PIRE GEMADARC Summer School, Collaboration Meeting, and Undergraduate Research Experience - 2023

Status and prospects of the CDEX dark matter search at CJPL

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On behalf of the CDEX collaboration

@ PIRE-GEMADARC collaboration meeting at AS in Taipei, 2023

June. 1st , 2023

CDEX

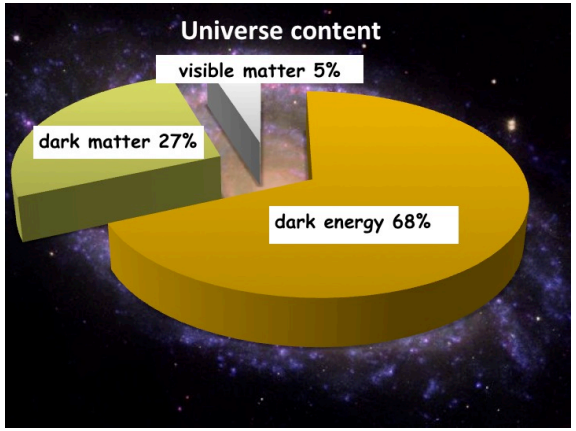
CJPL

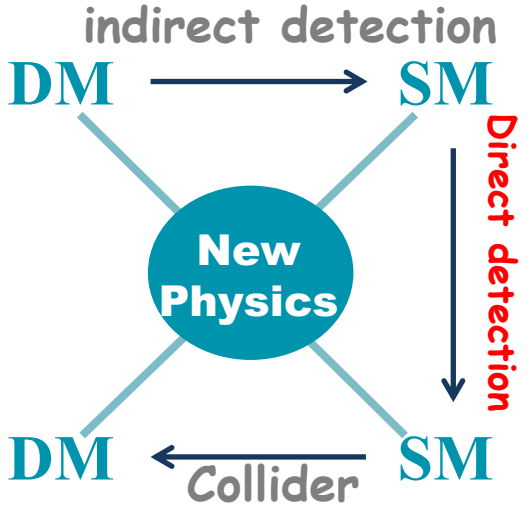
Outline

CDEX

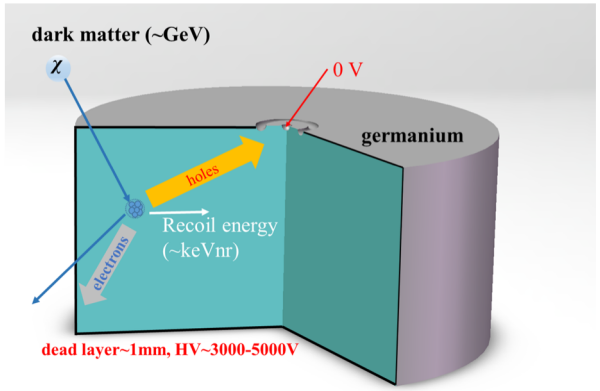
- ✓ CDEX collaboration and dark matter programs
- ✓ Recent results from CDEX-1 & CDEX-10 @CJPL-I
- ✓ CDEX-50dm Experiment of CDEX@CJPL-II
- ✓ R&D on the key Ge technologies & background controls
- ✓ New development of CJPL-II
- ✓ Summary & prospects

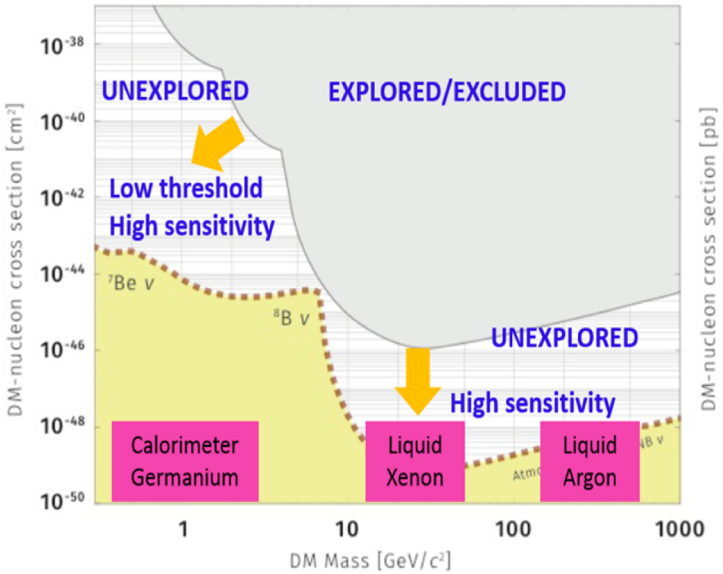
Direct detection in dark matter searches





A picture for IF DM is a particle…





- ✓ ~27% of the Universe consists of dark matter
- ✓ WIMP(χ) is one of the most popular dark matter candidates, and $\chi - N$ elastic scattering is intensively studied in recent years.
- ✓ Current wisdom in PP:

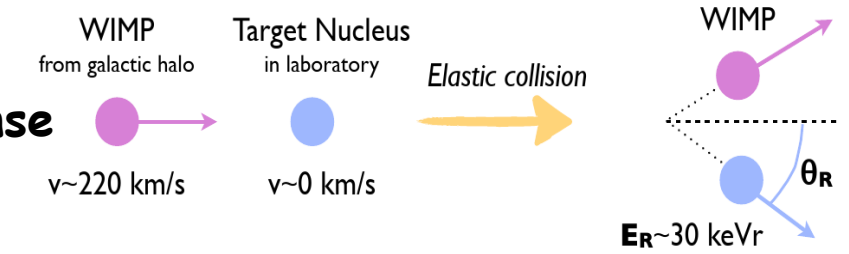
$[\sigma_{\chi N}$ VS $m_{\chi}]$

Conventional WIMPs and other alternatives

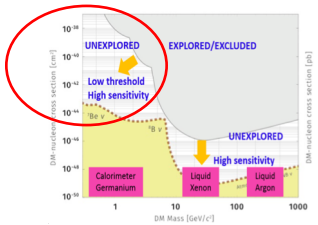
CDEX

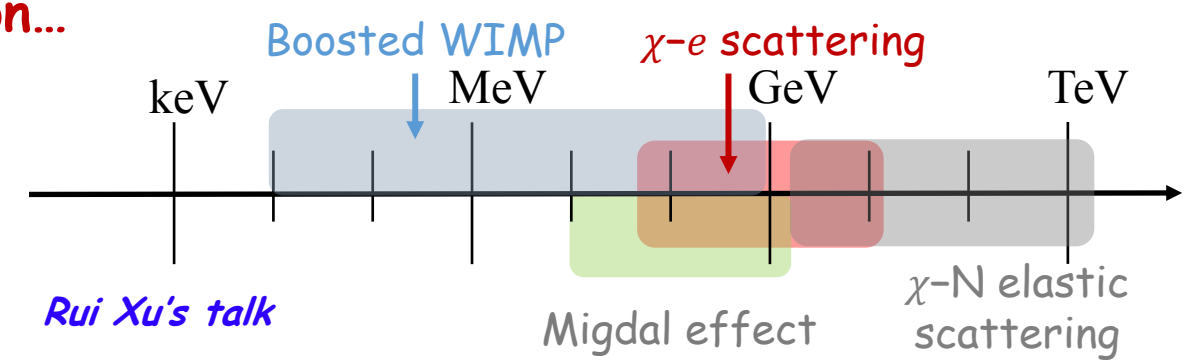
Astrophysics Particle physics

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



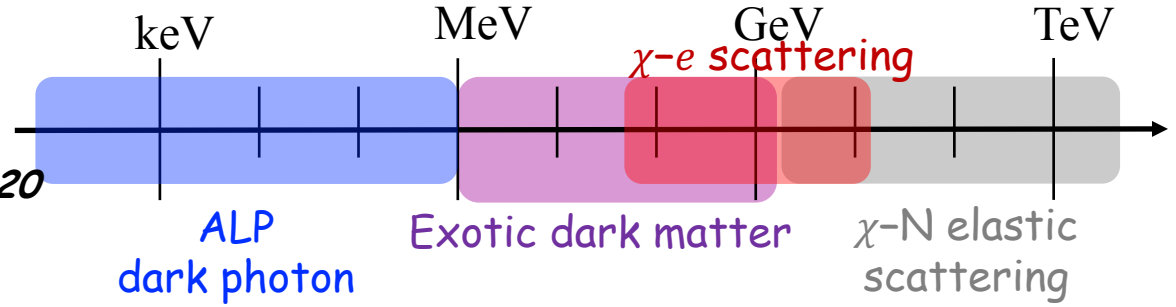
✓ **Toward to the unexplored lower mass region…**





WIMP search

- Annual modulation *PRL 2019*
- Boosted WIMP: down to $\mathcal{O}(10\,\mathrm{keV})$ *PRD 2022* *Rui Xu's talk*
- Migdal effect (bremsstrahlung) *PRL 2019*
- $\chi - e$ scattering down to $\mathcal{O}(10\,\mathrm{MeV})$ *PRL 2022* *Zhenyu Zhang's talk*
- DM from EFT *Science china 2021*



New physics beyond the WIMP

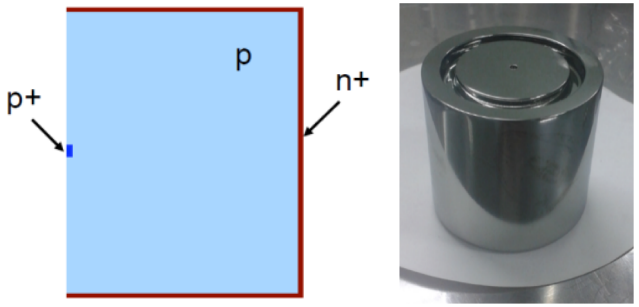
- Axion like particle: down to $\mathcal{O}(100\,\mathrm{eV})$ *PRD 2020*
- Dark photon: down to $\mathcal{O}(100\,\mathrm{eV})$ *PRL 2020*
- Exotic DM: down to $\mathcal{O}(1\,\mathrm{MeV})$ *PRL 2022*
- Boosted keV-MeV DM from evaporating primordial BH *PRD 2023 accepted* *Zhenhua Zhang's talk*

China Dark matter Experiment

- ✓ Established in 2009, 11 institutes, >100 members.
- ✓ DM and 0νββ experiment based on Ge detectors at CJPL.
- ✓ Many DM & Neutrino physics results published in last 10 years.

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

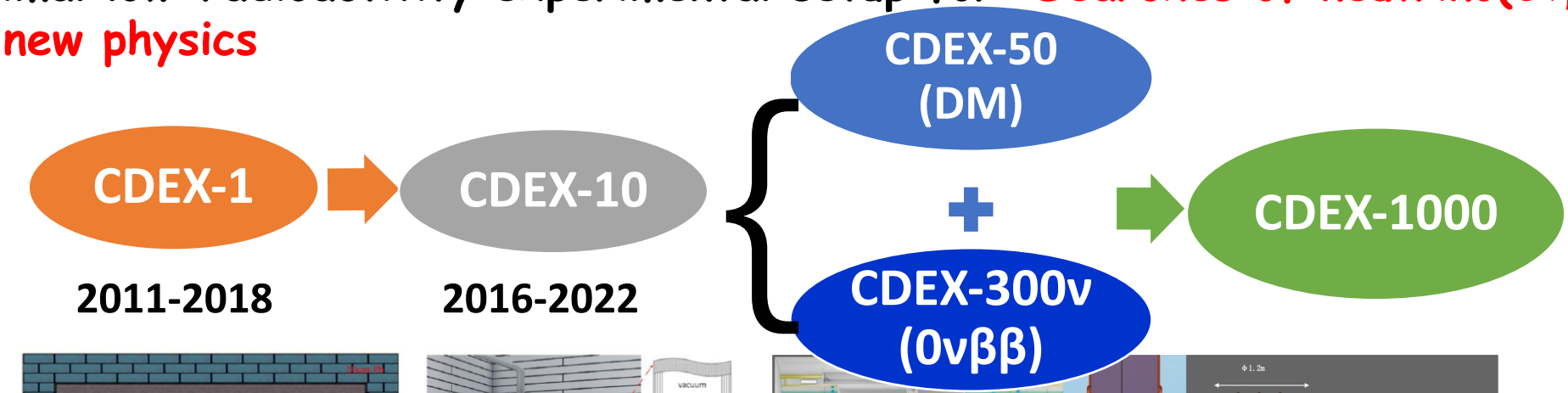
P-type Point-Contact(PPC) Germanium detector



- ✓ Best energy resolution (~200 eV @ 10.37 keV)
- ✓ Low energy threshold (~100 eV)
- ✓ Low background

CDEX Roadmap

- ✓ CDEX-1 (2011-2018): Development of PPC Ge detector, bkg understanding
- ✓ CDEX-10 (2016-2022): Performances of Ge detector(detector fabrication-homemade) immersed in LN_2
- ✓ CDEX-50dm (2021-2027): An array of 50 kg Ge detectors in cryogenic liquid for DM searches
- ✓ CDEX-300v (2021-2027): An array of enriched 300 kg Ge detectors in cryogenic liquid with an optimal low-radioactivity experimental setup for Searches of neutrino($0\nu\beta\beta$) and diversified new physics



CDEX-1A&B: 1kg PPC Ge×2

CDEX-10: ~10kg PPC Ge array

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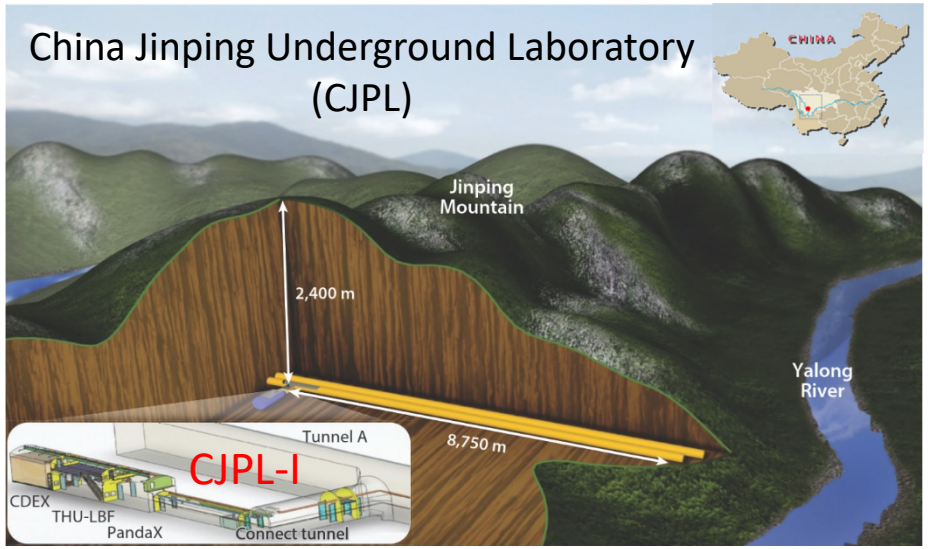
CDEX program

- CDEX program: A staged Ge experimental facilities
  - ✓ Mass of 1kg(N), 10kg(N), 300kg(E), 1T(E), and 10T(E), respectively.
  - ✓ At CJPL with 2400m rock overburden to dramatically reduce not only the comic-ray flux but comic-induced isotopes.
- Scientific goals:
  - ✓ Direct detection of dark matter : based on the low-energy spectra of <20 keV, especially the spectrum of sub-keV region.
  - ✓ Diversified physics : Solar neutrino via ν-N elastic scattering ;Search of 0νββ to understand whether neutrinos are their own particles, neutrino mass ordering, leptogenesis, GUT…..;

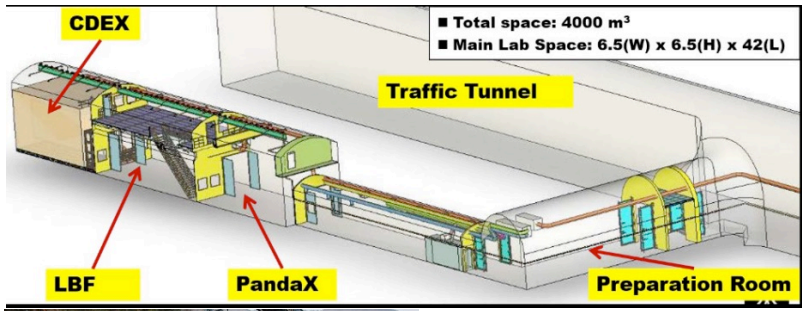
China Jinping Underground Laboratory(CJPL)

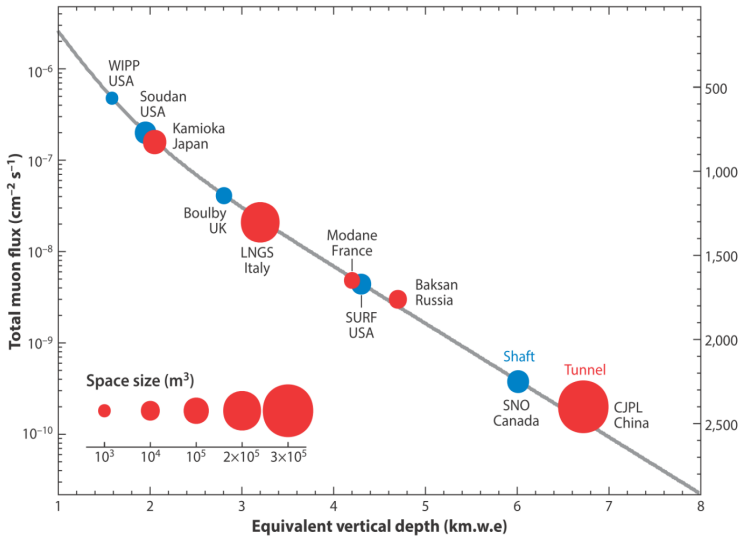
CDEX

- ✓World's deepest underground lab, CJPL
- ✓Near Xichang city, Sichuan Province, Southwest China
- ✓Two DM exp. (CDEX, PandaX)+LBF(radio-assay) operated now



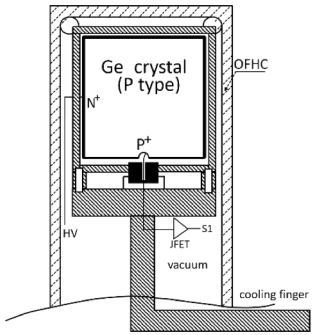
Cheng et al., Annu. Rev. Nucl. Part. Sci. 2017. 67:231

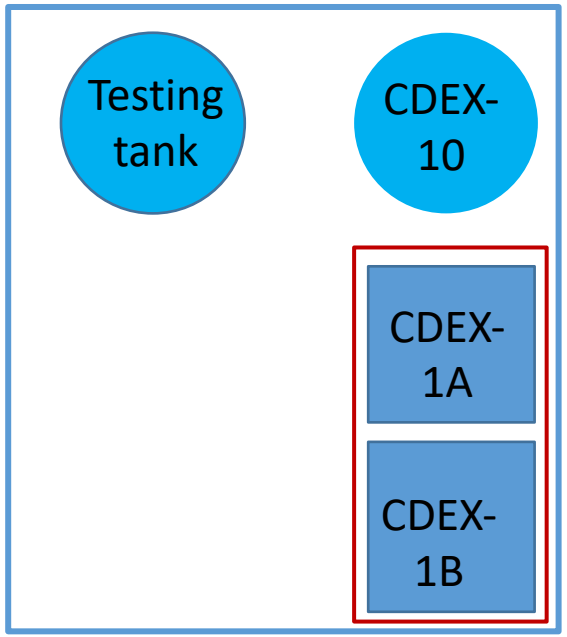


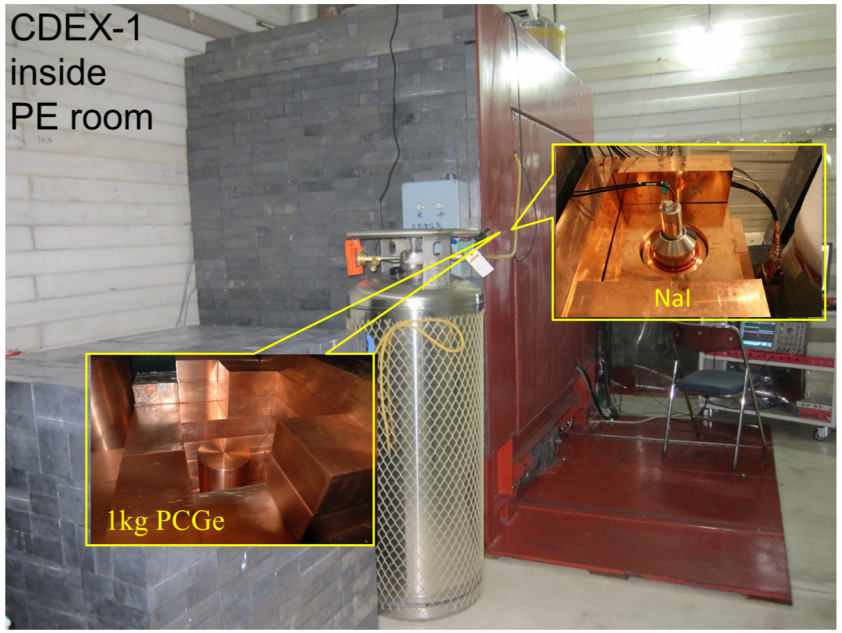


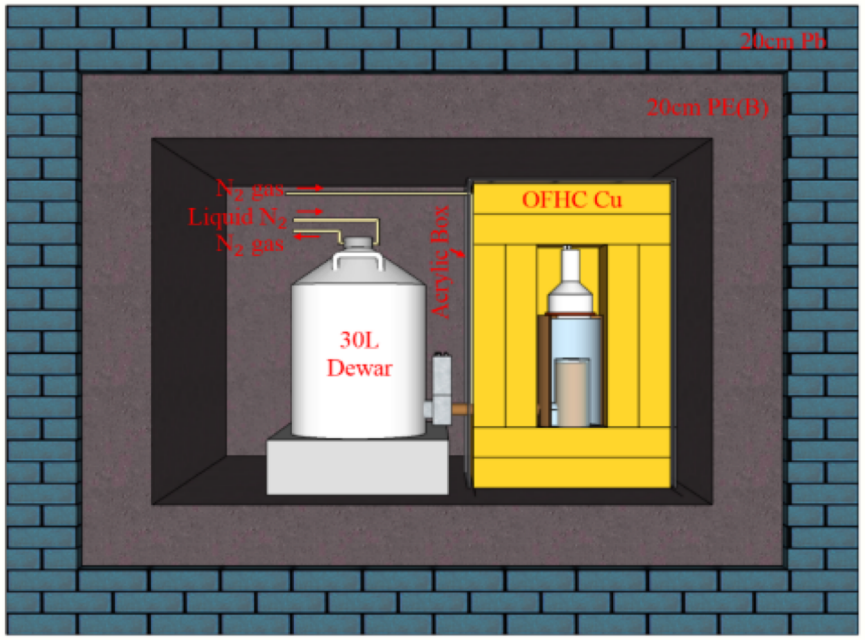
CDEX-1 Experiment

- ✓ 2 sub-stages: CDEX-1A(2011)→1B(upgraded, 2013);
- ✓ Single-element ~1kg PPC Ge detector;
- ✓ NaI, enclosed the cryostat of Ge, served as anti-Compton detector.
- ✓ Located in PE room at CJPL-I.









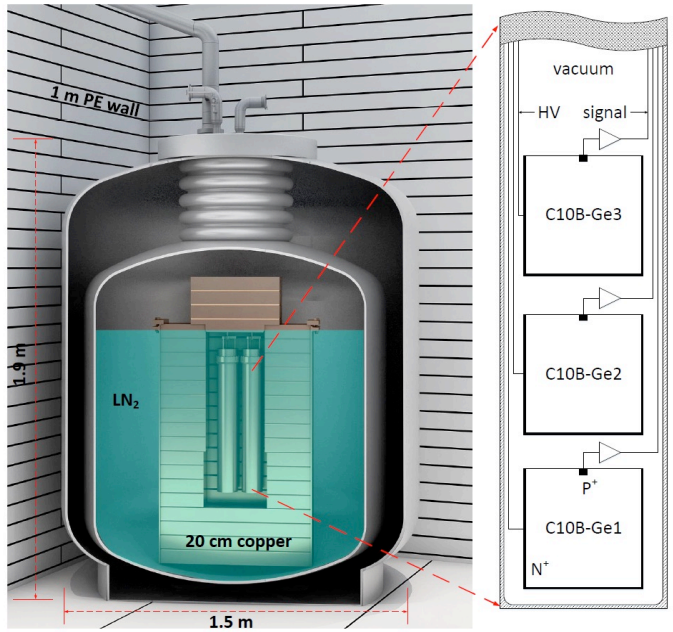
CDEX-1A&B: 1kg PPC Ge×2

CDEX-10 Experiment

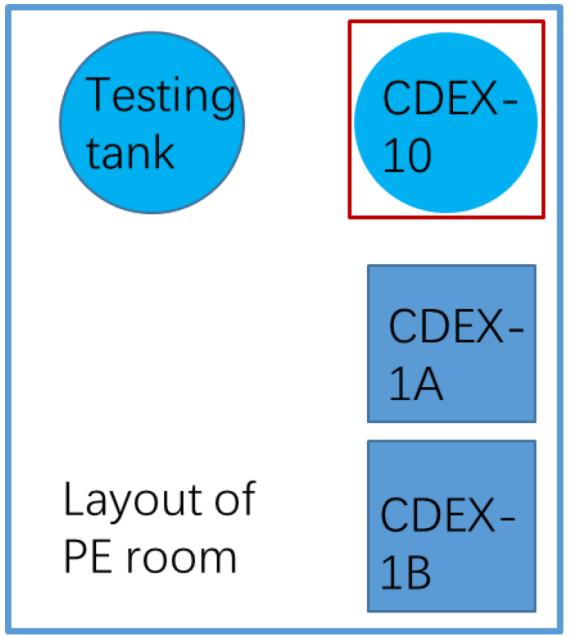
CDEX

- ✓ Array detectors: 3 strings with 3 detectors each, ~10 kg total;
- ✓ An array immersed directly 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)



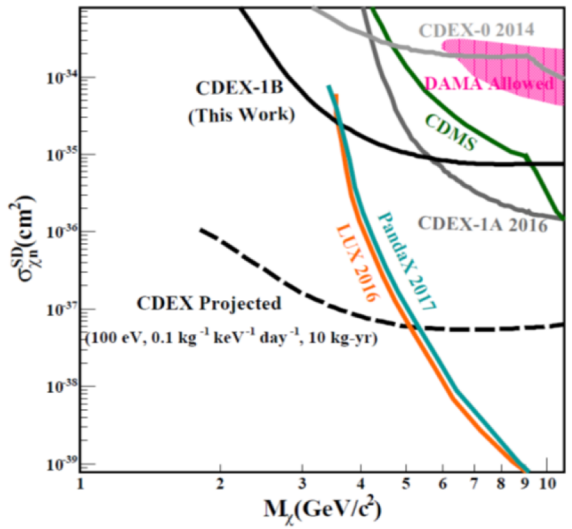
CDEX-10: ~10kg PPC Ge array



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

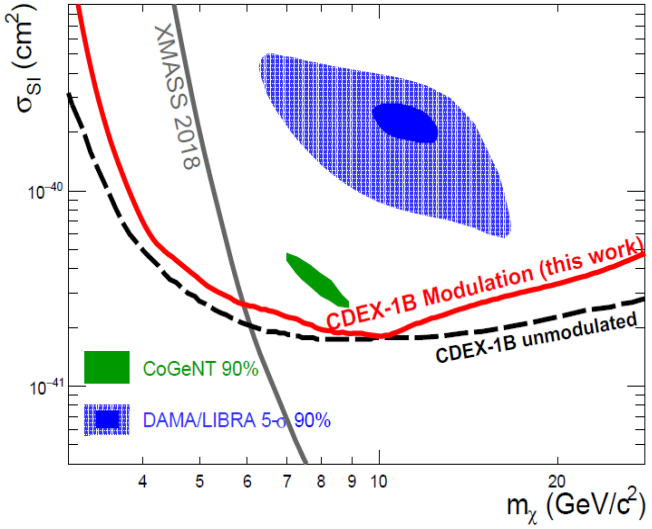
- CDEX-1B: ➢ Threshold of 160 eV is achieved.
  - ✓ First extended the mass to 2 GeV/c^2 among Ge experiments.
  - ✓ The most sensitive result on SD $\chi - N$ elastic scattering below 4GeV
  - ✓ The best result on the WIMP annual modulation below 6 GeV
- CDEX-10
  - ✓ The most sensitive result on SI $\chi - N$ elastic scattering at 4-5 GeV

C1B WIMP



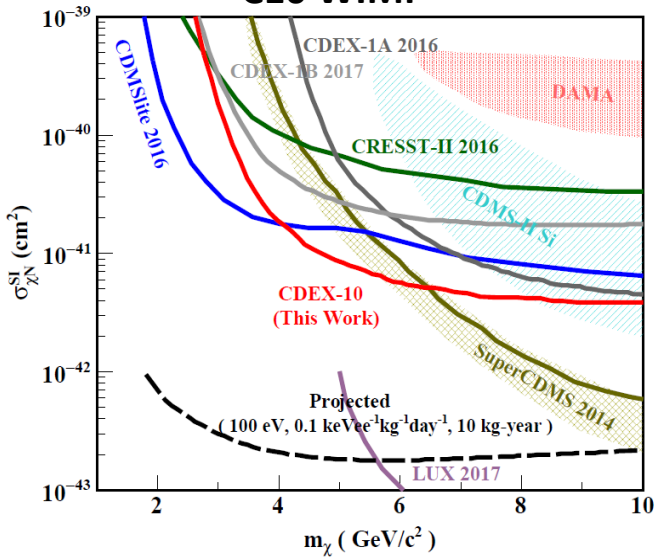
Chin. Phys. C 42, 023002 (2018)

C1B WIMP annual modulation



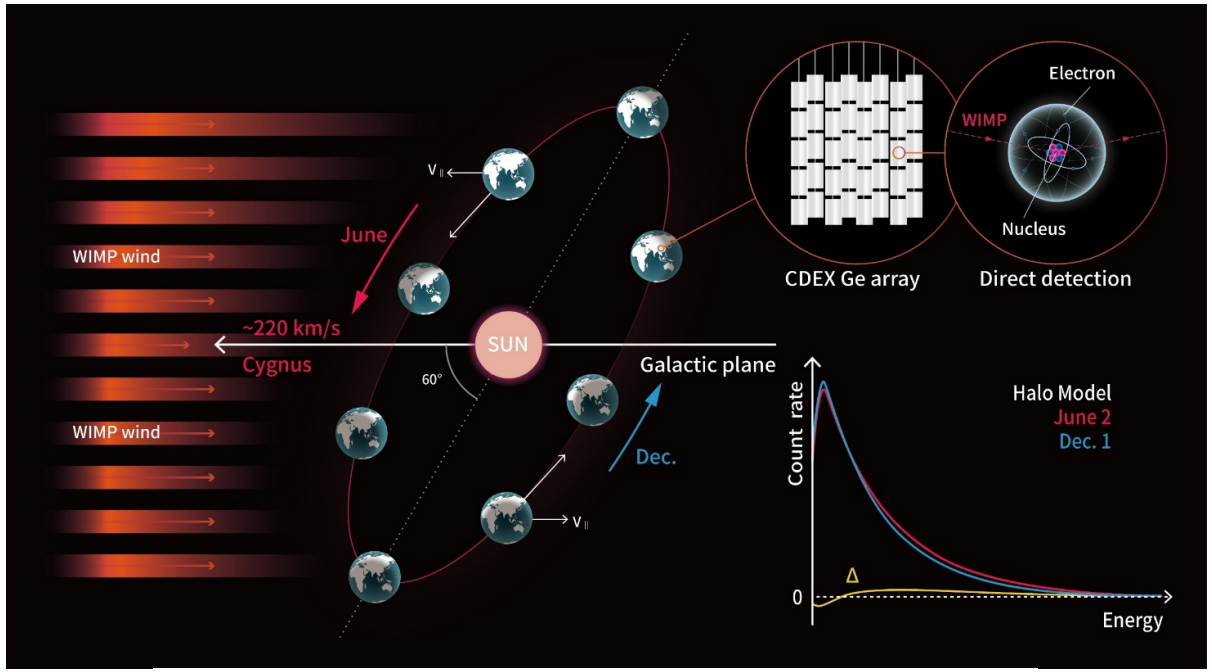
Phys. Rev. Lett. 123, 221301 (2019)

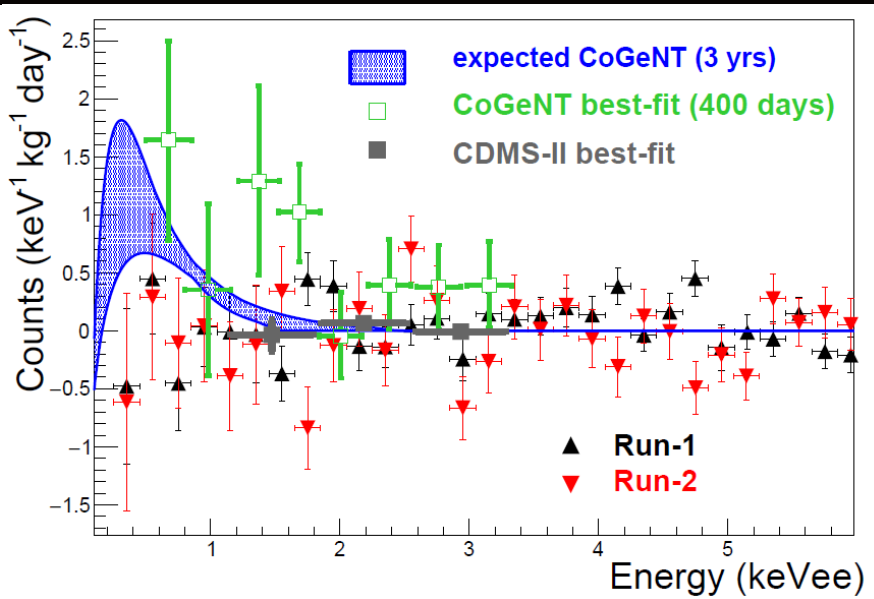
C10 WIMP



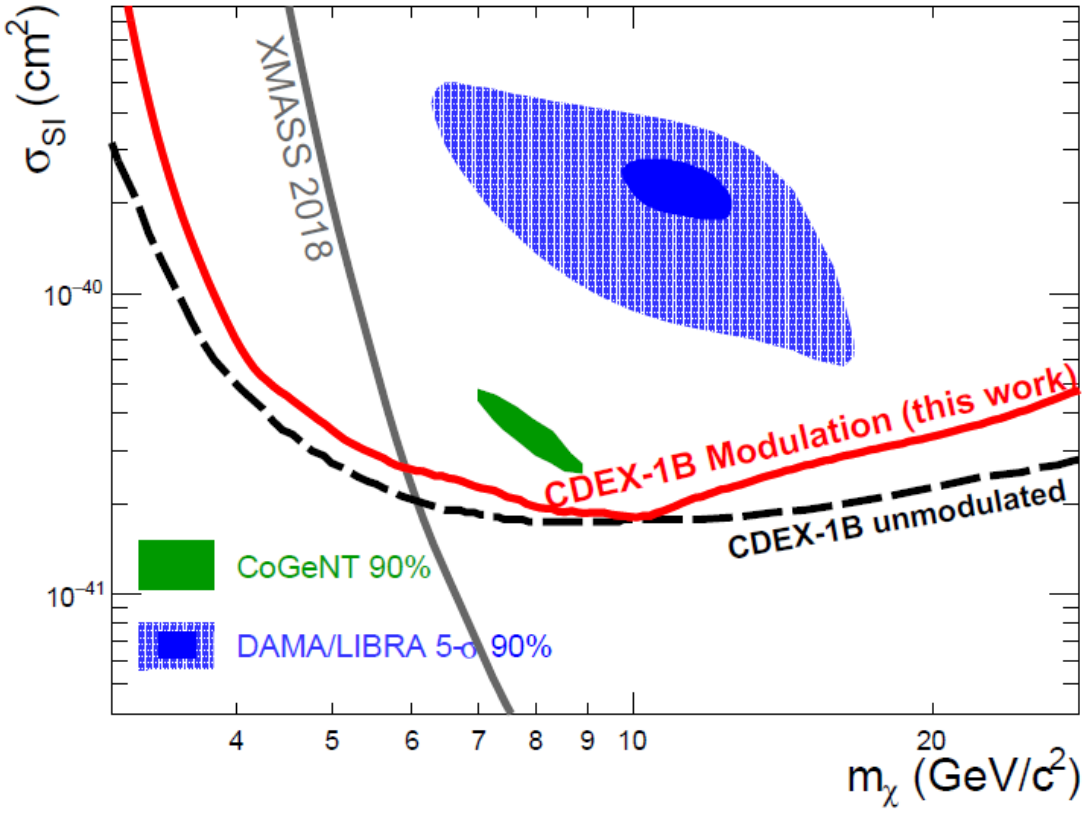
Phys. Rev. Lett. 120, 241301 (2018)

Annual Modulation Searches from CDEX-1B





✓ Explore the new AM detection channel below the mass of 6 GeV/c²

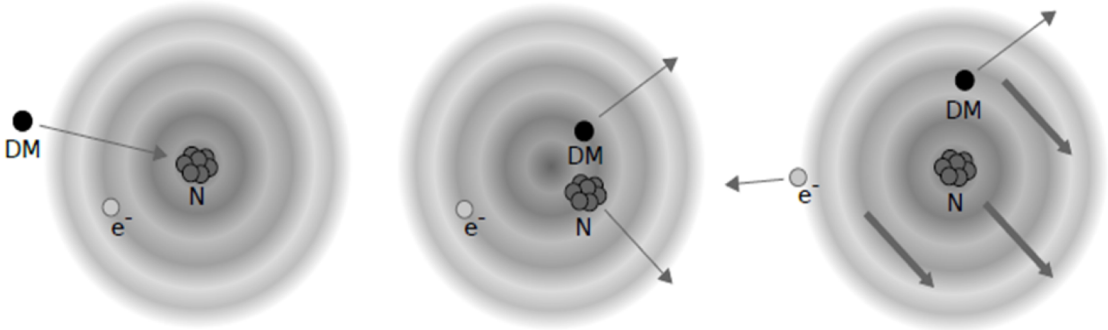


Phys. Rev. Lett. 123, 221301 (2019)

WIMP searches with Migdal Effect

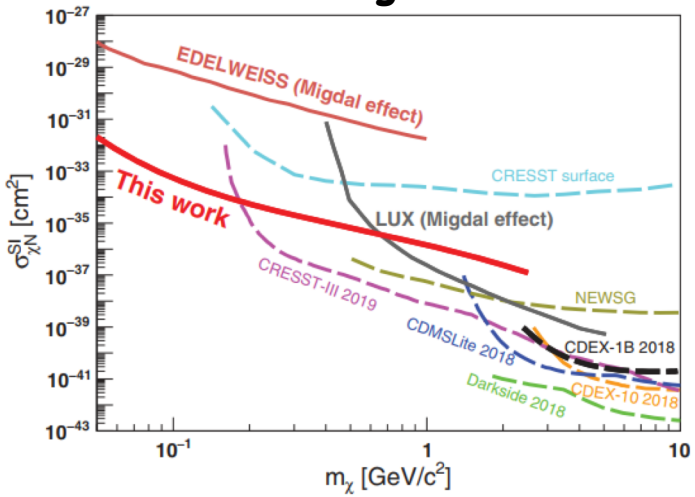
CDEX

- ✓ Migdal effect (ME):
  - Elastic scattering: $\chi + N \rightarrow \nu + N(E_R)$
  - Migdal effect: $\chi + A \rightarrow \chi + N(E_R) + e^-(E_{EM})$
- ✓ The electrons has finite probability that they do not follow the motion of the nuclei such that the electrons of the target atom will be excited or ionized, i.e., high-energy electrons are ejected via inelastic $\chi - N$ scattering process.

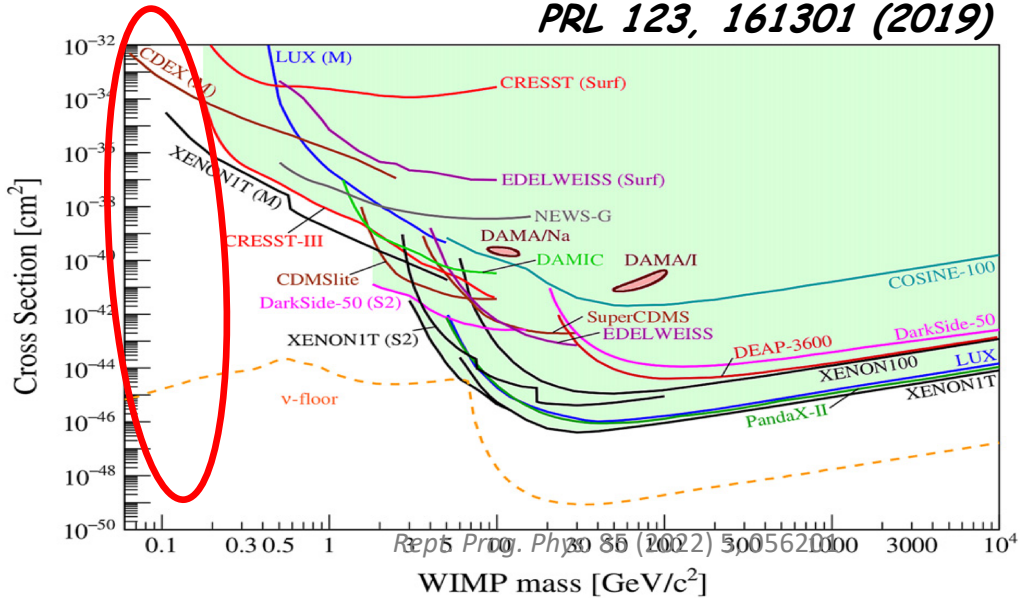


Secondary process

Best results at 50-180 MeV region for WIMP searches.



PRL 123, 161301 (2019)



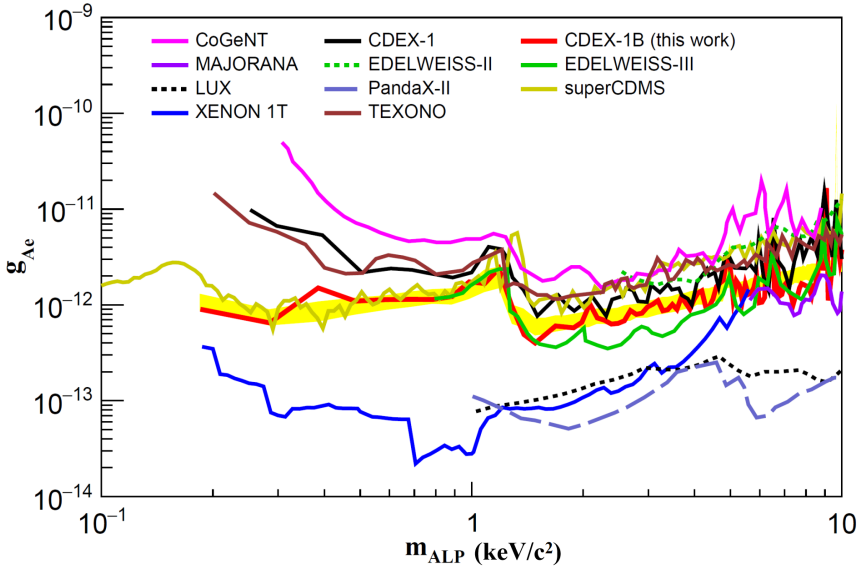
Rept. Prog. Phys. 85 (2022) 054201

European Astroparticle Physics Strategy 2017-2026.

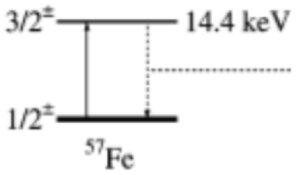
Solar Axion & ALP results

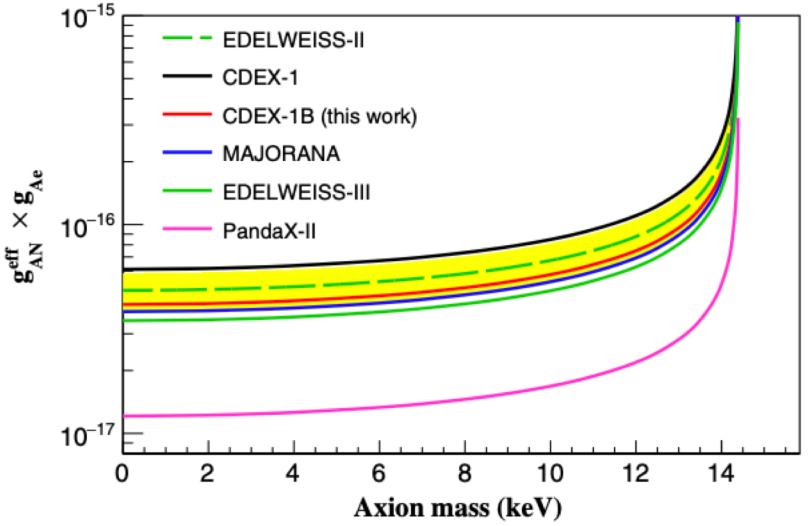
- ✓Background assumption:
  - Continuous background + X-rays
- ✓Profile likelihood method
- ✓Excellent energy resolution of Ge is suited for the monochromatic DM axion and Fe-57 axions
- ✓ Competitive g_{Ae} constraints exist for m_a: 100eV ~ 1keV

ALP dark matter

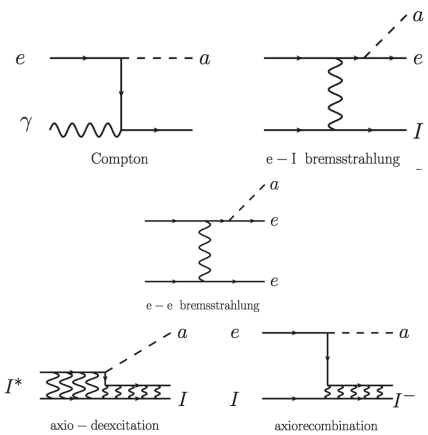


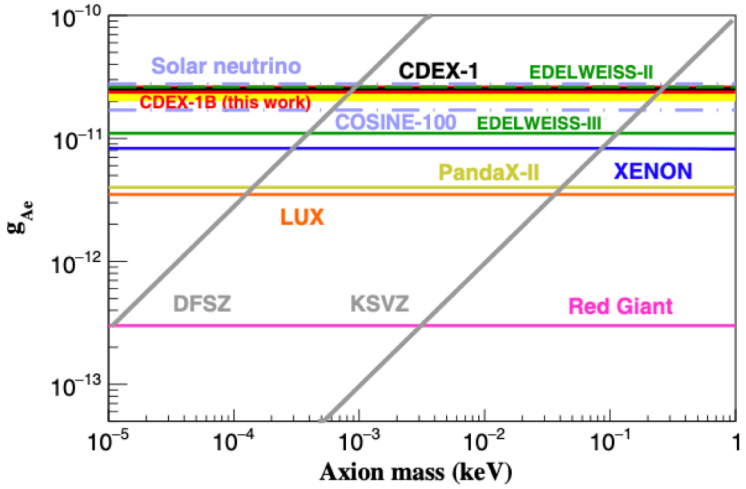
Fe-57 solar axion





CBRD Solar axion





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

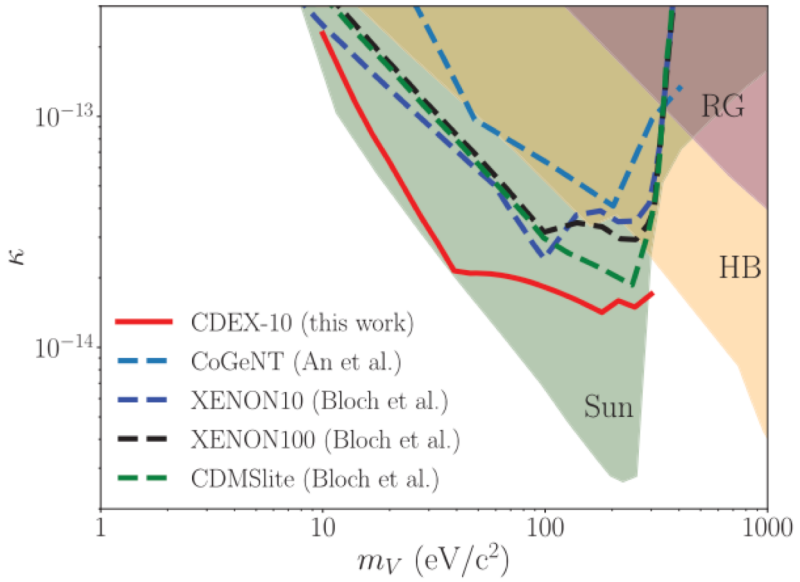
Solar dark photon & DPDM results

CDEX

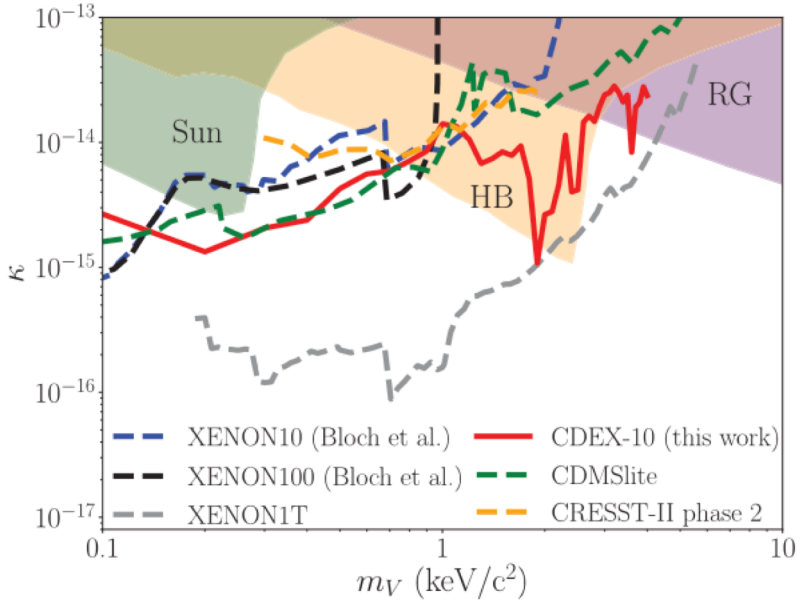
- ✓ Solar is the most significant dark photon source.
- ✓ Detection method: $V + A \rightarrow A^+ + e^-$
- ✓ The expected event rates:

$$\frac{dR}{dE} = V\frac{E}{|\vec{q}|}\left(\frac{d\phi_T}{dE}\Gamma_T + \frac{d\phi_L}{dE}\Gamma_L\right)$$

- depending on dark photon flux $\phi_{T,L}$, the dark photon absorption rates $\Gamma_{T,L}(m_V, \kappa)$ in Ge



- ✓ C10-B1 experiment
  - Threshold: 160eVee
  - Background level 2.5 cpkkd @ 2~4 keV
  - Exposure: 205.4 kg day
- ✓ The most stringent limits on κ with mass of 10 to 300 eV/c^2 for solar dark photon



Phys. Rev. Lett., 124, 111301, 2020

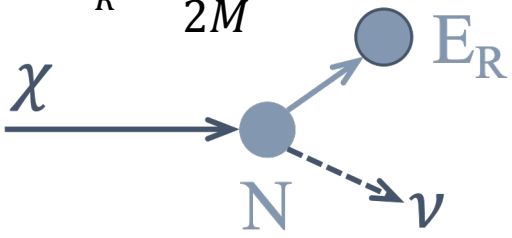
Exotic DM results

- ✓ New low mass $\mathcal{O}(\mathrm{MeV}/c^2)$ dark matter (χ) may interact with nucleon (N):

Neural current fermionic DM absorption: $\chi + N \rightarrow \nu + N$ [1]

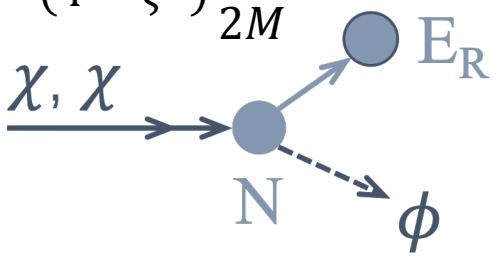
DM-nucleus 3->2 scattering: $\chi + \chi + N \rightarrow \phi + N$ [2]

$$E_R \approx \frac{m_\chi^2}{2M}$$



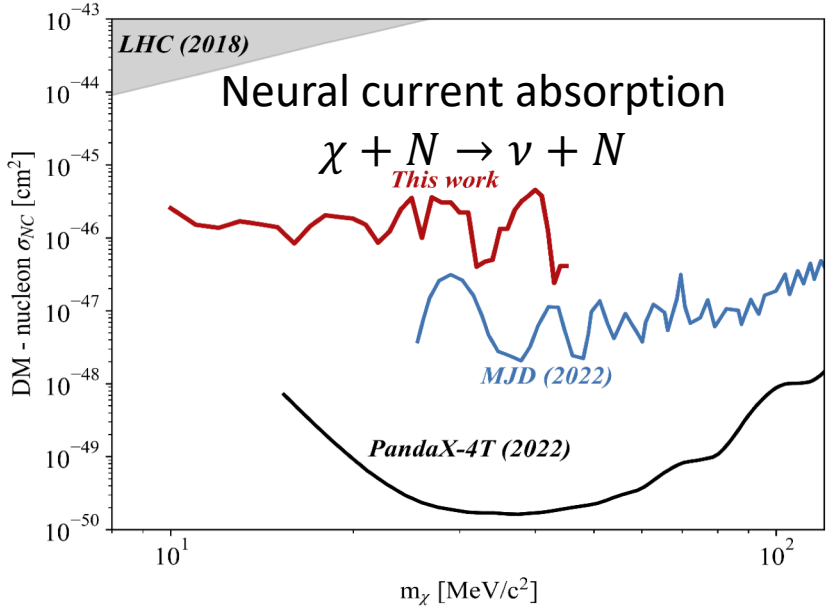
$\chi + N \rightarrow \nu + N$

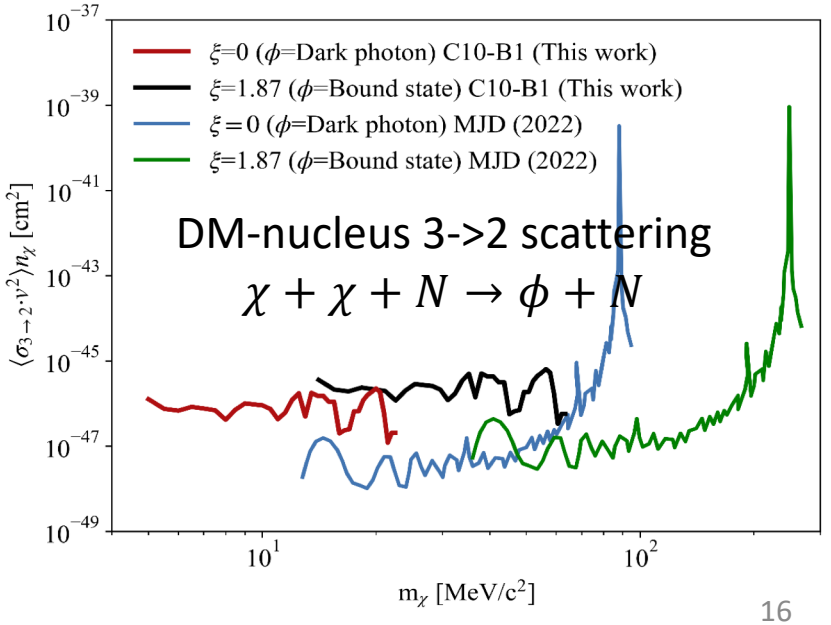
$$E_R = (4 - \xi^2)\frac{m_\chi^2}{2M}$$



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

- ✓ C10-B1 (205.4 kg-day exposure) with flat background assumption.
- ✓ New experimental limits on lowest mass range is placed for these two channels based on the low energy threshold of 160 eV.





arXiv:2209.00861, PRL 2022

$\chi - e$ scattering

Zhenyu Zhang's talk

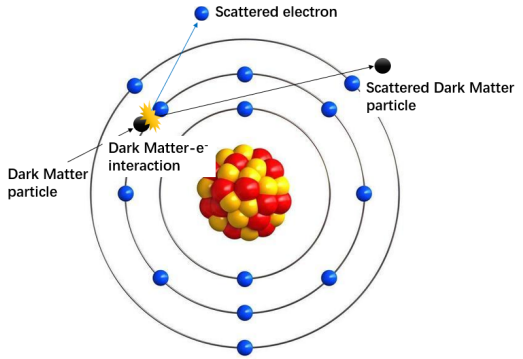
- ✓ Light χ can potentially pass most of the energy onto electrons, depositing observable energy via $\chi - e$ scattering
- ✓ A DM-electron scattering paradigm proves to be successful extend m_χ to $\mathcal{O}(10\ MeV)$
- ✓ The total rate can be written as

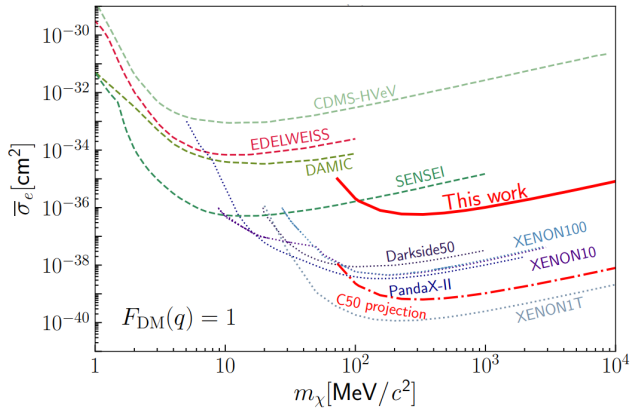
$$R_{i\to f} = \frac{2\pi\bar{\sigma}_e}{V\mu_{\chi e}^2 m_\chi}\frac{\rho_\chi}{\rho_T}.$$

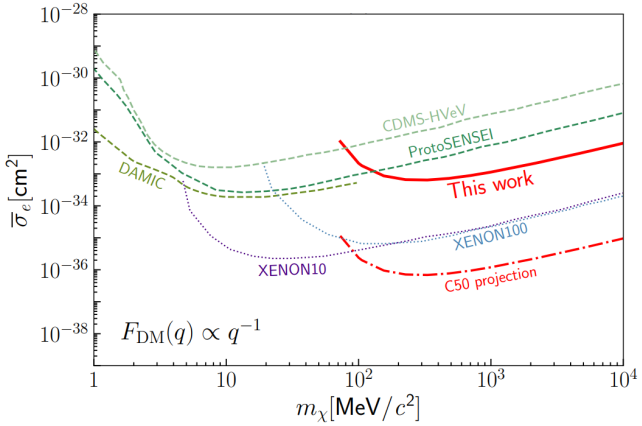
$$\sum_{i,f}\int \frac{\mathrm{d}^3q}{(2\pi)^3}\left(\frac{f_e}{f_e^0}\right)^2 F_{\mathrm{DM}}^2 g(\mathbf{q},\omega)\left|f_{i\to f}(\mathbf{q})\right|^2,$$

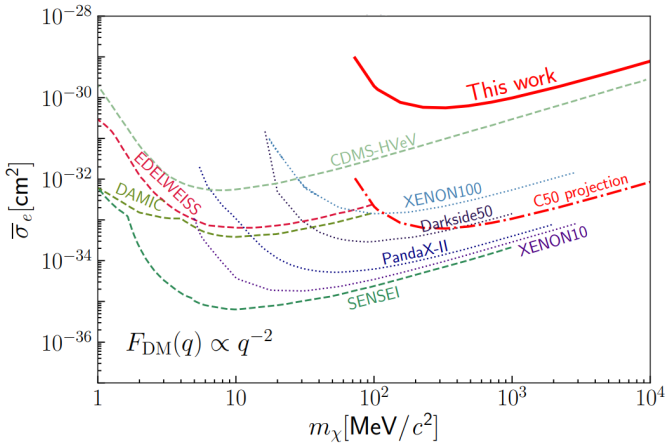
dark matter form factor
1: heavy mediator
q_0/q: electric dipole coupling
$(q_0/q)^2$: ultralight mediator

Crystal form factor









R&D on the Key Ge technologies

CDEX

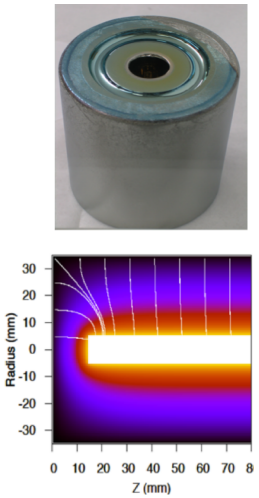
- ✓ Ge detector fabrication : Various types, P-type planar/coaxial, P-type point contact/ BEGe ~20 has been successfully done.
- ✓ HPGe crystal growth : On-going project
- ✓ ULB-VFE ASIC + Bare Ge immersed in LN_2 : Bare BEGe is successful to perform in LN_2
- ✓ ^{76}Ge enrichment: Coupled with cosmogenic-induced backgrounds & $0\nu\beta\beta$ experiment
- ✓ ULB-Copper production in underground : Goal: <μBq/kg
- ✓ LAr & SAr scintillating detectors : Active Anti-Compton & cryogenic system

HPGe Technology---Ge Detector Fabrication

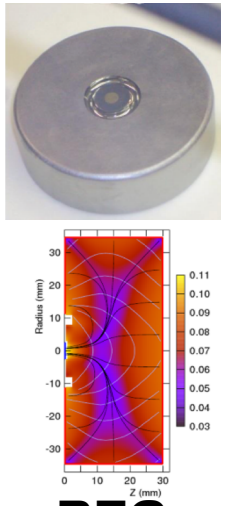
CDEX

- ✓ Home-made different types of Ge detectors by CDEX group;
- ✓ Detector performances are same with commercial products with long-term stability.

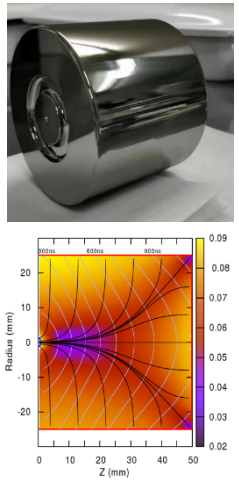
Ge Detector Passivation techniques -- ShaSha Lvs' talk



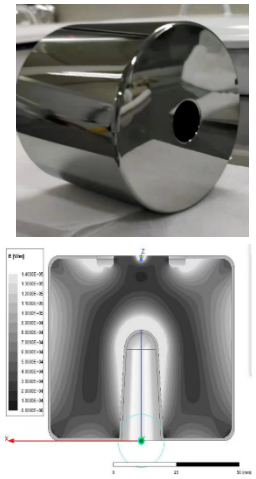
Co-axial



BEGe

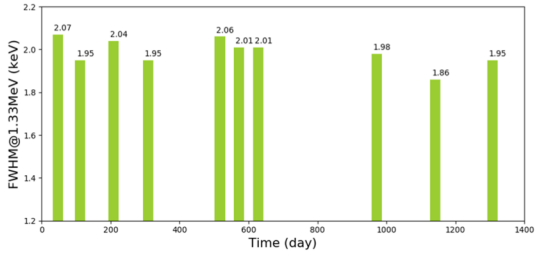


PCGe


ICPC

Key technical Steps:

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

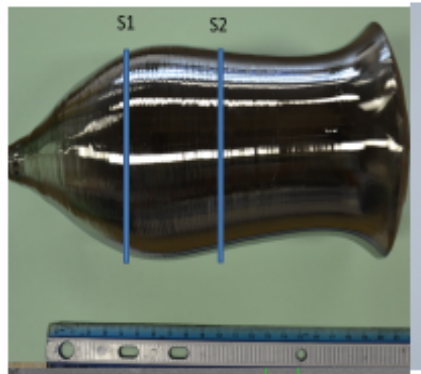


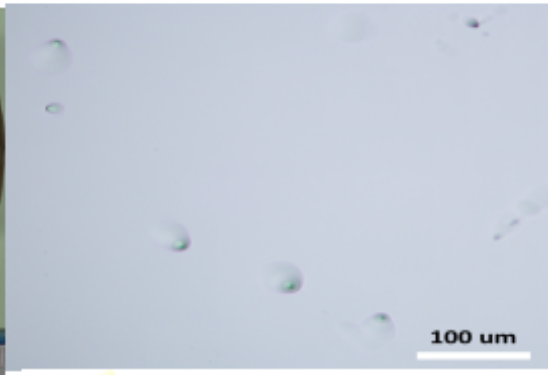
HPGe Technology---Ge Crystal Growth

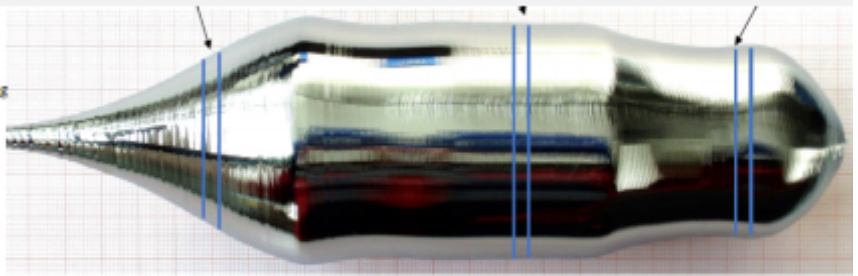
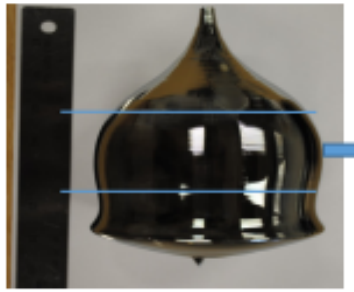
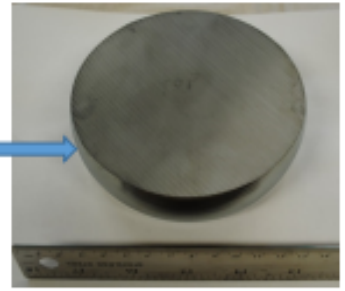
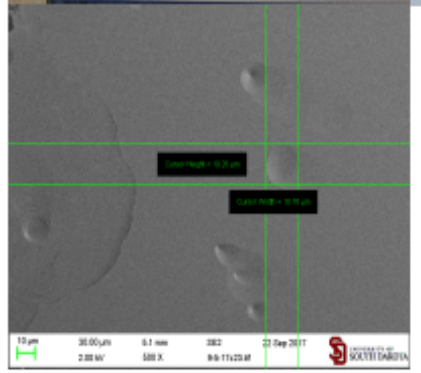
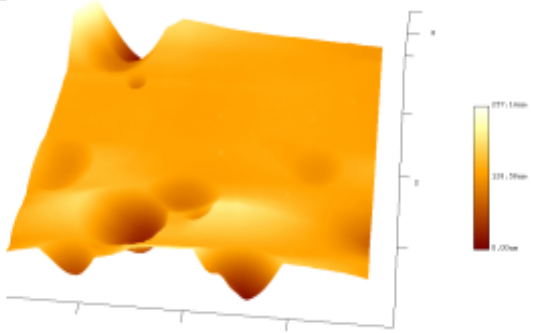
CDEX

- ✓ Long-term work: Ge crystal growth at underground Lab ;
- ✓ Ge crystal growth and detector fabrication at CJPL has been funded.





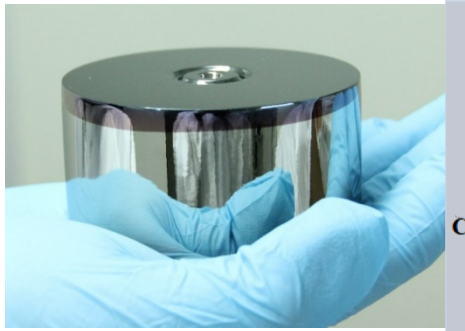
HPGe Technology---ASIC PreAMP + LN_2 Cryostat

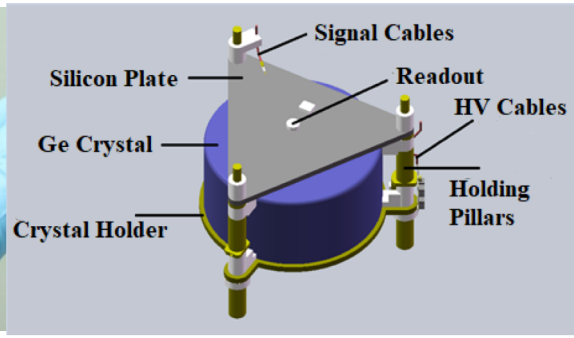
CDEX

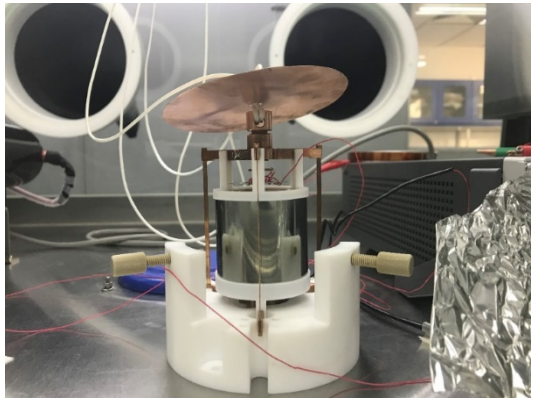
- The first Ge+ASIC+LN_2 detector in the world:

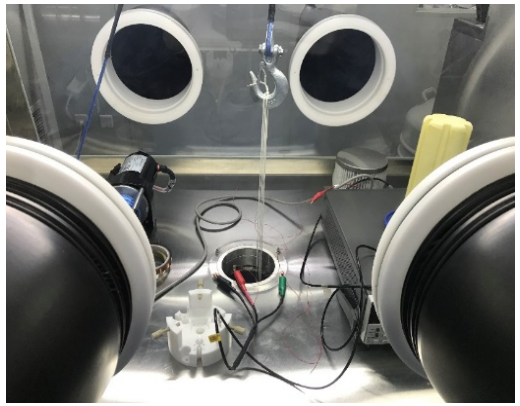
  500g Ge + home-made CMOS ASIC preamp immersed into LN_2

- Works with expected performances!

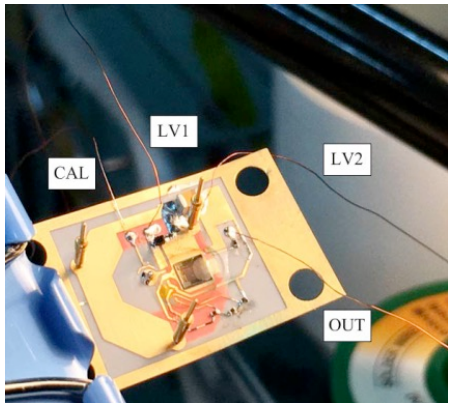




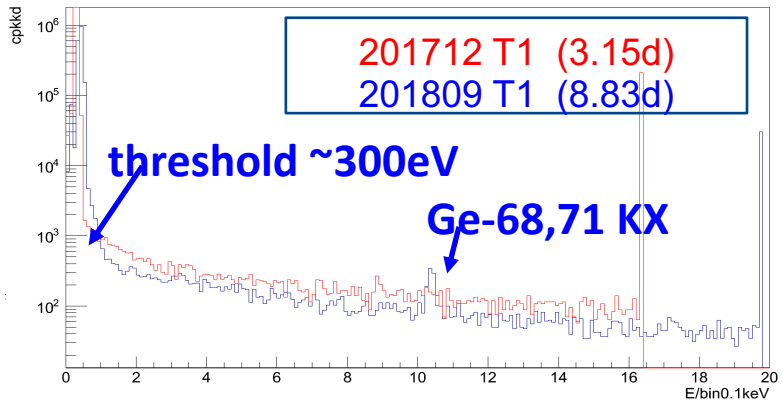




Fabricated and Tested in CJPL-I



ASIC PreAMP



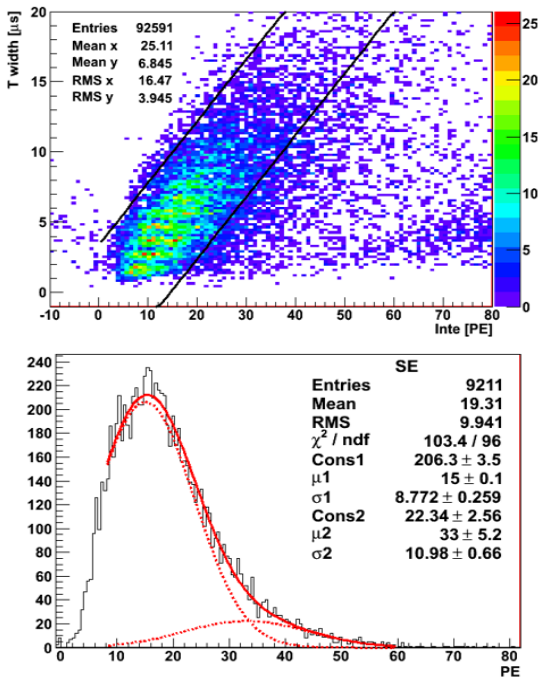
Background spectrum @CJPL

Electro-form Copper technology at underground & LAr/SAr

CDEX

- ✓ Successfully electro-form copper production by CDEX at CJPL-1;
- ✓ Involve in LAr/SAr veto-detector technology

Electro-form copper



LAr TPC

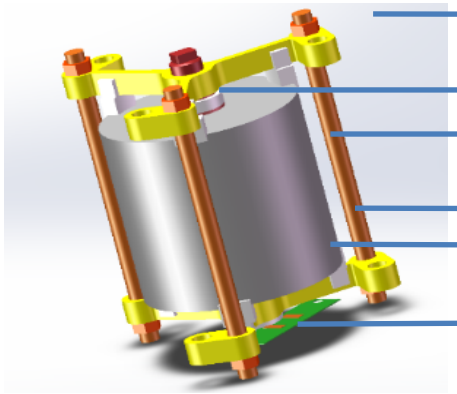
Solid Argon R&D

Simulation and Background Modelling

CDEX

Study the PSD performance of the PPCGe and BEGe detectors – Wenhan Dai's talk

✓ SAGE: A simulation software toolkit for CDEX developed for background simulation and pulse shape simulation.

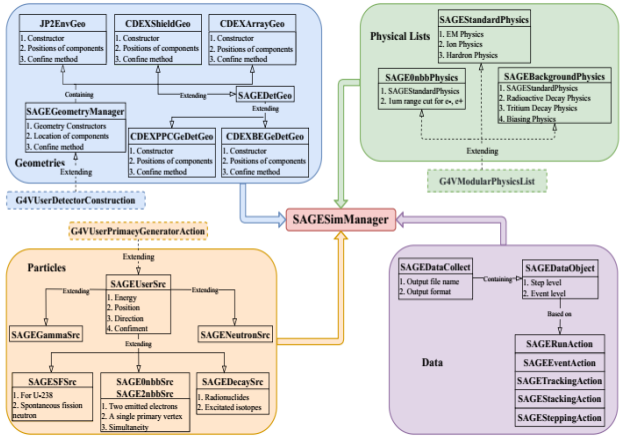


Shielding material (LN2 or LAr)

Structure materials

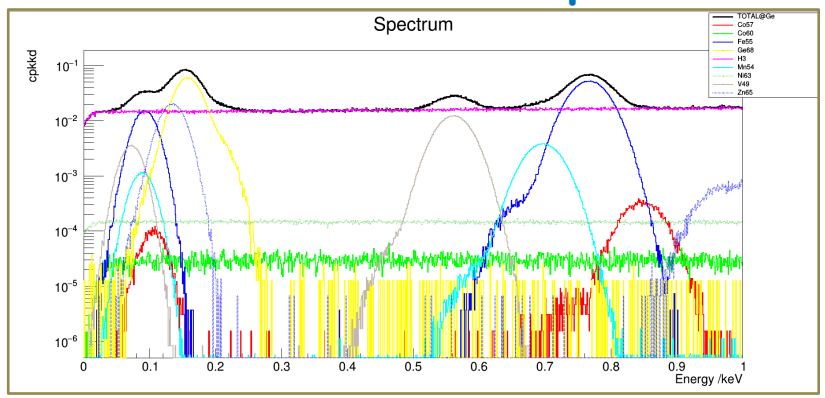
Cosmogenic isotopes

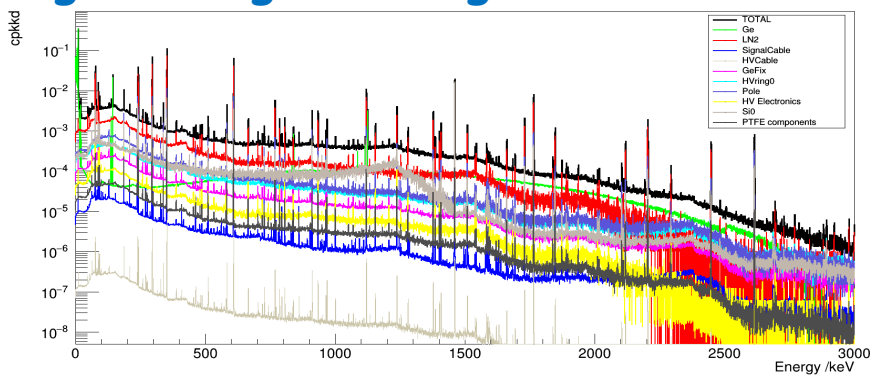
VFE materials

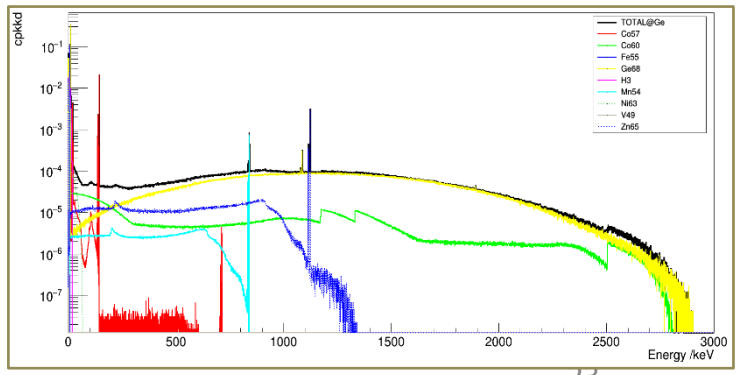


SAGE, 2021 JINST 16 T09005

Measurements and Ab initio calculation of atomic Compton scattering – ChangHao Fang's talk



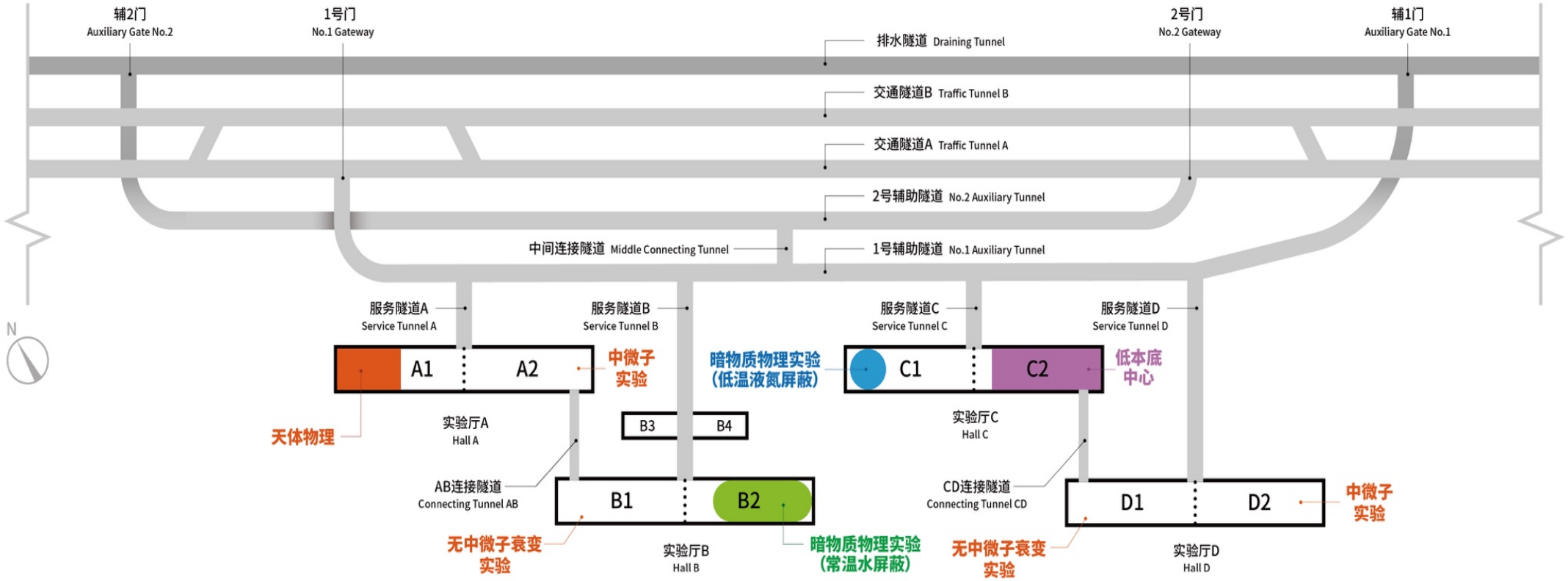




Upgraded CJPL

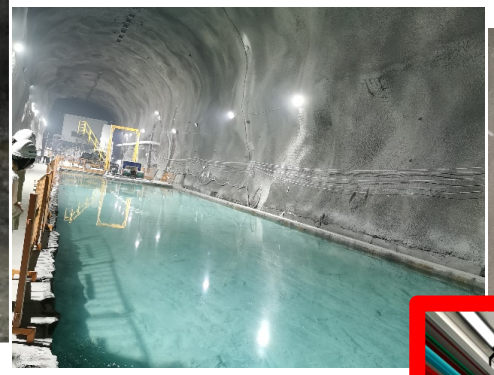
CJPL-I to CJPL-II

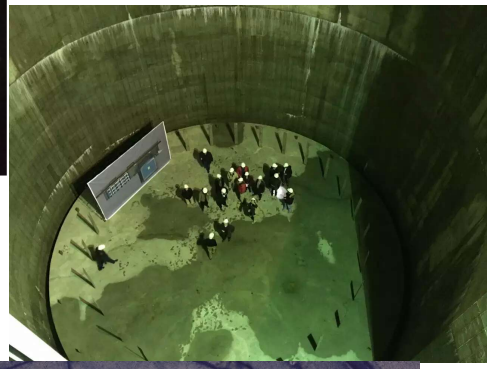
- ✓ Volume: 4000 m^3 to 300,000 m^3;
  main hall (6.5x6.5x42m) to 8 main halls (14x14x65m each);
- ✓ Additional pit for the CDEX experiments;

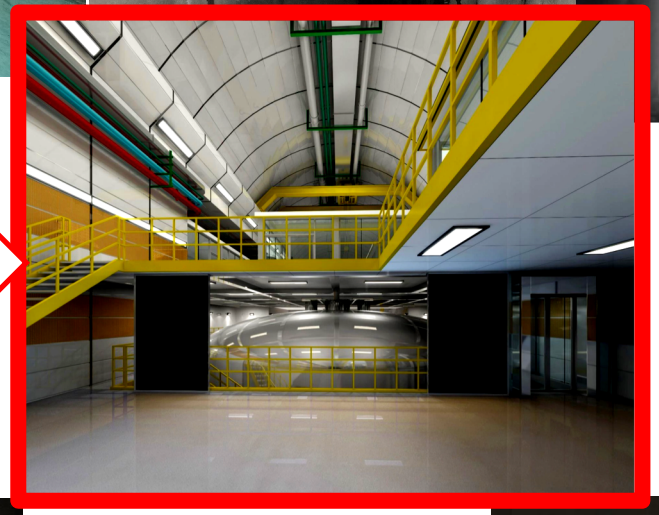
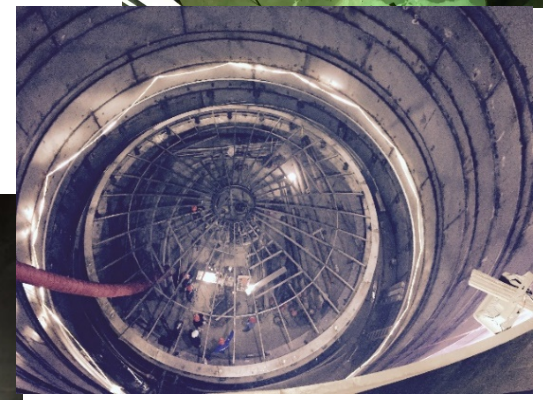
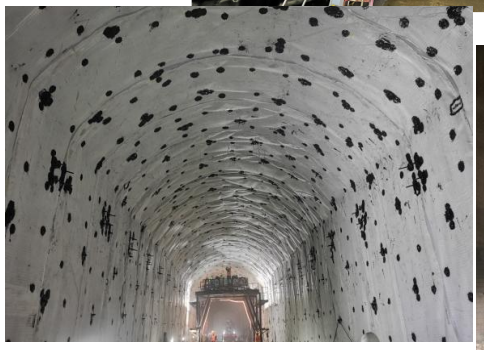


CJPL-II construction journey till now

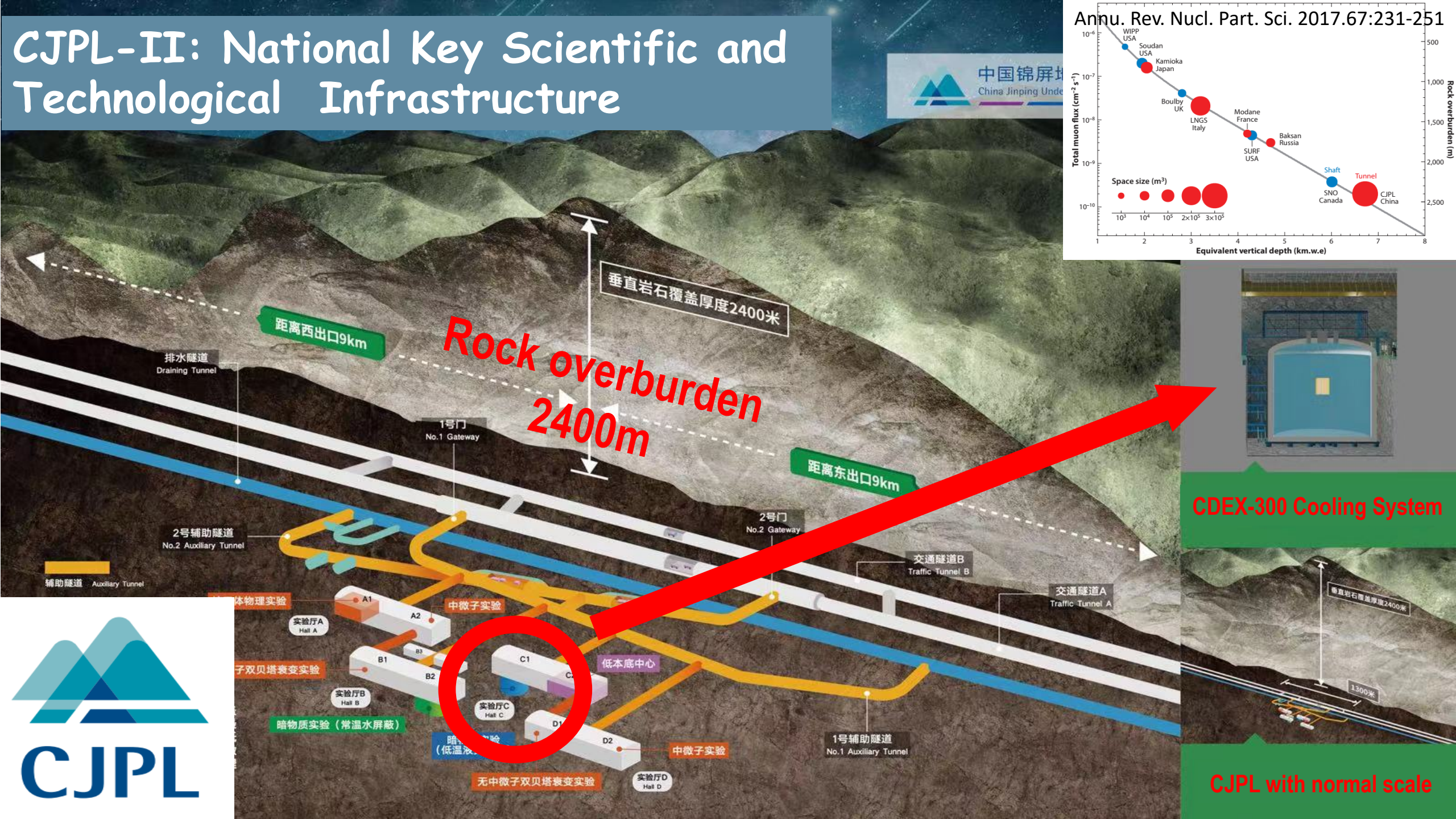
- ✓ Under construction: major infrastructure construction will be completed by the end of 2023.
- ✓ Expected the construction of the laboratory will be completed by the end of 2024


CJPL-II: National Key Scientific and Technological Infrastructure



Annu. Rev. Nucl. Part. Sci. 2017.67:231-251

CDEX-300 Cooling System

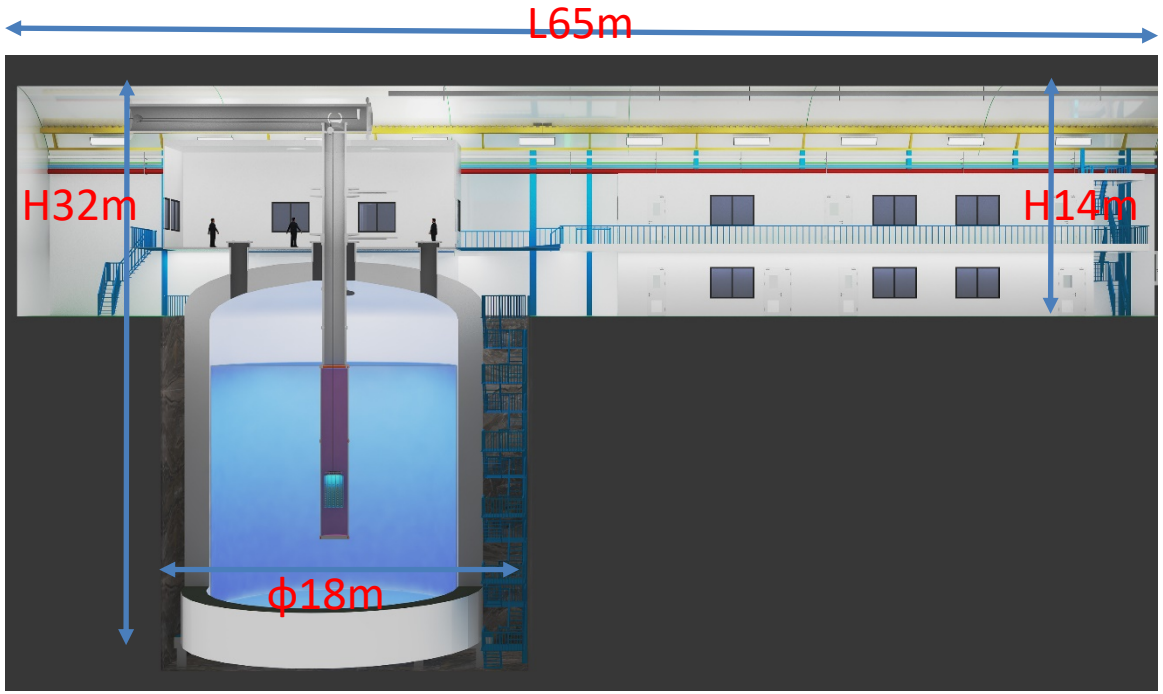
CJPL with normal scale

CJPL

Layout of C-hall at CJPL-II

CDEX

- ✓ A space of **L65m*W14m*H14m** at CJPL-II to be used by CDEX, optimized with **a pit of φ18m** at the end of Hall C1, a space of φ18m*H32m;
- ✓ **Excellent technical support:** electronic power, LN_2, LAr, Radon-free air clean room, screening facilities and **good logistics**.



Background Controls for CDEX-50dm

1. Construction/supporting material (Material screening)

✓ Brass/Aluminum/Lead Holder, cables, electronics

✓ Shield material/LN2 and others

✓ ^{40}K, ^{60}Co, Th and U series

2. Intrinsic contaminations in detectors.

(Ground time exposure control & crystal growing at UL in future)

✓ ^{3}H, beta decay with Q=18.6 keV. (Goal: <0.01 cpkd)

✓ Cosmogenic isotopes: $^{73,74}As$, $^{68,71}Ge$, ^{68}Ga, ^{65}Zn, ^{57}Ni, $^{56,57,58,60}Co$, ^{55}Fe,^{54}Mn,^{49}V

3.Radon mitigation (Screening facility & Surface emanation)

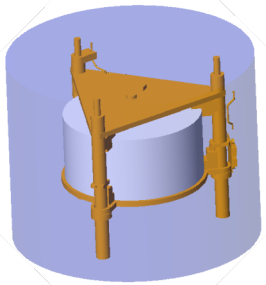
✓ Permeability ; surface of detector/tank (Radon in liquid nitrogen)

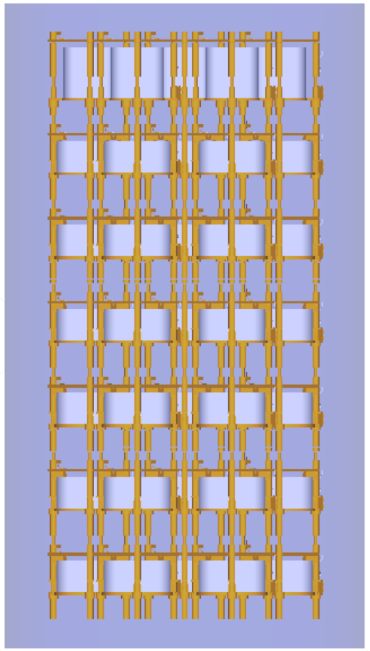
4. On surface of detectors (Detector simulation & test on the bare Ge)

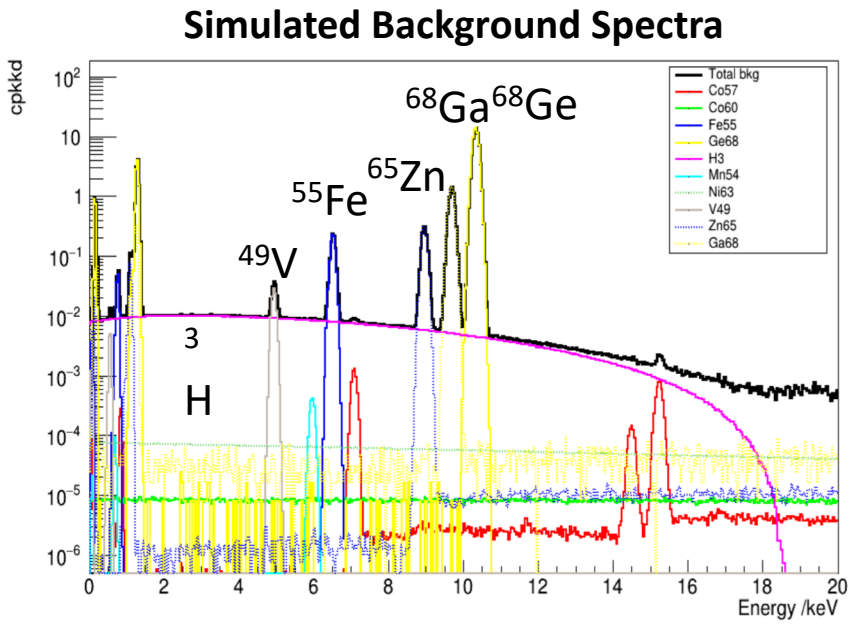
✓ α,β-rays to p-type, VERY Bulk/Bulk/surface differentiation.

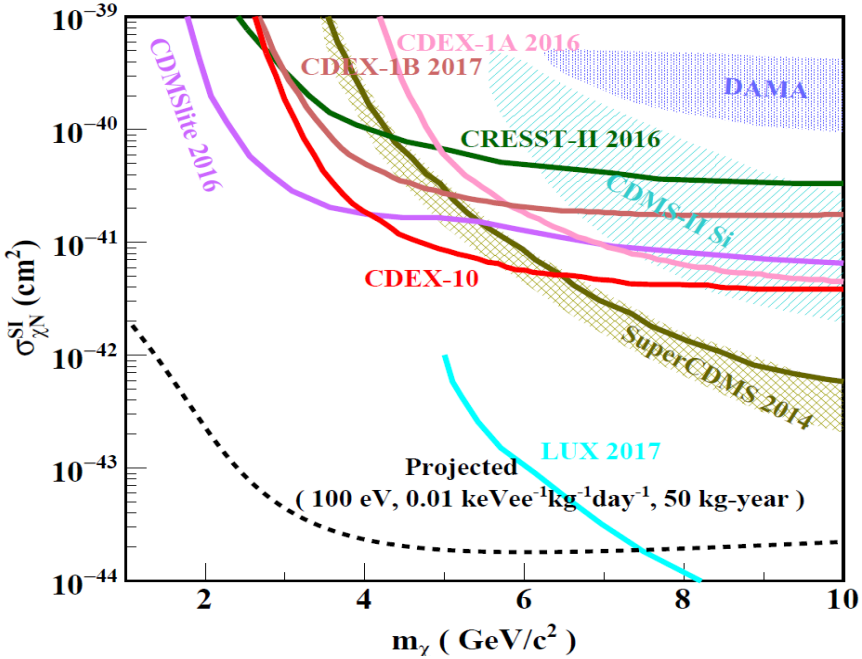
Goal and Sensitivities of CDEX-50dm

- ✓ Energy threshold: ~100eV;
- ✓ Background Level: 0.01 keV (~100 times less then CDEX-10)
- ✓ Next step: Array of 50kg natural germanium detectors in liquid nitrogen, not LAr;
- ✓ The sensitivities of CDEX-50: 10^{-44} cm^2 level @ 4-8GeV WIMP mass.









Outlook & Prospects

CDEX

- DM search: Missing Mass Density & GR Problem is the most intriguing & important one in basic science.
- Compelling evidence of Dark Matter existence inspires the searches of New Physics in particle physics. WIMPs, Axions, Dark Photons... are popular/motivated candidates. Other alternatives could be new favorite?
- CDEX has involved and made a diverse & significant contributions to the Ge technology/science community: Mass production of ^{76}Ge isotope material and Ge detectors; ASIC-PreAMP-Ge detectors; Large underground space at the deepest CJPL; Underground Ge crystal growth and detector fabrication for cosmogenic background control.
- The new Facilities AND Communities add to the world's arsenal on exciting dark matter & neutrino experiments requiring deep locations. Open to International collaboration.

CDEX

Thank you for listening.

CDEX

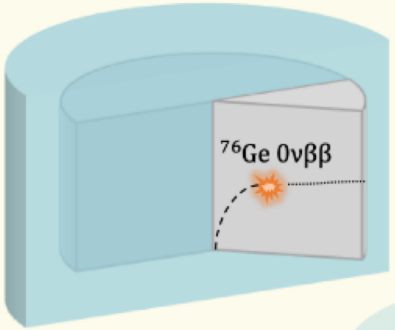
Backup

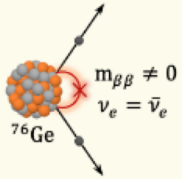
CDEX-300v Program (Enriched-Ge Array)

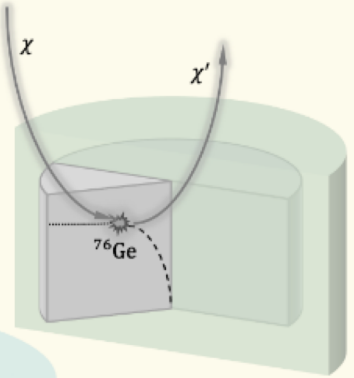
CDEX

Neutrinoless double beta decay (0νββ)

- Neutrino mass
- Majorana / Dirac nature of neutrino
- Lepton number violation

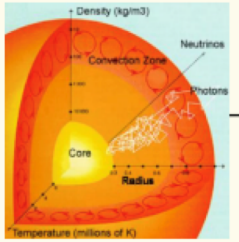






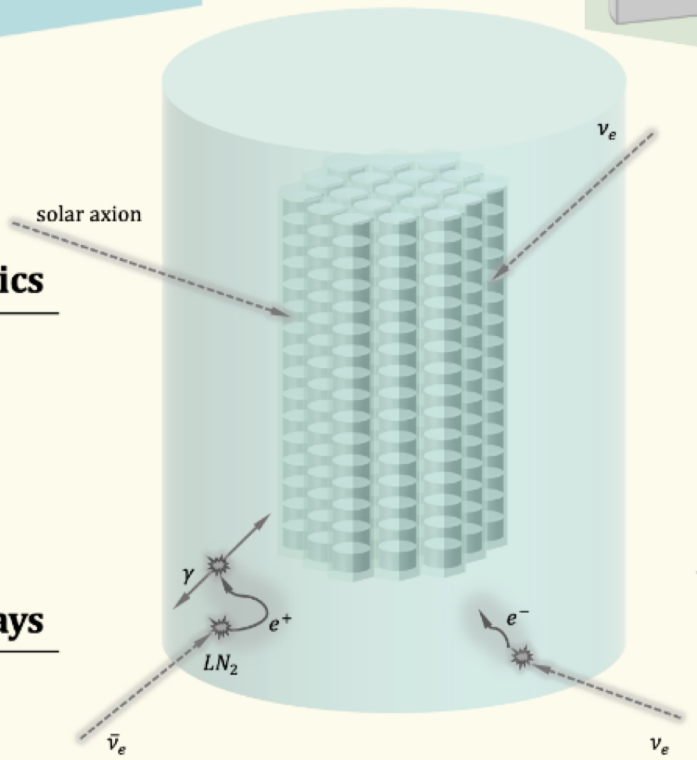
Dark Matter

- WIMPs dark matter
  - Spin-dependent
  - Spin-independent
  - Annual modulation
- Dark photons
- Axion dark matter



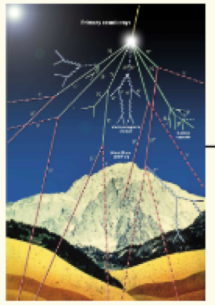
Solar physics

- Solar dark photons
- Solar pp/^{8}B neutrino
- Solar axions



Rare event search

- Electron decay ($e^- \rightarrow 3\nu$)
- Pauli exclusion principle violation transition

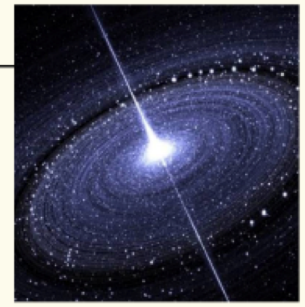


Cosmic Rays

- Atmospheric neutrino

Supernova

- Supernova neutrino
- Multi-messenger



HPGe Technology---Enriched ^{76}Ge Material Supply

CDEX

- 200kg ^{76}Ge (>86%) stored at CJPL, half from Russia and half from China.
- CDEX has the largest amount of $^{76}GeO_2$ powder in hand now in the world.
- The mass production power (Hundreds of kg each year) of enriched ^{76}Ge material has been setup in China and it is a crucial contribution to the International ^{76}Ge Ovββ experiment community.