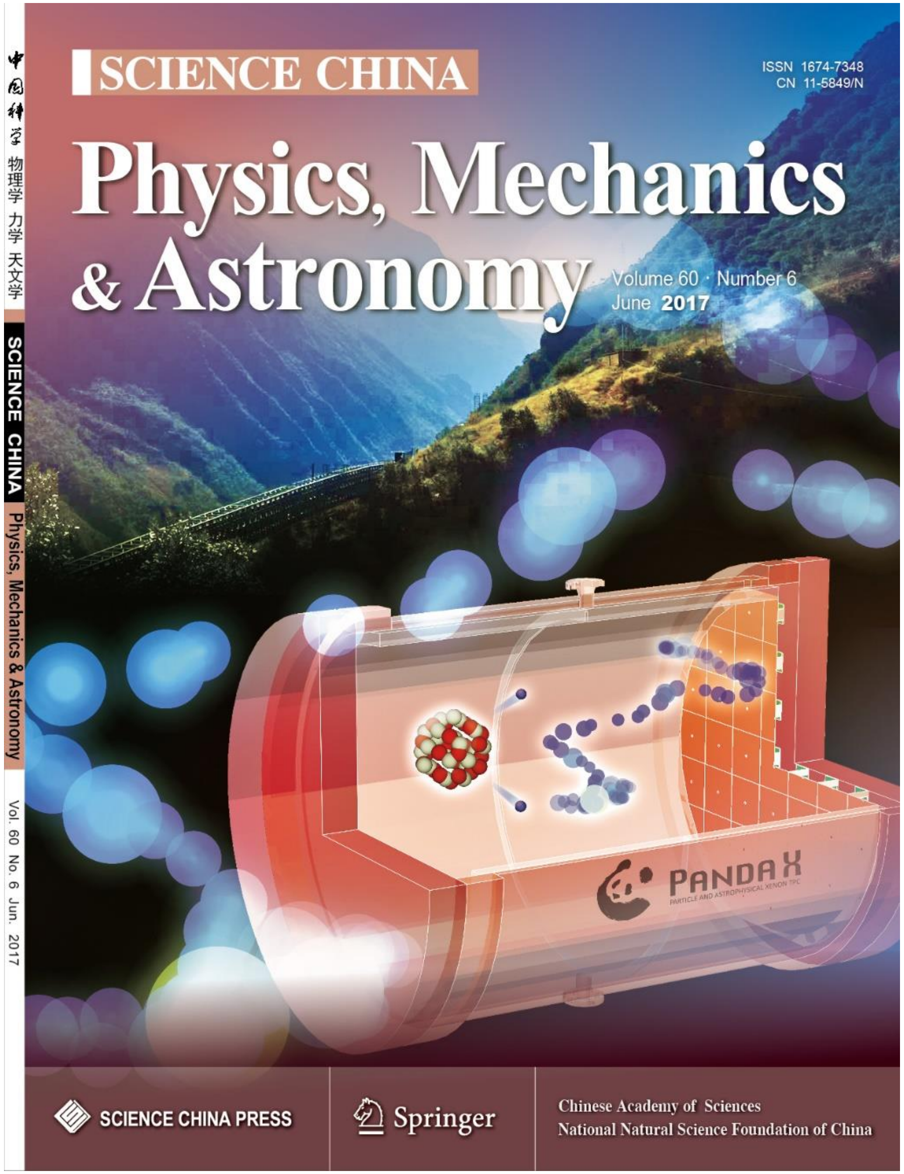
PandaX-III: Neutrinoless Double Beta Decay Search at CJPL

HAN, Ke (韩柯)
Shanghai Jiao Tong University
June 30, 2018

On Behalf of the PandaX-III Collaboration

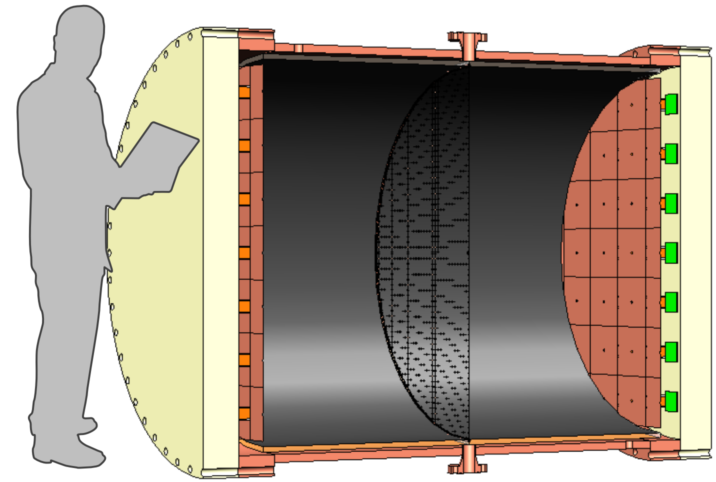
Outline

- PandaX-III project overview
  - Key concept
  - PandaX family
  - Jin-Ping Lab
- The first 200kg-scale module with Micromegas readout
  - Readout plane
  - Electronics
  - Background discrimination
  - Physics reach
- Prototype TPC
  - Design and construction
  - Initial commissioning data

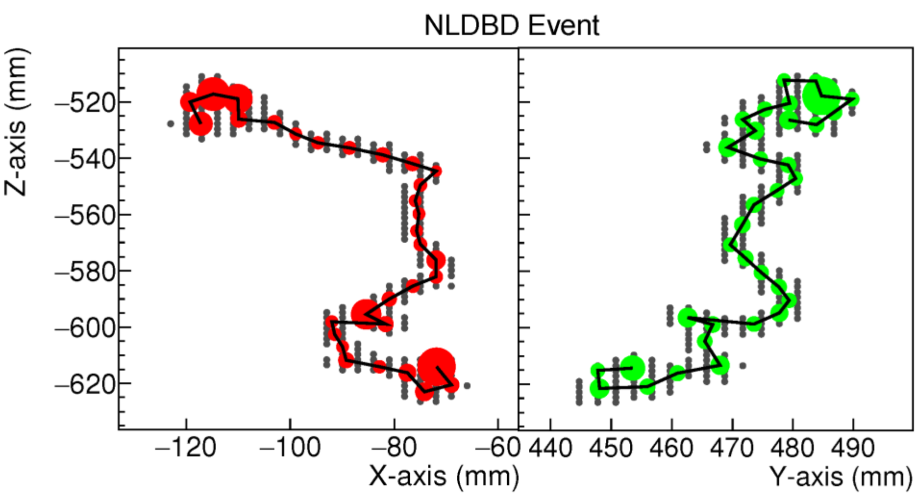


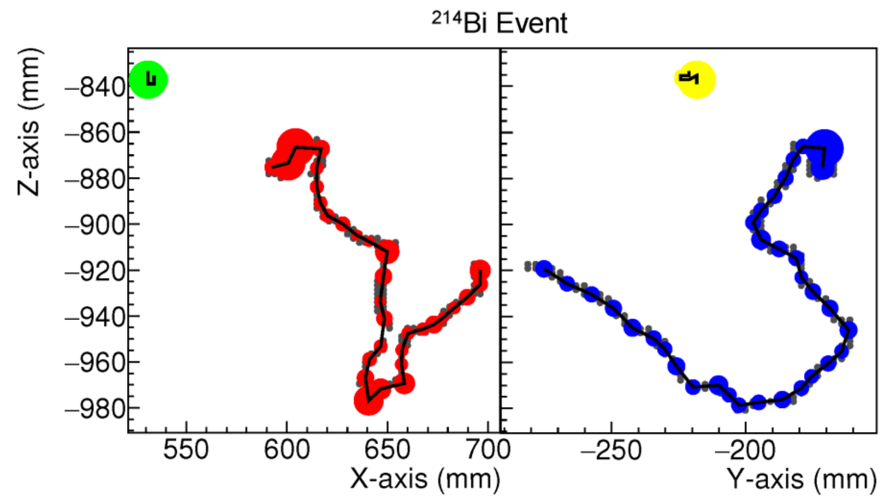
PandaX-III: high pressure gas TPC for $0\nu\beta\beta$ of ^{136}Xe

- 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

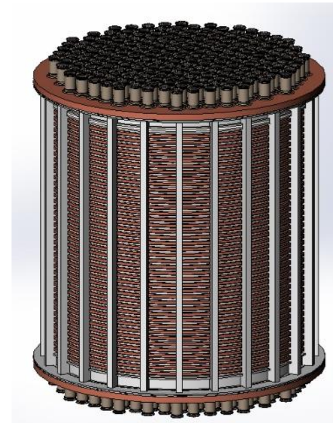




PandaX Projects

PandaX-I: 120kg LXe
(2009 – 2014)

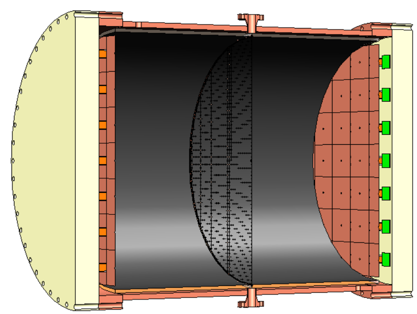
PandaX-II: 500kg LXe
(2014 – 2018)



PandaX-xT LXe
(Future)

Dark matter WIMP searches

PRL 117, 121303 (2016)

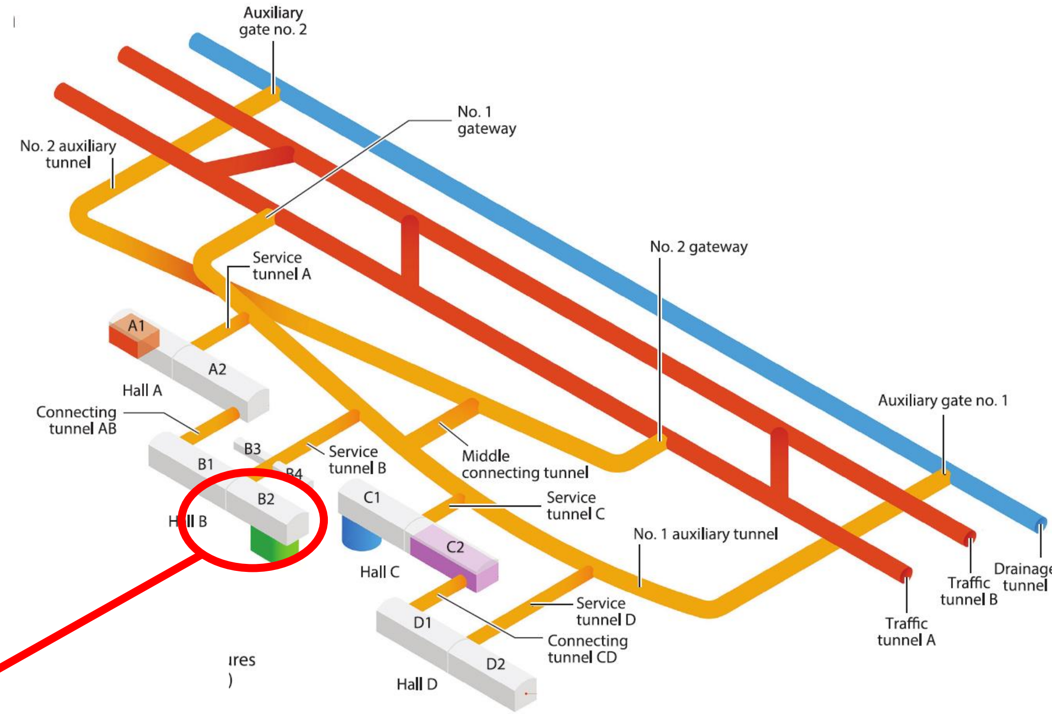


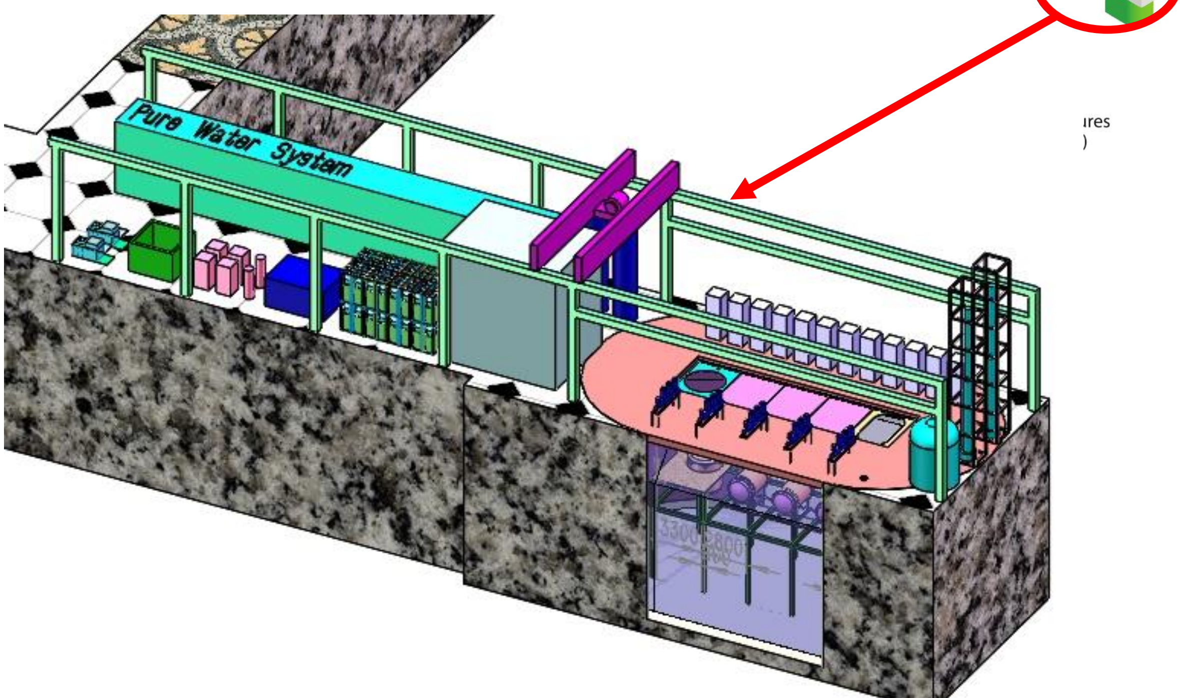
0νββ searches

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

PandaX hall at CJPL-II

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





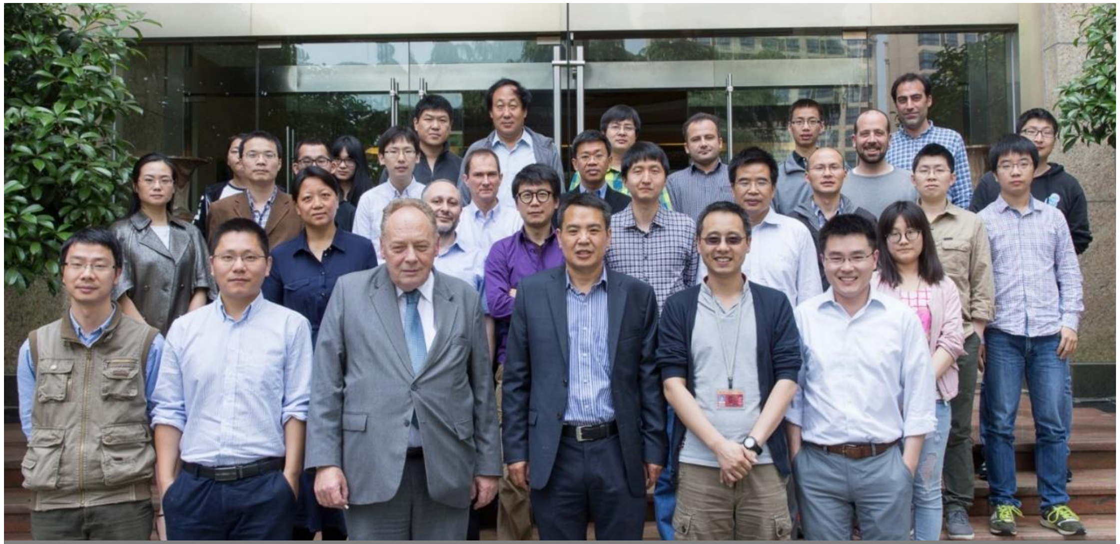
PandaX at Hall B2

- ~ 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.

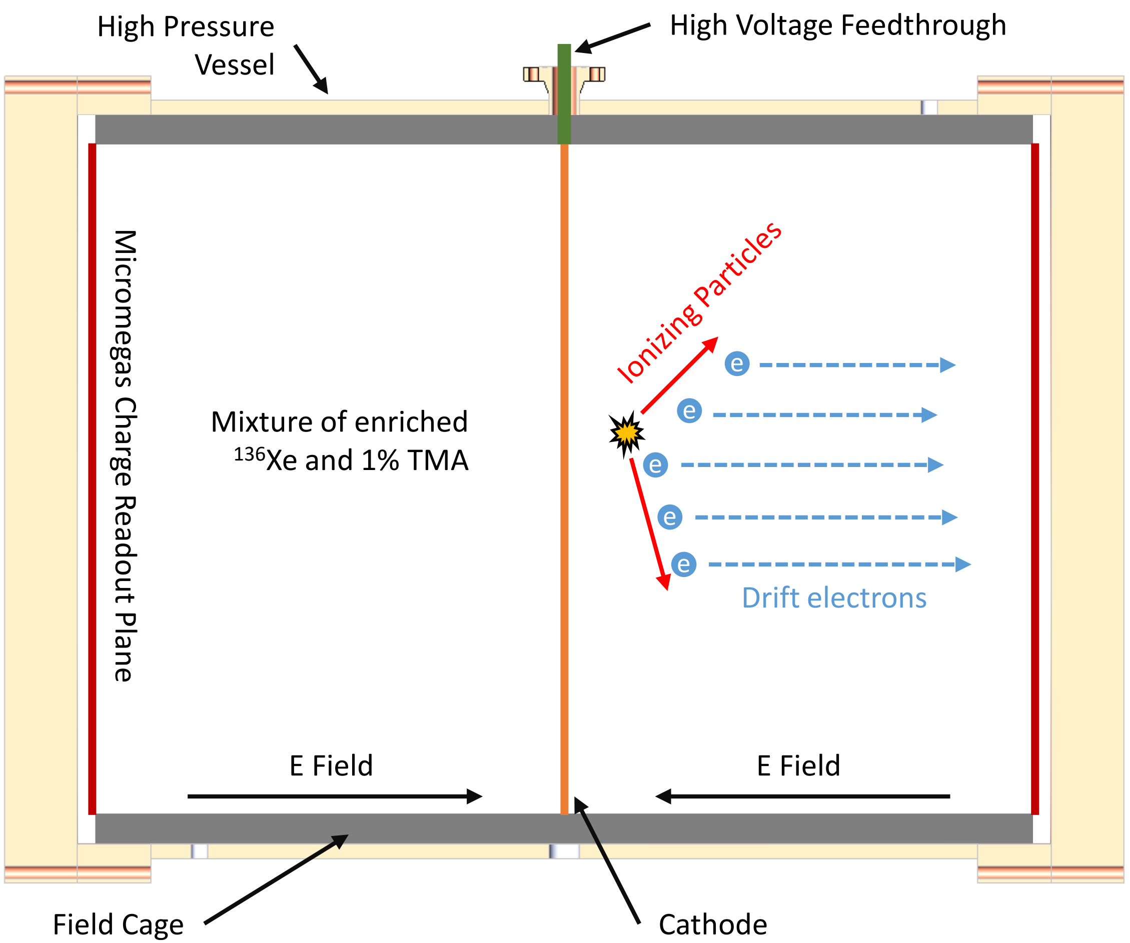
PandaX-III collaboration



PandaX-III Collaboration Meeting, Shanghai, China, May 2016

- Shanghai Jiao Tong University
- Univ. of Science and Technology of China
- Peking University
- China Institute of Atomic Energy
- Sun Yat-Sen University
- Central China Normal University
- Shandong University
- University of Maryland
- Berkeley Lab
- CEA Saclay
- University of Zaragoza
- Suranaree University of Technology (SUT)

PandaX-III first TPC

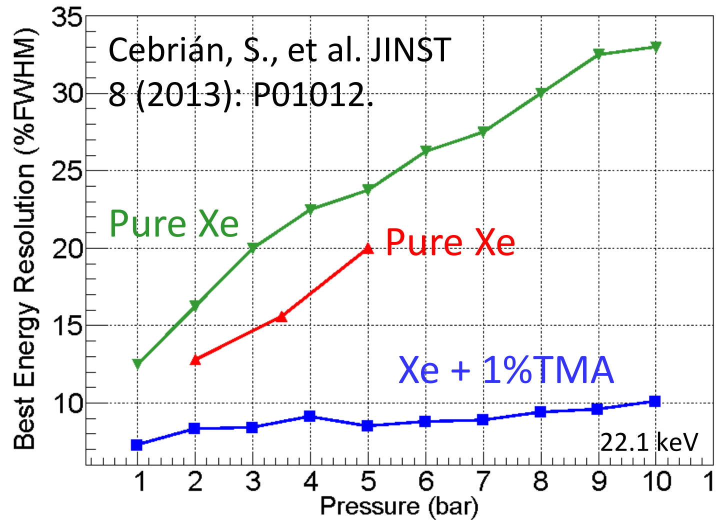


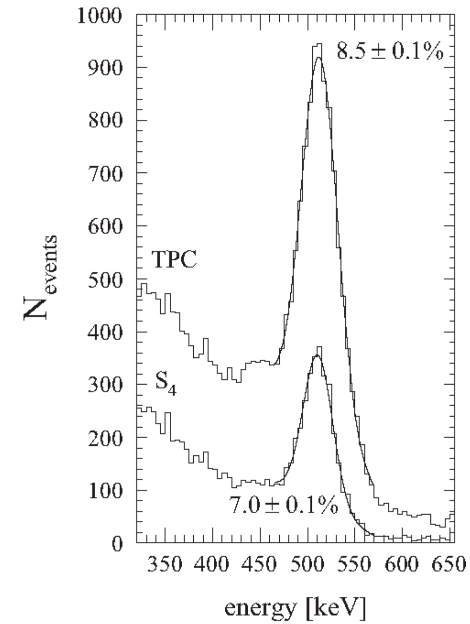
- ~4m^3 active volume
- Copper pressure vessel
- 10 bar working pressure
- 200 kg of enriched xenon
- Xe+TMA gas mixture
- Charge-only readout with Microbulk Micromegas
- Strip readout with 3 mm pitch size
- ~10000 readout channels

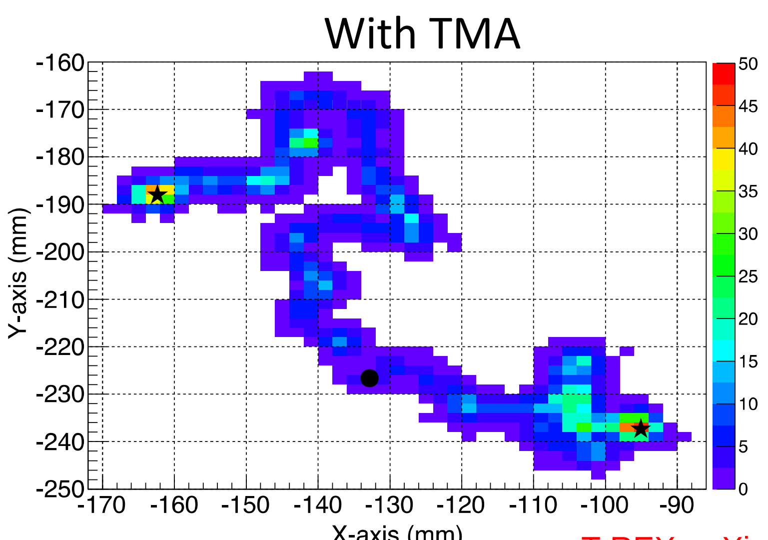
Xe +TMA (trimethylamine) mixture

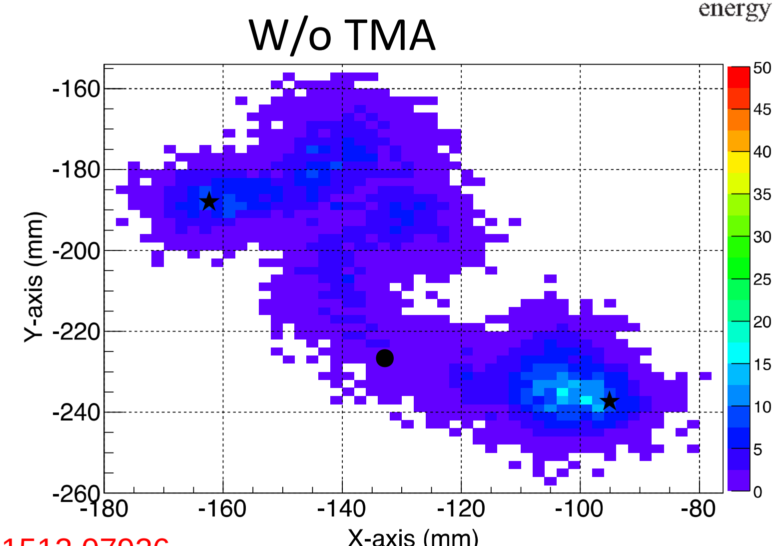
Gonzalez-Diaz, et al. *NIMA* 804 8 (2015)

- 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





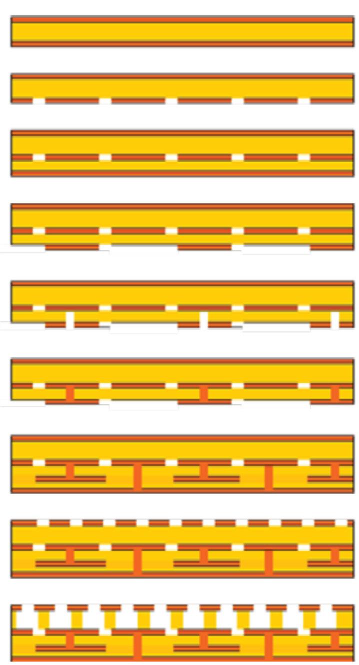




T-REX: arXiv:1512.07926

Microbulk MicroMegas (MM)

- Microbulk MicroMegas films made of Copper and Kapton only
  - Perfect for radio-purity purpose
- ~ 1000X gain
- 3% energy resolution expected at 2.5 MeV.



Double side Cu-coated (5 μm) Kapton foil (50 μm)

Construction of readout strips/pads (photolithography)

Attachment of a single-side Cu-coated Kapton foil

Construction of readout lines

Etching of Kapton

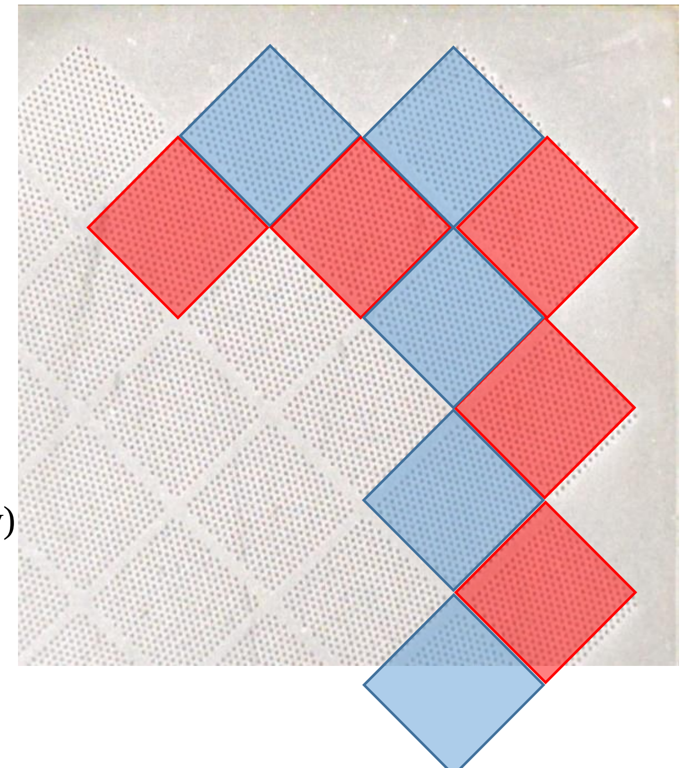
Vias construction

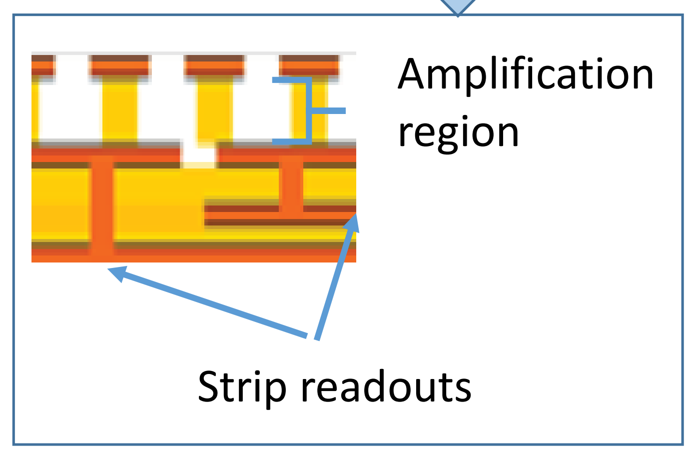
2nd Layer of Cu-coated Kapton

Photochemical production of mesh holes

Kapton etching / Cleaning

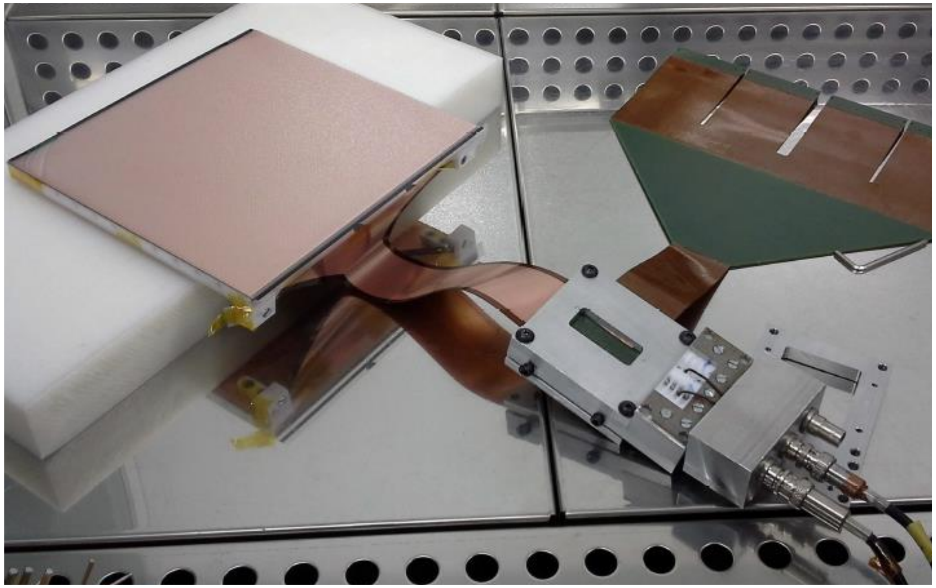
Andriamonje, S. et al. JINST 02 (2010): P02001

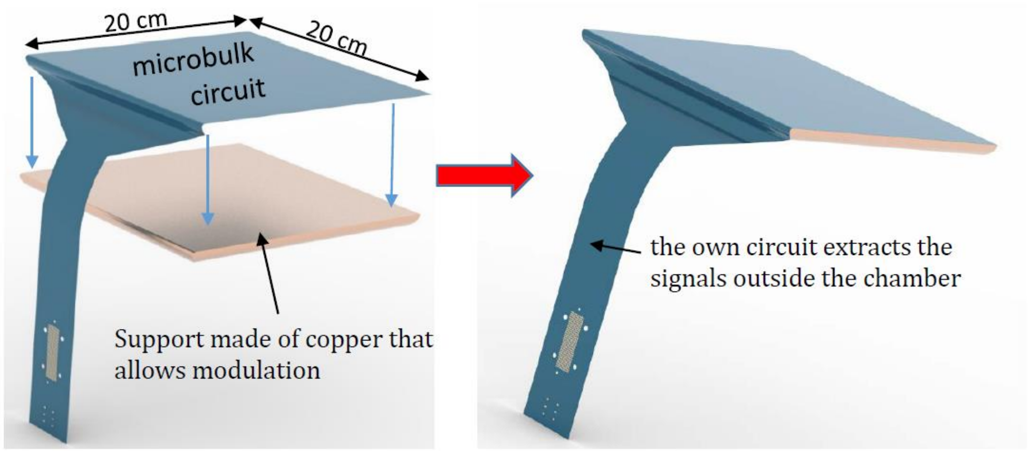


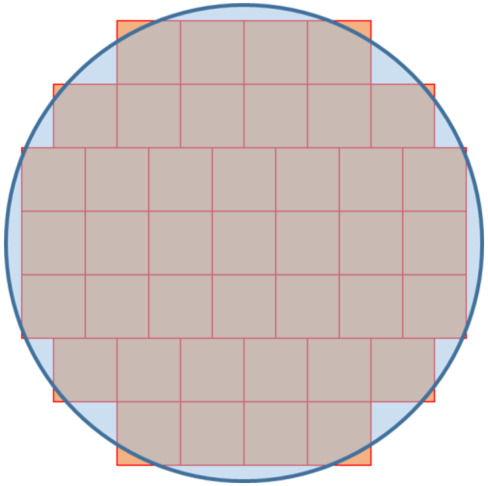


Scalable Radio-pure Readout Module (SR2M)

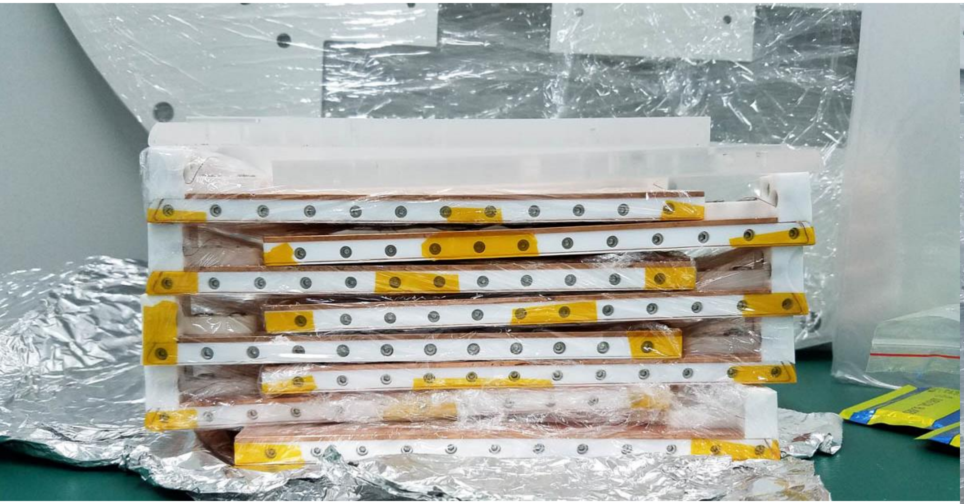
- SR2M: Mosaic layout to cover readout planes
  - Solderless system
  - Strip and mesh signal readout
  - Dead-zone-free arrangement
  - Designed by Zaragoza and SJTU

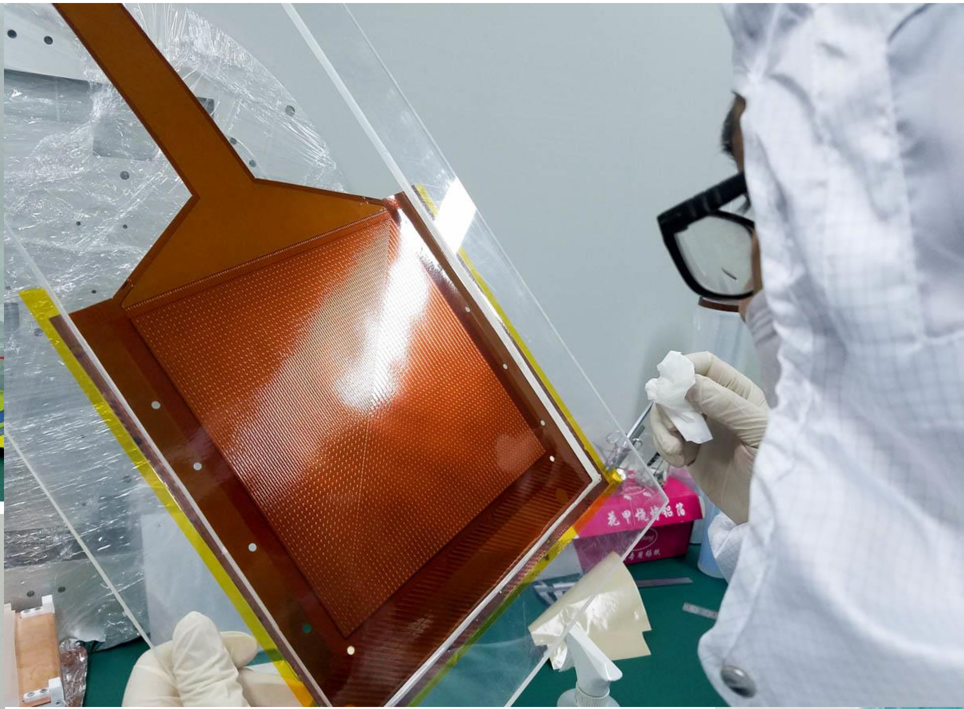


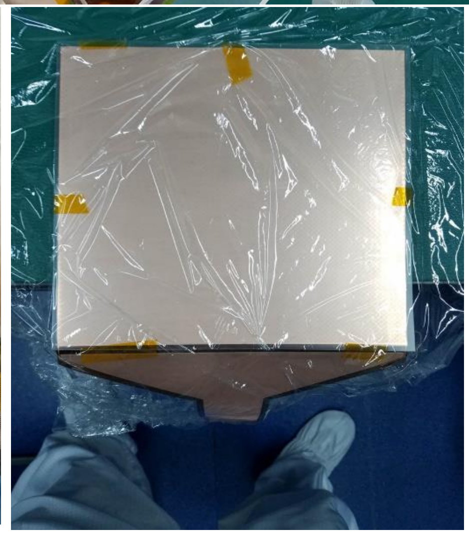




From MM films to SR2M

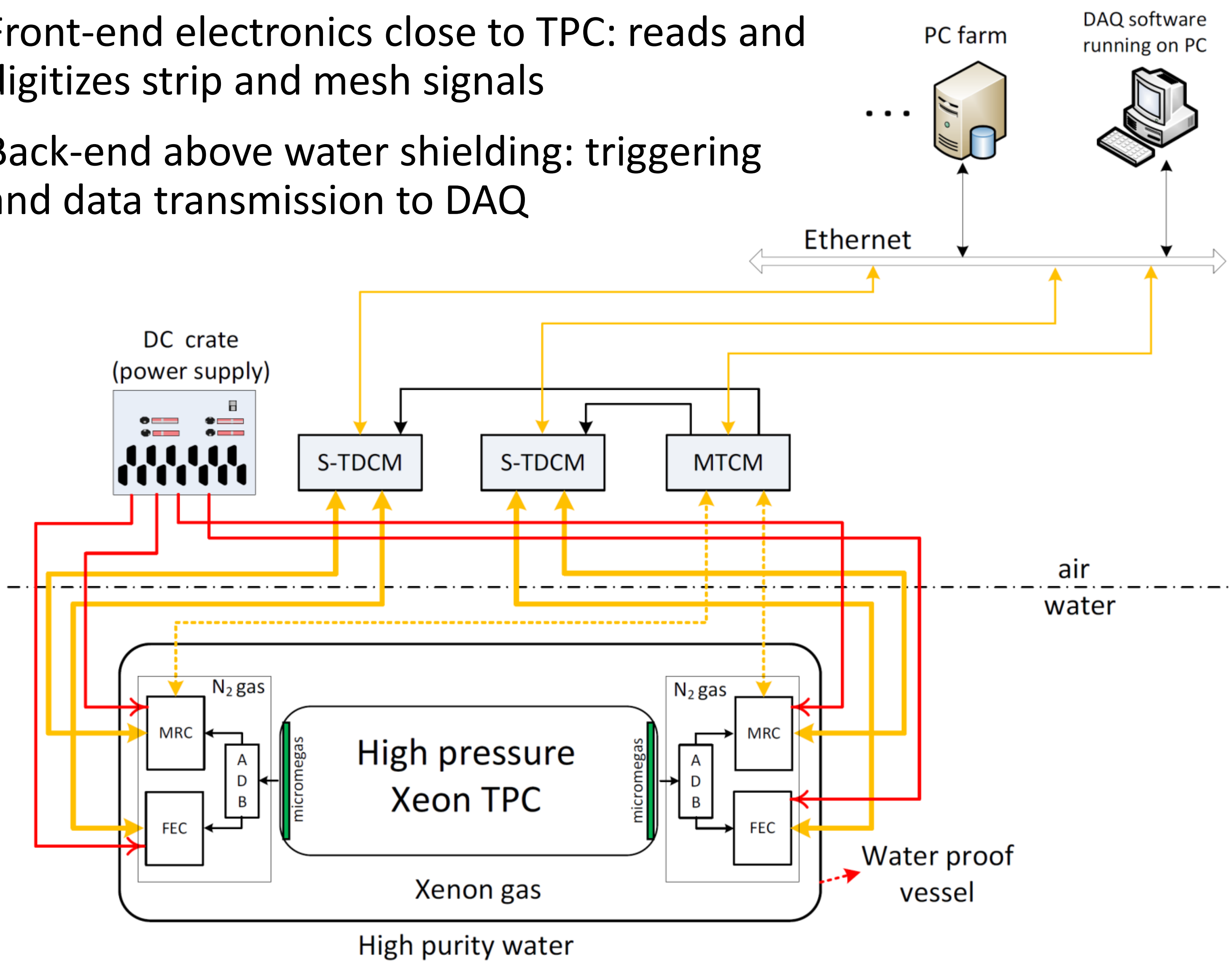






Overview of electronics

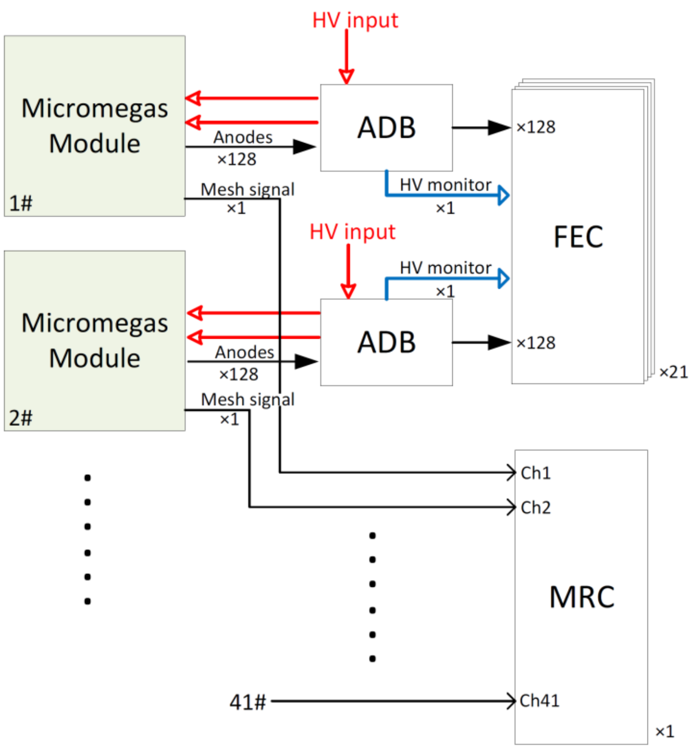
- Front-end electronics close to TPC: reads and digitizes strip and mesh signals
- Back-end above water shielding: triggering and data transmission to DAQ

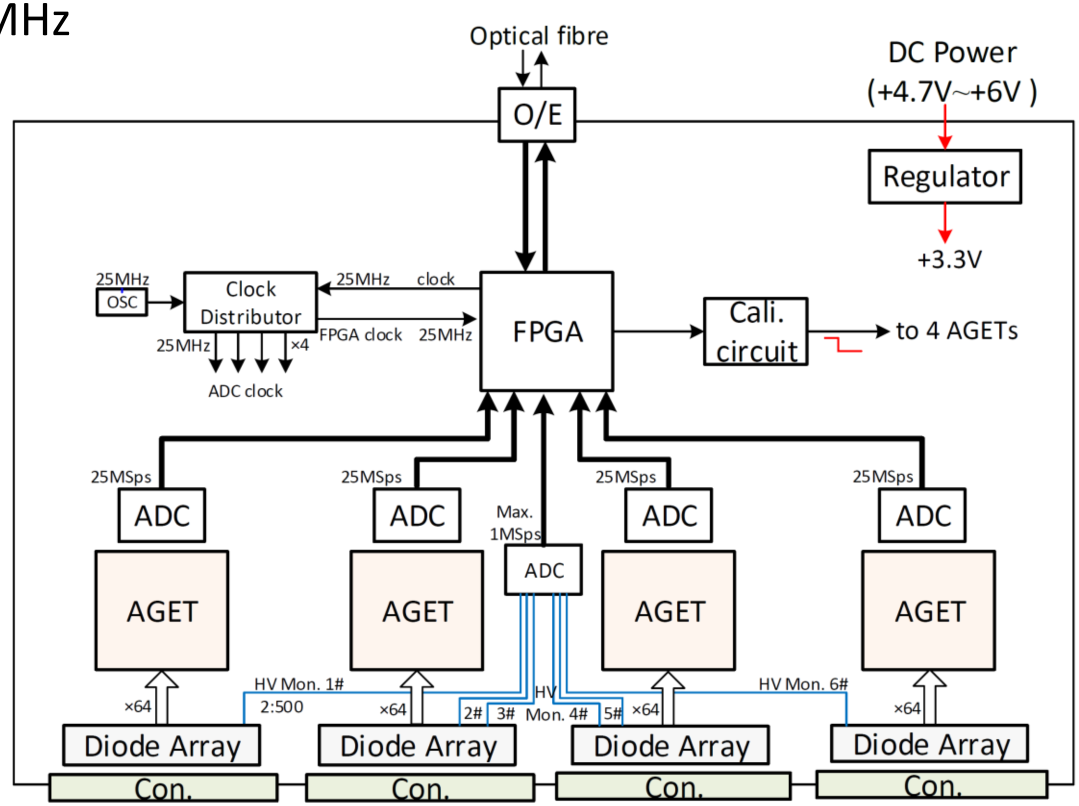


Front end

Based on AGET ASIC chips: generic electronics for TPC from CEA-Saclay

- 64 channel per AGET
- 512 sampling point per channel
- Dynamic range up to 10 pC
- Sampling rate: 1 MHz to 100 MHz



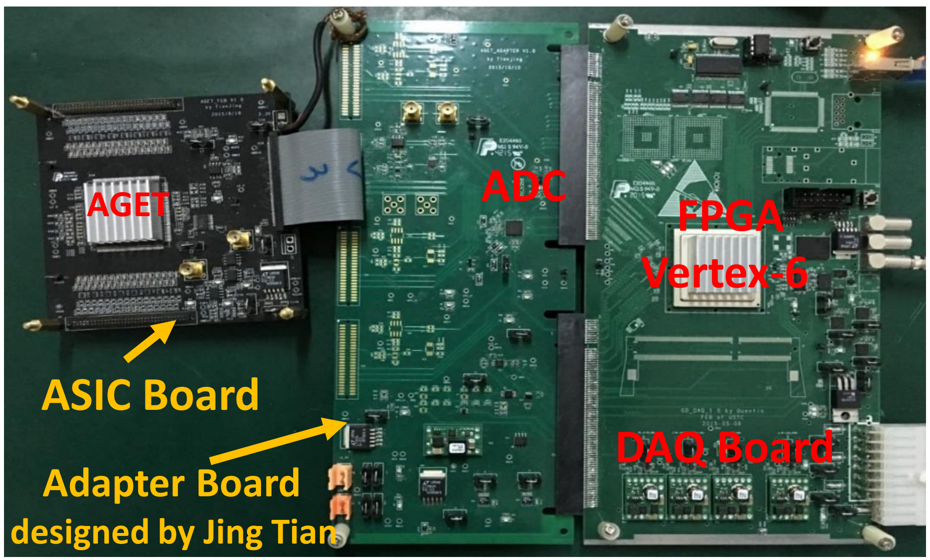


Front end

PANDA X
PARTICLE AND ASTROPHYSICAL XENON TPC

Based on AGET ASIC chips: generic electronics for TPC from CEA-Saclay

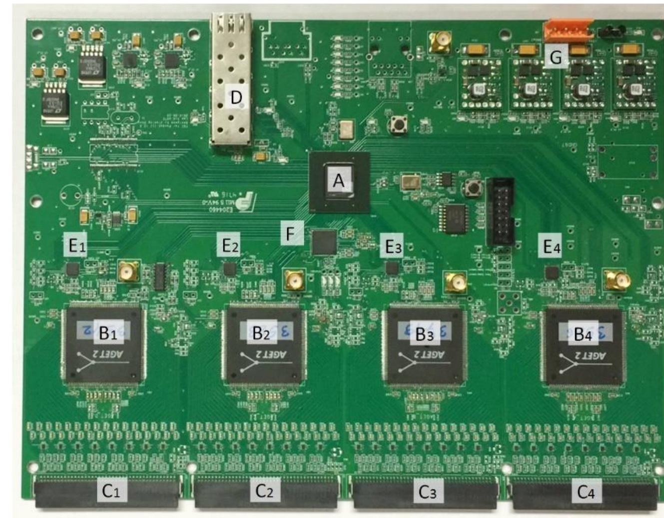
- 64 channel per AGET
- 512 sampling point per channel
- Dynamic range up to 10 pC
- Sampling rate: 1 MHz to 100 MHz



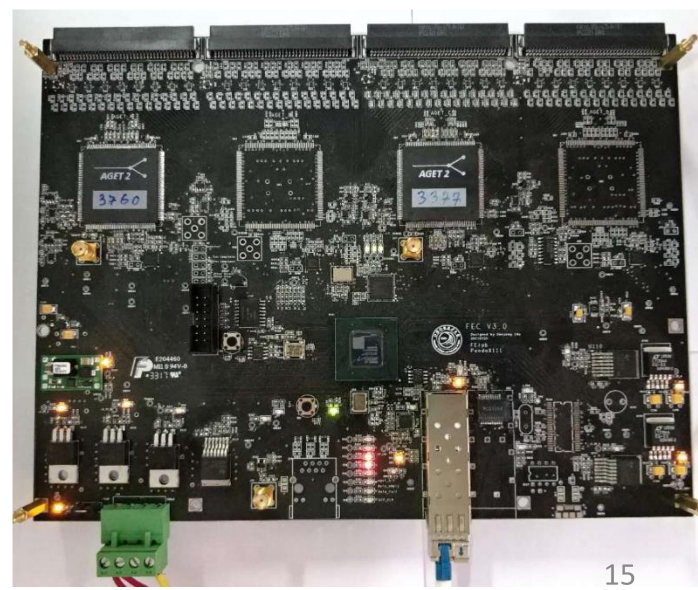
V1

D. Zhu, et al
arXiv:1806.09257

V2



V3



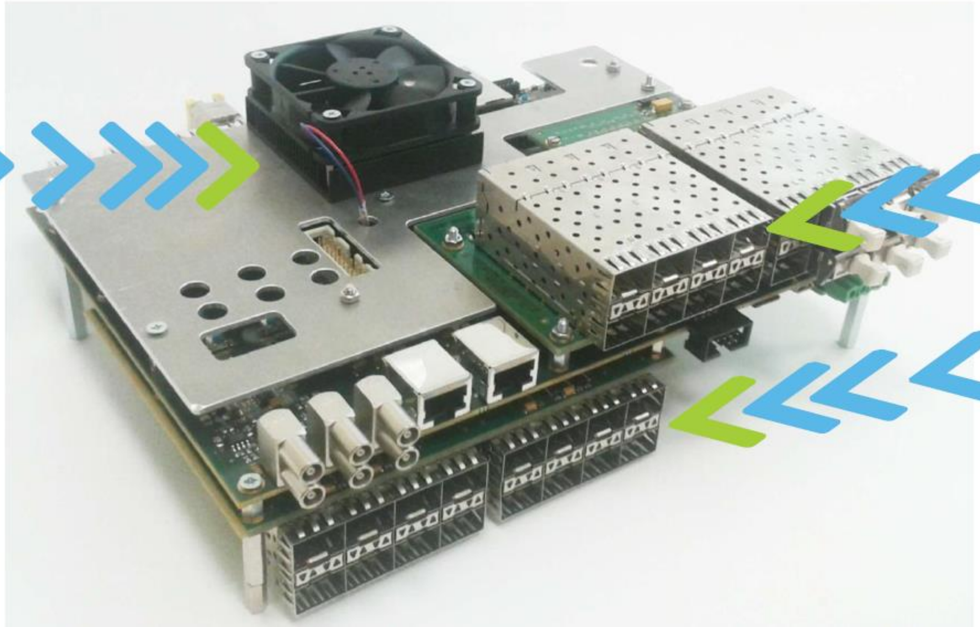
Back end and DAQ

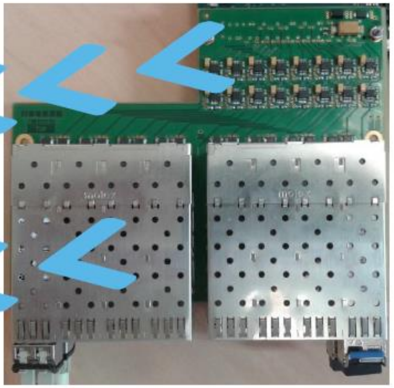
- The Trigger and Data Concentrator Module – TDCM
  - Designed by Saclay for PandaX-III and T2K-II
  - A custom-made 6U form factor carrier board, a commercial FPGA module, and up to two physical layer mezzanine cards
  - Controls up to 32 FECs
- DAQ software based on MIDAS are under development.

D. Calvet, arXiv:1806.07618

Mercury ZX1

ENCLUSTRA FPGA SOLUTIONS

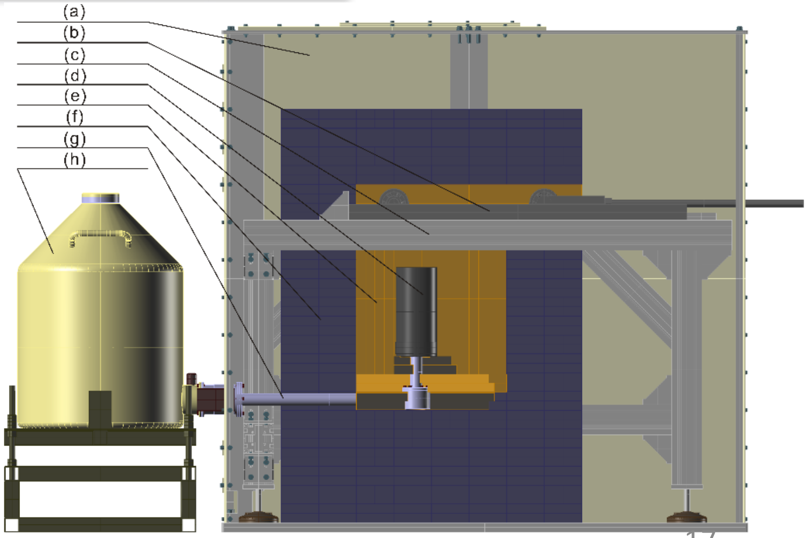




physical layer mezzanine card

Radio-purity control

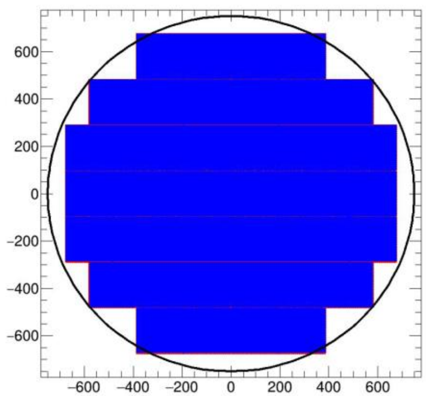
- ICP-MS at PKU (Beijing)
  - Agilent 7900 ICP-MS
  - Class 10 clean room; class 1 for the ICP-MS hood
  - Reaches sub-ppt level for U and Th in materials
- HPGe detectors at CJPL and SJTU
  - Radio-assay of detector materials and electronics components under way
- Low radioactivity environment
  - Rn-free air (by an Ateko system) in the detector assembly region of the lab
  - Rn-control in water shield
  - Rn-emanation measurements

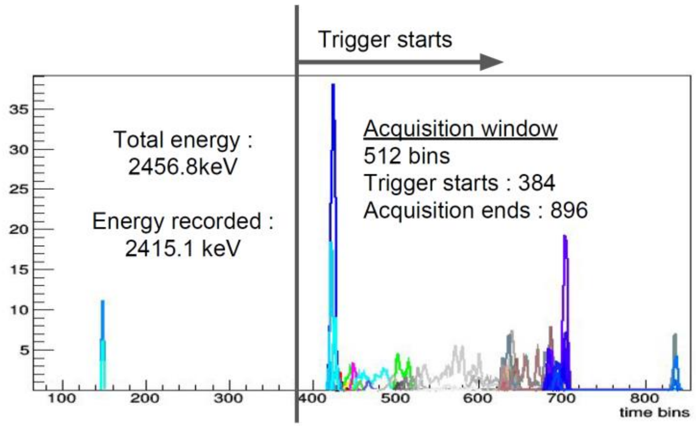


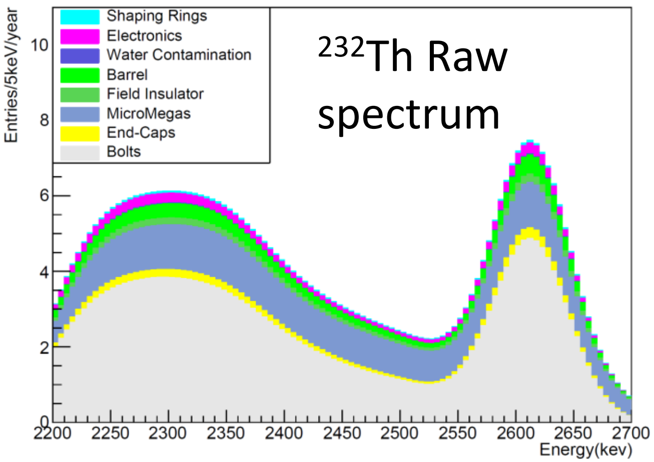
Background budget

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
    - Convoluted neural network



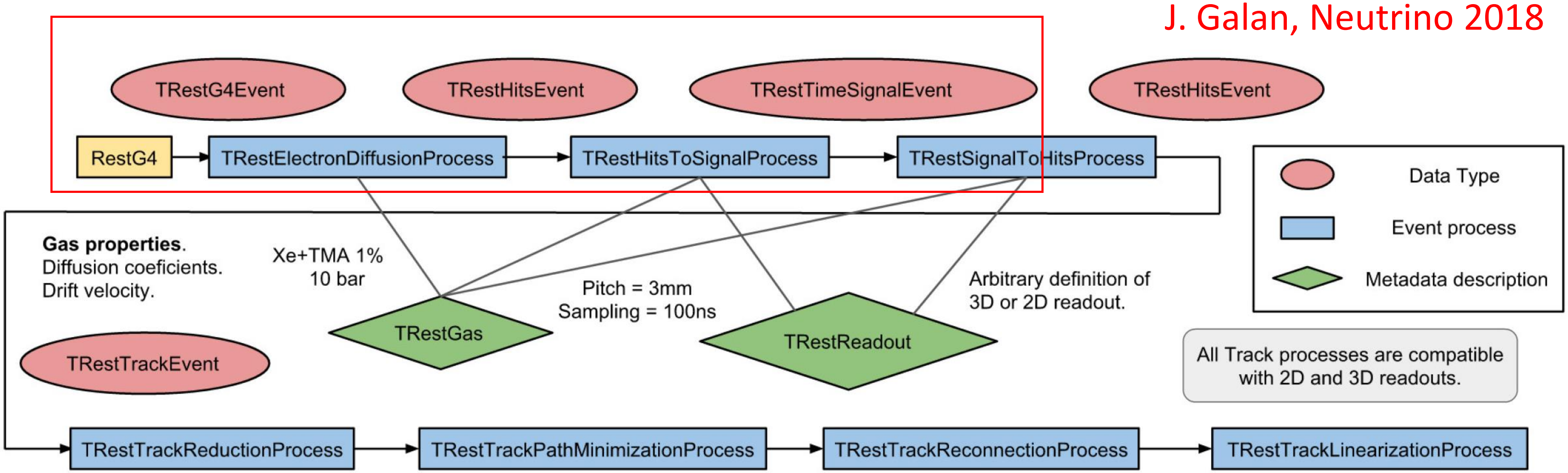




Generating MC signals

- Event tracks from Geant4 (Monte Carlo truth)
- Add electron drift and diffusion with gas parameter inputs from Garfield++
- With definition of a PandaX-III specific charge readout scheme, event tracks are converted to MC signal.
- MC signal pulses are identical to physical pulses from DAQ.

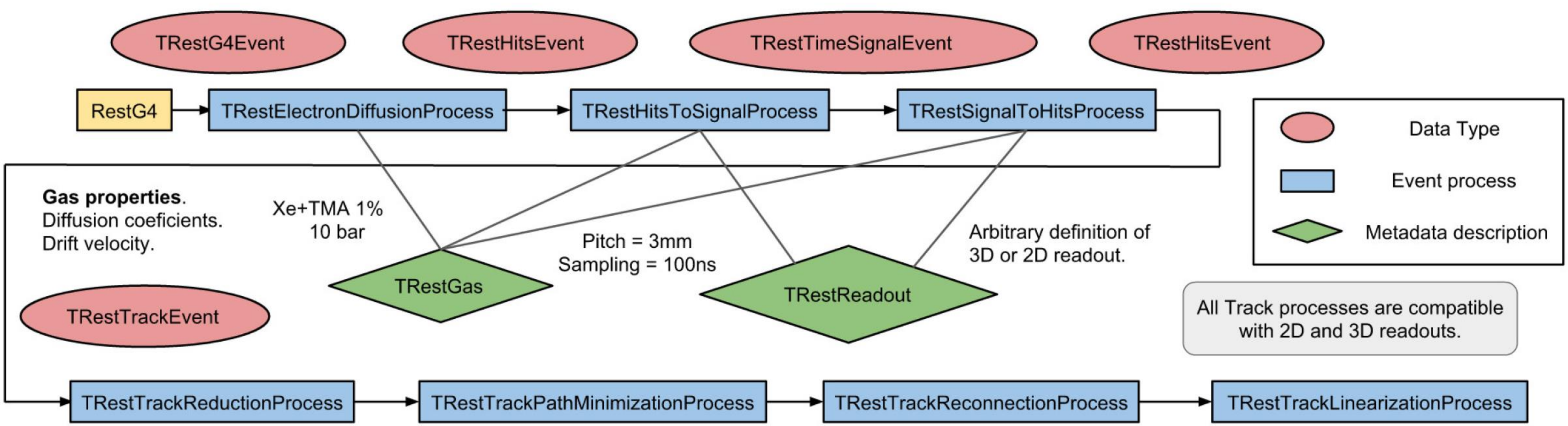
J. Galan, Neutrino 2018



Reconstructing a track

- Converts back from pulses to hits on XZ, YZ, and XY (optional) planes
- Reduces the number of hits inside a track by merging closer hits
- Finds the minimum path between hits inside each track
- Improves physical track description after track minimization
- Projects the hits along the reconstructed track to get dE/dx profile.

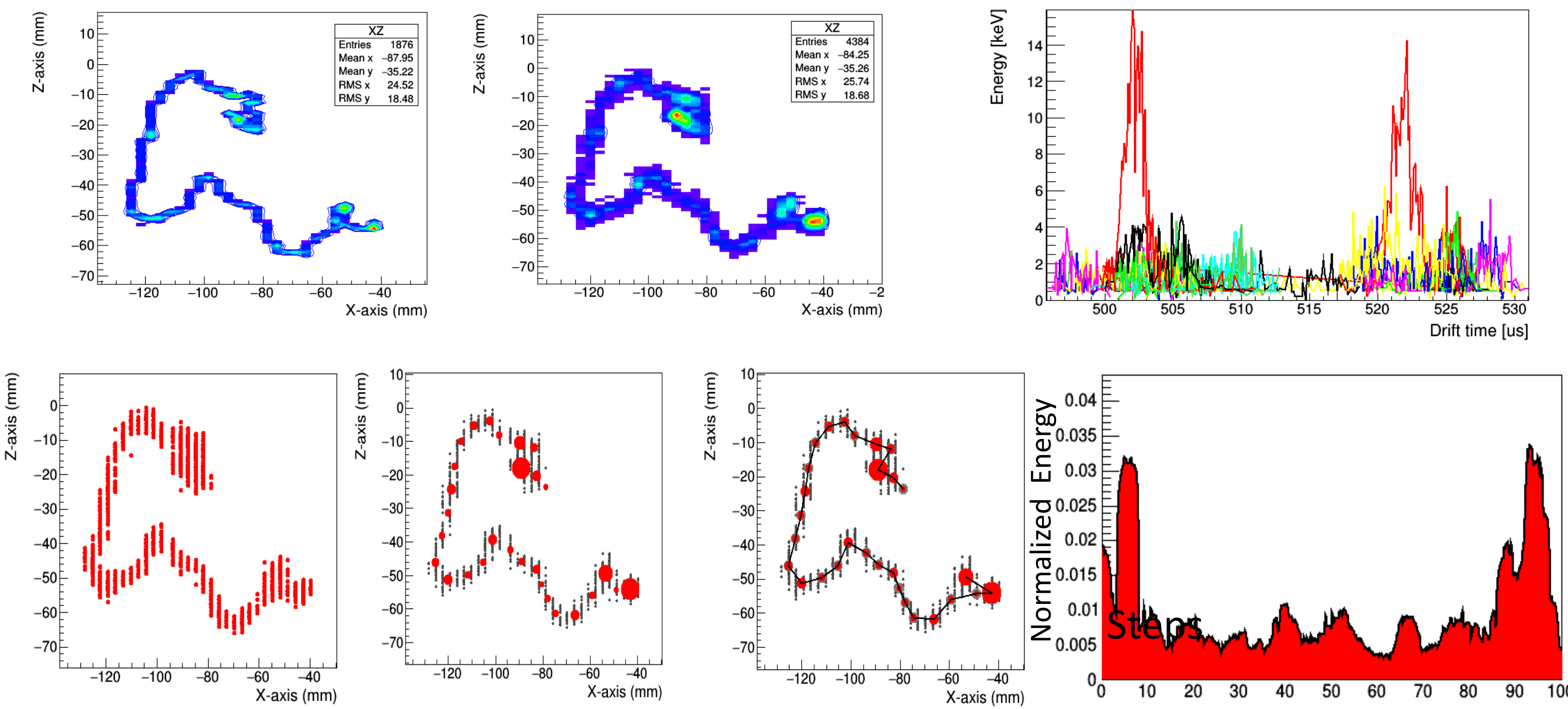
J. Galan, Neutrino 2018



Traditional “cut” based analysis

PANDA X
PARTICLE AND ASTROPHYSICAL XENON TPC

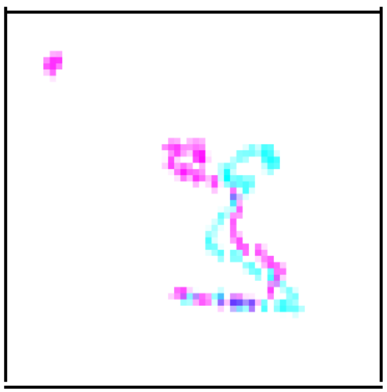
Define key parameters (such as energy deposition in a certain blob) and refine cuts

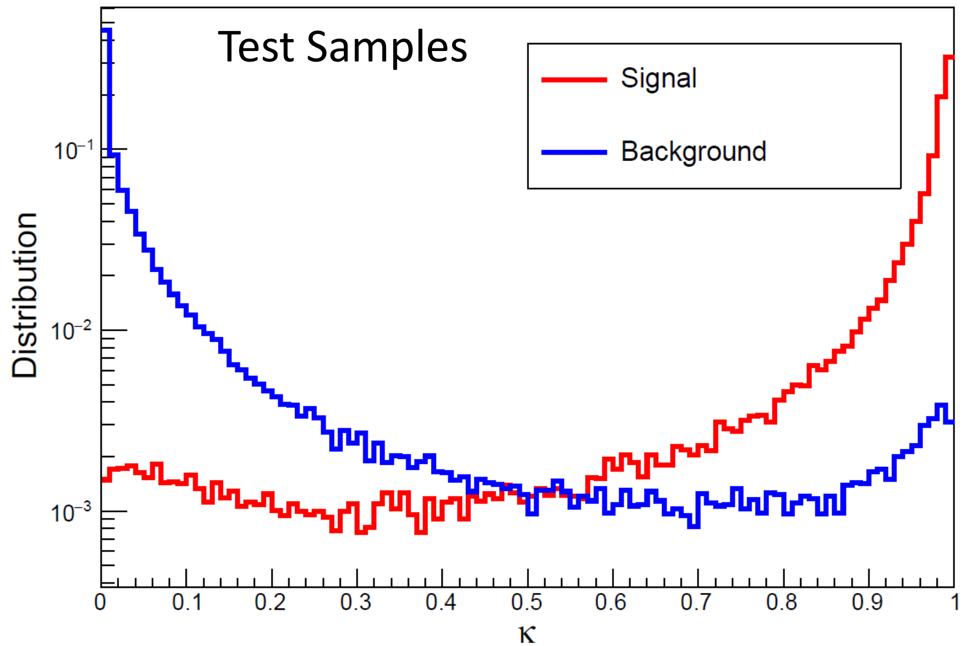


J. Galan, Neutrino 2018

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.

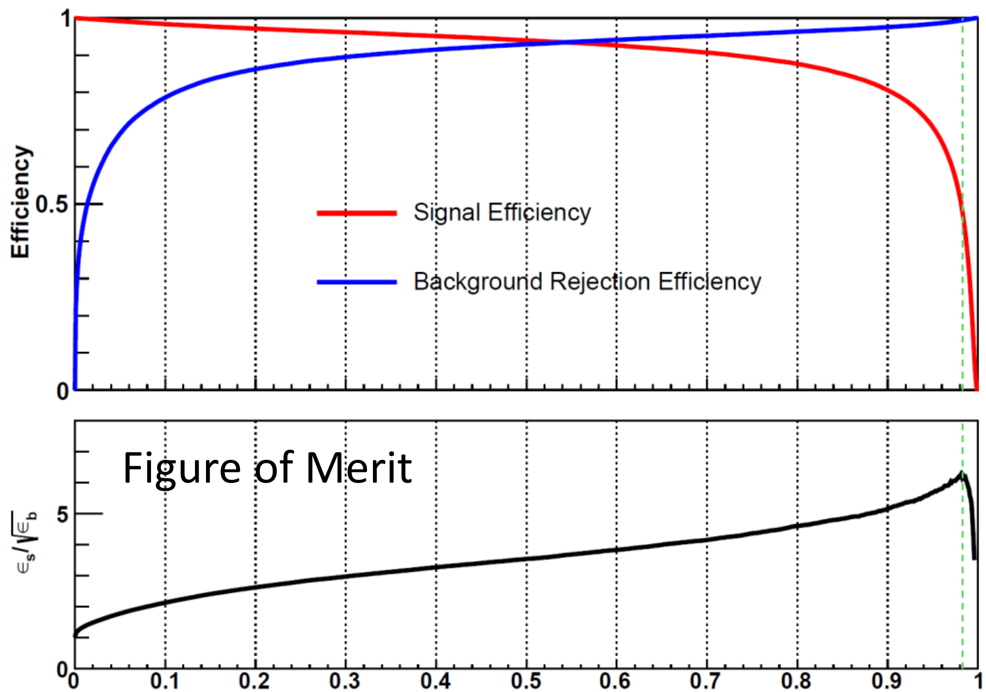




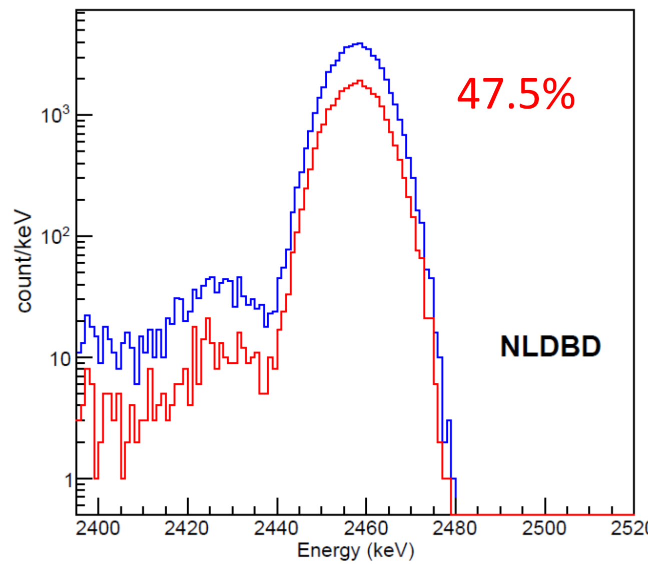
H. Qiao, et al arXiv:1802.03489

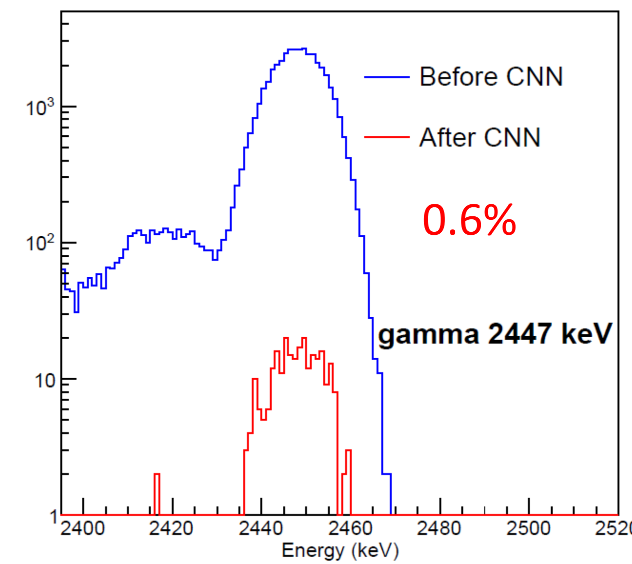
Impact on Signal/Background Spectra

- Signal/background selection based on the CNN index
- Improved figure of merit compared to the traditional method.

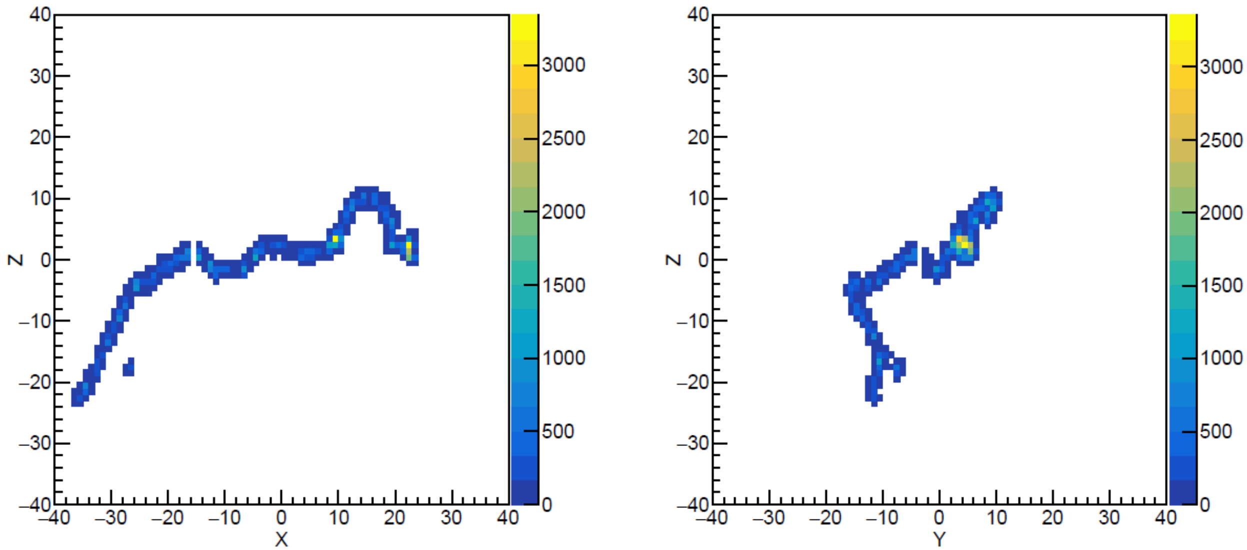


H. Qiao, et al arXiv:1802.03489

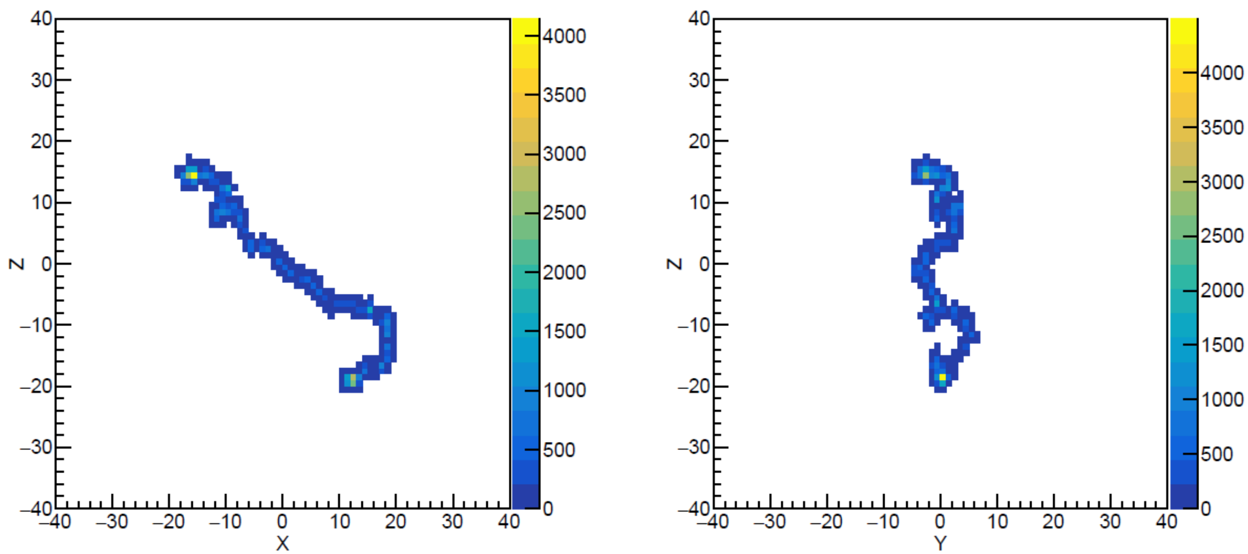




Examples of mis-identified events



Signal mis-identified as background

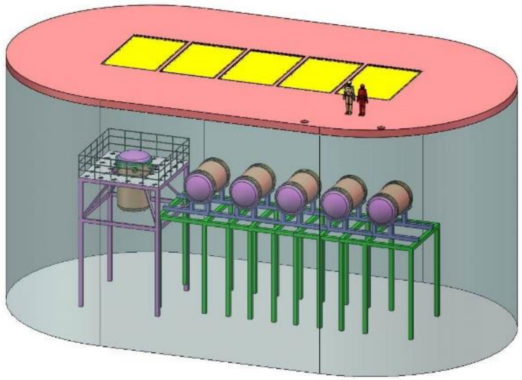


Background mis-identified as signal

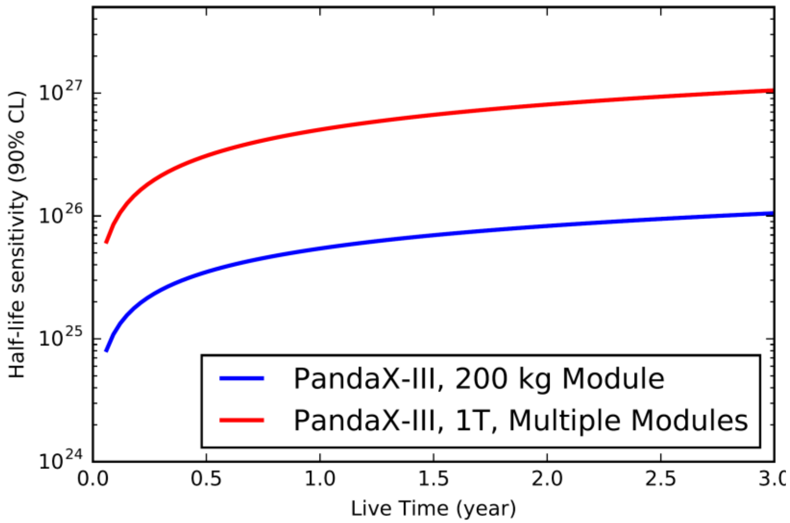
H. Qiao, et al arXiv:1802.03489

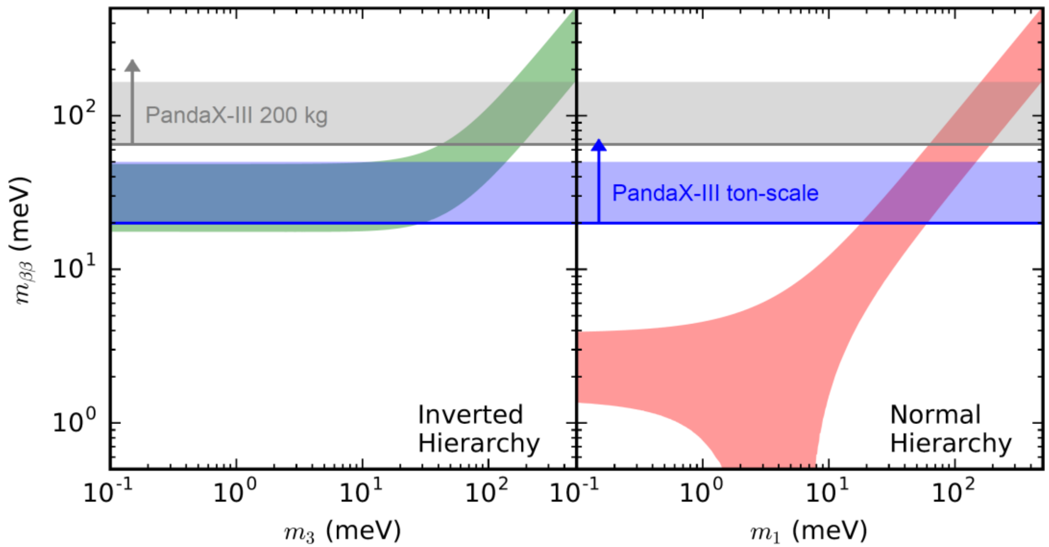
Sensitivity projection

- 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



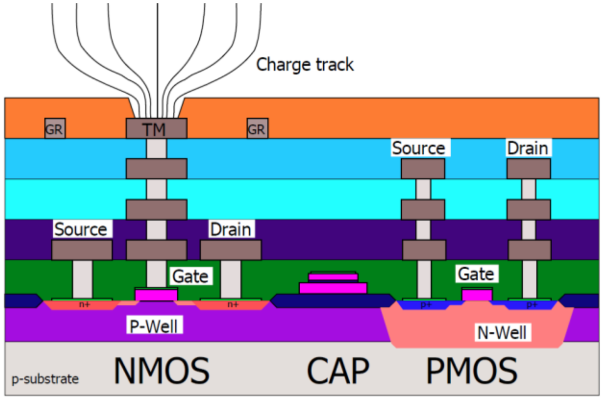
arXiv:1610.08883

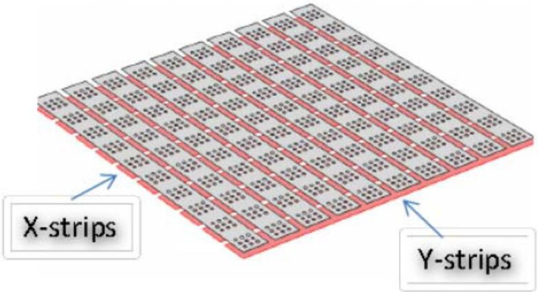


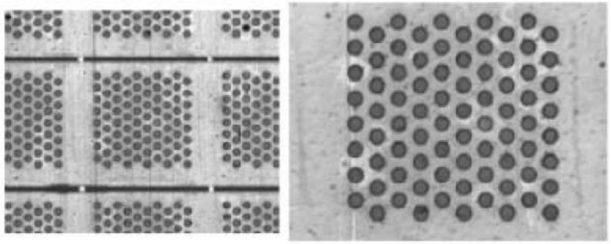


Future energy resolution improvement

- TopMetal Direct Charge Sensor
  - Direct pixel readout without gas amplification
- Alternative Micromegas technologies
  - Microbulk technology with segmented mesh for true X and Y strips
  - Bulk technology with better uniformity and less dead area





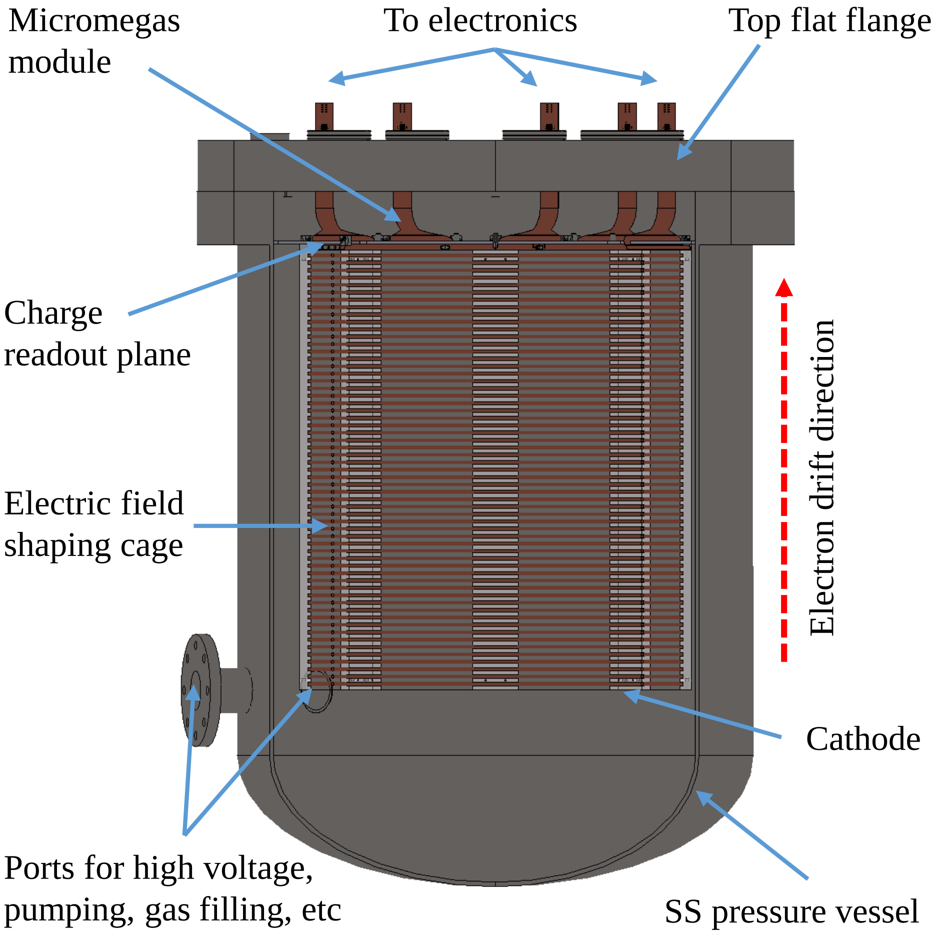


PandaX-III Prototype TPC

- To see MeV electron tracks
- To demonstrate required energy resolution with a large-scale high pressure TPC
- To optimize the design of Micromegas readout plane
- To develop algorithm of 2D/3D track reconstruction

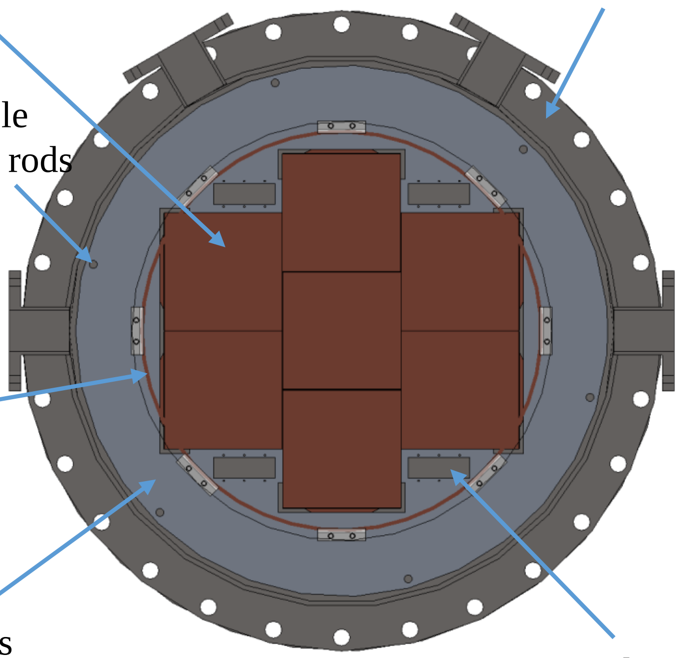
Prototype TPC at Shanghai

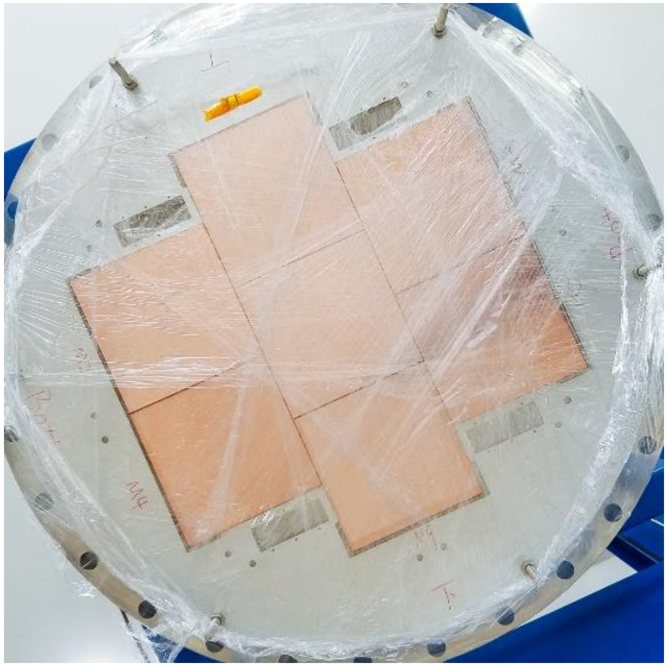
- About 600 L inner volume
- Field cage: 66 cm diameter, 78 cm drift length, single-ended
- 16 kg of xenon at 10 bar
- SS pressure vessel



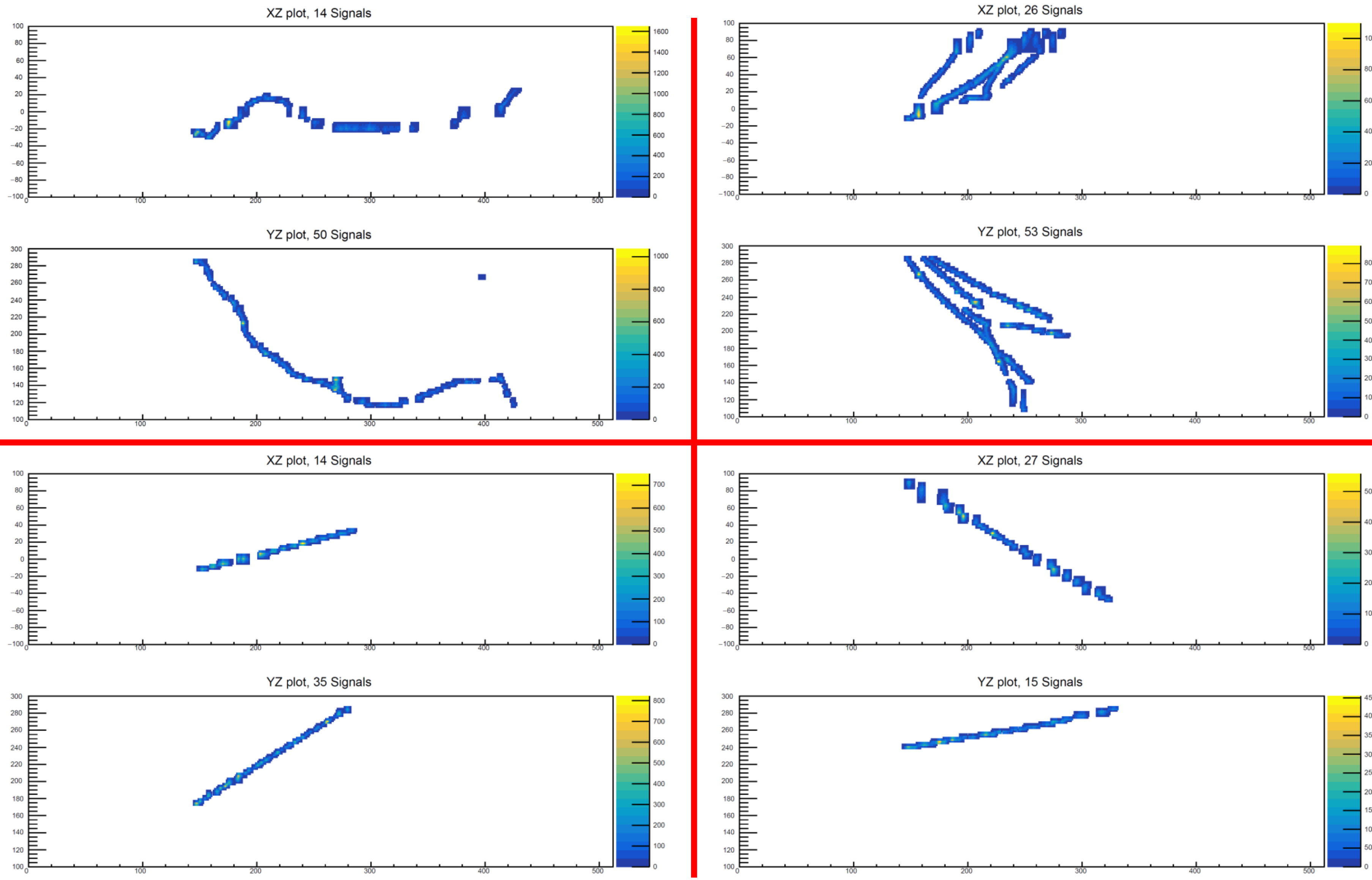
Charge readout plane

7 Microbulk Micromegas modules installed and commissioned





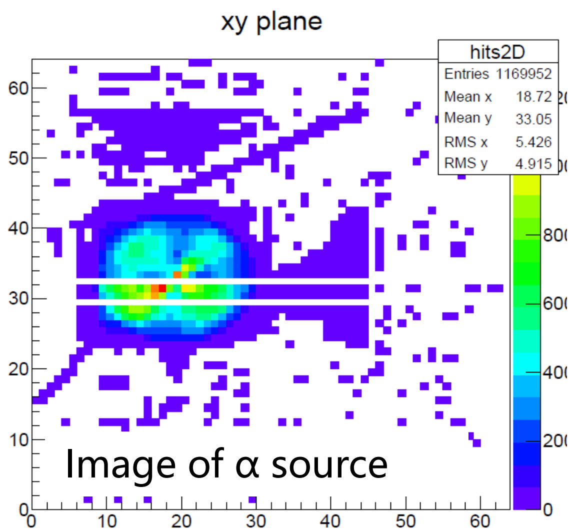
Some example tracks

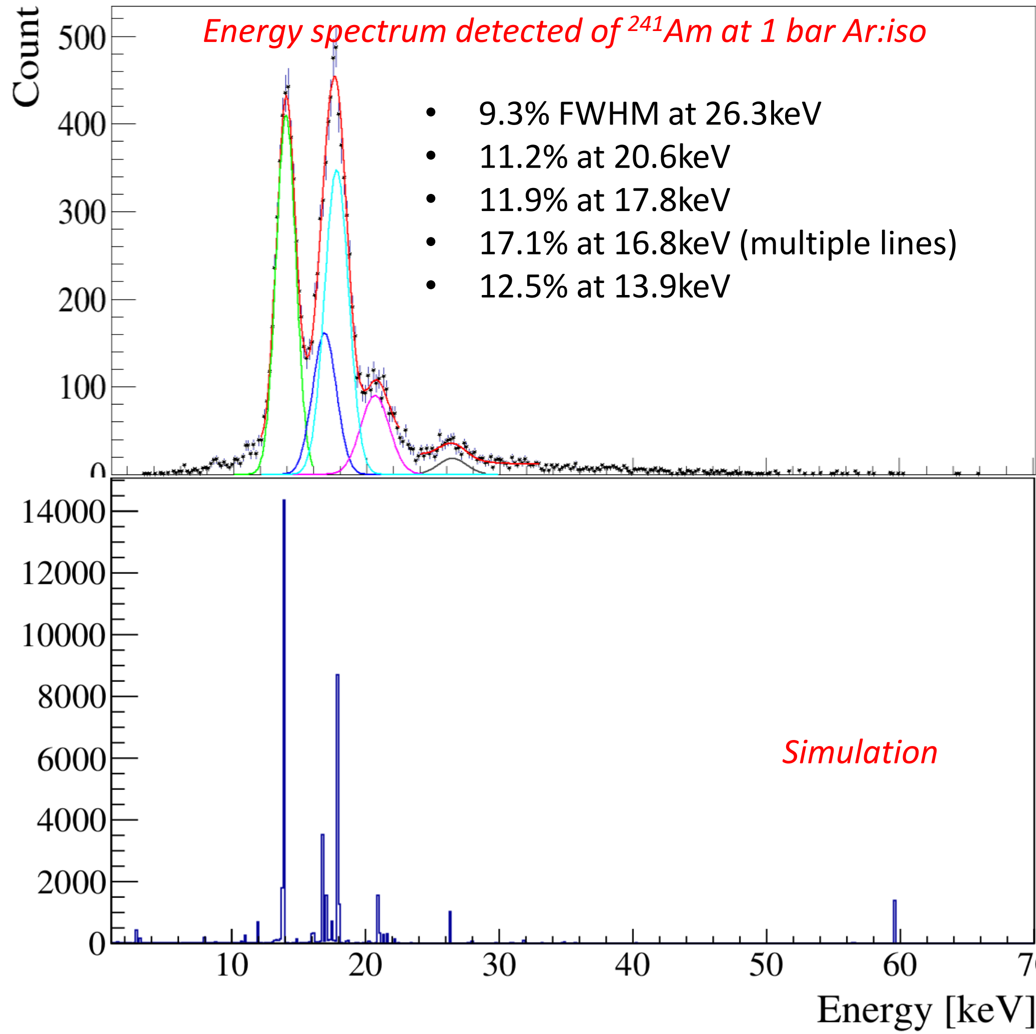


Data: 1 MM with 1bar Ar:(5%)Isobutane

- ^{241}Am Gamma source
- Voltage configuration:
  - Mesh: -370V
  - Drift: -2.8 kV ~-11.8 kV
- Electronics range: 1pC

Detector gain ~8000

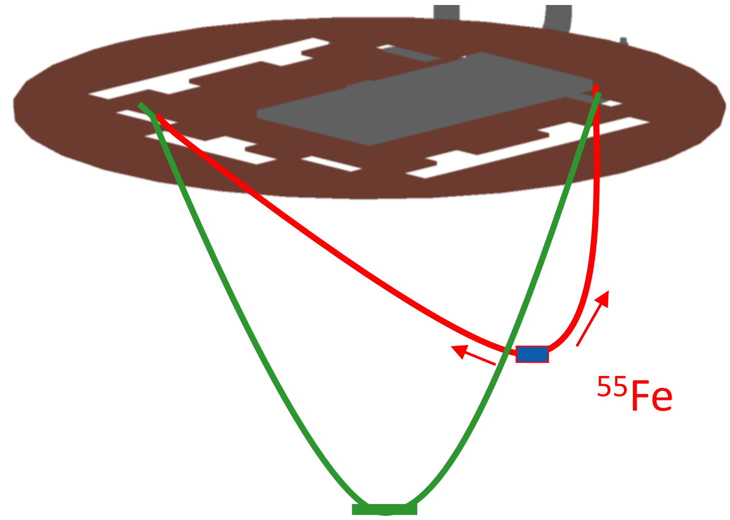


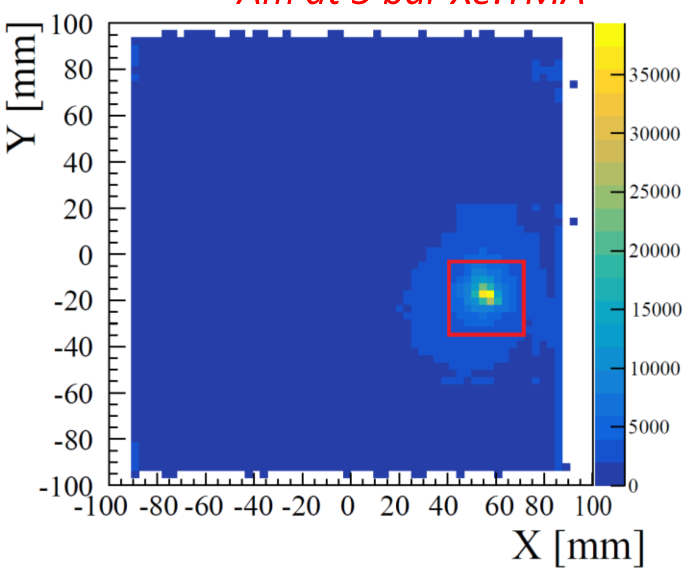


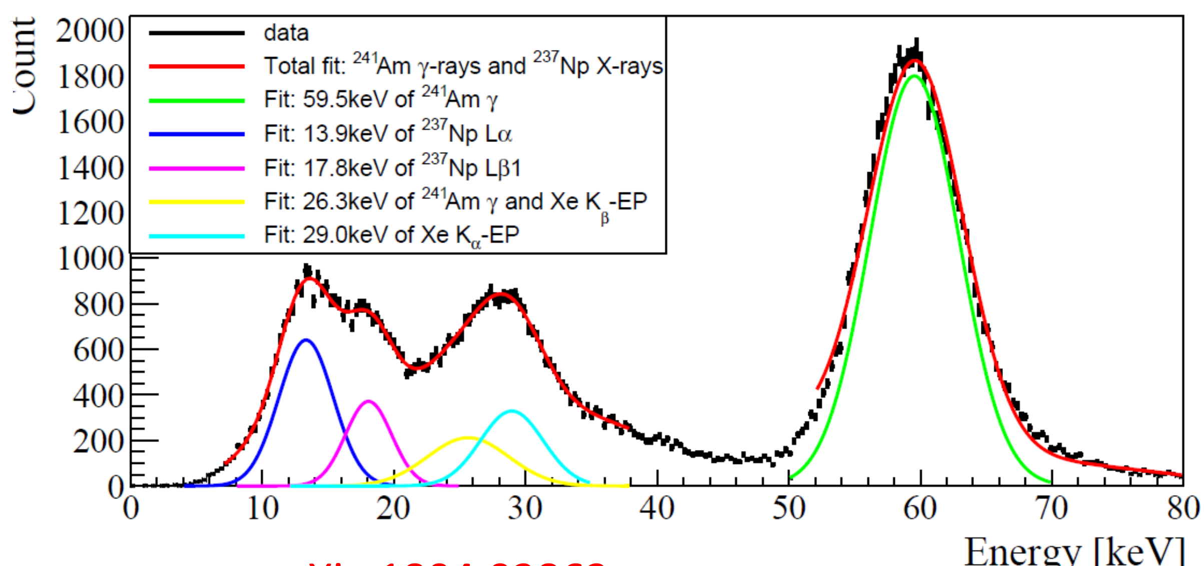
arXiv:1804.02863

Data: 5 bar Xe:(1%)TMA

- Reached stable gain after more than 1 week of circulation and purification
- FWHM: 14.1% at 59.5 keV
- Drift voltage of -26 kV; mesh voltage of -440 V.



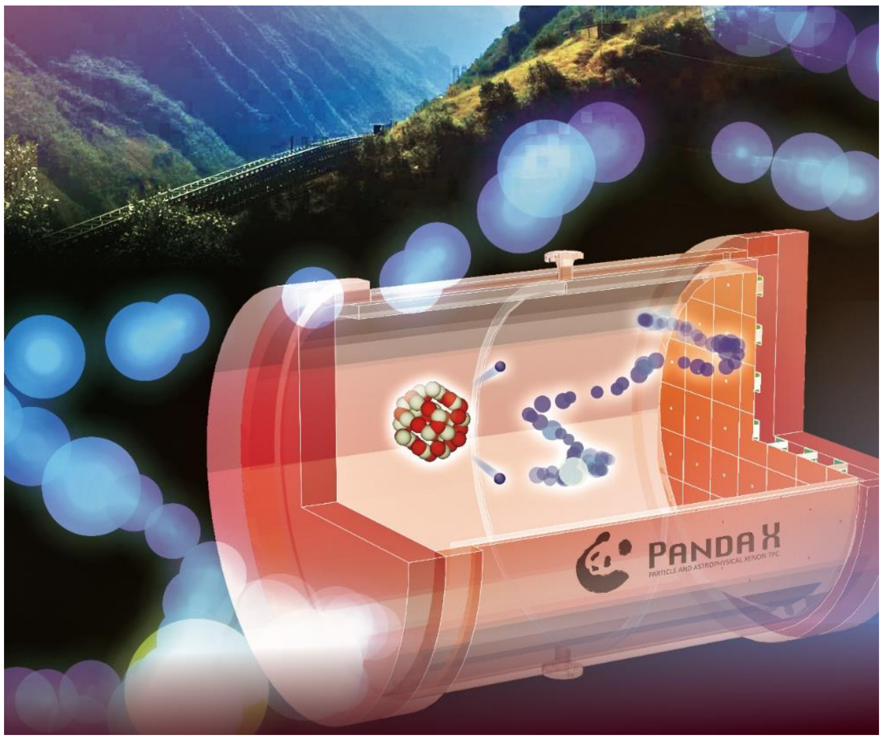




arXiv:1804.02863

Conclusions

- PandaX-III aims to build multiple 200-kg scale high pressure xenon TPC for NLDBD search at CJPL.
- The first module is under technical design phase.
- A 20-kg scale prototype TPC is under commissioning.
- With 7 modules of 20×20 cm, it's the largest application of Microbulk Micromegas.



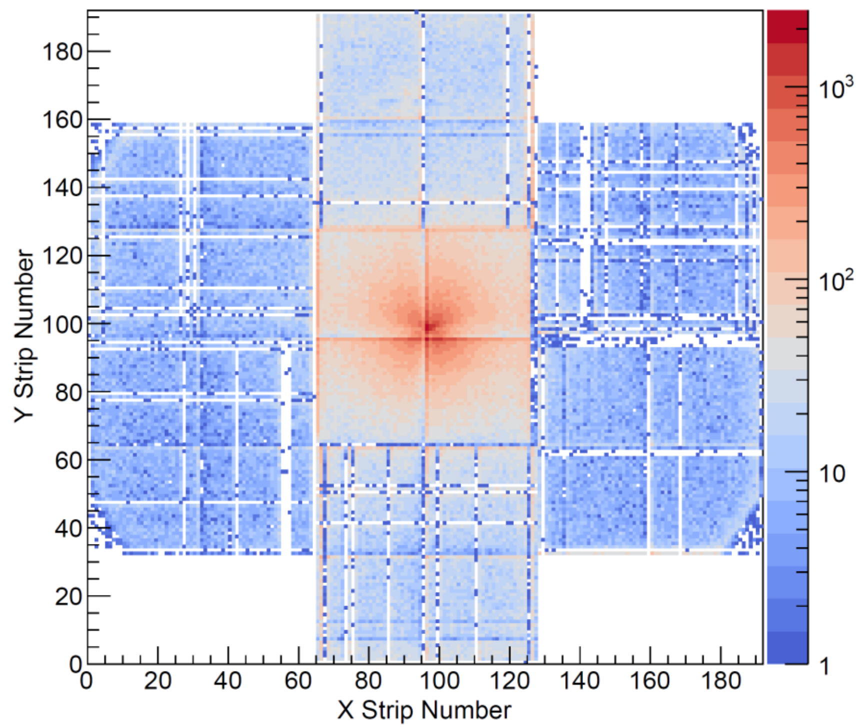


Table 5 The raw background contribution from different parts in the laboratory and the detector by taking the 3% FWHM detector resolution into account. BI stands for background index

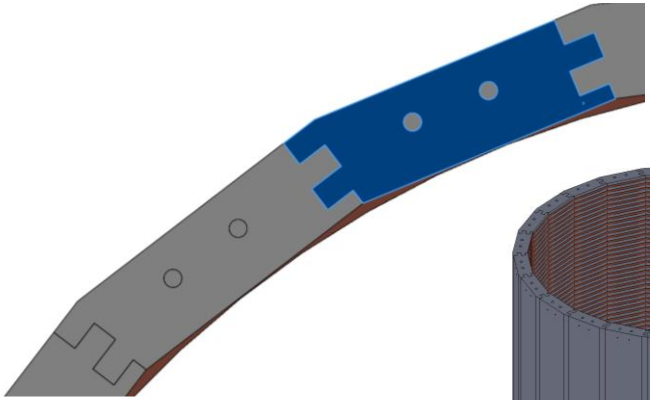
	Isotope	Activity	Background (CPY)		BI (10^{-5} c/(keV·kg·y))	
			BambooMC	RestG4	BambooMC	RestG4
Laboratory walls	^{238}U	9.9 Bq/kg	< 0.40 ± 0.03	< 0.09± 0.01	–	<0.4
	^{232}Th	4.4 Bq/kg	< 0.22 ± 0.02	< 0.15± 0.01	–	<0.6
Water	^{238}U	0.12 μBq/kg	0.20 ± 0.1	0.22 ± 0.03	0.74	0.86
	^{232}Th	0.04 μBq/kg	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

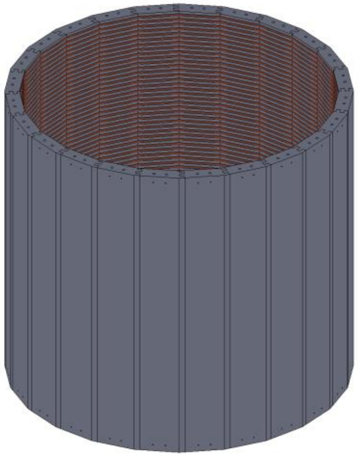
Table 7 Summary of the most relevant background contributions taking into account the detector response

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

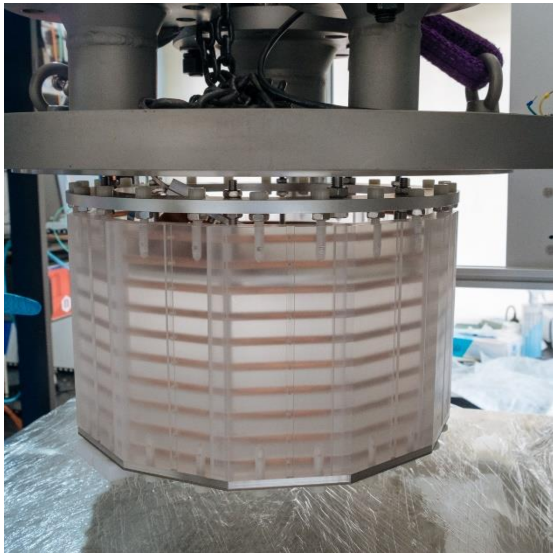
TPC Field Cage – option 1 (mature)

- Copper shaping rings + resistors + external Acrylic (or other insulating materials) barrel
  - Similar design used and tested extensively in PandaX-I and PandaX-II
- Supporting barrel are critical
  - Dielectric strength
  - Displacer for ^{136}Xe
- Designing a new version of with Kapton PCB + SMD resistors



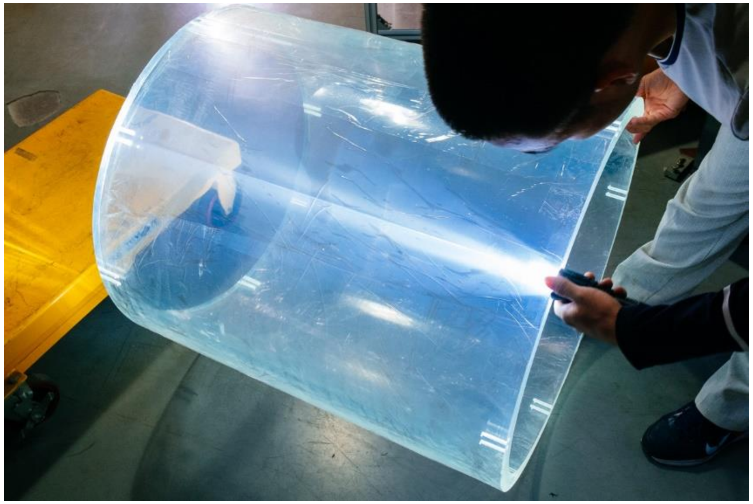


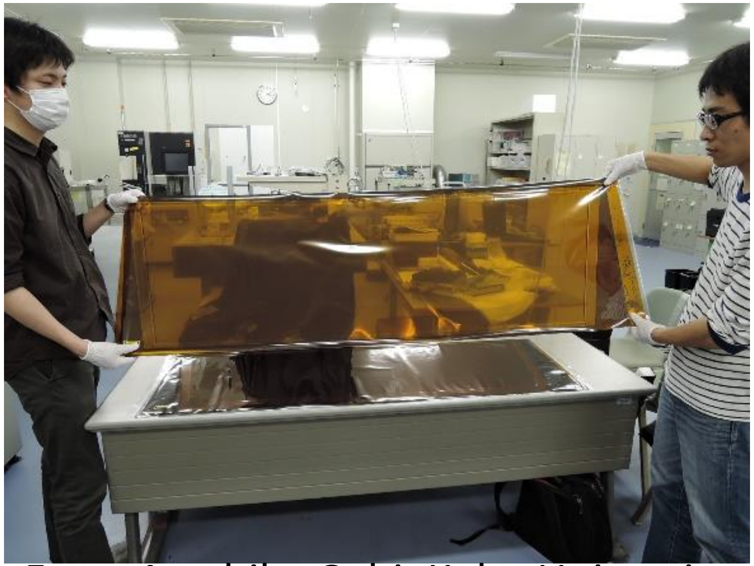
Mini TPC test field cage



TPC Field Cage – option 2

- Resistive coating layer + dielectric barrel
  - Works as continuous field shaping rings.
  - No more resistors
  - No more soldering
  - No copper rings
- Diamond-like carbon sputtering or commercial DLC or Ge film
- SUT (Thailand) is collaborating with SJTU on developing this option
- Acrylic barrel ready for prototype TPC at SJTU
- DLC coating on Kapton will be done in Japan.
  - Kobe developed DLC resistive strips for ATLAS Micromegas.
  - Resistivity and uniformity is key



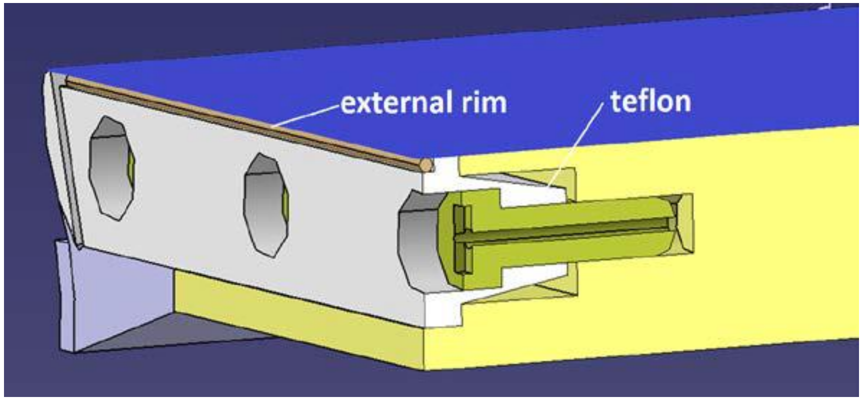


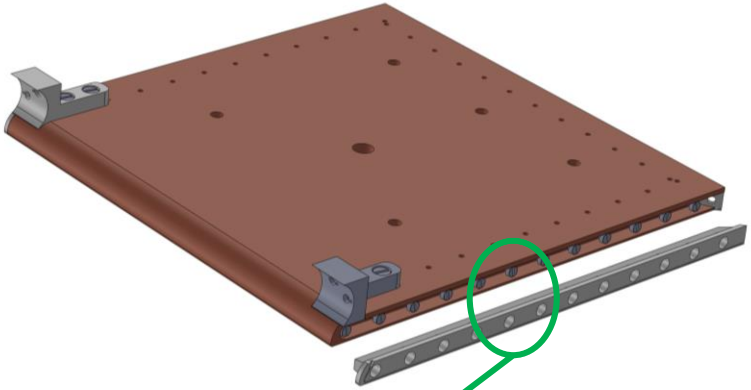
From Atsuhiko Ochi, Kobe University

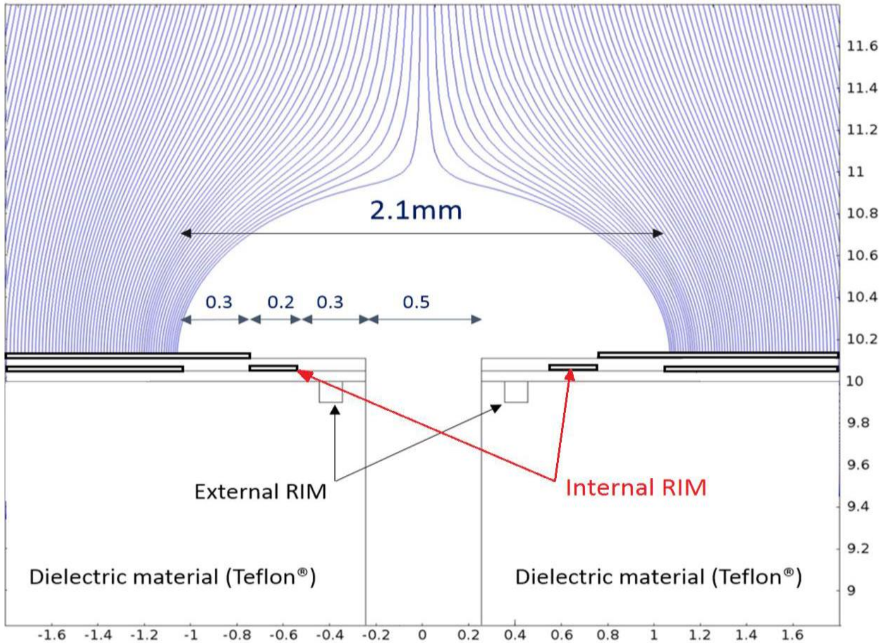
Field shaping around SR2M

Internal rim and external rim

- Shape E field
- Guide electrons to active area



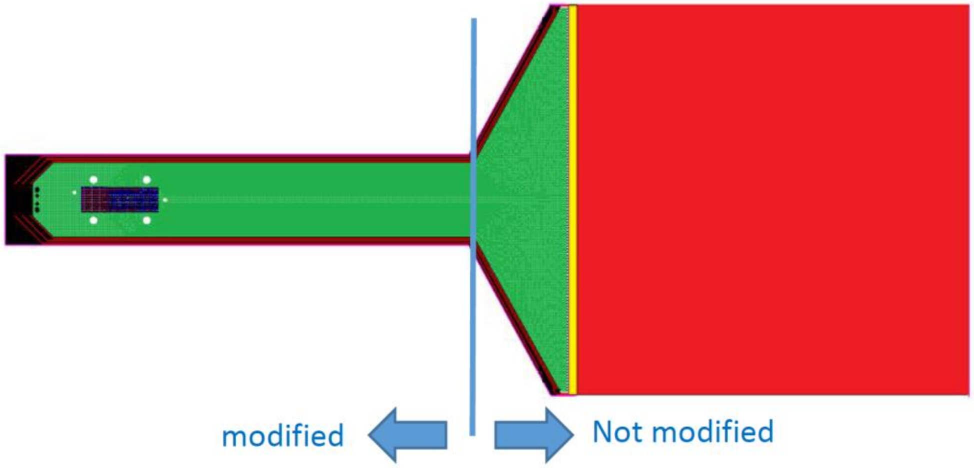




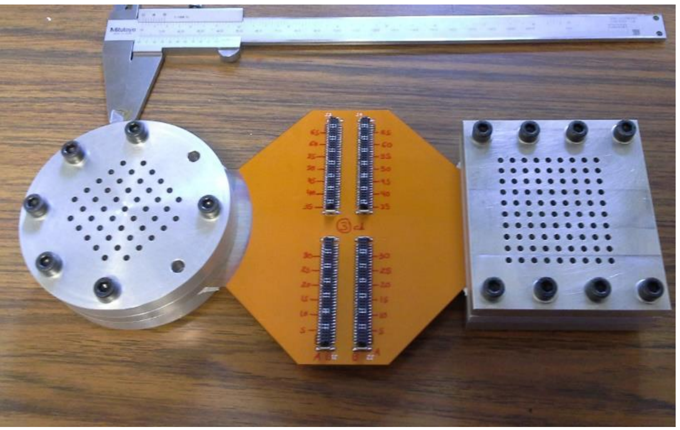
PandaX-III MM: a minor update

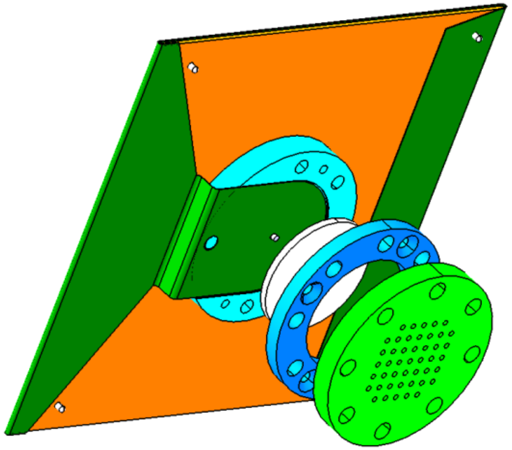
- Custom-designed connector instead of Samtec
- Face to face connection with expanded PTFE disk for elasticity.
- Dummy connectors is going through repeated thermal cycles to stress test reliability.

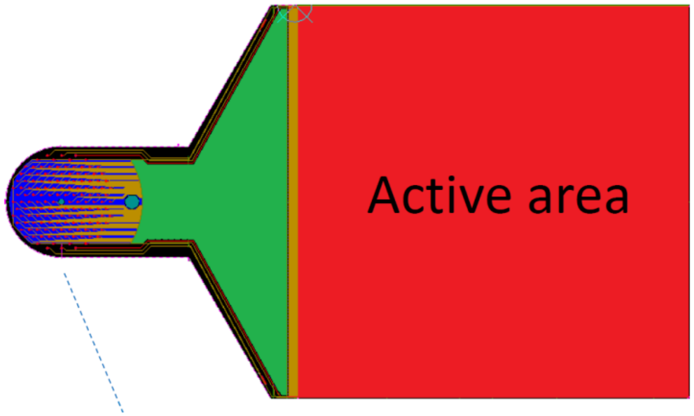
Current MM circuit



New design

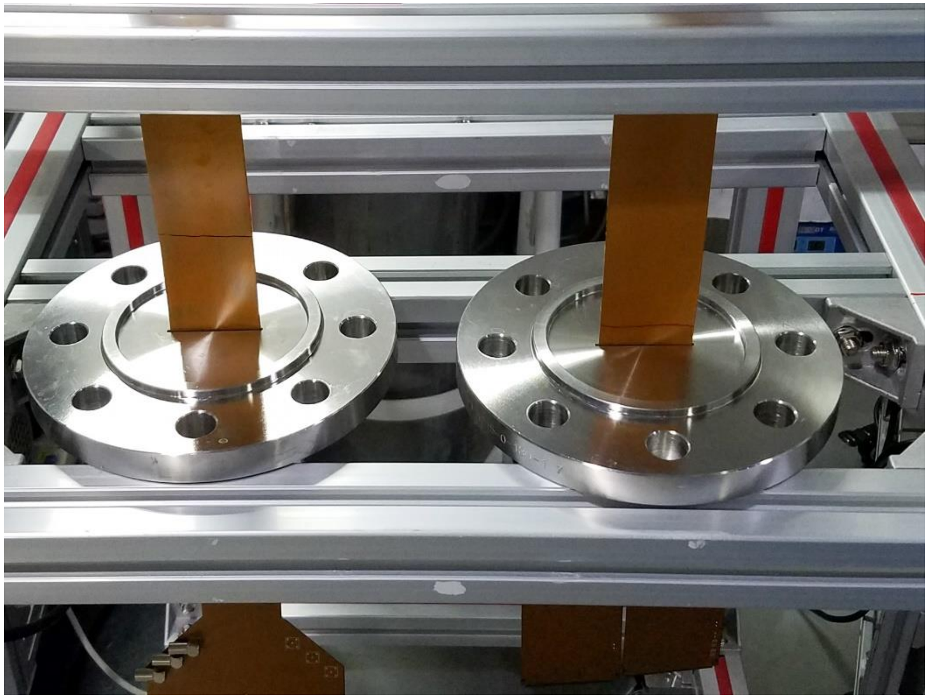






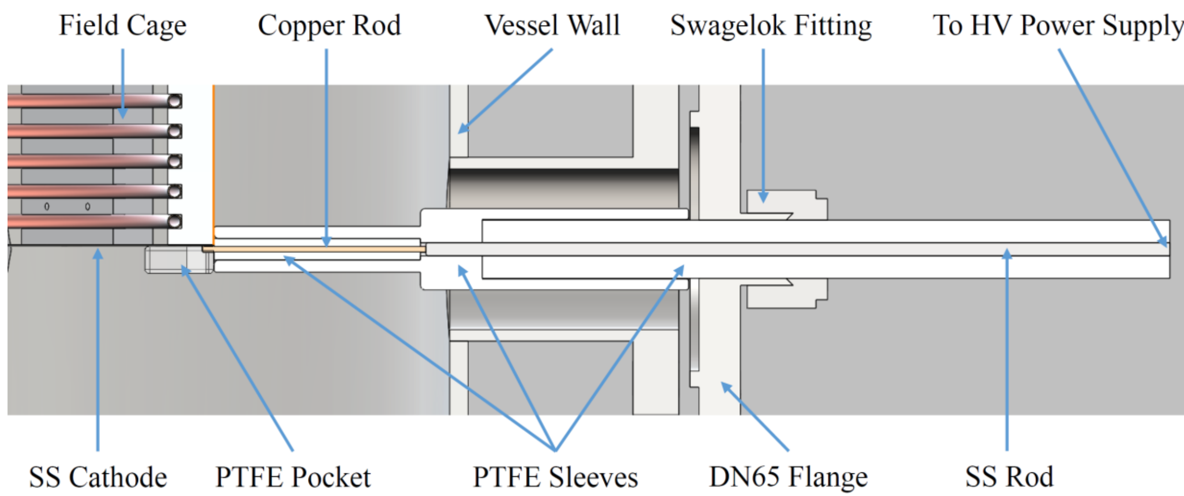
Signal feedthrough

- Micromegas signals are read out through Kapton extension cables.
- Extension cables glued in matching slots in flanges.
- Leak test shows upper limit for leak rate is gram level xenon per year per feedthrough at 10 bar.



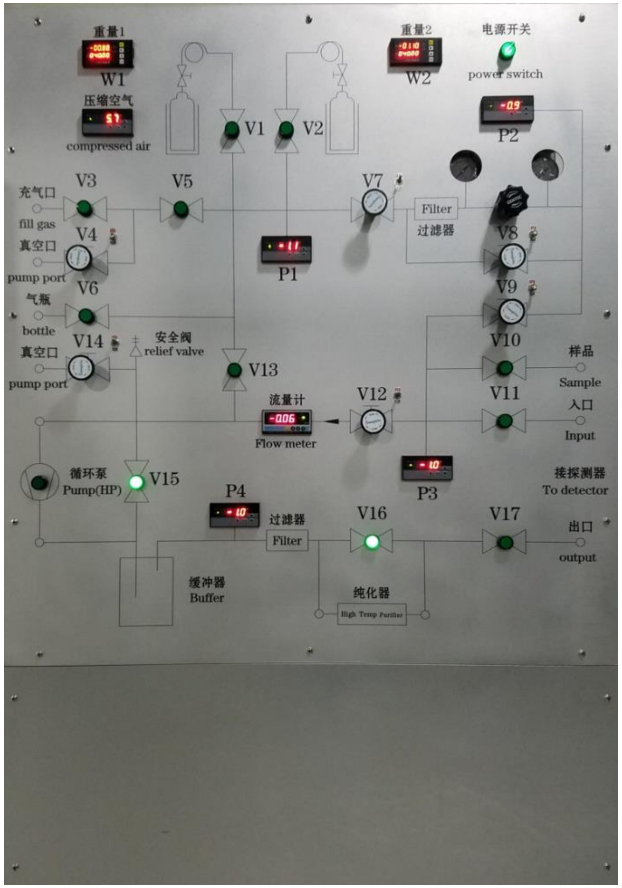
High voltage system

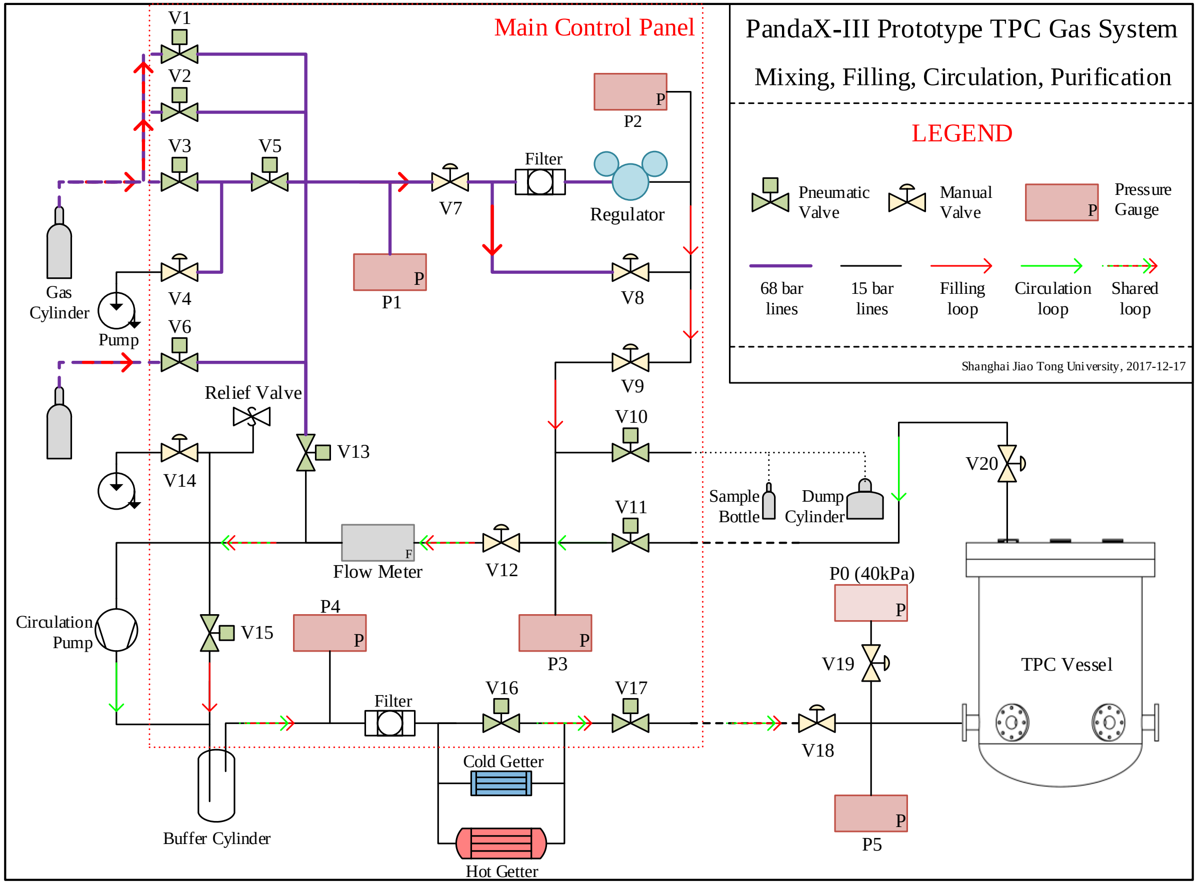
- Feedthrough for high voltage and withstand 10 bar gas pressure
  - PTFE wrap with a stainless steel rod
  - Squeezed by a Swagelok for gas tightness
- Tested on the prototype TPC
  - 70 kV in air
  - 95 kV in 10 bar N_2
- Extensive tests with 10 bar pressure : no leaks



Gas System

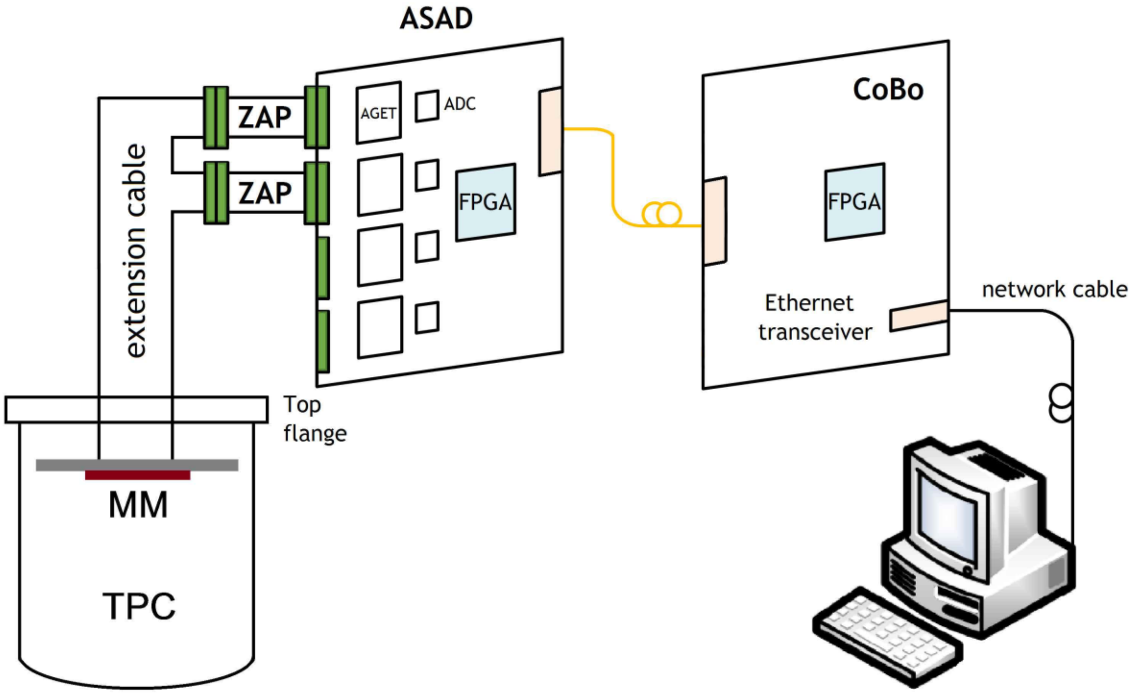
- A custom-designed system to fill, mix, circulate, purify and recuperate gas mixtures of xenon and argon gas.
- Room temperature and hot getters.



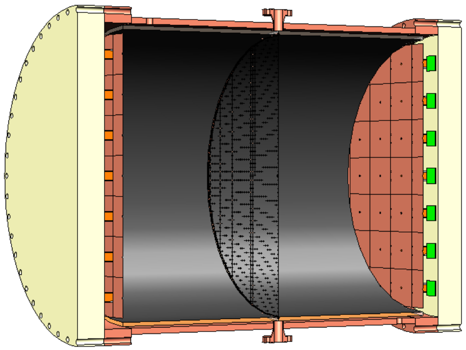


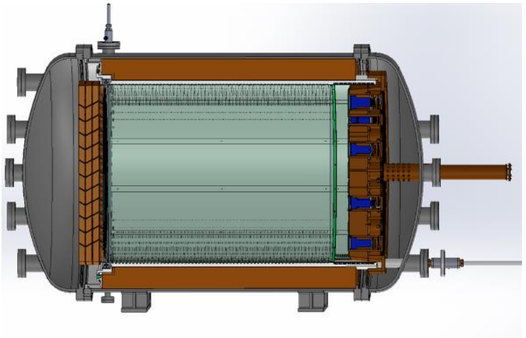
Electronics and DAQ

- Commercial front- and back-end electronics based on AGET chips.
- Established the data flow of 7 Micromegas simultaneously
- 896 channels tested with ASAD + CoBo
- Custom front-end electronics card tested on the prototype TPC data



PandaX vs. NEXT



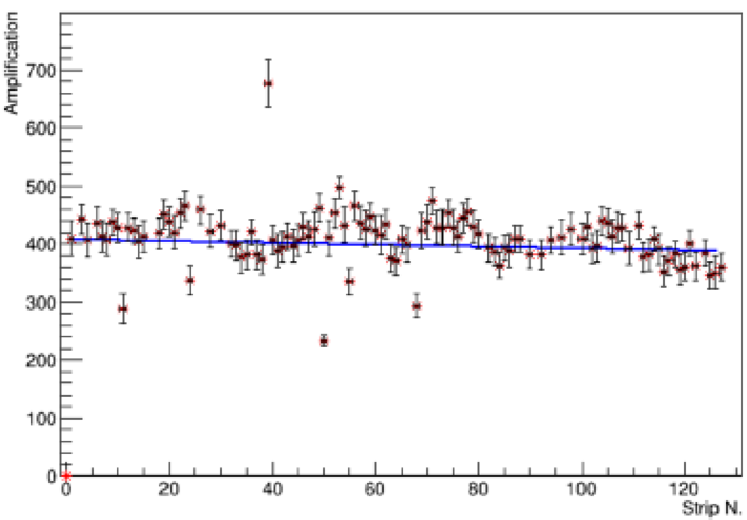


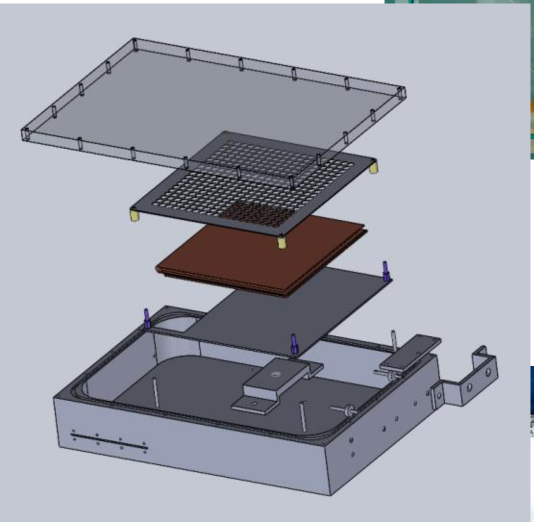
PandaX-III first TPC		NEXT-100
200 kg Xe(enriched) + 1% TMA	Detector medium	100 kg pure Xe (enriched)
------------------	Light	Primary + electroluminescence light readout by PMTs
Micromegas	Charge/Tracking	SiPM
3%	Projected energy resolution	0.7%
2-3 mm	Tracking pitch size	1 cm
X,Y	Fiducialization	X,Y,Z
Since 2015		Since ~2008

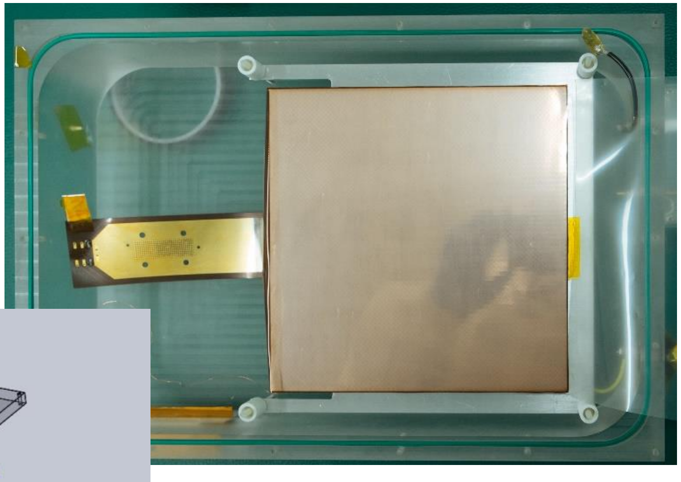
MM Characterization

Gain and gain uniformity measured

- Argon + CO_2 (30%)
- 1 bar flowing gas
- 7.5% RMS uniformity

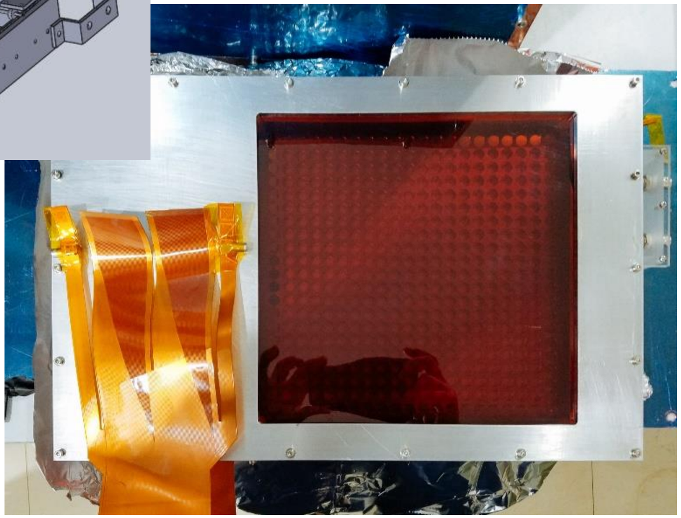






Without

with cathode, top lid



Future updates:

- Motorized source scanning
- More uniform drift field
- Pressurized xenon gas
- Multiple MM cross comparison

200 kg module vs prototype

	First 200 kg module	Prototype TPC
Design	Symmetric	Single-ended
Active volume	~$3.5m^3$	$0.25m^3$
Number of MM	82	7
Readout channels	10496	896
Electronics	AGET + Custom FEC	ASAD/CoBo; then Custom FEC
HP vessel	OFHC copper	Stainless Steel
Field cage	2π acrylic wall with resistive film	Copper rings with Teflon bars