FLASY2019: 8th Workshop on Flavor Symmetries and Consequences in Accelerators and Cosmology

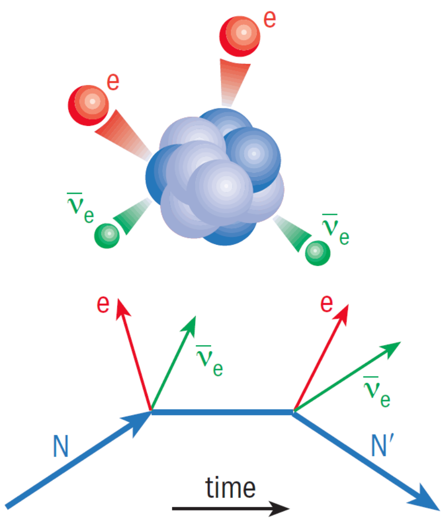
# Neutrinoless Double Beta Decay Searches: Status and Prospects

Ke Han (韩柯)
Shanghai Jiao Tong University
07/18, 2019

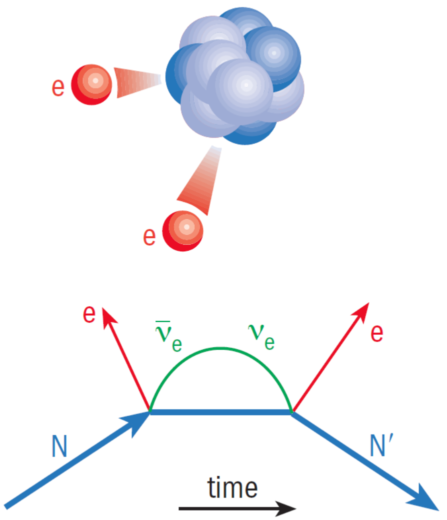
# Outline

- 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

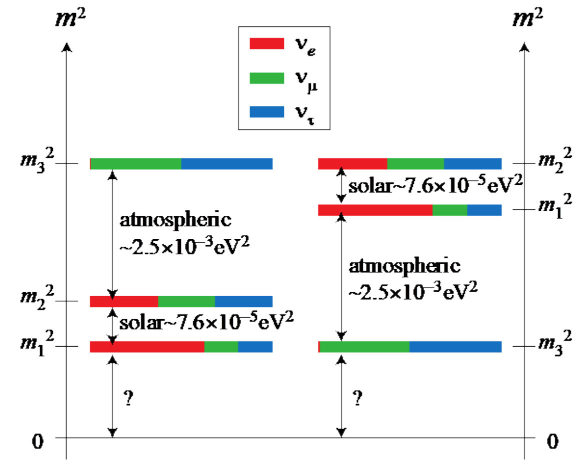
1933, Fermi

Beta decay theory

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

# NLDBD probes the nature of neutrinos

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




Normal Inverted

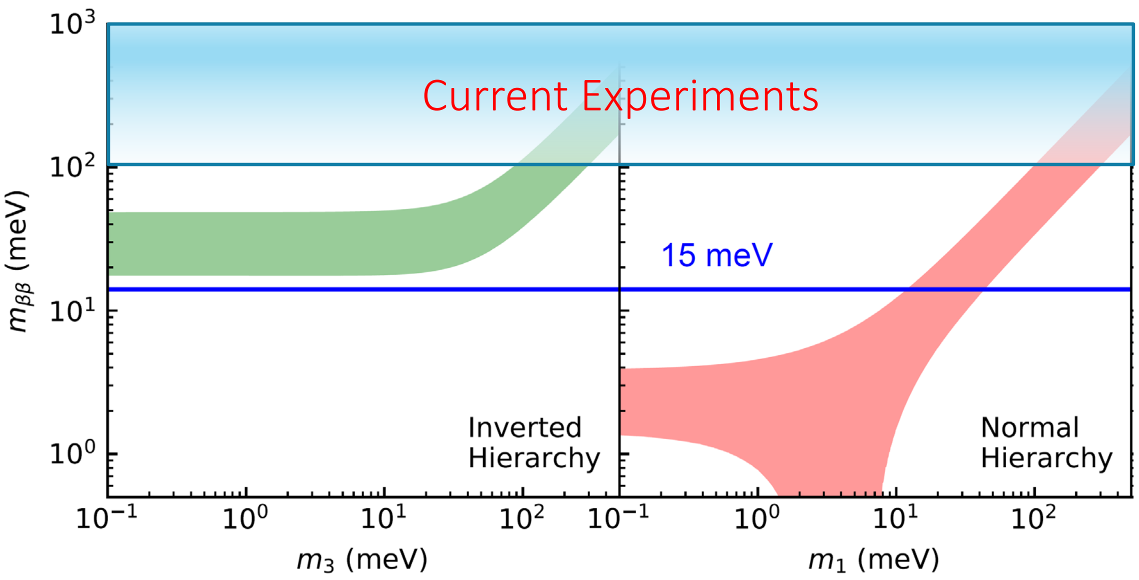
$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}(Q,Z)\ |M^{0\nu}|^2\ \frac{|\langle m_{\beta\beta}\rangle|^2}{m_e^2}$$

Phase space factor

Nuclear matrix element

Effective Majorana neutrino mass:

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



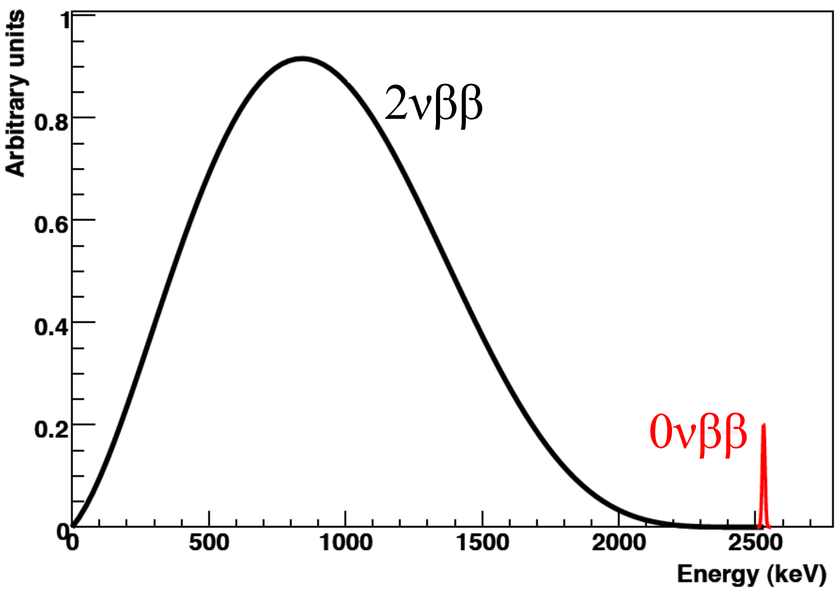
# Detection of double beta decay

- Examples:

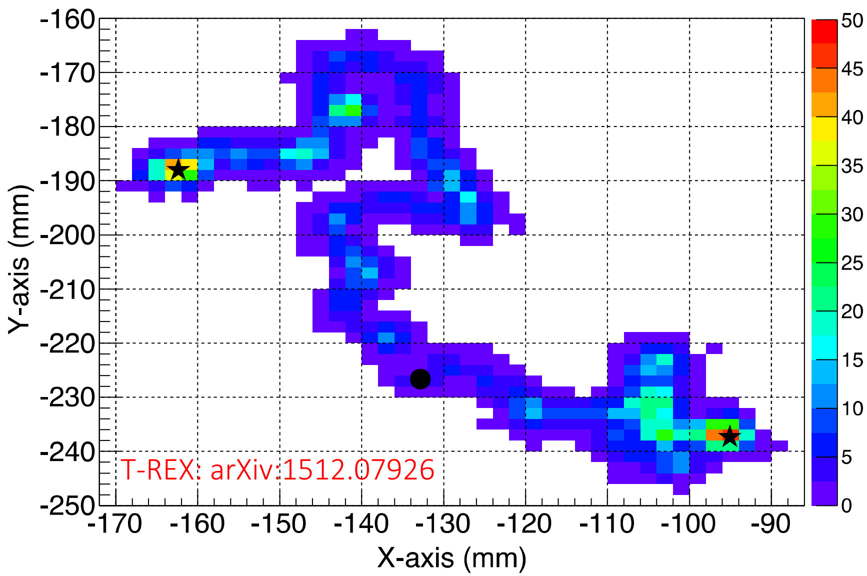
$$^{136}_{54}Xe \rightarrow ^{136}_{56}Ba + 2e^- + (2\bar{\nu})$$

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

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



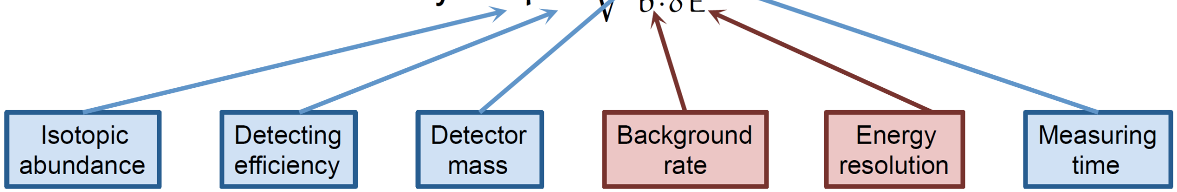

Sum of two electrons energy



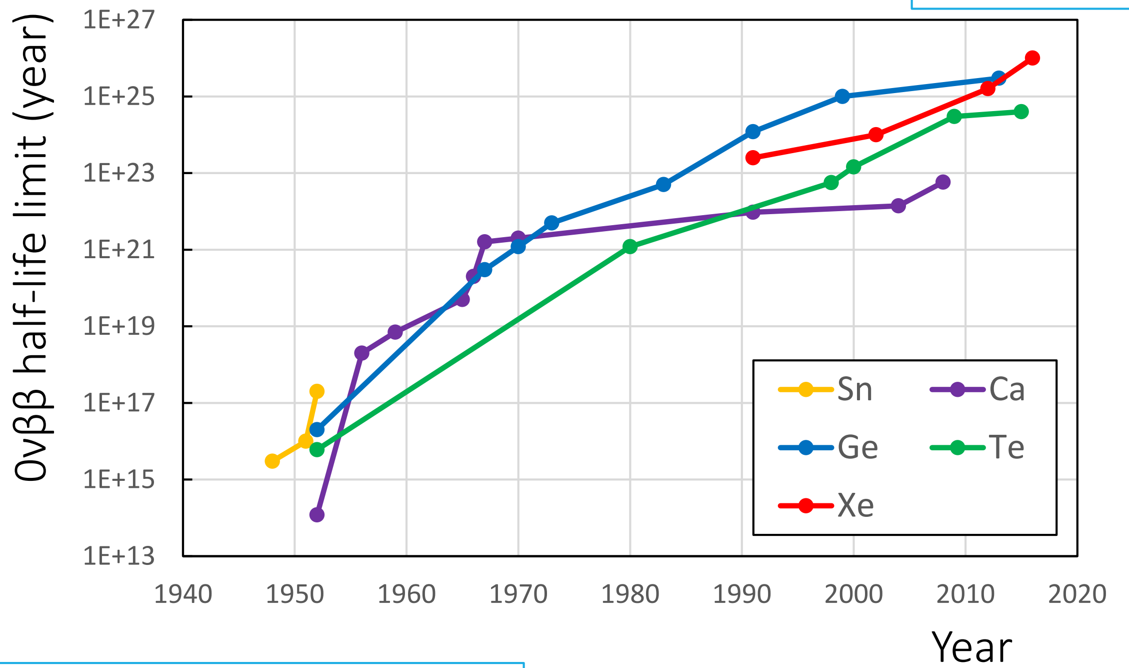

Simulated track of 0νββ in high pressure Xe

# Impressive experimental progress

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



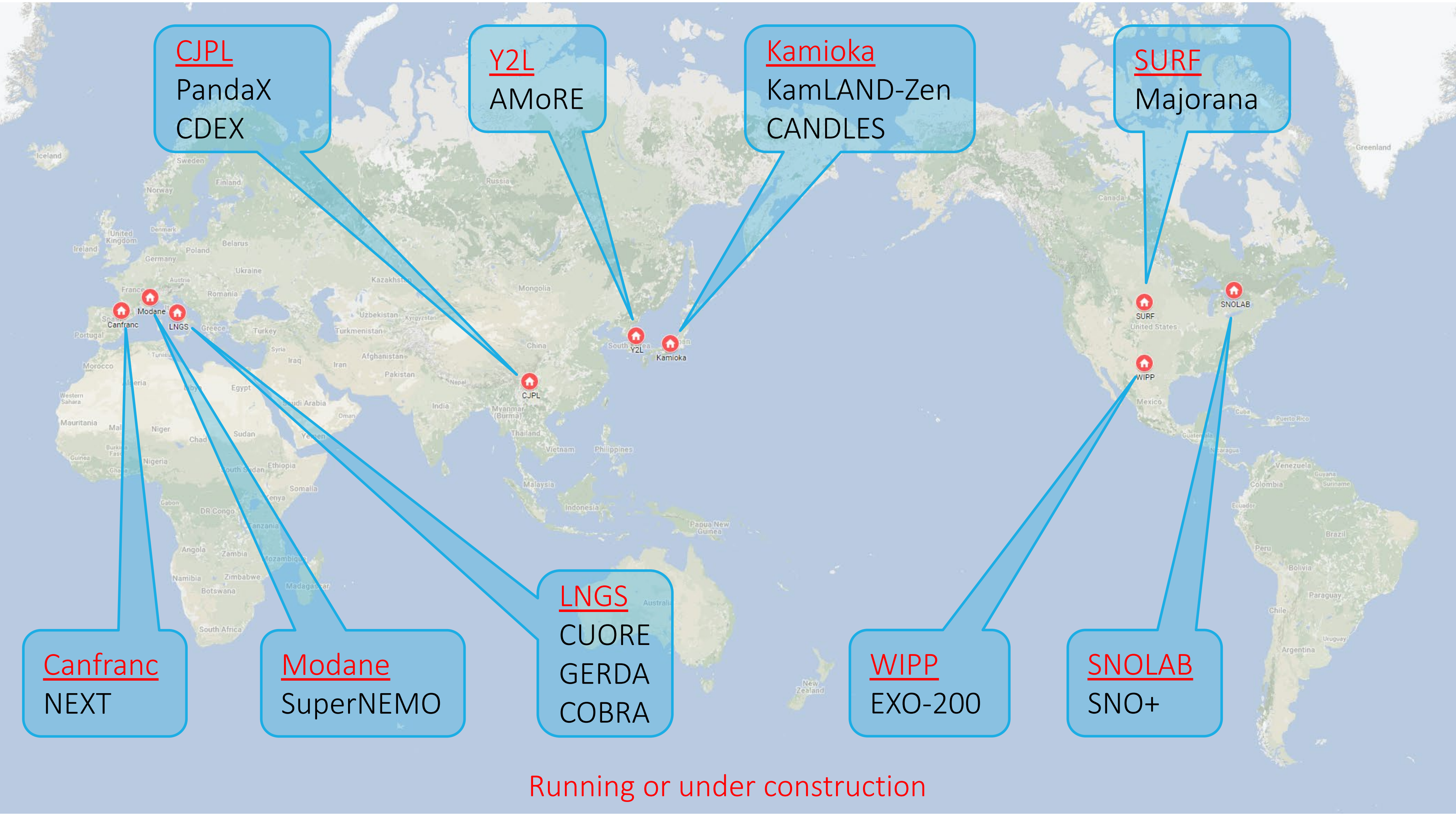

- ~100 kg of isotopes
- ~100-person collaborations
- Deep underground
- Shielding + clean detector




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

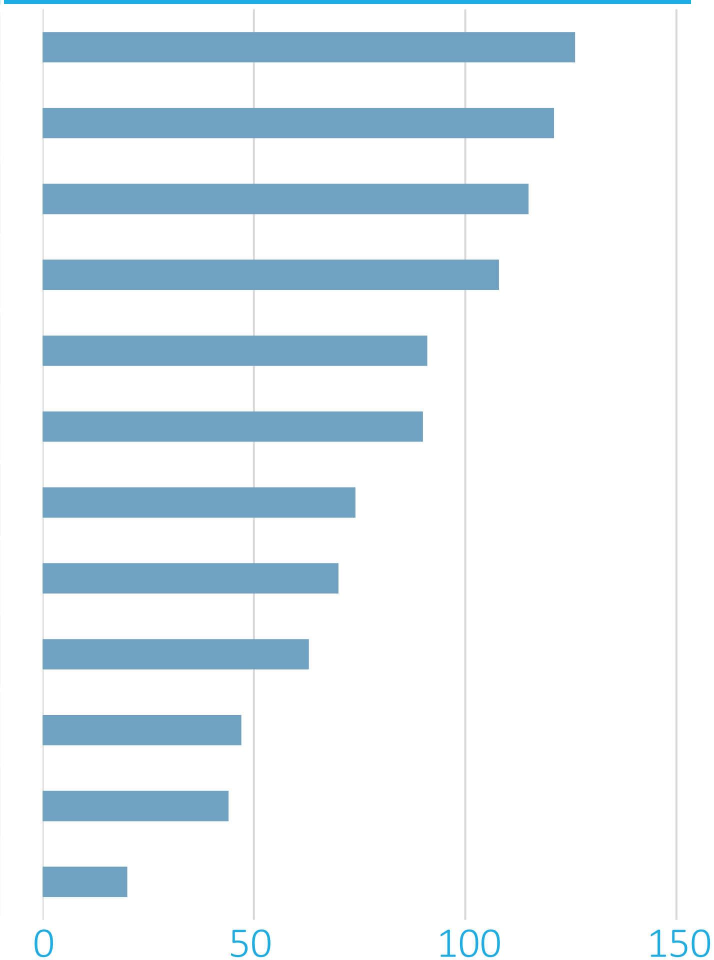
Partial list of selected isotopes; Pre-1984 data points from review article by Haxton and Stephenson, Jr.

# Major 0νββ experiments around the world



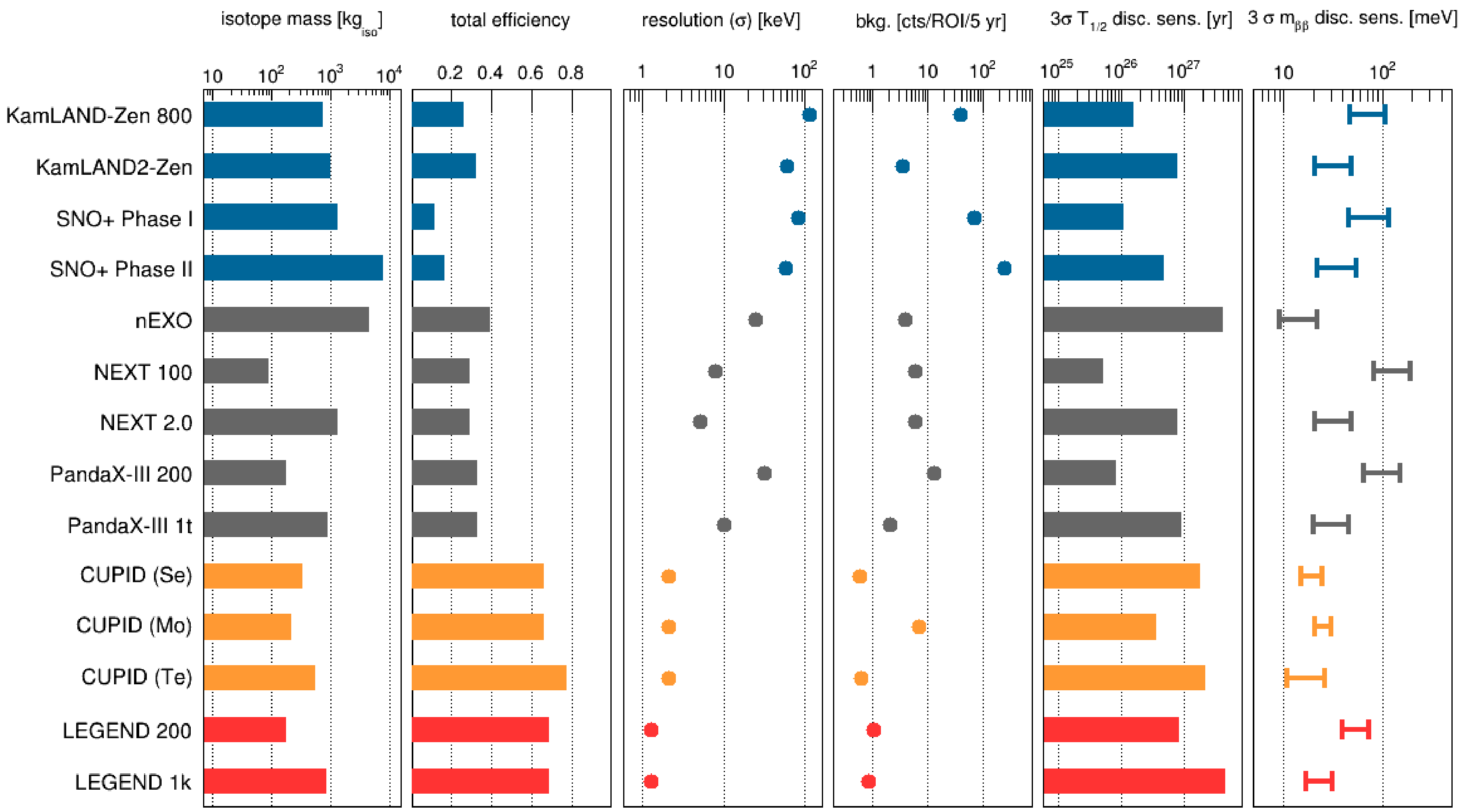
# A large community with diverse efforts

| Experiments | Isotopes | Techniques | Number of Signing authors |
|---|---|---|---|
| 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 | |



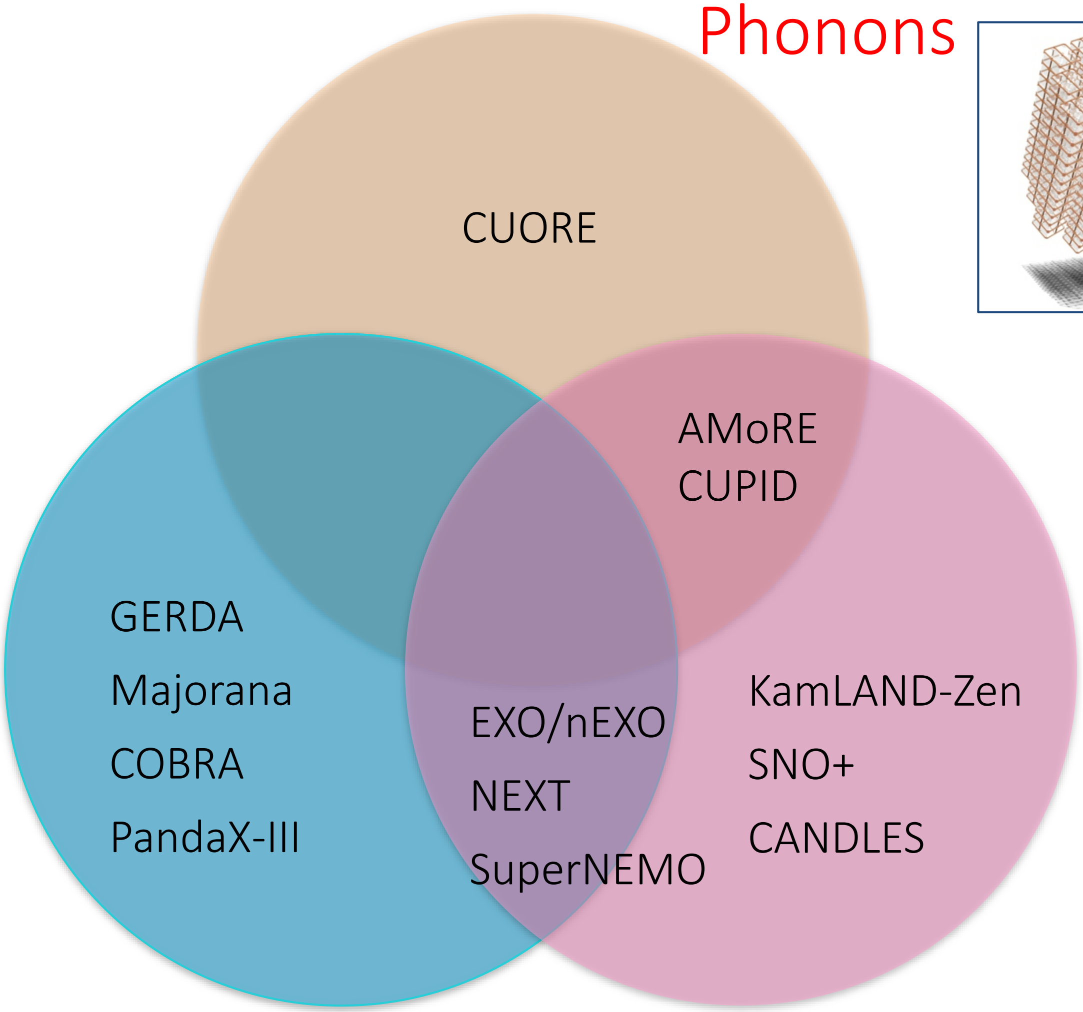

As of 2016/11

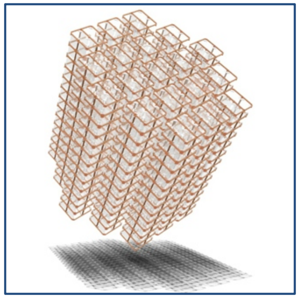
# Future experiments

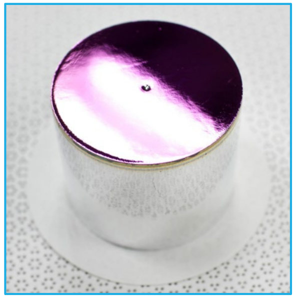


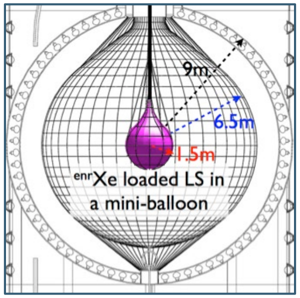

From: Jason Detwiler, et al

# Detection channels



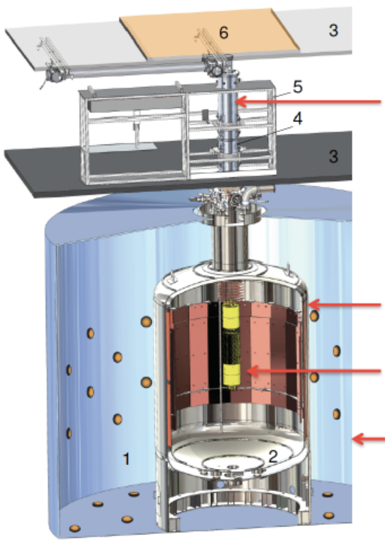



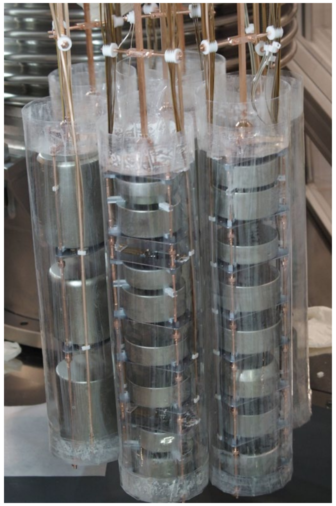




# HPGe detectors ($^{76}Ge$)

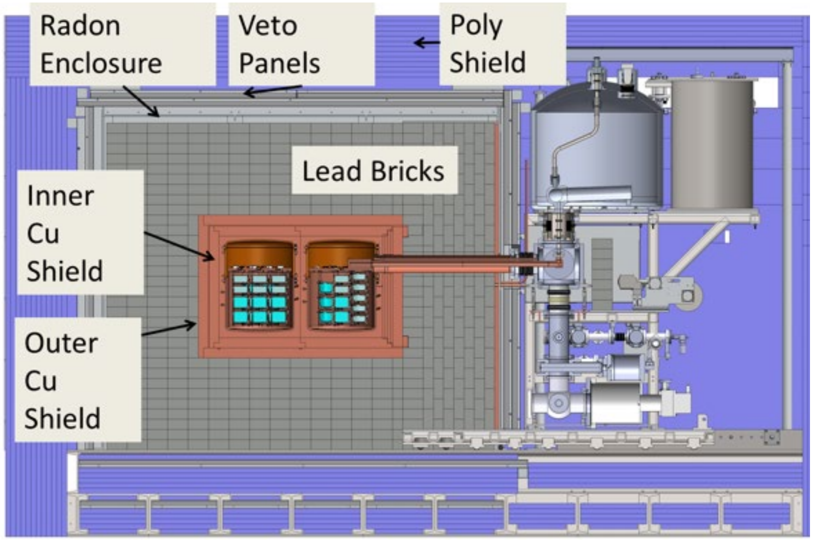
GERDA at LNGS, Italy



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

Majorana Demonstrator at Sanford, US



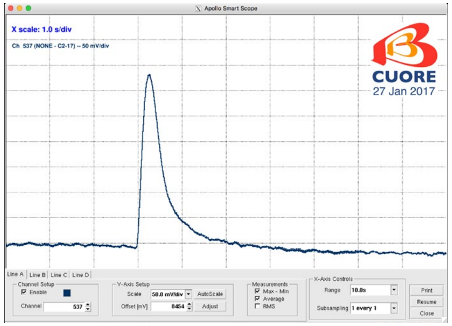

Half-life limit: $2.7 \times 10^{25}$ yr
Bkg: ~$5 \times 10^{-3}$ c/kev/kg/yr (ArXiv:1902.02299)

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: $1.5 \times 10^{25}$ yr




World-largest Dilution Refrigerator

<10mK

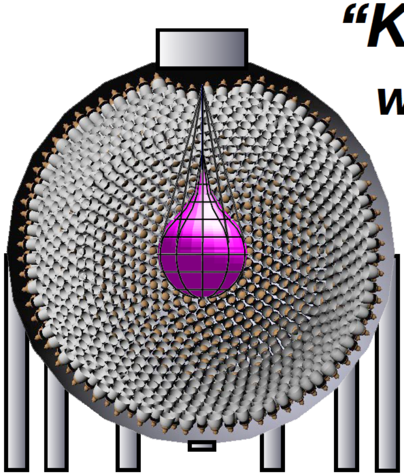
## Future

- 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 $1.07 \times 10^{26}$ yr (90%CL)
- New phase with twice the $^{136}$Xe is under construction.

Future:



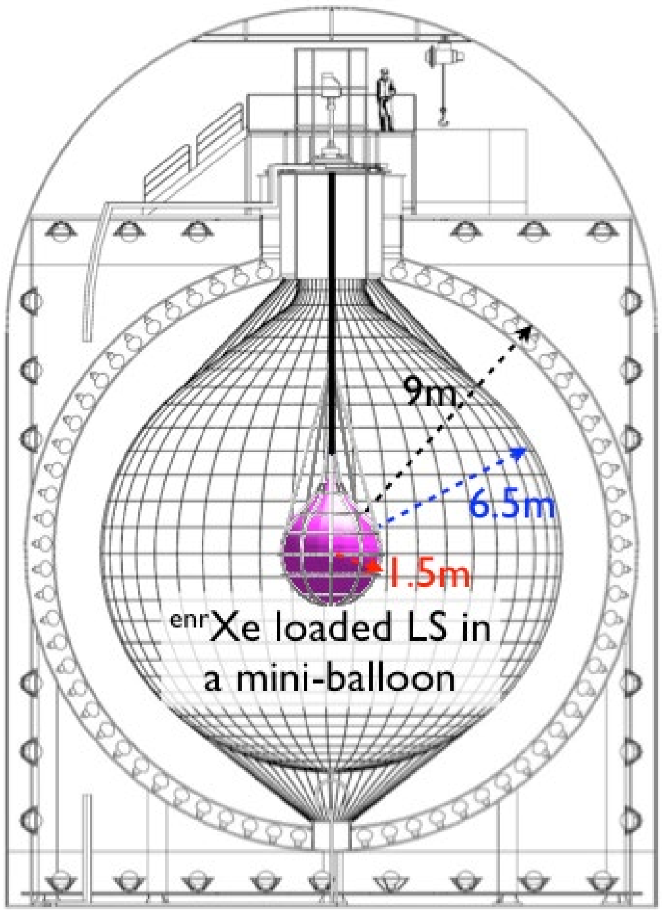
***"KamLAND2-Zen"***

***with 1000kg enriched Xe***

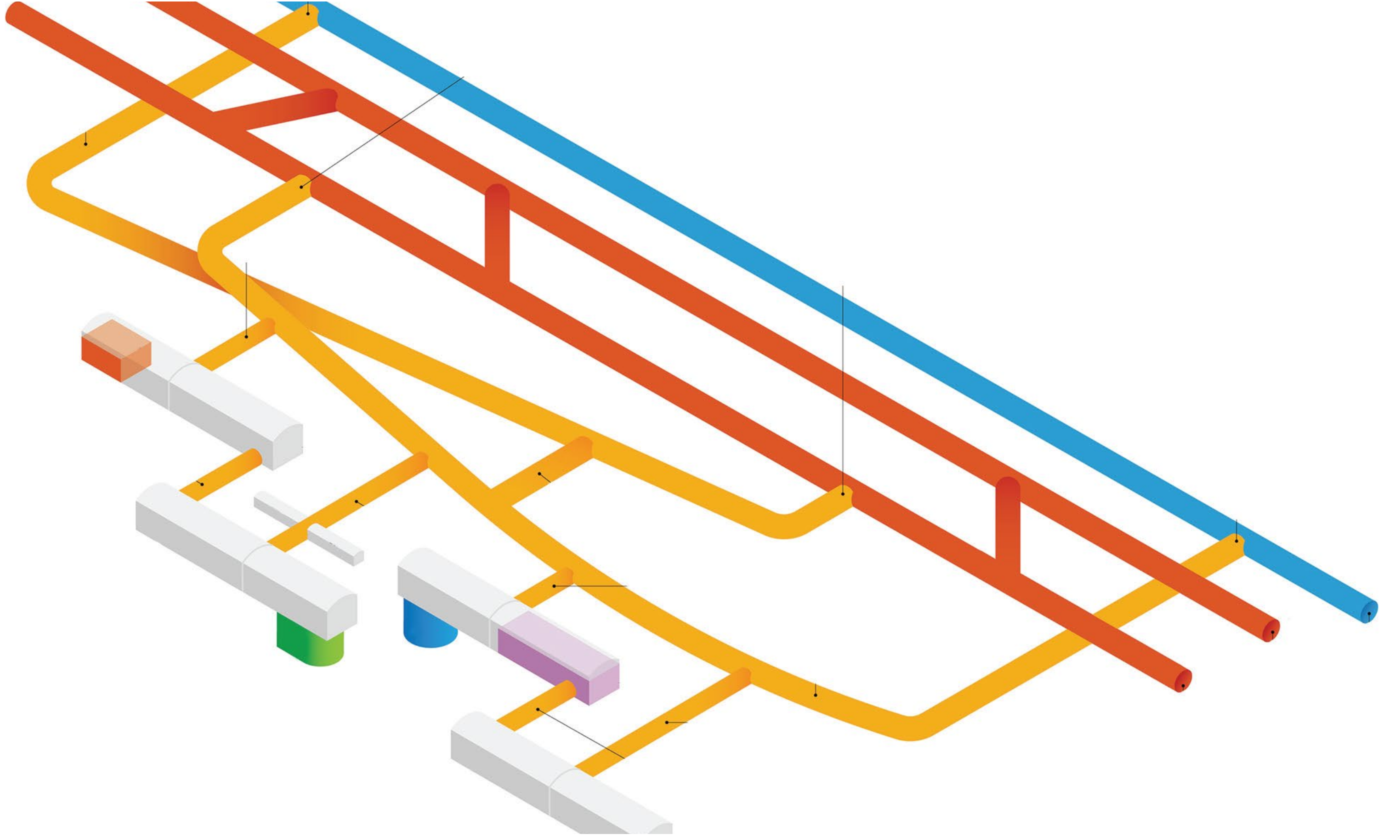
***Many R&Ds are ongoing !***

**More photons for better $\sigma_E$**

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




KamLAND-ZEN

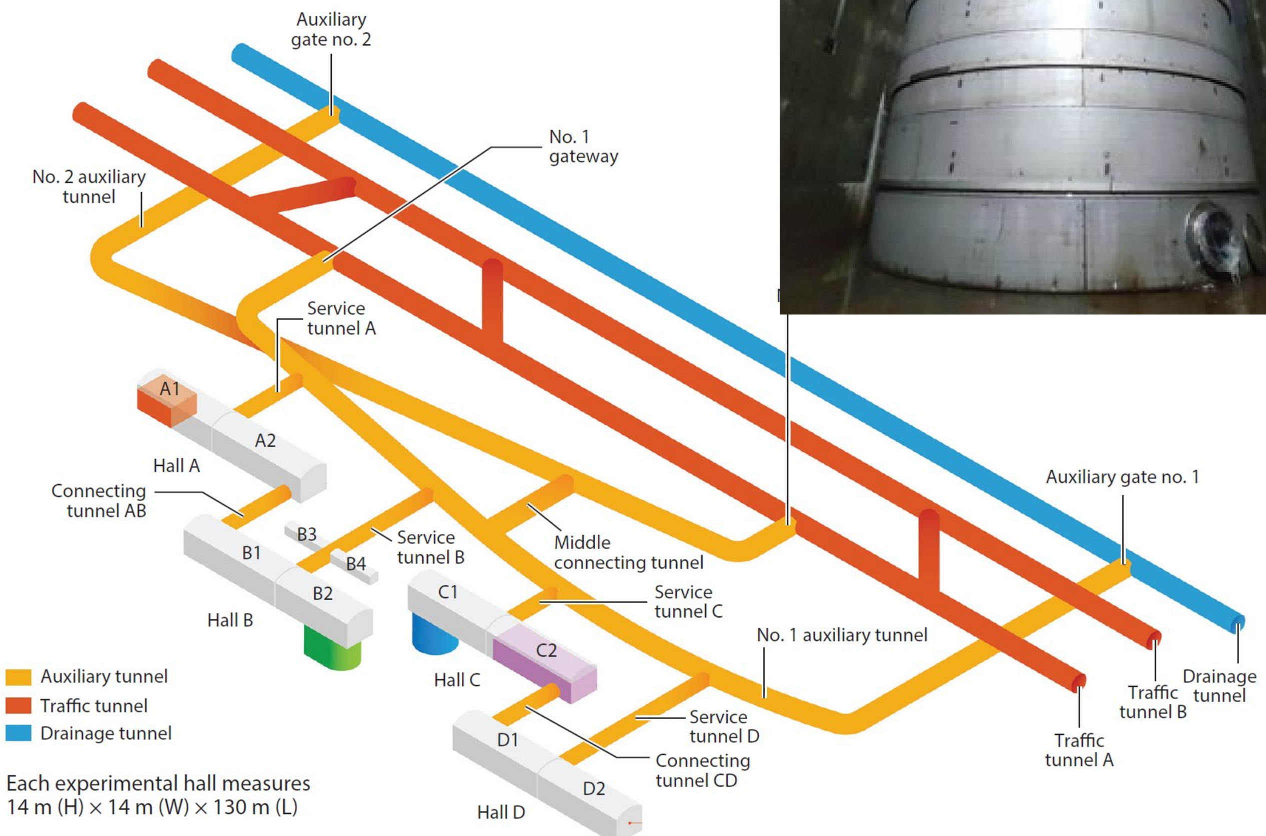


# NLDBD searches at CJPL-II

- 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**

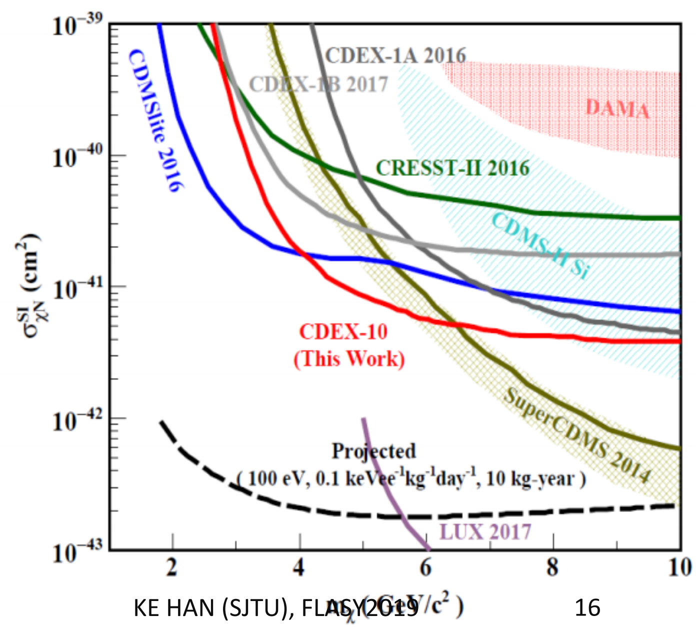



# CDEX: Pursuing DM and NLDBD

CDEX-10:

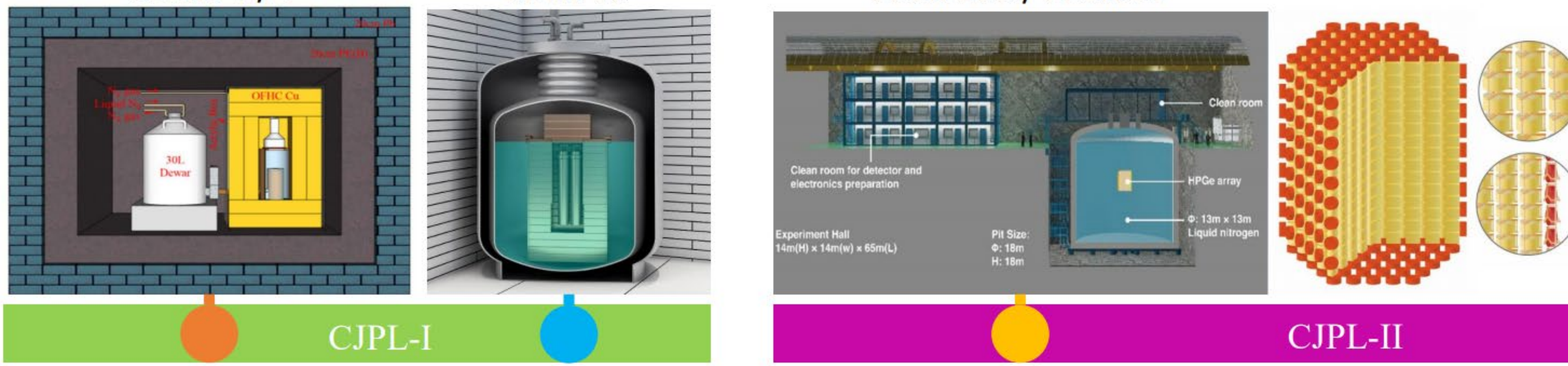
- Array detectors: 3 strings with 3 detector each, ~10kg total;
- Direct immersion in $LN_2$ ;
- Prototype system for future hundred-kg to ton scale experiment
- Light/radio-purer LN2 replacing heavy shield i.e. Pb/Cu;
- Arraying technology to scalable capability;

CDEX-10: ~10kg PPC Ge array



# CDEX Roadmap

CDEX-1A/B | CDEX-10 | CDEX-100 / CDEX-1T




2011 | 2016 | 202X

**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

**202X**

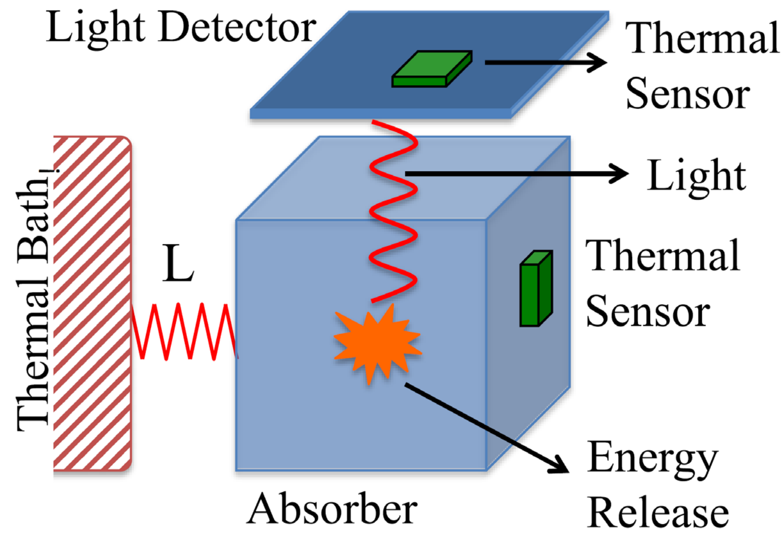
- ❑ **Ge array in large-volume $LN_2$**
- ❑ **multi-purpose: DM and 0νββ**

**Key technologies:**

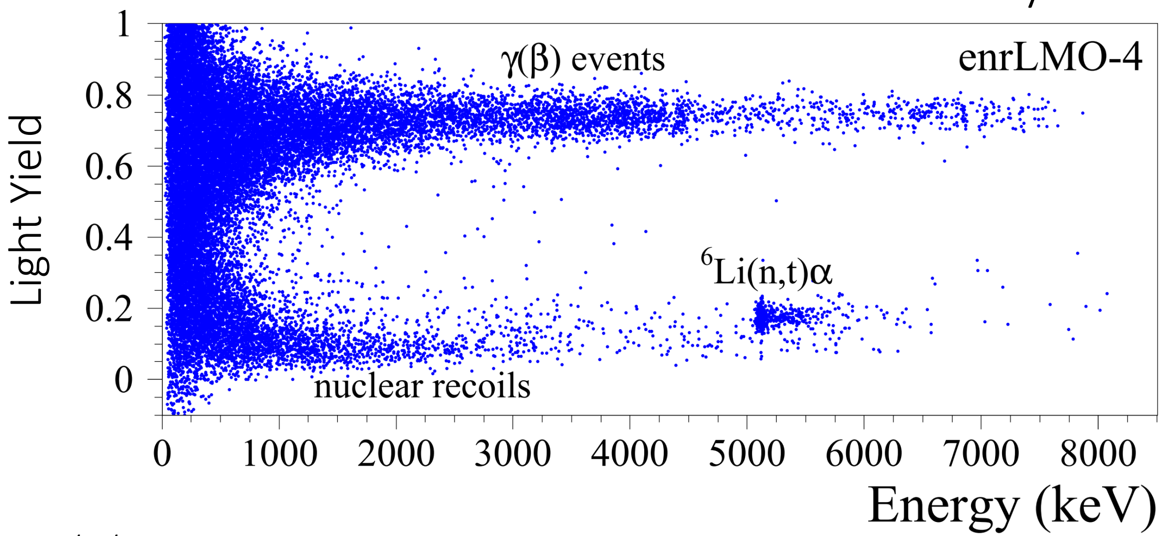
- ✓Ge crystal growth and $^{76}$Ge enrichment
- ✓Ge detector fabrication
- ✓Ultra-low background VFE
- ✓Ultra-pure copper for structure and cables
- ✓Natural Ge detectors as veto
- ✓......

From LT Yang

# CUPID-China

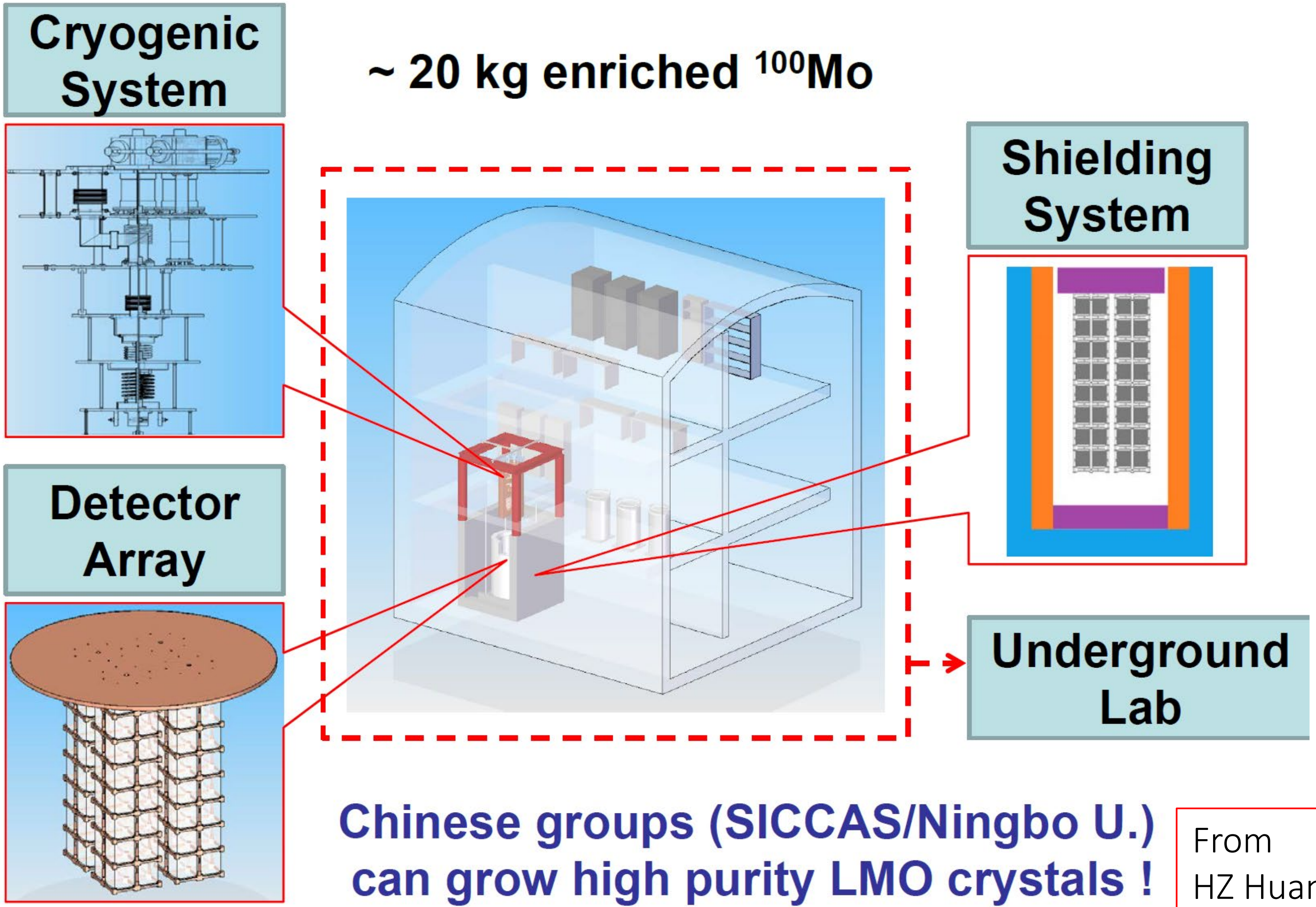



- Light and heat readout with two bolometer setups for one crystal
- $LiMoO_4$ scintillating bolometer arrays
- Particle ID to reject alpha background
- High Q-value (3.0 MeV) for low gamma background
- Technical development in the next 3-5 years




**CUPID-France**
**Andrea Giuliani**
**@CSNSM Orsay**

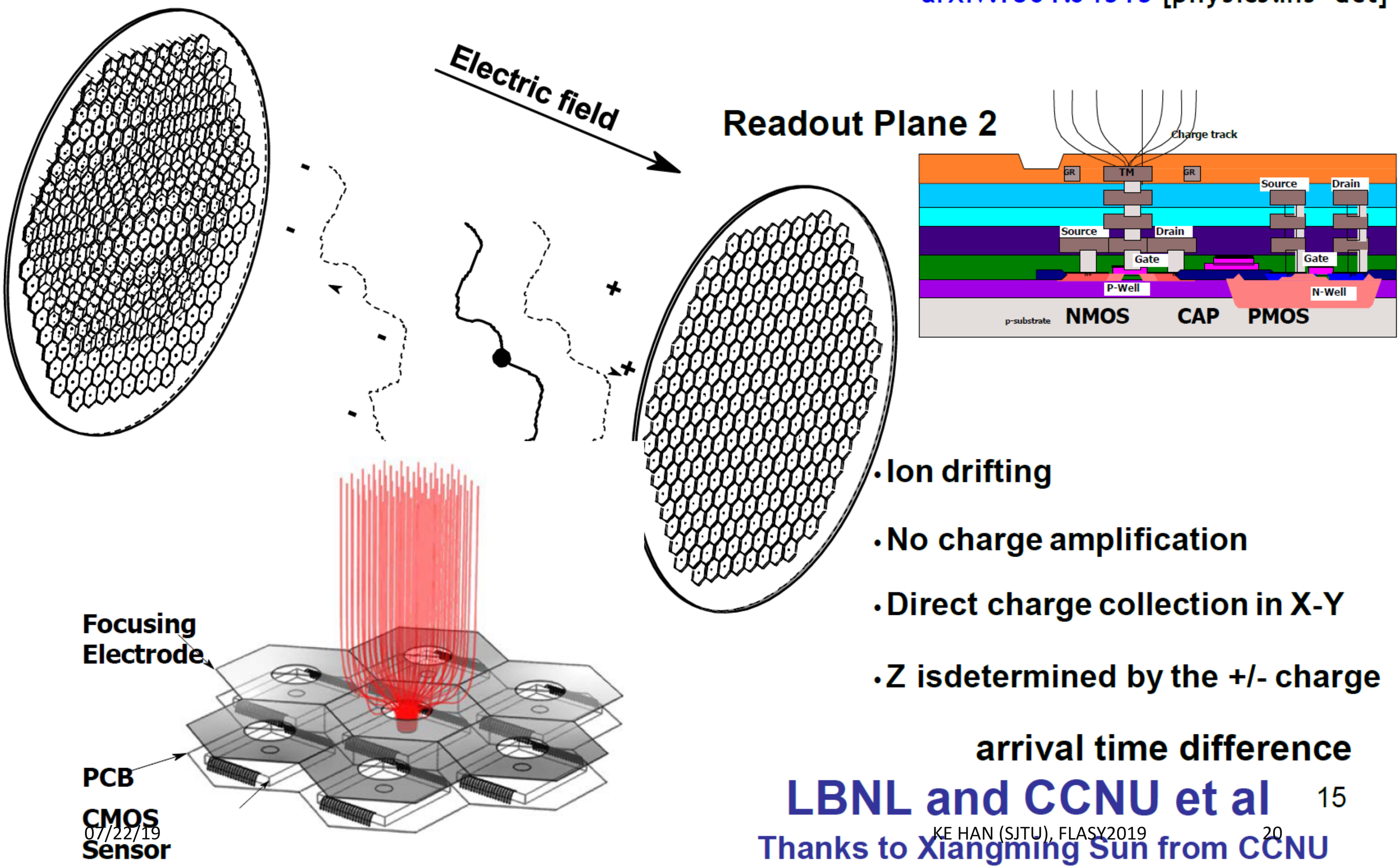
# CUPID-China concept




**Chinese groups (SICCAS/Ningbo U.) can grow high purity LMO crystals !**

From HZ Huang

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




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

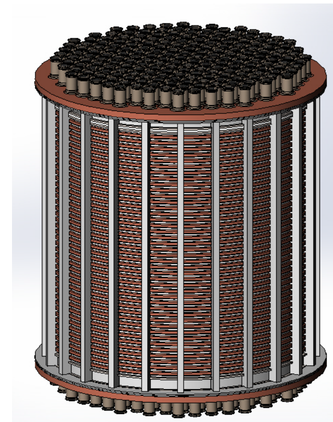
**LBNL and CCNU et al** 15

Thanks to Xiangming Sun from CCNU

# PandaX Projects

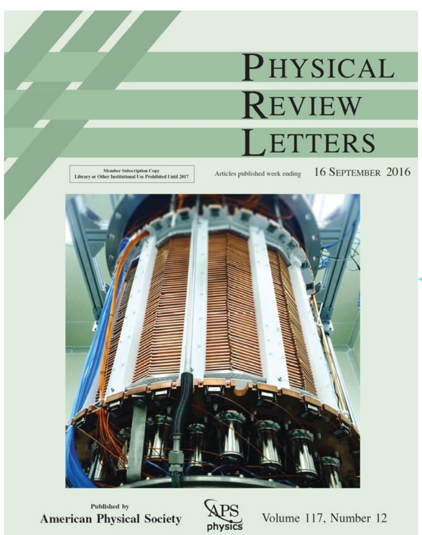
PandaX-I: 120kg LXe
(2009 – 2014)

PandaX-II: 500kg LXe
(2014 – 2018)

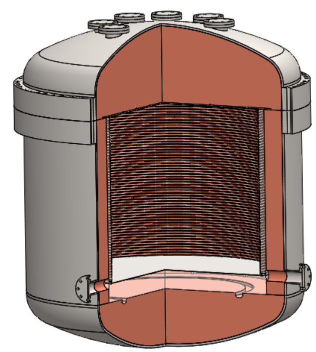


PandaX-xT LXe
(future)

Dark matter WIMP searches




PRL 117, 121303 (2016)

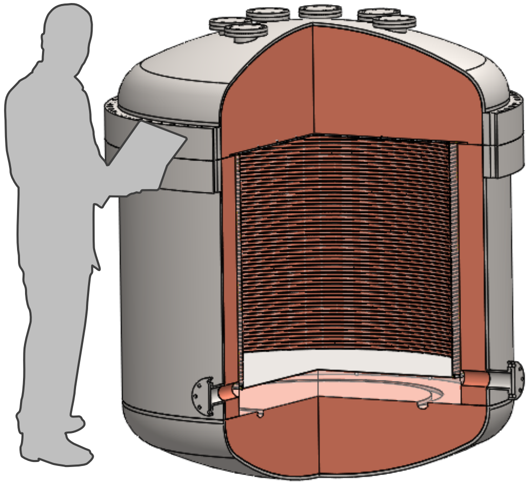


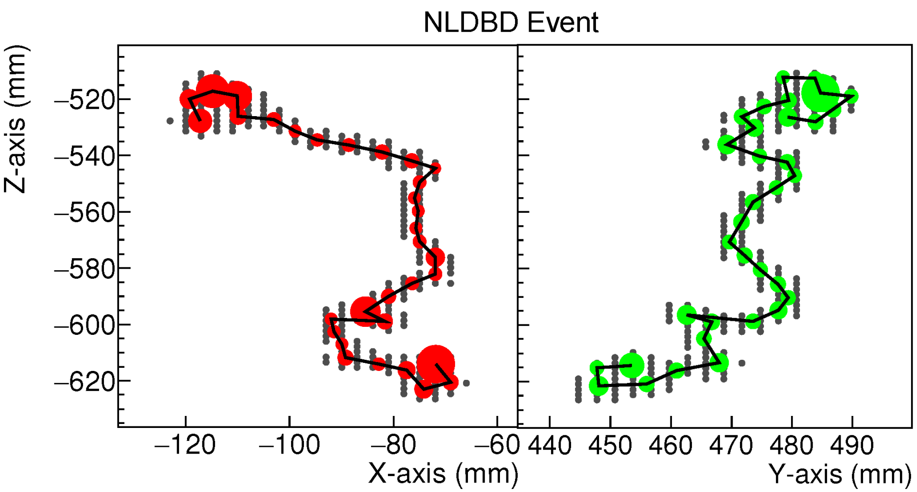
PandaX-III:
200kg - 1 ton HPXe (future)

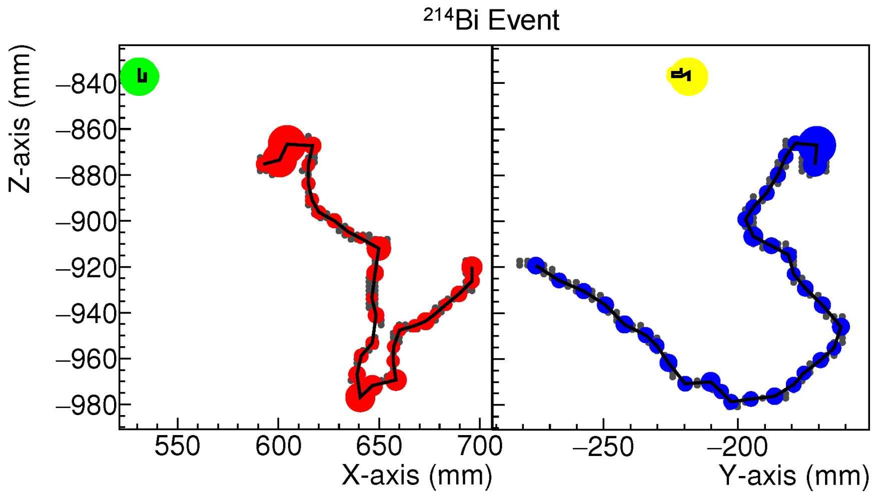
$0\nu\beta\beta$ searches

# 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).

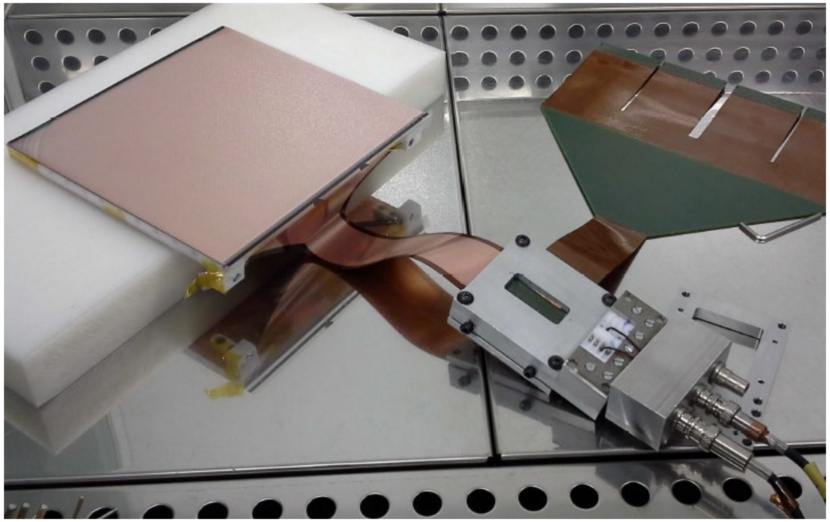


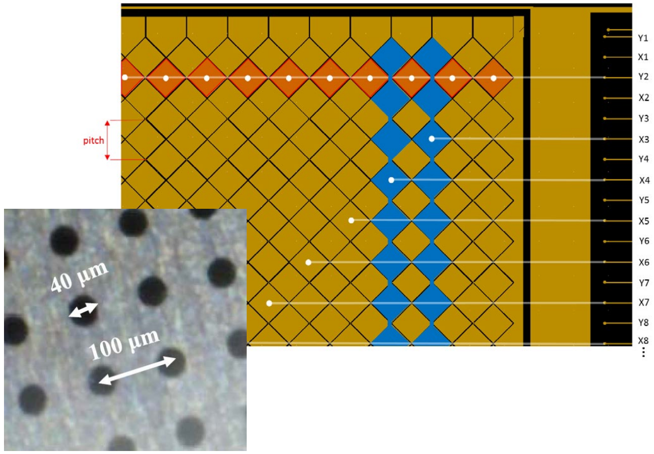


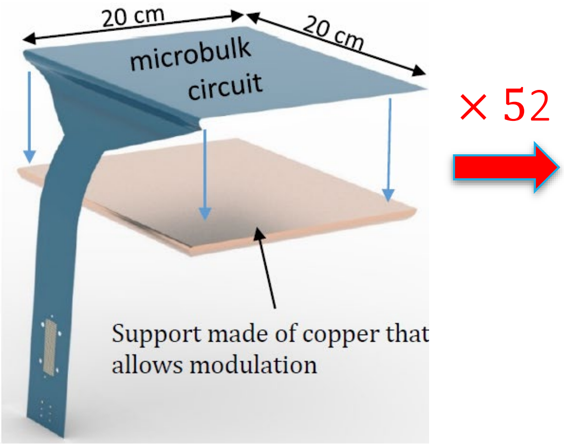



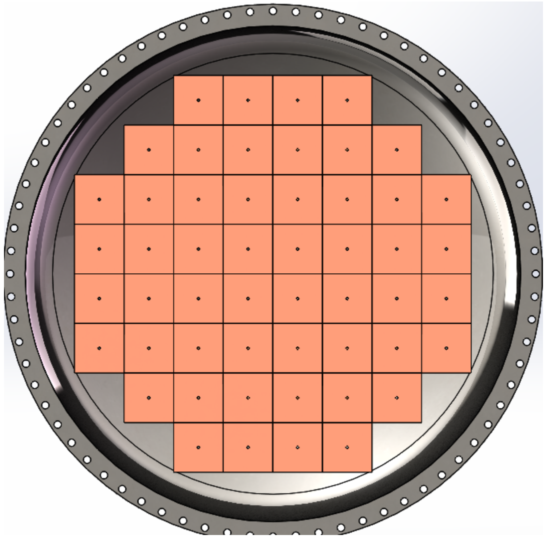
# Readout plane

- 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



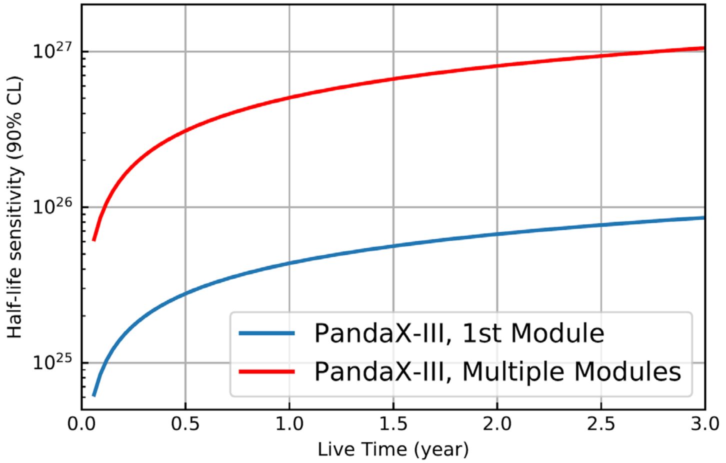


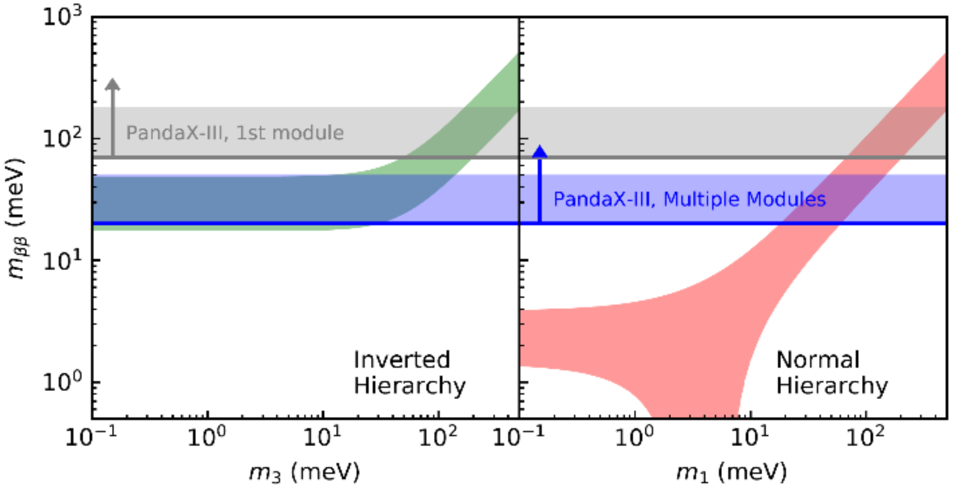



# Status and Sensitivity

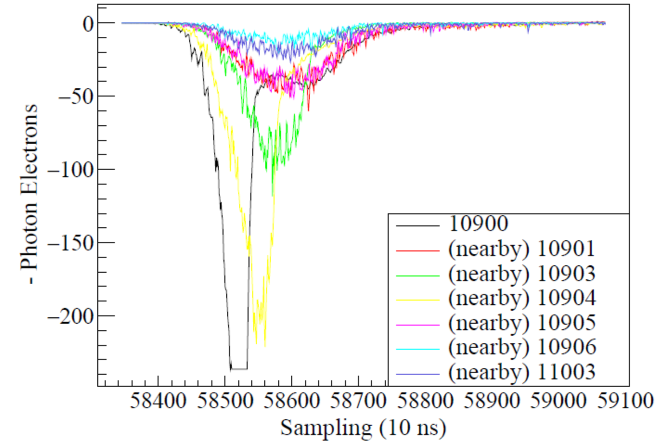
- A 20-kg scale prototype TPC is running (arXiv:1804.02863)
- 1st 100-kg scale module to commission in 2020
- Half-life sensitivity with 3 years of data: 9× $10^{25}$ yr (90% CL)

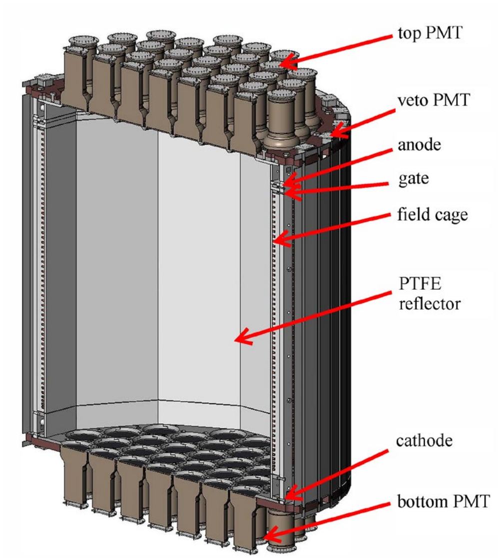


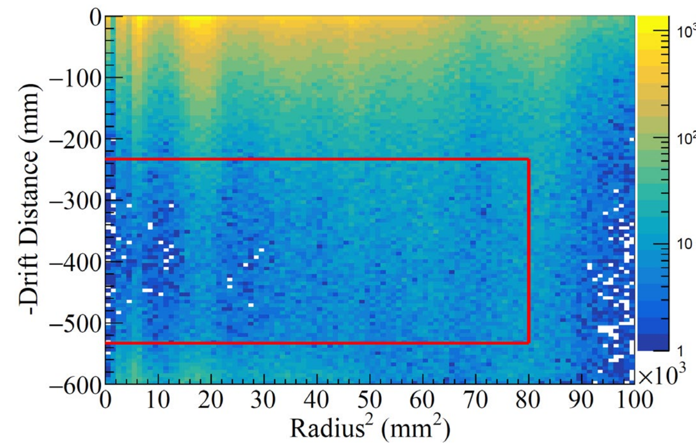



# NLDBD in PandaX LXe TPC

- 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

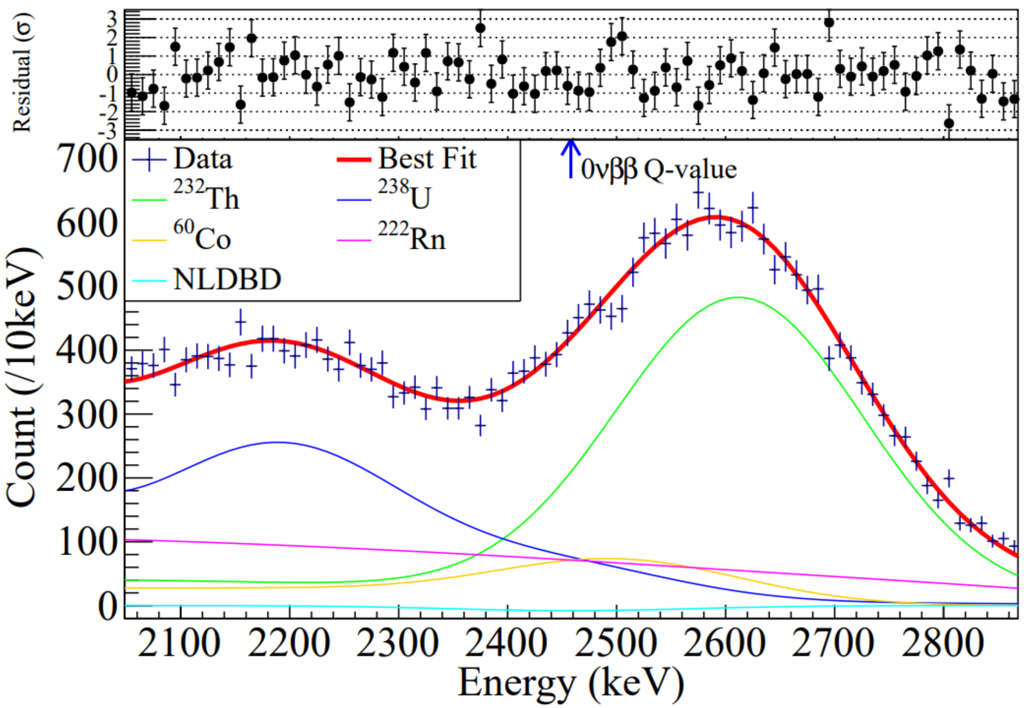



| Data set | Begin | End | Live days |
|---|---|---|---|
| Run 9 | Mar. 9, 2016 | Jun. 30, 2016 | 79.6 d |
| Run 10 | Apr. 22, 2017 | Jul. 16, 2017 | 77.1 d |
| Run 11 | Jul. 17, 2017 | Aug. 16, 2018 | 246.4 d |

# Final spectrum fit for PandaX-II data

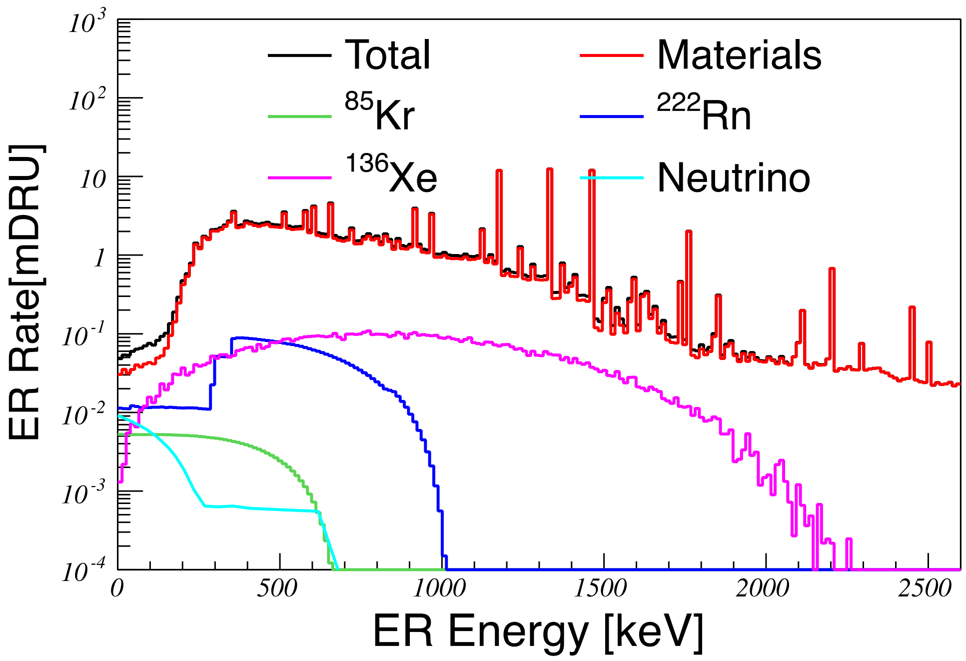


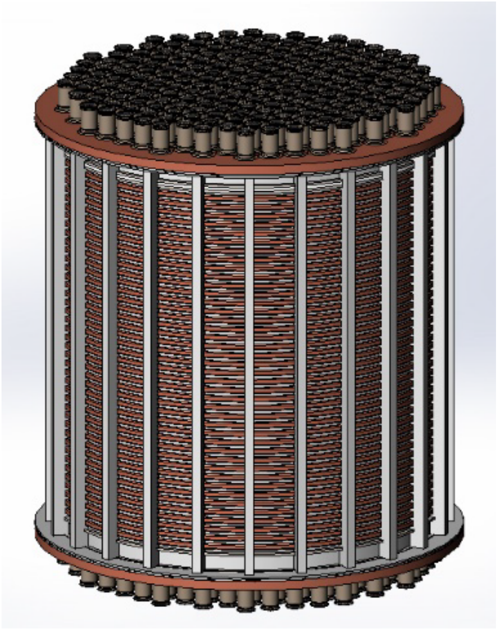

- Energy resolution: 4.2%
- Null results. Lower limit for decay half-life of $2.4\times10^{23}$ yr at the 90% confidence level
- Effective Majorana mass upper limit: 1.3-3.5 eV.
- First NLDBD result reported from a dual-phase xenon experiment

arXiv:1906.11457; submitted to Chinese Physics C

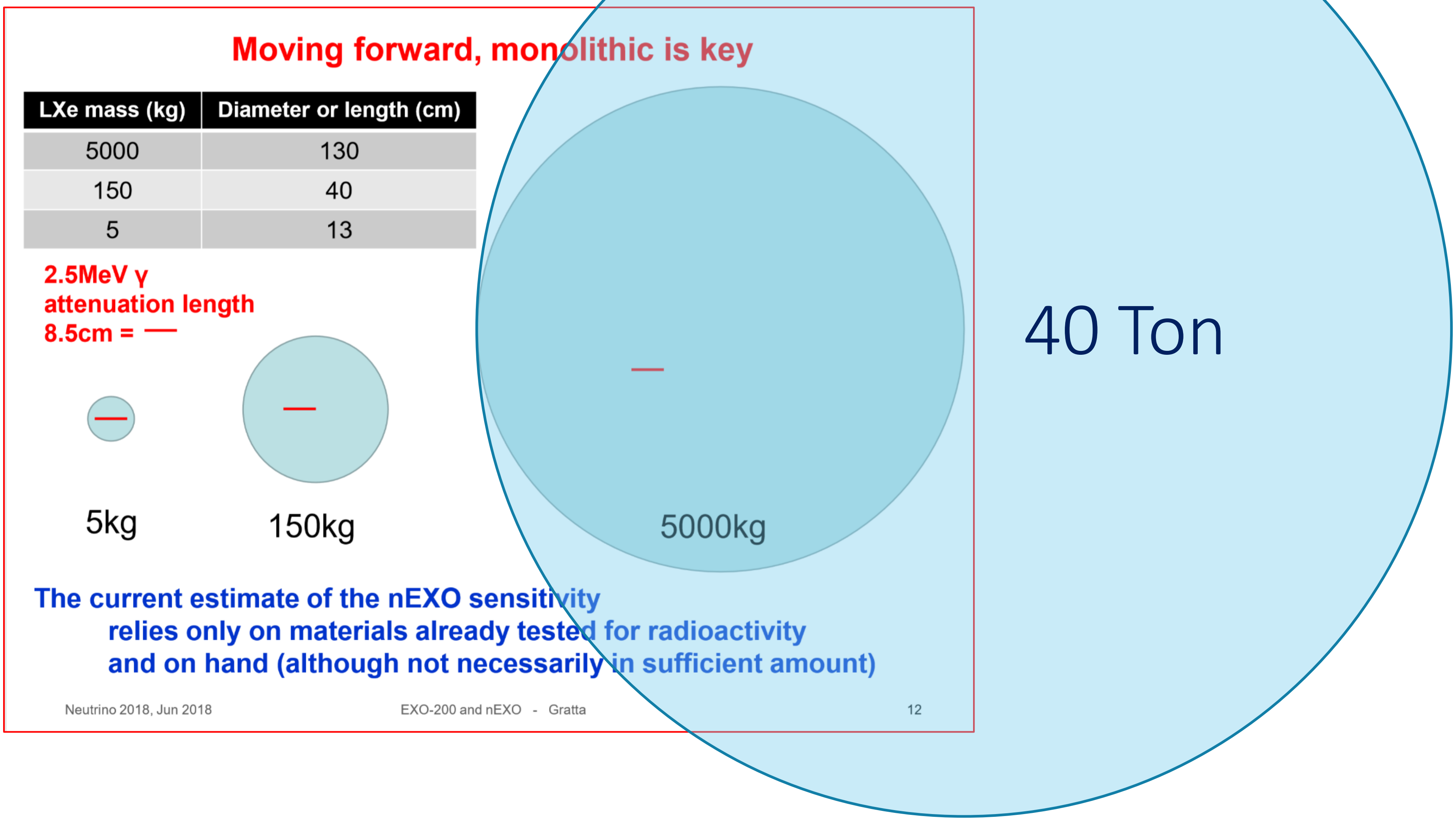
# PandaX-4T for NLDBD

- 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 ($3x10^{25}$yr)



# Self-shielding with future generations



**Moving forward, monolithic is key**

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



**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

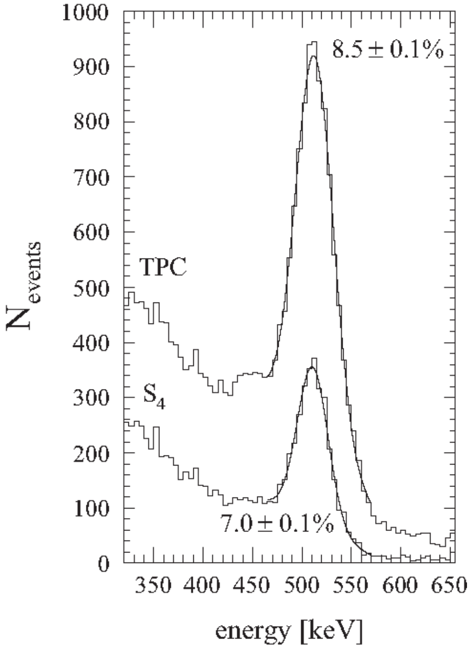
From Yury Kolomensky

# Summary: Chinese efforts

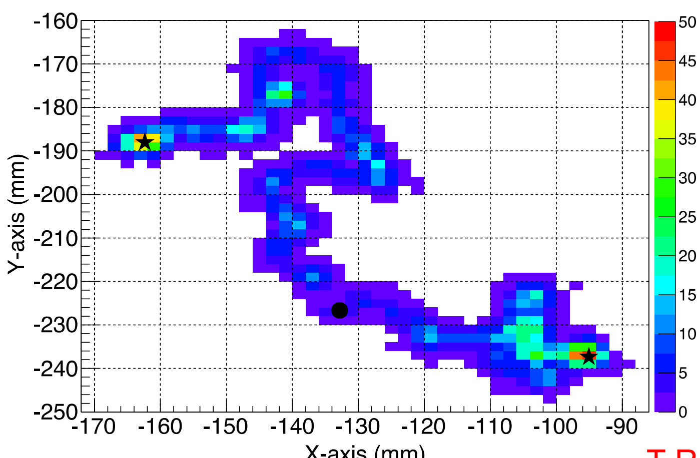
- CJPL-II, a State Major Research Infrastructure, provides tremendous opportunities for NLDBD
  - CDEX; CUPID-China; NvDEX
- PandaX searches for $0\nu\beta\beta$ of $^{136}Xe$ with gas and liquid TPCs
  - First result from dual-phase xenon TPC
  - High pressure TPC for tracking reconstruction

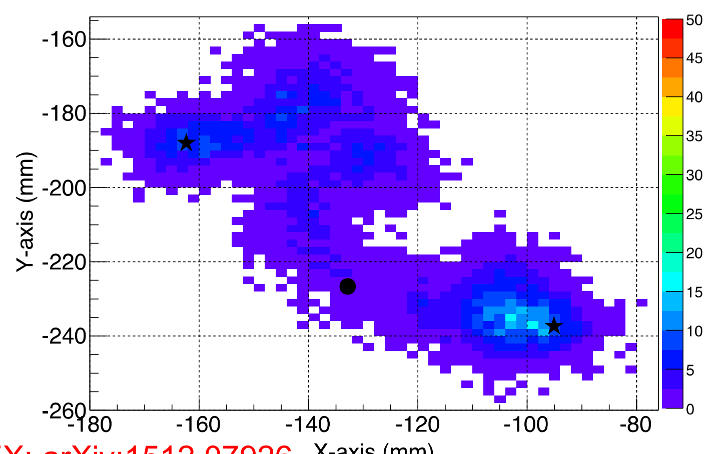
# Energy resolution and tracking with Micromegas

- 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)



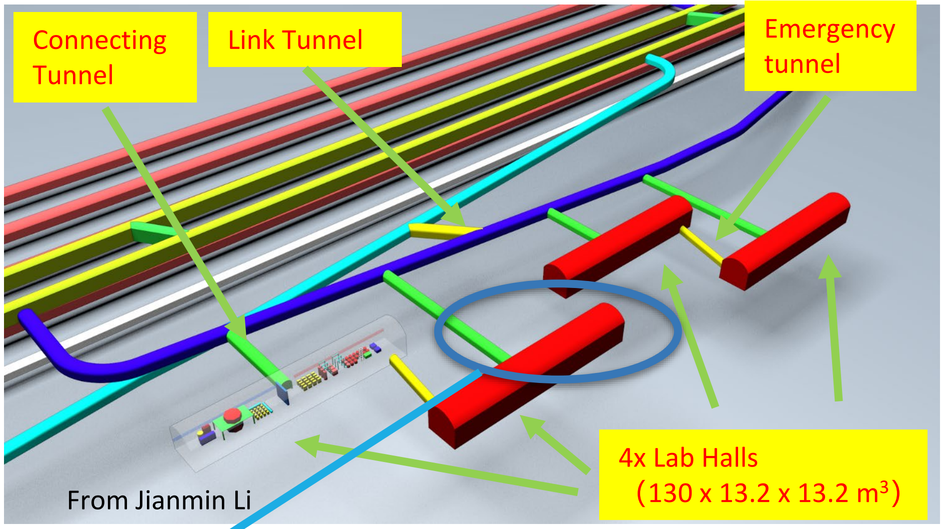



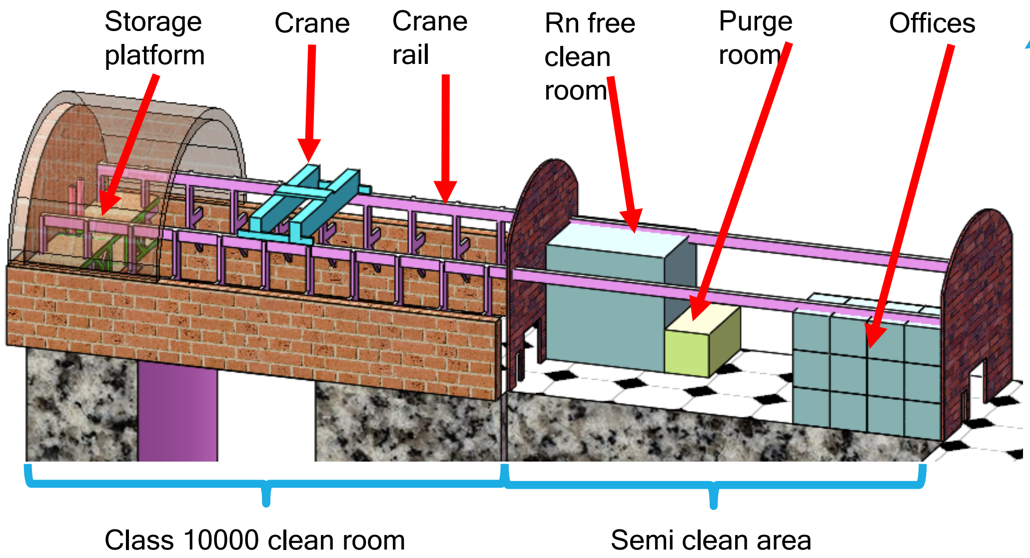

T-REX: arXiv:1512.07926

# PandaX hall at CJPL-II

Experiments at CJPL-II

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



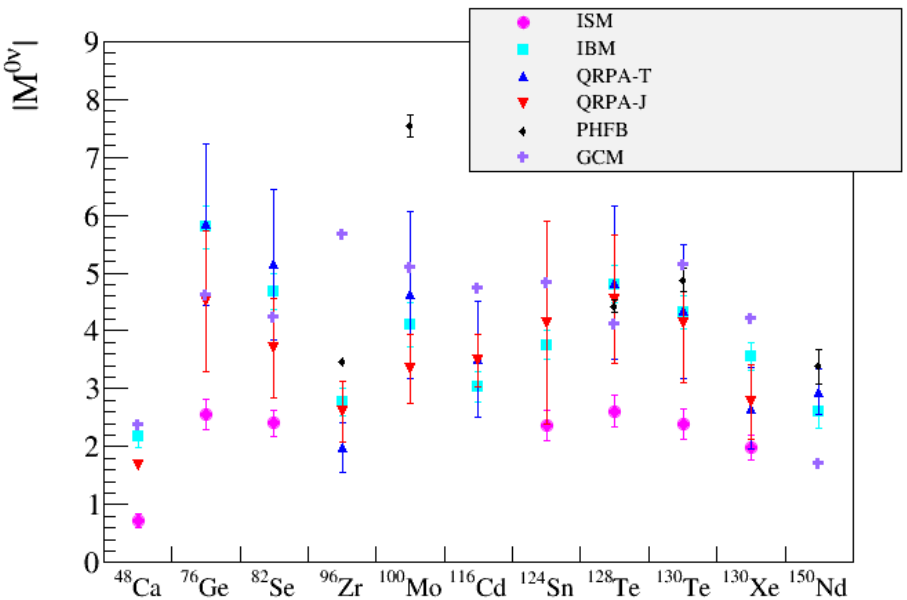




PandaX at Hall B2

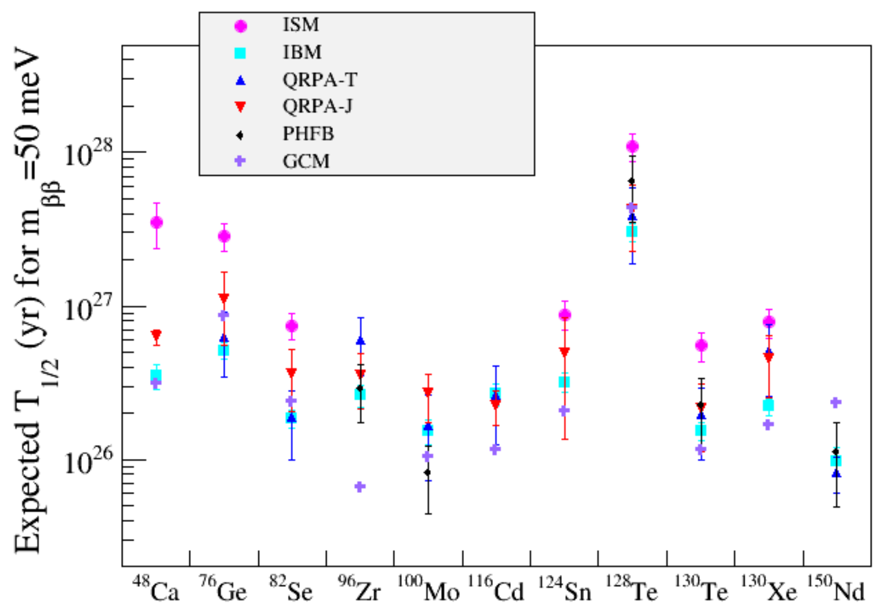
- Extra excavation for the water shielding pool (finished)
- Shared facility of DM and 0νββ searches
- Beneficial occupancy by the beginning of 2018

# Uncertainties of NME

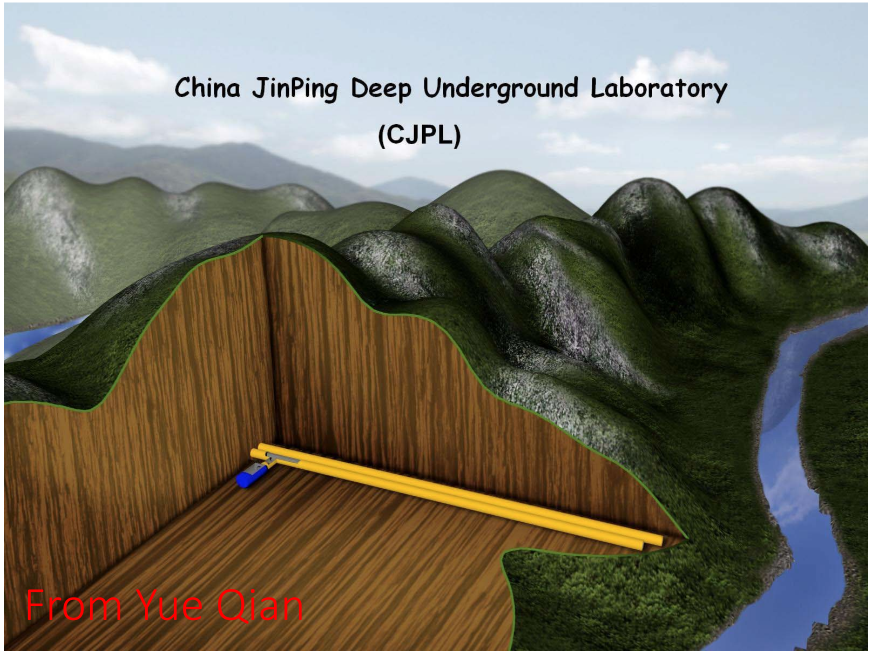
NME from different model calculations



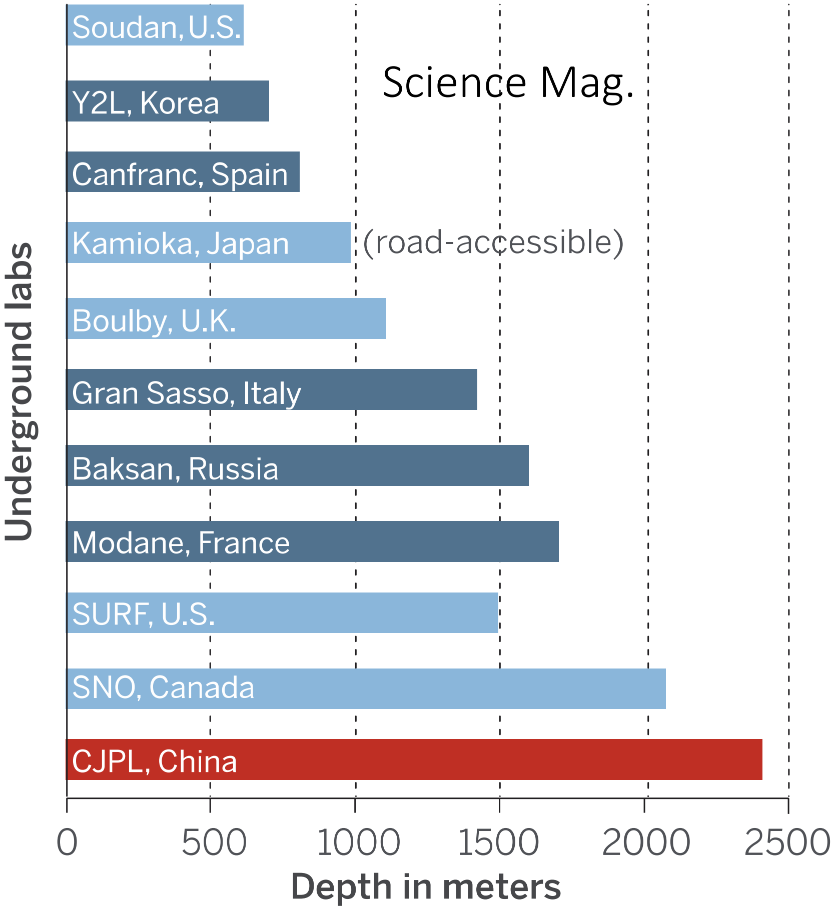

0νββ half-life assuming $m_{\beta\beta}$=50 meV

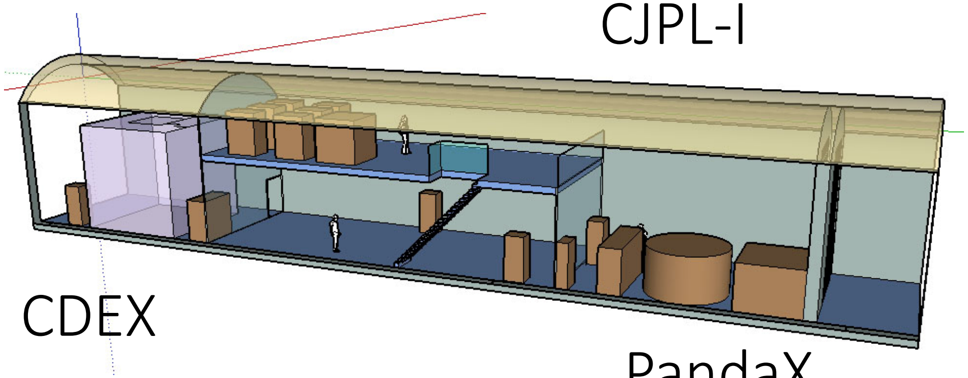


# CJPL boosts underground physics in China

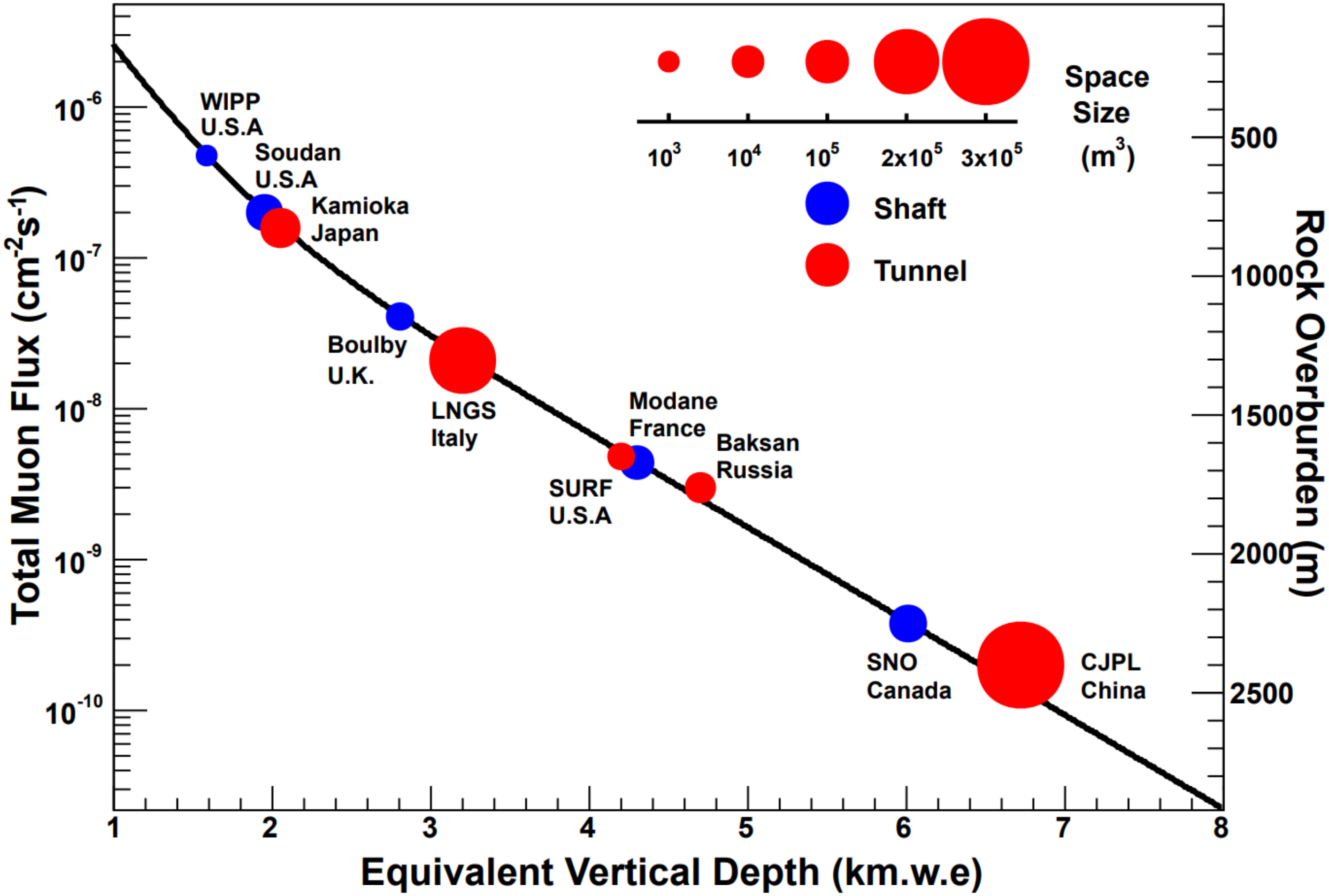



Labs are built in mines (light blue) and tunnels (dark blue and red).



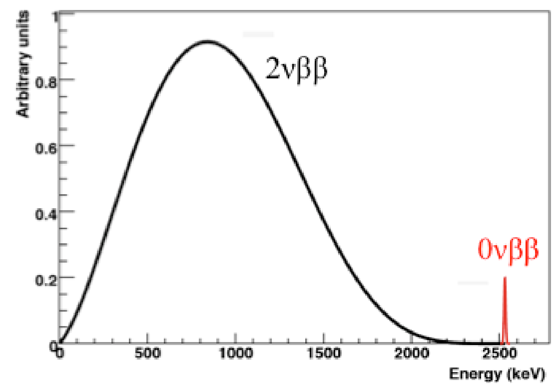
# Going underground

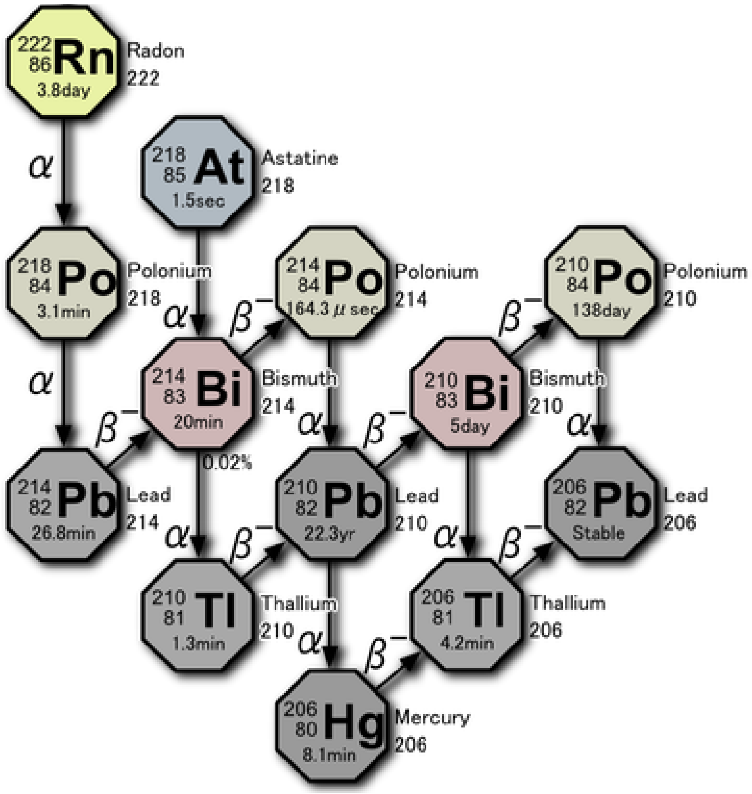



Ann.Rev.Nucl.Part.Sci. 67 (2017) 231

# Backgrounds in 0νββ searches

- Tail of 2νββ spectrum --- Irreducible
  - Mitigated with good energy resolution
- Cosmic rays
  - Muons and neutrons
  - Cosmogenic radioactivity ($^{60}Co$, $^{68}Ge$, etc)
  - Mitigated by going underground: muon flux is reduced by X10 per 1500 m.w.e.
- U and Th in the detector material
  - $^{208}Tl$ from the $^{232}Th$ chain gives 2615 keV γ
  - $^{214}Bi$ from $^{238}U$ chain gives γ in MeV region
  - Material screening
  - Coincident analysis such Bi-Po
- Surface contaminations in detector assembly
  - Radon daughters stick to surfaces and hard to clean off

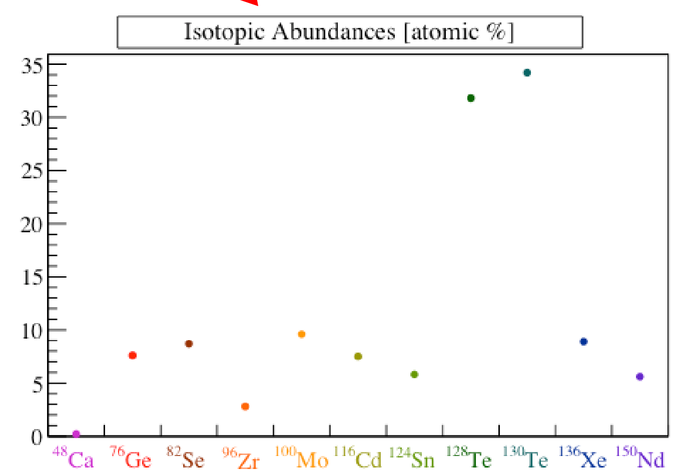


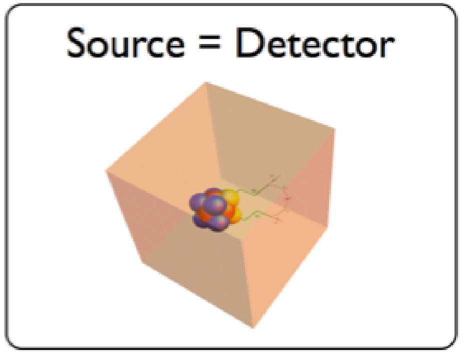



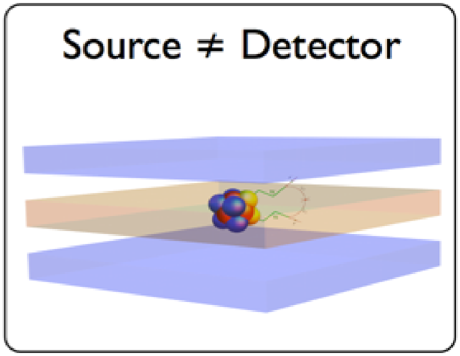
# Half life sensitivity from experiment

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

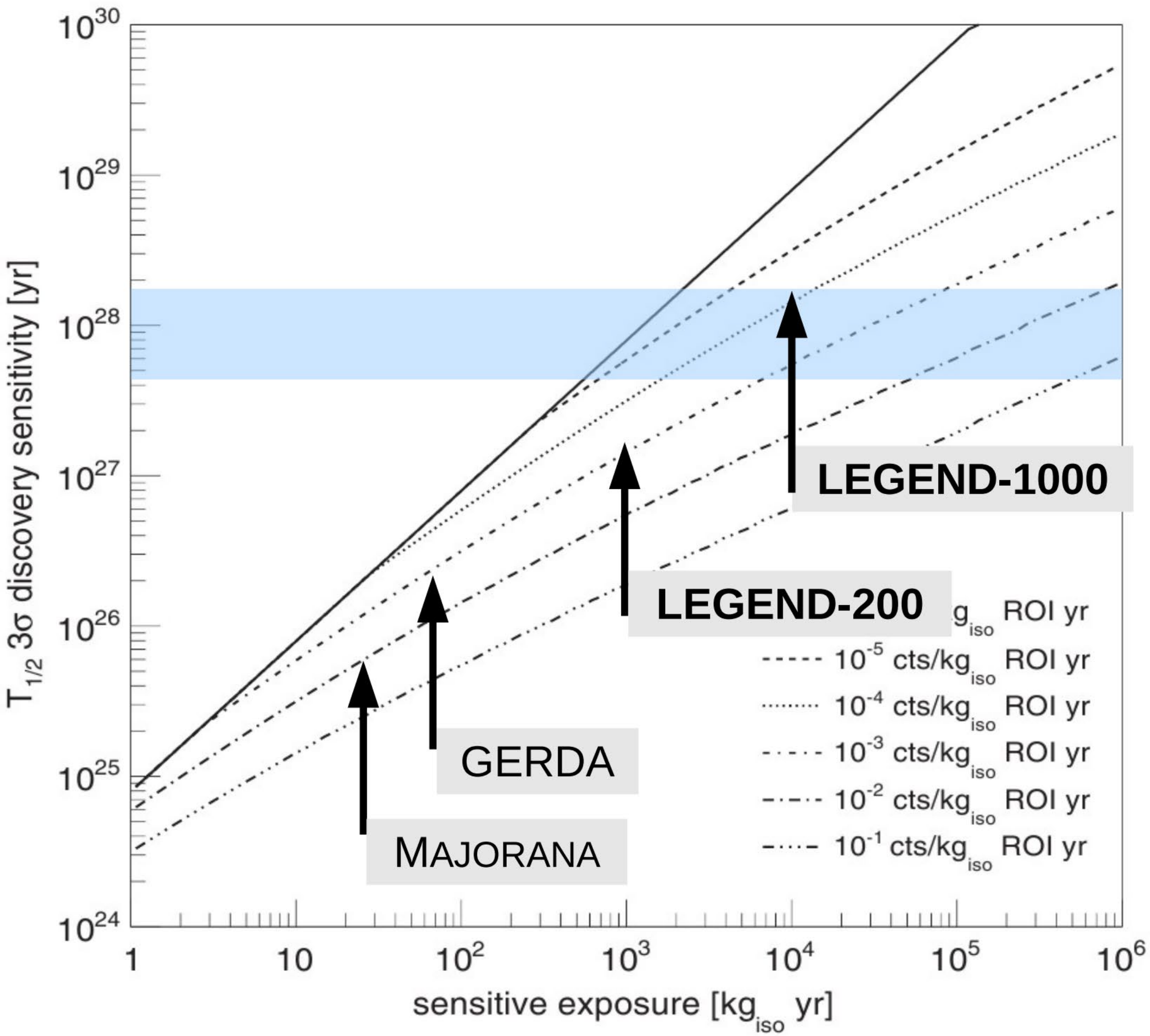
- Isotopic abundance
- Detecting efficiency
- Detector mass
- Background rate
- Energy resolution
- Measuring time



# LEGEND sensitivity




**Inverted hierarchy range (range for various theories)**

*Assuming ROI = 3σ ≈ 1.3 FWHM*

*Figure taken from PRD 96, 053001 (2017)*

R. Massarczyk, DBD18