Status and prospects of CDEX @CJPL

LiTao Yang（杨丽桃）

Tsinghua University

On behalf of CDEX Collaboration

The 3rd BNU dark matter workshop

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CJPL

中国锦屏地下实验室

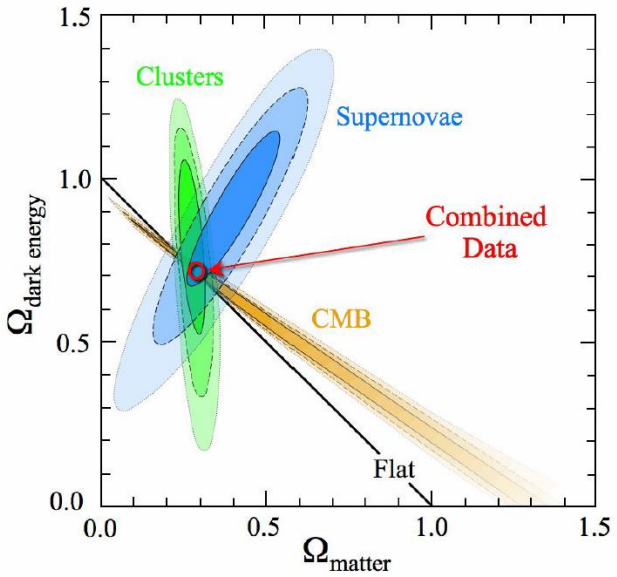
China Jinping Underground Laboratory

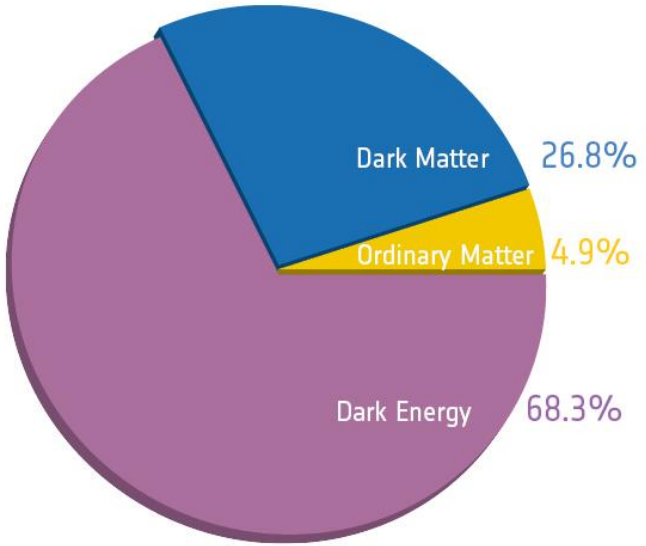
清华大学·雅砻江流域水电开发有限公司

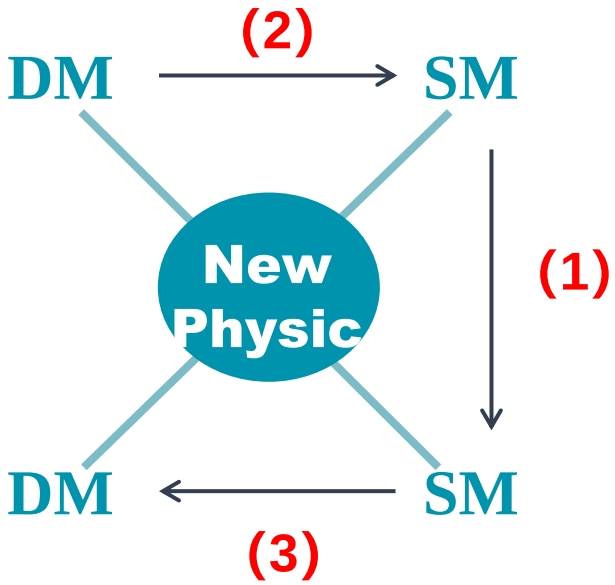
OUTLINE

- Dark Matter (DM) and its Direct detection
- Introduction to CDEX
- Recent status of CDEX-1 and CDEX-10
- R&D of key technologies
- Future plan of CDEX @CJPL-II
- Summary

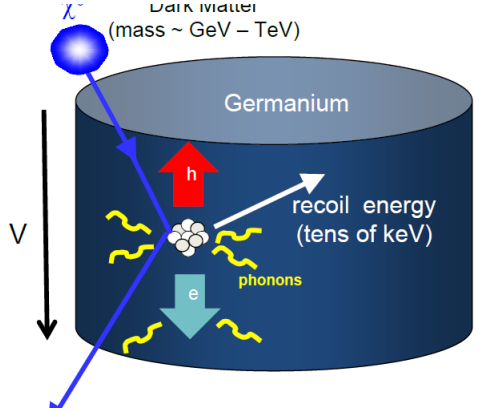
Dark Matter in Cosmology



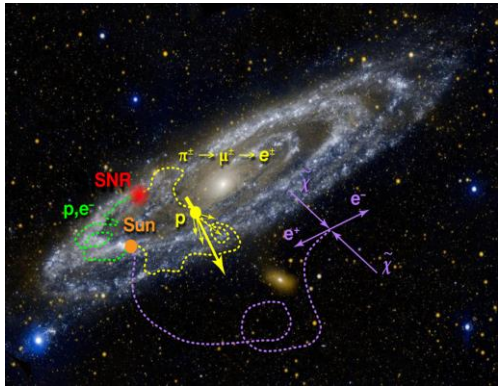




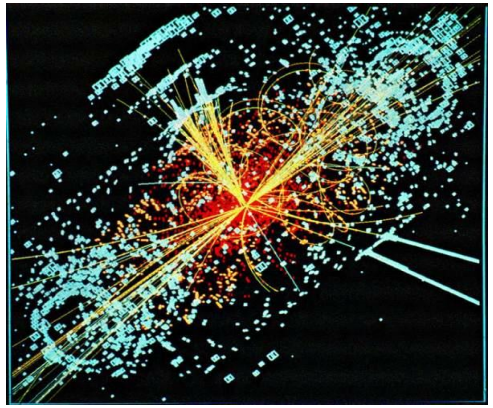
(1) Direct



(2) Indirect

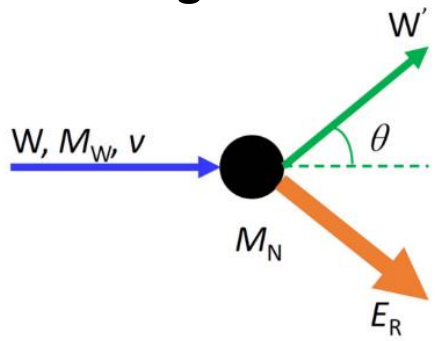


(3) Accelerator

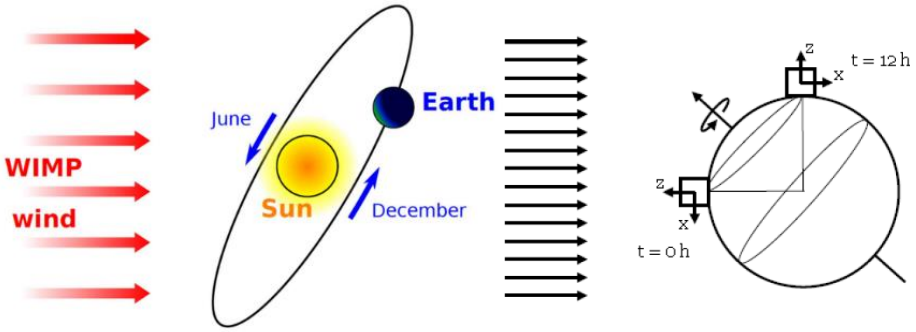


Direct detection of DM---Principle

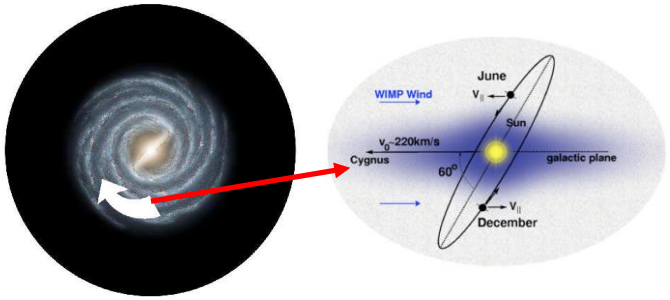
Elastic Scattering

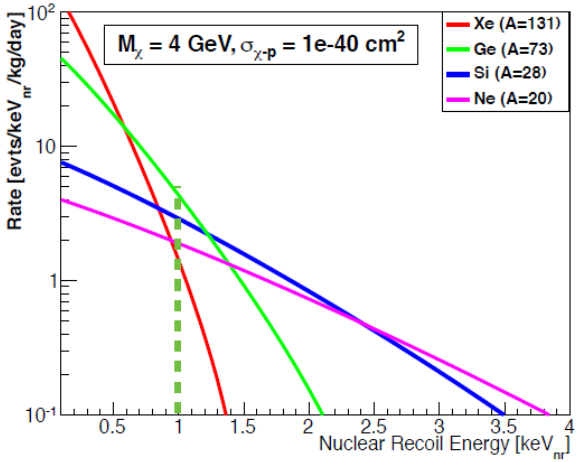


Annual/ Diurnal Modulation

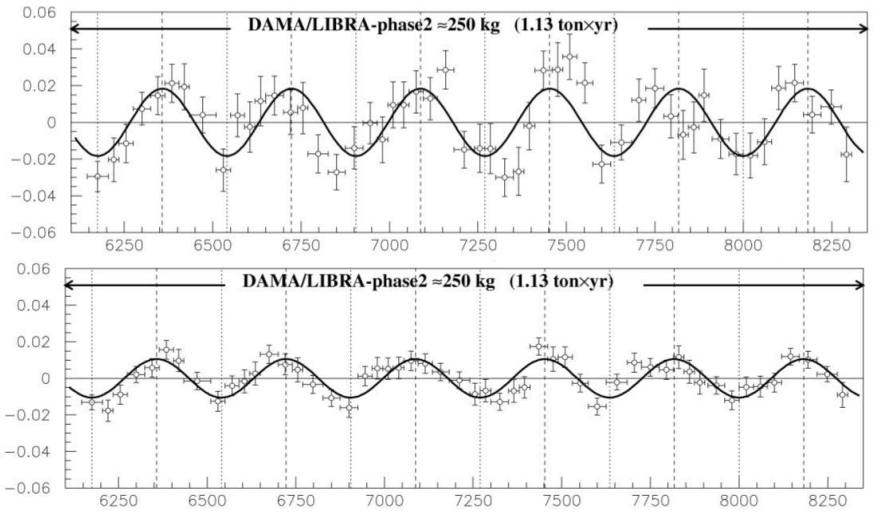


Direction Detection

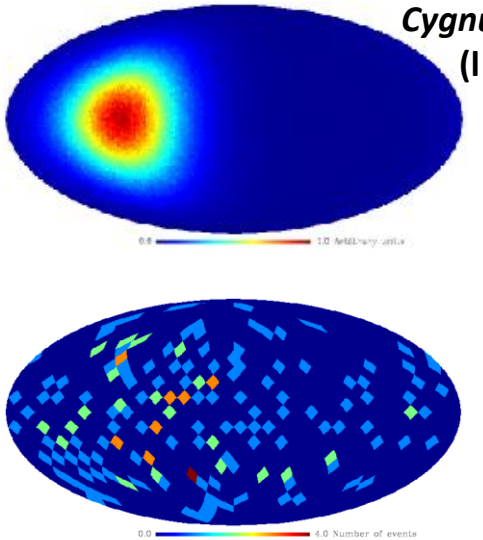




- Lower Background
- Lower Energy threshold
- Long-time stability



- Lower Background
- Long-time stability



Cygnus Constellation
(l = 90°,b = 0°)

- Angular Resolution (<20°)

China Dark matter EXperiment

- Formed in 2009, 11 institutions and ~70 people now;
- Direct detection of light DM by P-type Point-Contact (PPC) Ge detectors.

清華大學 Tsinghua University

四川大學 SICHUAN UNIVERSITY

北京師範大學 BEIJING NORMAL UNIVERSITY

中國原子能科學研究院 CHINA INSTITUTE OF ATOMIC ENERGY

南開大學 Nankai University

雅砻江水电 YALONG HYDRO

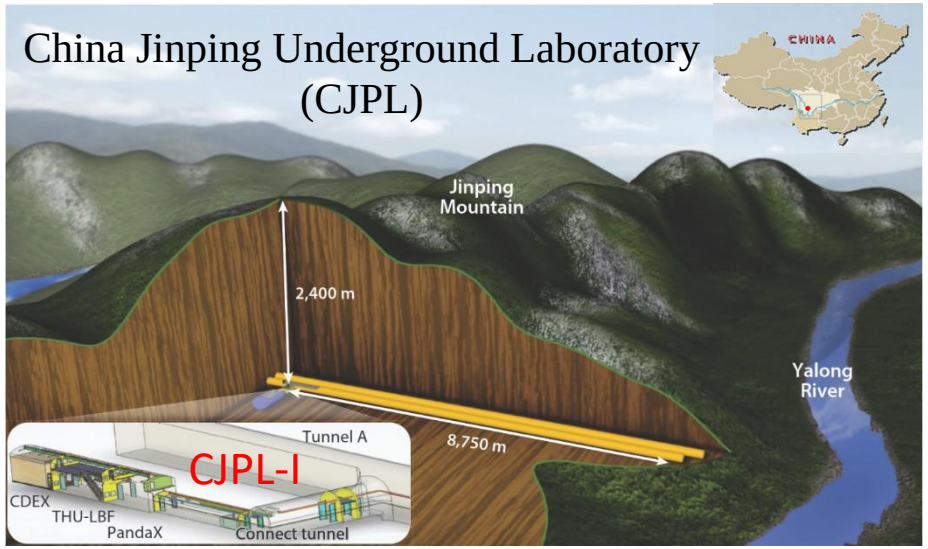
北京大學 PEKING UNIVERSITY

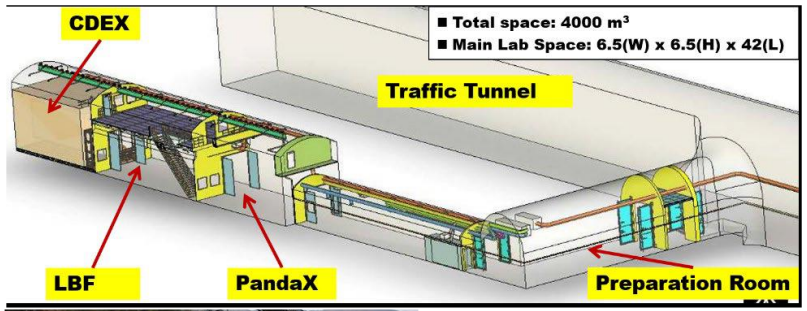
中山大學 SUN YAT-SEN UNIVERSITY

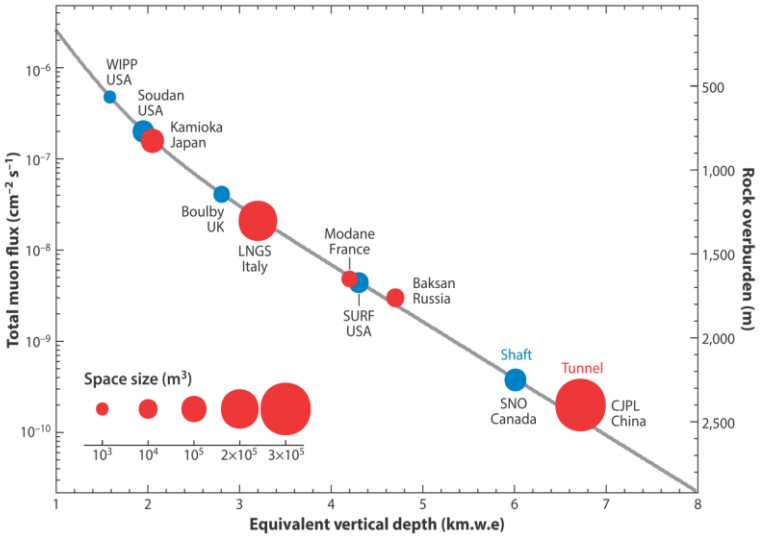
TEXONO

China Jinping Underground Laboratory

- 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, CJPL-II, final exam and expected to be completed in 2022



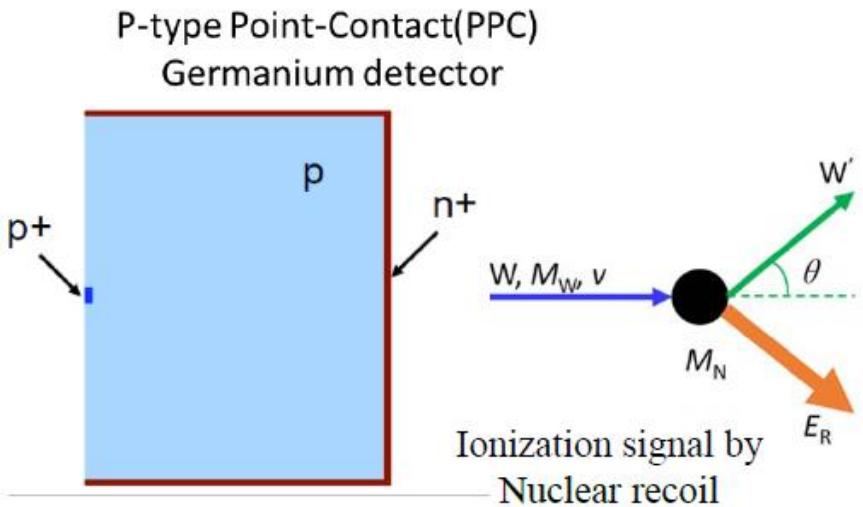




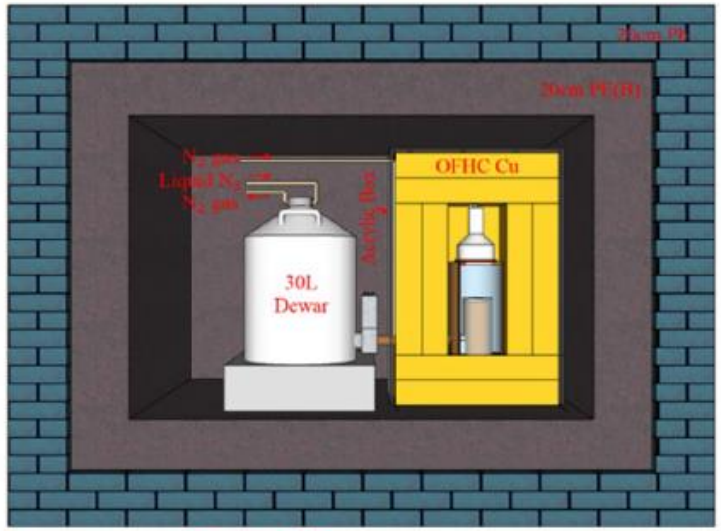
Cheng et al., Annu. Rev. Nucl. Part. Sci. 2017. 67:231

CDEX Experiment

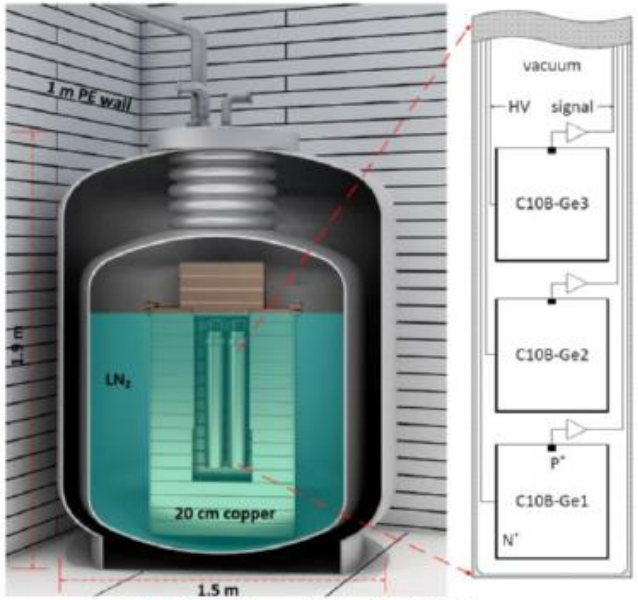
- DM detection w/ Ge prepared since 2003 and started in 2005 in Y2L (5g);
- **CDEX-1:** Development of PPC Ge detector, bkg understanding, since 2011;
- **CDEX-10:** Performances of Ge array detector immersed in LN_2, since 2016;
- **CDEX-10X:** Home-made Ge detector and Ge crystal growth;



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



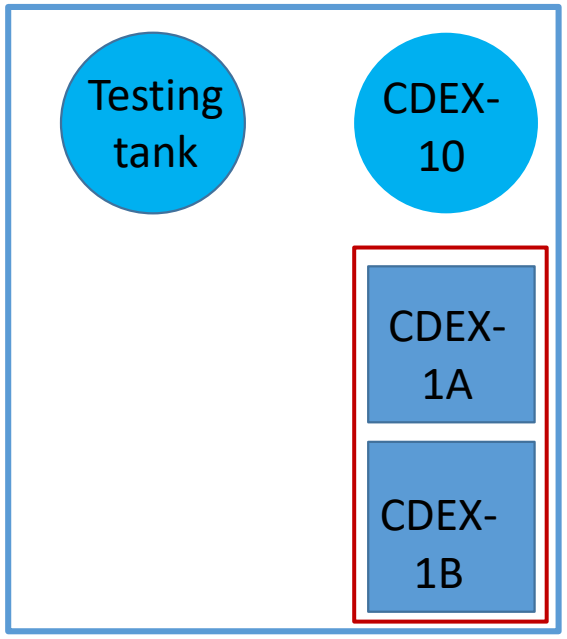
CDEX-1A&B: 1kg PPC Ge×2



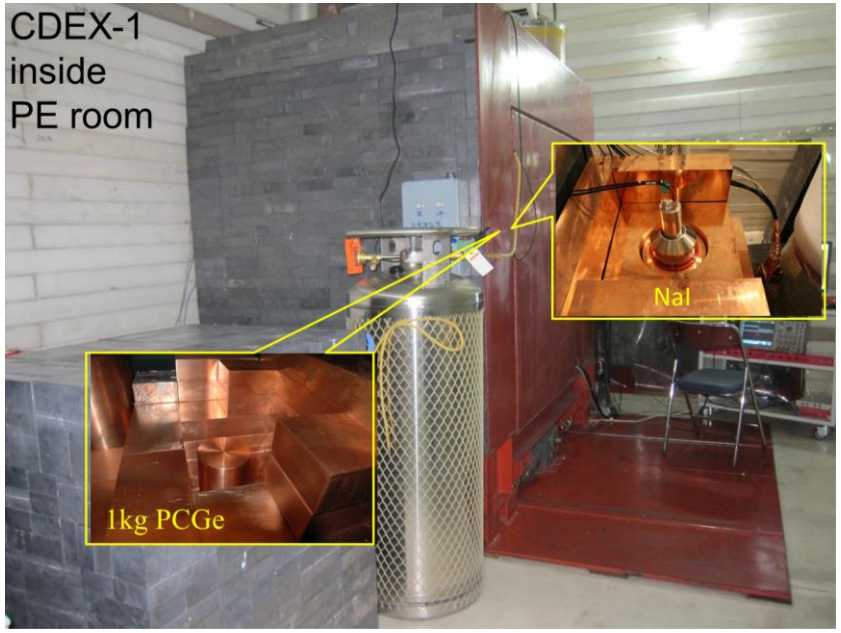
CDEX-10: ~10kg PPC Ge array

CDEX-1 Status

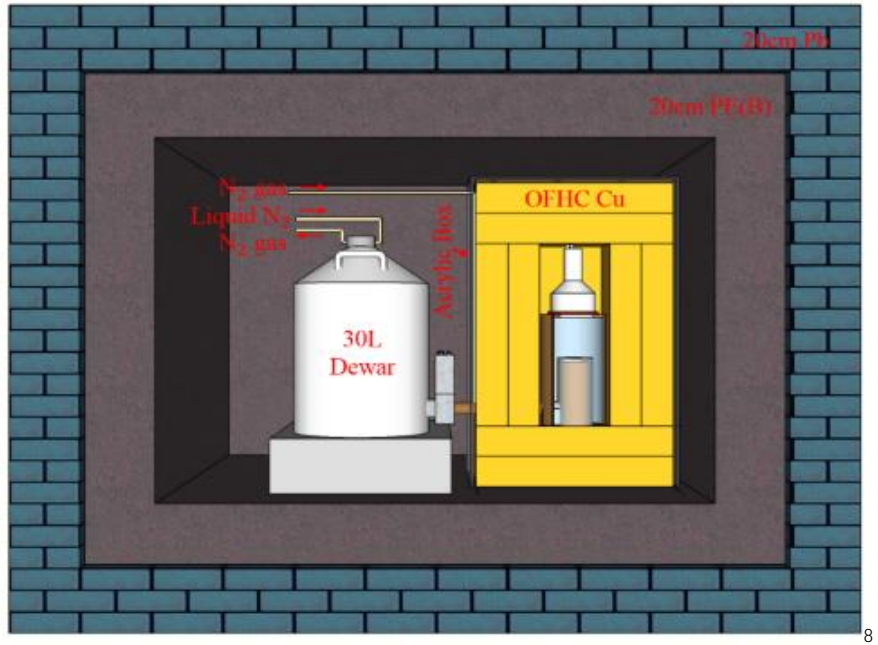
- 2 sub-stages: CDEX-1A(prototype, 2011)→1B(upgraded, 2013);
- Traditional single-element ~1kg PPC Ge detector;
- Low-bkg Pb&Cu passive shield + NaI veto detector;
- Located in PE room at CJPL-I;



Layout of PE room, CJPL-I



CDEX-1 inside PE room

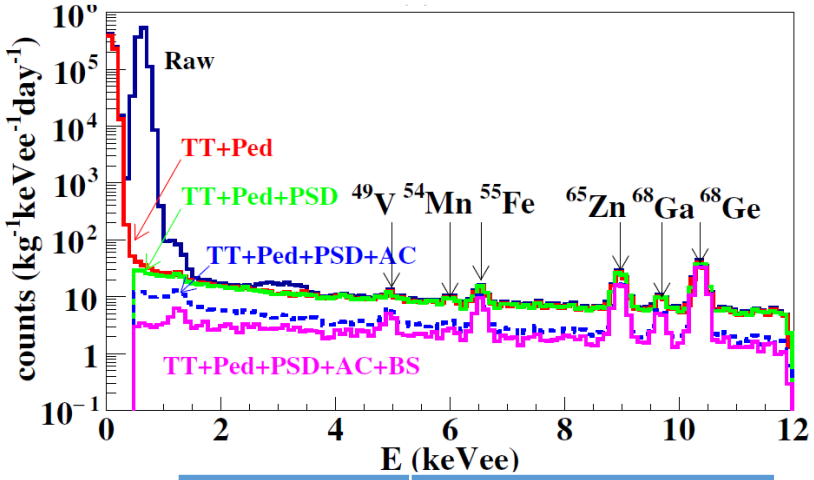


CDEX-1A&B: 1kg PPC Ge×2

CDEX-1A & CDEX-1B Status

CDEX-1A:

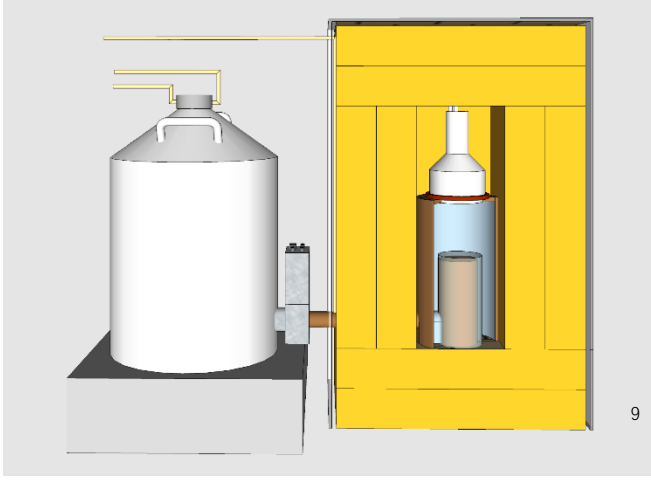
- >500 days run, ~336 kg·day dataset;
- Energy threshold: 475 eVee;
- Bulk/Surface disc. to cut events with slow rise-time and partial charge collection;
- K/L X-rays from cosmogenic nuclides to trace crystal history;



Detector	FWHM of pulser
CDEX-1A	130 eVee
CDEX-1B	80 eVee

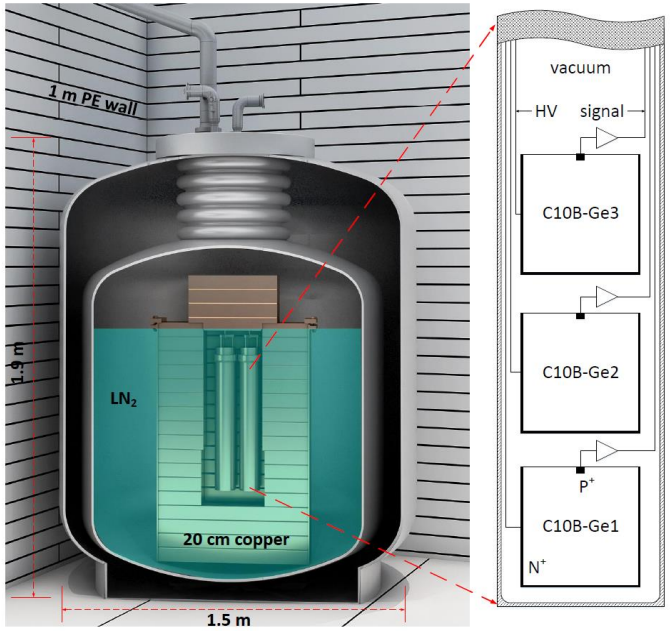
CDEX-1B:

- 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.

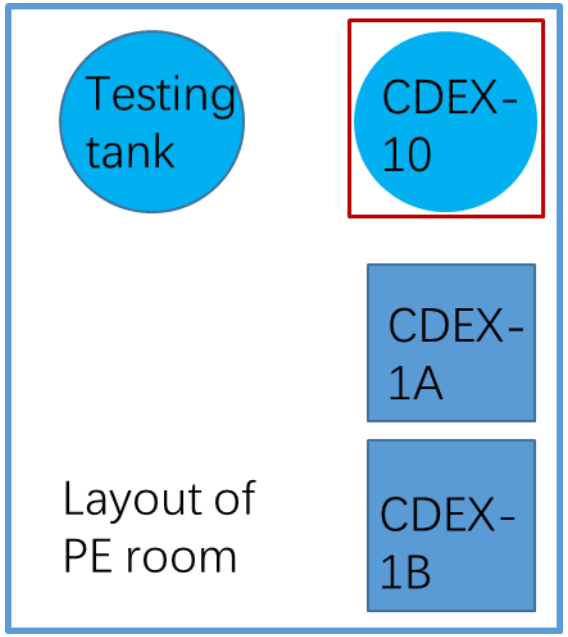


CDEX-10 Status

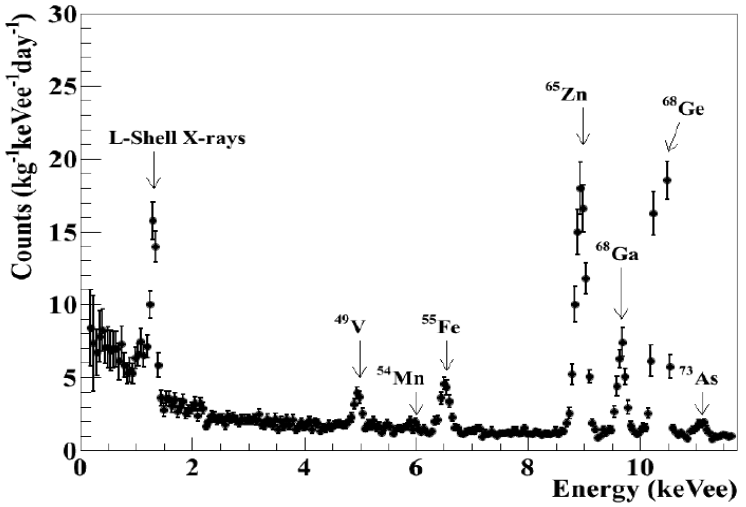
- Array detectors: 3 strings with 3 detectors each, ~10kg total;
- Direct immersion in LN_2;
- Prototype system for future hundred-kg to ton scale experiment
  - Light/radio-purer LN_2 replacing heavy shield i.e. Pb/Cu;
  - Arraying technology to scalable capability;



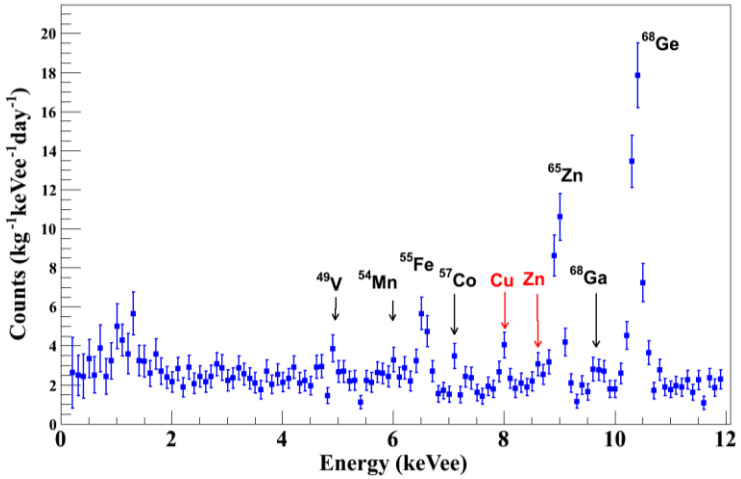
CDEX-10: ~10kg PPC Ge array



Data on hand from CDEX-1 and CDEX-10



CDEX-1B

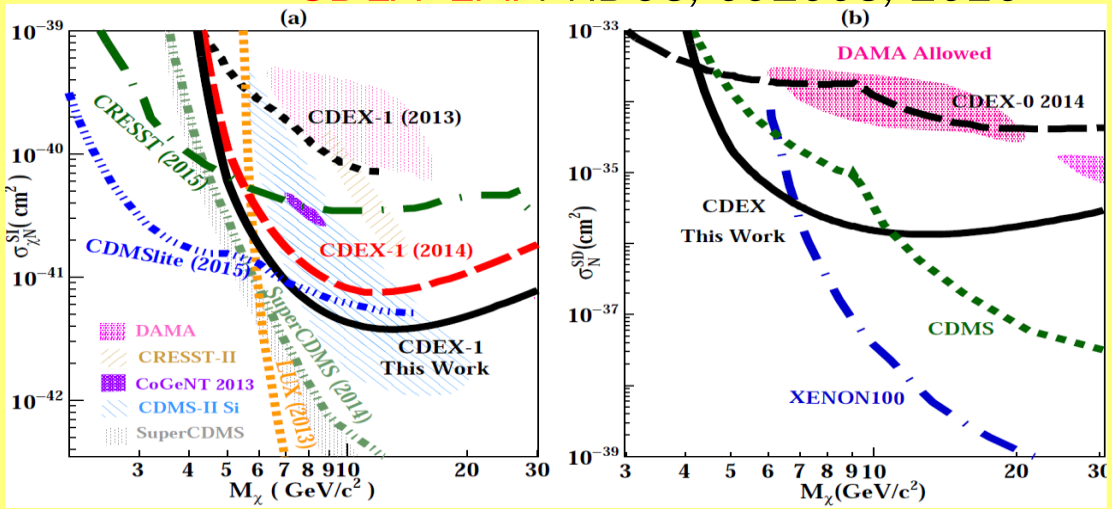


CDEX-10

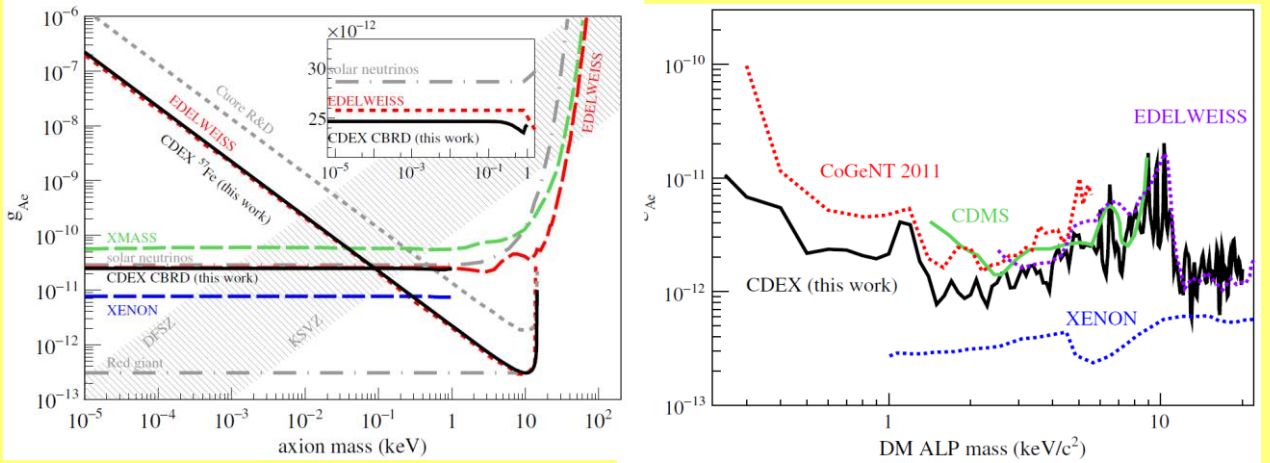
Detector	CDEX-1A	CDEX-1B	CDEX-10	
			C10B	C10C
Analysis Threshold	475 eVee	160 eVee	160 eVee	300 eVee
Time span	~520	1527 day (~4.2 year)	473 day	473 day
Live time	~365	1179.4 day	224.0 day	282.2 day
Exposure (kg days)	335.6	1107.5	210.3	265.0
Background Level @0.2-0.5keVee	~4 cpkkd	~8 cpkkd	~2.5 cpkkd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

Previous Physics results from CDEX-1 & CDEX-10 (DM)

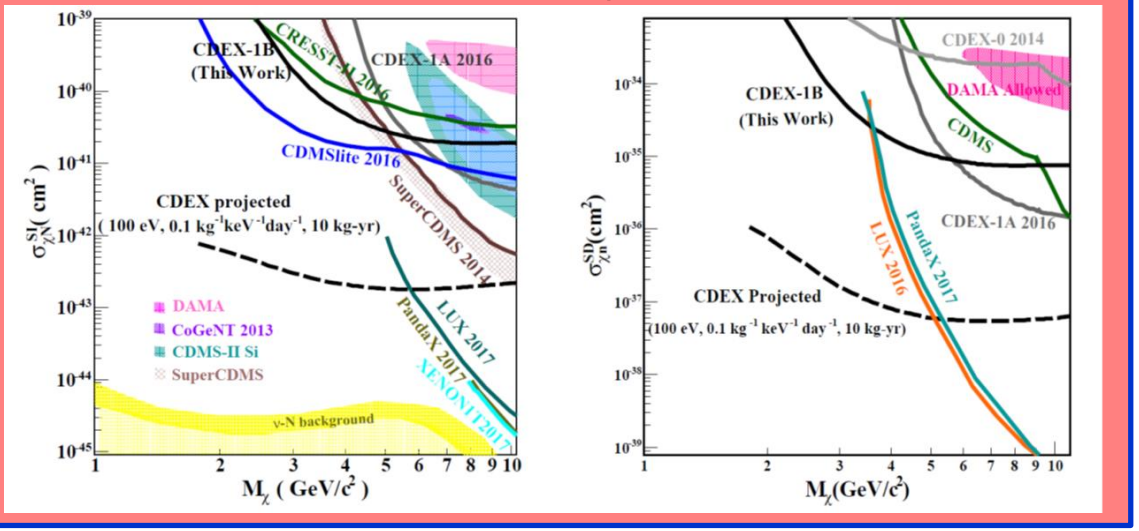
CDEX-1A: *PRD93, 092003, 2016*



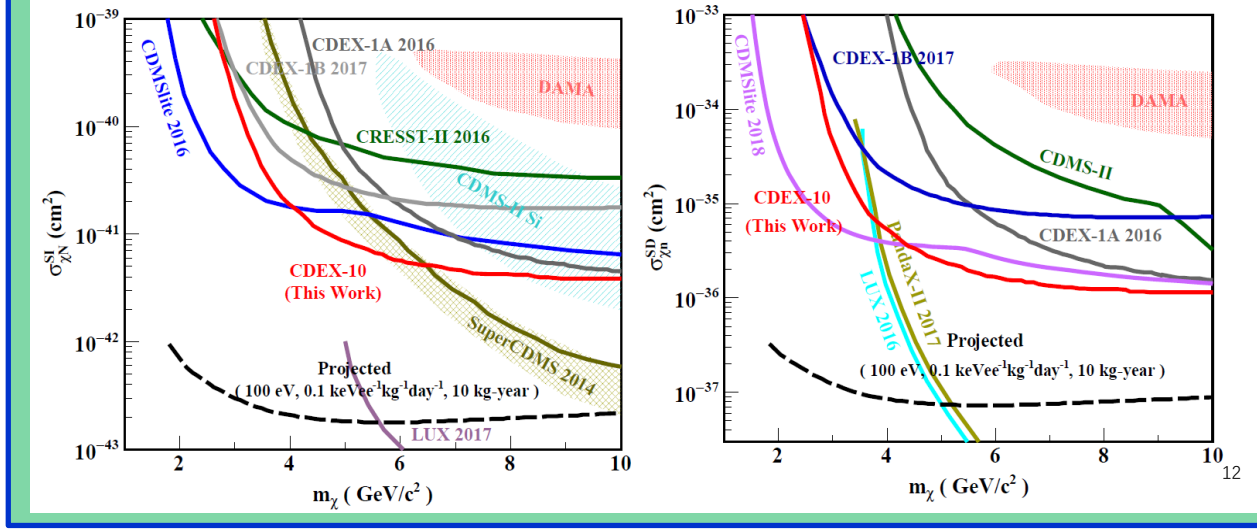
CDEX-1A: *PRD95, 052006, 2017*



CDEX-1B: *CPC 42, 023002 2018*



CDEX-10: *PRL 120,241301, 2018*

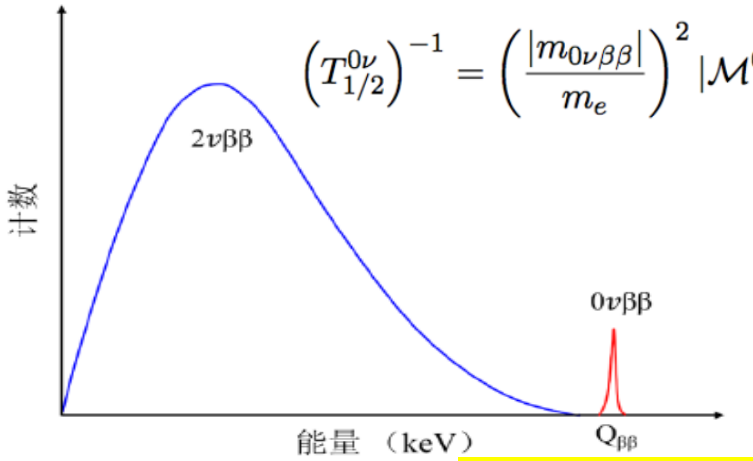


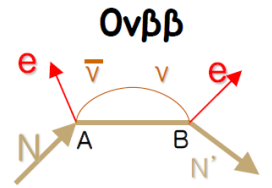
Previous Physics results from CDEX-1 (0νββ)

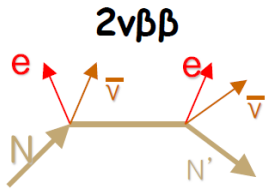
- 0νββ (304 kg·day CDEX-1A data)
  - Natural Ge crystal;

$$T_{1/2}^{0\nu} \geq 6.43\times10^{22}\ yr,\ 90\%\ C.L.$$

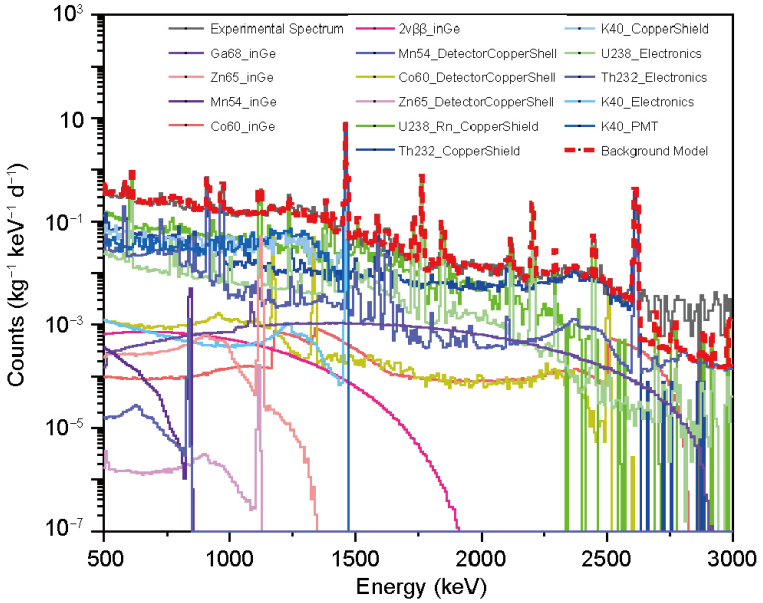
$$\left(T_{1/2}^{0\nu}\right)^{-1} = \left(\frac{|m_{0\nu\beta\beta}|}{m_e}\right)^2 |\mathcal{M}^{0\nu}|^2 G^{0\nu}$$



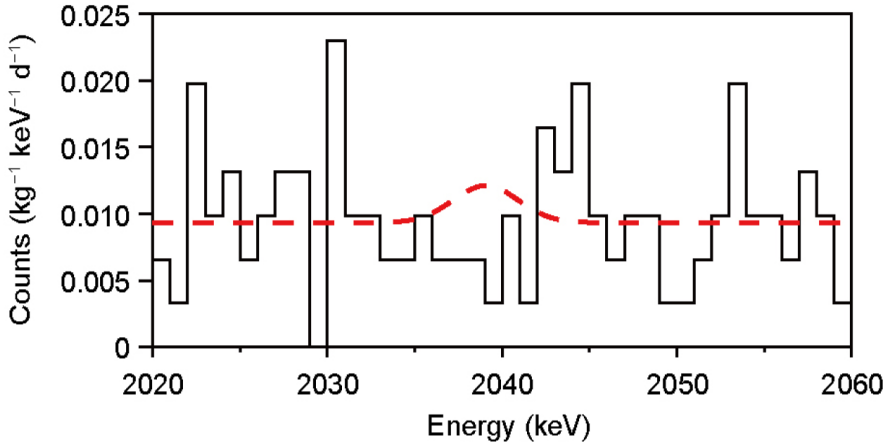


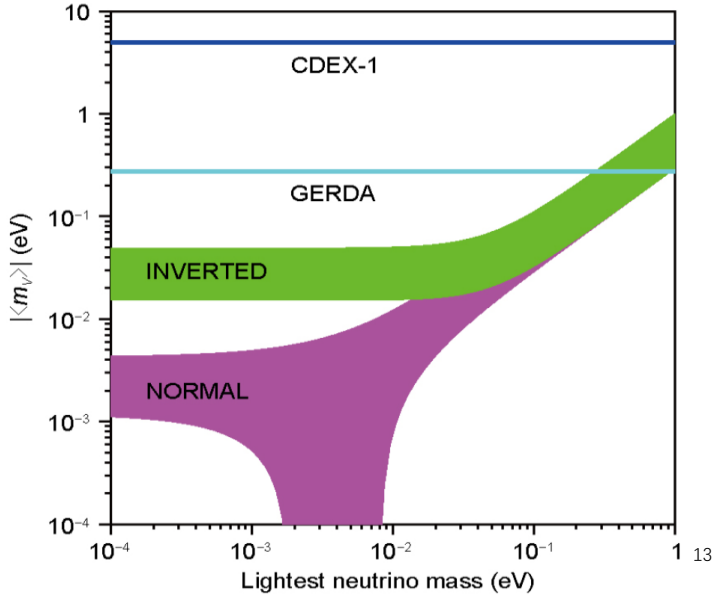


Science China PMA (2017) 60: 071011



$$T_{1/2}^{0\nu} = \frac{\ln 2 \cdot T \cdot M \cdot f_{76} \cdot N_A \cdot \varepsilon_1 \cdot \varepsilon_2 \cdot \varepsilon_3}{N^{0\nu} \cdot m}$$





Physics beyond the WIMP-nucleon SI

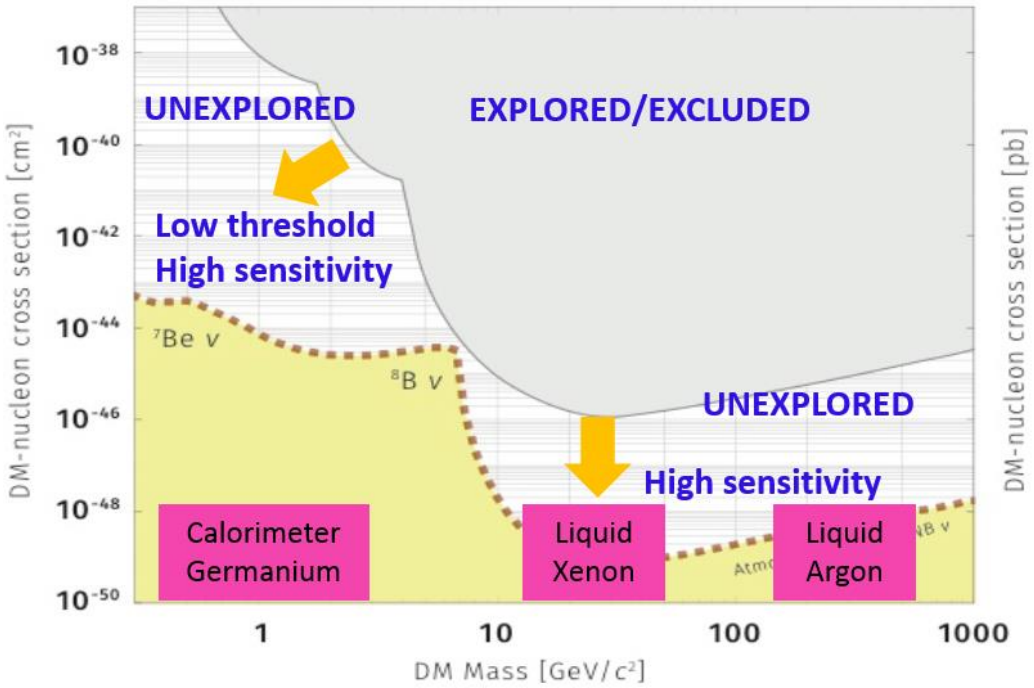
✓ **Annual Modulation**

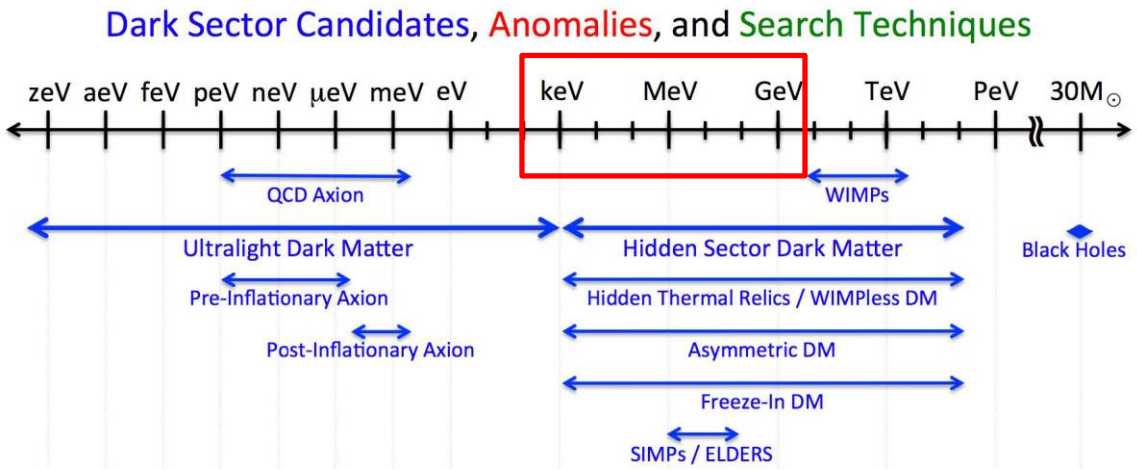
✓ **sub-GeV WIMPs:** Migdal effect/Bremsstrahlung

✓ WIMP-Electron scattering

✓ Axion Like Particles / Solar Axion

✓ Dark photon / Solar Dark photon

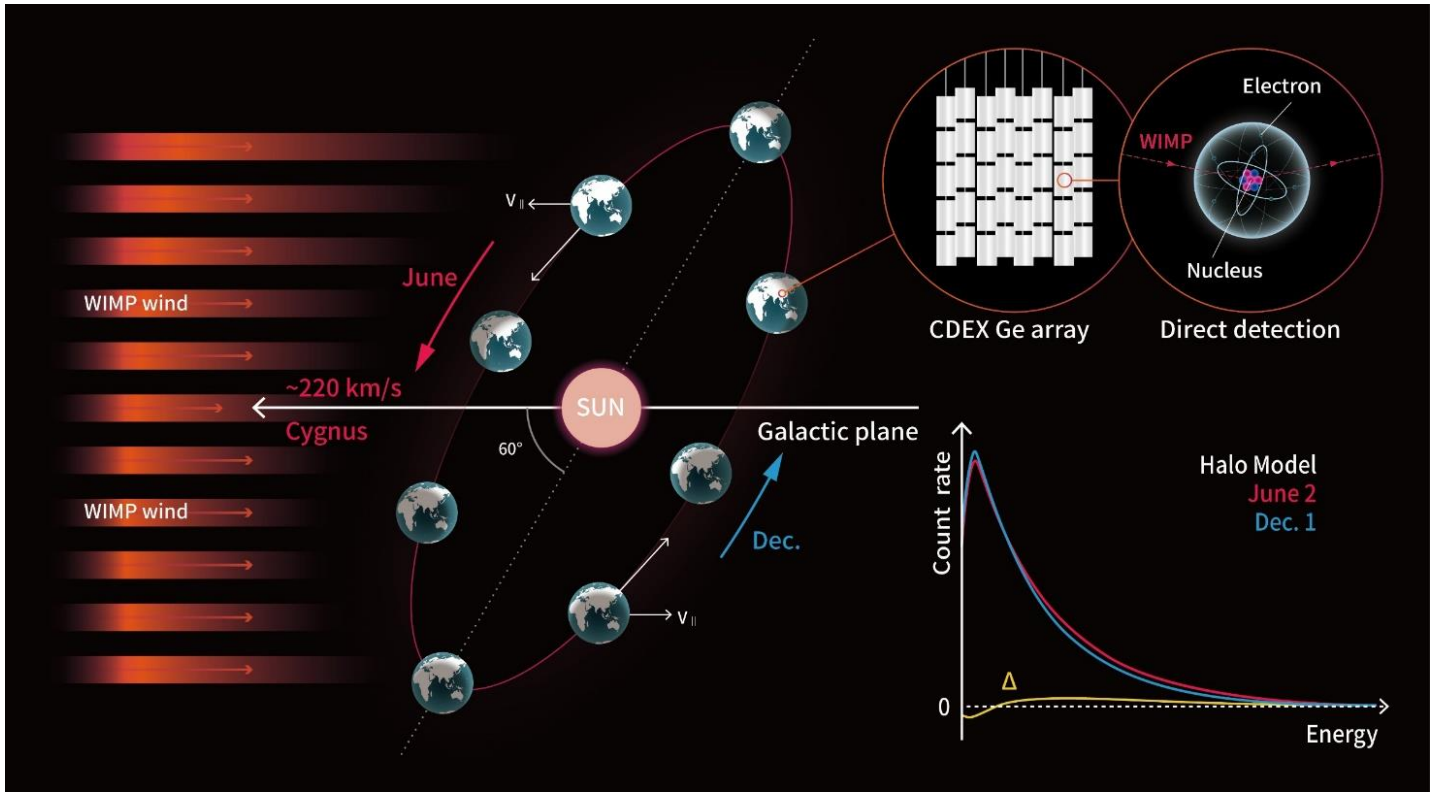




WIMPs: Annual Modulation analysis from CDEX-1B

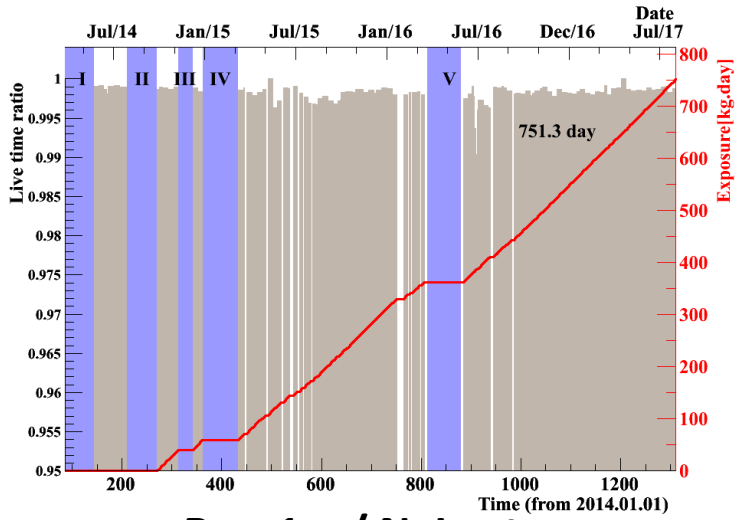
[PRL 123:221301 (2019)]

- 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.

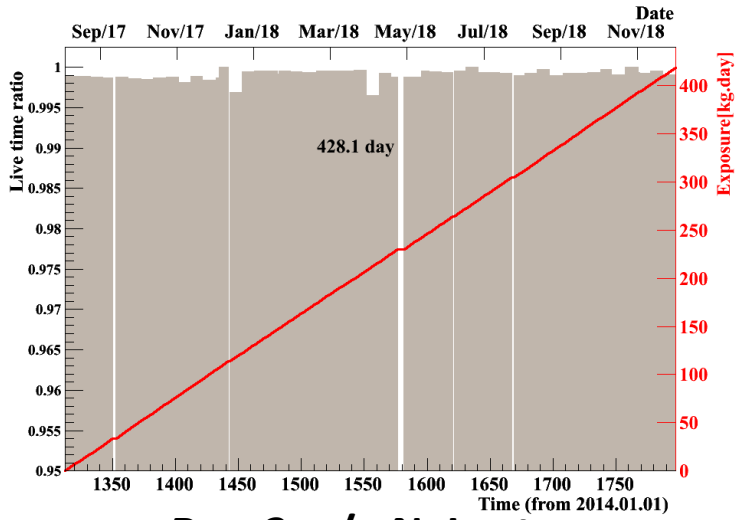


CDEX-1B Annual Modulation analysis

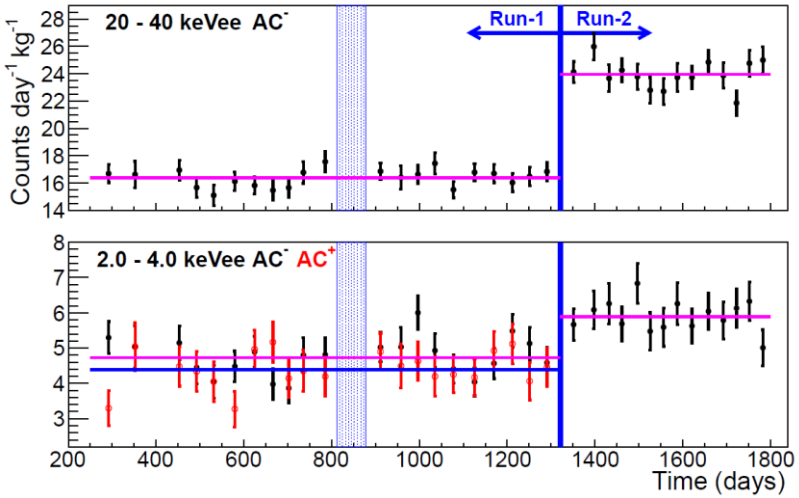
[PRL 123:221301 (2019)]



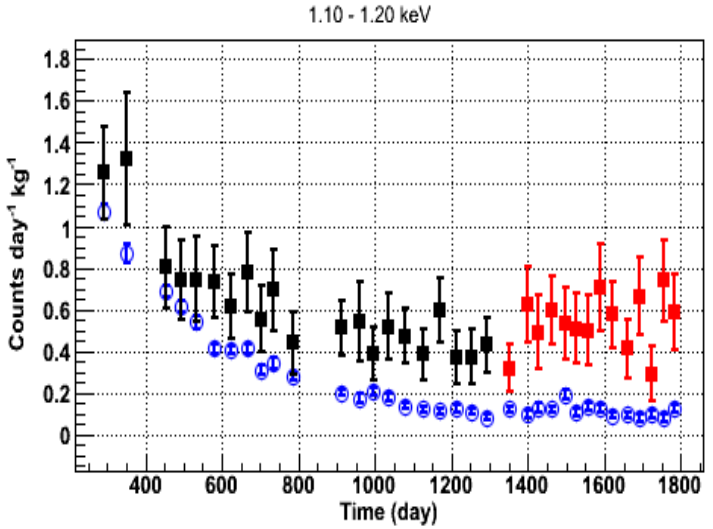
Run-1 w/ NaI veto



Run-2 w/o NaI veto

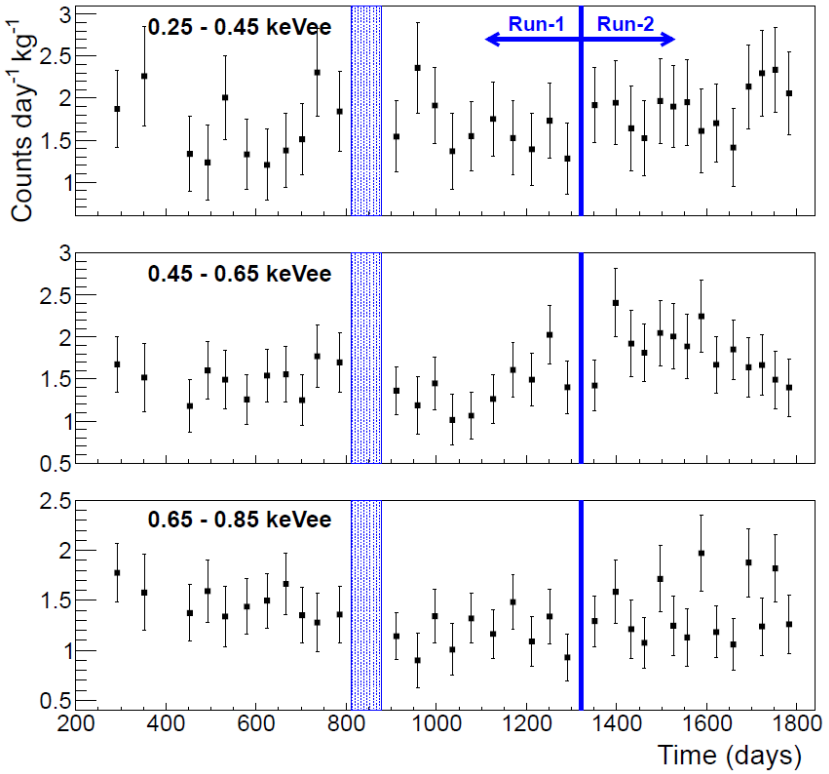


Compton contribution from High-energy gammas



L-Shell X-ray contribution – time varying

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

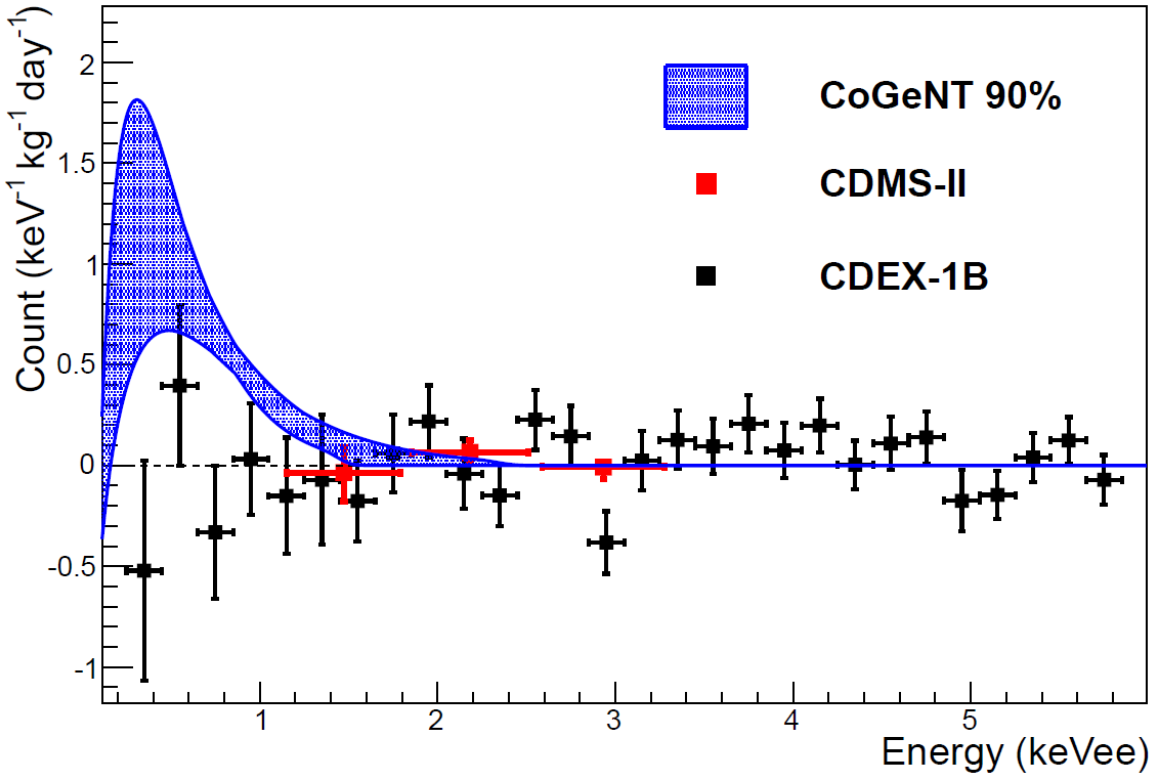


$$\chi^2_{ik} = \sum_{j \in \text{Time}}^{N} \frac{(n_{ijk} - P_{ijk} - B_{ik} - A_{ik} cos(\frac{2\pi(t_j - \phi)}{T_{yr}}))^2}{\Delta^2_{ijk}}$$

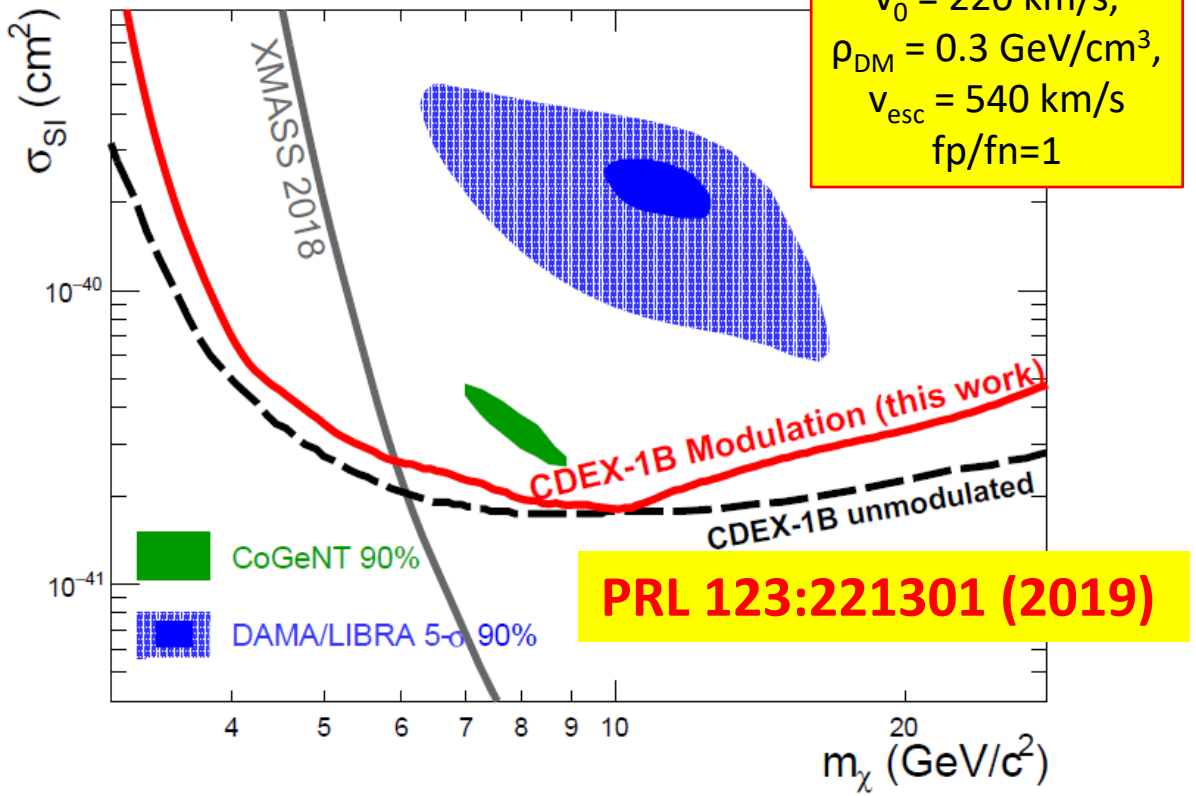
CDEX-1B Annual Modulation analysis

[PRL 123:221301 (2019)]

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



SI Limits at 90% C.L. from AM



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

PRL 123:221301 (2019)

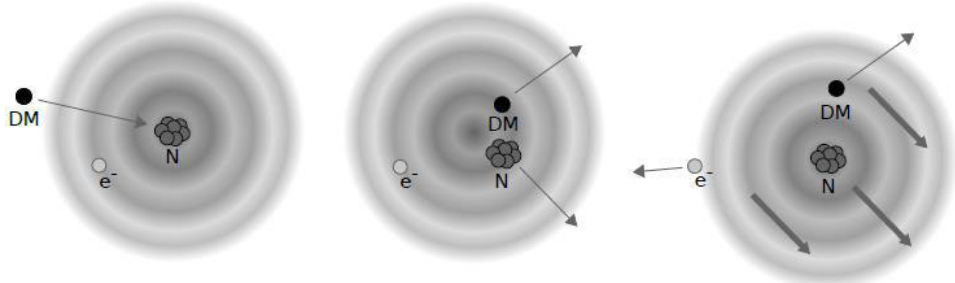
✓ **CDEX-1B excludes DAMA/LIBRA phase-1's interpretation with the spin-independent WIMP interaction with Standard Halo model in Germanium crystal.**

See details in LiuZZ' talk in Dec 8!

sub-GeV WIMPs: Migdal effect analysis

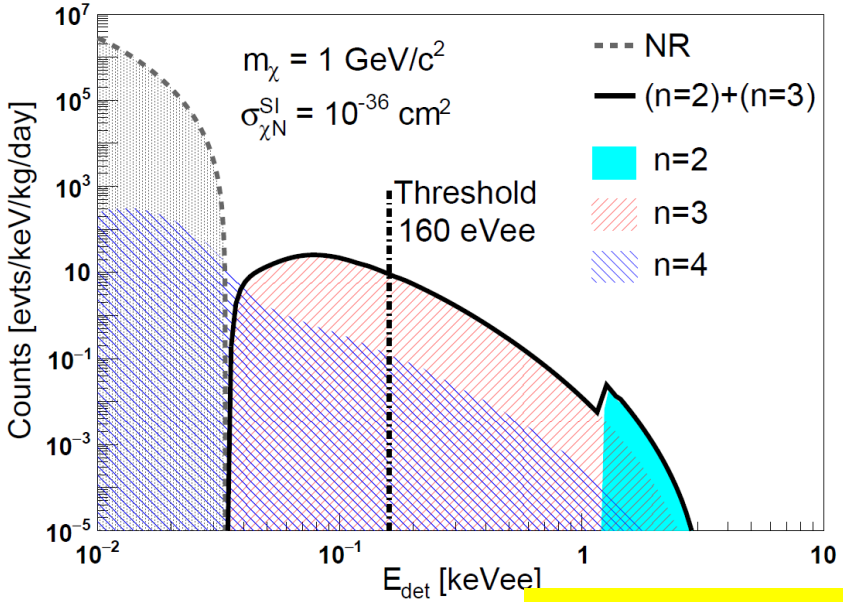
[PRL 123:161301 (2019)]

- 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;

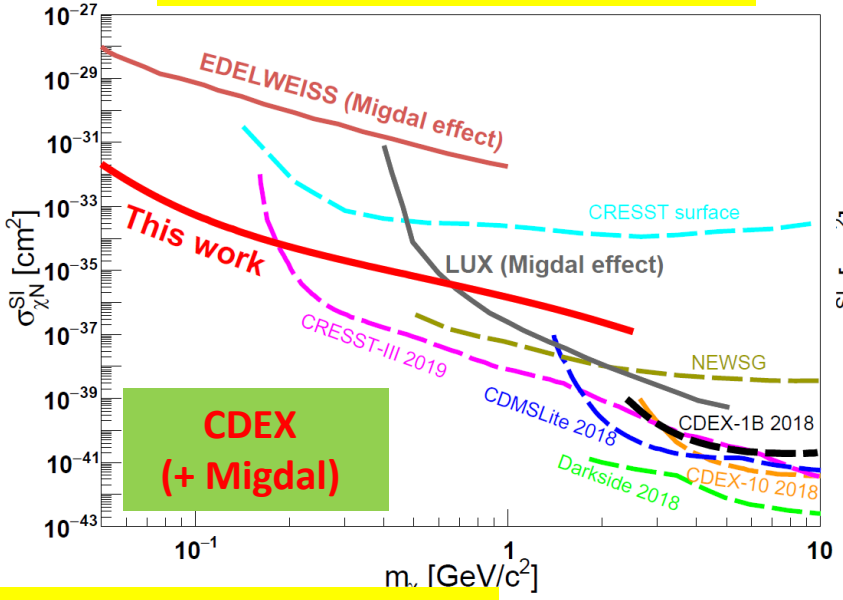


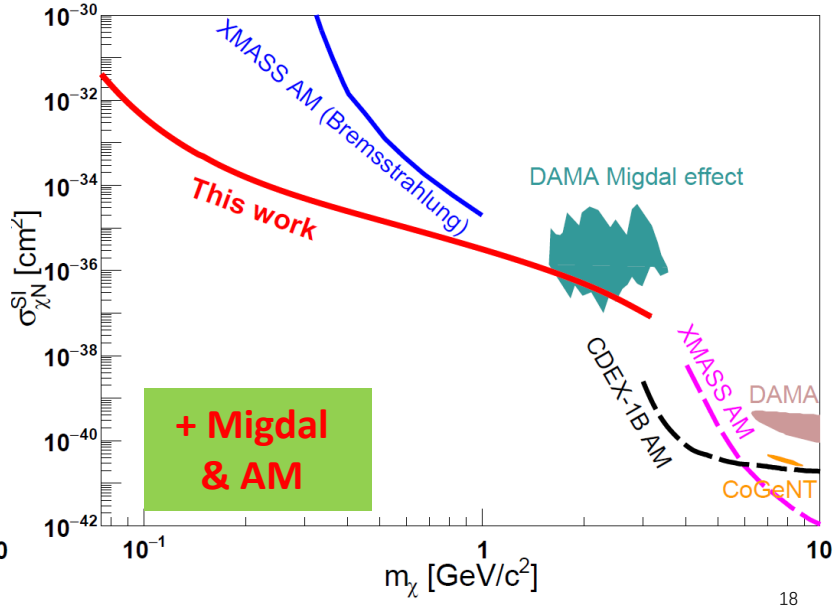
Migdal effect (M. Ibe et al.,2018)

Expected measurable spectra



PRL 123:161301 (2019)





See details in LiuZZ' talk in Dec 8!

Axions and dark photon

[arXiv: 1910.13234]
[arXiv: 1911.03085]

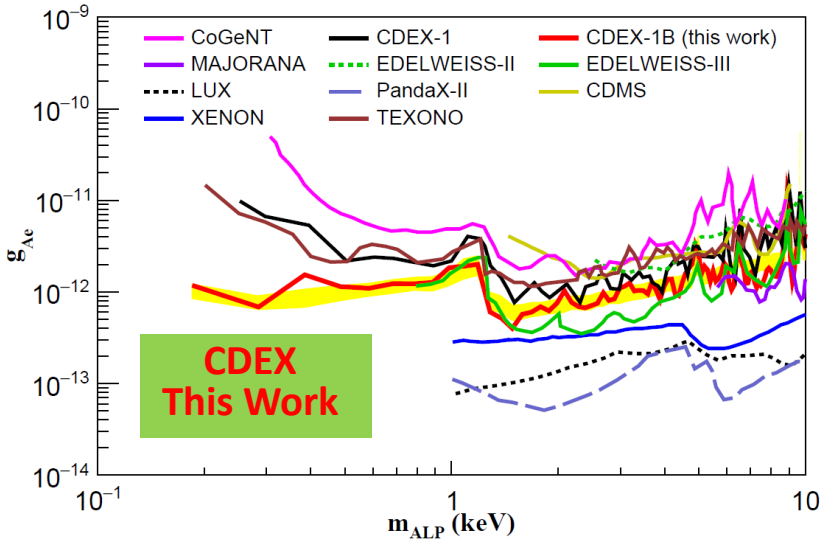
- AM Advantages of the low threshold!
- ALPs, Vector bosonic DM: leading sensitivity in <1 keV;

arXiv: 1911.03085 (2019)

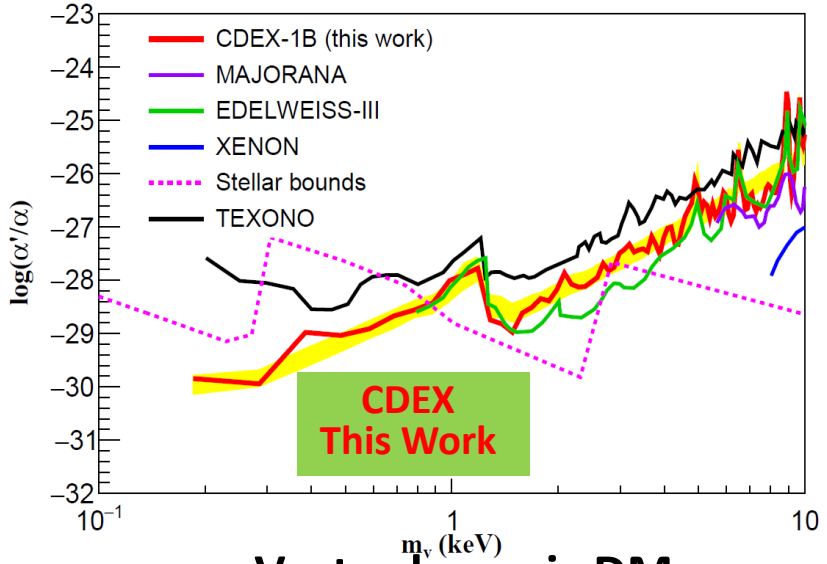
- Solar dark photon: leading sensitivity in m~10-300 eV;

arXiv: 1910.13234 (2019)

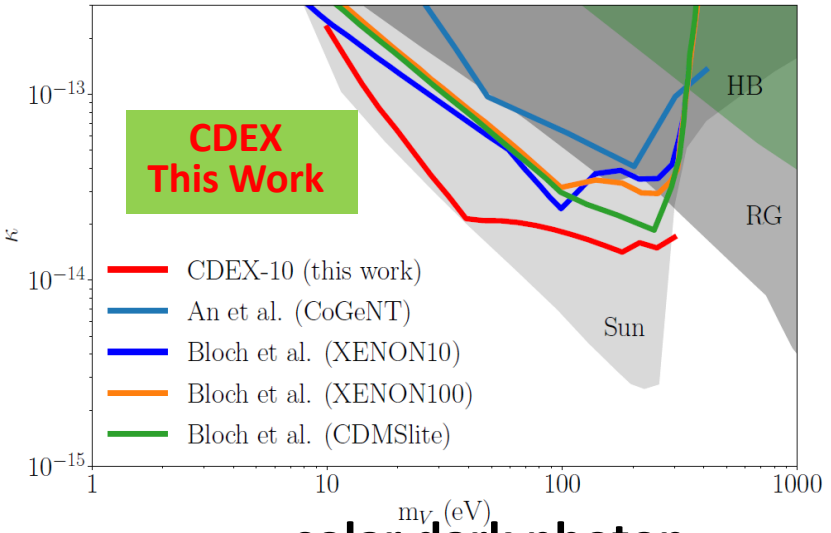
See details in SheZ' talk in Dec 9!



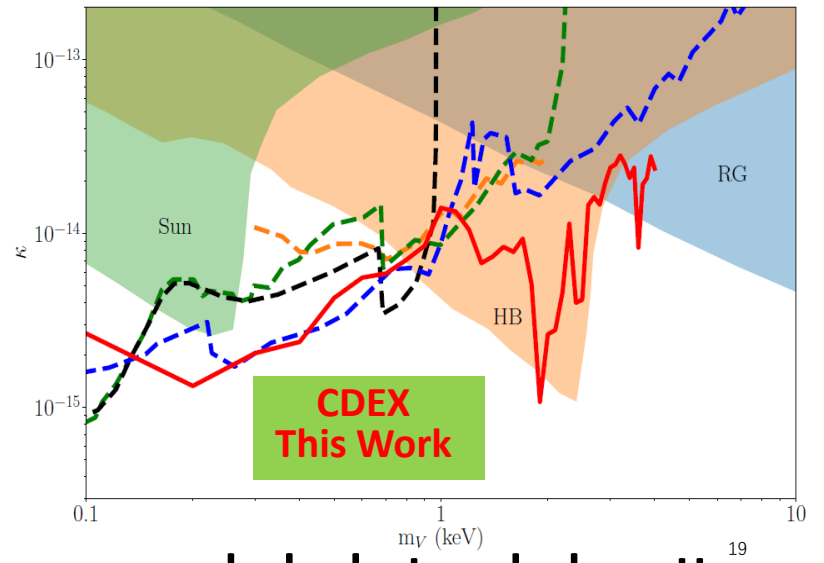
Pseudoscalar ALPs



Vector bosonic DM



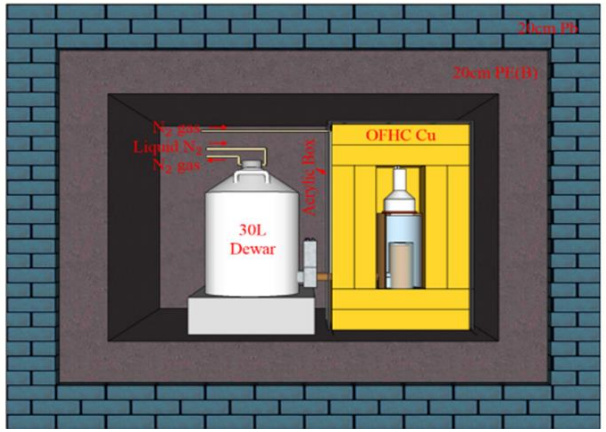
solar dark photon

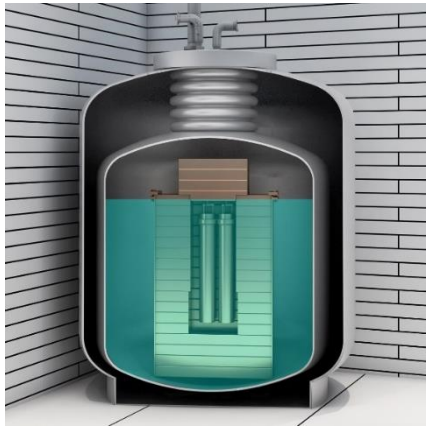


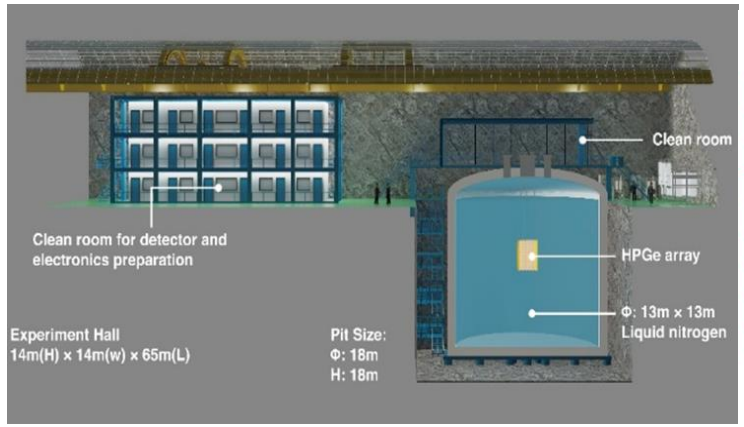
dark photon dark matter

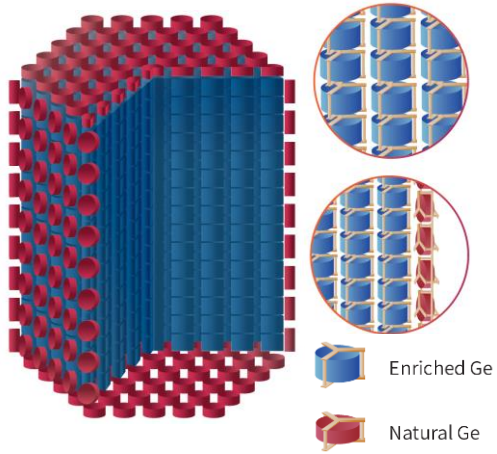
CDEX Roadmap

Direct detection of Dark Matter Particles
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 → CJPL-II

Key technologies:

- ✓**Ge crystal growth and ^{76}Ge enrichment / Ge detector fabrication**
- ✓**Ultra-low background VFE / Ultra-pure copper for structure and cables**
- ✓**Natural Ge detectors as veto**
- ✓**……**

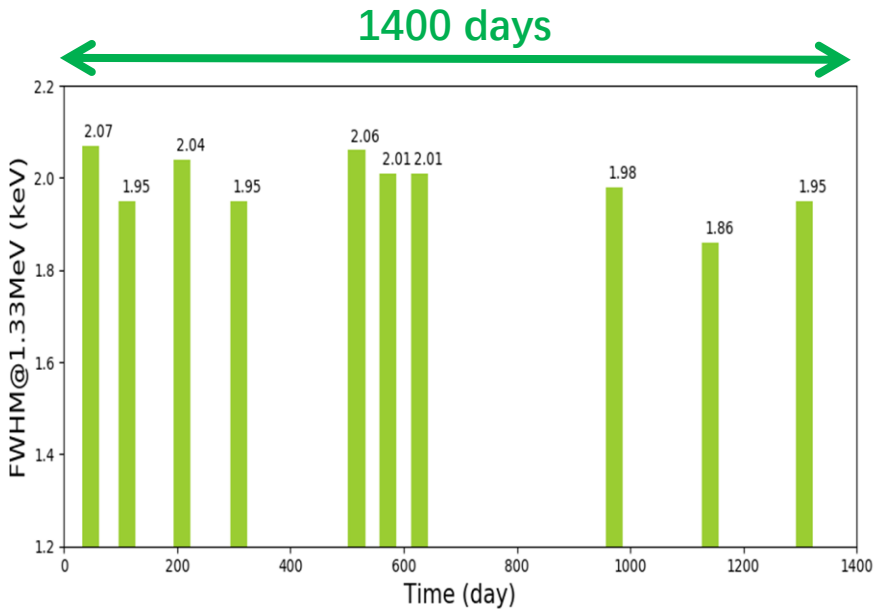
Lower background
Lower threshold

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;
✓ Underground EF-Cu;
✓ Underground assemble;
✓ Underground testing…

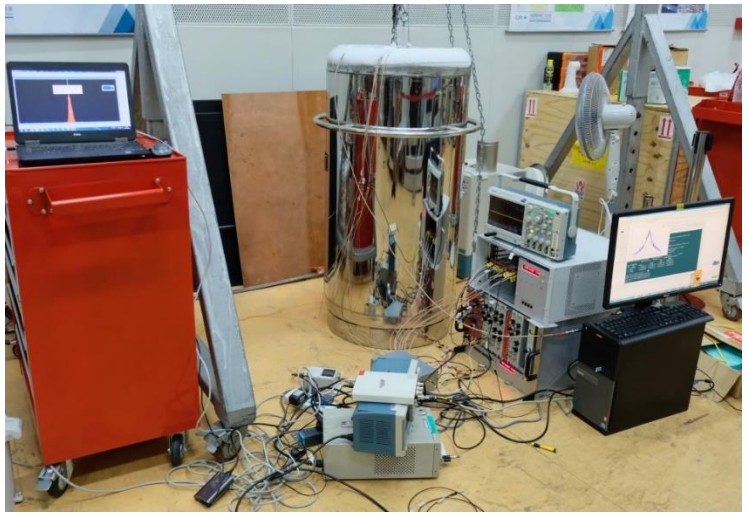
good performance keeping, >1400 days



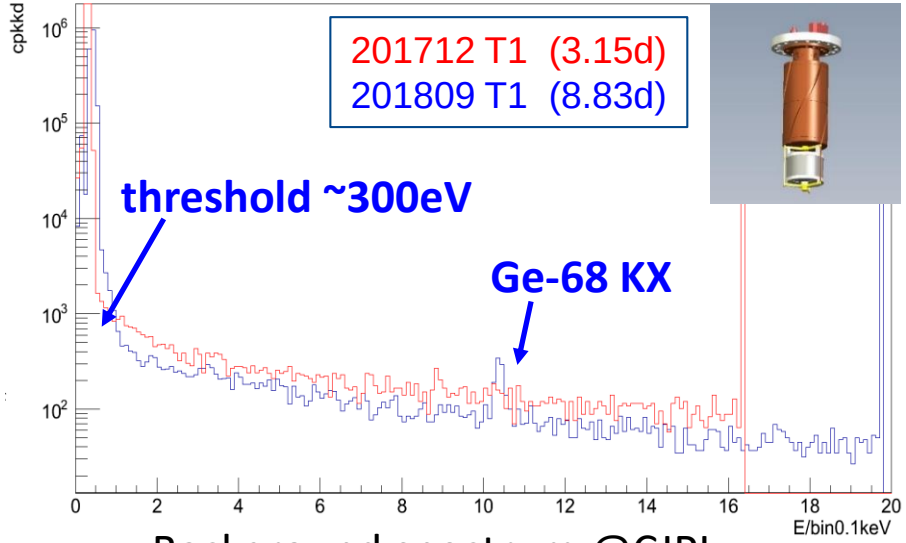
Vacuum systems

Technical R&D: Ge detector fabrication

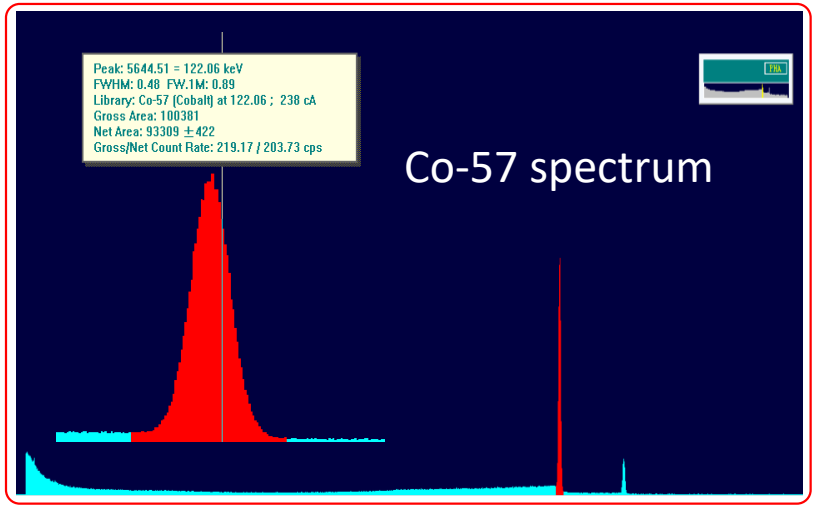
- Commercial Ge crystal + stainless steel canister;
- T1 detector: 500g Ge(φ50×50mm) + CMOS ASIC preAmp;
- Works w/ expected performance!
- Going on to improve bkg, low-noise electronics…



Tested in CJPL-I



Background spectrum @CJPL



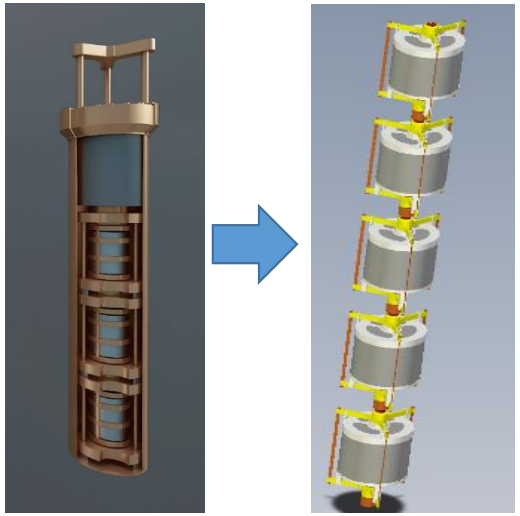
FWHM=0.48keV@122keV_Co57

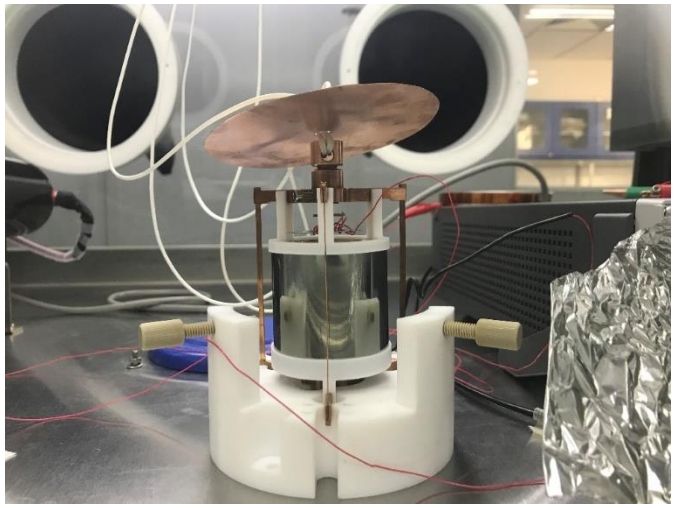
Technical R&D: Ge detector fabrication

- Vacuum chamber, structure materials, not conducive to further reduce the radioactive background;
- ASIC-based preamplifiers can work well in liquid nitrogen;

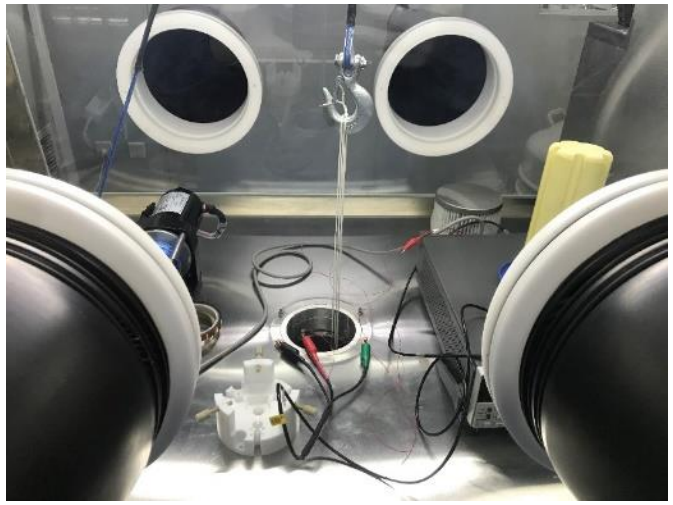
✓ Develop bare HPGe detectors immersed into LN_2!

✓ Immerse the detector into LN_2 for ~8 hours, we got a stable leakage current ~10 pA for 1000V bias voltage.



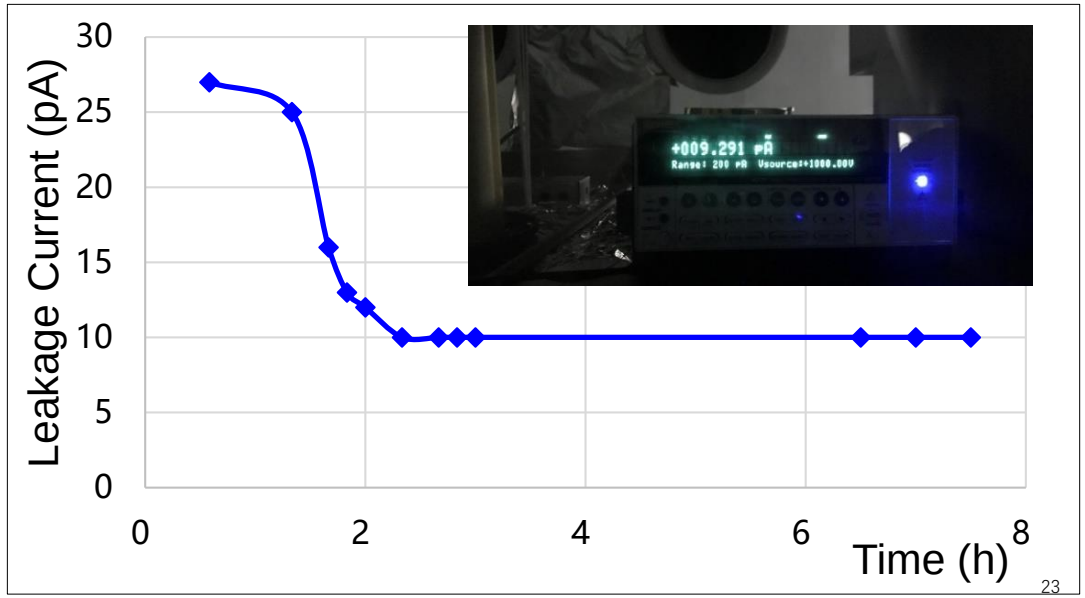


Bare HPGe detectors



Bare HPGe in LN_2

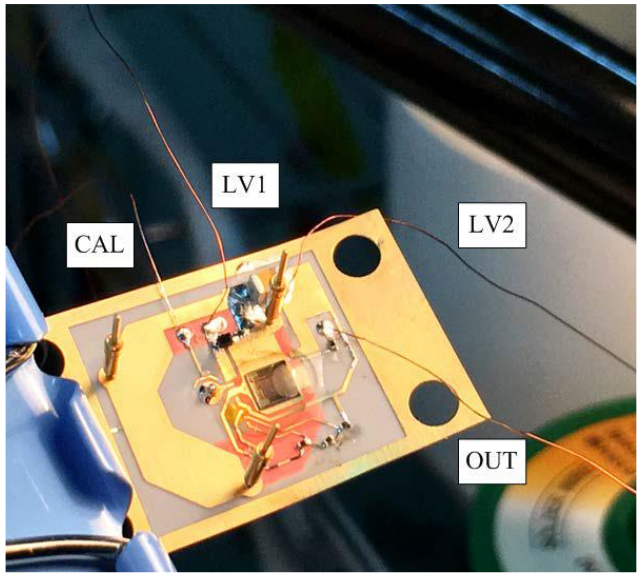
PPC: ϕ50mm x 50mm, Depleted voltage: ~800V

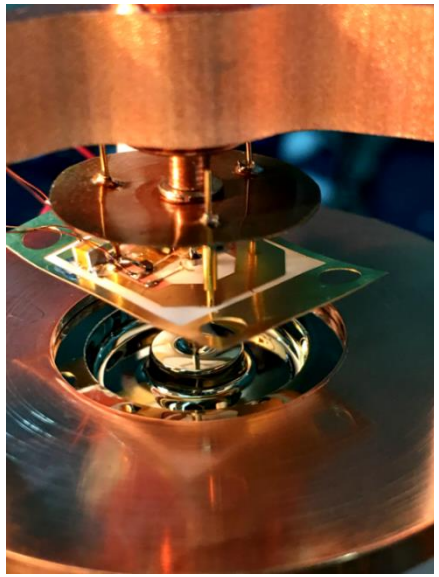


Technical R&D: CMOS ASIC Front-end Electronics

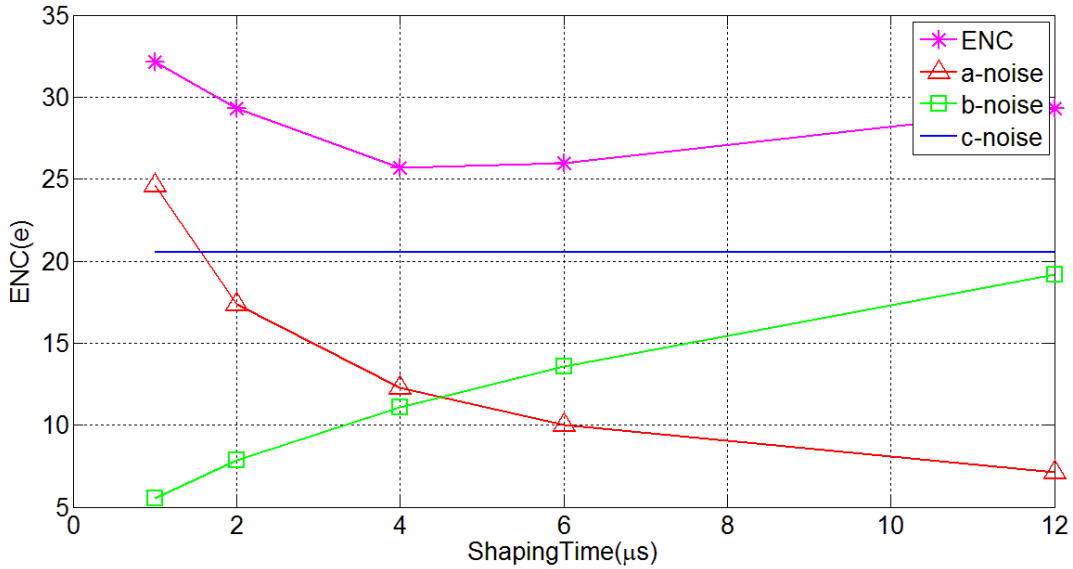
- Light DM search →low noise/threshold (low capacity, etc)
- Very close to Ge detectors →low bkg (radiopure, low-mass, etc)
- ASIC preamplifier @ 77K
  - PCB material: PTFE(Rogers 4850);
  - ENC ~26e(<200eV) w/ 4μs shaping time, mainly from 1/f noise (~21e);

Details in *JINST (2018) 13: 8019*





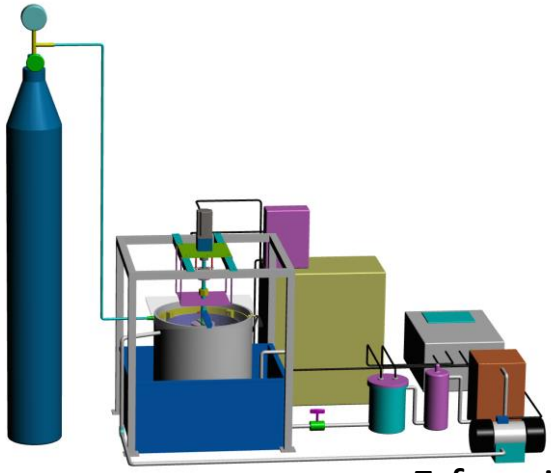
Noise components analysis



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
  - Wet chemistry testing… , blank sensitivity ~10^{-13}g/g

UG copper e-forming facilit@CJPL-I



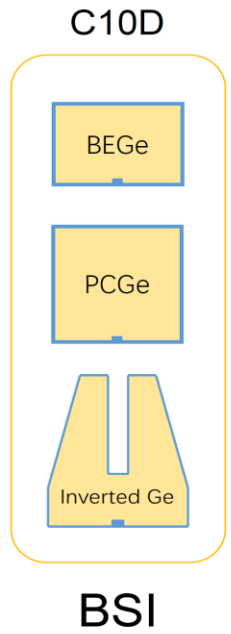
E-forming setup

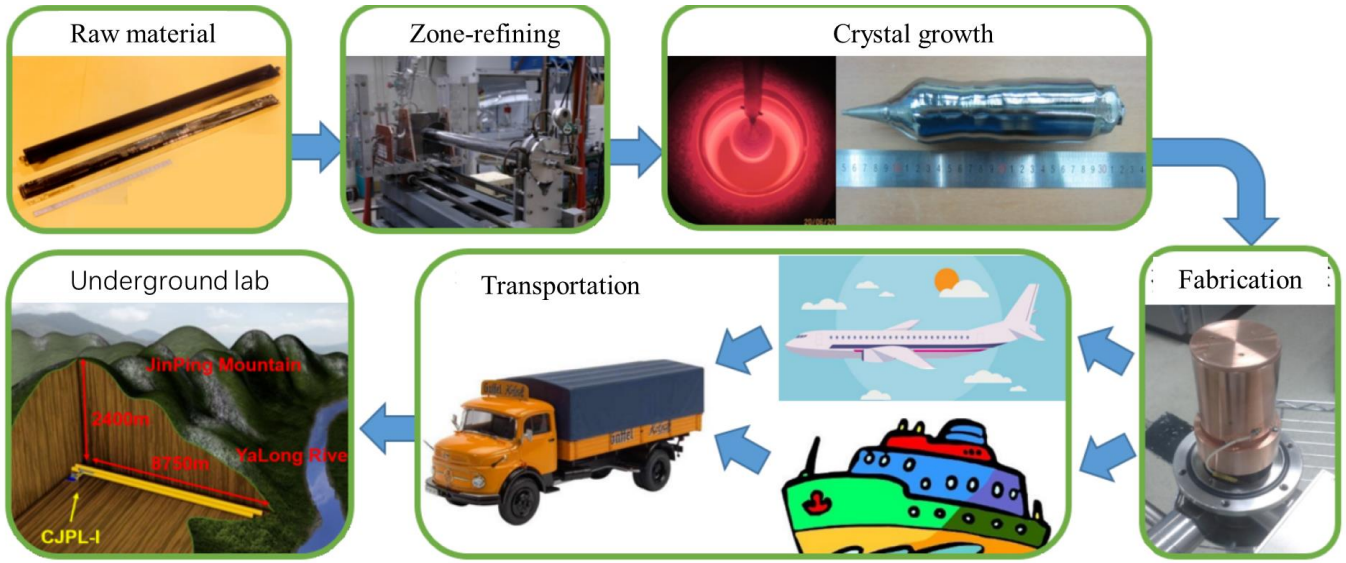
optimized electrical parameters

ICP-MS

Future Plan - Detectors

- New detectors cooperated with commercial companies
  - 3kg from BSI, 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;



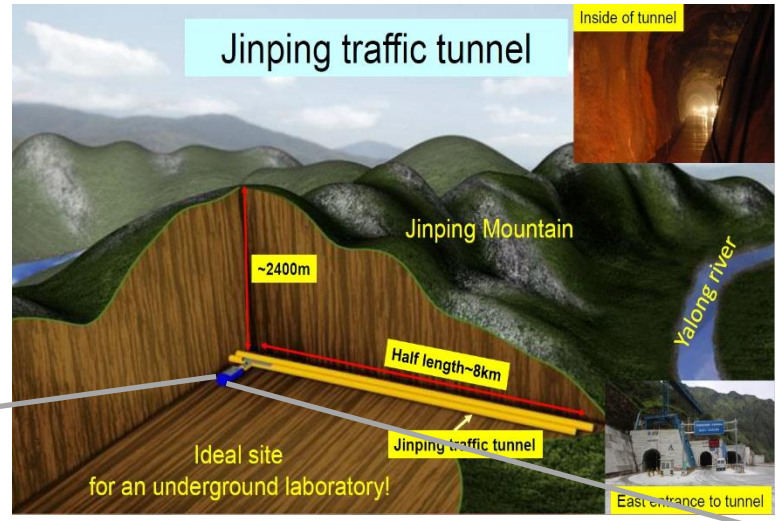


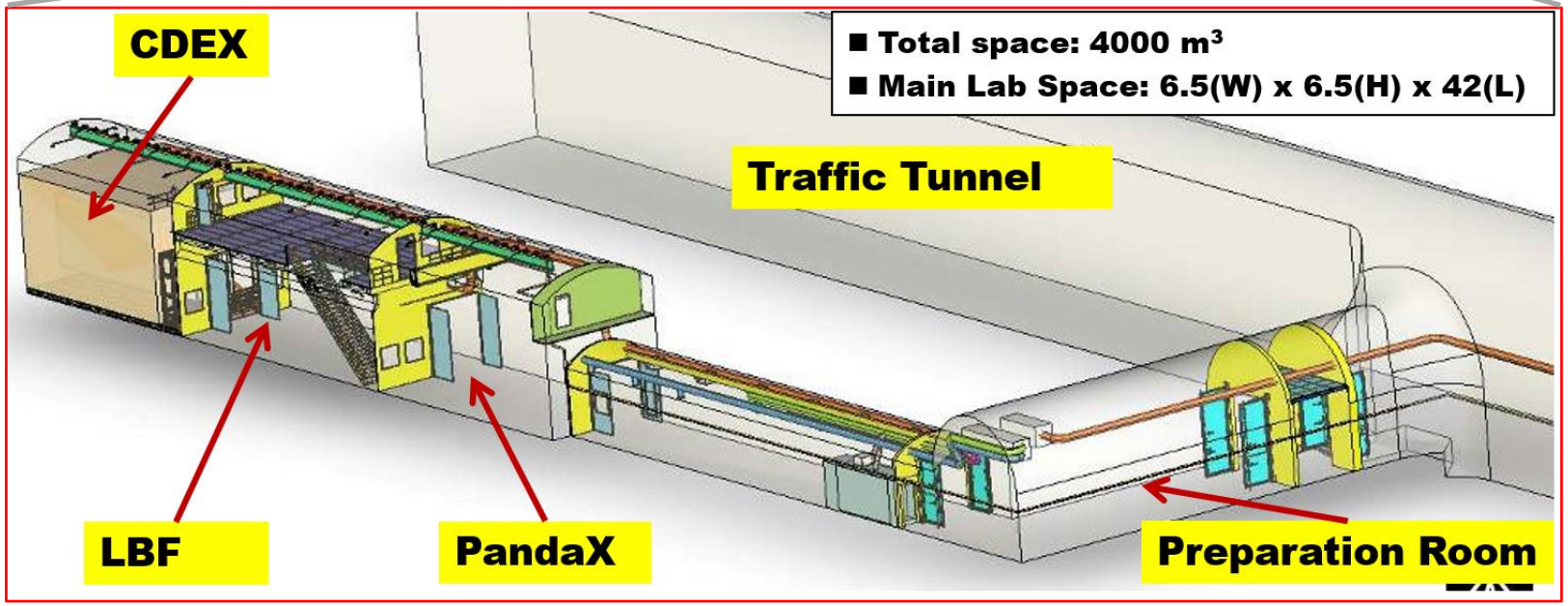
Detector production: 45days +
Ground transportation: 60 days +
Underground cooling: 180days →

Cosmogenic bkg: 0.03cpkkd(sim.)

Future Plan - Lab

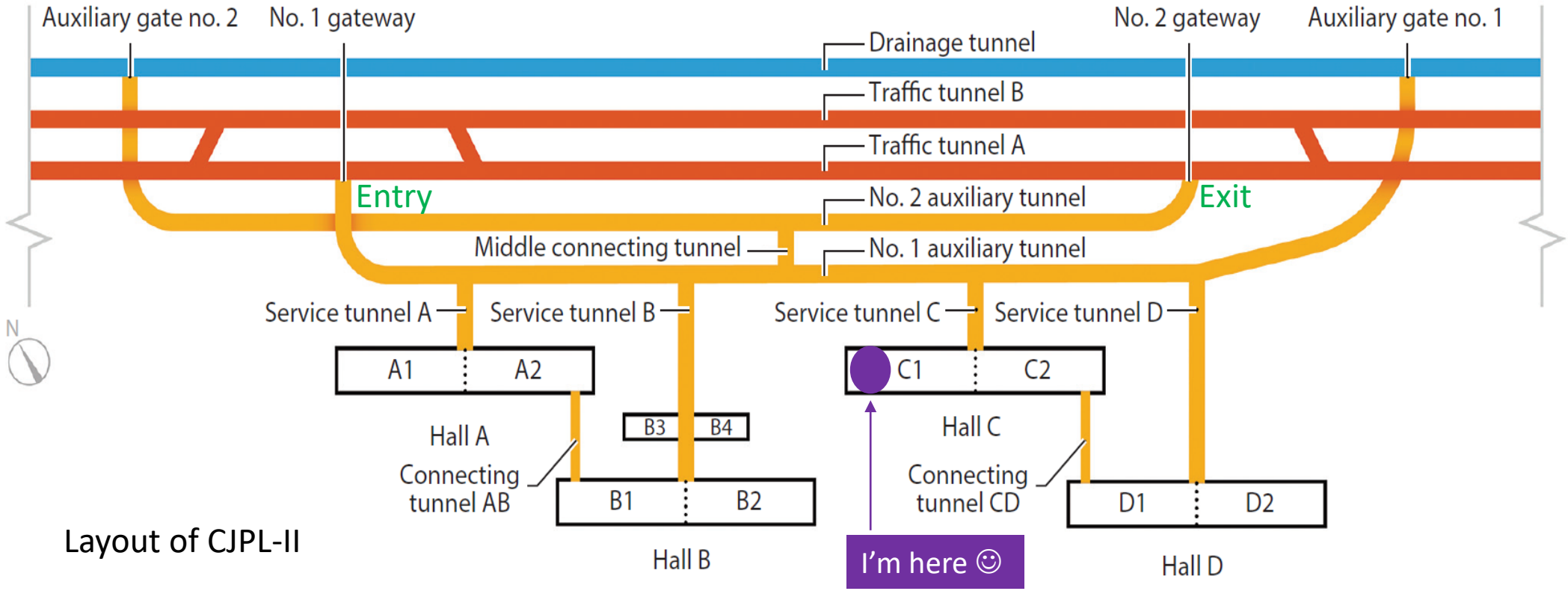
- CJPL-I
  - Volume: 4000 m^3
  - 1 main hall (6.5x6.5x42m)





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

CJPL-II construction next plan

Main Hall

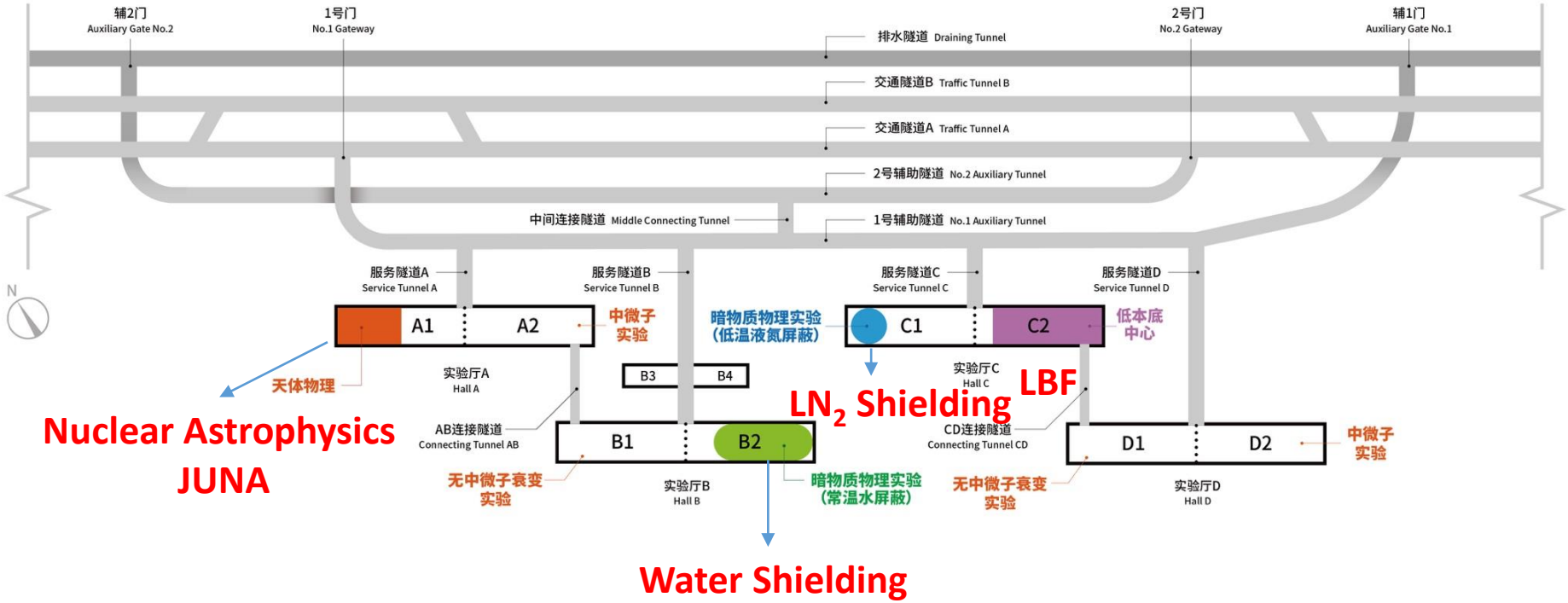
Service tunnel

- CJPL was selected to be a candidate project of **National Major S&T infrastructure of China** in 2016.
- Proposal has been approved in Dec. 2018. The funding, **~$180M**, just for the construction of the facility including the infrastructure, shielding, instrument and so on.
- Possible users:
  - CDEX-1T(DM, 0νββ), PandaX-xT, LAr DM, CUPID-China
  - Nuclear astroparticle physics
  - Solar neutrino experiment
  - Rock mechanics experiment
  - ……
- Service
  - Low background counting
  - Ultra pure copper
  - popularization of science

Ground campus

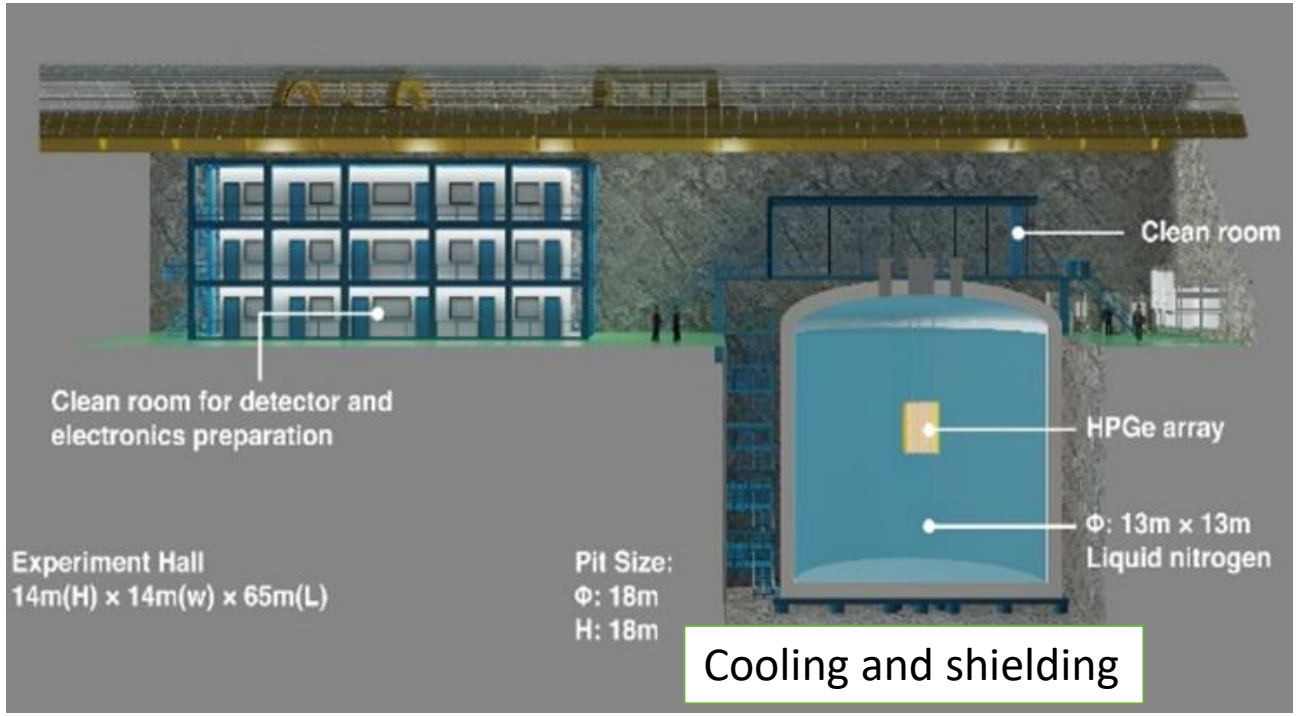
CJPL-II construction next plan

- CJPL will be an international platform for particle physics, nuclear physics, and so on.
- CJPL will aim to provide services to the researchers performing experiments there, and to develop it into an open and world-class research facility with first-rate working conditions used by internationally leading research teams.
- World-leading experiments will be highly encouraged to locate in CJPL-II.



Future Plan - CDEX

- CDEX-10X moving to a 1725m^3 LN_2 tank (φ13x13m) located in the pit;
- Construction of LN_2 tank kicked off in Nov. 2018 and done end of 2019;
- CDEX-100 stage under technical design, report comes soon.



Cooling and shielding


CDEX Pit (top view)

Future Plan - CDEX

- CDEX-10X moving to a 1725m^3 LN_2 tank (φ13x13m) located in the pit;
- Construction of LN_2 tank kicked off in Nov. 2018 and done end of 2019;
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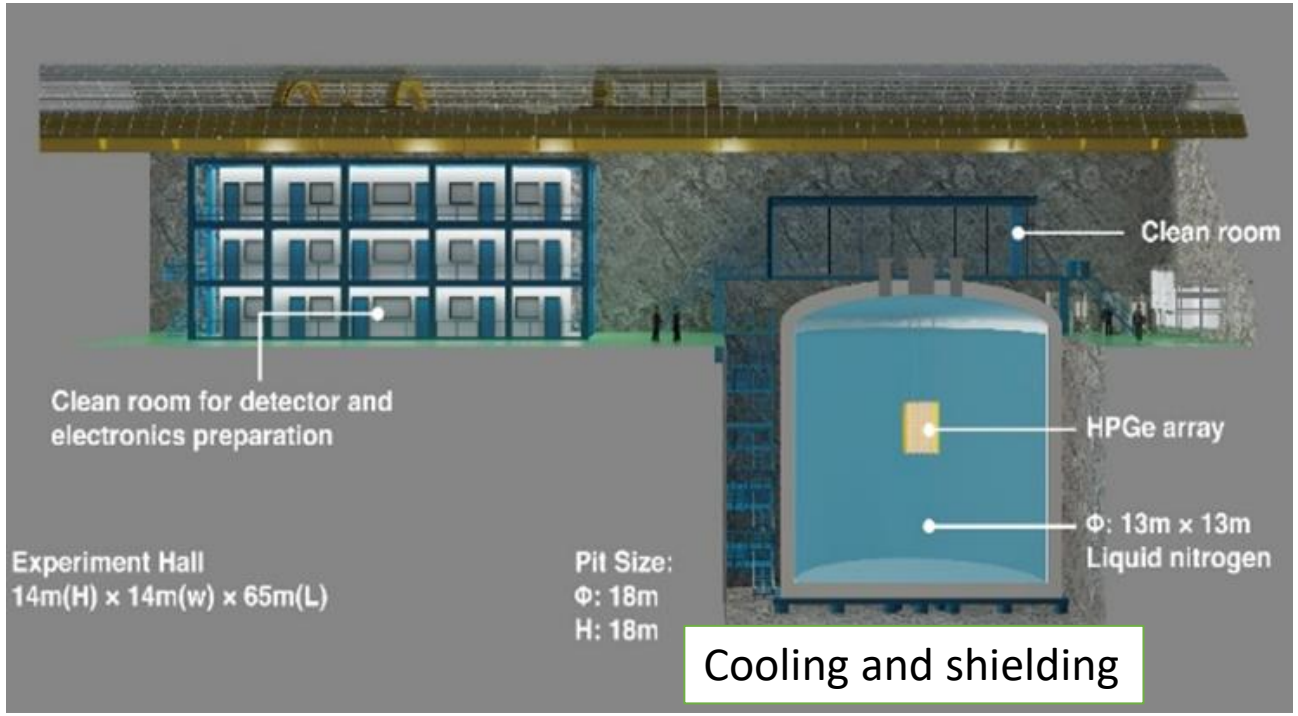
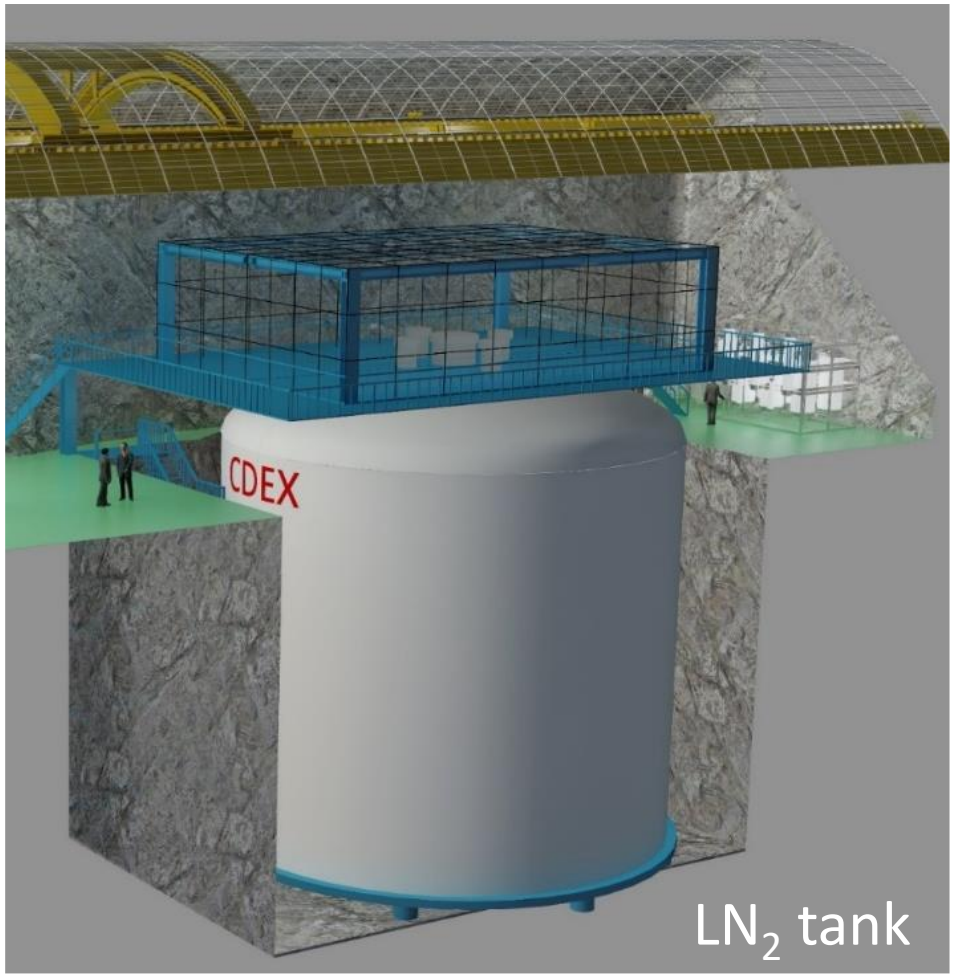


Future Plan - CDEX

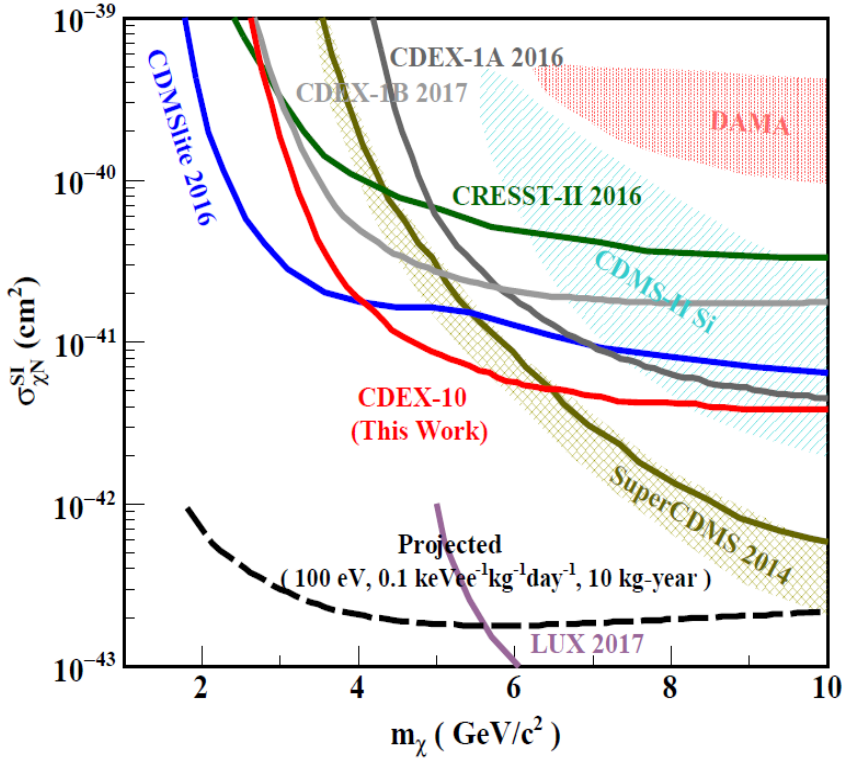


LN_2 tank

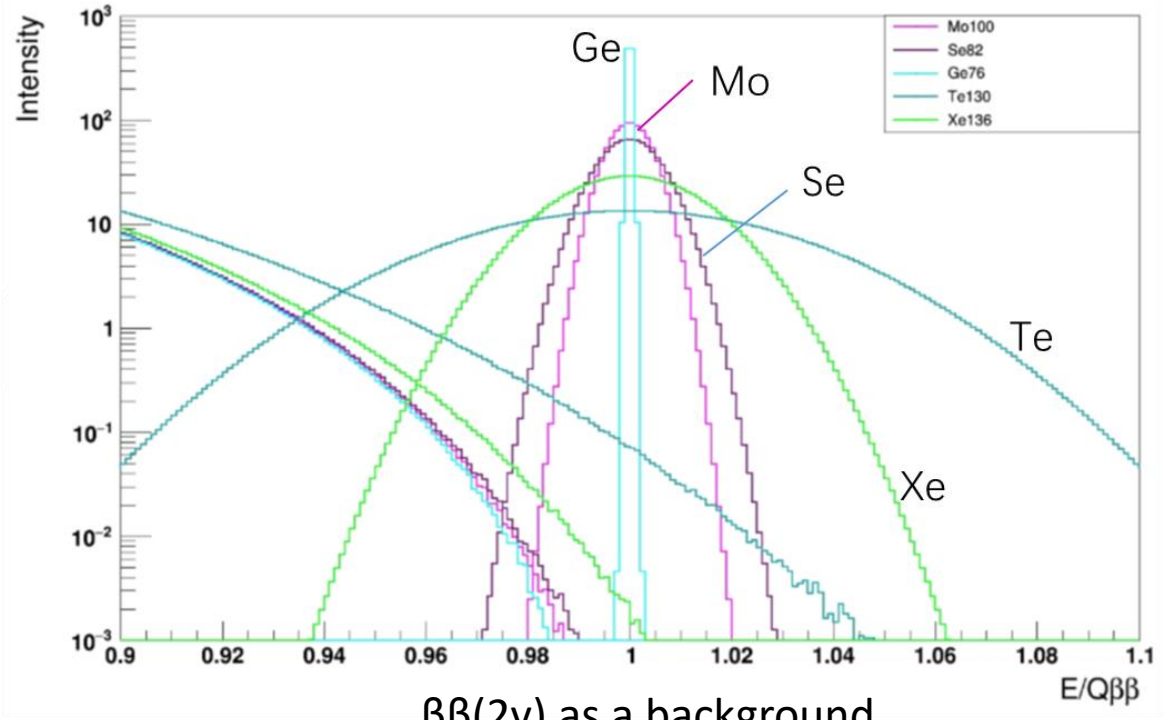

LN_2 tank at C1

Future Plan – Main Goals

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



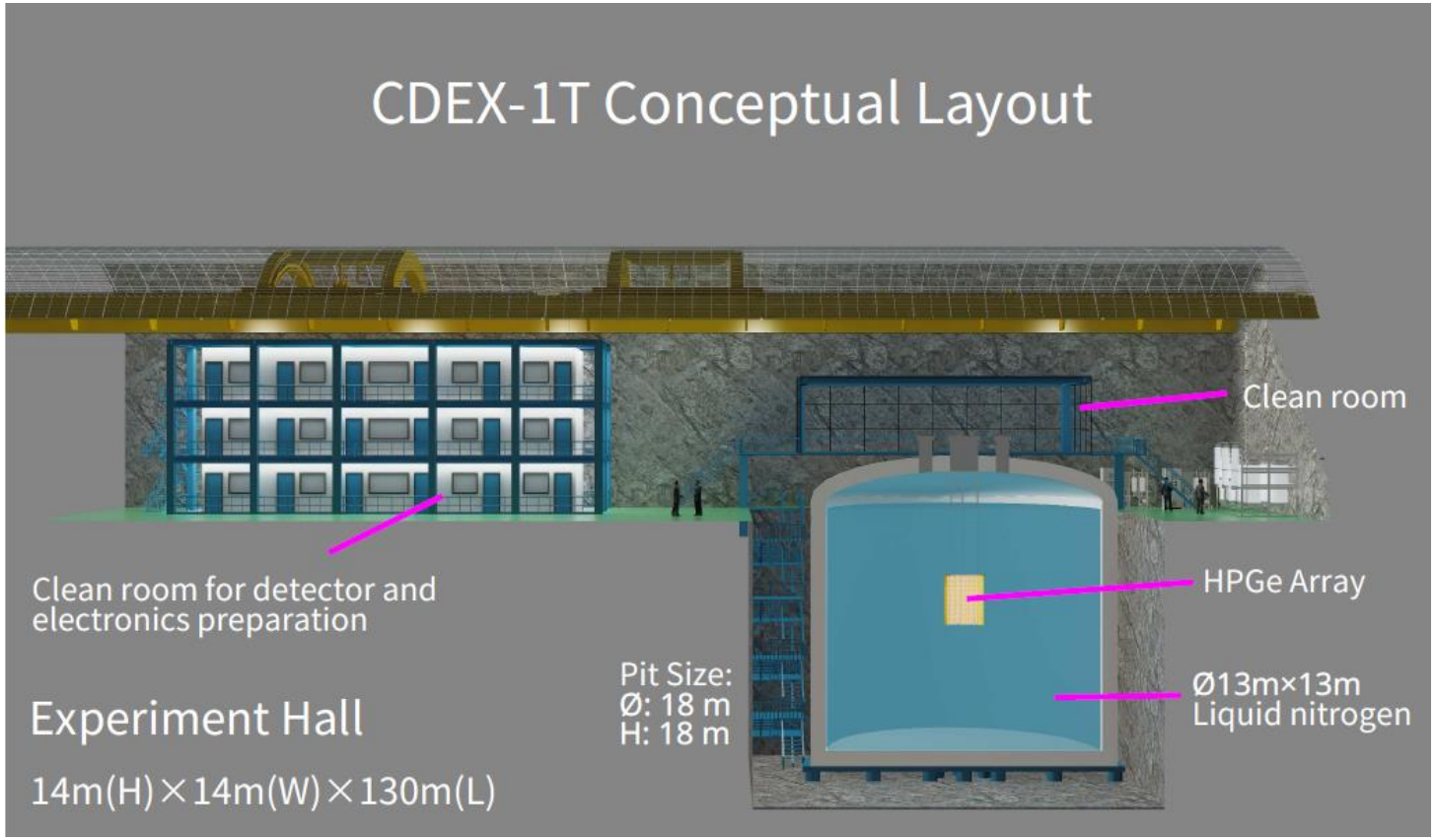
- 0νββ
  - Taking advantages of Ge detectors;
  - Combined with Legend-1T
  - Location Undetermined!

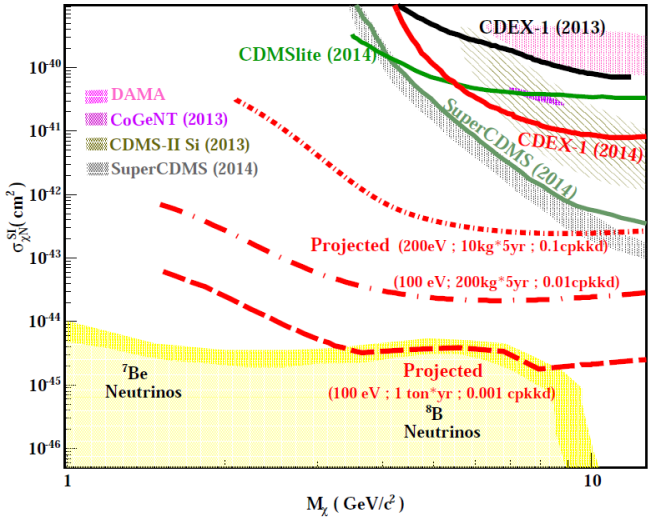


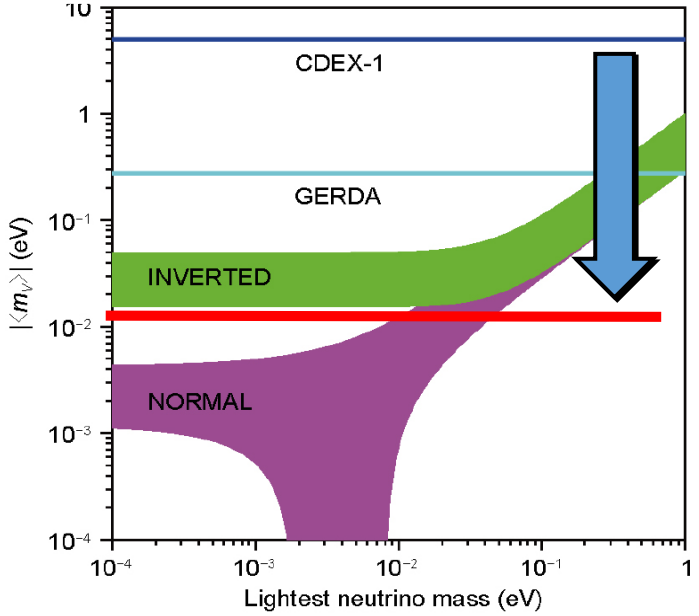
ββ(2v) as a background
Assuming $T_{0\nu}/T_{2\nu} = 1 \times 10^6$

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 $m_{\chi} \sim 50–180$ MeV.

- 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 effors on home-made Ge detector, FE electronics, crystal growth, UG copper e-forming…
- Other physics: Axion, dark photon, 0νββ (LEGEND),…

L.T. Yang, Tsinghua U., yanglt@mail.tsinghua.edu.cn


Thanks for your attention!
锦屏一级水电站世界最高坝

CDEX Roadmap