Recent status and prospects of CDEX @CJPL

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On behalf of CDEX Collaboration

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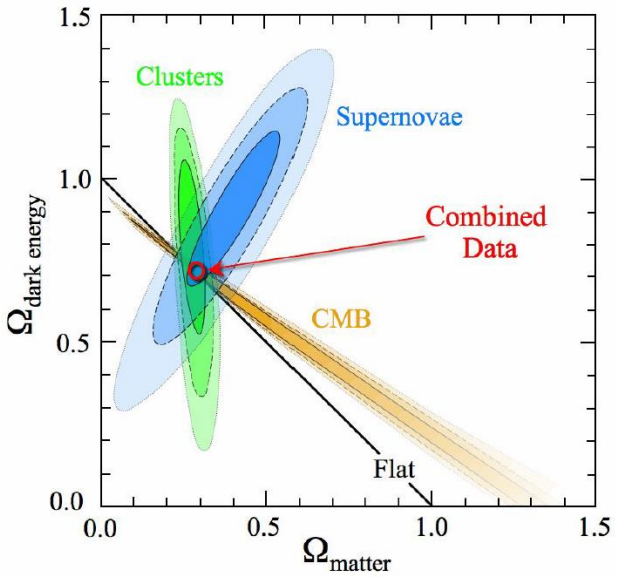
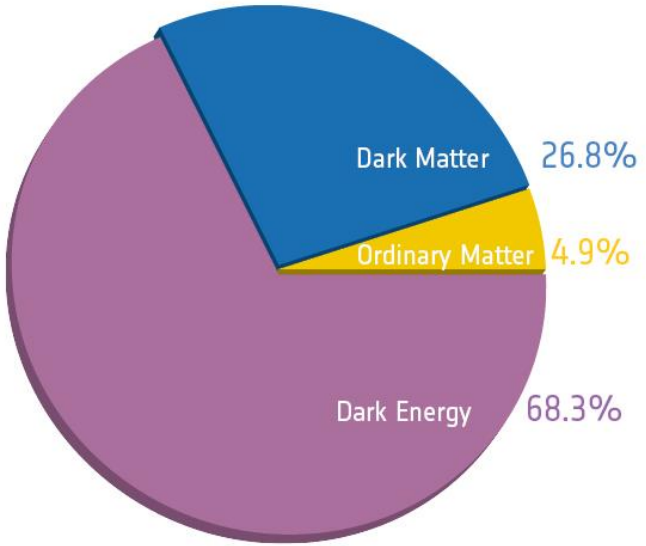
CJPL
中国锦屏地下实验室
China Jinping Underground Laboratory
清华大学 · 雅砻江流域水电开发有限公司

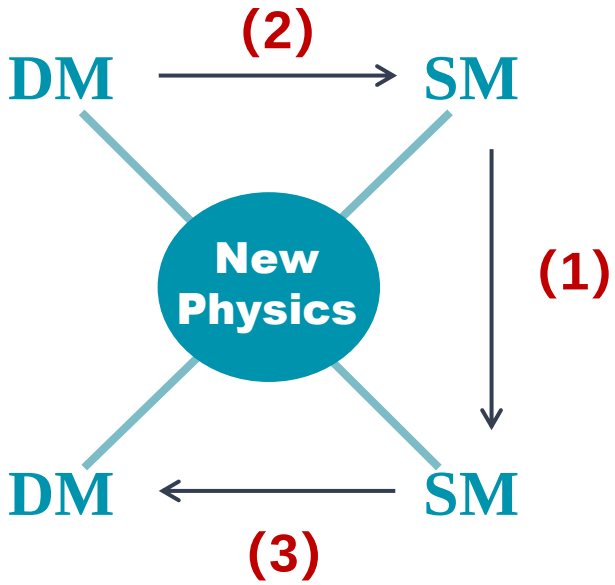
OUTLINE

- 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

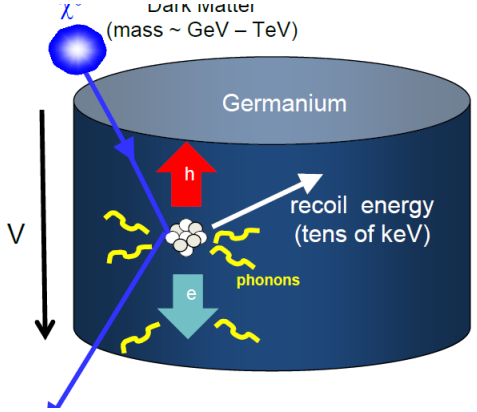
Dark Matter in Cosmology



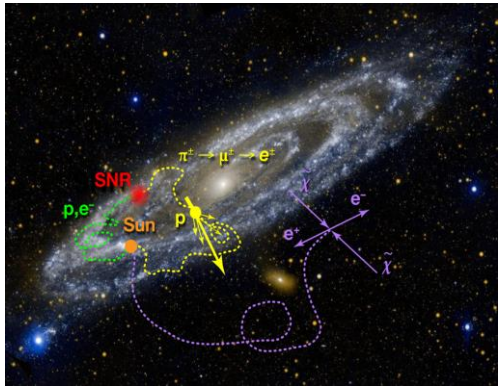




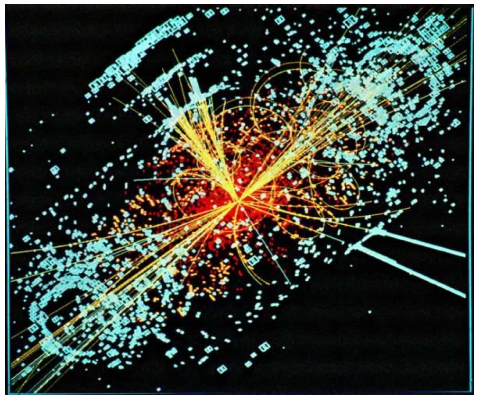
(1) Direct



(2) Indirect

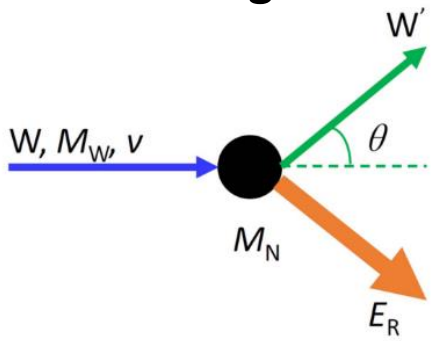


(3) Accelerator

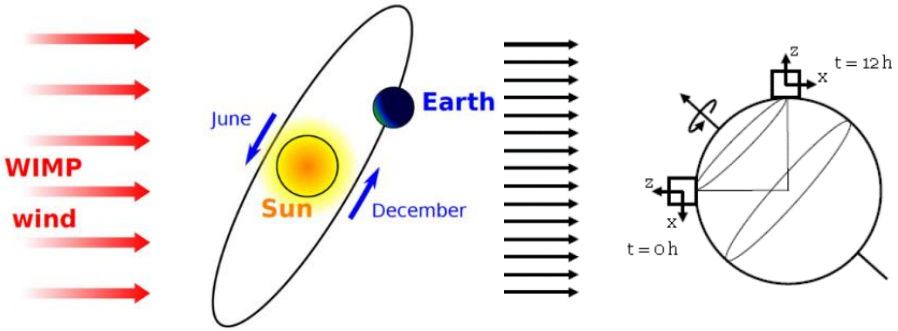


Direct detection of DM

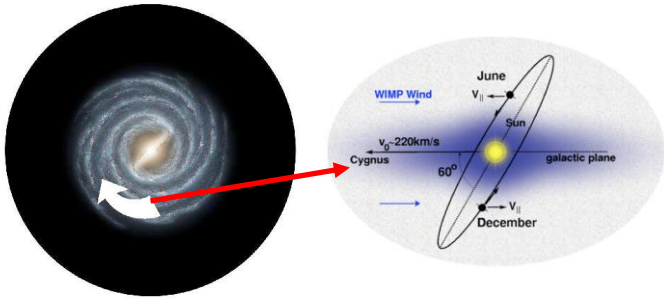
Elastic Scattering

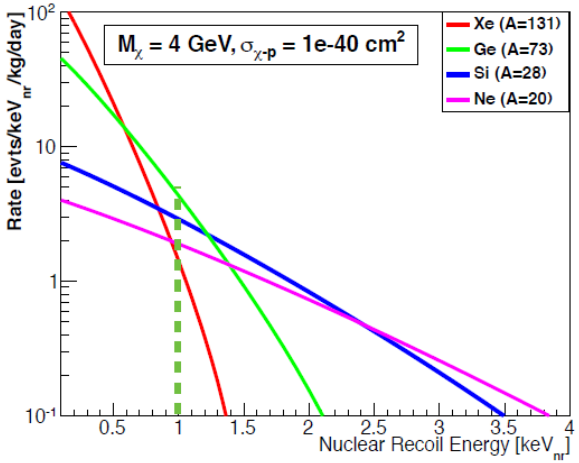


Annual/ Diurnal Modulation

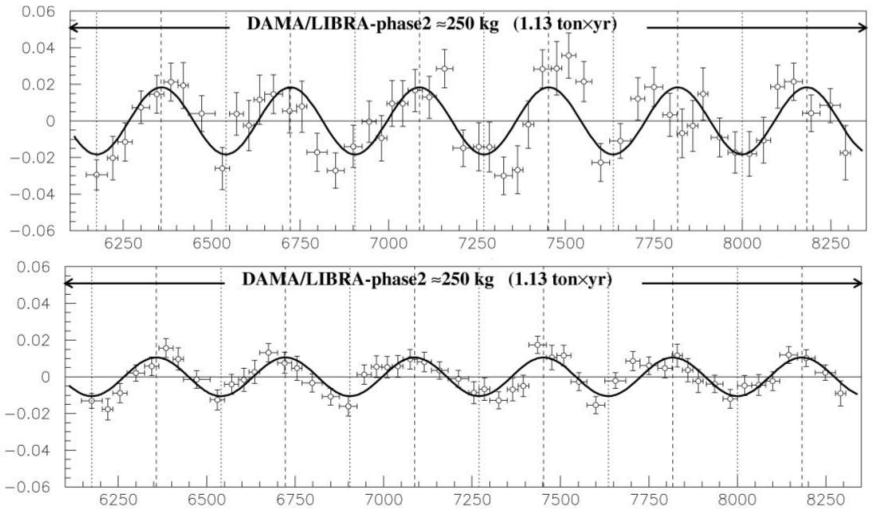


Direction Detection



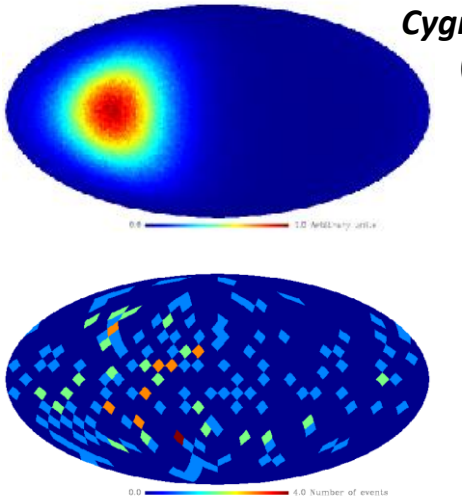


- Lower Background
- Lower Energy threshold
- Larger Exposure (Mass*Time)



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

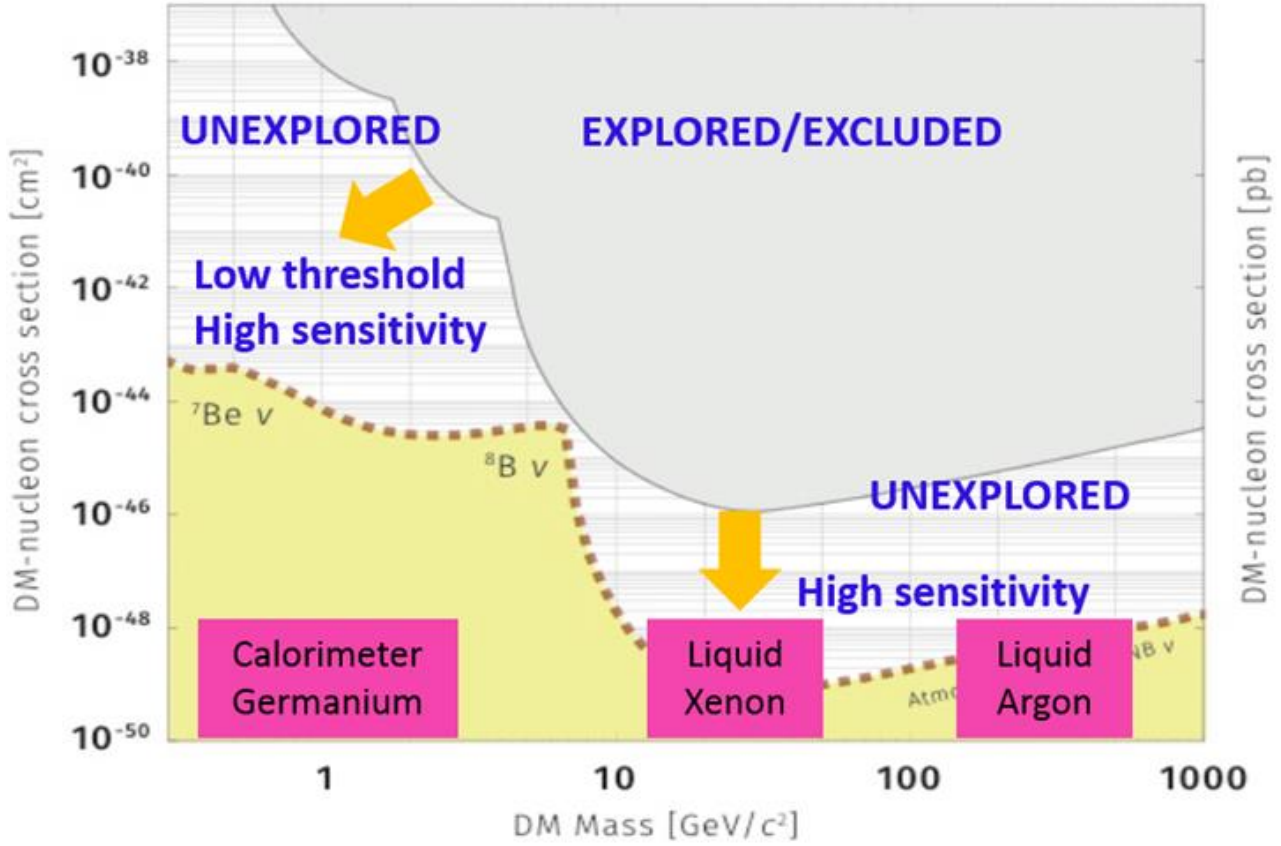
Cygnus Constellation
(l = 90°,b = 0°)



- Lower Background
- Lower Energy threshold
- Good Angular Resolution

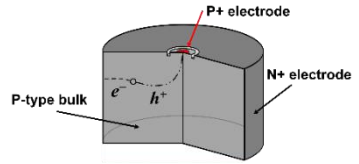
Direct detection of DM

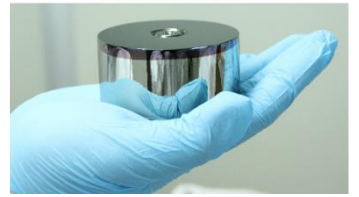
- Dark matter detection competition is becoming increasingly fierce;
- **Light dark matter detection**: low background level, low energy threshold, large mass detector target



China Dark matter Experiment

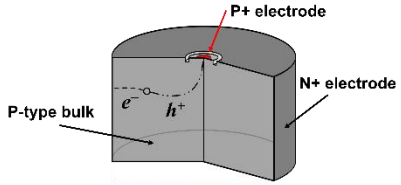
- Formed in 2009, 11 institutions and ~100 people now; http://cdex.ep.tsinghua.edu.cn/
- **Key technology:** P-type Point-Contact (PPC) Ge detectors;
- **Physics targets:** Direct detection of light DM + Ge-76 0νββ

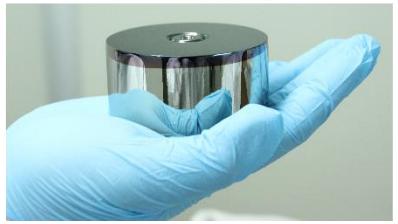




CDEX Roadmap

- **CDEX-1 (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.

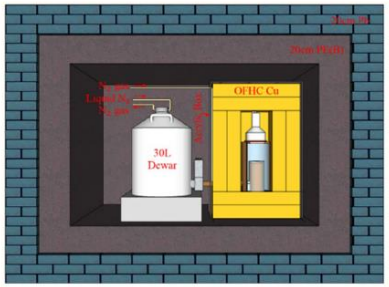




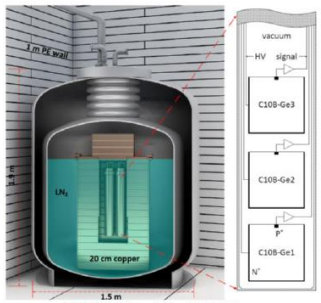
CDEX-1 → CDEX-10

2009-2016 2016-2022

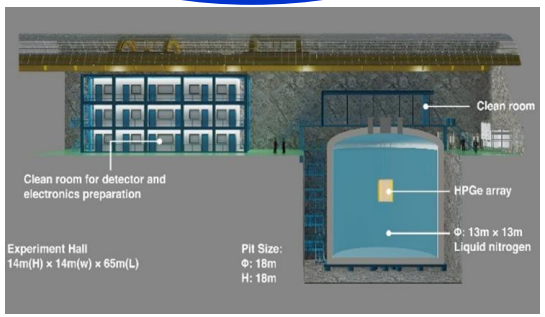
CDEX-50 (DM) + CDEX-300v (0νββ) → CDEX-1000



CDEX-1A&B: 1kg PPC Ge×2

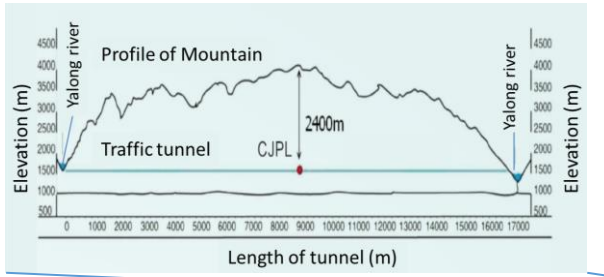


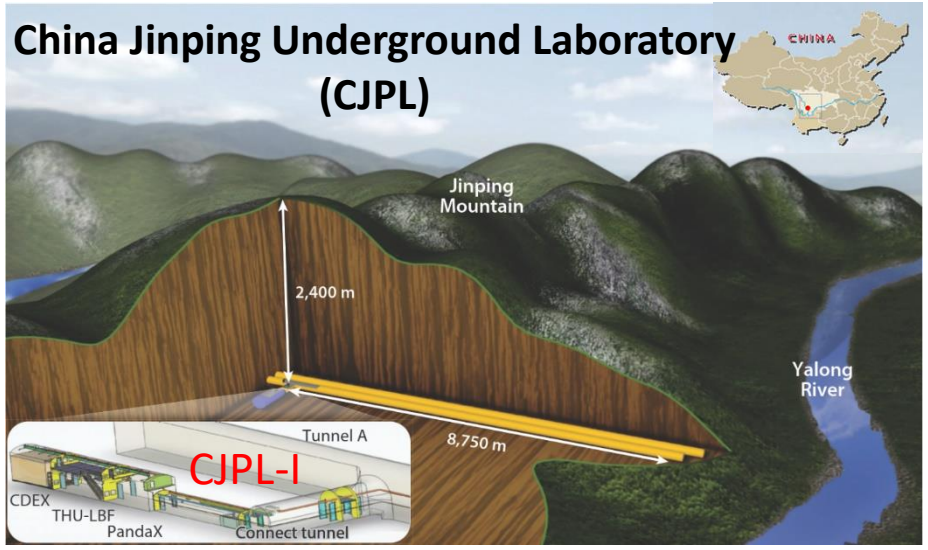
CDEX-10: ~10kg PPC Ge array

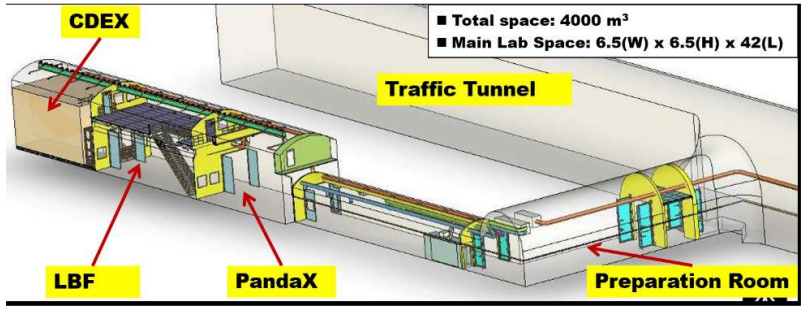


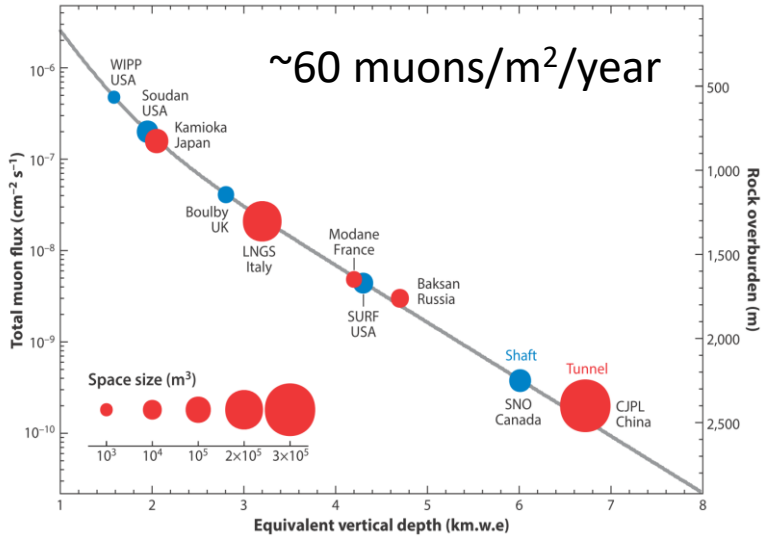
China Jinping Underground Laboratory

- World's deepest underground lab, CJPL
  - ✓ Near Xichang city, Sichuan Province, Southwest China
  - ✓ Rock overburden: 2400m (~6720 m. w. e.)
  - ✓ CJPL-I 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







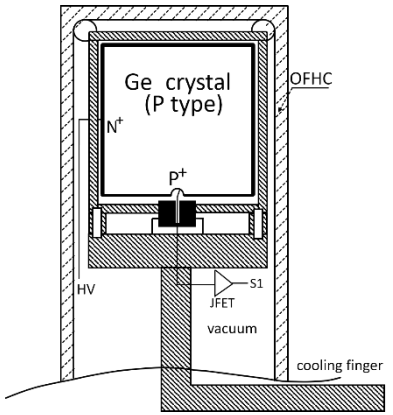


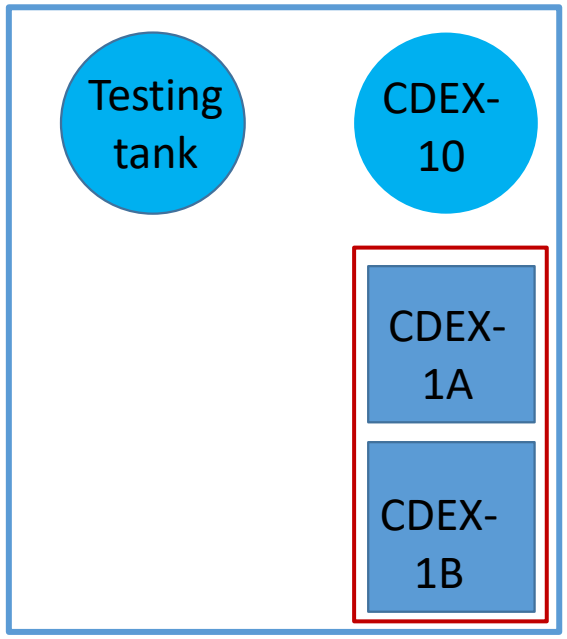
Cheng et al., ***Annu. Rev. Nucl. Part. Sci.*** 67:231 (2017)

Chinese Physics C 37:086001 (2013)

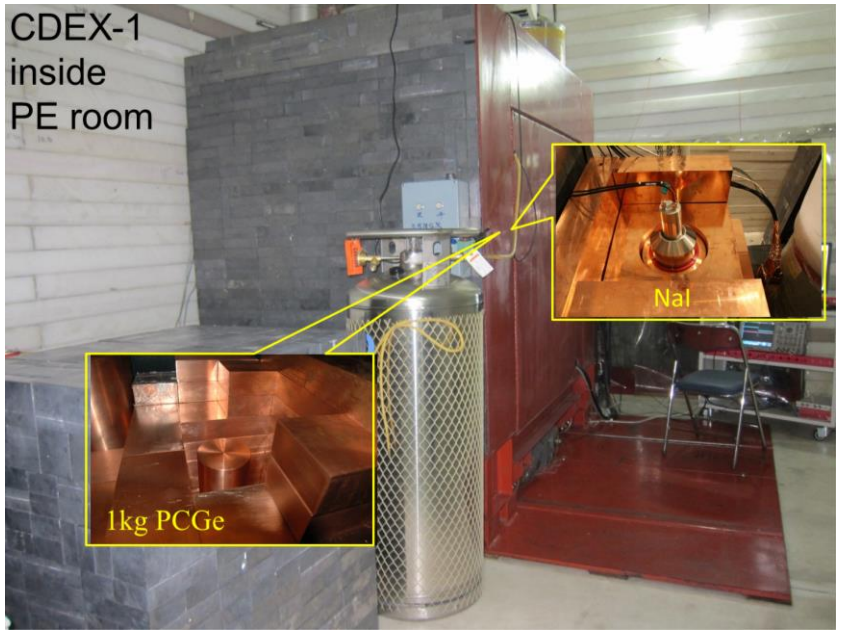
CDEX-1

- 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;

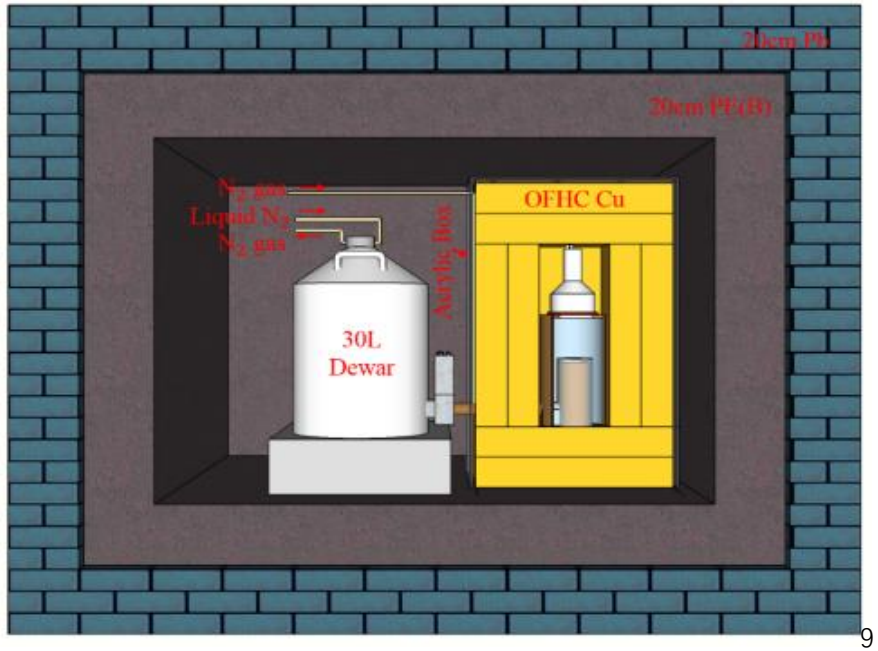




Layout of PE room, CJPL-I



CDEX-1 inside PE room



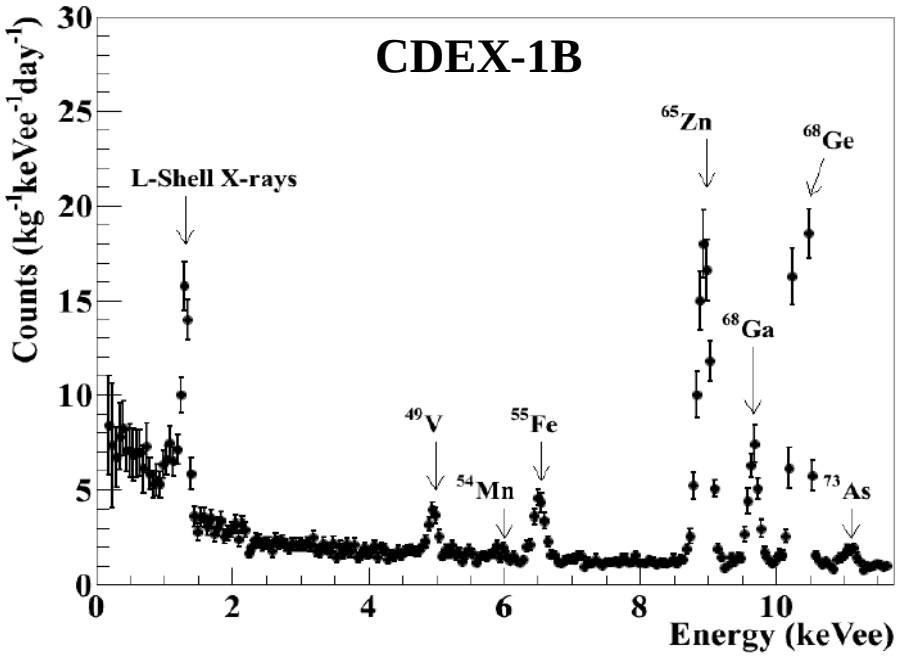
CDEX-1A&B: 1kg PPC Ge×2

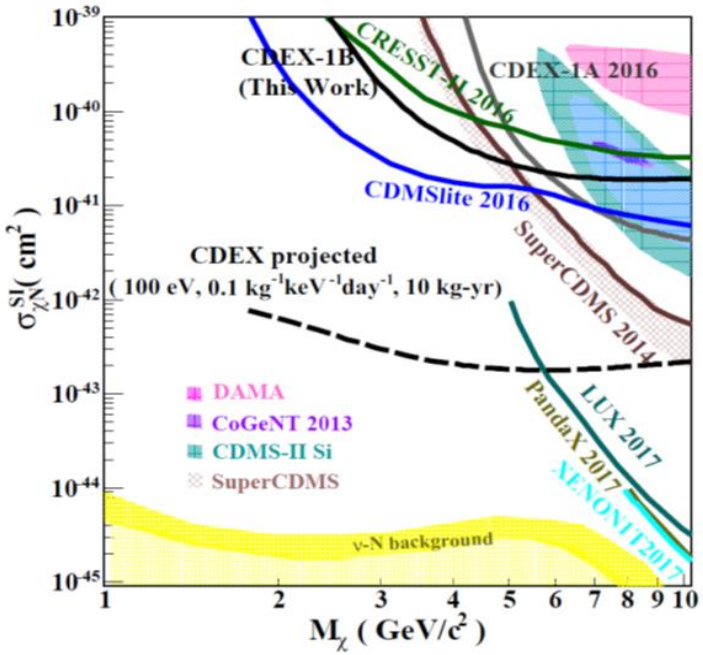
CDEX-1B Results

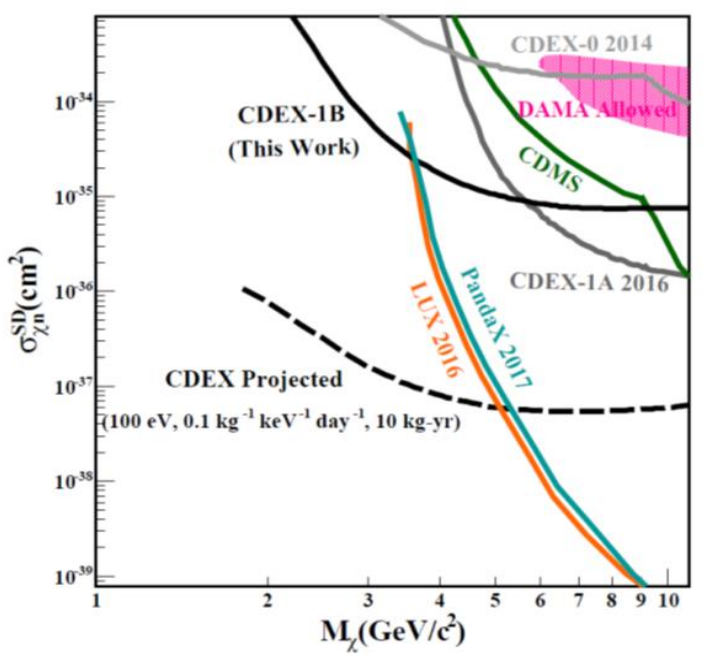
- Detector upgraded w/ lower JEFT noise and material bkg;
- >4 years run (Run-1&Run-2), >1200 kg·day exposure;
- Achieving 160 eVee energy threshold;
- Sensitivity improved and extending to 2 GeV/c^2.

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

Run-1 Time-integrated (TI) analysis: ***Chinese Physics C*** 42, 023002 (2018)



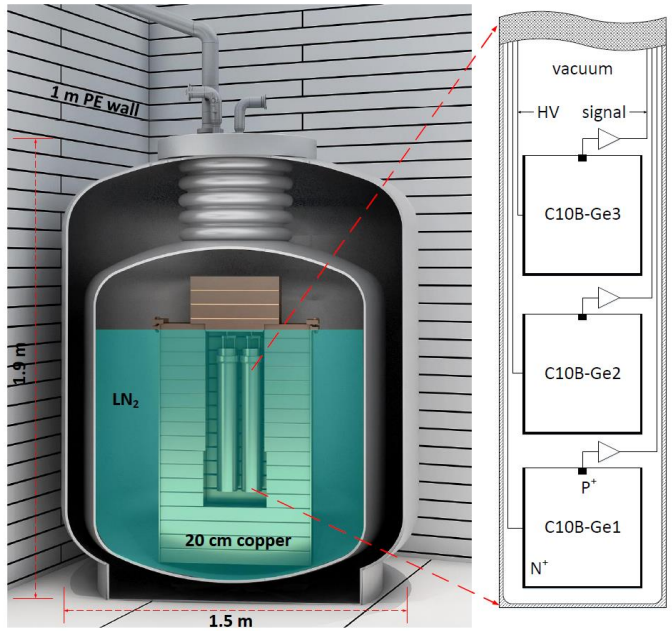




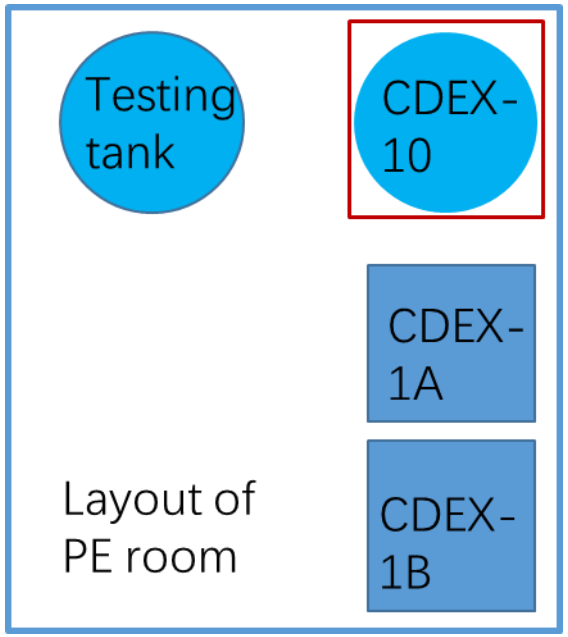
CDEX-10

- 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)



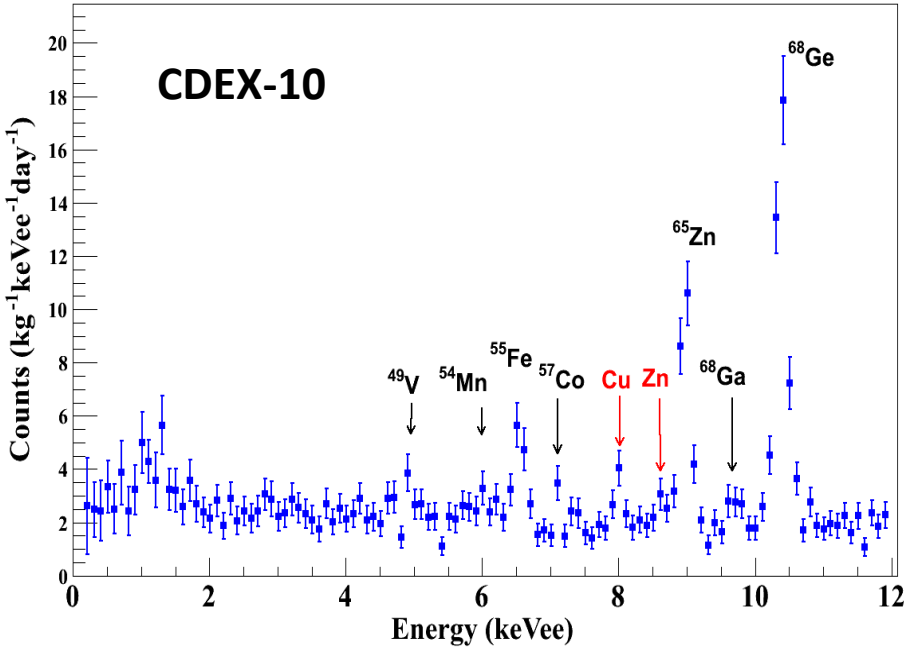
CDEX-10: ~10kg PPC Ge array

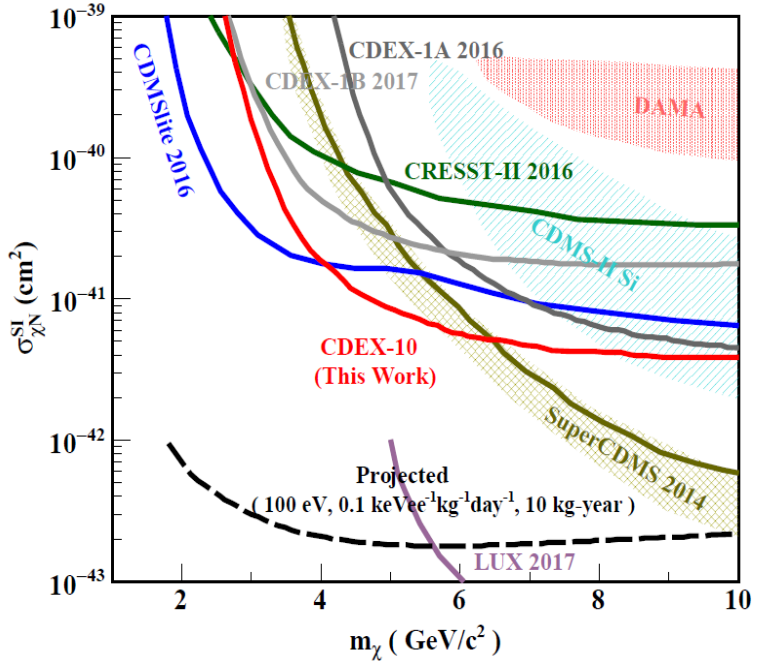


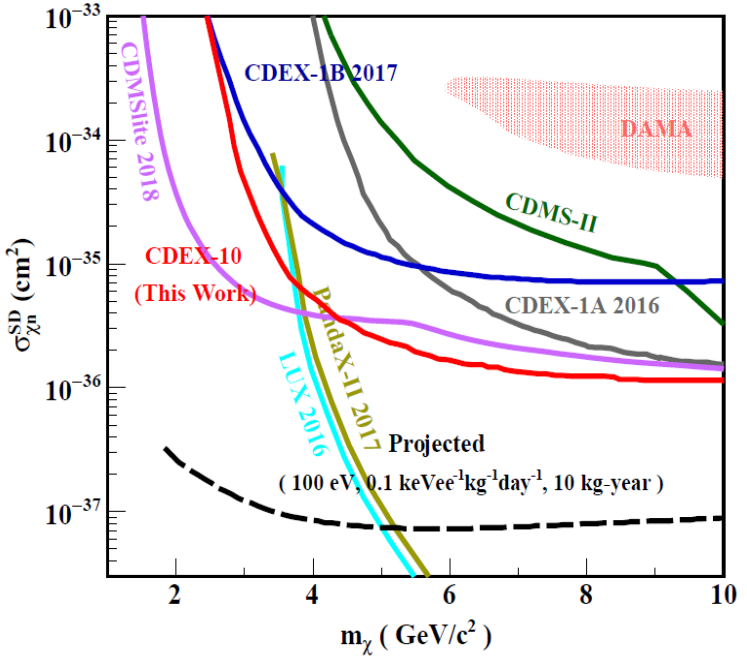
CDEX-10 Results

- 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

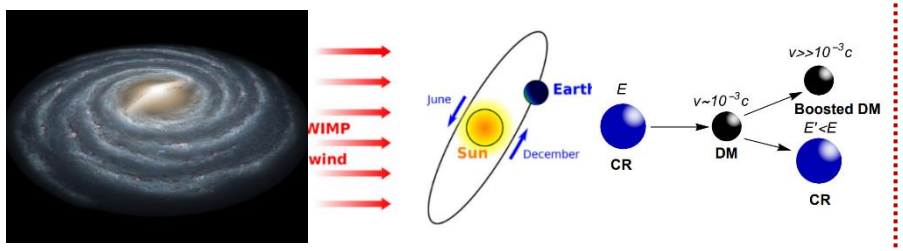
$$\frac{dR}{dE_R} = N_T \left[\frac{\rho_\chi}{m_\chi} \int d^3\vec{v} v f_v(\vec{v} + \vec{v}_E) \right] \frac{d\sigma}{dE_R}$$

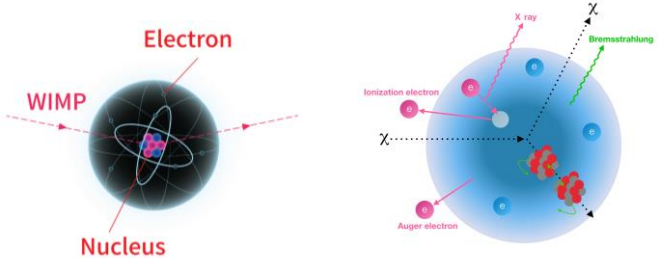
DM sources related：

- ✓ 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)

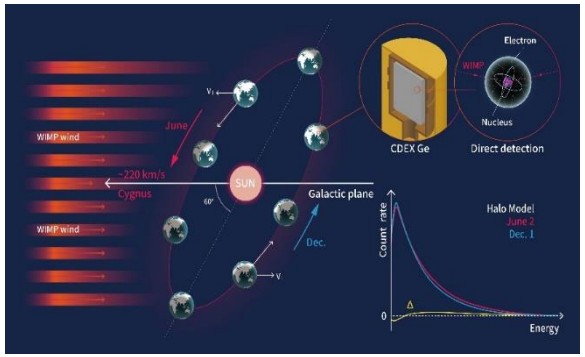


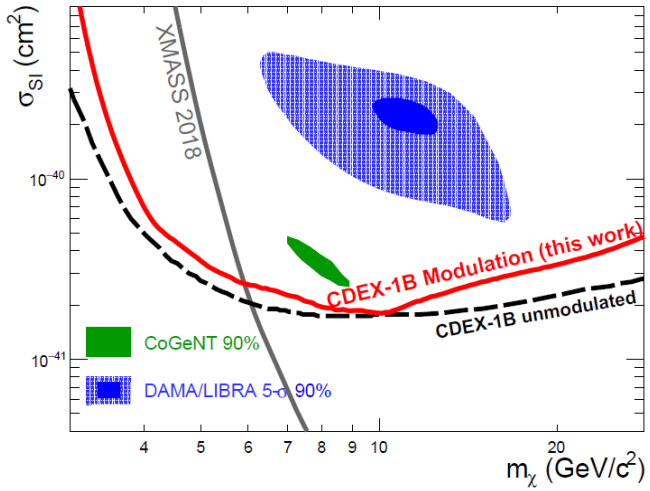


*WIMP: weakly interaction massive particles

More physics analysis

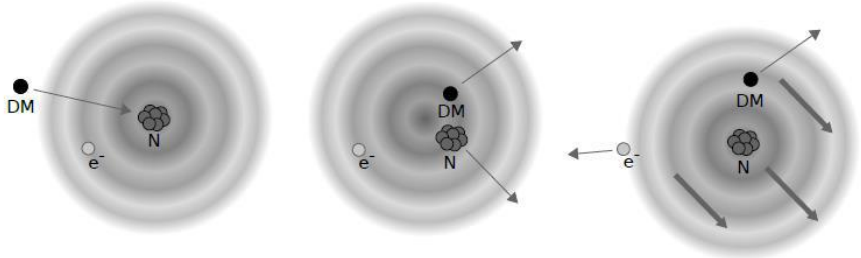
Annual Modulation + DM-nucleus elastic scattering

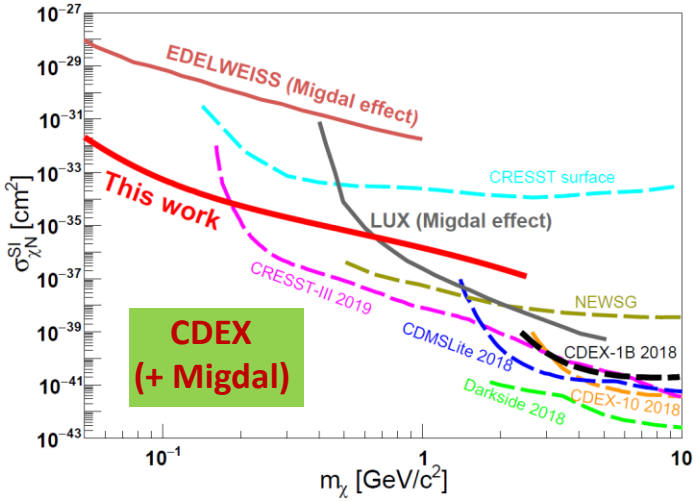




PRL 123:221301 (2019)

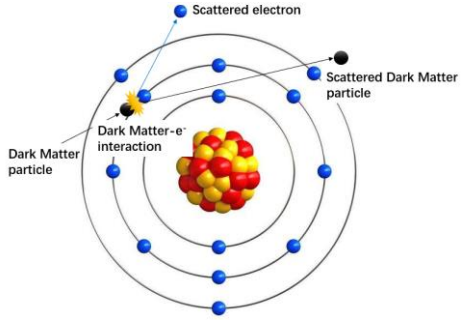
WIMP (Standard Halo Model) + Migdal effect

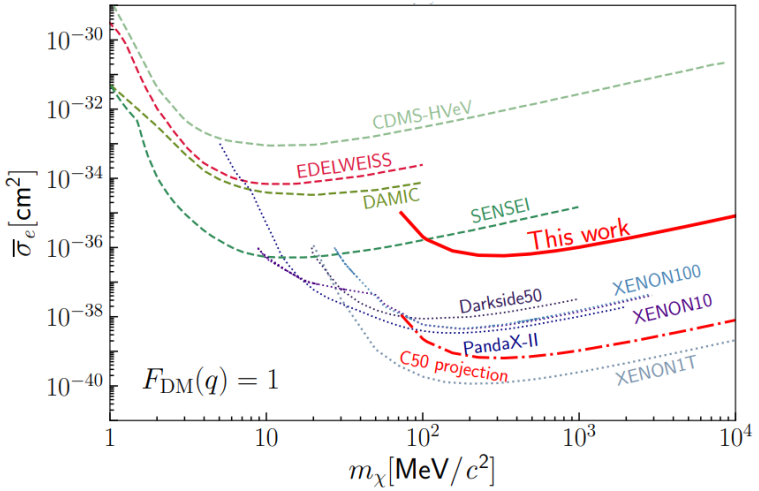




PRL 123:161301 (2019)

WIMP (Standard Halo Model) + DM–Electron Scattering

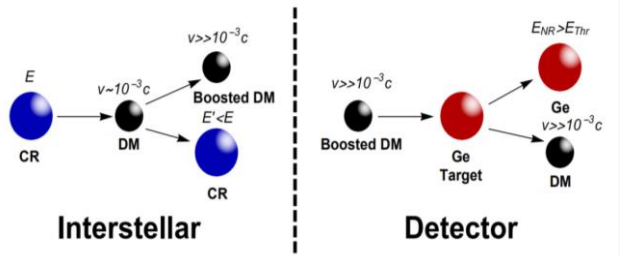




PRL 129:221301 (2022)

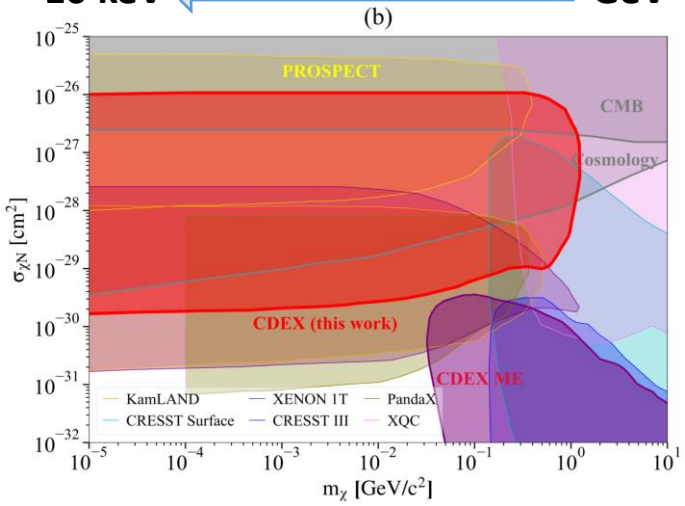
More physics analysis

CR Boosted DM +
DM-nucleus elastic scattering



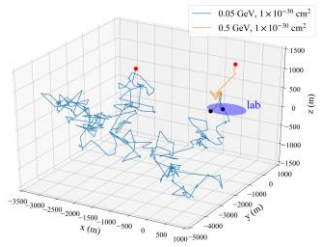
CRDM

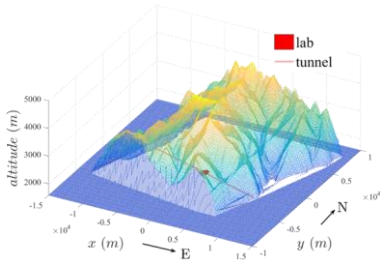
10 keV ⟵ GeV



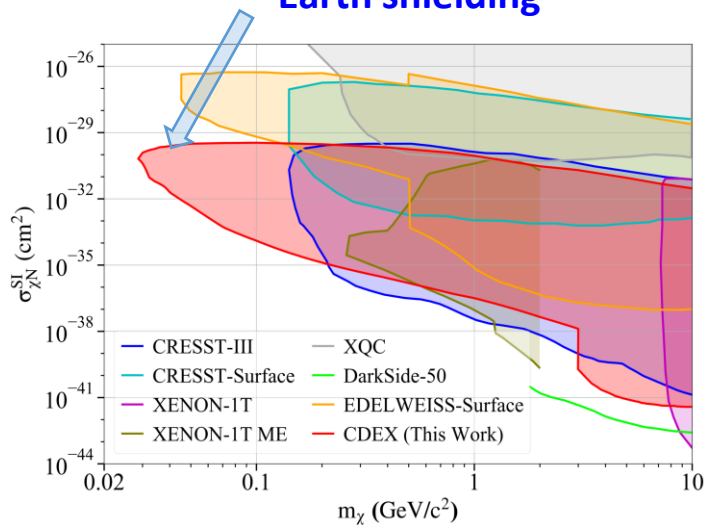
PRD 106:052008 (2022)

WIMP (Standard Halo Model) +
Earth shielding, Migdal effect



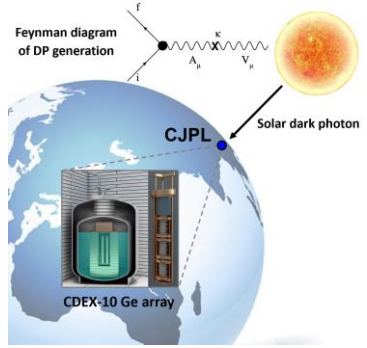


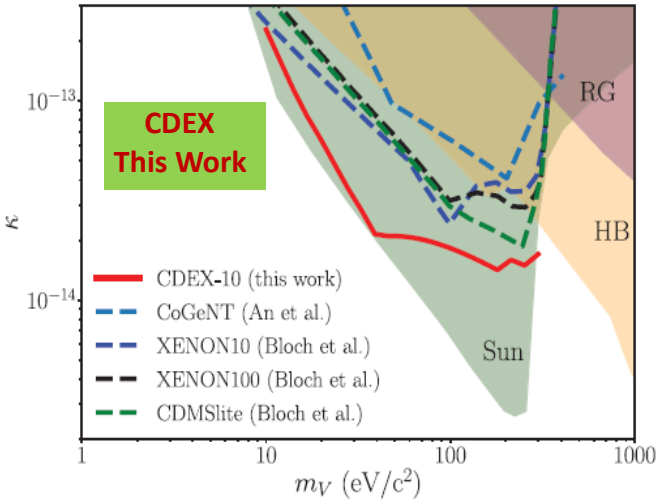
Earth shielding



PRD 105:052005 (2022)

Solar dark photon +
All energy deposited



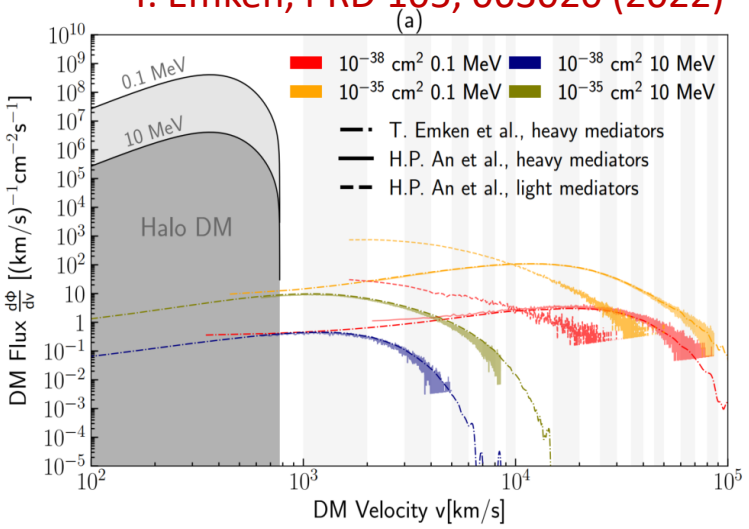


PRL 124:111301 (2020)

Boosted DM-electron: SRDM

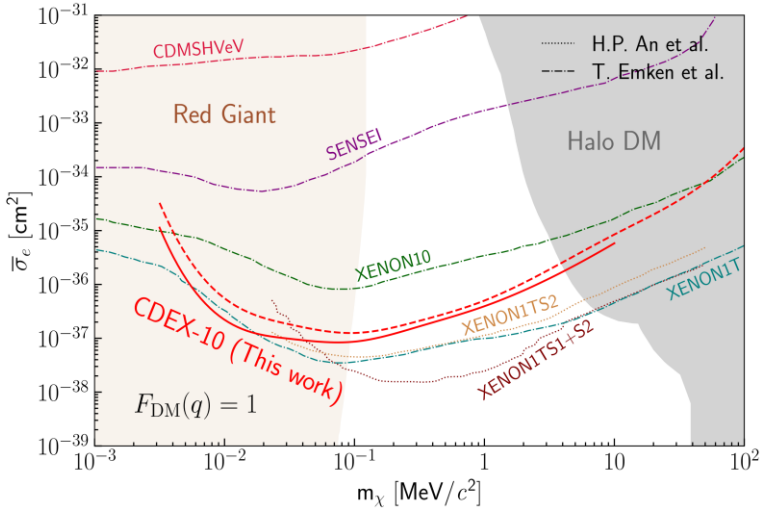
- **Boosted DM-electron calculation:** develop an energy spectrum reconstruction method for **non-SHM DM velocity distribution**, simplify the expected spectrum calculation in semiconductor det.;
- **Solar Reflected Dark Matter (SRDM) searches:** provide the strongest experimental limits for light mediator scenario for DM mass below 0.1 MeV;

H. An et al., PRD 104, 103026 (2021)
T. Emken, PRD 105, 063020 (2022)

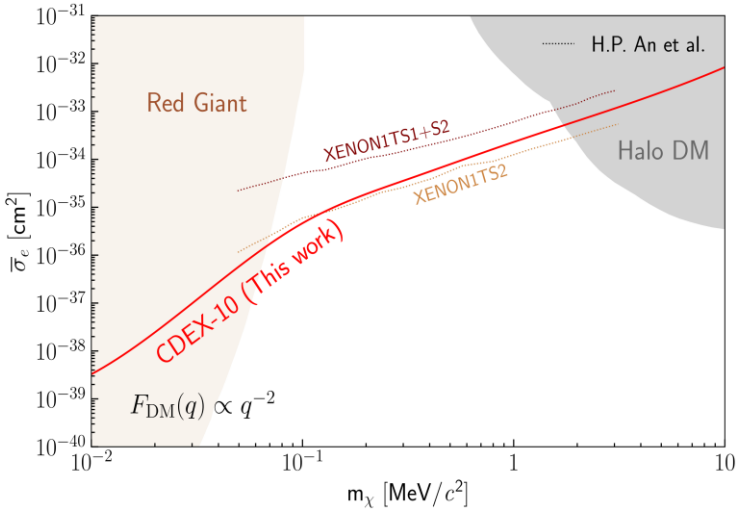


Solar Reflected Dark Matter velocity distribution

PRL 132:171001 (2024)



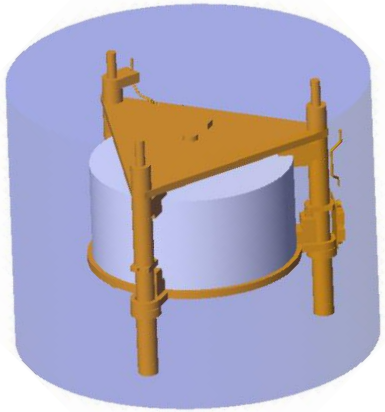
CDEX-10 SRDM results (heavy mediator)

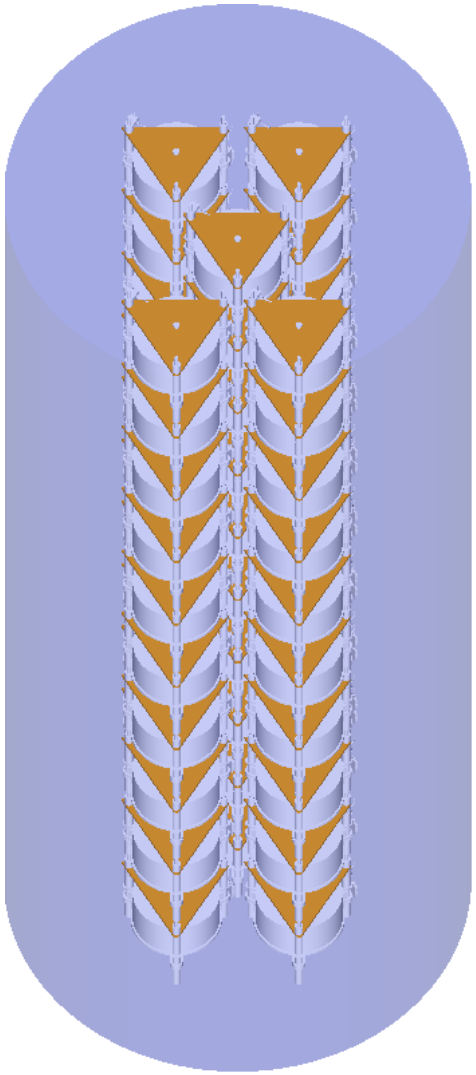


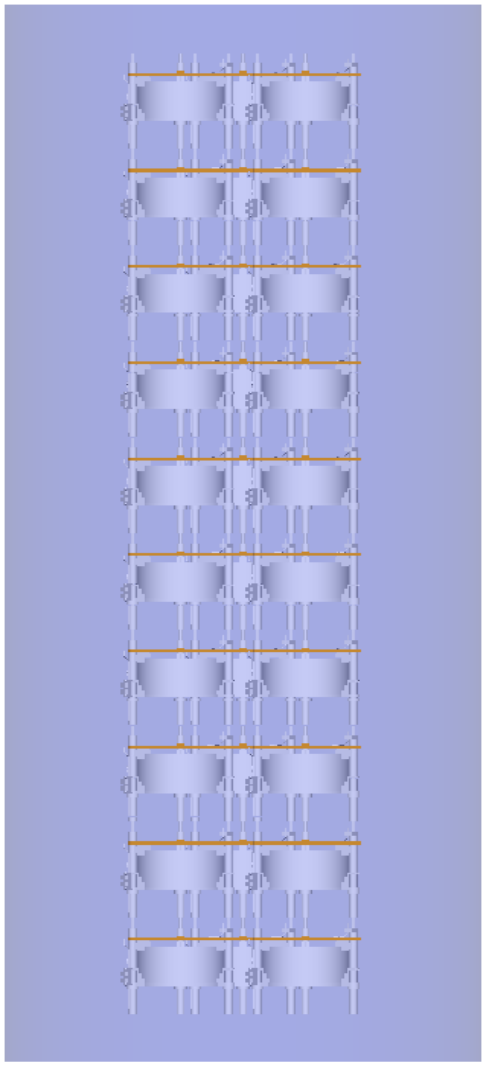
CDEX-10 SRDM results (light mediator)

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;

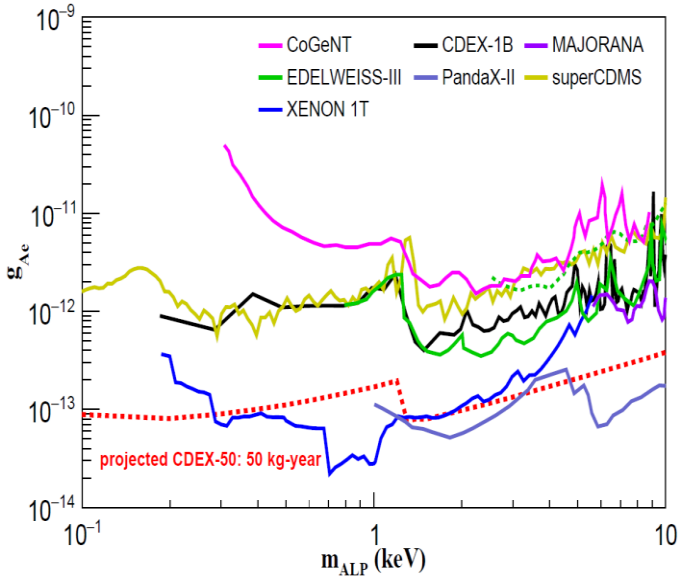




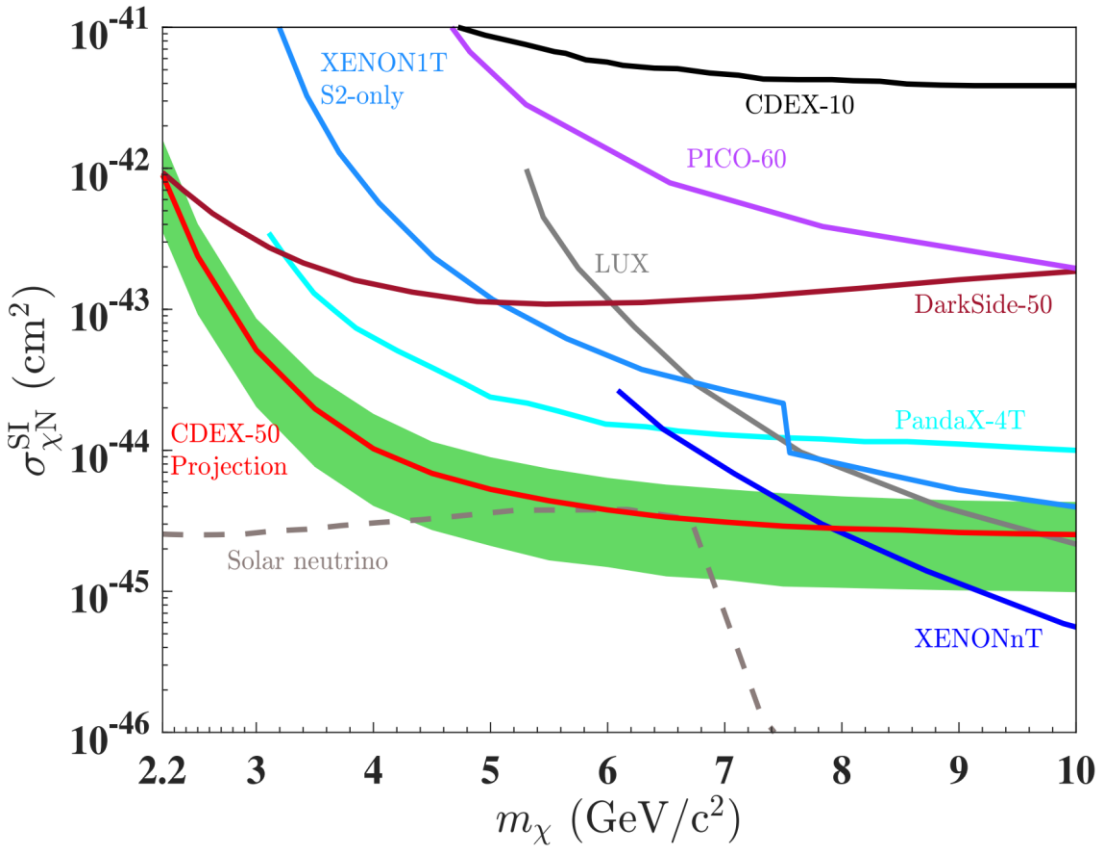


CDEX-50 Projected sensitivity

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



JCAP 07 (2024) 009

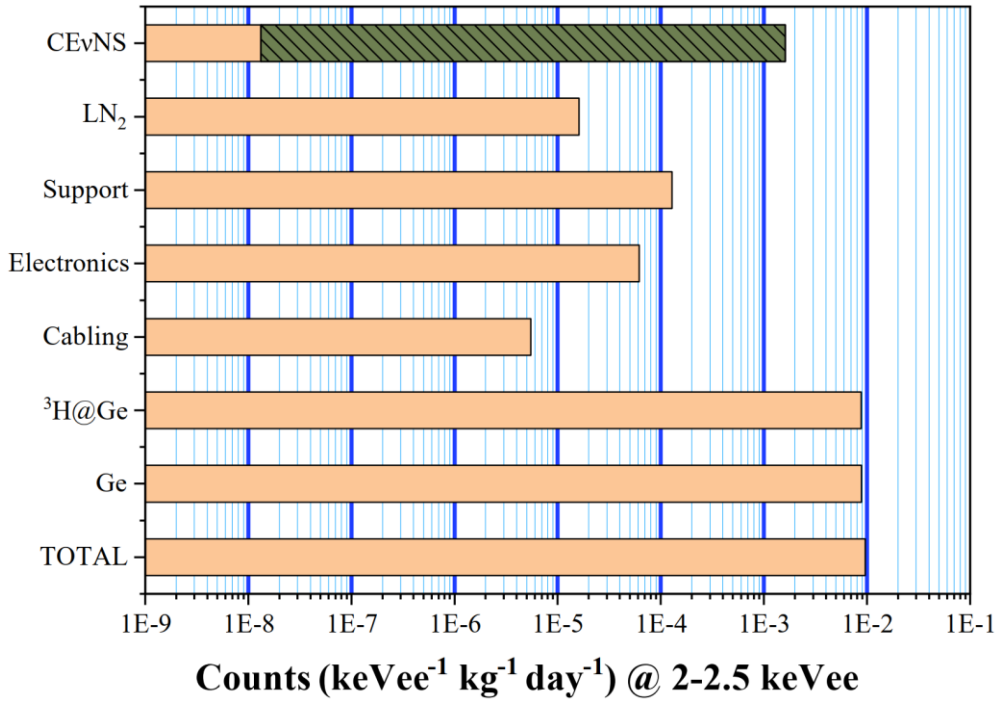


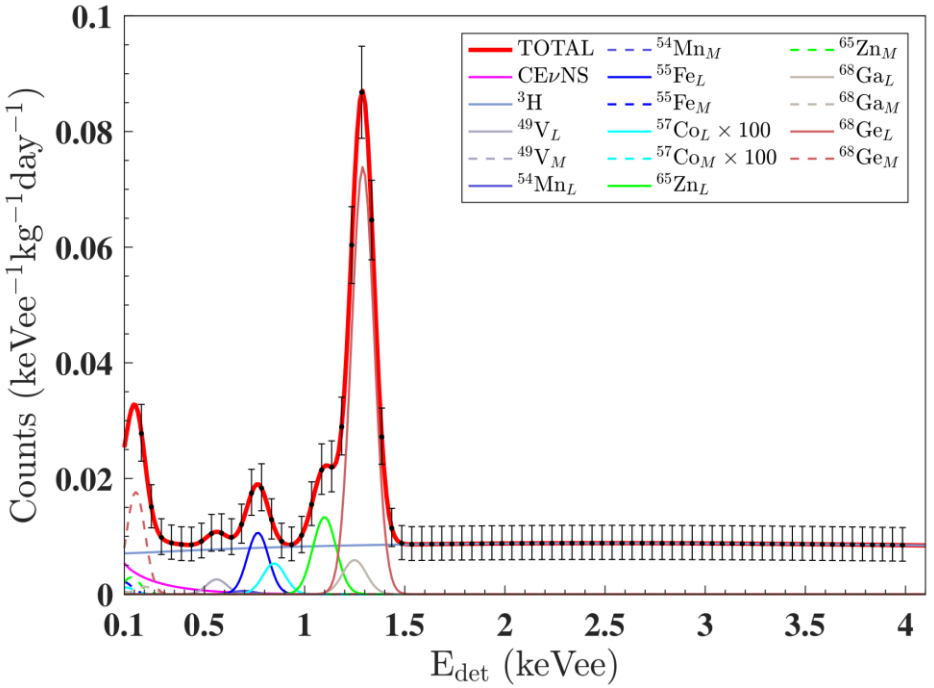
CDEX-50 Background Model and Simulation

- Bkg level: **<0.01 cts/(keV·kg·day) @1 keV**

JCAP 07 (2024) 009

- Mainly comes from the ^{3}H and cosmogenic radionuclides in crystal
- The contribution from CEvNS and M-shell X-rays should be well understood



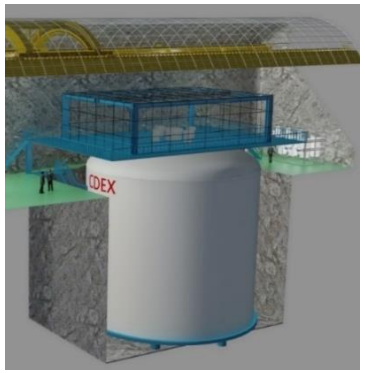


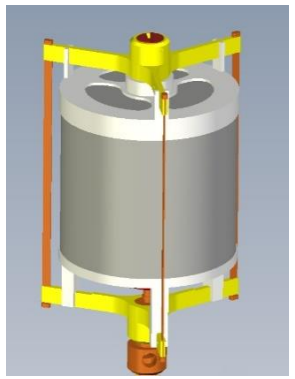
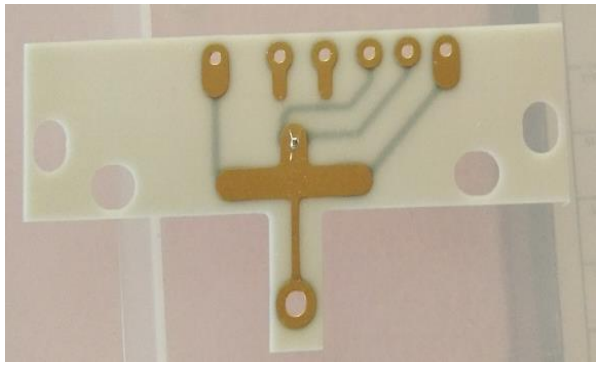
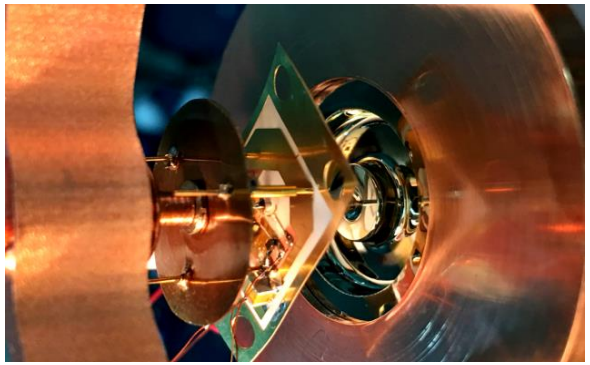
contribution of CE*v*NS in 0.16–0.5 keVee

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**

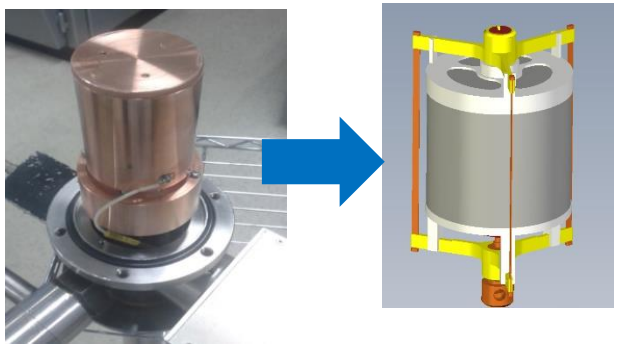


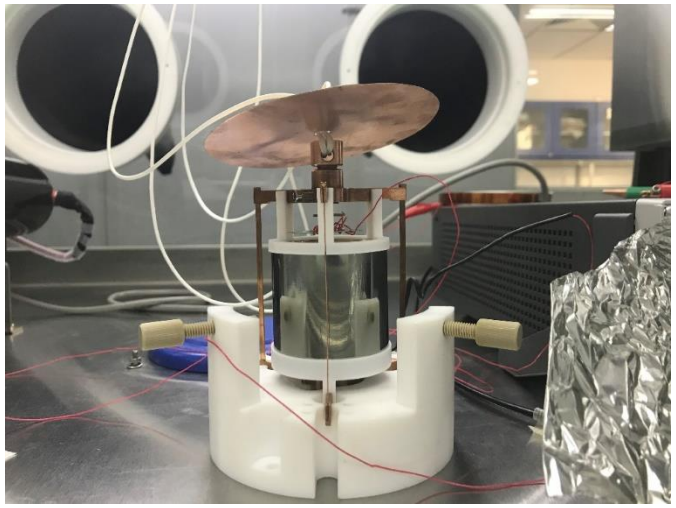





Ge detector fabrication

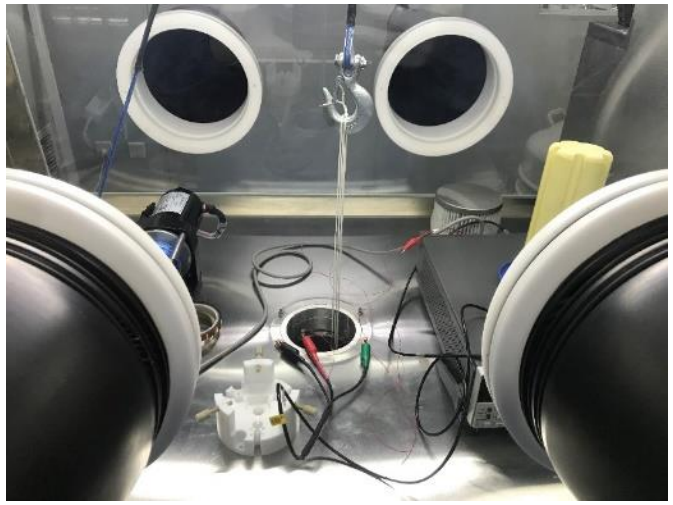
- Develop **bare HPGe detectors** immersed into LN_2;
- Long time stability;
- Further reduce the radioactive background;
- ASIC-based preamplifiers can work well in liquid nitrogen;

79 g Cu + 10 g PTFE

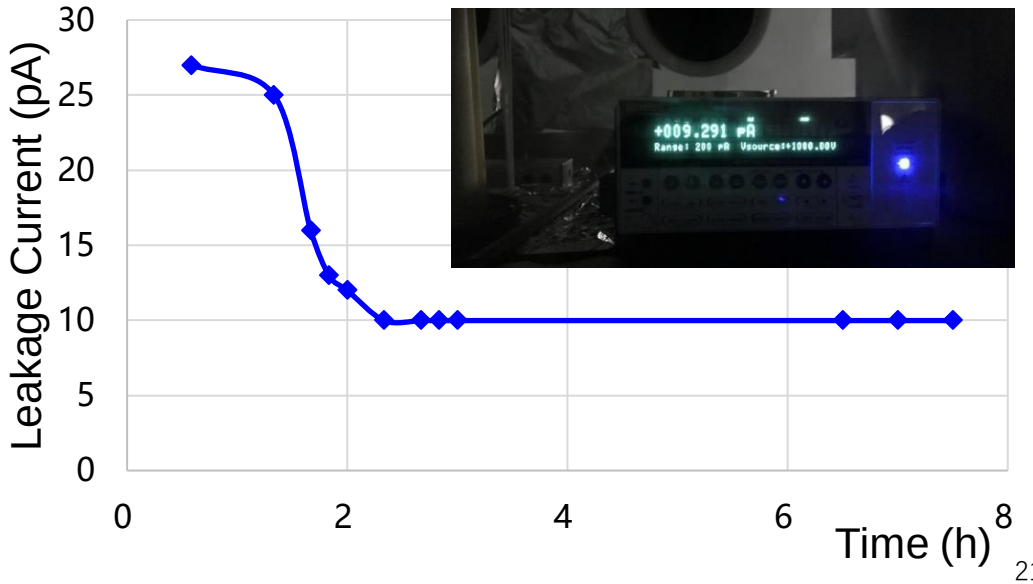




Bare HPGe detectors



Bare HPGe in LN_2

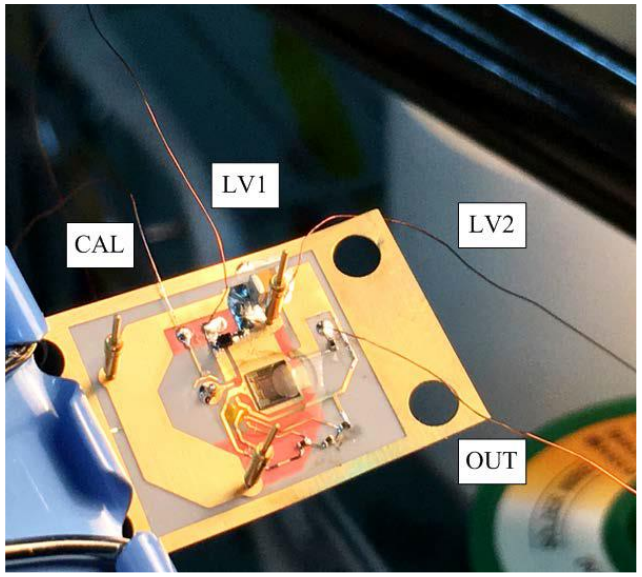


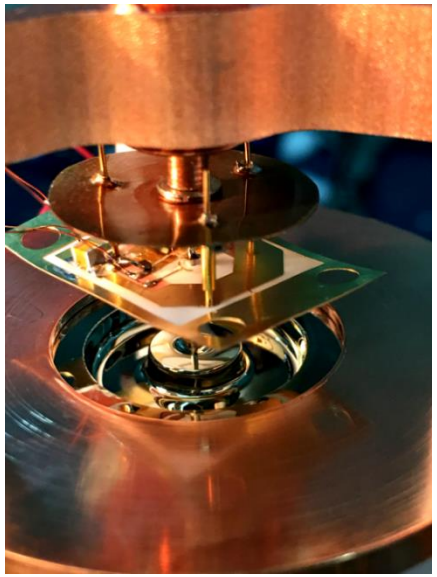
PPC: ϕ50mm x 50mm, Depleted voltage: ~800V

CMOS ASIC Front-end Electronics

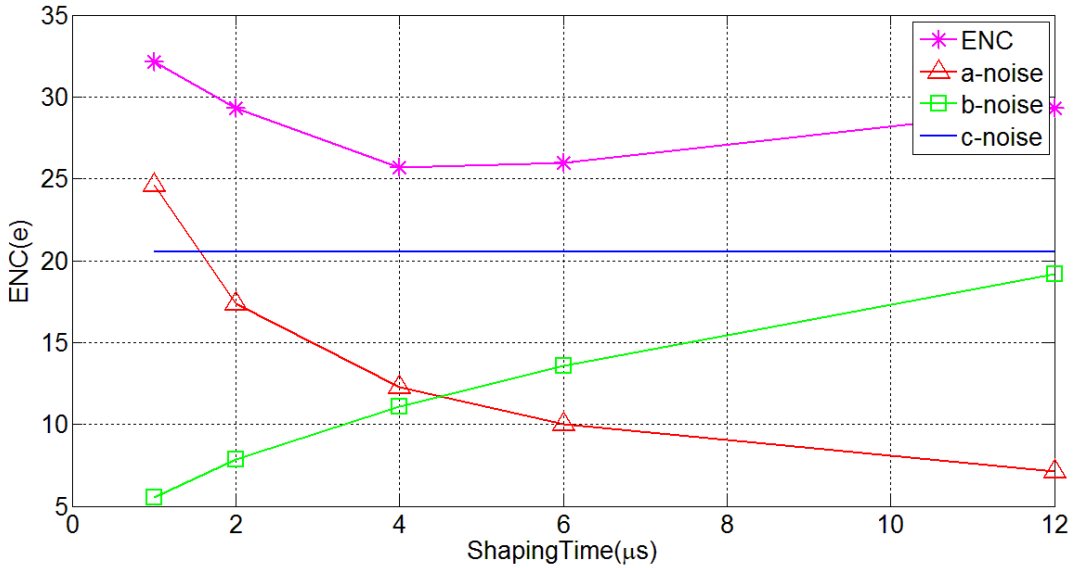
- Light DM search →low noise/threshold (low capacity, etc)
- Very close to Ge detectors →low bkg (radiopure, low-mass, etc)
- ASIC preamplifier @ 77K
  - PCB material: PTFE(Rogers 4850);
  - ENC ~26e(<200eV) w/ 4μs shaping time, mainly from 1/f noise (~21e);

Details in ***JINST*** (2018) 13: 8019





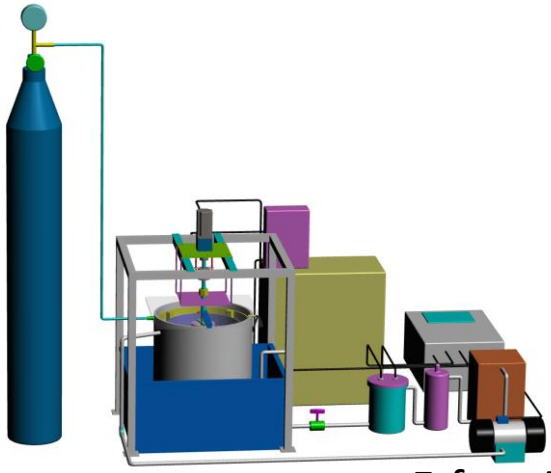
Noise components analysis



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



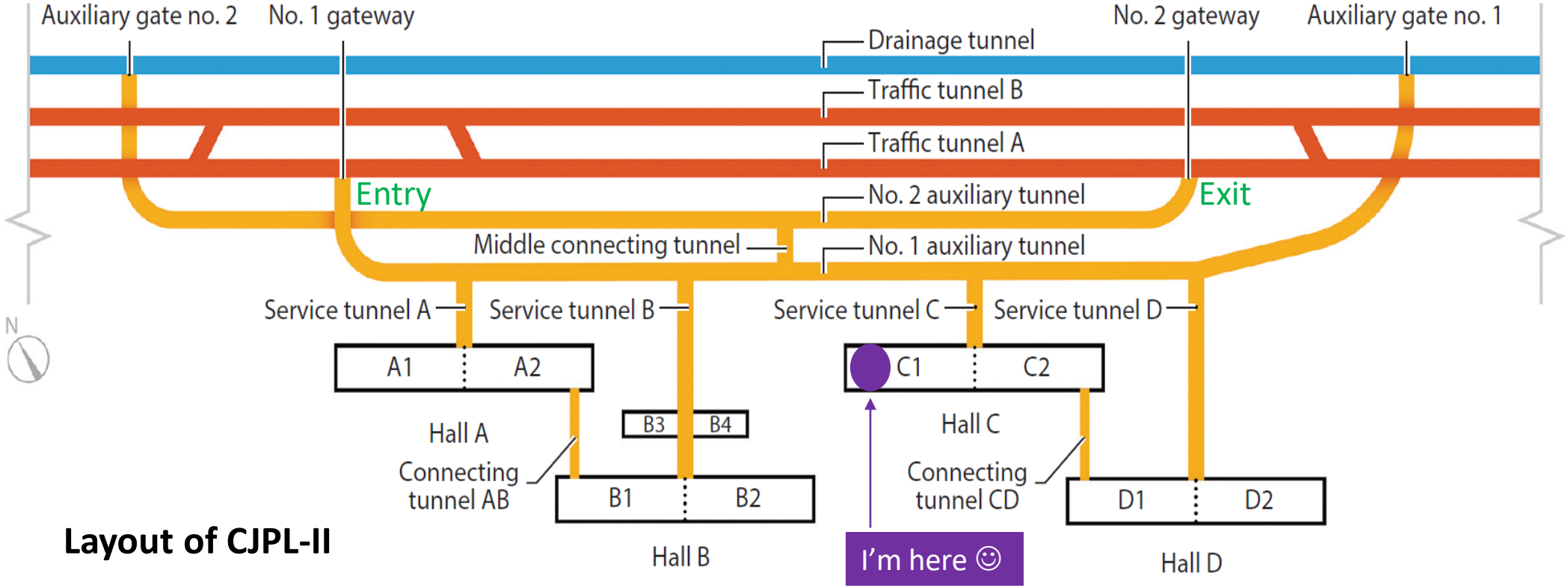
E-forming setup

optimized electrical parameters

ICP-MS

Future Plan – New location

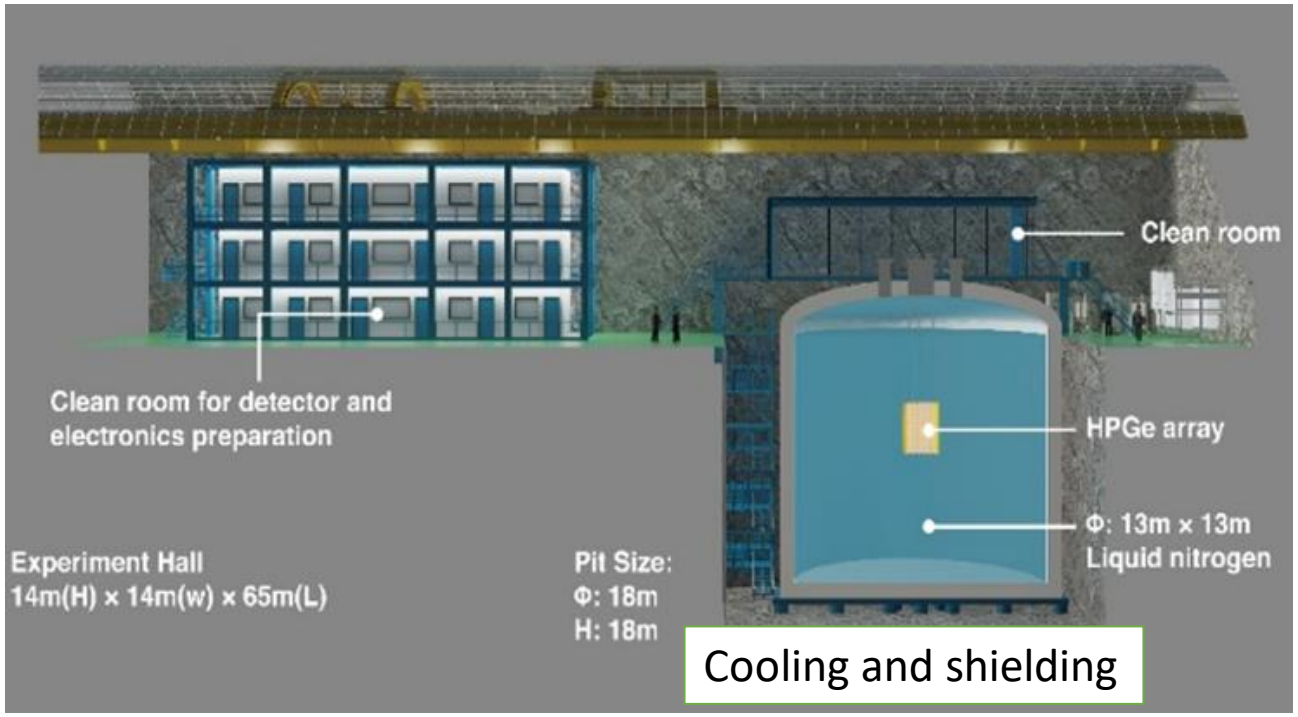
- CJPL-I to CJPL-II
  - Volume: 4000 m^3 to 300,000 m^3;
  - 1 main hall (6.5x6.5x42m) to 8 main halls (14x14x60m each);
  - Additional pit for next-generation CDEX;



Layout of CJPL-II

Future Plan - CDEX @CJPL-II

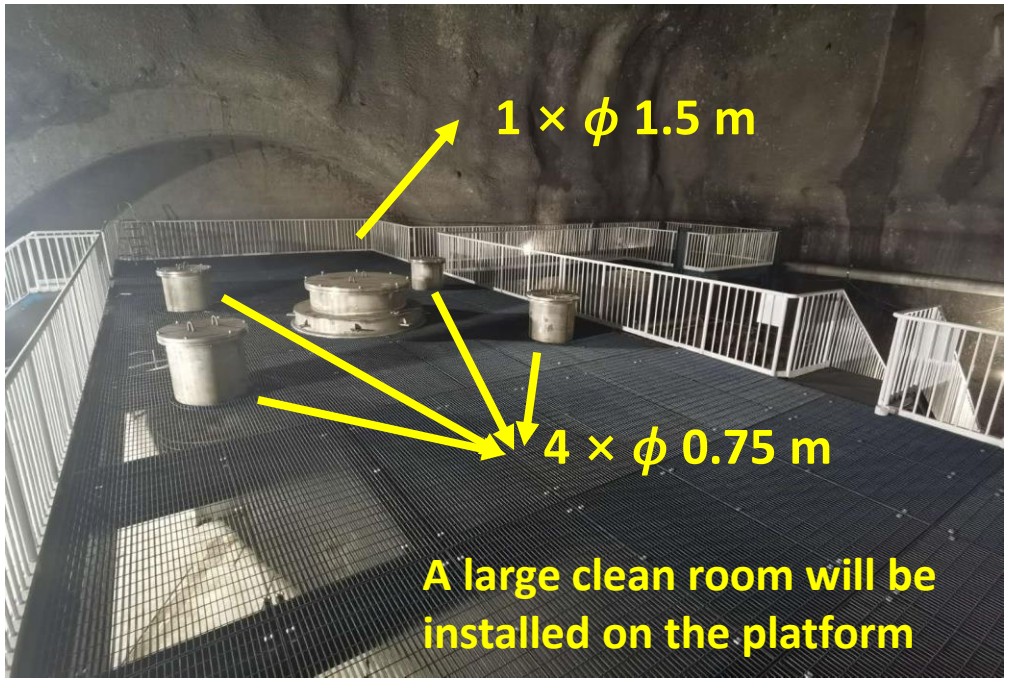
- Prepare for HPGe experiment in Hall C1 @ CJPL-II
- 1725m^3 liquid nitrogen, shielding and cooling system (inner: ϕ13m*H13m)
- Inner bkg level: <10^{-4} cpkkd@1keV, <10^{-6} cpkkd@2MeV



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 complete at the end of 2024
- Background level is hoped to be confirmed with PPCGe at the beginning of 2025



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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Thanks for your attention!

Litao YANG

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