清華大學
Tsinghua University

基于CDEX-1实验的亚GeV暗物质探测与调制效应研究

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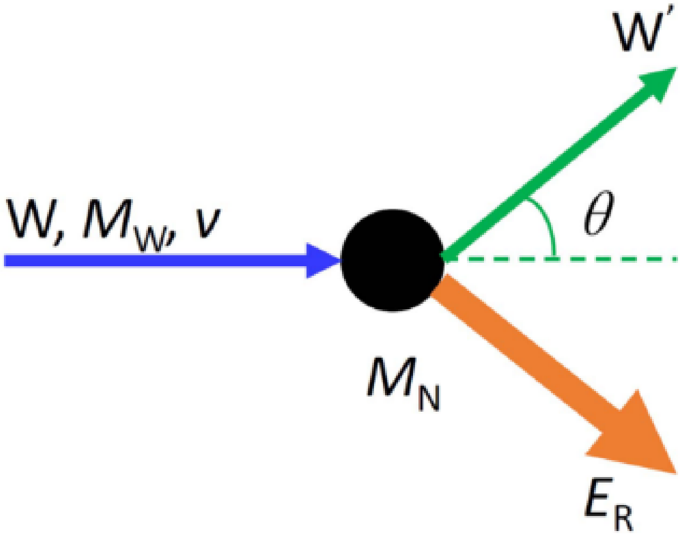
Outline

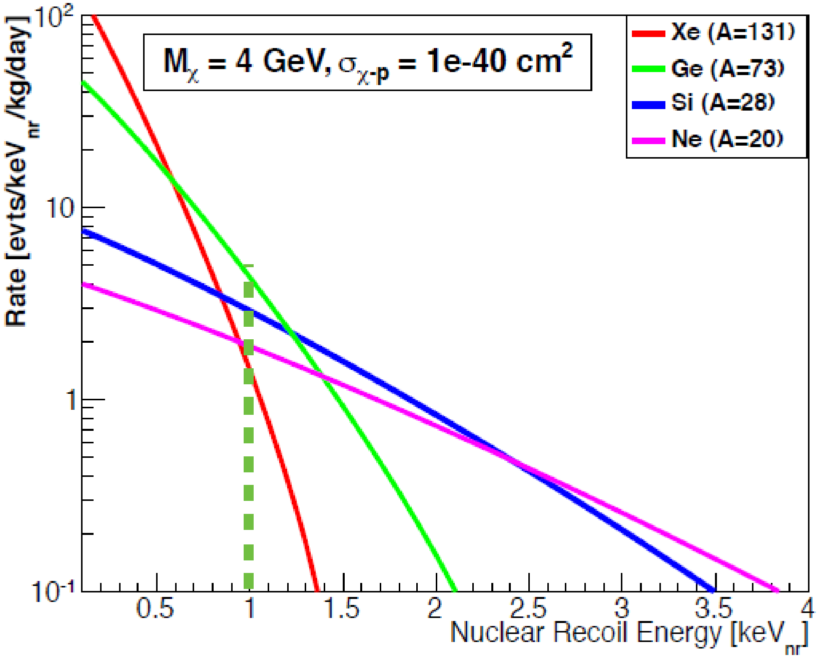
- Introduction of CDEX-1B experiment
- Annual modulation analysis
- Detection of sub-GeV dark matter
- Summary

Introduction of CDEX-1B experiment

Introduction of CDEX-1B experiment

Elastic Scattering

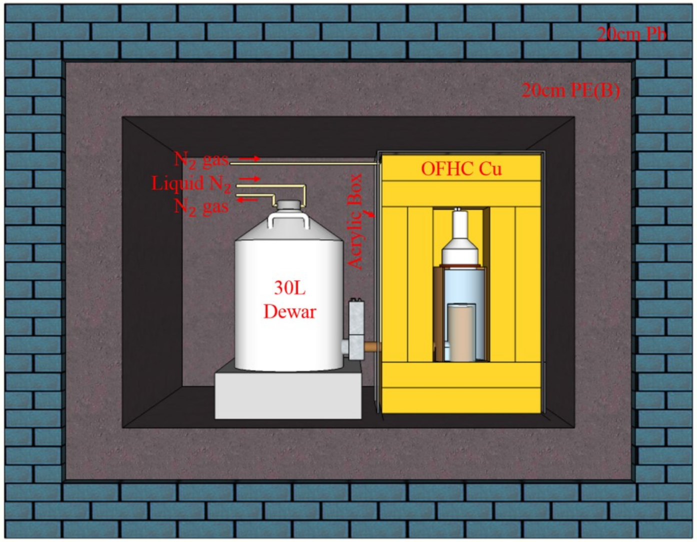


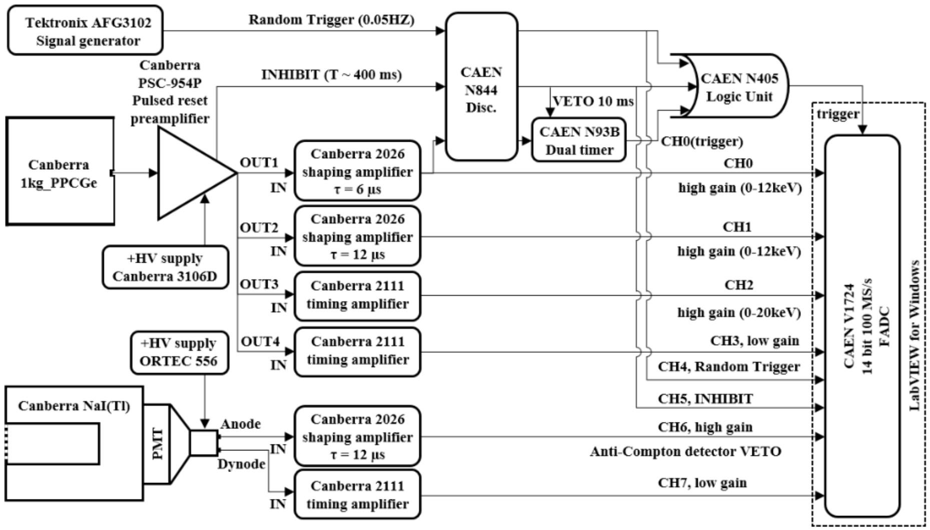


- ☐ **Lower Background**
- ☐ **Lower Energy threshold**
- ☐ **Long-time stability**

Introduction of CDEX-1B experiment

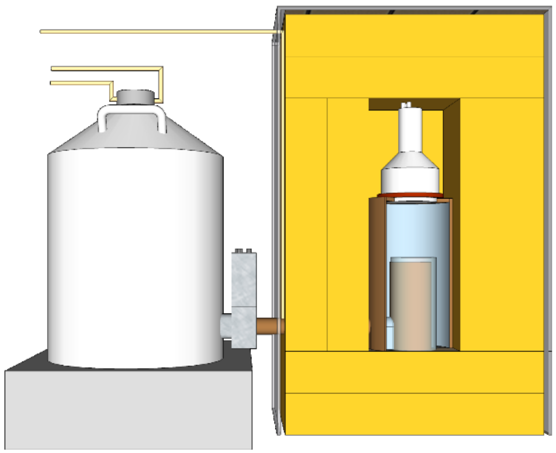
- 1 kg-scale-mass HPGe detector, cooled by cold finger.
- A NaI(Tl) detector is used as active shielding to veto the gamma-ray induced background events.
- The detector has been under stable data taking conditions since March 27th, 2014.



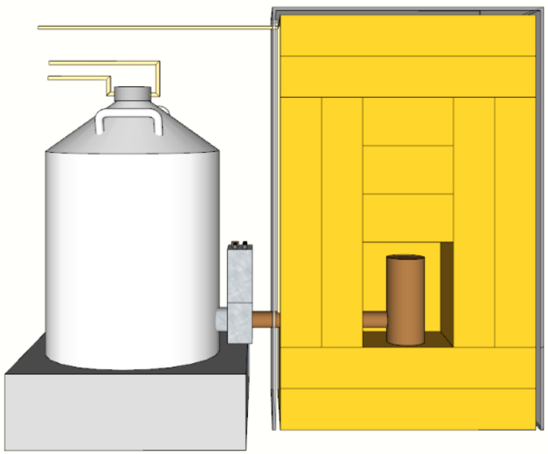


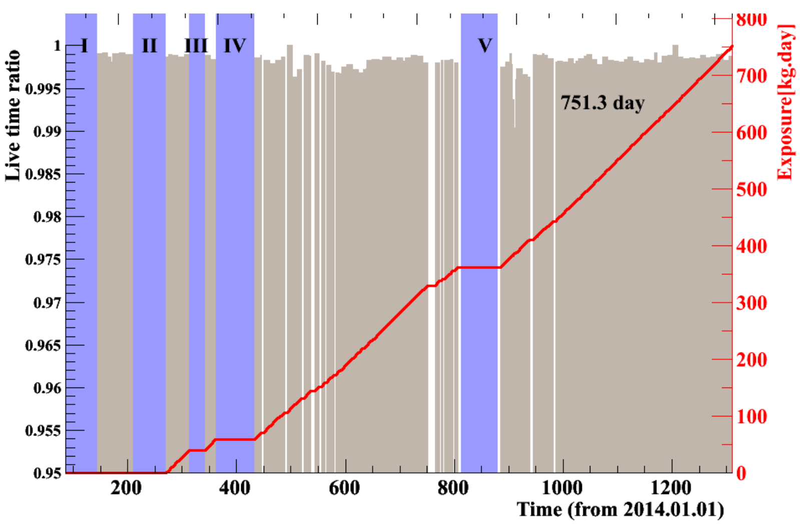
Introduction of CDEX-1B experiment

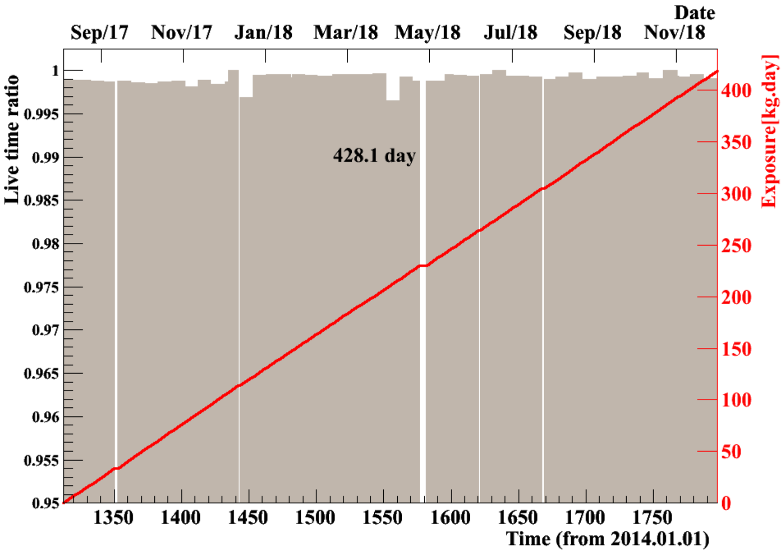
RUN-1



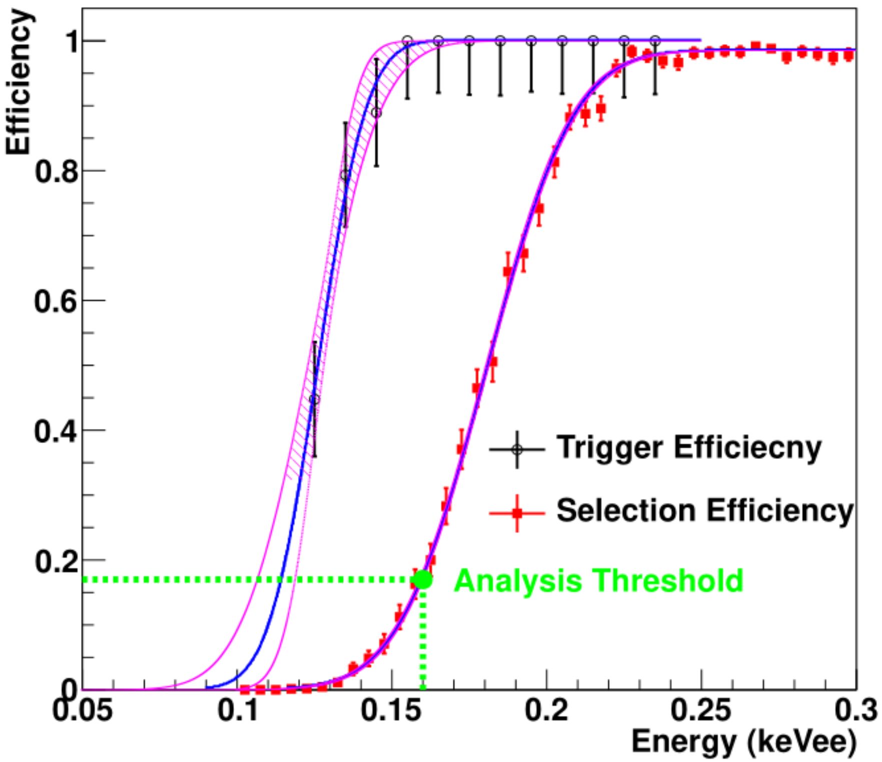
RUN-2

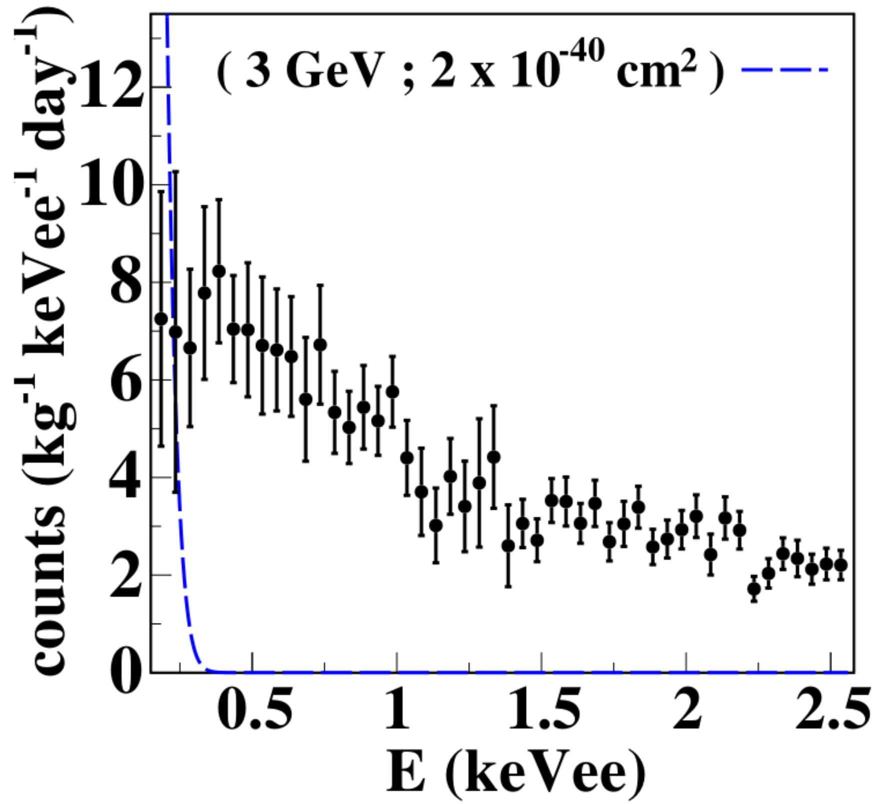






Introduction of CDEX-1B experiment



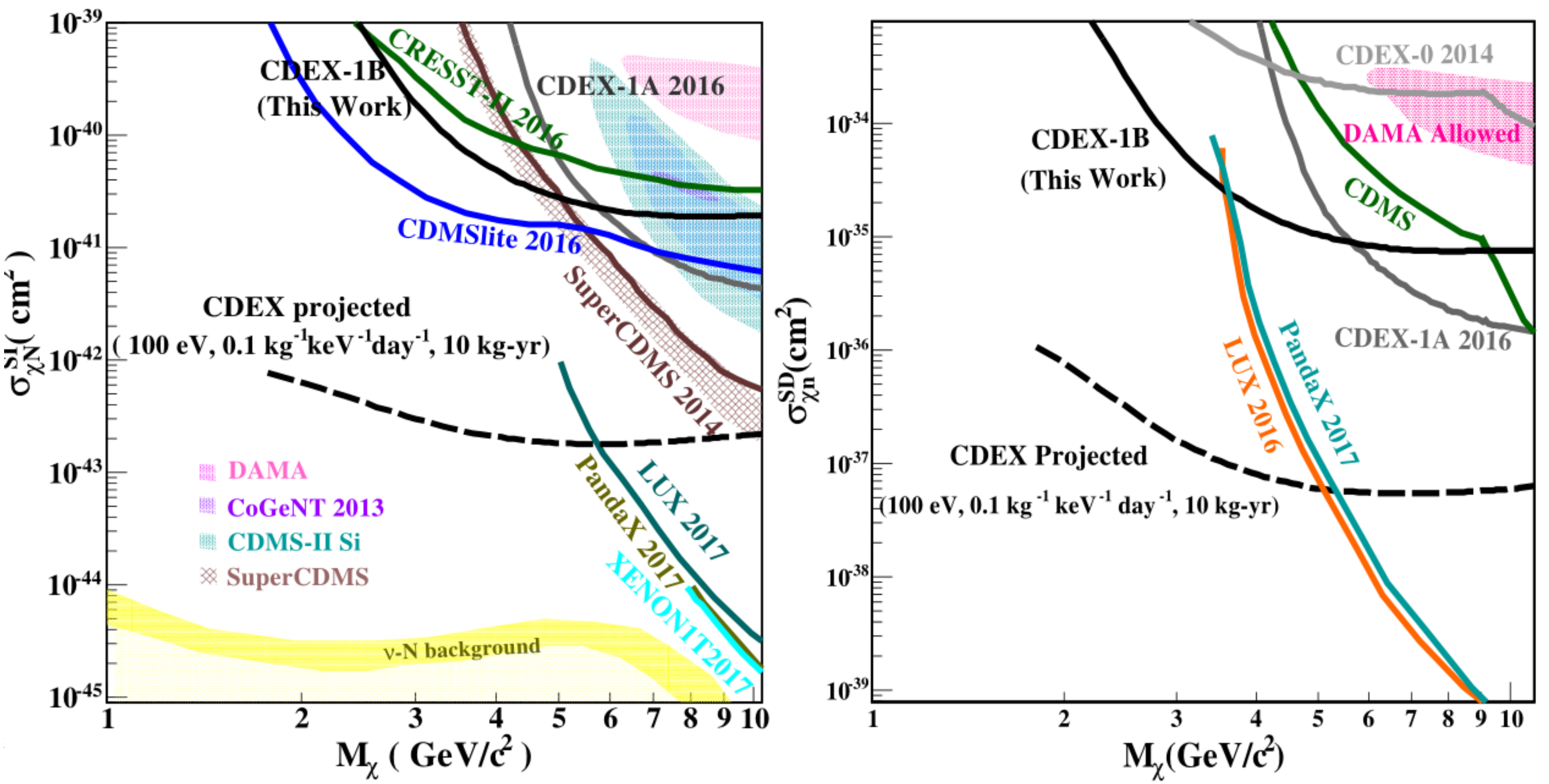


- ➢ The data used for the TI analysis is from March 2014 to July 2017, with a total exposure of **737.1 kg·day**.
- ➢ The energy threshold is **160 eVee**, with a combined efficiency of **17%**.

Introduction of CDEX-1B experiment

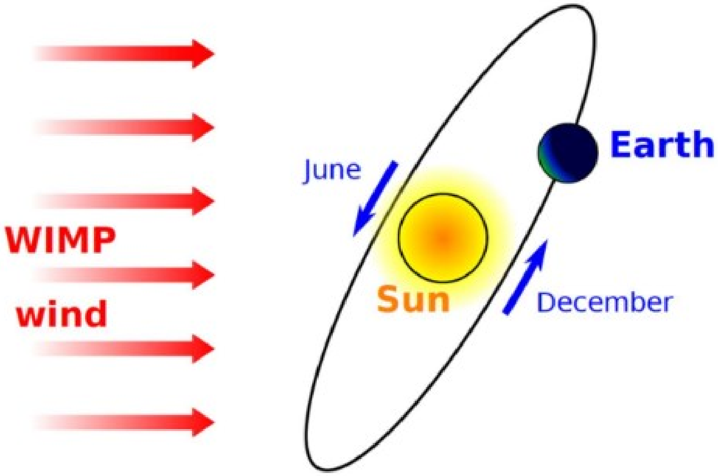
- Exclusion plots of spin-independent and spin-dependent χ-N scattering at 90% confidence level. (**derived by binned poisson method**)

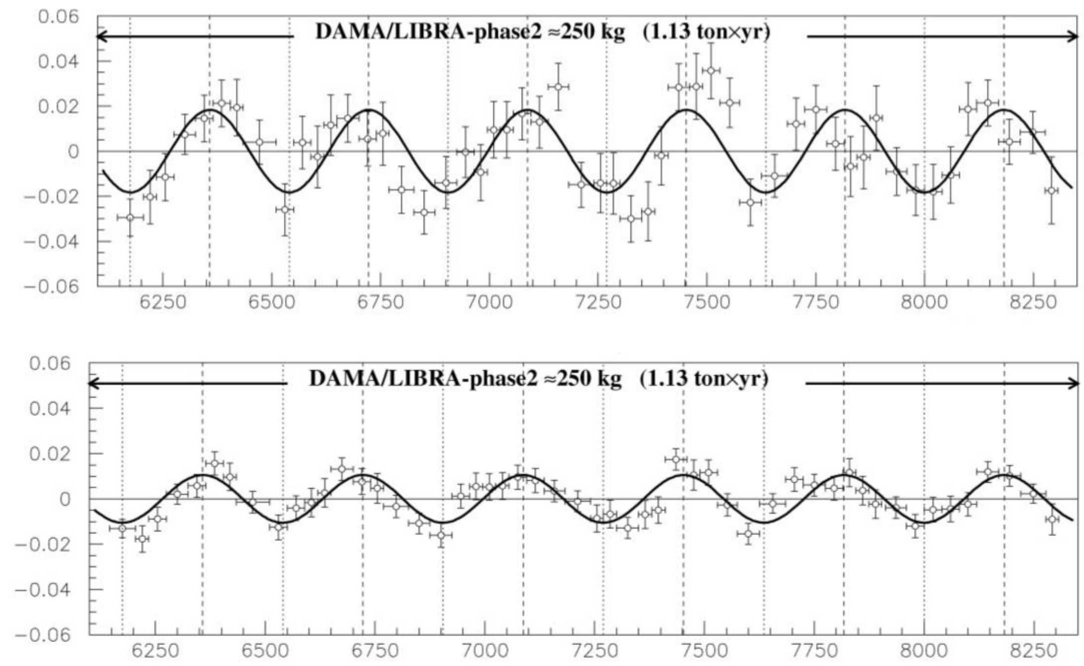
L. T. Yang et al., Chin. Phys. C 42, 23002 (2018)

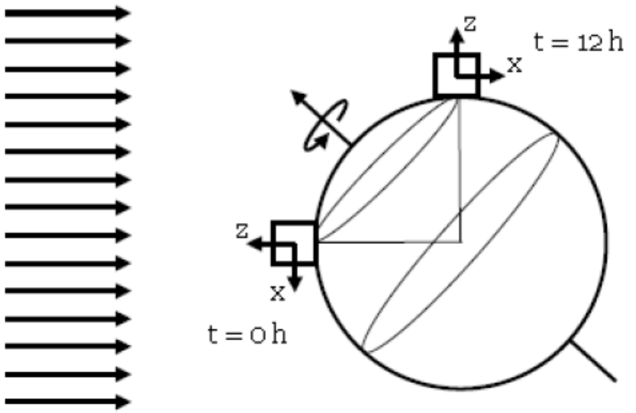


Annual modulation analysis

Annual modulation analysis





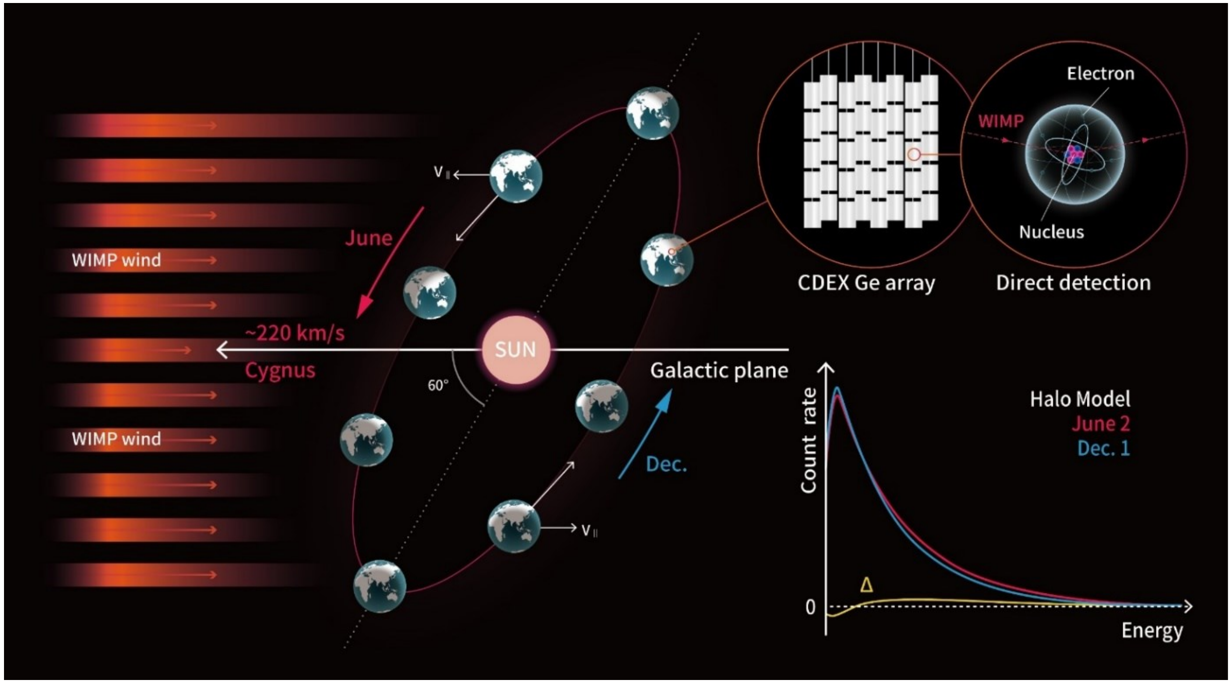


$$v_E = 232 + 30 \times 0.51 \cos(2\pi/T \times (t - \Phi)) \text{ km/s}$$

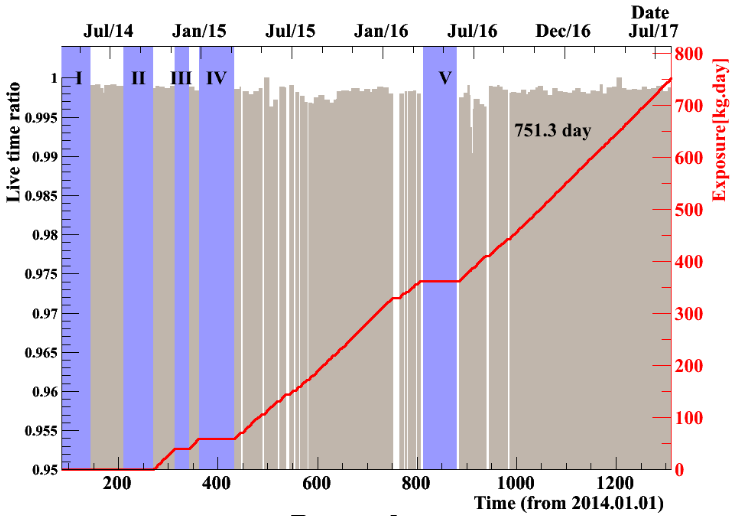
- ☐ **Lower Background**
- ☐ **Long-time stability**

Annual modulation analysis

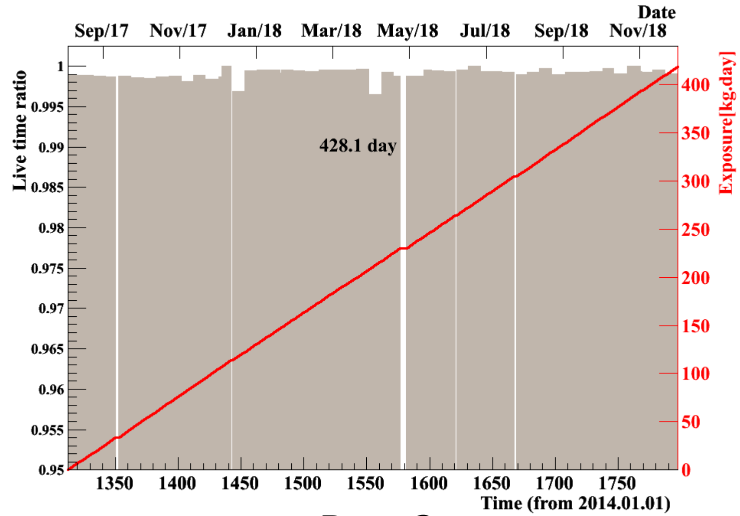
- AM provide smoking-gun signatures for WIMPs independent of background modeling, while only requires background at relevant energy range is stable with time;
- The expected χN rates have distinctive AM features with maximum intensity in June and a period of one year due to Earth's motion relative to the galactic WIMP-halo.



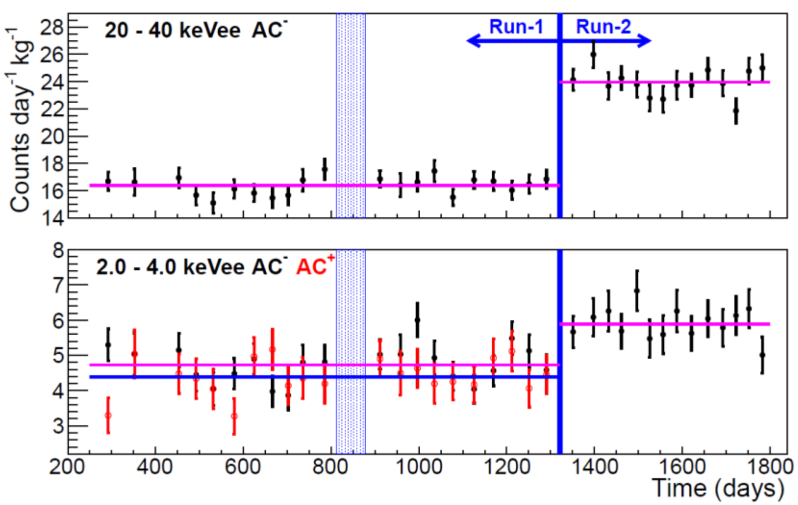
Annual modulation analysis



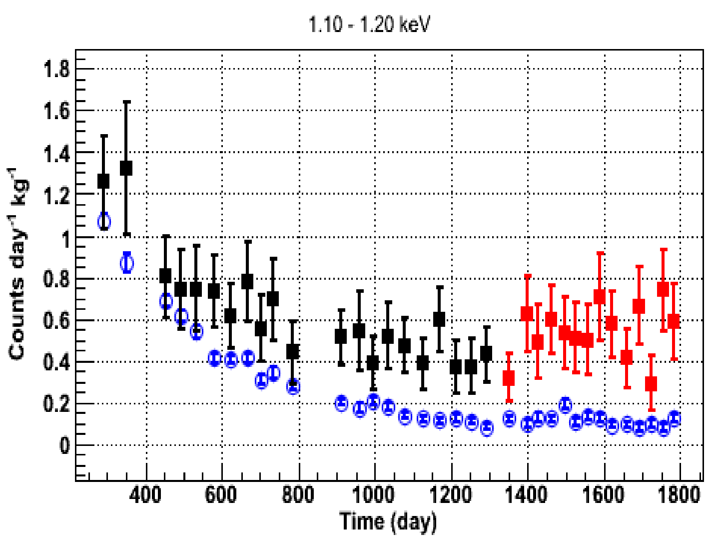
Run-1



Run-2



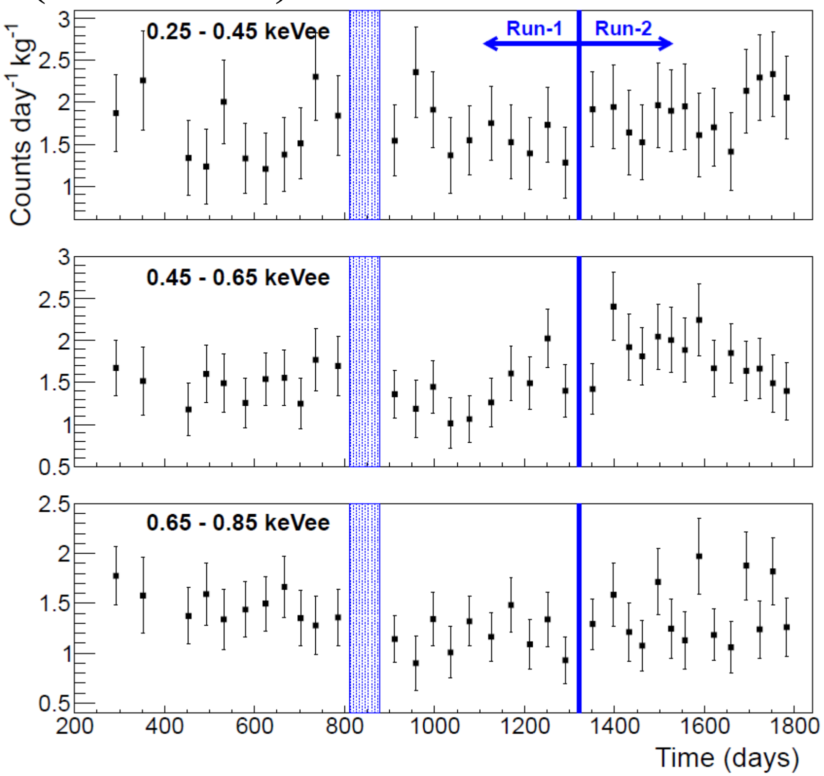
Compton contribution from High-energy gammas



L-Shell X-ray contribution – time varying

Annual modulation analysis

Bulk event count rates vs. time (after B/S)

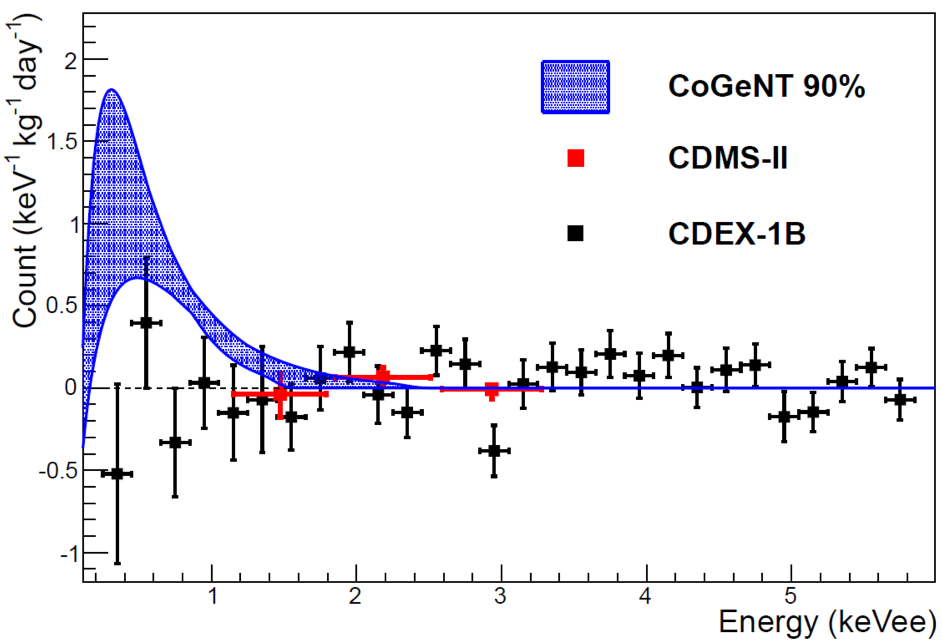


- There are two datasets, Run-1 with the NaI(Tl) anti-Compton detector, and Run-2 without NaI(Tl), having 751.3 and 428.1 live days, respectively, and together spanning a total of 1527 calendar days (~4.2 yr) and a total exposure of 1107.5 kg·day.

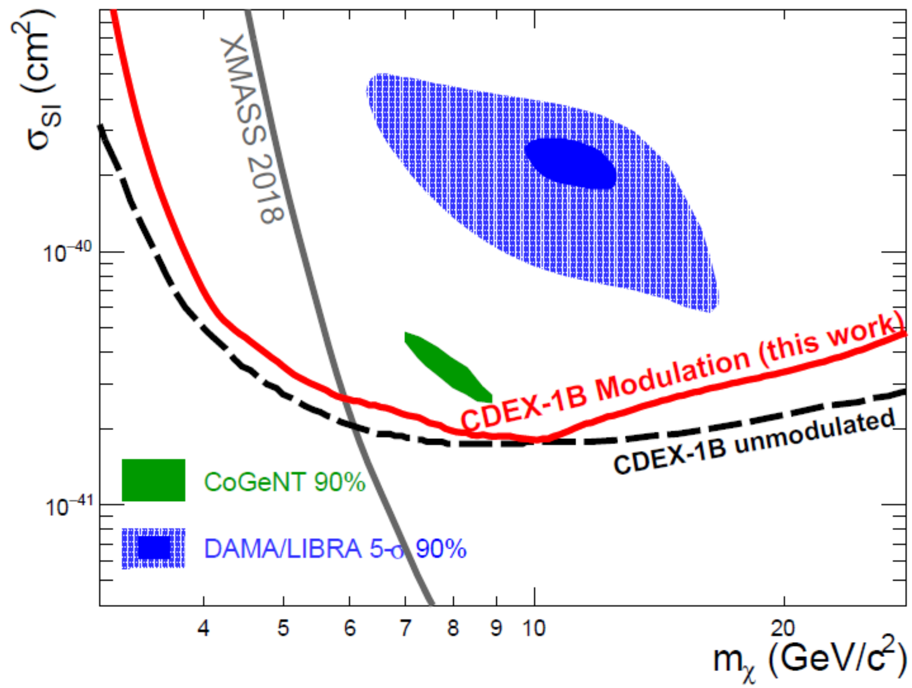
$$\chi^2_{ik} = \sum_{j\in \mathrm{Time}}^{N} \frac{(n_{ijk} - P_{ijk} - B_{ik} - A_{ik}cos(\frac{2\pi(t_j-\phi)}{T_{yr}}))^2}{\Delta^2_{ijk}}$$

Annual modulation analysis

Best-fit of modulation amplitude w/ phase=152.5day



SI Limits at 90% C.L. from AM



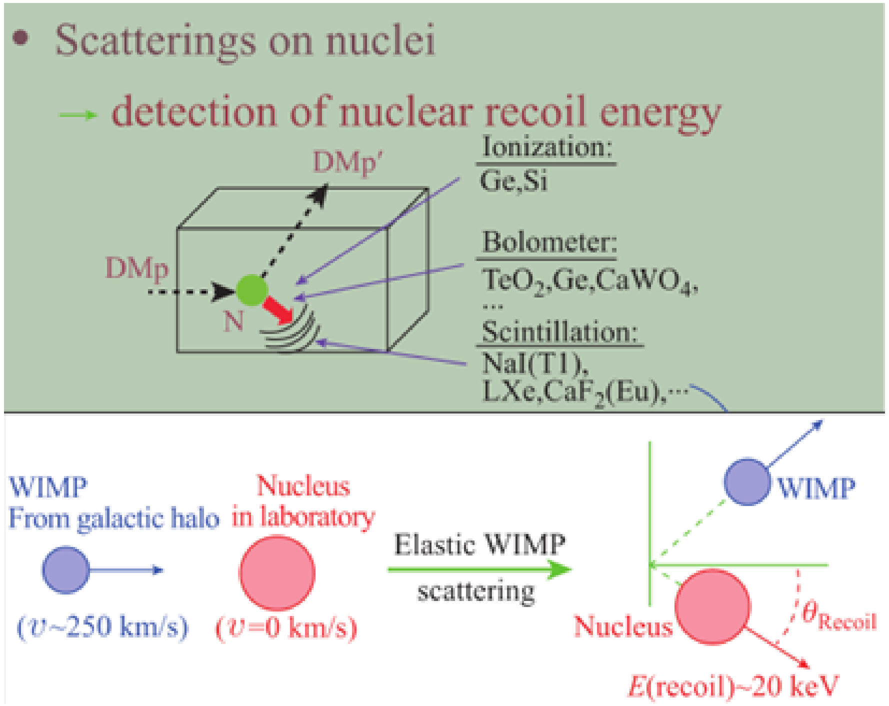
✓ CDEX-1B excludes DAMA/LIBRA phase-1's interpretation with the spin-independent WIMP interaction with Standard Halo model in Germanium crystal.

PRL 123.221301 (2019)

Detection of sub-GeV dark matter

Detection of sub-GeV dark matter

➢ In dark matter direct detection experiments, it is usually assumed that the extranuclear electrons around the recoil nucleus immediately follow the motion of the nucleus.



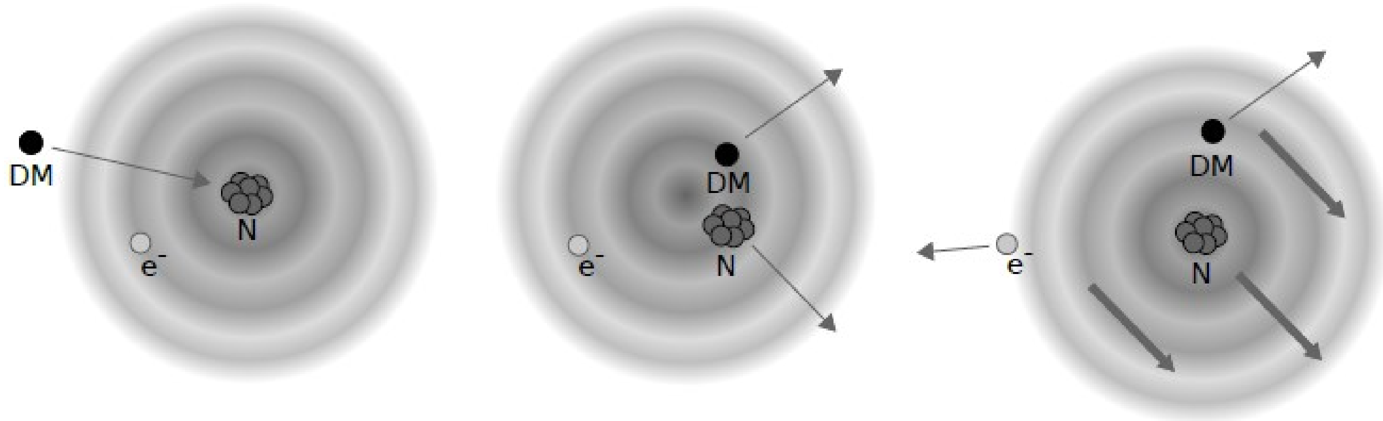
✓ **nuclear recoil without atomic excitation**

$$\chi + N \rightarrow \chi + N(E_R)$$

➢ The recoil “atom” loses its energy through scattering with adjacent atoms in the medium where the inelastic scatterings involve the ionization and excitation of the atoms.

Detection of sub-GeV dark matter

- However, it takes some time for the electrons to catch up, which causes ionization and excitation of the recoil atom. The ionization and the excitation result in extra electronic energy injections into the detectors.



χ-N inelastic scattering

M.J. Dolan, et al. Phys. Rev. Lett. 121, 101801 (2018)

Detection of sub-GeV dark matter

- Single electron transition rates:

$$\sum_F |Z_{FI}|^2 = |Z_{II}|^2 + \sum_{n,\ell,n',\ell'} p_{q_e}^d(n\ell \to n'\ell') + \sum_{n,\ell} \int \frac{dE_e}{2\pi} \frac{d}{dE_e} p_{q_e}^c(n\ell \to E_e)$$

excitation ionization

- The excitation probabilities are much smaller than the ionization probabilities for a given initial n.

- The event rates:

$$\frac{dR}{dE_R\, dE_e\, dv_{DM}} \simeq \frac{dR_0}{dE_R\, dv_{DM}} \times \frac{1}{2\pi} \sum_{n,\ell} \frac{d}{dE_e} p_{q_e}^c(n\ell \to E_e)$$

$$\frac{dR_0}{dE_R\, dv_{DM}} \simeq \frac{1}{2} \frac{\rho_{DM}}{m_{DM}} \frac{1}{\mu_N^2} \tilde{\sigma}_N(q_A) \times \frac{\tilde{f}(v_{DM})}{v_{DM}} .$$

M. Ibe, et al. J. High Energy Phys. 03 (2018) 194.

$$E_R \simeq \frac{q_A^2}{2m_A} , \quad q_e \simeq \frac{m_e}{m_A} q_A .$$

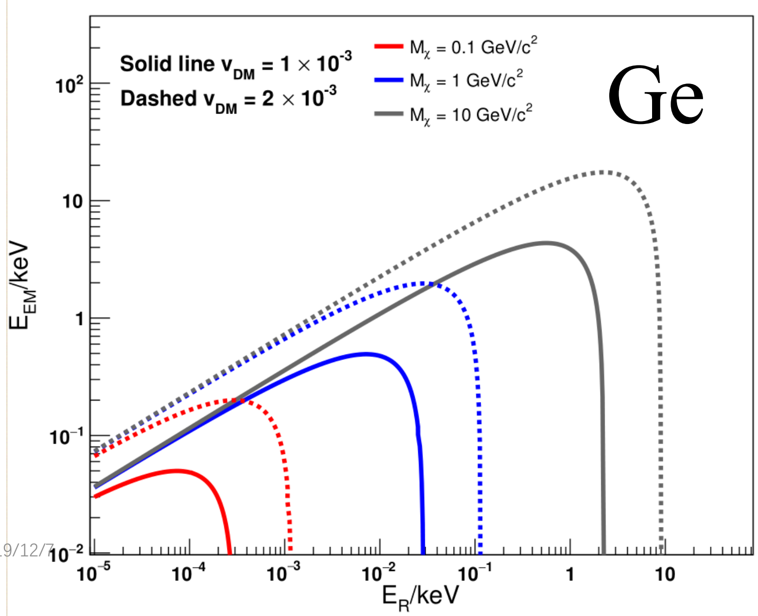
Detection of sub-GeV dark matter

- The total electronic energy released at the ionization is given by :

$$E_{EM} = E_e + E_{nl}$$

- The boundary of E_{EM}, v_{DM} and E_R :

$$v_{DM} \geq \frac{m_N E_R + \mu_N E_{EM}}{\mu_N \sqrt{2 m_N E_R}} \qquad E_{EM} \leq \frac{1}{2} \mu_N {v_{DM}}^2 \qquad E_R \leq \frac{2{\mu_N}^2 {v_{DM}}^2}{m_N}$$



- For Ge,

$$v_{max} = 764 km/s,$$
$$E_{th} = 0.16\ keV,$$
$$m_{DM,min} \approx 0.05 GeV$$

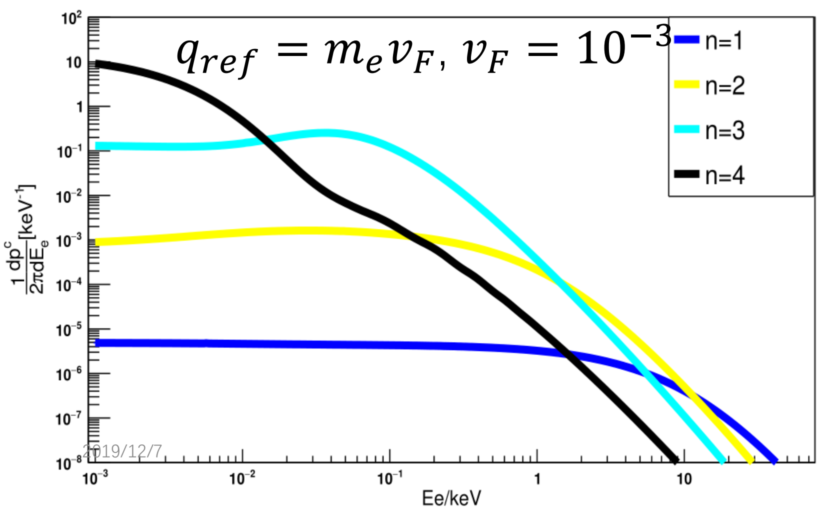
M. Ibe, et al. J. High Energy Phys. 03 (2018) 194.

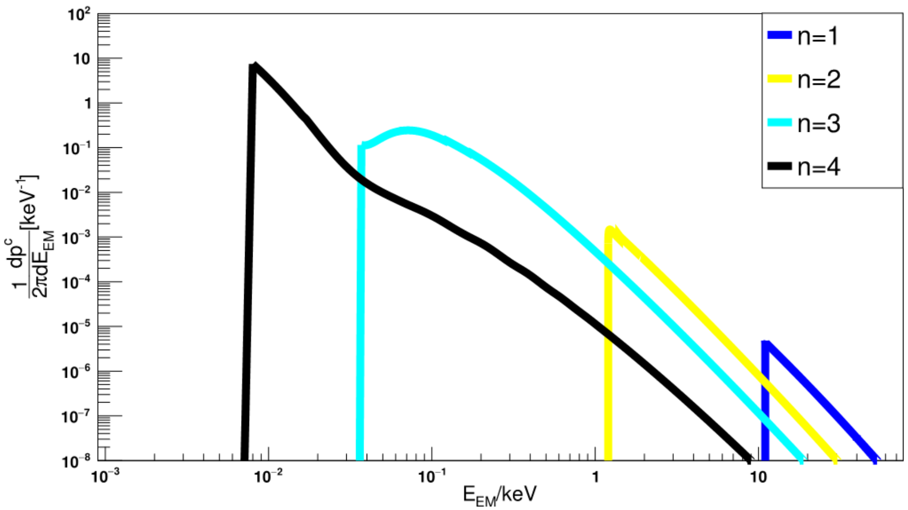
Detection of sub-GeV dark matter

- The most important is dp^c/dE_e M. Ibe, et al. J. High Energy Phys. 03 (2018) 194.
- The dp^c/dE_e for a different q_e is obtained by multiplying ${q_e}^2/{q_{ref}}^2$

The atomic structure of Ge

(n,l)	1s	2s	2p	3s	3p	3d	4s	4p
E_{nl}/eV	1.1×10^4	1.4×10^3	1.2×10^3	1.7×10^2	1.2×10^2	35	15	6.5





Detection of sub-GeV dark matter

- The energy HPGe detector will detect is :

$$E_{det} = E_{EM} + Q_{nr} E_R$$

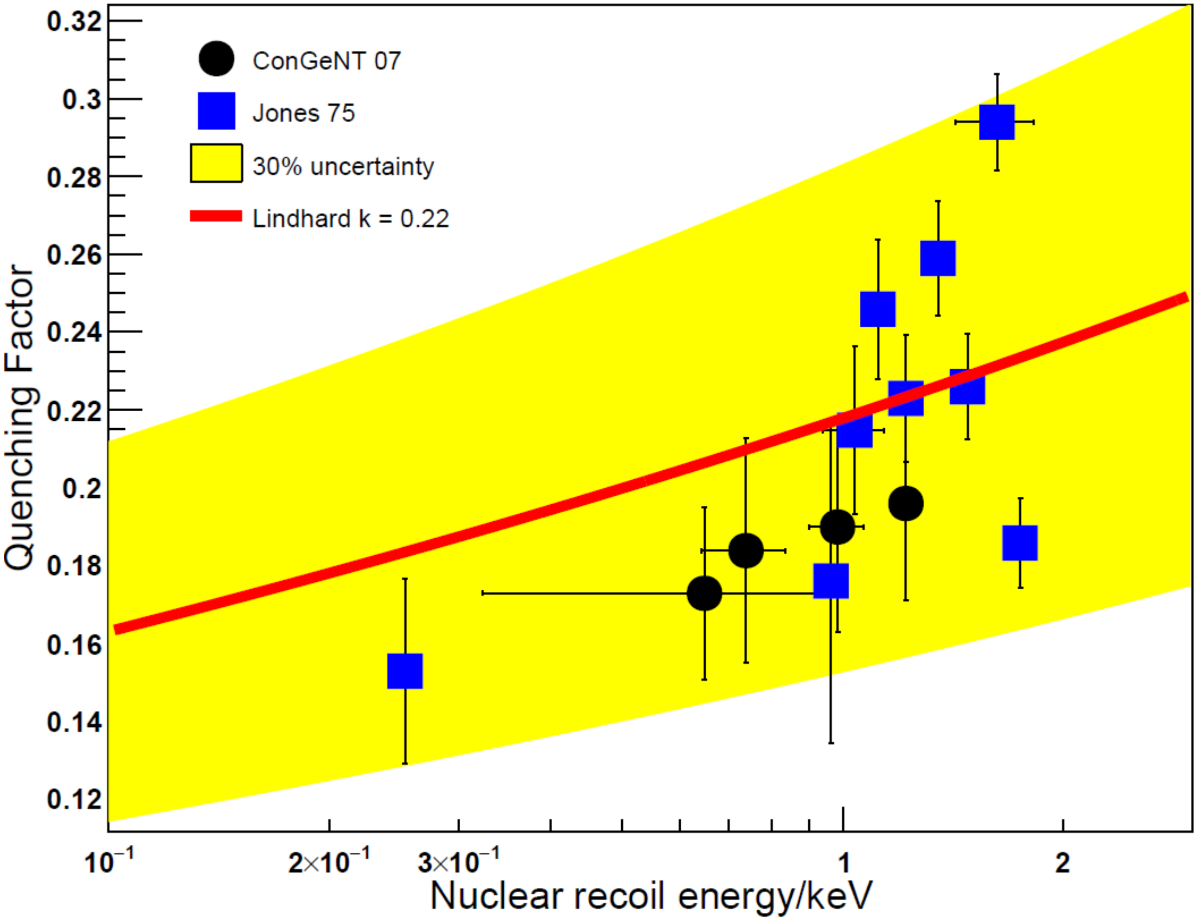
- So the spectrum is given by :

$$\frac{dR}{dE_{det} dv_{DM}} = \int d\, E_R dE_{EM} \delta(E_{det} - Q_{nr} E_R - E_{EM}) \frac{dR}{dE_R dE_{EM} dv_{DM}}$$

- parameter setting:
  - $\rho_{DM} = 0.3 GeV/cm^3$, $v_E = 232\ km/s$
  - Maxwell velocity distribution $v_0 = 220\ km/s$
  - the Galactic escape velocity $v_{esc} = 544\ km/s$
  - Helm form factor

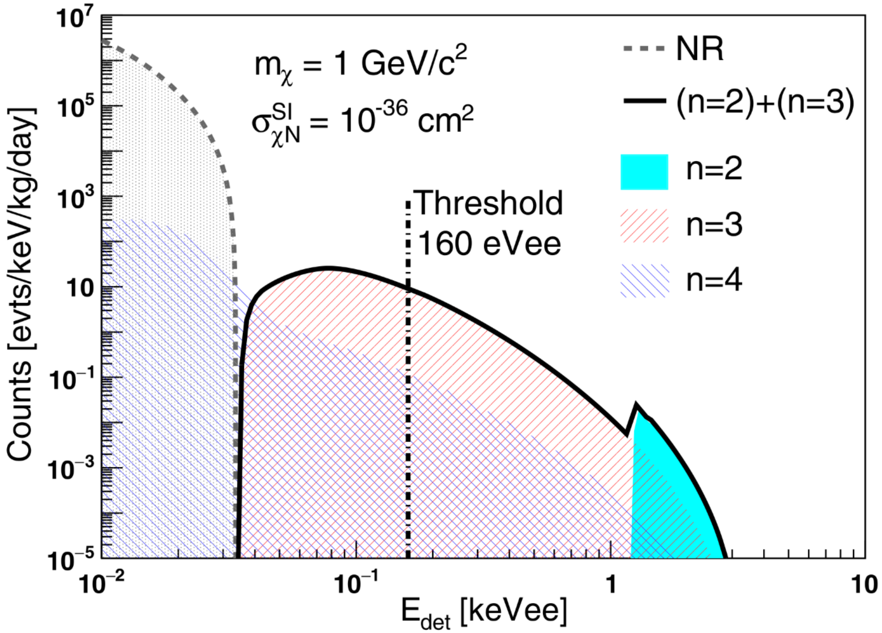
Detection of sub-GeV dark matter

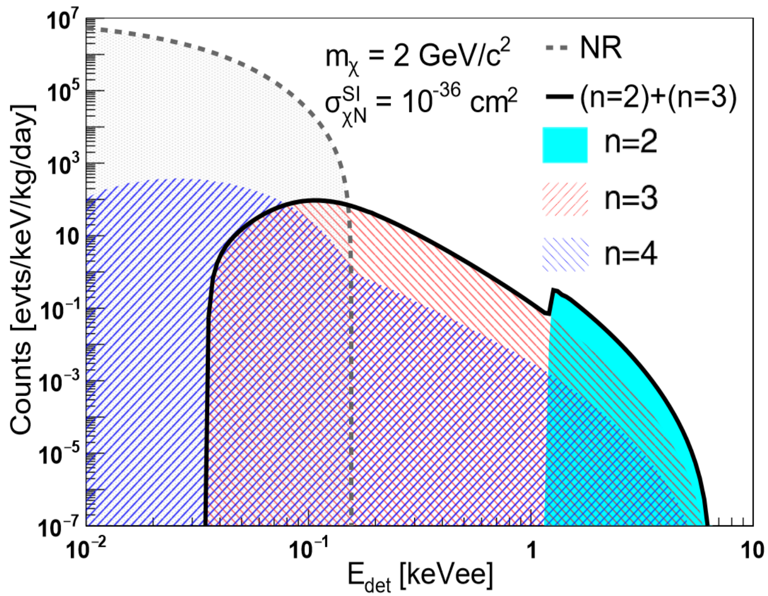
- Lindhard formula (semi-rational) → $Q_{nr} = \frac{\kappa g(\varepsilon)}{1+\kappa g(\varepsilon)}$

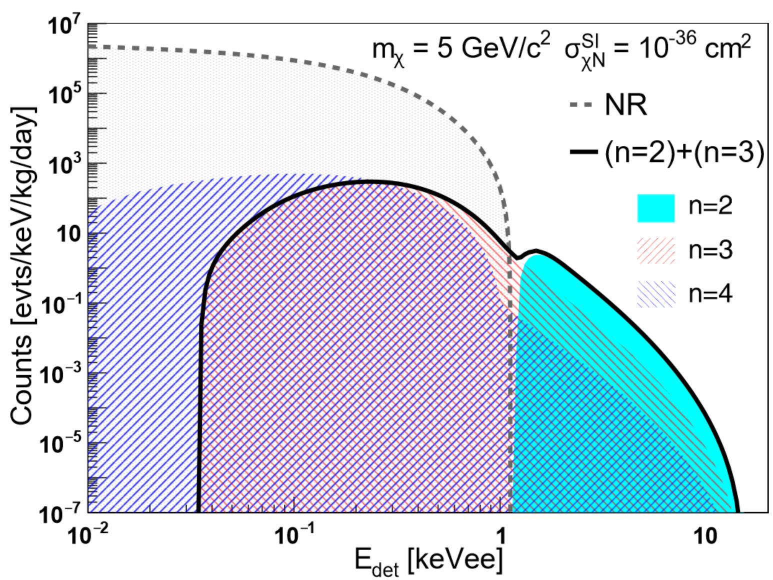


- The quenching factor in Ge used is calculated by Lindhard formula.
- The value of κ in Lindhard formula is fitted by experiment data under 2 keVnr with 30% uncertailty.

Detection of sub-GeV dark matter





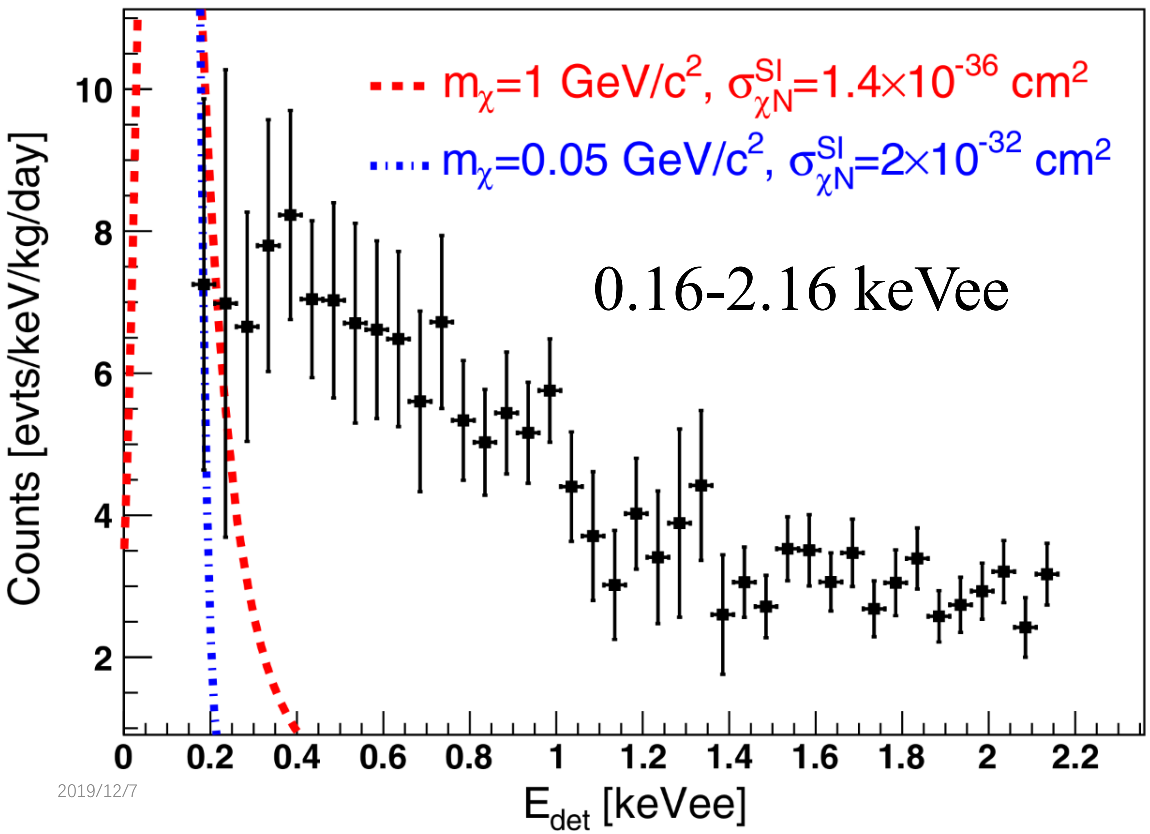


- Expected measureable spectra of the χ-N elastic SI-scattering and χ-N inelastic SI-scattering with Migdal effect incorporated.

TI analysis

Detection of sub-GeV dark matter

- Experiment data : from CDEX-1B
- Exposure : 737.1 kg · day



- **The ionization of N shell electrons were not considered.**

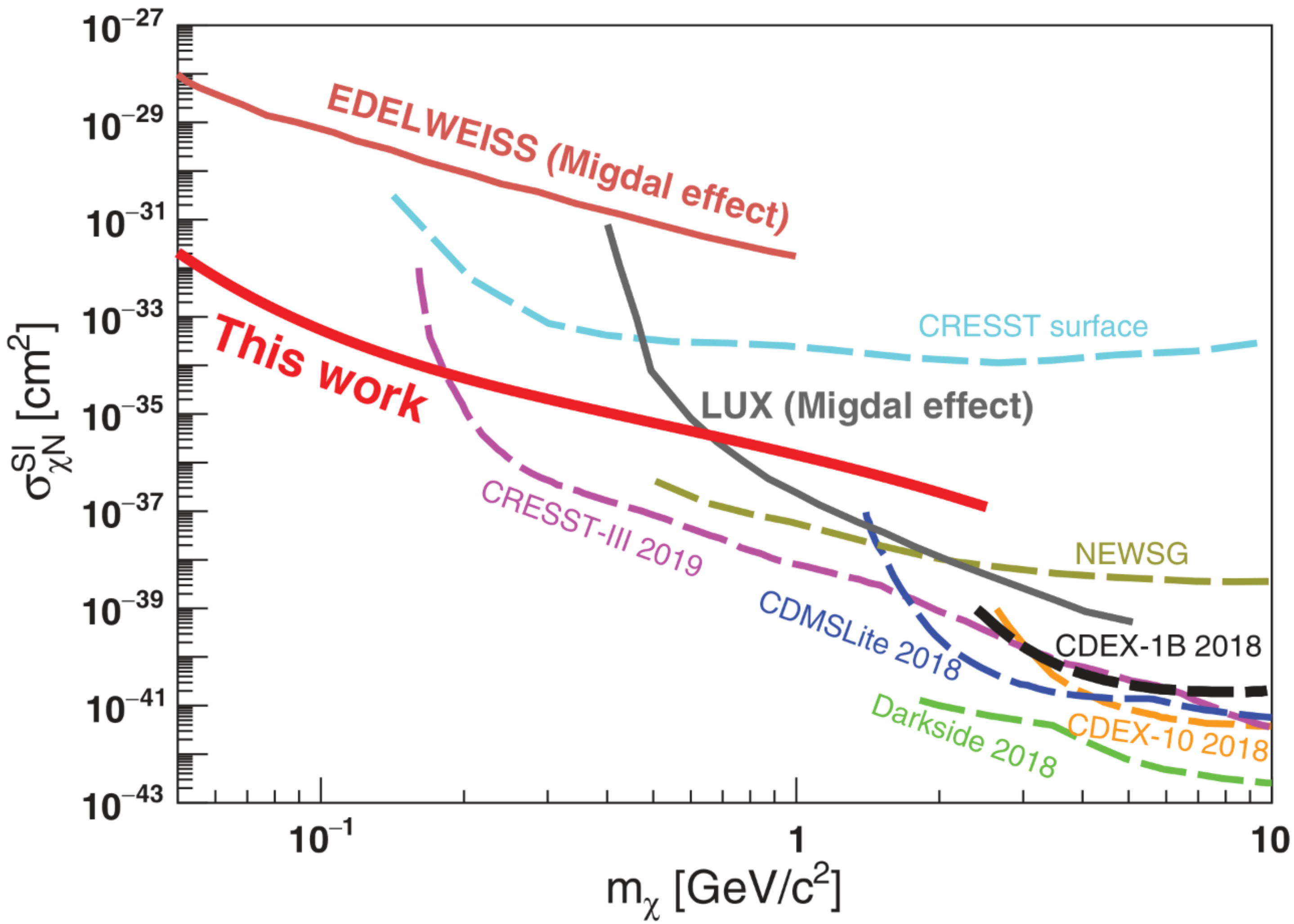
- Statistical method
  - Binned Poisson

There is some background we can not explain.

Detection of sub-GeV dark matter

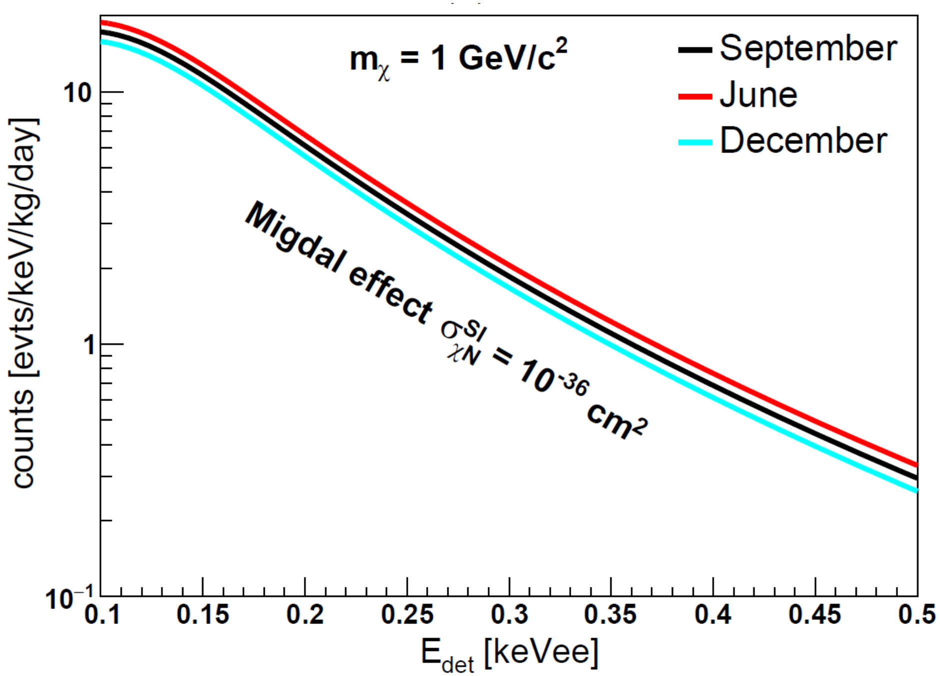
➢ The upper limit of $\sigma_{\chi N}^{SI}$

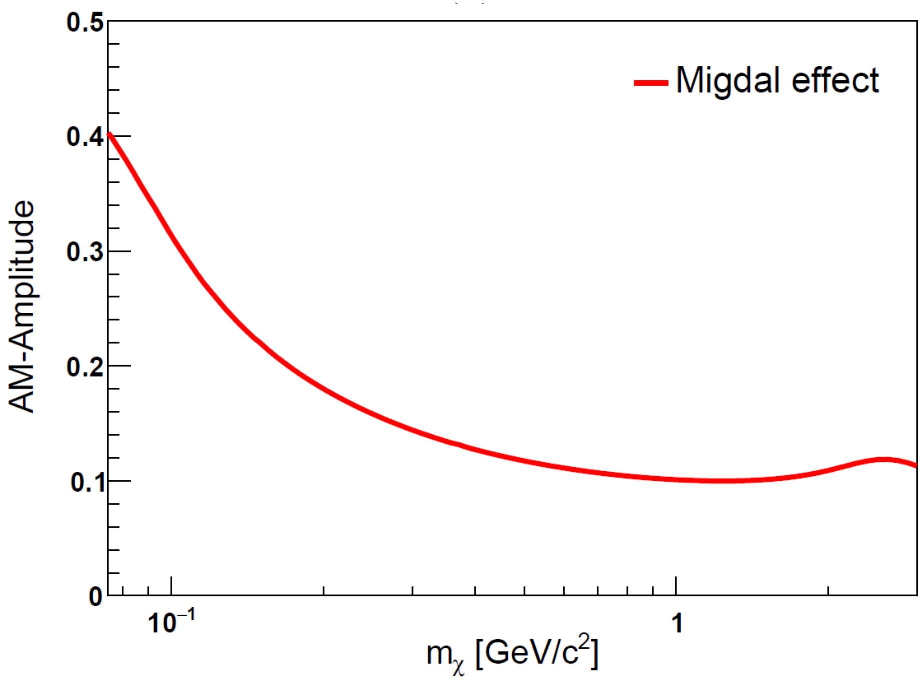
PRL 123.161301 (2019)



AM analysis

Detection of sub-GeV dark matter

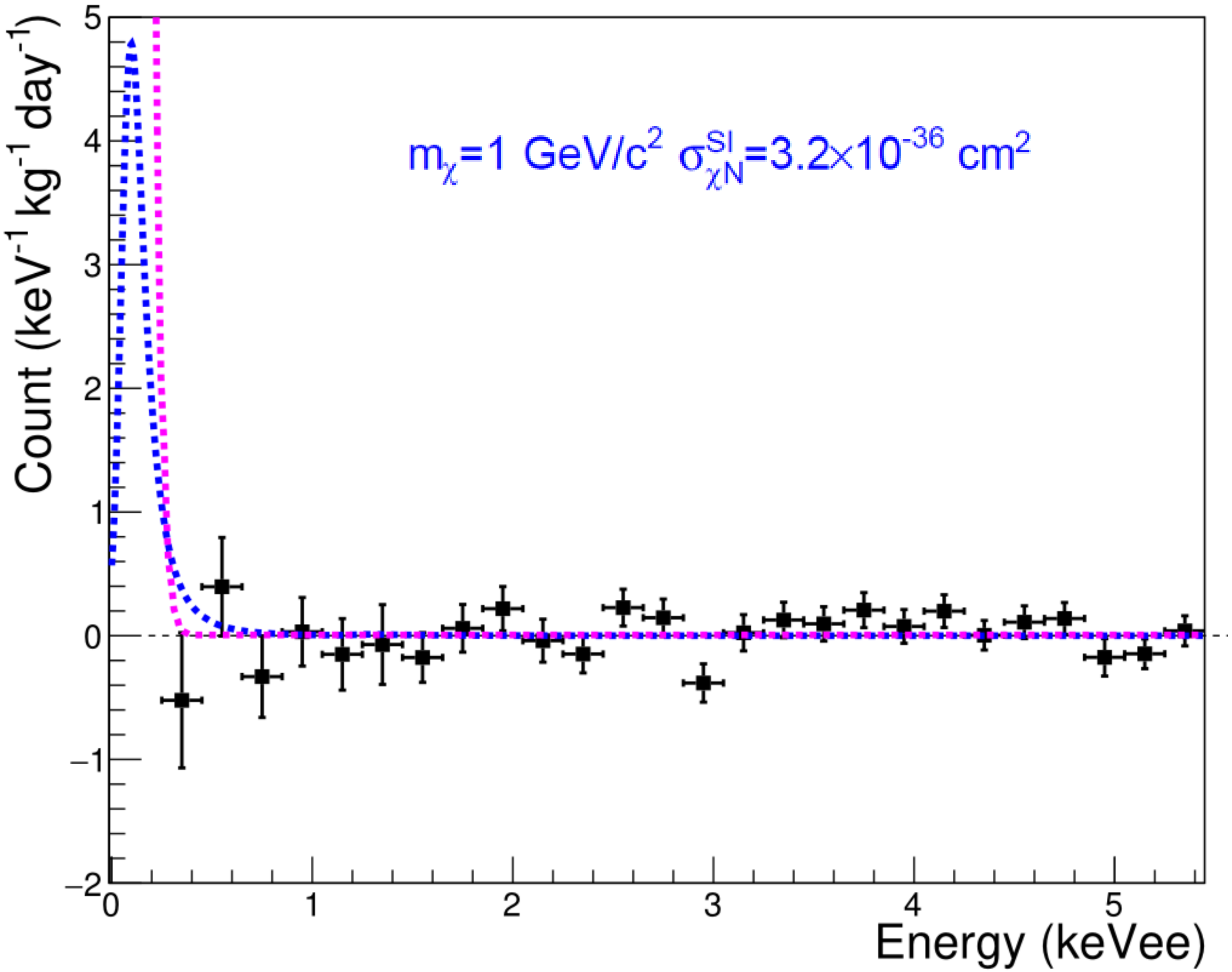




The solid lines are the expected spectra due to Migdal effect in June (red solid line), September (black solid line) and December (cyan solid line).

The AM-amplitude due to Migdal effect (red line) in 0.25-0.3 keVee energy range at different m_χ

Detection of sub-GeV dark matter



4.2 year

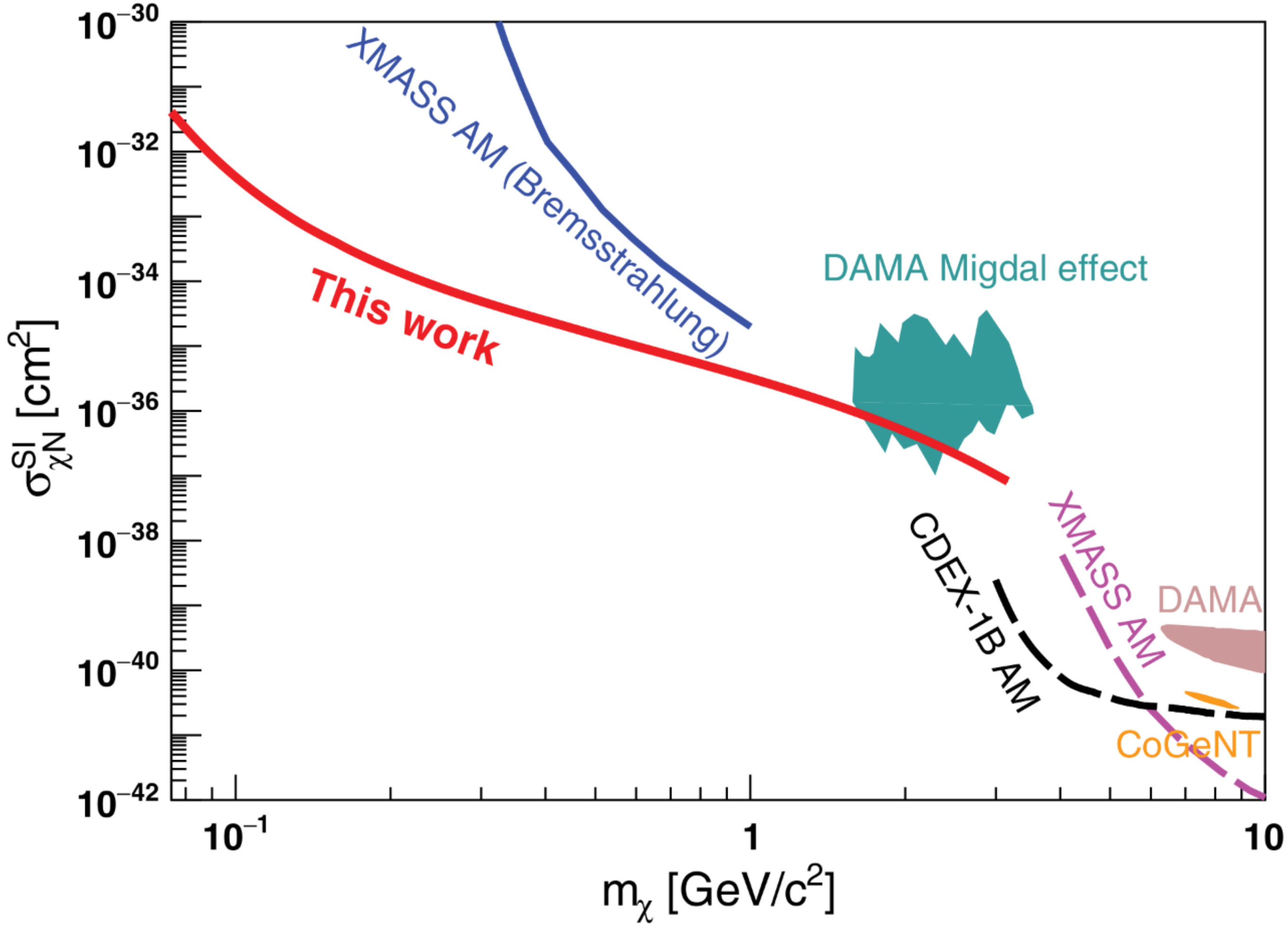
1107.5 kg•day

0.25-5.8 keVee

Detection of sub-GeV dark matter

- The upper limit of $\sigma_{\chi N}^{SI}$

PRL123.161301 (2019)



Summary

- CDEX-1B excludes DAMA/LIBRA phase-1's interpretation with the spin-independent WIMP interaction with Standard Halo model in Germanium crystal.

- Analysis on time-integrated (TI) and annual modulation (AM) effects on CDEX-1B data are performed, with 737.1 kg•day exposure and 160 eVee threshold for TI analysis, 1107.5 kg•day exposure and 250 eVee threshold for AM analysis.
- The sensitive windows in m_χ are expanded by an order of magnitude with Migdal effect incorporated. New limits on $\sigma_{\chi N}^{SI}$ at 90% confidence level at $m_\chi \sim$ 0.05-0.18 GeV/c^2 and 0.075-3.0 GeV/c^2 in the TI and AM analysis are derived, respectively.

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