The 17th International Symposium on Origin of Matter and Evolution of Galaxies

PandaX

Dark Matter and Neutrino Program

HAN, Ke 韩柯 (SJTU)

For the PandaX Collaboration

2024/9/8

PandaX: Particle and Astrophysical Xenon Experiment

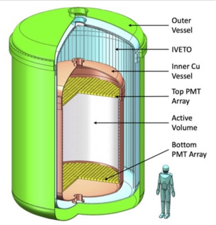
15 institutions, ~100 collaborators

PandaX detectors

PandaX-I: 120kg
LXe (2009 – 2014)

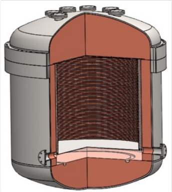
PandaX-II: 500kg
LXe (2014 – 2018)

PandaX-4T LXe
(2020-)

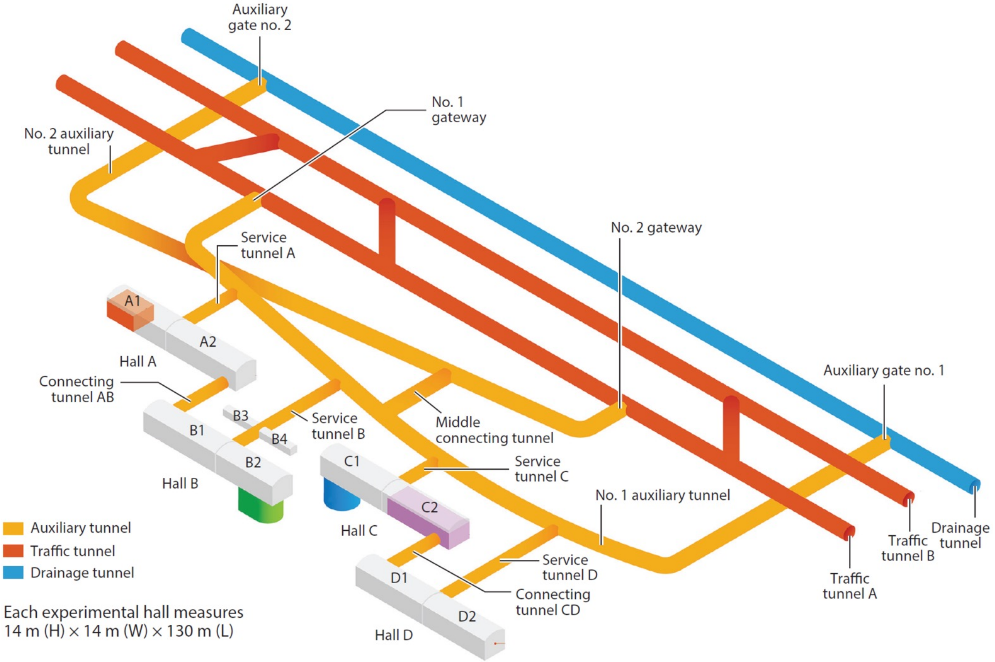


PandaX-xT LXe
(future)

PandaX-III: 100kg - 1 ton
HPXe for 0νββ (future)

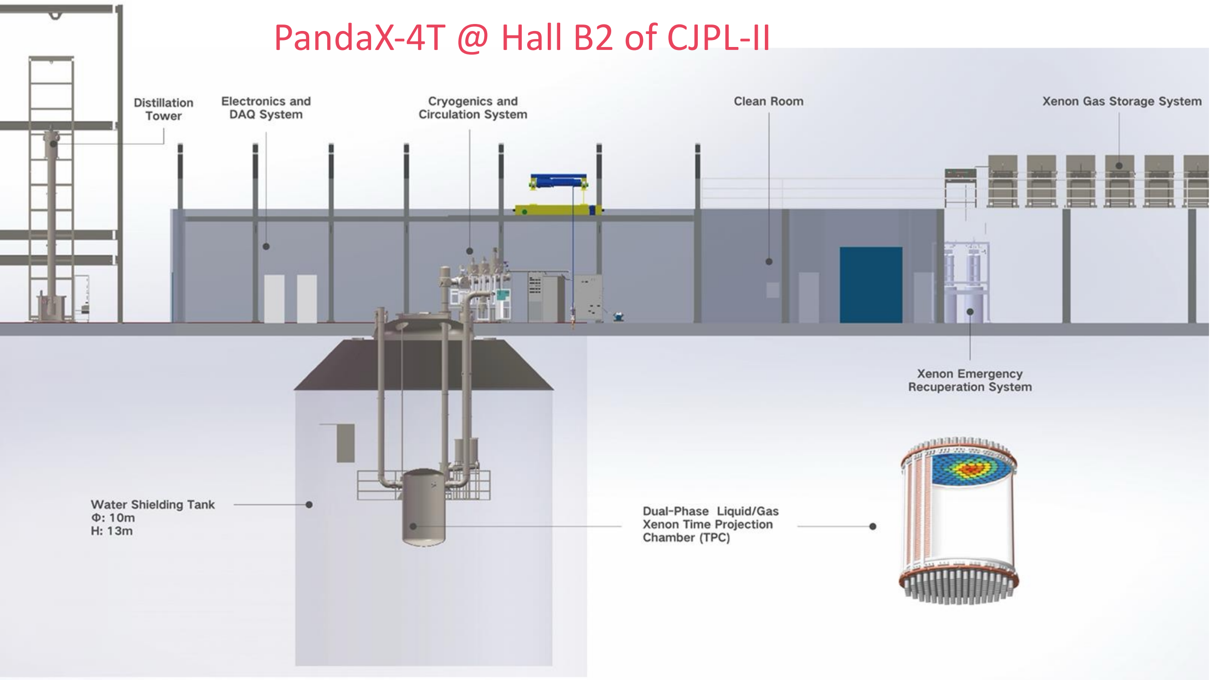


CJPL-II



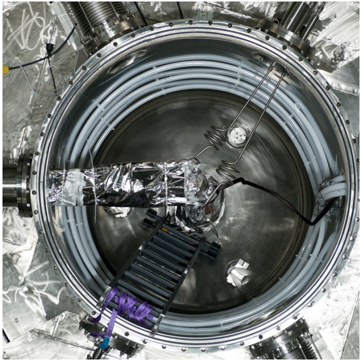
Auxiliary gate no. 2
No. 1 gateway
No. 2 auxiliary tunnel
Service tunnel A
No. 2 gateway
A1
A2
Hall A
Connecting tunnel AB
B3
B1
B4
Service tunnel B
Middle connecting tunnel
Auxiliary gate no. 1
B2
Hall B
C1
Service tunnel C
C2
No. 1 auxiliary tunnel
Hall C
Drainage tunnel
Traffic tunnel B
Traffic tunnel A
D1
Service tunnel D
Connecting tunnel CD
D2
Hall D
Auxiliary tunnel
Traffic tunnel
Drainage tunnel
Each experimental hall measures
14 m (H) × 14 m (W) × 130 m (L)

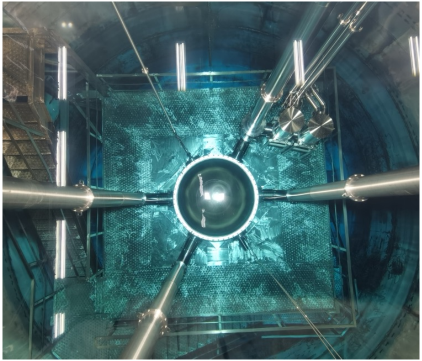
PandaX-4T @ Hall B2 of CJPL-II



PandaX-4T

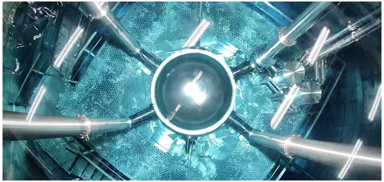
- A multi-ton dual-phase xenon TPC at B2 hall of China Jinping Underground Laboratory
- 1.2 m (D) ×1.2 m (H); Sensitive volume: 3.7-ton LXe; 3-inch PMTs: 169 top / 199 bottom
- Water shielding





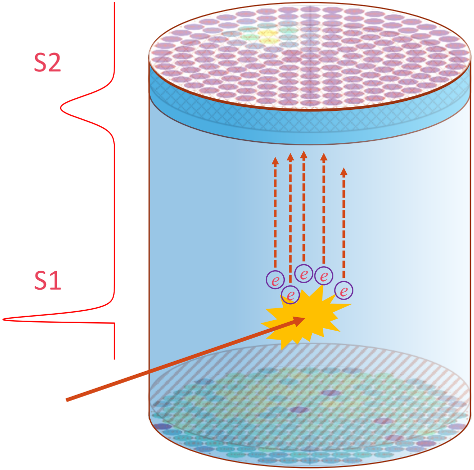
PandaX-4T timeline

2020/11 – 2021/04	**Commissioning (Run 0)** 95 days data
2021/07 – 2021/10	**Tritium removal** xenon distillation, gas flushing, etc.
2021/11 – 2022/05	**Physics run (Run 1)** 164 days data
2022/09 – 2023/12	**CJPL B2 hall construction** xenon recuperation, detector upgrade
Detector is taking Run 2 data	



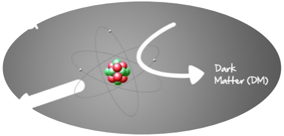
Liquid Xenon Time Projection Chamber (LXe TPC)

- Prompt scintillation signal (S1) followed by drift electron signal (S2)
- Measures the 3D position, energy, and time
- Nuclear Recoil (NR) and electron recoil (ER) discrimination
- Single-site (SS) and multi-site (MS) event discrimination
- Large monolithic target: High signal efficiency and effective self-shielding



- LXe TPC as a Total-Absorption 5D Calorimeter

Multiple physics goals in one detector

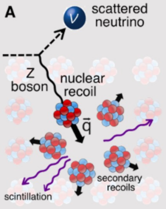


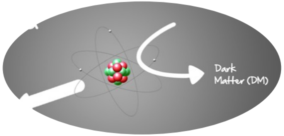
keV | 10 keV | 100 keV | 1 MeV

WIMP signals

- Large target mass
- Great energy threshold
- NR and ER discrimination

Multiple physics goals in one detector





keV — 10 keV — 100 keV — 1 MeV

CEνNS (NR)

- Large target mass
- Better energy threshold
- NR and ER discrimination

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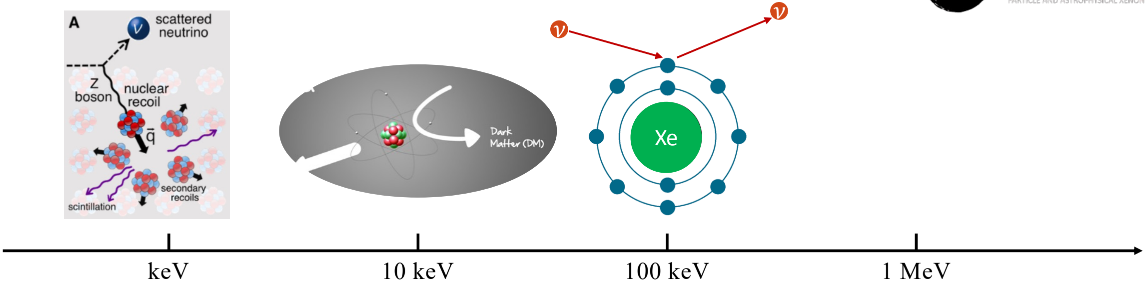

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Neutrino-electron scattering

- Large target mass
- Energy threshold and resolution

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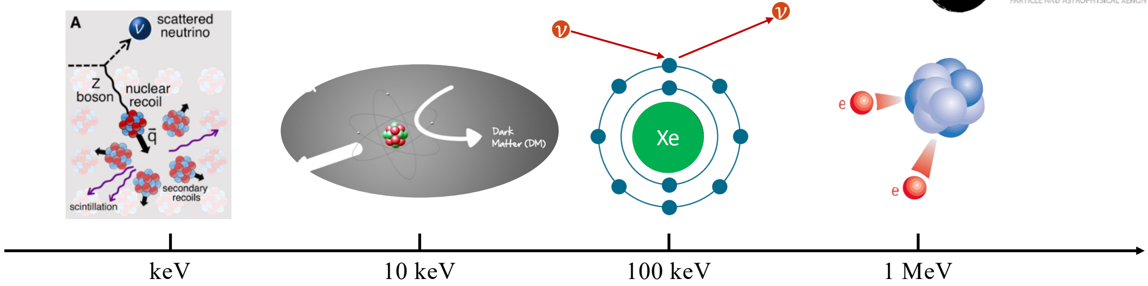

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Neutrino-electron scattering

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Double beta decay

- Large target mass
- Excellent energy resolution
- Single vs multiple site event

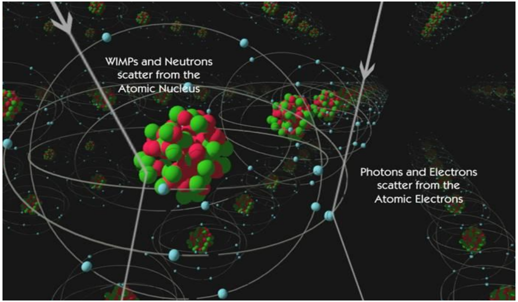
Detecting a possible DM particle

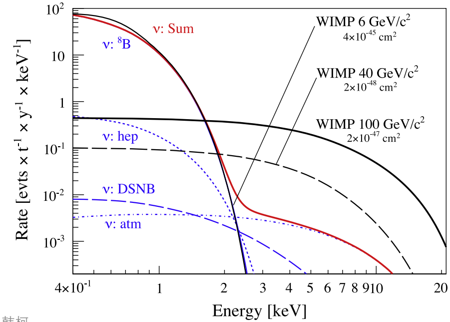
PHYSICAL REVIEW D VOLUME 31, NUMBER 12 15 JUNE 1985

Detectability of certain dark-matter candidates

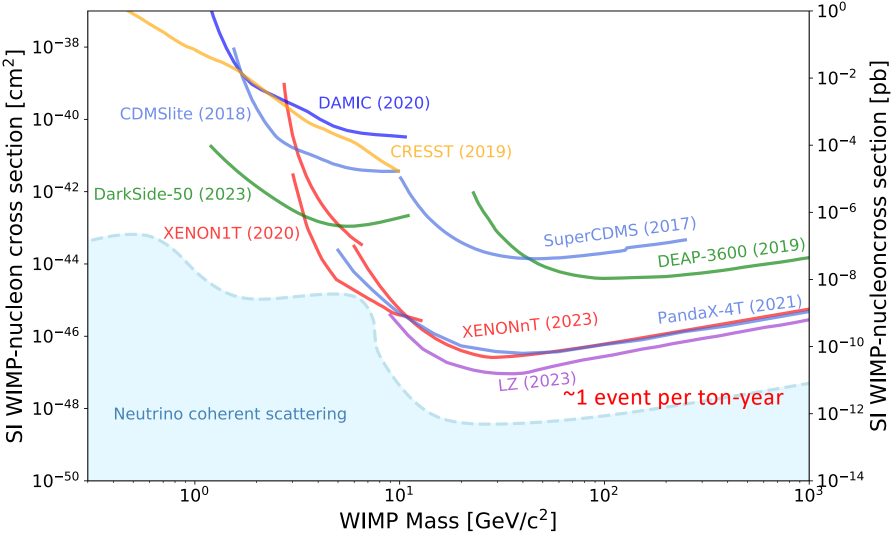
Mark W. Goodman and Edward Witten
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08544
(Received 7 January 1985)

We consider the possibility that the neutral-current neutrino detector recently proposed by Drukier and Stodolsky could be used to detect some possible candidates for the dark matter in galactic halos. This may be feasible if the galactic halos are made of particles with coherent weak interactions and masses $1-10^6$ GeV; particles with spin-dependent interactions of typical weak strength and masses $1-10^2$ GeV; or strongly interacting particles of masses $1-10^{13}$ GeV.





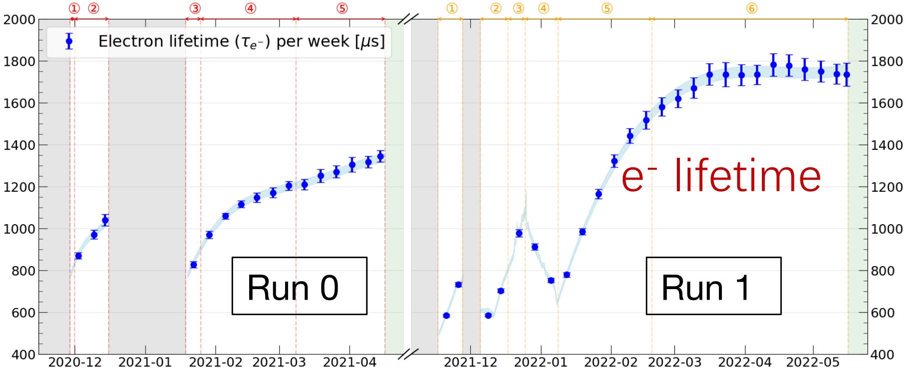
Current landscape



PDG 2024

PandaX-4T Summer 2024 data release (Run 0+Run 1)

- Run 1: Gate -6kV, Cathode -16kV (Gate trip once)
- Updated detector response and background budgets

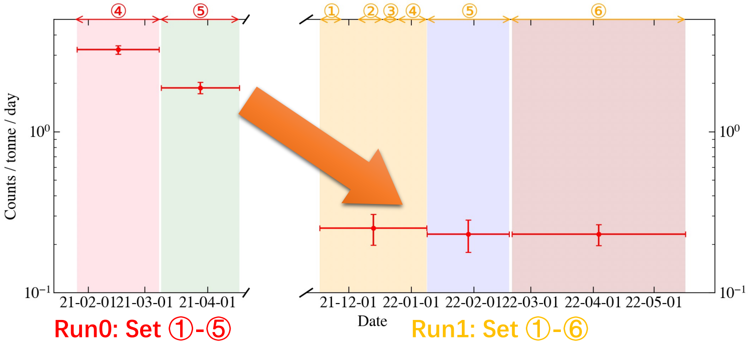


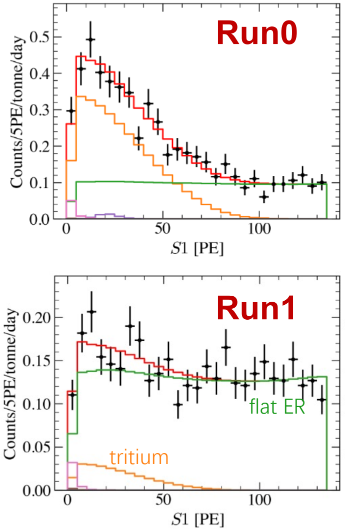
arXiv:2408.00664

Major improvement

PANDA X
PARTICLE AND ASTROPHYSICAL XENON TPC

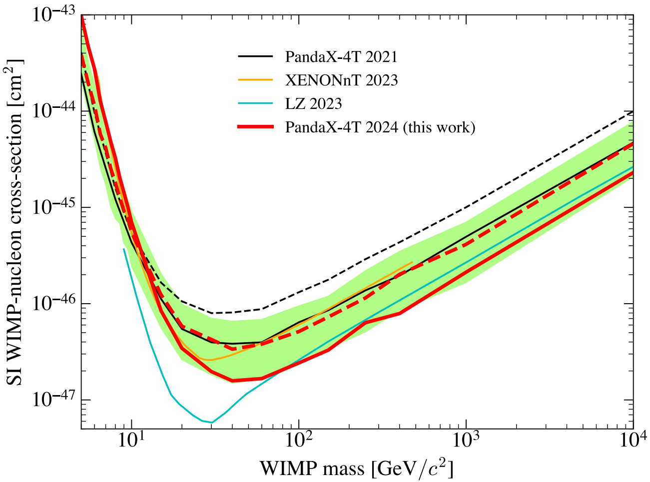
- Significant reduction from Run0 to Run1 (~8 times)
- Consistent with S1-only estimation used before unblinding



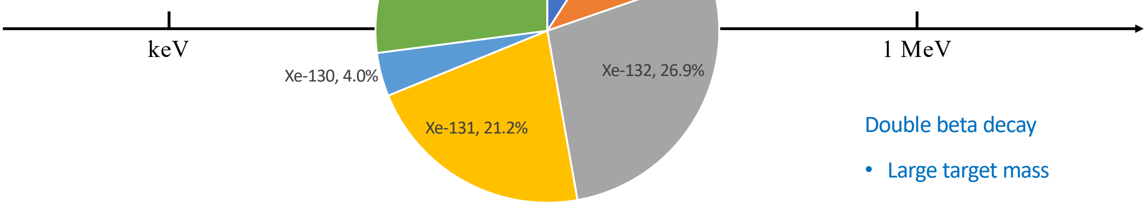


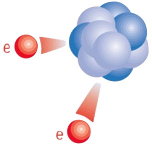
Most recent DM result

- Fully blind analysis Run0+Run1: Scanning WIMP mass from 5 to 10000 GeV/c^2
- No significant excess!
- State-of-the-art: >100 GeV/c^2
- Lowest upper limit: 1.6×10^{-47} cm^2 at 40 GeV/c^2 after -1σ power-constraint
- arXiv:2408.00664



Multiple physics goals in one detector



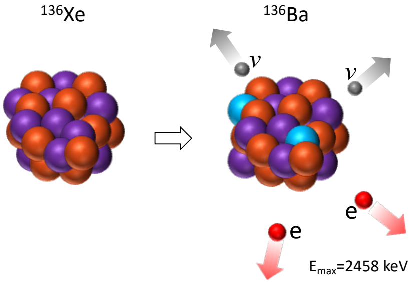


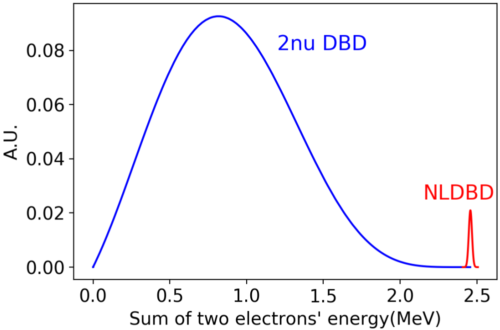
Double beta decay

- Large target mass
- Excellent energy resolution
- Single vs multiple site event

Neutrinoless Double beta decay (NLDBD)

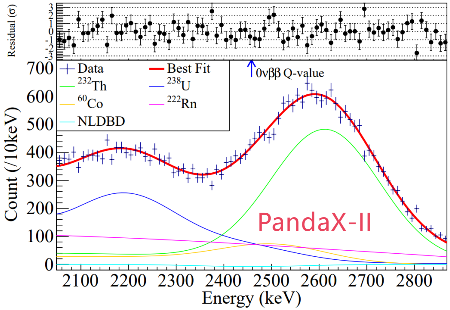
- Neutrinoless double beta decay probes the nature of neutrinos: Majorana or Dirac
- Lepton number violating process
- Measure energies of emitted electrons

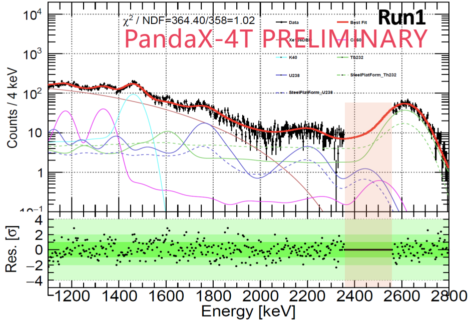




Search for ^{136}Xe $0\nu\beta\beta$ with LXe TPC

	Bkg rate (/keV/ton/y)	Energy resolution	FV mass (kg)	Run time	Sensitivity/Limit (90% CL, year)	Year
PandaX-II	~200	4.2%	219	403.1 days	2.4×10^{23}	2019
XENON1T	~20	0.8%	741	202.7 days	1.2×10^{24}	2022
PandaX-4T	6	1.9%	~650	~250 days	$> 10^{24}$	Expeted soon





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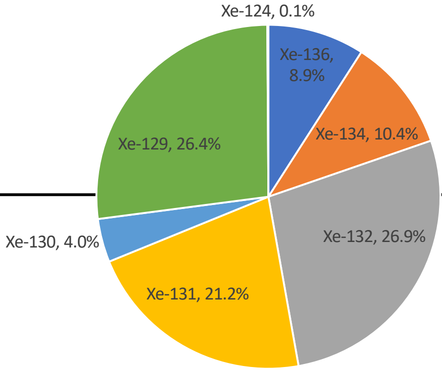

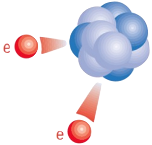

Double beta decay

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- Excellent energy resolution
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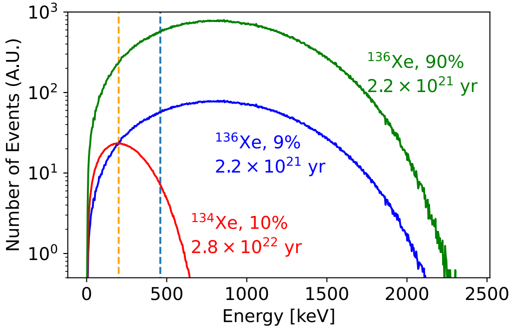
^{134}Xe (0)2νββ searches at PandaX-4T

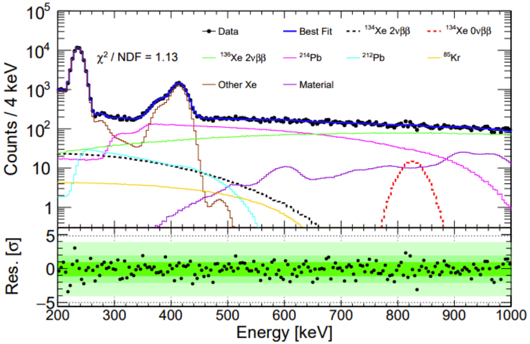
- Q=826 keV; Half-life from theoretical predictions: 10^{24}-10^{25} yr; Never been observed
- Previous 2νββ (0νββ) half-life limit from EXO-200 : T >8.7×10^{20} yr (1.1×10^{23} yr) at 90% CL
- PandaX-4T: more ^{134}Xe; much less ^{136}Xe; wider energy range; discovery possible

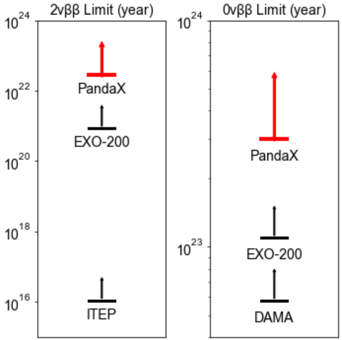
	PandaX-4T	EXO-200
^{134}Xe mass	68.7 kg	18.1 kg
^{136}Xe abundance	8.90%	81%
Analysis threshold	200 keV	460 keV
Live Time	94.9 days	600 days



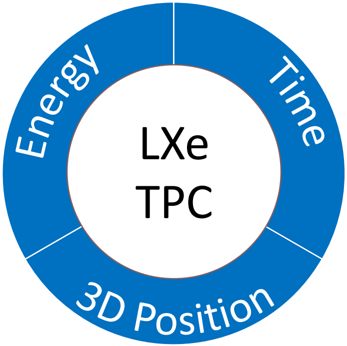
^{134}Xe half-life limits @ PandaX-4T

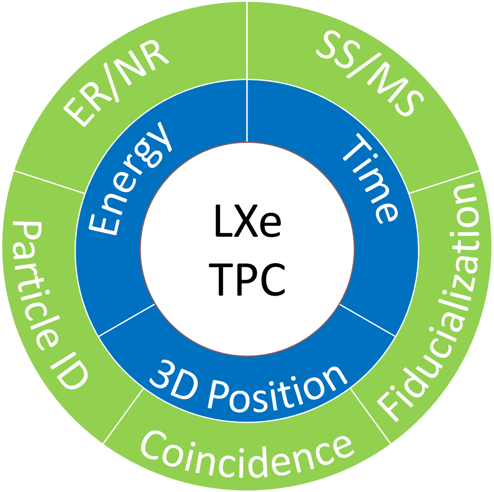
- Simultaneous fit for ^{134}Xe $2\nu\beta\beta$ and $0\nu\beta\beta$
- Final counts of $2\nu\beta\beta$ and $0\nu\beta\beta$: 10±269(stat.)±680(syst.) and 105±48(stat.)±38(syst.)
- 90% CL lower limits on the half-life: $T_{1/2}^{2\nu\beta\beta} > 2.8 \cdot 10^{22}$ yr and $T_{1/2}^{0\nu\beta\beta} >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

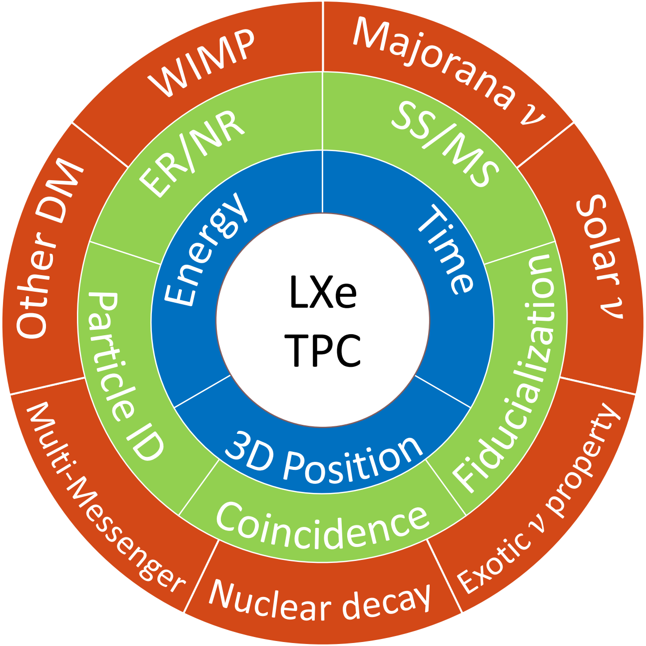


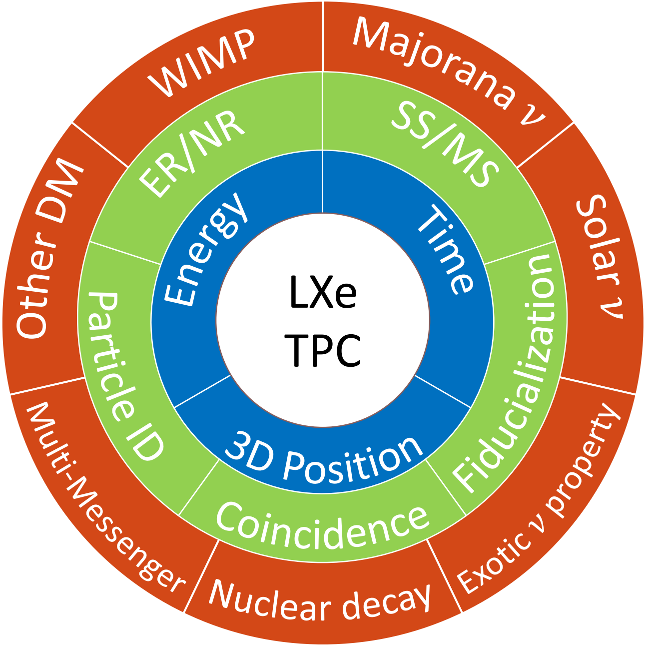


PandaX, Phys.Rev.Lett. 132 (2024) 15, 152502


LXe
TPC
Energy
Time
3D Position


LXe
TPC
Energy
Time
3D Position
ER/NR
SS/MS
Fiducialization
Coincidence
Particle ID

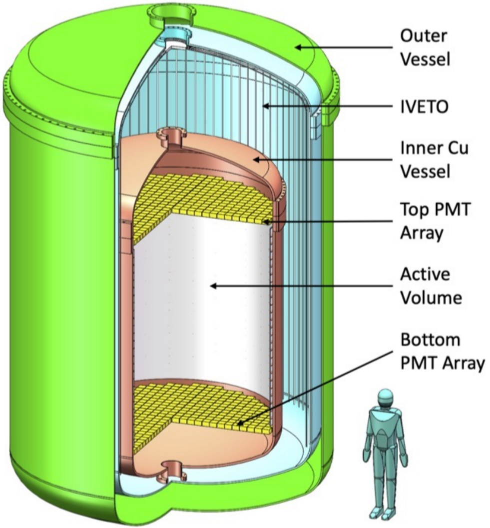

LXe
TPC
Energy
Time
3D Position
ER/NR
SS/MS
Fiducialization
Coincidence
Particle ID
WIMP
Majorana ν
Solar ν
Exotic ν property
Nuclear decay
Multi-Messenger
Other DM



+ Larger Cleaner Detector

PandaX-xT: Multi-ten-tonne Liquid Xenon Observatory

- Active target: 43 tons of Xenon
  - Test the WIMP paradigm to the neutrino floor
  - Explore the Dirac/Majorana nature of neutrino
  - Search for astrophysical or terrestrial neutrinos and other ultra-rare interactions
- Notable detector improvements:
  - High-granularity, low-background 2-in PMT array
  - Cu/Ti vessel for improved radiopurity
  - Inner liquid scintillator veto



arXiv:2402.03596

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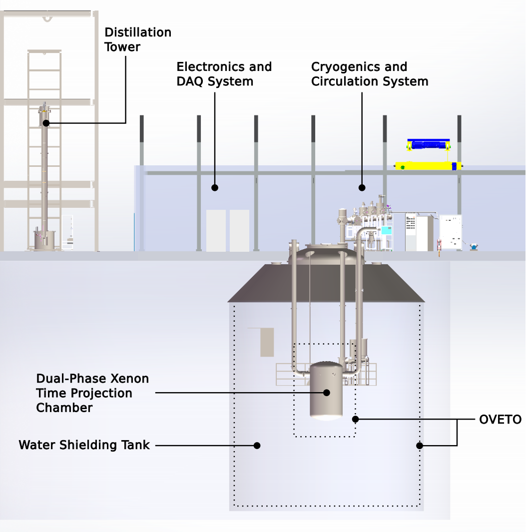
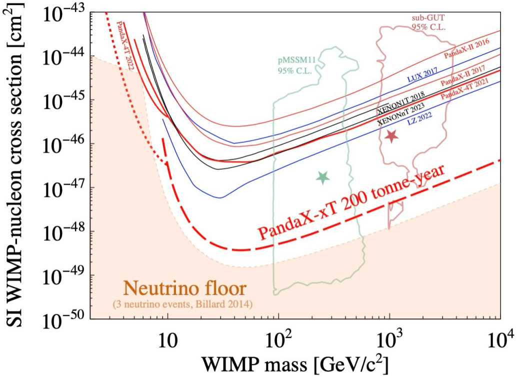


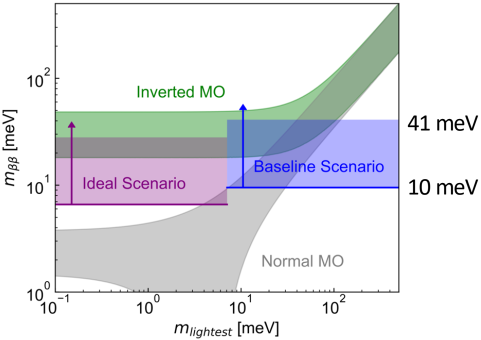
arXiv:2402.03596

PandaX-xT physics

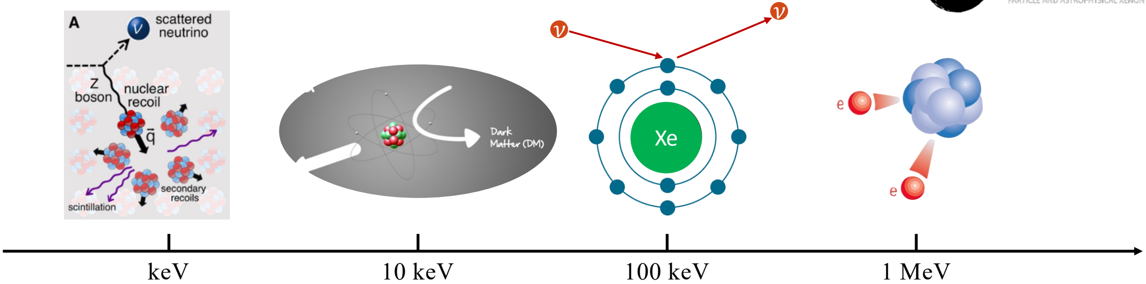
- WIMP search FV mass: 34 tons
- 99.7% ER rejection power and a 50% NR acceptance

- 4 ton of ^{136}Xe: one of the largest $0\nu\beta\beta$ experiments
- Effective self-shielding: Xenon-related background dominates in the 8.4-tonne center FV





Multiple physics goals in one detector

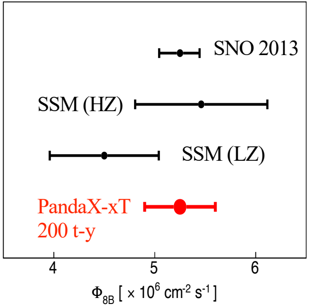


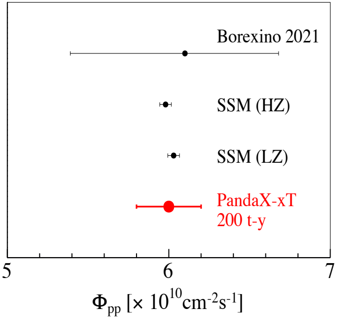
- LXe TPC as a Total-Absorption 5D Calorimeter is a powerful tool
- Fully exploit the entire energy range of LXe TPC for rich physics in dark matter and neutrino physics

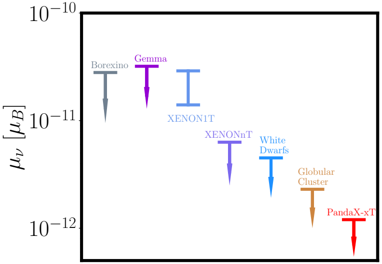

PANDA X
PARTICLE AND ASTROPHYSICAL XENON TPC
Thank you very much
We welcome new collaborators
at PandaX-xT

Competitive in other neutrino physics topics as well

- Coherent scattering of solar ^{8}B neutrino: from a first observation in LXe TPC to precision measurement
- Electron scattering of solar pp neutrino: competitive precision at a wider energy range
- Neutrinos with abnormal magnetic moments: a better sensitivity than astrophysical observations







arXiv:2402.03596

Head-to-head with other DM/0νββ experiments

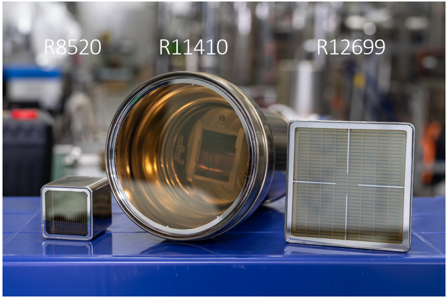
	Bkg rate (/keV/ton/y)	Energy resolution	Mass (ton)	Run time	Sensitivity/Limit (90% CL, year)
PandaX-4T	6	1.9%	4	94.9 days	$> 10^{24}$
XENONnT	1	0.8%	6	1000 days (expected)	2×10^{25}
LZ	0.3	1%	7	1000 days (expected)	1×10^{26}
KamLAND-ZEN	0.002	5%	0.8 (^{136}Xe)	1.5 years	2.3×10^{26}
nEXO	0.006	1%	5 (^{136}Xe)	10 years	1.35×10^{28} **
DARWIN	0.004*	0.8%	40	10 years	2×10^{27}
PandaX-xT	0.002*	1%	43	10 years	3×10^{27}

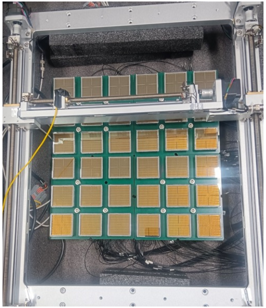
* Major difference from cosmogenic ^{137}Xe; ** $\frac{S}{\sqrt{B}}$ sensitivity is 6×10^{27} yr, for detector performance comparison in the table.

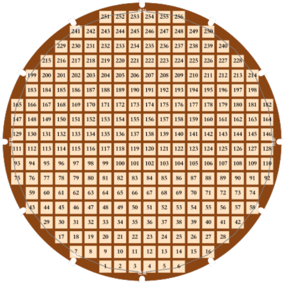
New 2” multi-anode R12699 PMT for LXe TPC

PANDA X
PARTICLE AND ASTROPHYSICAL XENON TPC

- Higher granularity while maintaining low dark noise: best of both large PMT and SiPM
  - Improved position reconstruction for better event topology
  - 2” array has an effectively wider dynamic range for DM and DBD simultaneously
  - Faster timing for possible pulse shape analysis or Cerenkov/Scintillation separation
- Collaboration between PandaX and Hamamatsu for a low-radioactivity version of R12699



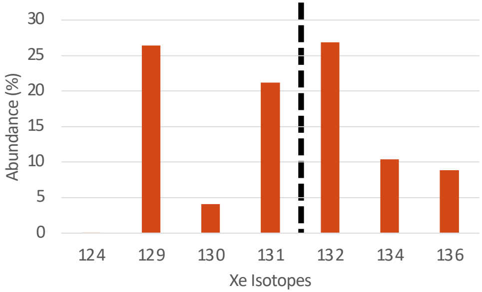


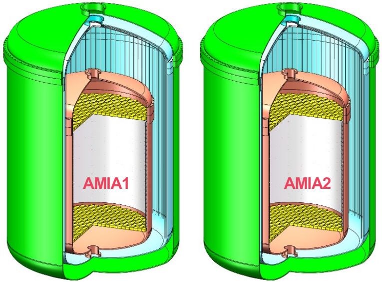


Conceptual array for a PandaX-4T-sized TPC

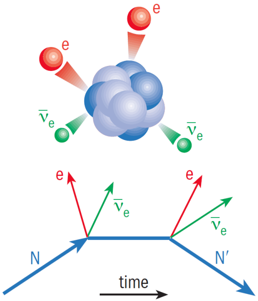
Possible isotope seperation/enrichment

- Xenon with artificially modified isotopic abundance (AMIA) for smoking gun discovery
  - A split of odd and even nuclei
  - Further enrichment of ^{136}Xe
  - to improve sensitivity to spin-dependence of DM-nucleon interactions and 0νββ

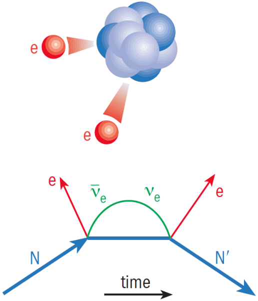




Majorana neutrino and Double beta decay



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



From Physics World

1935, Goeppert-Mayer
Two-Neutrino double beta decay

1937, Majorana
Majorana Neutrino

1939, Furry
Neutrinoless double beta decay

1930, Pauli
Idea of neutrino

1933, Fermi
Beta decay theory

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

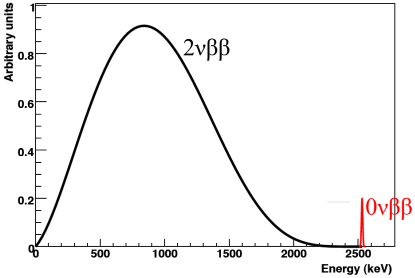
Detection of double beta decay

- Examples:

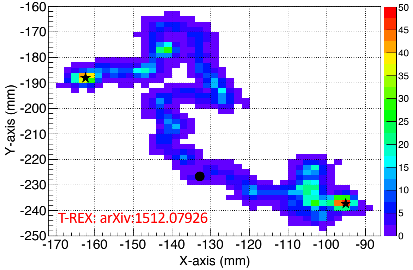
$$^{136}_{54}Xe \rightarrow ^{136}_{56}Ba + 2e^- + (2\bar{\upsilon})$$

$$^{130}_{52}Te \rightarrow ^{130}_{54}Xe + 2e^- + (2\bar{\upsilon})$$

- 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

Extremely slow process

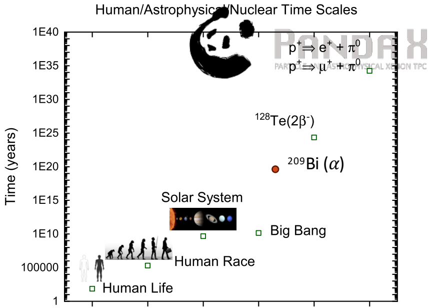
- 2νββ: Second-order weak interaction; half-life ~ 10^{20} yr
- Sensitivity of next-generation 0νββ experiment: 10^{27}yr
  - Ton-scale experiment ~ 1 signal per year

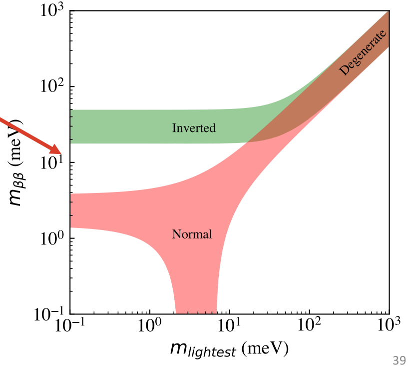
Half life sensitivity $\propto \eta \cdot \epsilon \sqrt{\frac{M \cdot t}{b \cdot \delta E}}$

Isotopic abundance | Detecting efficiency | Detector mass | Background rate | Energy resolution | Measuring time

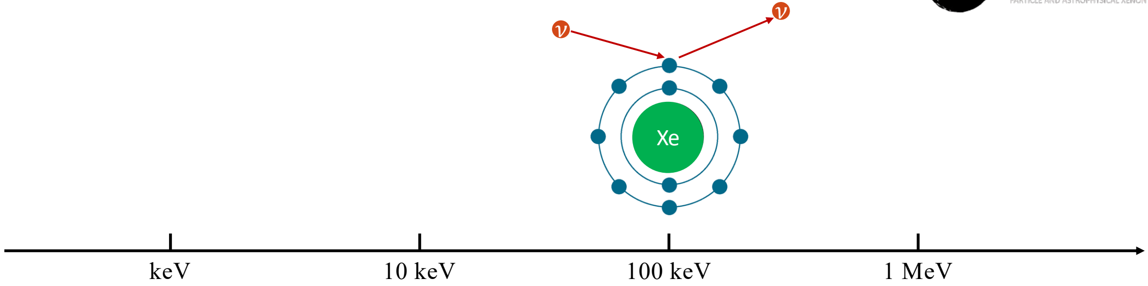
$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}(Q,Z)\,|M^{0\nu}|^2 \frac{|\langle m_{\beta\beta}\rangle|^2}{m_e^2}$$

Phase space factor **Nuclear matrix element**





Multiple physics goals in one detector

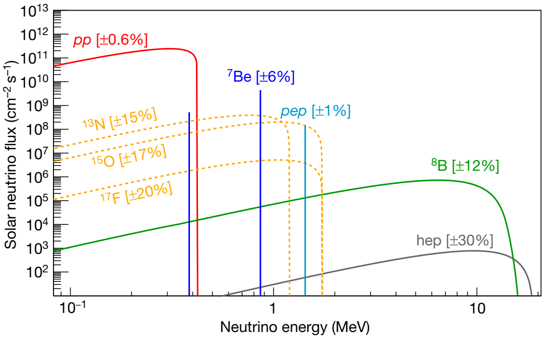


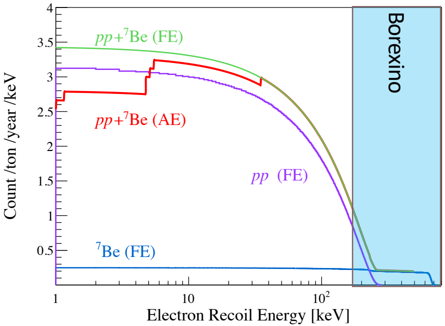
Neutrino-electron scattering

- Large target mass
- Energy threshold and resolution

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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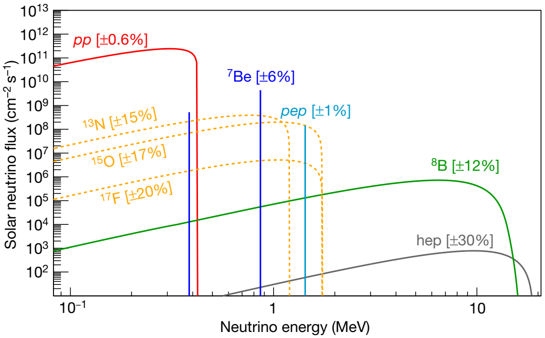
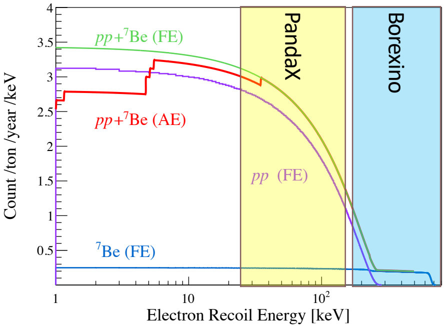
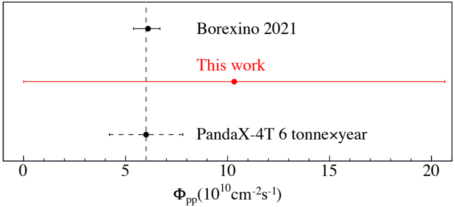


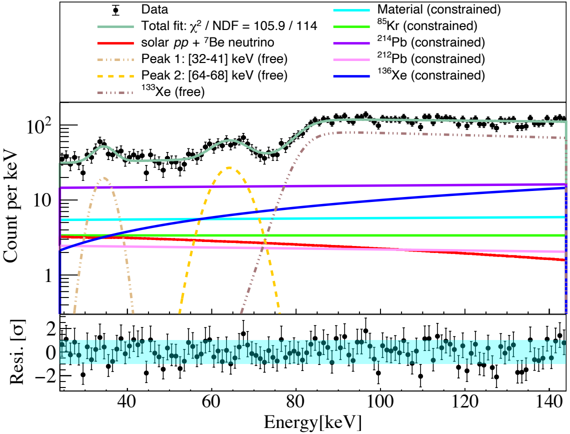


PandaX-4T result

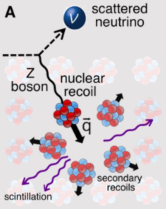
- The first solar pp neutrino measurement in recoil energy from 24 to 144 keV with 0.63-tonne × year of PandaX-4T Run 0 exposure
- Consistent with Standard Solar Model and existing measurements.

CPC 48 091001 (2024)/ArXiv: 2401.07045

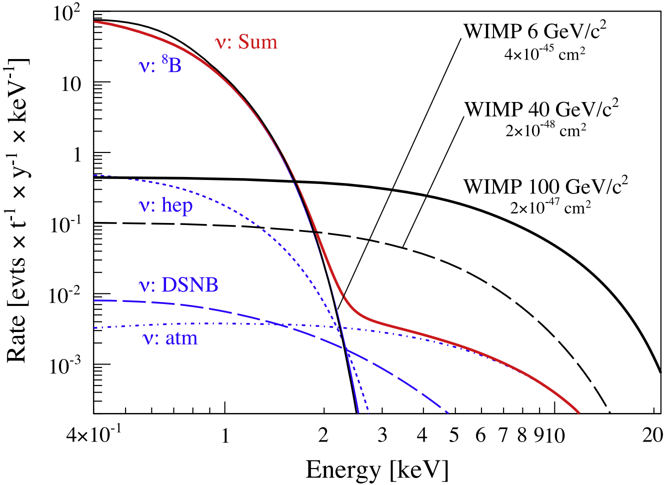




Multiple physics goals in one detector



keV 10 keV

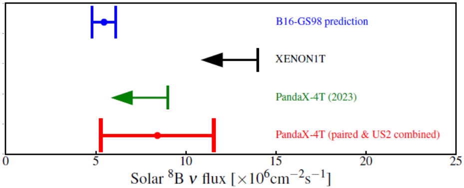


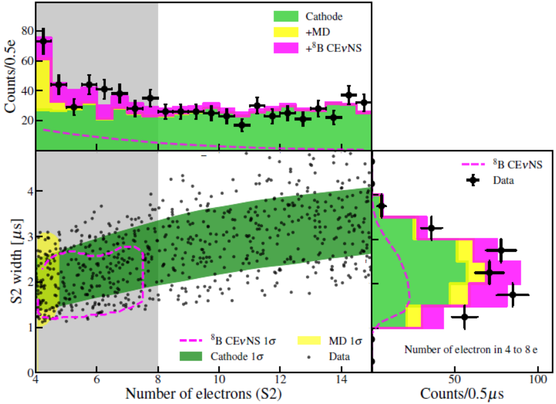
CEνNS (NR)

- Large target mass
- Better energy threshold
- NR and ER discrimination

First indication of solar ^{8}B neutrino CEνNS

- 1.5 tonne-year exposure
- (S1+S2) and (S2-only) data combined
- 2.64 σ!
- Announced on 2024/7/8 at IDM2024; 7/15 to arXiv and PRL

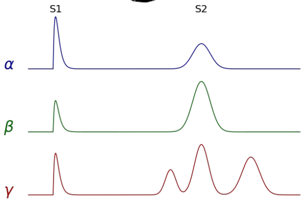


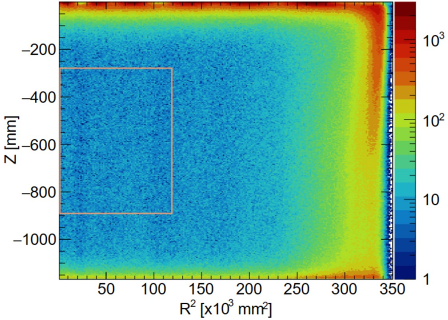


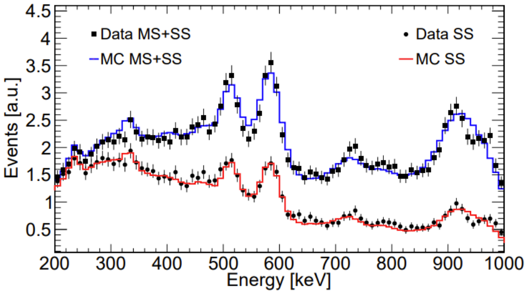
国际竞争：XENONnT 2.73 σ, 7/10 IDM公布，8/6 arXiv

Data selection

- An identical FV as in ^{136}Xe analysis, total isotopic exposure: 17.9 kg·yr
- Single site vs multi-site selection measured by ^{232}Th calibration data
  - Little impact to DBD signals (β SS events)





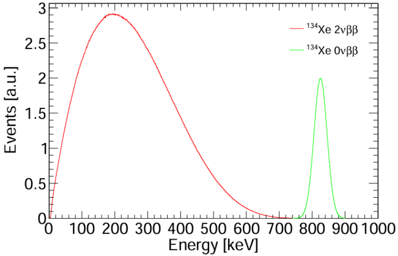


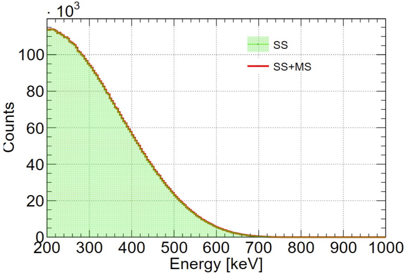
PandaX, Phys.Rev.Lett. 132 (2024) 15, 152502

Signal efficiencies

- ^{134}Xe $2\nu\beta\beta$ and $0\nu\beta\beta$ events generated with the theoretical calculation
- The signal events went through PandaX-4T simulation and data processing chain

- ROI [200,1000]keV cut:
  - $2\nu\beta\beta$: 60.56%
  - $0\nu\beta\beta$: 99.98%
- SS ratio in ROI:
  - $2\nu\beta\beta$: 99.89%
  - $0\nu\beta\beta$: 98.23%





Physical Review C 85, 034316 **(2012)**

Background model

	Component	Input Counts	Constraint	
	^{60}Co	130	13%	
Materials	^{40}K	133	8%	
	^{232}Th	950	5%	Measured in ^{136}Xe $2\nu\beta\beta$ analysis *Research* 2022 (2022) 9798721
	^{238}U	274	8%	
	^{136}Xe	12372	5%	
	^{212}Pb	1012	29%	Measured by its daughter ^{212}Po alpha decay
	^{85}Kr	296	52%	Determined by β−γ emission through the metastable state ^{85m}Rb
LXe	^{133}Xe	3423	10%	Estimated the β+γ shoulder of ^{133}Xe between 90 and 120 keV
	^{214}Pb	19429	Free	Determined by ^{222}Rn
	^{125}Xe	-	Free	short-lived xenon isotopes induced by neutron calibration
	Other Xe	-	Free	^{127}Xe and ^{129m}Xe