中科大核与粒子物理学科在线研讨会

寻找马约拉纳中微子

韩柯

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2020/08/21

Outline

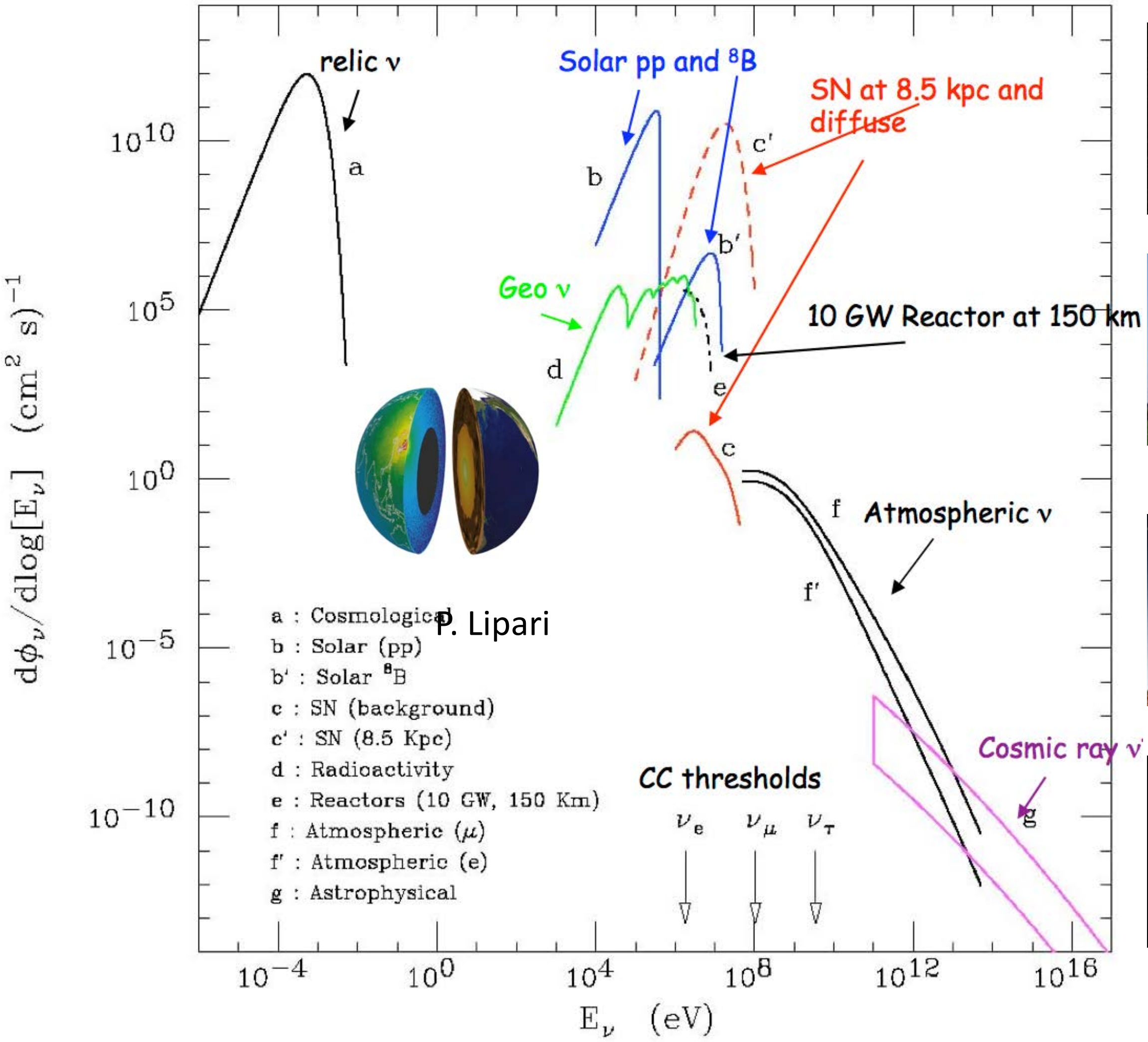
- Introduction to Neutrinoless double beta decay ($0\nu\beta\beta$): the search for Majorana neutrinos.

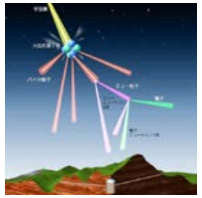
- Current status and plans for $0\nu\beta\beta$ searches worldwide

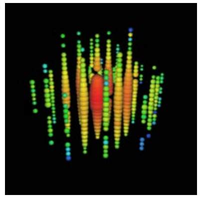
- Opportunities at CJPL-II
  - $0\nu\beta\beta$ proposals in China
  - PandaX series experiments for $0\nu\beta\beta$ of ^{136}Xe

Rewarding neutrinos

- Various sources
  - E.g. 10^{11} /cm^2 s from the Sun at Earth surface
- Extremely abundant:
  - ~100 /cm^3 relic ν
  - Connect the tiny particle to cosmological scale
  - Indirect observation
  - Cosmological constraints on sum of neutrino mass (and number of neutrino flavors)







Current neutrino picture

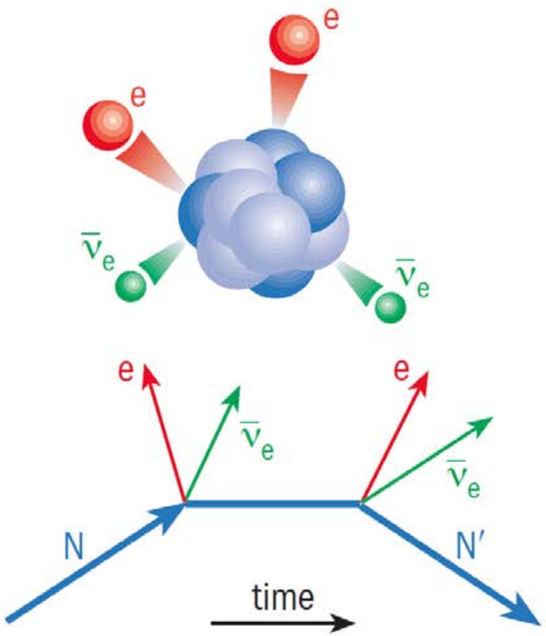
✓ Neutrinos are massive: First evidence of physics beyond the SM.

✓ Neutrino flavor oscillation 🡐 mixing of massive neutrinos

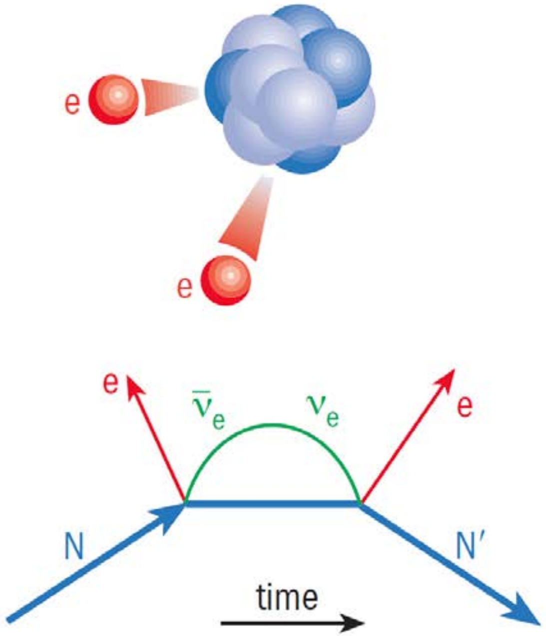
✓ Two hierarchical mass scales Δm^2

✓ Three mixing angles measured

Majorana neutrino and 0νββ



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



From Physics World

1935, Goeppert-Mayer
Two-Neutrino double beta decay

1937, Majorana
Majorana Neutrino

1939, Furry
Neutrinoless double beta decay 0νββ

1930, Pauli
Idea of neutrino

1933, Fermi
Beta decay theory

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

First round of experiments

- Initial calculation showed half-life of 2νββ of 10^{21} year, and 0νββ of 10^{15} year
- Triggered a large number of experiments
- Detect electrons and/or daughter nuclei

1948, First experiment

- 25 g of enriched ^{124}Sn

  $^{124}Sn \rightarrow {}^{124}Te + 2e^{-} + (2\bar{\nu}_e)$

- Geiger counters to measure the emitted electrons
- $0\nu\beta\beta$ half-life estimation: 3×10^{15} year

1950, First evidence of $2\nu\beta\beta$

- Geochemical experiment

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

- Count relative abundance of ^{130}Xe in a 1.5 billion year old Tellurium ore.

1956, Lee and Yang

Parity non-conservation

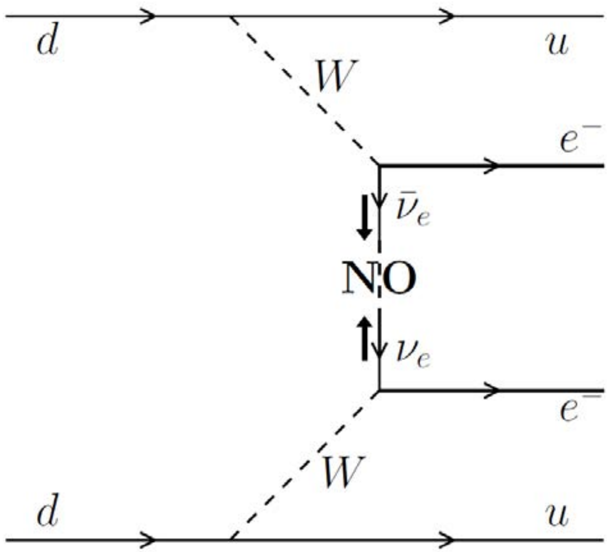
1957, Lee and Yang, and others

Two-component theory of neutrino

0νββ is forbidden in the SM

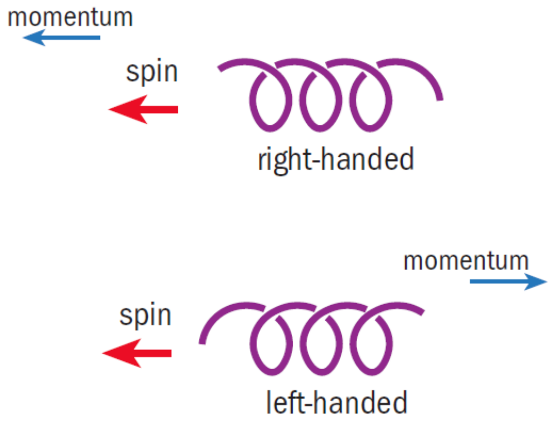
Two-component theory of neutrino

- Neutrinos are left-handed and antineutrinos are right-handed (helicity)
- Confirmed in experiments
- Incorporated into the SM



0νββ is forbidden in the SM

- Neutrino-antineutrino distinction
- Helicity mis-match



"Marked decline" of interests in 0νββ experiments during the decade after parity non-conservation

Renewed interest in experiment and theory

1967

Ge detector

10^{21}y half-life limit

Physics Letters B

Volume 26, Issue 2, 25 December 1967, Pages 112-116

Double beta decay in ^{48}Ca and the conservation of leptons ☆

R.K. Bardin, D.J. Gollon, J.D. Ullman, C.S. Wu

1984, Fiorini and Niinikoski

Low temperature detector

1987, Elliott, Hahn, Moe

First direct observation of $2\nu\beta\beta$(^{82}Se); used a TPC

Minghan Ye et al

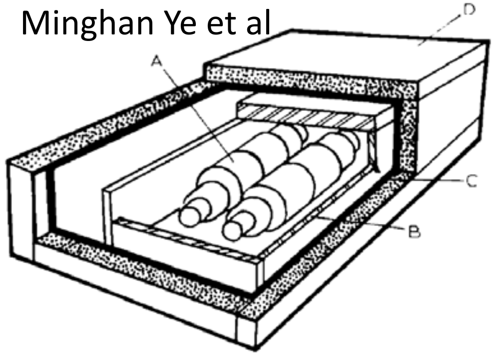


Fig. 1. Schematic drawing of detector assembly. A: CaF_2 crystal, B: plastic scintillator, C: steel shielding, D: lead shielding.

1982, Schechter and Valle

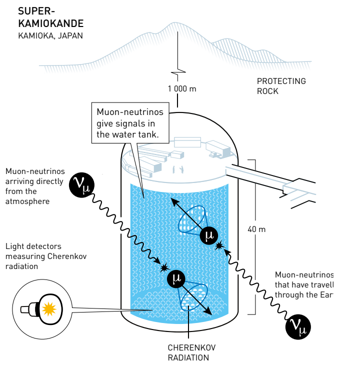
$0\nu\beta\beta \rightarrow$ Majorana neutrinos

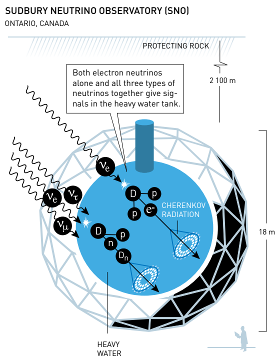
~2000, SK and SNO

Tiny but finite neutrino mass

Physics beyond the SM

Helicity flipping possible at $0\nu\beta\beta$





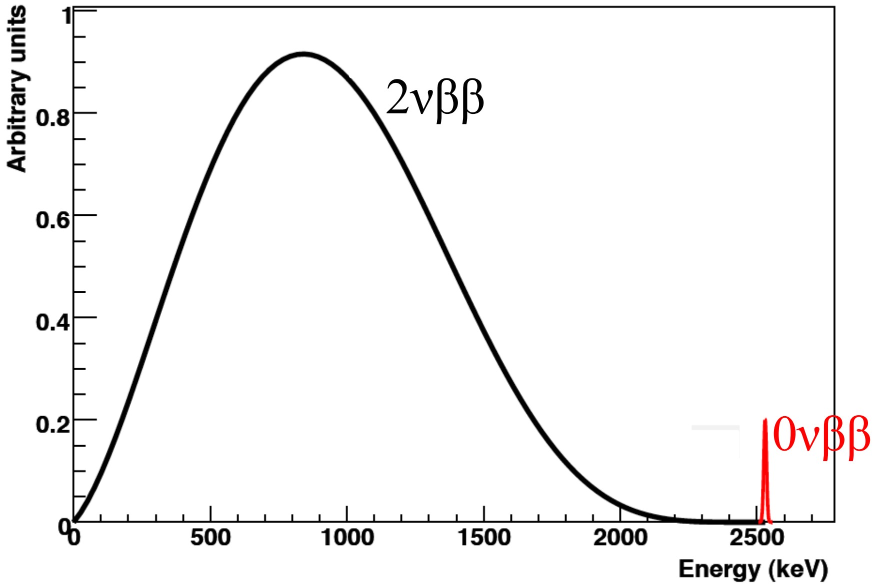
Detection of double beta decay

- Examples:

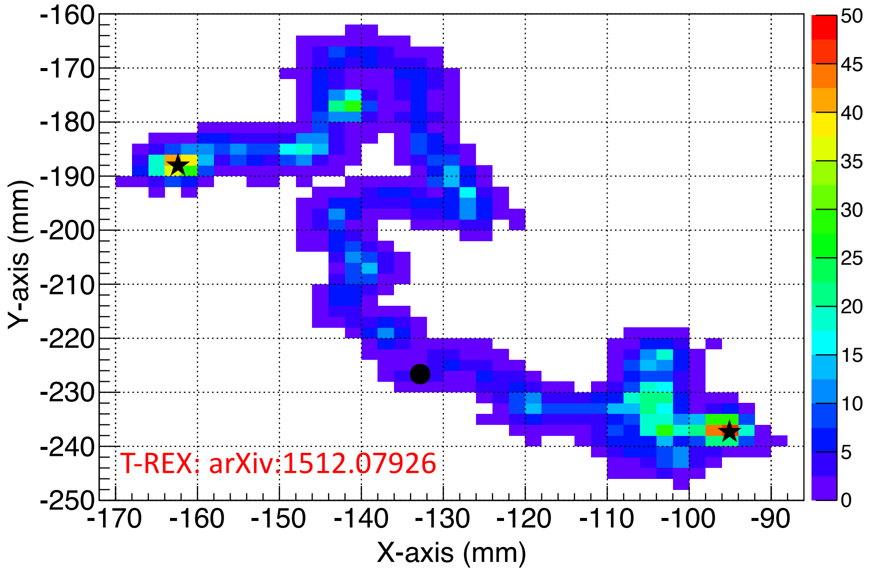
$$^{136}_{54}Xe \rightarrow\ ^{136}_{56}Ba + 2e^- + (2\bar{\upsilon})$$

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

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



Sum of two electrons energy



Simulated track of 0νββ in high pressure Xe

0νββ probes the nature of neutrinos

- Majorana or Dirac
- Lepton number violation
- Measures effective Majorana mass: relate 0νββ to the neutrino oscillation physics

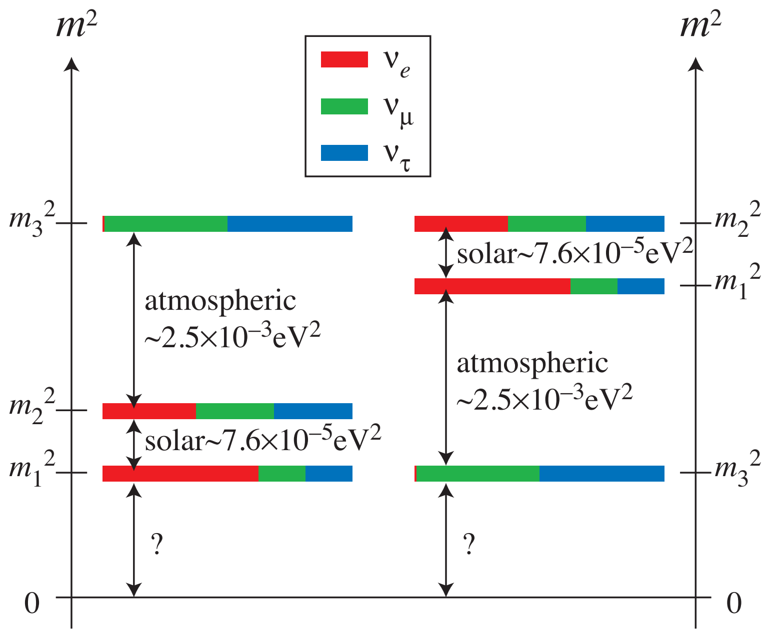
$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}(Q,Z)\,|M^{0\nu}|^2\,\frac{|\langle m_{\beta\beta}\rangle|^2}{m_e^2}$$

Phase space factor

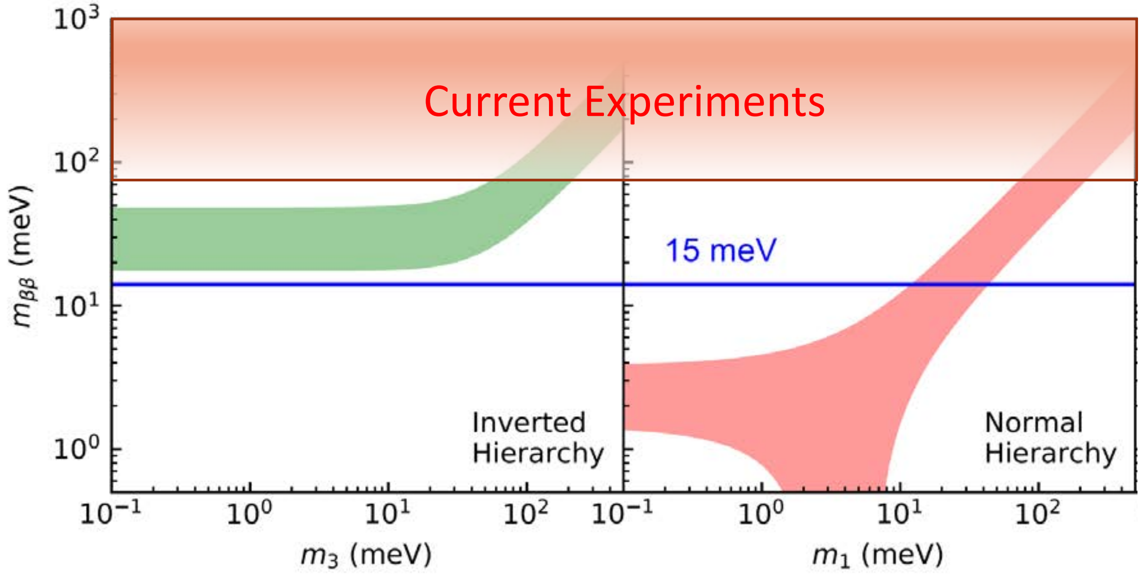
Nuclear matrix element

Effective Majorana neutrino mass:

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

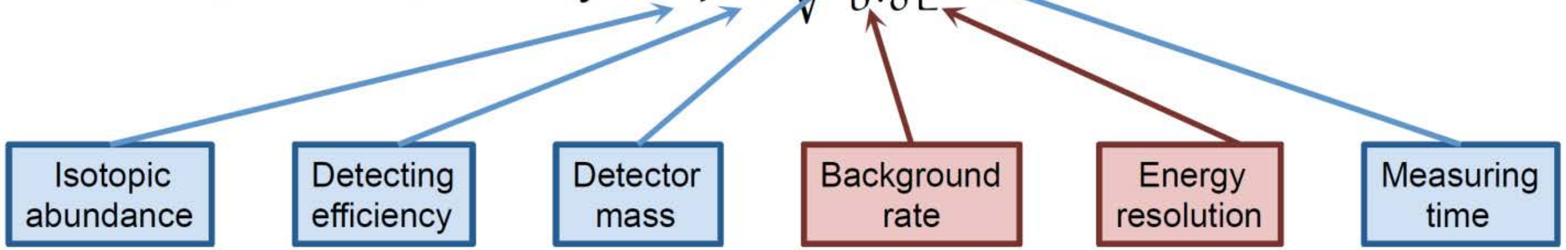


Normal Inverted

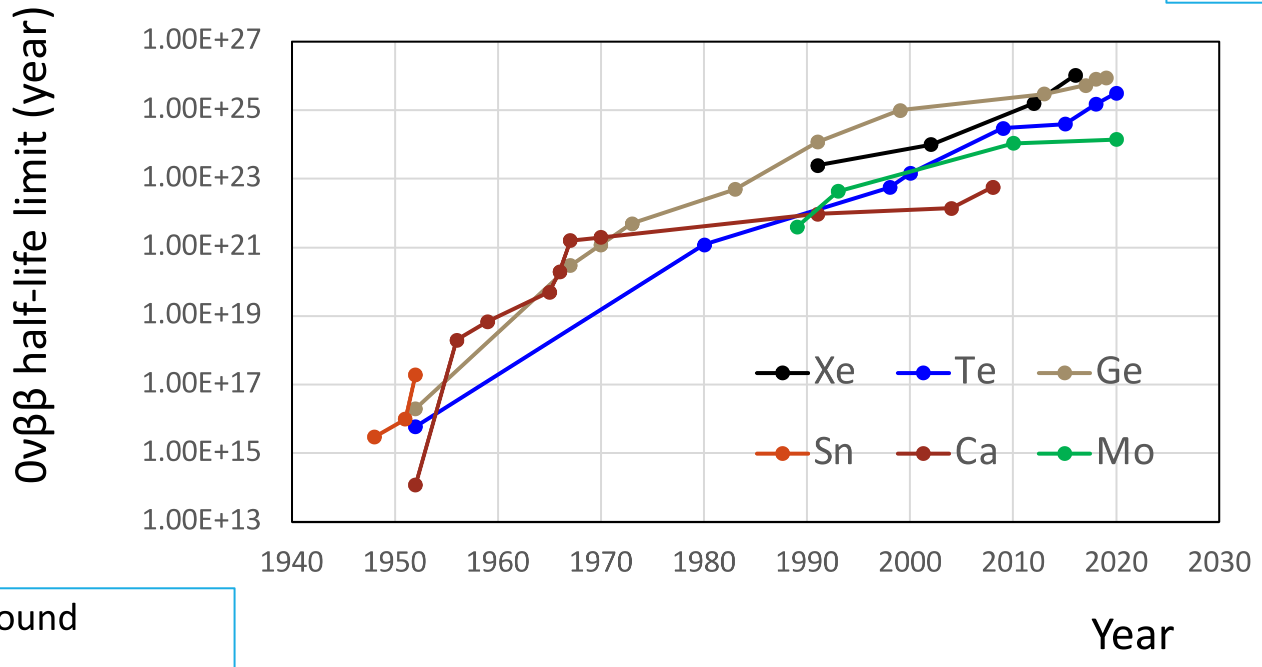


Impressive experimental progress

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



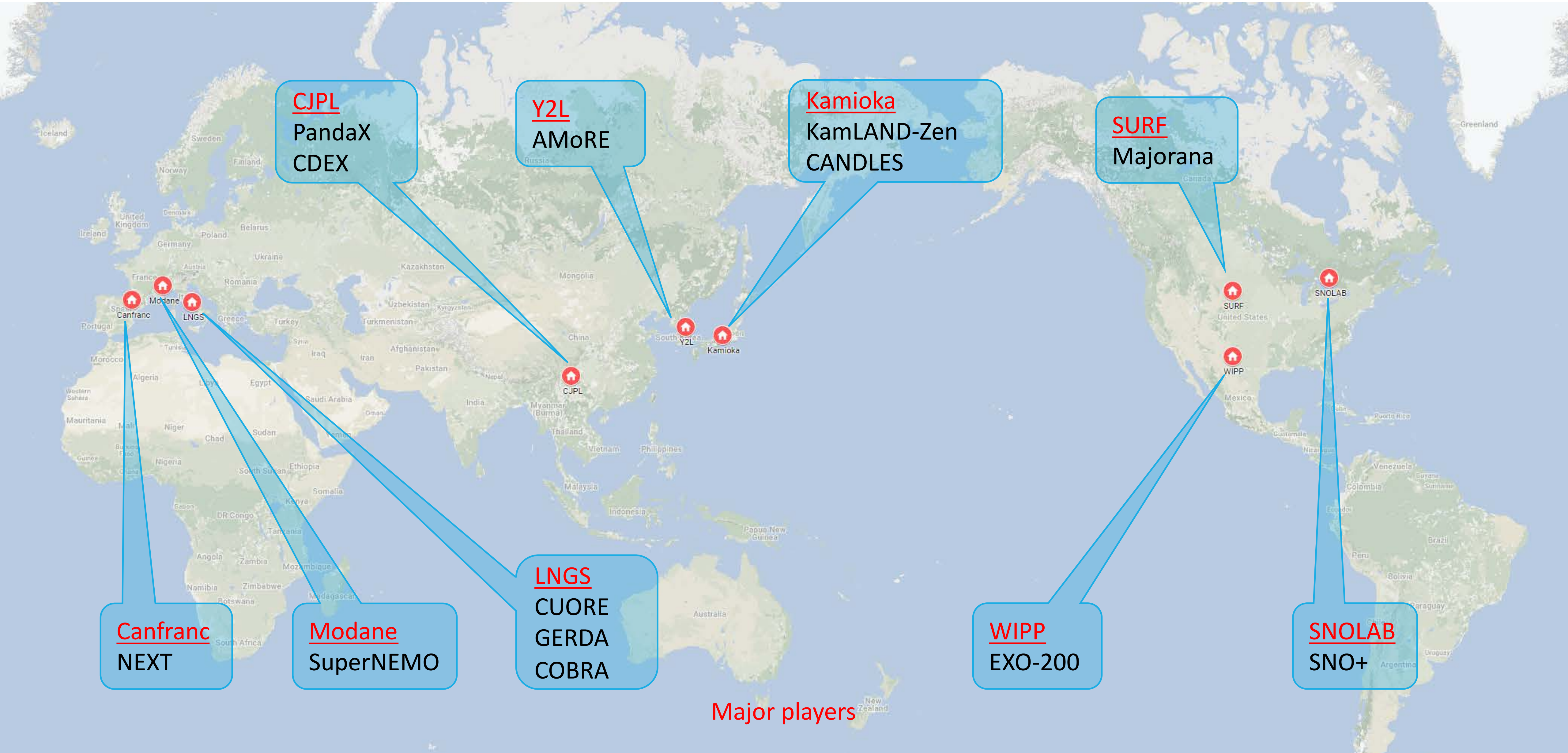
- ~100 kg of isotopes
- ~100-person collaborations
- Deep underground
- Shielding + clean detector



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

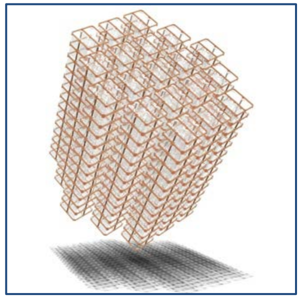
Partial list of selected isotopes; Pre-1984 data points from review article by Haxton and Stephenson, Jr.

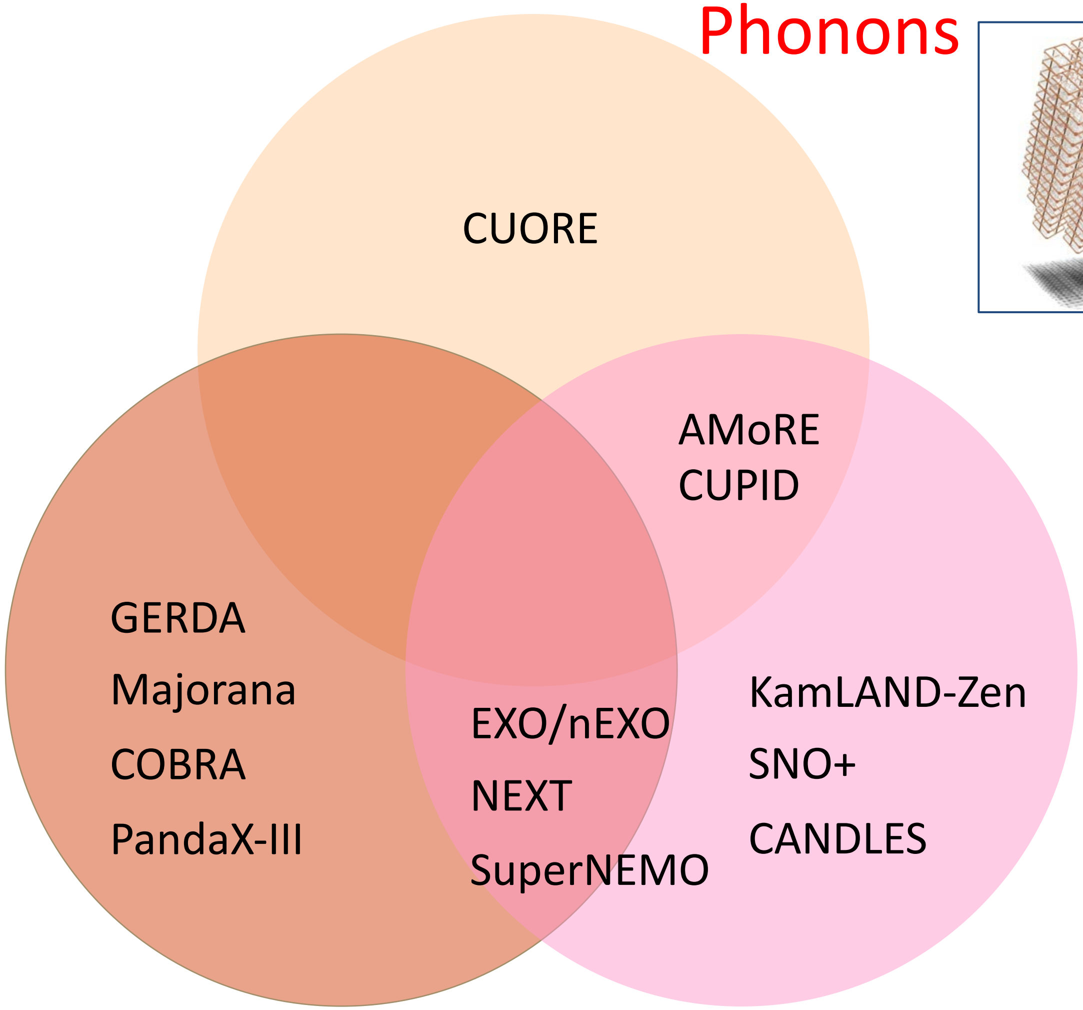
Major 0νββ experiments around the world



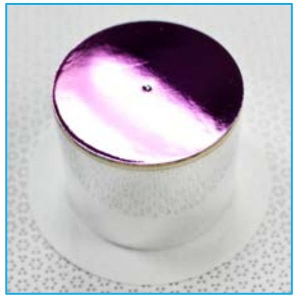
Detection channels

Phonons

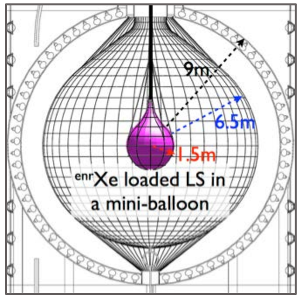




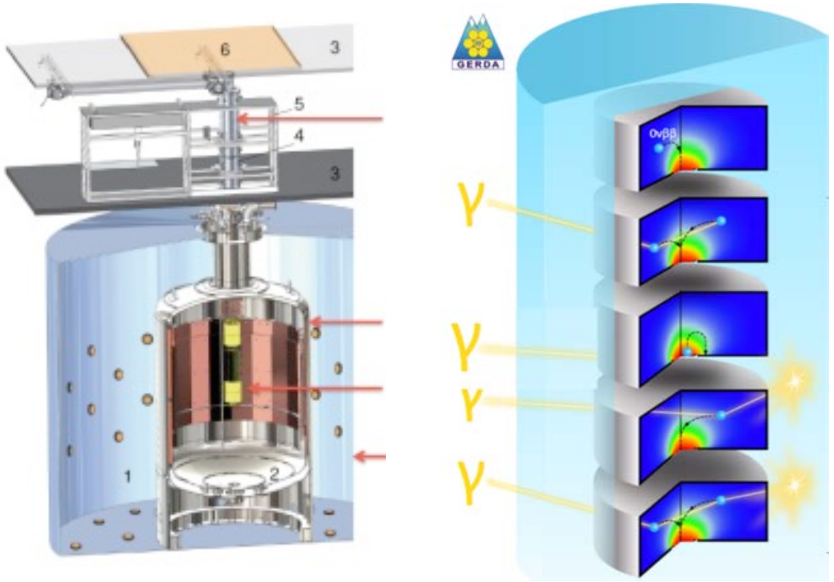
Electrons
holes



Photons

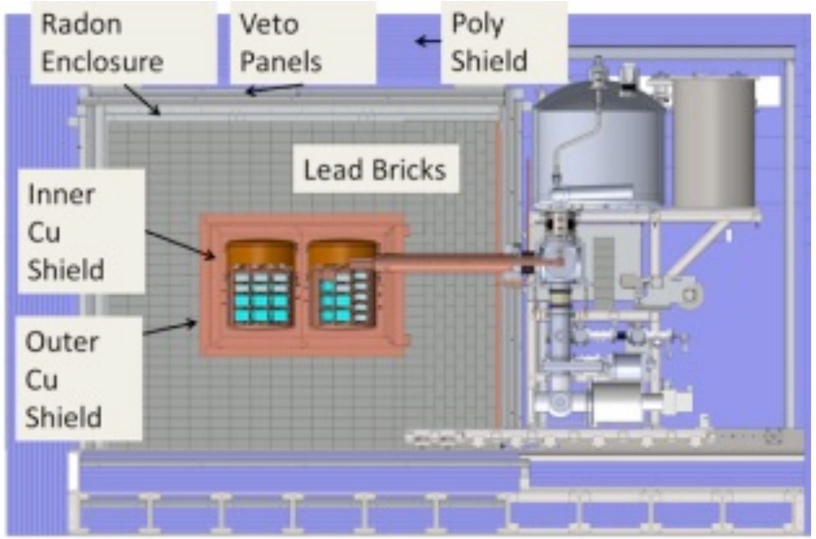


HPGe detectors (^{76}Ge)



GERDA at LNGS, Italy

Half-life limit: 0.9x10^{26} yr
Bkg: 5.7x10^{-4} c/kev/kg/yr (Science)



Majorana Demonstrator at Sanford, US

Half-life limit: 2.7x10^{25} yr
Bkg: ~5x10^{-3} c/kev/kg/yr (ArXiv:1902.02299)

CDEX-10: ~10kg PPC Ge array

Future:

- LEGEND (Large Enriched Ge Experiment for ββ Decay)
- First phase: 200 kg @ LNGS (2020--)

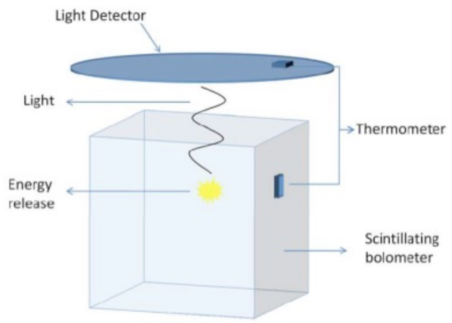
CUORE (^{130}Te)

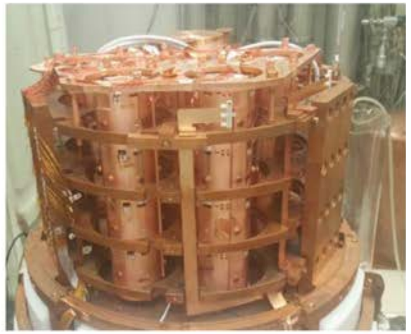
- Bolometric technique
- Excellent energy resolution by measuring temperature rise at mK level.
- Current limit: 3.2×10^{25} yr

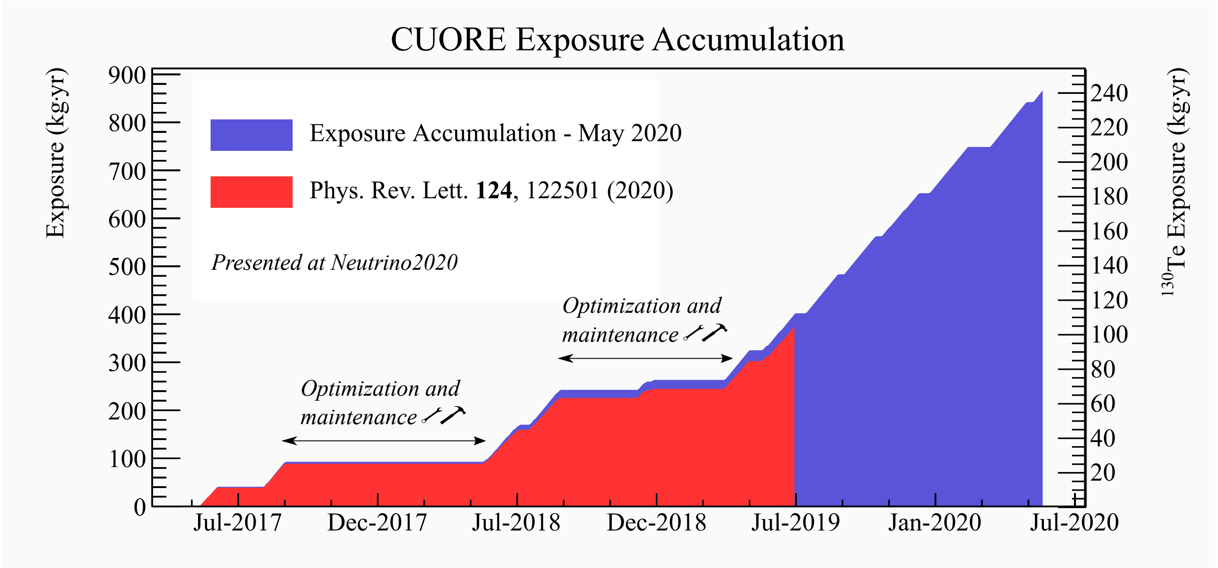
World-largest Dilution Refrigerator <10mK

Future

- CUPID (CUORE with particle ID)
  - Phonon + photon dual readout
  - $LiMoO_4$ scintillating bolometer array



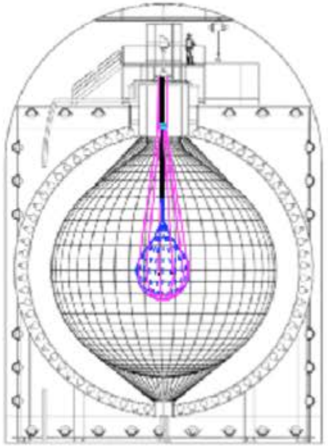




KamLAND-Zen (^{136}Xe)

- KamLAND-Zen is leading the field of 0νββ experiment
- ^{136}Xe half-life limit of 1.07 x 10^{26} yr (90%CL)
- KamLAND-ZEN 800 is taking data.

Past



KamLAND-Zen 400

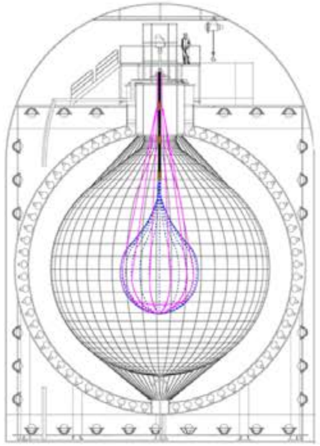
R = 1.54m mini-balloon

Xenon 320 ~ 380 kg

2011 ~ 2015

→

Ongoing



KamLAND-Zen 800

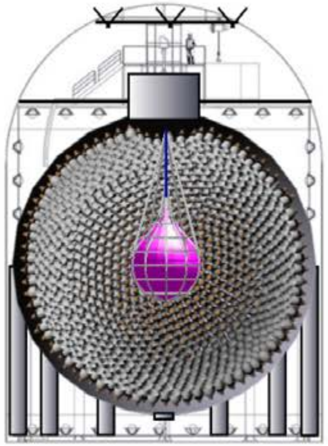
R = 1.90m mini-balloon

Xenon 745 kg

Jan. 22, 2019 ~

→

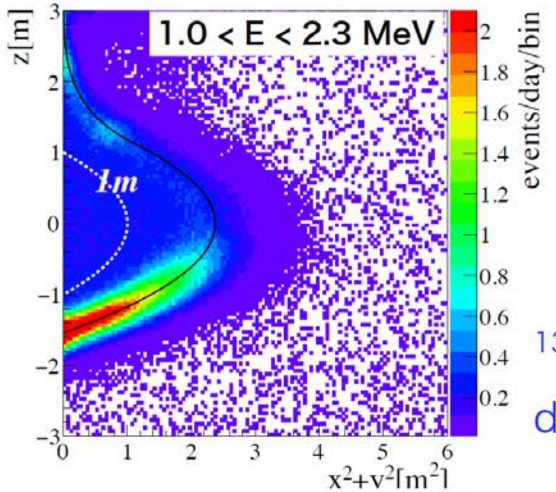
Future



KamLAND2-Zen

Xenon ~ 1 ton

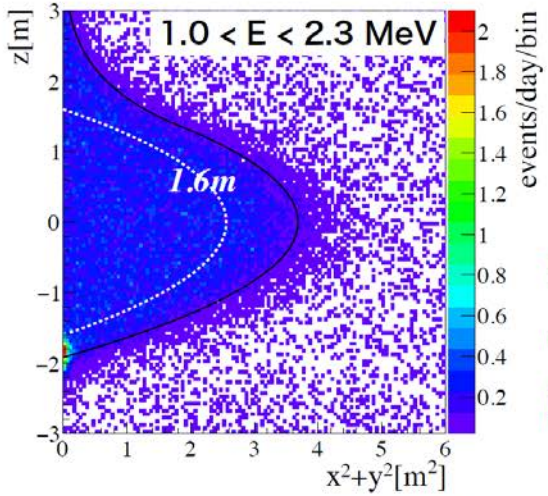
KamLAND-Zen 400 phaseII



^{134}Cs,

dust sank

KamLAND-Zen 800

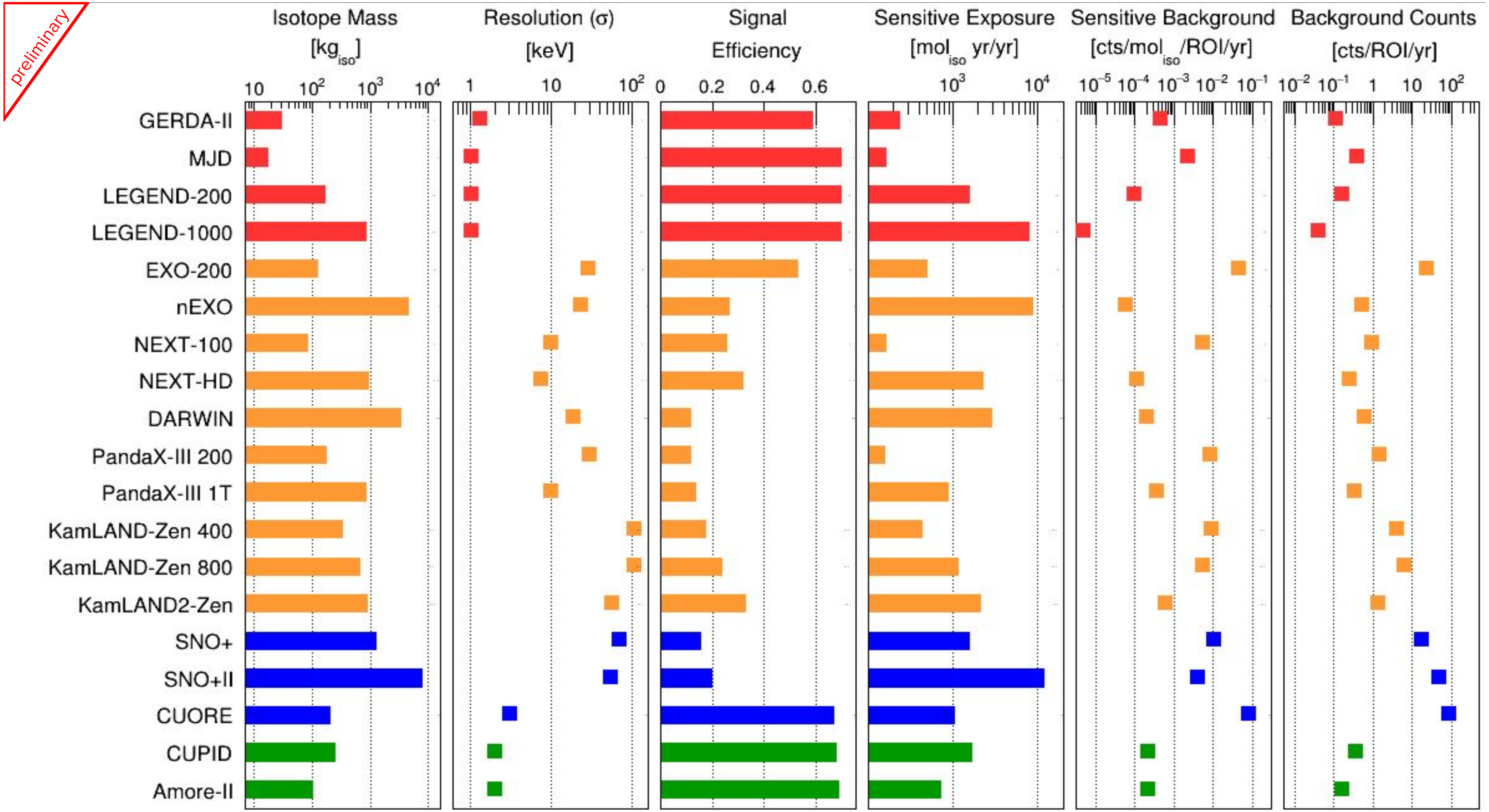


2νββ

dominates

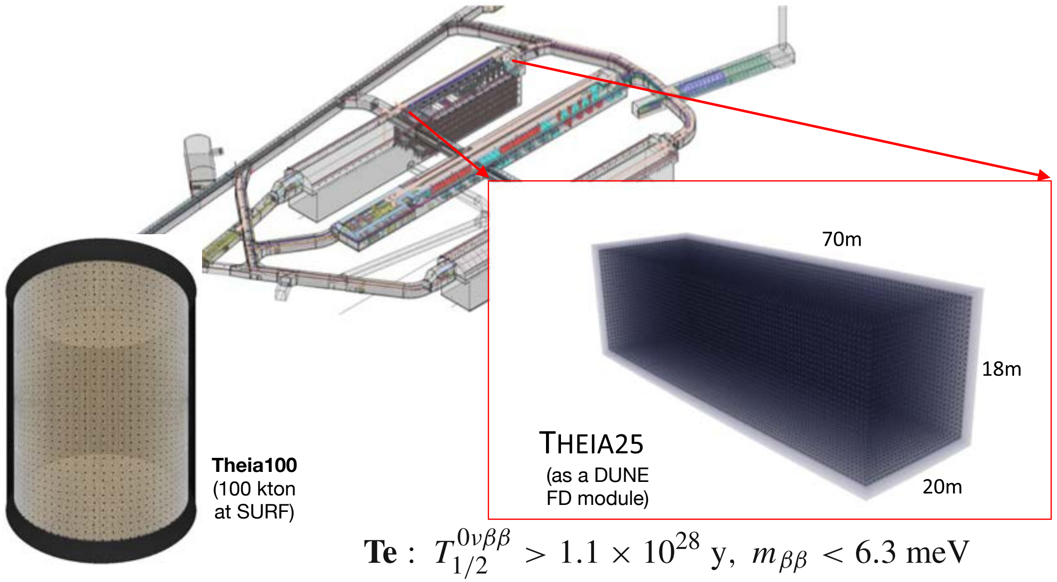
in all volume

Current experiments and future proposals



From: Matteo Agostini , et al, TAUP 2019

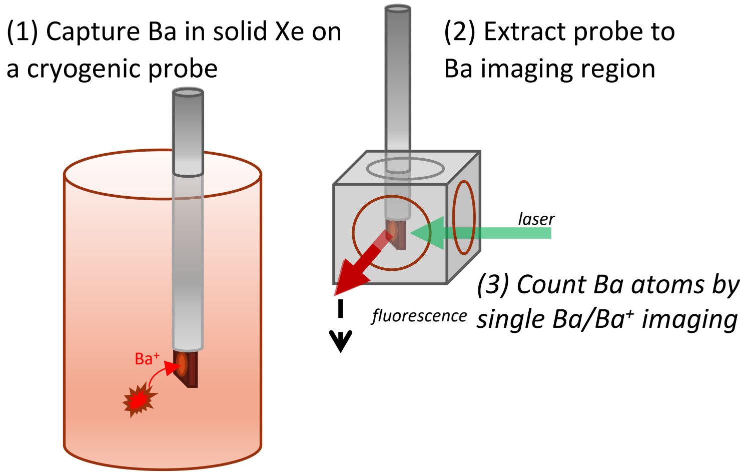
Even further into the future (from US Snowmass)

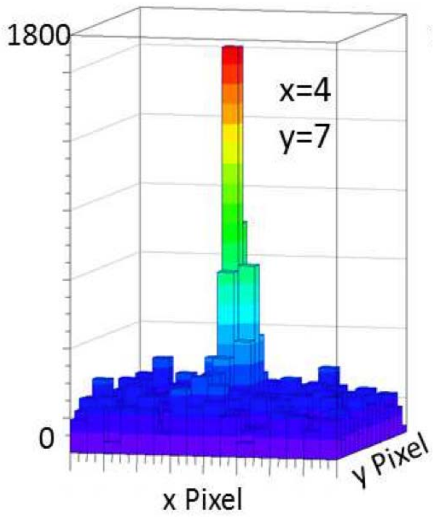


$$\mathbf{Te}: \ T_{1/2}^{0\nu\beta\beta} > 1.1 \times 10^{28} \text{ y}, \ m_{\beta\beta} < 6.3 \text{ meV}$$

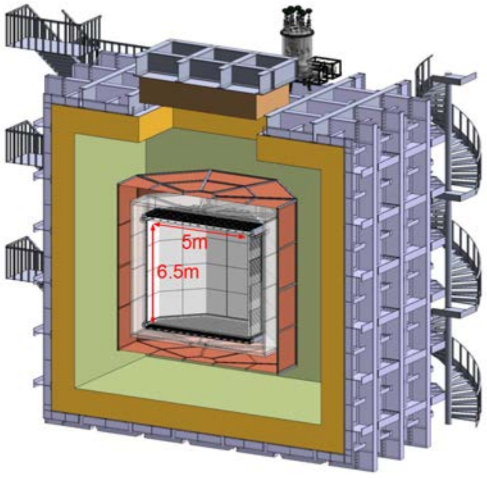
$$\mathbf{Xe}: \ T_{1/2}^{0\nu\beta\beta} > 2.0 \times 10^{28} \text{ y}, \ m_{\beta\beta} < 5.6 \text{ meV}.$$

Single barium ion in xenon ice: (nEXO)





DarkNoon



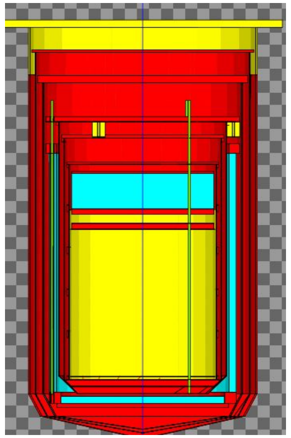
^{136}Xe target dissolved in LAr

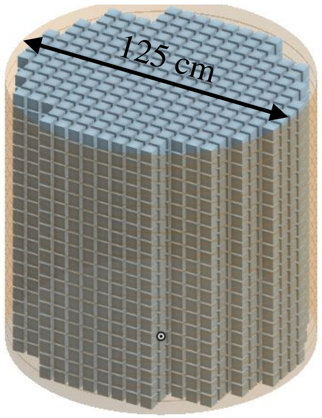
Sensitivity up to $T_{1/2} \sim 10^{30}$ years

50t fiducial volume dual-phase 20% molar fraction mixture of enriched LXe in LAr.*

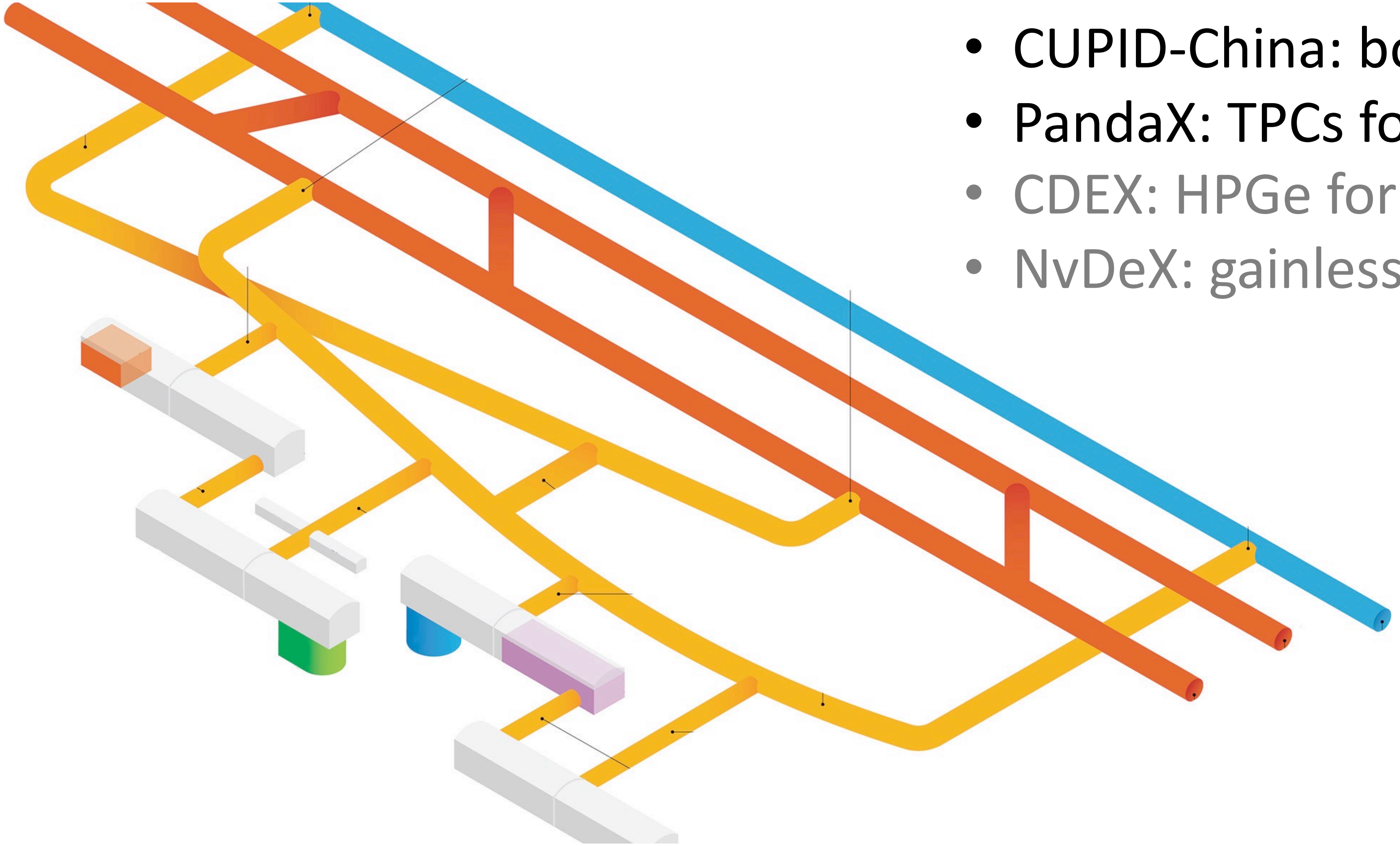
CUPID-1T: Hallmarks

- **1000 kg of ^{100}Mo** in a new cryostat and/or multiple facilities worldwide
- **Sensitivity: $T_{1/2}$> 8×10^{27} years (3σ)**, $m_{\beta\beta}$>4-7 meV (NH)



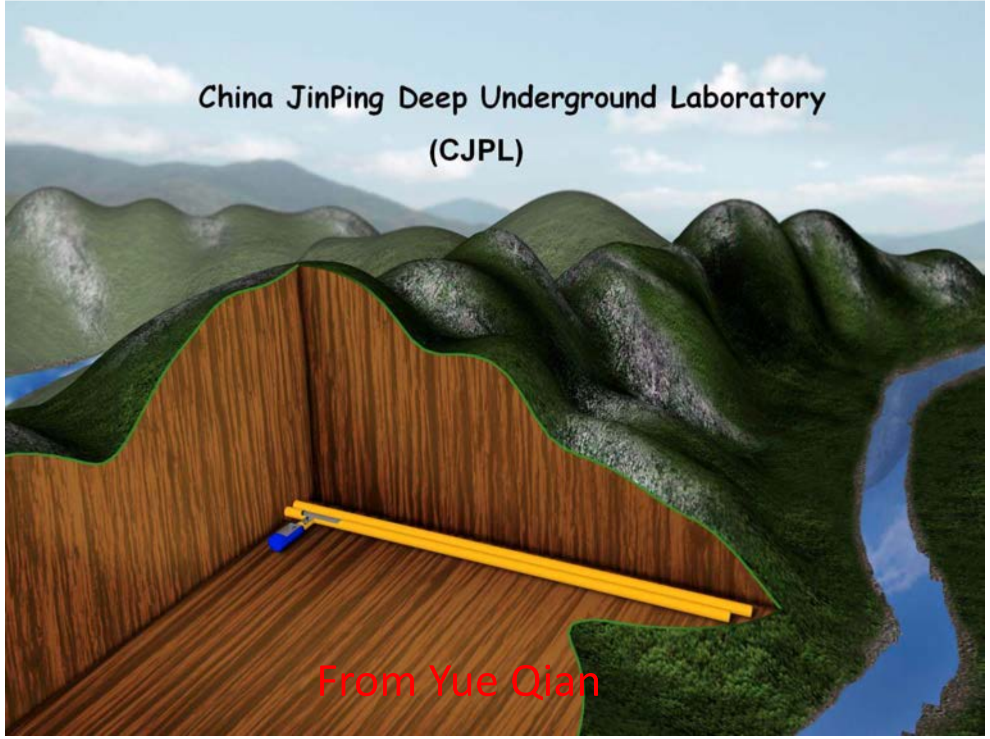


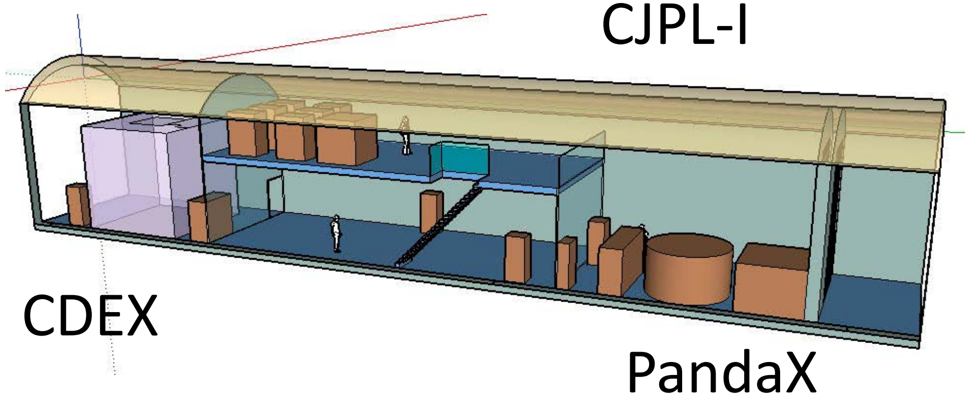
0νββ searches at CJPL-II



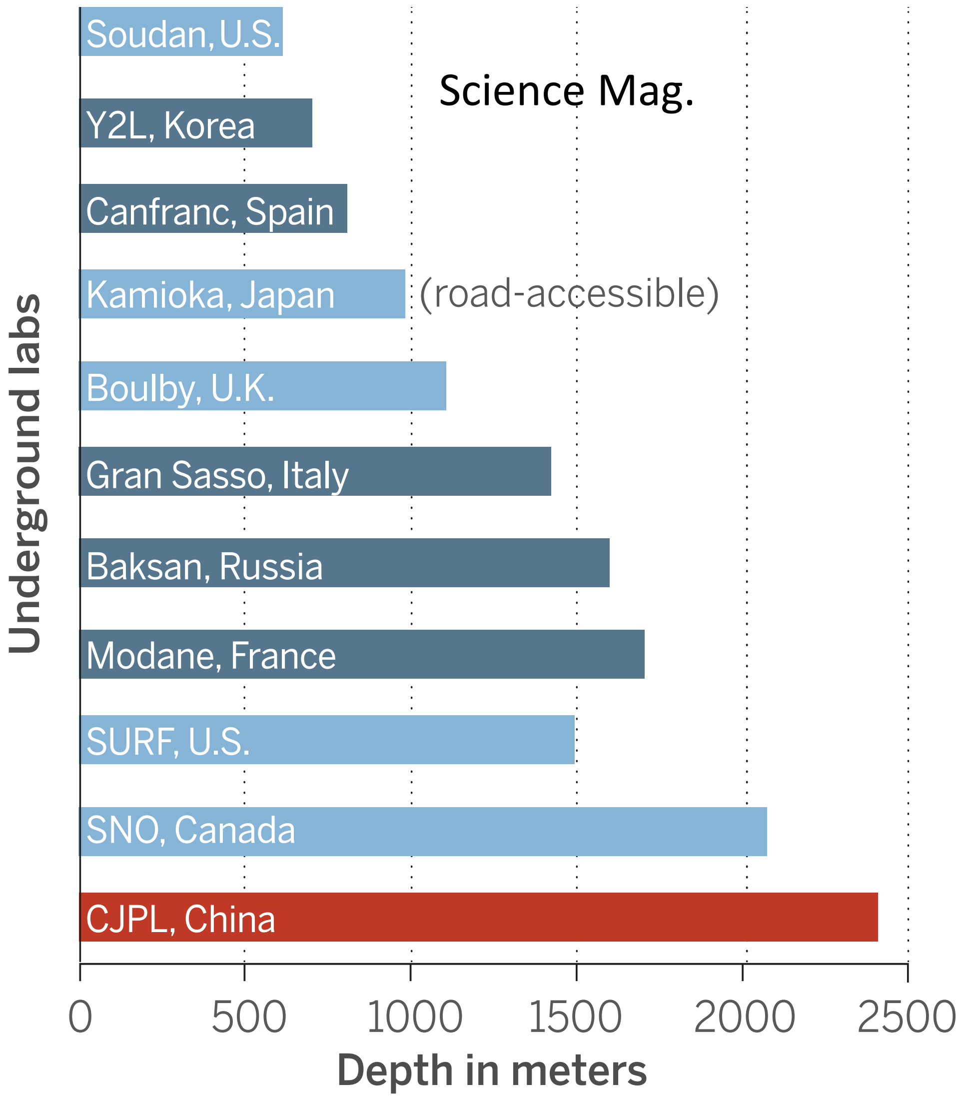
- CUPID-China: bolometers for ^{100}Mo
- PandaX: TPCs for ^{136}Xe
- CDEX: HPGe for ^{76}Ge
- NvDeX: gainless TPC for ^{82}Se

CJPL: Deepest underground lab

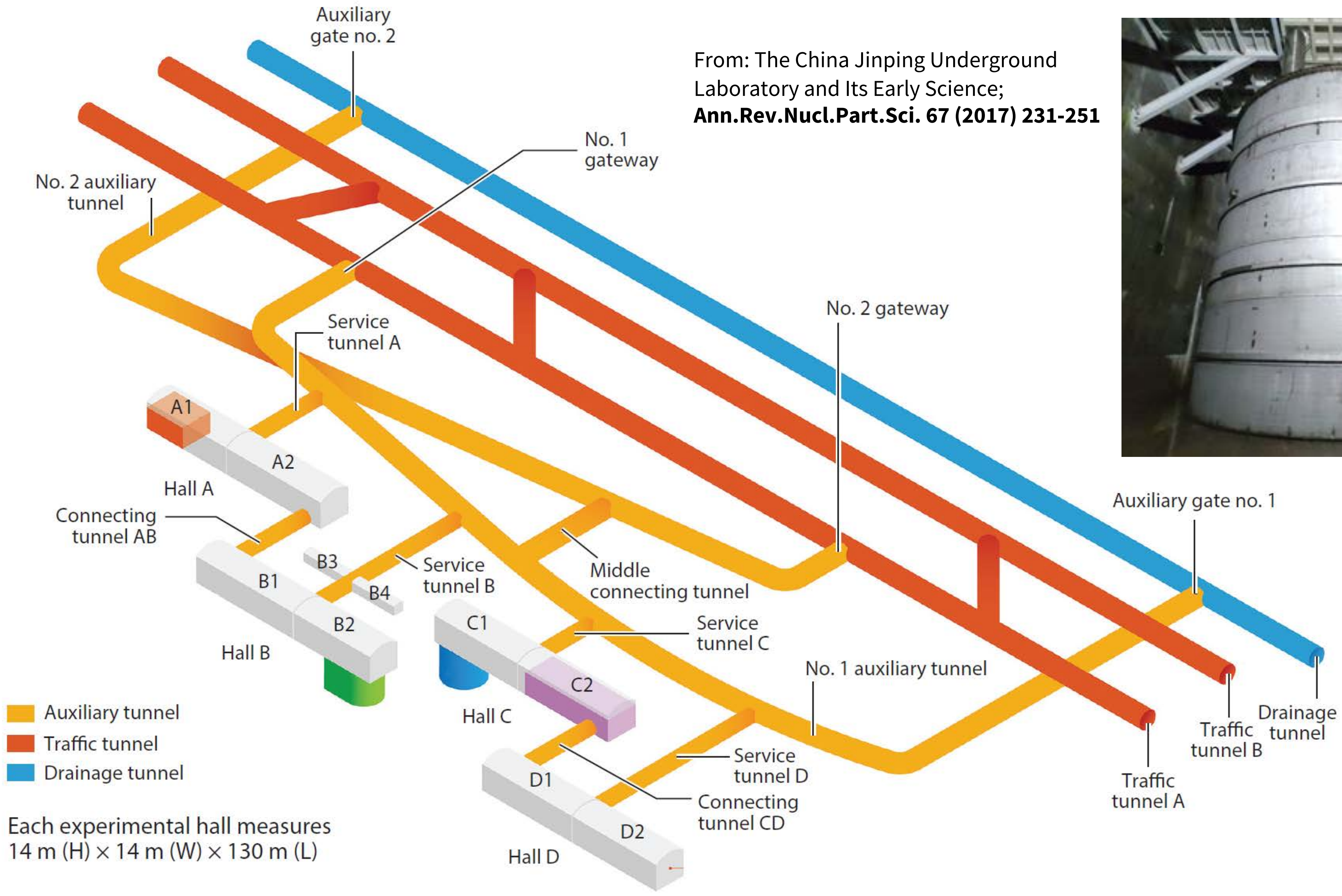




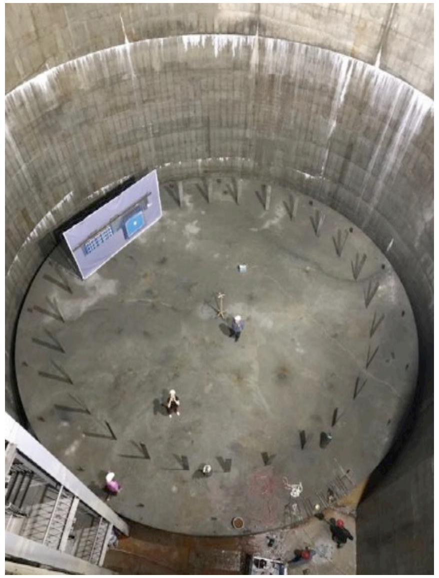
Labs are built in mines (light blue) and tunnels (dark blue and red).



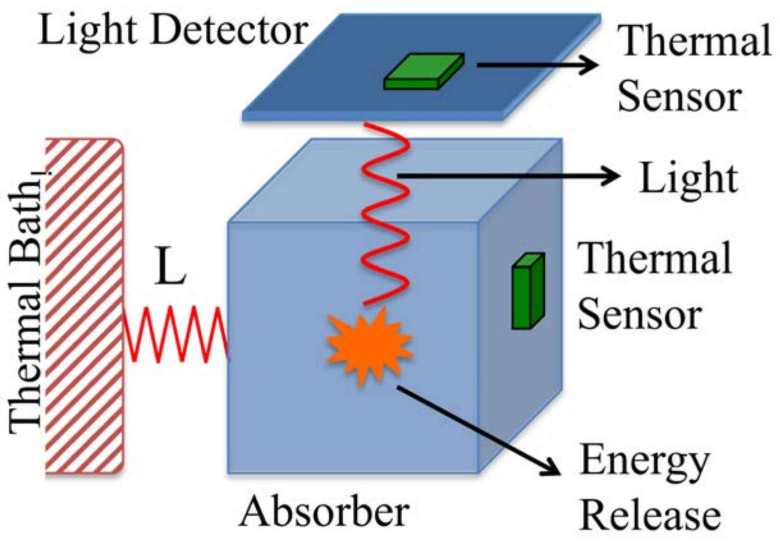
CJPL-II: much enlarged underground lab space



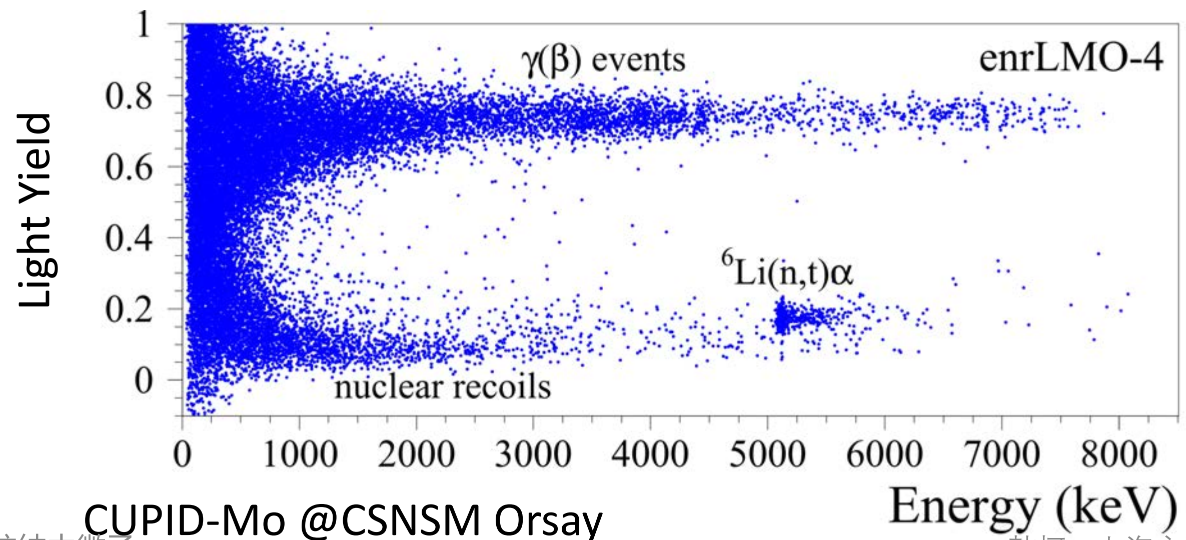
From: The China Jinping Underground Laboratory and Its Early Science; **Ann.Rev.Nucl.Part.Sci. 67 (2017) 231-251**

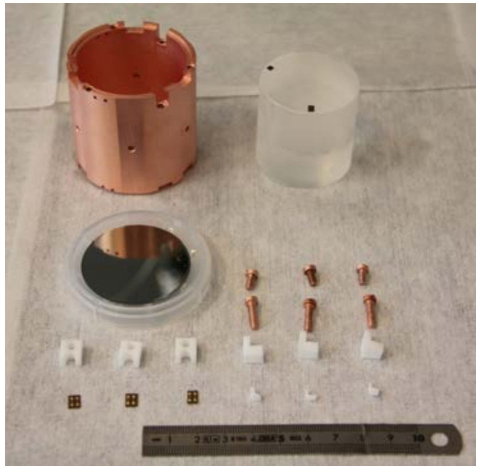


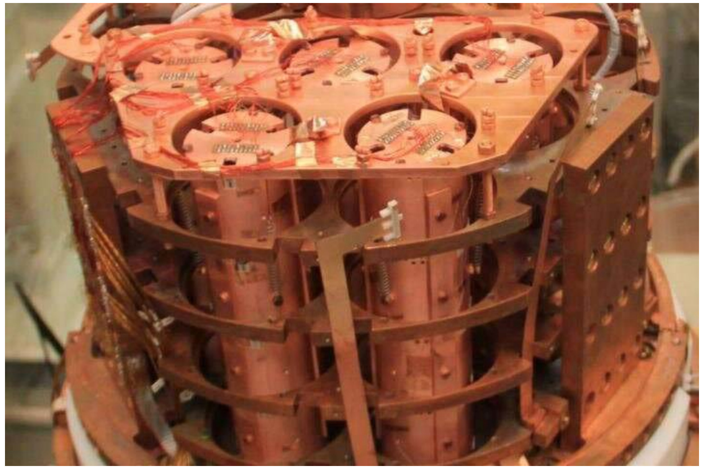
CUPID-China: scintillating bolometer



- Light and heat readout with two bolometer setups for one crystal
- LiMoO$_4$ scintillating bolometer arrays
- Particle ID to reject alpha background
- High Q-value (3.0 MeV) for low gamma background
- Technical development in the next 3-5 years

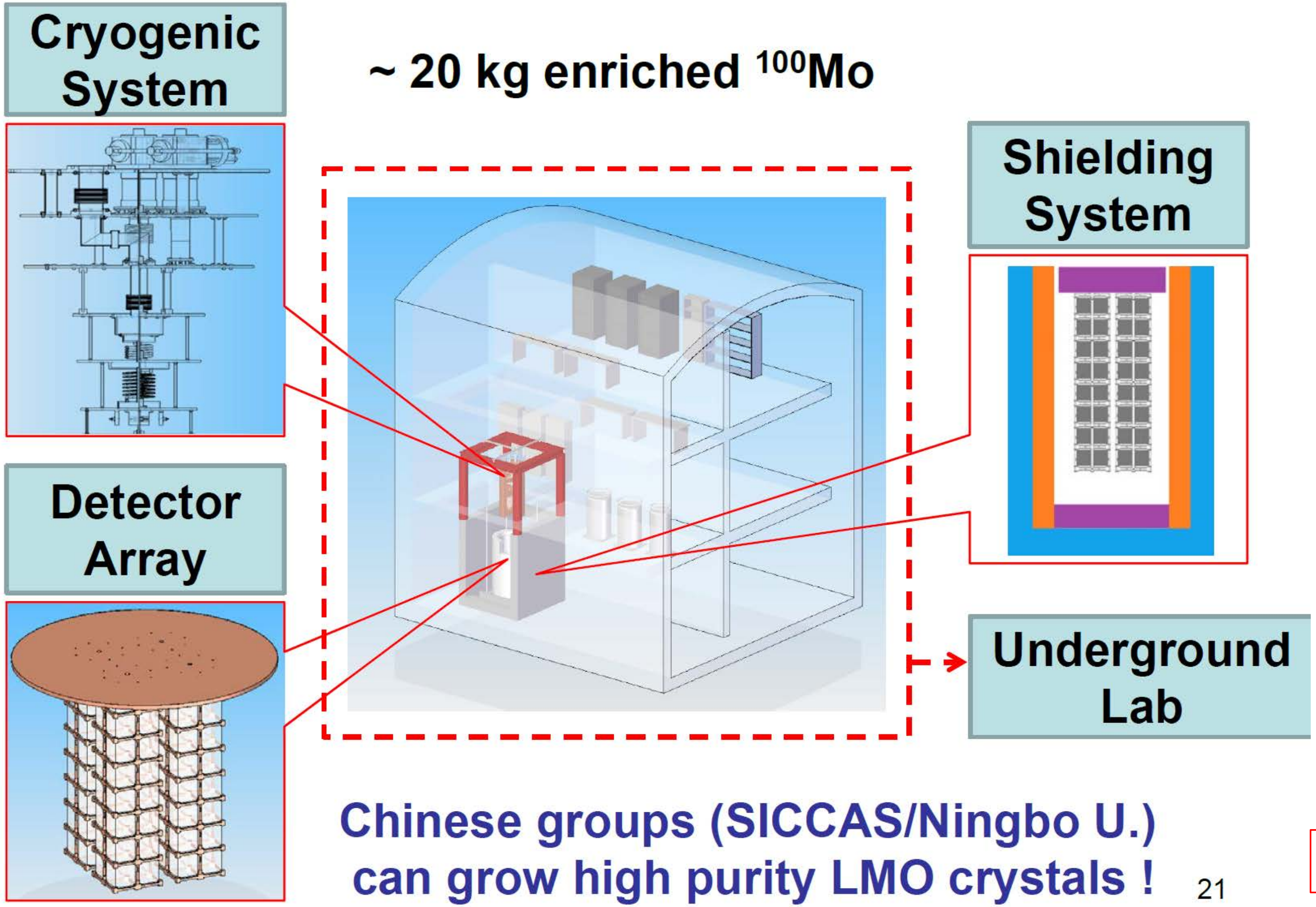






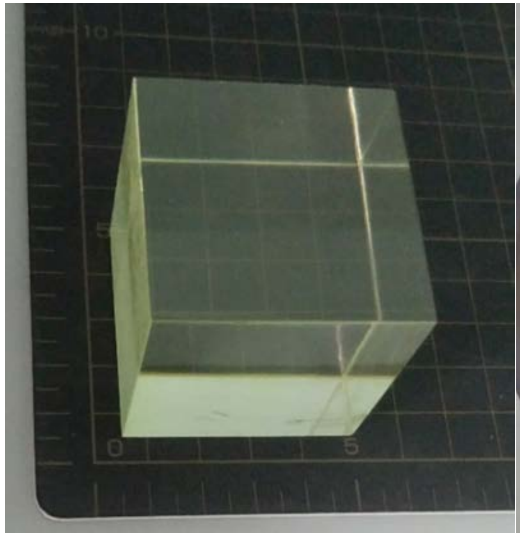
CUPID-Mo @CSNSM Orsay

CUPID-China concept

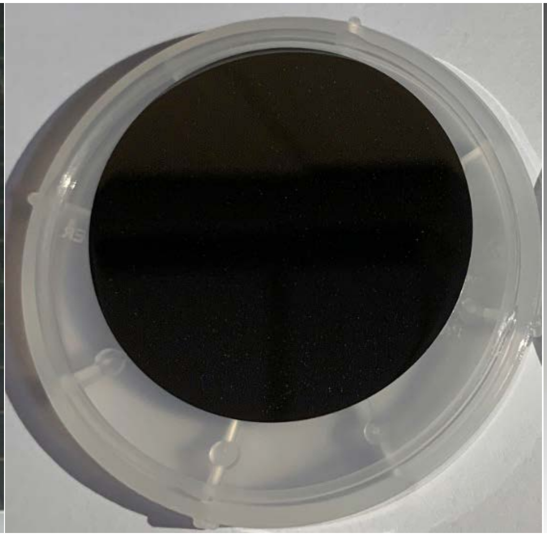


From HZ Huang

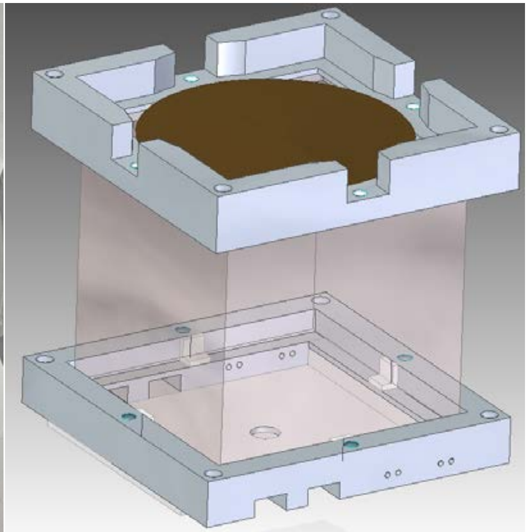
CUPID-China: USTC



LMO_SIC_45x45x45 mm³

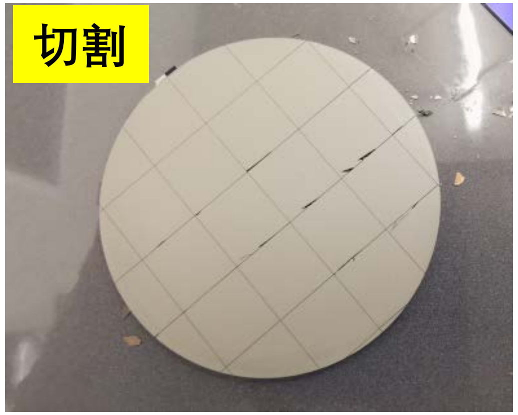


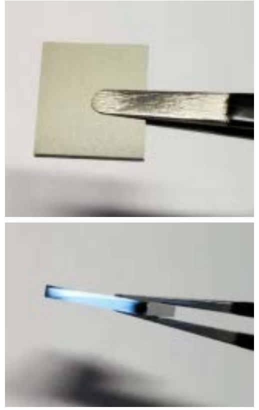
LD HPGe Phi45x0.175 mm



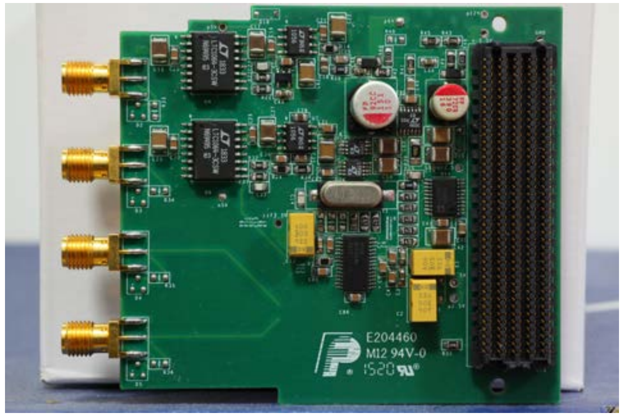
Proposed Assembly

Gluing NTD to crystal





Preparing Ge wafer for neutron transmutation



Custom designed ADC

From: Mingxuan Xue

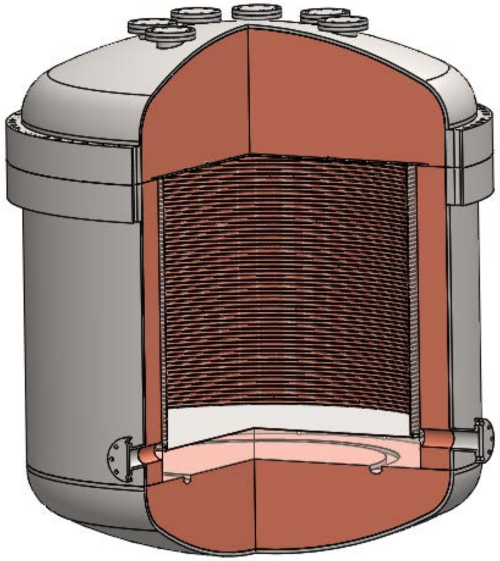
PandaX Detectors

WIMP searches
(0νββ as well)

PandaX-I: 120kg LXe
(2009 – 2014)

PandaX-II: 500kg LXe
(2014 – 2018)

PandaX-xT LXe
(future)

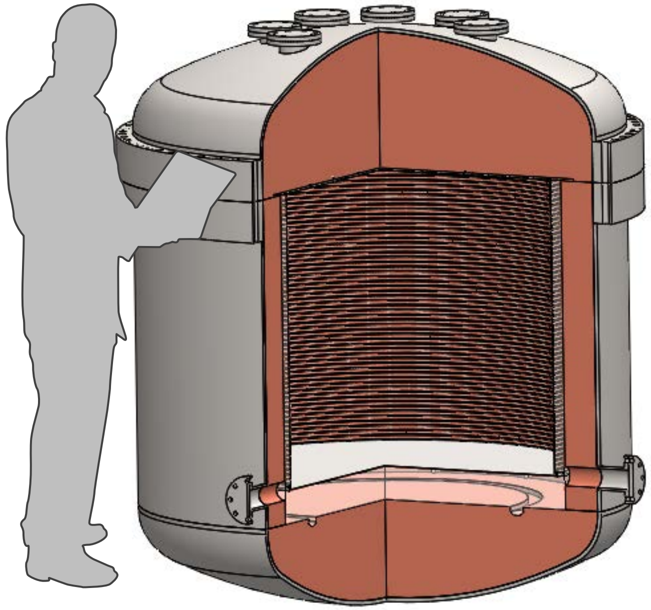


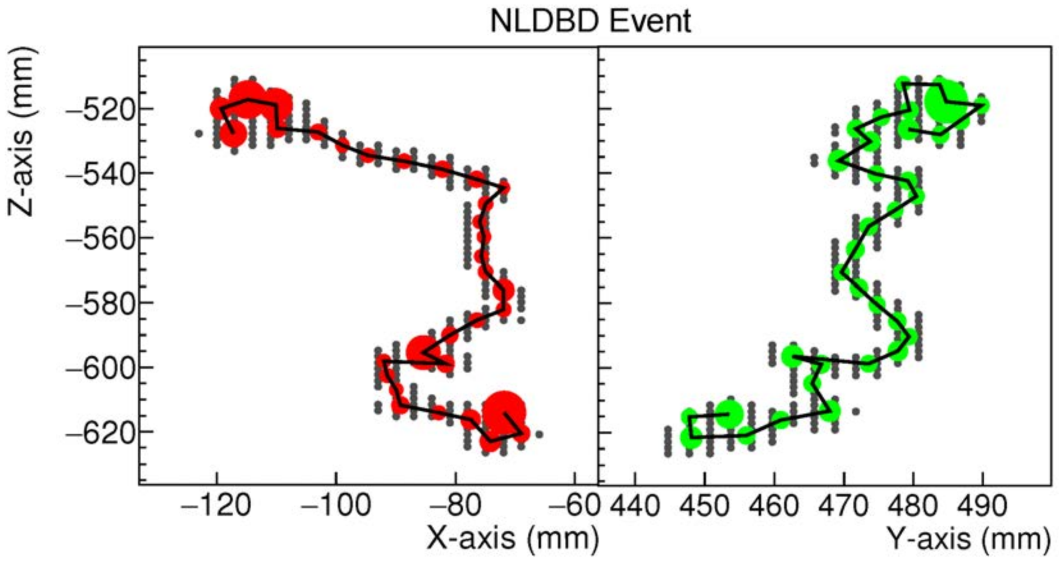
PRL 117, 121303 (2016)

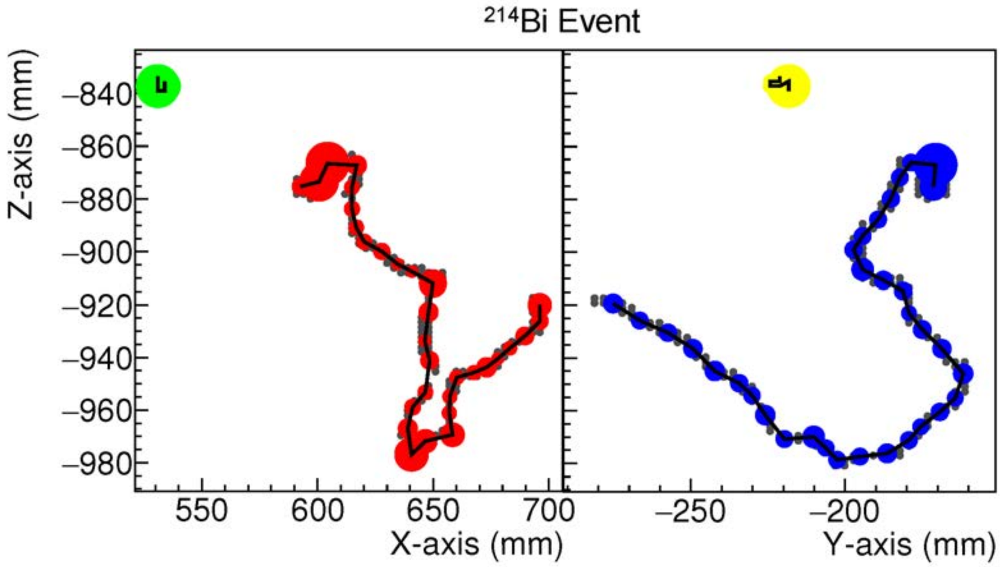
PandaX-III: 100kg - 1 ton
HPXe for 0νββ (future)

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

- TPC: 100 kg scale high pressure TPC with charge readout
- Main design features: good energy resolution and tracking capability
- Traditional cuts and neural network topological studies (arXiv:1903.03979 ;1802.03489).

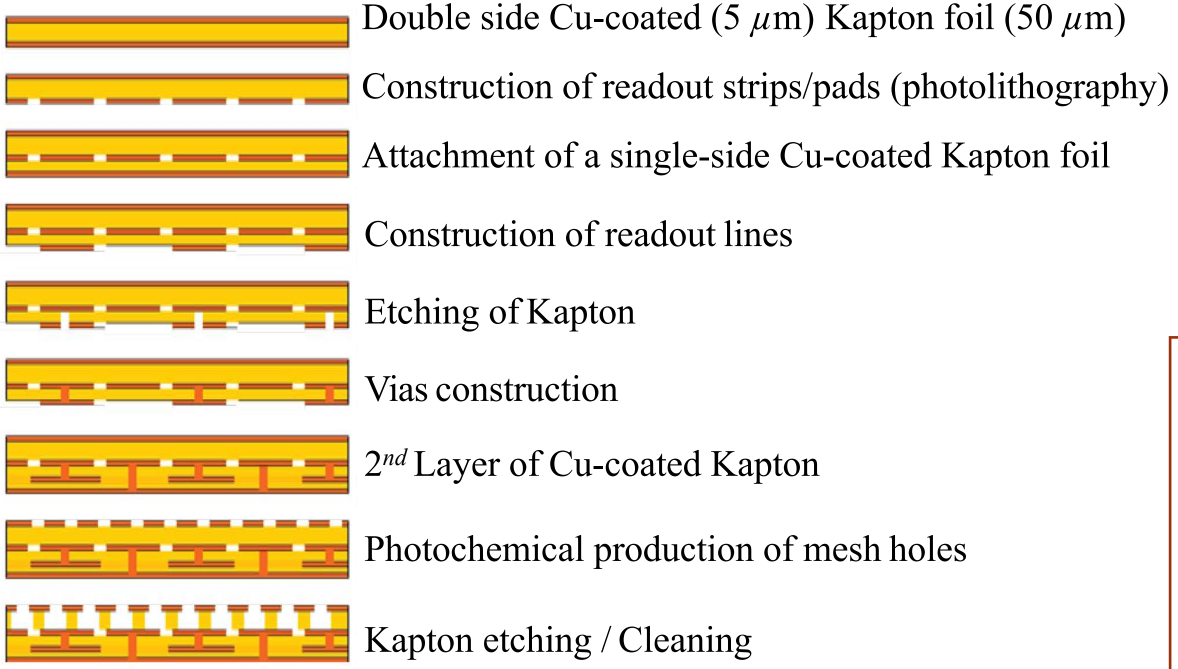




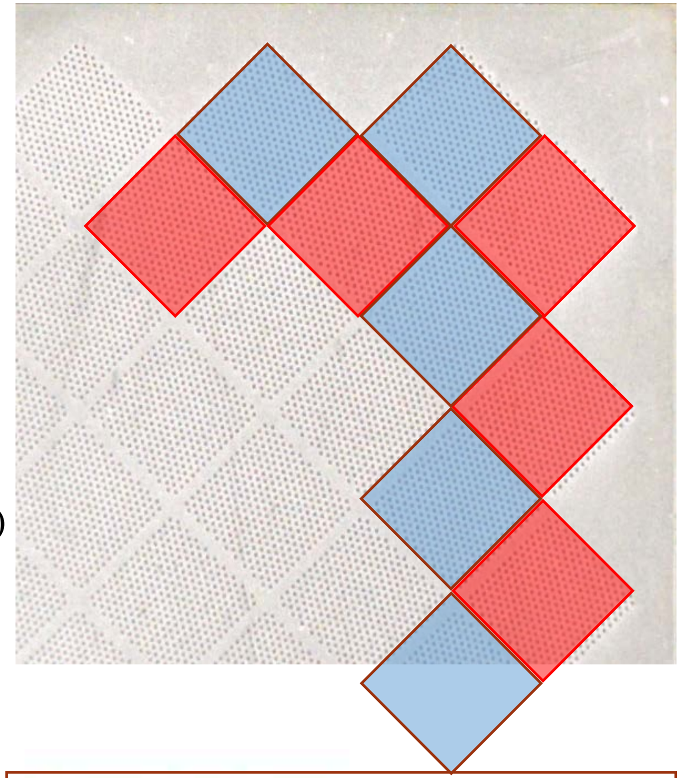


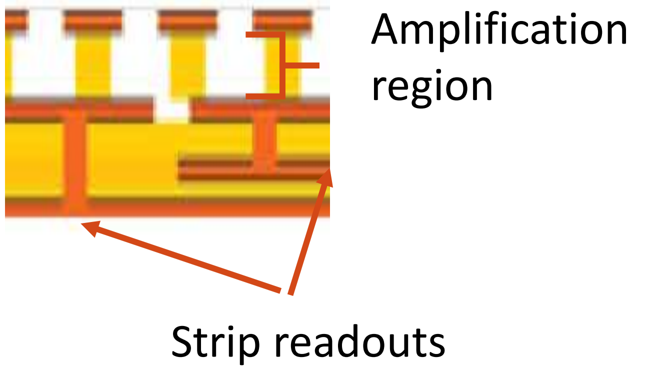
Charge-only readout plane with Microbulk MicroMegas (MM)

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

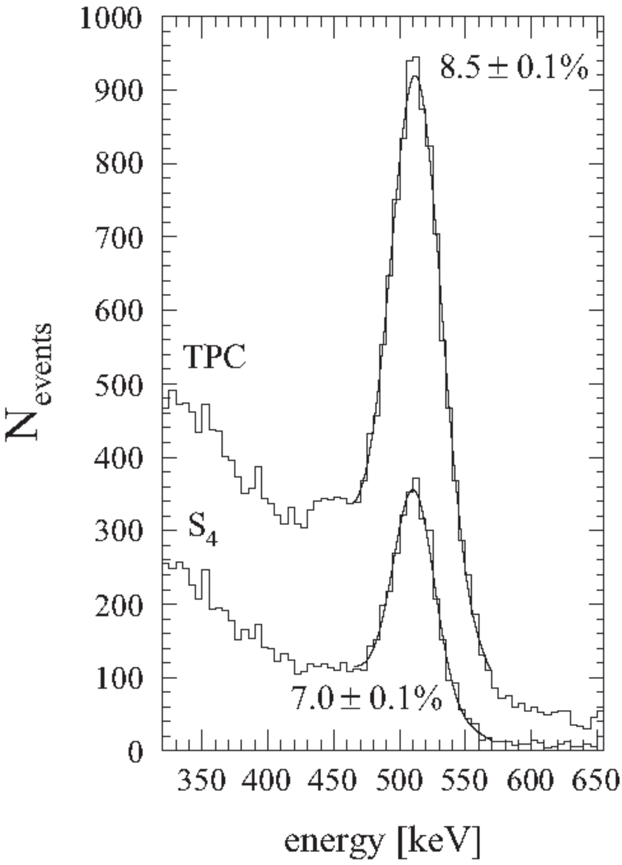


Andriamonje, S. et al. JINST 02 (2010): P02001





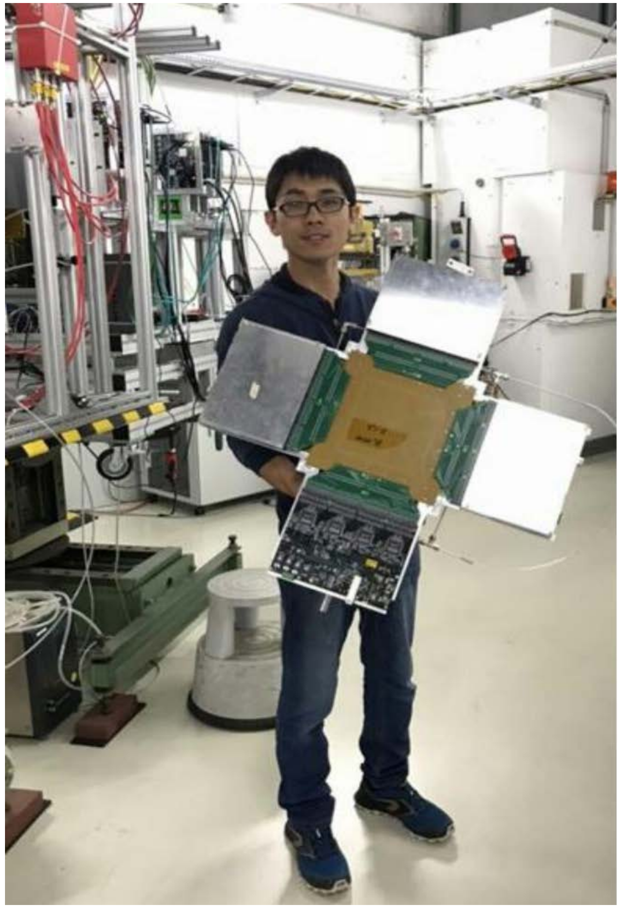
Gonzalez-Diaz, et al. *NIMA* 804 8 (2015)



Spectrum with MM

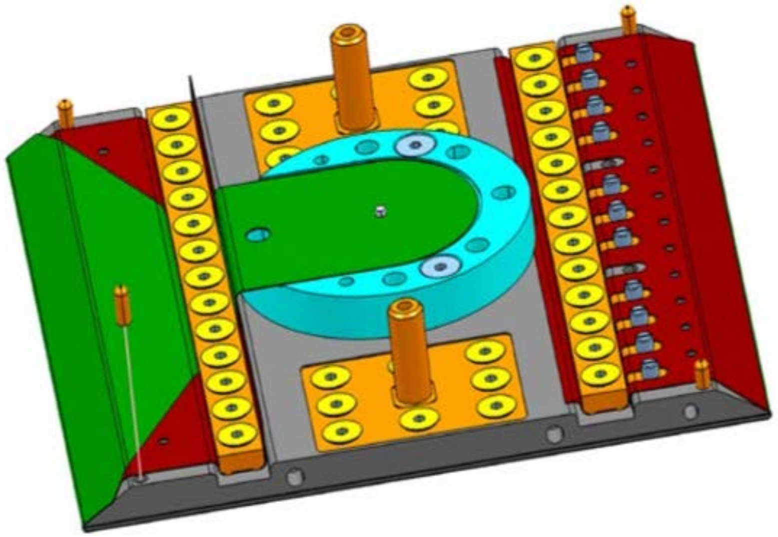
Exploring other Micromegas options

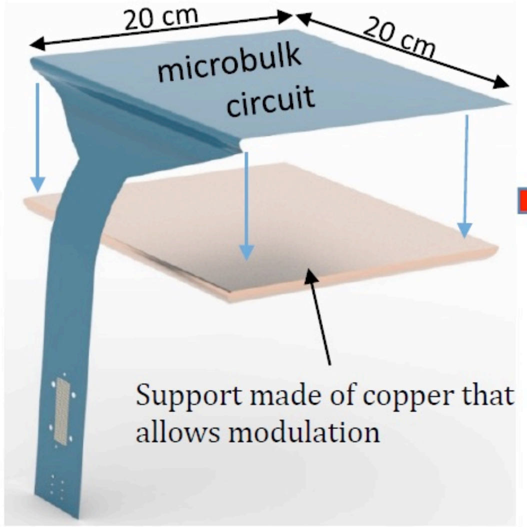
- Thermal bonding Micromegas from USTC
- Bulk Micromegas from CIAE
- Bulk Micromegas from Sacaly

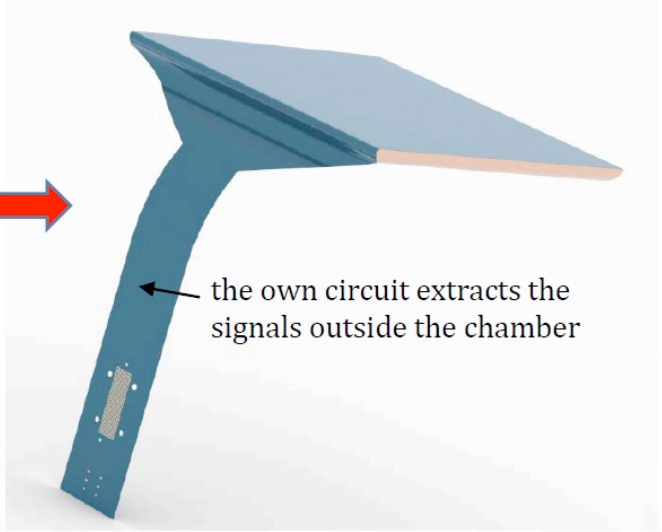


Scalable Radio-pure Readout Module (SR2M)

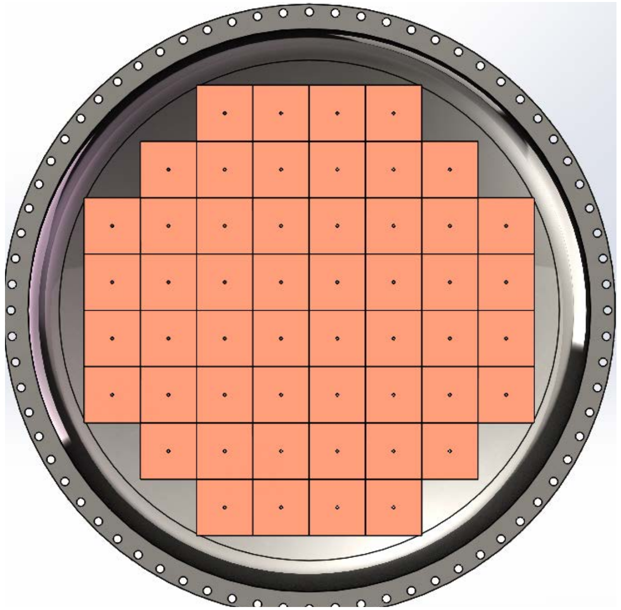
- SR2M: Mosaic layout to cover readout planes
  - Solderless system
  - Strip and mesh signal readout
  - Second iteration with custom-designed face-to-face connectors
- 52 tiled 20×20cm SR2Ms for charge readout





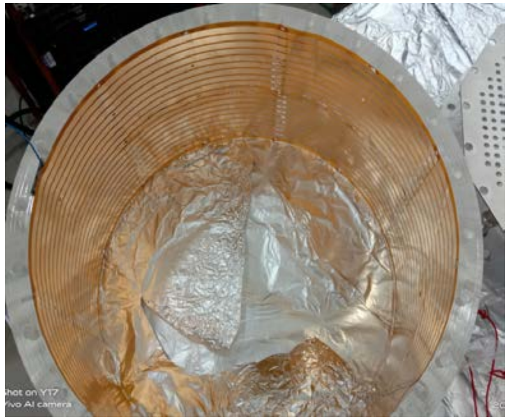


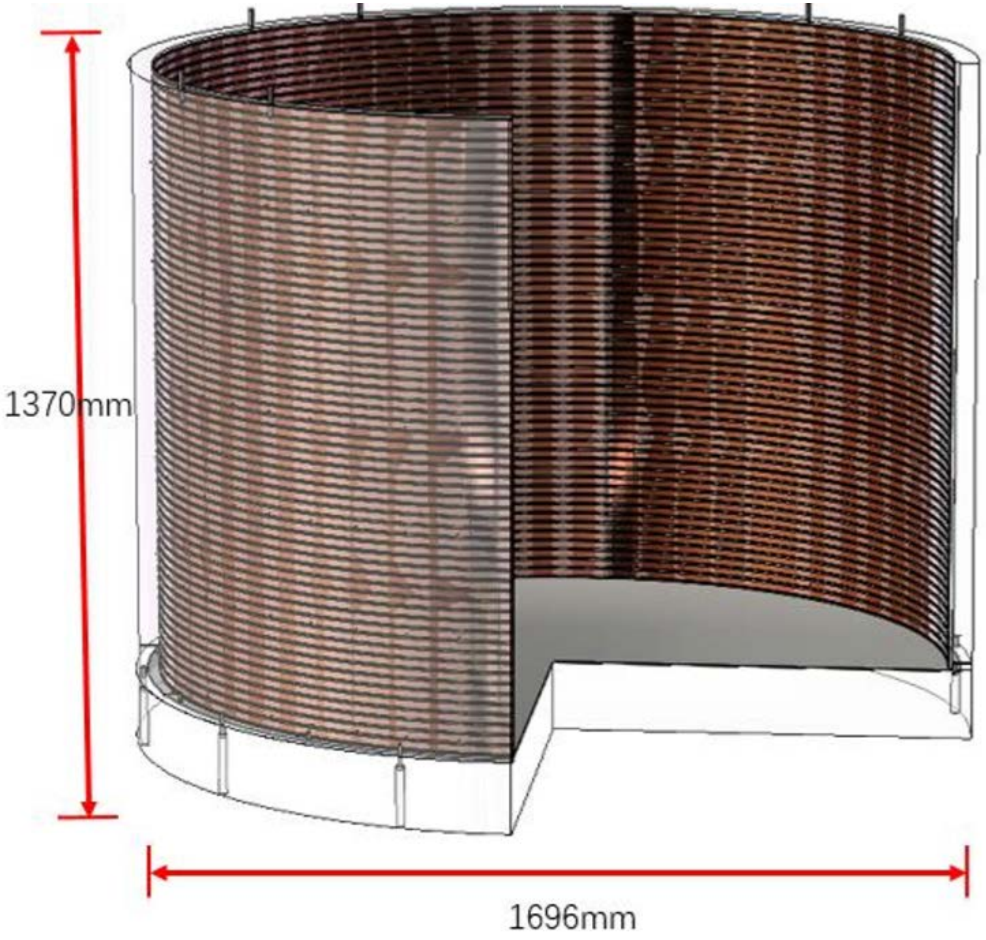
×52



Field cage

- Tiled Kapton Flexible PCB + SMD resistors
- Tested in small and medium scale
  - HV performance comparable with copper bar options
- Exploring production options





Design of field cage of full TPC

Electronics and DAQ

Frontend: PCB Based on AGET ASIC chips

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

Custom designed PCB for low radioactivity

- Kapton PCB
- Components assayed with HPGe

Backend: The Trigger and Data Concentrator Module – TDCM

- Designed by Saclay for PandaX-III and T2K-II
- A custom-made 6U form factor carrier board with two physical layer mezzanine cards for 32 FECs
- DAQ software based on MIDAS under development.

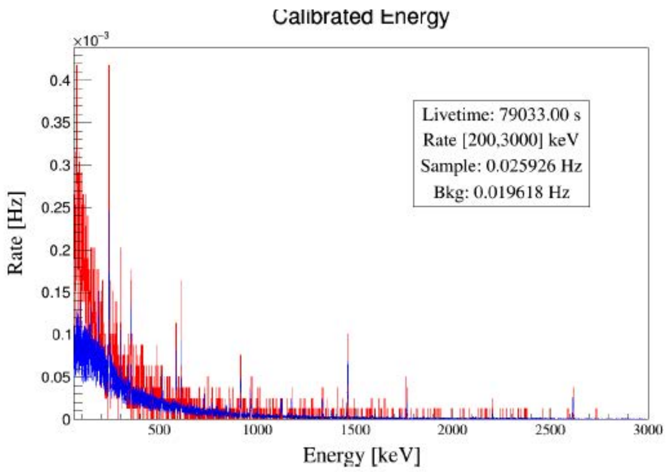
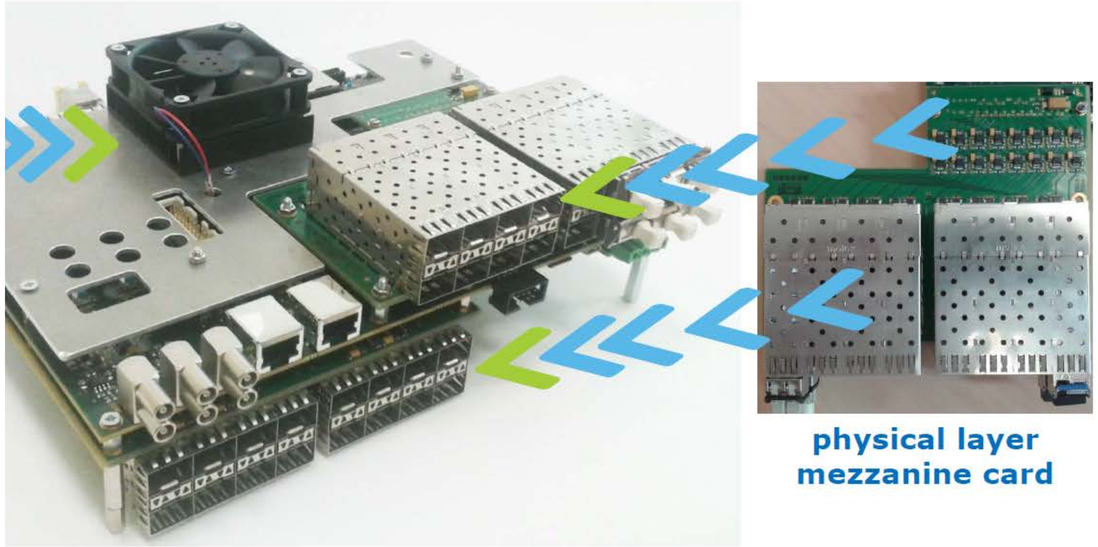
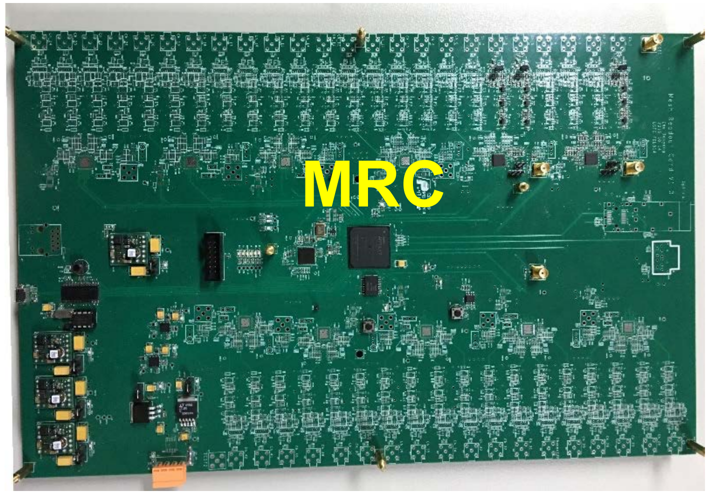
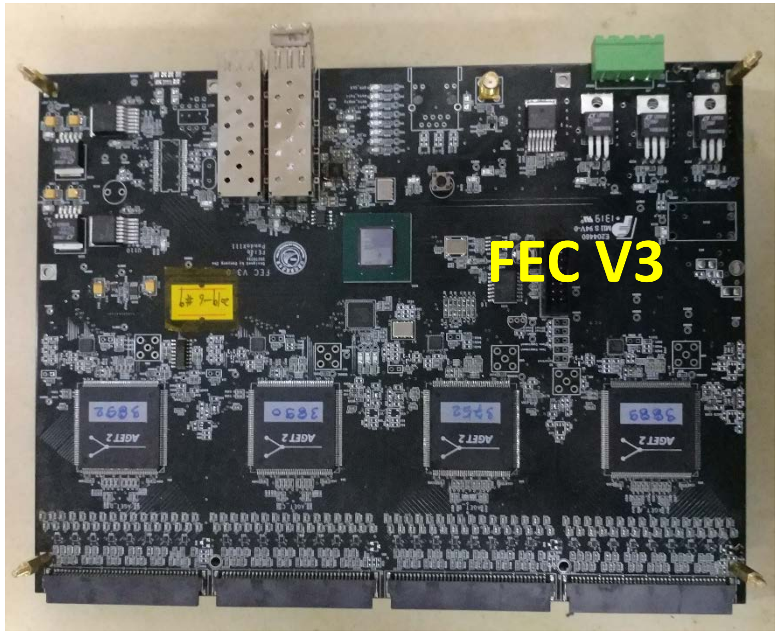


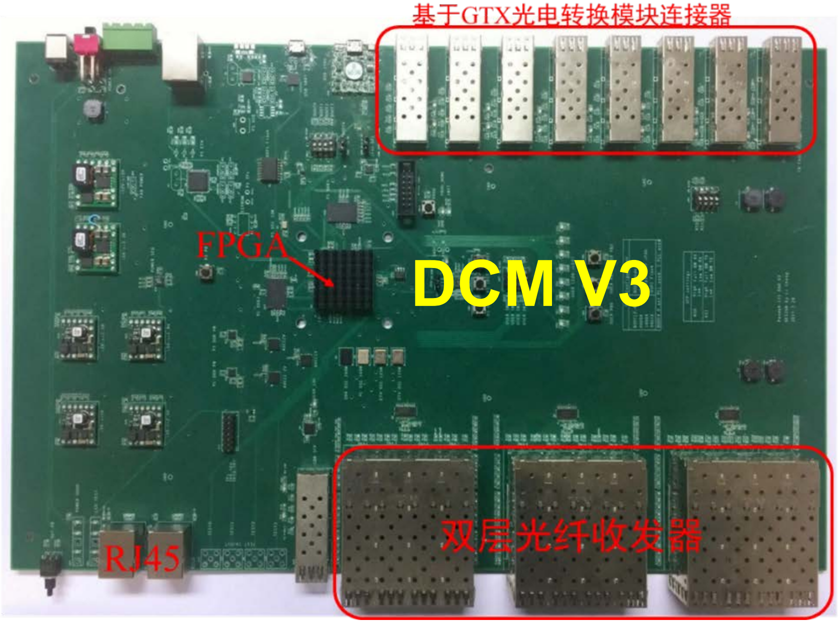
Figure 1: Energy spectrum for P301FECV4PCB.

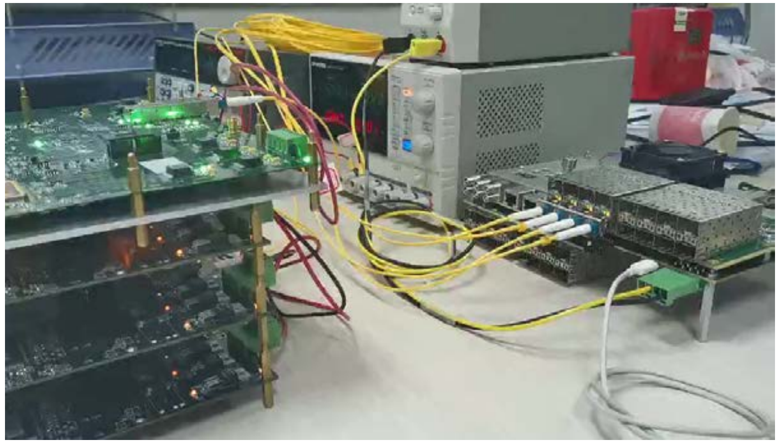


Custom designed PCB (USTC)





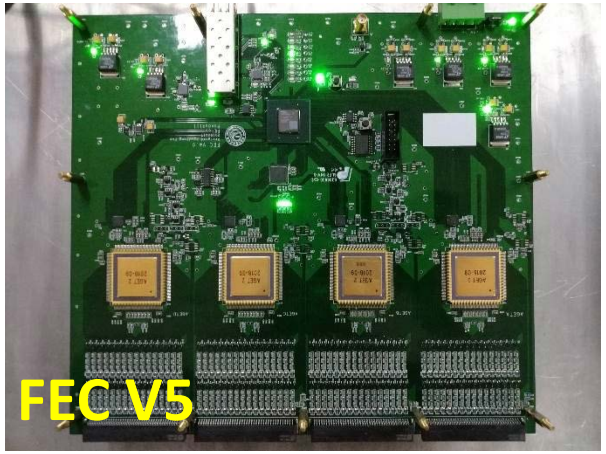




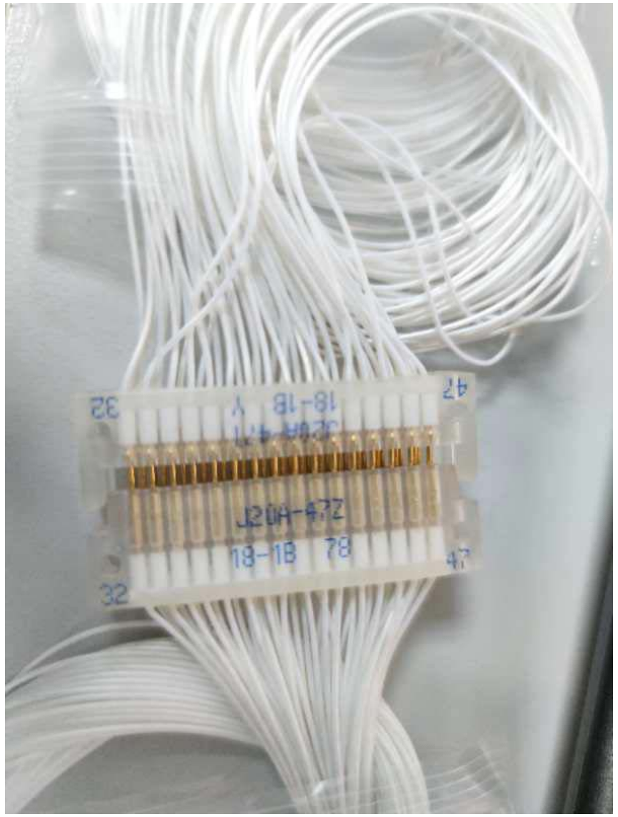
FECs (by USTC) TDCM (by Saclay)

Quest for low background

FEC with FR4

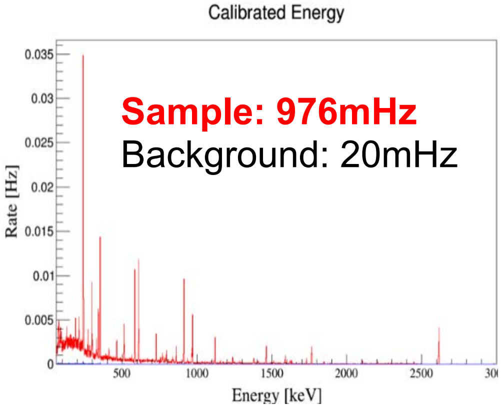


FEC with Kapton

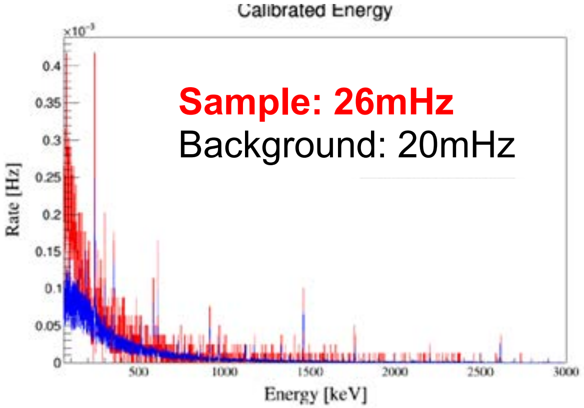


Low background connector

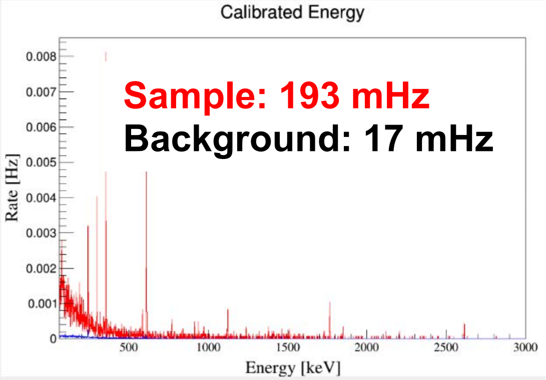
found by USTC



FEC with FR4



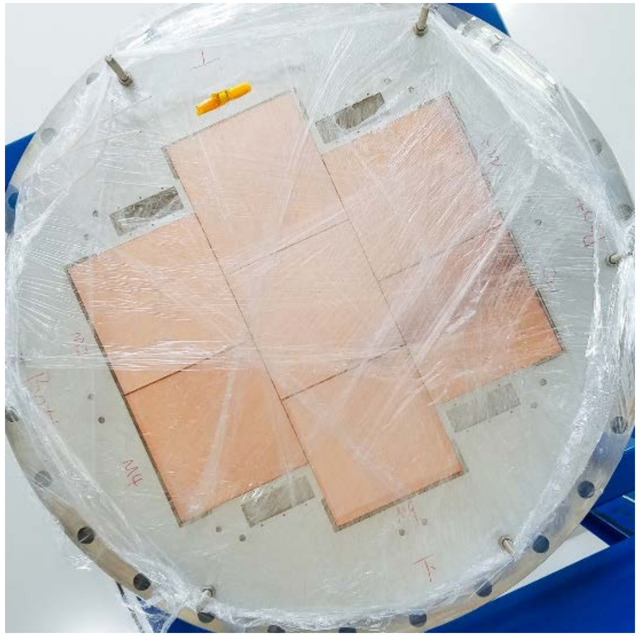
FEC board with Kapton

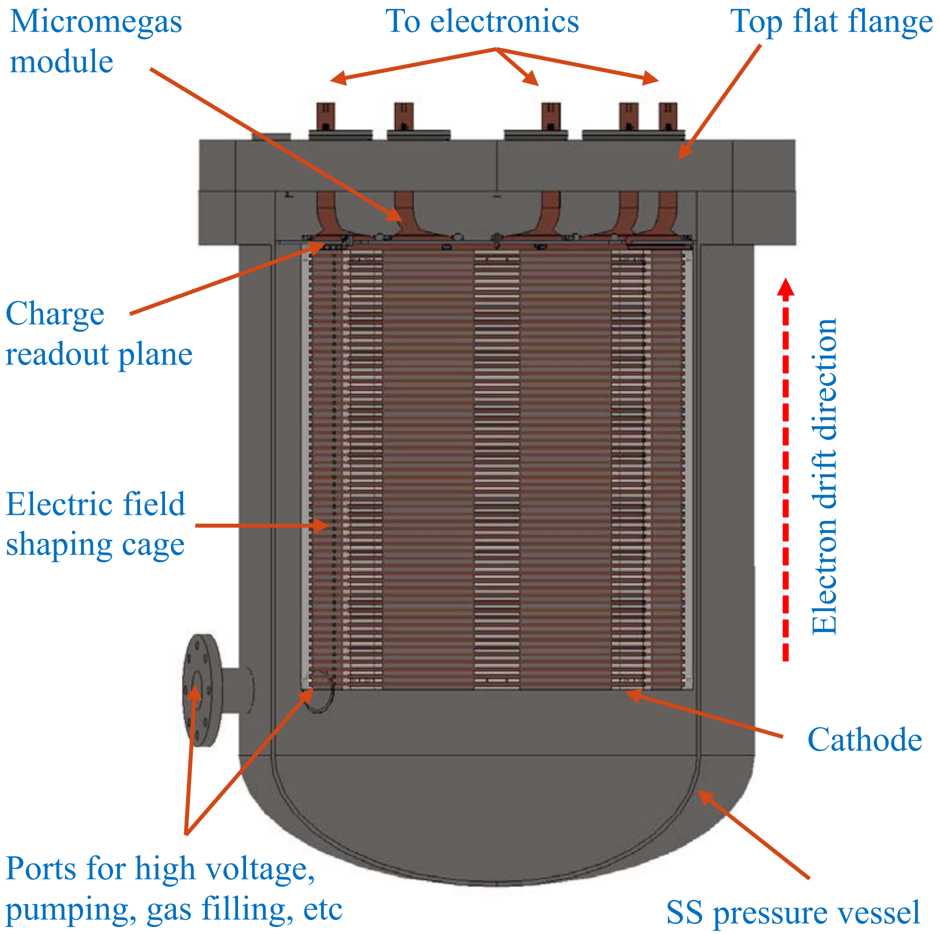


FEC with Kapton

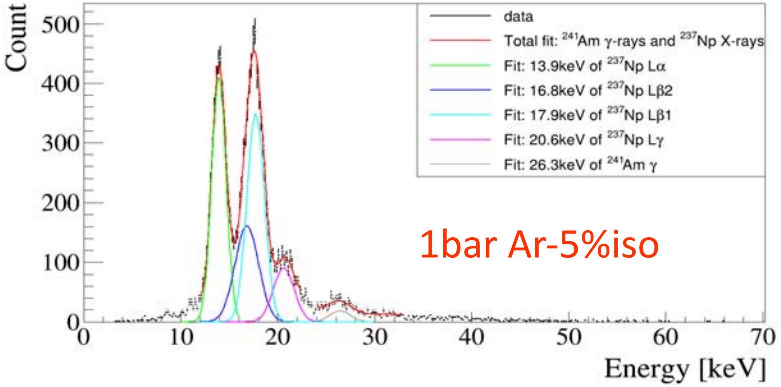
Prototype TPC at Shanghai

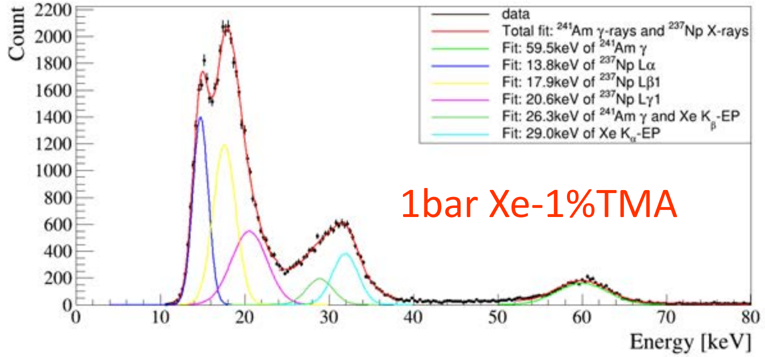
- About 600 L inner volume
- Field cage: 66 cm diameter, 78 cm drift length
- 16 kg of xenon at 10 bar
- SS pressure vessel
- 7 MM

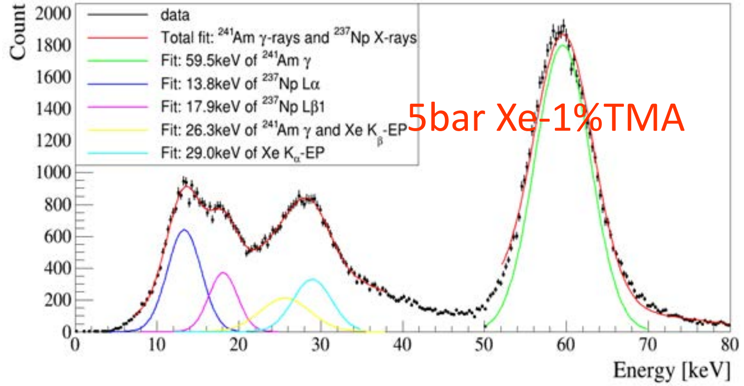




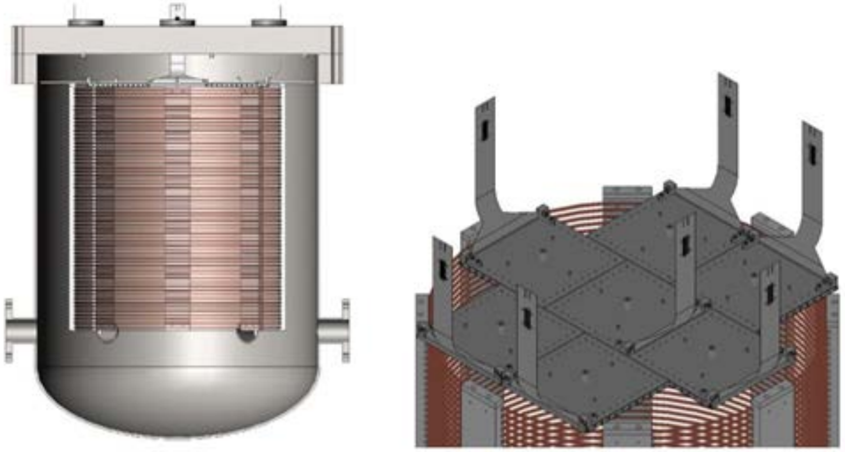
Data from Prototype TPC

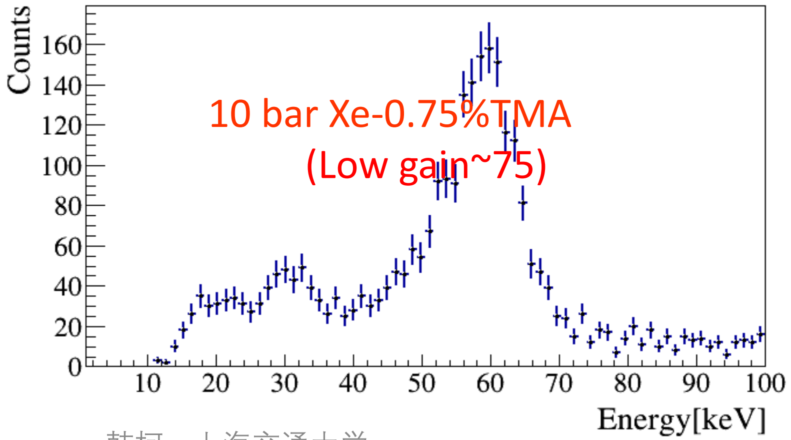




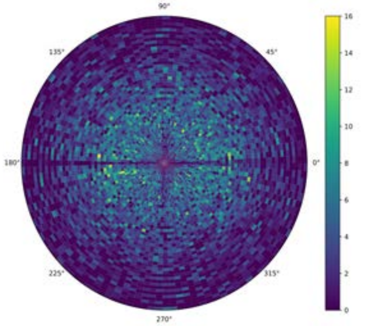


PandaX-III prototype TPC

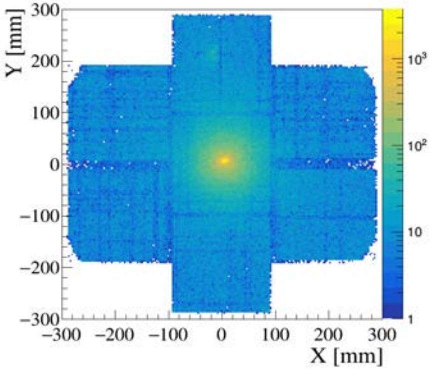




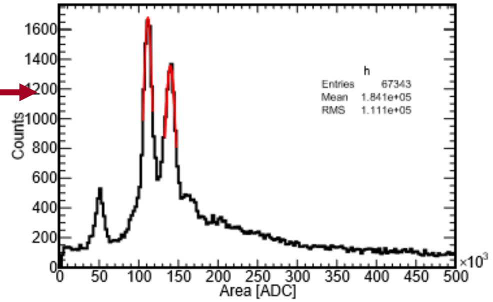
Muon track analysis



7 MMs data taking

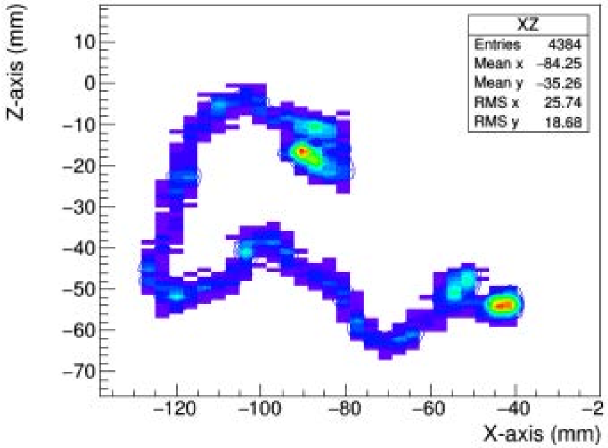


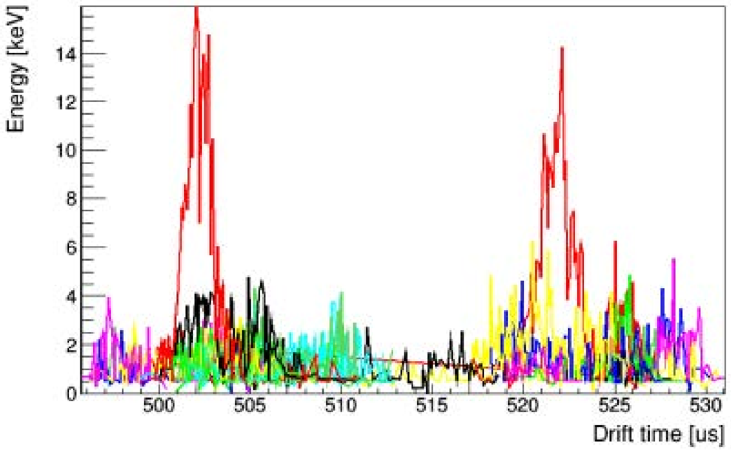
Electronics test with USTC

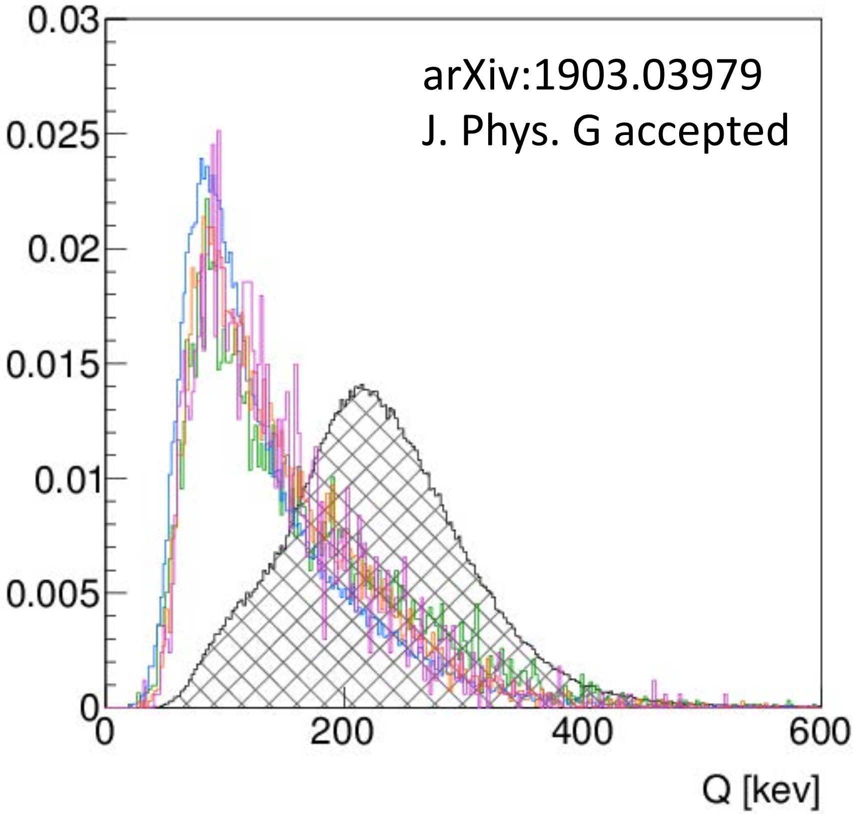


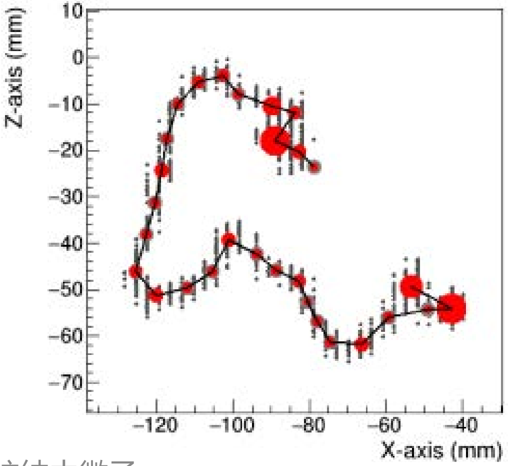
Traditional “cut” based analysis

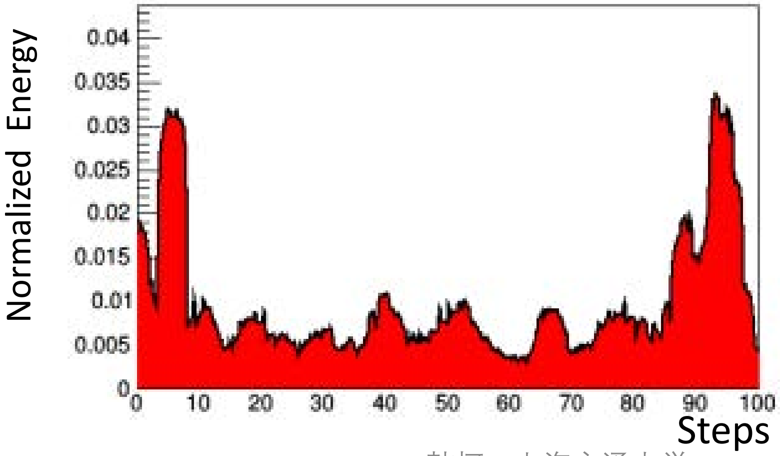
- Reconstructing tracks in XZ, YZ planes
- Number of tracks optimization by tuning “track distance”
- Energy of end blobs cut optimization







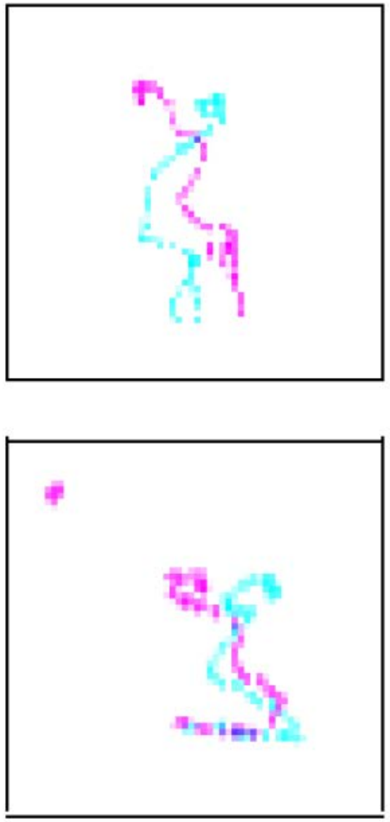


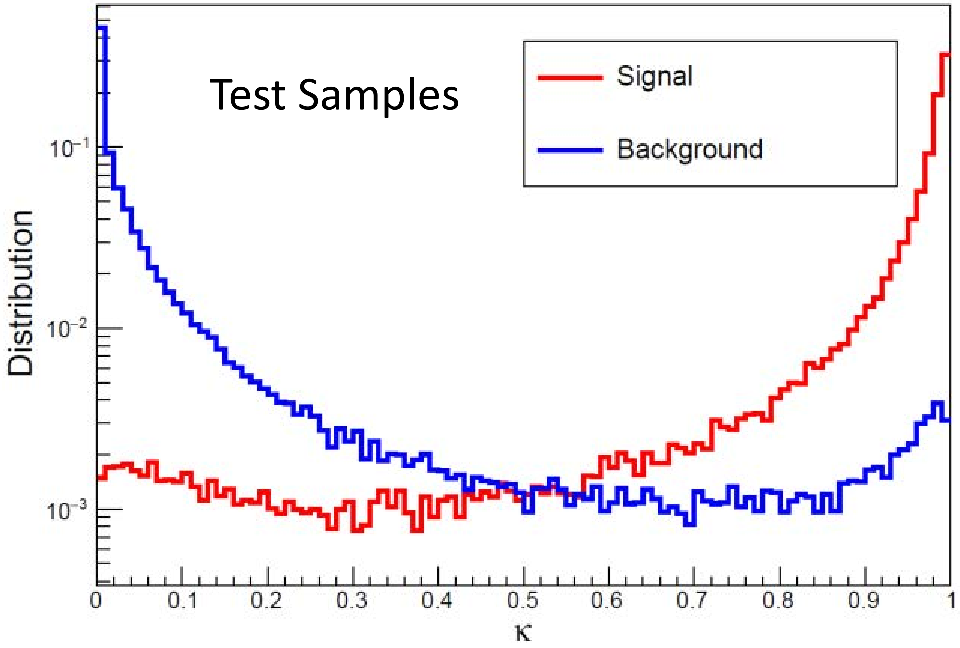


Energy of the smaller blob

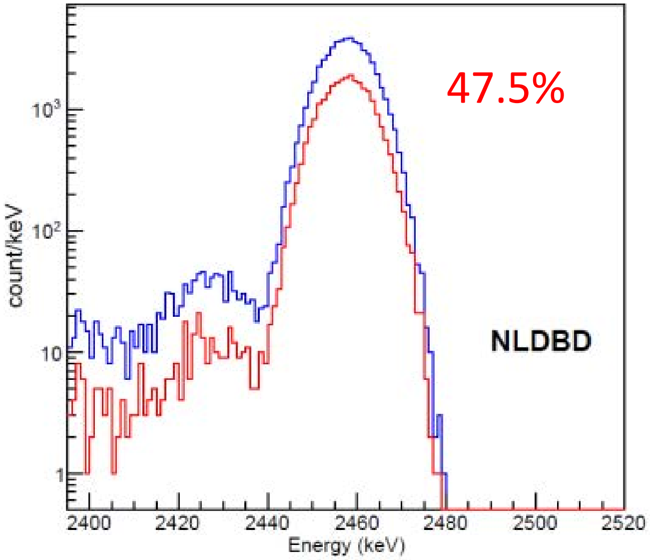
Convolutional Neural network (CNN) for track classification

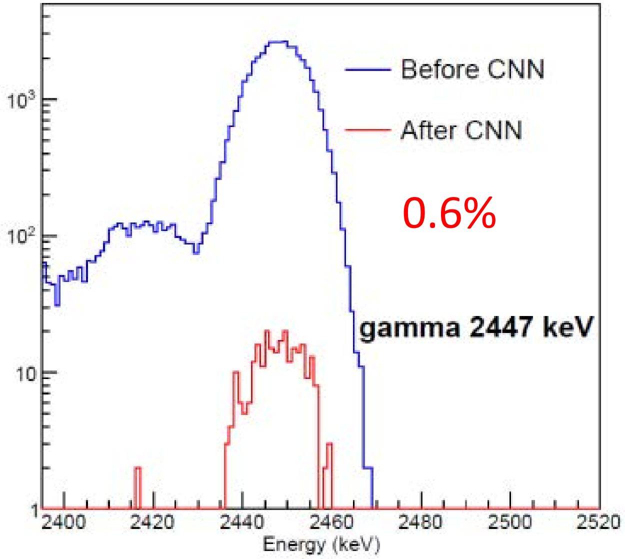
- XZ, YZ 2D snapshots of an event as input of CNN to spill out an index of signal/background
- Prepare image collections for CNN training, validation, and classification.
- No track reconstruction needed.
- More effective than traditional cut based approach.





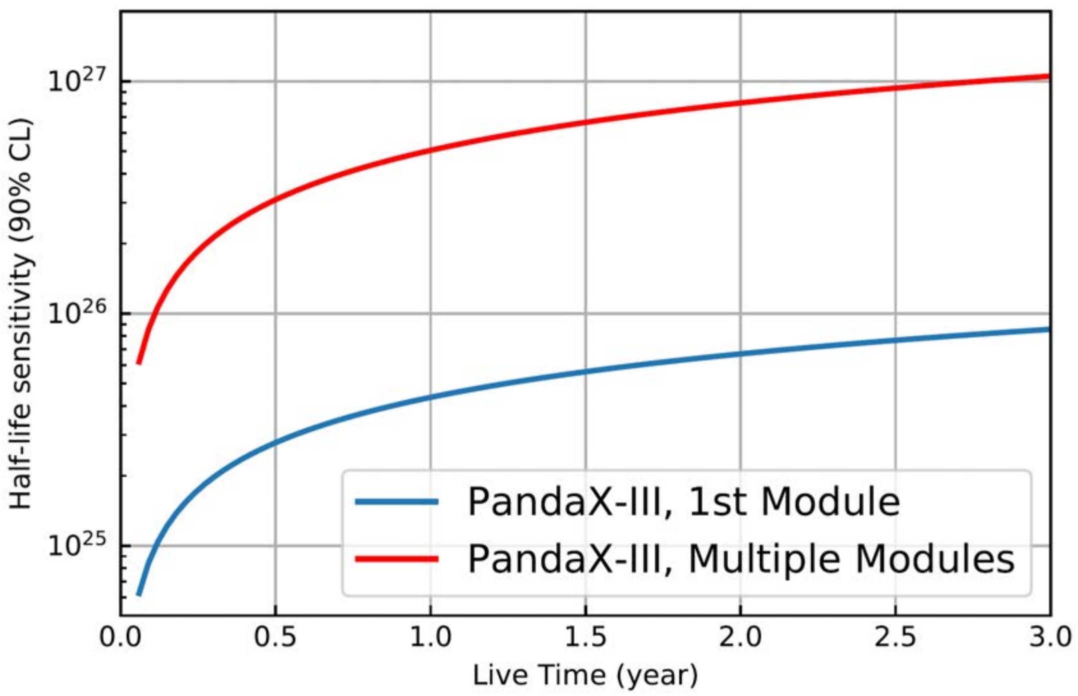
arXiv:1802.03489, Sci. China Phys. Mech. Astron. 61 (2018) 101007

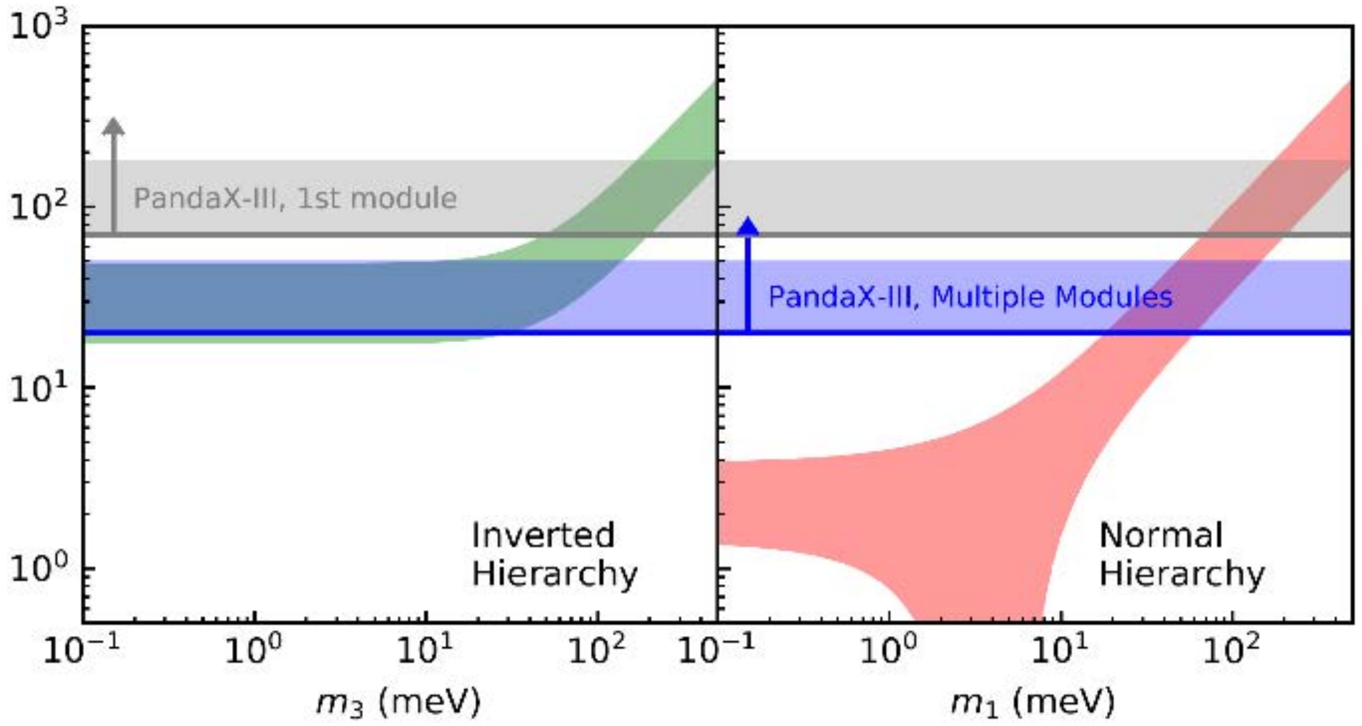




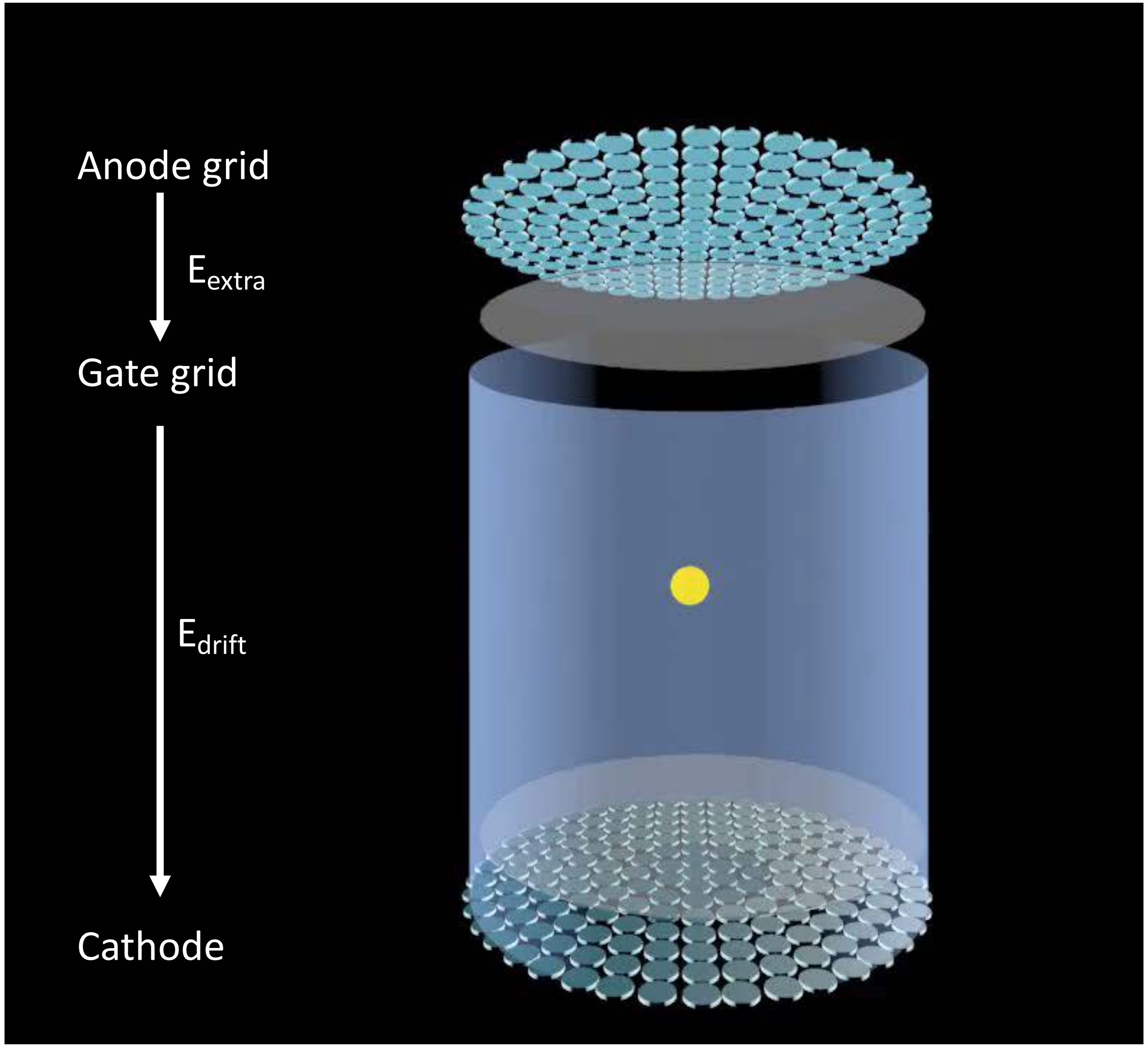
Summary

- Double beta decay: exciting physics ahead!
- PandaX-III 100-kg scale high pressure gas TPC module to start assembly in 2020
- Half-life sensitivity with 3 years of data: 9×10^{25} yr (90% CL)



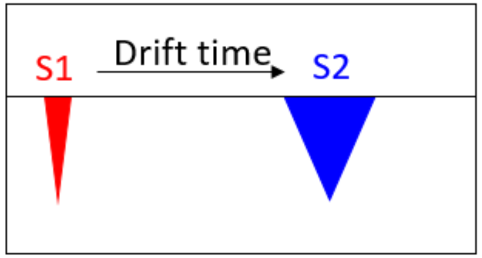


Dual phase Xe TPC for dark matter

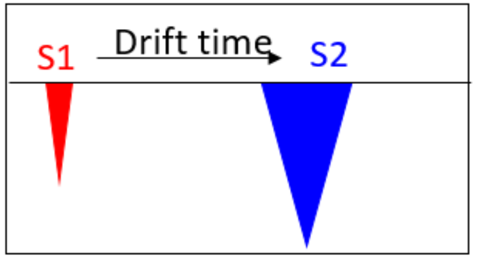


- **PandaX-II**: 2014-2018
  - 60 cm x 60 cm dual-phase xenon TPC
  - 580 kg LXe in sensitive volume
- Dual-phase xenon detectors:
  - Large monolithic target
  - 3D reconstruction and fiducialization
  - Calorimeter capable of seeing a couple of photons/electrons
  - Good ER/NR rejection

Dark matter: nuclear recoil (NR)



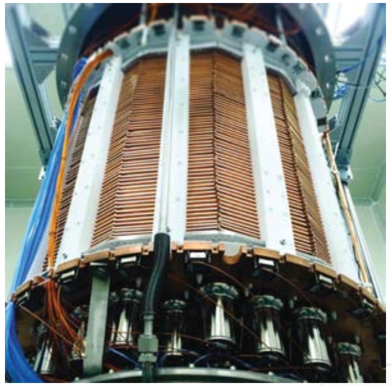
γ background: electron recoil (ER)



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

PandaX-II data taking

- Run9 =79.6 days, exposure: 26.2 ton-day
- Run10 = 77.1 days, exposure: 27.9 ton-day
- Run11 = 246.4 days, exposure 89.2 ton-day



2015 — 2016 — 2017 — 2018 — 2019

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)

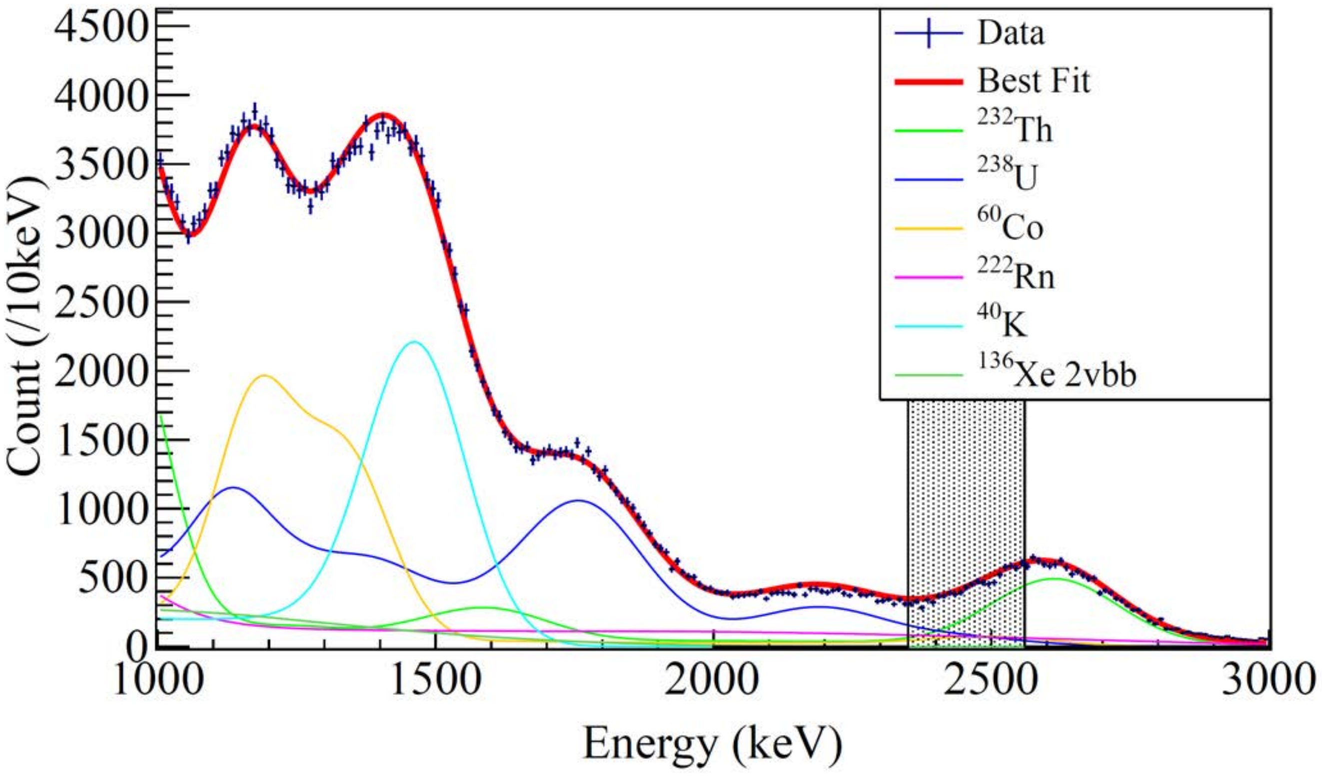
Jul. 2017-Aug. 2018, ^{220}Rn/AmBe runs, followed by DM data taking (Run11)

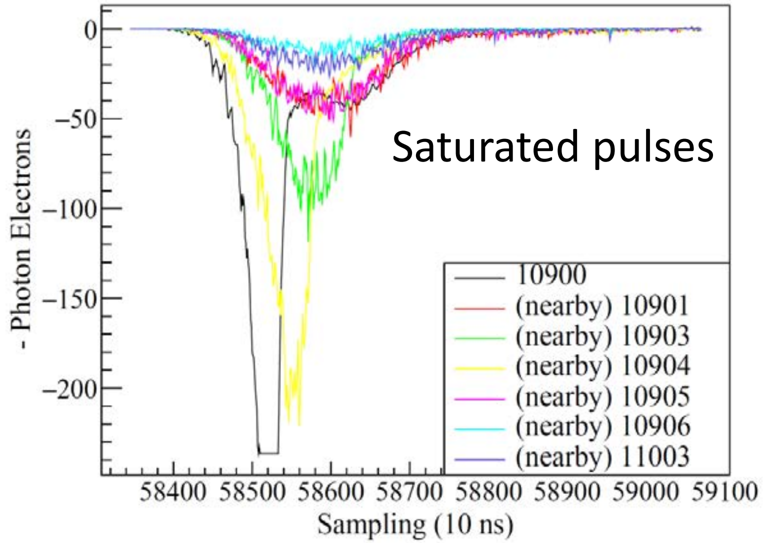
Aug. 2018 – June 2019 R&D runs for PandaX-4T

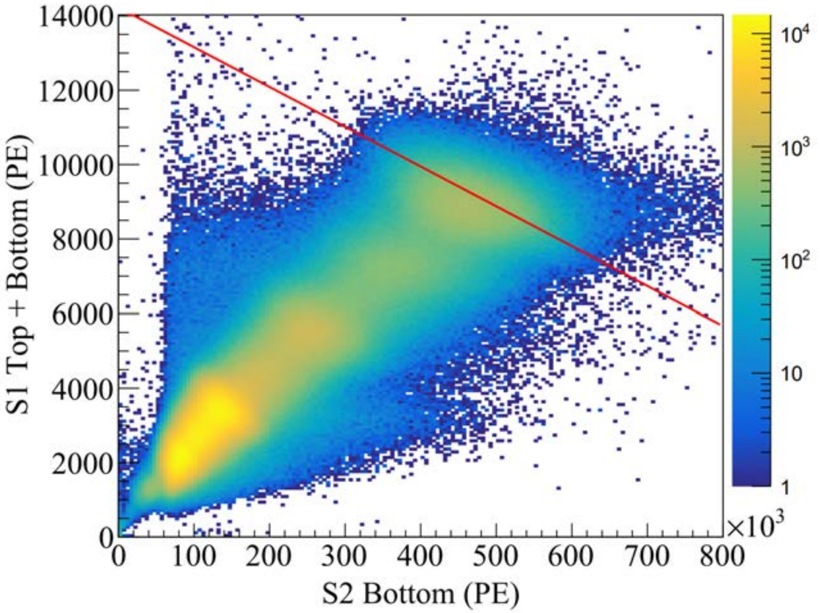
June 2019

Liquid xenon dark matter detectors for 0νββ

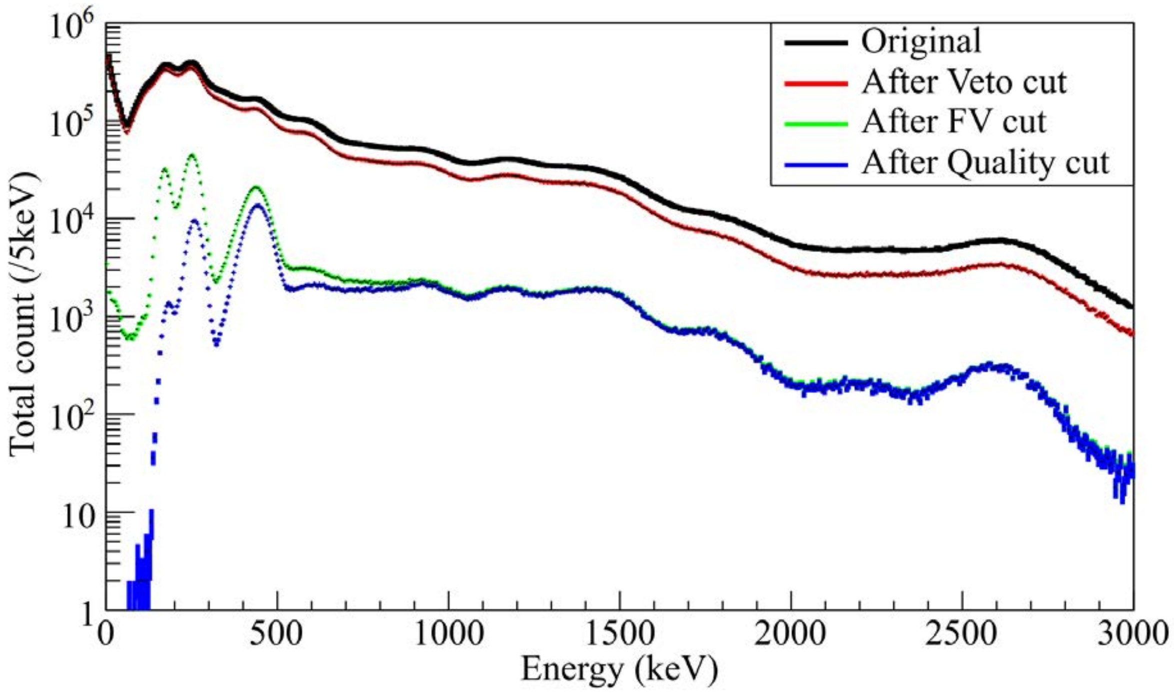
- Natural isotopic abundance of ^{136}Xe: 8.9%
  - Large amount of isotope for multi-ton LXe TPCs
- High signal efficiency ~90% and excellent up-time.
- Key challenges: background level and energy resolution at MeV

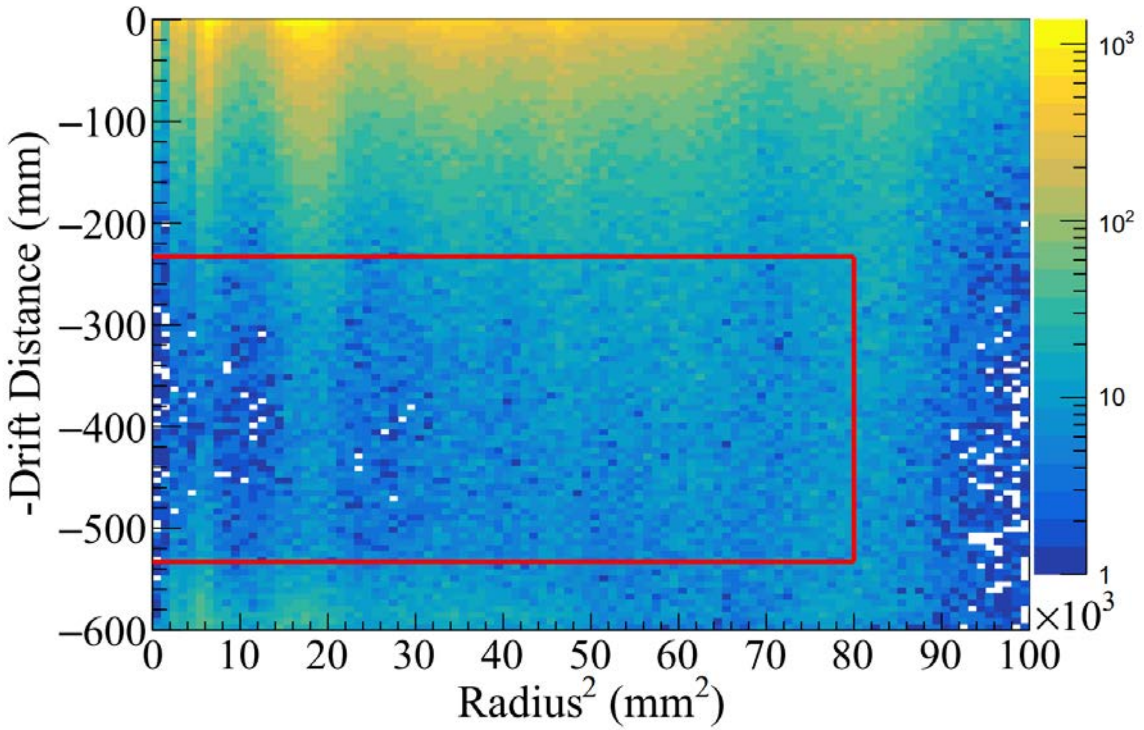






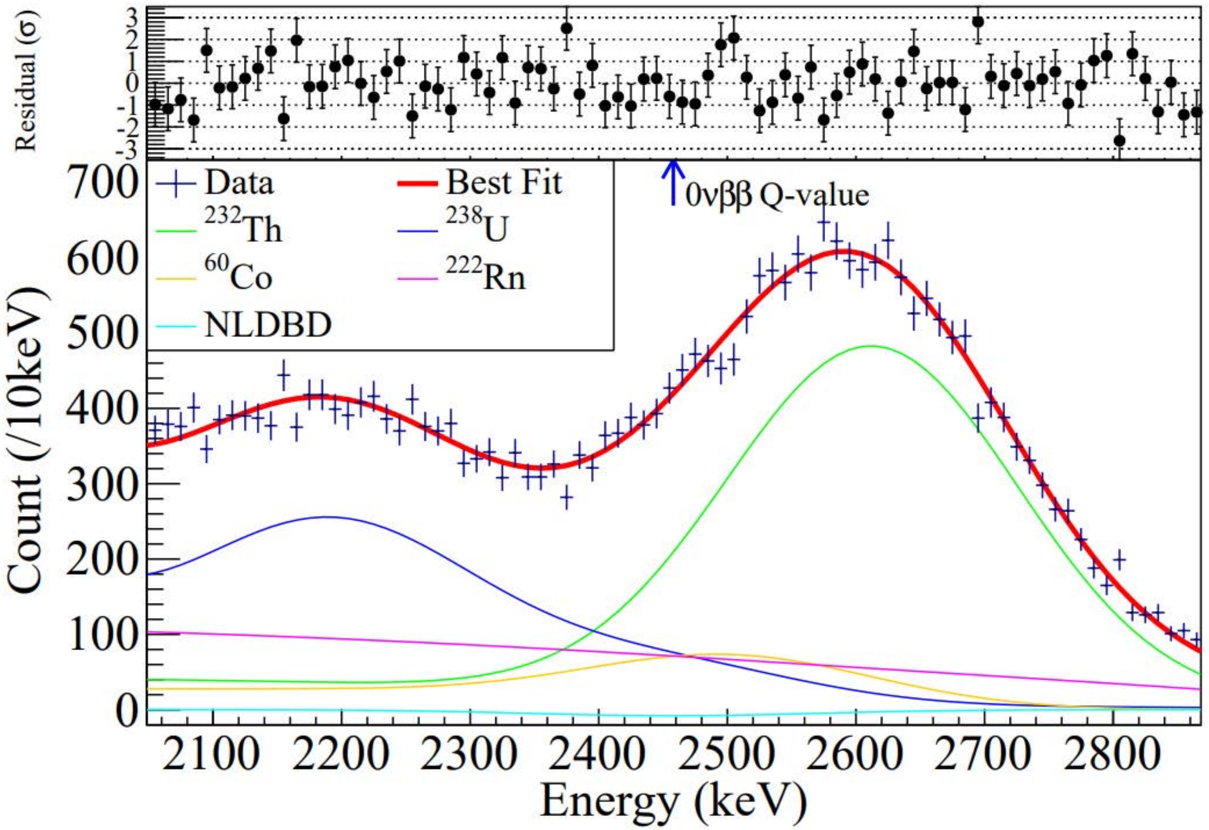
PandaX-II event selection





- Re-tuned pulse quality cuts at MeV
- Re-tuned fiducial volume according to the MeV event distribution

Final spectrum fit for PandaX-II data

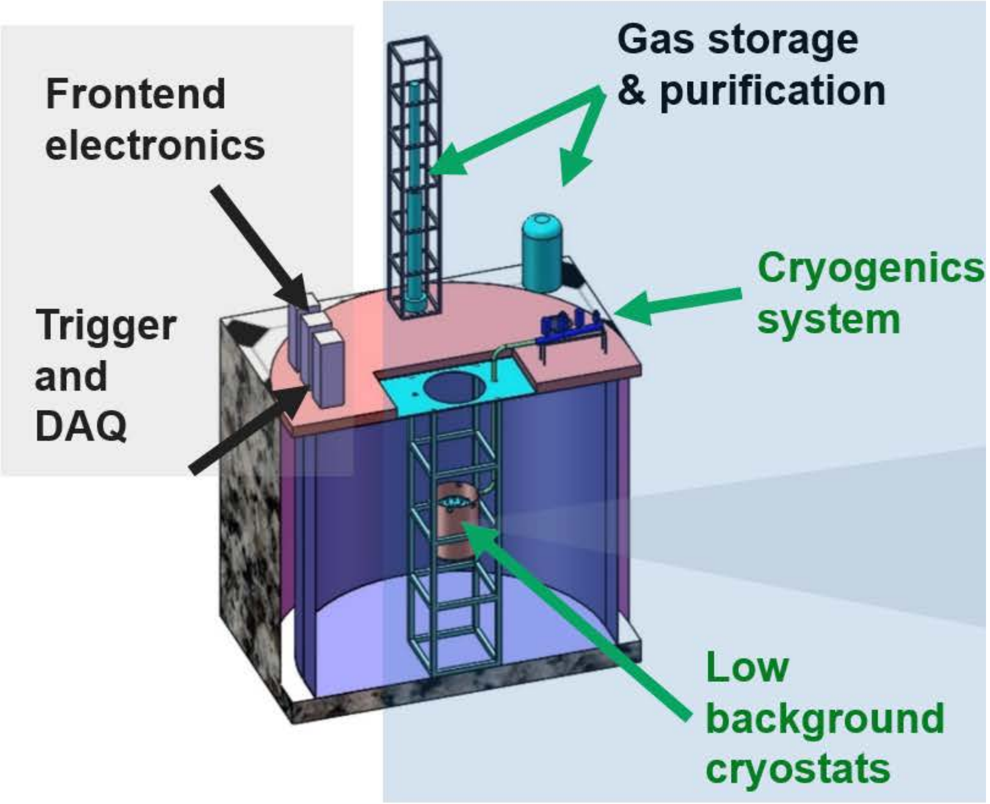


arXiv:1906.11457; Chinese Physics C 43, 113001 (2019)

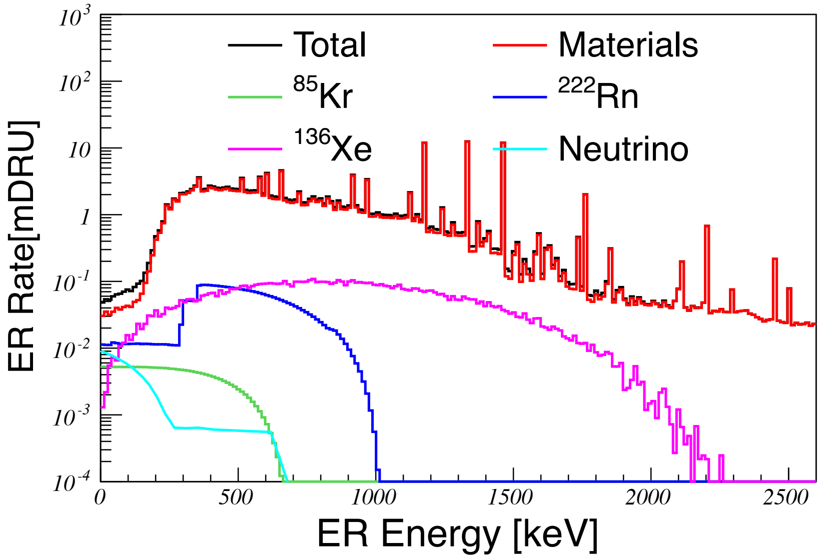
- Energy resolution: 4.2%
- Null results.
- Lower limit for decay half-life: 2.4×10^{23} yr at 90% CL
- Effective Majorana mass upper limit: 1.3-3.5 eV.
- First 0νββ result reported from a dual-phase xenon experiment

PandaX-4T for $0\nu\beta\beta$

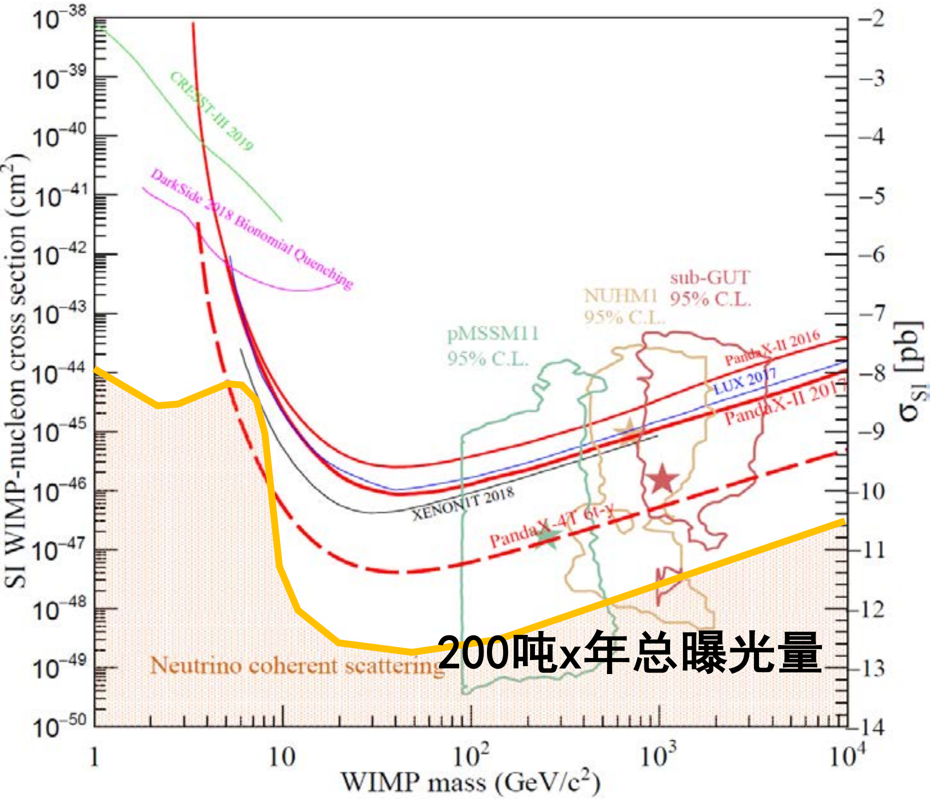
- Larger TPC with 4T of xenon in active region
- Ultra-pure water shielding
    - 5 m of water shielding in all directions
- Online xenon purification

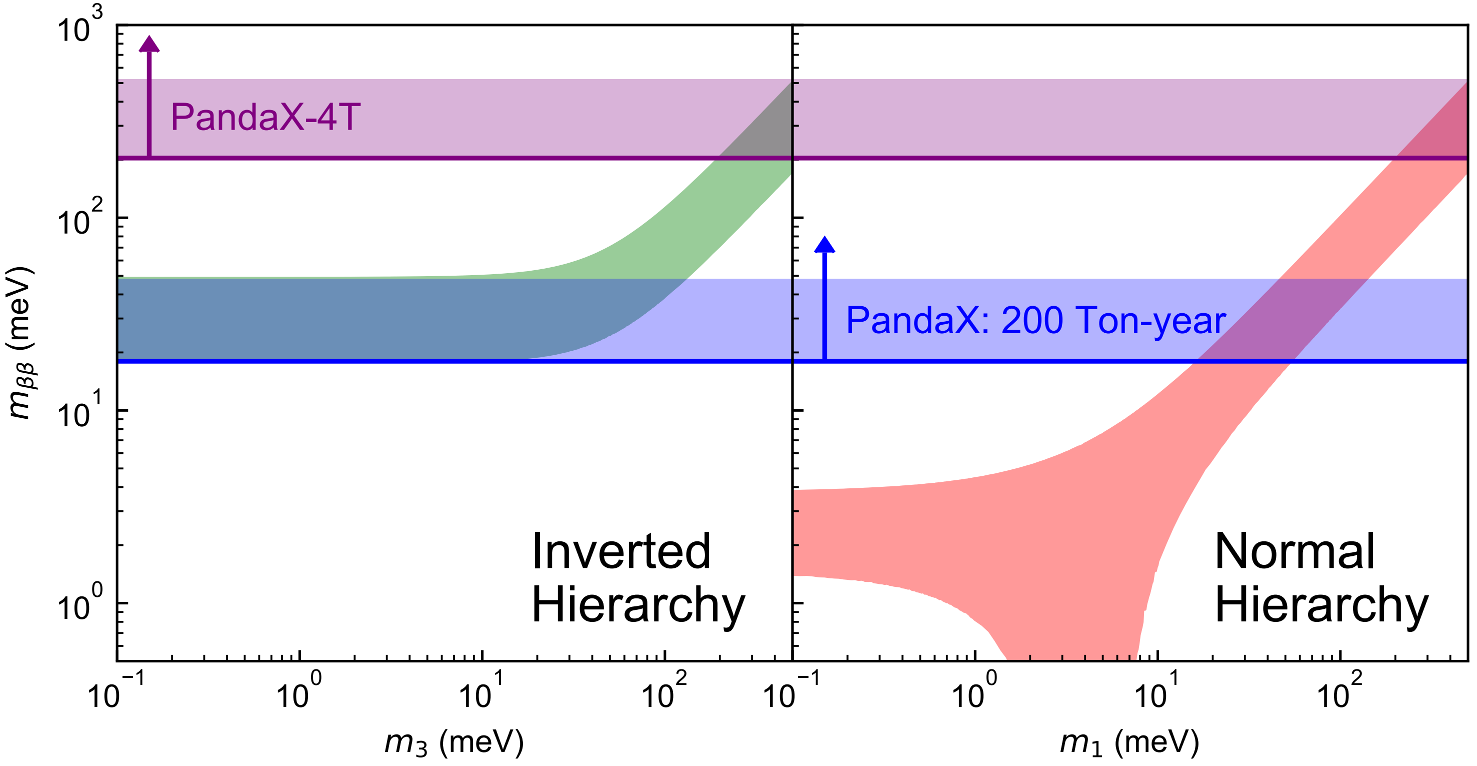


- Newly designed readout bases to avoid PMT saturation
- Dual-readout bases for center 7 PMTs
    - Signals are readout from a middle dynode and the last dynode.
- Expected half-life sensitivity is at 10^{25} yr level
    - 1% (σ) energy resolution
    - PanadaX-4T expected bkg
    - More aggressive fiducial cuts



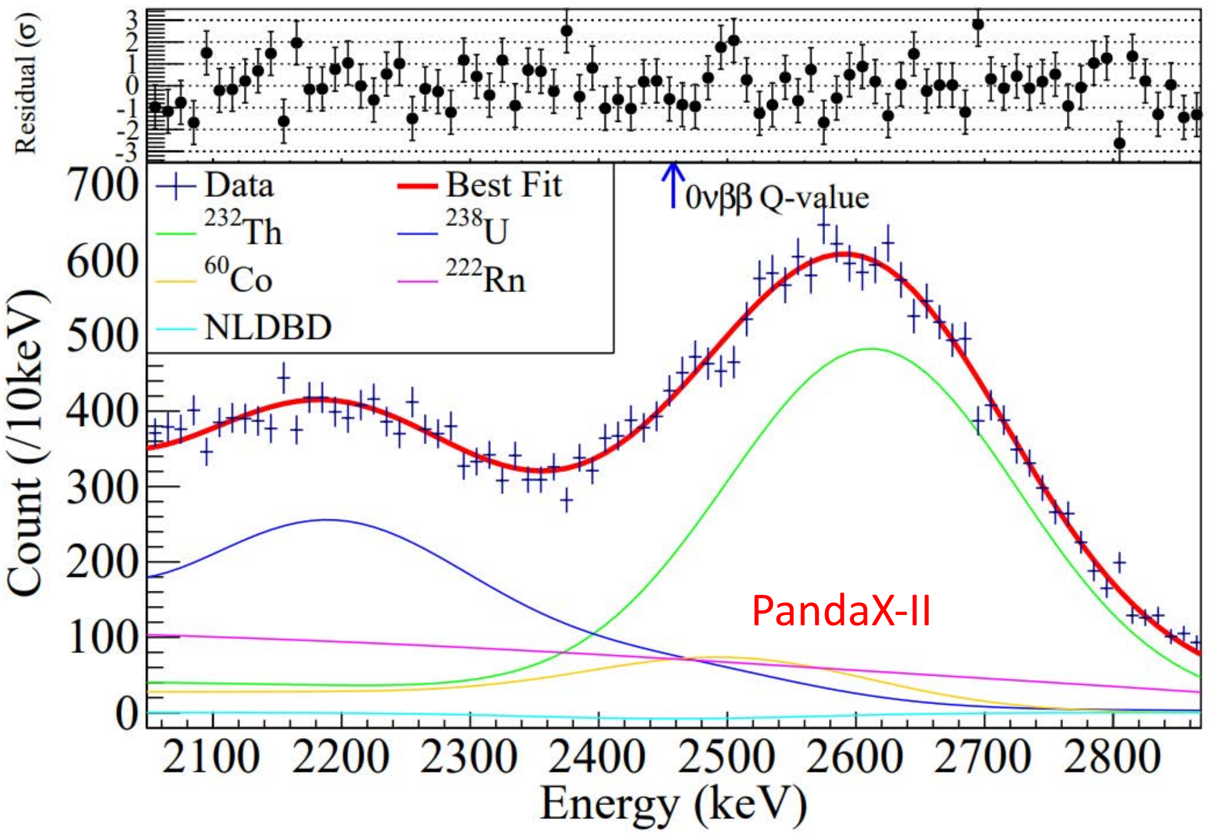
PandaX-xT: xenon TPC for multiple physics

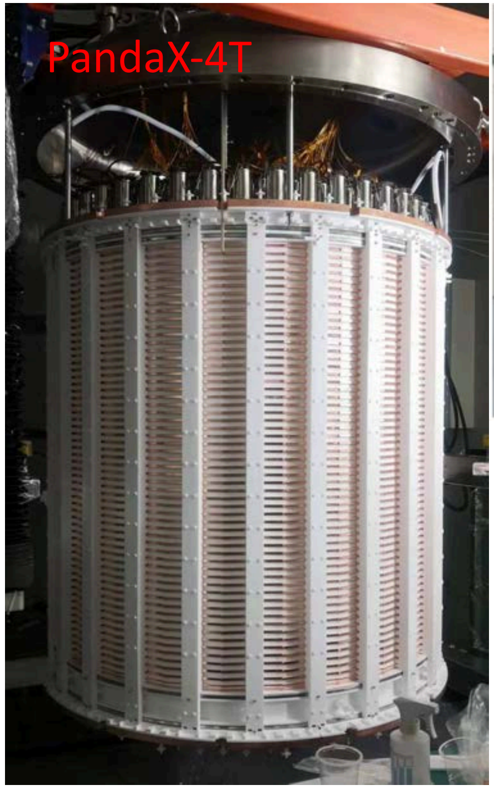


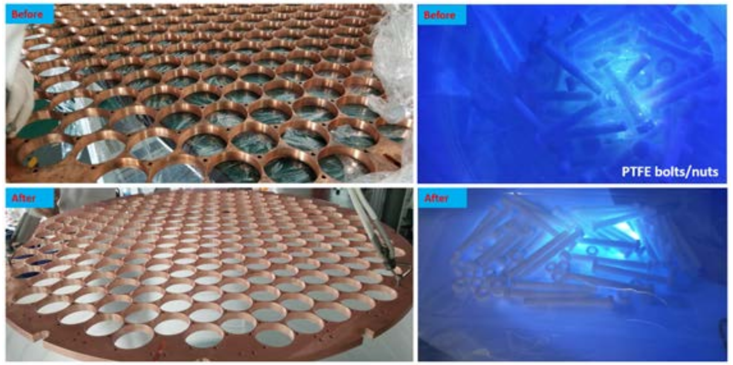


Summary

- With PandaX-II data, we demonstrated the feasibility to search for 0νββ with dual-phase xenon detectors.
- PandaX-4T will continue the effort besides dark matter searches.







Current neutrino picture

- ✓ Neutrinos are massive
- ✓ Neutrino flavor oscillation 🡐 mixing of massive neutrinos
- ✓ Two hierarchical mass scales Δm^2
- ✓ Three mixing angles measured

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

PMNS matrix (Pontecorvo–Maki–Nakagawa–Sakata)

$\theta_{12} = 34^\circ$

$\Delta m^2_{12} = 7.6 \times 10^{-5}\mathrm{eV}^2$

$$\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Solar
KamLAND

$\theta_{13} = 9^\circ$

$$\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix}$$

Short Baseline Reactor
Long Baseline Accelerator

$\theta_{23} = 40^\circ$

$|\Delta m^2_{23}| = 2.4 \times 10^{-3}\mathrm{eV}^2$

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}$$

Atmospheric
LBL Accelerator

$c_{ij} = \cos(ij),\ s_{ij} = \sin(ij)$