上海交通大學
SHANGHAI JIAO TONG UNIVERSITY

PANDA X

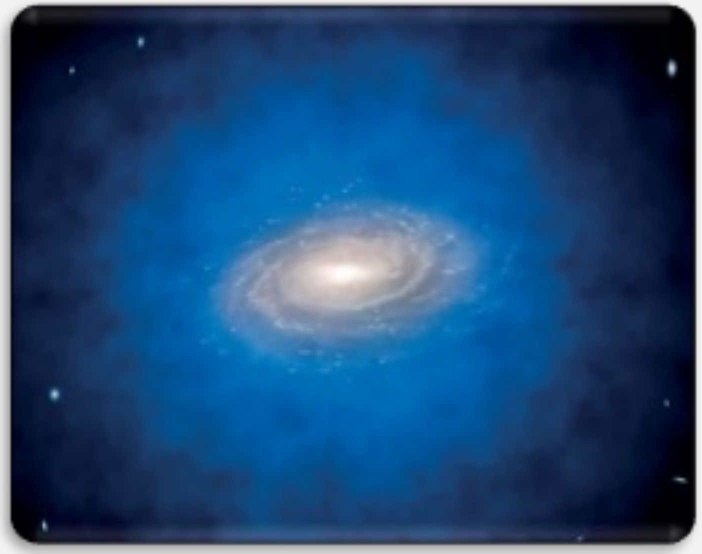
Dark Matter Searches @ PandaX

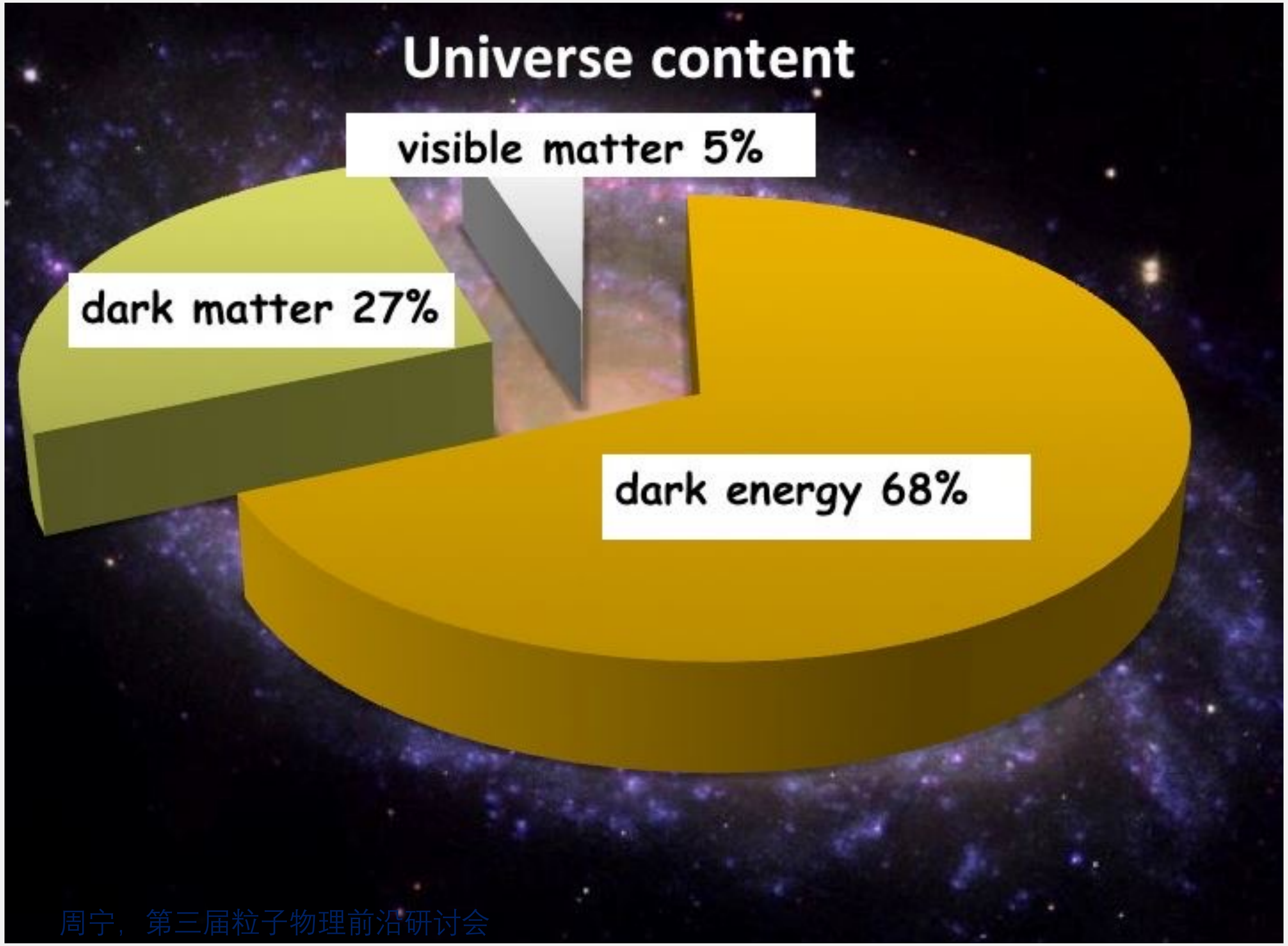
周宁(上海交通大学)

第三届粒子物理前沿研讨会
2022-07-23 中山大学

Dark Matter

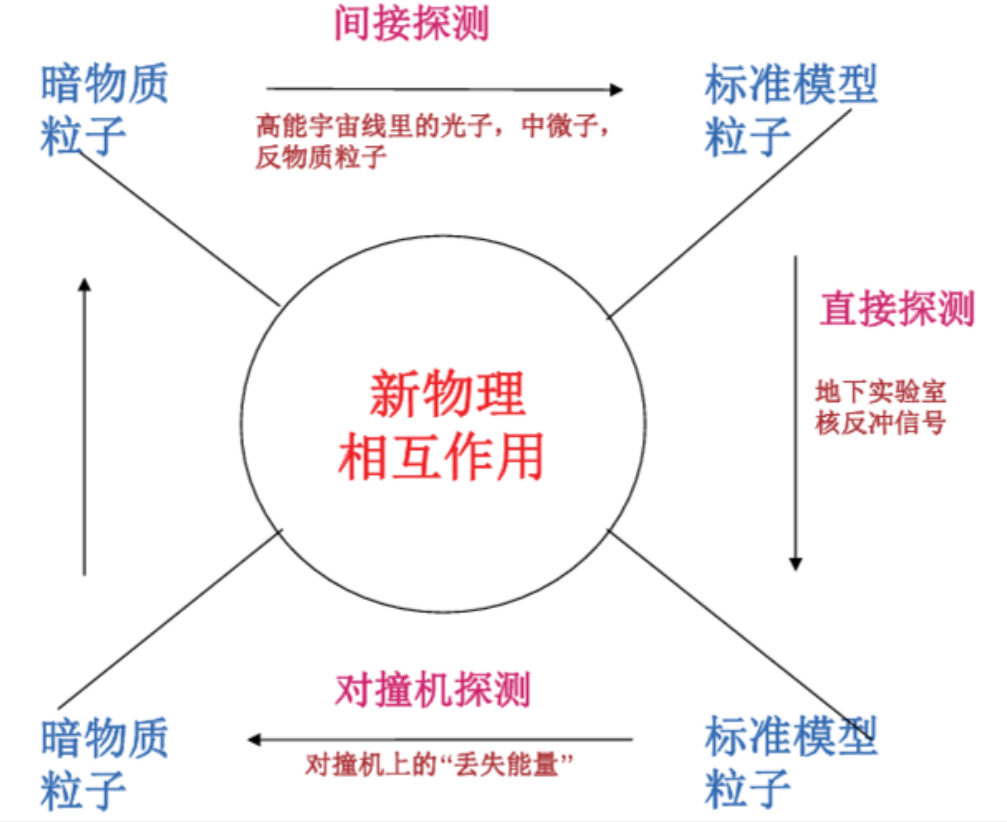
- Strong evidences for the existence of dark matter
- The nature of dark matter is unknown

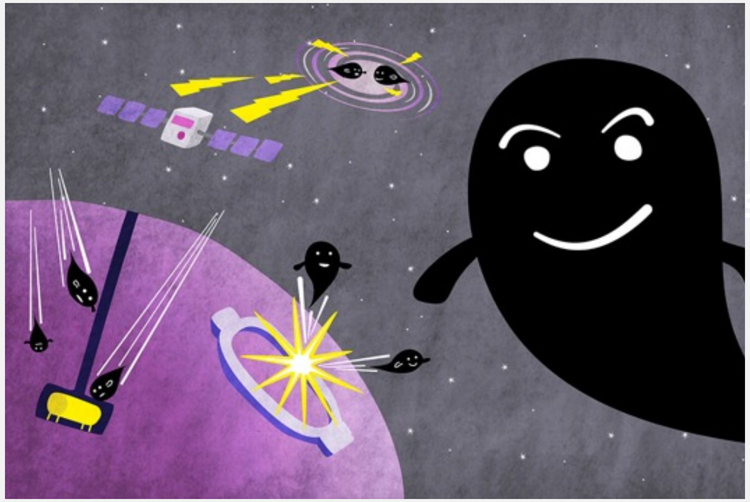


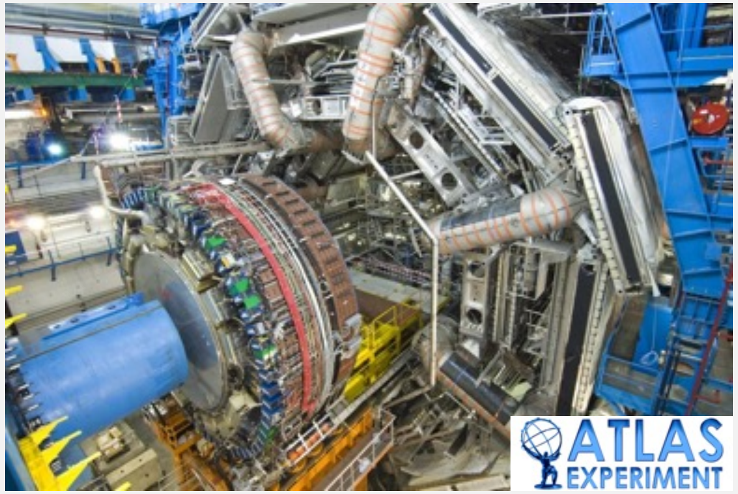


Dark Matter Detection

- General approaches
  - direct detection
  - indirect detection
  - collider search

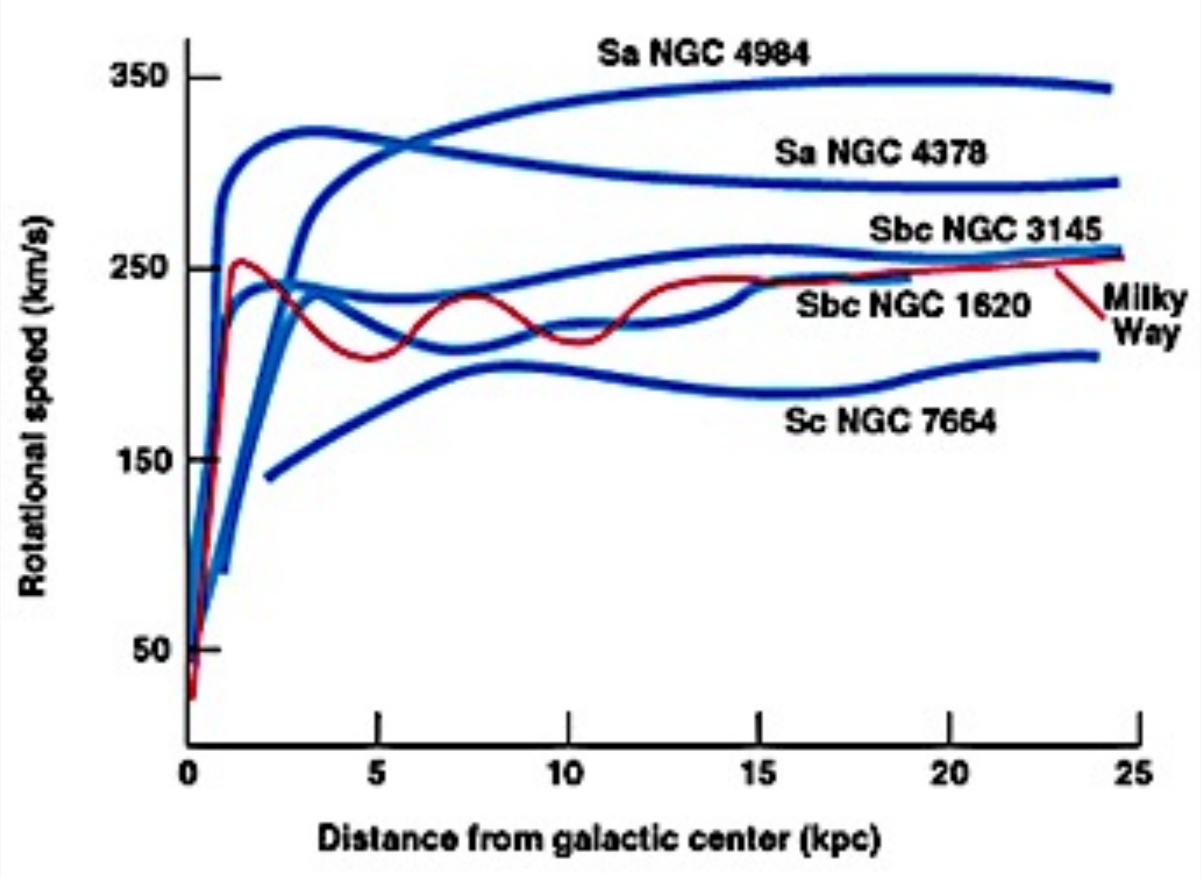


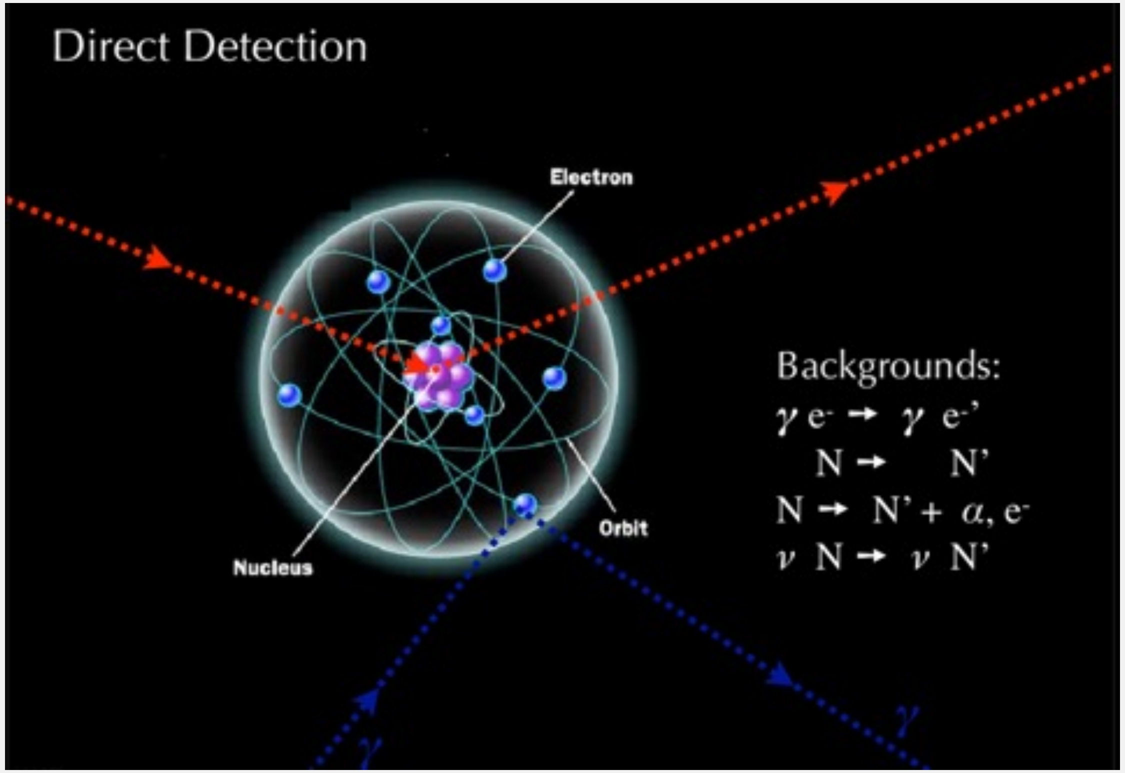




Direct Detection

- Near the Solar system，dark matter density 0.3 GeV/cm^3
  - Every second, 100k dark matter particles (100 GeV/c^2) pass through 1 cm^2
- Incoming DM scatters with target atoms

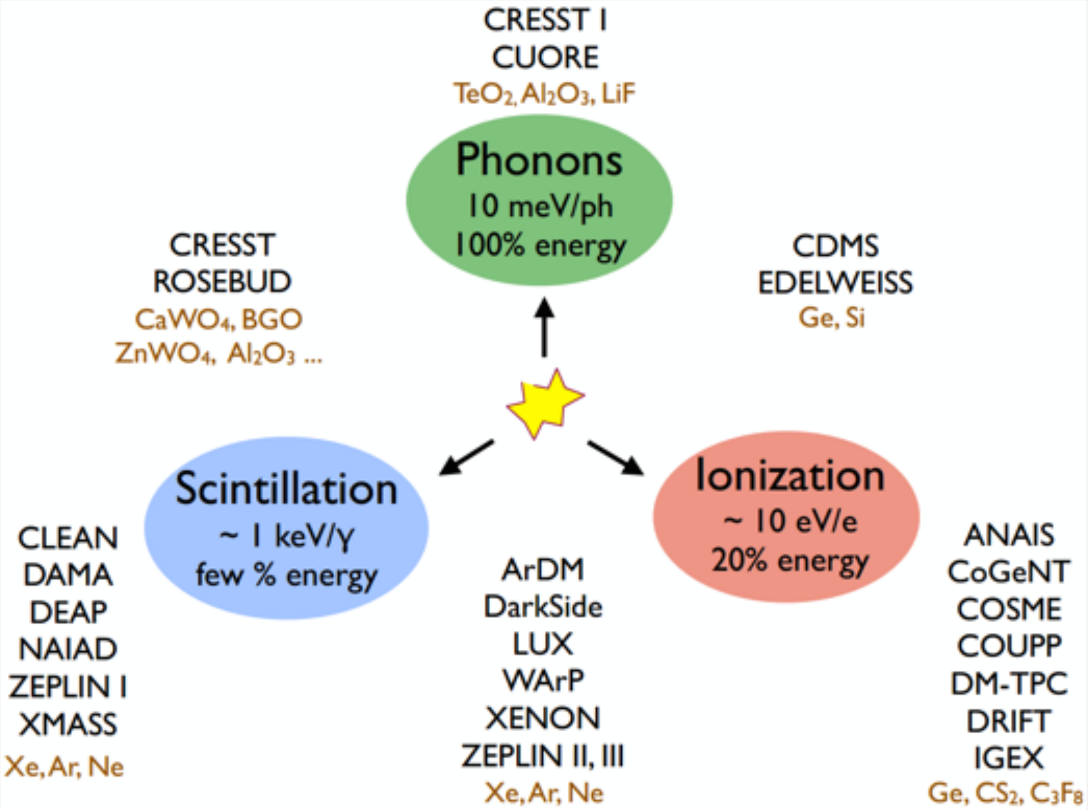




DARK MATTER OVERVIEW: COLLIDER, DIRECT AND INDIRECT DETECTION SEARCHES - QUEIROZ, FARINALDO S. ARXIV:1605.08788

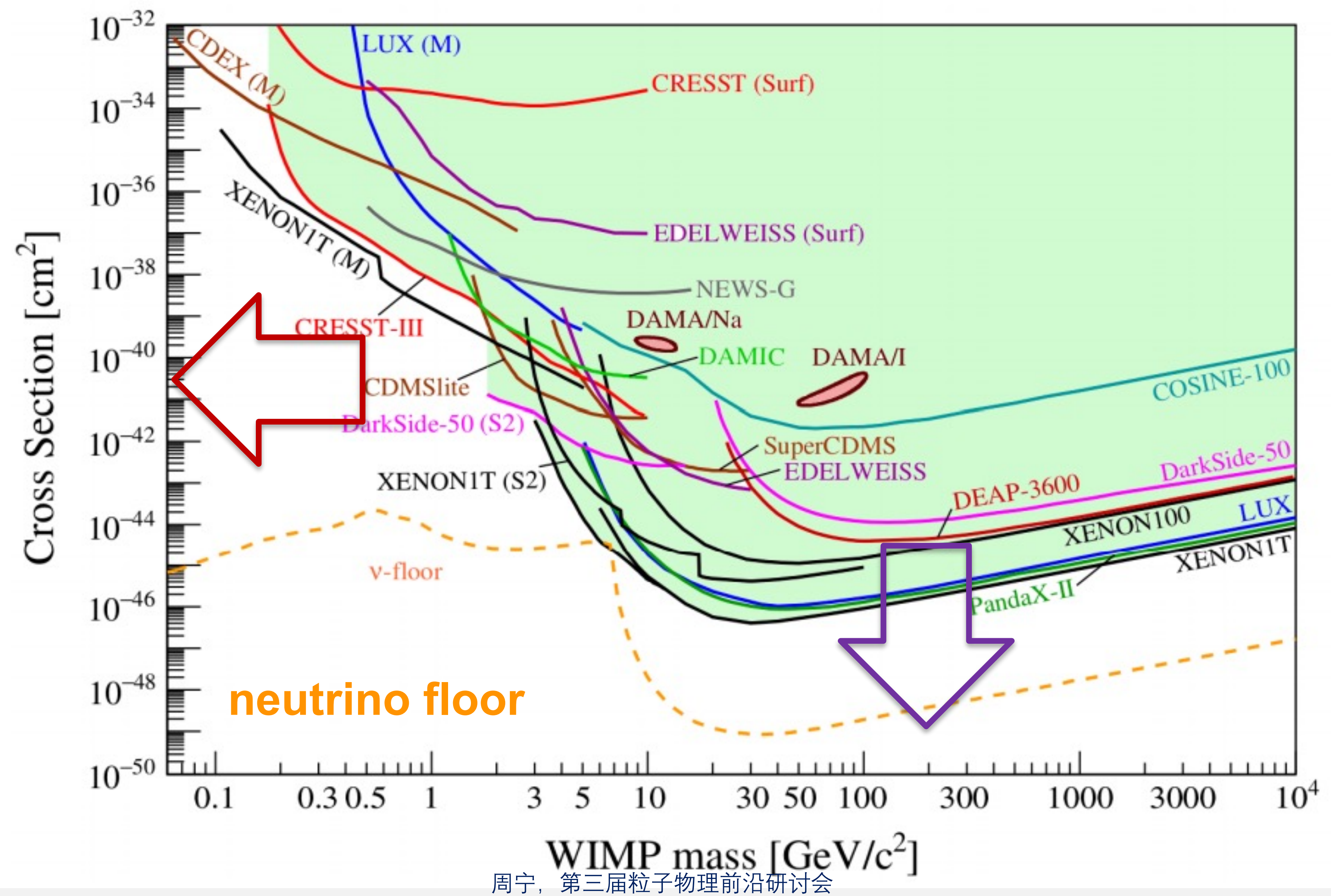
Detection Strategy

- Recoil energy: light, charge, heat
- Large target: multi-tonne scale
- Underground laboratory



Direct Detection

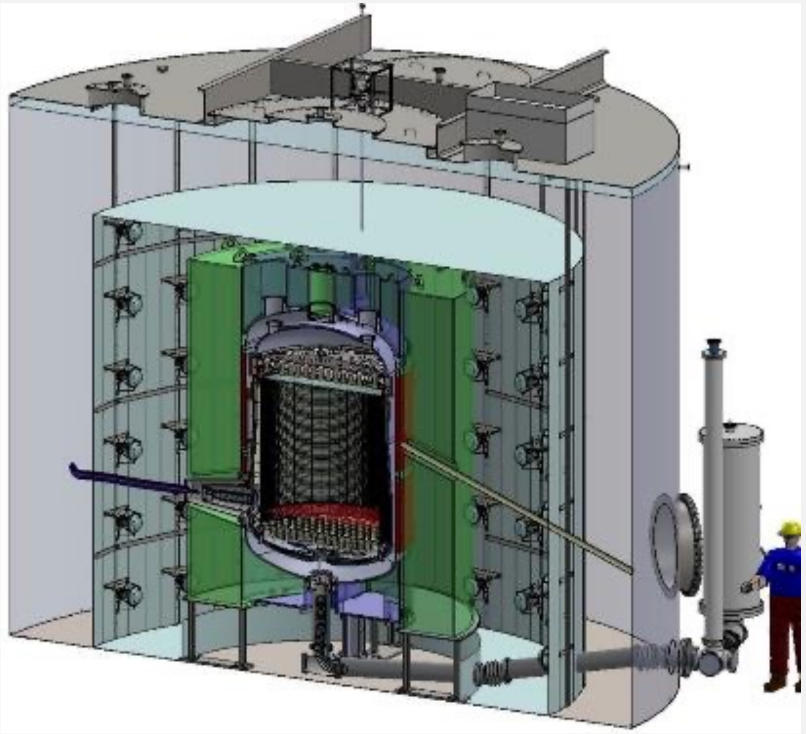
-



Multi-tonne Xenon Experiments

- PandaX-4T, XENONnT and LZ

PandaX-4T, 4 ton,
CJPL-II, China



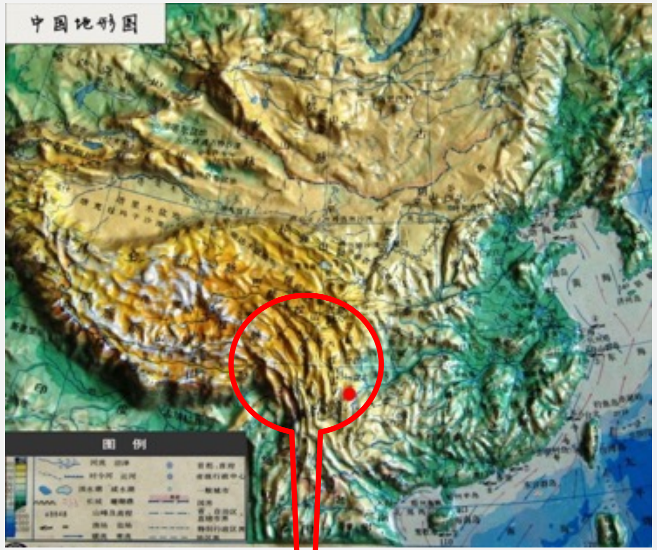
LZ, 7 ton,
Sanford Lab, US

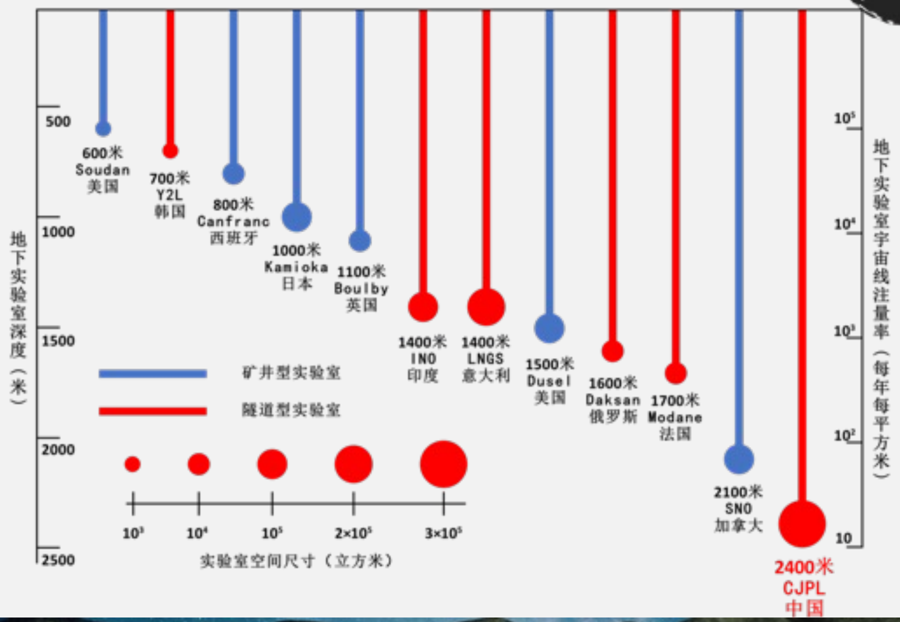
XENONnT, 6 ton
LNGS, Italy

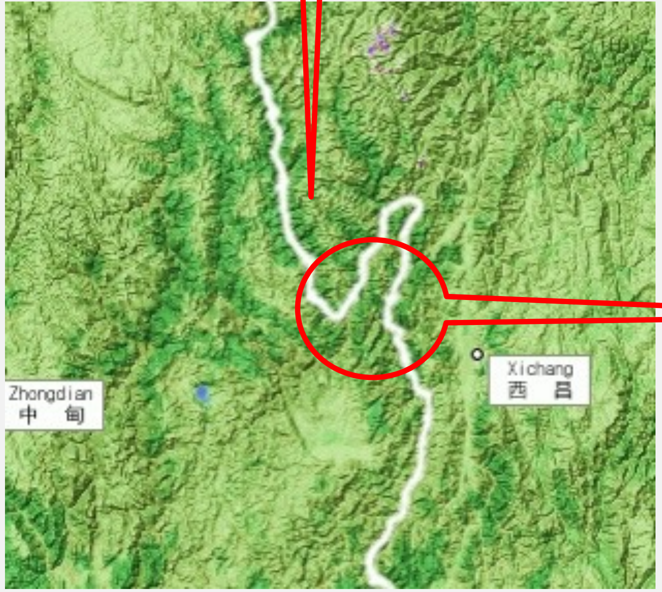
PandaX Collaboration

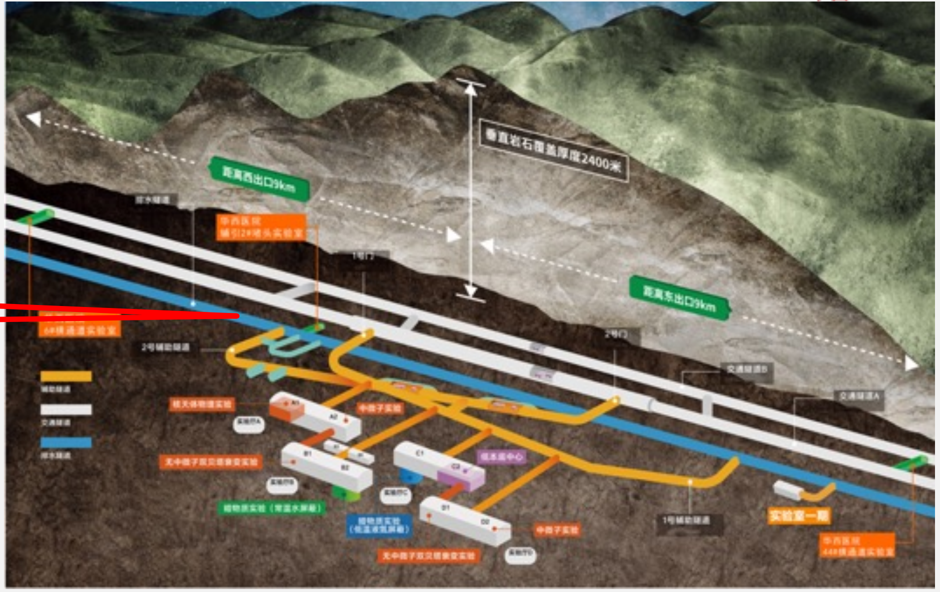
China Jinping Underground Laboratory (CJPL)

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

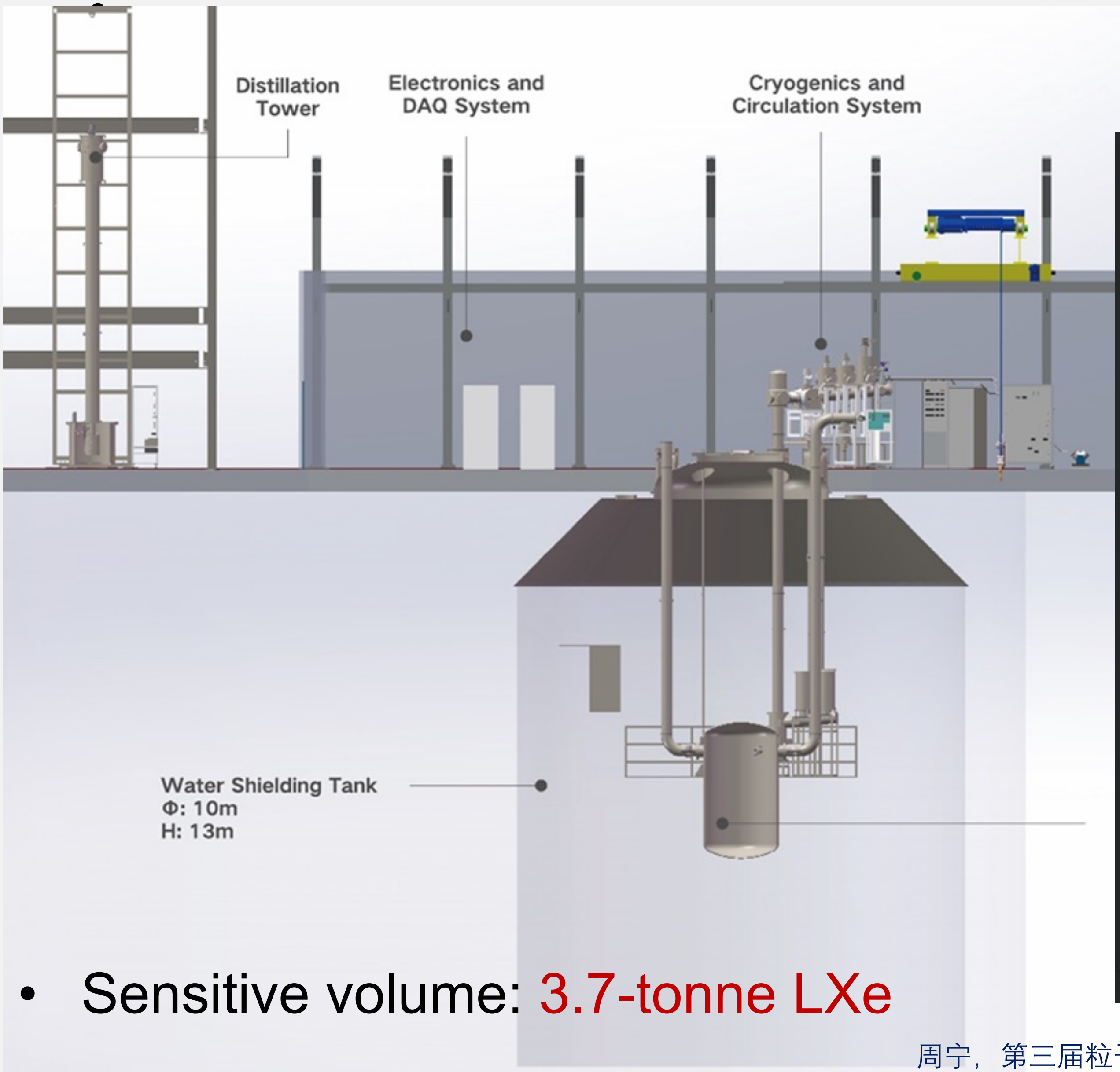


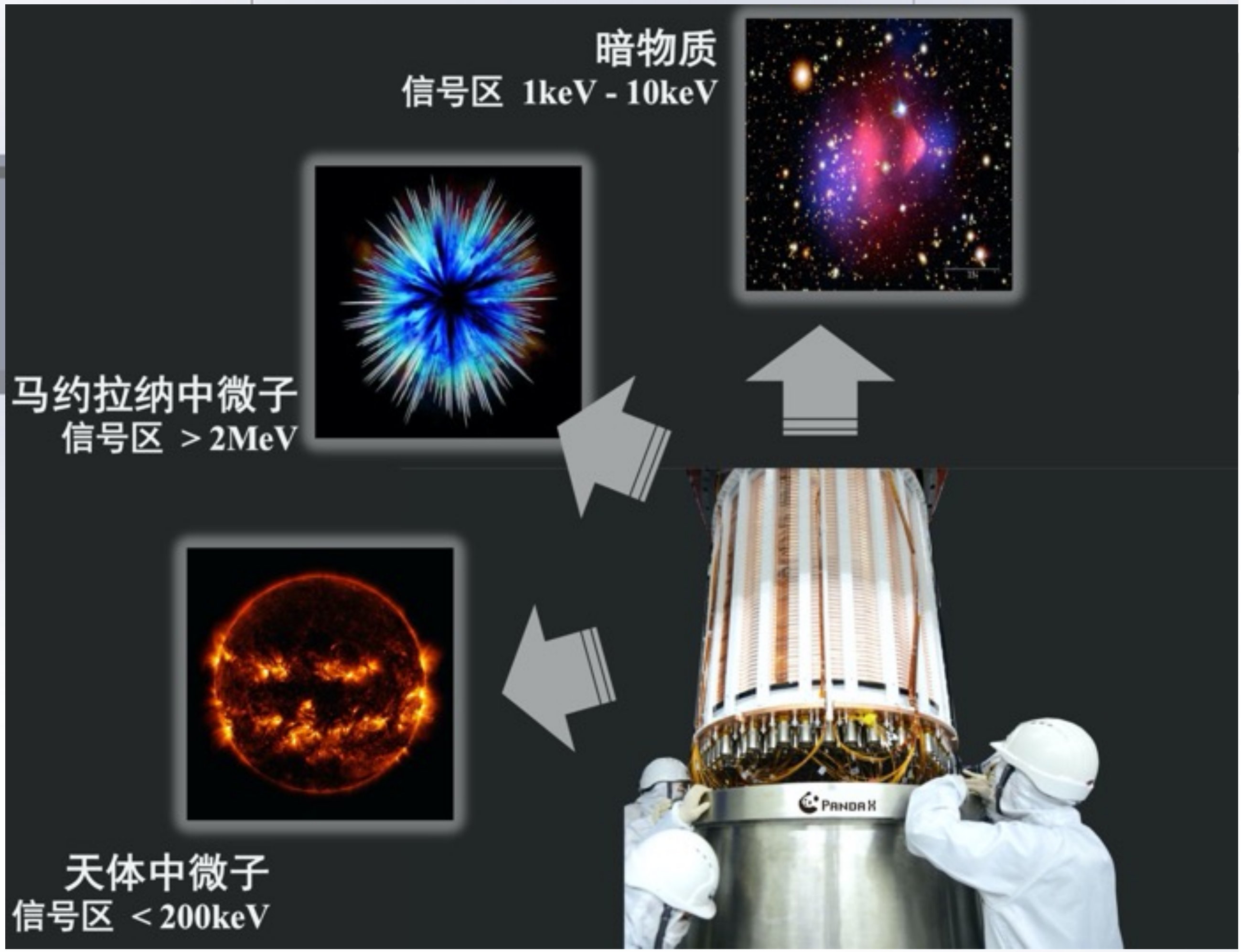






PandaX-4T @ CJPL-II

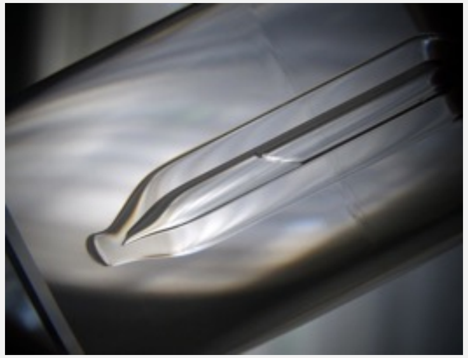


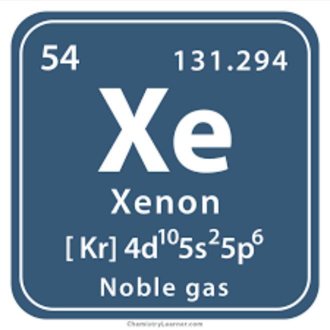


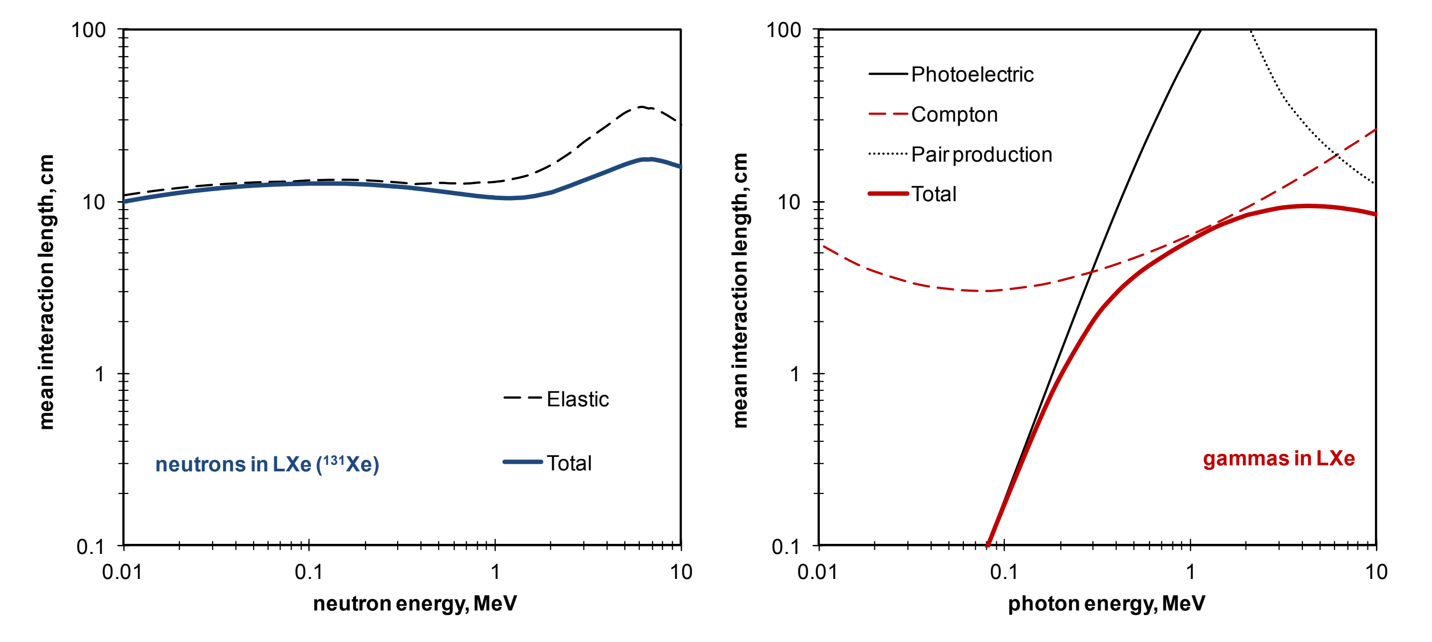
- Sensitive volume: 3.7-tonne LXe

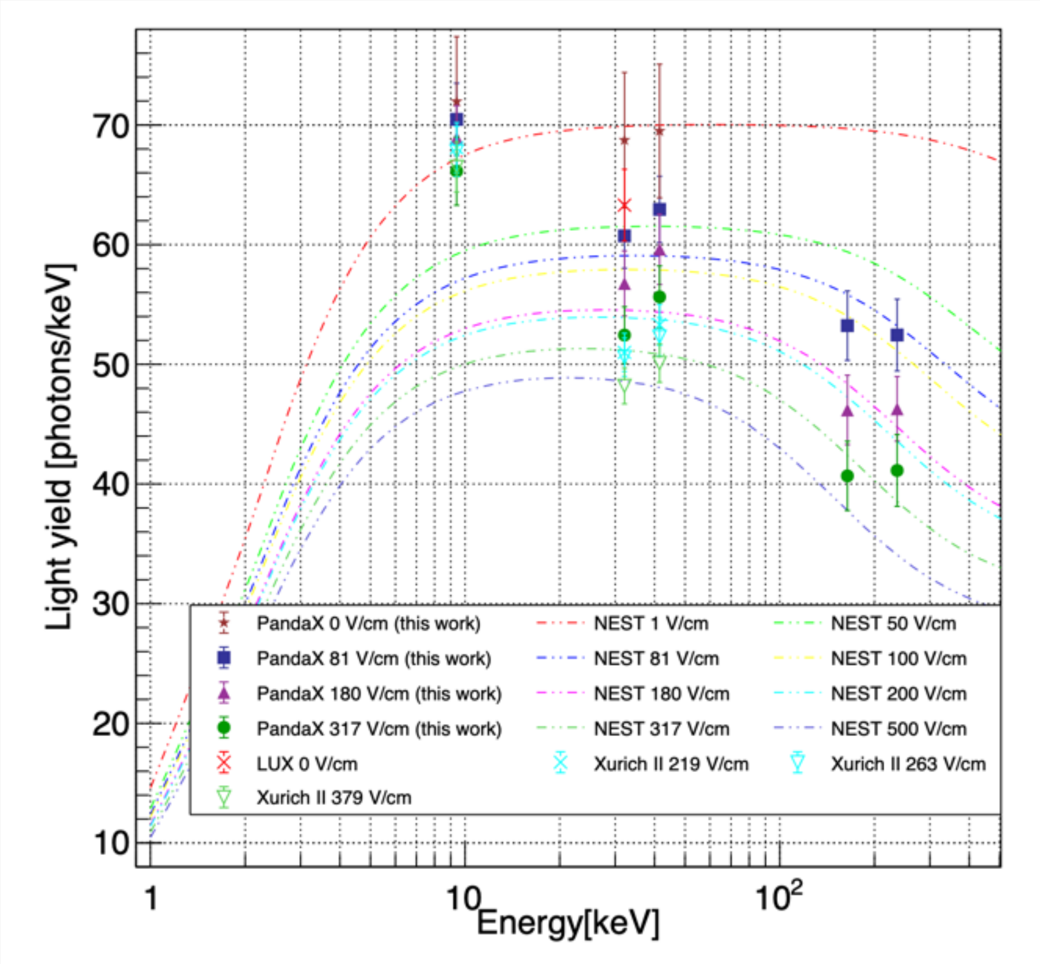
Xenon

- Dense and homogenous
- Self-shielding
- High light and charge yields





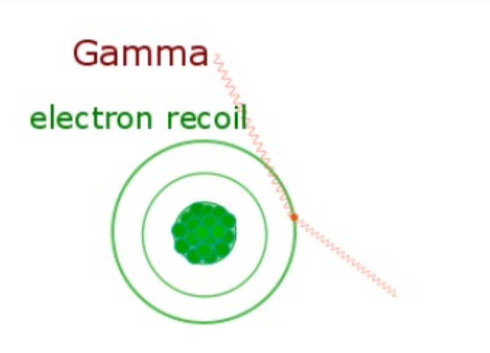


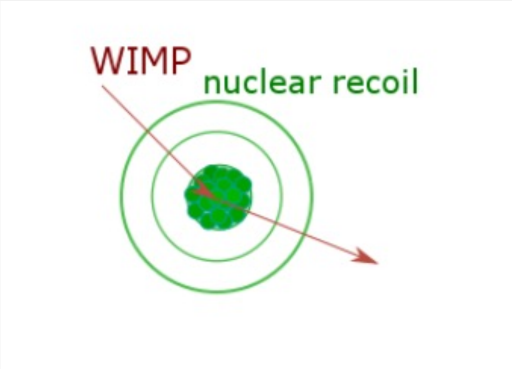


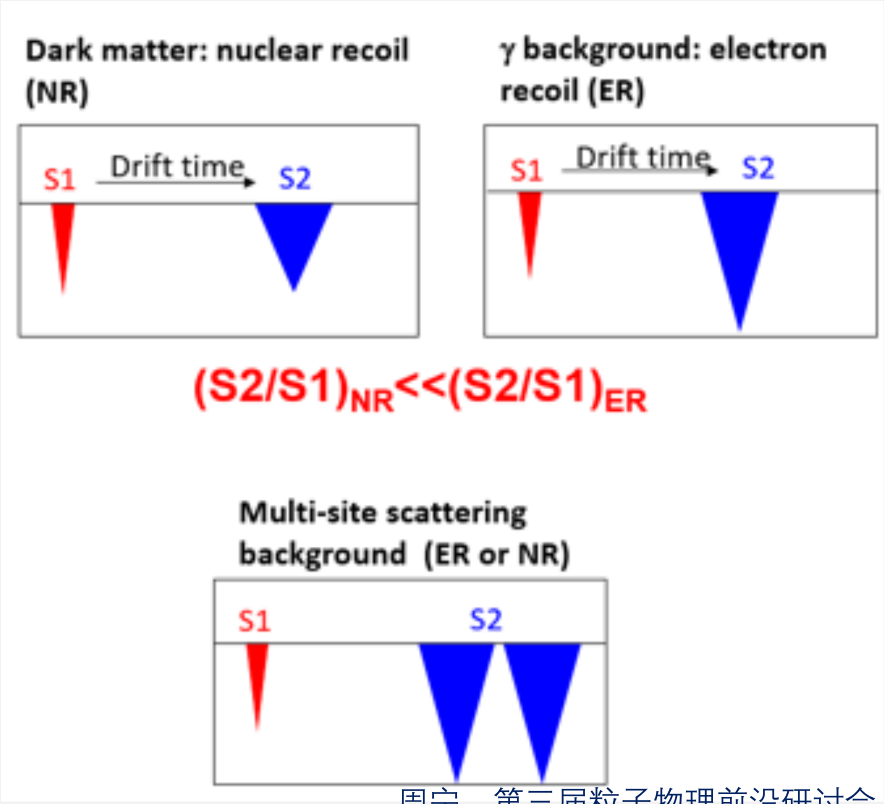
周宁，第三届粒子物理前沿研讨会 **JINST 17 P01008 (2022)**

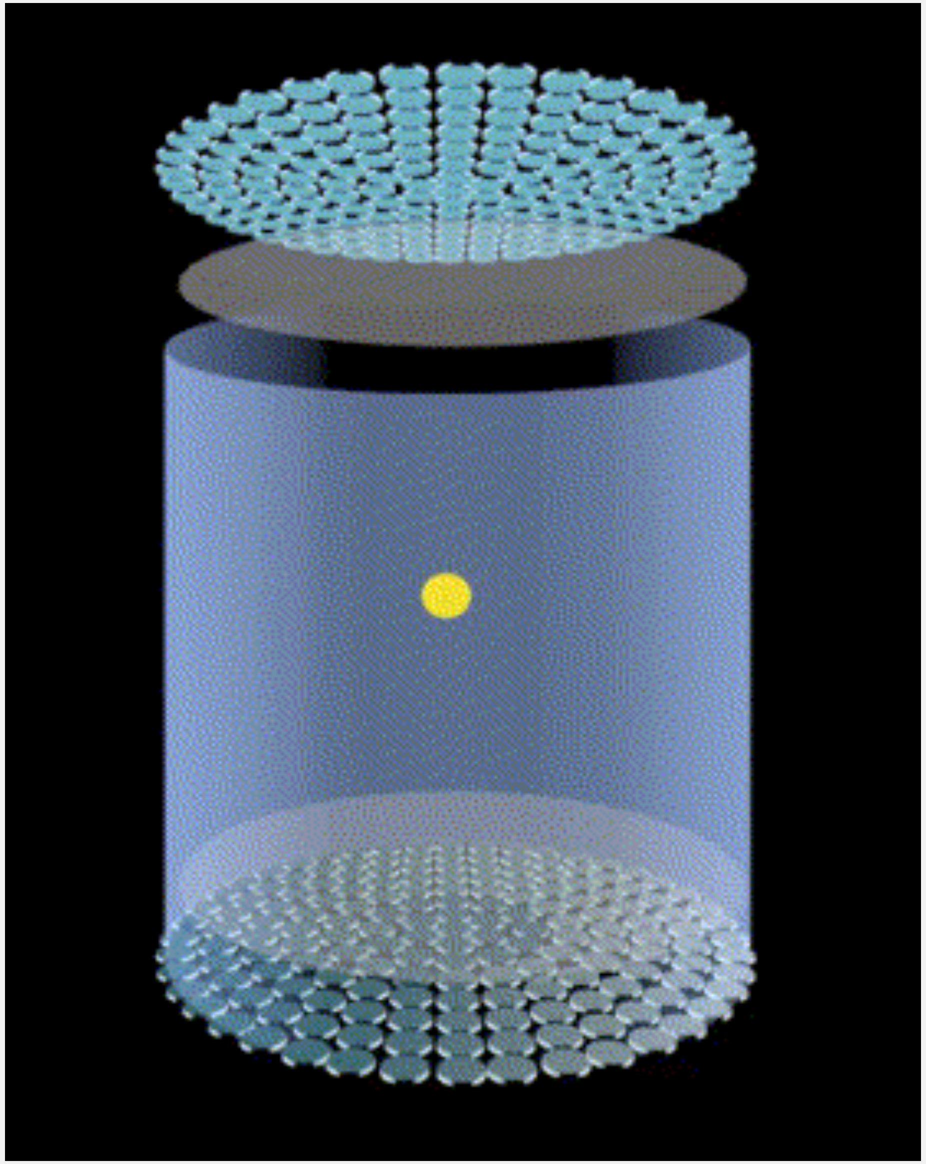
PandaX Detector

- Dual-phase xenon TPC
  - Large scale target
  - Precise energy and 3D-positon reconstruction
  - NR and ER discrimination power

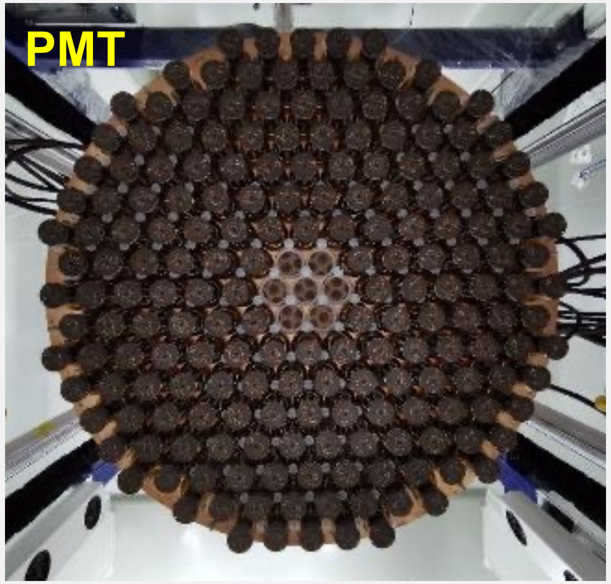


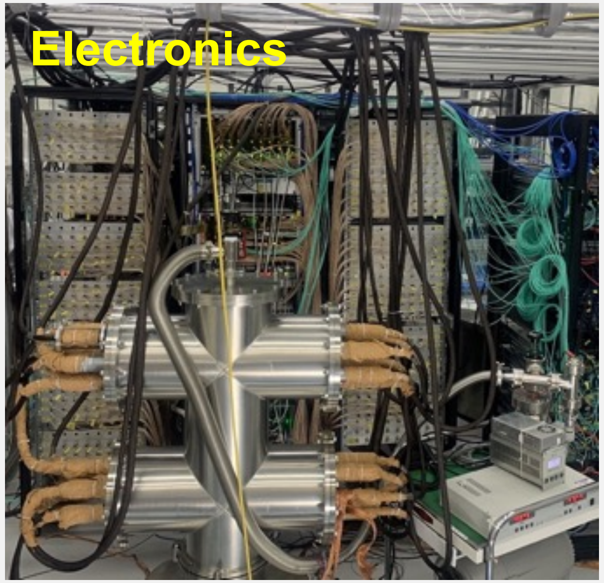






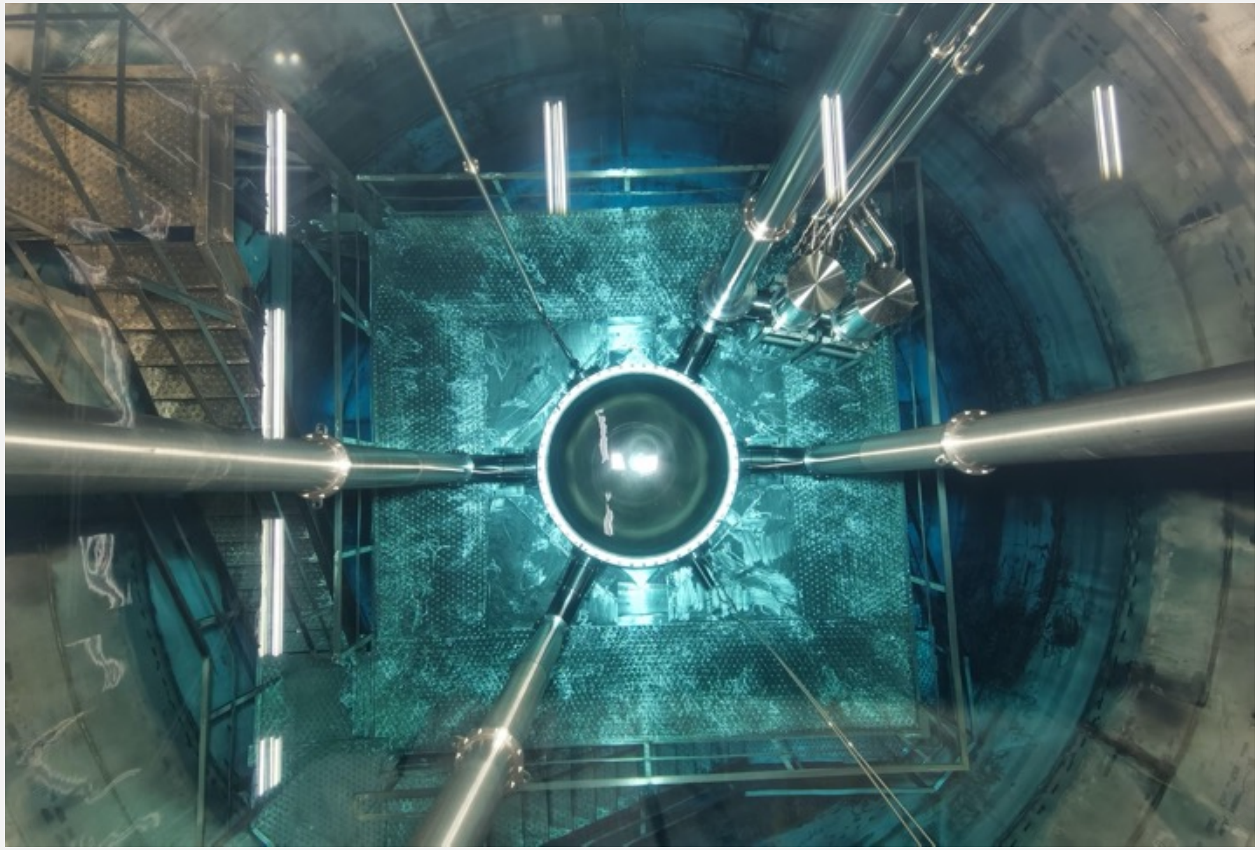
PandaX-4T Subsystems

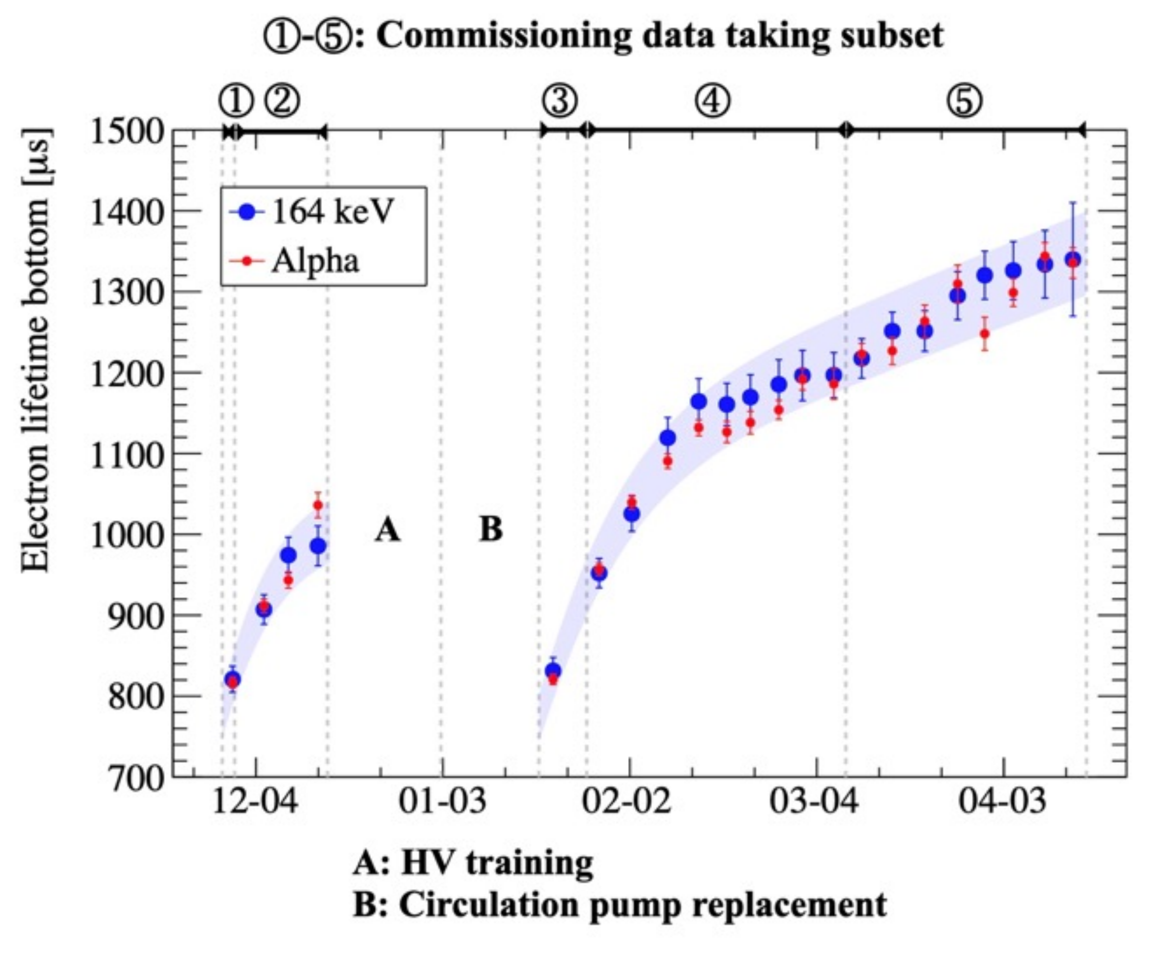




PandaX-4T Commissioning

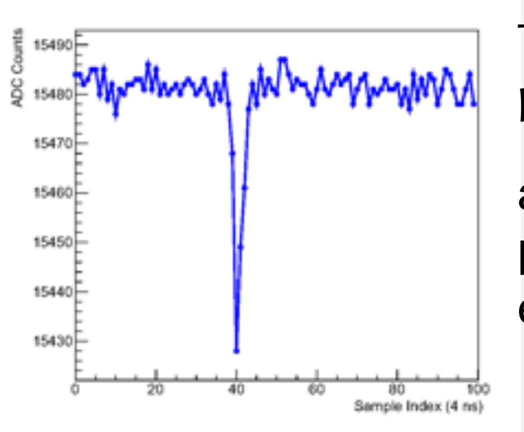
- Stable data running period: 95.0 calendar days





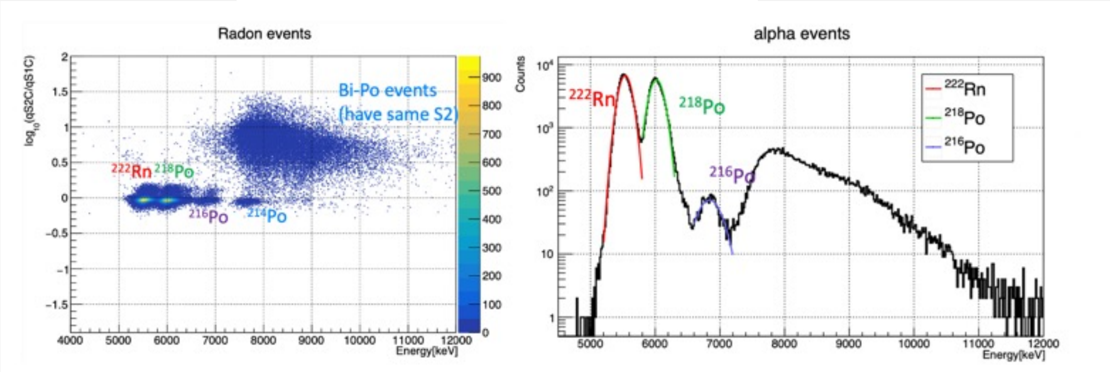
PandaX-4T major improvement

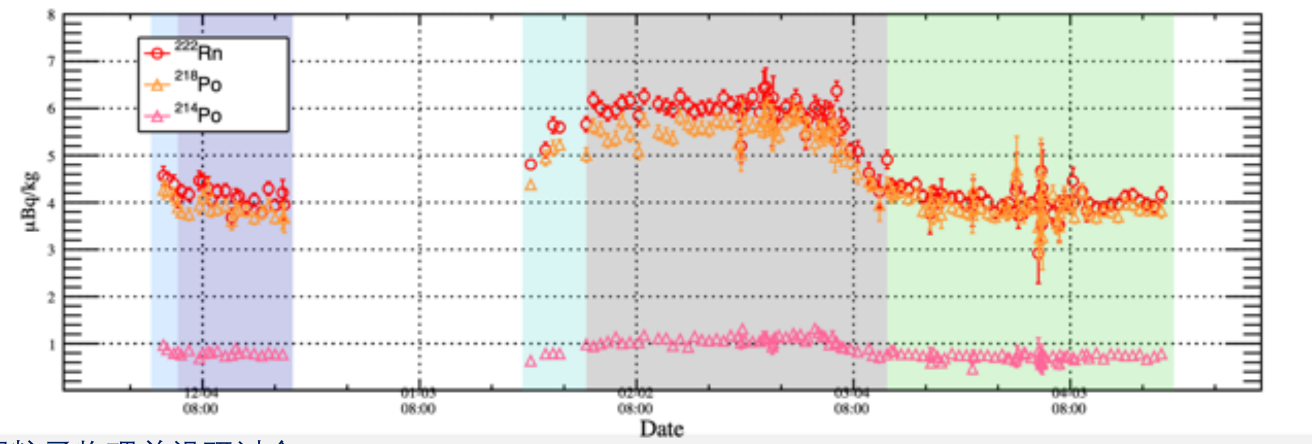
- **Triggerless DAQ**: low threshold
  - read out pulses above 20 ADC (~1/3 PE)
- **^{222}Rn**: ~ 5 uBq/kg
  - 1/6 of PandaX-II
- **^{85}Kr**: ~0.3 ppt mol/mol
  - 1/20 of PandaX-II

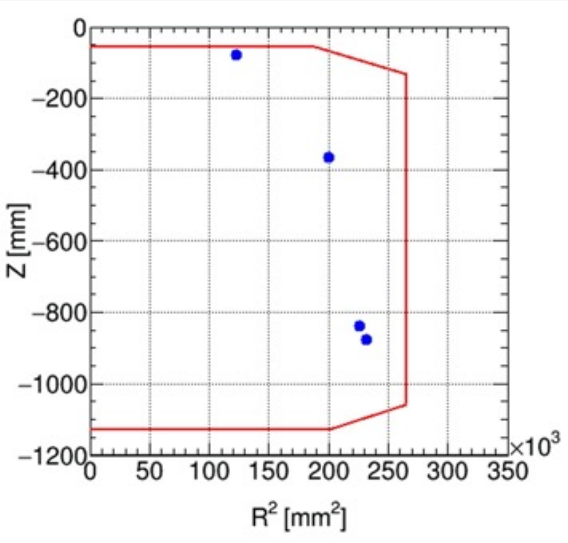


Typical single photon pulse

average single photon detection efficiency: 96%.



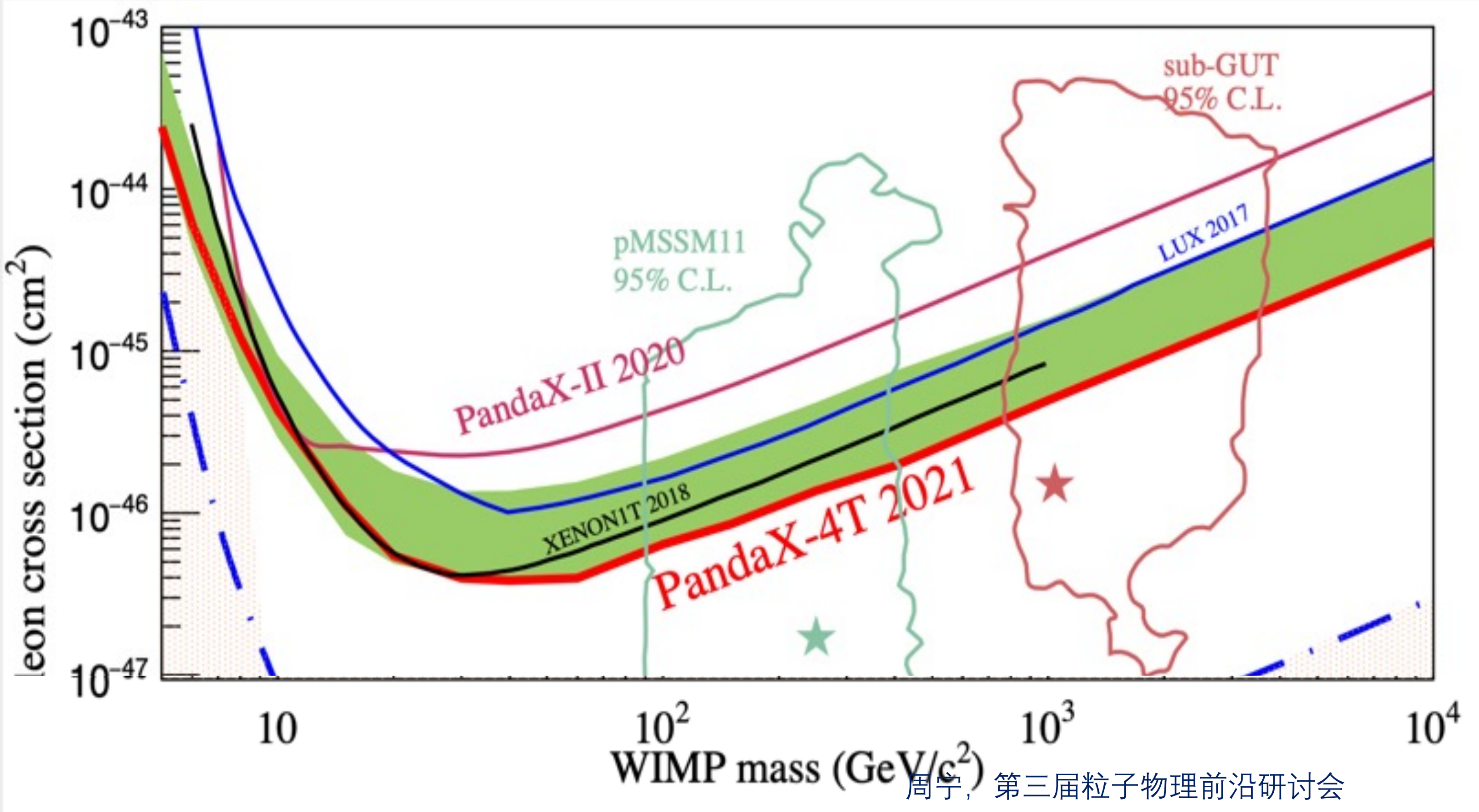




Vertex distribution of β-γ candidates

WIMP-nucleon SI exclusion limits

- Sensitivity improved from PandaX-II final analysis by 2.6 times at 40 GeV/c^2
- Dived into previously unexplored territory!
- Approaching the "low E" neutrino floor



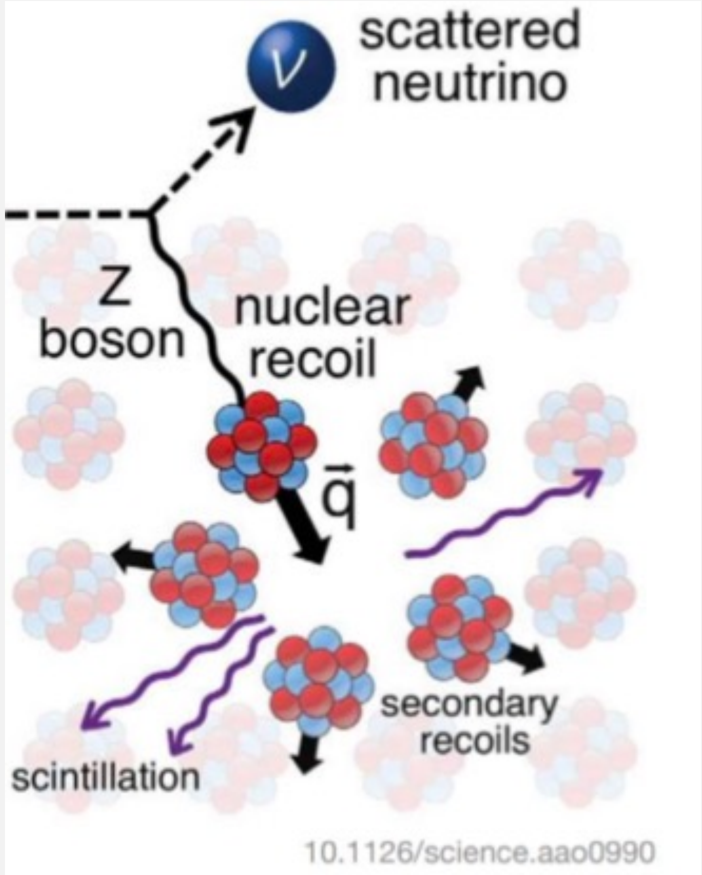
PRL 127, 261802 (2021)
Editors' Suggestion

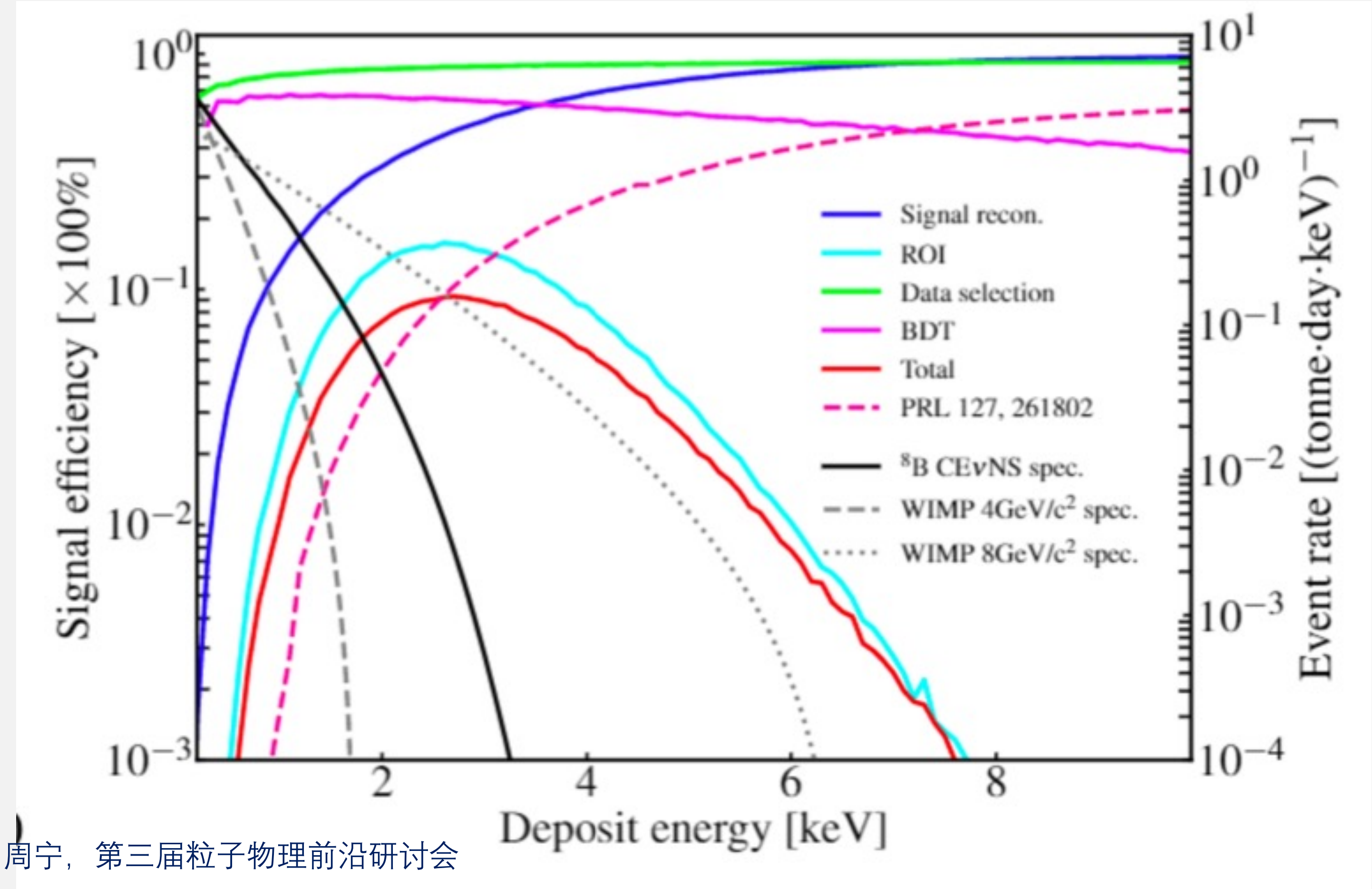
SUSY benchmark contours (MasterCode)

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

Low Mass Dark Matter

- Neutrino floor due to B8 CEvNS
- Lower S1 selection threshold to 2 hits

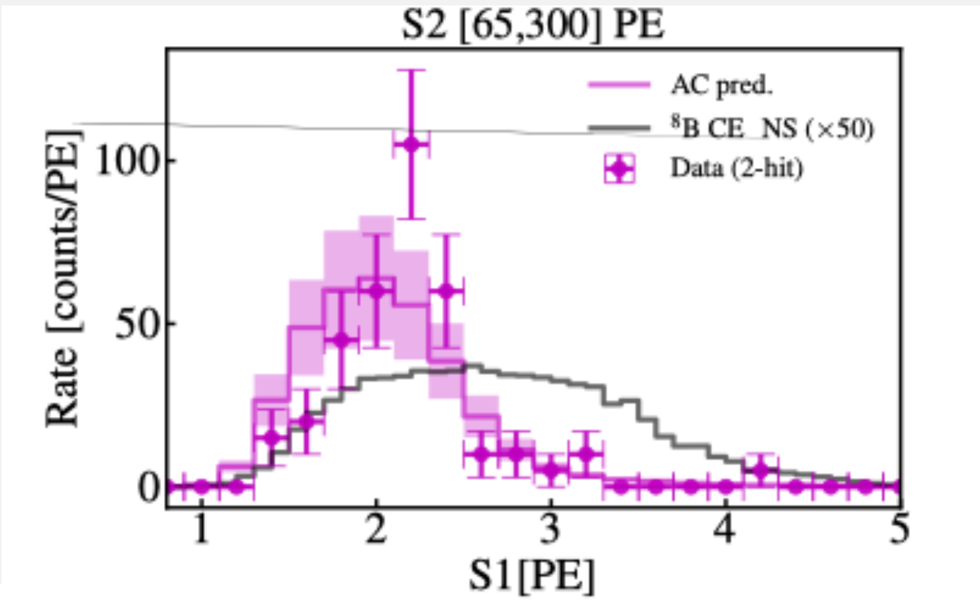


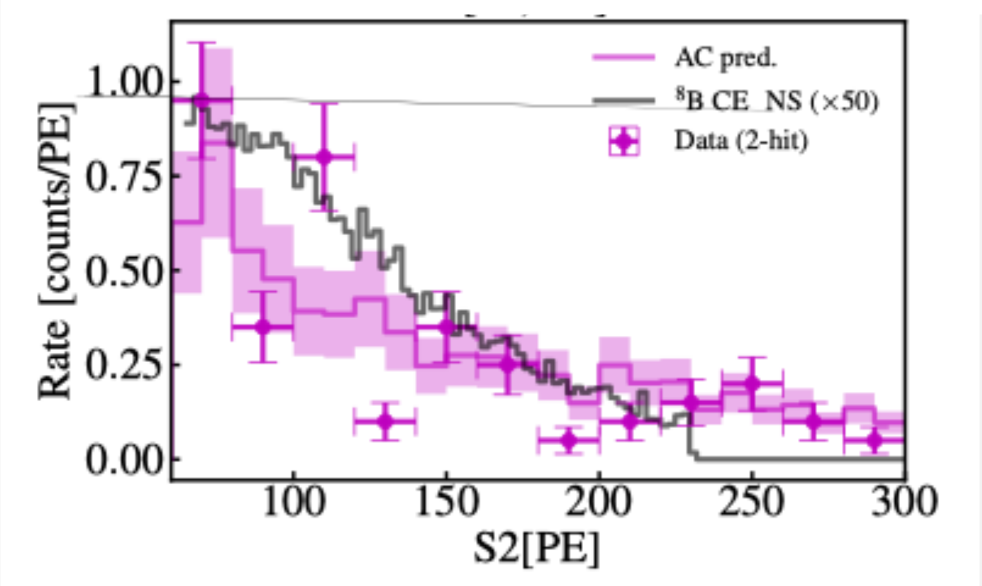


Data Analysis

- Blind analysis is performed with 0.48 tonne-year data, which has
- a software veto excluding time and position with high rates.
- Dominant background: accidental paired S1-S2
  - boosted decision tree

Nhit	BDT	Expected bkg	Expected B8	Observed
2	off	62.6	2.3	59
	on	1.5	1.4	1
3	off	0.8	0.4	2
	on	0.04	0.3	0

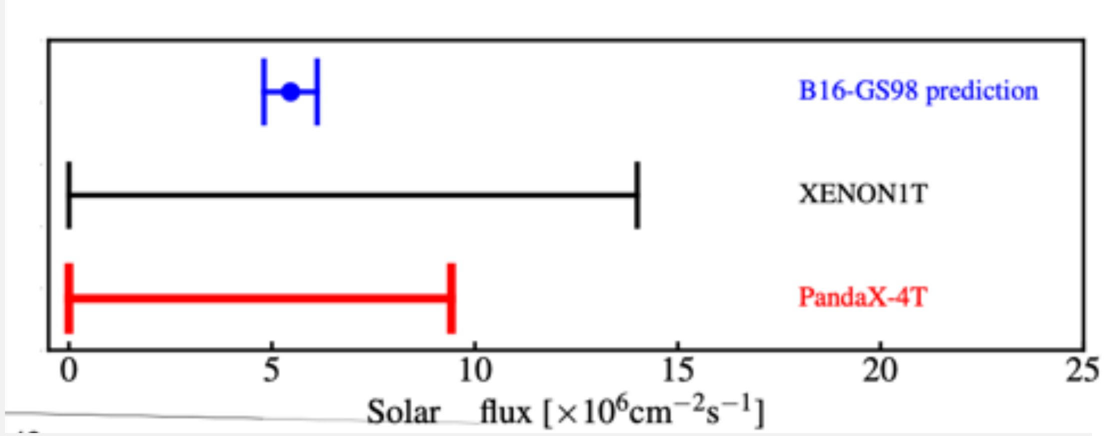


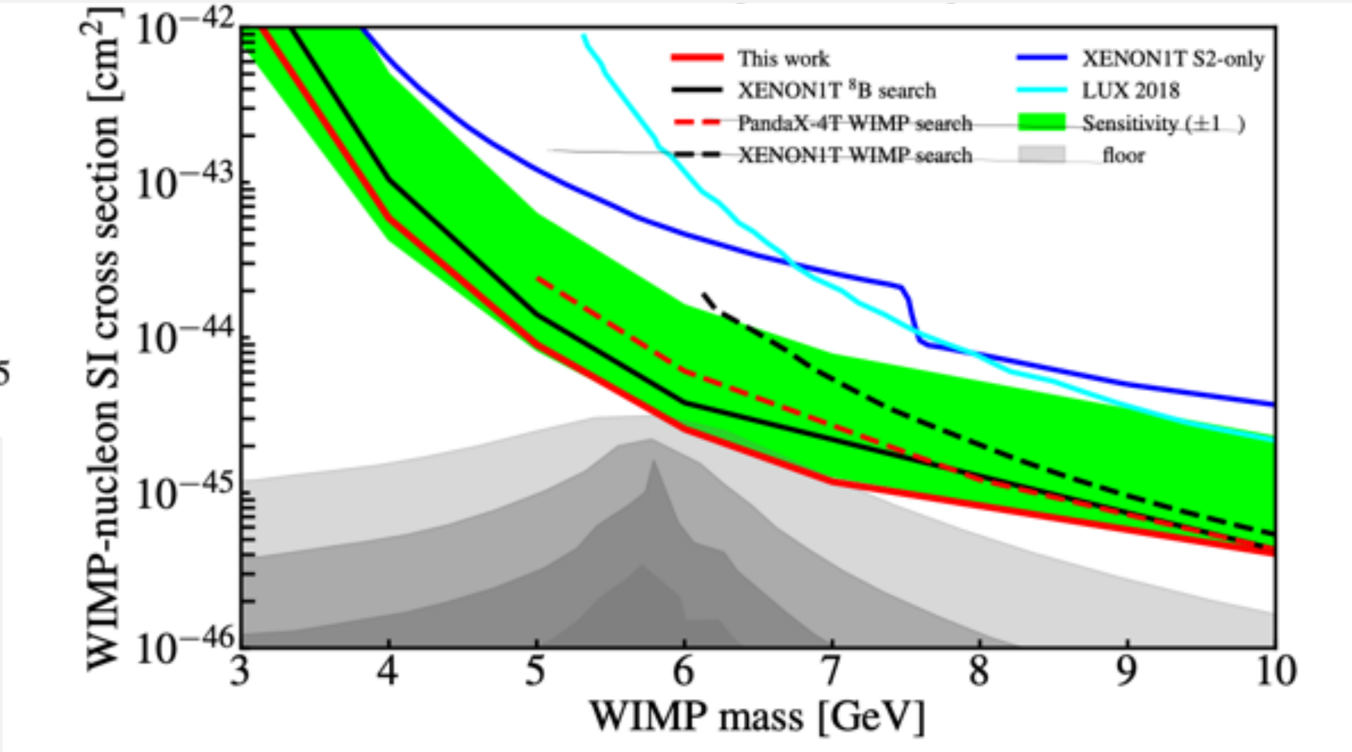


Constraints on B8 and WIMP

- 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

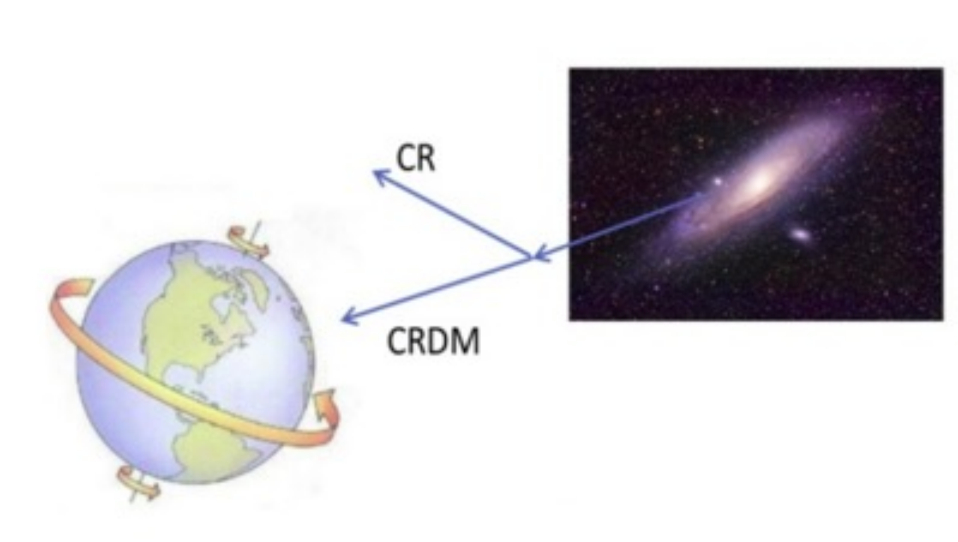
arXiv:2207.04883

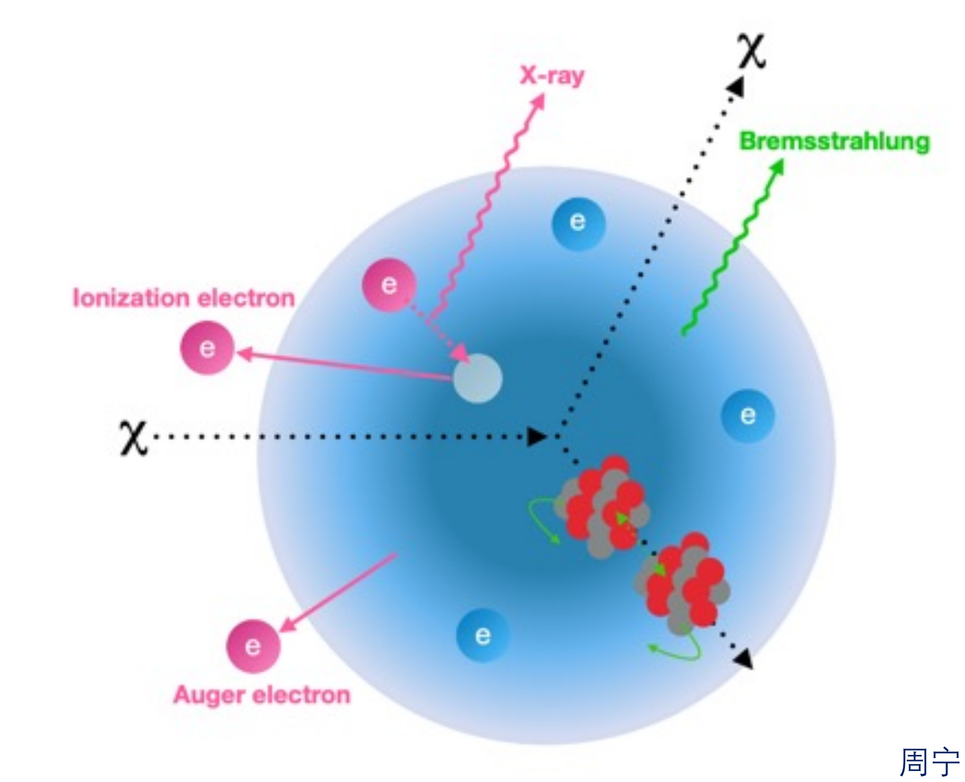




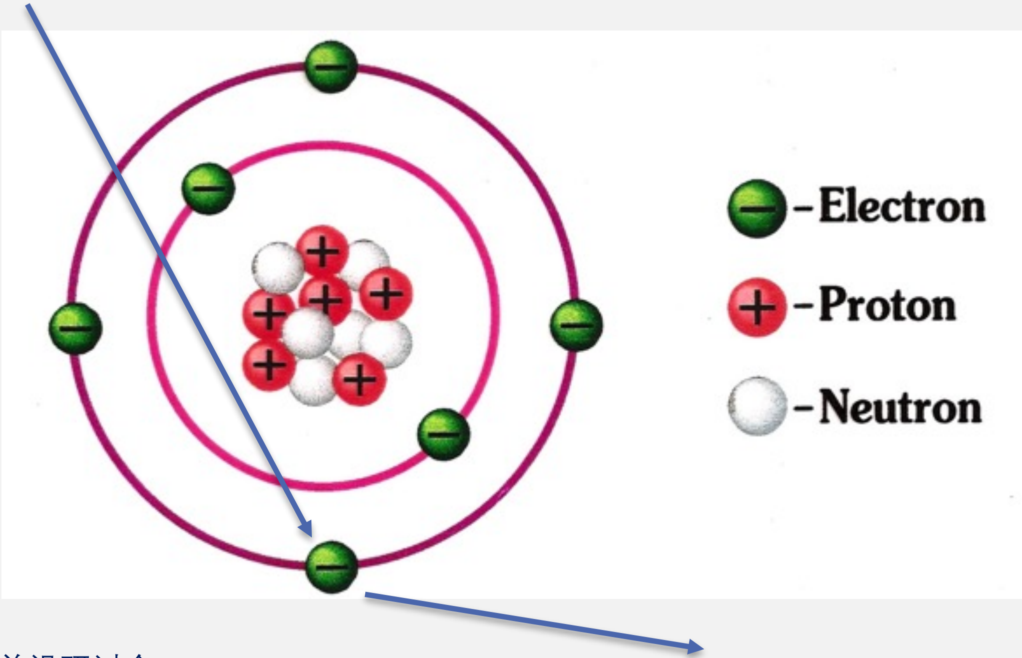
Other Scenarios

- Boosted DM
- Absorption DM
- Electron scattering





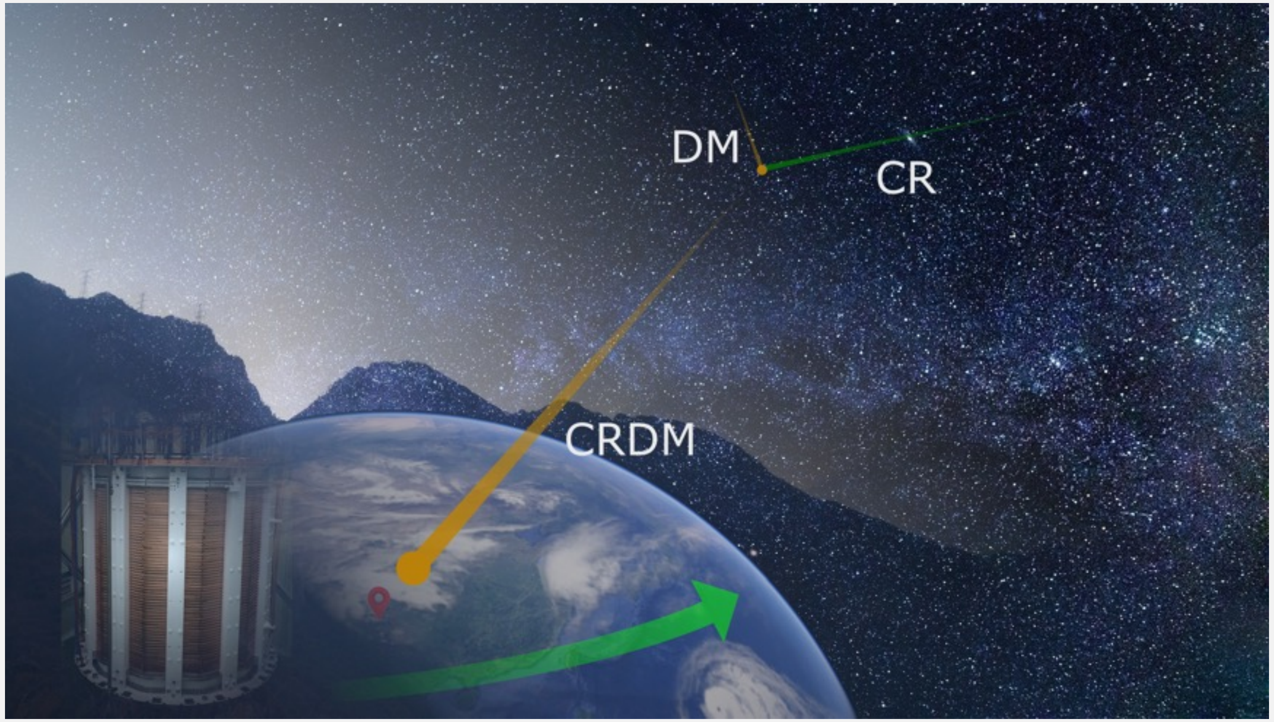
WIMP

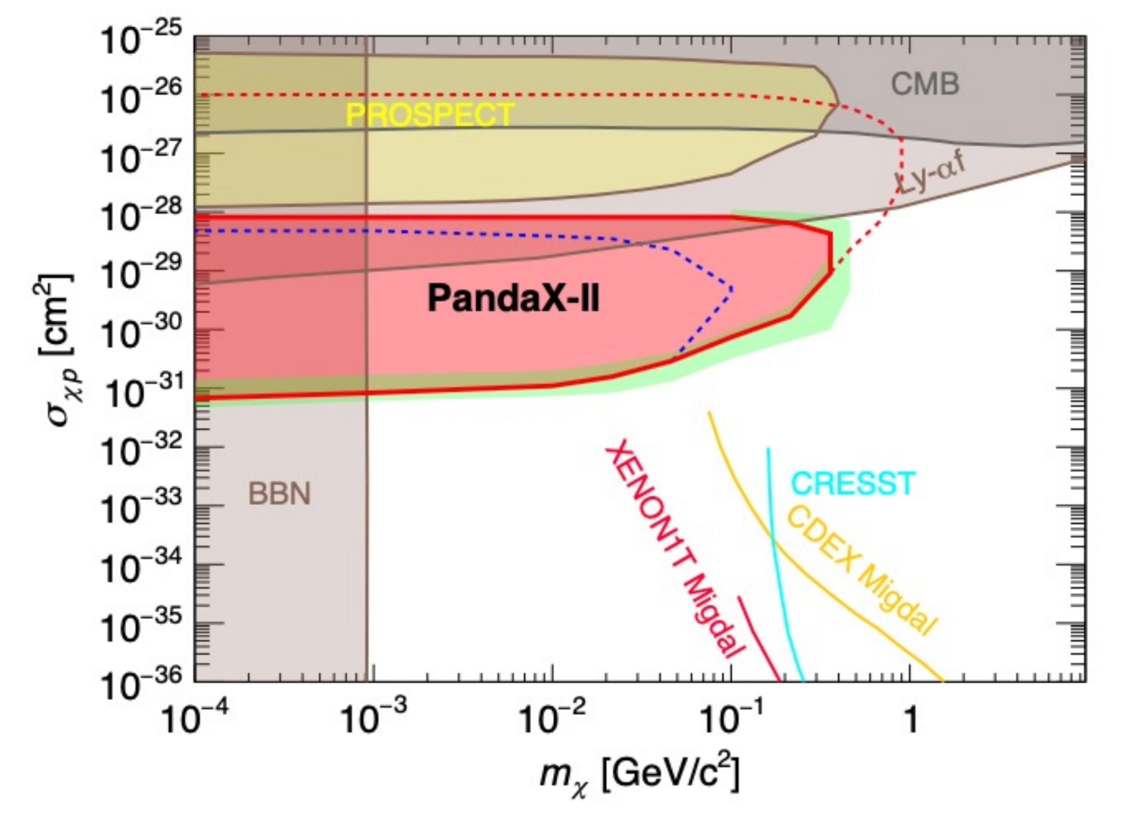


Cosmic-ray Boosted Dark Matter

- Attenuation due to the earth shielding
- Using events below NR median: 25 events (expected 26.6 background)
- Expand to the region beyond the astrophysical and cosmological probes

详见葛韶锋的报告





S. Ge, J. Liu, Q. Y, N. Zhou PRL 126 (2021) 9, 091804

PRL 128, 171801 (2022) Editors' Suggestion

Absorption DM-nucleus Interaction

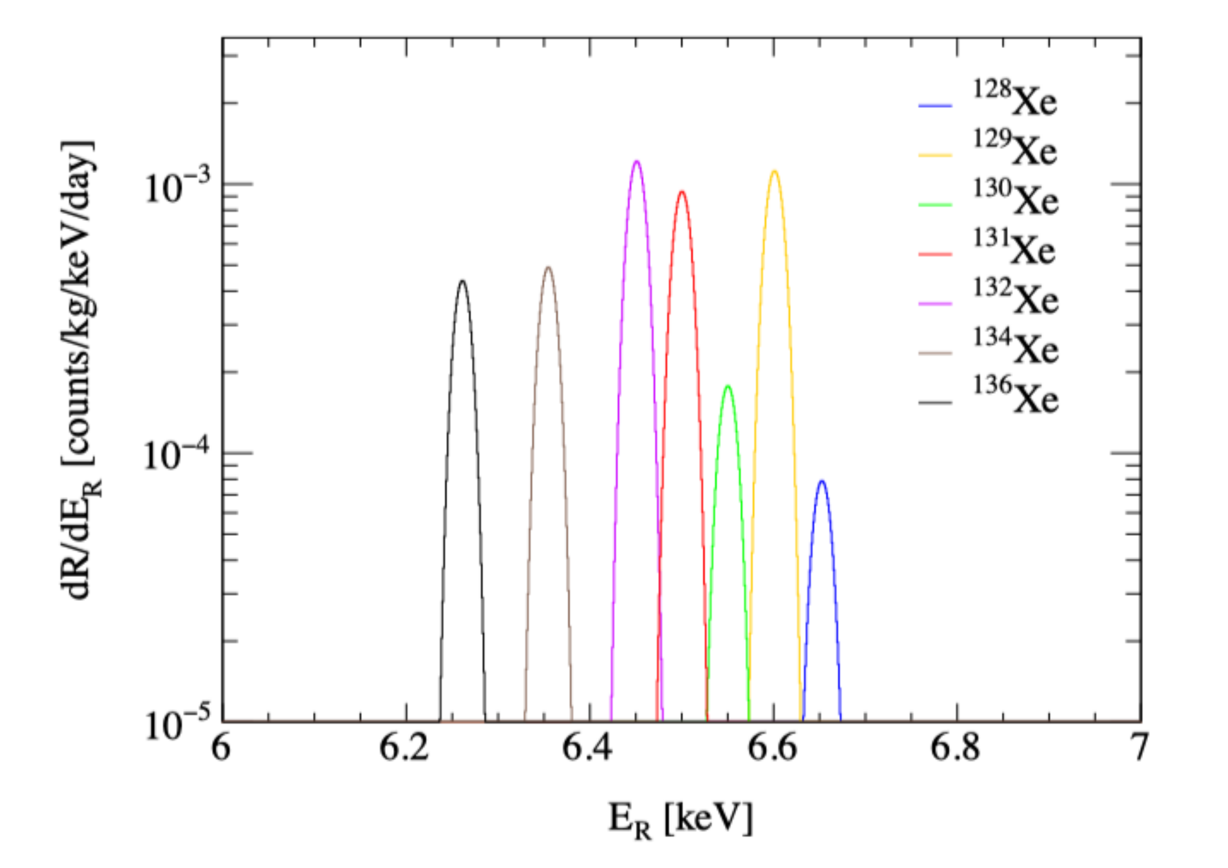
- Dark matter is mixed with right-handed neutrino

$$\mathcal{O}_{\rm NC} = \frac{1}{\Lambda^2}\left(\bar{n}\gamma^\mu n + \bar{p}\gamma^\mu p\right)\bar{\chi}\gamma_\mu P_R \nu + \text{h.c.}$$

- DM-nucleus interaction
  - incoming DM absorption

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

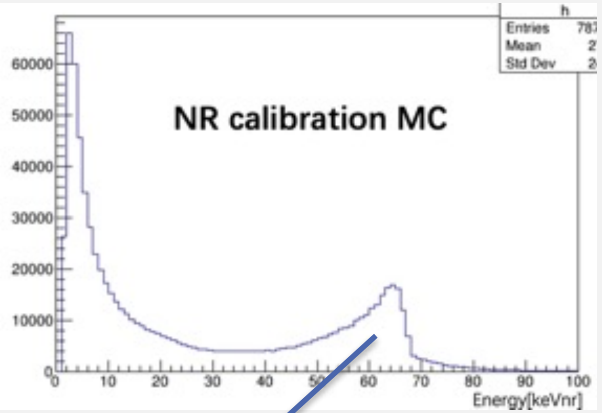
- **Mono-energetic recoil energy**
  - $E_R \simeq \frac{m_\chi^2}{2M_T}$
  - Key issue: **detector resolution**

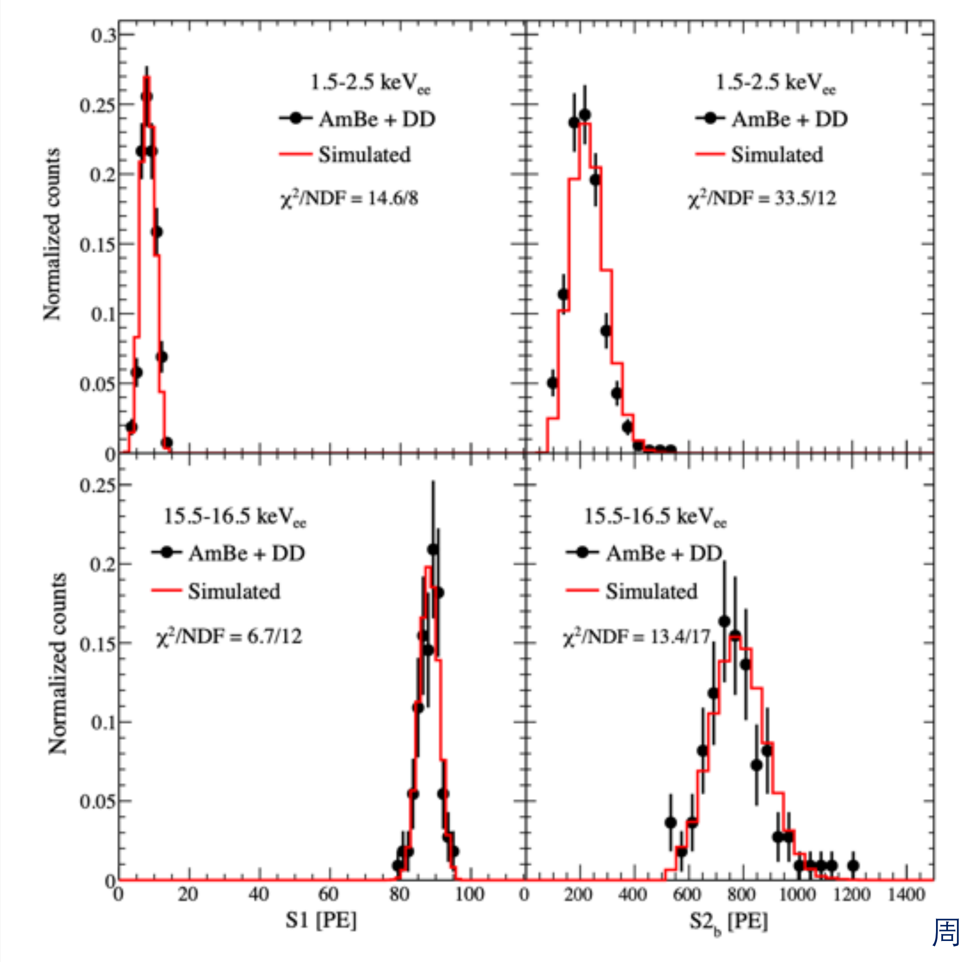


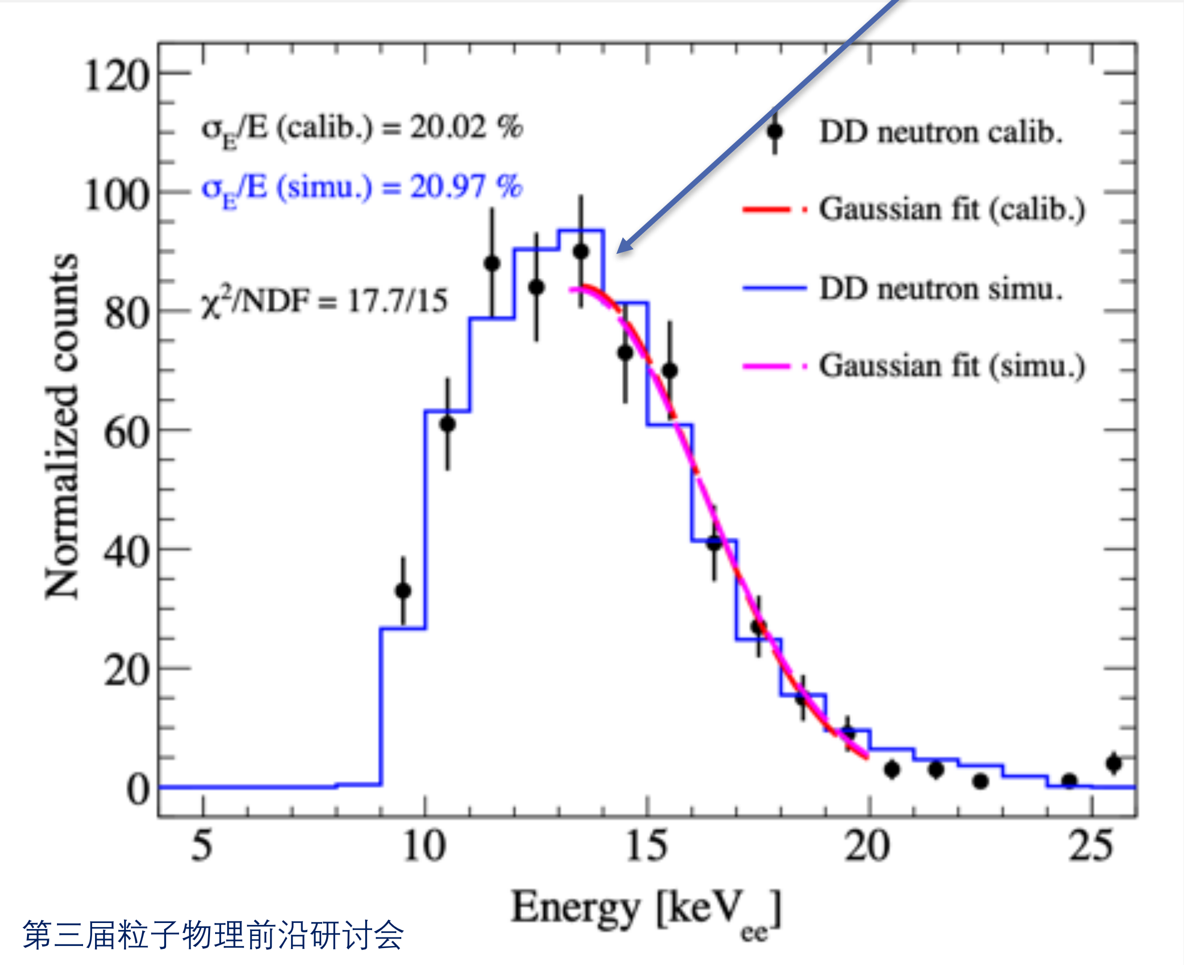
J. Dror, G. Elor, R. McGehee, PRL 2020

Energy Resolution Validation

- Signal response model vs NR calibration data
  - S1, S2 distribution in every energy window
  - D-D neutron back-scatter peak

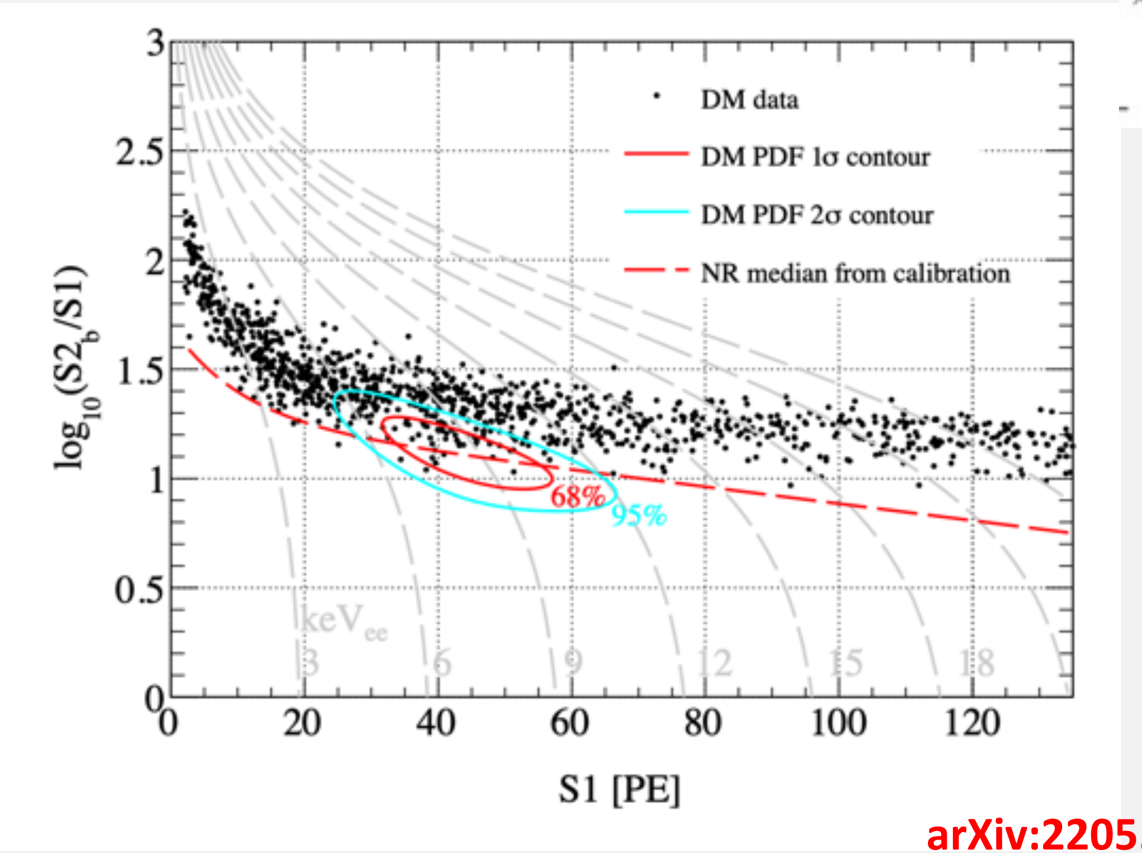


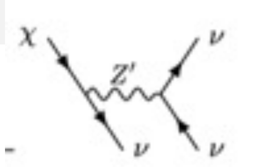


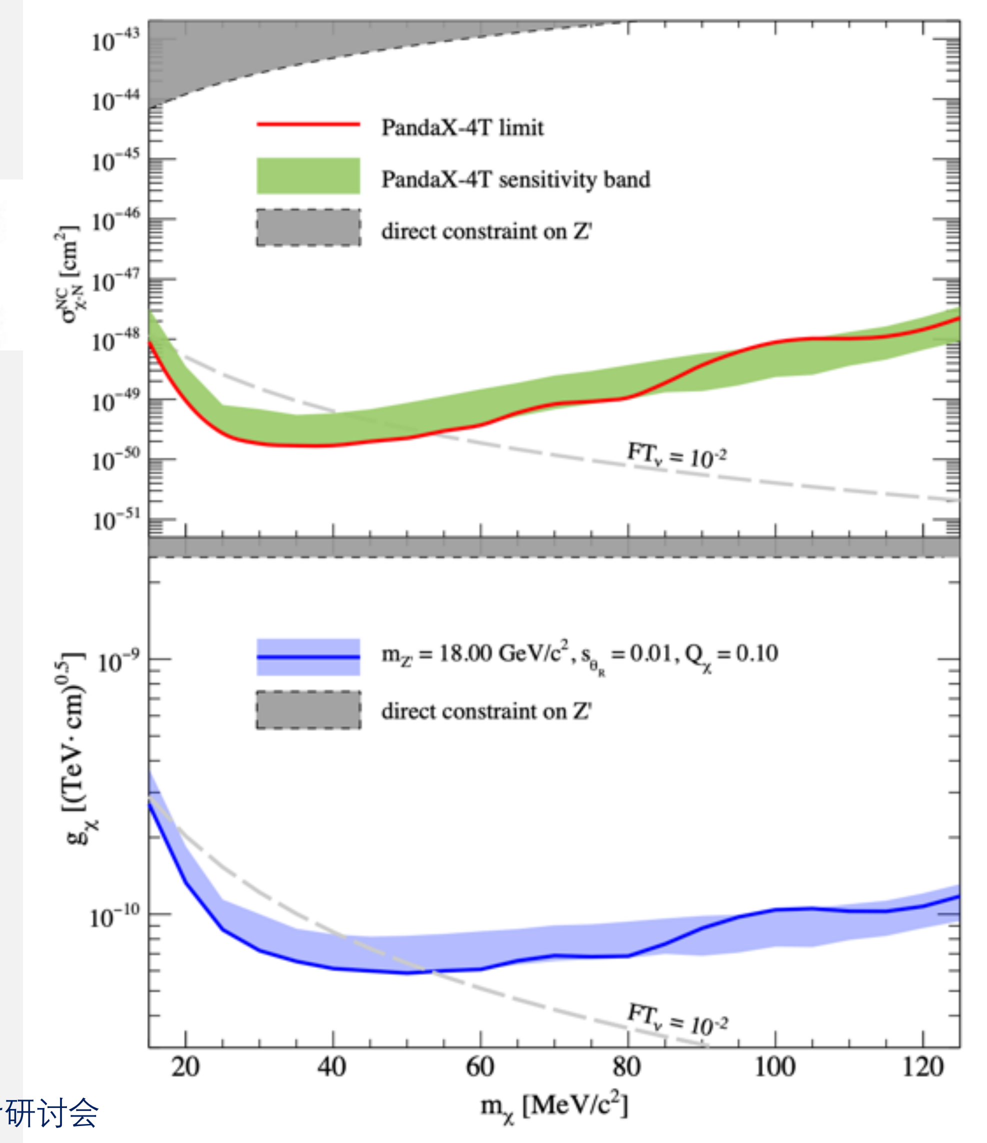


Constraints on Absorption DM-nucleon

- First mono-energetic NR signal search
- Strong constraints on sub-GeV DM
  - with collider and indirect detection ($\chi \rightarrow \nu\nu\nu$)







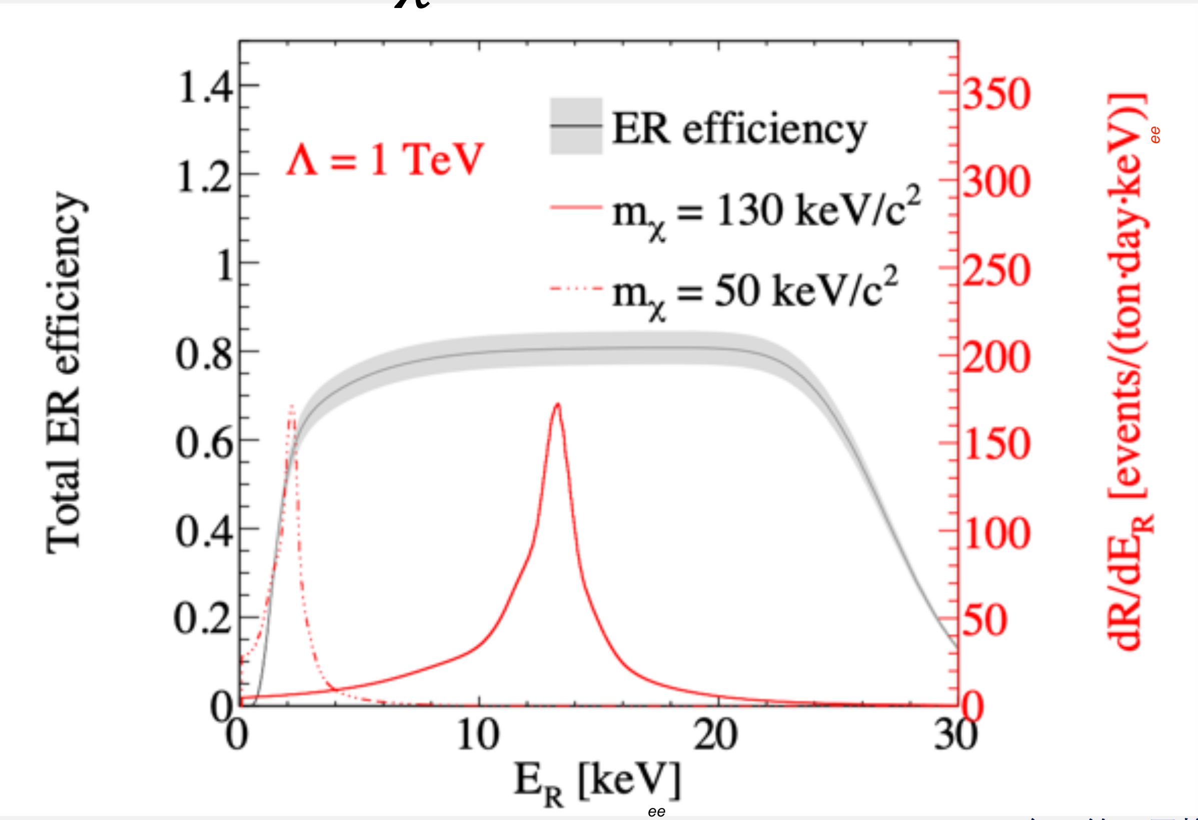
arXiv:2205.15771

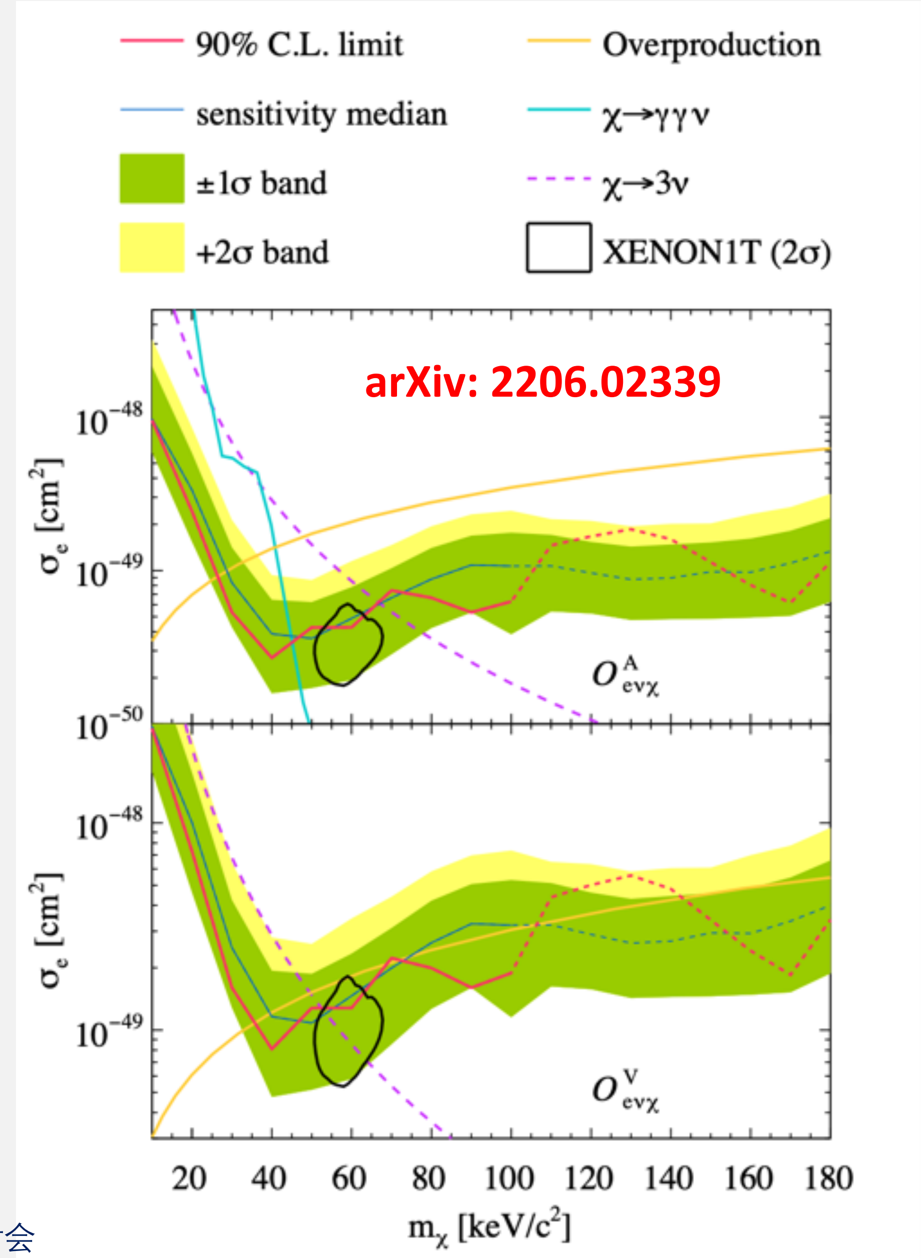
Absorption DM-electron Interaction

- A general Fermionic (sterile neutrino-like) dark matter absorption on electron
  - Similar signal as search for keV sterile neutrino DM in direct detection

$\chi e \rightarrow e\nu$

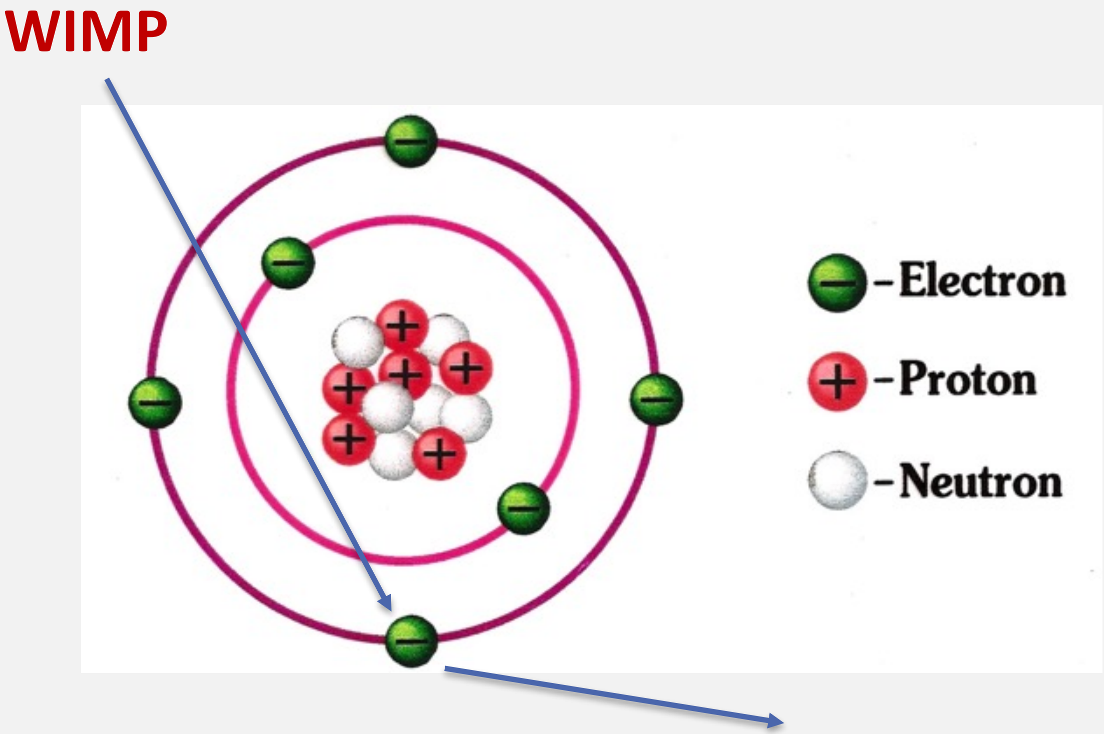
详见葛韶锋的报告

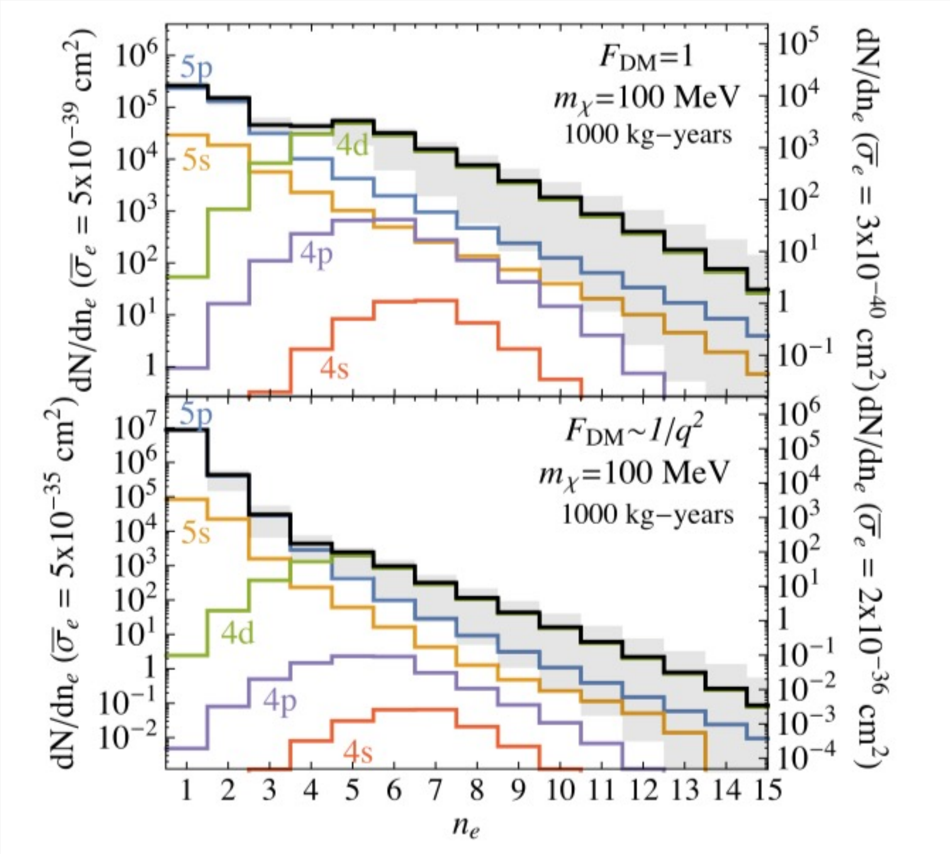




DM-electron interaction

- Much smaller energy deposit

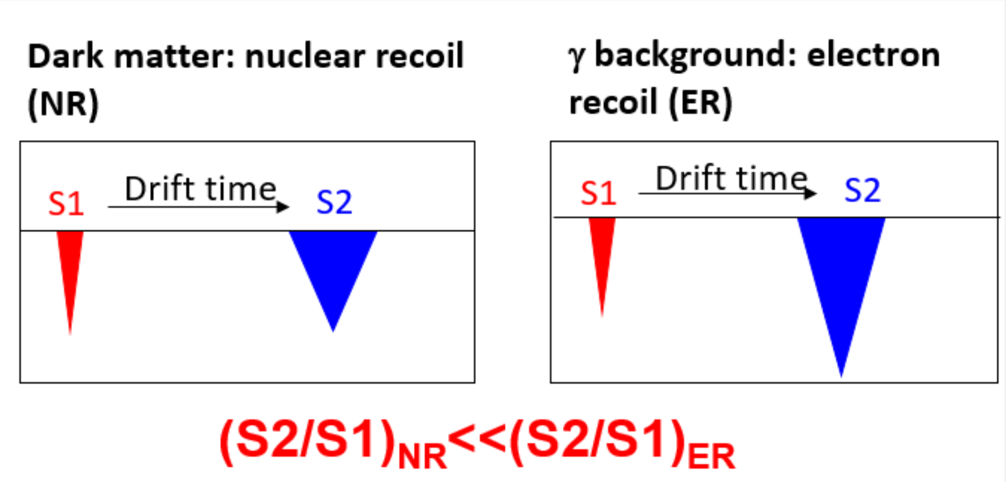


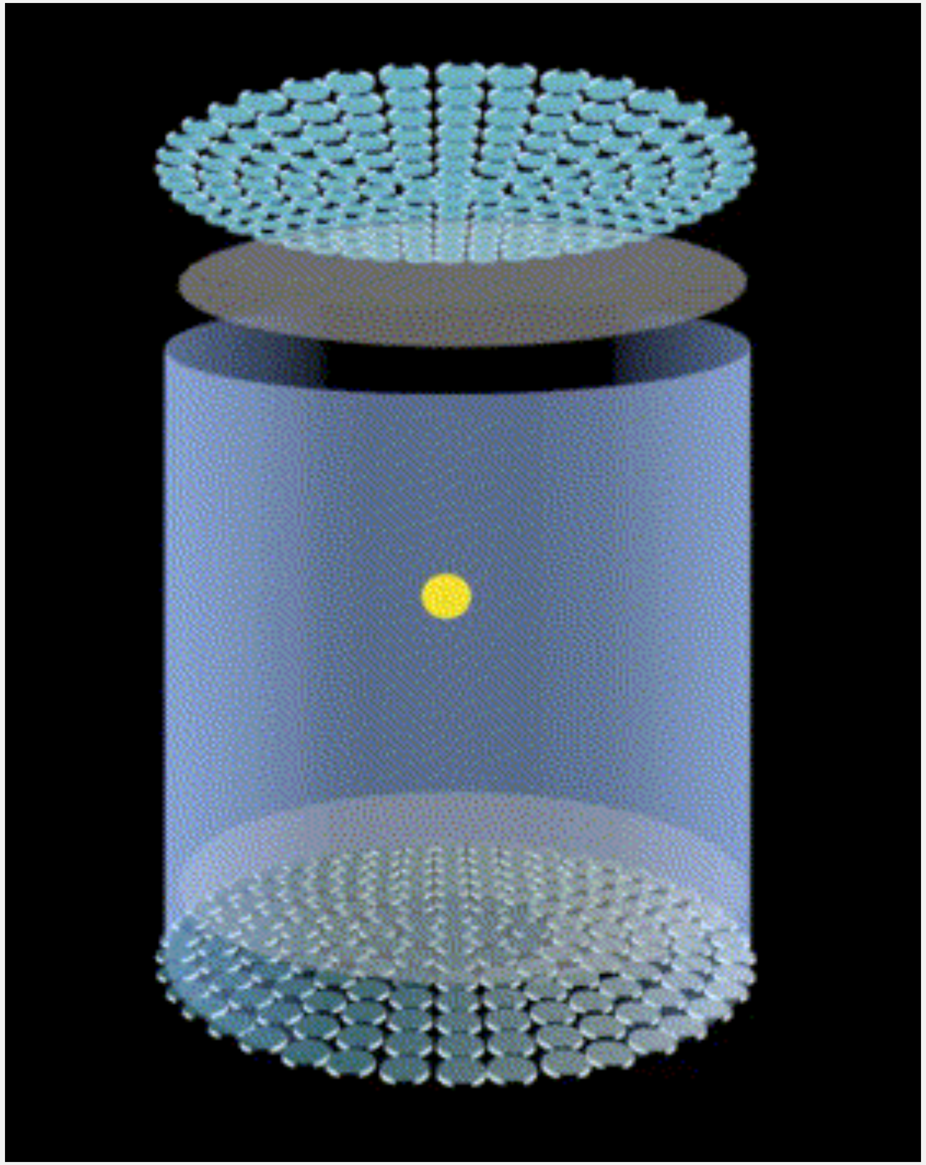


R. Essig, T. Volansky, T.-T. Yu PRD 96, 043017 (2017)

S2-only Strategy

- Dual-phase xenon TPC

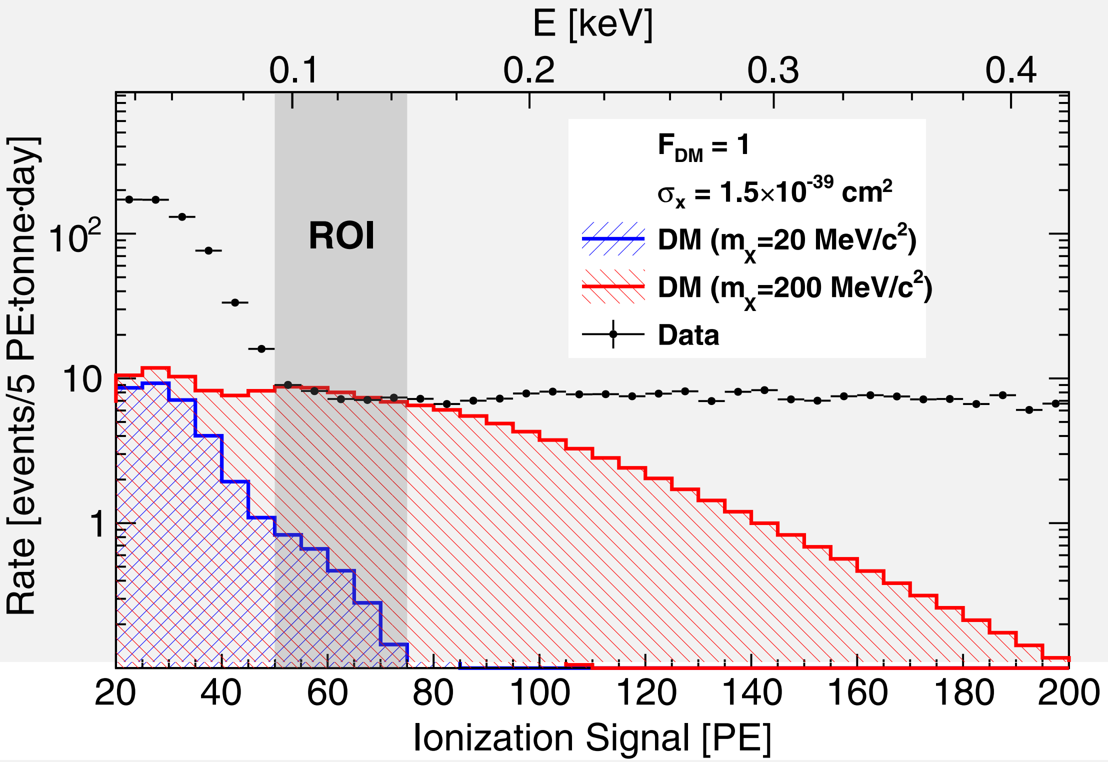




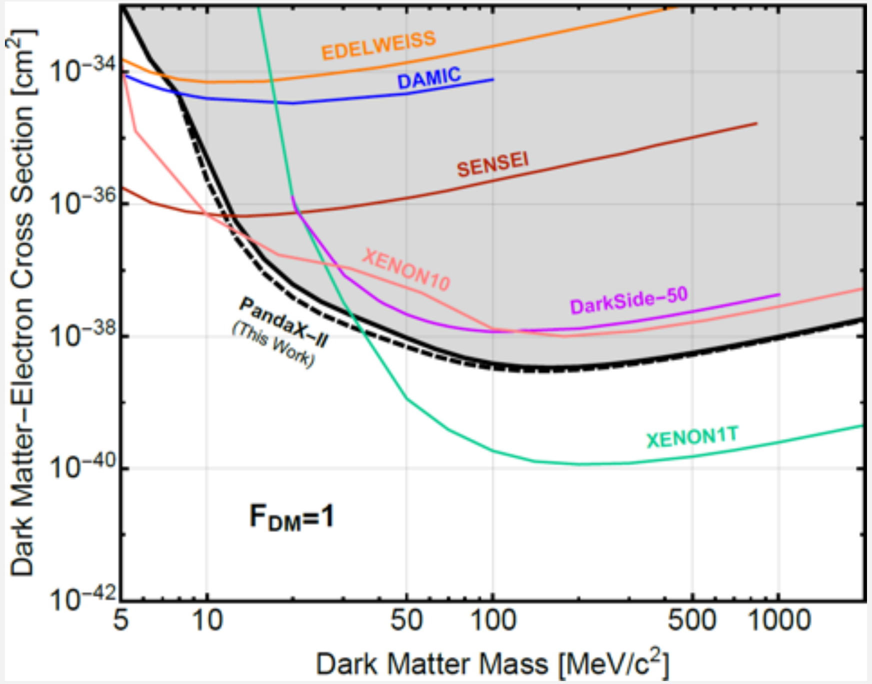
- To lower the threshold: S2-only

WIMP-electron scattering

- Light WIMP scattering with electrons
- S2-only analysis：effective threshold 80eV
- 15-30 MeV/c^2 WIMP: strongest constraints

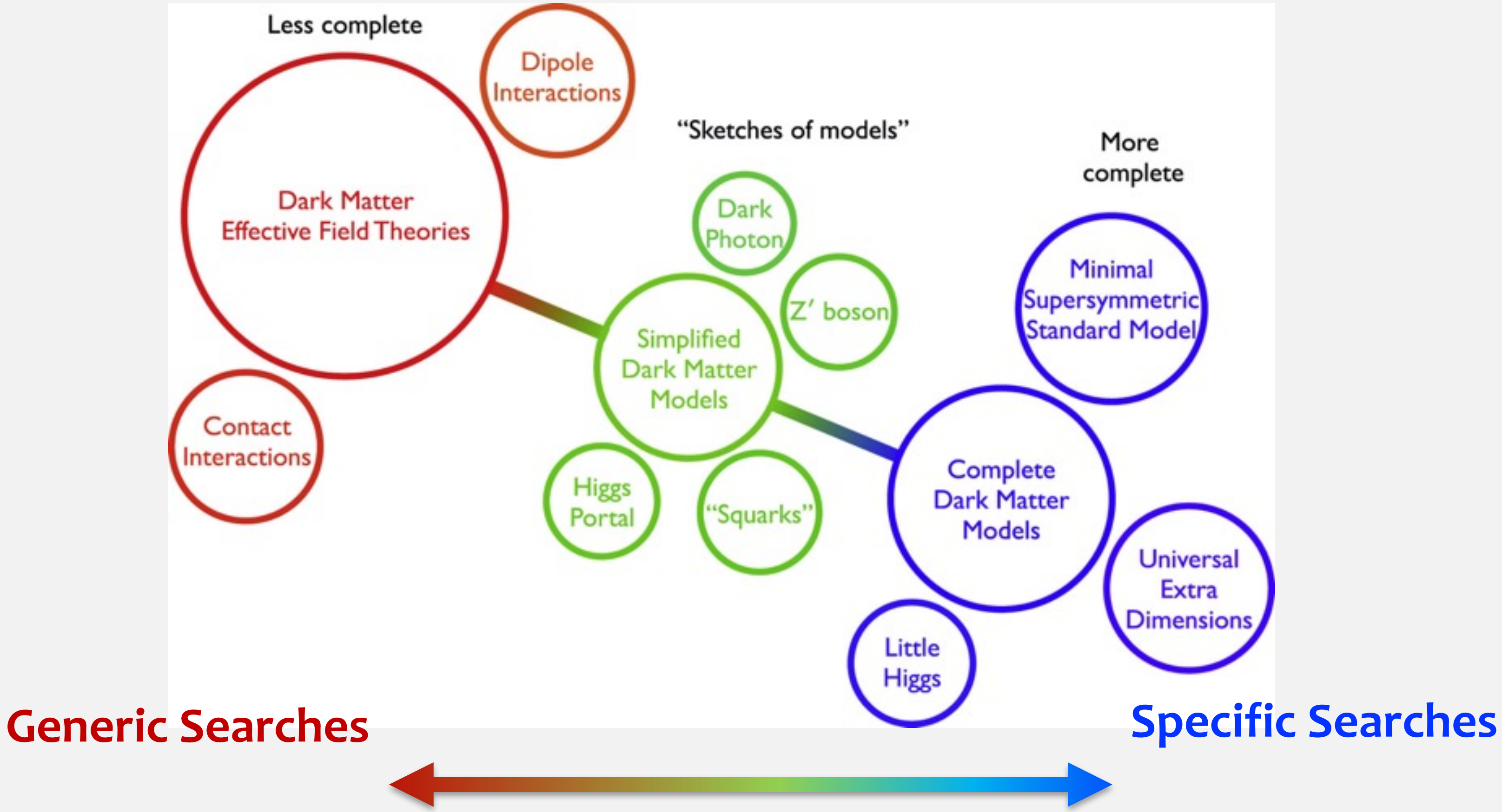


PRL 126, 211803 (2021)

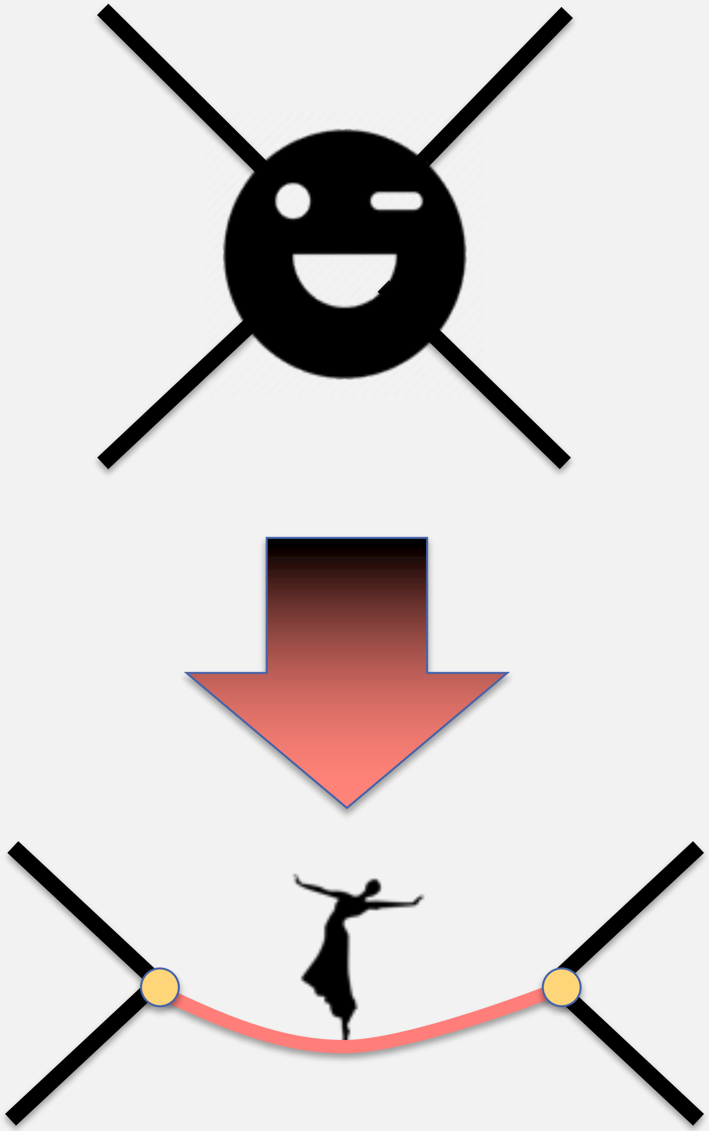


Dark Matter Models

- Toward simplified model or UV-complete model
  - some interesting signatures come out



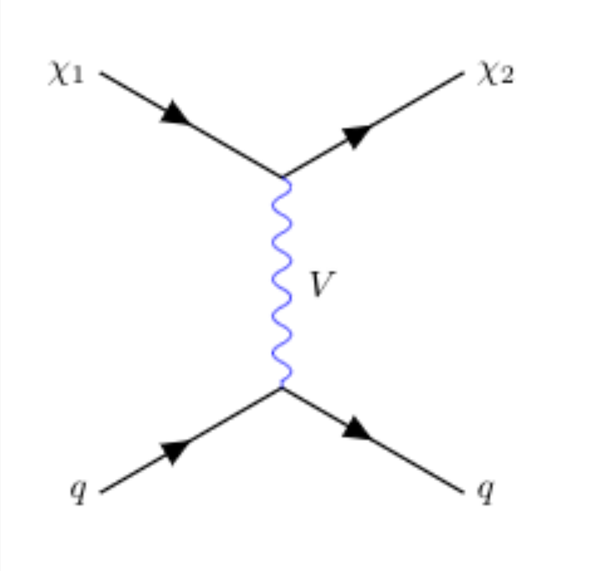
Phys. Dark Univ. 9-10 (2015) 8-23

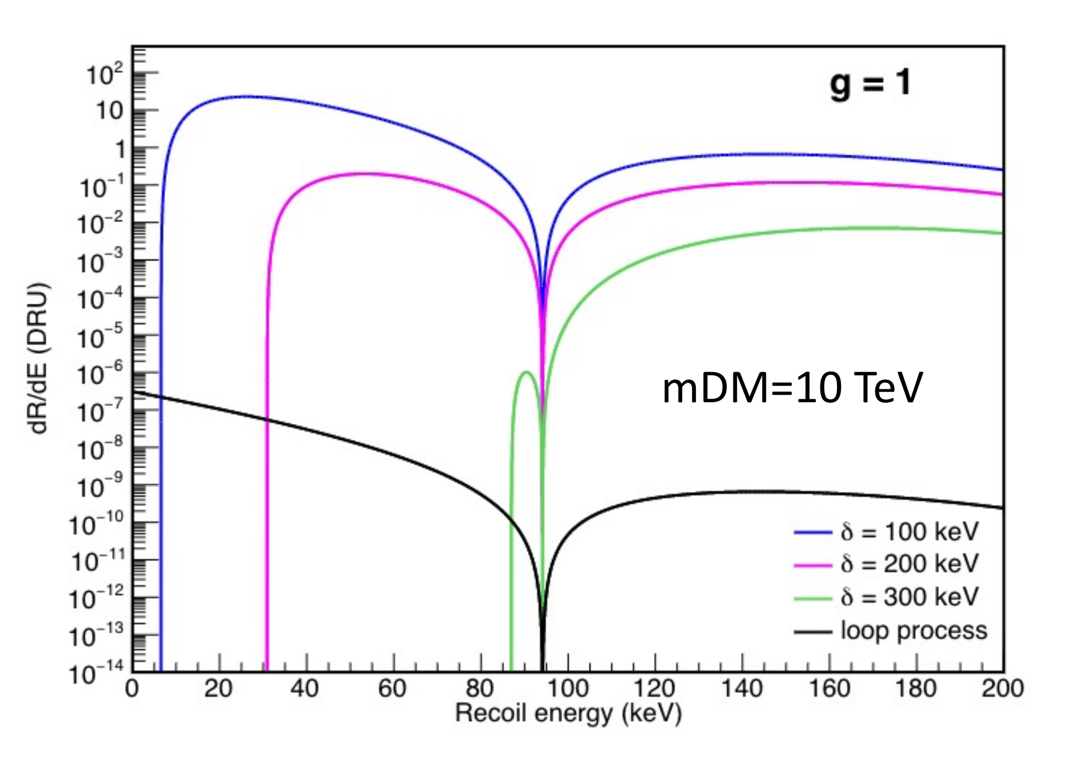


Two-component Majorana DM

- Strong constraints on DM-nucleon elastic scattering
- 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
  - 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

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



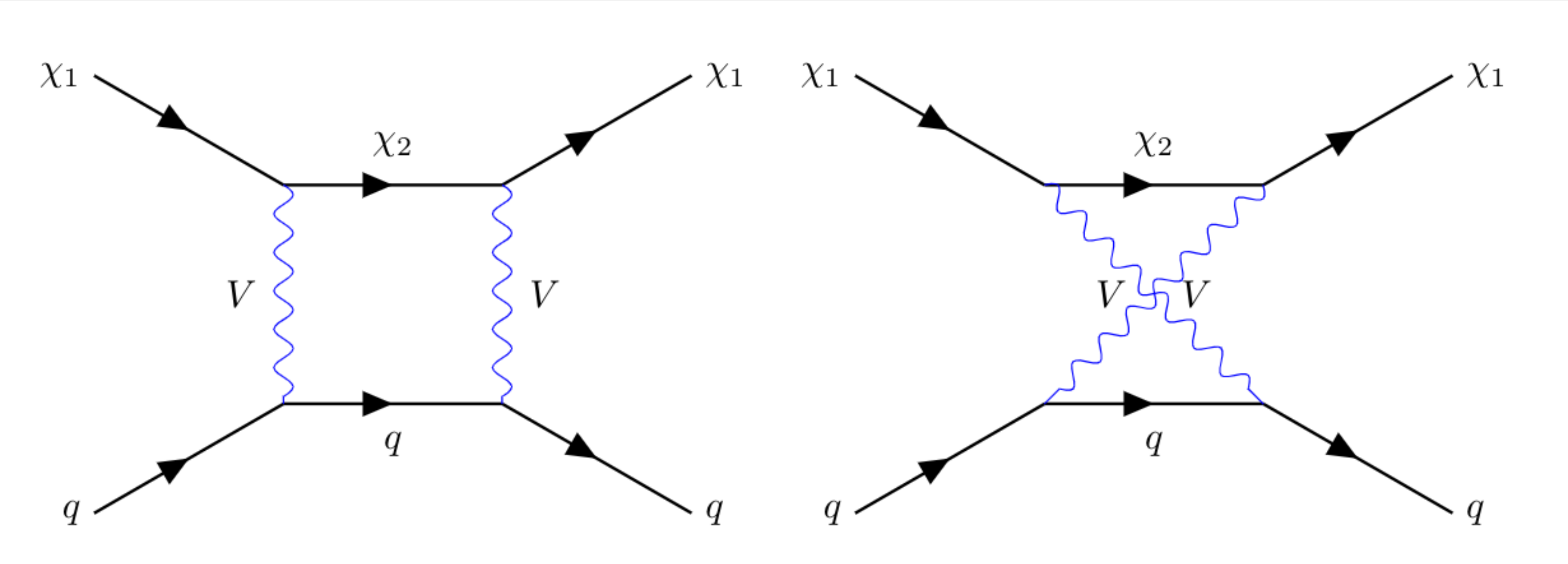


Loop Contribution

- Box diagram
  - elastic scattering
  - no kinematic suppression
  - but with mediator mass suppression

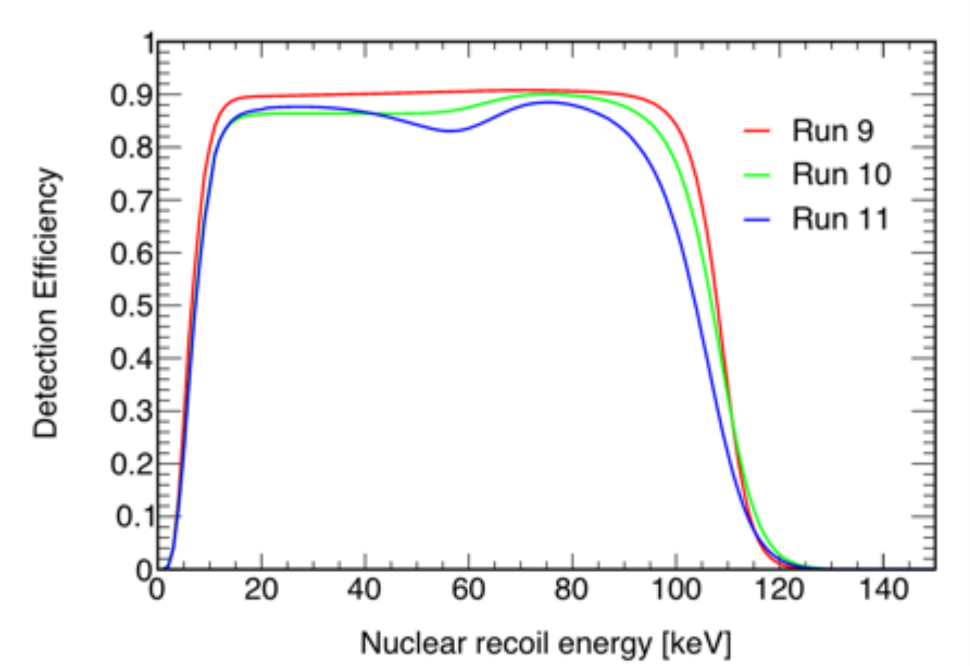
$$L_{\mathrm{loop}} = \frac{4g^4 m_{\chi_1} m_{\mathrm{q}}}{16\pi^2 M^4} F_3\left(\frac{m_{\chi_1}^2}{M^2}\right)\bar{\chi}_1\chi_1\bar{q}q \to c_1^{\mathrm{N}}\bar{\chi}_1\chi_1\bar{N}N,$$

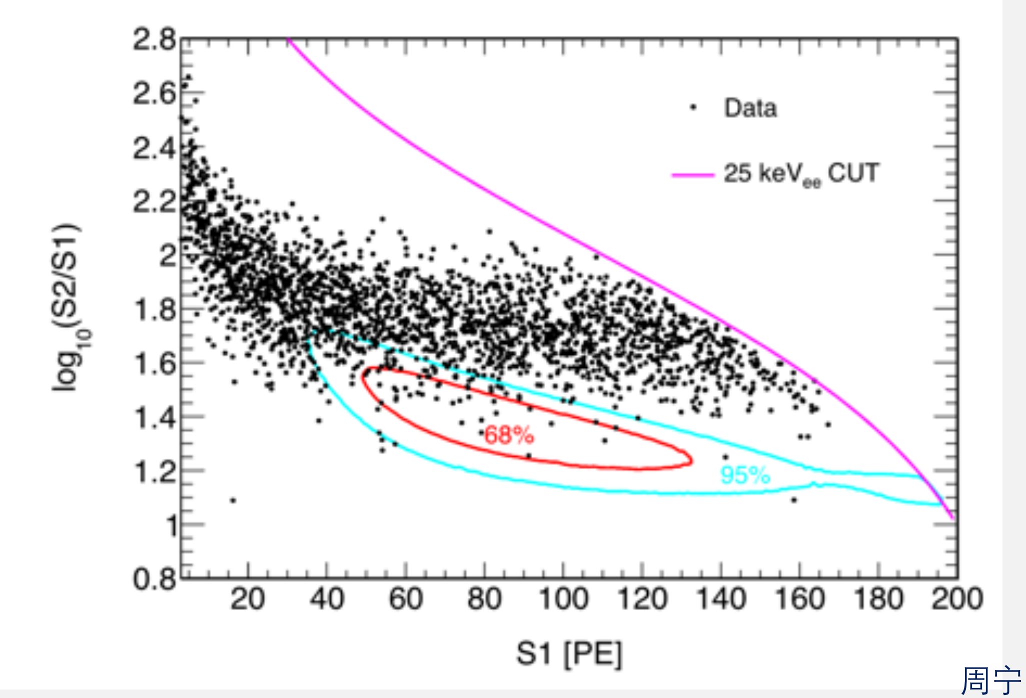
- Complementary to tree-level especially for large mass splitting

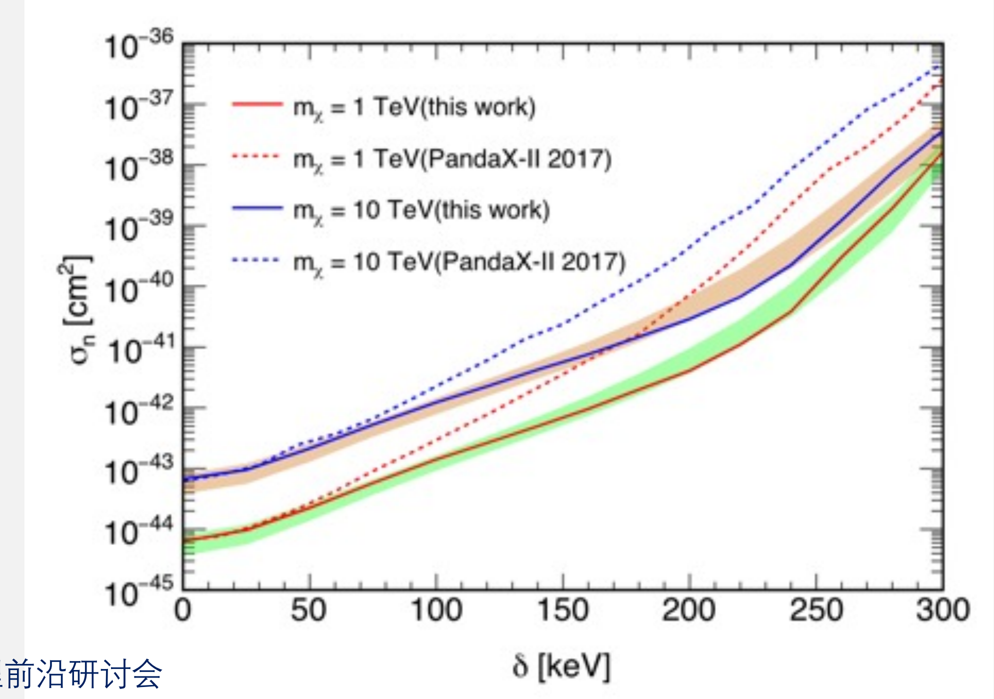


PandaX-II Search

- Extending signal region
  - Improve the sensitivity to high mass splitting
- PandaX-II full exposure data



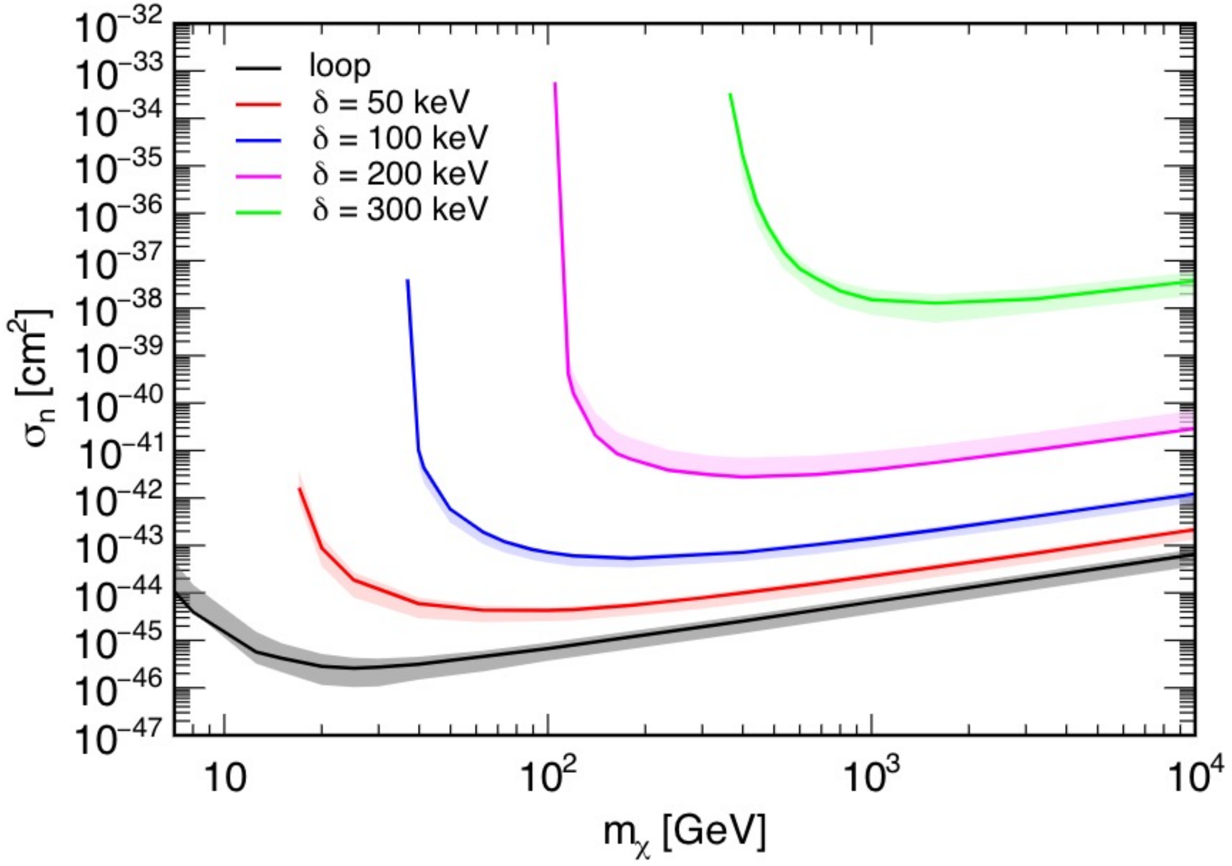


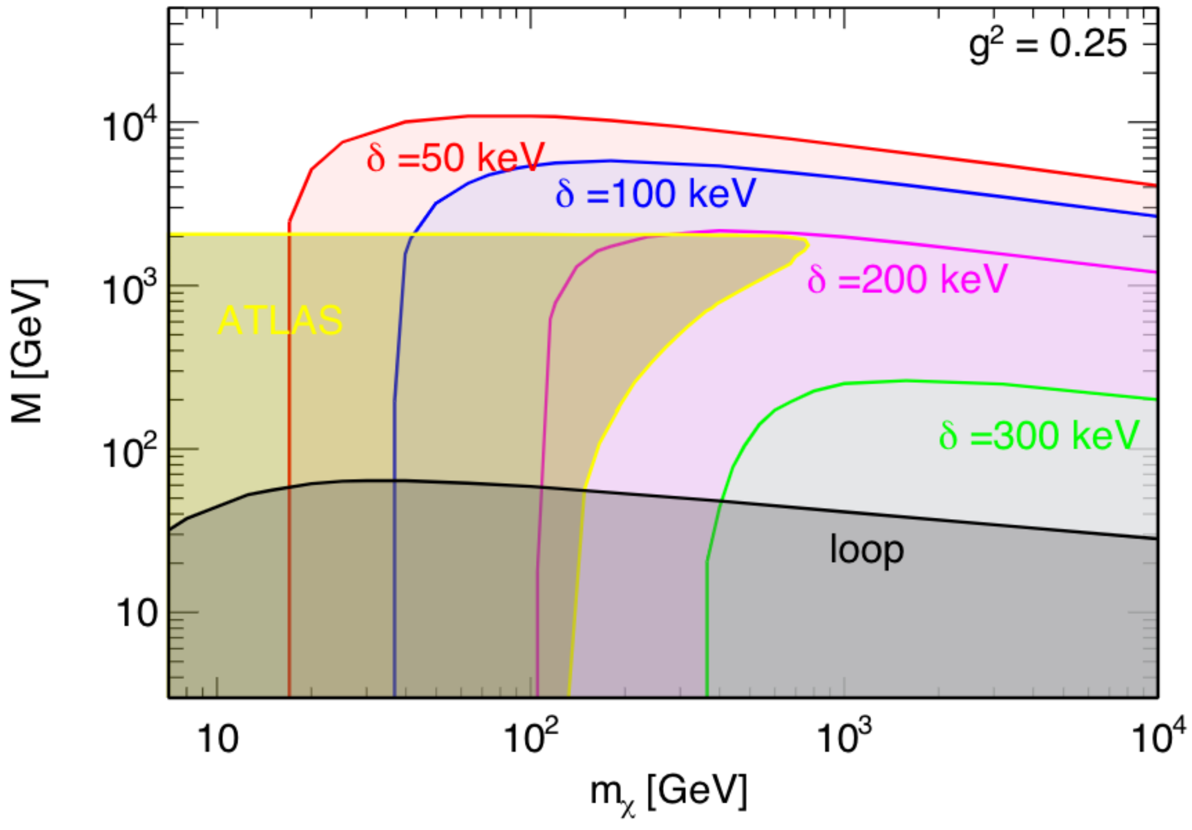


Combine Inelastic and Elastic

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

PLB 832 (2022) 137254



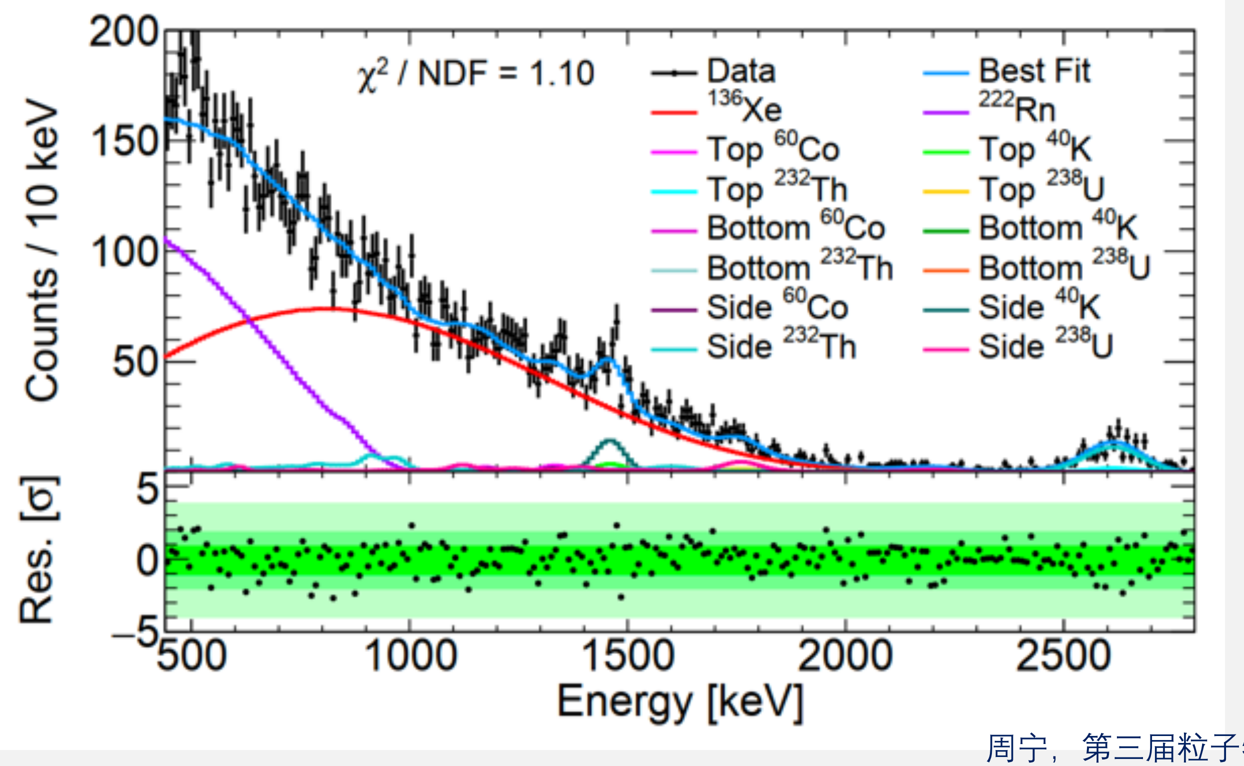


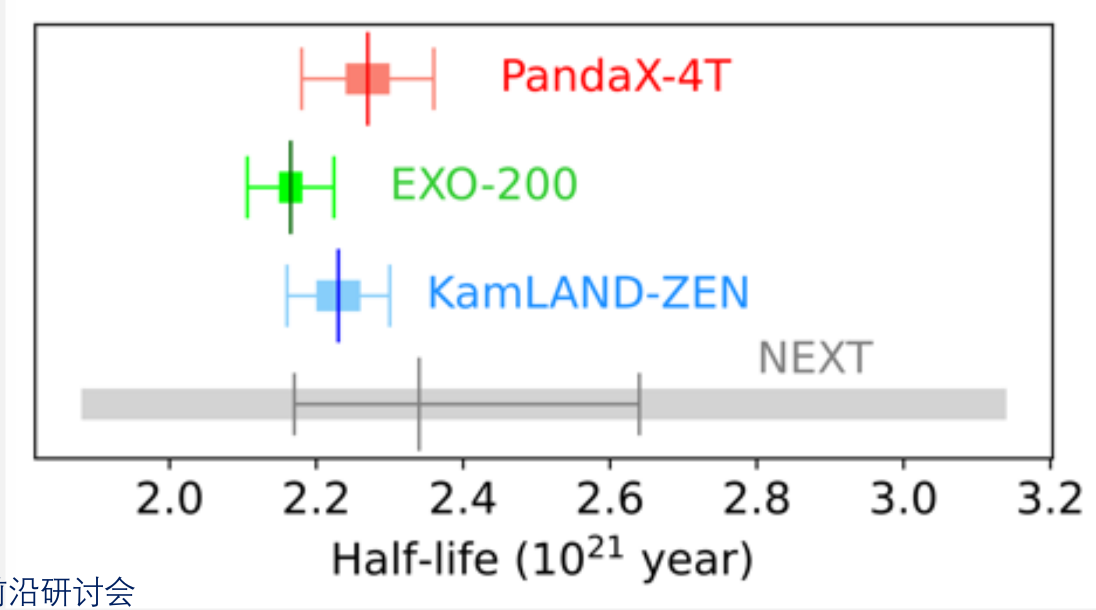
^{136}Xe DBD Measurement

详见成兆侃的报告

- First measurement from dark matter detector
- 649.7±6.5 kg natural xenon in FV and 94.9 days of data,
  – the total fitted number of Xe-136 DBD events is 17468±243 in ROI of 440 to 2800 keV
- Xe-136 DBD half-life is measured as: 2.27±0.03(stat.)±0.09(syst.)×10^{21} yr

arXiv:2205.12809





3rd Generation Xenon Experiments

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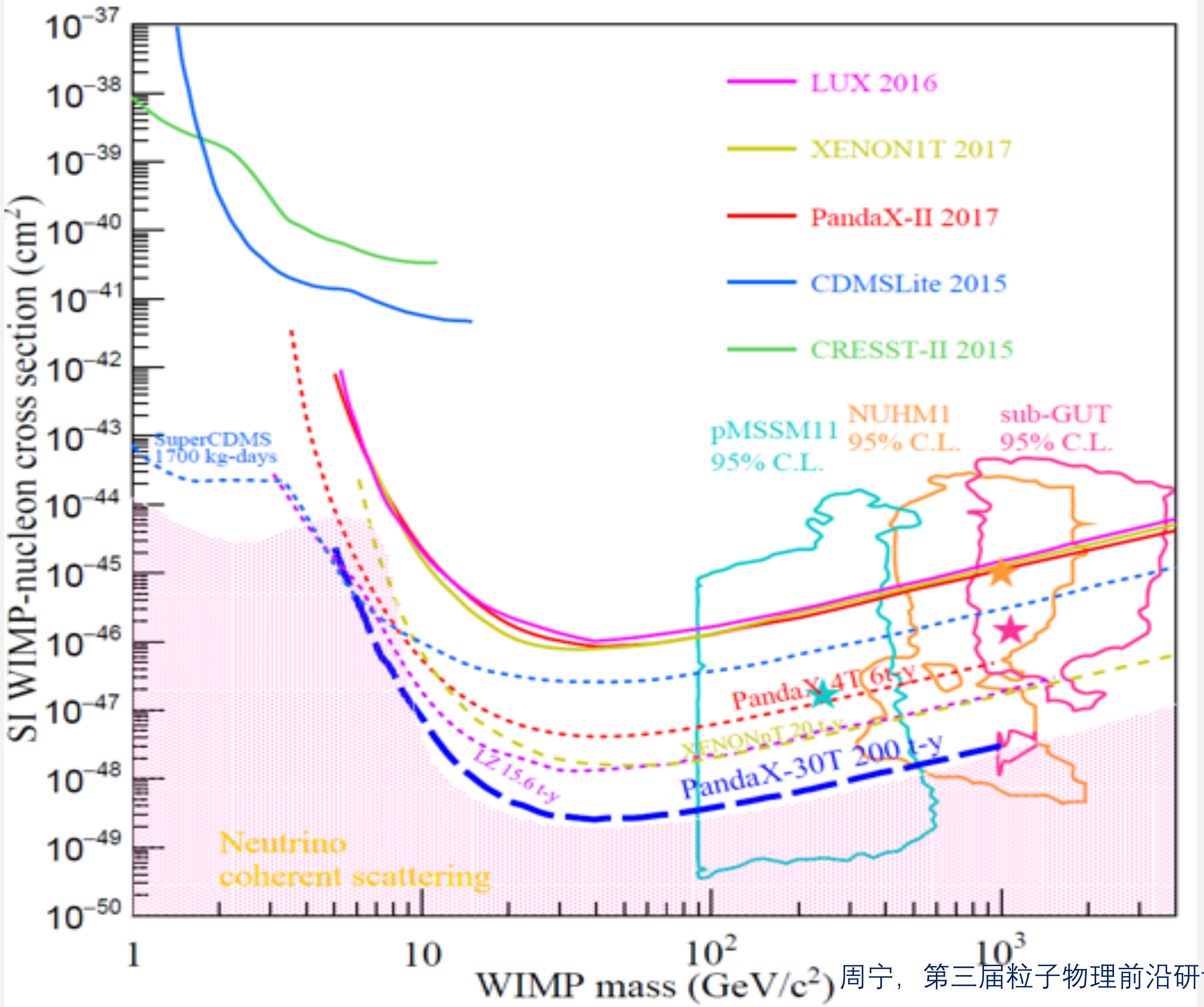
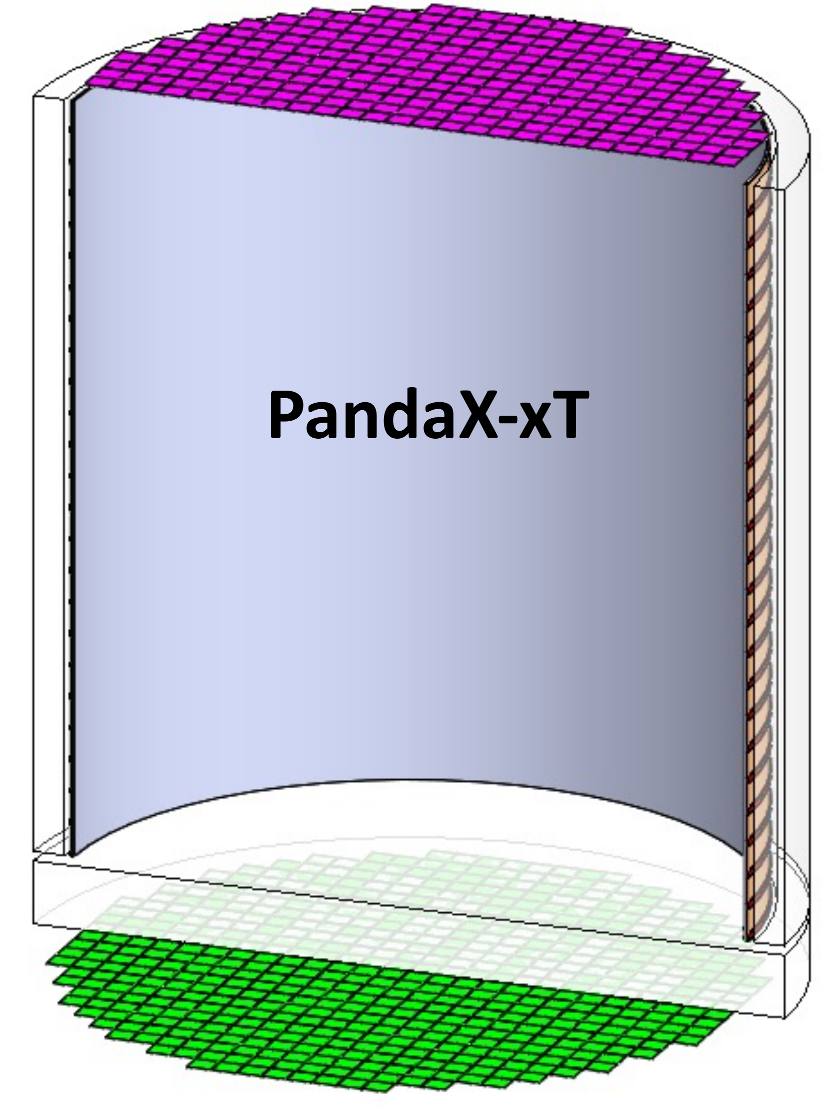


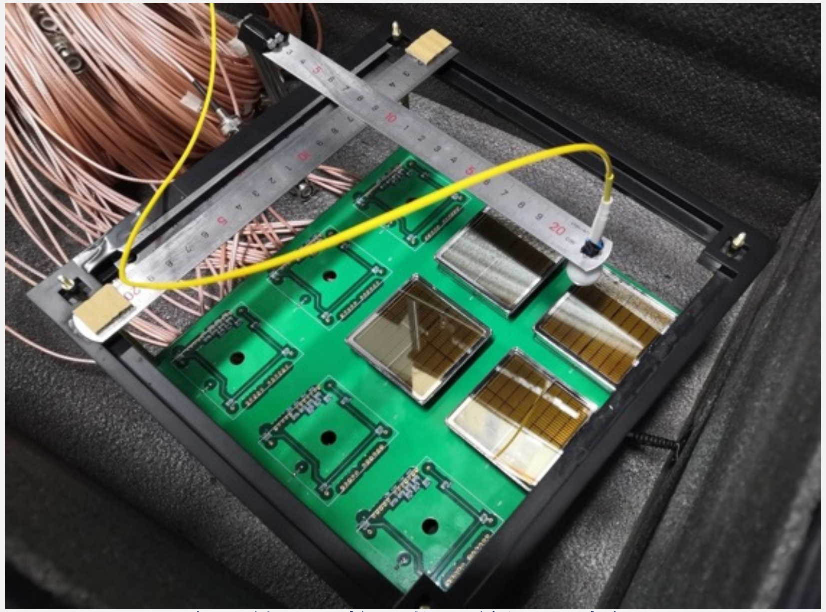


PandaX-xT R&D

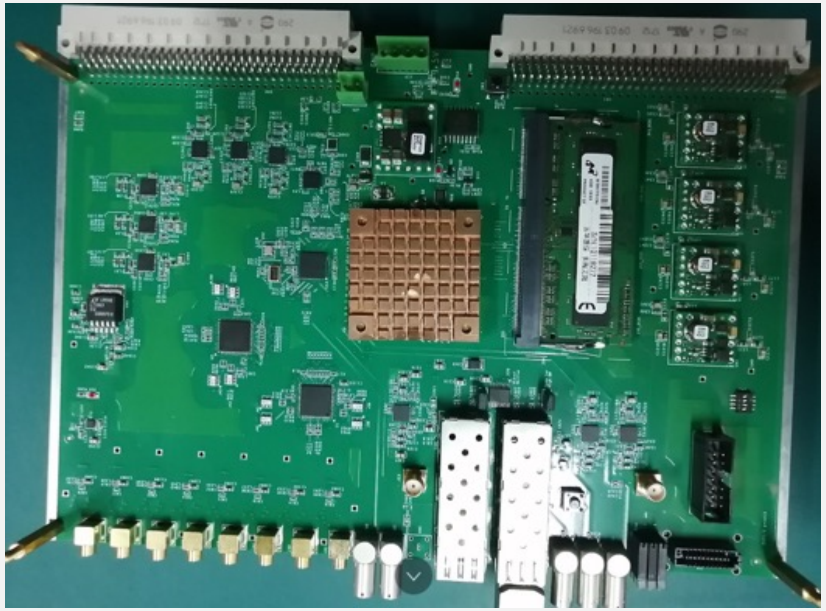
- 李政道研究所暗物质和中微子实验平台

研发时间投影室大尺寸高透光电极

研发新型两英寸超低本底光电管



自研高速波形采集卡（500MB/s）



Summary

- Dark matter detection plays a key role in new physics search.
- In China, a sizeable team has formed, producing leading results
- Active communication among theorists and experimentalists

Backup

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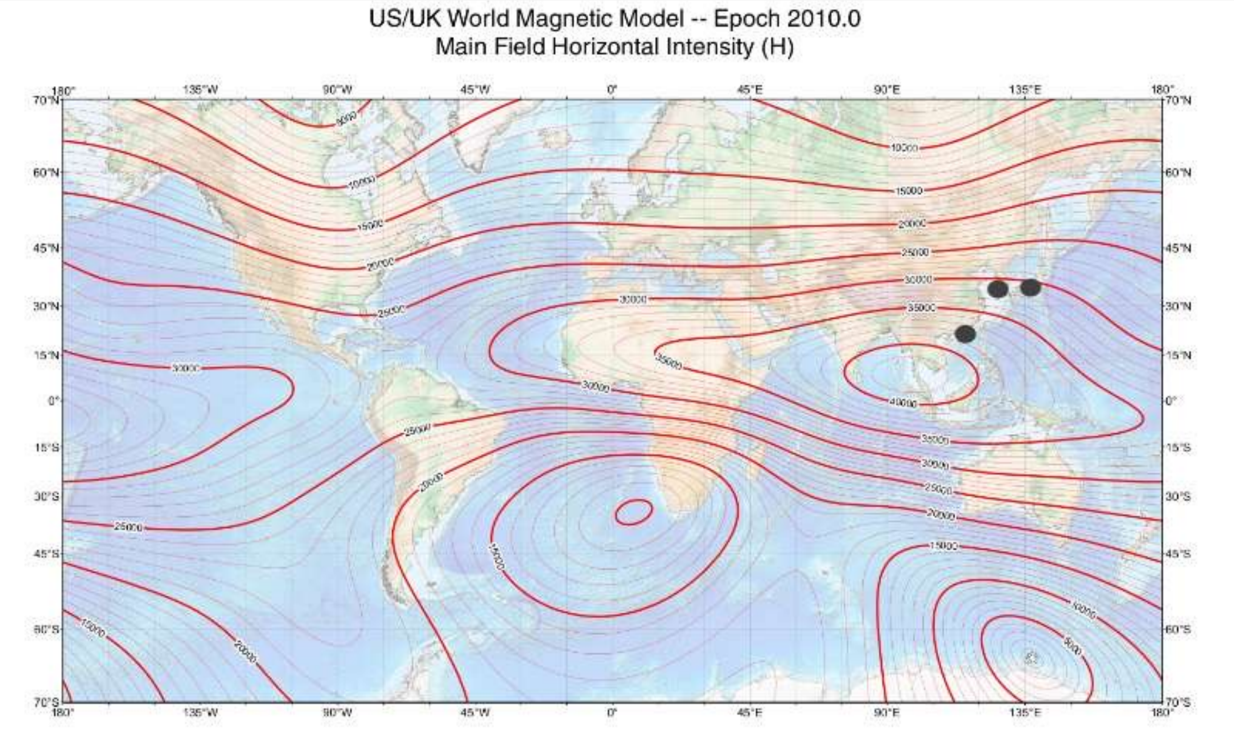
Neutrino floor

- Non-uniform atmosphere neutrinos distribution, due to magnetic field
- CJPL has a unique advantage towards the "neutrino floor"



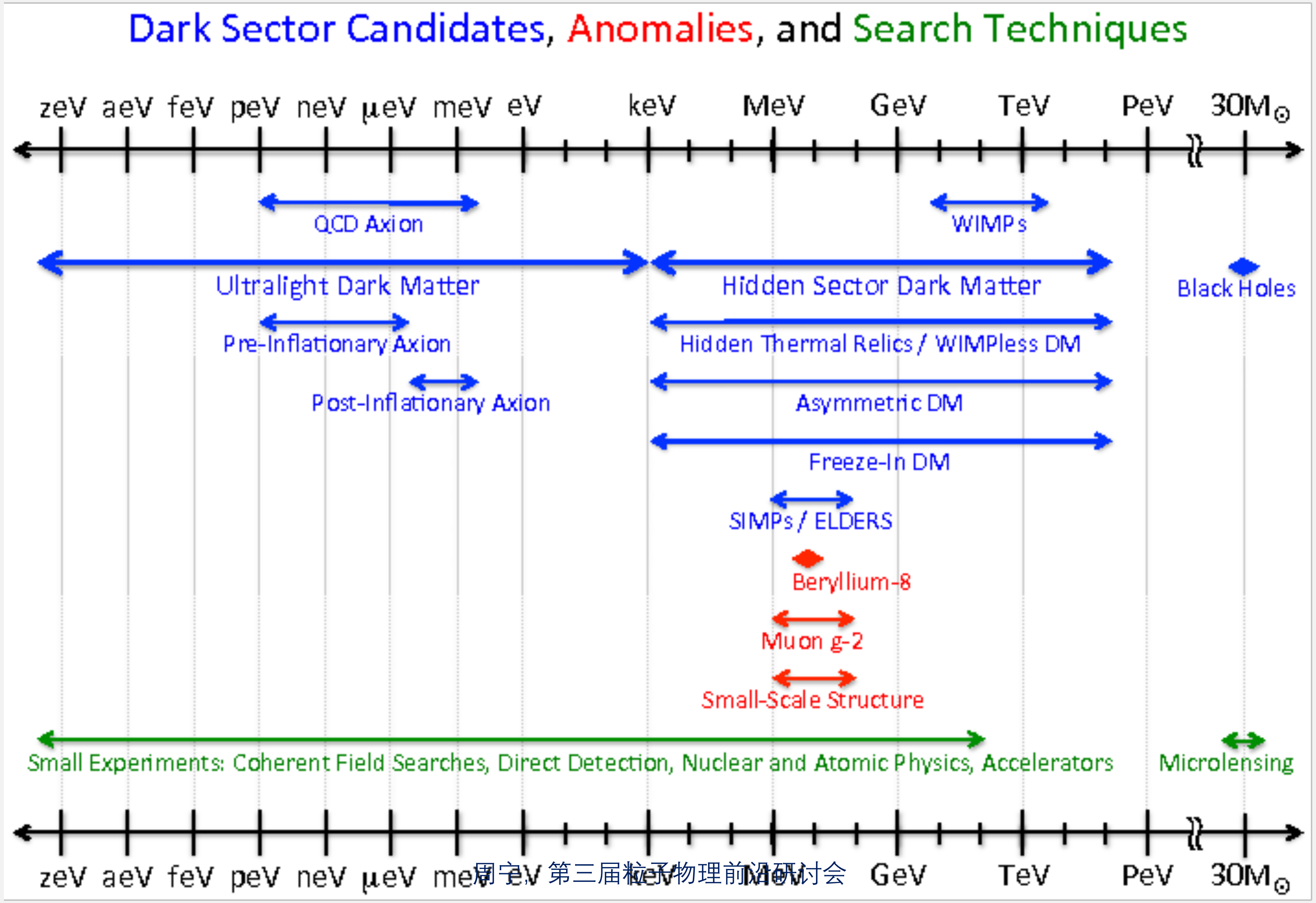
magnetic field

Site	Flux (m^2 sec sr GeV)^-1 [100MeV]
Kamioka	4249
Gran Sasso	7304
Sudbury	11879
Frejus	8215
INO	2554
South Pole	12001
Pythasalmi	12208
Homestake	11774
JUNO	2871

Honda et al. arXiv: 1502.03916 neutrino flux

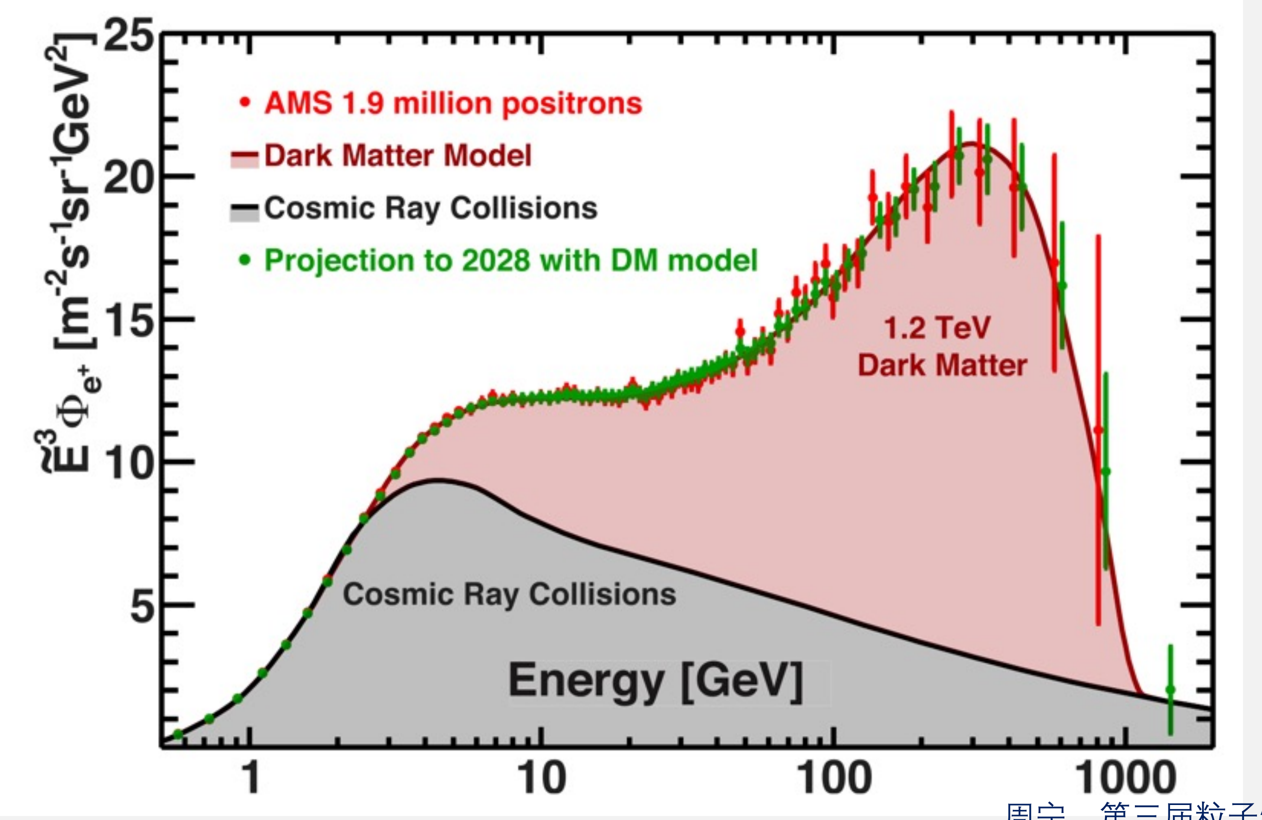
Dark Matter Candidates

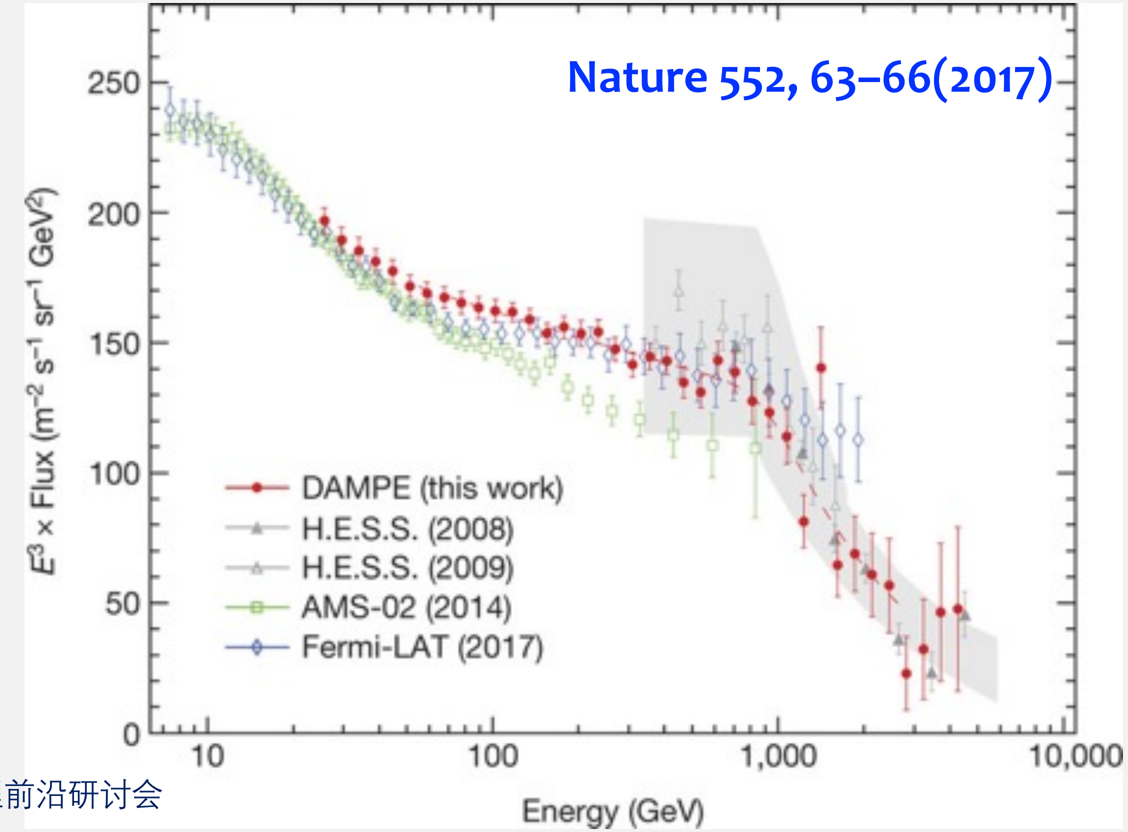
- WIMPs, Axions, ALPs, …: covering extremely large mass range



Indirect Detection

- AMS-02 experiment
  - positron spectrum
- DAMPE experiment
  - electron spectrum





Excess in Direct Detection

- XENON1T experiment， 1 tonne-year exposure， some small excess in nuclear recoil signal region
  - fitted with WIMP of 200 GeV mass, 3.56 events

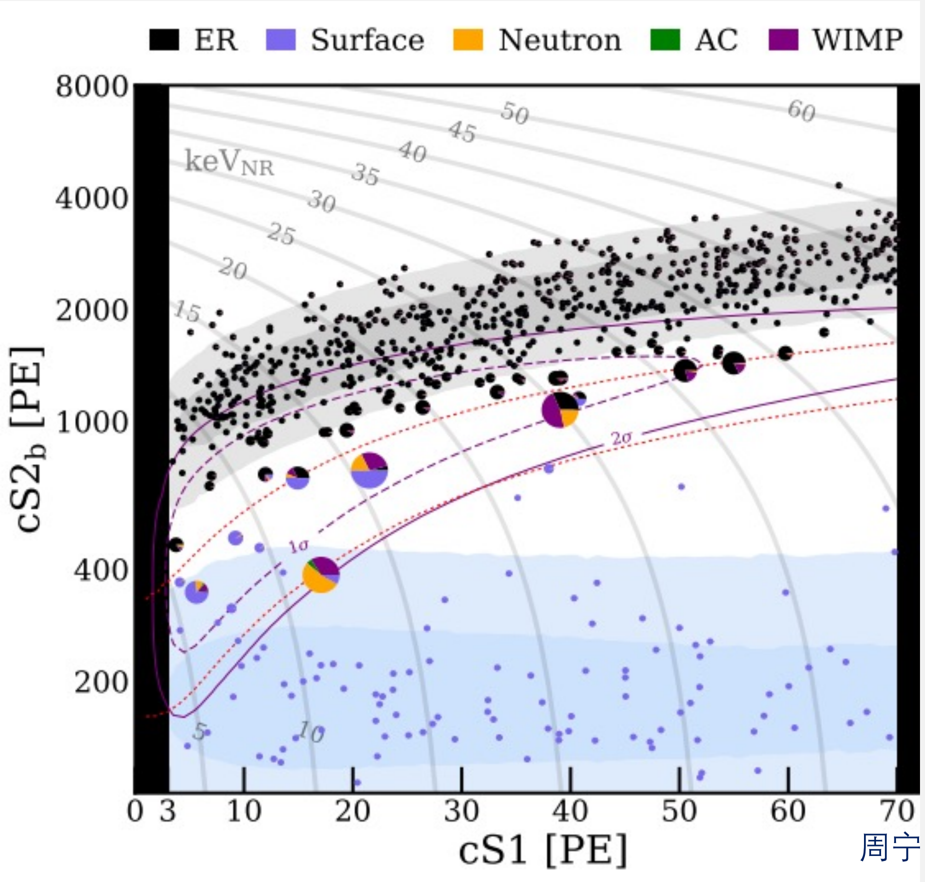


TABLE I: Best-fit expected event rates with 278.8 days livetime in the 1.3 t fiducial mass, 0.9 t reference mass, and 0.65 t core mass, for the full (cS1, cS2$_b$) ROI and, for illustration, in the NR signal reference region. The table lists each background (BG) component separately and in total, the observed data, and the expectation for a 200 GeV/c^2 WIMP prediction assuming the best-fit $\sigma_{SI} = 4.7 \times 10^{-47}$ cm^2.

Mass	1.3 t	1.3 t	0.9 t	0.65 t
(cS1, cS2$_b$)	Full	Reference	Reference	Reference
ER	627±18	1.62±0.30	1.12±0.21	0.60±0.13
neutron	1.43±0.66	0.77±0.35	0.41±0.19	0.14±0.07
CEνNS	0.05±0.01	0.03±0.01	0.02	0.01
AC	$0.47^{+0.27}_{-0.00}$	$0.10^{+0.06}_{-0.00}$	$0.06^{+0.03}_{-0.00}$	$0.04^{+0.02}_{-0.00}$
Surface	106±8	4.84±0.40	0.02	0.01
Total BG	735±20	7.36±0.61	1.62±0.28	0.80±0.14
WIMP$_{\text{best-fit}}$	3.56	1.70	1.16	0.83
Data	739	14	2	2

PRL 121, 111302 (2018)

Excess in Direct Detection

- XENON1T and XENONnT