Status and prospects of CDEX experiment

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On behalf of CDEX Collaboration

Low energy recoils from deep underground, Sep 26th, 2020

OUTLINE

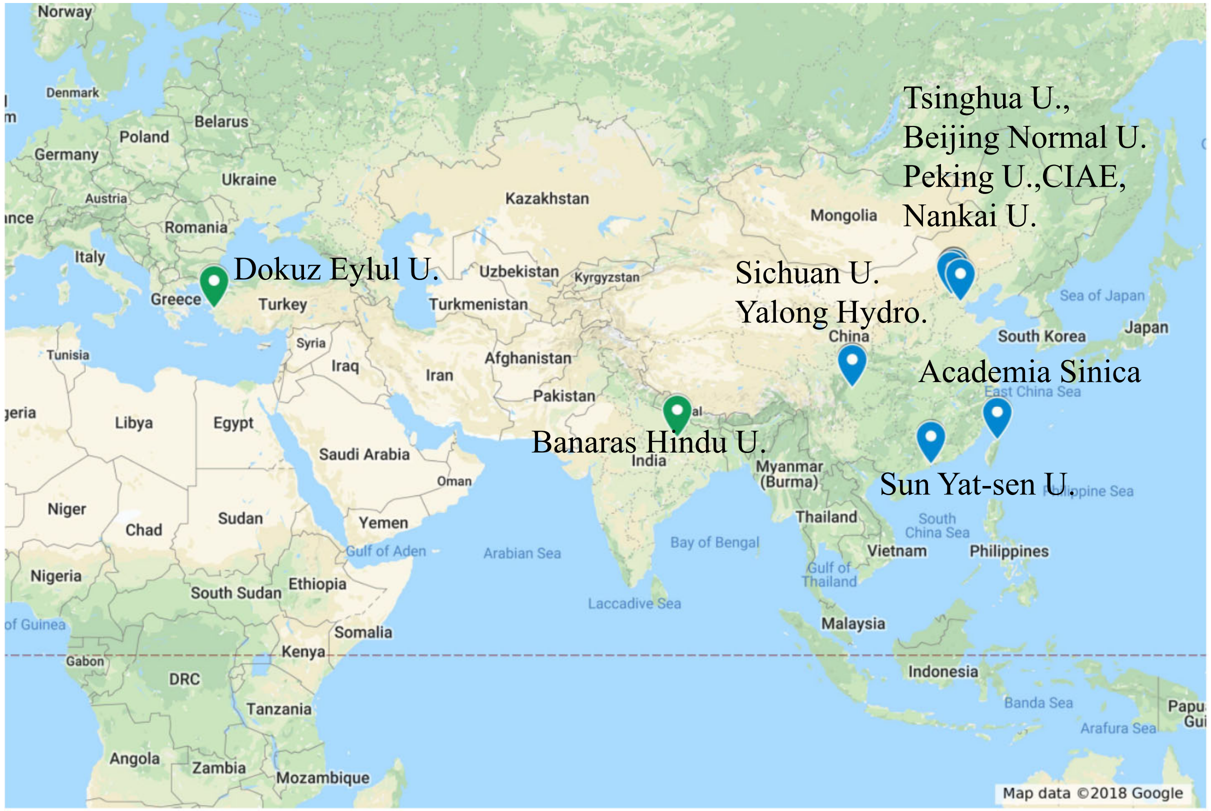
- Introduction to CDEX
- Recent status of CDEX-1 and CDEX-10
- R&D of key technologies
- Future plan of CDEX @CJPL-II
- Summary

China Dark matter Experiment

CDEX

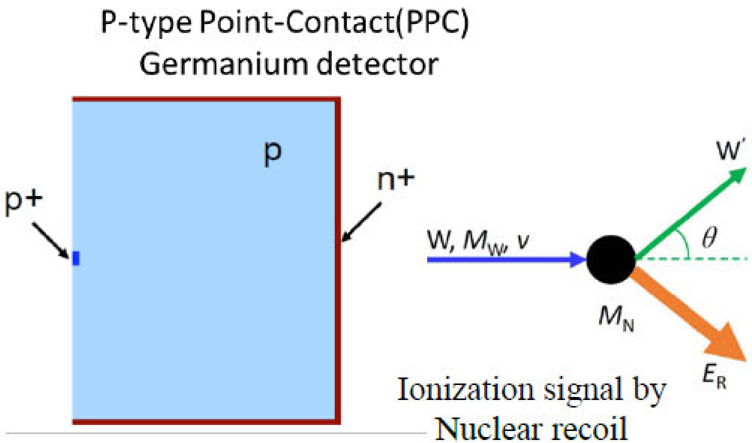
http://cdex.ep.tsinghua.edu.cn/

- Formed in 2009;
- 11 institutions;
- ~70 people;
- Direct detection of light DM and ^{76}Ge double-β decay;
- P-type Point-Contact (PPC) Germanium detectors;
- Located in CJPL.

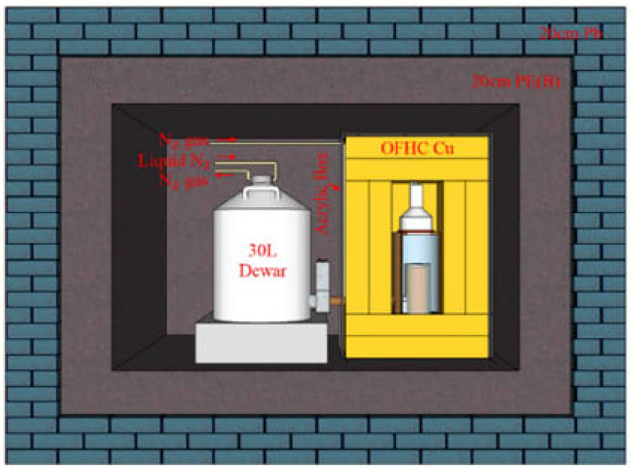


CDEX Experiment phases

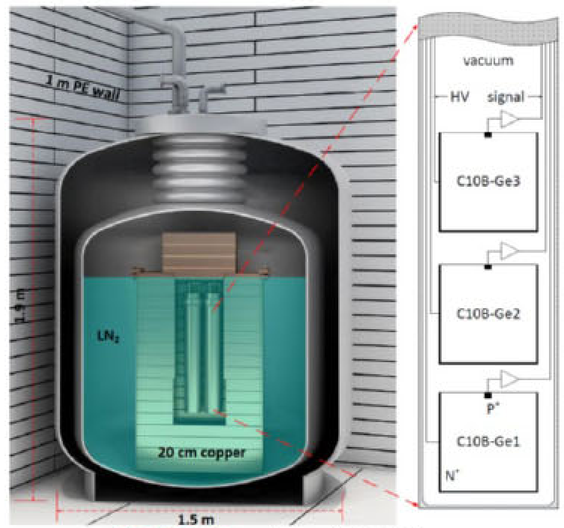
- Pre-CDEX: 5g Ge Det. prepared since 2003 and started in 2005 in Y2L;
- **CDEX-1:** Development of PPC Ge detector, bkg understanding, since 2011;
- **CDEX-10:** Performances of Ge array detector immersed in LN_2, since 2016;
- **CDEX-10X:** Home-made Ge detector and Ge crystal growth;



Direct detection of low-mass WIMPs w/ Ge detector at CJPL.



CDEX-1A&B: 1kg PPC Ge×2

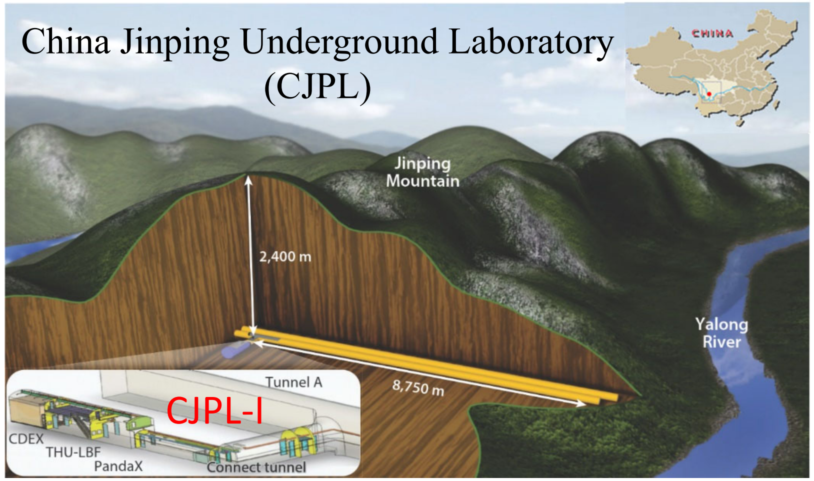


CDEX-10: ~10kg PPC Ge array

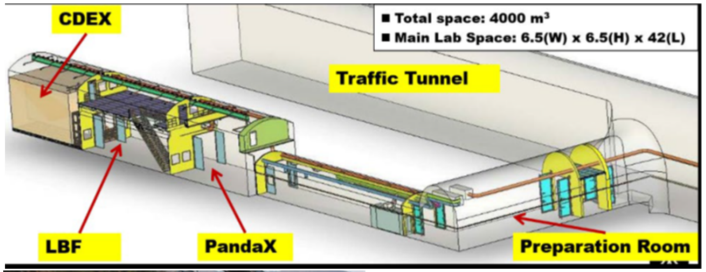
China Jinping Underground Laboratory

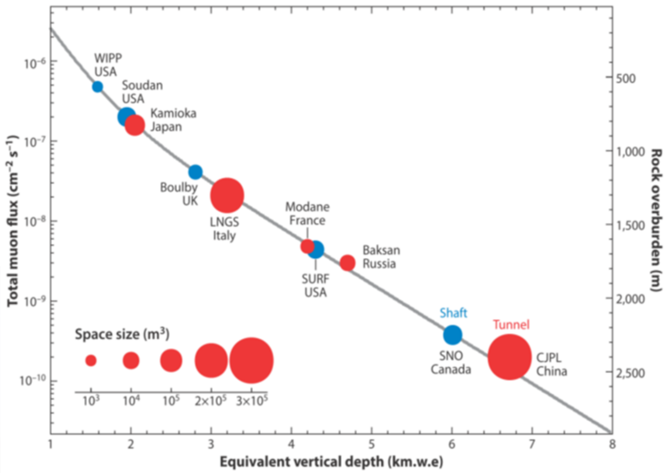
http://cjpl.ep.tsinghua.edu.cn/

- World's deepest underground lab, CJPL
  - Near Xichang city, Sichuan Province, Southwest China
  - Constructed by Tsinghua U. and Yalong Hydropower Company in 2009-2010
  - Two DM exp. (CDEX, PandaX)+LBF(radio-assay)operated now
  - Extension project, DURF/CJPL-II, expected to be completed in 2022



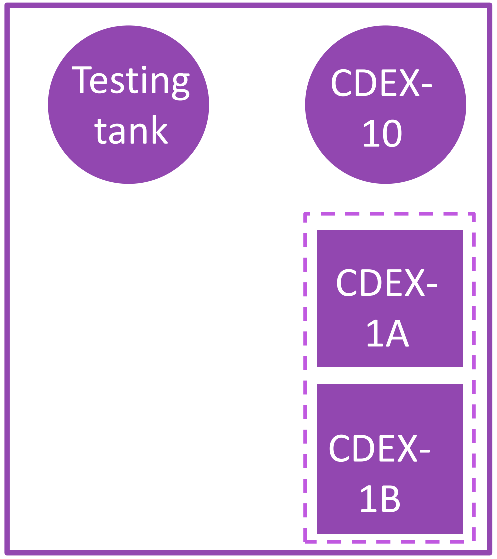
Cheng et al., Annu. Rev. Nucl. Part. Sci. 2017. 67:231



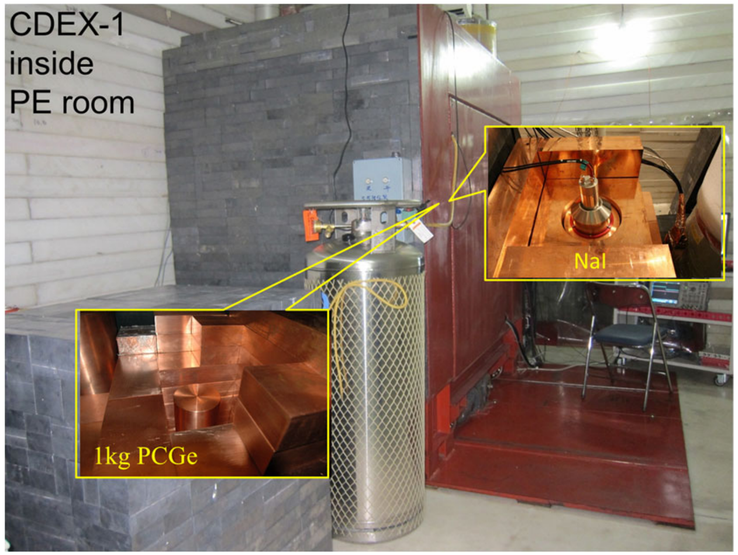


CDEX-1 Status

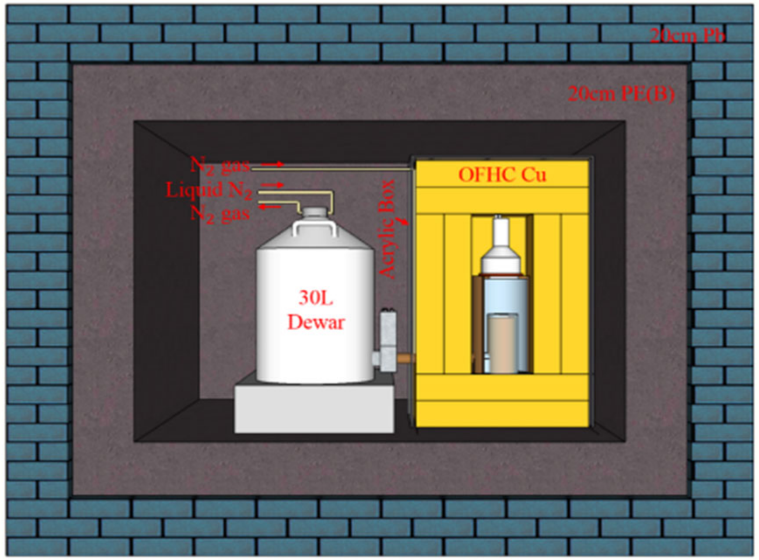
- 2 sub-stages: CDEX-1A(prototype, 2011)→1B(upgraded, 2013);
- Traditional single-element ~1kg PPC Ge detector;
- Low-bkg Pb&Cu passive shield + NaI veto detector;
- Located in PE room at CJPL-I;
- Science run finished in 2018;



Layout of PE room, CJPL-I



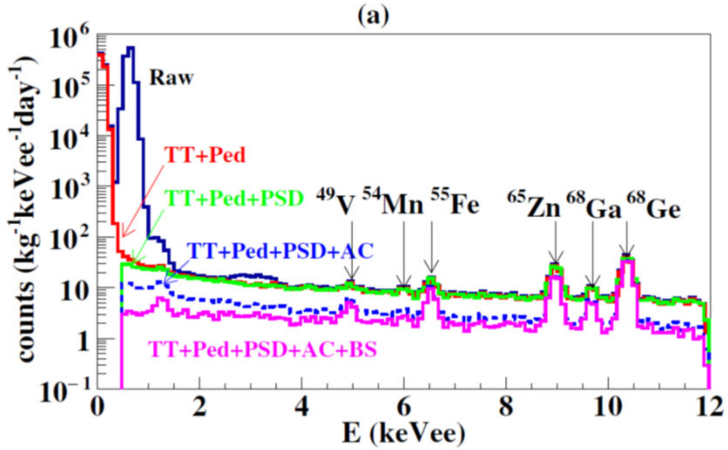
CDEX-1 inside PE room



CDEX-1A&B: 1kg PPC Ge×2

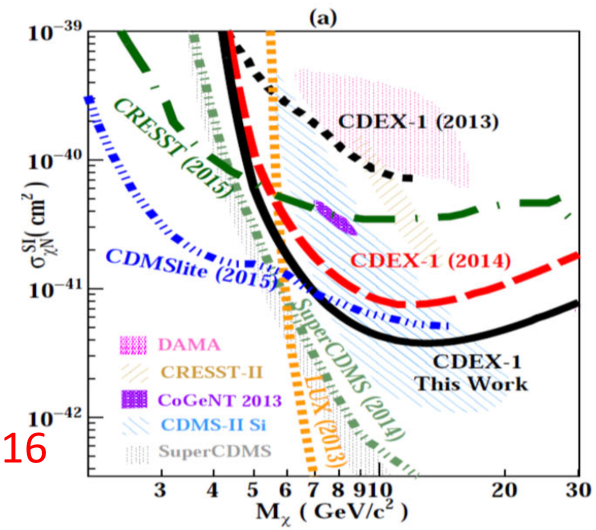
CDEX-1A Results

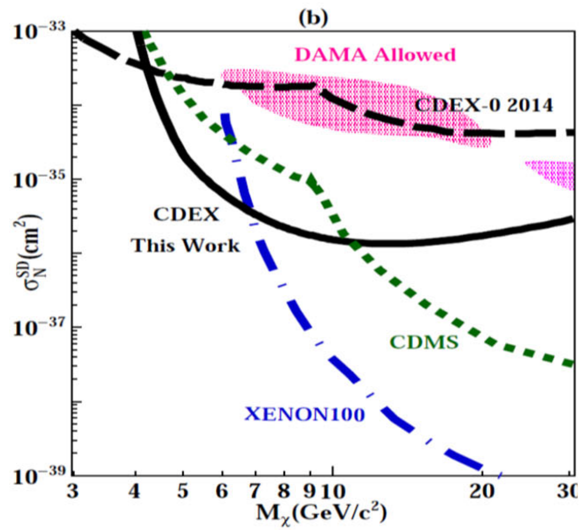
- >500 days run, ~336 kg·day dataset;
- Energy threshold: 475 eVee;
- Bulk/Surface disc. to cut events with slow rise-time and partial charge collection;
- K/L X-rays from Cosmogenic nuclides to trace crystal history;



- SI sensitivity improved;
- SD best below 6 GeV then;

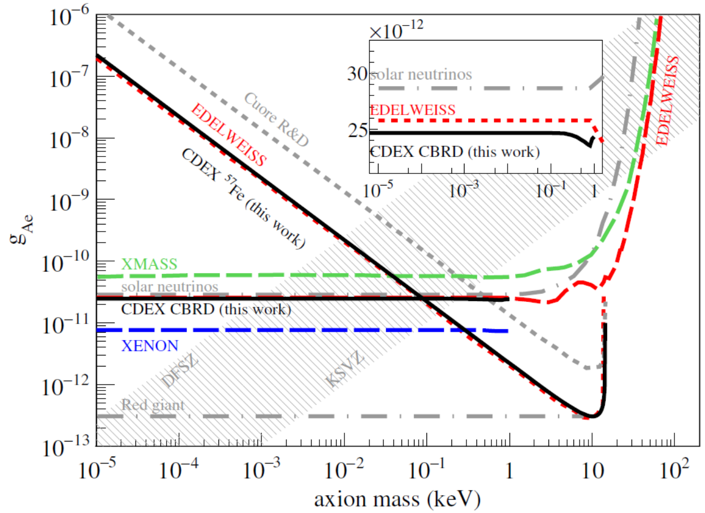
PRD93, 092003, 2016

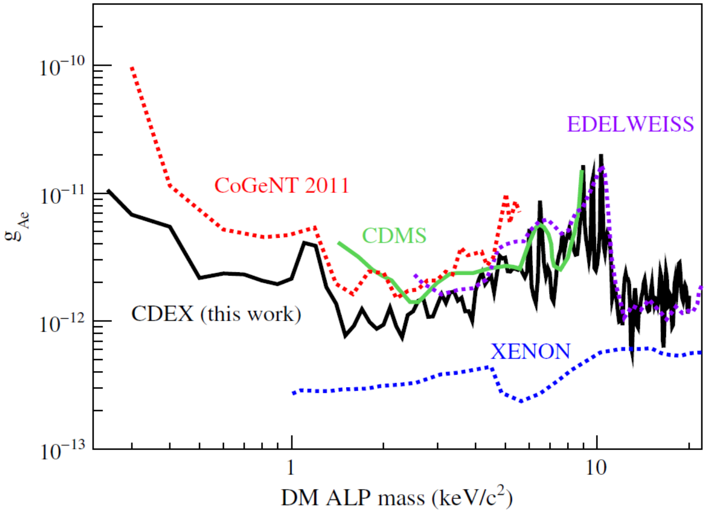




CDEX-1A Results

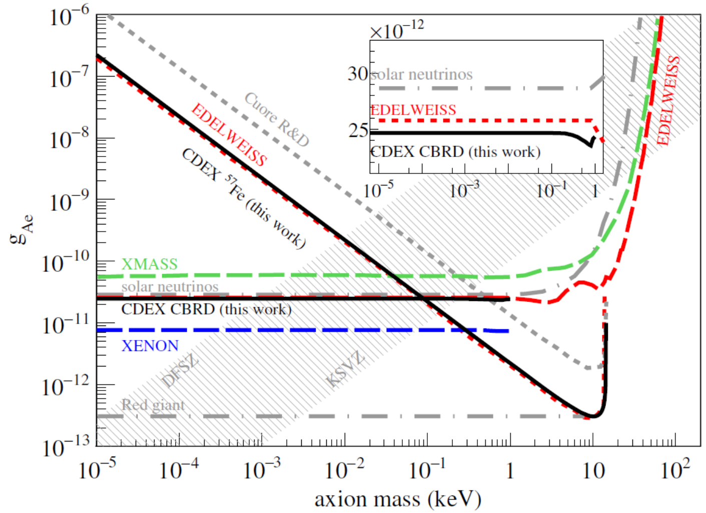
- Axion (335.6 kg·day data) [PRD95, 052006, 2017]
  - Solar axions: CBRD processes and ^{57}Fe M1 transition;
  - ALPs: more stringent constraint below 1 keV;



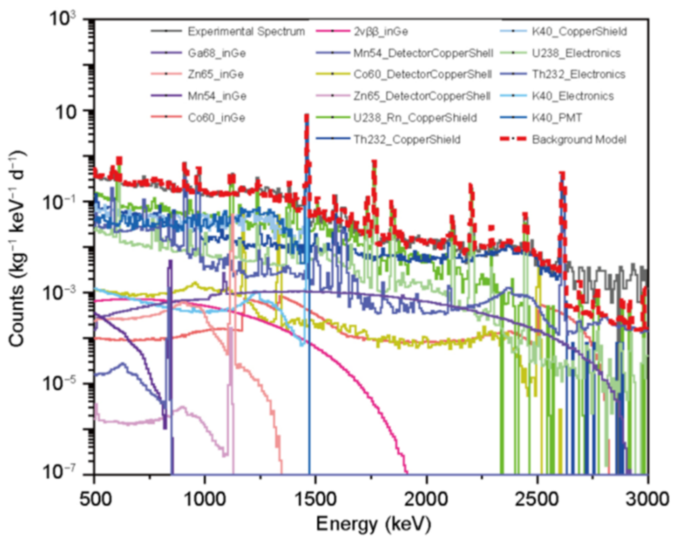


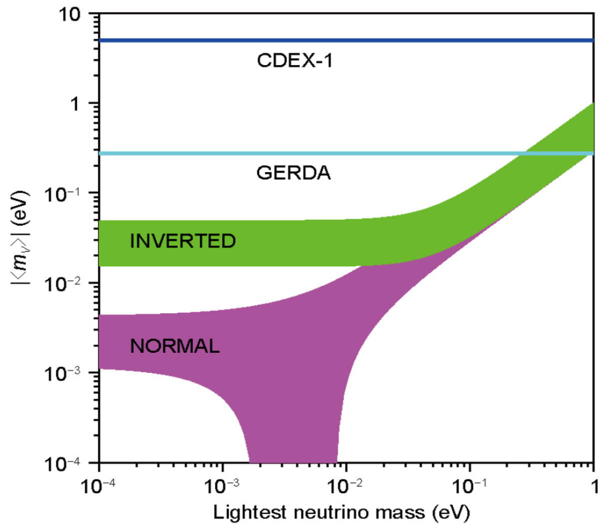
CDEX-1A Results

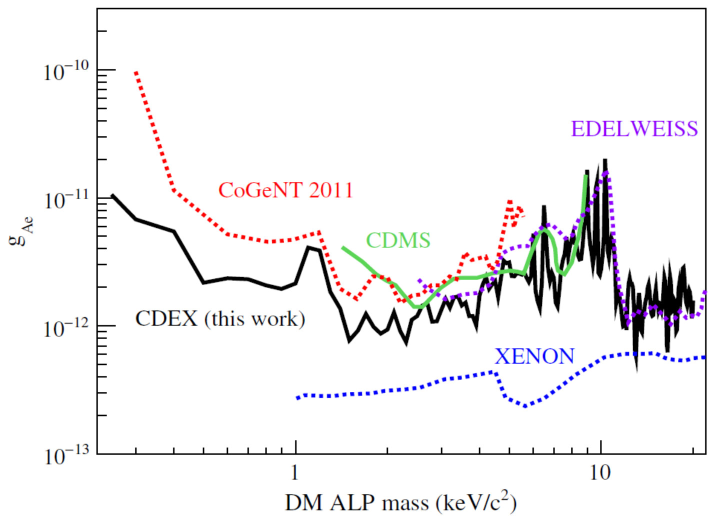
- Axion (335.6 kg·day data) [PRD95, 052006, 2017]
  - Solar axions: CBRD processes and ^{57}Fe M1 transition;
  - ALPs: more stringent constraint below 1 keV;
- 0νββ (304 kg·day data)
  - Natural Ge crystal; $T_{1/2}^{0\nu} \geq 6.43\times10^{22}\,yr,\;\; 90\%\;\; C.L.$



[Science China PMA (2017) 60: 071011]







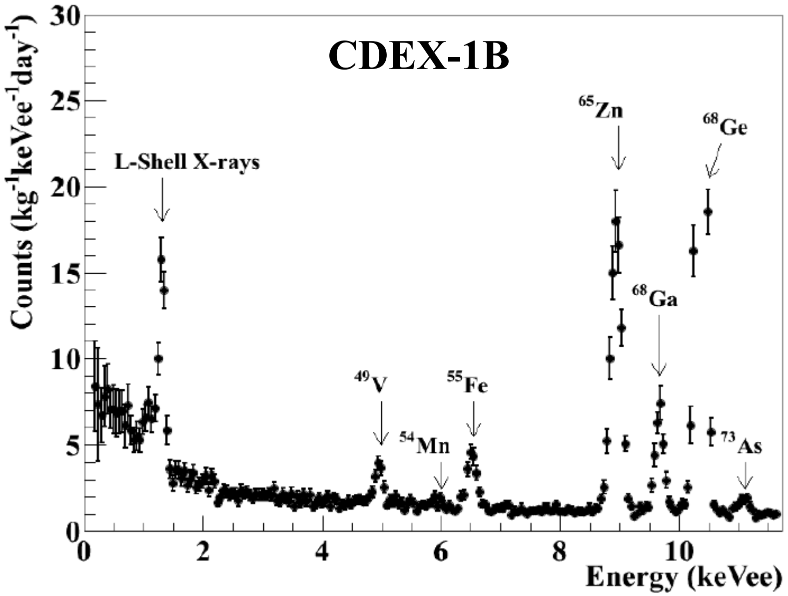
CDEX-1B Results

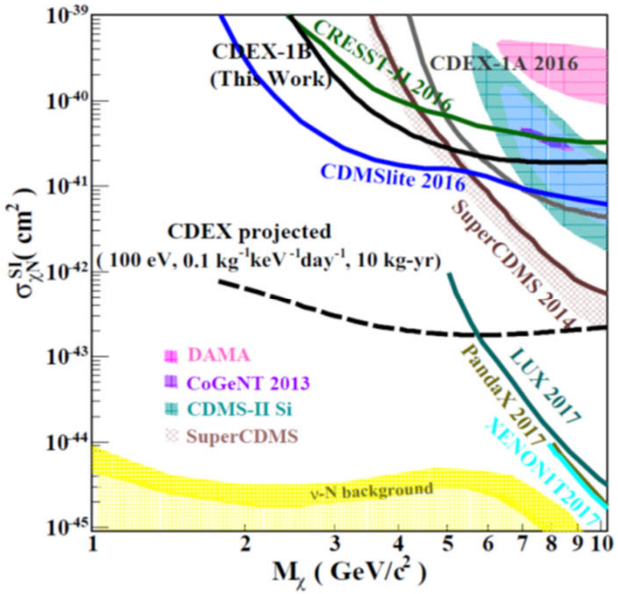
[CPC 42, 023002, 2018]

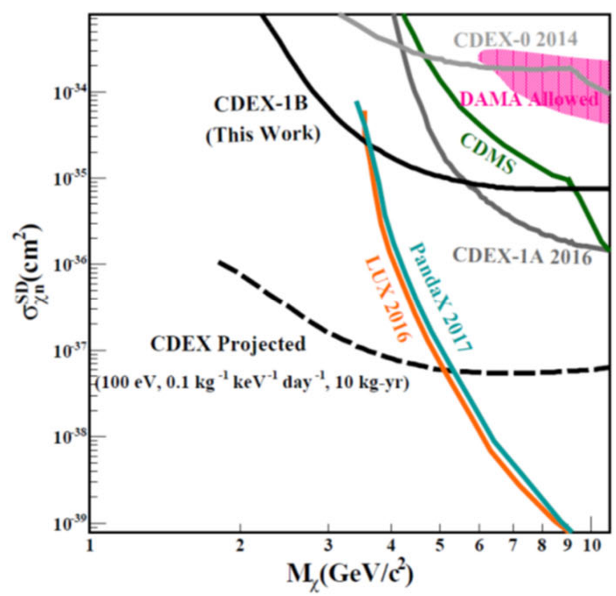
- Detector upgraded w/ lower JEFT noise and material bkg;
- >4 years run (Run-1&Run-2), >1200 kg·day exposure;
- Achieving 160 eVee energy threshold;
- Sensitivity improved and extending to 2 GeV/c^2.

Detector	FWHM (pulser)
CDEX-1A	130 eVee
CDEX-1B	80 eVee

Run-1 Time-integrated (TI) analysis

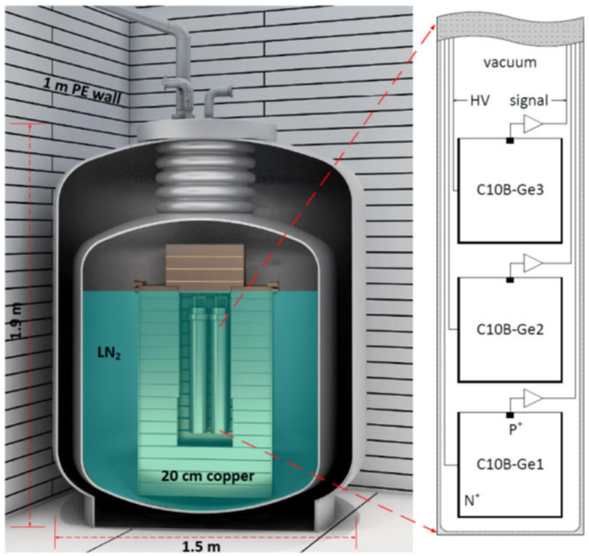




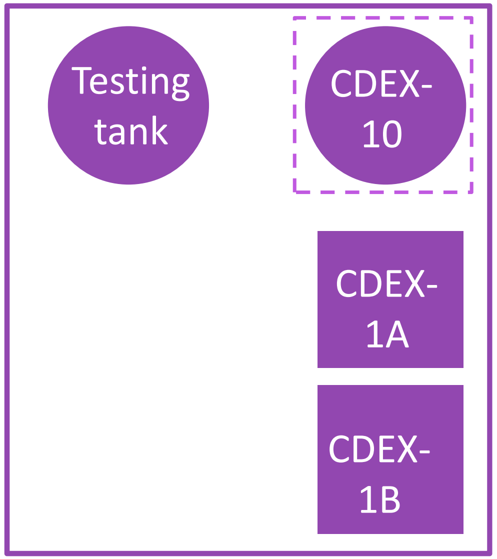


CDEX-10 Status

- Array detectors: 3 strings with 3 detectors each, ~10kg total;
- Direct immersion 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;



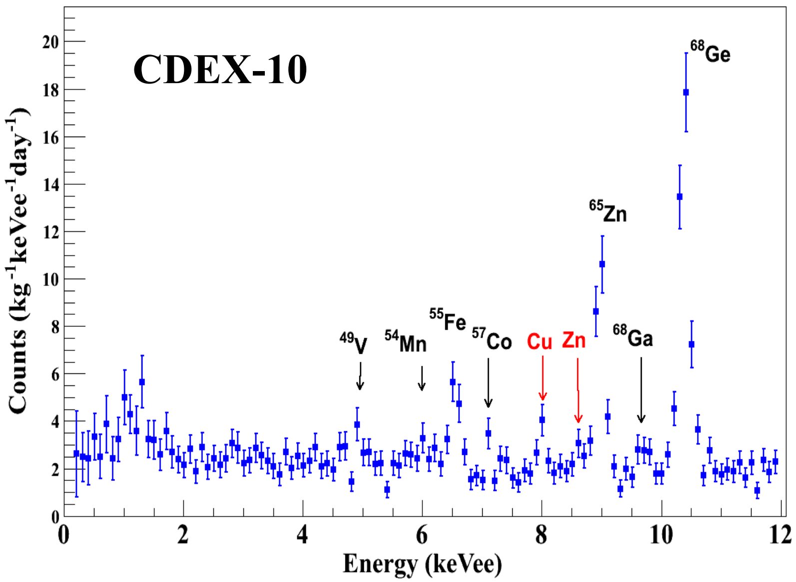
CDEX-10: ~10kg PPC Ge array

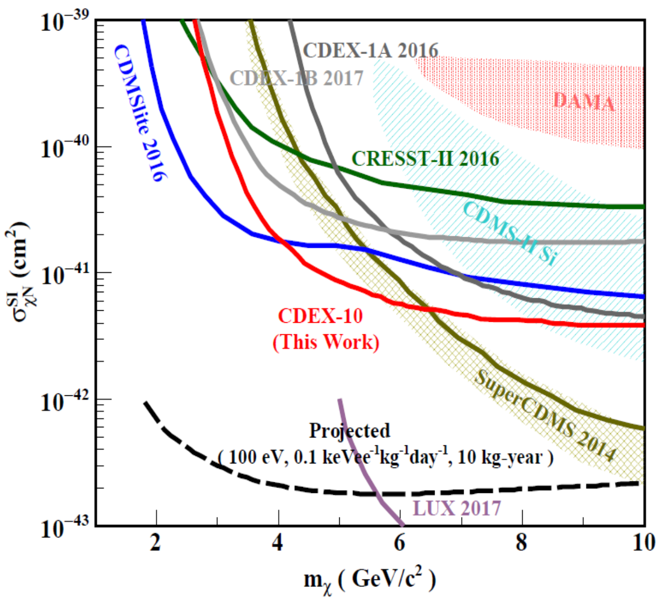


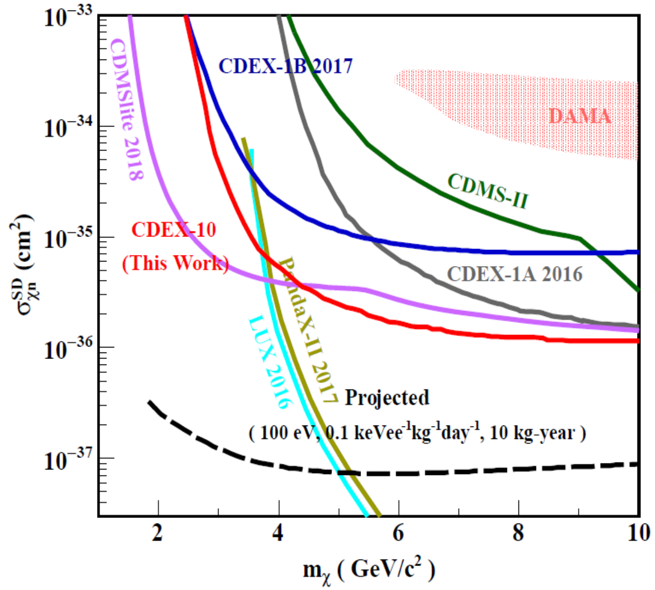
First Results from CDEX-10

- First results from 102.8 kg·day exposure w/ Eth 160eV;
- Bkg level: ~2 cpkkd @ 2-4 keV;
- New SI limit on 4-5 GeV/c^2;

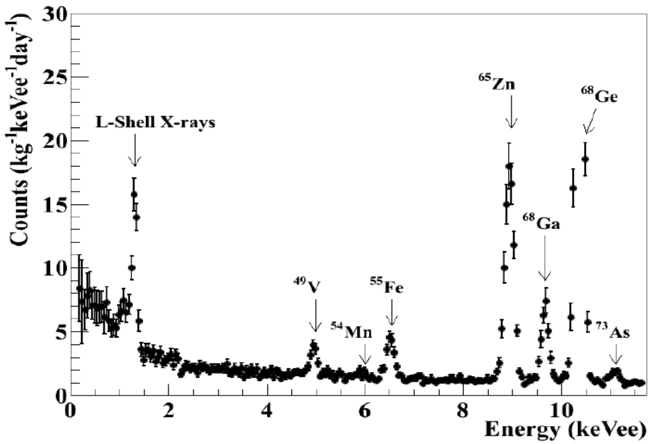
PRL120, 241301, 2018



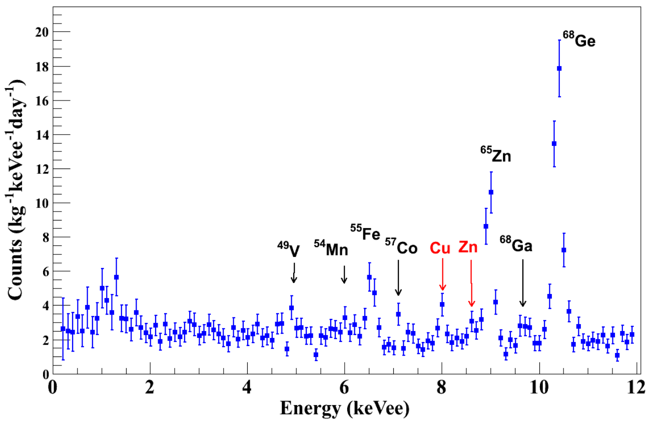




Data on hand from CDEX-1 and CDEX-10



CDEX-1B

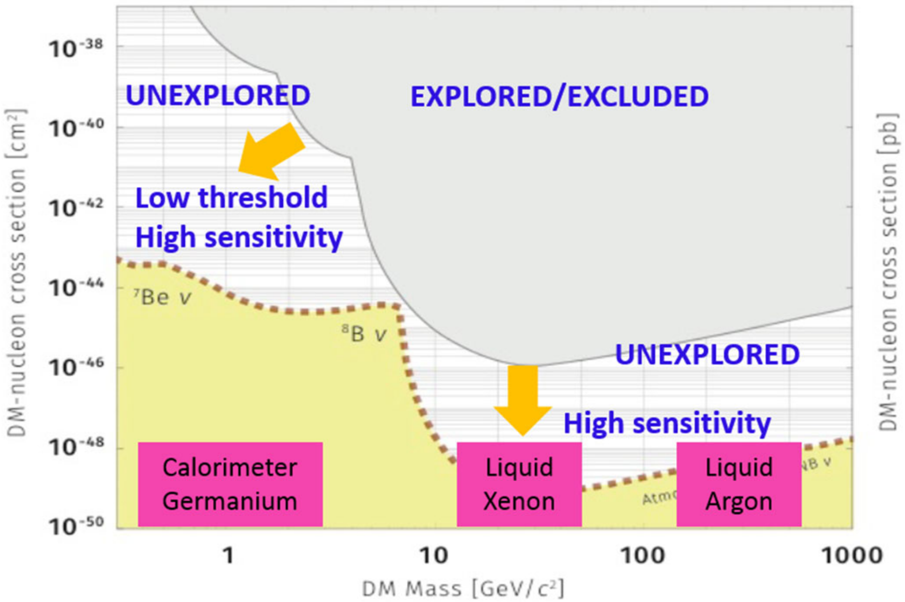


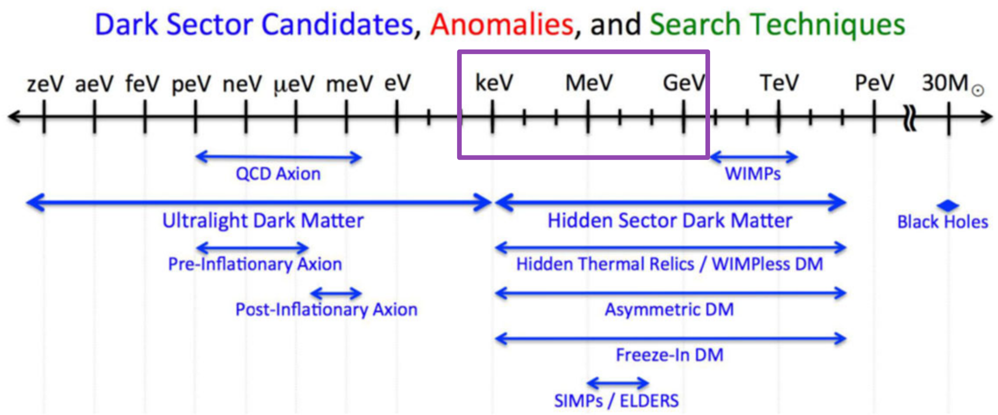
CDEX-10

Detector	CDEX-1A	CDEX-1B	CDEX-10	
			C10B	C10C
Analysis Threshold	475 eVee	160 eVee	160 eVee	300 eVee
Time span	~520	1527 day (~4.2year)	473 day	473 day
Live time	~365	1179.4 day	224.0 day	282.2 day
Exposure (kg days)	335.6	1107.5	210.3	265.0
Background Level @0.2-0.5keVee	~4 cpkkd	~8 cpkkd	~2.5 cpkkd	~12 cpkkd
Background Level @2-4keVee	~3.5 cpkkd	~2 cpkkd	~2 cpkkd	~10 cpkkd

Physics beyond the WIMP-nucleon SI

- ✓ Annual Modulation
- ✓ sub-GeV WIMPs: Migdal effect/Bremsstrahlung
- ✓ WIMP-Electron scattering
- ✓ Axion Like Particles / Solar Axion
- ✓ Dark photon / Solar Dark photon

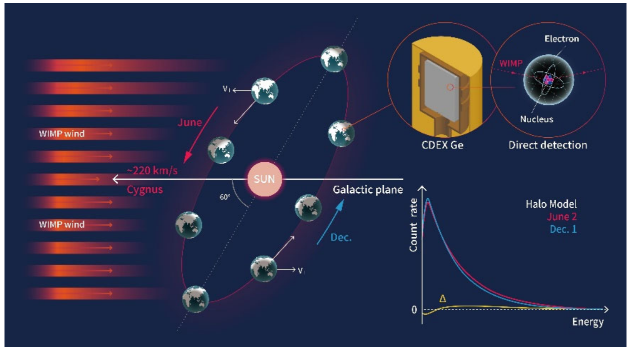




WIMPs: Annual Modulation analysis from CDEX-1B

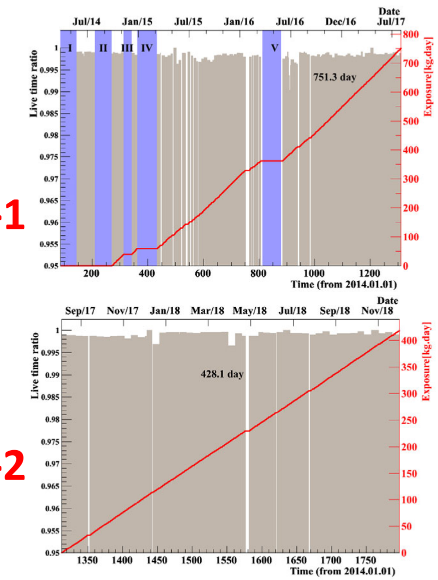
[PRL 123:221301,2019]

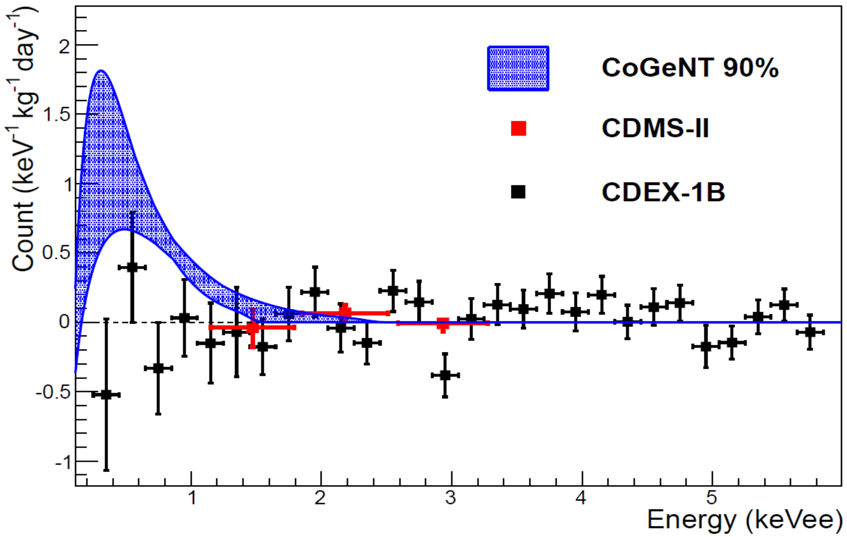
- AM provide smoking-gun signatures for WIMPs independent of background modeling, while only requires background at relevant energy range is stable with time;
- The expected χN rates have distinctive AM features with maximum intensity in June and a period of one year due to Earth's motion relative to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



Run-1

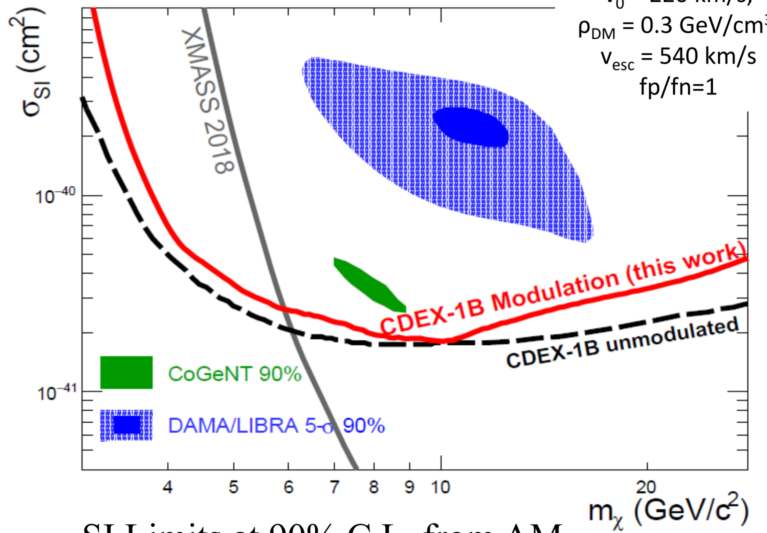
Run-2





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

<standard halo>
v_0 = 220 km/s,
ρ_{DM} = 0.3 GeV/cm^3,
v_{esc} = 540 km/s
fp/fn=1

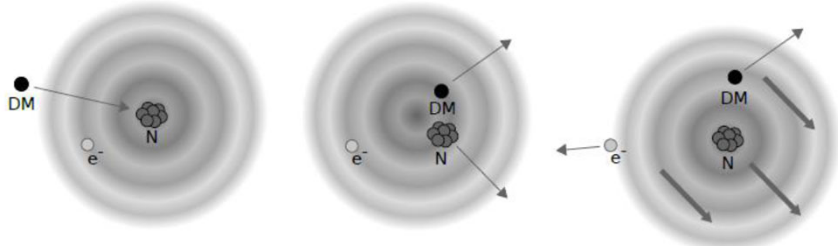


SI Limits at 90% C.L. from AM

sub-GeV WIMPs: Migdal effect analysis

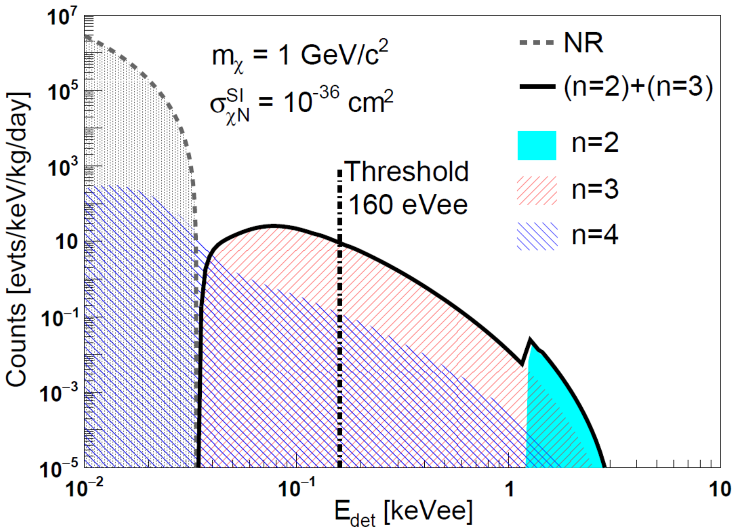
[PRL 123:161301, 2019]

- Time-Integrated Analysis with Migdal: 737.1 kg-d, w/ Eth 160 eVee;
- AM Analysis: 1107.5 kg-d, w/ Eth 250 eVee;
- Leading sensitivity in m_{DM} ~ 50-180 MeV;

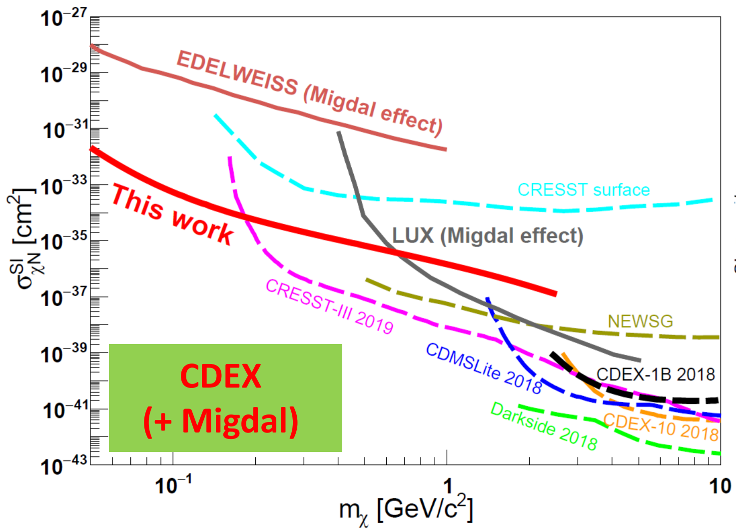


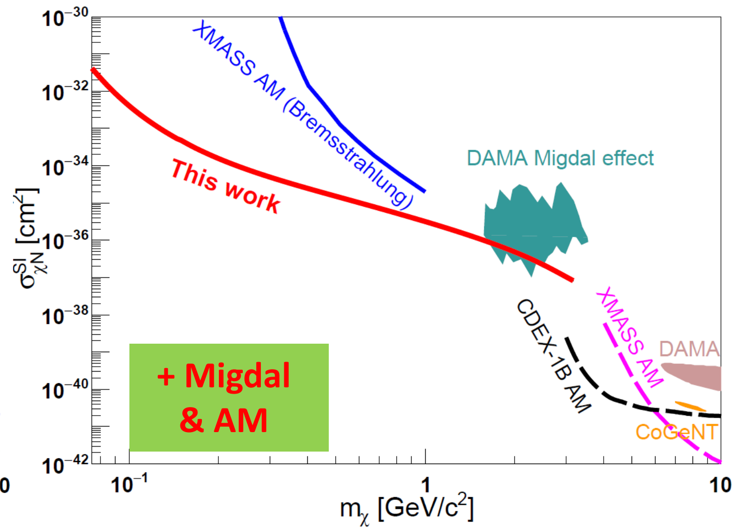
Migdal effect (M. Ibe et al.,2018)

Expected measurable spectra



PRL 123:161301 (2019)

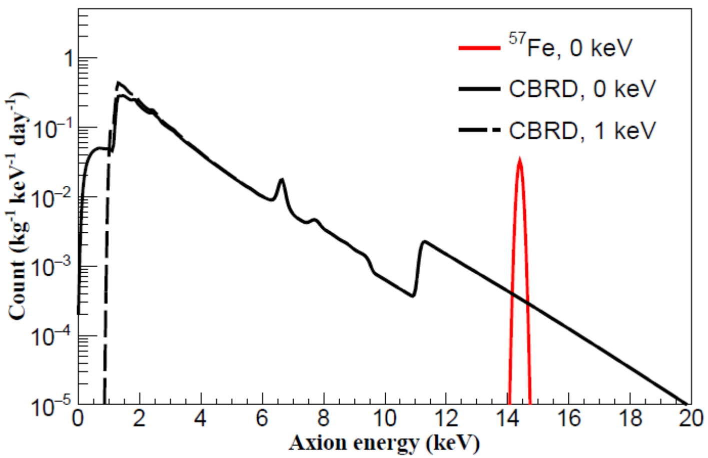


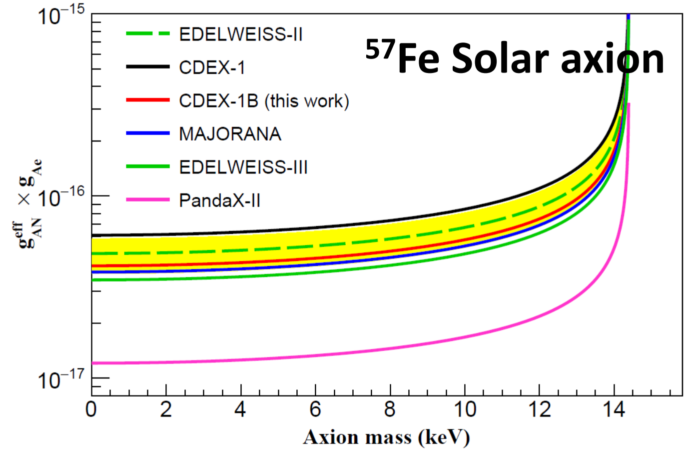


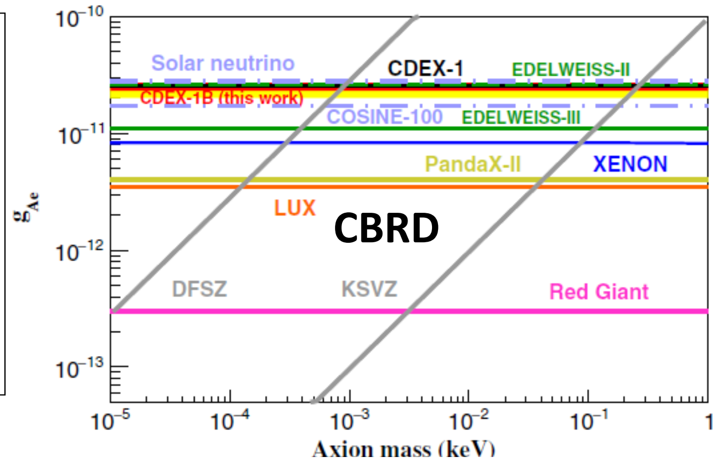
Solar Axions and Vector Bosonic DM: *Ae* coupling

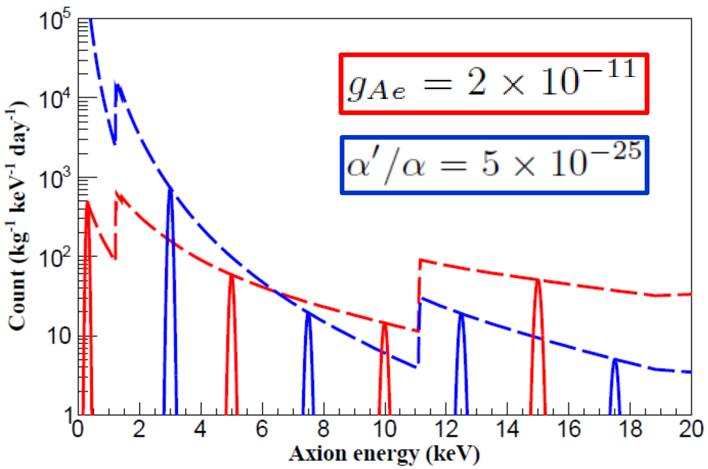
[PRD 101:052003, 2020]

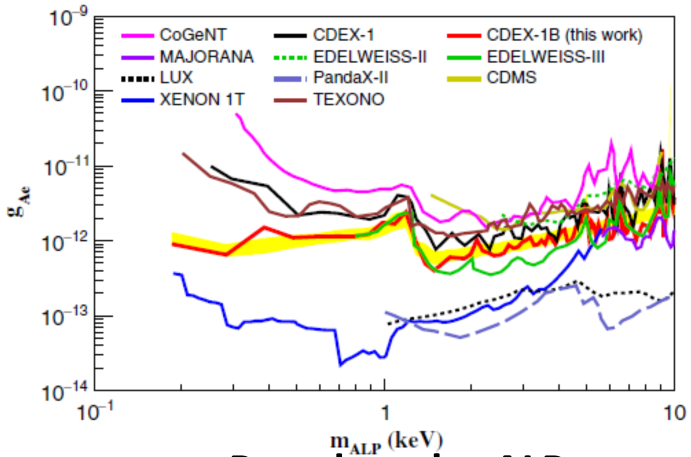
- 737.1 kg-d, w/ Eth 160 eVee; Leading sensitivity in m_{DM} < 800 eV for Ge-based experiment;



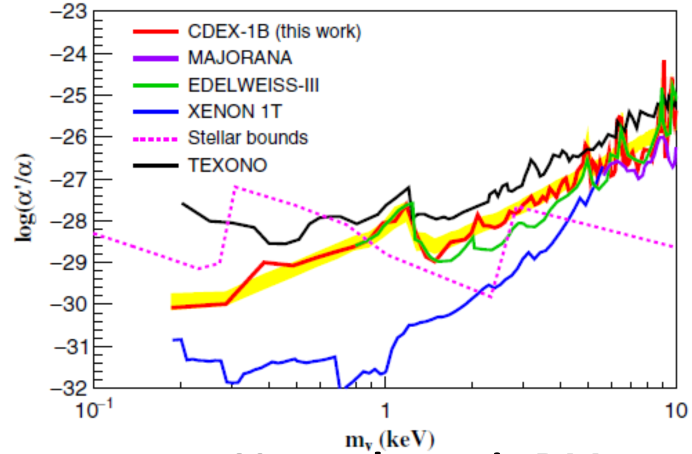








Pseudoscalar ALPs



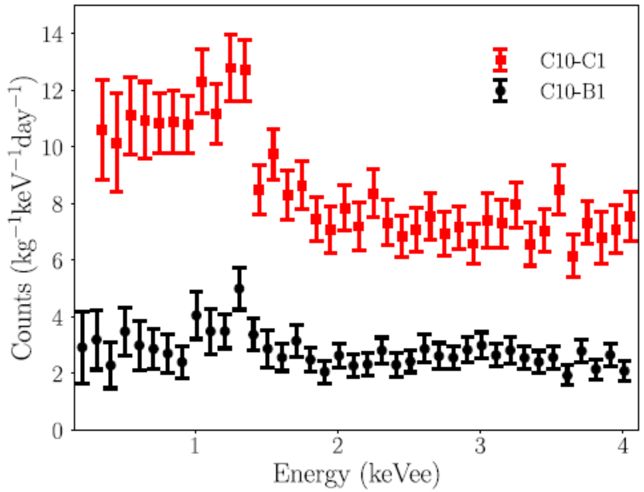
Vector bosonic DM

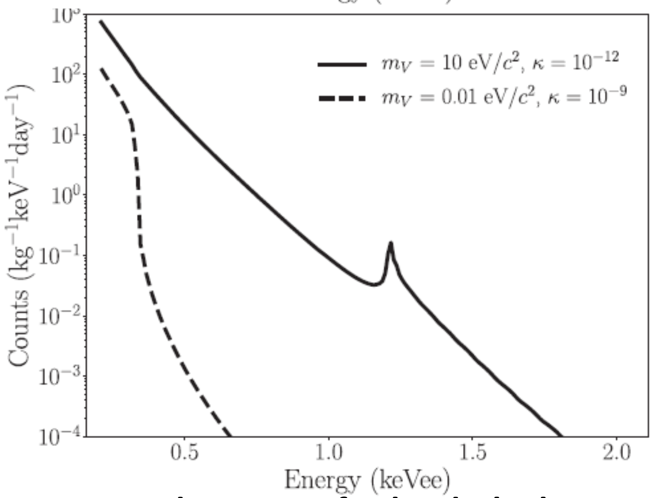
Solar dark photon and dark photon DM from CDEX-10

[PRL 124:111301, 2020]

Ref: An, H. et. al., PRL, 111:041302 (2013).

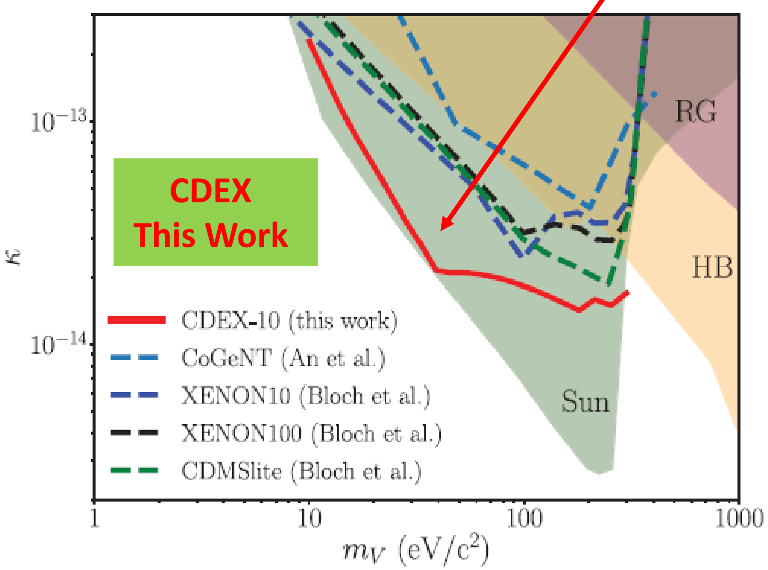
- Solar Dark photon Analysis: 205.4 kg-d, w/ Eth 160 eVee;
- Leading sensitivity in m_V ~10-300 eV for solar dark photon;



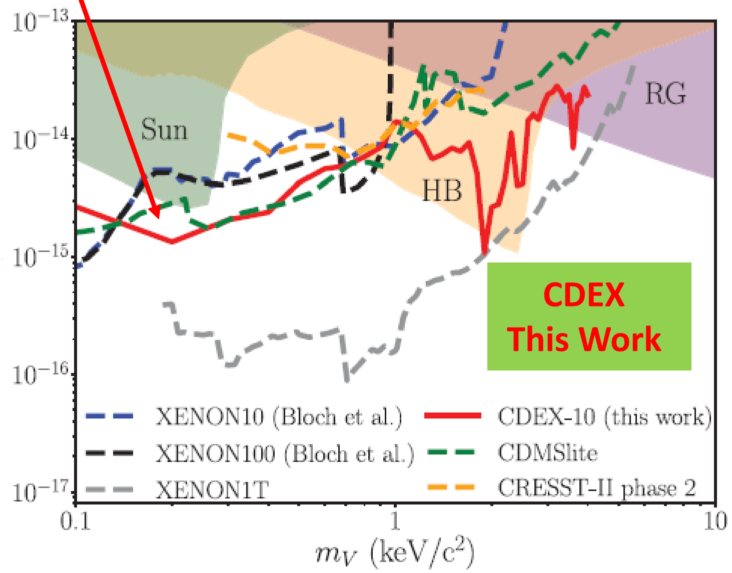


Expected spectra of solar dark photon

Advantages of the low threshold!



solar dark photon



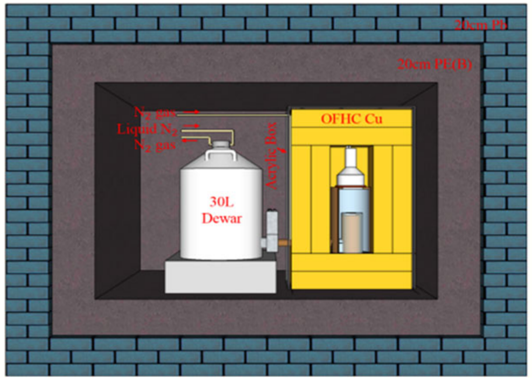
dark photon dark matter

CDEX Physics results summary

Physics Channels	Detectors	Analysis Threshold (eV)	Exposure (kg-day)	Publications
WIMP-nucleon SI	CDEX-1A	400	14.6	PRD 88, 052004, 2013
WIMP-nucleon SI	CDEX-20g	177	0.784	PRD 90, 032003, 2014
WIMP-nucleon SI	CDEX-1A	475	53.9	PRD 90, 091701, 2014
WIMP-nucleon SI/SD	CDEX-1A	475	335.6	PRD 93, 092003, 2016
Solar Axion and ALPs	CDEX-1A	475	335.6	PRD 95, 052006, 2017
$0\nu\beta\beta$	CDEX-1A	---	304.0	Sci. China 60, 071011, 2017
WIMP-nucleon SI/SD	CDEX-1B	160	737.1	CPC42, 023002, 2018
WIMP-nucleon SI/SD	CDEX-10	160	102.8	PRL 120, 241301, 2018
Sub-GeV WIMP-nucleon SI, Migdal Effect	CDEX-1B	160/250	737.1/1107.5	PRL 123, 161301, 2019
Annual Modulation	CDEX-1B	250	1107.5	PRL 123, 221301, 2019
Solar Axion, ALPs, Vector bosonic DM	CDEX-1B	160	737.1	PRD 101, 052003, 2020
Solar dark photon, dark photon DM	CDEX-10	160	205.4/449.6	PRL 124, 111301, 2020

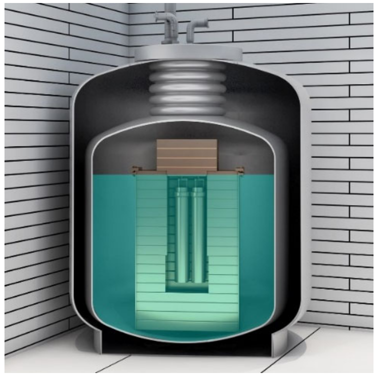
CDEX Roadmap

Direct detection of Dark Matter Particles and ^{76}Ge double-β decay process using P-type Point-Contact Germanium detectors at China Jinping Underground Laboratory.



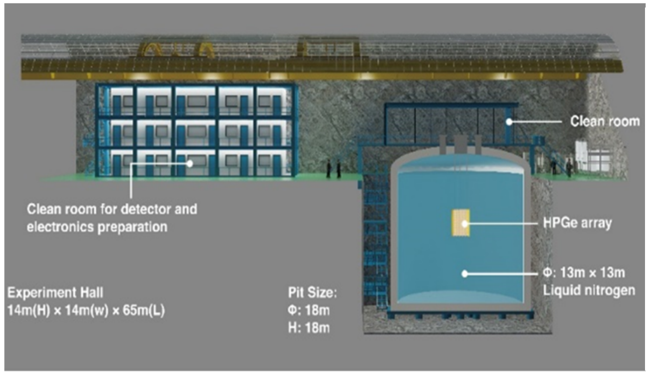
CDEX-1A/B (2011-2018)

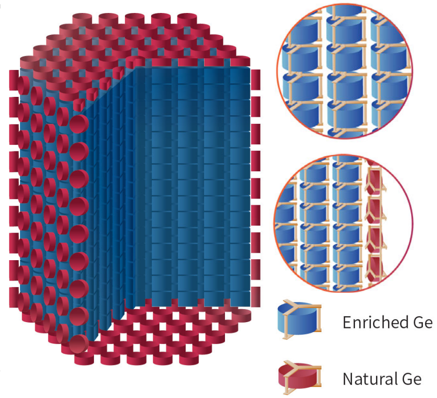
2 PPC Ge detectors with a mass of up to ~1 kg



CDEX-10 (2016-)

10 kg PPC Ge detector array immersed into LN_2





CDEX-100 (202X-)

100+ kg Ge array in large-volume LN_2

CJPL-I

Key technologies:
- ✓Ge crystal growth / Ge detector fabrication
- ✓Ultra-low background VFE
- ✓Ultra-pure copper for structure and cables

CJPL-II

- ✓ Larger scale detector array
- ✓ Lower background
- ✓ Lower threshold

Technical R&D towards next-stage

- **Large scale detector array**

  10 kg → 100 kg → 1000 kg

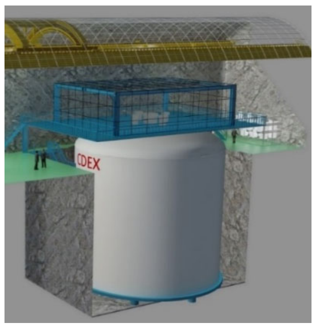
- **Low background**

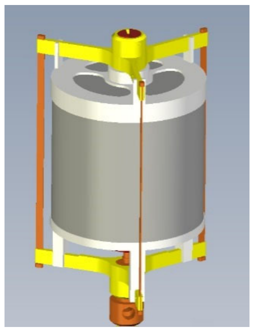
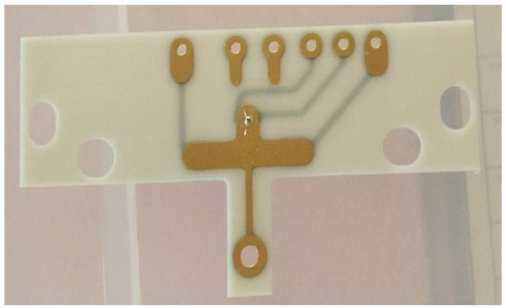
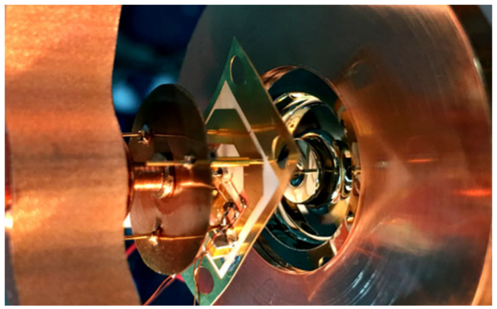
  2 cpkkd → 0.01cpkkd@ 2-4 keV

- **Low noise electronics**

  E threshold 160 eV

- **Large shielding and cooling system**
- **Ge detector fabrication**
  - Low mass detector unit and VFE design
  - Low bkg cables or flexible PCB
  - CMOS ASIC Front-end Electronics
- **Underground E-forming copper**
- **Cosmogenic bkg control**
- **Radon bkg in Liquid Nitrogen**




Technical R&D: Ge detector fabrication

- CDEX10+X home-made Ge detectors;
- Understand & reduce detector intrinsic bkg;
- Various types, ~20 detectors
  - P-type planar/coaxial;
  - P-type point contact/ BEGe;
- Long time stability

  ✓ Commercial Ge crystal;

  ✓ Structure machining;

  ✓ Li-drift and B-implanted;

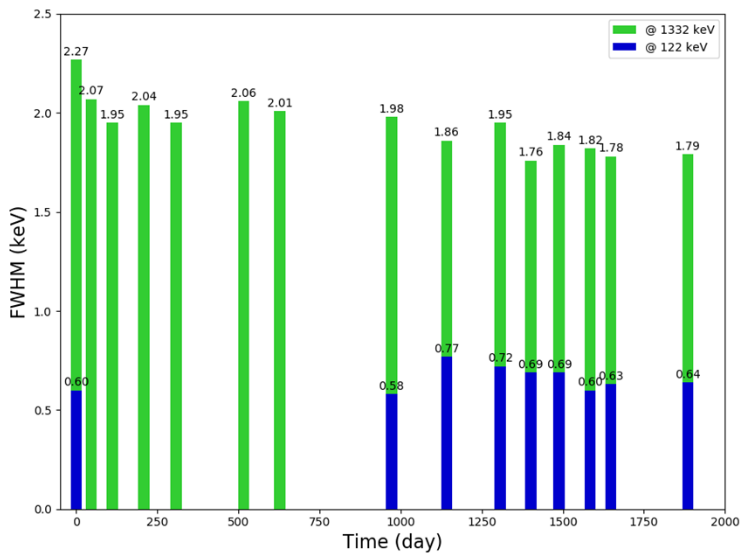
  ✓ Home-made ULB PreAmp;

  ✓ UG EF-Cu;

  ✓ UG assembly;

  ✓ UG testing…

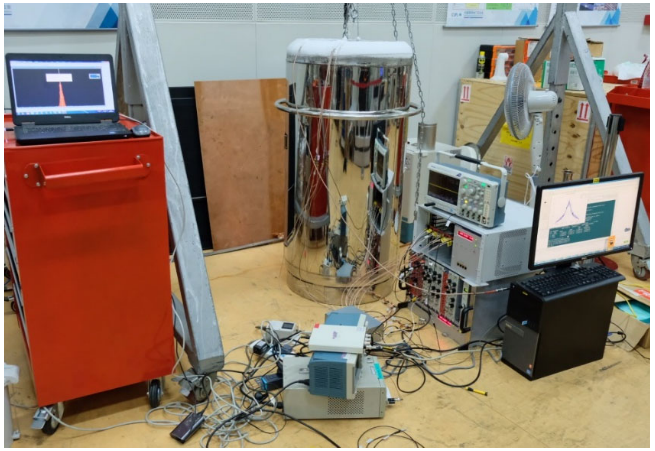
Good performance keeping, >1800 days



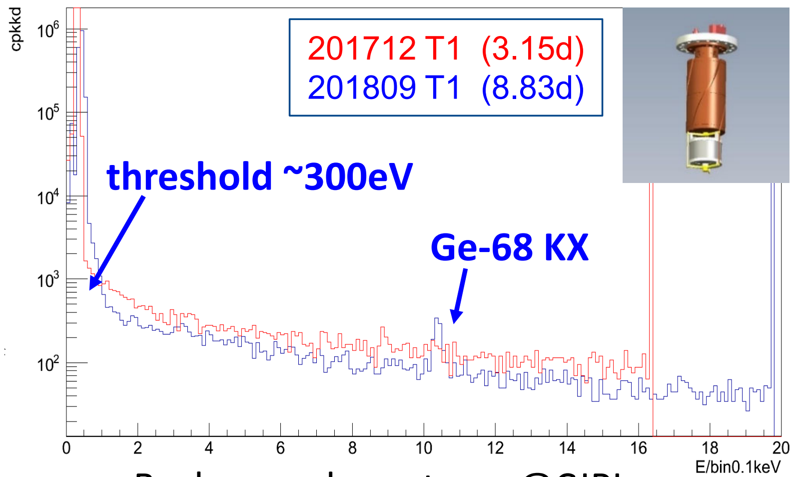
Vacuum systems

Technical R&D: Ge detector fabrication

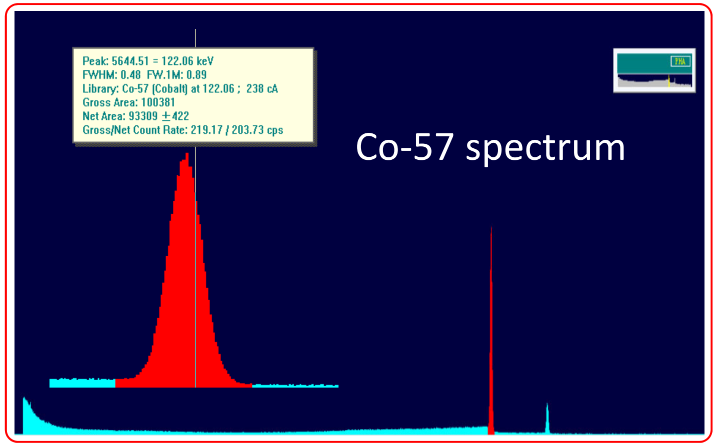
- Commercial Ge crystal + stainless steel canister;
- T1 detector: 500g Ge(φ50×50mm) + CMOS ASIC preAmp;
- Works w/ expected performance!
- Going on to improve bkg, low-noise electronics…



Tested in CJPL-I



Background spectrum @CJPL

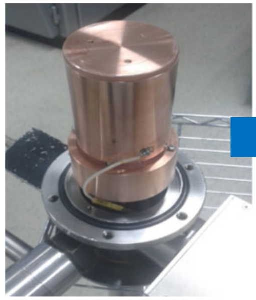


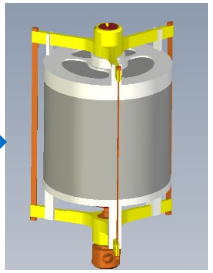
FWHM=0.48keV@122keV_Co57

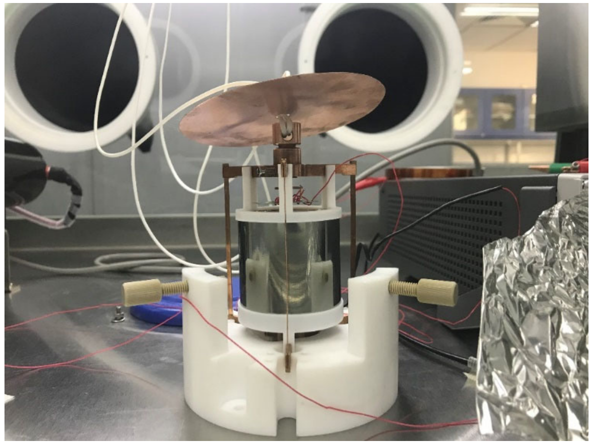
Technical R&D: Ge detector fabrication

- Vacuum chamber, structure materials, not conducive to further reduce the radioactive background;
- ASIC-based preamplifiers can work well in liquid nitrogen;
- ✓ Develop bare HPGe detectors immersed into LN_2!
- ✓ Immerse the detector into LN_2 for ~8 hours, we got a stable leakage current ~10 pA for 1000V bias voltage.

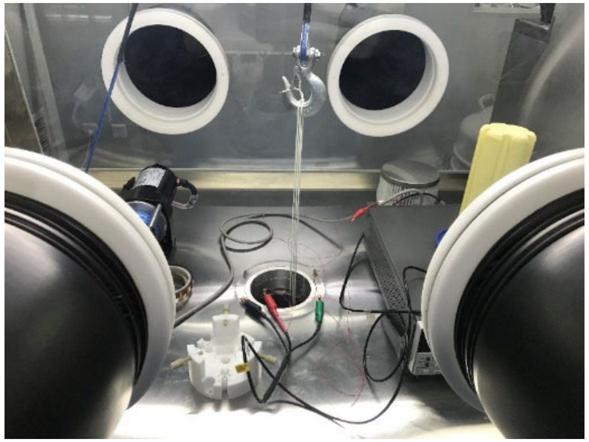
79 g Cu + 10 g PTFE





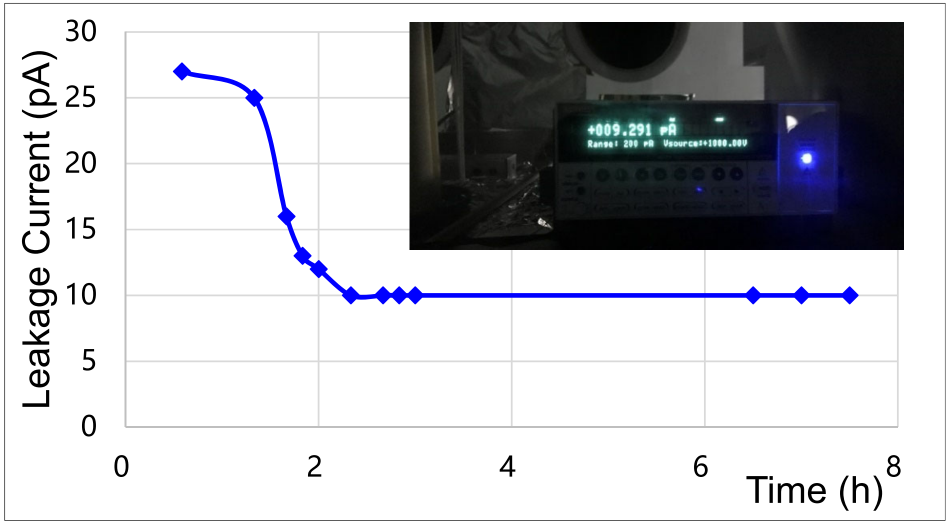


Bare HPGe detectors



Bare HPGe in LN_2

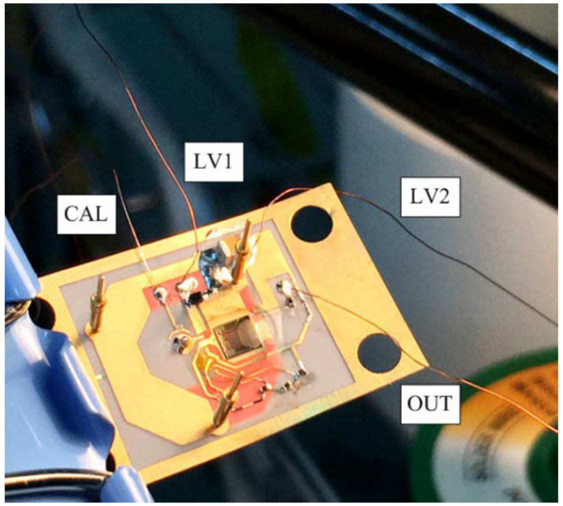
PPC: ϕ50mm x 50mm, Depleted voltage: ~800V

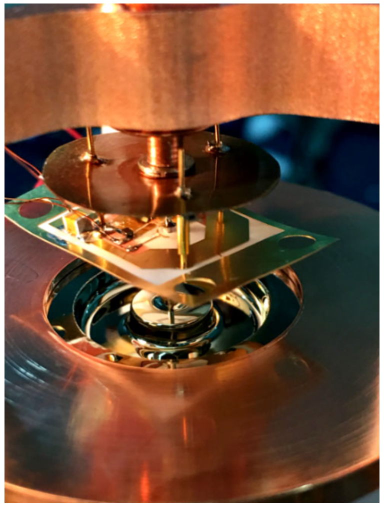


Technical R&D: CMOS ASIC Front-end Electronics

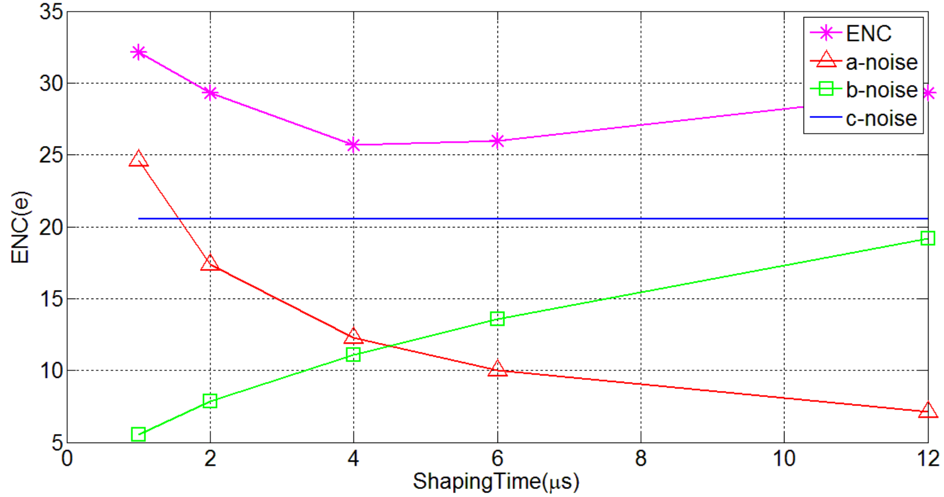
- Light DM search →low noise/threshold (low capacity, etc)
- Very close to Ge detectors →low bkg (radiopure, low-mass, etc)
- ASIC preamplifier @ 77K
  - PCB material: PTFE(Rogers 4850);
  - ENC ~26e(<200eV) w/ 4μs shaping time, mainly from 1/f noise (~21e);

Details in JINST (2018) 13: 8019





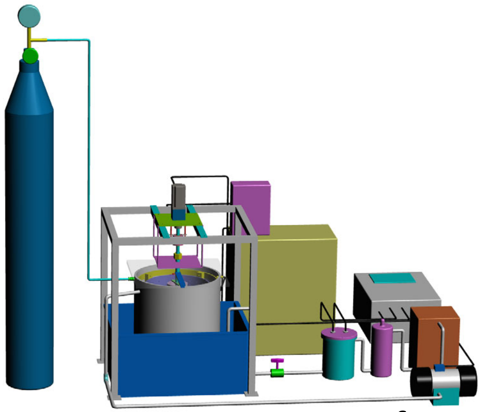
Noise components analysis



Technical R&D: Underground E-forming copper and Assay

- Prototype setup for underground EF-Cu production
  - Cathode mandrel: 316L stainless steel, φ95x380mm;
  - Plating bath: PE, φ400x500mm;
  - Goal: Majorana copper, U/Th content ~ O(0.1μBq/kg);
- Test run in Tsinghua U. and moved to CJPL-I;
- U/Th Analysis by ICP-MS
  - Procedure established , blank sensitivity ~10^{-13}g/g

UG Cu e-forming facility @CJPL-I



E-forming setup

optimized electrical parameters

ICP-MS

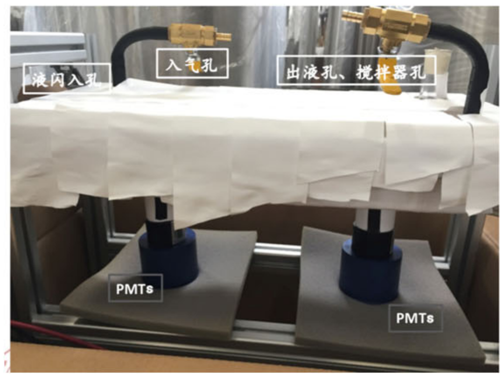
Technical R&D: Radon in Liquid Nitrogen

[by SCU group]

- ***O*(1 μBq/m³)** gives background free in DM searches;
- Goal: sensitivity of ***O*(10 nBq/m³)** for 0νββ experiment;
- R&D of the enriched Rn methods is on-going;
- Understanding of the transport of radon in liquid nitrogen and the solubility and distribution of radon in liquid nitrogen big tank at CJPL;

- **A cascade-LS detector built**
  - ✓ **Strong Particle ID(PSD)**
  - ✓ **b-a cascade events**
  - ✓ **Strong ^{222}Rn Dissolution in LS**
  - ✓ **Low U/Th**

$$
\begin{aligned}
{}^{214}\mathrm{Bi} &\rightarrow {}^{214}\mathrm{Po}+\bar{\upsilon}_e+e^-+\gamma's \\
&\quad (Q=3.28\ \mathrm{MeV},\ \tau_{1/2}=19.9\ \mathrm{min}), \\
{}^{214}\mathrm{Po} &\rightarrow {}^{210}\mathrm{Pb}+\alpha \\
&\quad (Q=7.83\ \mathrm{MeV},\ \tau_{1/2}=164\ \mu\mathrm{s}).
\end{aligned}
$$



Exhausted system

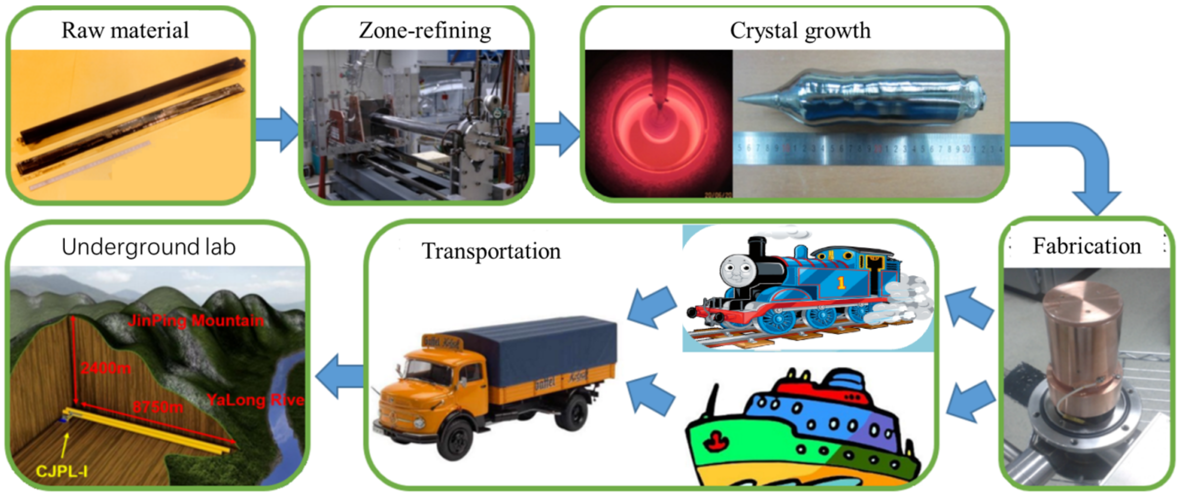
LS Stored tank

Radon mixed can

Upgraded

Future Plan - Detectors

- New detectors cooperated with commercial companies
  - 2kg from ORTEC, planning 5kg from CANBERRA/ORTEC;
  - Particular control of detector fabrication process above ground;
- Home-made detectors
  - Improve T1 w/ low bkg material and low noise electronics;
  - Set up underground fabrication and testing facility;



Cosmogenic bkg control

Detector production: 45days +
Ground transportation: 60 days +
Underground cooling: 180days →

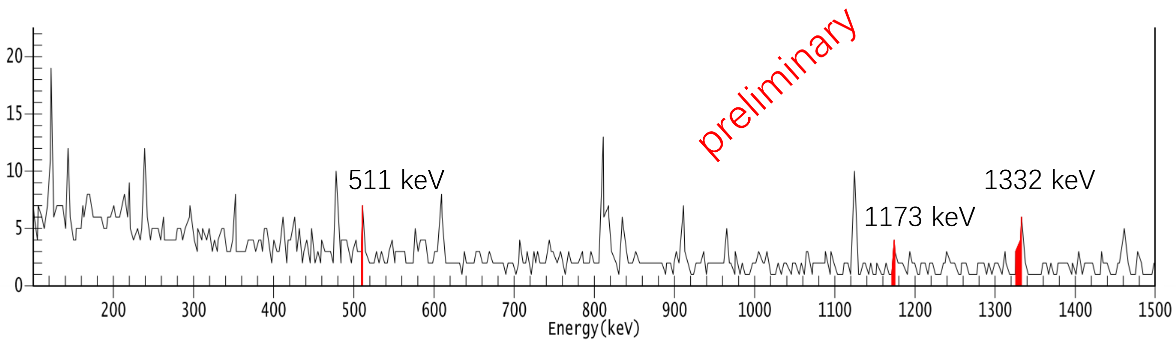
Cosmogenic bkg: 0.02cpkkd(sim.)

Future Plan - Detectors

- New detectors cooperated with commercial companies
  - 2kg from ORTEC, planning 5kg from CANBERRA/ORTEC;
  - Particular control of detector fabrication process above ground;
- Home-made detectors
  - Improve T1 w/ low bkg material and low noise electronics;
  - Set up underground fabrication and testing facility;

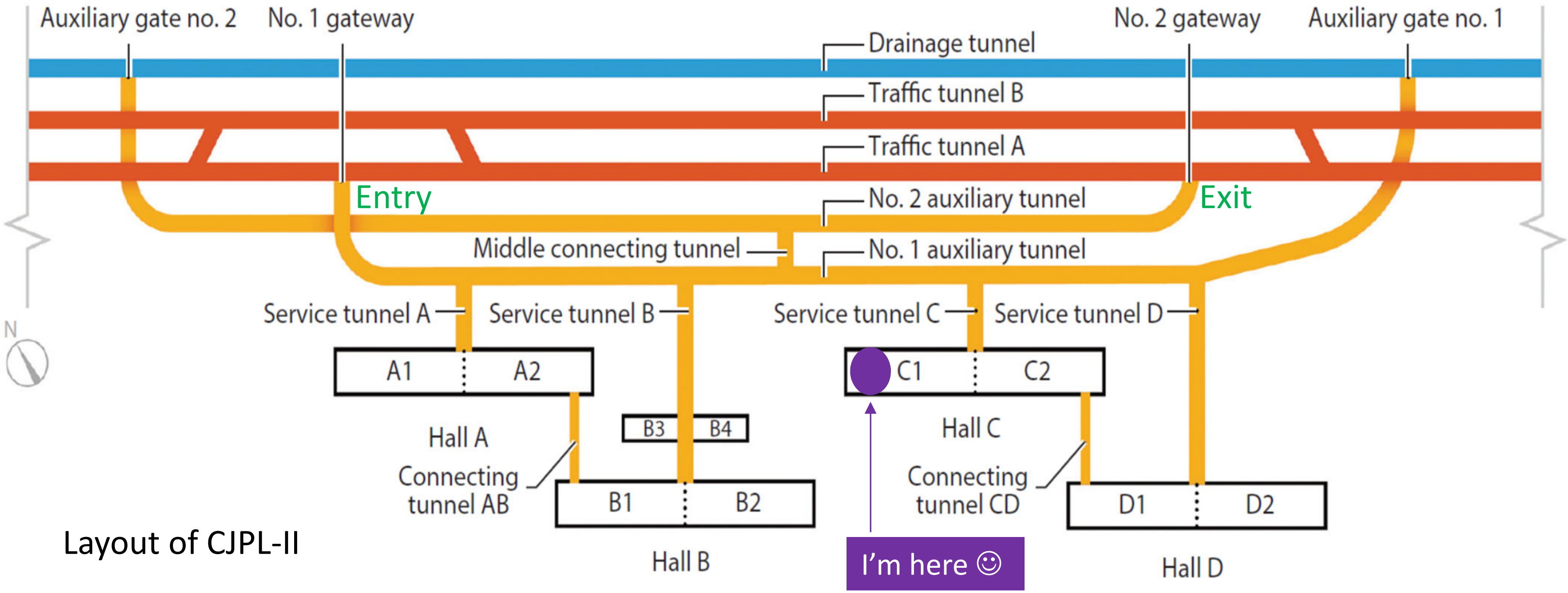
Cosmogenic bkg control

✓ France → Netherlands, by truck, 2d;
✓ Netherlands → Chengdu, by China-Euro train, 20d;
✓ Chengdu → Jinping, by truck, 3d.



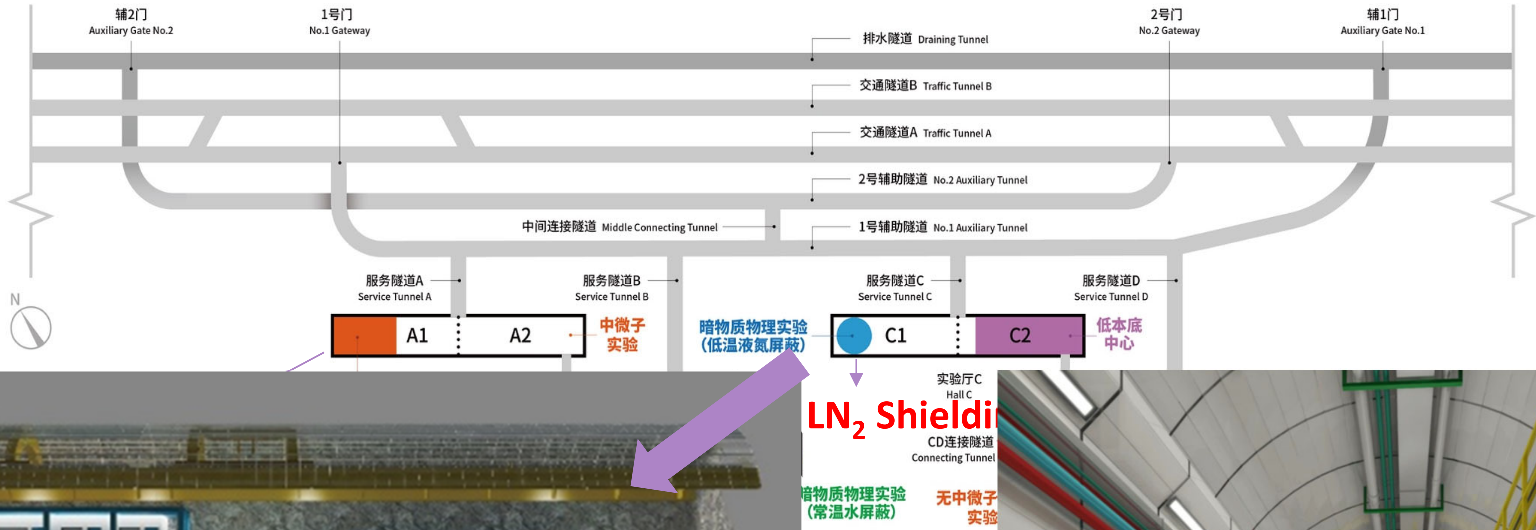
Future Plan – New location

- CJPL-I to CJPL-II
  - Volume: 4000 m^3 to 300,000 m^3;
  - 1 main hall (6.5x6.5x42m) to 8 main halls (14x14x60m each);
  - Additional pit for next-generation CDEX;



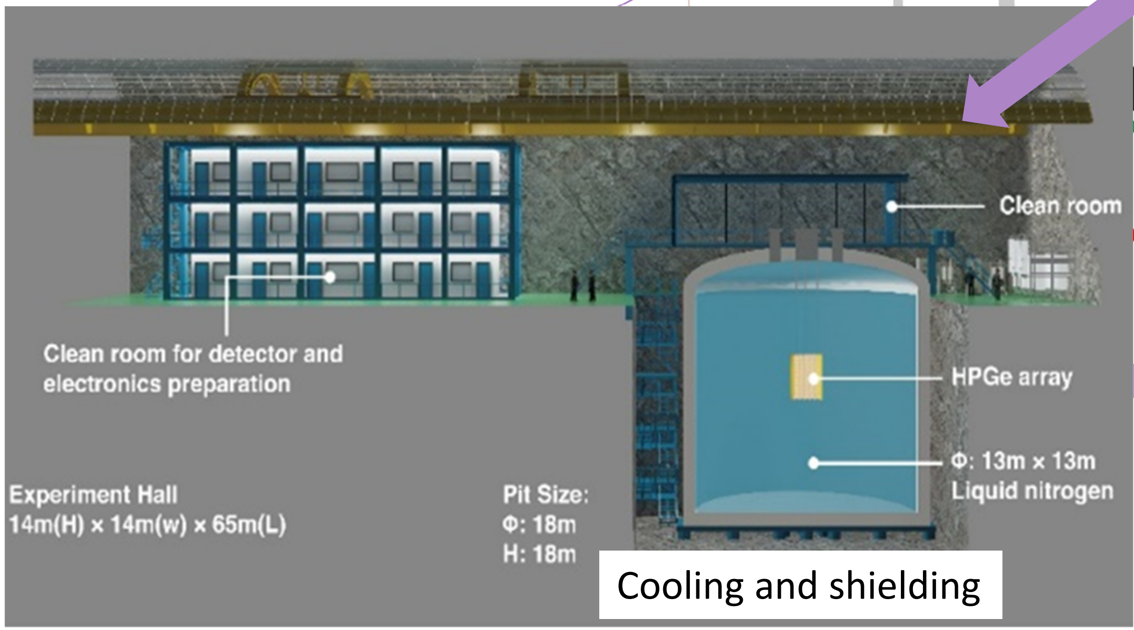
Layout of CJPL-II

Future Plan - CDEX



LN$_2$ Shieldi

elding

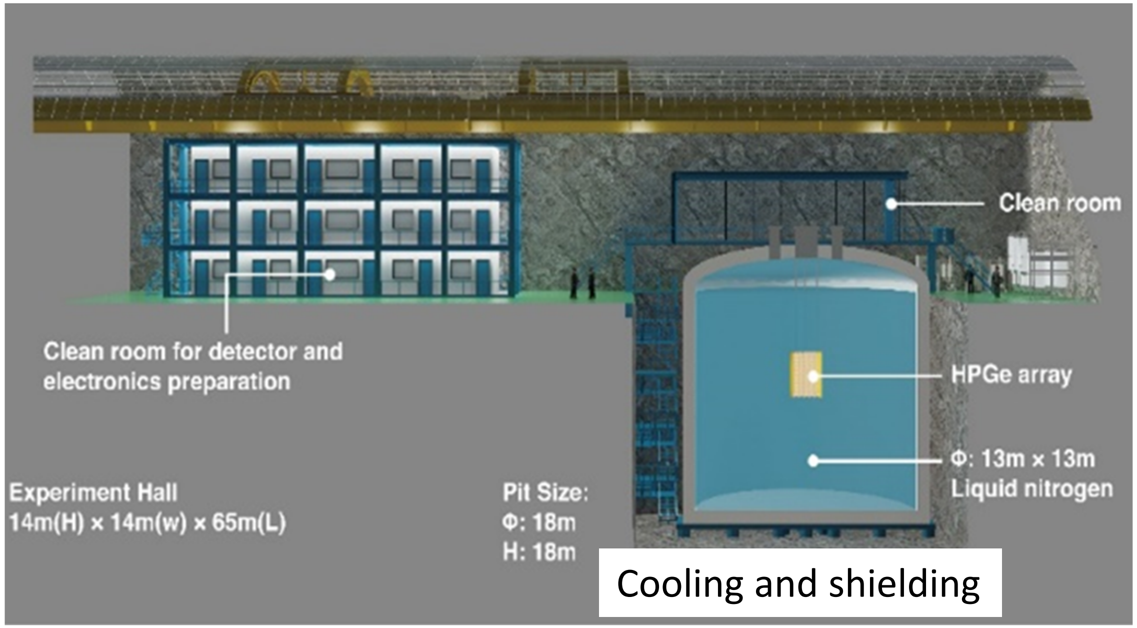


Cooling and shielding

LN2 tank at Hall C1

Future Plan - CDEX @CJPL-II

- Prepare for HPGe experiment in Hall C1 @ CJPL-II
- 1725m^3 liquid nitrogen, shielding and cooling system (inner: ϕ13m*H13m)
- Inner bkg level: <10^{-4} cpkkd@1keV, <10^{-6} cpkkd@2MeV
- A shield-design candidate for the next generation 0νββ experiment (e.g. L1T)

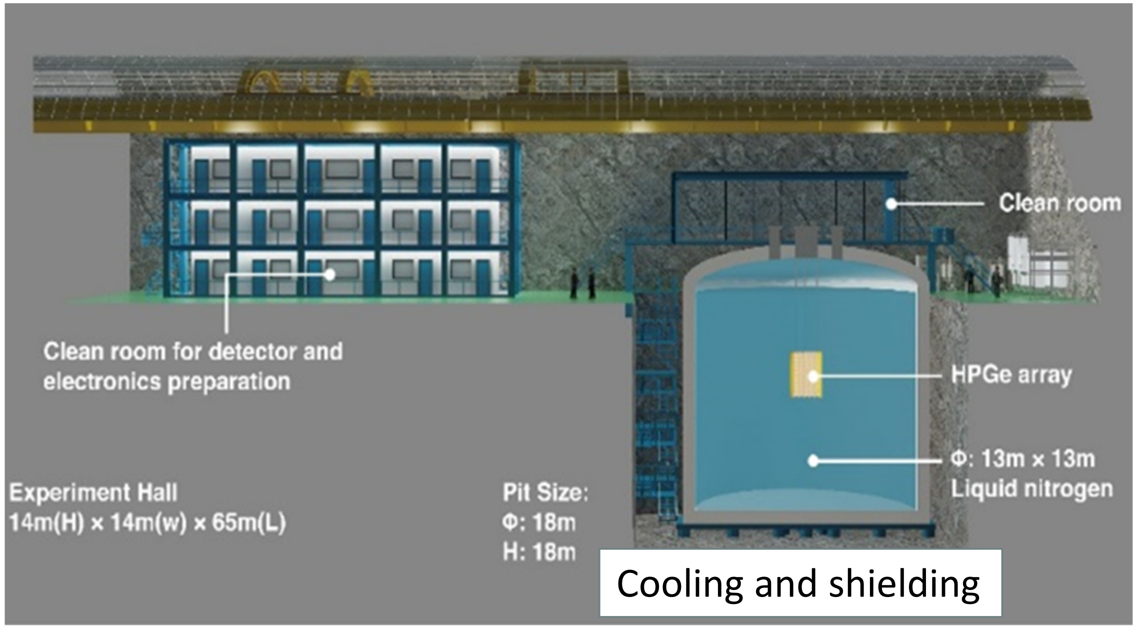


Cooling and shielding

CDEX Pit (top view)

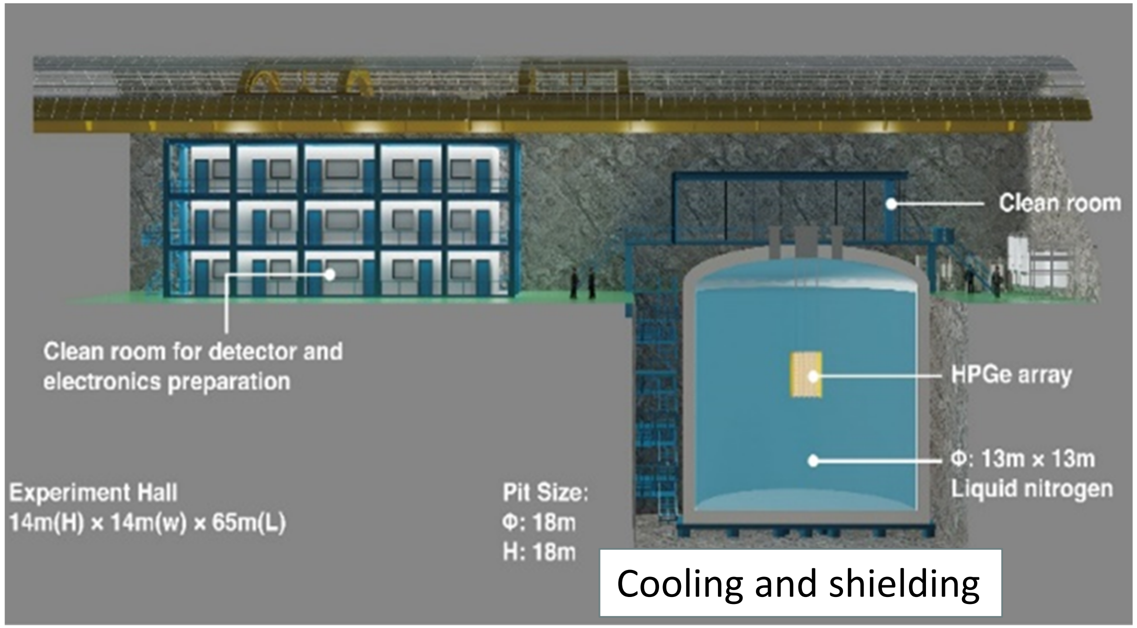
Future Plan - CDEX @CJPL-II

- Prepare for HPGe experiment in Hall C1 @ CJPL-II
- Construction of LN_2 tank kicked off in Nov. 2018 and done end of 2019.



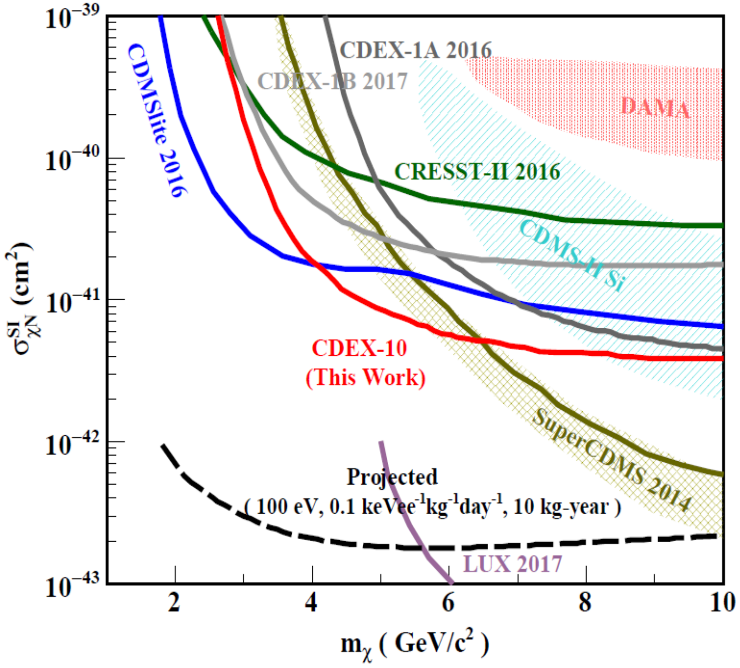
Future Plan - CDEX @CJPL-II

- Prepare for HPGe experiment in Hall C1 @ CJPL-II
- Construction of LN_2 tank kicked off in Nov. 2018 and done end of 2019;
- CDEX-10X to move to a 1725m^3 LN_2 tank (φ13x13m) located in the pit;
- CDEX-100 TDR on the way.

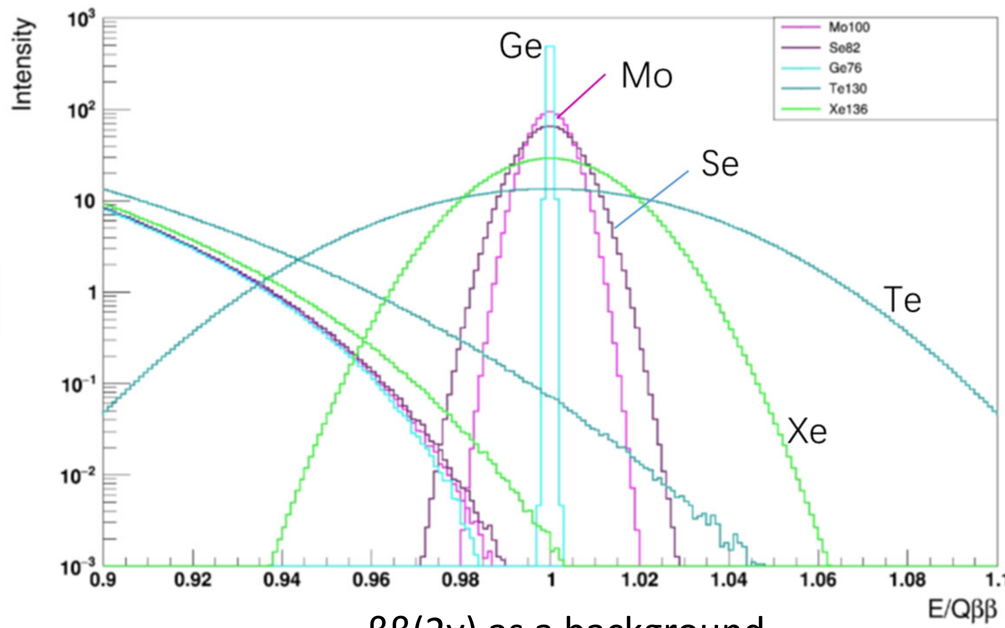


Future Plan – Main Goals

- DM
  - WIMPs, including AM;
  - Axion, Dark Photon…



- $0\nu\beta\beta$
  - Taking advantages of Ge detectors;
  - Combined with Legend-1T
  - Location Undetermined (SNOLAB, CJPL)

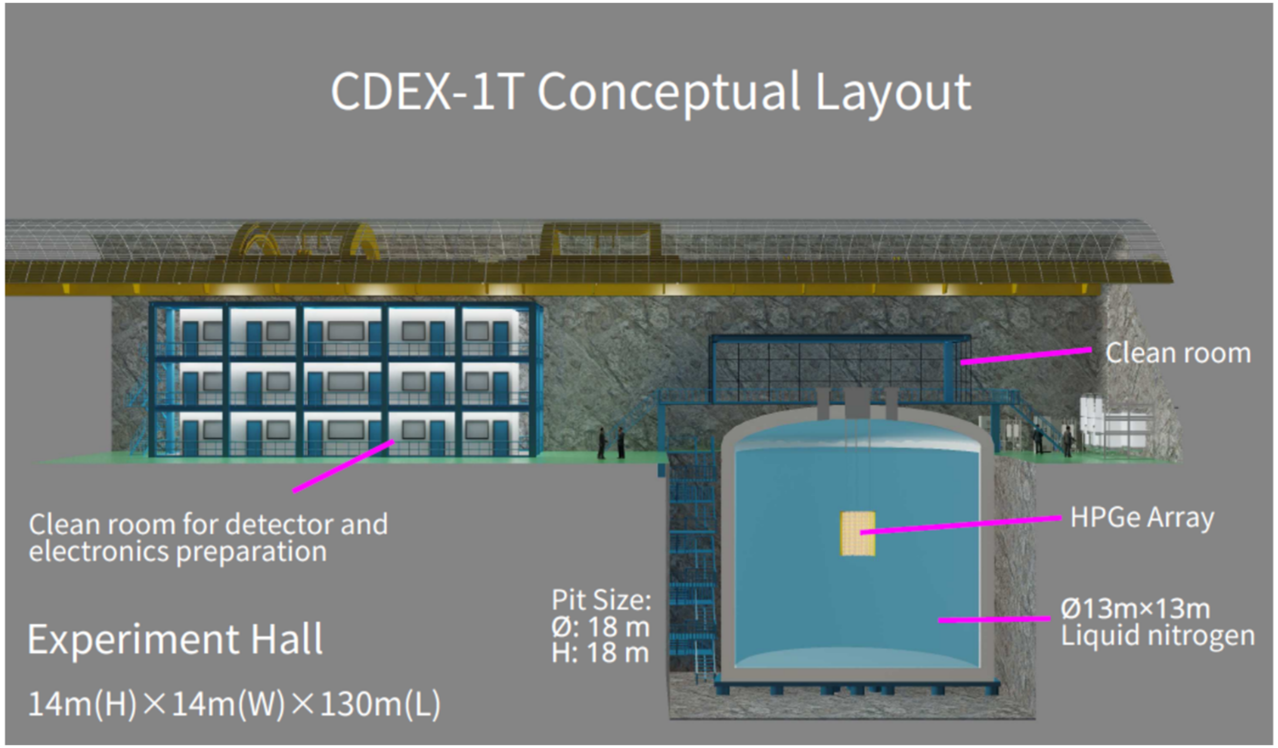


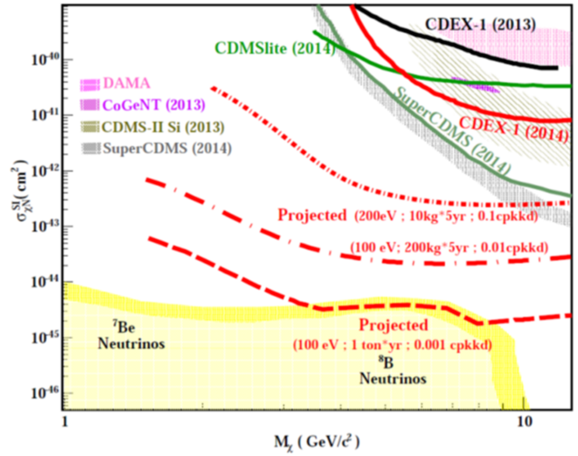
ββ(2ν) as a background

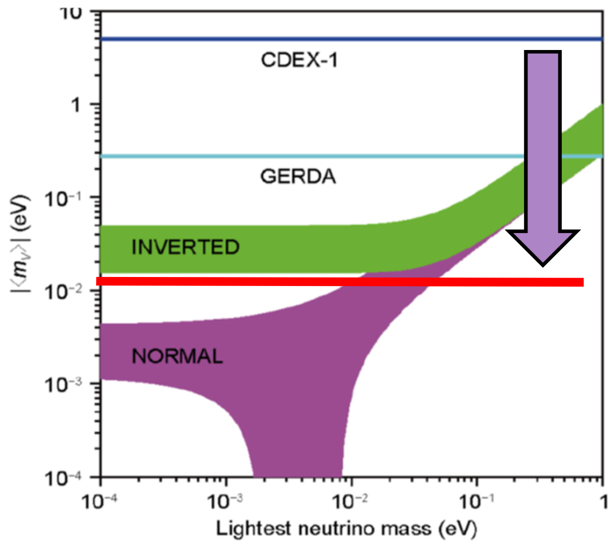
Assuming $T_{0\nu}/T_{2\nu} = 1 \times 10^6$

CDEX: Projected sensitivities

- Based on Ge technologies, to directly detect DM;
- For 0νββ, Combined with L1T.







Summary

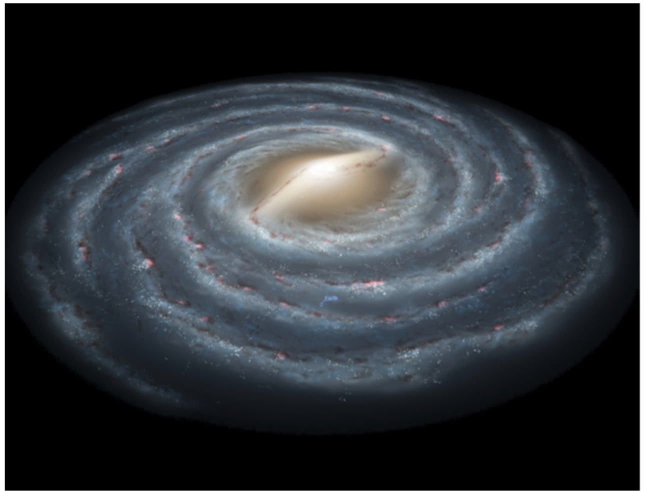
- CDEX: unique advantages of PPC Ge detectors for light DM search at CJPL;
- New AM limits from >4-year data ruled out DAMA/LIBRA-phase1 and CoGeNT results, best sensitivity below 6 GeV;
- New Migdal effect analysis: leading sensitivity for $m_\chi \sim 50\text{–}180$ MeV;
- Other DM candidate analysis: Axion, dark photon…

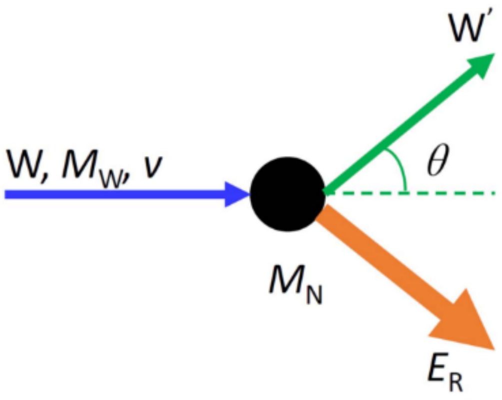
- New site for next-generation CDEX in Hall C1 of CJPL-II project;
- Easy scalability and lower bkg expected w/ new large cryo-tank;
- Ongoing efforts on homemade Ge detector, FE electronics, crystal growth, UG copper e-forming…


Thanks for your attention!

Standard Assumptions for WIMPs Direct Detection

- DM mass range: GeV~TeV
- local WIMP density: 0.3 GeV/cm^3
- Isothermal velocity distribution: v_0~220 km/s
- WIMP escape velocity ~544 km/s





Particle Physics | Nuclear Physics | Astrophysics

$$\frac{dR}{dE_r} = \frac{1}{2m_r^2}\frac{\sigma_0}{m_\chi} F^2(E_r)\, \rho_0 \int \frac{f(\vec{v})}{v} d^3v$$