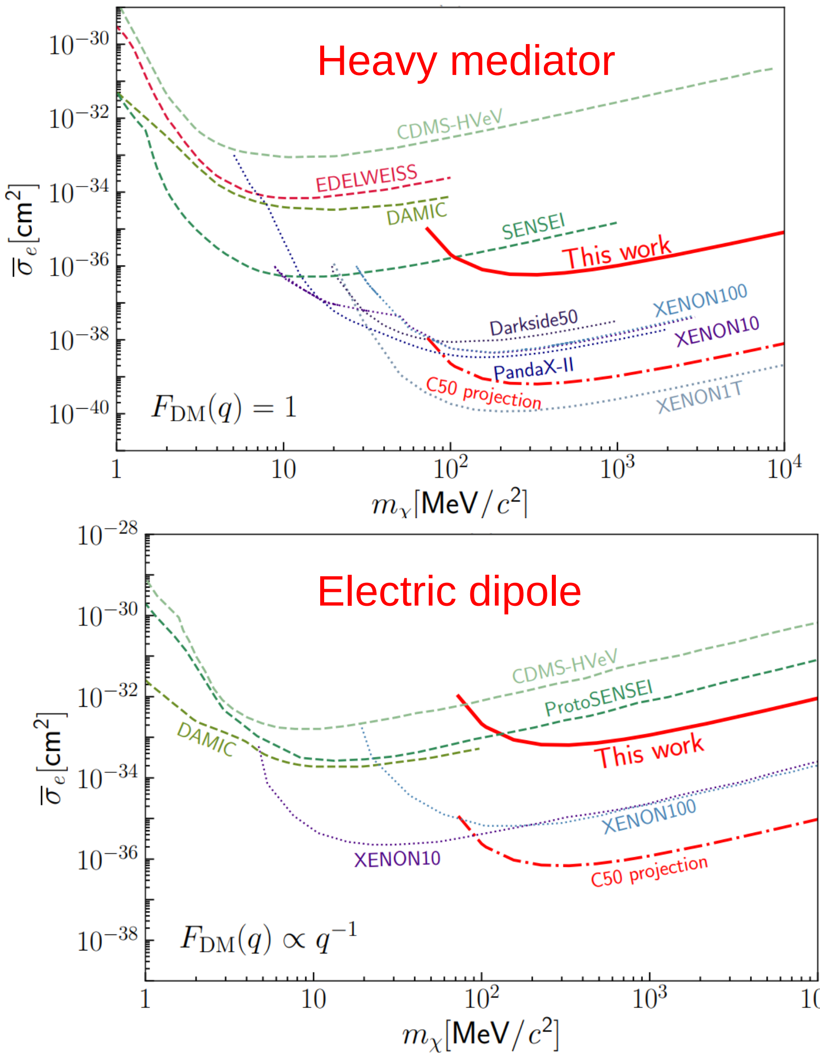
Phy. Rev. D ***106****, 052008 (2022)*



χ−e scattering in Ge detectors

- Light χ can potentially pass most of the energy onto electrons, depositing observable energy via $\chi - e$ **scattering**;
- Using EXCEED-DM to evaluate $\chi - e$ scattering in crystal;
- Leading results for the heavy mediator /electric dipole coupling scenario among solid-state detector-based experiments in high mass range.
- Revealing the vast potential of such technical route in probing the χ-e scattering.



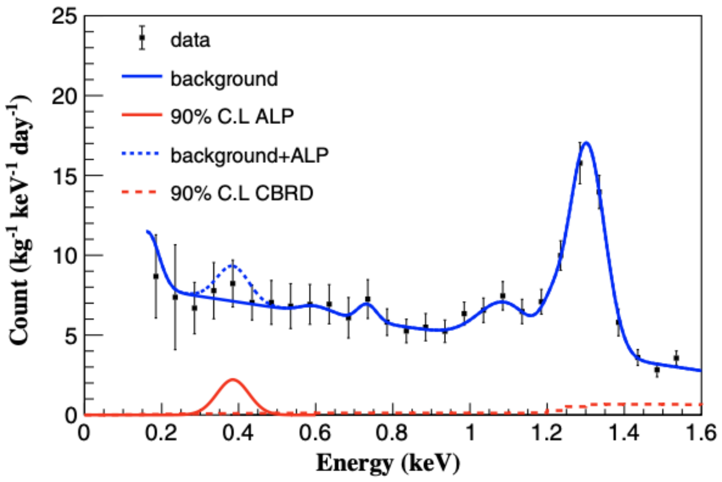


Phys. Rev. Lett. *129, 221301 (2022)*

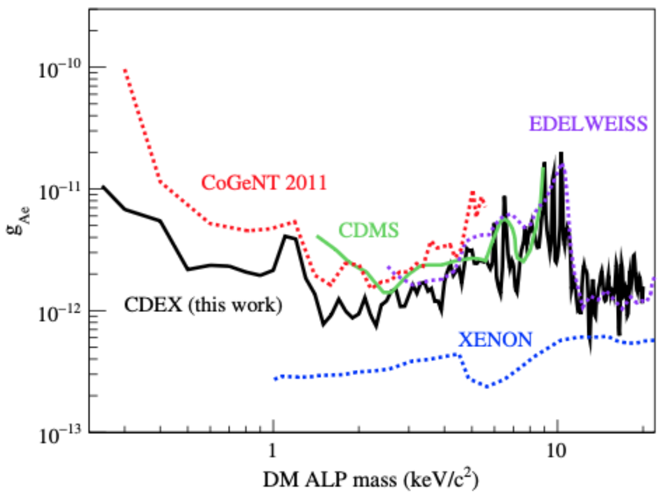
Solar Axions, ALPs

- Background assumption: continuous background + X-rays
- Profile likelihood method
- Excellent energy resolution of Ge is suited for the monochromatic DM axion and Fe-57 axions
- Competitive g_{Ae} constraints exist for m_a: 100 eV ~ 1 keV

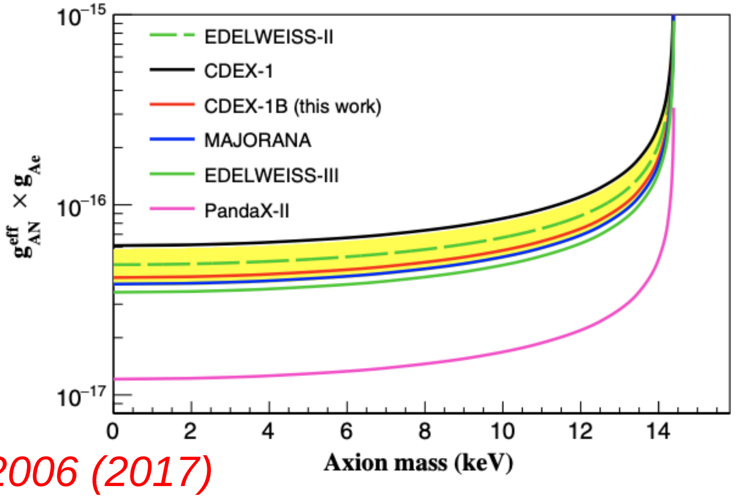
ALP dark matter expected spectrum



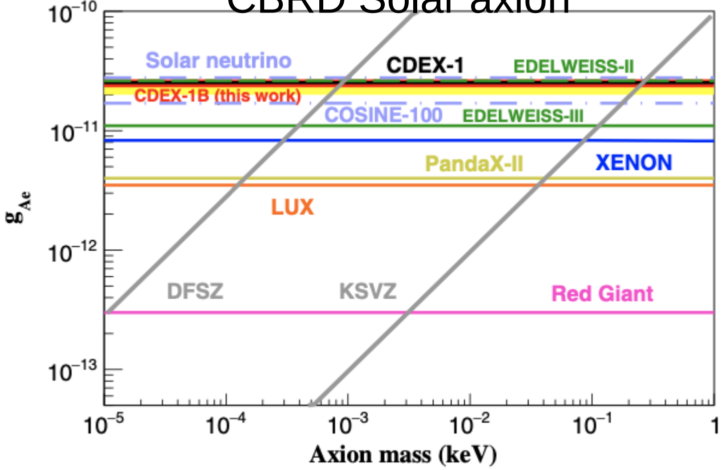
ALP dark matter in 2017



Fe-57 solar axion



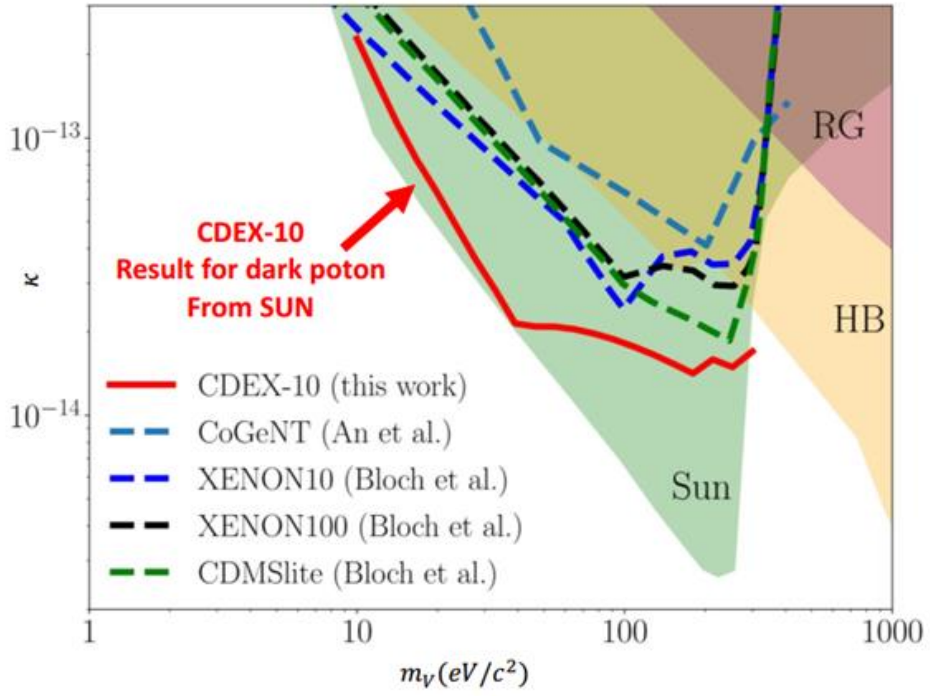
CBRD Solar axion

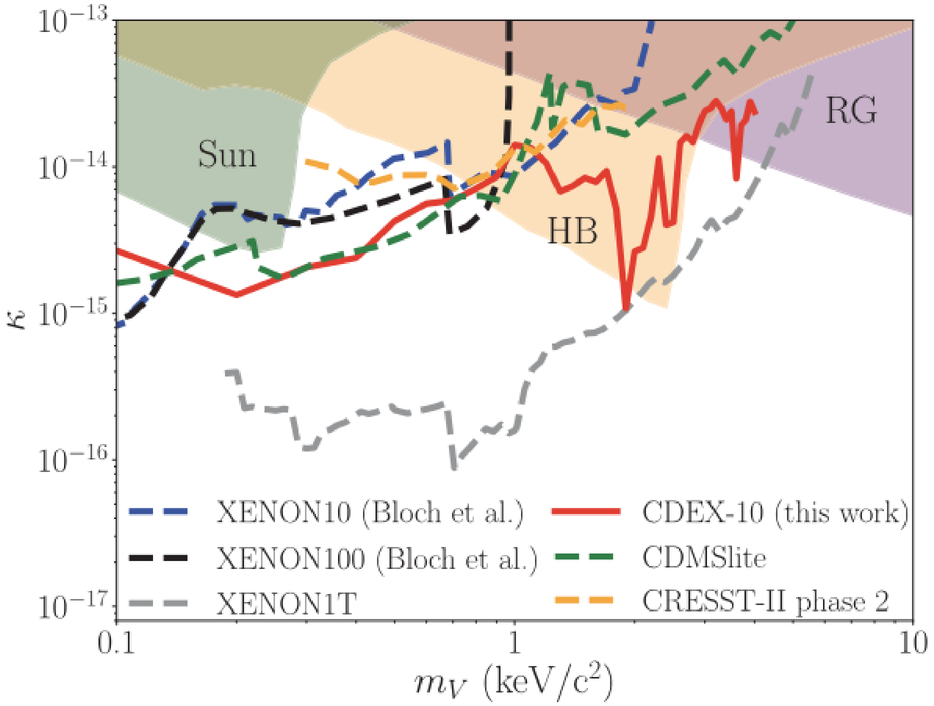


Phys. Rev. D *101, 052003 (2020);* ***Phys. Rev. D*** *95, 052006 (2017)*

Solar Dark Photon

- Solar is the most significant dark photon source.
- Detection method: $\boldsymbol{V+A \rightarrow A^{+}+e^{-}}$;
- The most stringent limits on $\boldsymbol{\kappa}$ with mass of 10 to 300 eV for solar dark photon;





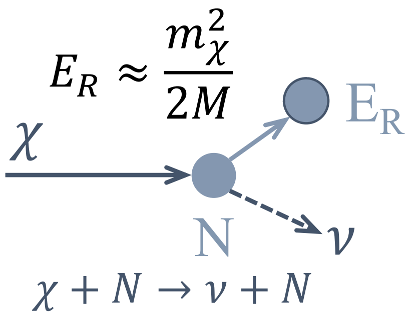
Phys. Rev. Lett. 124:111301 (2020)

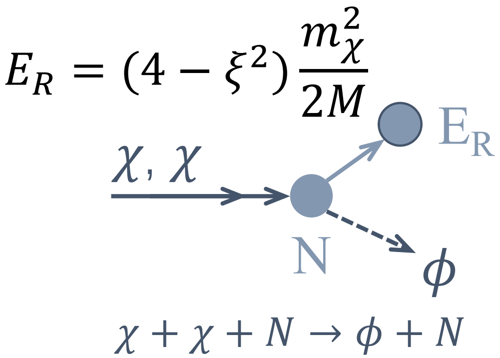
Exotic DM results

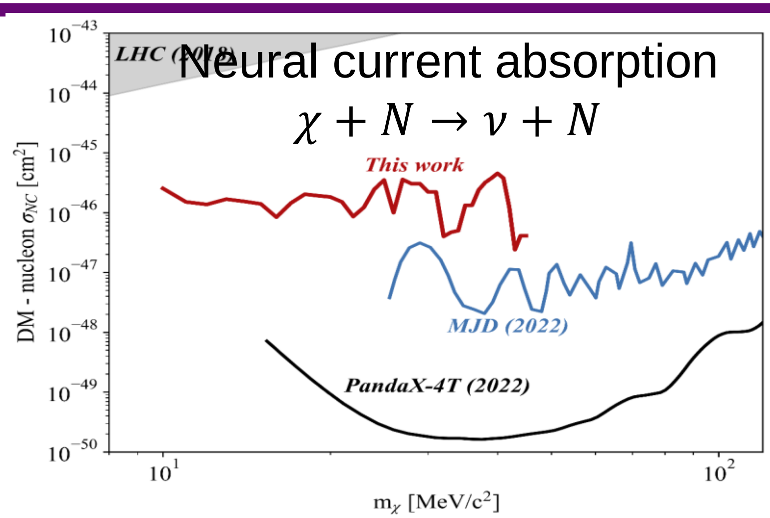
- Low mass dark matter (χ) may interact with nucleon (N):
  - ✓ Neural current fermionic DM absorption:

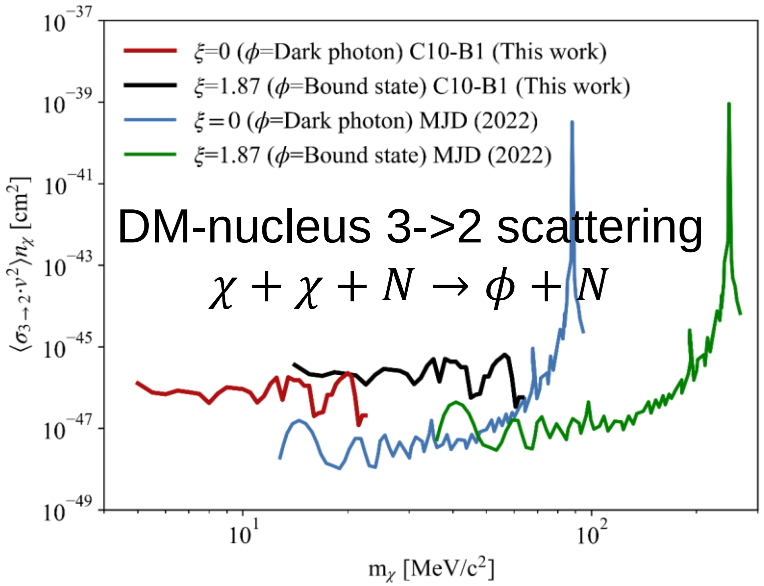
    $\chi + N \rightarrow \nu + N$
  - ✓ DM-nucleus 3->2 scattering:

    $\chi + \chi + N \rightarrow \phi + N$



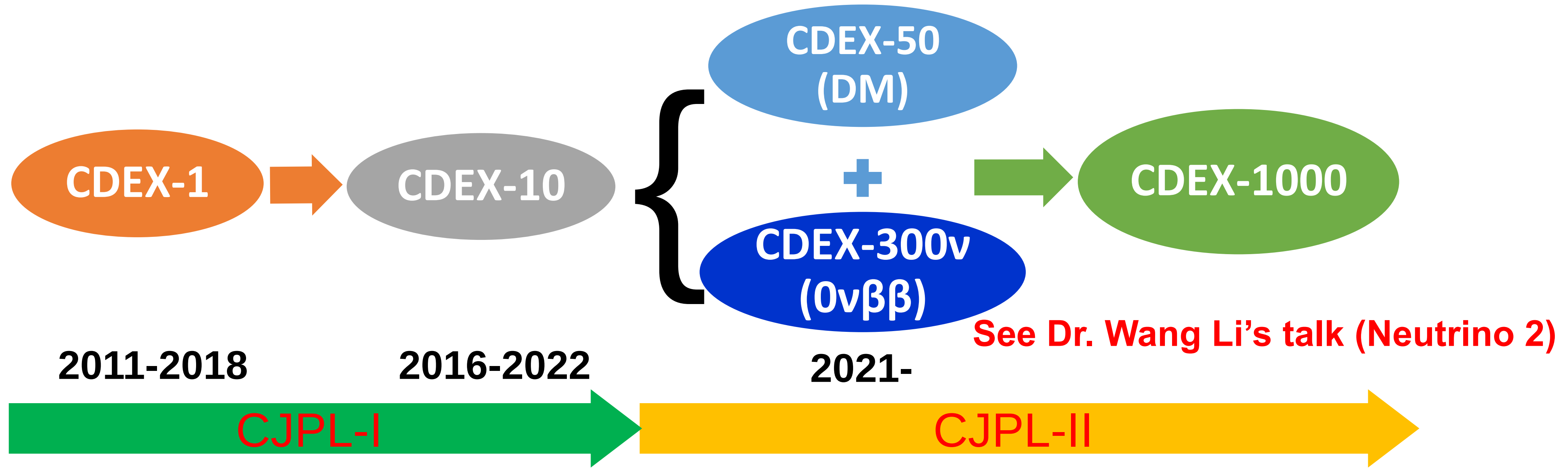






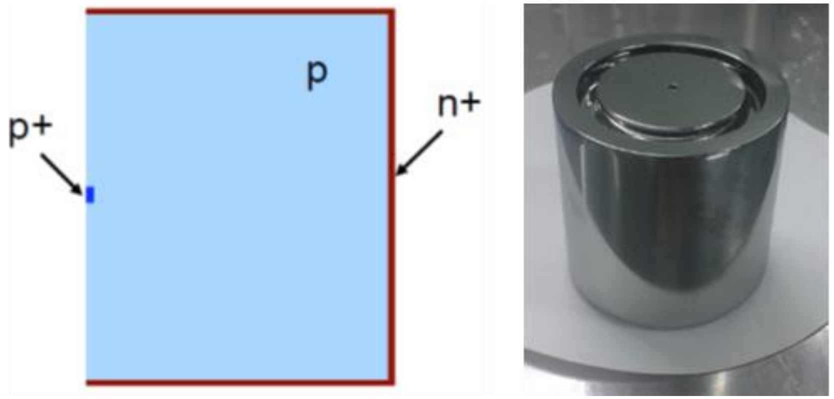
CDEX Roadmap

- **CDEX-1** (2011-2018): Development of PPC Ge detector, bkg understanding
- **CDEX-10** (2016-2022): Performances of Ge array detector immersed in LN2
- **CDEX-50** (2021-202X): 50kg Ge detector arrays for DM searches
- **CDEX-300ν** (2021-202X): 300kg enriched Ge detector arrays for 0νββ Exp.

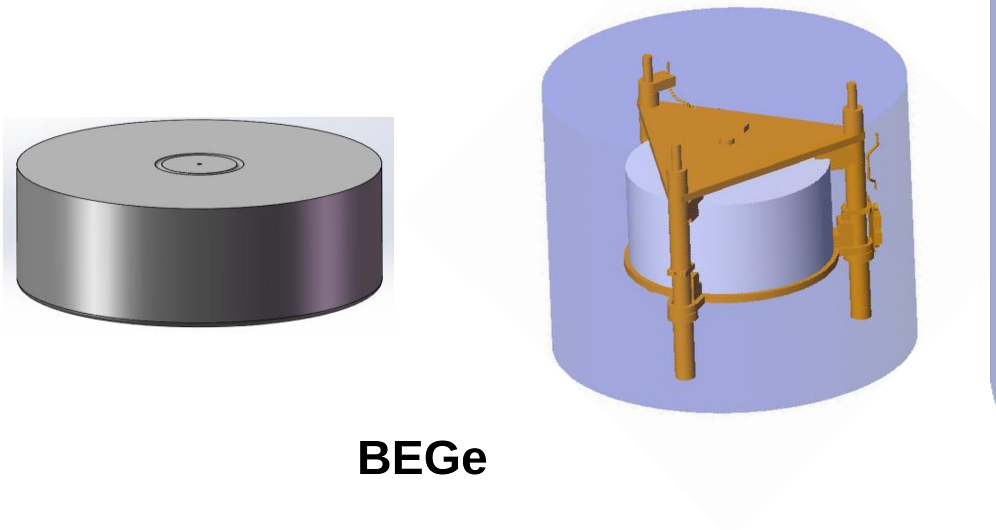


CDEX-50

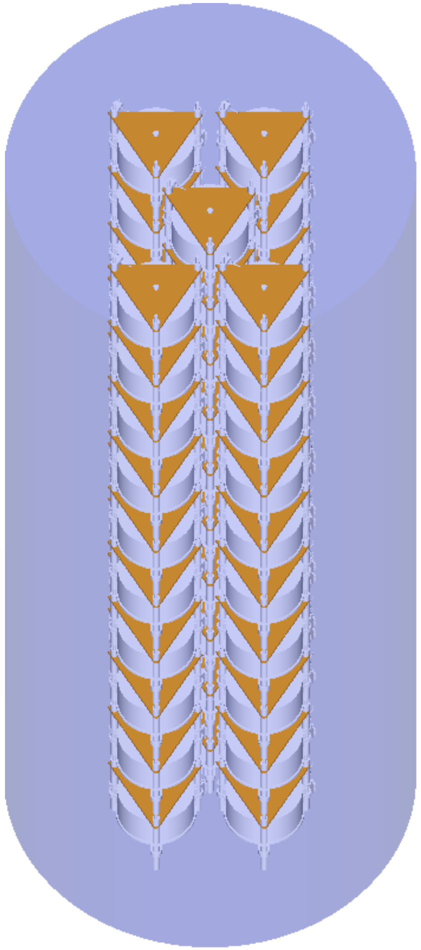
- Ge detectors array directly immerse into Liquid Nitrogen for cooling and shielding;
- Composed of 5 strings, 10 detectors/string;
- target mass (Ge) reaches ~50kg;
- Two types of Ge detectors: Broad Energy Ge (BEGe) & PPCGe;



PPCGe

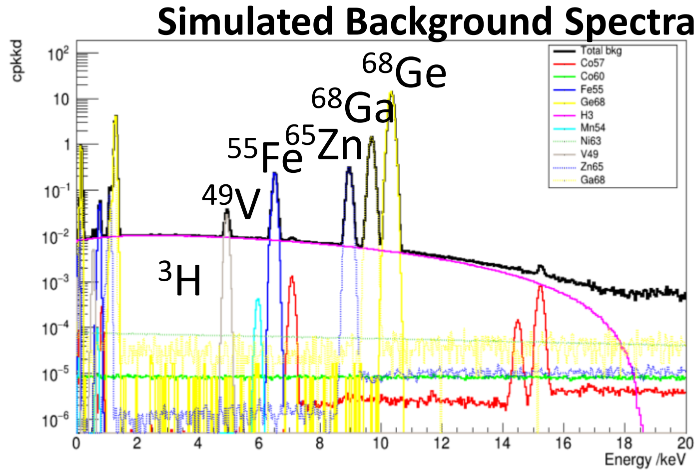


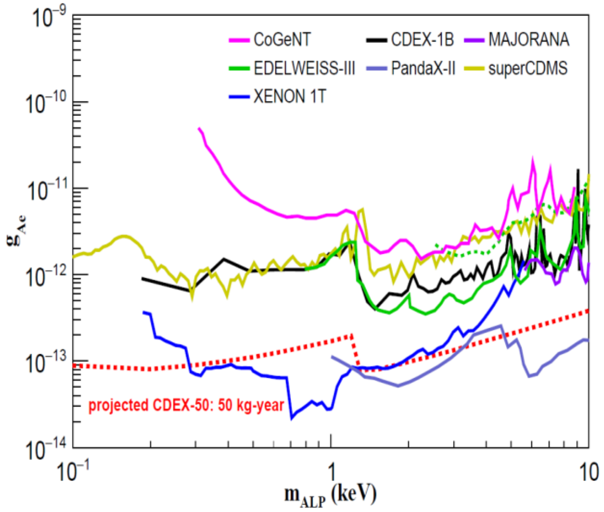
BEGe

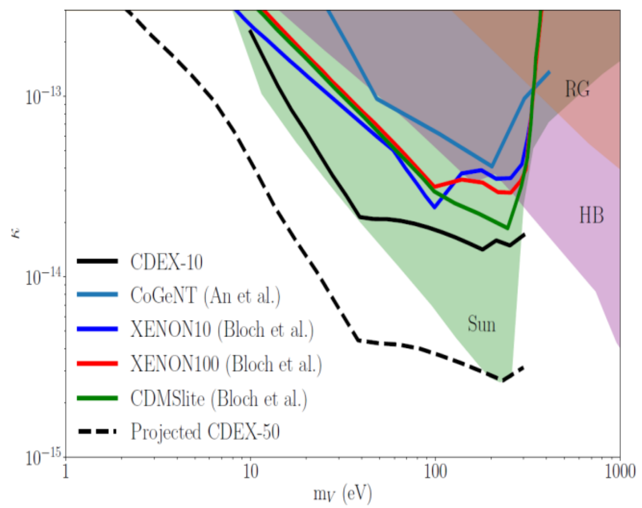


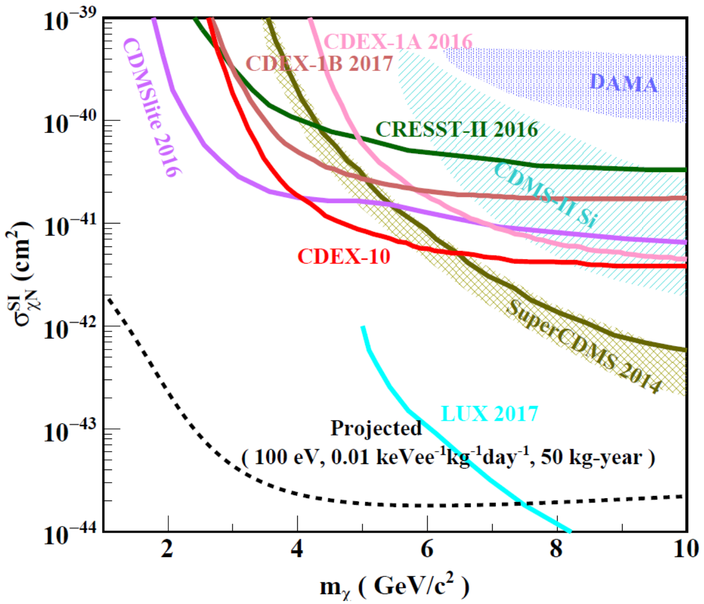
CDEX-50 Projected Sensitivity

- **Bkg level**: <0.01 cts/(keV·kg·day) @1 keV
- **Energy threshold** for data analysis: 100 eV
- **Exposure** reaches ~50 kg·year
- **WIMP SI sensitivity** reaches 10^{-44} cm^2
- Multi physics channel analysis: axions, dark photons…









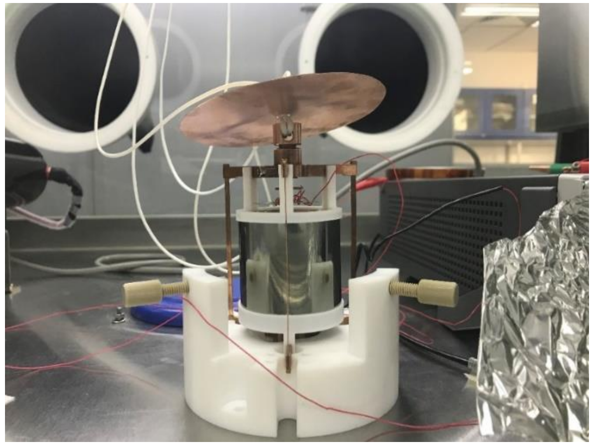
Technical R&D towards next stage

- ✓ **Ge detector fabrication** : Various types, ~20 has been successfully done.
- ✓ **HPGe crystal growth** : On-going project
- ✓ **Ultra Low bkg very-front-end ASIC + Bare Ge immersed in LN_2** : New ASIC tested; Bare BEGe successfully perform in LN_2
- ✓ **ULB-Copper production in underground lab** : Goal: < 0.1 μBq/kg
- ✓ **Cosmogenic background control**: ~10^{-2} cpkkd@2-4 keV(sim)

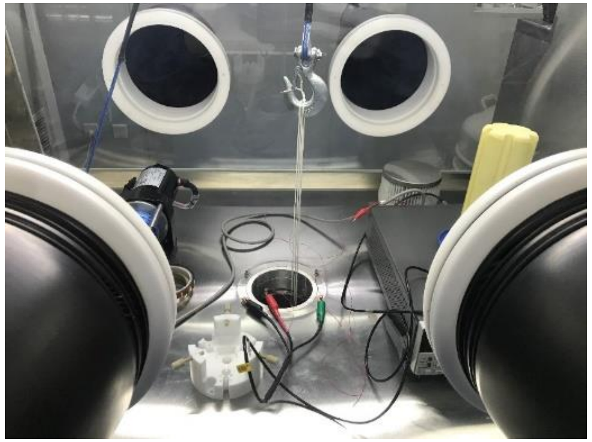
Ge Detector Fabrication & ULB ASIC

- **Ge detector fabrication**

Key technical Steps:
- ✓ Commercial Ge crystal;
- ✓ Structure machining;
- ✓ Li-drift and B-implanted;
- ✓ Home-made ASIC PreAmp;
- ✓ Underground EF-Cu;
- ✓ Underground assemble;
- ✓ Underground testing…

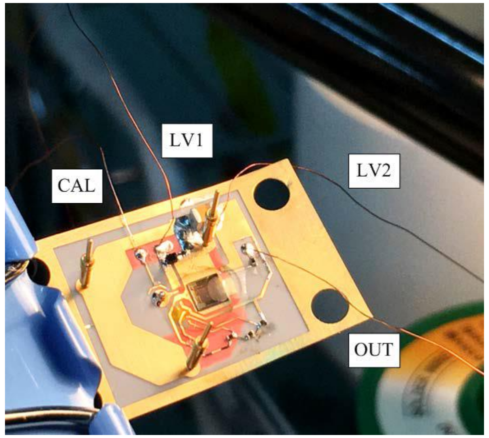


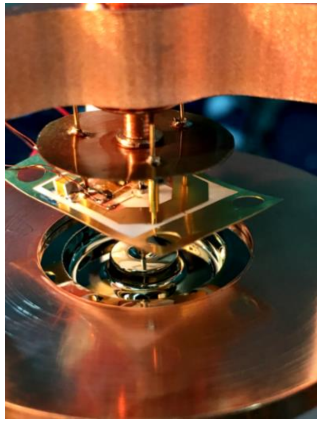
Bare HPGe detectors



Bare HPGe in LN_2

Home-made different Ge detectors

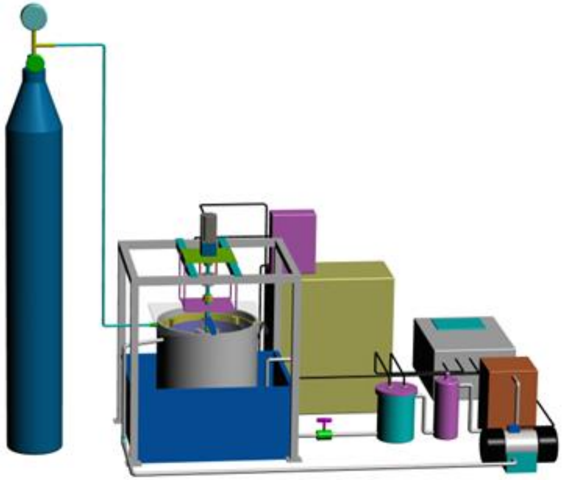




ASIC Front-end Electronics

E-forming Copper production Underground

- Prototype setup for underground EF-Cu production
  - ✓ Goal: Majorana copper, **U/Th content ~ O(0.1μBq/kg);**
- Test run in Tsinghua U. and moved to CJPL-I;
- U/Th Analysis by ICP-MS



E-forming setup

UG copper e-forming facility @ CJPL-I

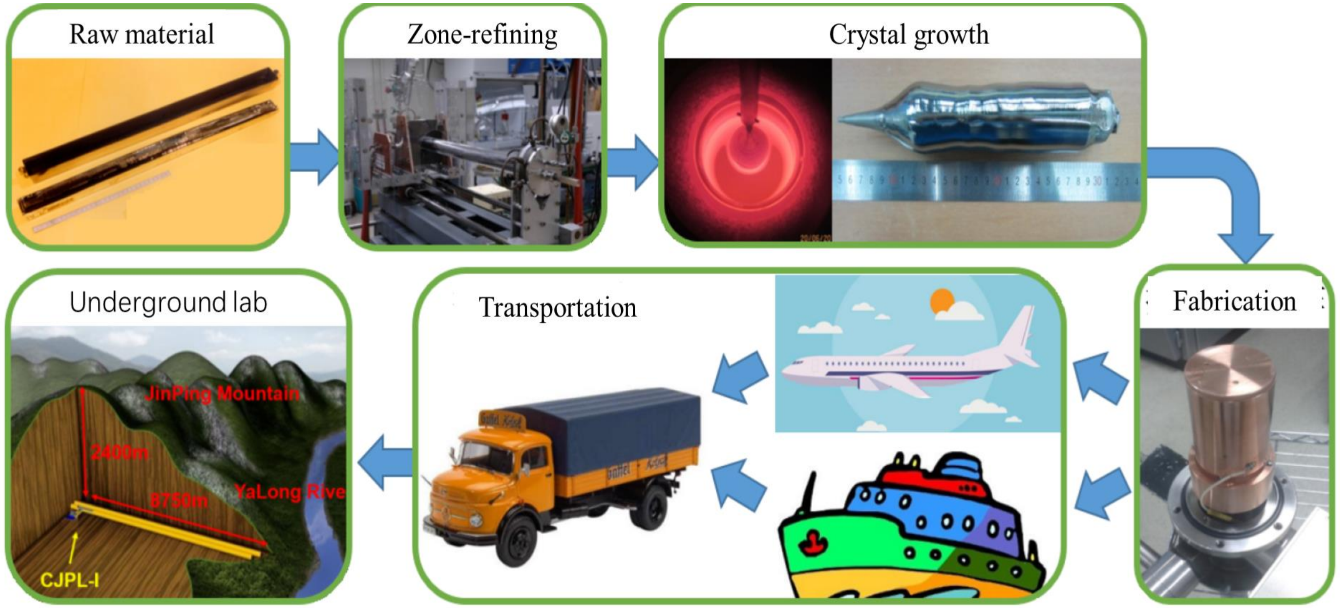
Cosmogenic Background Control

- **New detectors cooperated with commercial companies**
  - ✓ Particularly cosmogenic bkg control during detector fabrication and trasportation above ground;
- **Home-made detectors**
  - ✓ Improve with low bkg material and low noise electronics;
  - ✓ Set up underground fabrication and testing facility;

Cosmogenic bkg control

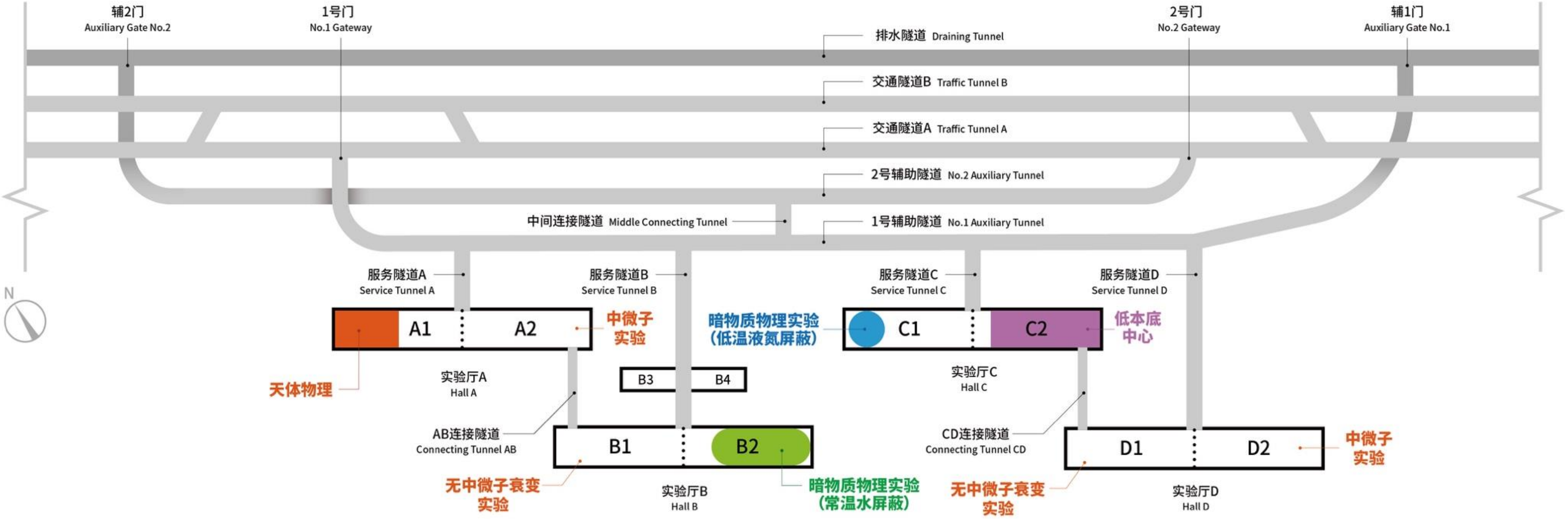
Detector production: 45days +
Ground transportation: 60 days +
Underground cooling: 180days →

Cosmogenic bkg: ~10^{-2}cpkkd(sim.)



CJPL-II

- **CJPL-I to CJPL-II**
  - ✓ Volume: 4000 m^3 to 300,000 m^3;
  - ✓ 1 main hall (6.5x6.5x42m) to 8 main halls (14x14x60m each);
  - ✓ Additional pit for next-generation CDEX;



CJPL-II

- Major infrastructure construction will be completed by the end of 2023.
- Expected the construction of the laboratory will be completed by the end of 2024.








Summary

- CDEX: unique advantages of Ge detectors for DM searches at CJPL;
- CDEX has made diverse and significant contributions: WIMP, axions, dark photons, exotic DM, AM, Migdal effect, boosted DM, χ-e scattering…..
- CDEX-50, the next stage experiment, at Hall C-1 of CJPL-II;
- Technical R&D developments to facility future experiments.

Thanks for your attention!