Hadron-China 2019: The 11th Workshop on Hadron Physics in China and Opportunities Worldwide

Neutrinoless Double Beta Decay Searches: Status and Prospects

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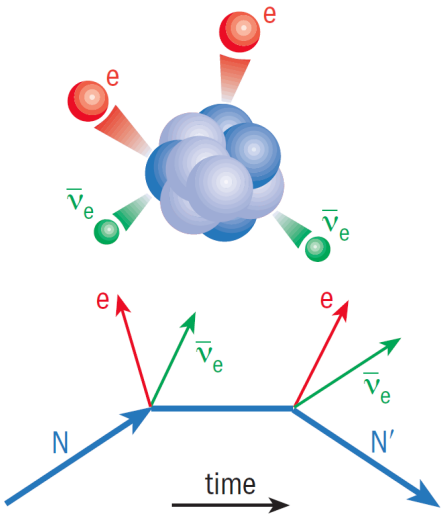
08/25, 2019

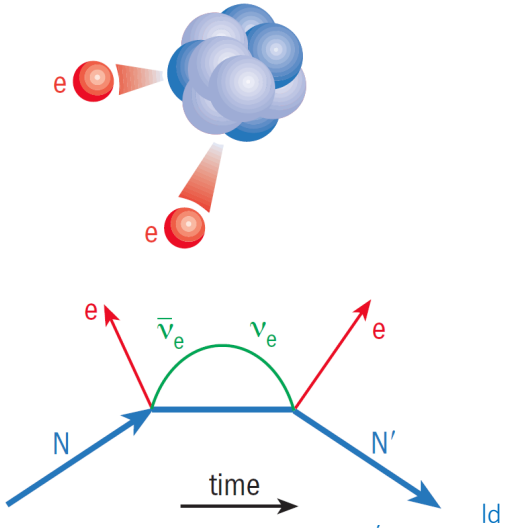
Outline

- General considerations for NLDBD experiments
- Current status and plans for NLDBD searches worldwide
- Opportunities at CJPL-II
  - NLDBD proposals in China
  - PandaX series experiments for NLDBD of ^{136}Xe

Majorana neutrino and NLDBD



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



[1935, Goeppert-Mayer](): Two-Neutrino double beta decay

[1937, Majorana](): Majorana Neutrino

[1939, Furry](): Neutrinoless double beta decay NLDBD

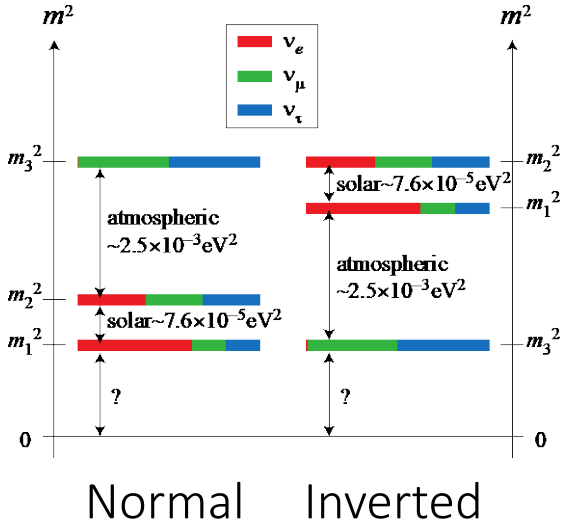
[1930, Pauli](): Idea of neutrino

[1933, Fermi](): Beta decay theory

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

NLDBD probes the nature of neutrinos

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



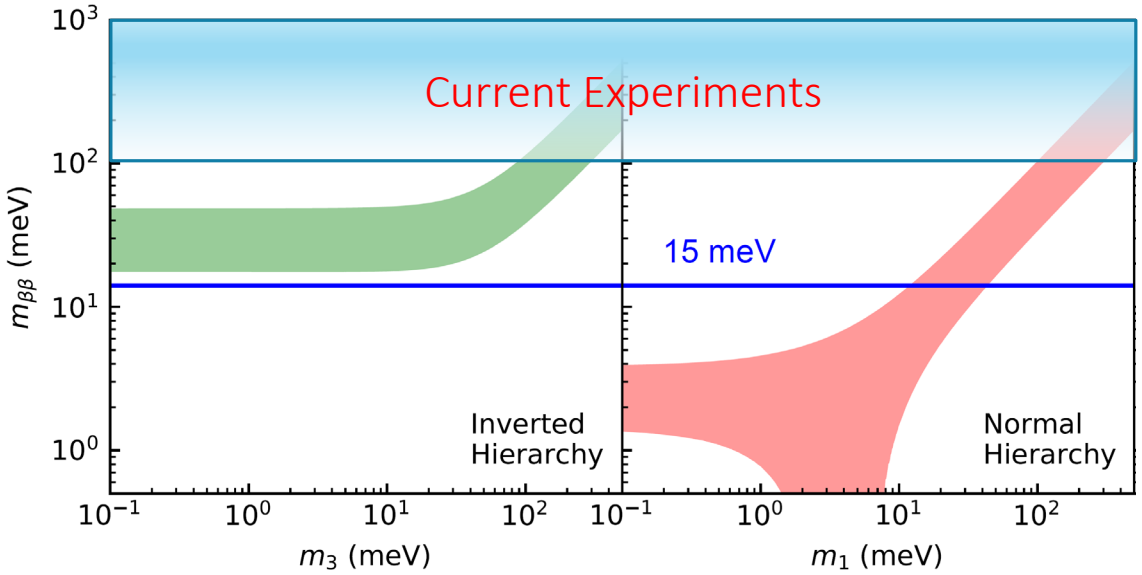
$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}(Q,Z)\ |M^{0\nu}|^2\ \frac{|\langle m_{\beta\beta}\rangle|^2}{m_e^2}$$

Phase space factor

Nuclear matrix element

Effective Majorana neutrino mass:

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



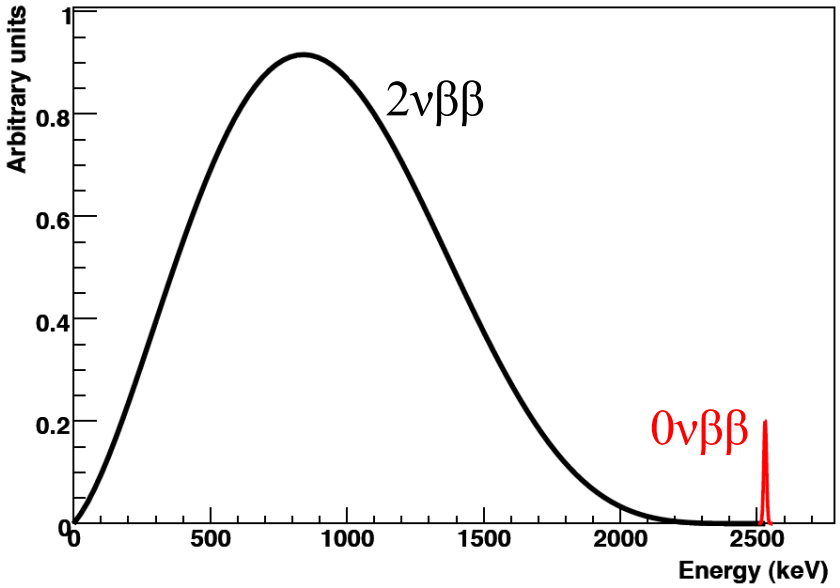
Detection of double beta decay

- Examples:

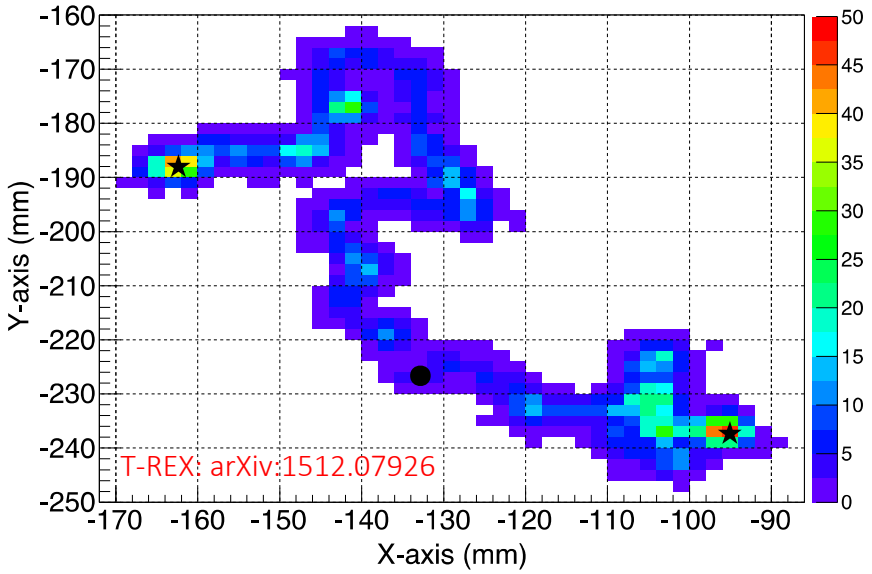
$$^{136}_{54}Xe \rightarrow {}^{136}_{56}Ba + 2e^- + (2\bar{\nu})$$

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

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

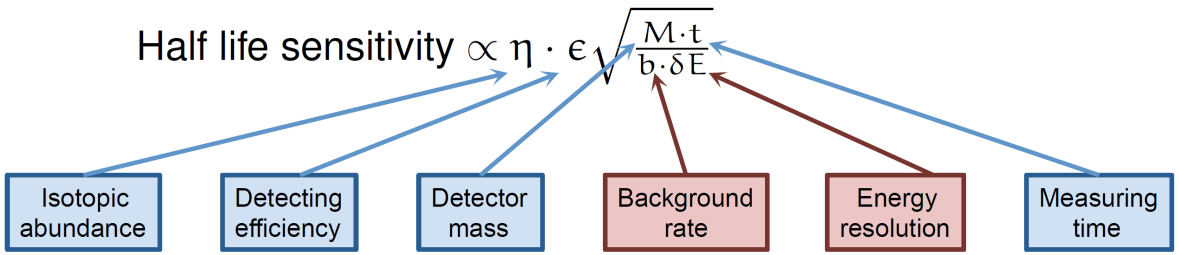


Sum of two electrons energy

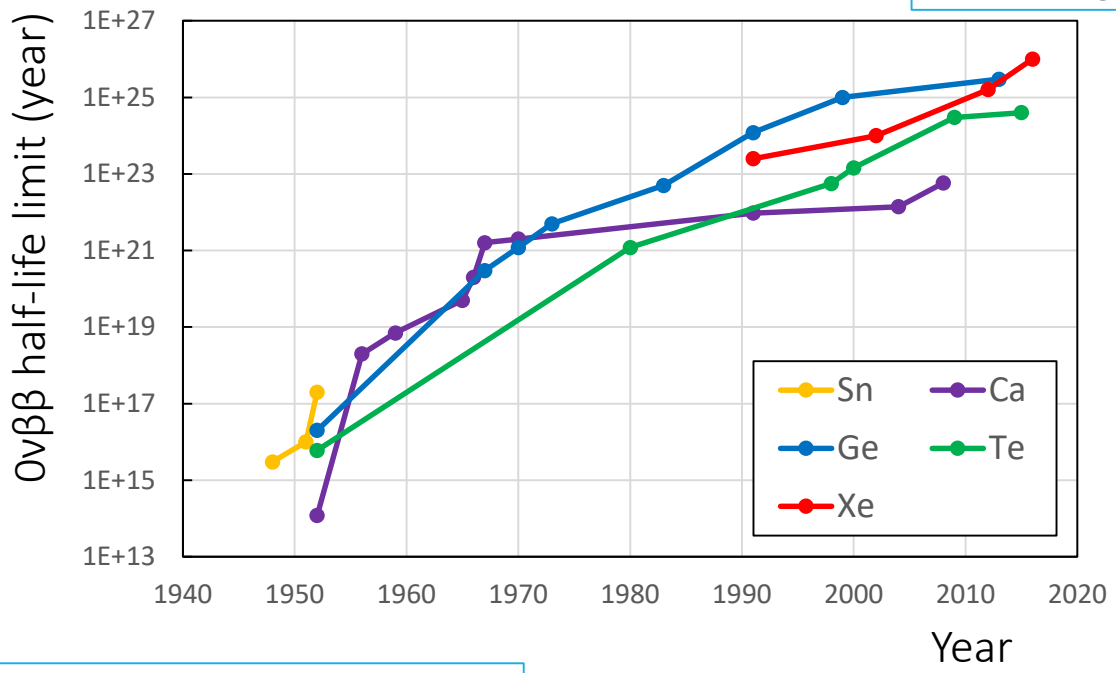


Simulated track of 0νββ in high pressure Xe

Impressive experimental progress



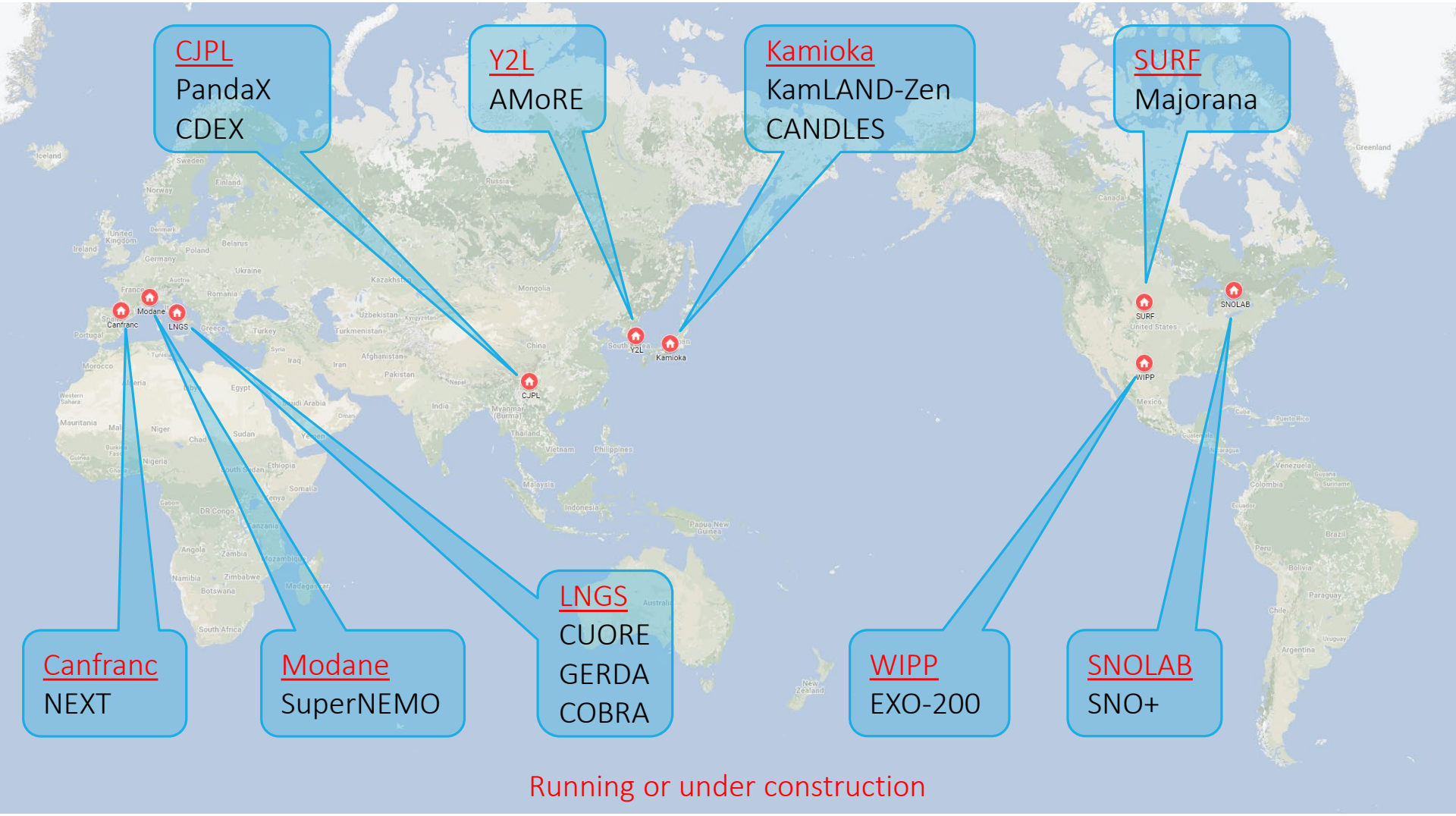
- ~100 kg of isotopes
- ~100-person collaborations
- Deep underground
- Shielding + clean detector



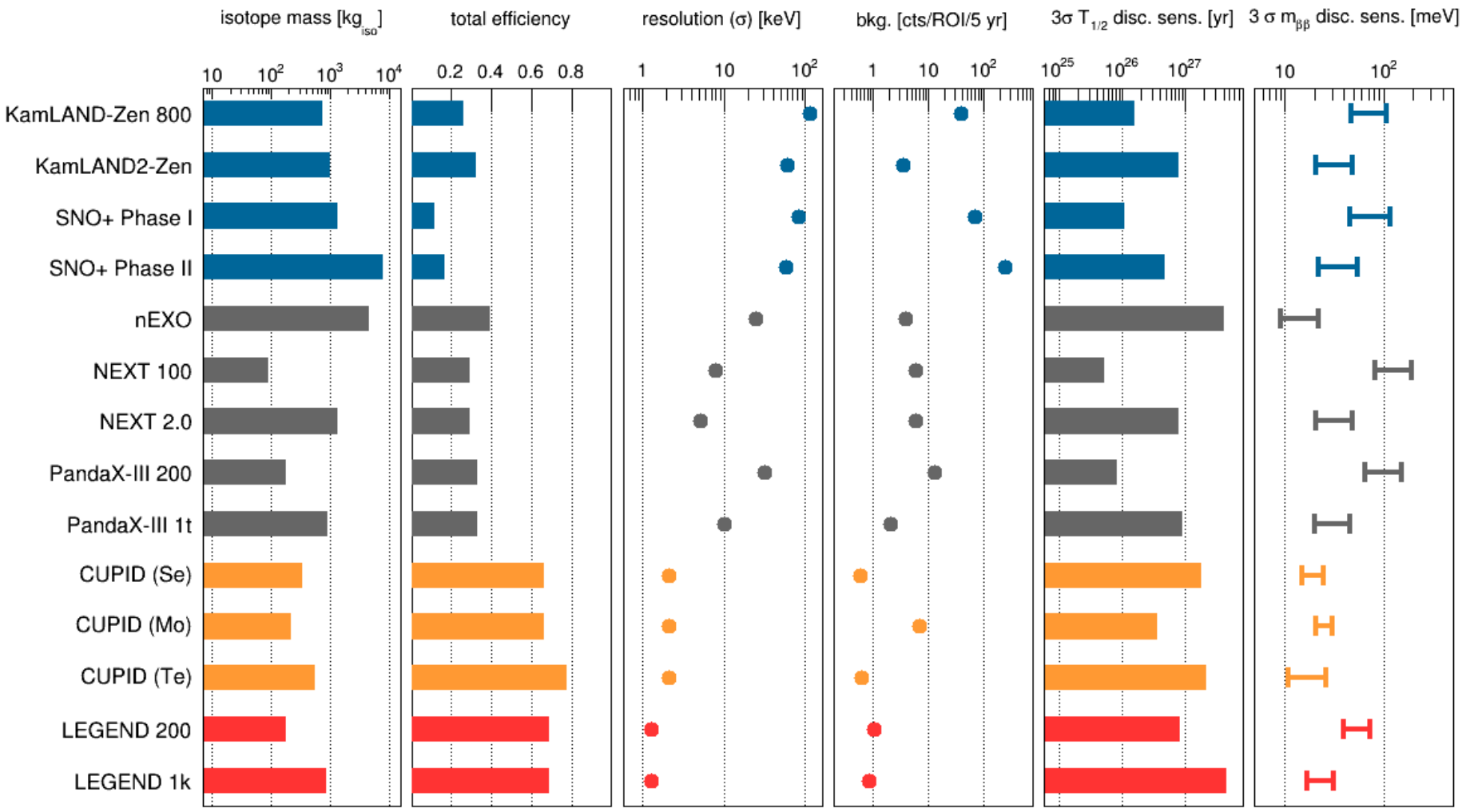
- Grams of isotopes
- Above-ground
- Table-top experiment
- Little shielding

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

Major 0νββ experiments around the world

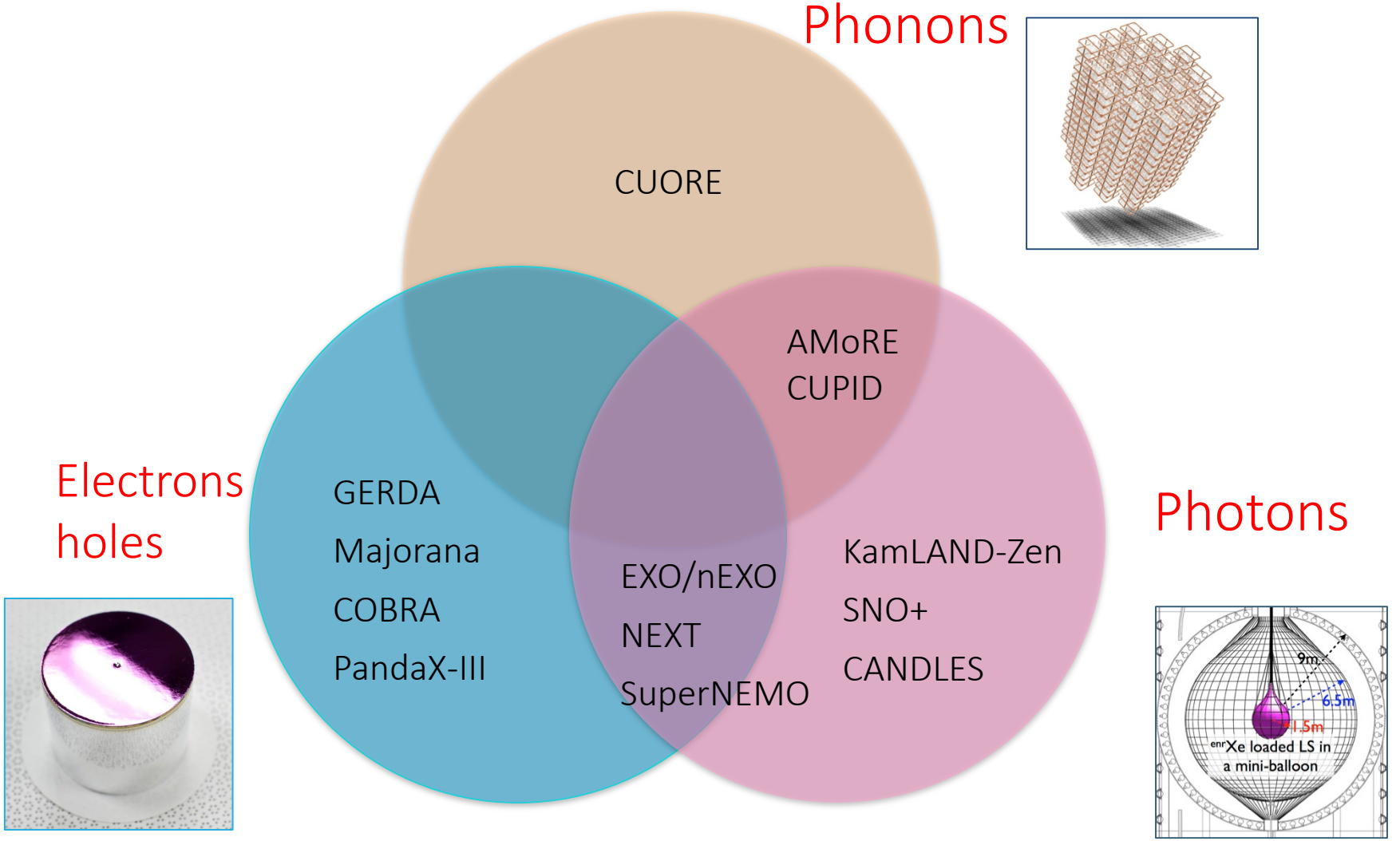


Future experiments



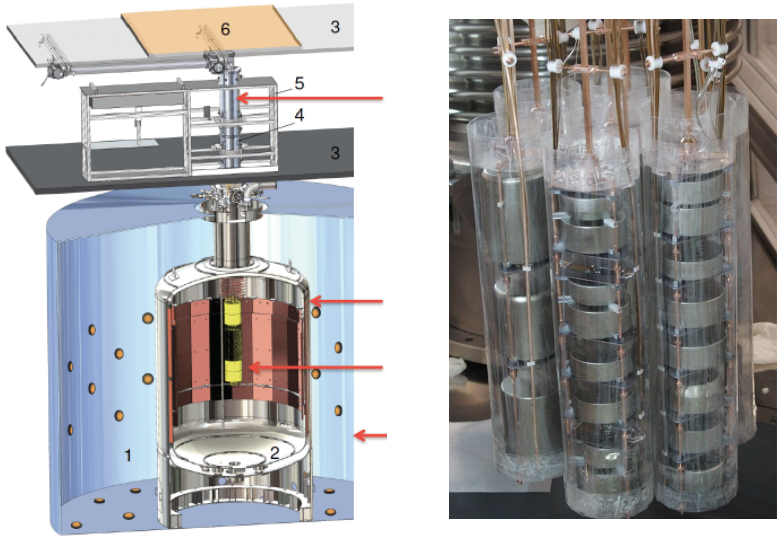
From: Jason Detwiler, et al

Detection channels



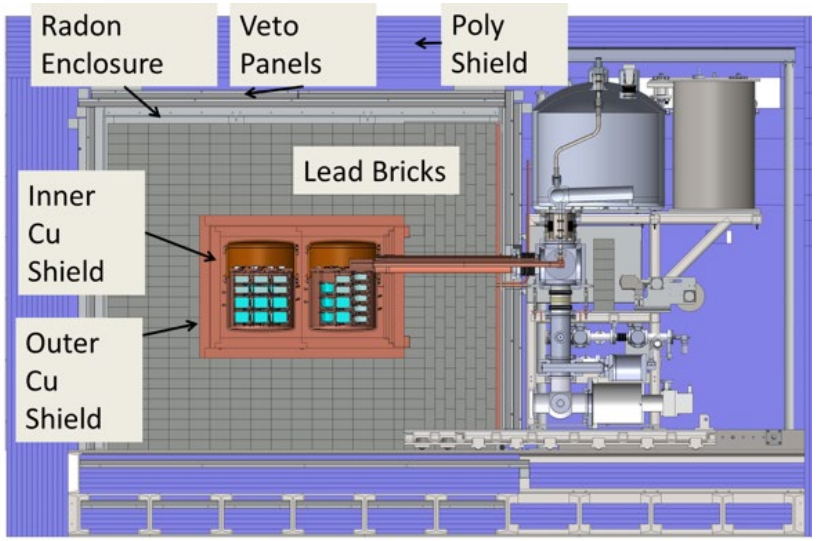
HPGe detectors (^{76}Ge)

GERDA at LNGS, Italy



Half-life limit: 0.9×10^{26} yr
Bkg: 5.7×10^{-4} c/kev/kg/yr (DBD18)

Majorana Demonstrator at Sanford, US



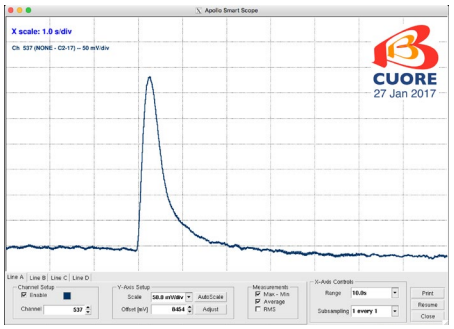
Half-life limit: 2.7×10^{25} yr
Bkg: ~5×10^{-3} c/kev/kg/yr
(ArXiv:1902.02299)

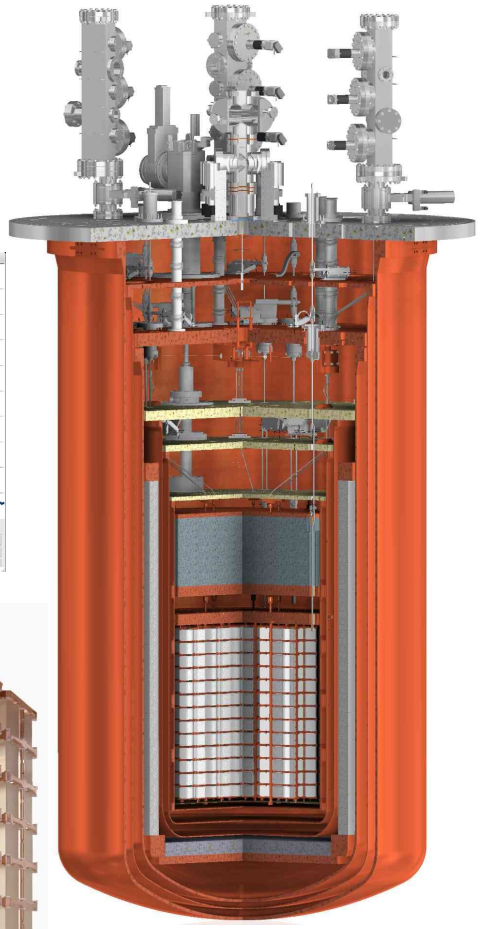
Future:

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

CUORE (^{130}Te)

- Bolometric technique
- Excellent energy resolution by measuring temperature rise at mK level.
- CUORE data taking started early 2017
- Current limit: 1.5x10^{25} yr





World-largest Dilution Refrigerator

<10mK

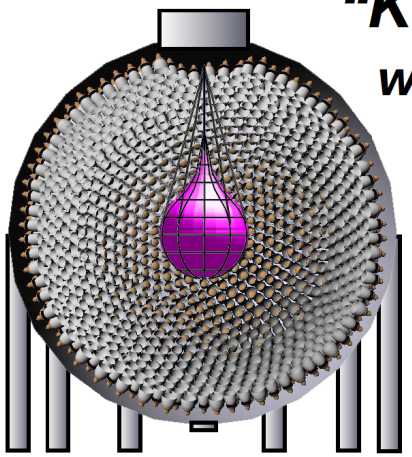
Future

- CUPID (CUORE with particle ID)
  - LiMoO4 scintillating bolometer array
  - Phonon + photon dual readout

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)
- New phase with twice the ^{136}Xe is under construction.

Future:



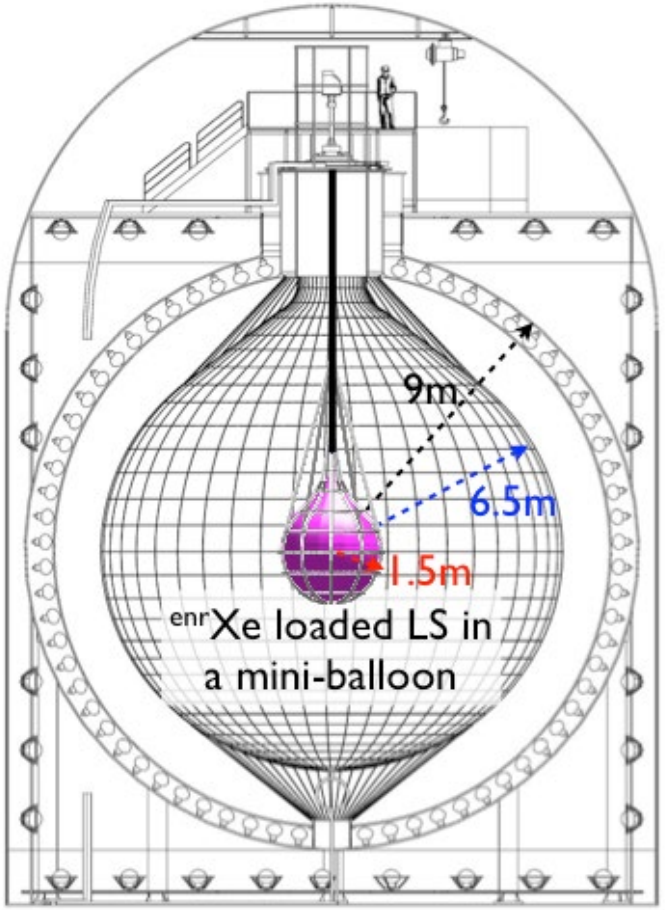
"KamLAND2-Zen"

with 1000kg enriched Xe

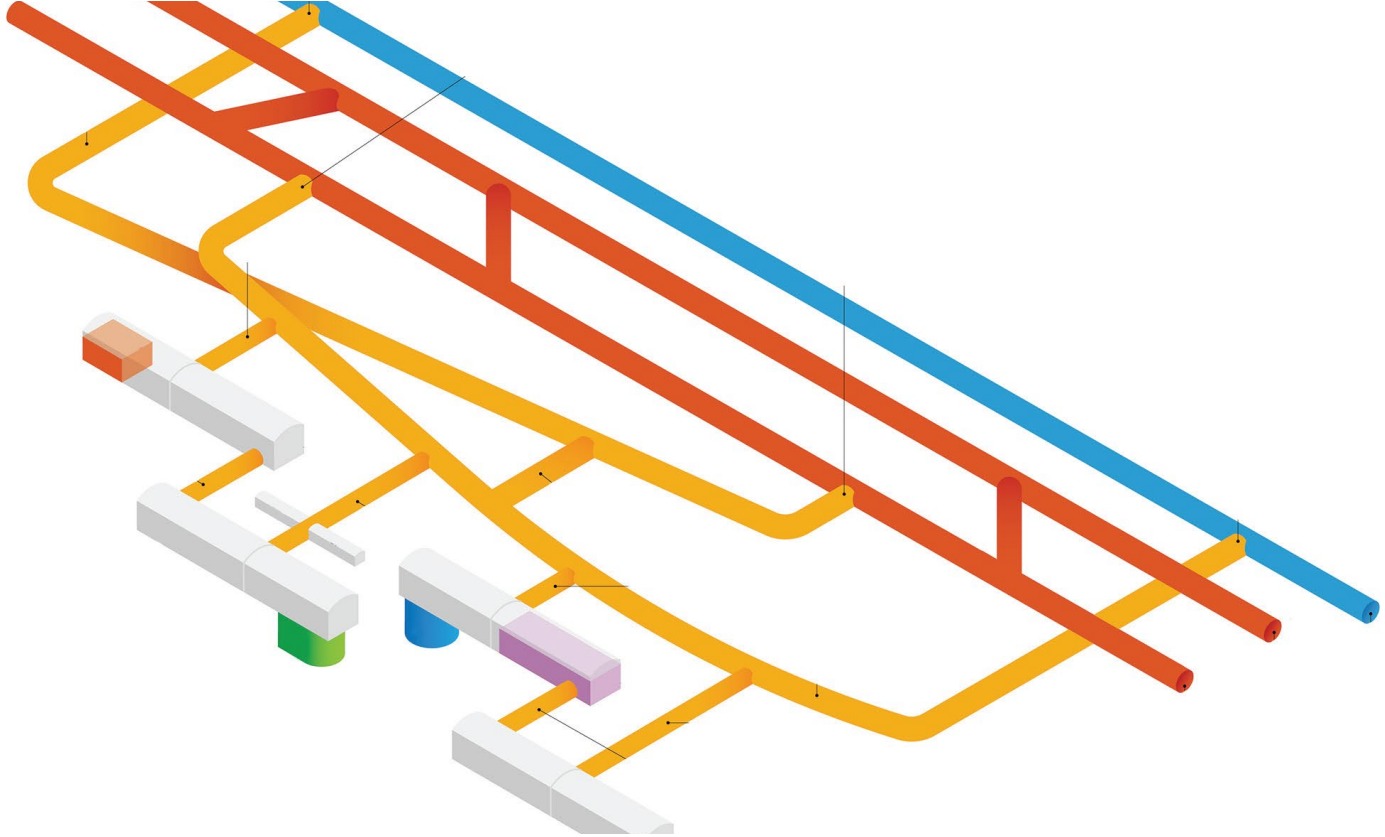
Many R&Ds are ongoing !

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

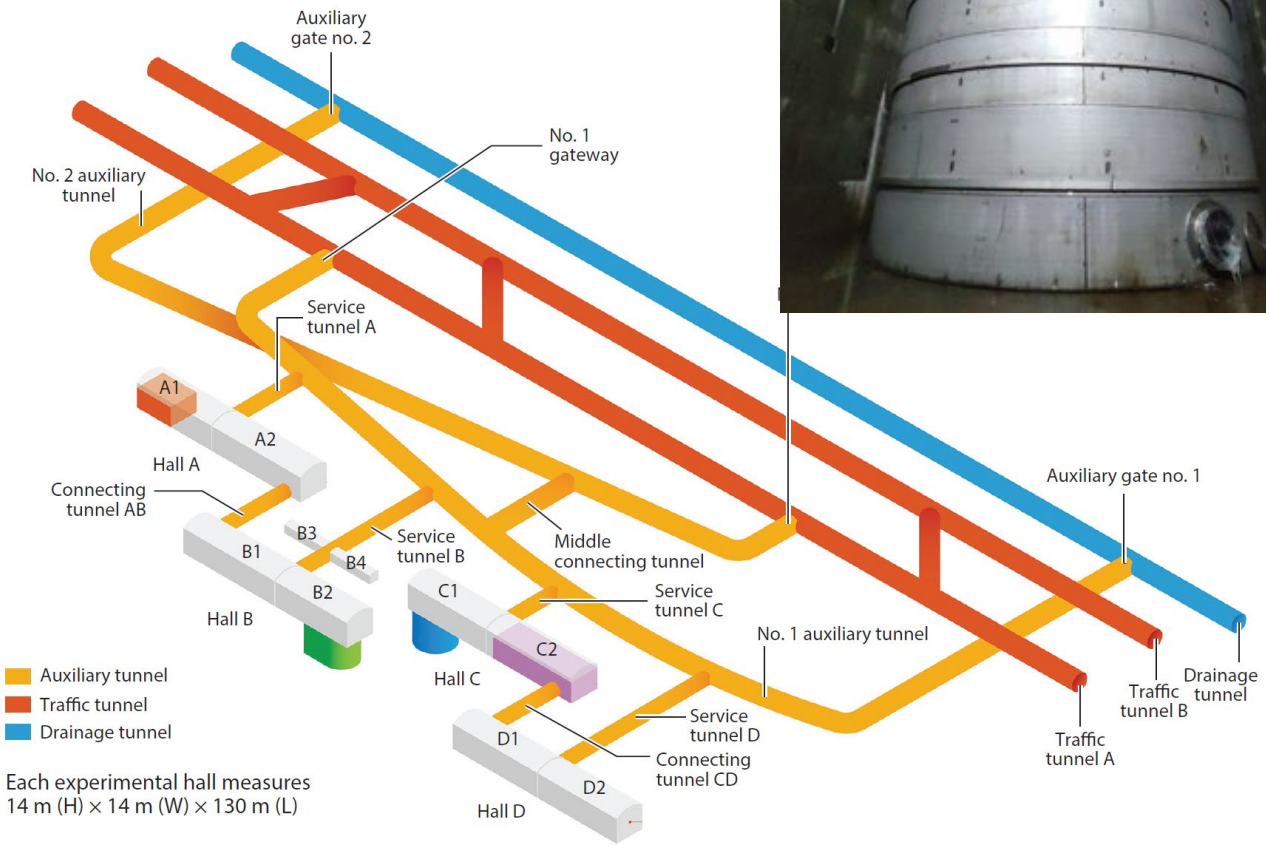


NLDBD searches at CJPL-II

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

CJPL-II: deepest underground lab

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

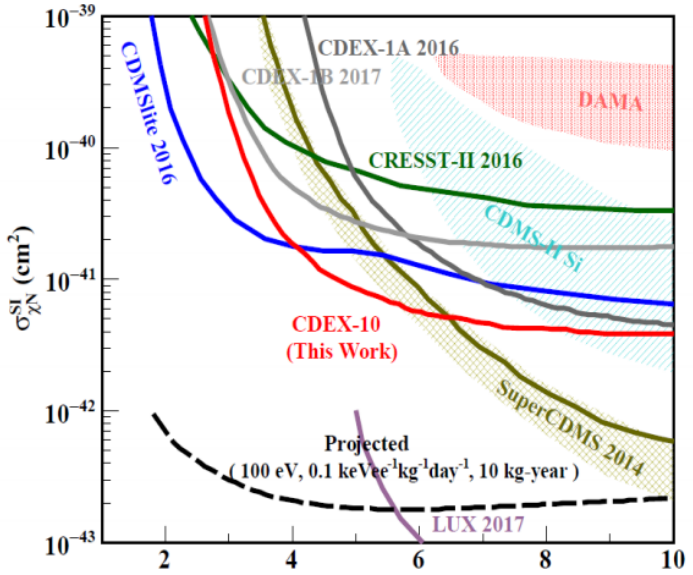


CDEX: Pursuing DM and NLDBD

CDEX-10:

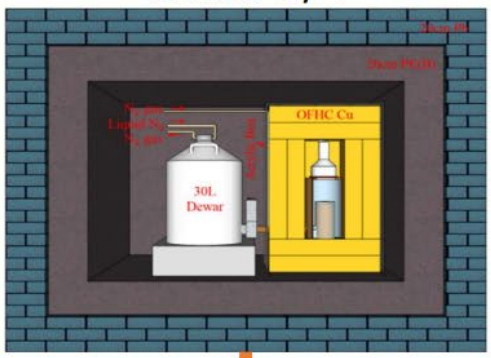
- Array detectors: 3 strings with 3 detector each, ~10kg total;
- Direct immersion in LN_2 ;
- Prototype system for future hundred-kg to ton scale experiment
- Light/radio-purer LN2 replacing heavy shield i.e. Pb/Cu;
- Arraying technology to scalable capability;

CDEX-10: ~10kg PPC Ge array

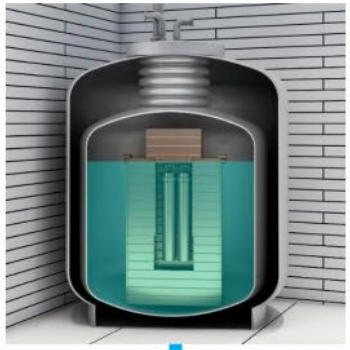


CDEX Roadmap

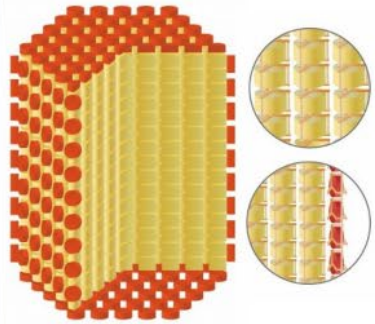
CDEX-1A/B



CDEX-10



CDEX-100 / CDEX-1T



CJPL-I

2011

- ❑ PPC Ge detector with a mass of up to ~1 kg
  - ✓PRD88, 052004, 2013
  - ✓PRD90, 032003, 2014
  - ✓PRD90, 091701, 2014
  - ✓PRD93, 092003, 2016
  - ✓PRD95, 052006, 2017 (Axion)
  - ✓Sci. China (2017) (0νββ)
  - ✓CPC42, 023002, 2018

2016

- ❑ 10 kg PPC Ge detector array immersed into LN_2
  - ✓PRL120, 241301, 2018

CJPL-II

202X

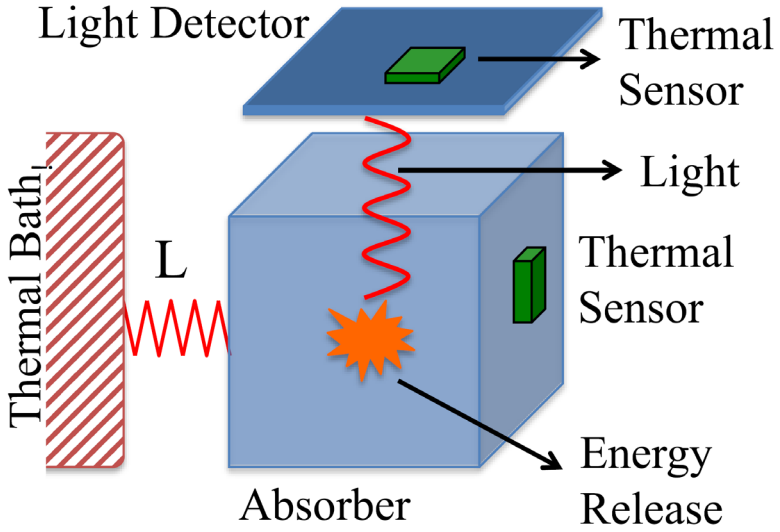
- ❑ Ge array in large-volume LN_2
- ❑ multi-purpose: DM and 0νββ

Key technologies:

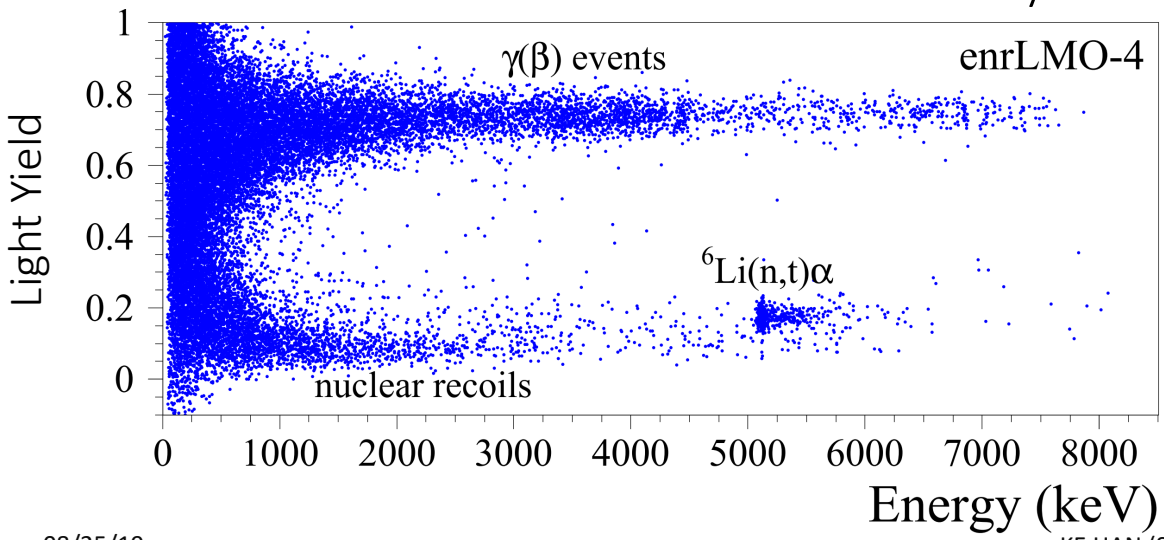
- ✓Ge crystal growth and ^{76}Ge enrichment
- ✓Ge detector fabrication
- ✓Ultra-low background VFE
- ✓Ultra-pure copper for structure and cables
- ✓Natural Ge detectors as veto
- ✓……

From LT Yang

CUPID-China

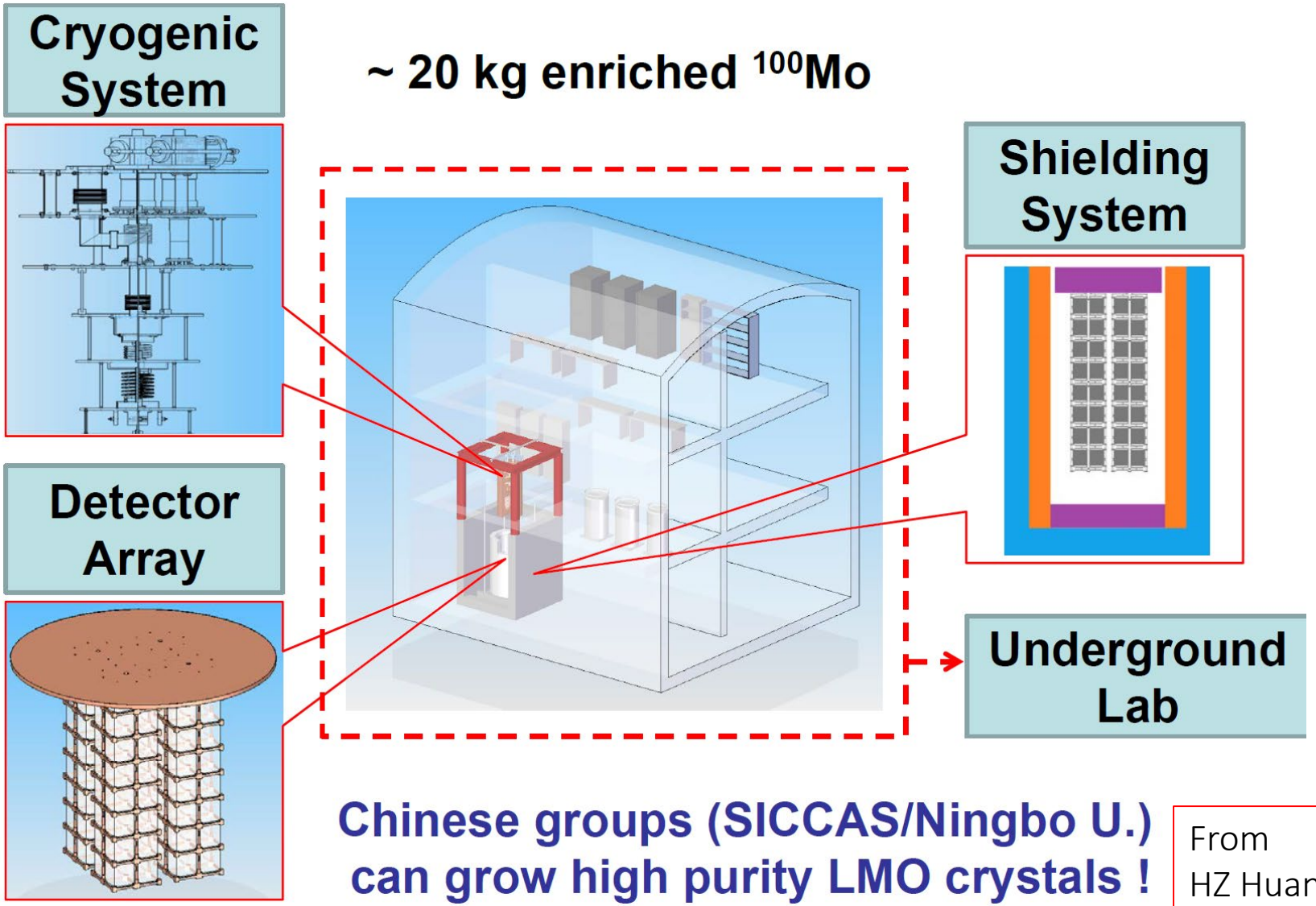


- Light and heat readout with two bolometer setups for one crystal
- $LiMoO_4$ scintillating bolometer arrays
- Particle ID to reject alpha background
- High Q-value (3.0 MeV) for low gamma background
- Technical development in the next 3-5 years



CUPID-France
Andrea Giuliani
@CSNSM Orsay

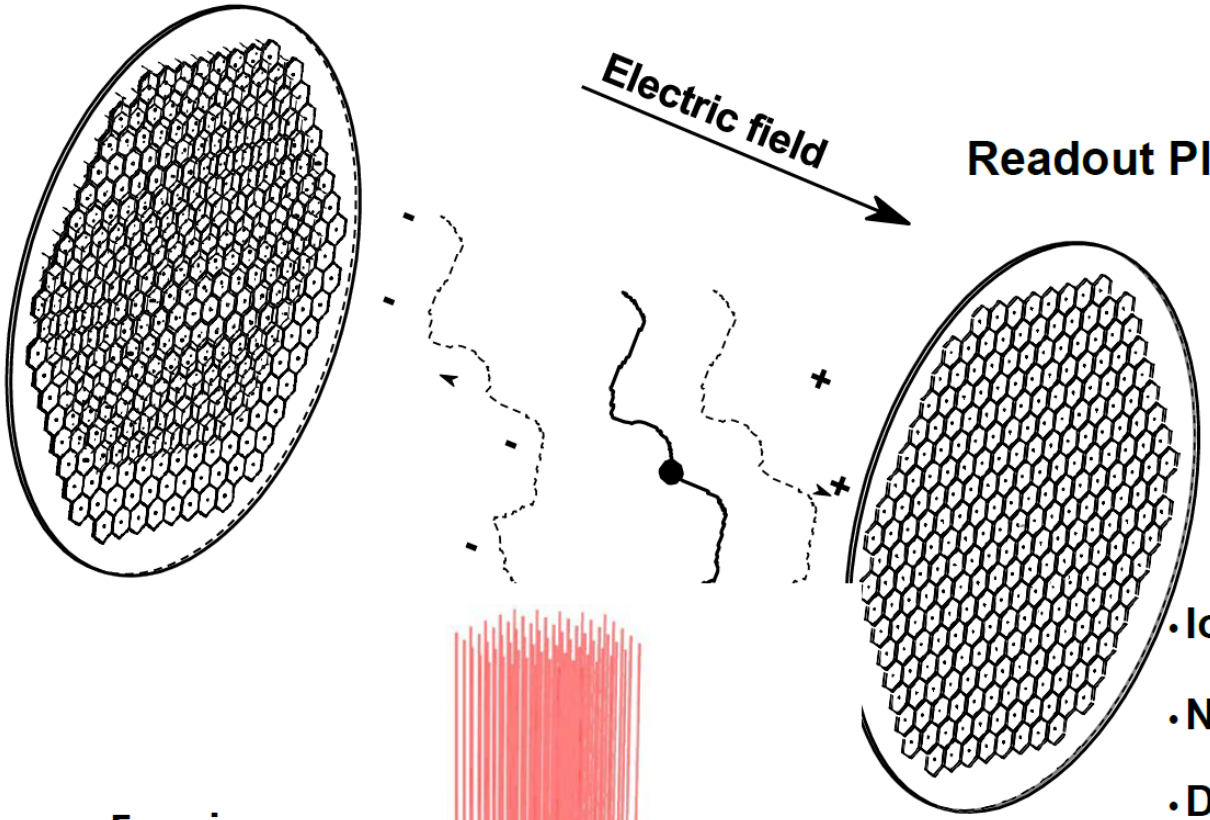
CUPID-China concept

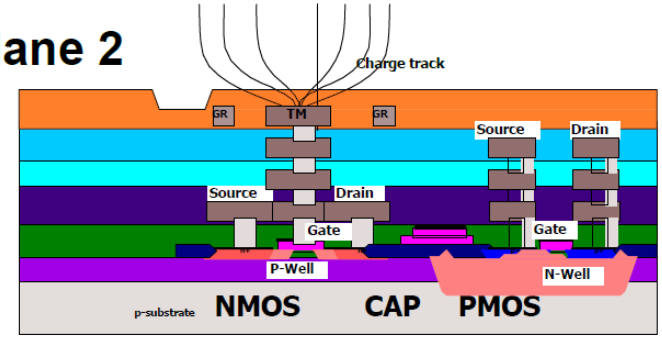


NvDeX: gain-less charge readout with TopMetal in $^{82}SeF_6$

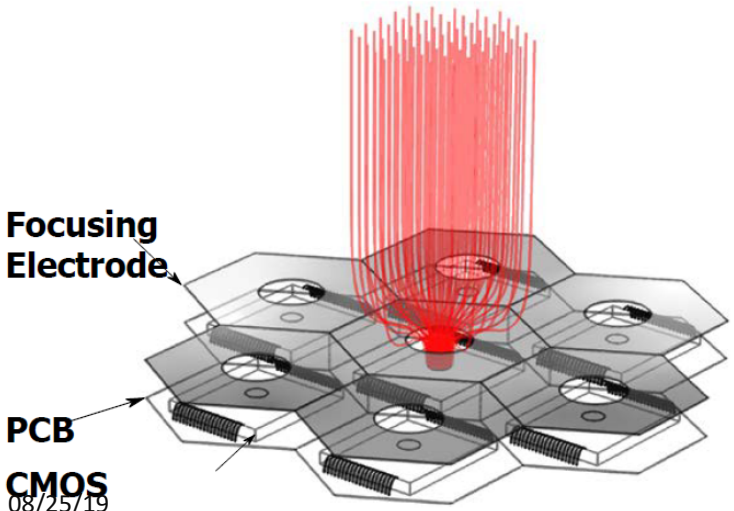
Readout Plane 1

Concept paper:
arXiv:1801.04513 [physics.ins-det]





- Ion drifting
- No charge amplification
- Direct charge collection in X-Y
- Z isdetermined by the +/- charge arrival time difference



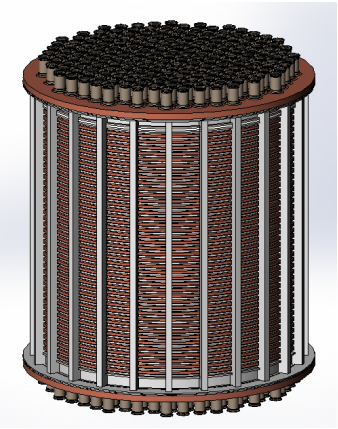
LBNL and CCNU et al

Thanks to Xiangming Sun from CCNU

PandaX Projects

PandaX-I: 120kg LXe
(2009 – 2014)

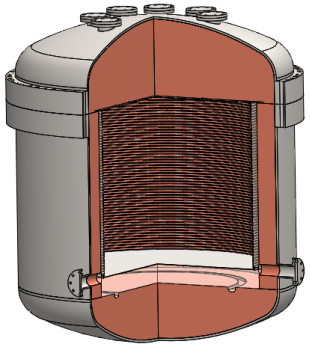
PandaX-II: 500kg LXe
(2014 – 2018)



PandaX-xT LXe
(future)

Dark matter WIMP searches

PRL 117, 121303 (2016)

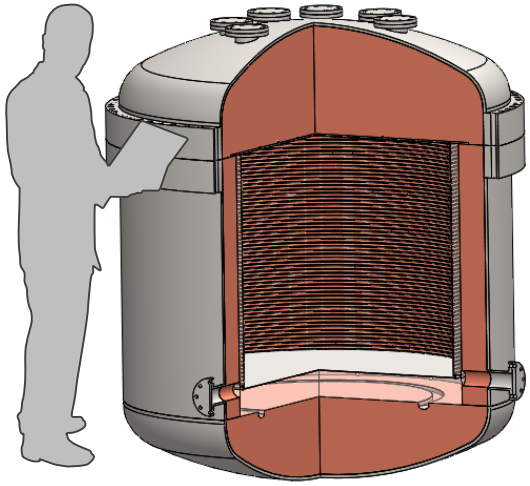


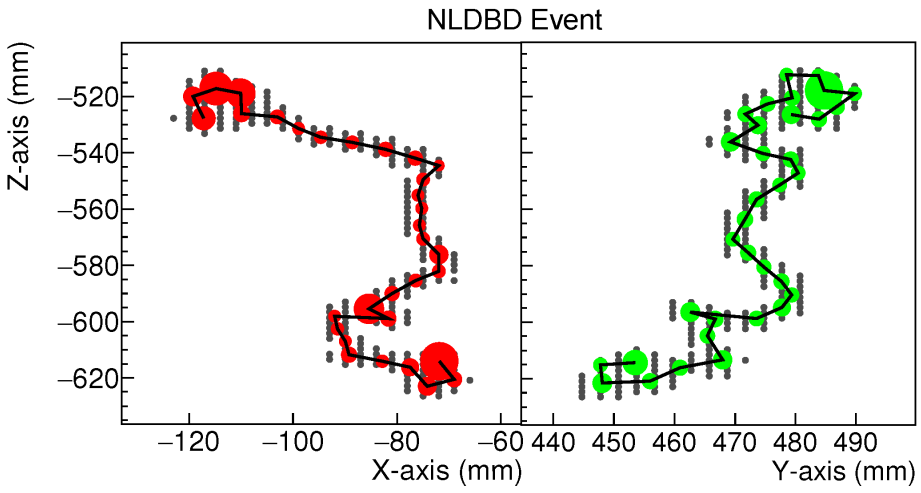
PandaX-III:
200kg - 1 ton HPXe (future)

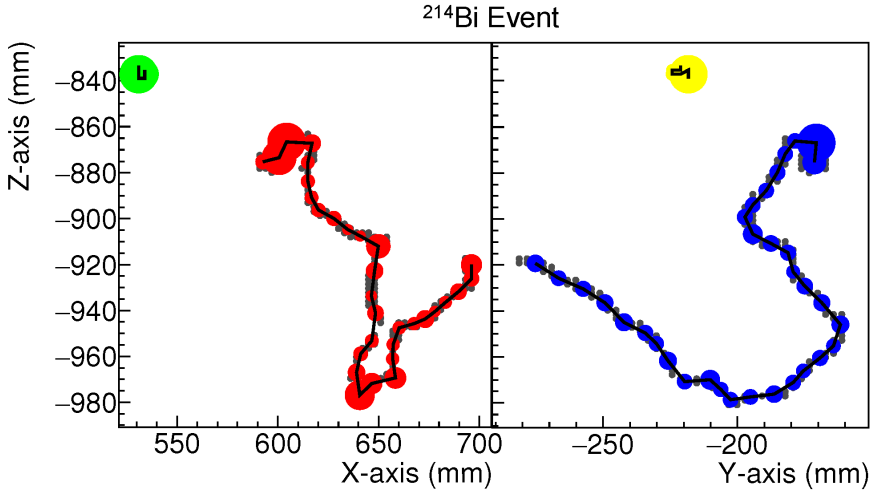
0νββ searches

PandaX-III: high pressure gas TPC for 0νββ 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).

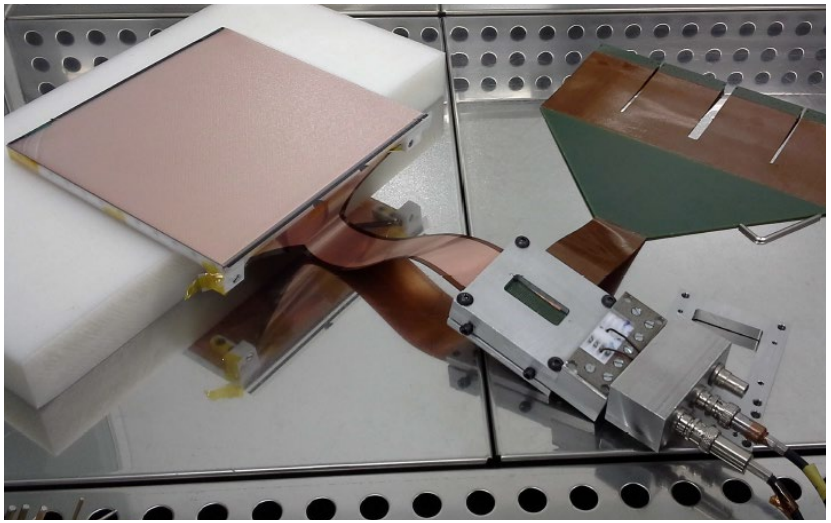


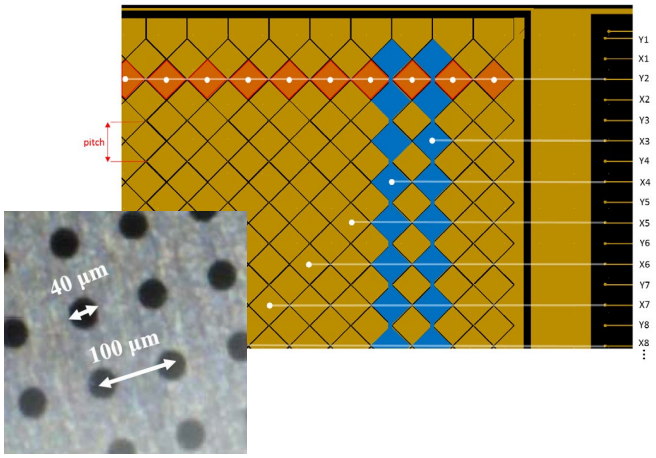


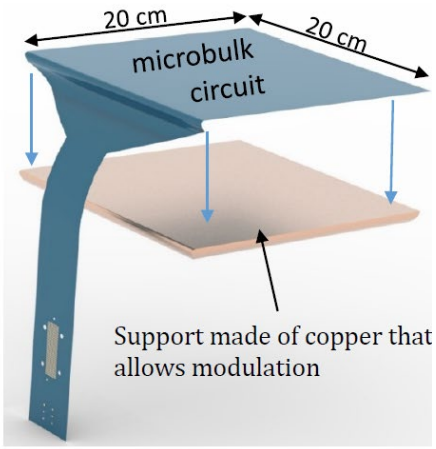


Readout plane

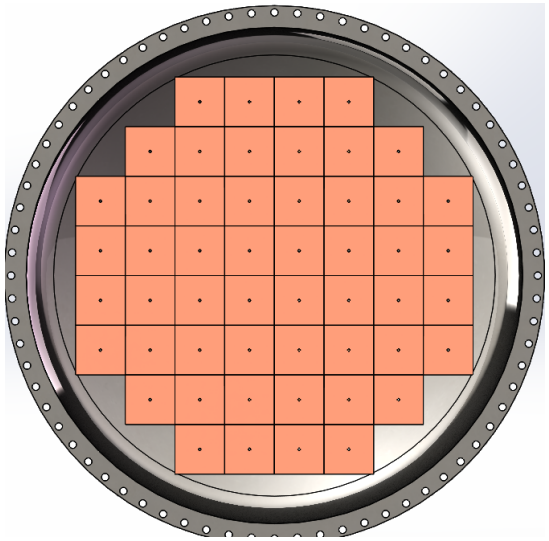
- Microbulk MicroMegas films made of Copper and Kapton only
  - Perfect for radio-purity purpose
  - 20 by 20 cm
  - 3 mm pitch size, 128 strip readouts
- Mosaic layout to cover readout planes





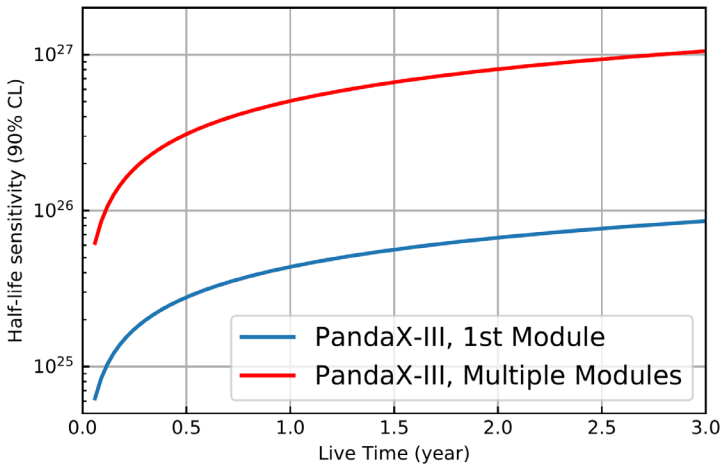


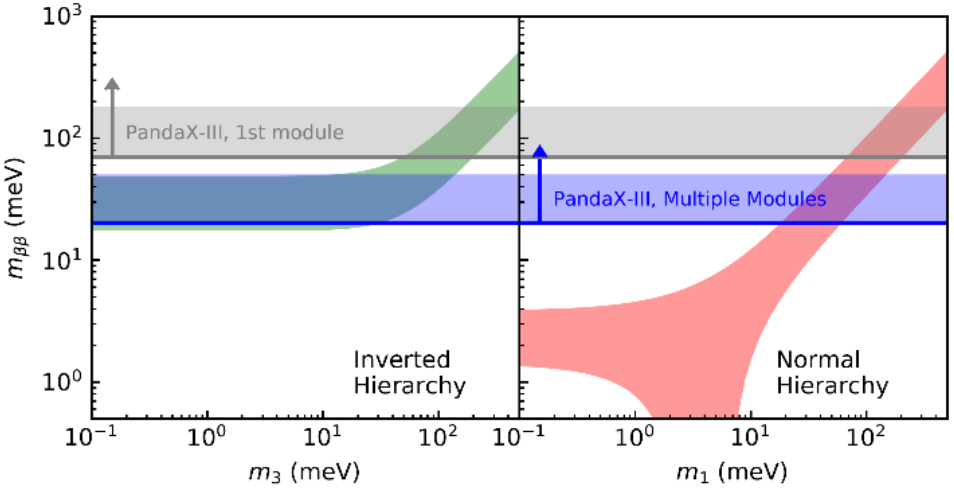
× 52



Status and Sensitivity

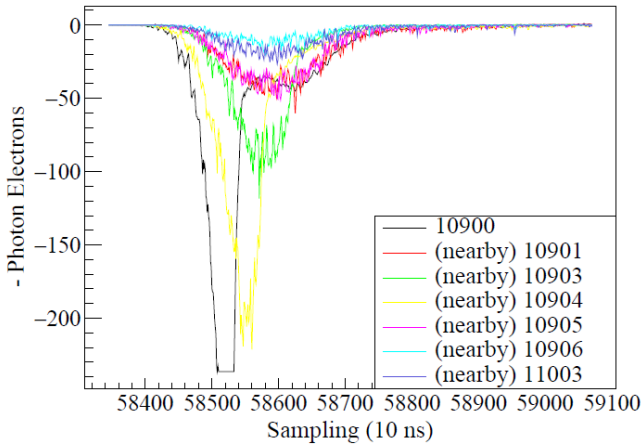
- A 20-kg scale prototype TPC is running (arXiv:1804.02863)
- 1st 100-kg scale module to commission in 2020
- Half-life sensitivity with 3 years of data: 9× 10^{25} yr (90% CL)

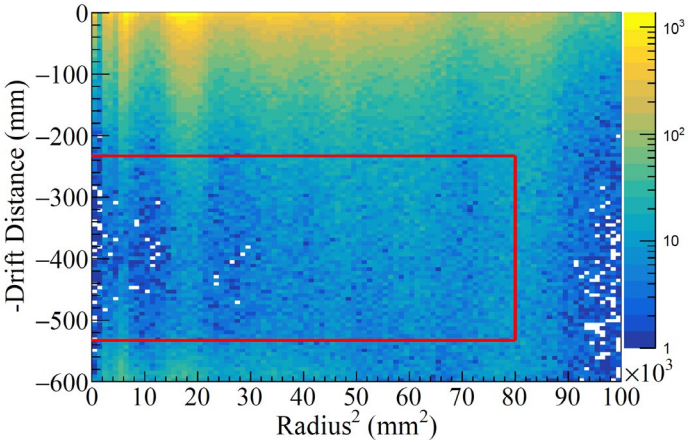


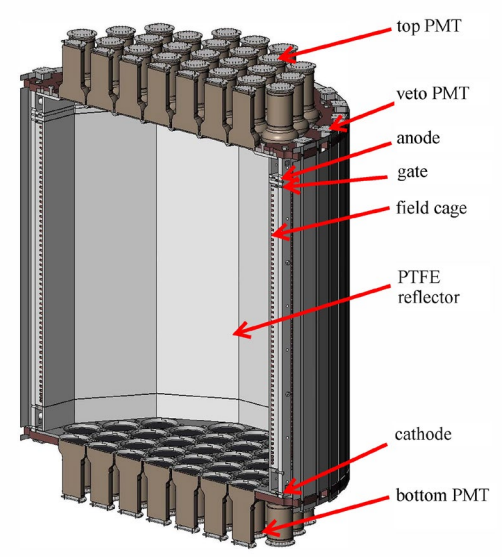


NLDBD in PandaX LXe TPC

- PandaX-II: 580 kg of ^{nat}Xe in the active volume
- A total of 403.1 days of data.
- MeV scale NLDBD signal vs. keV DM signal
- S2 Energy reconstruction with bottom PMT
- Optimize all cuts for event selections

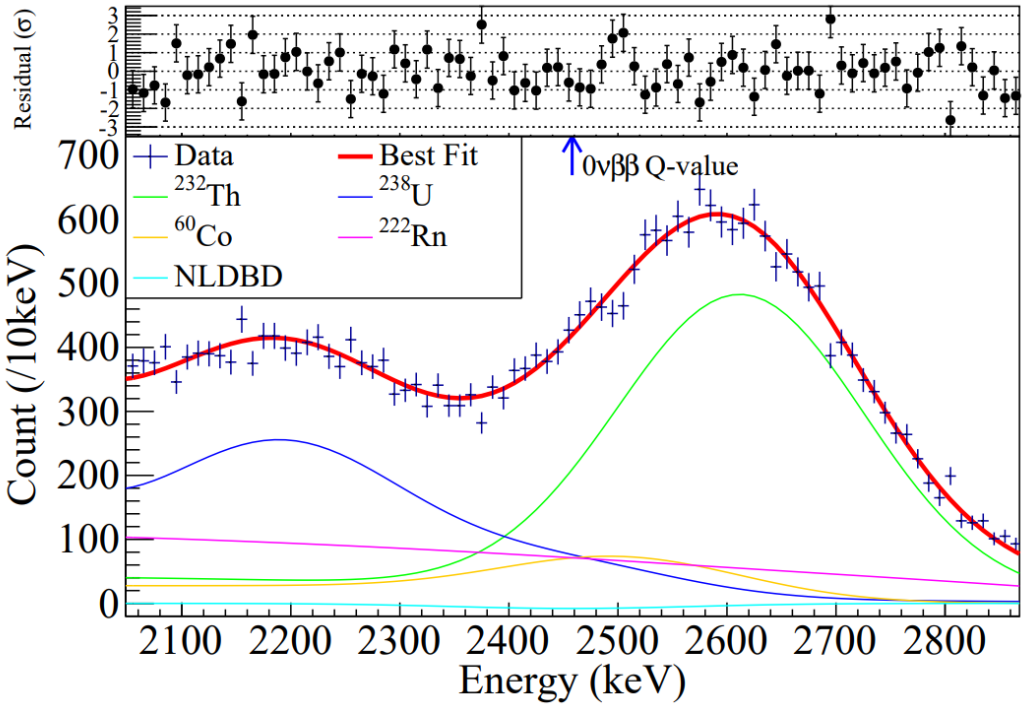






Data set	Begin	End	Live days
Run 9	Mar. 9, 2016	Jun. 30, 2016	79.6 d
Run 10	Apr. 22, 2017	Jul. 16, 2017	77.1 d
Run 11	Jul. 17, 2017	Aug. 16, 2018	246.4 d

Final spectrum fit for PandaX-II data

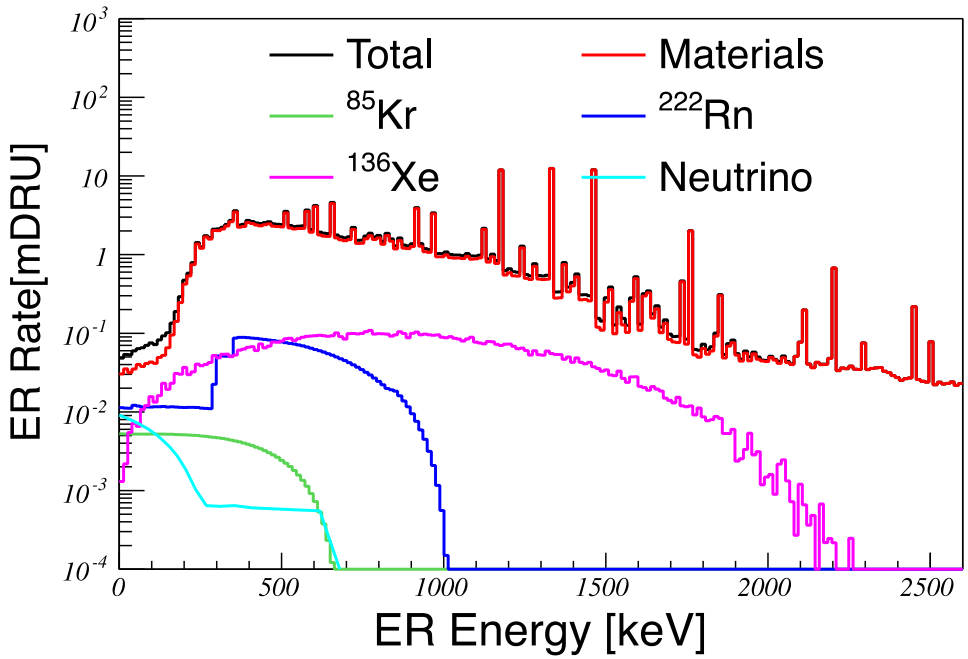


- Energy resolution: 4.2%
- Null results. Lower limit for decay half-life of 2.4×10^{23} yr at the 90% confidence level
- Effective Majorana mass upper limit: 1.3-3.5 eV.
- First NLDBD result reported from a dual-phase xenon experiment

arXiv:1906.11457; submitted to Chinese Physics C

PandaX-4T for NLDBD

- Dual-readout PMT base in initial R&D
  - MeV and keV signals are readout from a middle dynode and the last dynode.
- Optimize sensitivity with more aggressive fiducial cuts
- Expected half-life sensitivity is at EXO-200 level (3×10^{25}yr)

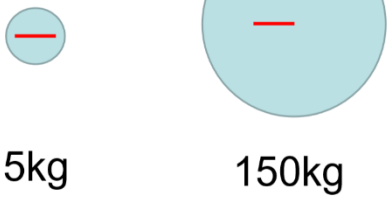


Self-shielding with future generations

Moving forward, monolithic is key

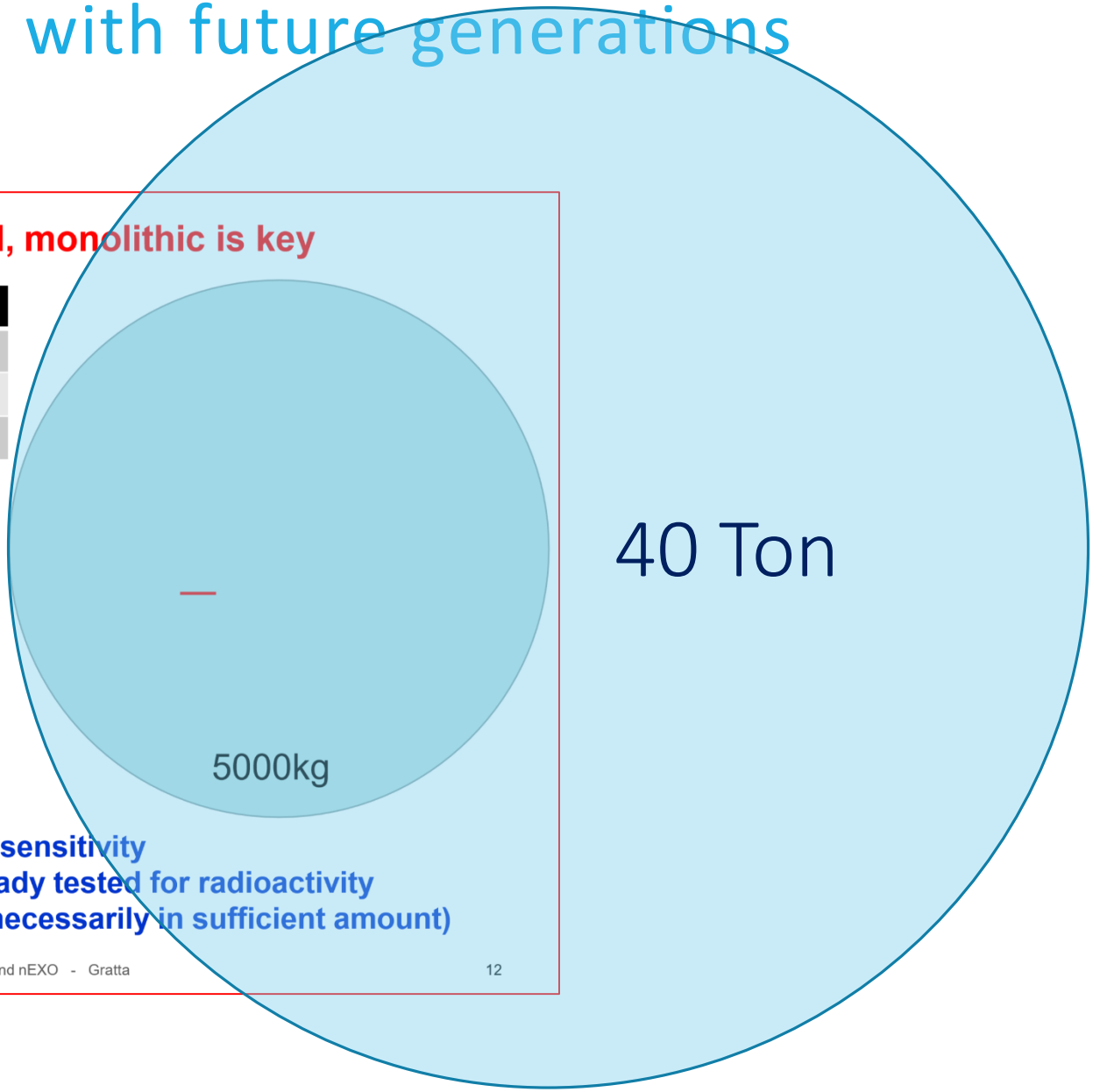
LXe mass (kg)	Diameter or length (cm)
5000	130
150	40
5	13

2.5MeV γ attenuation length 8.5cm = —



The current estimate of the nEXO sensitivity relies only on materials already tested for radioactivity and on hand (although not necessarily in sufficient amount)

Neutrino 2018, Jun 2018 EXO-200 and nEXO - Gratta 12



Summary: Next-generation experiments

- Worldwide consensus about importance of "ton-scale" NLDBD experiments
  - US: 2015 Long Range Plan; DOE CD-0 for NLDBD (2018)
  - Europe: APPEC prioritization
  - Initiatives in Asia (China, Korea)
- Stated sensitivity goals: inverted hierarchy region
  - $T_{1/2}>10^{27}$ years, $m_{\beta\beta}<15$ meV
- Readiness for construction: early 2020s

From Yury Kolomensky

Summary: Chinese efforts

- CJPL-II, a State Major Research Infrastructure, provides tremendous opportunities for NLDBD
  - CDEX; CUPID-China; NvDEX
- PandaX searches for 0νββ of ^{136}Xe with gas and liquid TPCs
  - First result from dual-phase xenon TPC
  - High pressure TPC for tracking reconstruction