Light Dark Matter Searches with the CDEX experiment at the Jinping Underground Laboratory

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OUTLINE

- CDEX experiments: overview.
- DM searches: time-integrated, annual modulation, Migdal effect.
- Summary.

CDEX: China Dark matter EXperiment

Established in 2009

- Tsinghua University (THU)
- Sichuan University (SCU)
- Nankai University (NKU)
- China Institute of Atomic Energy (CIAE)
- Beijing Normal University (BNU)
- Yalong River Company

+

- Academia Sinica, Taiwan
- Banaras Hindu University, India
- Dokuz Eylül University, Turkey

(as members of TEXONO Taiwan EXperiment On NeutronO)

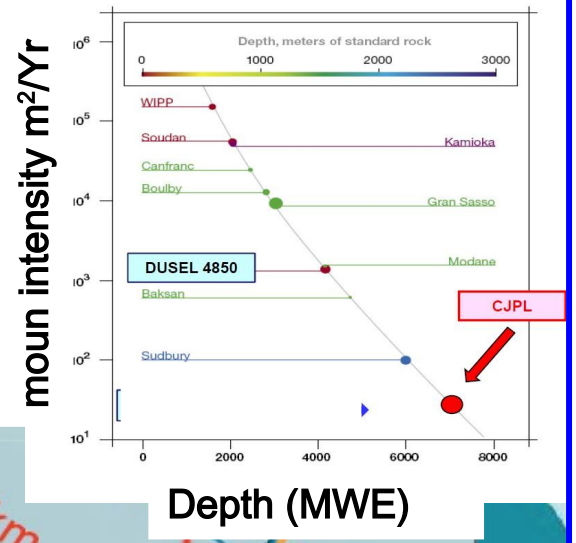
detectors setting at early phase, simulation, PCGe data/physics analysis, etc.

CJPL

Jinping Hydroelectric Power Plants

4 hydraulic tunnels
Φ13m×16.6km

Jinping-II Power Plant
4800MW
(8×600MW)



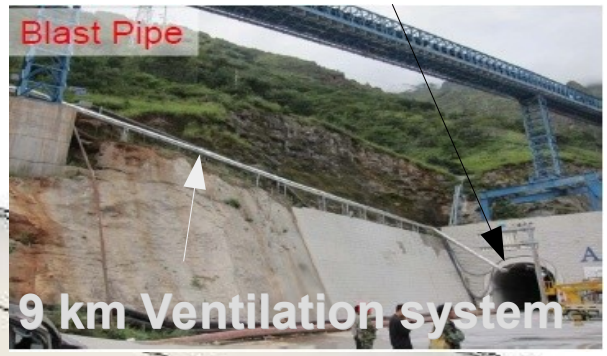
Jinping-I Power Plant
3600MW
(6×600MW)

2.4 km of rock

CJPL lab.

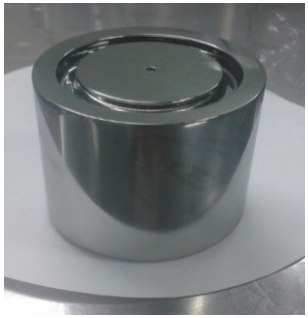
CDEX at CJPL-I

tunnel entrance

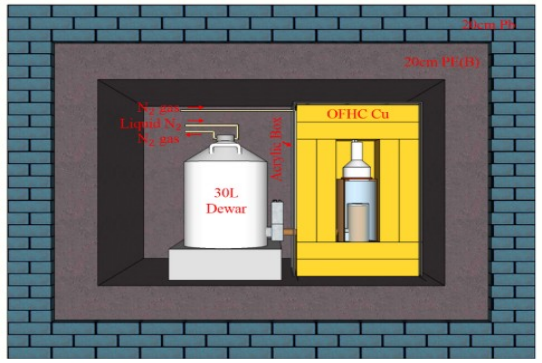


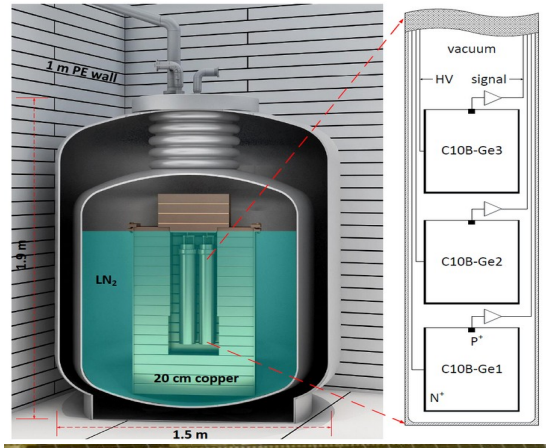
12m
15m
15m
CDEX
LBF
PandaX
6m
6m
cleaning room
Tunnel
CDEX-1 experiment
Low background facility
PandaX

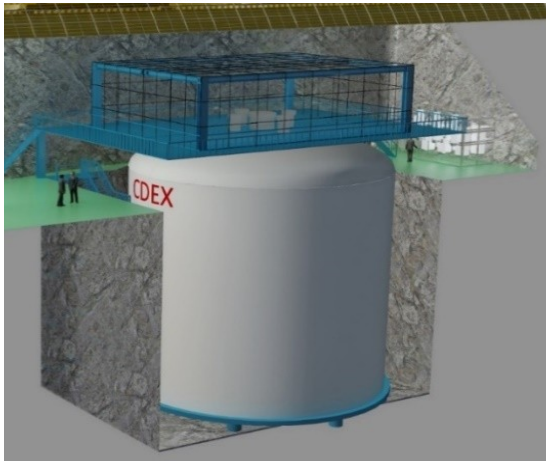
CDEX stages



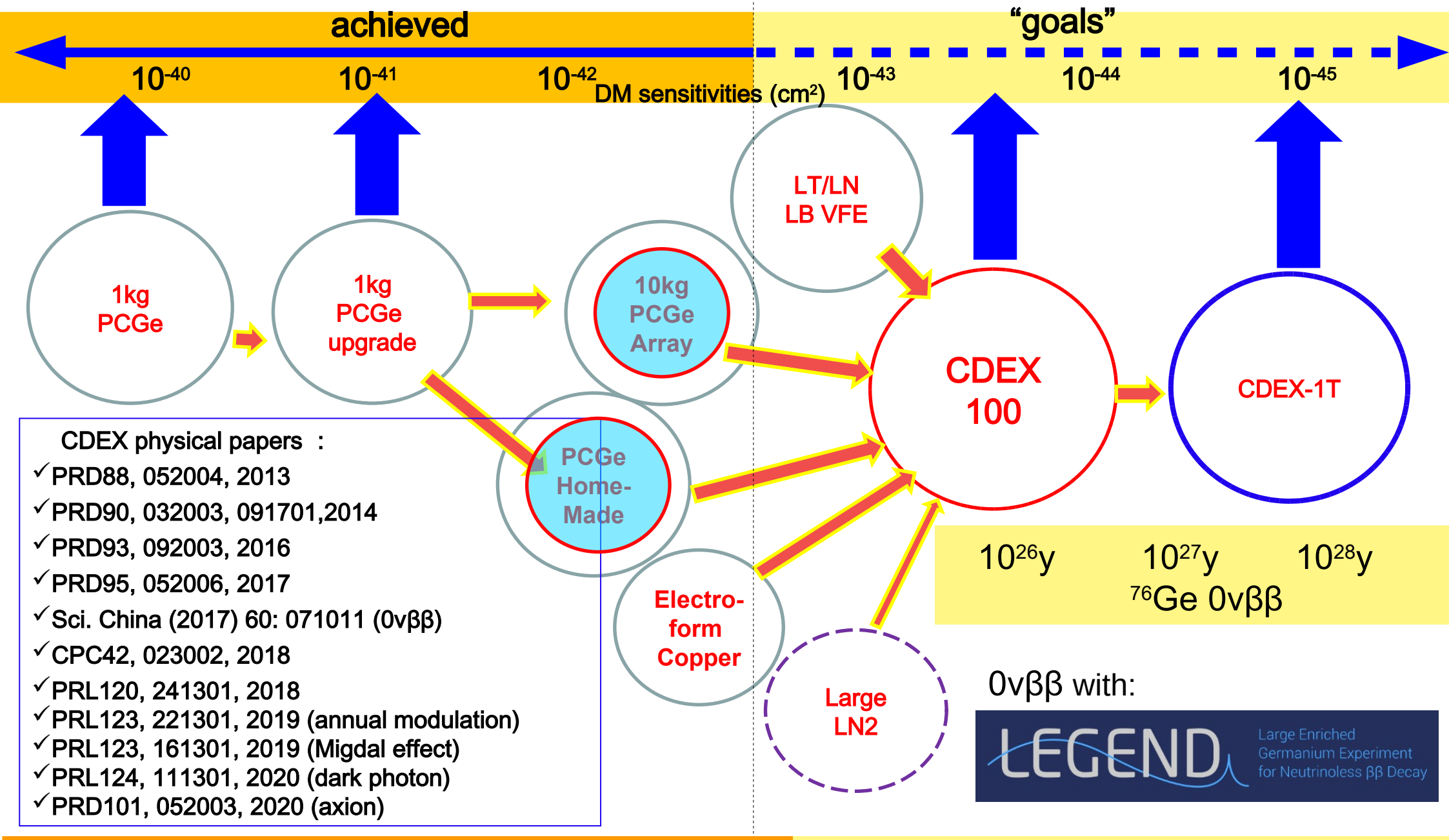
- Light WIMP mass searches on Ge
- CDEX-1: Development of pPC-HPGe detector, its background understanding, results published.
- CDEX-10: Performances of HPGe array detector system, results published.
- CDEX-10X: Fabrication of HPGe and Ge crystal growth by CDEX.
- CDEX-100: Ultra-low cosmogenic background and large LN_2 cooling and shielding system.
- CDEX-1T: Multi-purpose experiment for dark matter and double beta decay.







CDEX plan for DM & 0νββ



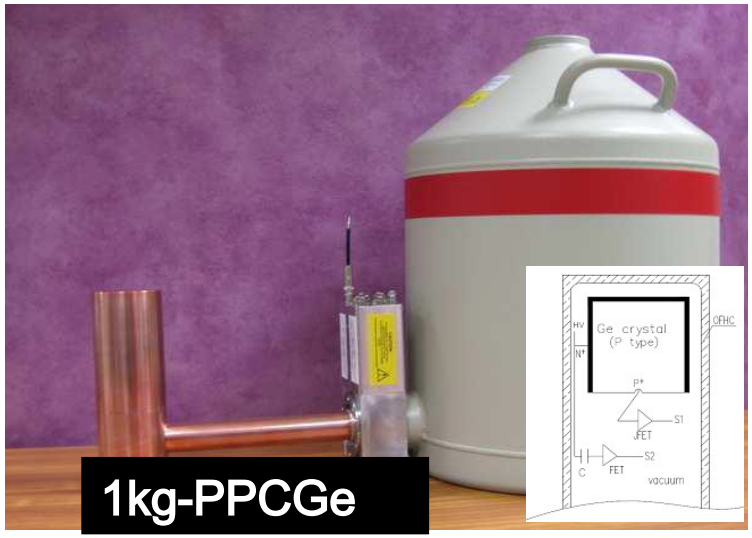
CDEX physical papers :

- ✓PRD88, 052004, 2013
- ✓PRD90, 032003, 091701,2014
- ✓PRD93, 092003, 2016
- ✓PRD95, 052006, 2017
- ✓Sci. China (2017) 60: 071011 (0νββ)
- ✓CPC42, 023002, 2018
- ✓PRL120, 241301, 2018
- ✓PRL123, 221301, 2019 (annual modulation)
- ✓PRL123, 161301, 2019 (Migdal effect)
- ✓PRL124, 111301, 2020 (dark photon)
- ✓PRD101, 052003, 2020 (axion)

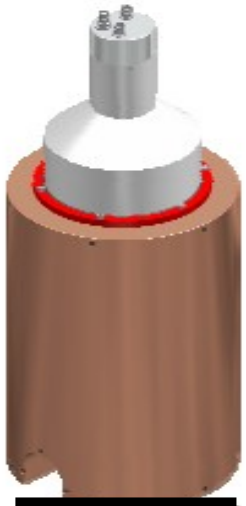
CJPL-I CJPL-II

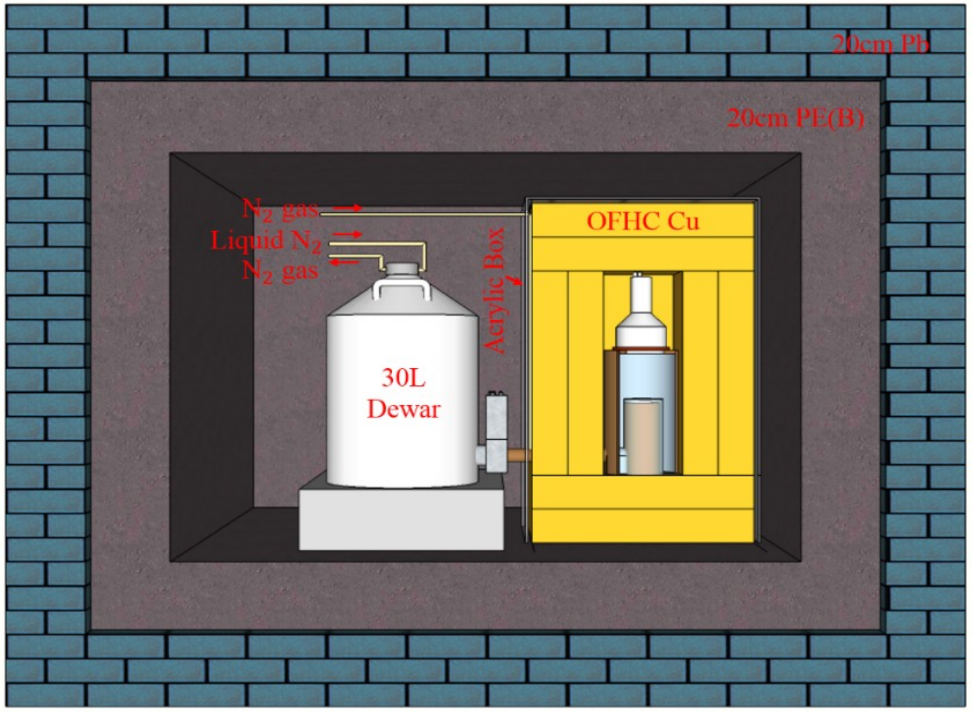
CDEX-1 experiment

1. HPGe technology
   - ✓ Designed the first one single module 1kg-scale p-type point-contact Ge detector (1kg-PPCGe) "prototype" CDEX-1A
   - ✓ Improved 1kg-PPCGe CDEX-1B
2. Active shielding technology: NaI(Tl) used as anti-Compton detector
   - ✓ CDEX-1A 1kg-PPCGe run
   - ✓ CDEX-1A 1kg-PPCGe + NaI(Tl) run (th~475 eV)
   - ✓ CDEX-1B 1kg-PPCGe + NaI(Tl) run (th~160 eV)



1kg-PPCGe


NaI(Tl)



CJPL

CDEX-1

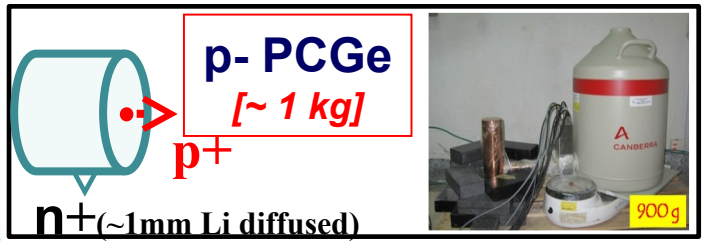
CDEX-1A 1kg PCGe

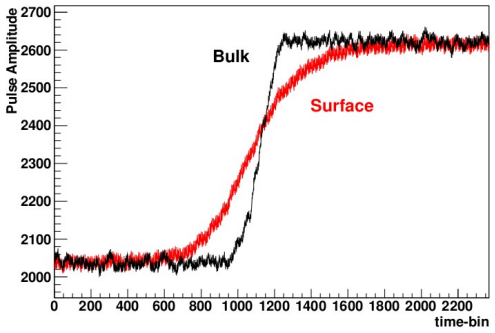
CDEX-1B 1kg PCGe

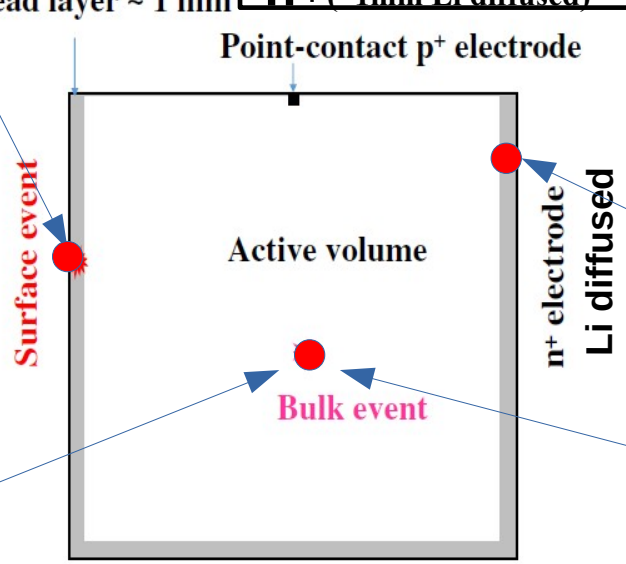
20cm OFHC Copper
+20cm Lead

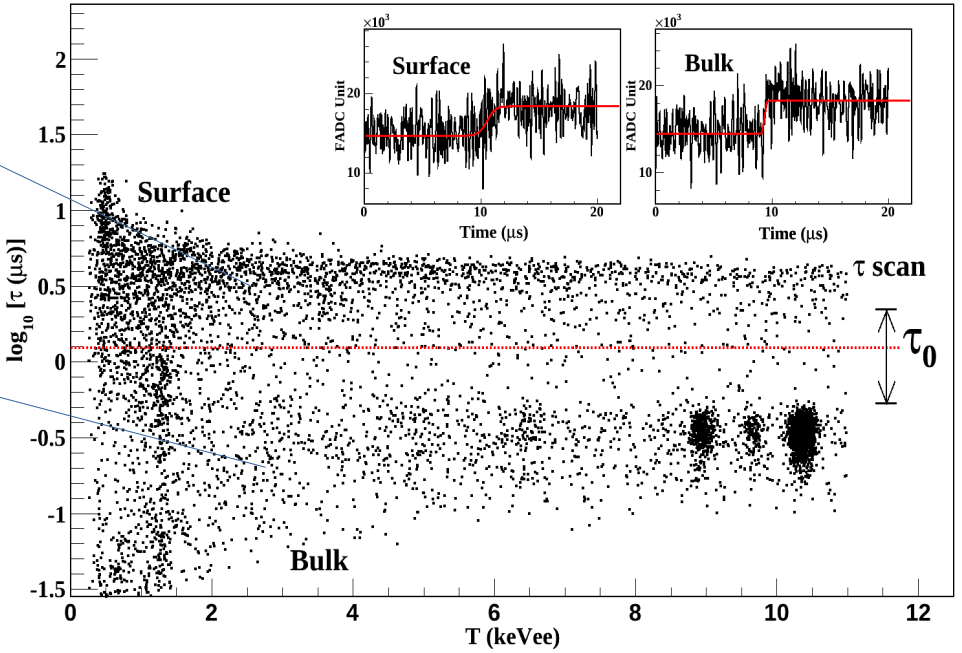
bulk/surface: largest sources of uncertainties

surface
- partial energy deposit
- diffuse and drift → slow









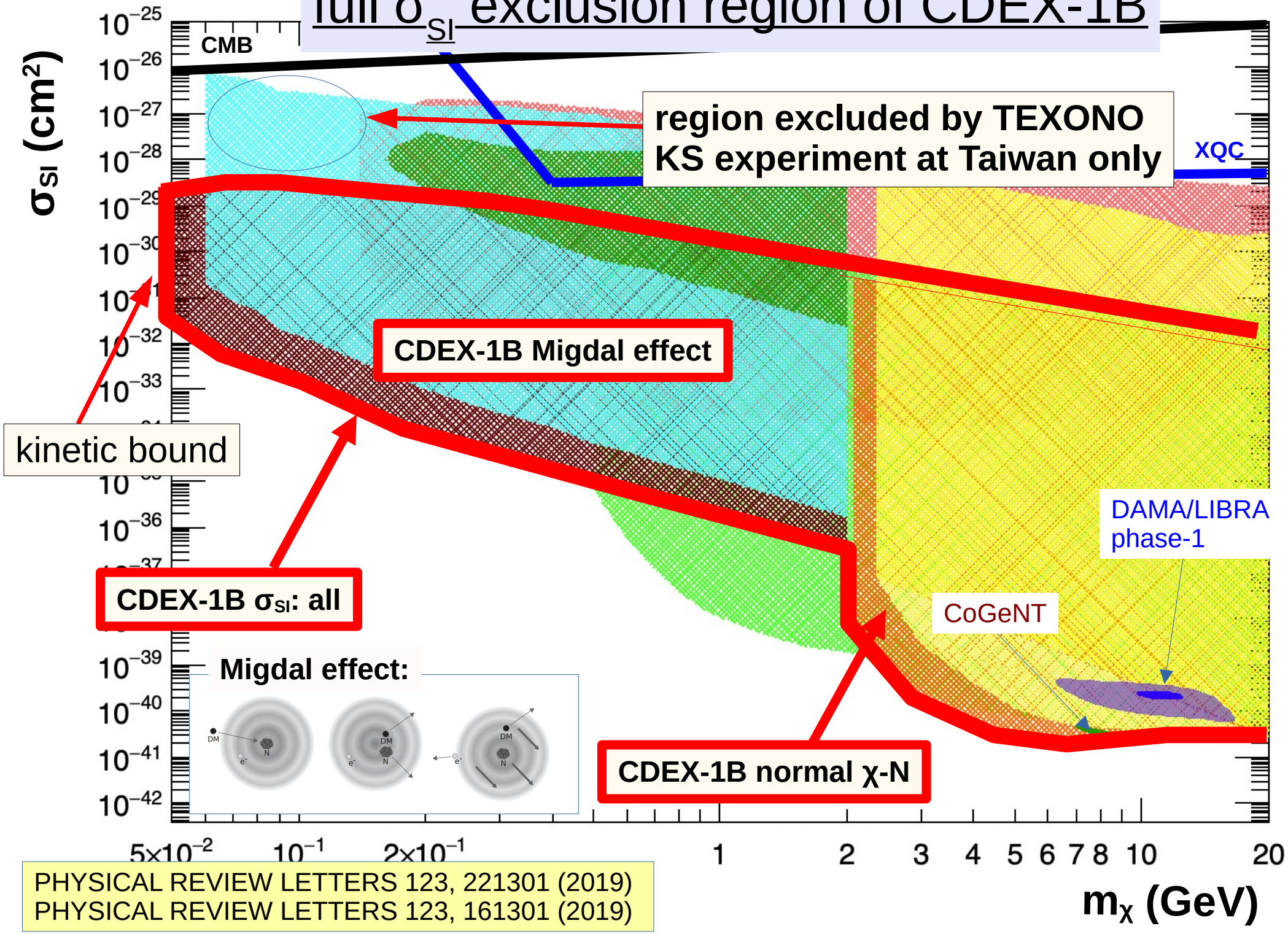
bulk
- full energy deposit
- drift → fast

- **a bless : gamma background veto and**
- **a curse : contaminate low energy spectrum**

Astropart. Phys. 56, p1-8 (2014) : based on understanding of energy spectrum
NIMA 886, p13-23 (2018) : comparing rise-time of different sources

most contributions are done by Taiwan team

full σ_{SI} exclusion region of CDEX-1B



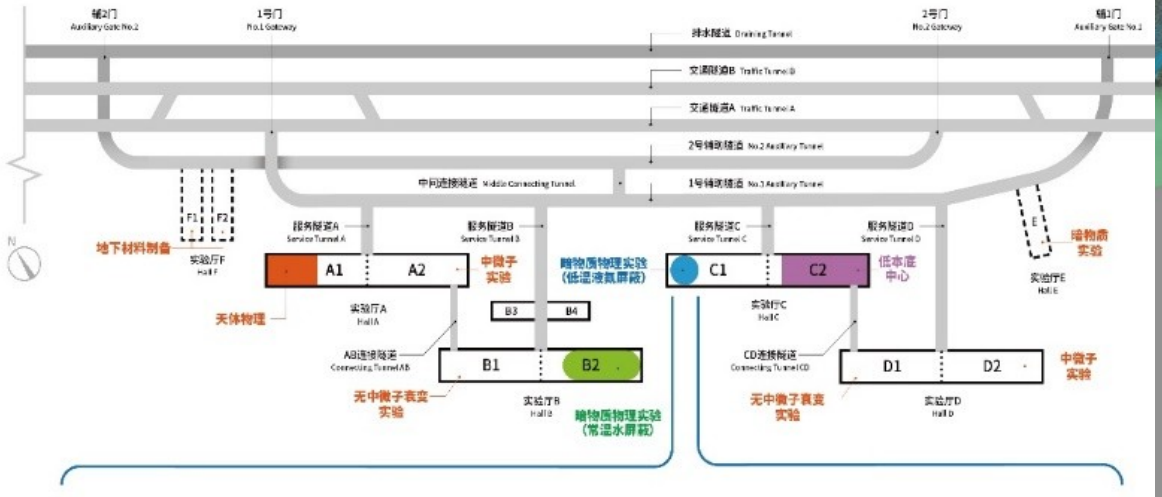
PHYSICAL REVIEW LETTERS 123, 221301 (2019)
PHYSICAL REVIEW LETTERS 123, 161301 (2019)

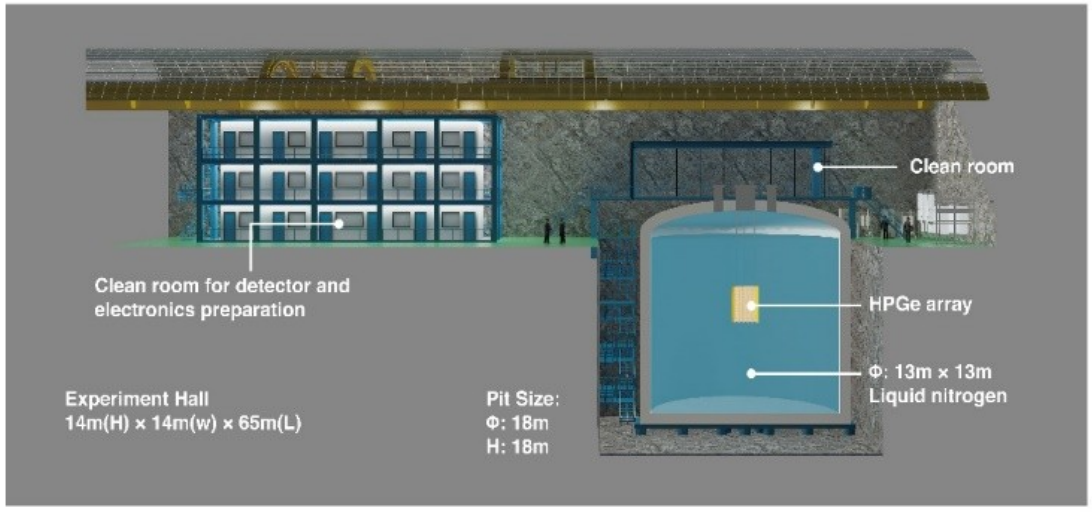
The layout of CJPL-II

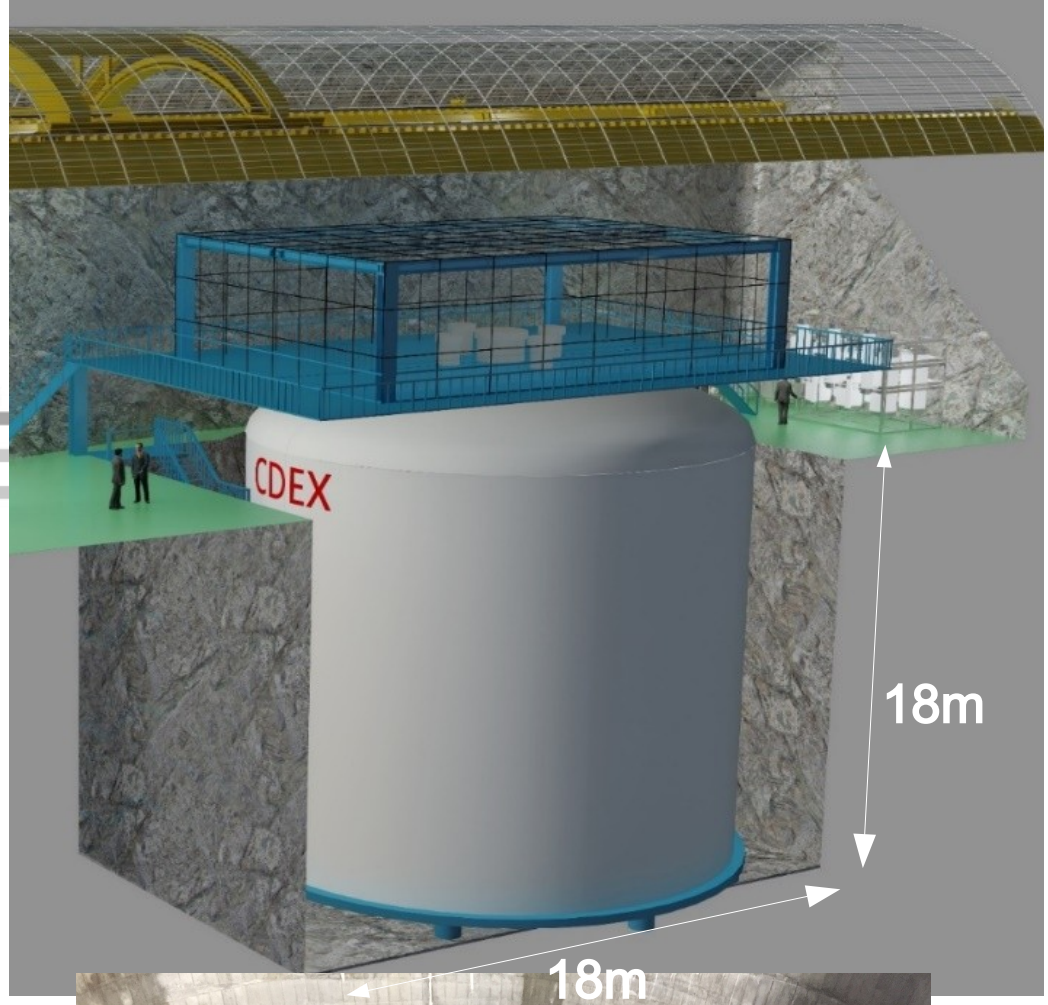
- 4 main halls : 14m(H)×14m(W)×130m(L);
- Total Volume: 300K m³;
- Two expanded spaces:
  C1--ϕ18m×32m(H)→CDEX-1T
  B2--27m(L)×14m(W)×30m(H)

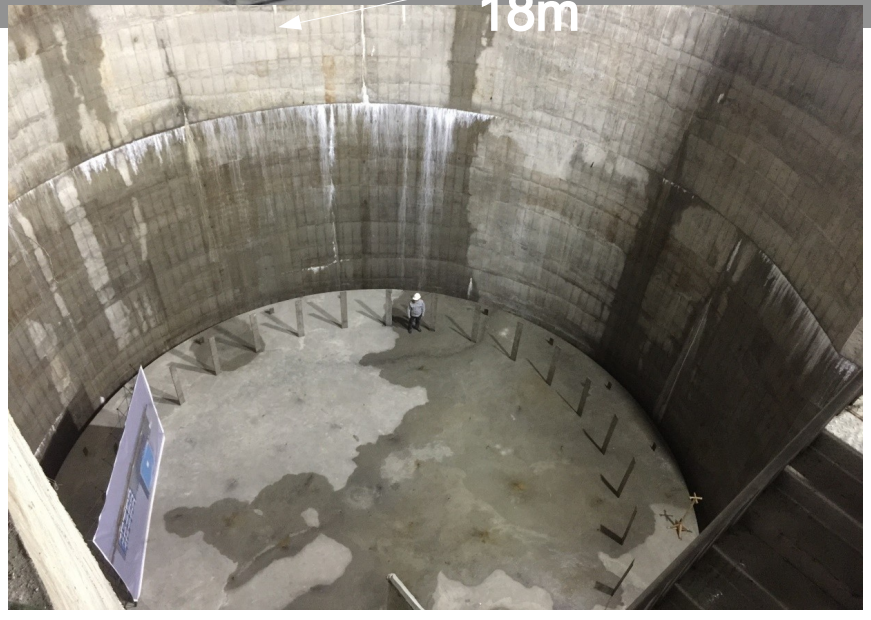
	CJPL-I	CJPL-II
Rock Work	4100 m³	210000+151000m³
Electric Power	70x2 kVA	10x2 MVA
Fresh Air	2400 m³/h	15000x3 m³/h

CDEX-1T at CJPL-II for 0νββ



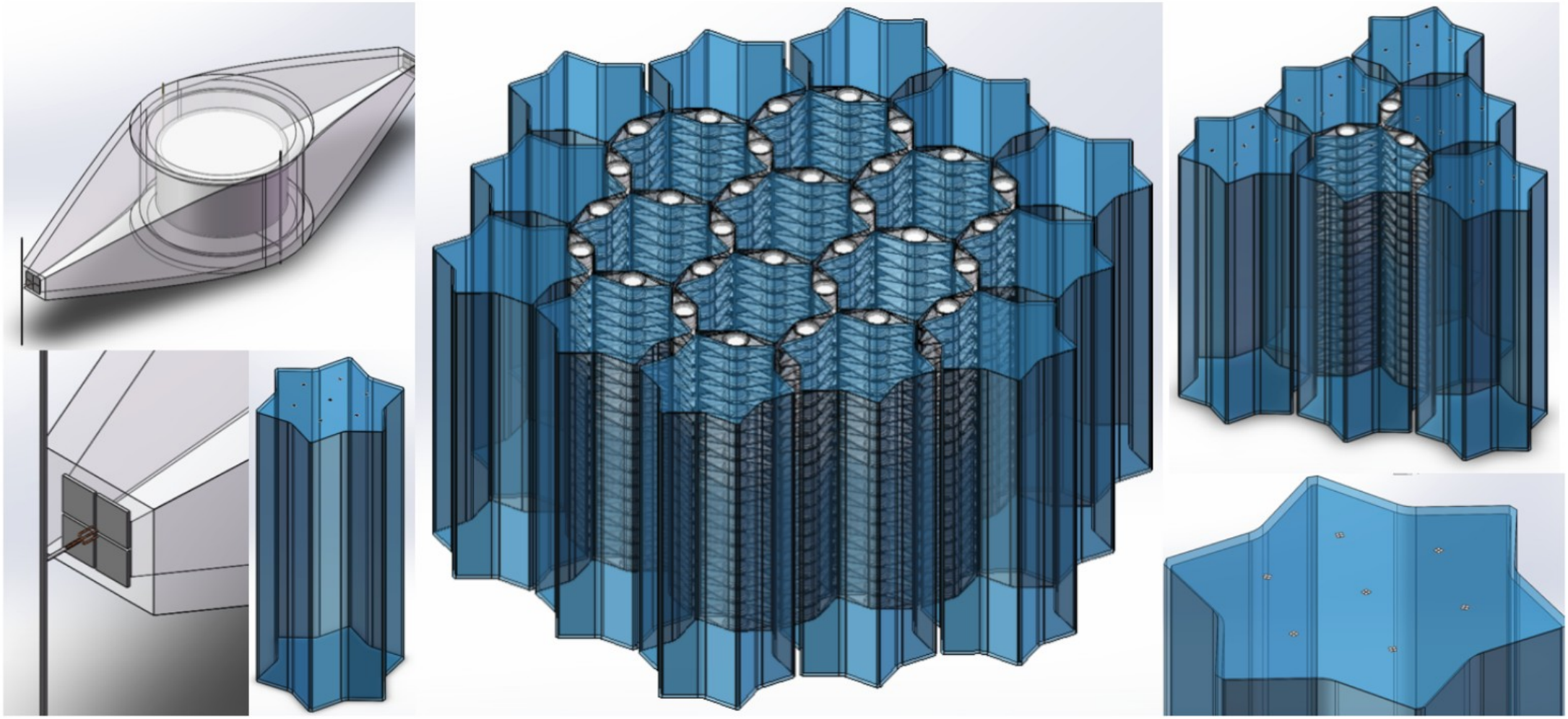






CJPL

Modularized HPGe-PEN-sAr Veto System



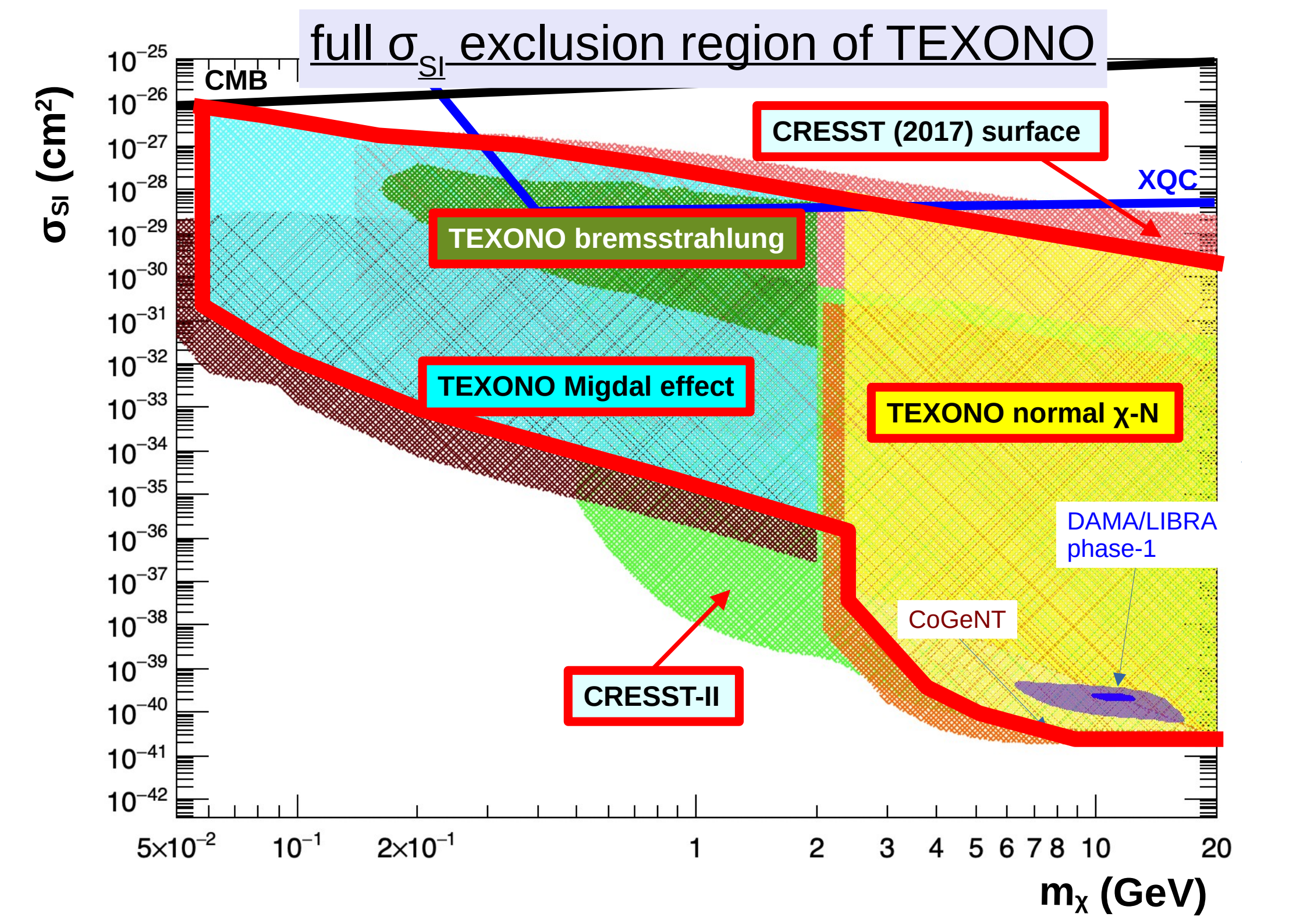
a promising detectors design for CDEX100 – CDEX-1T
PEN: holding, light-guide. sAr: active veto.

summary

- best modulation (χN) results < 6 GeV.
- best Migdal effect results at < 1 GeV.
- unique stable low threshold (250 eVee) Ge data with long time-span ~ 3.2 years.
- other results: axion PRD101, 052003, 2020
  & dark photon PRL124, 111301, 2020
- on the way to CDEX-100 and CDEX-1T.
- cooperate with LEGEND.

Thanks

supplemental material


full σ_{SI} exclusion region of TEXONO
σ_{SI} (cm^2)
m_χ (GeV)
CMB
XQC
CRESST (2017) surface
TEXONO bremsstrahlung
TEXONO Migdal effect
TEXONO normal χ-N
CRESST-II
CoGeNT
DAMA/LIBRA phase-1
10^{-25}
10^{-26}
10^{-27}
10^{-28}
10^{-29}
10^{-30}
10^{-31}
10^{-32}
10^{-33}
10^{-34}
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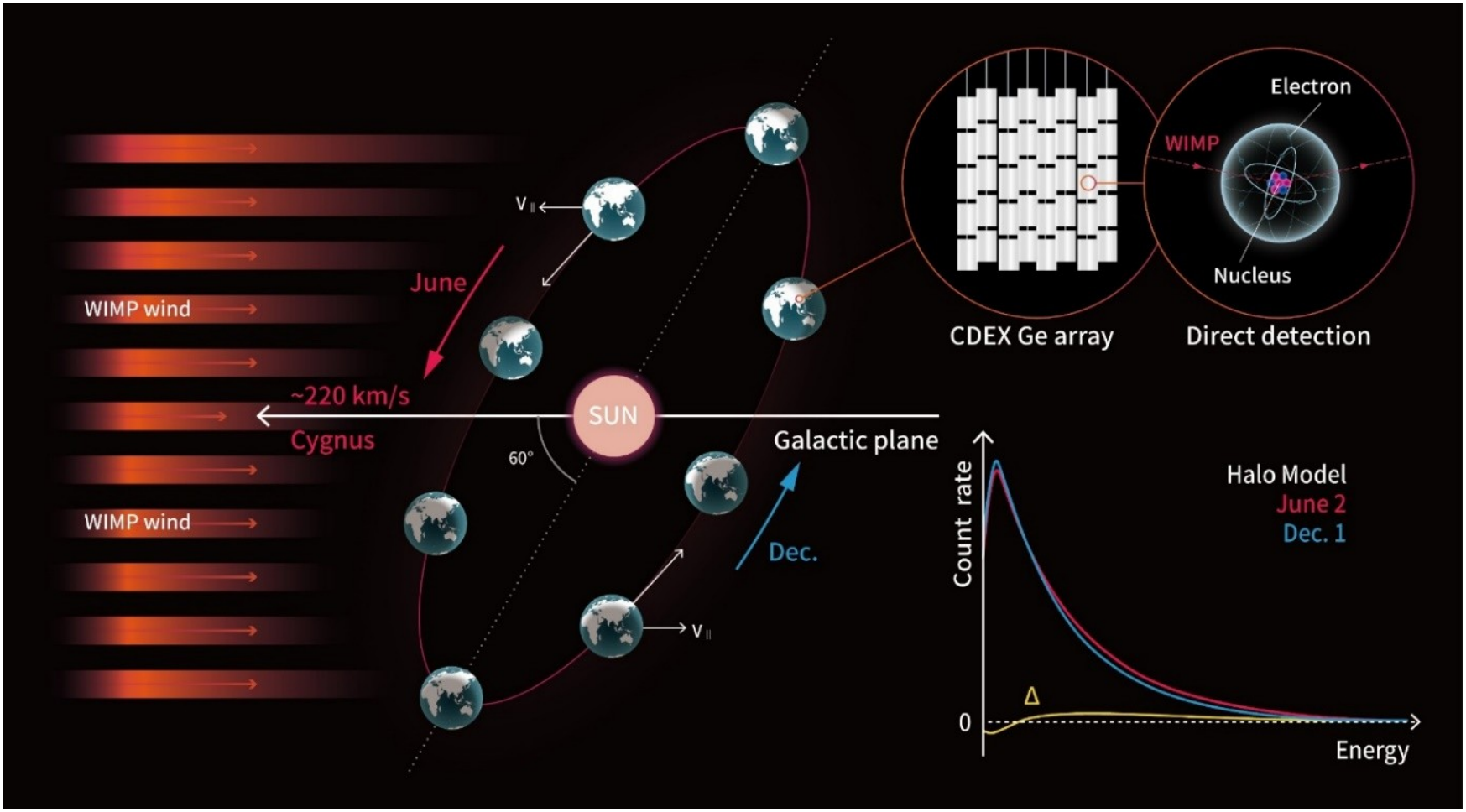
10^{-41}
10^{-42}
5×10^{-2}
10^{-1}
2×10^{-1}
1
2
3
4
5
6
7
8
10
20

Annual Modulation of WIMPs

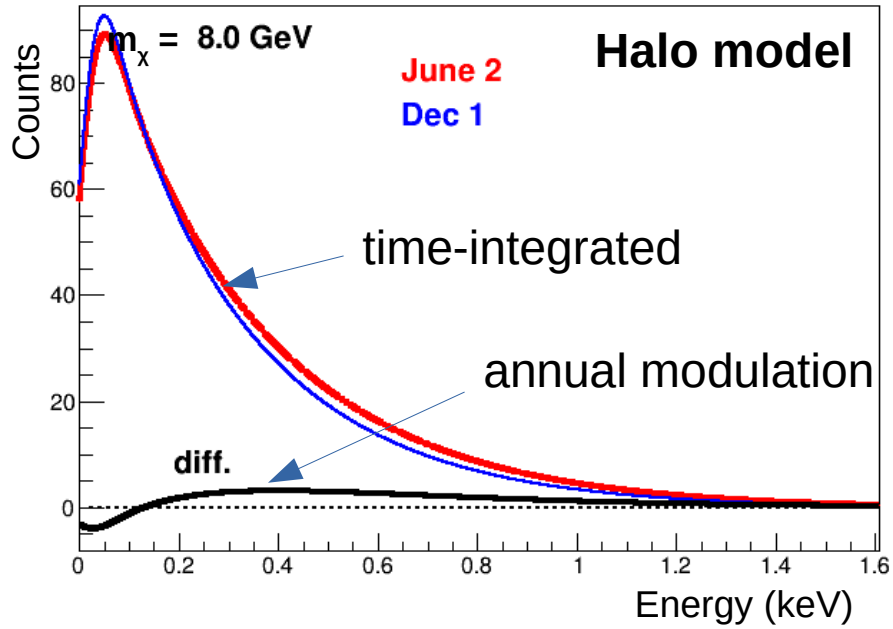
- velocity (earth ref.) of WIMP: max. at Jun, min. at Dec.
- look at Jun-Dec spec. diff.
- need stable run > 1 years
- decouple unexplained excess count



time-integrated vs. annual modulation

time-integrated	annual modulation
search for excess count (large)	search for different of count (small)
energy spectrum modeling (a lot of simulation → uncertainties)	time variation modeling (assume it is constant)
best sensitivities always at lowest energy (large uncertainties)	best sensitivities occur at higher energy (noise-free)

both are dark matter model dependent, both are needed for positive/negative results



TEXONO-CDEX Collaboration

TEXONO Taiwan EXperiment On NeutrinO (since 1997)

Neutrino Physics at Kuo-Sheng Reactor Neutrino Laboratory (KSNL)

- **Taiwan** (AS, NTHU, INER, KSNPS)
- **Turkey** (METU)
- **India** (BHU)

CJPL

CDEX China Dark Matter Experiment (birth 2009)

Dark Matter Searches at China Jin-Ping Underground Laboratory (CJPL)

- **China** (THU, CIAE, NKU, SCU,EHDC)

TEXONO Collaboration

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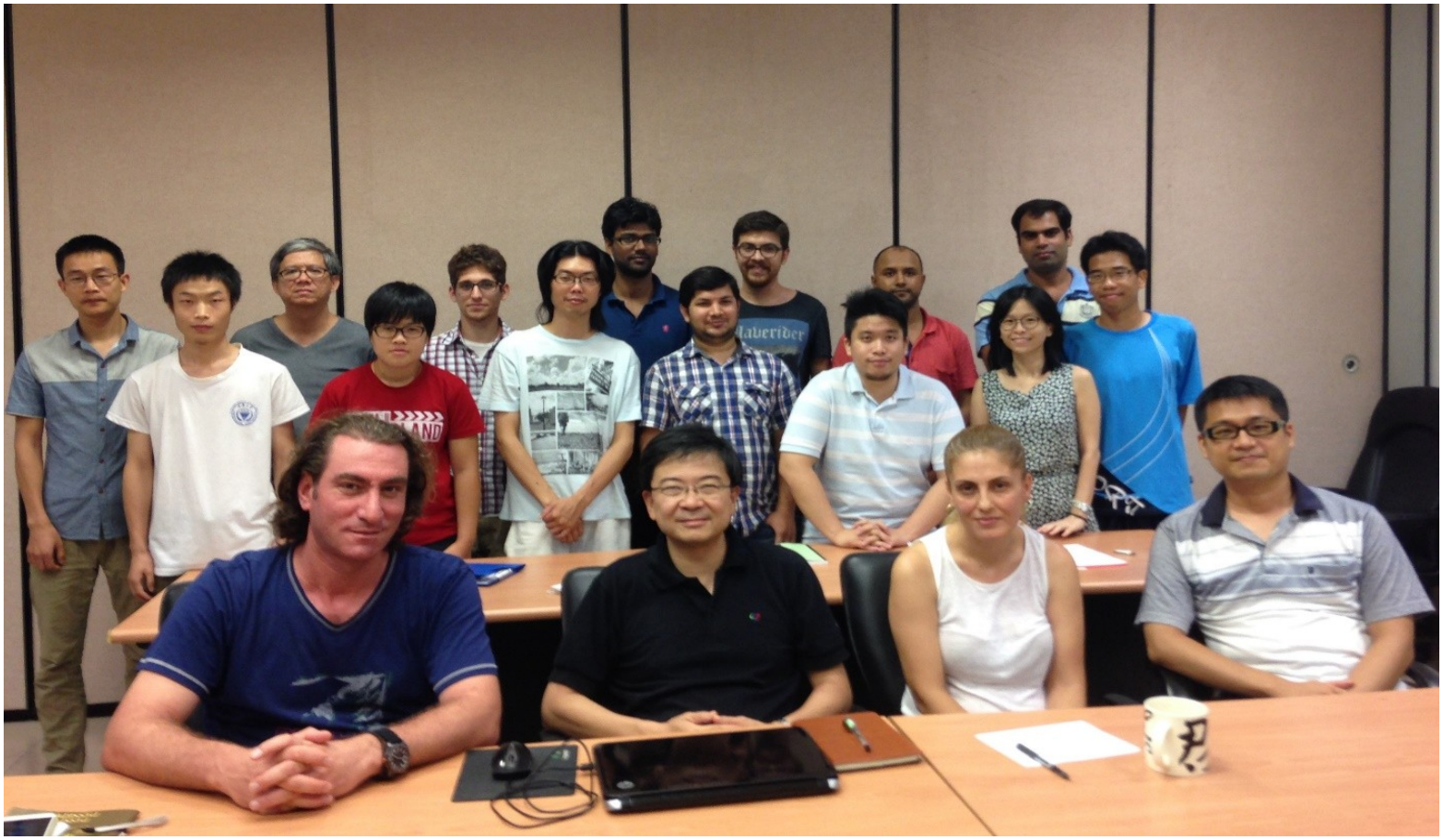
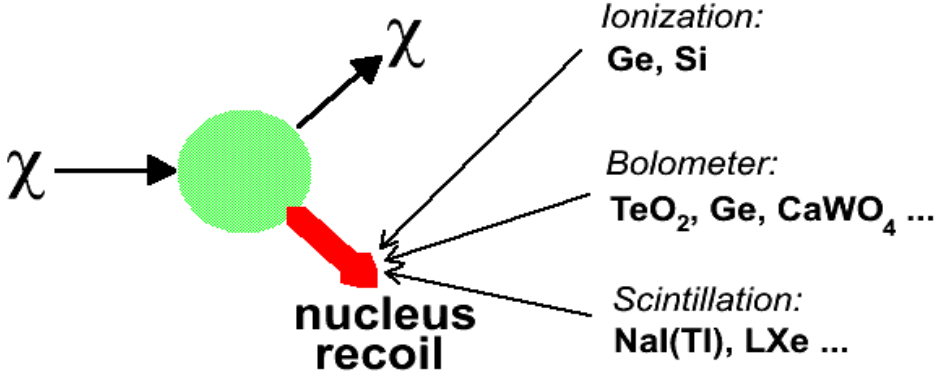


Partner : CDEX Collaboration

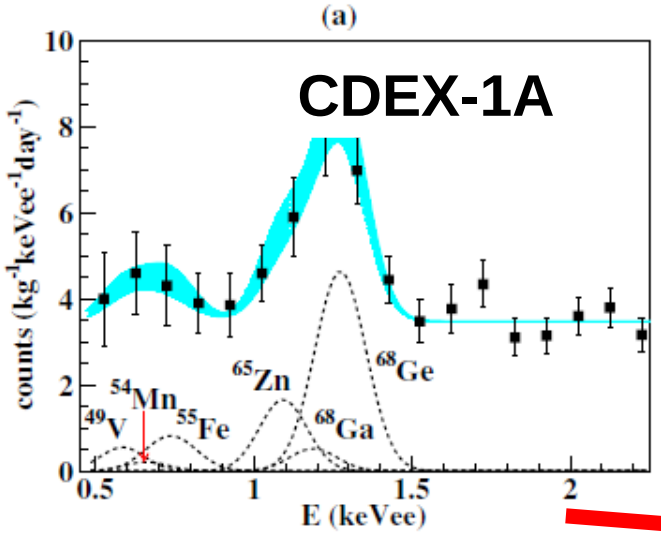
CDEX China Dark Matter Experiment (birth 2009)

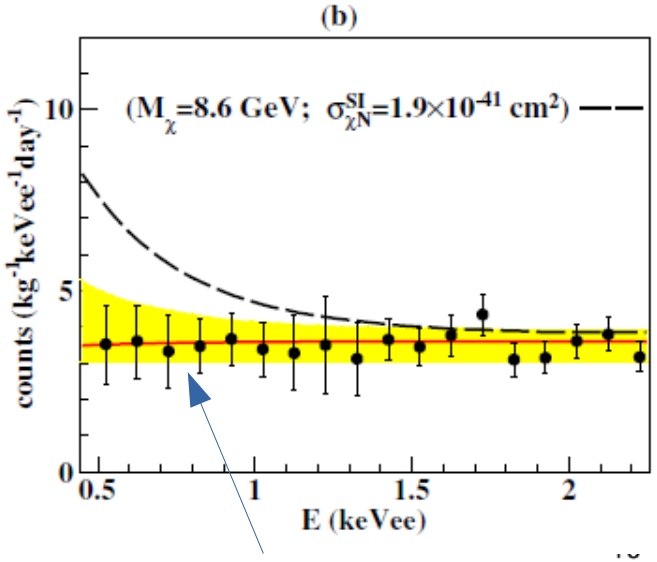
Dark Matter Searches at China Jin-Ping Underground Laboratory (CJPL)

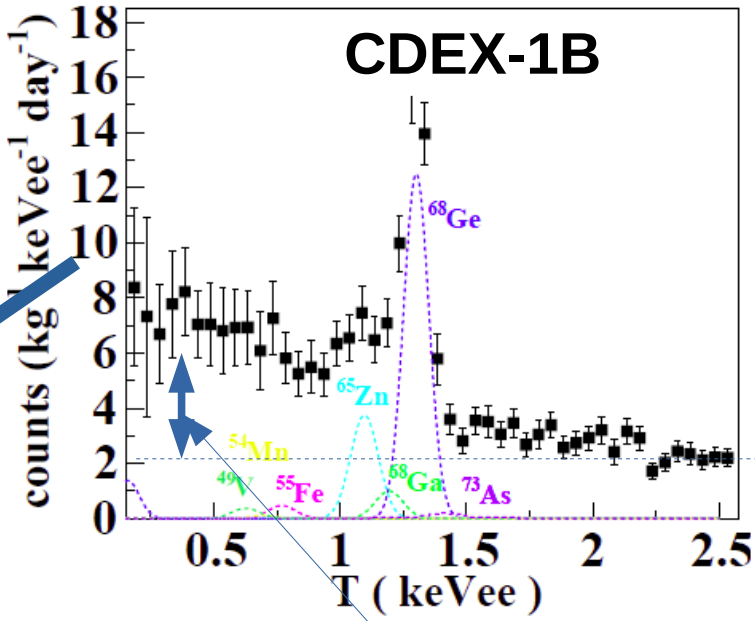
- China (THU, CIAE, NKU, SCU,YLJHD)
- Ge as primary detector.
- same detector technique, i. e. bulk/surface seperation, phys/noise seperation.



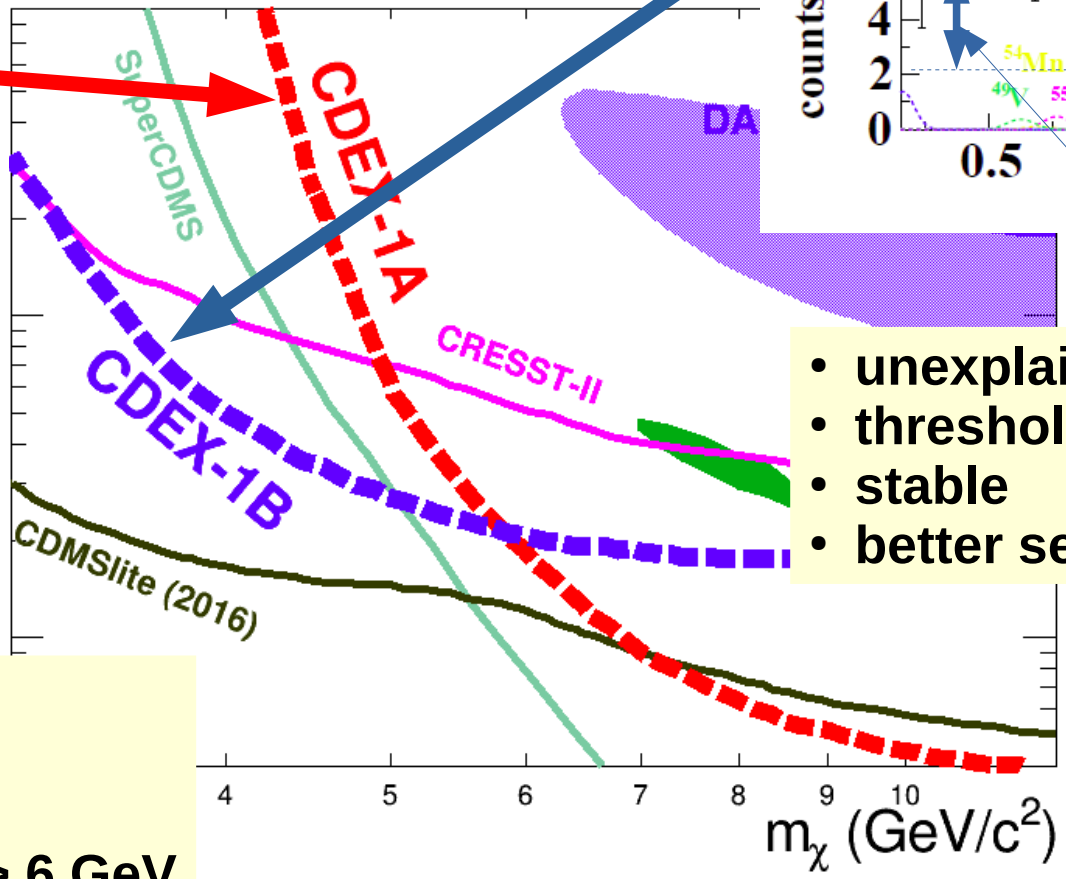
Compare with CDEX-1A:







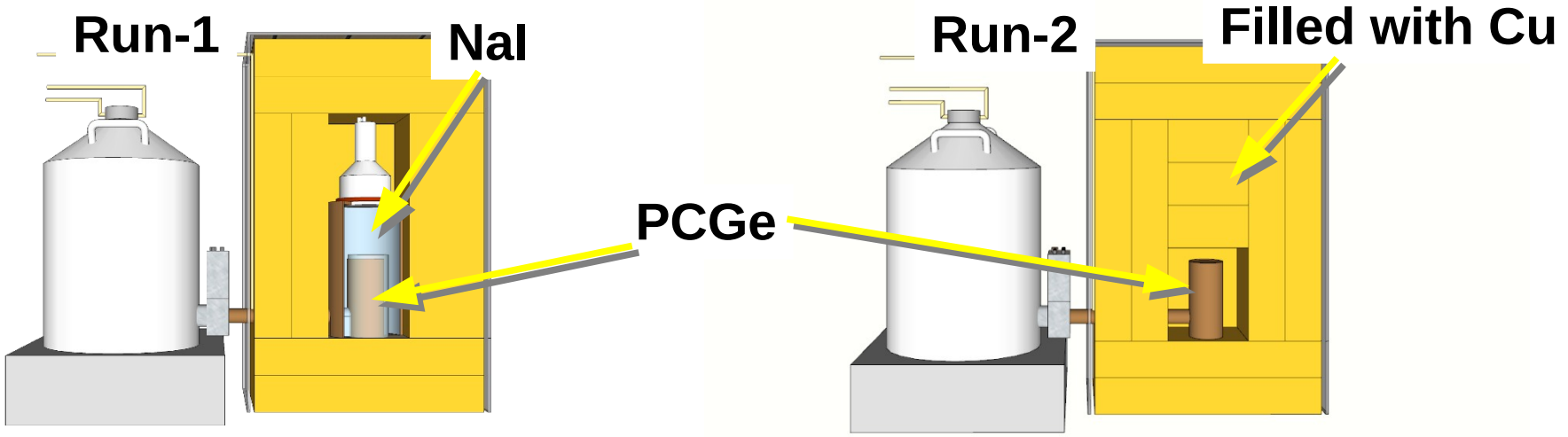
σSI sensitivities



- **unexplained excess count**
- **threshold ~ 160 eV**
- **stable**
- **better sensitivities < 6 GeV**

- **no excess count**
- **Threshold ~ 475 eV**
- **unstable**
- **better sensitivities at > 6 GeV**

CDEX-1B experiment

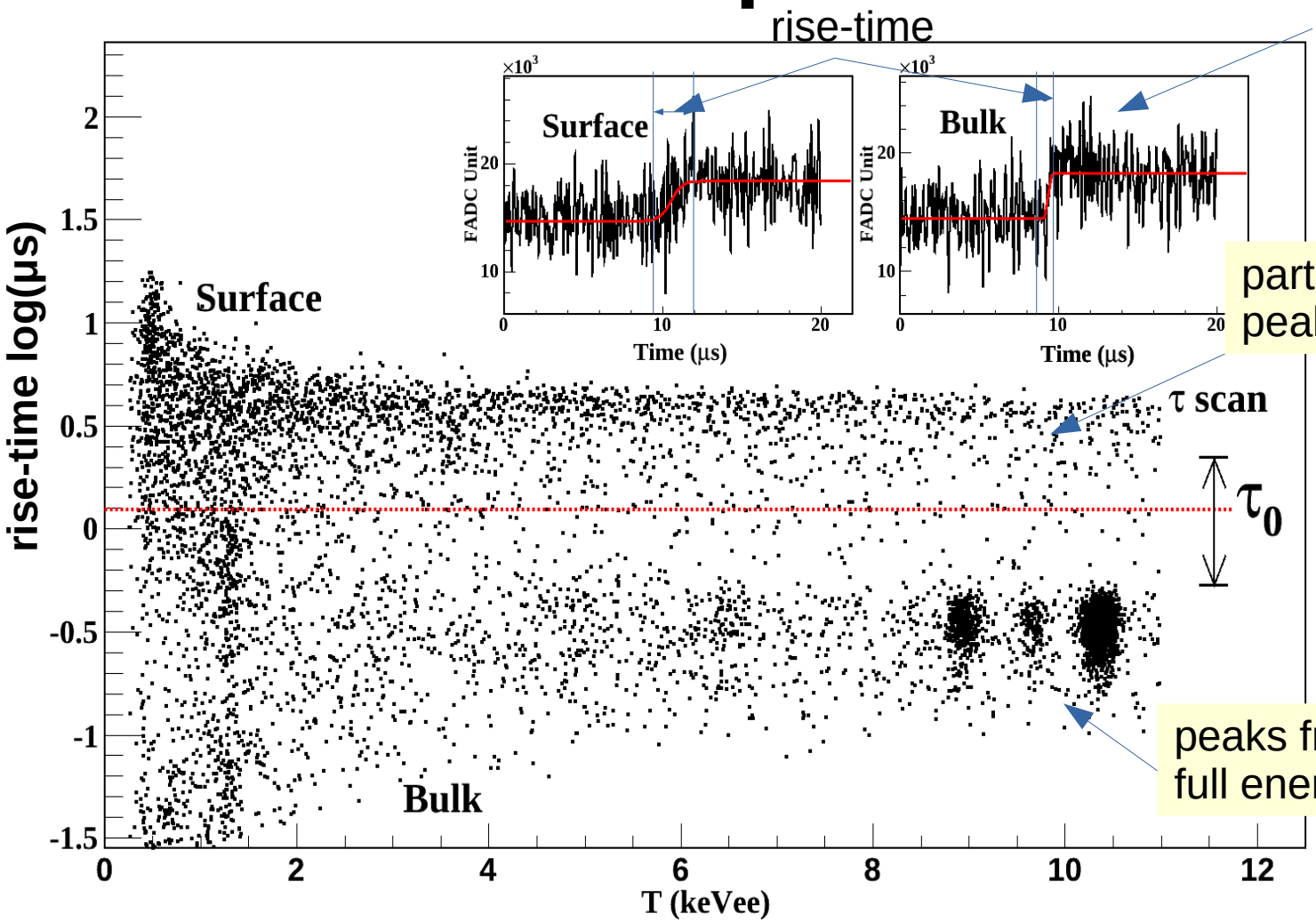


2014/09 – 2017/08
671 kg-days

2017/08 – 2018/12 →
340 kg-days

- 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.
- Threshold ~ 160 eVee. For modulation analysis, threshold ~ 250 eVee.
- Largest analysis uncertainties: bulk/surface separation at low energy.

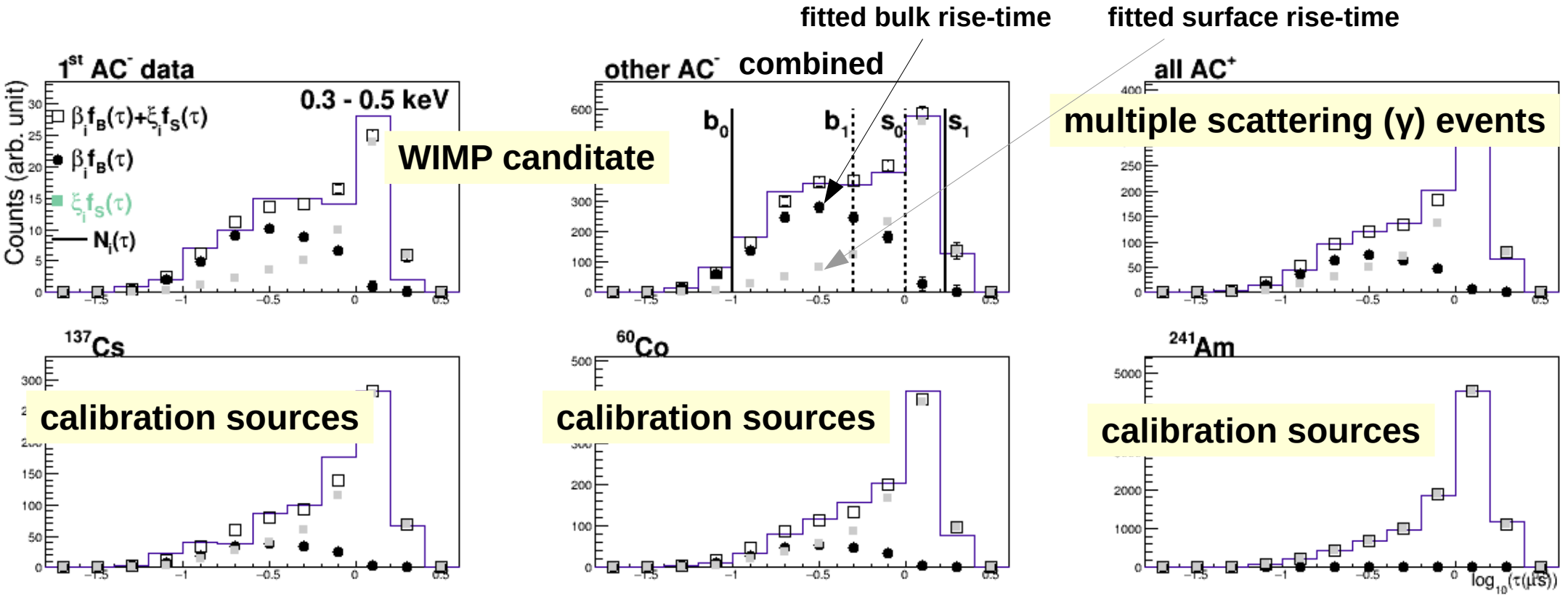
rise-time spectrum



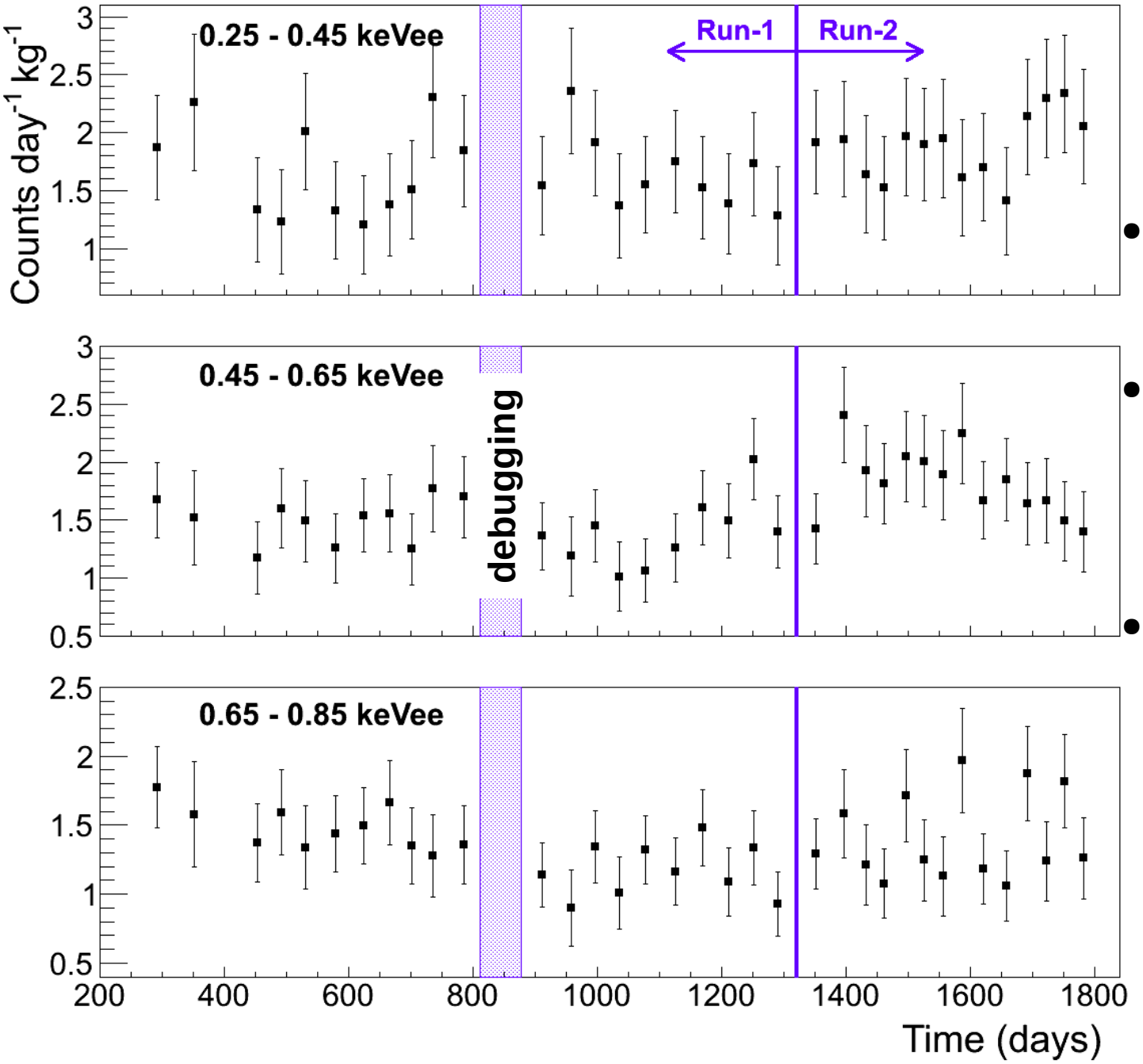
sample from typical DM/ν events (TEXONO), cosmic-vetoed + anti-Compton-vetoed

most probable rise-time distributions

- all the events samples share same bulk/surface rise-time distributions.
- unknown rise-time functions → bin-by-bin fitted.
- treat each month as individual sources.



CDEX-1B data < 0.85 keV



- run-1 to run-2: change of shielding.
- 0.25 – 0.85 keV: most important region for low mass WIMP
- χ2 test, (mean, RMS) consistent with null profile.

Model dependent/independent modulation analysis

fit the data to flat-bkg + cos (after K/L subtraction)

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

i, j, k : energy-bin, time-bin, number of run

n_{ijk} : count rates

P_{ijk} : contributions from K/L-shells

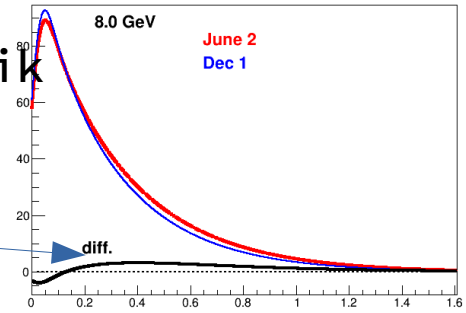
B_{ik} : time-independent background level, to be fitted

A_{ik} : modulation amplitudes, to be fitted.

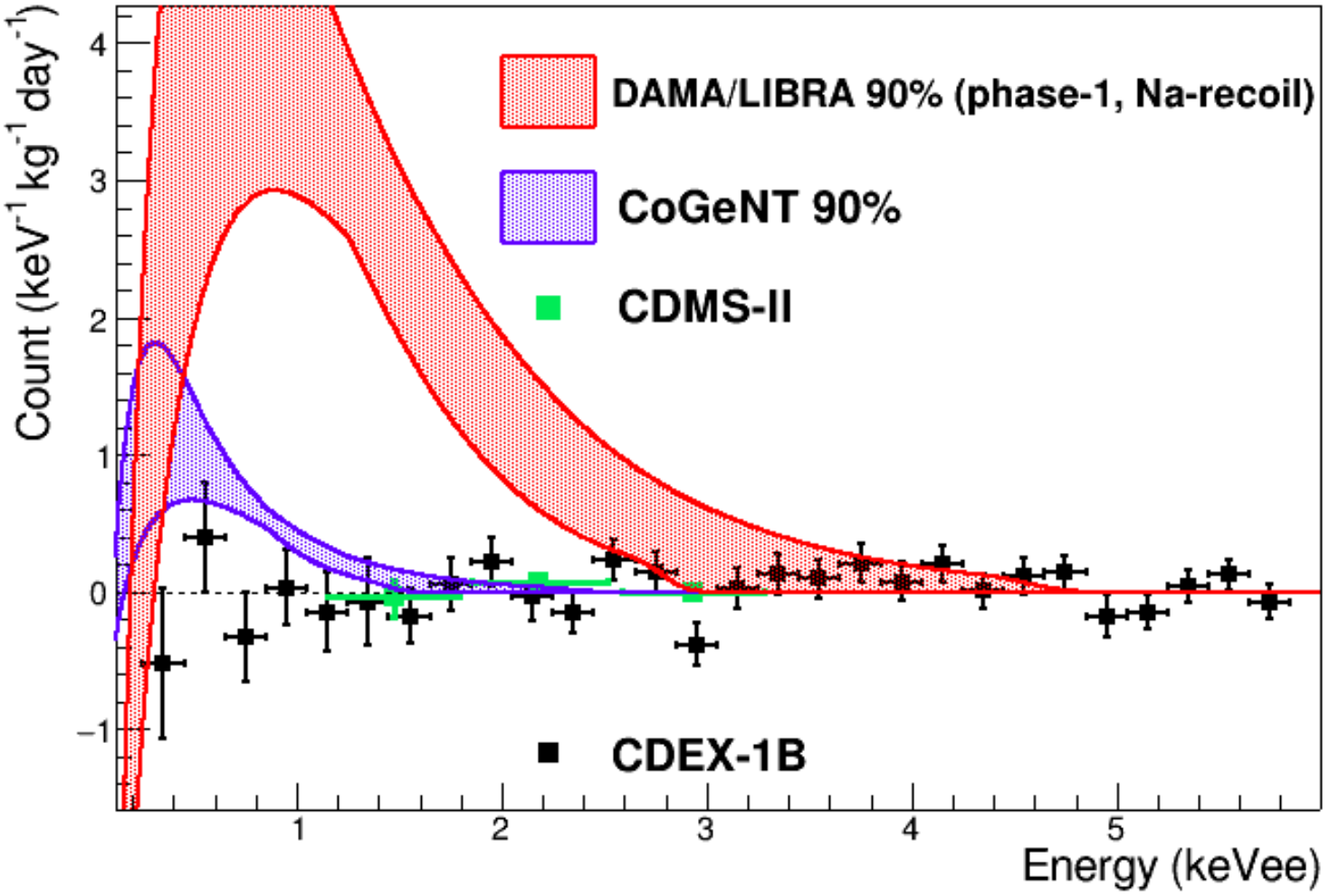
Model independent: modulation amplitudes of each χ^2_{ik}

Model dependent: astrophysics dependent A_{ik}, sum over χ^2_{ik}

A_{ik} of Halo-model

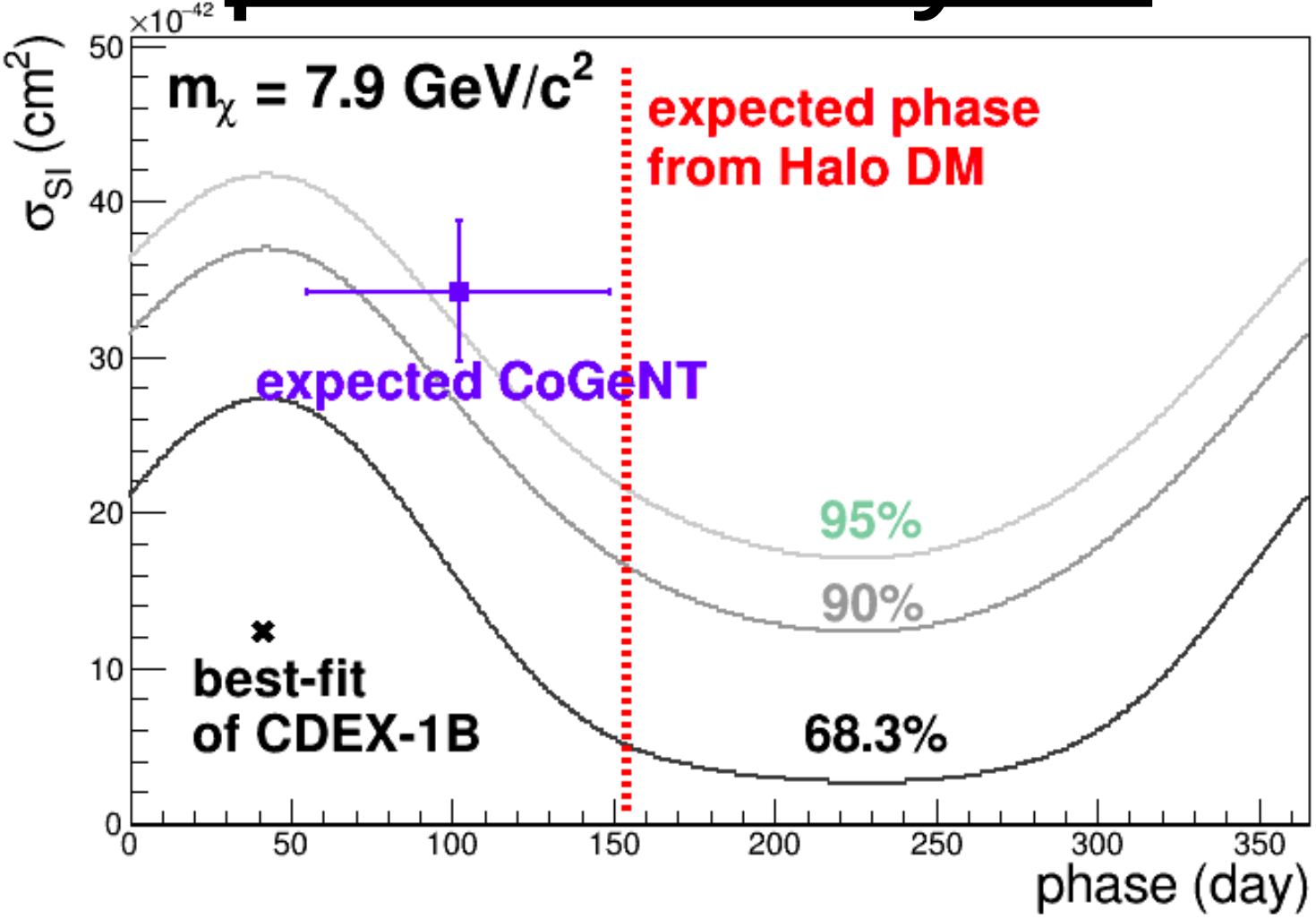


Model independent modulation



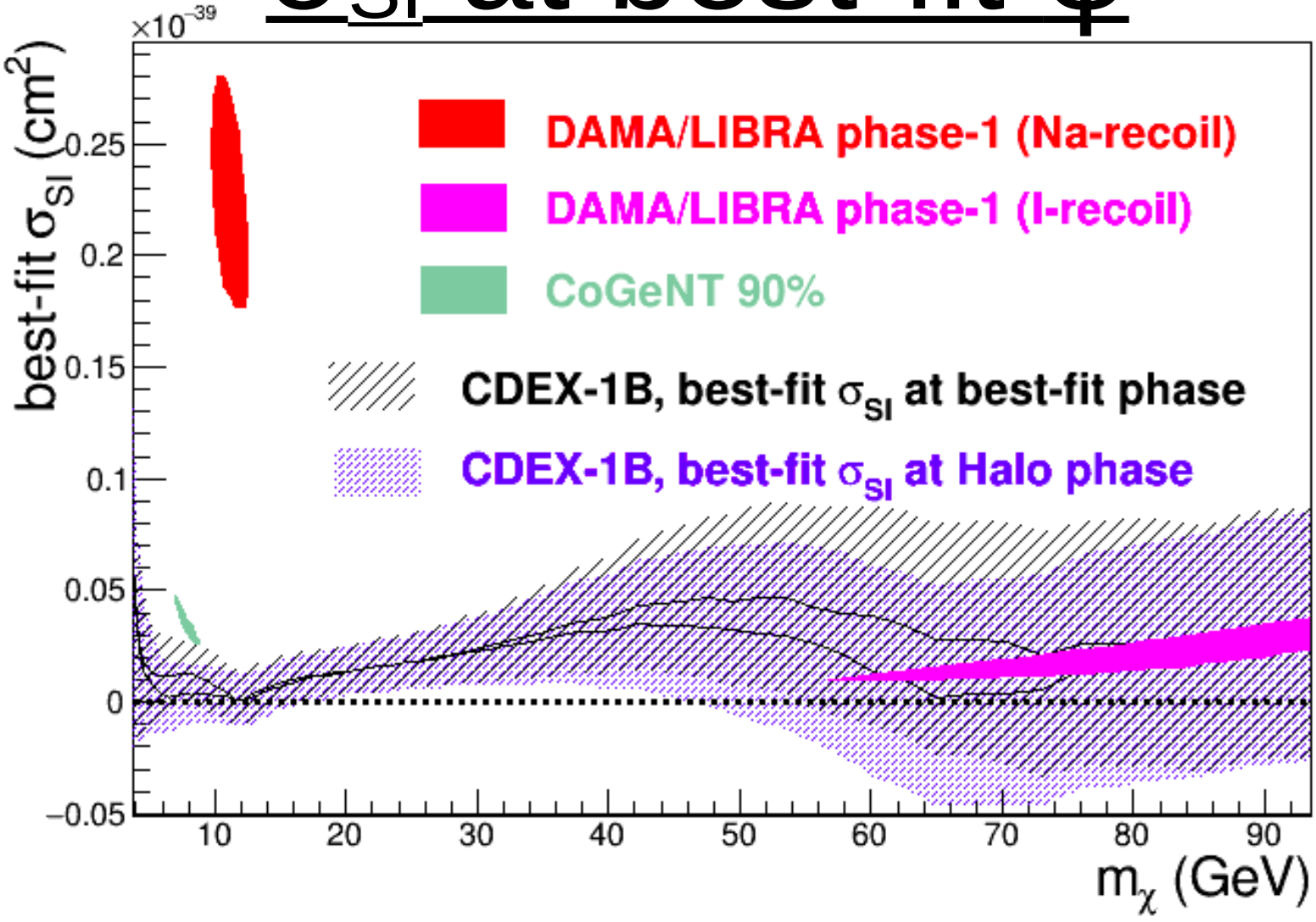
modulation amplitudes consistent with null-results by χ^2 test and (mean, RMS)

phase analysis



at < 20 GeV, best fitted phase is off by ~100 days,
however $\Delta\varphi > 0.5$ years (any φ is within 1-σ)
data consistent with null-hypothesis at any φ

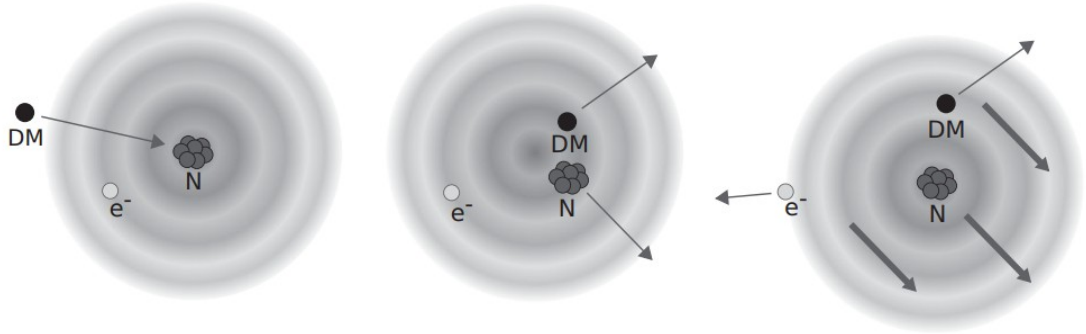
σ_{SI} at best-fit φ



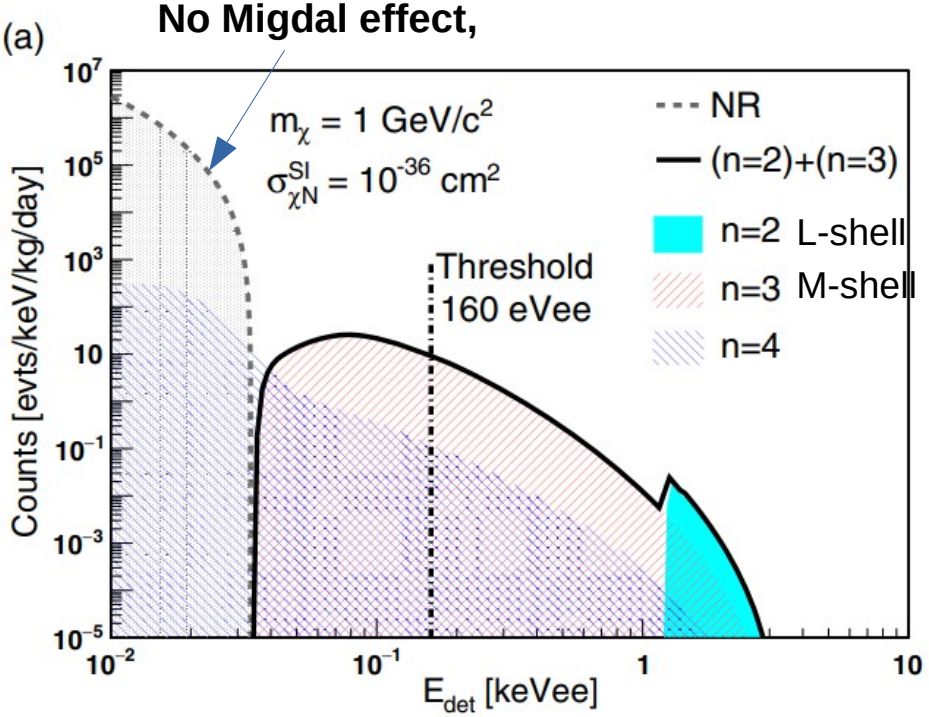
the results consistent with null-results at any phase (within 2-σ) up to 100 GeV

Migdal effect

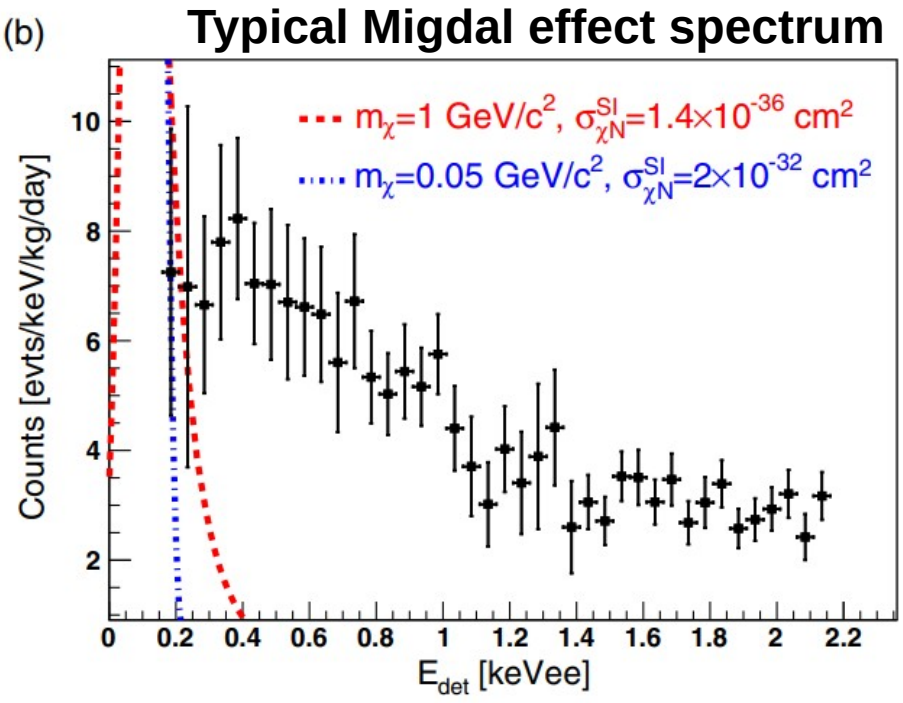
nuclear recoil → electrons cloud move, except one e- → ionization



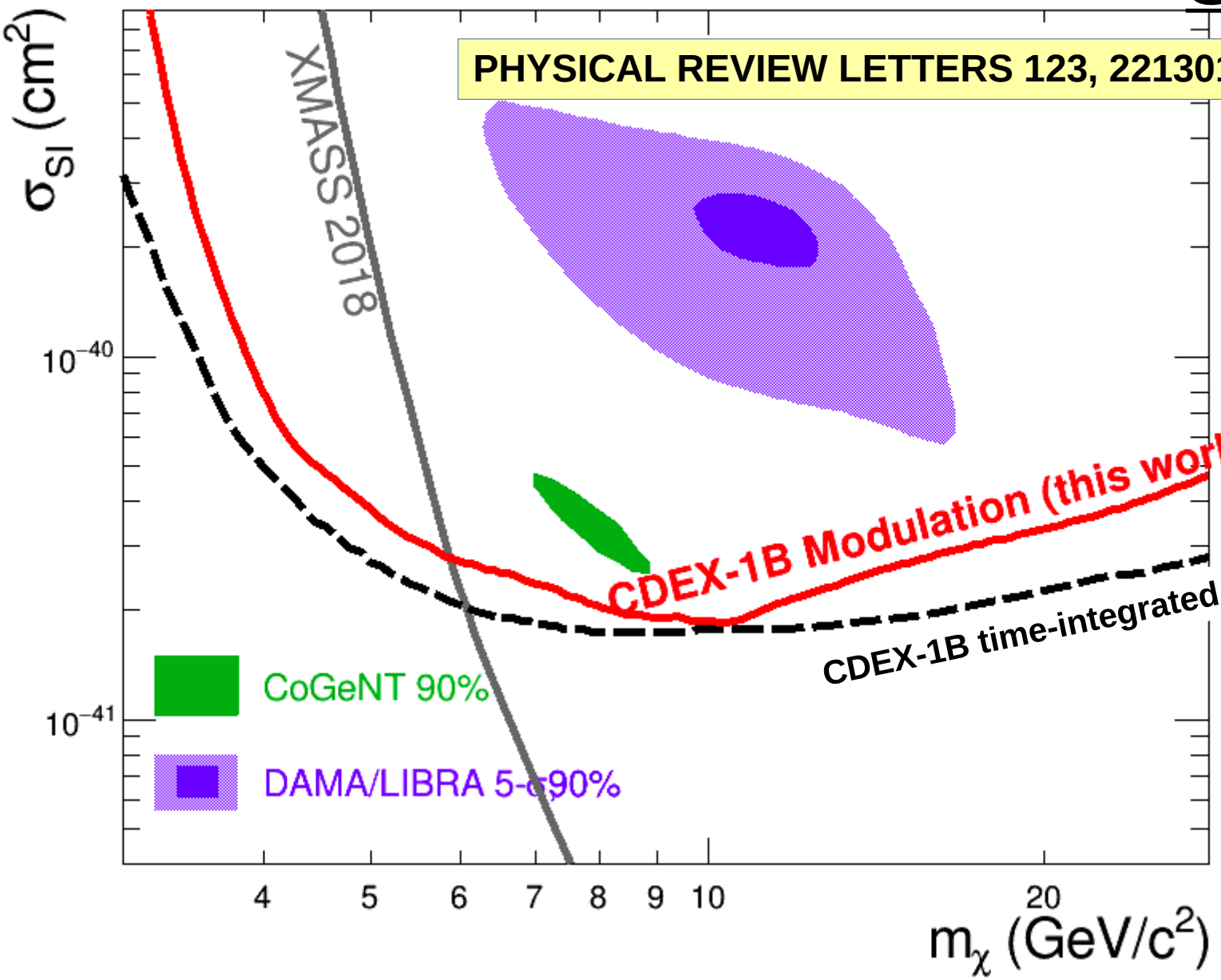
No Migdal effect,



Typical Migdal effect spectrum



Model dependent results: σ_{SI}



best annual modulation sensitivities < 6 GeV

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Migdal effect

- probing m_χ to < 1 GeV,
- best time-integrated results < 0.1 GeV
- best annual modulation results < 1 GeV

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