CDEX Search for Light Dark Matter Absorption Signal in PCGe

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(CDEX Collaboration)

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CJPL
中国锦屏地下实验室
China Jinping Underground Laboratory

中国暗物质实验
China Dark matter EXperiment

Outlines

I. Towards Light Dark Matter Direct Detection

II. CDEX Experiment using PCGe Detectors

III. CDEX Searches for Light Dark Matter Absorption Signal

(*Dark Photon, Axion & Axion-Like Particle, Fermionic Dark Matter)*

IV. Summary

I. Towards Light Dark Matter Direct Detection

Towards Light Dark Matter Direct Detection

☐ Motivation for Dark Matter Detection:

Dark Matter (DM) is well motivated by cosmological and astronomical observations

Plank CMB observation suggests DM composes about 27% of the universe

However, DM has not been confirmed (detected) in particle physics Yet

Rotation curve of spiral galaxy NGC 3198

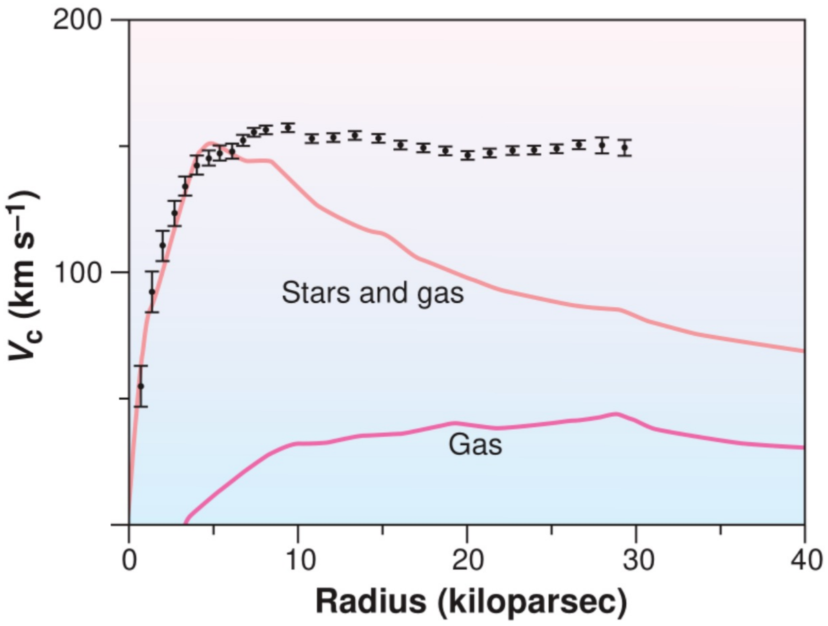


Fig from Freeman K C. The hunt for dark matter in Galaxies. Science, 2003.

Gravity map of cluster CL0024+17

Fig from Young B. A survey of dark matter and related topics in cosmology. Front. Phys., 2017

Collisions of the Bullet cluster

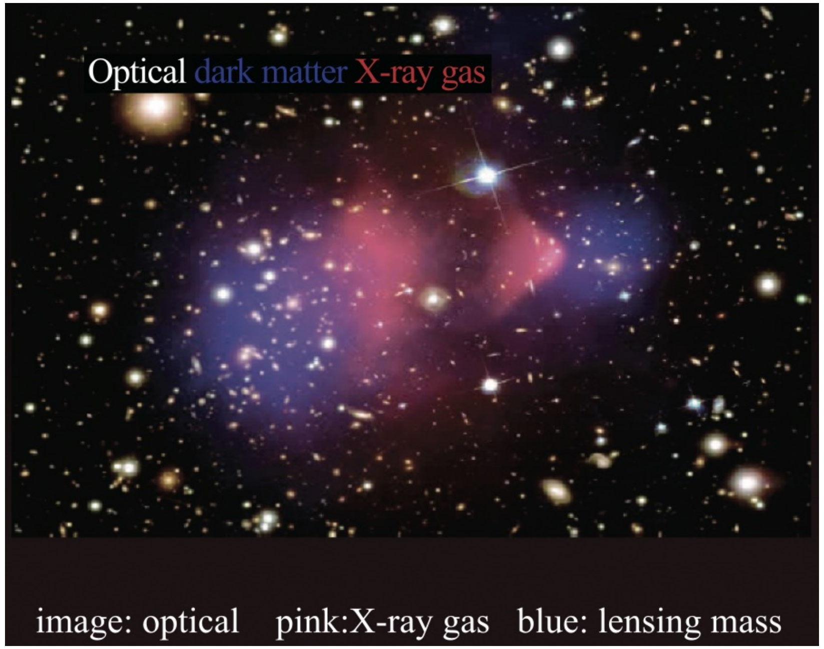


Fig from Young B. A survey of dark matter and related topics in cosmology. Front. Phys., 2017

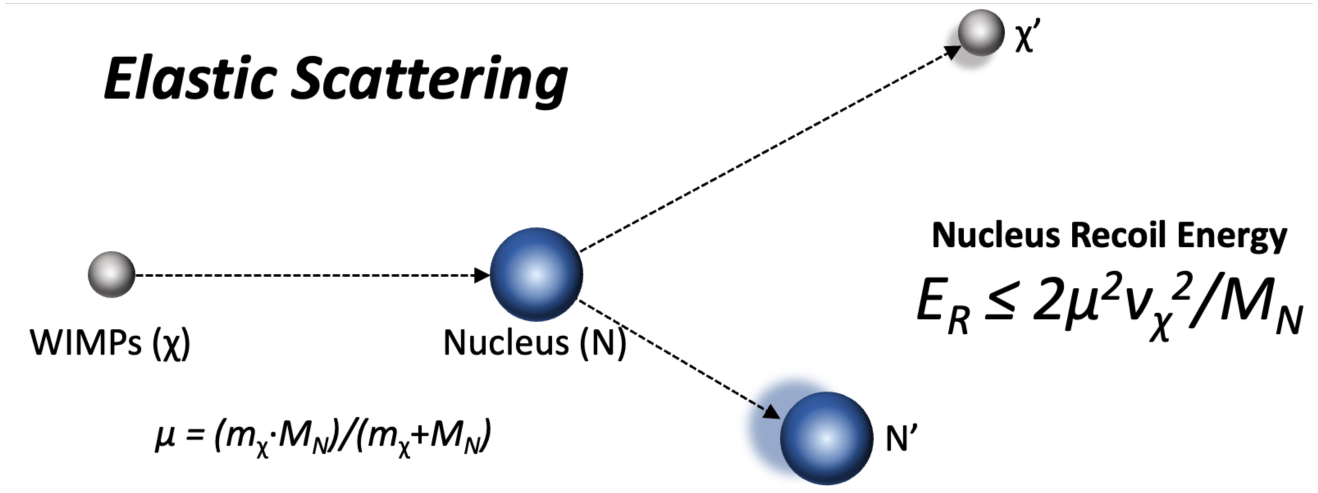
Towards Light Dark Matter Direct Detection

☐ GeV~TeV WIMPs and Its Detection:

Weakly interacting massive particles (WIMPs) with GeV~TeV mass is a well-motivated DM candidate

Direct Detection of WIMPs mainly relies on signals from ***elastic scattering*** of DM and target nucleus

Exclusion limits for GeV~TeV WIMPs are approaching Neutrino Floor

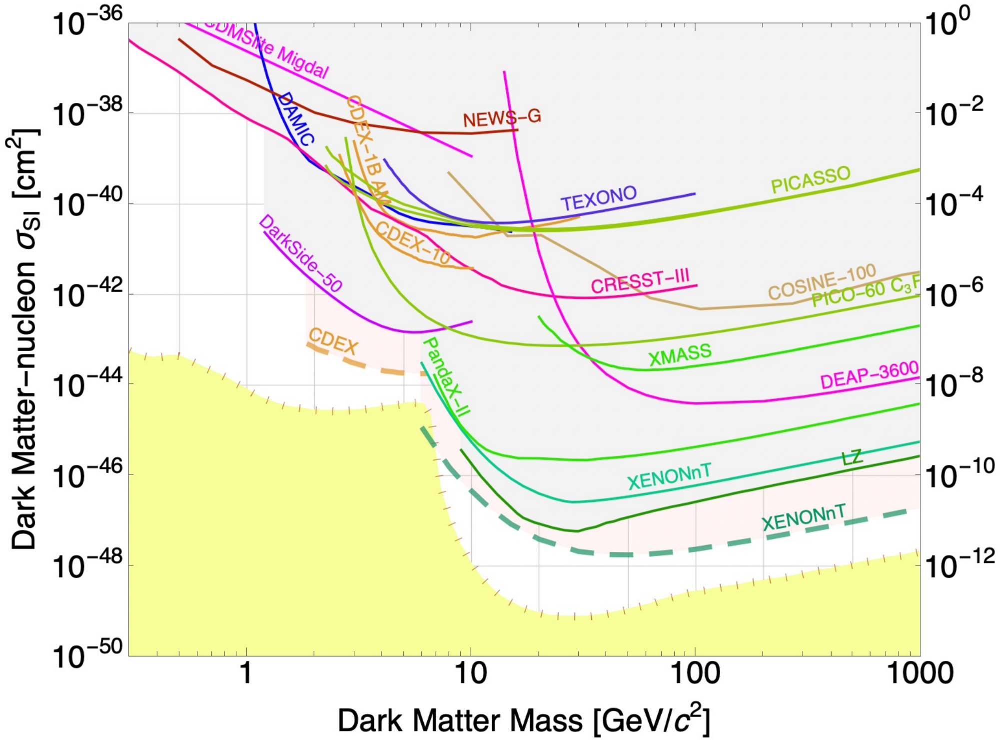


Nucleus Recoil Energy

$$E_R \leq 2\mu^2 v_\chi{}^2/M_N$$

$$\mu = (m_\chi \cdot M_N)/(m_\chi + M_N)$$

Searches for GeV ~ TeV scale WIMPs have been conducted by (Xe/Ar/Ge…) Detectors over decades



Draw by https://supercdms.slac.stanford.edu/dark-matter-limit-plotter

Towards Light Dark Matter Direct Detection

☐ Light Dark Matter Candidates:

Null results from WIMPs searches have motivated studies of Other DM candidates:

- ➢ *Dark Photon*, *Axion*, *Axion-like particles*, *Fermionic DM* …

Detection of Light DM requires observable signals in the Detector:

- ➢ ***Lower energy threshold (Detector) & Signal from DM absorption (Interaction)***
- ➢ ***Boosted DM, Migdal effect, and electron scattering…***

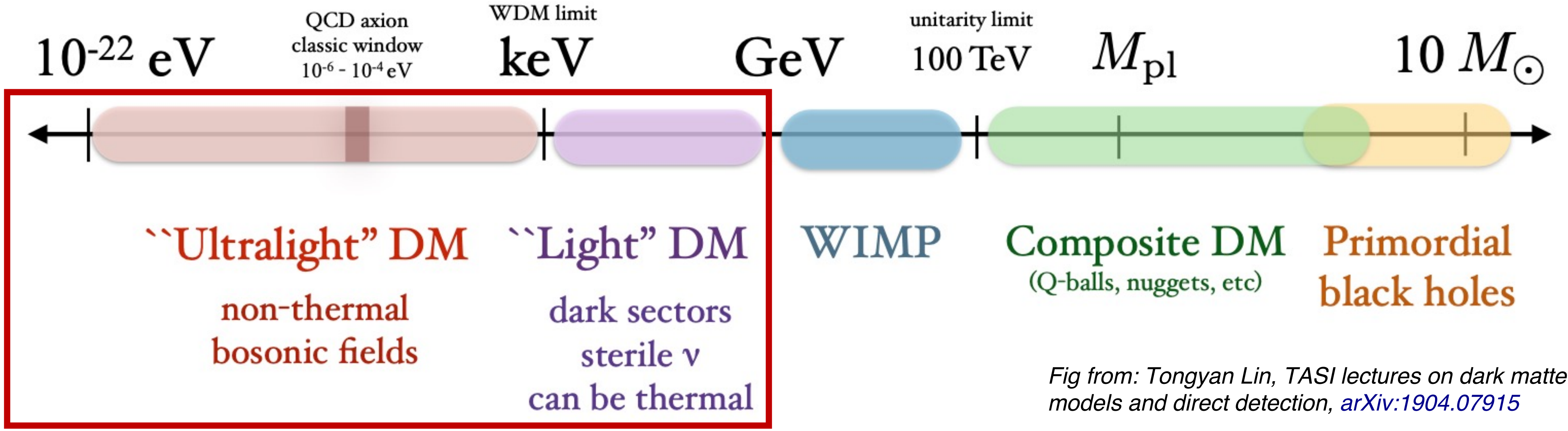


Fig from: Tongyan Lin, TASI lectures on dark matter models and direct detection, arXiv:1904.07915

II. CDEX Experiment

Using PCGe for DM Direct Detection

CDEX Collaboration

- Founded in 2009, 11 institutions, more than 100 people now
- Dark Matter direct detection via Point Contact Germanium (PCGe) Detector

CDEX Experiment at CJPL

- **China Jinping Underground Laboratory (CJPL):**

CJPL is the Deepest underground Lab worldwide with a vertical muon flux of 2×10^{-10} $cm^{-2}s^{-1}$

First two phases of CDEX experiments: *CDEX-1* & *CDEX-10* have been conducted at CJPL-I

- ***Muon & muon-induced background are negligible for CDEX***

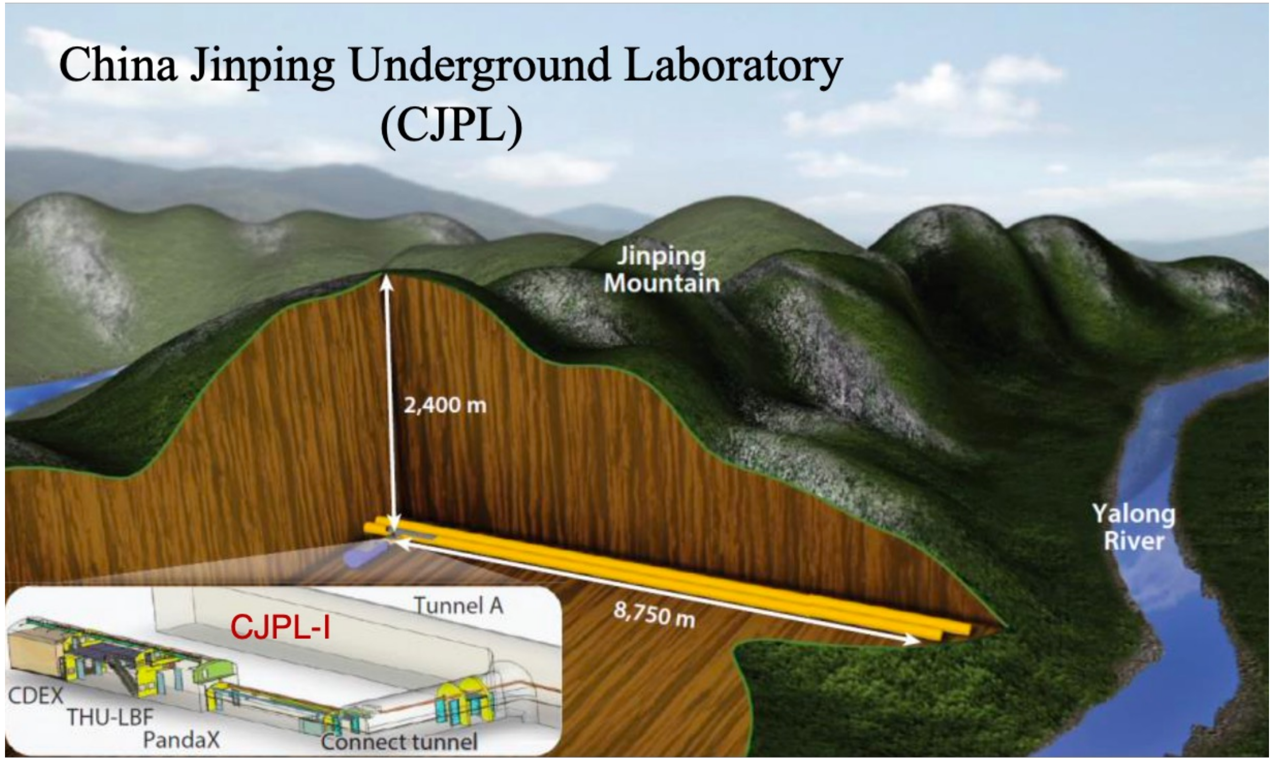
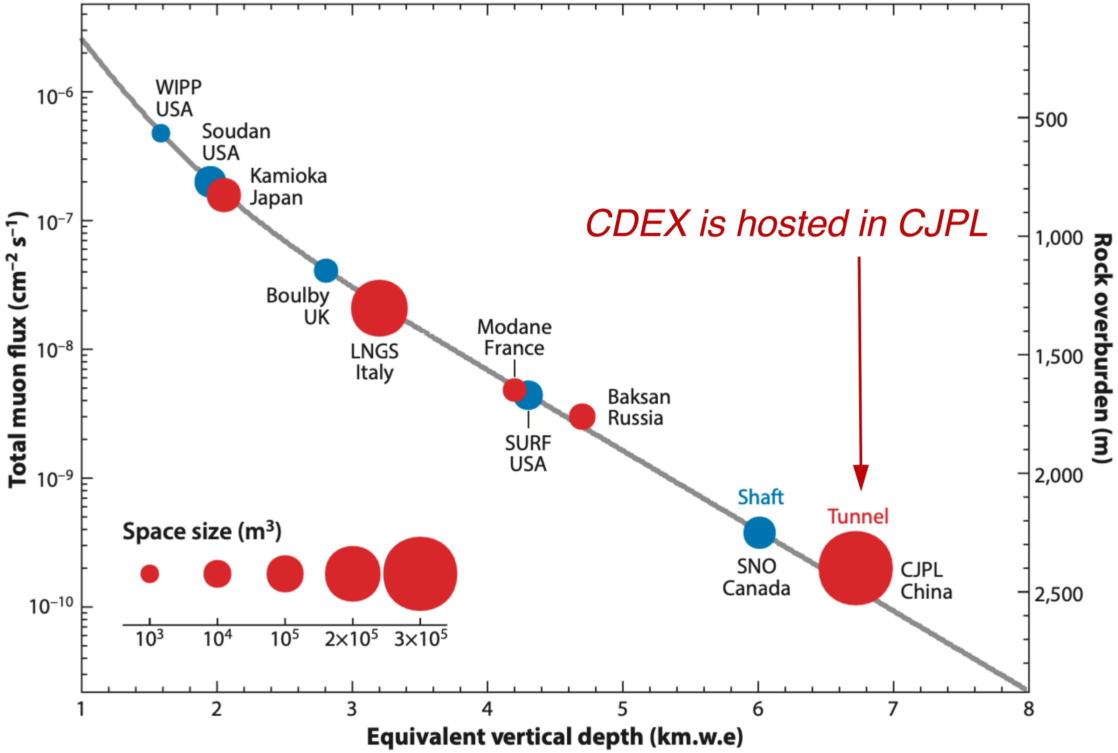


Fig from J.P. Cheng et al. Annu. Rev. Nucl. Part. Sci. 67:231–51, (2017)



CDEX is hosted in CJPL

Fig from J.P. Cheng et al. Annu. Rev. Nucl. Part. Sci. 67:231–51, (2017)

CDEX Experiment

☐ Point Contact Germanium (PCGe) Detector:

① ***CDEX-1:*** *Two PCGe (C1A & C1B), cold finger cooling, Cu / Pb / BPE / PE Shielding*

② ***CDEX-10:*** *PCGe array directly cooled by liquid nitrogen, Cu / LN / PE Shielding*

Data collected by ***4 PCGe (C1A, C1B, C10B1, C10C1)*** *are used in DM absorption signal analysis*

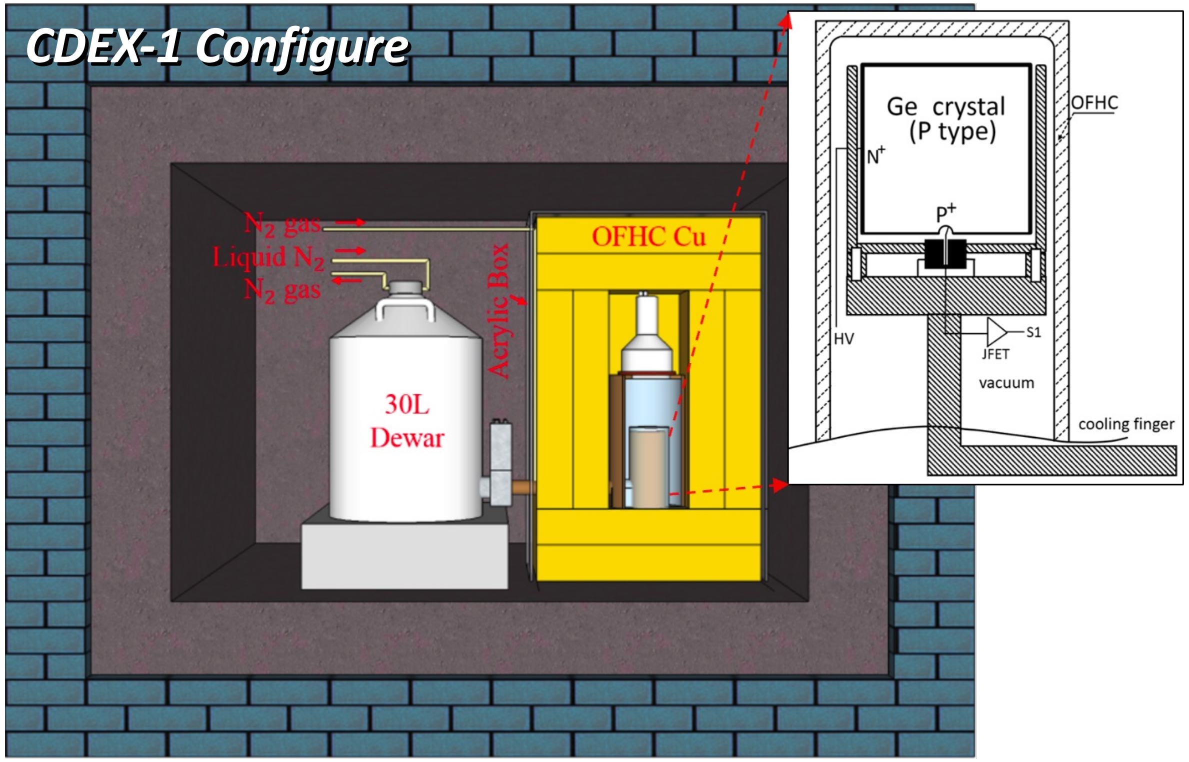


Fig from Phys. Rev. Lett. 123, 221301, 2019

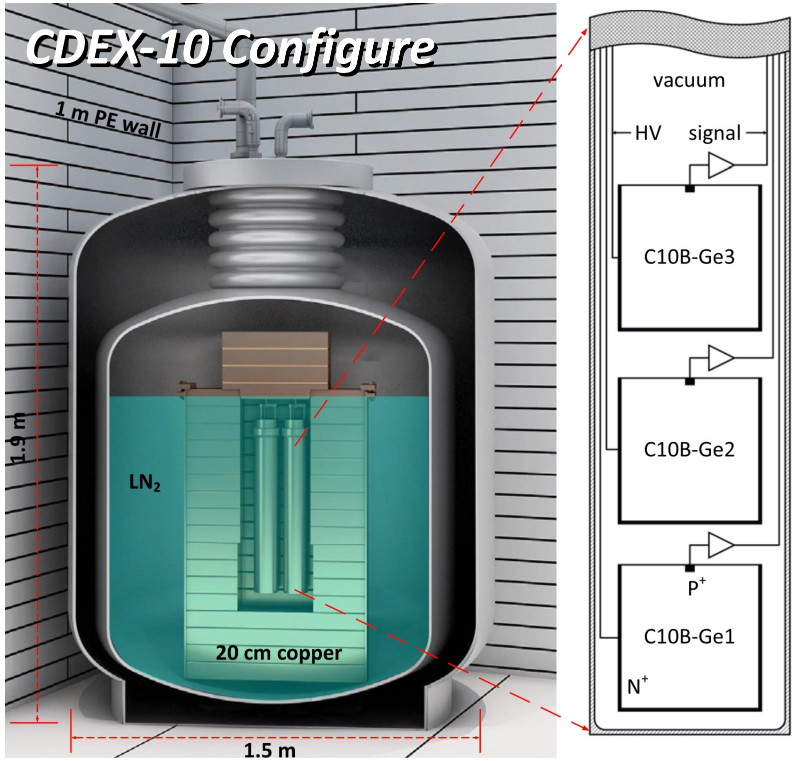
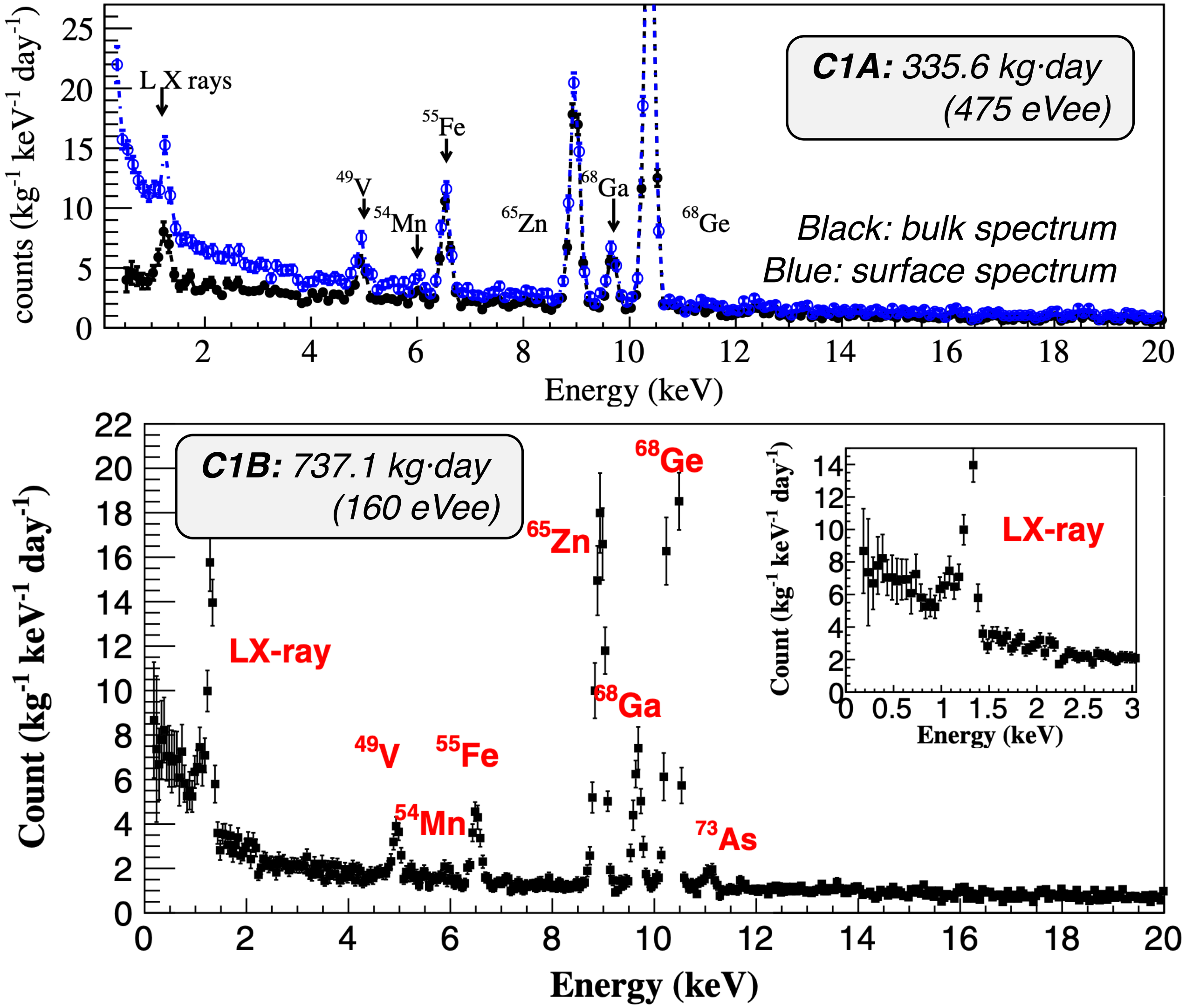


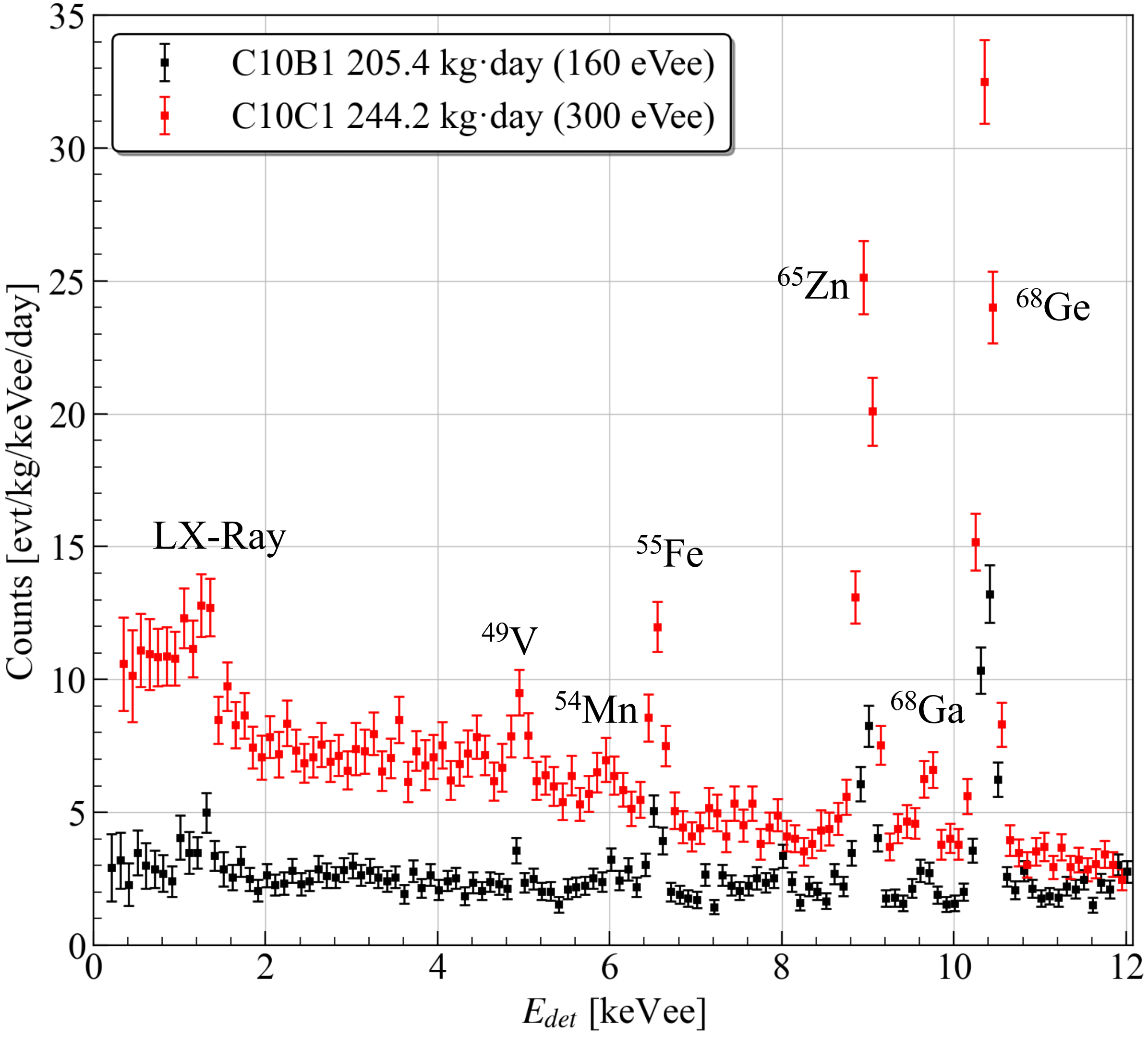
Fig from Phys. Rev. Lett. 120, 241301, 2018

CDEX Experiment Spectra

CDEX-1 (C1A & C1B)



CDEX-10 (C10B1 & C10C1)



III. CDEX Searches for Light Dark Matter via Absorption

(Dark Photon, Axion & Axion-Like particles, Fermionic DM)

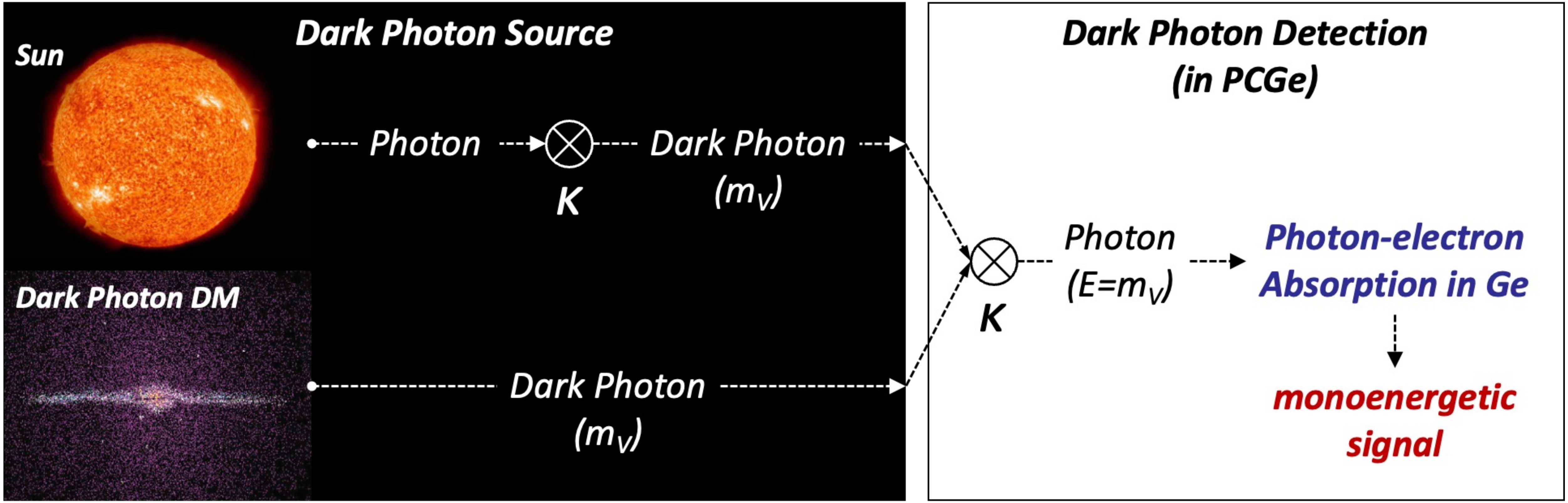
CDEX Dark Photon Search

Dark Photon Detection via PCGe:

Dark photon with mass (m_V) in keV scale is a possible DM candidate

Dark photon may convert to ***photon*** and be detected by PCGe as a ***monoenergetic signal***

- *κ being the effective kinetic mixing parameter between dark photon and photon*



Dark Photon Source

Sun

Photon → $\otimes$ K → Dark Photon (m_V)

Dark Photon DM

Dark Photon (m_V)

Dark Photon Detection (in PCGe)

$\otimes$ K → Photon ($E=m_V$) → **Photon-electron Absorption in Ge** → **monoenergetic signal**

CDEX Dark Photon Search

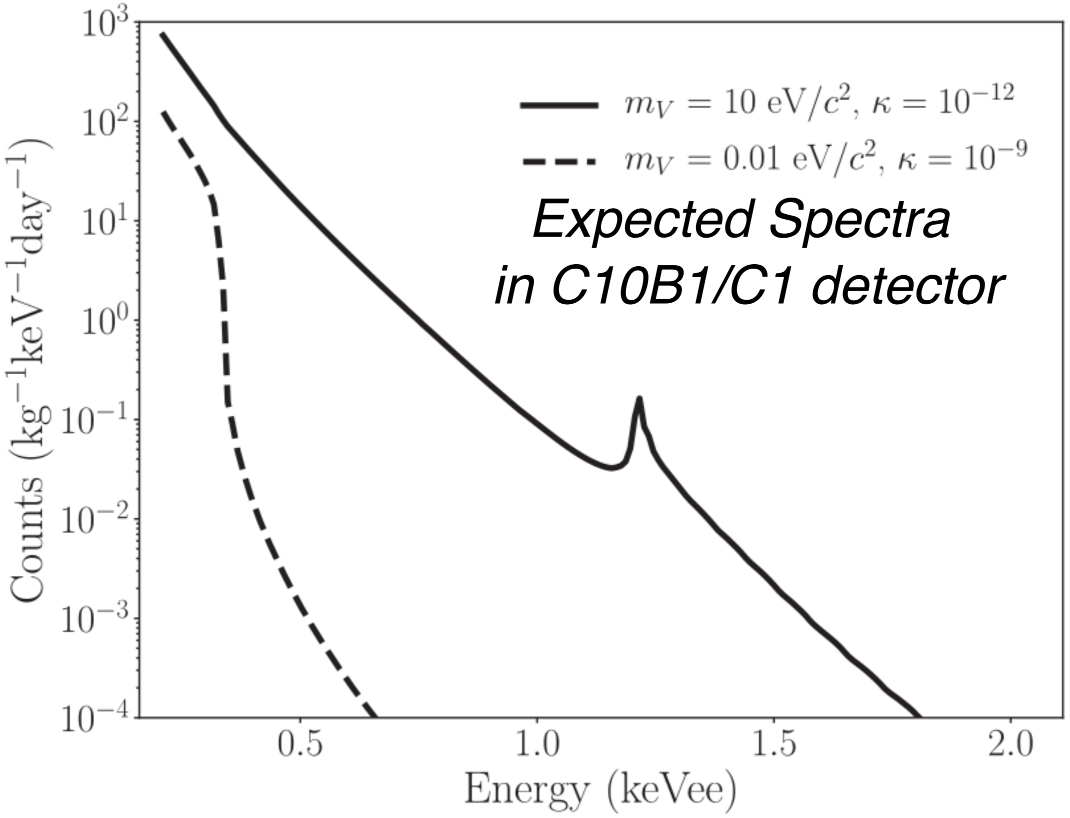
☐ Solar Dark Photon (CDEX-10):

[1] *Phys. Rev. Lett., 111, 041302 (2013)*
[2] *Phys. Lett. B, 725(4): 190-195. (2013)*

Adopting BP05(OP) solar model and DP from Stueckelberg case with nondynamic mass[1,2]

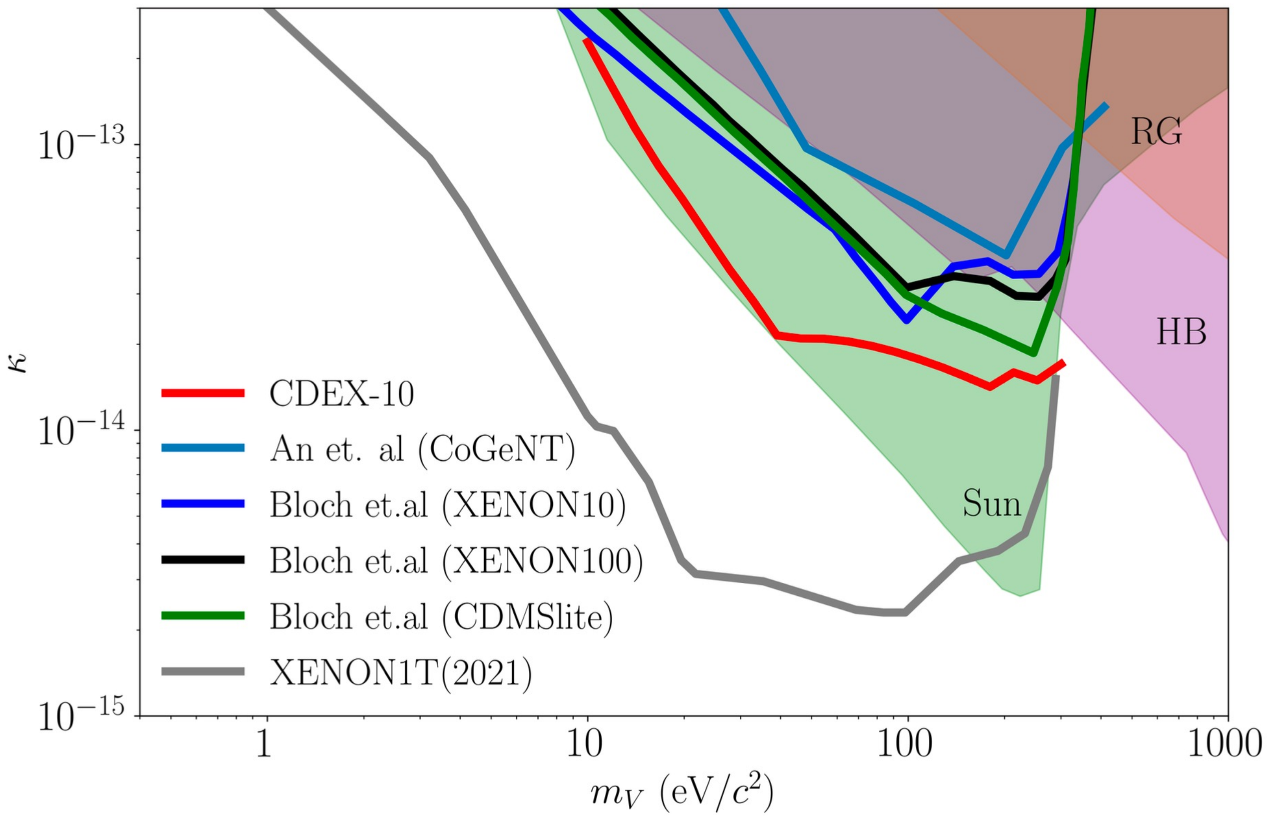
Set limits on mixing parameter (κ) for dark photon mass (m_V) in 10 ~ 300 eV

Most stringent direct detection limits on κ at the time of publication



Expected Spectra in C10B1/C1 detector

(PRL 124, 111301, 2020)



CDEX Dark Photon Search

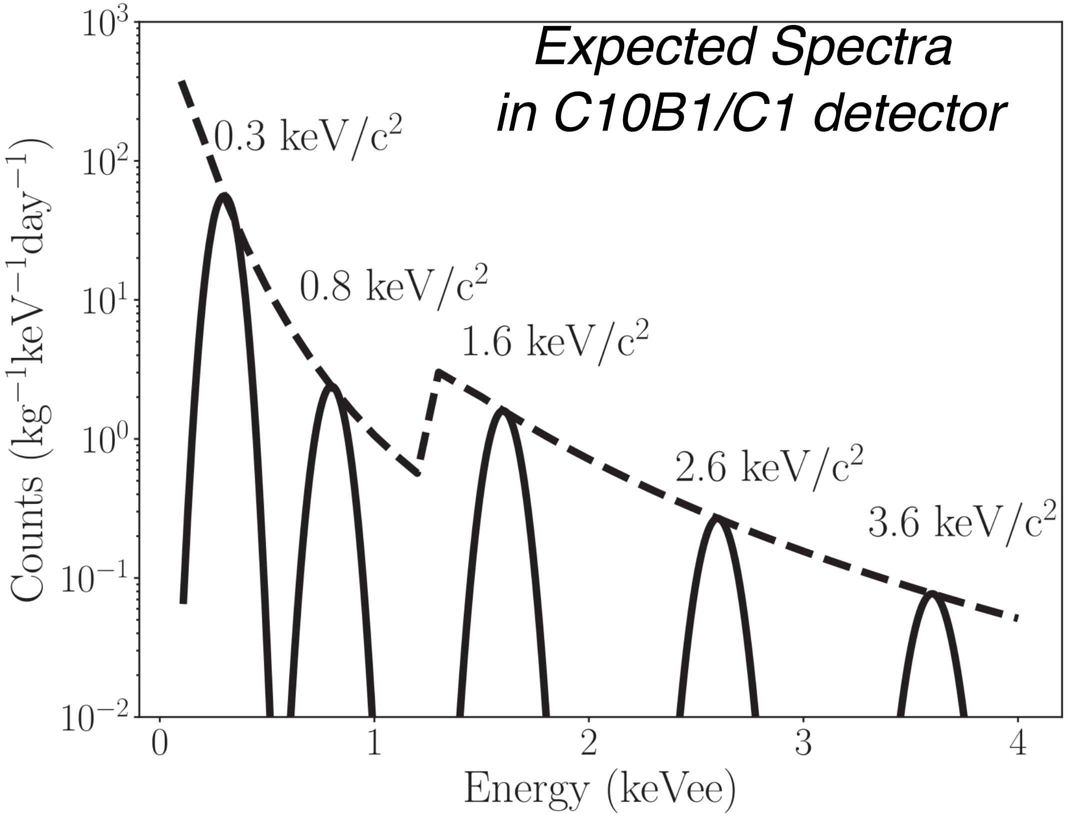
☐ Dark Photon Dark Matter (CDEX-1 & CDEX-10):

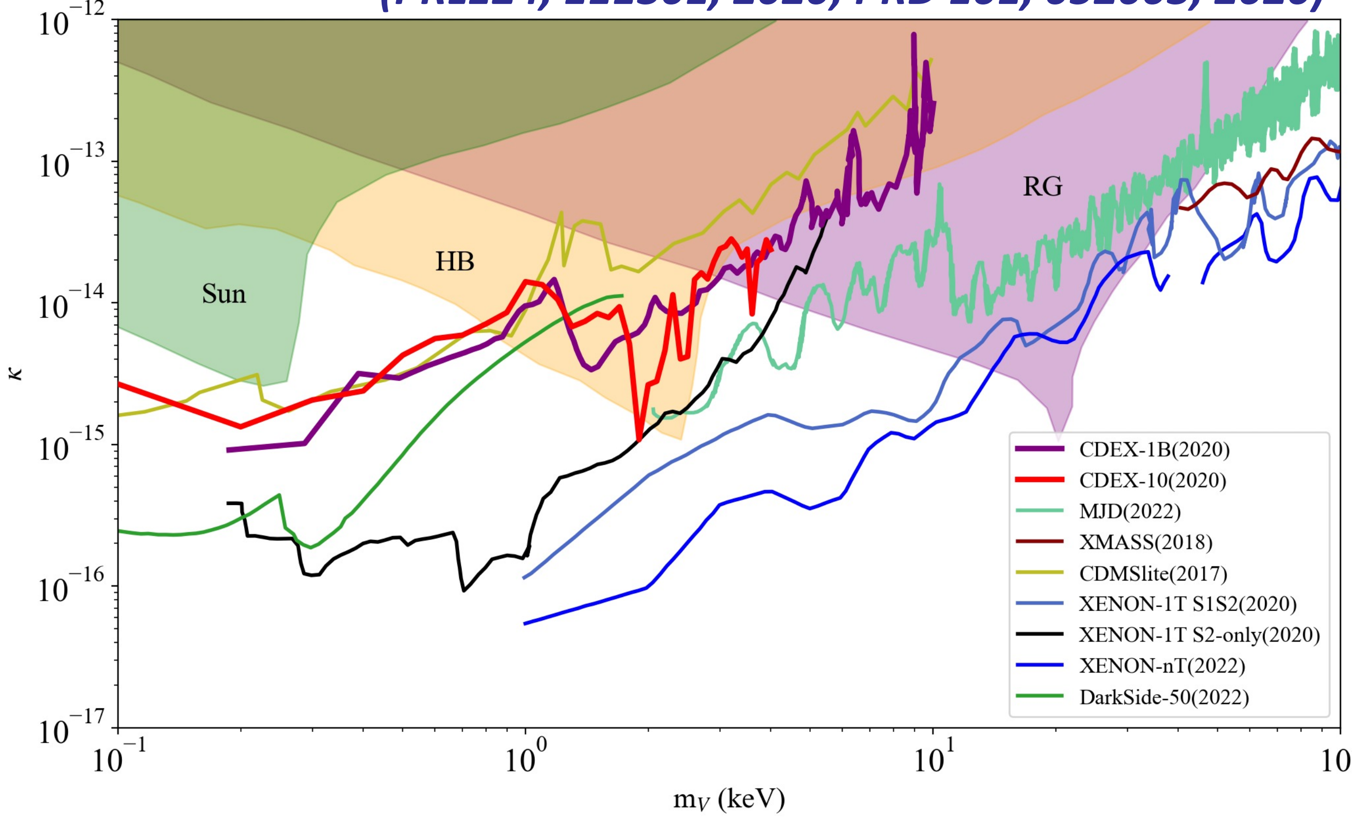
Assuming DPDM follows the *Standard Halo Model* with a local density of *$0.3\ GeV/cm^3$*

Set limits on mixing parameter (κ) for dark photon mass (m_V) in 0.1 ~ 10 keV

Exclude New parameter space at 0.1~0.2 keV at the time of publication

(PRL124, 111301, 2020; PRD 101, 052003, 2020)





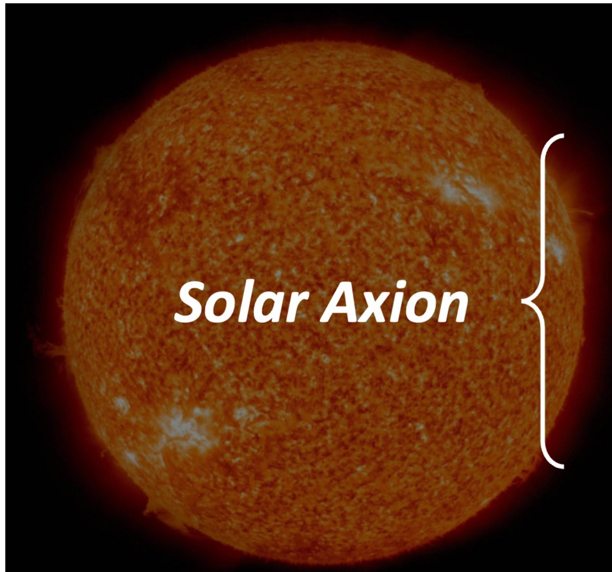
CDEX Axion & Axion-Like Particle Search

☐ Axion Sources:

① Solar Axion: CBRD Axion & Fe-57 Axion

② Axion-Like-Particles as Dark Matter Candidate

Reference for Solar Axion Flux:
S. Andriamonje et al., J. Cosmol. Astropart. Phys. 12 (2009) 002.
J. Redondo, J. Cosmol. Astropart. Phys. 12 (2013) 008.



Solar Axion

CBRD Axion

- *① C: Compton-like scattering*
- *② B: axion-bremsstrahlung*
- *③ R: atomic-recombination*
- *④ D: atomic-deexcitation*

$$\frac{d\Phi}{dE_A} = g_{Ae}^2 \times 1.33\times10^{33} \times E_A^{2.987} \cdot e^{-0.766E_A} + g_{Ae}^2 \times 2.63\times10^{35} \times \frac{E_A \cdot e^{-0.77E_a}}{1+0.667E_A^{1.278}}$$

↑ Axion-electron coupling

Fe-57 Axion

^{57}Fe → ^{57}Fe + Axion*
(14.4 keV monochromatic)

$$\Phi_{14.4} = \left(\frac{\kappa_a}{\kappa_\gamma}\right)^3 \times 4.56\times10^{23} \cdot \left(g_{AN}^{eff}\right)^2$$

↑ Effective nuclear coupling

Axion-Like-Particles (as DM Candidate)

Local density: 0.3 GeV/cm³
ALPs velocity: Standard Halo Model
(nonrelativistic)

$$\Phi_{ALP} = \rho_{DM} \cdot \frac{v_{ALP}}{m_{ALP}}$$

CDEX Axion & Axion-Like Particle Search

☐ Axion Detection via PCGe:

PCGe detects Axion by *axioelectric effect* produced electron:

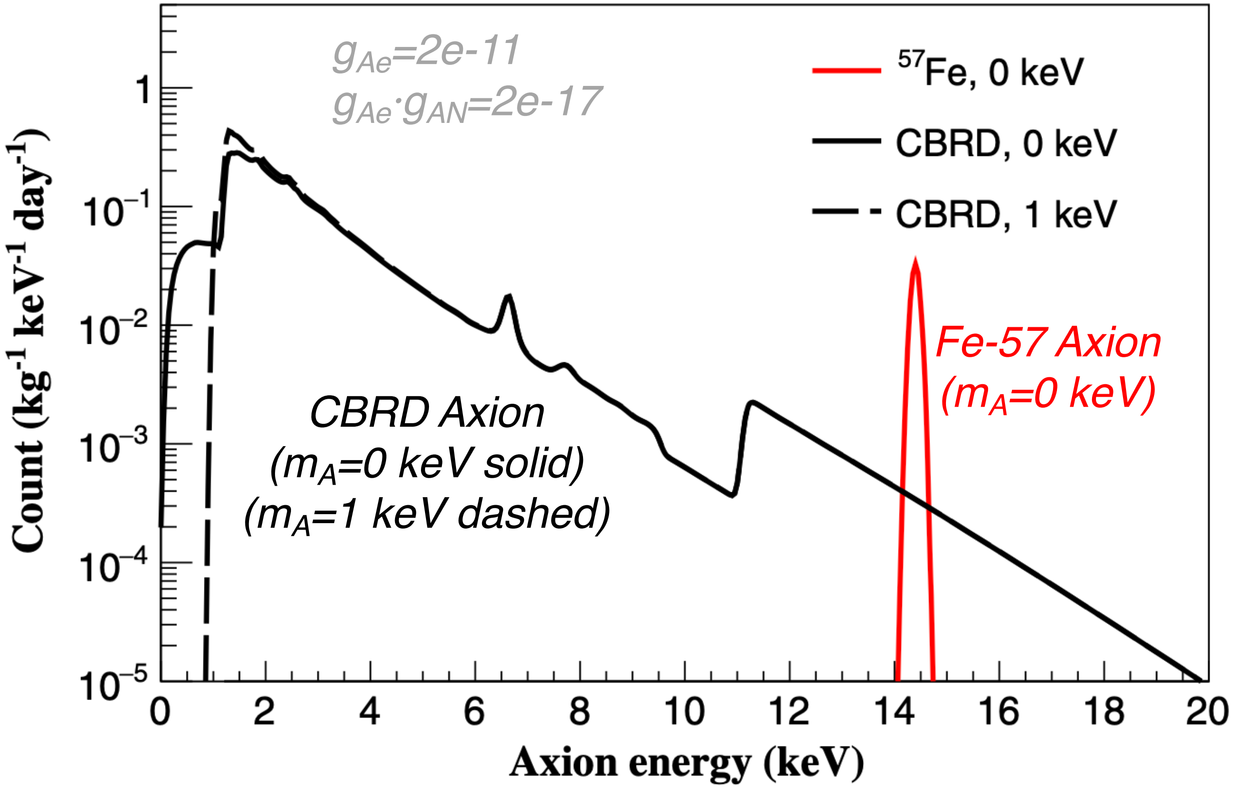
$$\sigma_{Ae}(m_A) = \sigma_{pe}(m_A)\frac{g_{Ae}^2}{\beta}\frac{3m_A^2}{16\pi\alpha m_e^2}\left(1-\frac{\beta^{\frac{2}{3}}}{3}\right)$$

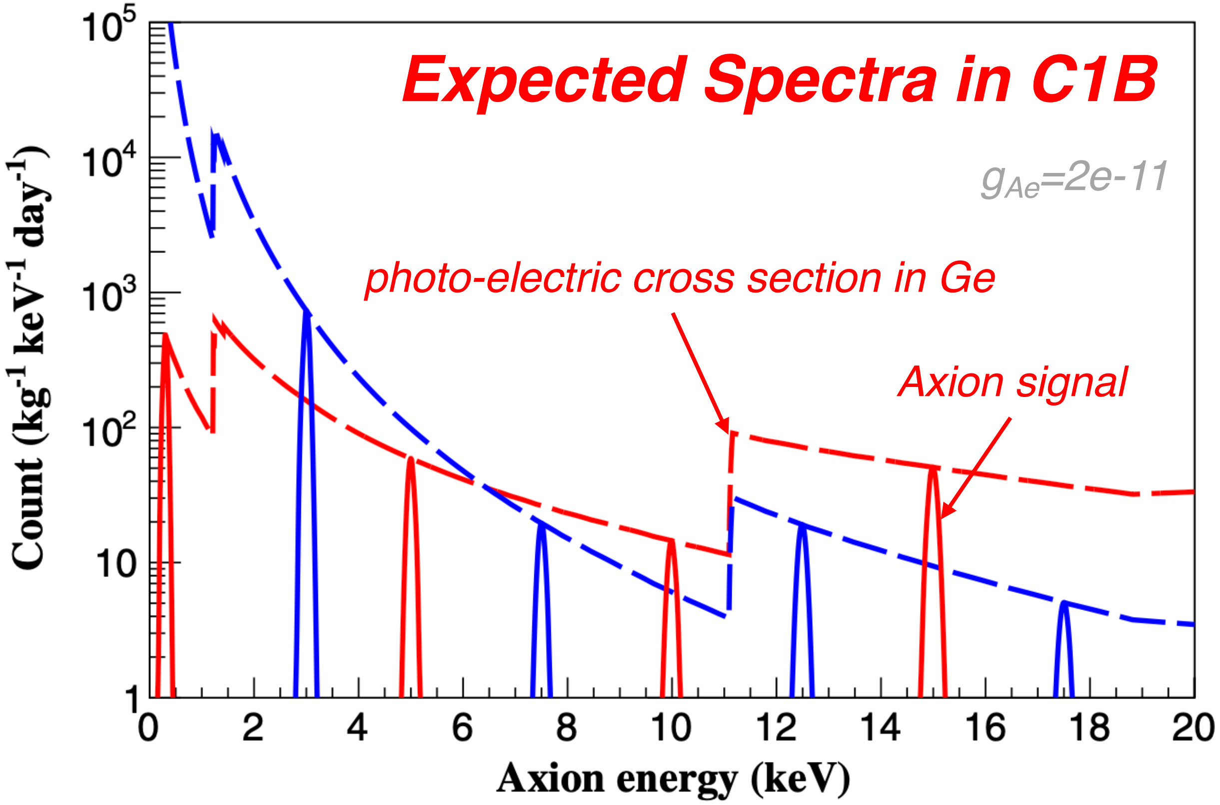
m_a: *axion mass*

σ_{ae}: *axion-electric cross section*

σ_{pe}: *photo-electric cross section*

β = *Axion velocity / c*





CDEX Axion & Axion-Like Particle Search

☐ Solar Axion Result (C1B data):

(PRD 101, 052003, 2020)

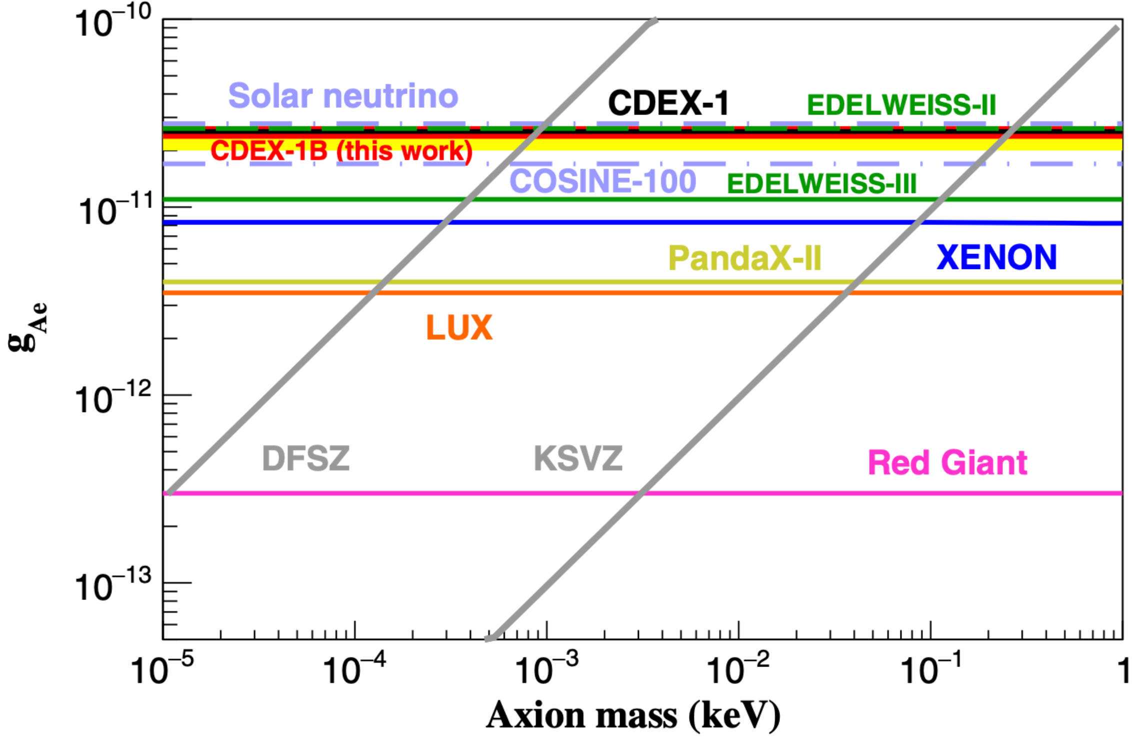
(PRD 96, 122002 2017)

Analyze Axion signal via *Profile Likelihood* method

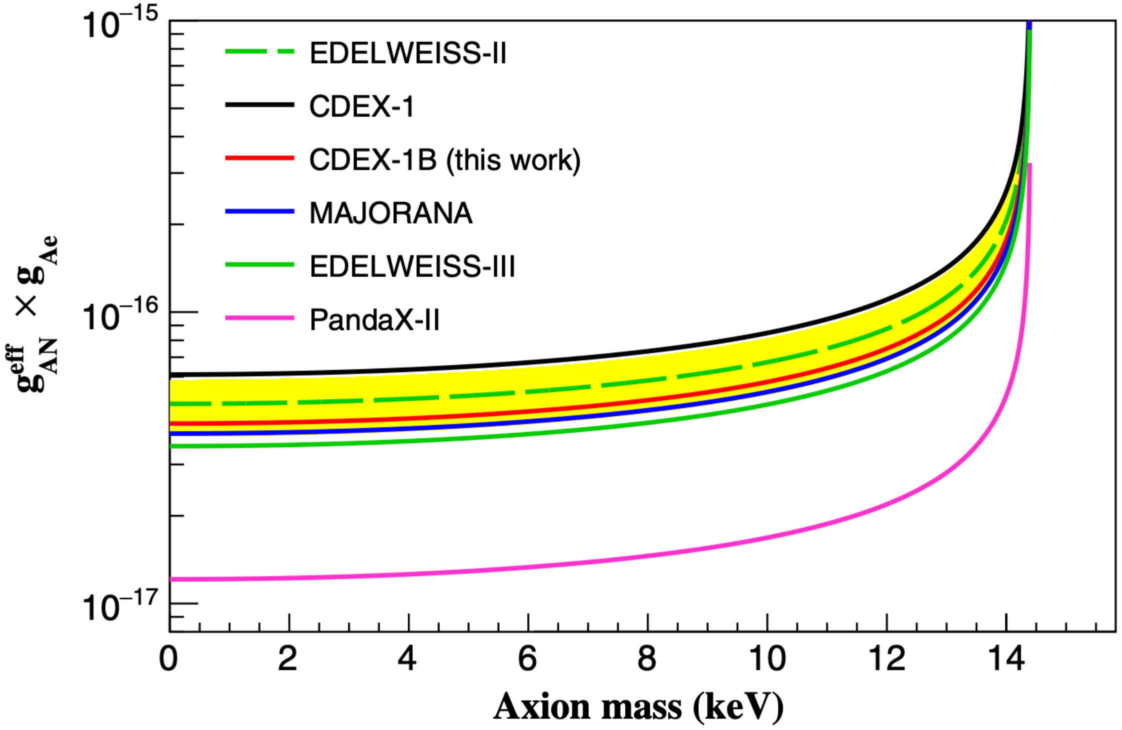
① *CRBD: limits on axion-electron coupling:* ***$g_{Ae} < 2.48E\text{-}11$***

② *Fe-57: limits on axion-electron coupling & axion-nuclear coupling:* ***$g_{Ae} \times g_{AN} < 4.14E\text{-}17$ (m_A=0)***

CBRD Axion



Fe-57 Axion

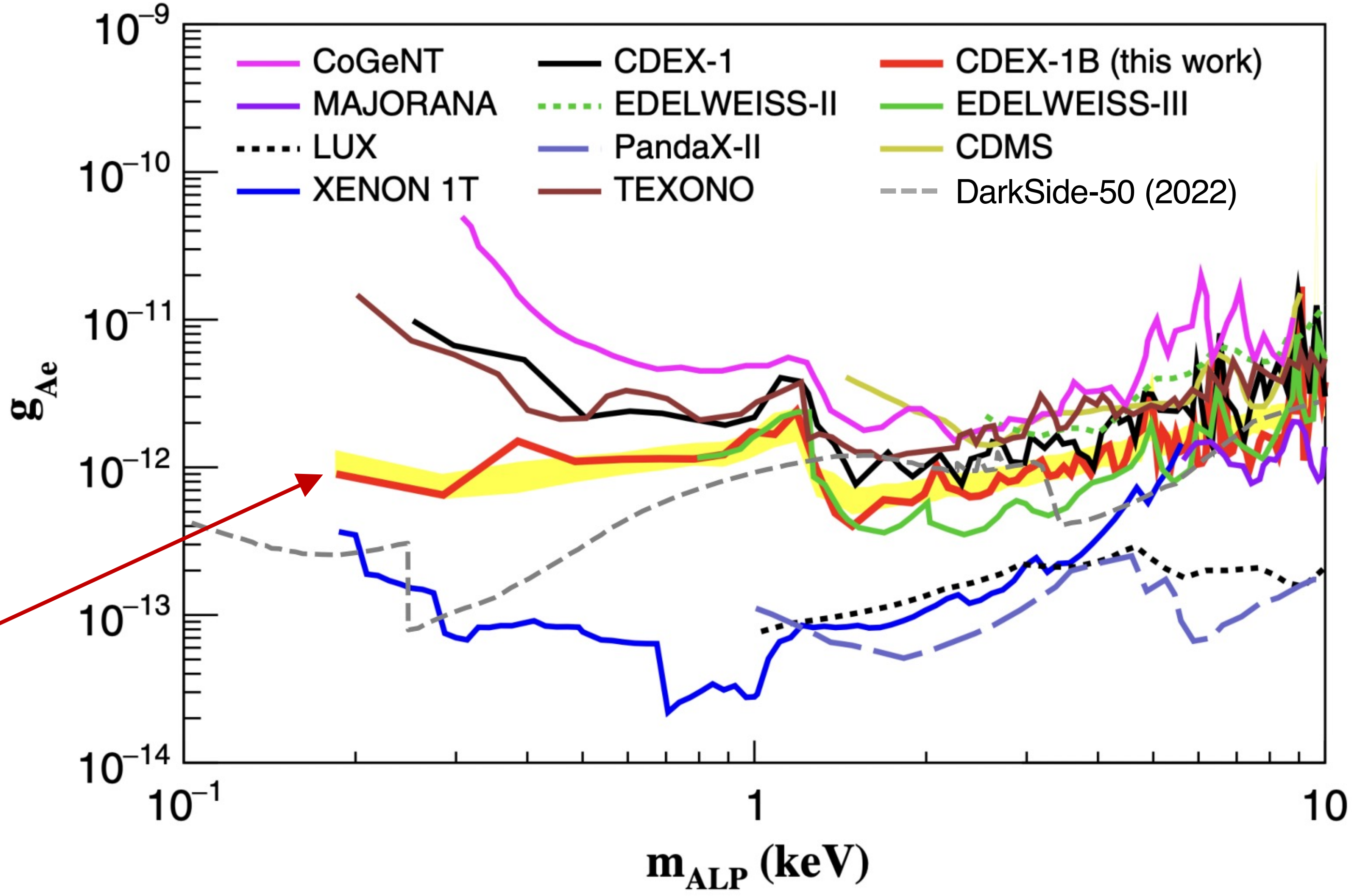


CDEX Axion & Axion-Like Particle Search

☐ Axion-Like-Particles Result:

Analyze Axion signal via *Profile Likelihood* method

- ➢ *CDEX-1B best limit on axion-electron coupling:* ***$g_{Ae} < 4.0E\text{-}13$ (m_A = 1.5 keV)***



Extend parameter space to 185 eV

(PRD 101, 052003, 2020)
(PRD 96, 122002 2017)

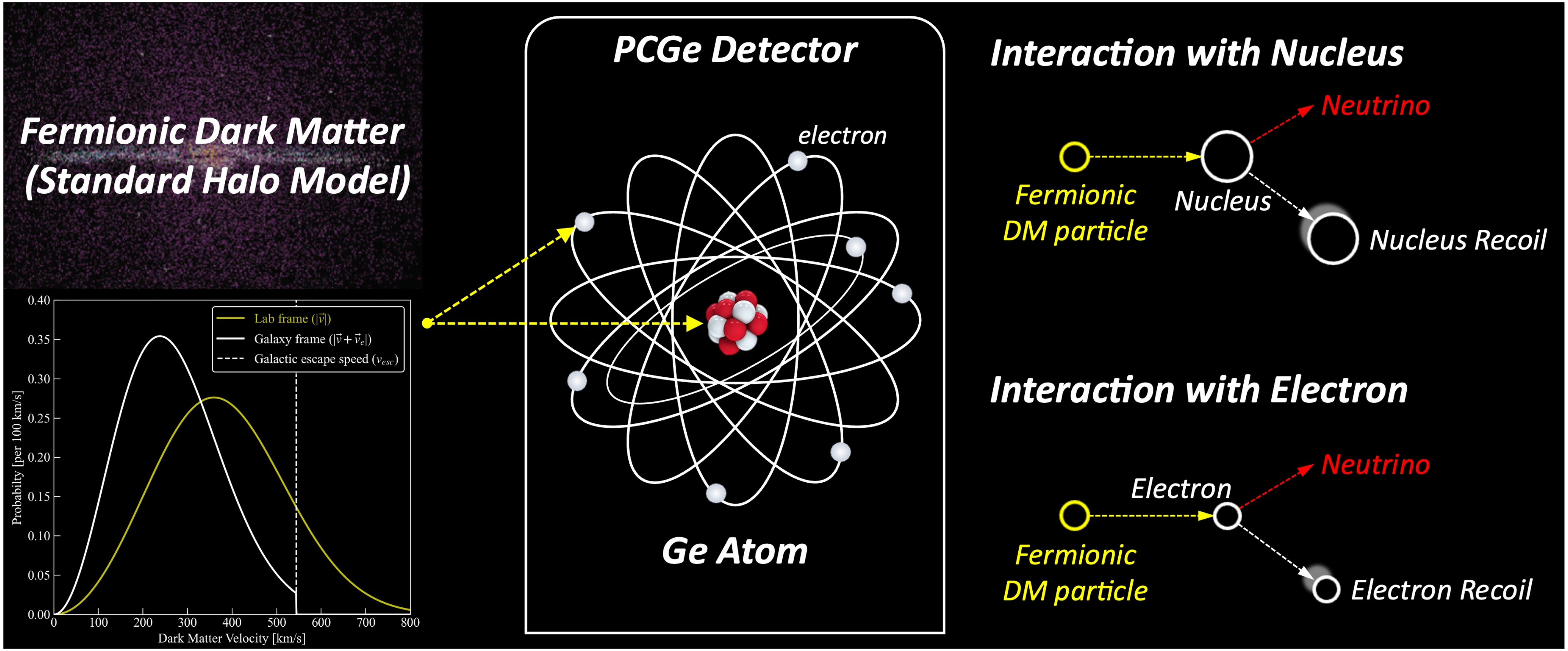
CDEX Fermionic Dark Matter Search

☐ Fermionic Dark Matter Detection:

Theory:
J. A. Dror, et al, JHEP, 2: 134 (2020)
J. A. Dror, et al, Phys. Rev. Lett. 124, 181301 (2020).
J. A. Dror, et al, Phys. Rev. D 103, 035001 (2021).
S.F. Ge, et al. J. HighEnergy Phys. 05, 191 (2022).

If Dark Matter particles are ***Fermion***:

they can induce ***neutral current absorption*** with ***nucleus*** or ***electron***



CDEX Fermionic Dark Matter Search

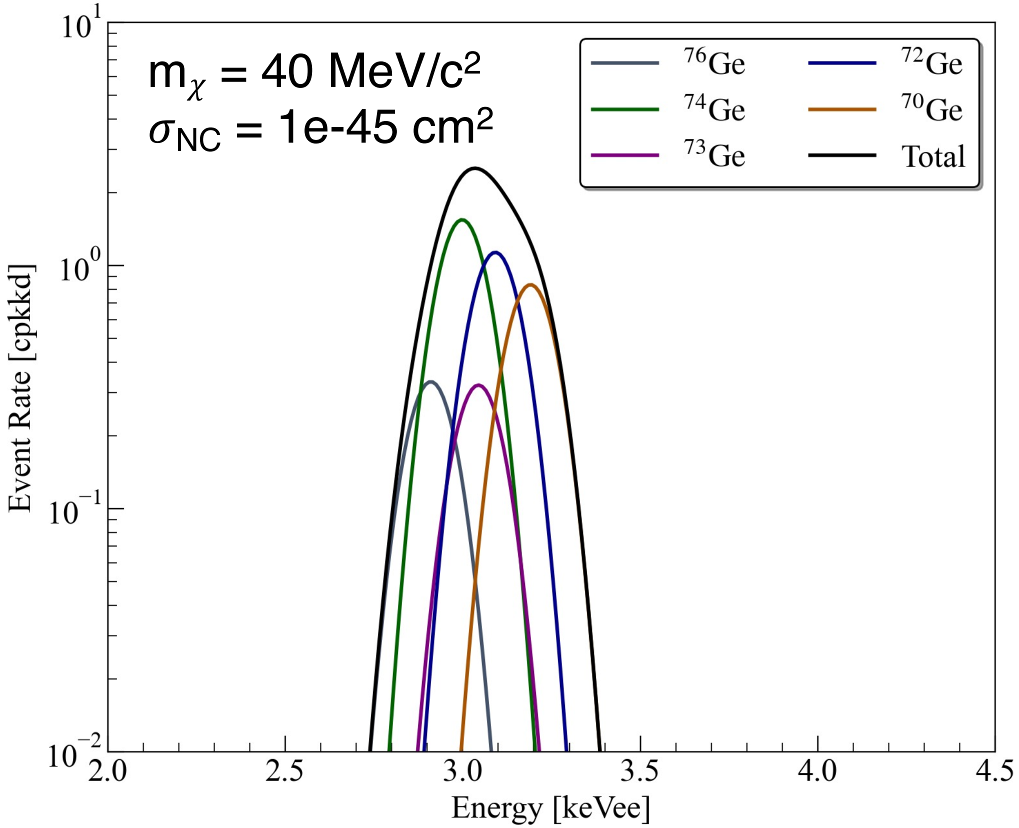
☐ Expected Spectra from Nucleus Absorption:

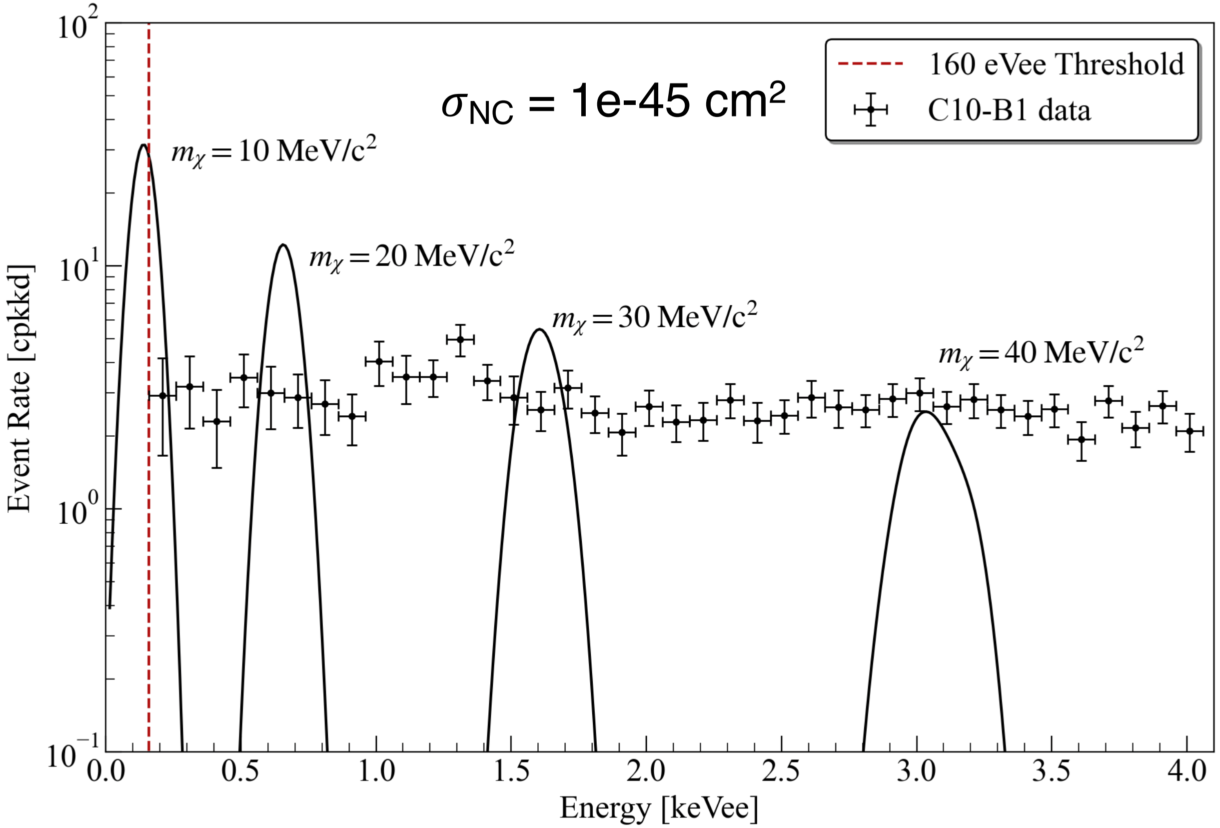
Nucleus Recoil Energy: $E_R \simeq m_\chi^2/(2M_N)$

Total Event Rate: $R = \rho_\chi/m_\chi \cdot \boldsymbol{\sigma_{NC}} \cdot \frac{1}{M_T}\sum_j N_j M_j A_j^2 F_j^2$

After Quenching & Energy Resolution:

- ***Monoenergetic peak for each DM mass***





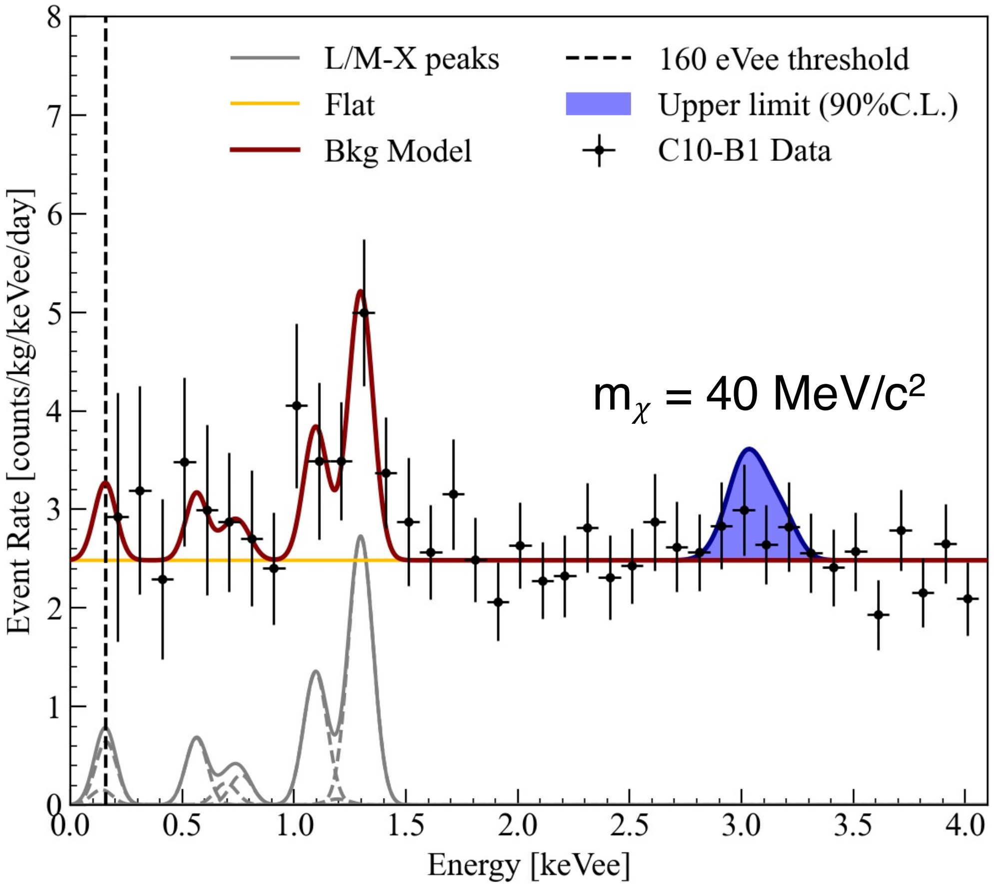
CDEX Fermionic Dark Matter Search

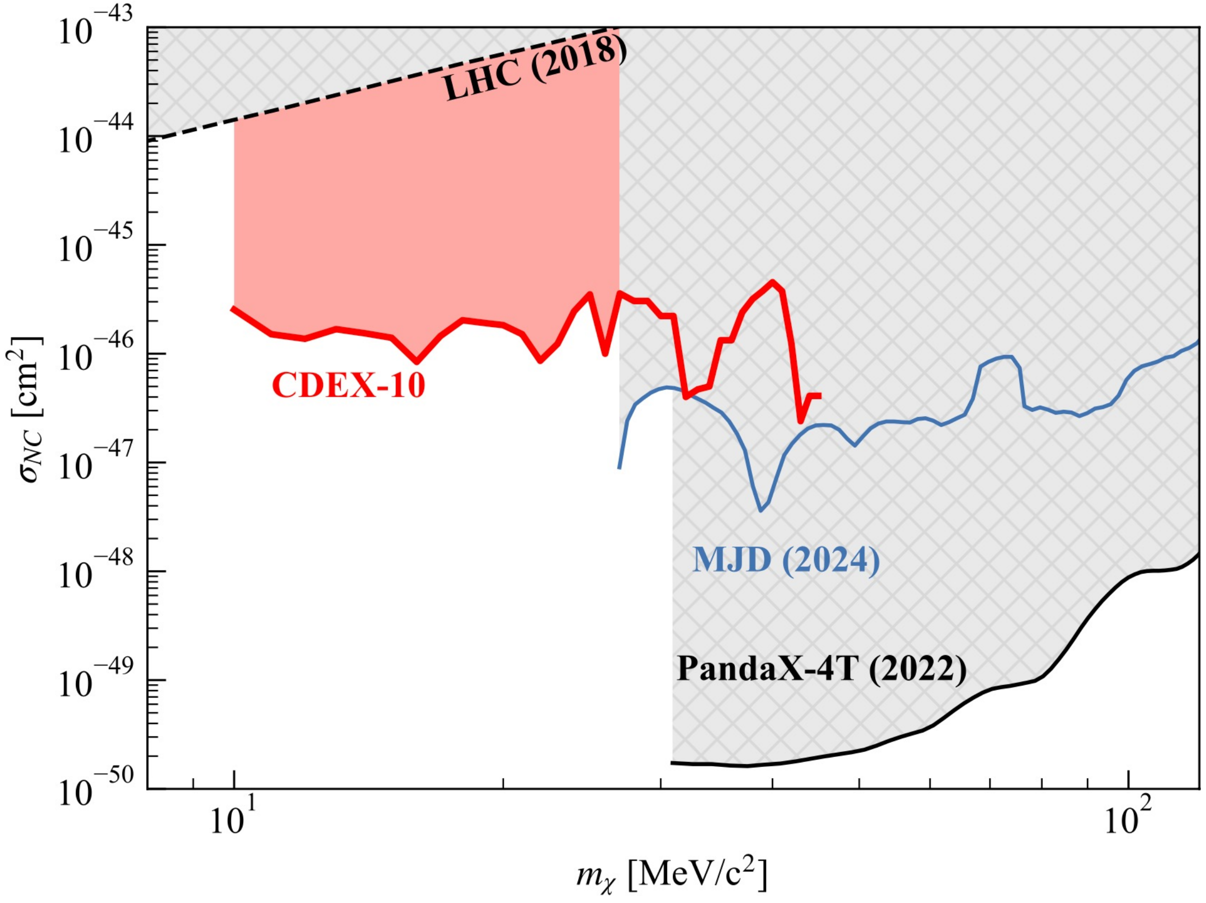
☐ Limits on Nucleus Absorption Cross-Section (σ_{NC}):

Analysis 10~45 MeV DM using C10B1 data

PRL 129, 221802, 2022

CDEX achieves the **lowest DM mass reach (10 MeV)** among direct detection experiments to date





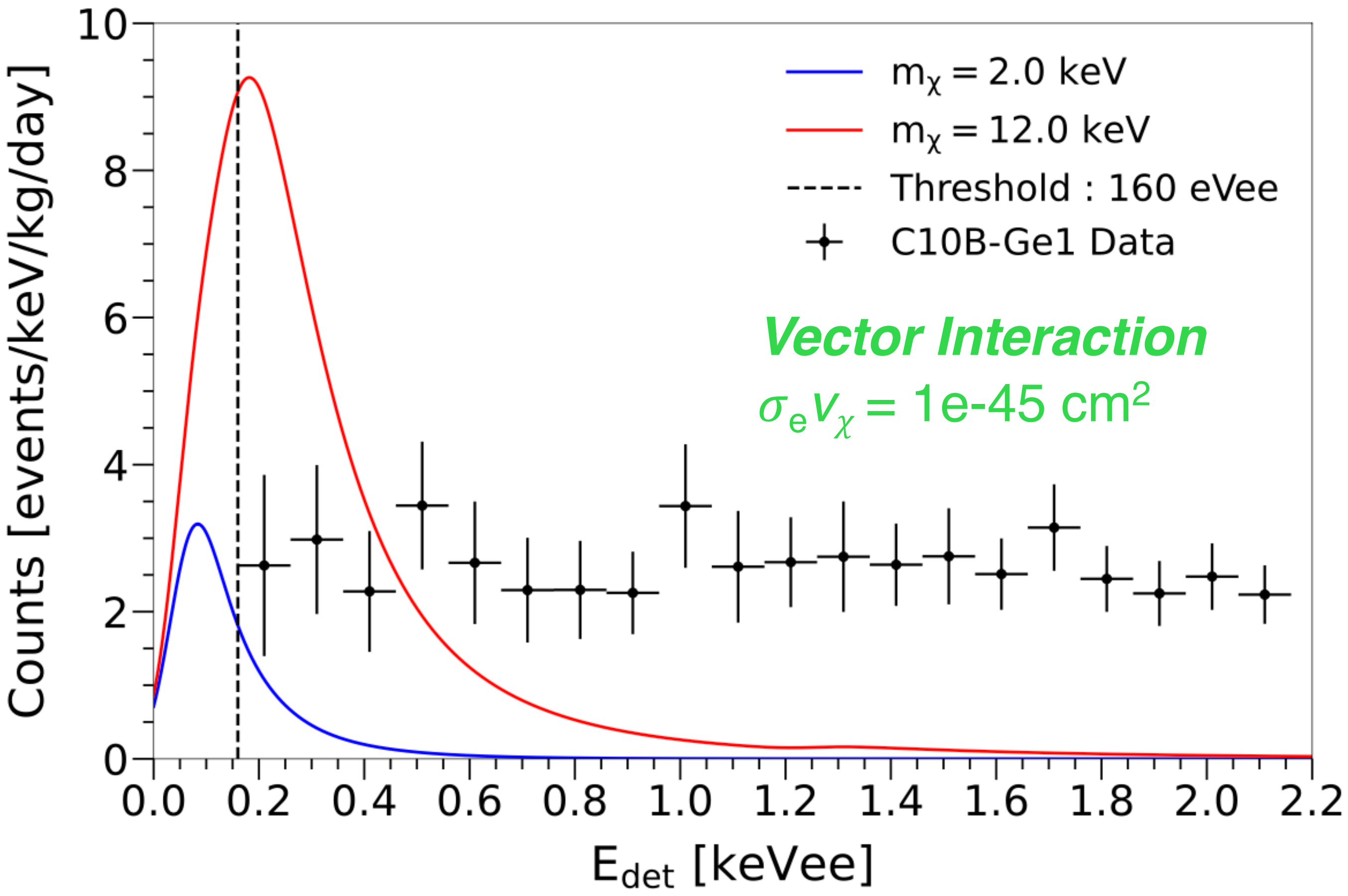
CDEX Fermionic Dark Matter Search

☐ Expected Spectra from Electron Absorption:

① Treat Ge as an ***isolated*** atom (a conservative assumption)

② Only consider absorption by ***core electrons in Ge (K-, L-, and M-shell electron)***

Theory:
J. A. Dror, et al, Phys. Rev. D 103, 035001 (2021).
S.F. Ge, et al. J. HighEnergy Phys. 05, 191 (2022).



Vector Interaction

$\sigma_e v_\chi$ = 1e-45 cm^2

neutrino energy *ionization form factor*

$$\frac{dR}{dE_{det}} = N_T \frac{\rho_\chi}{m_\chi} \sum_{n.l} \frac{|\mathcal{M}(q)|^2}{64\pi m_\chi m_e^2} \frac{q}{E_{det} - |E_B^{nl}|} |f_{ion}^{nl}(k', q)|^2$$

Binding energy

$$|\mathcal{M}^{V,A}(q)|^2 = (4, 12) \times \frac{4\pi m_e^2 q}{m_\chi} (\sigma_e v_\chi)$$

*① **V:** **Vector** type operators in χ-e coupling*

*② **A:** **Axis-vector** type operators*

For two types of operators:

- ***Same spectrum shapes***
- ***Different event rates***

CDEX Fermionic Dark Matter Search

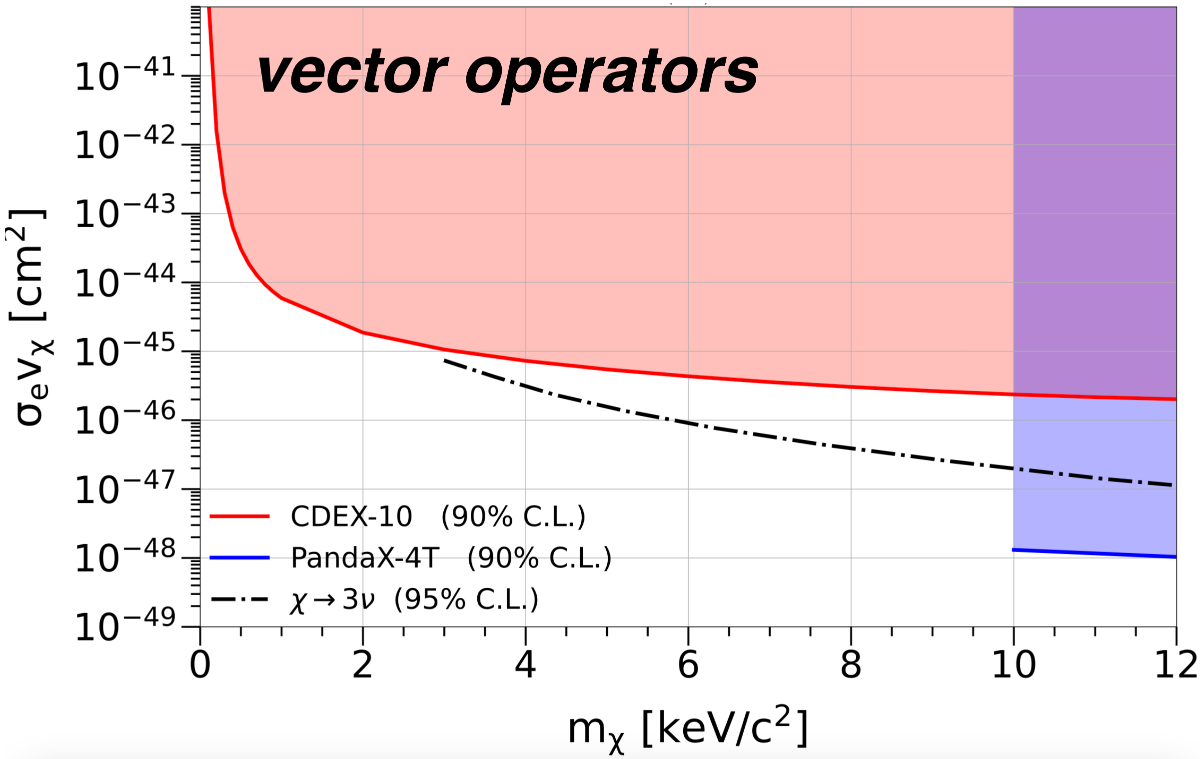
☐ Limits on Electron Absorption Cross-Section ($\sigma_e v_\chi$):

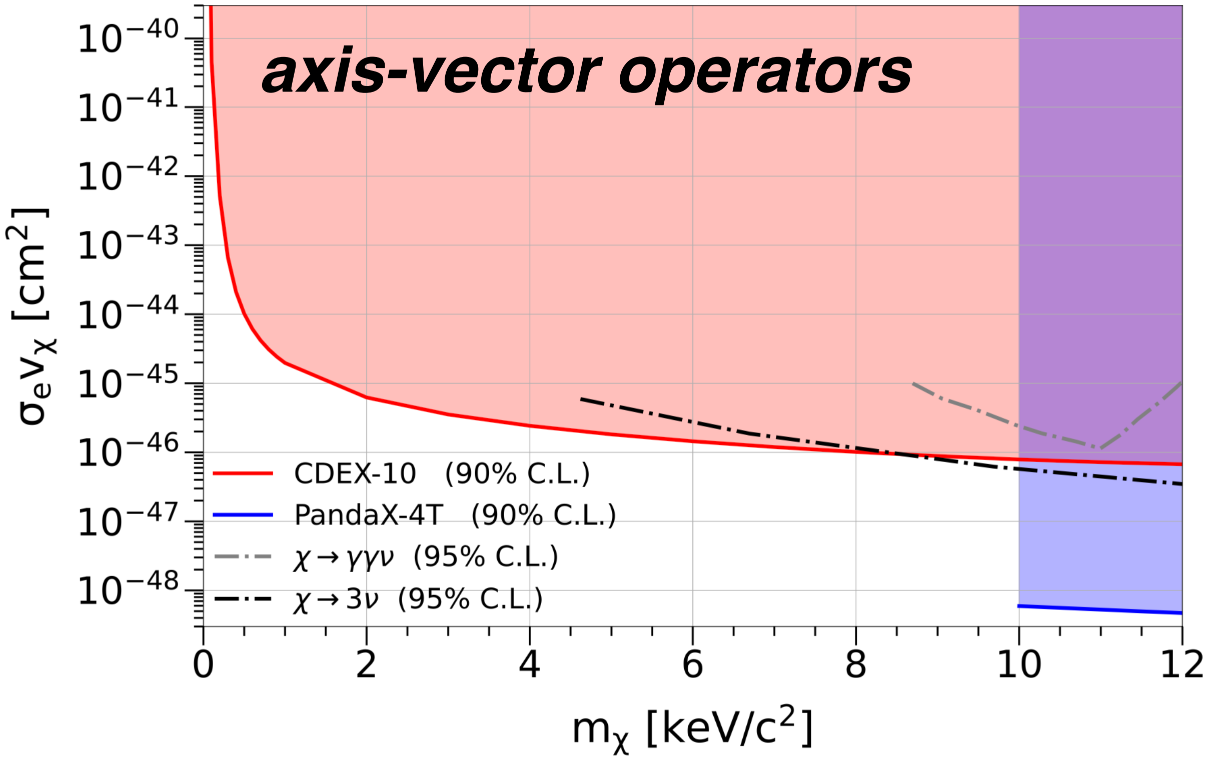
Analysis ***0.1~12 keV*** DM using C10B1 data

For vector and axis-vector operators:

- ***New Experiment results for m_χ = 0.1~10 keV***

arXiv:2404.09793v1





IV. Summary

CDEX Search for Light Dark Matter Absorption Signal in PCGe

(1) Dark Photon:

PRL 124, 111301, 2020
PRD 101, 052003, 2020

Solar Dark Photon (CDEX-10):

Best limit on mixing parameter (kappa) at the time of publication

Dark Photon Dark Matter (CDEX-10 & CDEX-1B):

Extend New parameter space at m_V=0.1~0.2 keV at the time of publication

(2) Axion and Axion-Like-Particles:

PRD 101, 052003, 2020
PRD 96, 122002 2017

Solar Axion (CDEX-1A & CDEX-1B):

Set limits on axion-electron & axion-nuclear coupling via solar CBRD & Fe-57 axion channel

Axion-Like-Particles (CDEX-1A & CDEX-1B):

Extend parameter space to m_A=185 eV at the time of publication

(3) Fermionic Dark Matter:

PRL 129, 221802, 2022
arXiv:2404.09793v1

Neutral current absorption with Nucleus (CDEX-10):

Extend New parameter space at m_χ=10~27 MeV for absorption cross-section

Neutral current absorption with Electron (CDEX-10):

New experiment results for m_χ=0.1~10 keV for axis-vector (vector) absorption cross-section

Thanks for your attention!

中国暗物质实验

China Dark matter EXperiment

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

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

http://cjpl.tsinghua.edu.cn

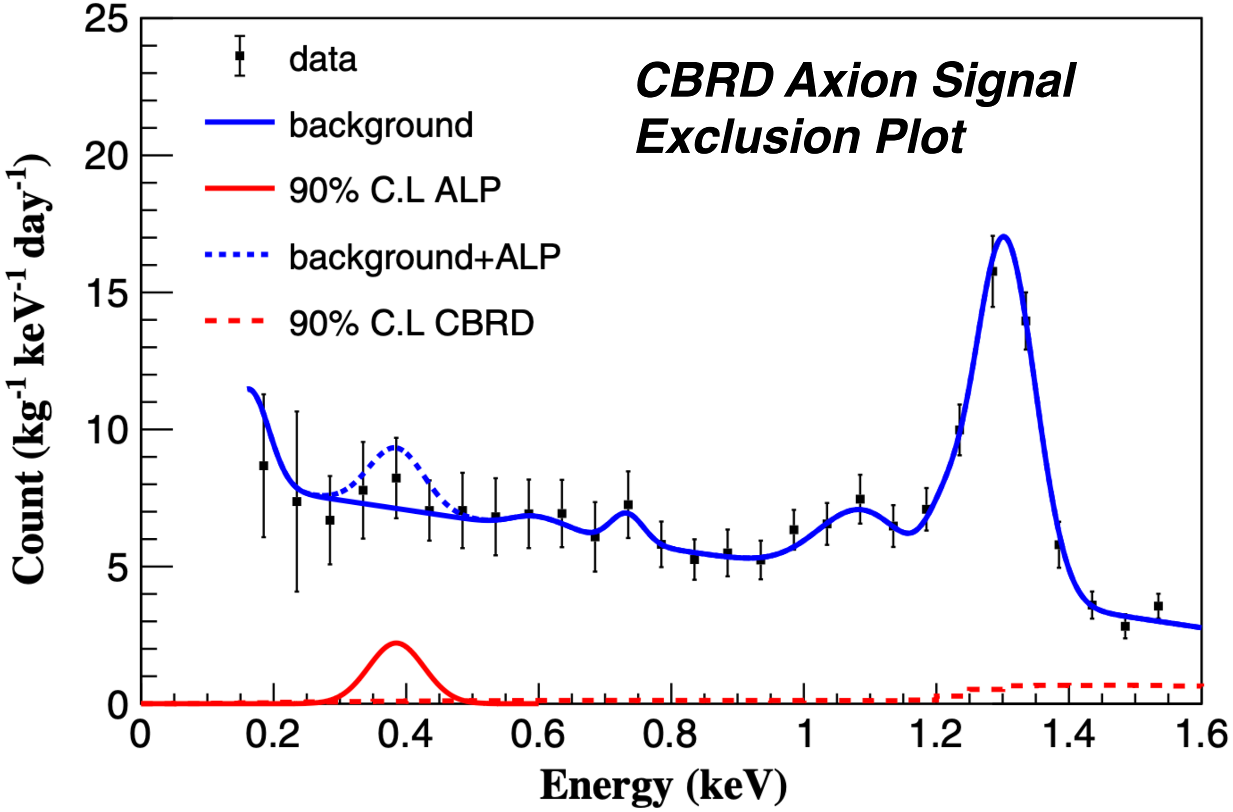
Back Up Material

CDEX Axion & Axion-Like Particle Search

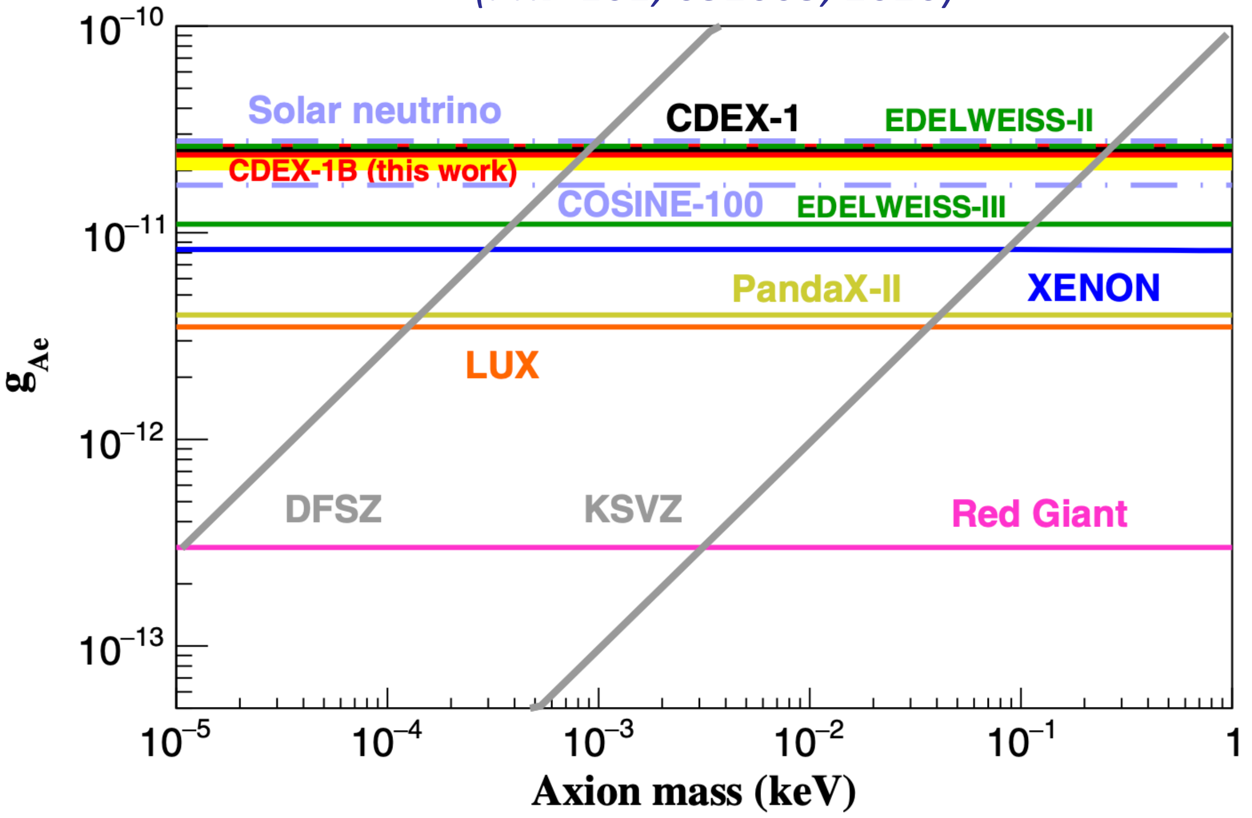
☐ Solar CBRD Axion Result:

Analyze Axion signal via *Profile Likelihood* method

Set limits on axion-electron coupling: $g_{Ae} < 2.48E\text{-}11$



(PRD 101, 052003, 2020)



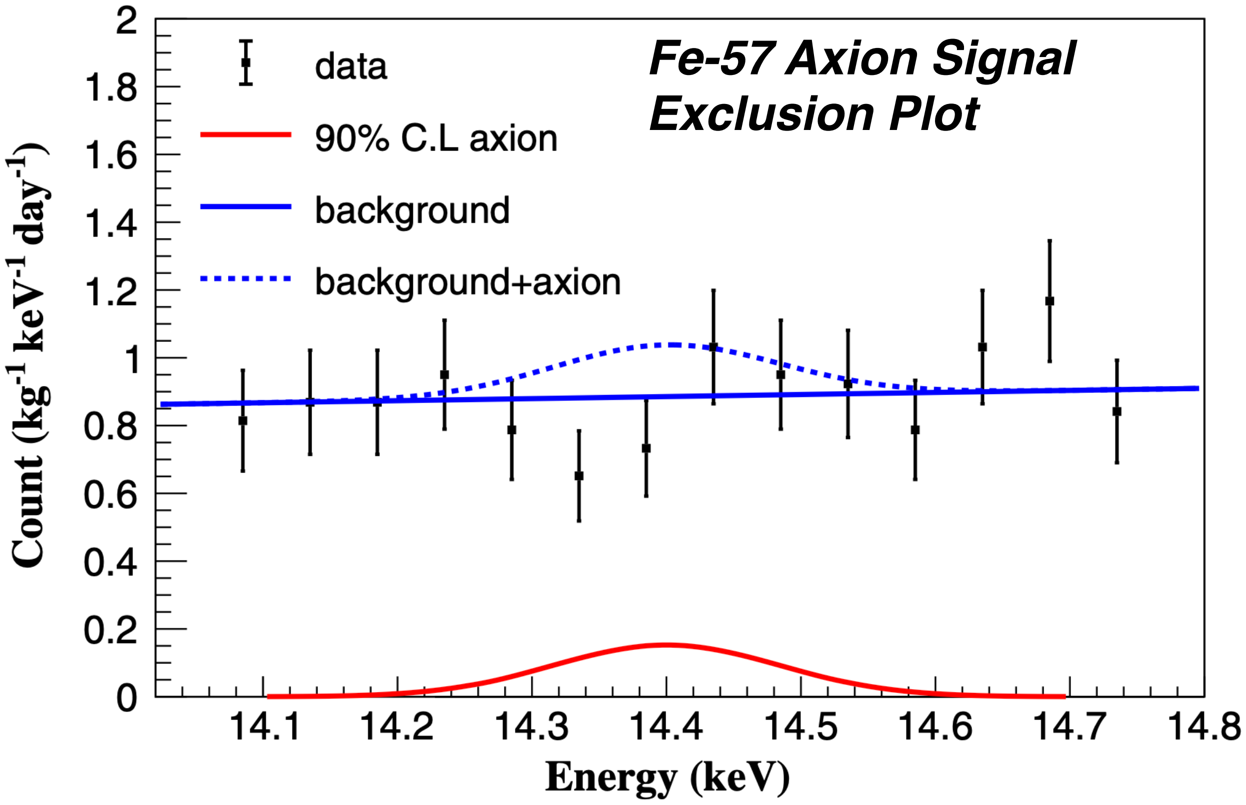
CDEX Axion & Axion-Like Particle Search

☐ Solar Fe-57 Axion Result:

Analyze Axion signal via *Profile Likelihood* method

Set limits on axion-electron coupling (g_{Ae}) & axion-nuclear coupling (g_{AN})

- ***For m_A=0, $g_{Ae} \times g_{AN}$ <4.14E-17***



(PRD 101, 052003, 2020)