Experimental dark matter search at China Jinping underground Laboratory

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Shanghai Jiao Tong University

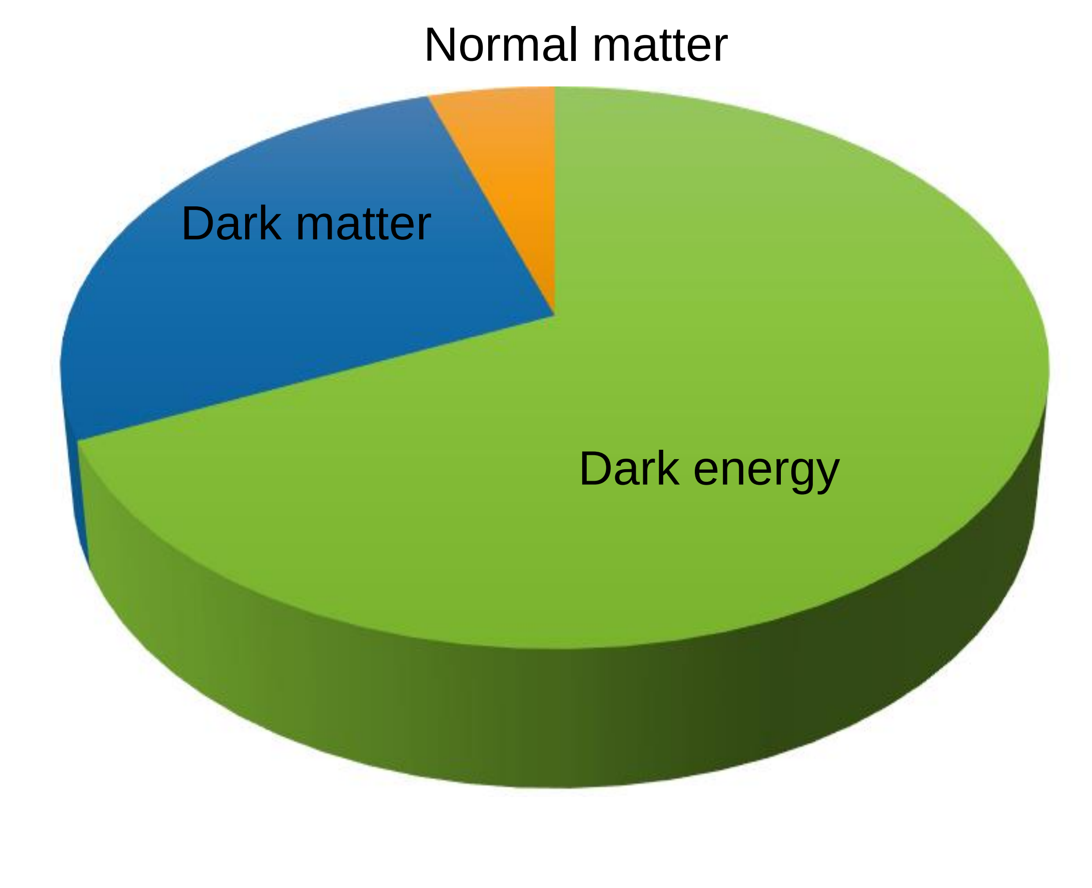
The GR view of the Universe

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi G T_{\mu\nu}$$

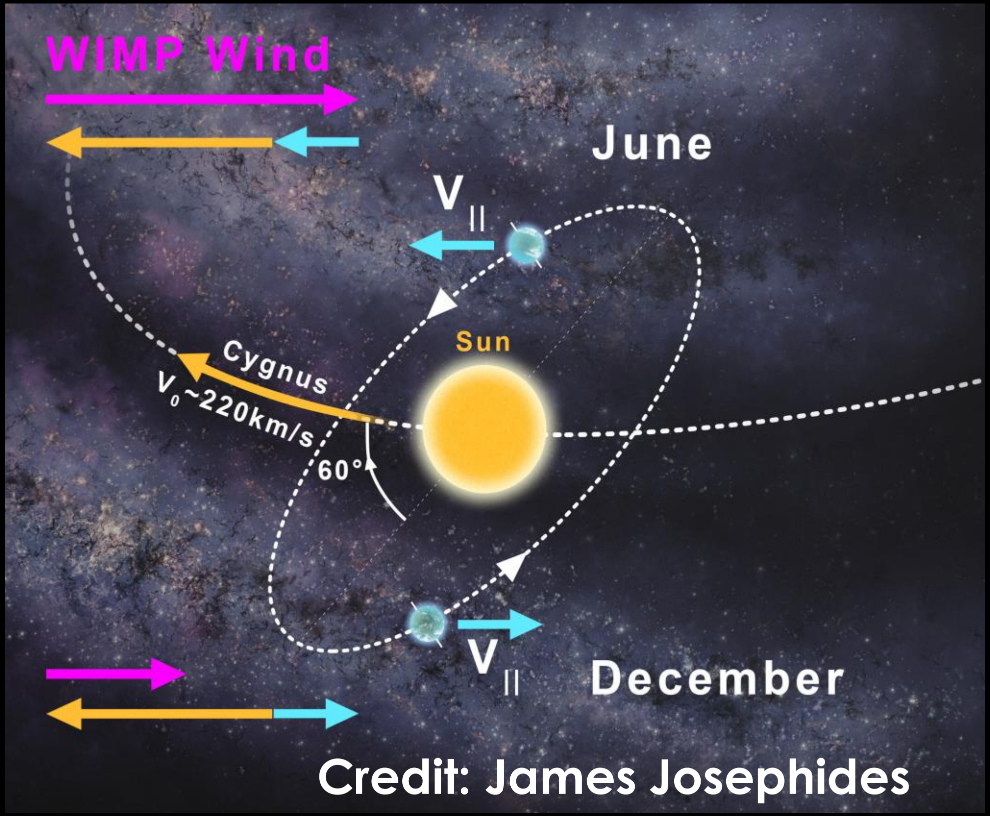
Law of universe expansion

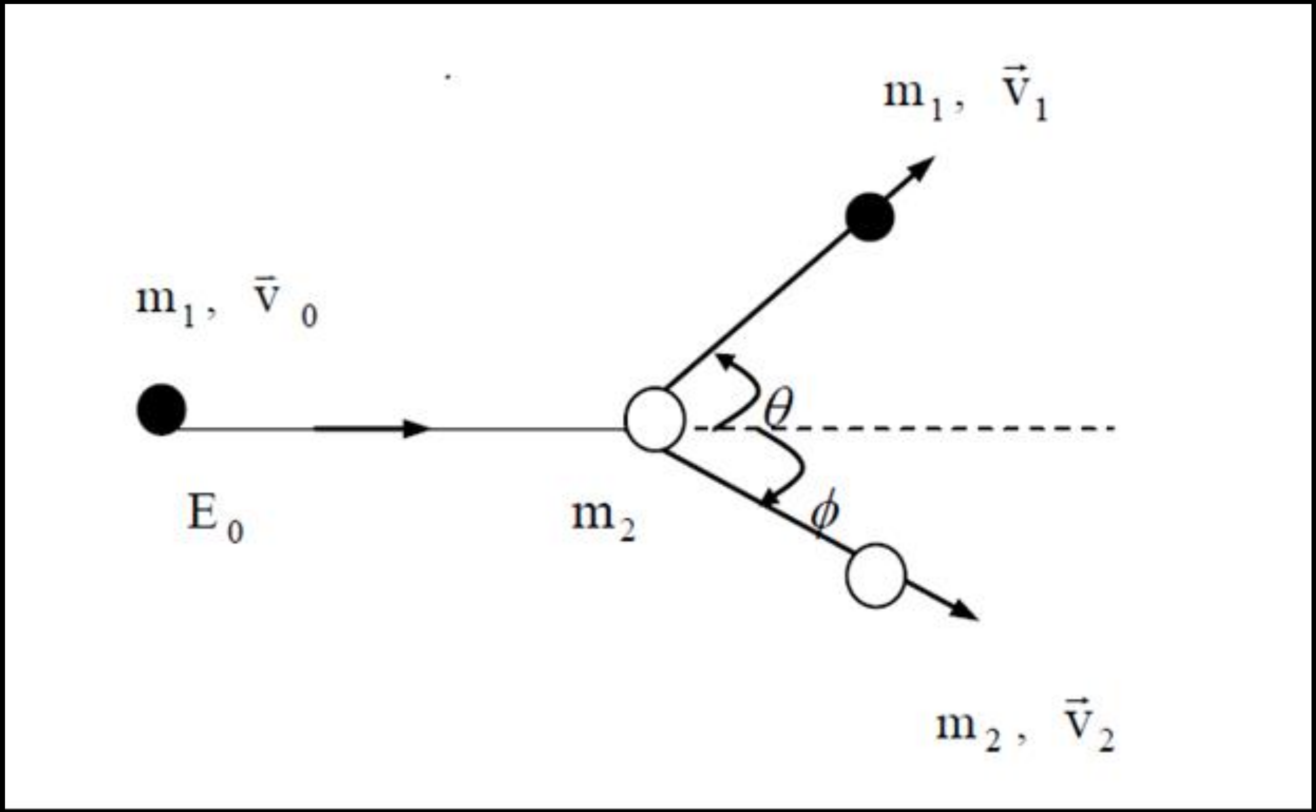
Dark Energy

All matter and energy in the universe

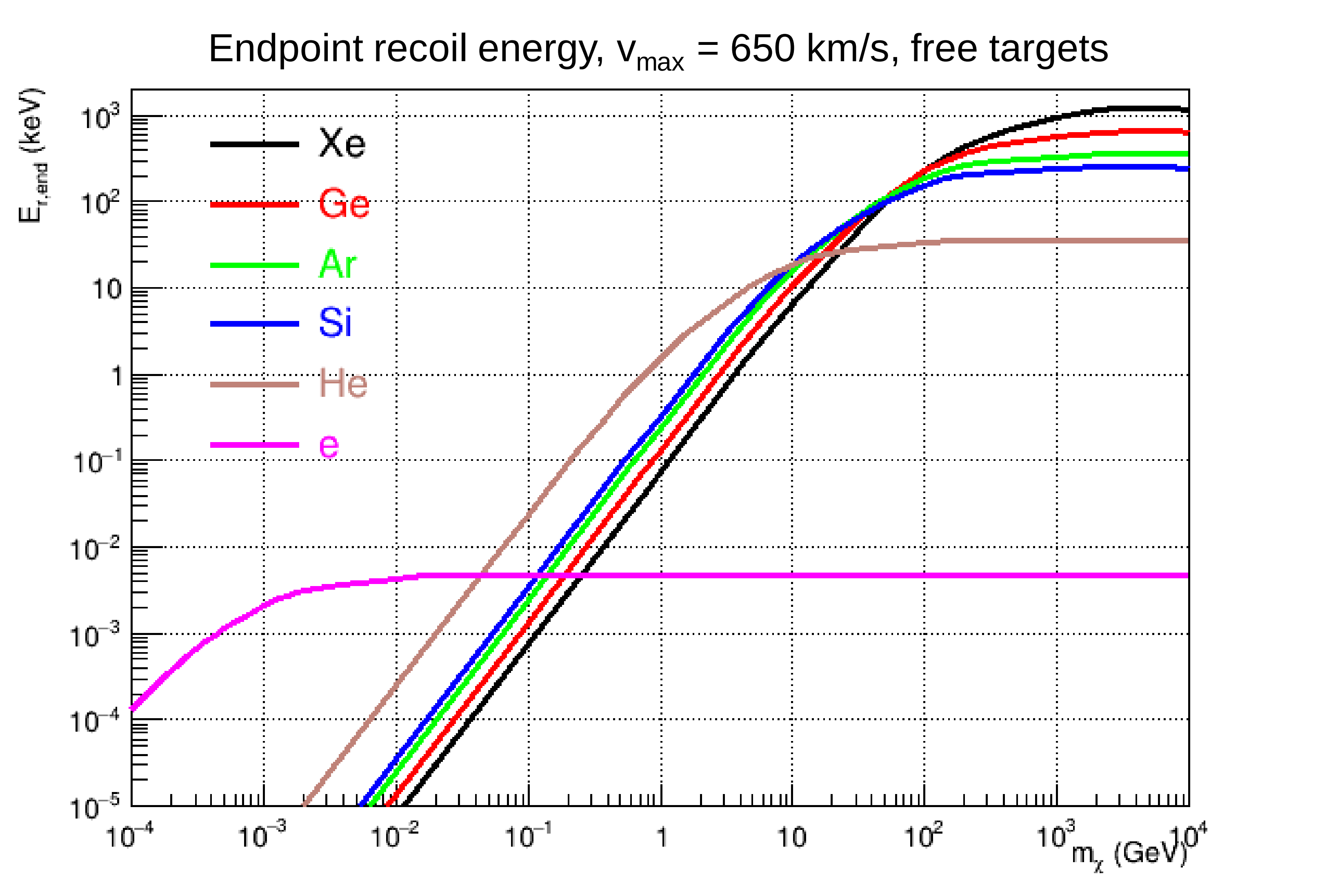


DM direct detection: classical beam experiment

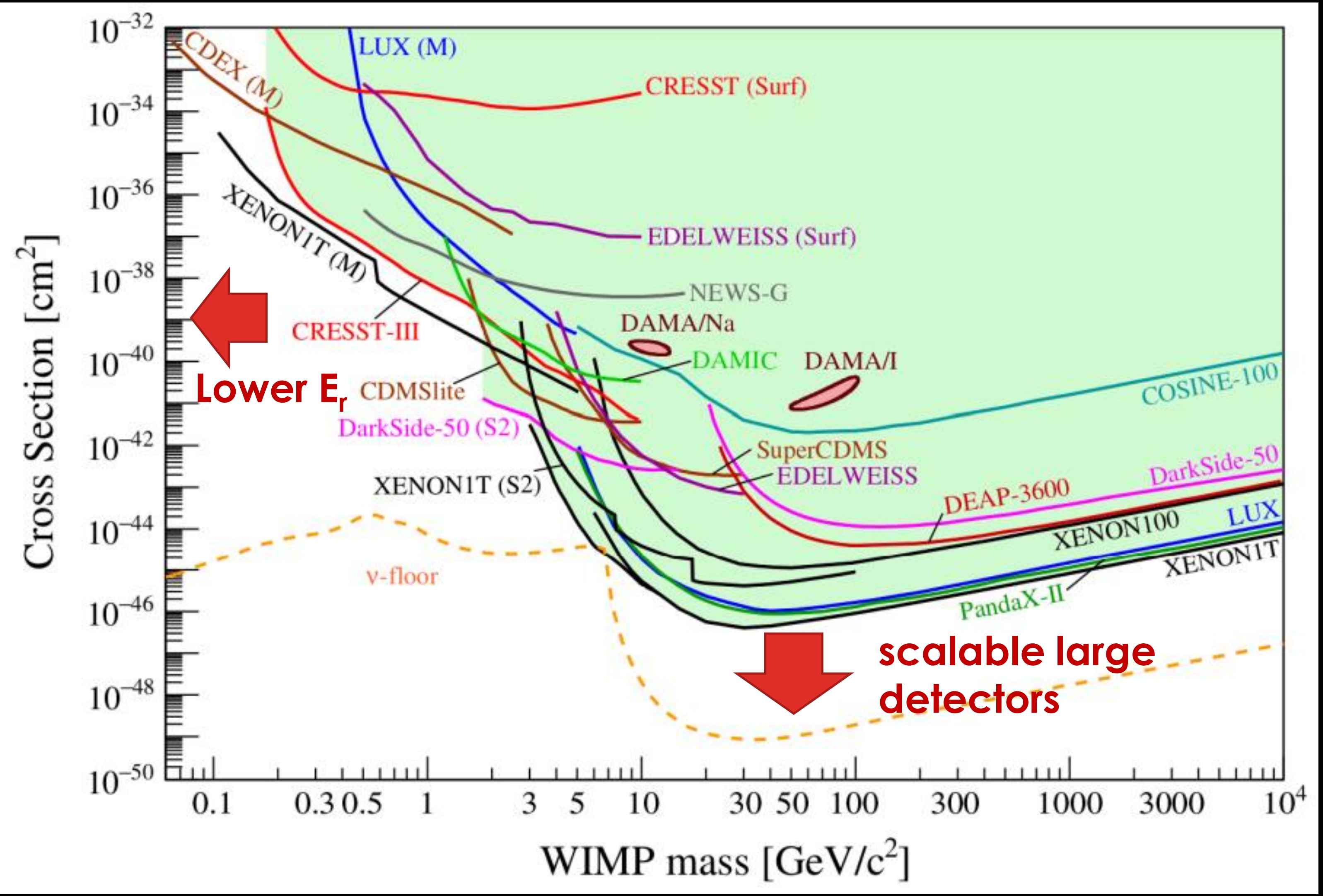




Visible recoil energy



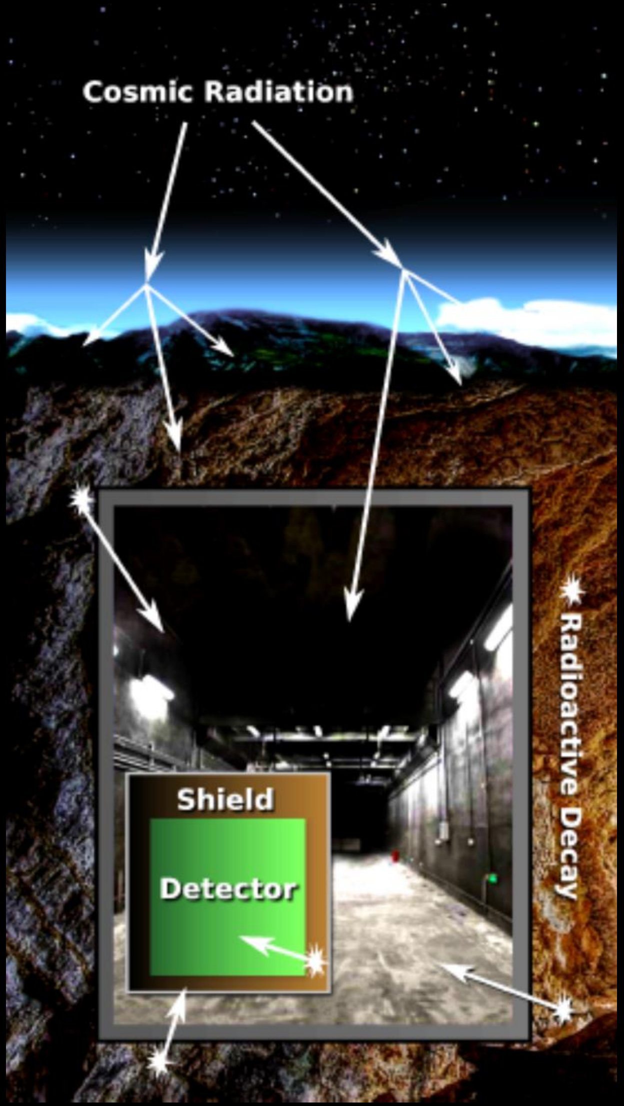
Global status: hide & seek



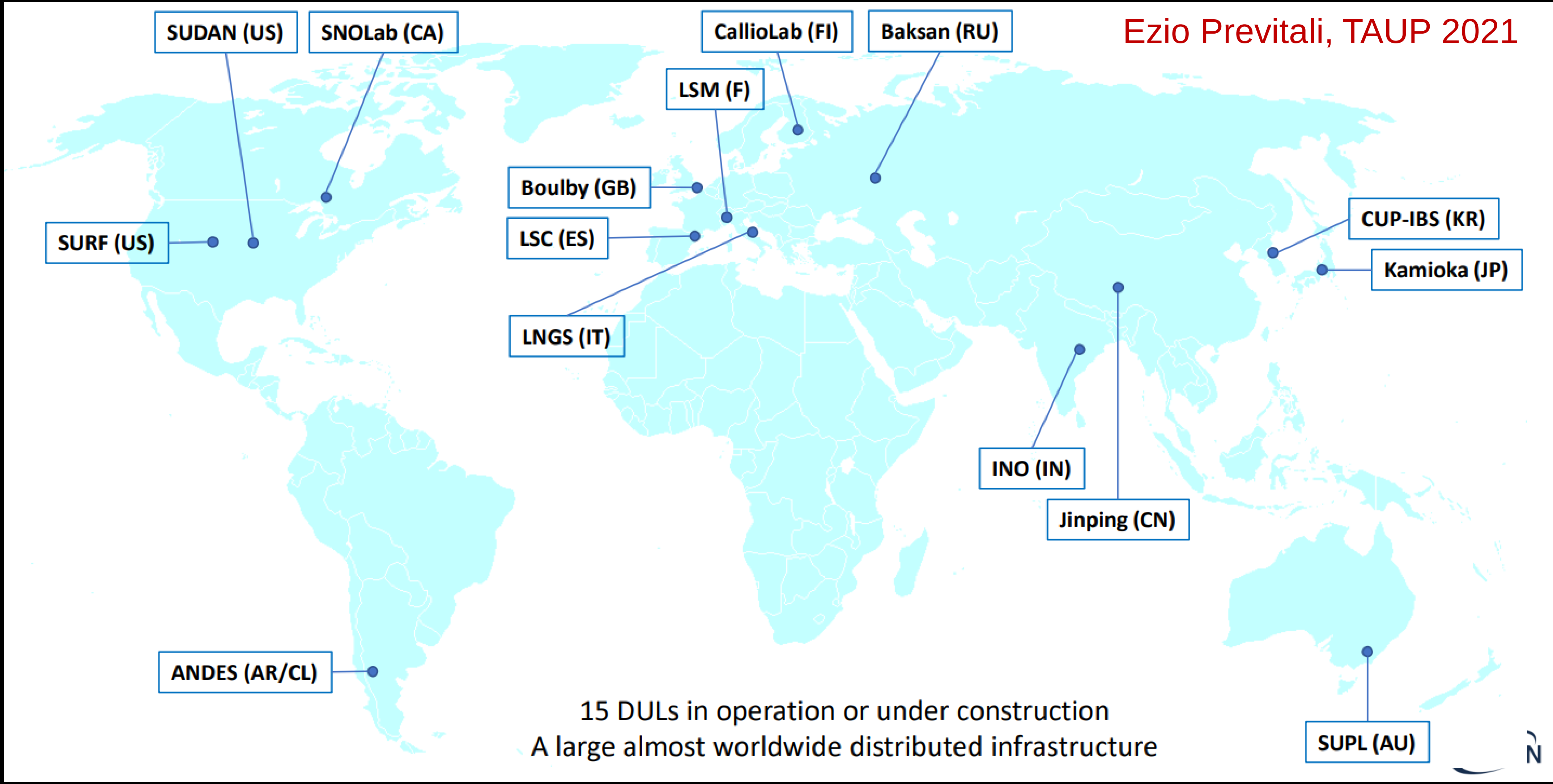
2104.07634, APPEC report on dark matter direct detection

Name of the game: background

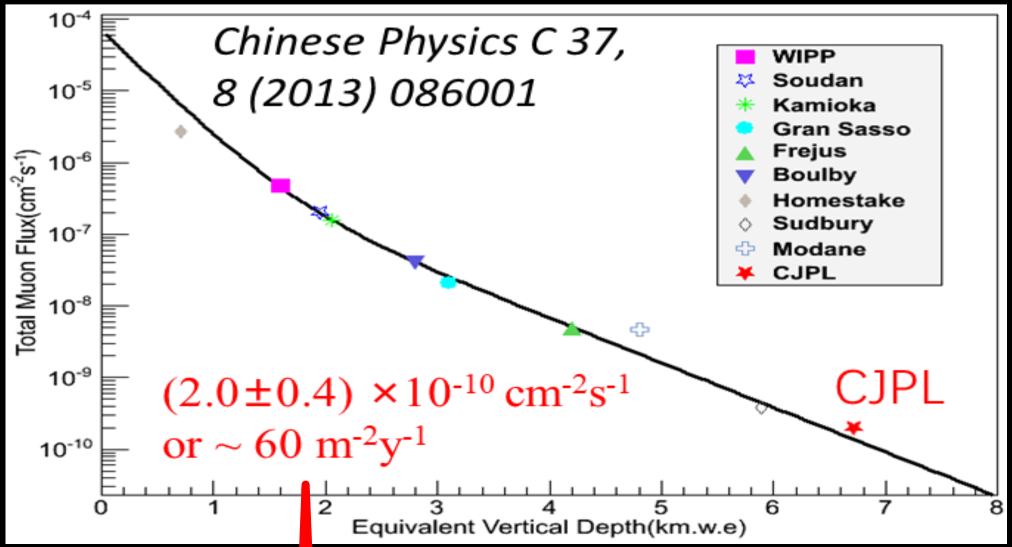
- <1 nucleus in our body is hit per year!
- But our body is hit 10^8/day by environmental background radiation!
- Hide detector in deep underground lab, and put massive shield

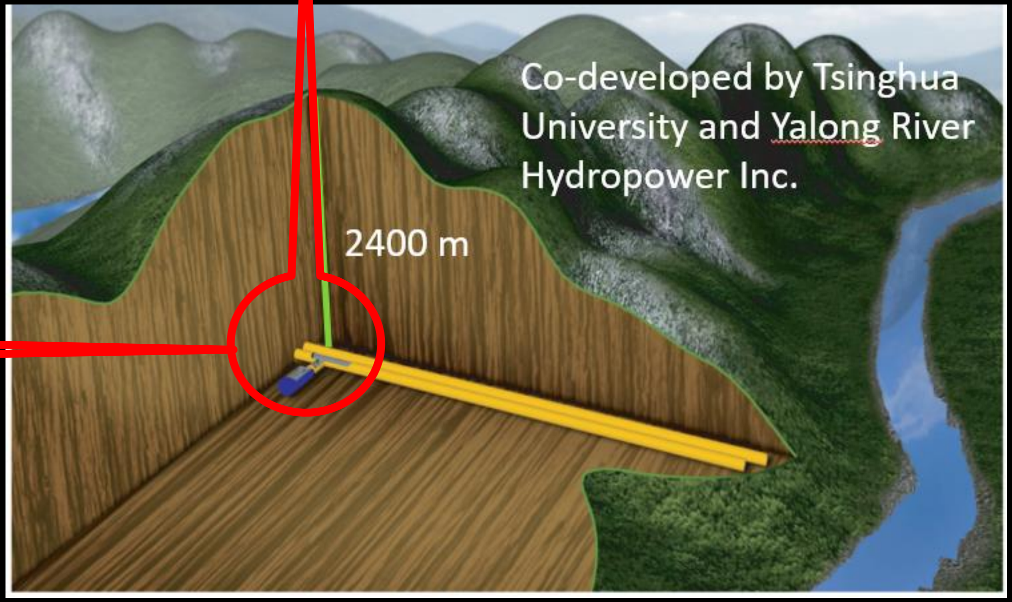


Underground labs



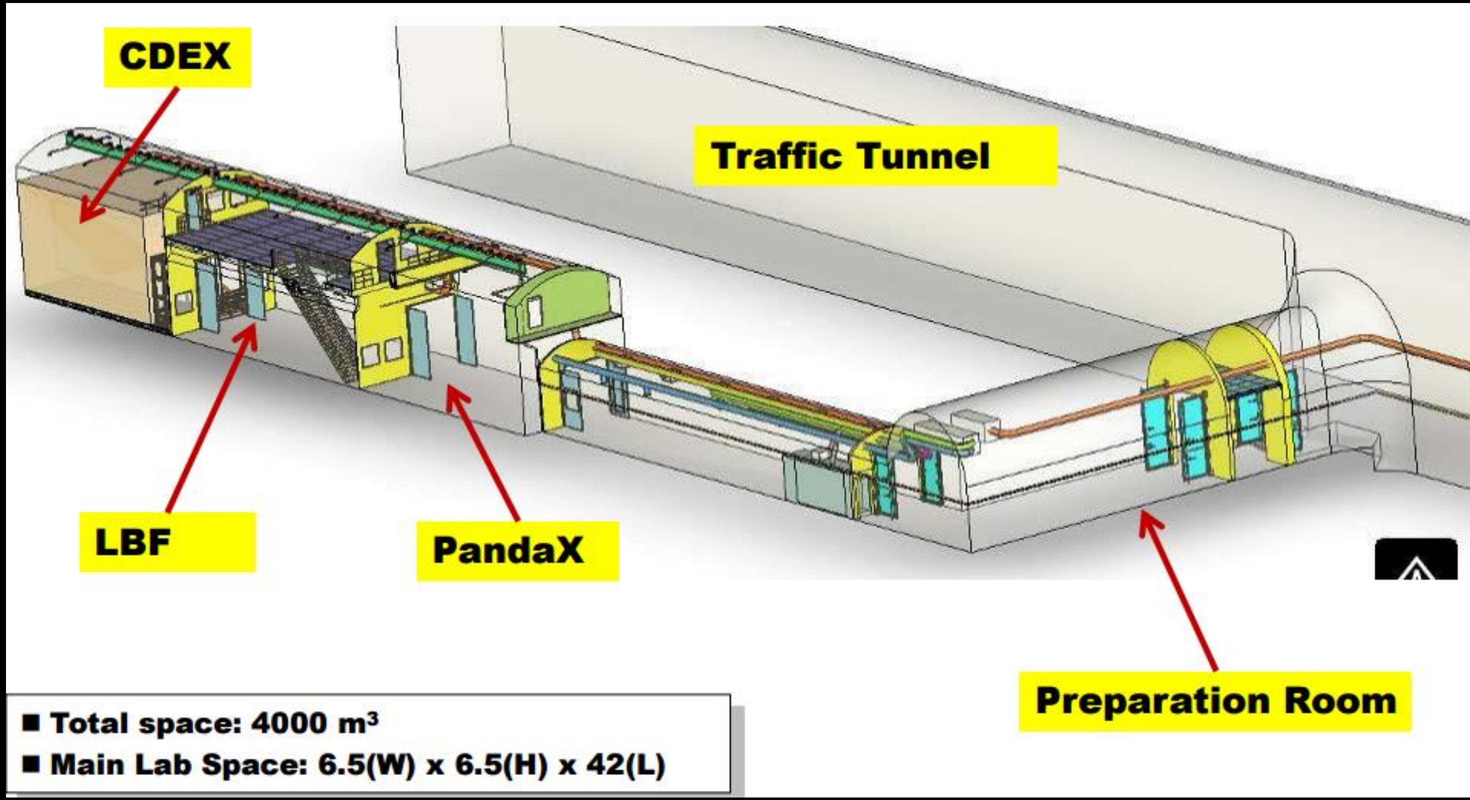
China Jinping underground Laboratory





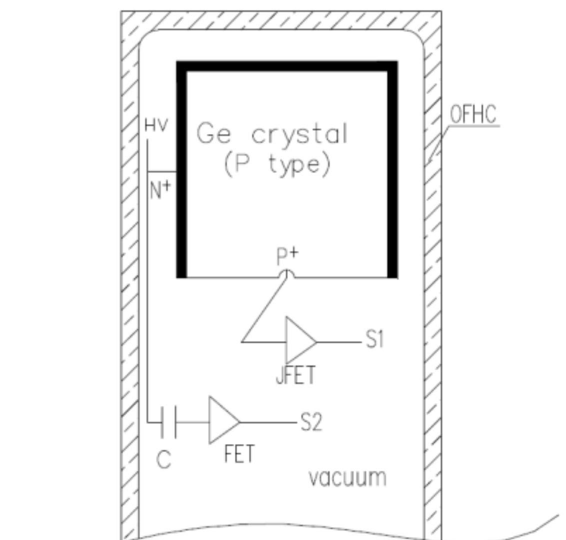
CJPL-I


CJPL


CDEX
Traffic Tunnel
LBF
PandaX
Preparation Room
■ Total space: 4000 m³
■ Main Lab Space: 6.5(W) x 6.5(H) x 42(L)

CDEX Collaboration

- China Dark Matter EXperiment
  - ✓ Formed in 2009, 11 institutions and ~70 people;
  - ✓ Searching for light DM by P-type Point-Contact Germanium detectors



CPC 37, 126002 (2013)

Particle and Astrophysical Xenon observatory

Collaboration formed

2009.3

2012.7

PandaX-I apparatus moved to Jinping

PandaX-I started

2014.3

2014.5-10

PandaX-I, 120 kg operation

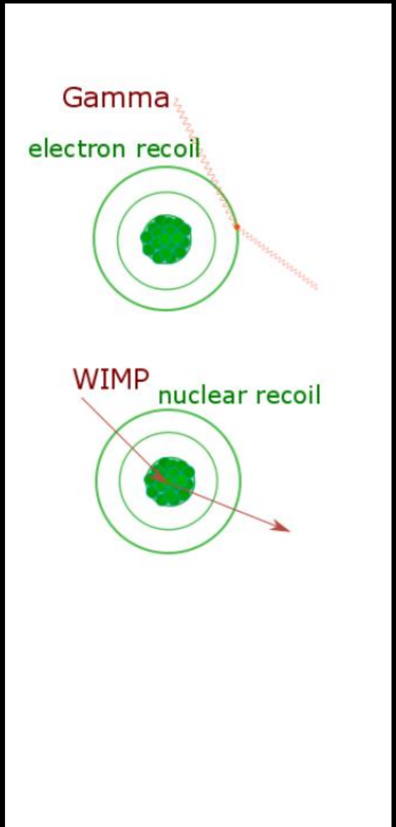
PandaX-II, 580 kg operation

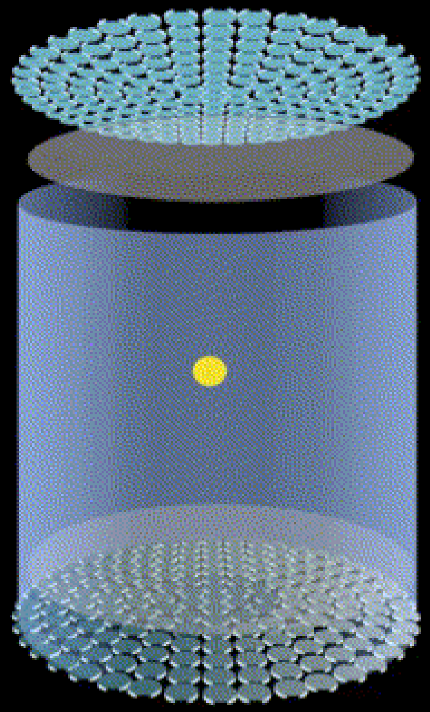
2016.7-2019.7

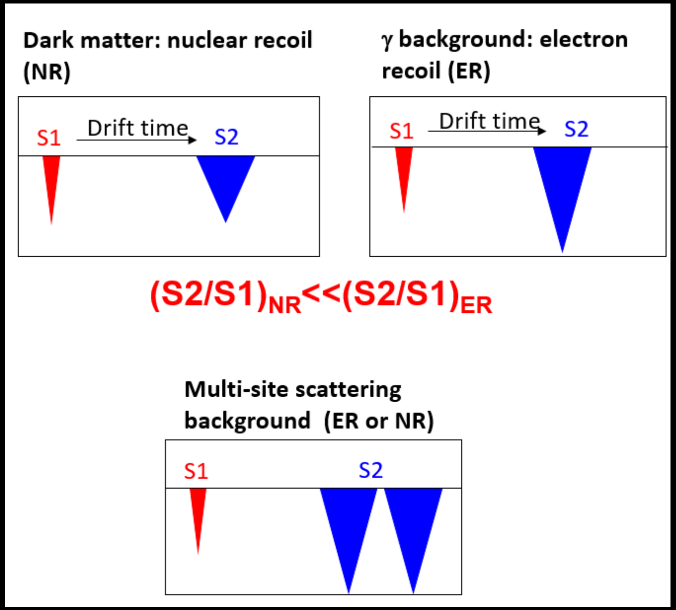
2019.8-

PandaX-4T moved to CJPL-II

Dual phase xenon TPC







Detector capability:

- Large monolithic target
- 3D reconstruction and fiducialization
- Good ER/NR rejection
- Calorimeter capable of seeing a couple of photons/electrons

CJPL-II Project (2014-)

PHYSICS

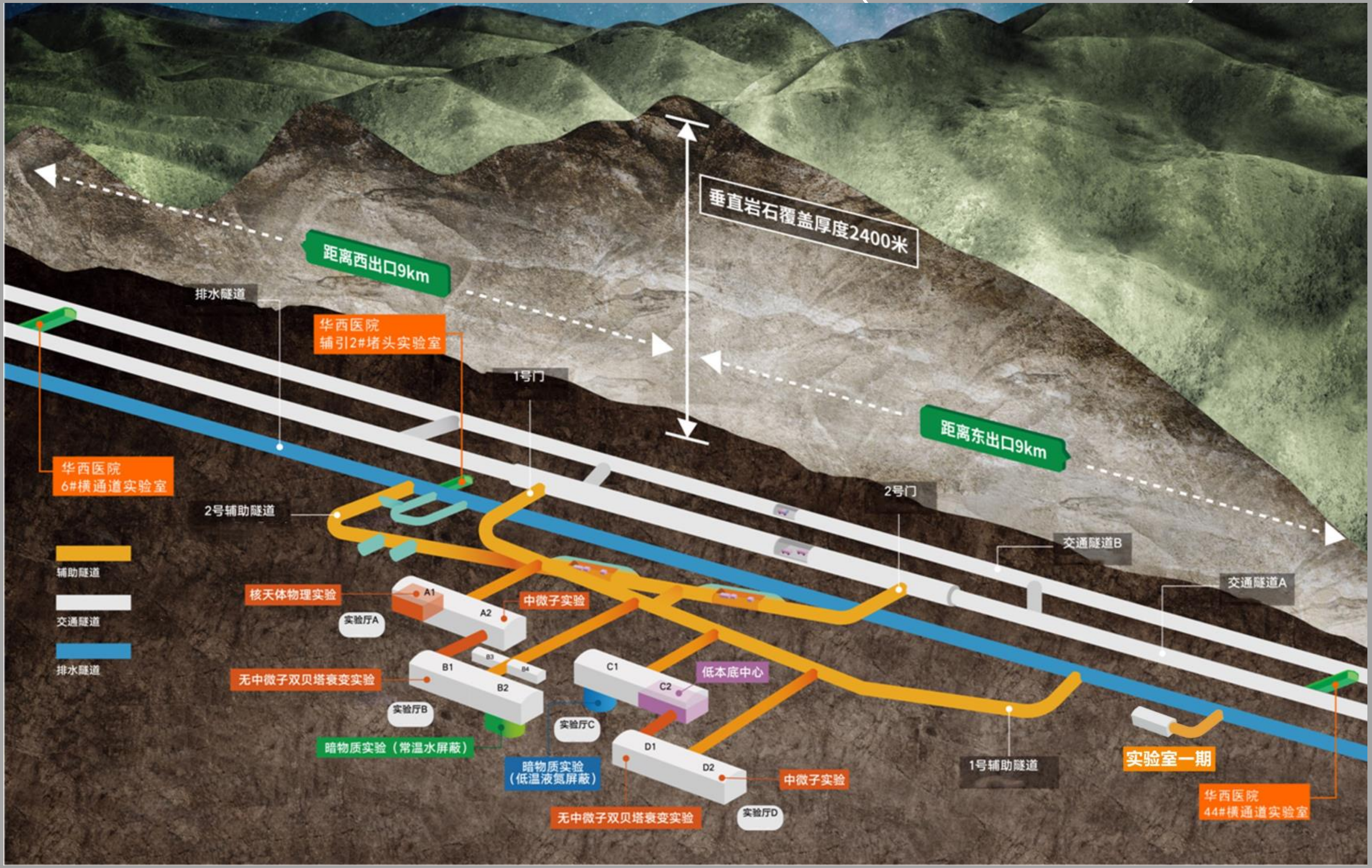
China supersizes its underground physics lab

Planned expansion could pave way for "ultimate dark matter experiment"

The world's deepest physics laboratory is about to become one of its largest. Early next year, workers will start carving four cavernous experiment halls along a tunnel through Jinping Mountain in China's Sichuan province. Once the science at the China Jinping Underground Laboratory (CJPL) is scaled up as well, "it will be a milestone for Chinese physics," says Nigel Smith, director of the underground SNOLAB in Sudbury, Canada.

Science, Nov. 30, 2014

300k m^3 with 8 main halls of 14x14x65 m (4000m^3 of CJPL-I).



CJPL-II Project (2014-)

DURF @ CJPL-II

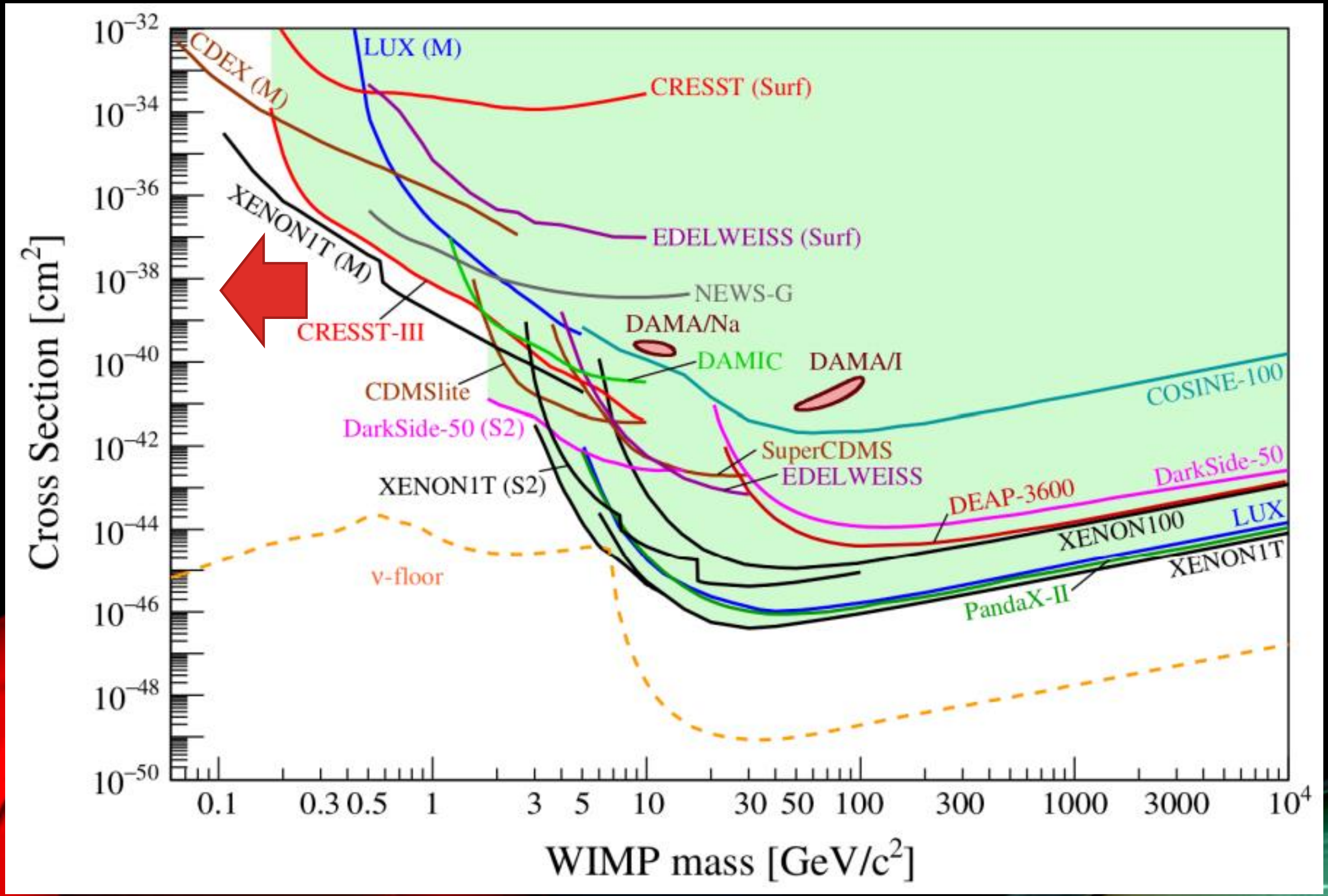
- December 2016, the National Development and Reform Commission of China issued the National Major Science and Technology Infrastructure Construction Projects for the 13th Five-year Plan

- **DURF @ CJPL-II**: Deep Underground and ultra-low Radiation background Facility for frontier physics experiments

- July 2019, DURF project commencement

- Second half, 2022, electromechanical equipment installation

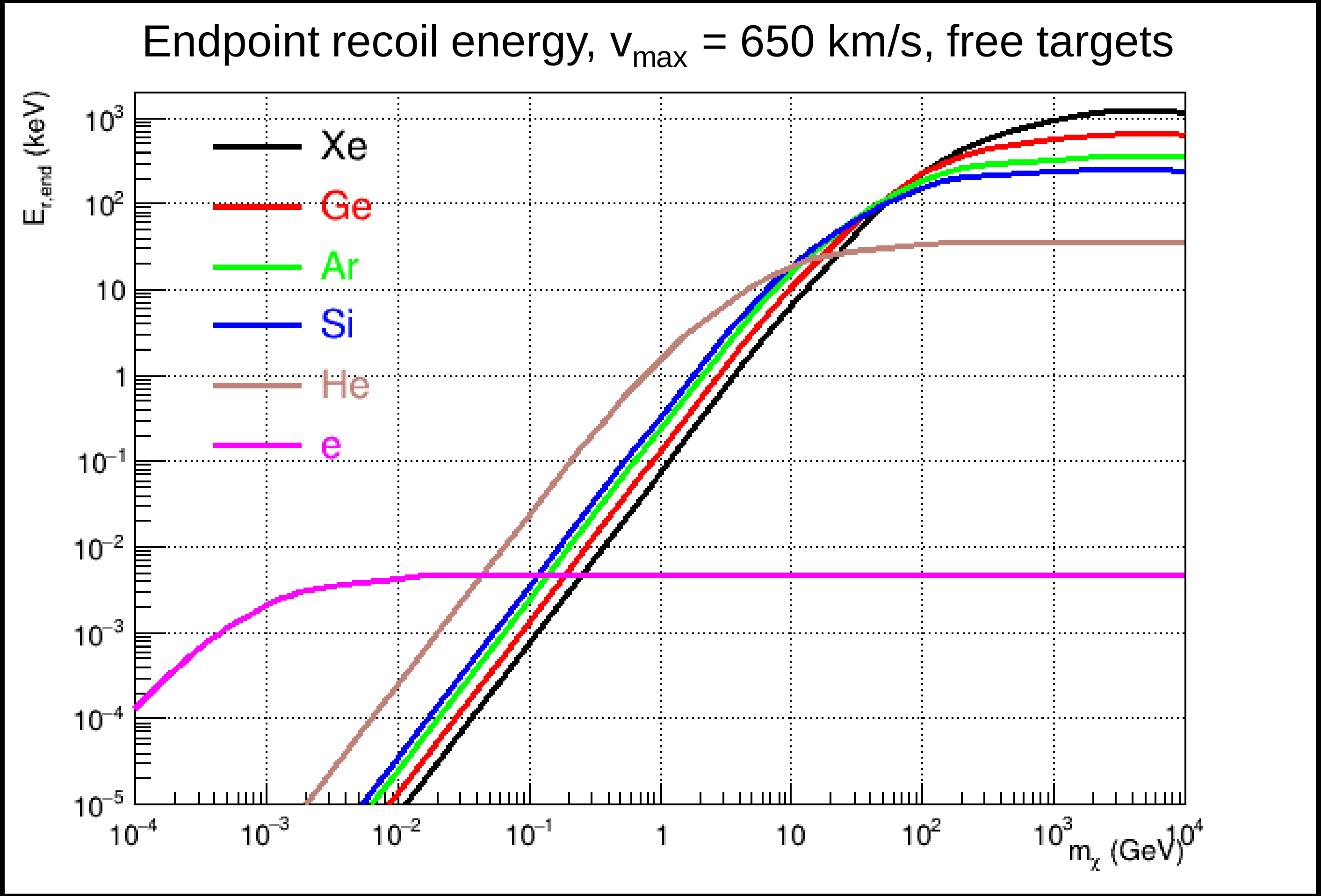
- **Early 2025, formal operation of DURF**



Light DM searches

Sub-GeV or so

Probing low mass DM



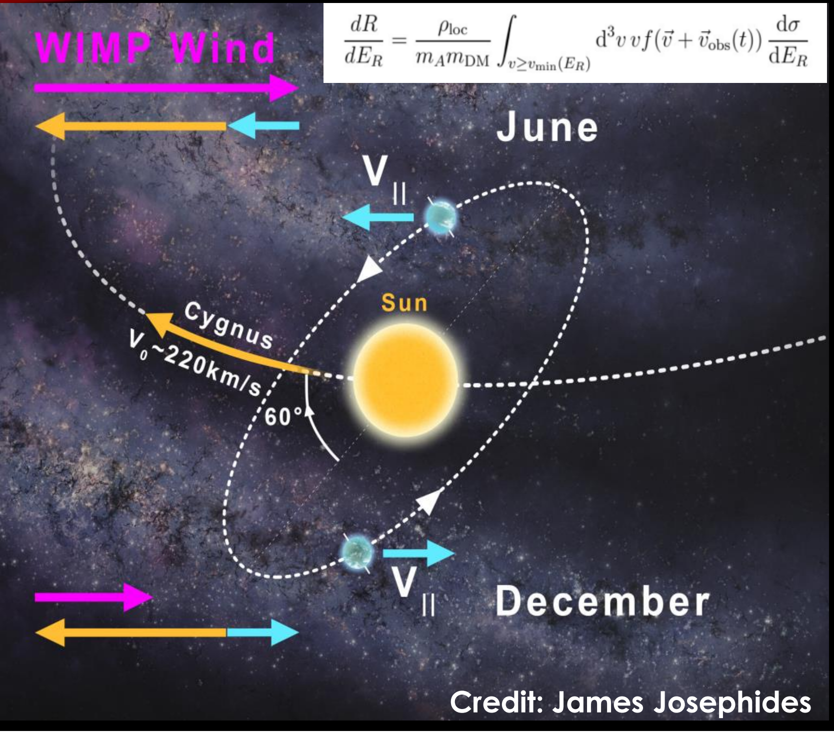
Strategies

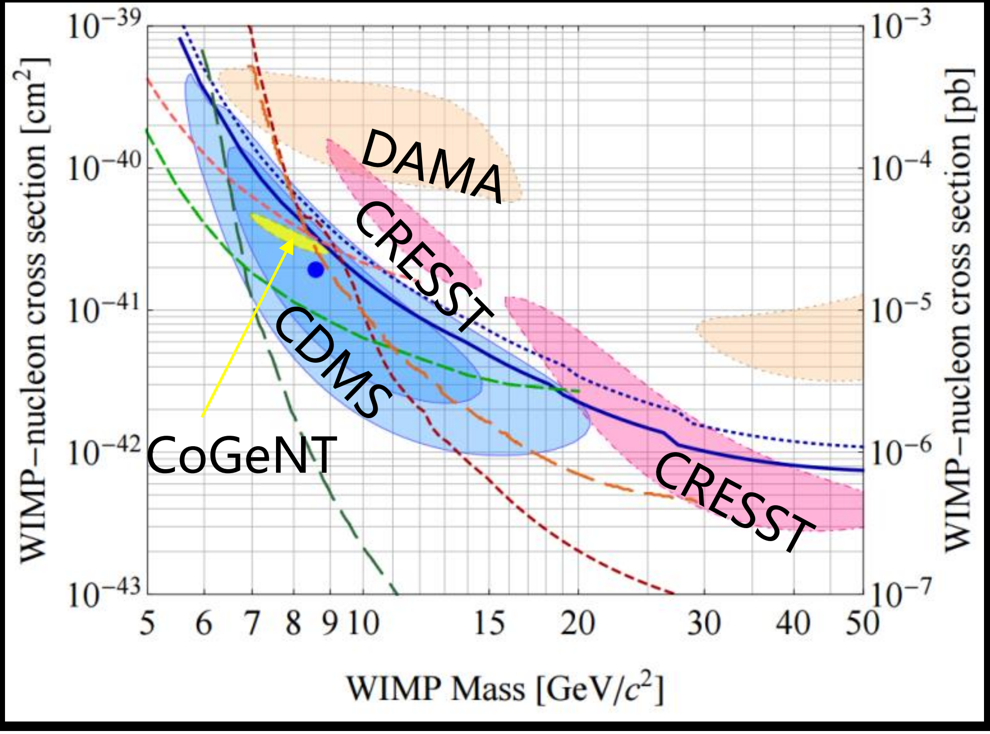
1. Lowering energy threshold

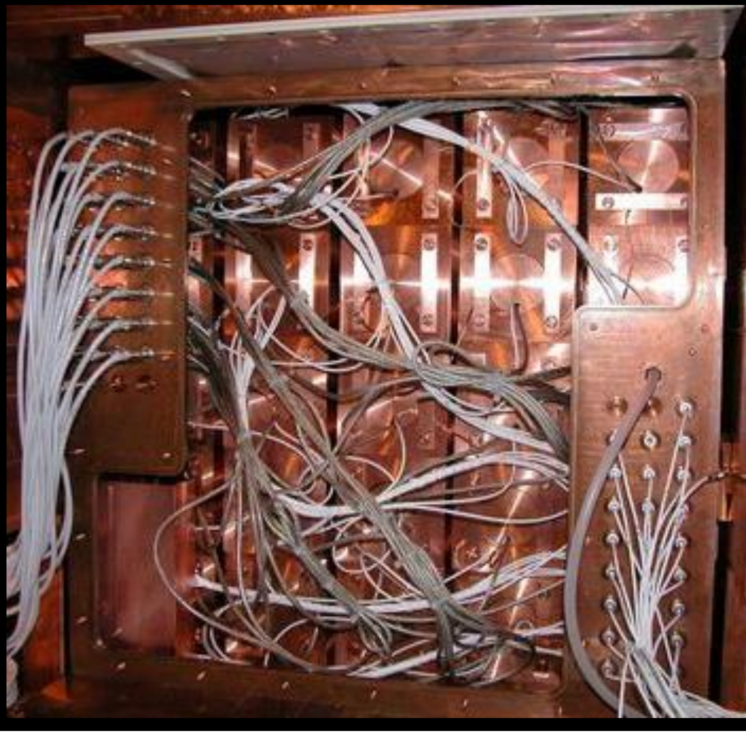
2. Going after electrons (via atomic effects)

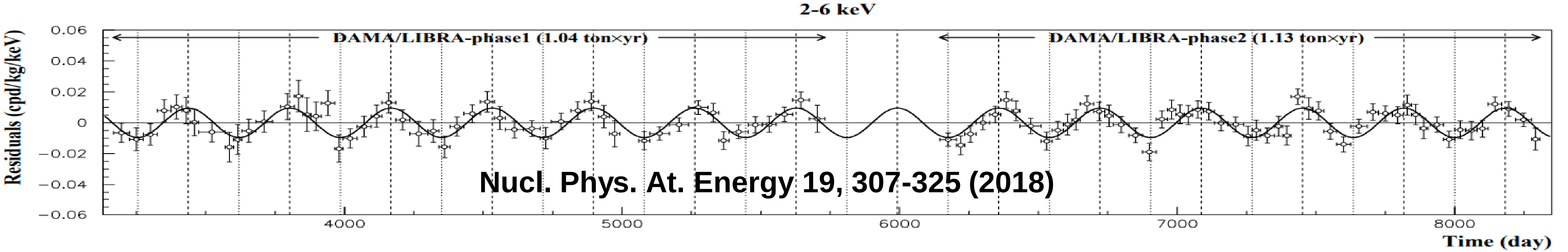
3. Boosting

Light DM Anomaly





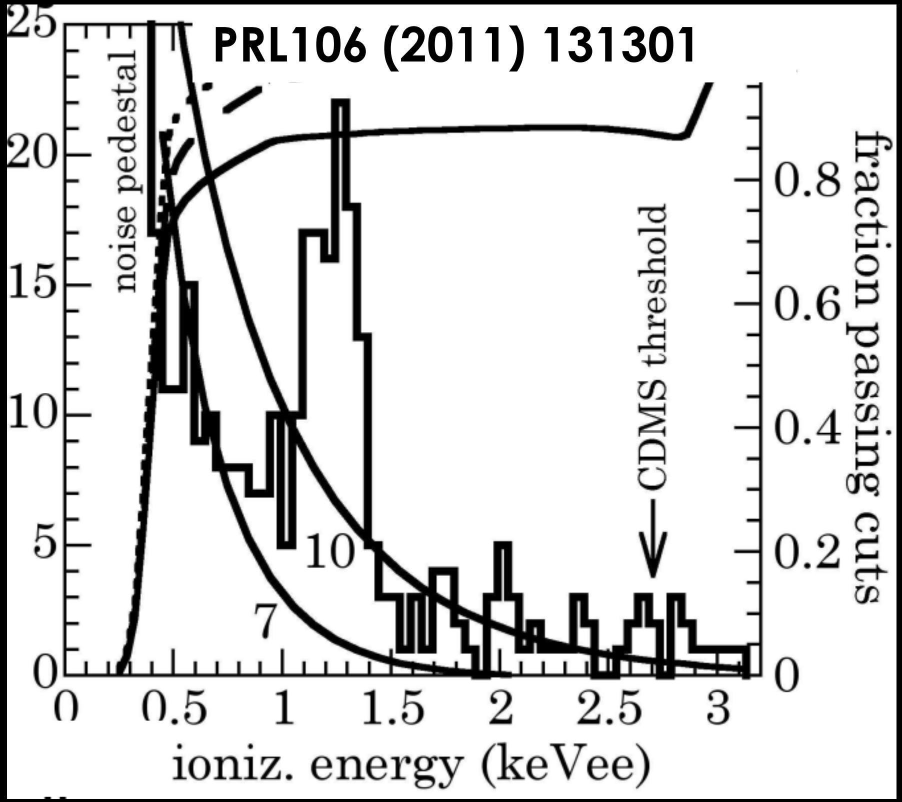


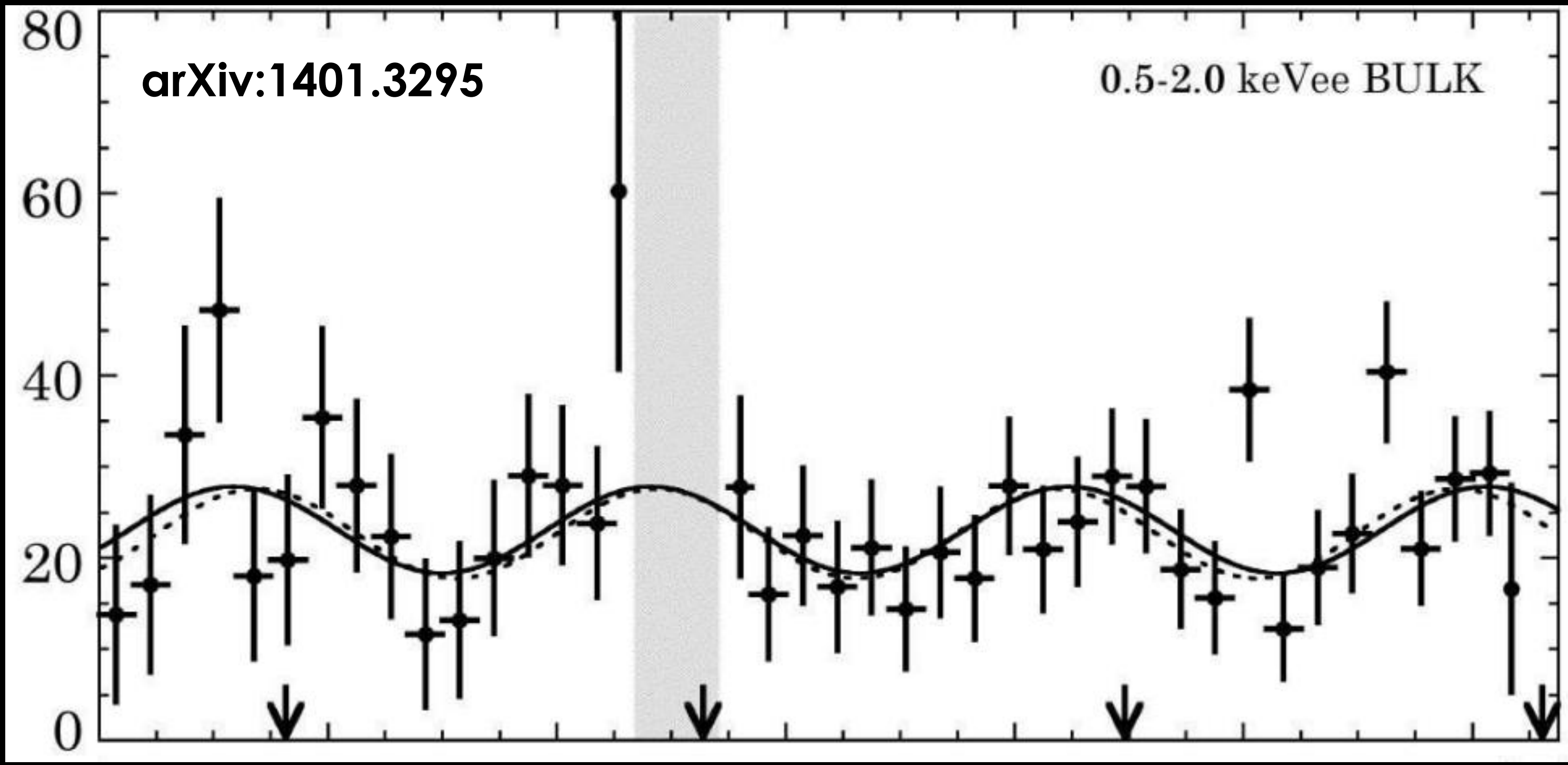


Nucl. Phys. At. Energy 19, 307-325 (2018)

CoGeNT Anomaly

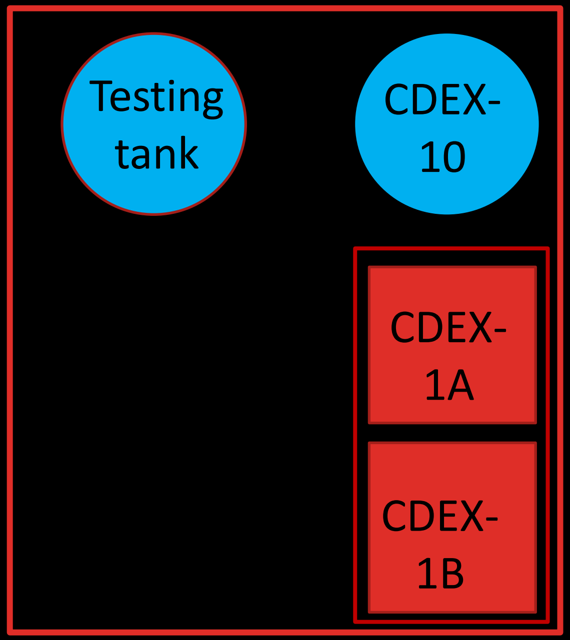
- CoGeNT: P-type point contact Ge detector

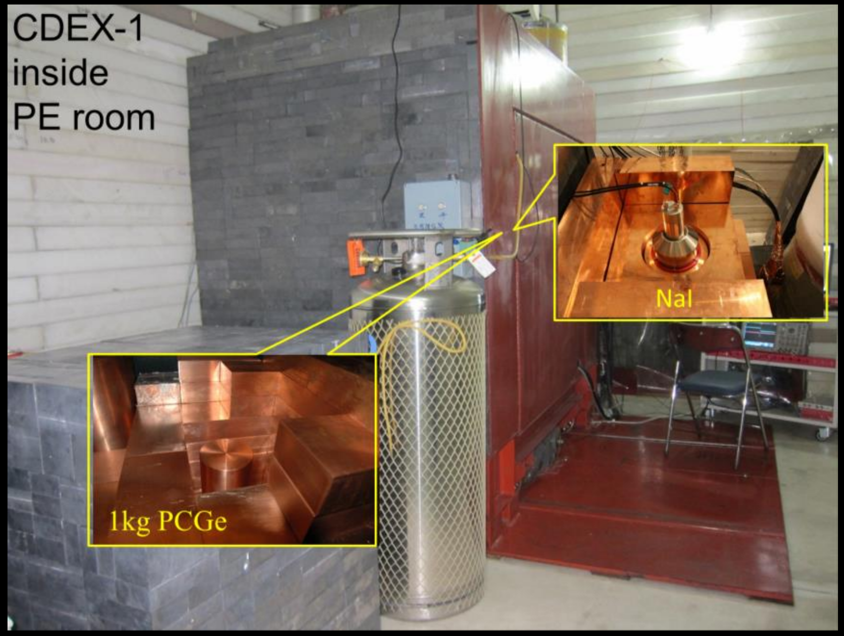


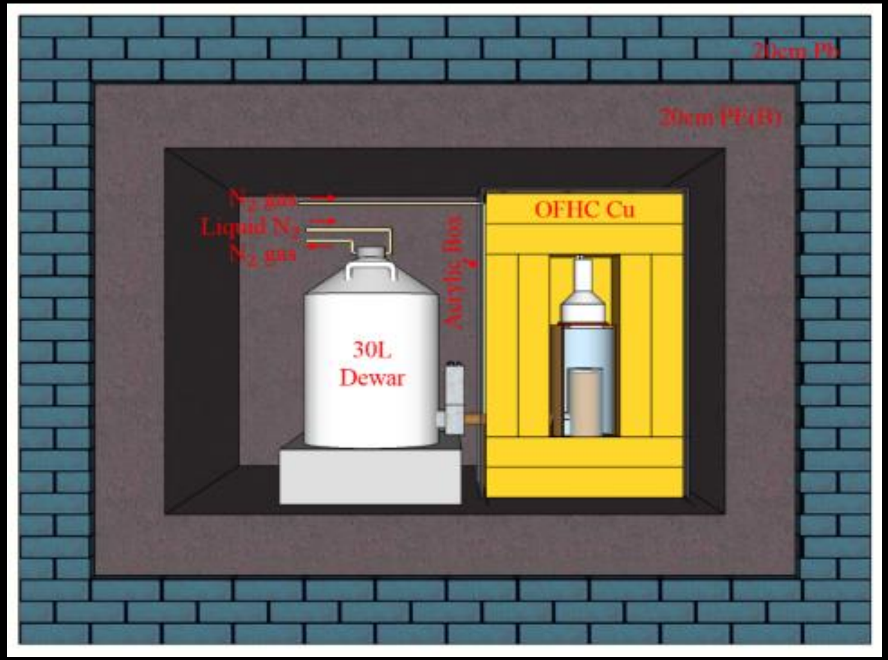


CDEX-1

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



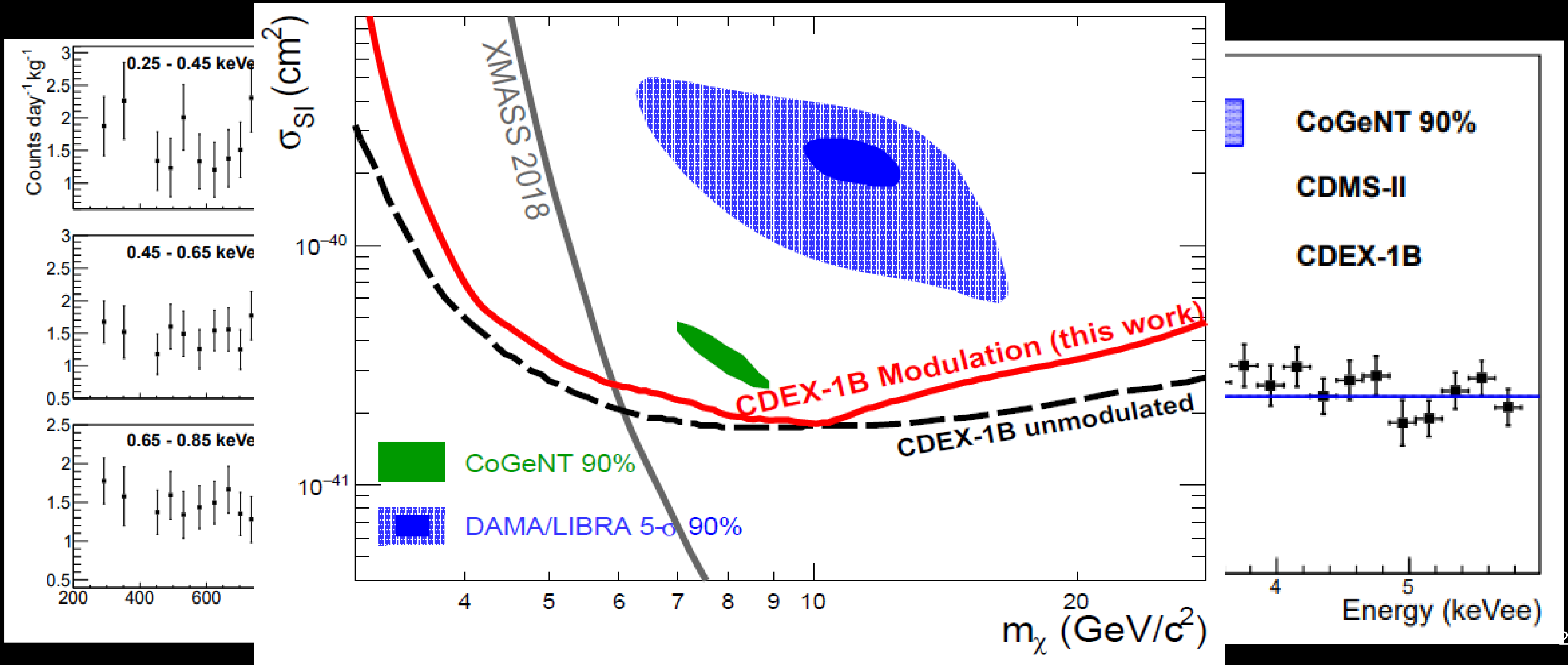




CDEX-1A&B:

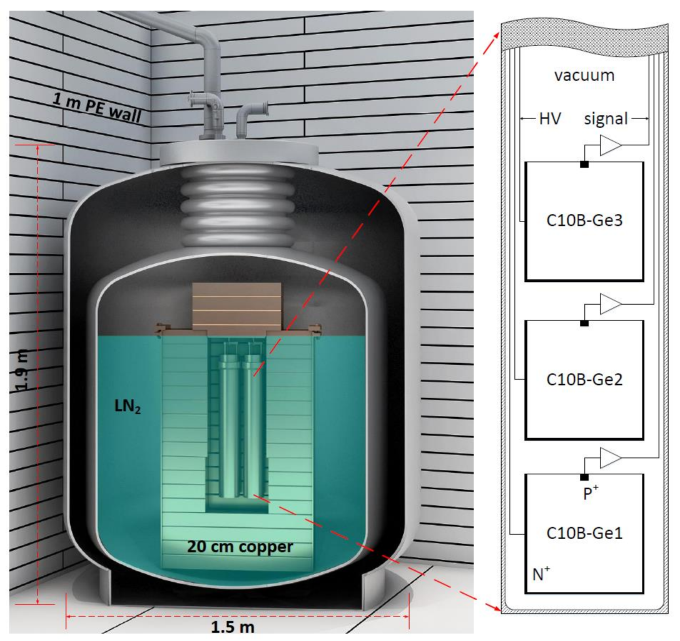
CDEX-1B results

- Annual Modulation analysis: more than 4 years of data, excluding CoGeNT and DAMA/LIBRA interpretation

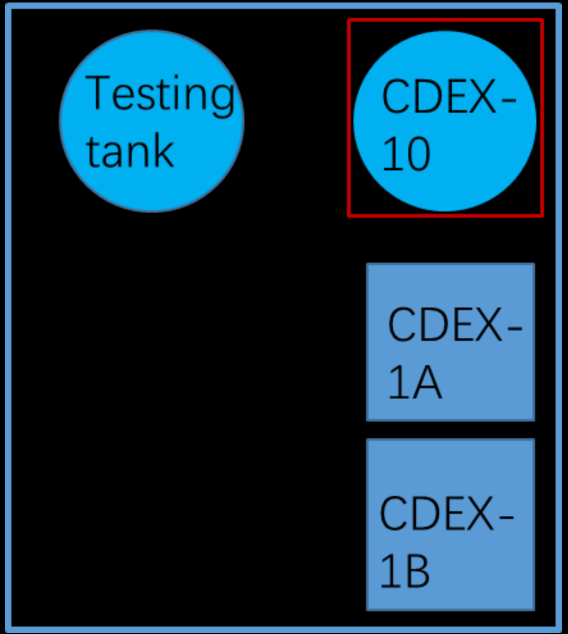


CDEX-10 Status

- 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;

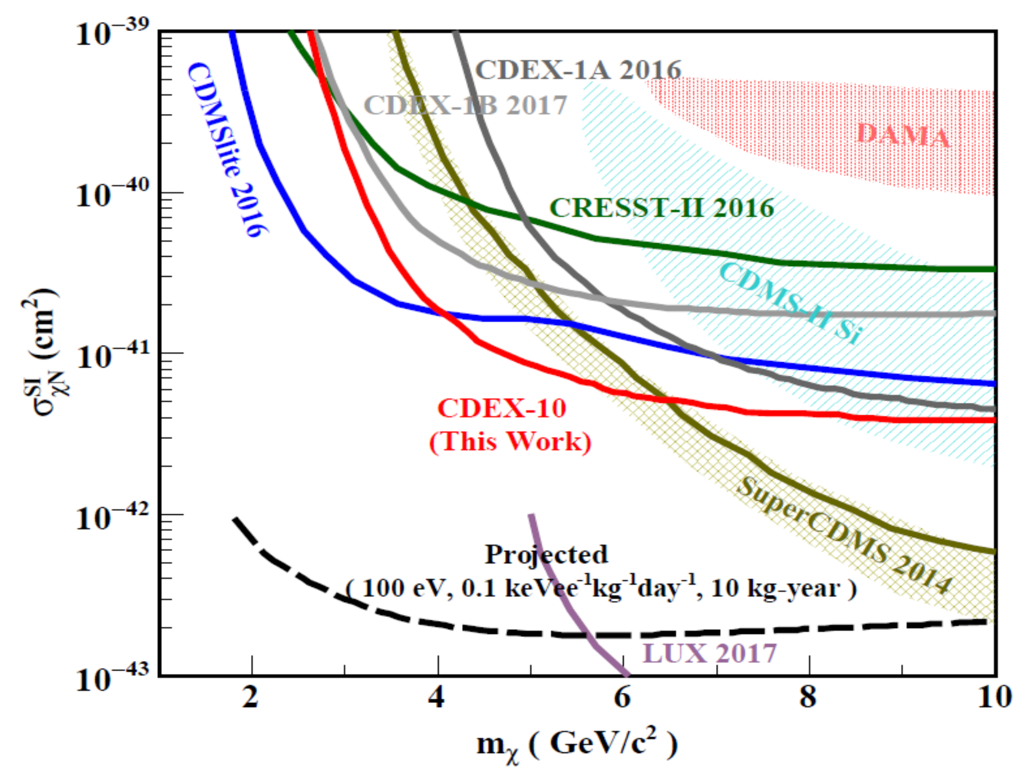


CDEX-10: ~10kg PPC Ge array

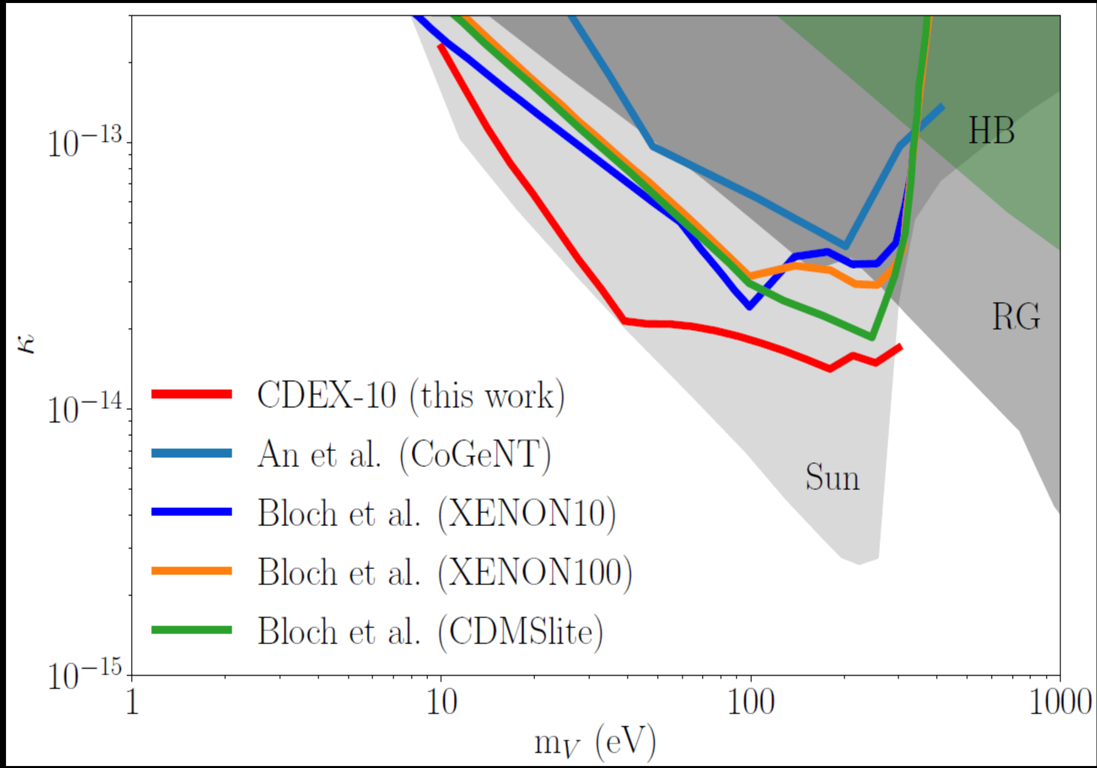


CDEX-10 results

- Threshold 160 eV
- Spin-independent results: competitive in 4-5 GeV/c^2
- Solar dark photon limit: improving direct detection results in 10-300 eV/c^2



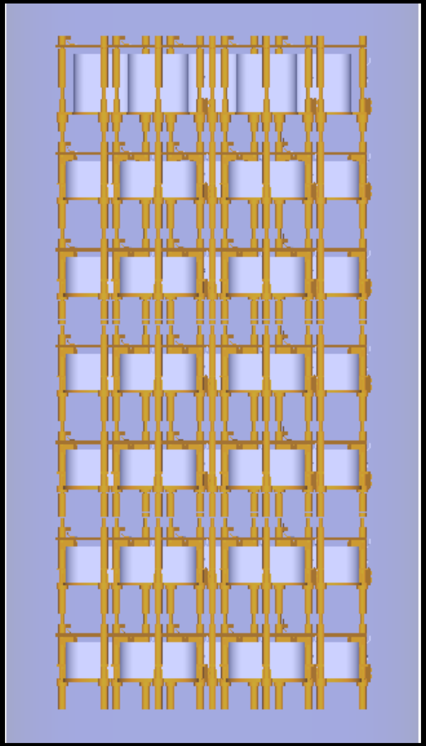
PRL 120, 241301 (2018)

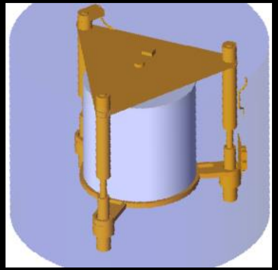


PRL 124, 111301 (2020)

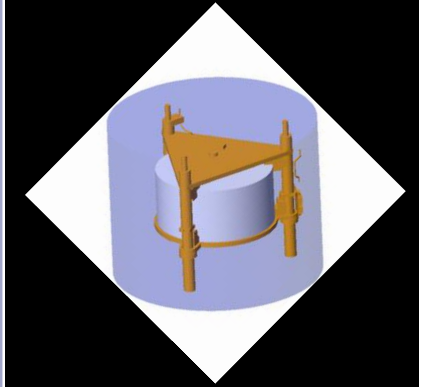
CDEX-50 Plan

- CDEX-50 for DM search
  - Natural Ge
  - Immersed in LN
  - PPC+BEGe detectors
  - 50kg-y, 0.01cpkkd BKG, expected sensitivity ~10^{-44}cm^2

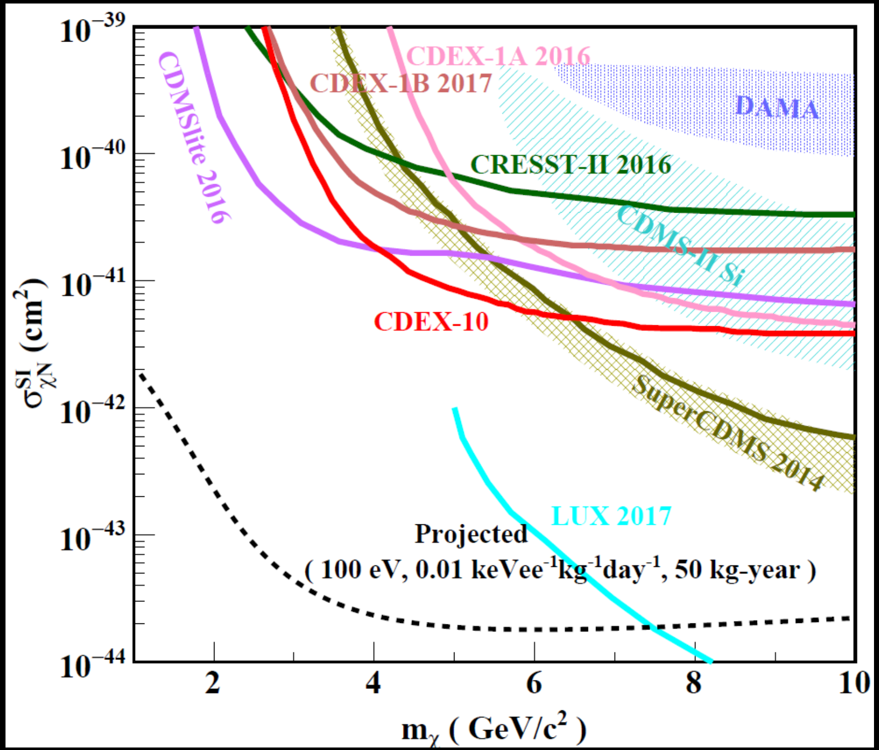


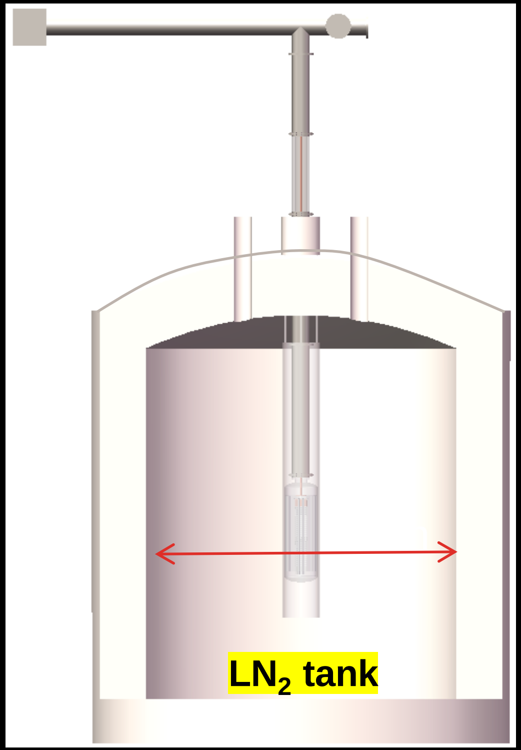


PPC

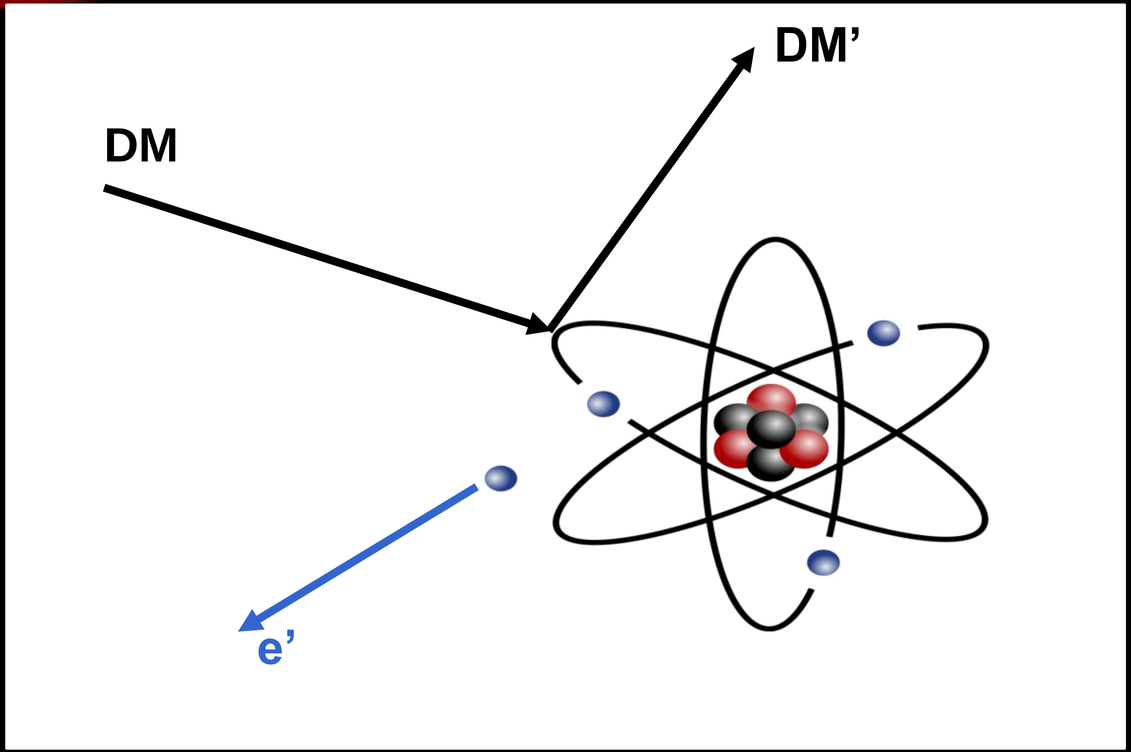


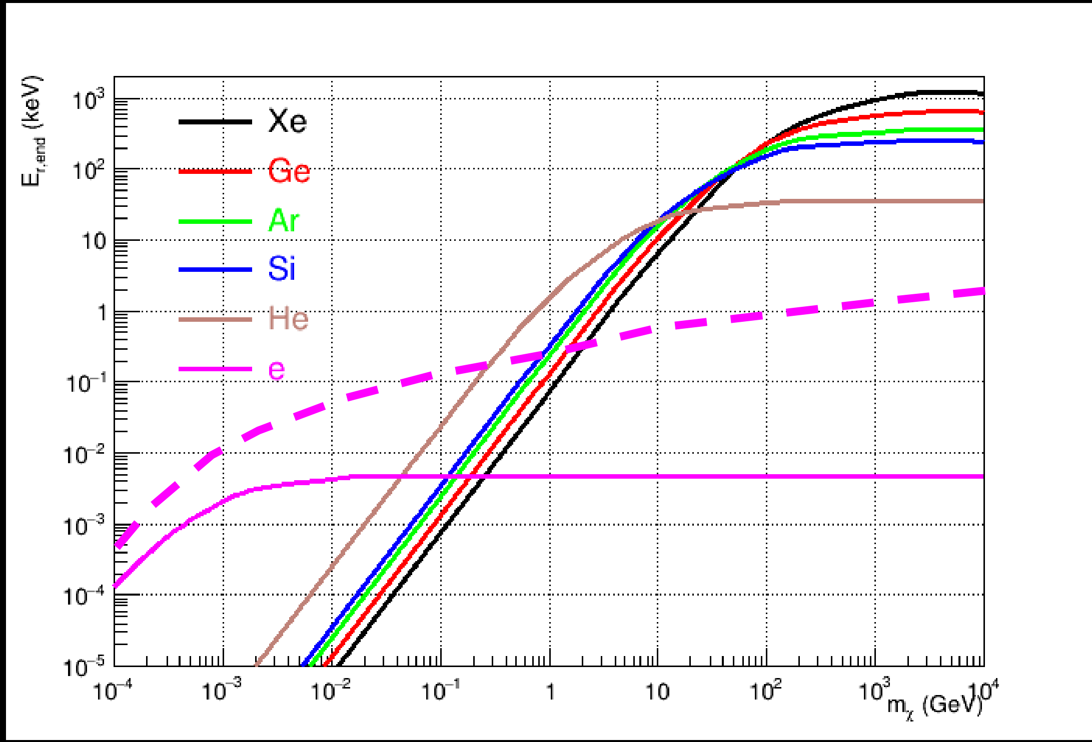
BEGe





Going after electrons

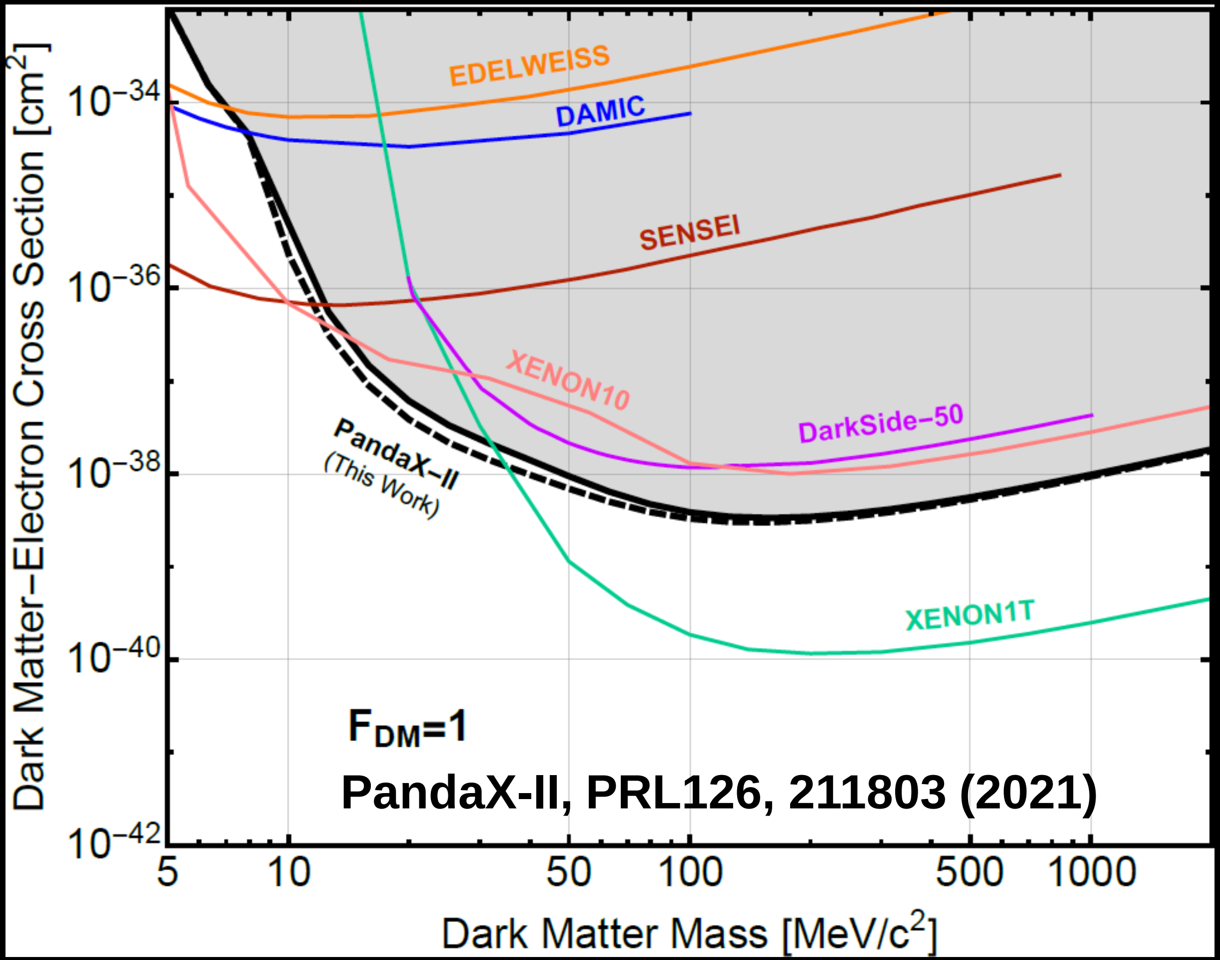




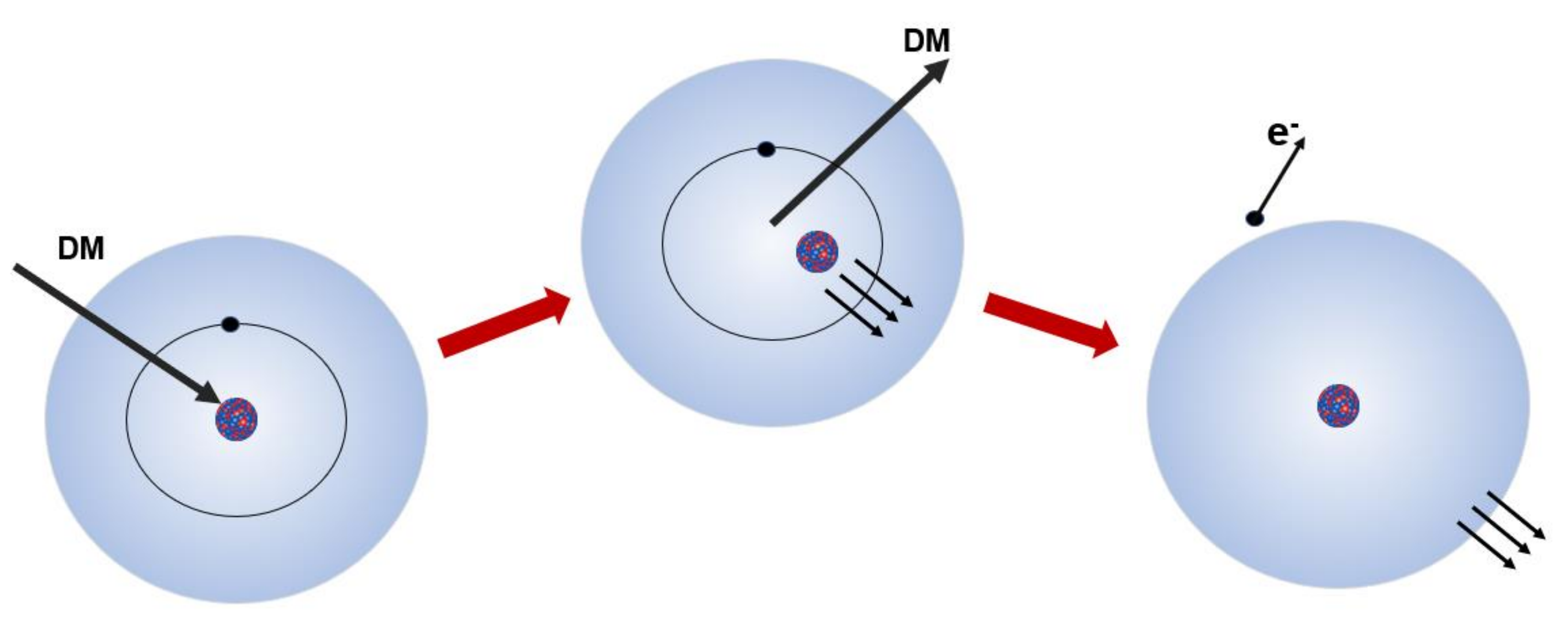
- DM could certainly interact directly with electrons
- Bound electrons in the atomic, leading to sizable energy deposition from electron ionization. Essig, Mardon, Volansky, PRD 85, 076007 (2012)

Latest search from PandaX

- Ionization-only signals (S2) in LXe TPC can see single e^- !
- Large target mass
- Lowered threshold to 80 eV
- Best constraint to DM-e interaction between 15-30 MeV/c^2

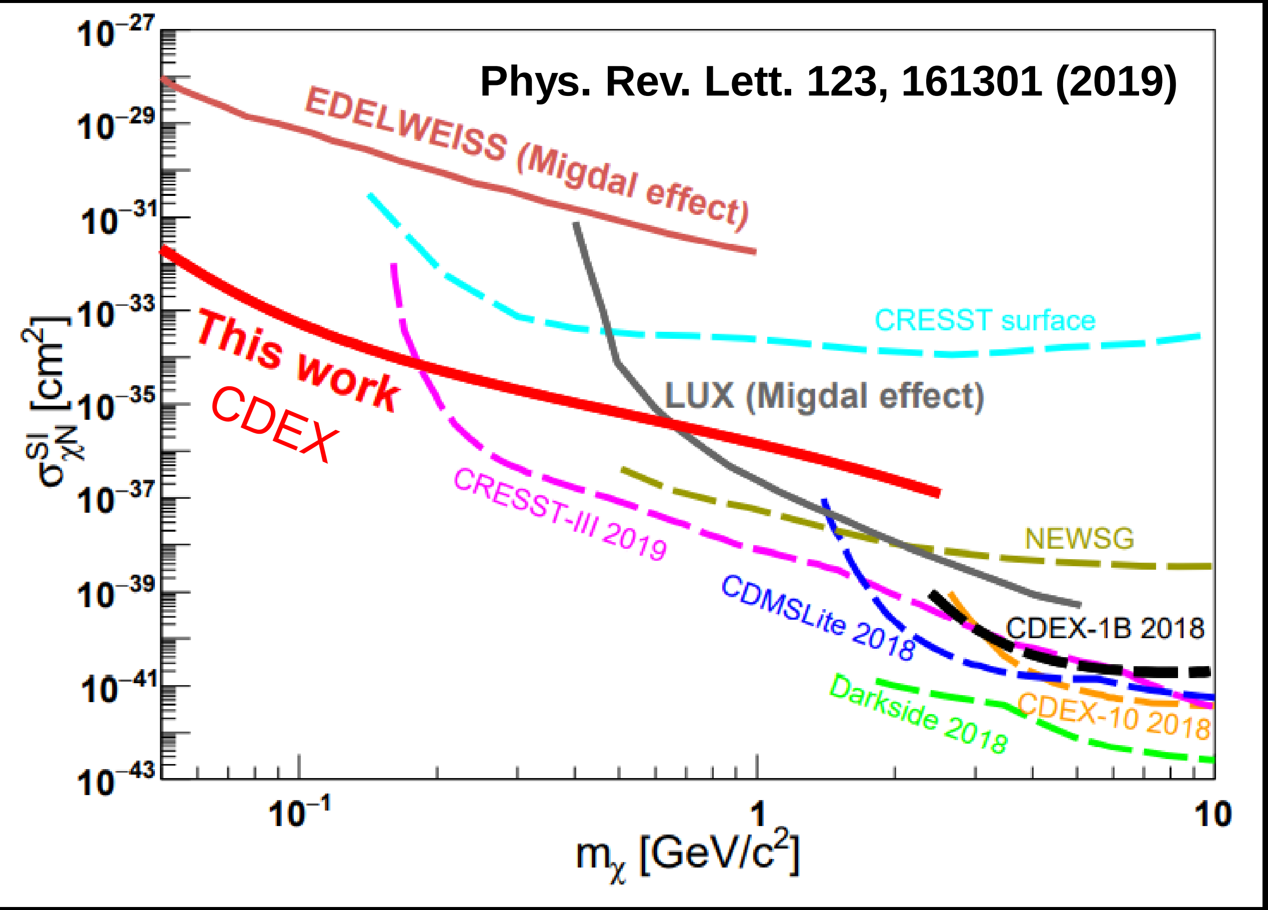


Migdal effects in DM-N scattering



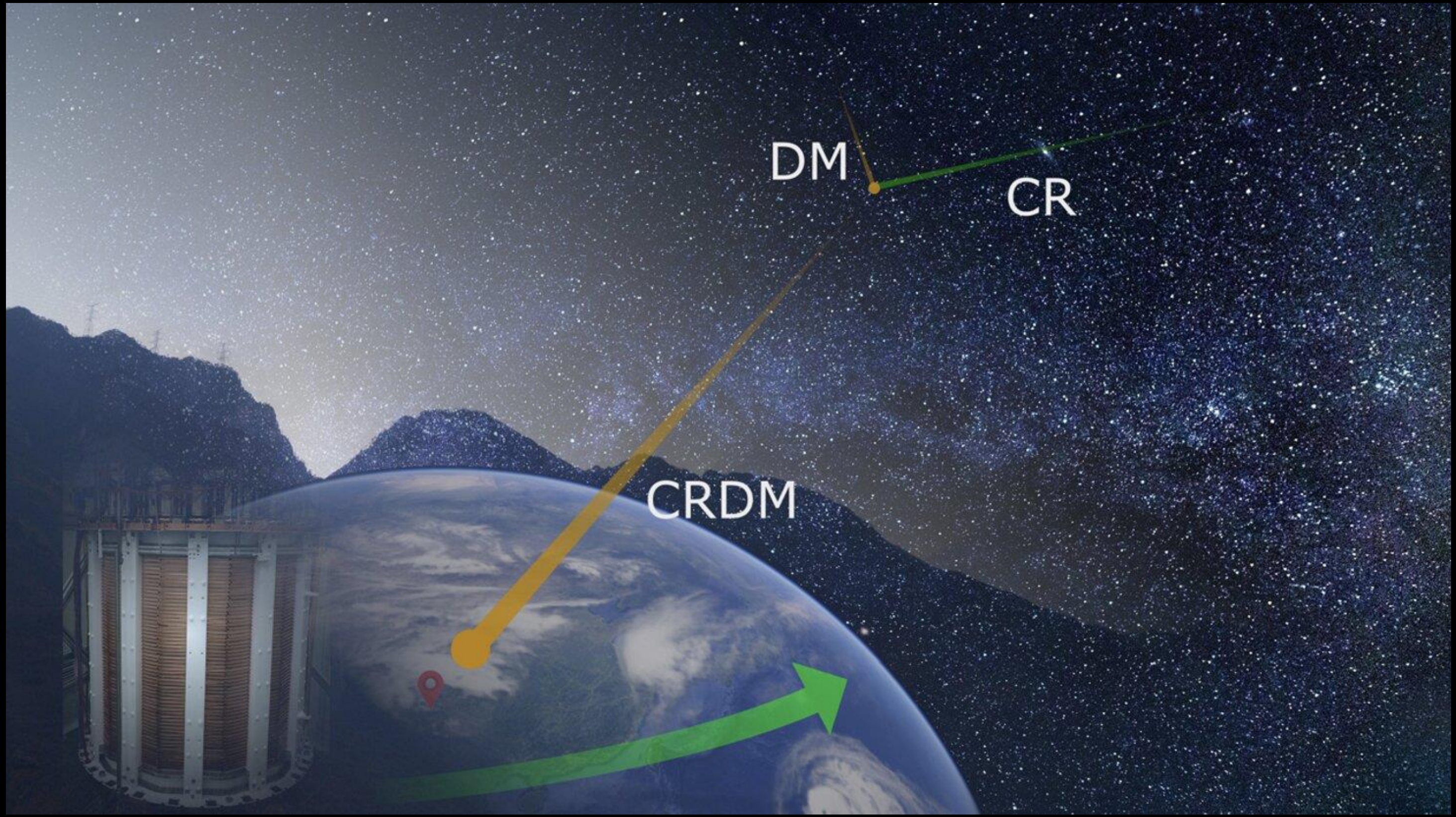
- Reformulated: Abe et al., JHEP 2018, 194 (2018); Dolan et al., PRL 121, 101801 (2018)
- Direct DM-e ionization and Midgal-induced ionization probability are closely related. Essig, Pradler, Sholapurkar, and Yu, PRL 124, 021801 (2020)

Low mass DM with Migdal



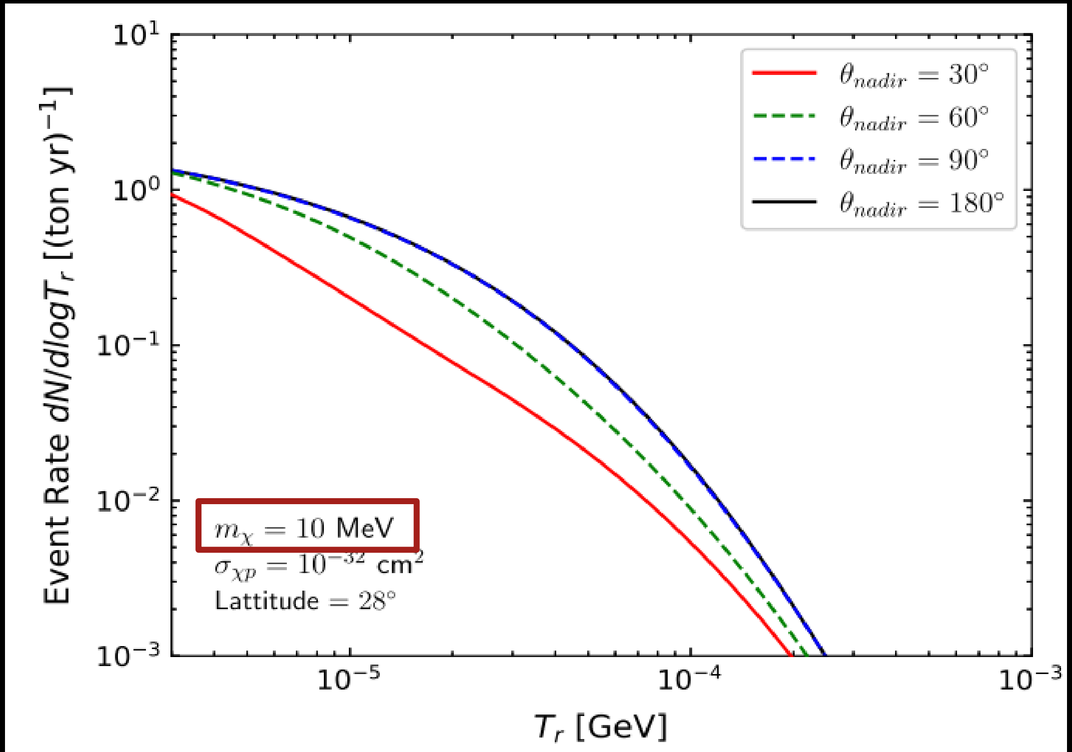
- Searches using expected signals from Migdal effect: XENON, LUX, EDELWEISS, CDEX
- Significant extension of DM-N interaction to the low mass region
- Number of experimental efforts to really see such an effect: Majewski, TAUP 2021; Nakamura et al., PTEP 1, 013C01 (2021); arXiv:2112.08514

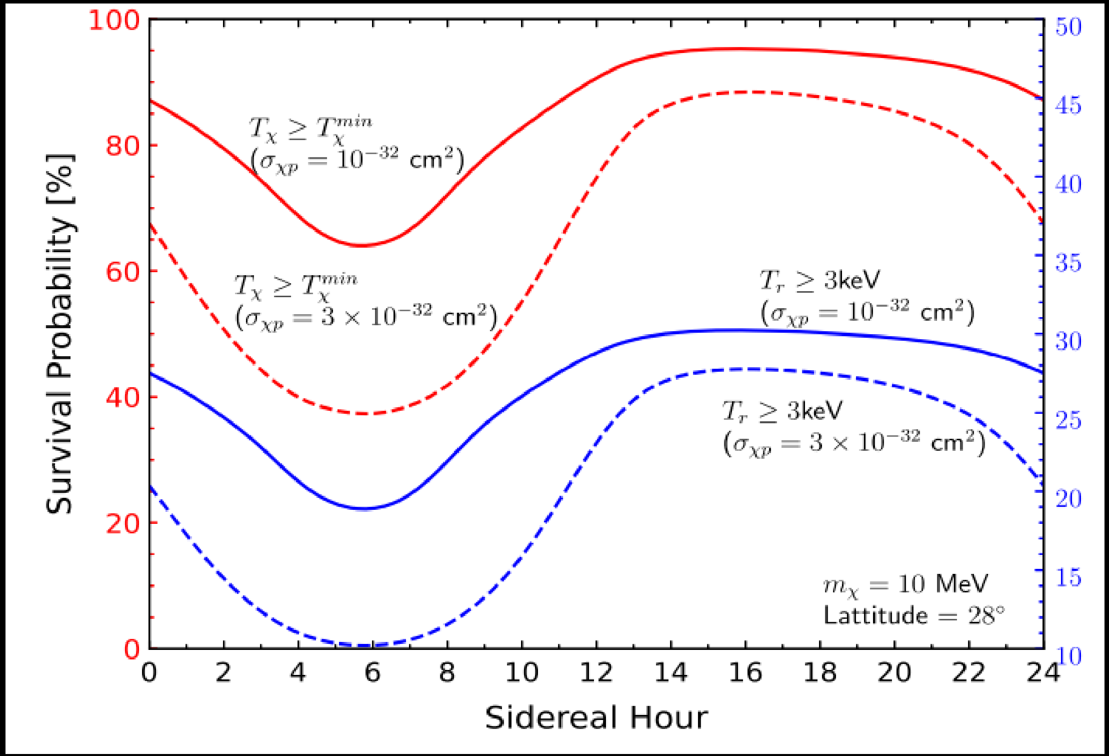
Cosmic Ray Boosted DM



- CR mostly p/He
- For finite DM-N scattering, DM acceleration by CR is inevitable!
- Bringmann and Pospelov, PRL **122**, 171801 (2019)

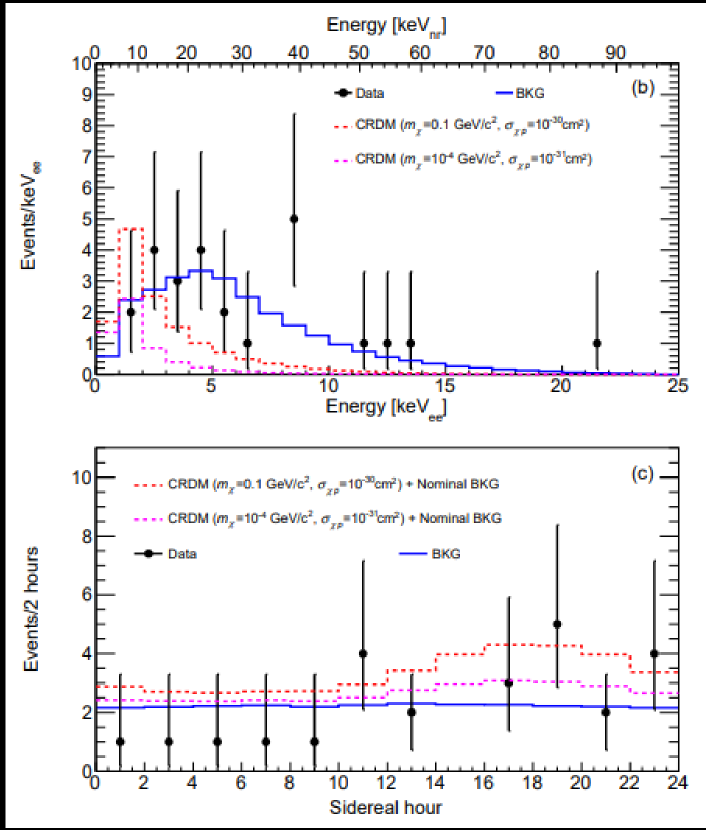
Diurnal effects

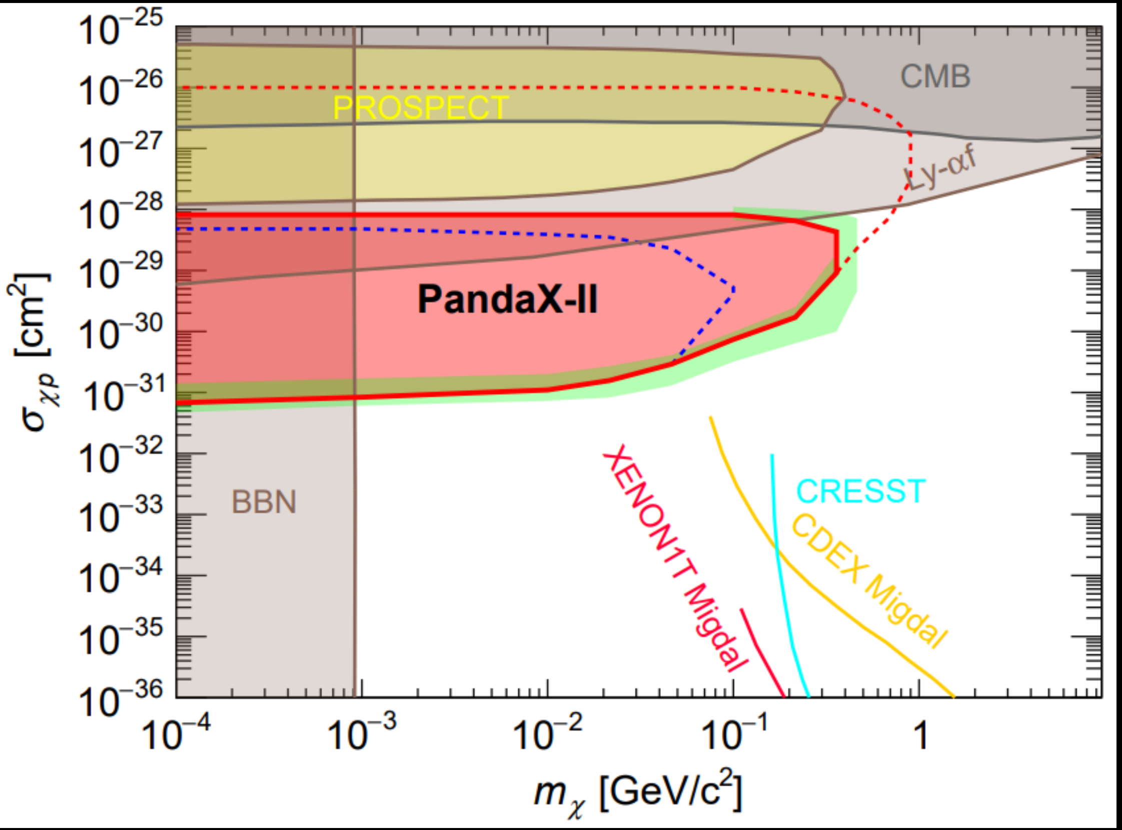




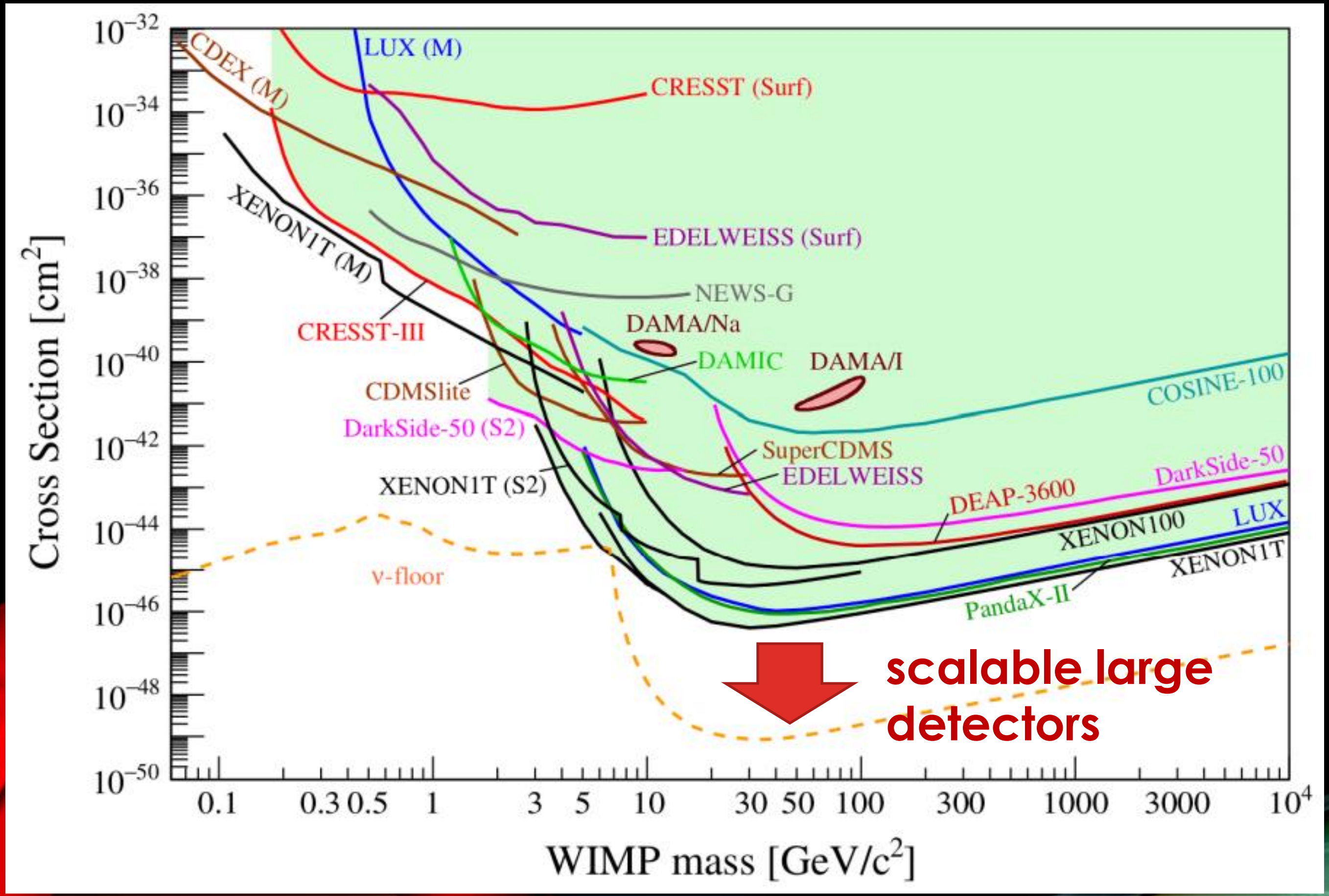
- A boost in recoil energy + a diurnal modulation in rate and E spectrum, Ge, Liu, Yuan, Zhou, PRL 126, 091804 (2021)

Search for diurnal modulation in PandaX





- First diurnal search carried by PROSPECT, PRD 104, 012009 (2021)
- PandaX: PRL 128, 171801 (2022)
- Similar search by CDEX, arXiv:2201.01704



Heavy DM searches

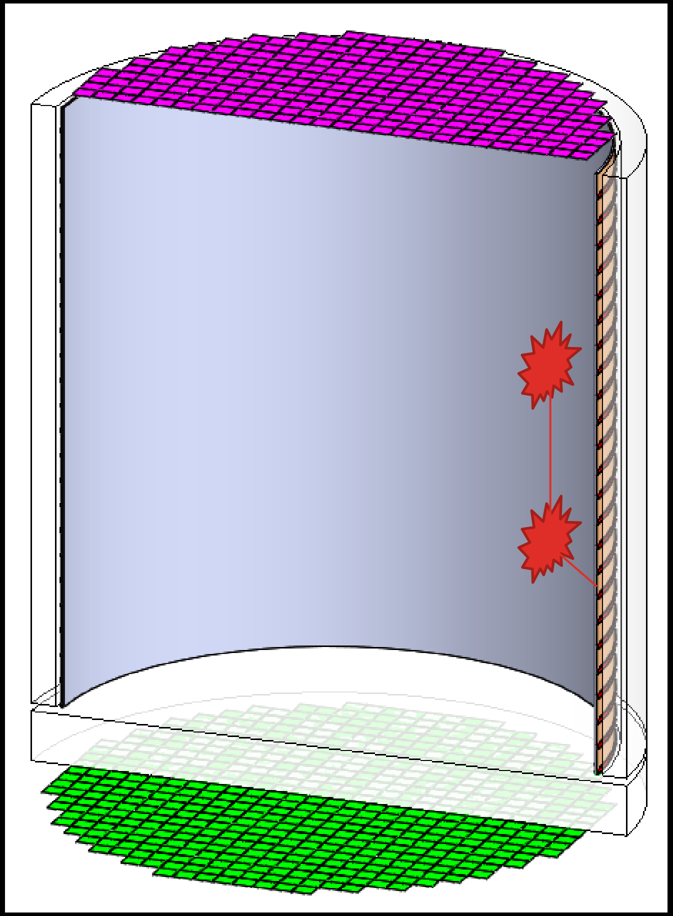
>10 GeV or so

Heavy DM search: scalable large detectors

Material background (gammas/neutrons)

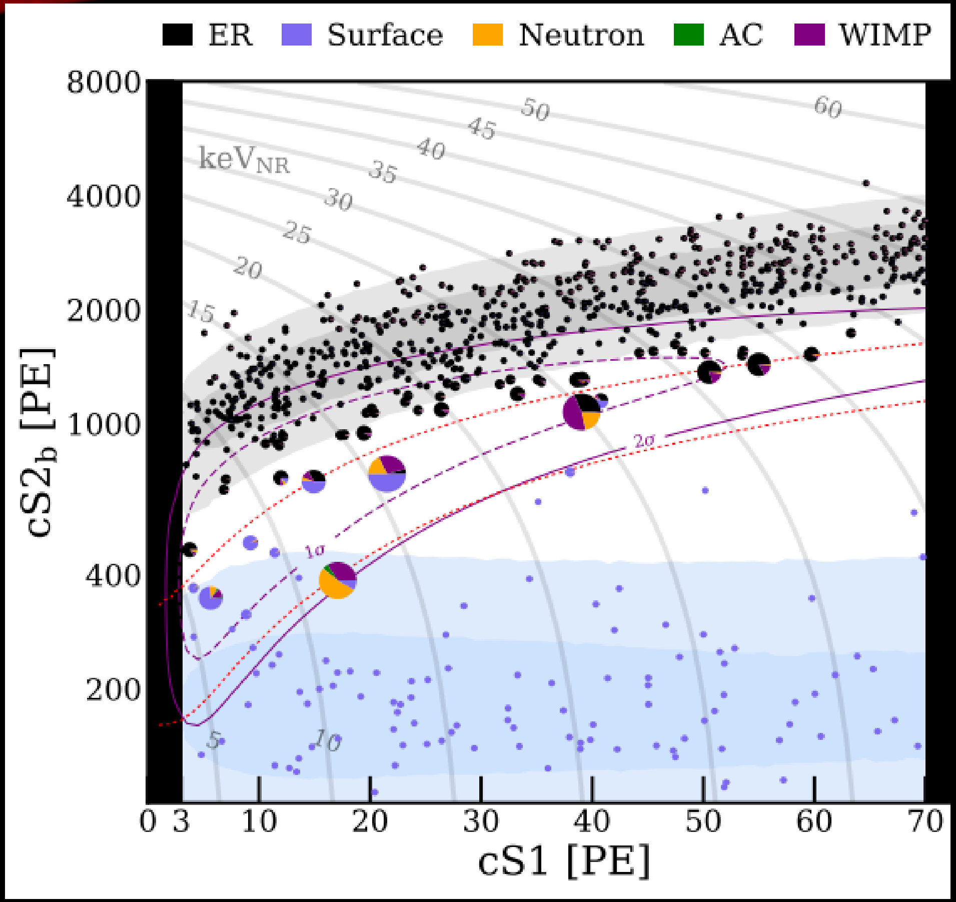
- Cluster @ boundary
- Multi-site
- Low energy scatter deep in target without high E scattering in outskirt further suppressed

$\Rightarrow$ “self-shielding” if reconstruct vertex

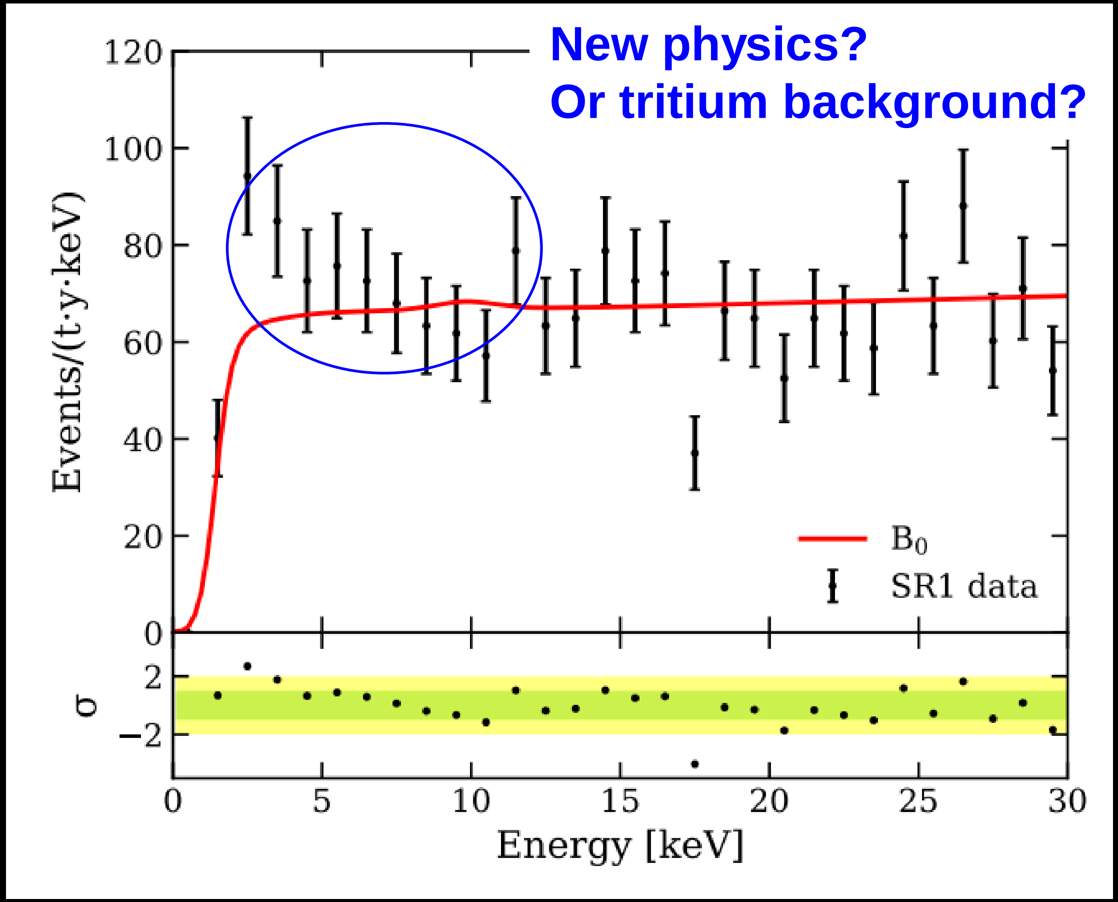


Liquid xenon experiments

XENON1T results



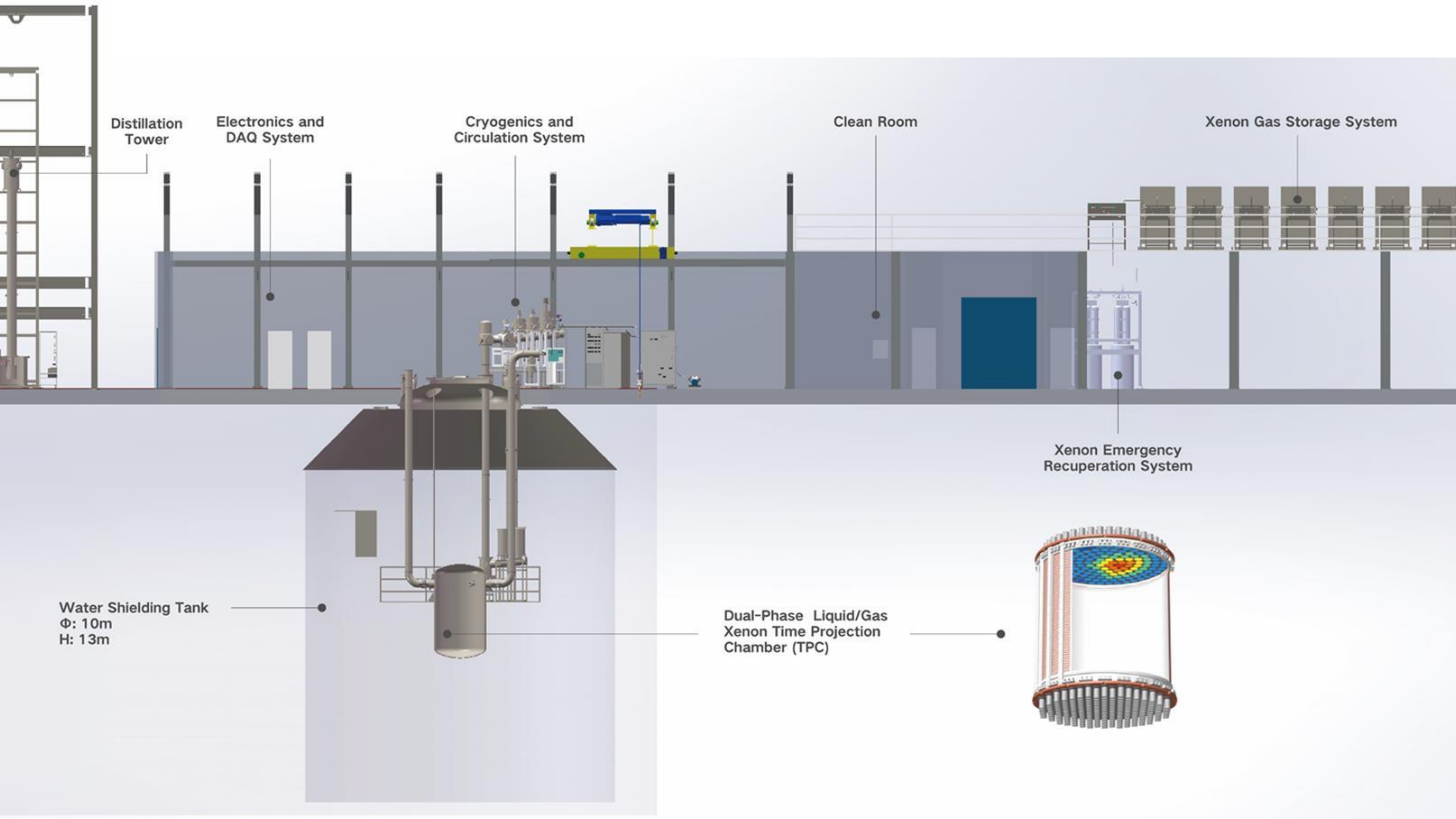
PRL 121, 111302 (2018)
1-tonne-year, +1σ upward fluctuation
best exclusion: 4.7×10^{-47} cm^2 @ 30 GeV



PRD 102, 072004 (2020)

PandaX-4T milestone

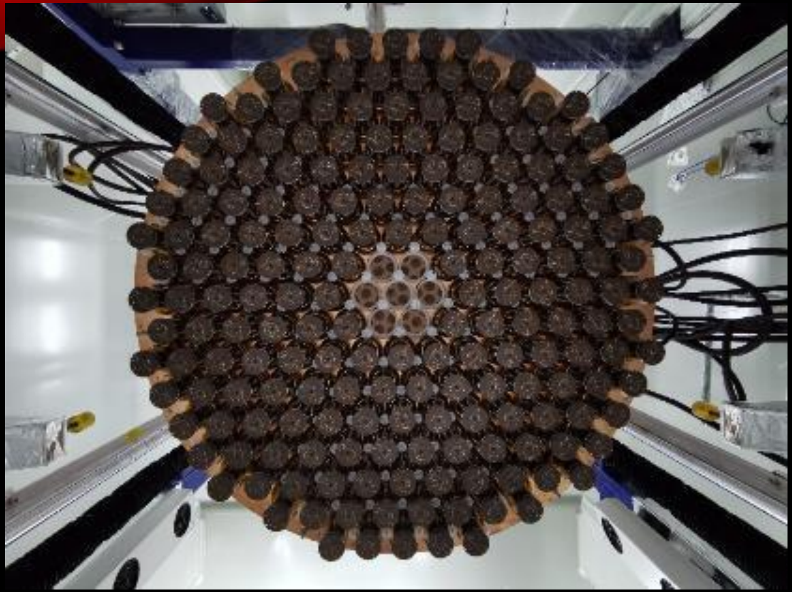
- Apr., 2018, permission from CJPL management to start construction in B2 hall
- Aug., 2019, infrastructure completed, detector installation in CJPL-II started
- Mar., 2020, offline distillation of xenon completed
- May, 2020, installation completed
- Nov., 2020 – Apr., 2021, commissioning run (Run 0)
- Nov., 2021 – , first physics run (Run 1)



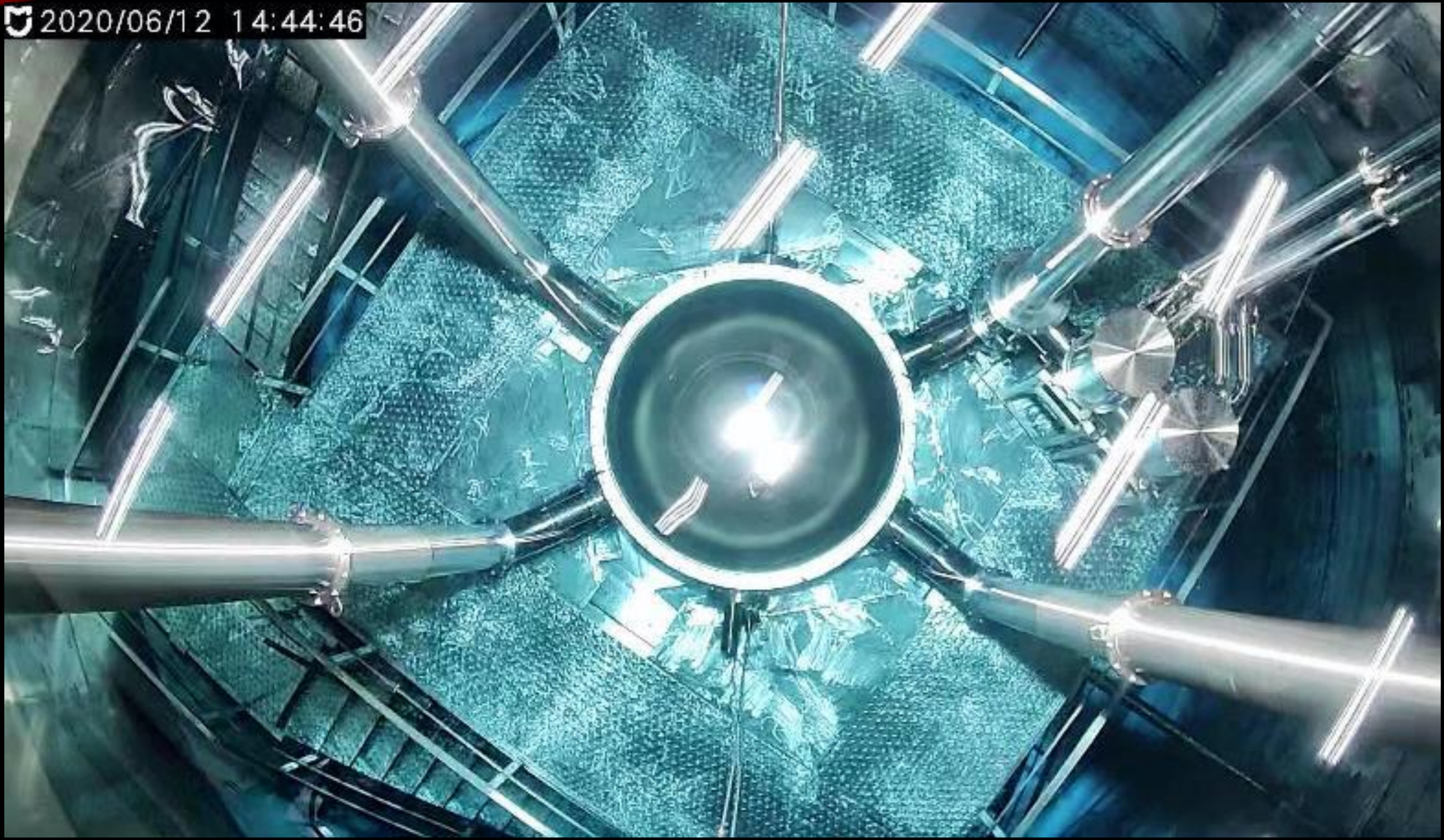
Distillation Tower
Electronics and DAQ System
Cryogenics and Circulation System
Clean Room
Xenon Gas Storage System
Xenon Emergency Recuperation System
Water Shielding Tank
Φ: 10m
H: 13m
Dual-Phase Liquid/Gas Xenon Time Projection Chamber (TPC)


上海交通大学PandaX暗物质与中微子实验平台

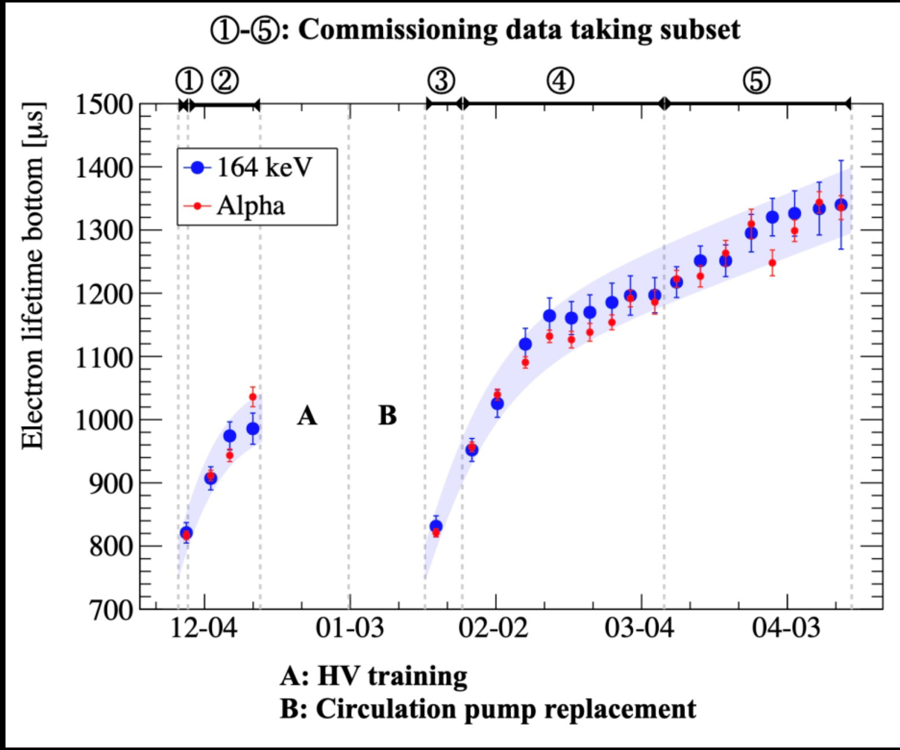
TPC installation

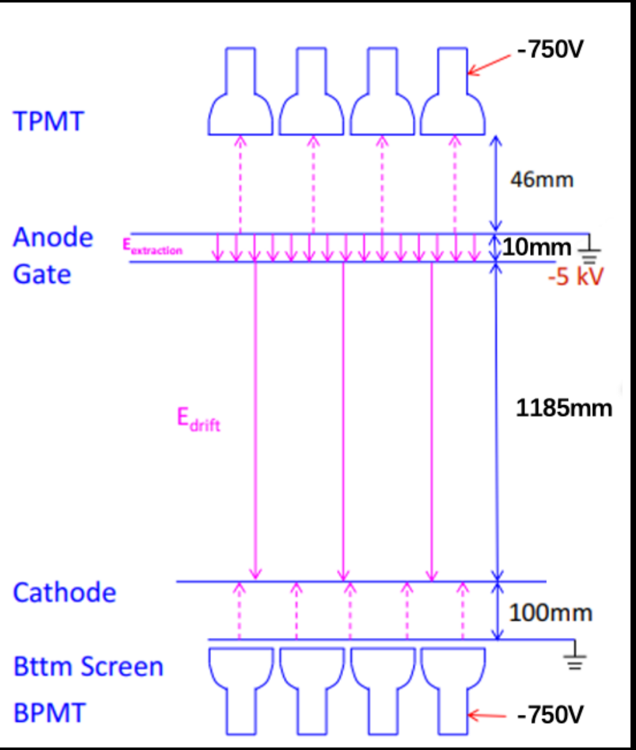


Ultrapure water filling



Run 0 configuration

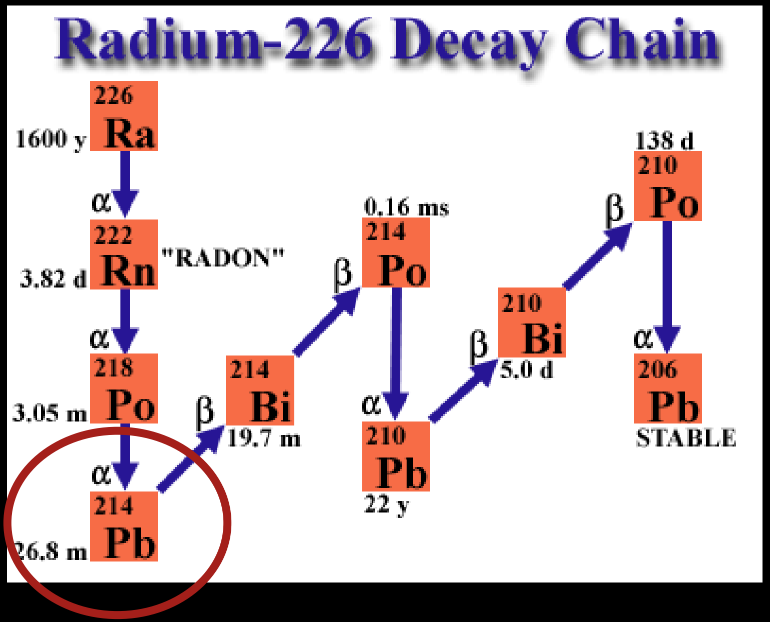




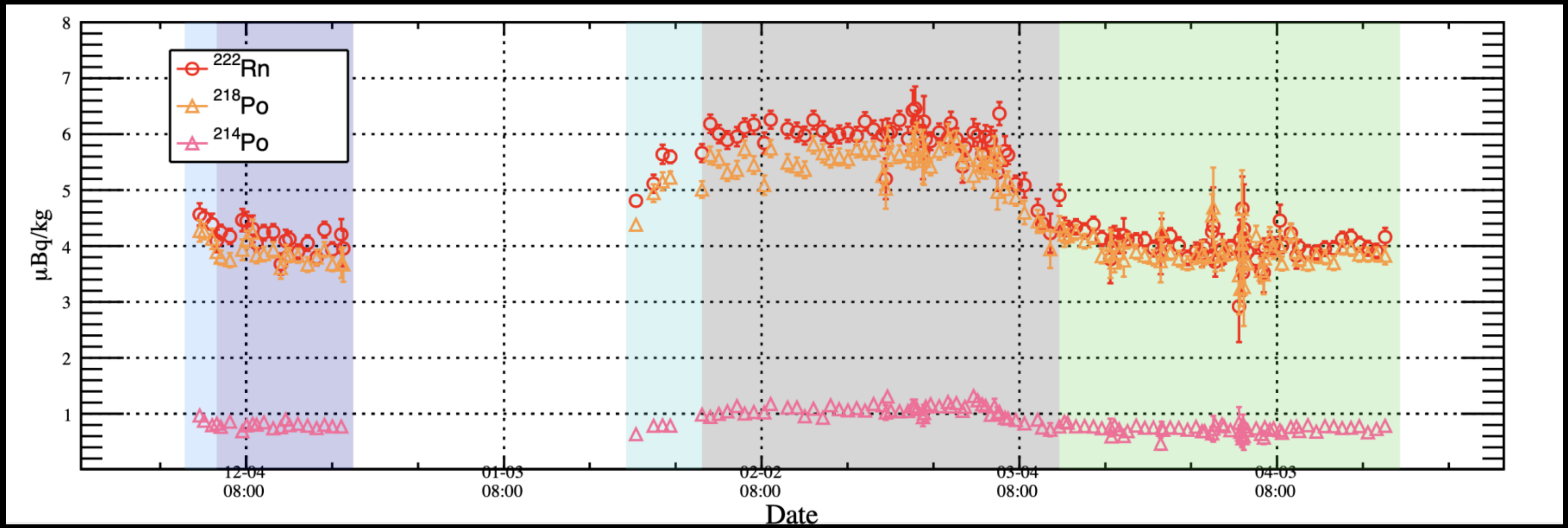
- Electron lifetime: *in situ* S2 vertical uniformity calibration
- Ref: the maximum drift time ~ 840 μs (field dependent)
- HV set at a few different values to avoid excessive discharges
- Stable data running period: 95.0 calendar days

	Set1	Set2	Set3	Set4	Set5
Gate(kV)	-4.9		-5	-5	
Cathode (kV)	-20	-18.6	-18	-16	

^{222}Rn level evolution

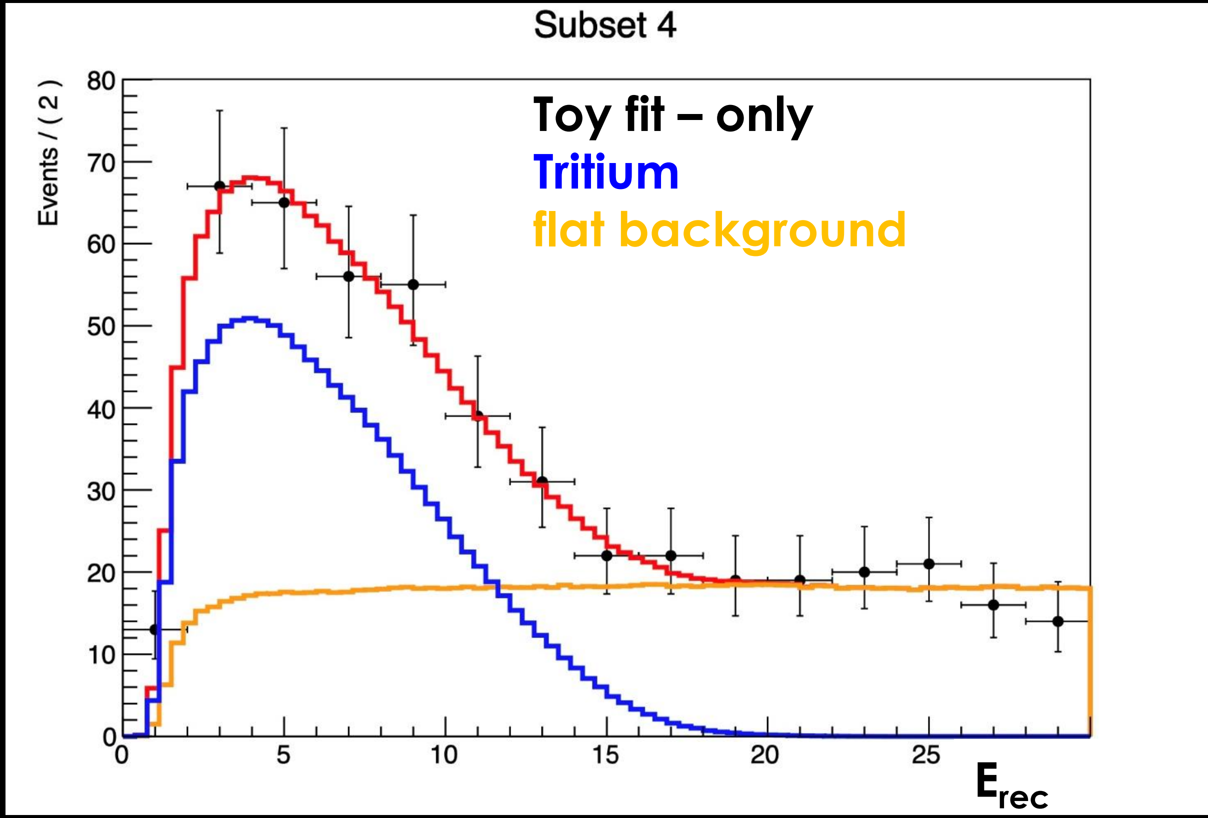


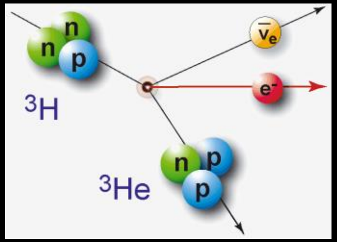
Set1 Set2 Set3 Set4 Set5



- Set 3→4: online Kr distillation (10 SLPM)
- Set 4→5: distillation off to reduce Rn emanation from the tower
- Rn level reduced from PandaX-II by 6 times

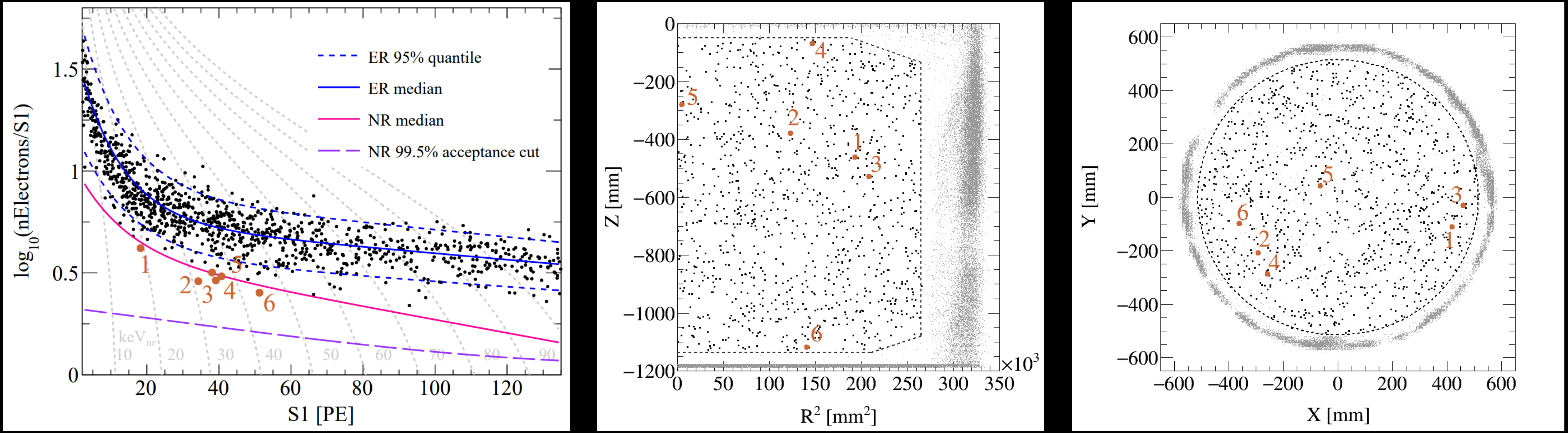
Tritium background





- Tritium spectrum identified in the data
- Likely originated from a tritium calibration at the end of PandaX-II
- Level floating in the final dark matter fit: $5(0.3)\times10^{-24}$ (mol/mol)

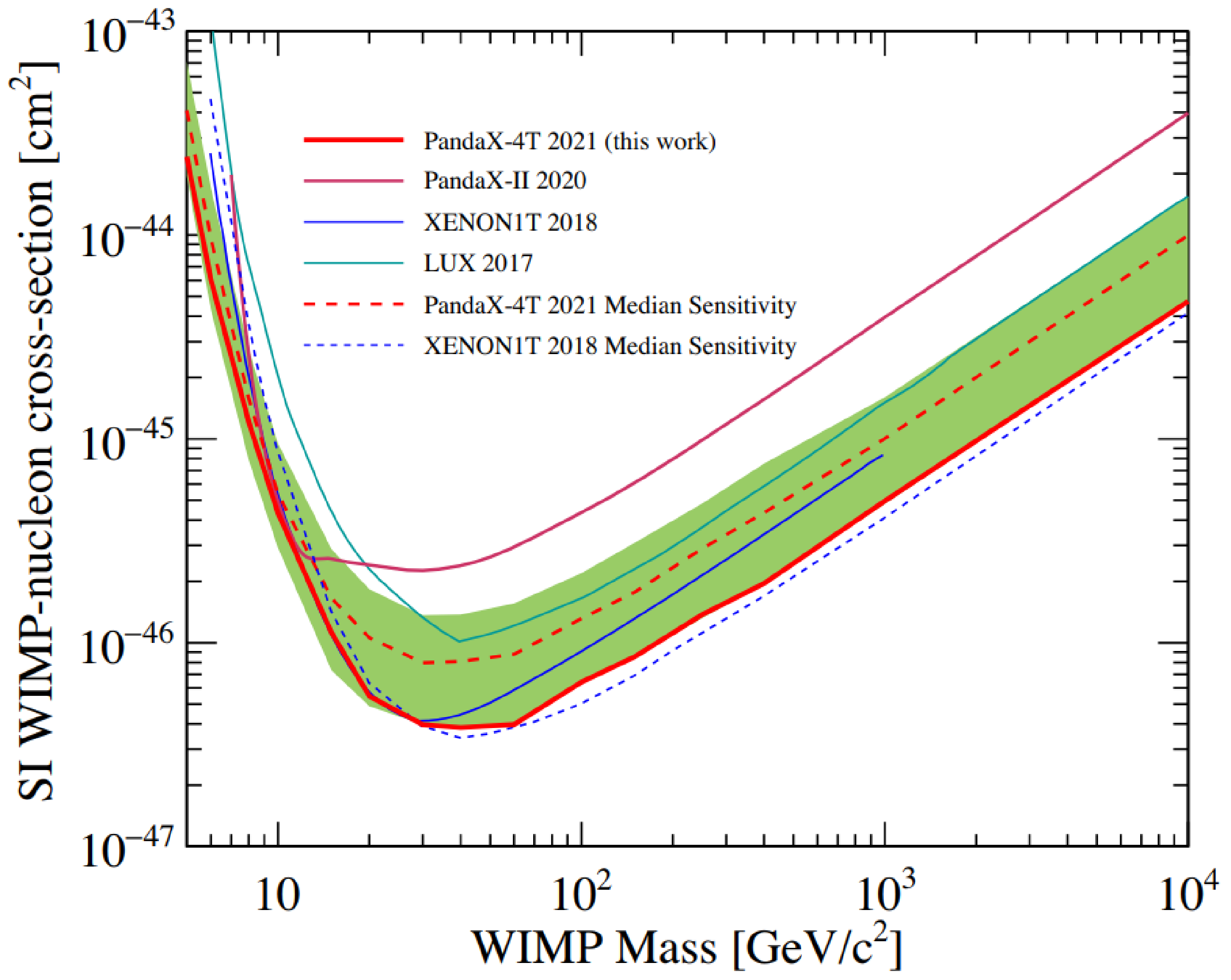
Dark matter candidates



- Events uniformly distributed in the FV, expected if dominated by tritium and radon.
- In FV, 1058 candidates, 6 below NR median line (~-1σ downward fluctuation from expected 9.8 evts)

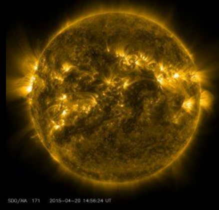
WIMP-nucleon SI exclusion limits

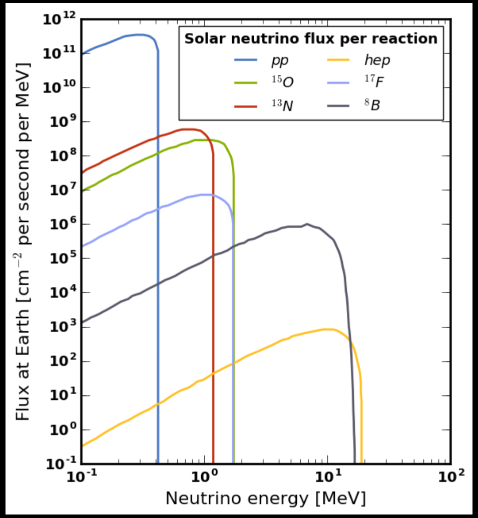
PRL 127, 261802 (2021)



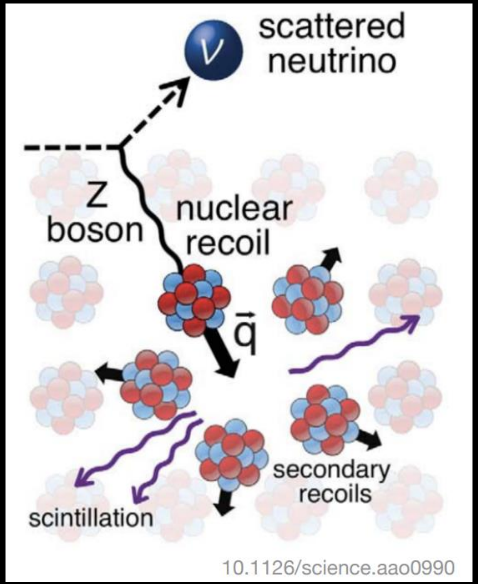
- Exposure: 0.63 tonne•year
- Sensitivity improved from PandaX-II final analysis by 2.6 times (40 GeV/c^2)
- Strongest exclusion limit to date (downward background fluctuation by -1σ)

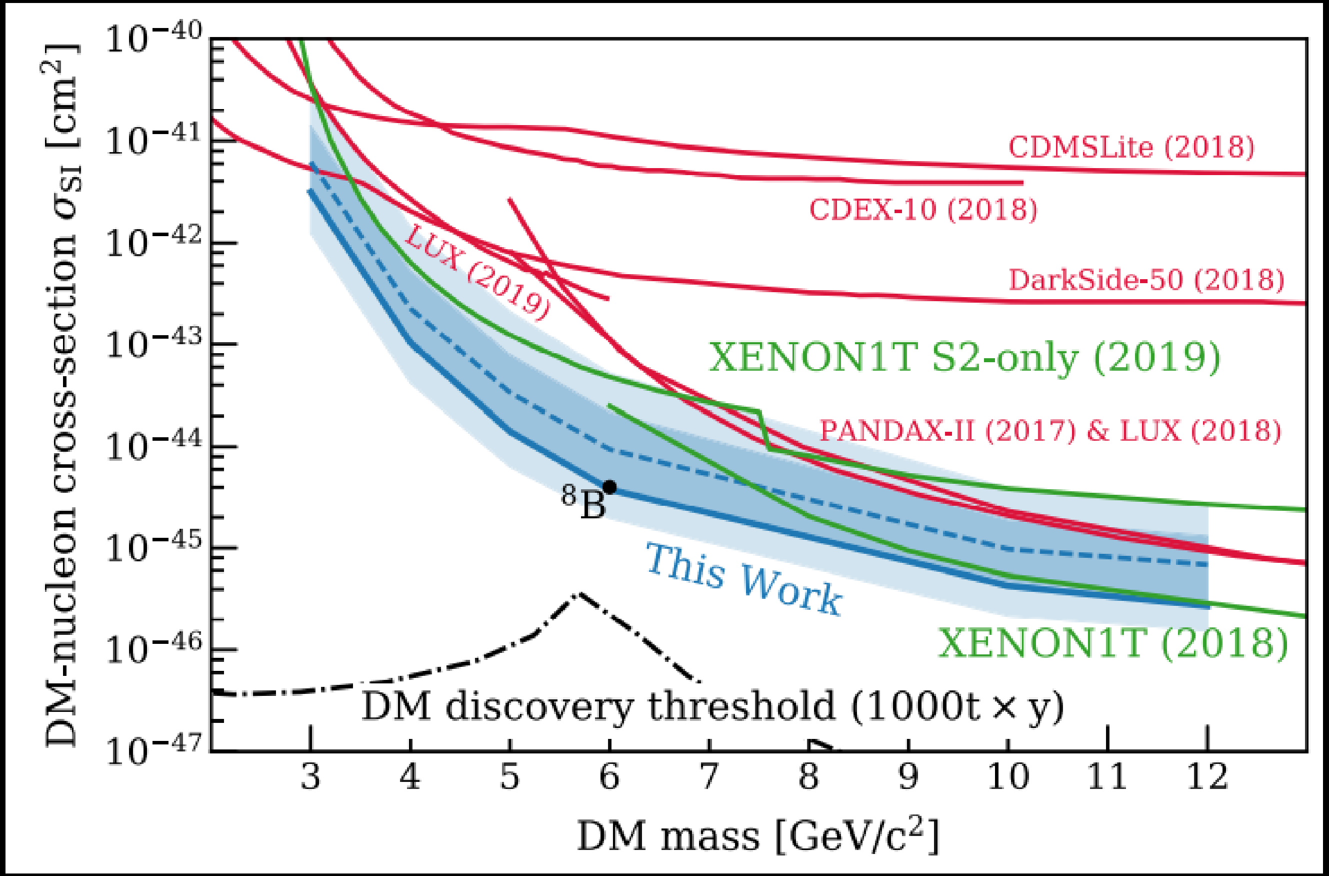
^{8}B neutrino floor?





CEvNS

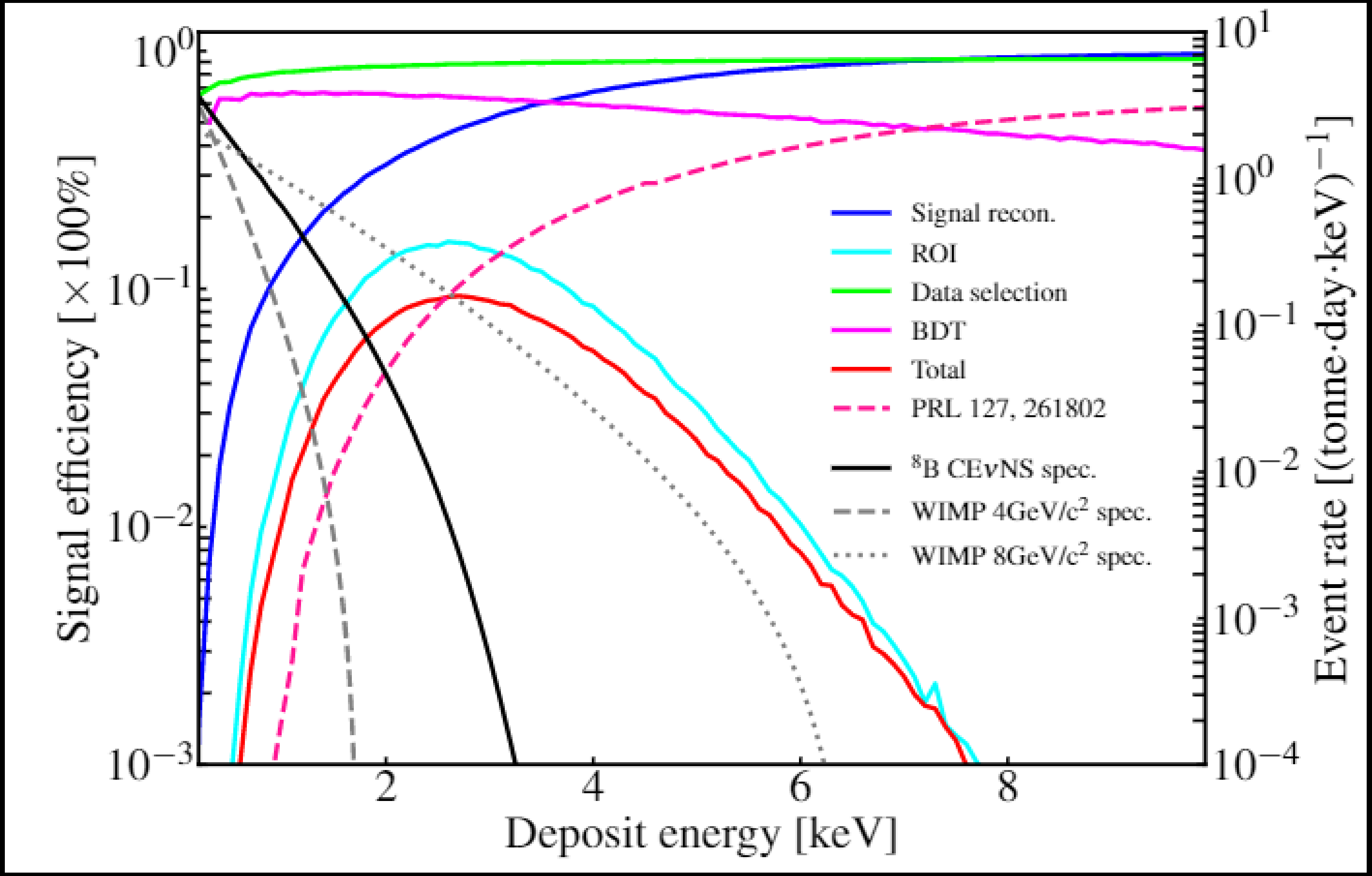




XENON1T, 1-tonne×year, PRL 126, 091301 (2021)

PandaX-4T Search on B8 CEvNS

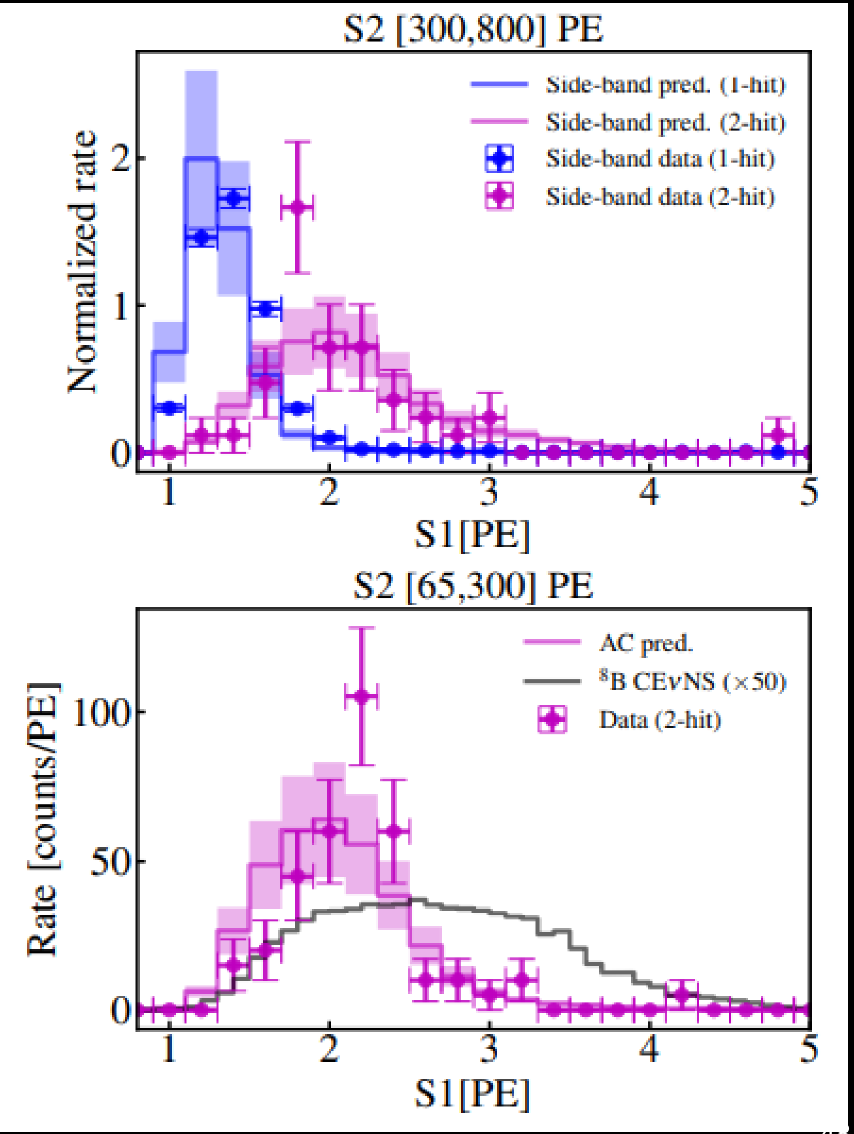
- To enhance sensitivity ^{8}B, need to lower the selection threshold (S1↓, S2 ↓)
- Key difficulty: accidental background ↑
- Blind analysis: with 0.48 ton-year data, excluding period when we see an increase of noises rates (micro-discharge)



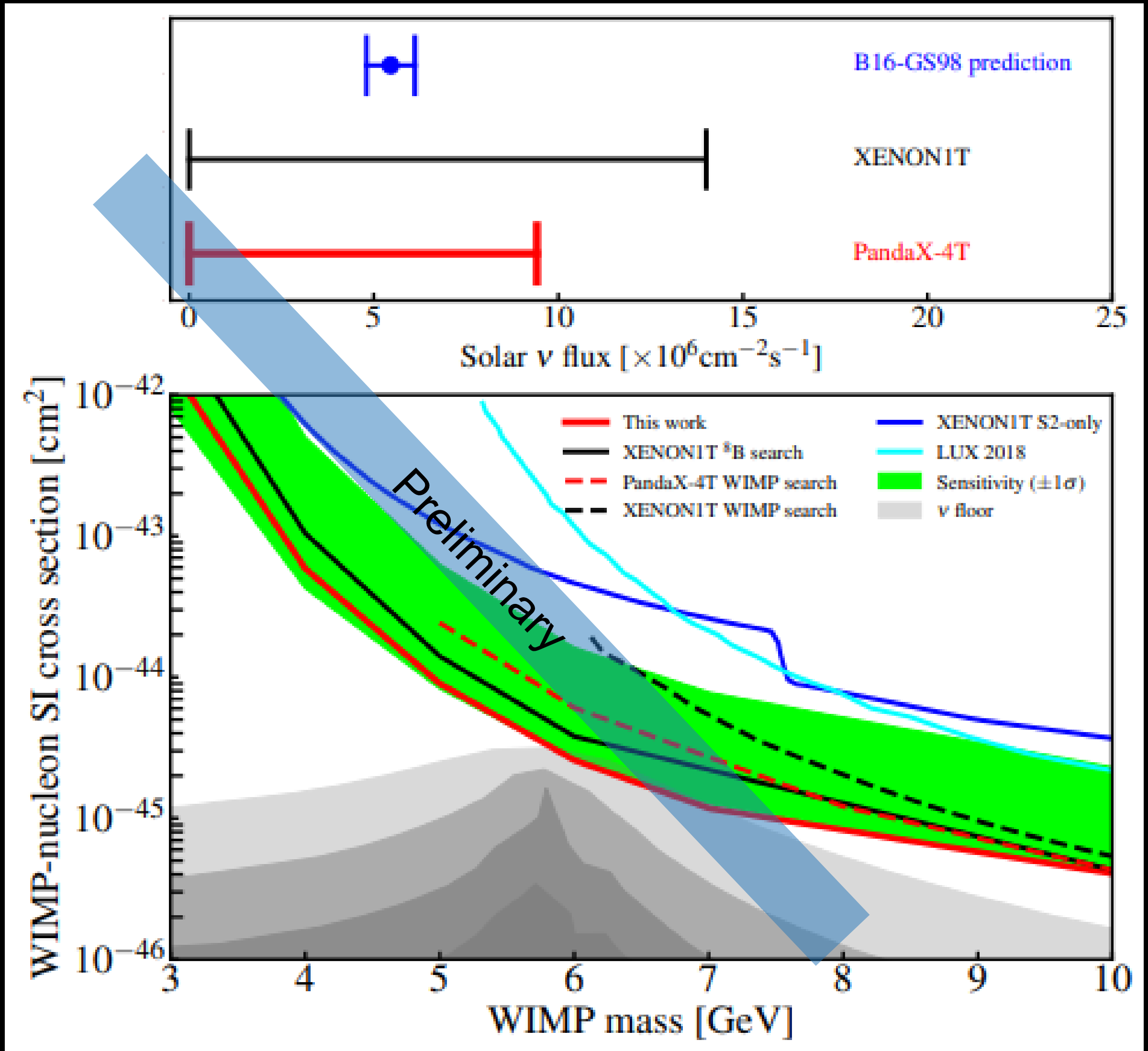
Control of accidental background

- Use "scrambled" real data to predict accidental background
- A machine-learning multivariant cut (BDT) was developed to further suppress such background from B8 signal
- Training/selection is entirely blinded
- 20% probability (with ^{8}B CEvNS and no WIMP)

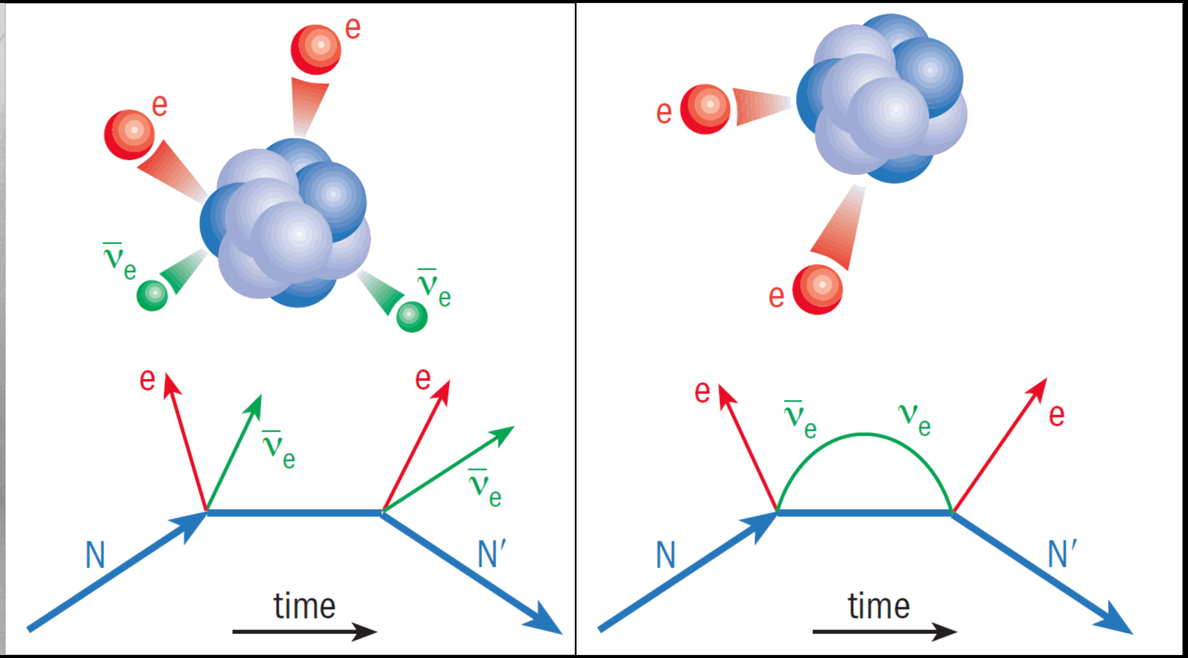
Nhit requirement on S1	BDT	Expected BKG (evt)	Expected 8B (evt)	Observed (evt)
2	Before	62.6	2.3	59
	After	1.5	1.4	1
3	Before	0.9	0.4	2
	After	0.04	0.3	0



^{8}B & low mass WIMP results



- Leading constraint on ^{8}B flux using CEvNS
- Can cast constraint on neutrino-nucleus interactions
- Assuming nominal ^{8}B background, also set tightest low mass WIMP-nucleon SI interaction limit between 5 and 10 GeV/c^2
- In arXiv this week



From Physics World

Neutrinoless double-β decay

$\bar{\nu} \stackrel{?}{=} \nu$

0vDBD, if found

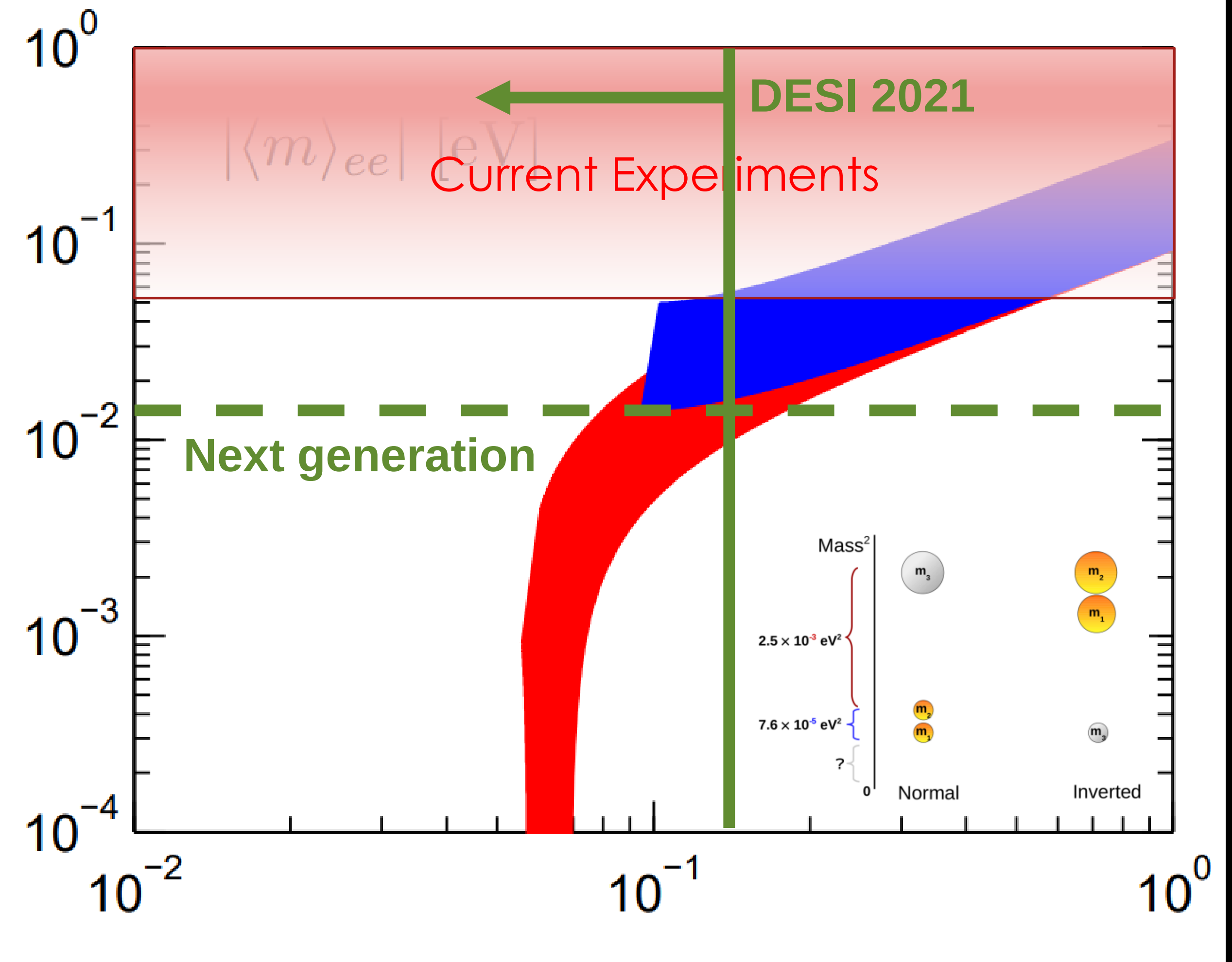
- Majorana or Dirac
- Lepton number violation
- Measures effective Majorana mass: relate 0vββ to absolute neutrino mass

$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}(Q,Z)\ |M^{0\nu}|^2\ \frac{|\langle m_{\beta\beta}\rangle|^2}{m_e^2}$$

Phase space factor

Nuclear matrix element

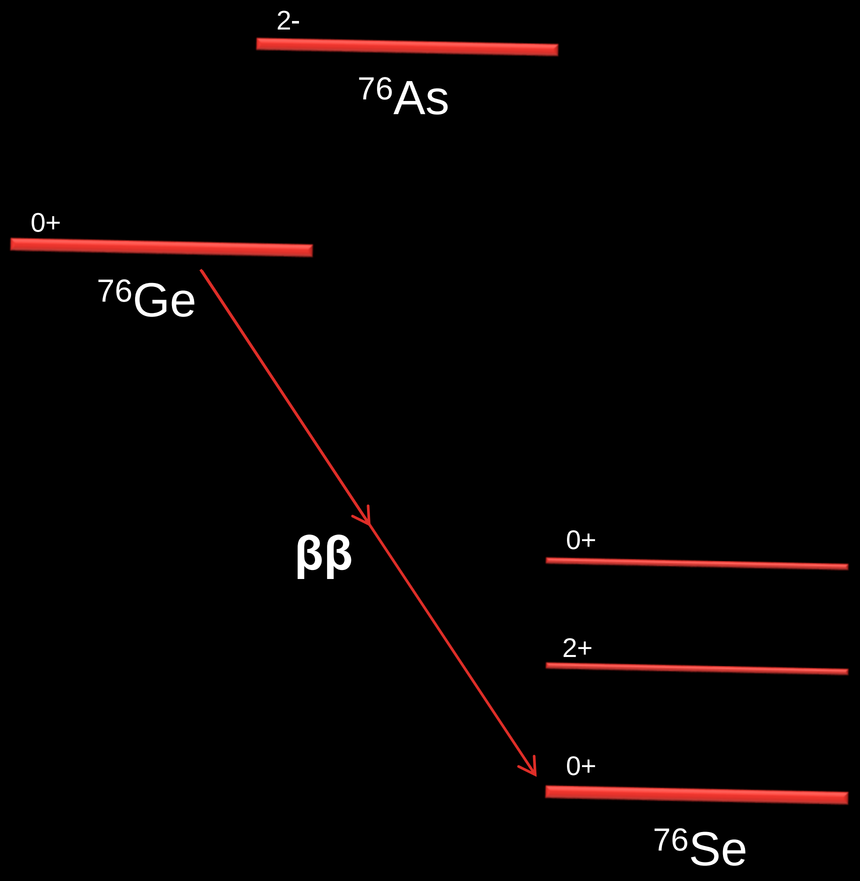
Effective Majorana neutrino mass: $|\langle m_{\beta\beta}\rangle| = \left|\sum_{i=1}^{3} U_{ei}^2 m_i\right|$



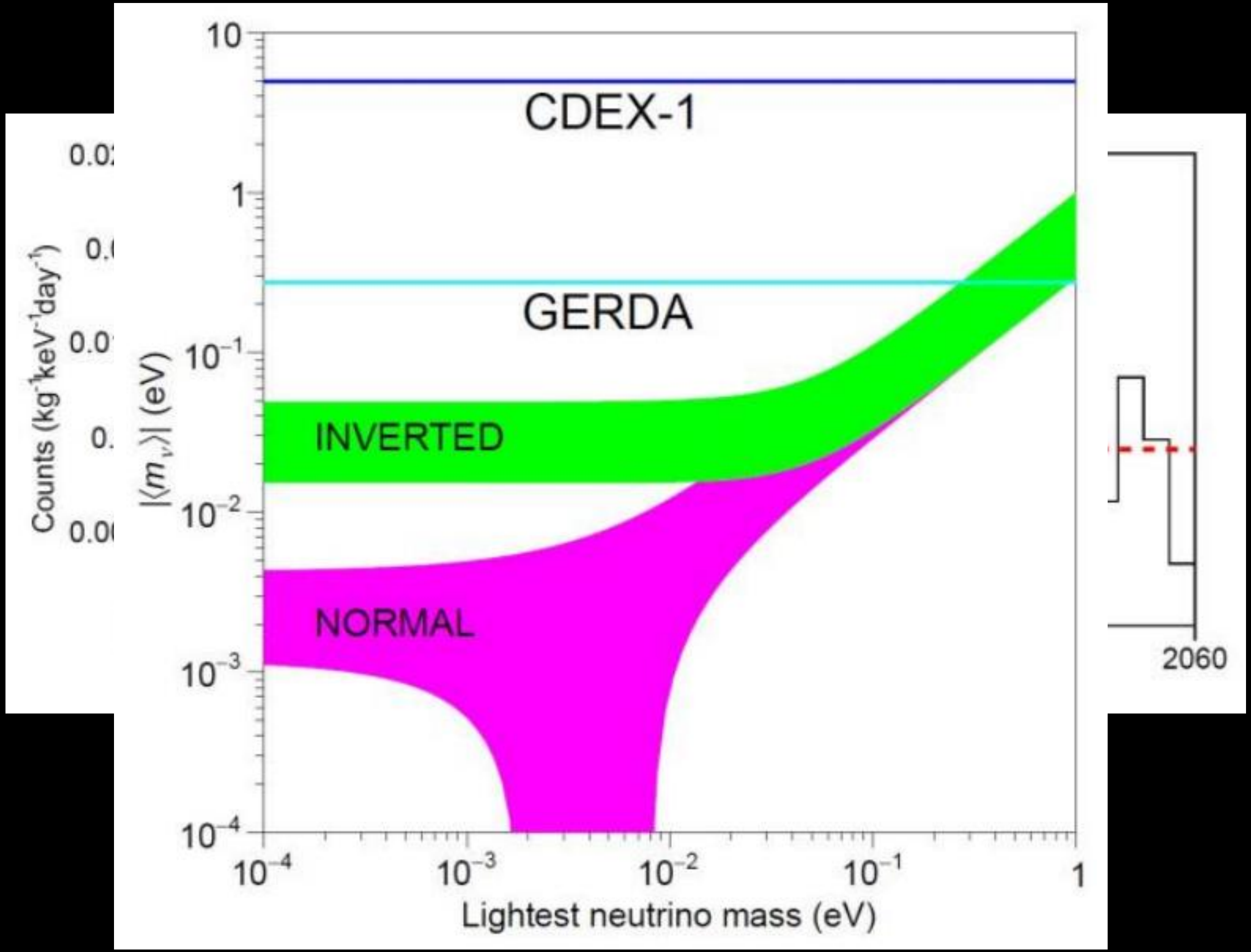
JPG 43 030401 (2016) Σ_ν [eV]

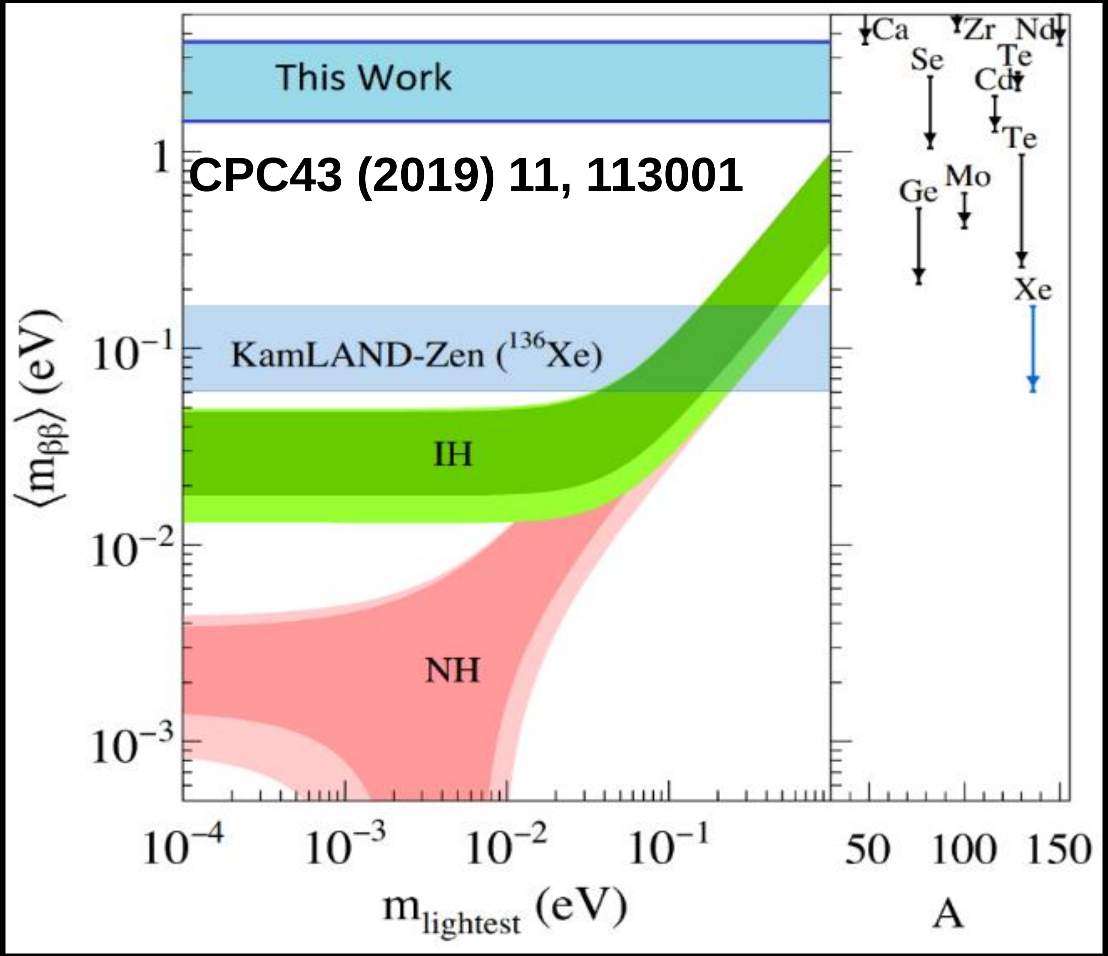
ββ isotopes

Isotope	Q-value [MeV]	Natural abudance [%]
^{48}Ca	4.27	0.187
^{150}Nd	3.37	5.6
^{96}Zr	3.35	2.8
^{100}Mo	3.03	9.8
^{82}Se	3.00	8.7
^{116}Cd	2.81	7.5
^{130}Te	2.53	34.1
^{136}Xe	2.46	8.86
^{124}Sn	2.29	5.8
^{76}Ge	2.04	7.73
^{110}Pd	2.02	11.7



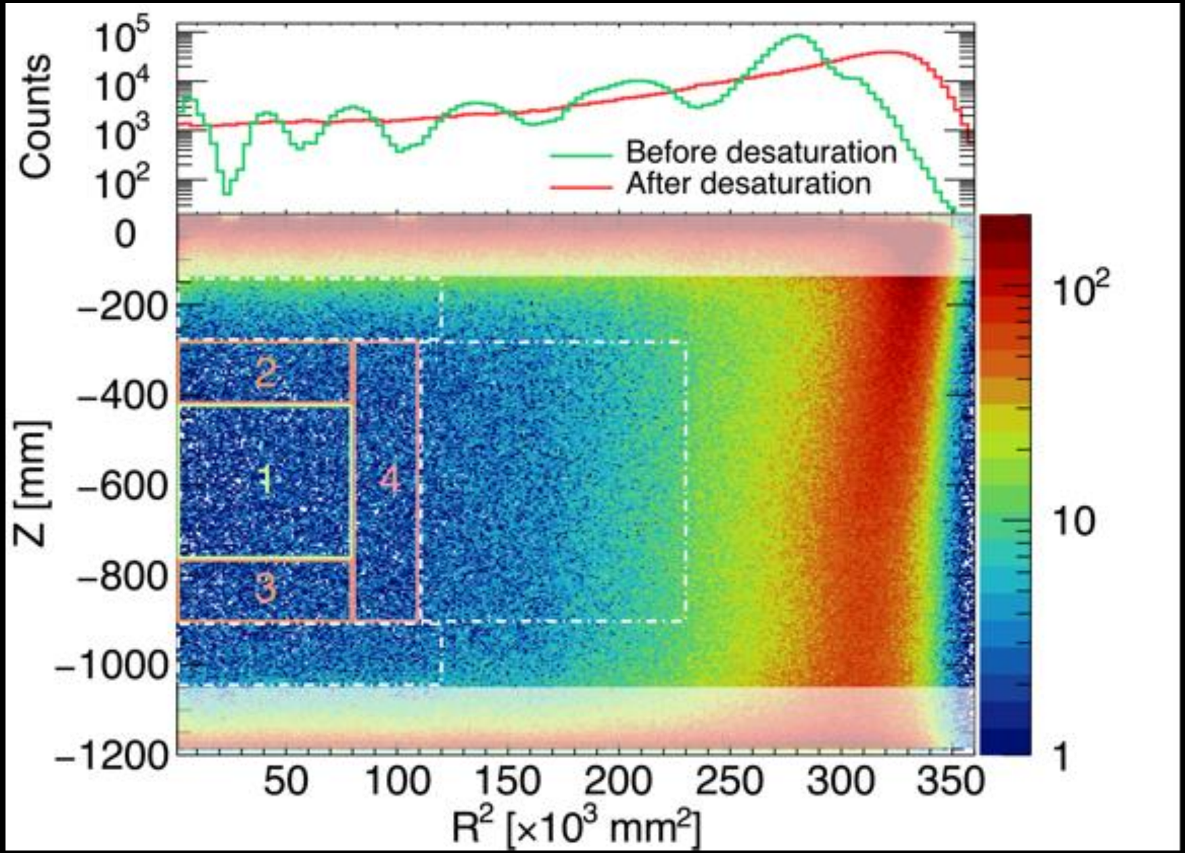
CDEX and PandaX first attempts to 0vDBD

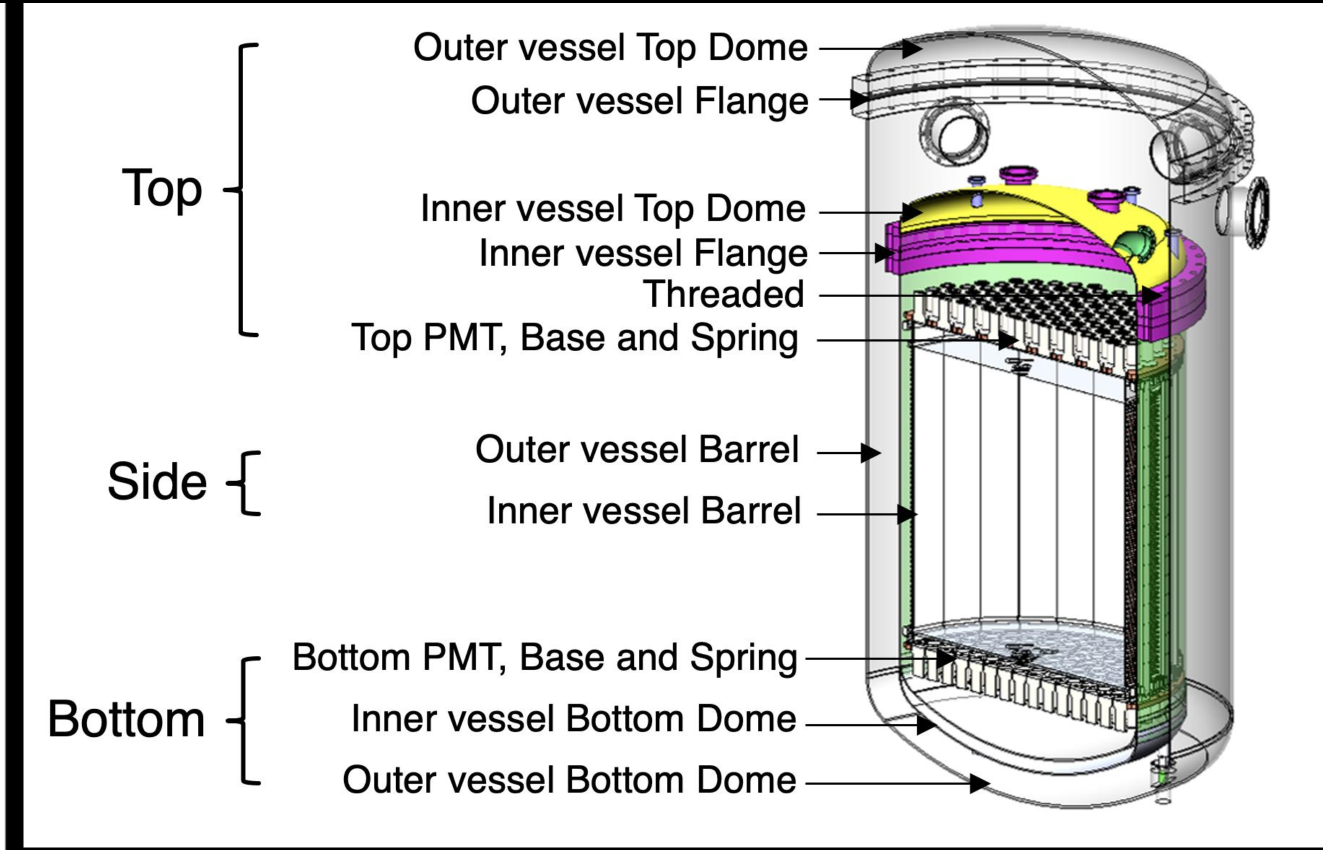




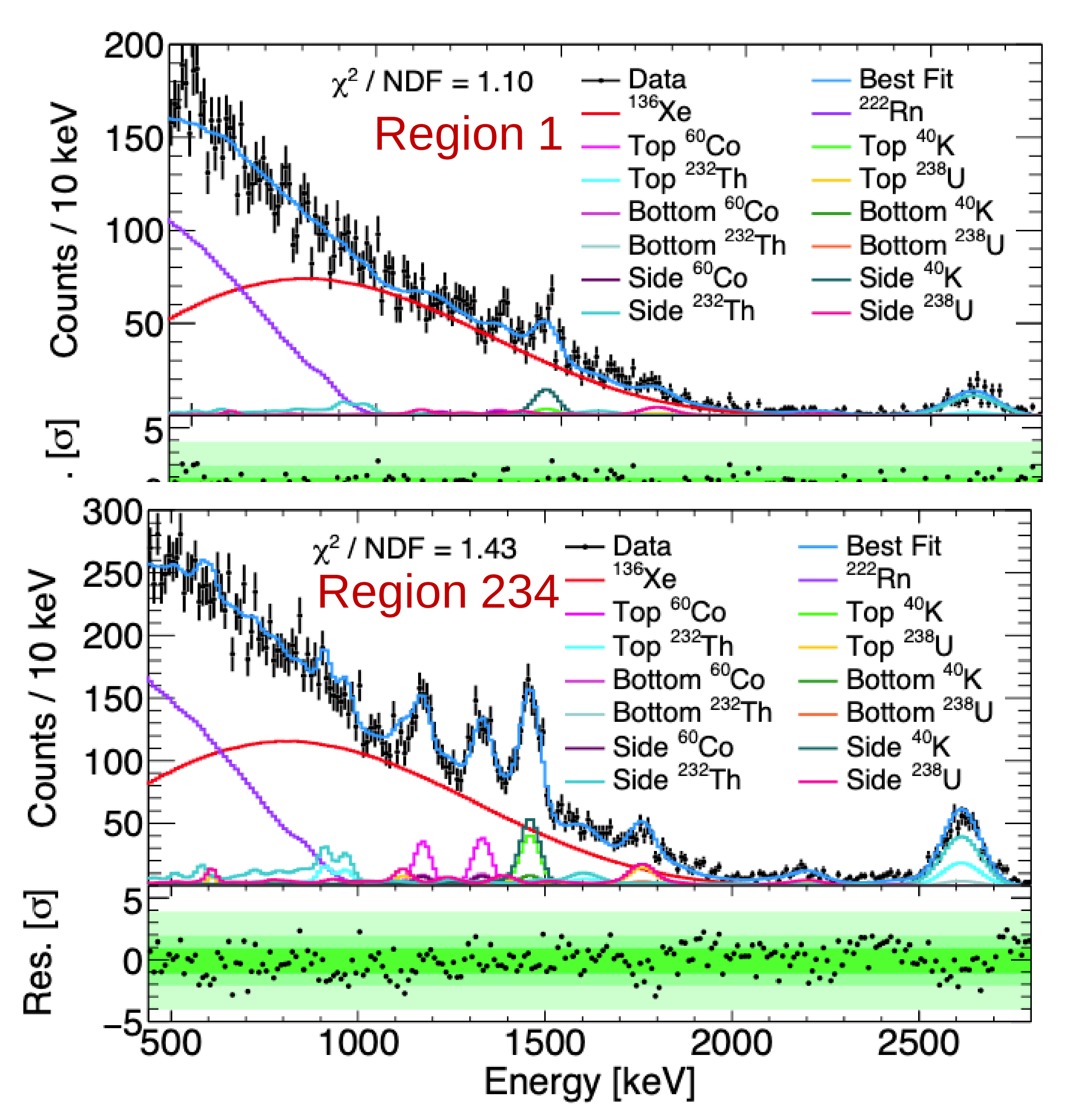
CPC43 (2019) 11, 113001

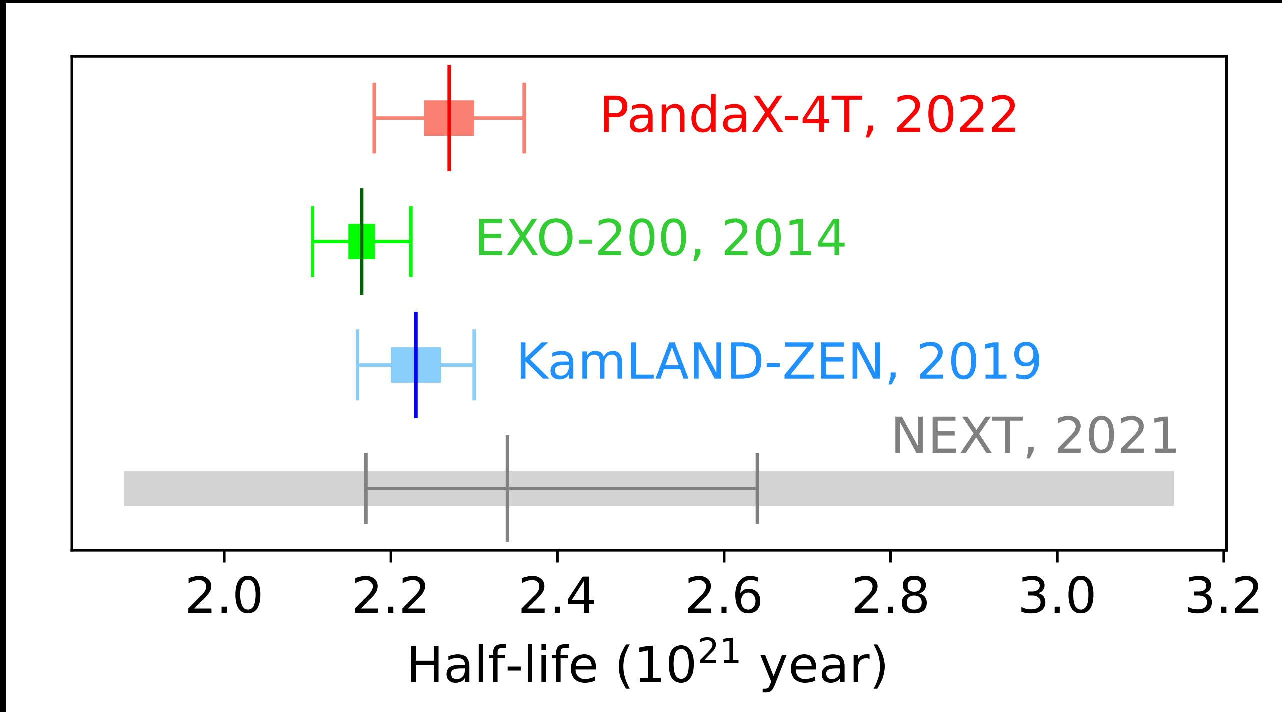
PandaX-4T, precise measurement of 2vDBD





PandaX-4T, precise measurement of 2vDBD

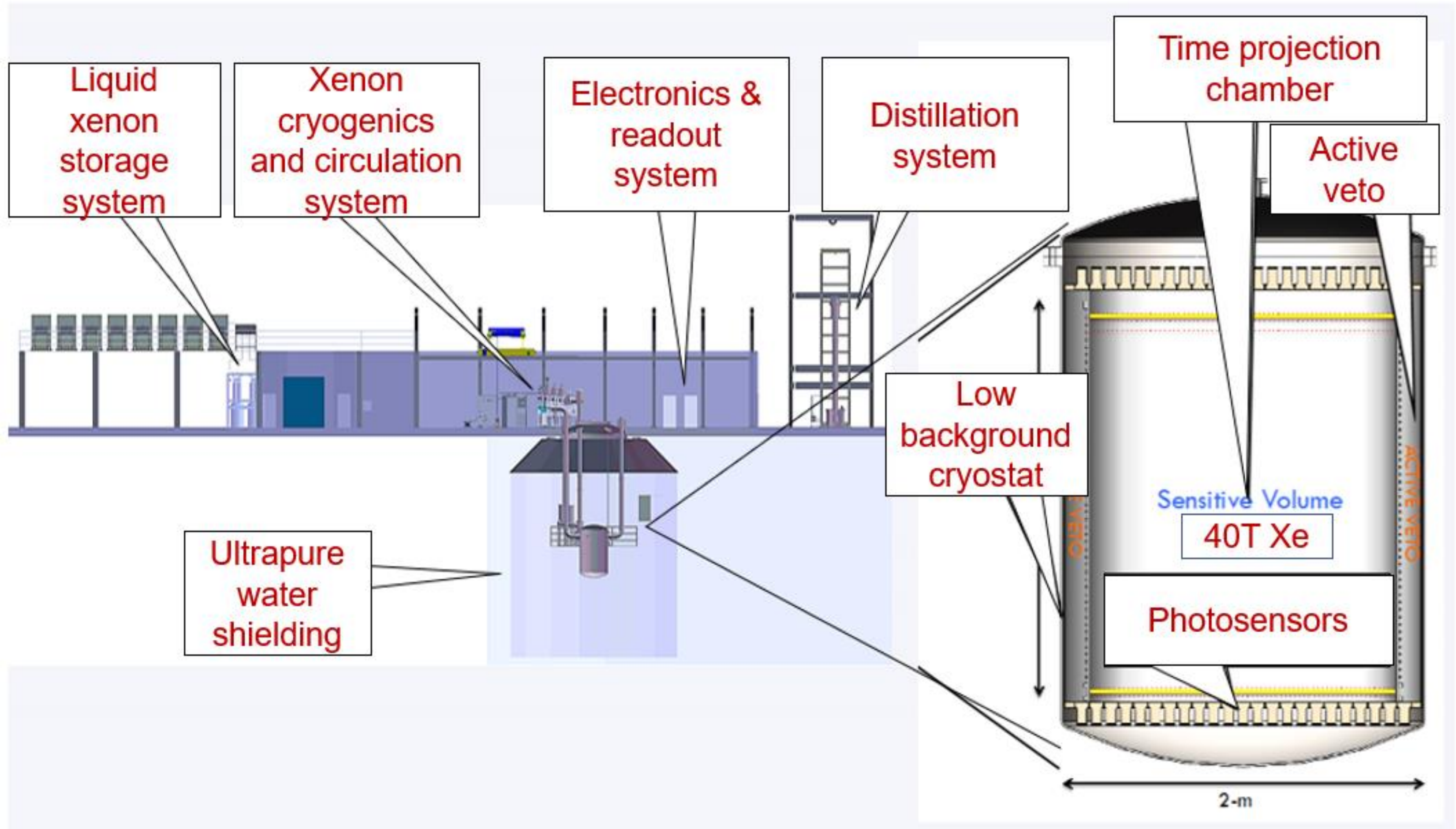




arXiv:2205.12809

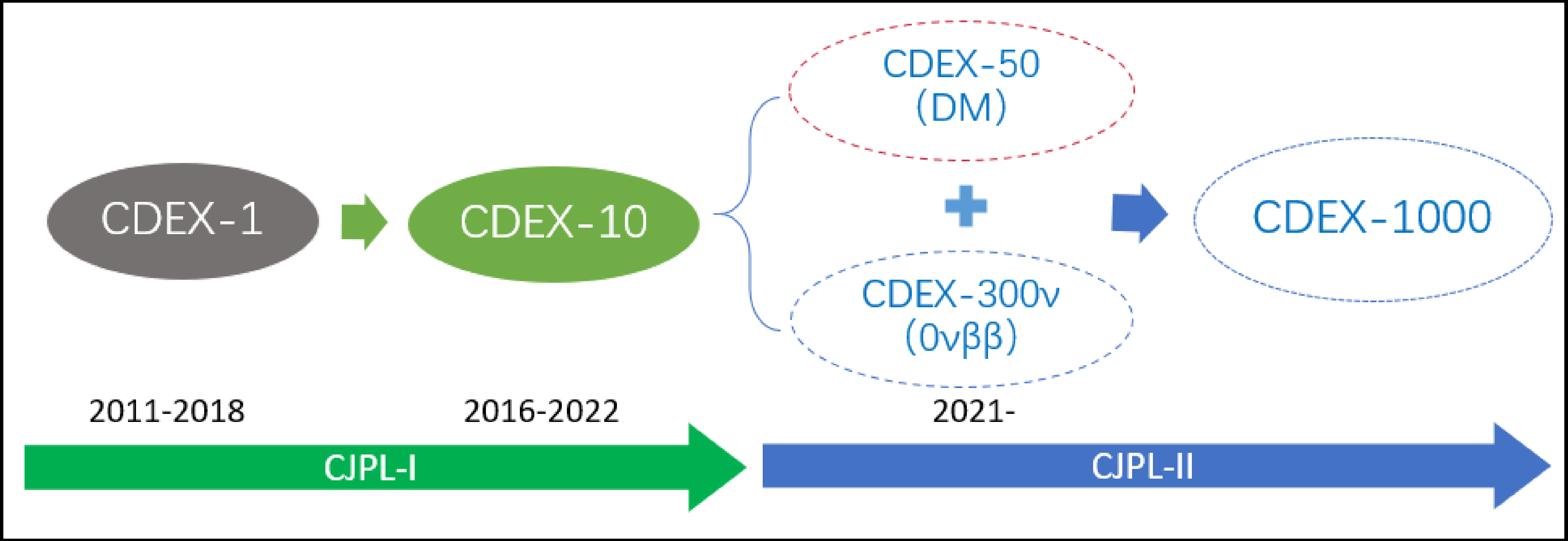
- ^{136}Xe DBD half-life:
  2.27 ± 0.03(stat.) ± 0.09(syst.) × 10^{21} year
- First such measurement with natural xenon
- 440 keV – 2800 keV range is the widest ROI

PandaX next plan



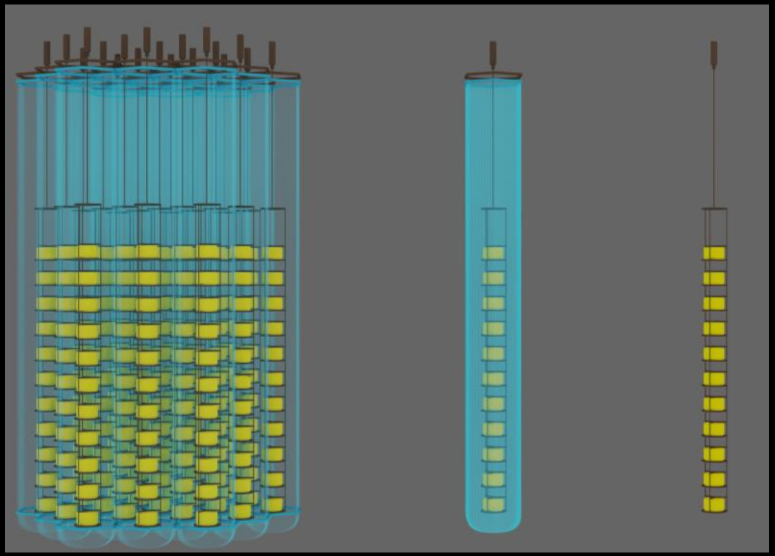
- Continue operates PandaX-4T till end of 2024
- Next: PandaX-xT, general-purpose observatory on dark matter, 0vDBD (^{136}Xe), neutrinos, other ultra-rare phenomena
- CJPL
  - DM: unique advantage on atmospheric neutrino background (low latitude)
  - 0vDBD: Low ^{137}Xe background (depth)

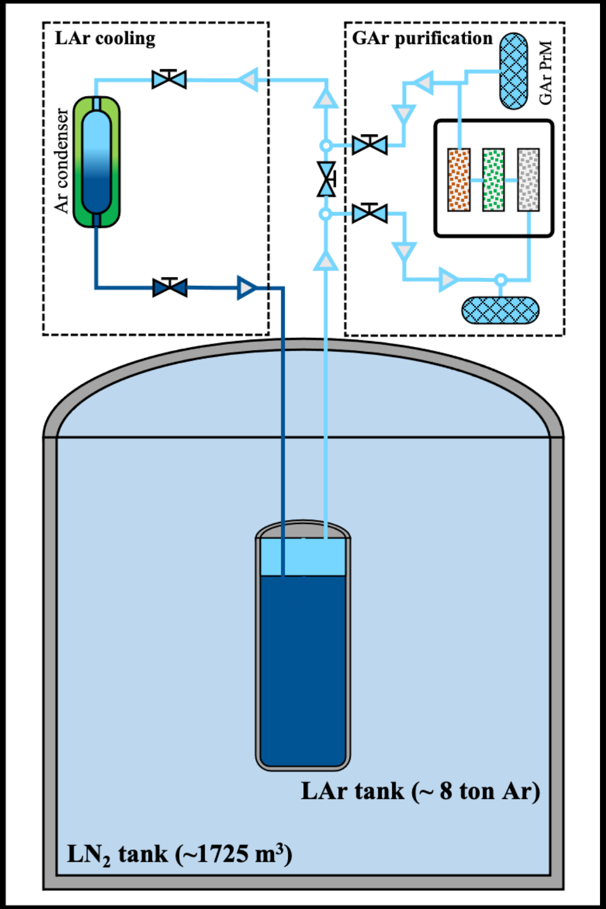
CDEX Next Plan

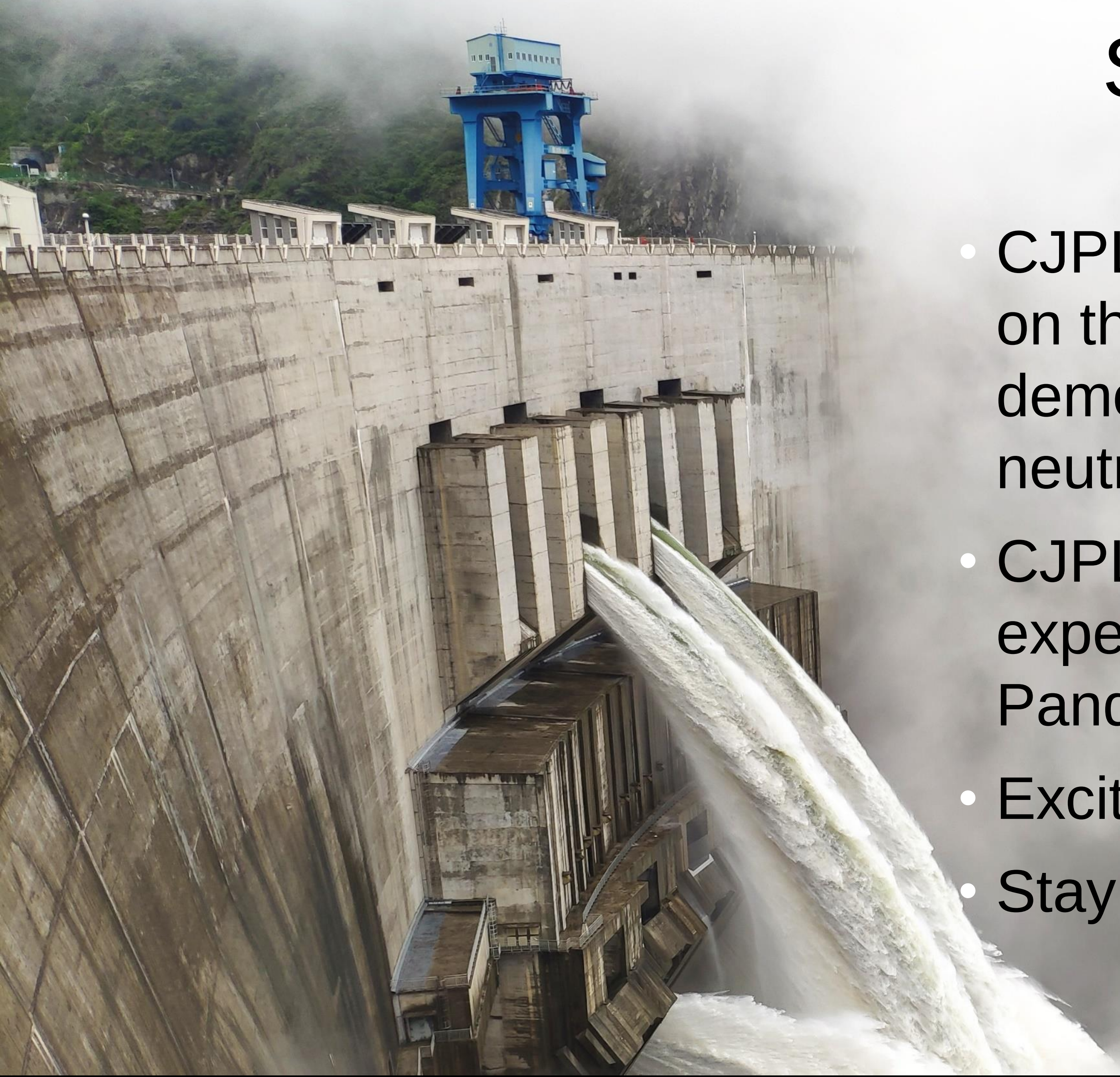


CDEX-300

- CDEX-300 for neutrinoless double beta decay
  - Ge-76 enriched >86%
  - LN + LAr (+WLS fiber + SiPM) + BEGe
  - ~200 BEGe detectors
  - Optional ICPC detector, more mass/unit
  - Data taking 2027-2030, $T_{1/2}$> 10^{27}y, <m_{ee}> ~50 meV







Summary and outlook

- CJPL has produced excellent science on the frontier of DM search, as well as demonstrating great potentials on neutrino physics
- CJPL-II upgrade is ongoing, with partial experimental occupancy in parallel (e.g. PandaX-4T)
- Exciting future opportunities at CJPL-II
- Stay tuned!