PandaX Dark Matter and Neutrinoless Double Beta Decay Programs

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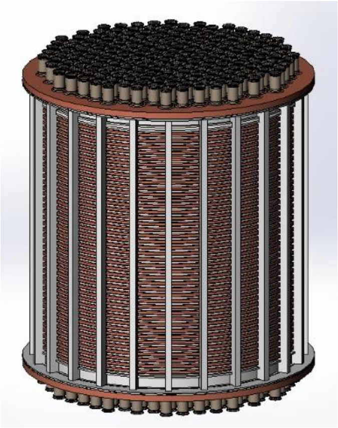
On Behalf of the PandaX Collaboration

PandaX: Particle and Astrophysical Xenon TPC

PandaX-I: 120kg LXe
(2009 – 2014)

PandaX-II: 500kg LXe
(2014 – 2018)

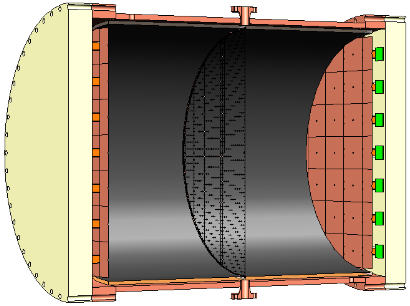


PandaX-xT LXe
(Future)

Dark matter WIMP searches

Exploring the invisible Universe from deep underground

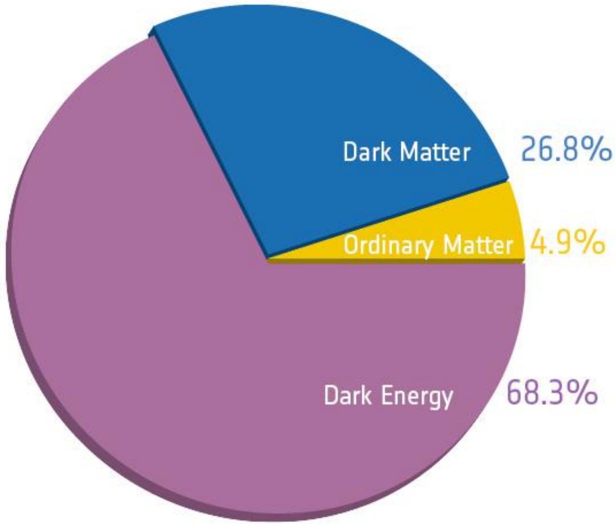
- Physics beyond the Standard Model.
- Interconnects particle physics, nuclear physics, cosmology, and astrophysics.

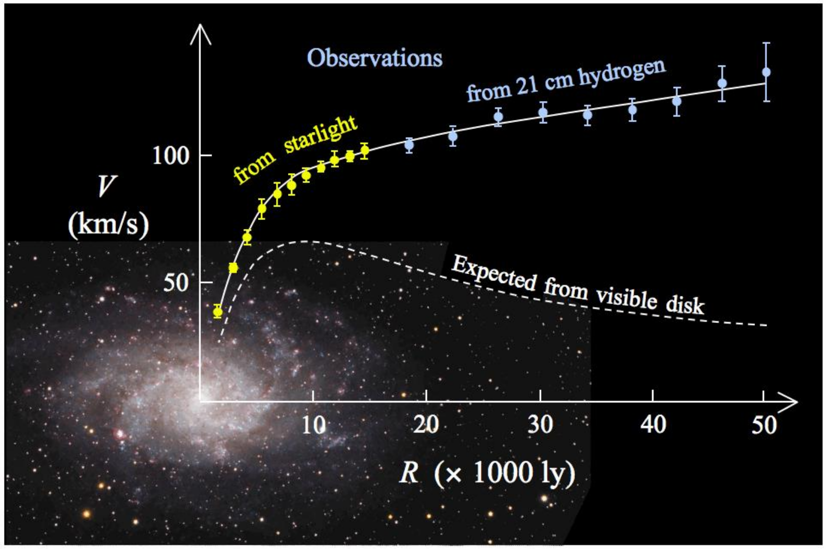


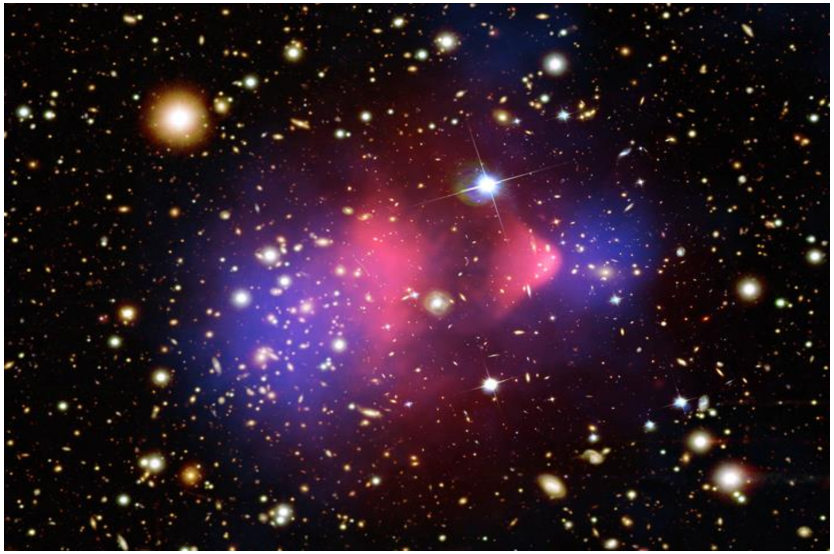
$0\nu\beta\beta$ searches

PandaX-III:
200kg - 1 ton HPXe (Future)

Dark Matter

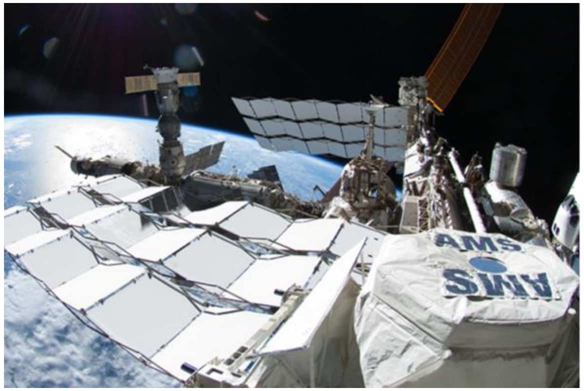


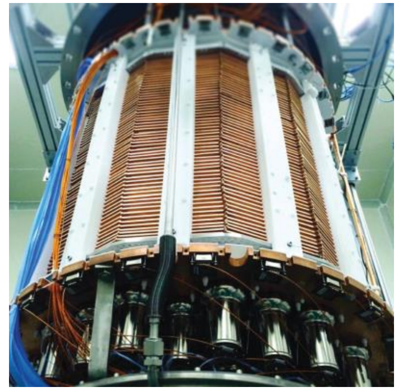


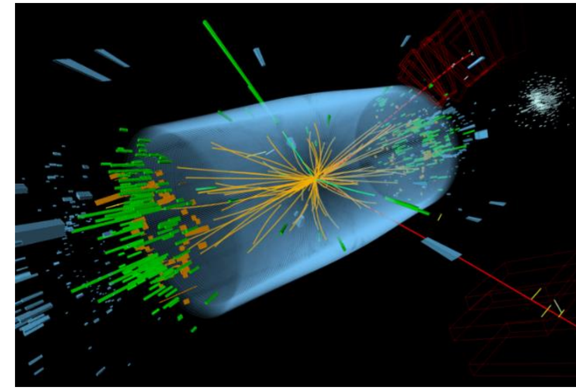


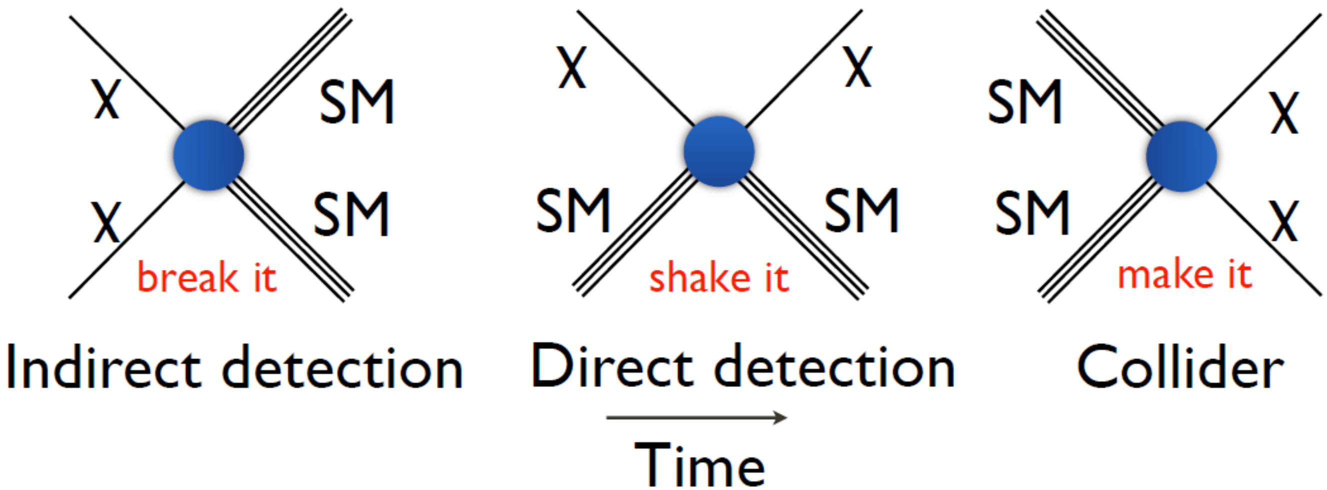
- Existence of dark matter is firmly established
- Particle nature of dark matter?
  - WIMP?

WIMP searches





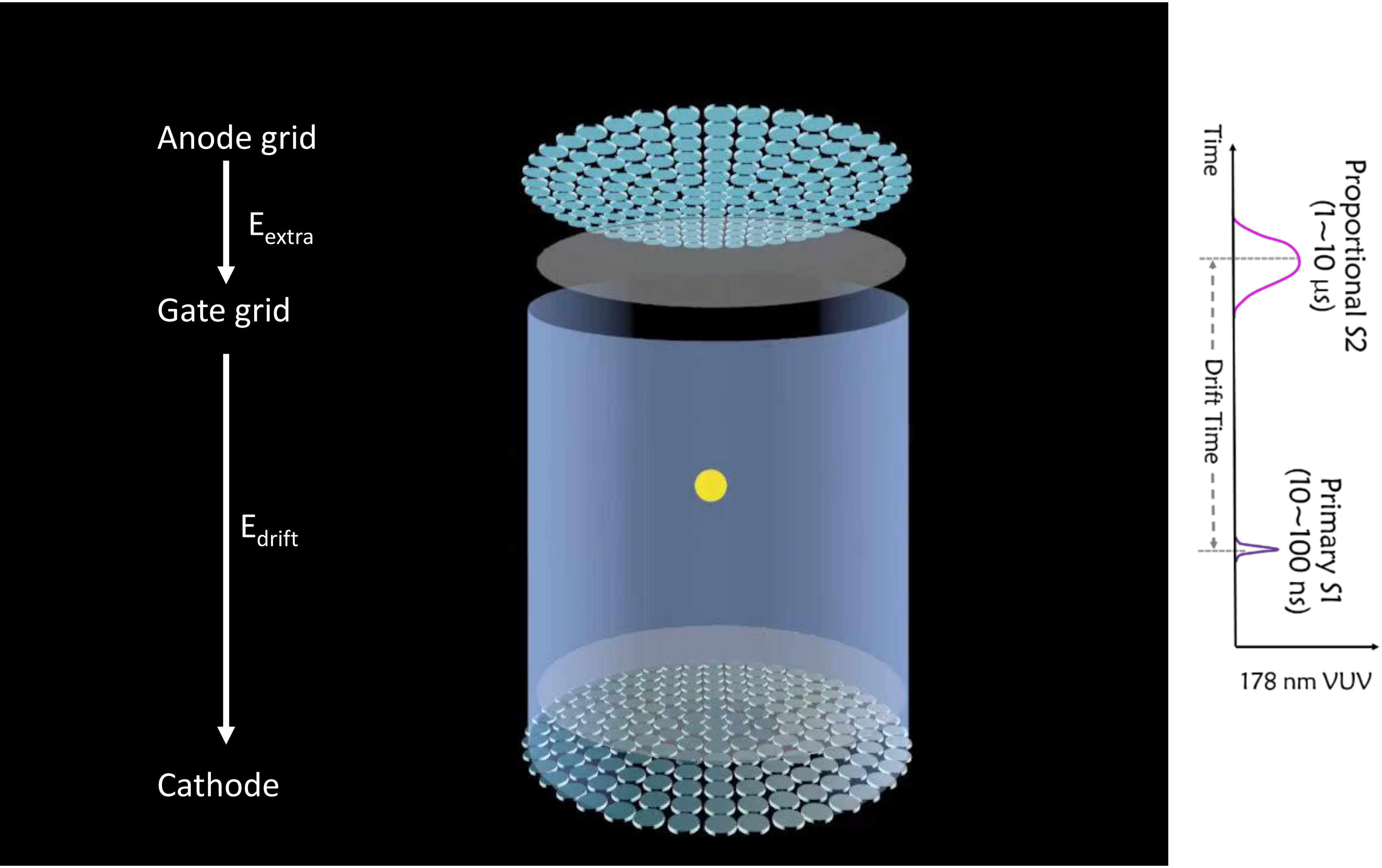




Tracy Slatyer

Direct detection: DM: velocity ~1/1500 c, mass ~100 GeV, KE ~ 20 keV
Nuclear recoil (NR): recoiling energy ~10 keV

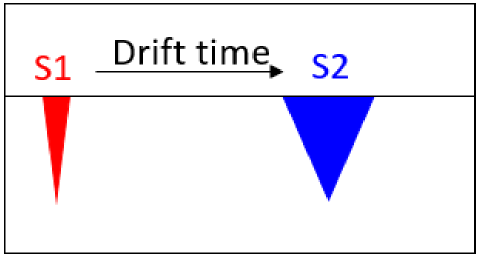
Dual phrase Xe TPC for dark matter



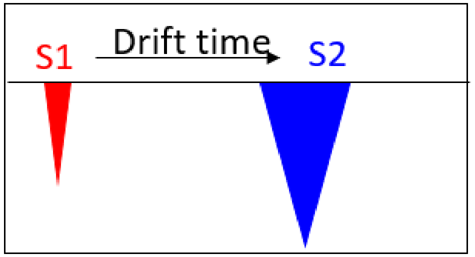
PandaX WIMP direct detection

- **PandaX-I**: 2009-2014
- **PandaX-II**: 2014-2018
  - 60 cm x 60 cm dual-phase xenon TPC
  - 580 kg LXe in sensitive volume
- Dual-phase xenon detectors:
  - Large monolithic target
  - 3D reconstruction and fiducialization
  - Good ER/NR rejection
  - Calorimeter capable of seeing a couple of photons/electrons

Dark matter: nuclear recoil (NR)



γ background: electron recoil (ER)



$(S2/S1)_{NR} << (S2/S1)_{ER}$

Phase I: 120 kg
2009-2014

Phase II: 580 kg
2014-2018

PandaX-II Run Status

- Run9 =79.6 days, exposure: 26.2 ton-day
- Run10 = 77.1 days, exposure: 27.9 ton-day

Nov. 22 – Dec. 14, Physics commission (Run8, 19.1 days, stopped due to high Krypton background)

Mar. 9 – June 30, low background with 10-fold reduction of Kr (Run9, 79.6 days)

Jul – Oct, ER calibration & tritium removal

Nov. 2016 – Mar. 2017, 2nd distillation campaign and recommissioning

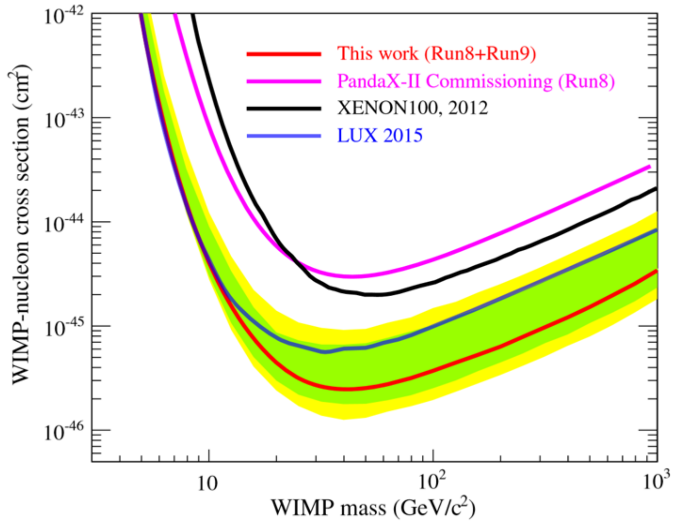
Apr.22 – July15, dark matter data taking (Run10, 77.1 days)

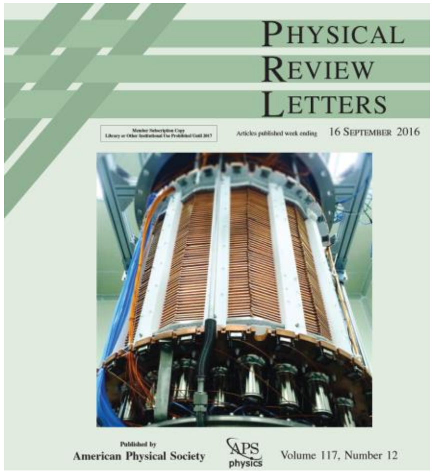
Jul. 2017-Now, a few months ^{220}Rn/AmBe runs, followed by DM data taking, 3x stat of Run10

Highlights of PandaX-II Results

PANDA X PARTICLE AND ASTROPHYSICAL XENON TPC

- 33 ton-day: spin independent search, **PRL 117, 121303 (2016)**

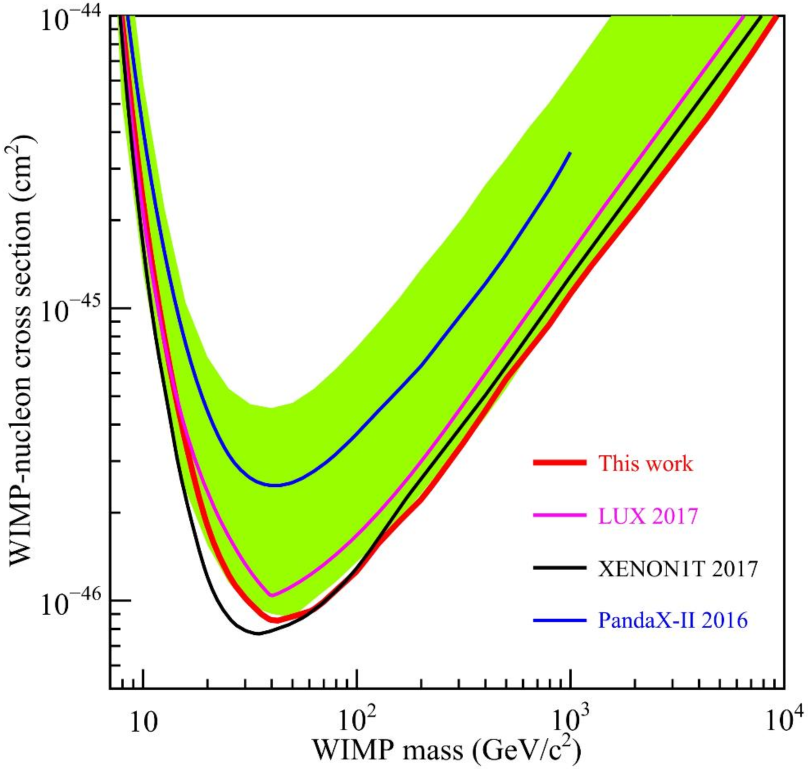


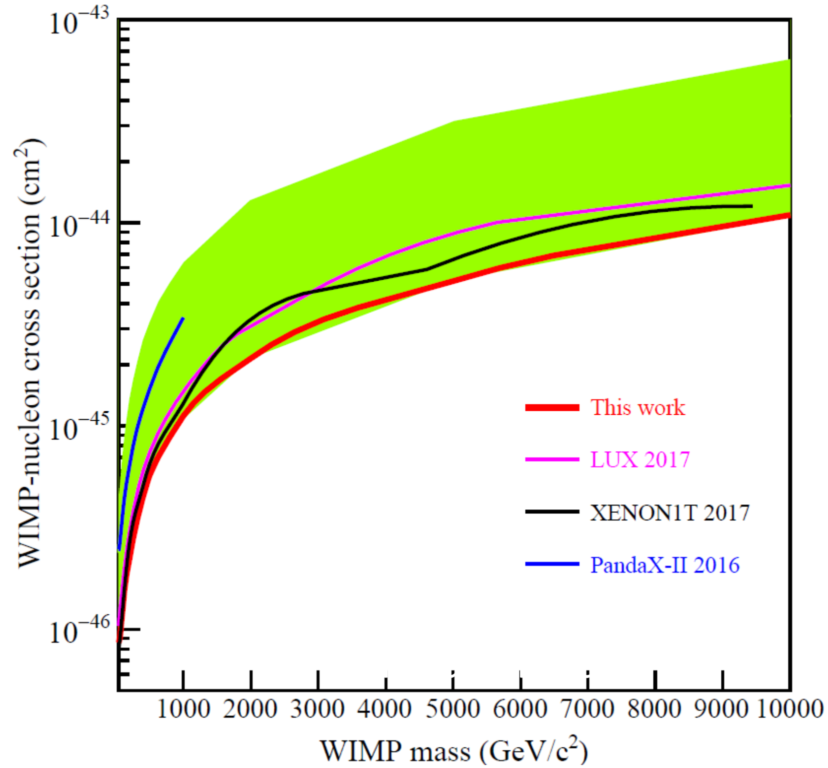


- 33 ton-day: spin dependent search, **PRL 118, 071301 (2017)**
- 27 ton-day: inelastic scattering search, **PRD 96, 102007 (2017)**
- 27 ton-day: Axion and ALP search, **PRL 119, 181806 (2017)**
- 54 ton-day: spin independent search, **PRL 119, 181302 (2017)**
- 54 ton-day: light mediator search, **PRL 121, 021304 (2018)**
- 54 ton-day: general EFT and spin-dependent search, **arXiv:1807.01936**

WIMP-nucleon SI result update

PRL 119, 181302 (2017)

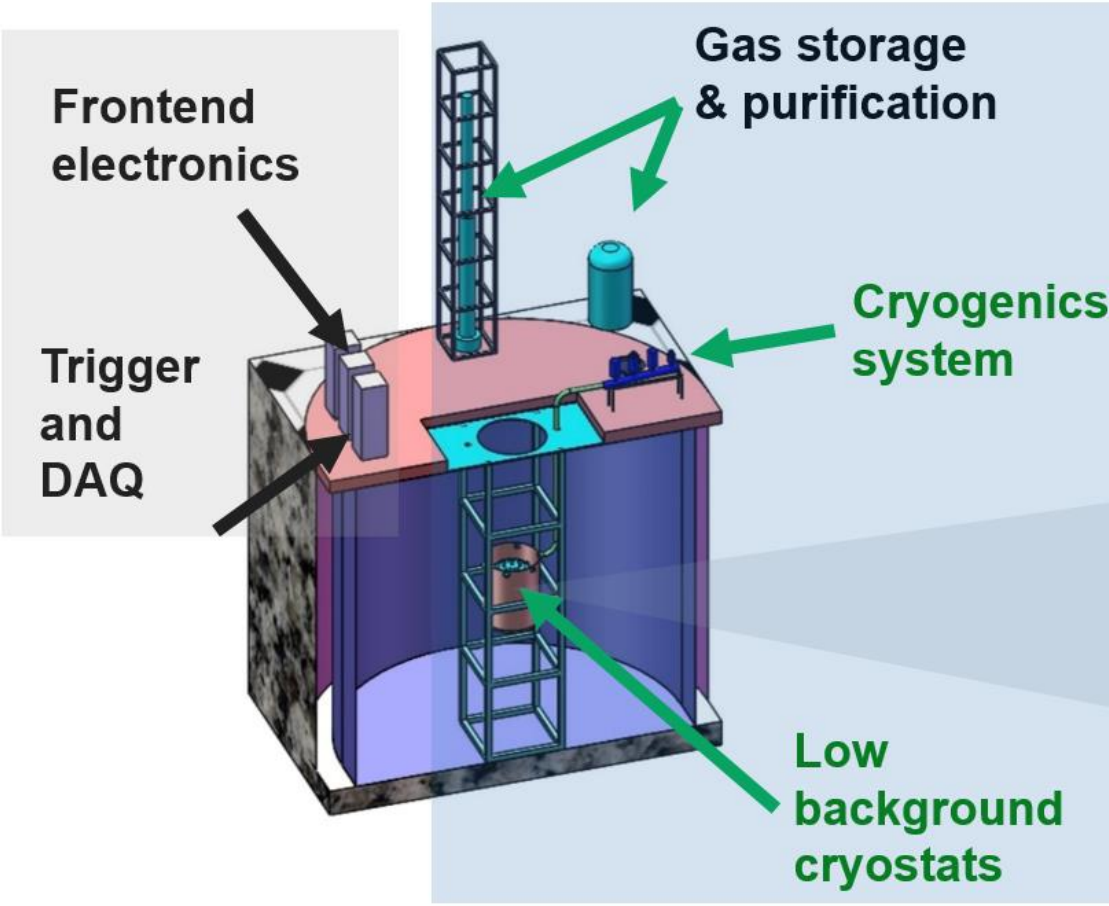




- Improved from PandaX-II 2016 limit about 2.5 time for >30GeV/c^2
- Lowest exclusion at 8.6×10^{-47}cm^2 at 40GeV/c^2
- Most stringent limit for WIMP-nucleon cross section for mass >100GeV/c^2 when published

DM direct direction next step: PandaX-xT

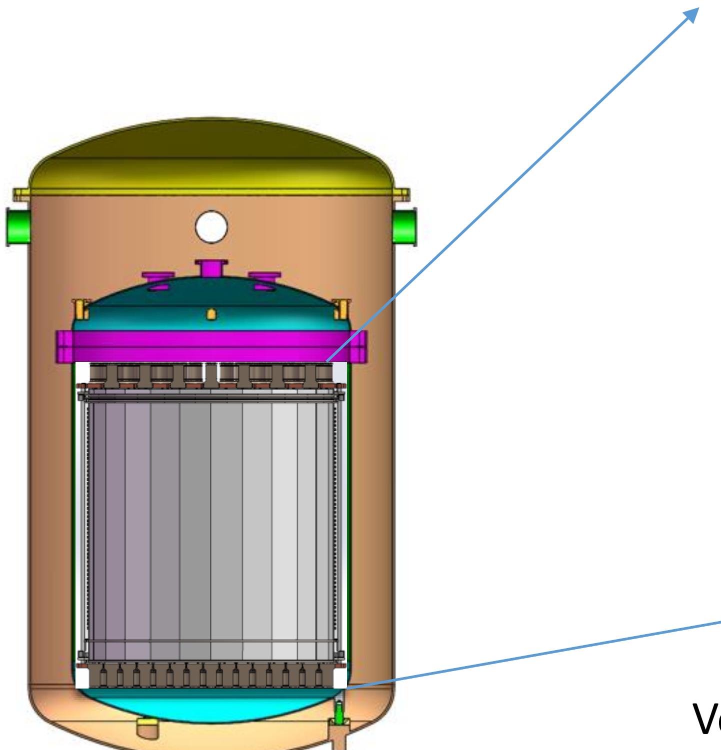
- Larger TPC with more detector mass
- Ultra-pure water shielding
- Online xenon purification
- Dual-range PMT readout
  - For DM and $0\nu\beta\beta$

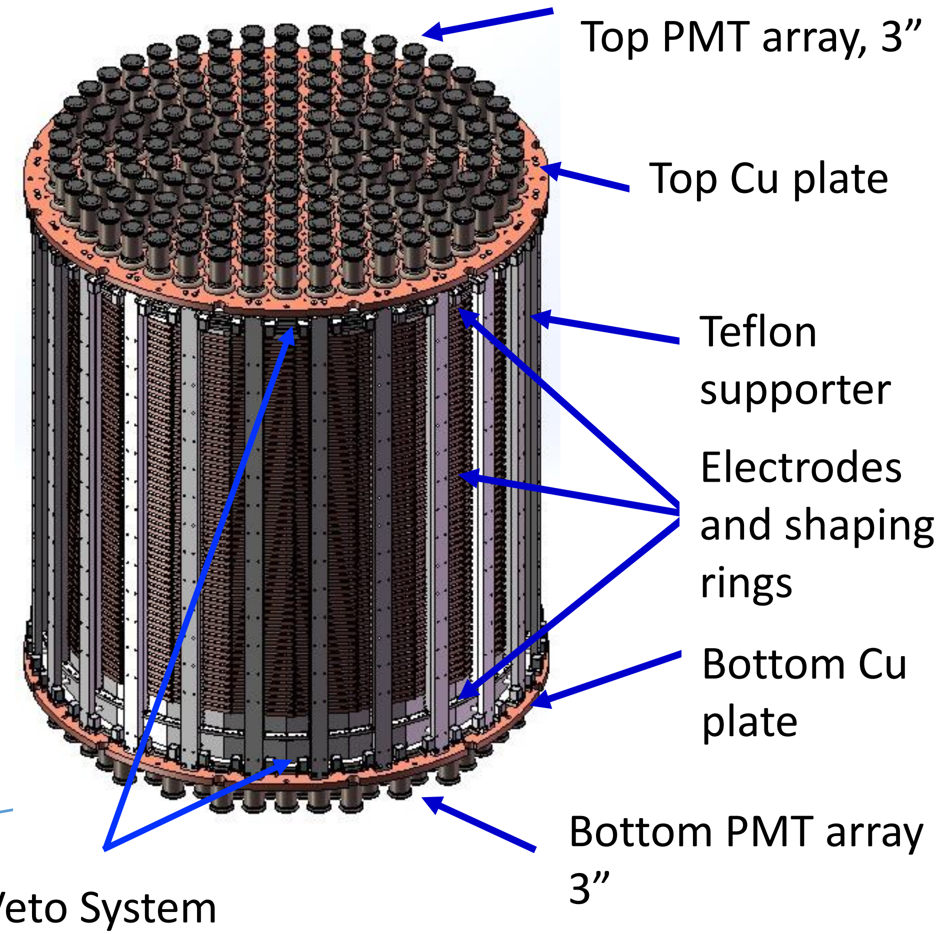


- Intermediate stage:
  - **PandaX-4T** (4-ton target) with SI sensitivity ~10^{-47} cm^2

PandaX-4T Large Scale TPC

- Drift region: Φ~1.2m, H~1.2m
  - Xenon in sensitive region ~ 4 ton, drift field 400 V/cm
- Design goal:
  - High signal collection efficiency
  - Uniform *E* field in a large volume
  - Veto facility



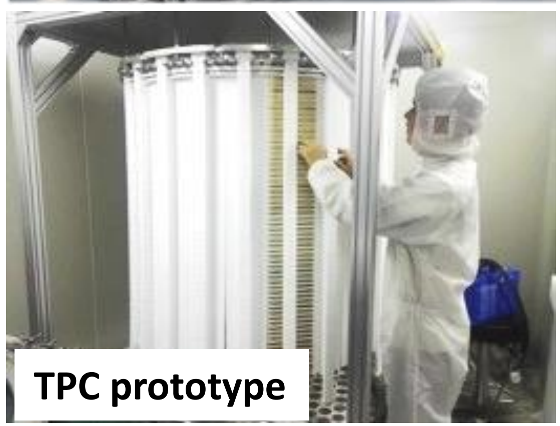


Current Status and Schedule

- R&D work-in-progress
- 2019-2020: assembly and commissioning

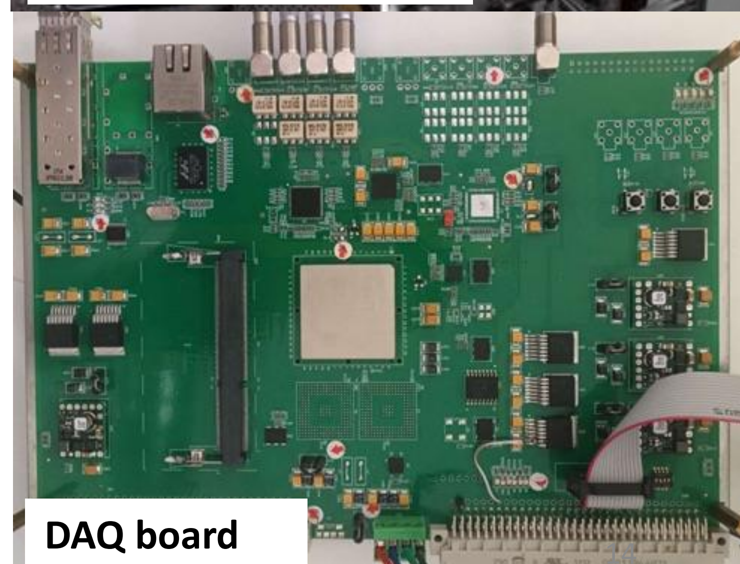

Inner vessel


Cooling bus


TPC prototype


PMT test


Krypton measurement


DAQ board

PandaX-4T Sensitivity study

- Simulated ER and NR events
  - Detector materials
  - Radioactivity in xenon: ^{85}Kr, ^{222}Rn, ^{136}Xe
  - Neutrino
- Background in signal region
  - Total ER background: 0.05 mDRU
  - Total NR background: 1 event / ton / year
- With two-year exposure, SI DM-nucleon sensitivity: 10^{-47}cm^2
  - About x10 improvement w.r.t. PandaX-II

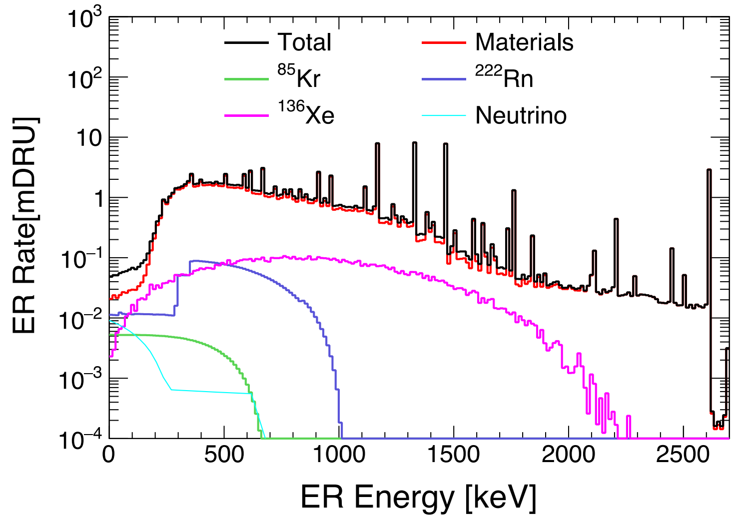
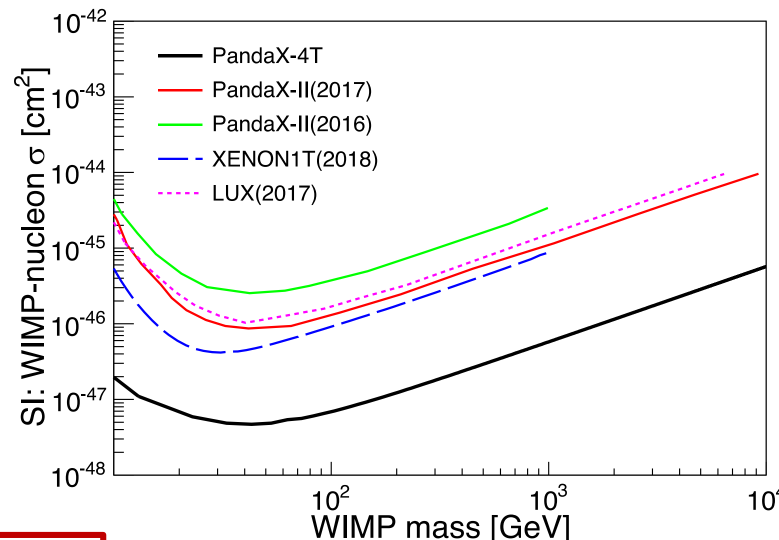


Table 4 Final background budget within the WIMP search window.

Sources	ER in mDRU	NR in mDRU
Materials	0.0210±0.0042	$2.0 \pm 0.3 \cdot 10^{-4}$
^{222}Rn	0.0114±0.0012	-
^{85}Kr	0.0053±0.0011	-
^{136}Xe	0.0023±0.0003	-
Neutrino	0.0090±0.0002	$0.8 \pm 0.4 \cdot 10^{-4}$
Sum	0.049 ±0.005	$2.8 \pm 0.5 \cdot 10^{-4}$
2-year yield (evts)	1001.6± 102.2	5.7±1.0
after selection (evts)	2.5±0.3	2.3±0.4



arXiv:1806.02229

Neutrinoless double beta decay

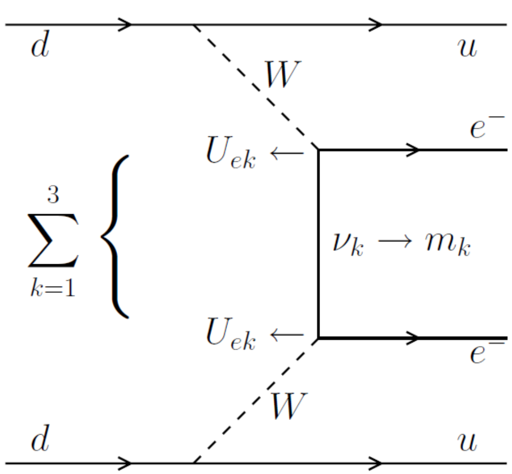
- Explores the Majorana nature of neutrinos
- Tests lepton number conservation
  - ΔL = +2
  - 0νββ is not just a neutrino experiment!
- Connects to broad neutrino oscillation physics picture

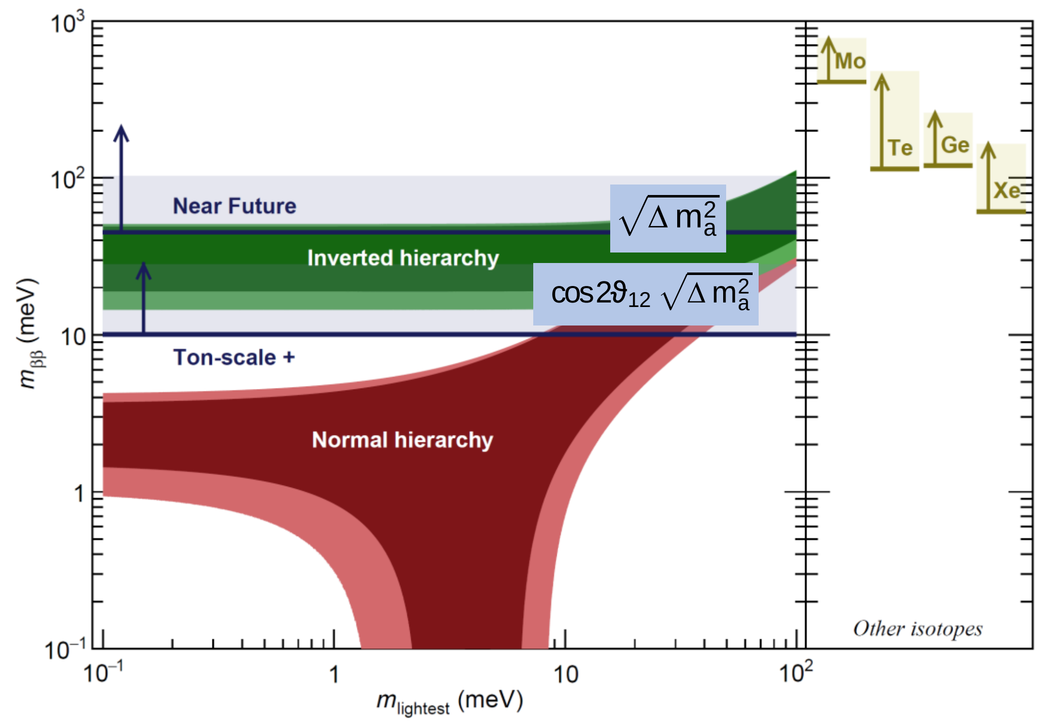
Majorana Neutrino

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

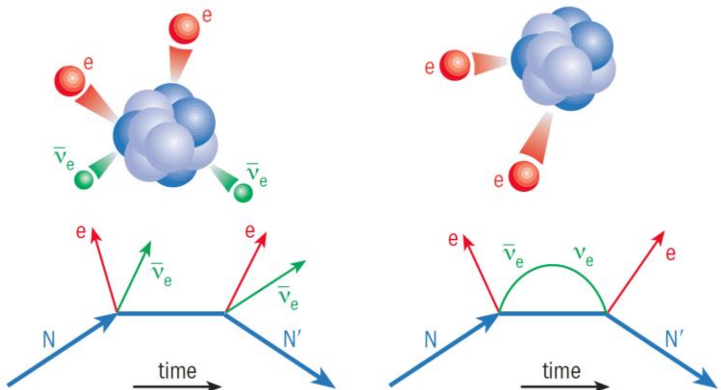
Example:

$$^{136}Xe \rightarrow {}^{136}Ba + 2e^{-} + (2\bar{\nu}_e)$$



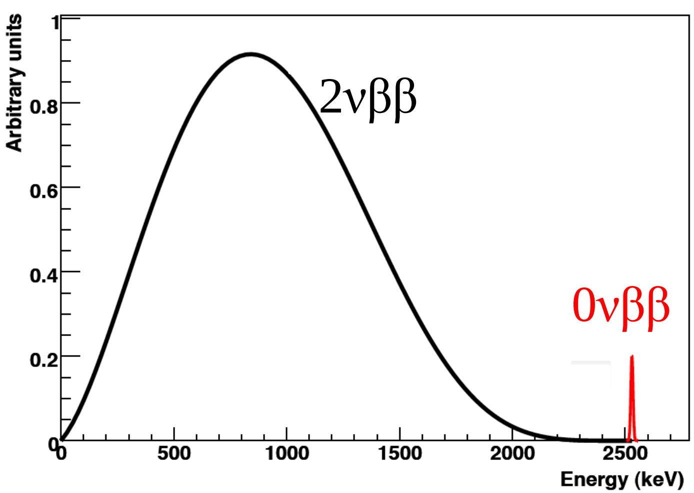


Neutrinoless double beta decay

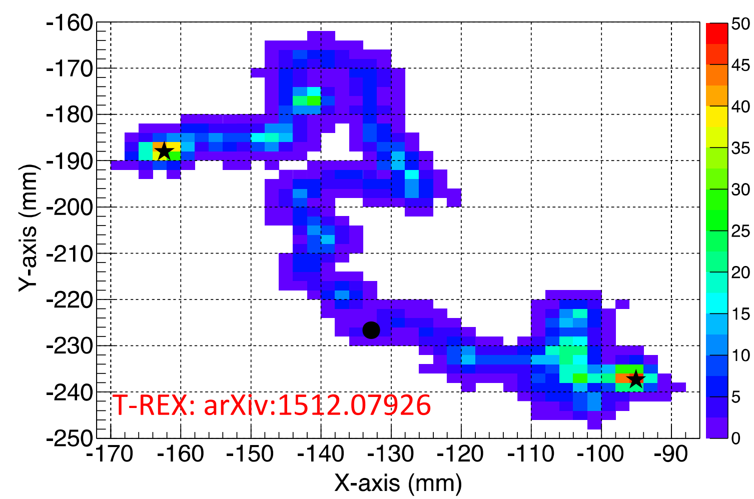


From Physics World

- Measure energies of emitted e^- (universal approach)
- Electron tracks are a huge plus (unique feature of certain experiments)
- Daughter nuclei identification (ultimate dream?)



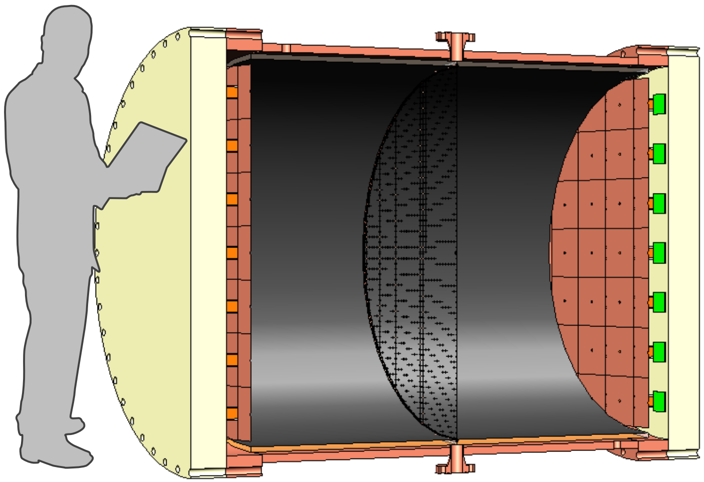
Sum of two electrons energy



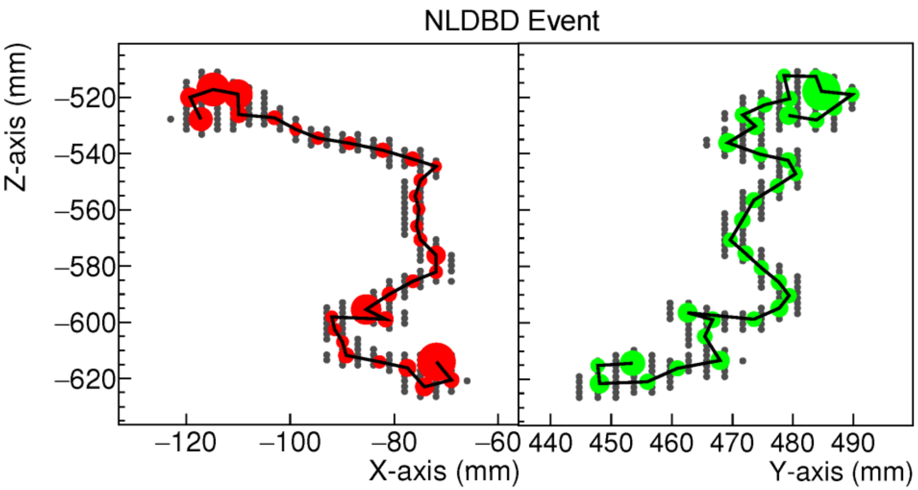
Simulated track of 0νββ in high pressure Xe

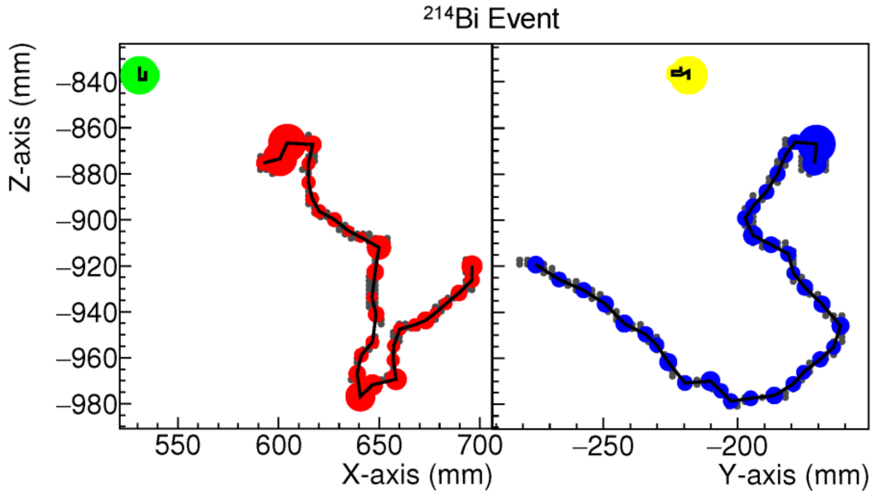
PandaX-III: high pressure gas TPC for 0νββ of ^{136}Xe

- TPC: 200 kg scale, symmetric, double-ended charge readout, with 10 bar of ^{136}Xe
- Main features: good energy resolution and background suppression with tracking

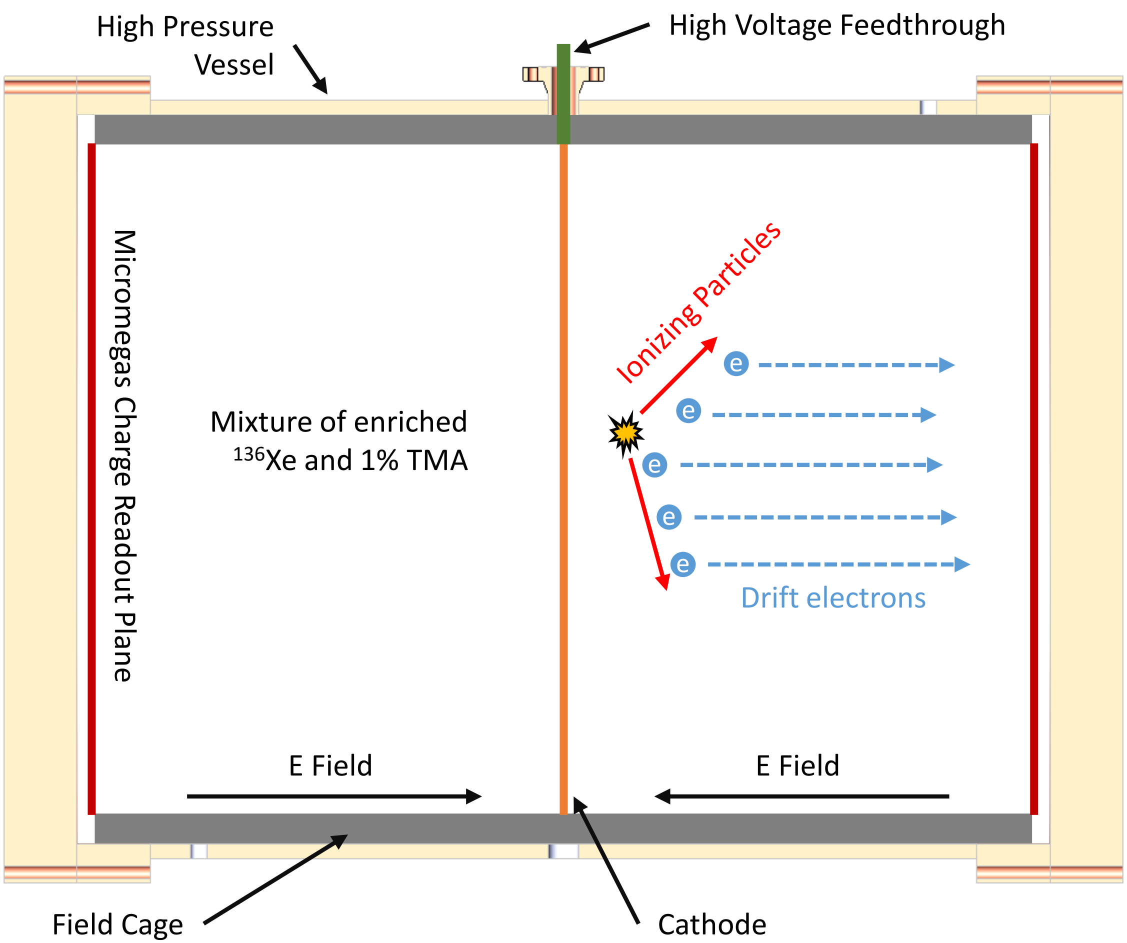


arXiv:1610.08883

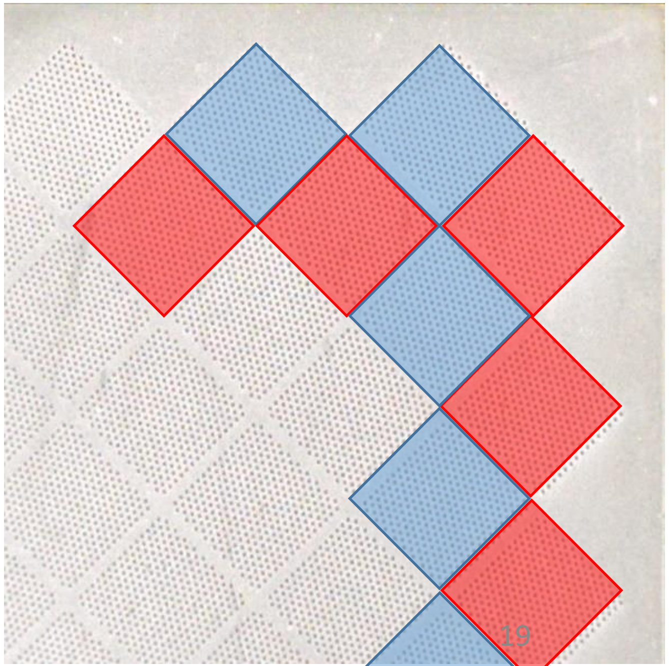




PandaX-III first TPC

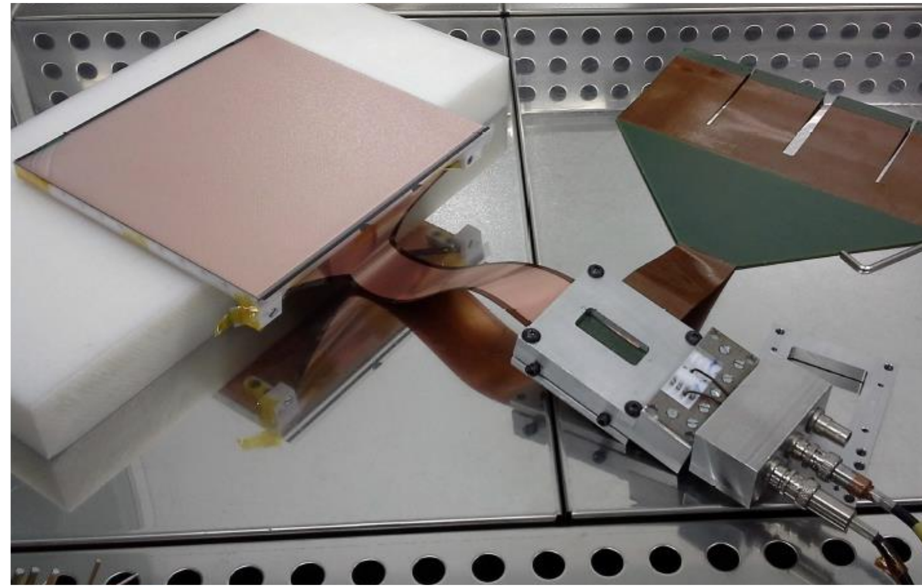


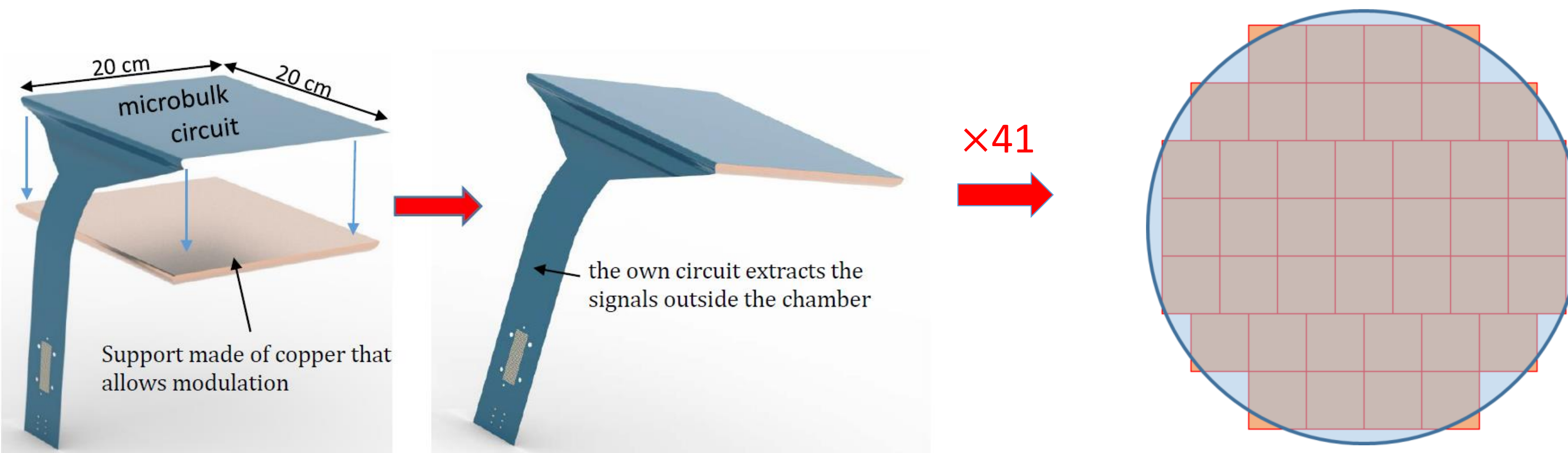
- ~4m^3 inner volume at 10 bar
- Charge-only readout with Microbulk Micromegas
- Strip readout; 3 mm pitch
- ~10000 readout channels



Scalable Radio-pure Readout Module (SR2M)

- SR2M: Mosaic layout to cover readout planes
  - Solderless system
  - Strip and mesh signal readout
  - Dead-zone-free arrangement
  - Designed by Zaragoza and SJTU

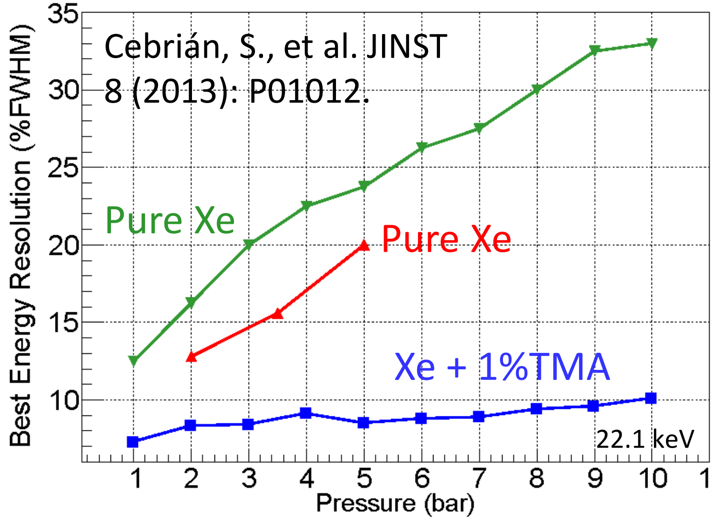


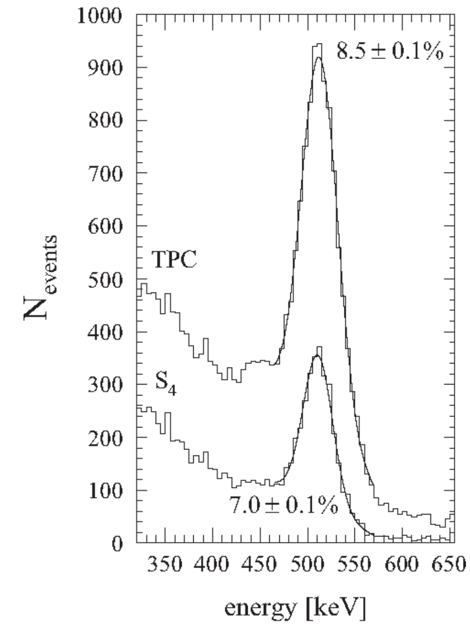


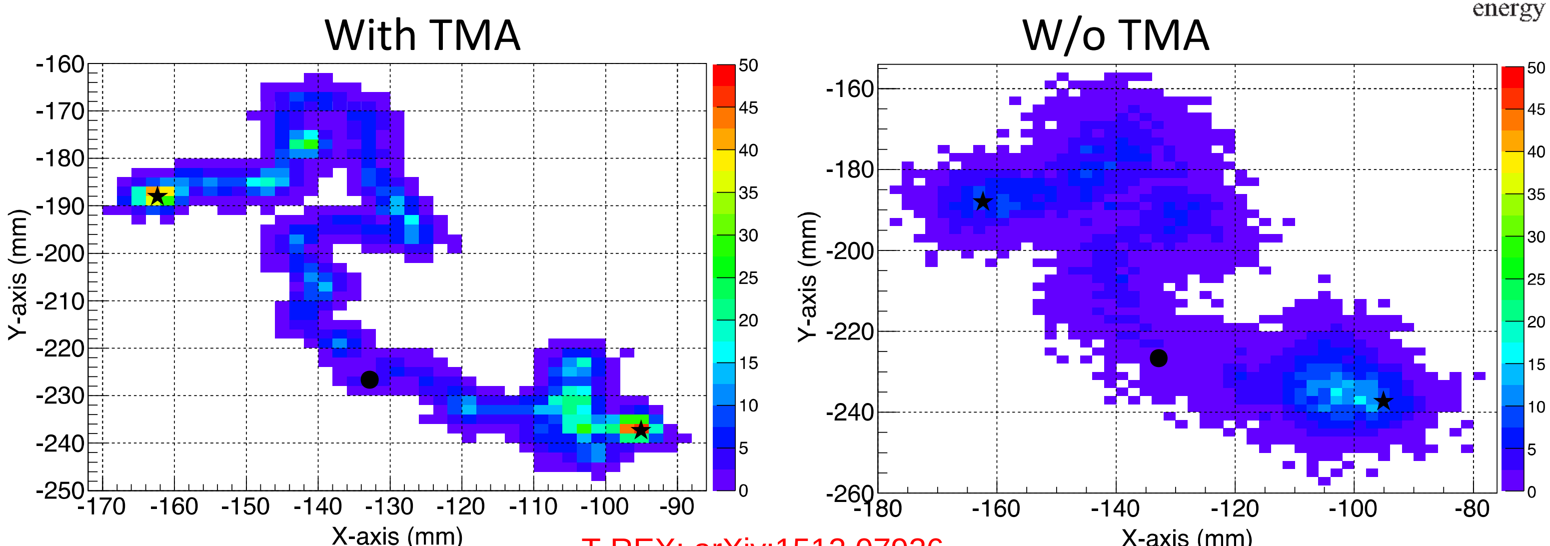
Xe +TMA (trimethylamine) mixture

Gonzalez-Diaz, et al. *NIMA* 804 8 (2015)

- Better energy resolution
  - Extrapolated from 511keV and 1.2MeV peaks: 3% FWHM (@$Q_{0\nu\beta\beta}$)
- Better tracks
  - TMA suppress electron diffusion
- Better operation
  - TMA as a quencher gas





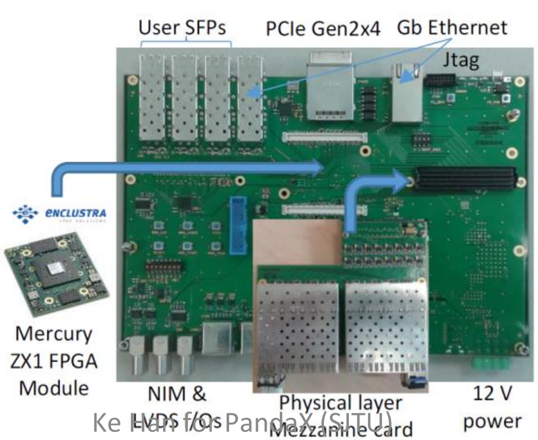


T-REX: arXiv:1512.07926

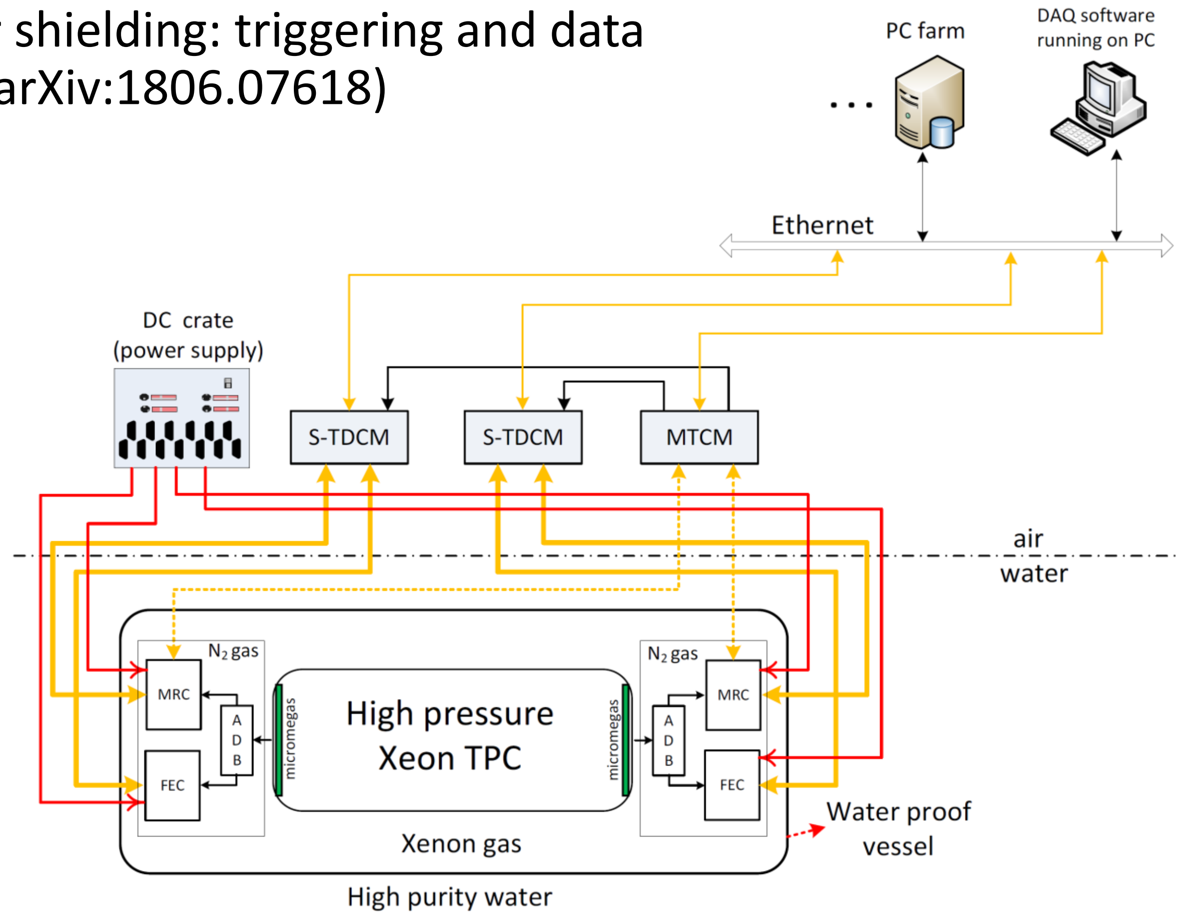
Electronics

- Front-end electronics close to TPC: reads and digitizes strip and mesh signals (arXiv:1806.09257)
  - Based on AGET ASIC chips from CEA-Saclay
- Back-end above water shielding: triggering and data transmission to DAQ (arXiv:1806.07618)

FEC



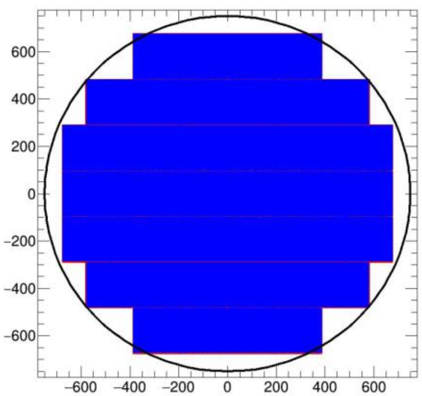
Backend

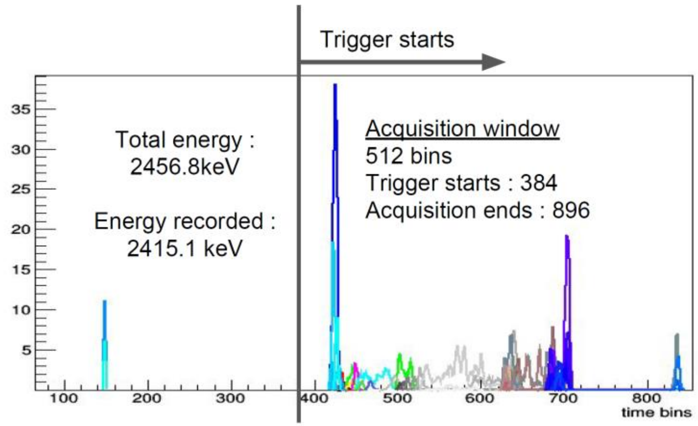


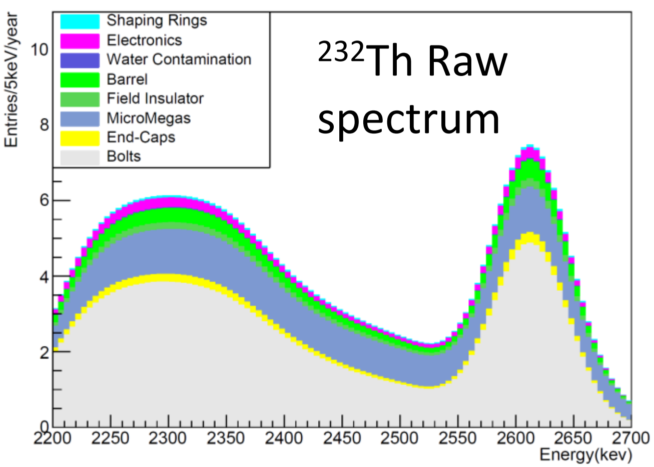
Background budget

Two independent Geant-4 based MC packages: RESTG4 and BambooMC

- Treat PandaX-III as a simple calorimeter
- Then add detector response
- Calculate signal efficiency and background rejection
- ×35 background reduction from topological analysis
  - Track reconstruction and blob identification at both ends
  - Convolutional neural network



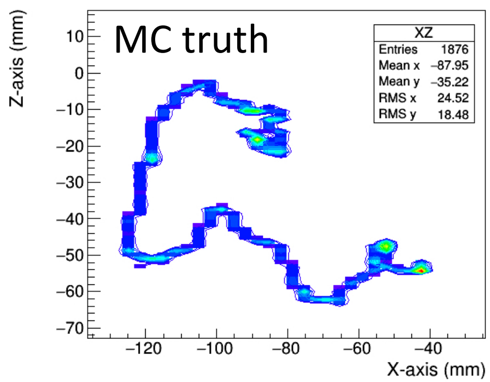


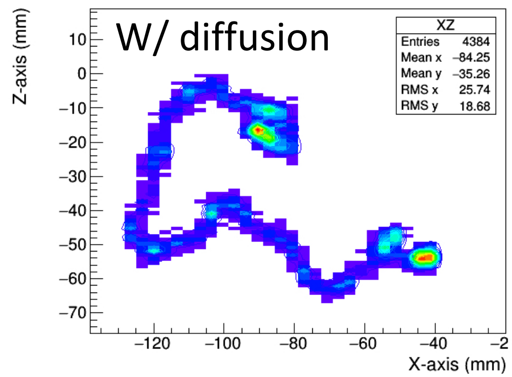


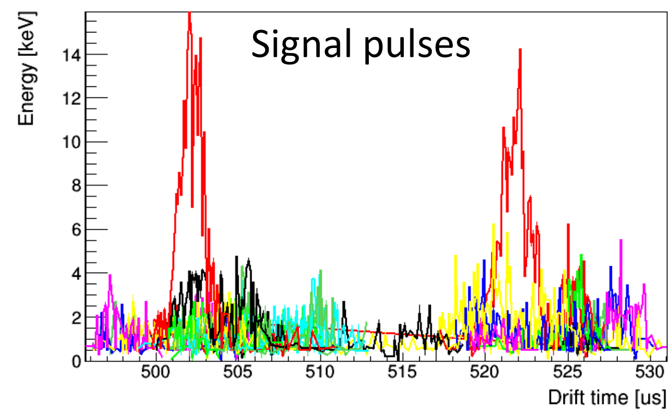
Cut-based track classification

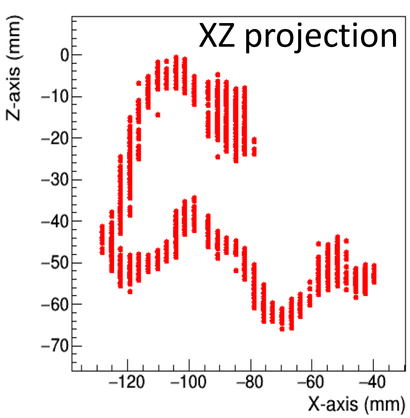
PANDA X
PARTICLE AND ASTROPHYSICAL XENON TPC

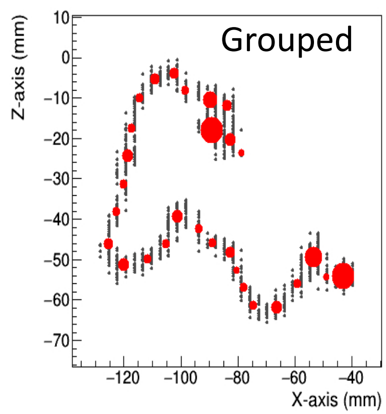
Define key parameters (such as energy deposition in a certain blob) and refine cuts

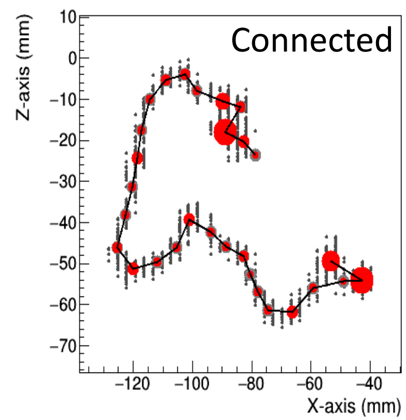


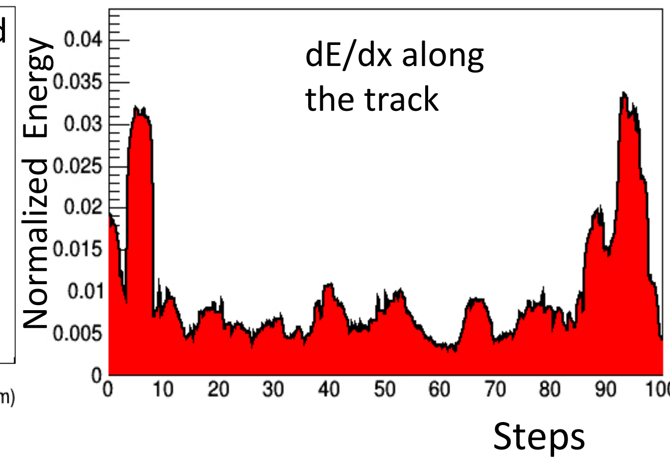








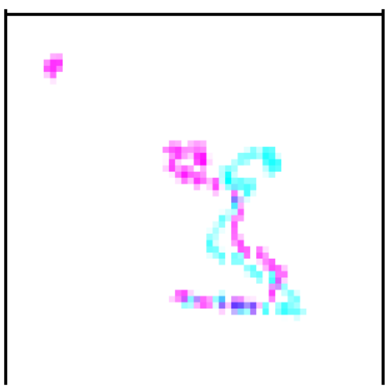


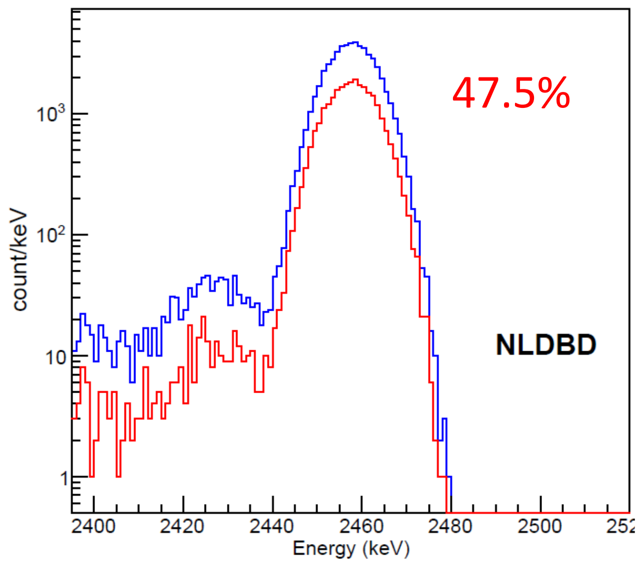


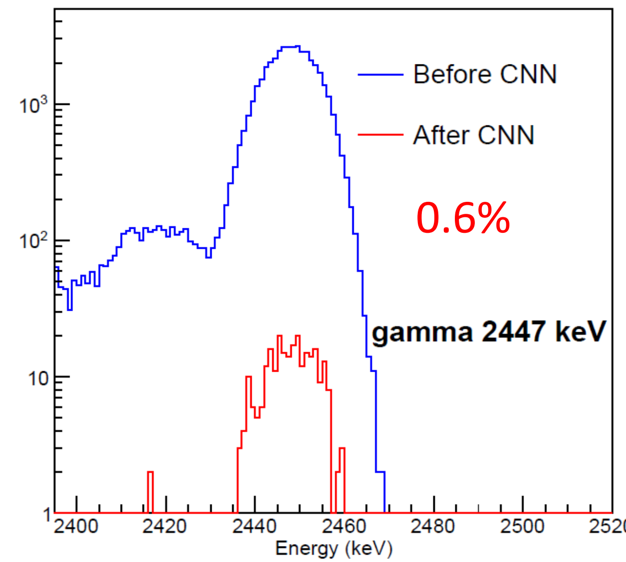
J. Galan, Neutrino 2018

Convolutional Neural network (CNN) for track classification

- XZ, YZ 2D snapshots of an event as input of R and G channels of an image and then rely on CNN to spill out an index of signal/background
- Prepare image collections for CNN training, validation, and classification.
- No track reconstruction needed.



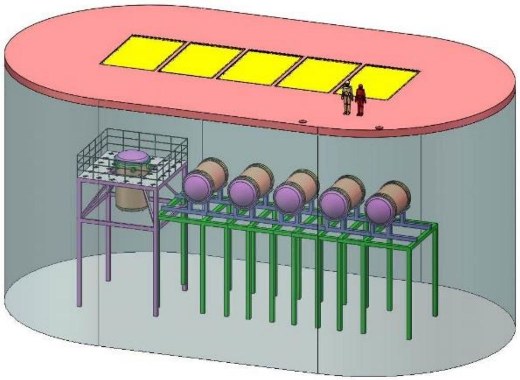




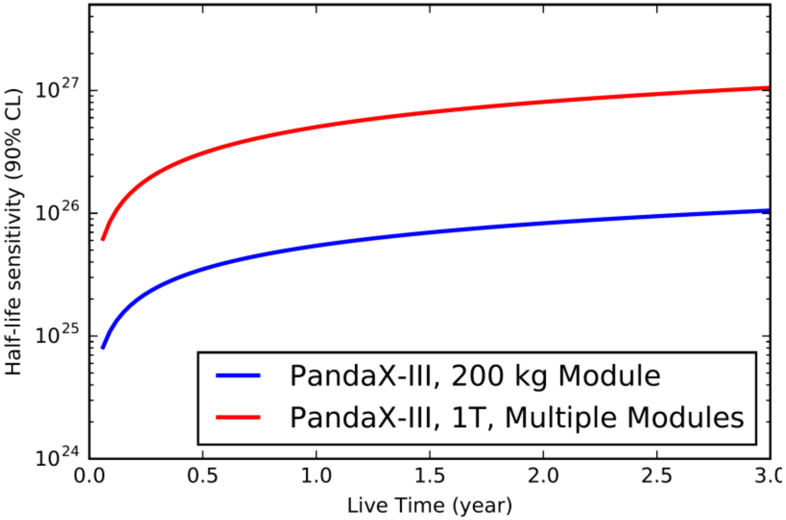
H. Qiao, et al arXiv:1802.03489

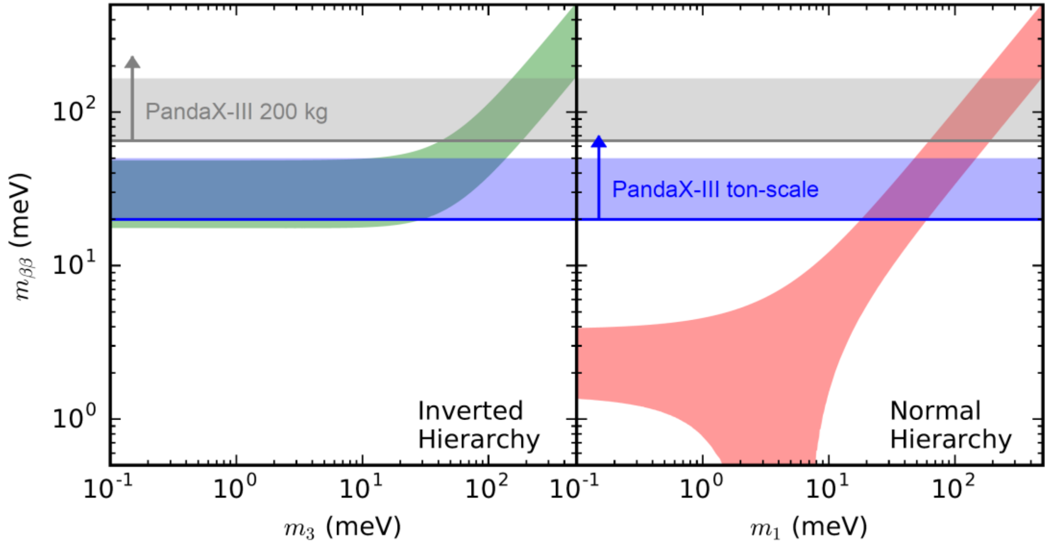
Sensitivity projection

- First 200-kg module:
  - Microbulk Micromegas for charge readout
  - 3% FWHM, 1×10^{-4} c/keV/kg/y in the ROI
- Ton-scale:
  - Four more modules with upgraded charge readout and better low-background material screening.
  - 1% FWHM, 1×10^{-5} c/keV/kg/y in the ROI



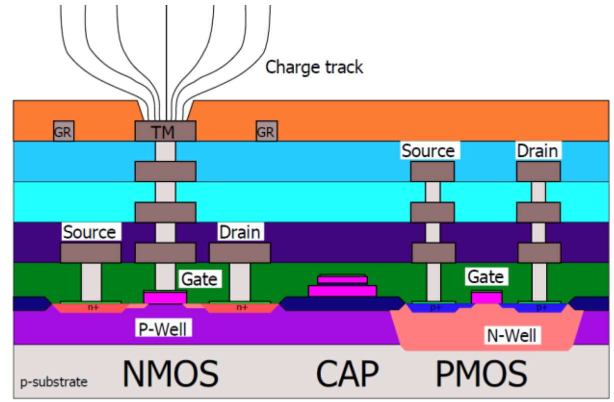
arXiv:1610.08883



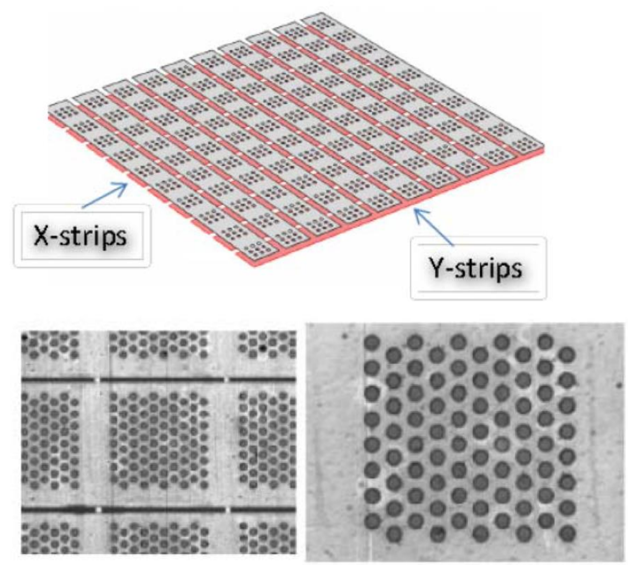


Future energy resolution improvement

- TopMetal Direct Charge Sensor
  - Direct pixel readout without gas amplification
  - Active development at CCNU and Berkeley

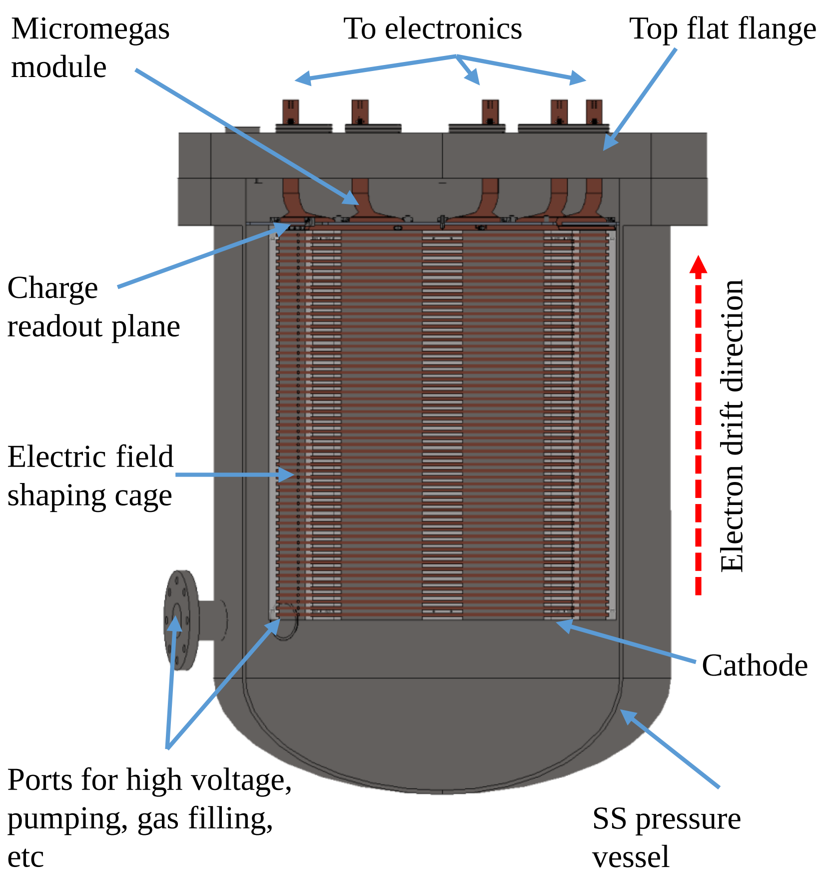


- Alternative Micromegas technologies (Saclay)
  - Microbulk technology with segmented mesh for true X and Y strips
  - Bulk technology with better uniformity and less dead area

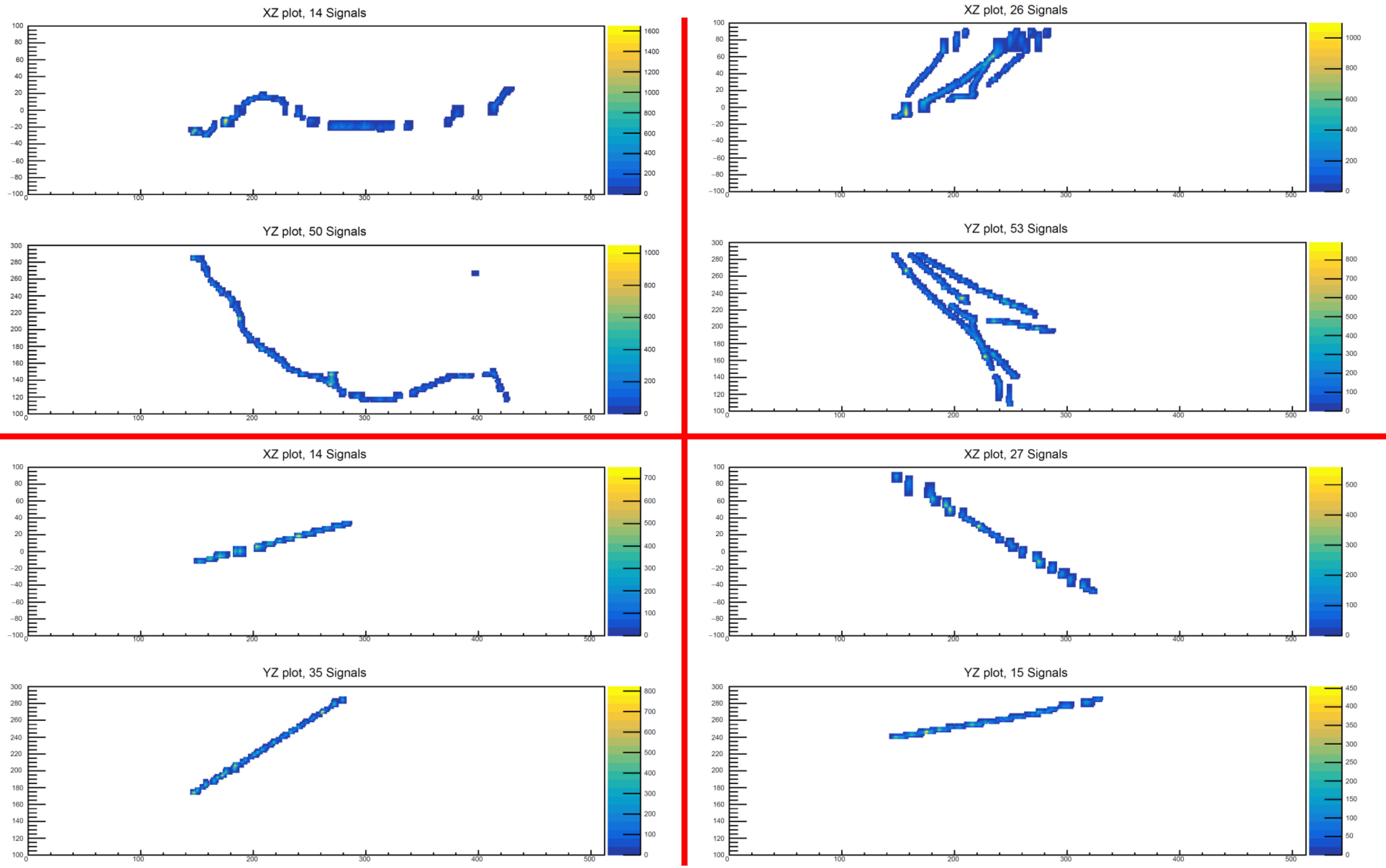


Prototype TPC at Shanghai

- To see MeV electron tracks and demonstrate required energy resolution with a large-scale high pressure TPC
- Field cage: 66 cm diameter, 78 cm drift length, single-ended
- 600 L of inner volum16 kg of xenon at 10 bar
- 7 Microbulk Micromegas modules

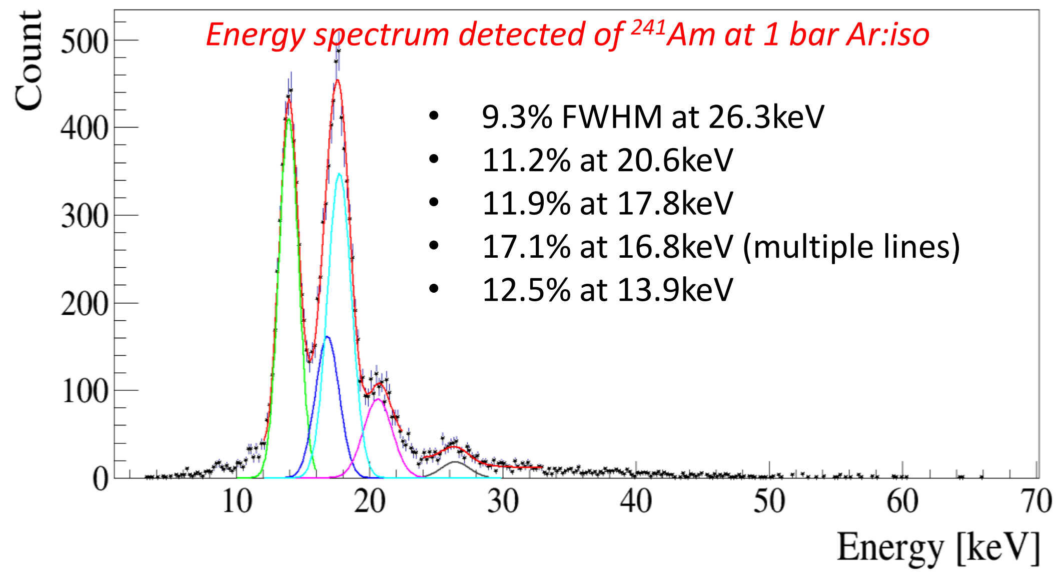


Some example tracks

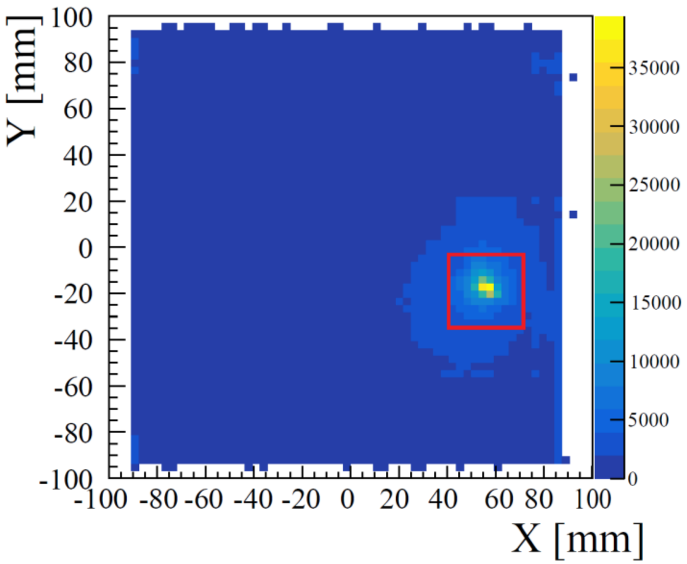


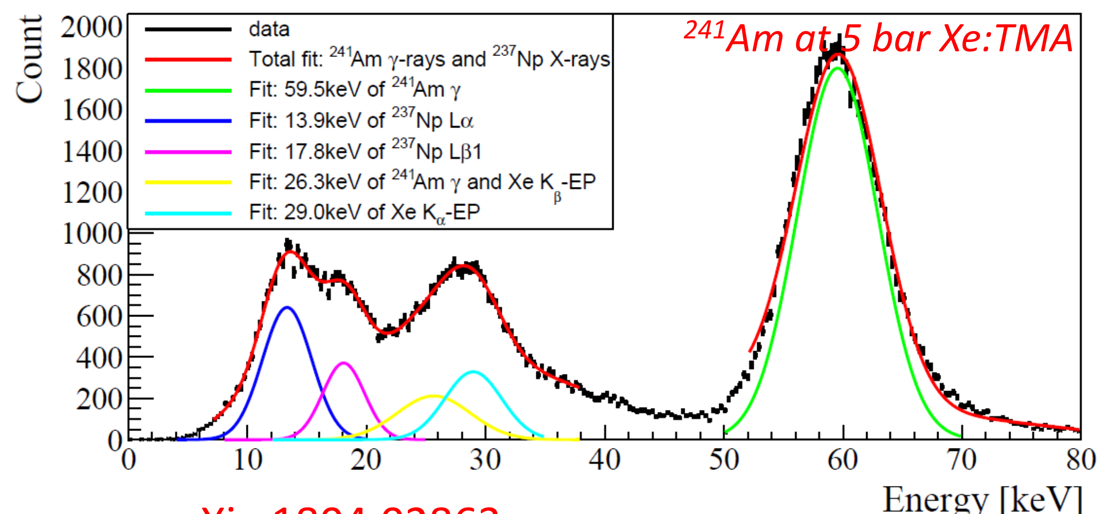
Data with 1 Micromegas

- Excellent gain of 7000 with 1 bar Ar:iso
- Improvement of run quality with 5 bar Xe:TMA is on-going
  - Current FWHM: 14.1% at 59.5 keV



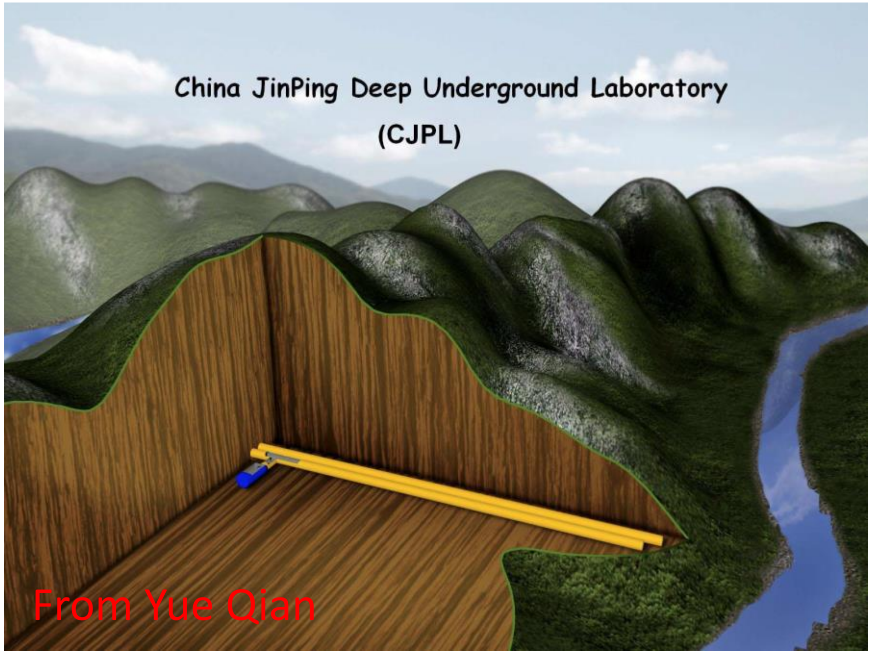
^{241}Am at 5 bar Xe:TMA

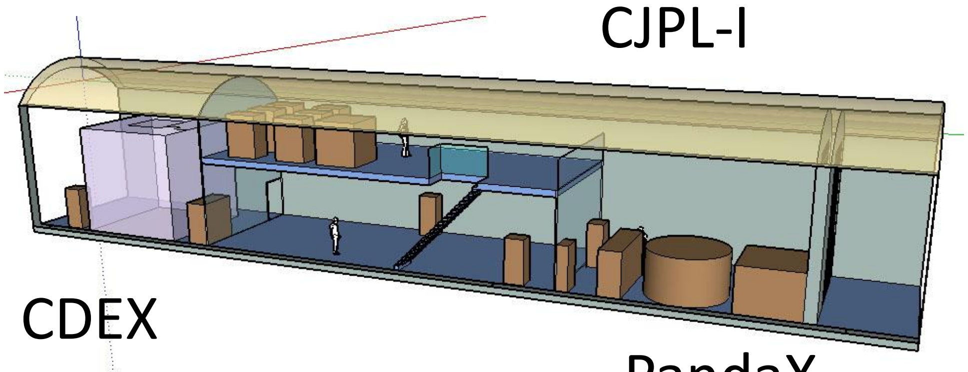




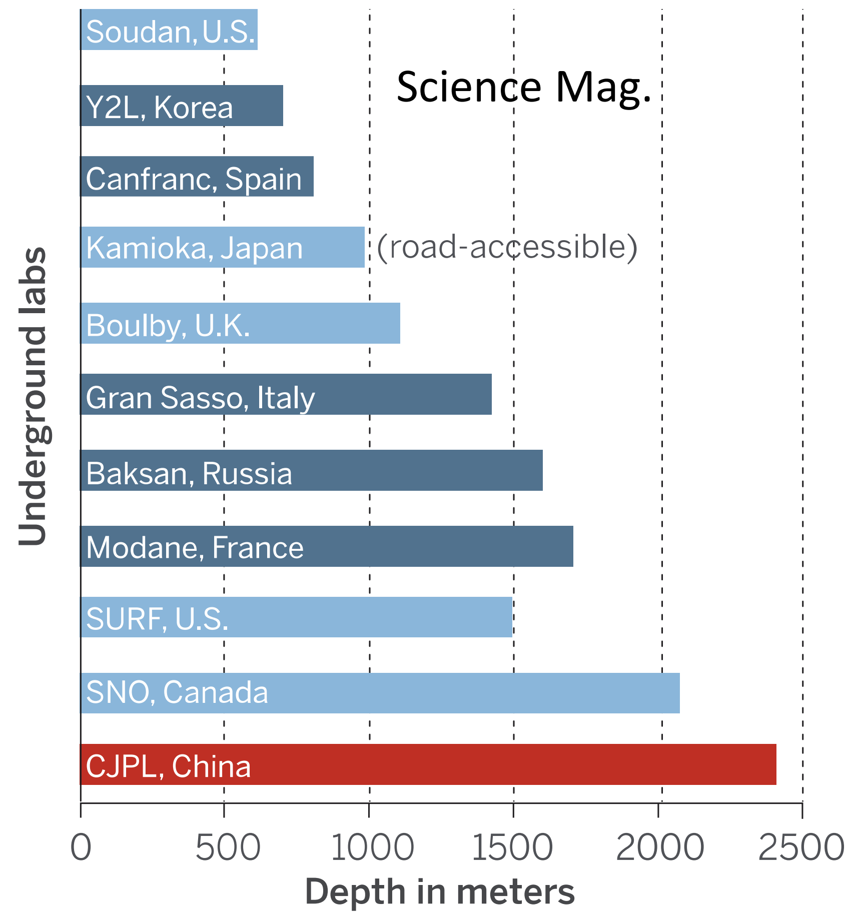
arXiv:1804.02863

CJPL – Deepest underground lab in the world



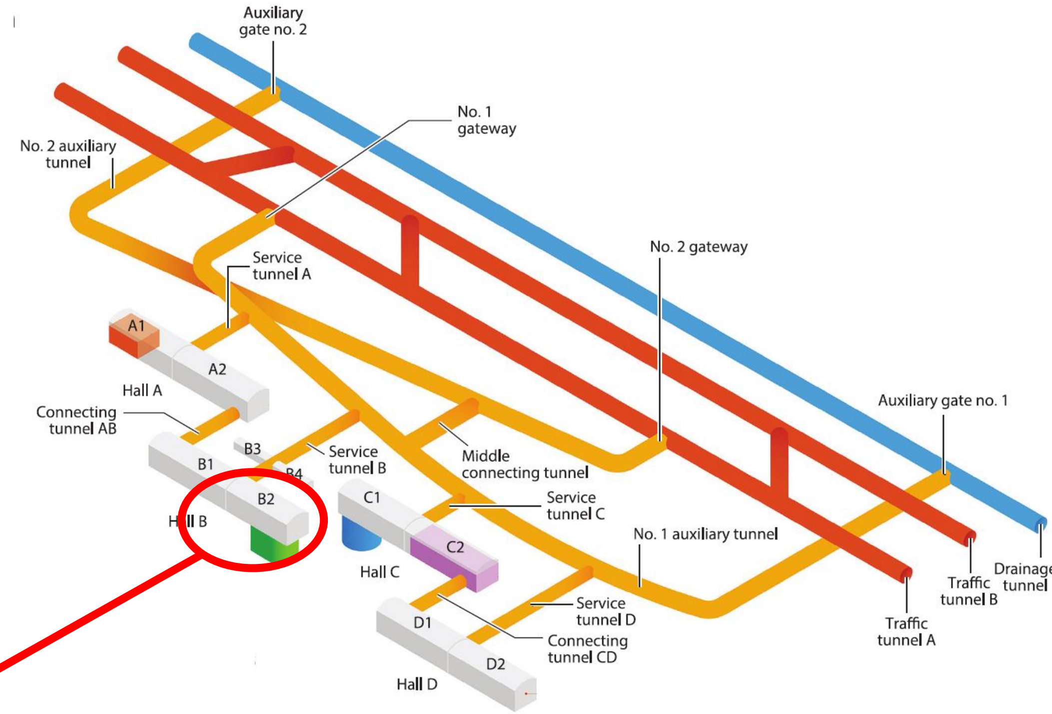


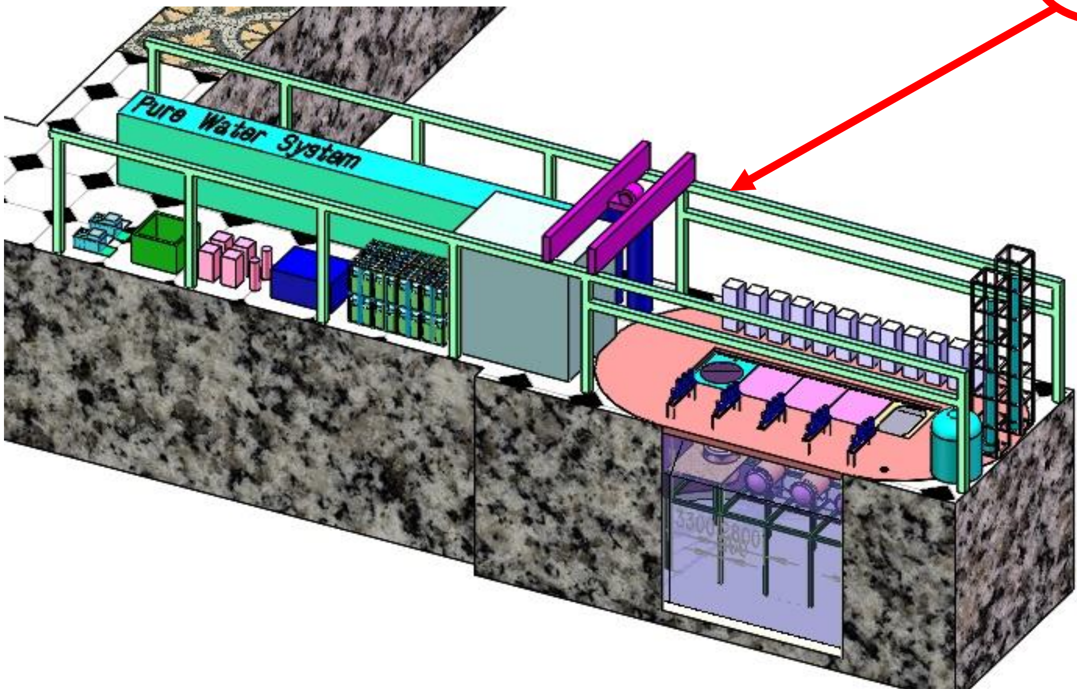
Labs are built in mines (light blue) and tunnels (dark blue and red).



PandaX hall at CJPL-II

- PandaX projects
- CDEX WIMP/ 0νββ search
- JUNA (accelerator)
- Geo/Solar neutrino detector
- Other 0νββ activities
- ……





PandaX at Hall B2

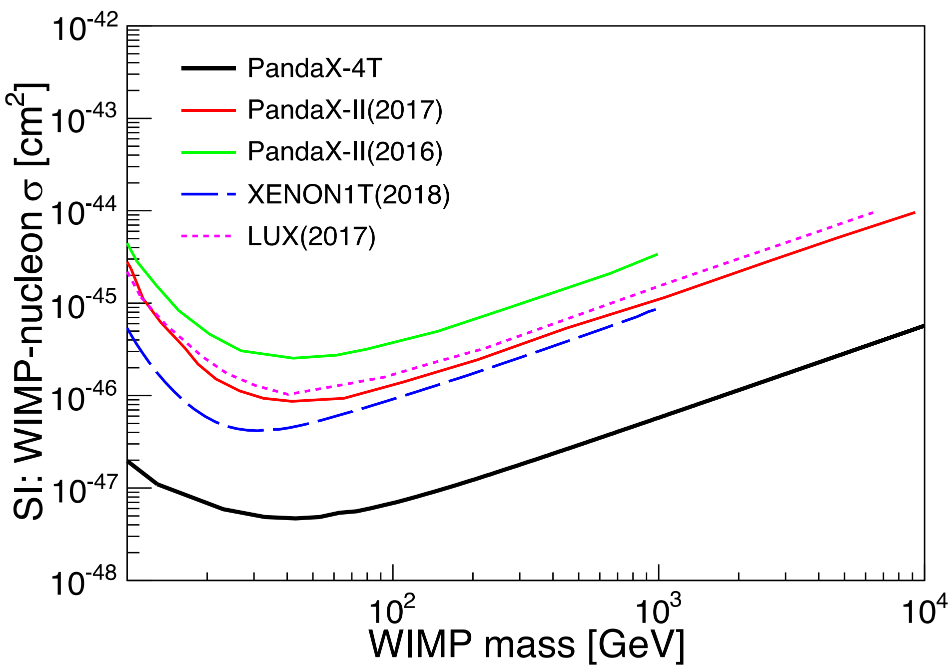
- ~ 900 m^2
- Extra excavation for the water shielding pool (finished)
- Shared facility of DM and 0νββ searches

Recent activities at PandaX hall

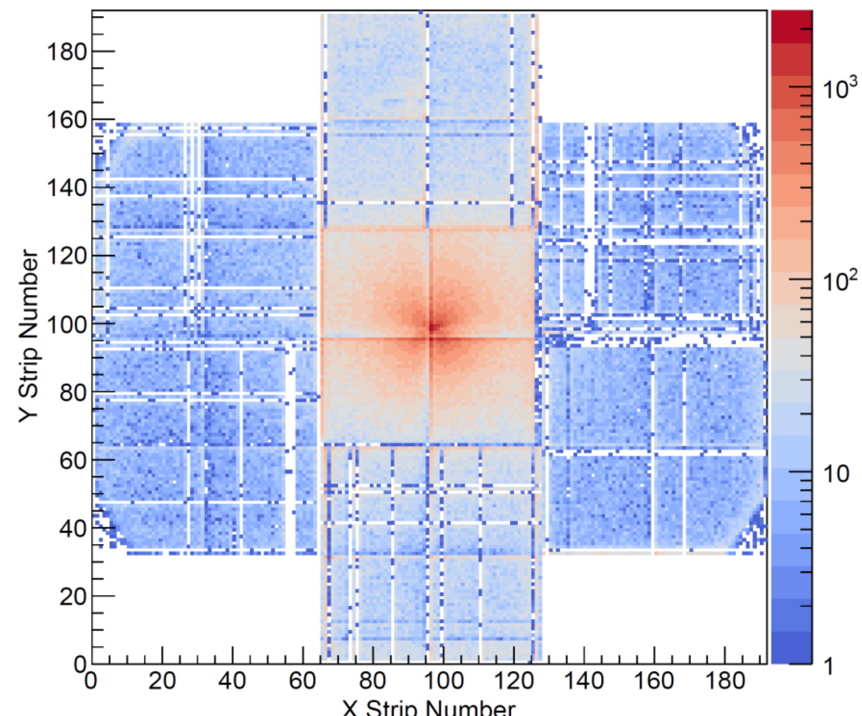
- Beneficial occupation started in 2017 for PandaX-II xenon distillation, etc.
- Infrastructure work in progress.

Conclusions and outlook

- PandaX-II with 580kg xenon has reached the world frontier of dark matter direct detection.
- PandaX-4T reaches an expected sensitivity to SI interaction of 10^{-47} cm^2 with 2 year live time.
  - Assembly and commissioning: 2019-2020



- PandaX-III aims to build multiple 200-kg scale high pressure xenon TPC for NLDBD search at CJPL.
- A 20-kg scale prototype TPC is under commissioning.
- First 200 kg module: 2020



PandaX Collaboration

- **P**article **and A**strophysical **X**enon Experiments
    - Formed in 2009, ~50 people

- Shanghai Jiao Tong University
- Peking University
- Shandong University
- Nankai University
- Shanghai Institute of Applied Physics
- Yalong Hydropower Company
- University of Science & Technology of China
- China Institute of Atomic Energy
- Sun Yat-Sen University
- University of Maryland
- Lawrence Berkeley National Lab
- CEA Saclay
- University of Zaragoza
- Suranaree University of Technology

Table 5 The raw background contribution from different parts in the laboratory and the detector by taking the 3% FWHM detector resolution into account. BI stands for background index

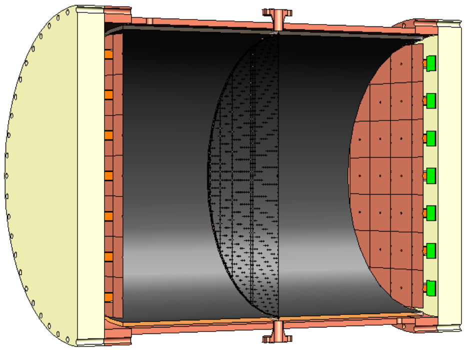
	Isotope	Activity	Background (CPY)		BI (10^{-5} c/(keV·kg·y))	
			BambooMC	RestG4	BambooMC	RestG4
Laboratory walls	^{238}U	9.9 Bq/kg	< 0.40 ± 0.03	< 0.09± 0.01	–	<0.4
	^{232}Th	4.4 Bq/kg	< 0.22 ± 0.02	< 0.15± 0.01	–	<0.6
Water	^{238}U	0.12 μBq/kg	0.20 ± 0.1	0.22 ± 0.03	0.74	0.86
	^{232}Th	0.04 µBq/kg	0.24 ± 0.06	0.55 ± 0.03	0.96	2.21
Barrel	^{238}U	0.75 µBq/kg	1.73 ± 0.12	1.77 ± 0.1	6.9	7.05
	^{232}Th	0.2 µBq/kg	4.63 ± 0.18	4.55 ± 0.05	18.5	18.2
	^{60}Co	10 µBq/kg	9.8 ± 1.0	9.9 ± 0.9	39.0	39.7
End-caps	^{238}U	0.75 µBq/kg	0.83 ± 0.11	0.90 ± 0.11	3.3	3.6
	^{232}Th	0.2 µBq/kg	2.4 ± 0.1	2.2 ± 0.1	9.8	9.0
	^{60}Co	10 µBq/kg	4.4 ± 1.0	4.2 ± 0.9	17.8	16.7
Bolts	^{238}U	0.5 mBq/kg	7.5 ± 1.5	7.3 ± 0.9	30.1	29.2
	^{232}Th	0.32 mBq/kg	39.8 ± 2.7	46.7 ± 1.9	159	186.3
Field insulator and rings	^{238}U	4.94 µBq/kg	15.0 ± 0.5	15.7 ± 0.3	59.9	62.6
	^{232}Th	0.1 µBq/kg	2.69 ± 0.03	2.61 ± 0.1	10.7	10.4
	^{238}U	0.75 µBq/kg	0.67 ± 0.01	0.72±0.05	2.7	2.9
	^{232}Th	0.2 µBq/kg	0.95 ± 0.01	0.92 ± 0.03	3.8	3.7
Electronics	^{238}U	0.26 Bq	1.0 ± 0.3	2.4 ± 0.5	4.2	9.5
	^{232}Th	0.07 Bq	2.8 ± 0.2	4.1 ± 0.5	11.3	16.3
Micromegas	^{238}U	45 nBq/cm^2	60.5 ± 1.7	63.7 ± 1.8	241.6	254.4
	^{232}Th	14 nBq/cm^2	23.5 ± 0.6	25.3 ± 0.6	93.9	101
Cathode	^{214}Bi	2 nBq/cm^2	4.1 ± 0.2	3.3 ± 0.1	16.5	13.2

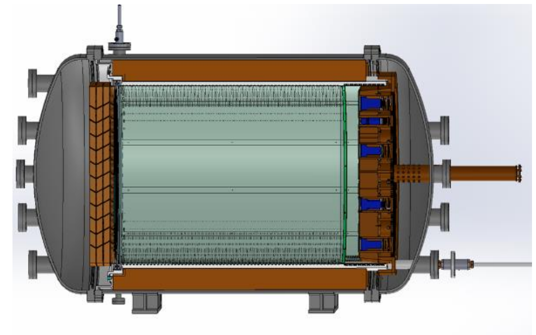
PANDA X
PARTICLE AND ASTROPHYSICAL XENON TPC

Table 7 Summary of the most relevant background contributions taking into account the detector response

Component	Isotope	Background (10^{-5} c/(keV·kg·y))	
		BambooMC	RestG4
Water	^{238}U	–	0.23
	^{232}Th	0.56	0.63
Barrel	^{238}U	1.07	2.41
	^{232}Th	7.54	7.86
	^{60}Co	3.02	2.11
End-caps	^{238}U	0.30	1.26
	^{232}Th	3.89	4.16
	^{60}Co	2.98	0.76
Bolts	^{238}U	3.50	11.9
	^{232}Th	73.8	78.5
Field insulator	^{238}U	19.5	16.5
	^{232}Th	3.80	3.86
and rings	^{238}U	1.52	0.45
	^{232}Th	1.41	1.17
Electronics	^{238}U	–	1.42
	^{232}Th	5.02	8.69
Micromegas	^{238}U	144	158
	^{232}Th	36.9	44.5
Total		308.8	344.4

PandaX vs. NEXT





PandaX-III first TPC		NEXT-100
200 kg Xe(enriched) + 1% TMA	Detector medium	100 kg pure Xe (enriched)
------------------	Light	Primary + electroluminescence light readout by PMTs
Micromegas	Charge/Tracking	SiPM
3%	Projected energy resolution	0.7%
3 mm	Tracking pitch size	1 cm
X,Y	Fiducialization	X,Y,Z
Since 2015		Since ~2008

Summary and Outlook

- PandaX experiment with 580kg Xenon has reached the world frontier of dark matter direct detection.
  - PandaX-II continues data-taking smoothly.
  - Recently, light mediator and EFT results are obtained
  - More results are expected.

- The future PandaX-4T experiment R&D is work-in-progress.
  - Expected sensitivity to SI interaction could reach 10^{-47} cm^2
  - Detector assembly and commissioning is scheduled in 2019-2020

- PandaX-III $0\nu\beta\beta$ search detector is in preparation.

- **Thank you!**

TABLE I. Summary of ER backgrounds from different components in Run 9 and Run 10. The tritium background for Run 10 in the table is based on the best fit to the data.

Item	Run 9 (mDRU)	Run 10 (mDRU)
^{85}Kr	1.19 ± 0.20	0.20 ± 0.07
^{127}Xe	0.42 ± 0.10	0.021 ± 0.005
^{3}H	0	0.27 ± 0.08
^{222}Rn	0.13 ± 0.07	0.12 ± 0.06
^{220}Rn	0.01 ± 0.01	0.02 ± 0.01
ER (material)	0.20 ± 0.10	0.20 ± 0.10
Solar ν	0.01	0.01
^{136}Xe	0.0022	0.0022
Total	1.96 ± 0.25	0.79 ± 0.16

TABLE III. The best fit total and below-NR-median background events in Run 9 and Run 10 in the FV. The fractional uncertainties of expected events in the table are 13% (Run 9 ER), 20% (Run 10 ER), 45% (accidental), and 50% (neutron), respectively, and are propagated into that for the total fitted events. The below-NR-median ER background for Run 9 was updated using the new ER calibration. The corresponding best fit background nuisance parameters [δ_b's in Eq. (2)] are 0.123 (^{127}Xe), 0.135 (tritium), −0.105 (flat ER), 0.111 (accidental), and −0.098 (neutron). The number of events from the data are shown in the last column.

	ER	Accidental	Neutron	Total Fitted	Total Observed
Run 9	376.1	13.5	0.85	390 ± 50	389
Below NR median	2.0	0.9	0.35	3.2 ± 0.9	1
Run 10	172.2	3.9	0.83	177 ± 33	177
Below NR median	0.9	0.6	0.33	1.8 ± 0.5	0

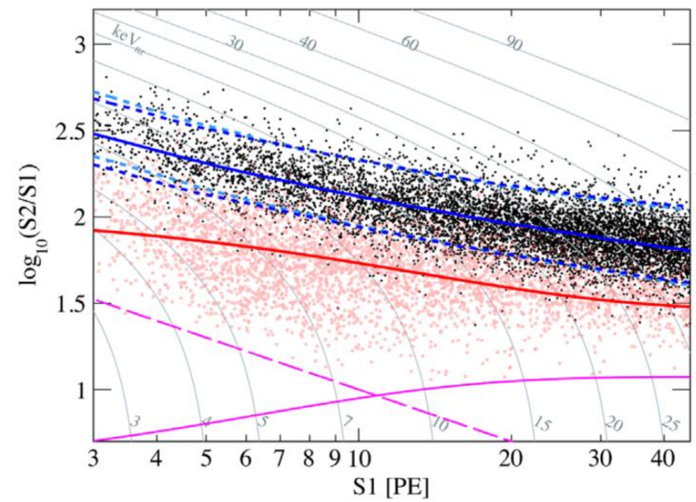


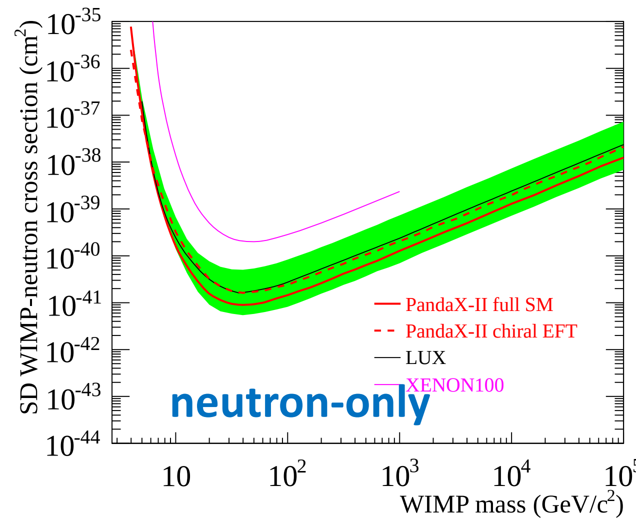
FIG. 2. Tritium (solid black dots) and AmBe data (open red circles) in $\log_{10}(S2/S1)$ vs $S1$. For comparison, the median (Runs 9 and 10 averaged, solid blue), 10% quantile, and 90% quantile (Run 9, dashed blue, Run 10, light dashed blue) of the ER background PDFs are overlaid. The solid red line is the median of the AmBe events. The dashed and solid magenta curves are the 100 PE selection cut for $S2$, and the 99.99% NR acceptance curve from the MC calculation, respectively. The gray curves represent the equal energy curves in nuclear recoil energy (keV$_{nr}$).

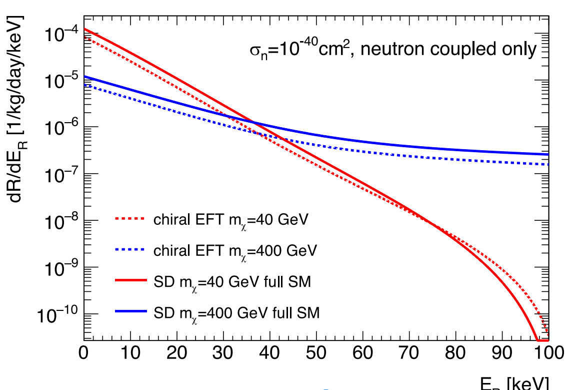
Constraints on Spin-Dependent Interaction

- ***O₄*** SD EFT operator $\mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_N$
  - Full basis shell-model GCN5082
- For proton-only coupling in Xe nucleus
  - *O_4* SD EFT interaction largely suppressed

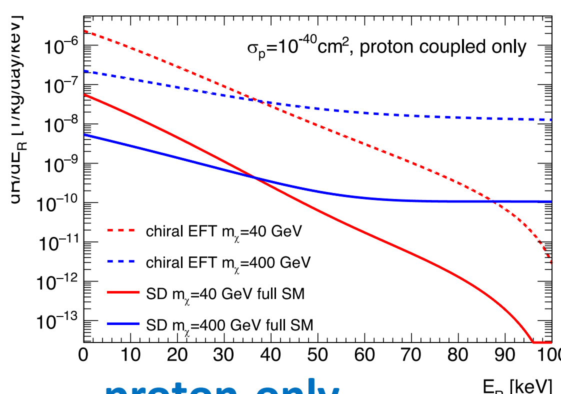
$$\sigma^{\mathrm{SD}}_{p,n}(v) = \left(\frac{c_4}{m_V^2}\right)^2 \frac{\mu^2_{p,n}}{\pi} \frac{J_\chi(J_\chi+1)}{4}$$

- "Standard" SD calculation…
  - chiral EFT
  - O4 + O6 + two nucleon pion-exchange





neutron-only



proton-only