# Neutrinoless Double Beta Decay Experiments In China

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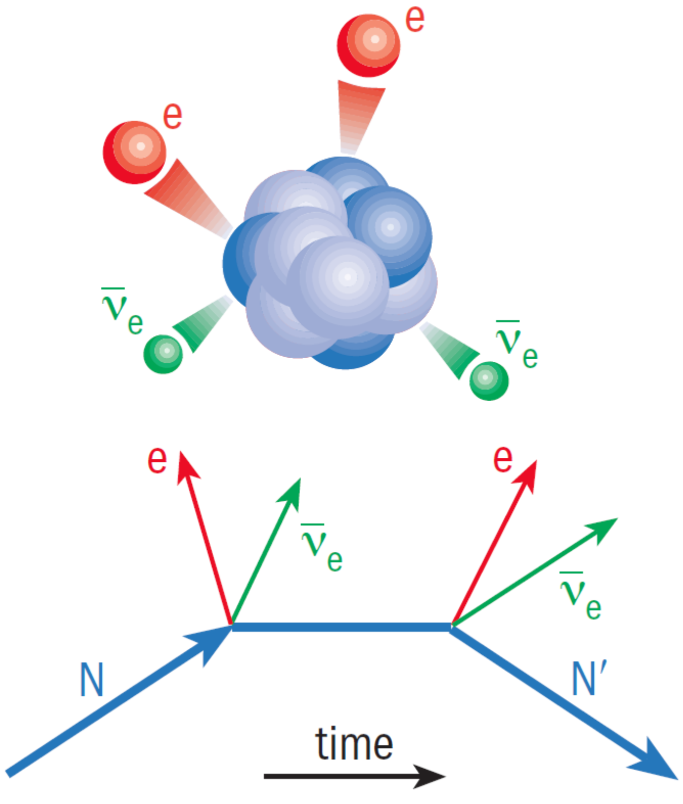
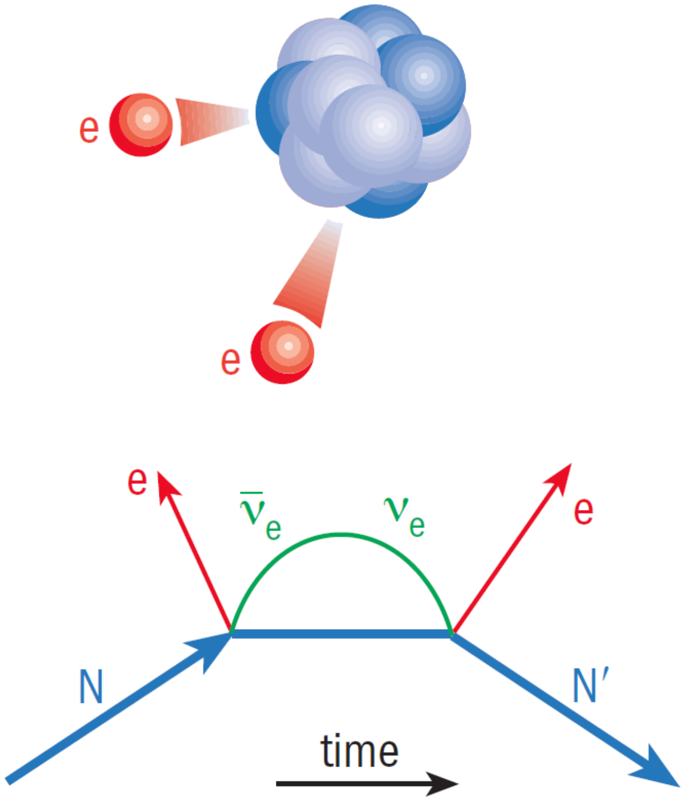
# Outline

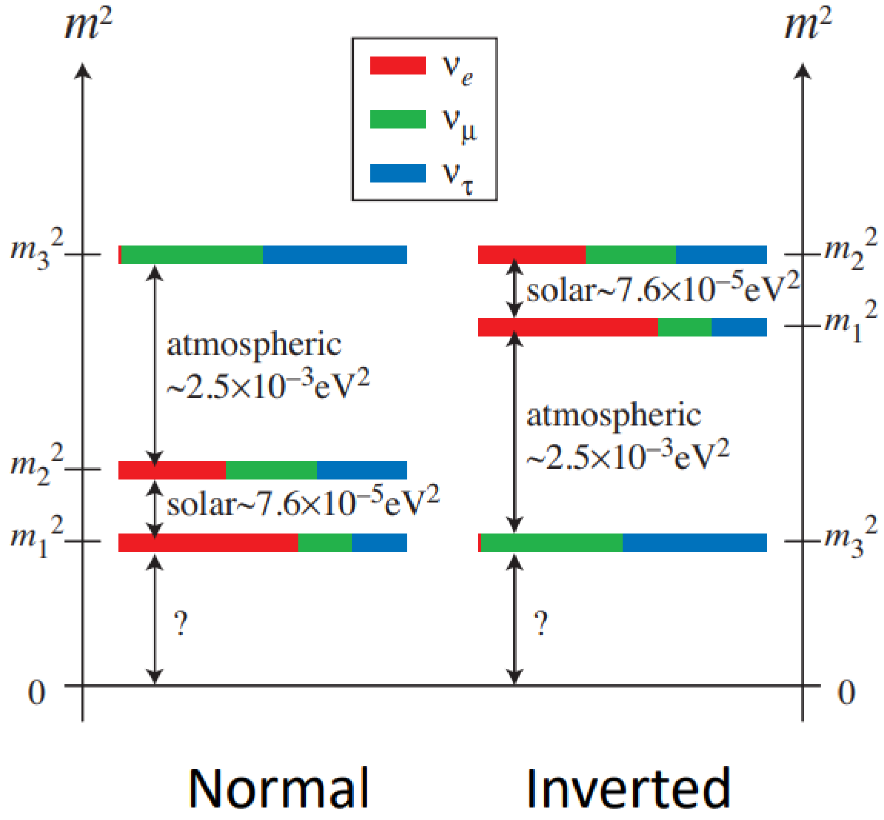
- Neutrinoless double deta decay
- Detection of double beta decay
- Neutrinuless double deta decay experiments in China
  - PandaX experiment
  - CDEX experiment
  - CUPID-CJPL experiment
  - NνDEx experiment
  - JUNO-0νββ experiment
- Summary

# Neutrinoless double beta decay ($0\nu\beta\beta$ )





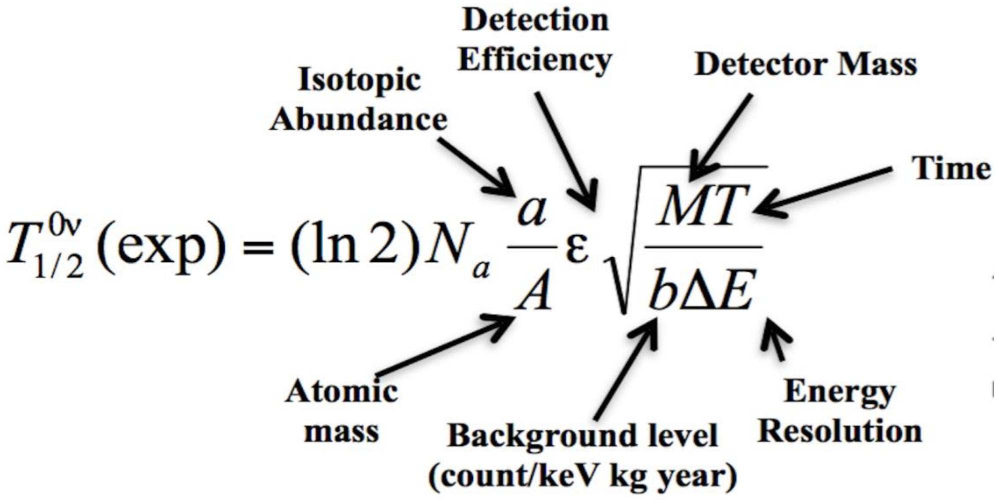
$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}(Q,Z)\ |M^{0\nu}|^2\ \frac{|\langle m_{\beta\beta}\rangle|^2}{m_e^2}$$



- $2\nu\beta\beta$ : 9 isotopes, including $^{136}$Xe, $^{76}$Ge, $^{130}$Te, $^{82}$Se and $^{100}$Mo
- $0\nu\beta\beta$ : Majorana Neutrino? Lepton number violation?
- Measures effective Majorana mass: relate $0\nu\beta\beta$ to the neutrino oscillation physics

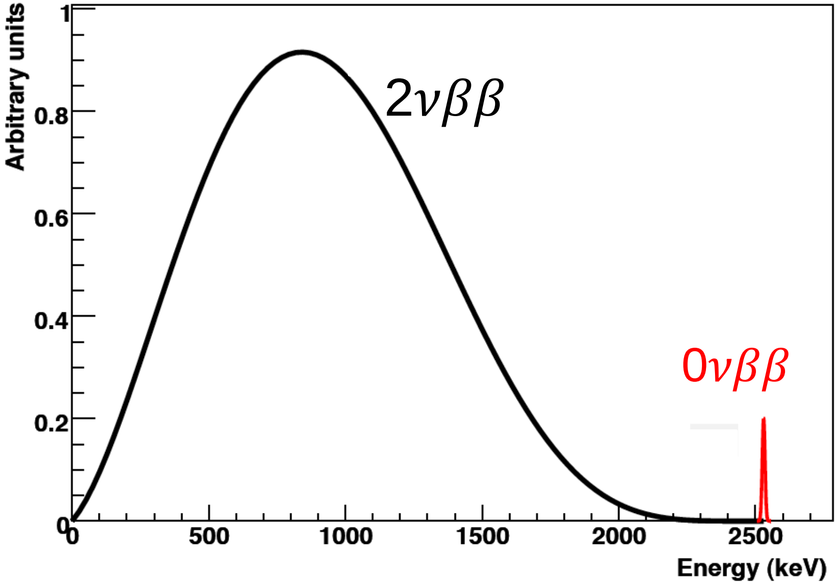
# Detection of $0\nu\beta\beta$

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

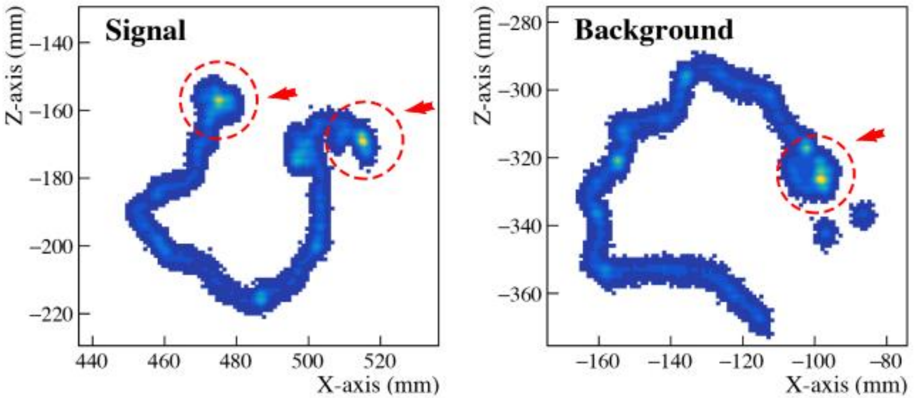


$$T^{0\nu}_{1/2}(\exp) = (\ln 2) N_a \frac{a}{A} \varepsilon \sqrt{\frac{MT}{b\Delta E}}$$

**Experiment**: large exposure, high energy resolution, low background level and signal-background discrimination

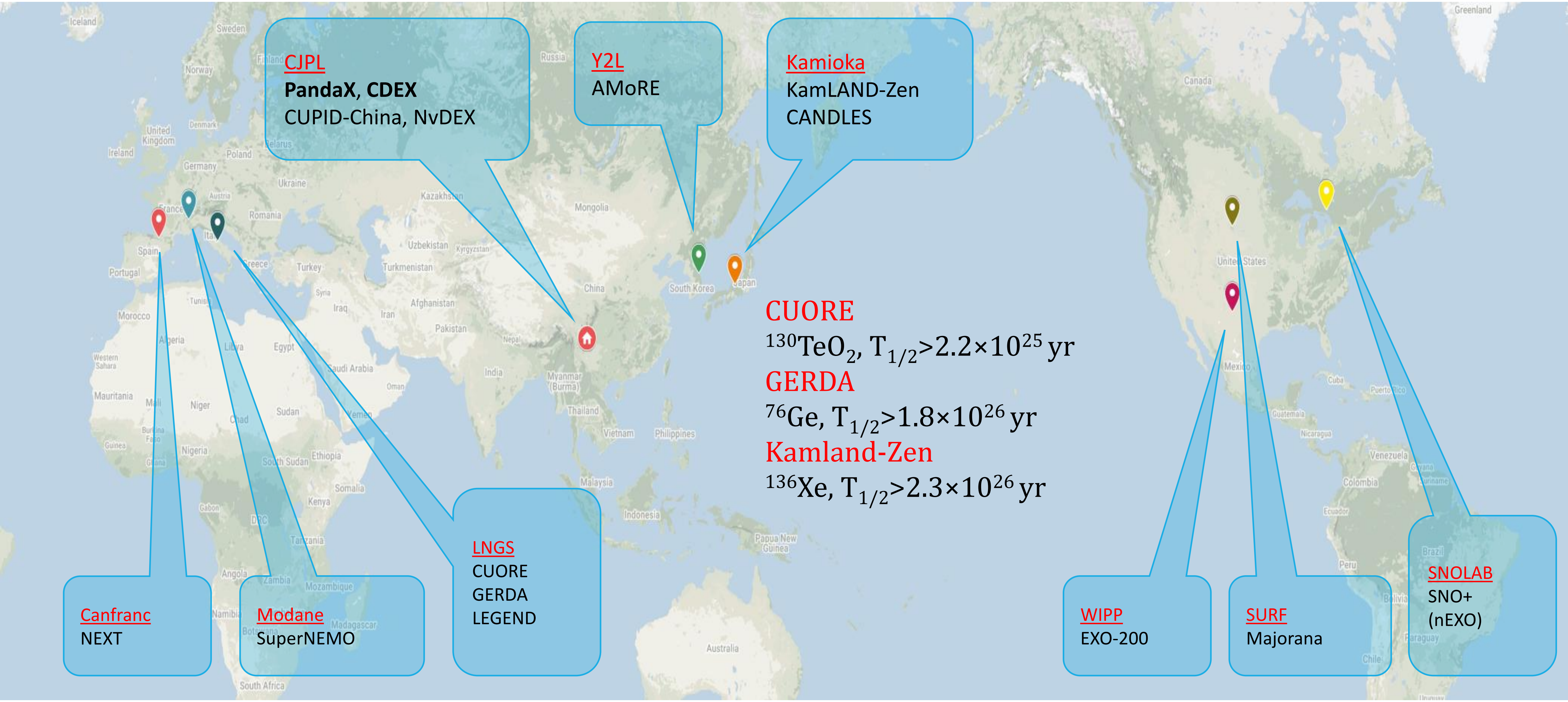


Sum of two electrons energy



Simulated tracks in high pressure Xe

# $0\nu\beta\beta$ experiments



CJPL
**PandaX, CDEX**
CUPID-China, NvDEX

Y2L
AMoRE

Kamioka
KamLAND-Zen
CANDLES

Canfranc
NEXT

Modane
SuperNEMO

LNGS
CUORE
GERDA
LEGEND

WIPP
EXO-200

SURF
Majorana

SNOLAB
SNO+
(nEXO)

CUORE

$^{130}TeO_2$, $T_{1/2}>2.2\times10^{25}$ yr

GERDA

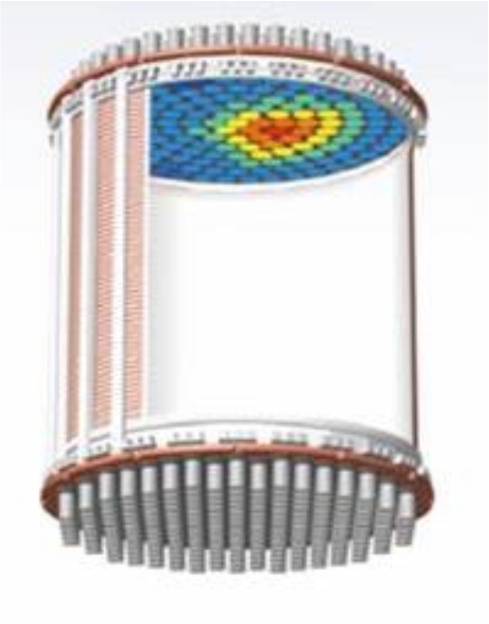
$^{76}Ge$, $T_{1/2}>1.8\times10^{26}$ yr

Kamland-Zen

$^{136}Xe$, $T_{1/2}>2.3\times10^{26}$ yr

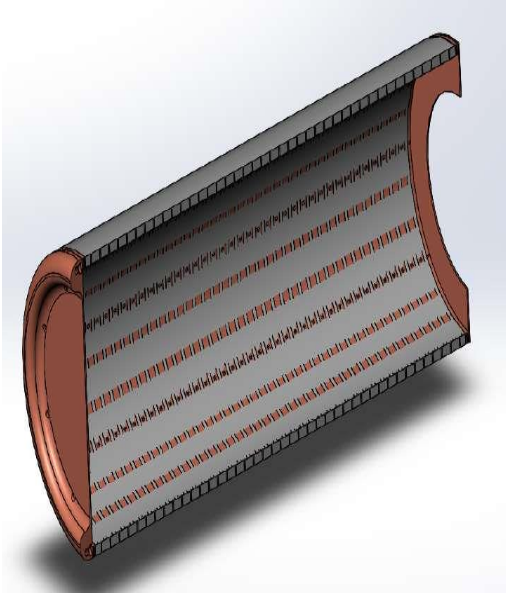
# Expected $0\nu\beta\beta$ experiments in China

CJPL-II (China Jin Ping underground Lab-II)



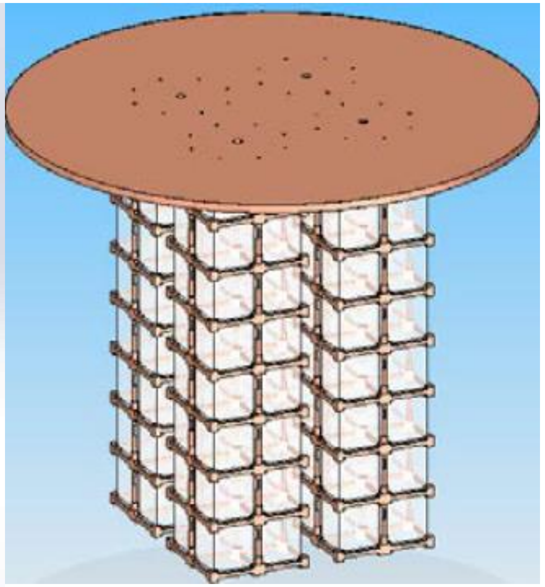
**PandaX**

Xe TPC



**NvDEx**

Ion TPC

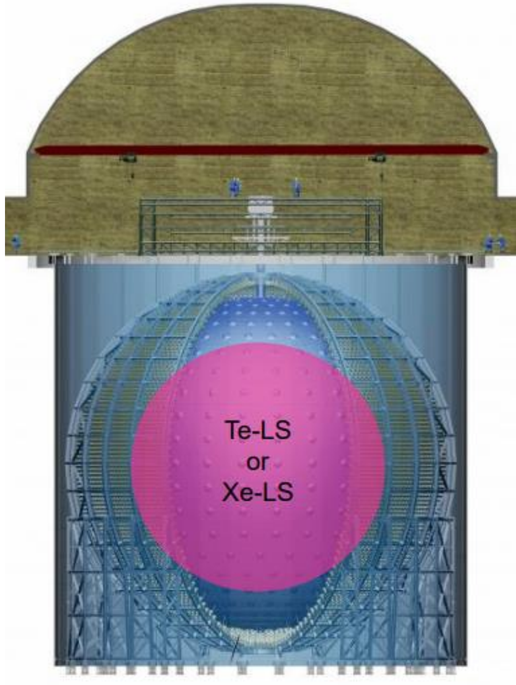


**CUPID-CJPL**

Bolometer

**CDEX**

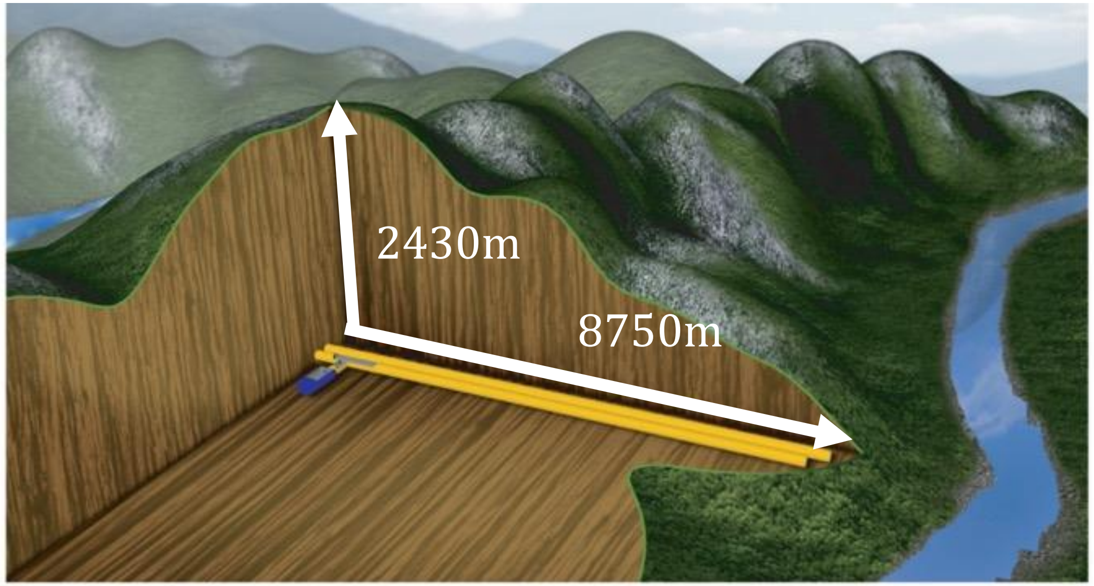
HPGe

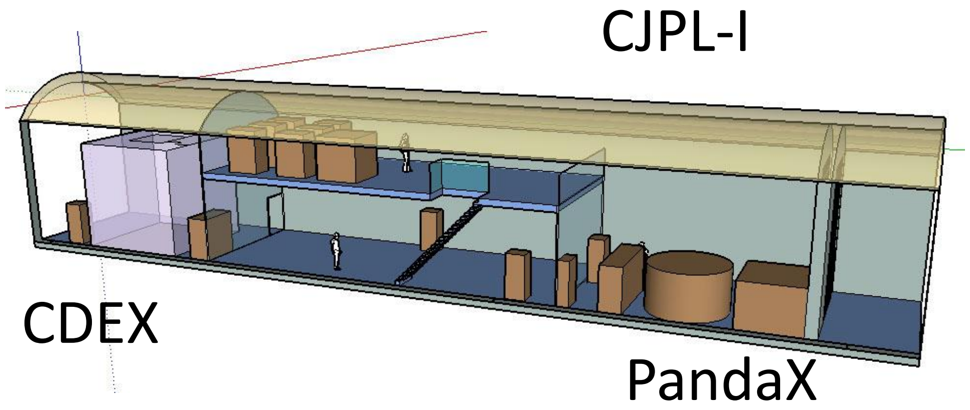


**JUNO-$0\nu\beta\beta$**

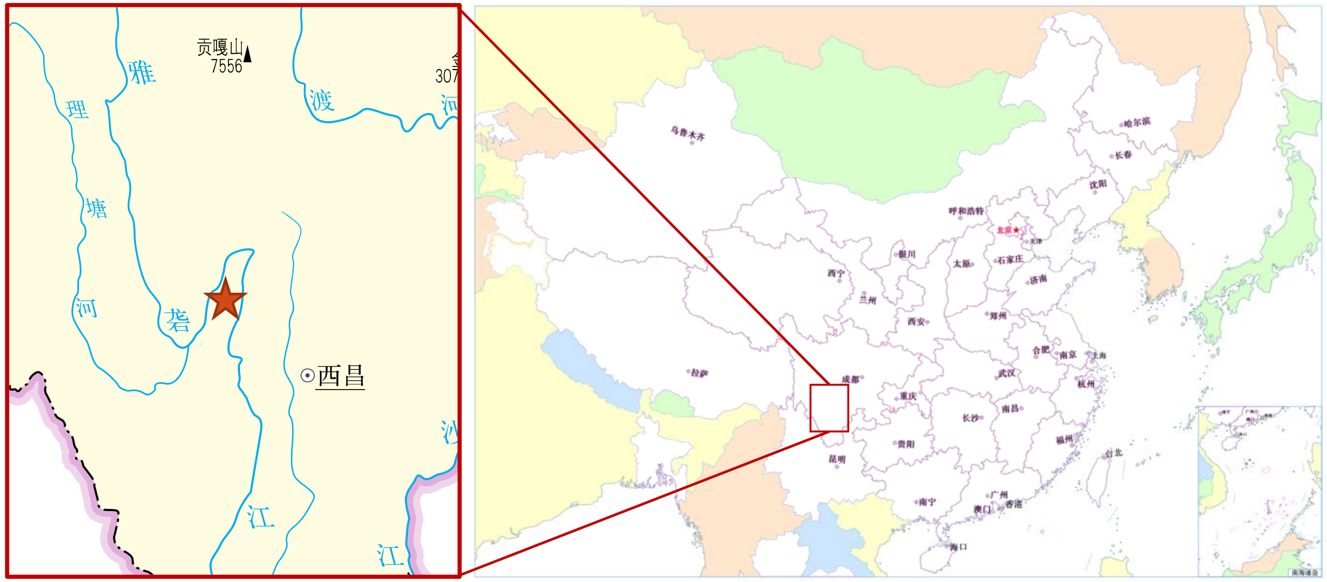
Te-LS or Xe-LS

# CJPL: Deepest underground lab

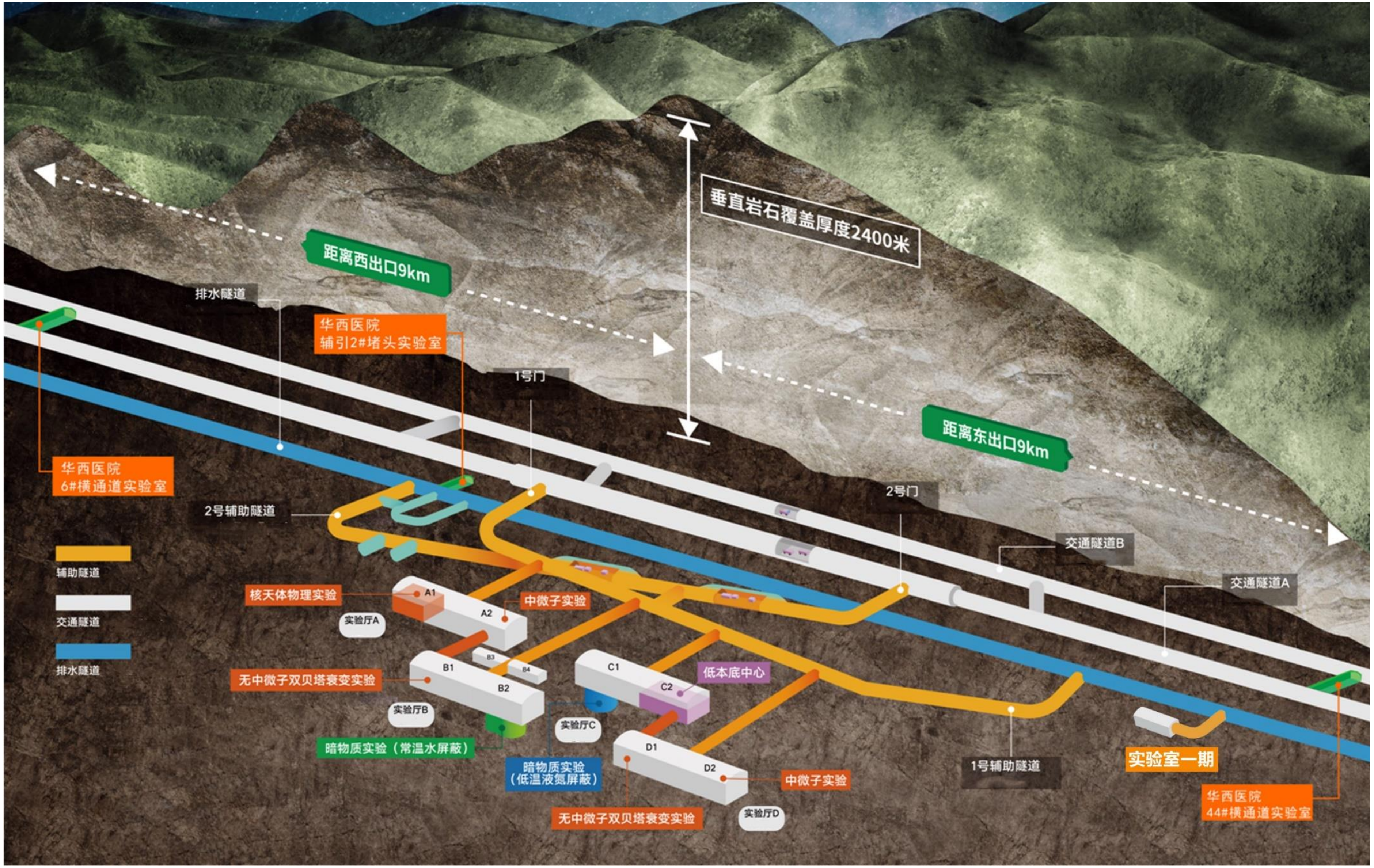


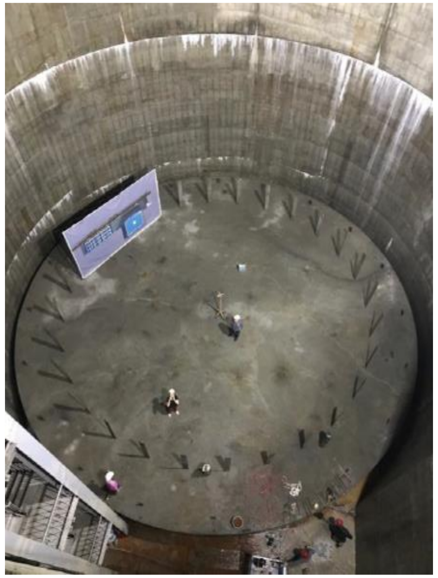


- Deepest (6800 m.w.e): < 0.2 muons/m$^2$/day
- Horizontal access with ~9 km long tunnel: large truck can drive in.
- National key science research facility for dark matter searches, neutrino physics, and astroparticle physics, etc.



# CJPL-II: much enlarged underground lab space





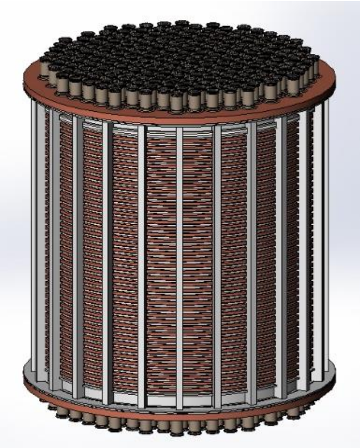
# PandaX project overview

Dark matter WIMP searches

0νββ searches

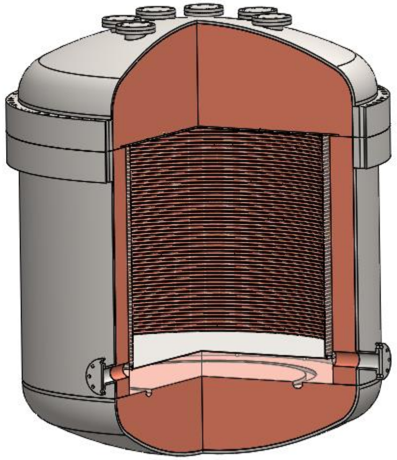
PandaX-I: 120kg LXe (2009 – 2014)

PandaX-II: 500kg LXe (2014 – 2019)



PandaX-4T: 4T LXe

PandaX-xT (future)

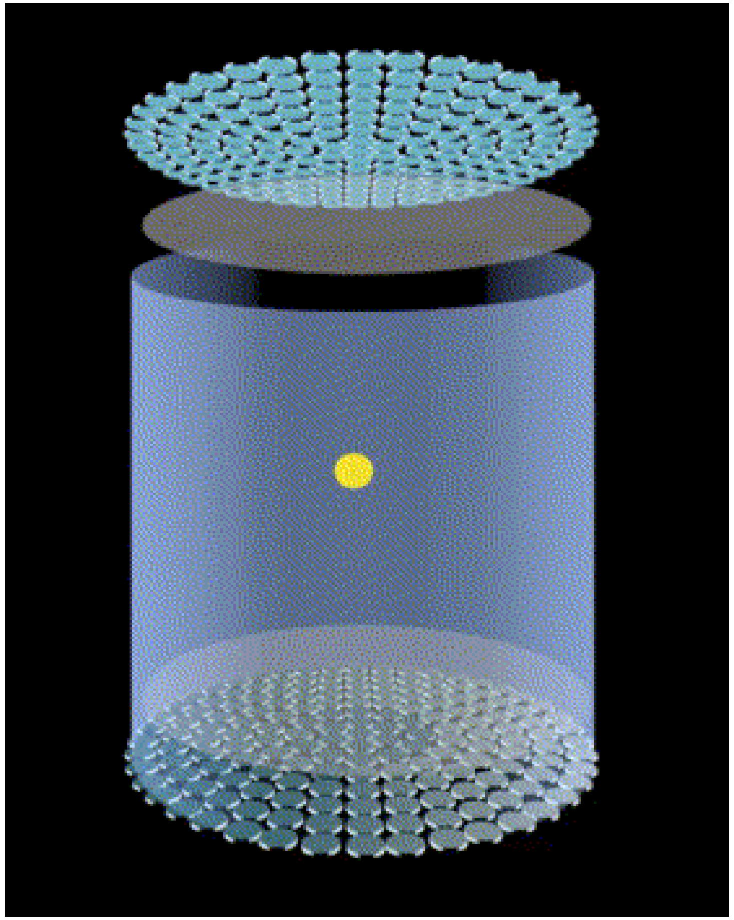


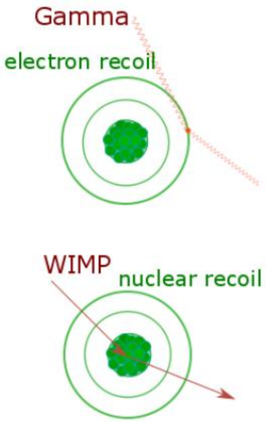
PandaX-III: HPXe 140kg - 1 ton (future)

Liquide natural Xe (8.7% $^{136}$Xe)

High pressure Xe (90% $^{136}$Xe)

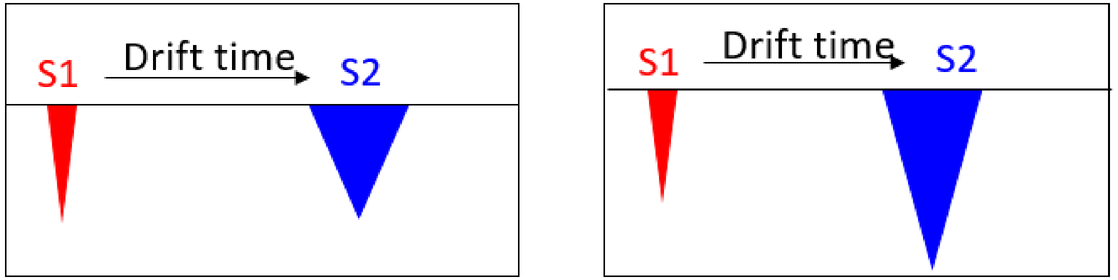
# Dual phase xenon TPC





**Dark matter: nuclear recoil (NR)**

**γ background: electron recoil (ER)**

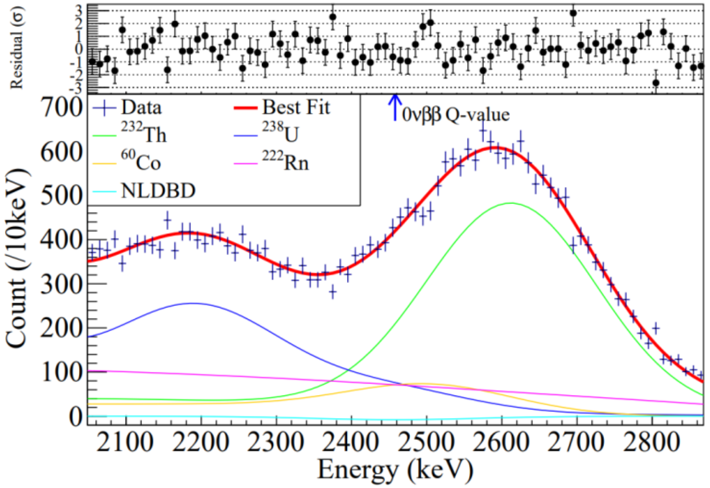


$$(S2/S1)_{NR} \ll (S2/S1)_{ER}$$

## Dual phase xenon detector capability:

- S1: prompt scintillation signal
- S2: delayed ionization signal
- ER/NR identification
- 3D reconstruction and fiducialization
- Calorimeter from sub keV to MeV
- Self shielding effect can effectively suppress the background

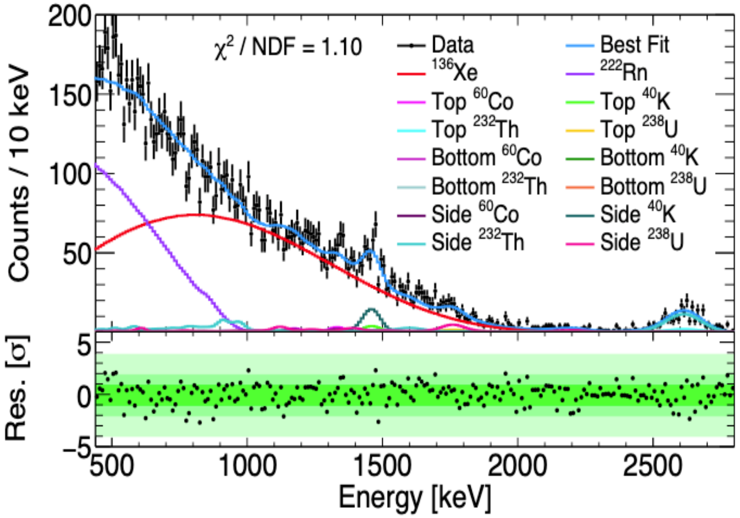
# $0\nu\beta\beta$ search in PandaX

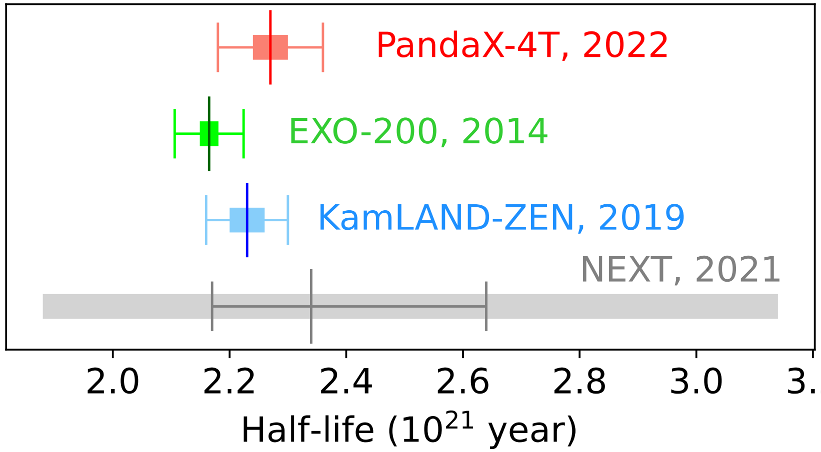


Chinese Physics C 43, 113001 (2019)

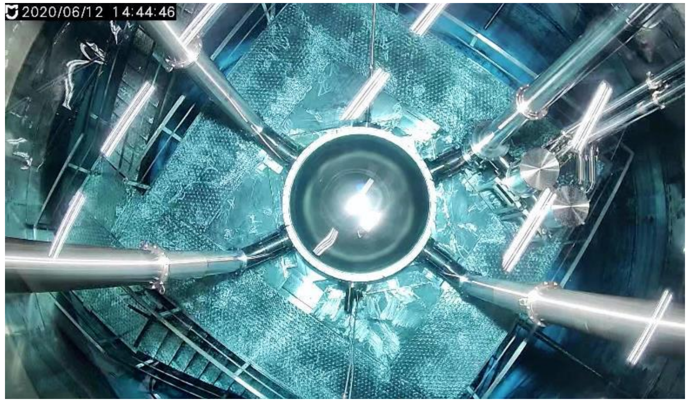
$^{136}$Xe $0\nu\beta\beta$ search by PandaX-II:

- 580kg natural xenon+403.1 day DM data
- First $^{136}$Xe $0\nu\beta\beta$ search from a DM detector ($2.4\times10^{23}$yr)
- Verified feasibility and potential of DM detector for $0\nu\beta\beta$ search





Research 2022



- $^{136}$Xe $2\nu\beta\beta$ half-life measured by PandaX-4T: $2.27 \pm 0.03(\text{stat.}) \pm 0.10(\text{syst.}) \times 10^{21}$ yr
- Comparable precision with leading results
- First such measurement from a DM detector with natural xenon
- 440 keV – 2800 keV range is the widest ROI

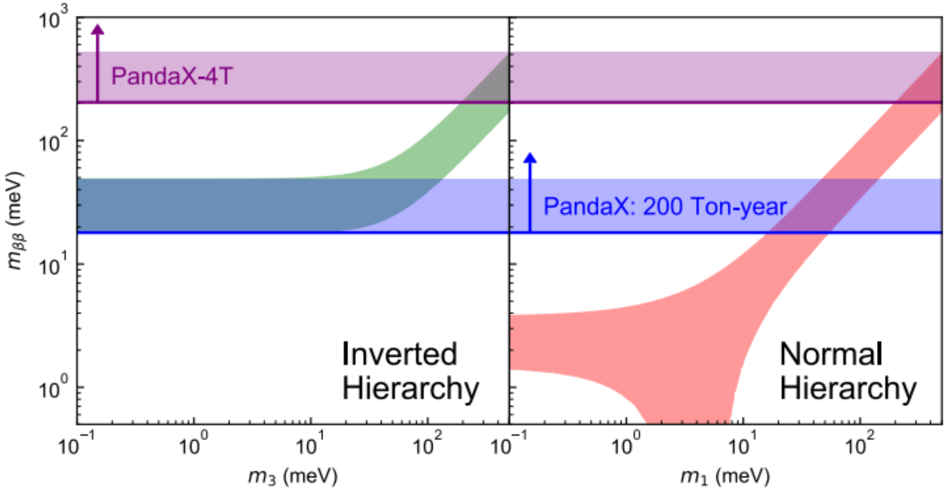
# Comparison with other natural LXe TPC for $0\nu\beta\beta$

| | Bkg rate (/keV/ton/y) | Energy resolution | FV mass (kg) | Run time | Sensitivity/Limit (90% CL, year) |
|---|---|---|---|---|---|
| PandaX-II | ~200 | 4.2% | 219 | 403.1 days | $2.4 \times 10^{23}$ |
| PandaX-4T | 9 | 1.9% | 649.7 ± 6.5 | 94.9 days | $> 10^{24}$ |
| XENON1T | ~20 | 0.8% | 741 ± 9 | 202.7 days | $1.2 \times 10^{24}$ |
| XENONnT | ~2 | 0.8% | 1128 | 1000 days | $2.1 \times 10^{25}$ |
| LZ | ~0.1 | 1% | 967 | 1000 days | $1.06 \times 10^{26}$ |
| DARWIN | ~0.004 | 0.8% | 5000 | 10 years | $2.4 \times 10^{27}$ |

Upgrade of PandaX-4T with improved PMT bases is planned

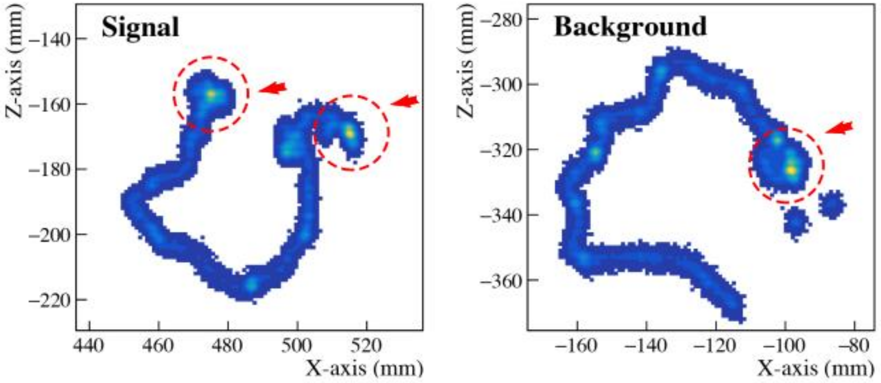
- Better energy resolution
- Better SS/MS discrimination

PandaX-xT: 47-ton xenon, including 43-ton sensitive volume

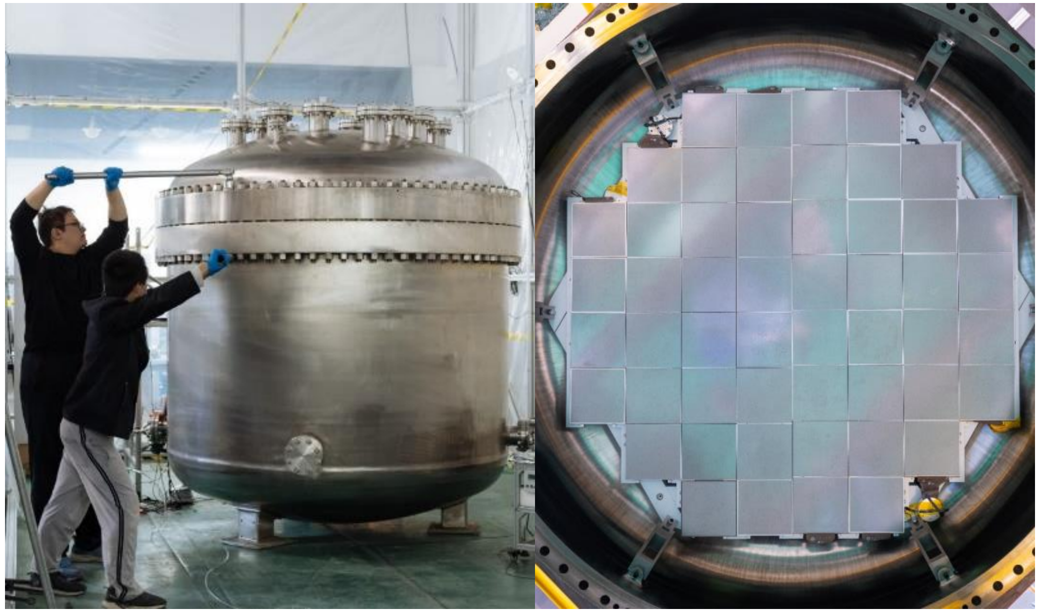


# PandaX-III experiment

- PandaX-III: high pressure (10 bar) gaseous TPC (140 kg $^{136}$Xe of 90%), 1.2m×1.6m active volume
- Readout plane: 52 20×20 cm$^2$ Micromegas modules of 3 mm strip (64 strips in each side)
- The topological information is powerful for signal and background discrimination
- Detection sensitivity: 2.7×10$^{26}$ yr with 5-year live time

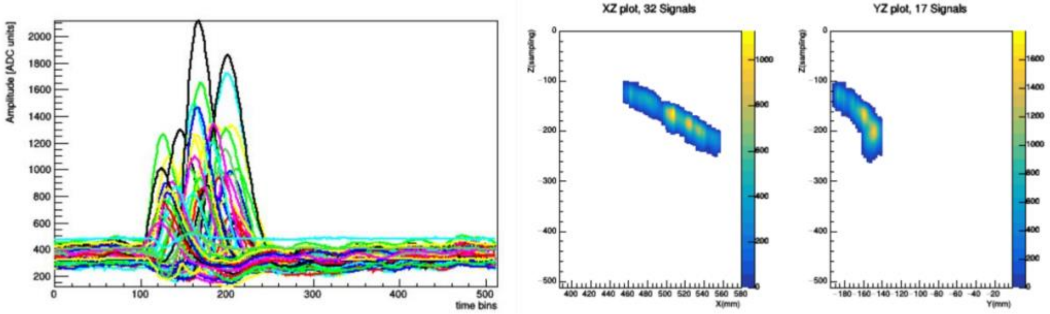


JHEP 06 (2021) 106



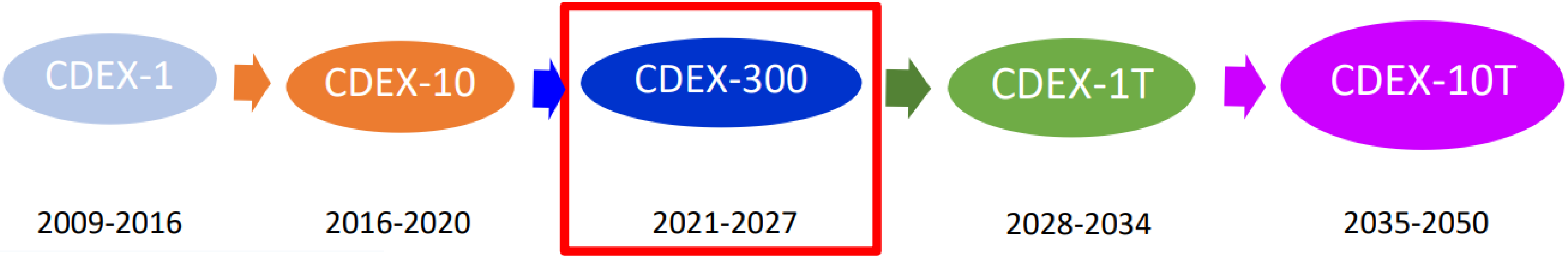
PandaX-III detector

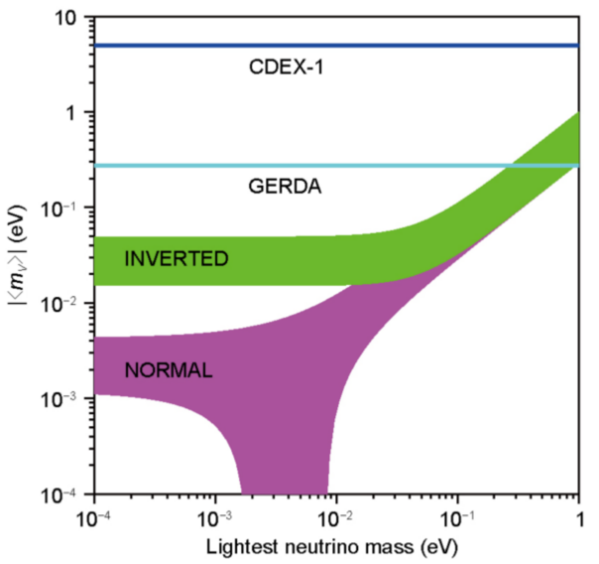
Micromegas



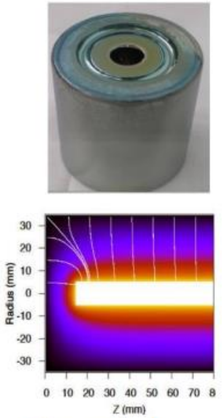
# CDEX experiment

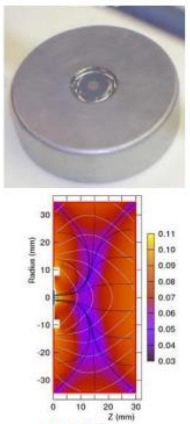
- HPGe detector for 0νββ: very good energy resolution and background control
- CDEX developed various HPGe detectors for 0νββ experiment
- CDEX has obtained 200kg of $^{76}$Ge (>86%) material, with 100kg from Russia and 100kg from China

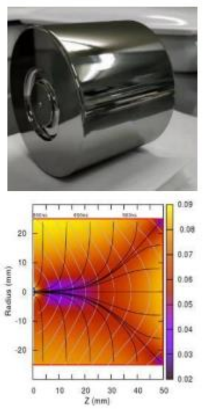


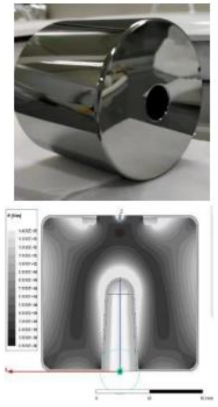


Sci. China PMA. 60, 071011 (2017)


Co-axial

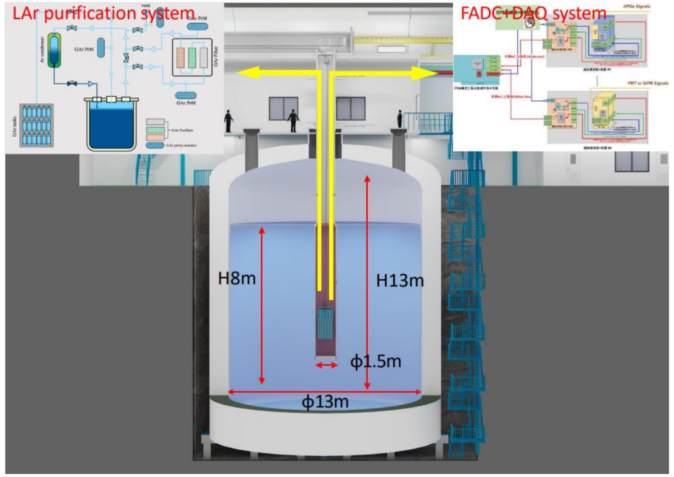

BEGe

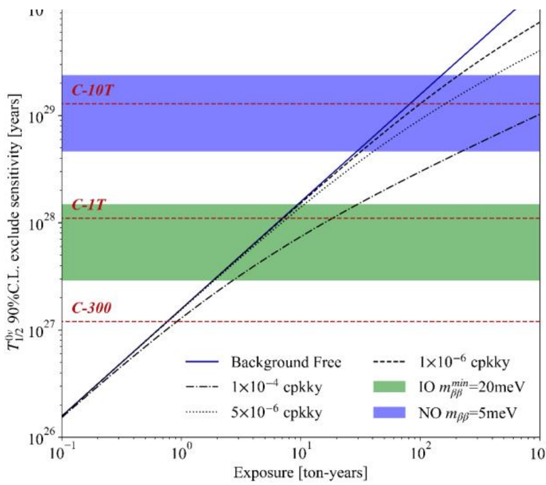

PCGe

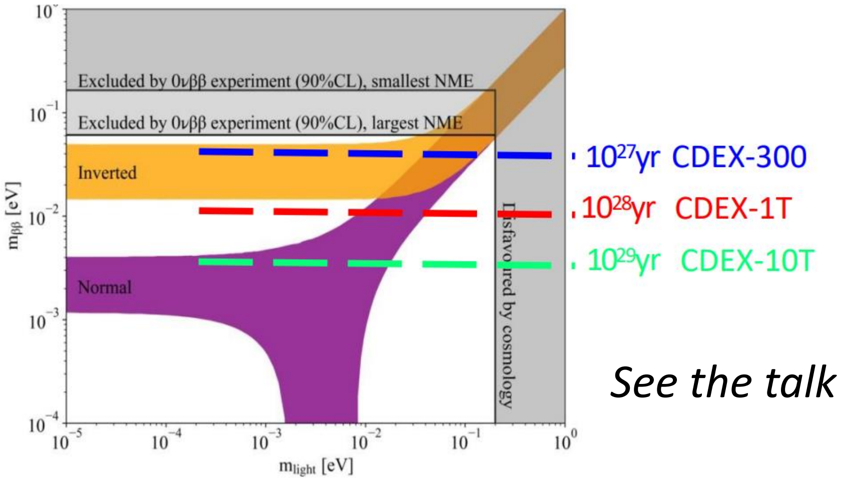

ICPC

# CDEX experiment

| Parameter | CDEX-300 | CDEX-1T | CDEX-10T |
|---|---|---|---|
| $^{76}$Ge mass | 225 kg | 1000 kg | 10000 kg |
| BI@2039keV | $10^{-4}$ cpkky | $5\times10^{-6}$ cpkky (20 times lower) | $1\times10^{-6}$ cpkky (5 times lower) |
| Run time | Construction 5y (2021-2027)<br>Run 5y (2027-2031) | Construction 5y (2028-2034)<br>Run 5y (2035-2039) | Construction 5y (2035-2039)<br>Run 10y (2040-2050) |
| Exposure | >1 t·y | 5 t·y | 100 t·y |
| $T_{1/2}$ | $>1.0\times10^{27}$y | $>1.0\times10^{28}$y | $>1.0\times10^{29}$y |
| $m_{\beta\beta}$ | <[28.5~68.0] meV | <[11.6~26.4] meV | <[2.9~6.7] meV |





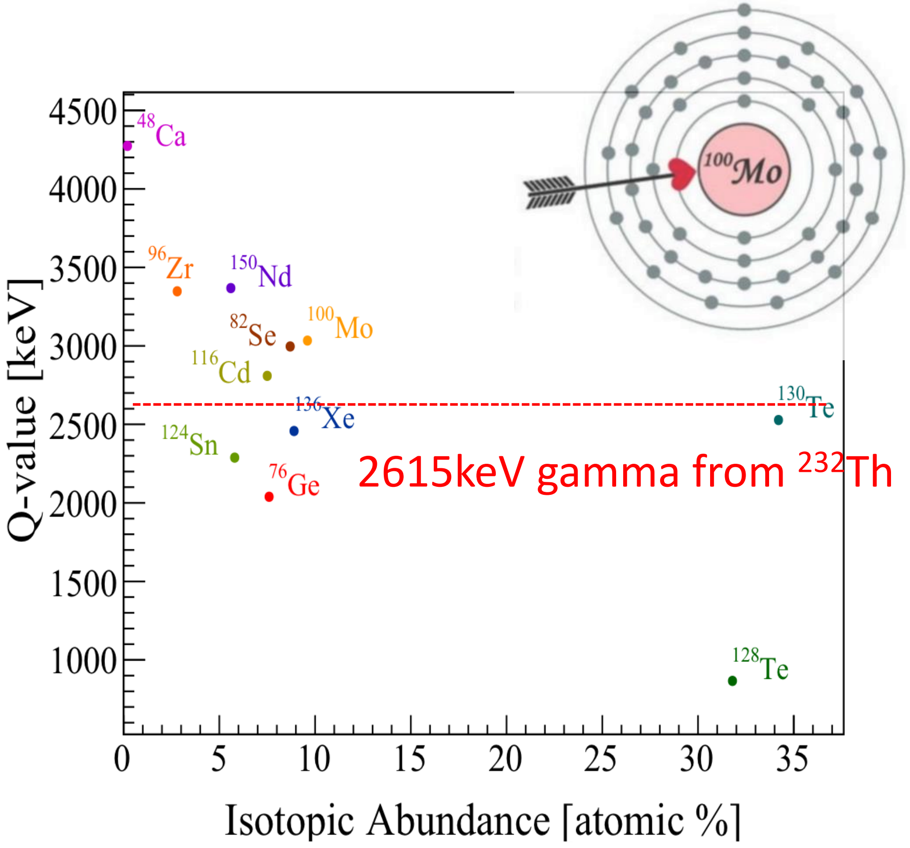


*See the talk of Wenhao Dai*

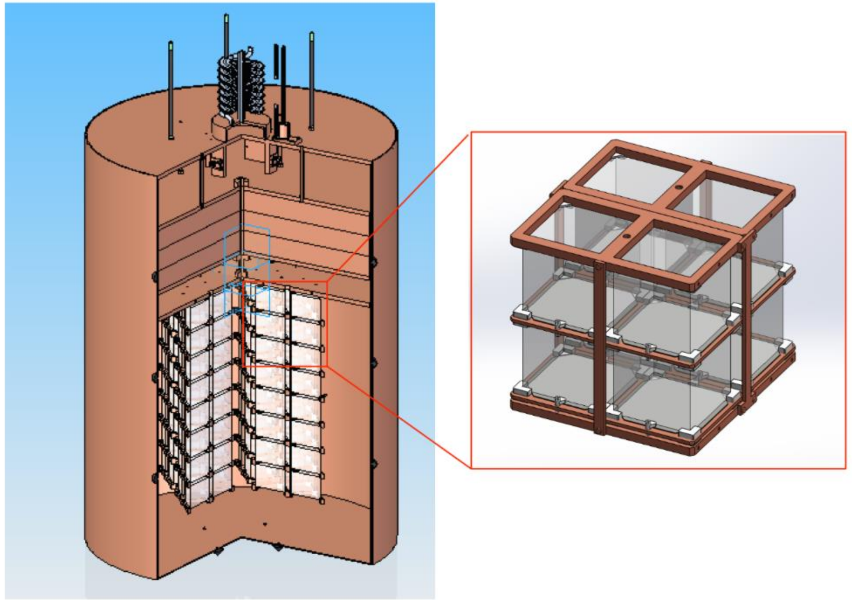
# CUPID-CJPL experiment

CUPID-CJPL: A $^{100}$Mo-based scintillating bolometer experiment for 0νββ search at CJPL-II

- $^{100}$Mo-enriched LMO crystals : high $Q_{\beta\beta}$ (~3034 keV)
- High energy resolution $\Gamma_Q$~0.2% (FWHM), $R_{2\nu\beta\beta/ROI}$ $<10^{-5}$
- Light-heat dual readout (particle identification)

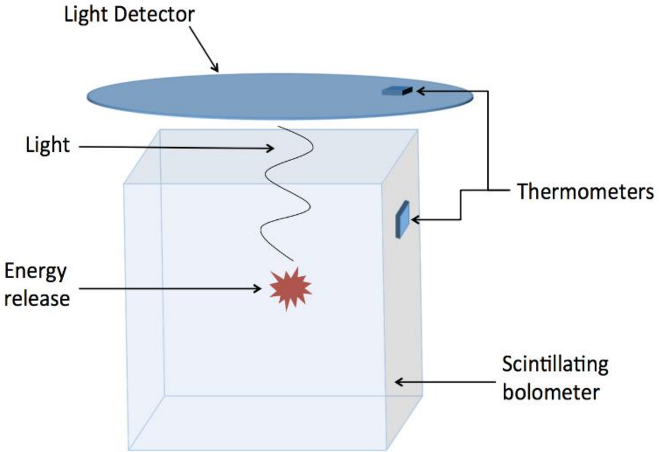


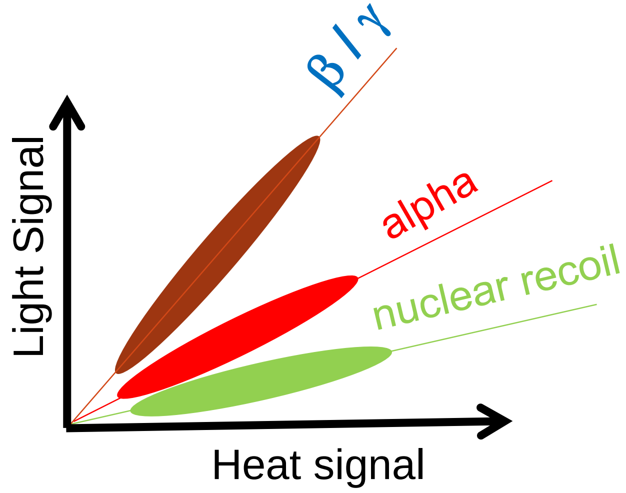
2615keV gamma from $^{232}$Th



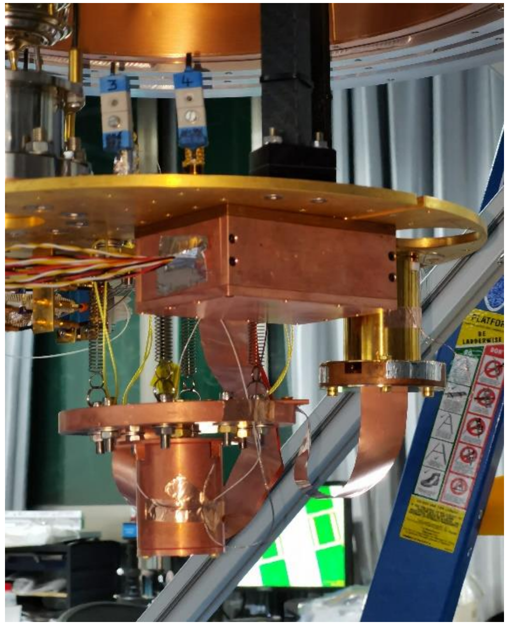
A bolometer experiment for 0νββ like CUORE

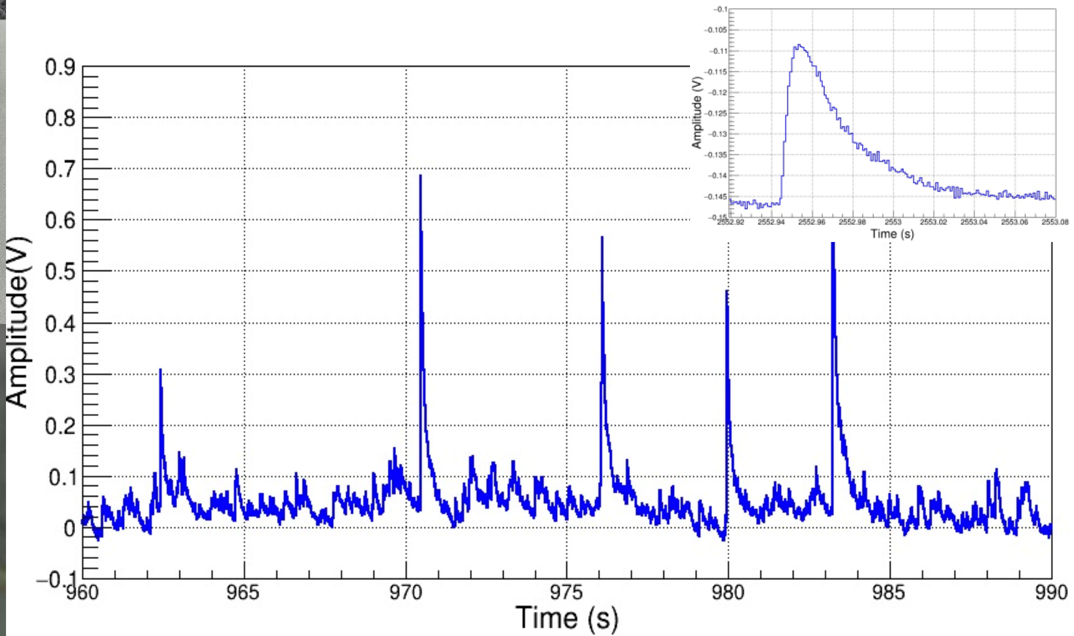
*See the talk of Claudia Tomei and Long Ma*





# CUPID-CJPL experiment

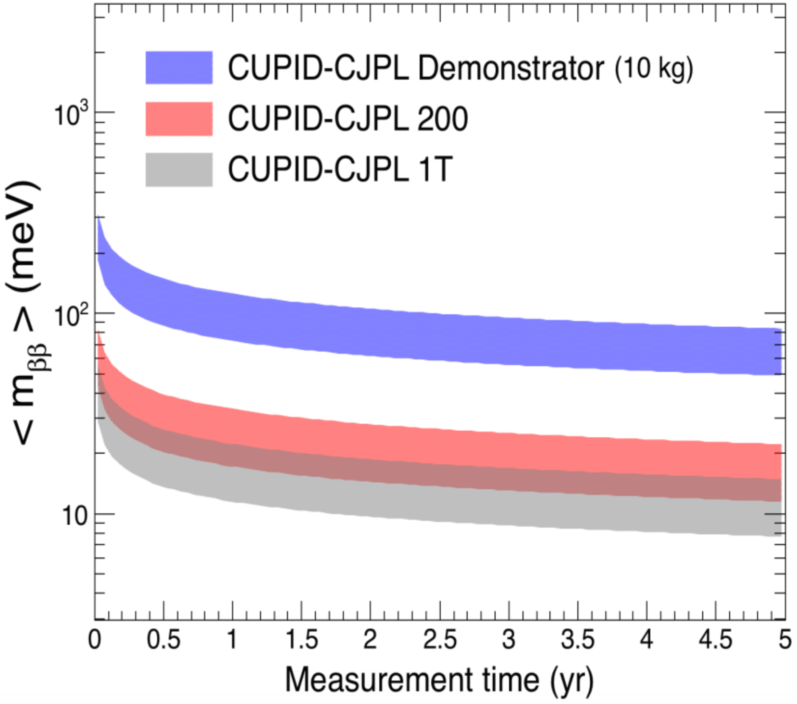


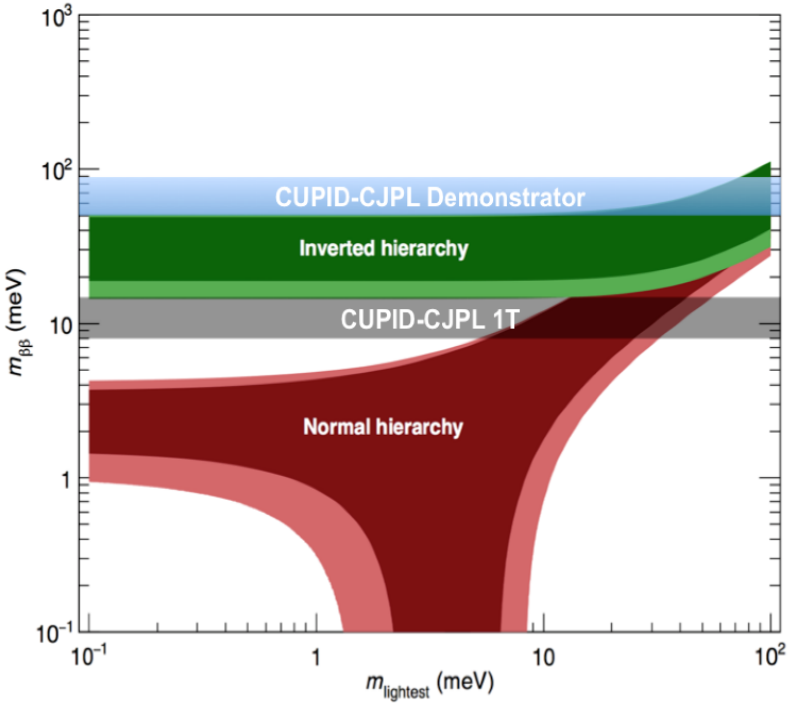


- **Crystal test at USTC/FDU:**
  - **USTC-DR**: commercial system for crystal test at ground
  - **FDU-DR**: customized system for underground experiment
- **Underground crystal test (2023.12):**
  - in CJPL with passive shielding

# CUPID-CJPL Roadmap

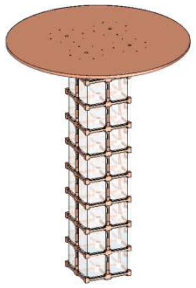
- 10 kg prototype experiment
  - demonstrate CUPID technologies
- 200 kg / 1T experiment
  - competitive results
  - probe effective mass down to 10meV or lower



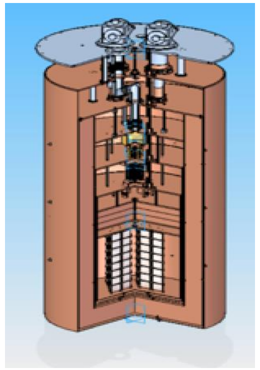


**Crystal testing**
(2023-2025)
6-12 natural crystals

**CUPID-CJPL Demo** (2025-2028)
10 kg enriched crystals

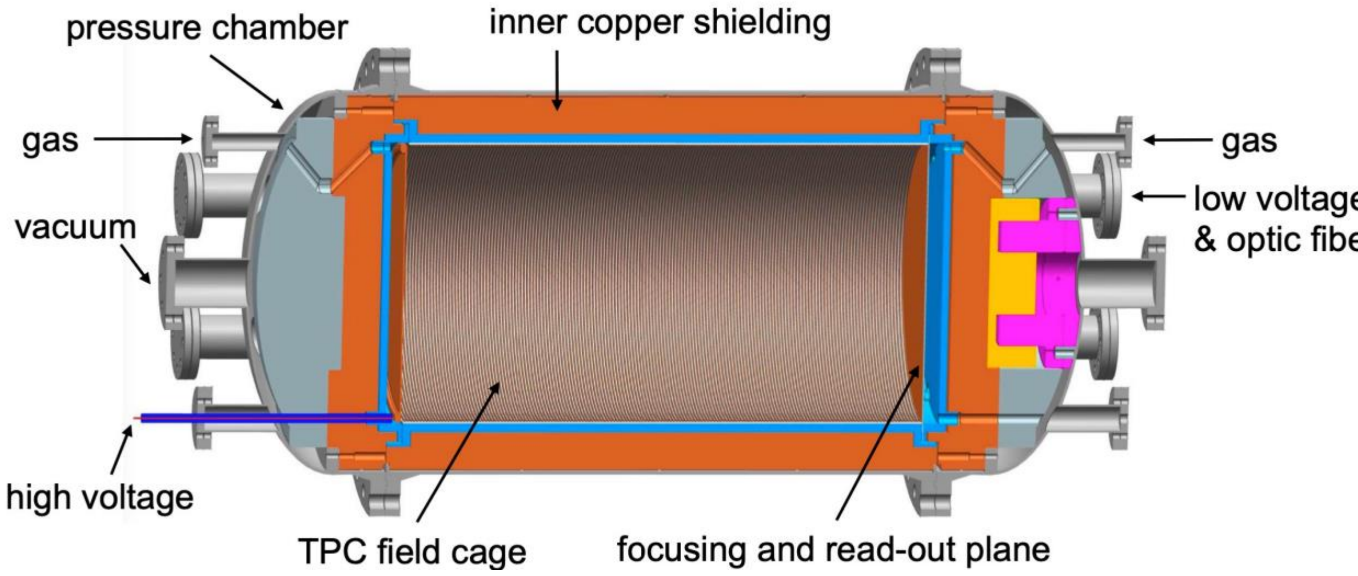


**CUPID-CJPL-200/1T**
(2028+)
> 200 kg enriched crystals

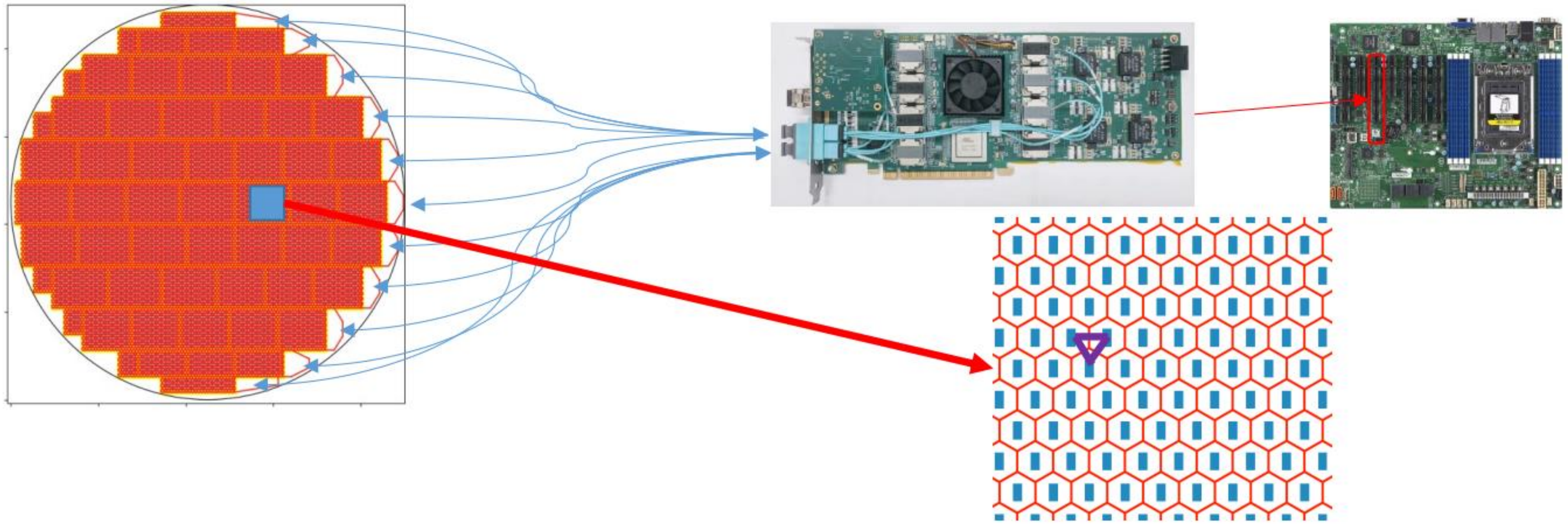


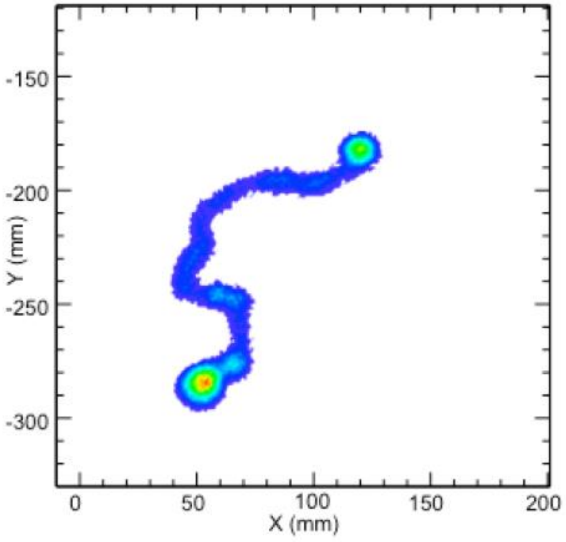
# NνDEx experiment

- Ion TPC using high-pressure $^{82}\mathrm{SeF}_6$ gas (10 bar) and the top-metal silicon sensors for read-out
- NνDEx-100 with 100 kg of $\mathrm{SeF}_6$ gas, is being built and planned to complete with installation at CJPL around year 2025
- Background suppression using event topology information



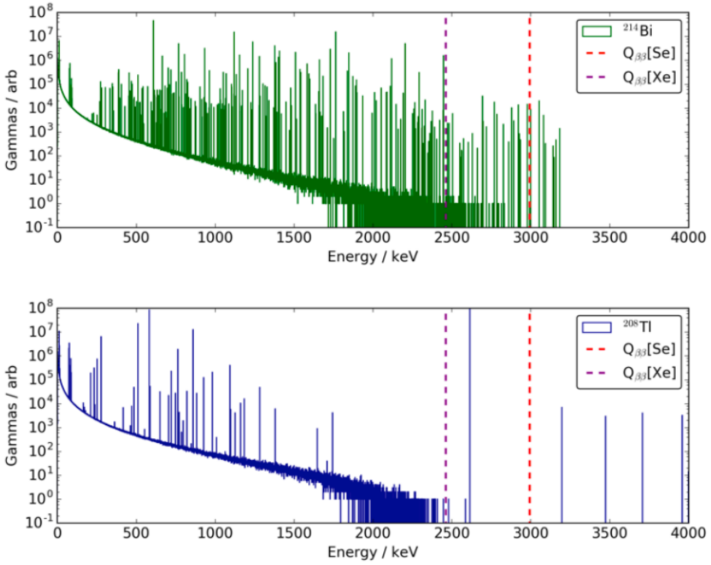
arXiv : 2304.08362 (NvDEx-100 CDR)





# N$\nu$DEx experiment

- High Q value (2.996 MeV) of $^{82}$Se and low background budget
- N$\nu$DEx-100 can achieve very low background level of 0.05 cts / yr in ROI
- $T_{1/2}$ sensitivity of $4 \times 10^{25}$ ($4 \times 10^{26}$) yr at 90% CL after 5 years of running, using 100 kg of natural SeF$_6$ (enriched $^{82}$SeF$_6$) gas



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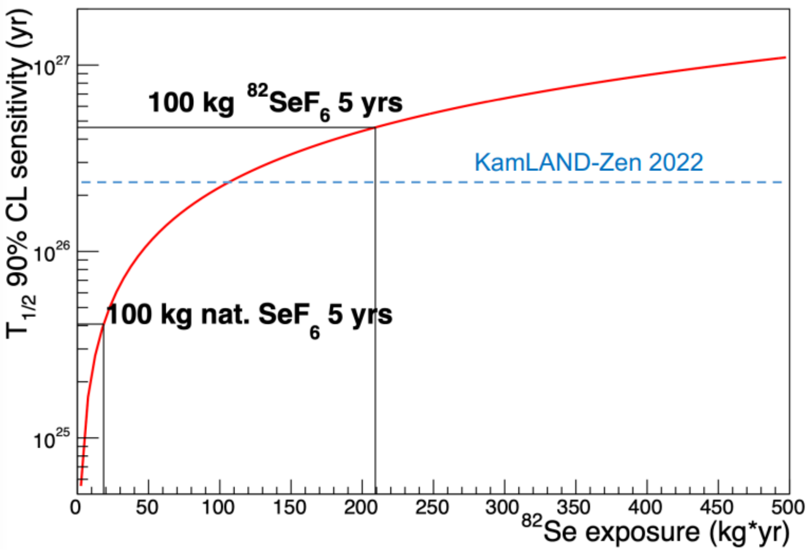
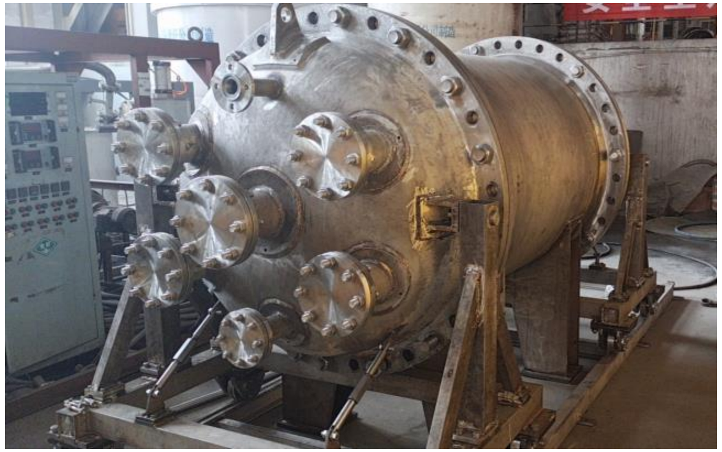
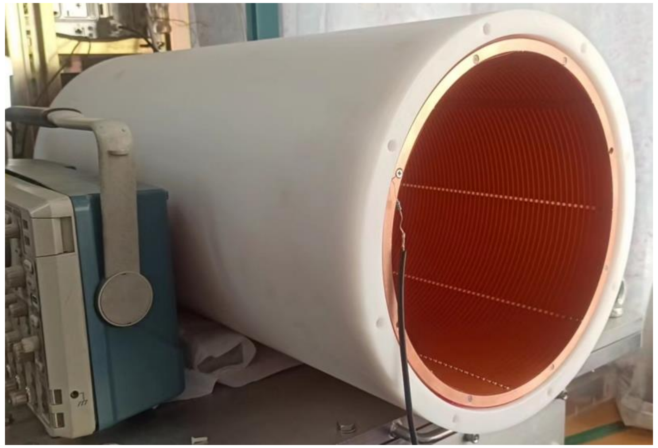
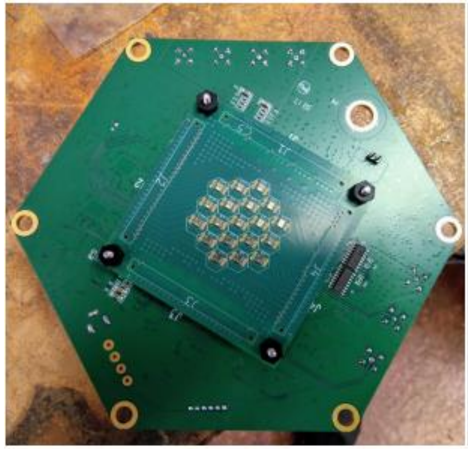
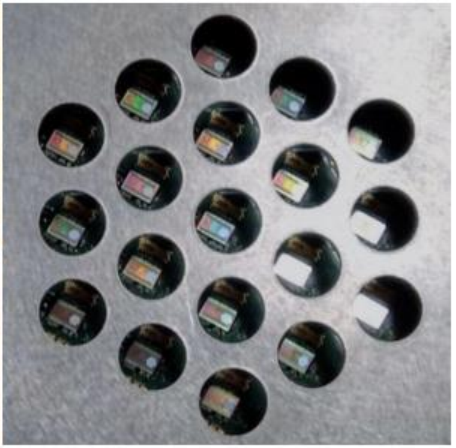


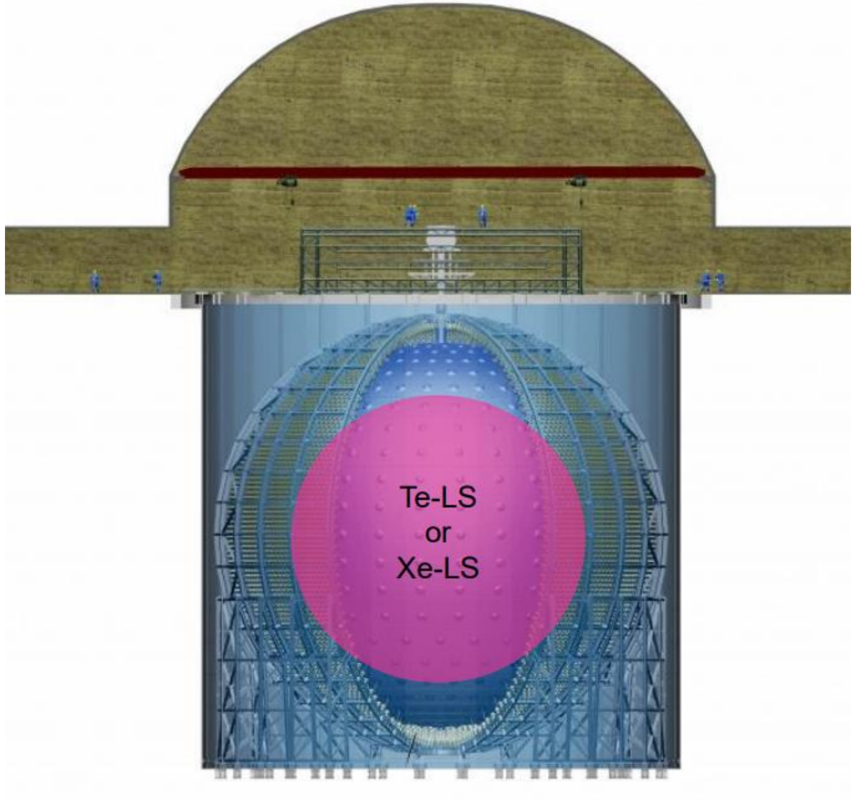
# JUNO- $0\nu\beta\beta$ experiment

JUNO: 20 kton multi-purpose neutrino detector with the primary goal : *See the talk of Yee Bob Hsiung*

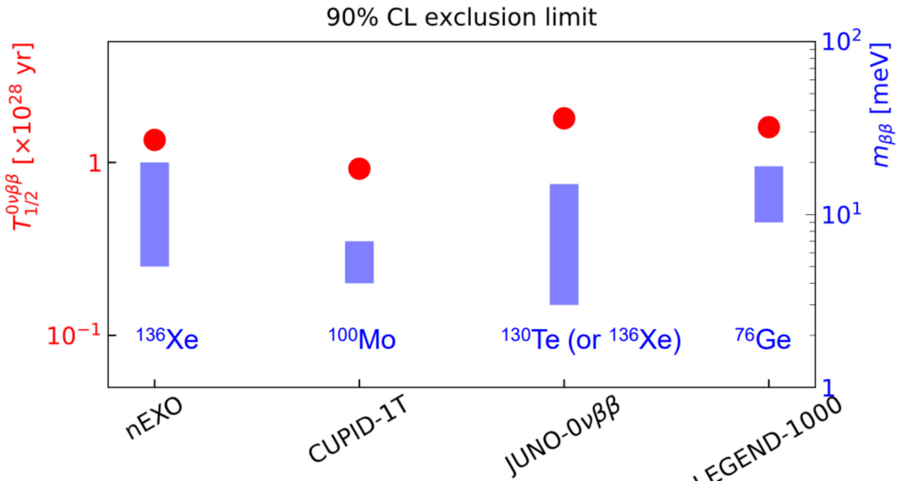
- Determine Neutrino mass ordering
- Precision measurement of neutrino oscillation

JUNO offers an unique opportunity to search for $0\nu\beta\beta$ (JUNO- $0\nu\beta\beta$ ):

- 20 kton LS → 100-ton scale isotope loading (e.g., Tellurium)
- Energy resolution < 3% @ 1 MeV → 2.4x better than KamLAND-Zen *See the talk of Nanami Kawada*
- JUNO- $0\nu\beta\beta$ has the potential to explore the |mββ|~meV region w/ >100 tons of $0\nu\beta\beta$ isotope



Concept of the experiment



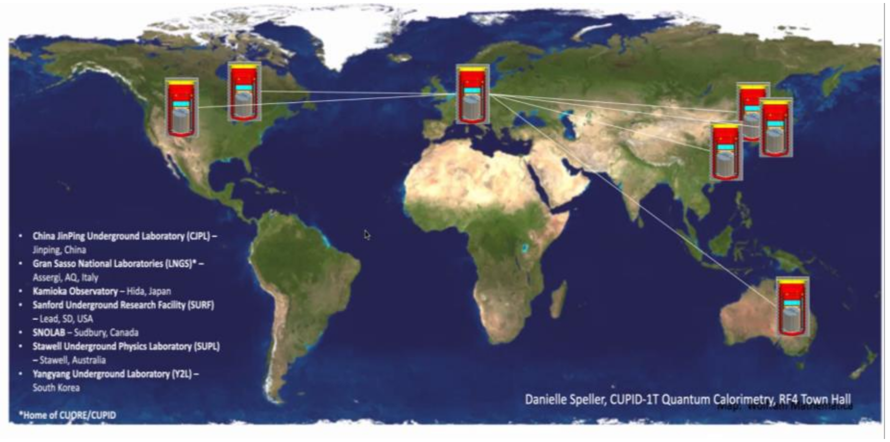
Searching for $0\nu\beta\beta$ decays in JUNO, Snowmass2021 LOI Snowmass2021 Topical group report for NF05, arXiv 2209.03340

# Summary

- Searching for 0νββ decay is the most sensitive to probe the nature of neutrino mass and absolute neutrino masses
- 0νββ experiments in China
  - ➢PandaX experiment: PandaX-4T → PandaX-xT
  - ➢CDEX experiment: CDEX-300→CDEX-1T→CDEX-10T
  - ➢CUPID-CJPL experiment: CUPID-CJPL 10 kg →200kg/1T
  - ➢NvDEx experiment: 100 kg natural $SeF_6$ or enriched $^{82}SeF_6$
  - ➢JUNO-0νββ experiment: 100-ton scale isotope of Te or Xe

# CUPID-CJPL

## International CUPID collaboration

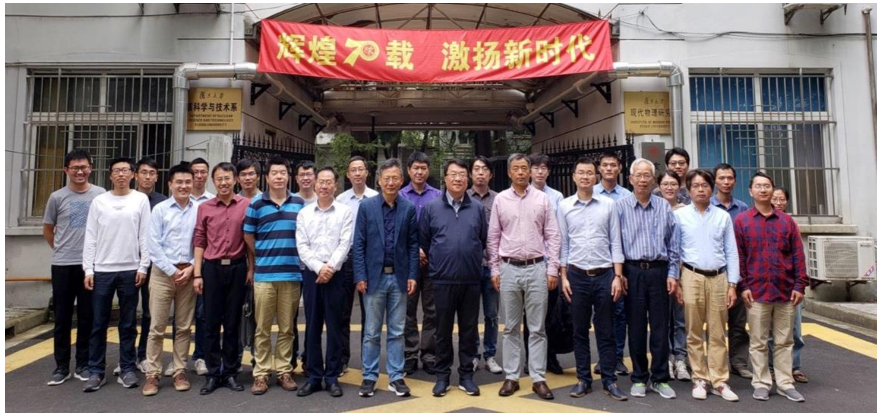


Danielle Speller, CUPID-1T Quantum Calorimetry, RF4 Town Hall

**International Collaboration:**
**CUPID – Italy**
**CUPID – US**
**CUPID – France**
**CUPID – China**

**~ 30 institutes, >150 collaborators**

## CUPID-China collaboration

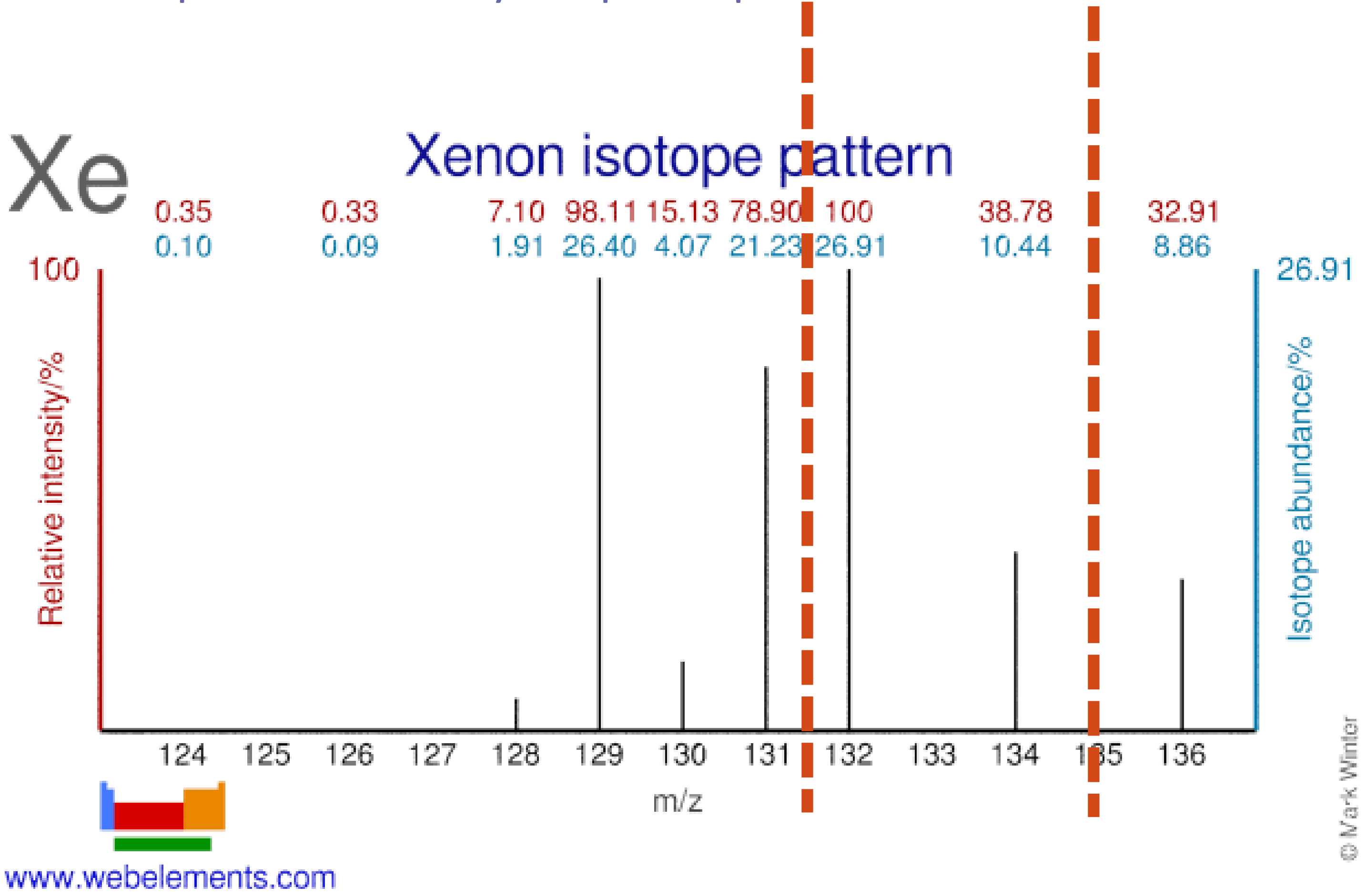


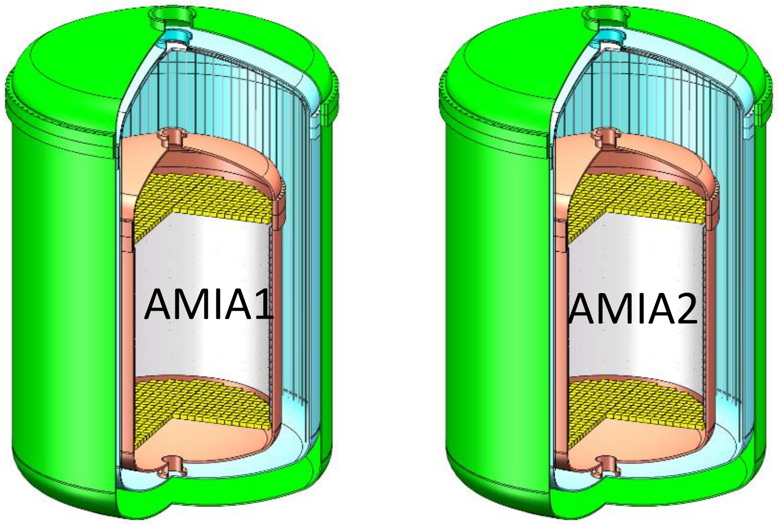
**~ 9 institutes, > 40 collaborators**

**CUPID-China is actively collaborating with CUPID- France, Italy and US**

# Possible isotope seperation/enrichment

- Xenon with artificially modified isotopic abundance (AMIA), either via a split of odd and even nuclei, or further enrichment of Xe-136
- To improve sensitivity to spin-dependence of DM-nucleon interactions and NLDBD

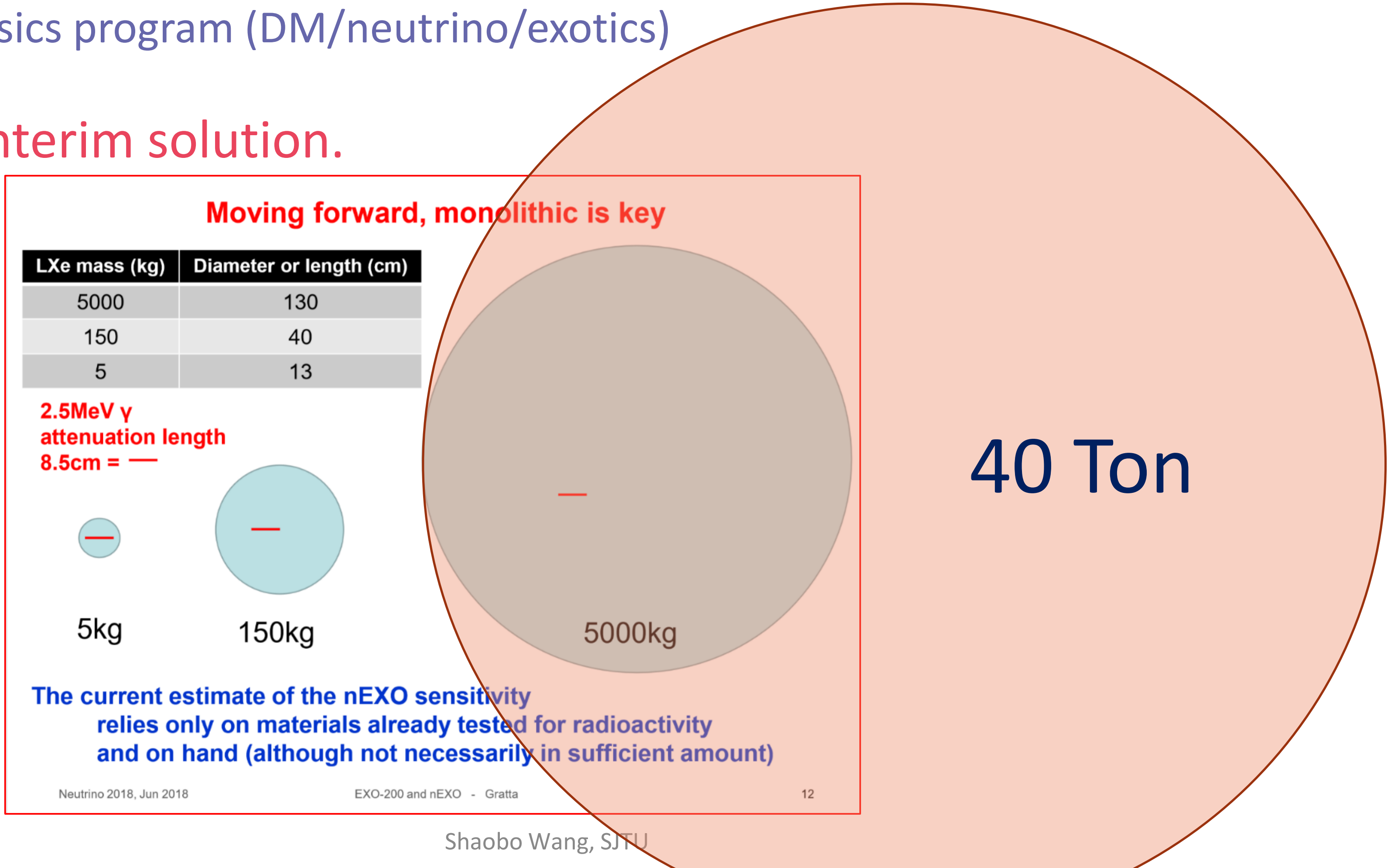




# Major advantages of natural xenon measurement

- Fiducialization (and MS/SS discrimination) to suppress background.
- Robust determination of background throughout the FV
- Extremely versatile physics program (DM/neutrino/exotics)

⇒ A very appealing interim solution.



**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

# JUNO- $0\nu\beta\beta$ experiment

- Liquid scintillator is a competitive technology to go beyond $10^{28}$ yr of $\boldsymbol{T}_{1/2}$
- By 2030, the current LS experiments (KamLAND, SNO+) may reach $10^{27}$ yr, next generation projects (LEGEND, nEXO, CUPID) may start running
- JUNO- $0\nu\beta\beta$ has the potential to explore the |mββ|~meV region w/ >100 tons of $0\nu\beta\beta$ isotope