上海交通大學
SHANGHAI JIAO TONG UNIVERSITY

Dark Matter Direct Detection @ CJPL

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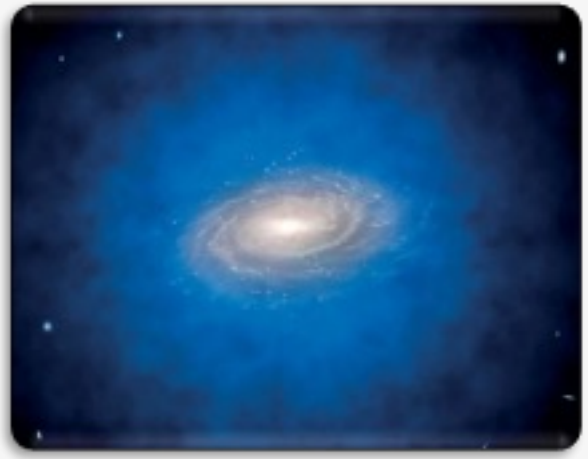
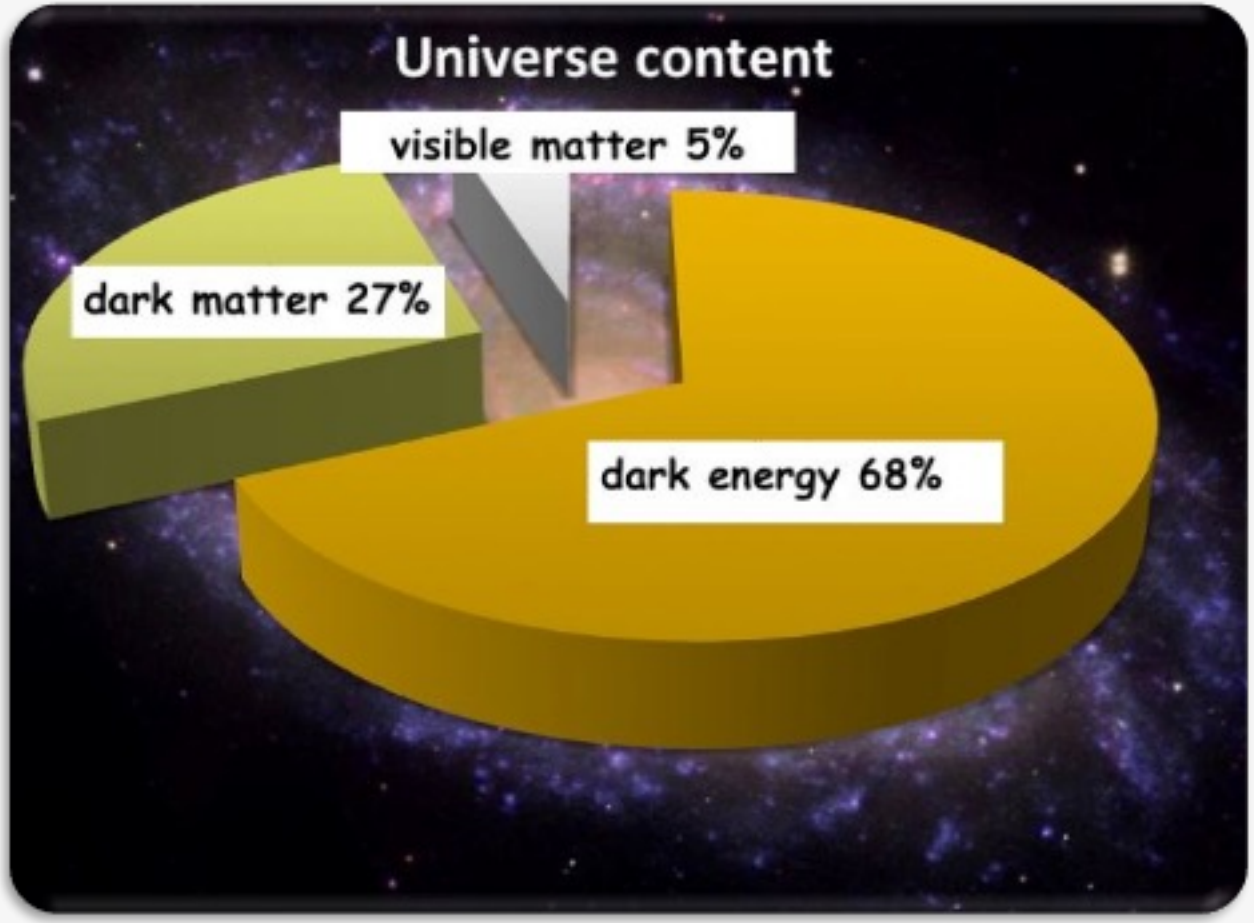
第十六届TeV物理工作组学术研讨会暨
邝宇平院士学术思想研讨会

2022-11-10

Dark Matter

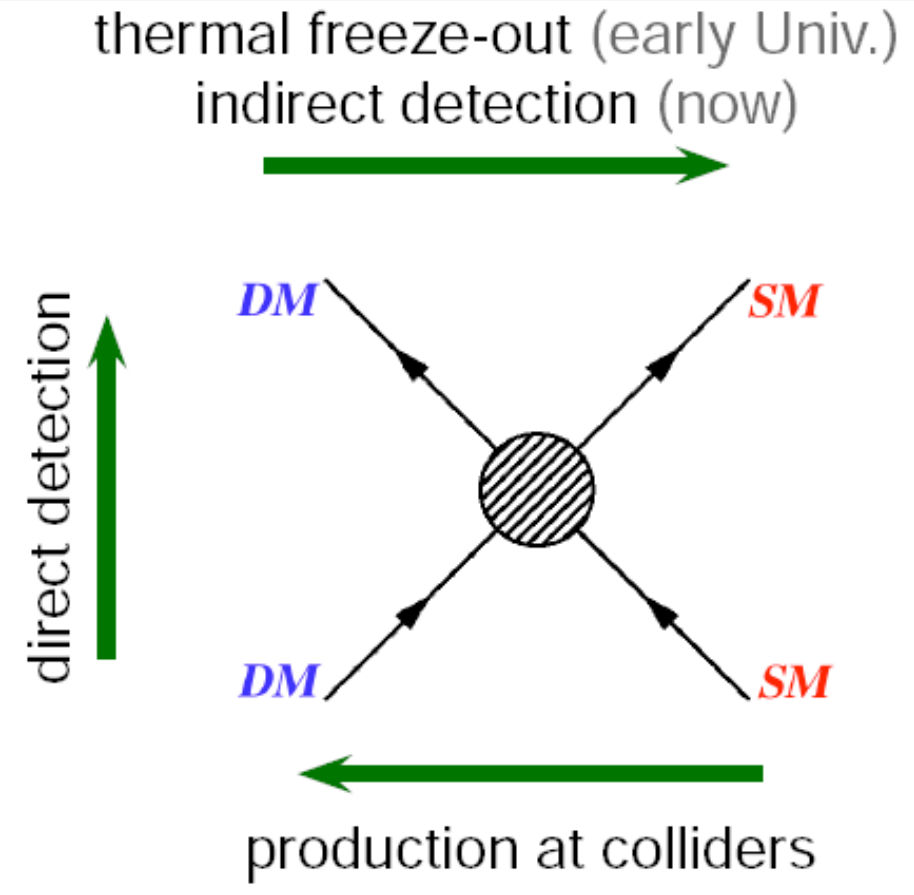
- Strong evidences for the existence of dark matter
- The nature of dark matter is unknown

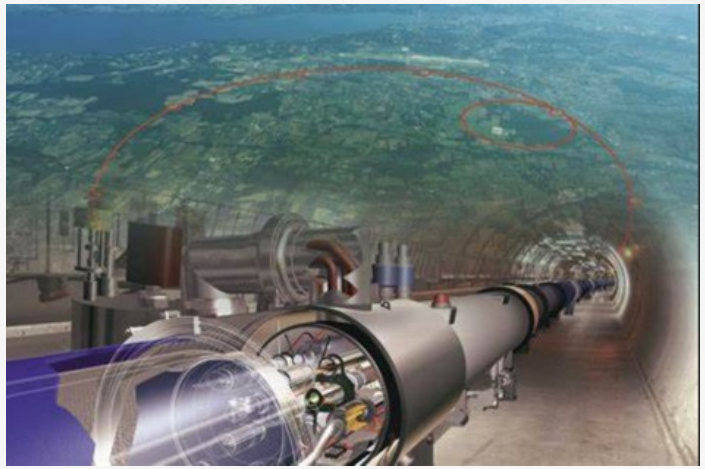




Dark Matter Searches

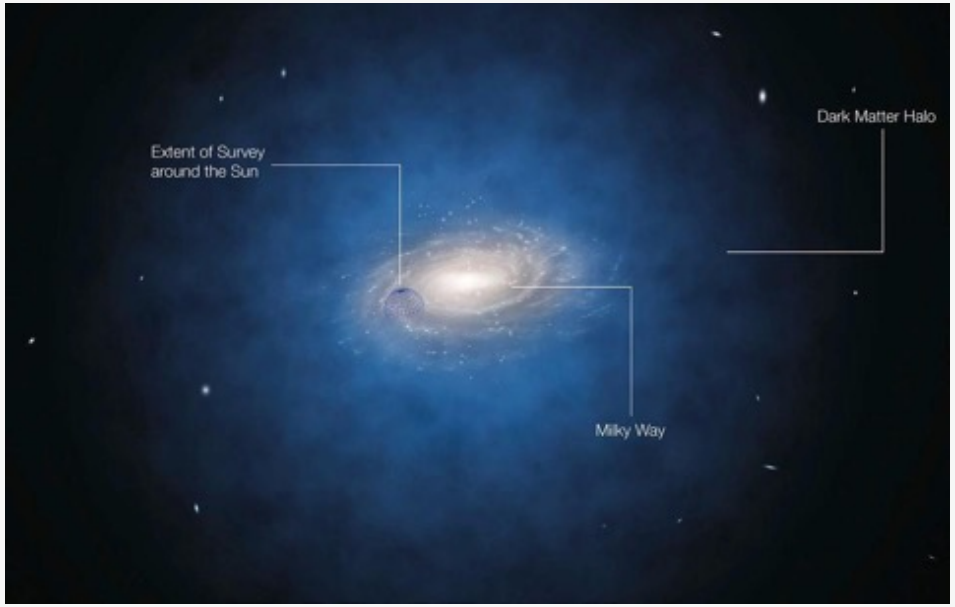
- **Direct detection, indirect detection, collider search**



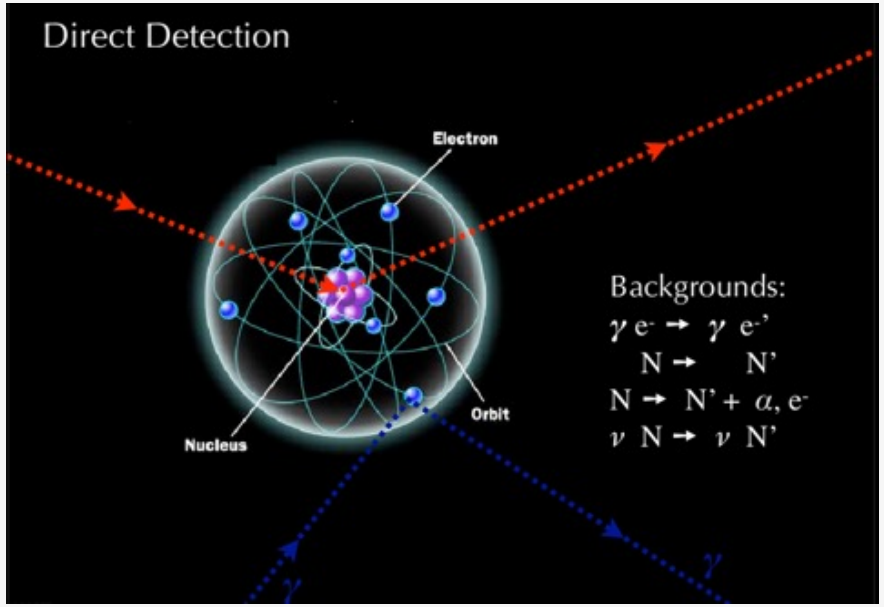


Direct Detection

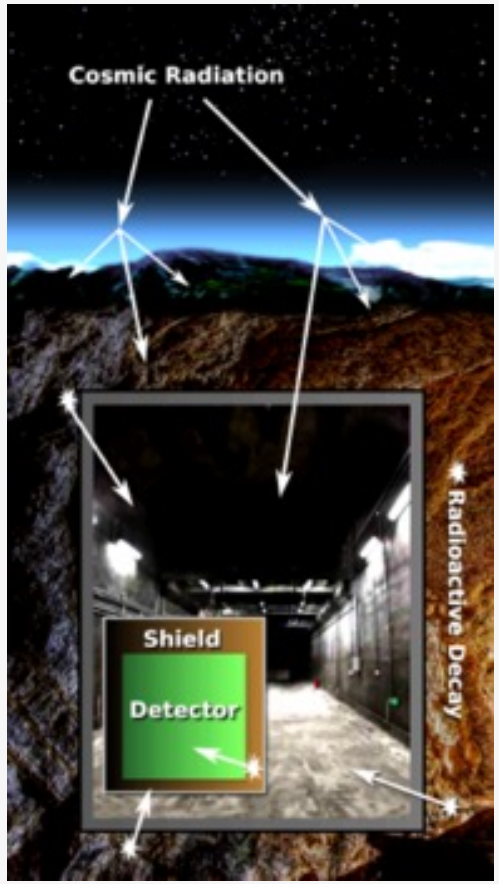
- **Solar system in the dark matter halo**
- **Detection of incoming dark matter scattering off target atom**
  - Nuclear recoil (NR) or electronic recoil (ER) signature
  - Small and rare signals: underground laboratory



ESO / L. Calçada.



DARK MATTER OVERVIEW: COLLIDER, DIRECT AND INDIRECT DETECTION SEARCHES - QUEIROZ, FARINALDO S. ARXIV:1605.08788



Global Efforts

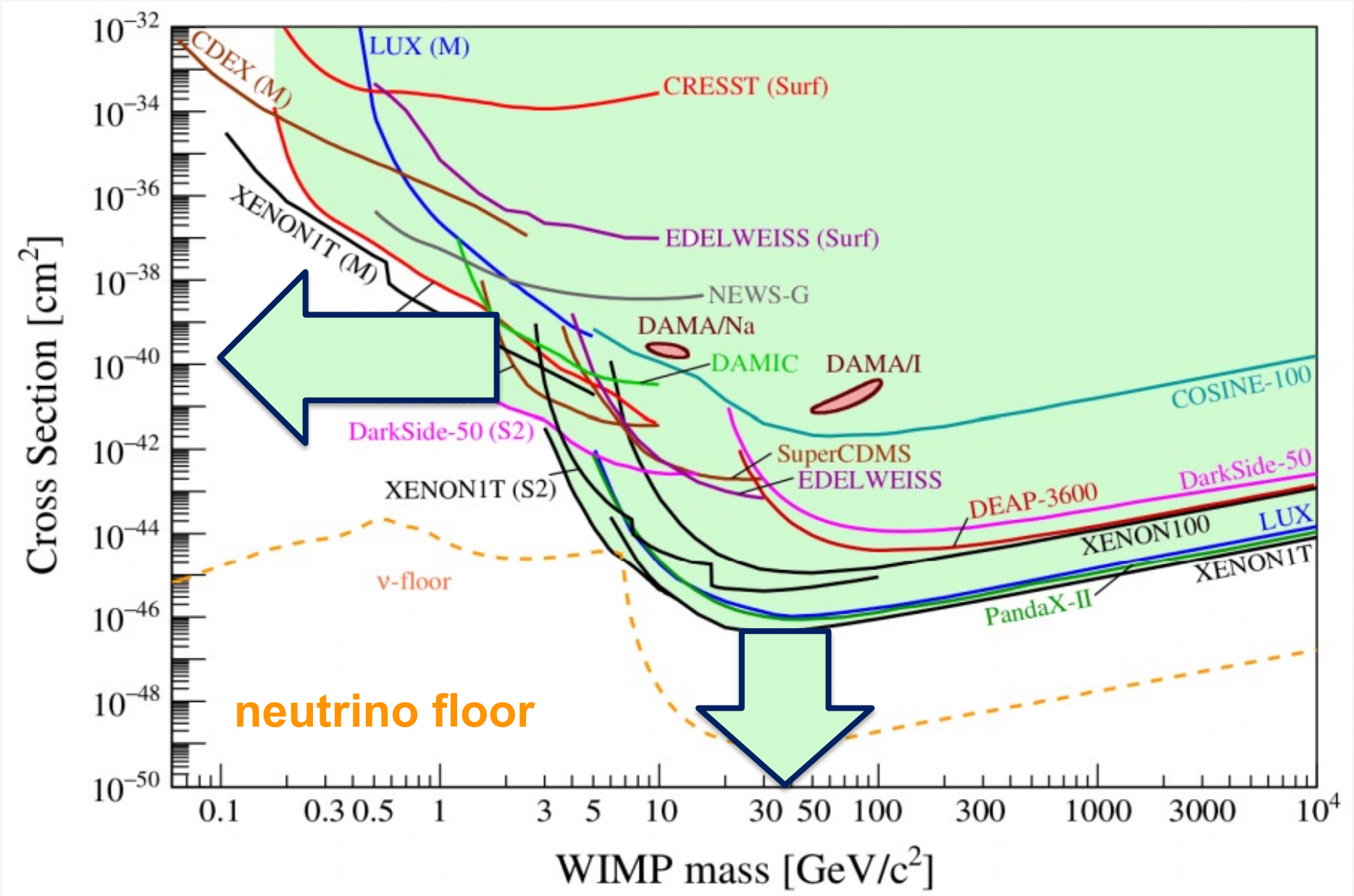
- **Multi-tonne scale direct detection experiments @ underground labs**

LZ, 7t LXe,
Sanford Lab, US

XENONnT, 6t LXe
LNGS, Italy

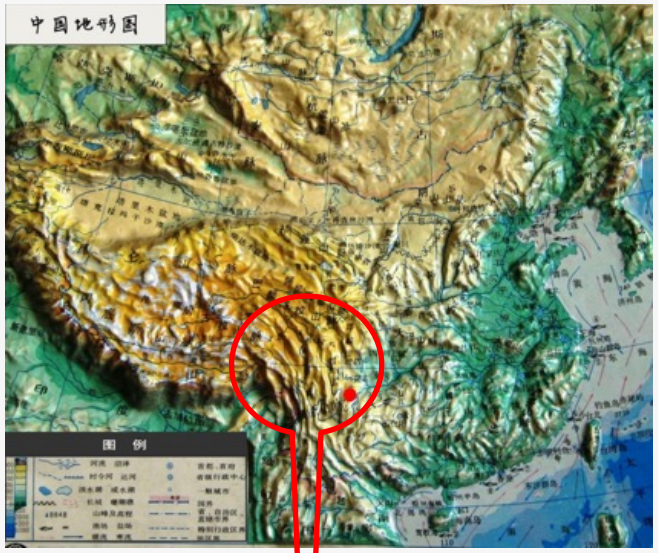
PandaX-4T, 4t LXe
CJPL, China

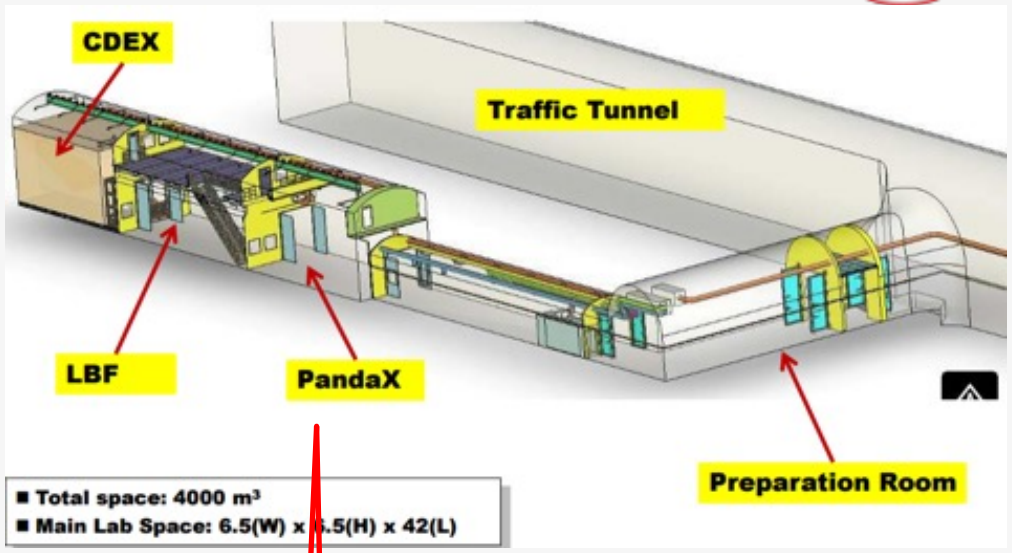
Direct Detection

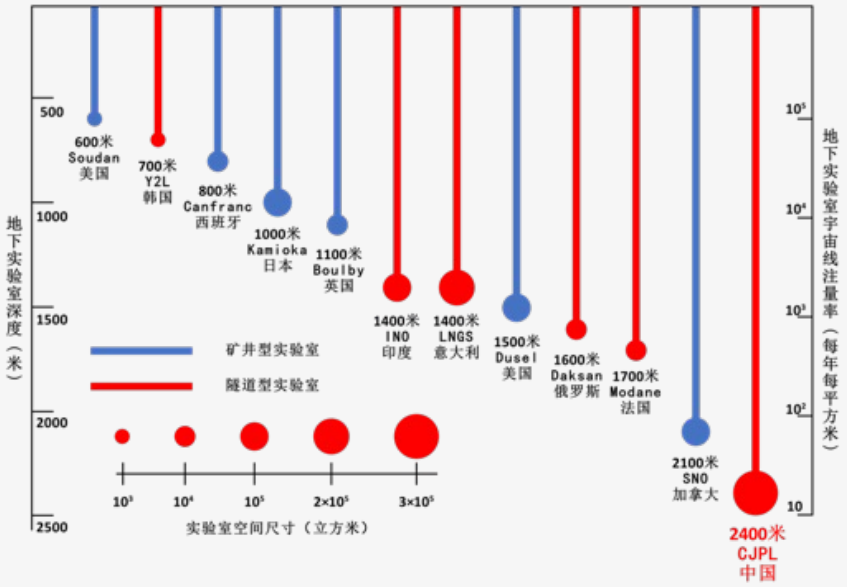
- 

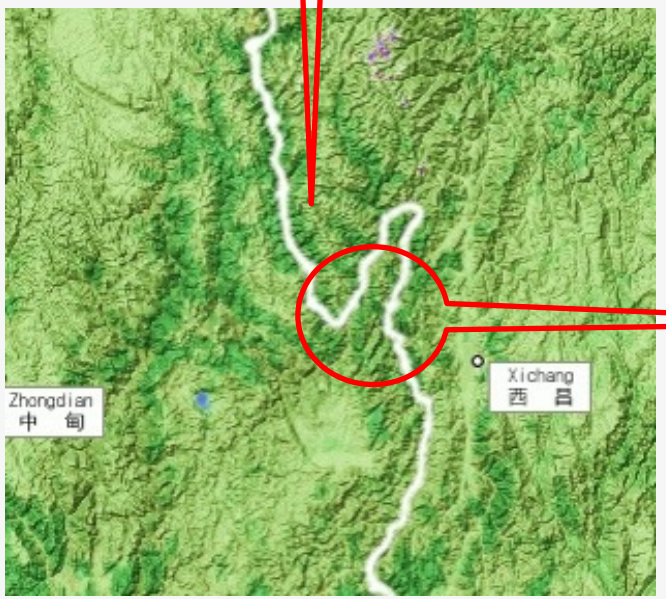
China Jinping Underground Laboratory (CJPL)

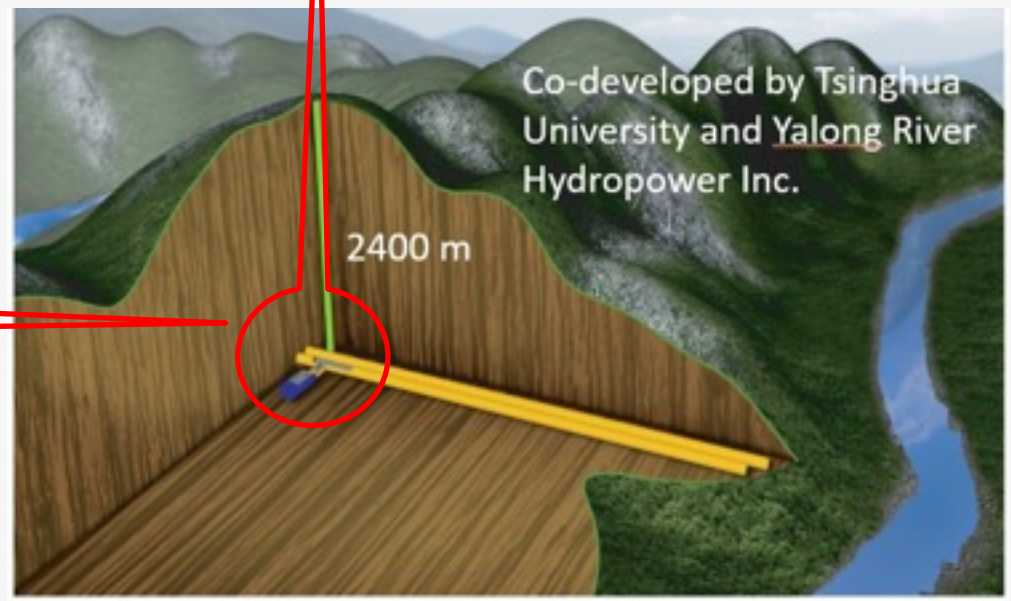
- **Deepest**
  - 6800 m.w.e.
  - < 0.2 muons/m^2/day
- **Horizontal access**
  - 9 km long tunnel





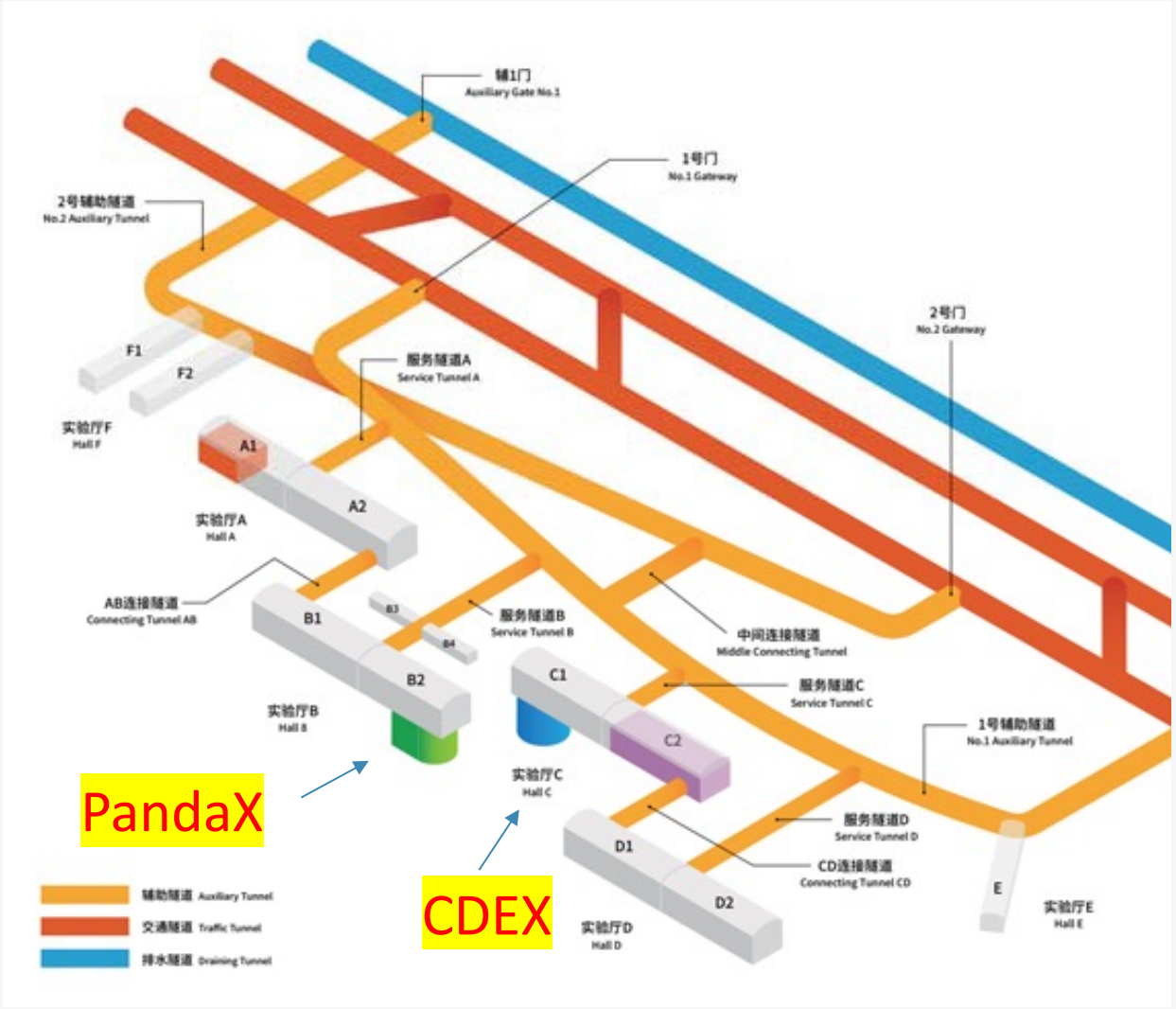






CJPL-II

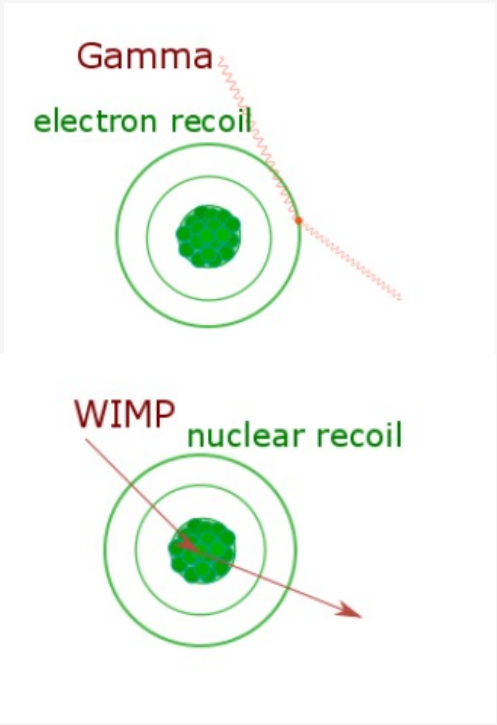
- 8 new experimental halls (L: 65m H: 14m W: 14m)
- PandaX and CDEX experiments

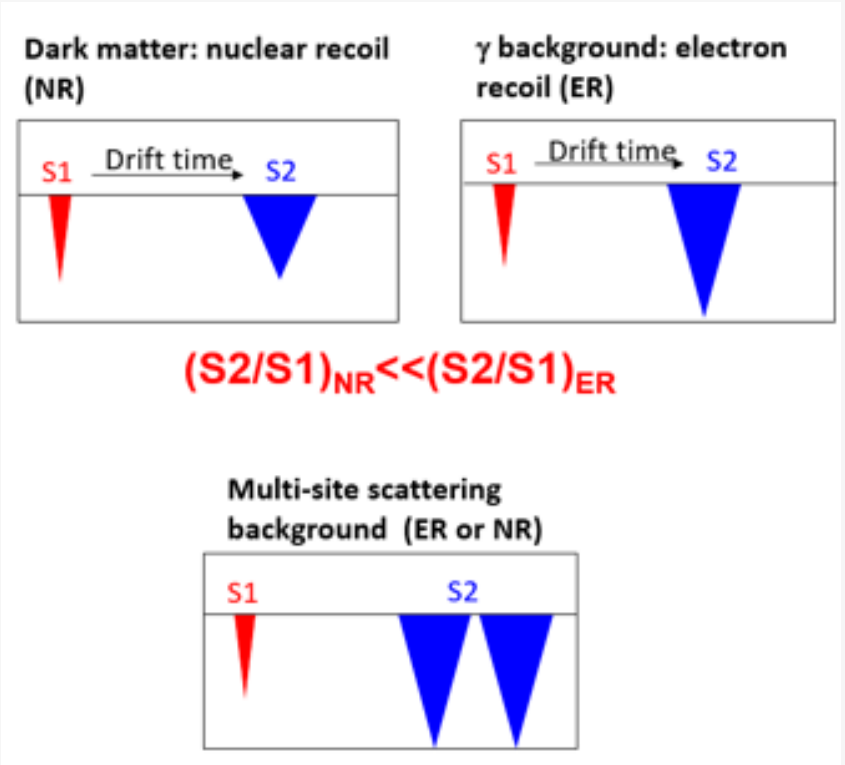


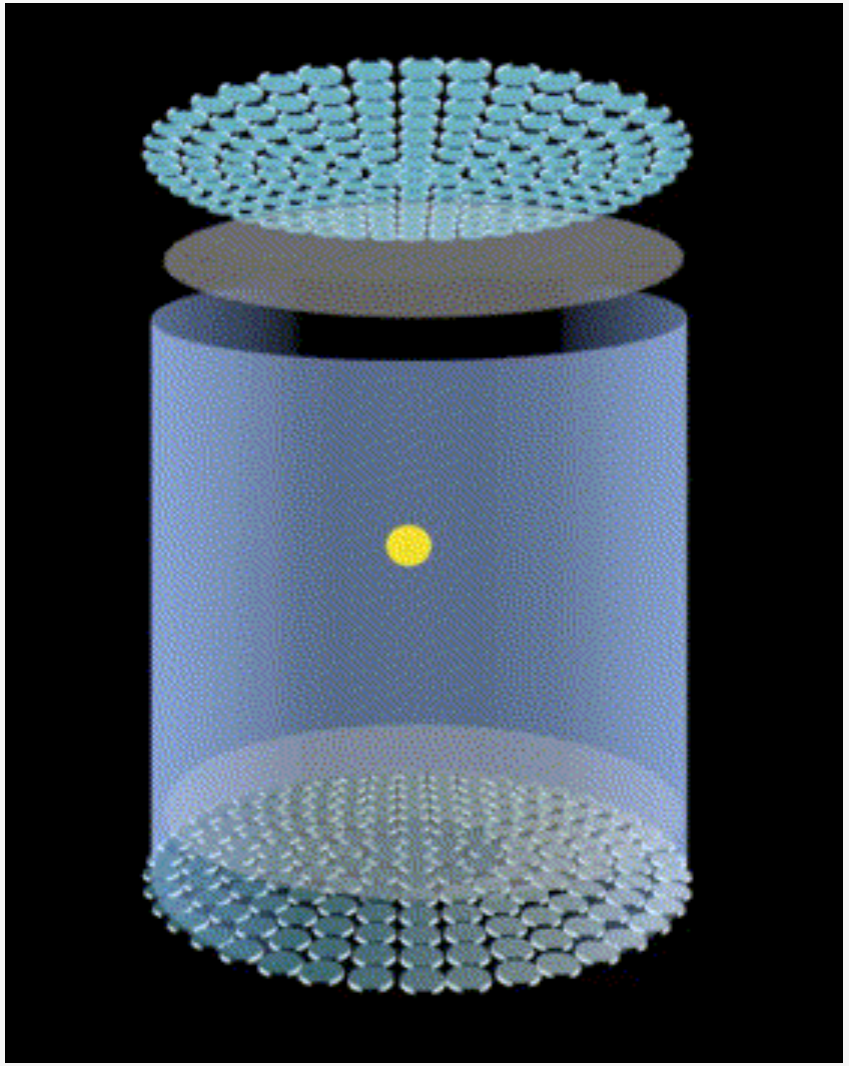
PandaX Collaboration

PandaX Detector

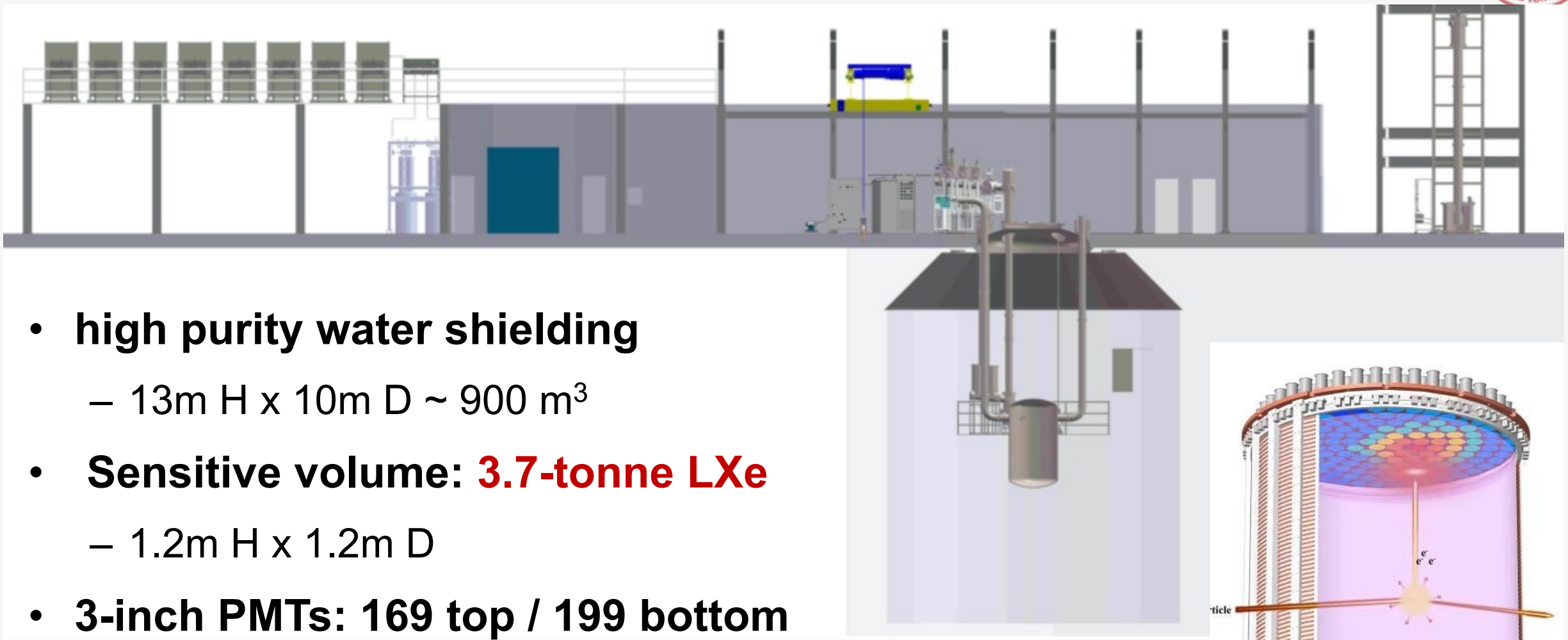
- **Dual-phase xenon TPC**
  - Scintillation light (S1) and ionized electrons (S2)
  - Precise energy and 3D-positon reconstruction
  - NR and ER discrimination power







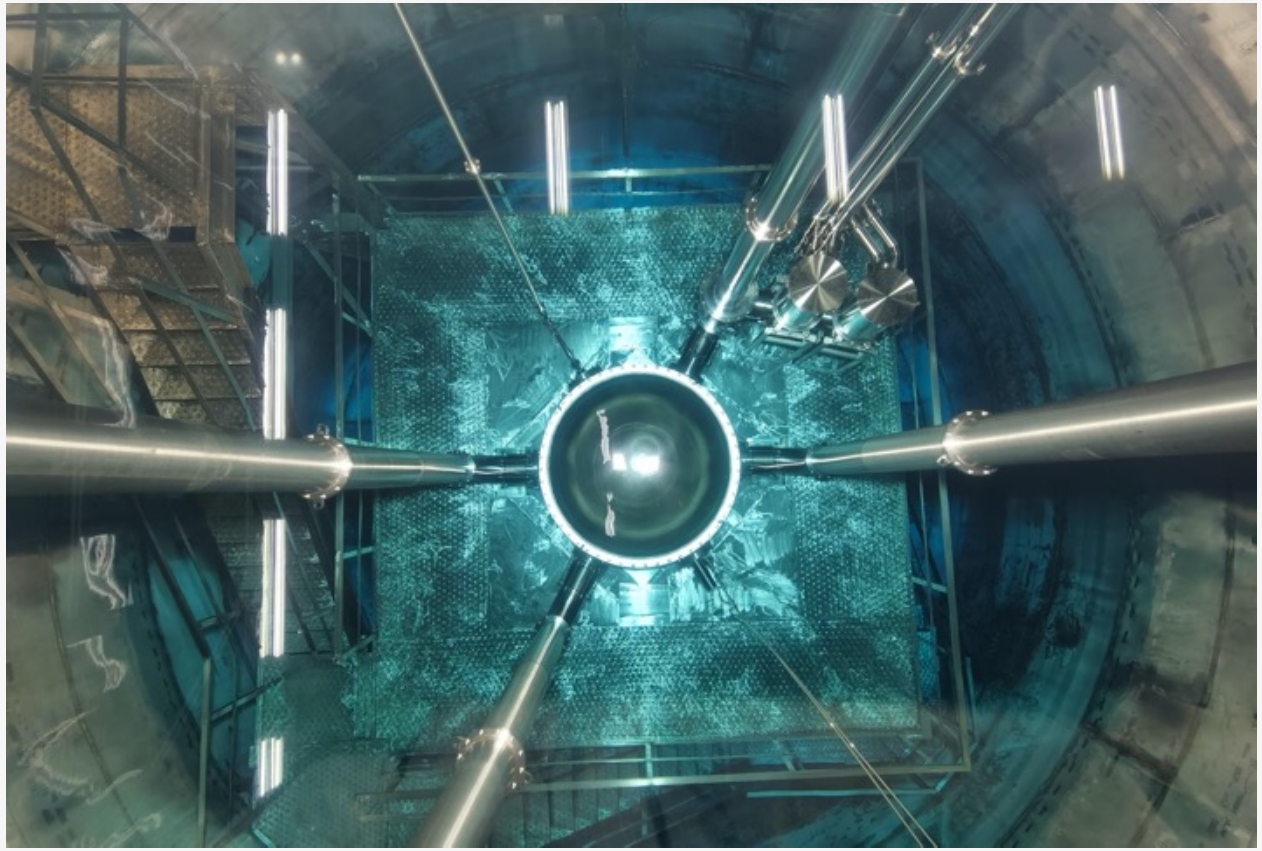
PandaX-4T @ CJPL-II

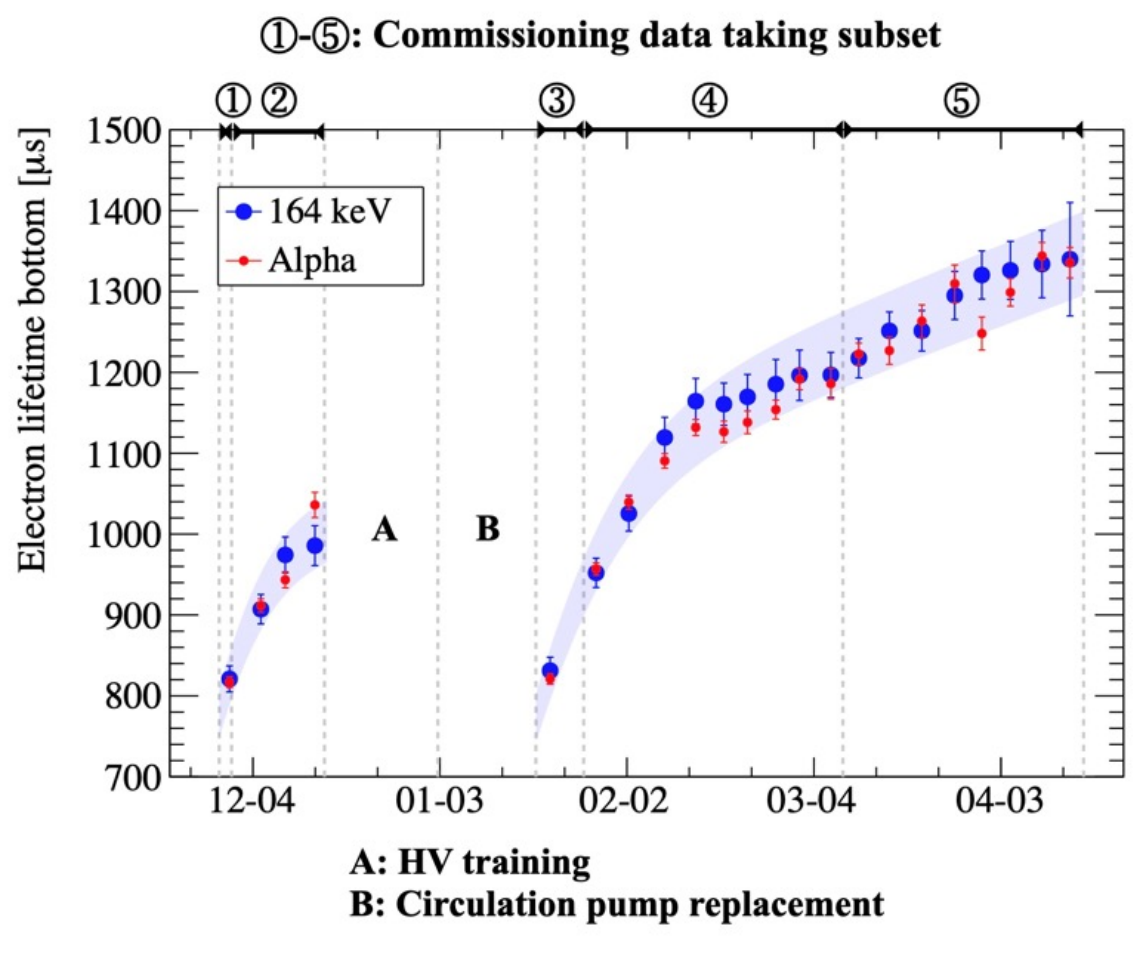


- **high purity water shielding**
  - 13m H x 10m D ~ 900 m^3
- **Sensitive volume: 3.7-tonne LXe**
  - 1.2m H x 1.2m D
- **3-inch PMTs: 169 top / 199 bottom**

PandaX-4T Operation

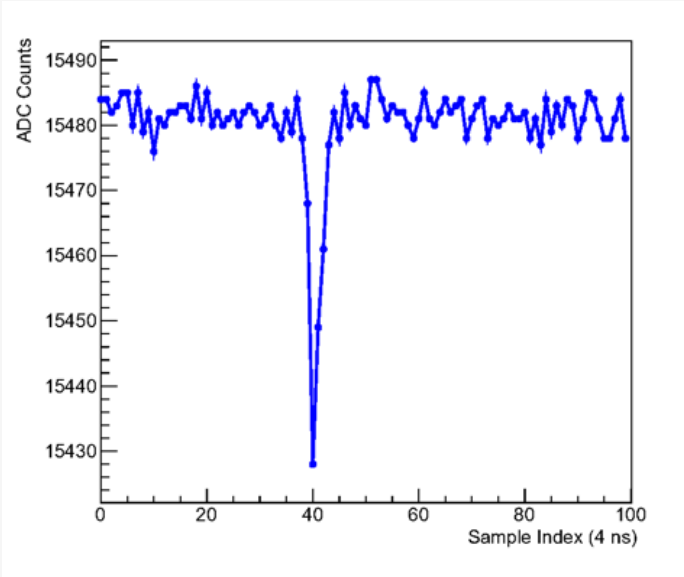
- **Start physics data taking from 2020/12**
- **Commissioning data: 95.0 calendar days**





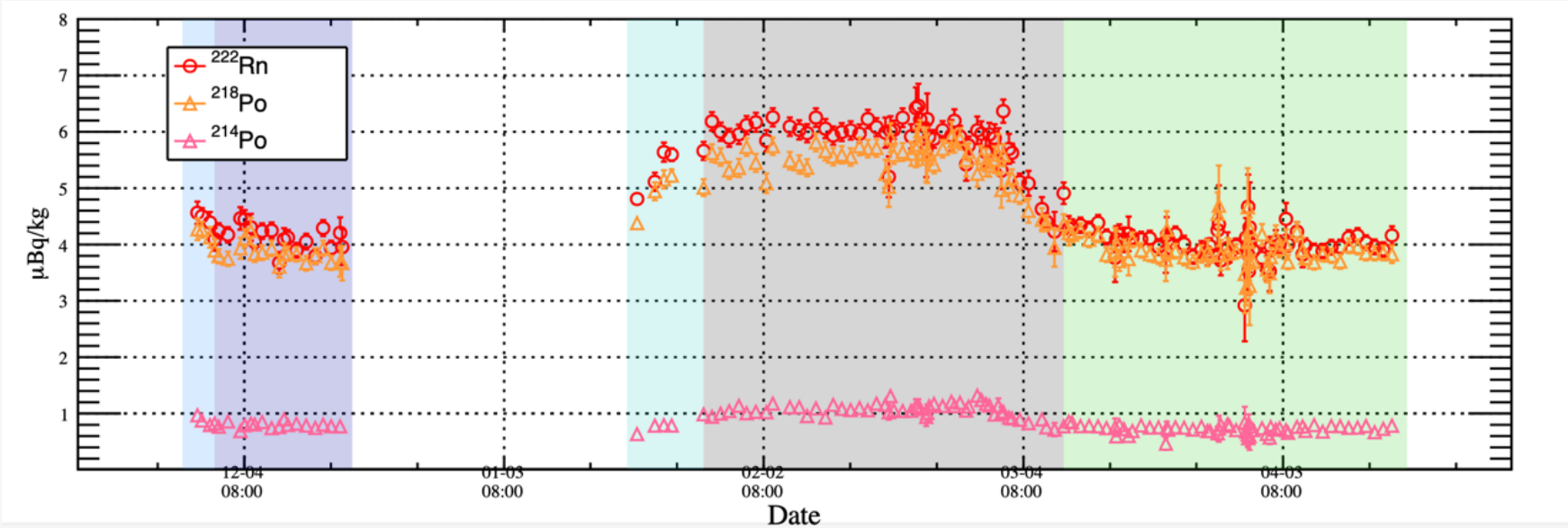
PandaX-4T major improvement

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



Typical single photon pulse

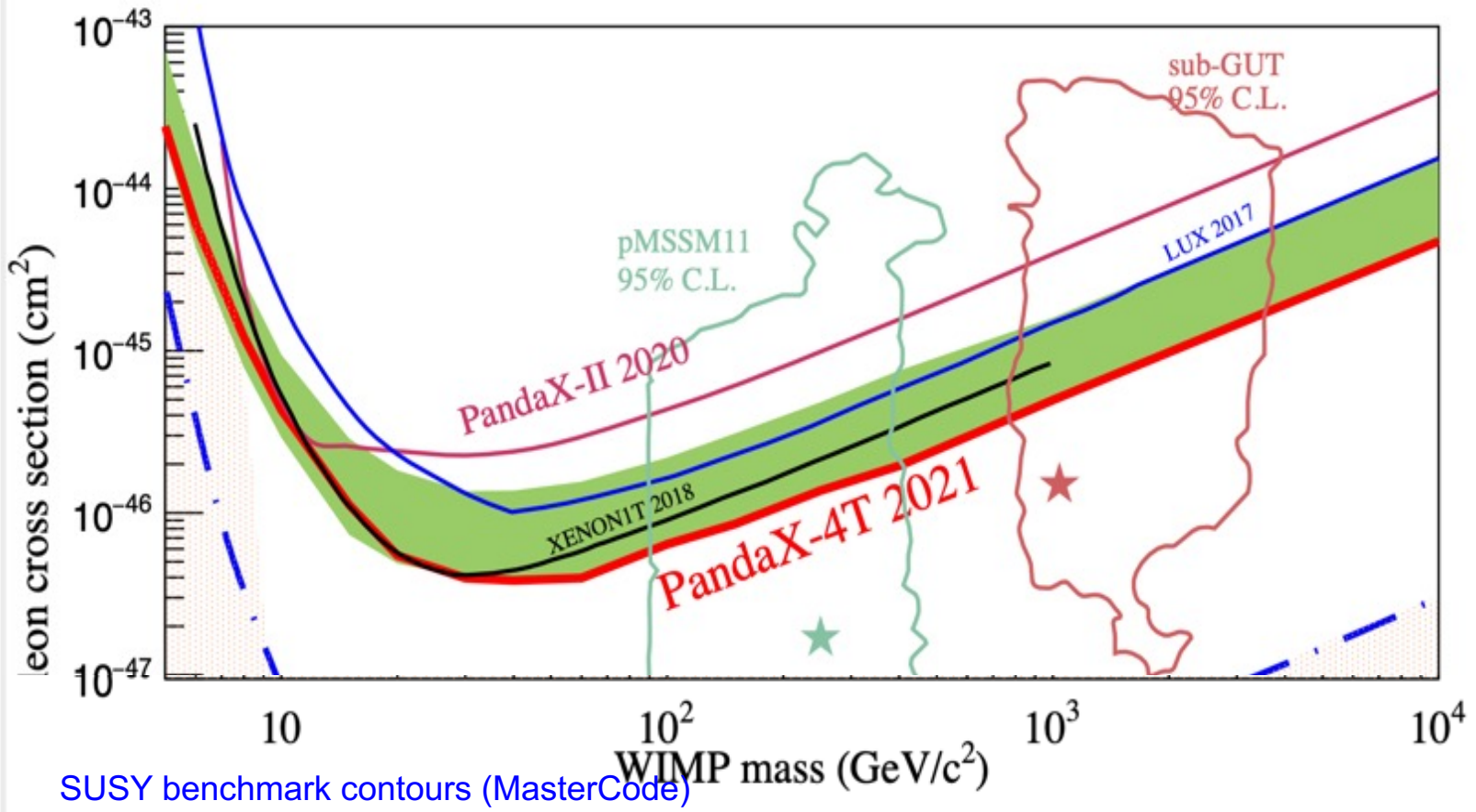
average single photon detection efficiency: 96%.

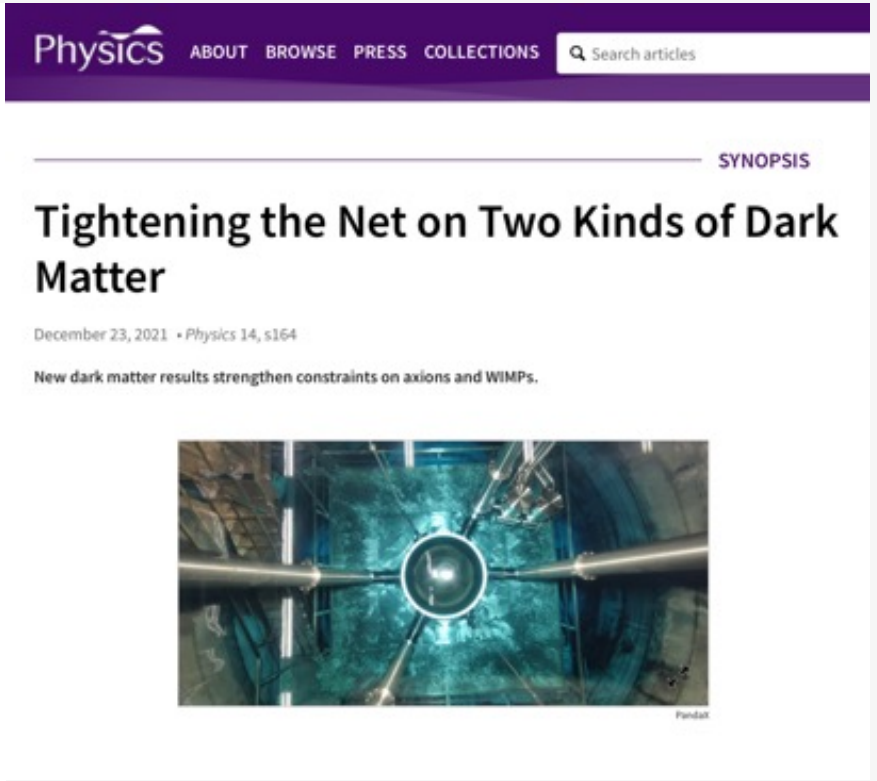


WIMP-nucleon SI exclusion limits

- **Dived into previously unexplored territory!**
- **Approaching the "low E" neutrino floor**

PRL 127, 261802 (2021)
Editors' Suggestion



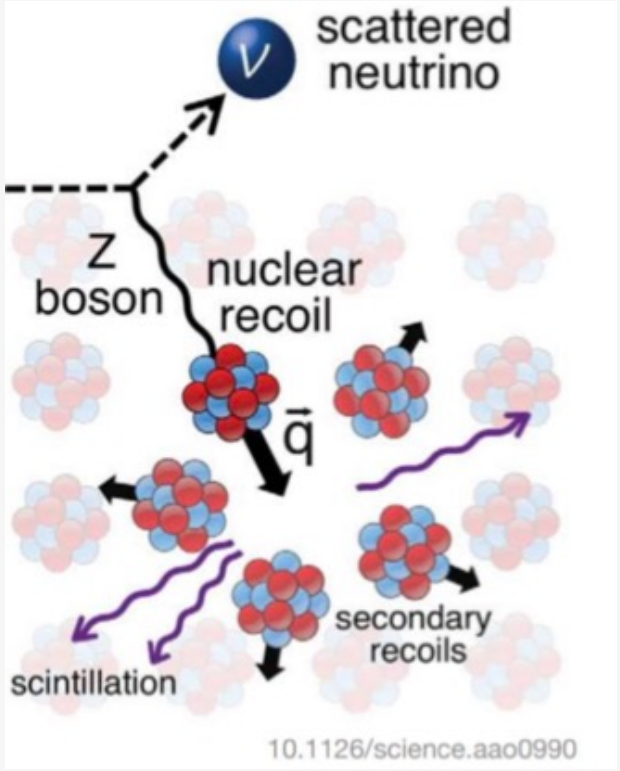


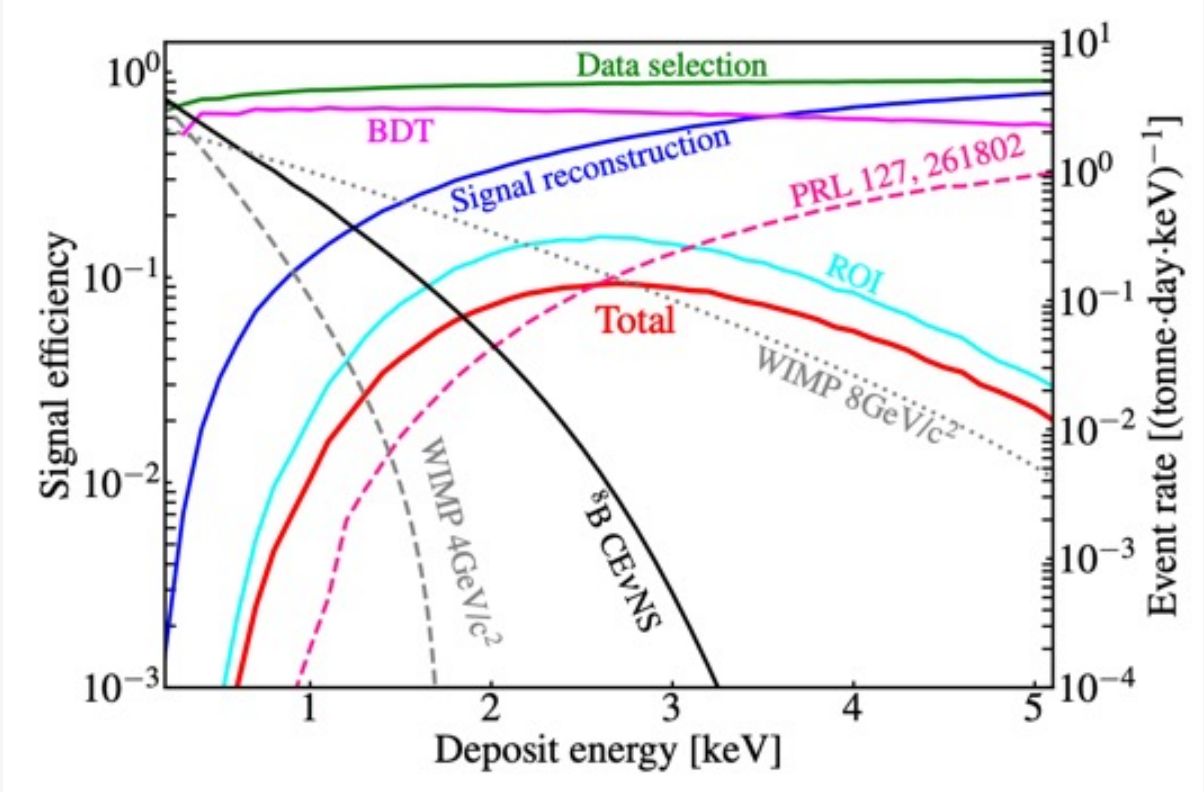
SUSY benchmark contours (MasterCode)

EPJC 78, no.3, 256 (2018), EPJC 78, 158 (2018)

Neutrino Floor

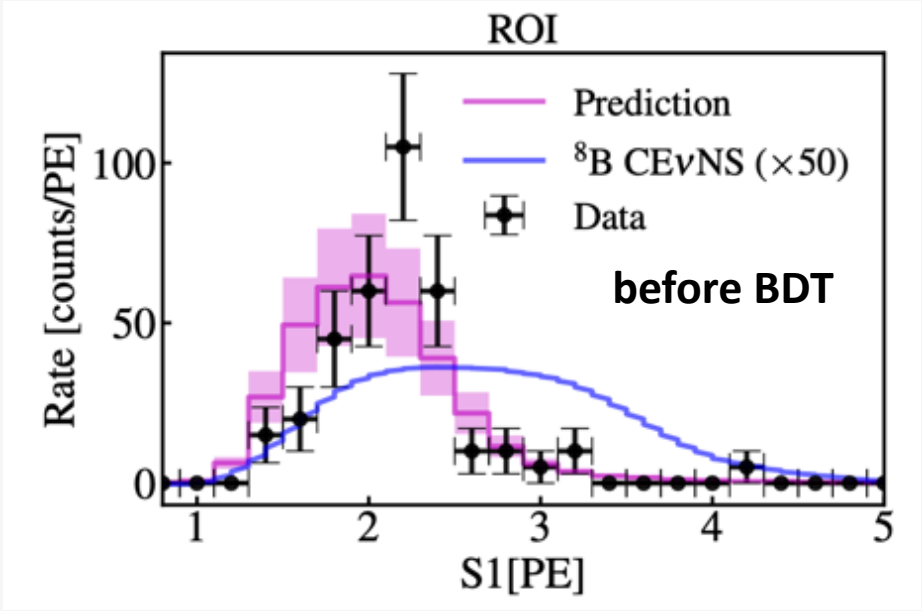
- **Neutrino floor due to B8 CEvNS**
- **Reduce the threshold**
  - Lower scintillation light (S1) signal selection threshold
  - Further optimize the quality cuts for low energy region





Data Analysis

- **Dominant background: accidentally paired S1-S2**
  - develop a boosted decision tree (BDT)
- **Blind analysis is performed with 0.48 tonne-year data**



ROI

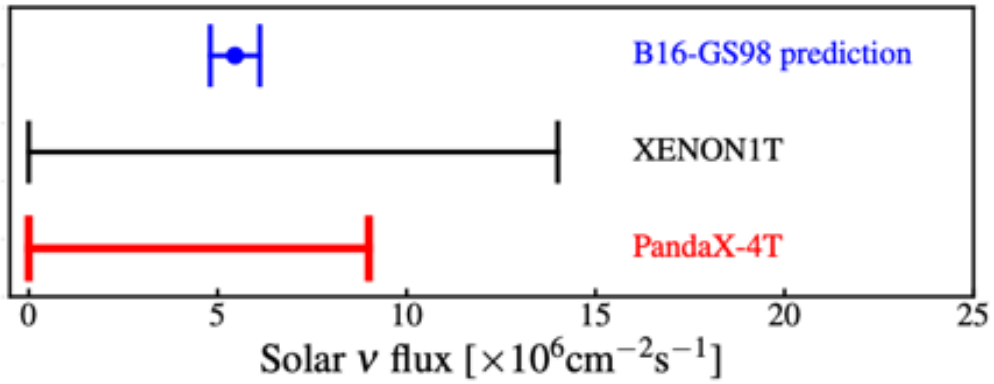
	ER+NR+AC	8B	**Total prediction**	**Unblind data**
Two Photon	62.57	2.32	**64.89**	**59**
Three Photon	0.85	0.42	**1.27**	**2**

ROI (BDT applied)

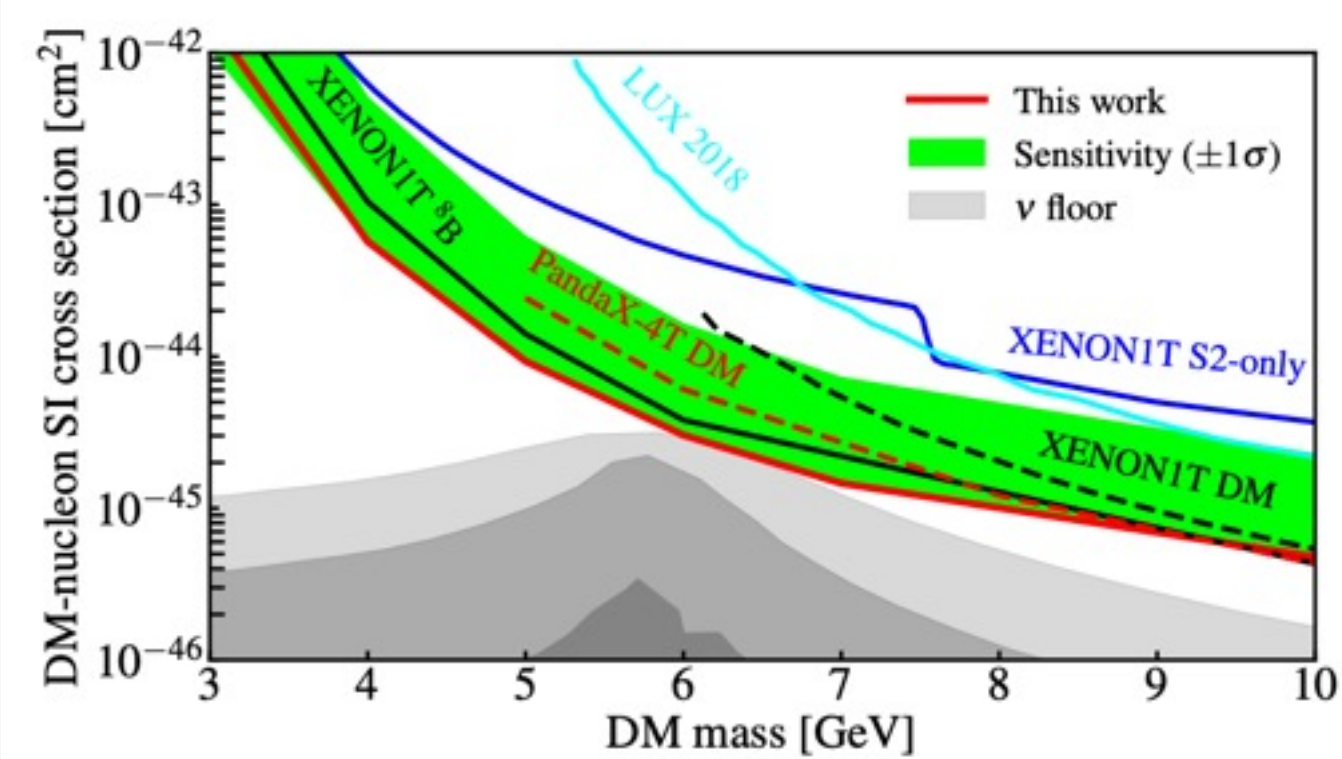
ER+NR+AC	8B	**Total prediction**	**Unblind data**
1.46	1.42	**2.88**	**1**
0.04	0.29	**0.33**	**0**

Constraints on B8 and WIMP

- **Leading constraints on B8 neutrino flux through CEvNS**
  - Into sensitivity of the “neutrino floor”. Can cast new insight on neutrino-nucleus interactions.
- **Strongest constraints on WIMP in 3-10 GeV region**



arXiv:2207.04883



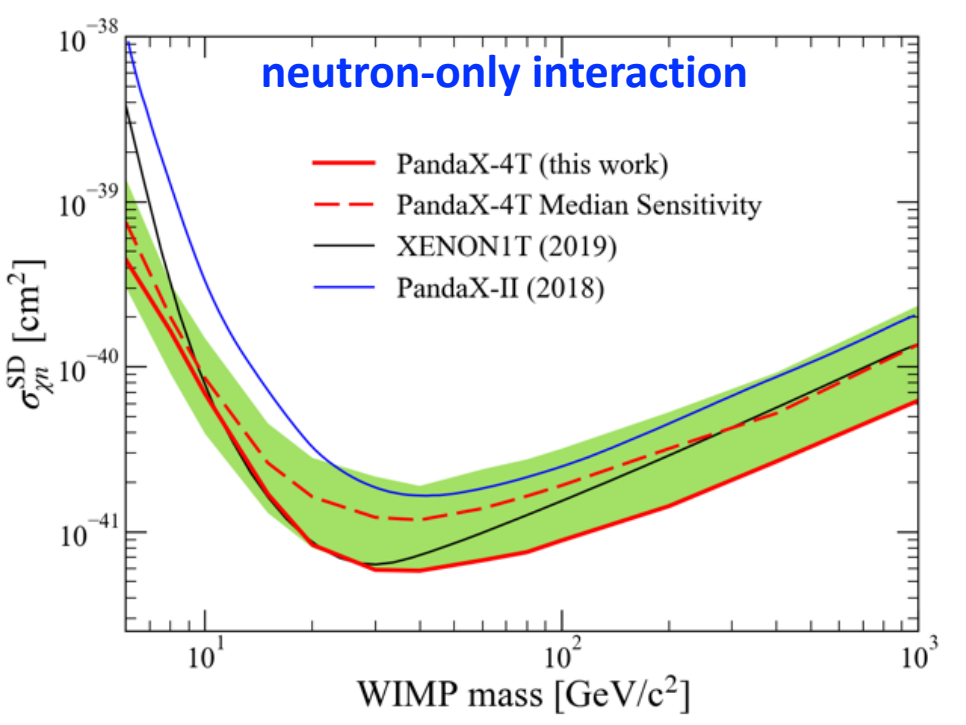
Spin-Dependent Interaction

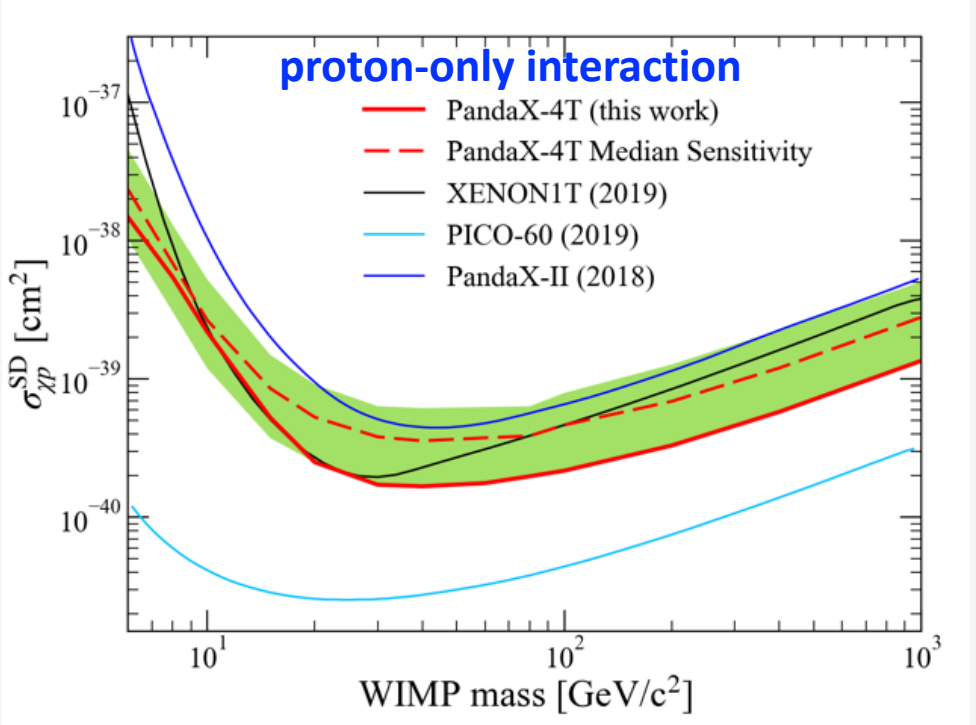
- **Scattering cross-section could be connected to the spin of nucleus**
- **Typical SD interaction is through axial-vector effective operator**

$$-\mathcal{L} = \bar{\chi}\gamma^{\mu}\gamma^{5}\chi\bar{N}\gamma_{\mu}\gamma^{5}N \rightarrow \vec{S}_{\chi} \cdot \vec{S}_{N}$$

- **^{129}Xe, ^{131}Xe with unpaired neutron**

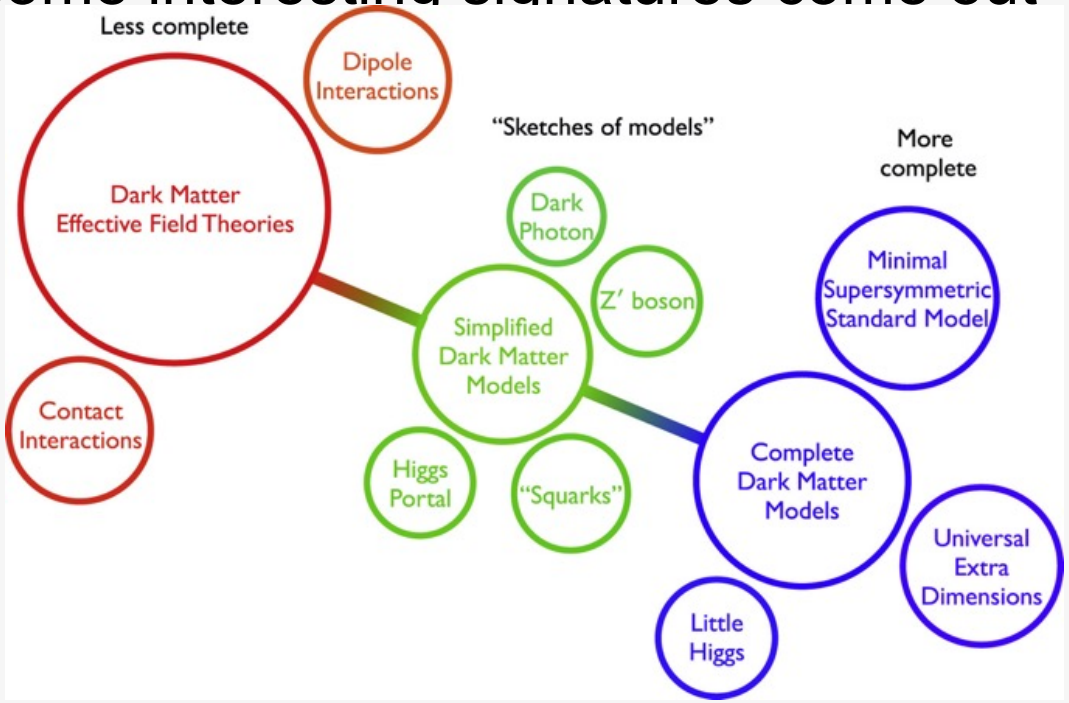
PLB 834 (2022) 137487

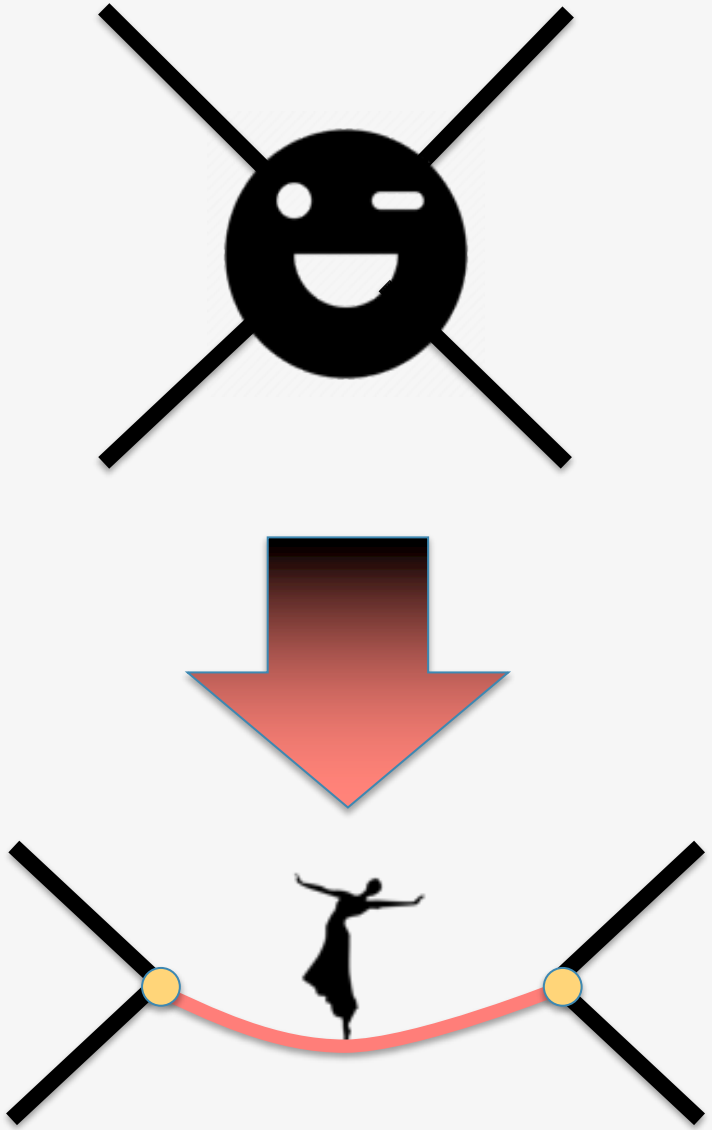




Mediator of Interaction

- **Toward simplified model or UV-complete model**
  - keeping mediator information
  - some interesting signatures come out





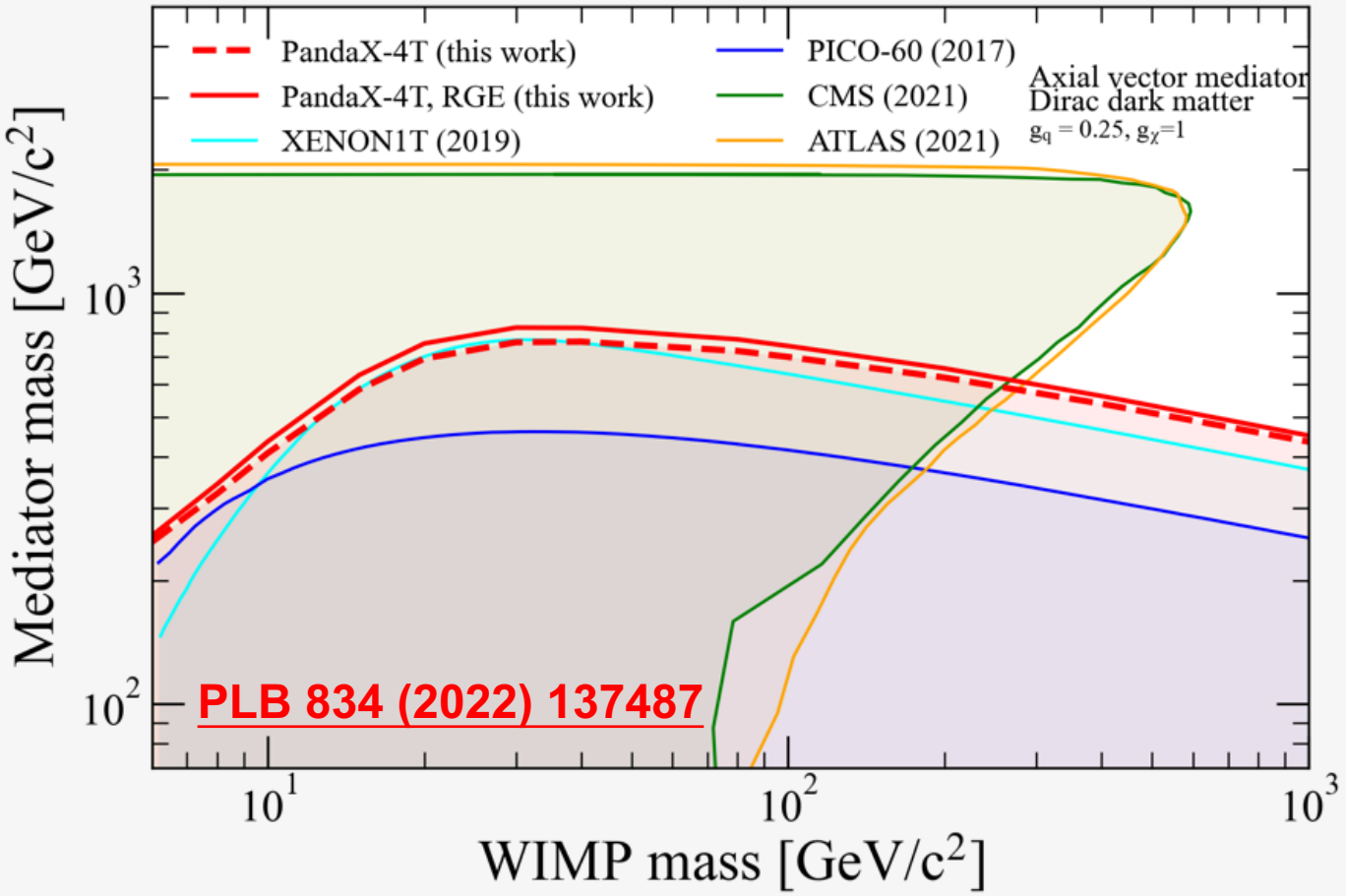
Generic Searches

Specific Searches

Phys. Dark Univ. 9-10 (2015) 8-23

Axial-vector Mediator

- **Axial-vector mediator with universal couplings to quarks**
- **Scan mediator and WIMP mass parameters**



complementary information from collider search and direct detection

Pseudoscalar Mediator

- **Tree-level process:** $\bar{\chi}\gamma^5\chi N\gamma^5 N \rightarrow -(\vec{S}_\chi \cdot \vec{q})(\vec{S}_N \cdot \vec{q})$

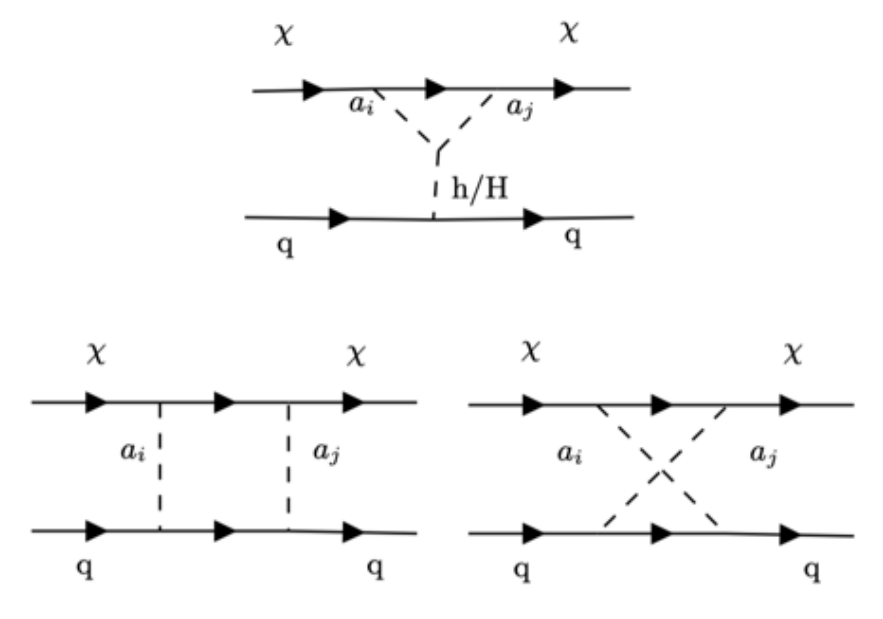
  T. Li, P. Wu 1904.03407

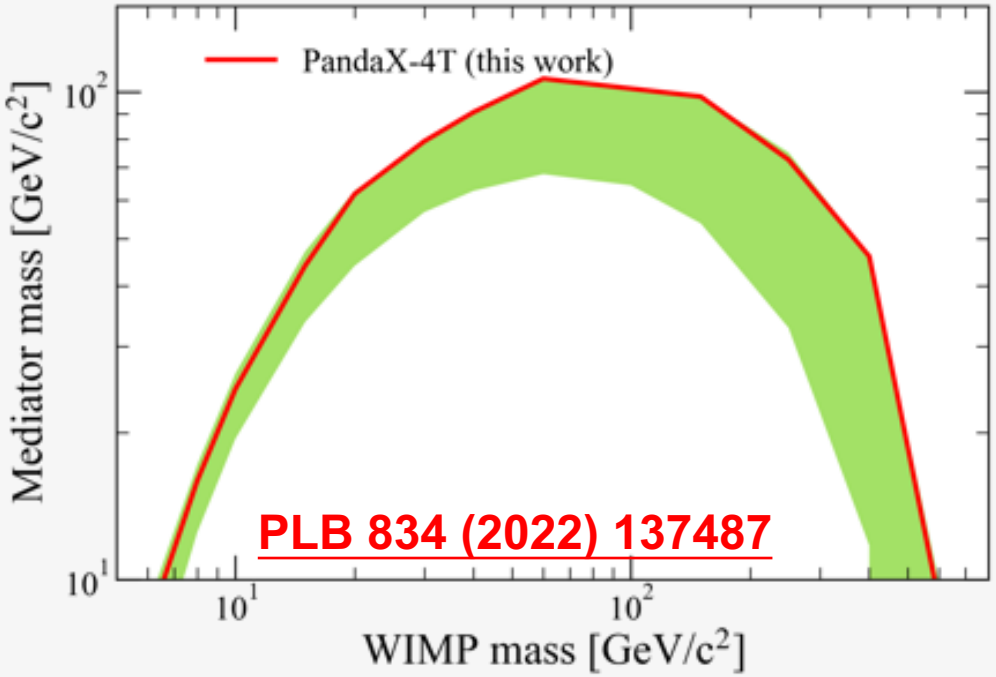
  – momentum-suppressed spin-dependent scattering cross section

  – undetectable signal rate

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

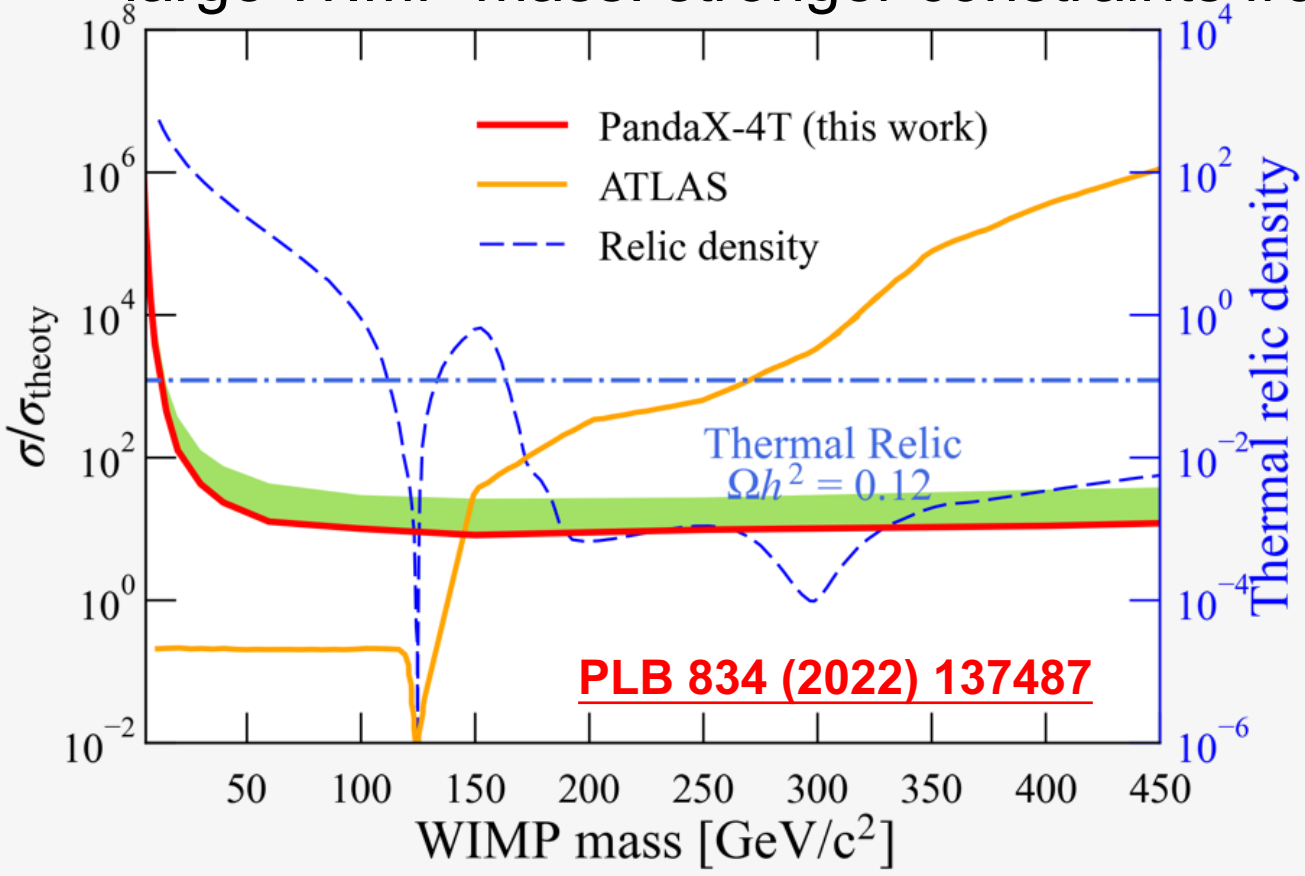
  – Example: 2HDM+a model





2HDM+a Model

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



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

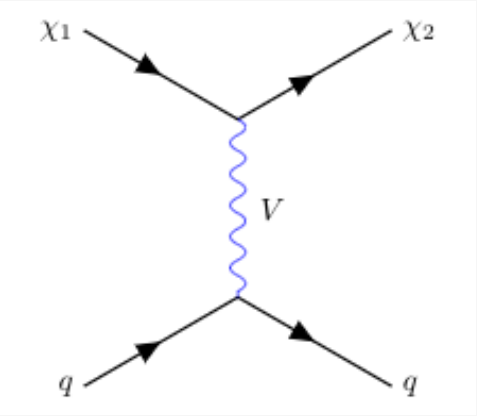
Parameters recommended by LHC DM group

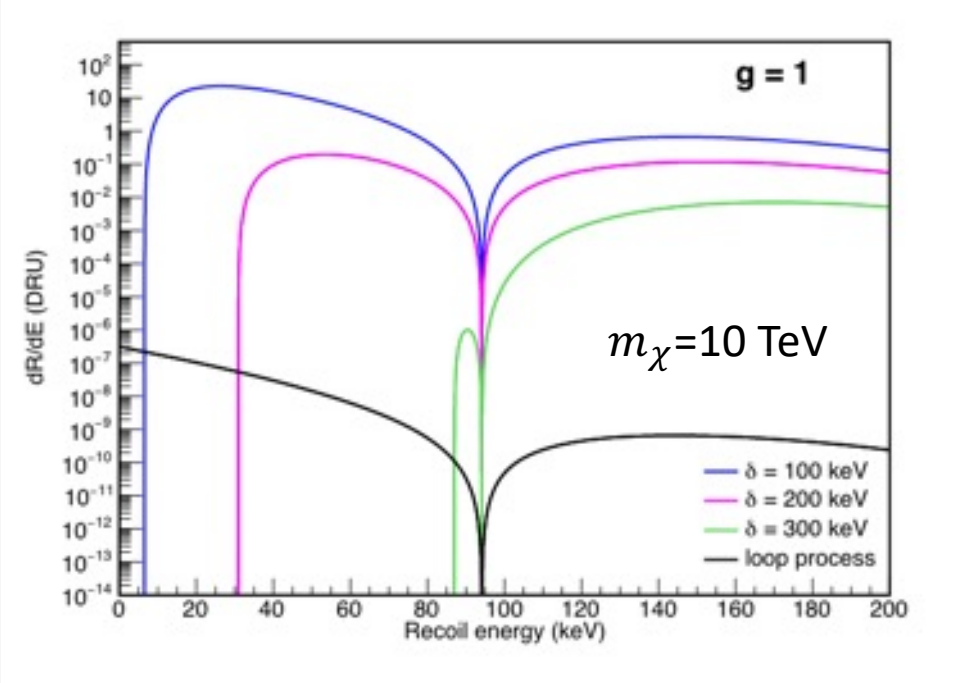
Direct detection is expected to cover the remaining parameter space in near future

Two-component Majorana DM

- **A pair of dark Majorana fermions with a large Dirac mass, split by a small Majorana mass term**
  - reduce the elastic scattering rate, avoid strong constraints from direct detection
  - keep enough annihilation rate
- **χ_1 (DM candidate) is lighter than χ_2**
  - inelastic scattering at tree-level
  - mass splitting $\delta = m_2 - m_1$
  - kinematically suppression

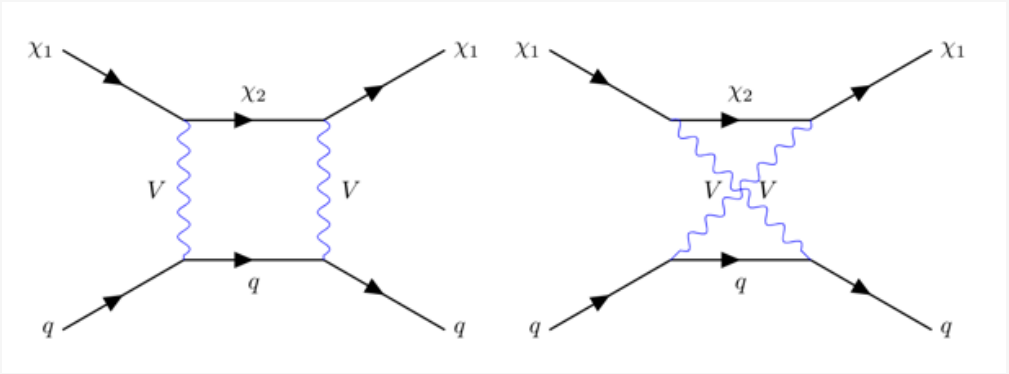
$$L_{\text{tree}} = \frac{g^2}{M^2}\bar{\chi}_1\gamma^\mu\chi_2\bar{q}\gamma_\mu q \rightarrow c_5^N\bar{\chi}_1\gamma^\mu\chi_2\bar{N}\gamma_\mu N$$



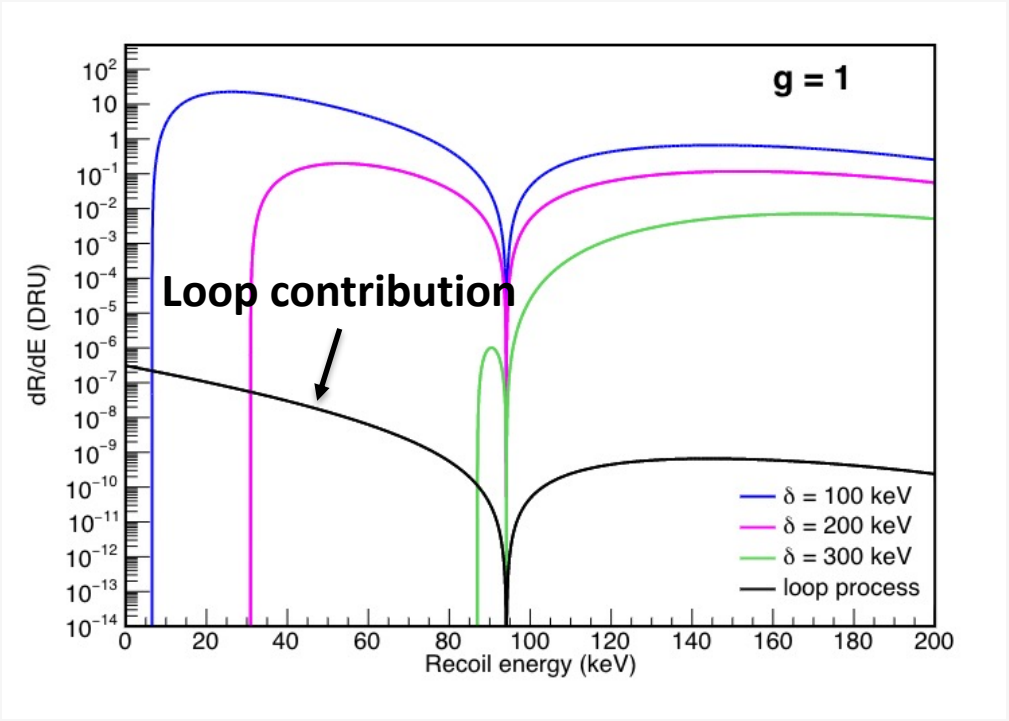


Loop Contribution

- **Box diagram**
  - elastic scattering, no kinematic suppression
  - but with mediator mass suppression
- **Complementary to tree-level especially for large mass splitting**

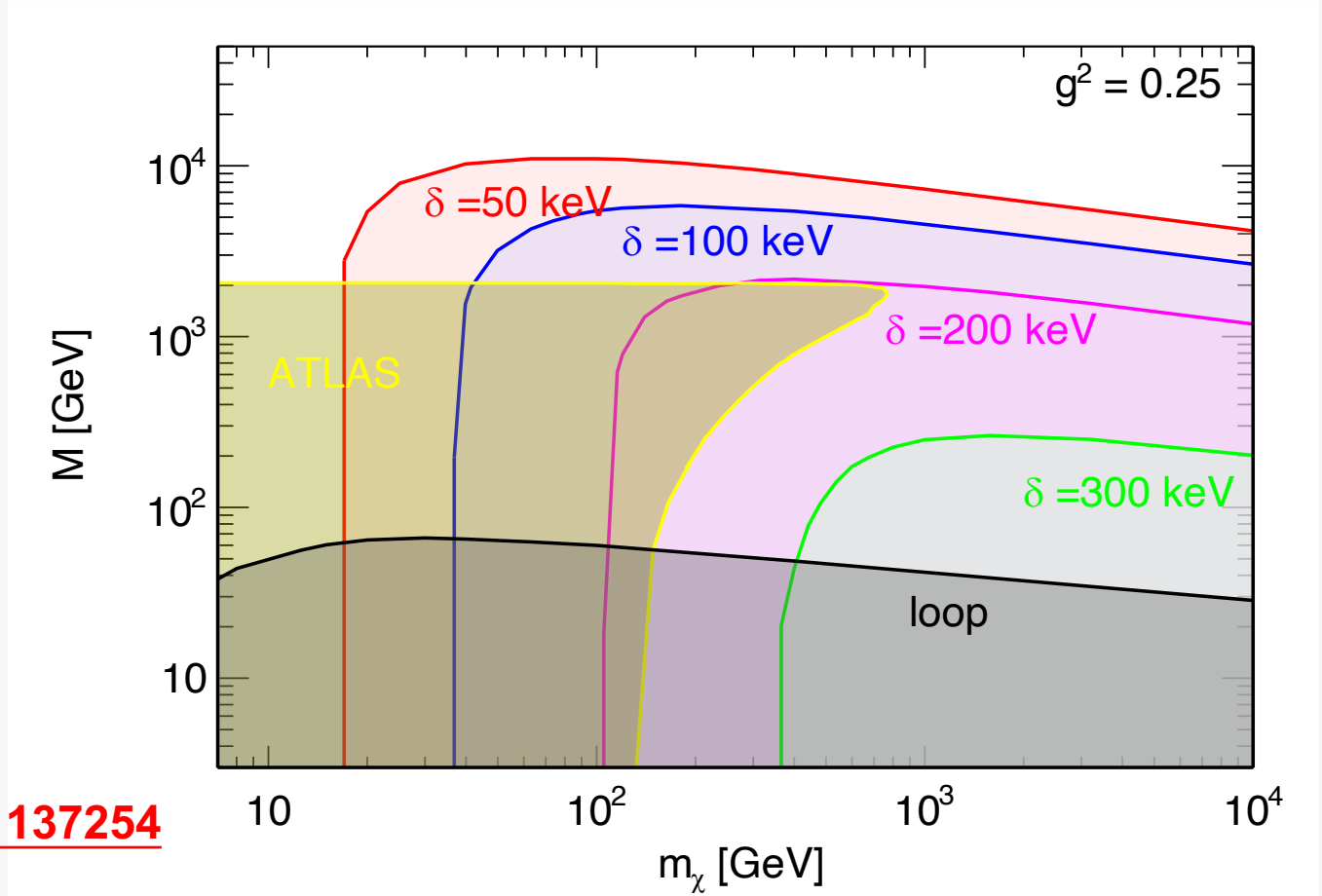


$$L_{\text{loop}} = \frac{4g^4 m_{\chi_1} m_q}{16\pi^2 M^4} F_3\left(\frac{m_{\chi_1}^2}{M^2}\right) \bar{\chi}_1 \chi_1 \bar{q} q \rightarrow c_1^N \bar{\chi}_1 \chi_1 \bar{N} N,$$



Combine Inelastic and Elastic

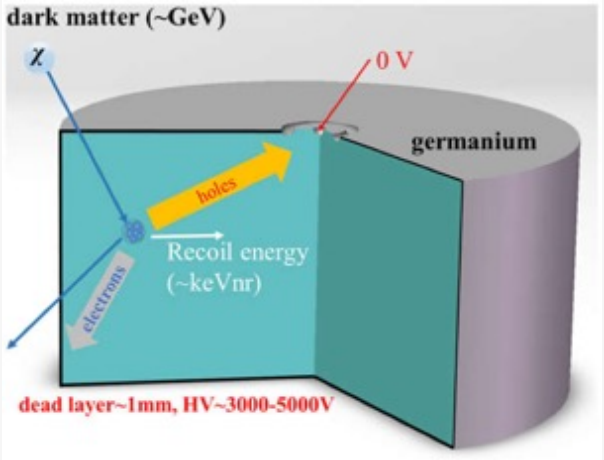
- **Loop-level: Competitive constraints for large DM mass and large mass splitting**
- **Collider constraints from ATLAS mono-jet search**

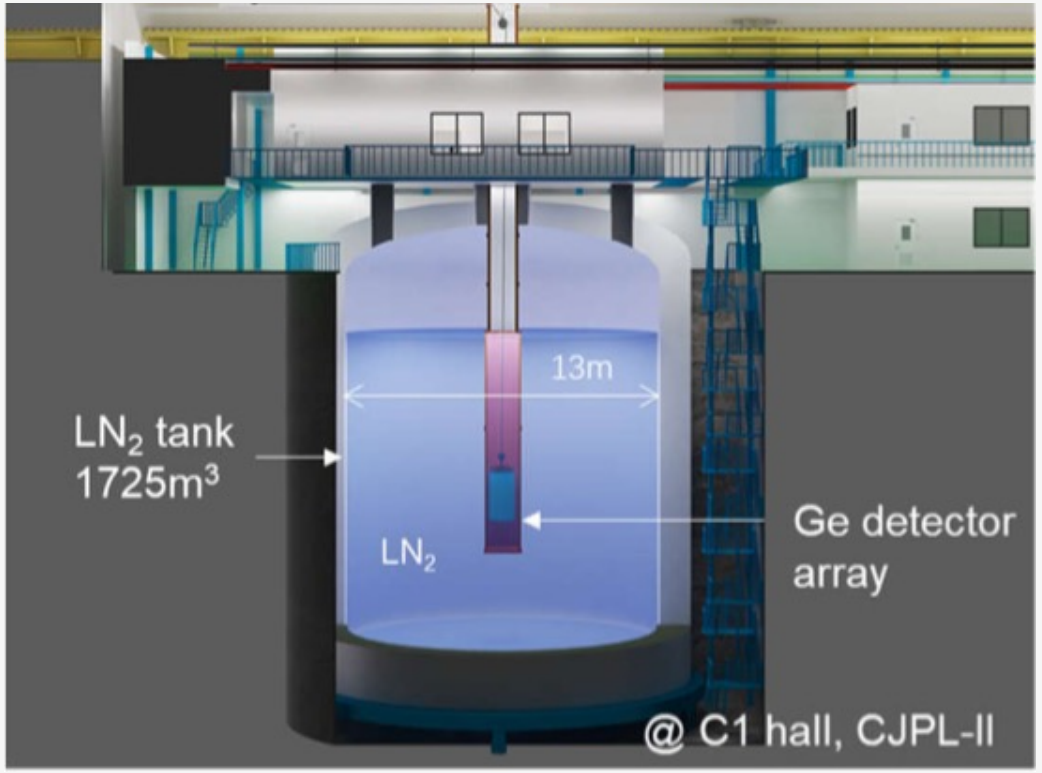


PLB 832 (2022) 137254

CDEX Experiment

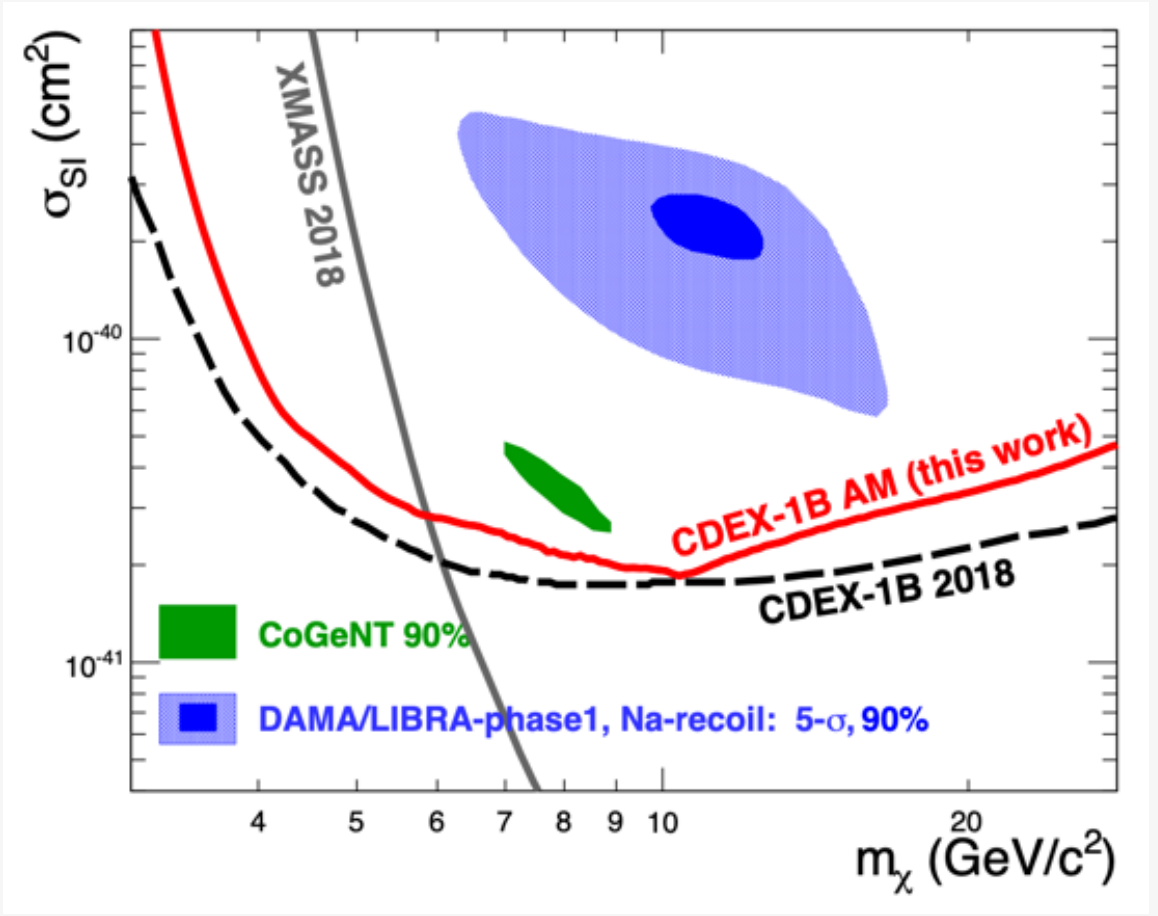
- **Point-contact Germanium detector**
- **Low threshold: sensitive to light mass DM**





Dark Matter Annual Modulation Search

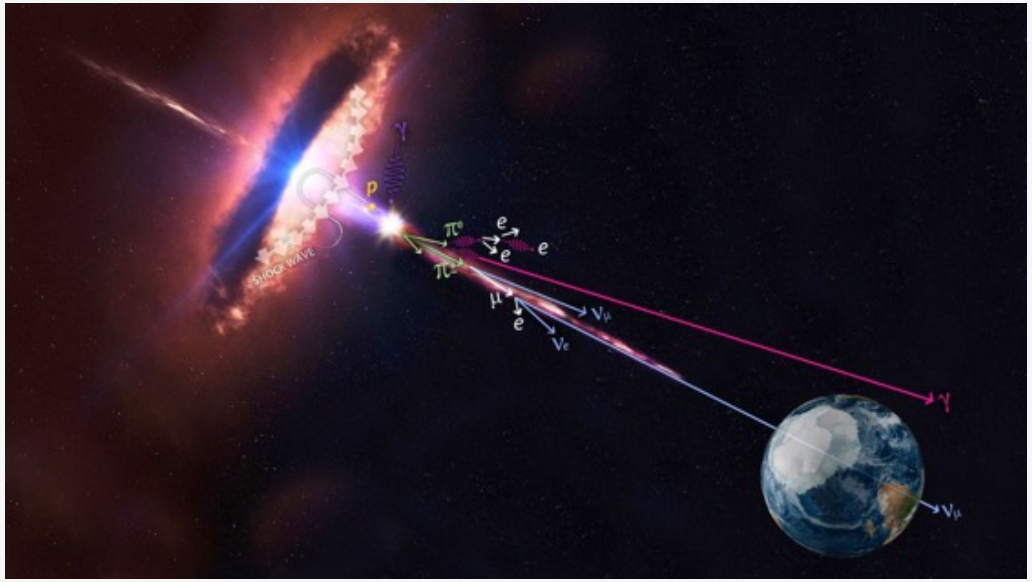
- **CDEX-1B data**
  - 4.2 years: 1107.5 kg-day exposure
  - energy threshold at 250 eV (electron equivalent)
  - Search for annual modulation signal of spin-independent WIMP-nucleon interaction
- **More stringent bounds excluding DAMA/LIBRA and CoGeNT regions**

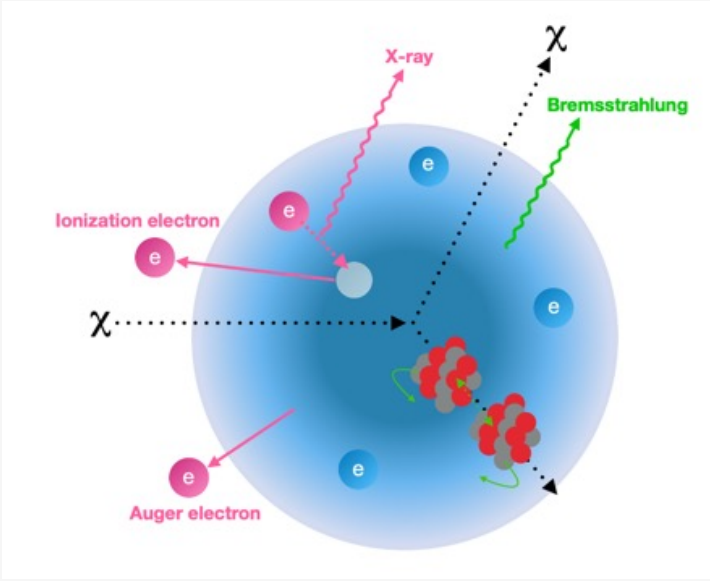


PRL 123, 221301 (2019)

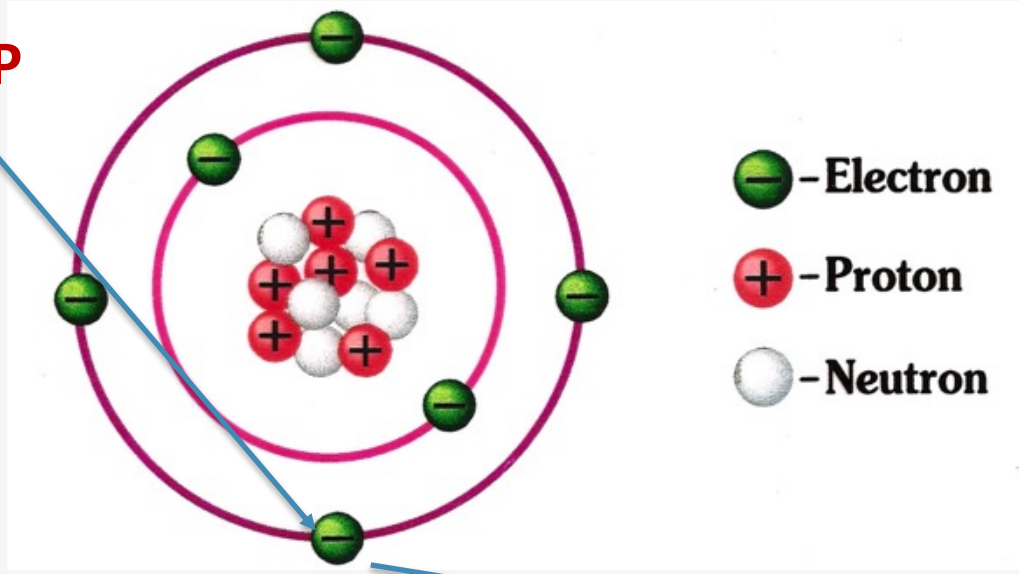
Towards sub-GeV DM

- Migdal effect
- Boosted DM
- Absorption DM
- Electron scattering





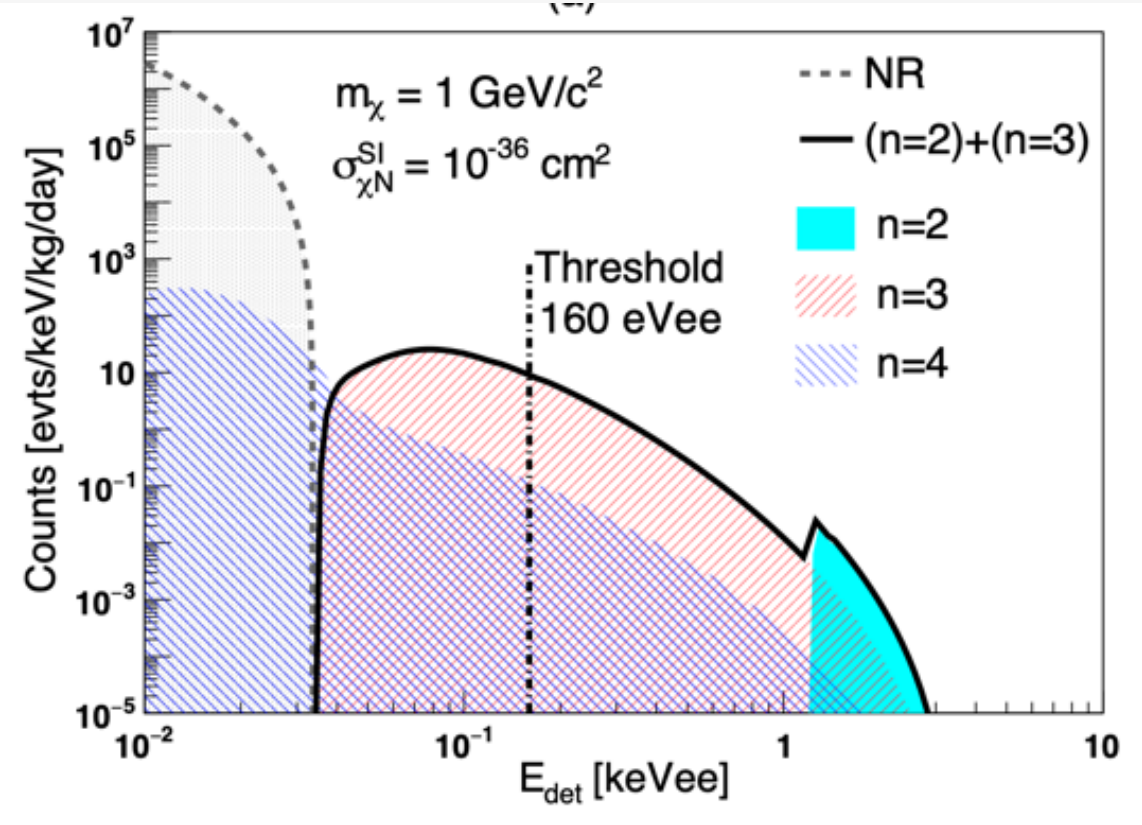
WIMP

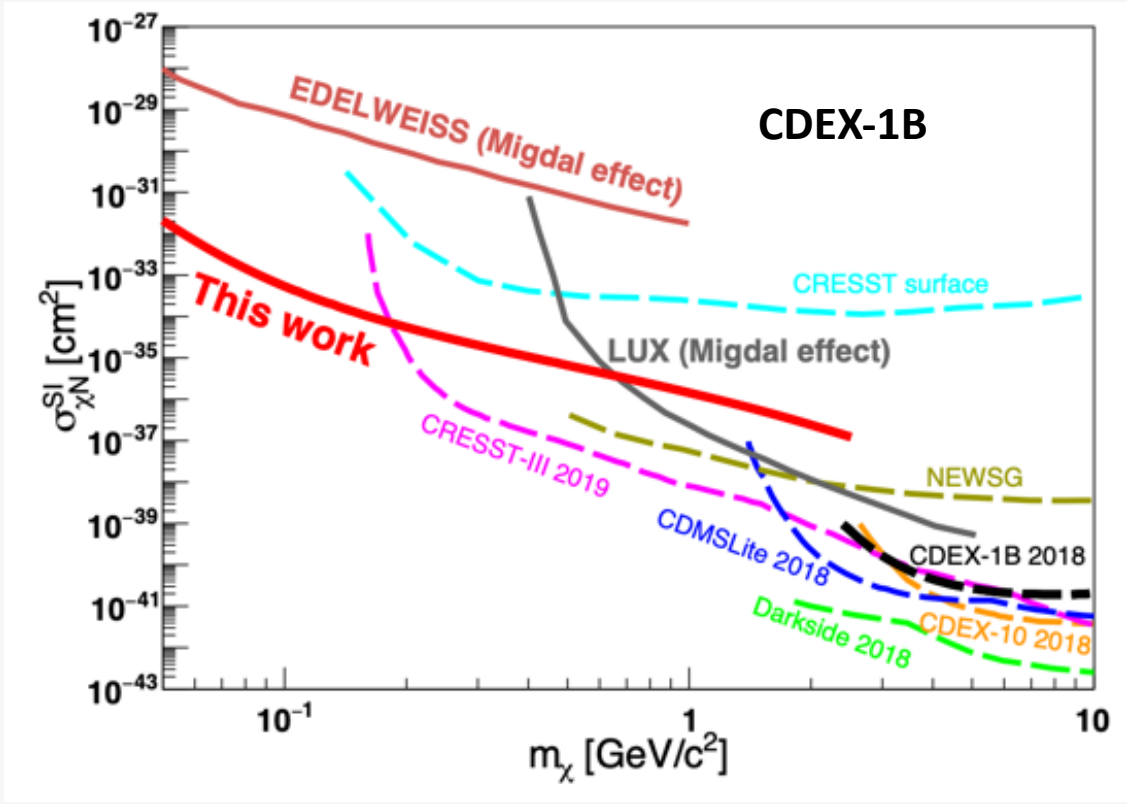


Dark Matter with Migdal Effect

- Ionized electron from inelastic DM-nucleon scattering
- CDEX-1B data: 160 eVee threshold
- Constraints derived for DM mass as low as 50 MeV

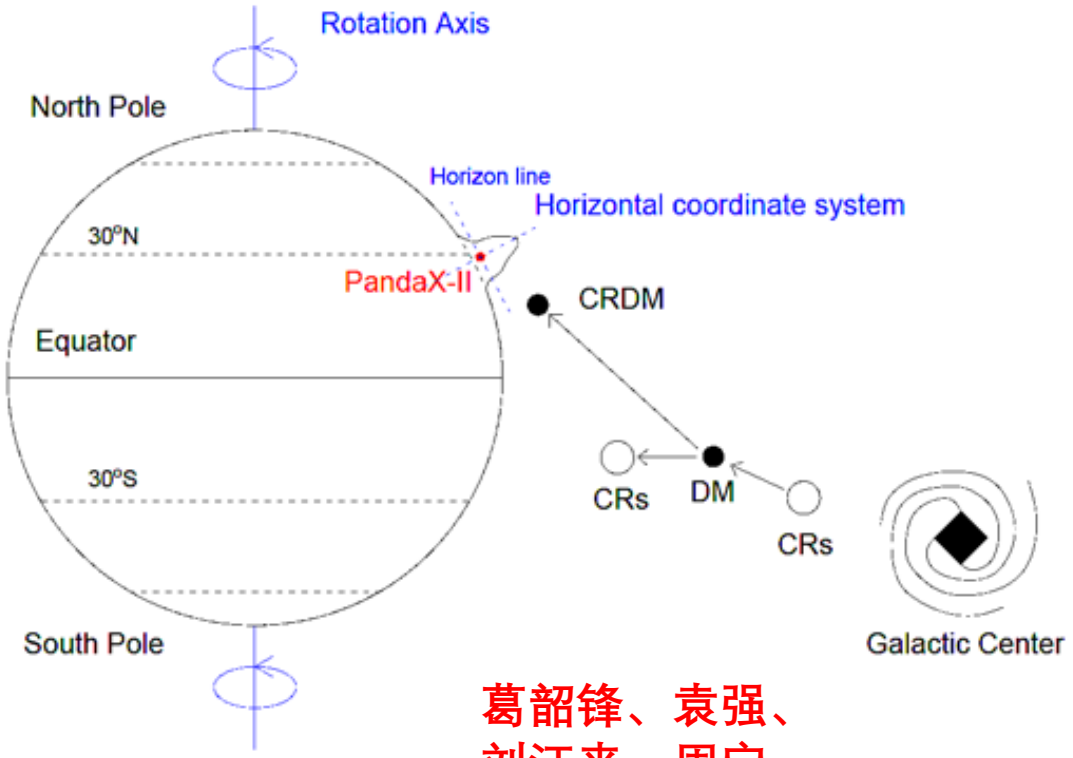
PRL 123, 161301 (2019)



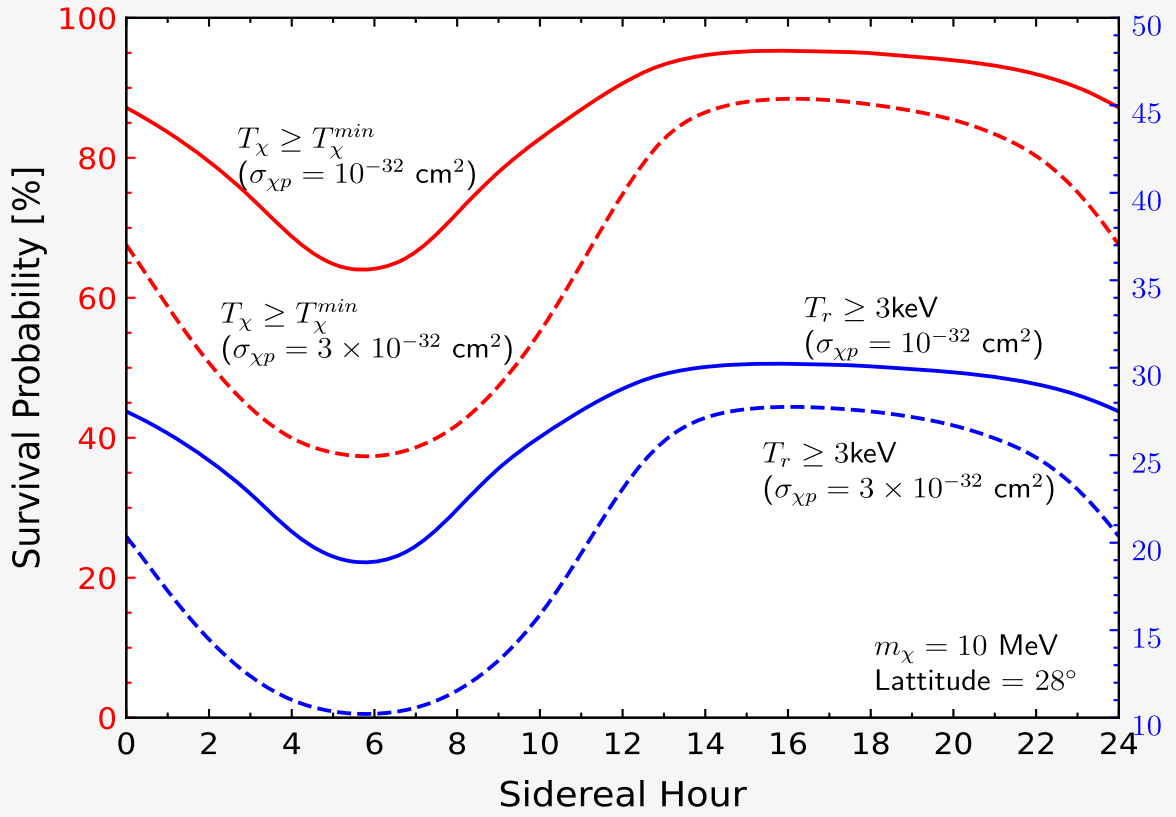


Cosmic-ray Boosted Dark Matter

- **Light DM with cosmic ray boosting**
- **New signature: diurnal modulation due to earth shielding**

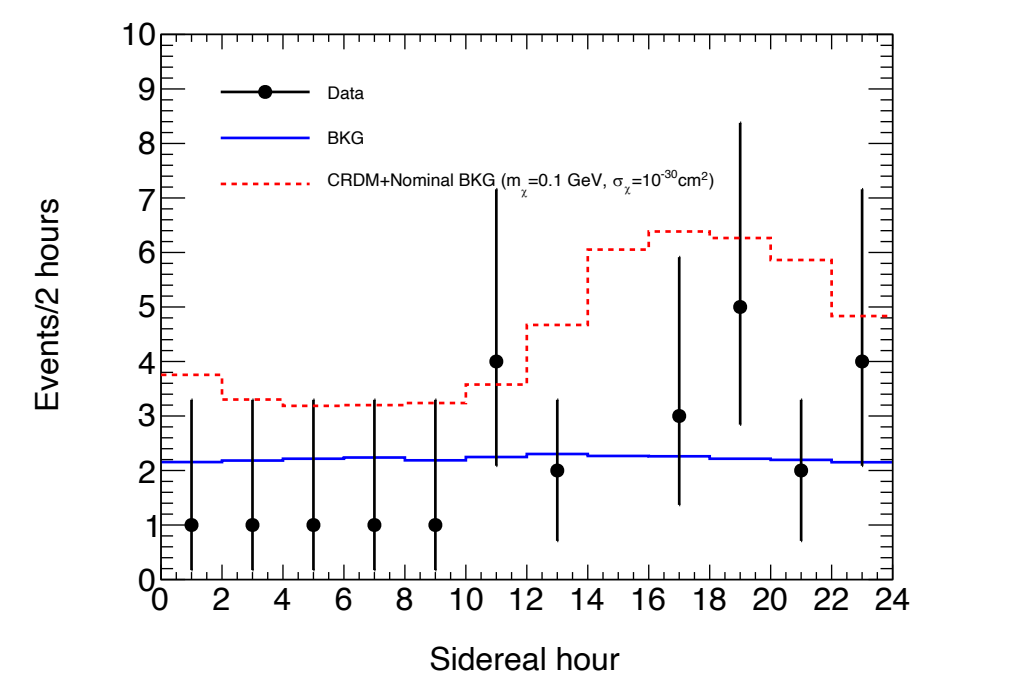


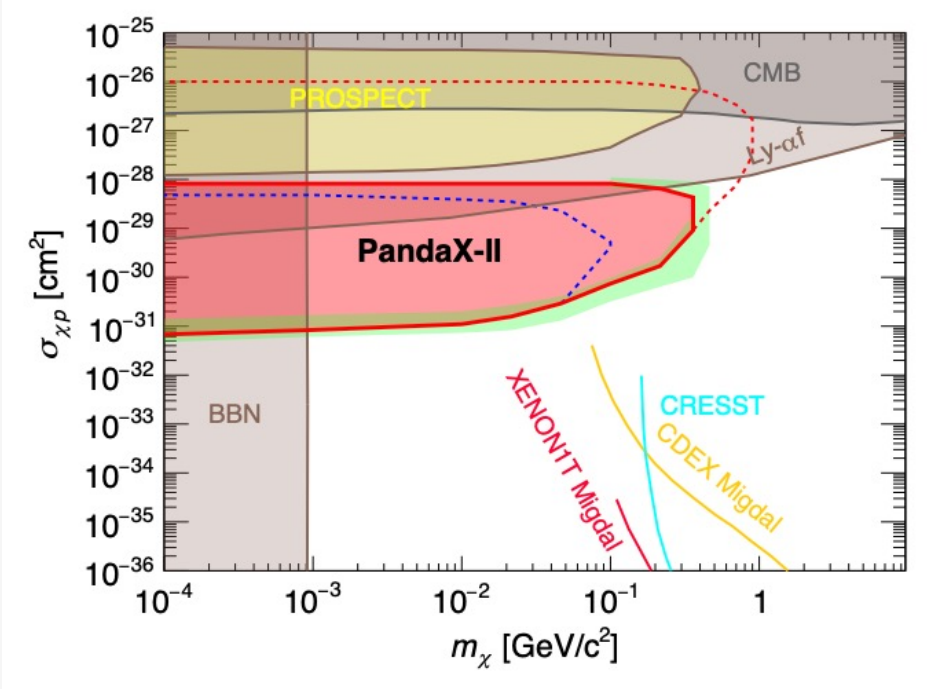
葛韶锋、袁强、
刘江来、周宁
PRL 126, 091804 (2021)



Cosmic-ray Boosted Dark Matter

- **PandaX-II data**
  - Using events below NR median: 25 events (expected 26.6 background)
- **Extend the DM search window to sub-GeV**
  - Expand to the region beyond the astrophysical and cosmological probes





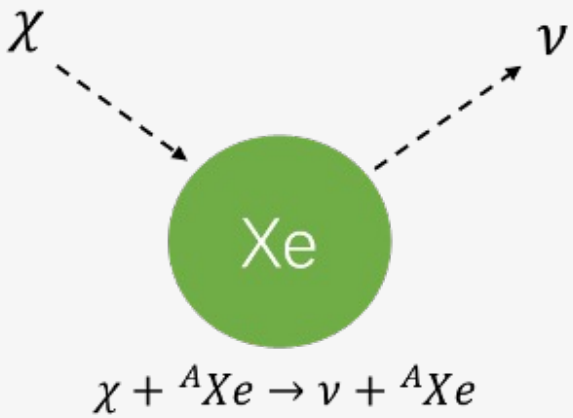
PRL 128, 171801 (2022) Editors' Suggestion

Absorption DM-nucleon Interaction

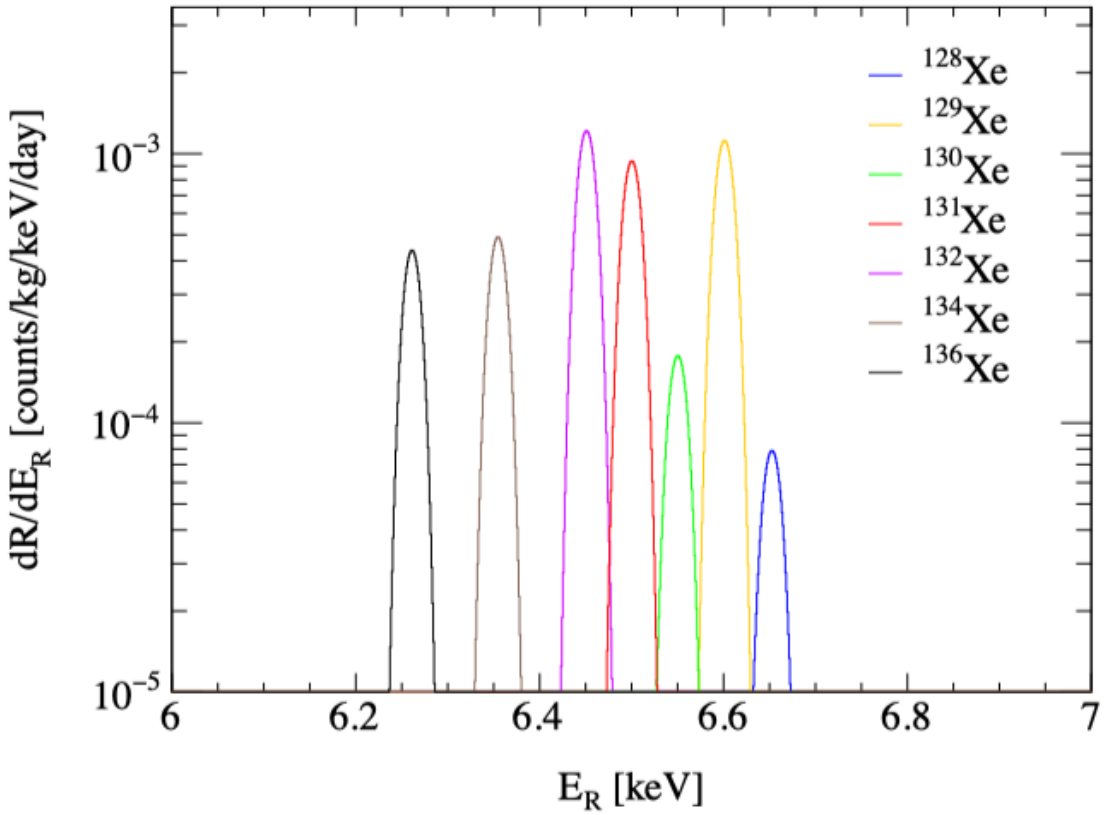
- **Dark matter is mixed with right-handed neutrino**
- **DM-nucleus interaction**
  - incoming DM absorption

$$\overset{(-)}{\chi} + {}^{A}\mathrm{Xe} \rightarrow \overset{(-)}{\nu} + {}^{A}\mathrm{Xe}$$

- **Mono-energetic recoil energy**
  - $E_R \simeq \frac{m_\chi^2}{2M_T}$



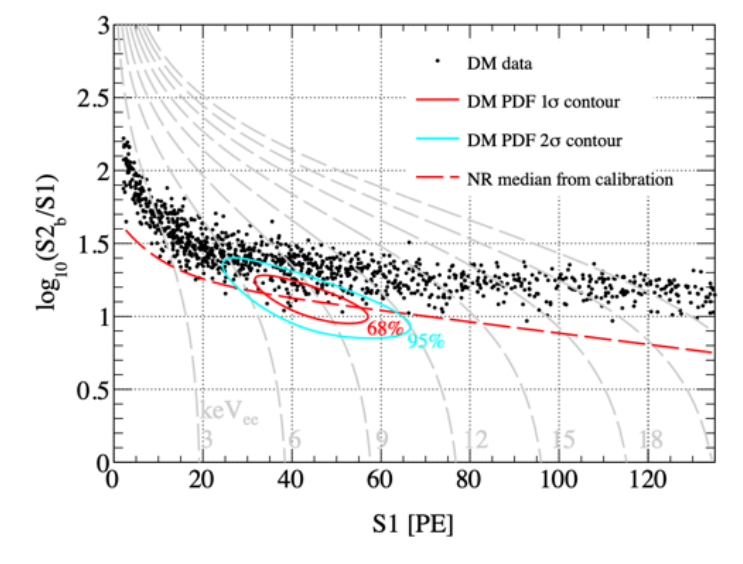
$\chi + {}^{A}Xe \rightarrow \nu + {}^{A}Xe$



J. Dror, G. Elor, R. McGehee, PRL 2020

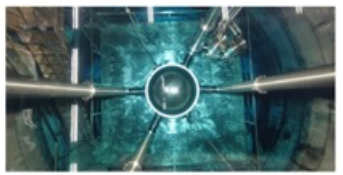
Absorption DM-nucleon Interaction

- **First mono-energetic NR signal search**



- **PandaX-4T gives extreme strong constraints on sub-GeV DM**
  - reaching 10^{-50} cm^2

PRL 129, 161803 (2022) **Editors' Suggestion**



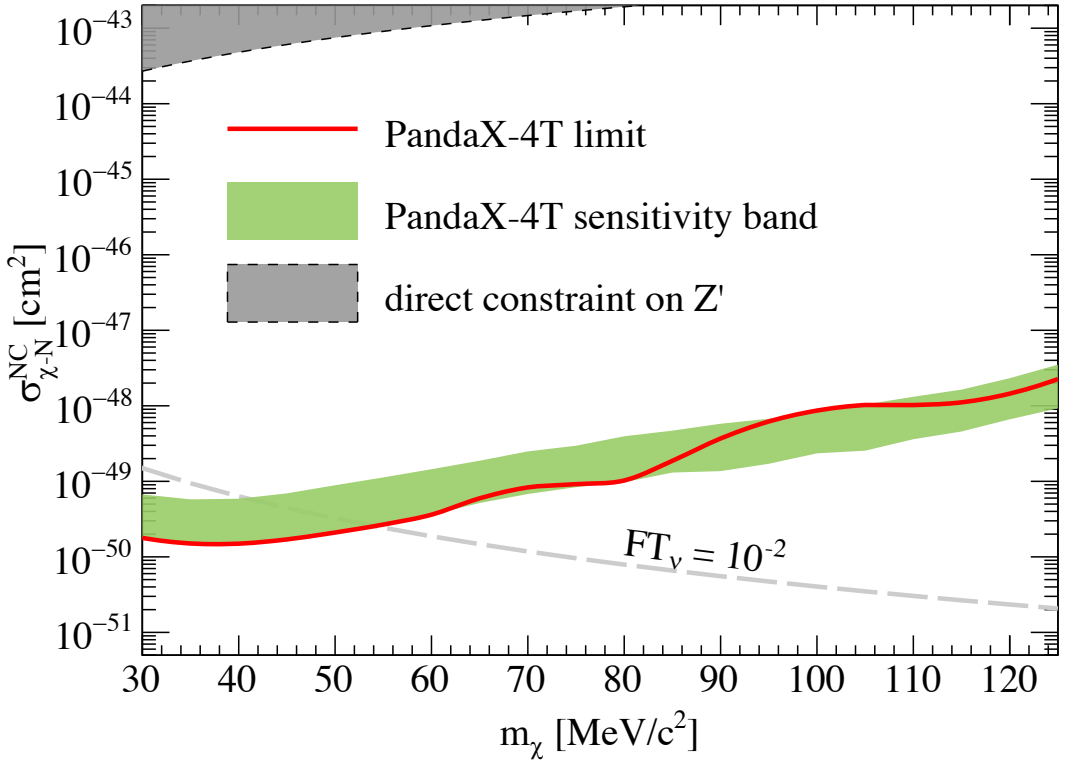
Physics NEWS AND COMMENTARY

An Absorbing Dark Matter Experiment

October 13, 2022

Researchers have analyzed the first data from a new direct-detection-by-absorption experiment for a little-studied form of dark matter known as fermionic dark matter.

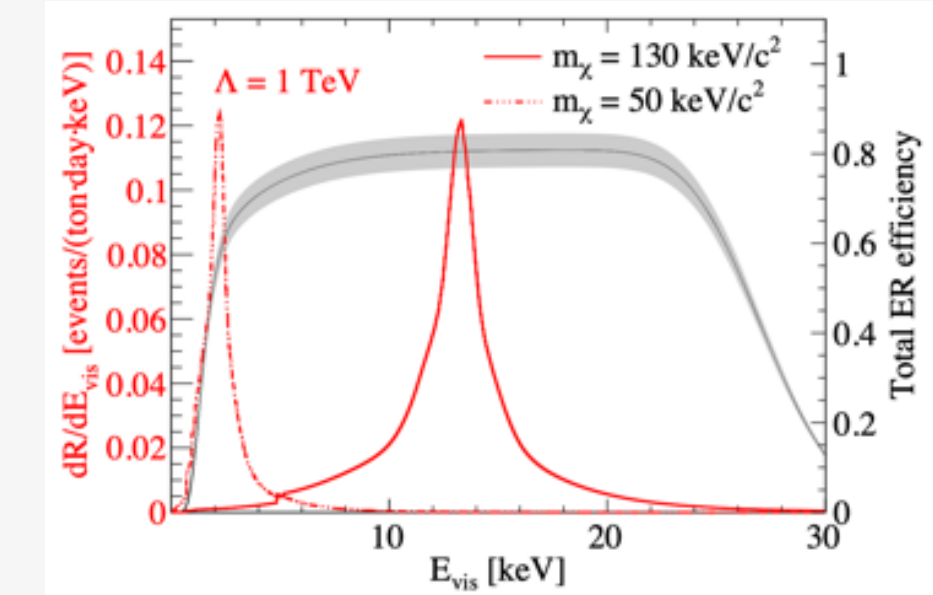
Synopsis on:
Linhui Gu *et al.* (PandaX Collaboration)
Phys. Rev. Lett. **129**, 161803 (2022)



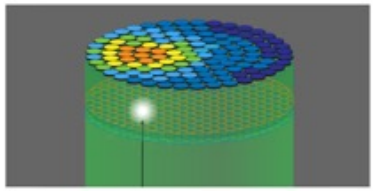
Absorption DM-electron Interaction

$\chi e \rightarrow e\nu$

- **A general Fermionic dark matter absorption on electron**
  - Similar signal as search for keV sterile neutrino DM in direct detection
- **Challenging XENON1T low energy excess**



PRL 129, 161804 (2022)



Physics NEWS AND COMMENTARY

Potential Dark Matter Signal Gives Way to New Limits

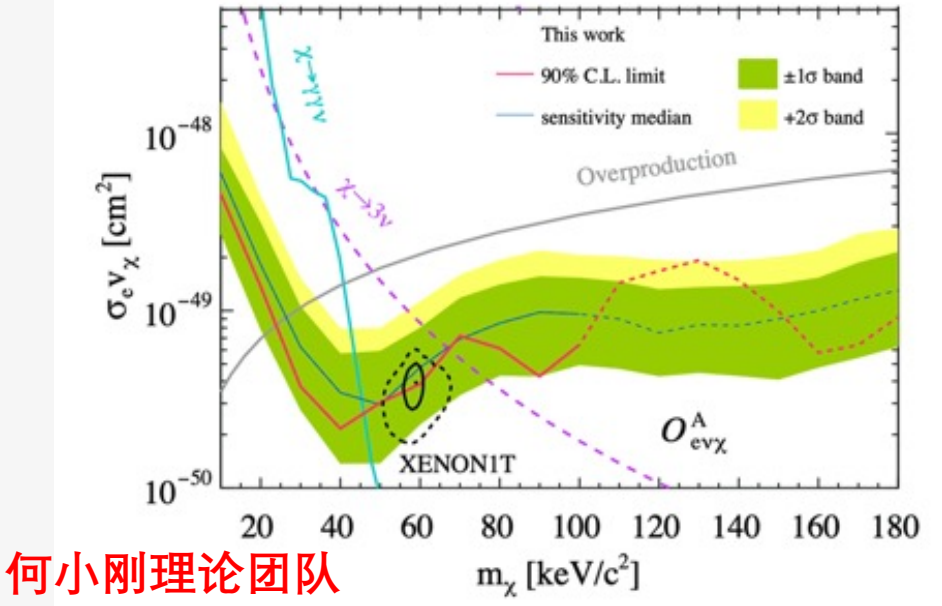
October 13, 2022

Results from two leading dark matter experiments—XENONnT and PandaX-4T—rule out an enigmatic signal detected in 2020 and set new constraints on dark matter particle candidates consisting of light fermions, respectively.

Feature on:

E. Aprile *et al.* (XENON Collaboration)
Phys. Rev. Lett. **129**, 161805 (2022)

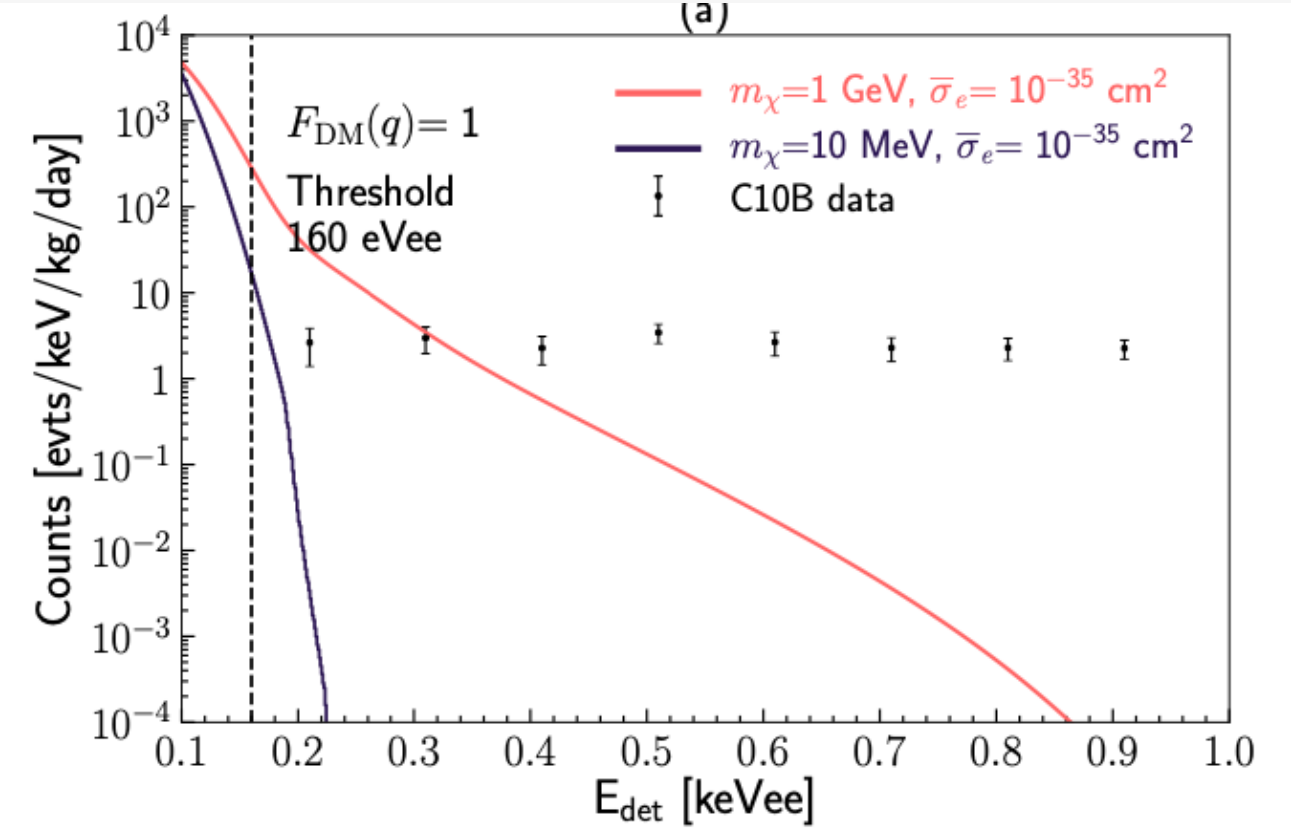
Dan Zhang *et al.* (PandaX Collaboration)
Phys. Rev. Lett. **129**, 161804 (2022)

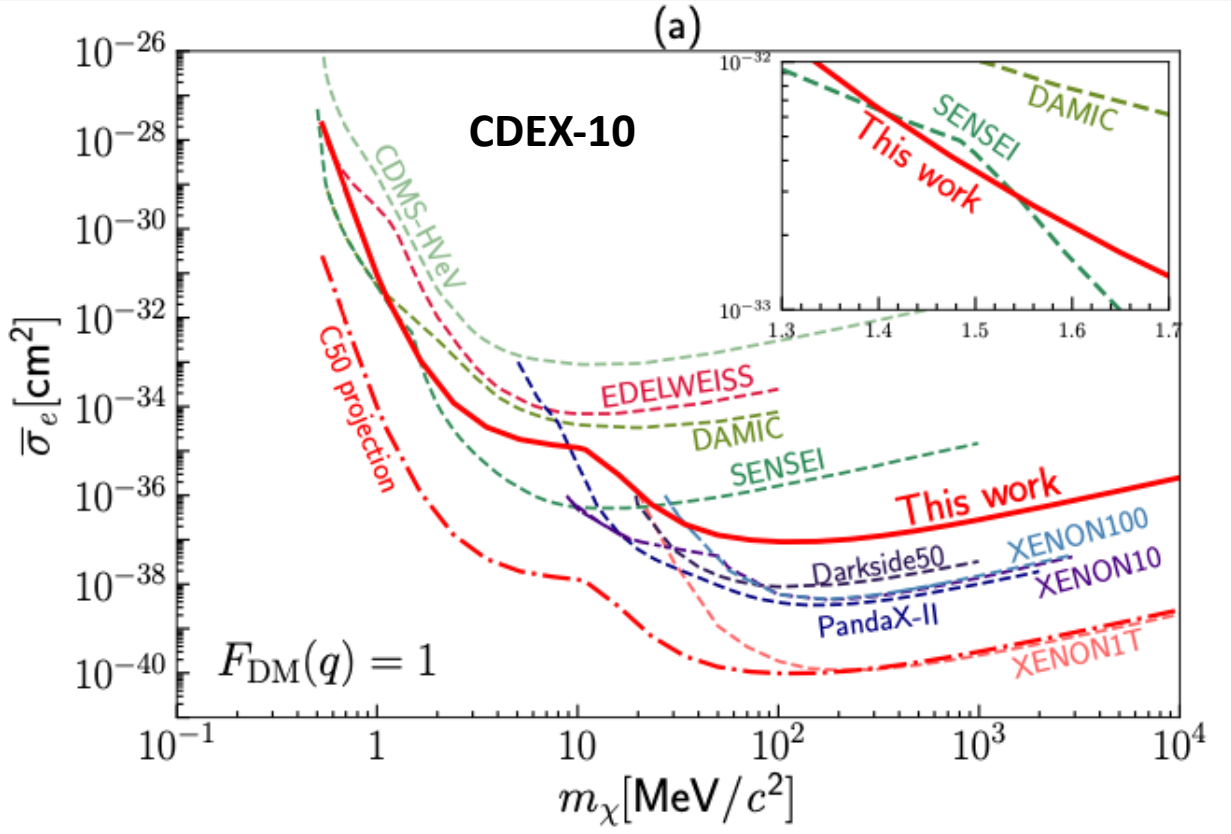


葛韶锋、何小刚理论团队

DM-electron Scattering

- **CDEX-10: 205.4 kg·day**
  - gives the most stringent DM-e cross-section limit to date amongst experiments utilizing solid-state detectors for DM mass larger than 20 MeV

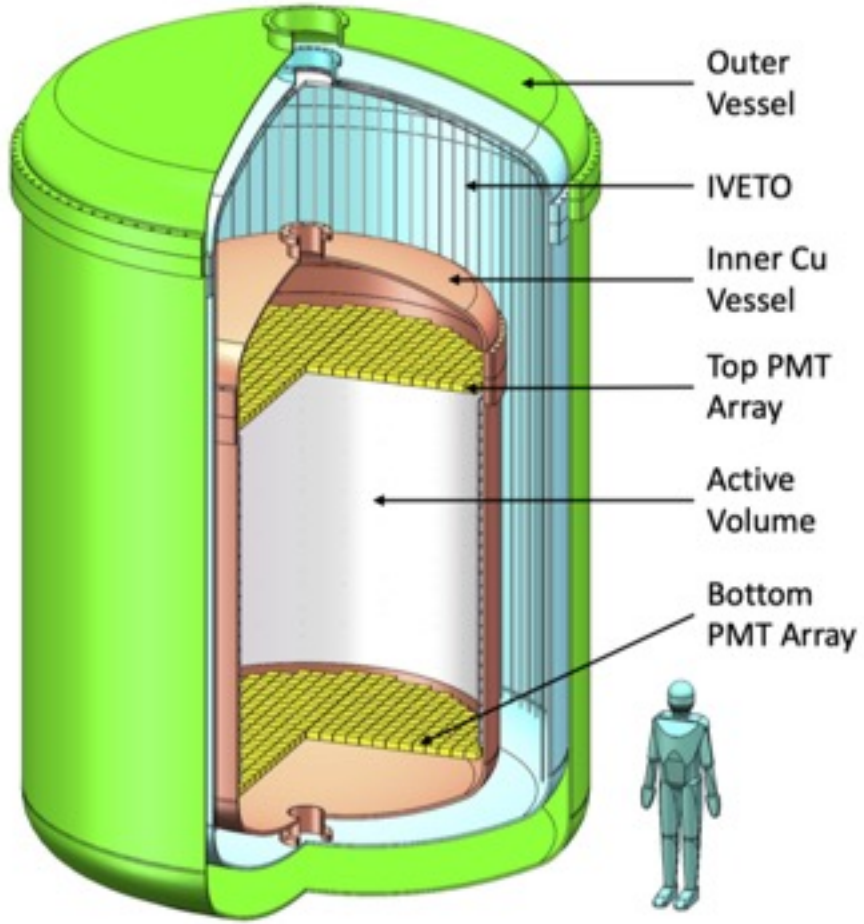


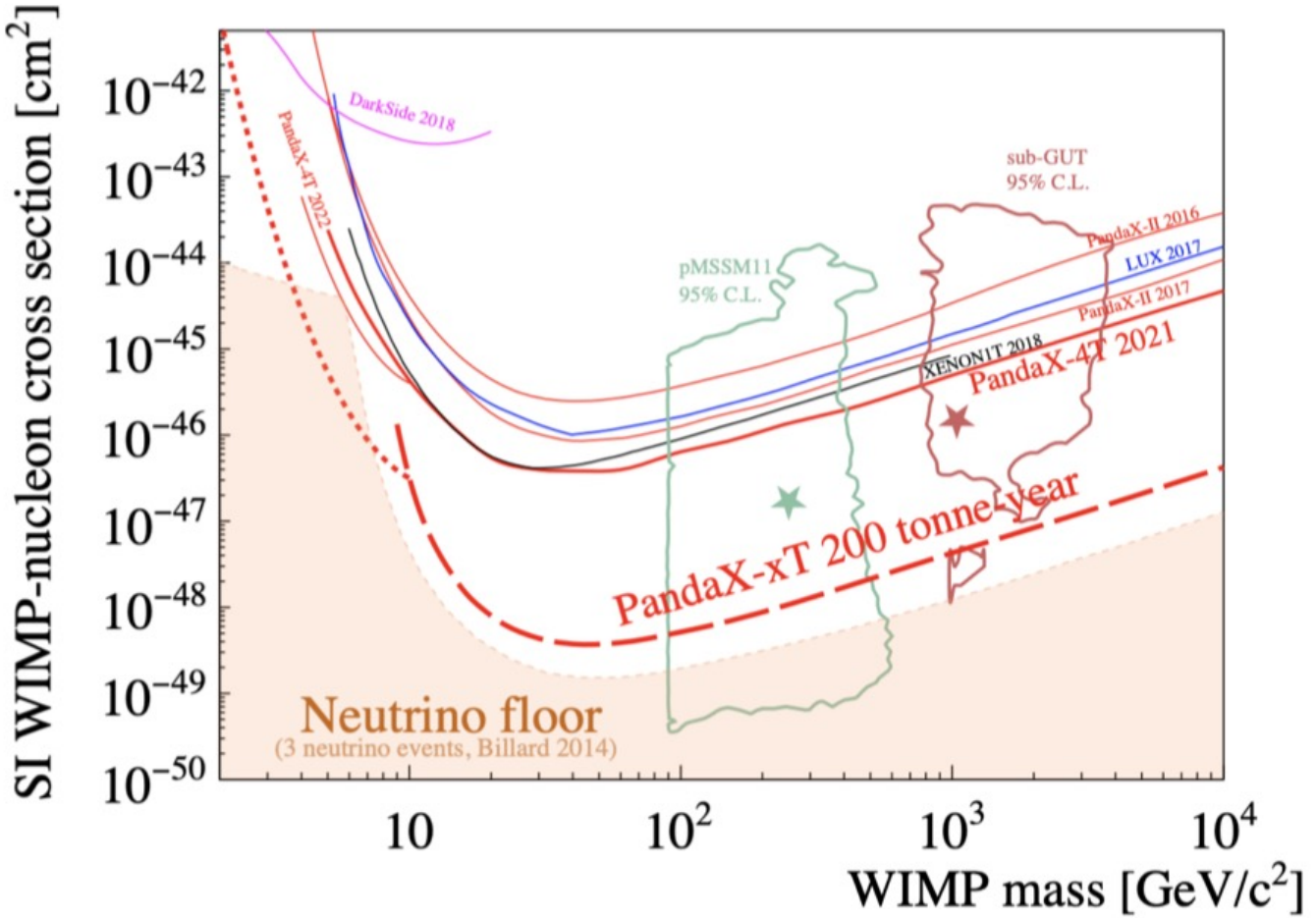


arXiv: 2206.04128

Future Plan: PandaX

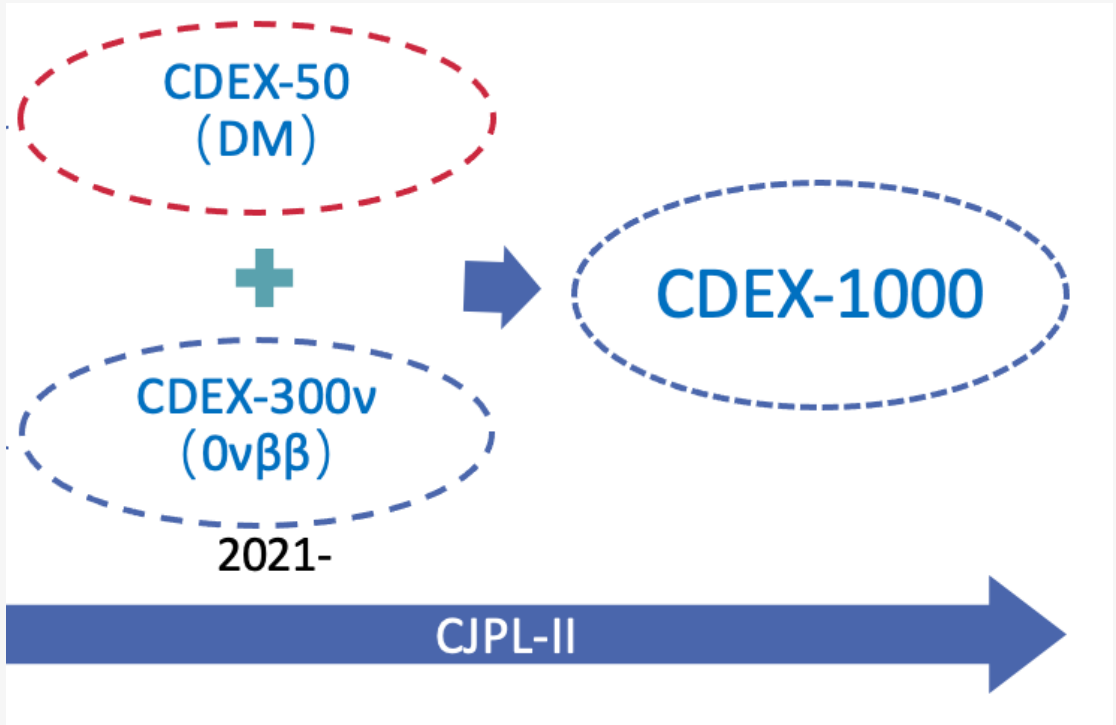
- **PandaX-xT: “ultimate” liquid xenon experiment**
  - Towards the neutrino floor

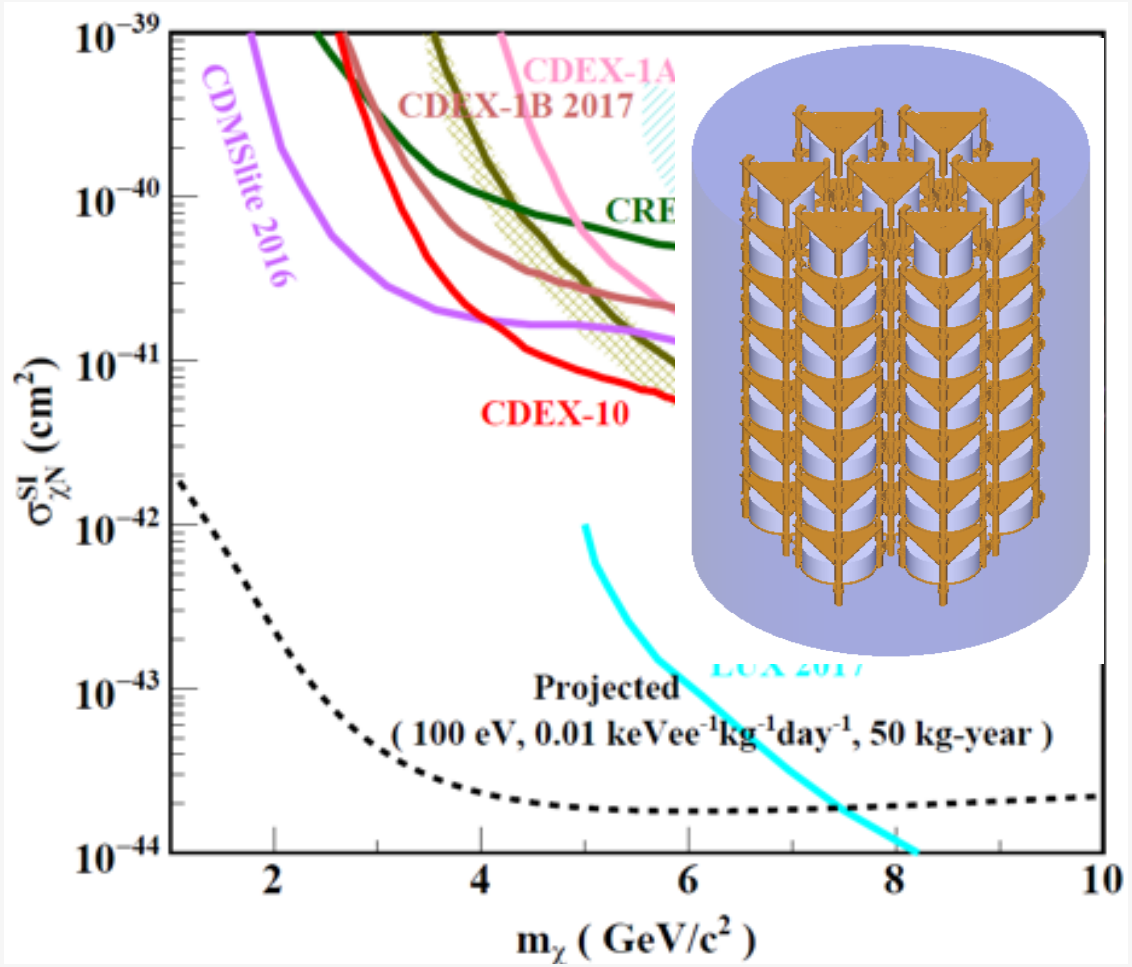




Future Plan: CDEX

- **From CDEX-50 to CDEX-1000**
  - CDEX-50: 50kg, SI sensitivity reaching 10^{-44} cm^2





Summary

- Dark matter detection plays a key role in new physics search.
- China teams keep producing world-leading results
- Active communication among theorists and experimentalists
- Expecting more results at CJPL

谢谢！