# Recent status and prospects of CDEX @CJPL

TWENTY-FIRST LOMONOSOV CONFERENCE ON ELEMENTARY PARTICLE PHYSICS


Moscow, August 24 - 30, 2023

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**On behalf of CDEX Collaboration**

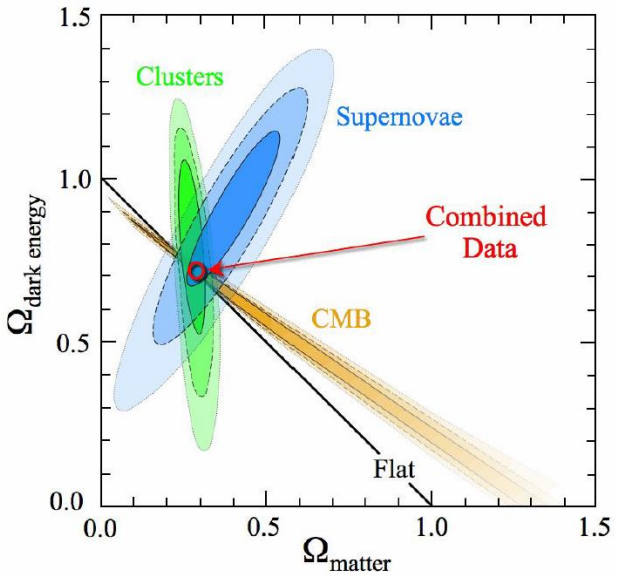
CJPL 中国锦屏地下实验室 China Jinping Underground Laboratory 清华大学 · 雅砻江流域水电开发有限公司

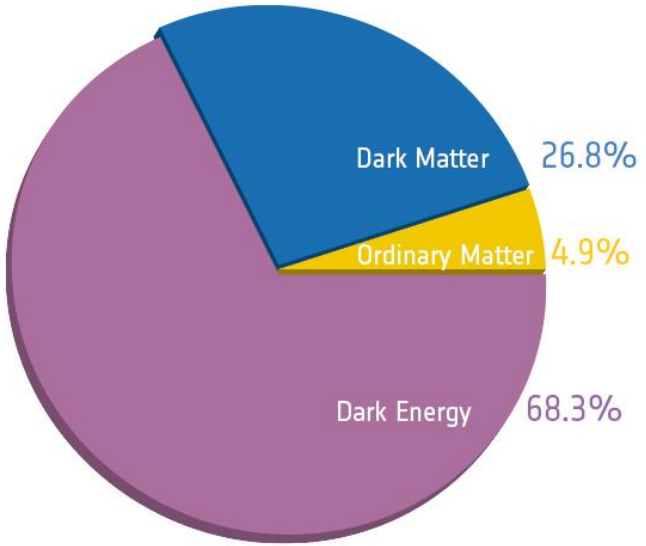
**21th Lomonosov Conference @Moscow, Aug. 26th, 2023**

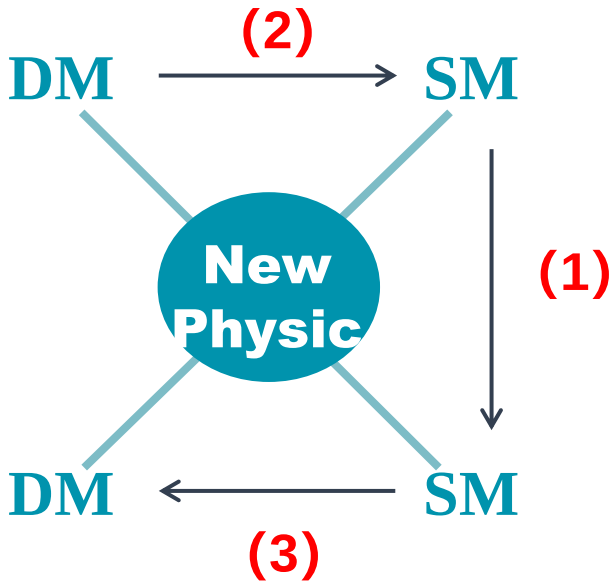
# OUTLINE

- Direct detection of Dark Matter
- Introduction to CDEX
- Recent status of CDEX-1 and CDEX-10
- Future prospect of CDEX@CJPL-II, R&D of key technologies
- Summary

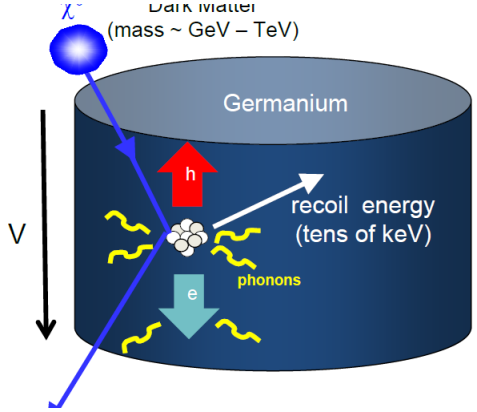
# Dark Matter in Cosmology



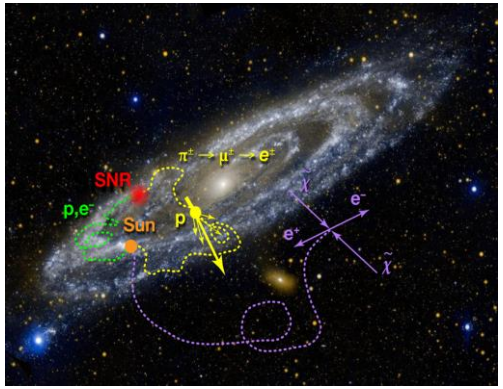



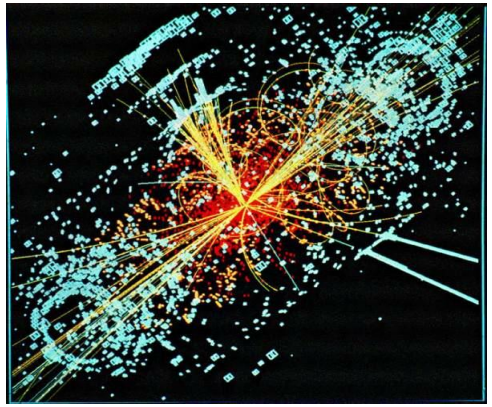

## (1) Direct




## (2) Indirect

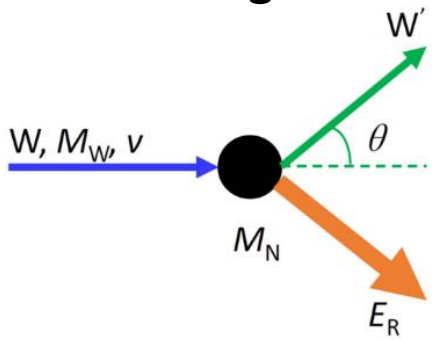



## (3) Accelerator

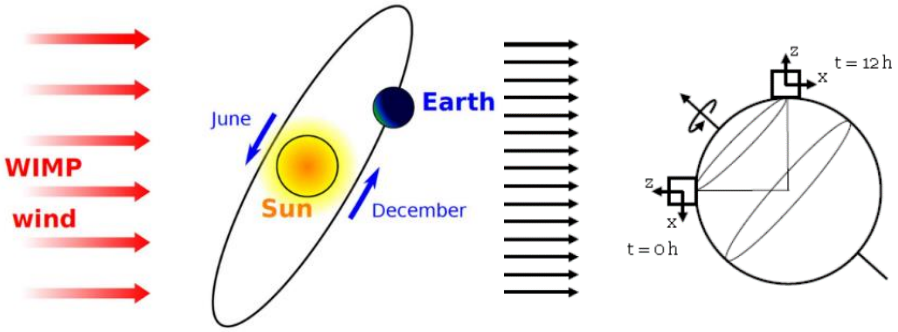


# Direct detection of DM

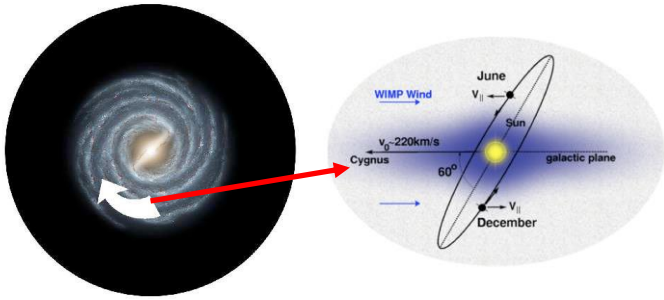
## Elastic Scattering

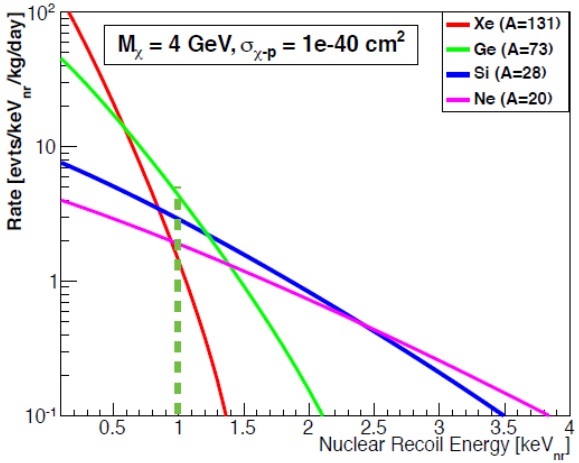



## Annual/ Diurnal Modulation

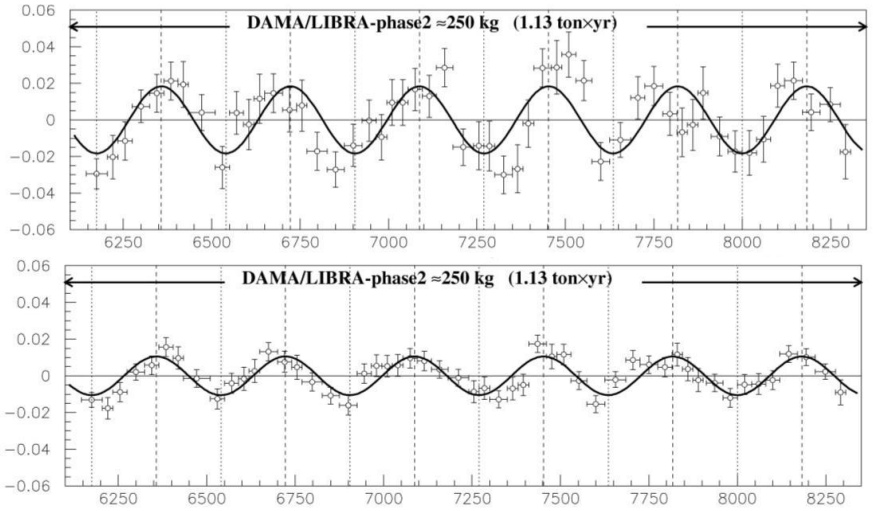



## Direction Detection



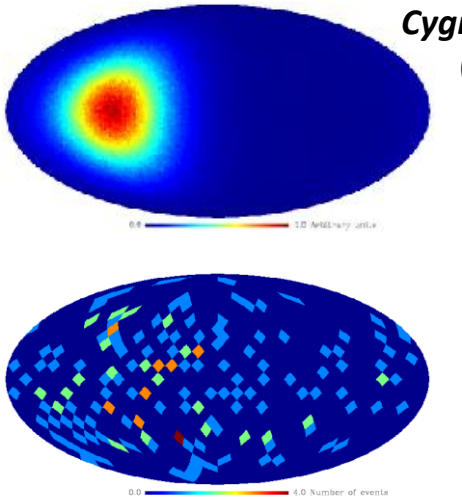




- Lower Background
- Lower Energy threshold
- Larger Exposure (Mass*Time)




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

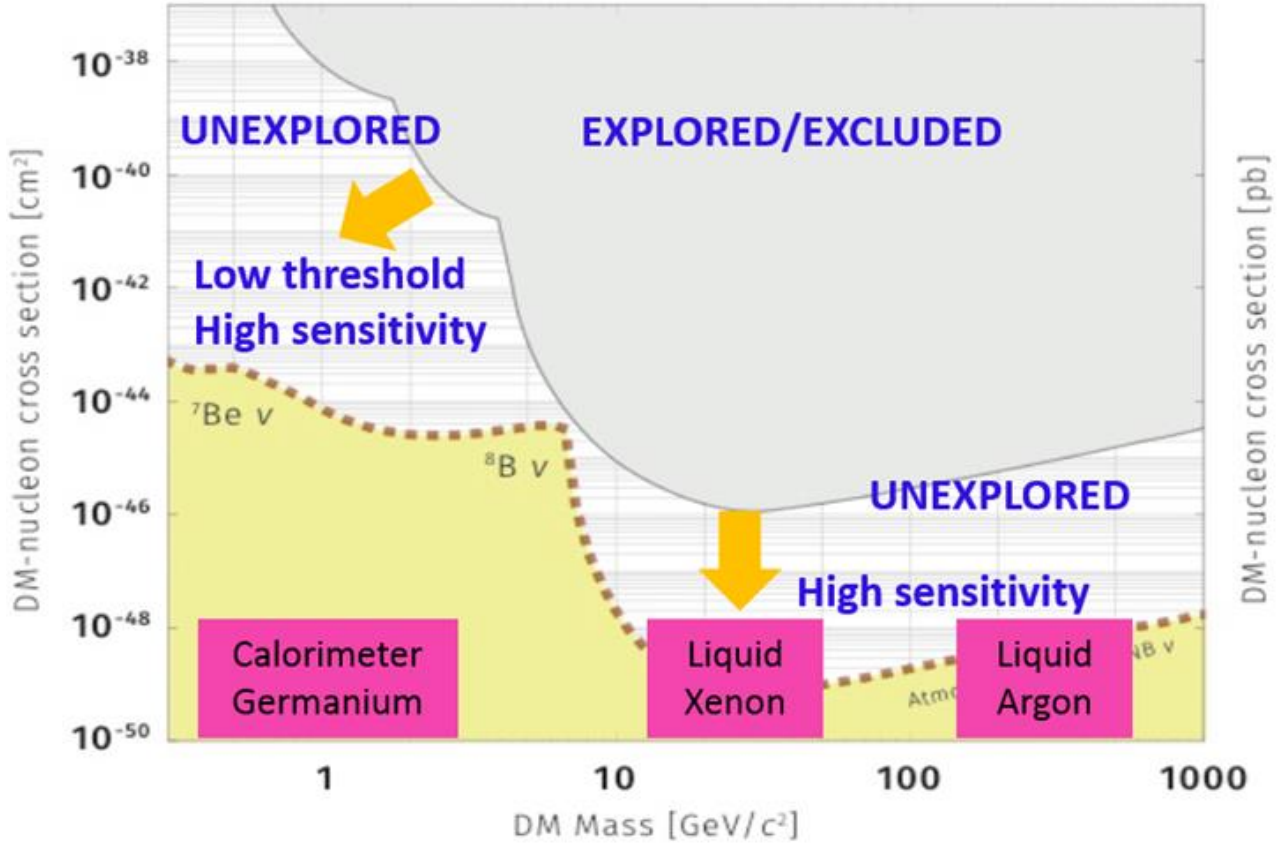
*Cygnus Constellation*
(l = 90°,b = 0°)



- Lower Background
- Lower Energy threshold
- Good Angular Resolution

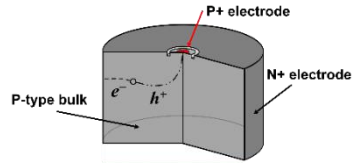
# Direct detection of DM

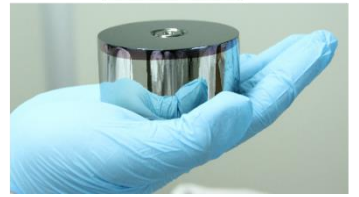
- Dark matter detection competition is becoming increasingly fierce;
- **Light dark matter detection**: low background level, low energy threshold, large mass detector target



# China Dark matter Experiment

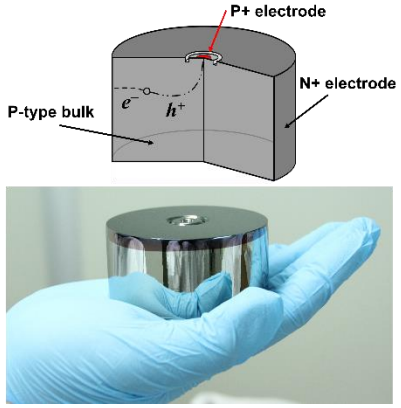
- Formed in 2009, 11 institutions and ~100 people now; http://cdex.ep.tsinghua.edu.cn/
- **Key technology:** P-type Point-Contact (PPC) Ge detectors;
- **Physics targets:** Direct detection of light DM + Ge-76 0νββ



# CDEX Roadmap

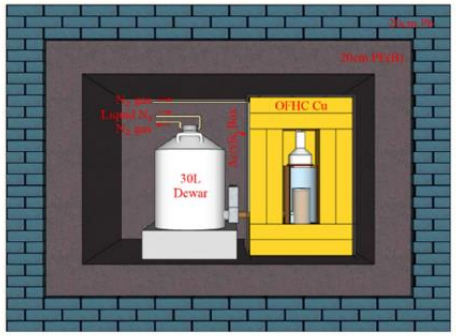
- **CDEX-1 (2011-2018):** Development of PPC Ge detector, bkg understanding
- **CDEX-10 (2016-2022):** Performances of Ge array detector immersed in $LN_2$
- **CDEX-50 (2021-202X):** 50kg Ge detector arrays for DM searches
- **CDEX-300v (2021-202X):** 300kg enriched Ge detector arrays for 0νββ Exp.



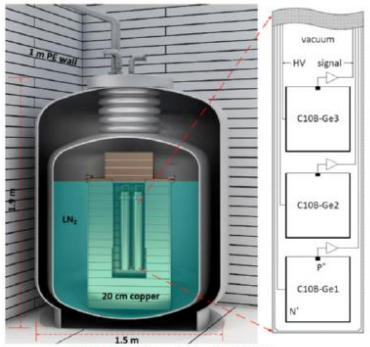

CDEX-1 → CDEX-10

2011-2018 2016-2022

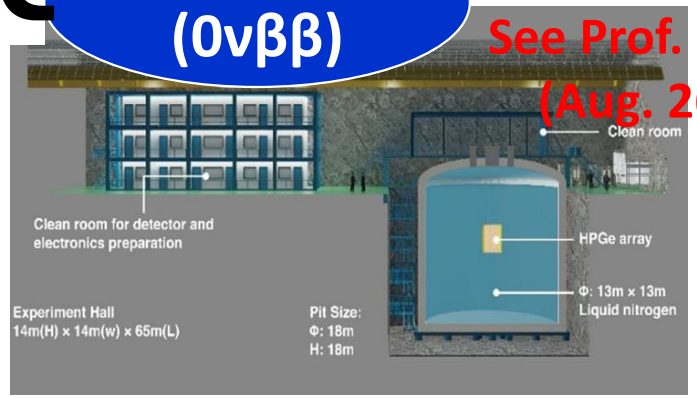
CDEX-50 (DM) + CDEX-300v (0νββ) → CDEX-1000




CDEX-1A&B: 1kg PPC Ge×2



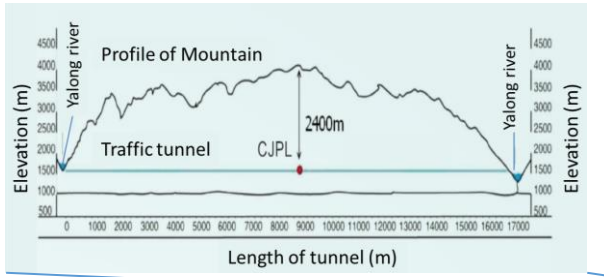

CDEX-10: ~10kg PPC Ge array



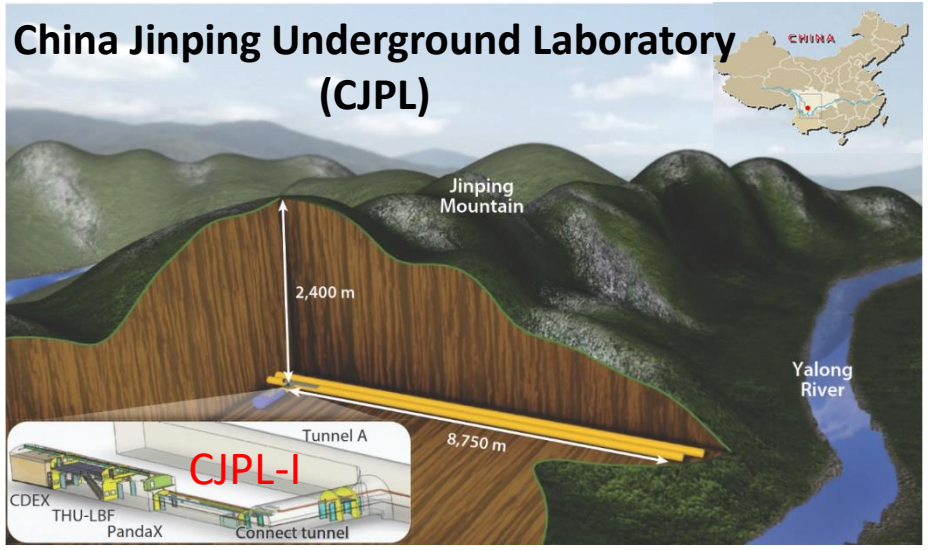

See Prof. L. Wang's talk (Aug. 26th, afternoon)

# China Jinping Underground Laboratory

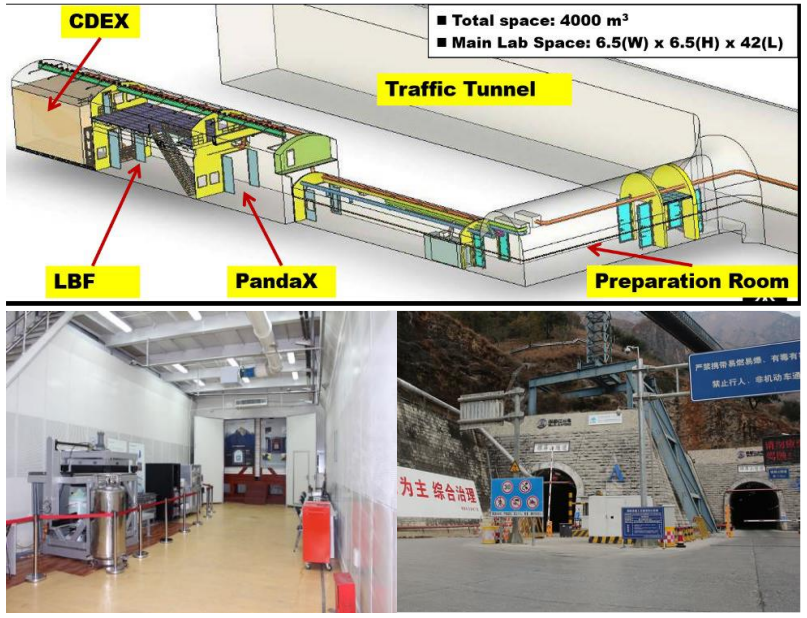
- World's deepest underground lab, CJPL
  - ✓ Near Xichang city, Sichuan Province, Southwest China
  - ✓ Rock overburden: 2400m (~6720 m. w. e.)
  - ✓ Main Hall: 6.5m(W) x 6.5m(H) x 42m(L), Total space: ~4000 $m^3$
  - ✓ Two DM exp. (CDEX, PandaX)+LBF(radio-assay) operated in CJPL-I
  - ✓ Extension project, CJPL-II, final exam and expected to be completed in 2025

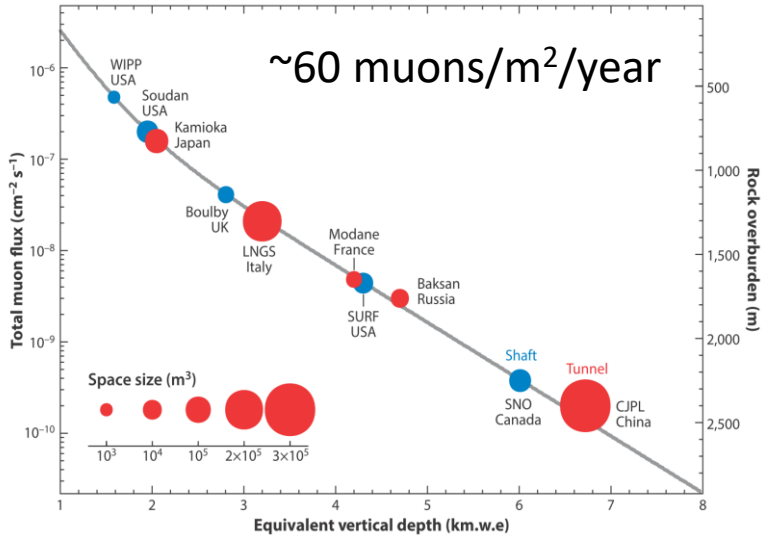







Cheng et al., Annu. Rev. Nucl. Part. Sci. 67:231 (2017)

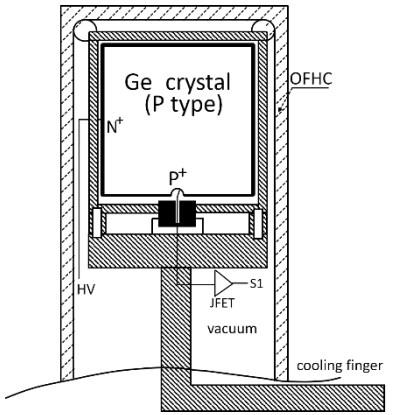


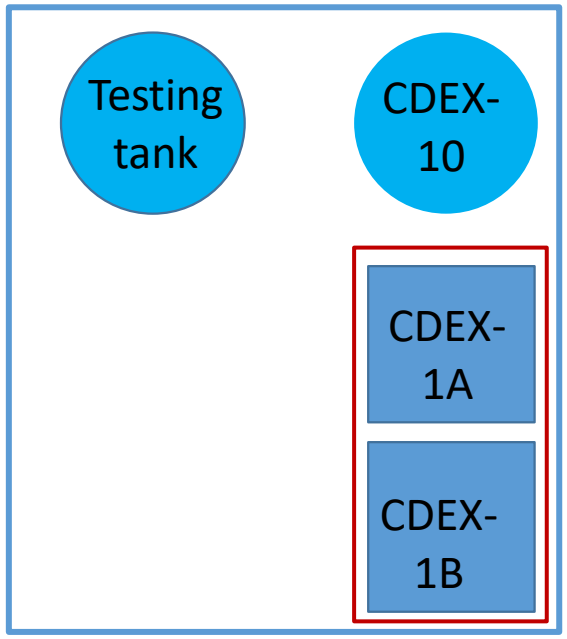

Chinese Physics C 37:086001 (2013)

# CDEX-1

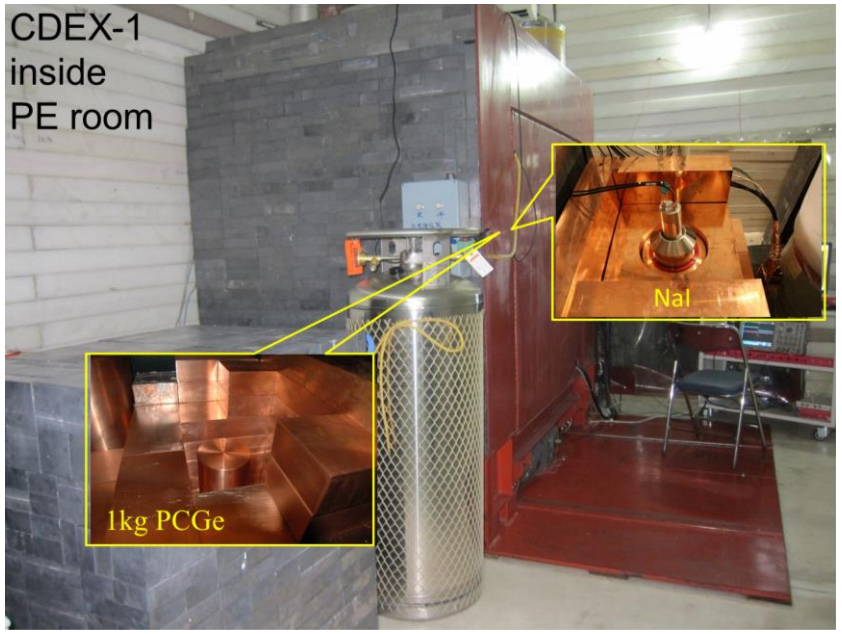
- Two single-element 1kg pPCGe detectors;
- Traditional cold finger refrigeration;
- Passive shield: Low-bkg Pb, OFHC Cu, PE;
- NaI(Tl) anti-Compton detector;
- Located in PE room at CJPL-I;



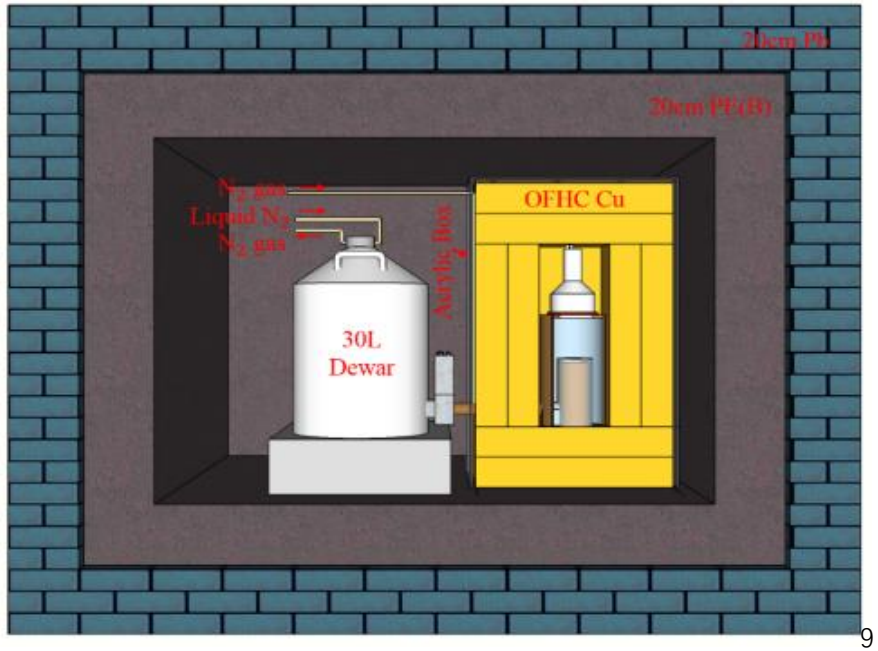





Layout of PE room, CJPL-I




CDEX-1 inside PE room



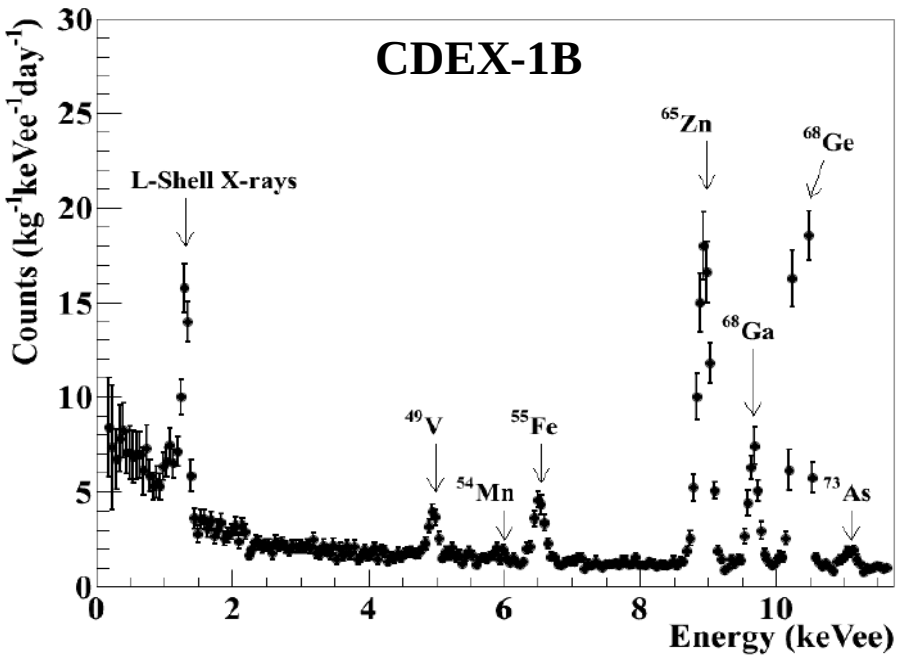

CDEX-1A&B: 1kg PPC Ge×2

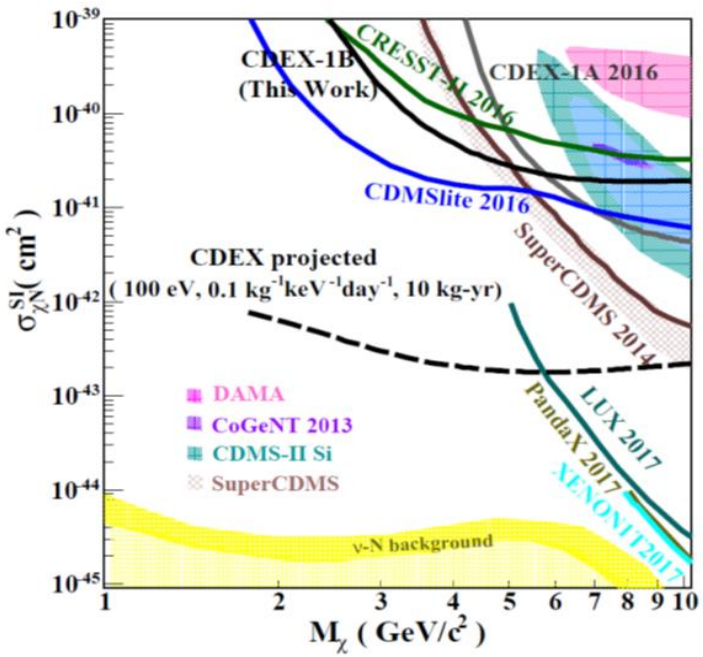
# CDEX-1B Results

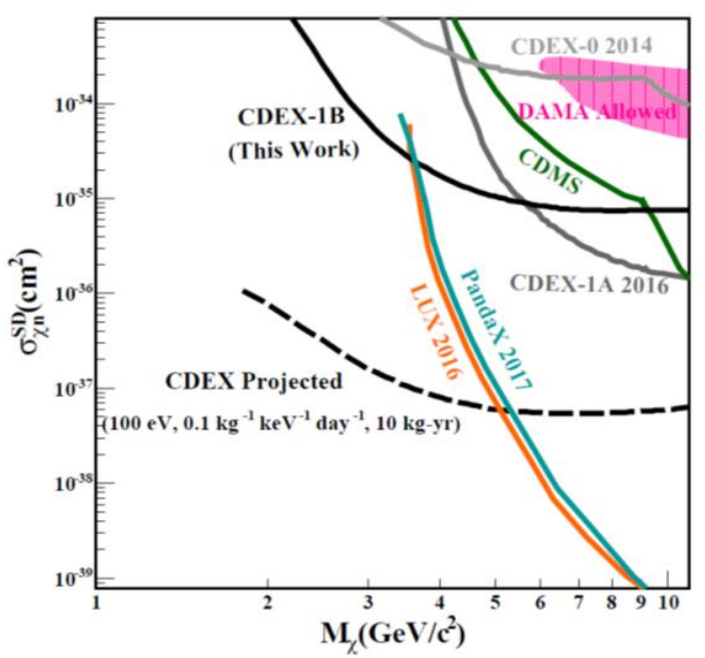
- Detector upgraded w/ lower JEFT noise and material bkg;
- >4 years run (Run-1&Run-2), >1200 kg·day exposure;
- Achieving 160 eVee energy threshold;
- Sensitivity improved and extending to 2 GeV/$c^2$.

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

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



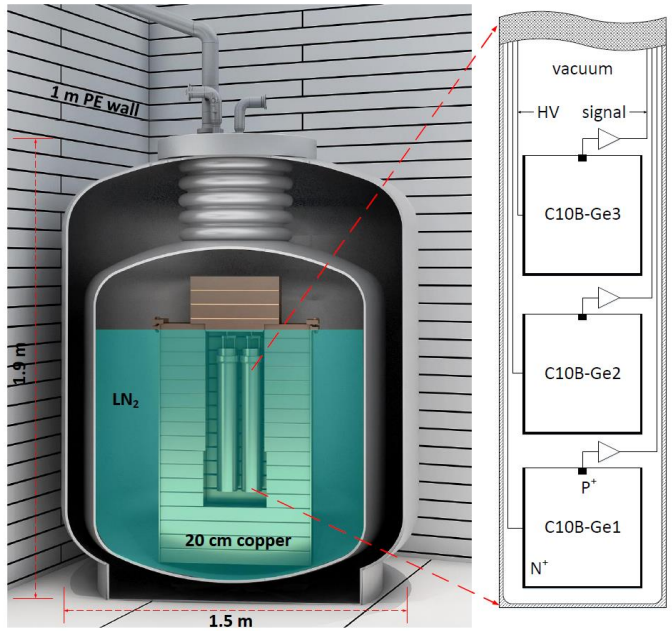



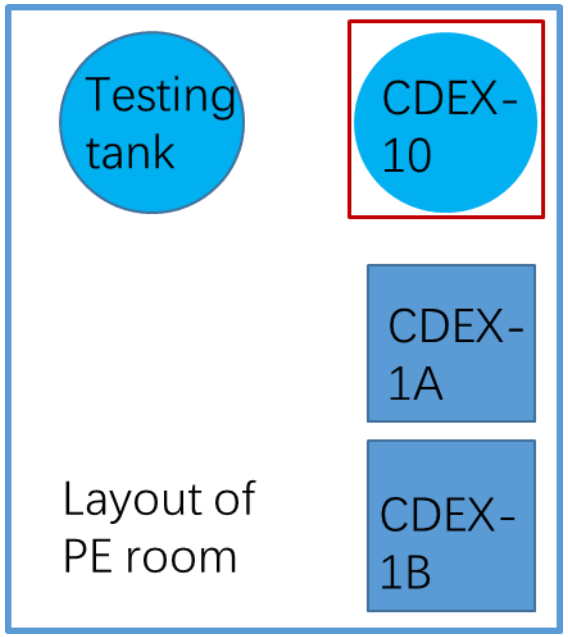
# CDEX-10

- 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;

***Science China-PMA*** 62, 031012 (2019)



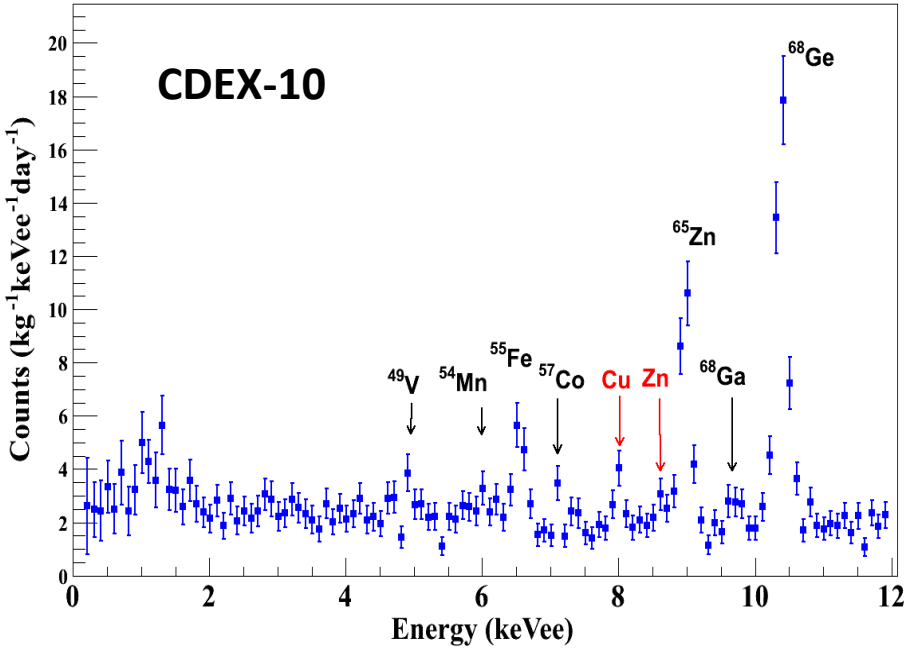

CDEX-10: ~10kg PPC Ge array

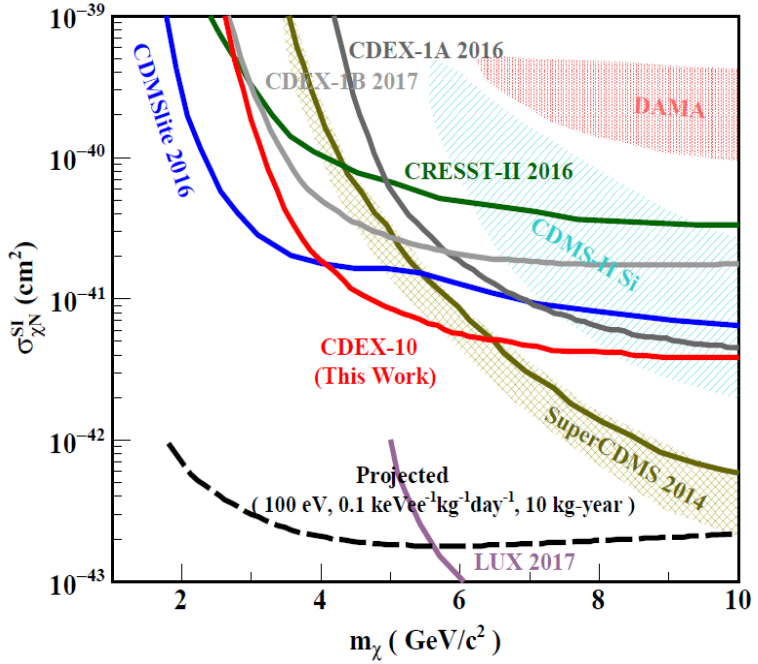


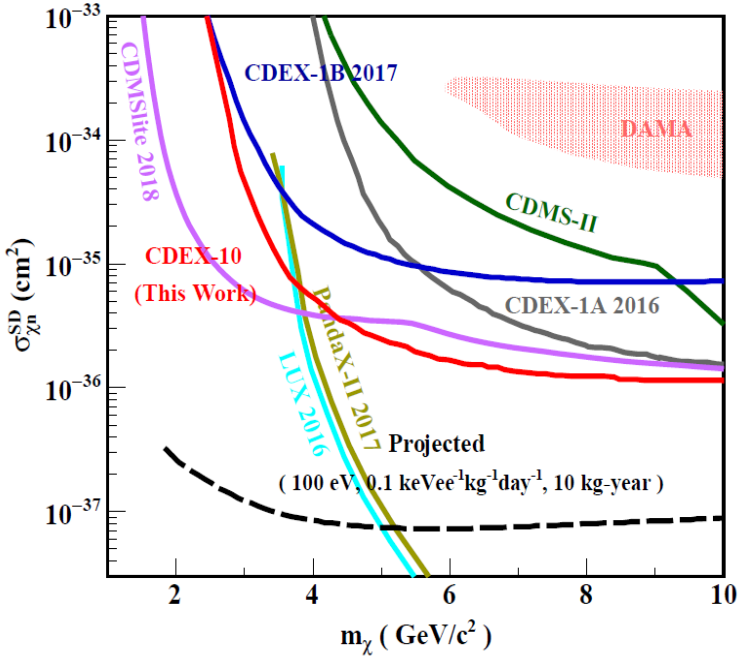
# CDEX-10 Results

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

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



# Dark Matter Direct Detection

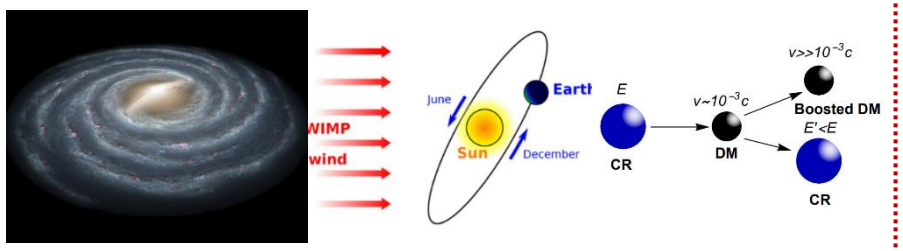
$$\frac{dR}{dE_R} = N_T \left[ \frac{\rho_\chi}{m_\chi} \int d^3\vec{v} v f_v(\vec{v} + \vec{v}_E) \right] \frac{d\sigma}{dE_R}$$

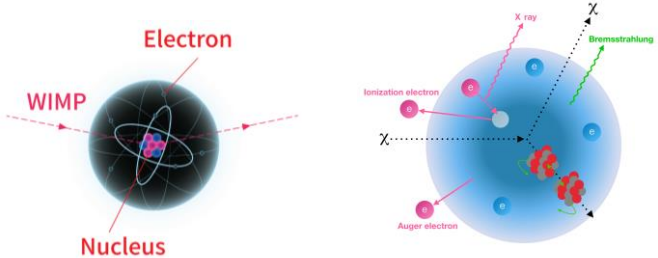
**DM sources related：**

- ✓ WIMP (Standard Halo Model)
- ✓ Annual Modulation (velocity change)
- ✓ Boosted DM
- ✓ Dark Photon, axions et al.

**Interaction process：**

- ✓ DM-nucleus elastic scattering
- ✓ DM-nucleus inelastic scattering
- ✓ DM-electron scattering
- ✓ Others (All energy deposited)



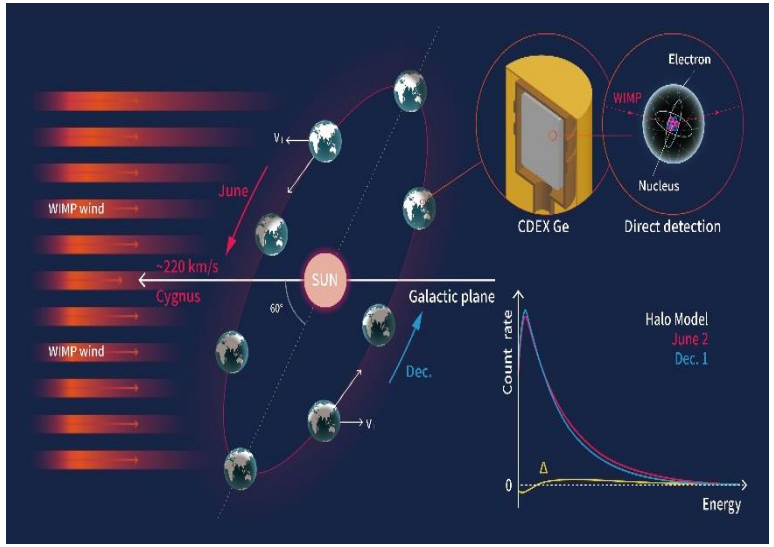



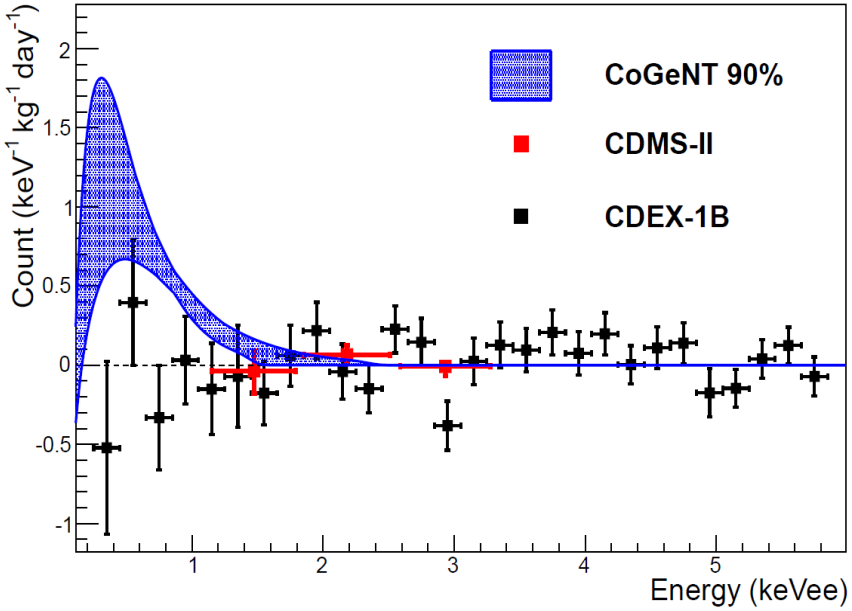

*WIMP: weakly interaction massive particles

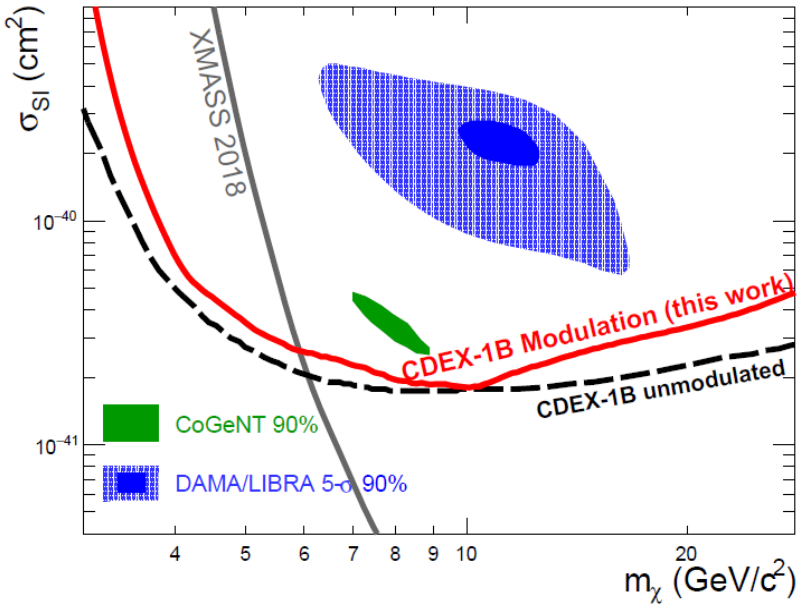
# Annual Modulation analysis from CDEX-1B

- 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)



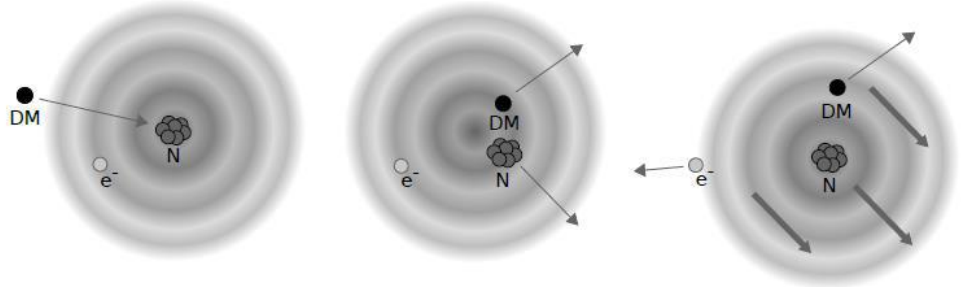




**Best-fit of modulation amplitude** w/ phase=152.5day **SI Limits from AM**

# sub-GeV WIMPs: Migdal effect analysis

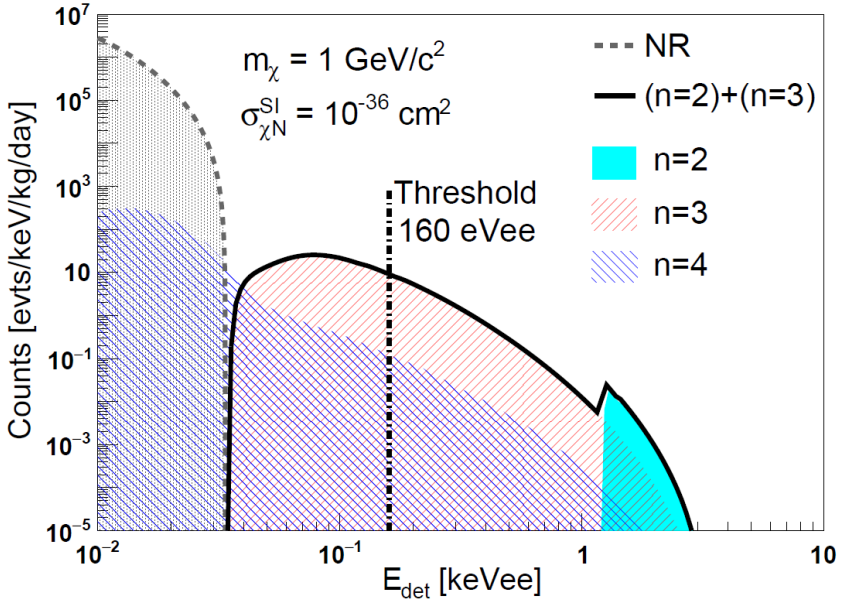
- Time-Integrated Analysis with Migdal: 737.1 kg-d, w/ Eth 160 eVee;
- AM Analysis: 1107.5 kg-d, w/ Eth 250 eVee;
- **Leading sensitivity in $m_{DM}$ ~ 50-180 MeV;**

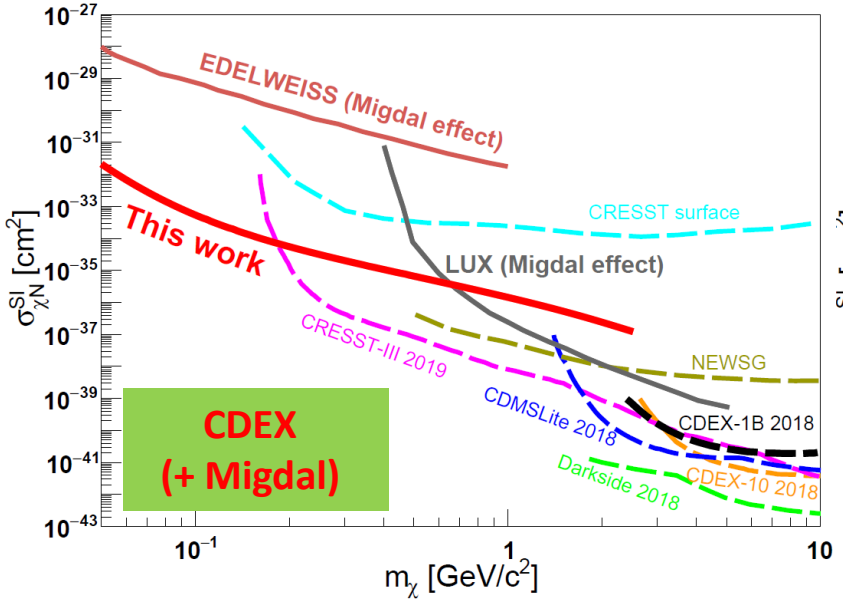
ref: Migdal effect (M. Ibe et al.,2018)

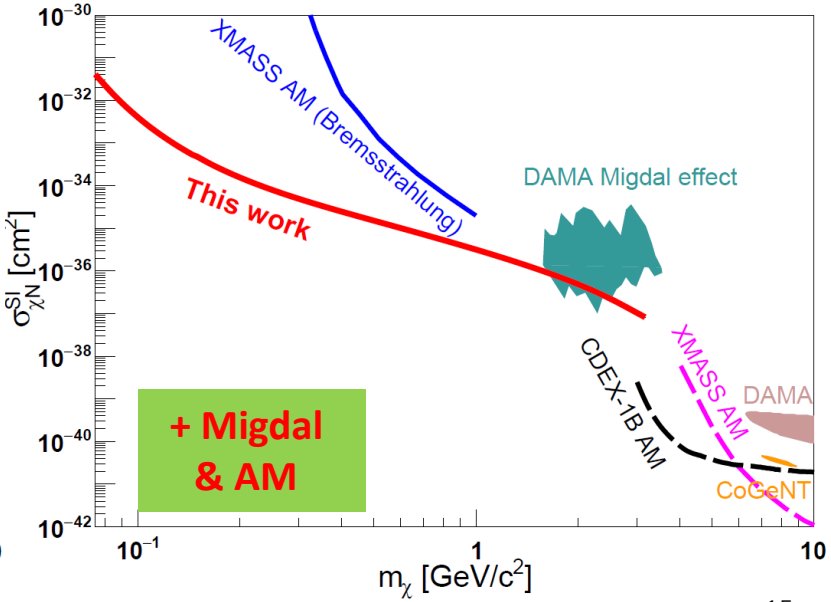



Expected measurable spectra

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



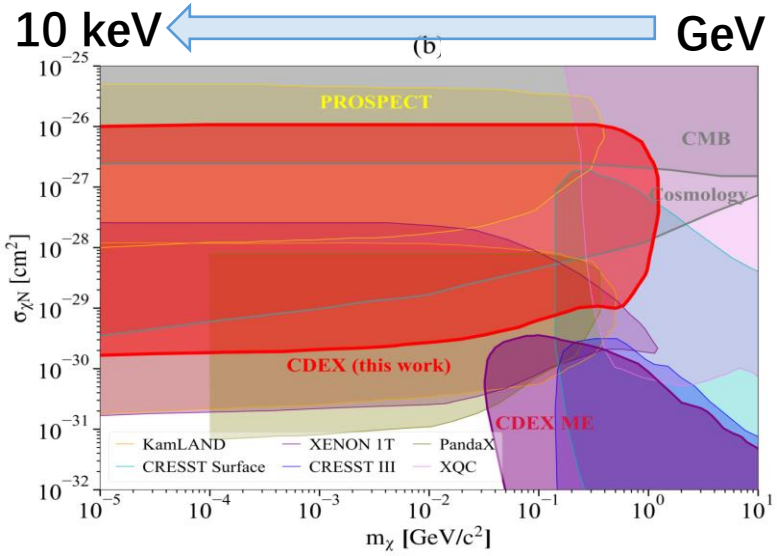



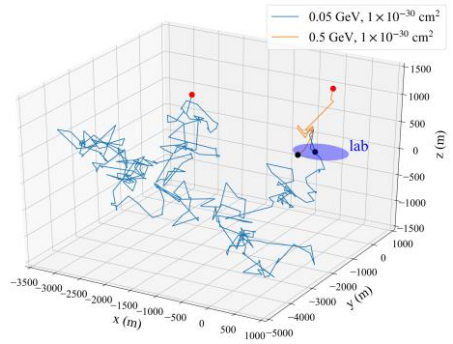
# sub-GeV DM: CRDM, Earth shielding

- **Searches on cosmic ray boosted dark matter**, the low mass reach of DM has been extended from GeV to keV, and CDEX-10 results are more sensitive than cosmology;
- **To calculate the earth shielding effect for low mass DM**, CJPL_ESS package has been developed with detail topography of Jinping mountain.

PRD *106, 052008 (2022)*

**CRDM**



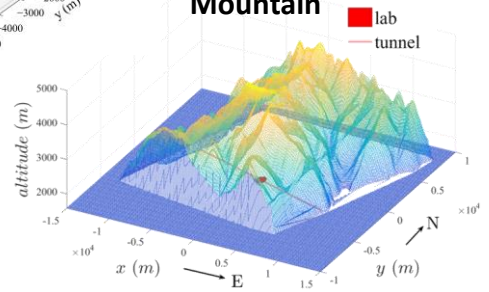




Scattering tracks of DM in the crust (simulation)

**Exclusion line**

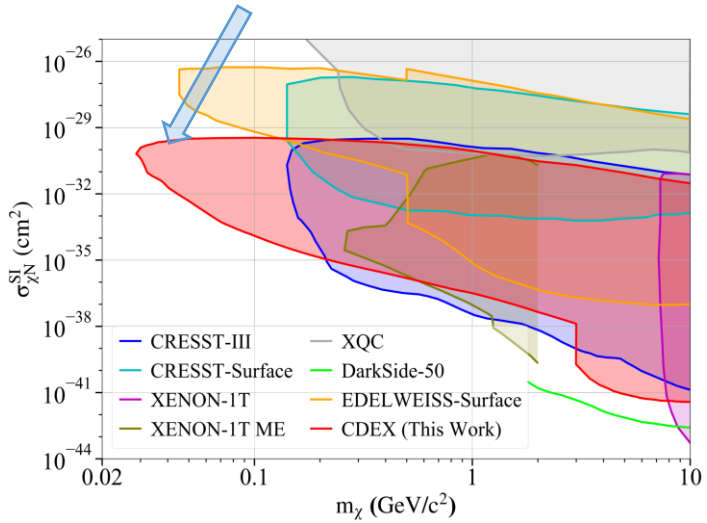
**→Exclusion region**

**Jinping Mountain**



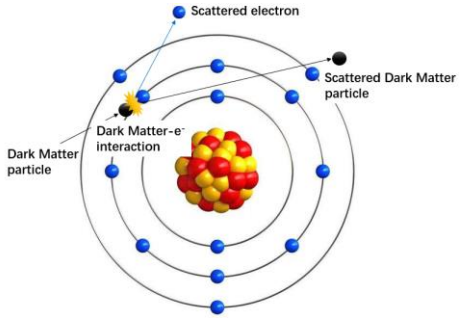

PRD *105, 052005 (2022)*

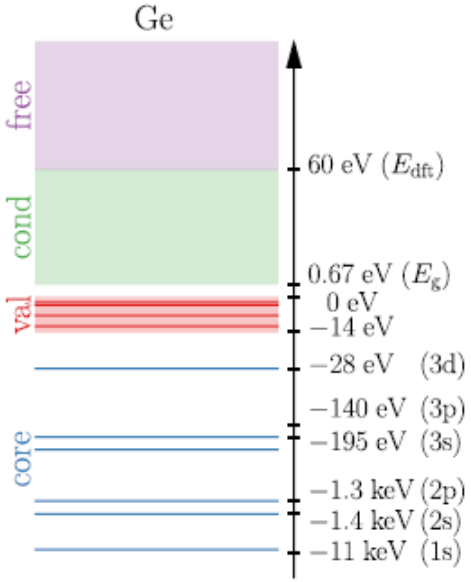
**Earth shielding**

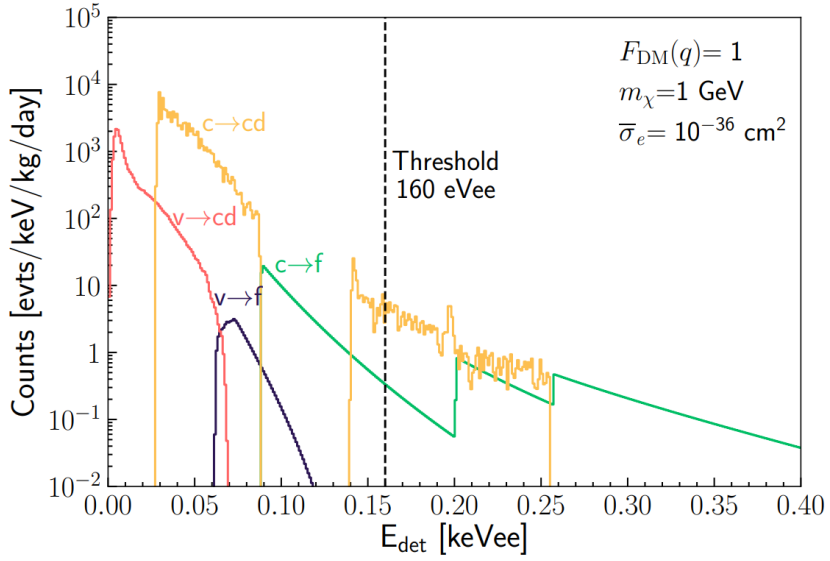


# sub-GeV Dark Matter–Electron Scattering

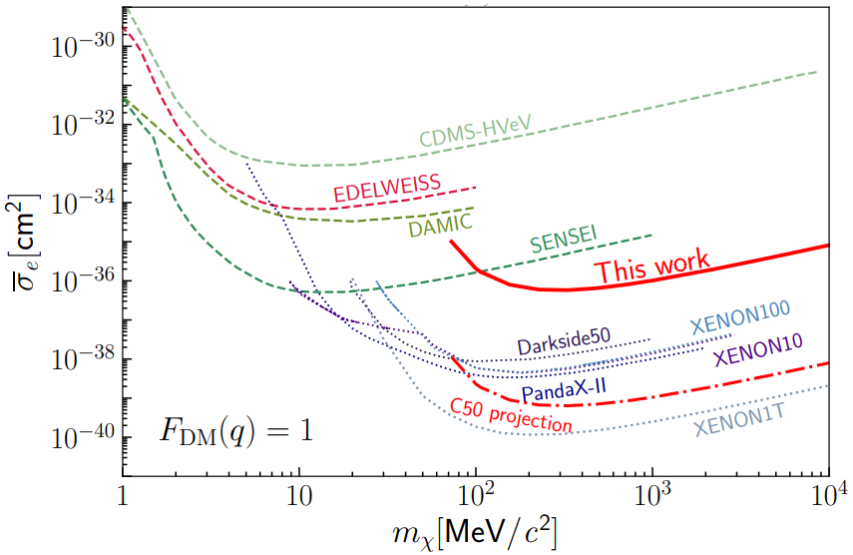
- **The first HPGe detector-based DM-e scattering limits from CDEX**;
- The **most stringent χ-e cross-section limit to date among experiments using solid-state** detectors for $m_\chi$ larger than 100 MeV with heavy mediators;




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



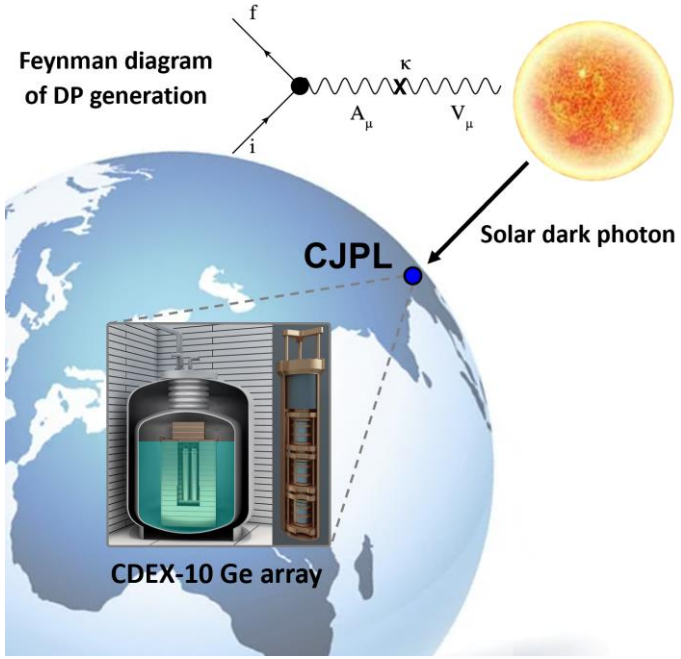

Expected rates and CDEX-10 result in the heavy mediator scenario

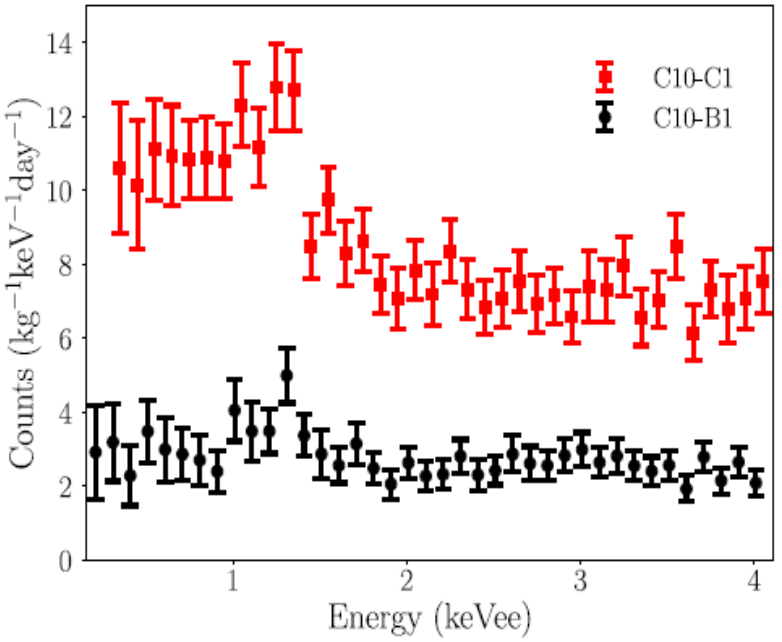
# Solar dark photon and dark photon DM

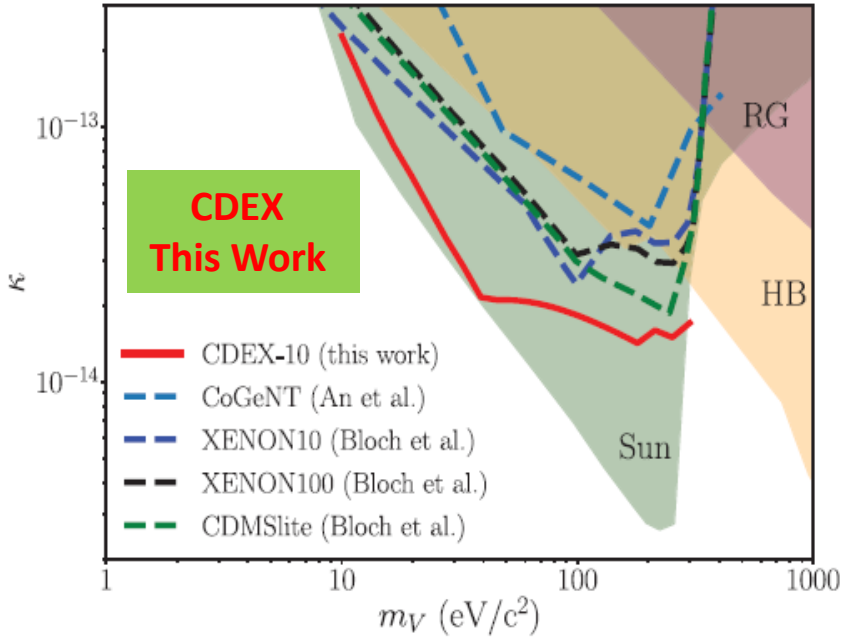
- Dark photon Analysis: 205.4 kg-d, w/ Eth 160 eVee;
- Leading sensitivity in $m_V$ ~10-300 eV for solar dark photon;

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

*ref: An, H. et. al., PRL,* 111:041302 (2013)



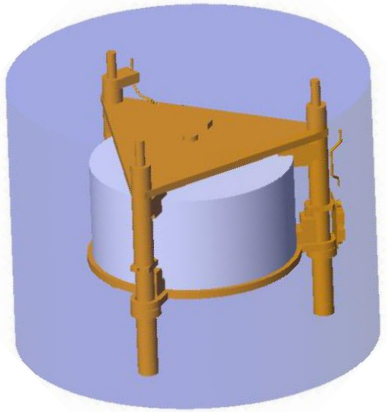



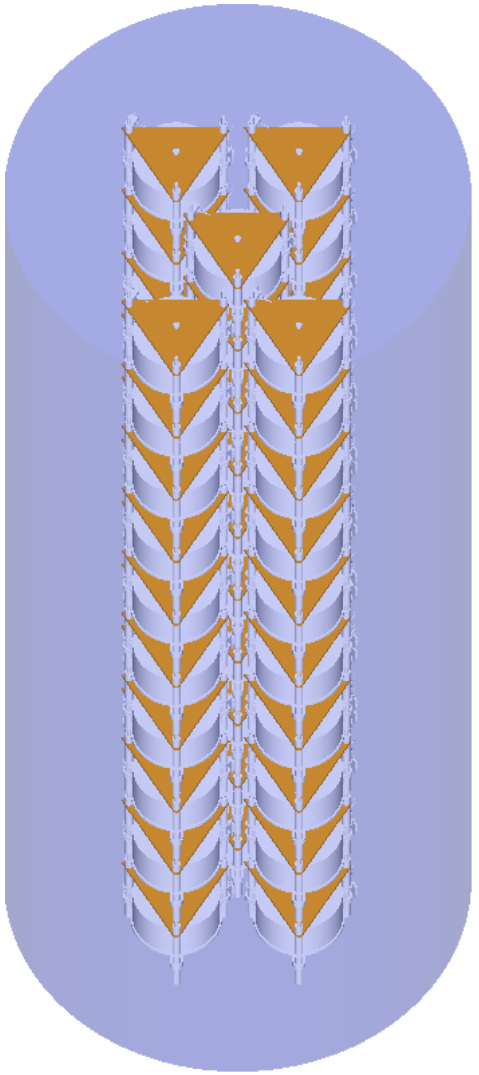



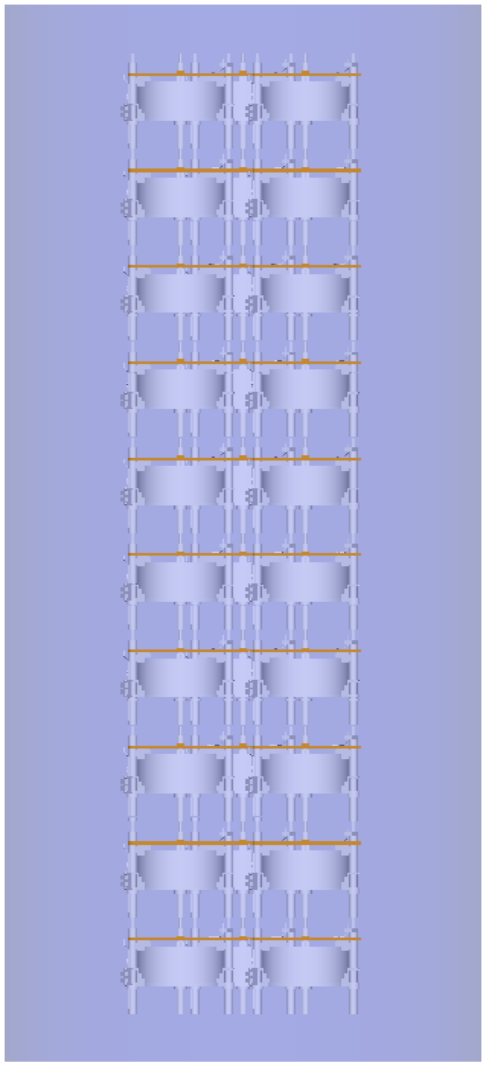

**solar dark photon**

# 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;
- BEGe+PPCGe;

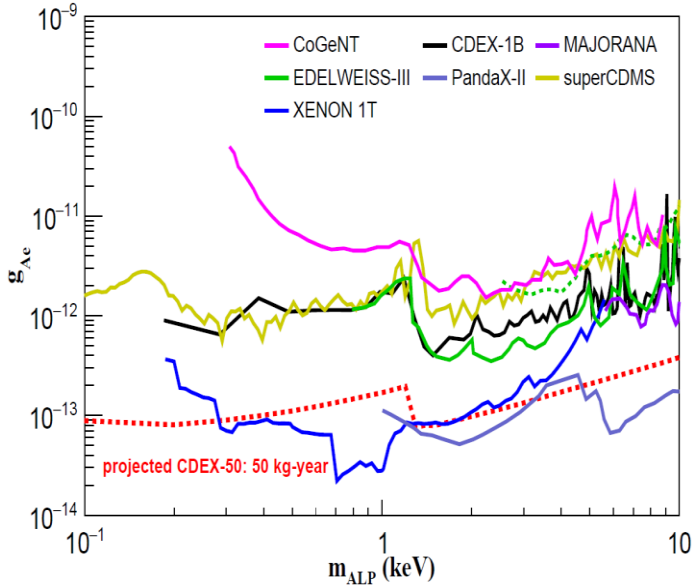


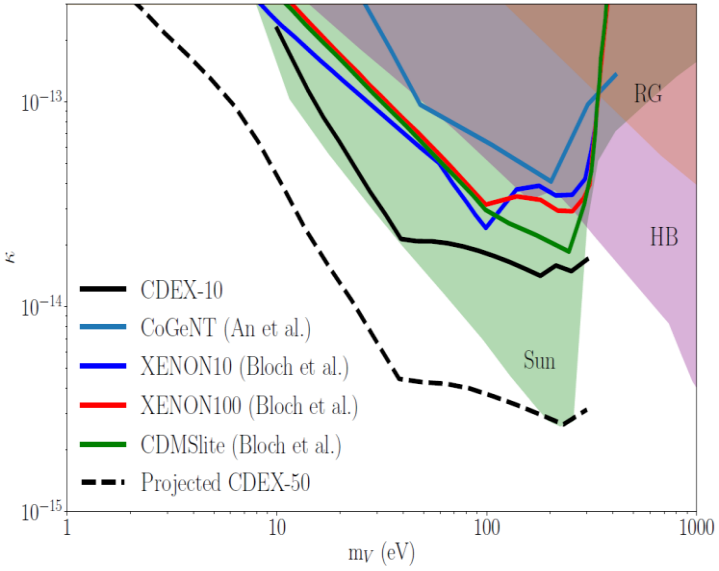


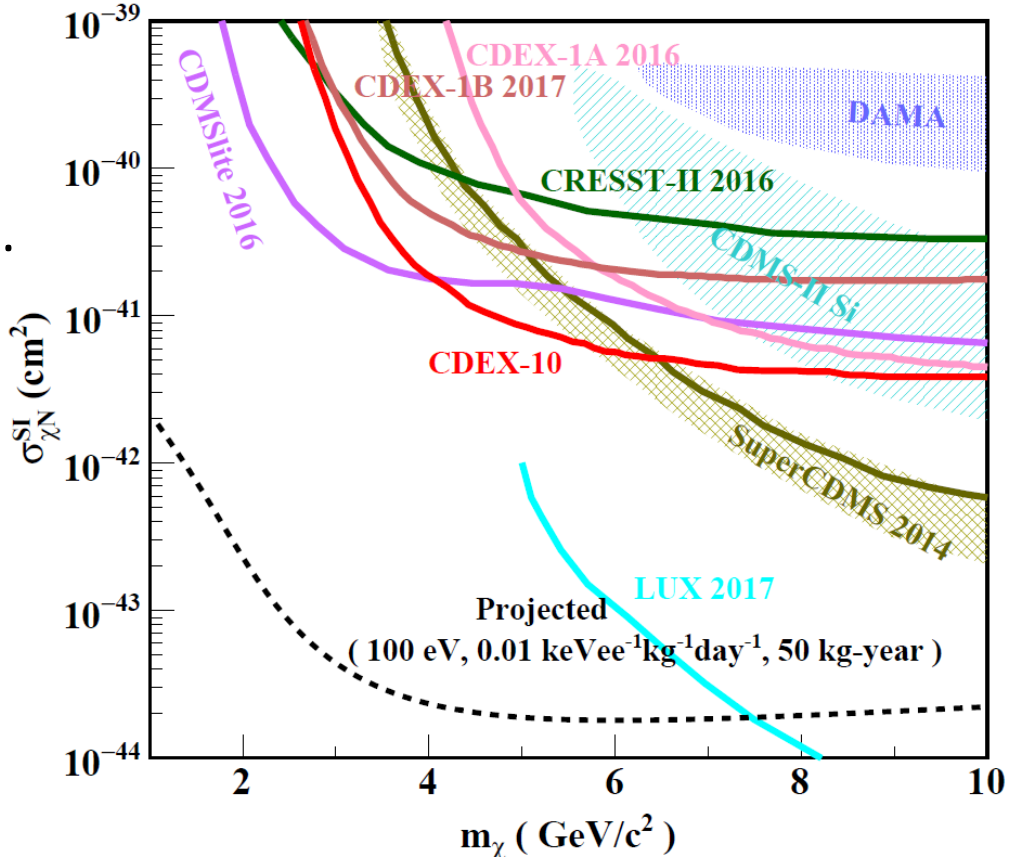


# CDEX-50 Projected sensitivity

- 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 **$10^{-44}$ cm²**
- **Multi physics channel** analysis: axions, dark photons…



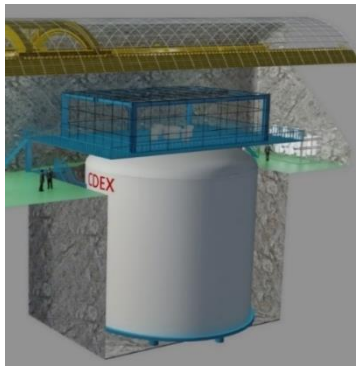



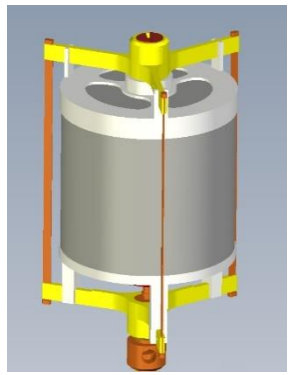
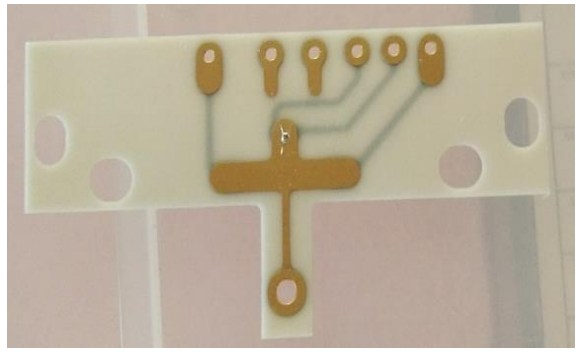
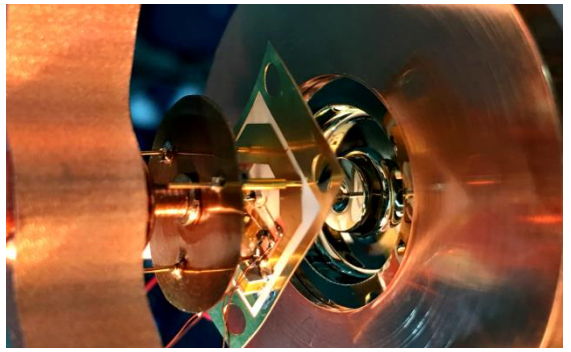



# Technical R&D towards next-stage

- **Large scale detector array**
  - 10 kg → 50 kg
- **Low background**
  - 2 cpkkd → 0.01cpkkd@ 2-4 keV
- **Low noise electronics**
  - E threshold 160 eV → 100 eV
- **Prototype detectors → Strings**
- **Strings → Arrays**

- **Large shielding and cooling system**
- **Ge detector fabrication**
  - Low mass detector unit and VFE design
  - Low bkg cables or flexible PCB
  - CMOS ASIC Front-end Electronics
- **Underground E-forming copper**
- **Cosmogenic bkg control**
- **Radon bkg in Liquid Nitrogen**

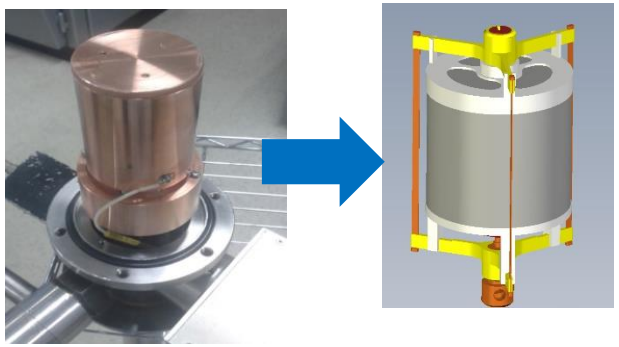


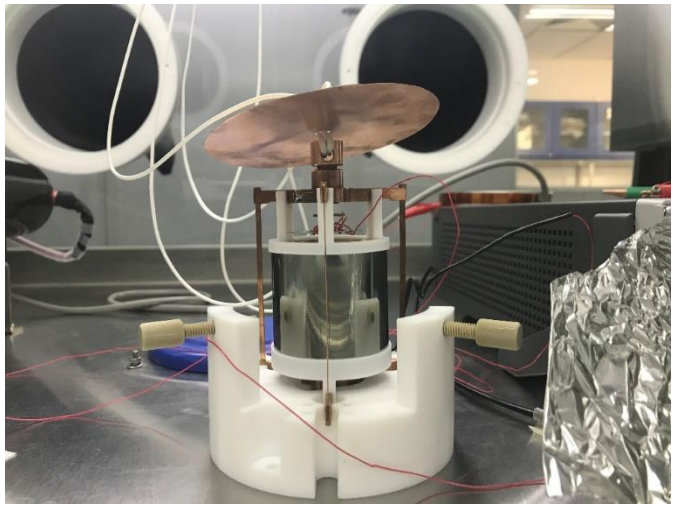





# Ge detector fabrication

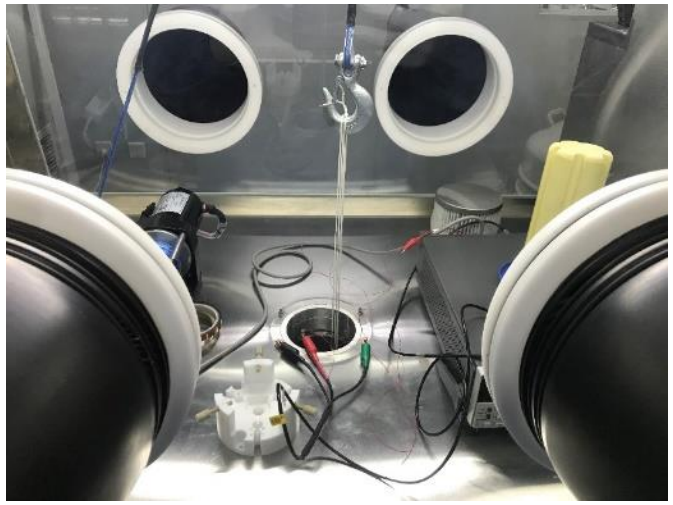
- Develop bare HPGe detectors immersed into $LN_2$;
- Long time stability;
- Further reduce the radioactive background;
- ASIC-based preamplifiers can work well in liquid nitrogen;

79 g Cu + 10 g PTFE



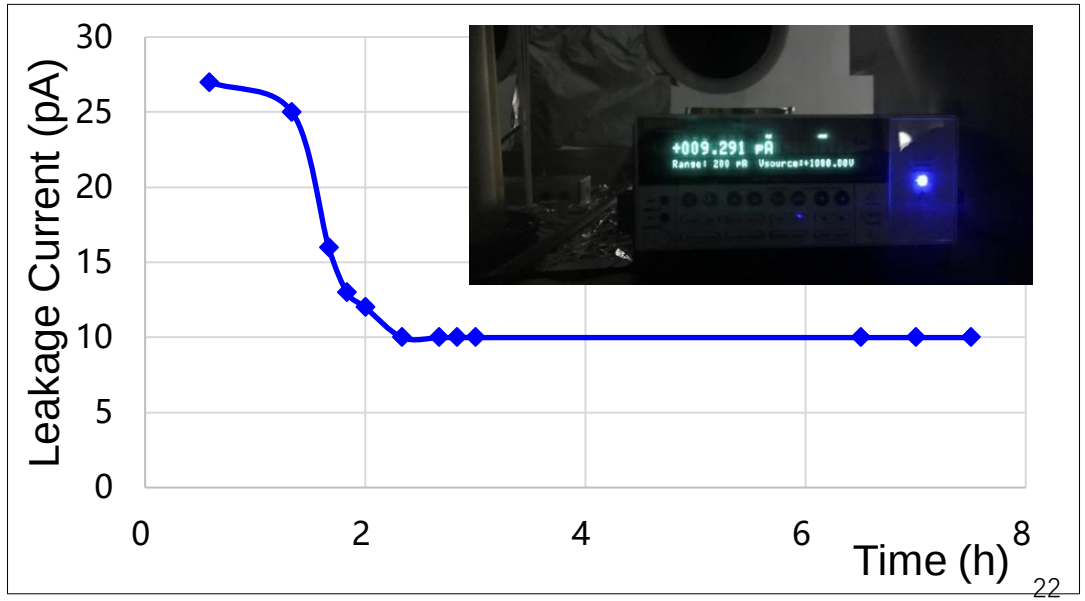


Bare HPGe detectors



Bare HPGe in $LN_2$

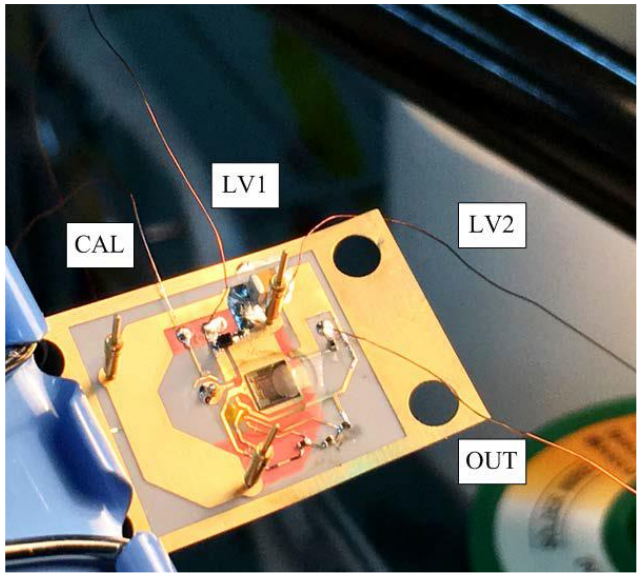
PPC: ϕ50mm x 50mm, Depleted voltage: ~800V

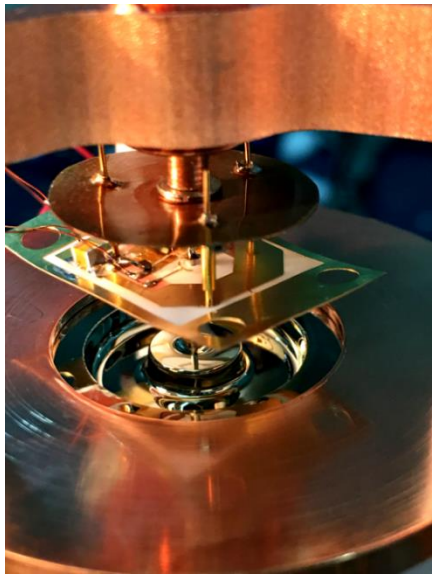


# CMOS ASIC Front-end Electronics

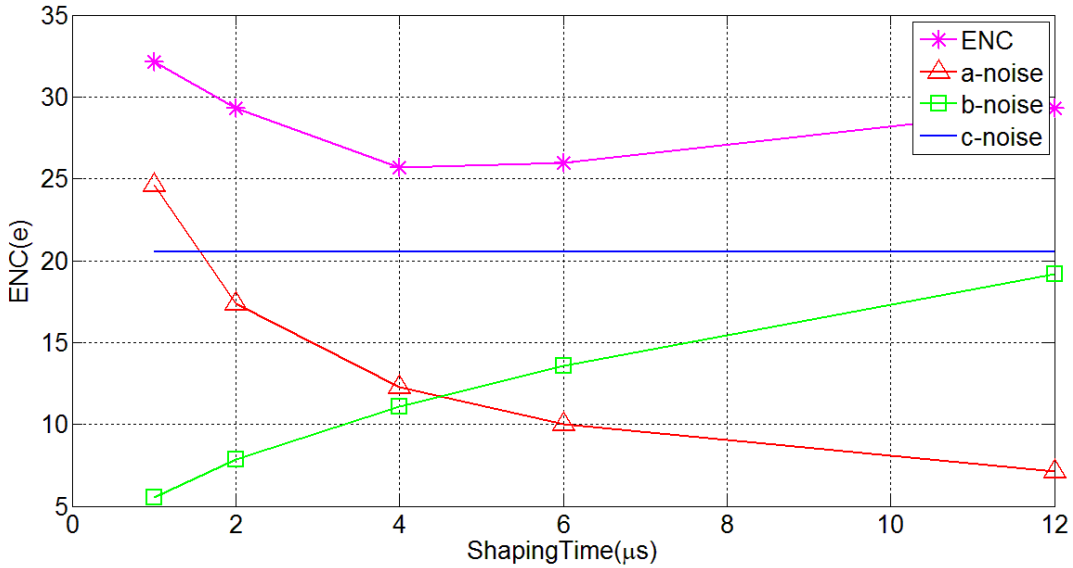
- Light DM search →low noise/threshold (low capacity, etc)
- Very close to Ge detectors →low bkg (radiopure, low-mass, etc)
- ASIC preamplifier @ 77K
  - PCB material: PTFE(Rogers 4850);
  - ENC ~26e(<200eV) w/ 4μs shaping time, mainly from 1/f noise (~21e);

Details in JINST (2018) 13: 8019



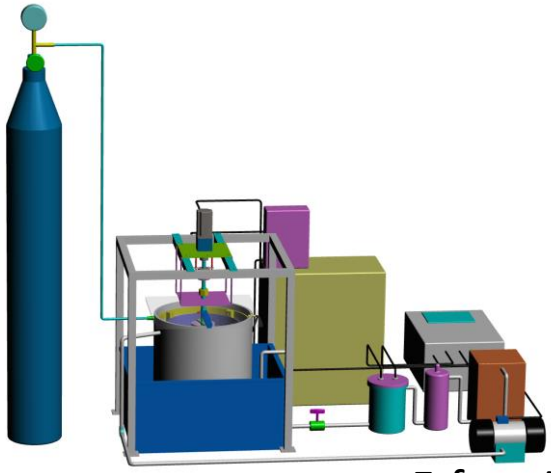
Noise components analysis



# Underground E-forming copper and Assay

- Prototype setup for underground EF-Cu production
  - Cathode mandrel: 316L stainless steel, ϕ95x380mm;
  - Plating bath: PE, ϕ400x500mm;
  - 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
  - Wet chemistry testing… , blank sensitivity ~$10^{-13}$g/g

UG copper e-forming facility@CJPL-I



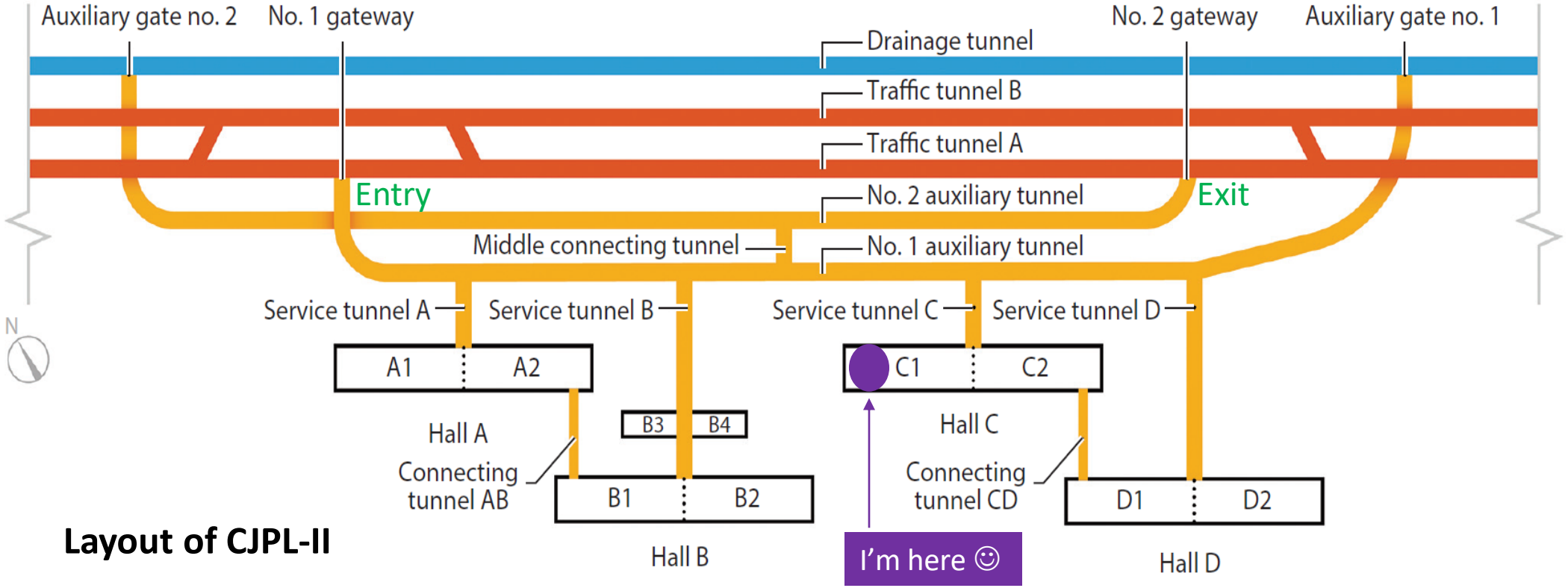
E-forming setup

optimized electrical parameters

ICP-MS

# Future Plan – New location

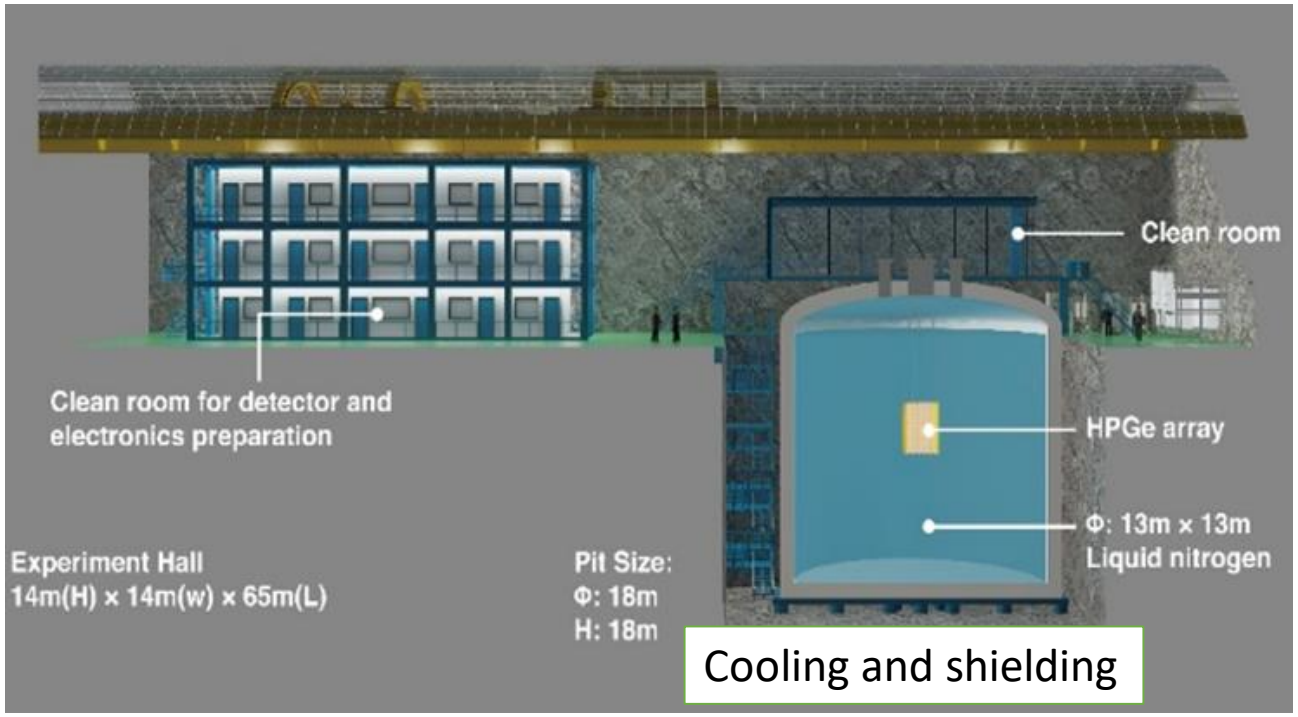
- CJPL-I to CJPL-II
  - Volume: 4000 $m^3$ to 300,000 $m^3$;
  - 1 main hall (6.5x6.5x42m) to 8 main halls (14x14x60m each);
  - Additional pit for next-generation CDEX;




**Layout of CJPL-II**

# Future Plan - CDEX @CJPL-II

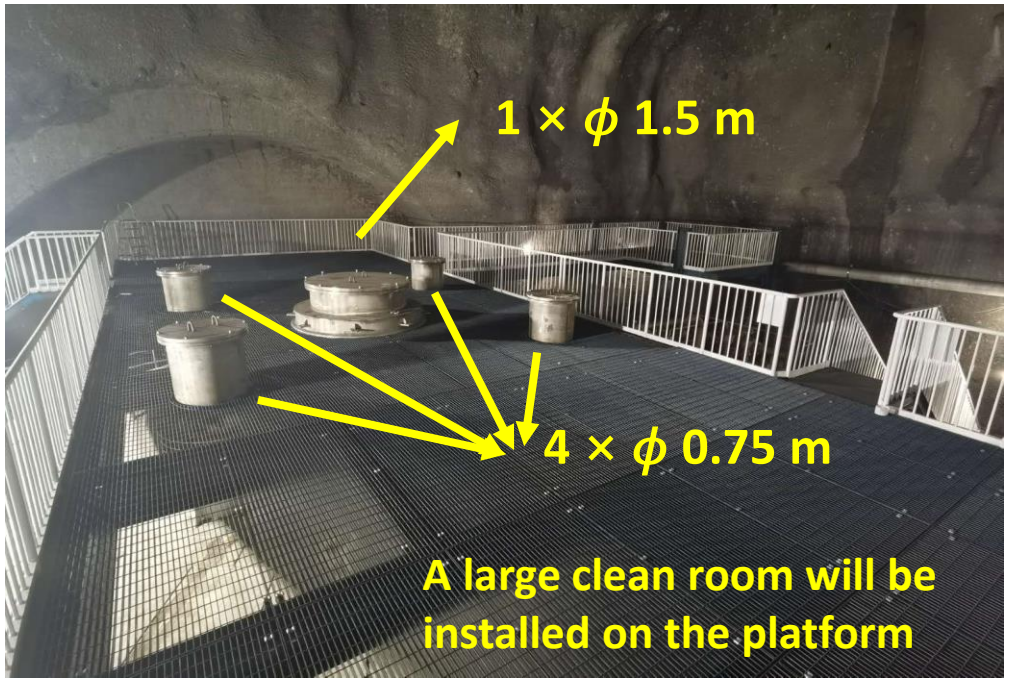
- Prepare for HPGe experiment in Hall C1 @ CJPL-II
- 1725m$^3$ liquid nitrogen, shielding and cooling system (inner: $\phi$13m*H13m)
- Inner bkg level: <$10^{-4}$ cpkkd@1keV, <$10^{-6}$ cpkkd@2MeV




Cooling and shielding

# Future Plan - CDEX @CJPL-II

- Construction of $LN_2$ tank has completed at end of 2019
- A new steel working platform has been constructed in October 2022
- Liquid nitrogen filling is expected to start at the end of 2023
- CDEX-50 stage under technical design, report comes soon

# Summary

- CDEX:  unique advantages of Ge detectors for light DM search at CJPL;
- Recently CDEX has made great progress, published many leading results for low mass DM, with multi physics channels analysis and different DM candidates;
- CDEX-50 has started and will locate in Hall C1 of CJPL-II;
- Many key technologies R&D are ongoing and have made very good progress.

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***Thanks for your attention!***

中国暗物质实验
China Dark matter EXperiment
http://cdex.ep.tsinghua.edu.cn/

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