Scientific Prospects and Technical Innovations in the CDEX-50 Experiment

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On behalf of the CDEX collaboration

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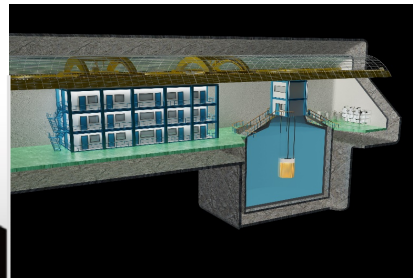


Outline

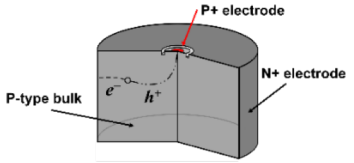
CDEX

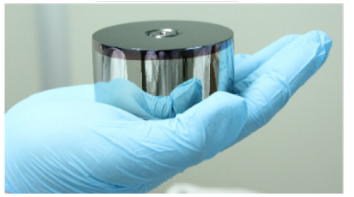
- ✓ CDEX collaboration/program
- ✓ Recent results from CDEX-1 & CDEX-10 @CJPL-I
- ✓ Advancing key Ge technologies: R&D and Background Reduction
- ✓ Current status of CDEX-50 Experiment@CJPL-II
- ✓ Summary & prospects

China Dark matter Experiment

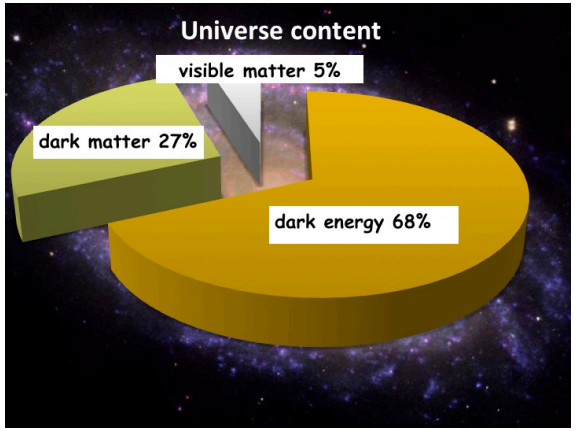
- ✓ Established in 2009, 11 institutes, ~100 members.
- ✓ DM and 0νββ experiment based on Ge detectors at CJPL.
- ✓ Many DM & Neutrino physics results published in last 10 years.

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

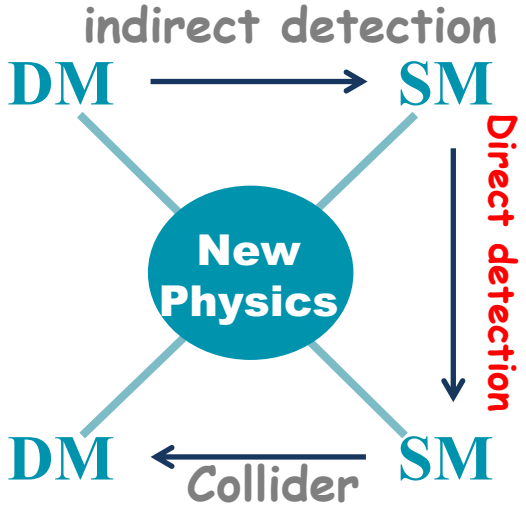




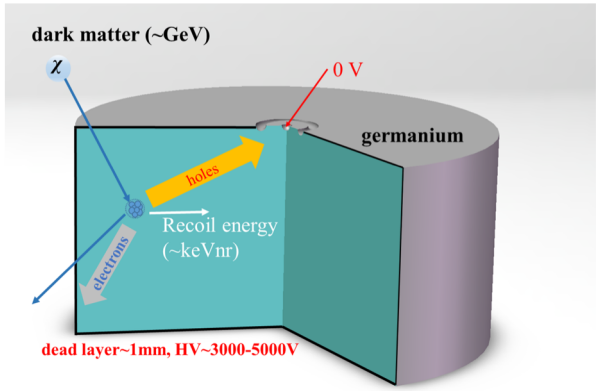
Direct detection in dark matter searches

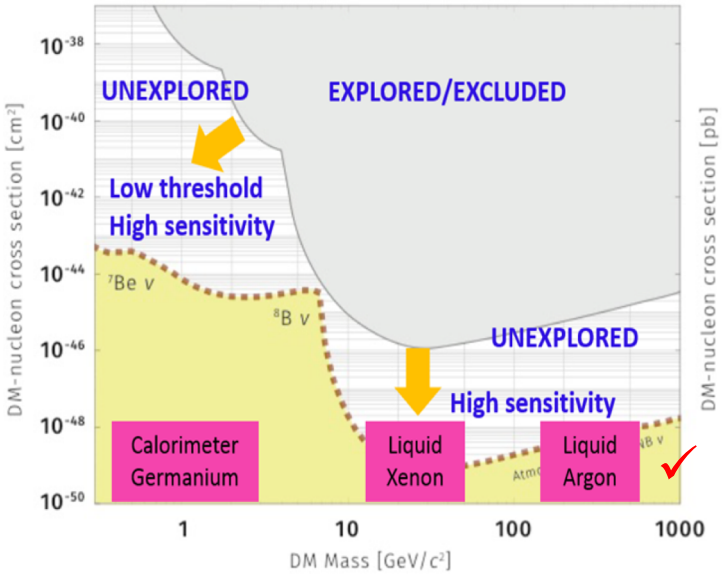


We know only 5% of what the universe made of?



A picture for IF DM is a particle, unitality invariant, …





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

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

✓ Toward the unexplored lower mass region…

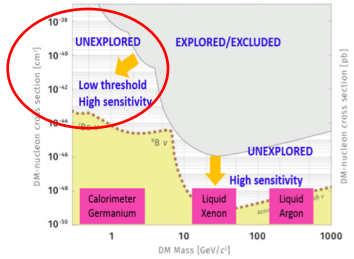
Conventional WIMPs and other alternatives

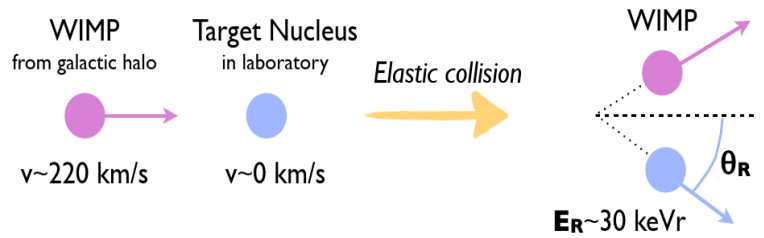
CDEX

Astrophysics Particle physics

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

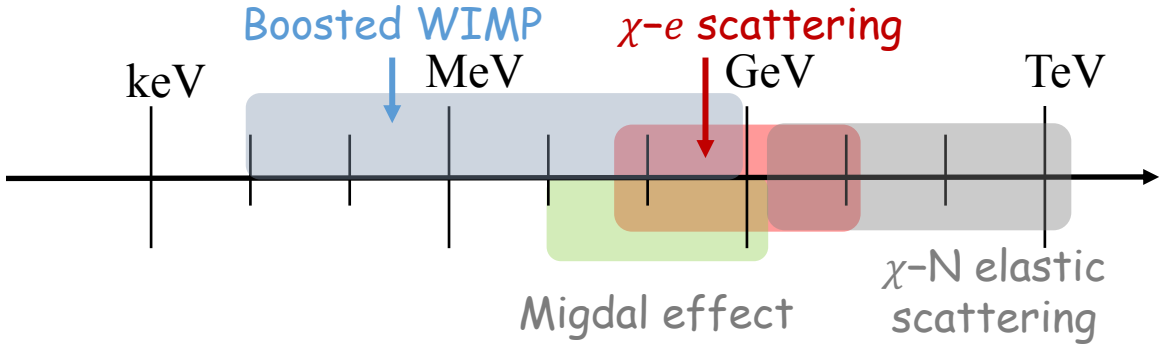
Detector response





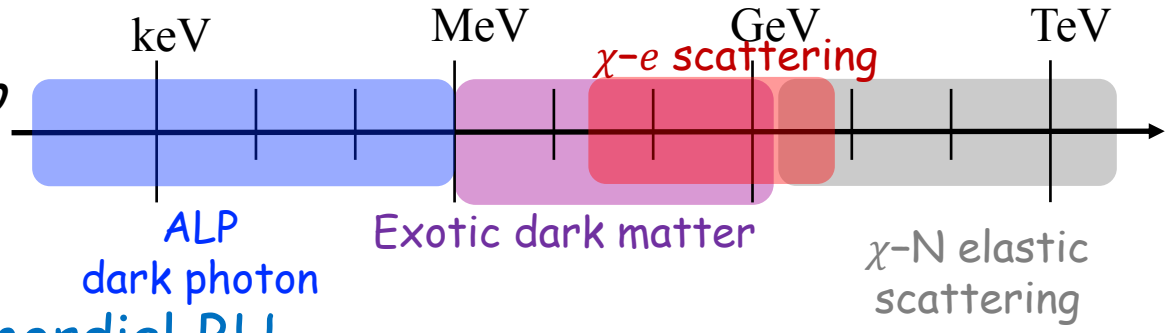
WIMP search

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



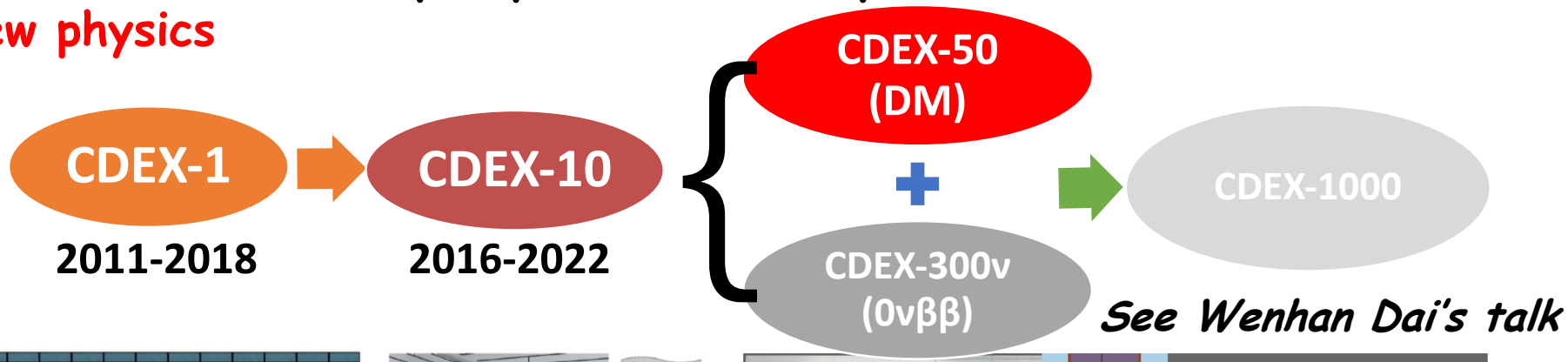
New physics beyond the WIMPs

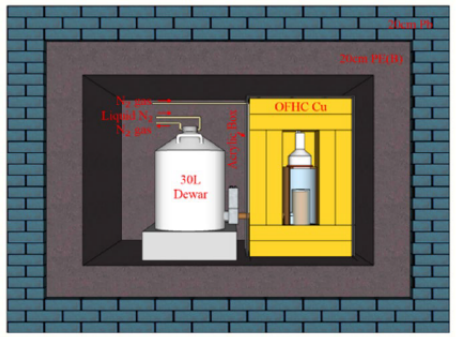
- Axion like particle: down to $\mathcal{O}(100\,\mathrm{eV})$ *PRD 2020*
- Dark photon: down to $\mathcal{O}(100\,\mathrm{eV})$ *PRL 2020*
- Exotic DM: down to $\mathcal{O}(1\,\mathrm{MeV})$ *PRL 2022*
- Boosted keV-MeV DM from evaporating primordial BH. *PRD 2023*



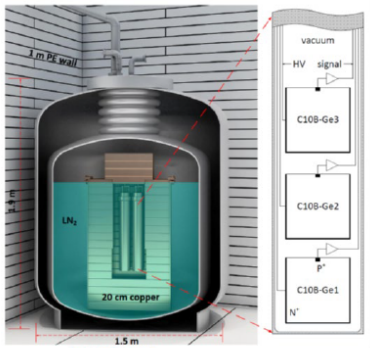
CDEX Roadmap

- ✓ 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 (2021-202x): An array of 50 kg Ge detectors in cryogenic liquid for DM searches [Energy region of interest: O(100 eV)]
- ✓ CDEX-300v (2021-202x): 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

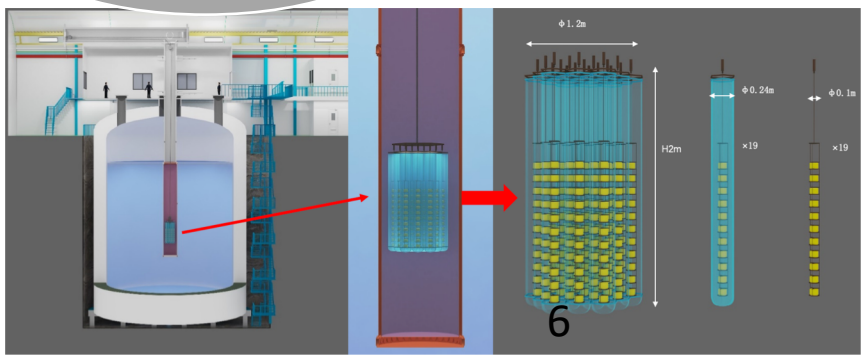




CDEX-1A&B: 1kg PPC Ge×2



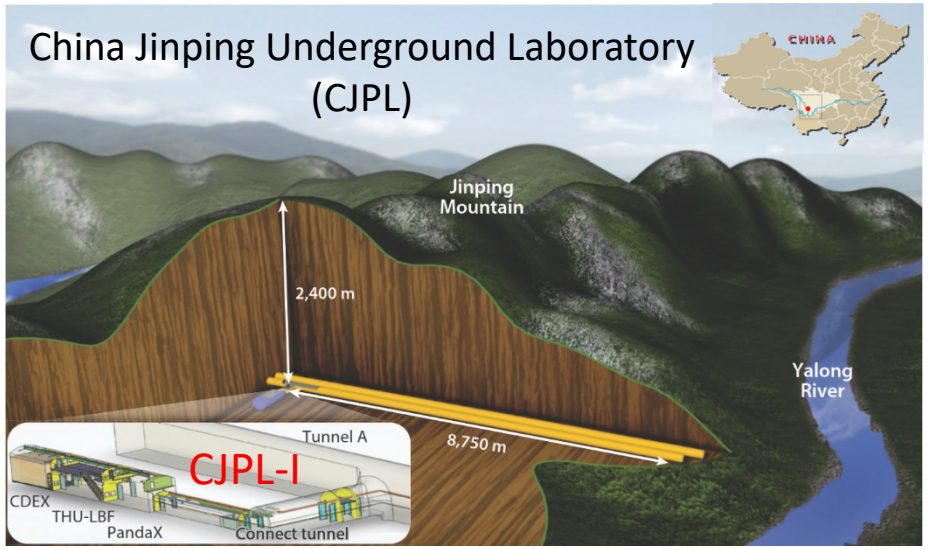
CDEX-10: ~10kg PPC Ge array



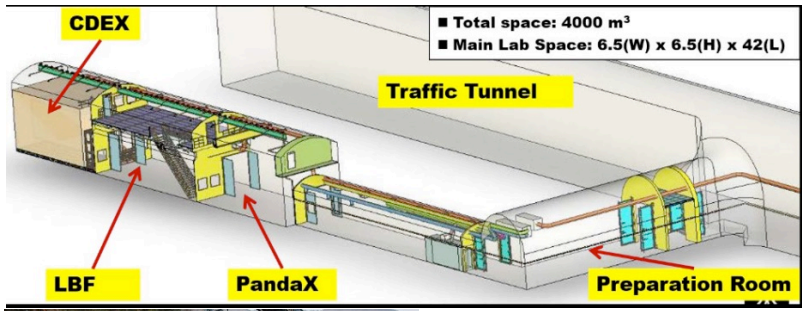
China Jinping Underground Laboratory(CJPL)

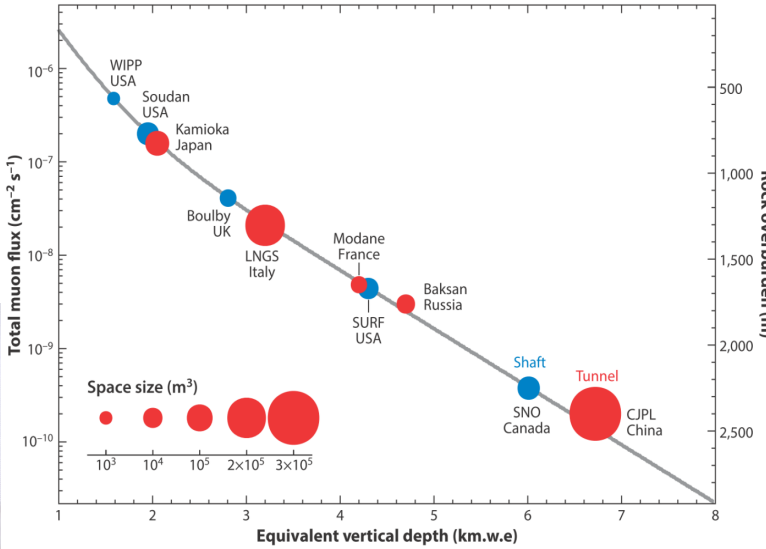
CDEX

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



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

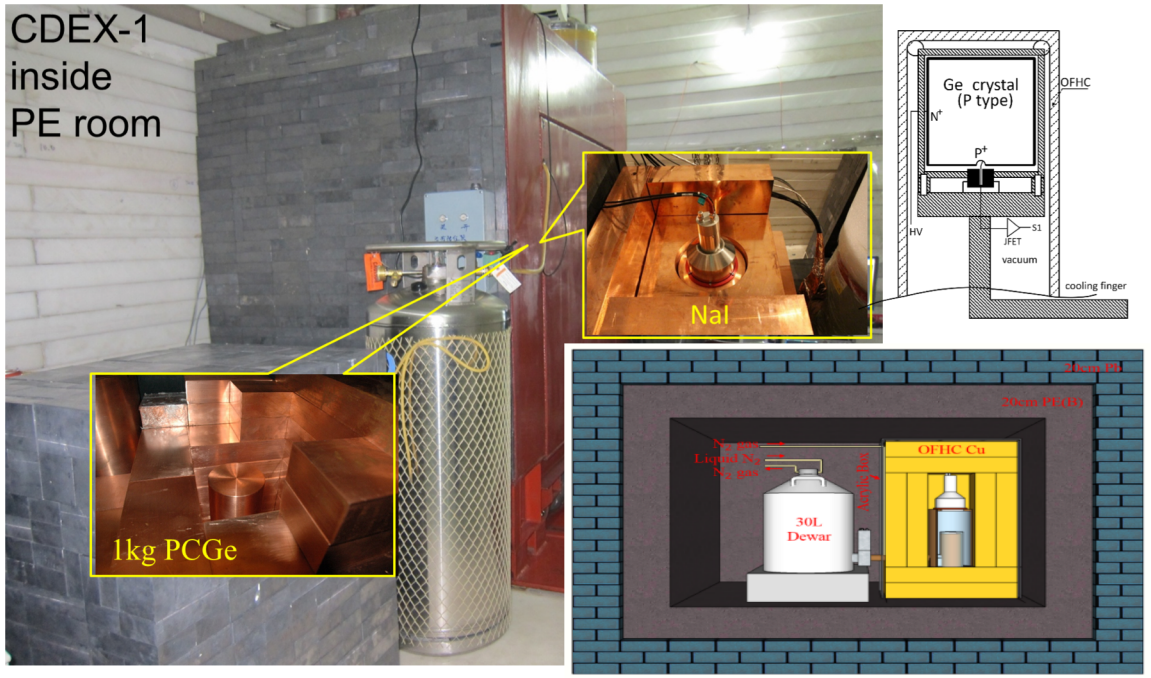




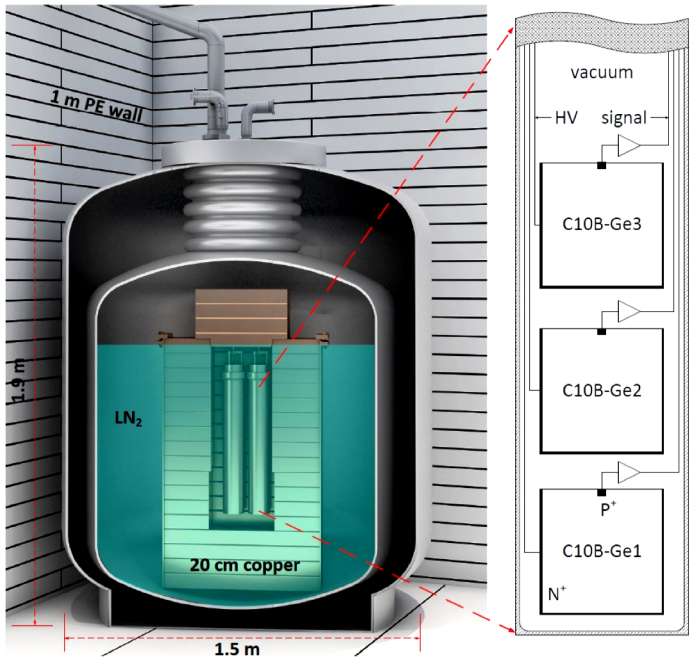
CDEX-1, CDEX-10 Experiments

CDEX

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



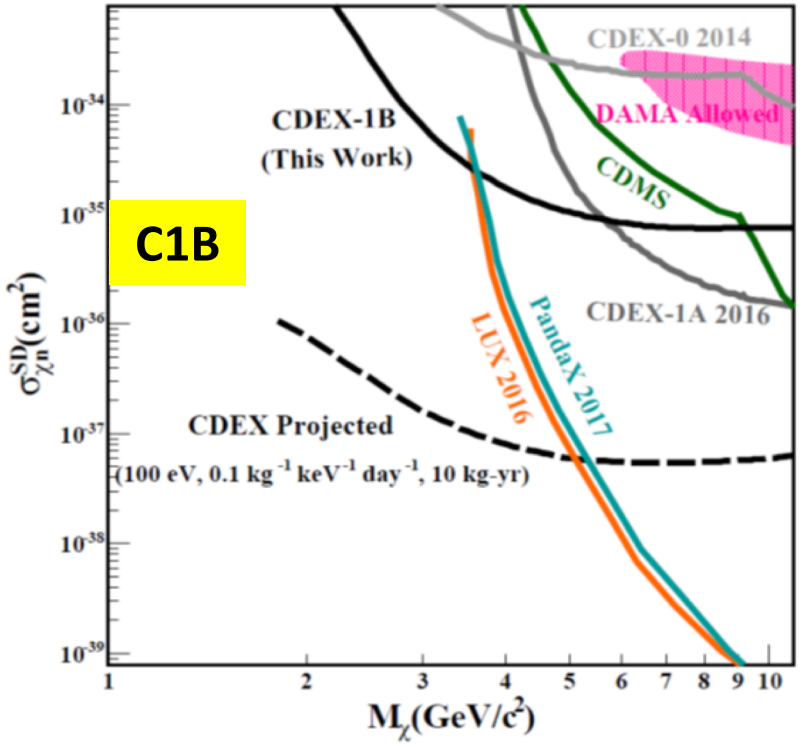
- ✓ Array detectors: 3 strings with 3 detectors each, ~10 kg total;
- ✓ An array immersed directly in LN_2;
- ✓ Prototype system for future hundred-kg to ton scale experiment
  - Light/radio-purer LN_2 replacing heavy shield i.e. Pb/Cu;
  - Arraying technology to scalable capability;

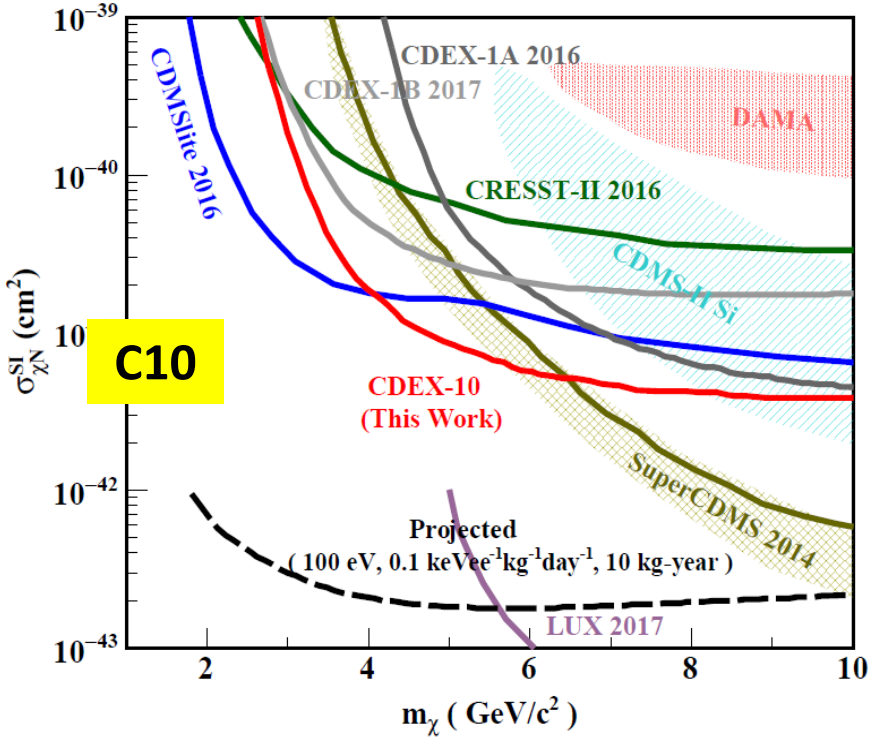


$\chi - N$ elastic scattering results from CDEX-1B &10

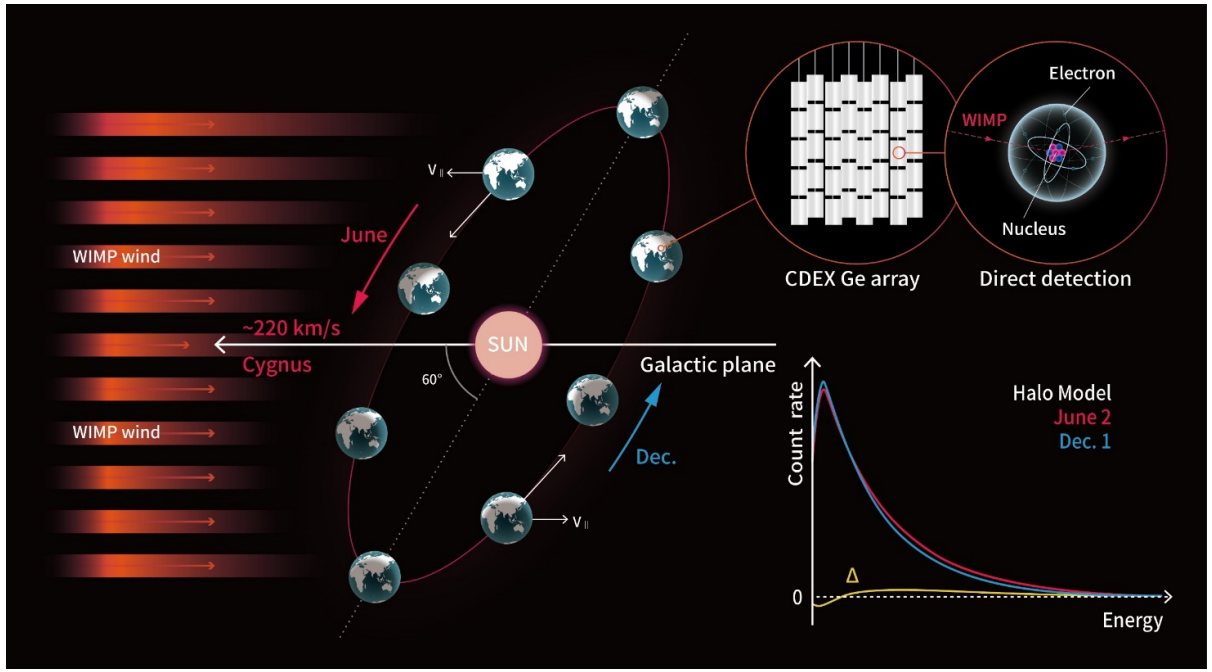
CDEX

- CDEX-1B: ➢ Threshold of 160 eV is achieved.
  - ✓ First extended the mass to 2 GeV/c^2 in Ge-based experiments.
  - ✓ The most sensitive results on SD $\chi - N$ elastic scattering below 4 GeV
- CDEX-10: ➢ No event exceeds the expected background level near the threshold.
  - ✓ The leading bounds on SI $\chi - N$ elastic scattering at 4-5 GeV

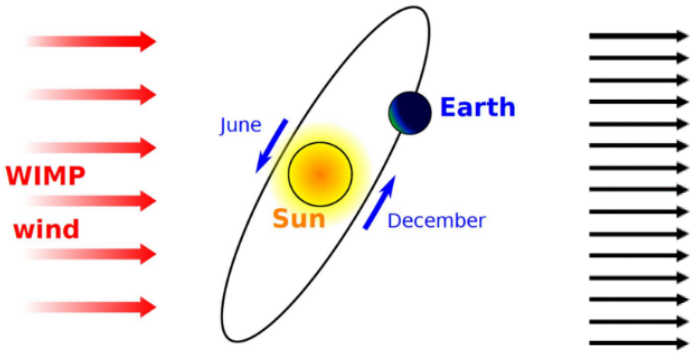


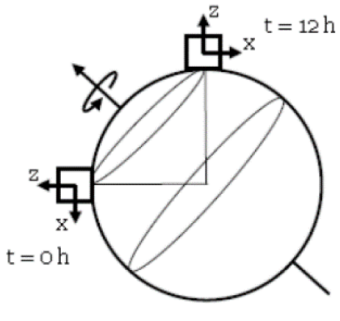


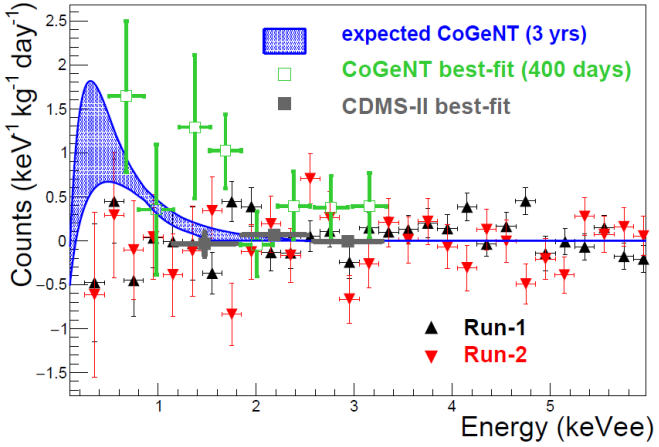
Annual Modulation WIMPs Searches from CDEX-1B

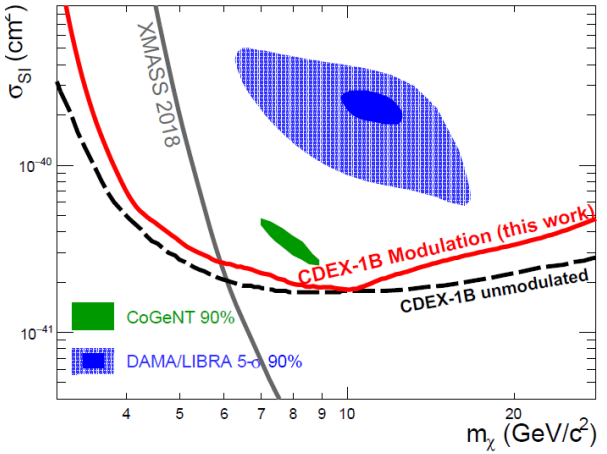


- ✓ Long-time stability with low background & low energy threshold.
- ✓ Explore the new AM detection channel below the mass of 6 GeV/c^2





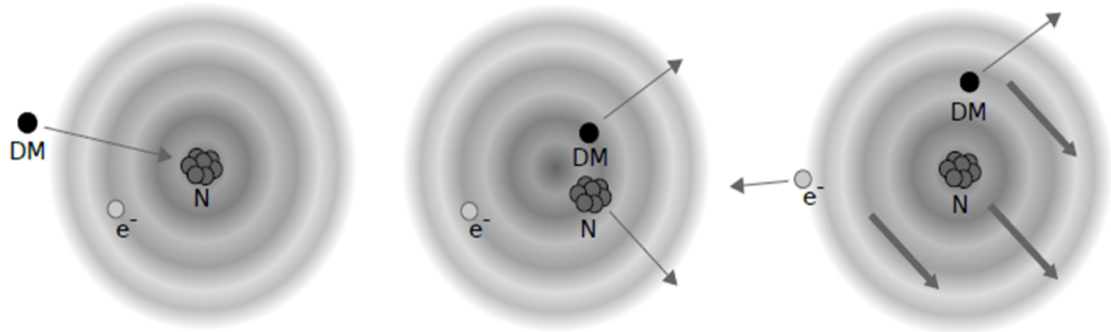




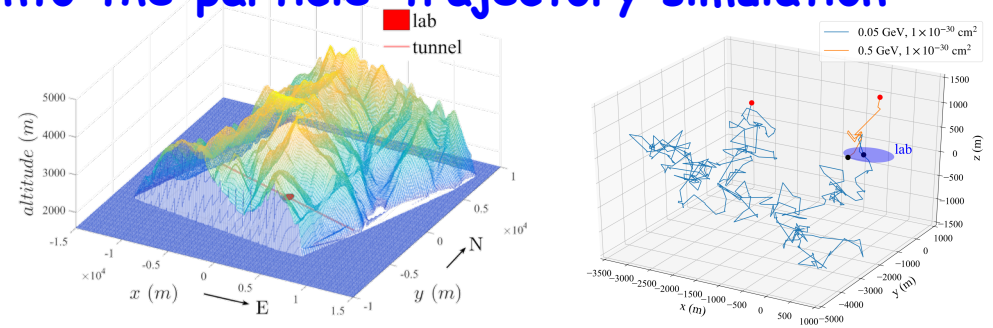
Light WIMP searches with Migdal Effect

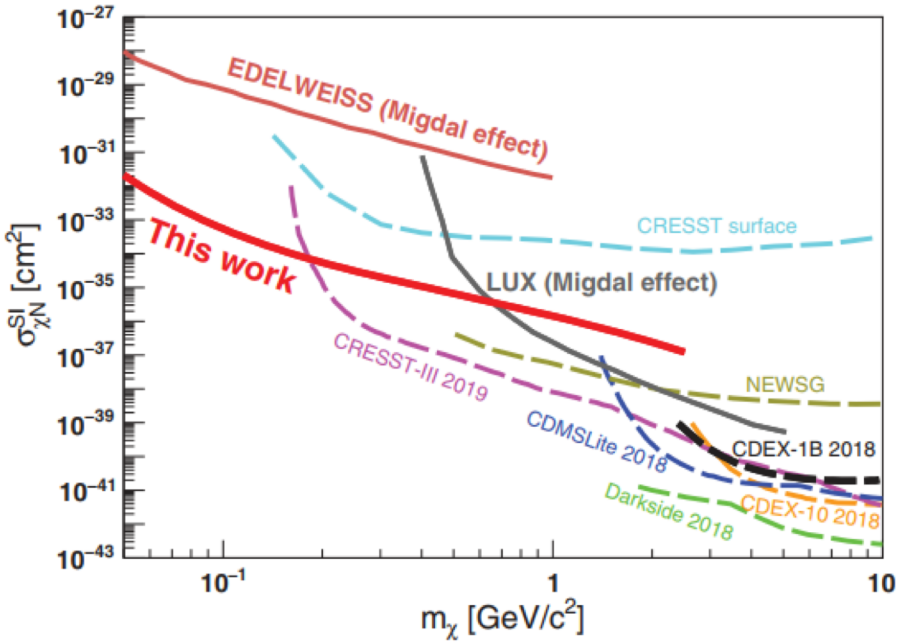
CDEX

- ✓ 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.



ME with Earth's effects are integrated into the particle-trajectory simulation





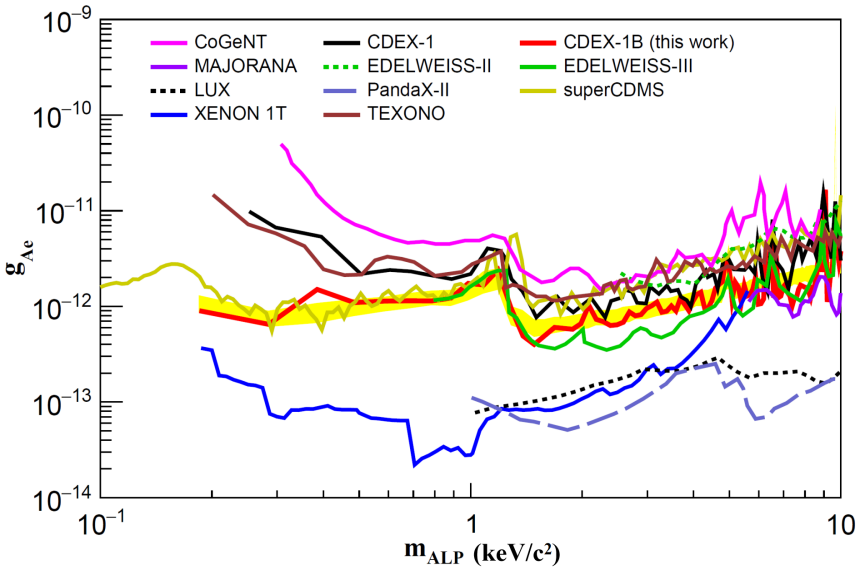
Best results at 50-180 MeV region for light WIMPs searches.

Solar Axion & ALP results

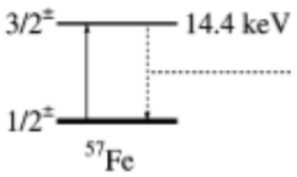
CDEX

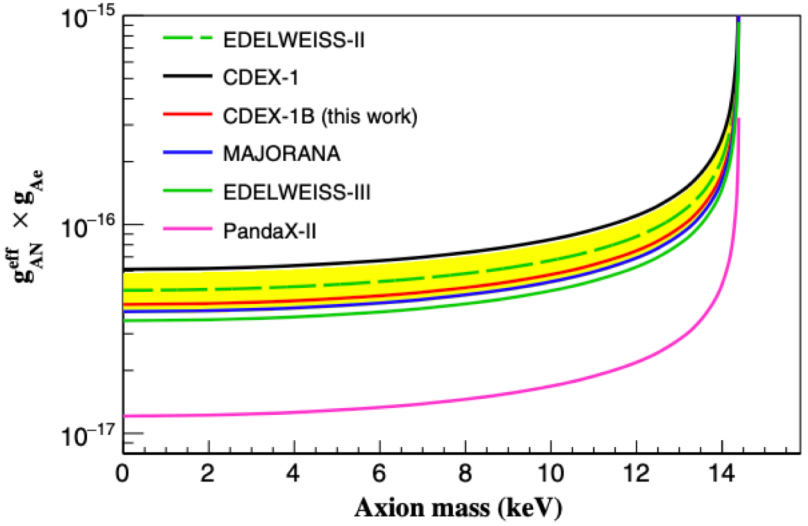
- ✓Background assumption:
  - Continuous background + X-rays
- ✓Profile likelihood method
- ✓Excellent energy resolution of Ge is suited for the monochromatic DM axion and Fe-57 axions
- ✓ Competitive g_{Ae} constraints exist for m_a: 100eV ~ 1keV

ALP dark matter

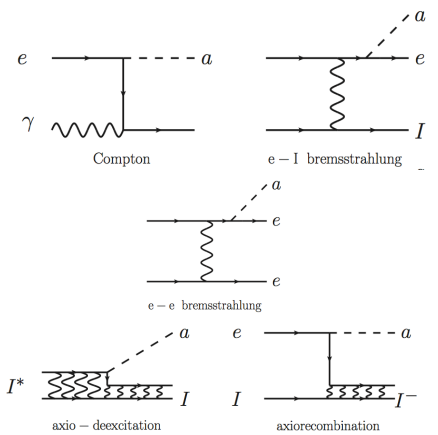


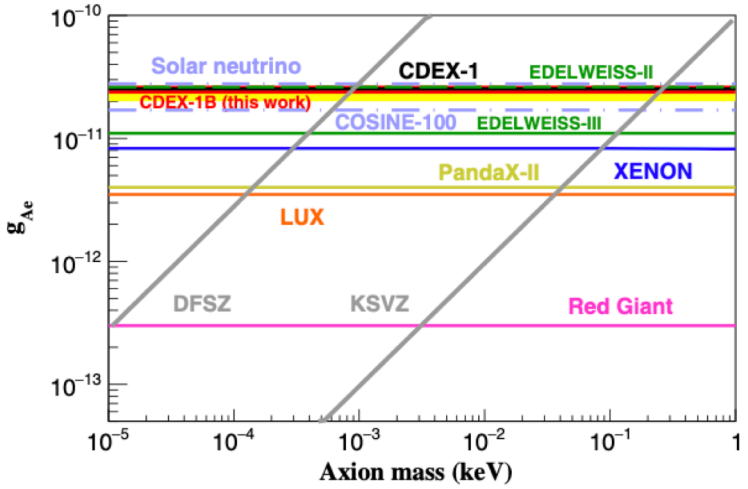
Fe-57 solar axion





CBRD Solar axion





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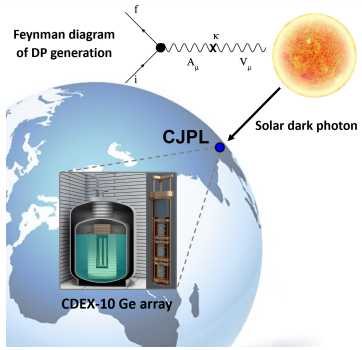
Solar dark photon & DPDM results

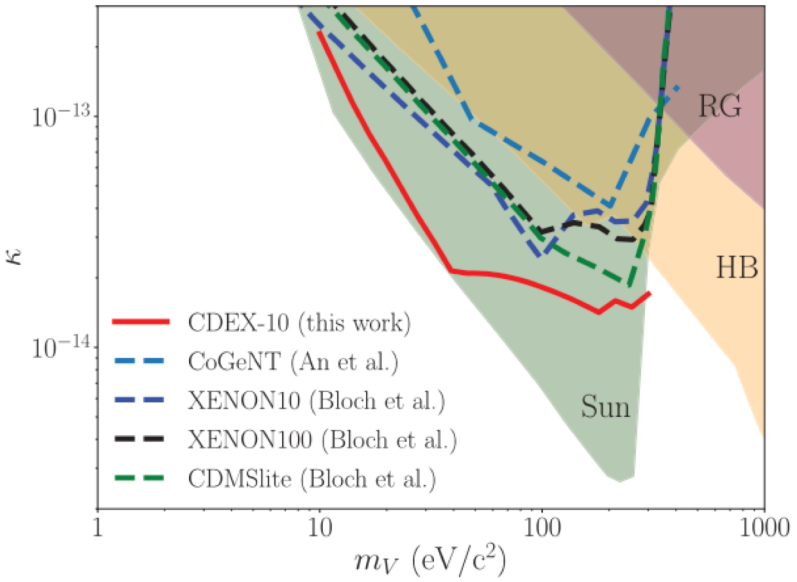
CDEX

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

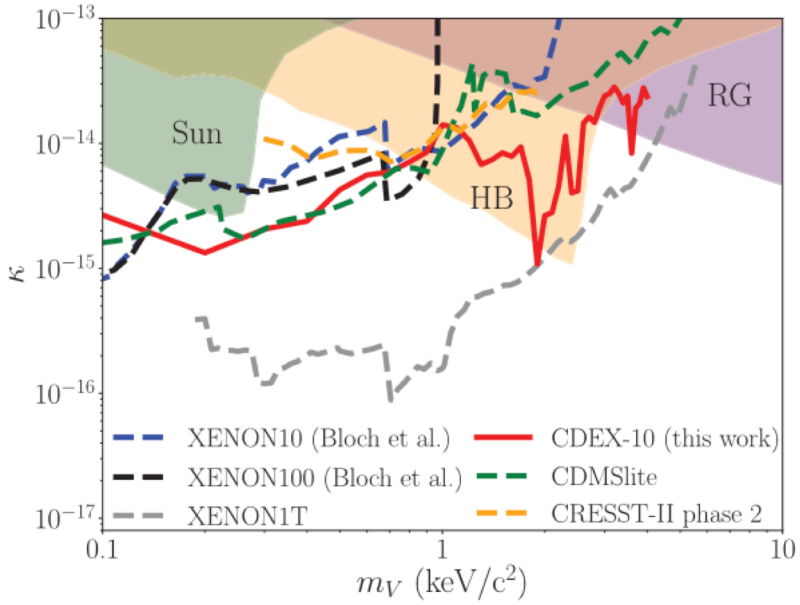
$$\frac{dR}{dE} = V\frac{E}{|\vec{q}|}\left(\frac{d\phi_T}{dE}\Gamma_T + \frac{d\phi_L}{dE}\Gamma_L\right)$$



- 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



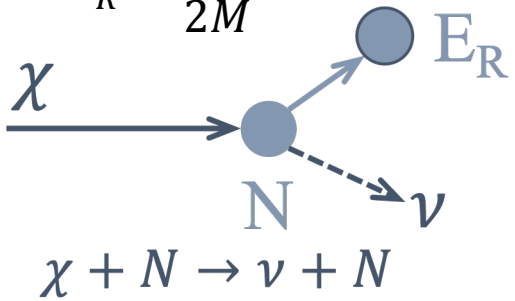
Exotic DM results

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

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

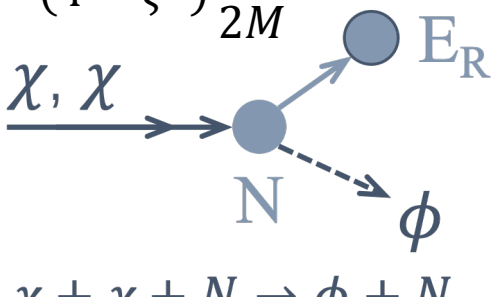
DM-nucleus 3->2 scattering: $\chi + \chi + N \rightarrow \phi + N$ [2]

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

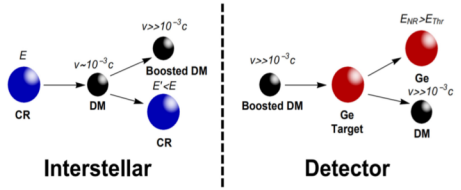


$\chi + N \rightarrow \nu + N$

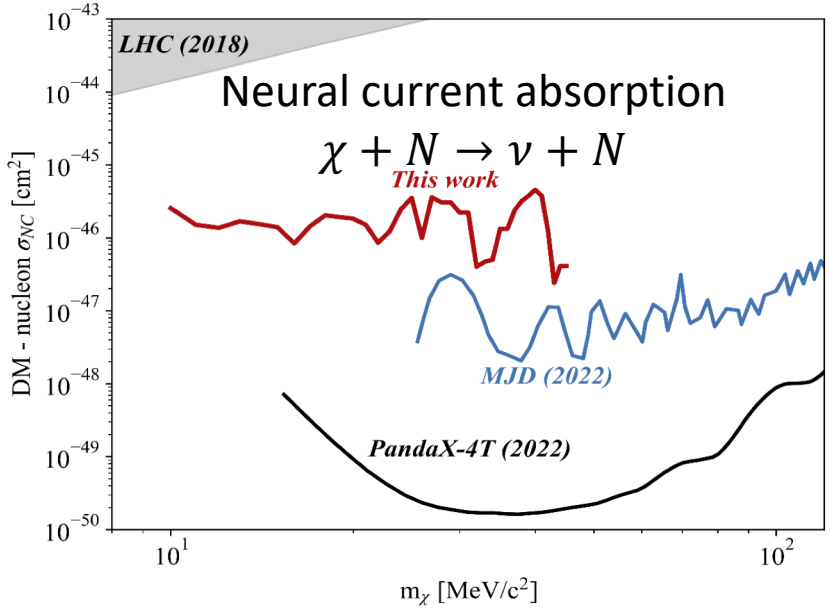
$$E_R = (4 - \xi^2)\frac{m_\chi^2}{2M}$$

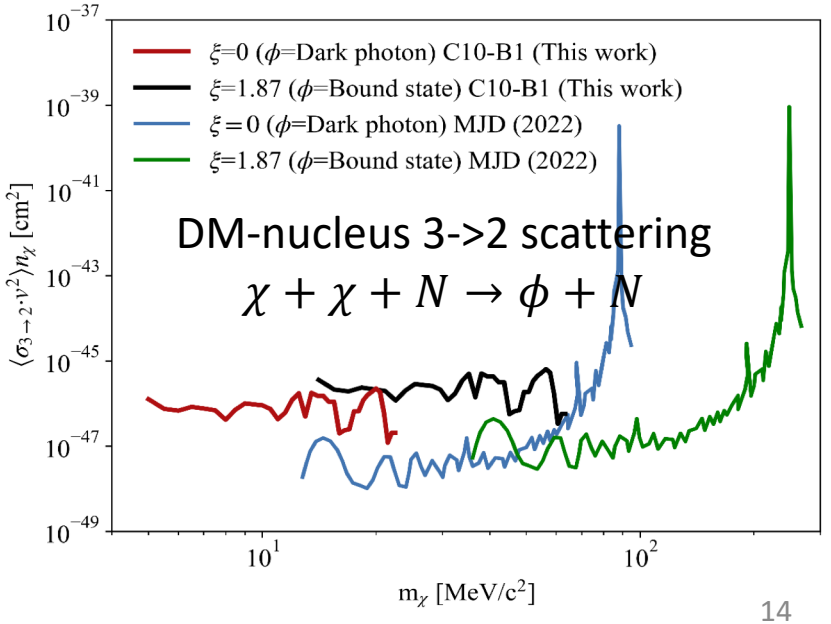


$\chi + \chi + N \rightarrow \phi + N$



- ✓ 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.





$\chi - e$ scattering

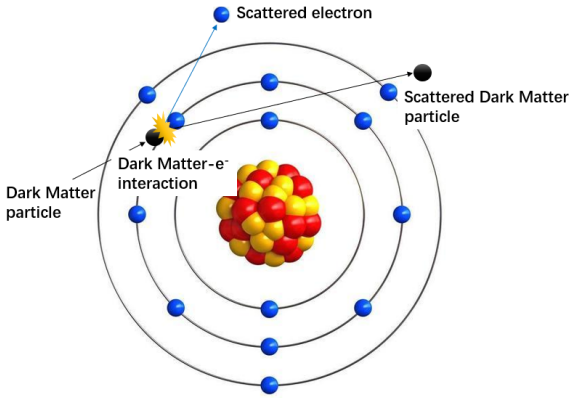
- ✓ Light χ can potentially pass most of the energy onto electrons, depositing observable energy via $\chi - e$ scattering
- ✓ A DM-electron scattering paradigm proves to be successful extend m_χ to $\mathcal{O}(10\ MeV)$
- ✓ The total rate can be written as

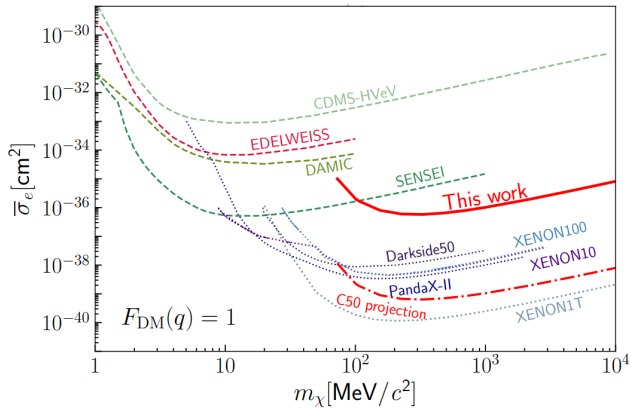
$$R_{i\to f} = \frac{2\pi\bar{\sigma}_e}{V\mu_{\chi e}^2 m_\chi}\frac{\rho_\chi}{\rho_T}.$$

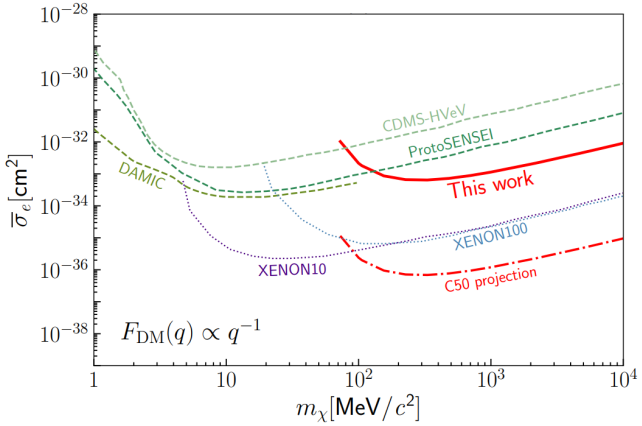
$$\sum_{i,f}\int \frac{\mathrm{d}^3q}{(2\pi)^3}\left(\frac{f_e}{f_e^0}\right)^2 F_{\mathrm{DM}}^2 g(\mathbf{q},\omega)\left|f_{i\to f}(\mathbf{q})\right|^2,$$

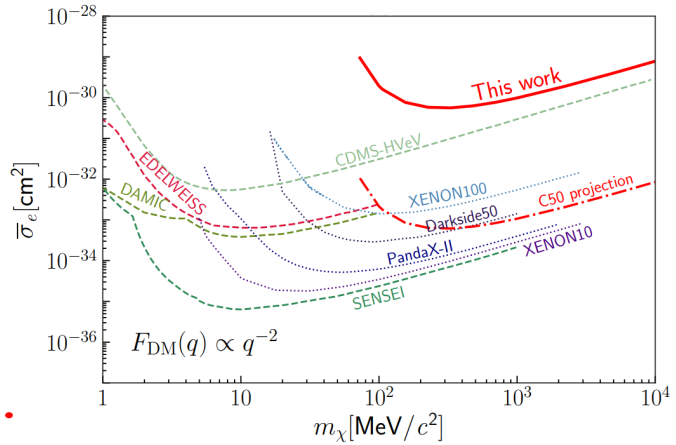
dark matter form factor
1: heavy mediator
q_0/q: electric dipole coupling
$(q_0/q)^2$: ultralight mediator

Crystal form factor





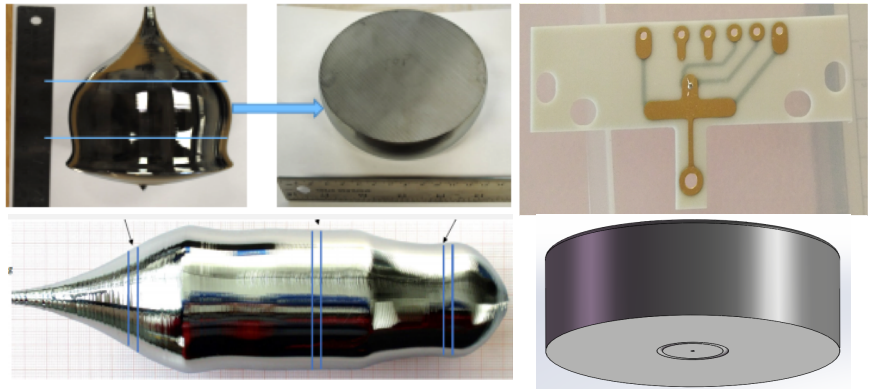


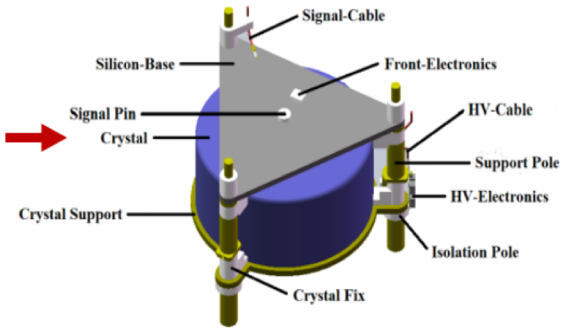


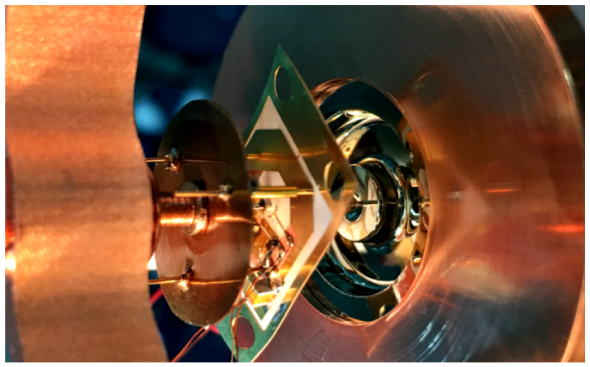
➢ Ge crystal: incorporated by the effects of Semiconductor & Atoms.

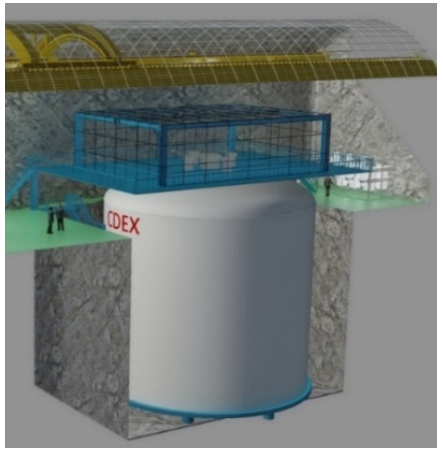
R&D on Key Ge Technologies to the CDEX's goals

- **Ge detector fabrication :** Various types, P-type planar/coaxial, P-type point-contact/BEGe/ICPC successfully fabricated. Two batches of commercial enriched Ge detector arrived in CJPL, 22 det. in total.
- **Ge crystal growth :** Developing technology ; 200kg ^{76}Ge (>86%) arrived, half from Russia and half from China, where the shield tunneling technique has been employed for surface transportation.
- **ULB-VFE(Very Front End) ASIC + Bare Ge immersed in LN_2 cryostat :** ENC ~10 e-; silicon substrate (U/TH < 60 μBq/kg)
- **Low counting facilities in underground:** U/Th analysis by ICP-MS, blank sensitivity ~10^{-13}g/g ; Electro-form Copper technology is built.
- **R&D on LAr/SAr/(LN with scintillating) detectors**



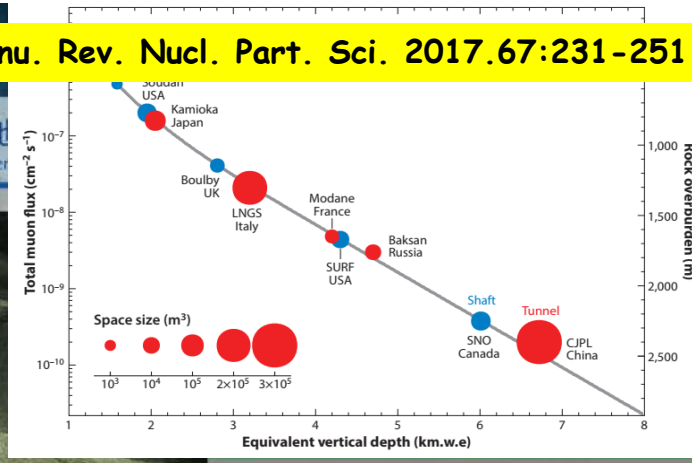






CJPL-II: National Key Scientific and Technological Infrastructure

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



垂直岩石覆盖厚度2400米

Rock overburden 2400m

距离西出口9km

距离东出口9km

排水隧道 Draining Tunnel

1号门 No.1 Gateway

2号门 No.2 Gateway

2号辅助隧道 No.2 Auxiliary Tunnel

交通隧道B Traffic Tunnel B

交通隧道A Traffic Tunnel A

1号辅助隧道 No.1 Auxiliary Tunnel

中微子实验

低本底中心

实验厅C Hall C

实验厅D Hall D

无中微子双贝塔衰变实验

Cryogenic System for CDEX50, CDEX-300v

Nature, Jan. 22, 2024

nature

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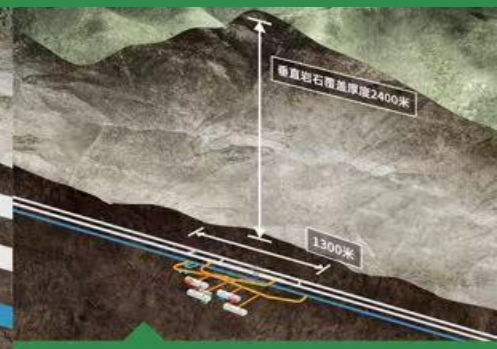
NEWS | 22 January 2024

China's new dark-matter lab is biggest and deepest yet

The laboratory is scaling up its equipment to hunt for dark matter.

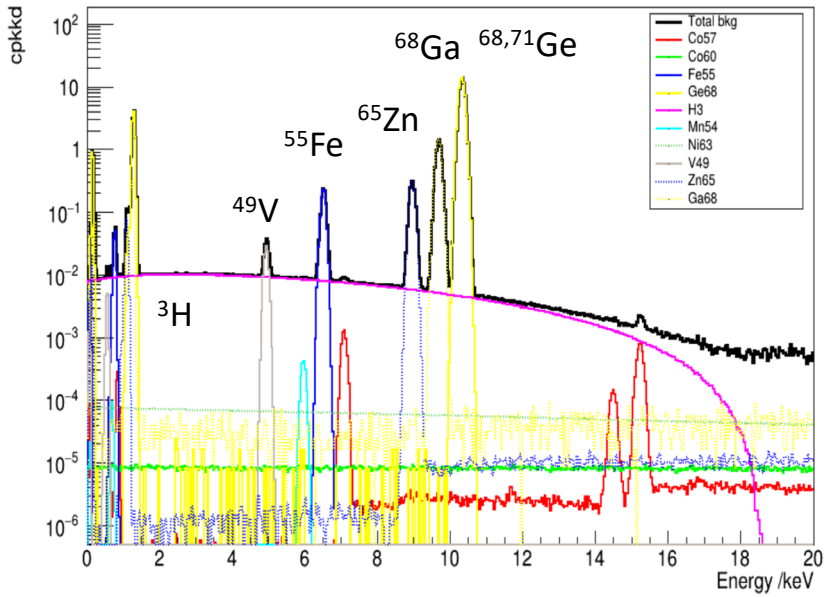


CJPL with normal scale

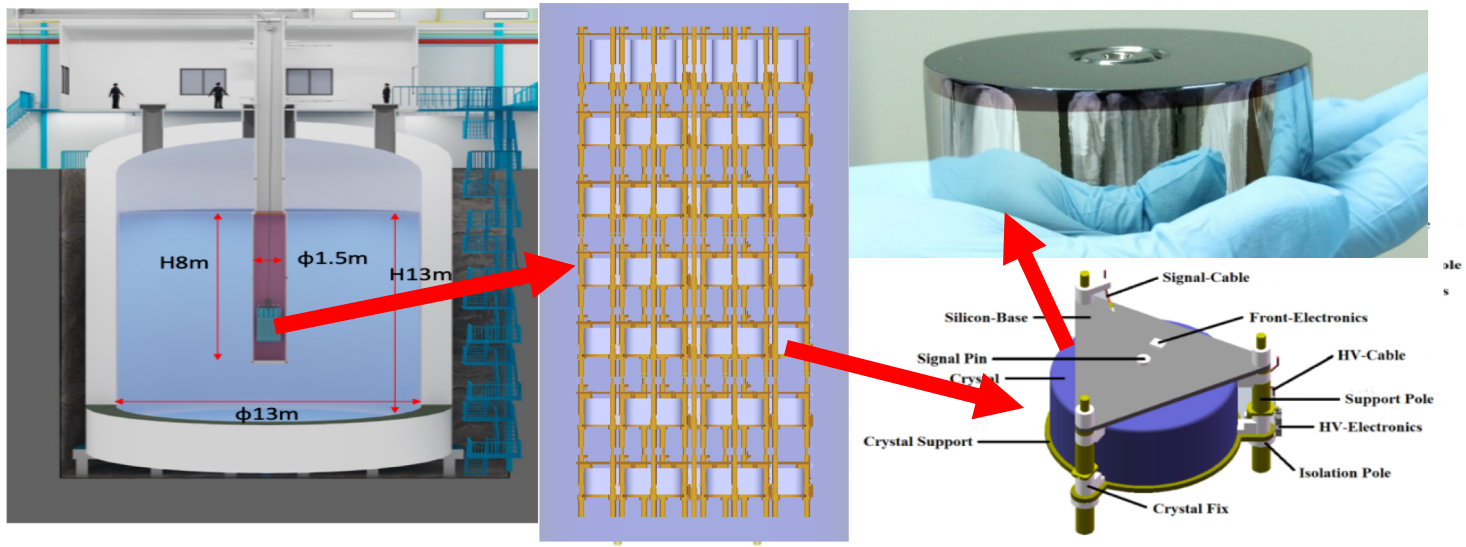
CDEX-50 Experiment

- ✓ Technical Indicators
- Background: <0.01 cts/(keV·kg·day) during 2-4 keV;
- Energy analysis threshold : 160 eV;
- Exposure volume : 50 kg·year;
- ➢ ^{3}H cosmogenic radionuclides in crystal's dominate background

Simulated Background Spectra

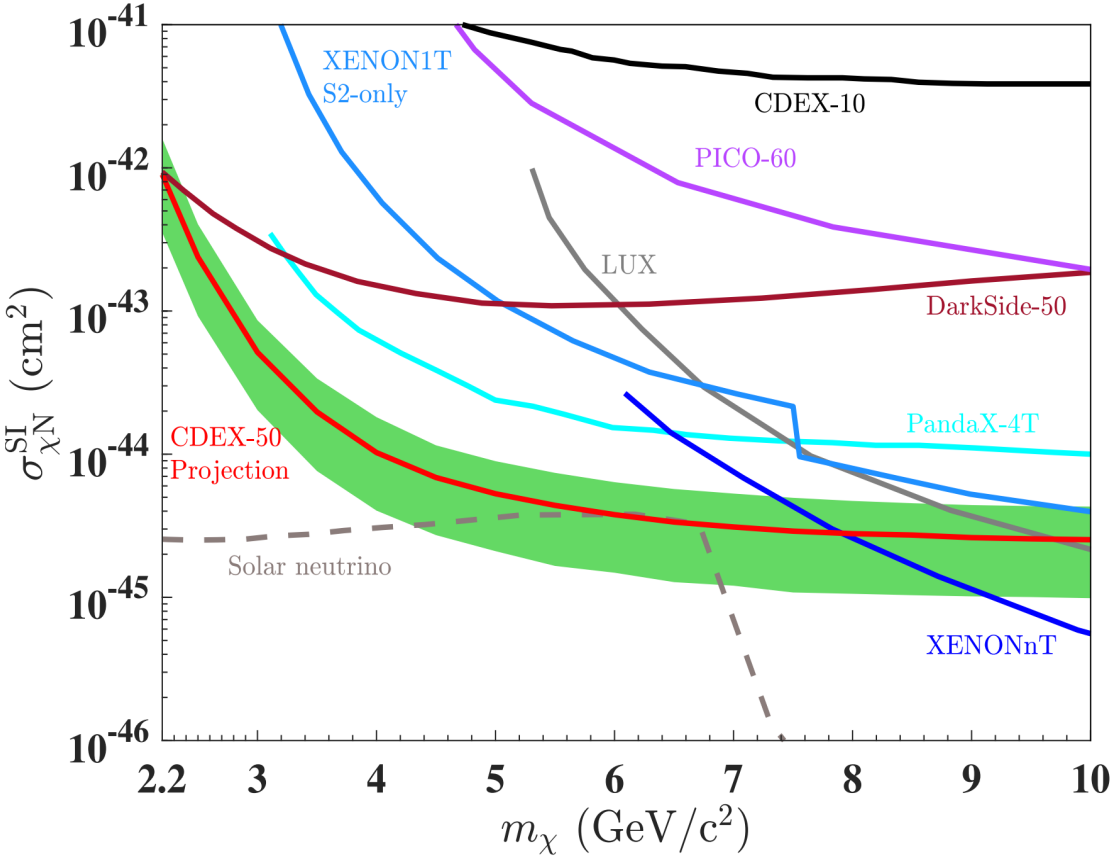


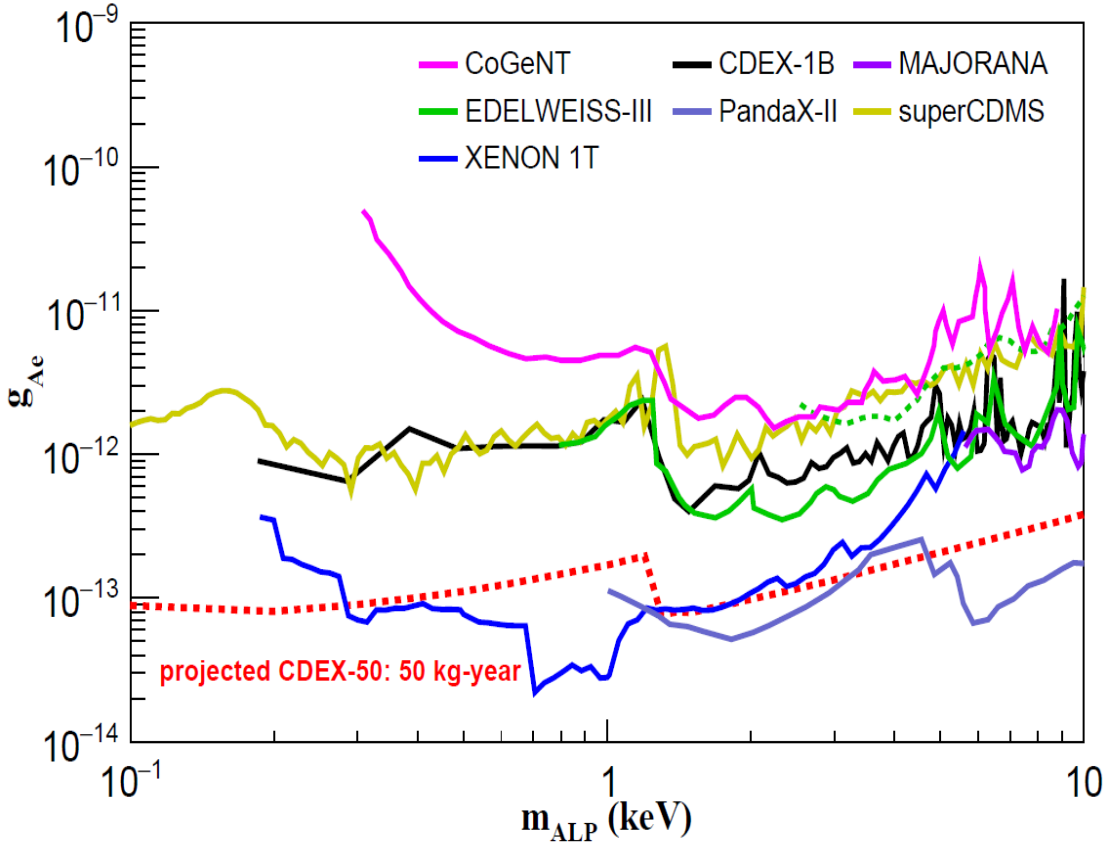
- ✓ Experimental setup: Array of 50 kg natural germanium detectors in liquid nitrogen



Projected sensitivities of CDEX-50 experiment

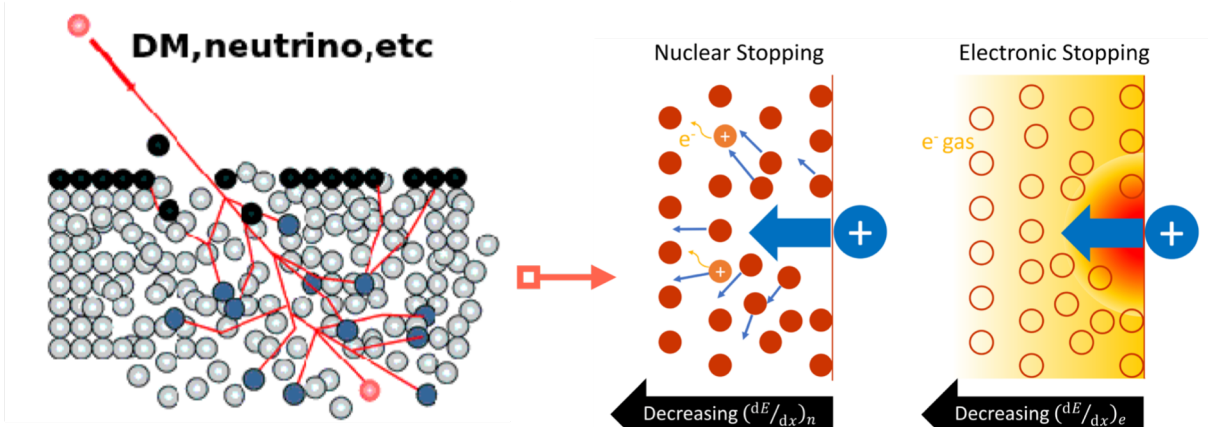
- ✓ The sensitivities of CDEX-50: 10^{-44} cm^2 level @ 4-8GeV WIMP mass.
- ✓ Exploration of multi physics channels as well as the annual modulation effect



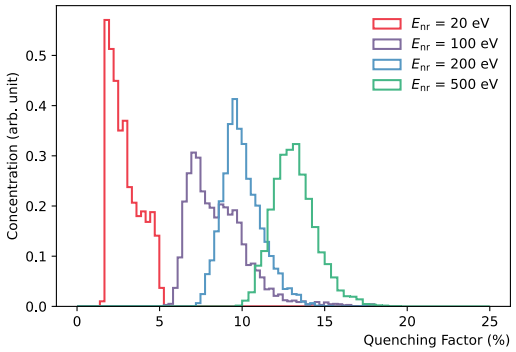


Modeling Detector Response: A Molecular Dynamics Simulation Approach to the Quenching Factor

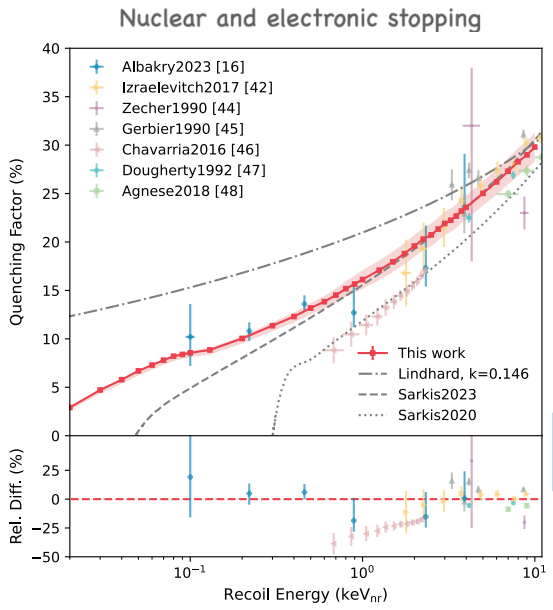
CDEX



Stopping process of nuclear recoil event



QF distribution: recoil energy @ $\mathcal{O}$(10 eVnr)

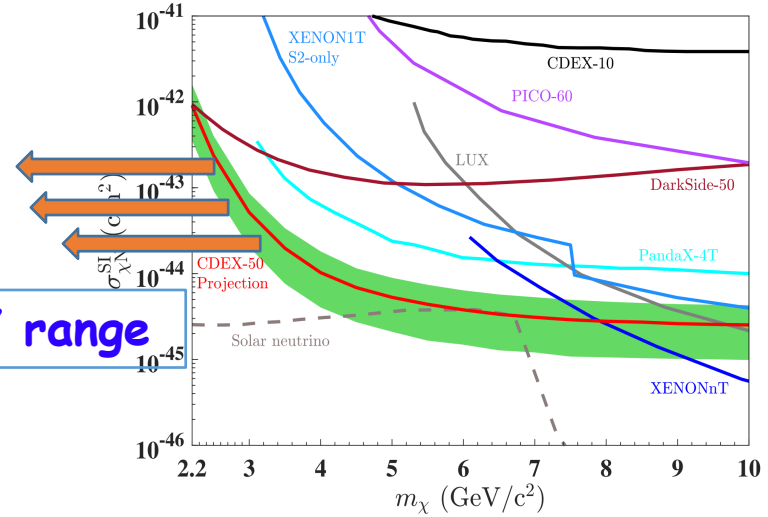


➢ A good agreement with experimental data is achieved in Si detectors.

See Chang-Hao Fang's talk

➢ Unlike Lindhard's QF models, which yield a deterministic recoil energy function, our molecular dynamics approach accounts for probabilistic variations in monoenergetic reionization energy.

➢ Extending the search for WIMPs into the GeV to sub-GeV range with germanium ionization detectors



sub-GeV range

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 DM/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 reduction.
- The new Facilities AND Communities add to the world's arsenal on exciting dark matter & neutrino experiments requiring deep locations.

CDEX

Thank you for your time and participation.

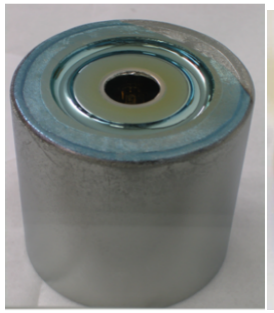
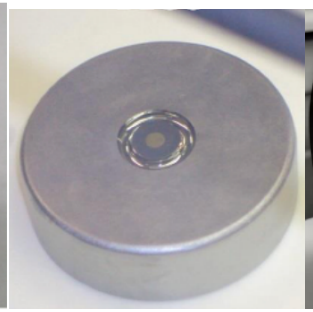
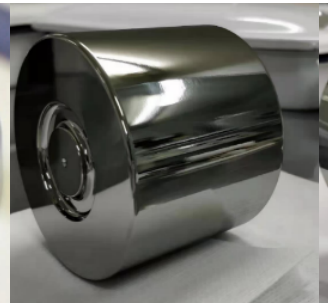
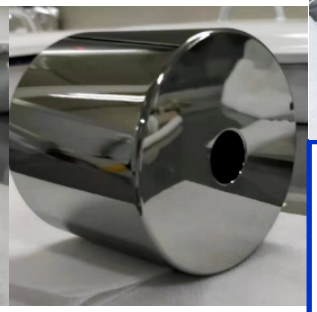
CDEX

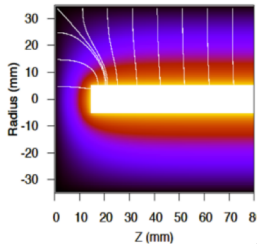
Backup Slides

HPGe Technology---Ge Detector Fabrication

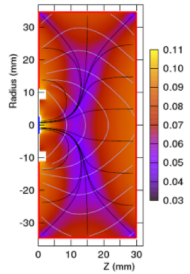
CDEX

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

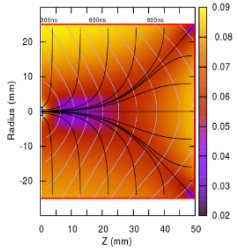







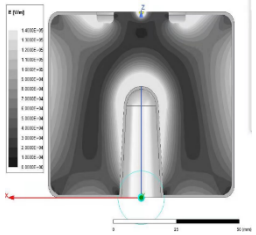
Co-axial



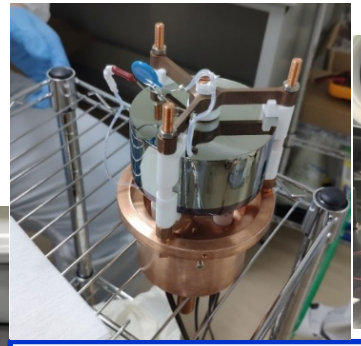
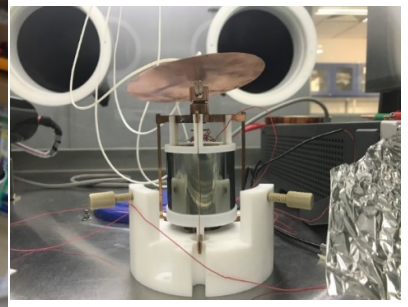
BEGe



PCGe

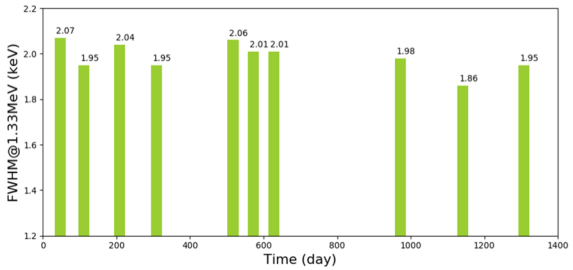


ICPC


Key technical Steps:

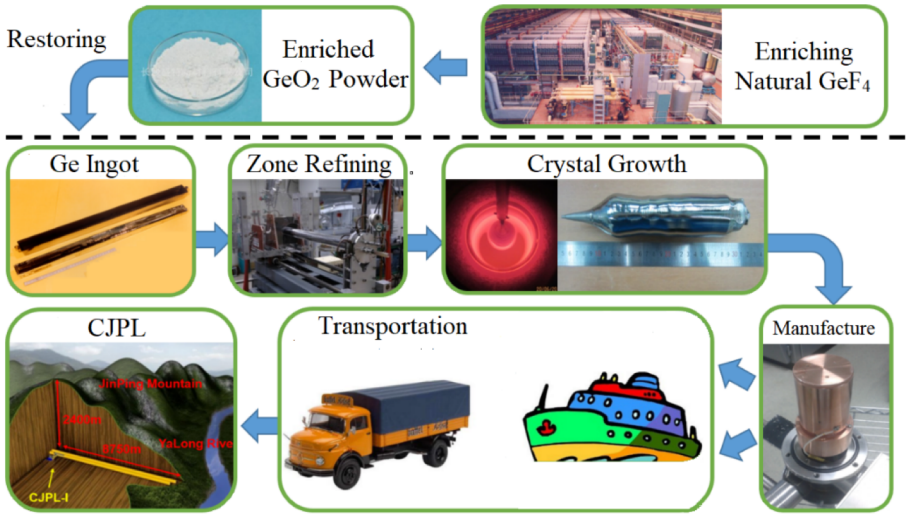
- ✓ Commercial Ge crystal;
- ✓ Structure machining;
- ✓ Li-drift and B-implanted;
- ✓ Home-made ASIC PreAmp;
- ✓ Underground EF-Cu;
- ✓ Underground assemble;
- ✓ Underground testing…



Enriched ^{76}Ge Material Supply

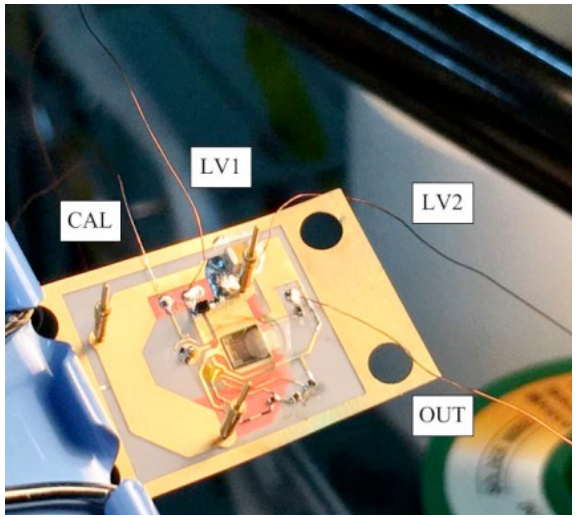
CDEX

- 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.



HPGe Technology-ASIC PreAMP + LN_2 Cryostat

CDEX

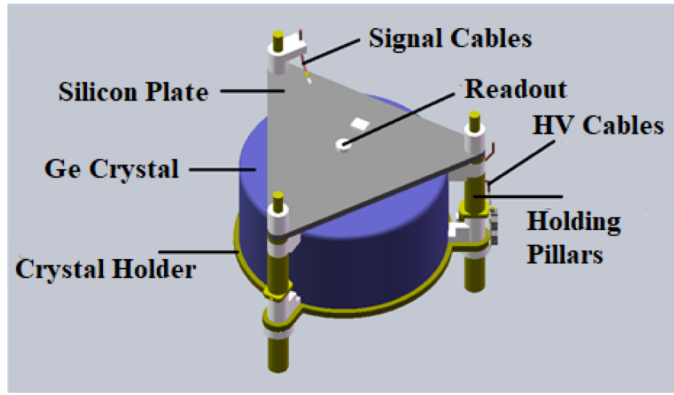


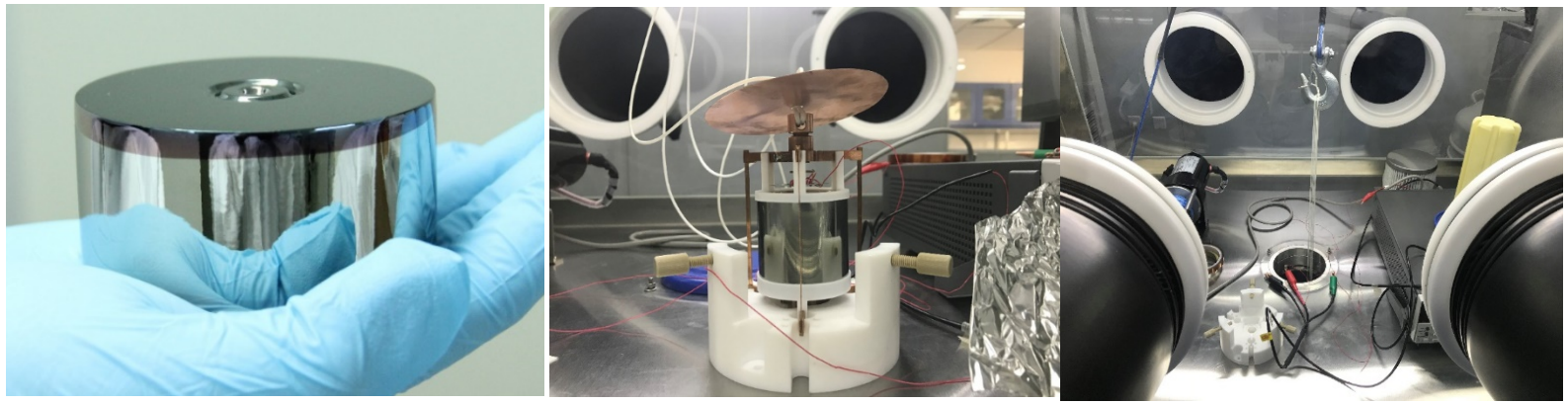
ASIC PreAMP

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

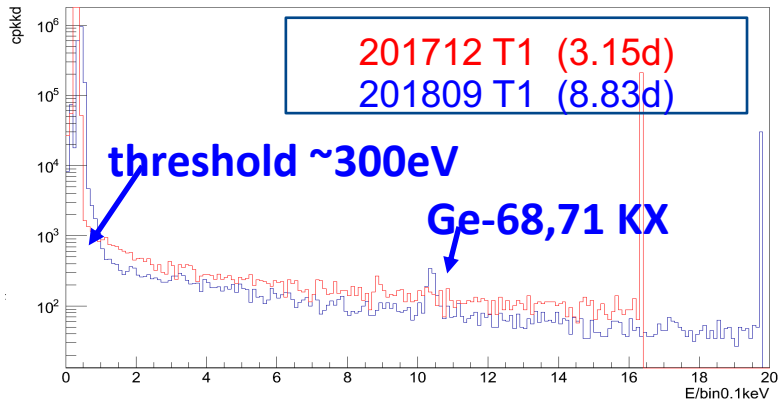
  500g Ge & home-made CMOS ASIC preamp immersed into LN_2

- Works with expected performance





Fabricated and Tested in CJPL-I



Background spectrum @CJPL