Probing Majorana Neutrinos and Dark Matter at MeV-scale with PandaX

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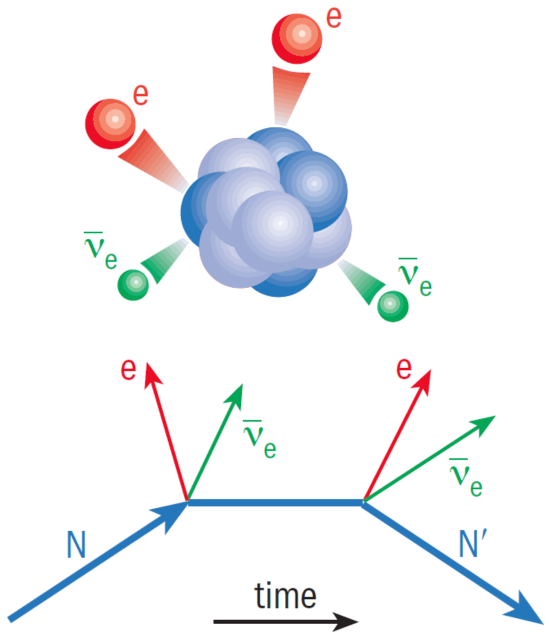
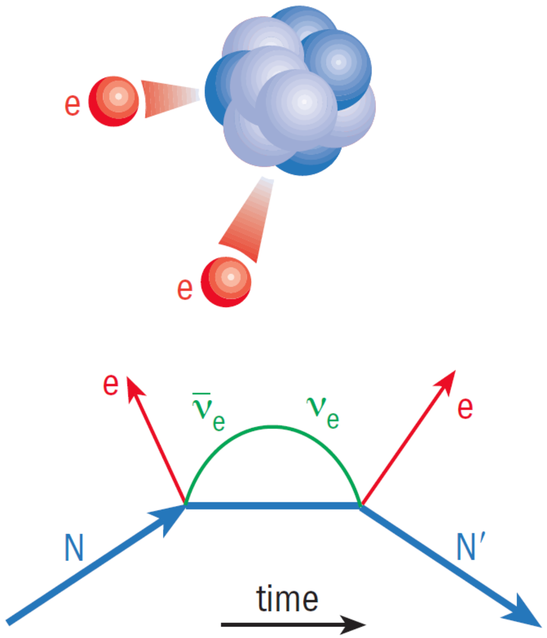
@ IHEP

Majorana neutrino and double-beta decay



$$\bar{\nu} = \nu$$



From Physics World

1935, Goeppert-Mayer
Two-Neutrino double beta decay (2νββ)

1937, Majorana
Majorana Neutrino

1939, Furry
Neutrinoless double beta decay (0νββ)

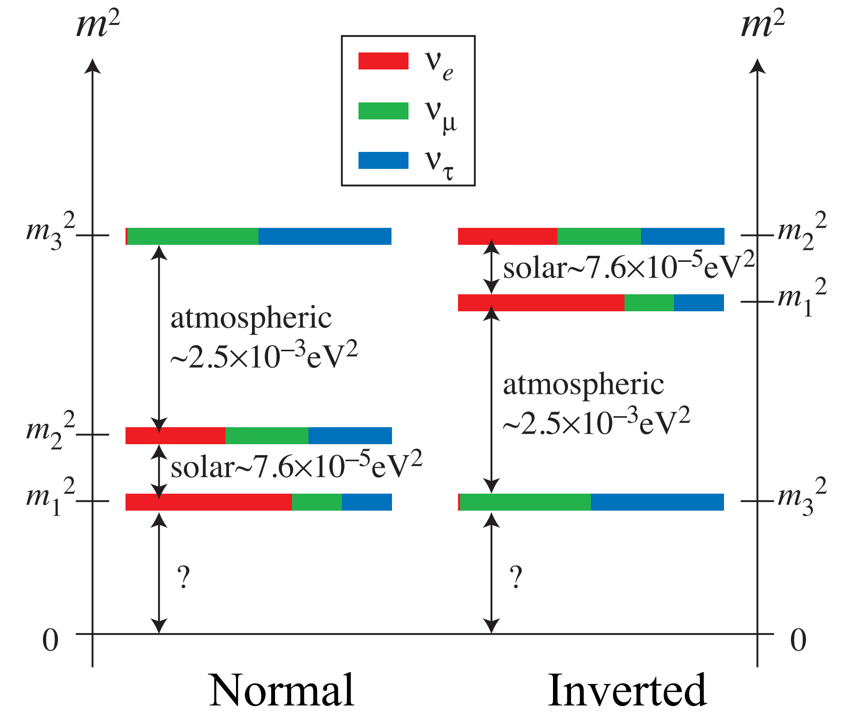
1930, Pauli
Idea of neutrino

1933, Fermi
Beta decay theory

$$^{136}_{54}Xe \rightarrow {}^{136}_{56}Ba + 2e^{-} + (2\bar{\upsilon})$$

0νββ probes the nature of neutrinos

- Majorana or Dirac
- Lepton number violation
- Effective Majorana mass
- Matter-antimatter asymmetry of the Universe



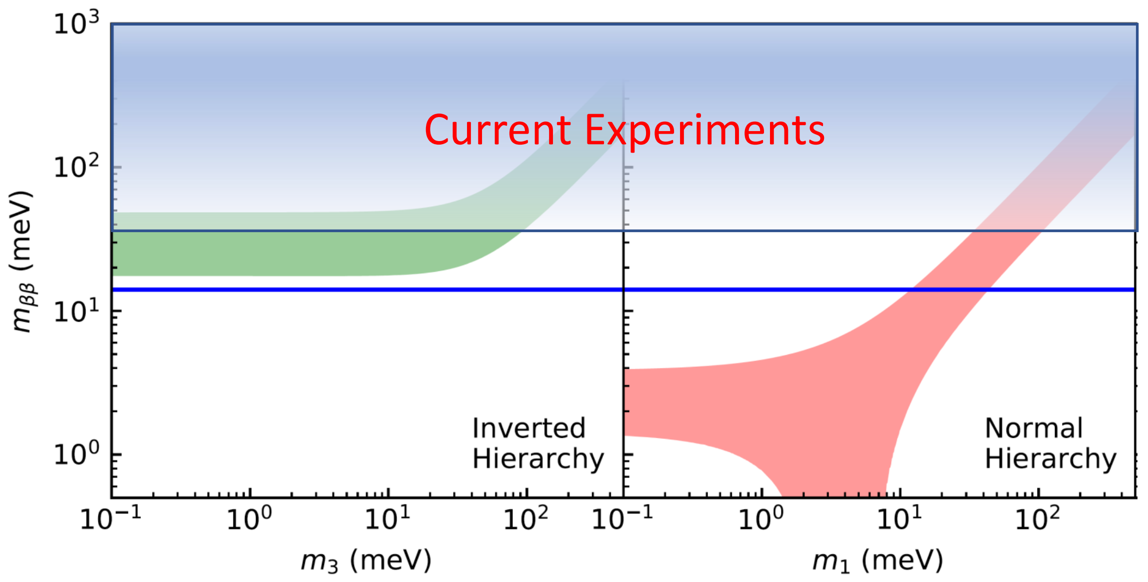
$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}(Q,Z)\,|M^{0\nu}|^2\,\frac{|\langle m_{\beta\beta}\rangle|^2}{m_e^2}$$

Phase space factor

Nuclear matrix element

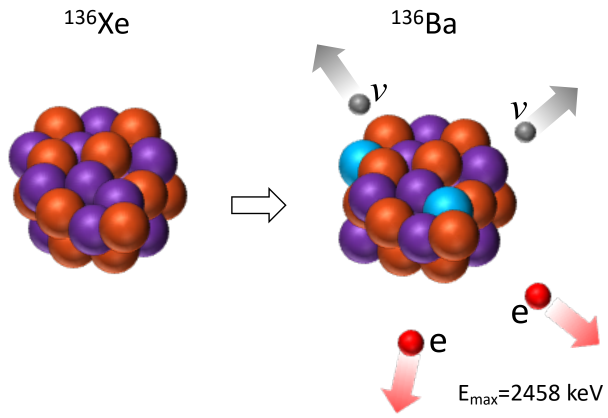
Effective Majorana neutrino mass:

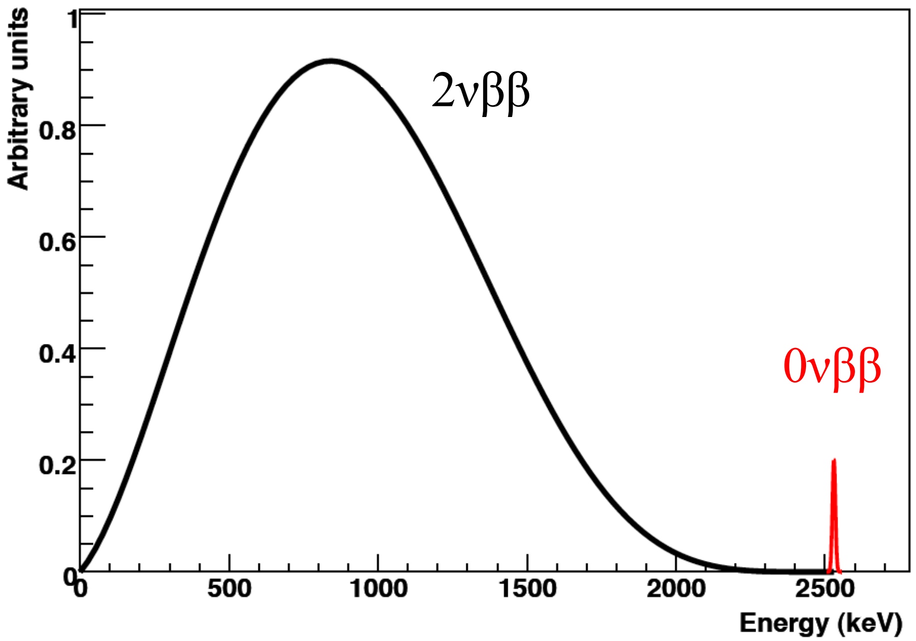
$$|\langle m_{\beta\beta}\rangle| = \left|\sum_{i=1}^{3} U_{ei}^2 m_i\right|$$



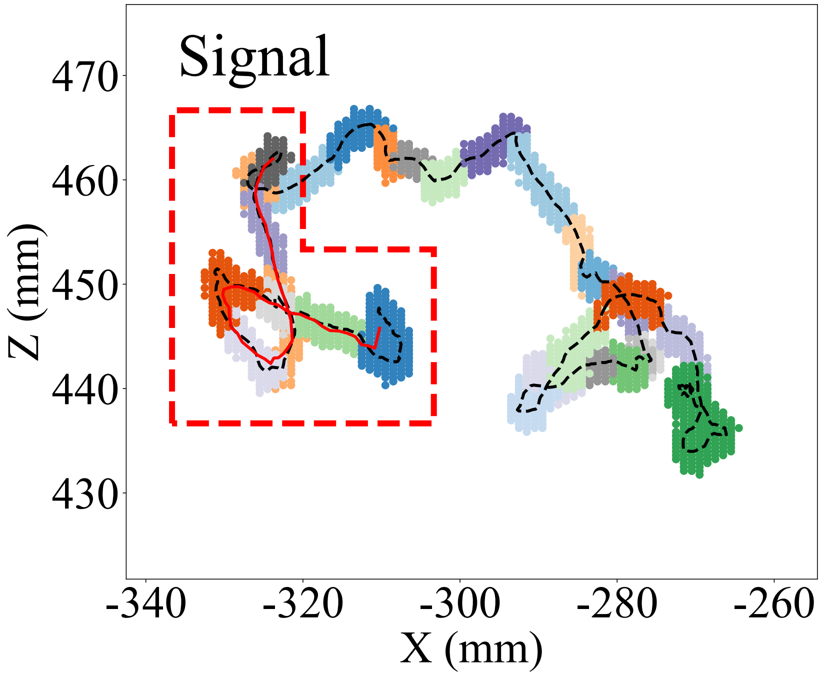
Detection of 0νββ

- Measure energies of emitted electrons
- Electron tracks are a huge plus
- Daughter nuclei identification





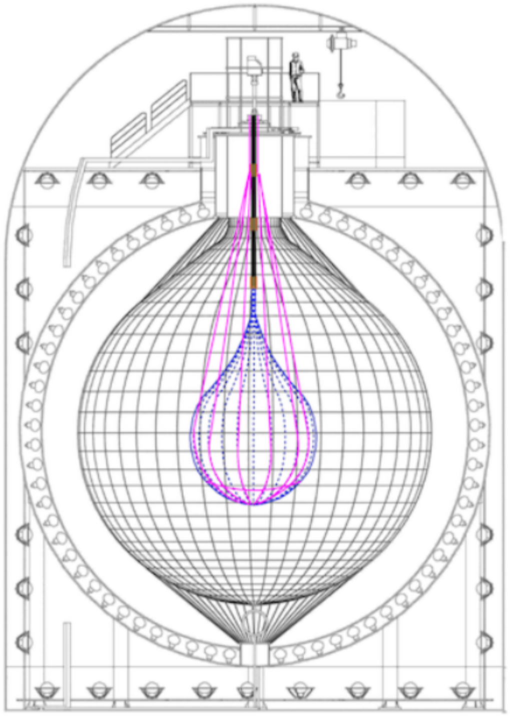
Sum of two electrons energy

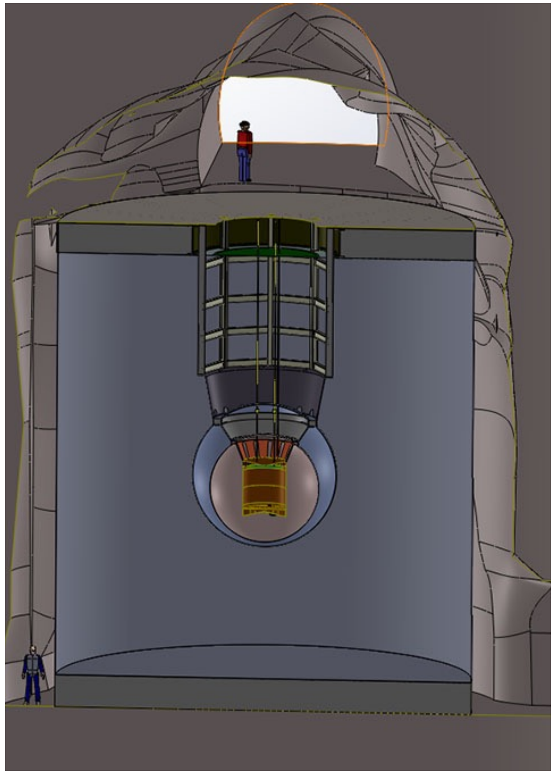


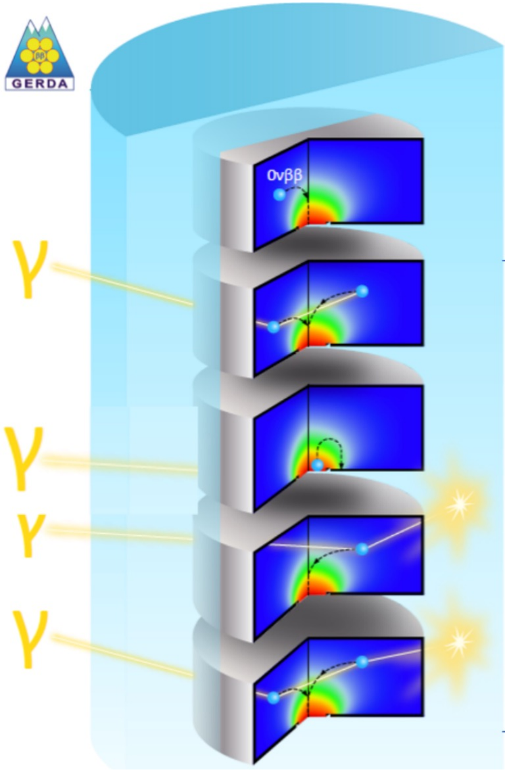
Simulated track of 0νββ in high pressure Xe

Leading 0νββ experiments (isotope-enriched)

PANDA X
PARTICLE AND ASTROPHYSICAL XENON TPC

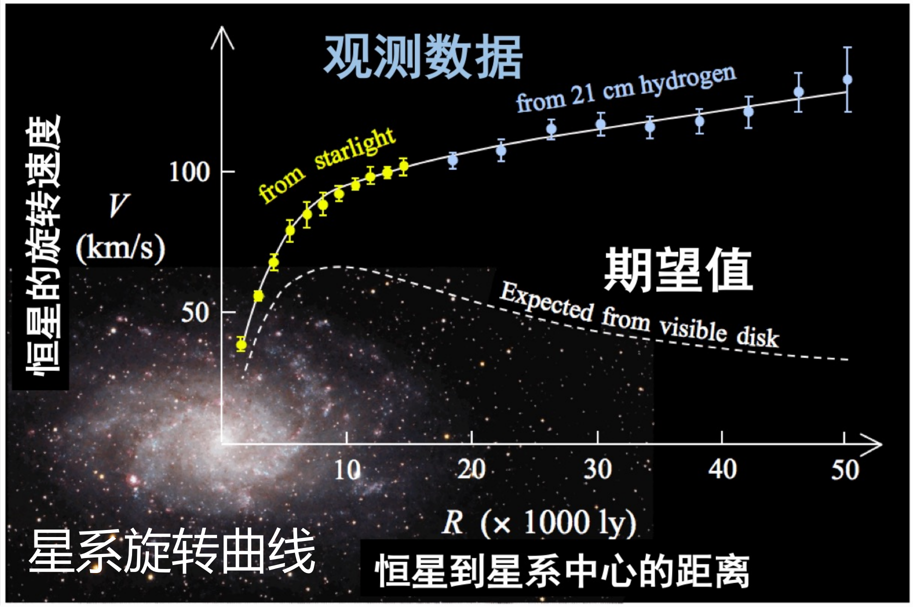


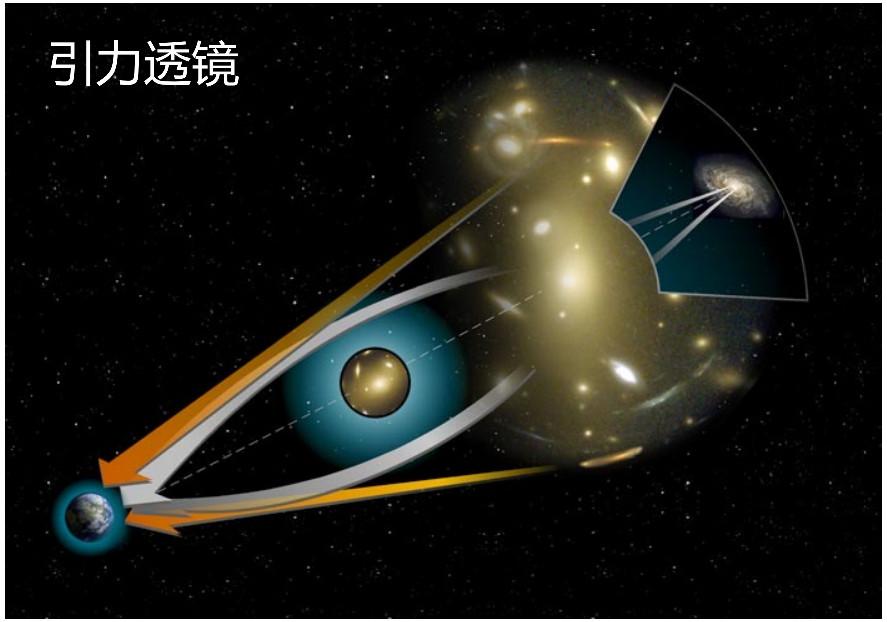


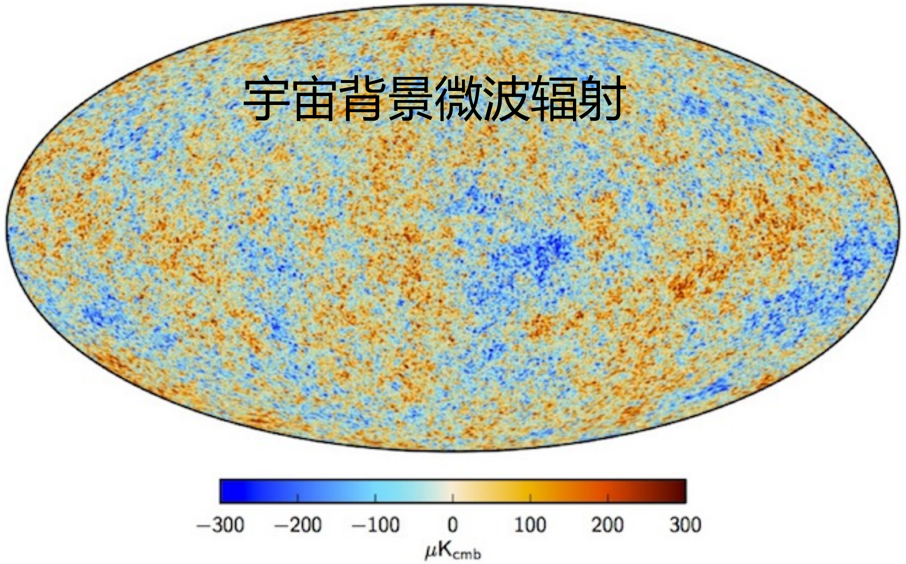


KamLAND-ZEN	EXO/nEXO	LEGEND family	CUORE/CUPID
Doped LS	LXe TPC	HPGe	Bolometer
^{136}Xe	^{136}Xe	^{76}Ge	^{130}Te, ^{100}Mo, ^{82}Se

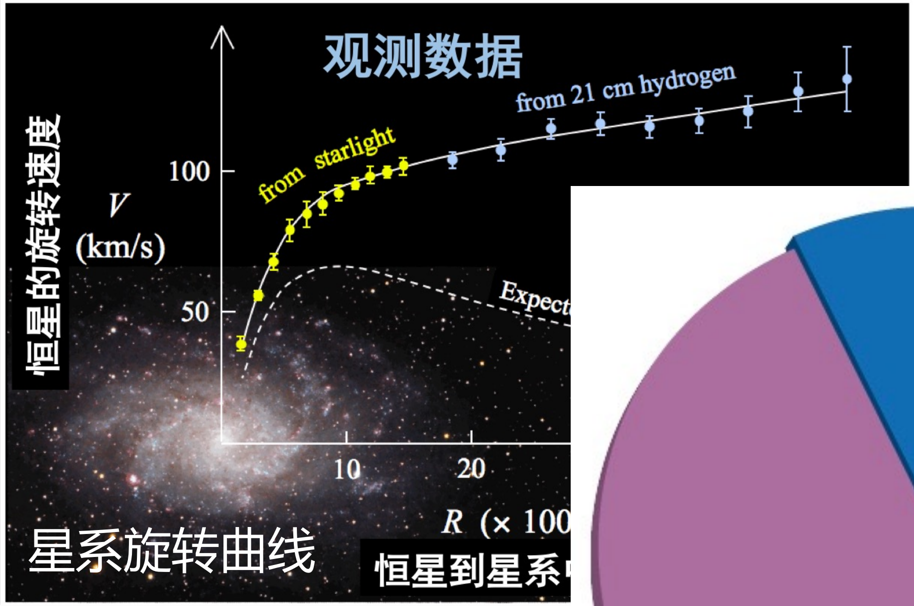
Astronomical evidence of dark matter (DM)

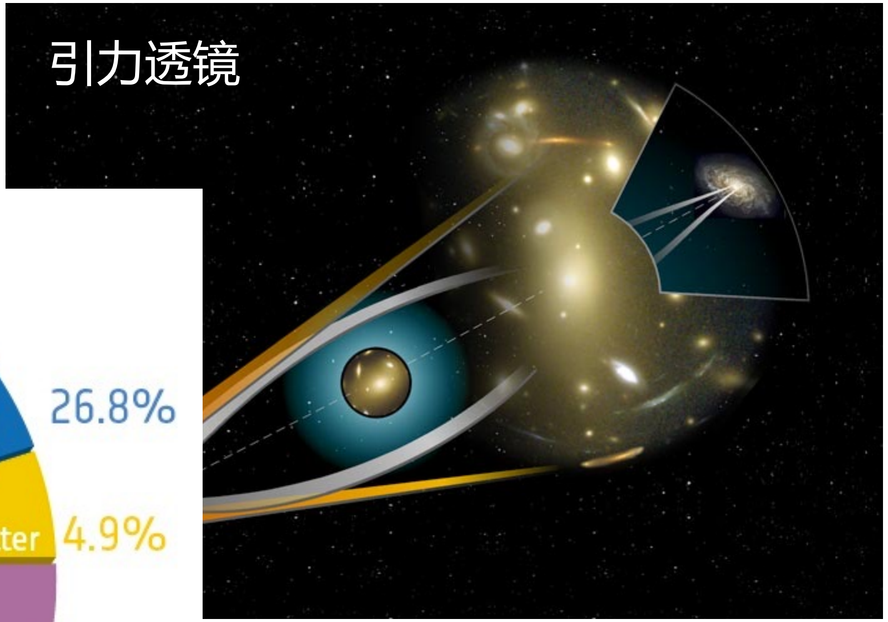


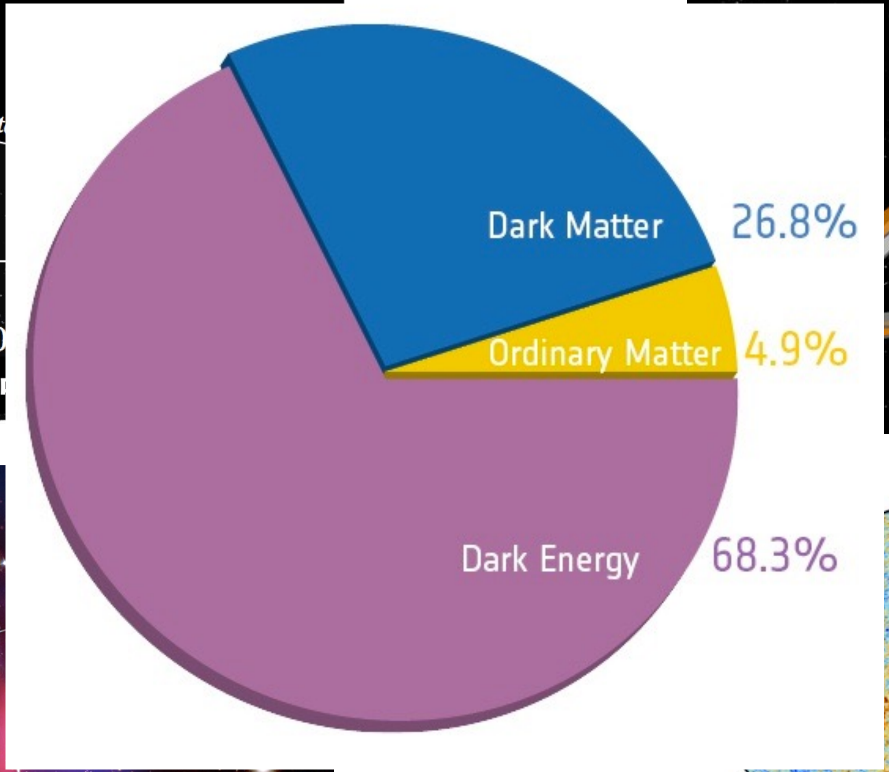


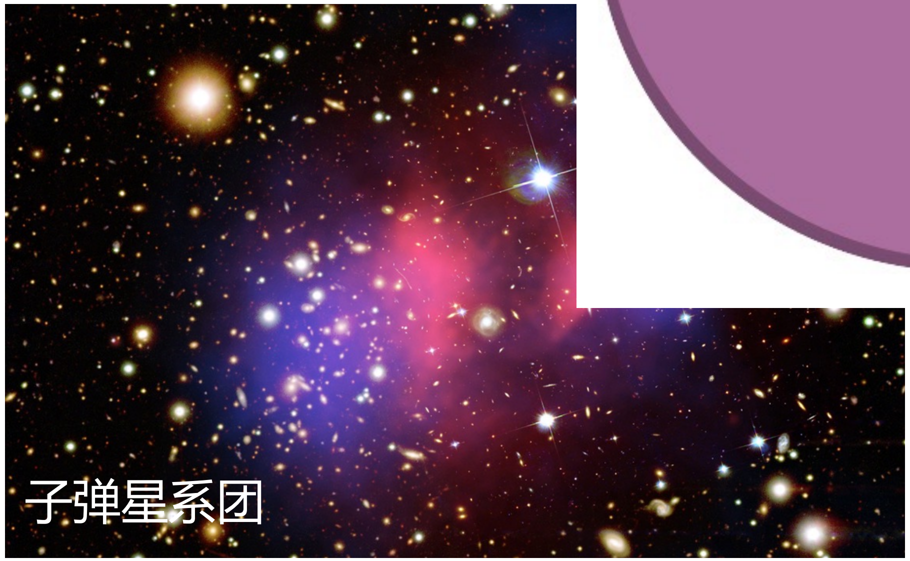


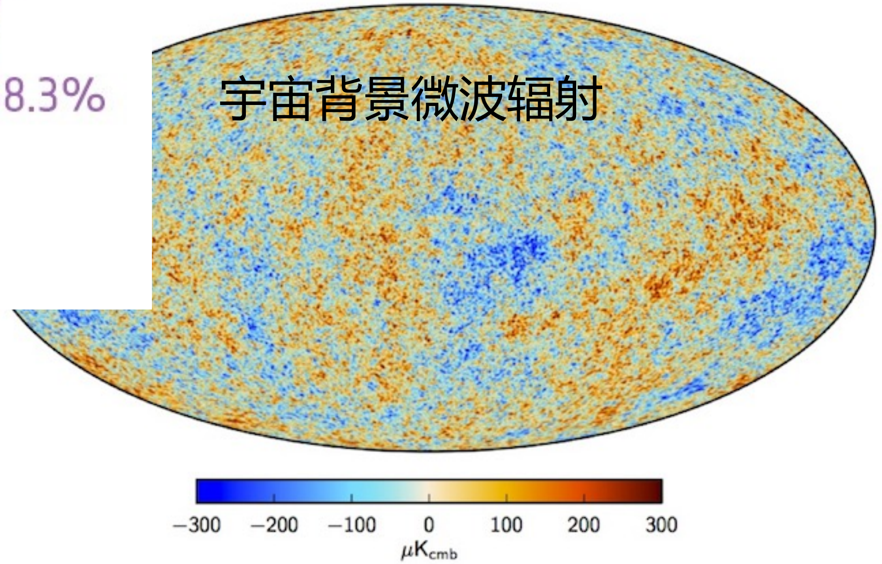
Astronomical evidence of dark matter (DM)



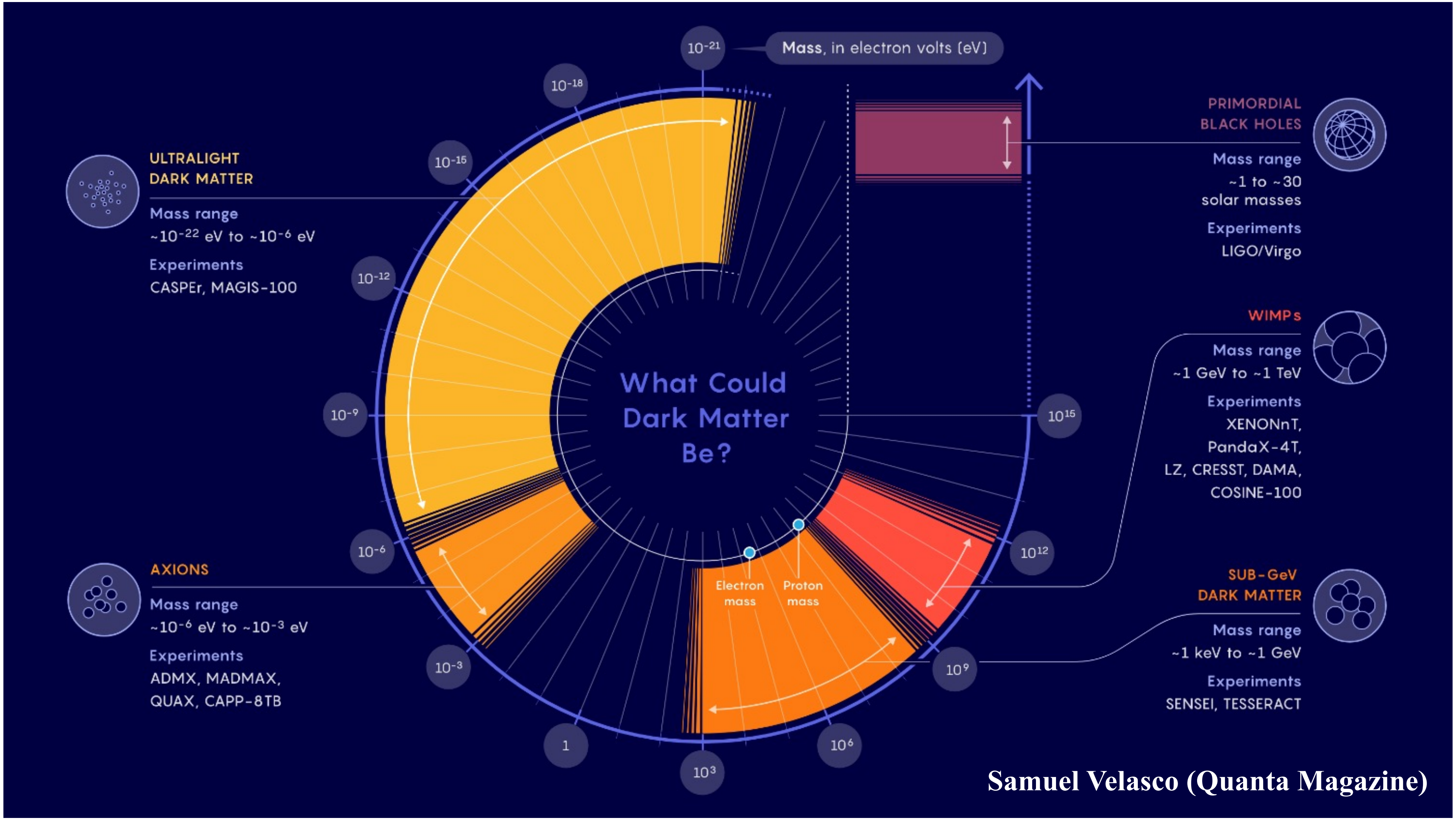






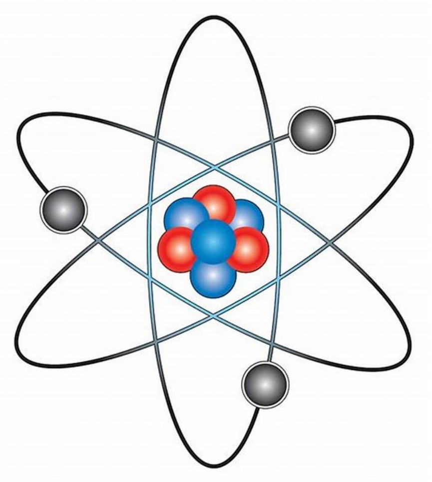


What could DM be...



DM direct detection

暗物质粒子

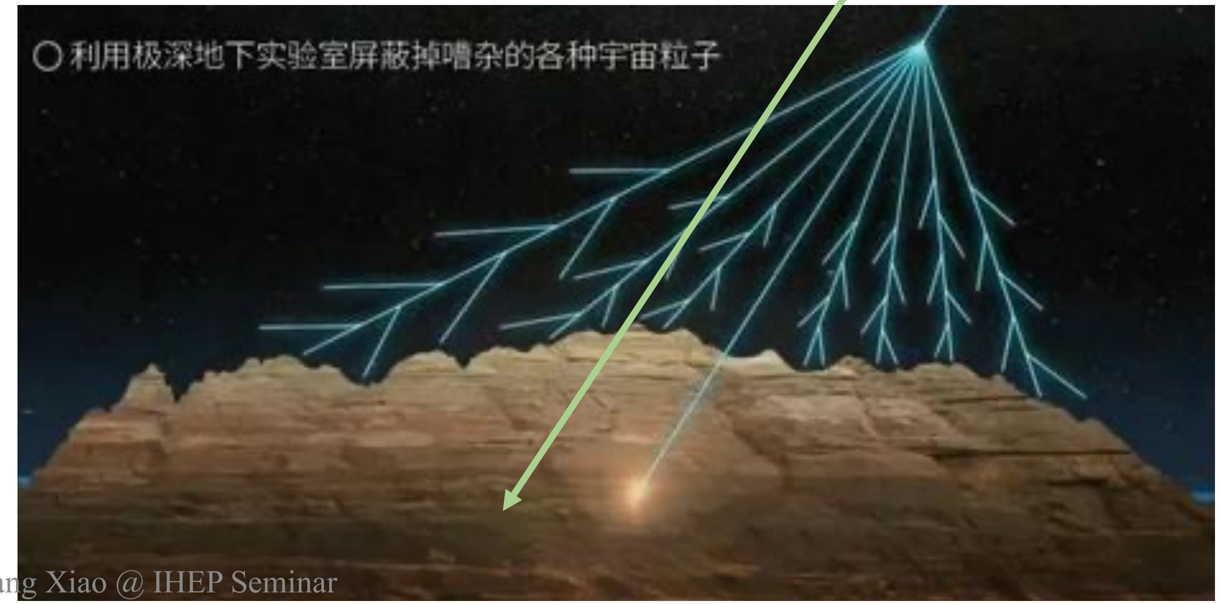


普通物质的原子

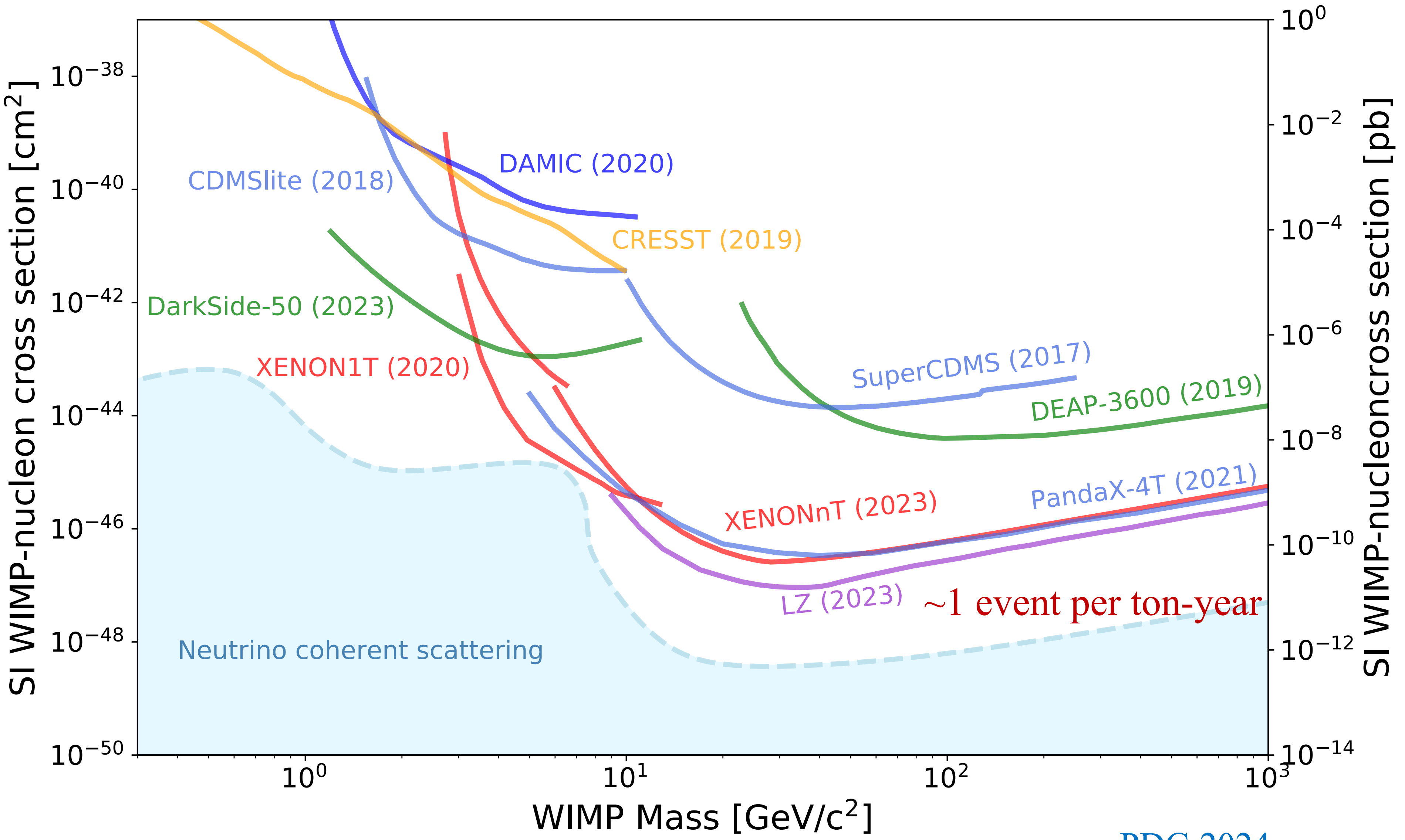
反冲能量

暗物质探测器

“守株待兔”



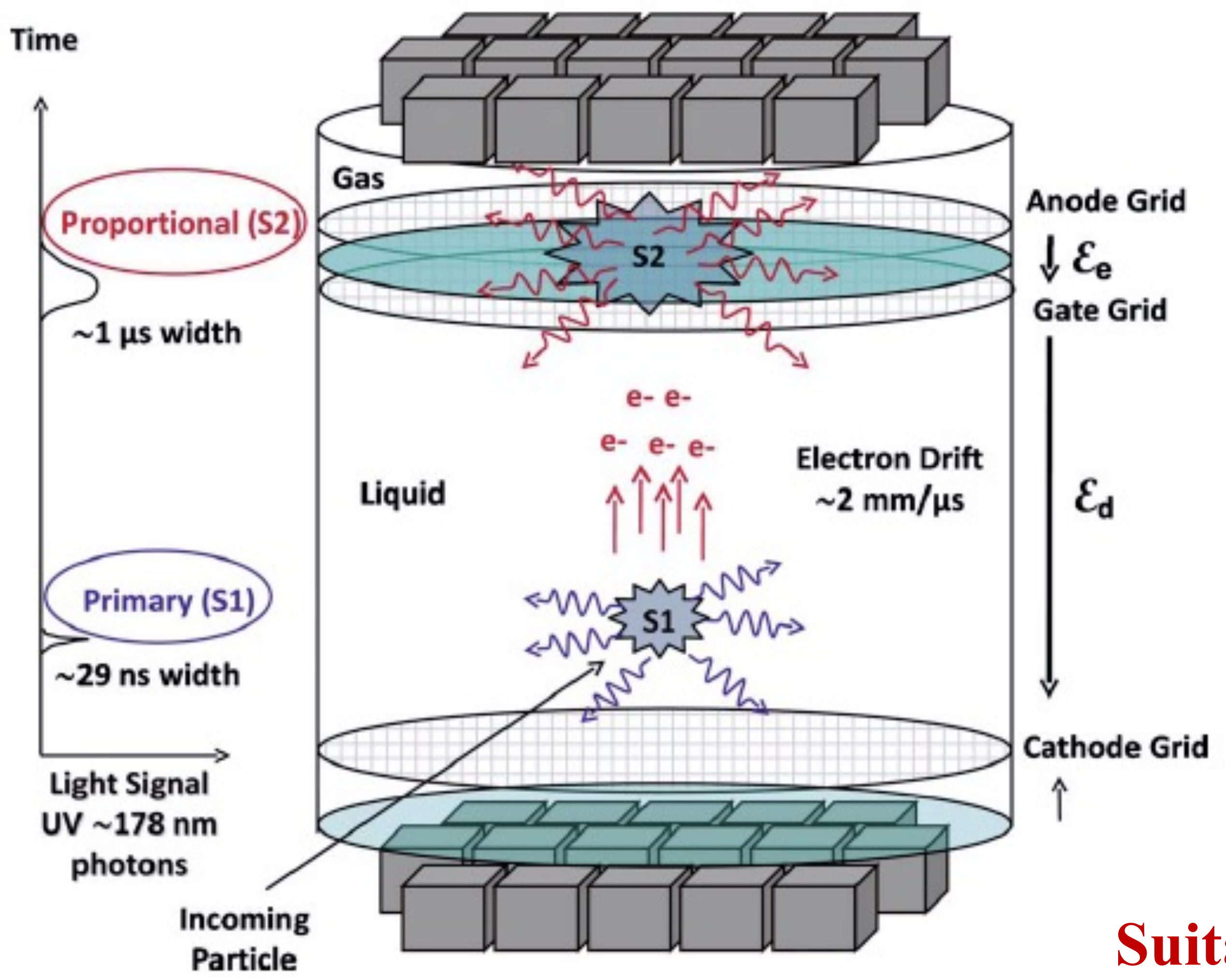
Current landscape of WIMP search



PDG 2024

Possible to combine searches for 0νββ and WIMP?

Dual-phase Xenon Time Projection Chamber (TPC)



- **3D position reconstruction**
  - Fiducialization
  - Single-Site (SS) and Multi-Site (MS) discrimination
- **Particle identification among α, neutron, and γ/electron**
- **Calorimeter from sub keV to a few MeV**
- **Monolithic and scalable**

- **Low background**
- **Large target mass**
- **High detection efficiency**

Suitable for detection of dark matter, 0νββ, and astrophysical neutrinos at the same time!

PandaX: Particle and Astrophysical Xenon Experiment

PandaX pathway

- Increasing sensitive target volume
- Lowering radioactive background

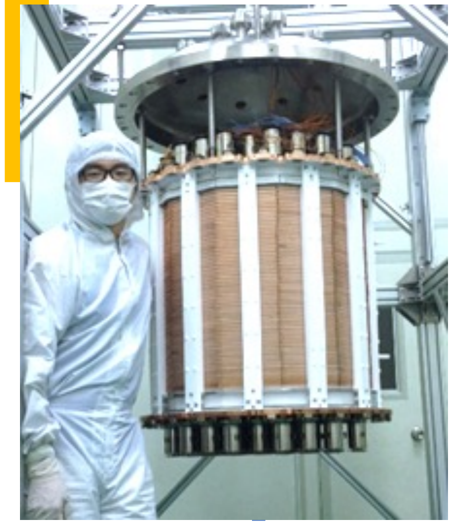
PandaX initiated

2009

PandaX-I
120 kg

2010-2014

PandaX-II
580 kg

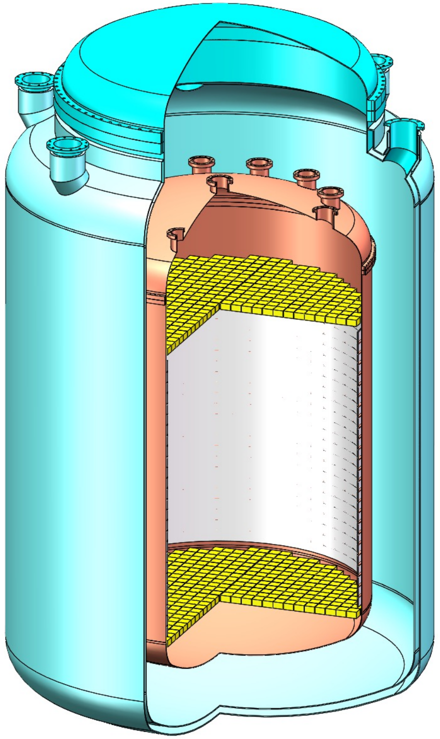


2015-2019

PandaX-4T
3.7 tonne

2020-

PandaX-xT
20 tonne -> 47 tonne

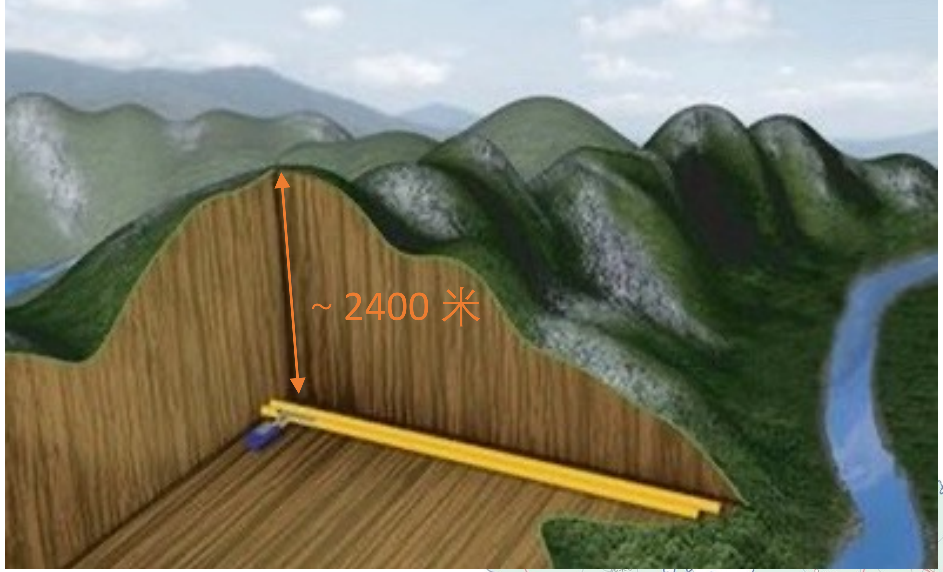


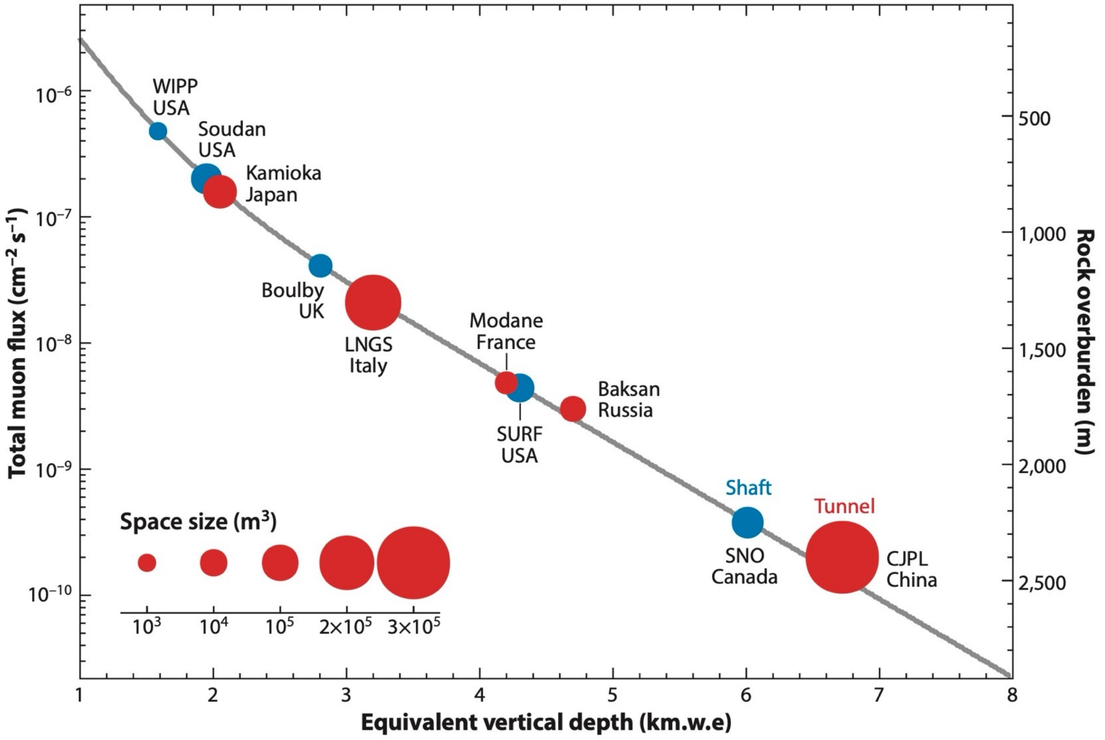
2027-

China Jinping Underground Laborotary (CJPL)

PANDA X
PARTICLE AND ASTROPHYSICAL XENON TPC

- Deepest (6800 m.w.e): < 0.2 muons/m²/day
- Horizontal access with ~9 km long tunnel: large truck can drive in

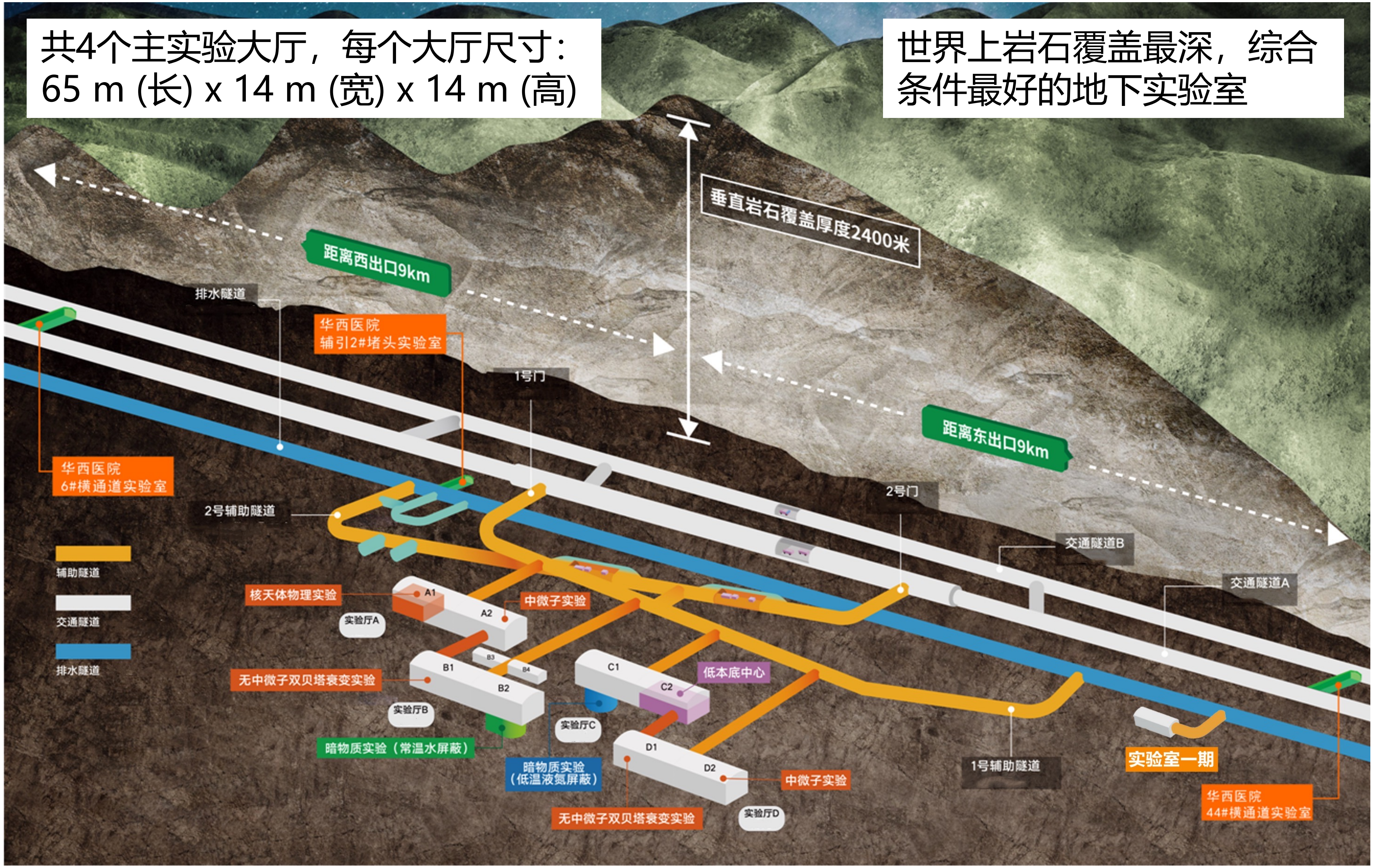




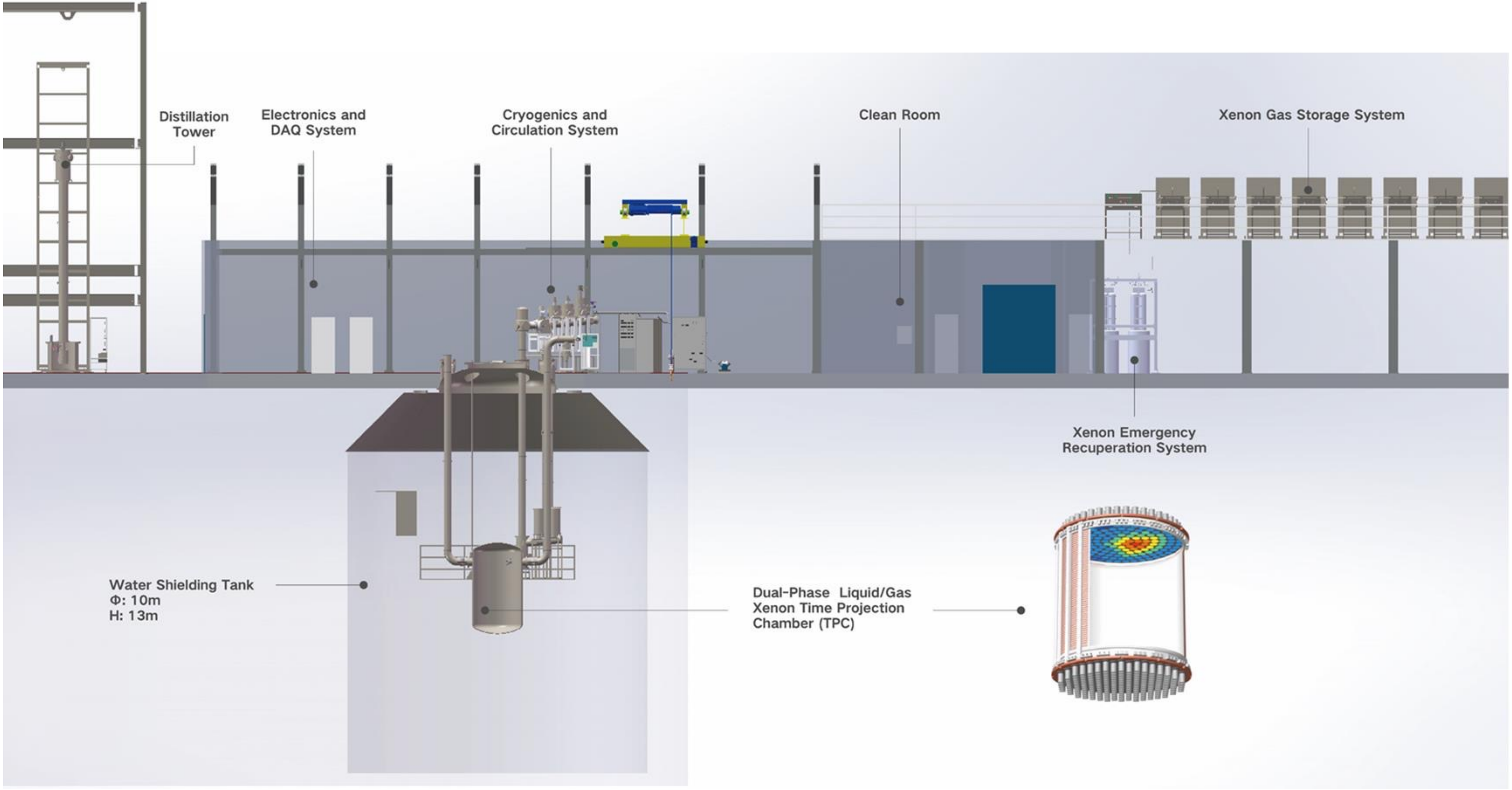
CJPL-II layout

共4个主实验大厅，每个大厅尺寸：
65 m (长) x 14 m (宽) x 14 m (高)

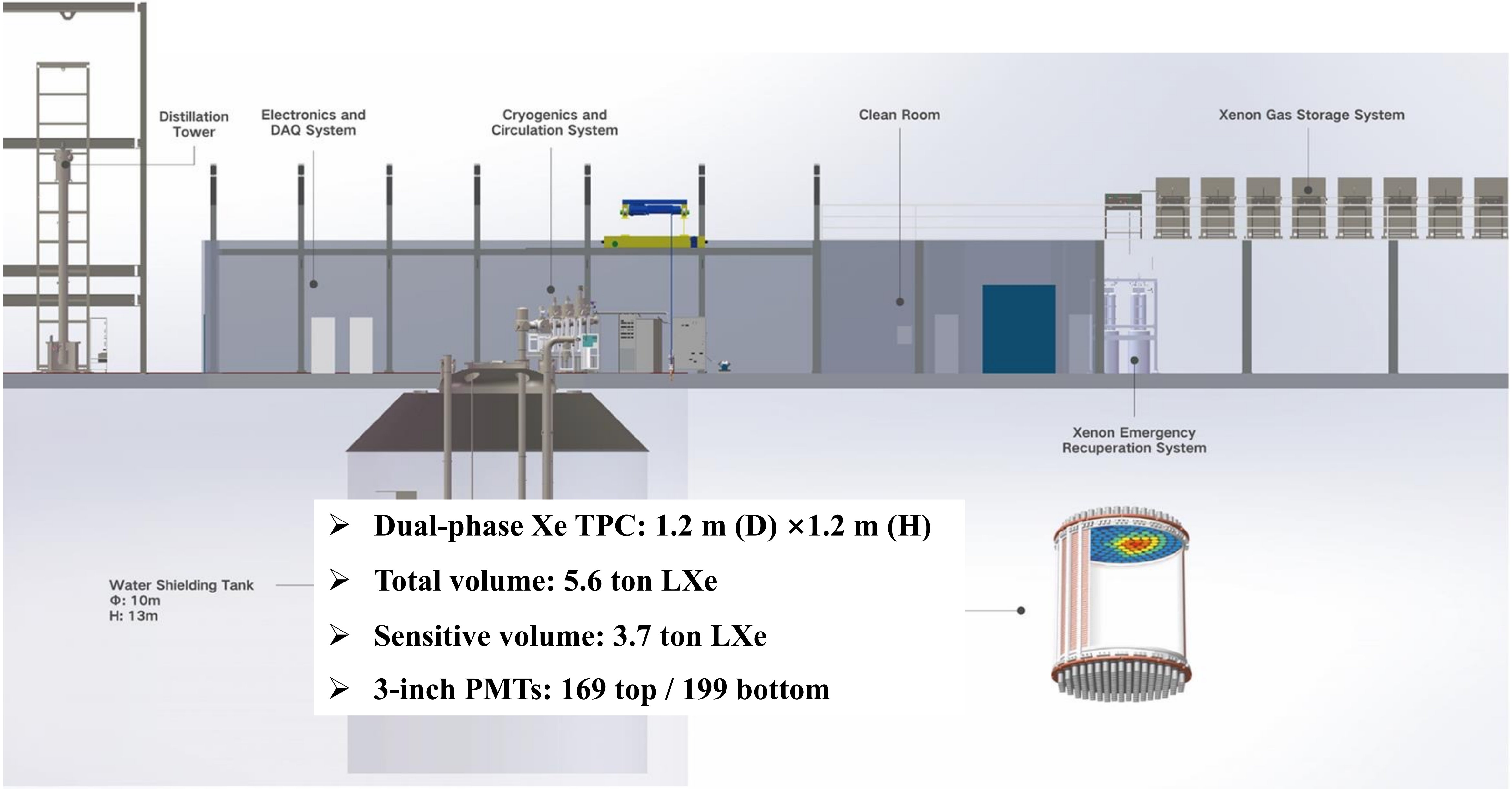
世界上岩石覆盖最深，综合
条件最好的地下实验室



PandaX-4T @ CJPL-II B2 Hall

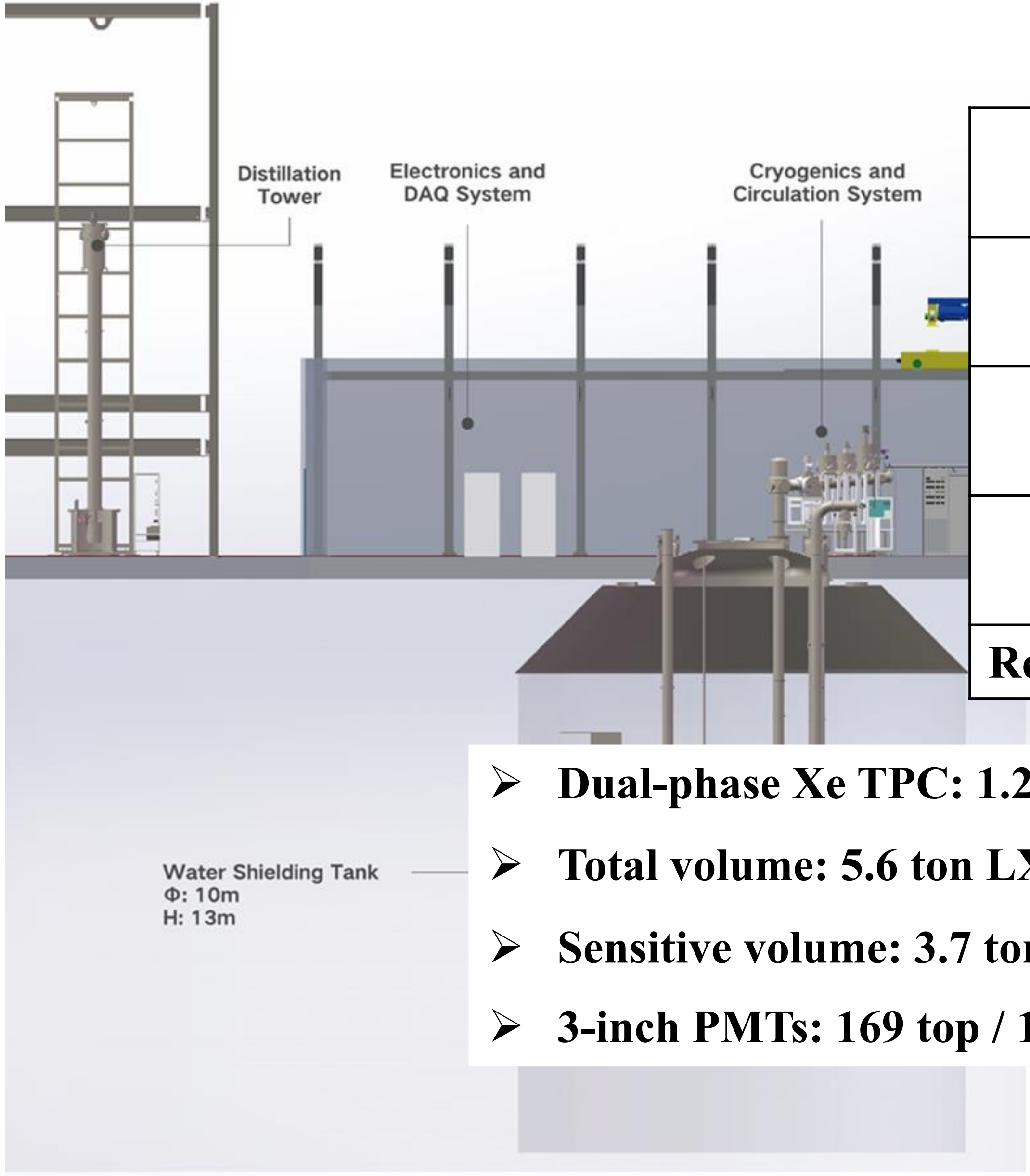


PandaX-4T @ CJPL-II B2 Hall



- **Dual-phase Xe TPC: 1.2 m (D) ×1.2 m (H)**
- **Total volume: 5.6 ton LXe**
- **Sensitive volume: 3.7 ton LXe**
- **3-inch PMTs: 169 top / 199 bottom**

PandaX-4T @ CJPL-II B2 Hall



2020/11 – 2021/04	**Commissioning run (Run0)** 95 days of physics data
2021/07 – 2021/10	**Tritium removal** xenon distillation, gas flushing, etc
2021/11 – 2022/05	**First science run (Run1)** 164 days of physics data
2022/09 – 2023/12	**CJPL-II B2 hall construction** xenon recuperation, detector upgrade
Resume data-taking (Run2)	

- **Dual-phase Xe TPC: 1.2 m (D) ×1.2 m (H)**
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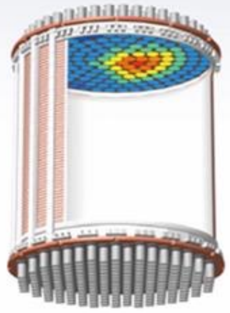
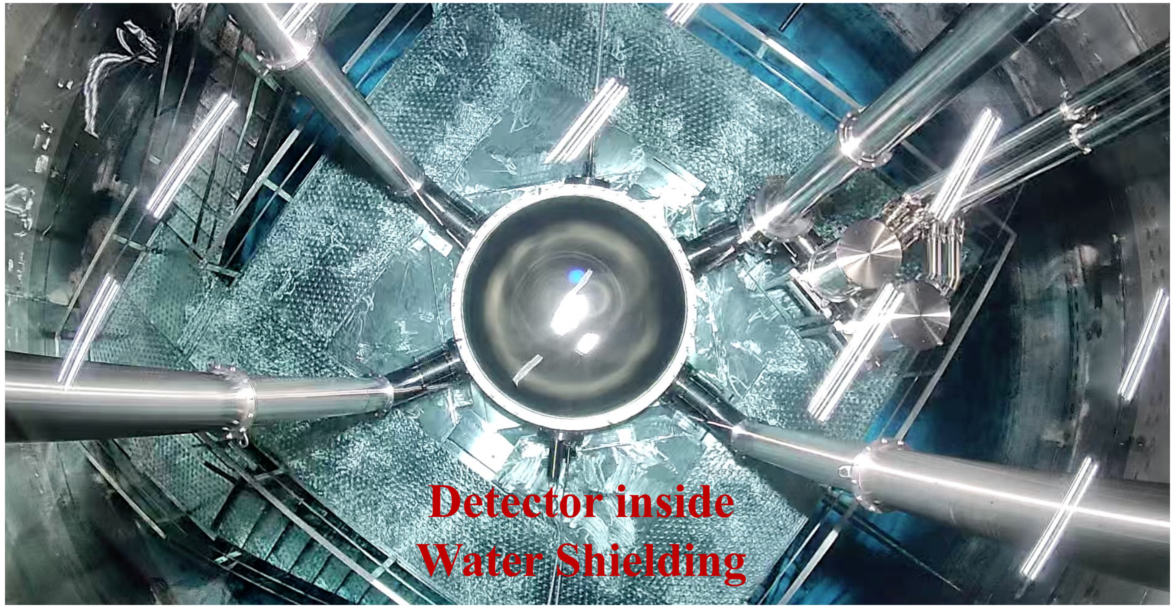
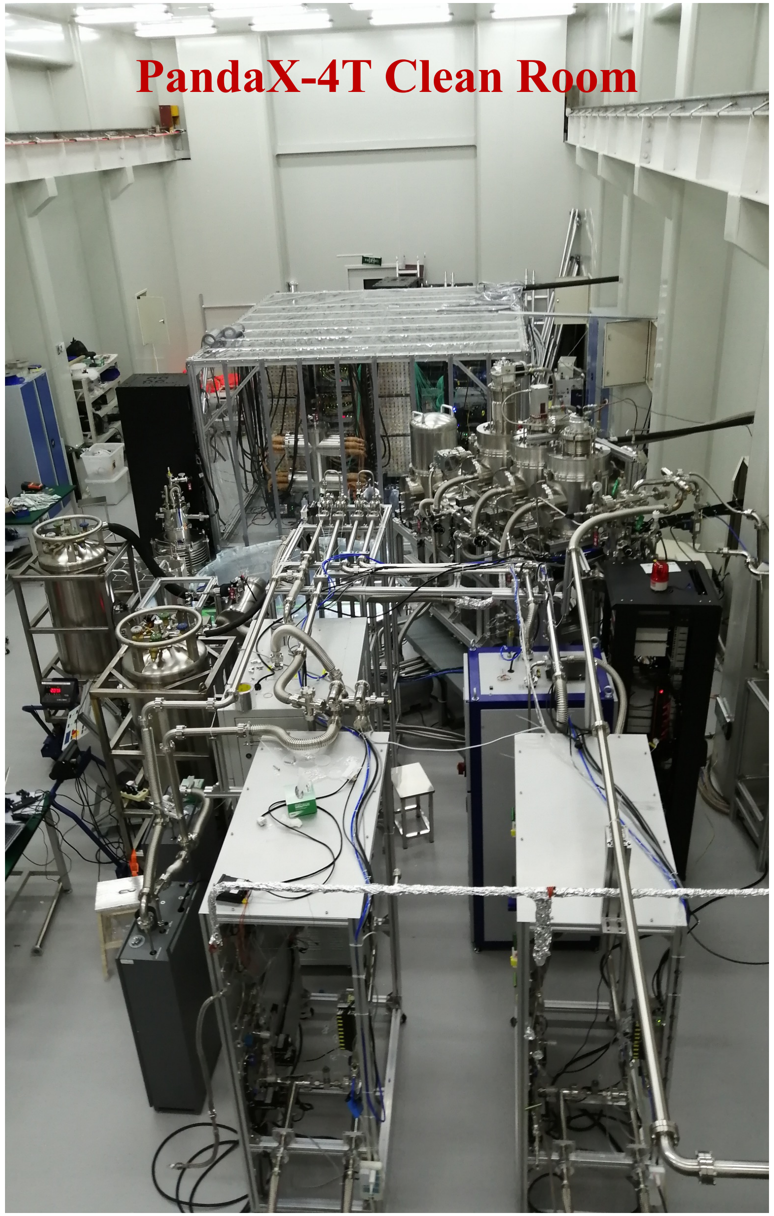


Some photos...

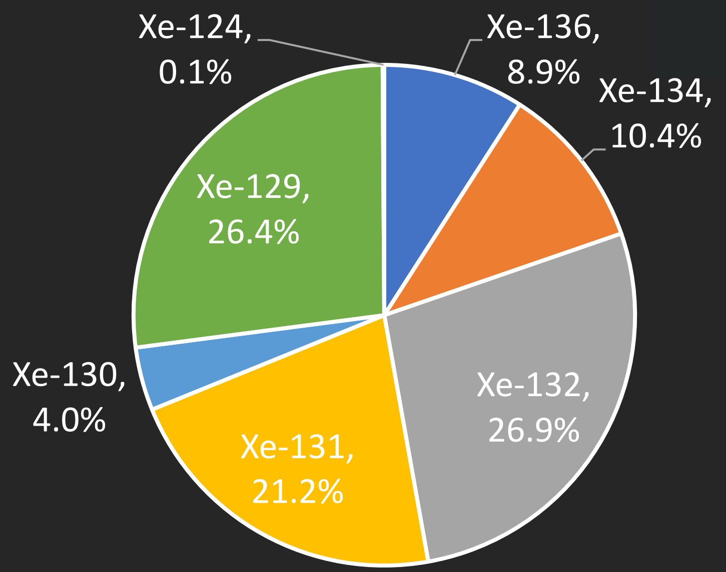
PANDA X
PARTICLE AND ASTROPHYSICAL XENON TPC





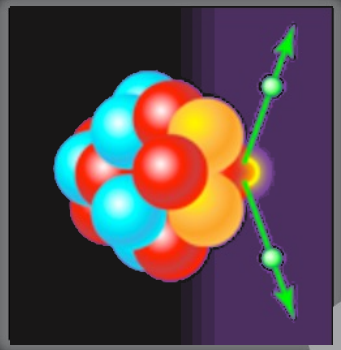
PandaX-4T as multi-physics observatory

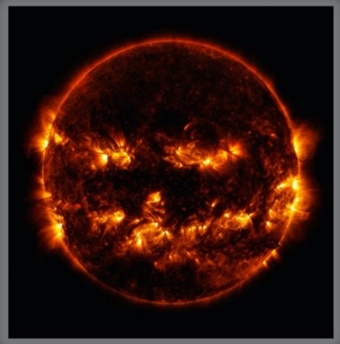
- Wide energy range: sub keV ~ a few MeV
- Large volume nature xenon target
- Background control and mitigation



Dark Matter
1 keV – 10 keV

Majorana Neutrino
~2 MeV



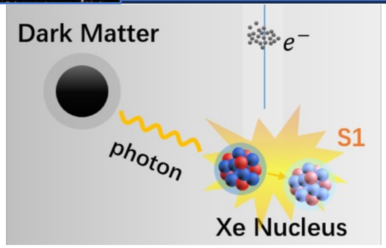


Astrophysical Neutrino
~100 keV & sub-keV

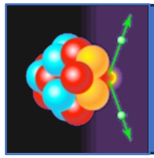
Some recent results...

PandaX
PARTICLE AND ASTROPHYSICAL XENON TPC

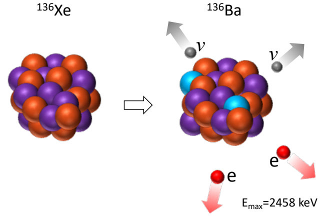
Dark Matter



- **Run0+Run1 combined 1.54 tonne-year exposure**
  - Leading constraints for WIMP mass above 100 GeV — **PRL** 134, 011805 (2025)
  - Leading constraints for ALP and dark photon 150 keV - 1 MeV — **PRL** 134, 071004 (2025)
  - Competieve constaints on axion, neutrino magnetic moment, etc — **PRL** 134, 041001 (2025)
- **Limits on the luminance of dark matter**
  - First constraints on DM charge radius — **Nature** 618, 47-50 (2023)

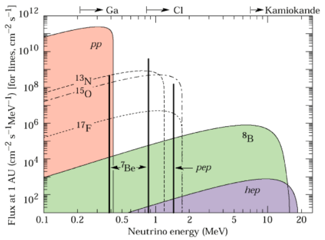


Majorana Neutrino



- **First ^{136}Xe 2νββ half-life precise measurement from natural xenon detector**
  - $T_{1/2} = 2.27 \pm 0.03(\text{stat.}) \pm 0.10(\text{syst.}) \times 10^{21}$ yr — **Research** 2022, 9798721 (2022)
- **Leading ^{136}Xe 0νββ half-life constraints from natural xenon detector**
  - 90% CL limits on half-life $T_{1/2} > 2.1 \times 10^{24}$ yr — **arXiv**: 2412.13979, available online at **Sci. Bulletin**
- **Leading ^{134}Xe 2νββ and 0νββ half-life constraints**
  - 90% CL limits on half-life $T_{1/2}^{2\nu\beta\beta} > 2.8 \times 10^{22}$ yr and $T_{1/2}^{0\nu\beta\beta} > 3.0 \times 10^{23}$ yr — **PRL** 132, 152402 (2024)

Astrophysical Neutrino



- **First indication of solar ^{8}B neutrinos through CEνNS**
  - 2.64σ significance — **PRL** 133, 191001 (2024)
  - Two ROI regions: paired (3.5±1.3 events) and S2-only (75±28 events)
- **First attempt to detect solar pp neutrinos in xenon detector**
  - Flux: $8.0 \pm 3.9(\text{stat.}) \pm 10.0(\text{syst.}) \times 10^{10}\ \text{s}^{-1}\,\text{cm}^{-2}$ — **CPC** 48, 091001 (2024)

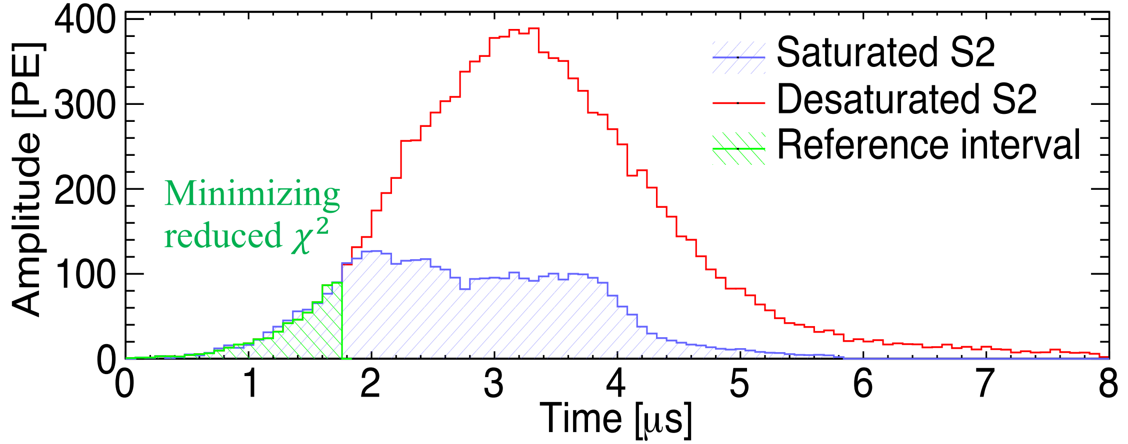
Extending energy from keV to MeV in Run0

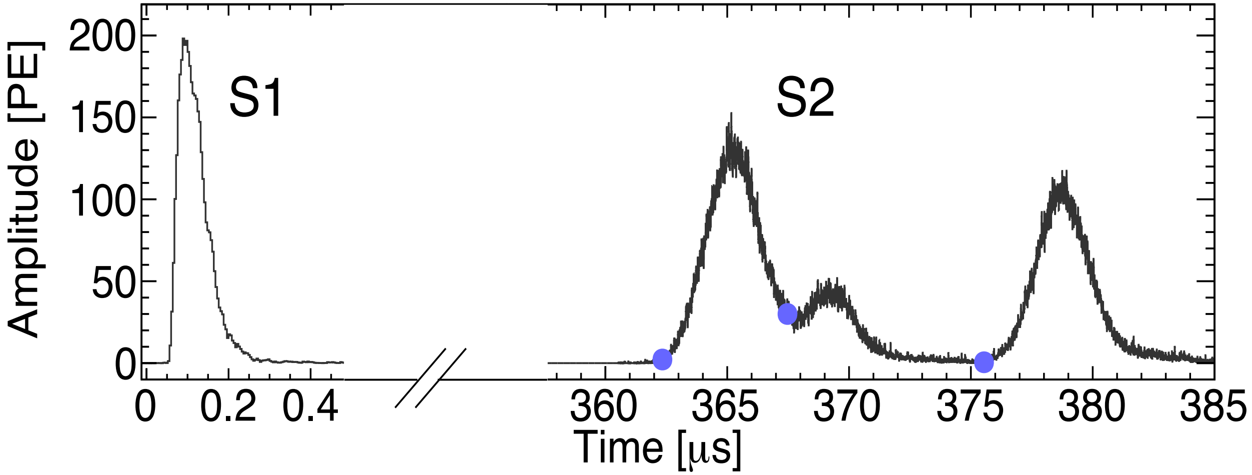
PANDA X
PARTICLE AND ASTROPHYSICAL XENON TPC

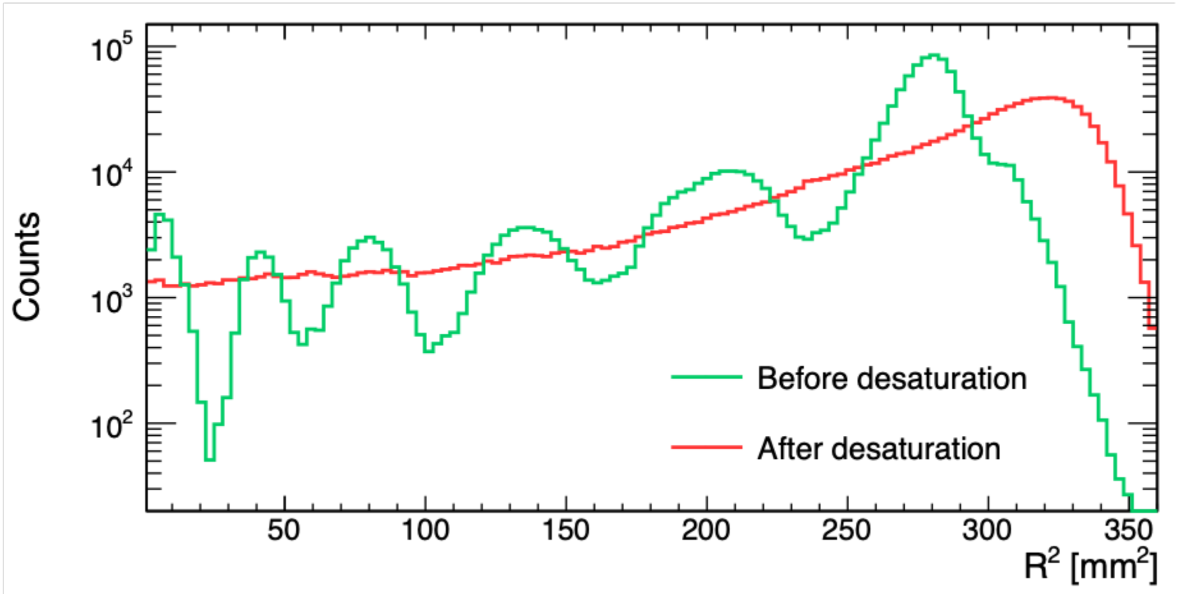
Dedicated data analysis pipeline is developed for *O*(100 keV) – *O*(MeV) energy range

- S2 waveform slicing to improve SS and MS identification
- PMT desaturation for large S2 signals
- Improvement of X-Y position reconstruction, energy linearity and energy resolution

Research 2022 9798721 (2022)

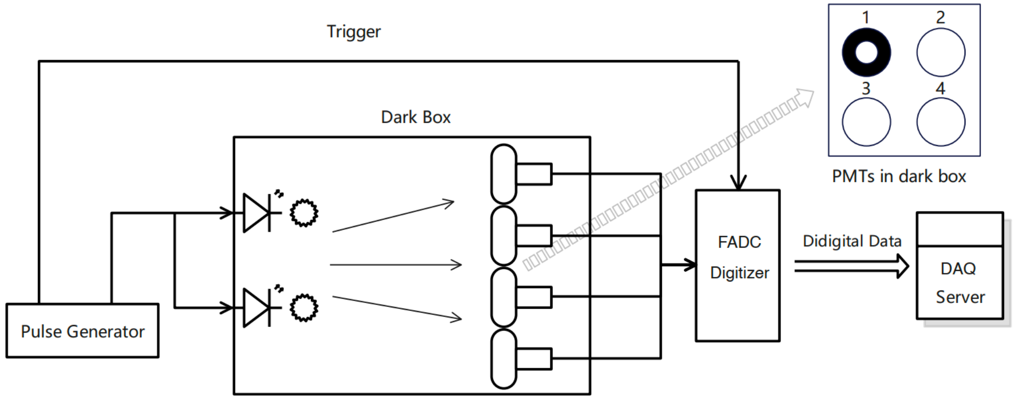


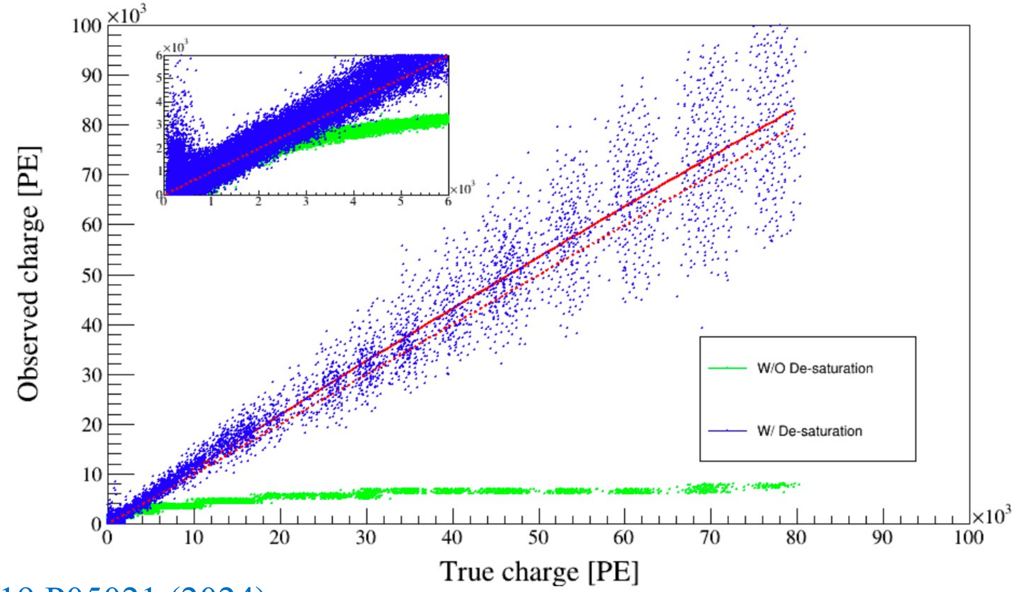




Bench test for saturation and new PMT base design

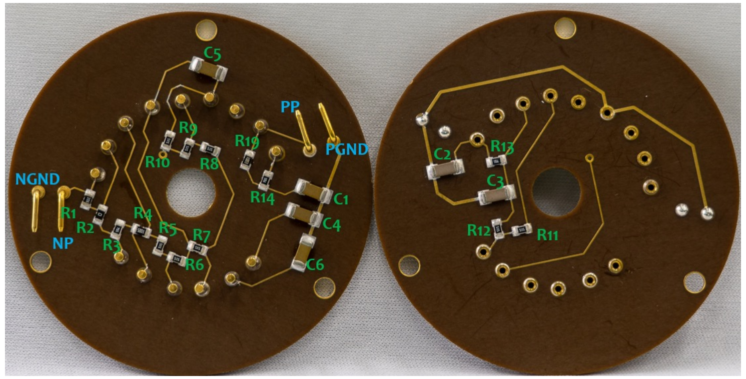
- PMT waveform saturation is studied by independent bench tests
- Desaturation algorithm is checked and verified

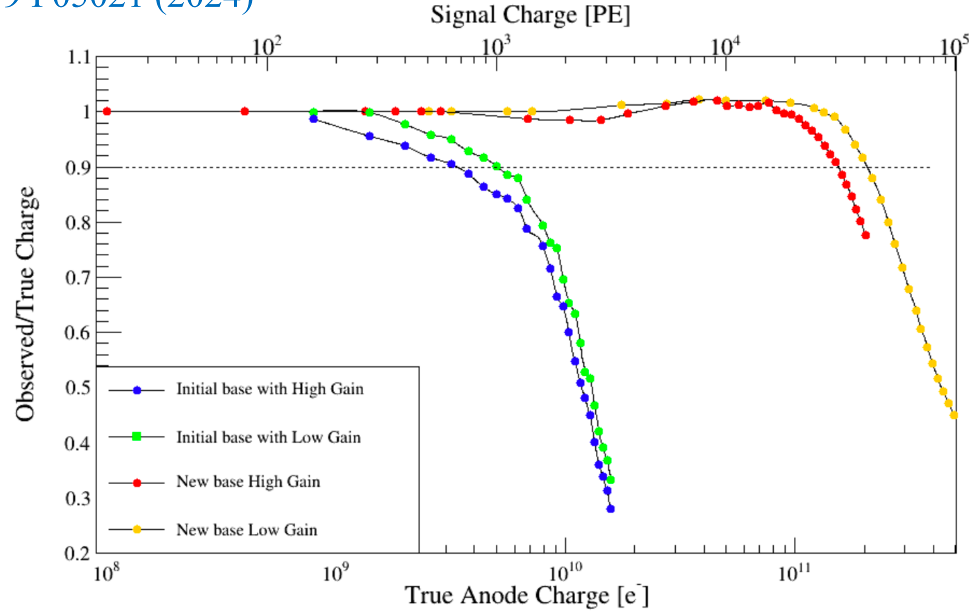




JINST 19 P05021 (2024)

- New PMT base design to increase the dynamic range
- All PMT bases have been changed in Run2



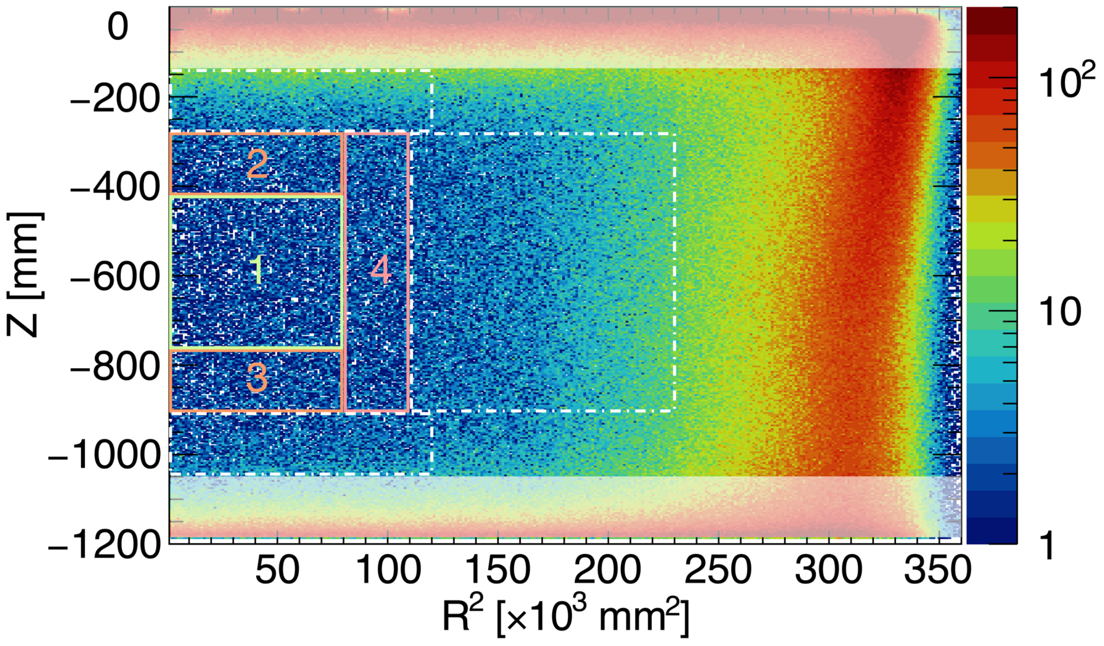


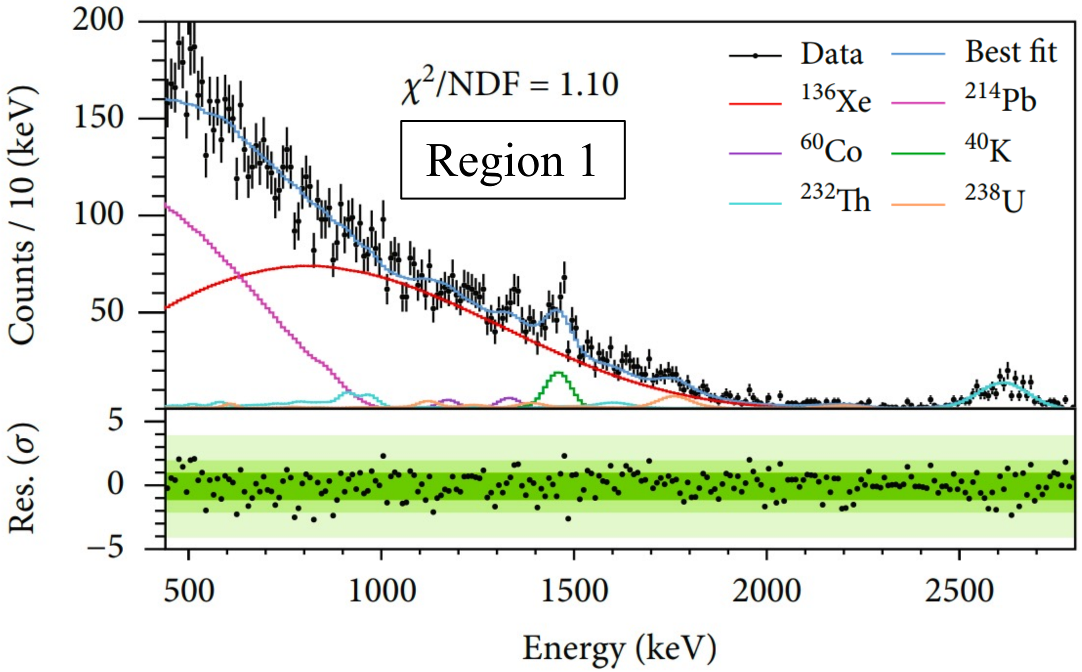
^{136}Xe 2νββ spectrum and background fitting

PANDA X
PARTICLE AND ASTROPHYSICAL XENON TPC

- Run0 commissioning data (95-day, 15.5 kg-year ^{136}Xe exposure)
- Segmented FV to partially include position information
- Binned Poisson likelihood fitting on SS energy spectrum performed simultaneously in four regions
- Outer regions to check background model, consistent at ~1%

$$L = \prod_{i=1}^{N_R} \prod_{j=1}^{N_{bins}} \frac{(N_{ij})^{N_{ij}^{obs}}}{N_{ij}^{obs}!} e^{-N_{ij}} \prod_{k=1}^{N_{bkgs}} \frac{1}{\sqrt{2\pi}\sigma_k} e^{-\frac{1}{2}(\frac{\eta_k}{\sigma_k})^2}, \quad N_{ij} = n_{Xe} S_{ij}^{Xe} + \sum_{k=1}^{N_{bkgs}} (1+\eta_k) n_{ij}^k B_{ij}^k$$



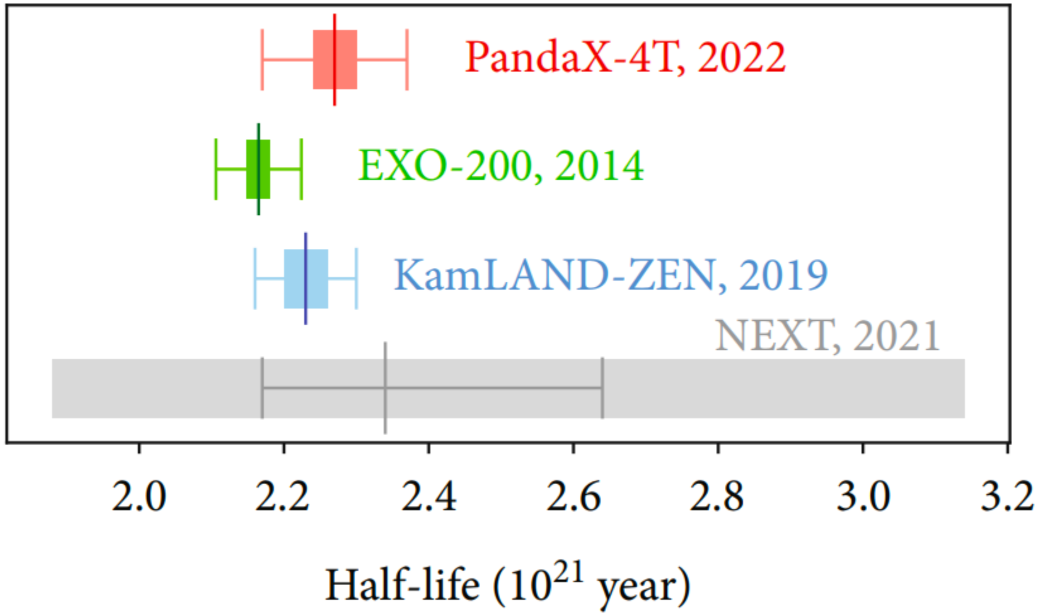


^{136}Xe 2νββ half-life and background estimation

PANDA X
PARTICLE AND ASTROPHYSICAL XENON TPC

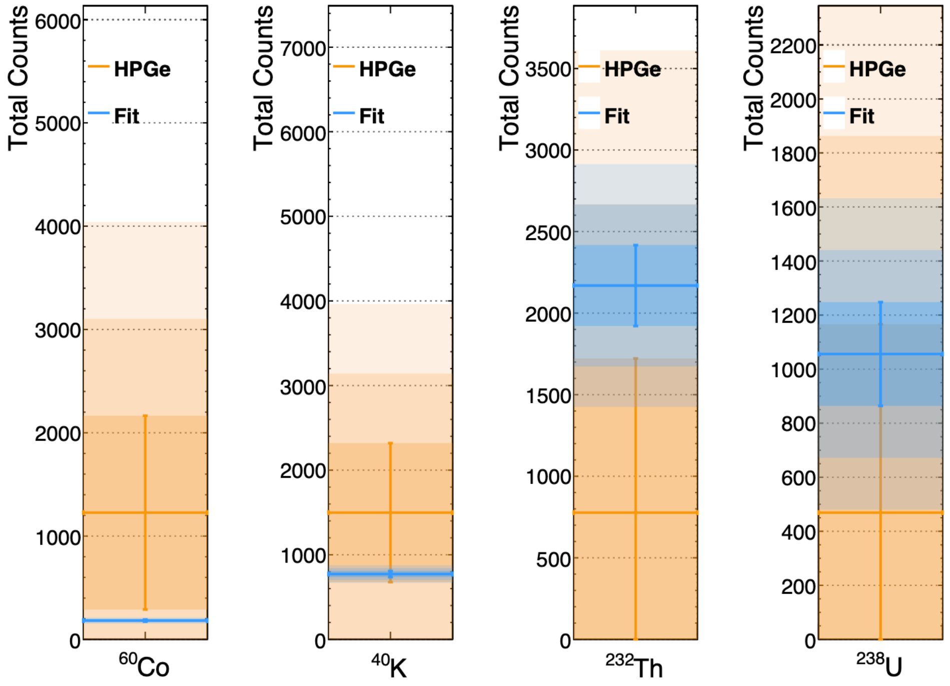
^{136}Xe 2νββ half-life measured as: $2.27 \pm 0.03(\text{stat.}) \pm 0.10(\text{syst.}) \times 10^{21}$ year

- First such measurement from natural xenon detector
- Comparable precision with dedicated ^{136}Xe-enriched 0νββ experiments
- Much lower analysis threshold compared with previous measurements
- *"in-situ"* material background fitting results compatible and more precise than HPGe assay



Research 2022, 9798721 (2022)

Material, "Side" category

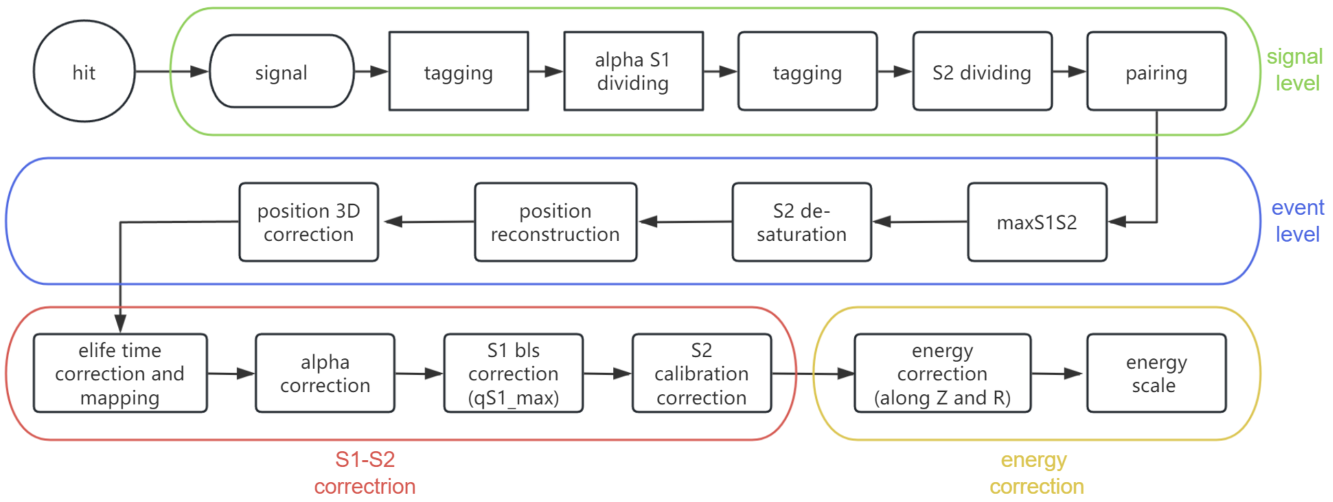


Unified data reconstruction for Run0 and Run1

PANDA X
PARTICLE AND ASTROPHYSICAL XENON TPC

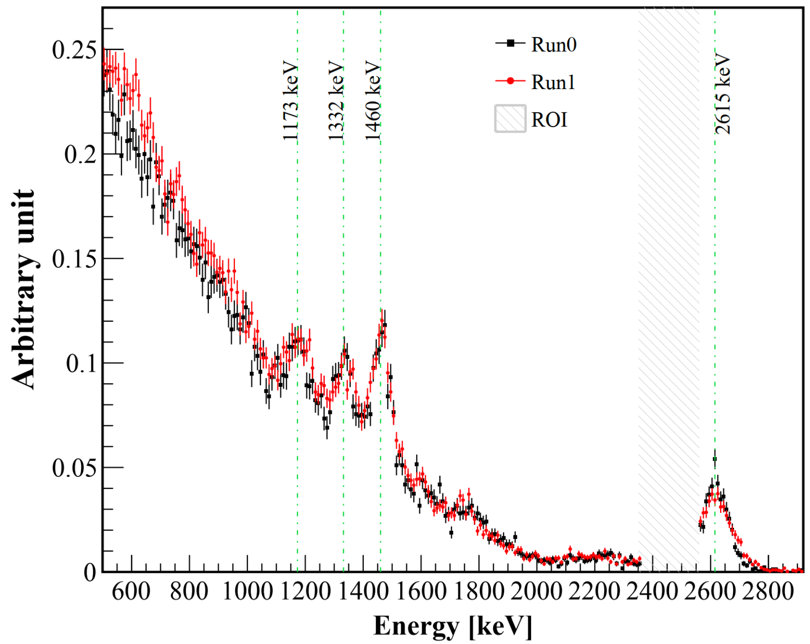
Optimizations in data processing:

- Recovered ~0.5% SS events by an improved time window cut
- S1 waveform slicing to improve alpha events reconstruction
- 3.5 ms dead-time cut before ^{214}Po events to remove isolated ^{214}Bi events: ~1% background reduction and negligible data loss
- And more...



Unified pipeline for Run0 and Run1

- Reconstructed spectra of Run0 and Run1 are consistent, considering the ^{222}Rn increase in Run1



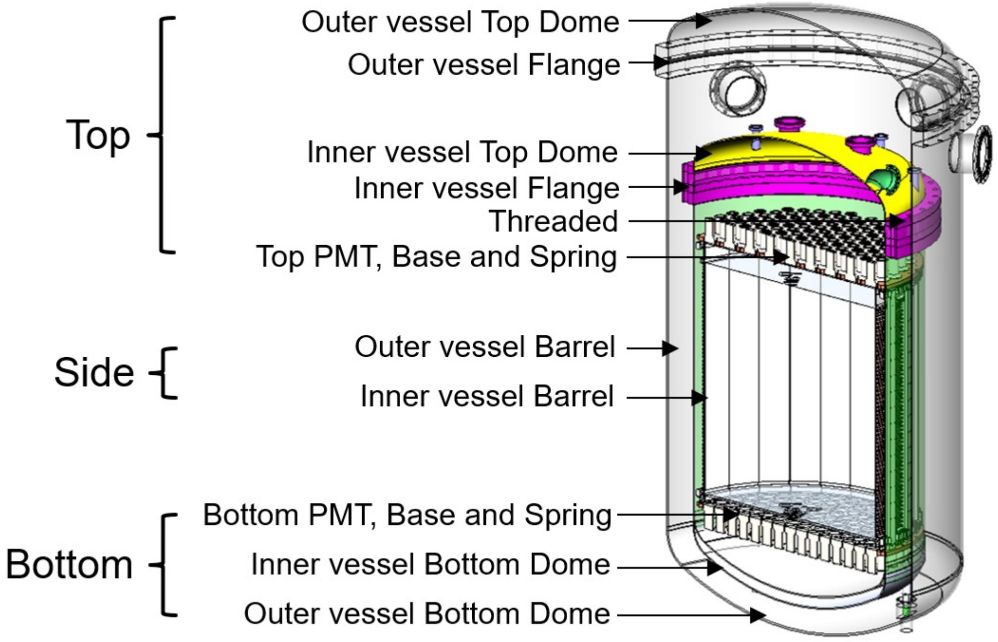
Blind analysis: ROI = [2356, 2560] keV, only SS events used

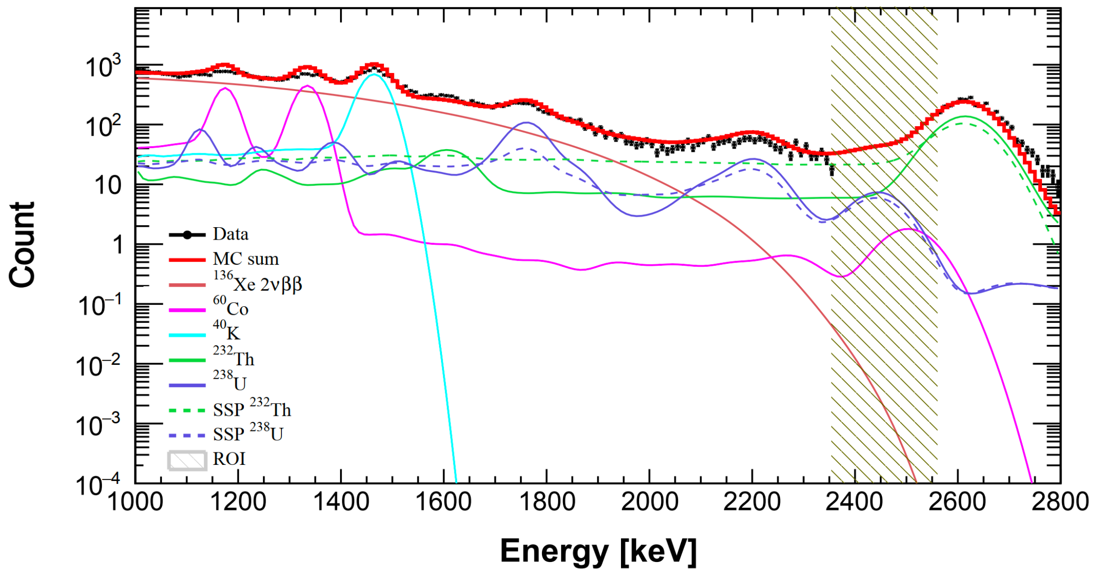
Background model

Spectrum fitting range chosen as [1100, 2800] keV, to fully exclude ^{214}Pb

Background components:

- ^{136}Xe $2\nu\beta\beta$ (from ^{136}Xe $2\nu\beta\beta$ half-life measurement)
- Detector material: ^{60}Co, ^{40}K, ^{232}Th, ^{238}U (from HPGe material assay), and grouped into top, side, and bottom parts
- Stainless steel platform (SSP): ^{232}Th, ^{238}U (from MS fitting)

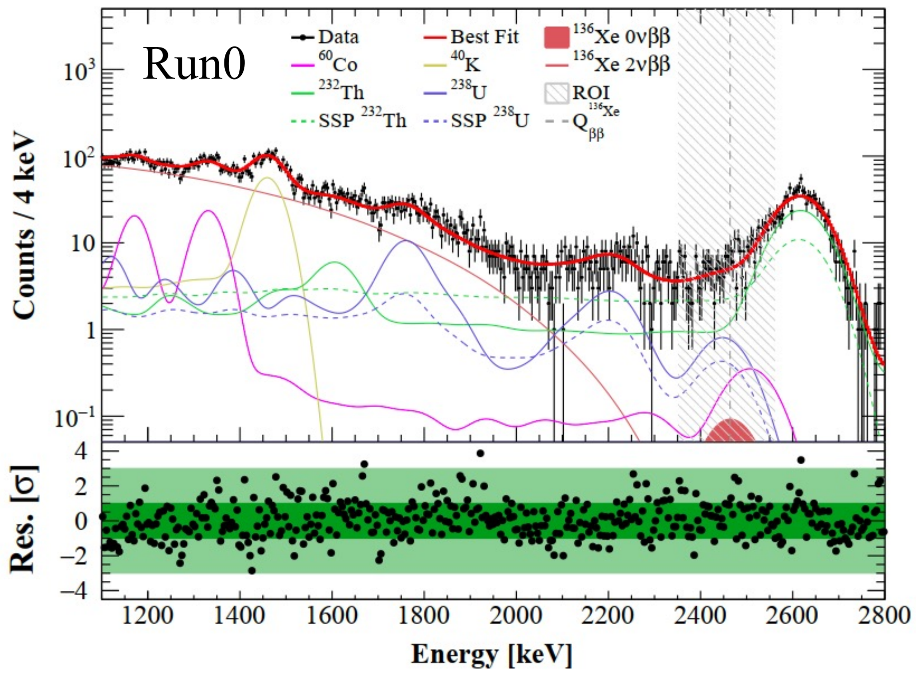


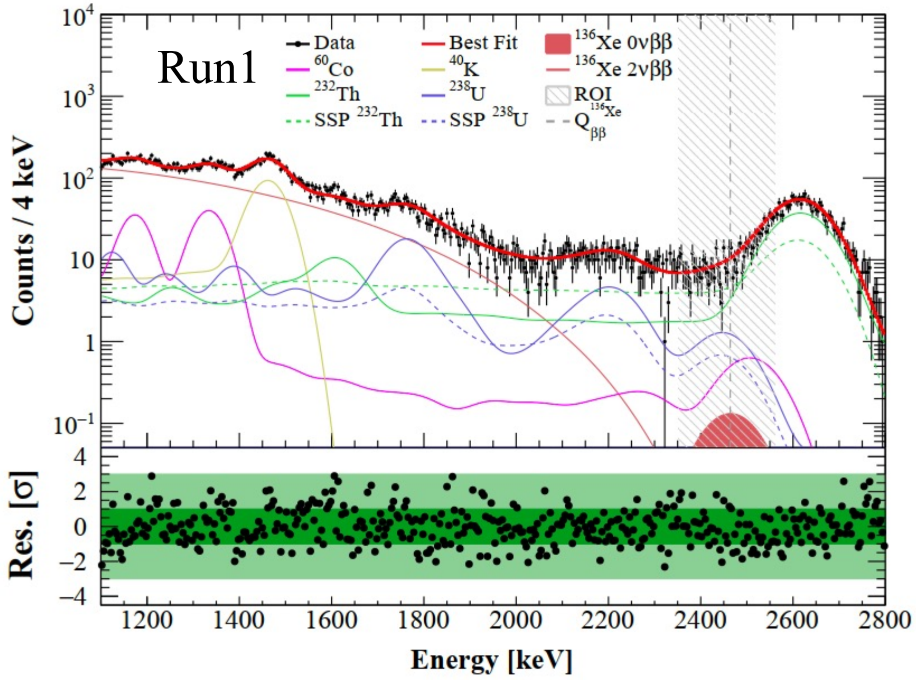


Other background components are checked:

- Residual ^{214}Bi in TPC -> negligible
- Gammas of ^{214}Bi from LXe skin region -> negligible
- 2.5 MeV peak from ^{60}Co cascade gammas -> well modelled

Unblinded Fitting and Results of ^{136}Xe 0νββ





Goodness-of-fit:
χ^2/NDF = 1.15

^{136}Xe exposure:
44.6 kg-yr

Energy resolution @ 2615 keV in FV:
2.0% in Run0 and
2.3% in Run1

^{136}Xe $0\nu\beta\beta$ event rate is fitted to be $\mathbf{14 \pm 37}$ $\boldsymbol{t^{-1} yr^{-1}}$, with a p-value of 0.49 for null results.

$$T_{1/2}^{0\nu\beta\beta} > 2.1\times 10^{24}\ yr \text{ at 90\% C.L.}$$

Upward fluctuation, the limit is consistent with the median sensitivity within 1.1σ.

$$\langle m_{\beta\beta} \rangle = (0.4 - 1.6)\ \text{eV/c}^2$$

- **Best results among natural xenon detectors so far**
- Improvement to our previous PandaX-II results by an order of magnitude and to the XENON1T results by a factor of 1.8
- Demonstrating the potential of ^{136}Xe 0νββ search with next-generation multi-ten-tonne natural xenon detectors

arXiv: 2412.13979
available online at **Sci. Bulletin**

A blessing: ^{134}Xe 2νββ/0νββ searches

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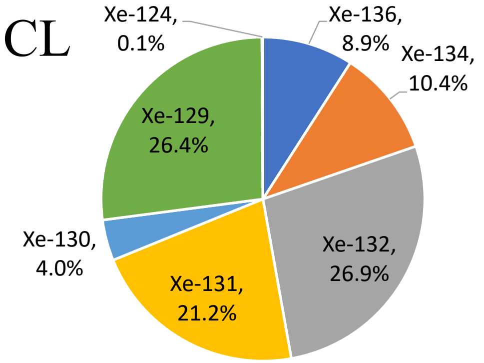
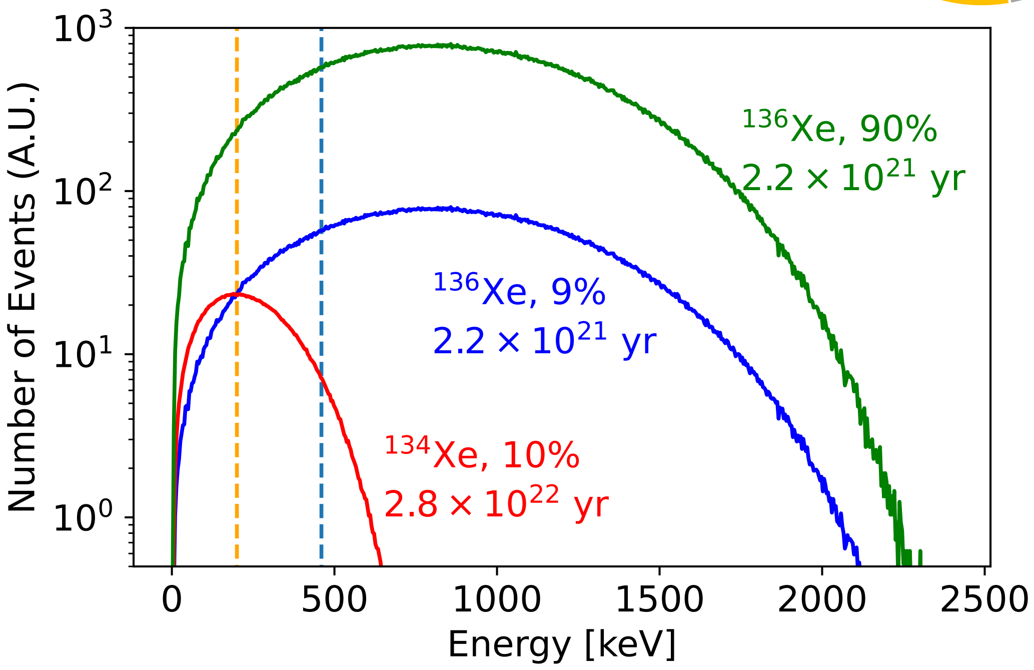
- Q=826 keV; Half-life from theoretical predictions: 10^{24}-10^{25} yr; Never been observed yet
- Previous 2νββ (0νββ) half-life limit from EXO-200: $T > 8.7 \times 10^{20}$ yr (1.1×10^{23} yr) at 90% CL
- PandaX-4T: more ^{134}Xe; much less ^{136}Xe; wider energy range; discovery possible

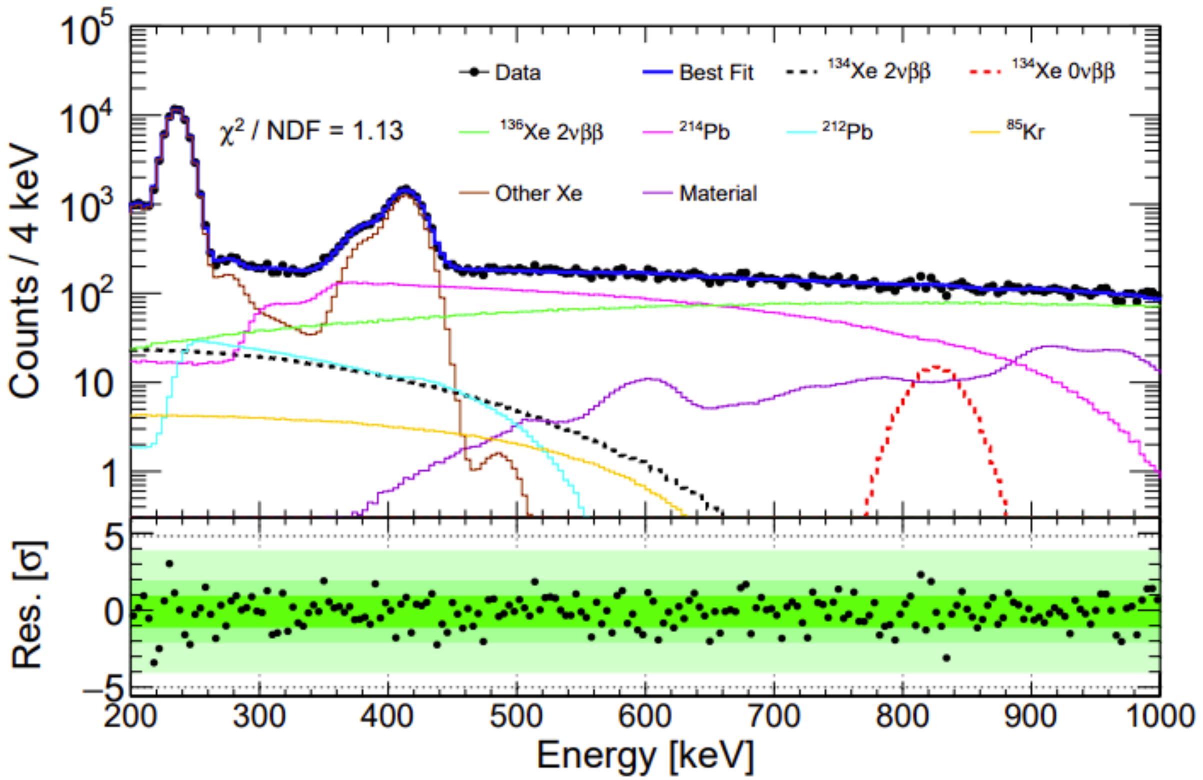


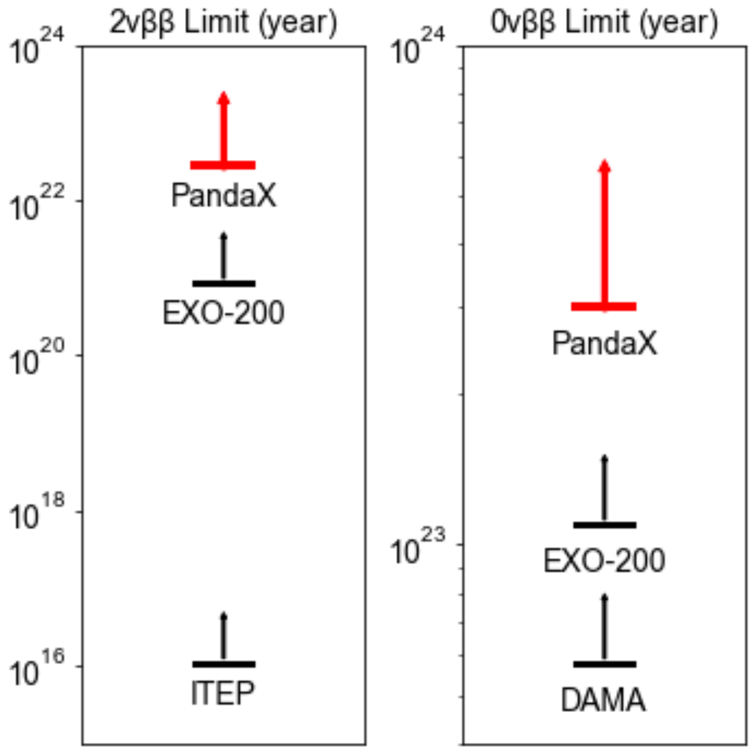
	PandaX-4T	EXO-200
^{134}Xe mass	68.7 kg	18.1 kg
^{136}Xe abundance	8.90%	81%
Analysis threshold	200 keV	460 keV
Live Time	94.9 days	600 days



^{134}Xe 2νββ/0νββ searches with Run0

- Simultaneous fit for ^{134}Xe 2νββ and 0νββ
- Final counts of 2νββ and 0νββ: 10±269(stat.)±680(syst.) and 105±48(stat.)±38(syst.)
- 90% CL lower limits on the half-life: $T_{1/2}^{2\nu\beta\beta} > 2.8 \times 10^{22}$ yr and $T_{1/2}^{0\nu\beta\beta} > 3.0 \times 10^{23}$ yr





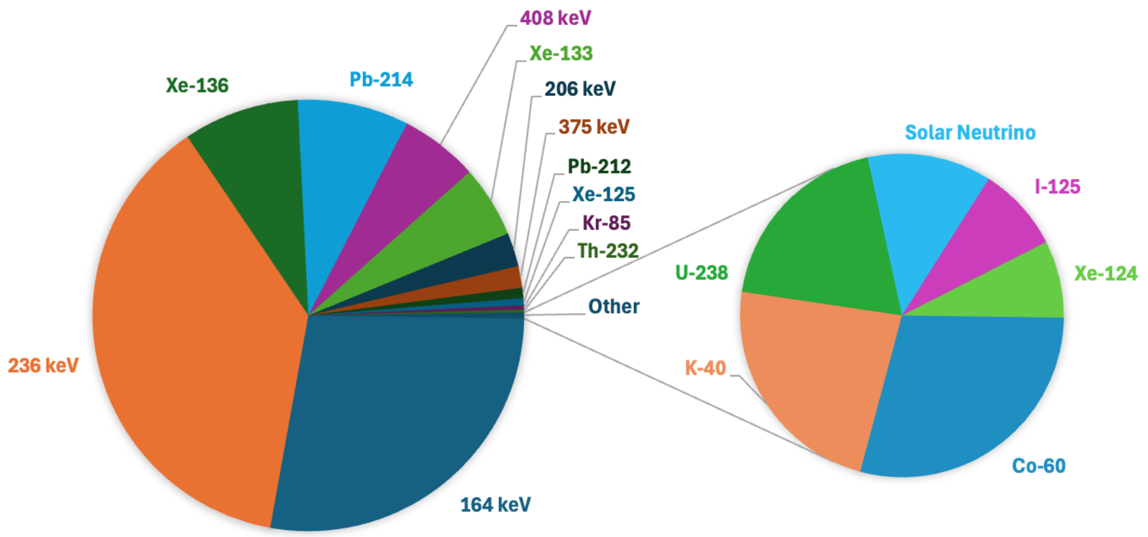
PRL 132, 152402 (2024)

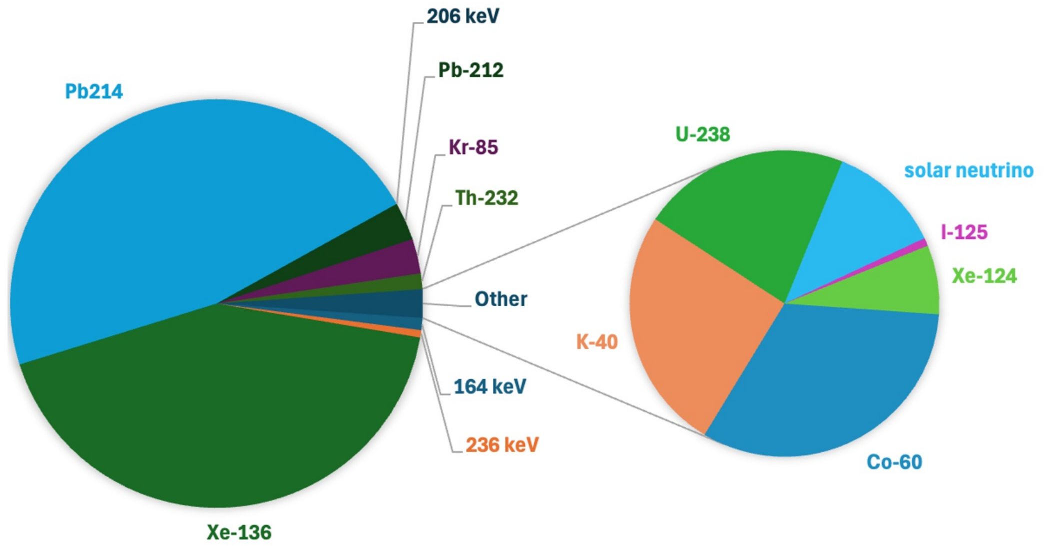
Search for axion-like particle and dark photon

$$R_{\mathrm{ALP}} = \frac{1.47 \times 10^{19}}{A} g_{ae}^2 \cdot m_a \sigma_{pe} \, [\mathrm{kg}^{-1}\mathrm{d}^{-1}],$$

$$R_{\mathrm{DP}} = \frac{4.7 \times 10^{23}}{A} \frac{(e\kappa)^2}{4\pi\alpha} \frac{\sigma_{pe}}{m_d} \, [\mathrm{kg}^{-1}\,\mathrm{d}^{-1}],$$

- Single-site only, [25, 1050] keV, total exposure of 440 kg-yr with Run0 + Run1
- Material contribution (^{60}Co, ^{40}K, ^{232}Th, ^{238}U) is constrained by side band fit from previous analysis
- Background component: In Run0, 164 and 236 keV peaks from ^{131m}Xe and ^{129m}Xe dominates; In Run1, ^{214}Pb and ^{136}Xe dominates

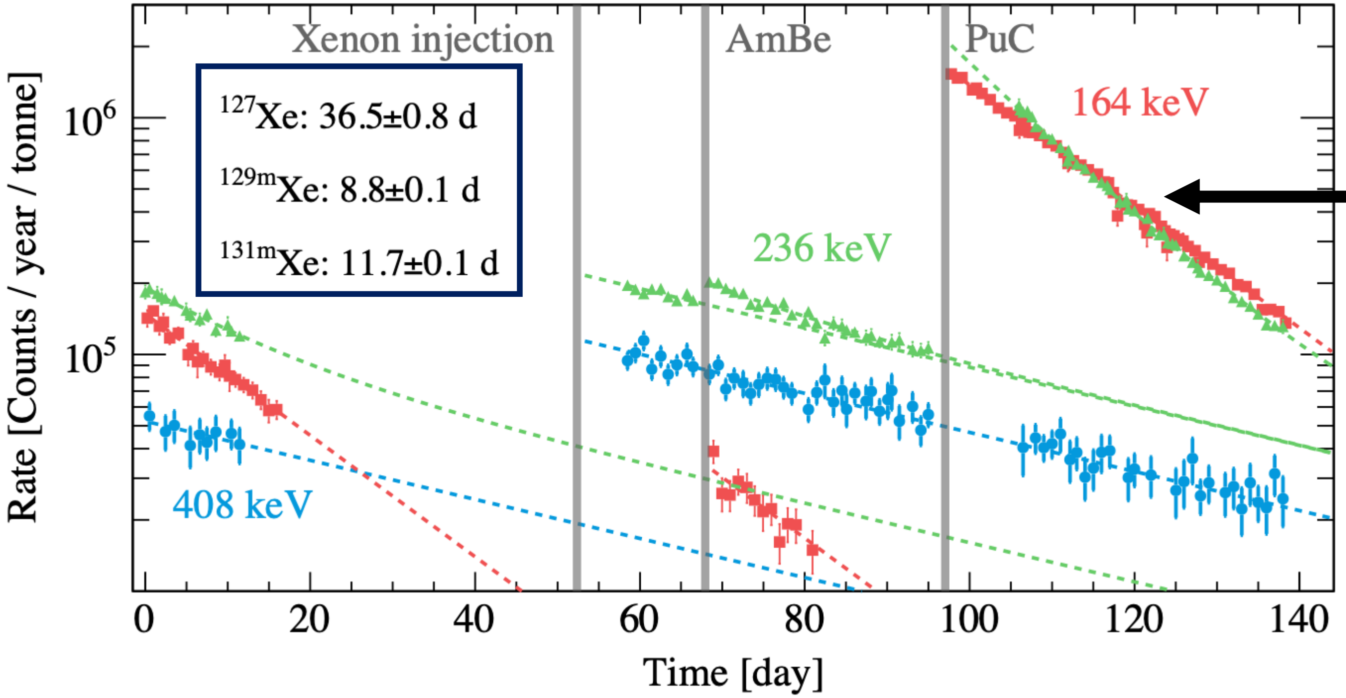


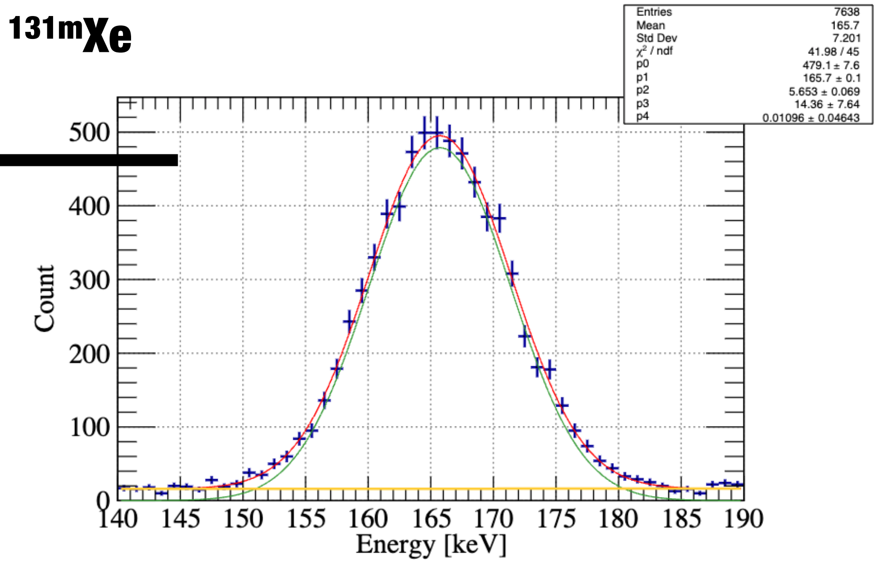


Time evolution model of short-live Xe isotopes

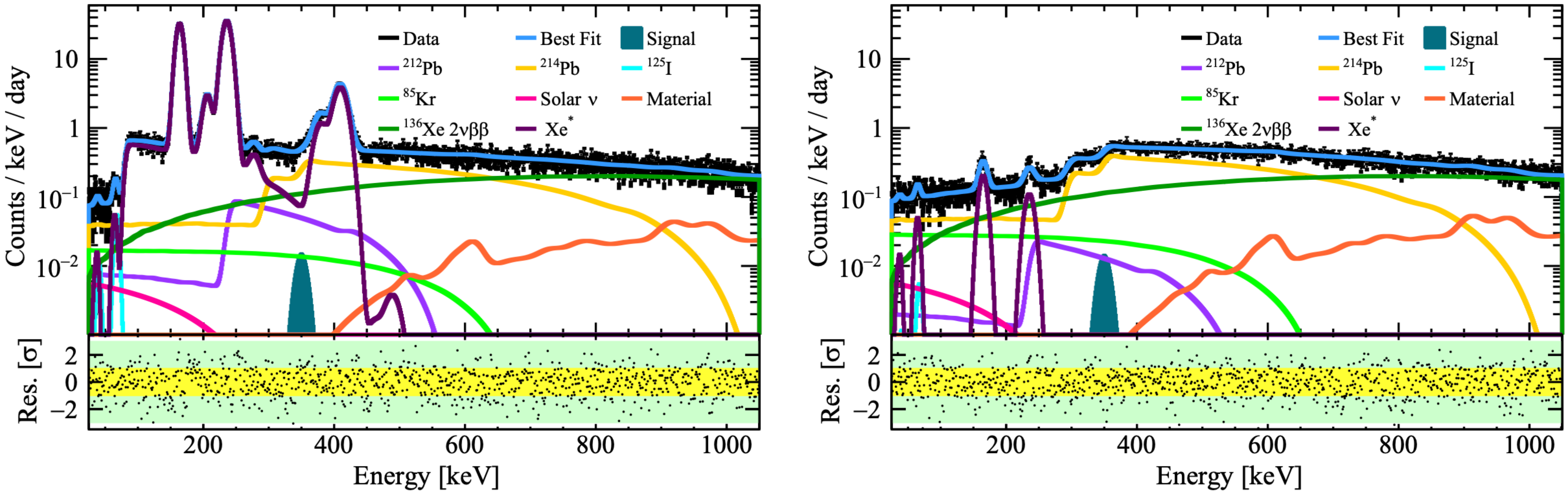
- Time evolution model of short-live Xe isotopes: ^{127}Xe, ^{129m}Xe and ^{131m}Xe
  - ^{127}Xe from the xenon injection, ^{129m}Xe and ^{131m}Xe from neutron calibration
  - Characterize with a Gaussian + linear function for each Gaussian component
  - The measured half-lives of these xenon isotopes agree with the theoretical values

Components	Expected
164 keV	41071 ± 1678
208 keV	3724 ± 129
236 keV	54934 ± 5536
380 keV	2397 ± 130
408 keV	8599 ± 318





Spectrum fitting



- Mass scan of MeV ALPs/DPs in [30, 1000] keV/c^2 with a step of 10 keV/c^2
- No excess; the look-elsewhere effect taken into account, the global significance is 1.5σ

Limits of ALP/DP couplings

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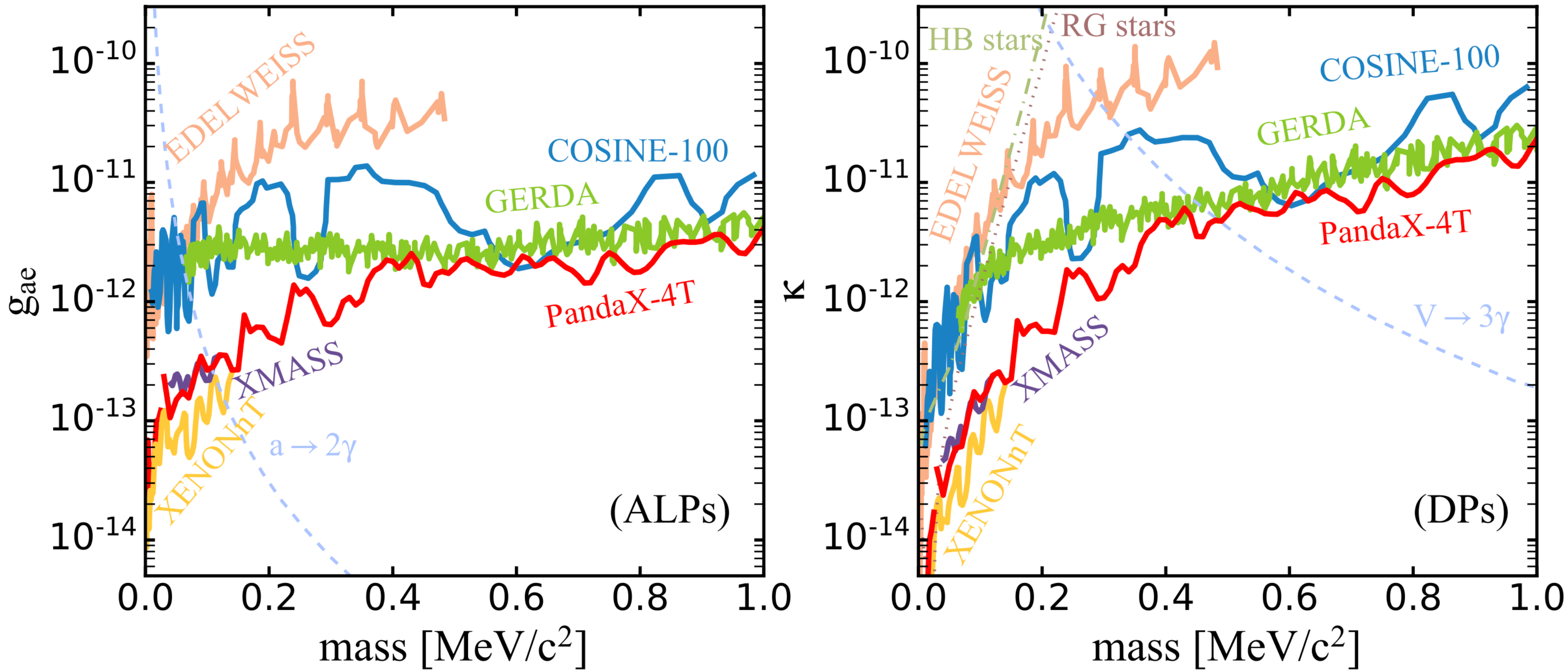
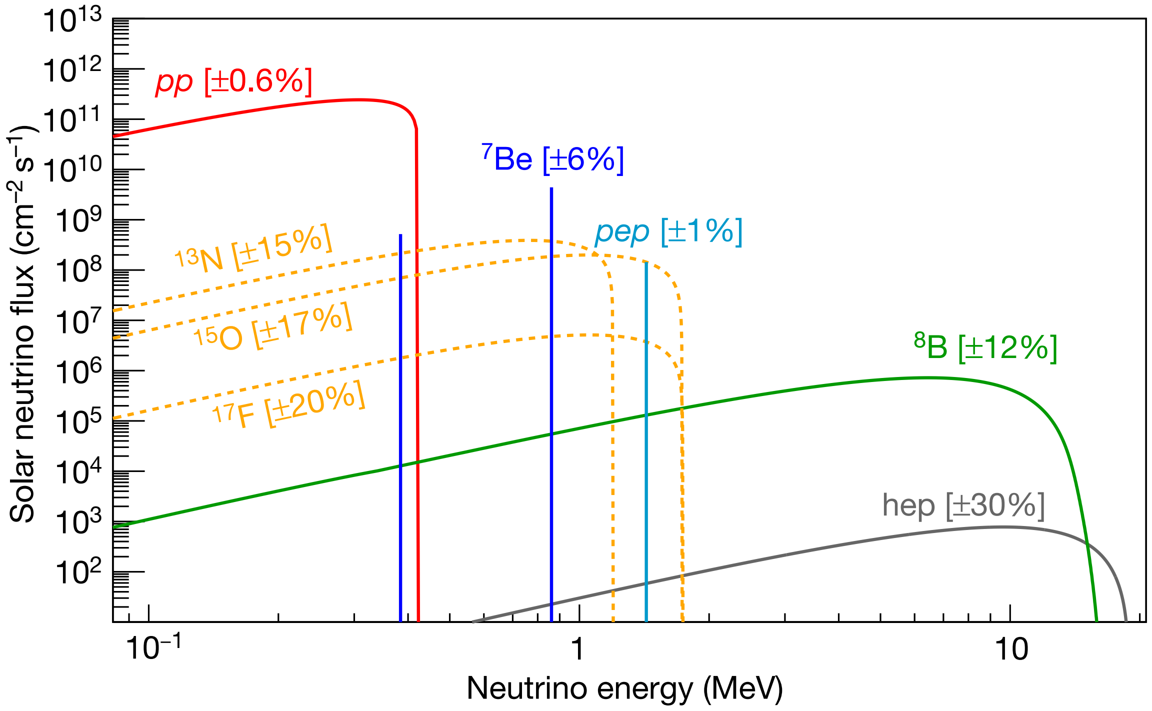


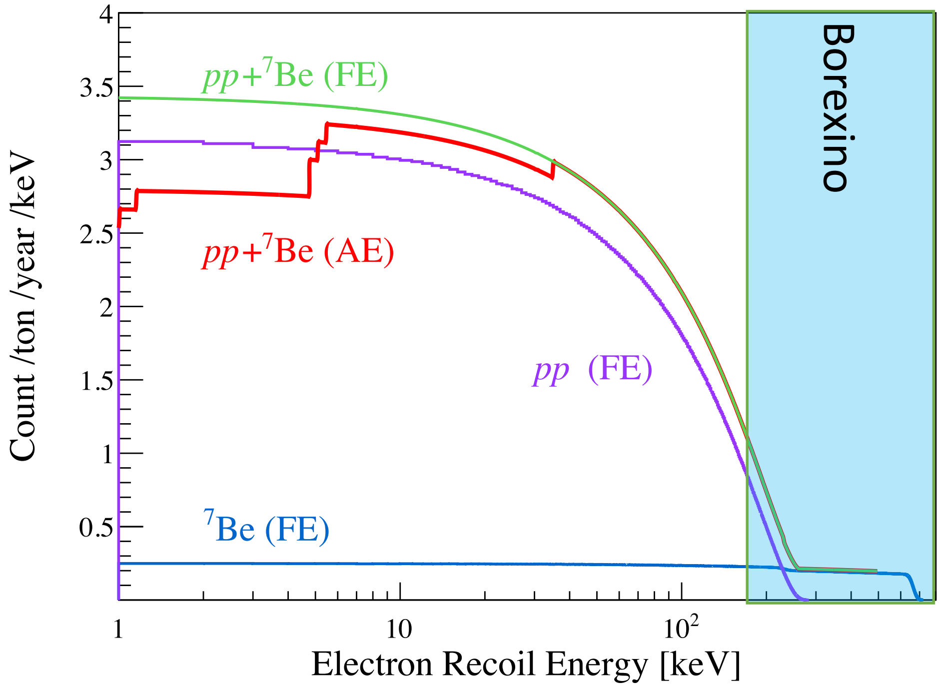
- The most competitive limits almost range from 150 keV/c² to 1 MeV/c², with an average improvement of 1.5 times better
- Only considered absorption process, Compton-like process (mostly MS events) will be studied later

PRL 134, 071004 (2025)

Solar pp neutrino scattering on electrons

- **The world's leading direct detection result is from Borexino with a recoil energy of >165 keV**
- **PandaX-4T aims to measure the lower energy spectrum than Borexino**





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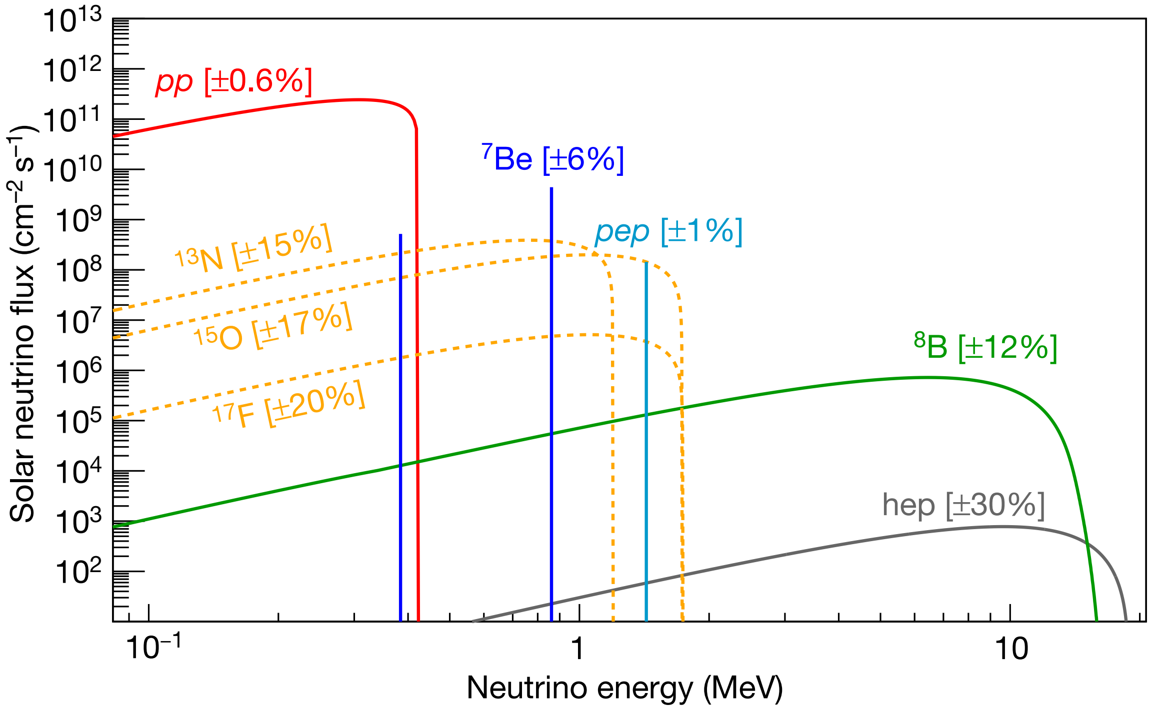
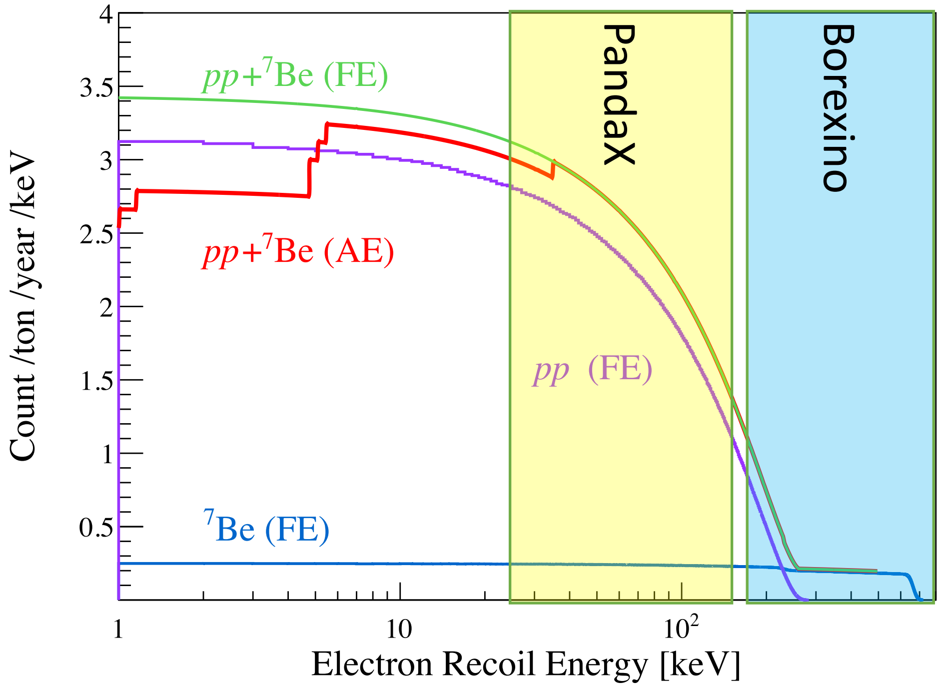


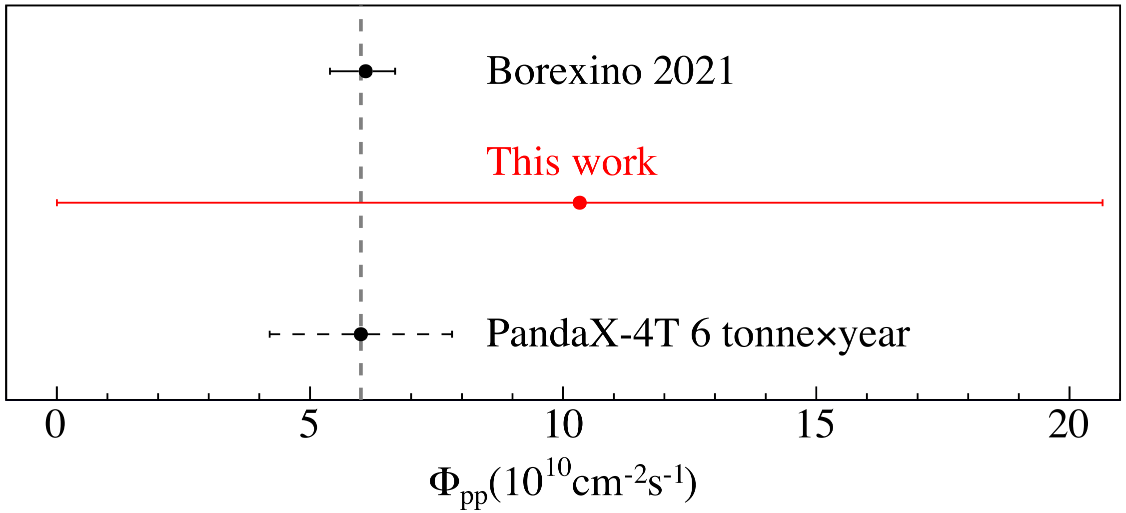


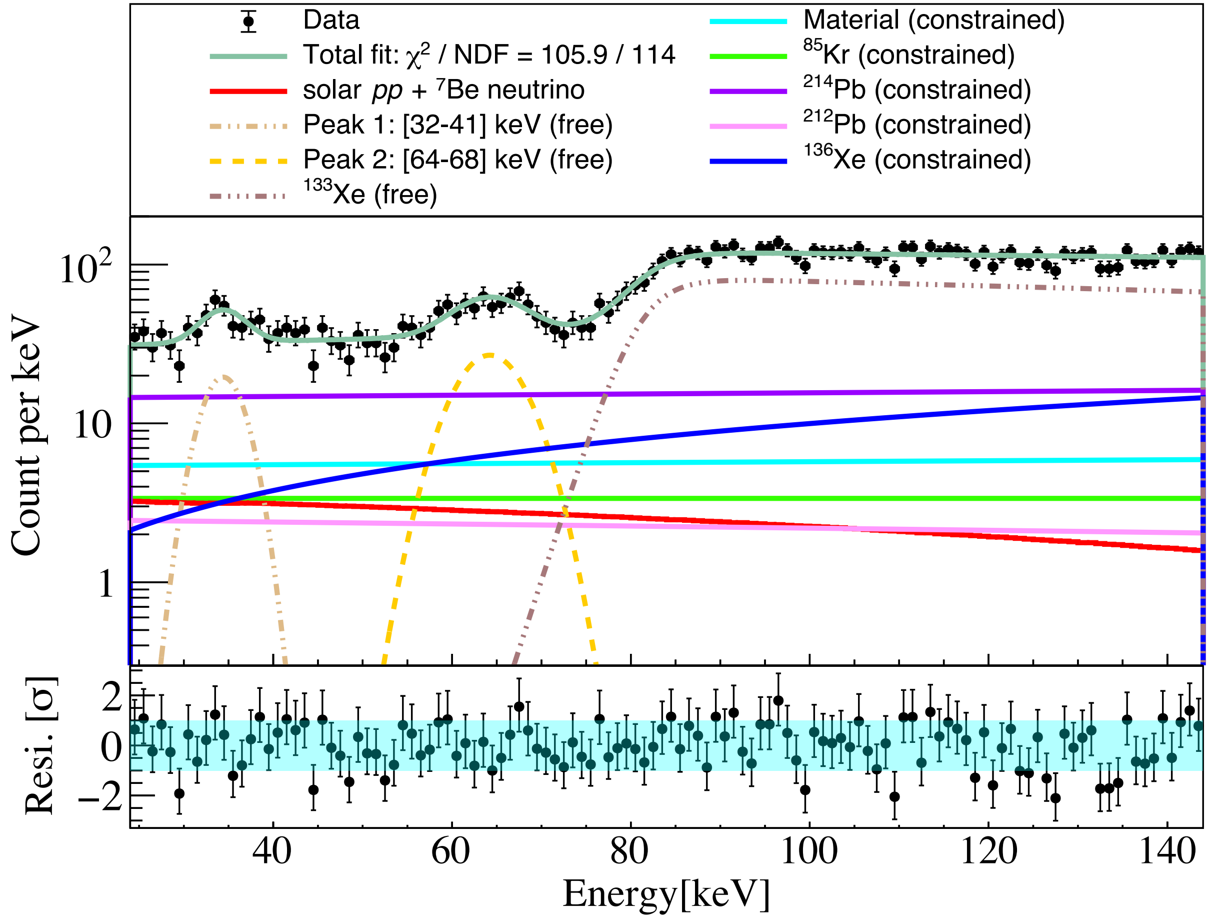
An attempt: solar pp neutrino results with Run0

PandaX
PARTICLE AND ASTROPHYSICAL XENON TPC

- The first solar pp neutrino measurement in recoil energy from 24 to 144 keV with 0.63 ton-yr of Run0
- Consistent with Standard Solar Model and existing measurements

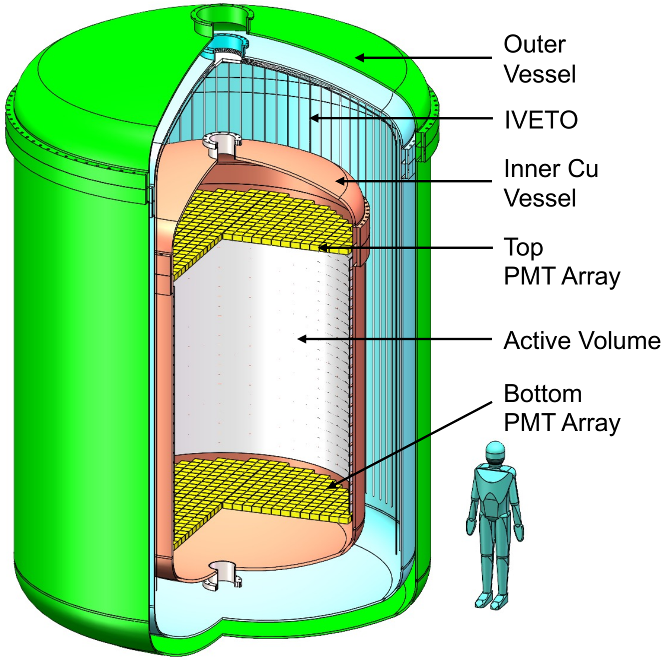
CPC 48, 091001 (2024), cover story

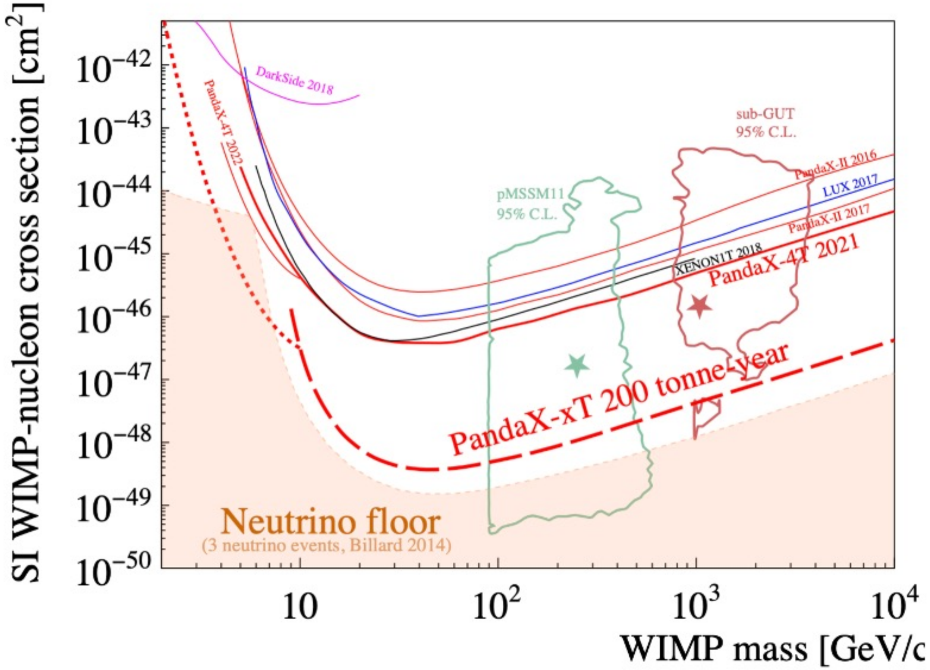


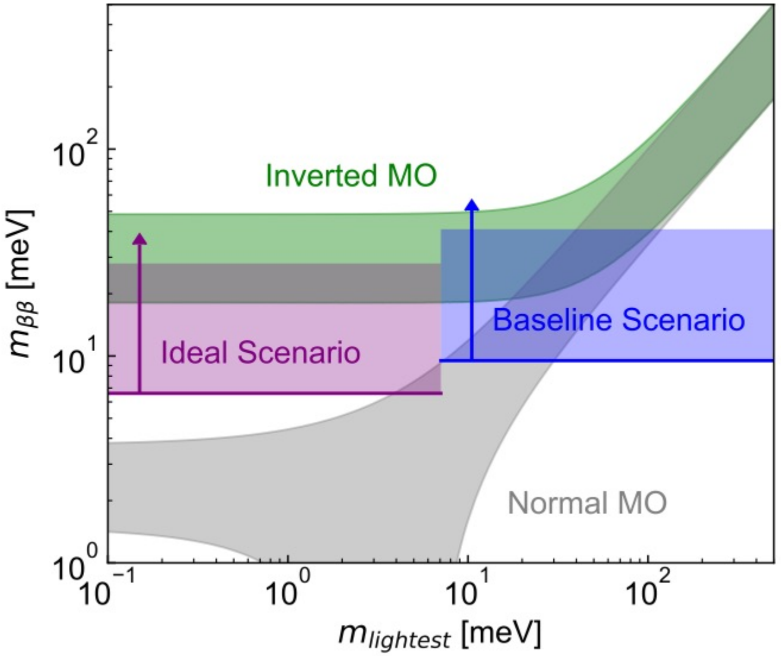


Future plan: PandaX-xT

- **Staged plan, finally reaching 43 tonne natural Xe in sensitive volume**
- **Key tests on WIMP and Dirac/Majorana neutrino**





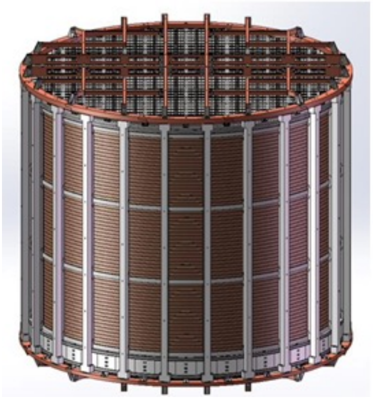


arXiv:2402.03596, **SCPMA** 68, 221011 (2025)

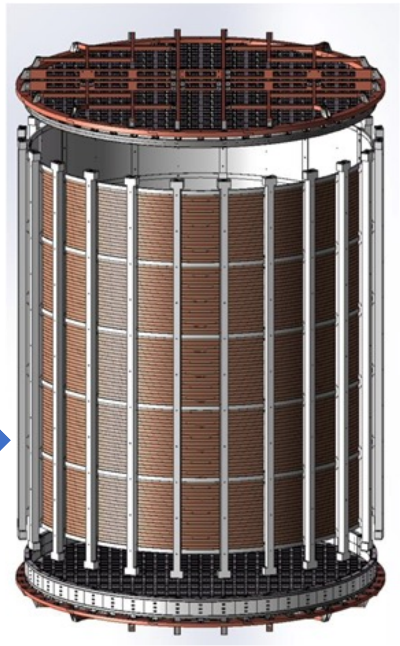
PandaX-20T: intermediate stage

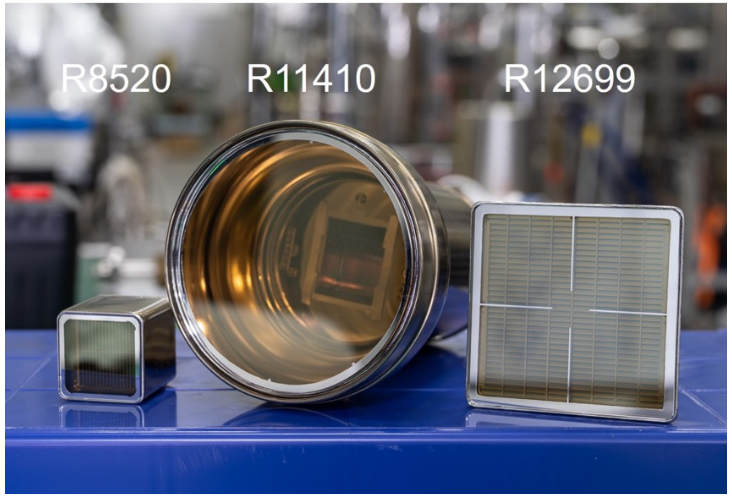
- **Multi-physics targets**
  - **Energy range 100 eV – 10 MeV**
- **Estimated timeline**
  - **2026: move to CJPL and assembling**
  - **2027: commissioning**

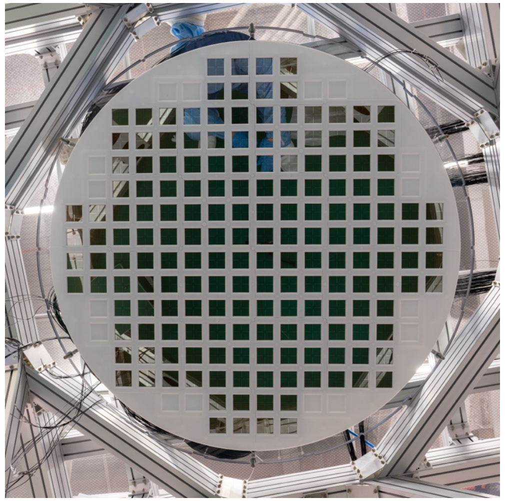
PandaX-20T

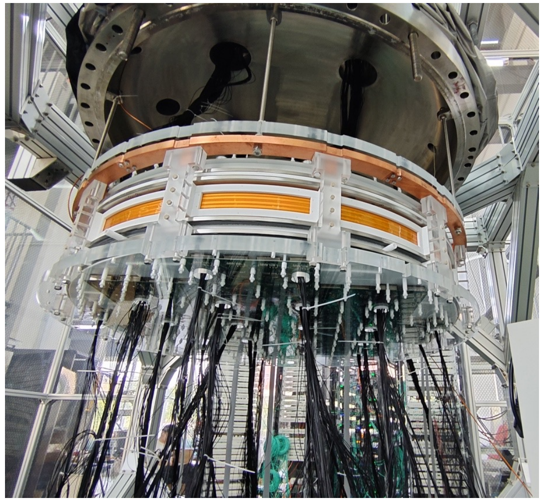


PandaX-xT

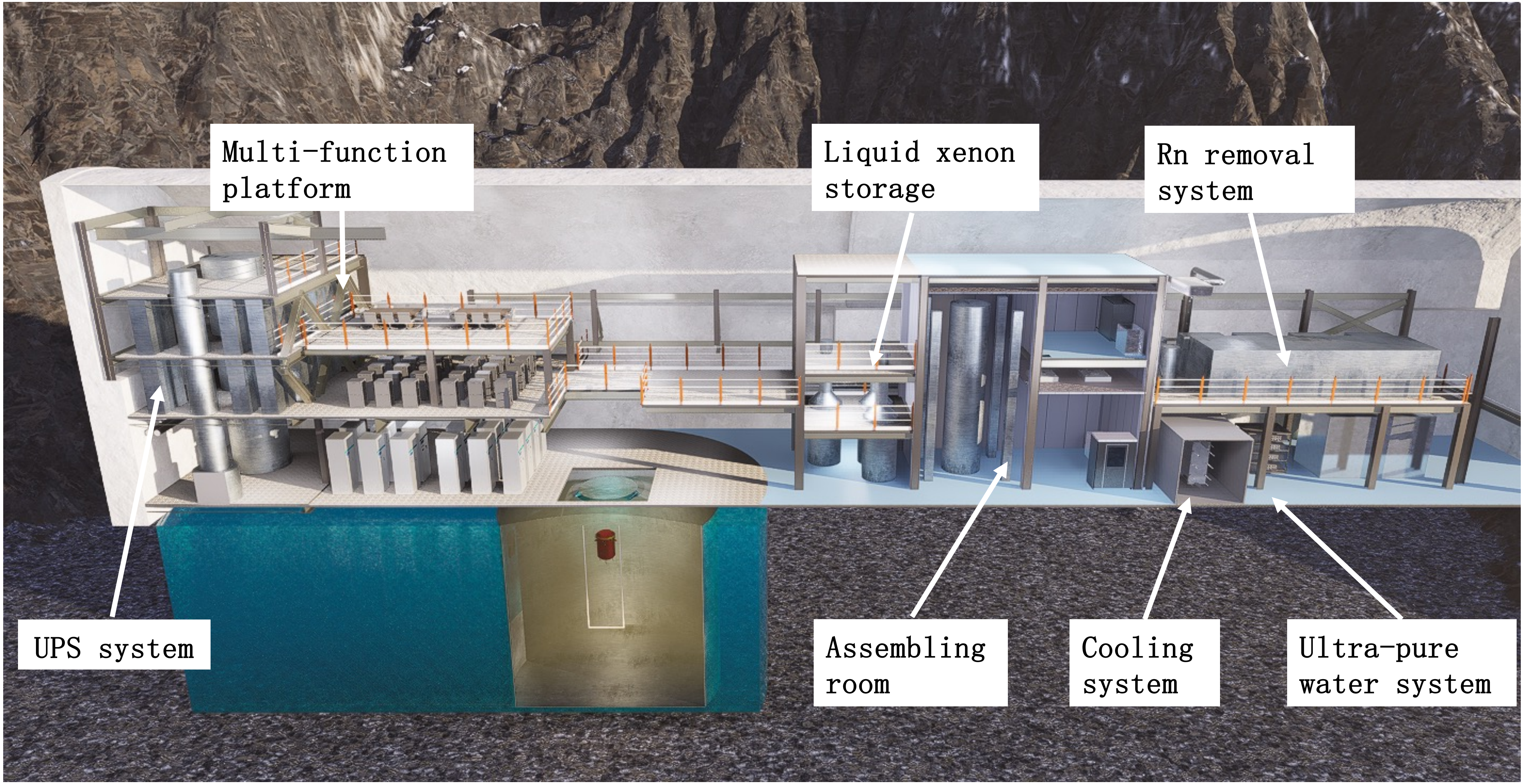








Planed layout at CJPL-II B2 Hall for PandaX-xT



PandaX-xT First Open Meeting

PANDAX
PARTICLE AND ASTROPHYSICAL XENON TPC

PandaX-xT First Open Meeting

Apr 10 – 11, 2025
Tsung-Dao Lee Institute
Asia/Shanghai timezone

Enter your search term

- Overview
- Registration
- Travel Information

Contact

pandax-meetings@goog...

Open meeting: April 10-11, Tsung-Dao Lee Institute

Theory/pheno Program: April 7-9, Tsung-Dao Lee Institute

Jinping Laboratory Visit: April 12-13, Shanghai-Xichang-Shanghai

We will hold an International Open Meeting for PandaX-xT. PandaX (**P**article **and** **A**strophysical **X**enon project, https://pandax.sjtu.edu.cn/) is an experimental program that employs a series of xenon detectors to search for elusive dark matter particles and to study the fundamental properties of neutrinos. Up to now, the collaboration has constructed and operated three generations of experiments, PandaX-I, PandaX-II, and PandaX-4T, with active target masses of 120 kg, 580 kg, and 3.7 tonnes, respectively, producing many results at the forefront of dark matter search and neutrino studies.

The PandaX collaboration is actively preparing for the next phase, PandaX-xT, a multi-ten-tonne liquid xenon, ultra-low background, and general-purpose observatory. The full-scaled PandaX-xT contains a 43-t liquid xenon active target, opening new windows of discovery in dark matter, Majorana neutrinos, low-energy astrophysical neutrinos, and other ultra-rare interactions. PandaX-xT may seek further upgrades utilizing isotopic separation of natural xenon. The published conceptual design of PandaX-xT can be found at https://arxiv.org/pdf/2402.03596.

PandaX-xT First Open Meeting


Thank you!