Dark Matter Searches

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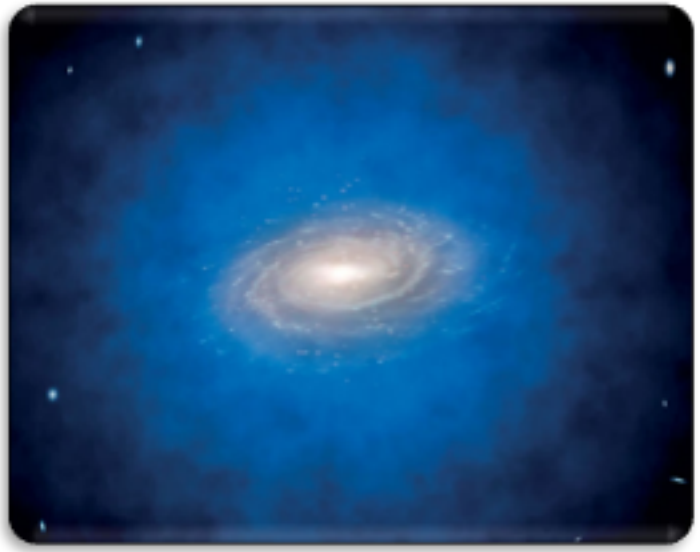
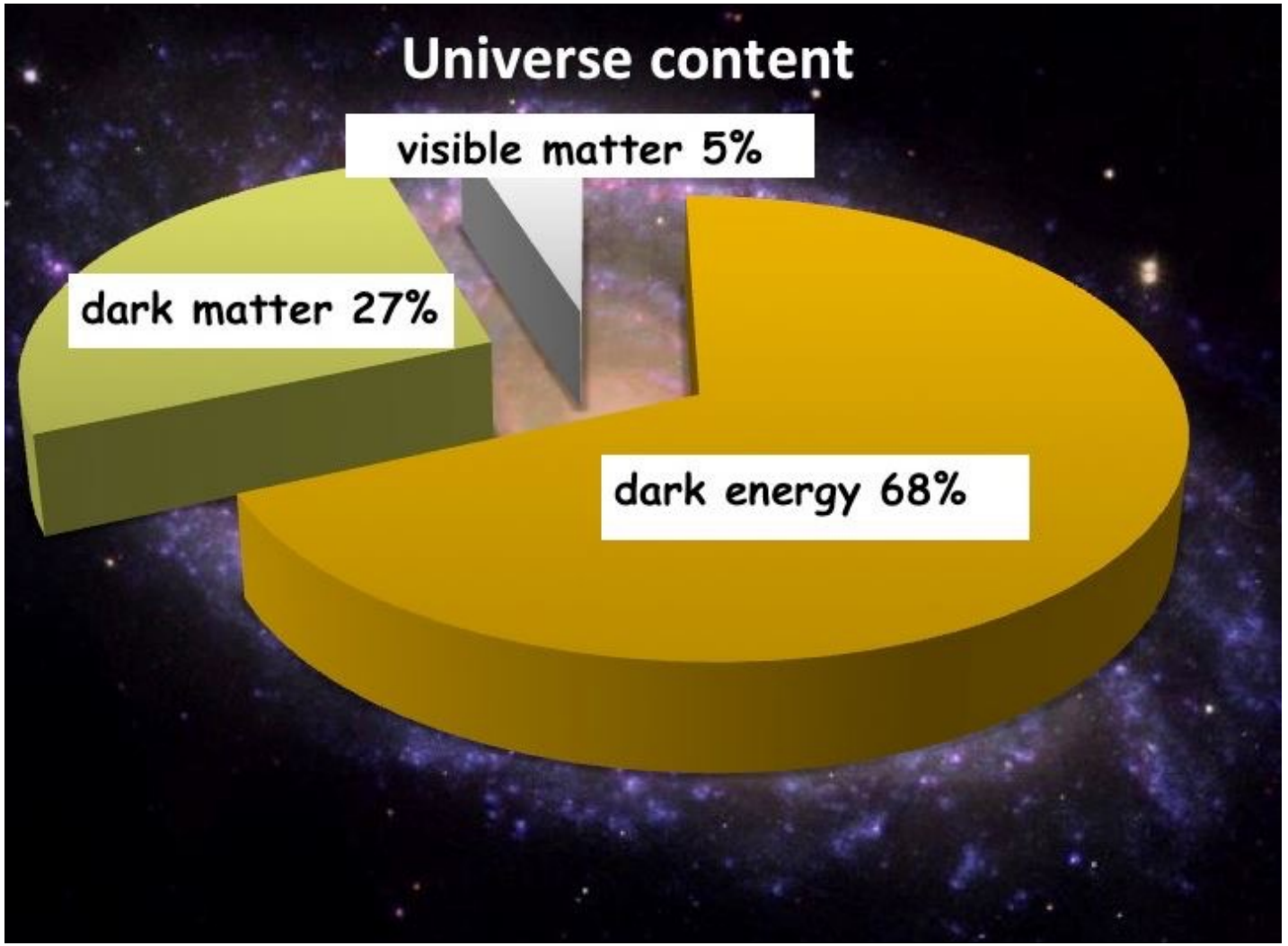
2022-05-07 IHEP

Dark Matter

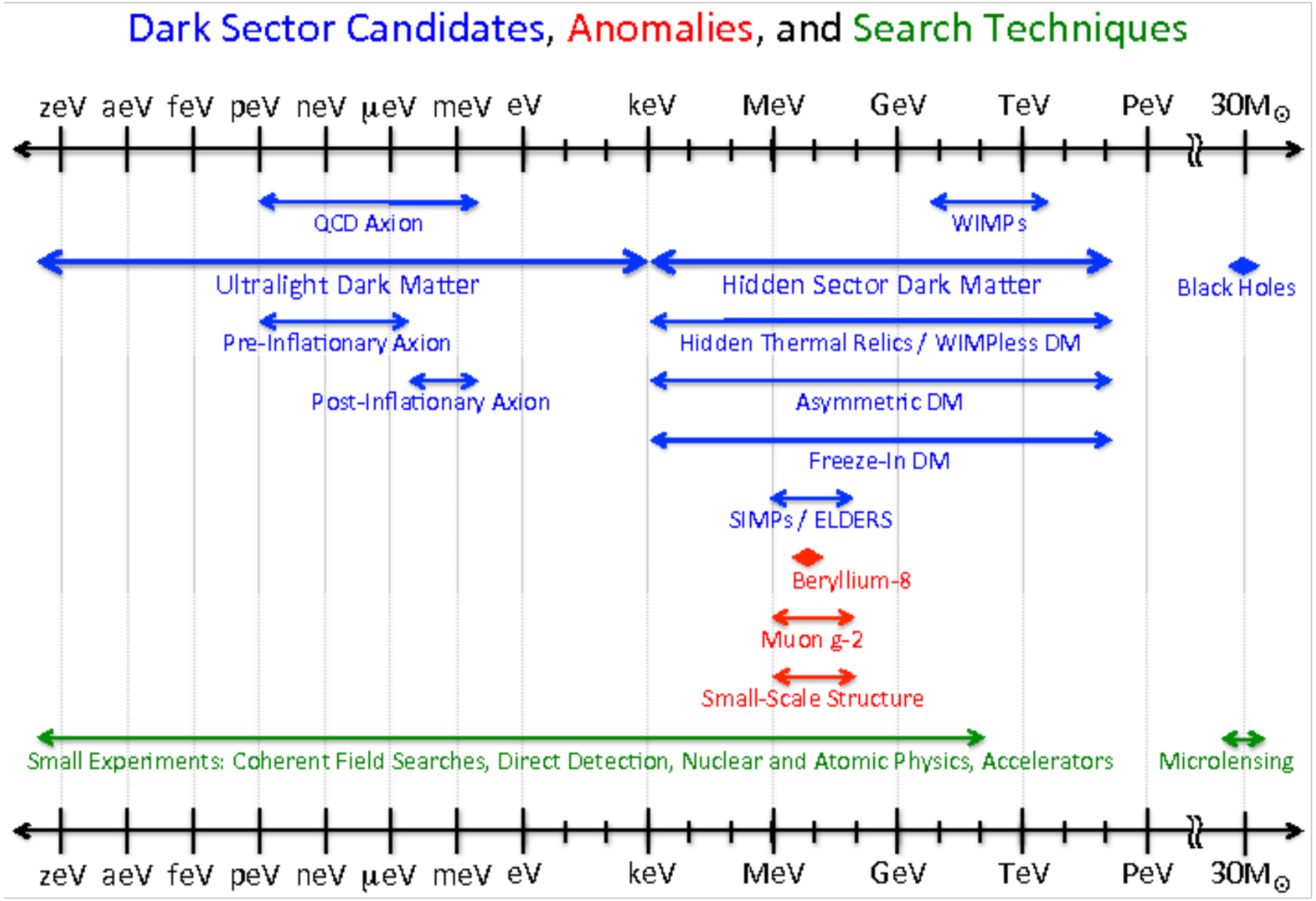
- Strong evidences for the existence of dark matter
- The nature of dark matter is unknown





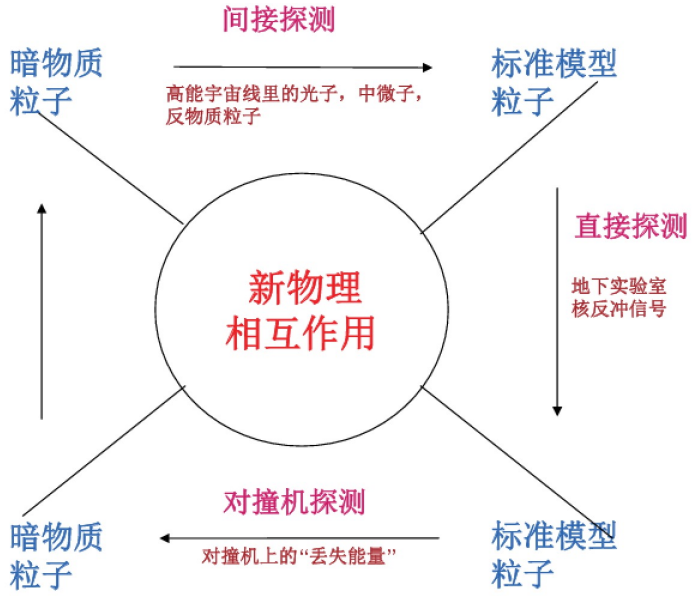
Dark Matter Candidates

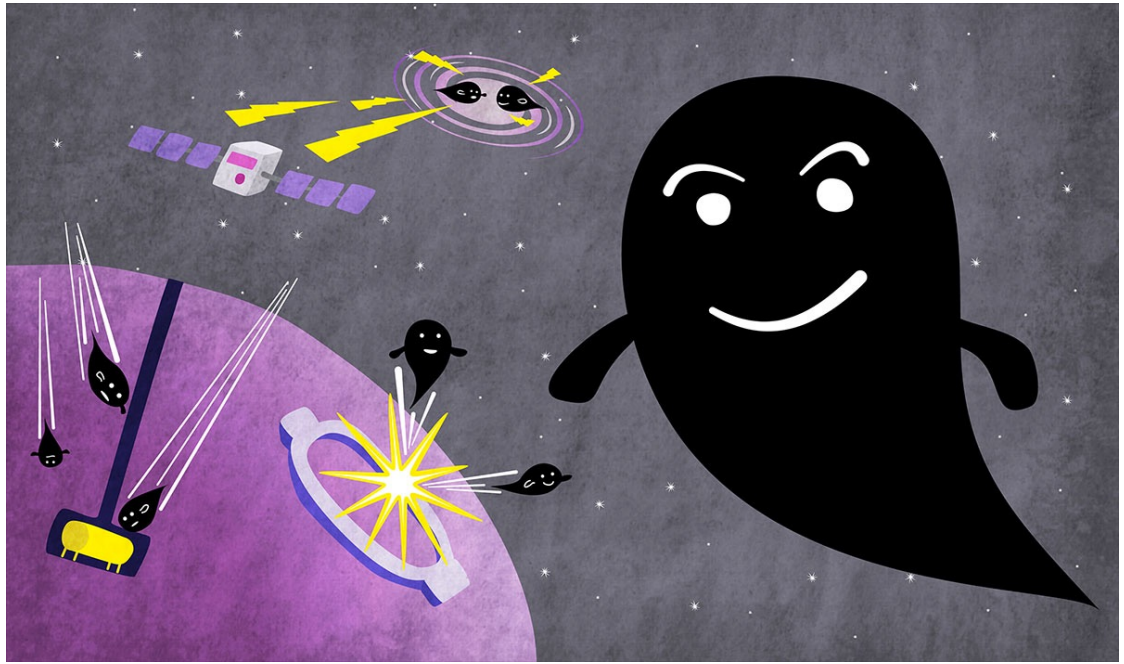
- WIMPs, Axions, ALPs, …: covering extremely large mass range

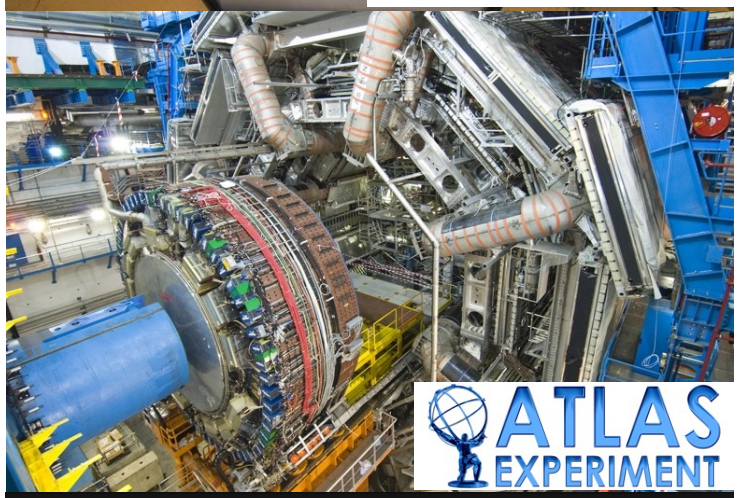


Dark Matter Detection

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

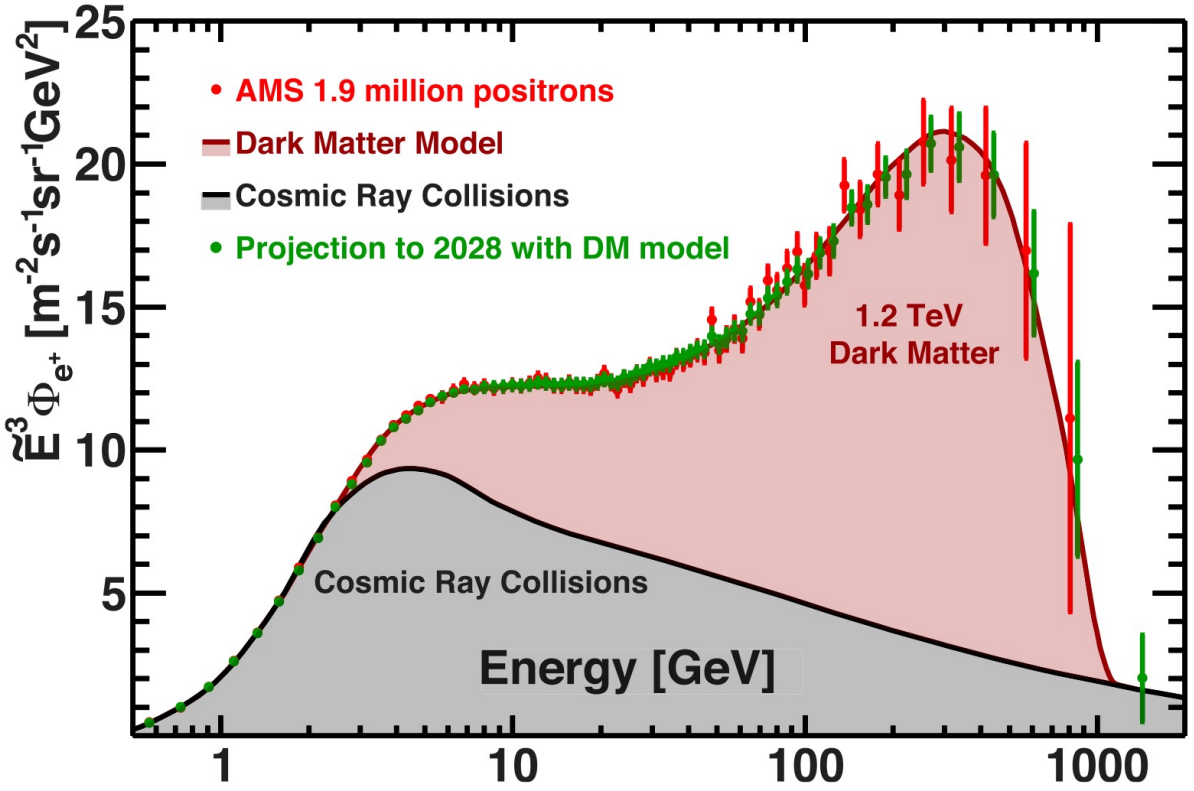


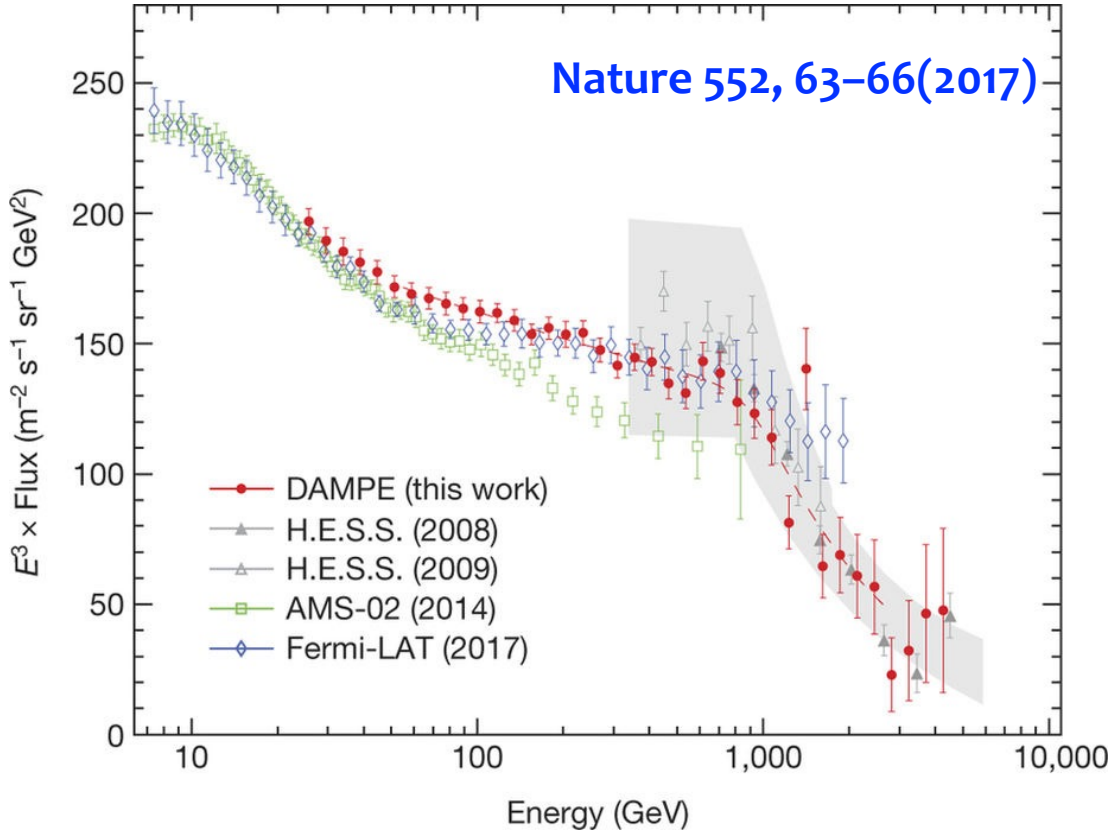




Indirect Detection

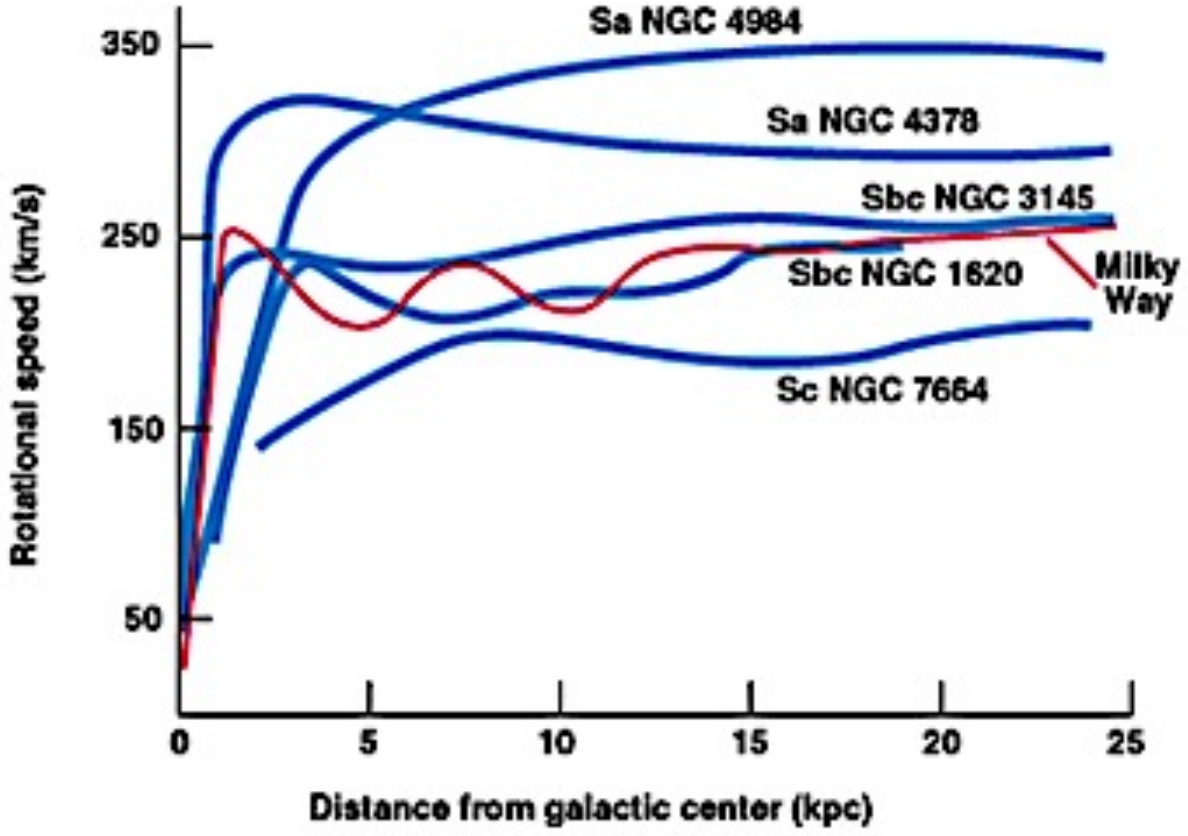
- AMS-02 experiment
  - positron spectrum
- DAMPE experiment
  - electron spectrum

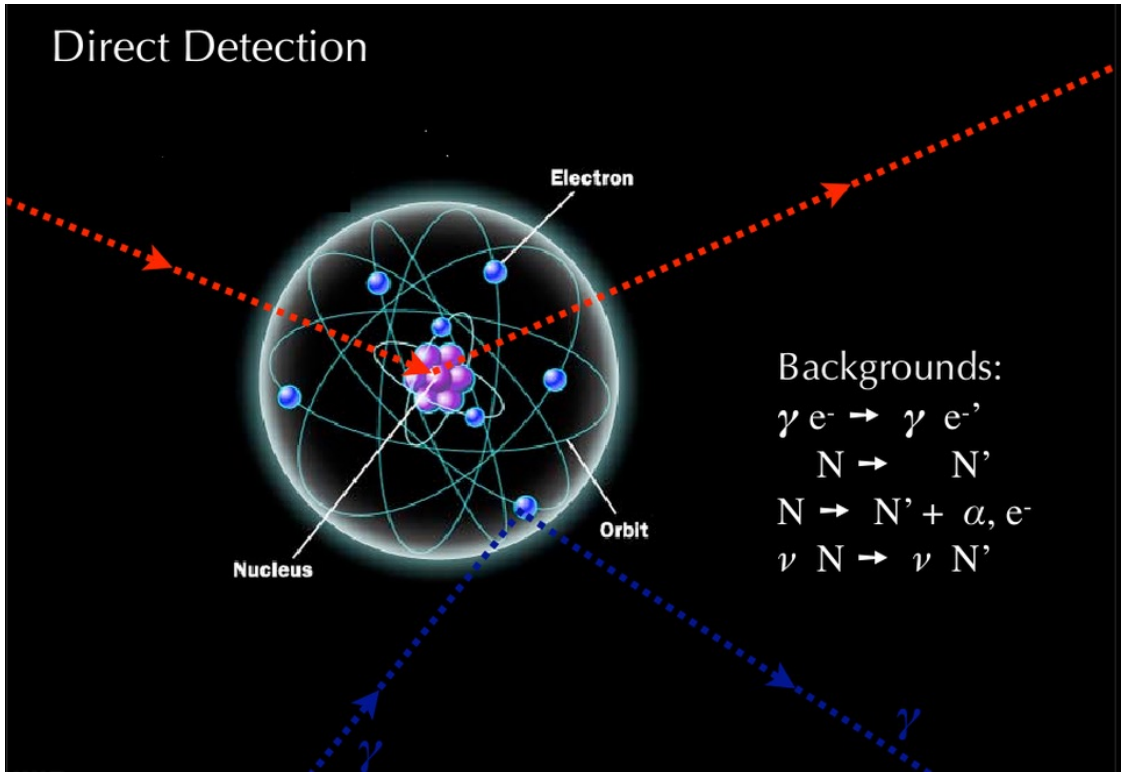




Direct Detection

- 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

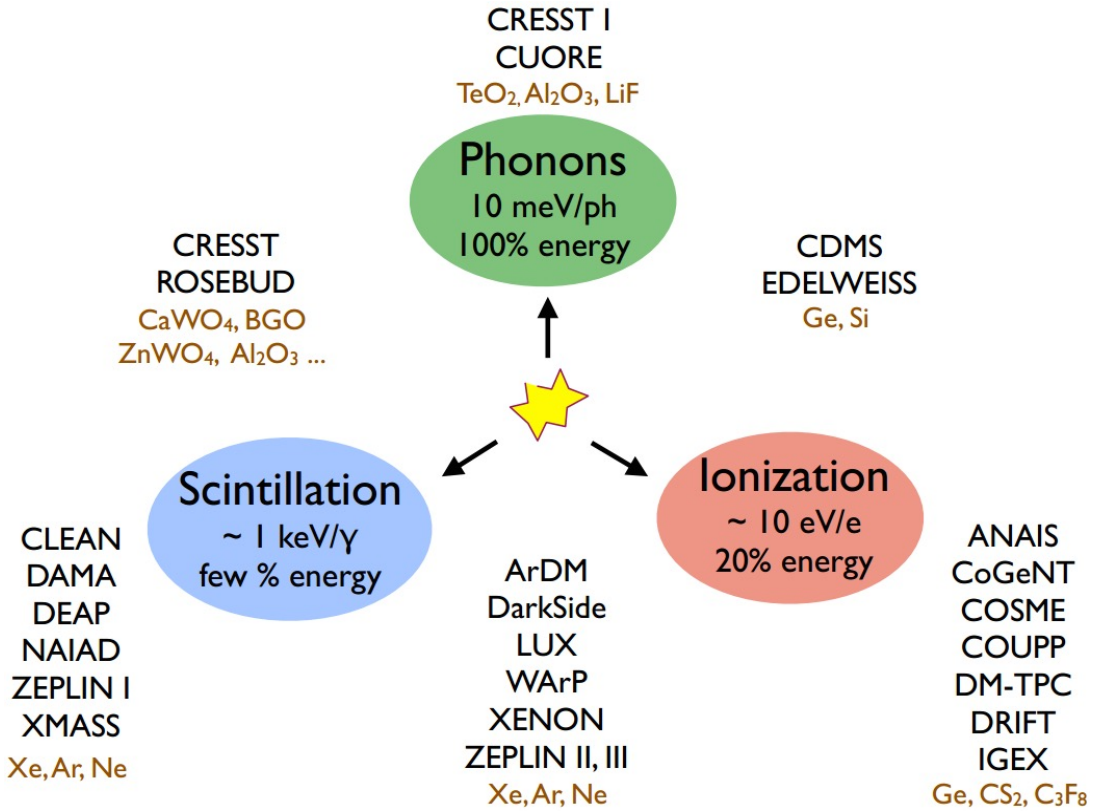


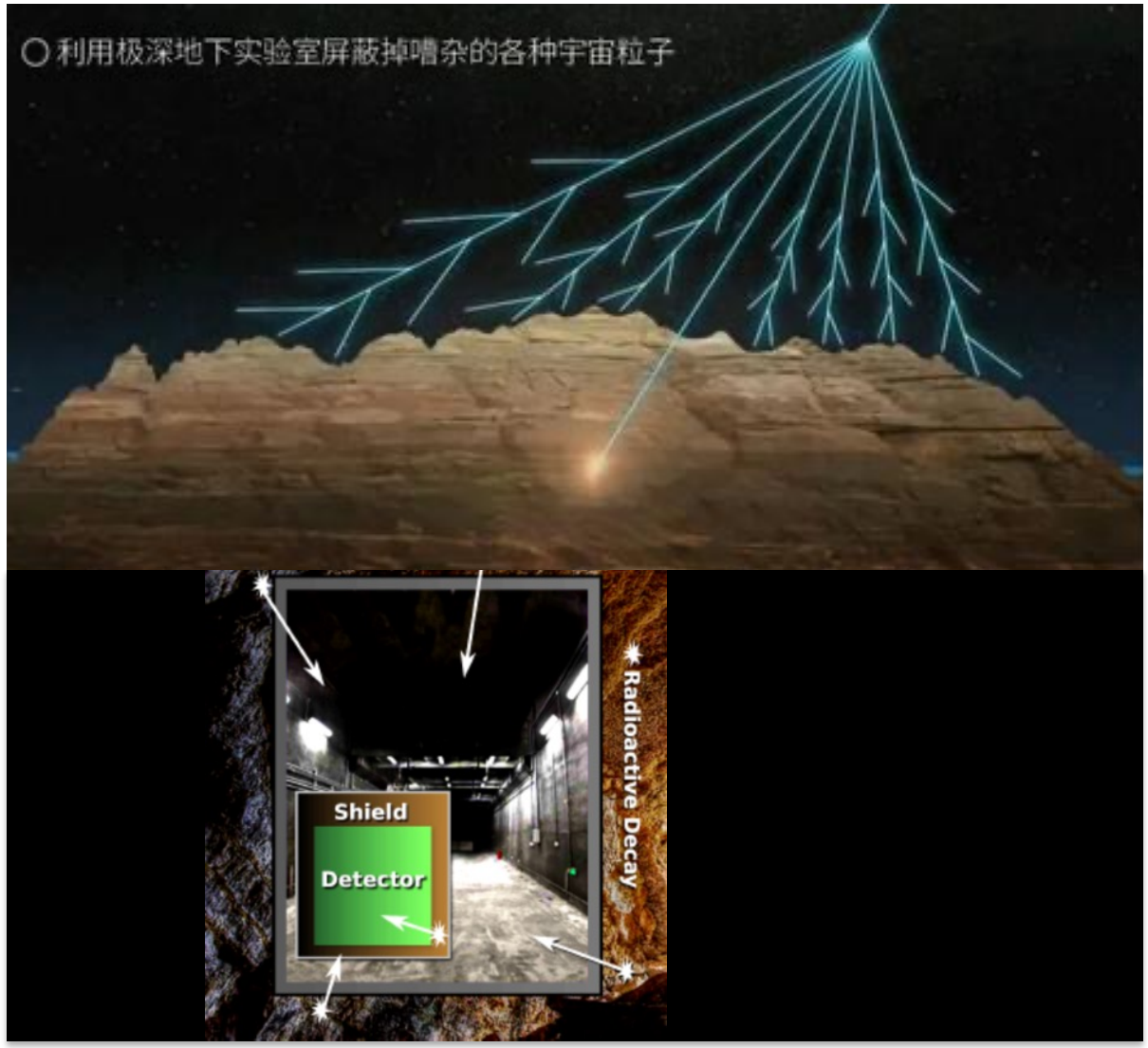


DARK MATTER OVERVIEW: COLLIDER, DIRECT AND INDIRECT DETECTION SEARCHES - QUEIROZ, FARINALDO S. ARXIV:1605.08788

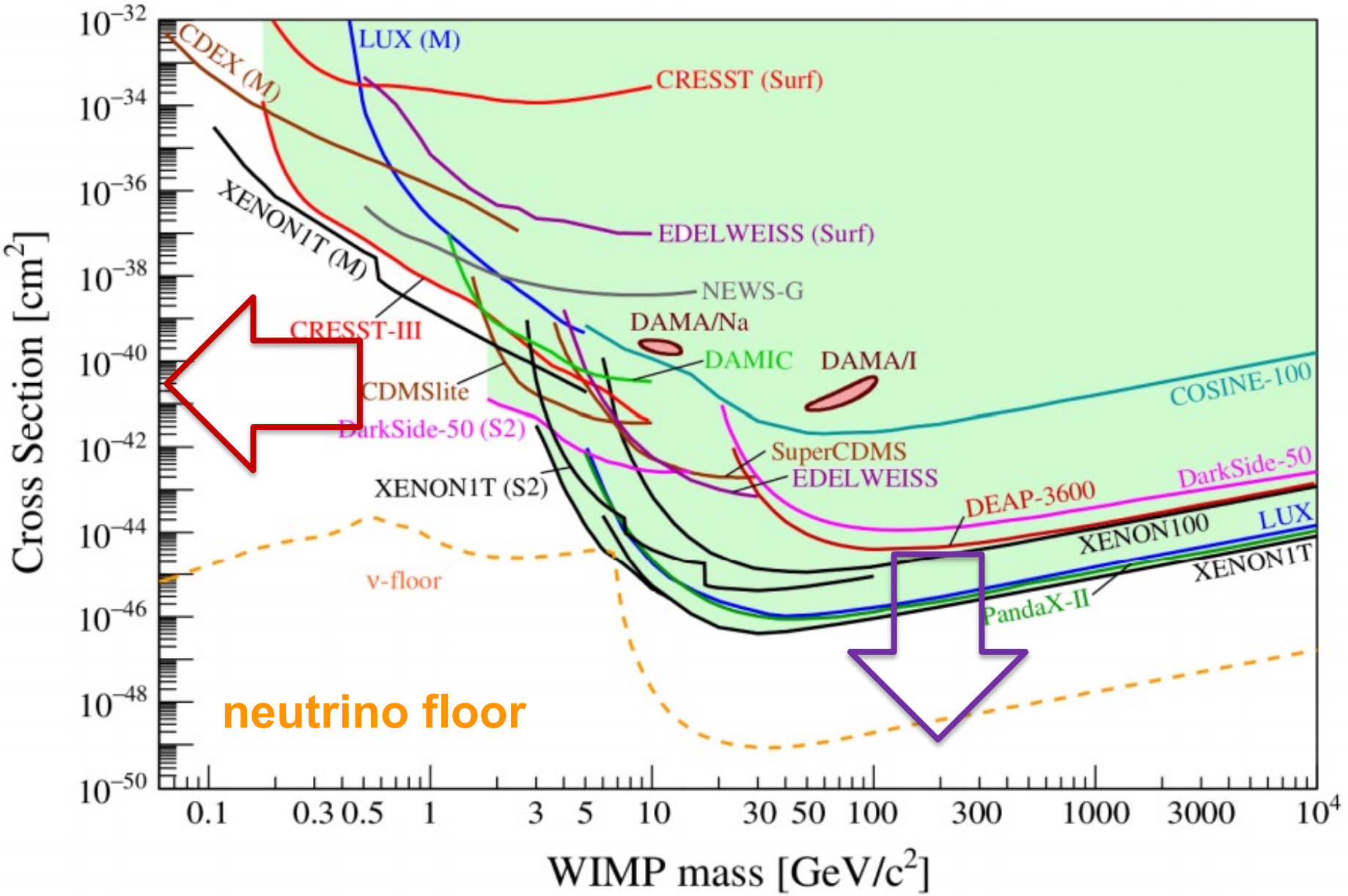
Detection Strategy

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





Direct Detection



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

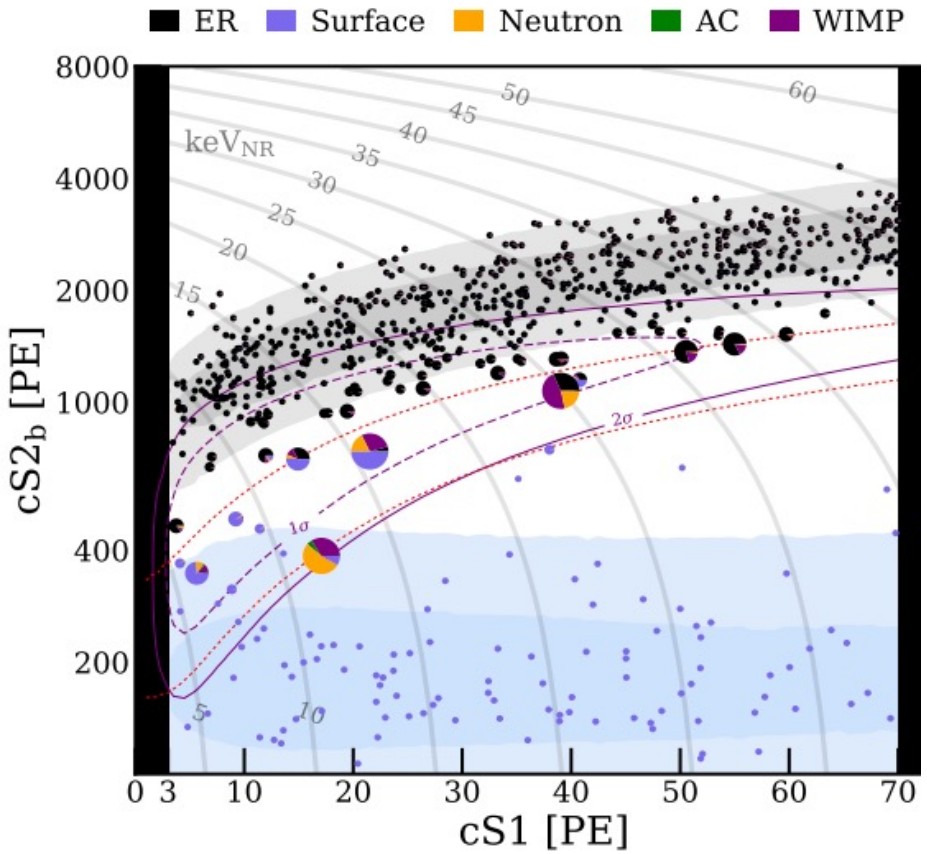


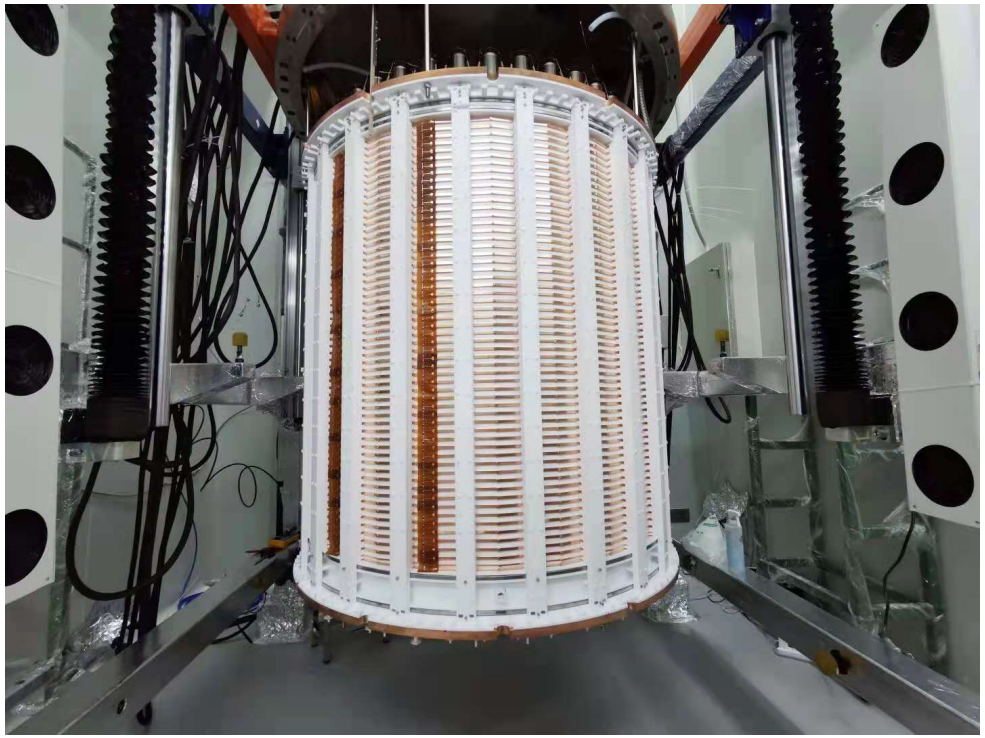
TABLE I: Best-fit expected event rates with 278.8 days live-time in the 1.3 t fiducial mass, 0.9 t reference mass, and 0.65 t core mass, for the full (cS1, $cS2_b$) ROI and, for illustration, in the NR signal reference region. The table lists each background (BG) component separately and in total, the 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
$WIMP_{best\text{-}fit}$	3.56	1.70	1.16	0.83
Data	739	14	2	2

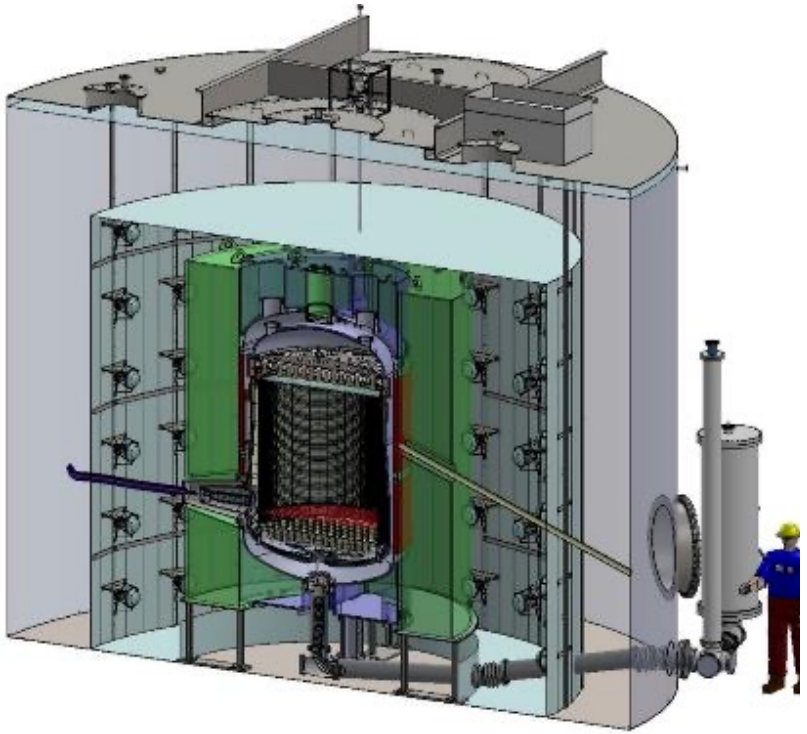
PRL 121, 111302 (2018)

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

PandaX Experiment

Collaboration formed

2009.3

2012.7

PandaX-I apparatus moved to Jinping

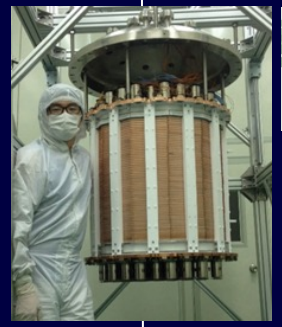
PandaX-I started

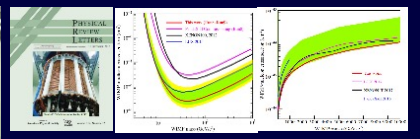
2014.3

2014.5-10

PandaX-I, 120 kg operation

PandaX-II, 580 kg operation





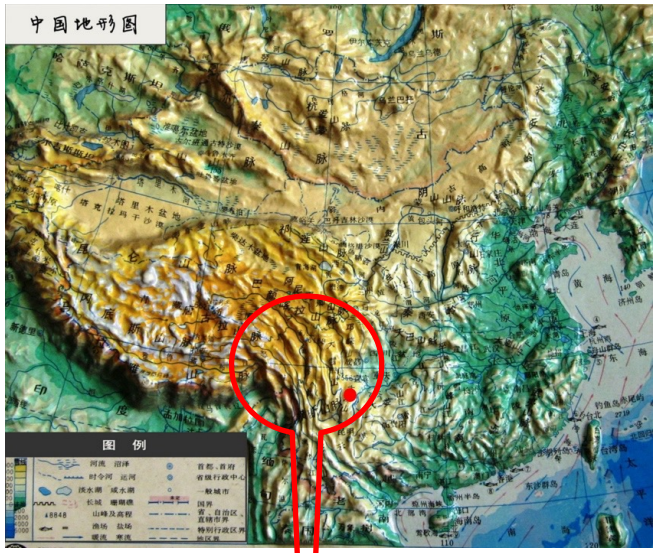
2016.7 -2019.7

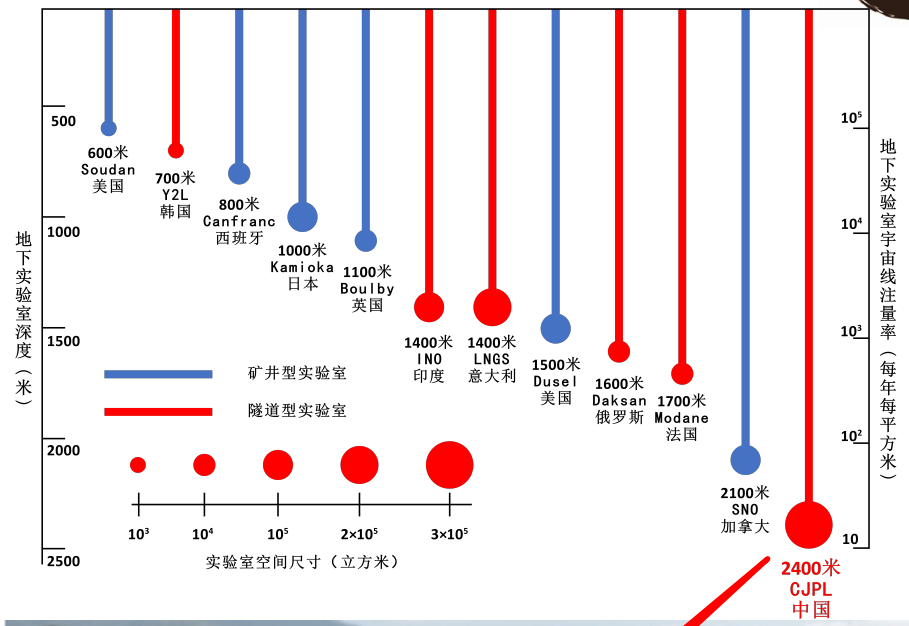
2019.8-

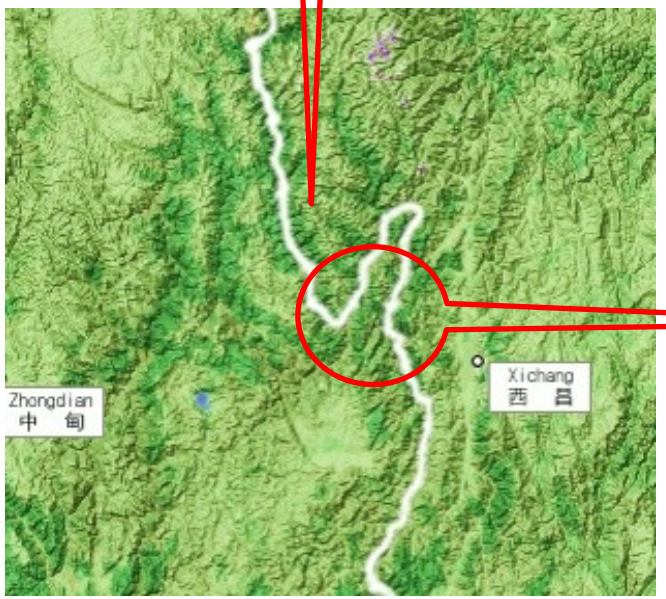
PandaX-4T moved to CJPL-II

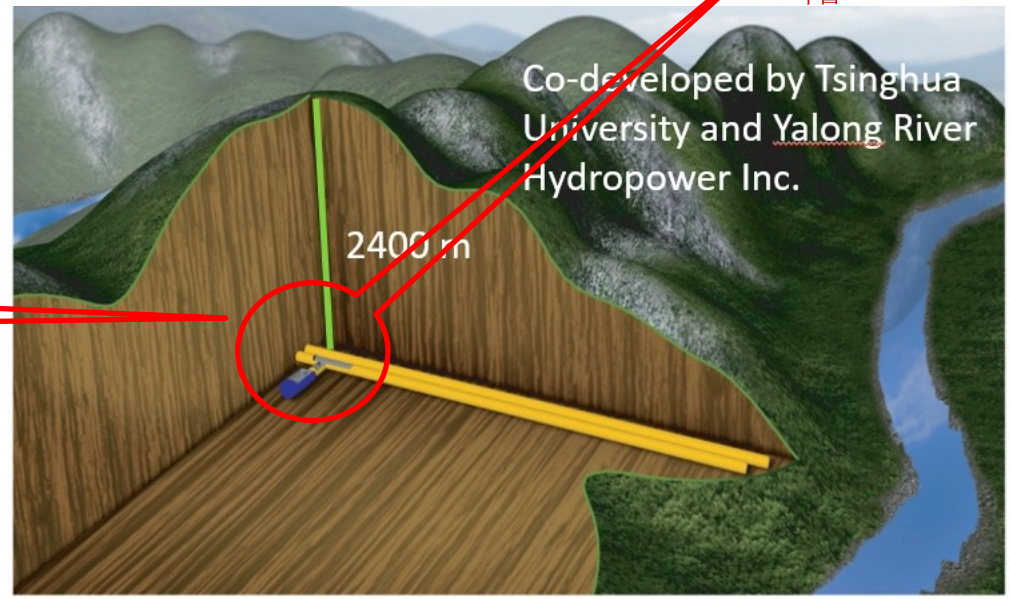
China Jinping Underground Laboratory (CJPL)

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



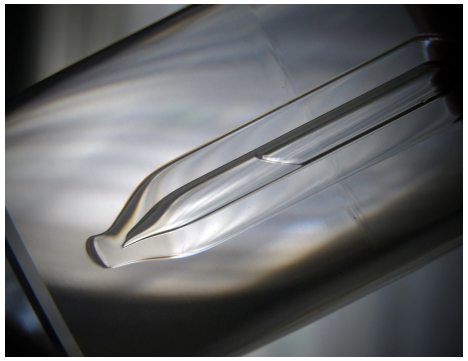


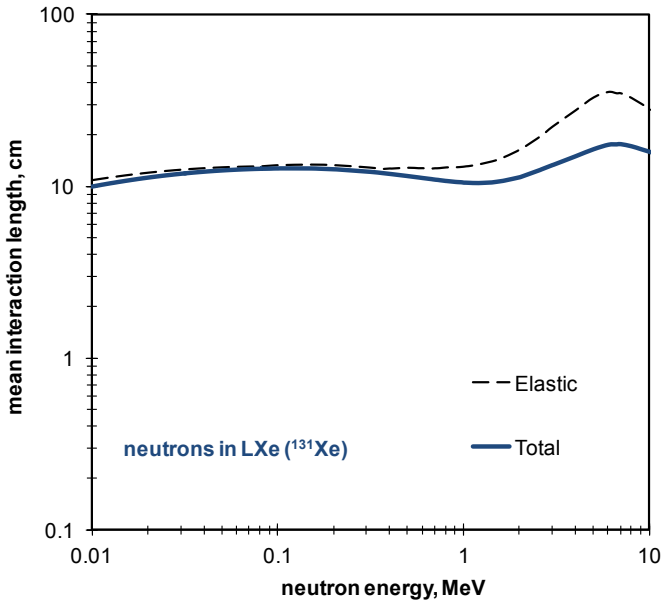


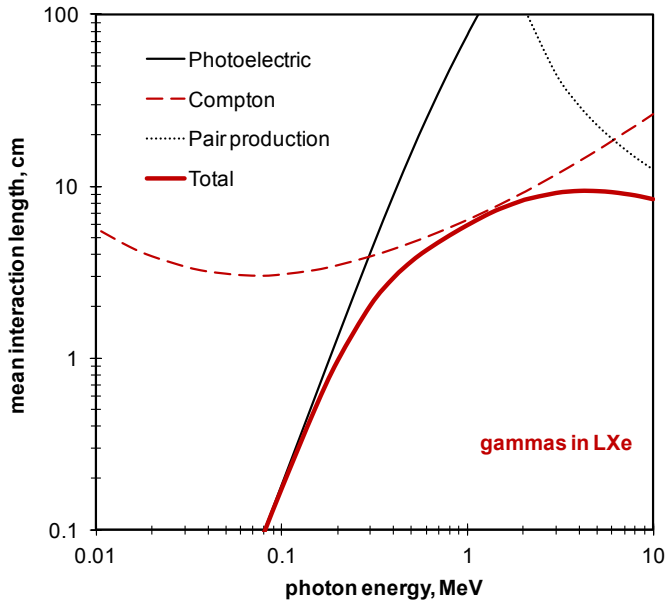


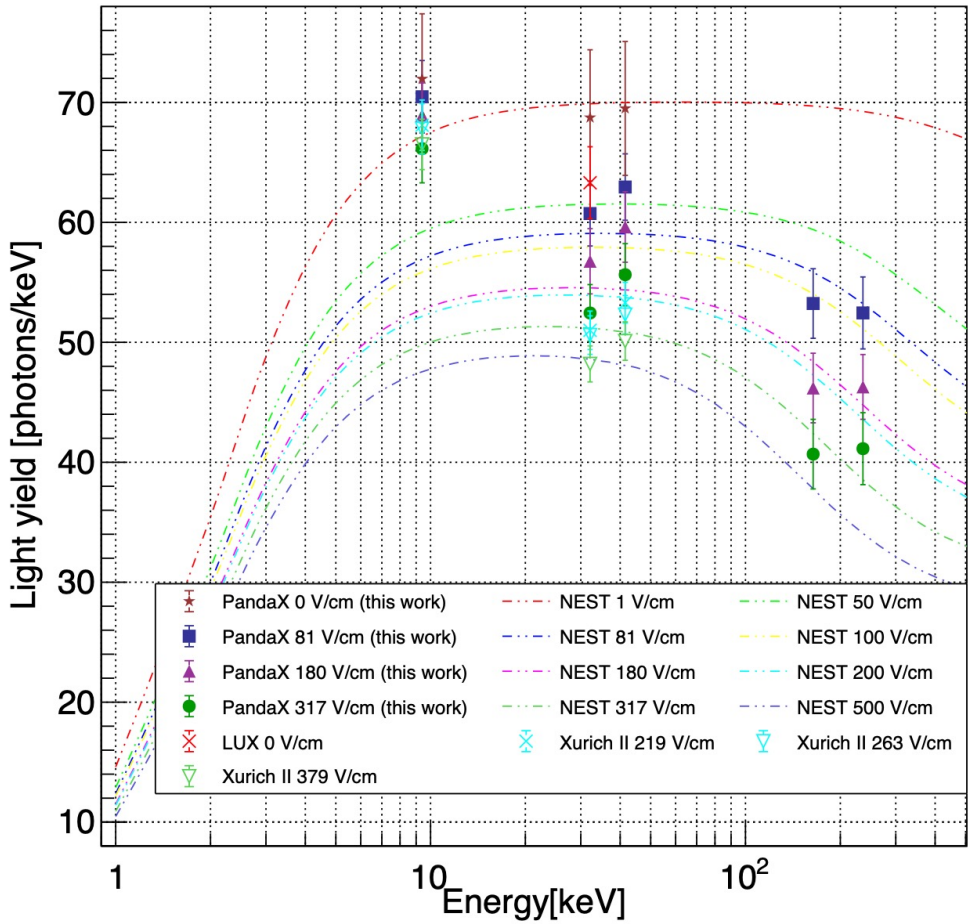
Xenon

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





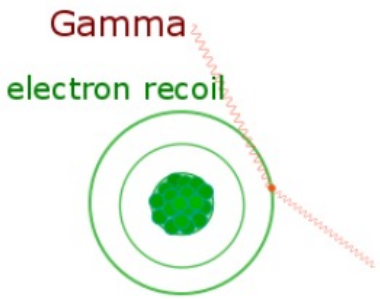


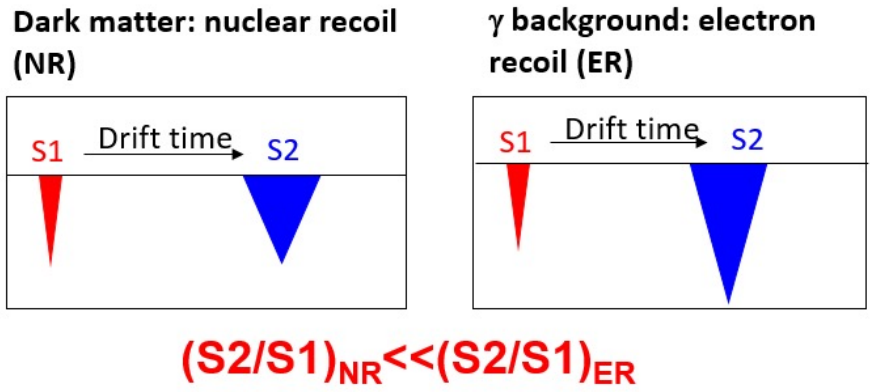


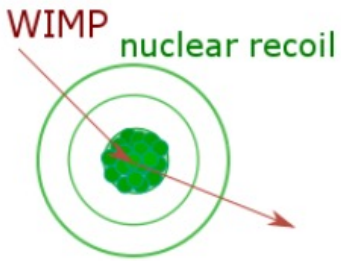
JINST 17 P01008 (2022)

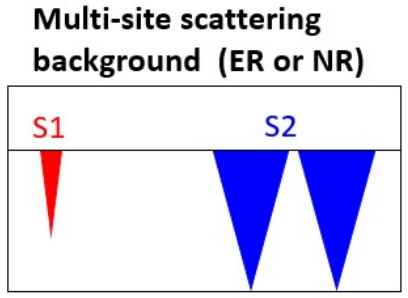
PandaX Detector

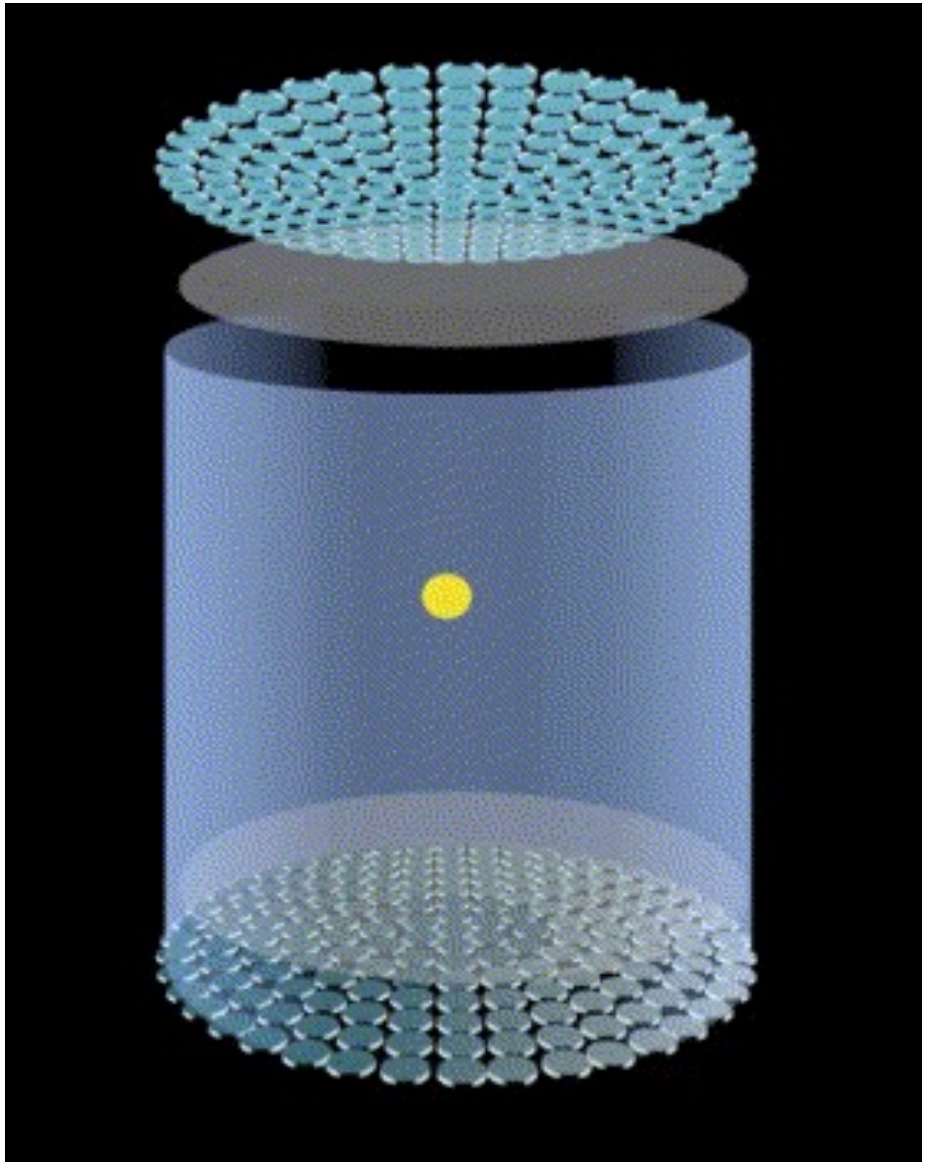
- Dual-phase xenon TPC
  - Large scale target
  - Precise energy and 3D-positon reconstruction
  - NR and ER discrimination power



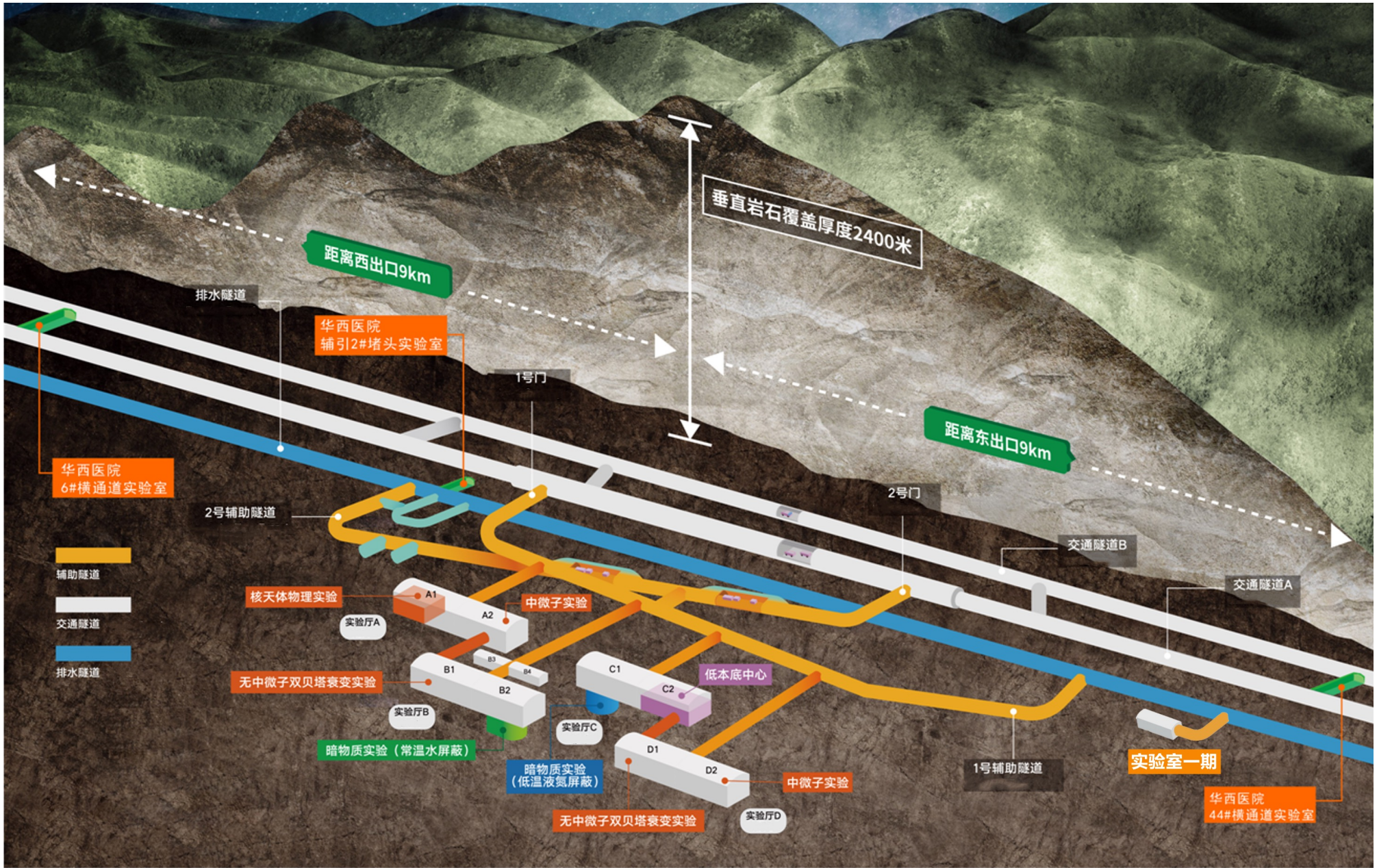




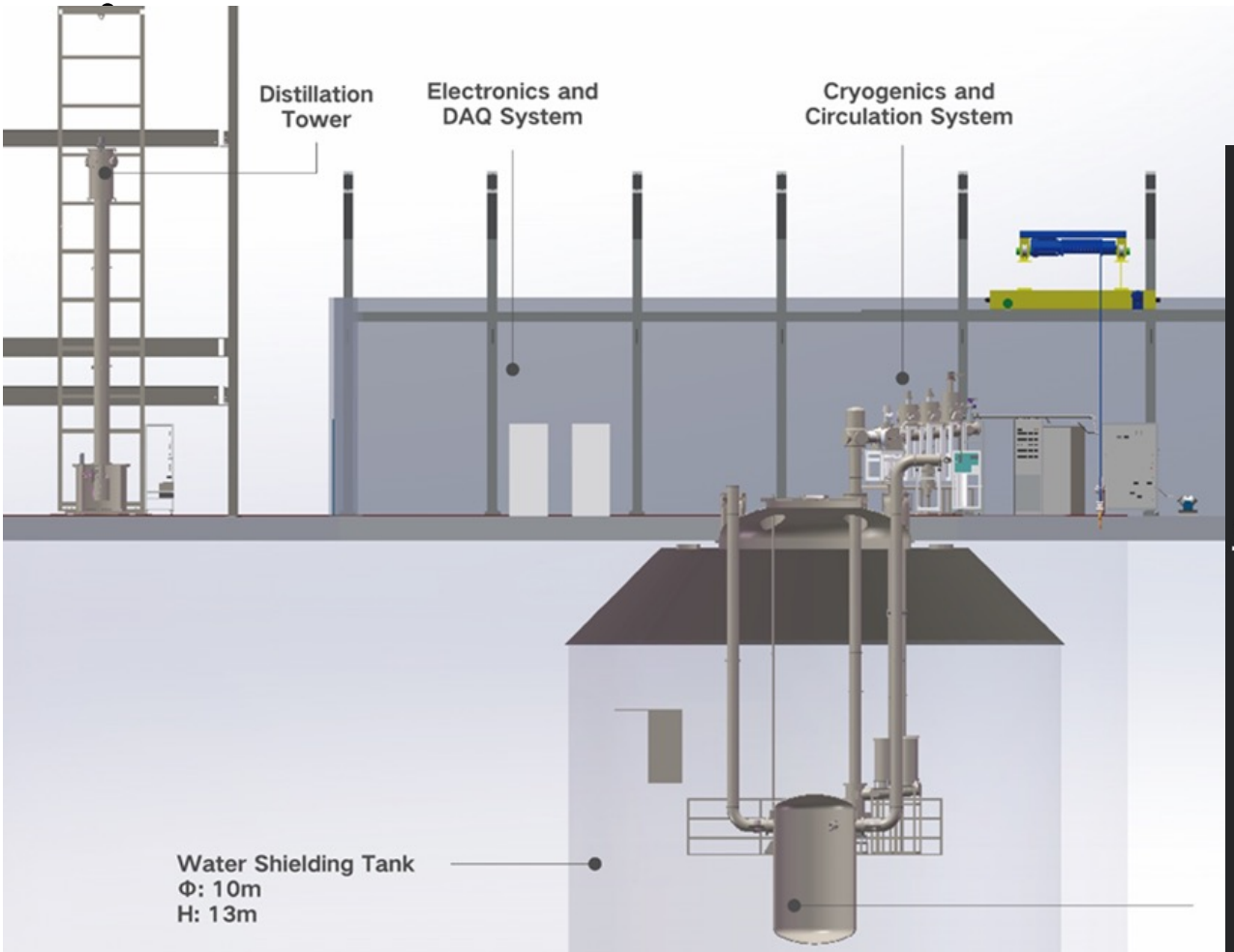




CJPL-II

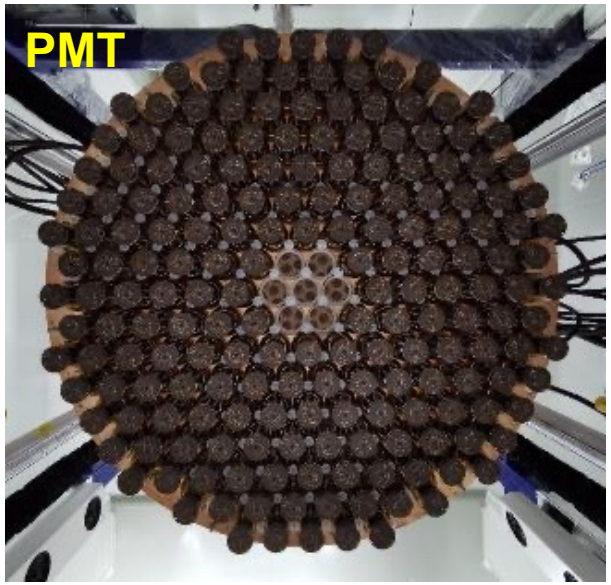

垂直岩石覆盖厚度2400米
距离西出口9km
距离东出口9km
排水隧道
华西医院
辅引2#堵头实验室
1号门
2号门
华西医院
6#横通道实验室
2号辅助隧道
交通隧道B
交通隧道A
辅助隧道
交通隧道
排水隧道
核天体物理实验
A1
A2
实验厅A
中微子实验
无中微子双贝塔衰变实验
B1
B2
B3
B4
实验厅B
C1
C2
低本底中心
实验厅C
暗物质实验（常温水屏蔽）
暗物质实验
（低温液氮屏蔽）
D1
D2
中微子实验
无中微子双贝塔衰变实验
实验厅D
1号辅助隧道
实验室一期
华西医院
44#横通道实验室

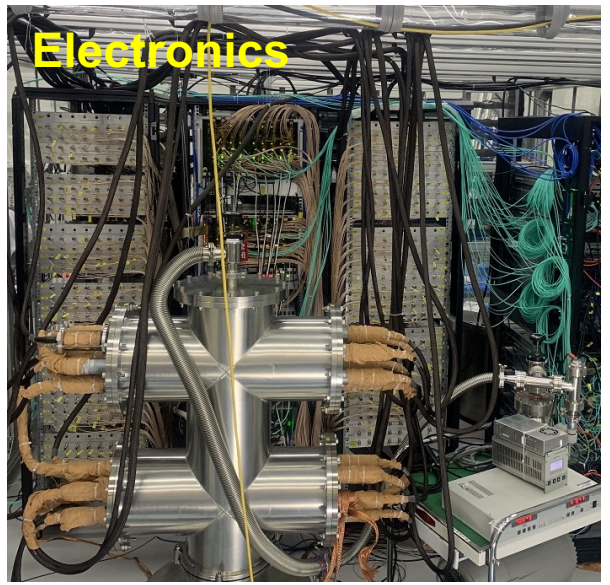
PandaX-4T @ CJPL-II

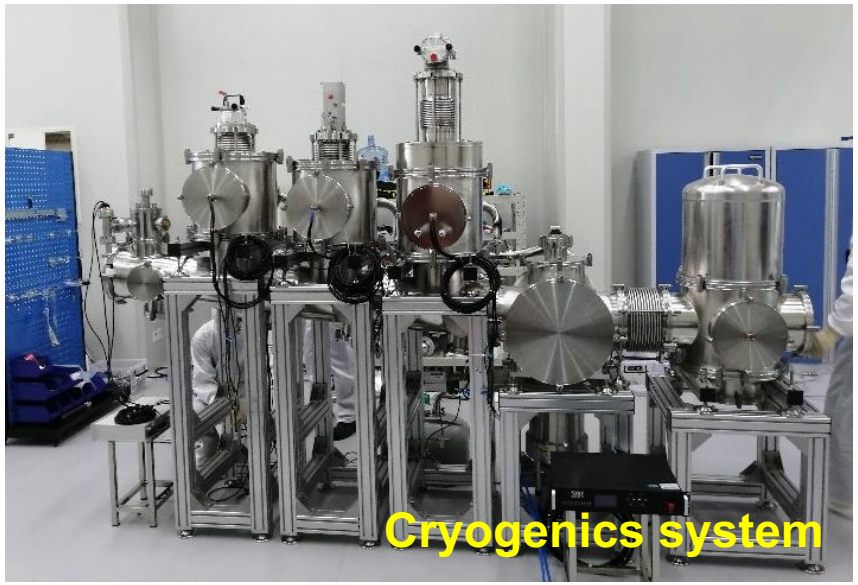


Sensitive volume: 3.7-tonne LXe

PandaX-4T Subsystems

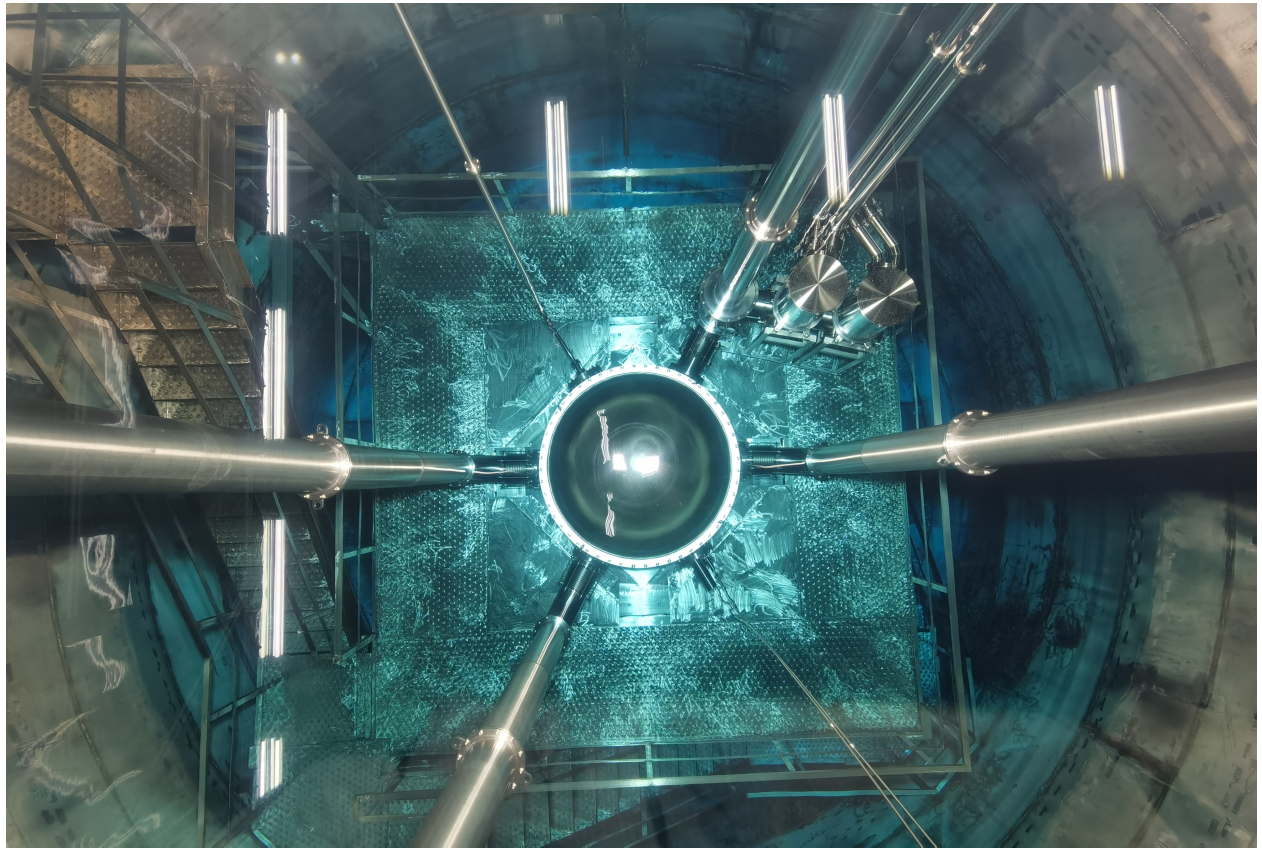


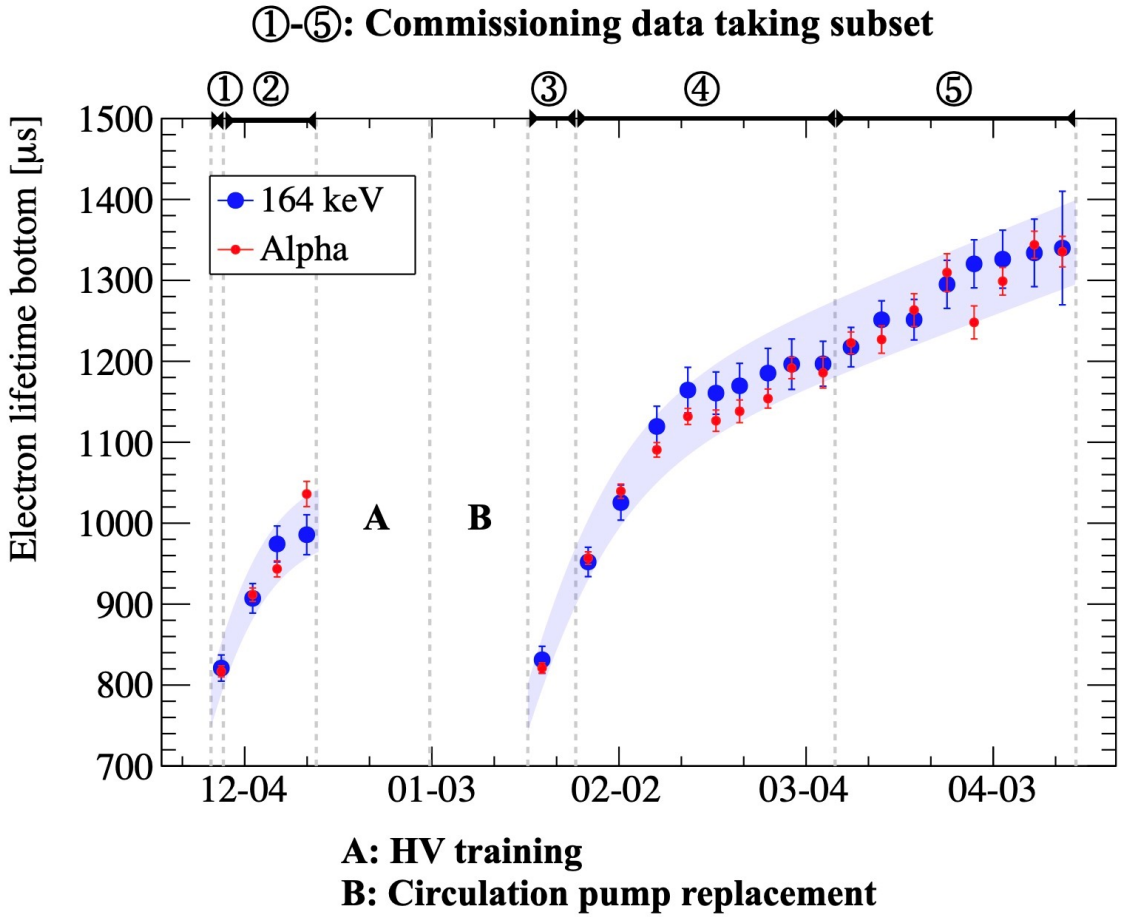




PandaX-4T Commissioning

- Stable data running period: 95.0 calendar days

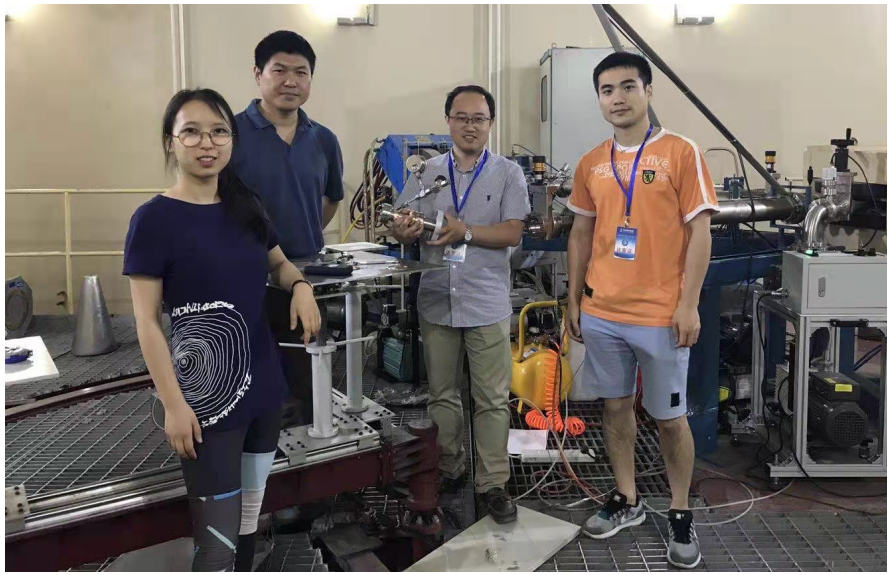


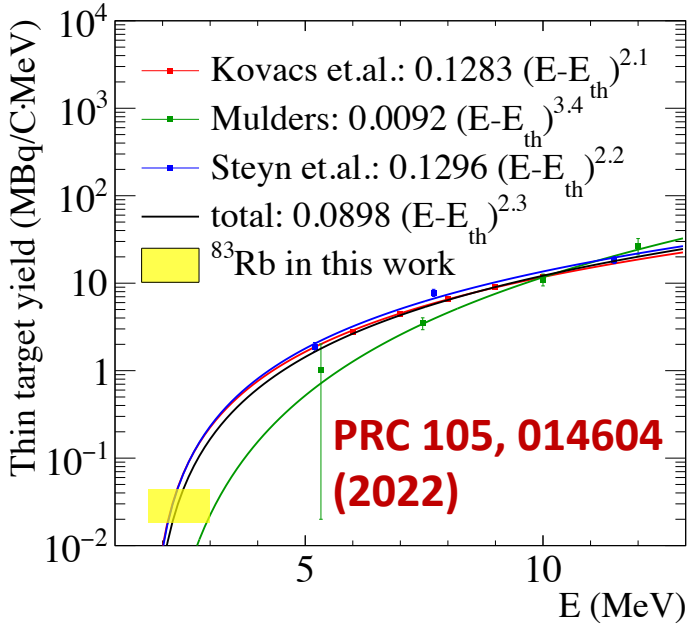


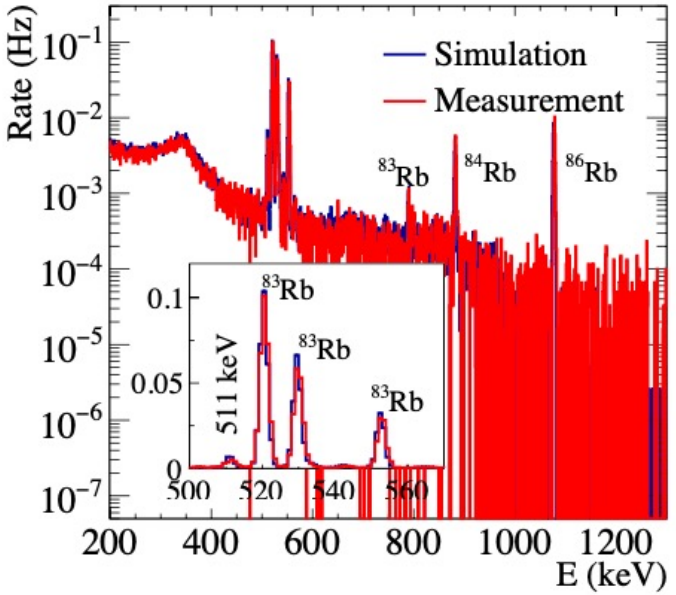
Internal Calibration Source

- Large size of TPC
  - External calibration sources can hardly produce events in the center
  - Internal calibration sources: ^{83m}Kr, ^{220}Rn
- ^{83m}Kr: proton beam bombarding ^{nat}Kr ($p + {}^{nat}Kr \rightarrow {}^{83}Rb \rightarrow {}^{83m}Kr$)
  - optimal proton beam energy 20 MeV: limited access in China
  - successfully produced with 3.4 MeV: first measurement of the low energy yield

^{84}Rb threshold 3.46MeV

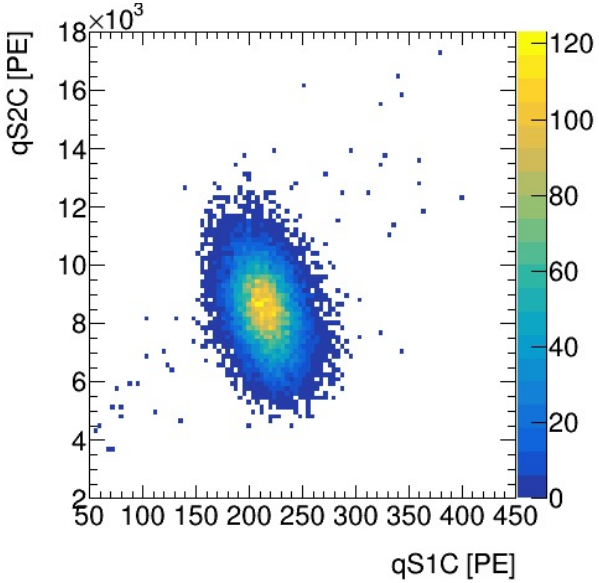


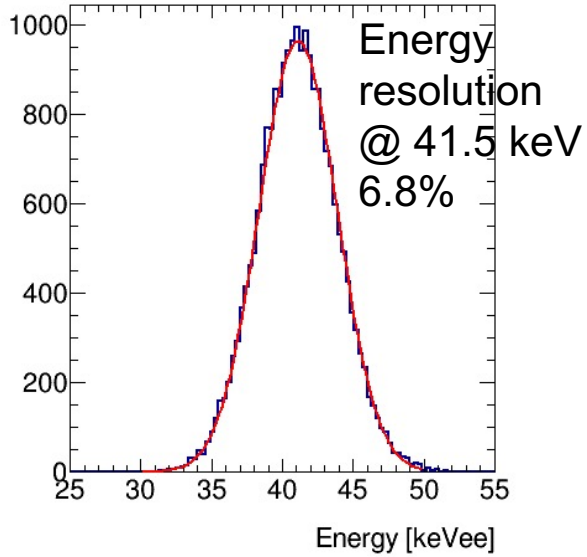


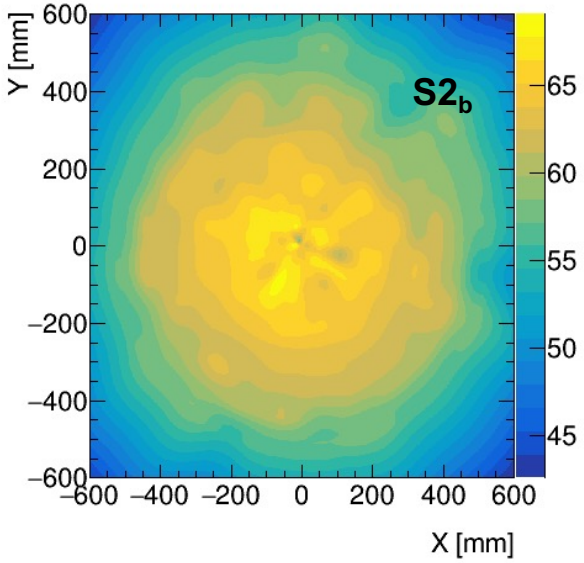


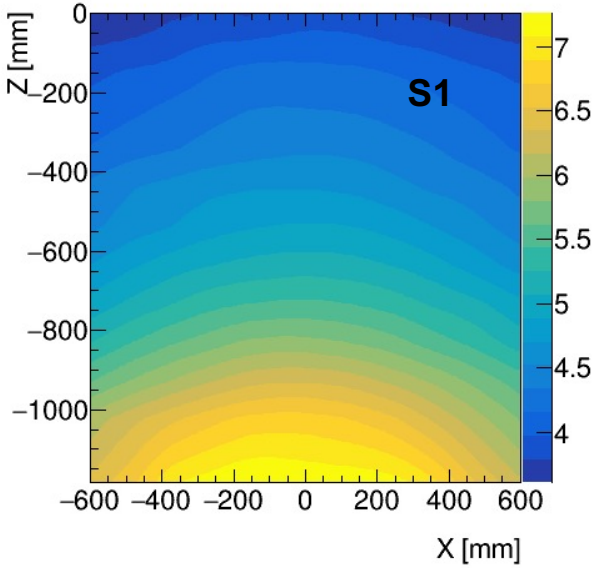
Detector Response Model

- Uniformity correction with ^{83m}Kr



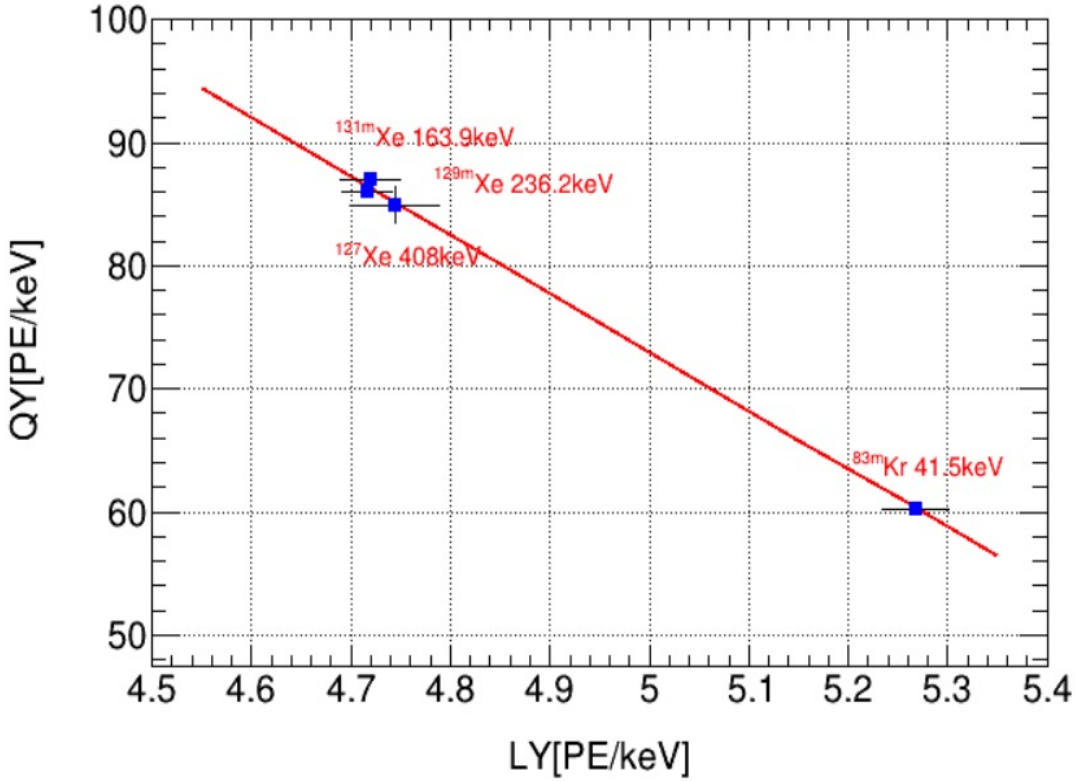






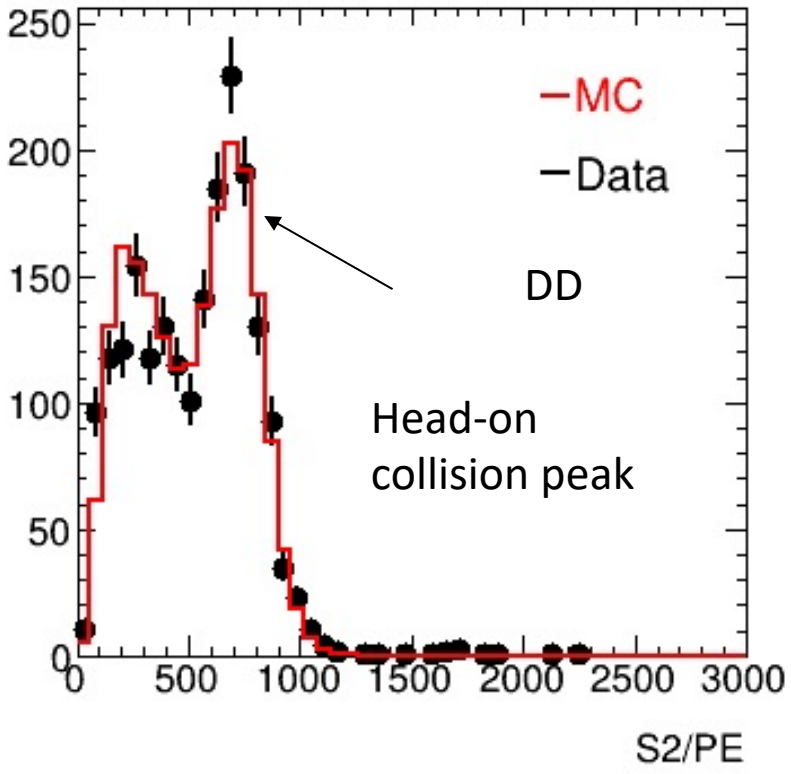
- Detector parameters determination

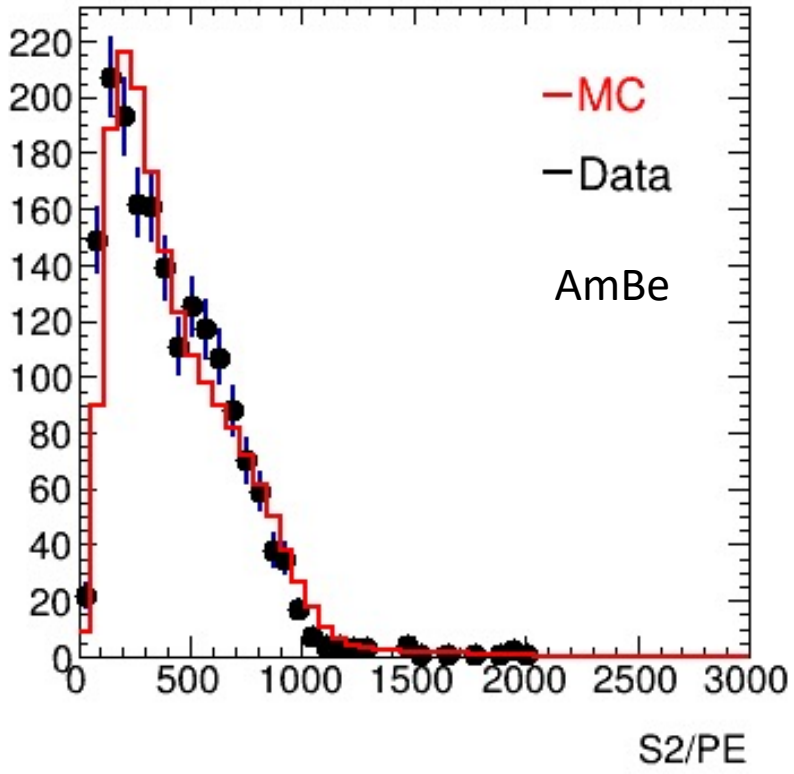
$$E = 13.7\text{eV} \times \left(\frac{\text{S1}}{\text{PDE}} + \frac{\text{S2}_\text{b}}{\text{EEE} \times \text{SEG}}\right)$$

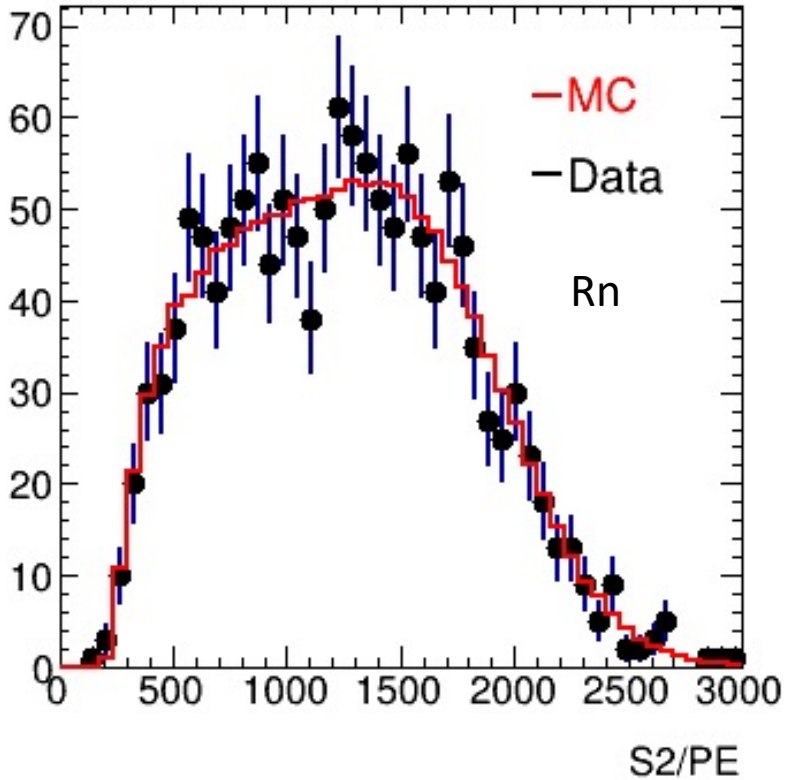


Detector Response Model

- Light/charge yield, as well as fluctuations
  - Deuteron-deuteron (DD) neutron data used together with AmBe
  - Rn data

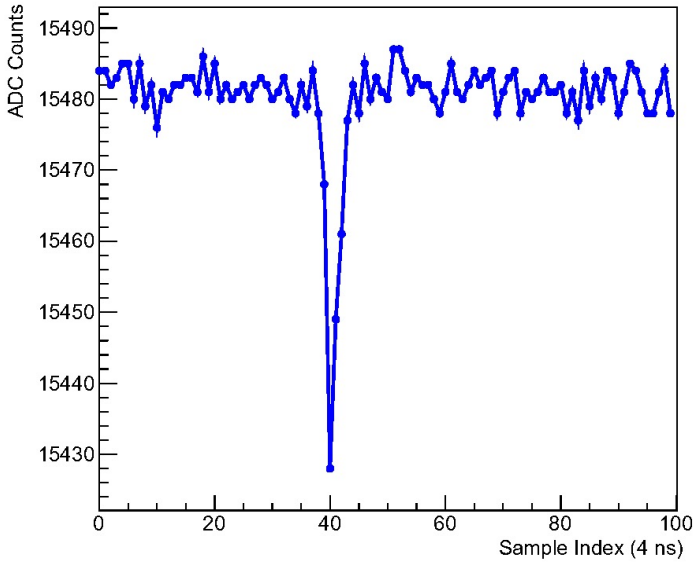






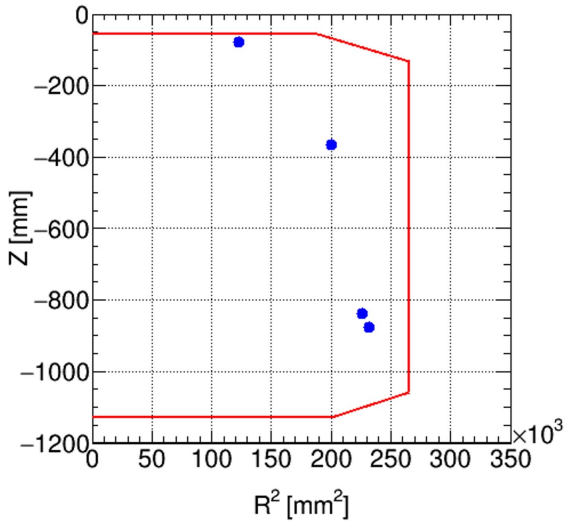
PandaX-4T Major Improvement

- **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

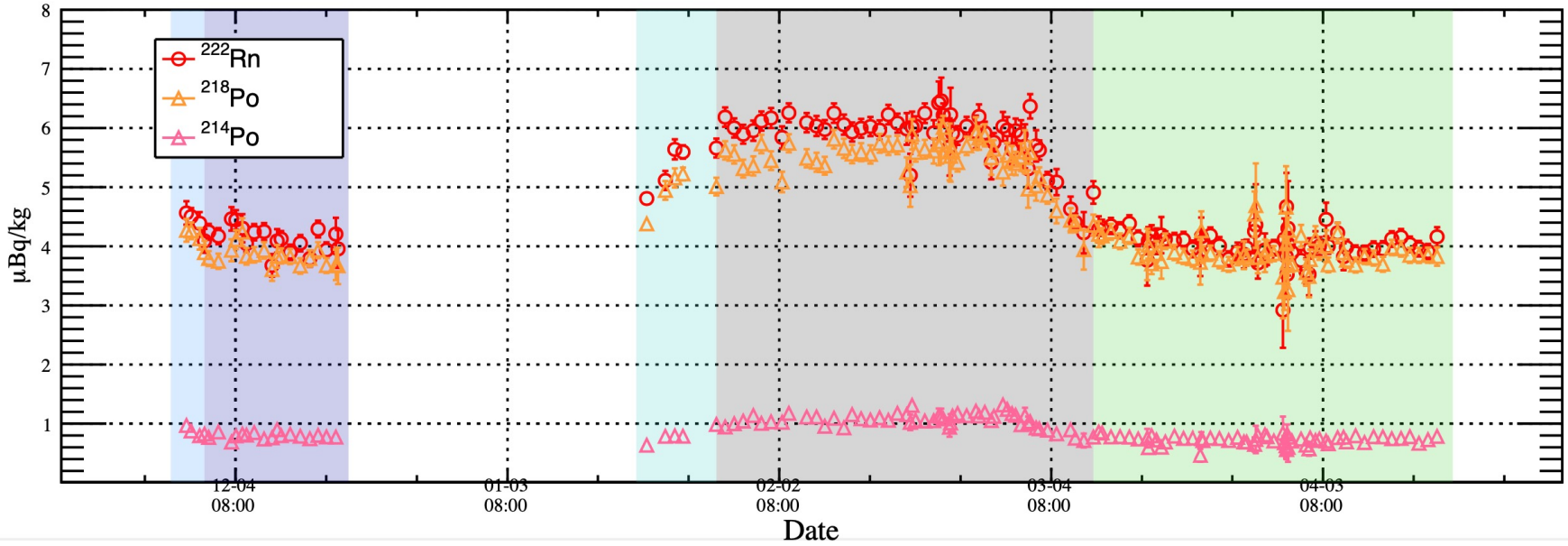


Typical single photon pulse

average single photon detection efficiency: 96%.

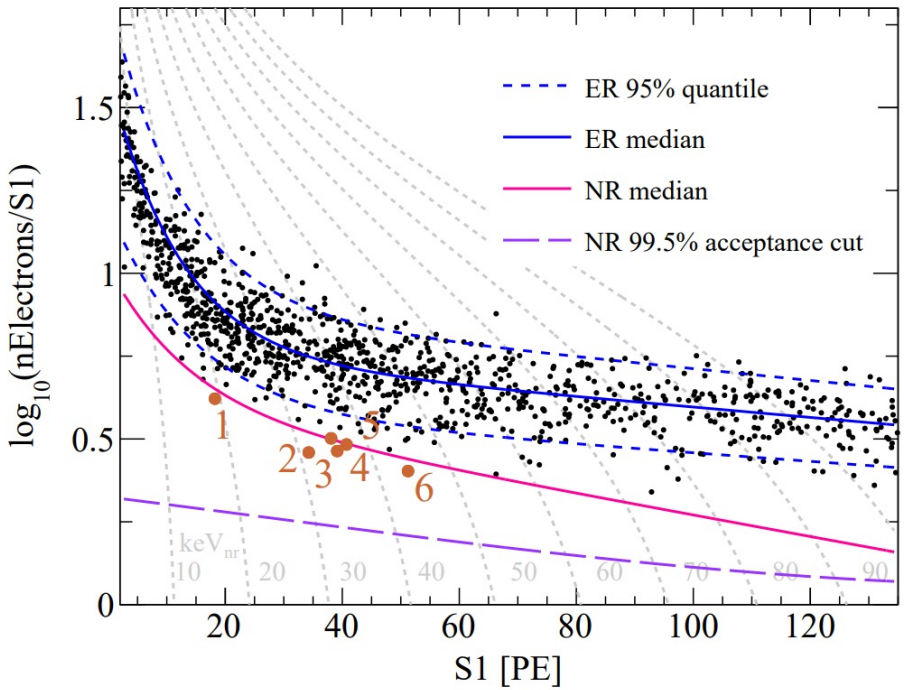


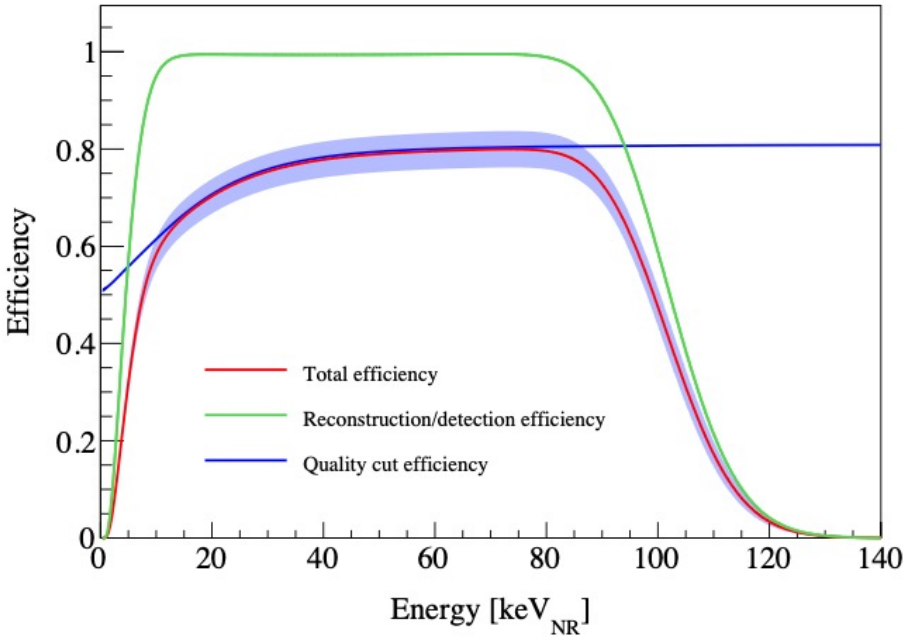
Vertex distribution of β-γ candidates

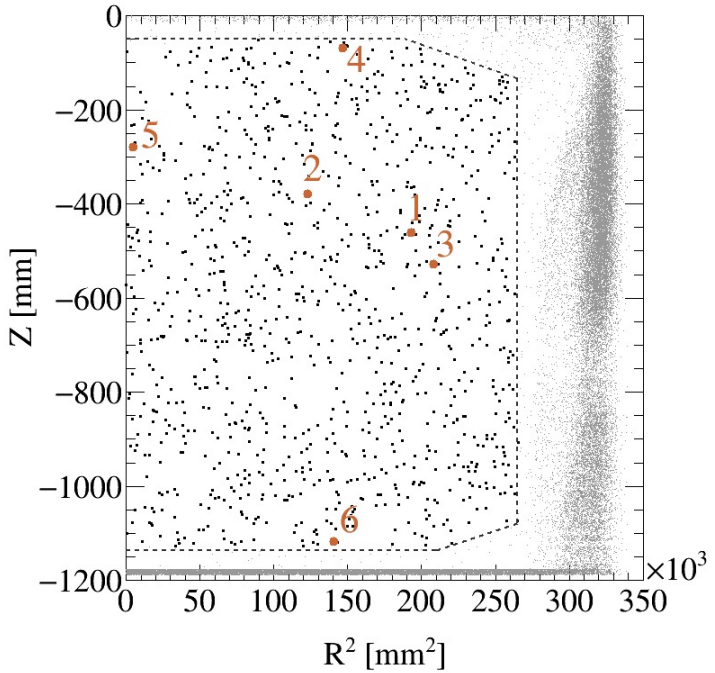


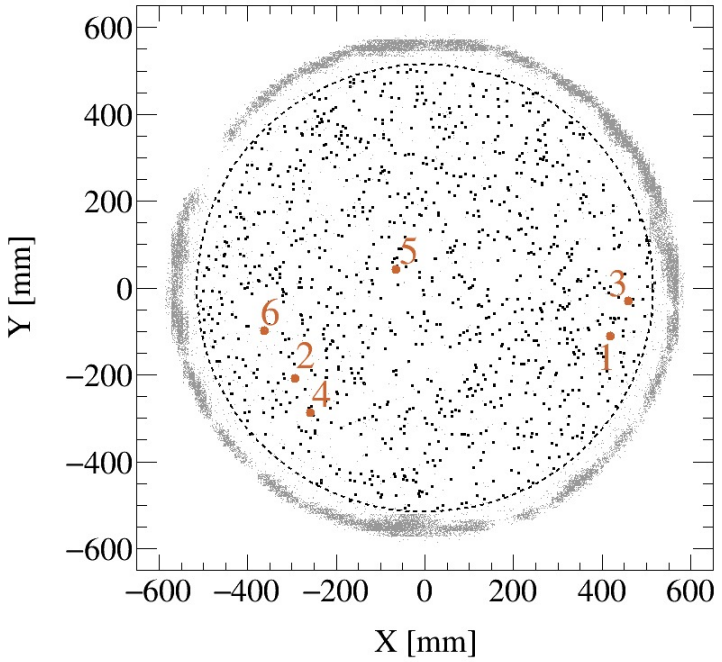
DM Candidates

- FV: 2.67 tonne
- Exposure: 0.63 tonne-year
- Candidates
  - 1058 candidates (Expected 1054±39)
  - 6 below NR median line (Expected 9.8±0.6)



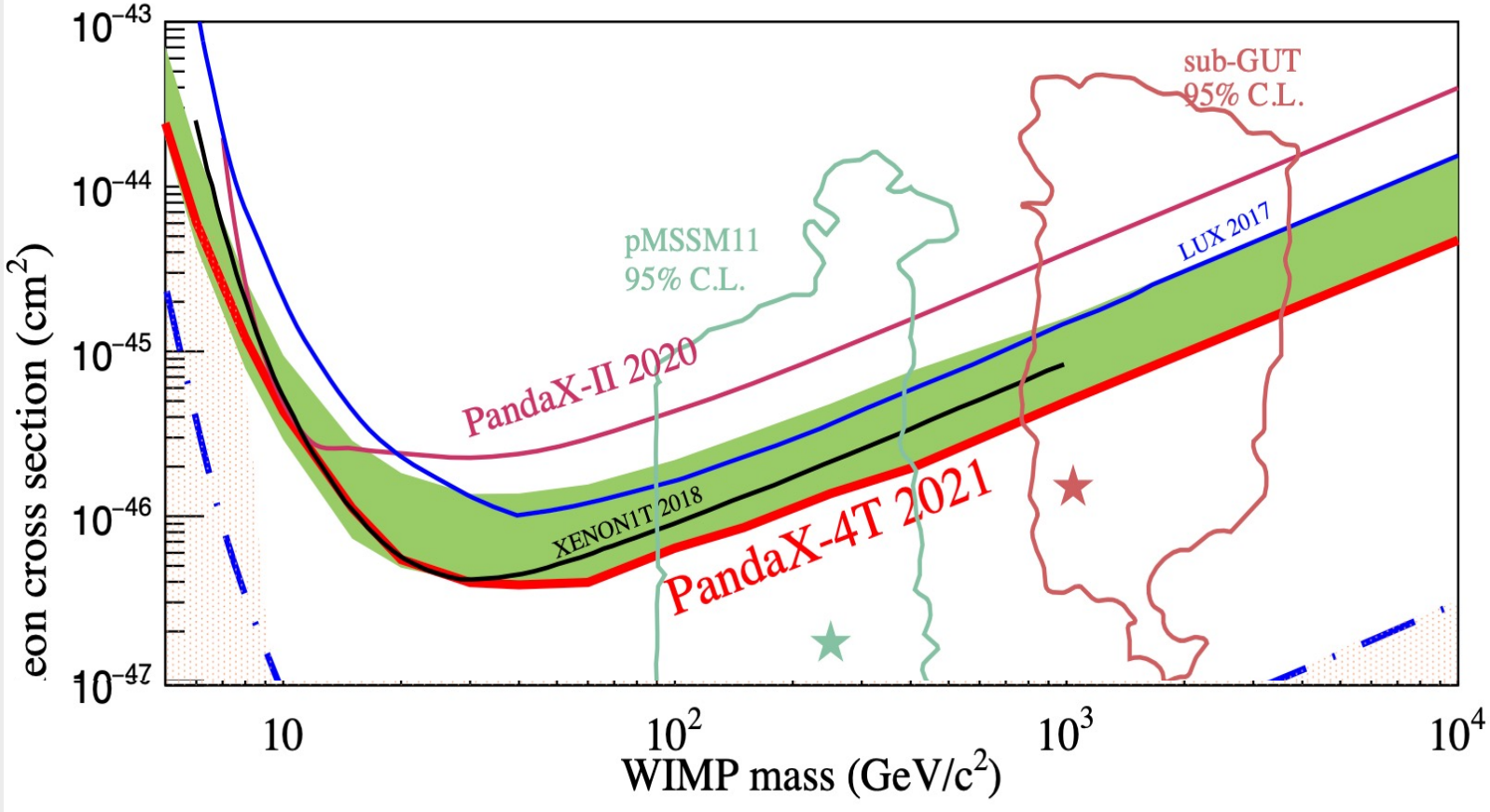






WIMP-nucleon SI exclusion limits

- 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



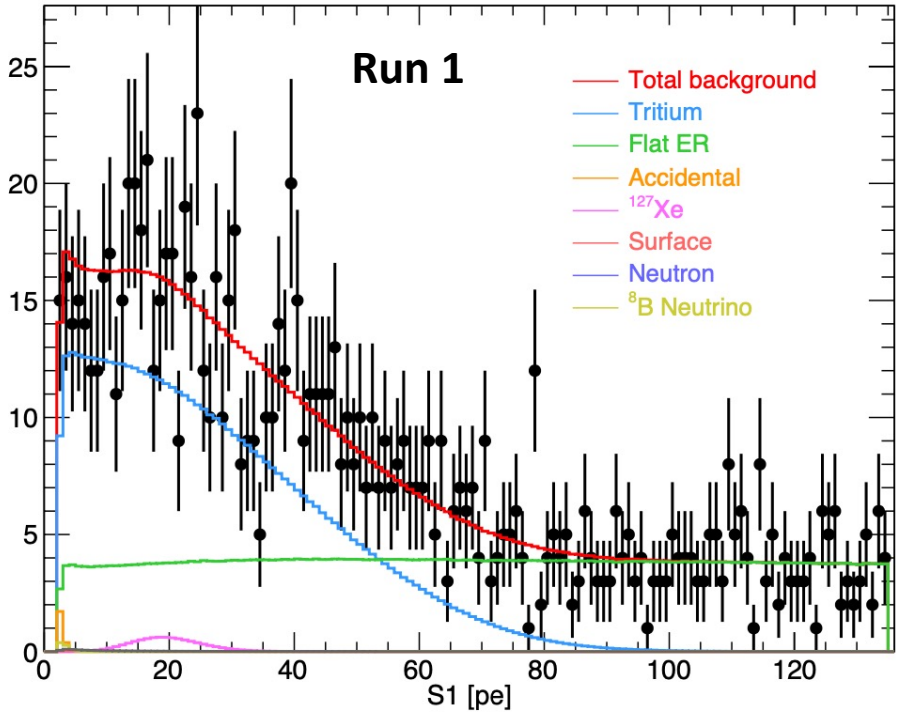
PRL 127, 261802 (2021)
Editors’ Suggestion

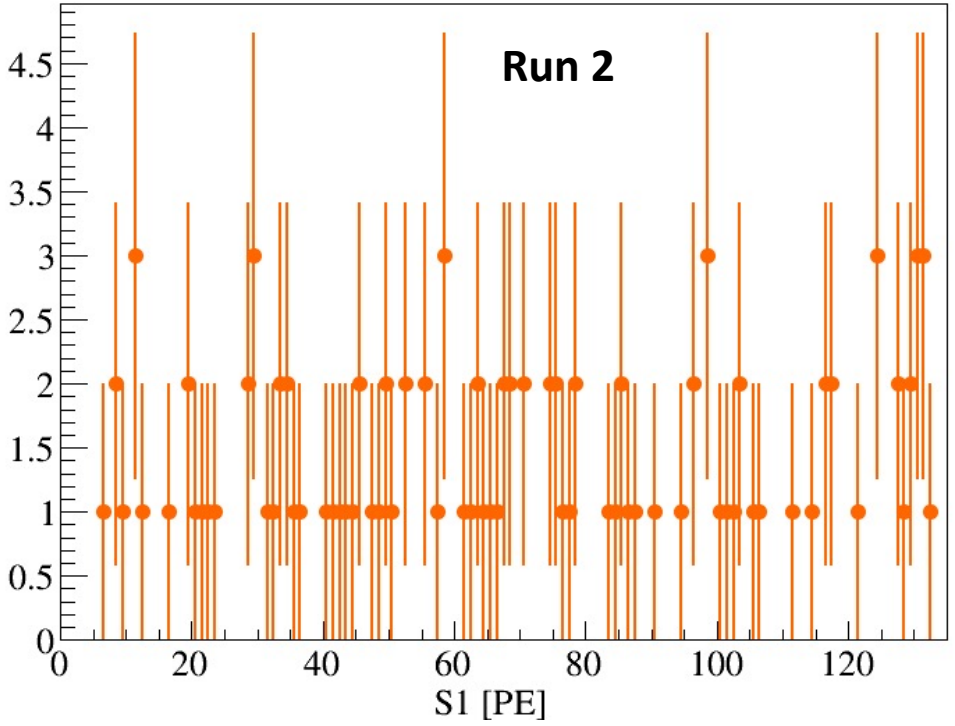
SUSY benchmark contours (MasterCode)

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

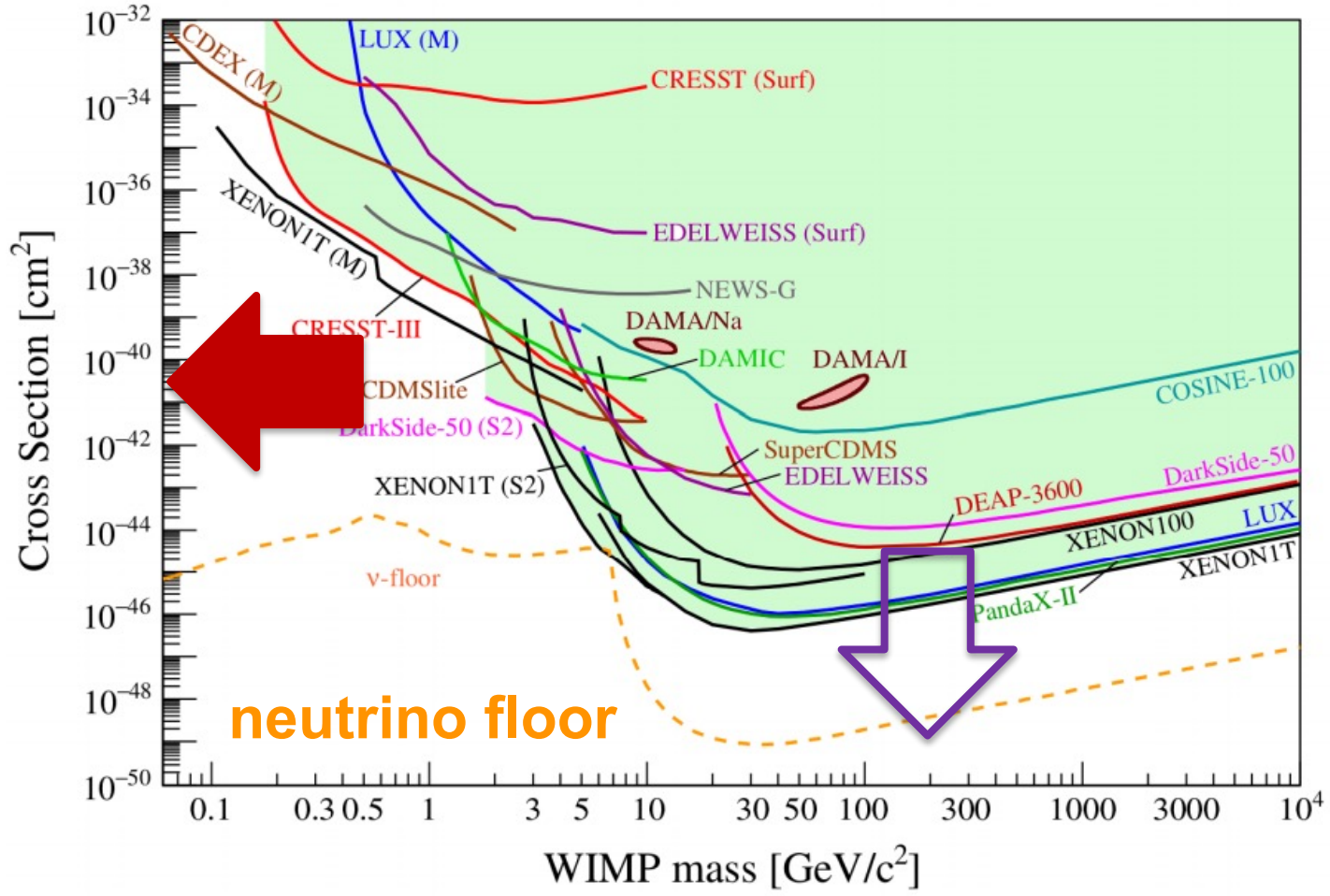
Tritium Removal before Run 2

- Tritium spectrum identified in the data
- Likely originated from a tritium calibration at the end of PandaX-II
- Level floating in the final dark matter fit: ~ $5(0.3)\times10^{-24}$ (mol/mol)
- **Xenon distillation to remove radioactive impurity like tritium**



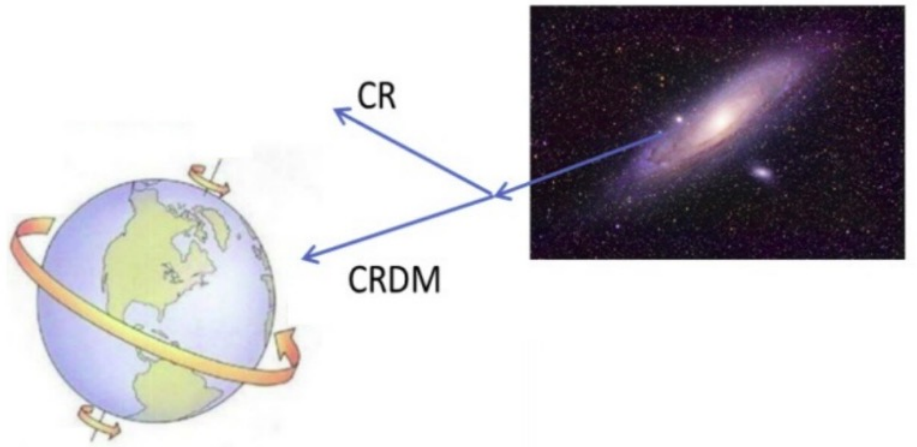


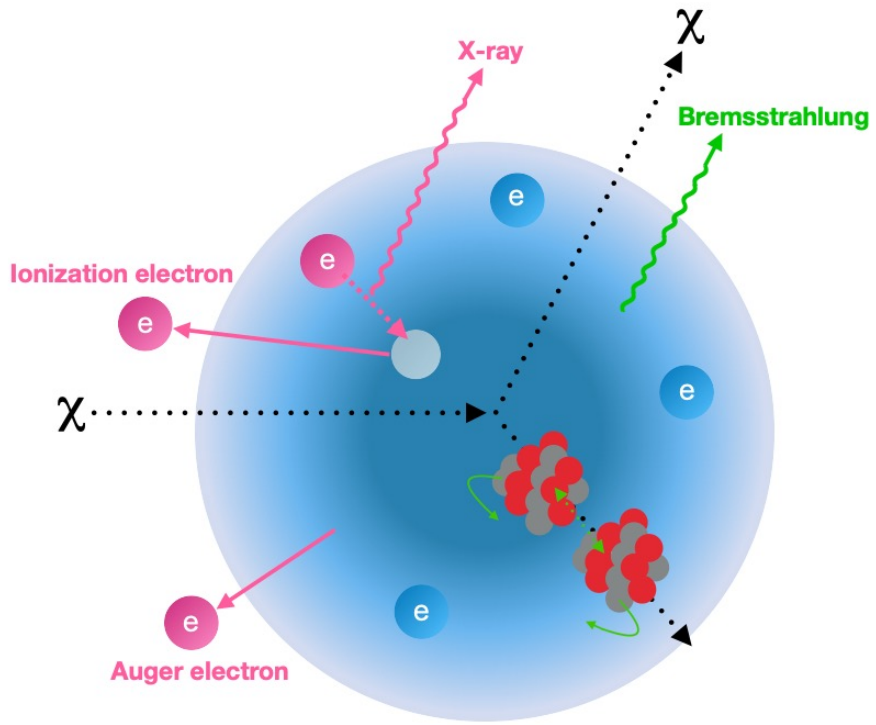
Low Mass Dark Matter

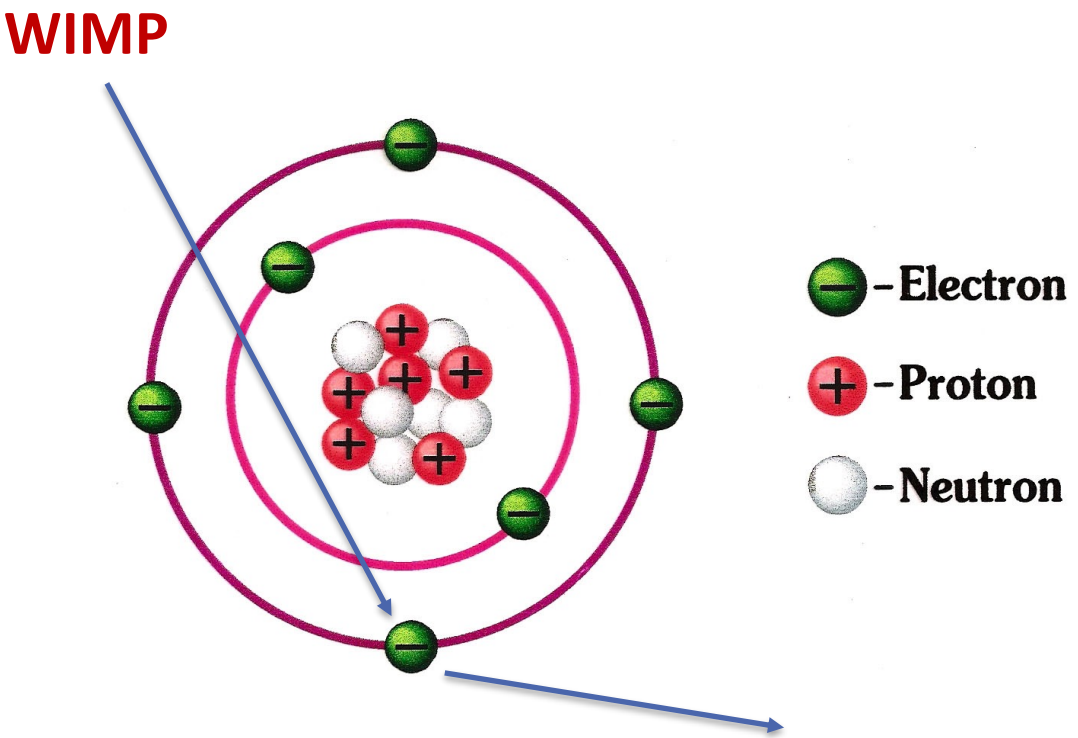


Low Mass Dark Matter

- Boosted WIMP
- Migdal effect
- Electron scattering

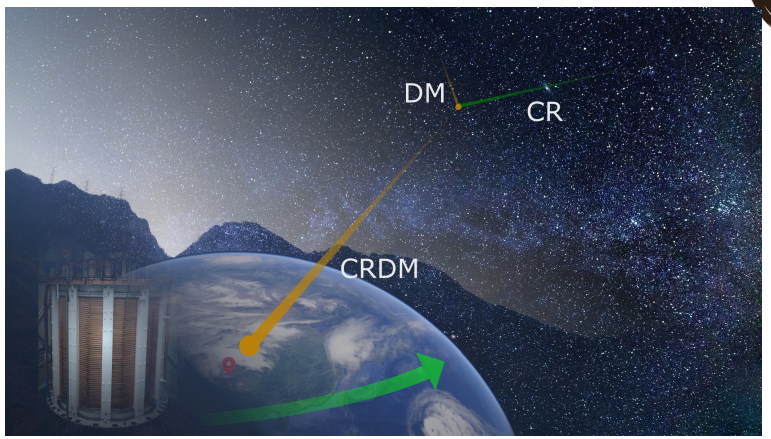


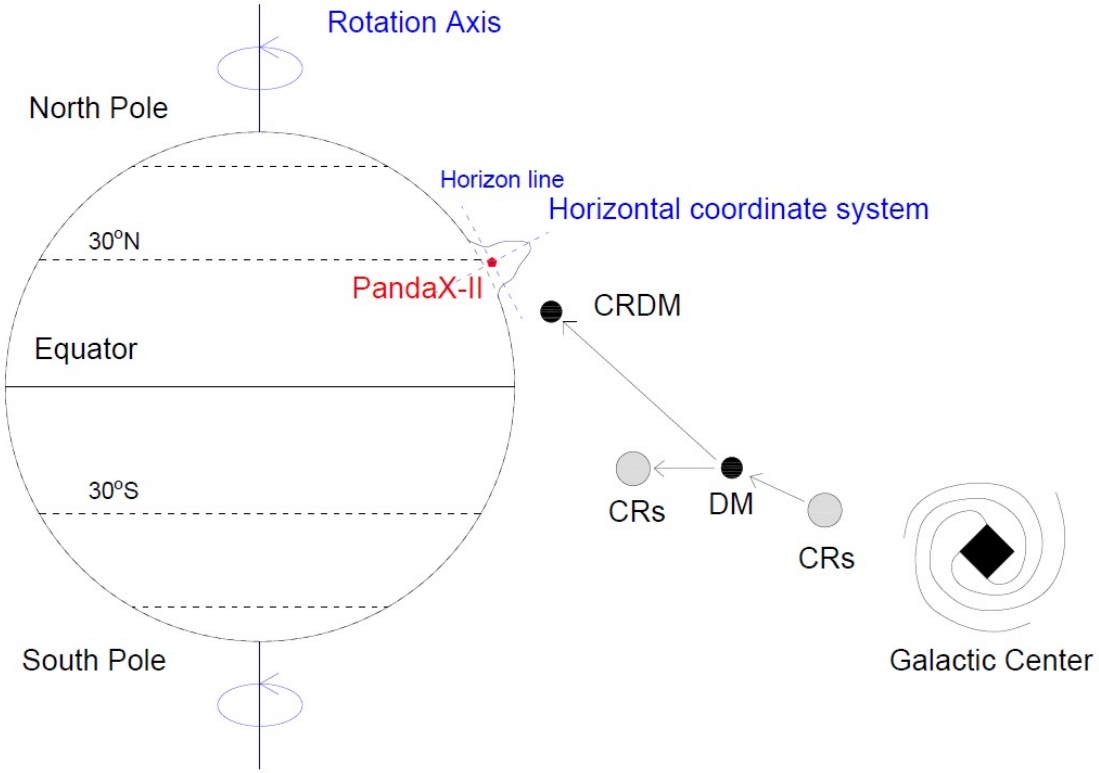


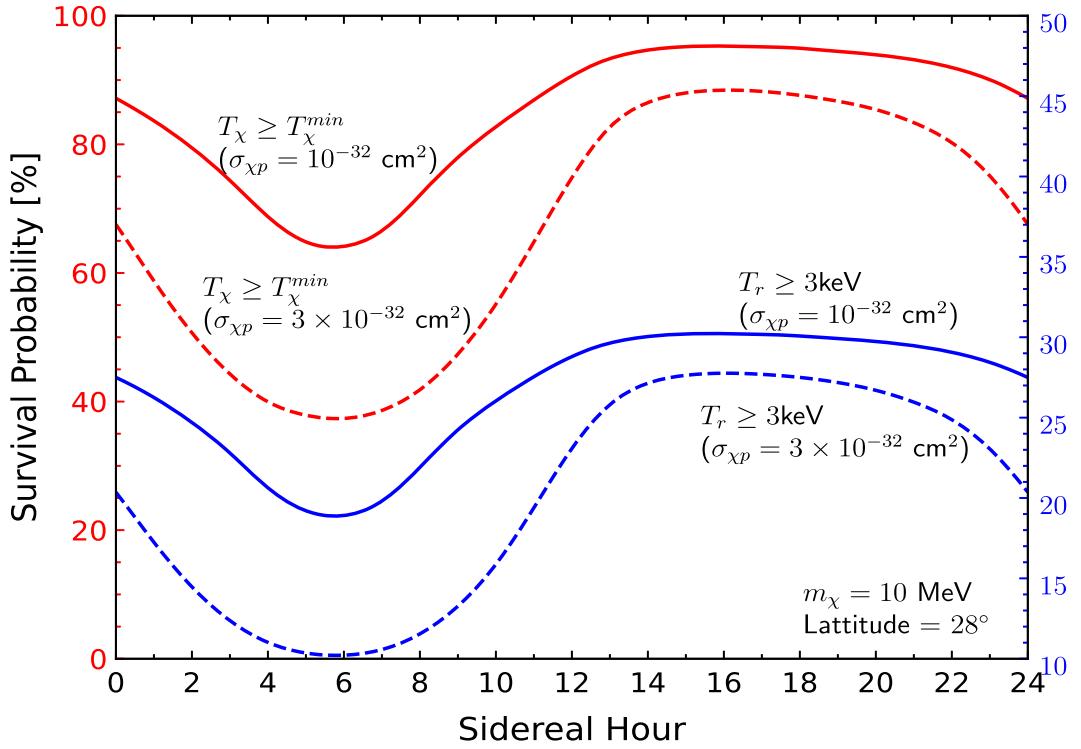


Cosmic-ray Boosted Dark Matter

- Cosmic-ray boosting
- Attenuation due to the earth



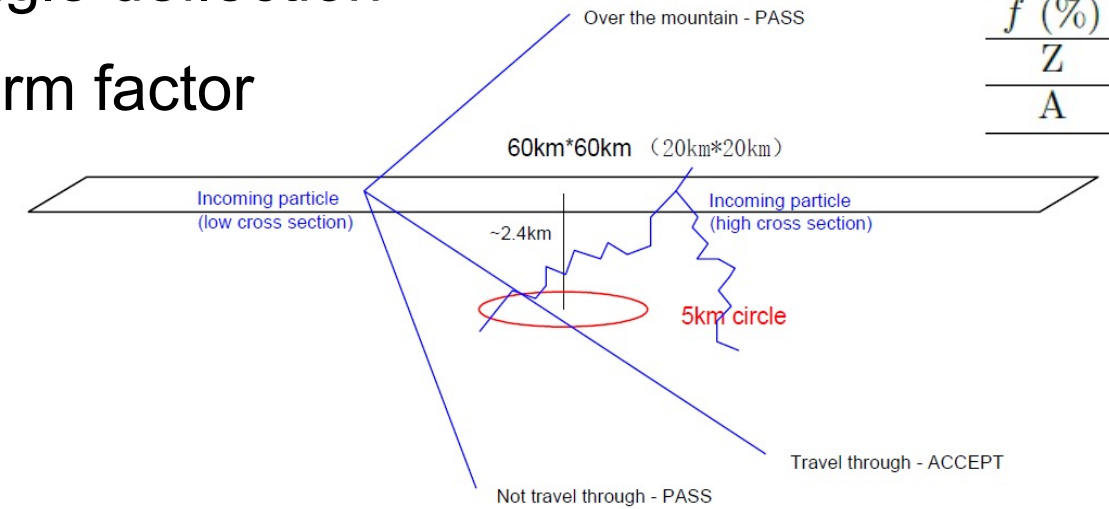




S. Ge, J. Liu, Q. Y, NZ
PRL 126 (2021) 9, 091804

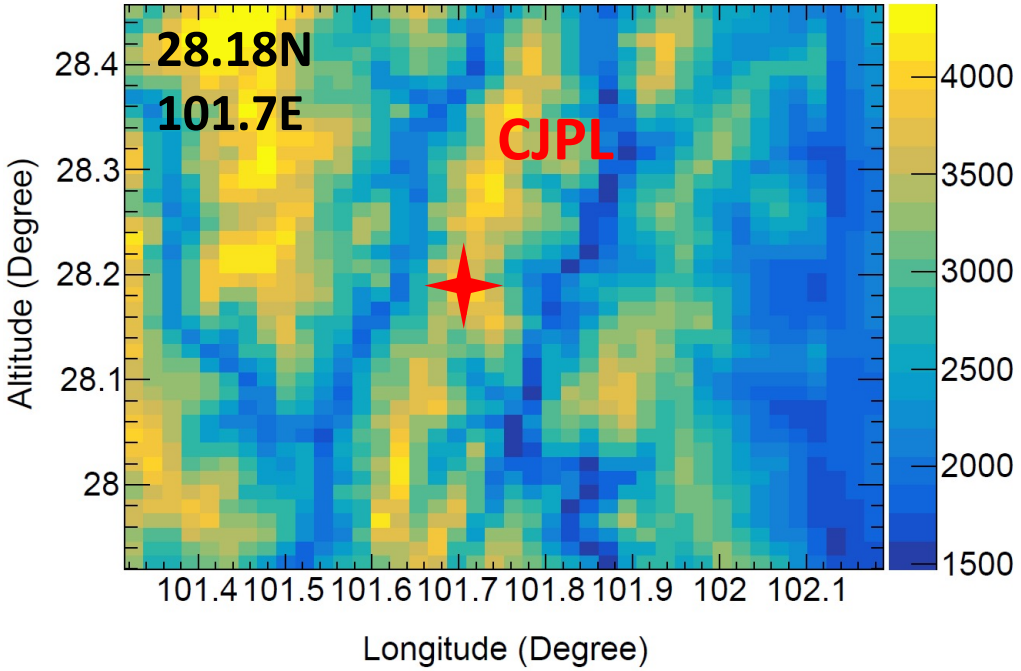
Earth Attenuation of CJPL

- Angle deflection
- Form factor

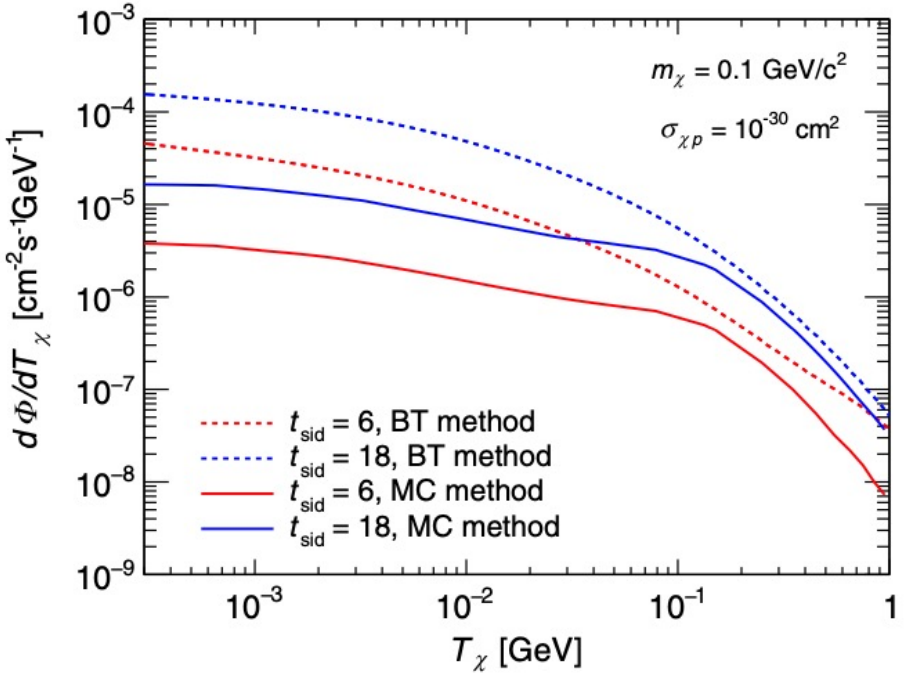


element	O	Ca	Mg	C	Si	Al	Fe	K	Na	P
f (%)	46.42	31.96	11.50	9.59	0.19	0.15	0.10	0.07	0.01	0.01
Z	8	20	12	6	14	13	26	19	11	15
A	16	40	24	12	28	27	56	39	23	31

$$\frac{d\sigma_{\chi A}}{dT_r} = \frac{\sigma_{\chi p} A^2}{T_r^{max}} \left[\frac{m_A(m_\chi + m_p)}{m_p(m_\chi + m_A)}\right]^2 G_A^2(Q^2)$$

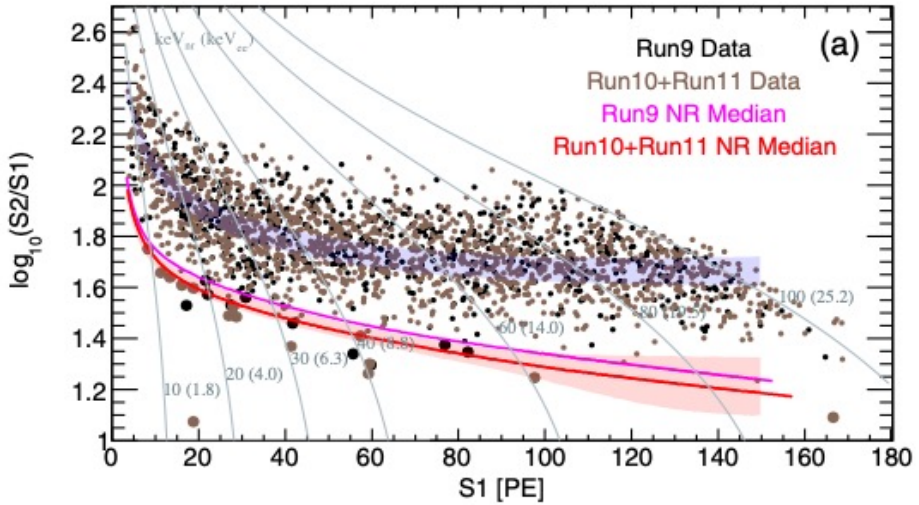


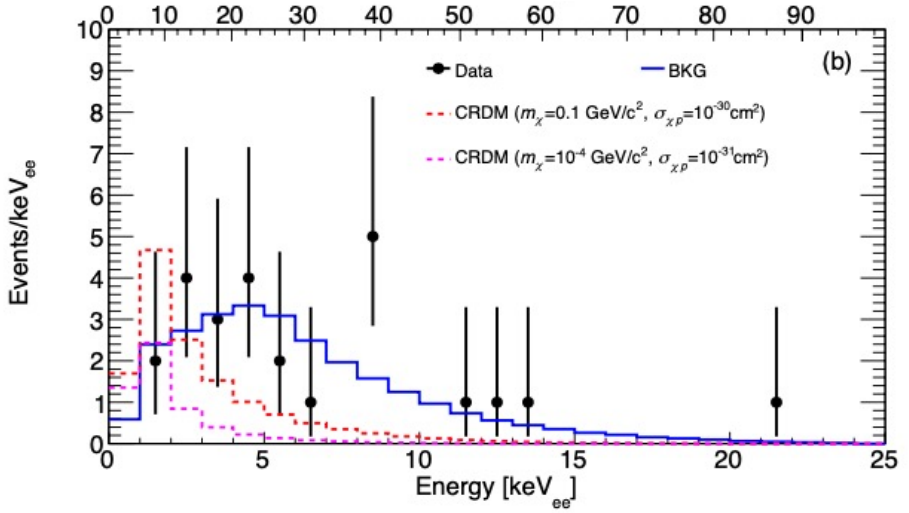
to be conservative, only Tchi < 0.2 GeV is considered to avoid incoherent and inelastic scattering region.

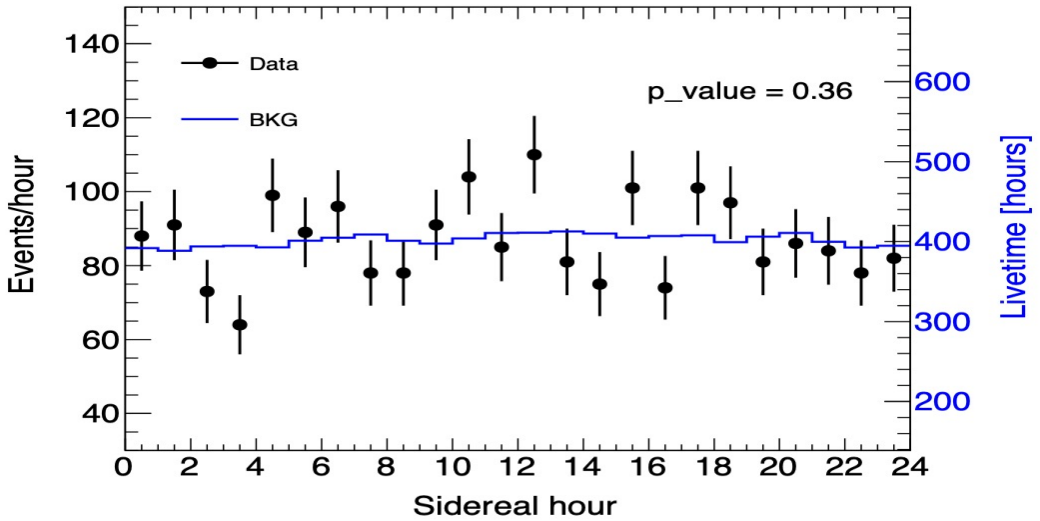


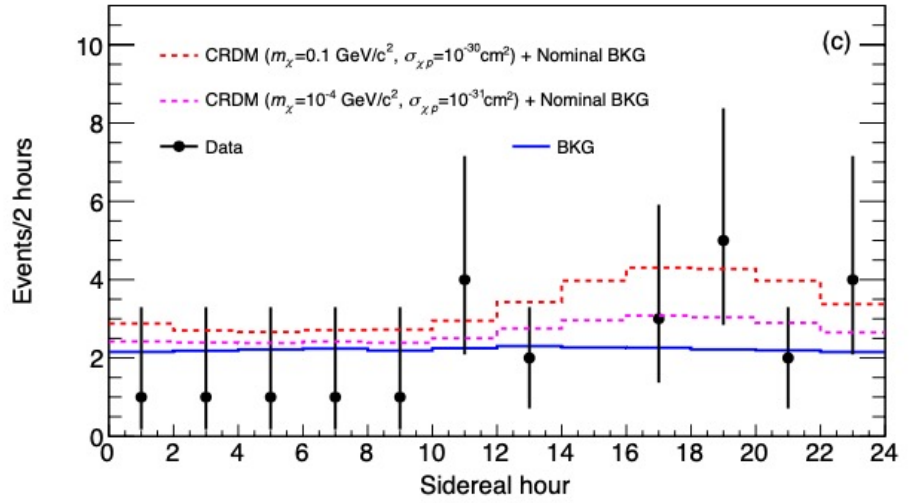
PandaX-II Sidereal Hour

- Using events below NR median
  - 25 events (expected 26.6 background)



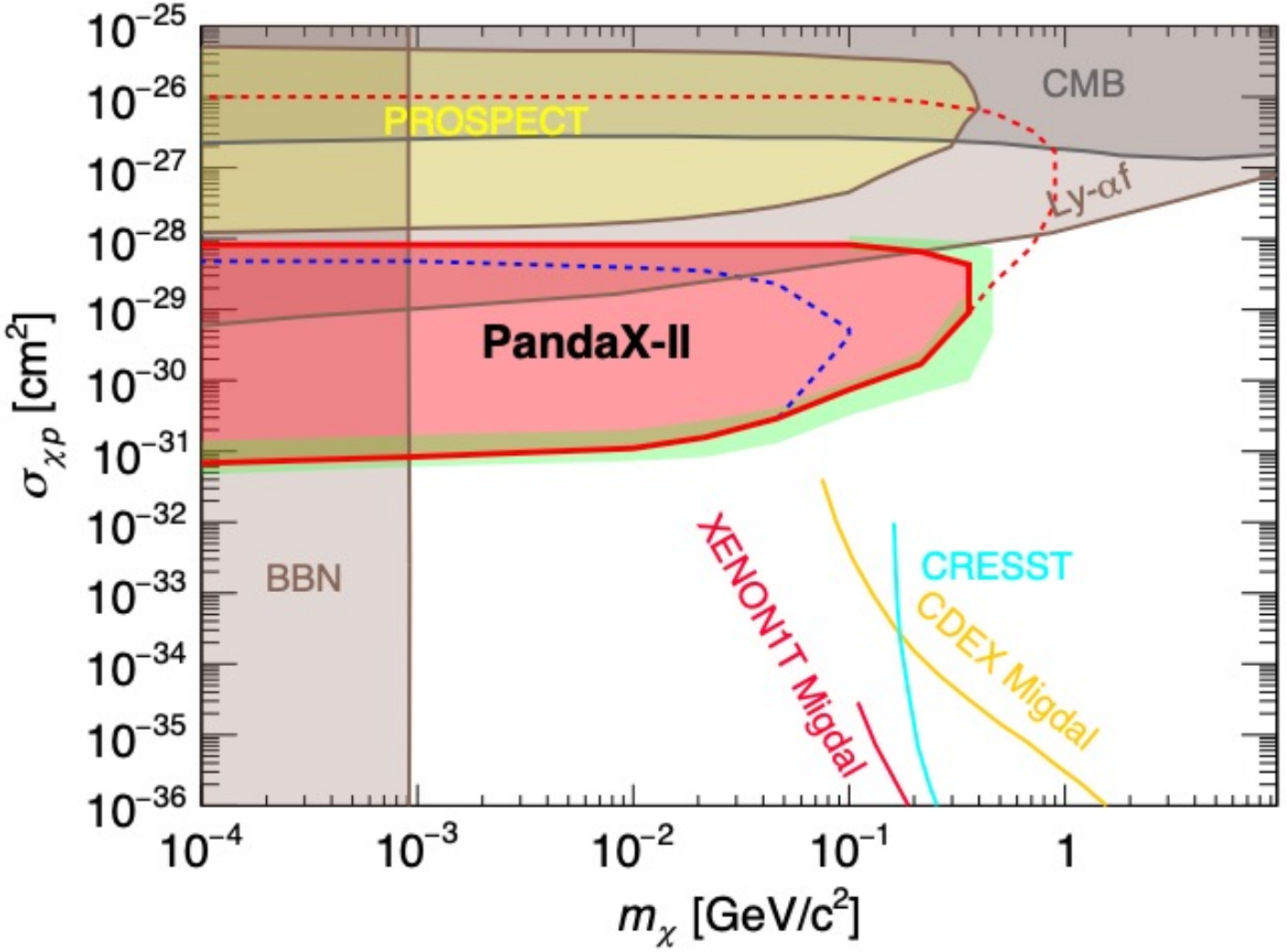






Constraints on sub-GeV mass region

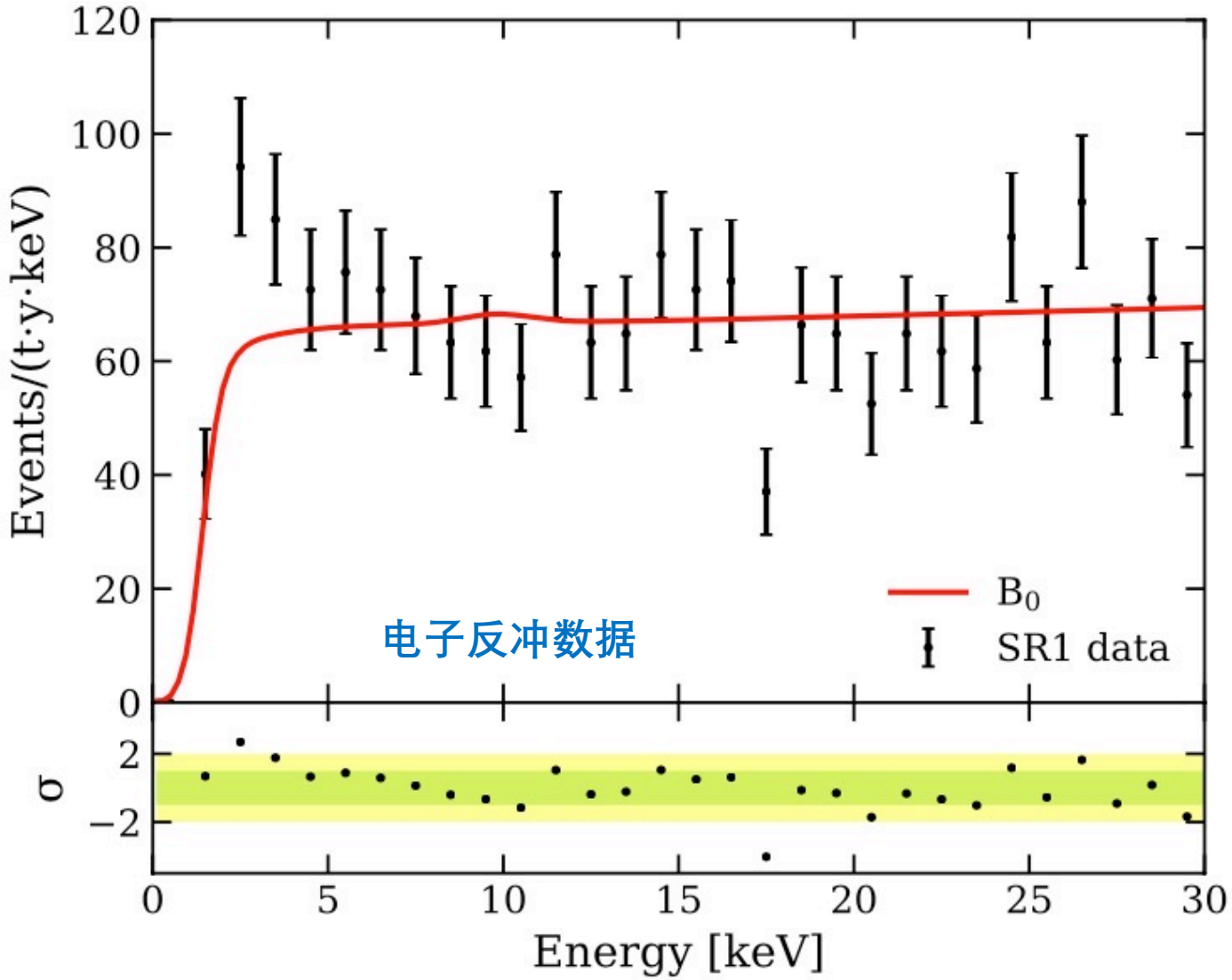
- Expand to the region beyond the astrophysical and cosmological probes



PRL 128, 171801 (2022)
Editors' Suggestion

XENON1T Excess in Electron Recoil Events

- 0.65 tonne-year exposure of XENON1T experiment
- 3σ excess in electronic recoil signal region
- Fitted with solar axion, etc
- Need further cross-check with more sensitive detectors

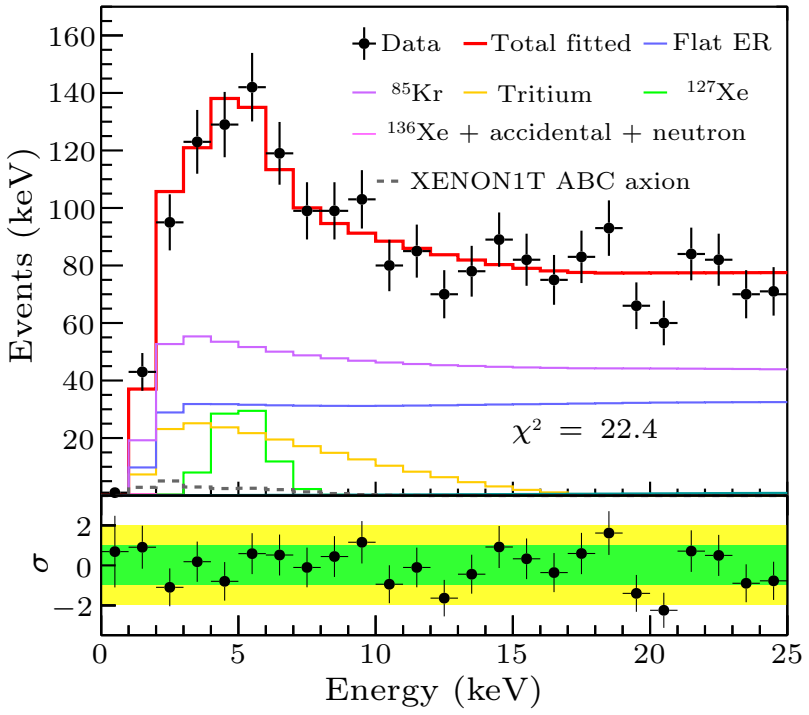


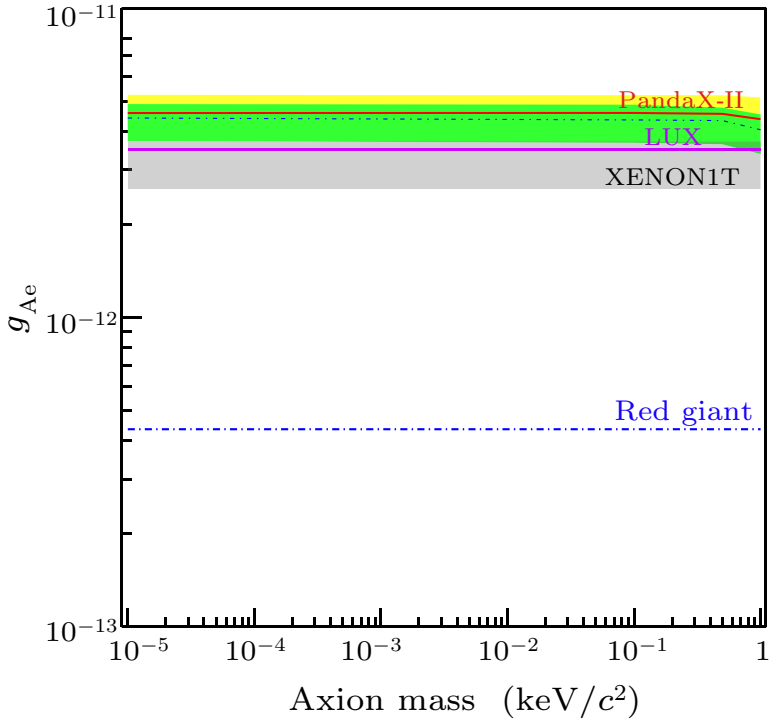
PRD 102, 072004 (2020)

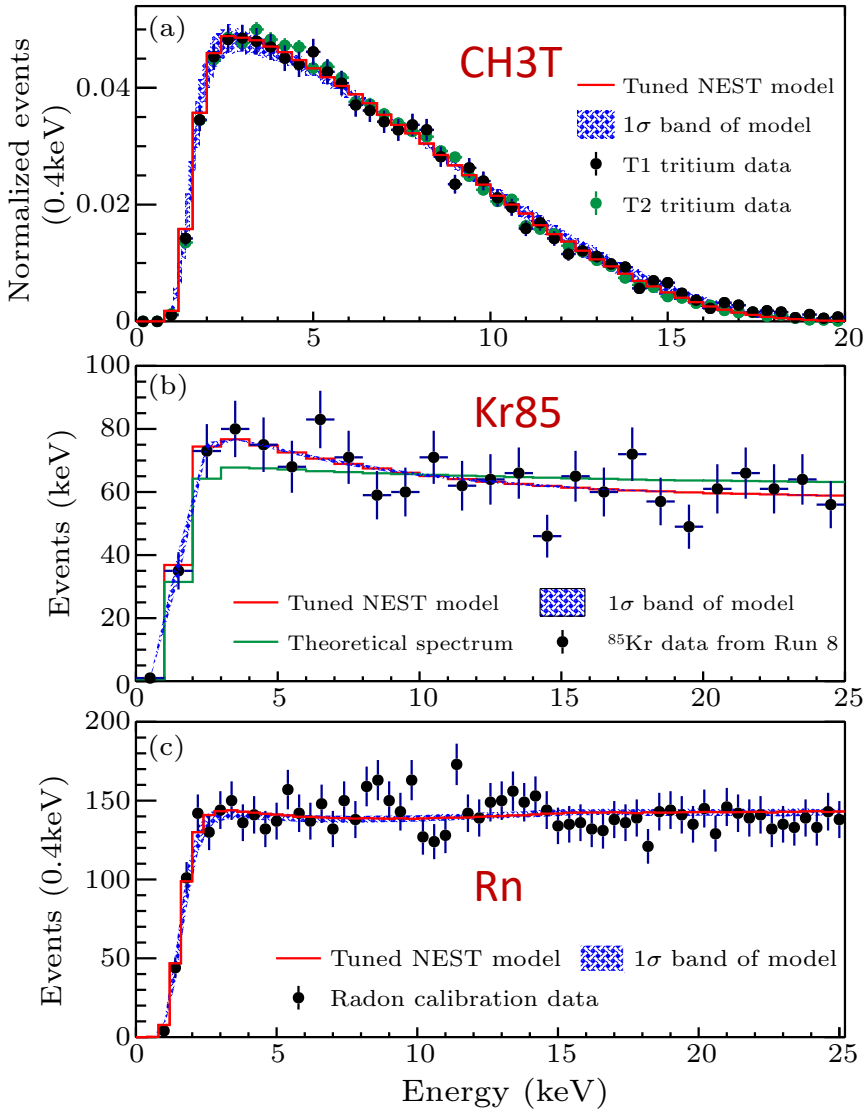
Independent Check from PandaX-II

- Signal: axions, neutrino magnetic moment
- Major background spectra obtained from calibration data directly
- Independent check of XENON1T low energy ER excess

CPL Vol 38, No. 1 (2021) 011301

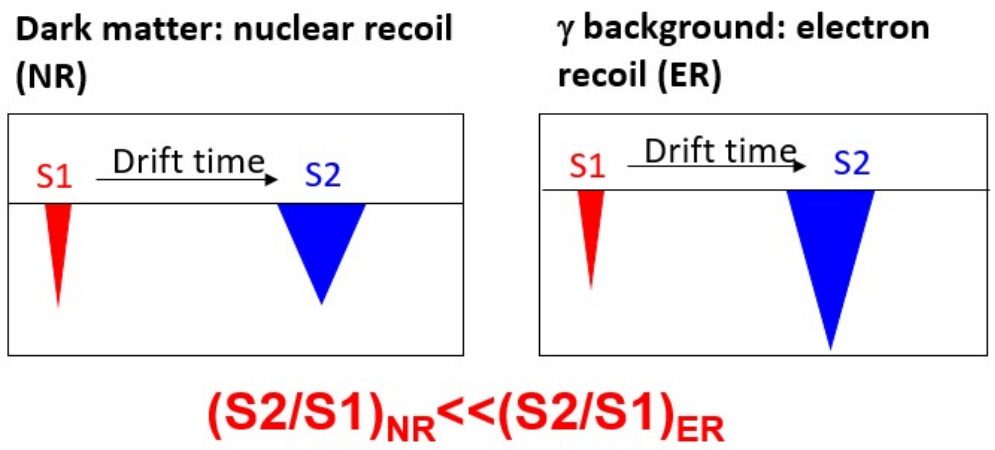




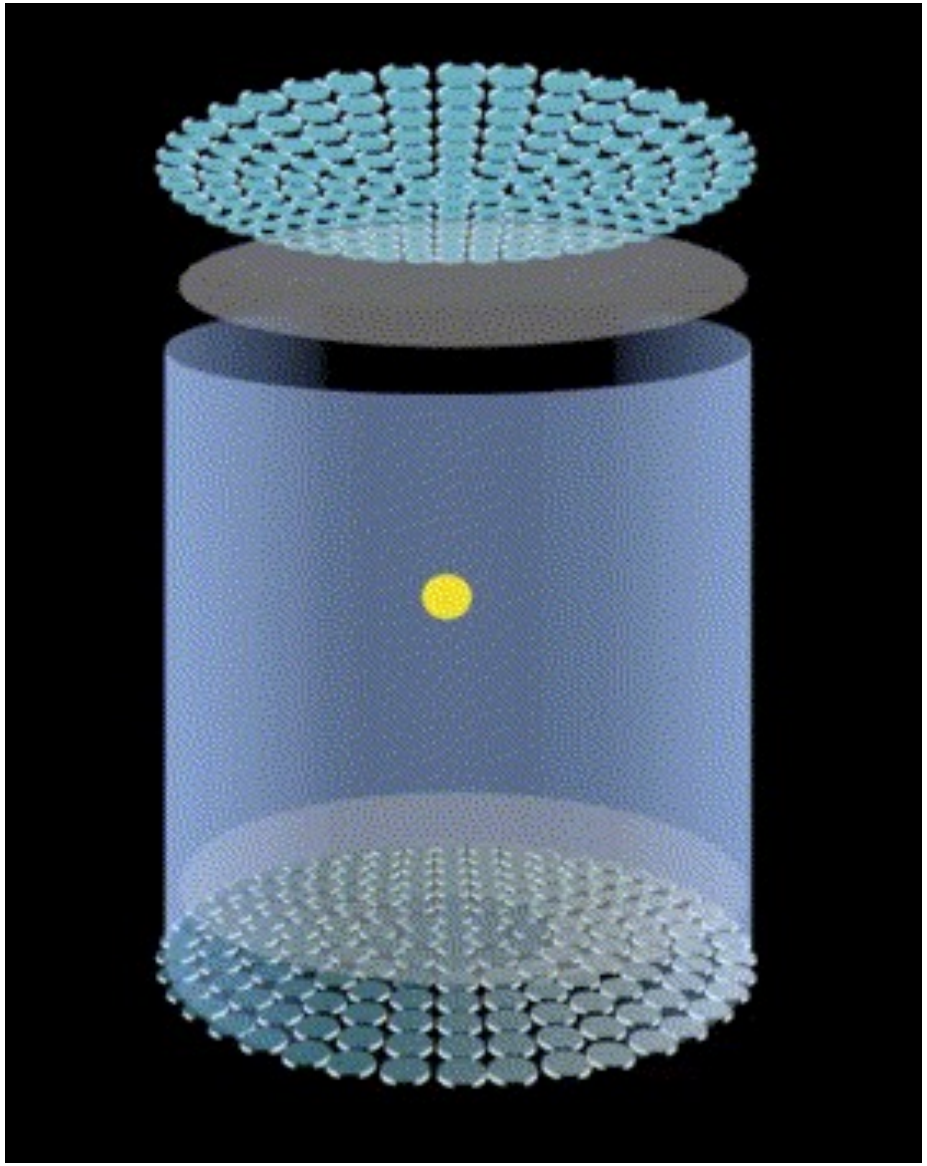


S2-only Strategy

- Dual-phase xenon TPC

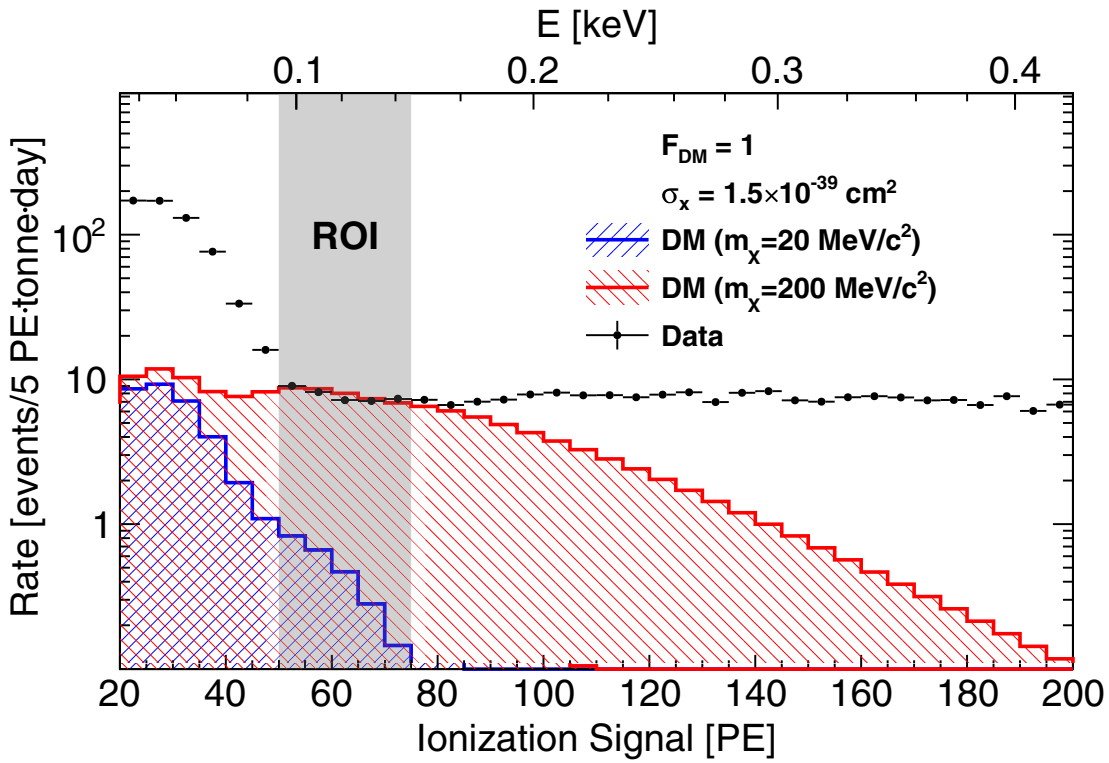


- To lower the threshold: S2-only

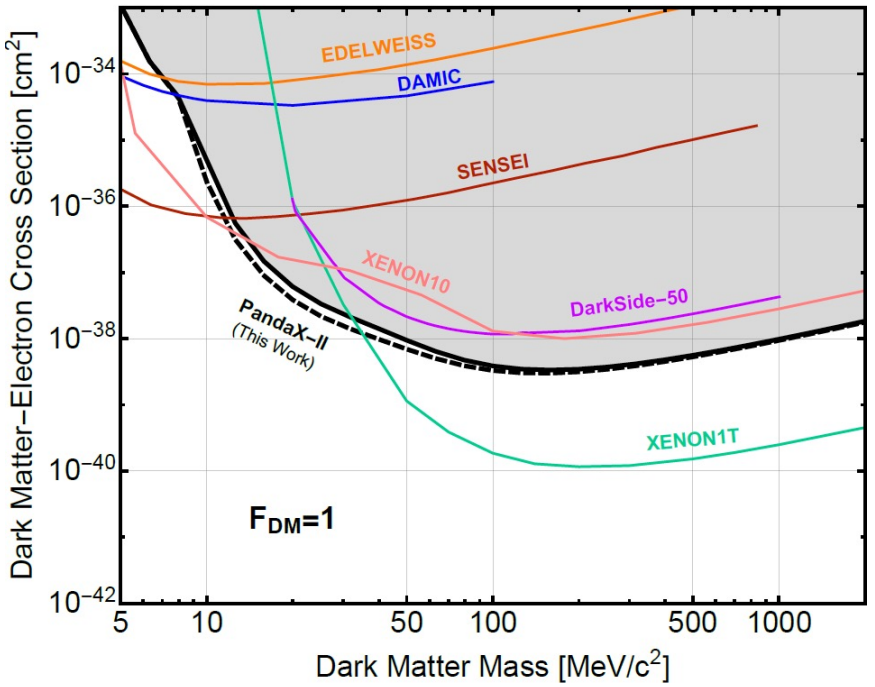


WIMP-electron scattering

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

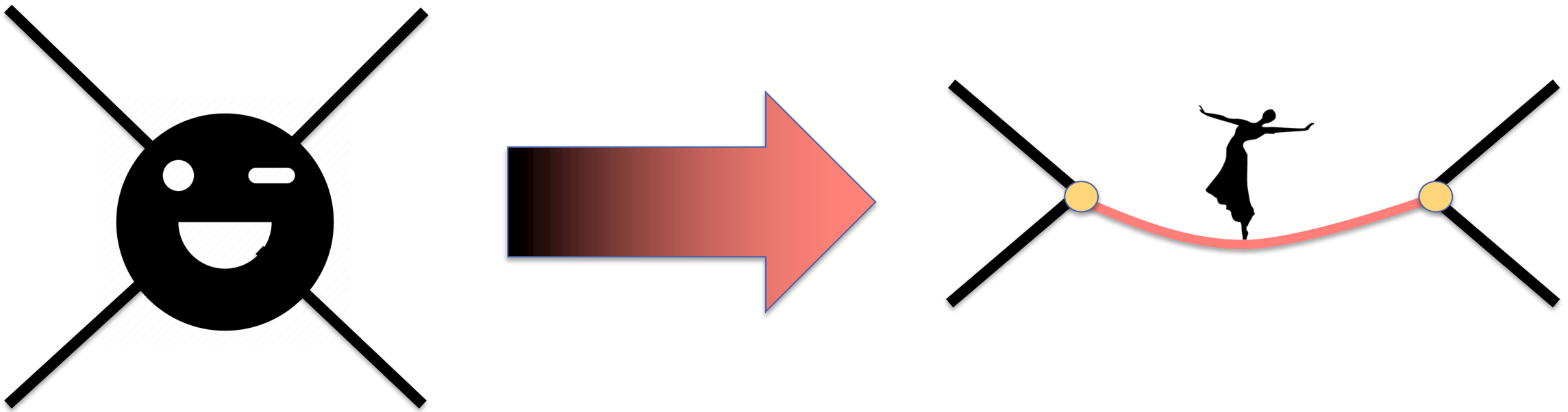


PRL 126, 211803 (2021)



Simplified Model in DM direct detection

- Effective field theory: a good approximation to DM-nucleon interaction
- Simplified model with mediator information
  - some interesting signatures come out



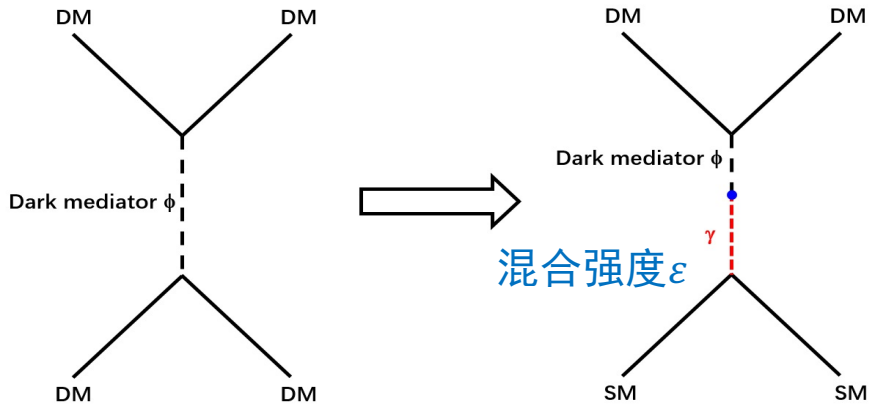
Self-interactive DM

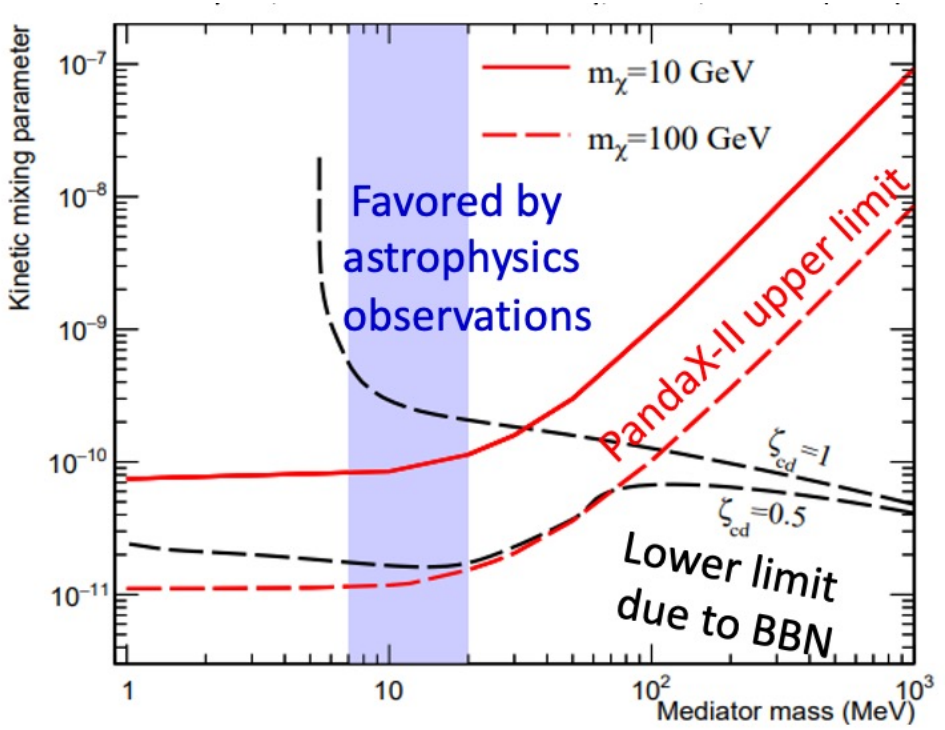
SCPMA Vol. 64, 111062 (2021)

- Light mediator: mediator m_ϕ is compared to or smaller than q
  - Signal spectrum more peaked towards to low-energy
- PandaX-II result

$$\sigma(\text{暗物质和核子}) \propto \frac{\varepsilon^2}{m_\phi^4}$$

  - Upper limits on the mixing parameter
  - Combination with astrophysics and cosmology
  - Under SIDM，for 10-200 GeV/c^2 DM mass，dark sector is colder than visible sector in early universe





Editorial | Published: 29 September 2021

New connection between dark matter direct detections, astrophysical and cosmological observations with self-interacting dark matter

YiPeng Jing

Editor's Focus

Research Highlight | Published: 28 September 2021

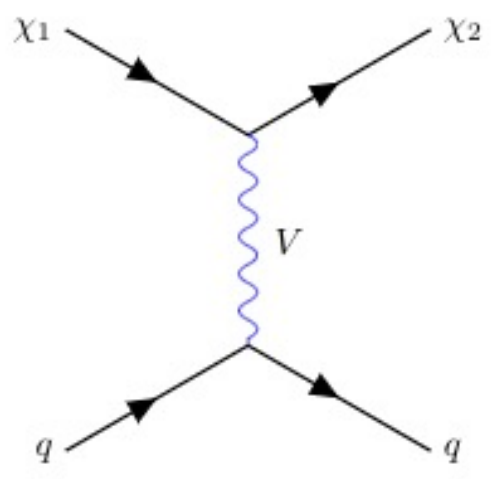
PandaX-II set constraints to self-interacting dark matter using the full dataset

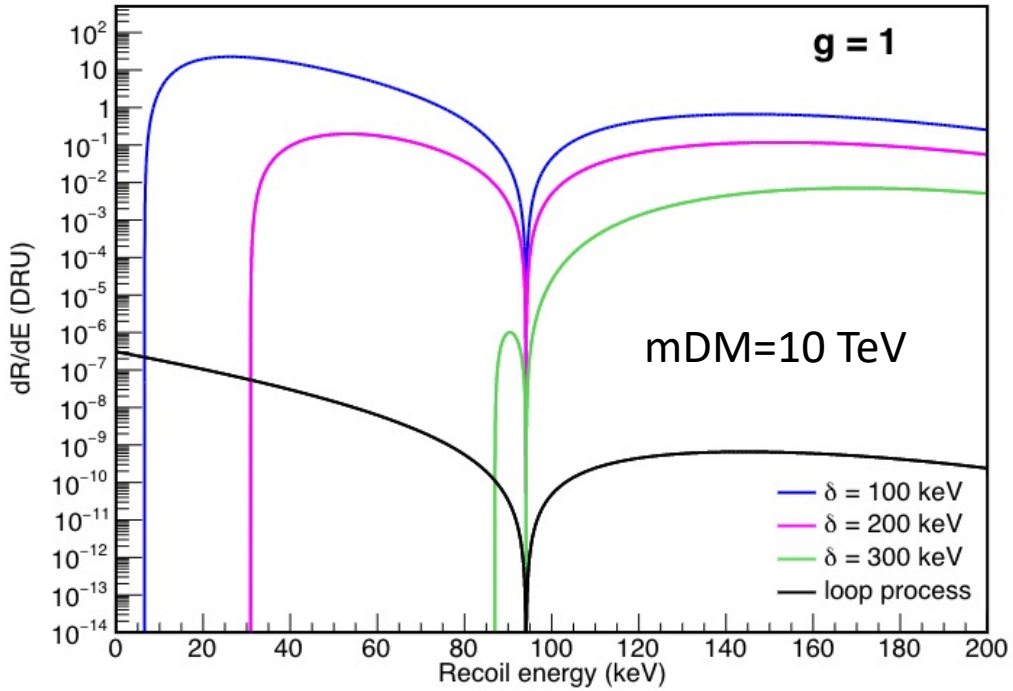
Wan-Zhe Feng

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

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



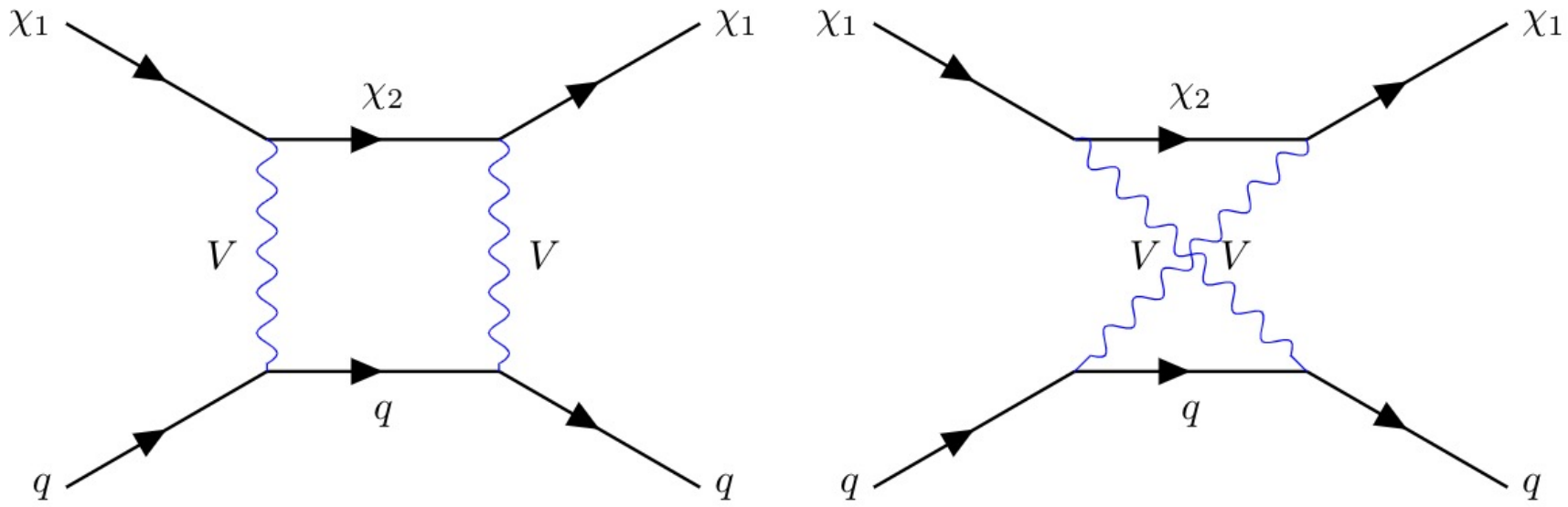


Loop Contribution

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

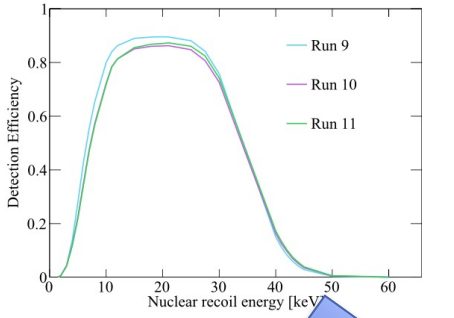
$$L_{\text{loop}} = \frac{4g^4 m_{\chi_1} m_q}{16\pi^2 M^4} F_3\left(\frac{m_{\chi_1}^2}{M^2}\right)\bar{\chi}_1\chi_1\bar{q}q \to c_1^N\bar{\chi}_1\chi_1\bar{N}N,$$

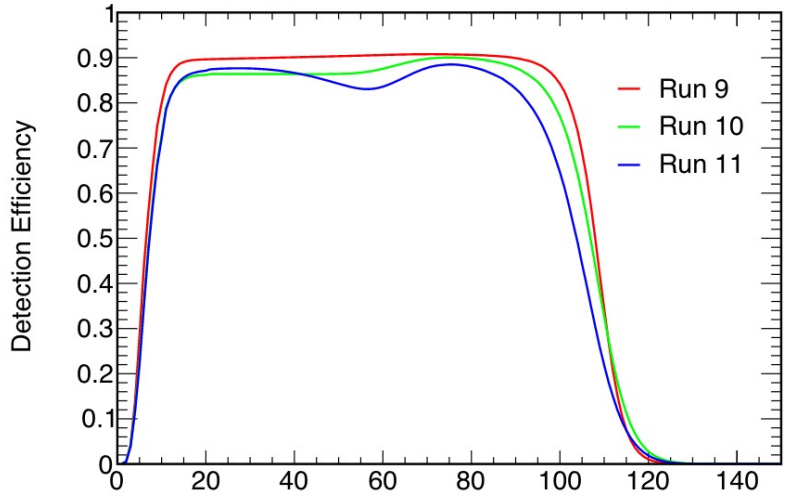
- Complementary to tree-level especially for large mass splitting

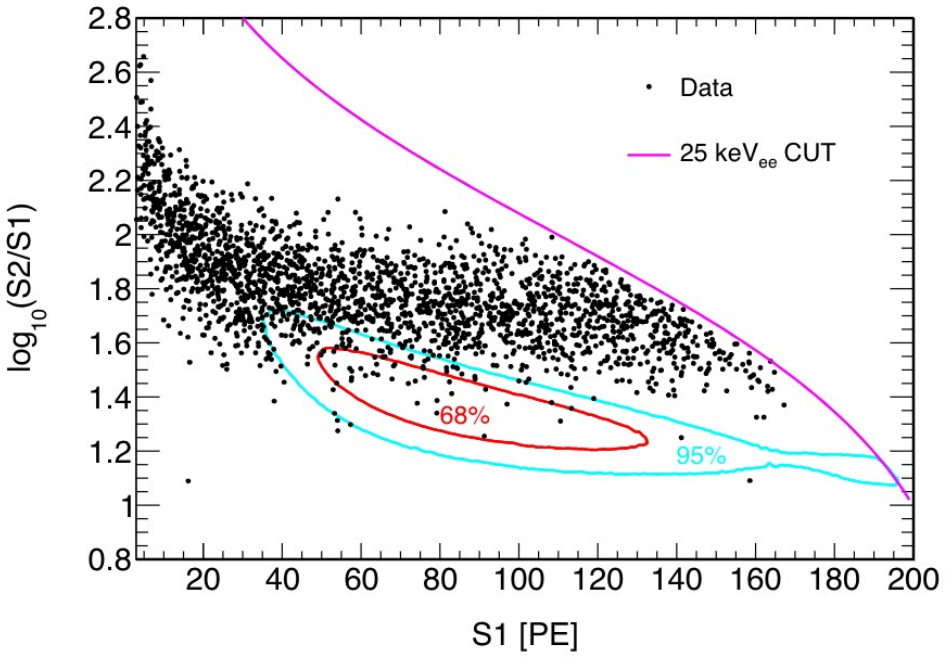


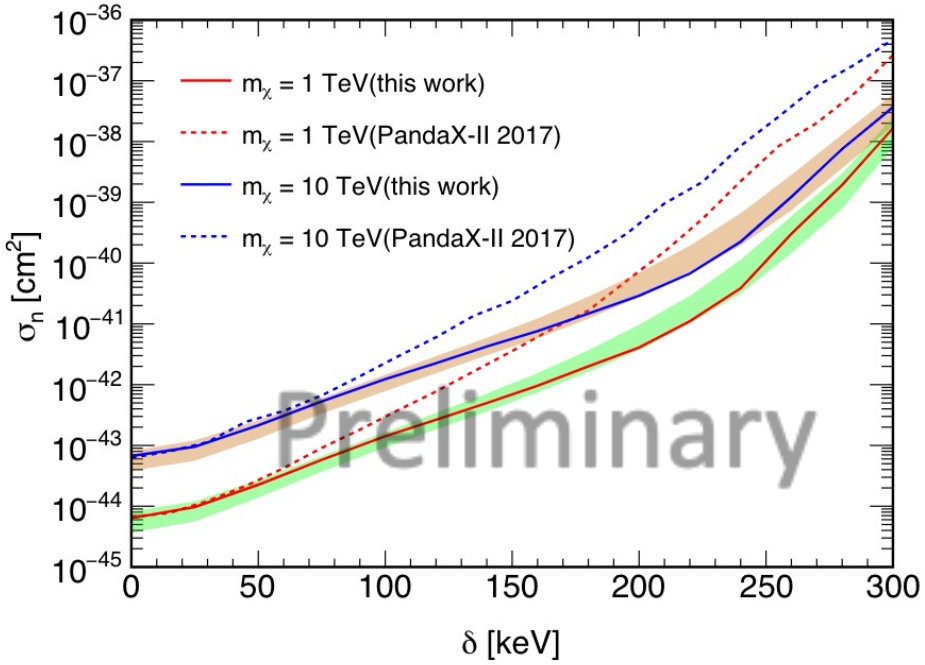
PandaX-II Search

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



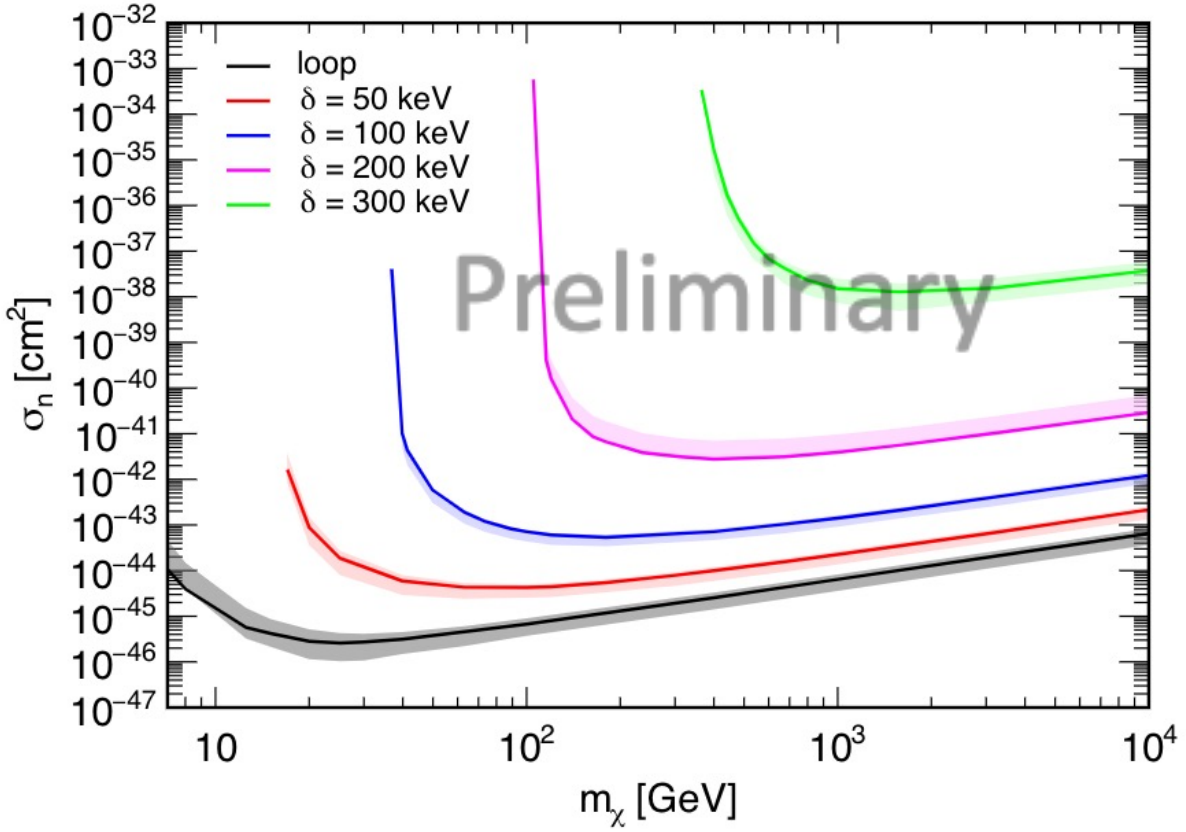


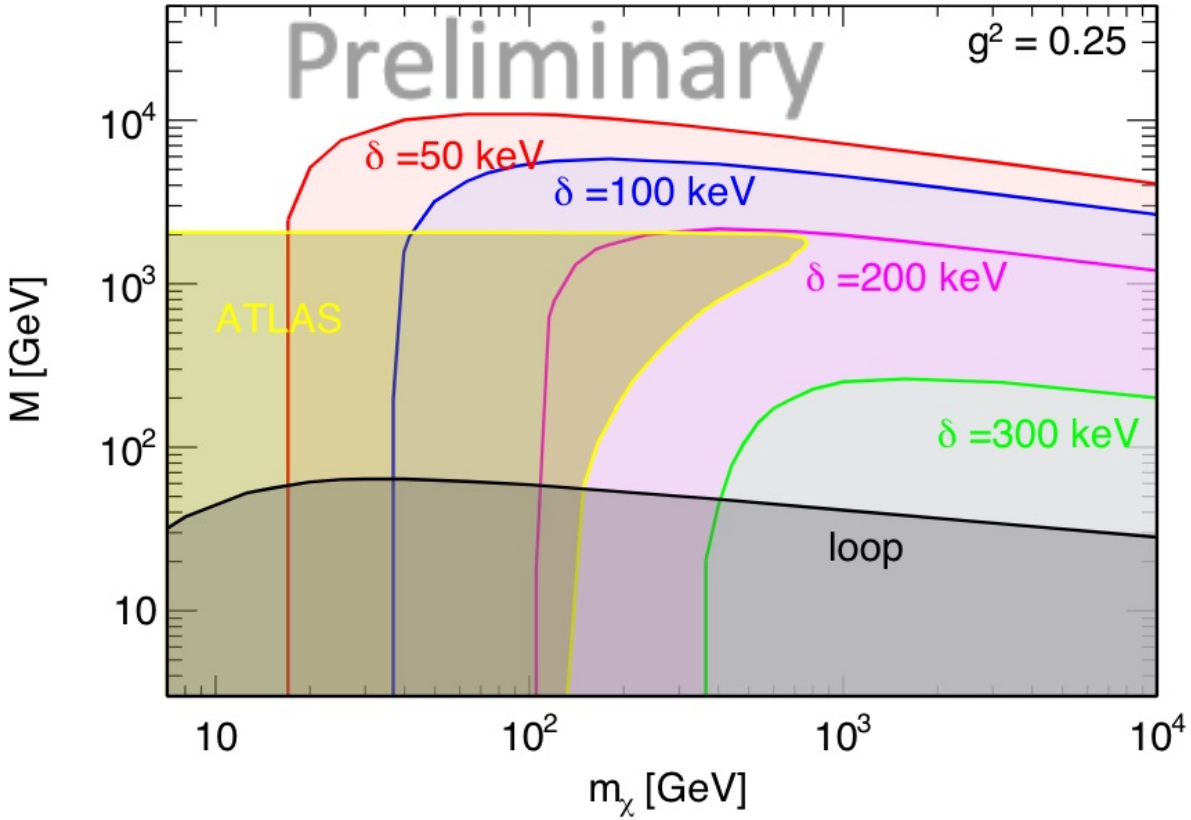




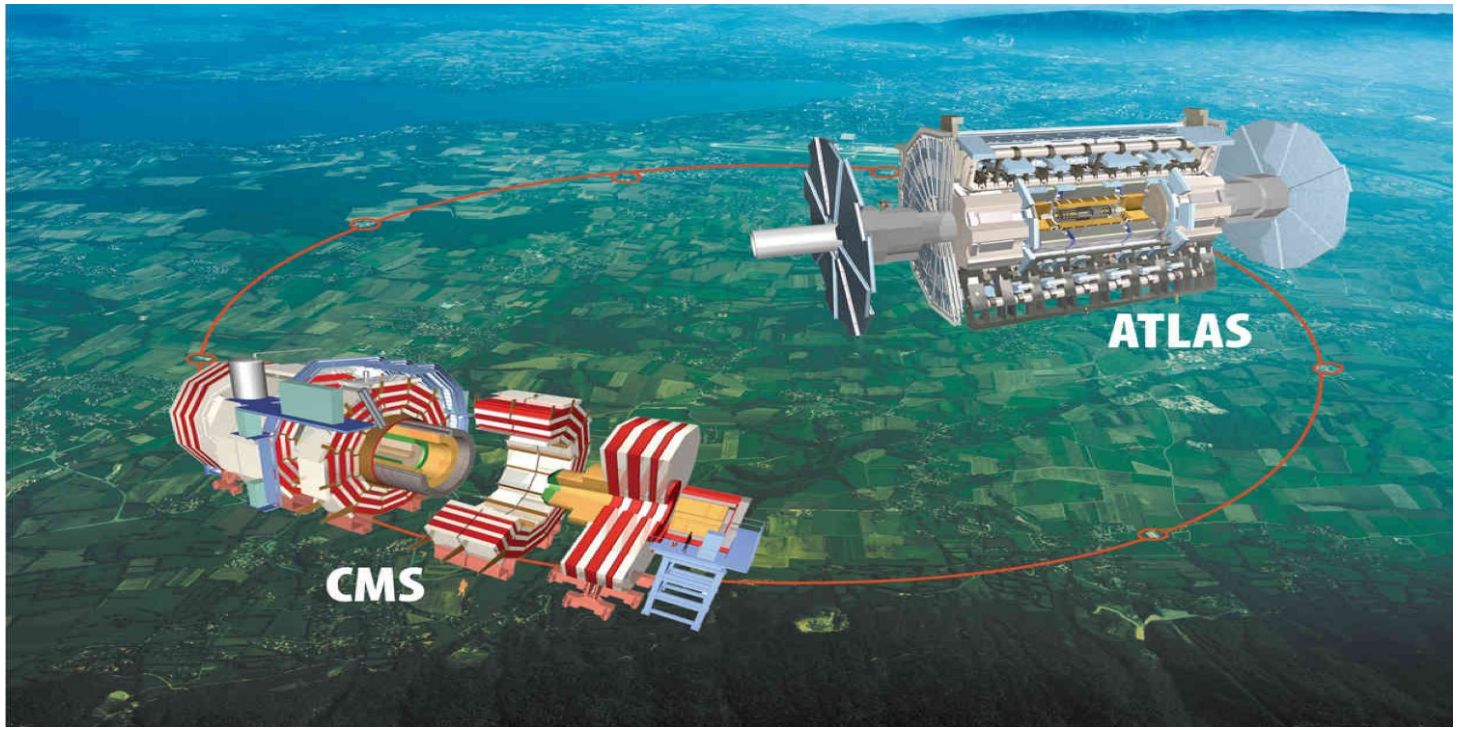
Combine Inelastic and Elastic

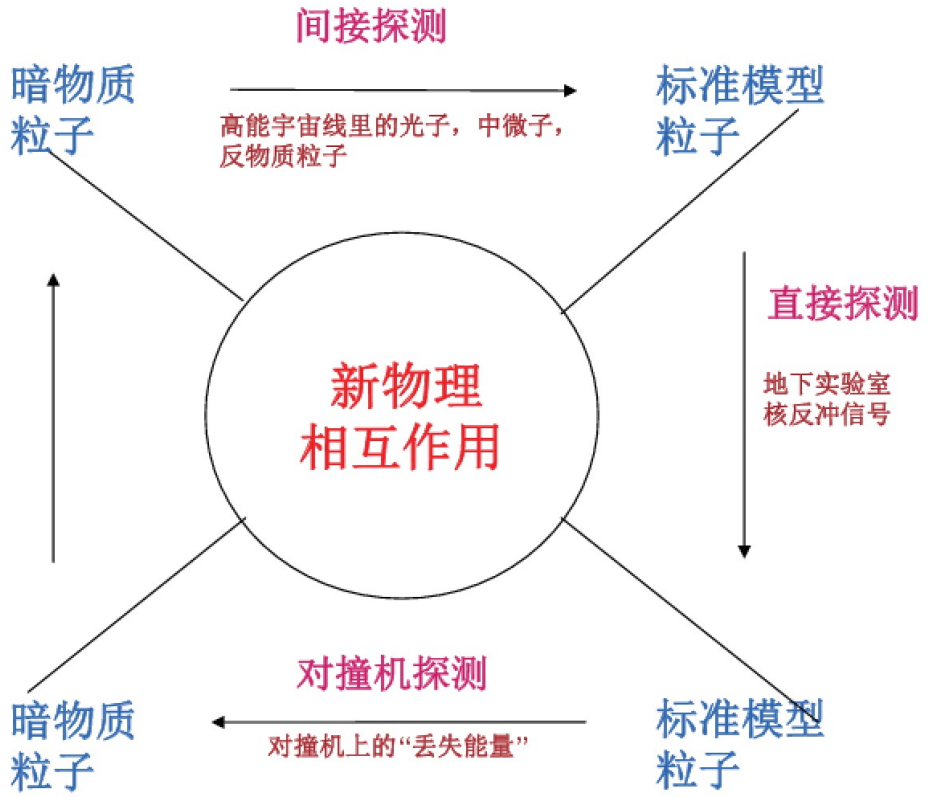
- Loop-level: Competitive constraints for large DM mass and large mass splitting
- Collider constraints from ATLAS mono-jet search



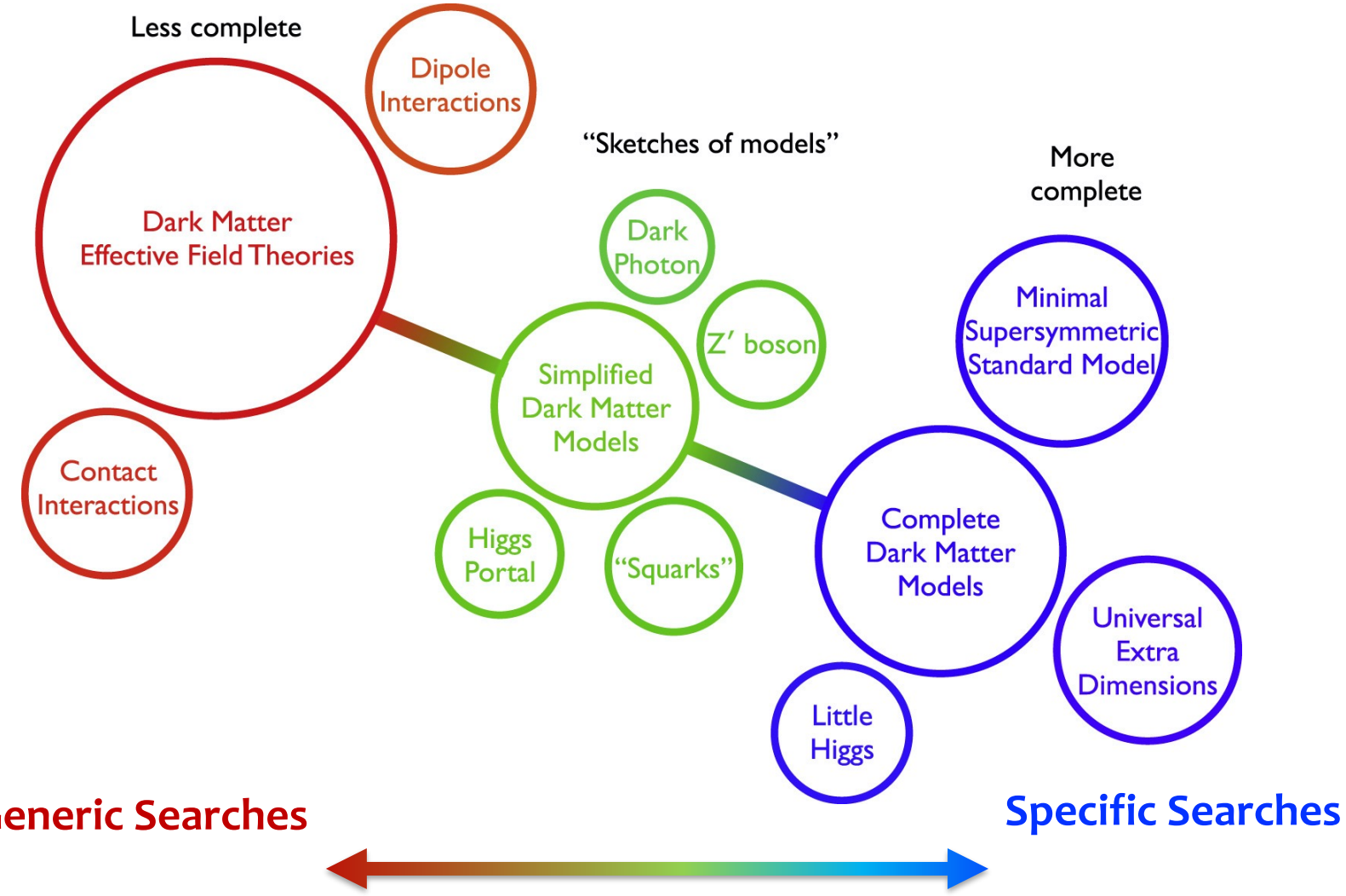


Collider Searches





Dark Matter Models

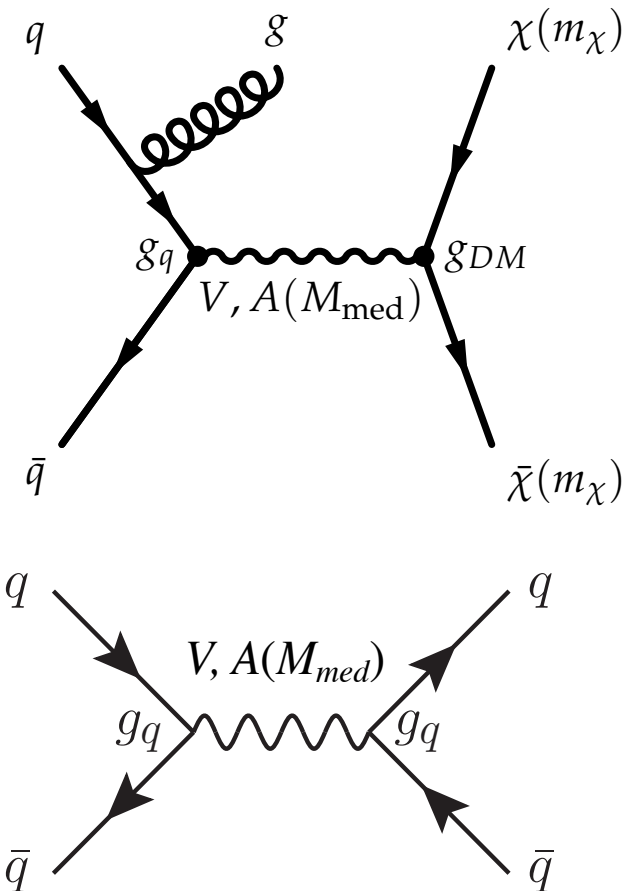


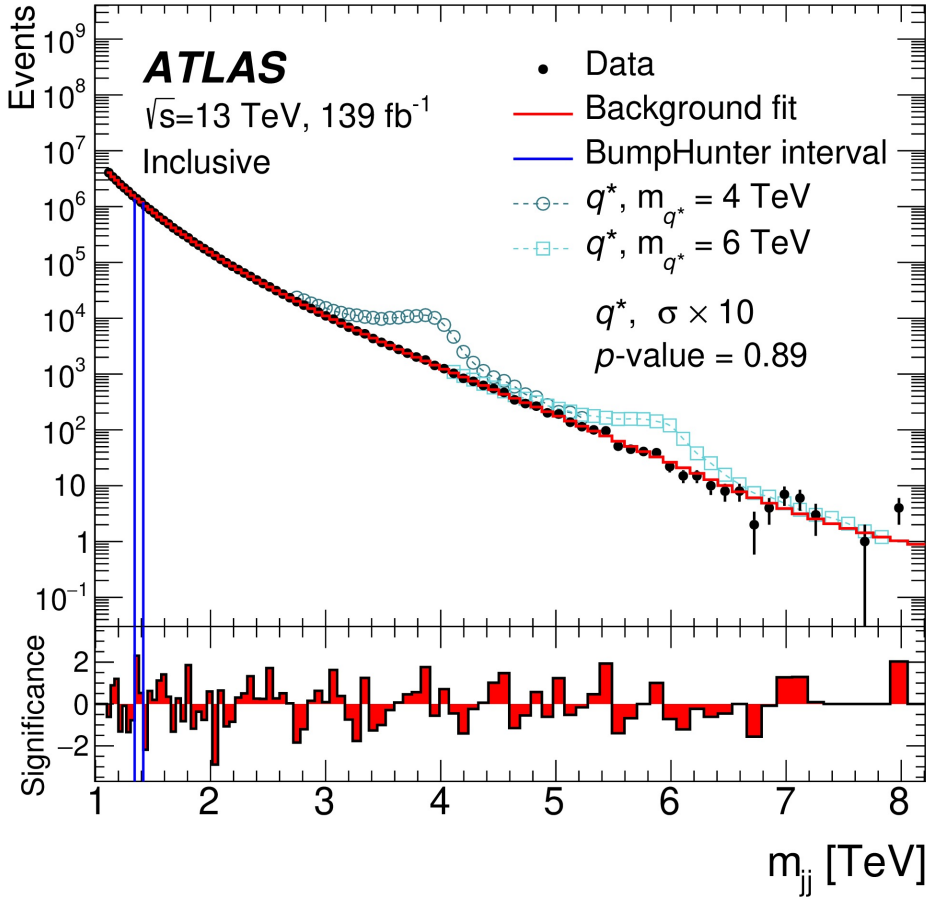
Phys. Dark Univ. 9-10 (2015) 8-23

- Toward simplified model or UV-complete model
- Search for the mediator information

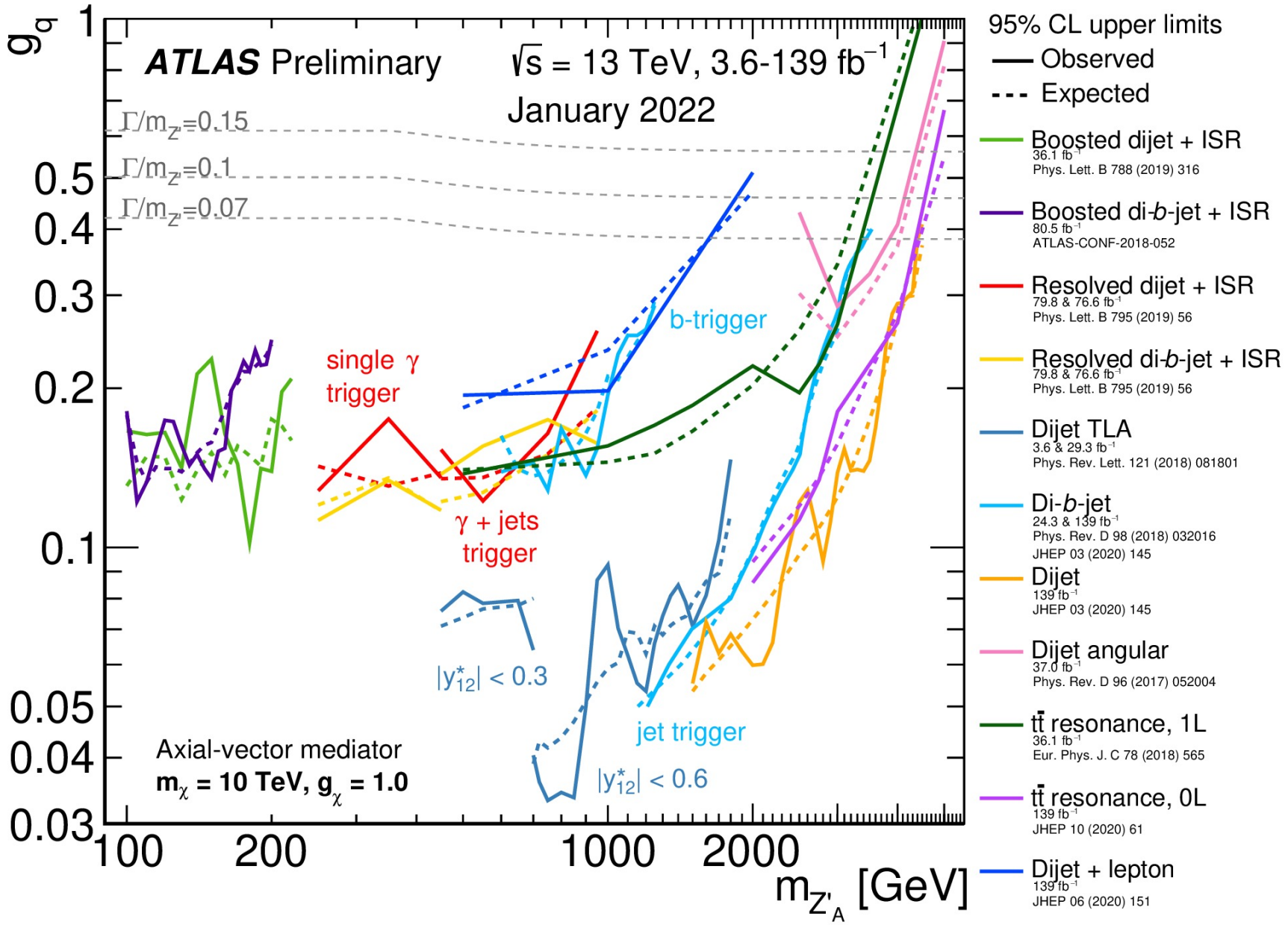
Mediator Search at collider

- direct search of the mediator
- dijet resonance: inclusive, 1 or 2 b-jets



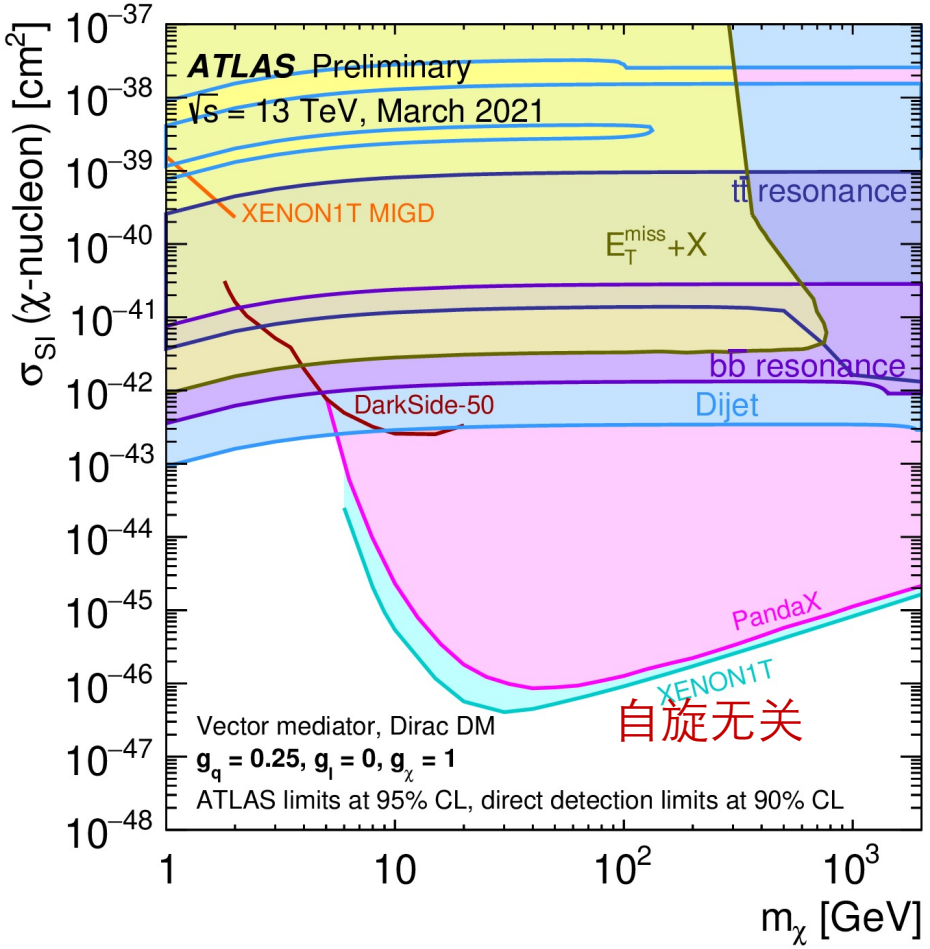


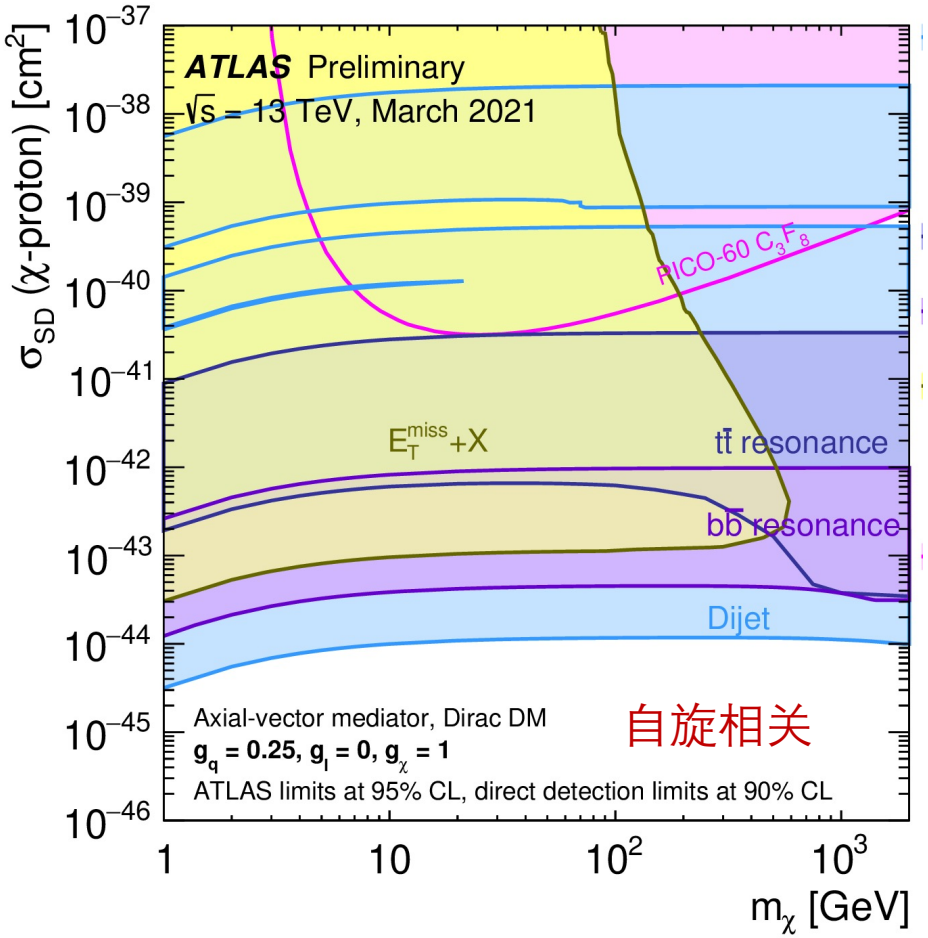
Constraints on Mediator



Combined Constraints

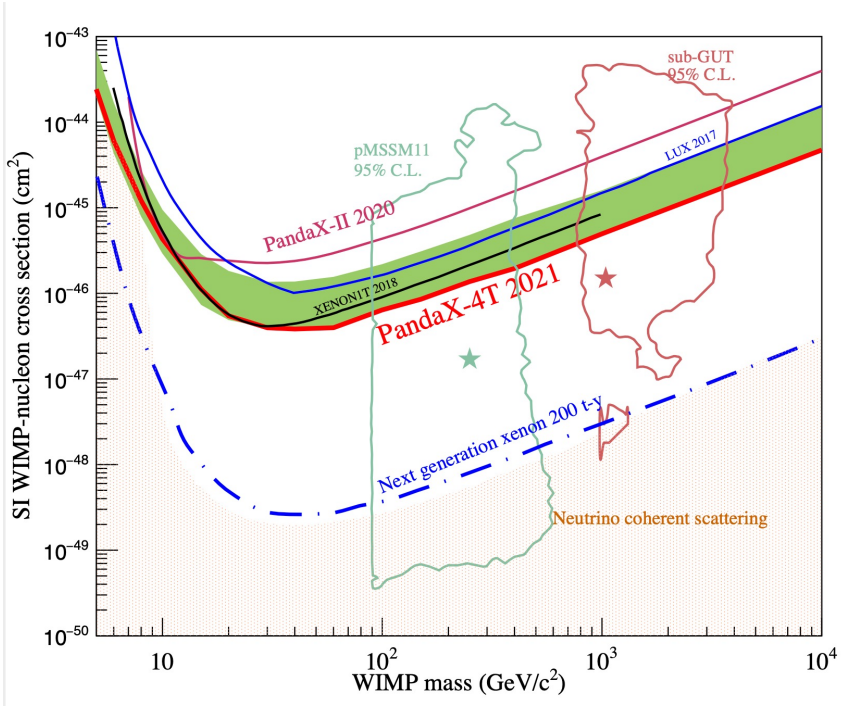
- With direct detection experiments

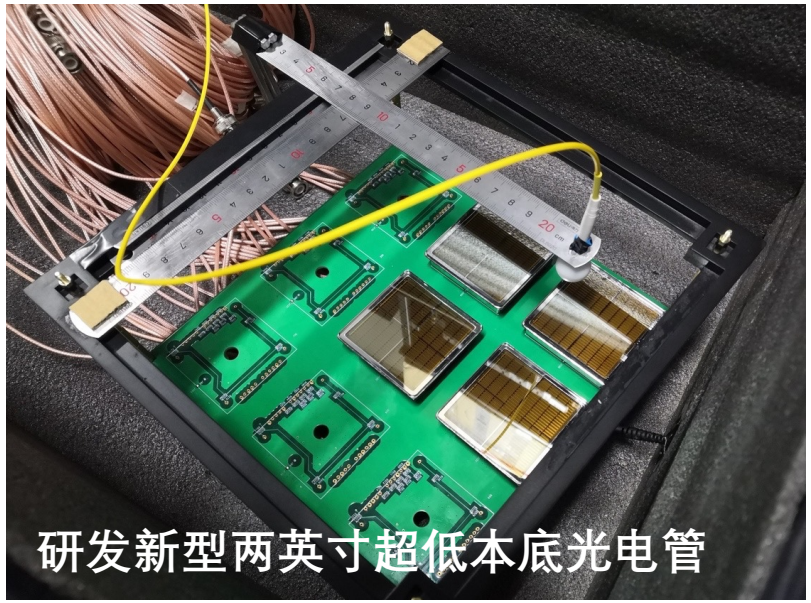


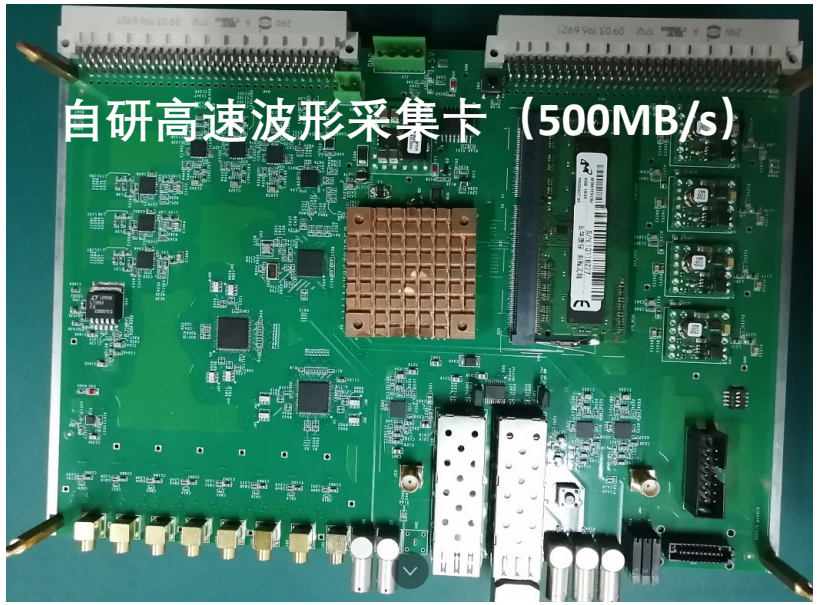


Next Generation: PandaX-xT

- **Towards the “neutrino floor”**
- Low background PMT
- Large size TPC
- Xenon isotope separation

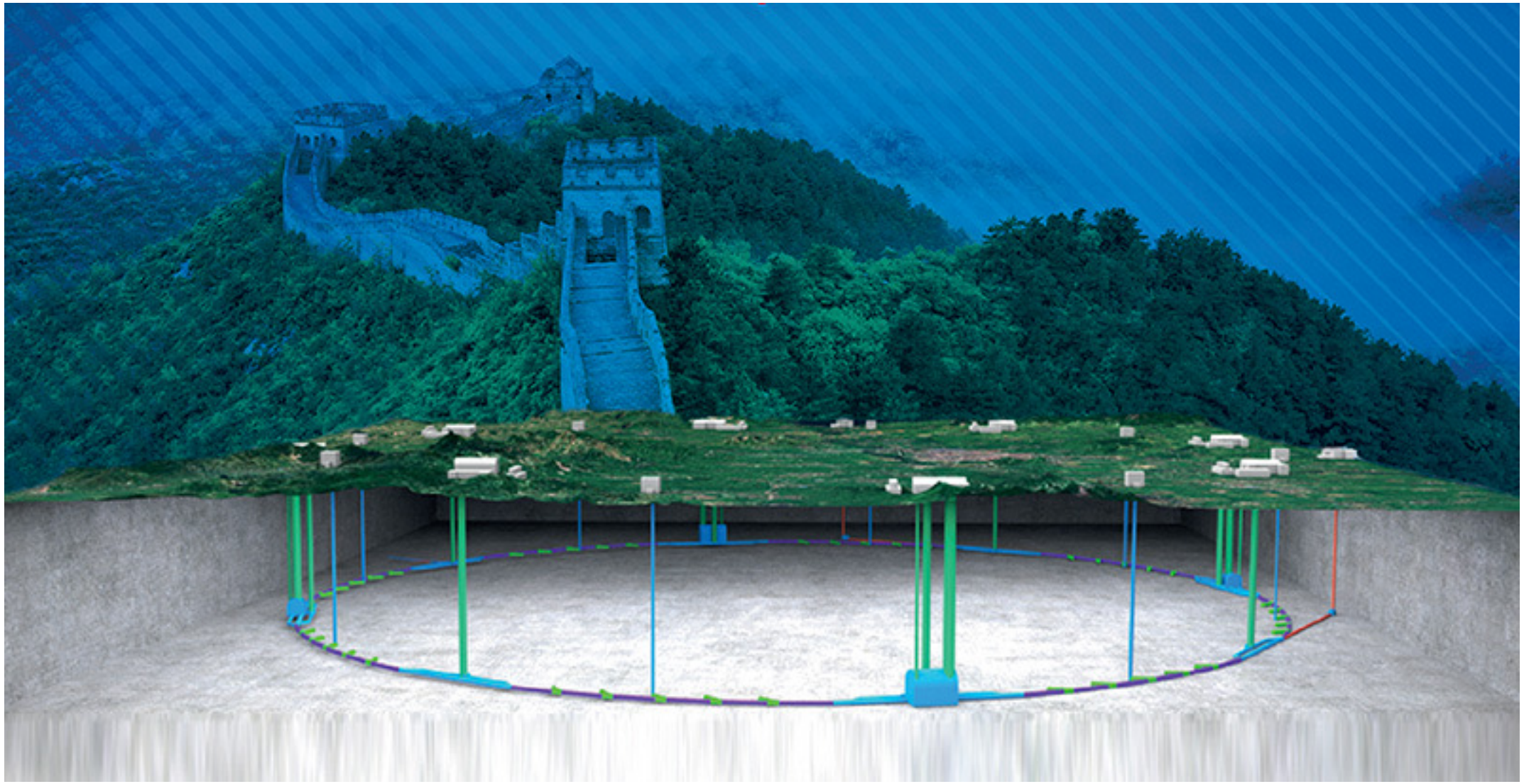






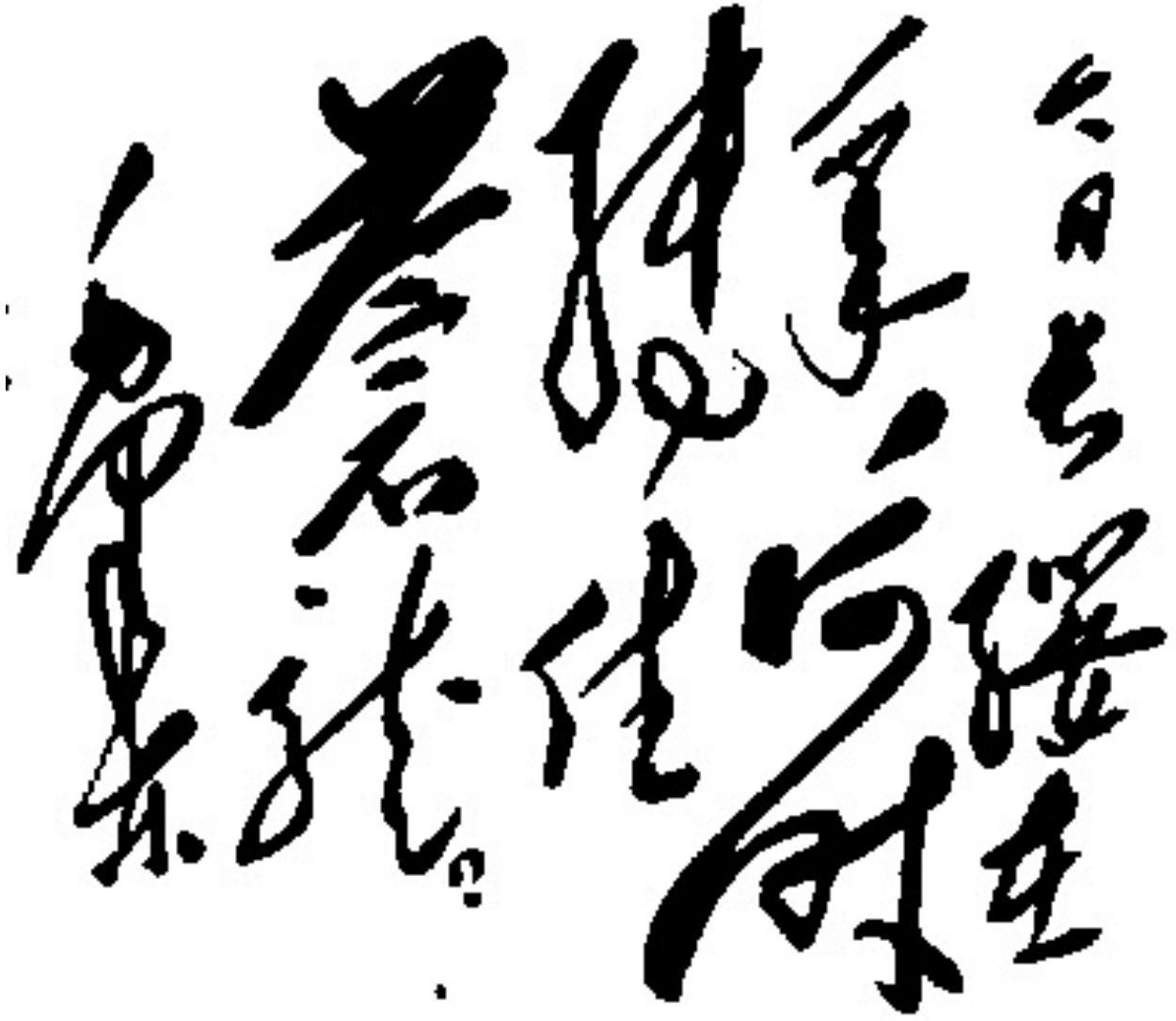
Next Generation Collider

- Higgs-related dark matter scenario



Summary

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



谢谢大家！

3rd Generation Xenon Experiments

- Darwin experiment
  - 60tonne xenon，100-150M Euros

Home › News › XENON/DARWIN and LZ members have agreed to w...

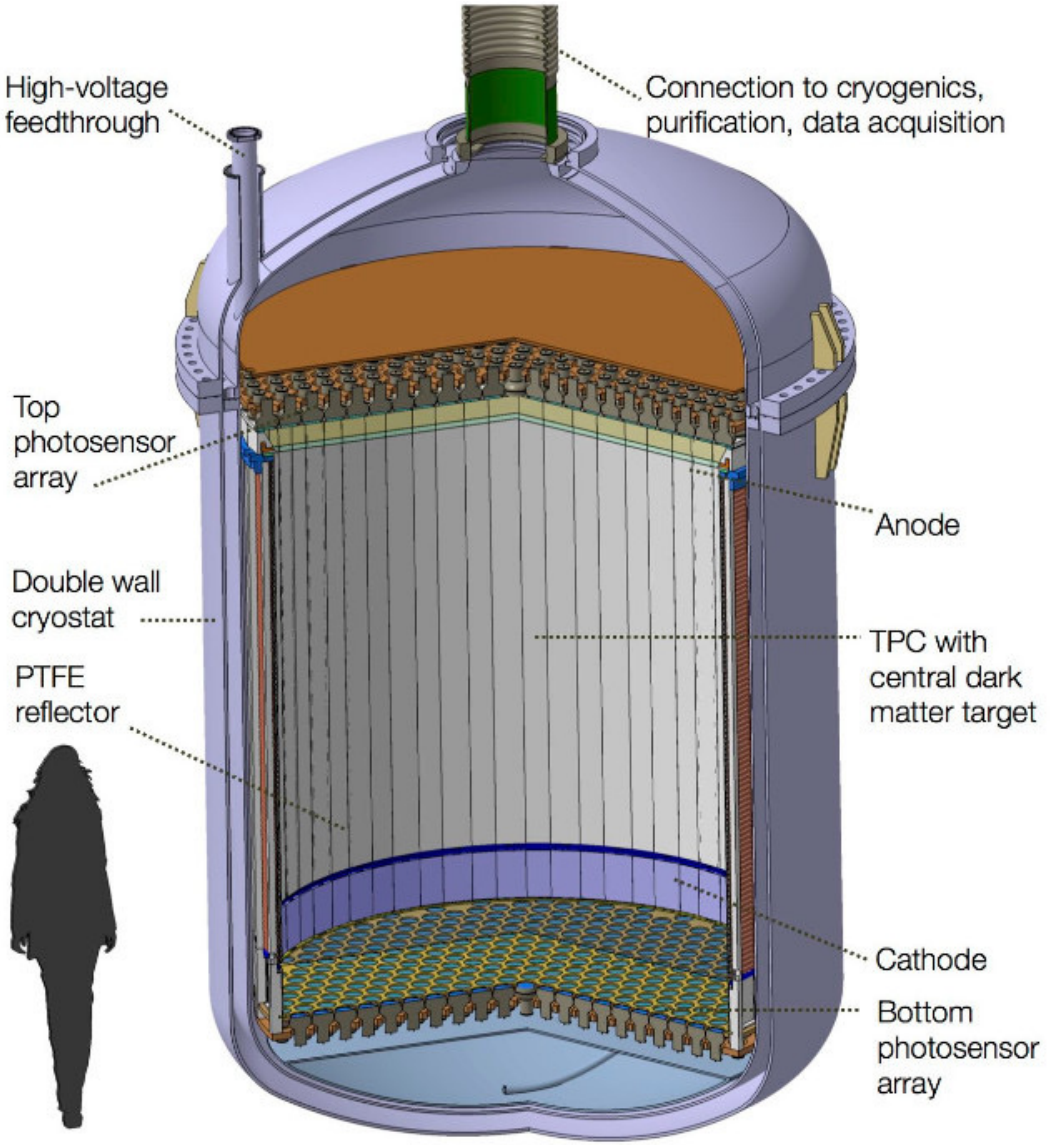
XENON/DARWIN and LZ members have agreed to work together on next generation dark matter search experiment

The XENON/DARWIN and LUX-ZEPLIN (LZ) collaborations have now joined forces to work together on the design, construction, and operation of a new, single, multi-tonne scale xenon observatory to explore dark matter. The detector will be highly sensitive to a wide range of proposed dark matter particles and their interactions with visible matter. Over the last 20+ years, experiments using liquefied xenon targets have delivered world-leading results in the global quest for direct dark matter detection. This next-generation detector aims to continue the pursuit.

Press release: darwin.physik.uzh.ch

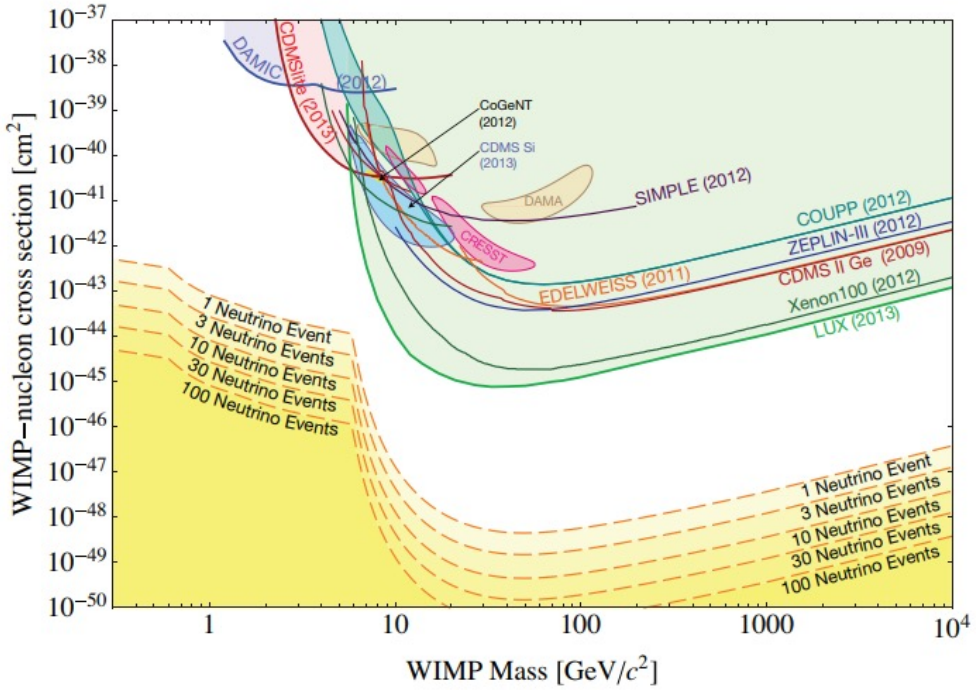
July 29, 2021

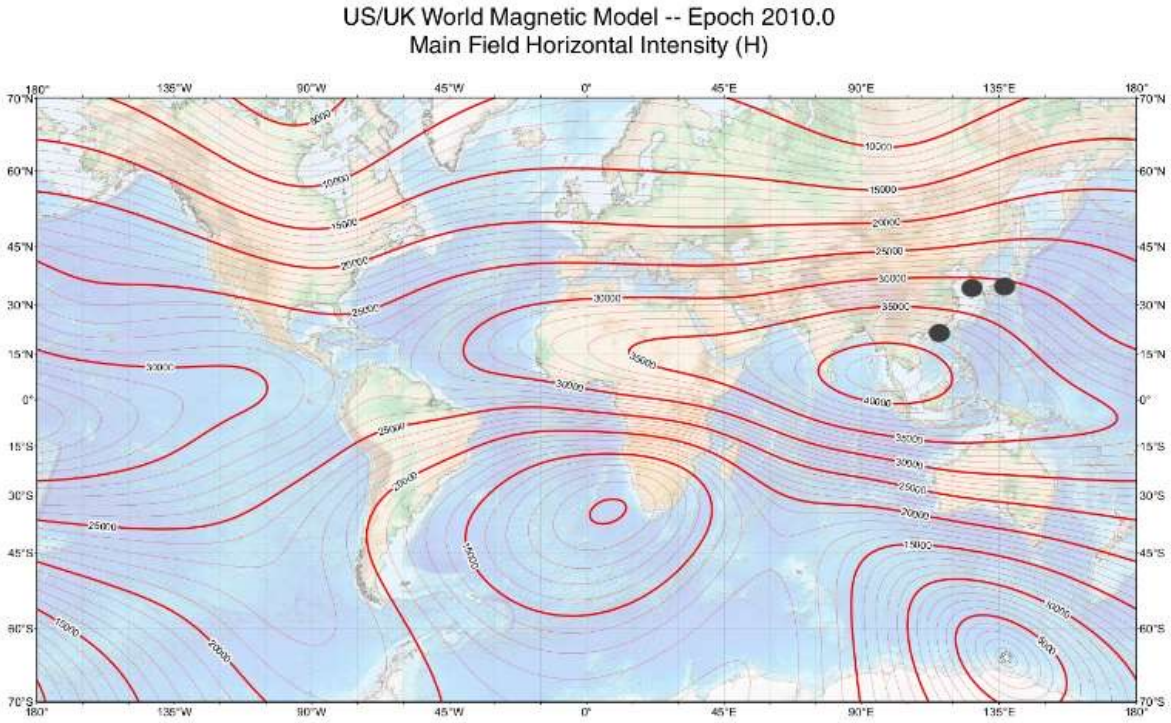
Nature **586,** 344-345 (2020)



“Neutrino Floor”

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





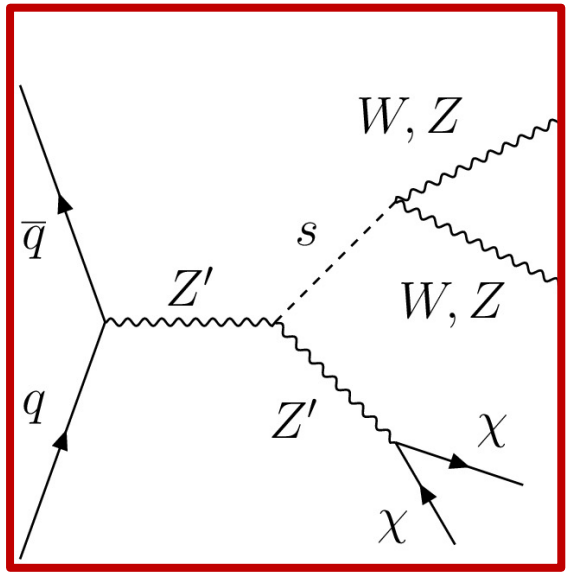
magnetic field

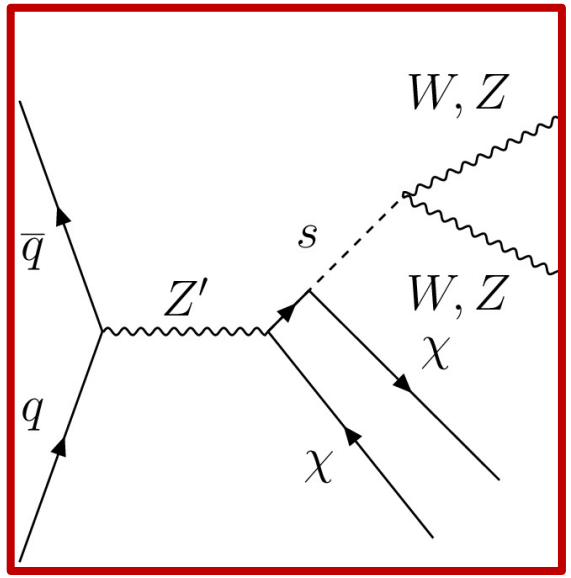
Site	Flux (m^2 sec sr GeV)^-1 [100MeV]
Kamioka	4249
Gran Sasso	7304
Sudbury	11879
Frejus	8215
INO	2554
South Pole	12001
Pythasalmi	12208
Homestake	11774
JUNO	2871

Honda et al. arXiv: 1502.03916 neutrino flux

Dark Higgs

- dark matter mass from Higgs mechanism in dark sector
  - dark Higgs boson *s* : can be even lighter than DM
  - simplified model: dark Higgs + Z' mediator + DM
  - dark Higgs mixing with SM Higgs: decay to vector bosons

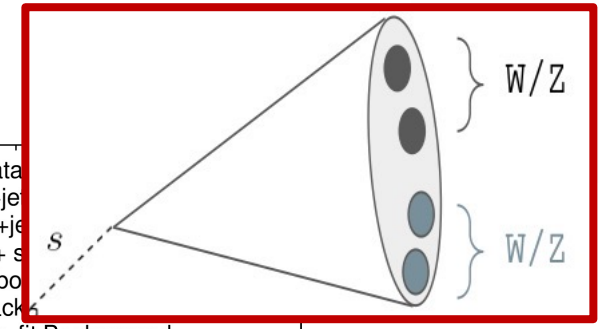


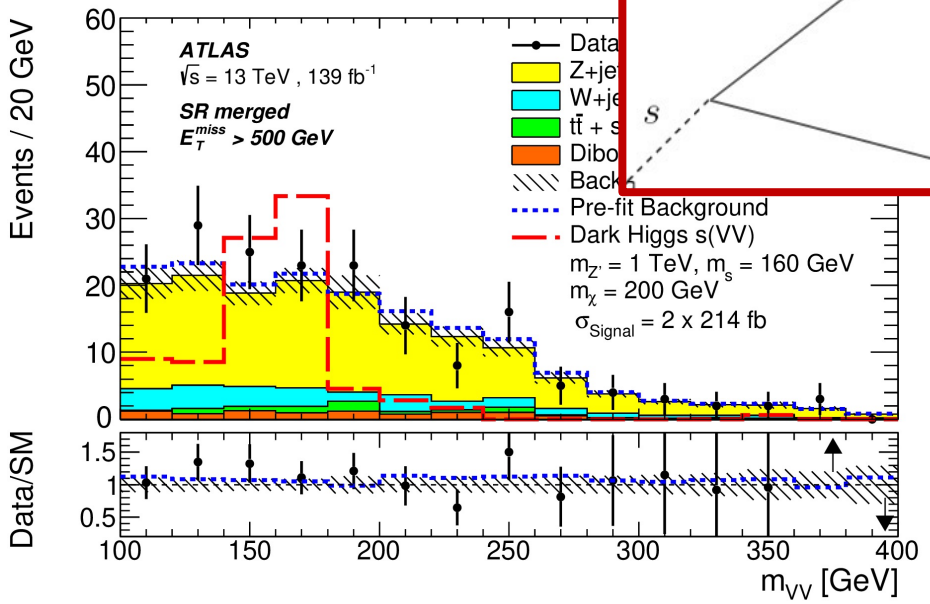


JHEP 1704 (2017) 143

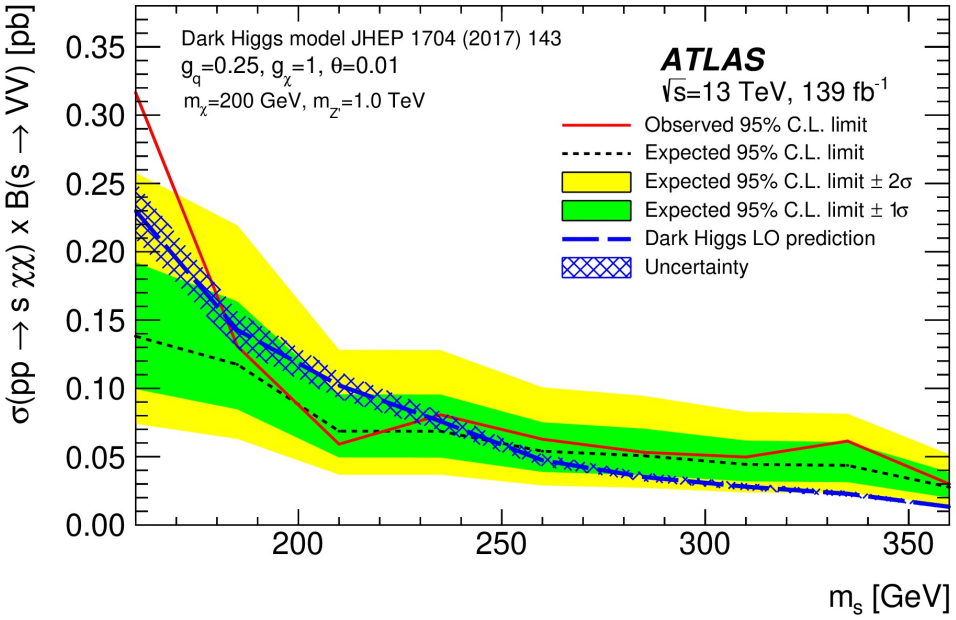
Mono-S(VV)

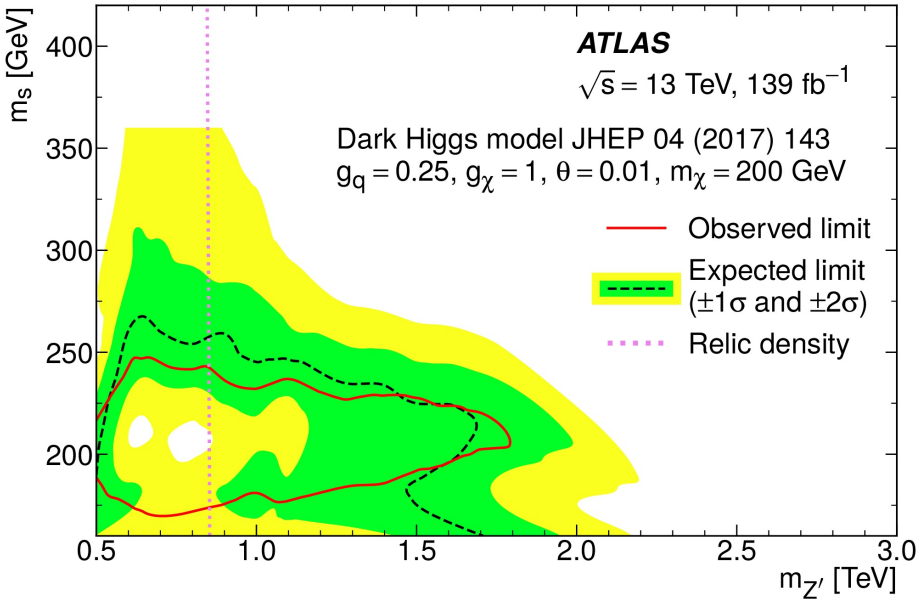
- reconstruct dark Higgs with a fat jet (containing 2 V -> 4 jets)
  - track-assisted reclustering (TAR) algorithm: better jet substructure resolution





PRL 126 (2021) 121802

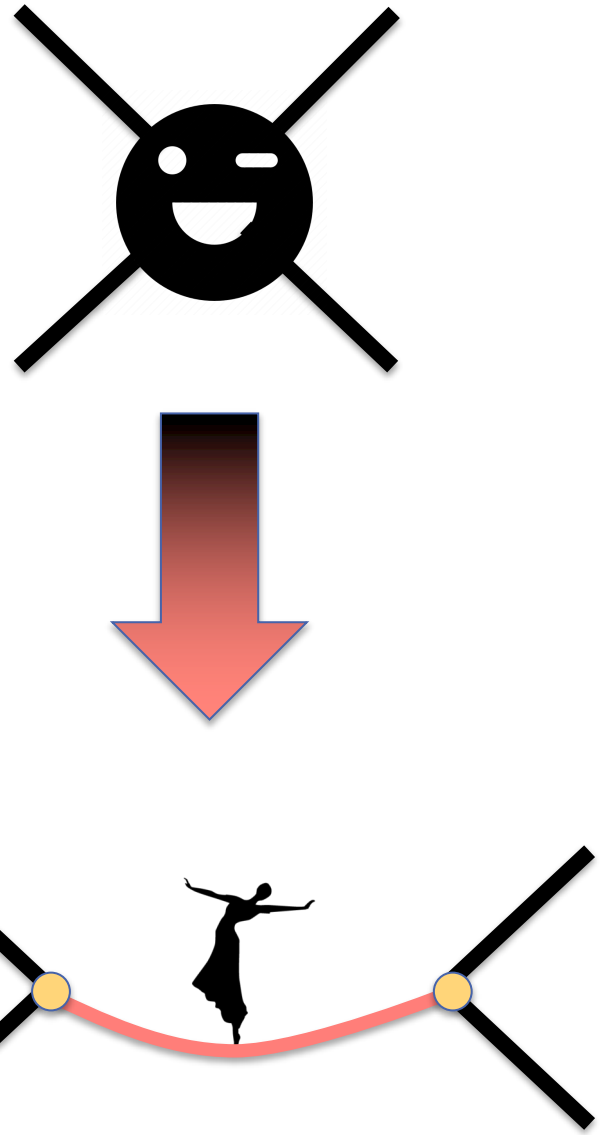




Simplified Model with Mediator

- keep the mediator information
  - mass: $m_{Z'}$
  - spin : vector, axial-vector, etc
  - coupling: g_q g_l g_{DM}

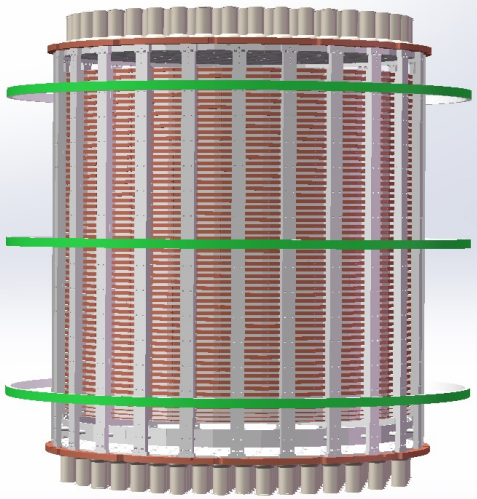
- simplified model:
  - starting point to build complete theories
  - colliders can search for the mediator directly

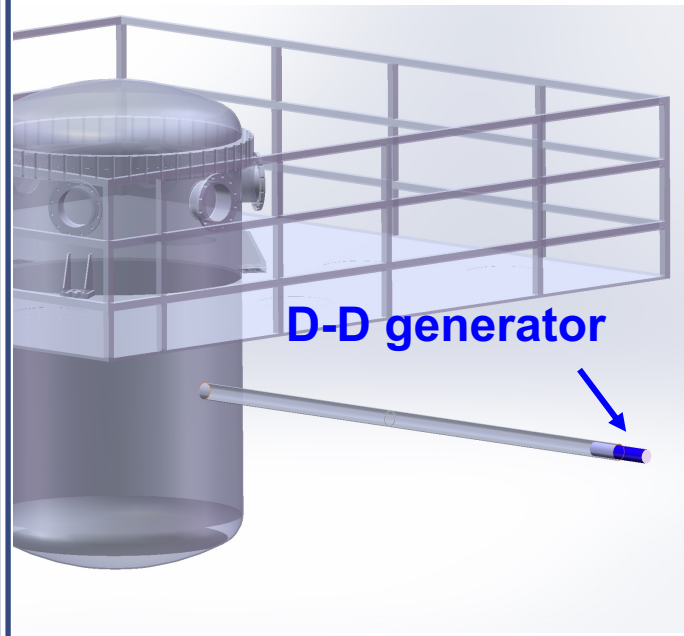


Calibration Methods

Gaseous source injection panel

Calibration tubes





Calibration source	Position
$^{83m}Kr/^{220}Rn$	Injected from gas panel
^{241}Am-Be	Calibration tubes
D-D neutron	Beam pipe

Excess in Direct Detection

- XENON1T experiment，1 tonne-year exposure，some small excess in nuclear recoil signal region

  PRL 121, 111302 (2018)

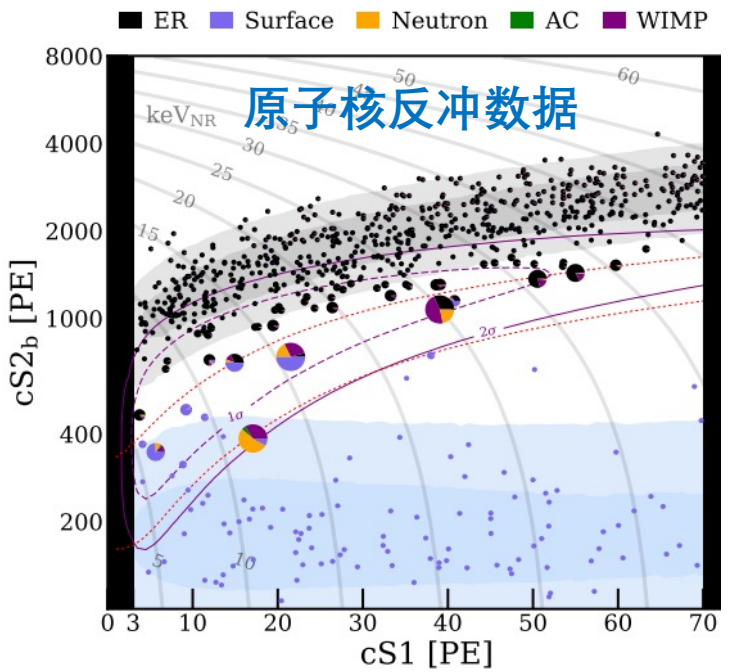
  – fitted with WIMP of 200 GeV mass, 1.7 events

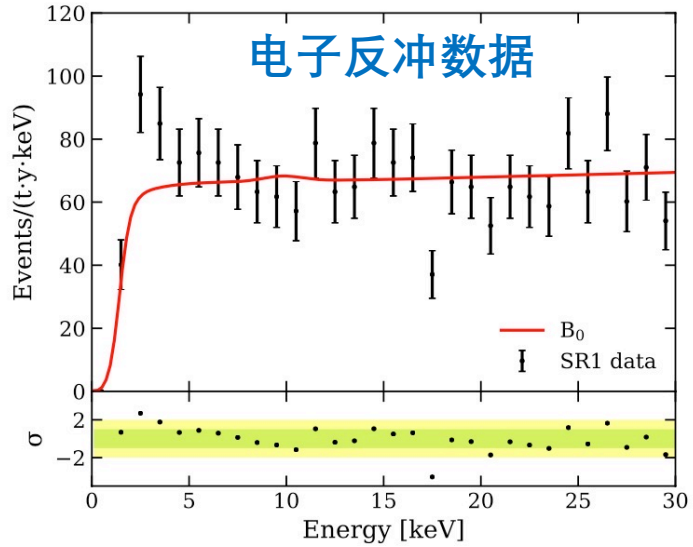
- 0.65 tonne-year exposure，3σ excess in electronic recoil signal region

  – fitted with solar axion, etc

  PRD 102, 072004 (2020)

- Need further cross-check with more sensitive detectors



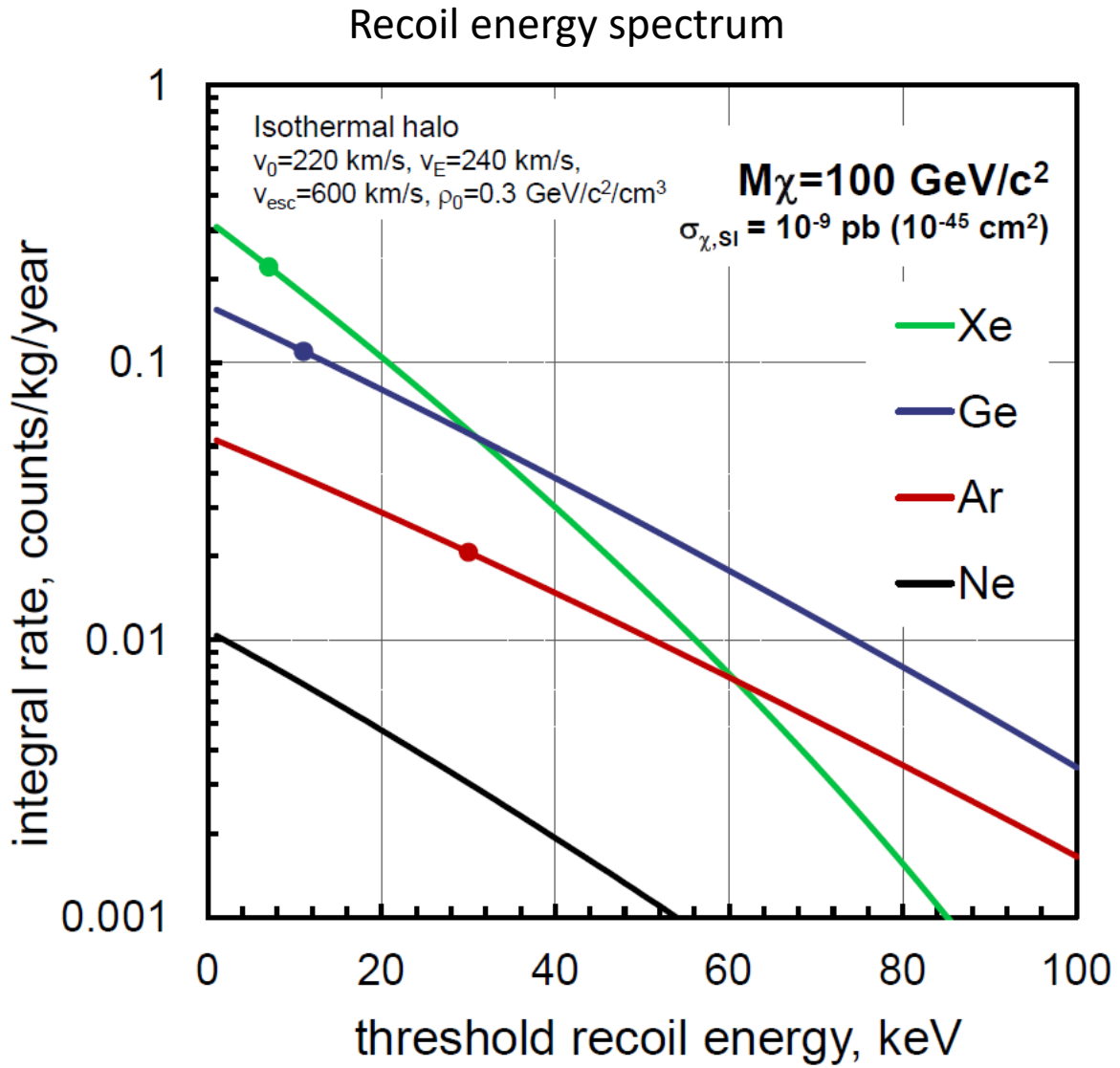


Dark Matter Signals

- Scattering cross section on nuclei
  - Spin-independent, $\propto A^2$, Form factor
  - Spin-dependent, spin structure factor

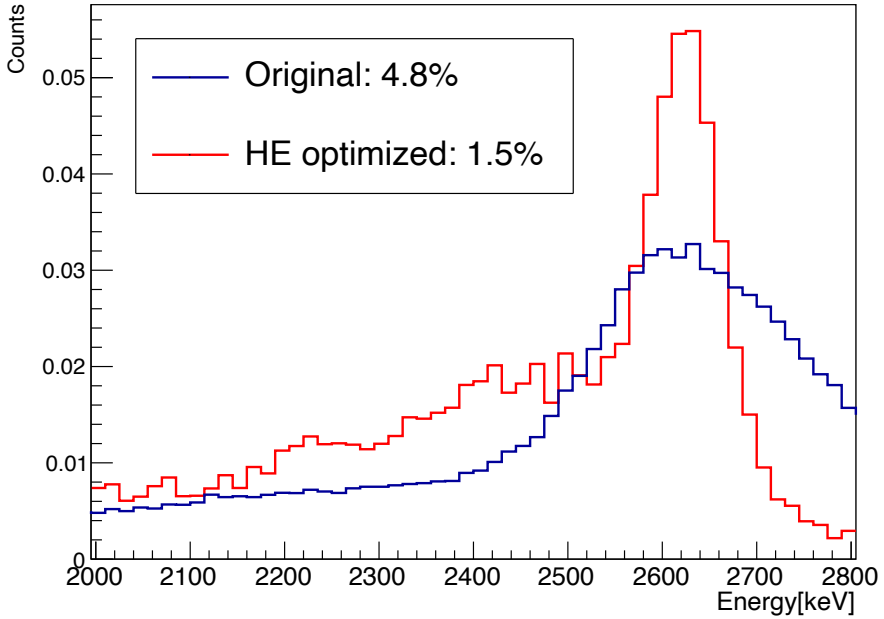
$$\frac{dR}{dE_R} = \frac{\rho_0}{m_\chi m_N} \int_{v_{min}}^{v_{esc}} \frac{d\sigma_{\chi N}}{dE_R}(v, E_R) v f(v) dv$$

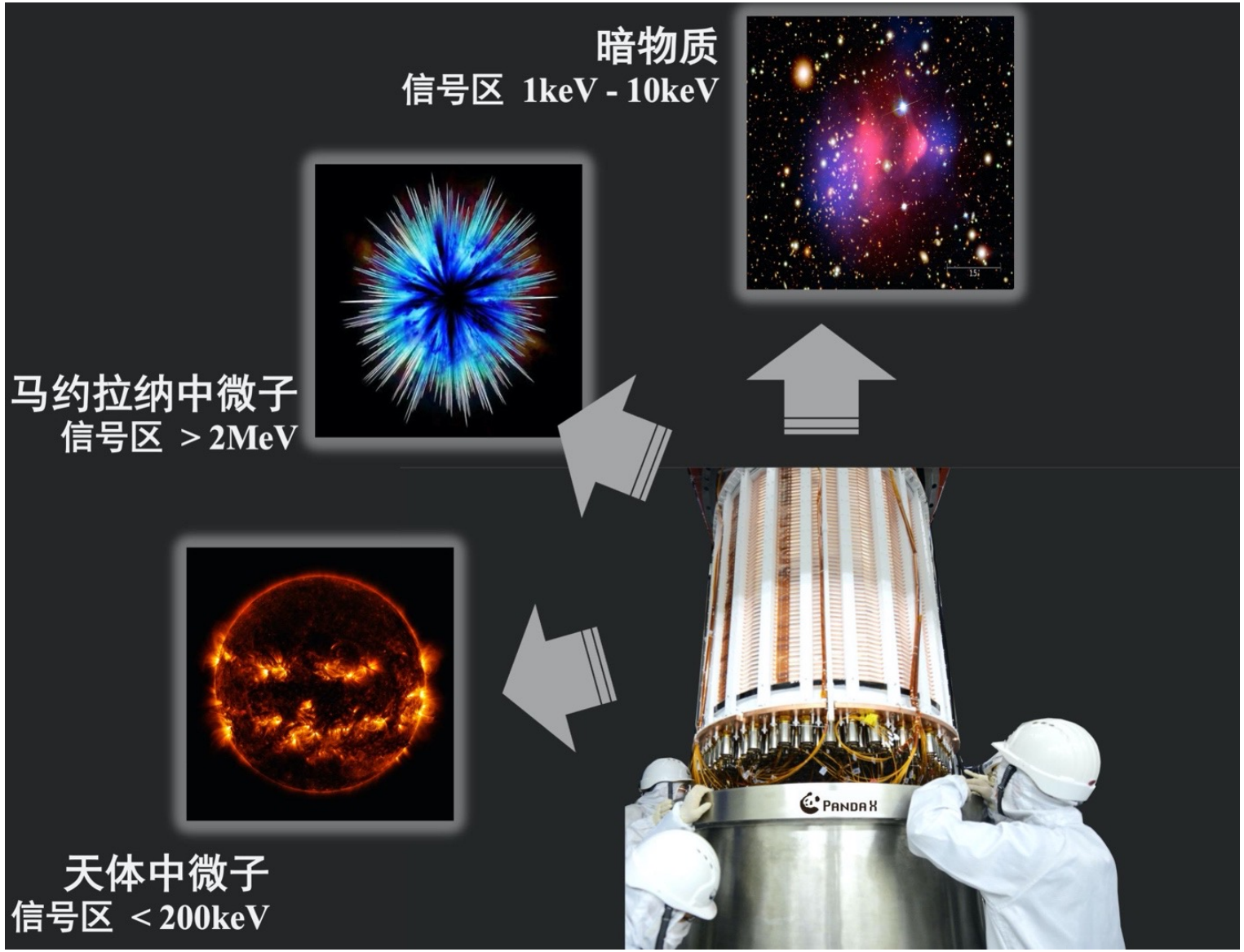
$$\frac{d\sigma_{\chi N}}{dE_R} = \frac{m_N}{2\mu_N^2 v^2}(\sigma_0^{SI} F_{SI}^2(E_R) + \sigma_0^{SD} F_{SD}^2(E_R))$$



Multiple Physics Tasks

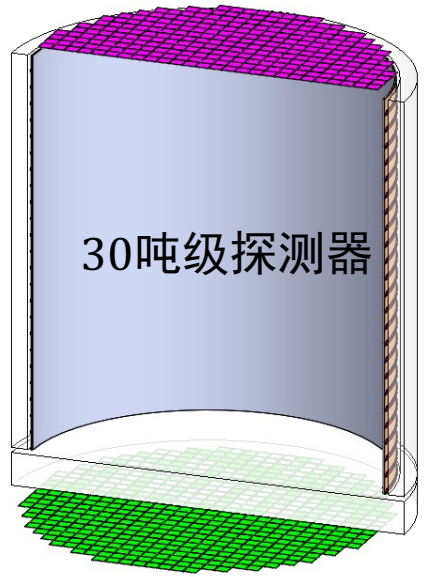
- Energy 1-30 keVee
  - Dark Matter
- Energy < 200 keVee
  - Astro neutrinos
- Energy > 2MeVee
  - 0vDBD





R&D of PandaX-xT

- Low background PMT
- Large size TPC
- Xenon isotope separation



Unit: mBq/pc	R12699 (30T)	R11410 (4T)
Co-60	0.05±0.06 <0.15	1.16±0.72 <2.34
Cs-137	0.12±0.08 <0.25	0.52±0.81 <1.85
K-40	36.91±2.45	8.37±8.47 <22.31
Th-232(early)	0.35±0.35 <0.92	4.33±2.16 <7.88
Th-232(late)	0.80±0.29 <1.28	1.50±0.96 <3.08
U-235	0.00±0.17 <0.28	13.13±8.53 <27.16
U-238(early)	2.26±4.36 <9.44	26.29±16.90 <54.09
U-238(late)	0.63±0.26 <1.07	2.05±1.18 <3.99