Dark Matter and Majorana Neutrino Searches with PandaX Experiment

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on behalf of PandaX Collaboration

EW Moriond 2024.03.30

Dark Matter Detection

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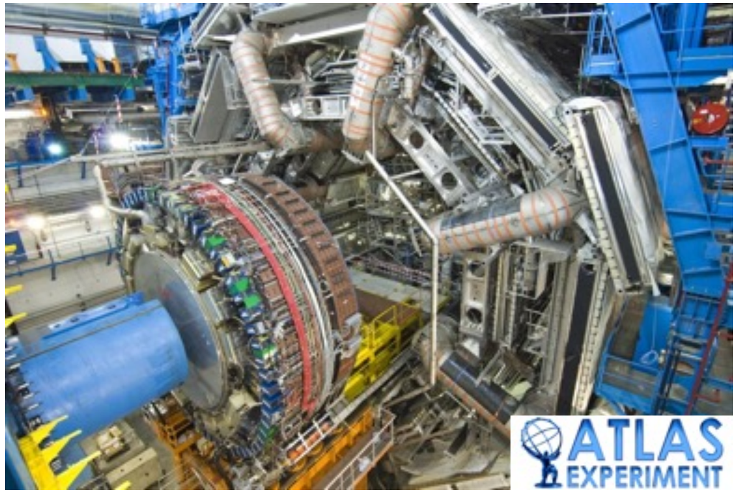
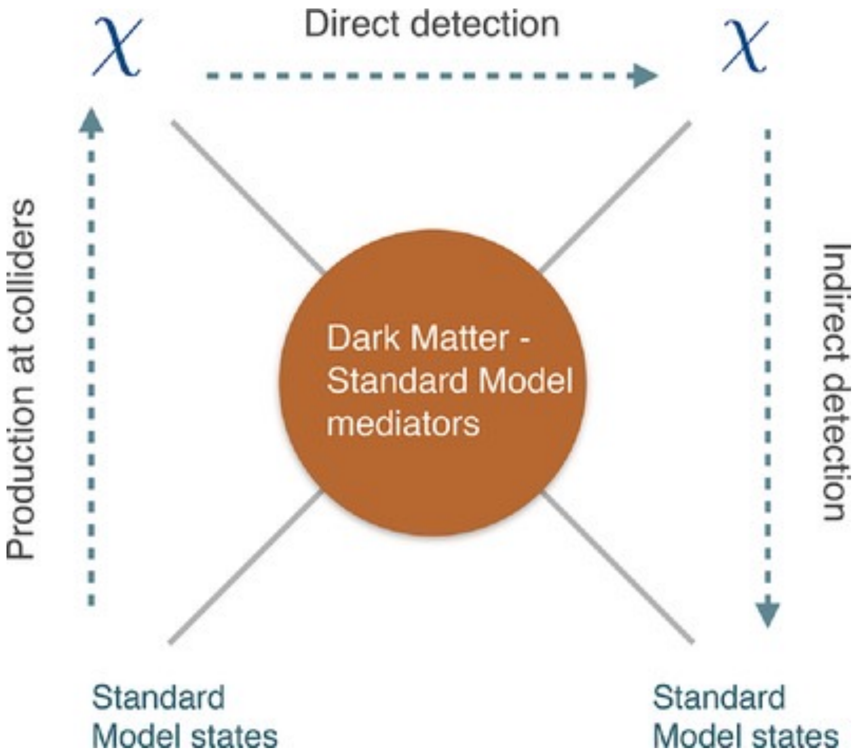
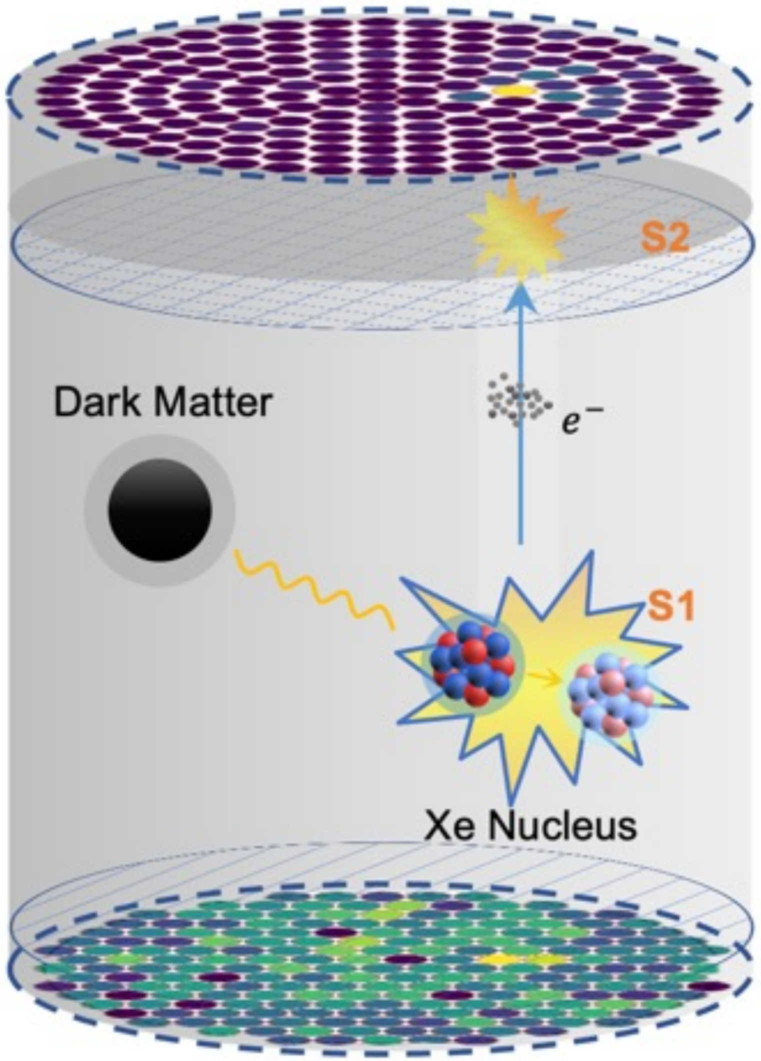




PandaX: Dual-phase xenon TPC

- **PandaX: Particle and Astrophysical Xenon Observatory**
  - Incoming DM scattering off xenon atom (nucleus or electrons)
- **TPC: paired scintillation (S1) and ionization (S2) signals**
  - Precise energy measurement
  - 3-D position reconstruction
  - Discrimination between nuclear recoil and electron recoil signals



PandaX Detectors

- Increasing the detector sensitive target volume
- Lowering radioactive background

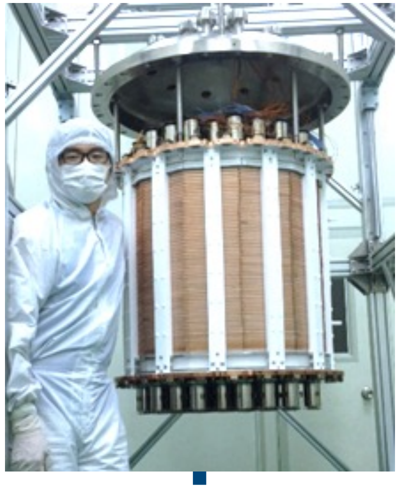
PandaX start

2009

PandaX-I
120kg

2010-2014

PandaX-II
580kg



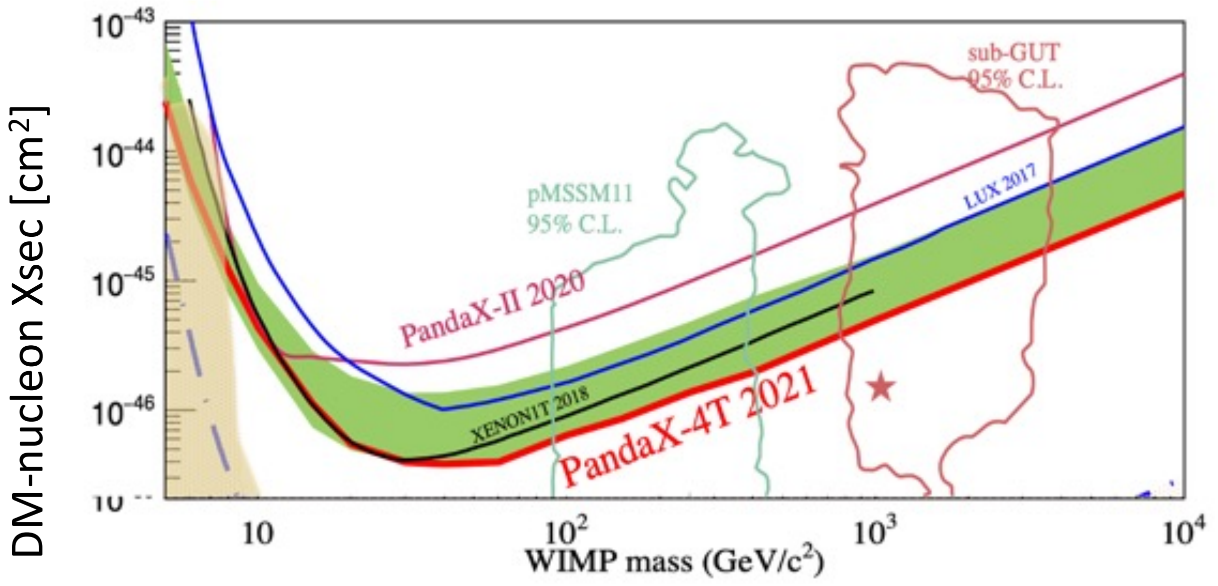
2015-2019

PandaX-4T
(3.7 tonne)

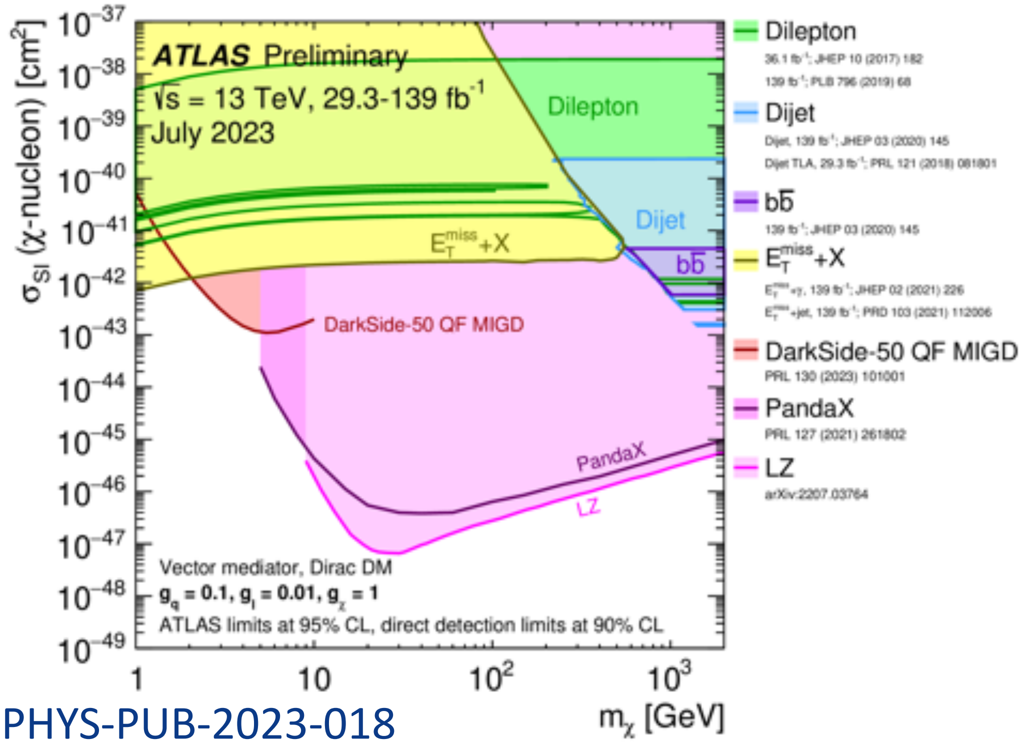
2020-

PandaX-4T

- **Sensitive volume: 3.7 tonne xenon**
- **Commissioning started from Nov/2020 (95 days)**
  - 0.63 tonne-year exposure
  - limits on DM-nucleon scattering xsec reaching $3.8 \times 10^{-47} cm^2$



PandaX, PRL 127, 261802 (2021)



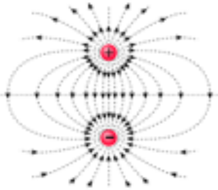
ATL-PHYS-PUB-2023-018

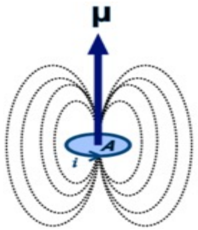
How dark is dark matter?

Image Credit: Public Domain

Luminance of Dark Matter

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





millicharge	charge radius	electric dipole	magnetic dipole	anapole

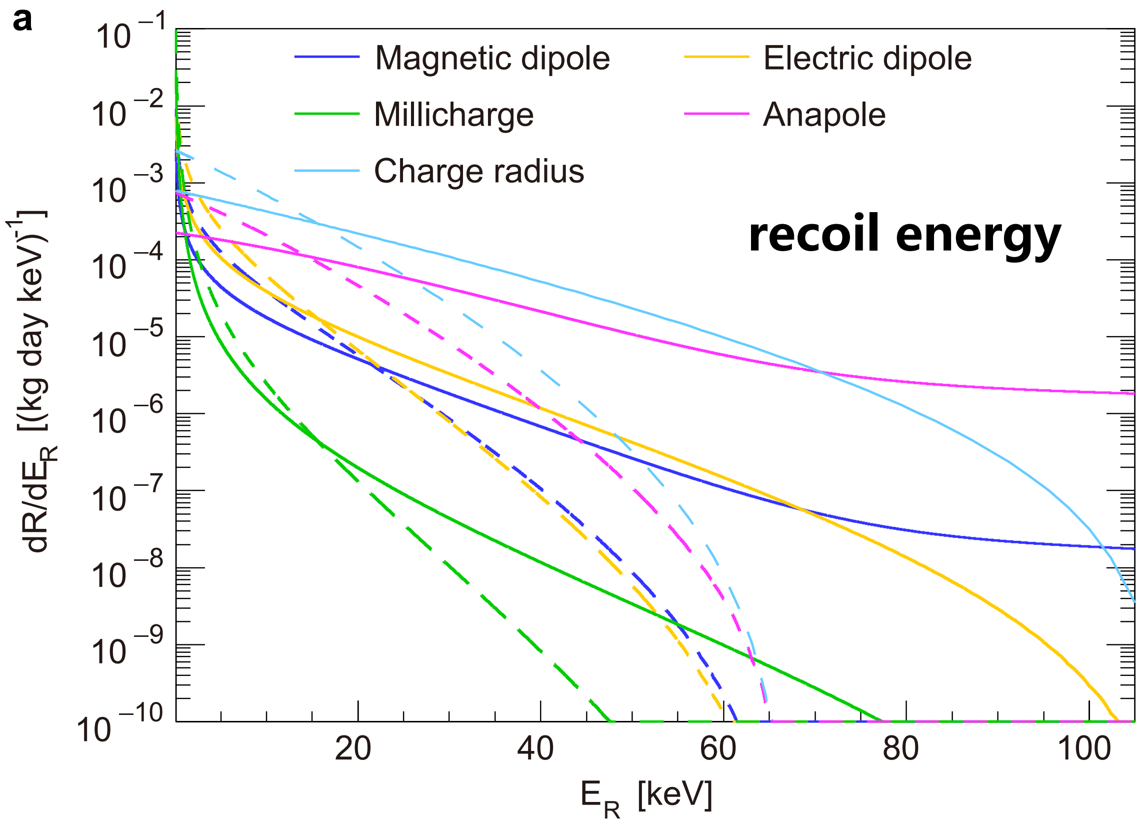
$$\mathcal{L} = Qe\bar{\chi}\gamma^{\mu}\chi A_{\mu} + \frac{\mu_\chi}{2}\bar{\chi}\sigma^{\mu\nu}\chi F_{\mu\nu} + i\frac{d_\chi}{2}\bar{\chi}\sigma^{\mu\nu}\gamma^5\chi F_{\mu\nu} + b_\chi\bar{\chi}\gamma^{\mu}\chi\partial^{\nu}F_{\mu\nu} + a_\chi\bar{\chi}\gamma^{\mu}\gamma^5\chi\partial^{\nu}F_{\mu\nu}$$

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

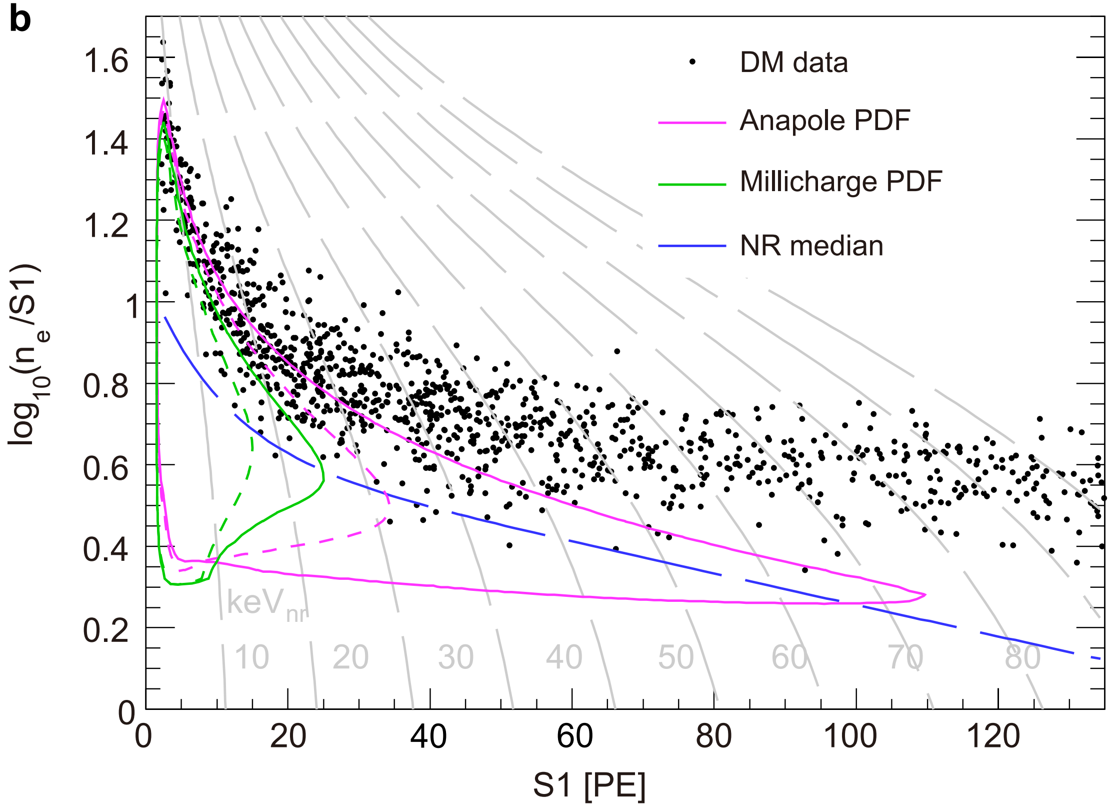
tree-level (millicharge) — **higher-order loop-level** (magnetic dipole, electric dipole, charge radius, anapole)

Photon-Mediated Interaction

- **Various nuclear recoil energy spectra**
- **Dedicated searches of these EM properties**



30 and 100 GeV/c² DM



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

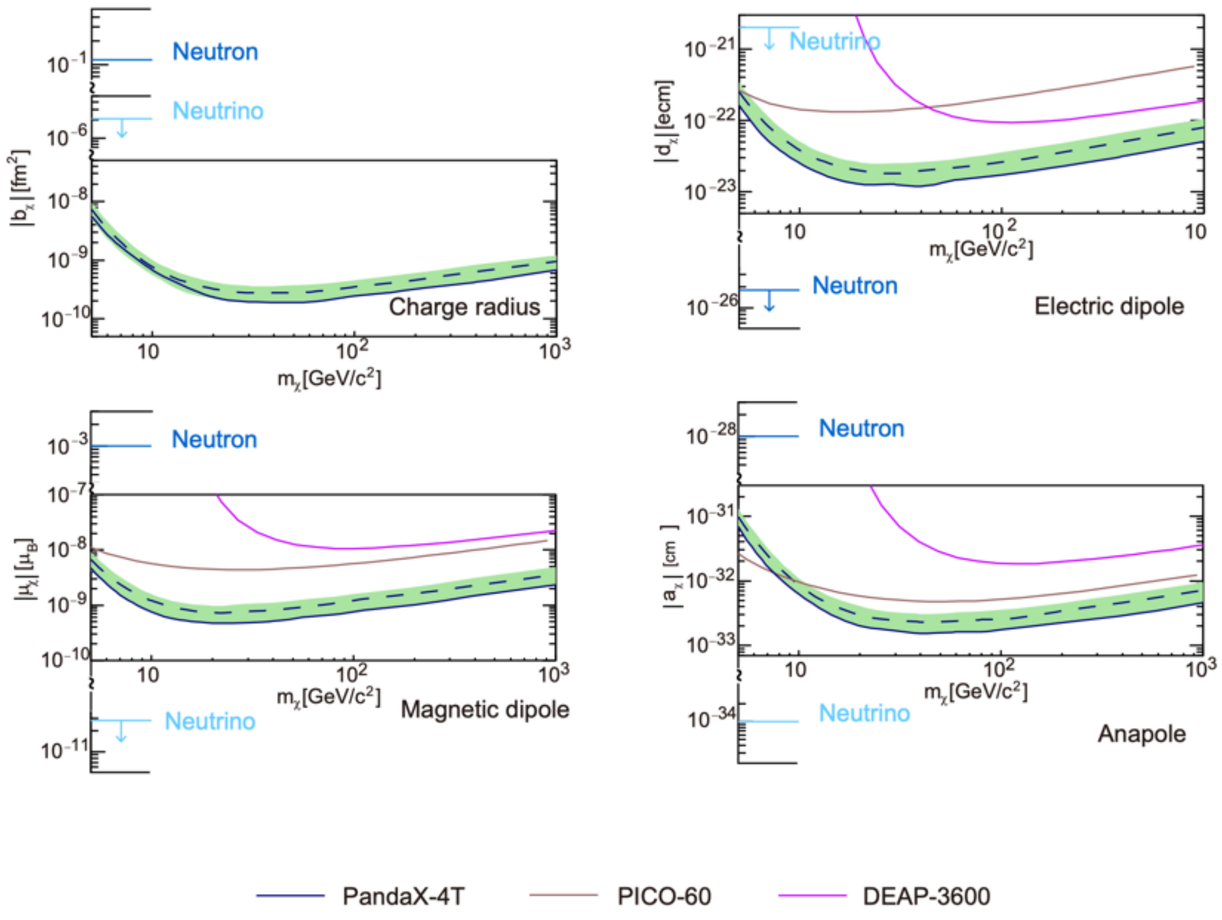


Table 1 | Comparison of electromagnetic properties

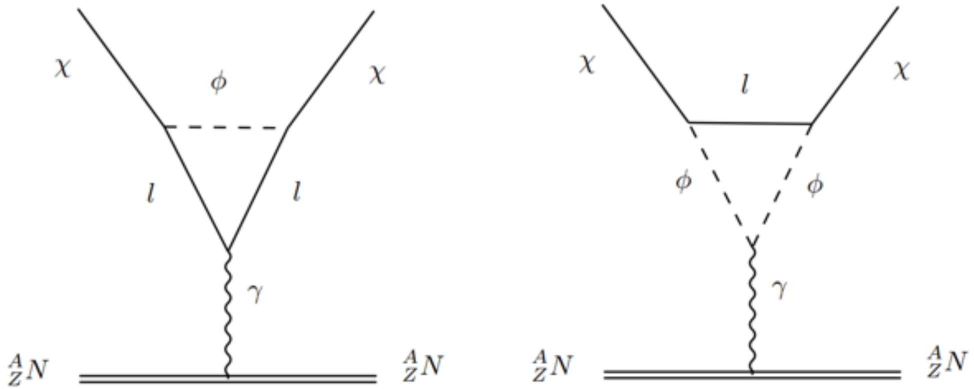
	dark matter	neutrino	neutron
Charge radius (fm^2)	$<1.9\times10^{-10}$	$[-2.1,3.3]\times10^{-6}$ *	-0.1155 *
Millicharge (e)	$<2.6\times10^{-11}$	$<4\times10^{-35}$ *	$(-2\pm8)\times10^{-22}$ *
Magnetic dipole (μ_B)	$<4.8\times10^{-10}$	$<2.8\times10^{-11}$ *	-1×10^{-3} *
Electric dipole (ecm)	$<1.2\times10^{-23}$	$<2\times10^{-21}$ †	$<1.8\times10^{-26}$ *
Anapole (cm^2)	$<1.6\times10^{-33}$	$\sim10^{-34}$ ‡	$\sim10^{-28}$ §

* Datas are taken from PDG [32]
† Taken from [31]
‡ Taken from [33]
§ Taken from [34]

PandaX, Nature 618, 47-50 (2023)

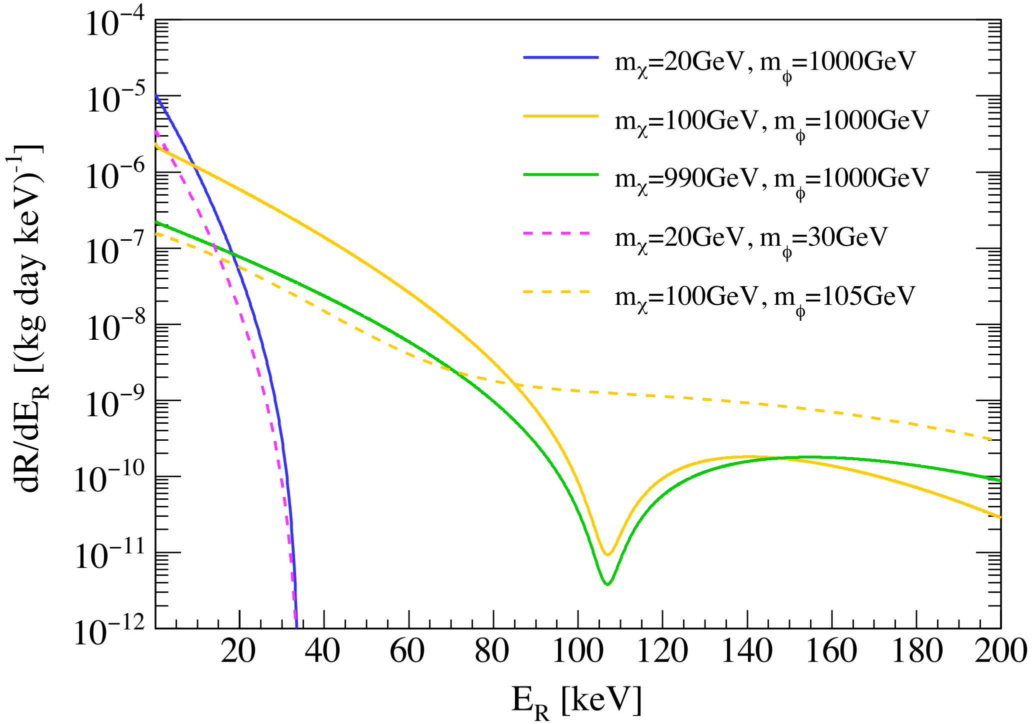
UV Complete Model with EM properties

- **Lepton Portal DM Model (LPDM) with a charged mediator**
  - coupling to single flavor lepton, here assuming muon (avoid flavor-violating process from dark sector)



$$\mathcal{L}_{\rm LPDM} \supset \lambda_i \phi_i \overline{\chi}_L e^i_R + h.c.$$

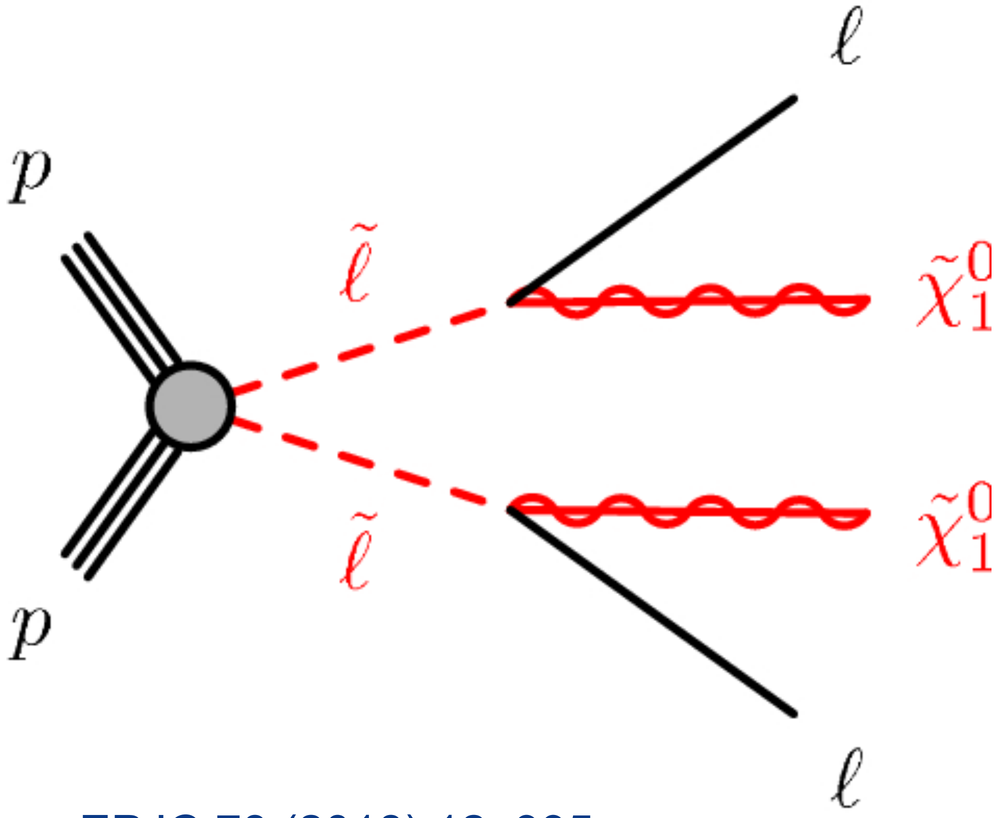
$$\begin{aligned}\mathcal{L}_{\rm LPDM} &= \mathcal{L}_{\rm CR} + \mathcal{L}_{\rm MD} + \mathcal{L}_{\rm A} + \mathcal{L}_{\rm ED} \\ &= b_\chi \overline{\chi}\gamma^\mu \chi \partial^\nu F_{\mu\nu} + \frac{\mu_\chi}{2}\overline{\chi}\sigma^{\mu\nu}\chi F_{\mu\nu} \\ &\quad + a_\chi \overline{\chi}\gamma^\mu\gamma^5\chi\partial^\nu F_{\mu\nu} + i\frac{d_\chi}{2}\overline{\chi}\sigma^{\mu\nu}\gamma^5\chi F_{\mu\nu}\end{aligned}$$



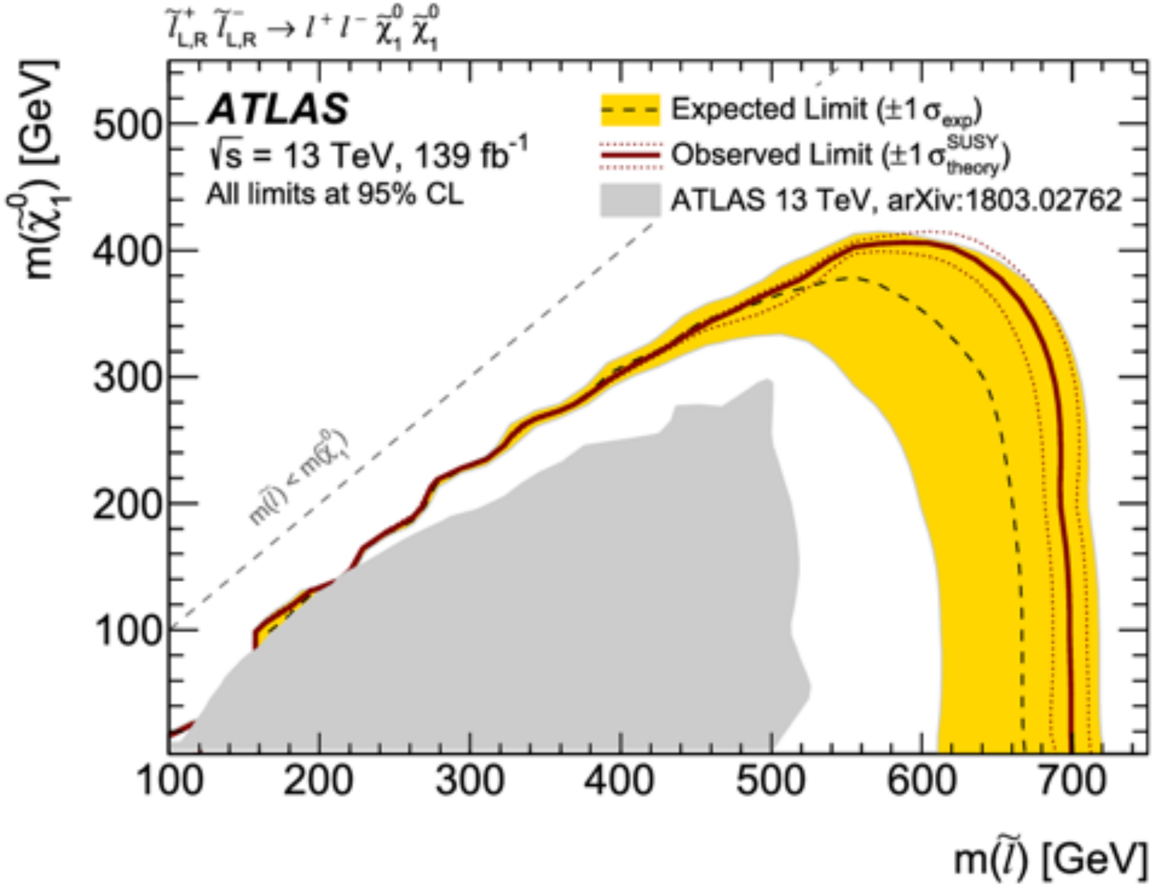
Y. Bai, J. Berger arXiv:1402.6696

LPDM @LHC

- **Similar final state as SUSY slepton pair production**

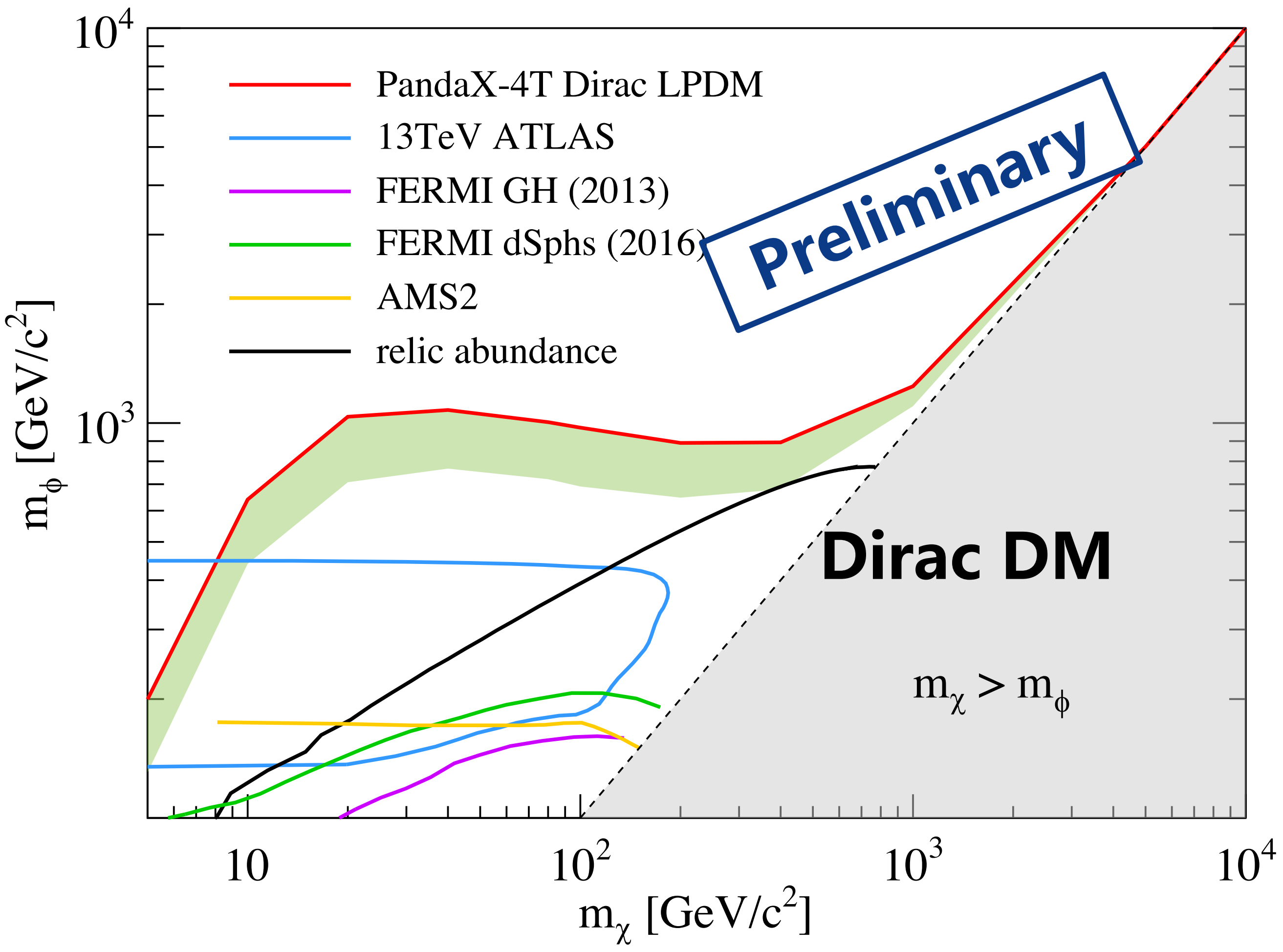


EPJC 78 (2018) 12, 995



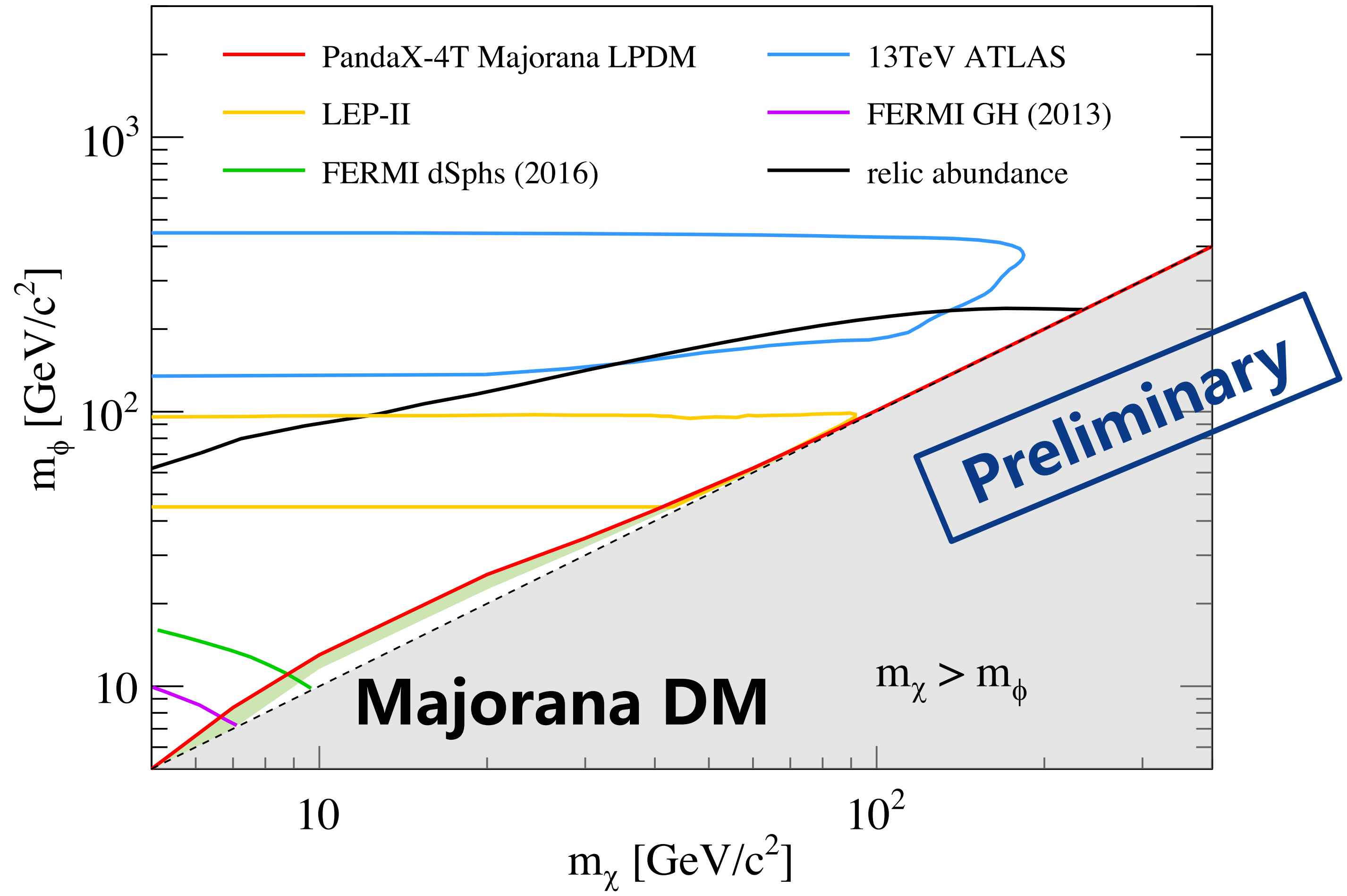
Constraints on LPDM from PandaX

- **Dirac DM: Significant space being excluded**
  - main contribution from charge radius and magnetic dipole moment



Constraints on LPDM from PandaX

- **Majorana DM: large parameter space still valid**
  - the only contribution from anapole moment

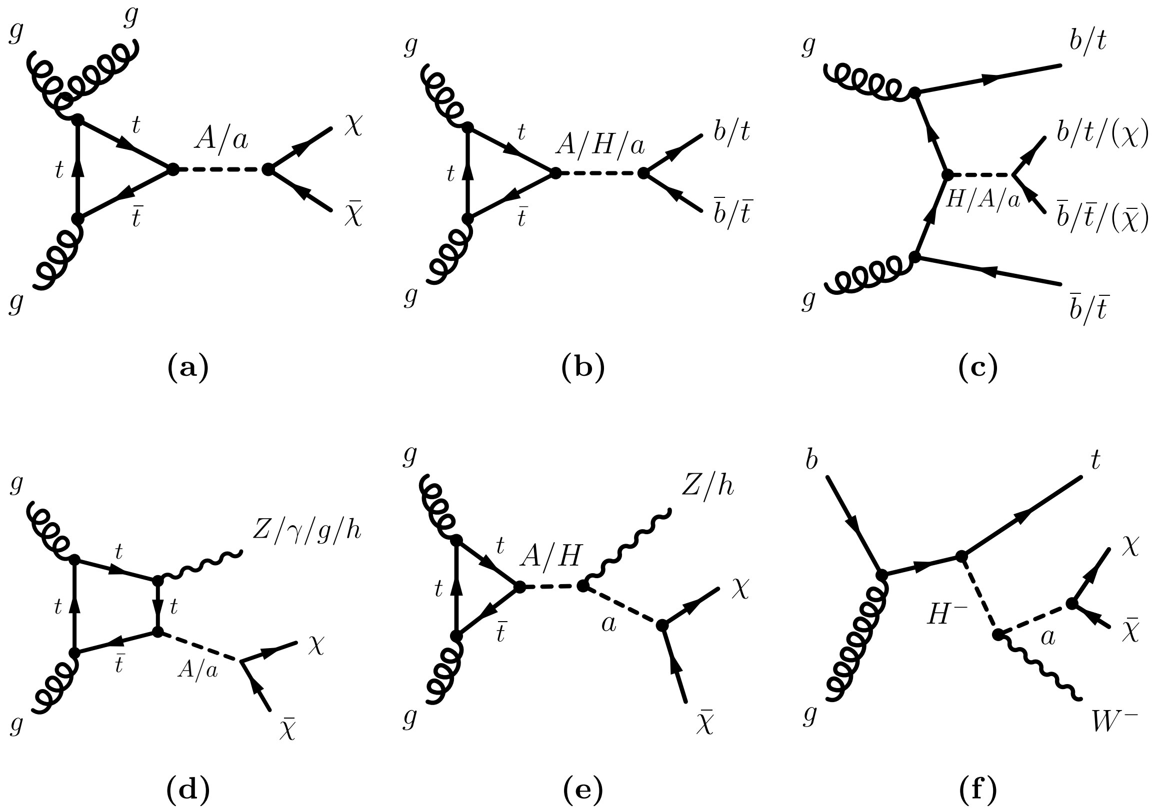


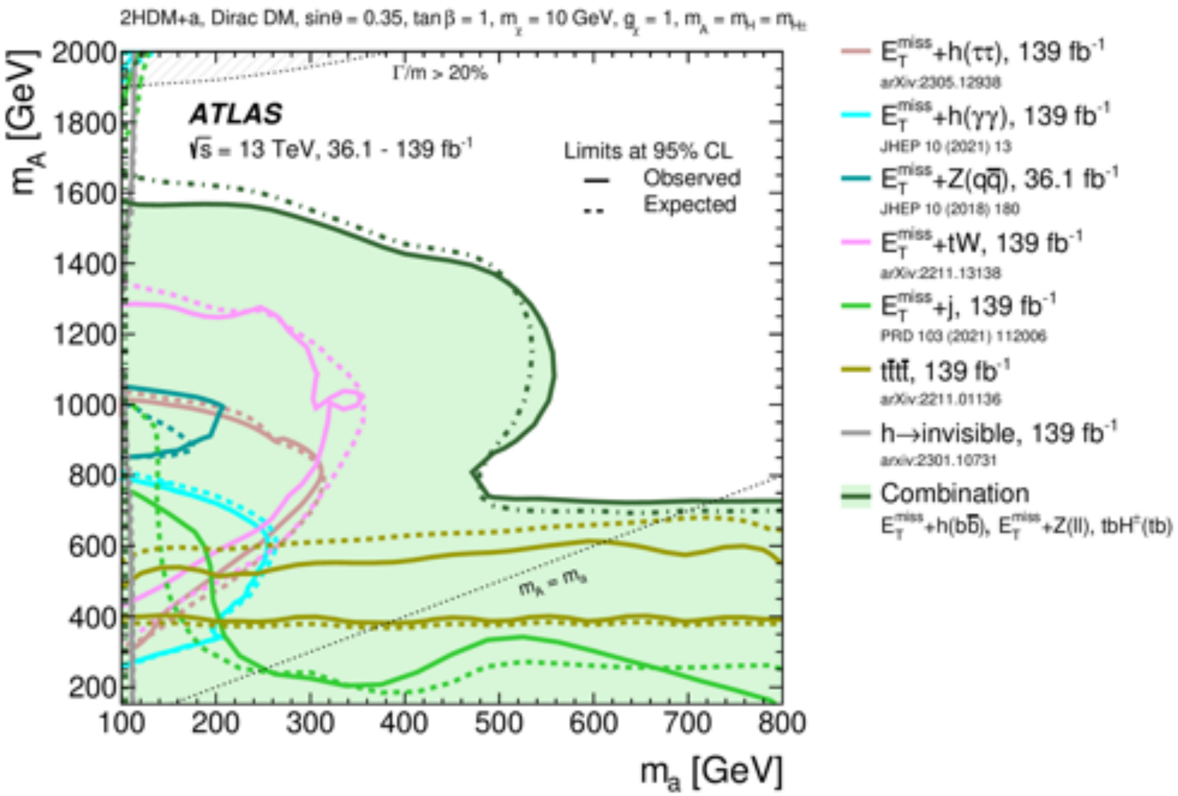
Dark Mediator

- **Connecting dark sector with SM particles**

Pseudo-scalar Mediator

- **2HDM+a**
  - type-II 2HDM (***h, H⁰, H±, A***) with additional pseudo-scalar mediator ***a***
  - rich phenomenology at LHC

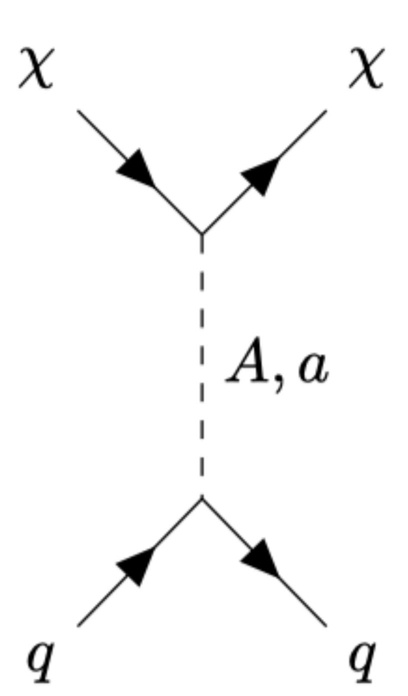




arXiv:2306.00641

2HDM+a @PandaX

- **Tree-level process:** $\bar{\chi}\gamma^5\chi N\gamma^5 N \rightarrow -(\vec{S}_\chi \cdot \vec{q})(\vec{S}_N \cdot \vec{q})$
  - spin-dependent scattering cross section
  - momentum-suppressed
- **undetectable signal rate**



$$\frac{d\sigma_{\rm SD}(\rm D4)}{dE_R} = \frac{1}{32\pi}\frac{m_T}{m_\chi^2 m_N^2 v^2}\frac{q^4}{m_a^4}\sum_{N,N'=p,n} C_N^{\rm tree}(\rm D_4) C_{N'}^{\rm tree}(\rm D_4) F_{\Sigma''}^{(N,N')}(q^2),$$

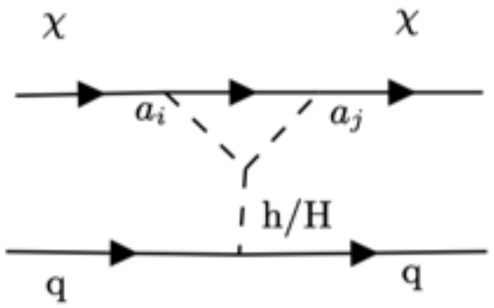
T. Li, P. Wu 1904.03407

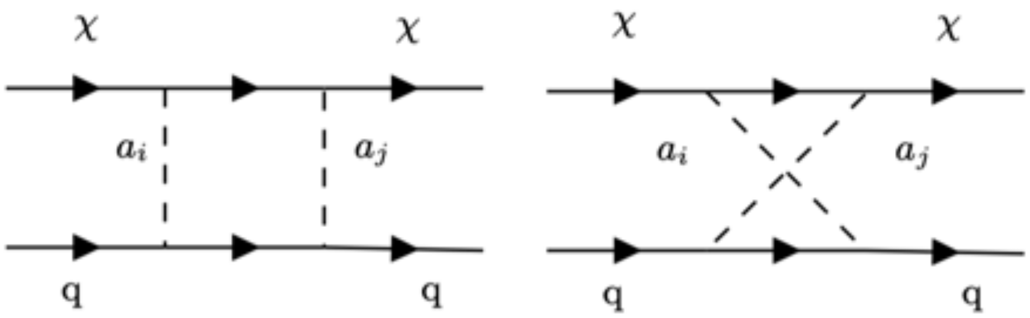
2HDM+a @PandaX

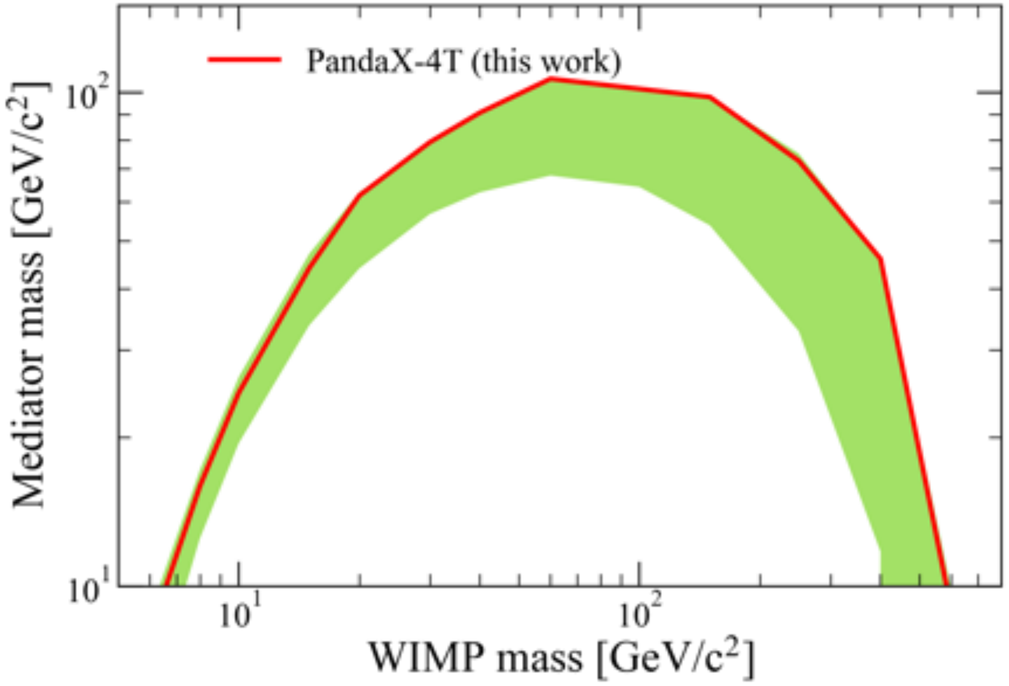
- **Loop-level process**: **spin-independent scattering**

$$O_1^N = \bar{\chi}\chi\bar{N}N, \qquad c_N^1 = m_N\left(\sum_{q=u,d,s}\frac{c_q}{m_q}f_{T_q}^N + \frac{2}{27}f_{T_g}\sum_{q=c,b,t}\frac{c_q}{m_q}\right)$$

$$m_H = m_{H^\pm} = m_A = 600\ \mathrm{GeV}/c^2,$$
$$\cos(\beta-\alpha)=0,\ \tan\beta = 1,\ \sin\theta = 0.35,$$
$$g_\chi = 1,\ \lambda_3 = \lambda_{P1} = \lambda_{P2} = 3.$$



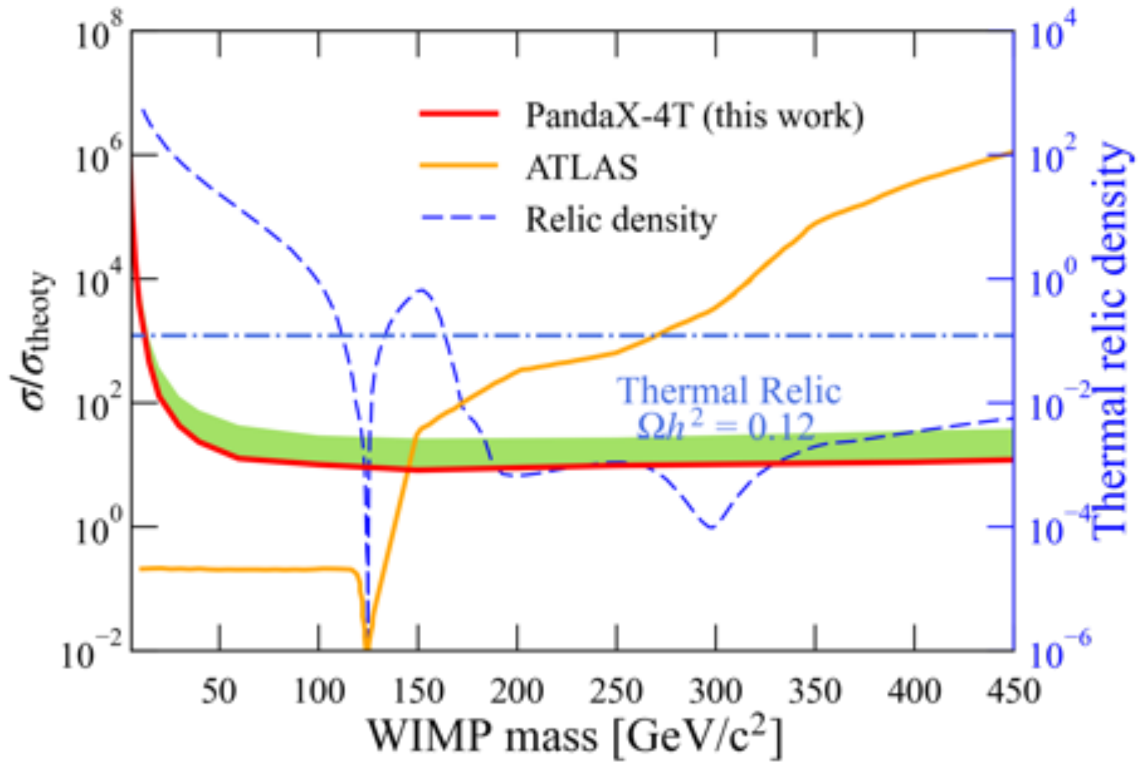




PandaX, PLB 834 (2022) 137487

2HDM+a @PandaX

- **For** $m_a = 250\ \mathrm{GeV}$
  - small WIMP mass: excluded by ATLAS
  - large WIMP mass: stronger constraints from direct detection



$$m_H = m_{H^\pm} = m_A = 600\ \mathrm{GeV}/c^2,$$
$$\cos(\beta - \alpha) = 0,\ \tan\beta = 1,\ \sin\theta = 0.35,$$
$$g_\chi = 1,\ \lambda_3 = \lambda_{P1} = \lambda_{P2} = 3.$$

Parameters recommended by LHC DM group

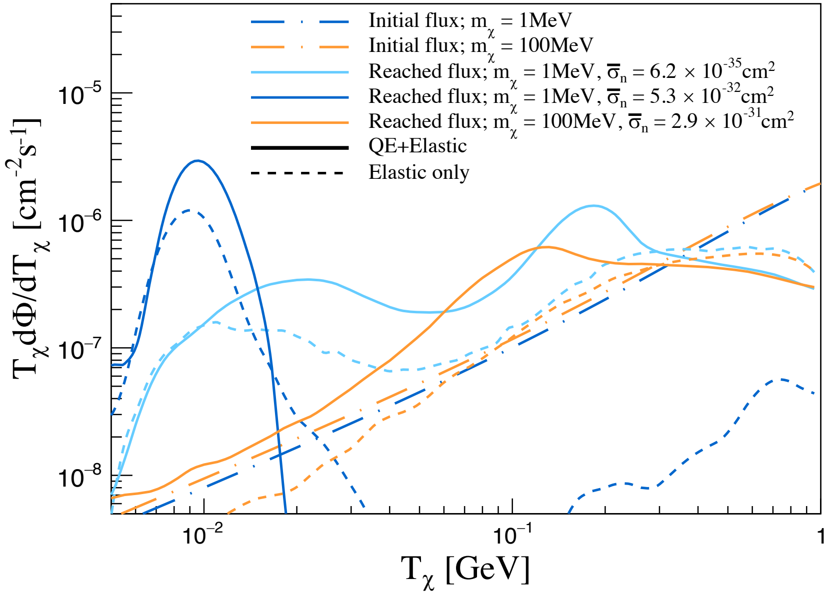
Direct detection is expected to cover the remaining parameter space in near future

Scalar Mediator

- **η mesons from cosmic-ray beam dump in atmosphere may decay into DMs**
  - 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

- $\boldsymbol{BR(\eta \to \pi^0 S \to \pi^0 \chi\bar{\chi})}$
  - no dedicated measurements on this semi-invisible yet

- **Strongly boosted atmospheric dark matter**

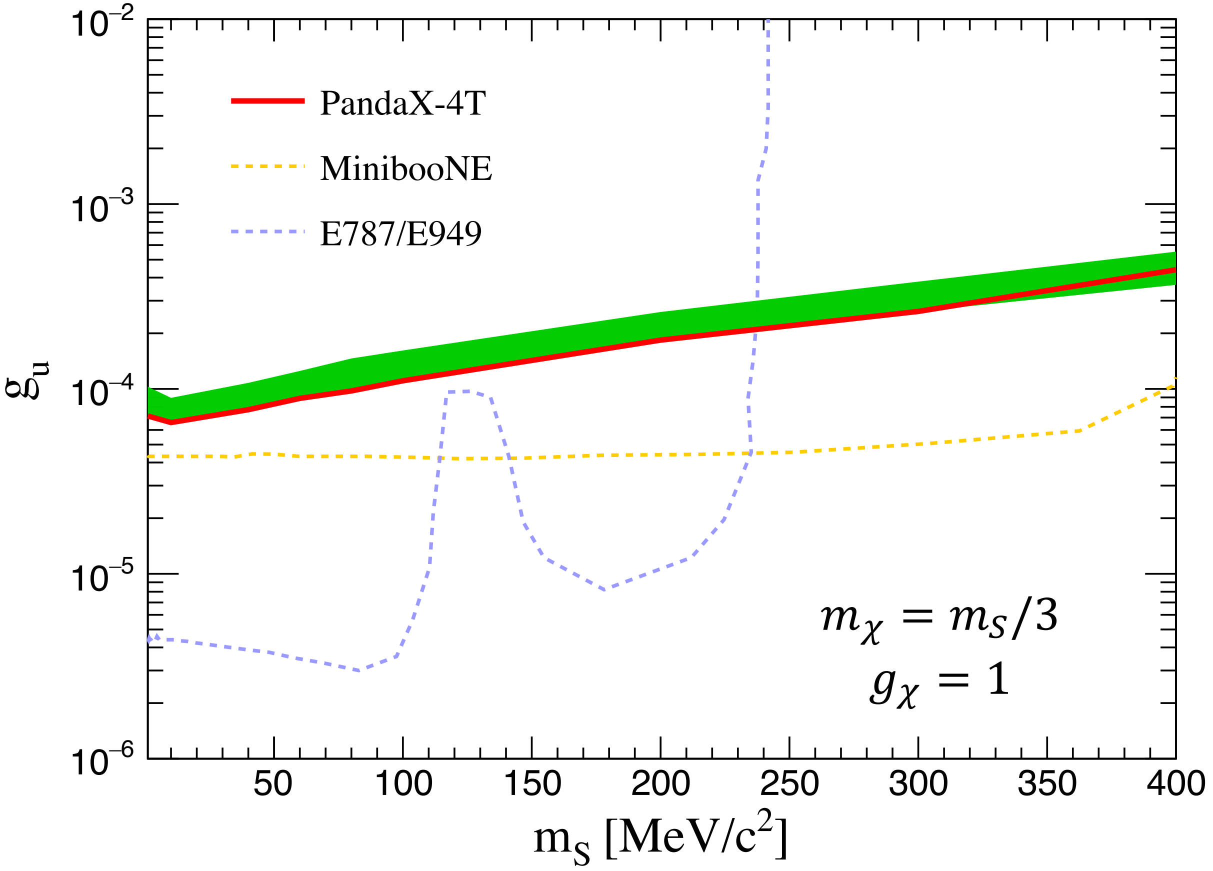


J. Alvey, M. Campos, M. Fairbairn, T. You, PRL 123, 261802 (2019)

L. Su, L. Wu, NZ, B. Zhu, PRD 108, 035004 (2023)

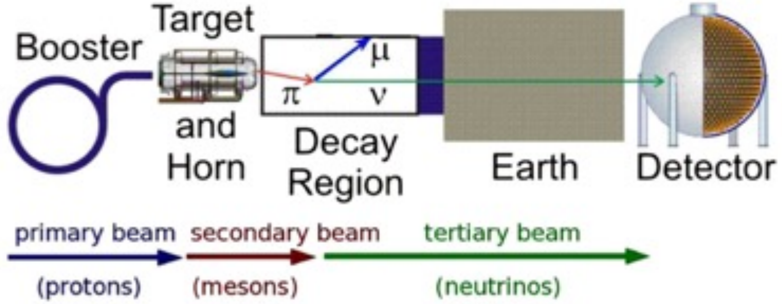
Constraints on the coupling strength

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

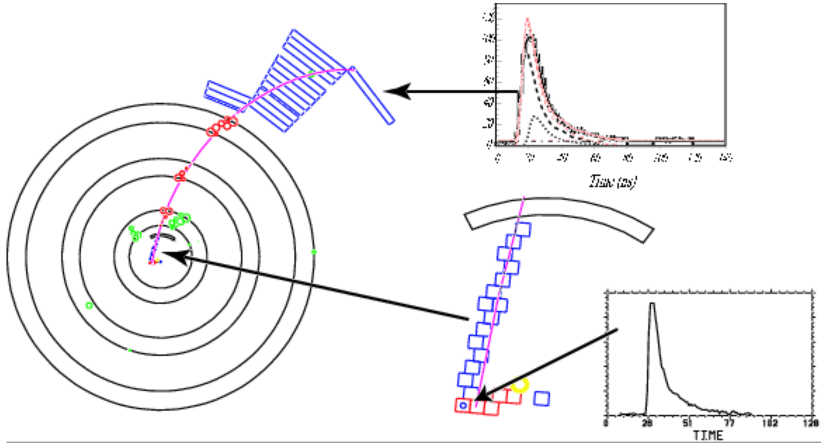


PandaX, PRL 131, 041001 (2023)

MiniBooNE



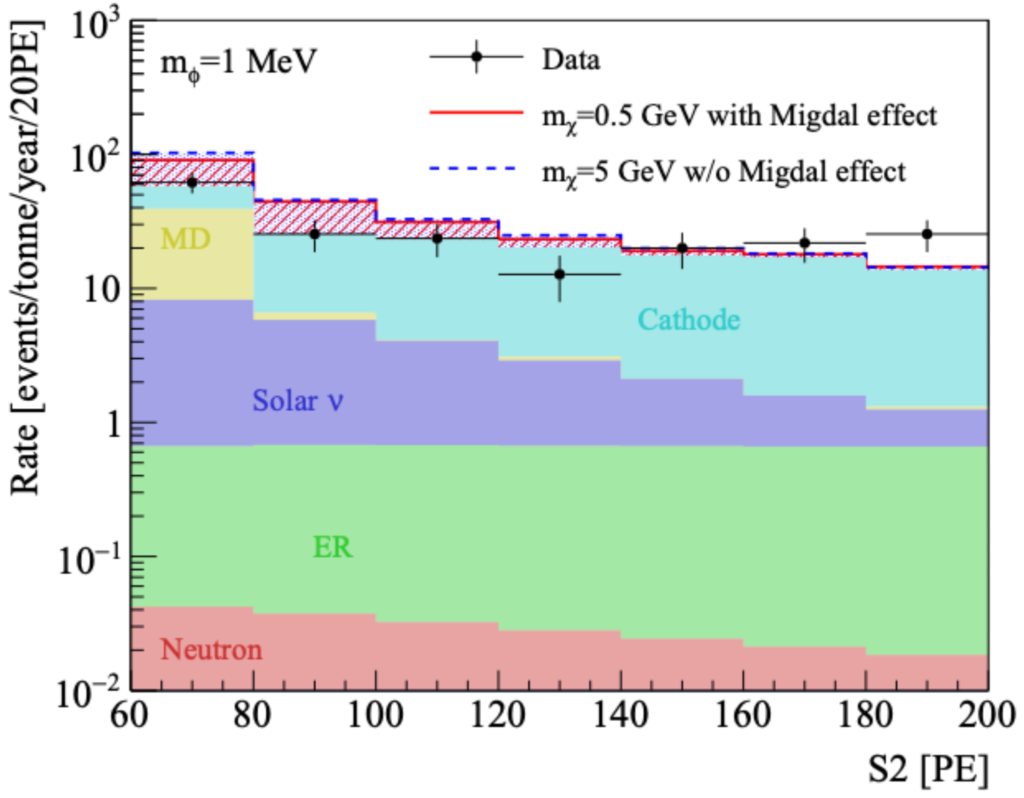
E787/E949: rare Kaon decay

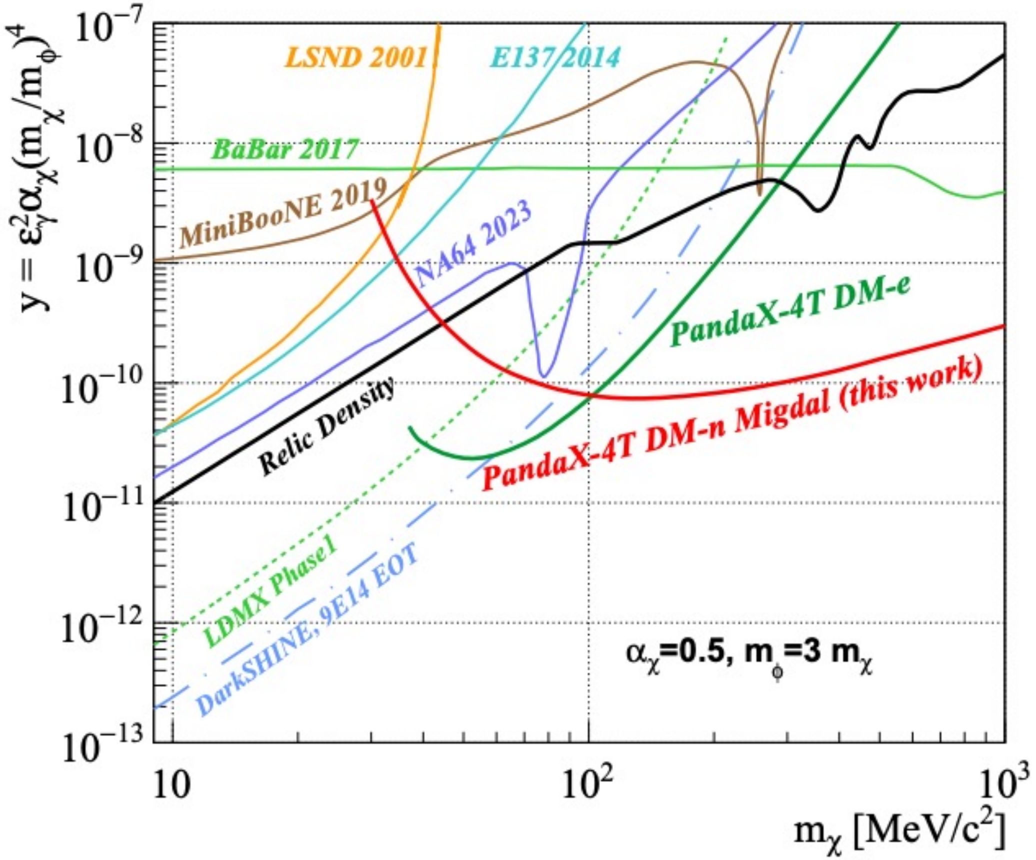


Dark Photon Mediator

- **Scalar DM with dark photon**
- **Low-threshold detection mode**
  - Ionization-only signal: threshold 1 keV -> 0.1 keV

PandaX, PRL 131, 191002 (2023)



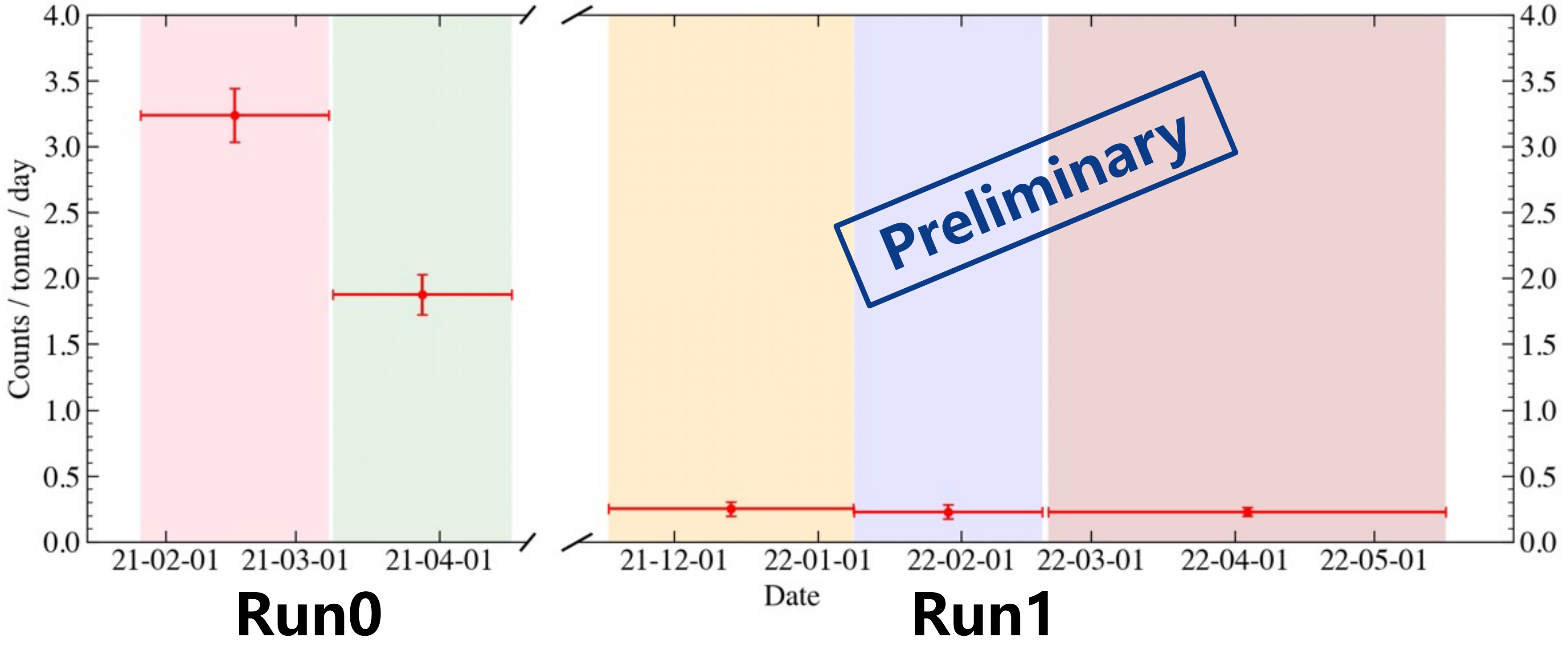


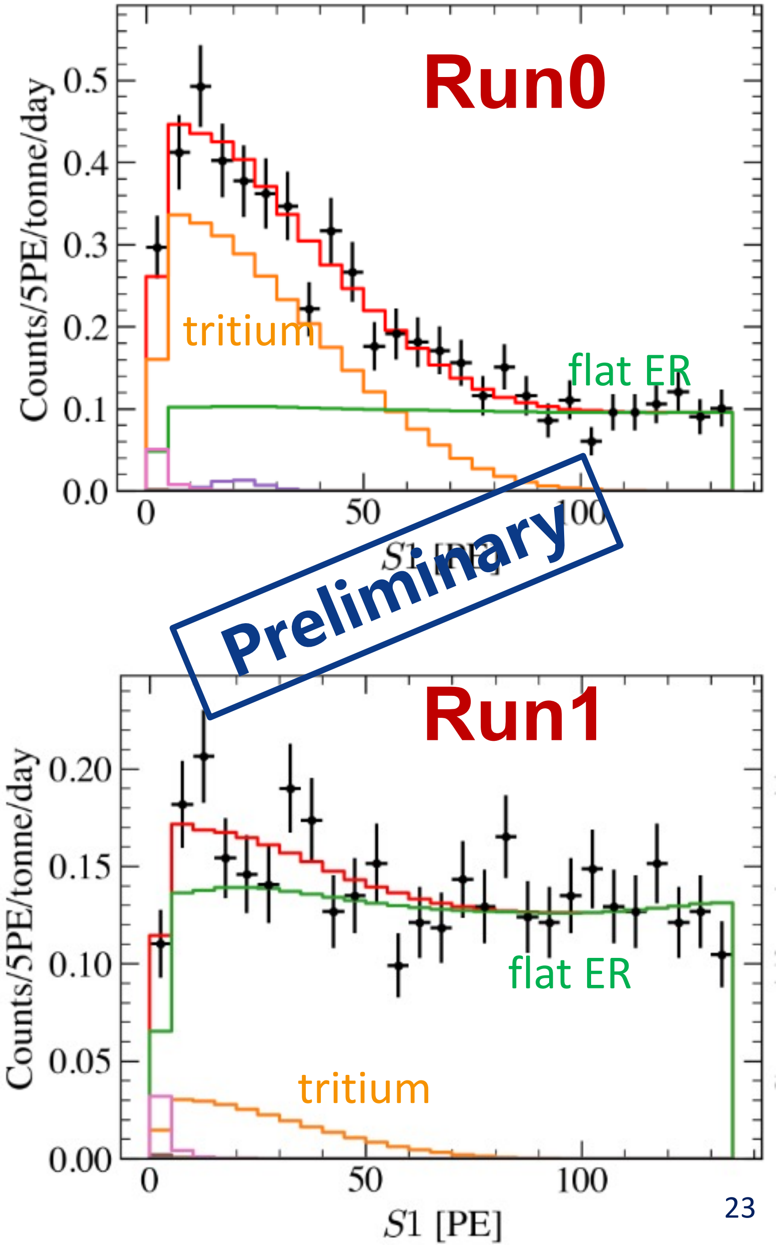
PandaX-4T Physics Run

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 construction** xenon recuperation, detector upgrade
Current Status	**Resuming physics data-taking**

Status of Run-1 Data Analysis

- **Tritium background**
  – excess of low electron-recoil energy
- **Significant reduction from Run0 to Run1**





Multi-physics targets

Large energy range: keV ~ MeV

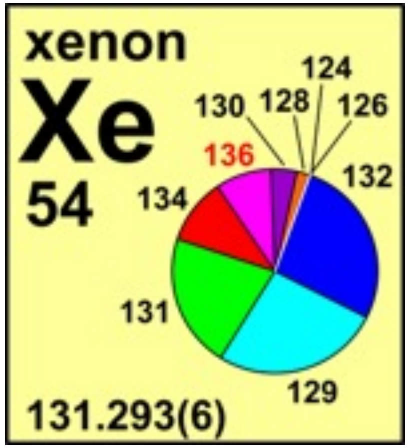
Dark Matter
1 keV – 10 keV

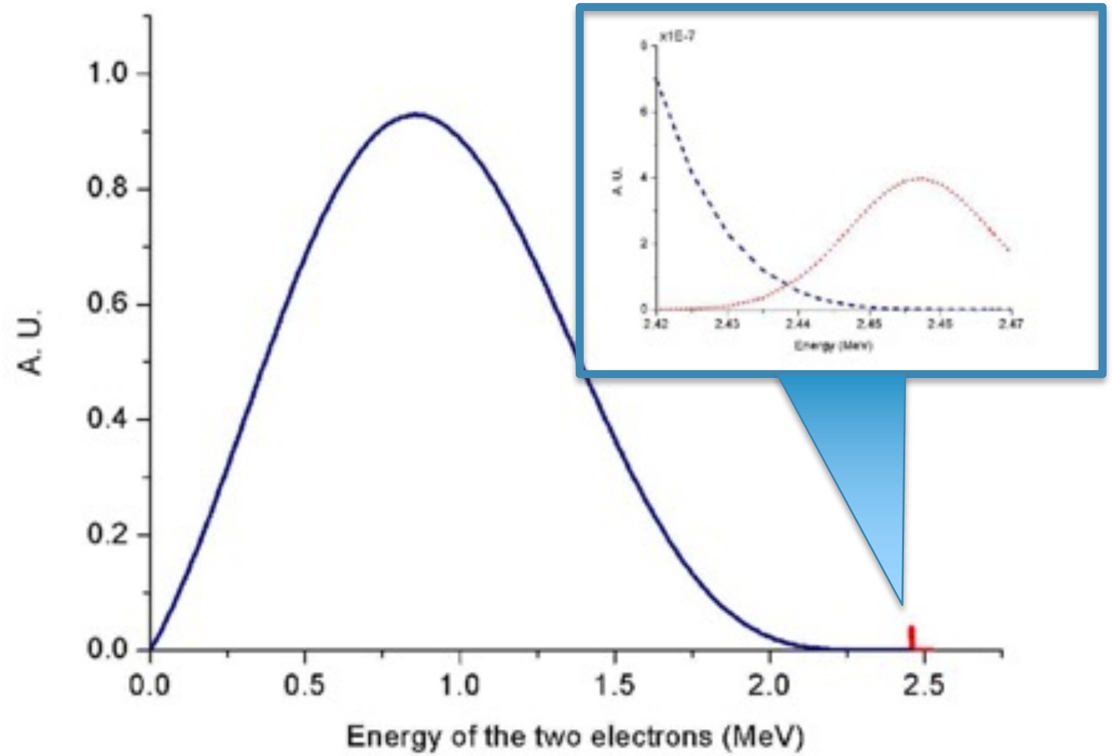
Majorana Neutrino
> 2 MeV

Astrophysical Neutrino
< 300 keV

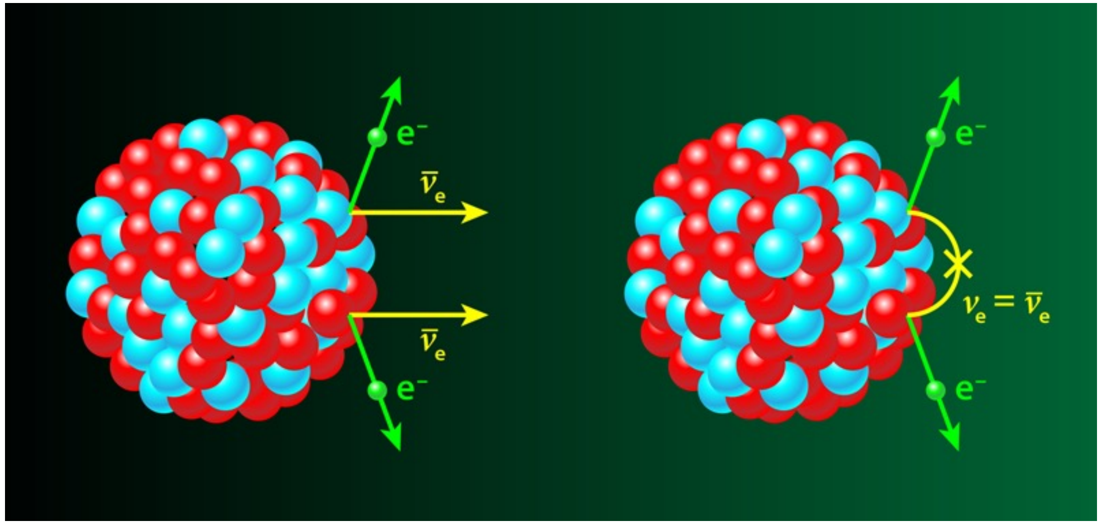
Majorana Neutrino

- **Neutrinoless double-beta decay**
  - Golden channel for Majorana neutrino searches
- **Xe-136: natural abundance 8.9%**
  - $2\nu\beta\beta$ $T_{1/2}$ $2.2\text{x}10^{21}$ years, $Q_{\beta\beta}$ 2.46 MeV



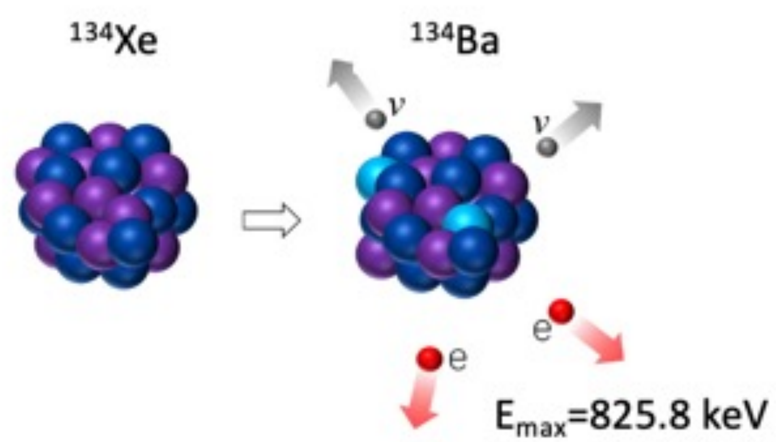


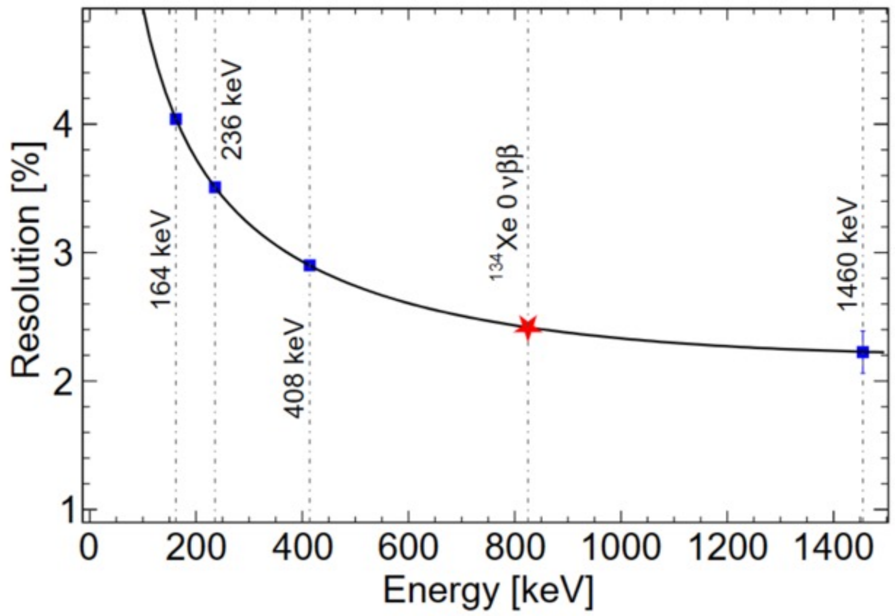
$$^{136}\text{Xe} \rightarrow {}^{136}\text{Ba} + 2e^{-} + ?\,\nu$$

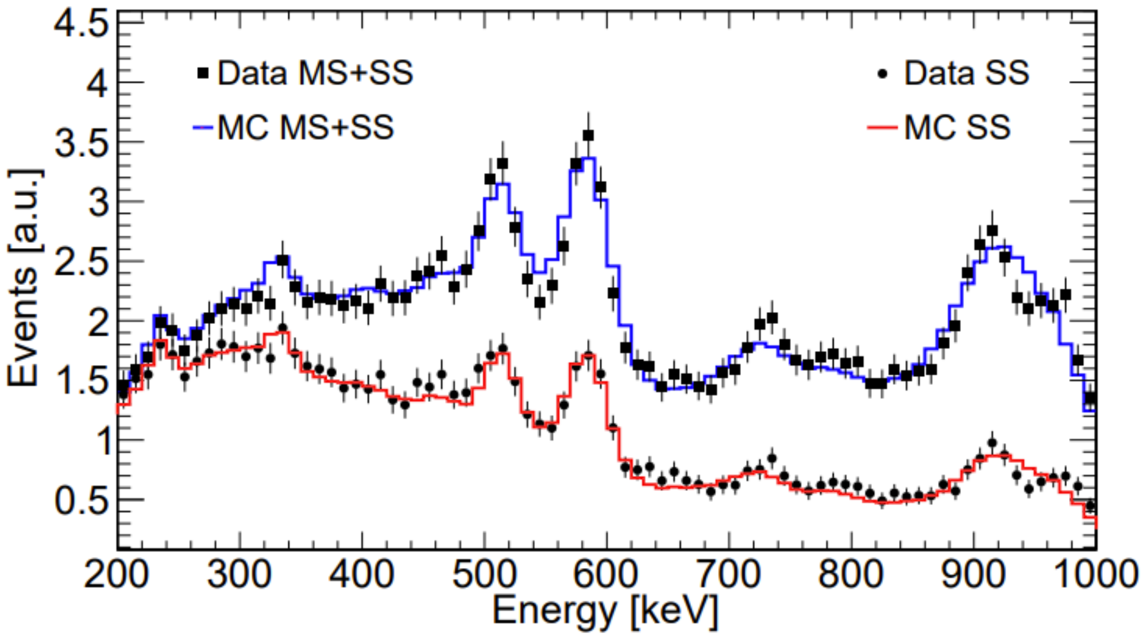


Xe-134 @ PandaX-4T

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

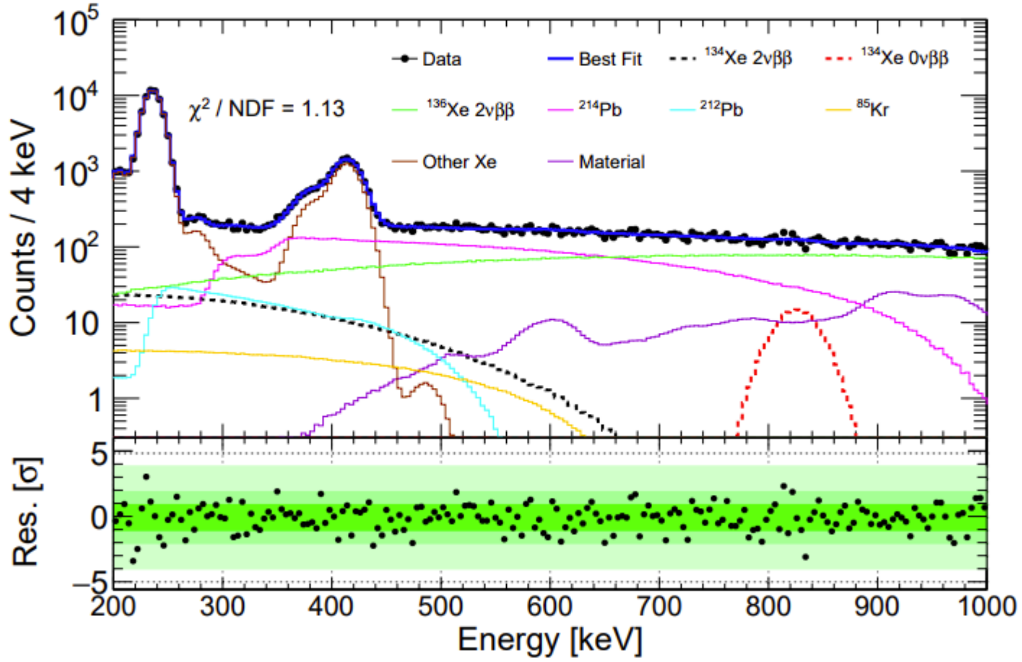


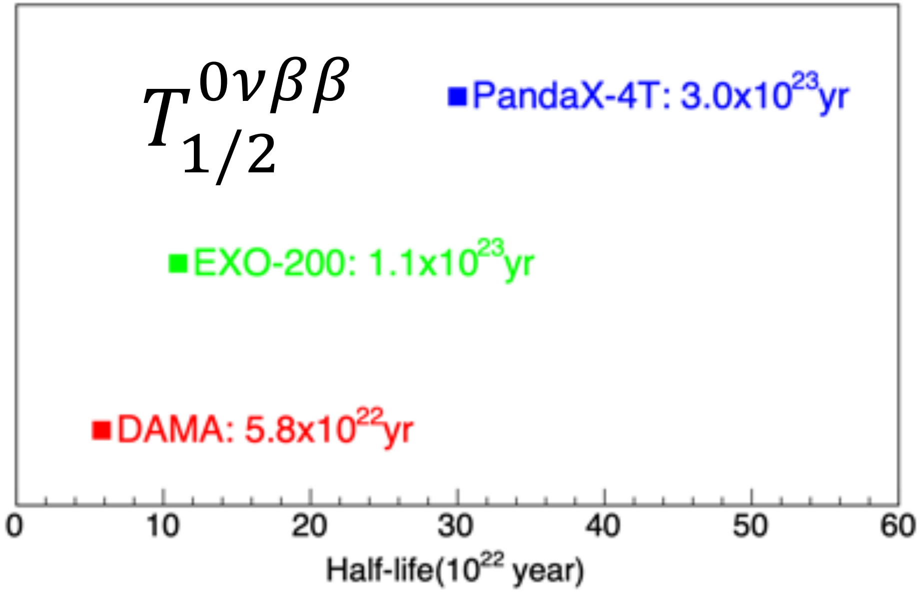




Xe-134 @ PandaX-4T

- **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**
  - $T_{1/2}^{2\nu\beta\beta} > 2.8 \cdot 10^{22}$ yr
  - $T_{1/2}^{0\nu\beta\beta} > 3.0 \cdot 10^{23}$ yr

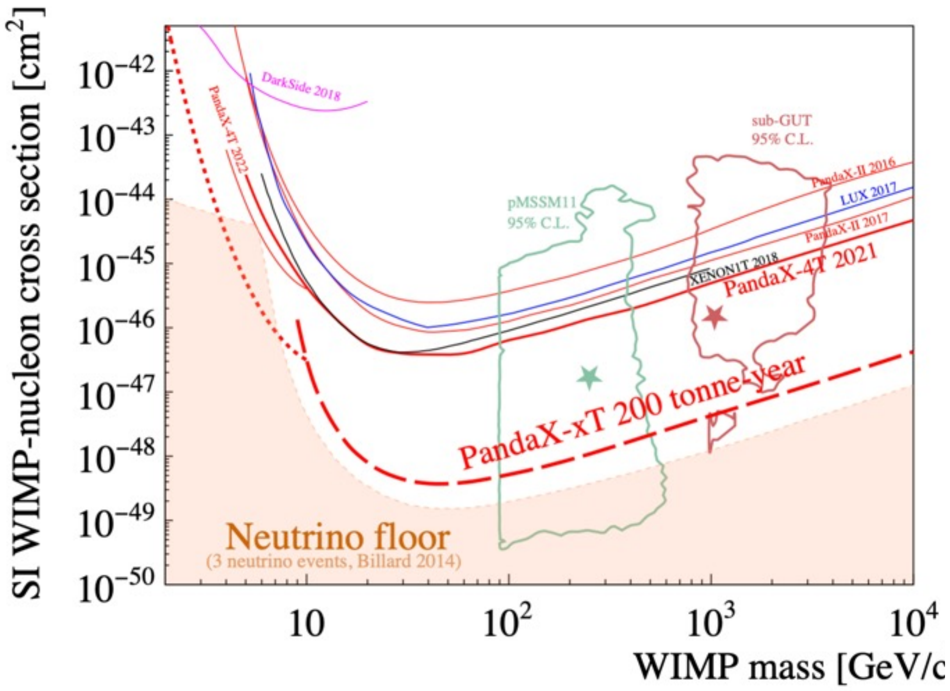


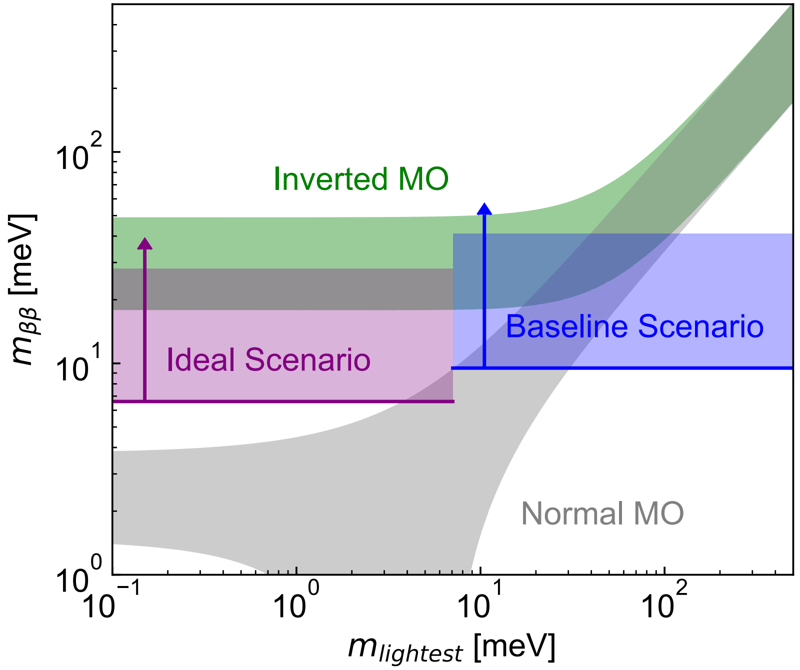


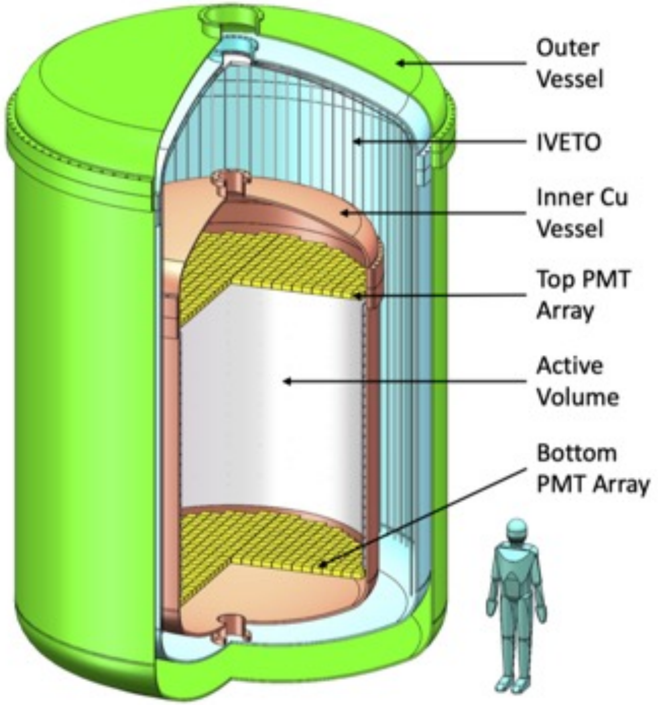
PandaX, arXiv:2312.15632, accepted by PRL

Future plan: PandaX-xT

- **"Ultimate" liquid xenon experiment**
  - With >30 tonne sensitive volume
  - Letter-of-interest sent to Chinese funding agency
  - Key tests on WIMP and Dirac/Majorana neutrino







PandaX, arXiv:2402.03596

Summary

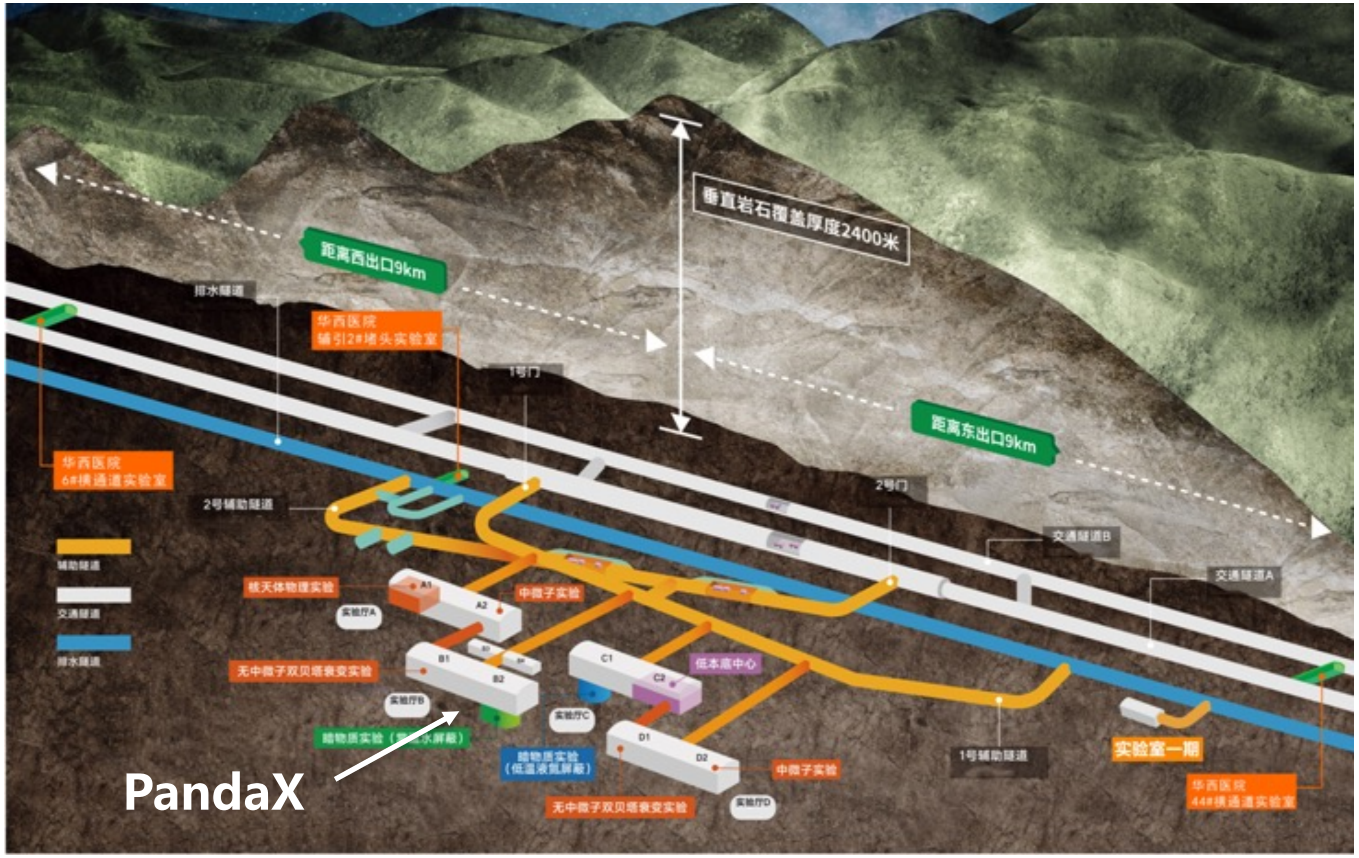
- PandaX-4T is one of the new generation multi-tonne xenon experiments
- Intense searches for various types of physics, including DMs and neutrinos
- Expecting more interesting results
- Highly welcome new collaborators!

Thank You

- **PandaX: Particle and Astrophysical Xenon Observatory**
  - ~100 members

China Jinping Underground Laboratory

- **Deepest underground lab**
  - 6700 m.w.e. and horizontal access
- **CJPL-II: 8 experiment halls (14m x 14m x 60m)**



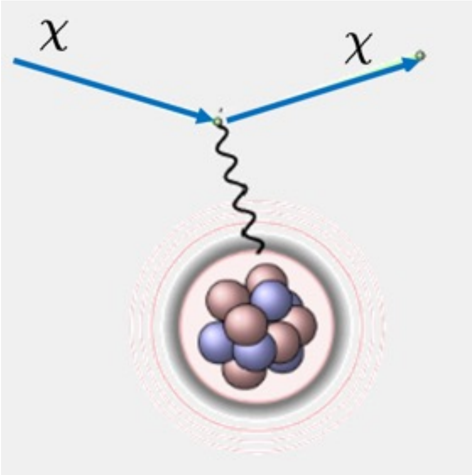
DM – nucleus interaction

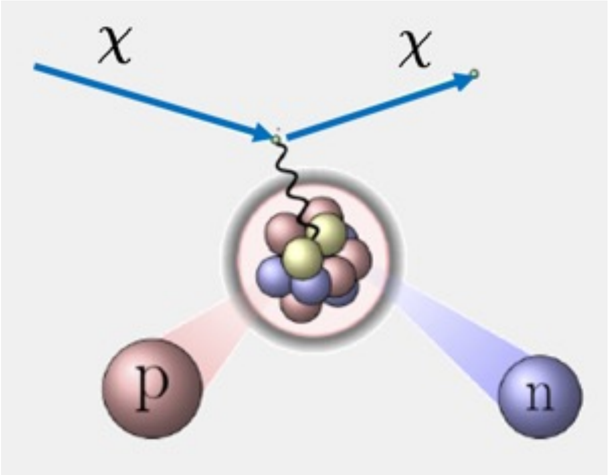
- **Elastic coherent, quasi-elastic (QE), and inelastic scatterings**
  - For $T_\chi > 0.2$ GeV, QE becomes significant
  - **Dedicated QE scattering calculation with light mediator**

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

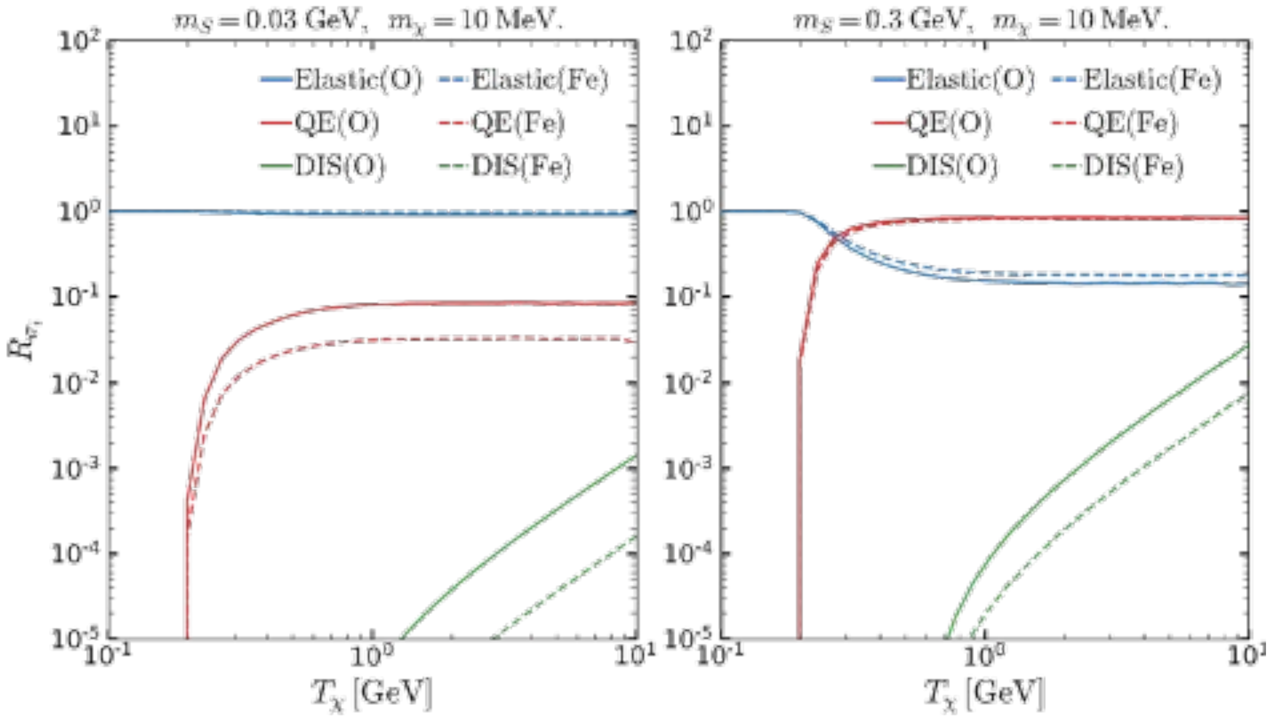
$$\frac{d\sigma_{QE}}{dT'_\chi d\Omega} = Z\frac{d\sigma_p}{dT'_\chi d\Omega} + (A - Z)\frac{d\sigma_n}{dT'_\chi d\Omega},$$

L. Su, L. Wu, NZ, B. Zhu, PRD 108, 035004 (2023)



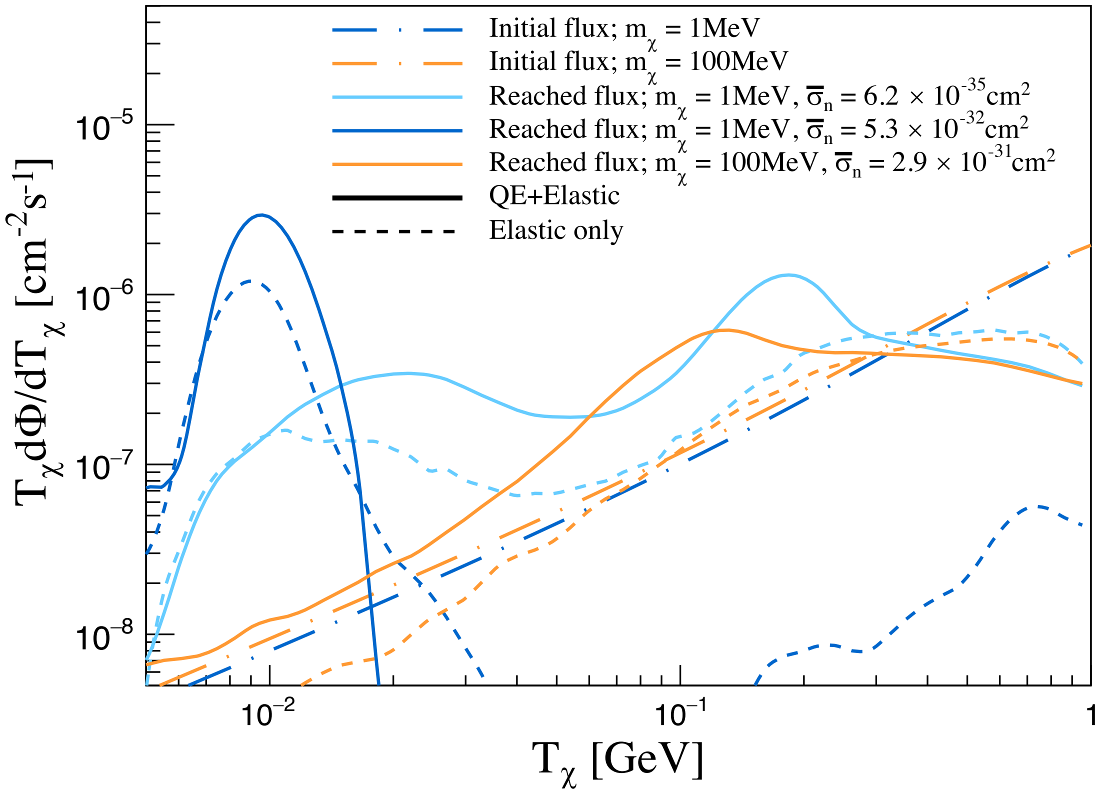


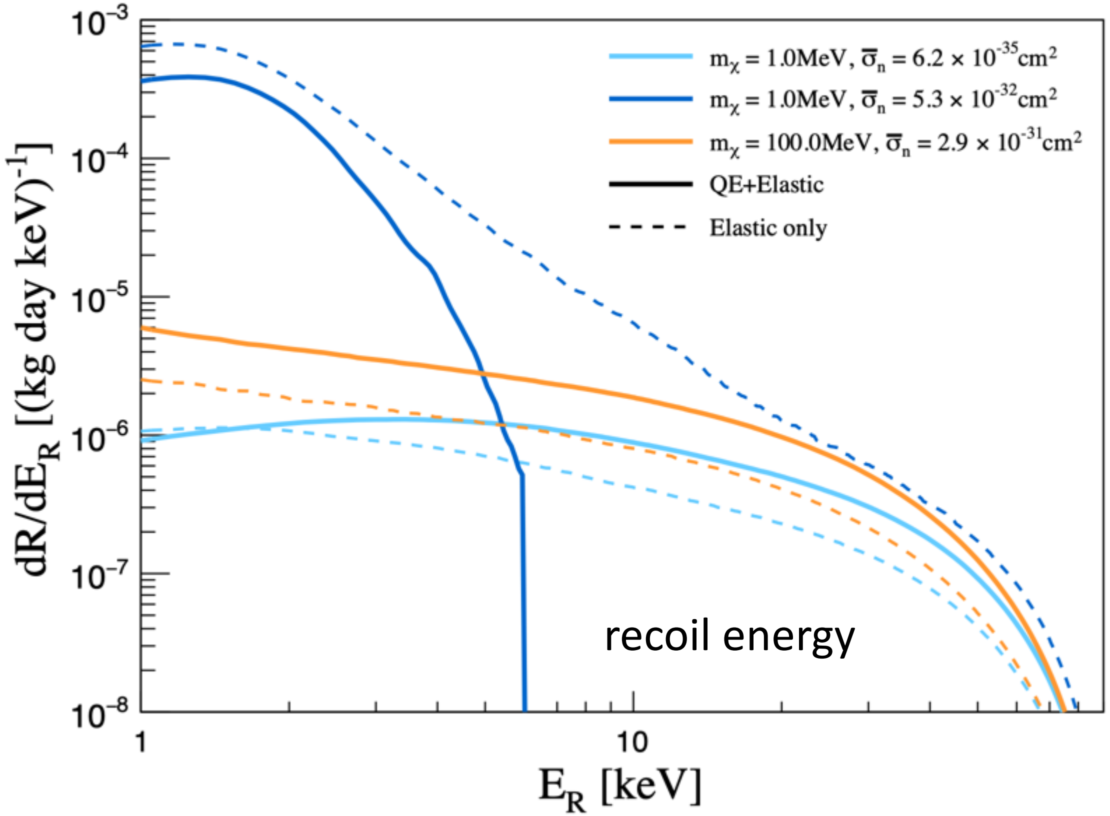
$$R_{\sigma_i} = \frac{\sigma_i}{\sigma_{tot}}, \quad i = \mathrm{ES, QES, DIS}$$



Signal in detector

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





Constraints on the DM-nucleon

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

PandaX, PRL 131, 041001 (2023)