Latest results of the PandaX-4T experiment

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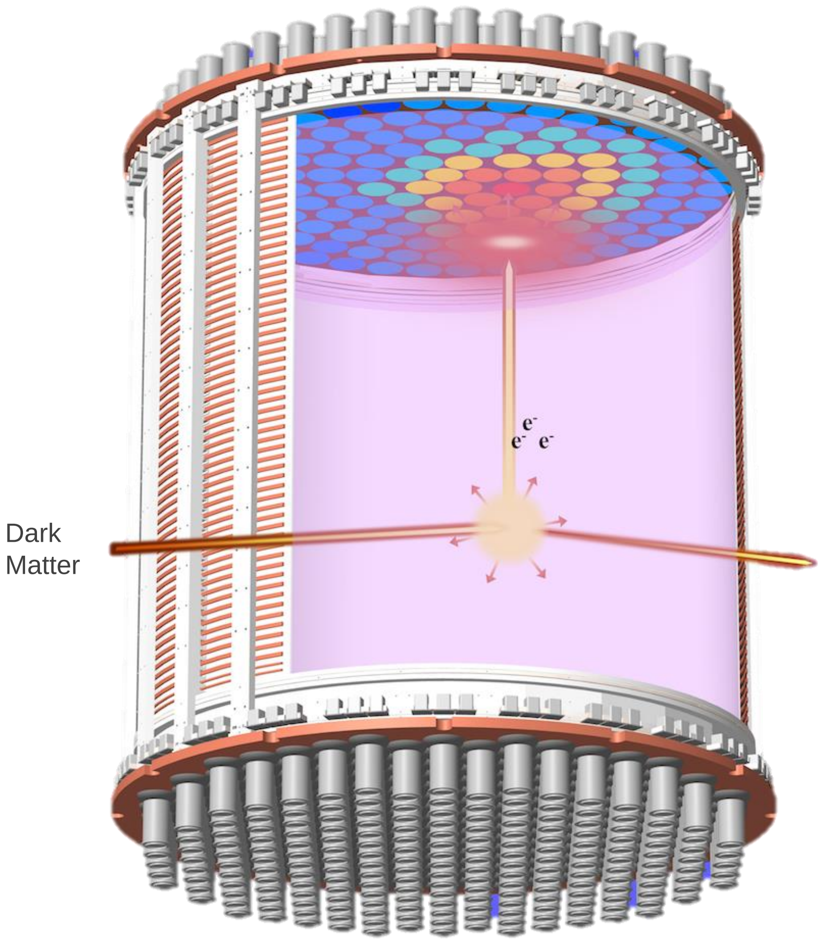
On behalf of PandaX Collaboration

May 15th, 2024

Outline

- **Brief introduction of PandaX**
- **Current status of PandaX-4T**
- **Luminance of dark matter**
- **Towards to sub-GeV dark matter**
  - lower threshold (S2-only)
  - Migdal effect
- **Multi-physics targets**
  - ^{8}B CEvNS
  - ^{136}Xe $2\nu\beta\beta$
  - ^{134}Xe $2\nu\beta\beta$ and $0\nu\beta\beta$



Brief introduction of PandaX

PandaX: Particle and Astrophysical Xenon

Brief introduction of PandaX

- Increasing the detector sensitive target volume
- Lowering radioactive background

PandaX start

2009

PandaX-I
120kg

2010-2014

PandaX-II
580kg

2015-2019

PandaX-4T
(3.7 tonne)

2020-now

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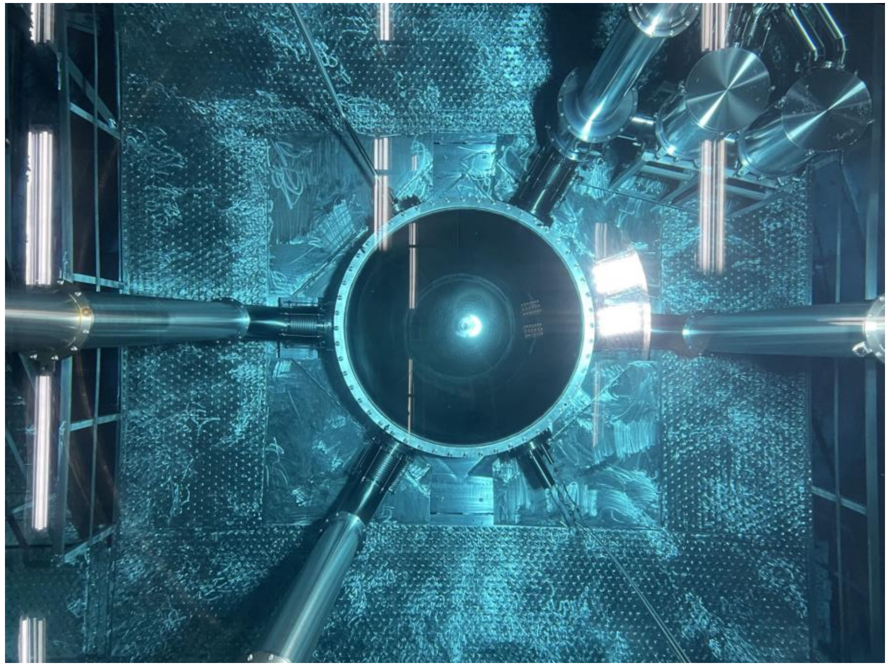
Status of PandaX-4T detector

Status of Run 1 WIMP analysis



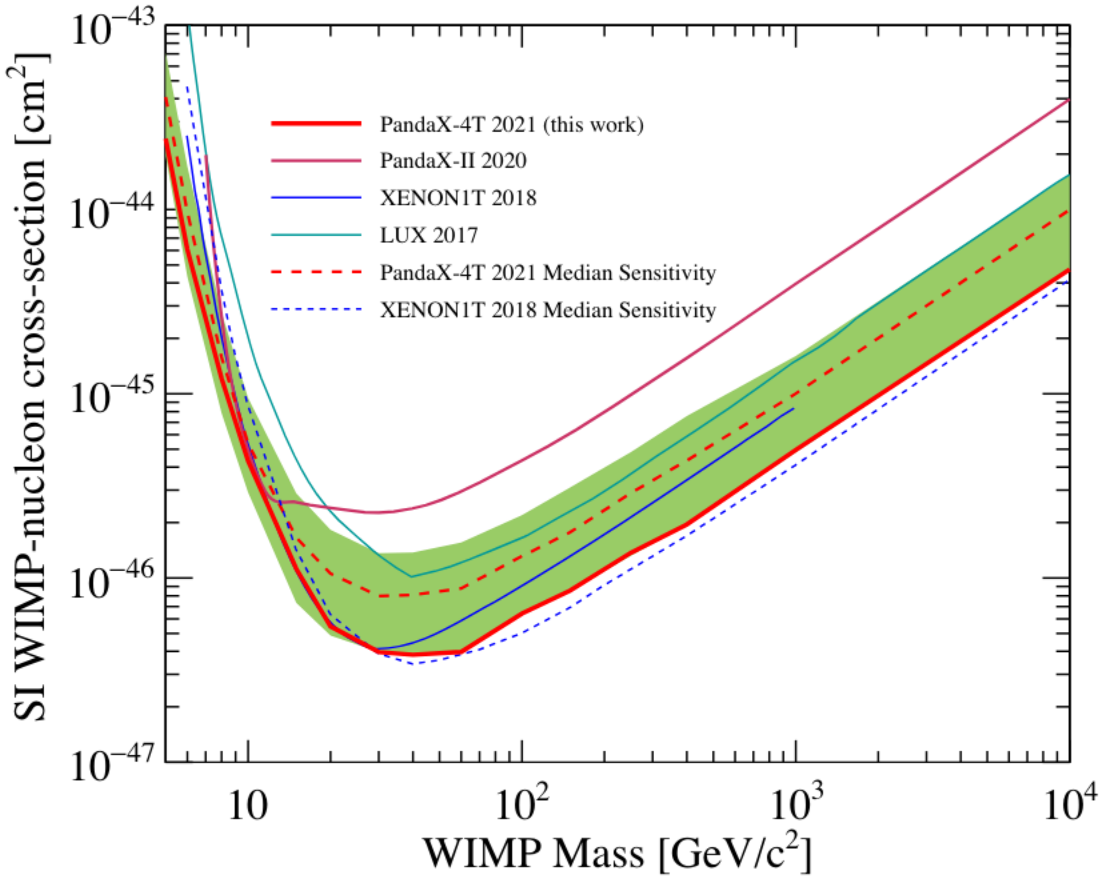
Current status of PandaX-4T

PANDA X
PARTICLE AND ASTROPHYSICAL XENON TPC

2020/11 – 2021/04	**Commissioning (Run 0)** 95 days
2021/07 – 2021/10	**Tritium removal** xenon distillation, gas flushing, etc
2021/11 – 2022/05	**Physics run (Run 1)** 164 days
2022/09 – 2023/12	**CJPL B2 hall renovation** xenon recuperation, detector upgrade
Current Status	**Resuming physics data-taking**

Current status of PandaX-4T data analysis

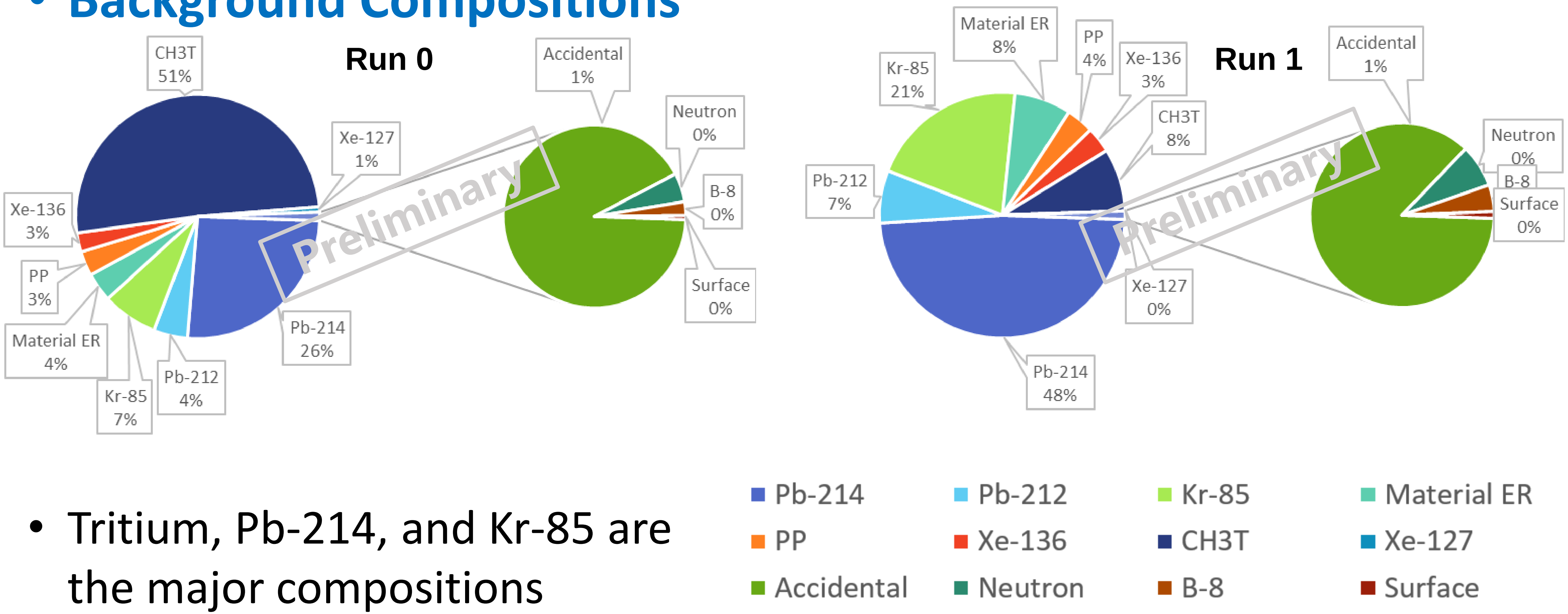
- Result of commissioning run (Run 0) has been published in 2021
- Run1 data is currently under analysis
- A combined analysis of run0 and run1



PhysRevLett.127.261802

Current status: Run-1 Data Analysis

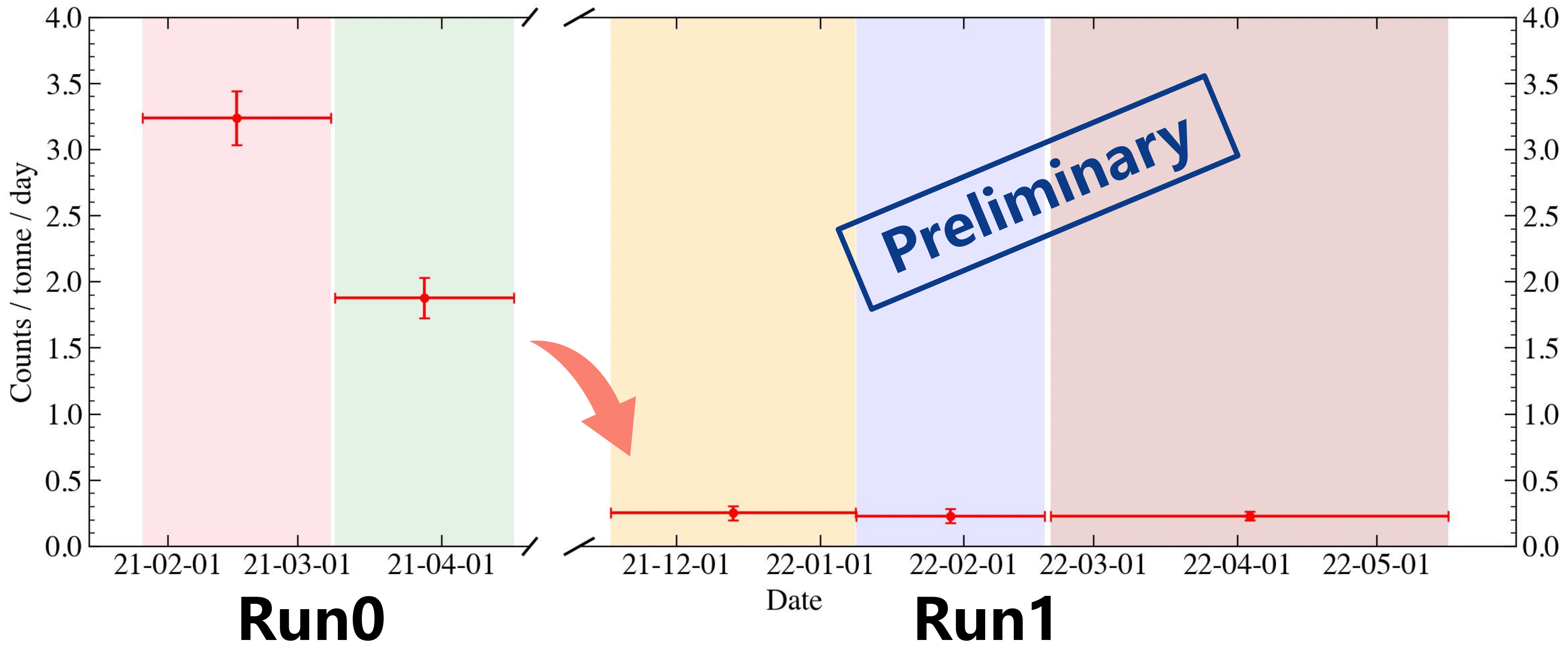
- **Background Compositions**

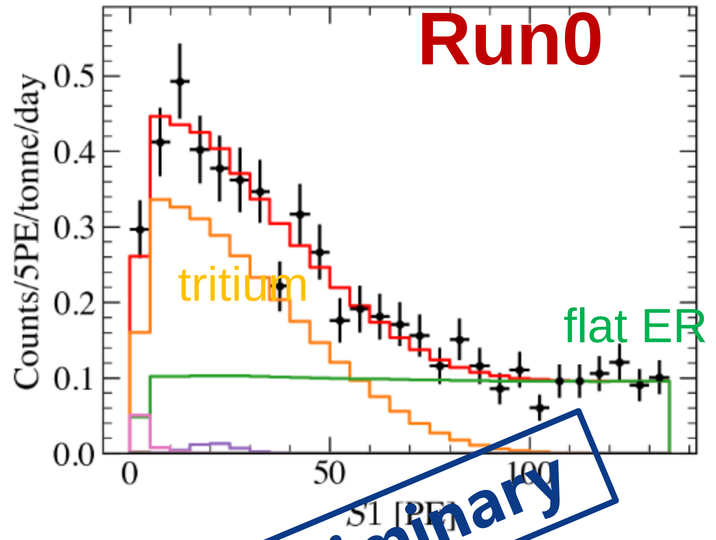


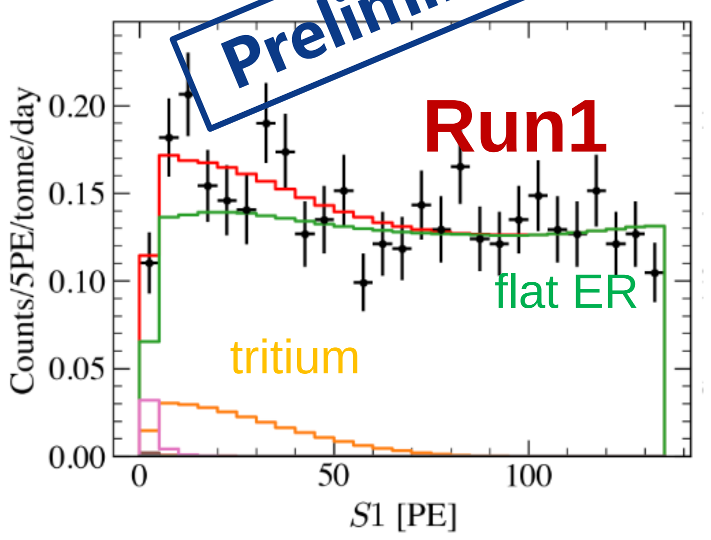
- Tritium, Pb-214, and Kr-85 are the major compositions

Current status: Run-1 Data Analysis

- **Tritium background**
  - excess of low electron-recoil energy
  - S1 fitting (keep S2 blind)
- **Significant reduction from Run0 to Run1**



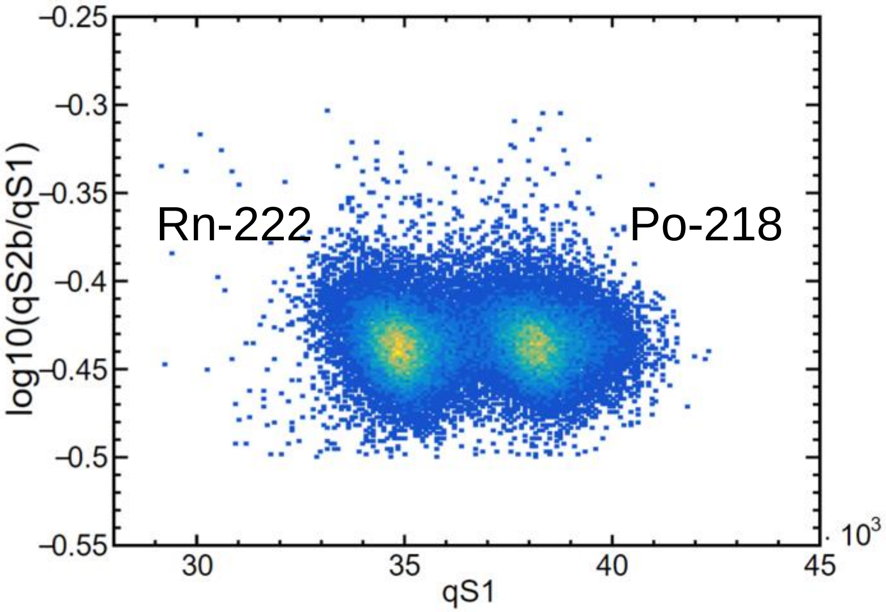


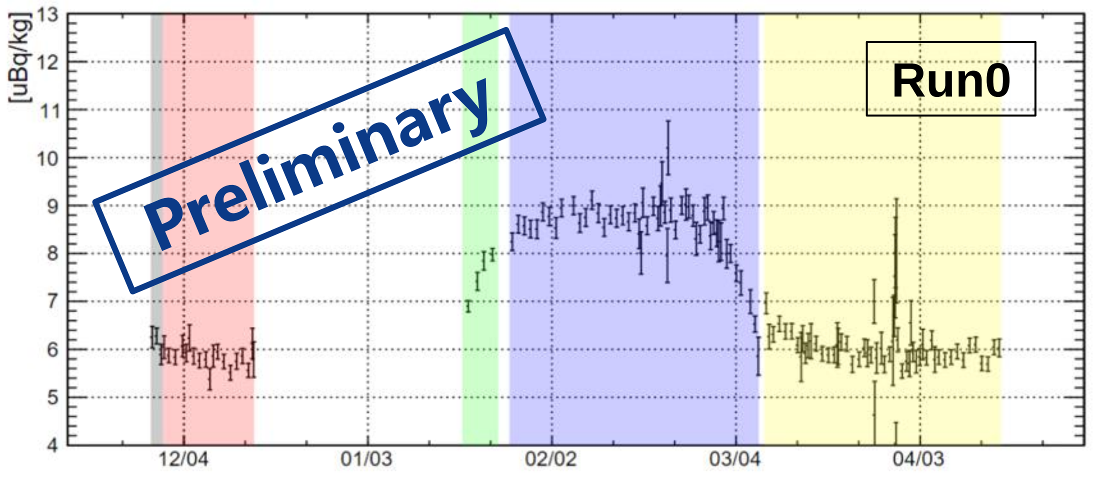


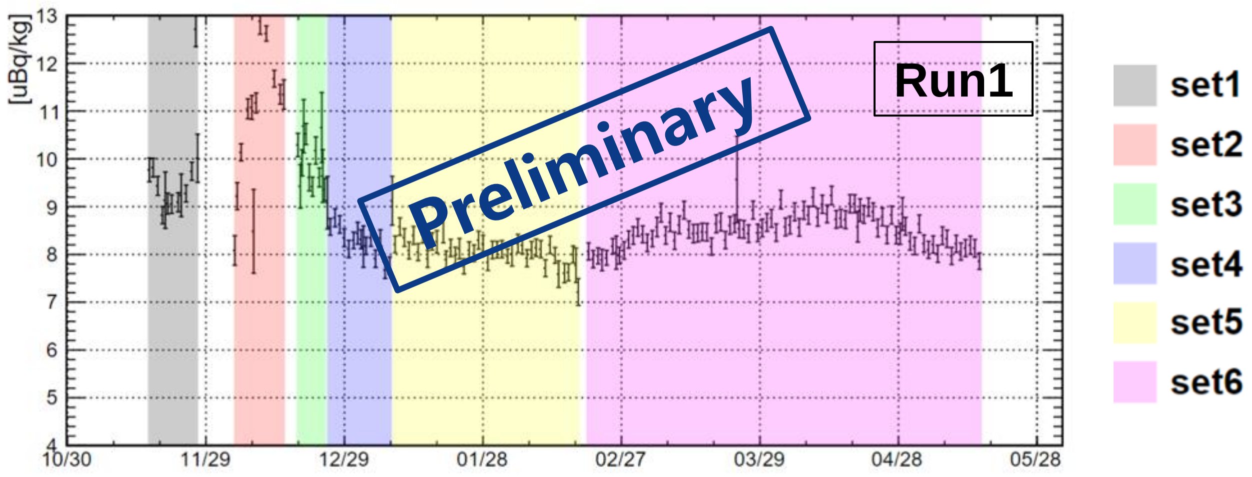
Current status: Run-1 Data Analysis

- **Pb-214 background**
  - Pb-214 is a daughter nuclei of Rn-222
  - Select Rn-222 alpha events
  - Rn-222 level varies with running condition

Rn-222 level	[μBq/kg]
Run 0	**7.07 ± 0.02(stat.) ± 0.23(sys.)**
Run 1	**8.67 ± 0.01(stat.) ± 0.27(sys.)**

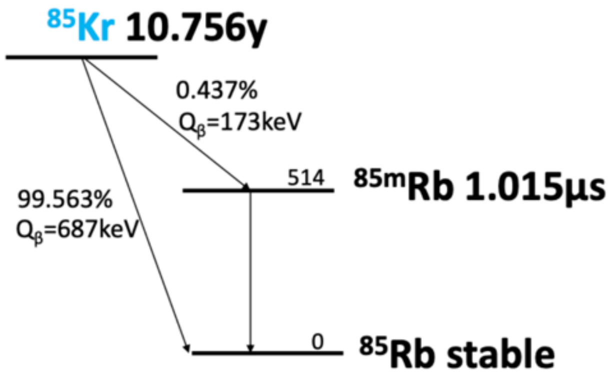


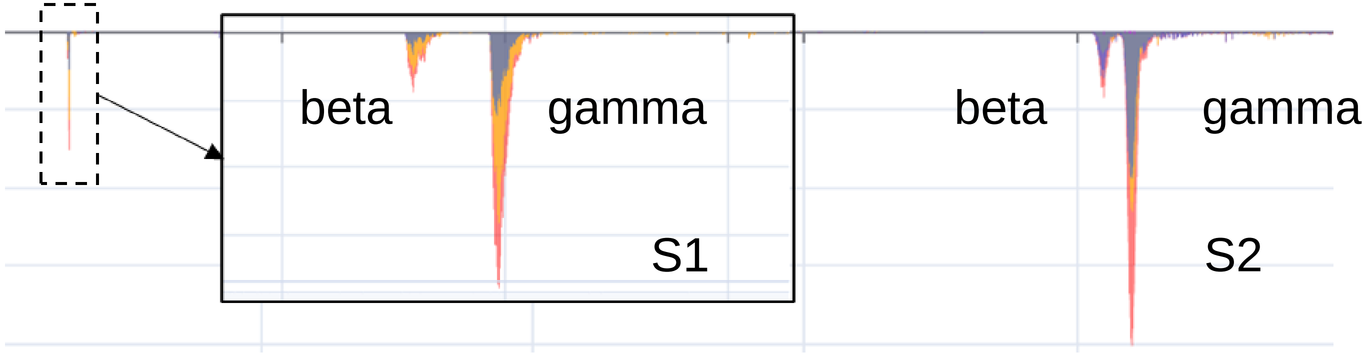




Current status: Run-1 Data Analysis

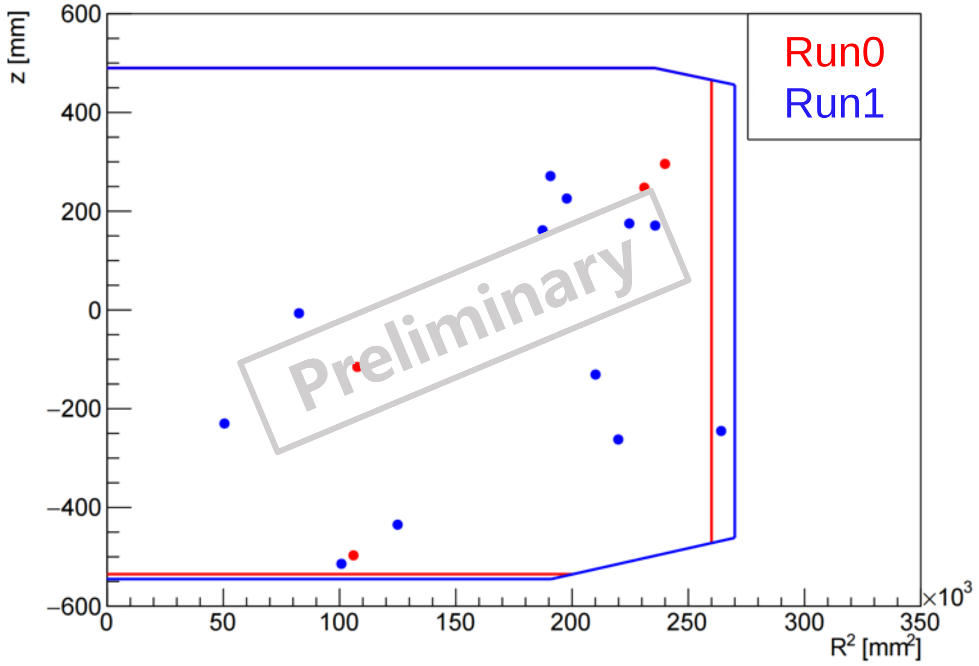
- **Kr-85 background**
  - beta-gamma coincidence selection





Waveform of ^{85}Kr's β-γ coincidence

Kr/Xe	[ppt]
Run 0	**0.5 ± 0.3**
Run 1	**0.9 ± 0.3**

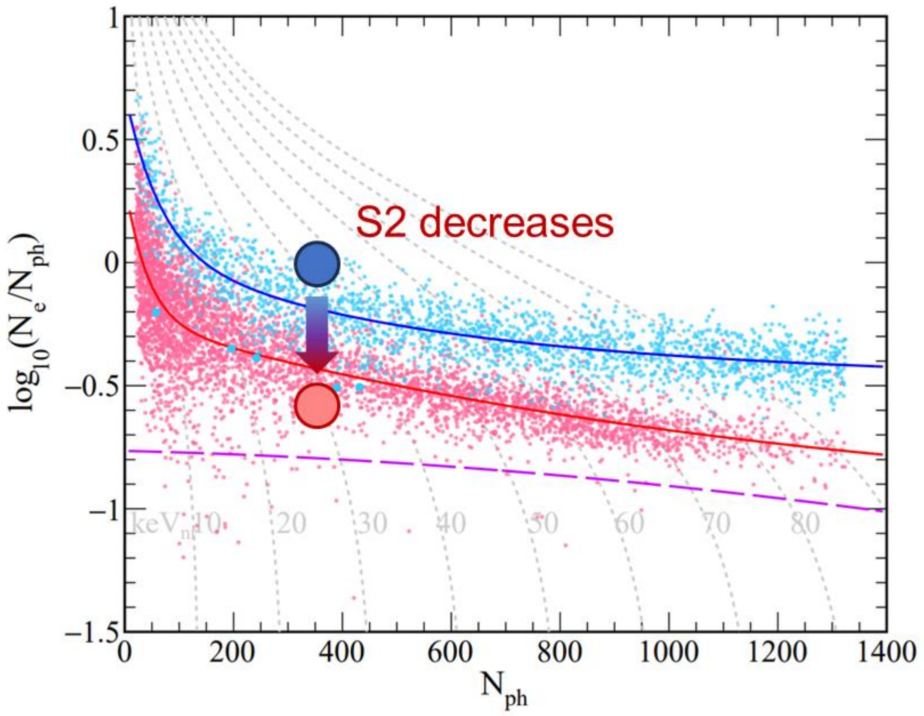


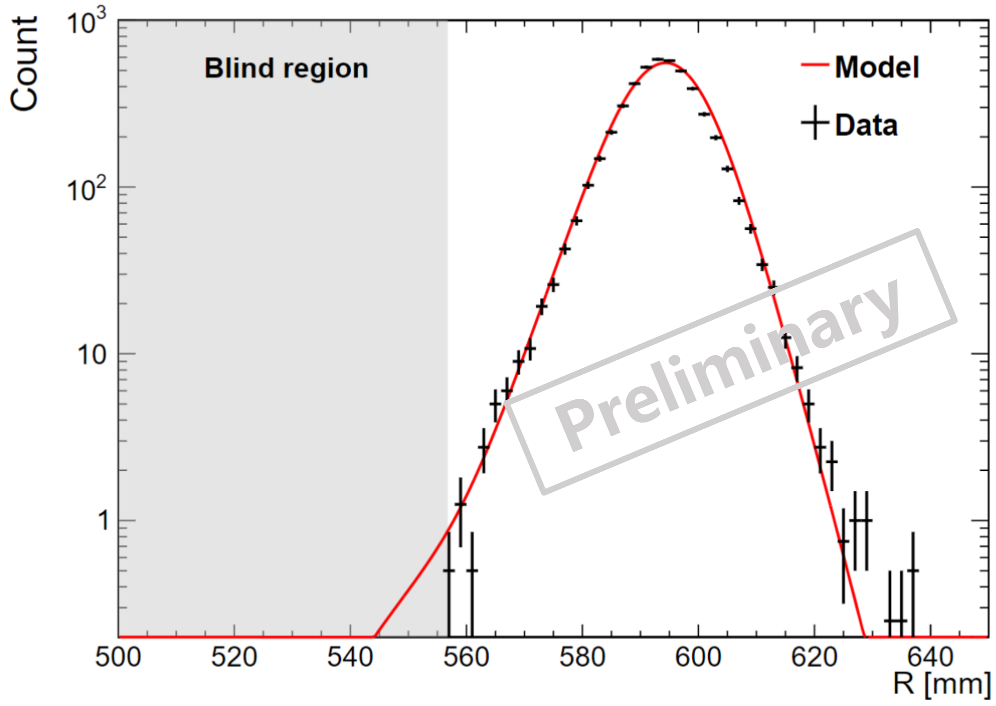
Current status: Run-1 Data Analysis

PANDA X
PARTICLE AND ASTROPHYSICAL XENON TPC

- **Surface background**
  - ER events, whose S2 is “eaten” by the surface
  - Estimate the radial distribution by ^{210}Po events
  - Good consistency with data outside blind region

Surface events in fiducial volume	
Run0	0.10 ± 0.06
Run1	0.17 ± 0.10





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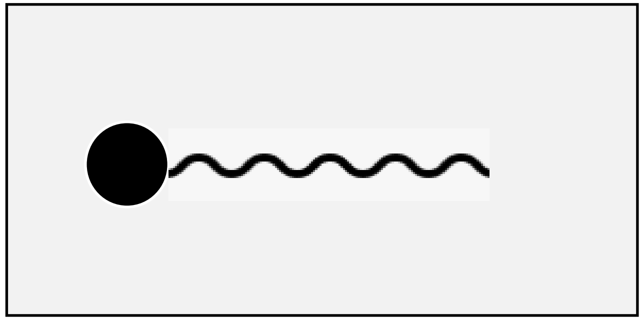
How dark is dark matter?

- Electromagnetic effect

Image Credit: Public Domain

Luminance of Dark Matter

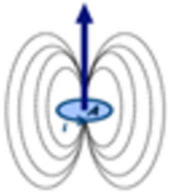
- Possible residual weak EM properties
- Coupling with photons



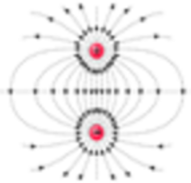
$$\mathcal{L} = Qe\bar{\chi}\gamma^{\mu}\chi A_{\mu} + \frac{\mu_{\chi}}{2}\bar{\chi}\sigma^{\mu\nu}\chi F_{\mu\nu} + i\frac{d_{\chi}}{2}\bar{\chi}\sigma^{\mu\nu}\gamma^{5}\chi F_{\mu\nu} + b_{\chi}\bar{\chi}\gamma^{\mu}\chi\partial^{\nu}F_{\mu\nu} + a_{\chi}\bar{\chi}\gamma^{\mu}\gamma^{5}\chi\partial^{\nu}F_{\mu\nu}$$

millicharge

magnetic dipole



electric dipole



charge radius

anapole

EFT **tree-level** **higher-order loop-level**

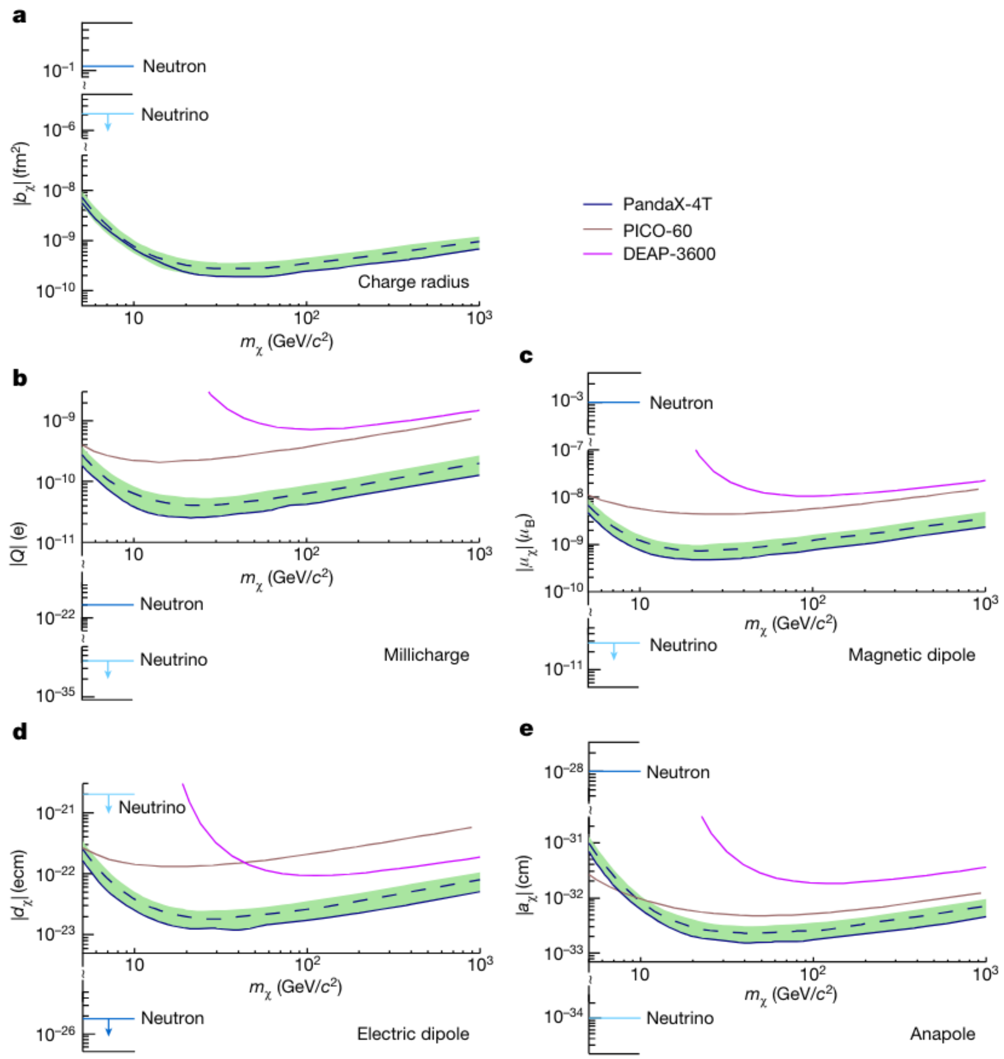
Luminance of Dark Matter

- **First experimental constraint on DM charge radius**
  - 4 orders of magnitude smaller than neutrino
- **Other EM properties**
  - Up to 3 – 10 times improvement

Table 1 | Comparison of electromagnetic properties

	Dark matter	Neutrino	Neutron
Charge radius (fm^2)	$<1.9\times10^{-10}$	$(-2.1,3.3)\times10^{-6}$ [a]	-0.1155 [a]
Millicharge (e)	$<2.6\times10^{-11}$	$<4\times10^{-35}$ [a]	$(-2\pm8)\times10^{-22}$ [a]
Magnetic dipole (μ_B)	$<4.8\times10^{-10}$	$<2.8\times10^{-11}$ [a]	-1×10^{-3} [a]
Electric dipole (ecm)	$<1.2\times10^{-23}$	$<2\times10^{-21}$ [b]	$<1.8\times10^{-26}$ [a]
Anapole (cm^2)	$<1.6\times10^{-33}$	roughly 10^{-34} [c]	roughly 10^{-28} [d]

X. Ning et al. **Nature** 618 (2023)



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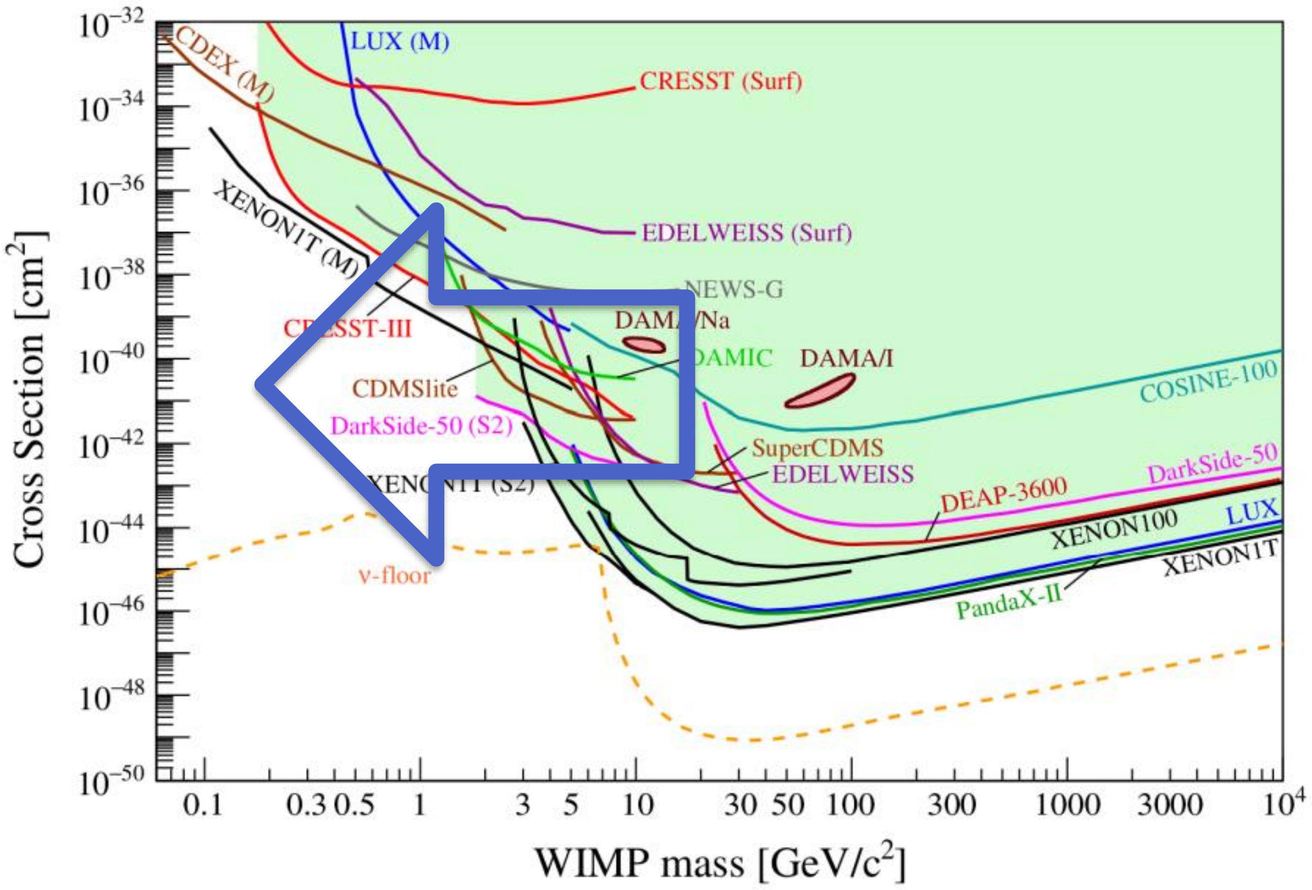
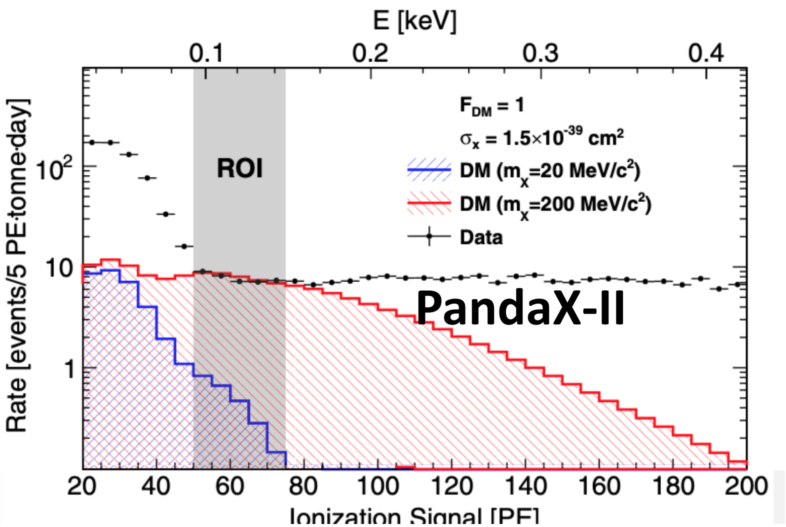
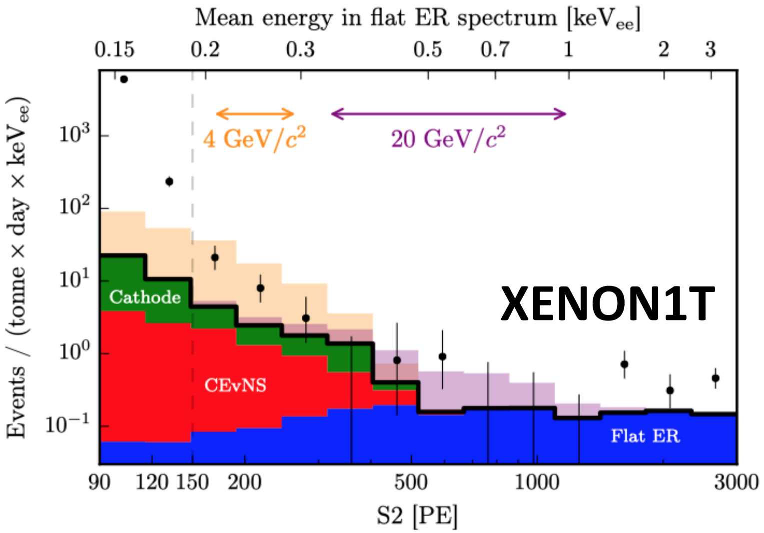
Generally very weak signals from sub-GeV DM

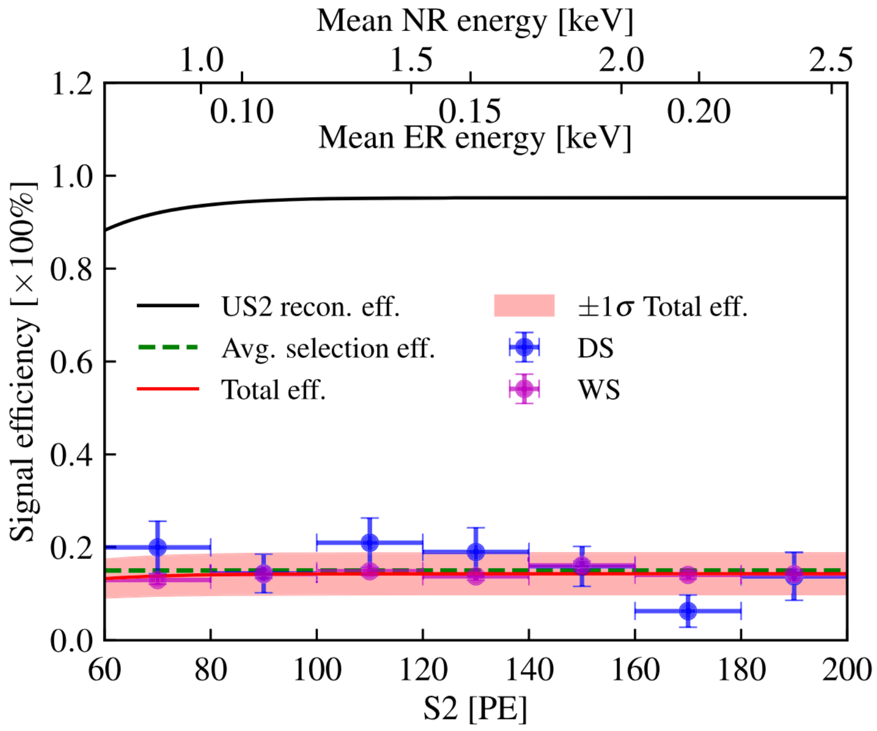


Sub-GeV DM: Lower threshold (Ionization-only)

- **Ionization-only: no scintillation signal requirement**
  - ROI S2 [60, 200]PE: threshold down to **~100 eV** (from ~1 keV)
  - Tight quality cuts on the ionization signal
- **Key challenge: background components**
  - No full picture in previous xenon-based experiments
  - Conservative results only



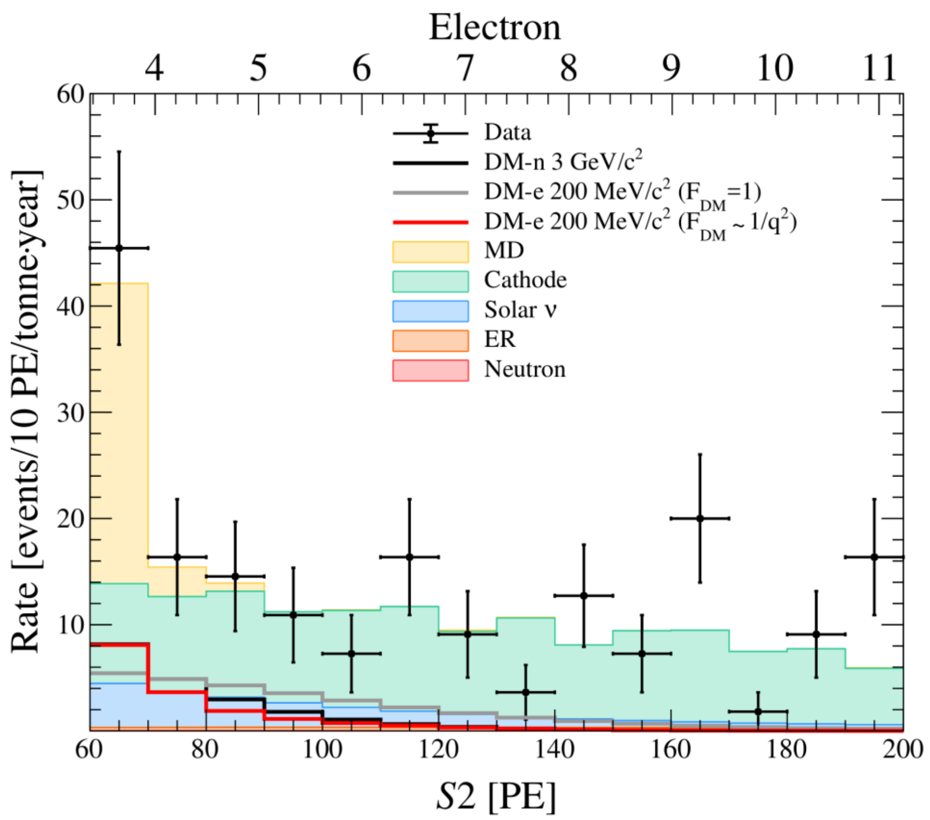




Sub-GeV DM: Lower threshold (Ionization-only)

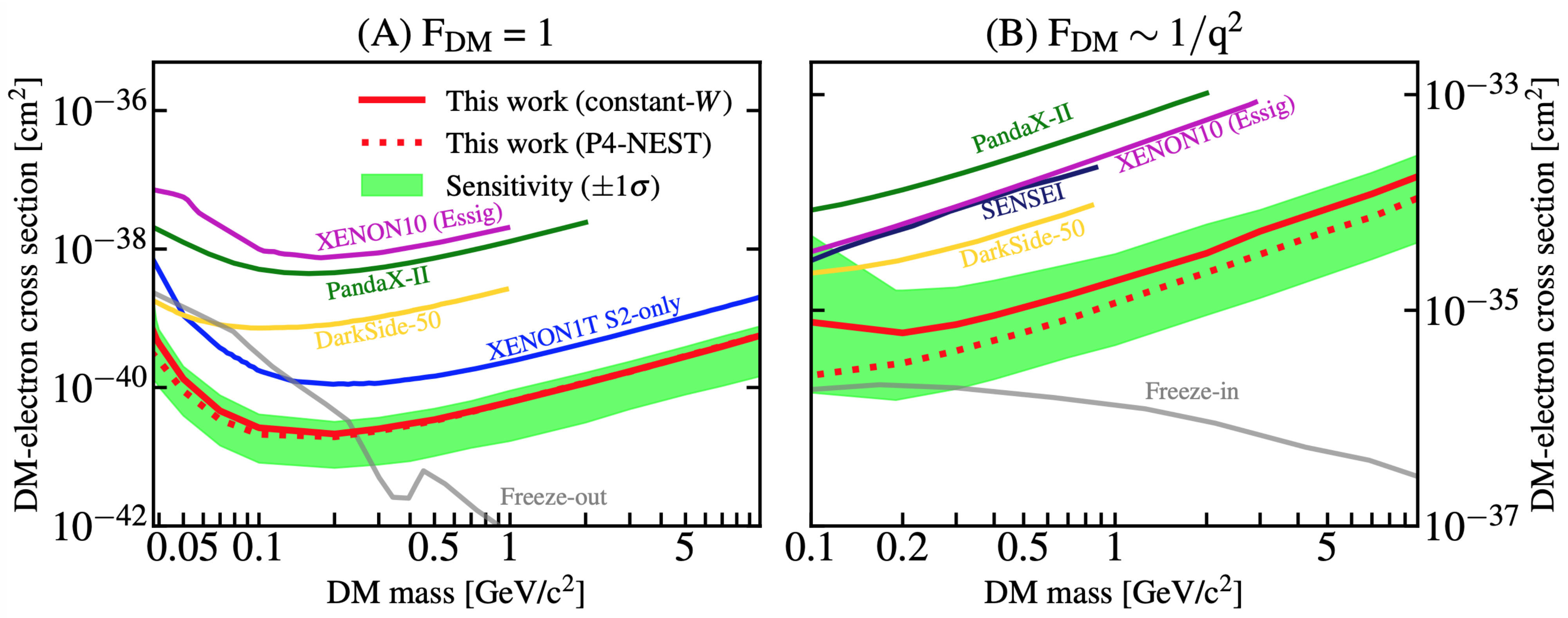
Ionization-only Data of PandaX-4T

- **First complete understanding of all the main background**
  - Micro-discharging (MD)
    - ➢Small charge, strong run-condition dependence
  - Cathode activity
    - ➢Large charge, large pulse-shape width
- **Blind analysis of 0.55 tonne-year exposure**
  - 105 events
  - Best-fit background: 95.8 ± 11.3 events



Sub-GeV DM: Lower threshold (Ionization-only)

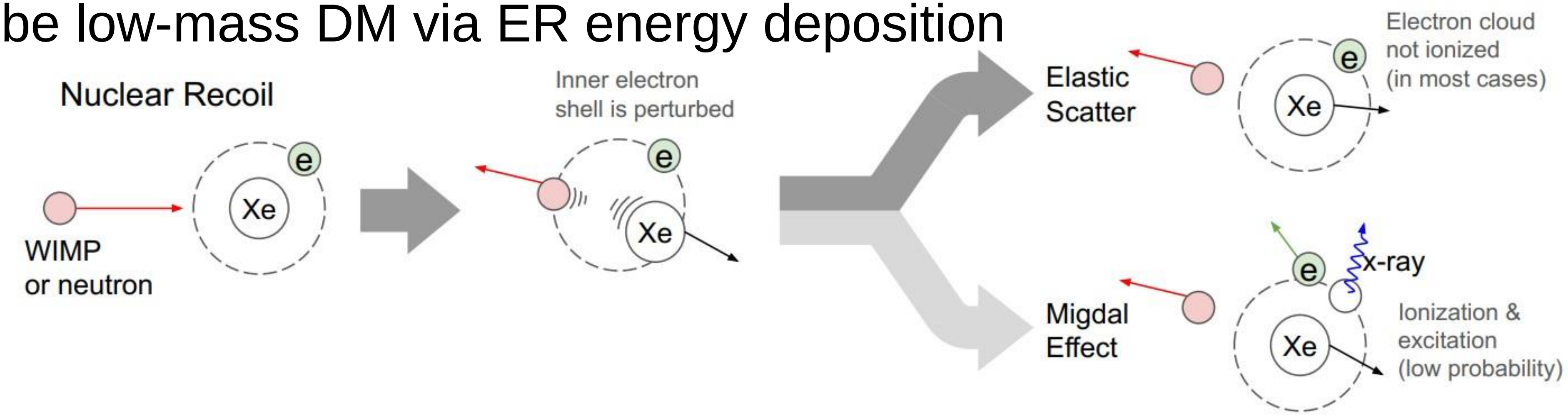
- **Most stringent constraints of DM-e⁻ scattering are derived**
  - DM-electron interaction with heavy mediator, 2×10^{-41} cm²



S. Li et al. PRL 130, 261001 (2023)
Editors' Suggestion

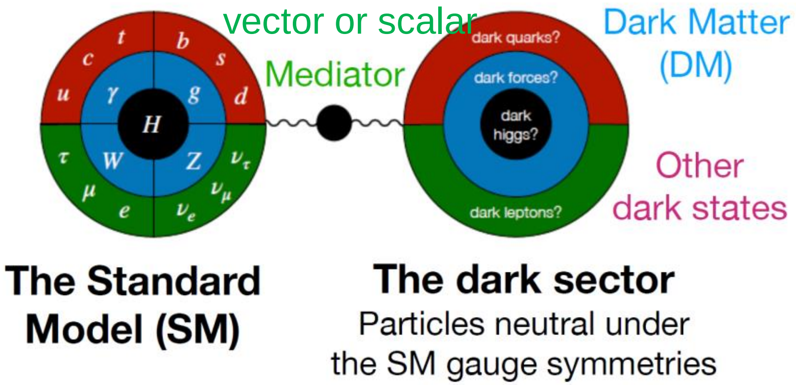
Sub-GeV DM: Migdal Effect

- **NR-induced ER signals by the Migdal effect**
  - Probe low-mass DM via ER energy deposition



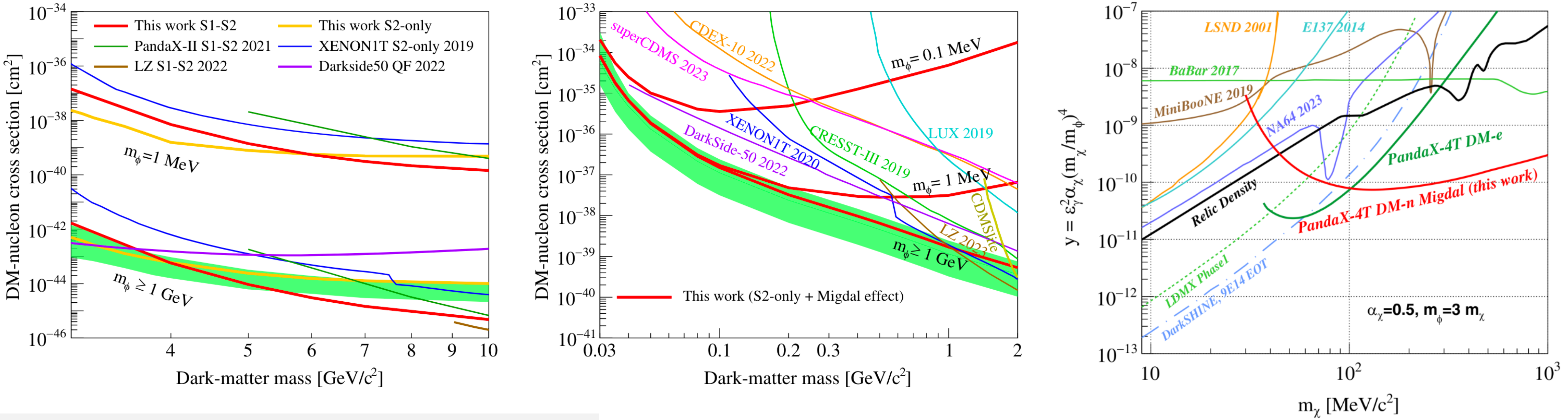
- **DM-nucleon interaction with a dark mediator**

$$\frac{dR}{dE_{\mathrm{NR}}} = \sigma|_{q^2=0} \frac{A^2}{\mu_p^2} \frac{m_\phi^4}{(m_\phi^2 + q^2)^2} F^2(q^2) \times \frac{\rho}{2m_\chi} \int_{v \geq v_{\min}} \frac{f(v)}{v} d^3v$$



Sub-GeV DM: Migdal Effect

- **With ionization-only data + Migdal effect, set most stringent constraints**
  - DM-nucleon interaction with dark mediator, for DM mass [30 MeV, 2 GeV]
  - enhancing the potential for low-mass DM detection
- **Assume dark mediator is a dark photon**
  - Rule out significant parameter space of such thermal relic dark-matter model
  - Complementary with future experiment (like DarkSHINE)



D. Huang et al. **PRL** 131, 191002 (2023)

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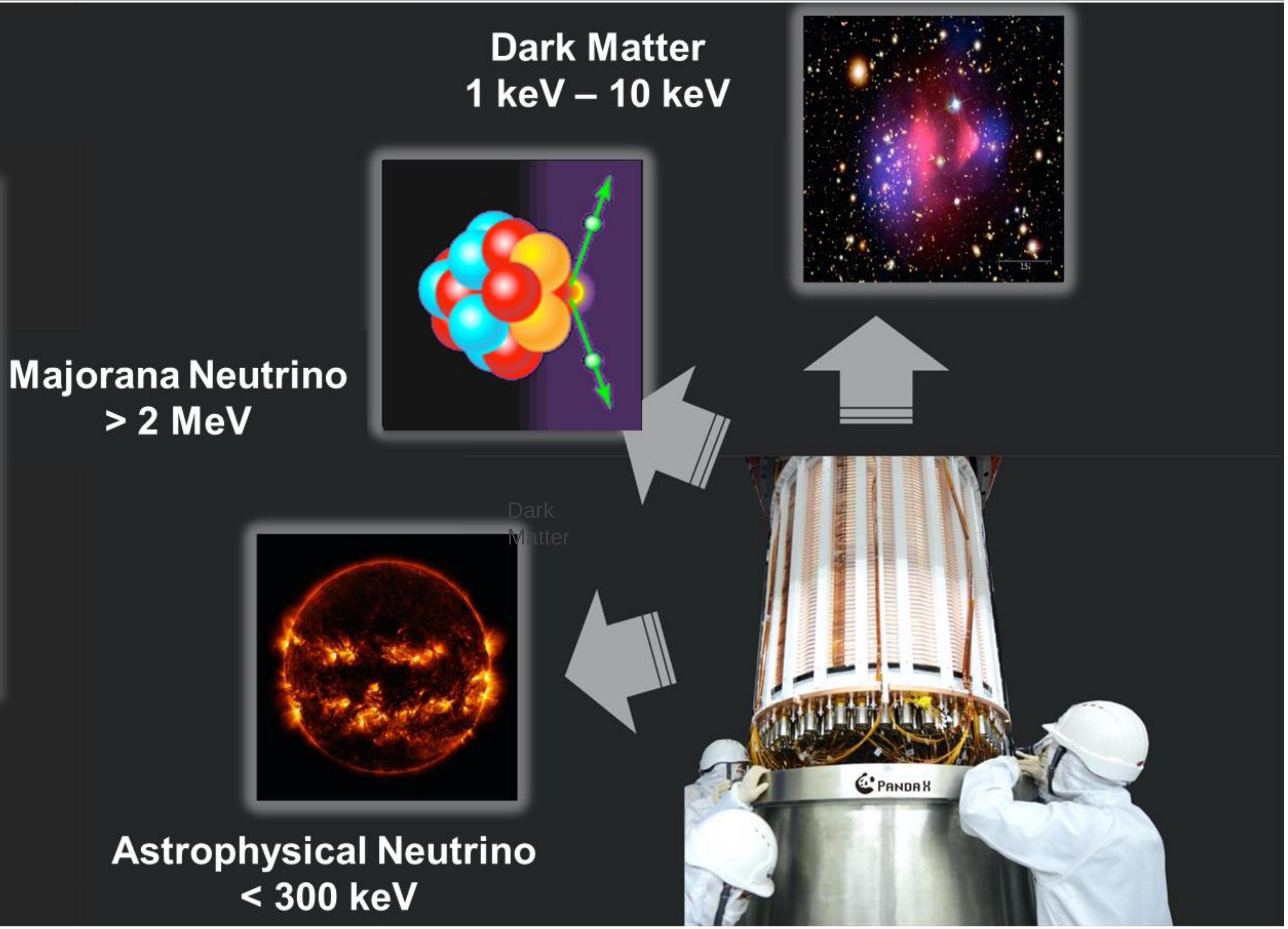
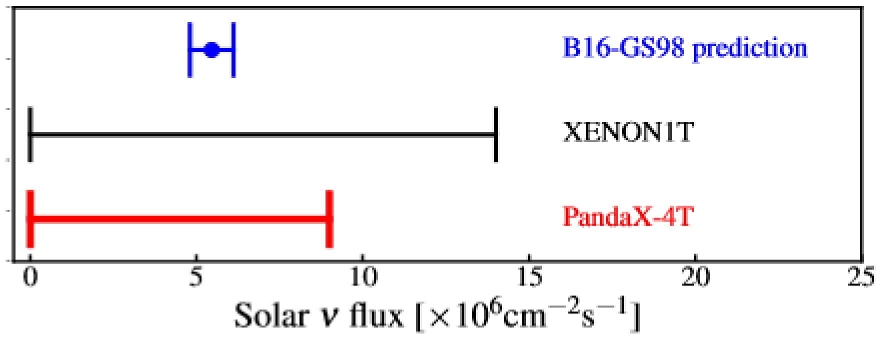
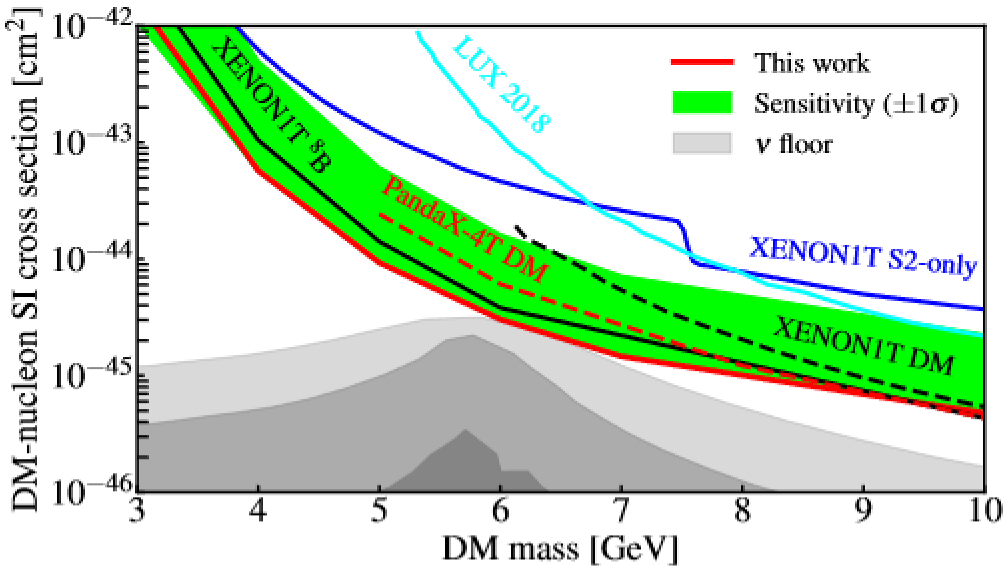


^{8}B CEvNS

- Blind analysis: 0.48 ton-year data
- Major challenge: Accidental background
- A multi-variate (BDT) algorithm trained to suppress AC background
- Leading constraint on ^{8}B neutrino flux through CEvNS
- Assuming a nominal ^{8}B background, set strongest constraints on light WIMP of 3 -9 GeV

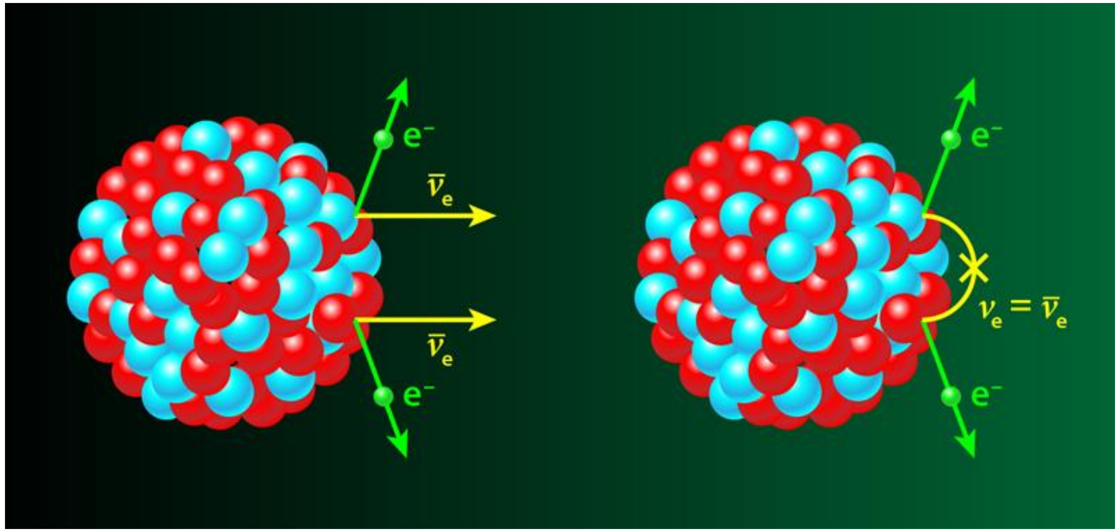


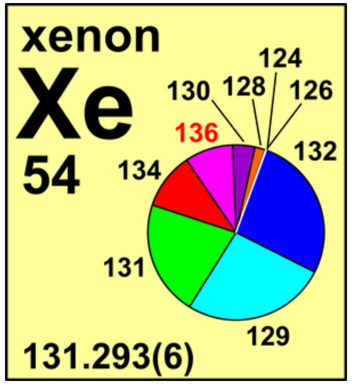


W. Ma et al. PRL 130, 021802 (2023)

^{136}Xe double-beta decay

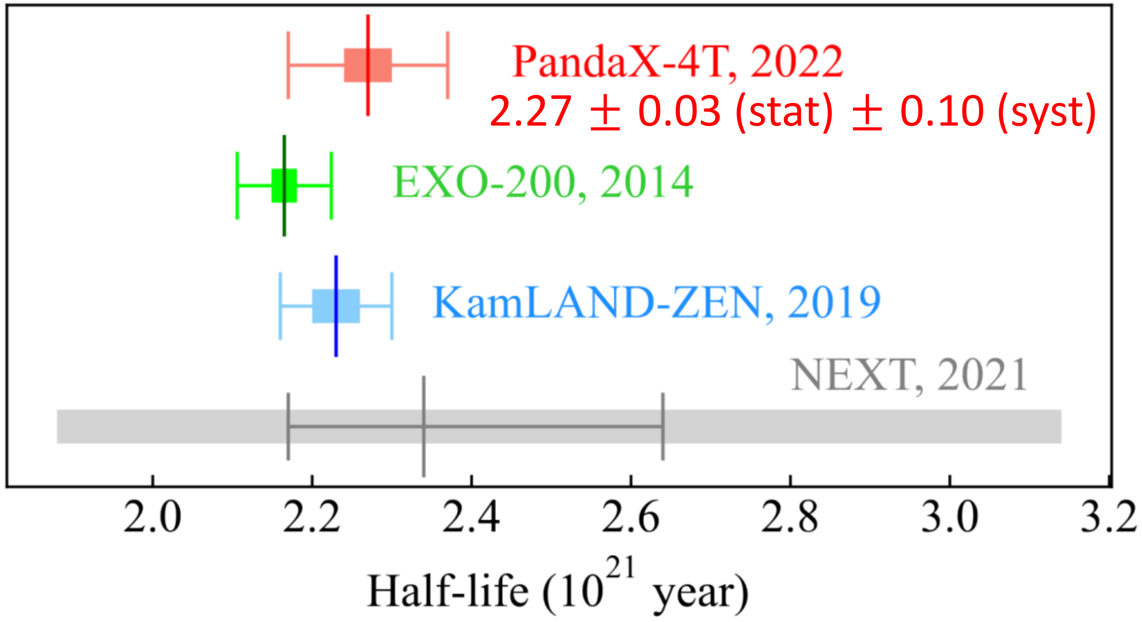
- **Neutrinoless double-beta decay (0νββ)** Golden channel for Majorana neutrino searches





$$^{136}\mathrm{Xe} \rightarrow {}^{136}\mathrm{Ba} + 2e^{-} + ?\,\nu$$

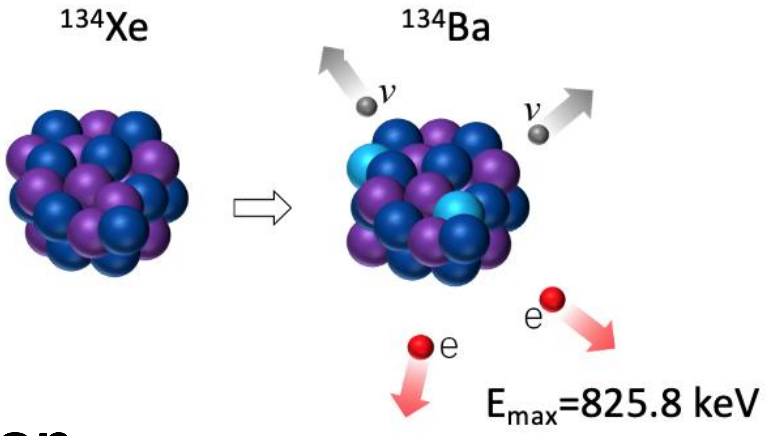
- PandaX-4T: **First** natural xenon measurement with a dark matter detector (2νββ measurement)
- Consistent with ^{136}Xe-enriched experiments.

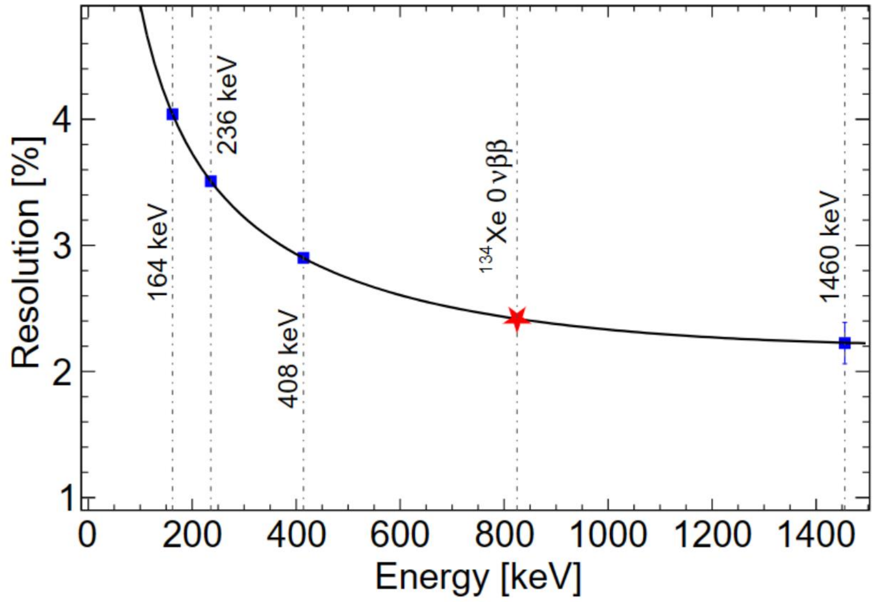


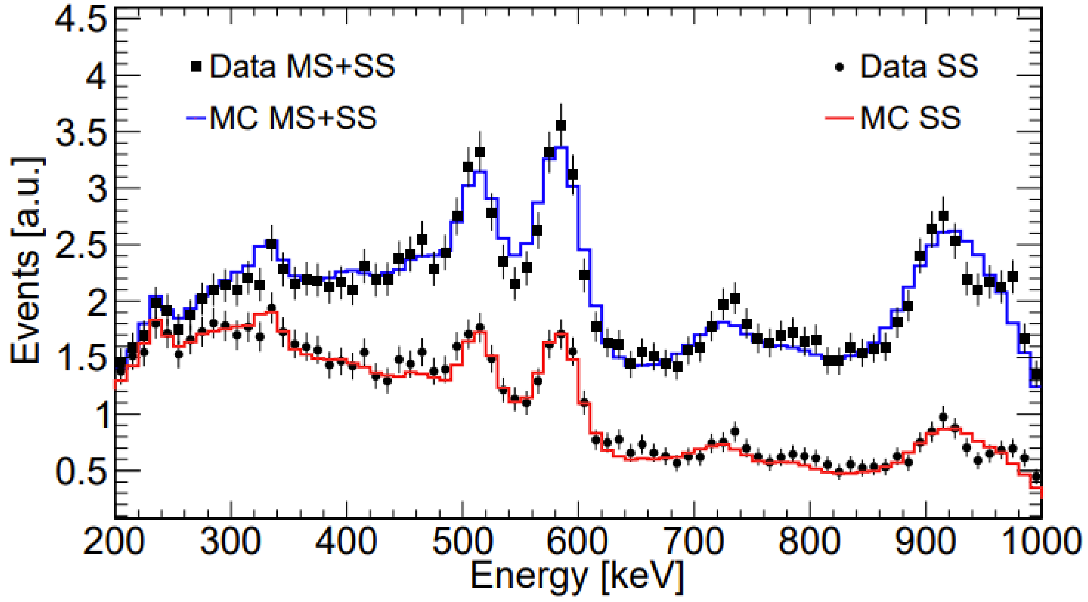
Research Vol 2022, 9798721 (2022)

^{134}Xe double-beta decay

- **Next promising discovery of 2νββ decay**
  - natural abundance 10.4%
  - 2vbb $T_{1/2}$ ~10^{24} years, Q_{bb} 0.83 MeV
- **Extended range: 200-1000 keV**
- **Energy resolution @ Q-value : σ/E=2.4%**
- **Single-site (SS) and multi-site (MS) discrimination**



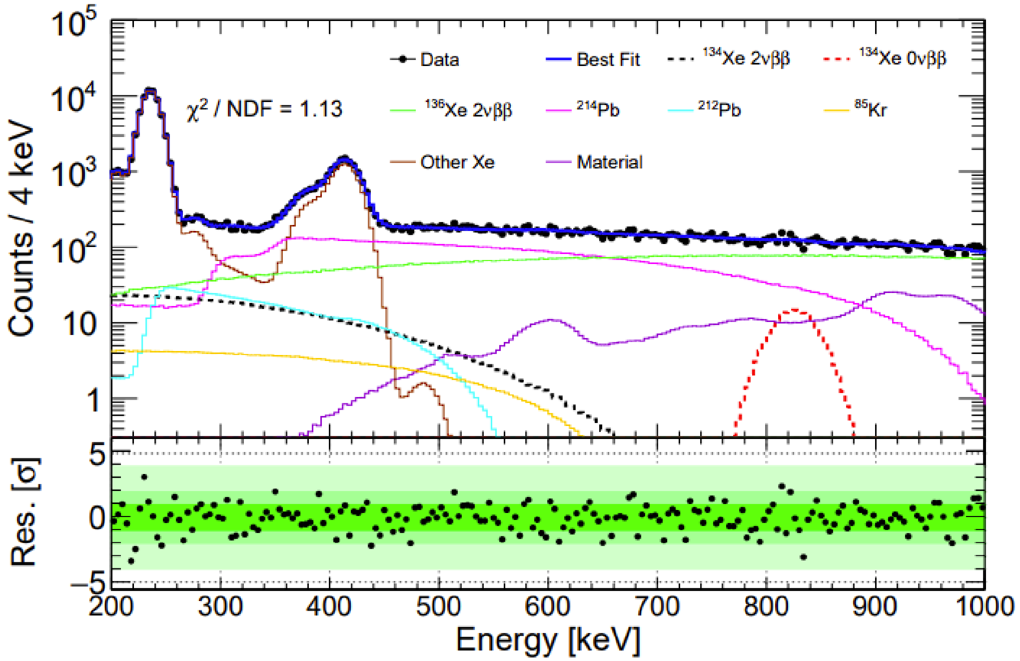




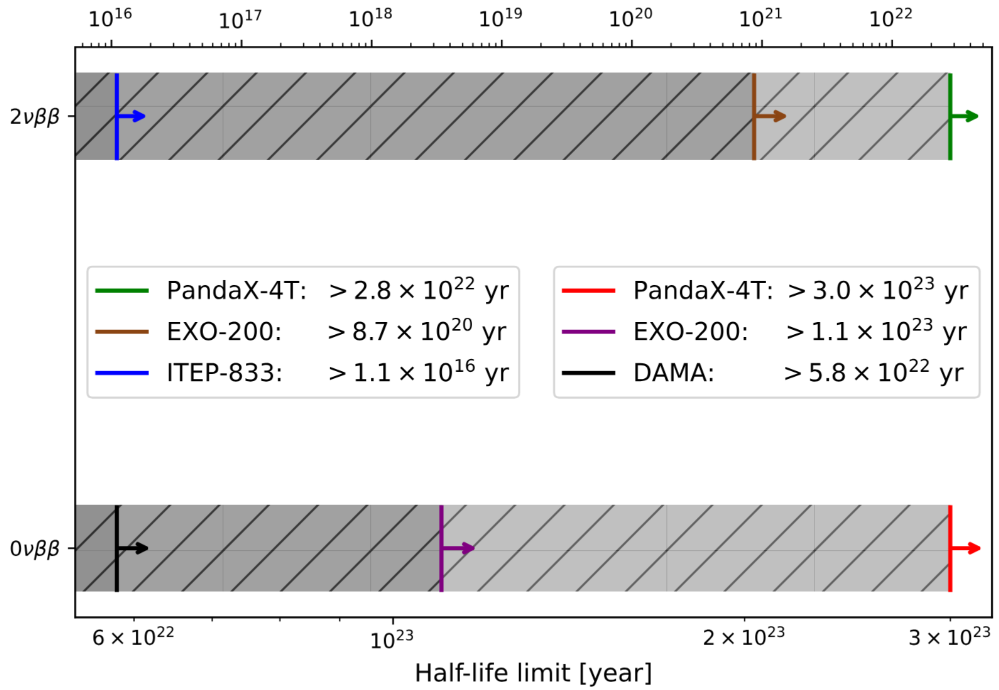
^{134}Xe DBD measurements

PANDA X
PARTICLE AND ASTROPHYSICAL XENON TPC

- **95 live-days with 656 kg natural xenon**
  - $2\nu\beta\beta$: 10±269(stat.)±680(syst.)
  - $0\nu\beta\beta$: 105±48(stat.)±38(syst.)



- **90%CL limits on half-life**
  - $2\nu\beta\beta$: surpasses the existing limit by a factor of **32**
  - $0\nu\beta\beta$: **2.7** times stronger than the previous best result



10.1103/PhysRevLett.132.152502

Summary

- PandaX-4T is one of the new generation multi-tonne xenon experiments
- Run 1 data is under analysis
- Run 2 data-taking will start soon
- Intense searches for various types of physics, including DMs and neutrinos

PANDA X

PARTICLE AND ASTROPHYSICAL XENON TPC

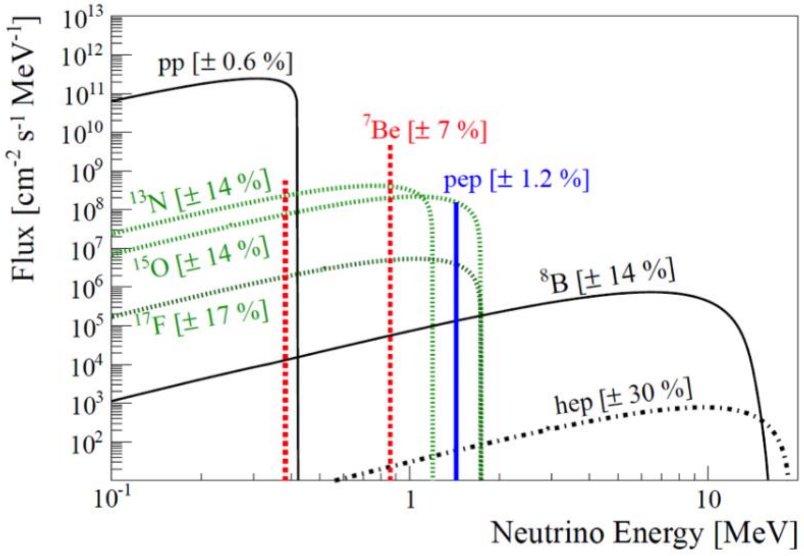
Thanks

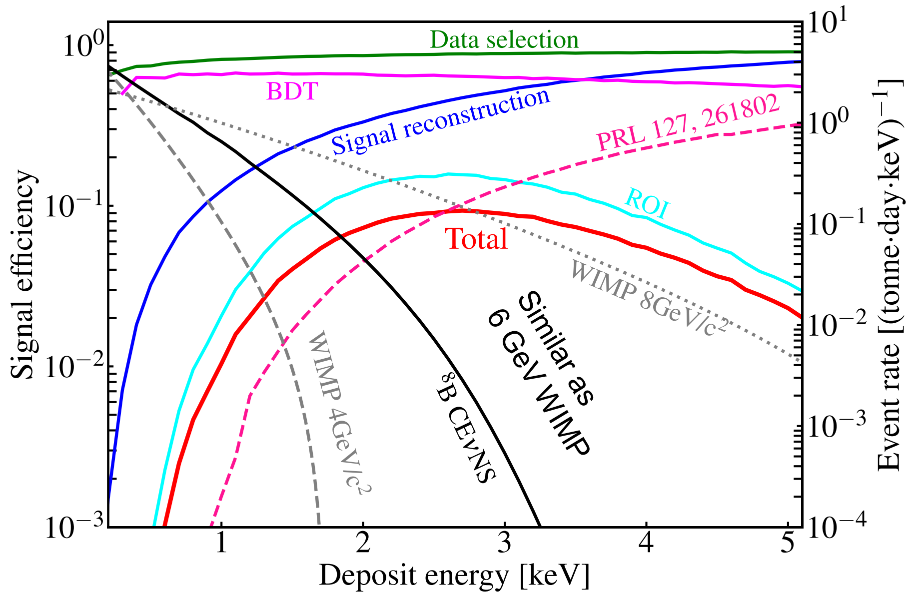
Backup

PANDA X
PARTICLE AND ASTROPHYSICAL XENON TPC

PandaX-4T Search for ^{8}B CEvNS

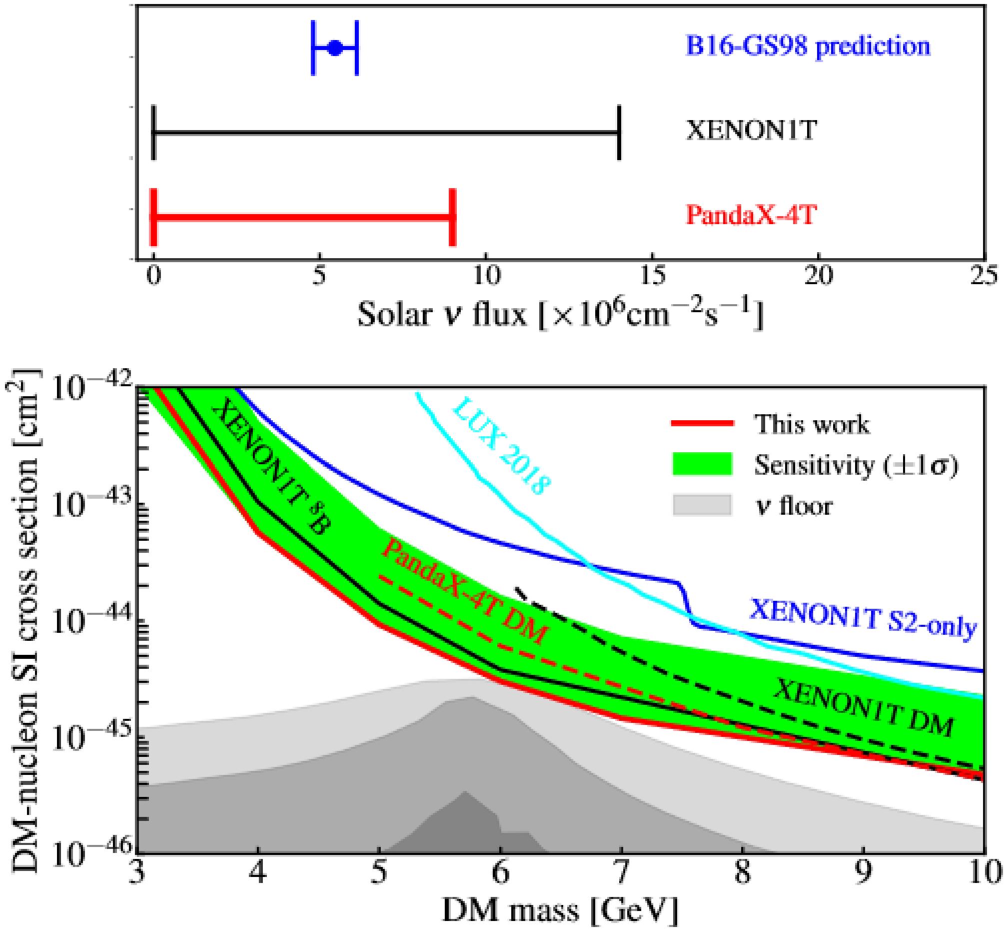
- To enhance sensitivity on ^{8}B (like a 6 GeV WIMP), need to lower the selection threshold (S1↓, S2 ↓)
- Major challenge: Accidental background (AC, non-physical S1 and S2 randomly paired)
- Blind analysis: 0.48 ton-year data, excluding data with an increase in noise rate (micro-discharge)





Constraints on ^{8}B neutrino

PANDA X
PARTICLE AND ASTROPHYSICAL XENON TPC



W. Ma et al. PRL 130, 021802 (2023)

- A multi-variate (BDT) algorithm trained to suppress AC background
  - Some downward fluctuation

ROI (BDT applied)

ER+NR+AC	8B	Total prediction	Unblind data
1.46	1.42	2.88	1
0.04	0.29	0.33	0

- Leading constraint on ^{8}B neutrino flux through CEvNS

- Assuming a nominal ^{8}B background, set strongest constraints on light WIMP of 3 -10 GeV