Recent status and prospects of CDEX @CJPL

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Tsinghua University

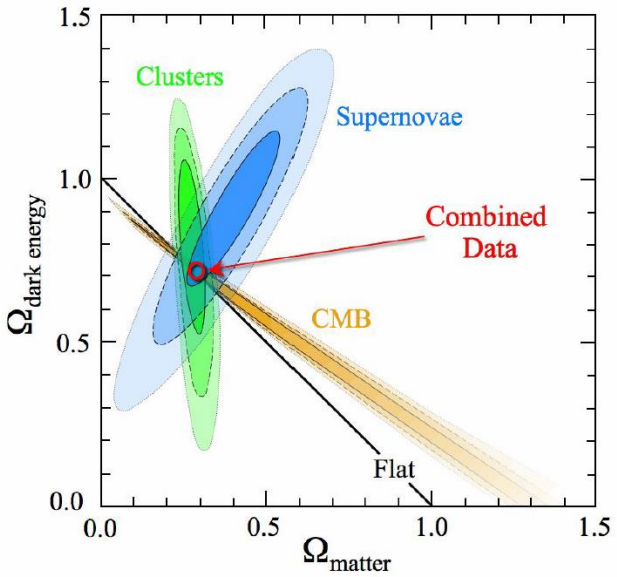
On behalf of CDEX Collaboration

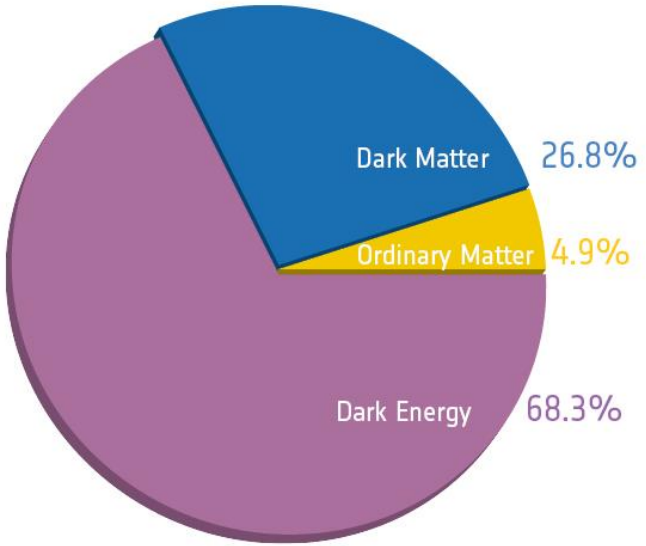
Symposium on Frontiers of Underground Physics @Chengdu, Oct. 29th-Nov. 2nd, 2023

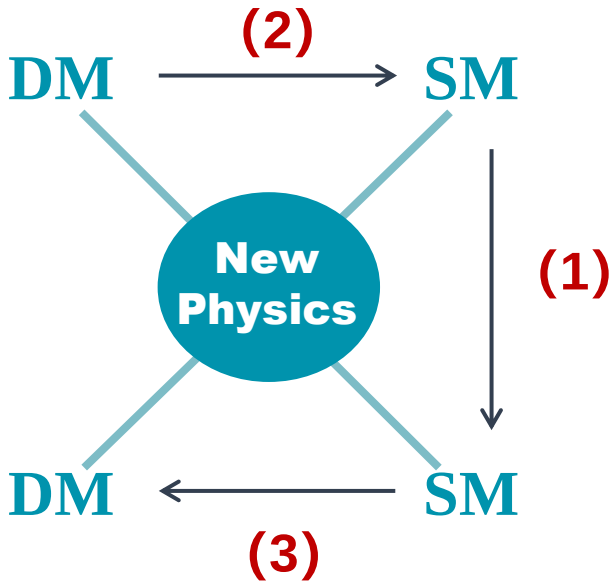
OUTLINE

- 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

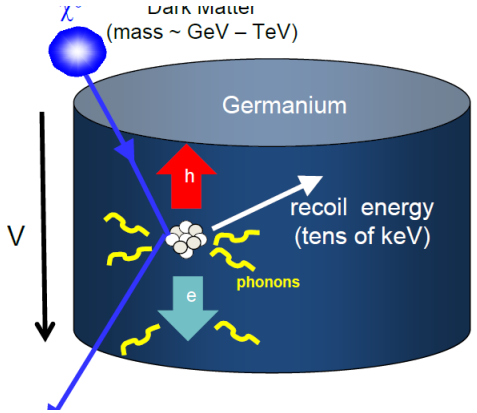
Dark Matter in Cosmology



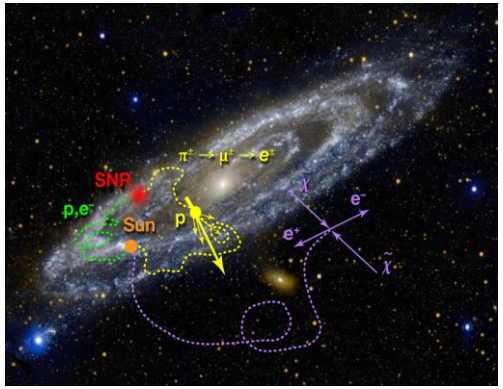




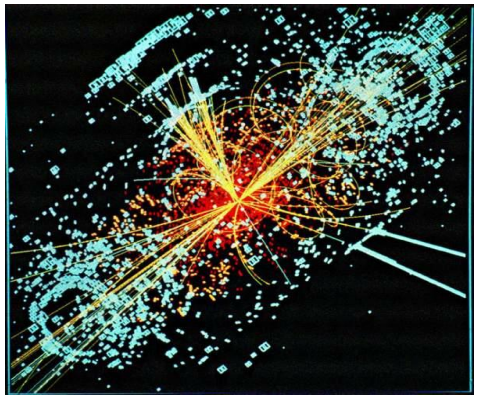
(1) Direct



(2) Indirect

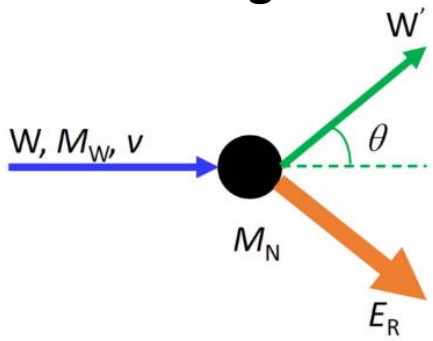


(3) Accelerator

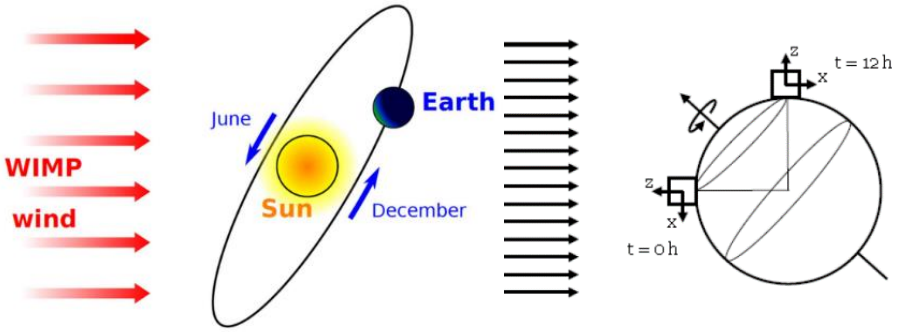


Direct detection of DM

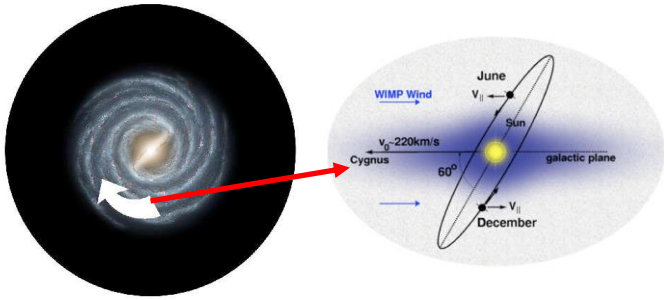
Elastic Scattering

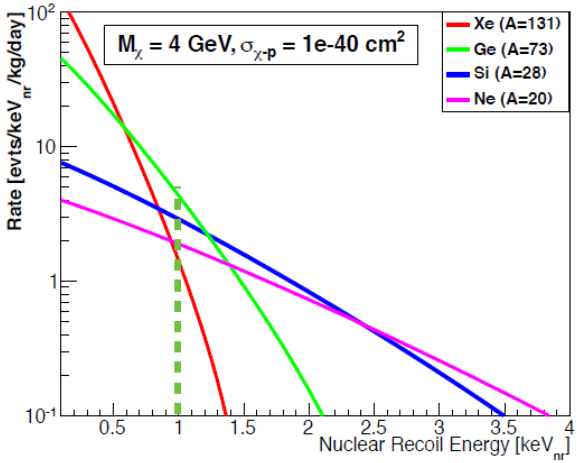


Annual/ Diurnal Modulation

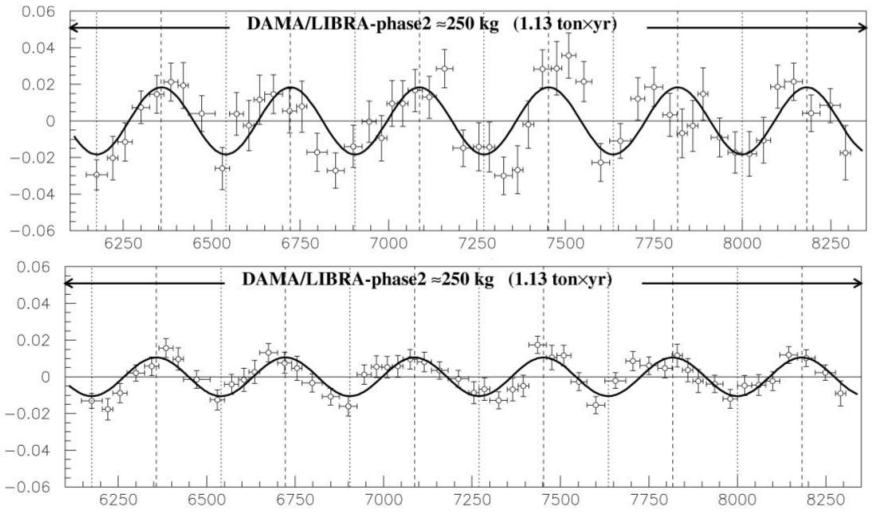


Direction Detection

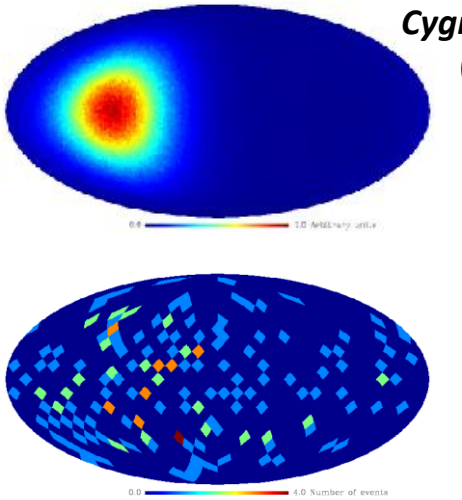




- Lower Background
- Lower Energy threshold
- Larger Exposure (Mass*Time)



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

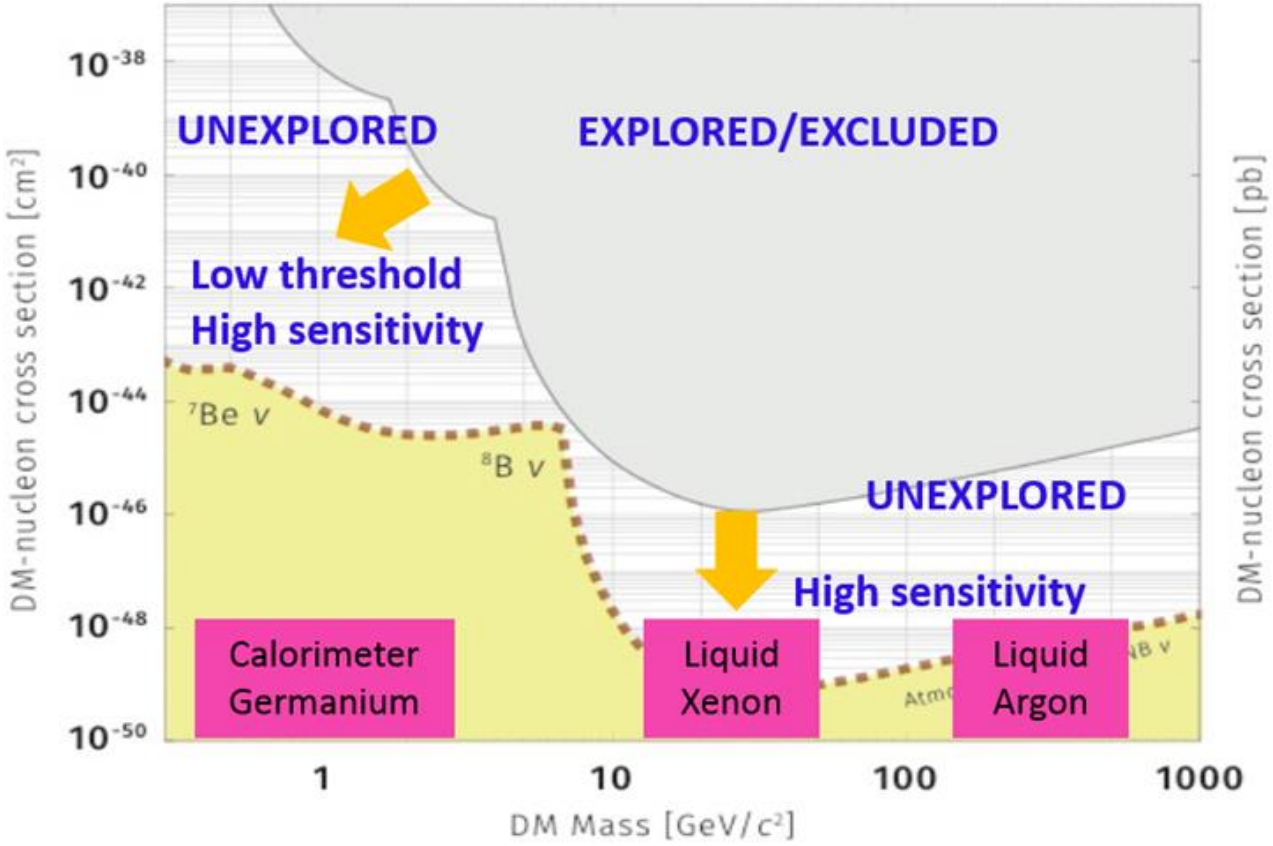


Cygnus Constellation
(l = 90°,b = 0°)

- Lower Background
- Lower Energy threshold
- Good Angular Resolution

Direct detection of DM

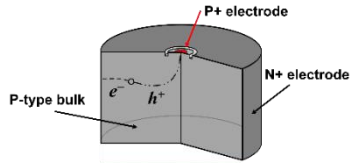
- Dark matter detection competition is becoming increasingly fierce;
- **Light dark matter detection**: low background level, low energy threshold, large mass detector target

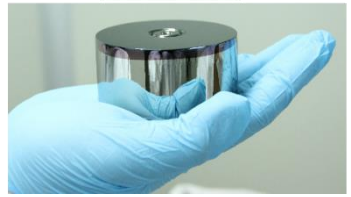


China Dark matter Experiment

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

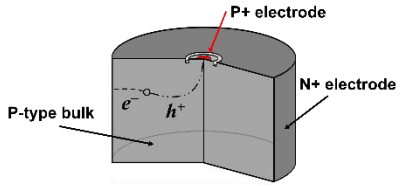
http://cdex.ep.tsinghua.edu.cn/

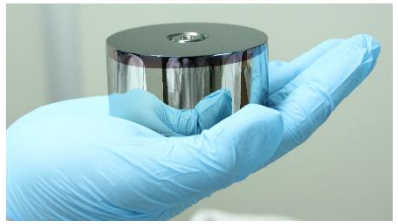




CDEX Roadmap

- **CDEX-1 (2009-2016):** 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.



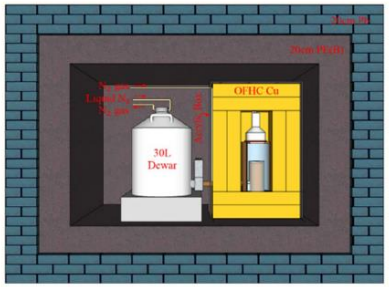


CDEX-1 → CDEX-10

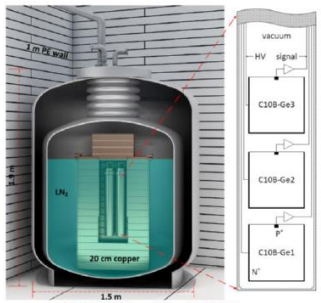
2009-2016 2016-2022

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

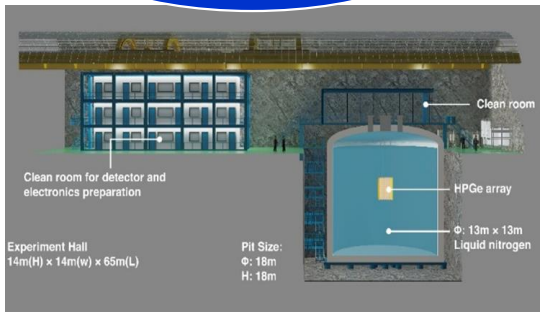
See Li Wang's talk, 1st Nov.



CDEX-1A&B: 1kg PPC Ge×2

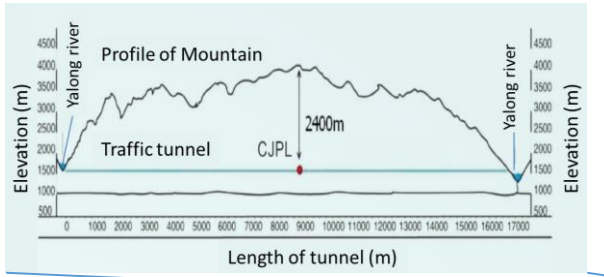


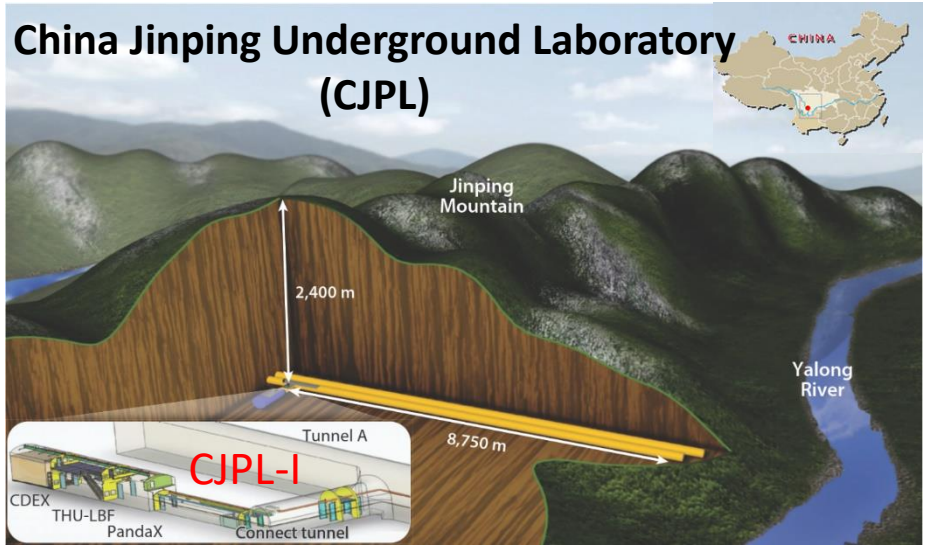
CDEX-10: ~10kg PPC Ge array



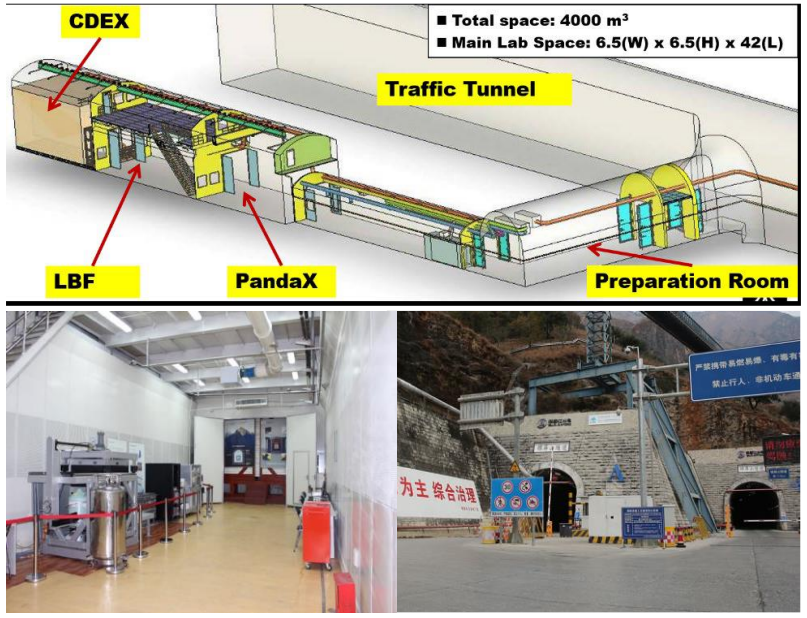
China Jinping Underground Laboratory

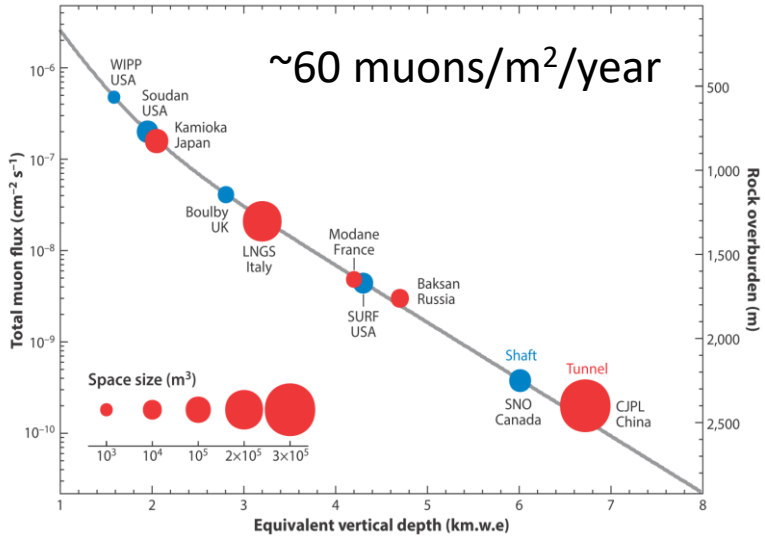
- World's deepest underground lab, CJPL
  - ✓ Near Xichang city, Sichuan Province, Southwest China
  - ✓ Rock overburden: 2400m (~6720 m. w. e.)
  - ✓ Main Hall: 6.5m(W) x 6.5m(H) x 42m(L), Total space: ~4000 m^3
  - ✓ Two DM exp. (CDEX, PandaX)+LBF(radio-assay) operated in CJPL-I
  - ✓ Extension project,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





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

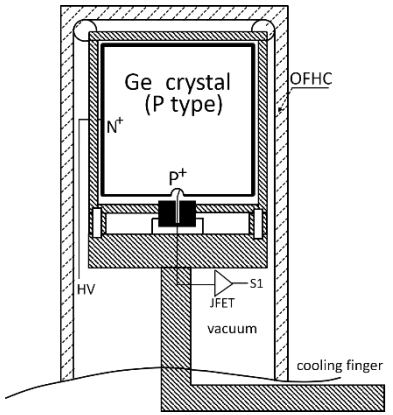


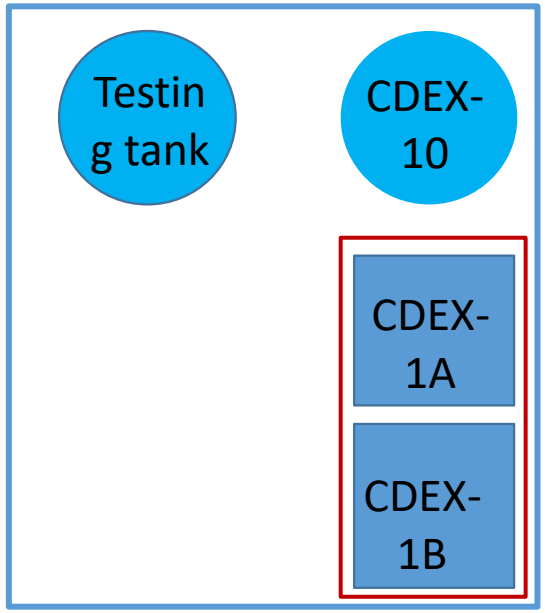


Chinese Physics C 37:086001 (2013)

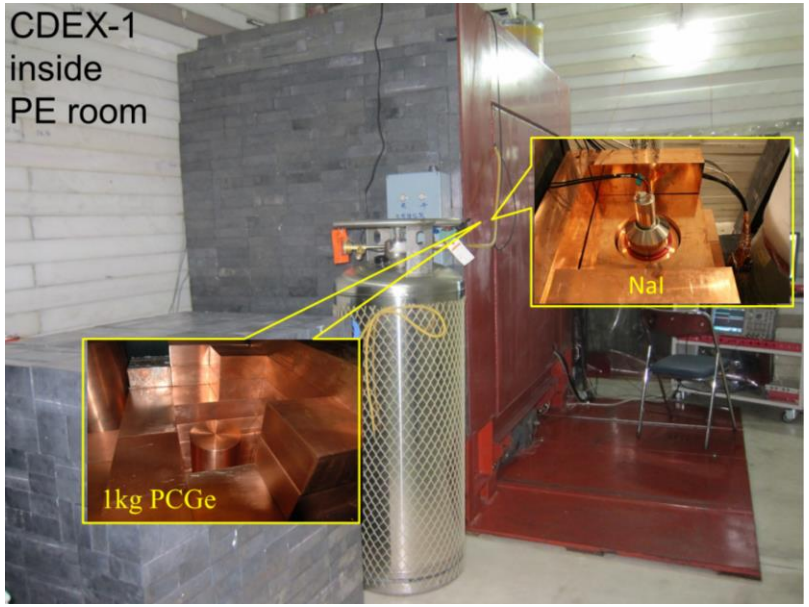
CDEX-1

- 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;

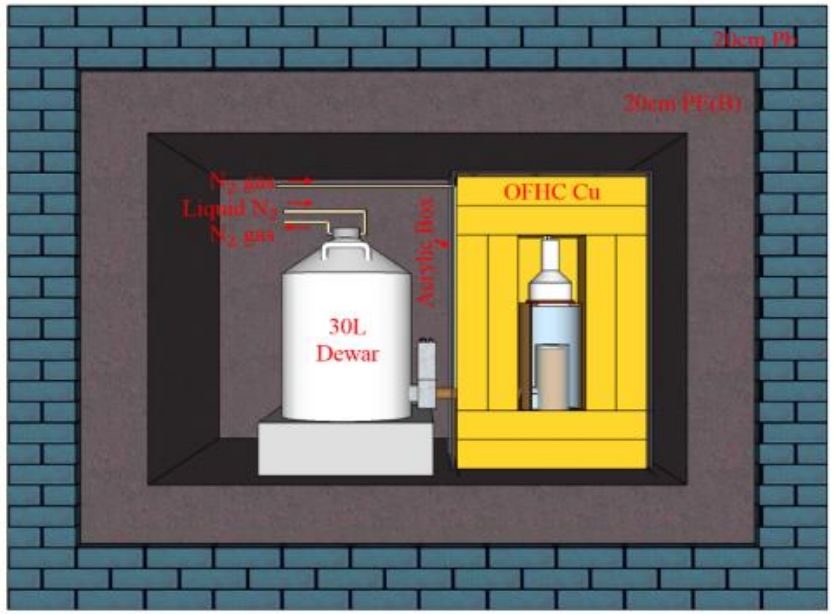




Layout of PE room, CJPL-I



CDEX-1 inside PE room

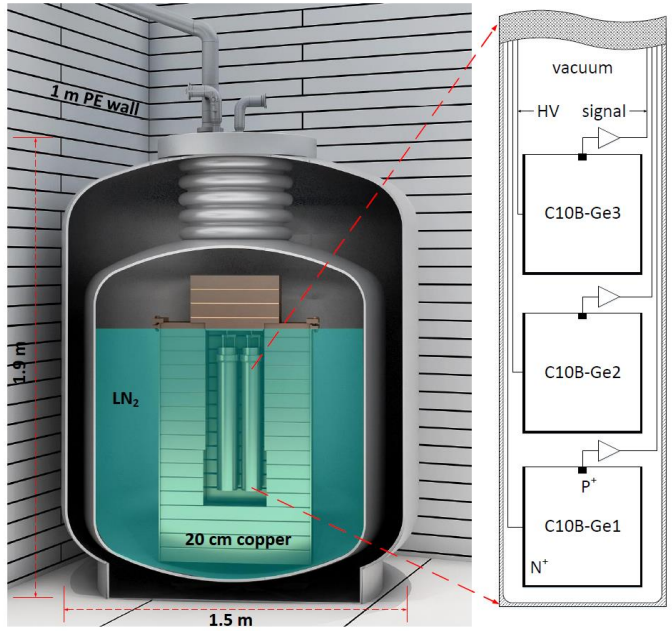


CDEX-1A&B: 1kg PPC Ge×2

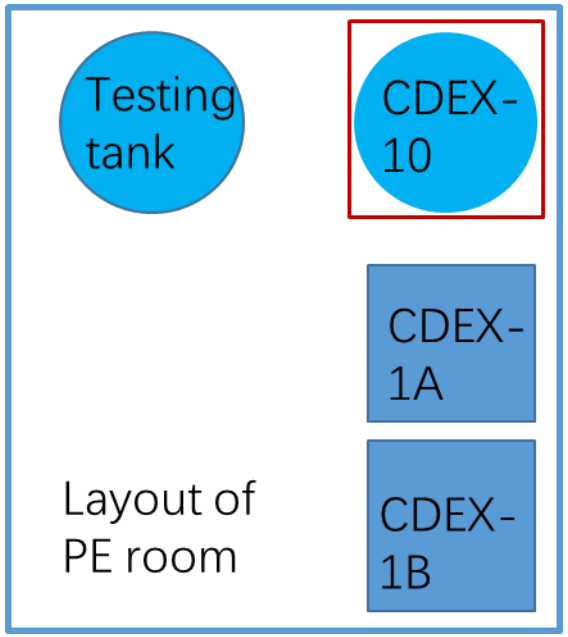
CDEX-10

- 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



Dark Matter Direct Detection

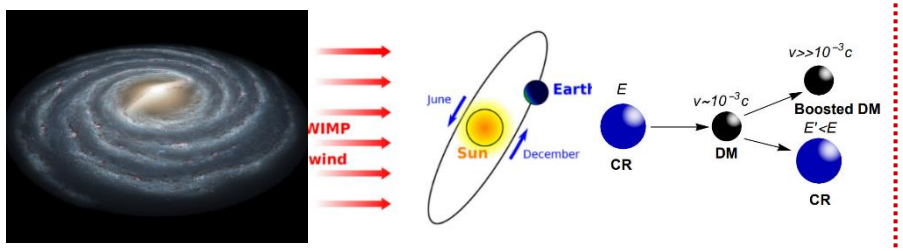
$$\frac{dR}{dE_R} = N_T \left[\frac{\rho_\chi}{m_\chi} \int d^3\vec{v} v f_v(\vec{v} + \vec{v}_E) \right] \left[\frac{d\sigma}{dE_R} \right]$$

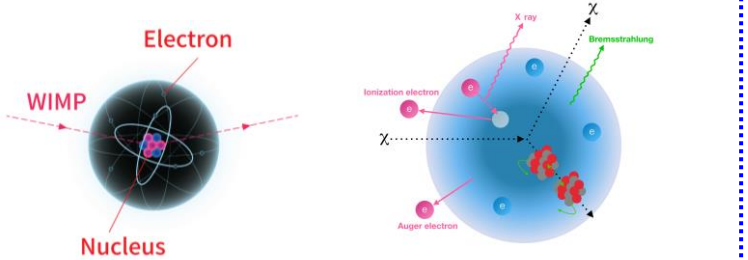
DM sources related：

- ✓ **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

CDEX-1 Results

- Detector w/ lower JEFT noise and material bkg;
- >4 years (Run-1&Run-2), >1200 kg·day exposure;
- CDEX-1: Eth 160 eVee, sensitivity extending to 2 GeV;
- CDEX-10: Bkg level 2 cpkkd @ 2-4 keV, Best SI limit on 4-5 GeV;

DM sources:
- ✓ **WIMP (Standard Halo Model)**
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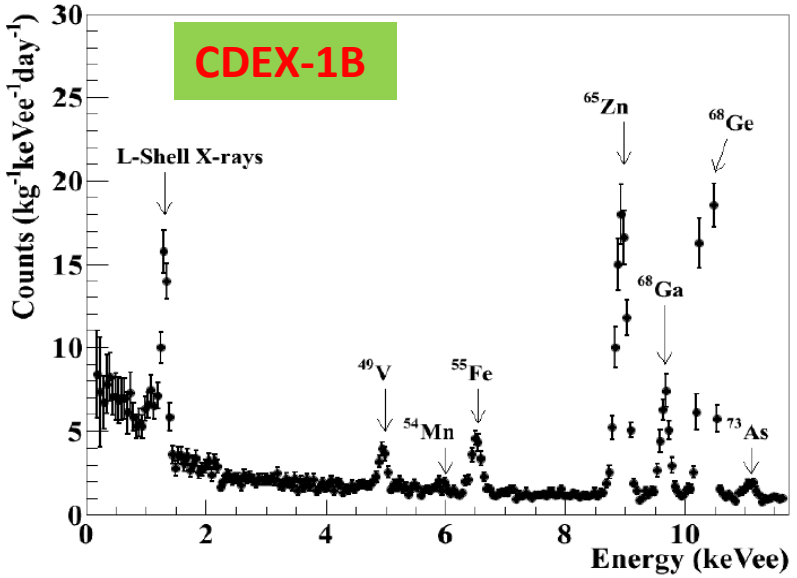
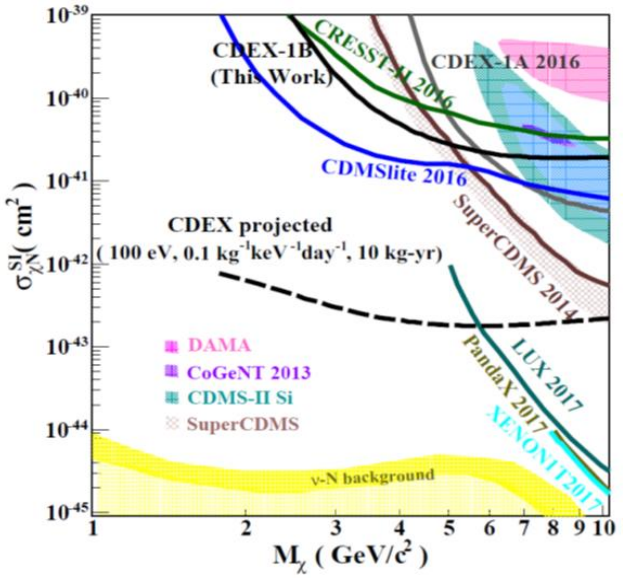
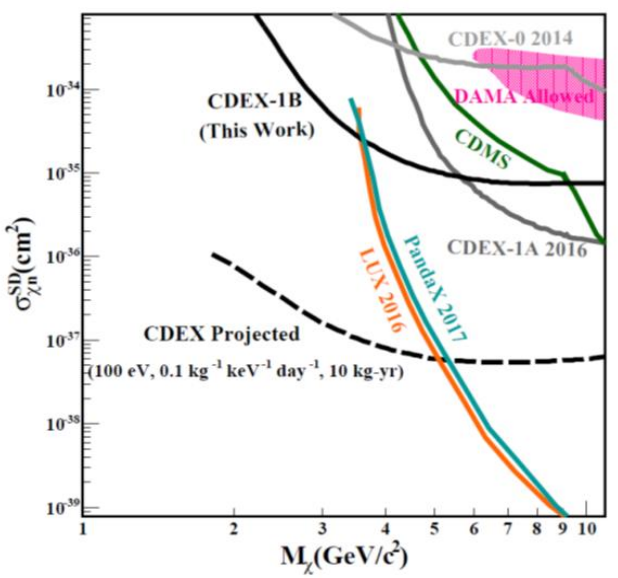
Time-integrated (TI) analysis: CPC 42, 023002, 2018







CDEX-10 Results

- Detector w/ lower JEFT noise and material bkg;
- >4 years (Run-1&Run-2), >1200 kg·day exposure;
- CDEX-1: Eth 160 eVee, sensitivity extending to 2 GeV;
- CDEX-10: Bkg level 2 cpkkd @ 2-4 keV, Best SI limit on 4-5 GeV;

DM sources:

- ✓ **WIMP (Standard Halo Model)**
- ✓ Annual Modulation (velocity change)
- ✓ Boosted DM
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Interaction process:

- ✓ **DM-nucleus elastic scattering**
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- ✓ DM-electron scattering
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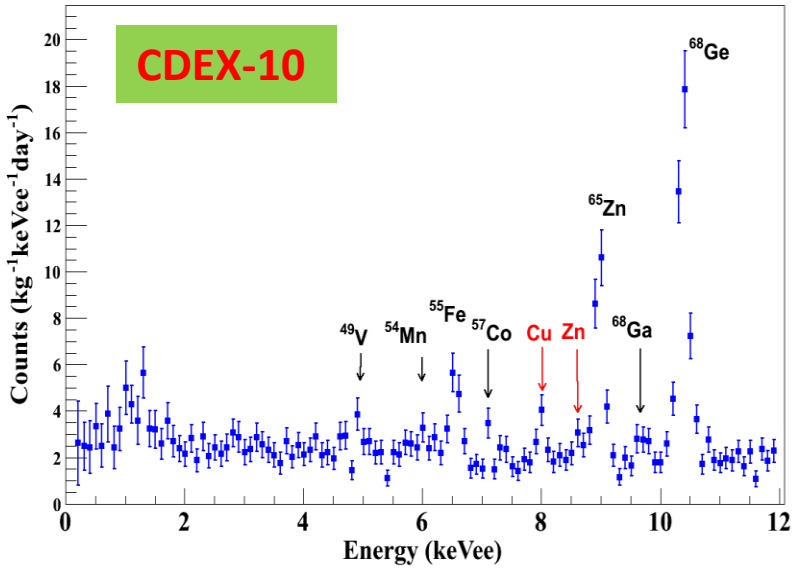
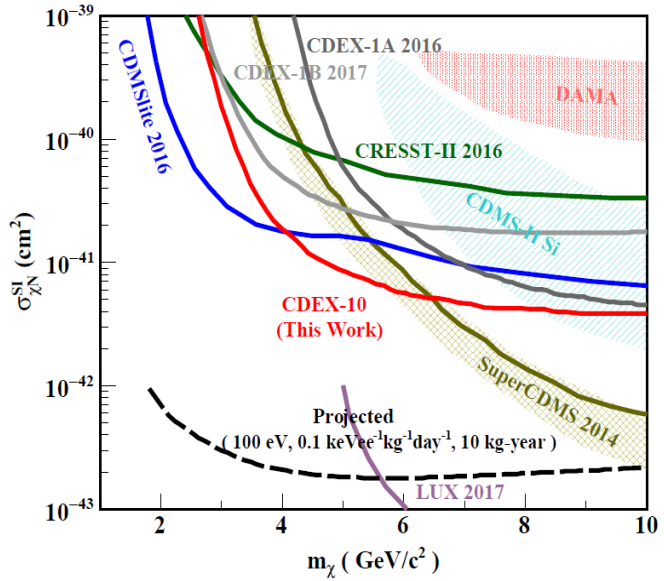
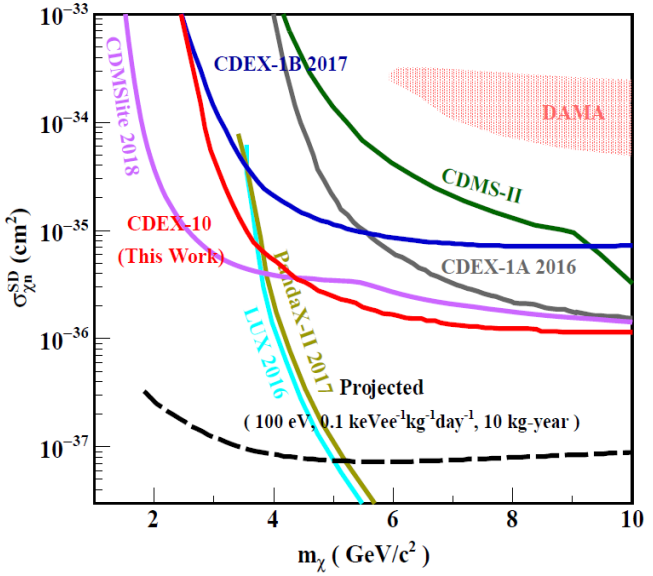
Phys. Rev. Lett. 120, 241301 (2018)







Inelastic scattering: Migdal effect

- Time-Integrated Analysis: 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;**

DM sources:
- ✓ **WIMP (Standard Halo Model)**
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Interaction process:
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- ✓ DM-electron scattering
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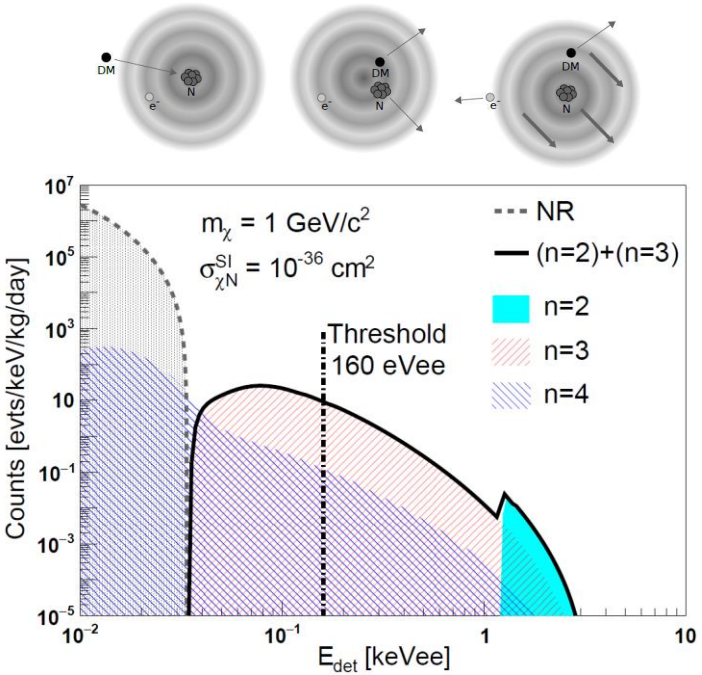
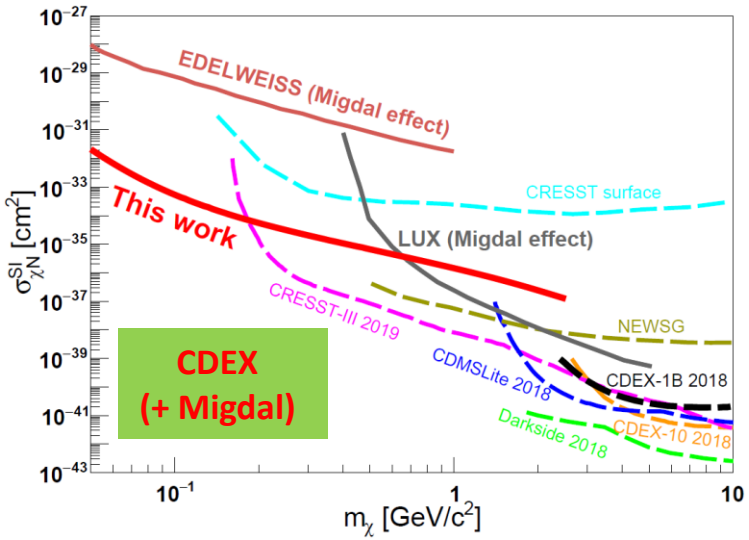
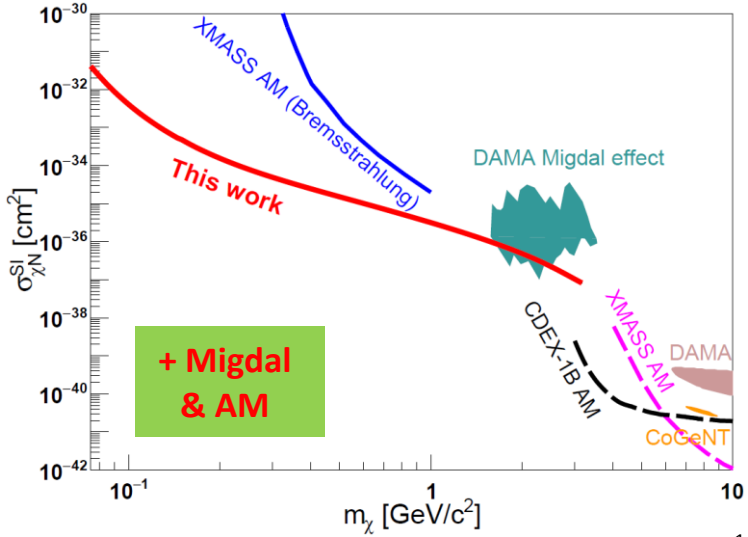
ref: Migdal effect (M. Ibe et al.,2018)



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





Dark Matter–Electron Scattering

- **First HPGe detector-based DM-e scattering limits from CDEX**;
- **Most stringent χ-e limit to date among experiments using solid-state** detectors for m_χ > 100MeV with heavy mediators;

DM sources:
- ✓ **WIMP (Standard Halo Model)**
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Interaction process:
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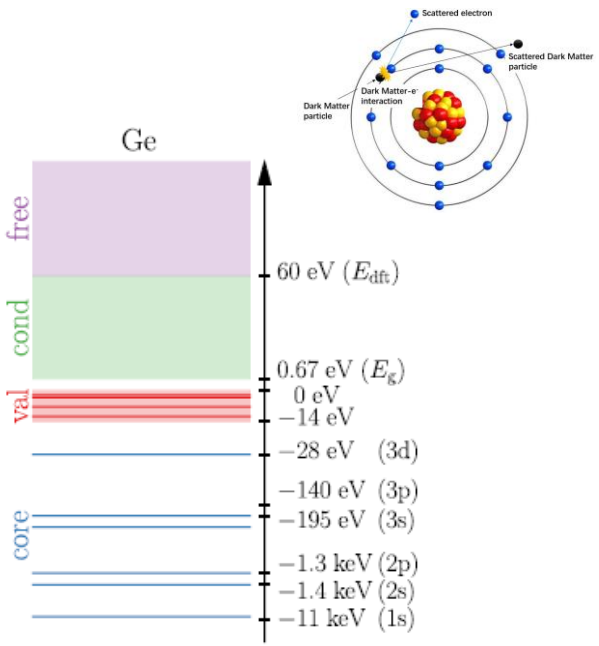
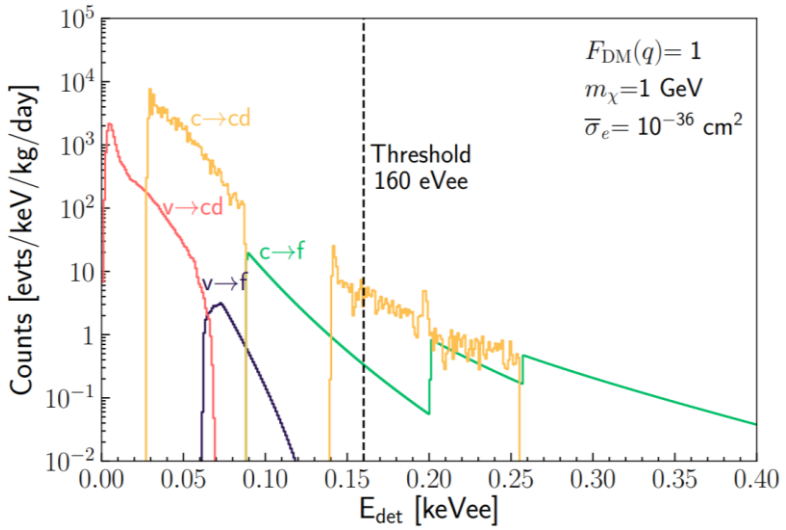
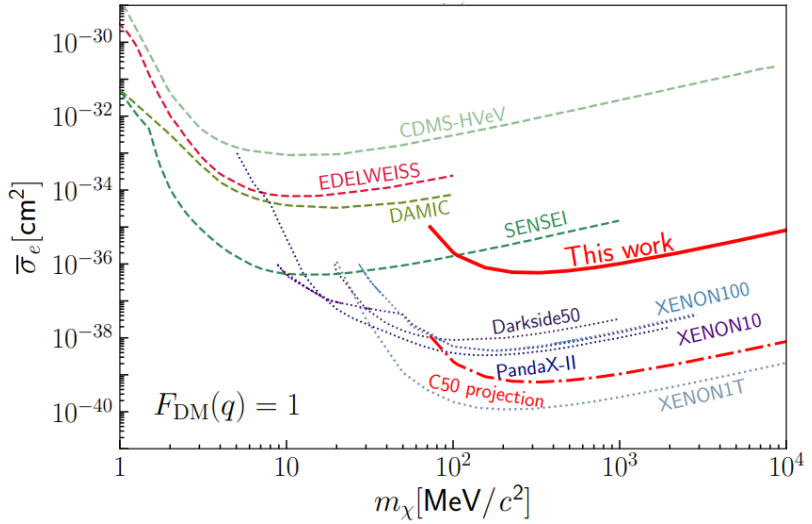


Phys. Rev. Lett. 129:221301 (2022)





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

Annual Modulation analysis

- Smoking-gun signatures for WIMPs independent of bkg modeling, only requires stable background with time;
- CDEX-1B excludes CoGeNT's signal region, also DAMA/LIBRA phase-1's interpretation with the WIMP SI interaction under SHM in Germanium crystal.

DM sources:
- ✓ WIMP (Standard Halo Model)
- ✓ **Annual Modulation (velocity change)**
- ✓ Boosted DM
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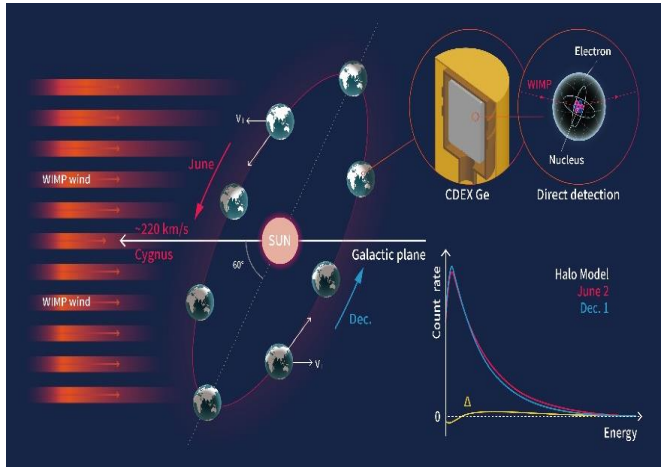
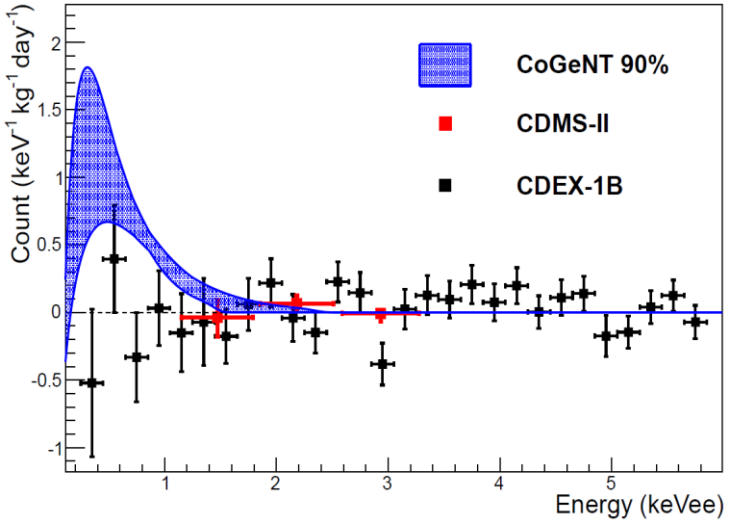
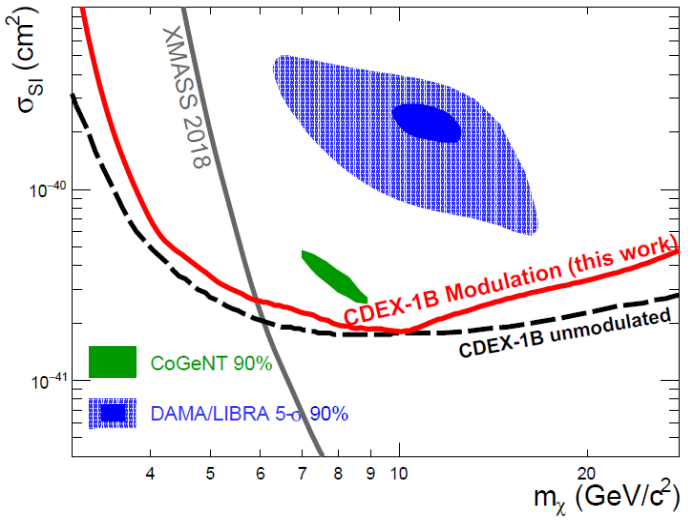




Best-fit of modulation amplitude



SI Limits from AM

sub-GeV DM: CRDM, Earth shielding

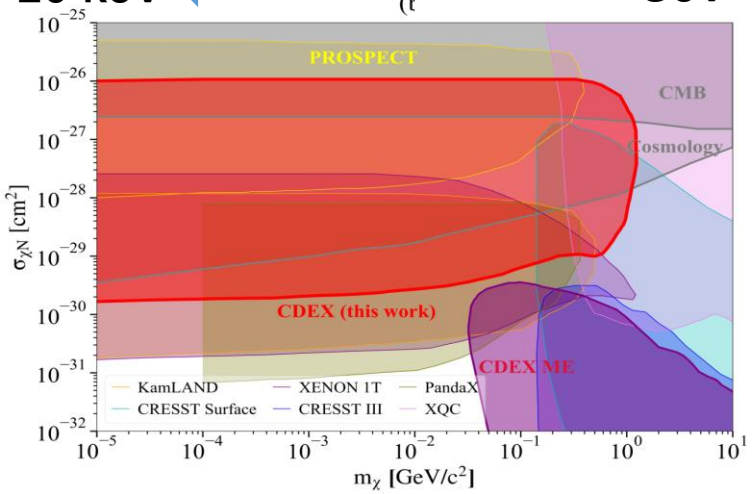
- **CRDM searches:** the low mass reach of DM has been extended from GeV to keV, more sensitive than cosmology;
- **Earth shielding effect calculation:** CJPL_ESS package has been developed with detail topography of Jinping mountain.

DM sources:
- ✓ 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)

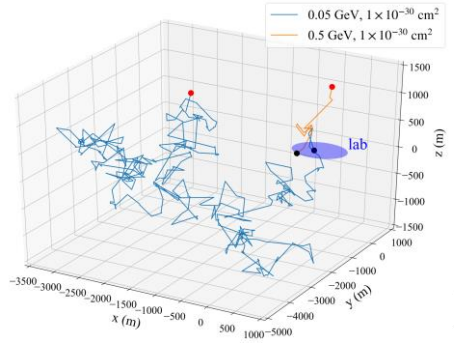
CRDM

10 keV ← GeV

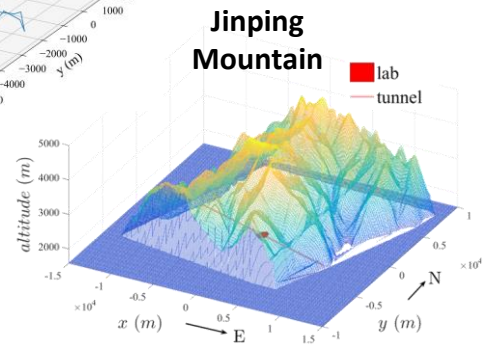


Exclusion line

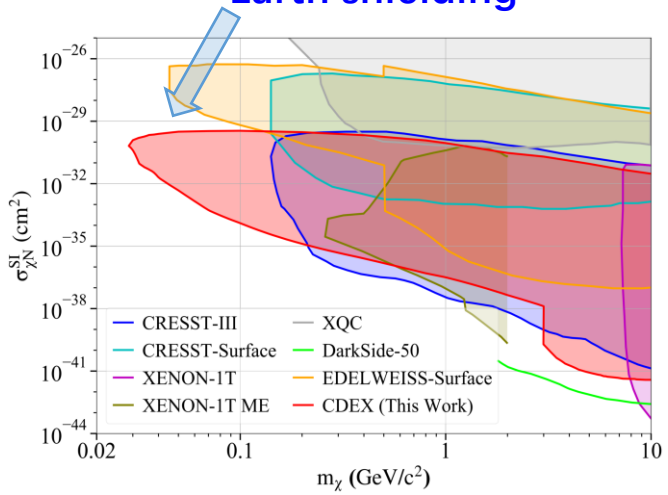
→Exclusion region



Scattering tracks of DM in the crust (simulation)



Earth shielding



PRD *106, 052008 (2022)*

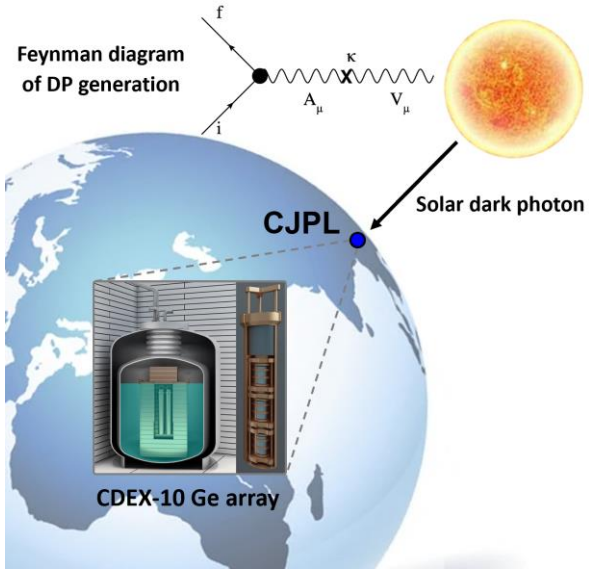
PRD *105, 052005 (2022)*

Other DM candidates

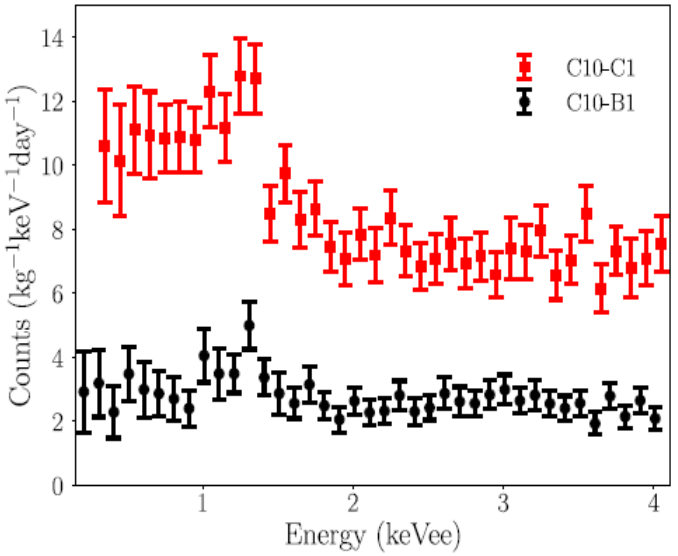
- Dark photon Analysis: 205.4 kg-d, w/ Eth 160 eVee;
- Leading sensitivity in m_V ~10-300 eV for solar dark photon;

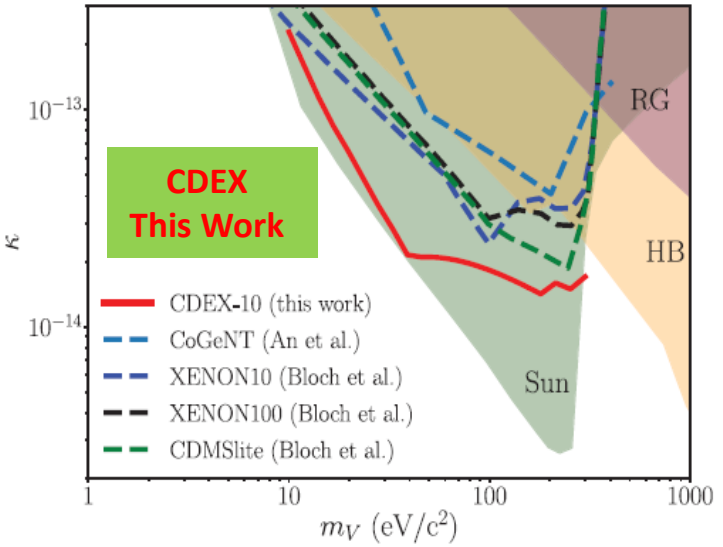
DM sources:
- ✓ WIMP (Standard Halo Model)
- ✓ Annual Modulation (velocity change)
- ✓ Boosted DM
- ✓ **Dark Photon, axions et al.**

Interaction process:
- ✓ DM-nucleus elastic scattering
- ✓ DM-nucleus inelastic scattering
- ✓ DM-electron scattering
- ✓ **Others (All energy deposited)**



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





solar dark photon

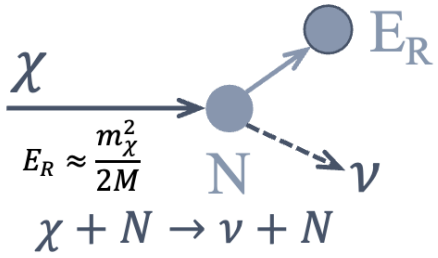
ref: An, H. et. al., PRL, 111:041302 (2013)

Exotic dark matter

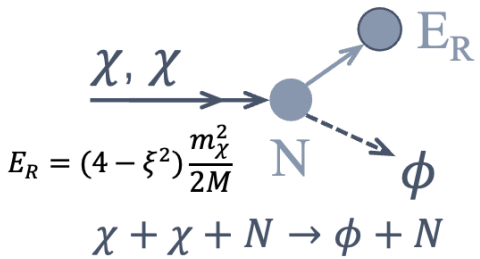
- Exotic DM interactions:
  - **Neural current fermionic DM absorption**: $\chi + N \rightarrow \nu + N$
  - **DM-nucleus 3->2 scattering**: $\chi + \chi + N \rightarrow \phi + N$
- Set new experimental limits on lowest mass range for these two channels based on the **low energy threshold of 160 eV**.

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

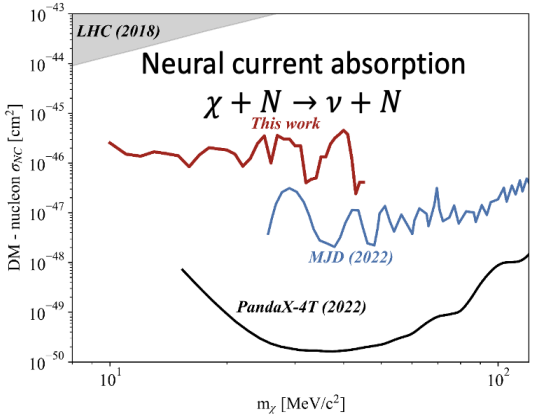
Interaction process:
- ✓ DM-nucleus elastic scattering
- ✓ DM-nucleus inelastic scattering
- ✓ DM-electron scattering
- ✓ **Others (All energy deposited)**

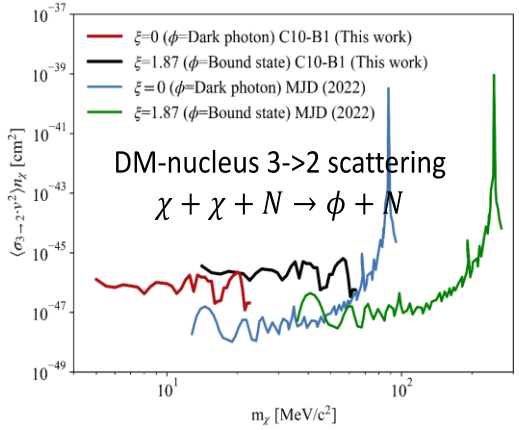


- ν is neutrino
- Generates a monoenergetic signal



- ϕ is either a DM composite state or any dark radiation
- Generates a monoenergetic signal



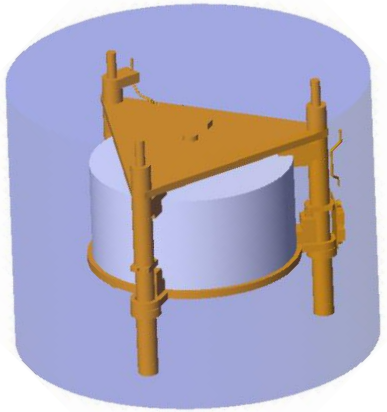


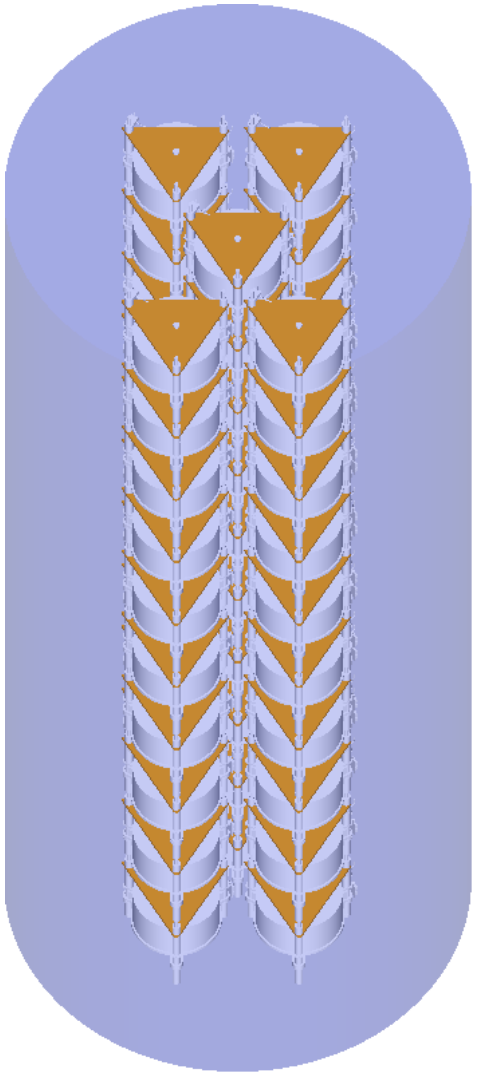
[1] Jeff A. Dror, et al., Phys. Rev. Lett. 124, 181301 (2020);
[2] W. Chao, et al., arXiv:2109.14944 (2021)

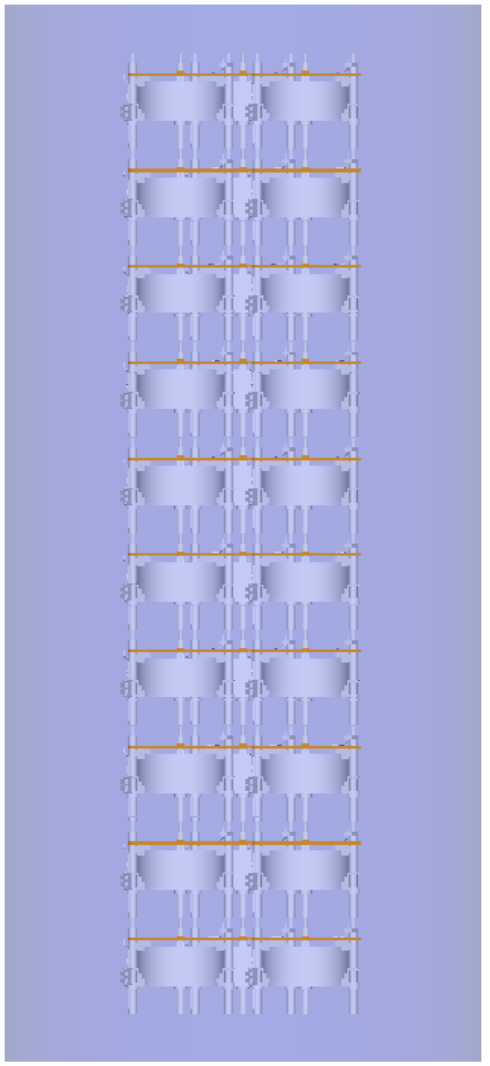
Phys. Rev. Lett. 129, 221802 (2022)

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;







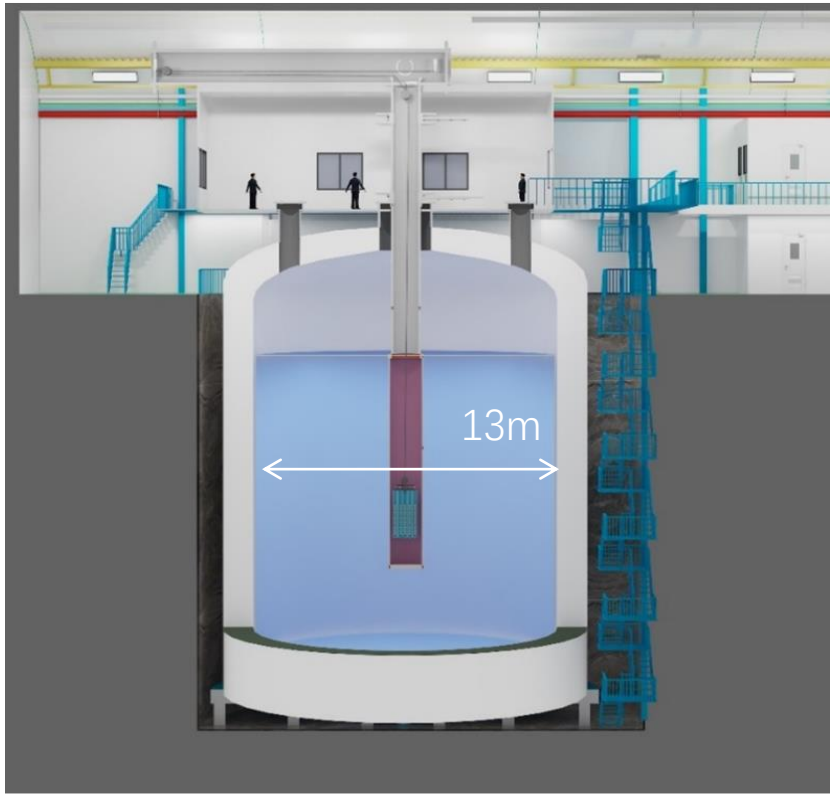
LN_2 tank

Specification

- Total volume: ~2000 m^3
- LN_2 volume: ϕ13m×H13m, ~1725 m^3
- LN_2 as Passive Shield & Cryogen
- Five top flanges for detector deployment
  - 1×ϕ1.5m, 4×ϕ750mm
  - **Reentrant tube containing LN_2 submerged in LN_2**
  - **LN_2 constantly purified (**Removing O_2/H_2O/Rn**)**

Background

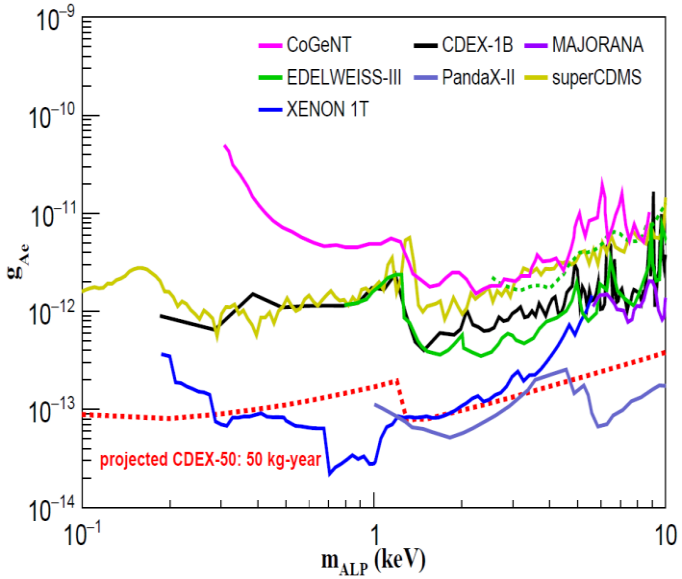
- >4m LN_2 shields most bkg from surroundings



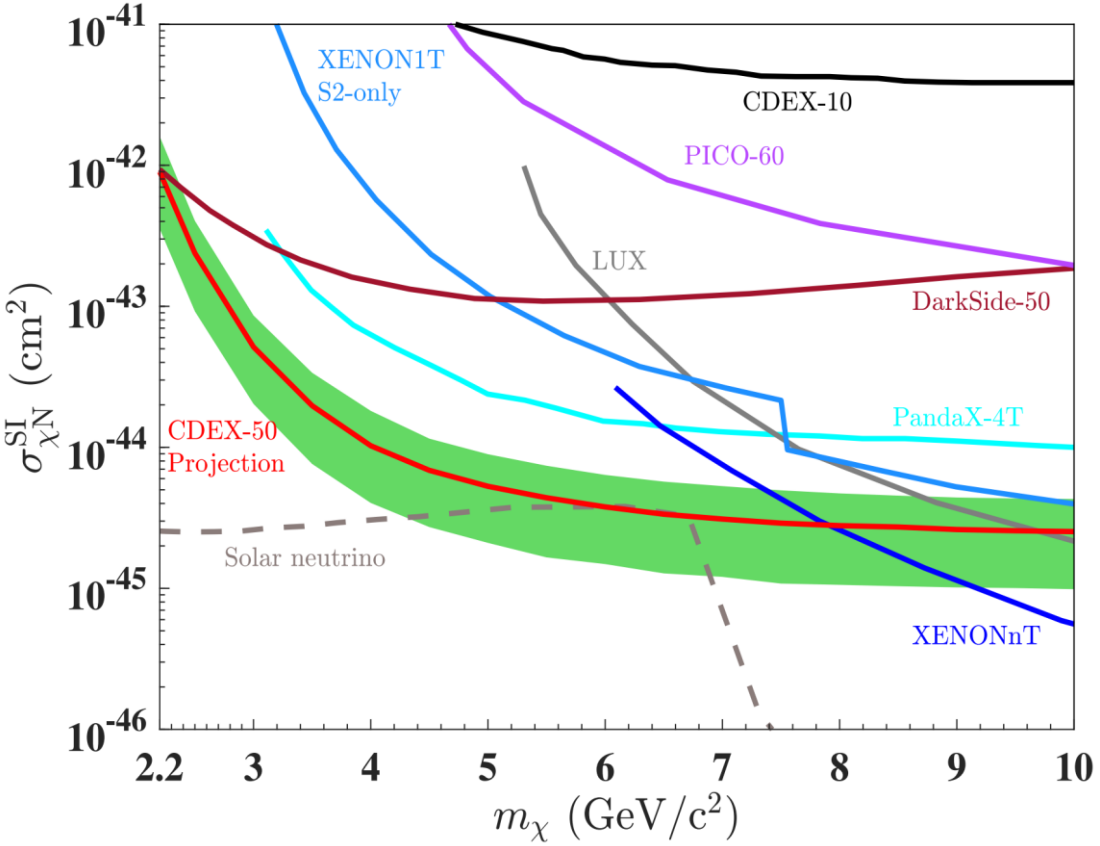
1725 m^3 Liquid Nitrogen

CDEX-50 Projected sensitivity

- Bkg level: **<0.01 cts/(keV·kg·day) @1 keV**
- Energy threshold for data analysis: **160 eV**
- Exposure reaches **~50 kg·year**
- WIMP SI sensitivity reaches **10^{-44} cm²**
- **Multi physics channel** analysis:
  - axion
  - dark photon
  - …

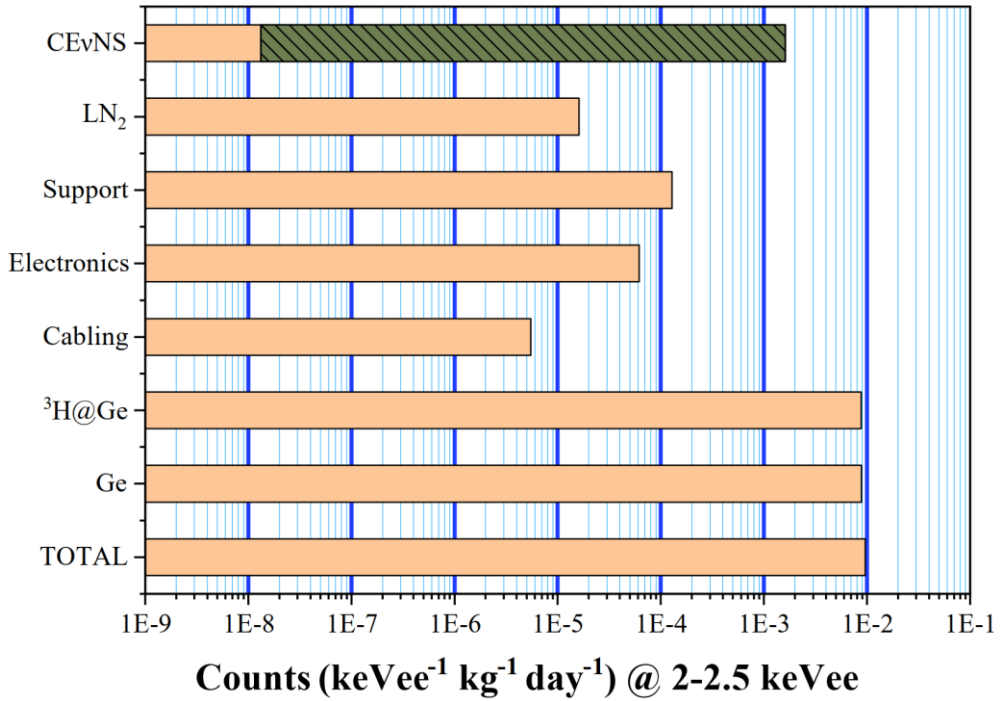


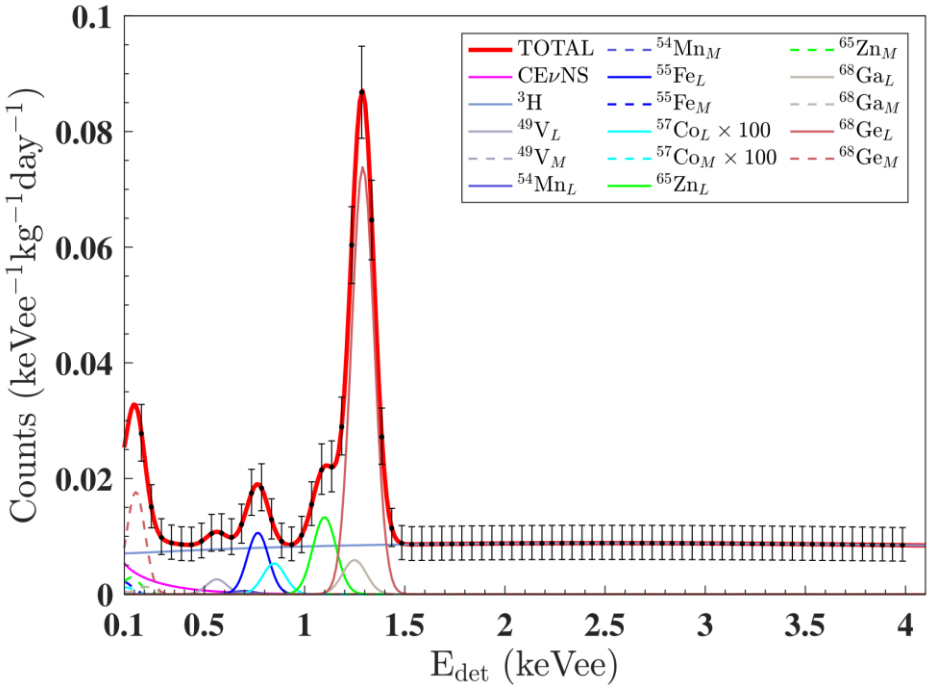
arXiv:2309.01843 (2023)



CDEX-50 Background Model and Simulation

- Bkg level: **<0.01 cts/(keV·kg·day) @1 keV**
- Mainly comes from the ^{3}H and cosmogenic radionuclides in crystal
- The contribution from CEvNS and M-shell X-rays should be well understood



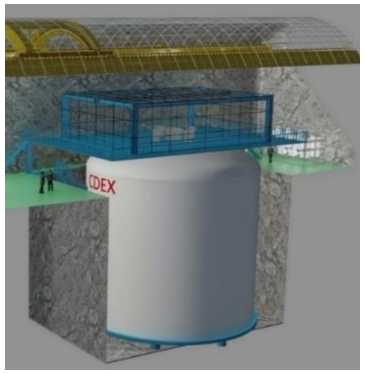


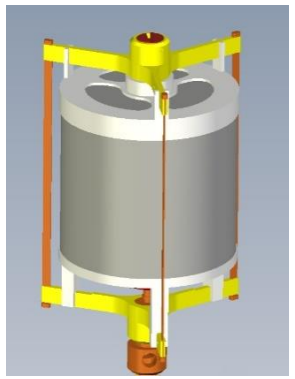
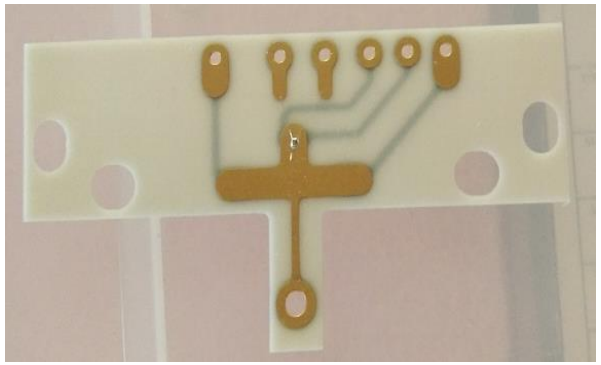
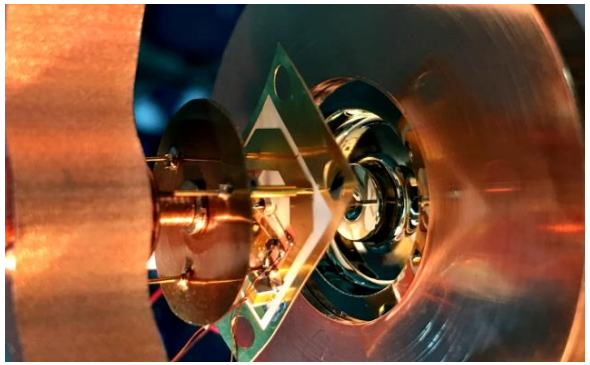
contribution of CE*v*NS in 0.16–0.5 keVee

Technical R&D towards next-stage

- **Large scale detector array**
  - 10 kg → 50 kg
- **Low background**
  - 2 cpkkd → 0.01cpkkd@ 2-4 keV
- **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**

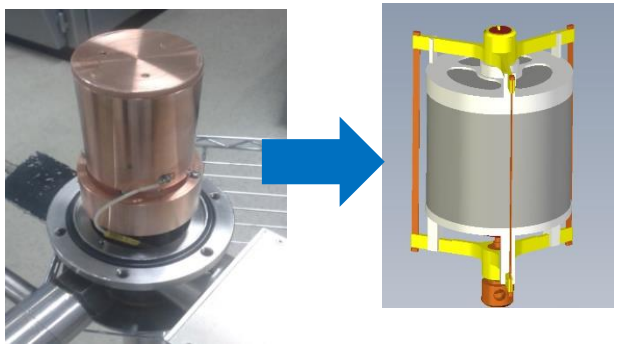


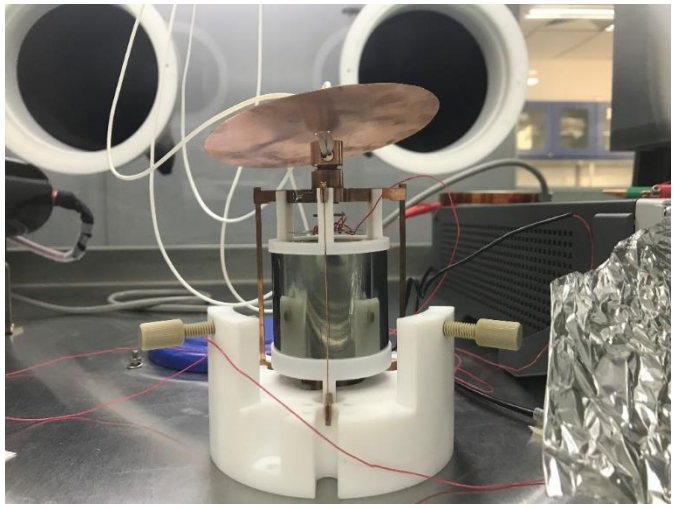





Ge detector fabrication

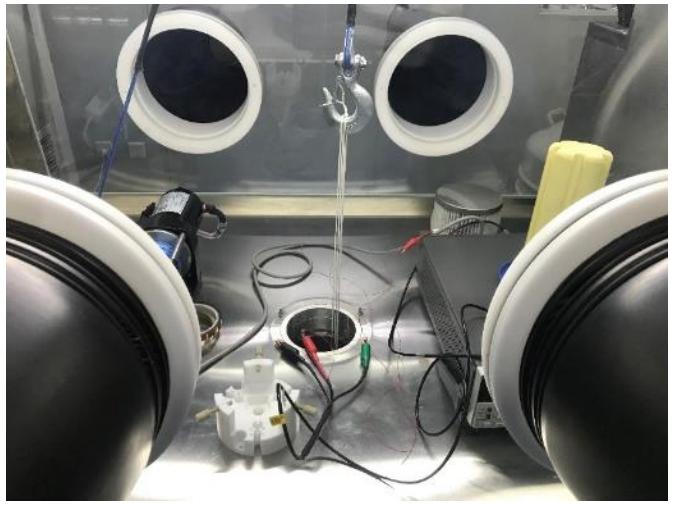
- Develop bare HPGe detectors immersed into LN_2;
- Long time stability;
- Further reduce the radioactive background;
- ASIC-based preamplifiers can work well in liquid nitrogen;

79 g Cu + 10 g PTFE

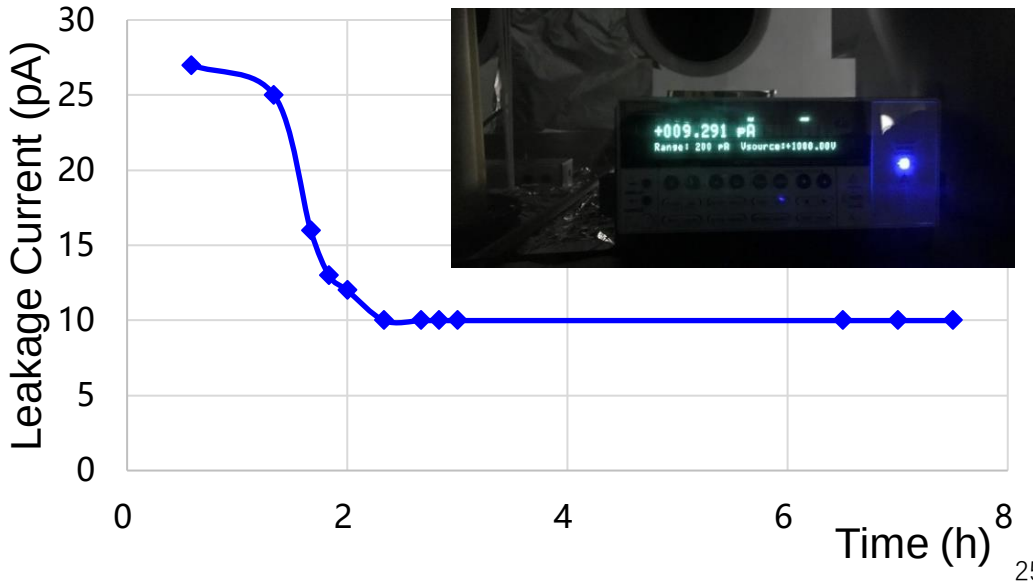




Bare HPGe detectors



Bare HPGe in LN_2

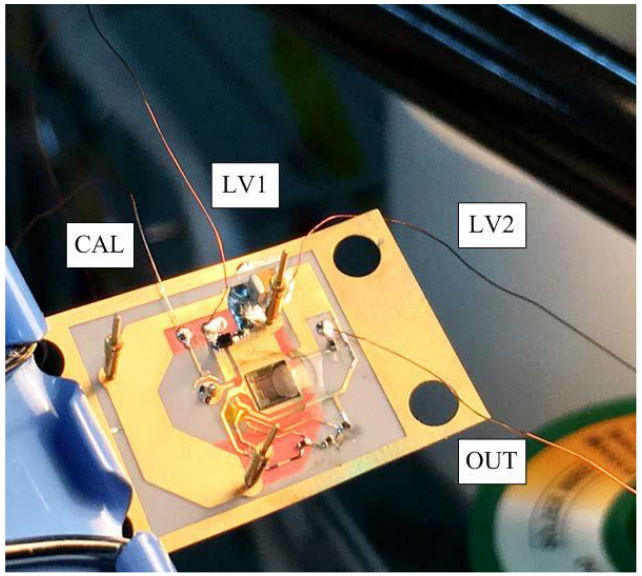


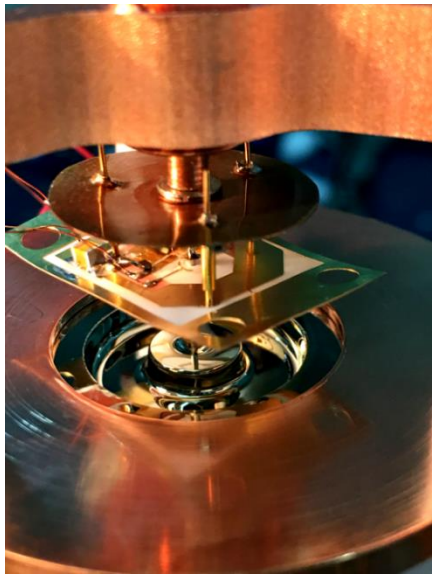
PPC: ϕ50mm x 50mm, Depleted voltage: ~800V

CMOS ASIC Front-end Electronics

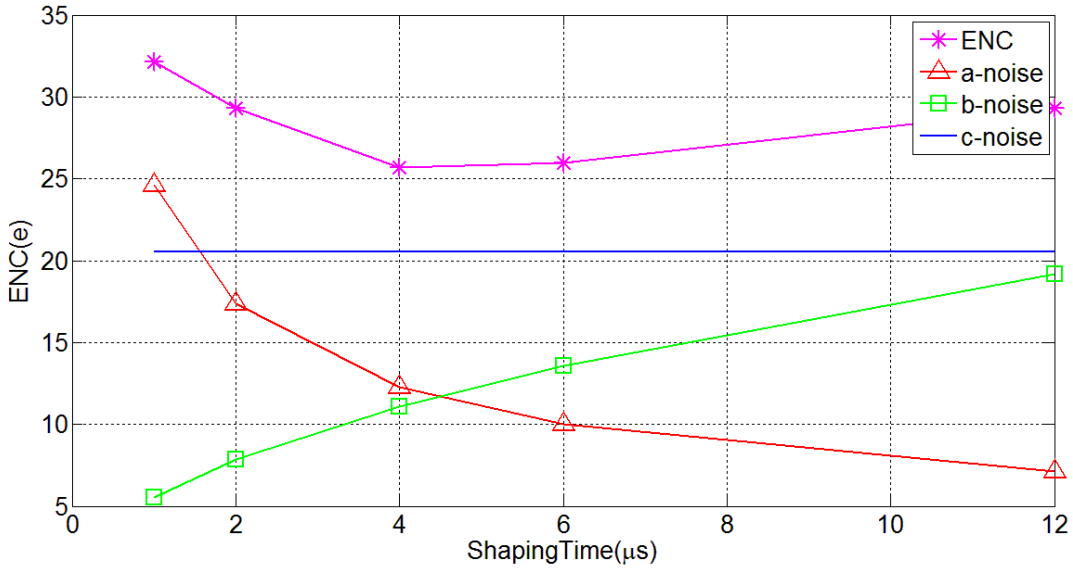
- Light DM search →low noise/threshold (low capacity, etc)
- Very close to Ge detectors →low bkg (radiopure, low-mass, etc)
- ASIC preamplifier @ 77K
  - PCB material: PTFE(Rogers 4850);
  - ENC ~26e(<200eV) w/ 4μs shaping time, mainly from 1/f noise (~21e);

Details in JINST (2018) 13: 8019





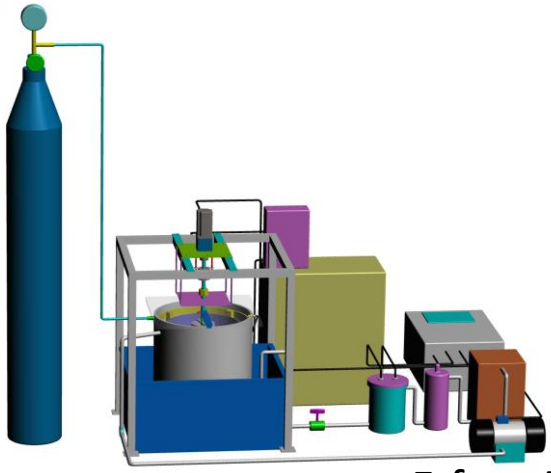
Noise components analysis



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



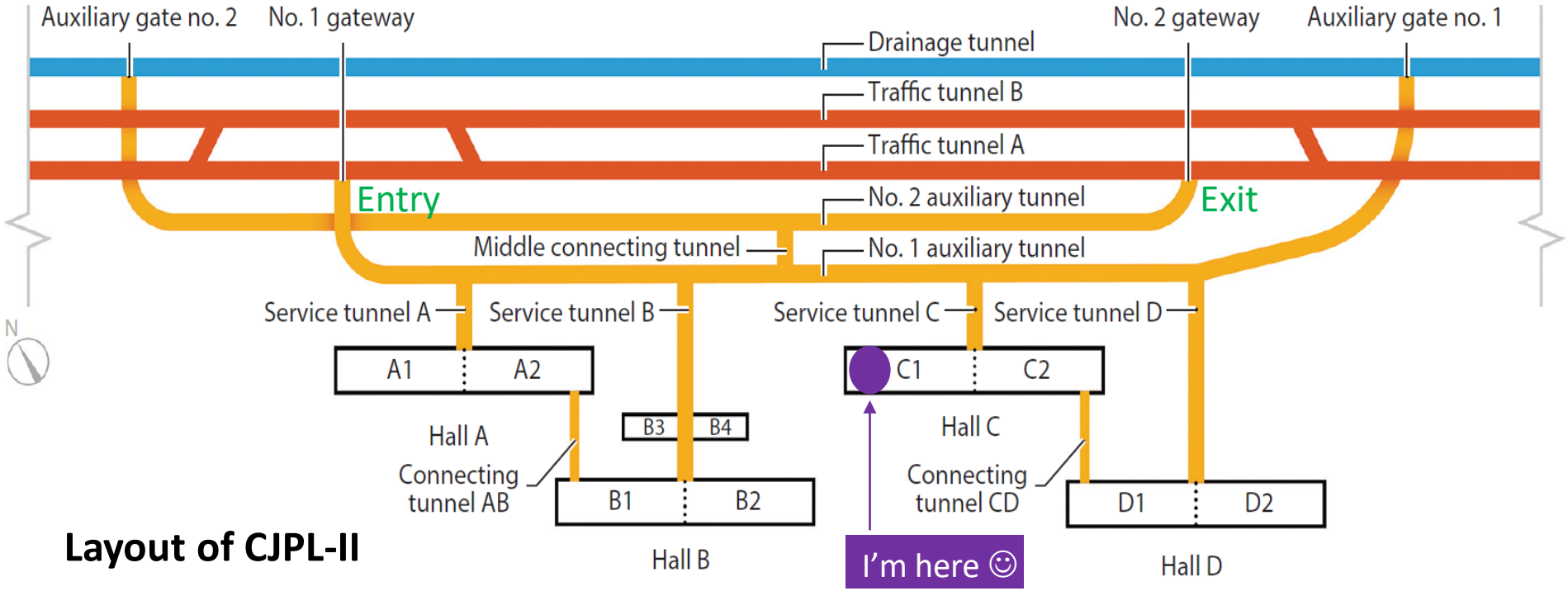
E-forming setup

optimized electrical parameters

ICP-MS

Future Plan – New location

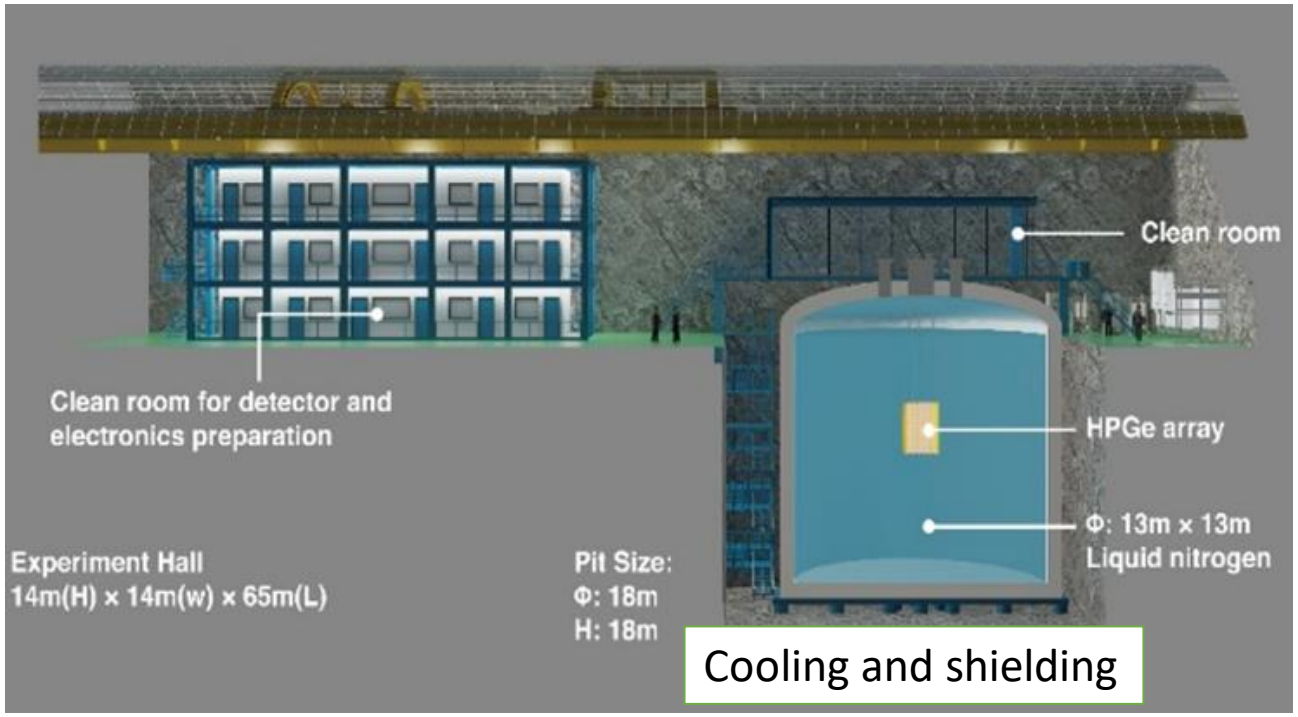
- CJPL-I to CJPL-II
  - Volume: 4000 m^3 to 300,000 m^3;
  - 1 main hall (6.5x6.5x42m) to 8 main halls (14x14x60m each);
  - Additional pit for next-generation CDEX;



Layout of CJPL-II

Future Plan - CDEX @CJPL-II

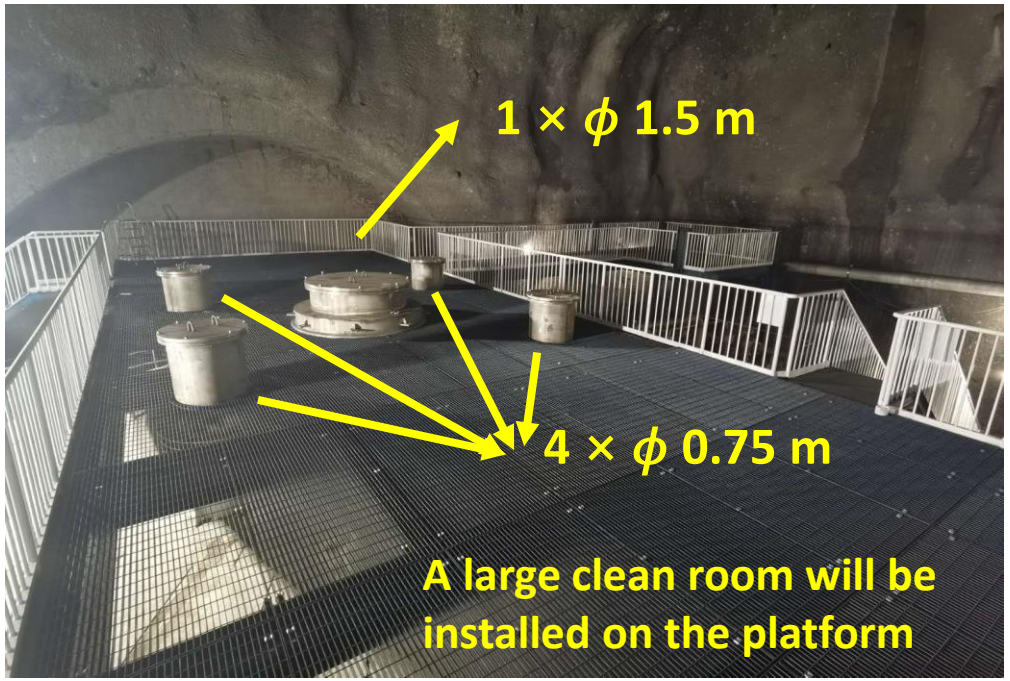
- Prepare for HPGe experiment in Hall C1 @ CJPL-II
- 1725m^3 liquid nitrogen, shielding and cooling system (inner: ϕ13m*H13m)
- Inner bkg level: <10^{-4} cpkkd@1keV, <10^{-6} cpkkd@2MeV



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.

Summary

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- Many key technologies R&D are ongoing and have made very good progress.

Thanks for your attention!

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

中国锦屏地下实验室
China Jinping Underground Laboratory
CJPL
清华大学 · 二滩水电开发有限责任公司
http://cjpl.tsinghua.edu.cn

M-shell X-rays contribution

- **M-shell X-rays contribution near the threshold**, L-shell X-rays contribution near keV, are derived from the corresponding K-shell line intensities