Neutrinoless Double beta decay and PandaX-III at CJPL

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June 20, 2018

On Behalf of the PandaX-III Collaboration

Implications of 0νββ

- Explores the Majorana nature of neutrinos
  - Explains naturally the tiny neutrino mass from seesaw mechanism

- Tests lepton number conservation
  - $\Delta L = +2$
  - 0νββ is not just a neutrino experiment!

$$(A,Z) \rightarrow (A,Z+2) + 2e^-$$

- Connects to broad neutrino oscillation physics picture

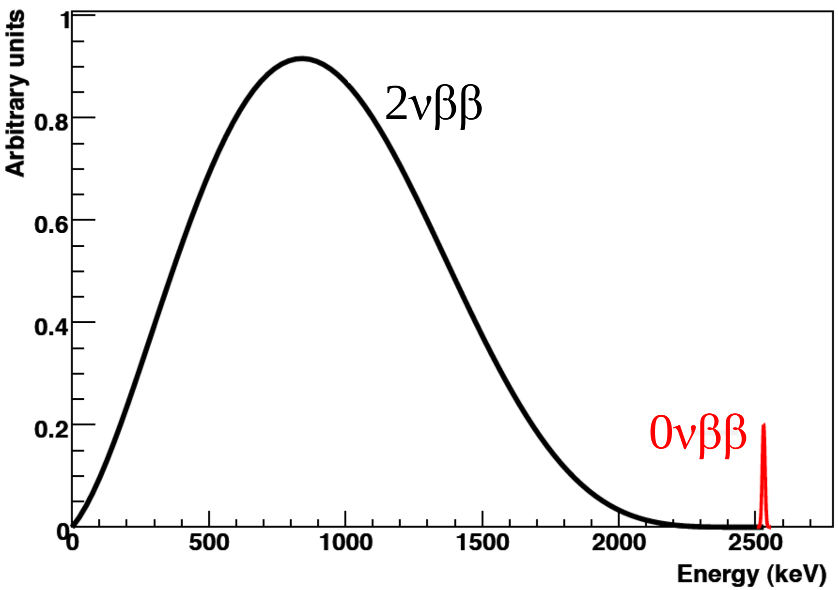
Detection of double beta decay

- Examples:

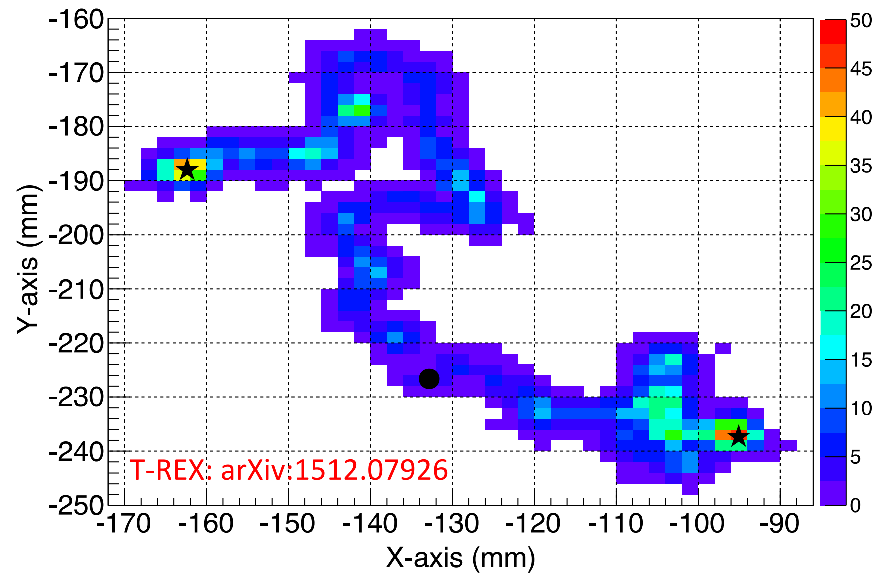
$$^{136}Xe \rightarrow 136Ba + 2e^- \ + (2\overline{\nu}_e)$$

$$^{130}Te \rightarrow 130Xe + 2e^- \ + (2\overline{\nu}_e)$$

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

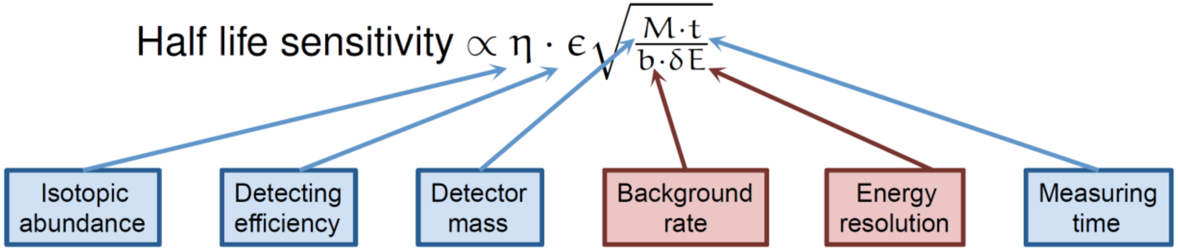


Sum of two electrons energy

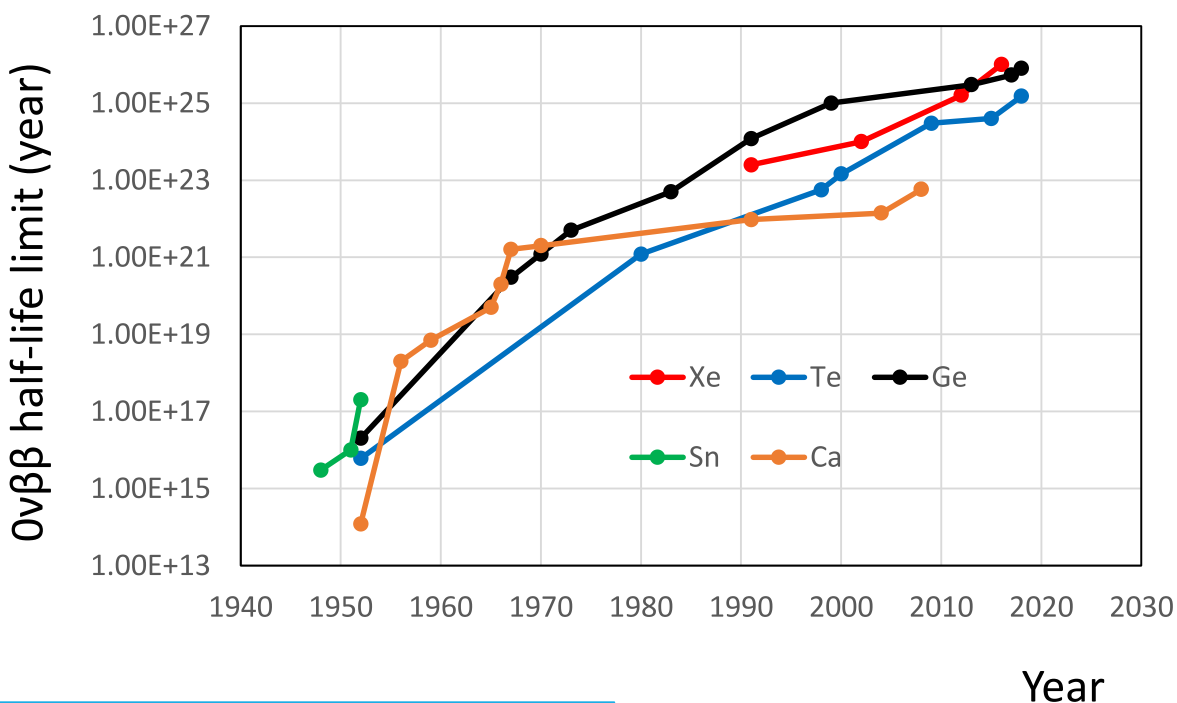


Simulated track of 0νββ in high pressure Xe

Impressive experimental progress



- ~100 kg of isotopes
- ~100-person collaborations
- Deep underground
- Shielding + clean detector

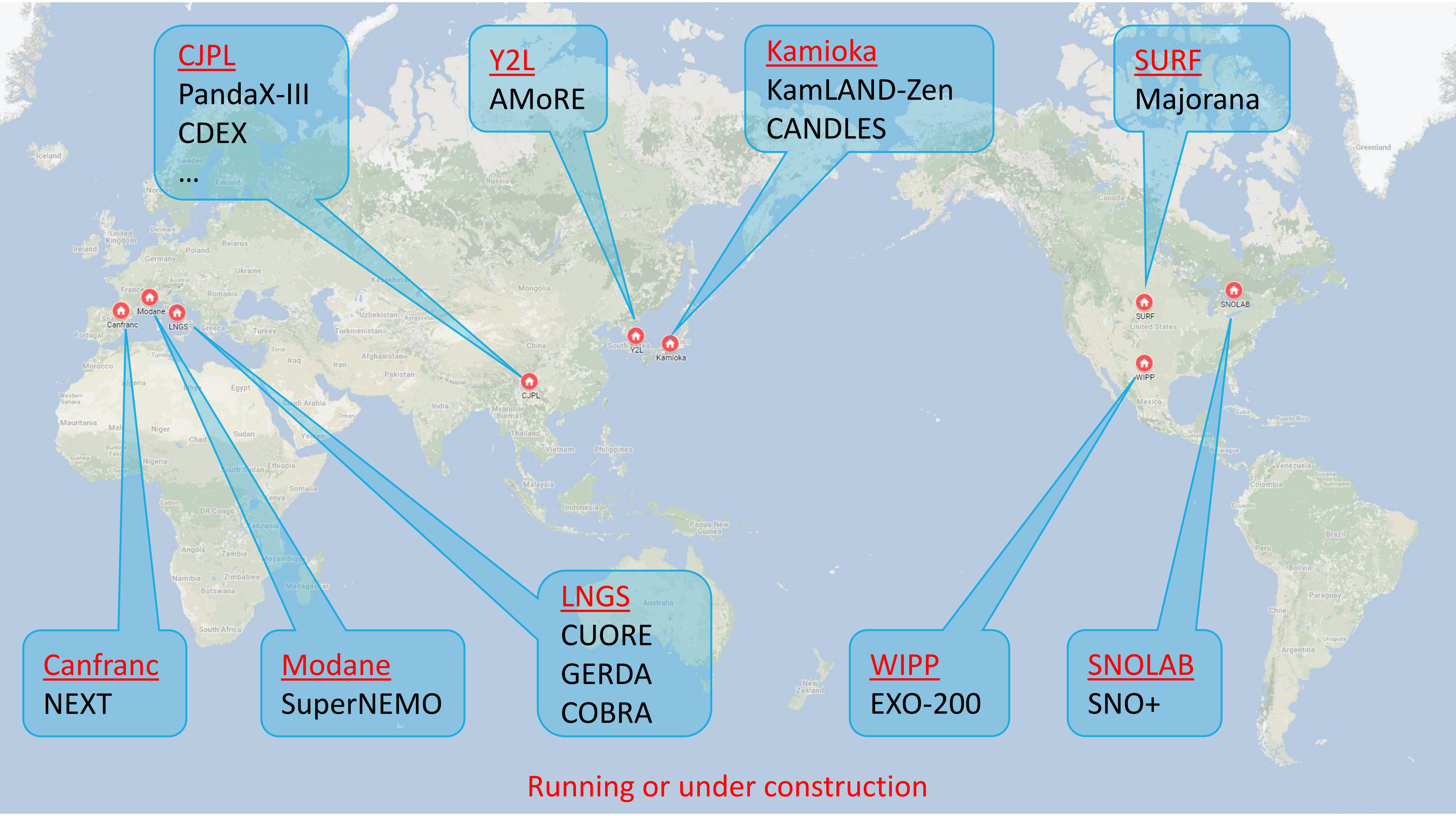


- Grams of isotopes
- Table-top experiment
- Above-ground
- Little shielding

Partial list of selected isotopes; Pre-1984 data points from review article by Haxton and Stephenson, Jr.

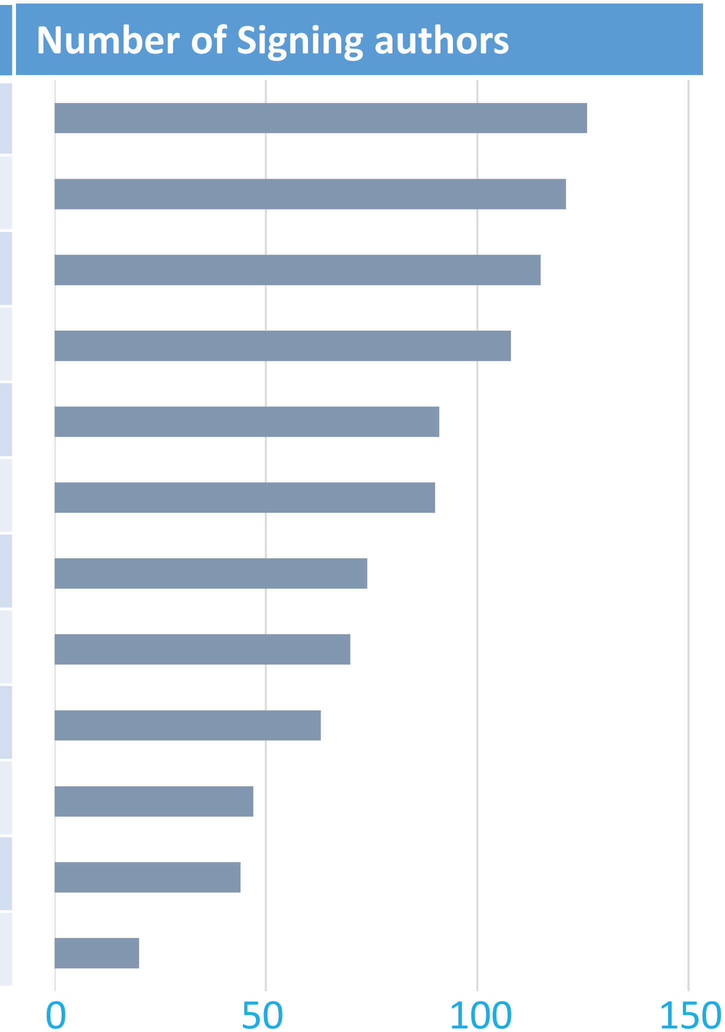
Major 0νββ experiments around the world

PANDA X
PARTICLE AND ASTROPHYSICAL XENON TPC



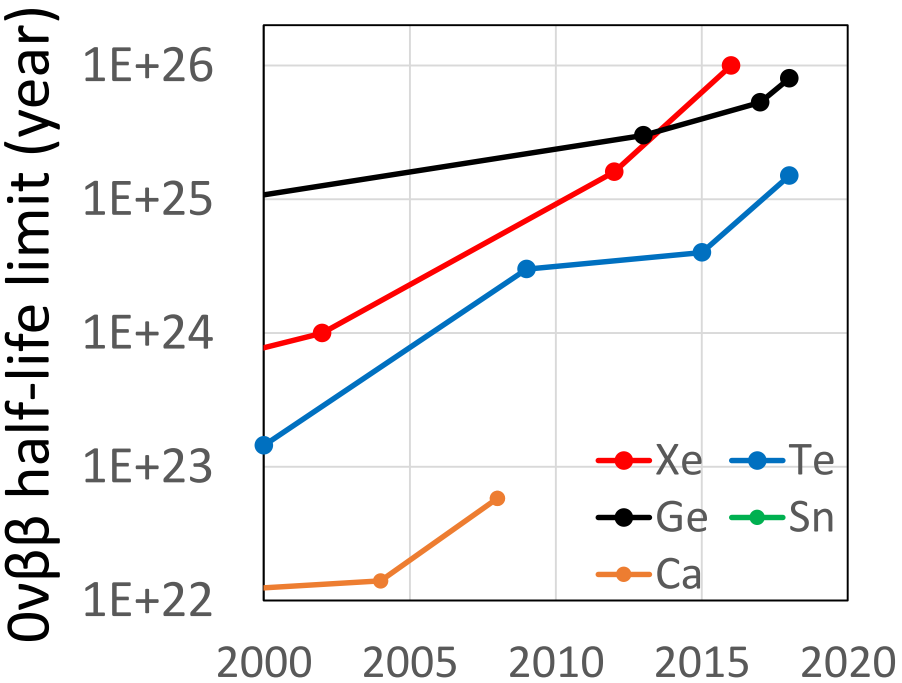
A large community with diverse efforts

Experiments	Isotopes	Techniques
CUORE	^{130}Te	Bolometer
SNO+	^{130}Te	Loaded LS
Gerda	^{76}Ge	HPGe
EXO/nEXO	^{136}Xe	Liquid Xe TPC
SuperNEMO	^{82}Se	Tracker
AMoRE	^{100}Mo	Hybrid bolometer
Majorana	^{76}Ge	HPGe
PandaX-III	^{136}Xe	Gas Xe TPC
NEXT	^{136}Xe	Gas Xe TPC
Candles	^{48}Ca	Scintillator
KamLAND-Zen	^{136}Xe	Loaded LS
COBRA	^{116}Cd	CZT semiconductor



Recent excitements

- GERDA, "Improved Limit on Neutrinoless Double-β decay of 76Ge from GERDA Phase II," PRL. 120, 132503 (2018).
- MAJORANA, "Search for Neutrinoless Double-β decay in 76Ge with the Majorana Demonstrator," PRL. 120, 132502 (2018).
- CUORE, "First Results from CUORE: A Search for Lepton Number Violation via 0νββ decay of 130Te," PRL. 120, 132501 (2018).
- EXO-200, "Search for Neutrinoless Double-Beta Decay with the Upgraded EXO-200 Detector," PRL. 120, 072701 (2018).
- KamLAND-Zen, "Search for Majorana Neutrinos Near the Inverted Mass Hierarchy Region with KamLAND-Zen," PRL. 117, 082503 (2016).



Physics ABOUT BROWSE PRESS COLLECTIONS

Viewpoint: The Hunt for No Neutrinos

Jonathan Engel, Department of Physics and Astronomy, University of North Carolina, Chapel Hill, NC 27599, USA

Petr Vogel, Kellogg Radiation Laboratory and Physics Department, California Institute of Technology, Pasadena, CA 91125, USA

March 26, 2018 • *Physics* 11, 30

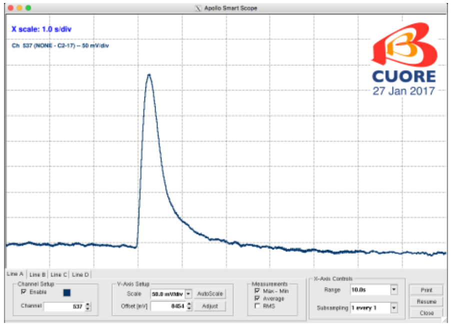
Four experiments have demonstrated new levels of sensitivity to neutrinoless double-beta decay, a process whose existence would prove that neutrinos are their own antiparticles.

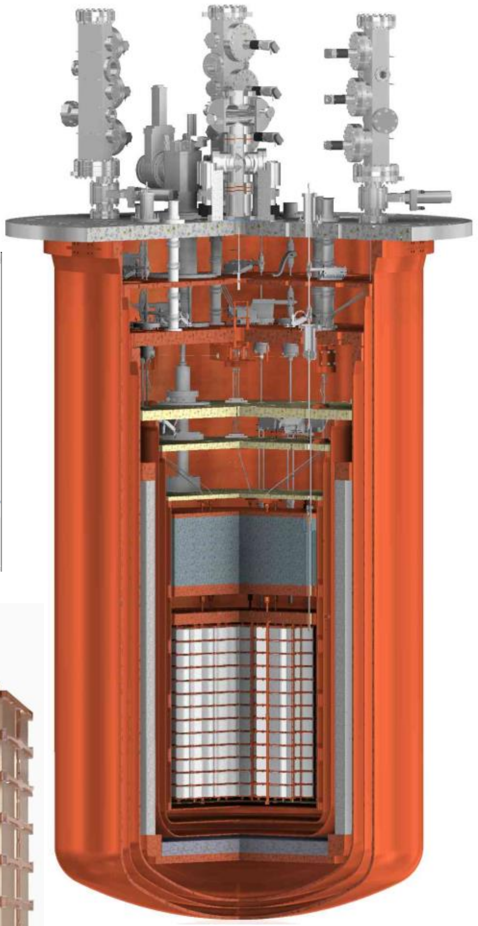
CUORE (^{130}Te)

- Bolometric technique
- Excellent energy resolution by measuring temperature rise at mK level.
- half-life limit (2018): 1.5×10^{25} yr (90% C.L.)

Future

- CUPID (CUORE with particle ID)
  - Enrichment
  - Phonon + photon dual readout
  - Multiple crystal choices
  - Active discussion of CUPID-China



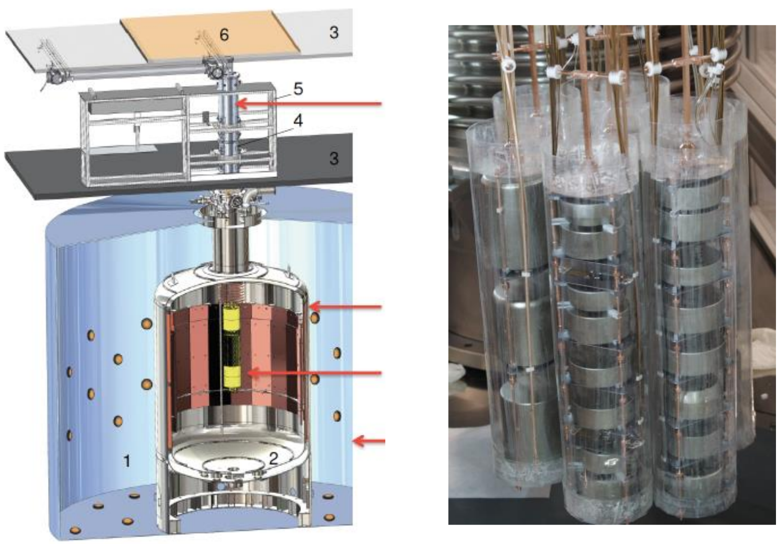


World-largest Dilution Refrigerator

<10mK

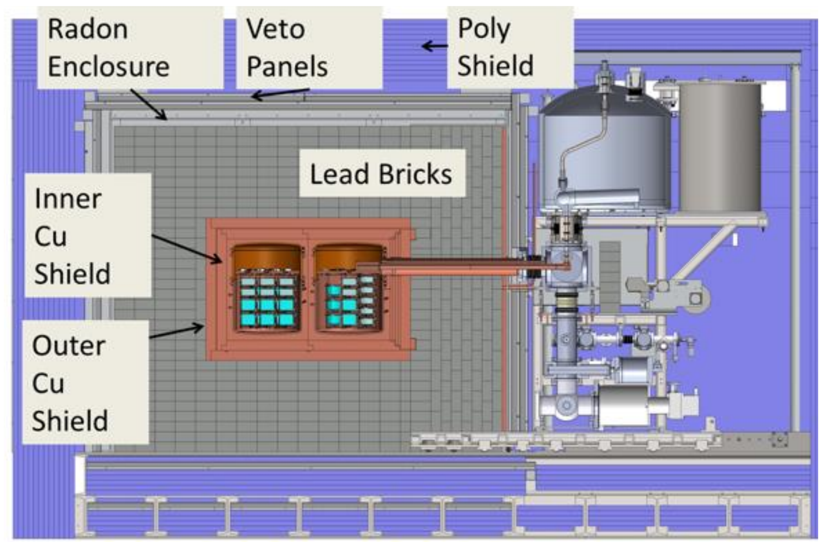
HPGe detectors (^{76}Ge)

GERDA at LNGS, Italy



half-life limit (2018): 8.0×10^{25} yr (90% C.L.)

Majorana Demonstrator at Sanford, US



half-life limit (2018): 1.9×10^{25} yr (90% C.L.)

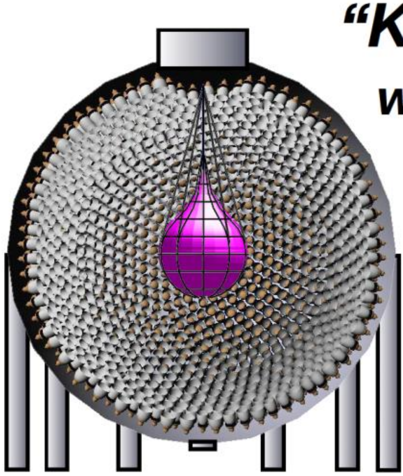
Future:

- LEGEND (Large Enriched Ge Experiment for ββ Decay)
- First phase: 200 kg @ LNGS
- 47 Institutions, 219 Scientists (mostly GERDA + MJD + CDEX)

KamLAND-Zen (^{136}Xe)

- KamLAND-Zen is leading the field of 0νββ experiment
- ^{136}Xe half-life limit of 1.07×10^{26} yr (90%CL) (2016)
- New phase with twice the ^{136}Xe is under construction.

Future:



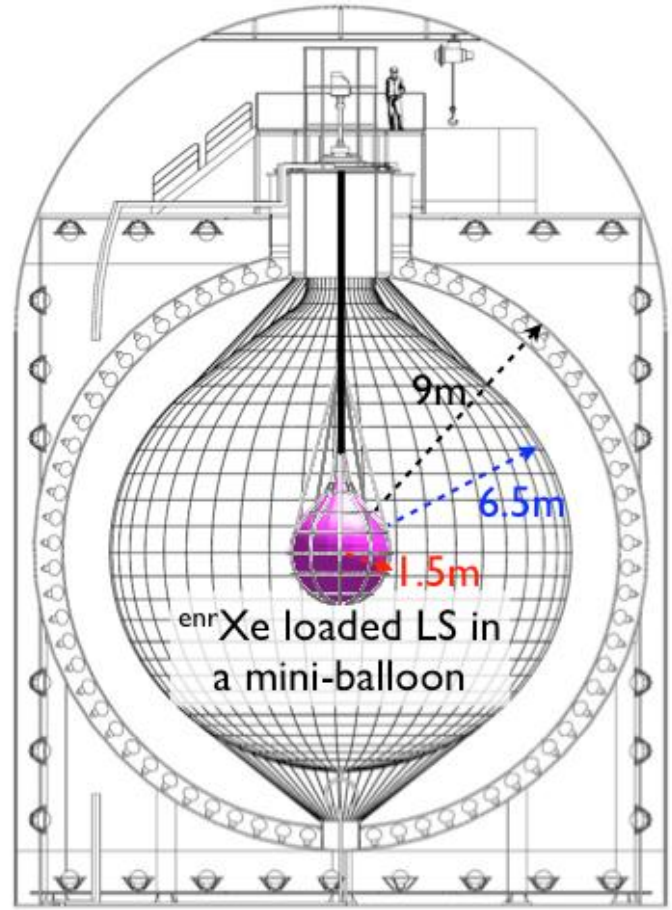
"KamLAND2-Zen"

with 1000kg enriched Xe

Many R&Ds are ongoing !

More photons for better σ_E

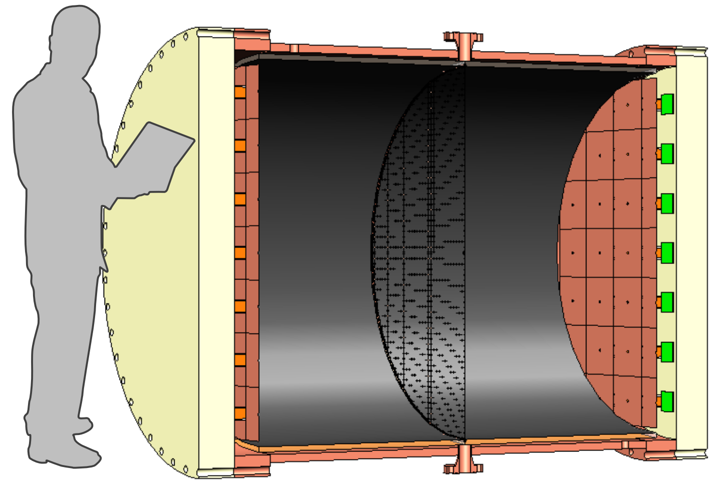
- New LAB-based LS (L.Y.×1.4),
- New High Q.E. PMT (×1.9),
- Light collector of PMT(×1.8)



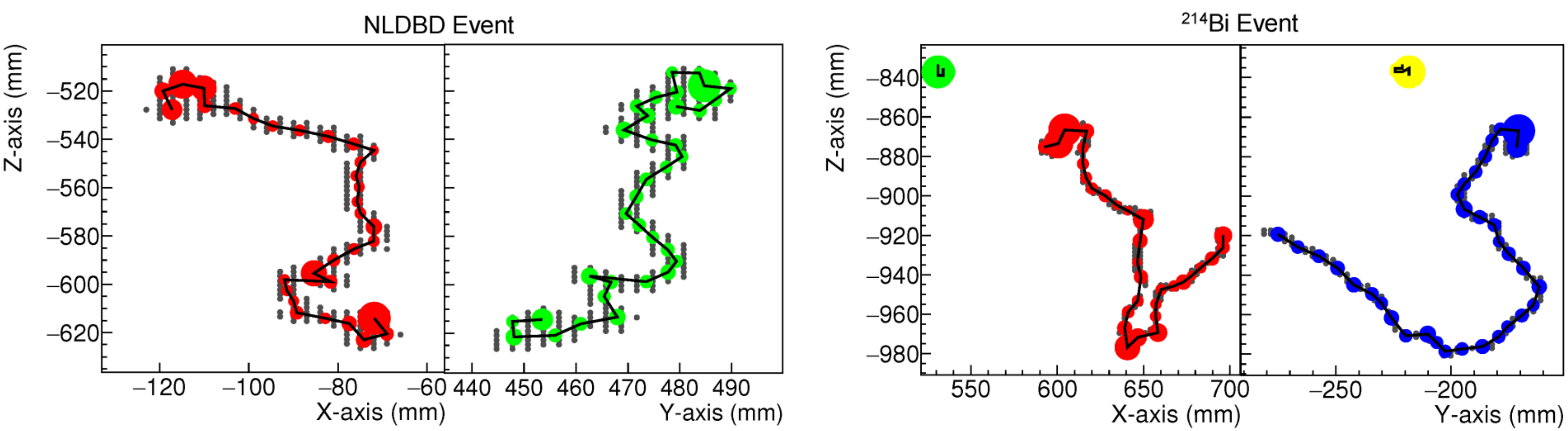
KamLAND-ZEN

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



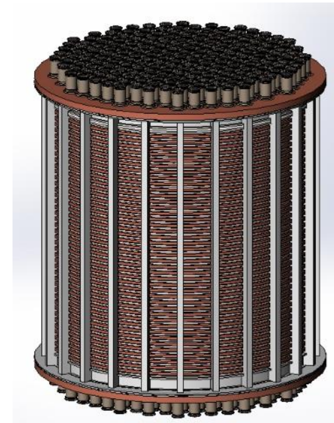
arXiv:1610.08883



PandaX Projects

PandaX-I: 120kg LXe
(2009 – 2014)

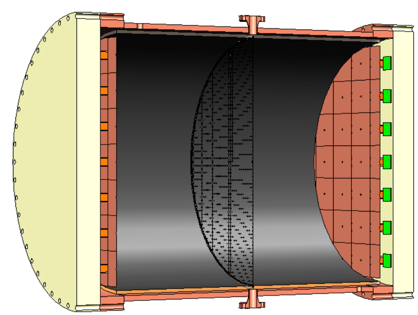
PandaX-II: 500kg LXe
(2014 – 2018)



PandaX-xT LXe
(Future)

Dark matter WIMP searches

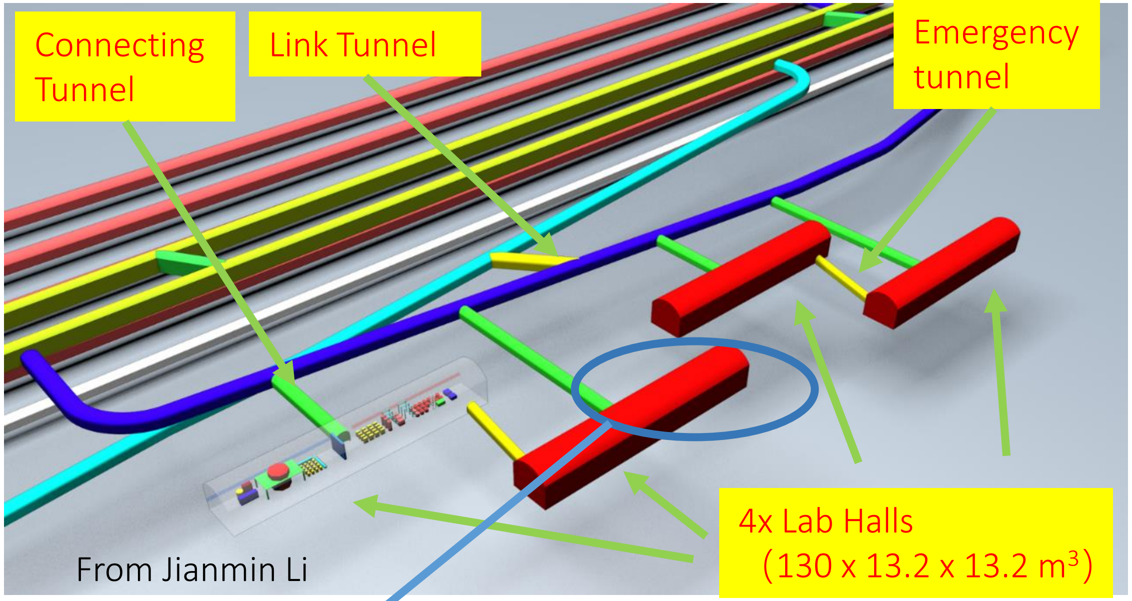
PRL 117, 121303 (2016)



0νββ searches

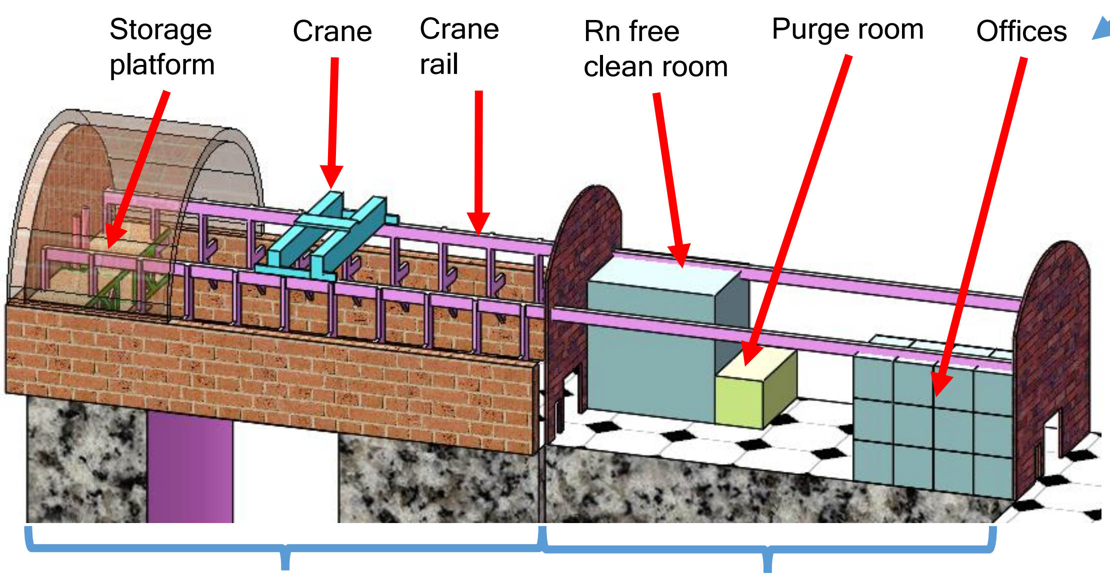
PandaX-III:
200kg - 1 ton HPXe (Future)

PandaX hall at CJPL-II



CJPL phase II Experiments

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



PandaX at Hall B2

- Extra excavation for the water shielding pool (finished)
- Shared facility of DM and $0\nu\beta\beta$ searches

PandaX-III collaboration

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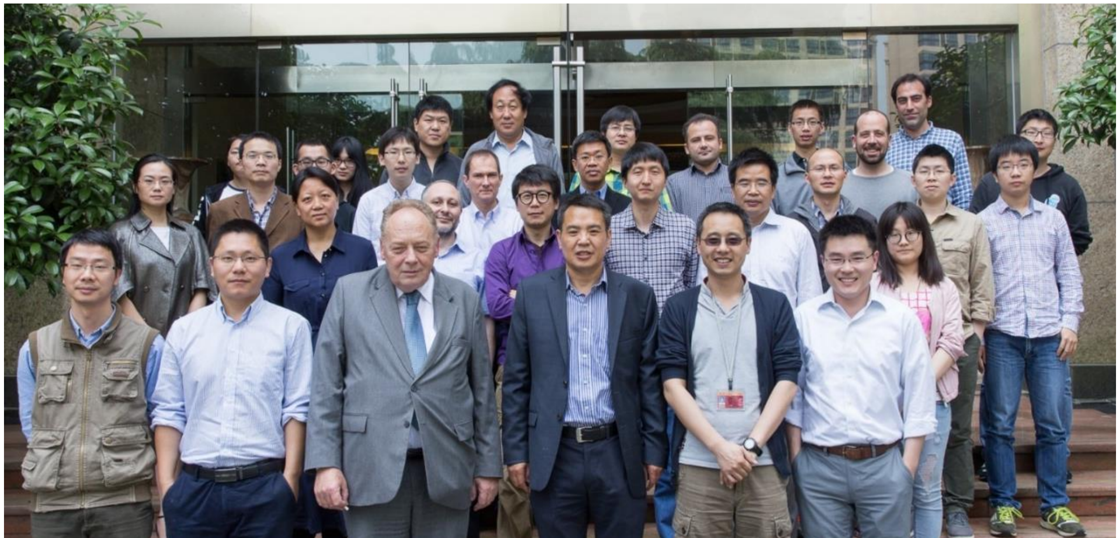
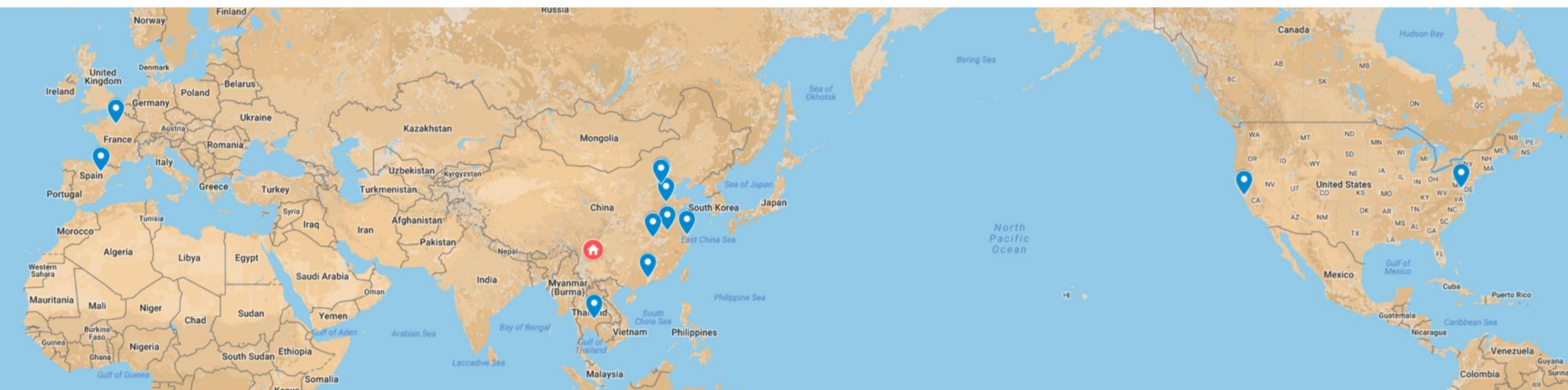
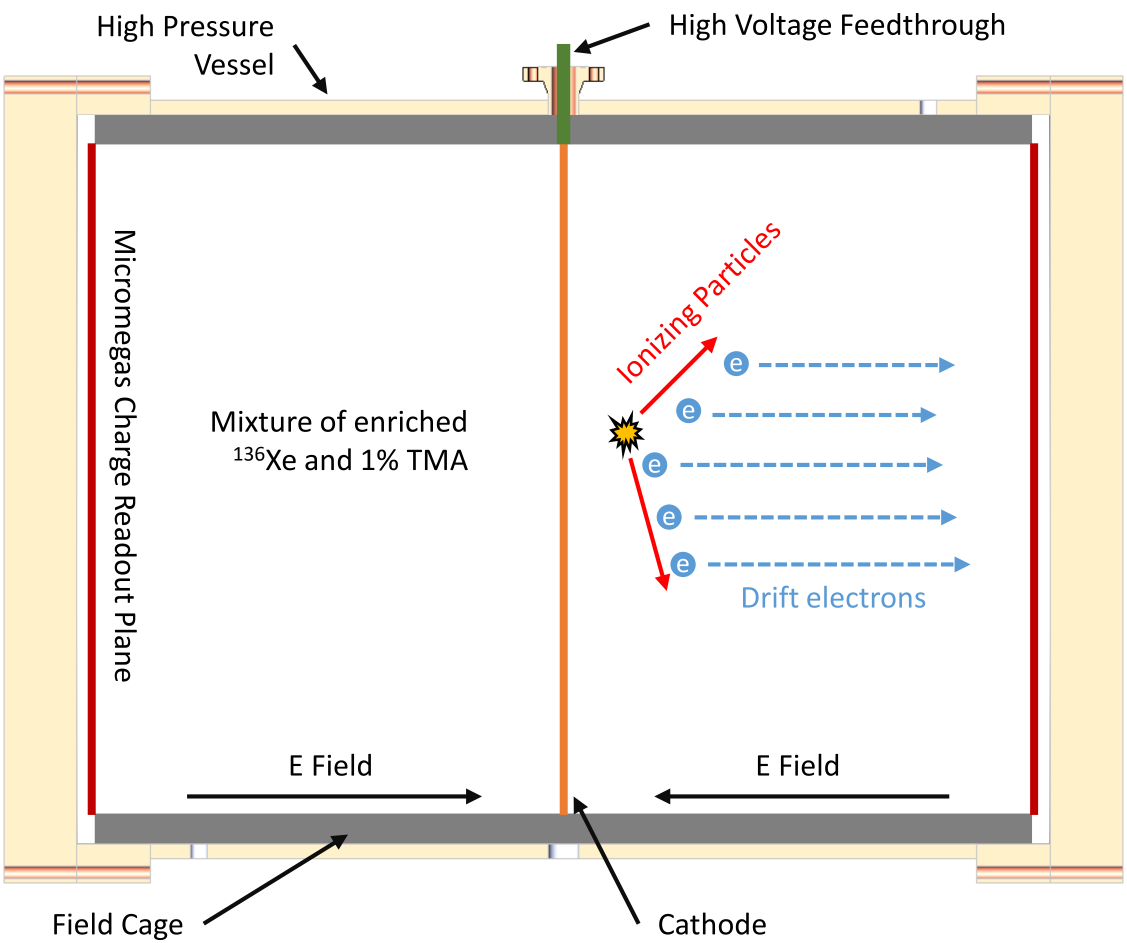


PandaX-III Collaboration Meeting, Shanghai, China, May 2016

- 上海交通大学
- 中国科学技术大学
- 北京大学
- 中山大学
- 中国原子能科学研究院
- 华中师范大学
- 山东大学
- 美国University of Maryland
- 美国Berkeley Lab
- 法国CEA Saclay
- 西班牙University of Zaragoza
- 泰国苏拉那里技术大学 SUT



PandaX-III first TPC



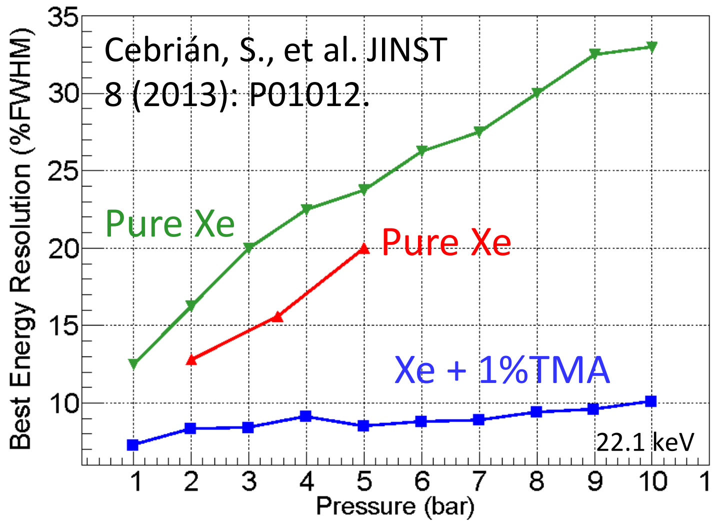
- ~4m^3 active volume
- Copper pressure vessel
- 10 bar working pressure
- 200 kg of enriched xenon
- Xe+TMA gas mixture
- Charge-only readout with Microbulk Micromegas
- Strip readout with 3 mm pitch size
- ~10000 readout channels

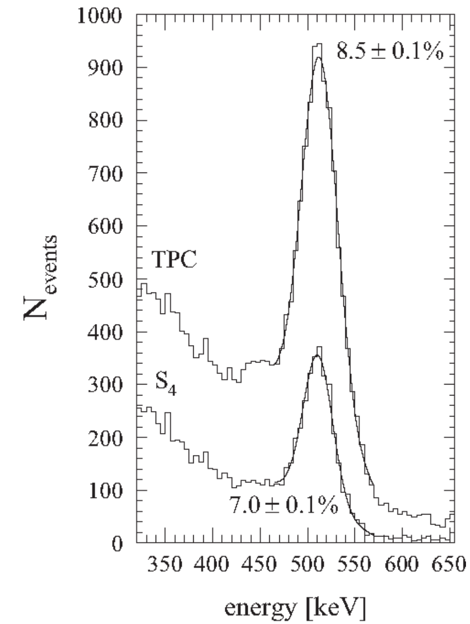
Xe +TMA (trimethylamine) mixture

PANDA X
PARTICLE AND ASTROPHYSICAL XENON TPC

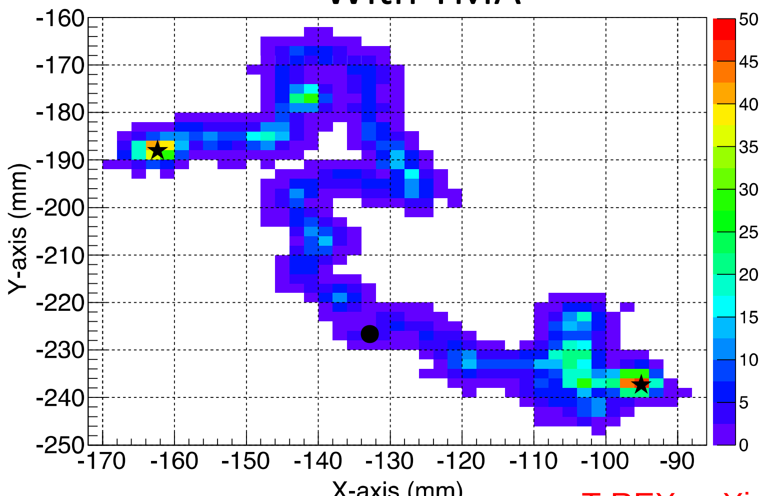
Gonzalez-Diaz, et al. *NIMA* 804 8 (2015)

- 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

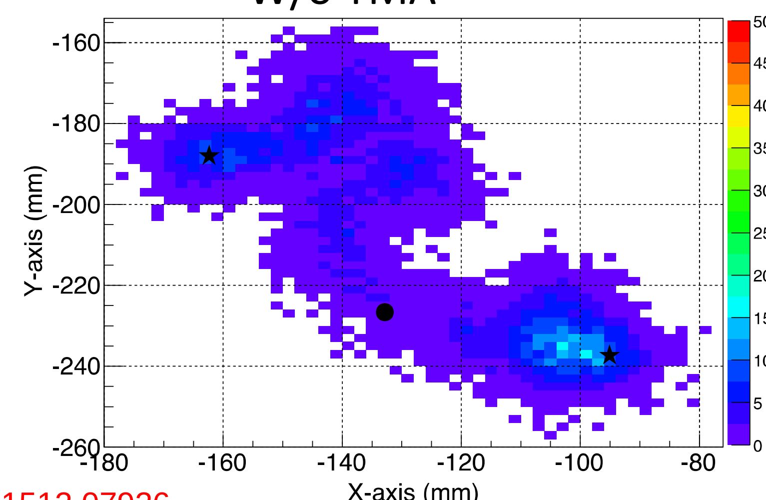




With TMA



W/o TMA



T-REX: arXiv:1512.07926

Microbulk MicroMegas (MM) with strips

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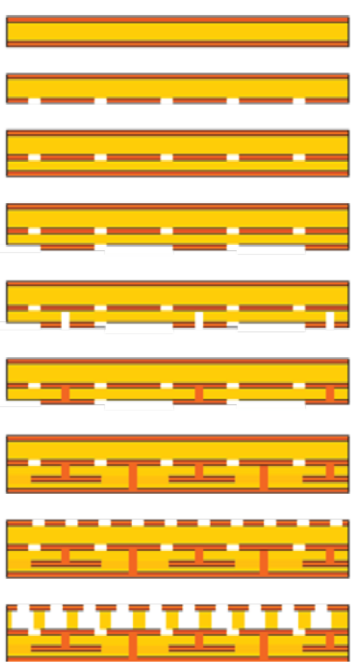
PARTICLE AND ASTROPHYSICAL XENON TPC

- Microbulk MicroMegas films made of Copper and Kapton only
  - Perfect for radio-purity purpose
- Strip readout with 3 mm pitch size
- 3% energy resolution expected at 2.5 MeV.



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

Construction of readout strips/pads (photolithog

Attachment of a single-side Cu-coated Kapton f

Construction of readout lines

Etching of Kapton

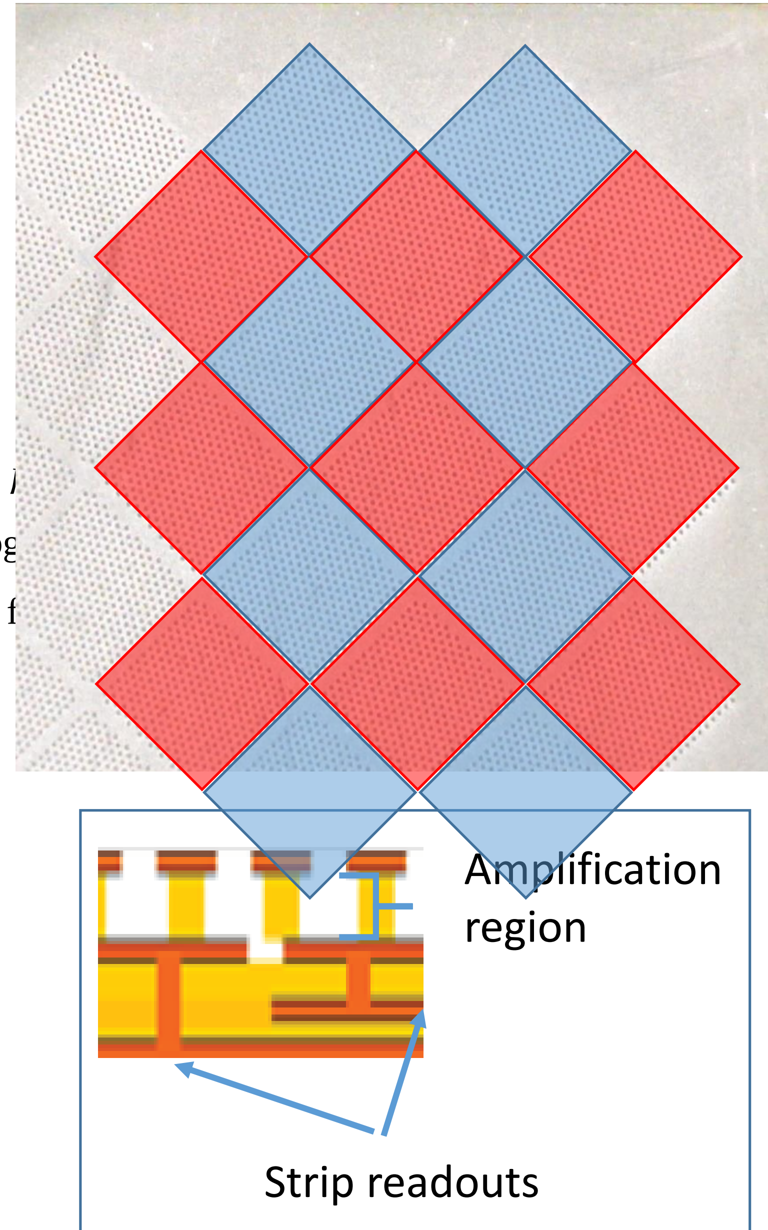
Vias construction

2nd Layer of Cu-coated Kapton

Photochemical production of mesh holes

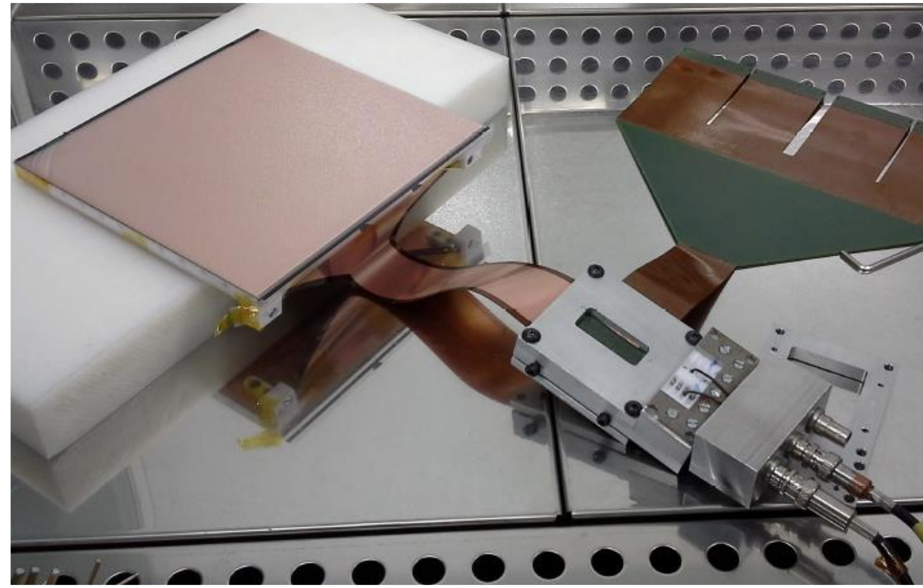
Kapton etching / Cleaning

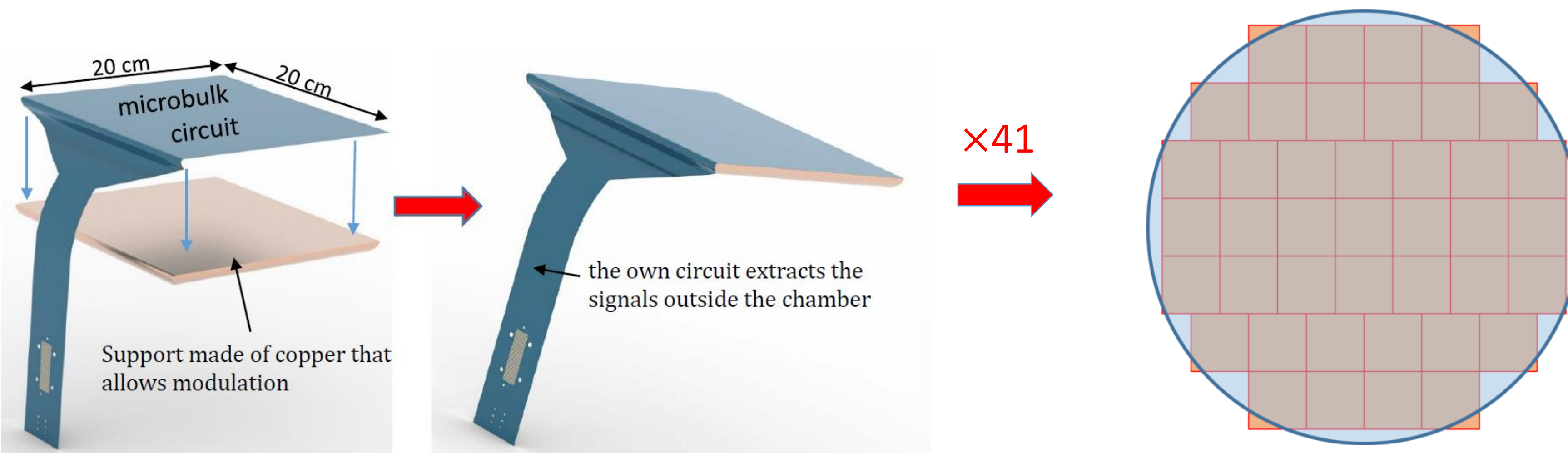
Andriamonje, S. et al. JINST 02 (2010): P02001



Scalable Radio-pure Readout Module (SR2M)

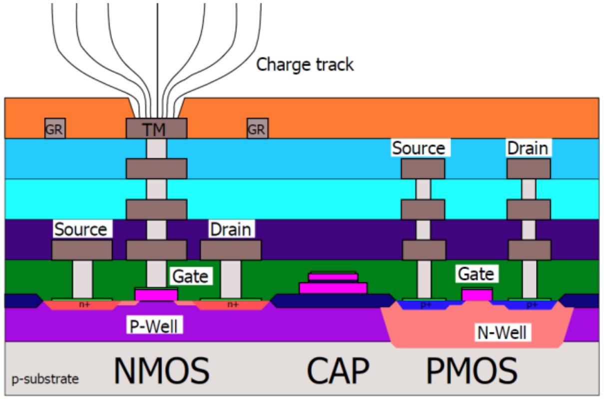
- SR2M: Mosaic layout to cover readout planes
  - Solderless system
  - Strip and mesh signal readout
  - Dead-zone-free arrangement
  - Designed by Zaragoza and SJTU



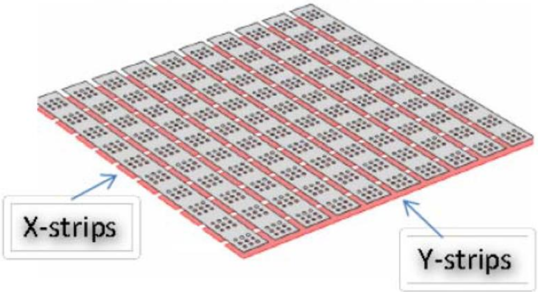


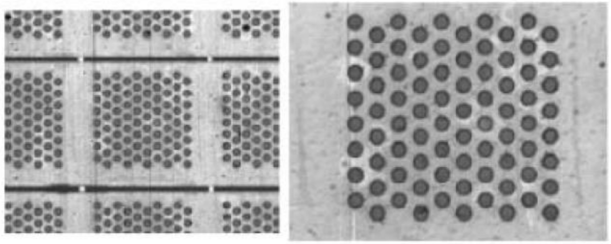
Future energy resolution improvement

- TopMetal Direct Charge Sensor
  – Direct pixel readout without gas amplification



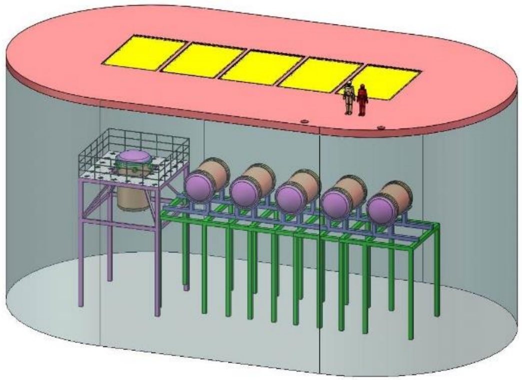
- Alternative Micromegas technologies
  – Microbulk technology with segmented mesh for true X and Y strips
  – Bulk technology with better uniformity and less dead area

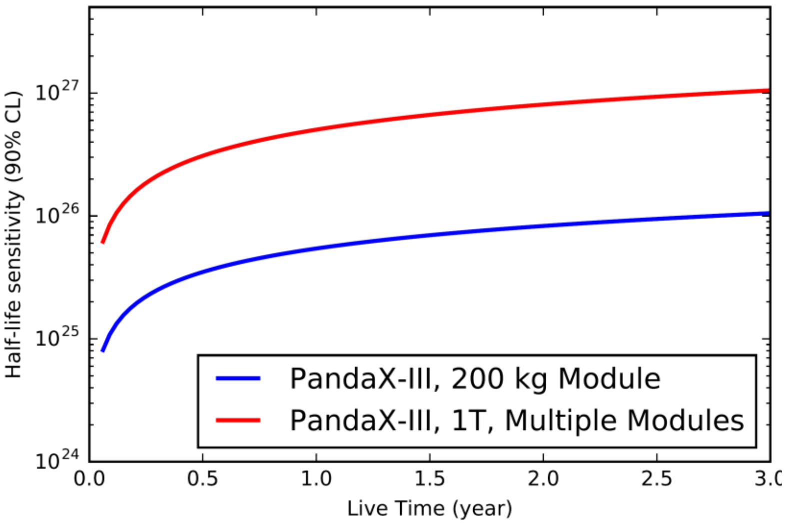


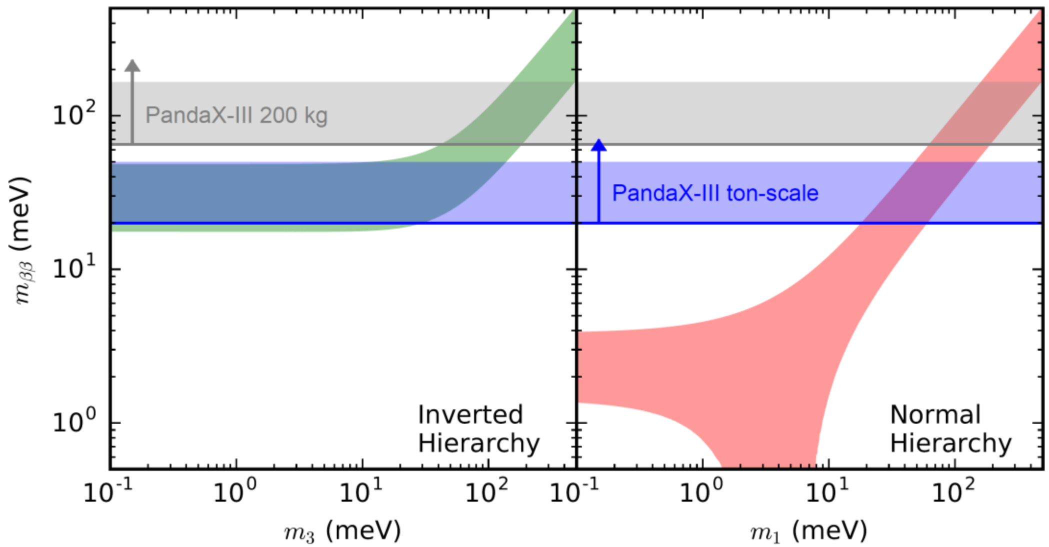


Sensitivity projection

- First 200-kg module:
  - Microbulk Micromegas for charge readout
  - 3% FWHM, 1 x 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 x 10^{-5} c/keV/kg/y in the ROI







Prototype TPC at SJTU

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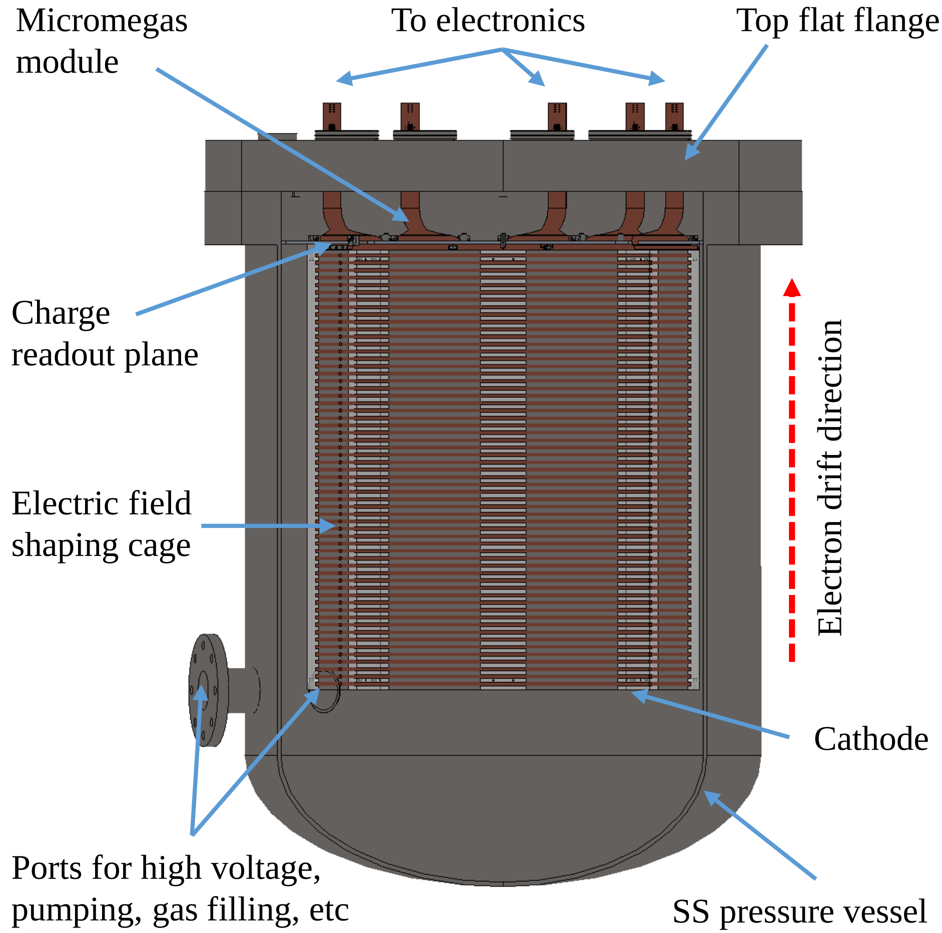
PARTICLE AND ASTROPHYSICAL XENON TPC

- To see MeV electron tracks
- To demonstrate required energy resolution with a large-scale high pressure TPC



See talks from Shaobo Wang and Kaixiang Ni

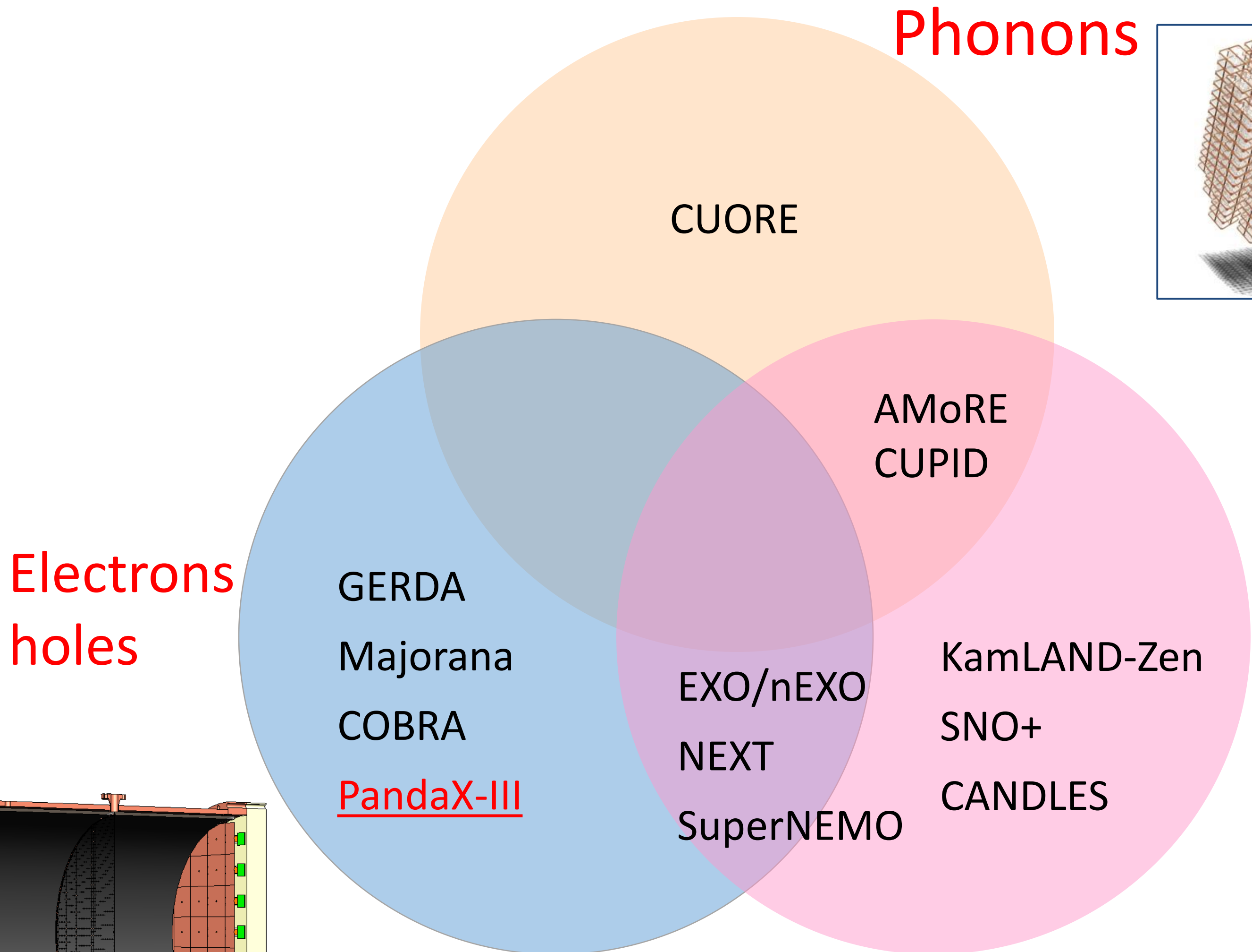
Summary

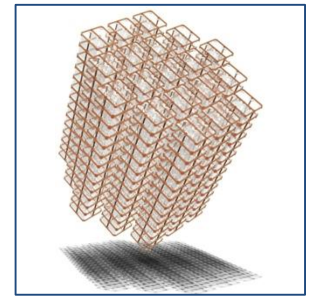
- Neutrinoless double beta decay explores the neutrino mass origin and tests lepton number conservation

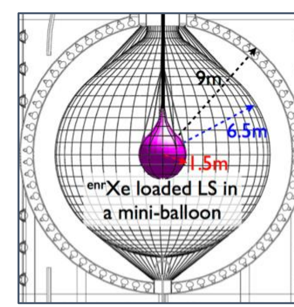
- 80 years of exciting double beta decay physics

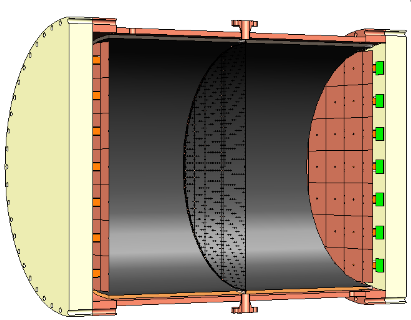
- PandaX-III searches for $0\nu\beta\beta$ of ^{136}Xe with 200-kg scale TPCs

Detection channels





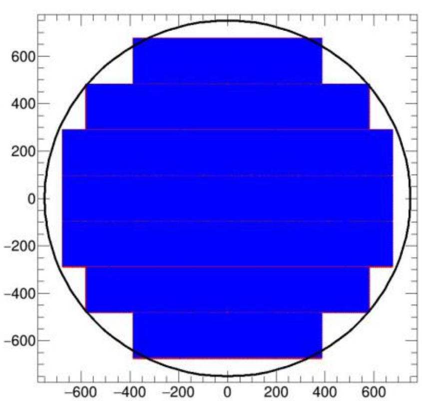


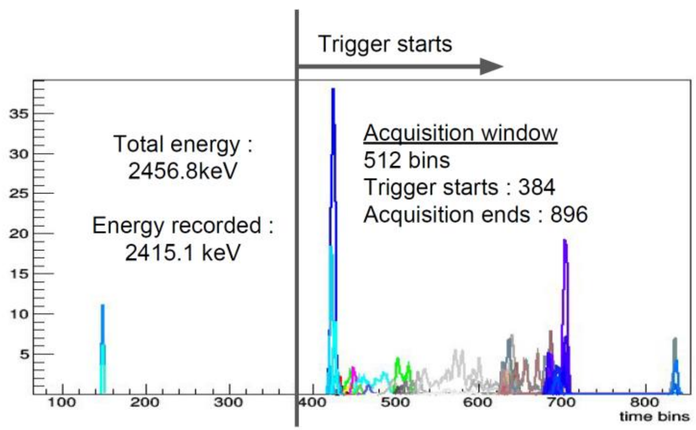


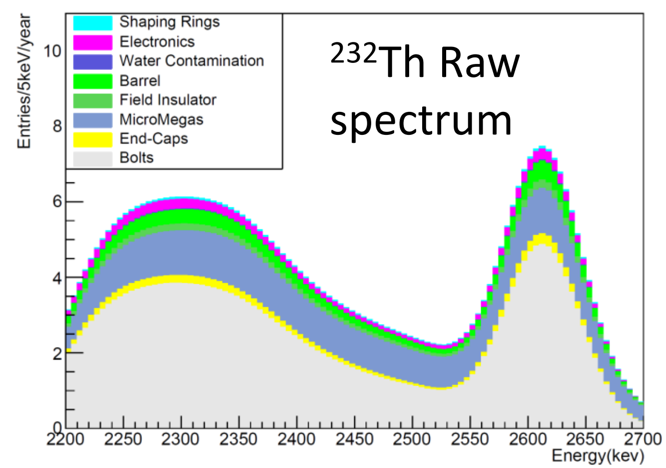
Background budget

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

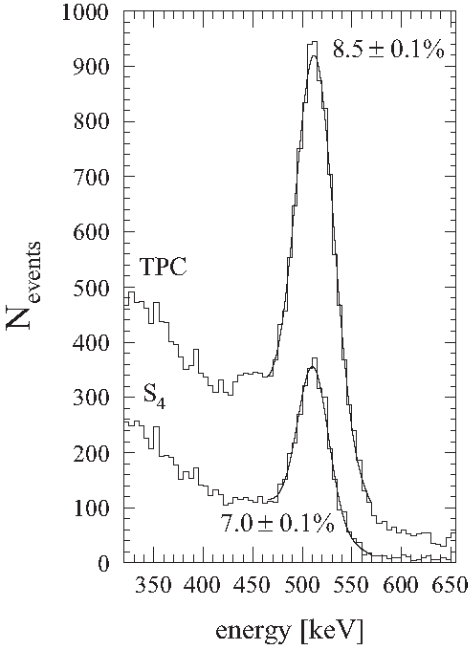




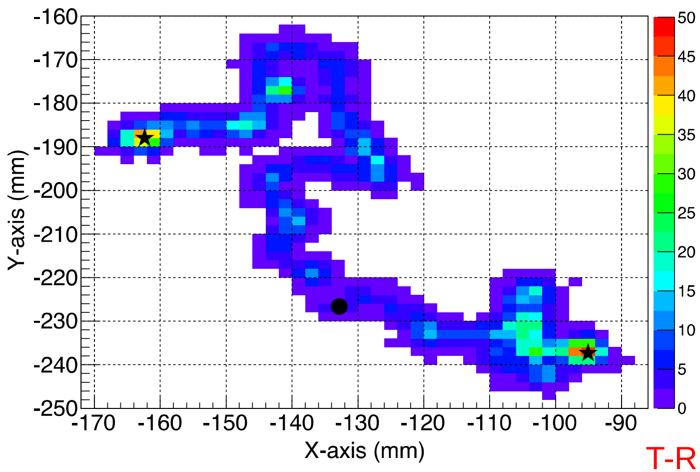


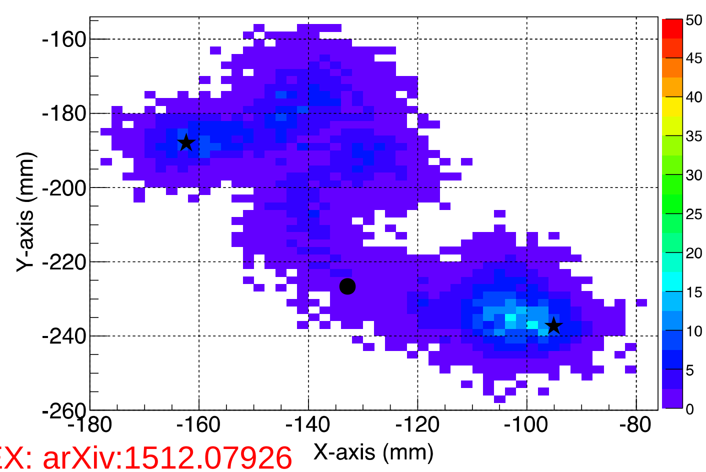
Energy resolution and tracking with Micromegas

- 3% FWHM at Q $_{0\nu\beta\beta}$
  - Extrapolated from 511keV and 1.2MeV peaks
  - Xenon+TMA mixture
- Tracking and 0νββ identification with Bragg peaks
  - Fine mm level pixel/strip pitches
  - TMA suppresses electron diffusion and enhances tracking



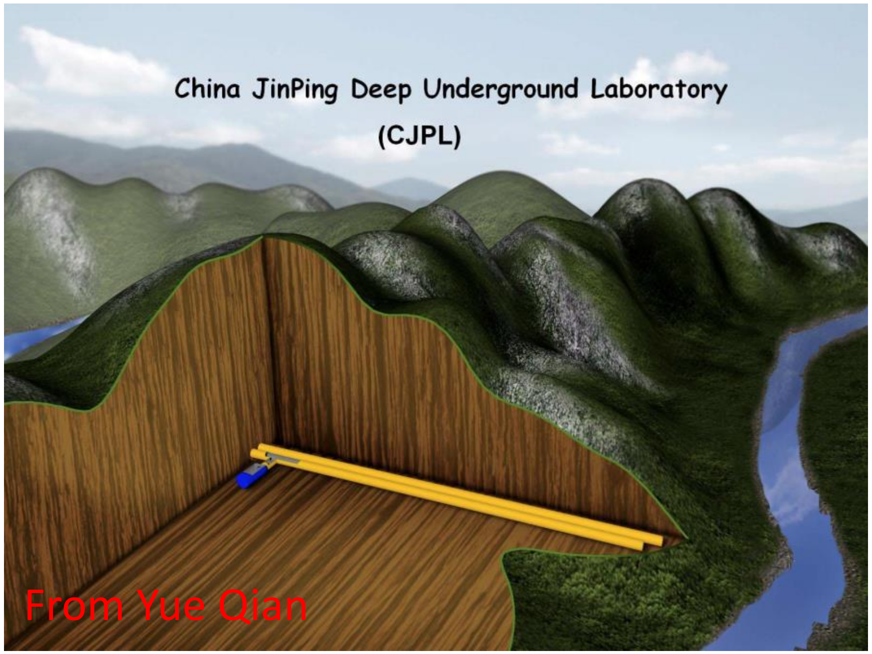
Gonzalez-Diaz, et al. *NIMA* 804 8 (2015)

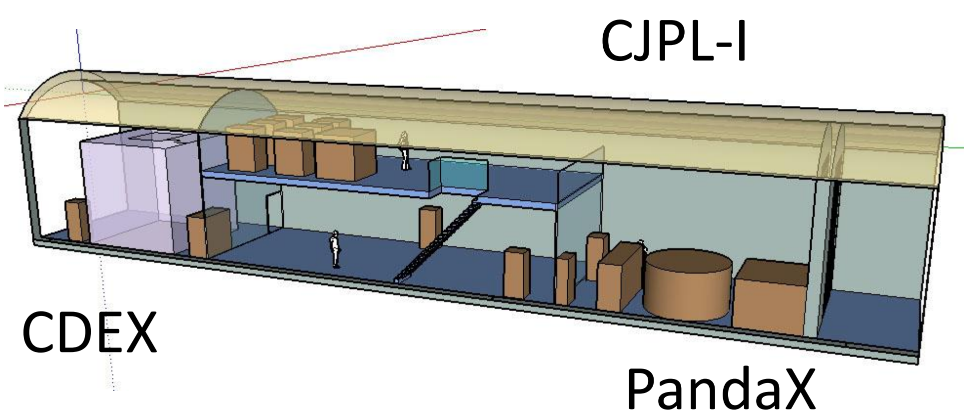




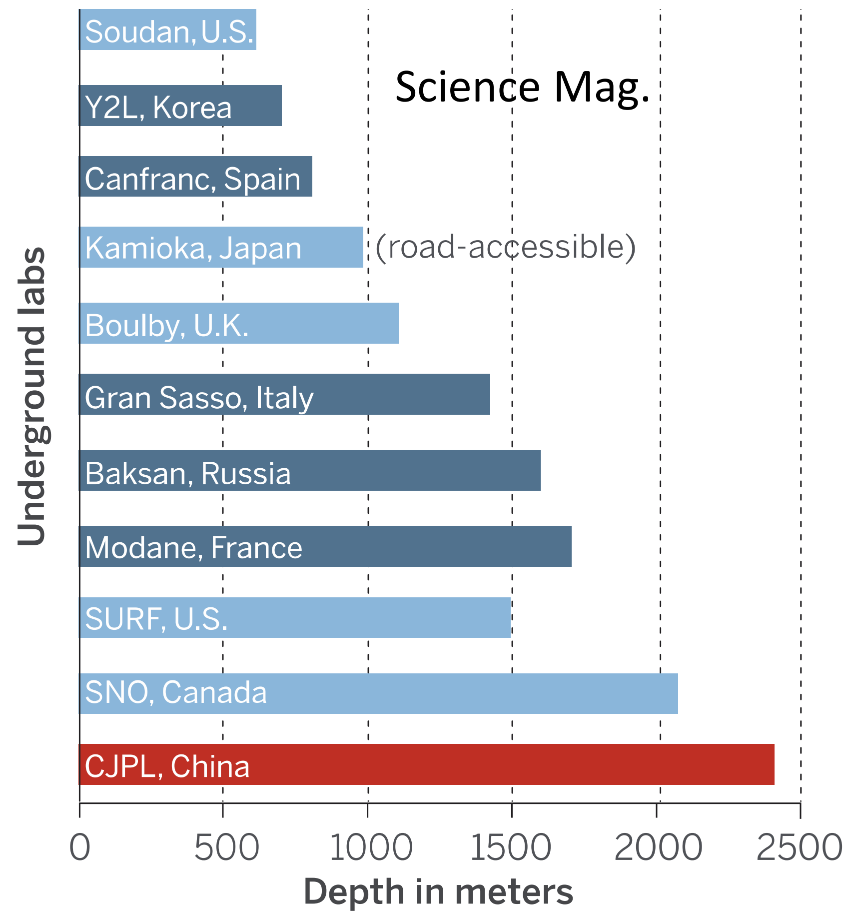
T-REX: arXiv:1512.07926

CJPL boosts underground physics in China





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



0νββ → Lepton number violation

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- Lepton number conservation is accidental: we have never observed any lepton number violation process.

- Normal double beta decay conserves lepton number:

$$(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\bar{\nu}_e$$

- But neutrinoless case → ΔL = +2

$$(A,Z) \rightarrow (A,Z+2) + 2e^-$$

→New Physics

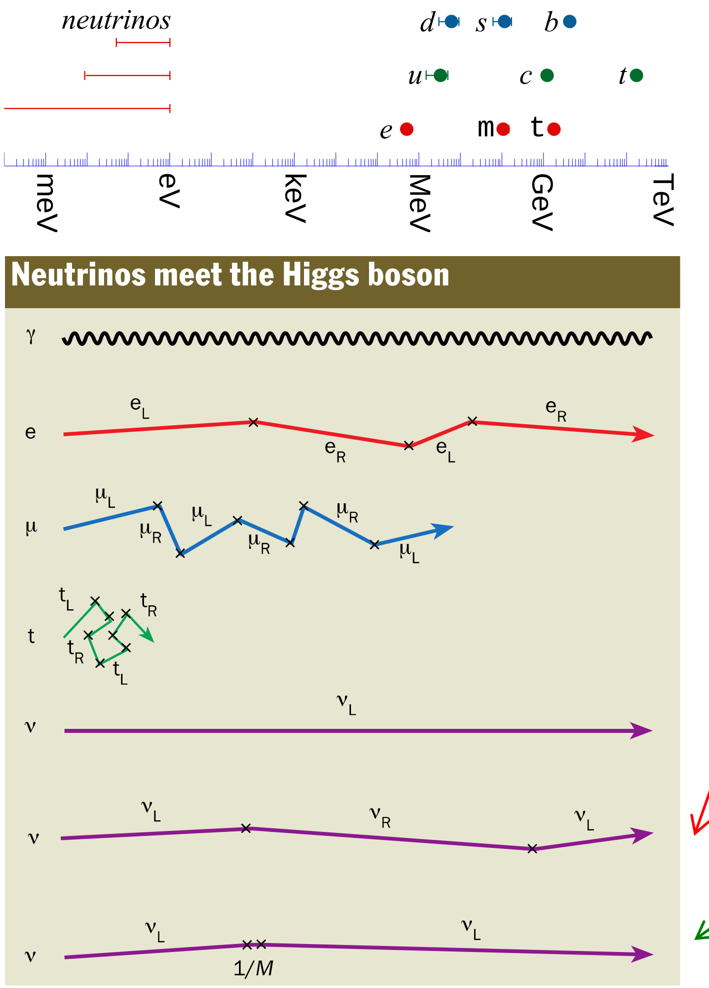
→Matter-Antimatter asymmetry??

→Leptongenesis??

Lepton	Lepton Number
e^-	+1
e^+	-1
ν_e	+1
anti-ν_e	-1

Tiny neutrino mass from Seesaw Mechanism

PANDA X
PARTICLE AND ASTROPHYSICAL XENON TPC



H. Murayama

Dirac Neutrinos

- Same as charged fermions
- ν_R is not observed because of no weak coupling
- Tiny mass is just a measured quantity

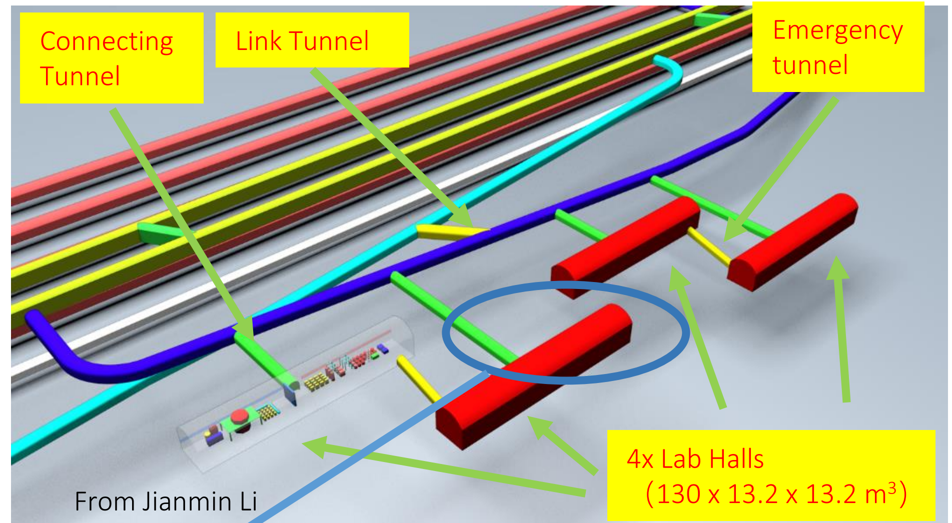
Majorana Neutrinos

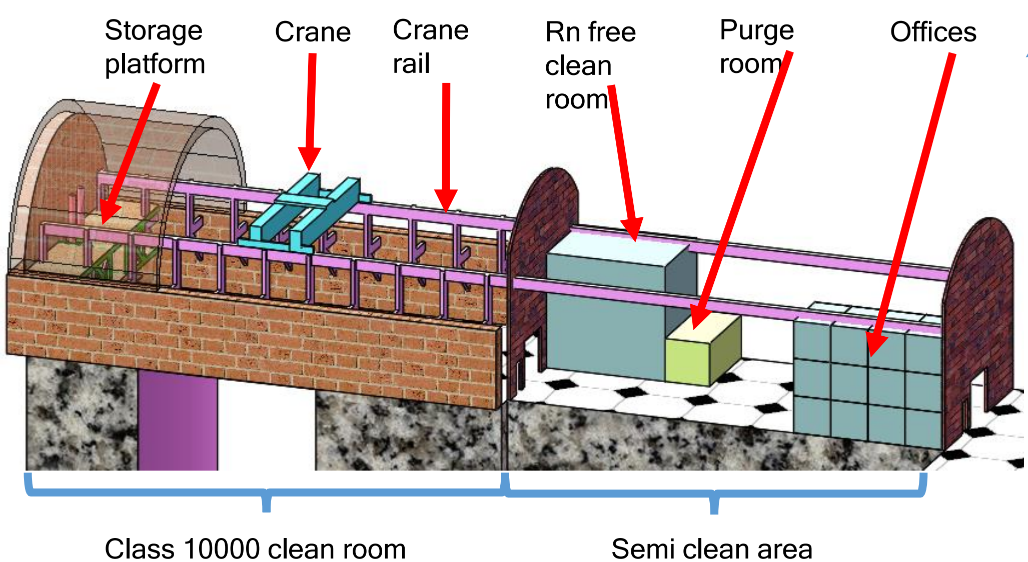
- No distinction between neutrino and anti-neutrino
- Tiny mass generated as m_D^2/M, ~eV (Seesaw Mechanism)

PandaX hall at CJPL-II

Experiments at CJPL-II

- PandaX projects
- CDEX
- JUNA (accelerator)
- Jinping neutrino experiment (LS)
- …





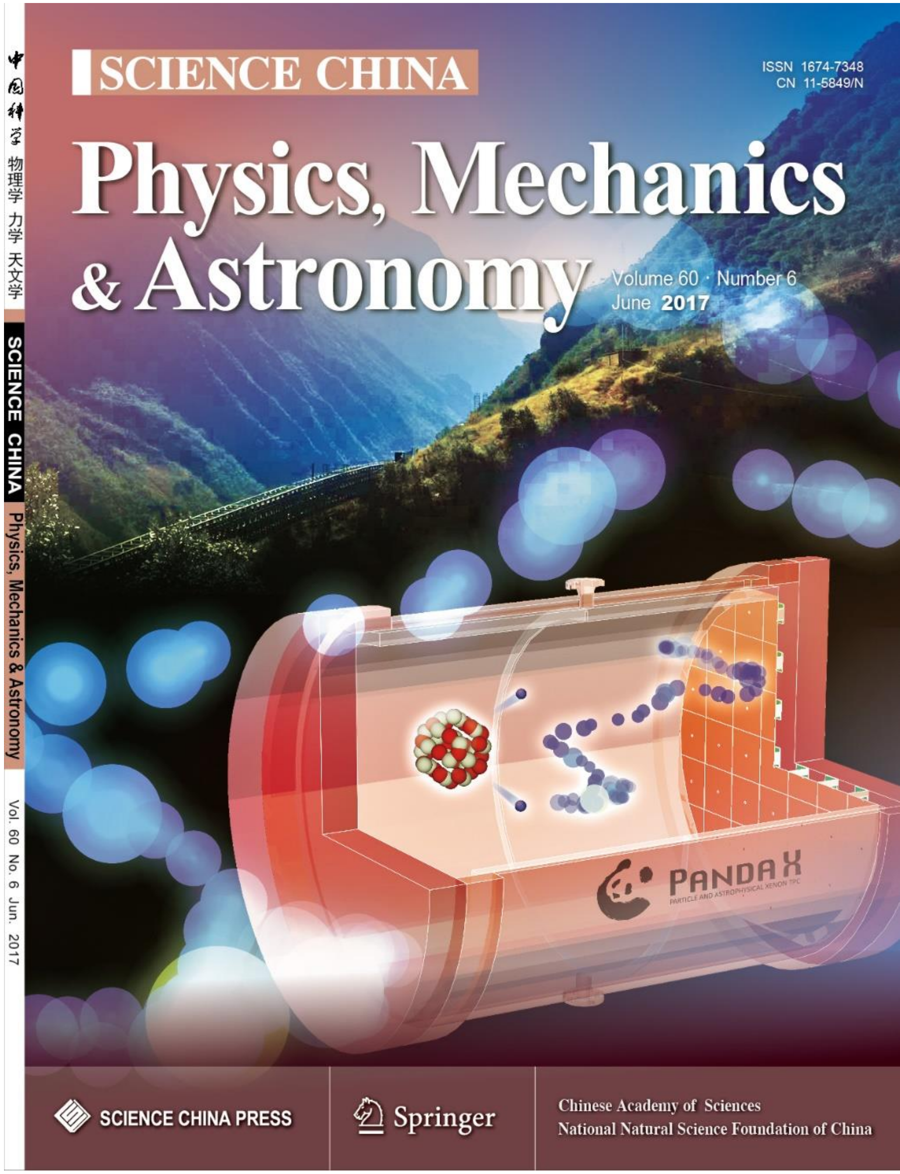
PandaX at Hall B2

- Extra excavation for the water shielding pool (finished)
- Shared facility of DM and 0νββ searches
- Beneficial occupancy by the beginning of 2018

Outline

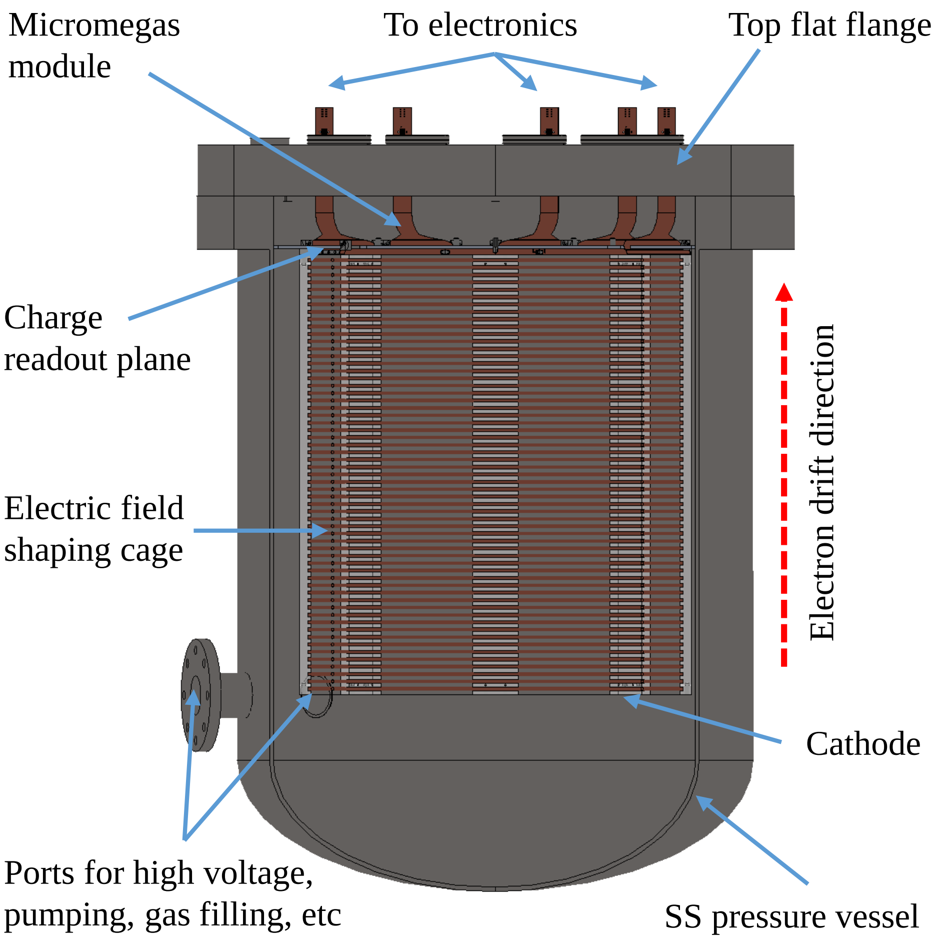
PANDA X
PARTICLE AND ASTROPHYSICAL XENON TPC

- ~~Neutrinoless double beta decay~~
    - ~~physics and detection~~
- PandaX-III project overview
- The first module with Micromegas modules
    - Field cage
    - Readout plane
    - Electronics
    - Physics reach
- Prototype TPC
    - Design and construction
    - Initial commissioning data



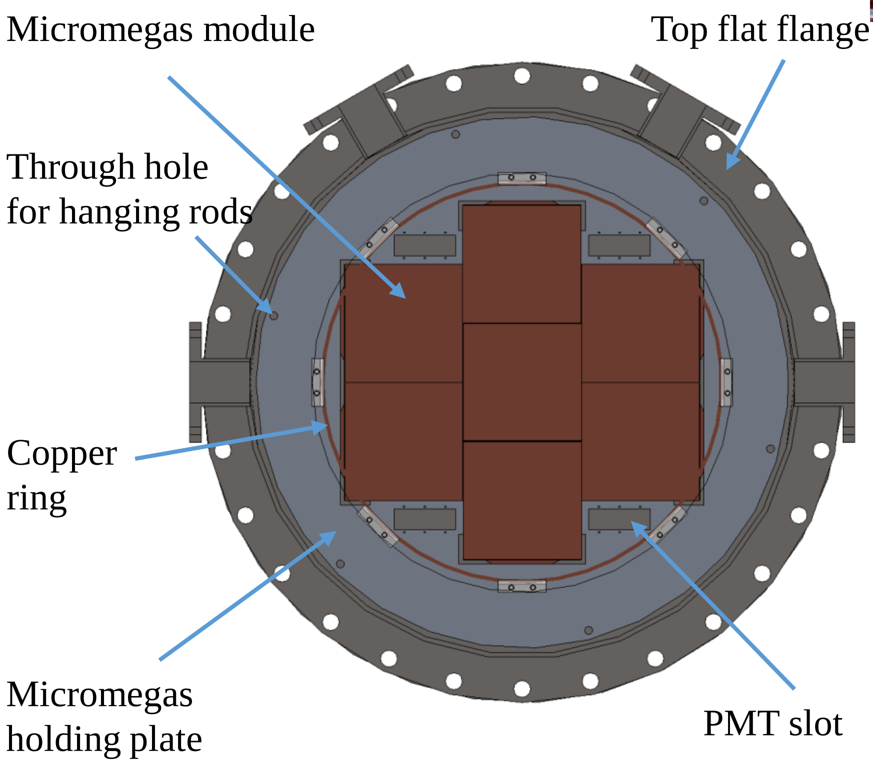
Prototype TPC at SJTU

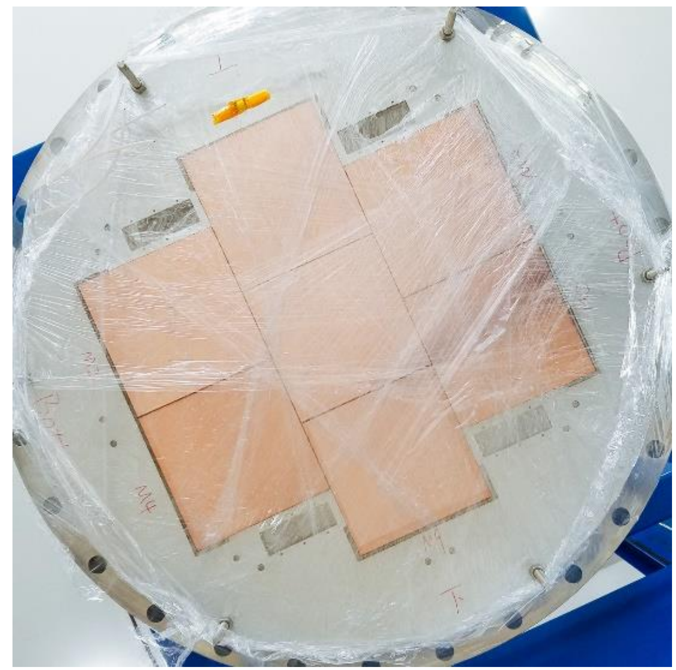
- About 600 L inner volume
- Field cage: 66 cm diameter, 78 cm drift length, single-ended
- 16 kg of xenon at 10 bar
- SS pressure vessel



Charge readout plane

- 7 Microbulk Micromegas modules installed and commissioned

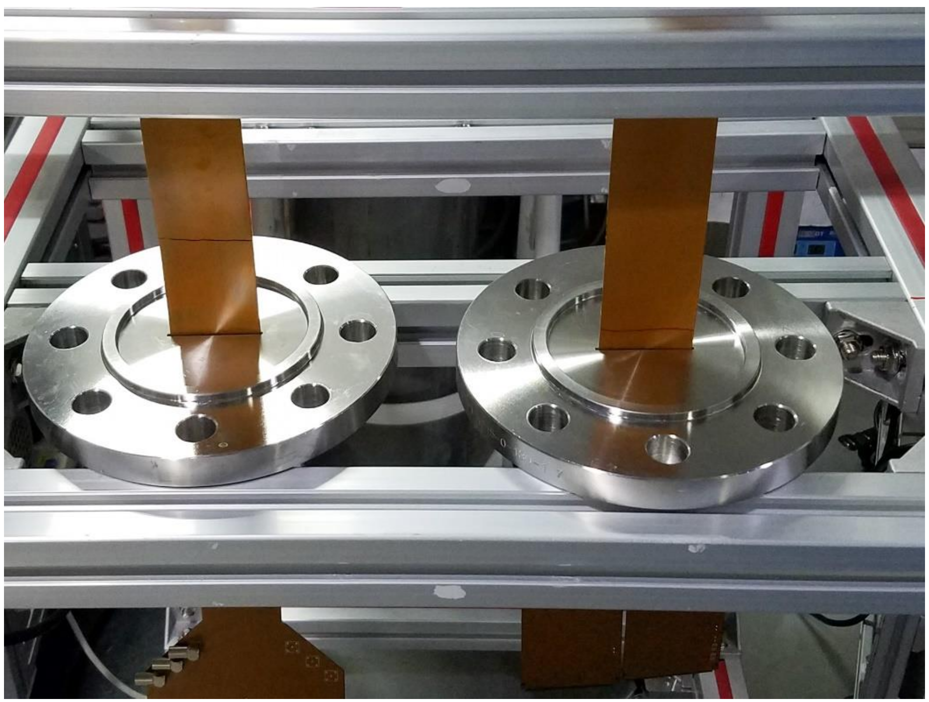




Signal feedthrough

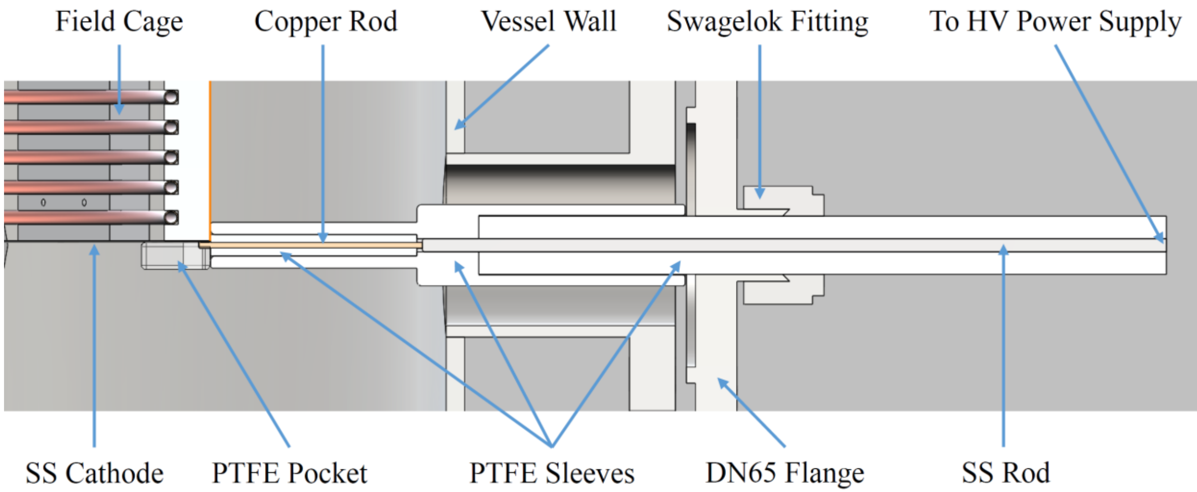
PANDA X
PARTICLE AND ASTROPHYSICAL XENON TPC

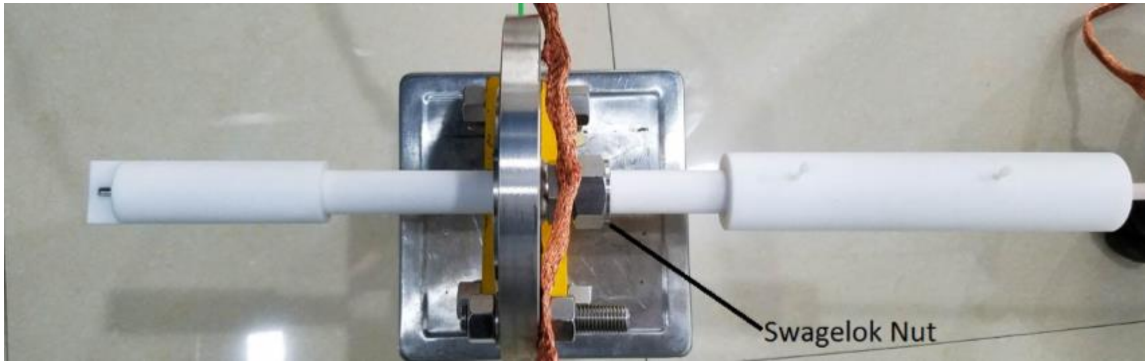
- Micromegas signals are read out through Kapton extension cables.
- Extension cables glued in matching slots in flanges.
- Leak test shows upper limit for leak rate is gram level xenon per year per feedthrough at 10 bar.



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

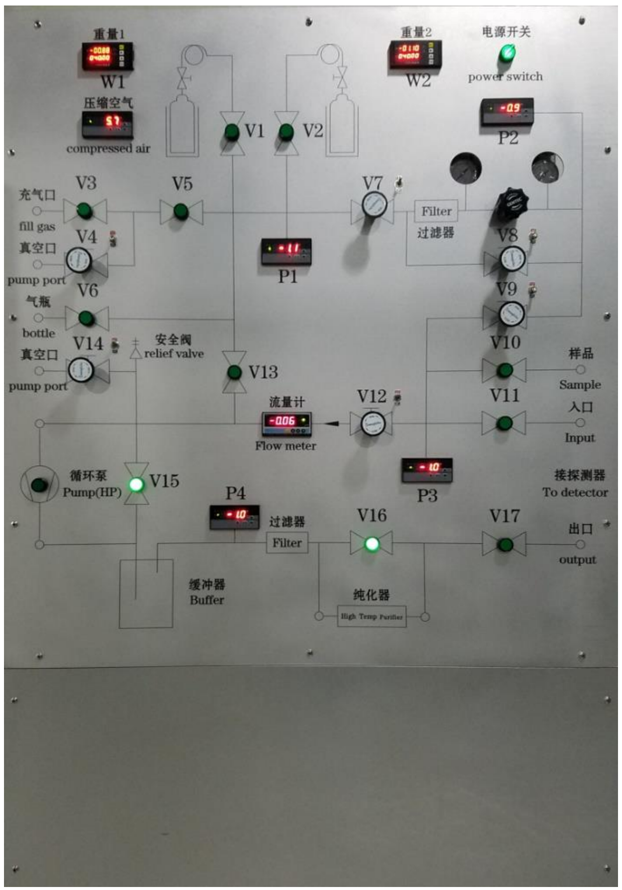


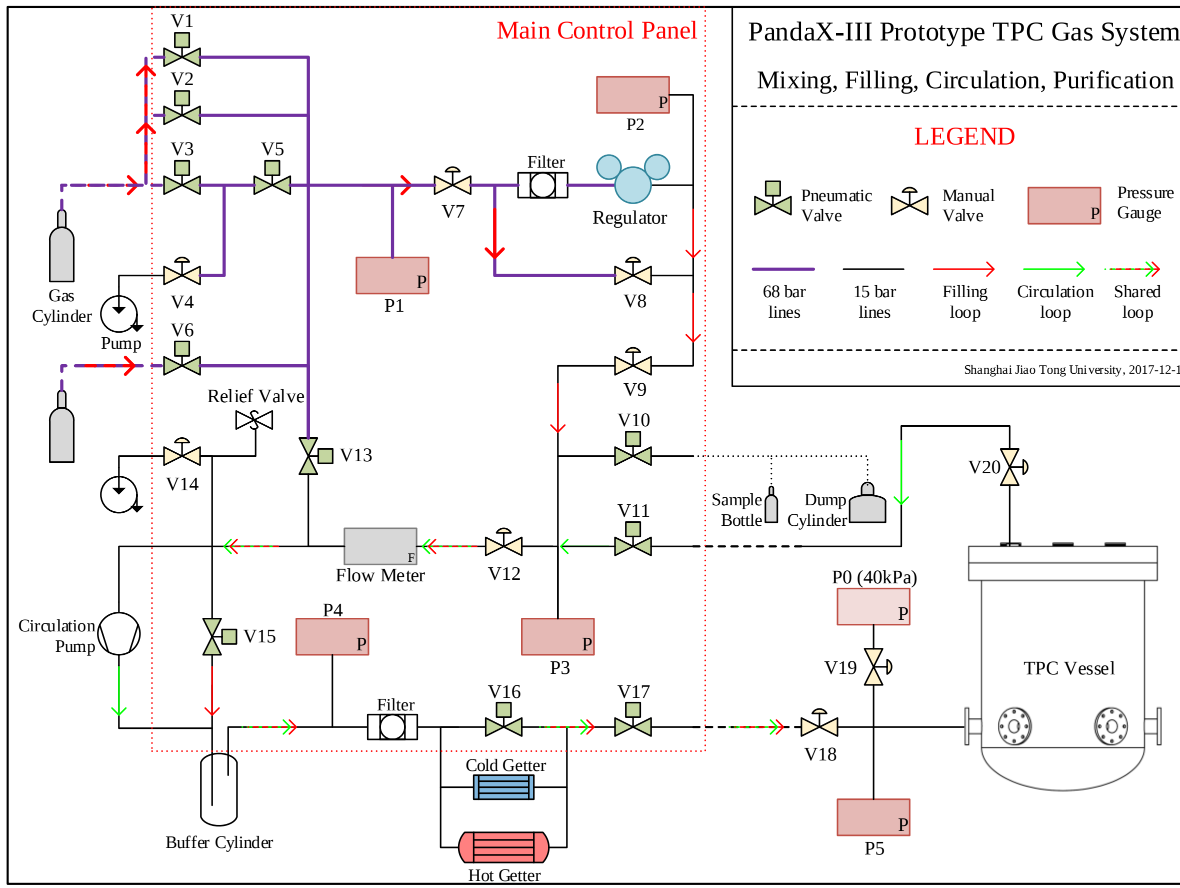


Gas System

PandaX
PARTICLE AND ASTROPHYSICAL XENON TPC

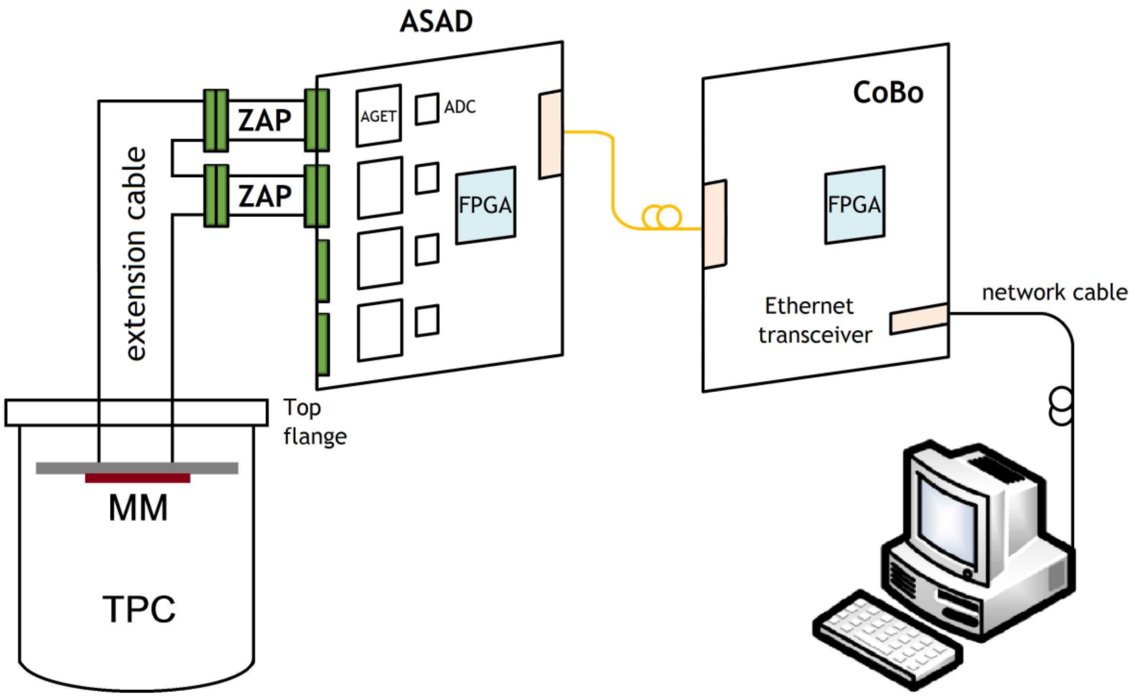
- A custom-designed system to fill, mix, circulate, purify and recuperate gas mixtures of xenon and argon gas.
- Room temperature and hot getters.



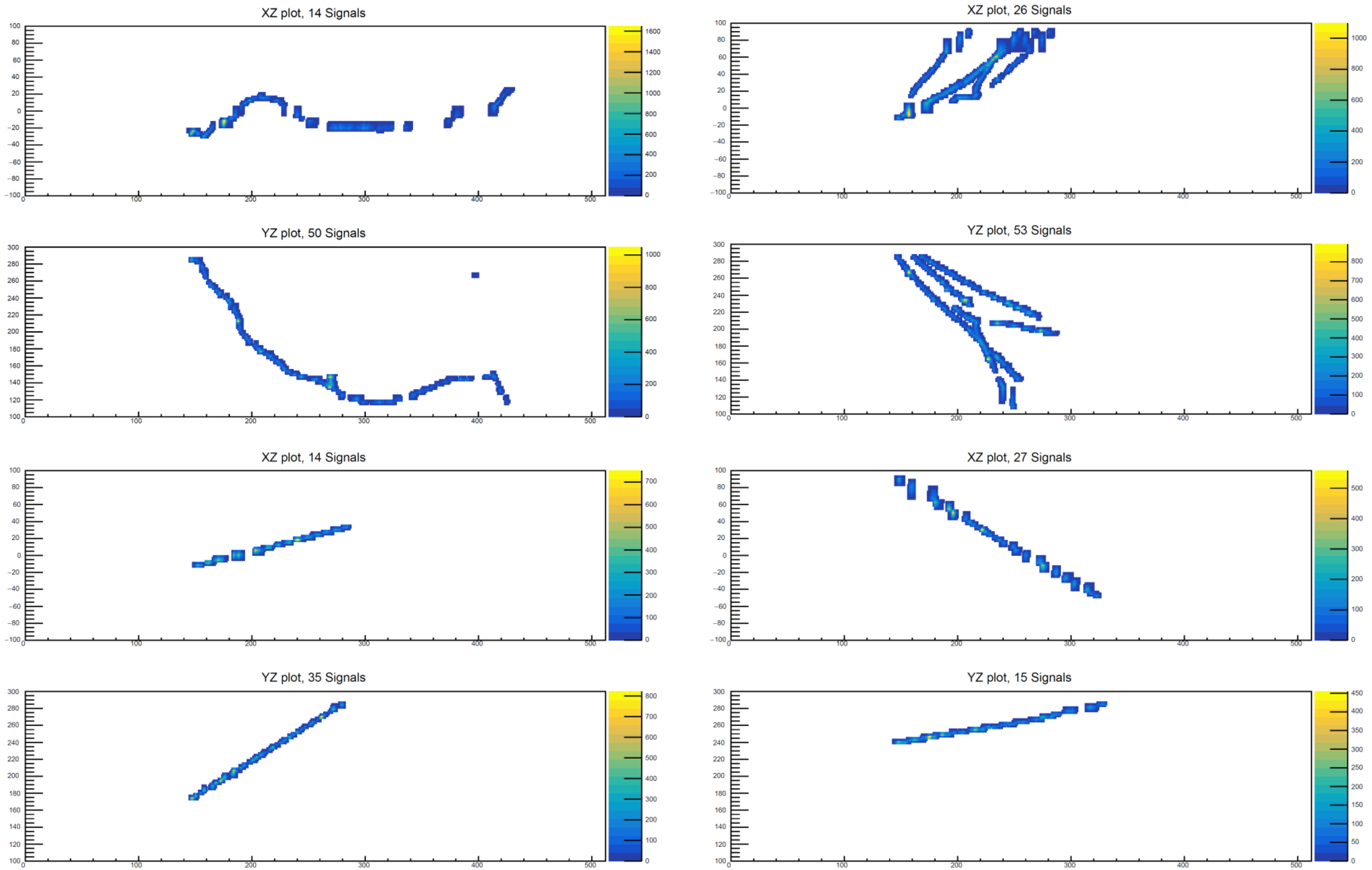


Electronics and DAQ

- 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



Some example tracks

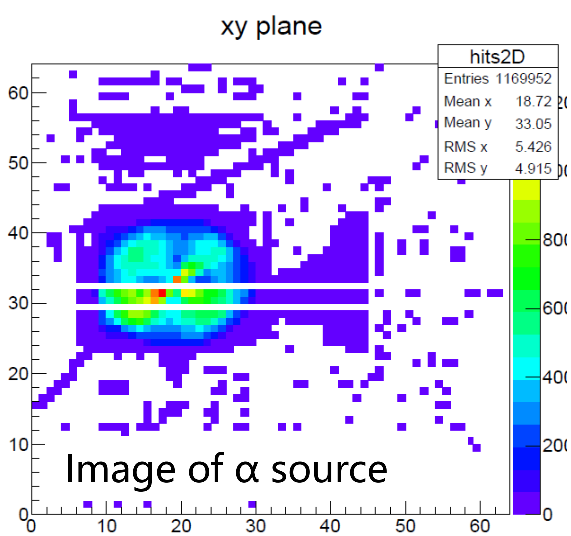


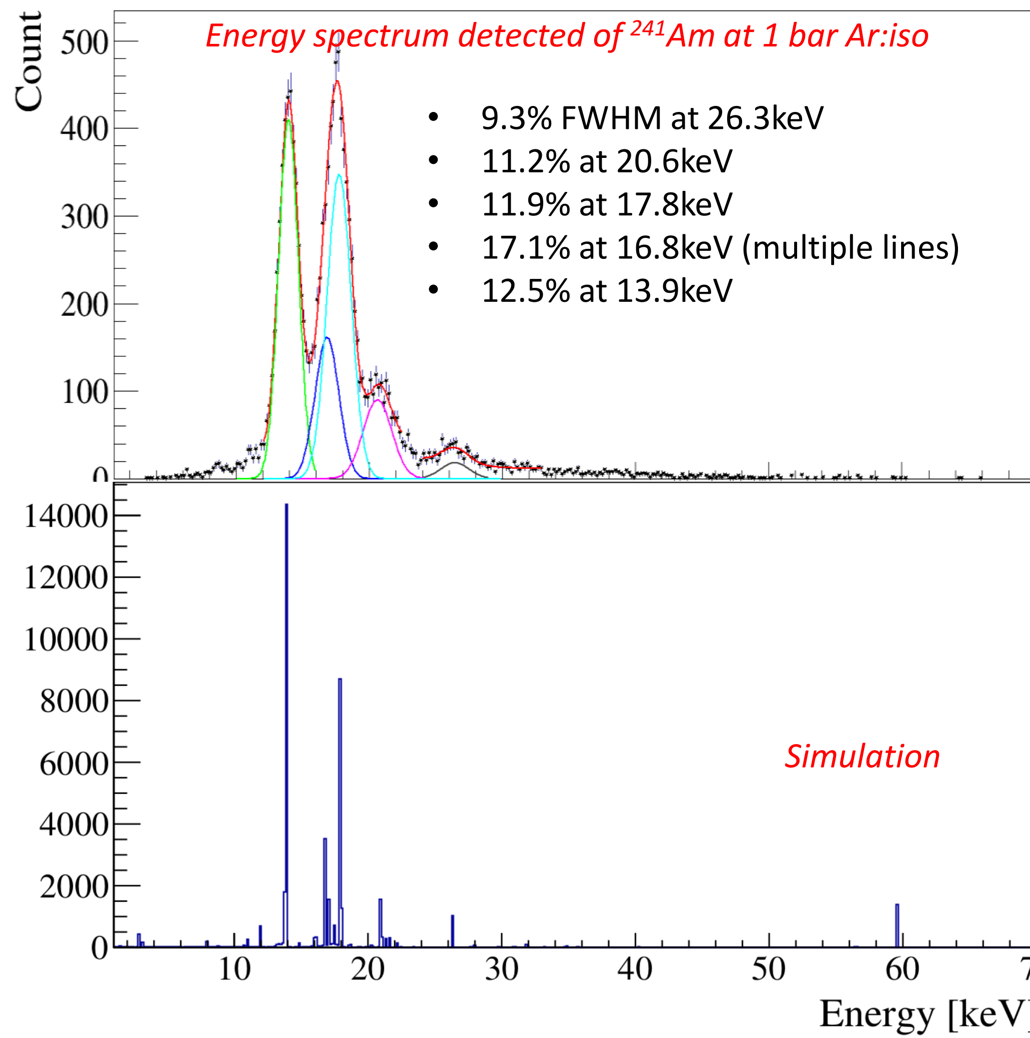
Data: 1 MM with 1bar Ar:(5%)Isobutane

PANDA X
PARTICLE AND ASTROPHYSICAL XENON TPC

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

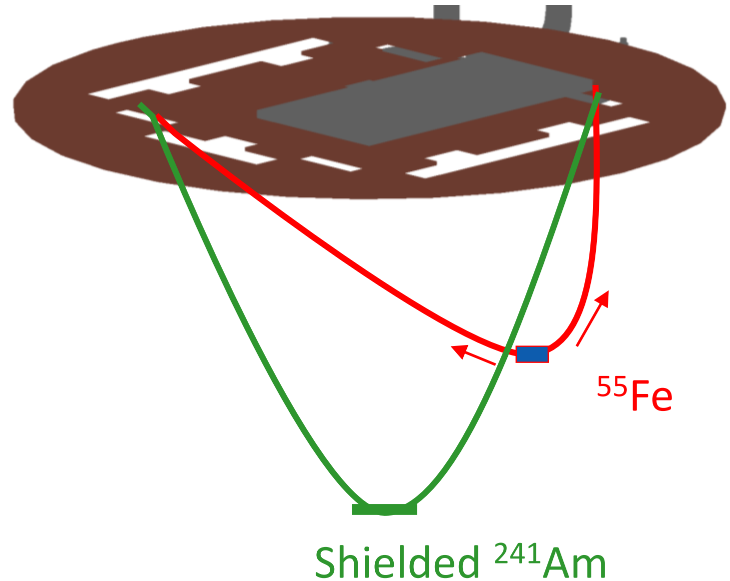
Detector gain ~8000

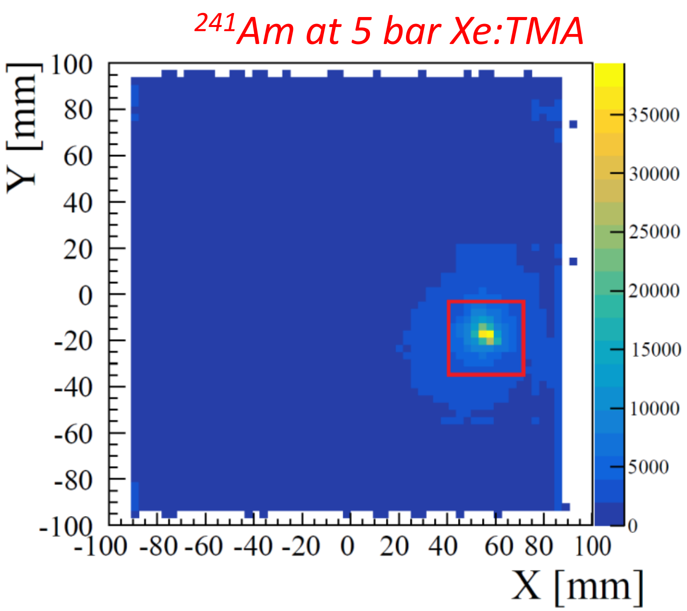


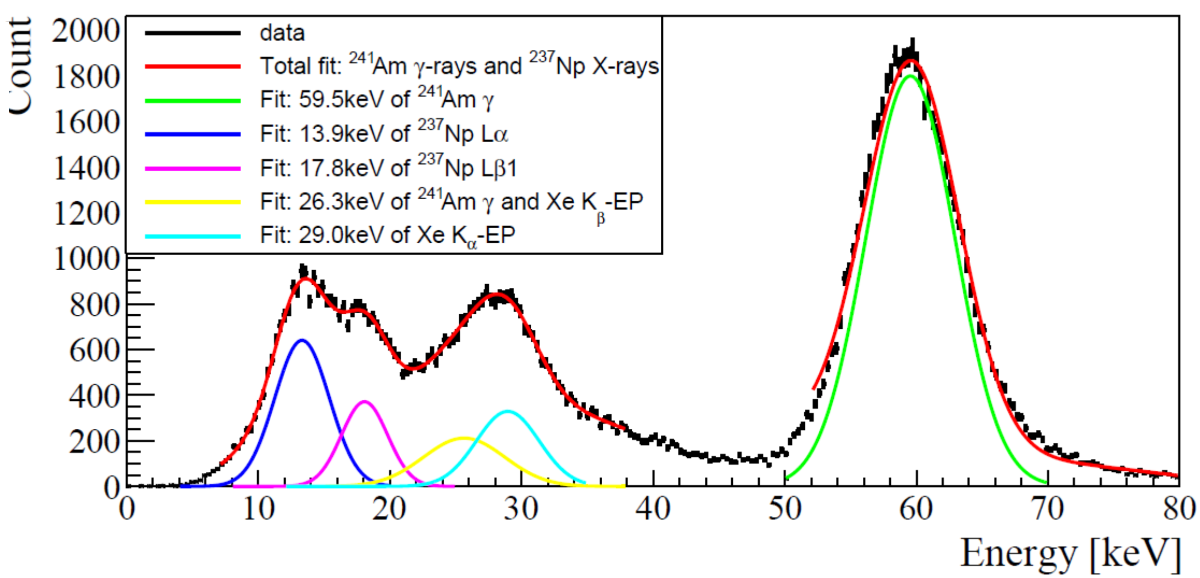


Data: 5 bar Xe:(1%)TMA

- 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.

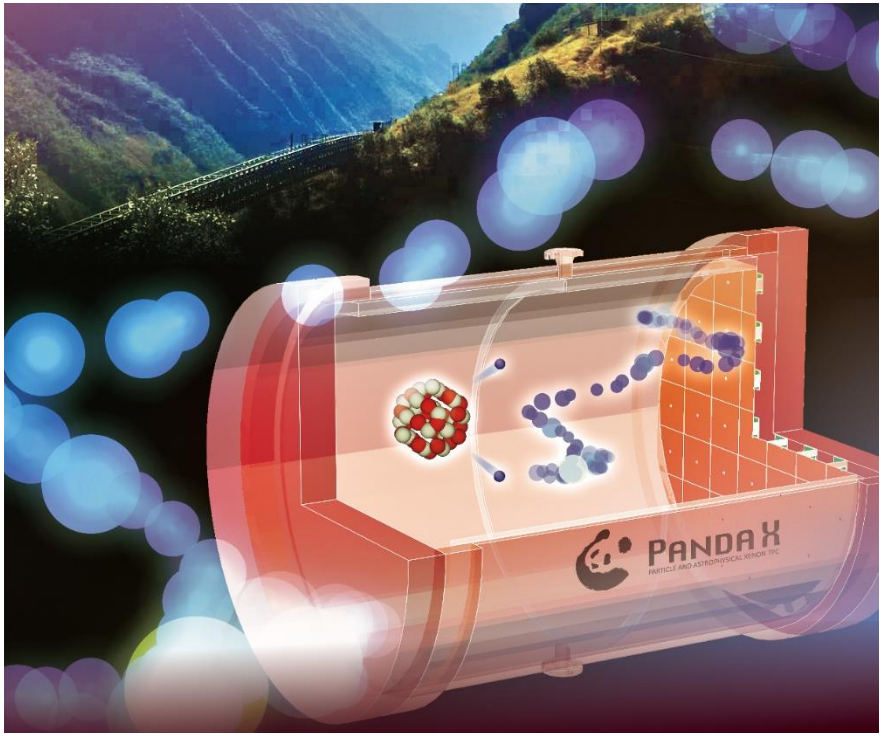


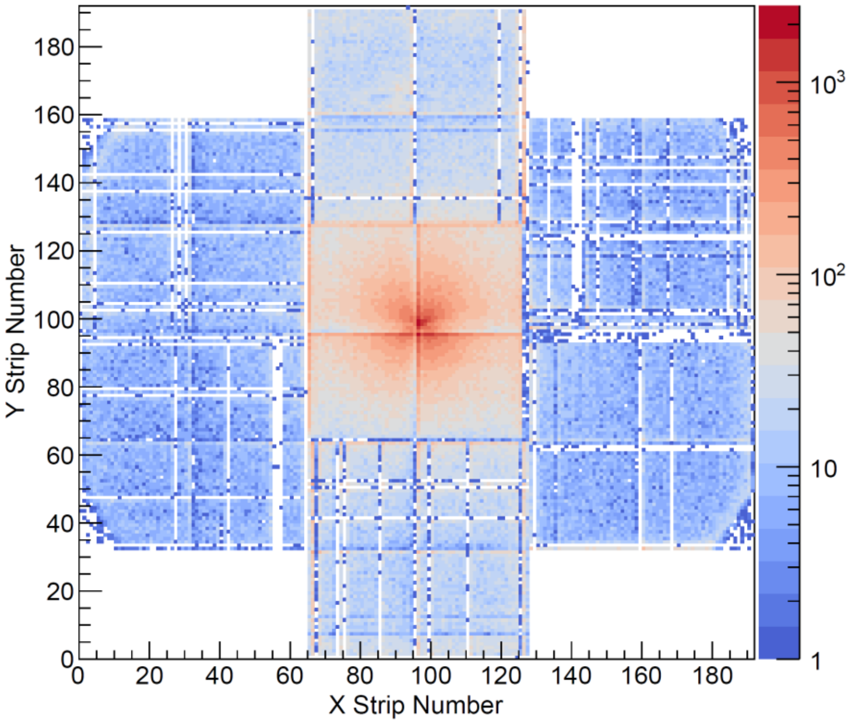




Conclusions

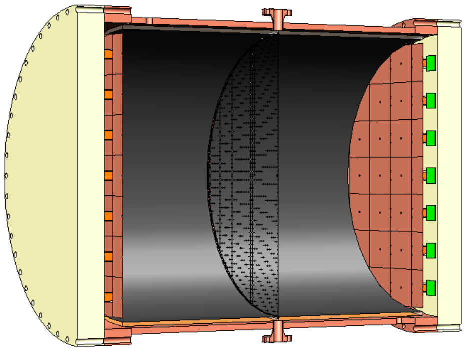
- PandaX-III aims to build multiple 200-kg scale high pressure xenon TPC for NLDBD search at CJPL.
- The first module is under technical design phase.
- A 20-kg scale prototype TPC is under commissioning.
- With 7 modules of 20×20 cm, it's the largest application of Microbulk Micromegas.

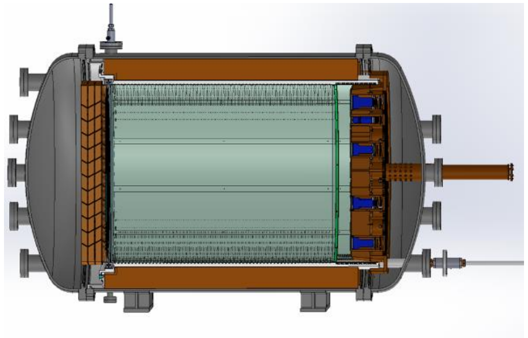




TMA

PandaX vs. NEXT

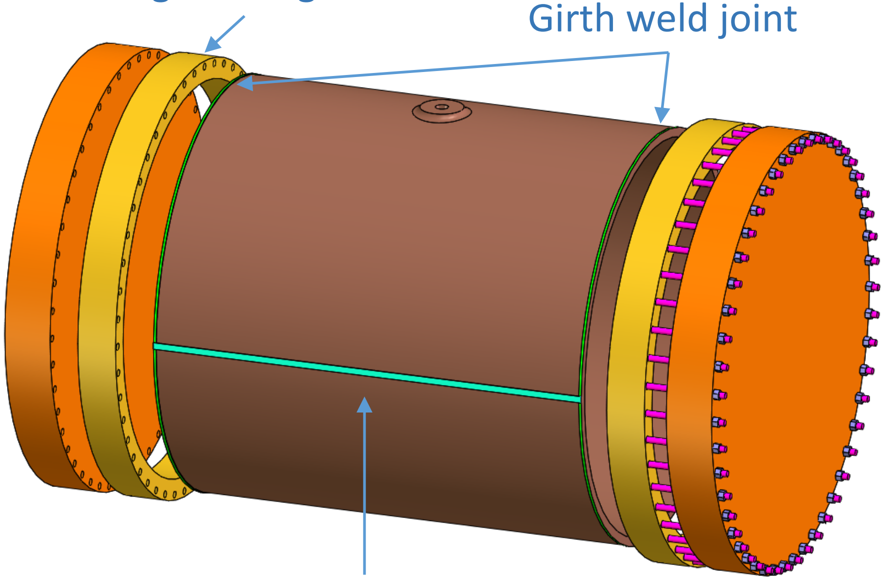




PandaX-III first TPC		NEXT-100
200 kg Xe(enriched) + 1% TMA	Detector medium	100 kg pure Xe (enriched)
------------------	Light	Primary + electroluminescence light readout by PMTs
Micromegas	Charge/Tracking	SiPM
3%	Projected energy resolution	0.7%
2-3 mm	Tracking pitch size	1 cm
X,Y	Fiducialization	X,Y,Z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

High pressure vessel

- High gas pressure and radio-pure
- Baseline approach: oxygen-free copper welded with E-beam technique
  - Technologically challenging
  - Still a major contributor to our background budget
- Alternatively:
  - Titanium vessel with copper lining



Copper Vessel:

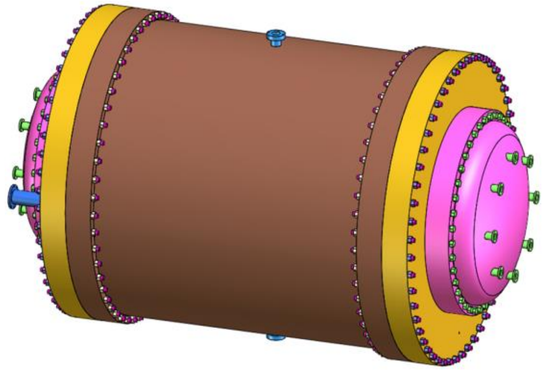
- Barrel thickness 32mm, weighs 3.6 T
- Flat cover thickness 180mm, 3.6 T
- Endcap weighs 0.5 T
- Bolts weight 220 kg in total

Possibility of fabrication in China or Germany

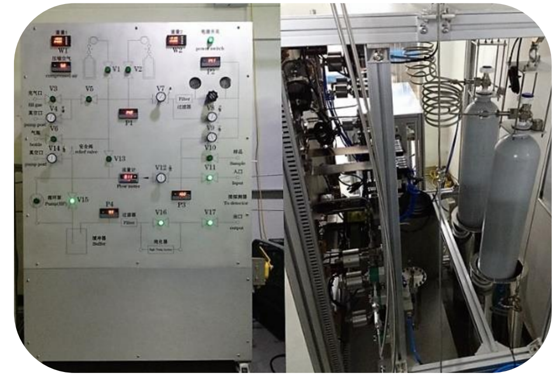
- Connex (contractor, machining)
- Pro-Beam (E-beam welding)
- CSN (OFHC copper)

“Other” critical pieces of PandaX-III

145 kg of 90% enriched ^{136}Xe at Shanghai

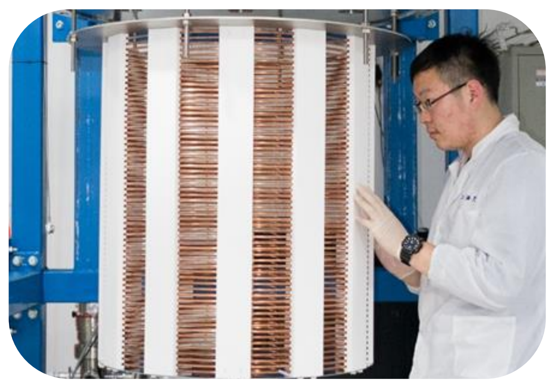


Design and Fabrication of copper vessel in progress



Gas mixing, circulation, and purification system ready

Third version of FEC ready for testing with MM



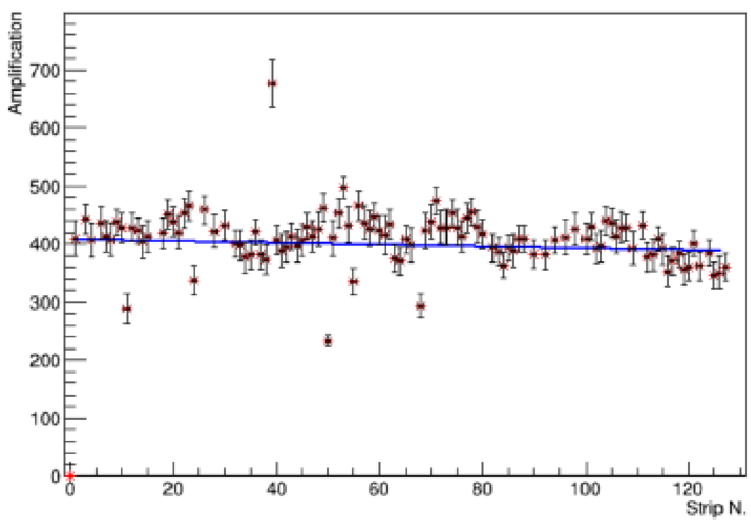
Prototype TPC has been running with Micromegas

CJPL-II infrastructure under construction

MM Characterization

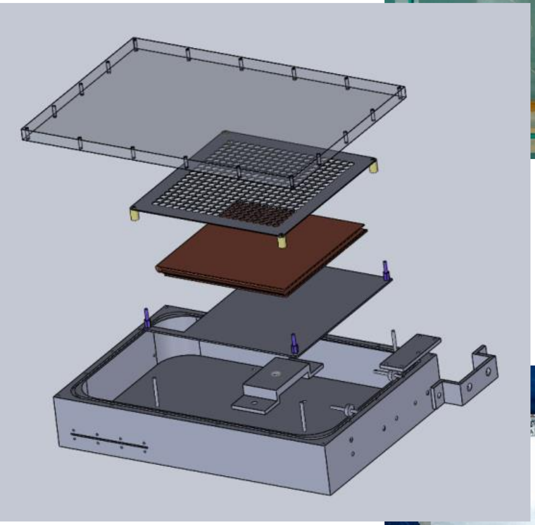
Gain and gain uniformity measured

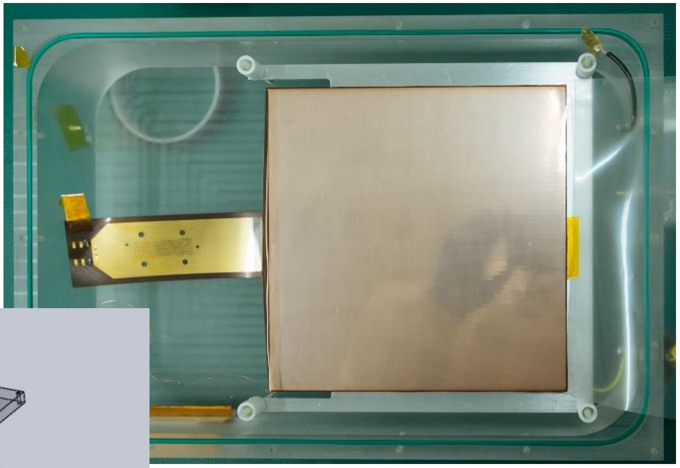
- Argon + CO_2 (30%)
- 1 bar flowing gas
- 7.5% RMS uniformity



Future updates:

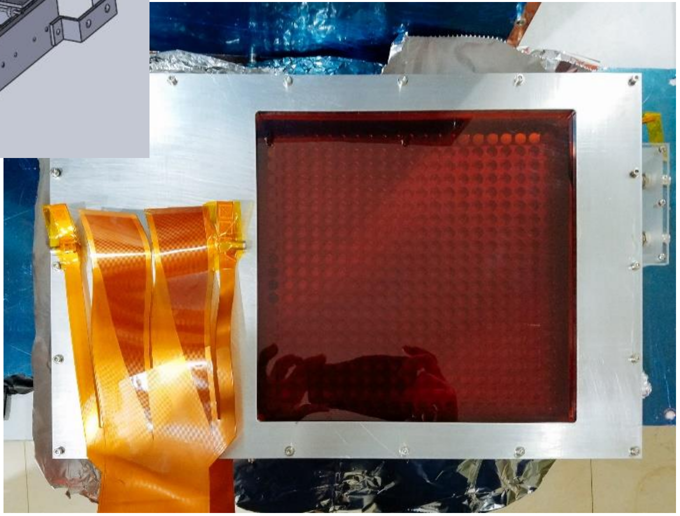
- Motorized source scanning
- More uniform drift field
- Pressurized xenon gas
- Multiple MM cross comparison





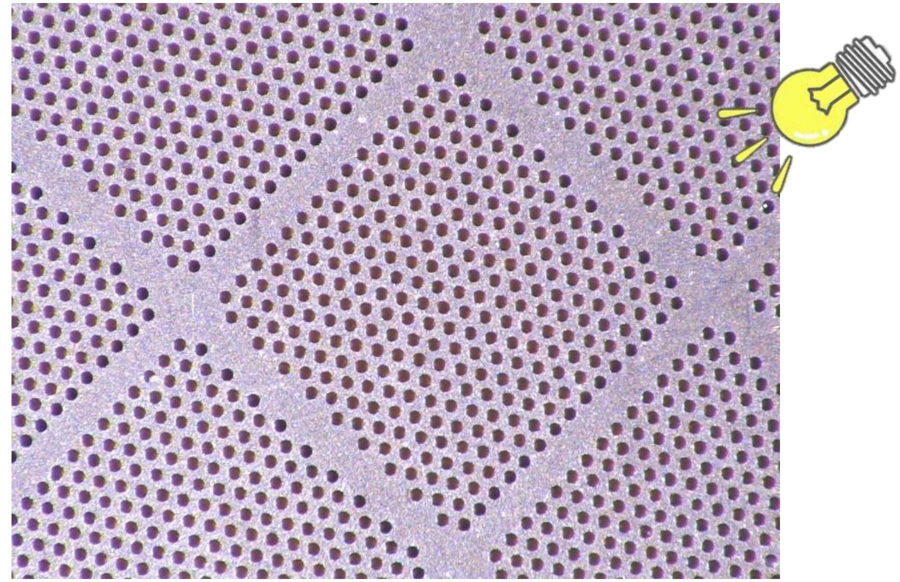
Without

with cathode, top lid

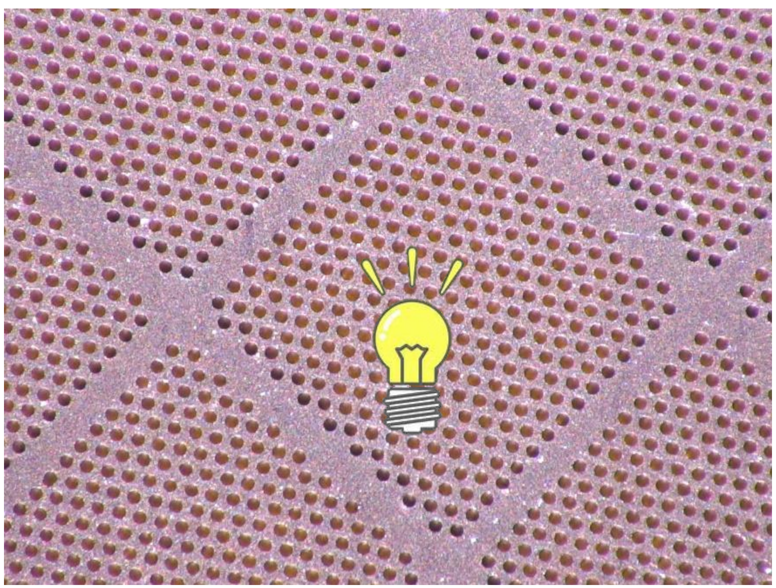


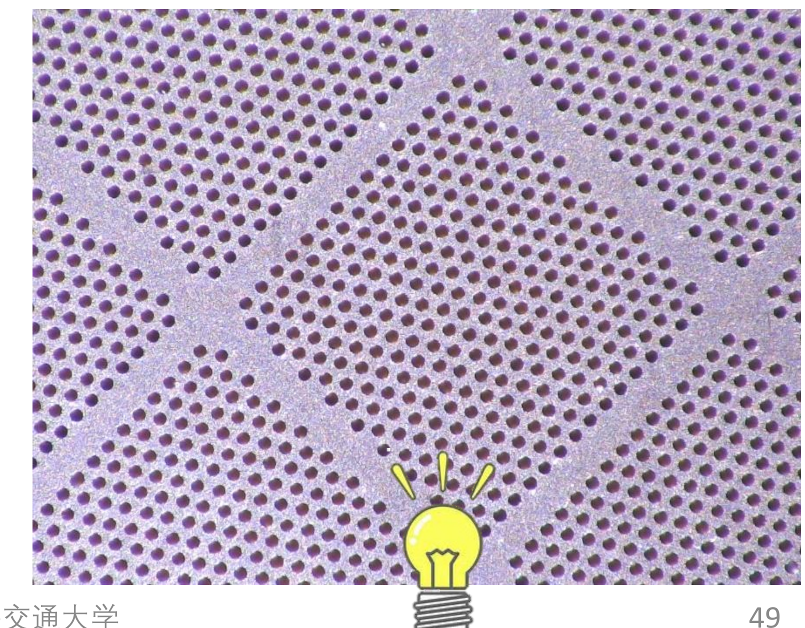
Visual check of bad channels

- Hard to spot defects from microscope images
- Lighting plays a critical role



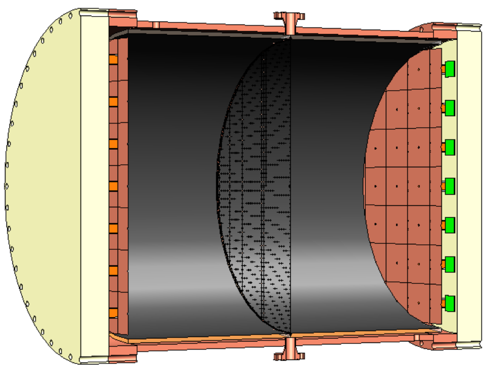
MM under different lighting conditions





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



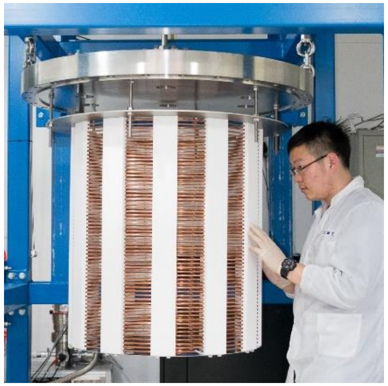


Table 5 The raw background contribution from different parts in the laboratory and the detector by taking the 3% FWHM detector resolution into account. BI stands for background index

	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