上海交通大学
SHANGHAI JIAO TONG UNIVERSITY

PandaX液氙实验进展和计划

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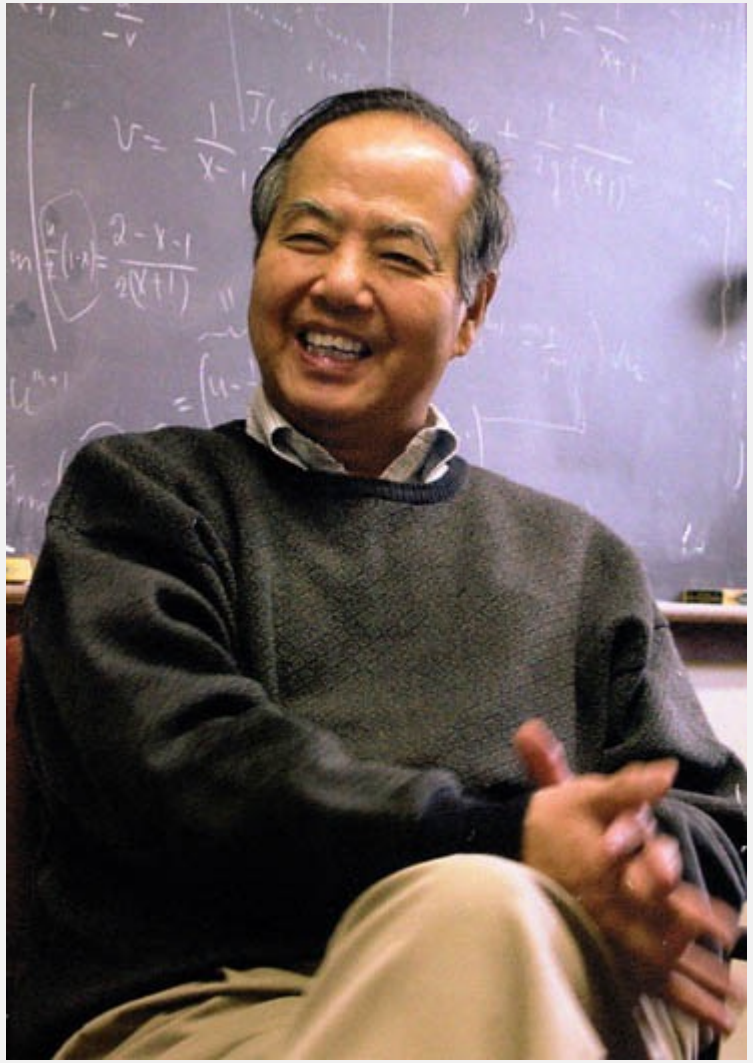
上海交通大学

2023-07-01

第十六届粒子物理、核物理和宇宙学交叉学科前沿问题研讨会

暗物质是笼罩20世纪末和21世纪初现代物理学的最大乌云，它将预示着物理学的又一次革命。

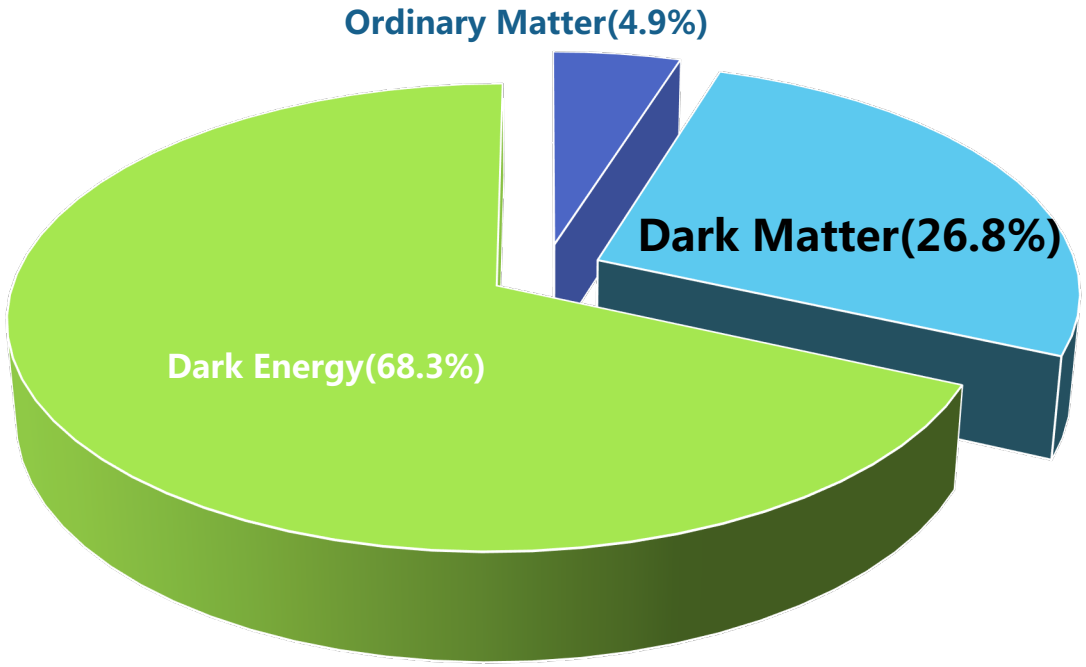
——李政道

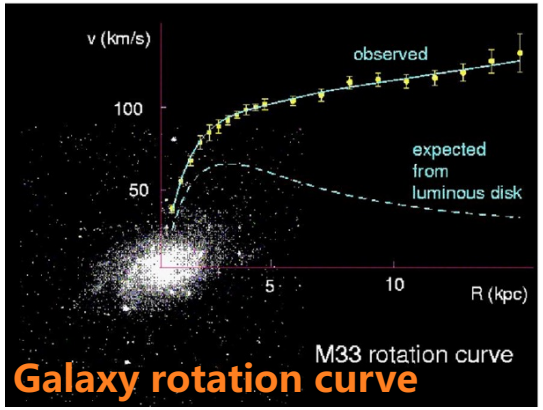


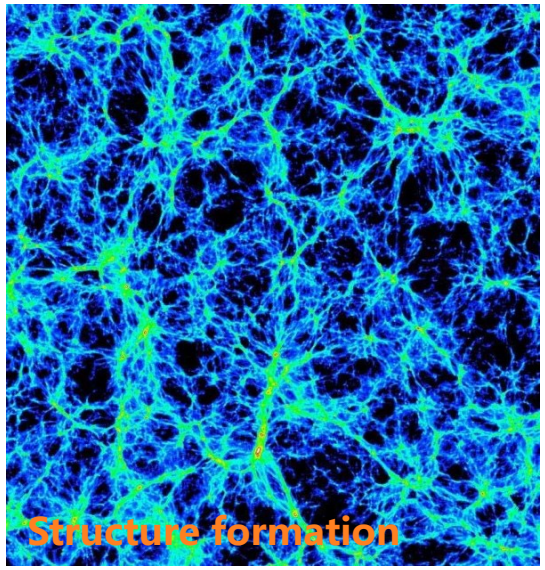
关于李政道先生引言的参考文献：
秦波，精确宇宙学时代的暗物质问题，《现代物理知识》2007 Vol19 (5):17-24

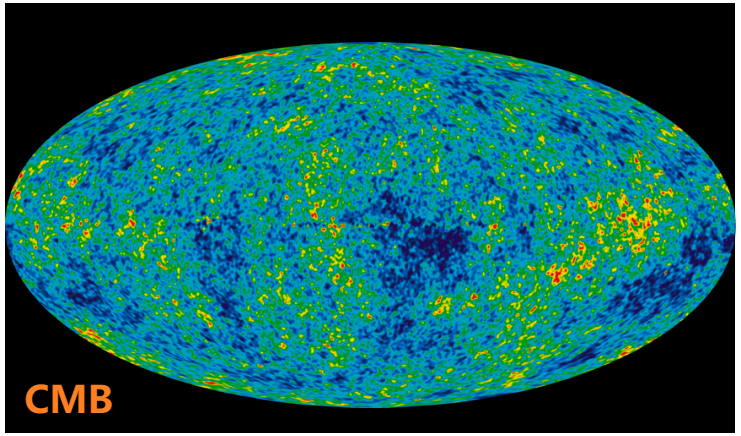
Dark Matter

- Strong evidences for the existence of dark matter
- Unknown physical nature





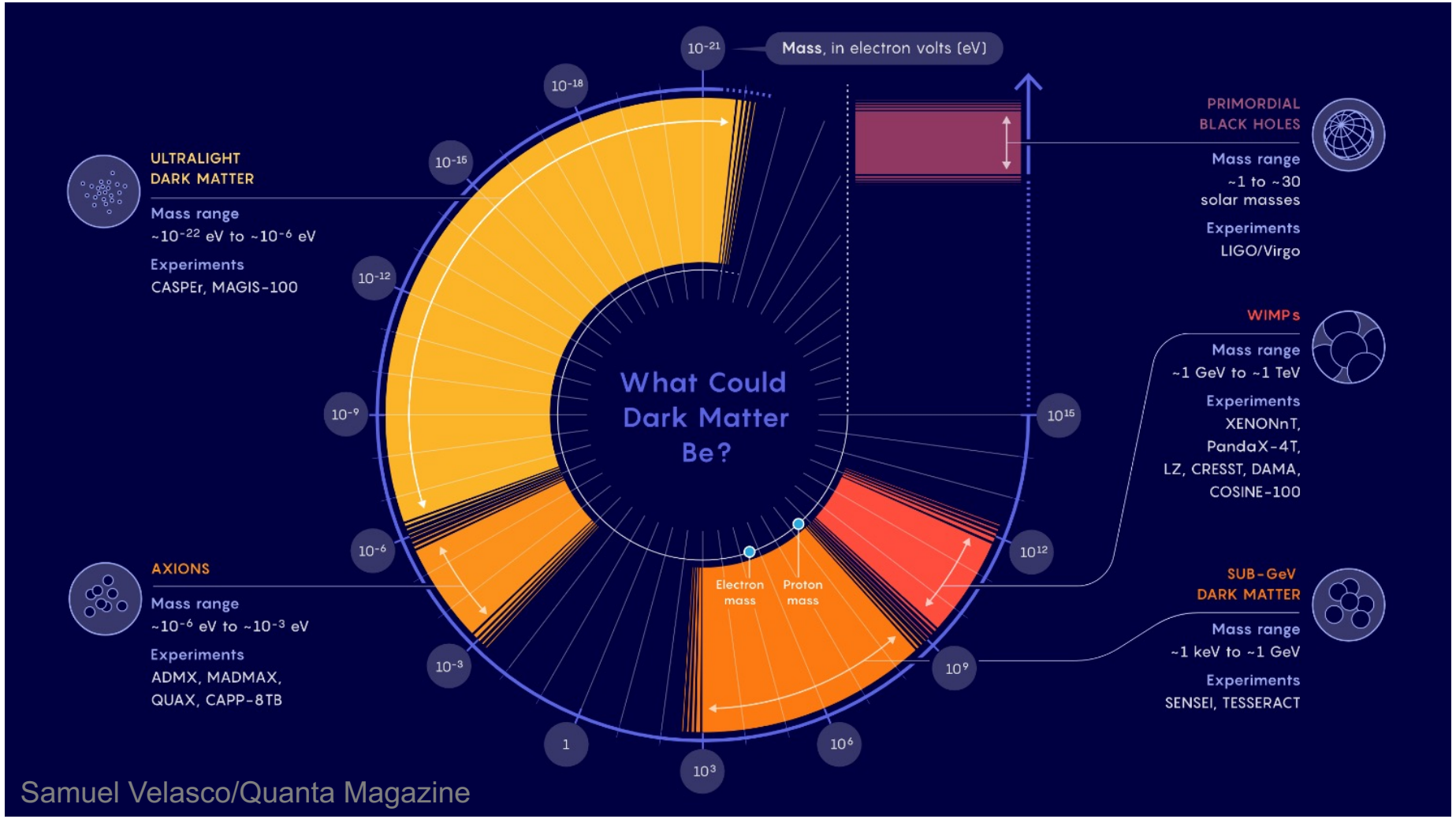




Dark Matter Candidates

- **Various types, covering extremely large mass range**

极轻暗物质
10^{-22} – 10^{-6} eV



轴子
10^{-6} – 10^{-3} eV

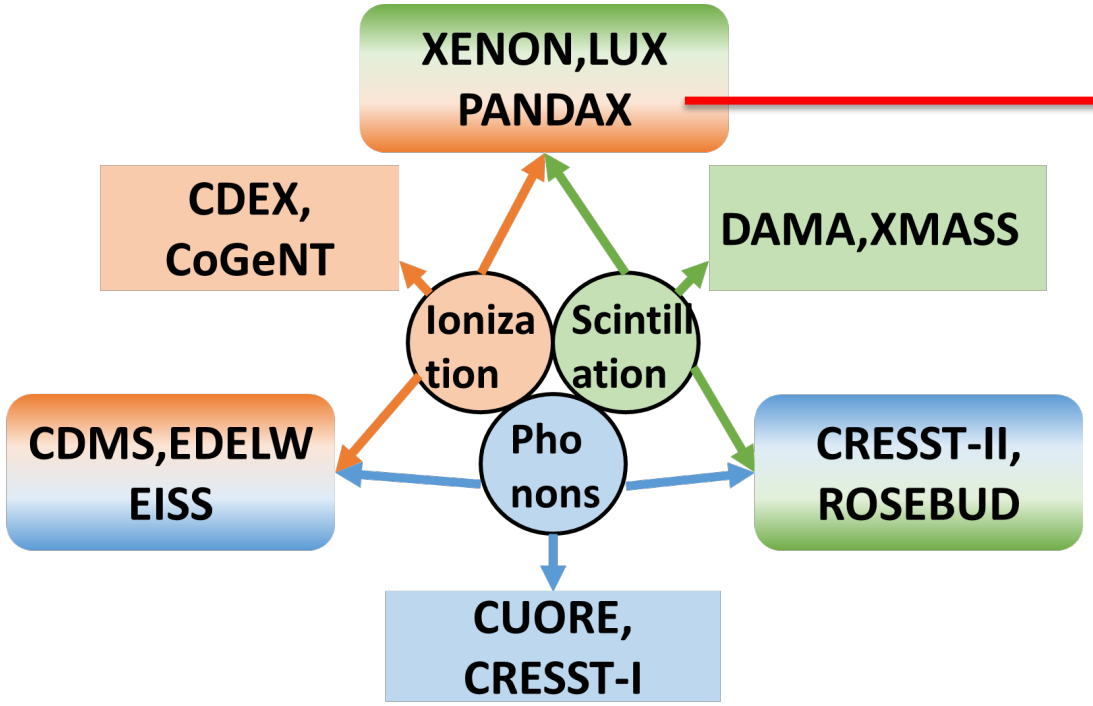
原初黑洞
1 – 30 M_{sun}

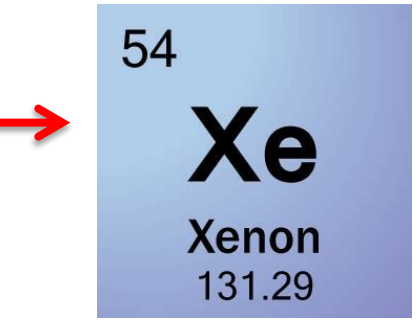
重质量暗物质
GeV – TeV

轻质量暗物质
keV - GeV

Direct Detection

- Incoming dark matter from the universe
- Scattering with target atom
- Energy deposit → scintillation, ionization, phonons





PANDA X

PandaX Collaboration

- Particle and astrophysical Xenon experiment

PandaX Detectors

- **Increase the detector sensitive target volume**
- **Lower radioactive background**

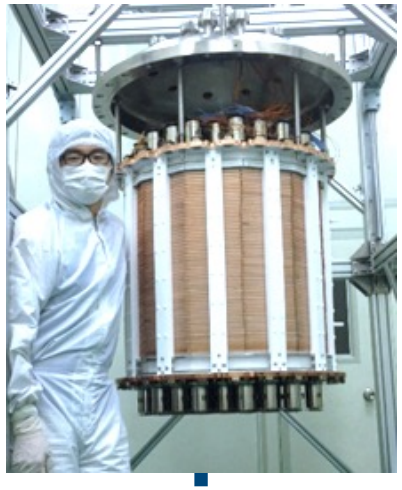
PandaX start

2009

PandaX-I
120kg

2010-2014

PandaX-II
580kg



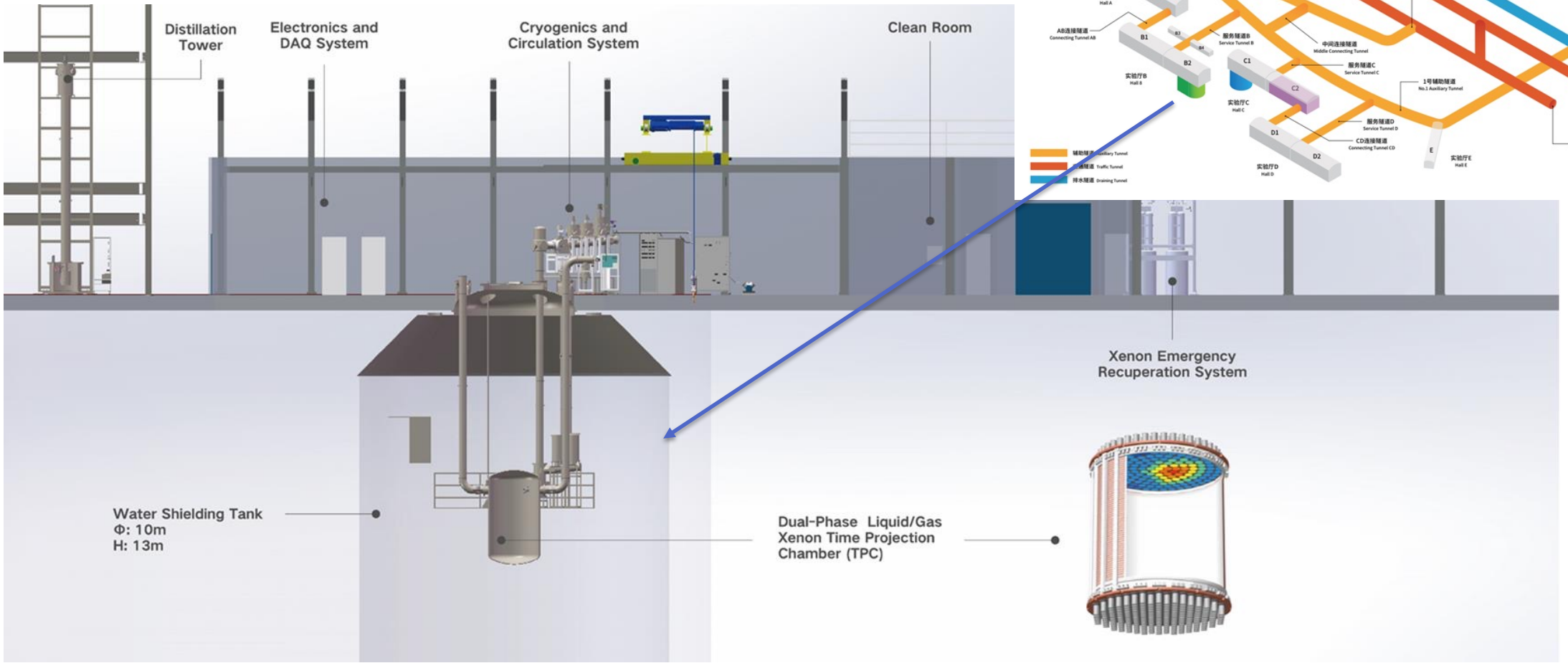
2015-2019

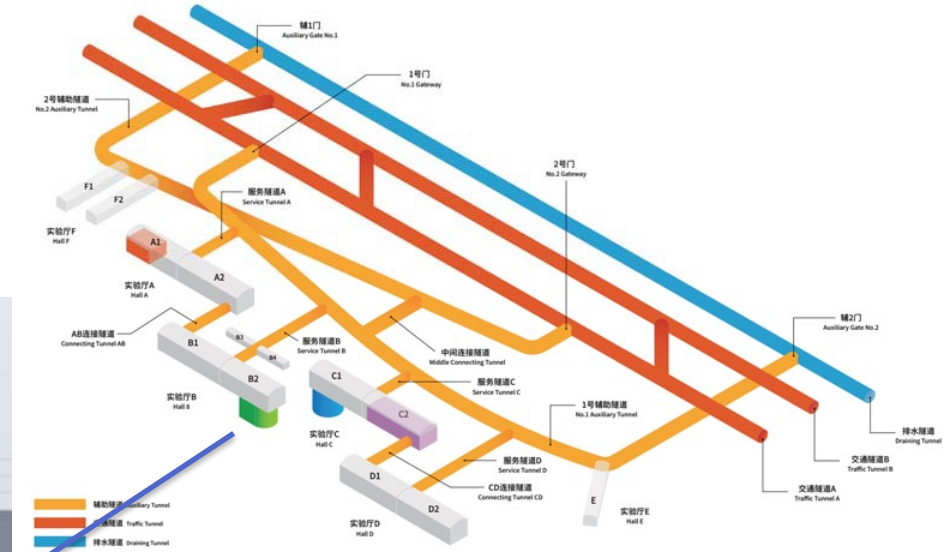
PandaX-4T
(3.7 tonne)

2020-

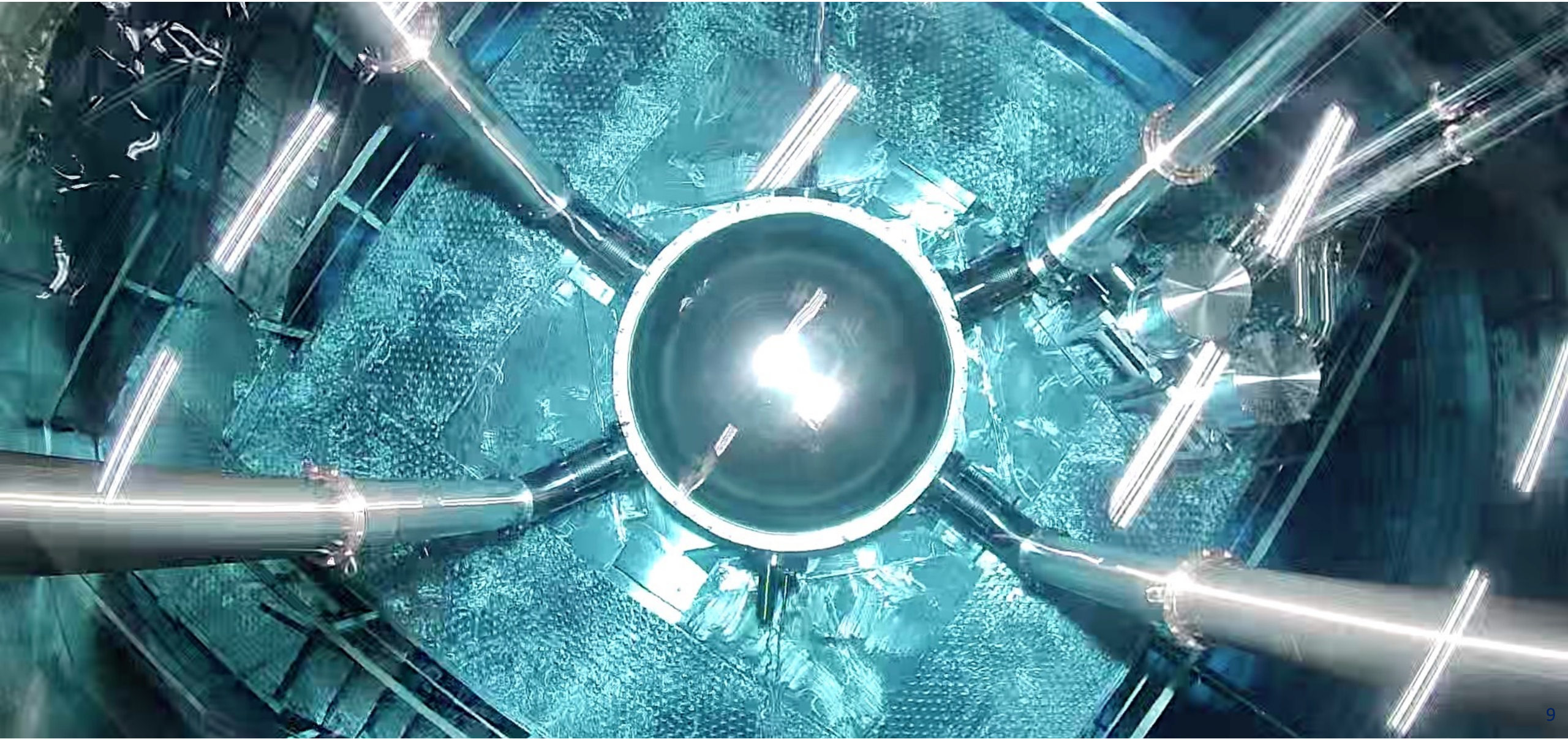
PandaX-4T @ CJPL-II

- **Sensitive volume: 3.7 tonne xenon**
- **900m³ high purity water shielding**



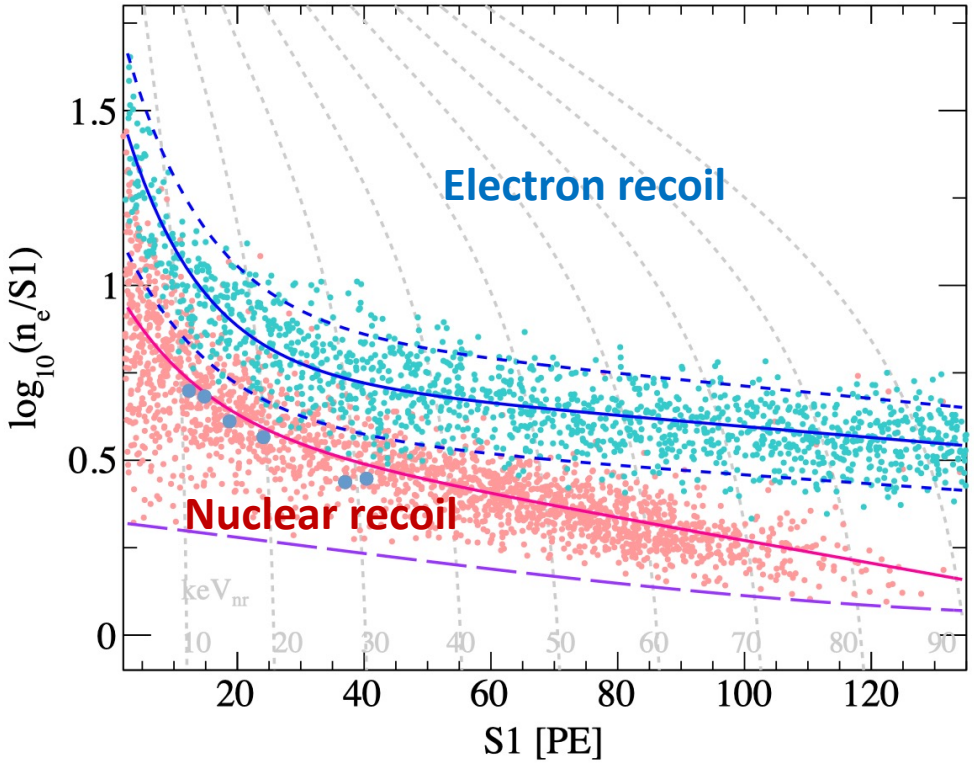


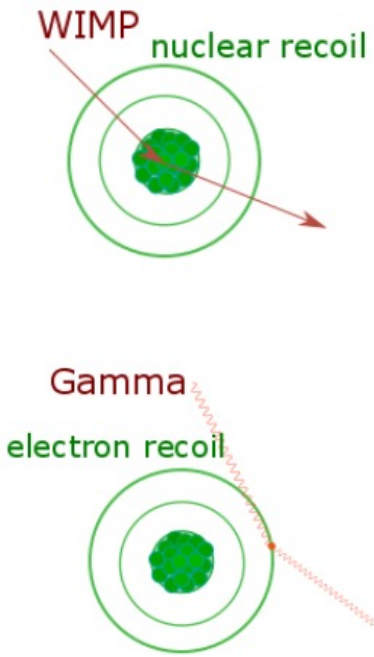
PandaX-4T Operation

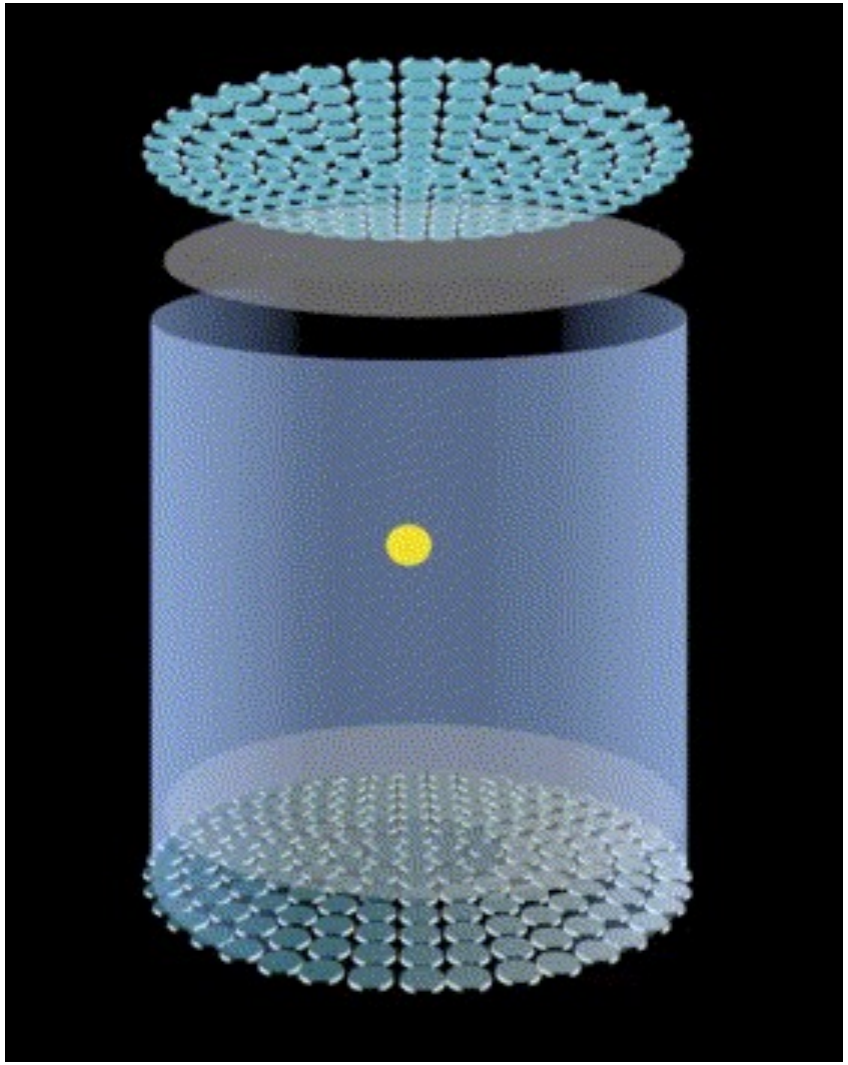


Dual-Phase Xenon TPC

- **Paired scintillation (S1) and ionization (S2) signals**
  - Energy and 3-D position
  - NR vs ER discrimination



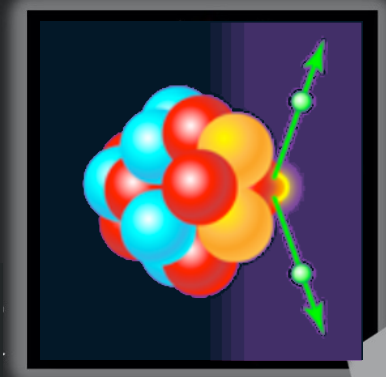




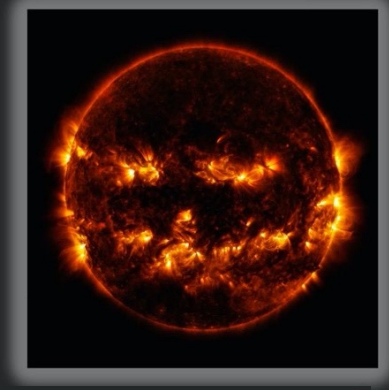
Multi-Physics Targets

Large energy range: keV ~ MeV

Dark Matter
1 keV – 10 keV



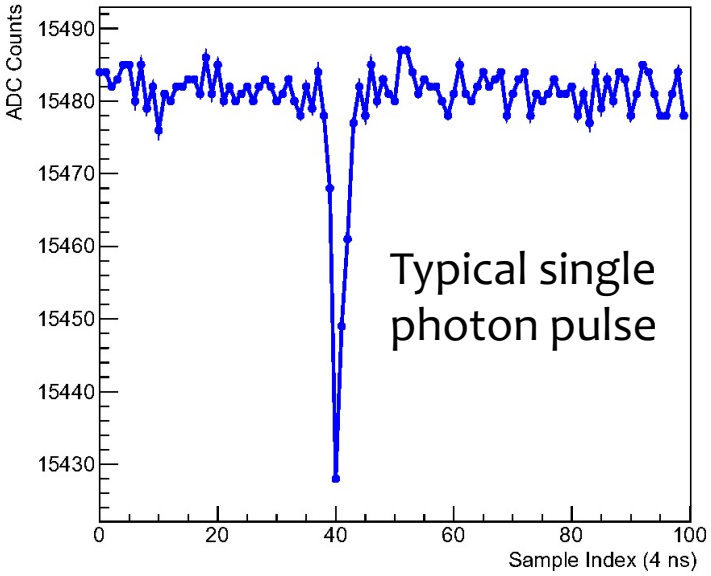
Majorana Neutrino
> 2 MeV

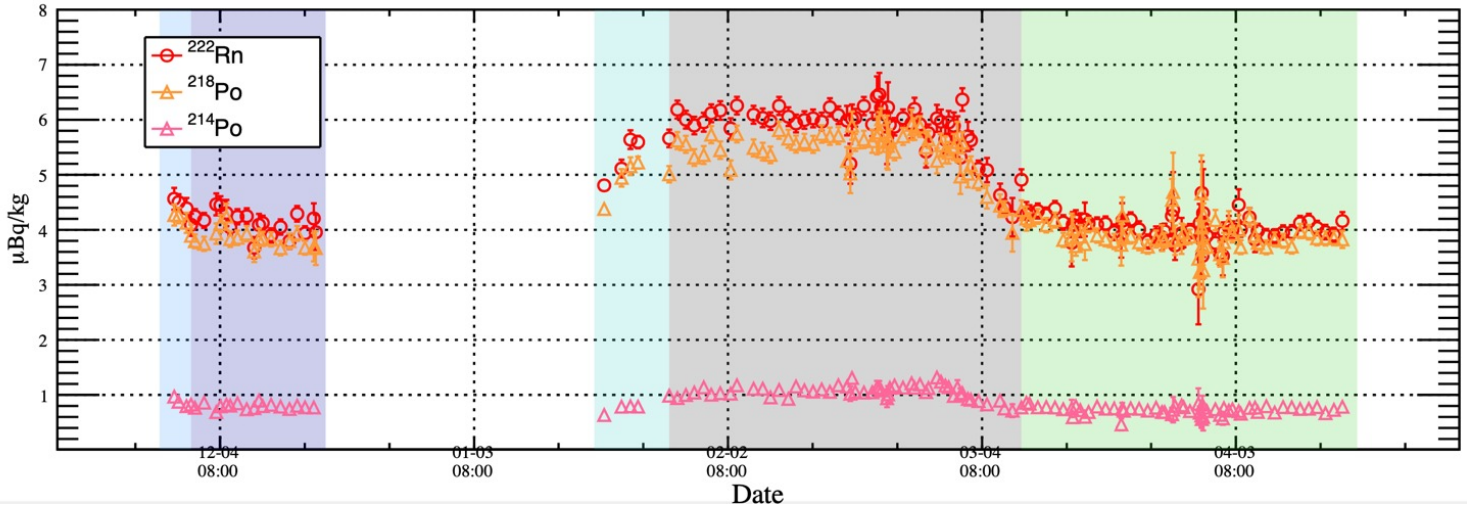


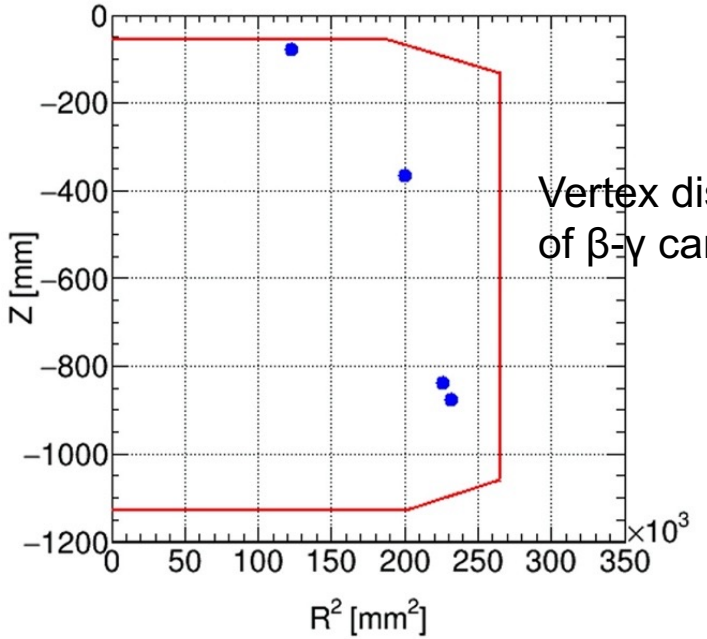
Astrophysical Neutrino
< 300 keV

Major Improvement

- **Low threshold: triggerless DAQ**
  - read out pulses above 20 ADC (~1/3 PE)
- **Low ^{222}Rn background**
  - 5 uBq/kg, 1/6 of PandaX-II
- **Low ^{85}Kr background**
  - 0.3 ppt ^{nat}Kr, 1/20 of PandaX-II



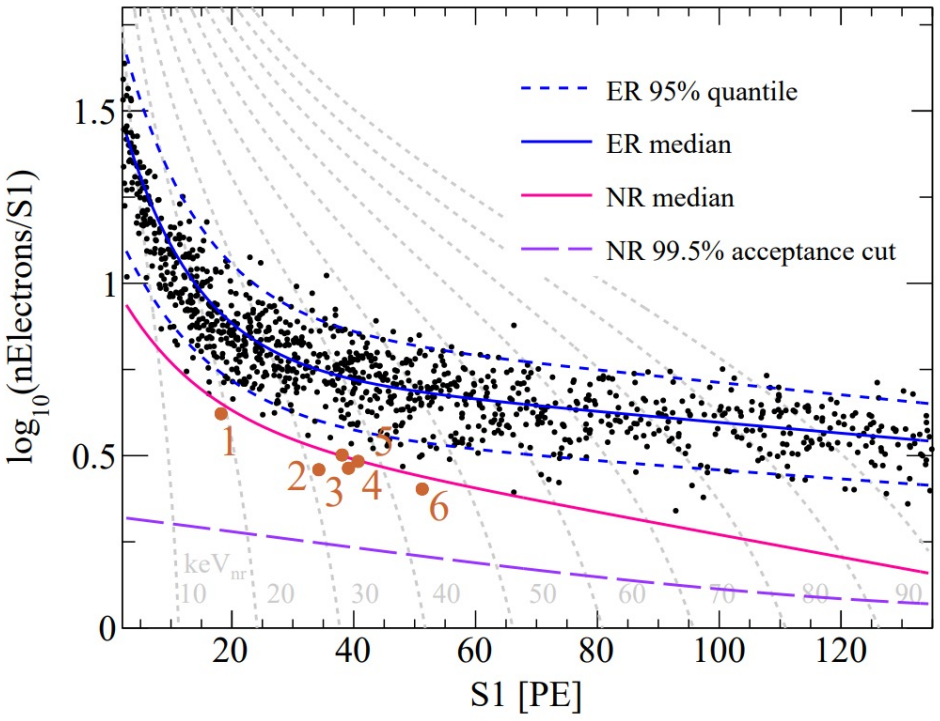


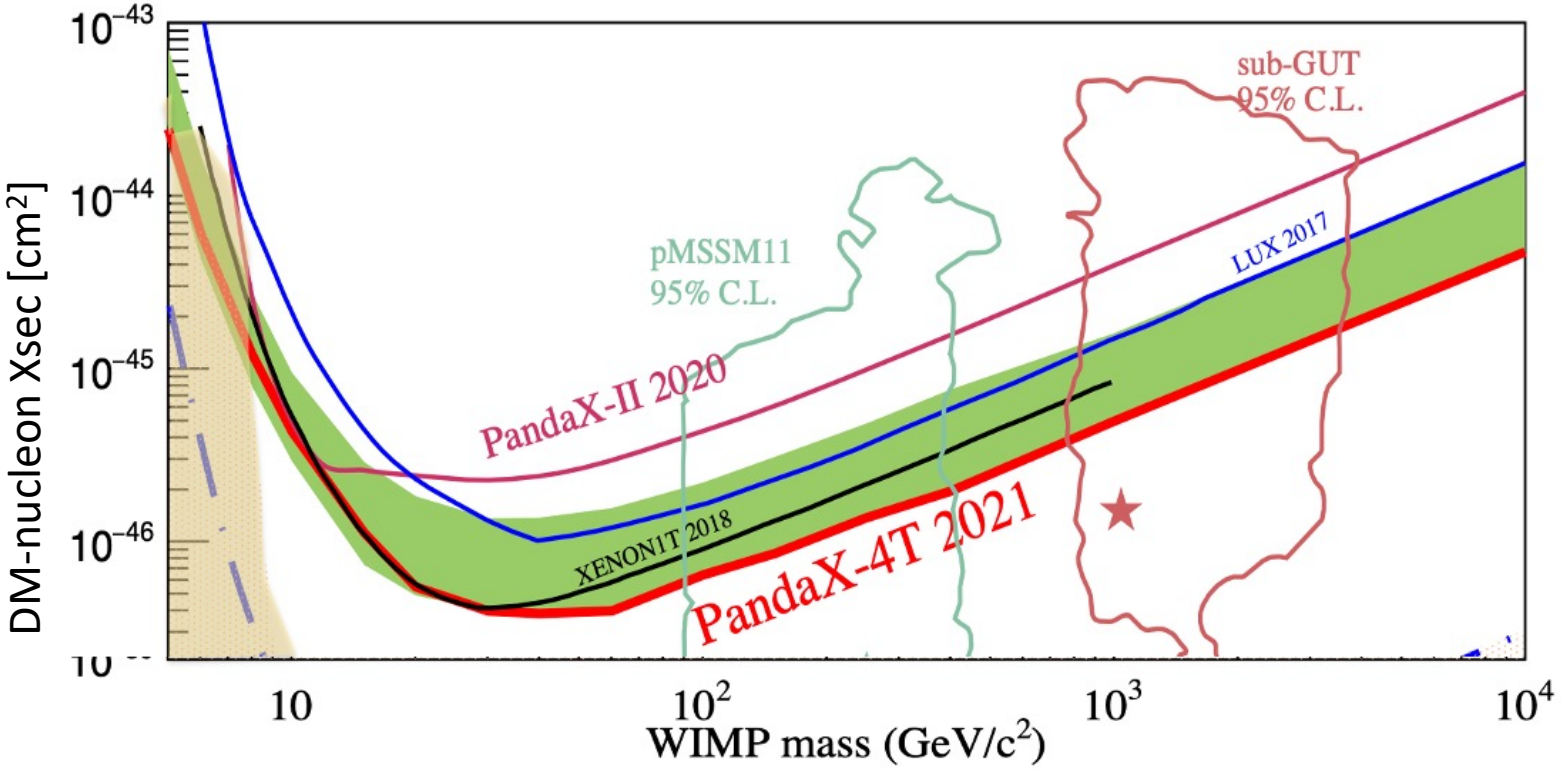


Vertex distribution of β-γ candidates

Run0 First Results

- **Run0: 0.63 tonne-year exposure**
  - Limits on WIMP-nucleon spin-independent xsec down to 3.8×10^{-47} cm^2





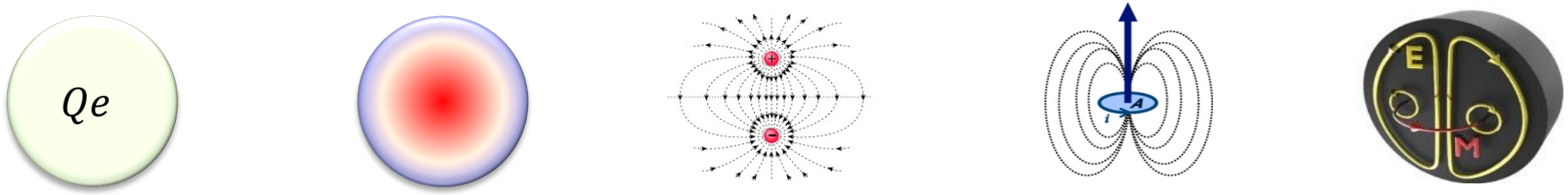
Y. Meng et al. PRL 127, 261802 (2021) Editors' Suggestion

How dark is dark matter?

Image Credit: Public Domain

Luminance of Dark Matter

- **Residual weak EM properties: coupling with photons**



微弱电荷	电荷半径	电偶极矩	磁偶极矩	零极矩
milicharge	charge radius	electric dipole	magnetic dipole	anapole

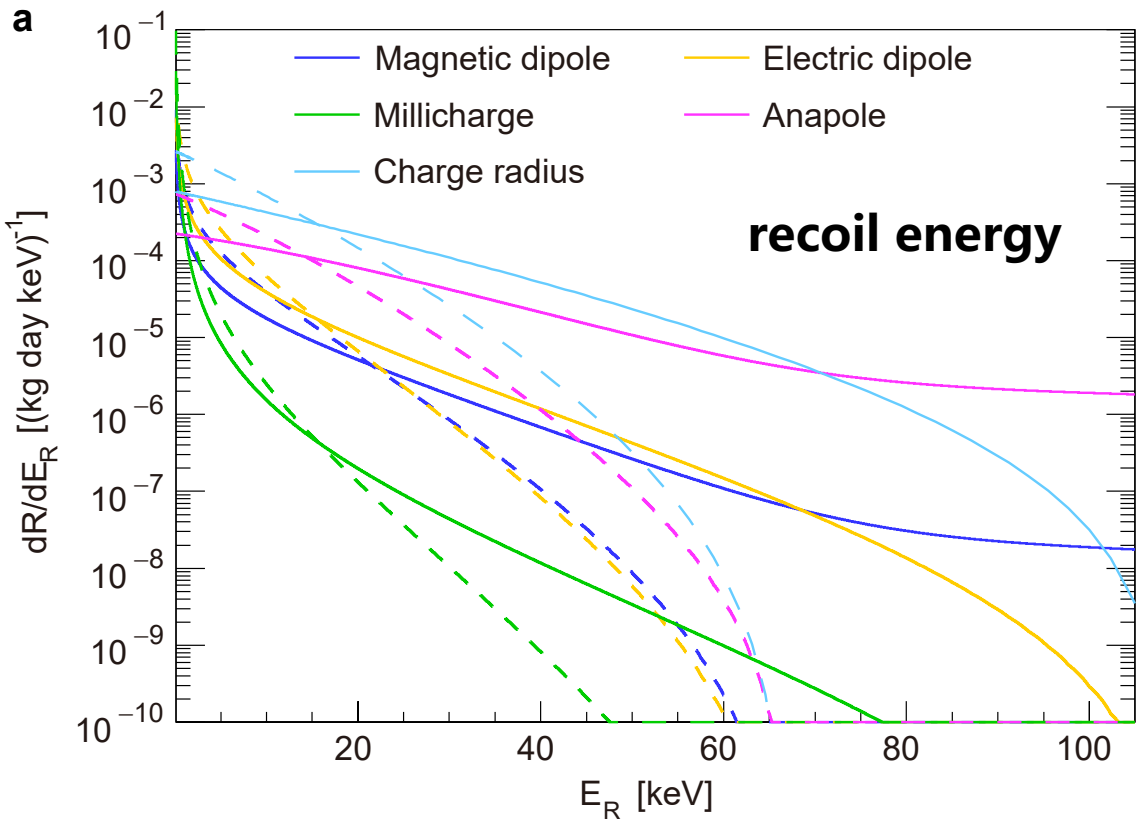
$$\mathcal{L} = Qe\bar{\chi}\gamma^{\mu}\chi A_{\mu} + \frac{\mu_{\chi}}{2}\bar{\chi}\sigma^{\mu\nu}\chi F_{\mu\nu} + i\frac{d_{\chi}}{2}\bar{\chi}\sigma^{\mu\nu}\gamma^{5}\chi F_{\mu\nu} + b_{\chi}\bar{\chi}\gamma^{\mu}\chi\partial^{\nu}F_{\mu\nu} + a_{\chi}\bar{\chi}\gamma^{\mu}\gamma^{5}\chi\partial^{\nu}F_{\mu\nu}$$

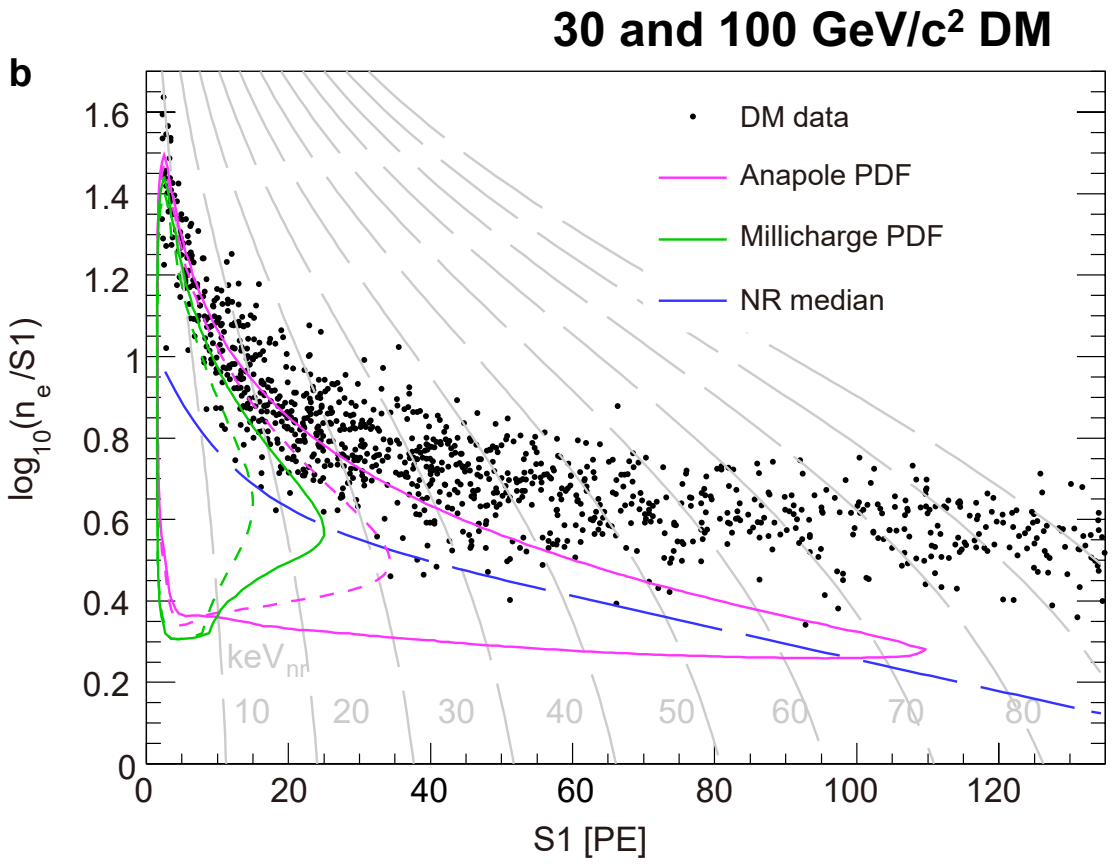
millicharge | magnetic dipole | electric dipole | charge radius | anapole

tree-level | higher-order loop-level

Photon-Mediated Interaction

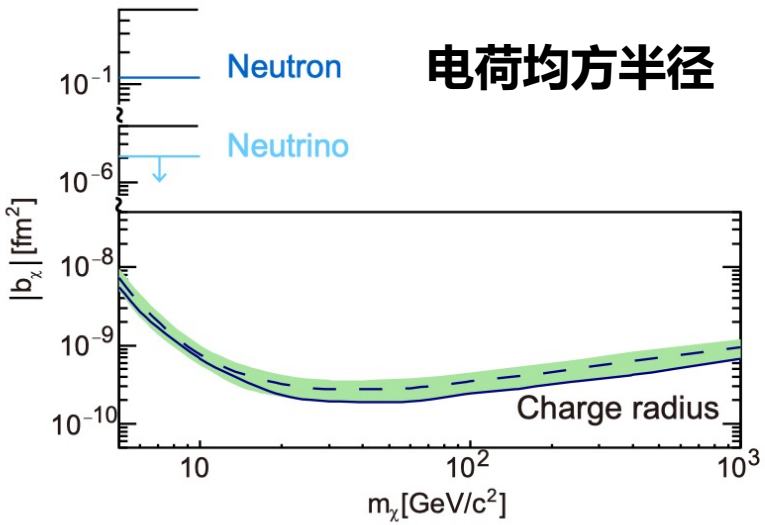
- Various nuclear recoil character
- Dedicated searches of these EM properties





Results from Xenon Recoil Data

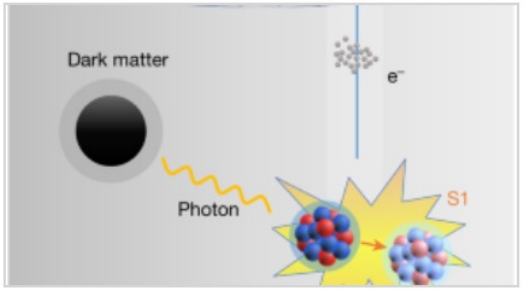
- **First experimental constraints on DM charge radius**
  - 4 orders of magnitude smaller than neutrino
- **Other EM properties**
  - up to 3 – 10 times improvement



nature › research articles

Limits on the luminance of dark matter from xenon recoil data

A direct search for effective electromagnetic interactions between dark matter and xenon nuclei that produce a recoil of the latter is carried out and the first constraint on charge radius of dark matter is derived.

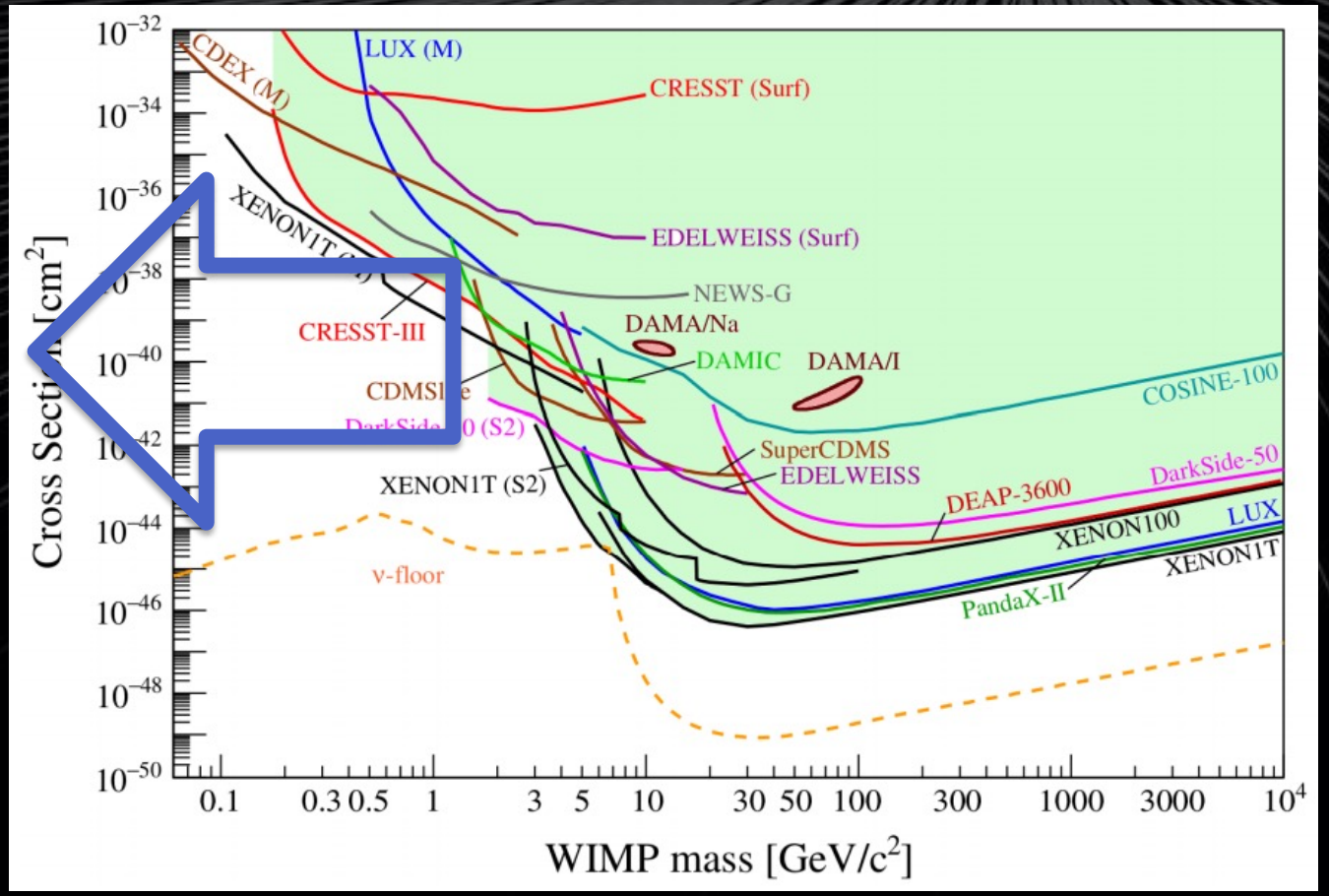


Xuyang Ning, Abdusalam Abdukerim ... Yubo Zhou

Article | 17 May 2023

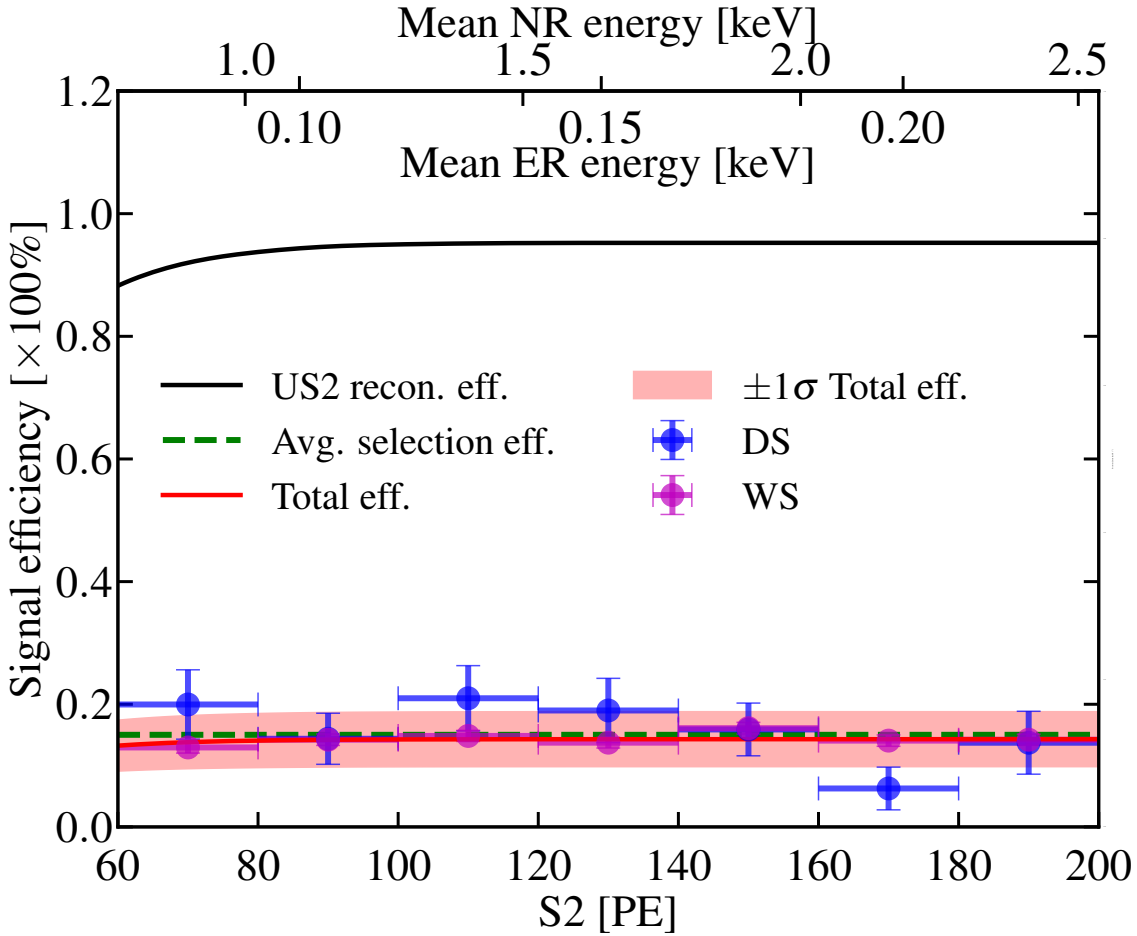
Nature 618, 47-50 (2023)

How to detect light dark matter?



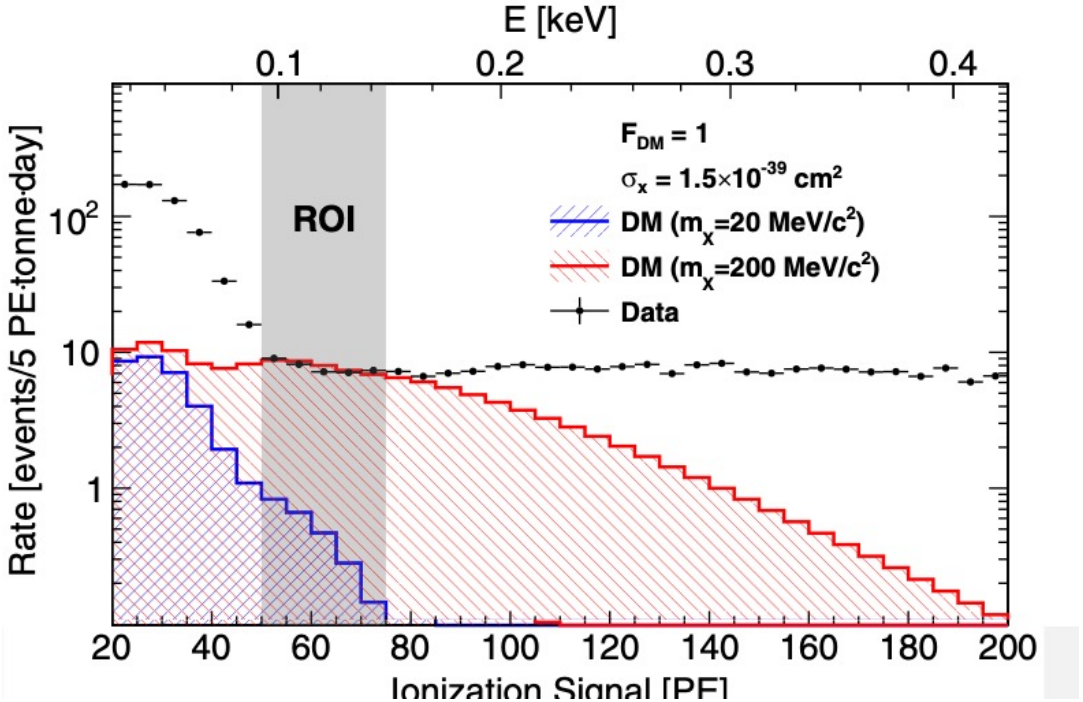
Low Threshold

- **Ionization-Only: no scintillation signal requirement**
  - ROI S2 [60, 200]PE: threshold down to ~100 eV (from ~1 keV)

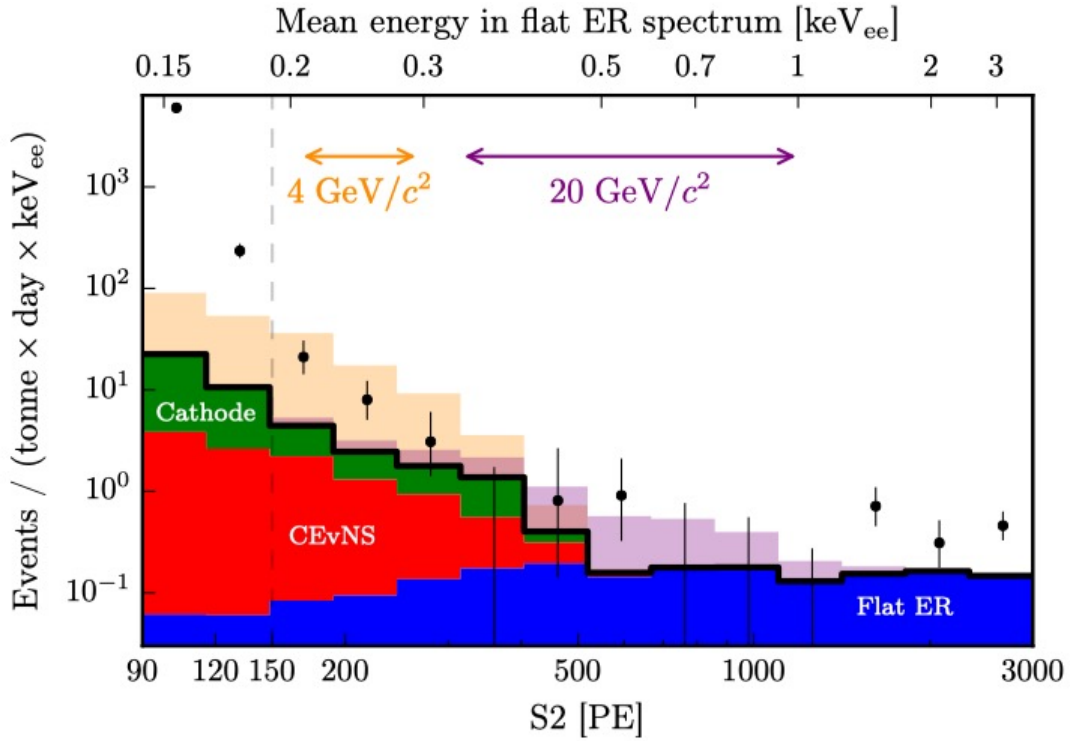


Ionization-only ROI

- **Key challenge: background components**
  - No full picture in previous xenon-based experiments
  - Conservative results only



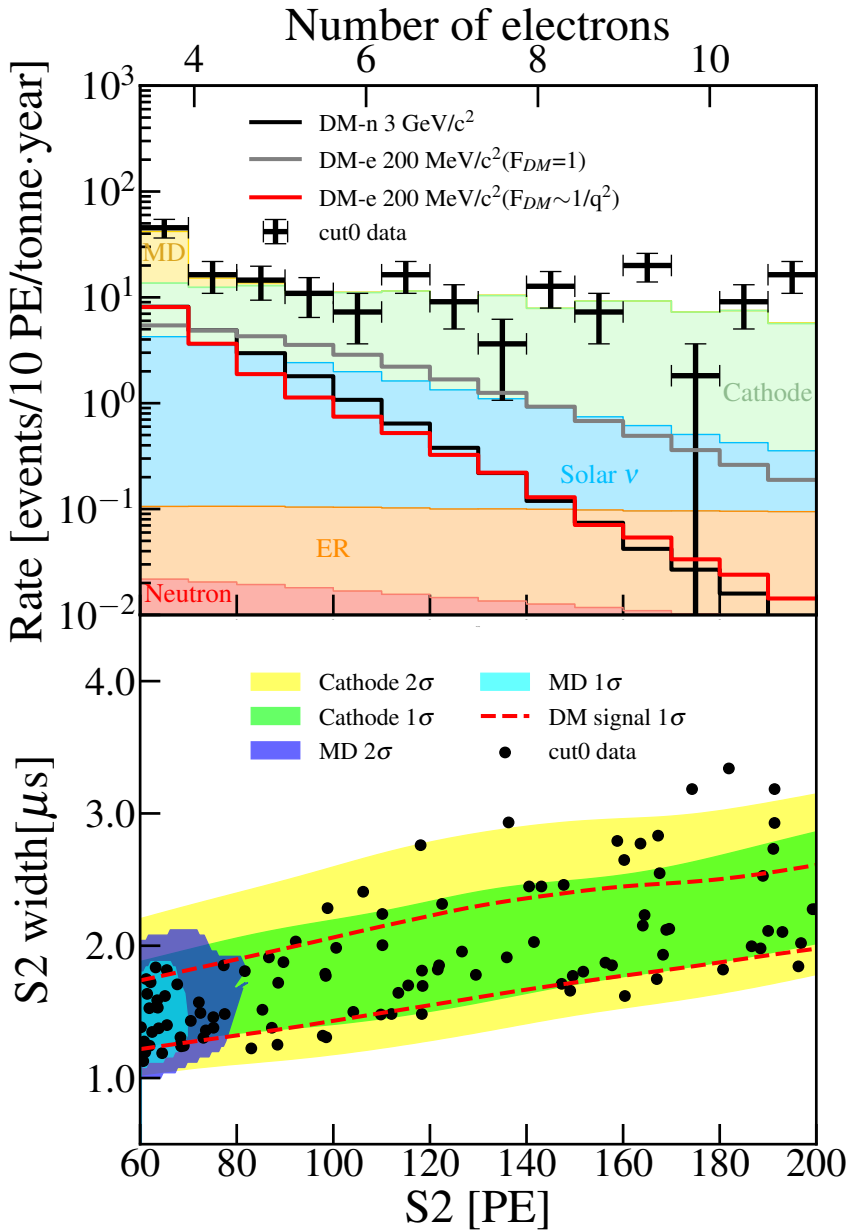
PandaX-II PRL



XENON1T PRL

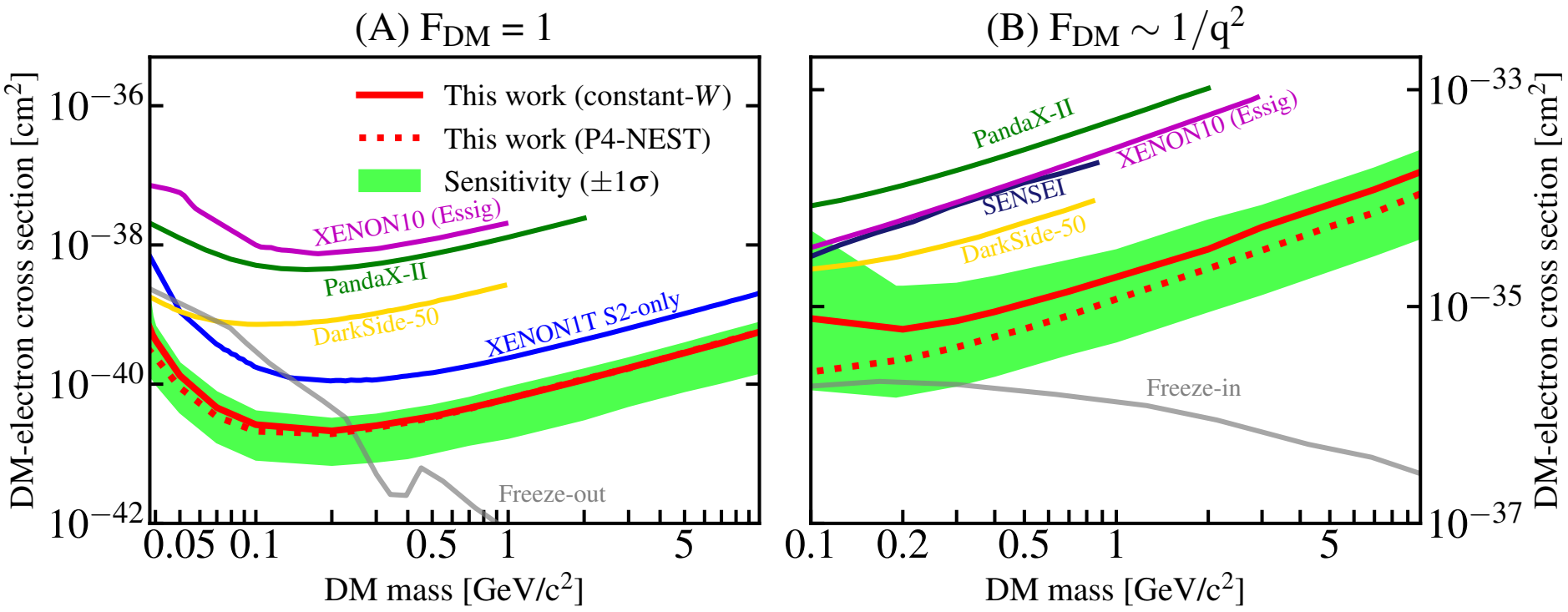
Ionization-only Data

- **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



Constraints on Light Dark Matter

- **Most stringent constraints are derived**
  - DM-electron interaction with heavy mediator, 2×10^{-41} cm^2
  - Freeze-out and Freeze-in



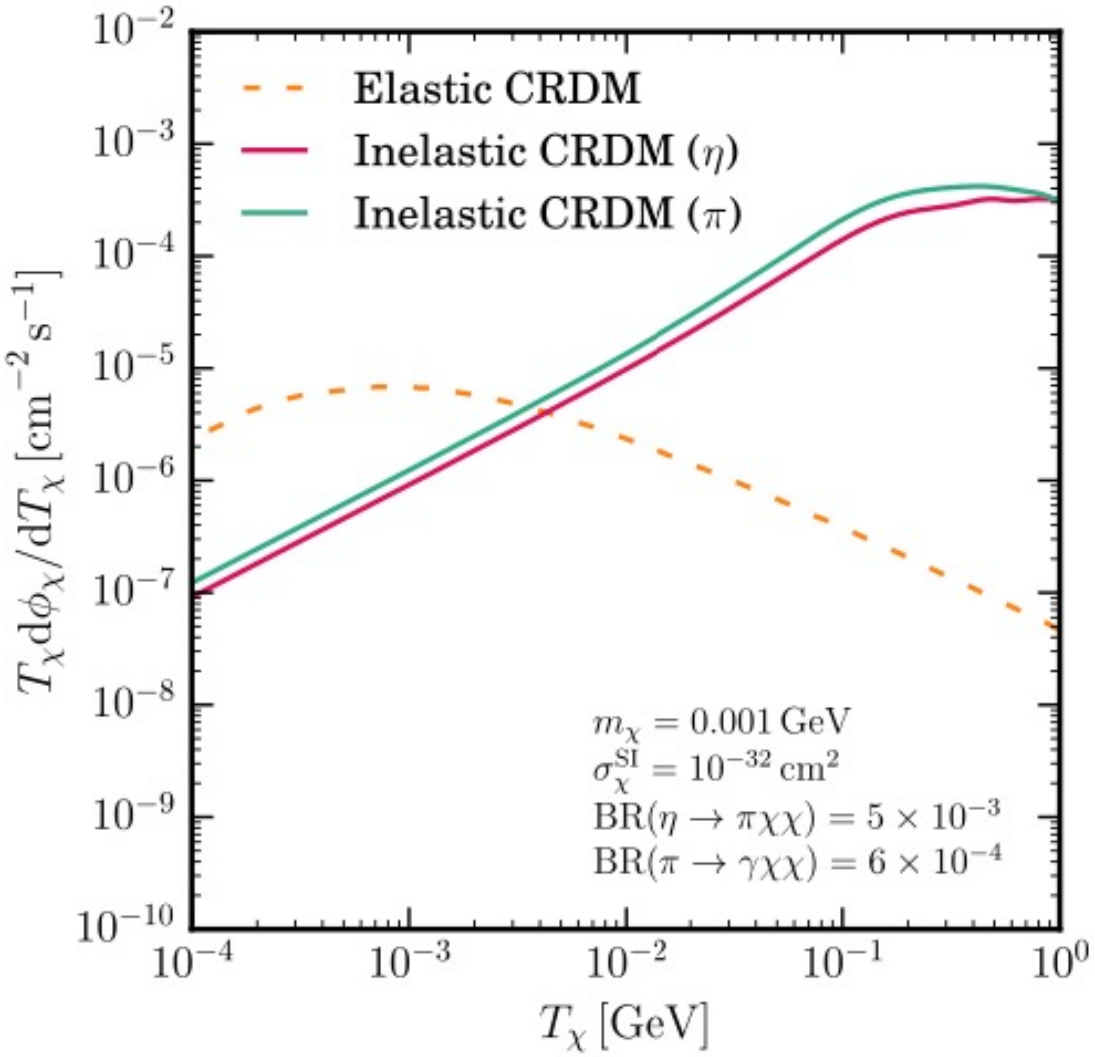
S. Li et al. PRL 130, 261001 (2023), Editors' Suggestion

Can light dark matter be boosted?

-

Dark Matter from Atmosphere

- **Hadrophilic scalar mediator**
  - $L \supset -g_\chi S \bar{\chi}_L \chi_R - g_u S \bar{u}_L u_R + h.c.$
  - Free parameters: g_χ, g_u, m_S, m_χ
- **Mesons from cosmic-ray beam dump in atmosphere**
  - $BR(\eta \to \pi^0 S \to \pi^0 \chi \bar{\chi})$
  - no dedicated measurements on this semi-invisible yet
- **Strongly boosted atmospheric dark matter**



J. Alvey, M. Campos, M. Fairbairn, T. You, PRL 123, 261802 (2019)

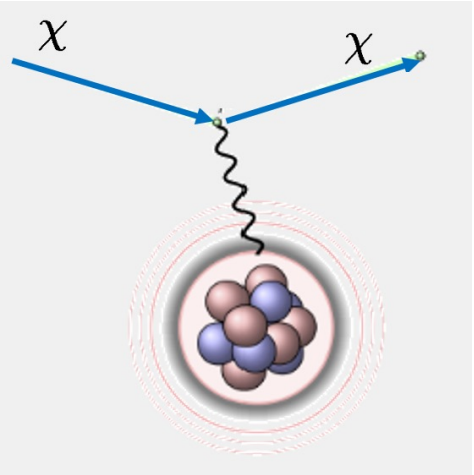
DM – Nucleus Interaction

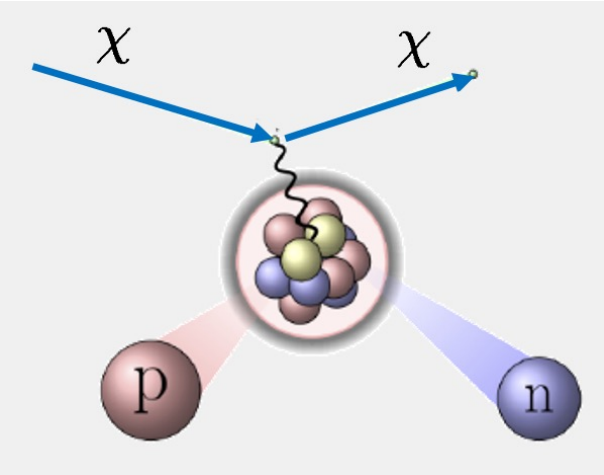
- **Elastic coherent, quasi-elastic (QE), and inelastic scatterings**
  - For $T_\chi > 0.2$ GeV, QE becomes significant
  - **Dedicated QE scattering calculation with light mediator**

$$\chi(k) + A(p_A) \to \chi(k') + X(\to n + Y)$$

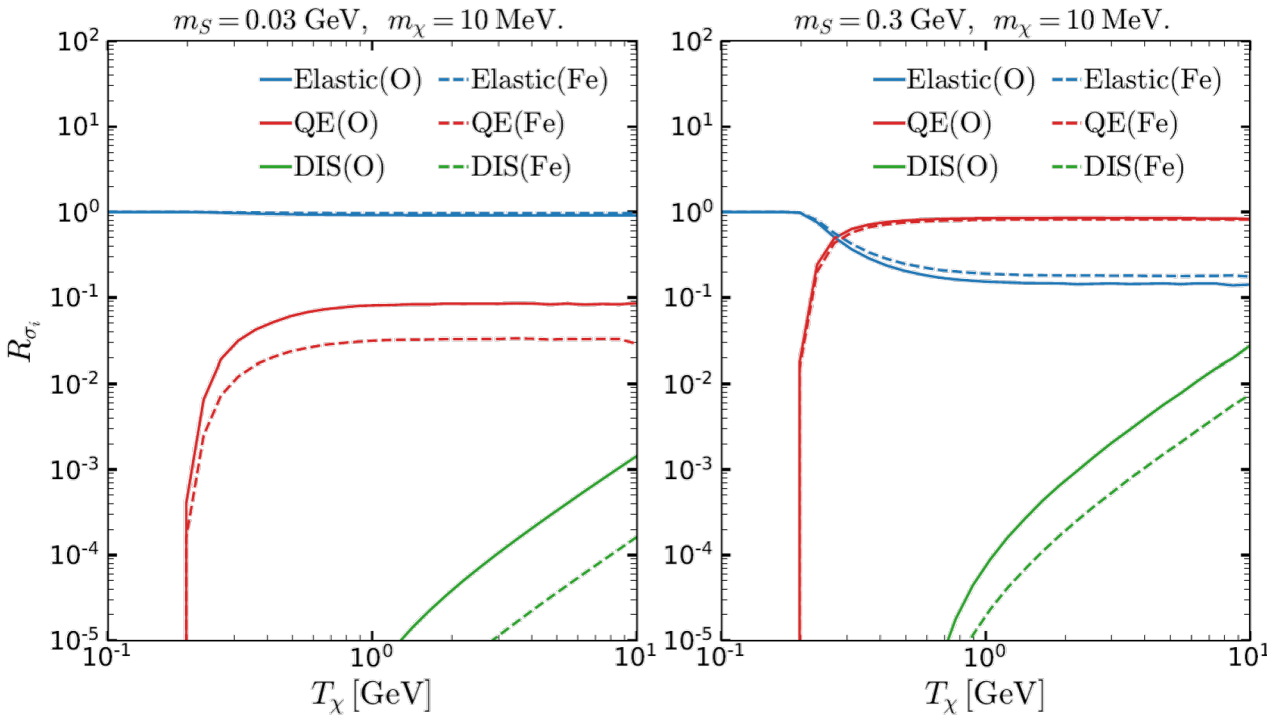
$$\frac{\mathrm{d}\sigma_{\mathrm{QE}}}{\mathrm{d}T'_\chi \mathrm{d}\Omega} = Z\frac{\mathrm{d}\sigma_p}{\mathrm{d}T'_\chi \mathrm{d}\Omega} + (A-Z)\frac{\mathrm{d}\sigma_n}{\mathrm{d}T'_\chi \mathrm{d}\Omega},$$

L. Su, L. Wu, NZ, B. Zhu arXiv:2212.02286



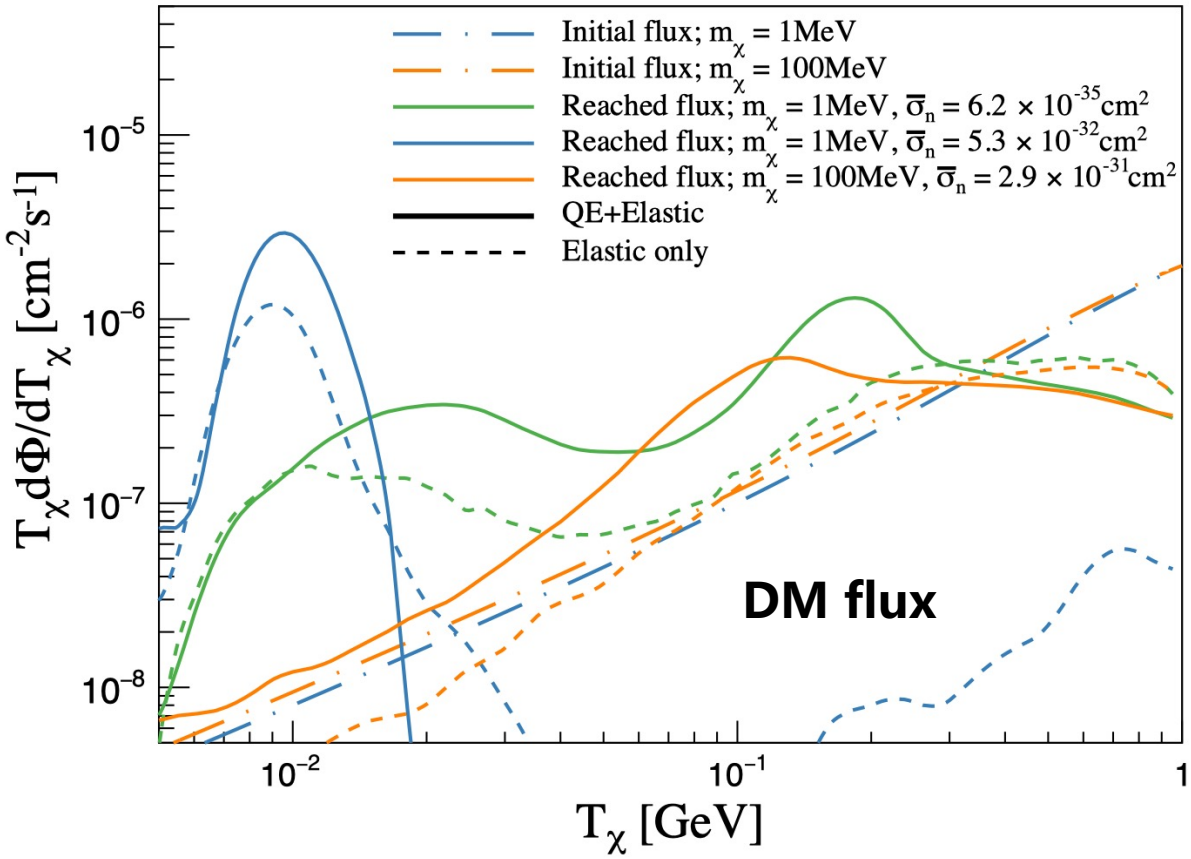


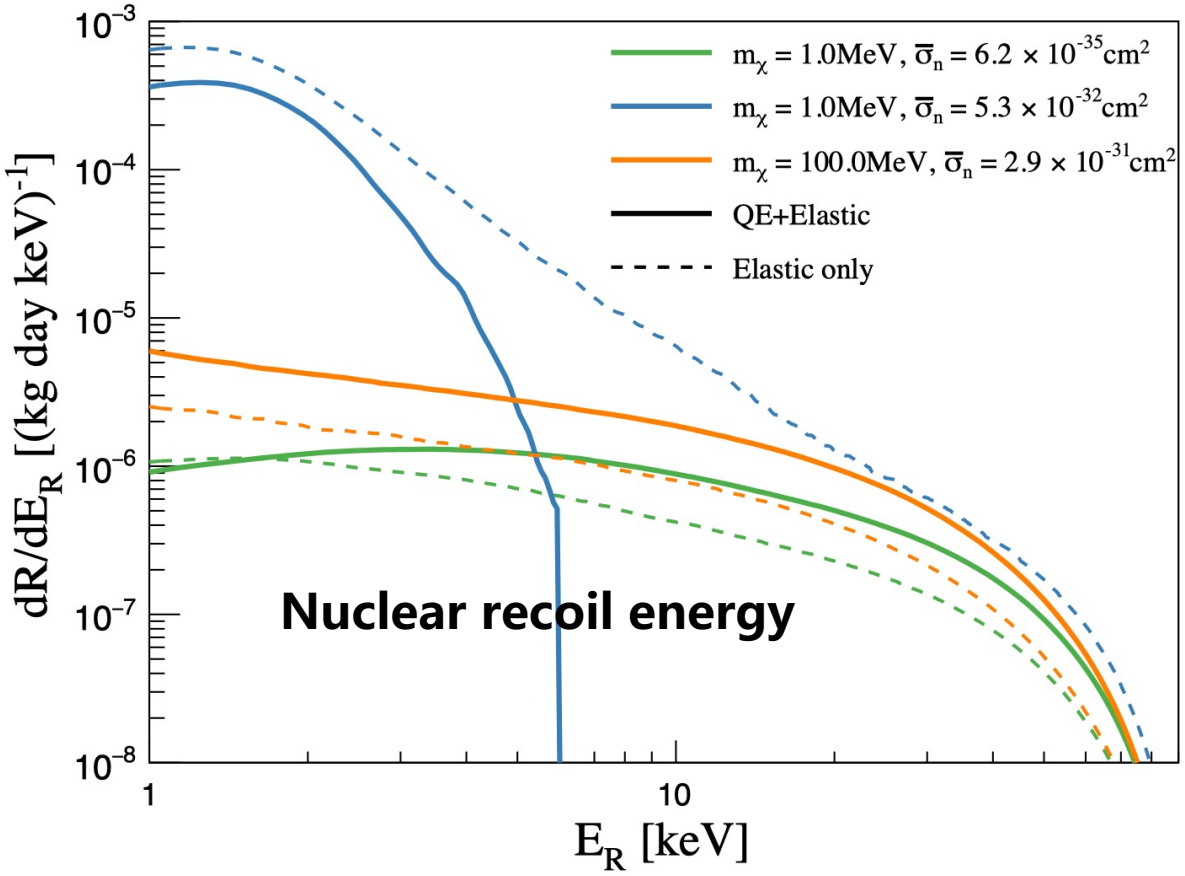
$$R_{\sigma_i} = \frac{\sigma_i}{\sigma_{tot}}, \quad i = \mathrm{ES}, \mathrm{QES}, \mathrm{DIS}$$



Boosted DM in Detector

- **Earth attenuation**
  - Monte Carlo simulation with QE and Elastic process included

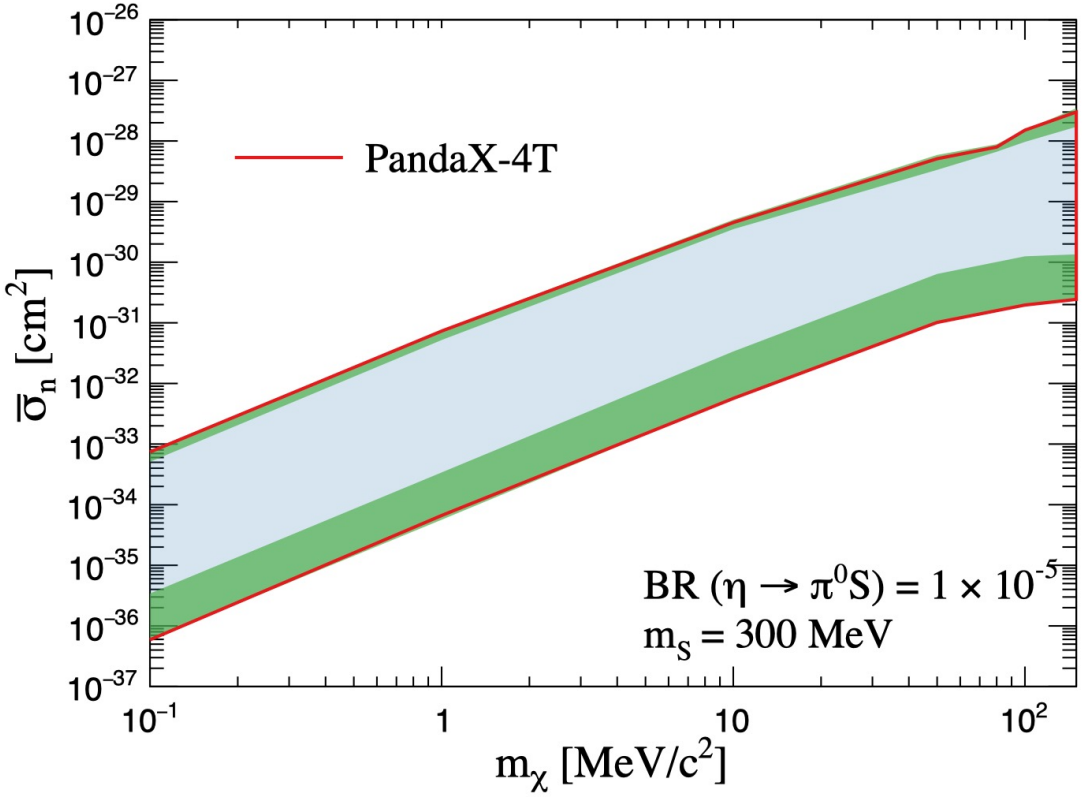


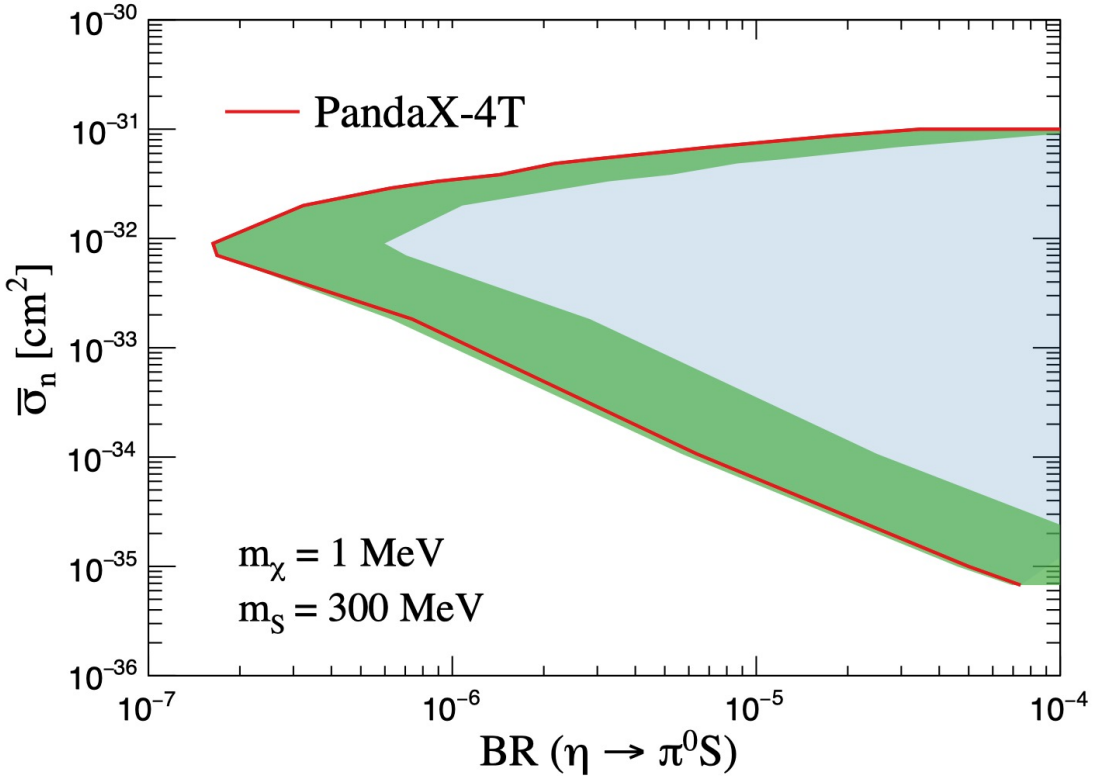


Constraints on DM-Nucleon Scattering

- **Cosmic-ray beam dump gives a unique window to search this scalar mediated DM-nucleon interaction**
  - DM mass scanning range ~ MeV/c^2

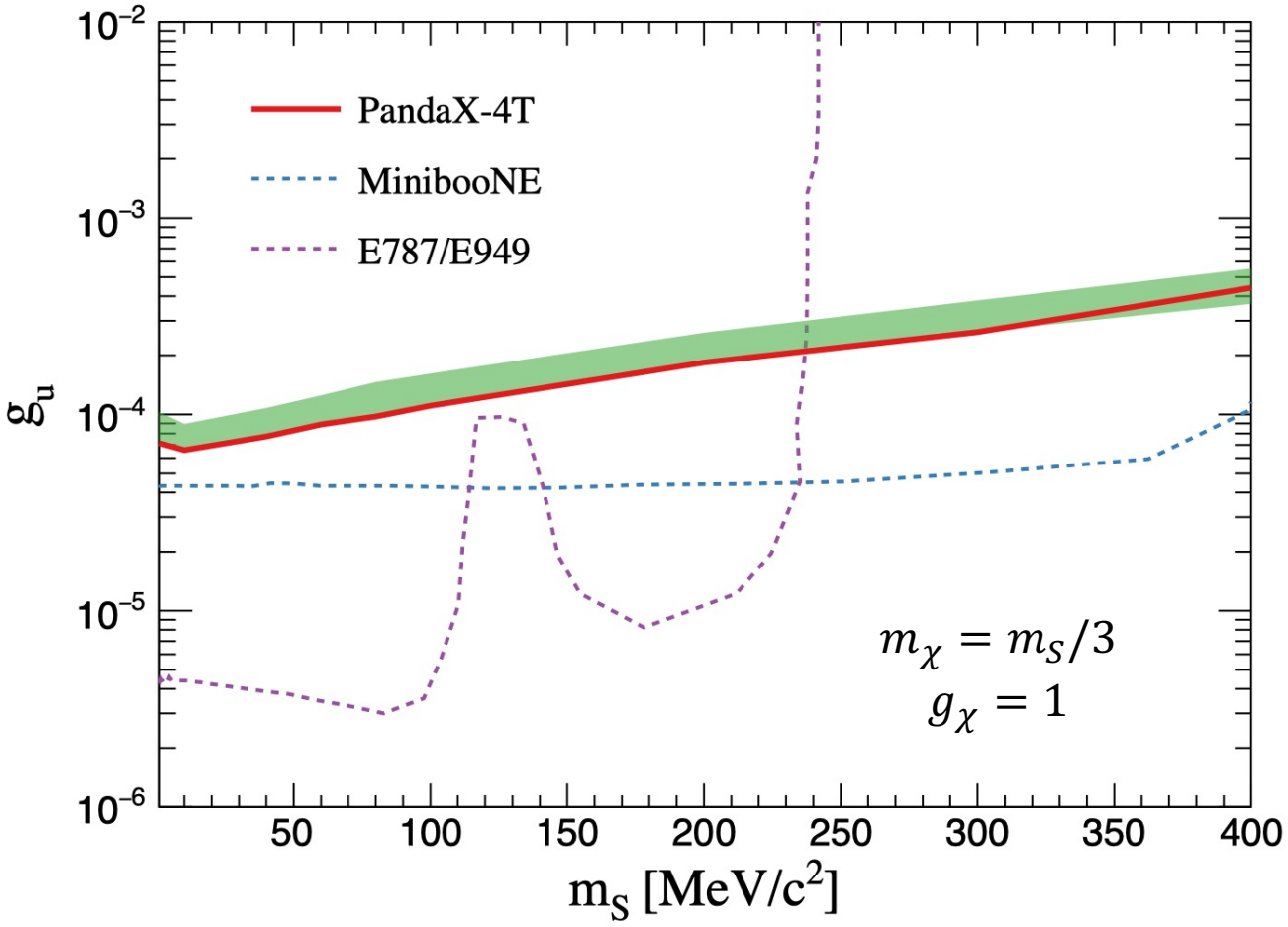
X. Ning et al. arXiv:2301.03010 accepted by PRL



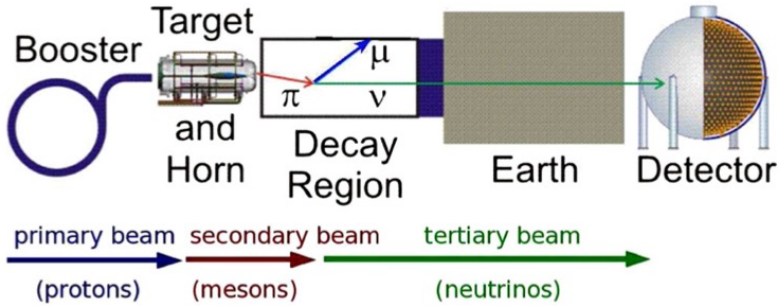


Constraints on Coupling Strength

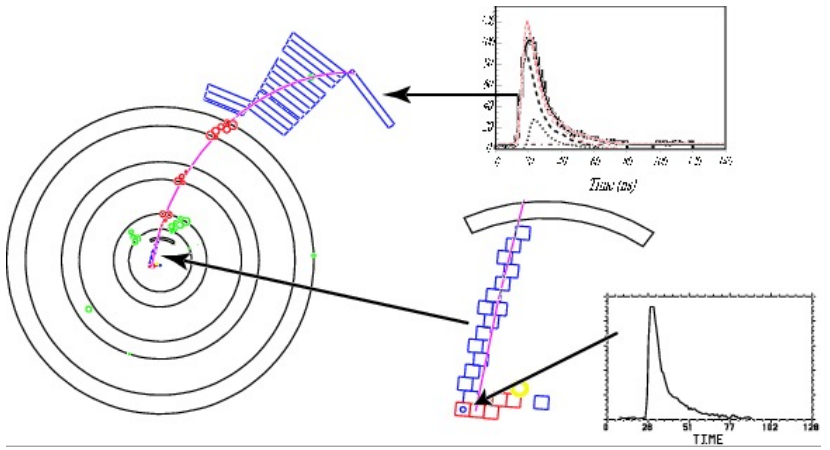
- **Same model could be tested in beam experiments, like MinibooNE and E787/E949**



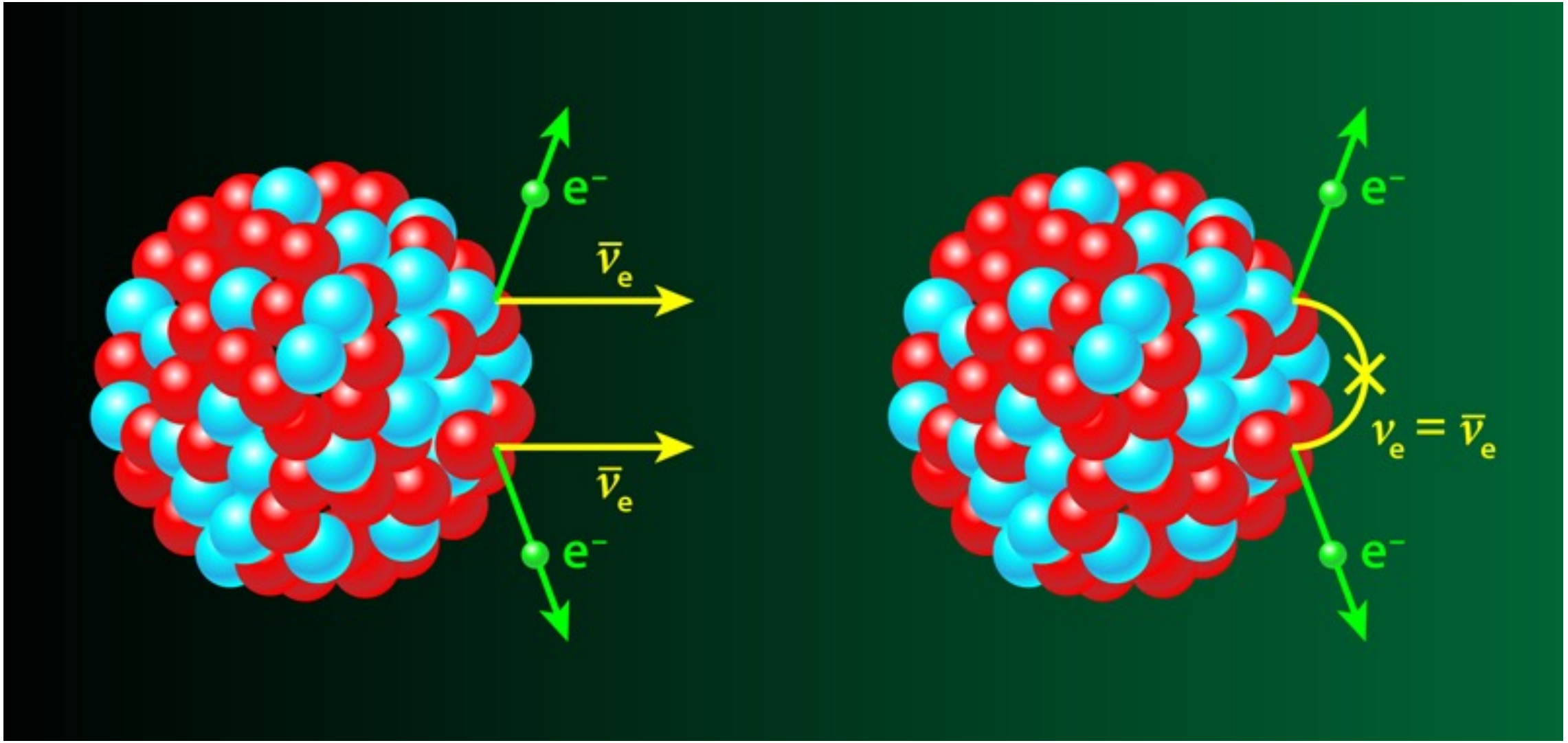
MiniBooNE



E787/E949: rare Kaon decay

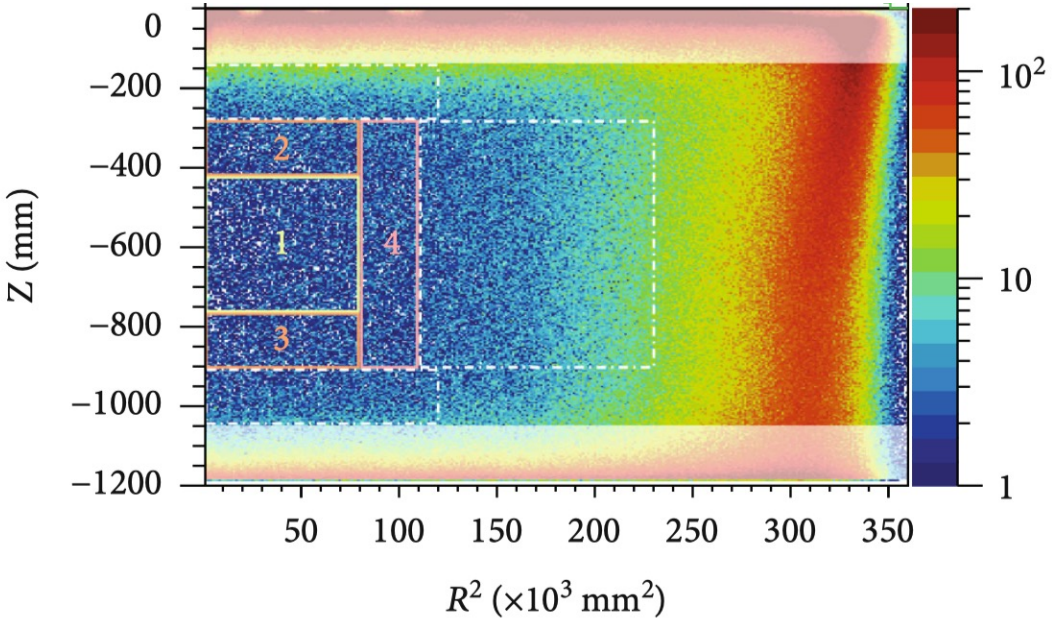


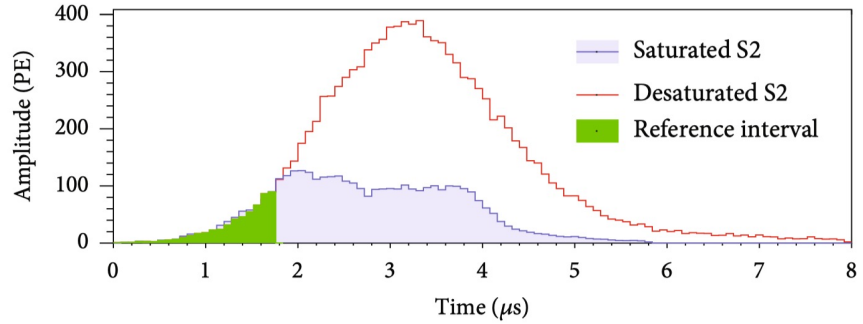
Majorana Neutrino

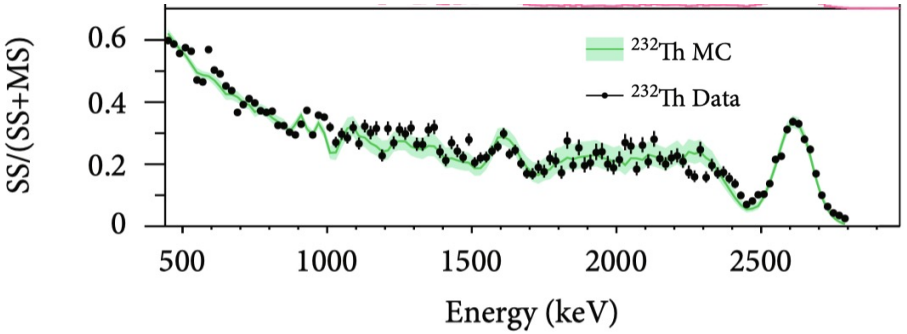


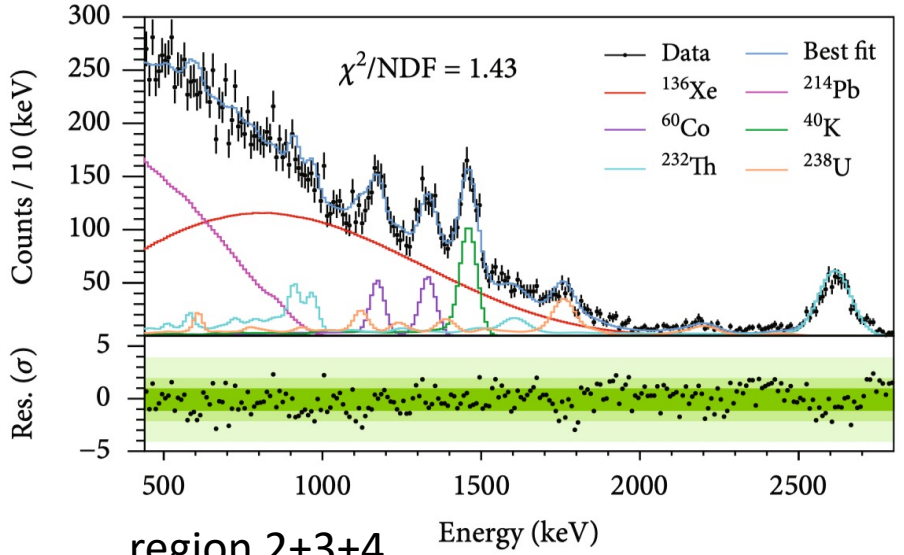
^{136}Xe 2vDBD Half-life Measurement

- **Energy window [440, 2800] keV**
  - PMT desaturation algorithm
  - Multi-site vs single-site discrimination
- **Robust estimation of backgrounds**
  - Simultaneous fit in 4 regions





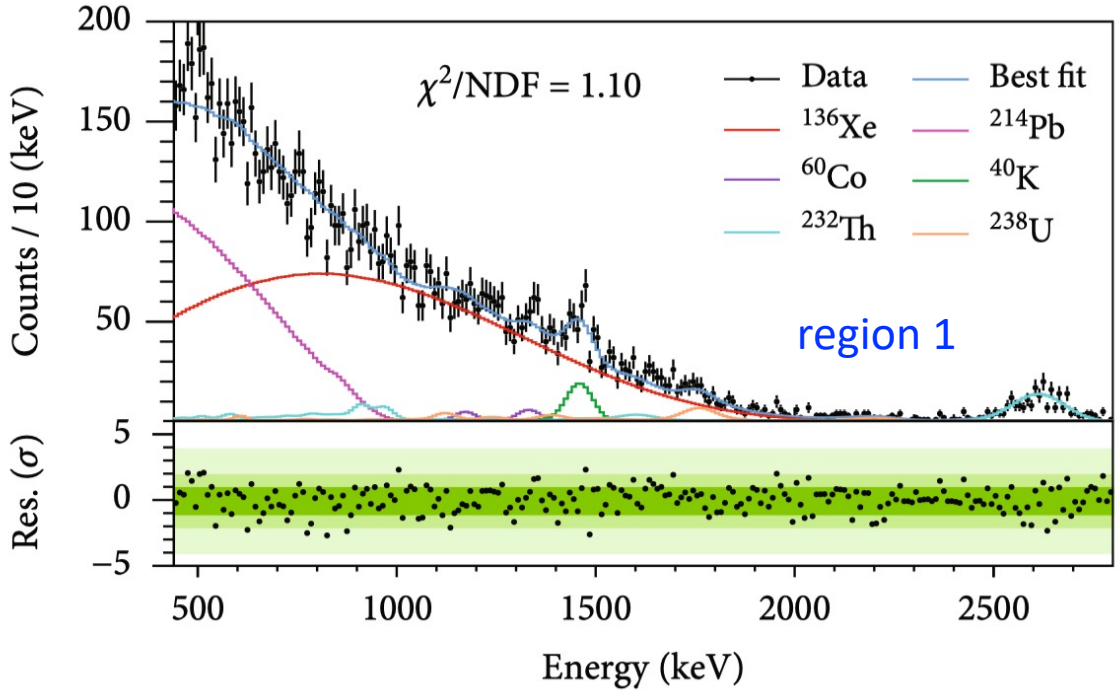




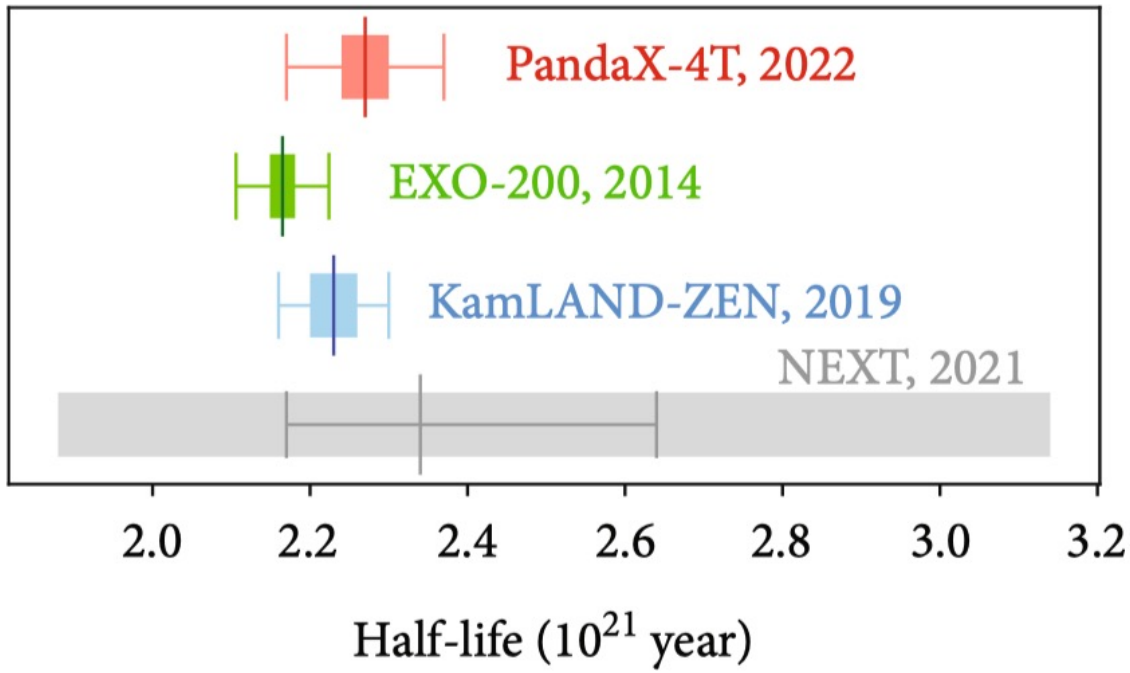
region 2+3+4

^{136}Xe 2vDBD Half-life Measurement

- **First result derived from natural xenon experiment**
  - 2.27 +/- 0.03 (stat) +/- 0.10 (syst) x 10^{21} years
  - One of the most precise measurements to date
  - **Comparable with enriched ^{136}Xe experiments**

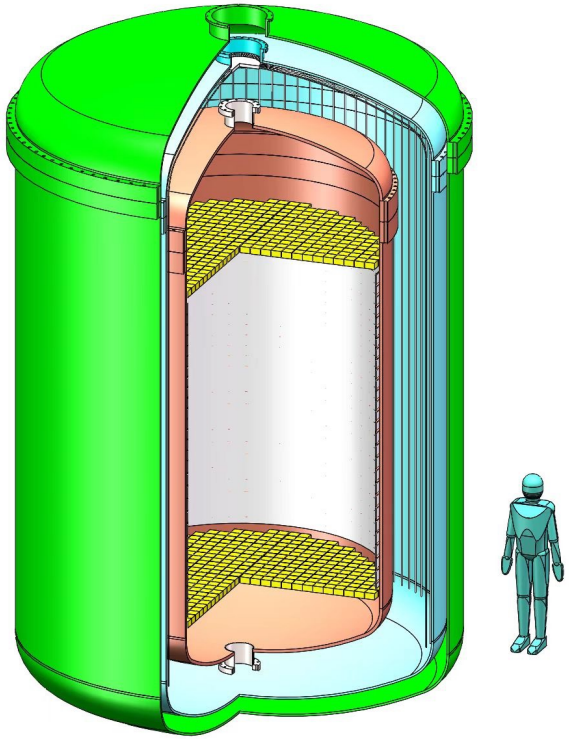


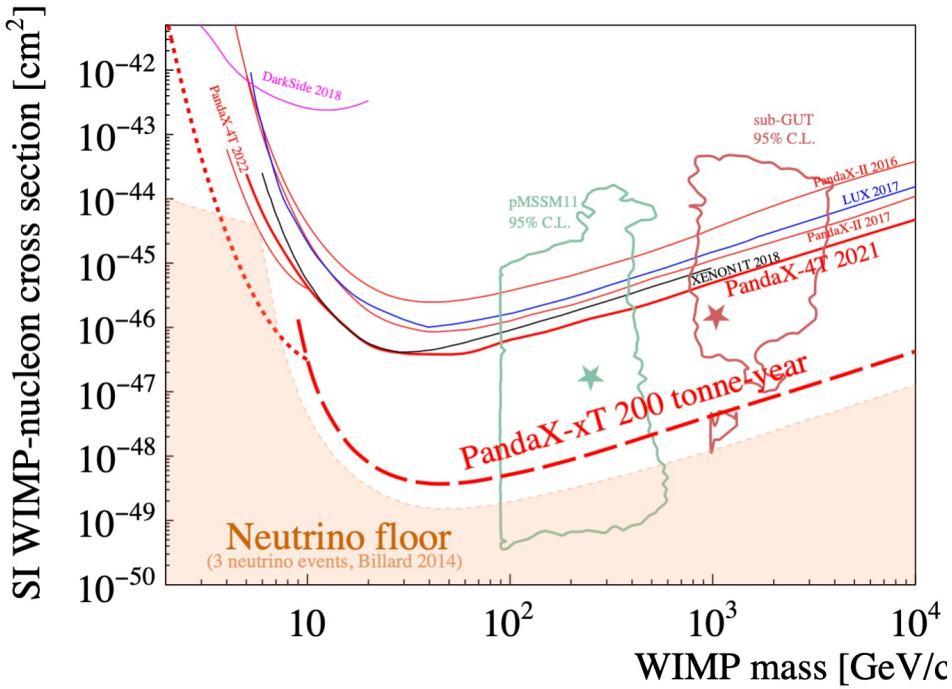
Research Vol 2022, 9798721 (2022)

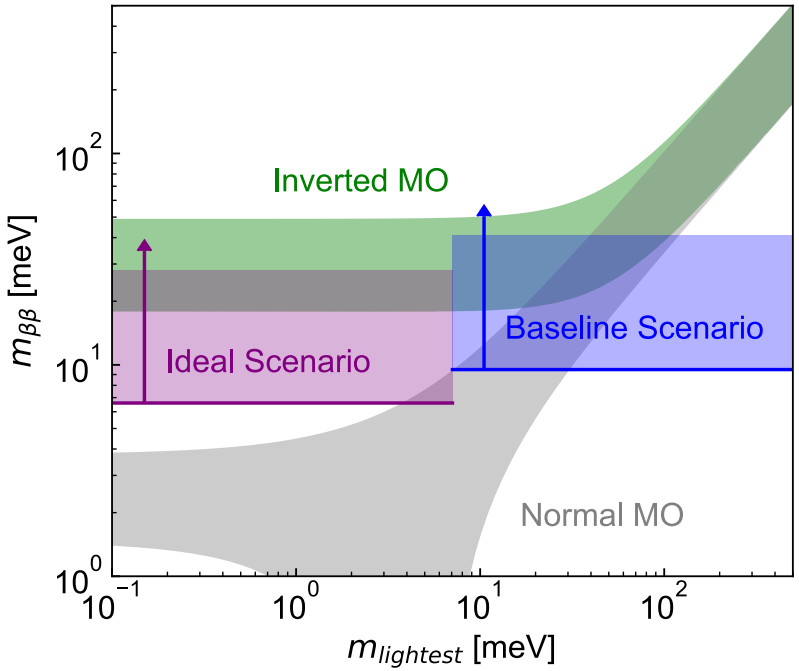


Future Plan: PandaX-xT

- **"Ultimate" liquid xenon experiment**
  - With >30 tonne sensitive volume
  - Decisive test on WIMP and key test on Dirac/Majorana neutrino



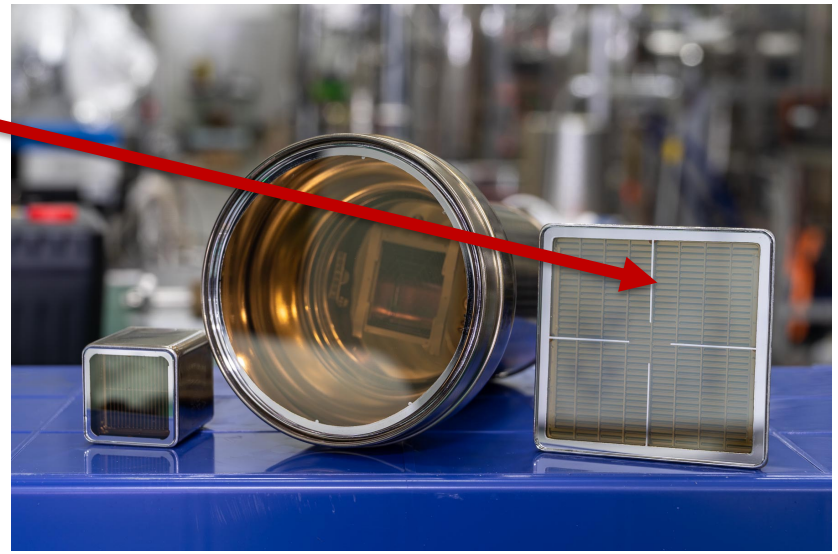




PandaX-xT R&D

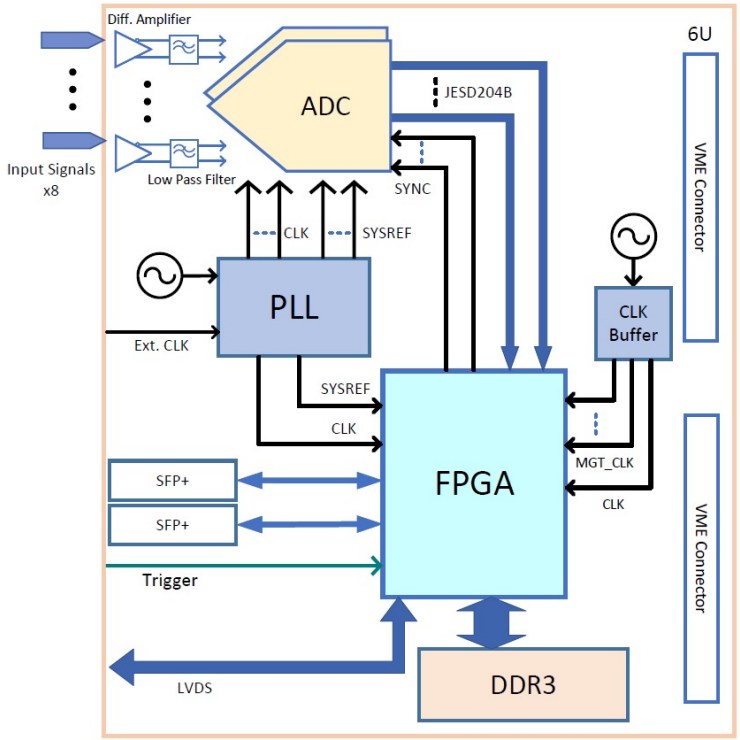
- **TPC of diameter 2.5m**
  - Large size high light transmission electrode
- **R12699 2-inch PMTs**
  - 4 independent anode readout;
  - Better time response for better waveform building

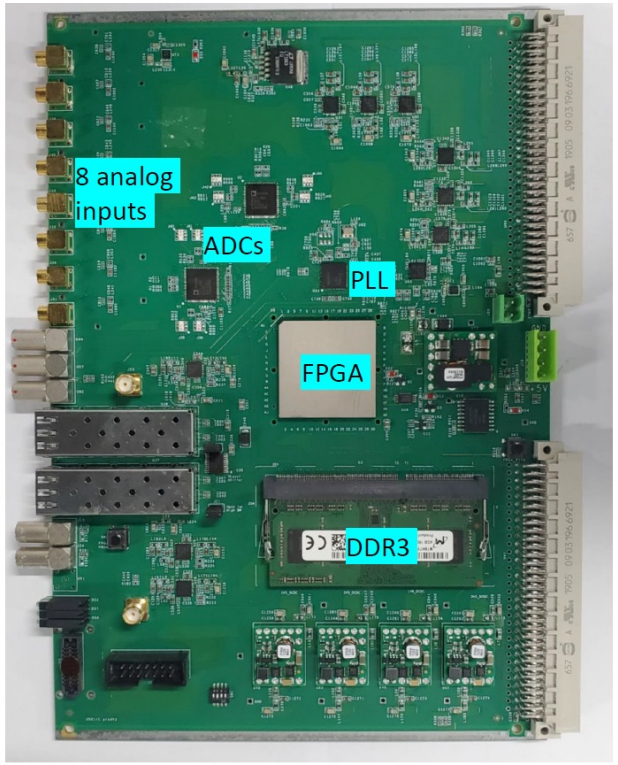
		R11410	R12699 (4ch/piece)
Time Response [ns]	Rise Time	5.5	1.2
	Transit Time	46	5.9
Radioactivity [mBq/pc]	Co-60	<2.34	<0.07
	$Th\text{-}232^{early}$	<7.82	<0.40
	$Th\text{-}232^{late}$	<3.06	<0.40
	$U\text{-}238^{early}$	<56.48	<1.03
	$U\text{-}238^{late}$	<3.99	0.47±0.11

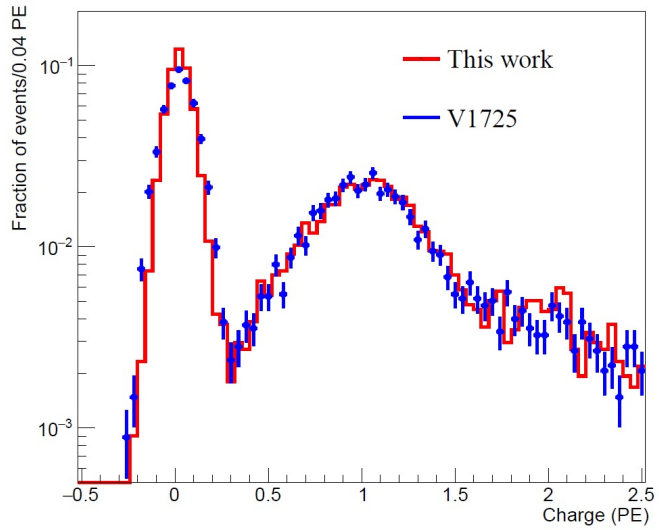


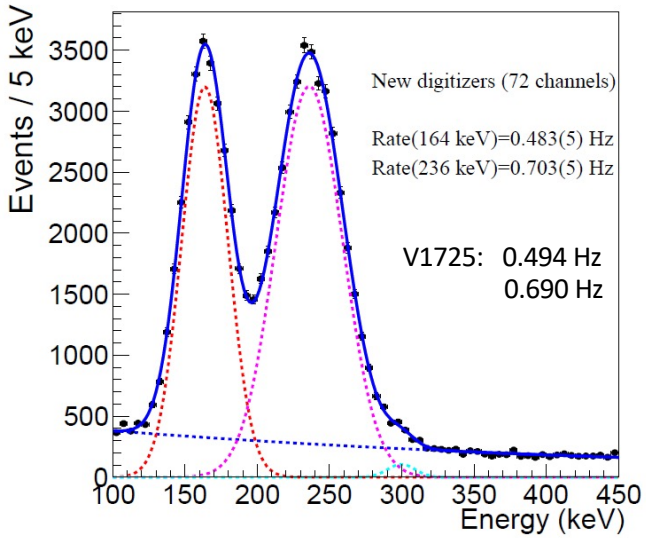
PandaX-xT R&D

- **Electronics** Custom-developed: 14-bit, 500MS/s
  - Custom-developed: 14-bit, 500MS/s
  - Accept out-trigger mode



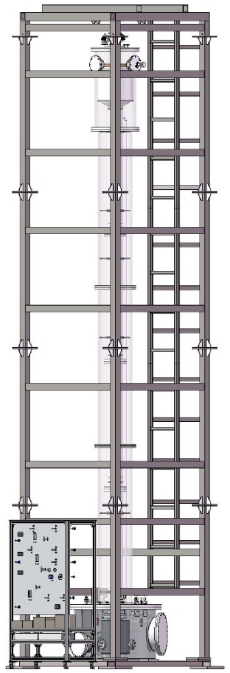


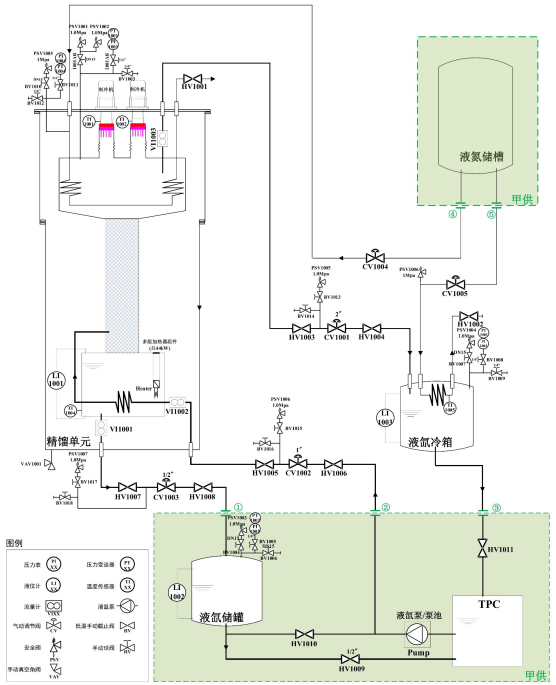




C. He et al, JINST 16 T12015 (2021)

PandaX-xT R&D

- 



Distillation		PandaX-4T	Upgraded
Flow rate [kg/h]	Kr	10	30
	Rn	56.5	856
Reduction factor	Kr	10^6	10^8
	Rn	2.2	4.4

- Low outgassing

- High flow rate

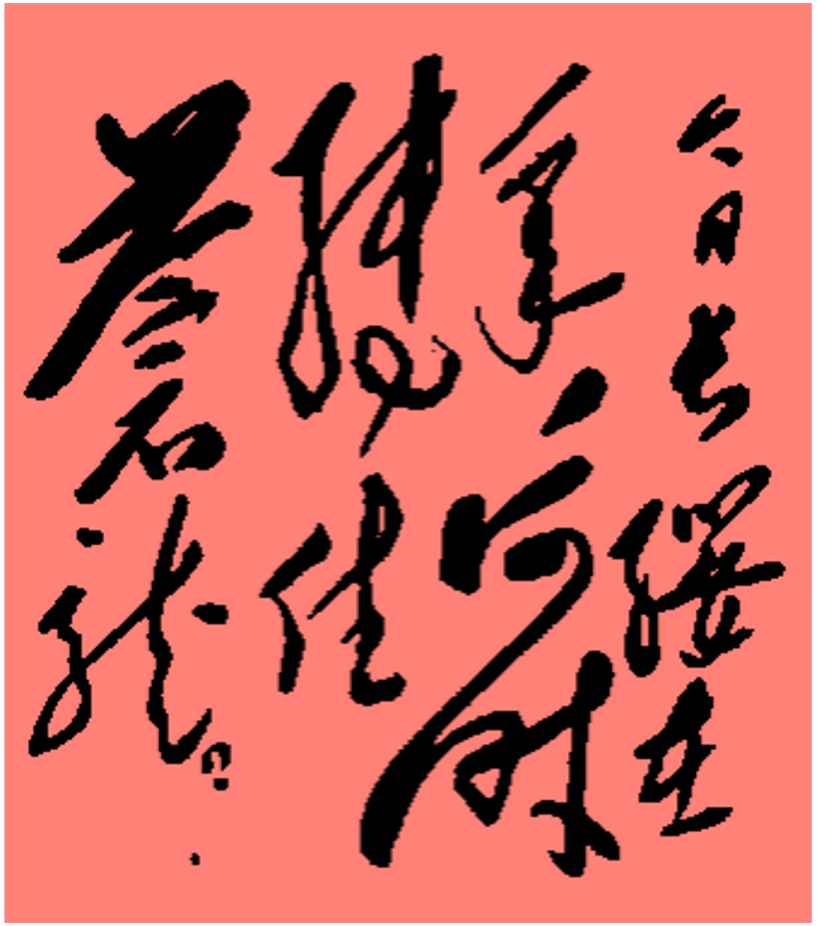
PandaX-xT R&D

- **30 tonne liquid xenon storage:**
  - liquid xenon transfer speed 1.5 tonne/hour

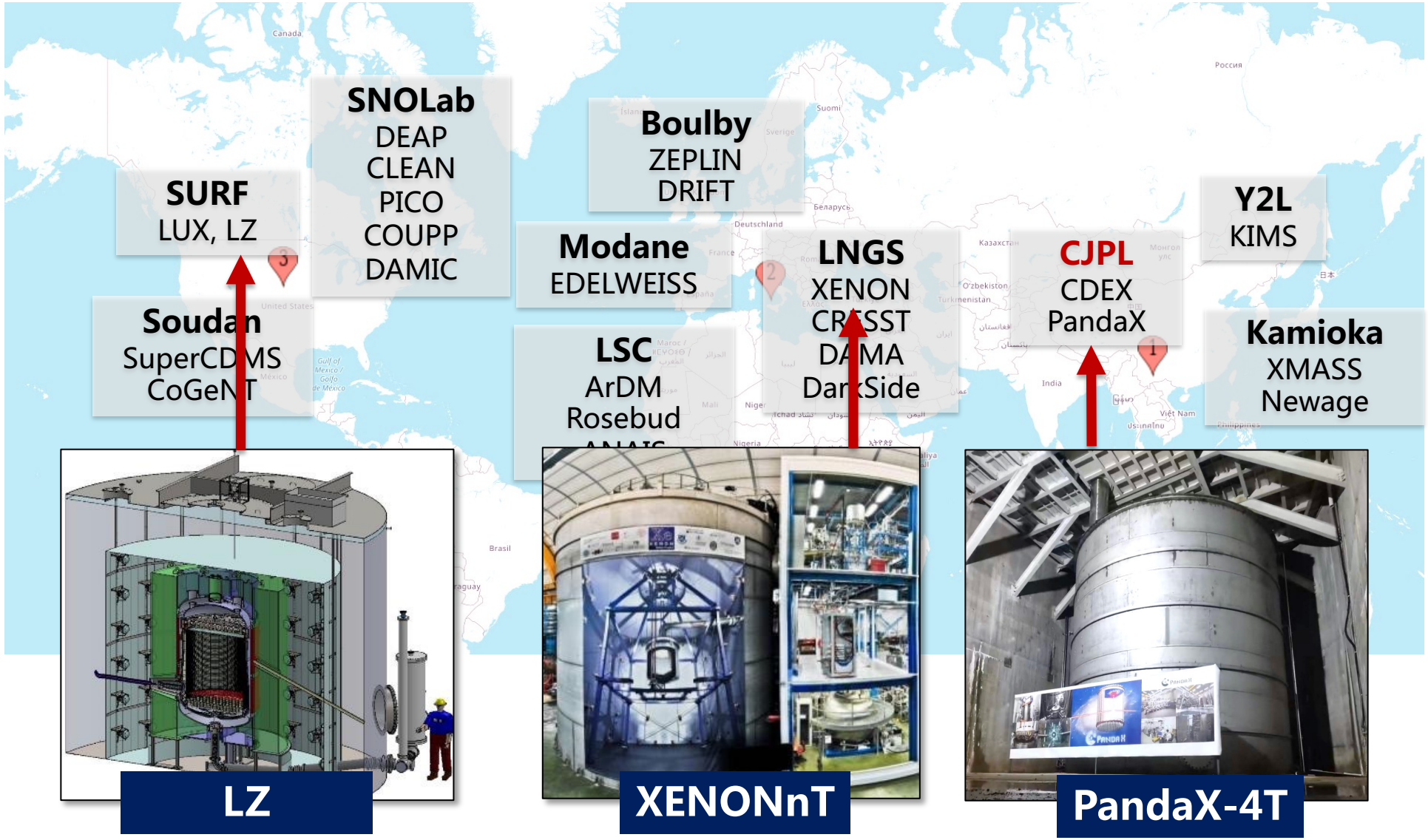
X. Wang et al, JINST 18 P05028

Summary

- PandaX-4T is one of the new generation multi-tonne xenon experiments
- Intense searches for various types of physics, including DMs and neutrinos
- Planning future PandaX-xT project
- **Highly welcome new collaborators!**



Xenon-based Experiments



After commissioning

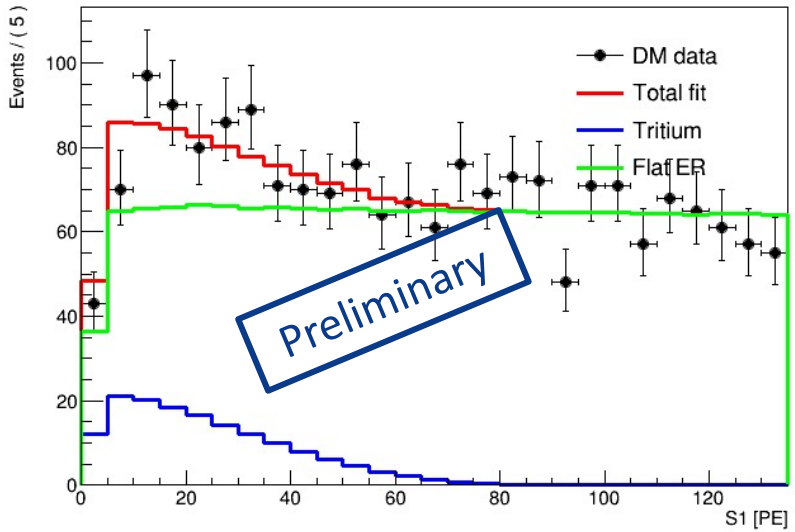
- Tritium identified in commissioning data
- Offline xenon distillation
- 1st physics run (Run1)
  - Data still under blind analysis
- CJPL-II B2 hall construction
- Detector upgrade

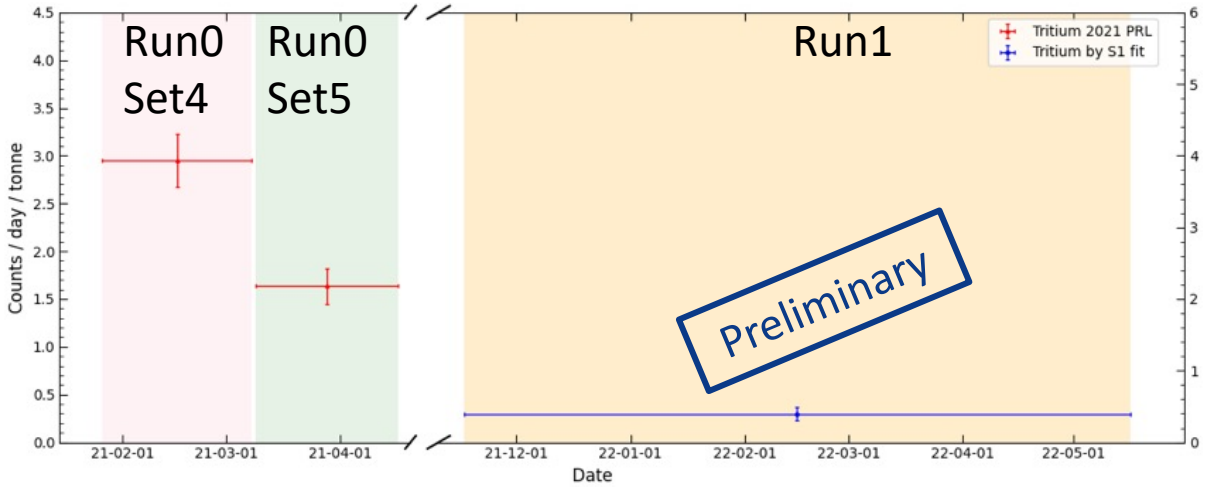
Commissioning (Run 0)	Calibration	Distillation	Physics Run (Run 1)	Calibration	Detector Upgrade
2020/11/28 – 2021/04/16	2021/04/17 – 2021/06/09		2021/11/15 – 2022/05/15	2022/05/16 – 2022/07/08	

Tritium removal

- **Preliminary estimation of tritium level**
  - Fitting S1 spectrum, **keeping S2 blinded**
- **Extensive tritium measures planned for next run (Run 2)**

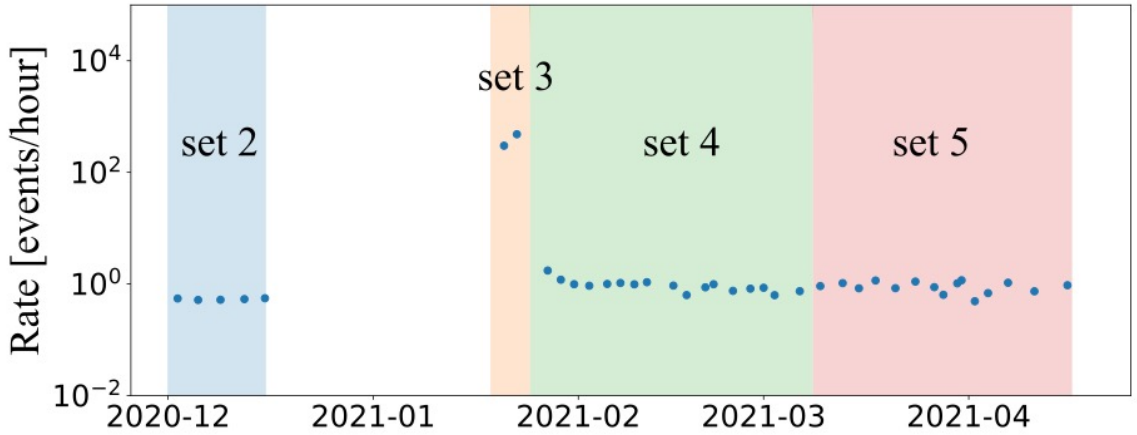
Period	Run0 Set 4	Run0 Set 5	Run1
Tritium Counts/day/tonne	3.0 ± 0.3	1.6 ± 0.2	0.4 ± 0.1

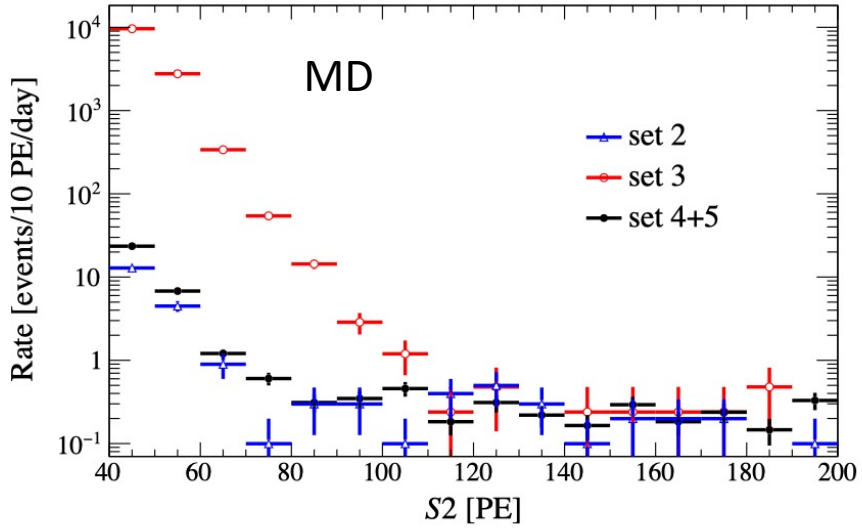




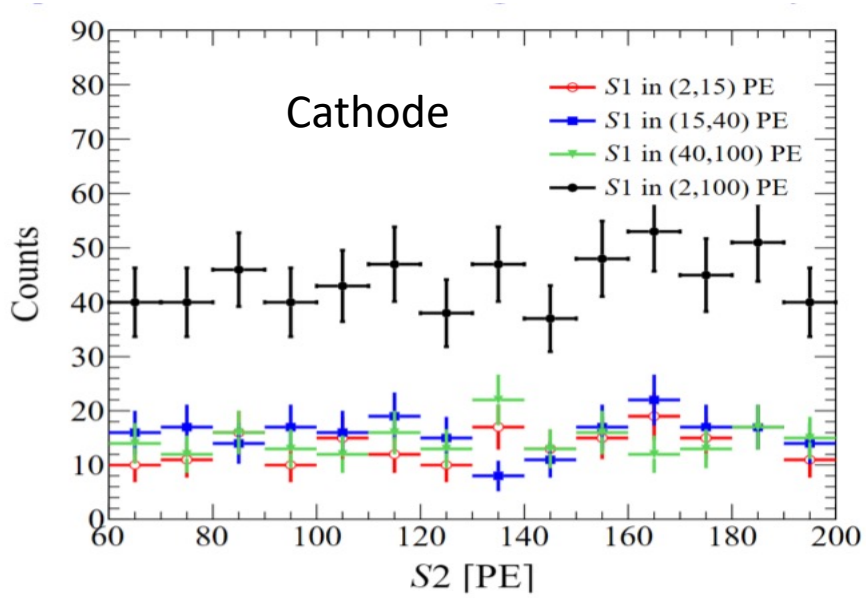
Background Components

- **Micro-discharging (MD)**
  - Small charge, strong run-condition depend



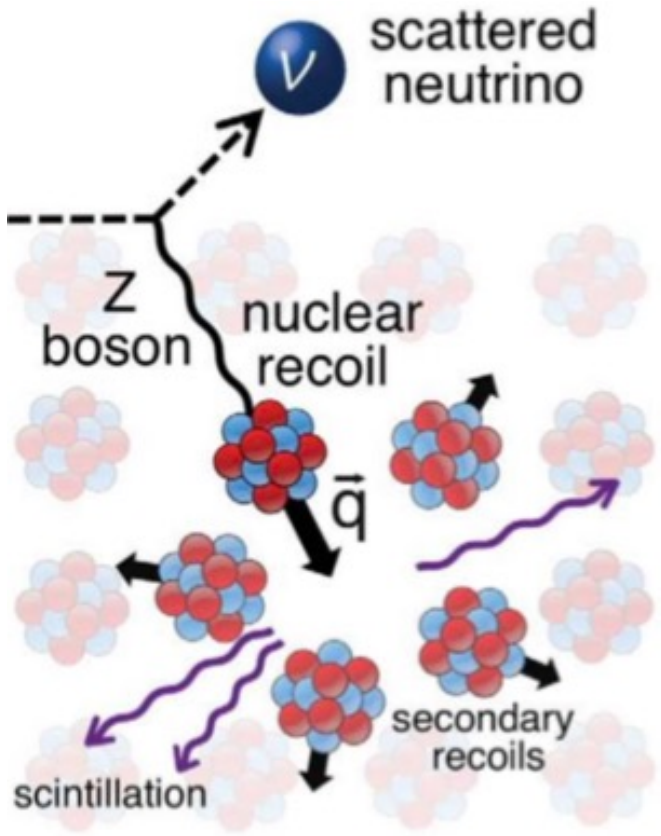


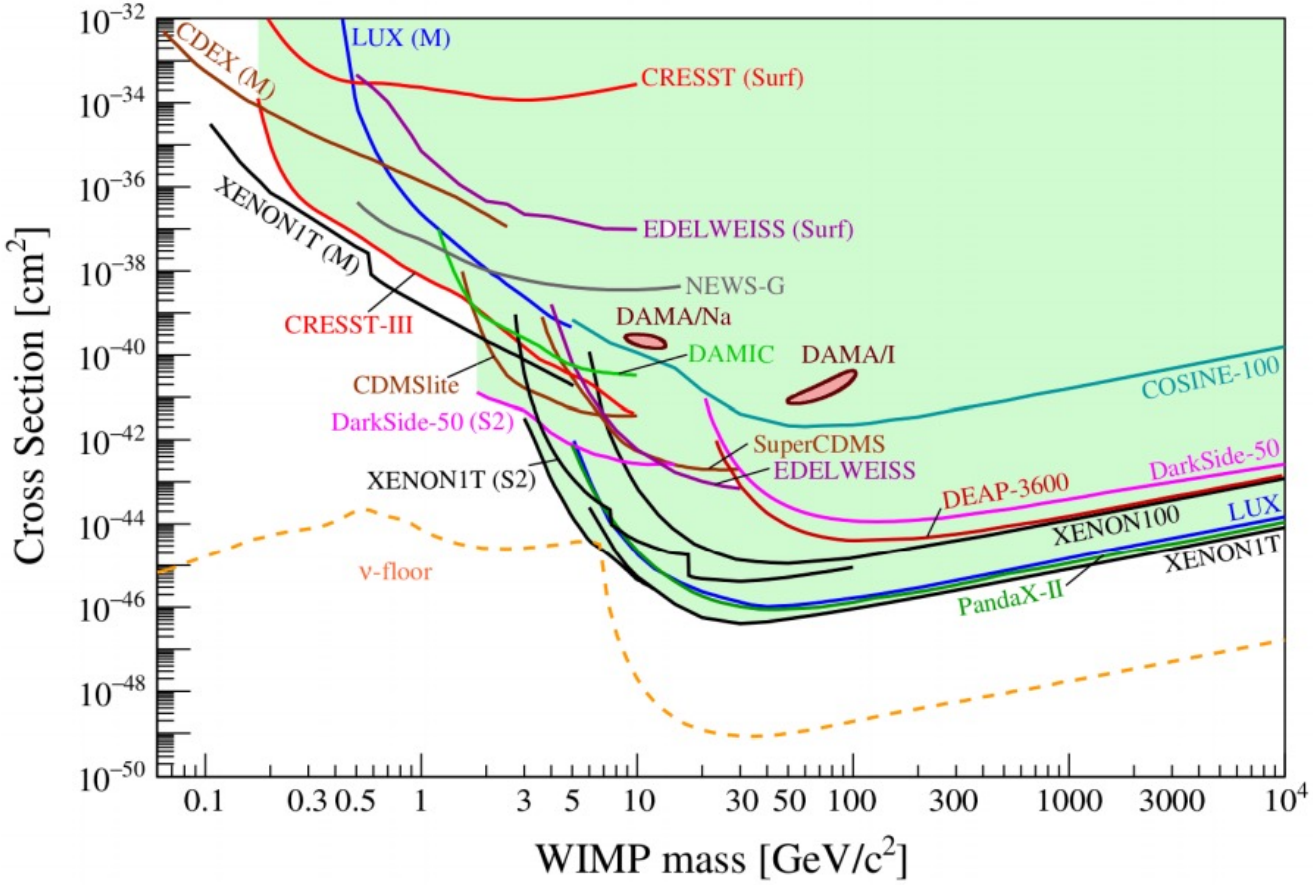
- **Cathode activity**
  - Large charge, large pulse-shape width
  - Flat S2 spectrum



Neutrino Floor

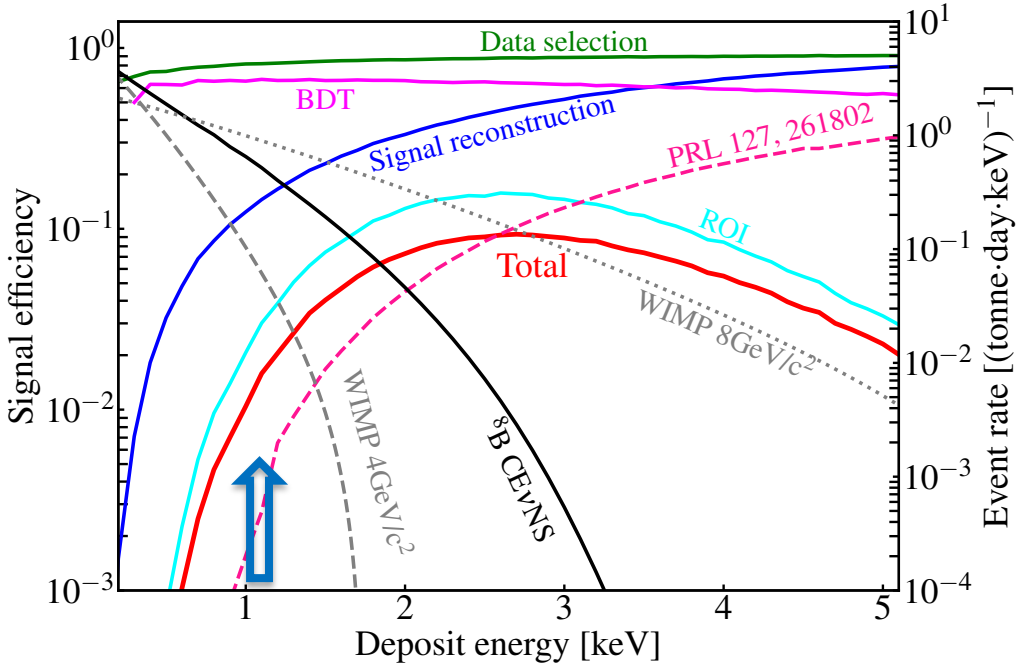
- **Coherent Elastic Neutrino-Nucleus Scattering (CEvNS)**

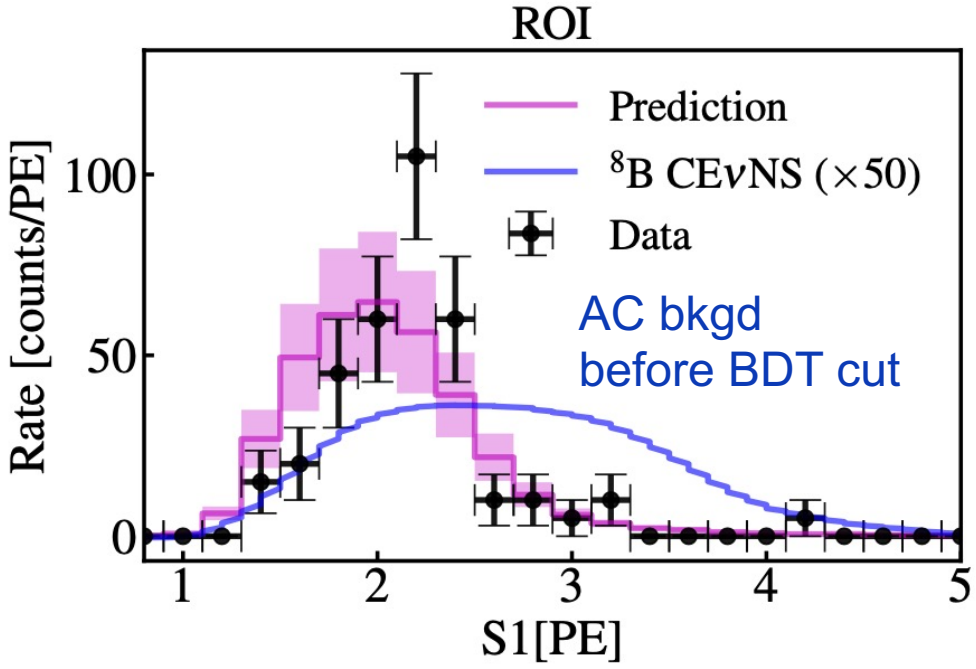




Towards the neutrino floor

- **Lowering selection threshold for solar B8 CEvNS**
  - Cut on the scintillation signal (S1) from 2 PE to 0.3 PE
  - Optimizing signal selection cuts with waveform simulation
- **Accidental paired (AC) background modeling and rejection**





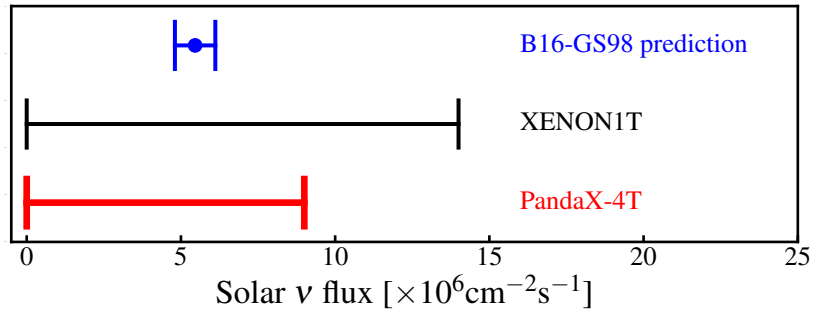
Constraints on B8 and WIMP

- **Blind analysis with 0.48 tonne-year data**

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

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



- **Leading constraint on B8 neutrino flux through CEvNS**
- **Strongest constraints on light WIMP of mass 3 -10 GeV/c²**