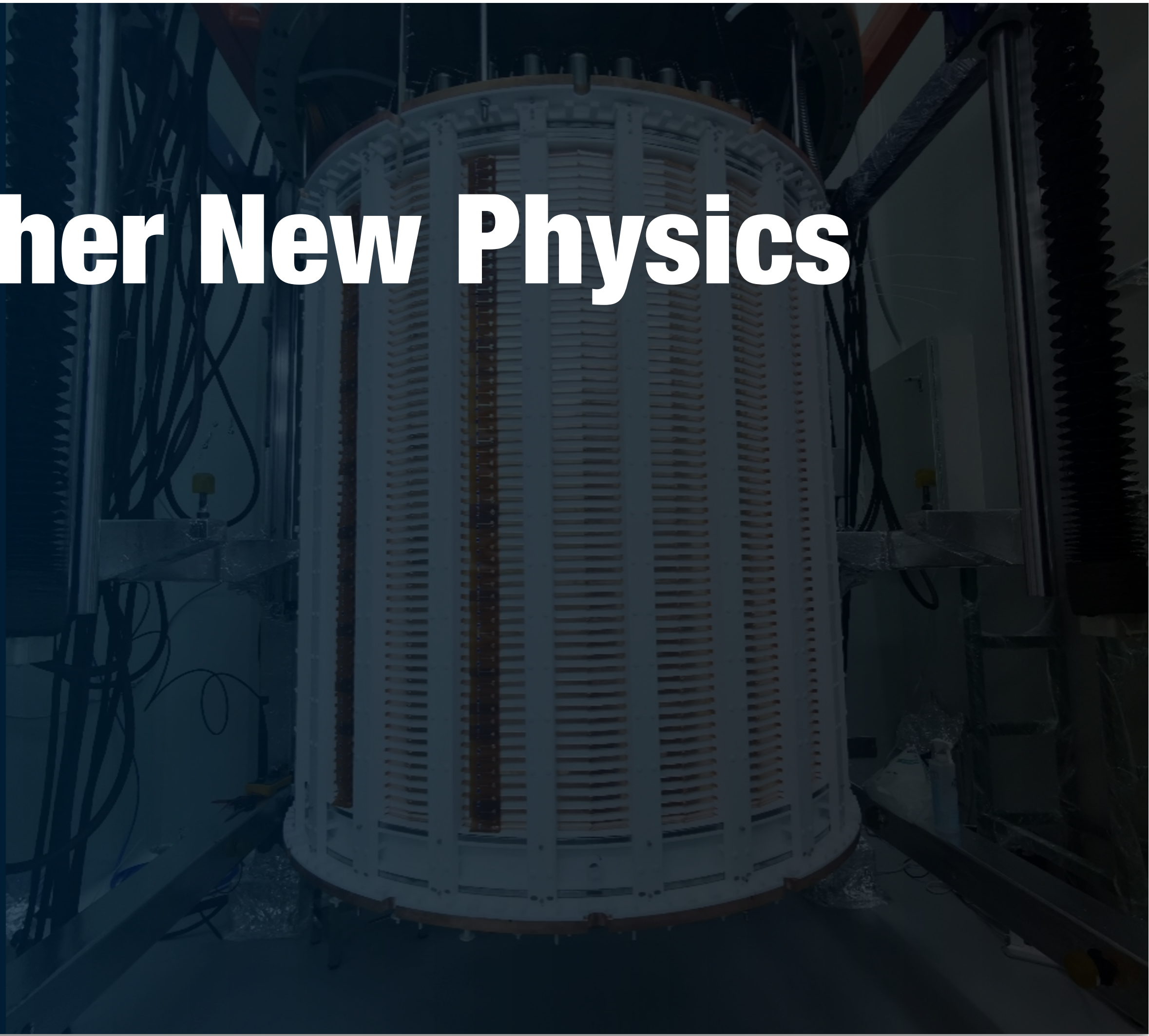
Search for Axions and Other New Physics Signals with PandaX-4T

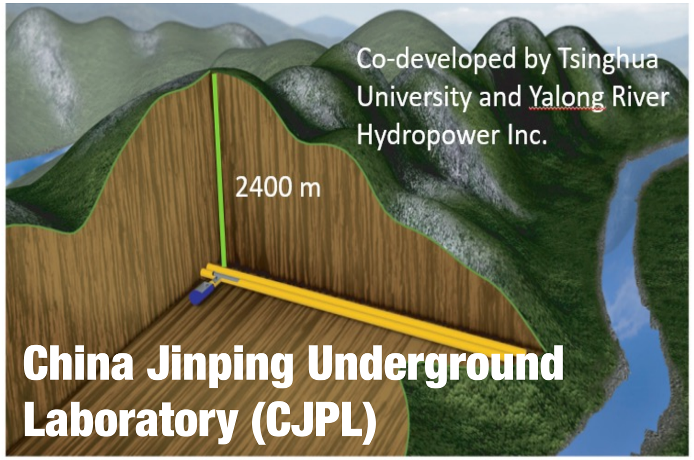


Xiaopeng Zhou, PandaX

PANDA X
PARTICLE AND ASTROPHYSICAL XENON TPC

the XIX International Conference on Topics in Astroparticle and Underground Physics (TAUP2025)

PandaX: Particle and Astrophysical Xenon Experiments



- 16 institutions, ~100 collaborators
- CJPL: Deepest (2400 m rock, 6800 m.w.e);
- PandaX-4T data-taking is ongoing now.

PANDA X
PARTICLE AND ASTROPHYSICAL XENON TPC

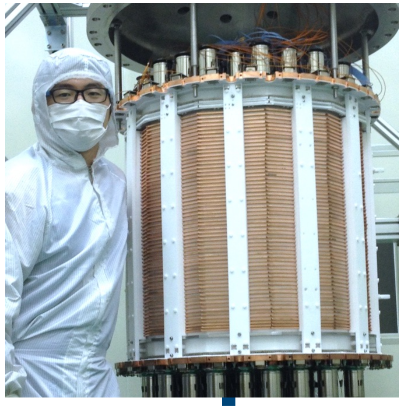
PandaX start

2009.3

PandaX-I 120kg

2010 - 2014

PandaX-II 580kg

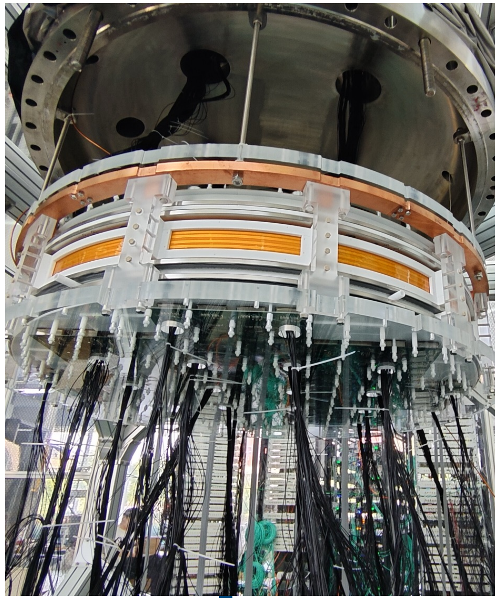


2015 - 2019

PandaX-4T(3.7 ton)

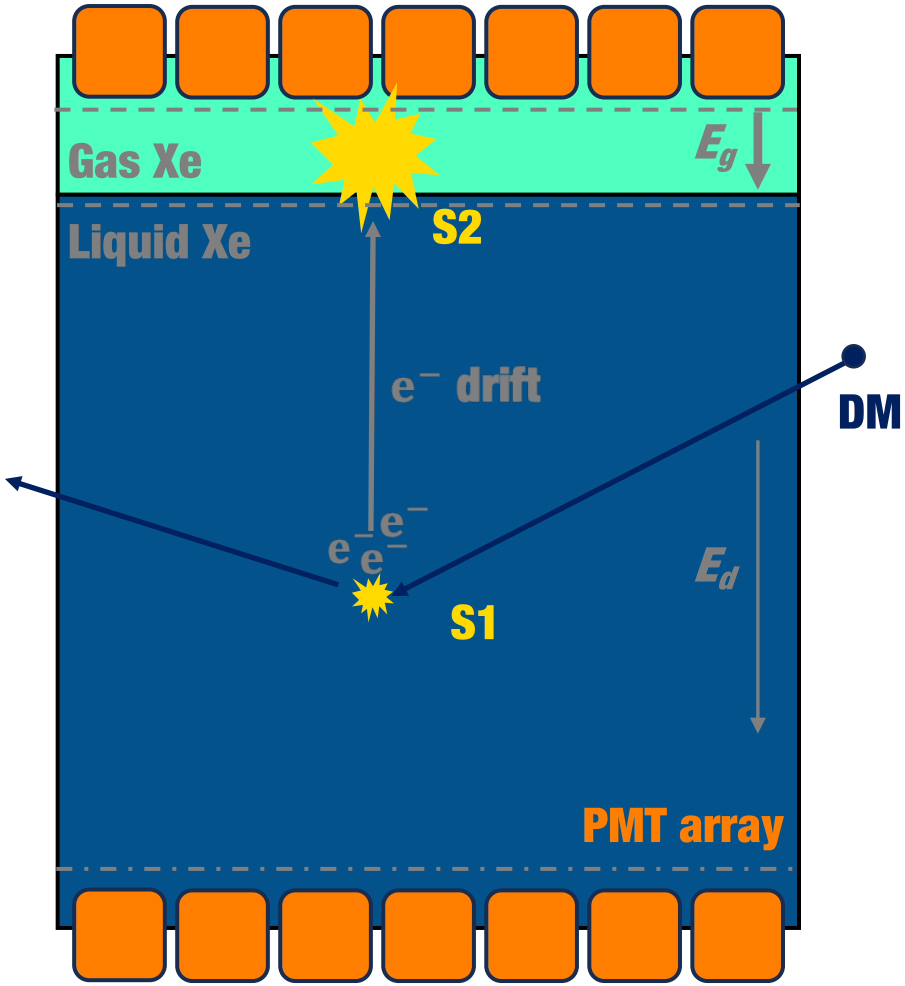
2020 - Current

PandaX-xT(20 ton)



~ 2027

Dual-Phase Xenon Time Projection Chamber



Liquid Xenon Properities

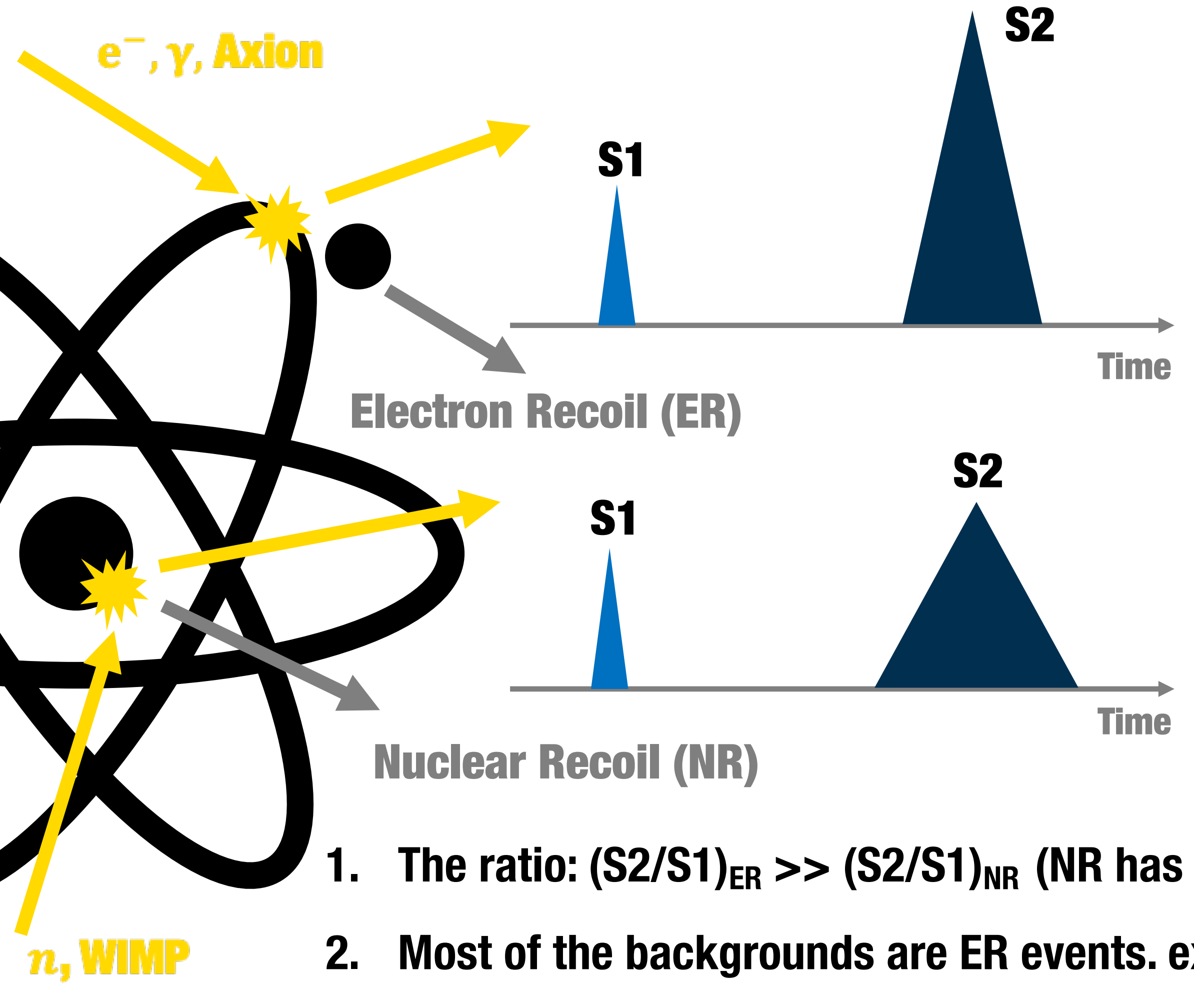
- ❑ Large atomic number Z = 54; High mass number ⟨A⟩ = 131.3
- ❑ High density @ 177K, $\langle \rho \rangle = 2.86\ g/cm^3$
- ❑ No long-lived radioisotopes in WIMP ROI
- ❑ Efficient UV scintillator (178 nm)

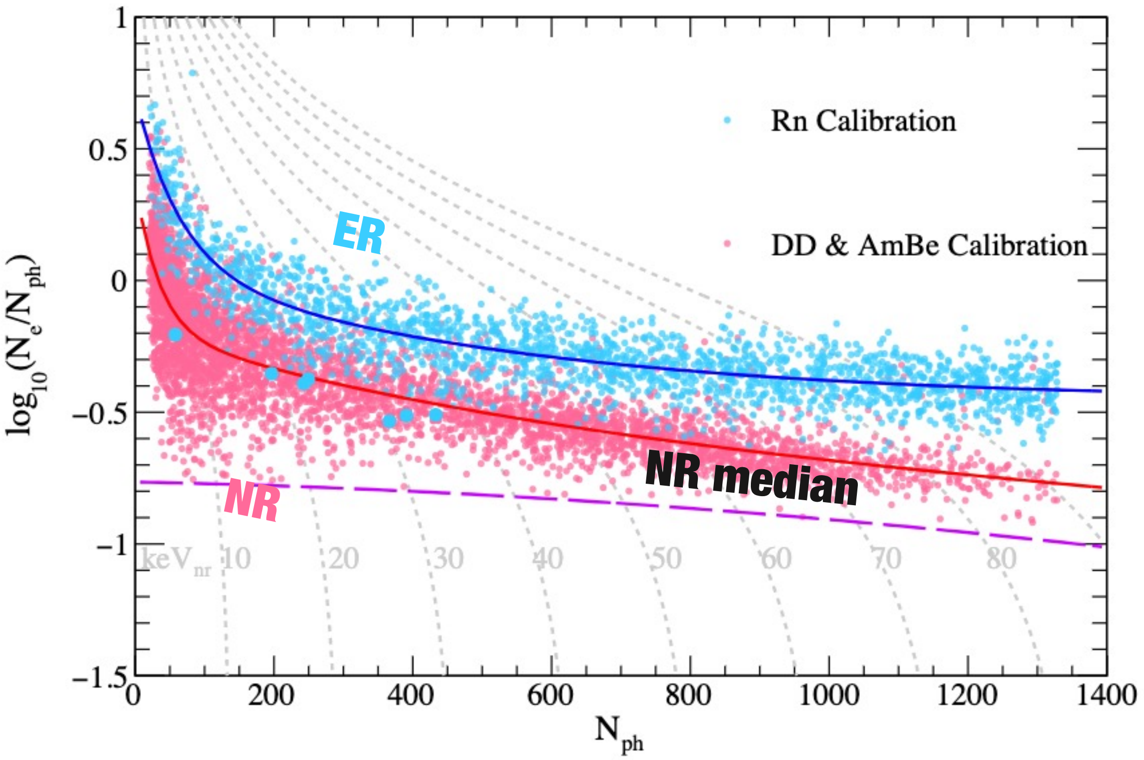
Liquid Xenon As DM Detection Medium

- ❑ Maximised interaction cross section for WIMP ($\propto A^2$)
- ❑ High stopping power and self-shielding
- ❑ Ultra-low intrinsic background
- ❑ Scintillation and Ionization Combined: Discrimination of nuclear recoil and electron recoil; 3D position reconstruction
- ❑ Scalable – further sensitivity improvement

https://indico.bnl.gov/event/9858/

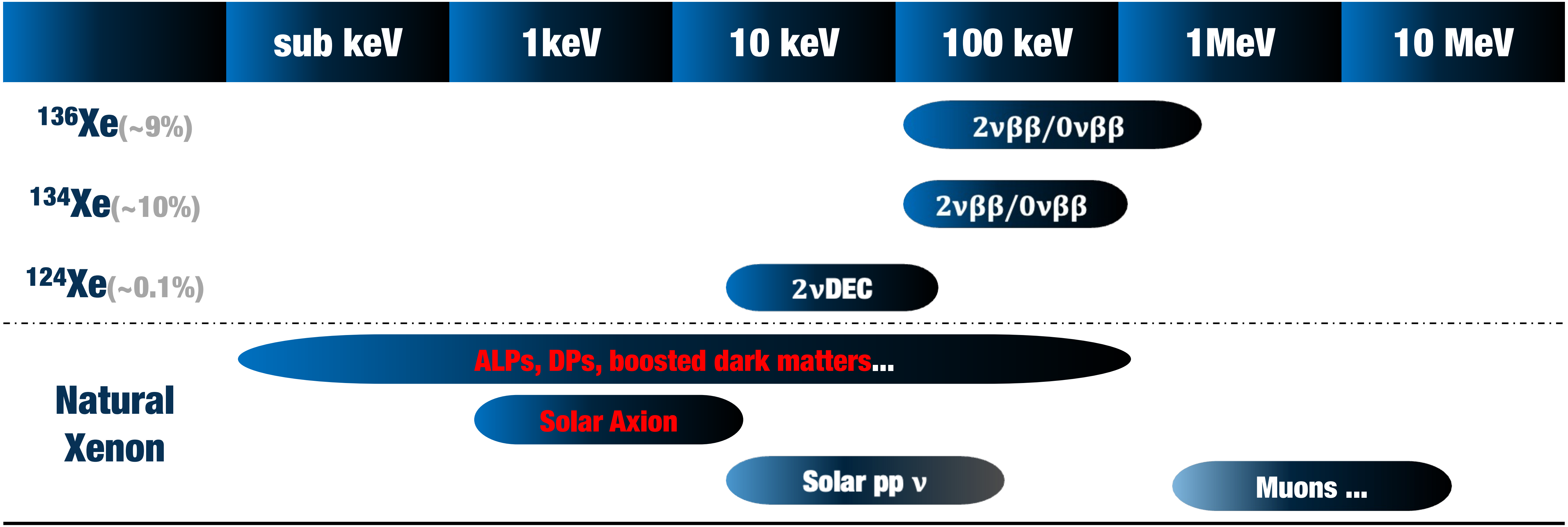
Nuclear Recoil V.S. Electron Recoil



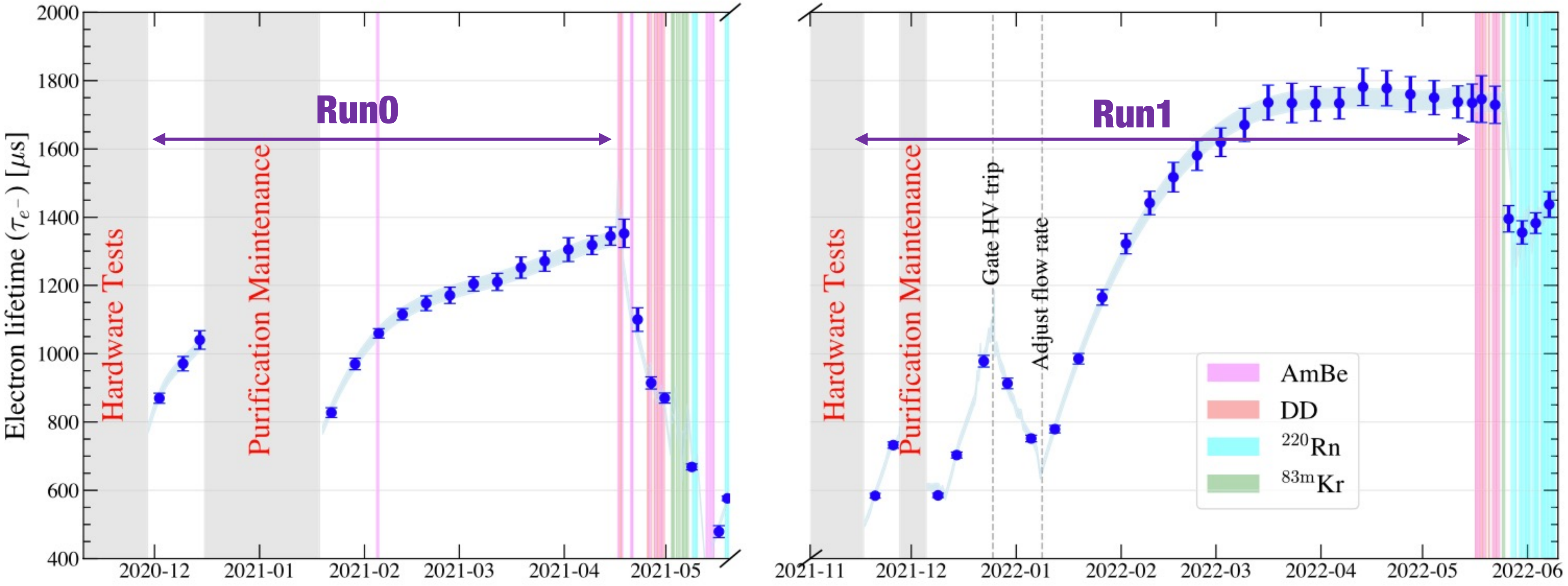


1. The ratio: $(S2/S1)_{ER} >> (S2/S1)_{NR}$ (NR has lower ionization rate but higher charge density);
2. Most of the backgrounds are ER events. exploring the ER region also holds promise for discovering new physics.
3. ER and NR response are calibrated separately: ^{220}Rn (ER), DD + AmBe (NR);

Rich Physics with Electron Recoil Data

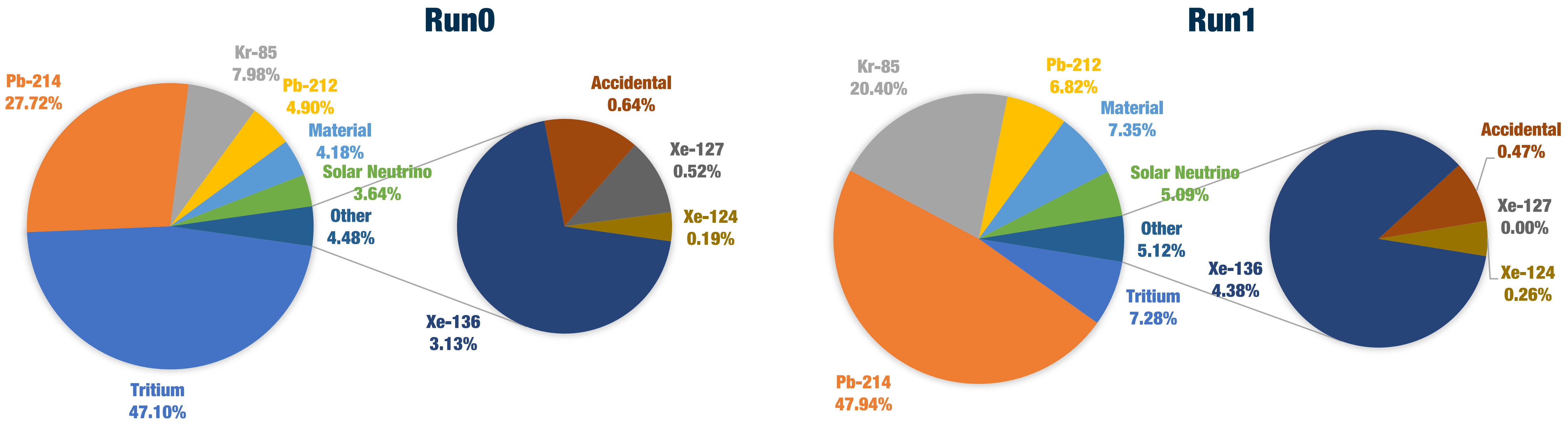


Data-taking of PandaX-4T



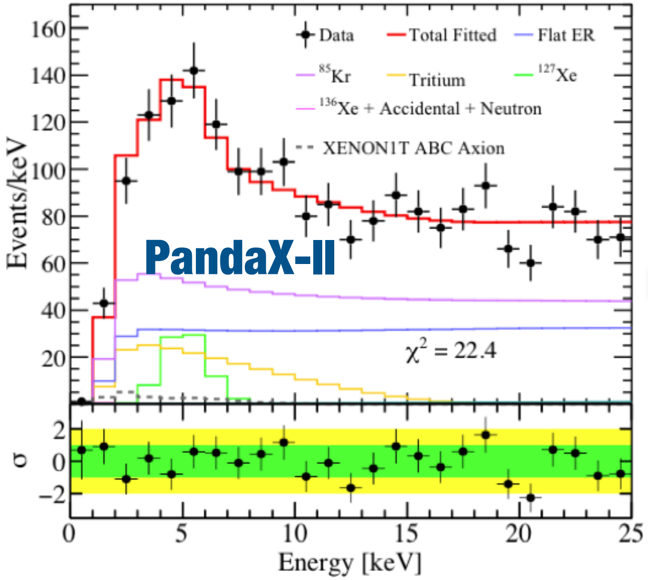
1. PandaX-4T has finished two phyiscs runs: Run0 and Run1, a total exposure of 1.54 ton×year after removed low-quality data;
2. Run0 results published @ 2021; Run0 + Run1 combined blind-analysis published @ 2025.

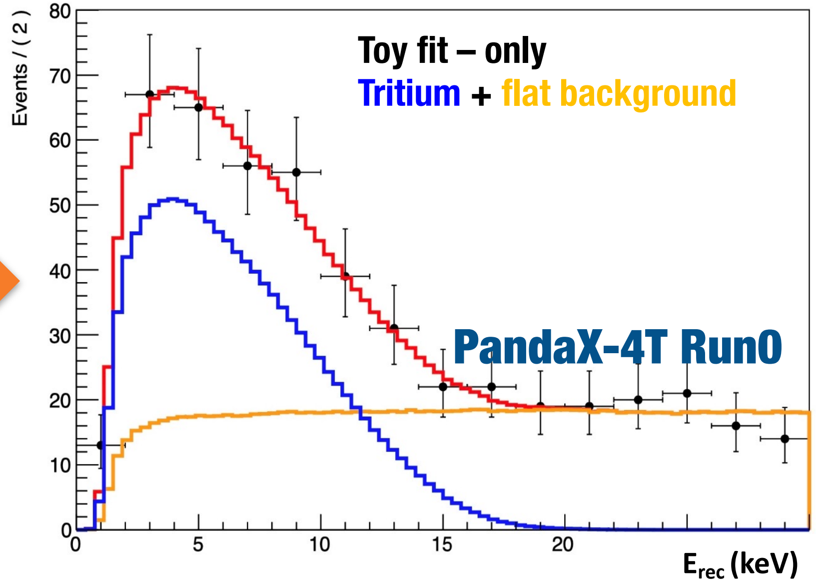
Background Model for keV region

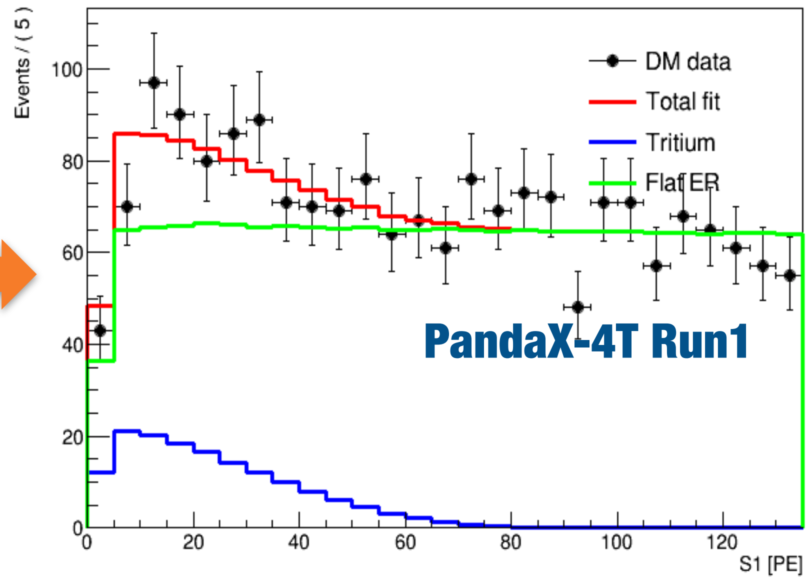


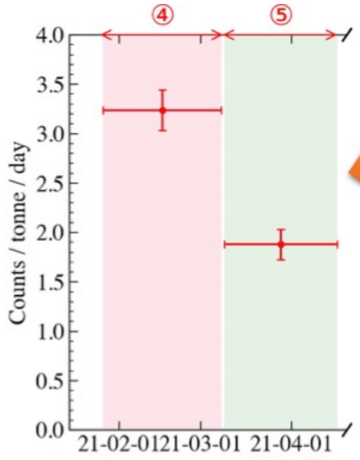
1. Energy Region of Interest: *S1* > 2 Photoelectrons (PE), E_{rec} < 30 keV, and ER 99.5% acceptance;
2. Background Composition: Tritium, ^{214}Pb, ^{85}Kr dominates the background level
   - Run0: 0.20 events/day/ton/keV   Run1: 0.14 events/day/ton/keV

Tritium







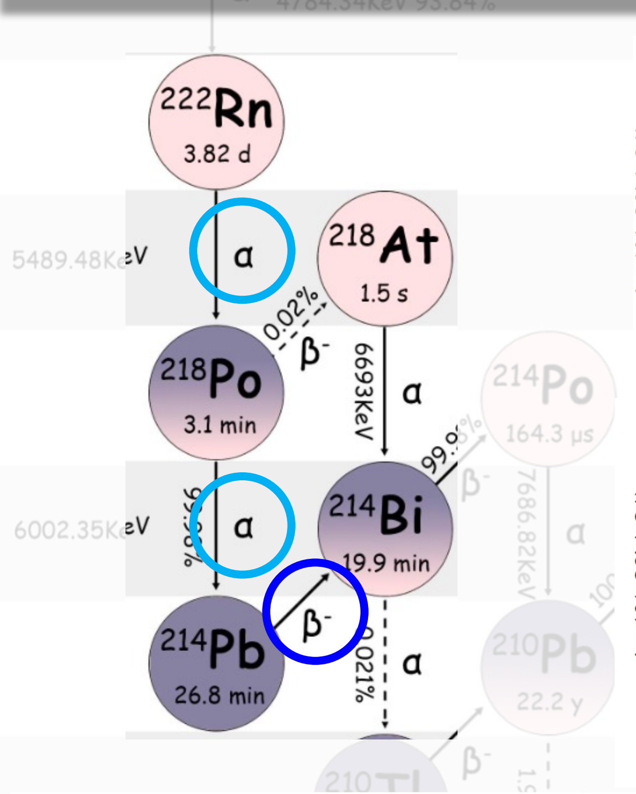


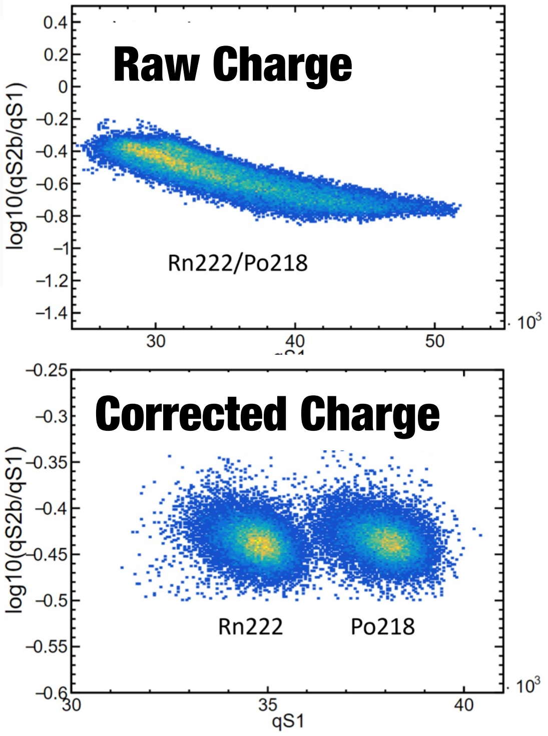
Run0: Set ①-⑤

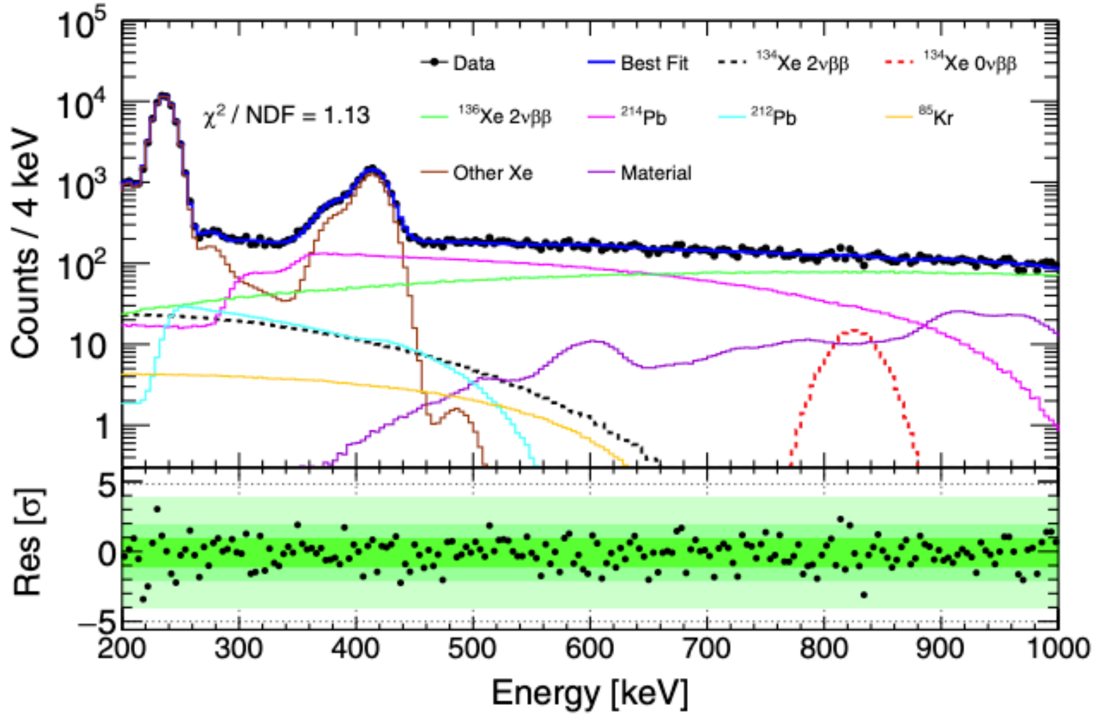
Run1: Set ①-⑥

- Tritium spectrum identified in the data;
- Likely originated from the tritium calibration at the end of PandaX-II;
- Estimation of tritium level in Run 1: fitting S1 spectrum, keeping S2 blinded (Set to free in fit);
- Been suppressed by a factor of 5.

Radon



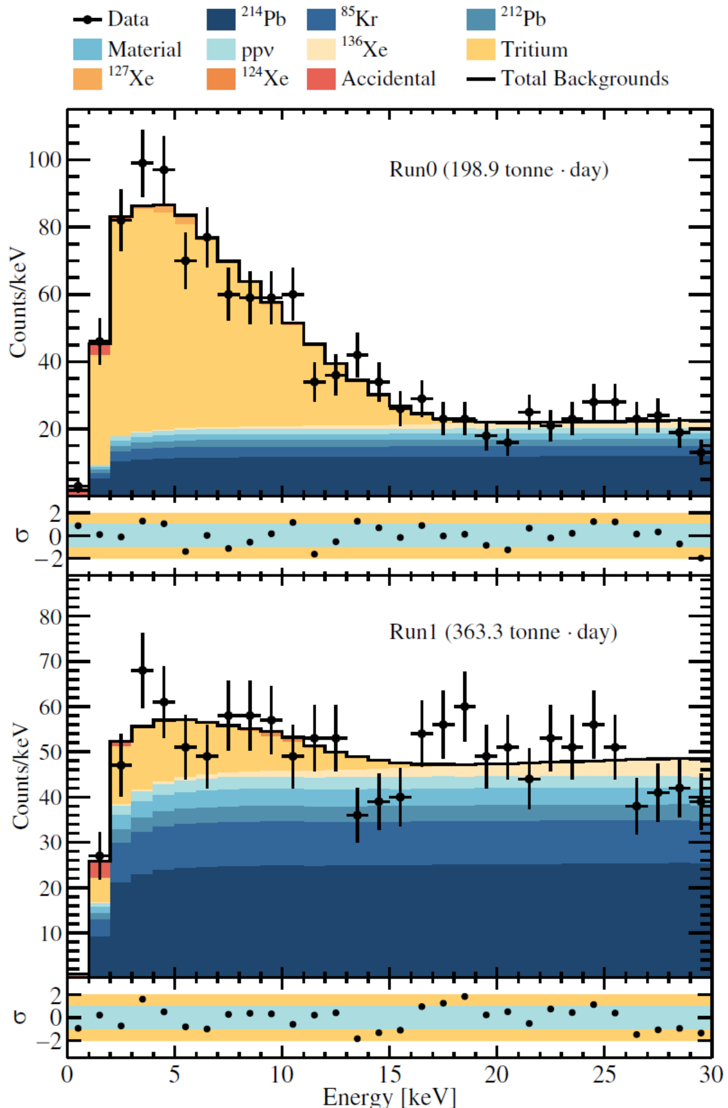




Rn level	μBq/kg
Run 0	7.07 ± 0.02(stat.) ± 0.23(sys.)
Run 1	8.67 ± 0.01(stat.) ± 0.27(sys.)

1. Depletion effect: decreased concentration of longer-lived daughter nuclide compared to the parent;
2. Side band fit to determine exact contribution: from 200 keV to 1000 keV.

Best-fit of keV Background Model

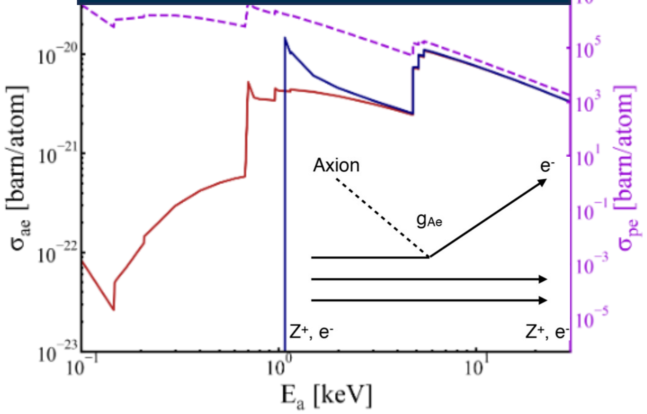


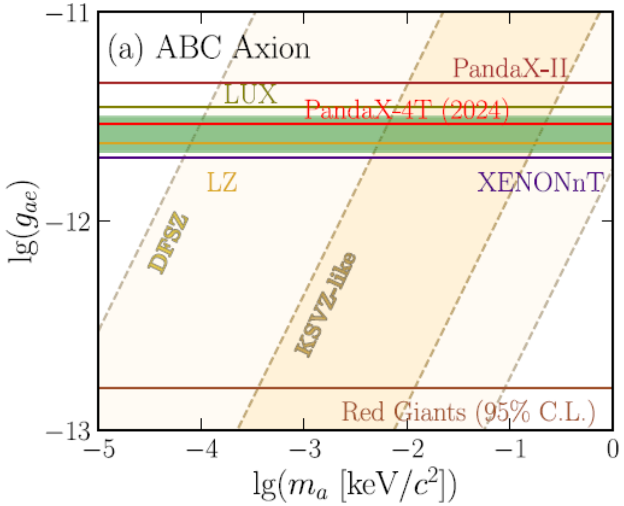
	Run0		Run1	
Run	Expected	Fitted	Expected	Fitted
Tritium	···	578.6 ± 32.5	···	118.4 ± 31.1
^{214}Pb	327.2 ± 18.8	328.0 ± 17.1	724.0 ± 61.5	700.3 ± 45.3
^{212}Pb	57.8 ± 14.7	57.3 ± 14.1	103.3 ± 26.9	96.5 ± 23.8
^{85}Kr	94.2 ± 47.3	87.3 ± 31.2	308.1 ± 95.2	272.2 ± 58.9
Material	49.4 ± 3.3	49.5 ± 3.1	111.7 ± 9.9	105.9 ± 7.8
^{136}Xe	36.9 ± 2.5	36.9 ± 2.4	66.2 ± 5.9	62.3 ± 4.6
^{127}Xe	6.1 ± 0.3	6.1 ± 0.3	0.0 ± 0.0	0.0 ± 0.0
^{124}Xe	2.3 ± 0.6	2.3 ± 0.6	4.0 ± 1.1	3.9 ± 1.1
Solar ν	43.0 ± 4.6	42.9 ± 4.5	76.8 ± 9.4	72.6 ± 8.1
Accidental	7.6 ± 2.4	7.8 ± 2.1	7.1 ± 2.3	7.0 ± 1.9
Total	···	1196.6 ± 32.6	···	1439.2 ± 36.2
Observed	1197		1431	

- **A combined fit of Run0 and Run1 in 1D energy space;**
- **Tritium is set to free in fit;**
- **No excess found: consistent with background model (p-value = 0.16).**

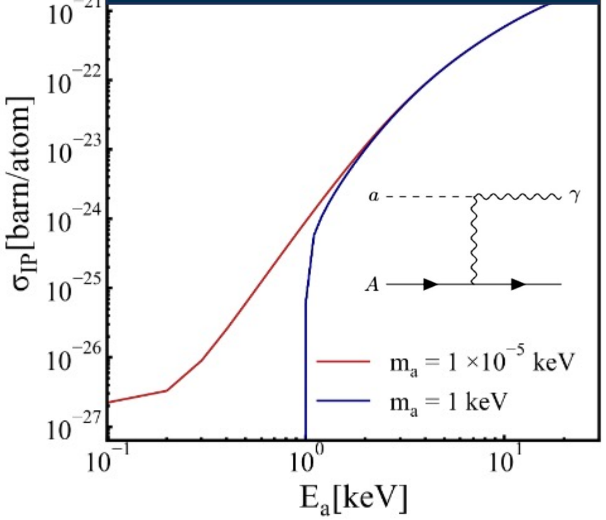
Solar Axions

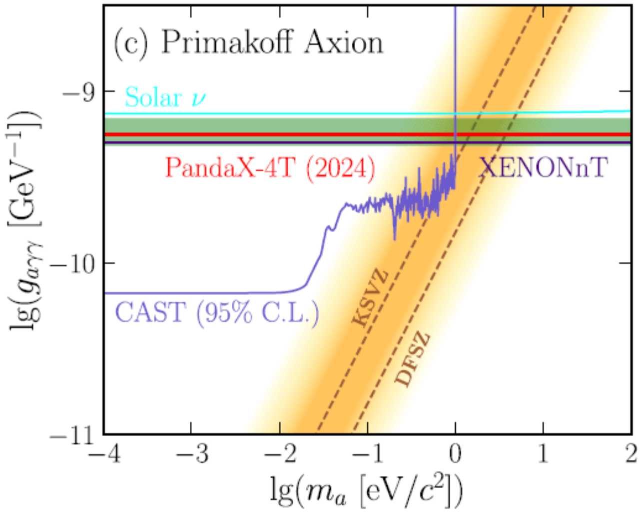
axio-electric





inverse Primakoff





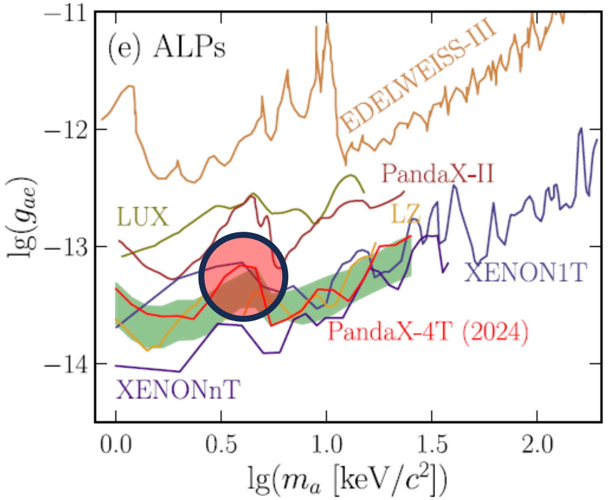
1. **Solar axion can have O(keV) energy deposition in liquid xenon;**
2. **Two detection channels for solar axion: axio-electric effect and inverse Primakoff effect;**
3. **Indpendent fit of different couplings in energy space: g_{ae} , $g_{a\gamma\gamma}$.**

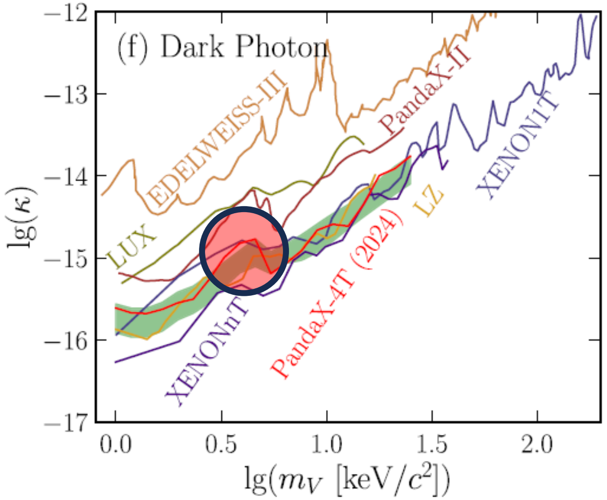
$$\frac{dR_{ABC}}{dE_r} = \frac{N_A}{A}\left(\frac{d\Phi_A}{dE_a}(E_r) + \frac{d\Phi_B}{dE_a}(E_r) + \frac{d\Phi_C}{dE_a}(E_r)\right) \times \sigma_{ae}(E_r).$$

$$\frac{dR}{dE_r} = \frac{N_A}{A} \times \frac{d\Phi_P}{dEa}(E_r) \times \sigma_{IP}(E_r)$$

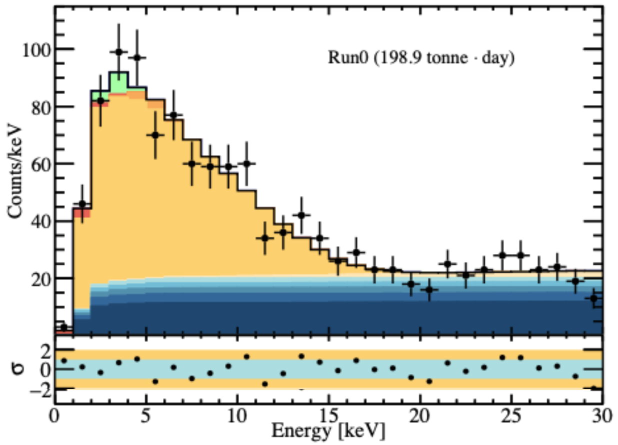
Phys. Rev. Lett. a134, 041001

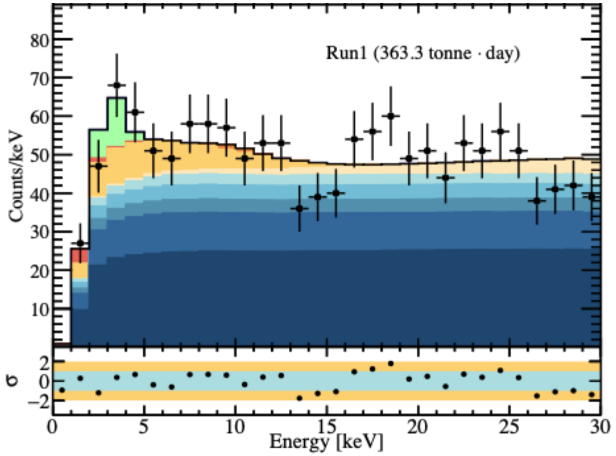
Light Dark Matters

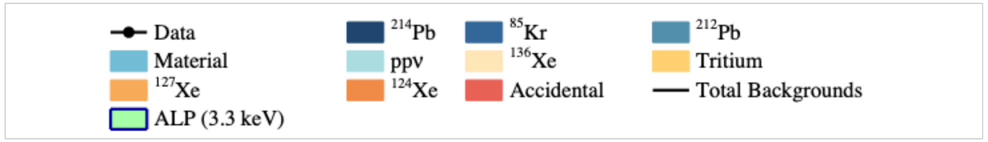




1. **Light Dark matter searching: Mono-energetic signals scan.**
   - **Axionlike Particles (ALPs) and Dark Photons (DPs)**
   - **Fermionic Dark Matter – ν conversion**
2. **Data fluctuation yields a 1.9σ (local) excess @ 3-5 keV;**

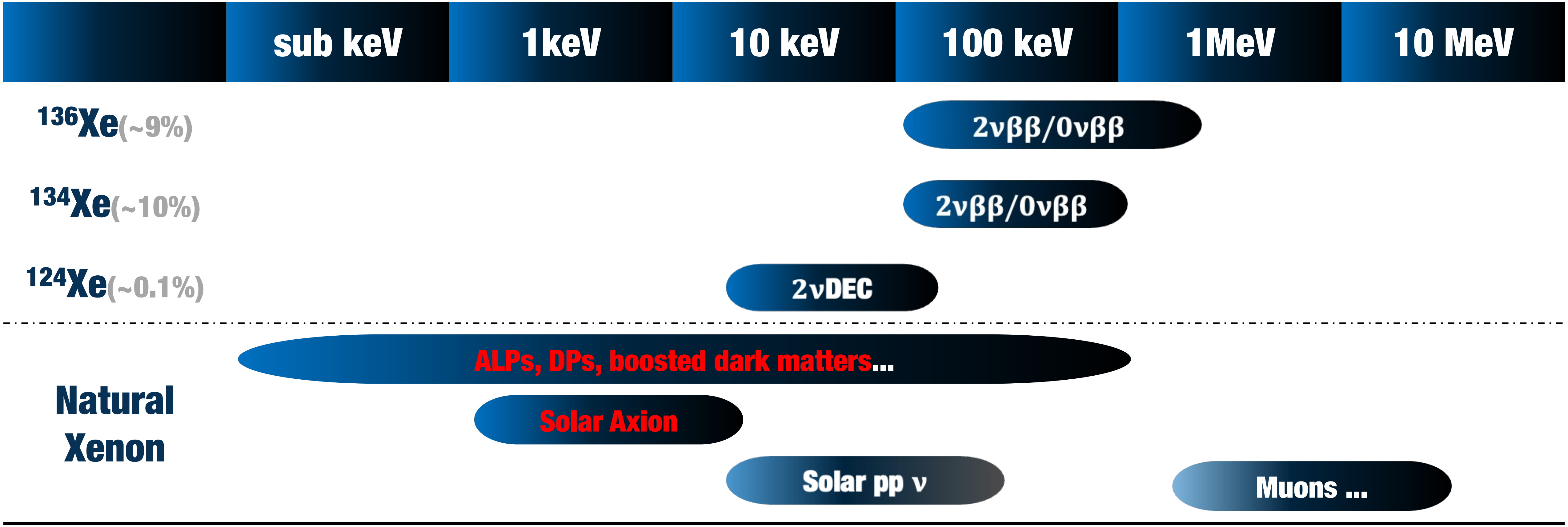






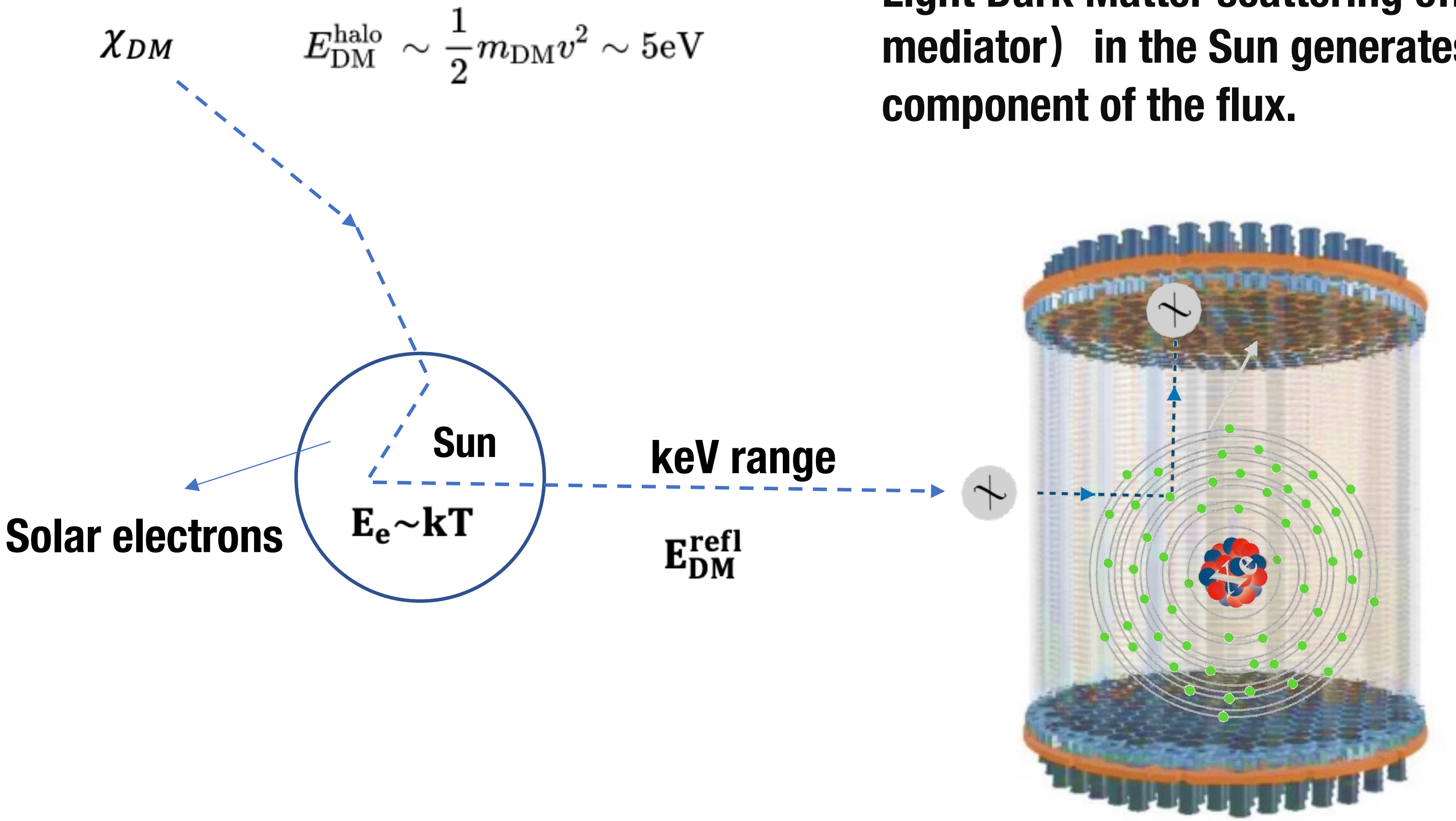
Phys. Rev. Lett. 134, 041001

Rich Physics with Electron Recoil Data



Solar Boosted Dark Matter

Light Dark Matter scattering off free electrons （heavy mediator） in the Sun generates a new (more energetic) component of the flux.



- ➢ Dark Matter mass:

  10keV-10MeV

- ➢ Energy deposition:

  10 to ~10^3eV

Solar Boosted Dark Matter

Target density of Xenon

Reference cross section

- Solar Reflected DM Flux

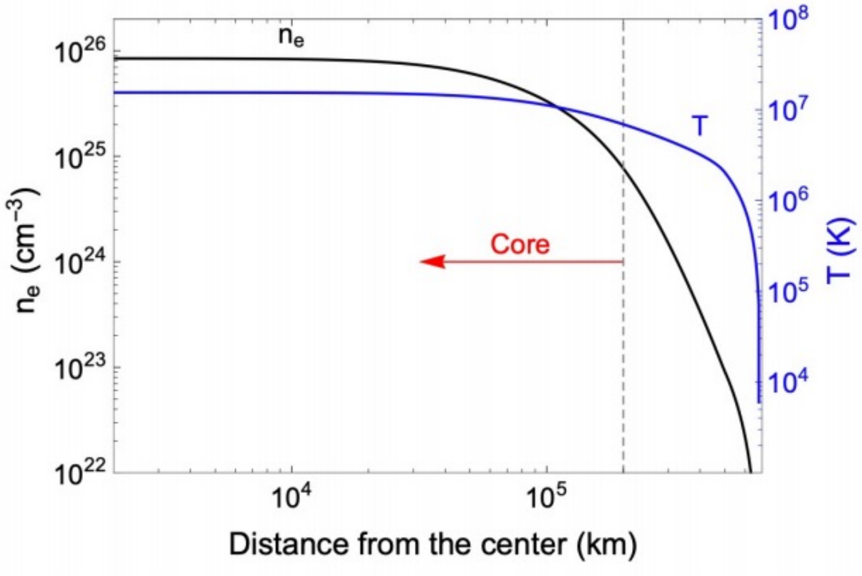
$$\frac{\mathrm{d}R}{\mathrm{d}E_R} = N_T \Phi_{halo} \cdot \frac{1}{E_R} \frac{\sigma_e}{8\mu^2_{\mathrm{DM,e}}} \int dqq \left|f_{nl}\left(q, p'_e\right)\right|^2 \left|F_{\mathrm{DM}}(q)\right|^2 \cdot \int_{E_{\mathrm{min}}} dE \frac{m_{\mathrm{DM}}}{2E} \frac{16\pi R^2_{\odot}}{4\pi(1\ \mathrm{A.U.})^2} \cdot F_{A_\rho}(E)$$

- Ionization Form Factor
  - ✓ Depends on momentum transfer q and final state electron momentum.
  - ✓ DarkART （used） same as CRBDM

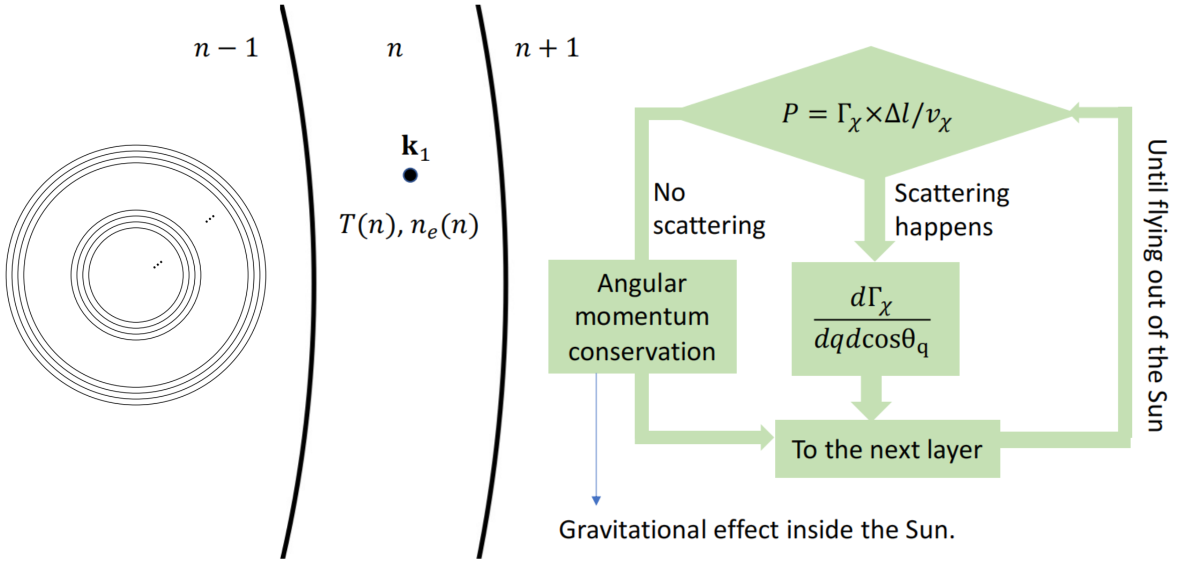
- Dark Matter Form Factor
  - ✓ FDM = 1 heavy mediator(contact interaction)
  - ✓ FDM ~ 1/q2 light mediator

Solar Boosted Dark Matter

From Haipeng An's team



The details of the simulation



- temperature and electron density distributions are isotropic.
- divide the Sun into slices.
- Gravitational effect considered in an effective R = 4R_sun

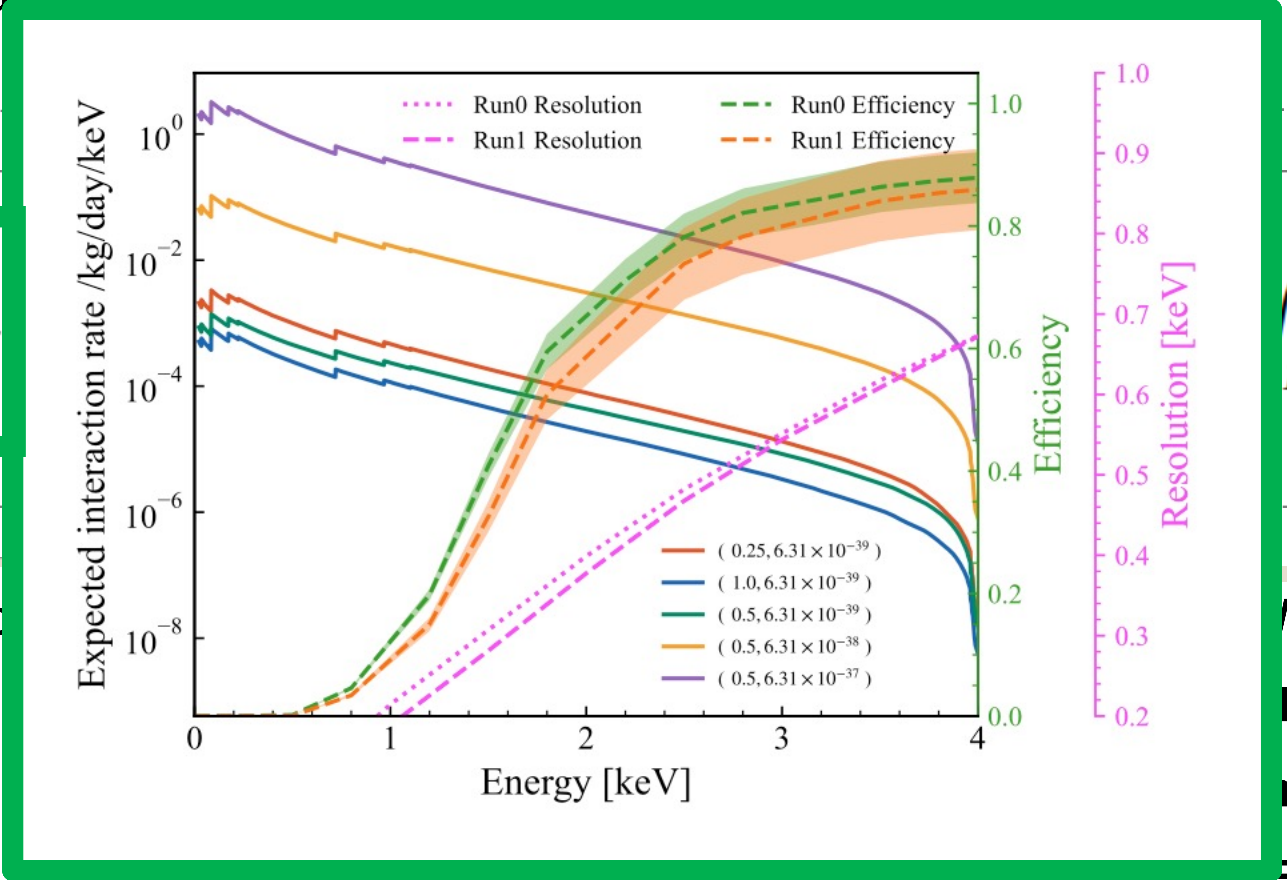
Solar Boosted Dark Matter

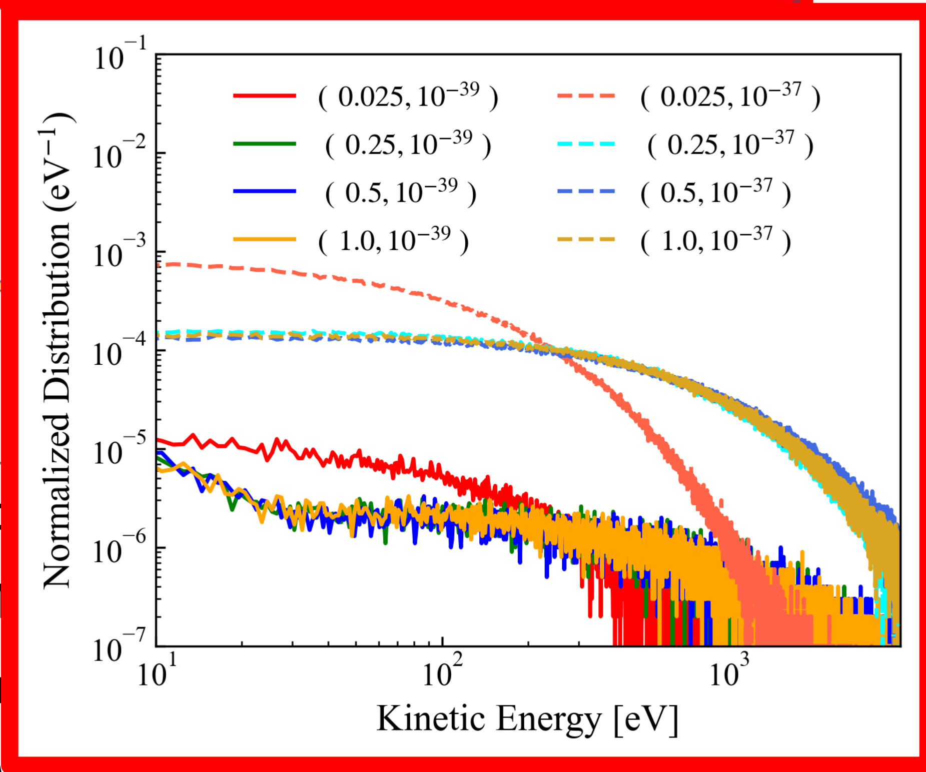
Target density of Xenon

Reference cross section

➢ **Solar Reflected DM Flux**

$\frac{dR}{dE_R}$





➢ Io

DarkART (used) same as CRBDM

Mat

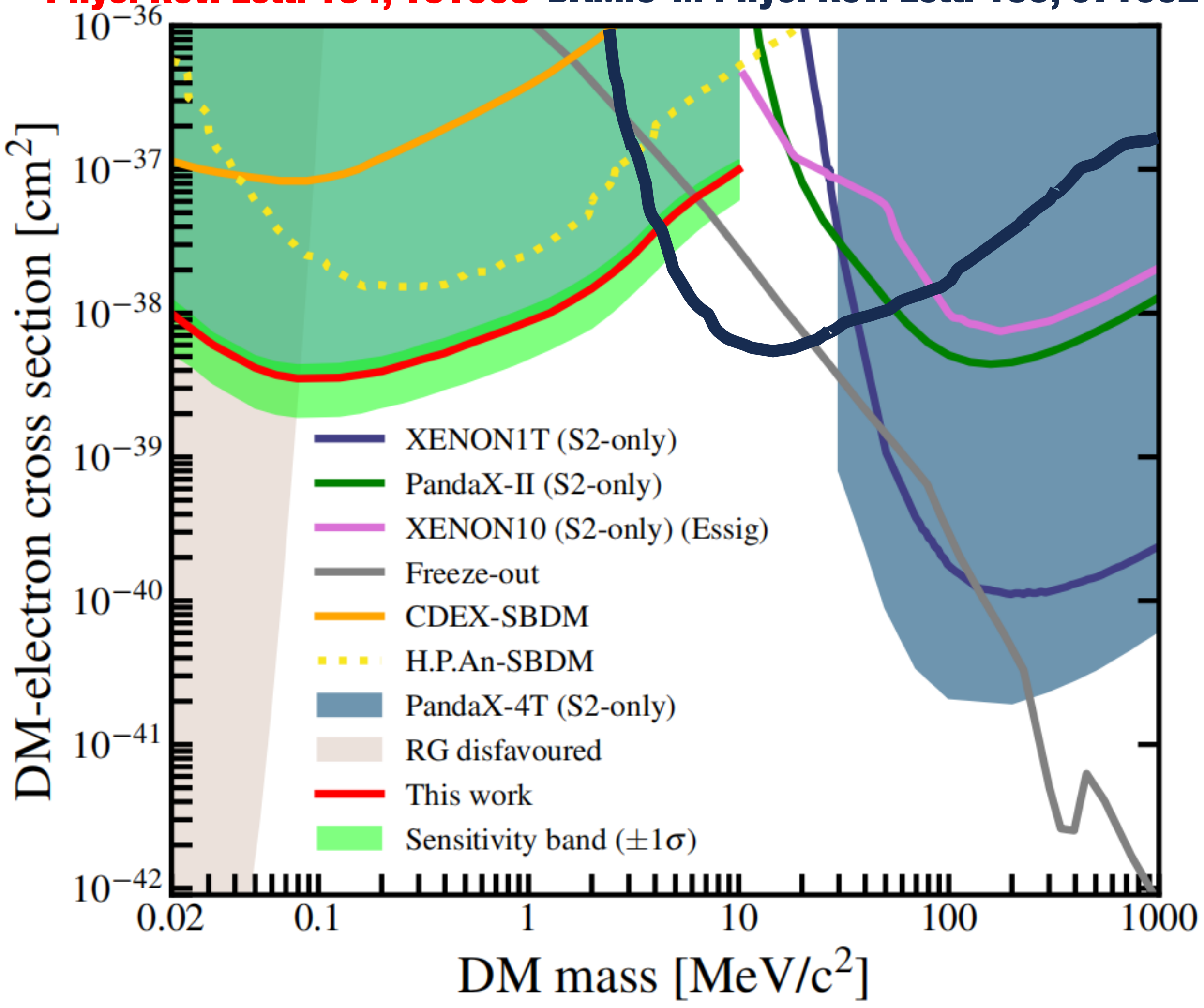
DM

ter

FDM ~ 1/q2 light mediator

Solar Boosted Dark Matter

Phys. Rev. Lett. 134, 161003 DAMIC-M Phys. Rev. Lett. 135, 071002



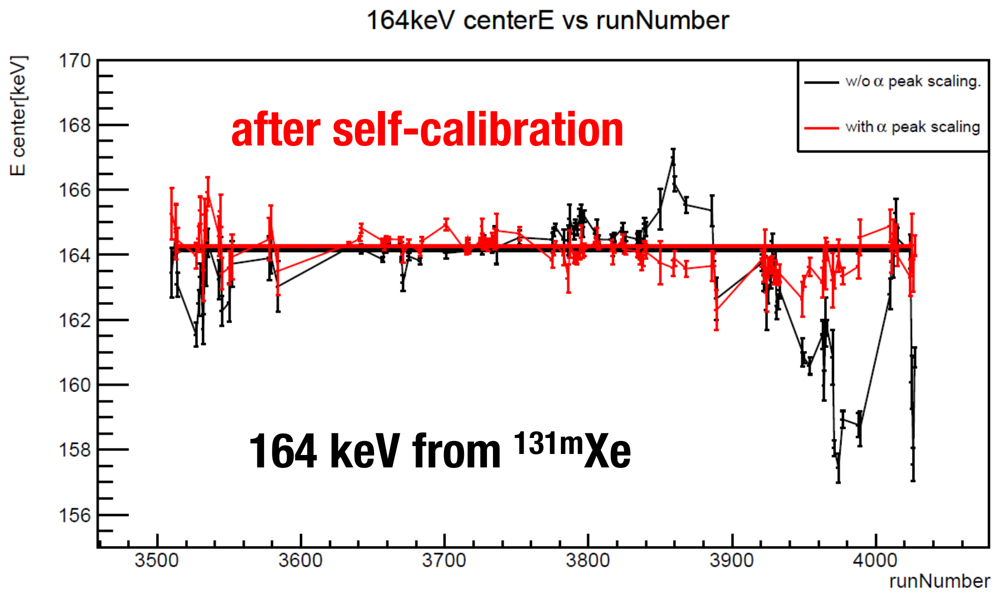
- The experimental search results using the xenon detector yield the most stringent cross-section for mass ranging from 0.02 to 10 MeV/c^2
- Combined with DAMIC-M new result, almost all the parameter space below 200 MeV for Freeze-out model was ruled out.

Thanks for attentions

Backup

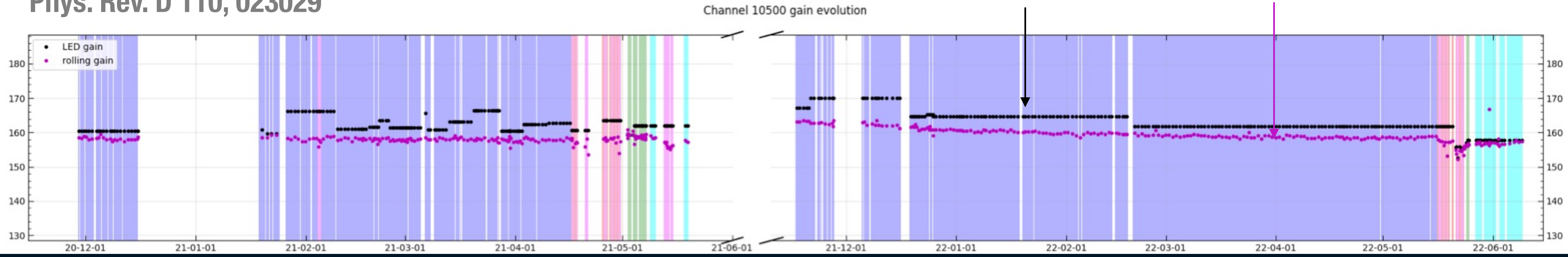
Updates in Data Reconstruction

- ❑Additional 10 top PMTs turn-off
- ❑Degrading of PMTs: LED-calibration to Self-calibration
- ❑Temporal variation of signal yield
- ❑Event builder: Fix-window and S1 quality in prior
- ❑others ......



Phys. Rev. D 110, 023029

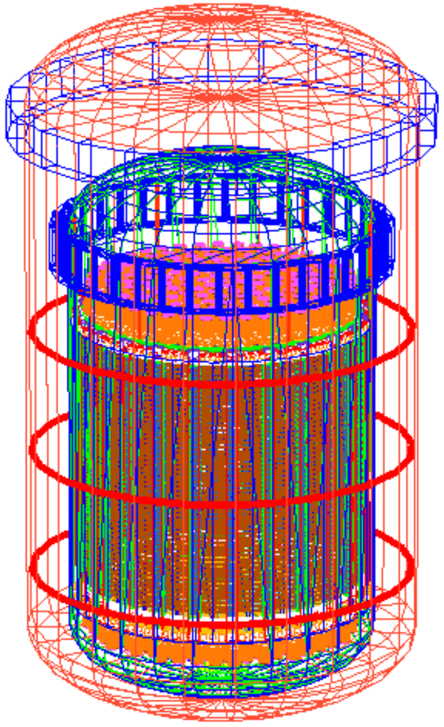
LED calibration vs Self-calibration



Building the Background Model

1. Material Screening and Geant4-based Simulation

- HPGe, ICP-MS, etc
- BambooMC

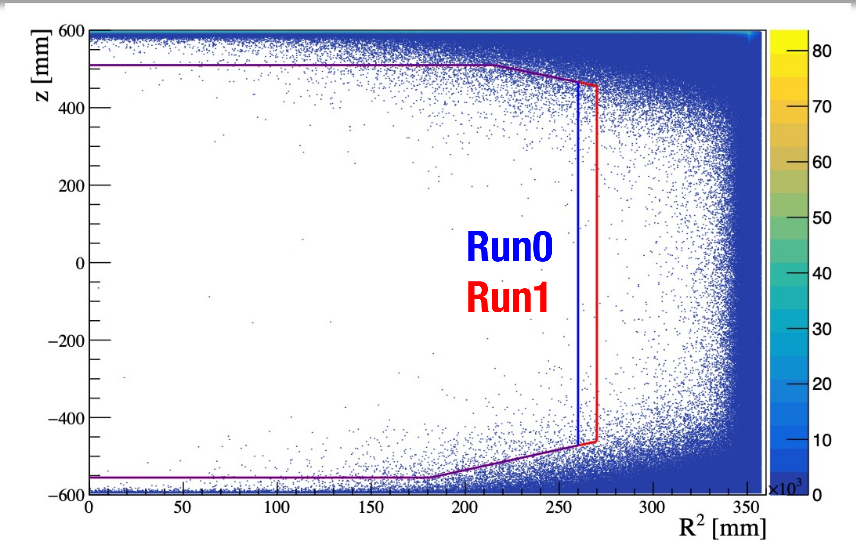


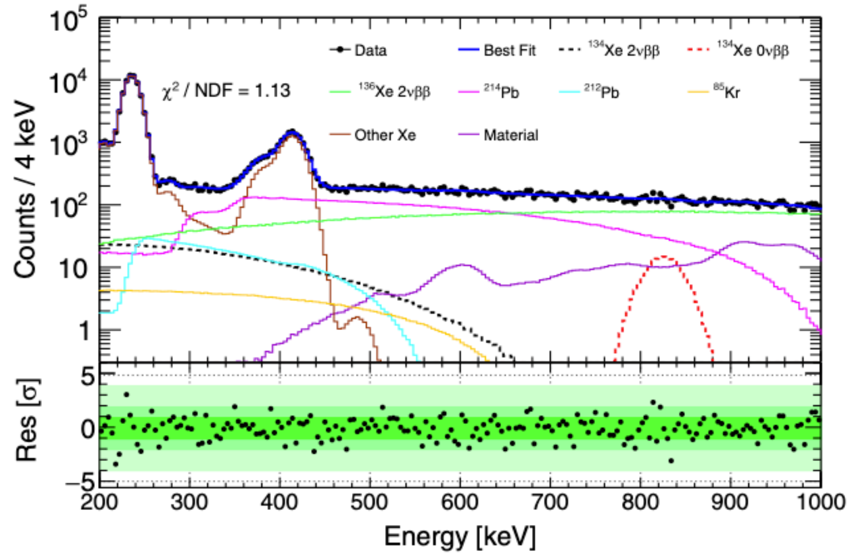
2. Fiducial Volume and Quality Selection

- r - dependent material background
- S1/S2 pulse shape and hit pattern

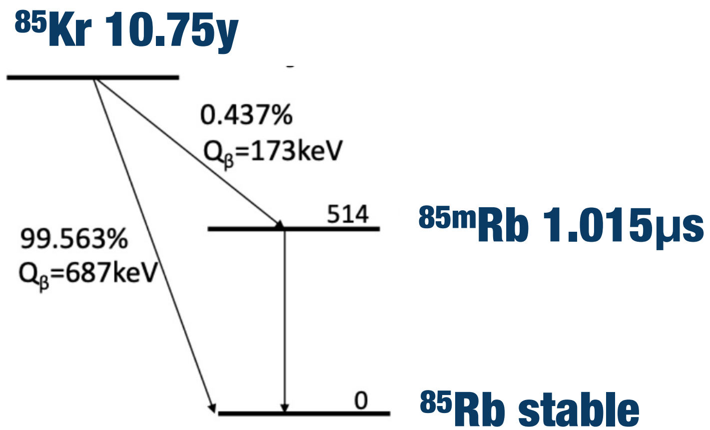
3. Side band analysis:

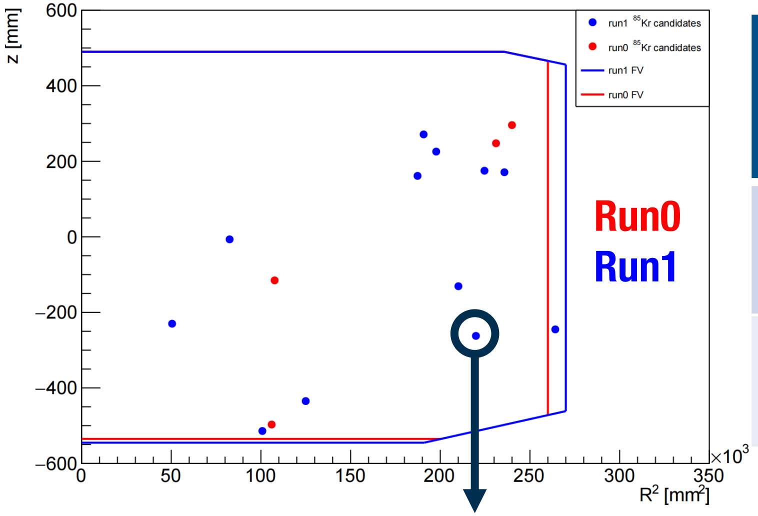
- high energy alphas in decay chain
- spectrum fitting in high energy: uncertainty reduction





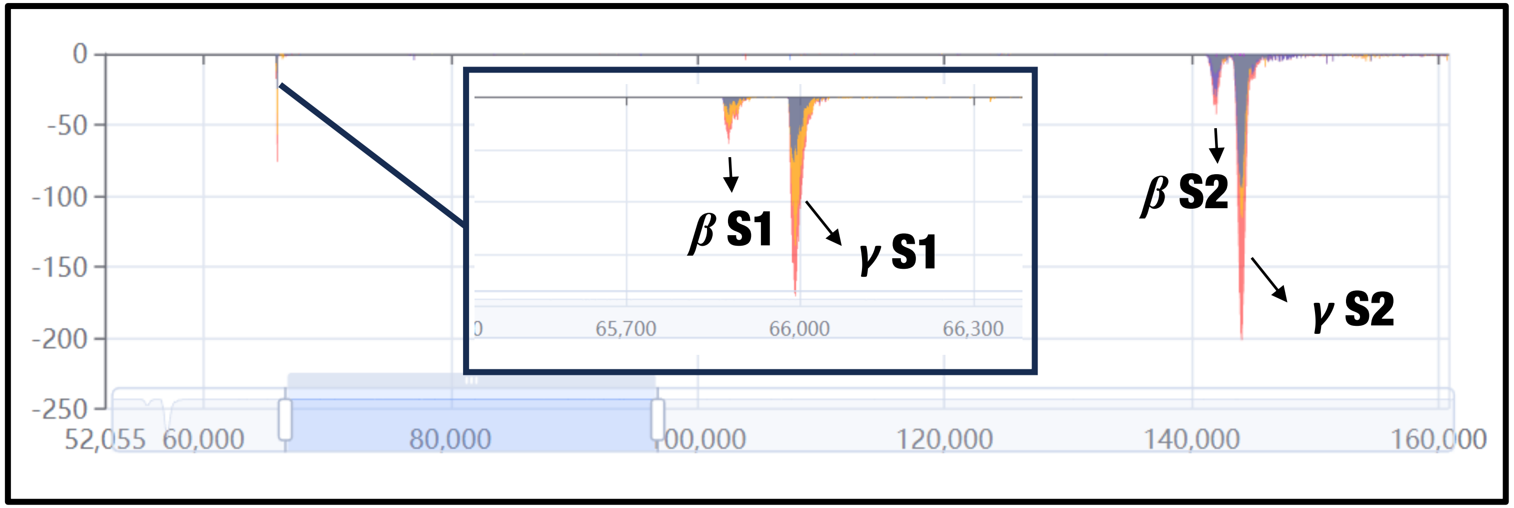
Krypton





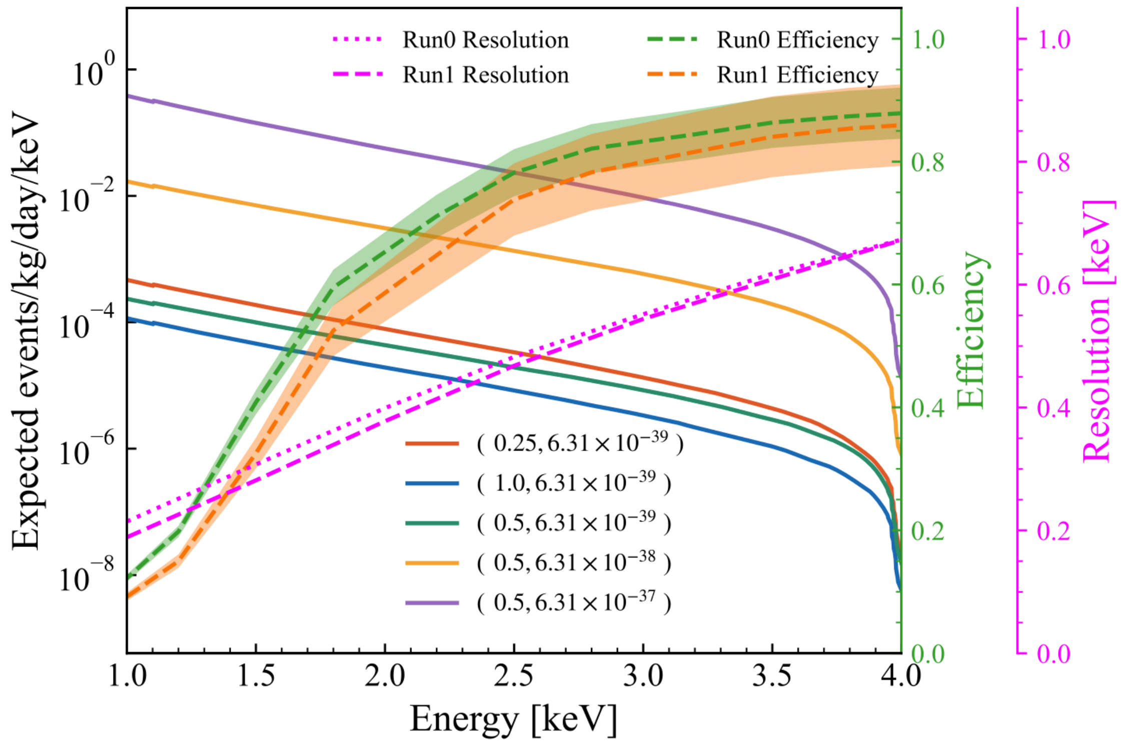
a typical waveform

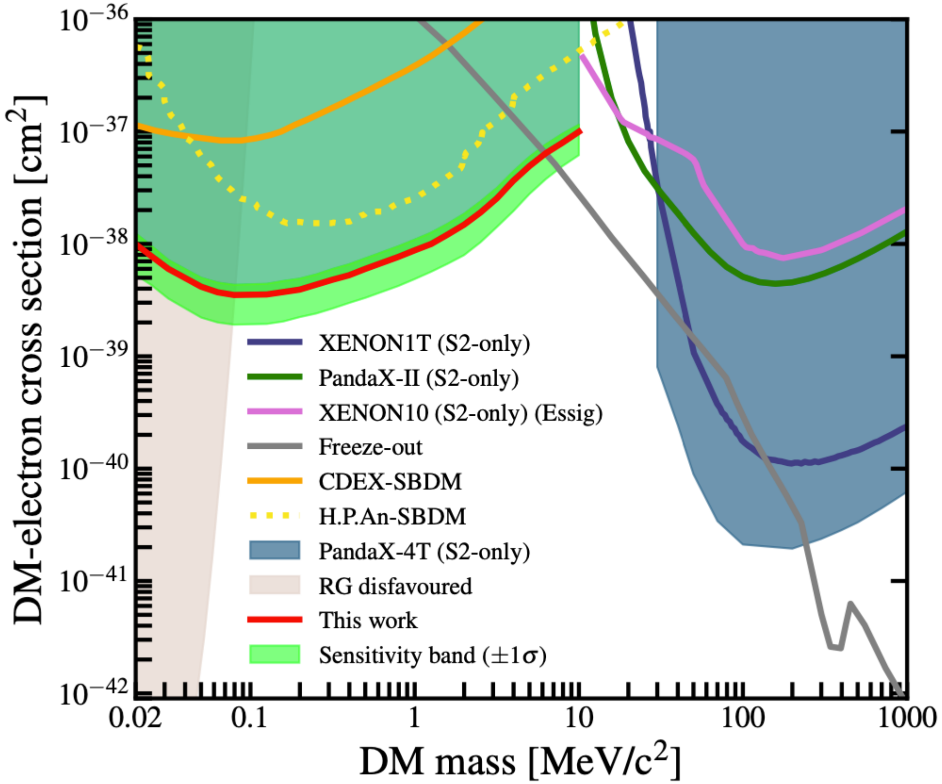
	$\beta-\gamma$ events	accidental events	Kr/Xe [ppt (10^{-12})]
Run0	4	0.14 ± 0.04	0.5 ± 0.3
Run1	12	0.25 ± 0.05	0.9 ± 0.3



1. isotopic abudance: 2×10^{11}
2. $\beta-\gamma$ coincidence events with a branching ratio of 0.473%
3. Limited statistics lead to a large uncertainty

Solar Boosted Dark Matter

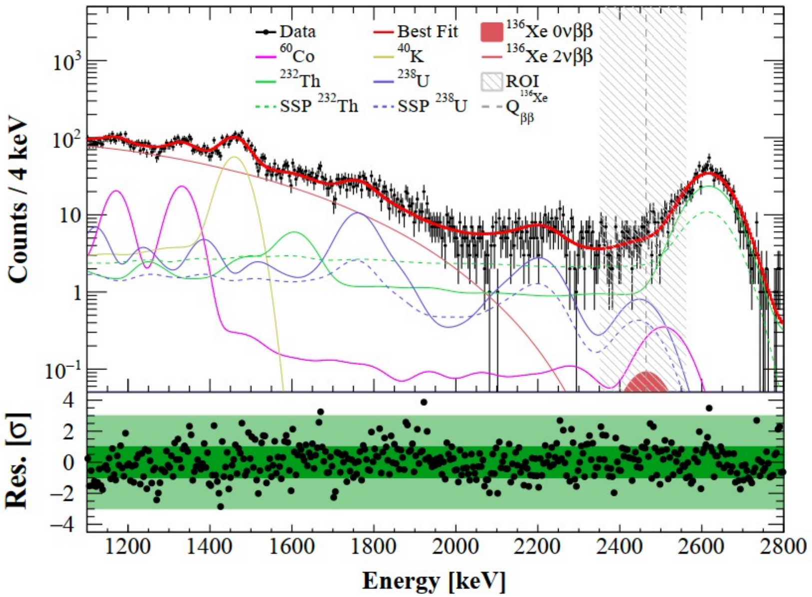


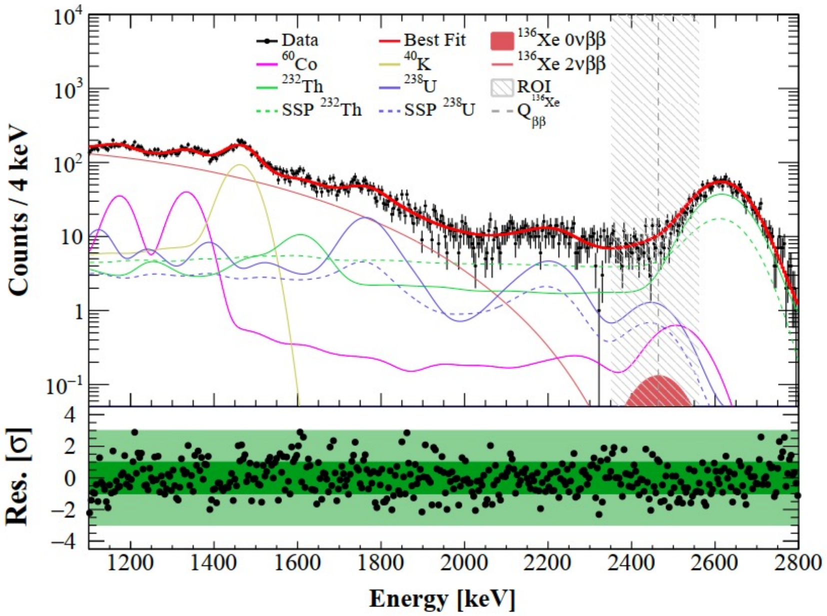


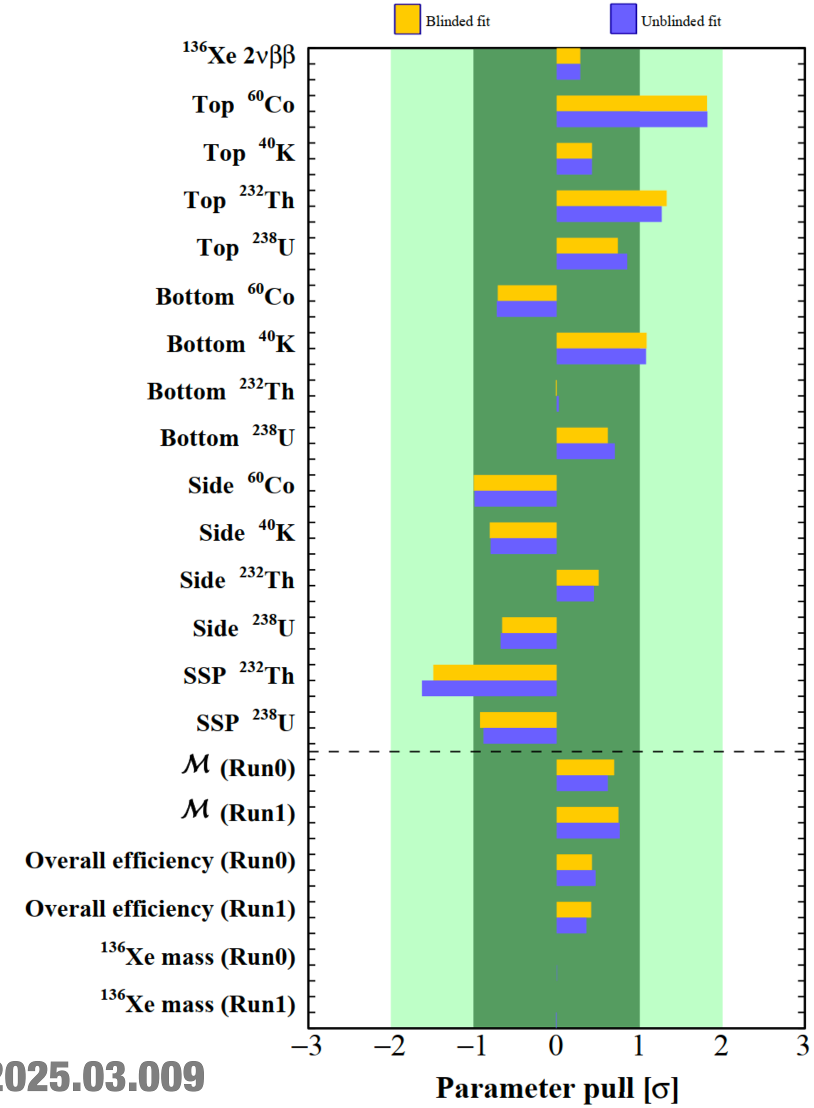
- Assume the temperature and electron density distributions are isotropic;
- The first experimental search results using the xenon detector yield the most stringent cross-section for mass ranging from 0.02 to 10 MeV/c^2, (23 fold improvement compared with earlier studies)

arXiv:2412.19970

Neutrinoless Double Beta Decay of Xe-136







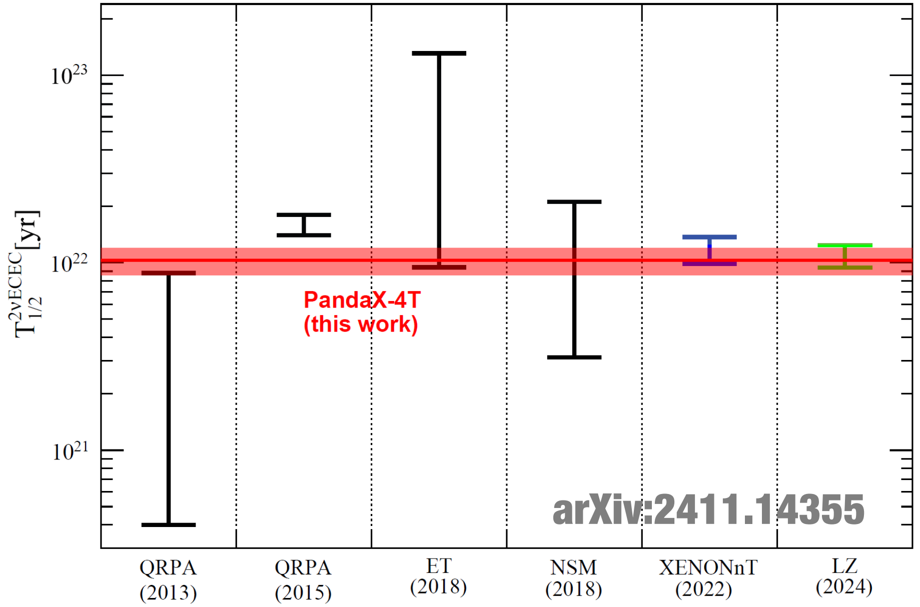
- ^{136}Xe $0\nu\beta\beta$ event rate is fitted to be 14±55 $t^{-1}yr^{-1}$, the upper limit of 111 $t^{-1}yr^{-1}$ at 90% C.L. is derived

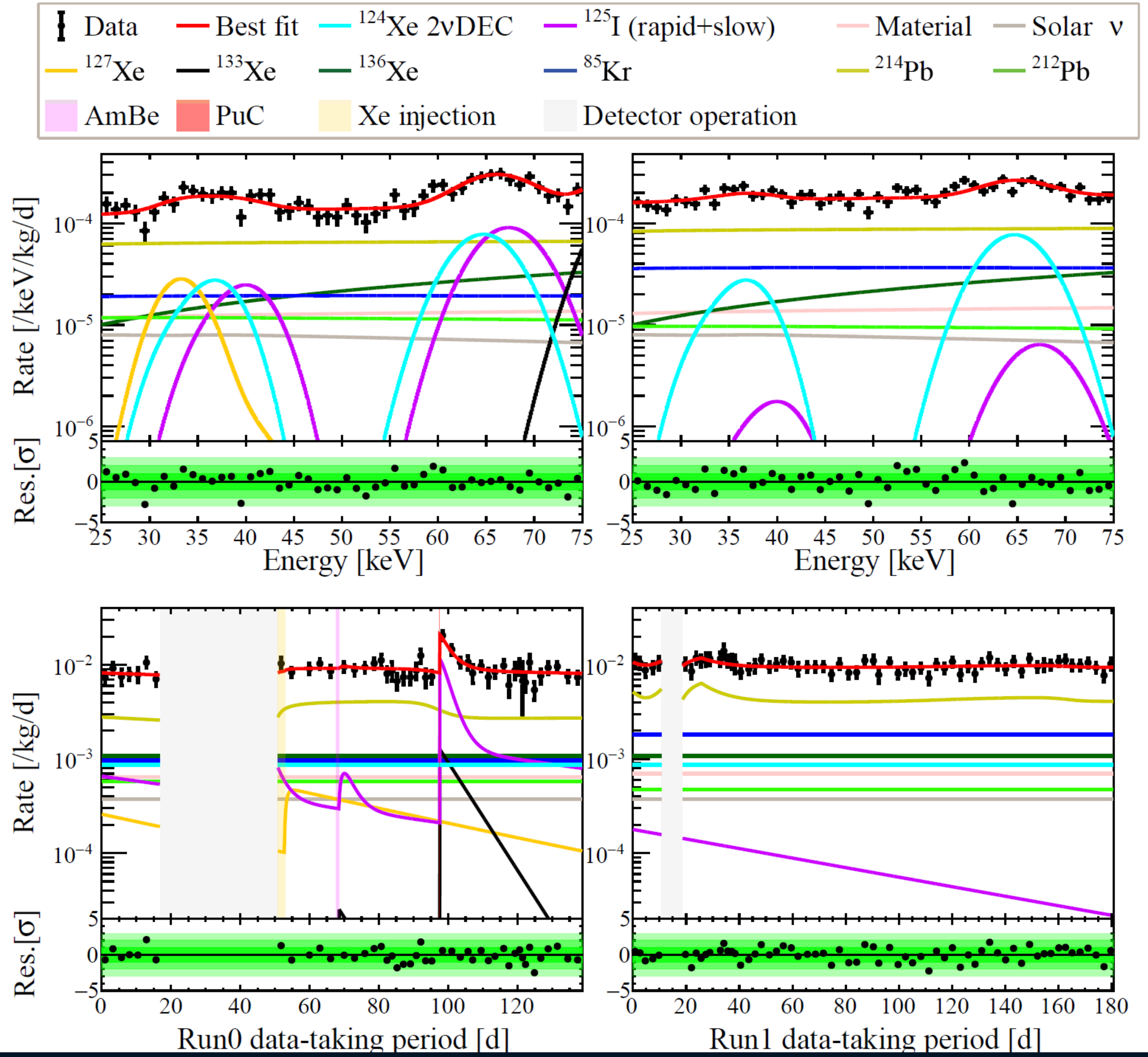
$$T_{1/2}^{0\nu\beta\beta} > 2.1\times 10^{24} \text{ yr at 90\% C.L.}$$

- Improvement to our previous PandaX-II results by an order of magnitude and to the XENON1T results by a factor of 1.8

Science Bulletin, 2025.03.009

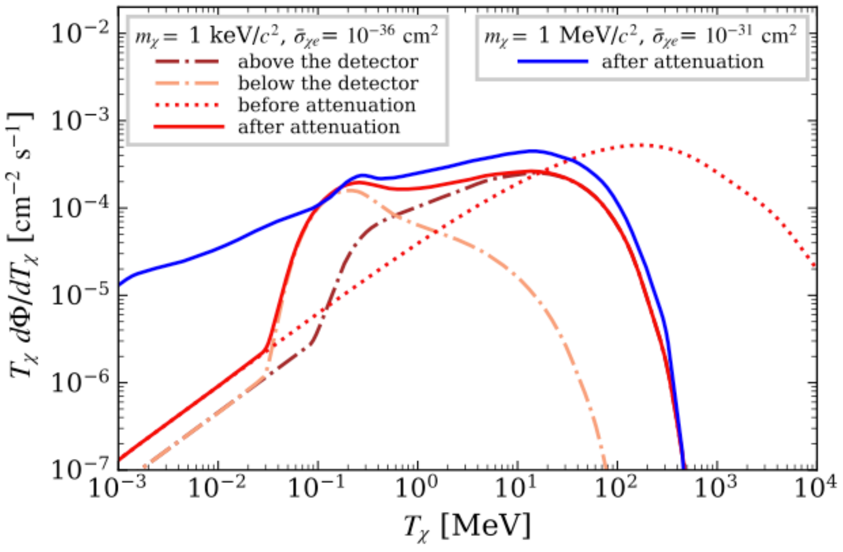
Measurement of 2υDEC Half-life of Xe-124

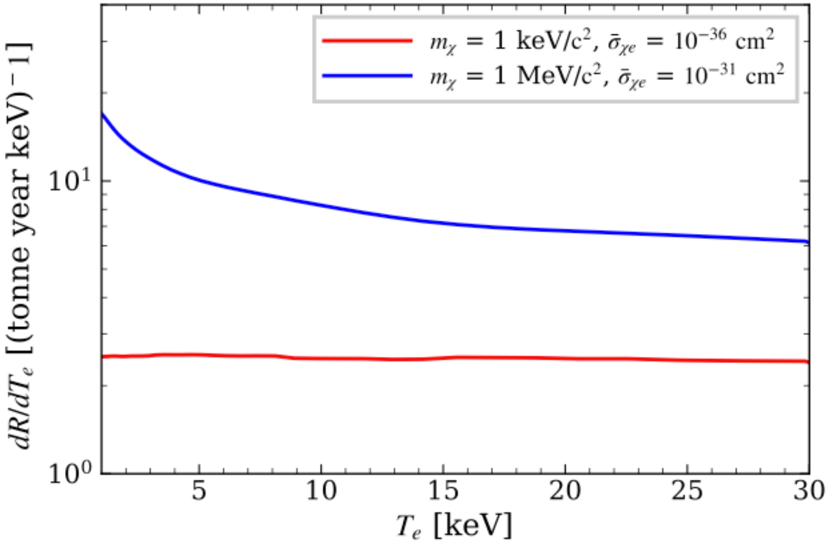


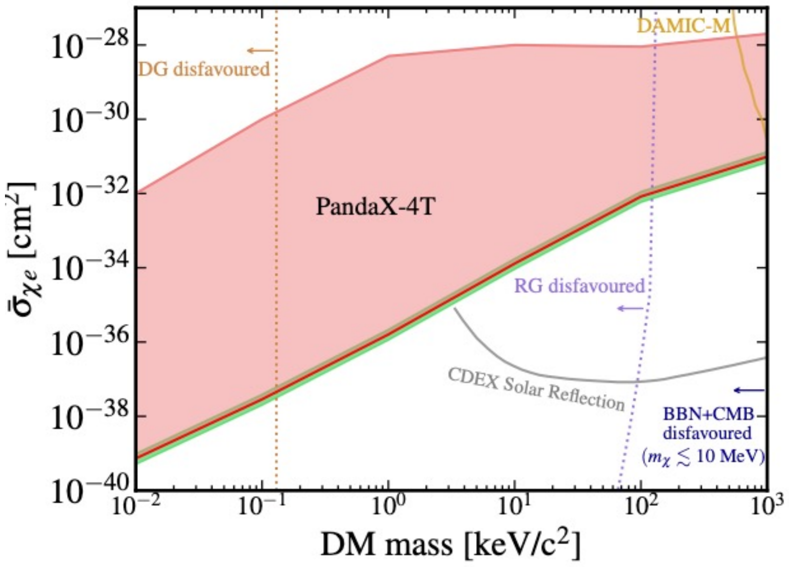


- **Time-dependent background modeling;**
- **Consistency with existing theoretical and experimental results;**
- **Future analysis of other decay channels and 0υ modes.**

Cosmic-Ray Boosted Dark Matter







- Cosmic-Ray electron Boosted DM have the same interaction mechanism with DM- electron detection in the detector;
- Self-developed MC simulation for the calculation of the DM Earth attenuation;
- push the current mass range down by two orders of magnitude, achieve the minimum fermionic DM mass allowed by the Pauli principle;

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