Status of Asian Underground Labs

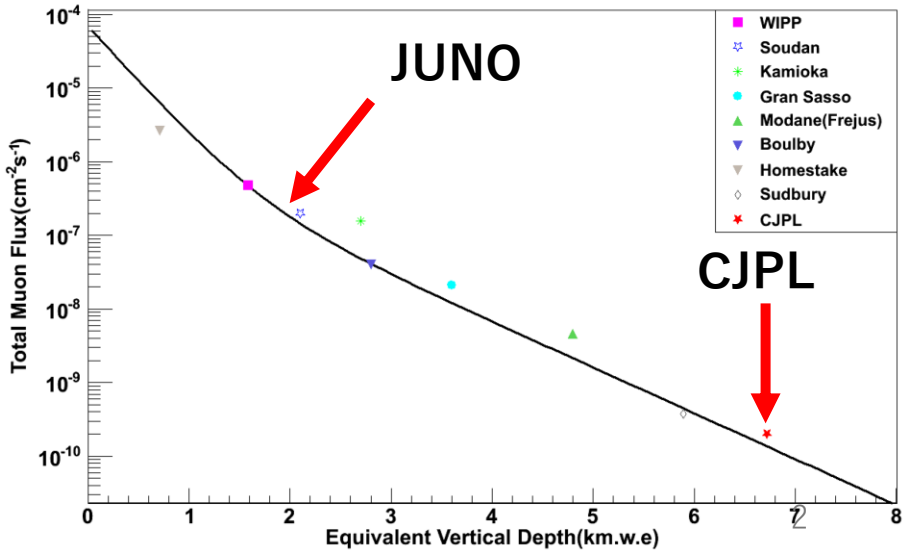
2024/10/01 (9:45～10:10)

LRT2024 (Krakow, Poland)

Atsushi Takeda (Kamioka Observatory, ICRR, U. of Tokyo)

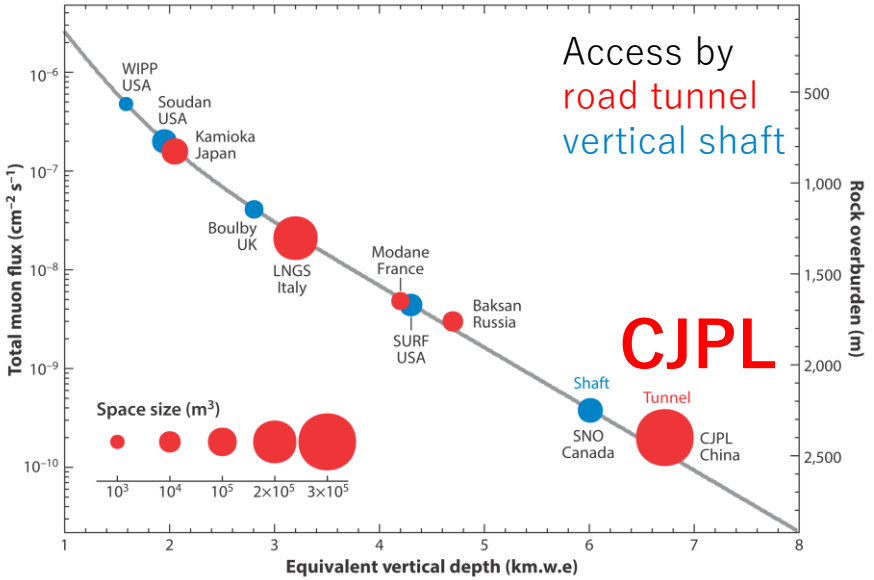
Underground labs in China

- **CJPL**
  - China Jinping Underground Laboratory
  - 2400 m overburden
  - 330k m^3 volume
- **JUNO**
  - Jiangmen Underground Neutrino Observatory
  - 650 m overburden

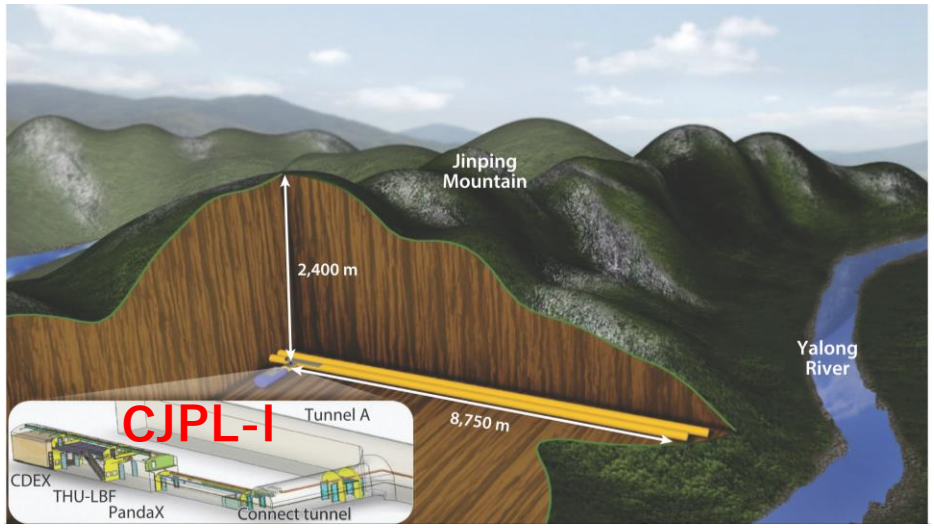


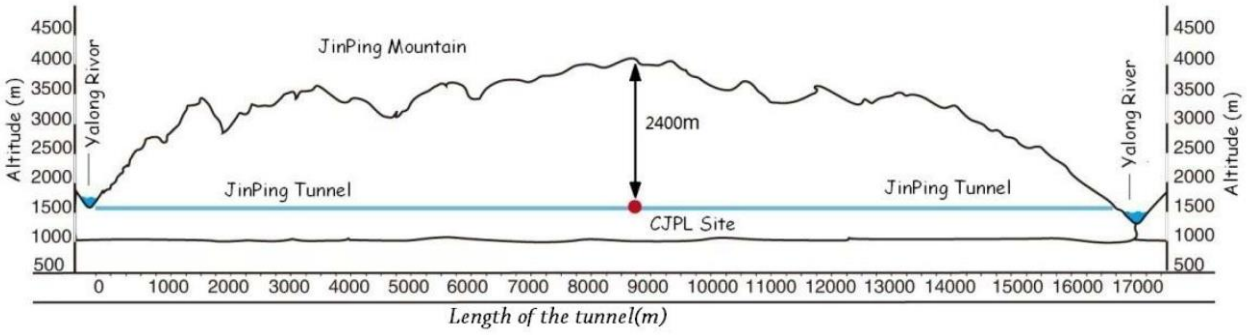
China JinPing underground Laboratory (CJPL)

- Located in the Jinping tunnel in Sichuan Province since 2010.
- The deepest rock overburden (2400 m) and largest space by volume (~330k m^3) in the world.
- Marble has lower U/Th than igneous rocks, resulting in lower Rn concentrations in the air.
- Two DM experiments (CDEX and PandaX) are running.
- **CJPL-I**
  - Started in Dec. 2010.
  - Main hall: 6.5m (W) × 6.5m(H) × 42m(L).
  - THU-LBF (radio-assay): Four Ge detectors (GeTHU-1~4)
- **CJPL-II**
  - Started in 2017.
  - Total volume: ~300k m^3 with 4 main halls (A~D) of 14m(W) × 14m(H) × 130m(L).



Cheng et al., Annu. Rev. Nucl. Part. Sci. 67:231 (2017)

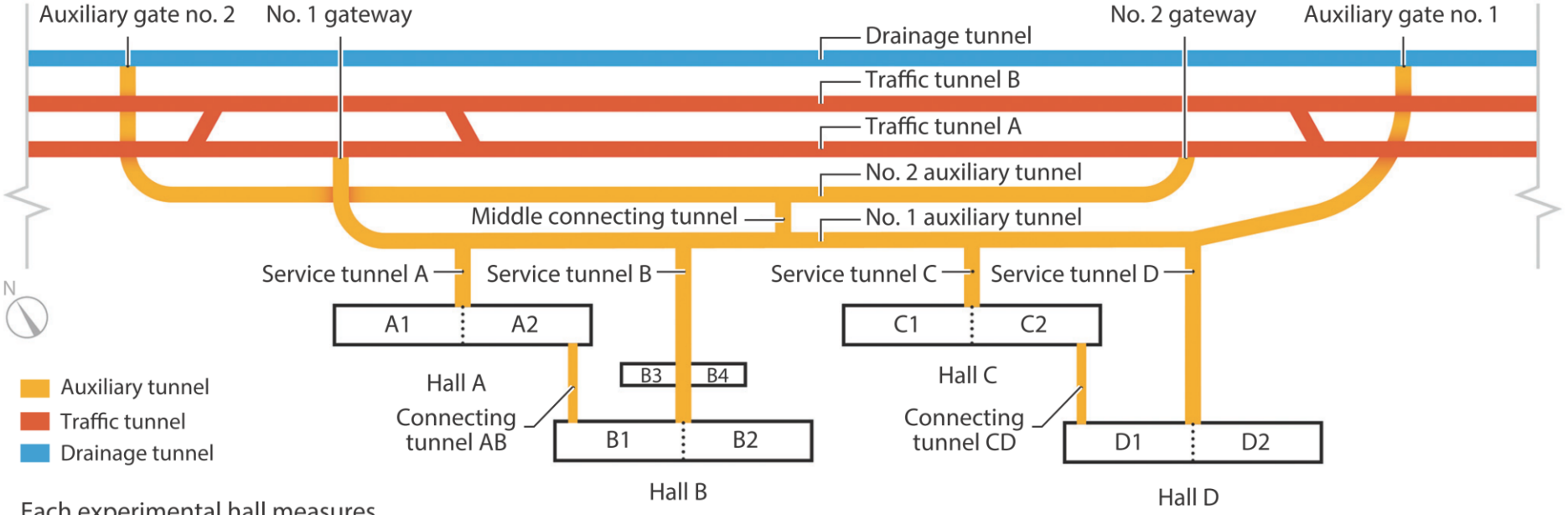


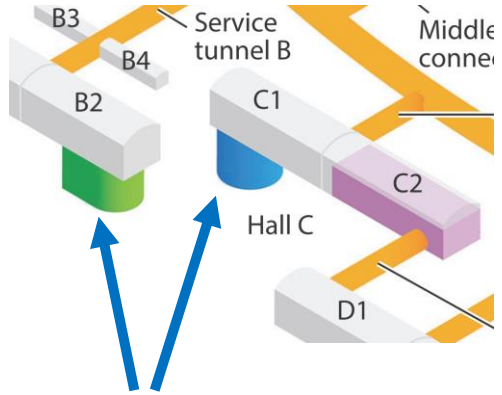


CJPL is located in the center of Jinping tunnel (17 km long).

CJPL-II Project

- It is located 500 m west of CJPL-I along the same road tunnel.
- Total volume: ~300k m^3 with 4 main halls (A~D) of 14m(W)×14m(H)×130m(L) including internal traffic tunnels and common facilities.
- Two pits: Hall B pit (27m(L)×16m(W)×14m(D)) and Hall C pit (18m(dia.)×18m(D)).
  - Hall B: PandaX-4T
  - Hall C: CDEX-50, CDEX-300ν





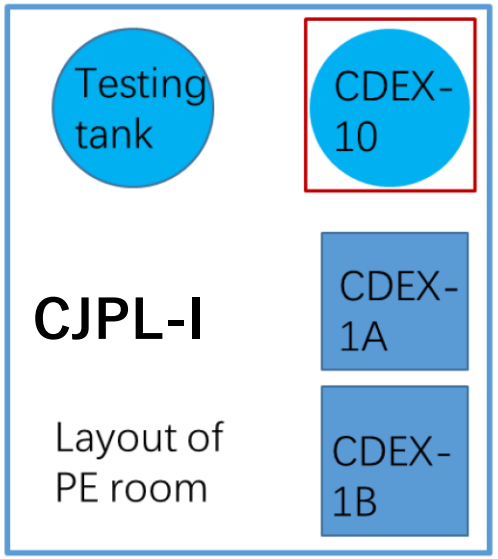
There are two pits in Hall B2 and C1.

Cheng et al., Annu. Rev. Nucl. Part. Sci. 67:231 (2017)

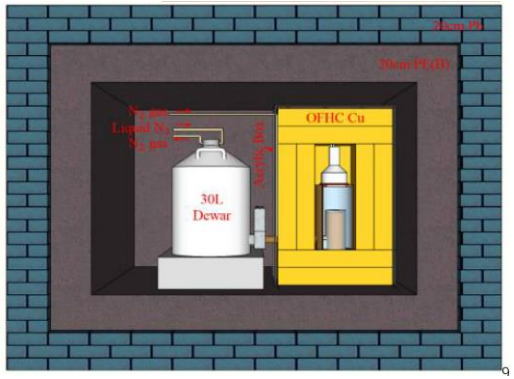
China Dark matter Experiment (CDEX)

https://cdex.ep.tsinghua.edu.cn/

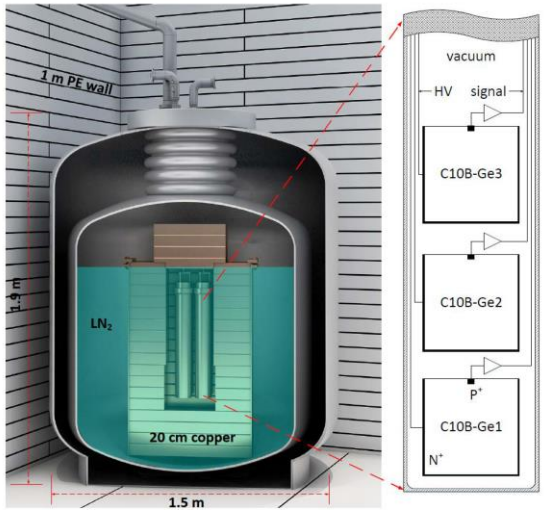
- P-type Point-Contact (PPC) Ge detector.
- Targets: Direct detection of light DM + Ge-76 0νββ.
- CJPL-I
  - CDEX-1 (2009-2016): Development of PPC Ge detector.
  - CDEX-10 (2016-2022): Performances of Ge array immersed in liquid nitrogen.
- CJPL-II
  - CDEX-50 (2021-202X): 50 kg Ge detector arrays for DM searches.
  - CDEX-300ν (2021-202X): 300 kg enriched Ge detector arrays for 0νββ experiments.



CDEX-I

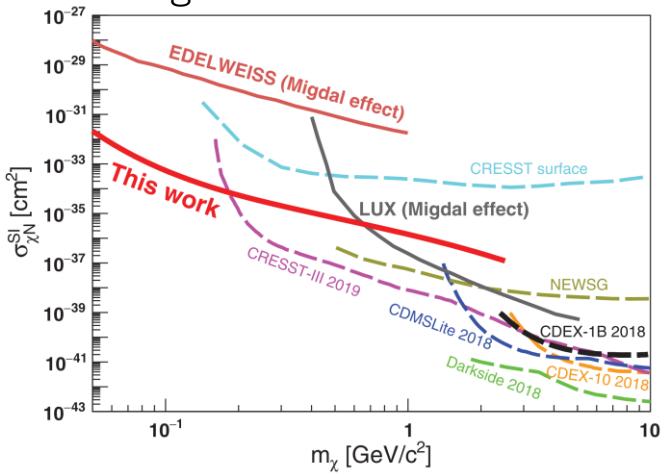


CDEX-I0

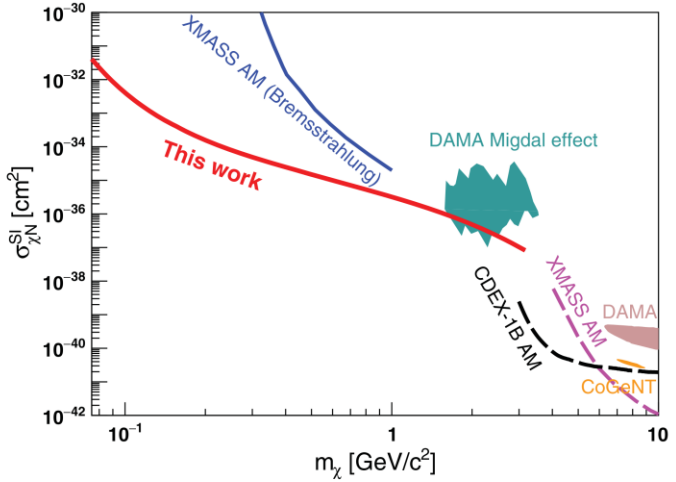


Results from CDEX-1B

Migdal effect



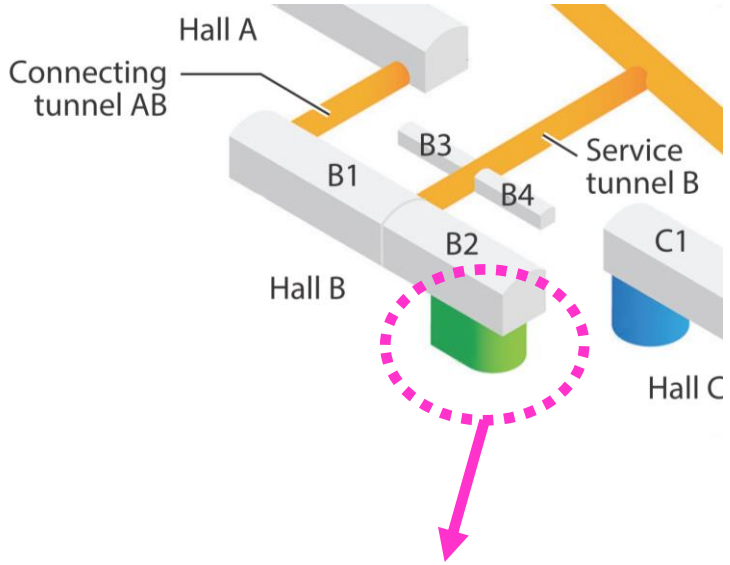
Annual modulation



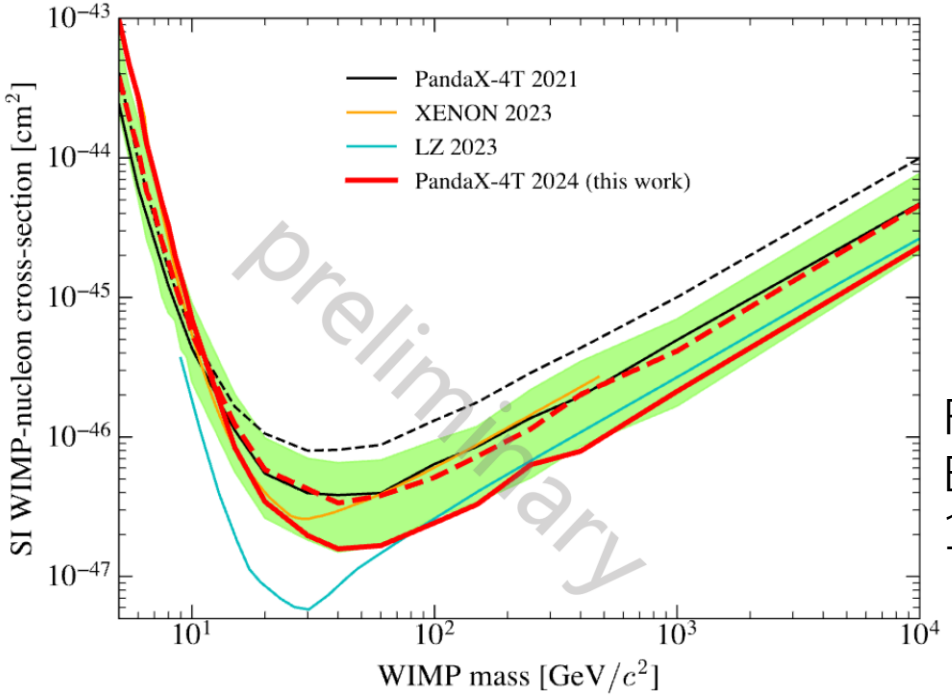
Phys. Rev. Lett. 123, 161301 (2019)

PandaX

- Direct dark matter search experiment using liquid xenon TPC.
- PandaX-4T
  - 2020/11-2021/04: Commissioning (**Run 0**)
  - 2021/07-2021/10: Tritium removal
  - 2021/11-2022/05: Physics run (**Run 1**)
  - 2022/09-2023/12: CJPL B2 hall renovation, detector upgrade
  - Current: resuming physics data-taking



Qing Lin, IDM2024, July 8, 2024.



Run 0+1 (1.54 ton-year)
Best constraint > 100 GeV
1.6×10^{-47} cm^2 @40GeV/c^2

Jiangmen Underground Neutrino Observatory (JUNO)

- Proposed as a reactor neutrino experiment in 2008 and approved in 2013.
- ~650 m overburden.
- Vertical shaft (564 m) and slope tunnel (1266 m)
- Construction in 2015-2024:
- Main goals: neutrino mass ordering
- Targets: solar-, supernova-, atmosphere-, geo-neutrinos, proton decay, exotic searches.

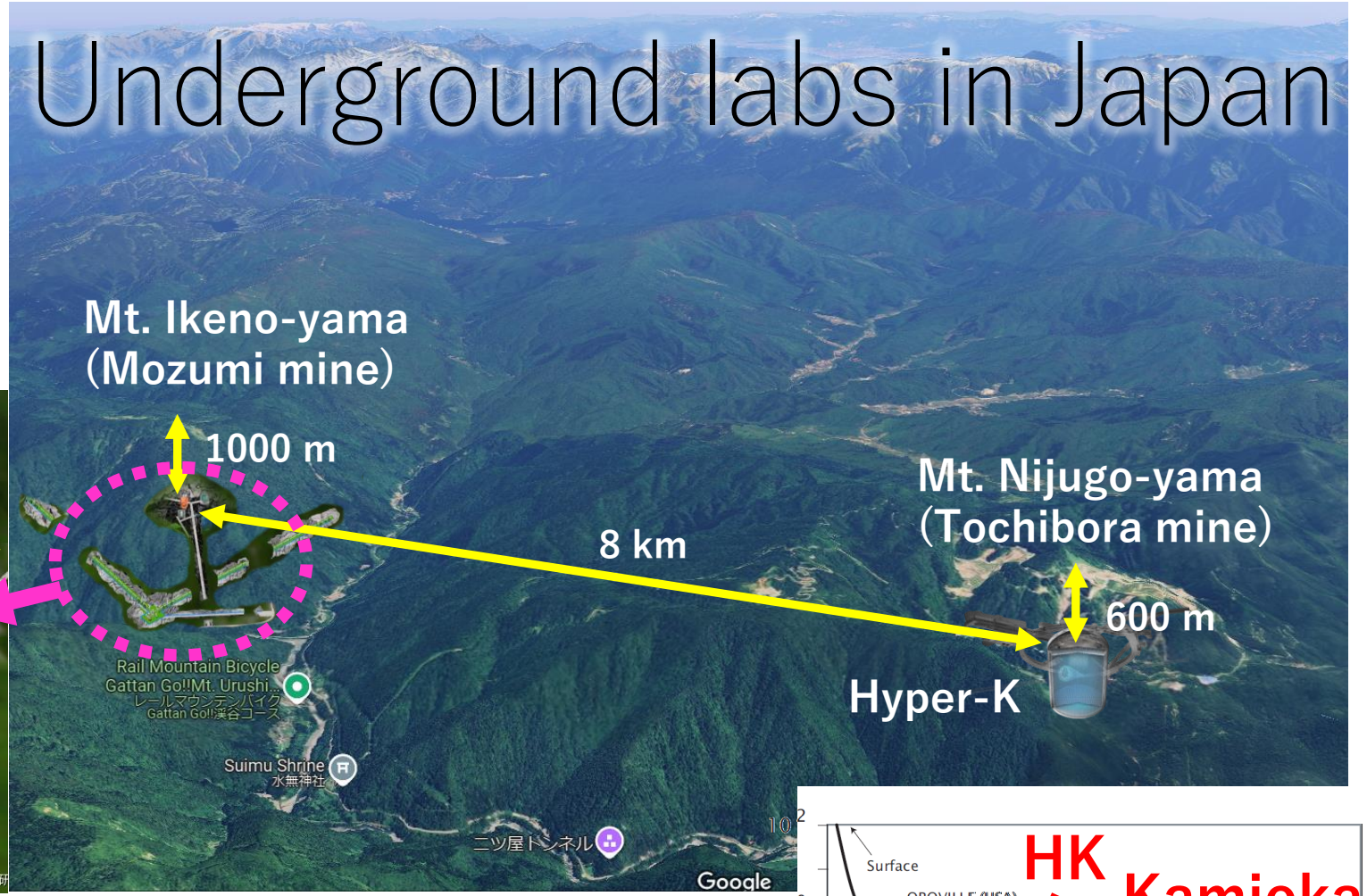
- **JUNO detector**
  - Next step of the Daya Bay experiment using reactor neutrinos and liquid scintillator
  - To determine the mass ordering
  - Equal baseline to two reactor power plants, Yangjian and Tajshan.
  - Multiple baseline reactors may wash out the oscillation structure (difference < 500 m).

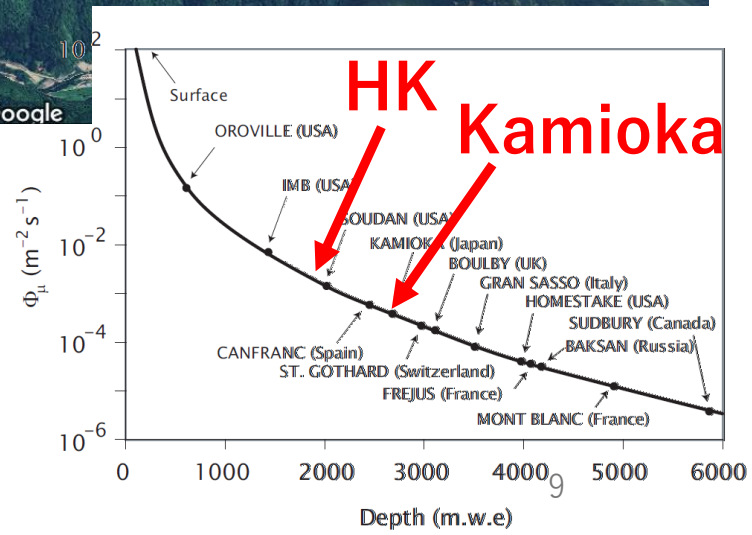
JUNO radioactivity control

The JUNO collaboration, Journal of High Energy Physics, 11 (2021) 102

- **HPGe**
  - Screening stainless steels from truss, bars and nodes, glass from LPMTs and SPMTs, electronics, and calibration parts, etc.
  - CJPL, Modane, LNGS, JHEP, Milano-Bicocca, CENBG Bordeaux
- **Neutron Activation Analysis (NAA)**
  - Quality control of acrylic, LAB, Teflon, and PPO.
- **ICP-MS**
  - Screening the surface treatment of acrylic panels and other critical materials.
- **Low background radon facilities**
  - Monitoring Rn concentration in the ultra-pure water of the water Cherenkov detector and sealed nitrogen gas in top of water tank.

Underground labs in Japan





- Kamioka underground (Mozumi mine)
  - 1000 m overburden
  - Super-K, KamLAND, EGADS, CADLES, NEWAGE, XMASS, KAGRA, CLIO
- Tochibora mine
  - 600 m overburden
  - 8 km far from Mozumi mine.
  - It is now being excavated.

Kamioka underground facilities (Mozumi mine)

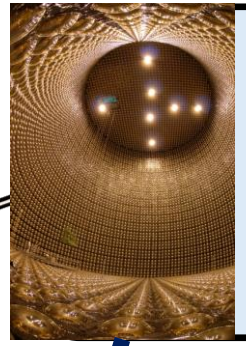
KamLAND (Tohoku Univ.)

- 1 kton liquid scintillator detector.
- Reactor, geo, low-energy astrophysical neutrinos, ^{136}Xe 0νββ decay.

Details of KamLAND area → Ichimura-san's talk

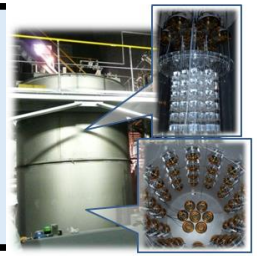
Super-Kamiokande

- 50 kton Gd-water Cherenkov detector.
- Atmospheric, solar, SN neutrinos, DSNB, proton decay, indirect DM searches, far detector for T2K.



CANDLES (Oosaka Univ.)

- CaF_2 scintillator.
- ^{48}Ca 0νββ decay.
- Low BG HPGe in Lab-D

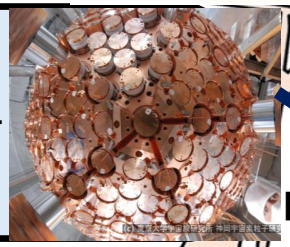


Clean room in storage

- ICP-MS (Agilent7900)

XMASS

- 1 ton single-phase LXe detector.
- Direct DM searches.
- Data taking was completed.

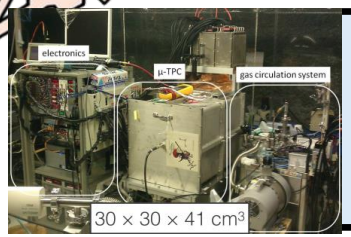


EGADS

- 200 ton Gd-water test tank

Others in Lab-C

- Two ultra-low BG HPGe



NEWAGE (Kobe Univ.)

- Low pressure TPC+MPGD
- Direction-sensitive direct DM searches.

Lab-I

- Three HPGe
- Low-BG α counter
- ICP-MS

CLIO (Gravitational-wave)

- 100 m × 100 m prototype.

Geophysics

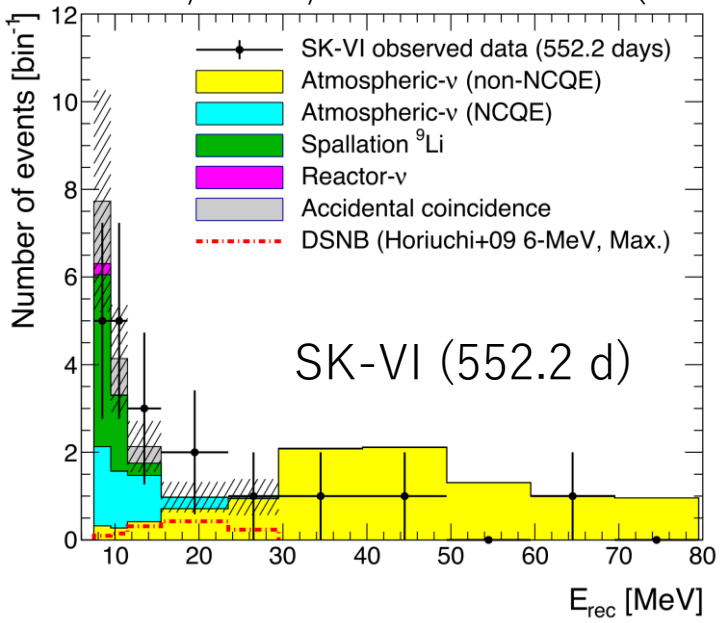
- 100 m × 2 laser strain meter.

Super-Kamiokande

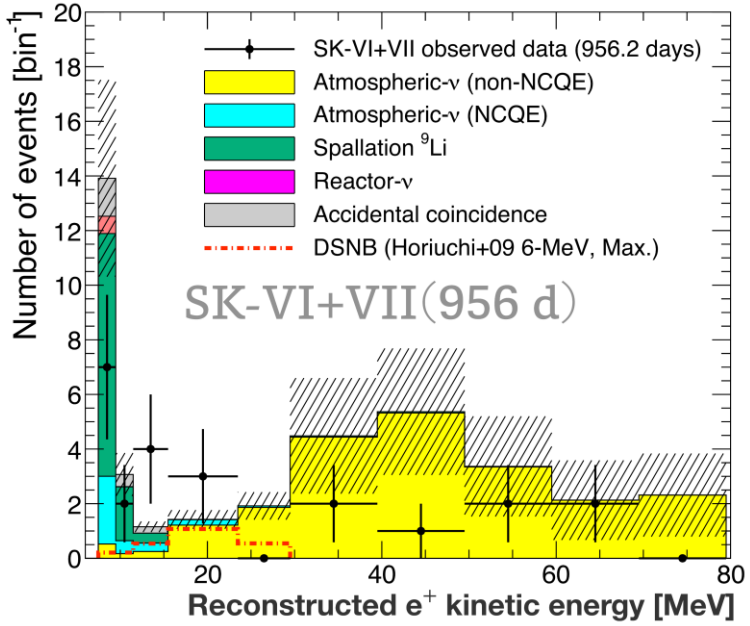
Latest progress

- Diffuse Supernova Neutrino Background (DSNB) searches with SK-Gd.
- Gd concentration was increased from 0.01% to 0.03% (July 2022).
  - SK-VI (0.01%) 2020 Aug.~2022 Jun.
  - SK-VII (0.03%) 2022 Jul.~2023 Sep.
- From total 6779 days of SK data (5823 d pure-water and 956 d Gd-water), some excess appears in the signal region, which is 2.3σ tension from non-DSNB hypothesis.

M. Harada, et al., APJ. L 951 L27 (2023)

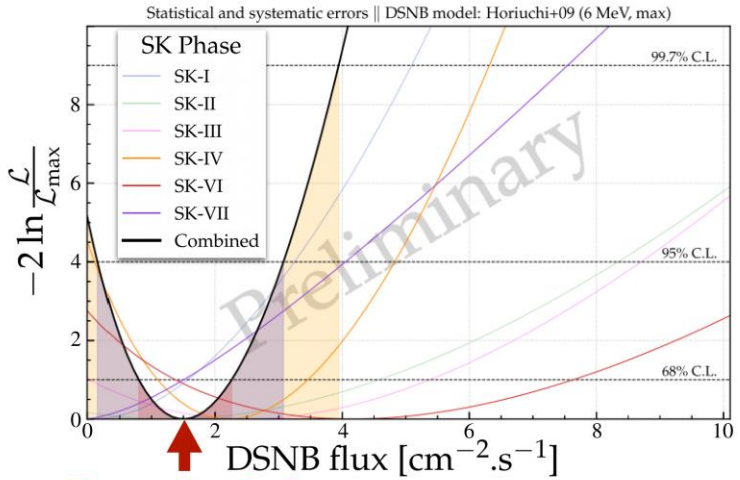


M. Harada, Neutrino2024, June 20, 2024.



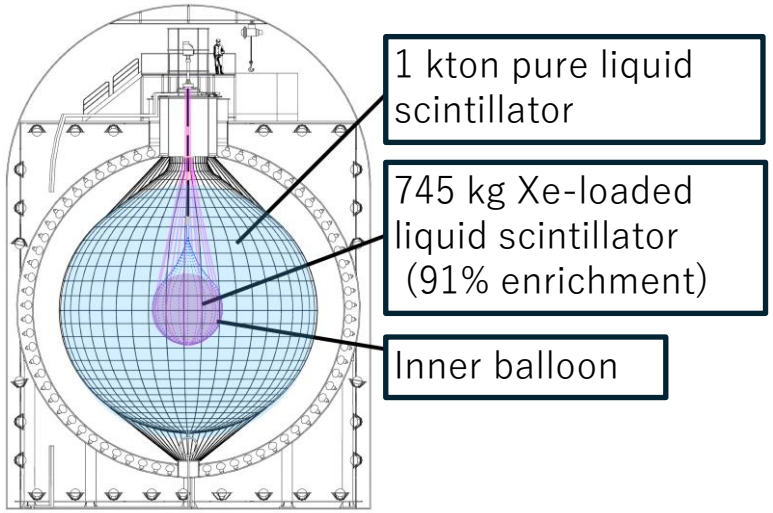
New n-tag, NCQE reduction

Tension from zero assumption (2.3σ excess) from combined data.



(Rogly, poster 79)

KamLAND-Zen (0νββ experiment)

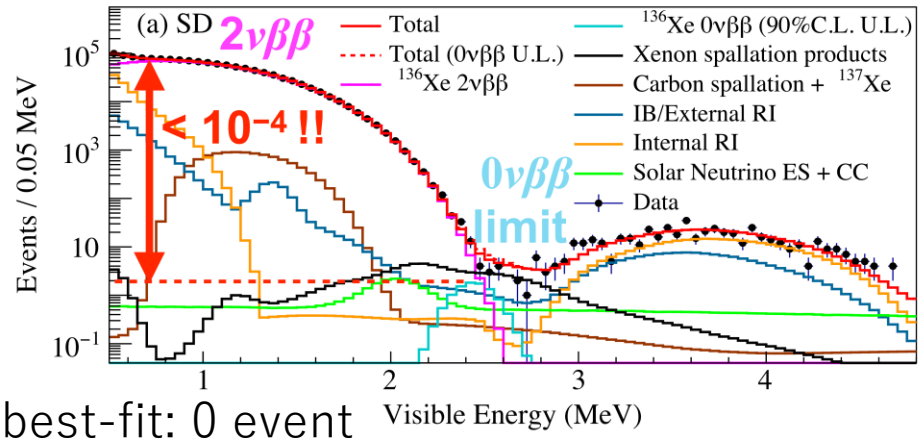


- KamLAND-Zen 800 data taking was completed on Jan. 12, 2024.
- Most stringent limits for the neutrino mass in the IO region was derived.
- KamLAND2-Zen to achieve the sensitivity covering the entire IO region is now being prepared.

Details of KamLAND and related facilities → Ichimura-san's talk "Status and future prospect of the Kamioka ultra-low BG facility"

Results from complete KamLAND-Zen 800 (750 kg Xe) data (Feb. 5, 2019 – Jan. 12, 2024).

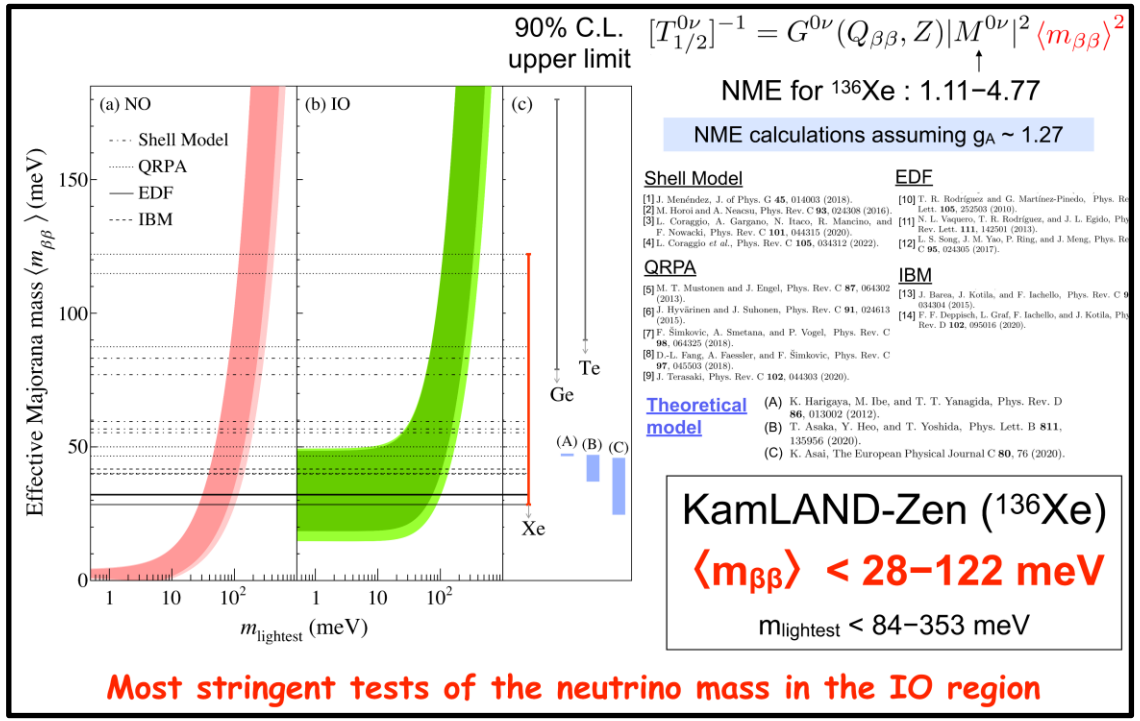
- 1131 days livetime (0νββ candidate)
- R < 1.57 m



best-fit: 0 event

→ upper limit: < 10.0 events at 90% C.L.

Results from combined KamLAND-Zen 400 and 800 data.



I. Shimizu, Neutrino2024, June 18, 2024.

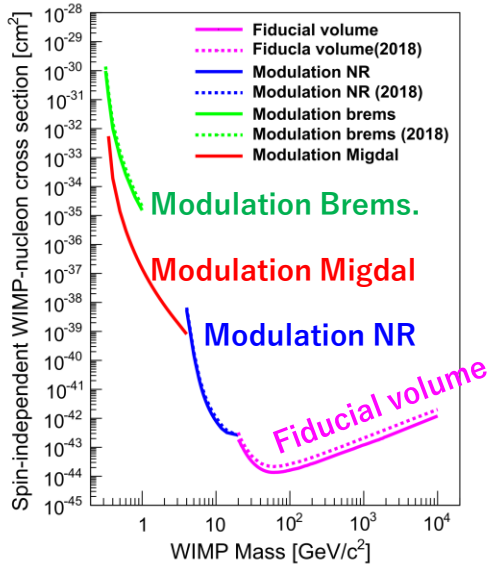
XMASS-I/NEWAGE(DM), CANDLES($0\nu\beta\beta$)

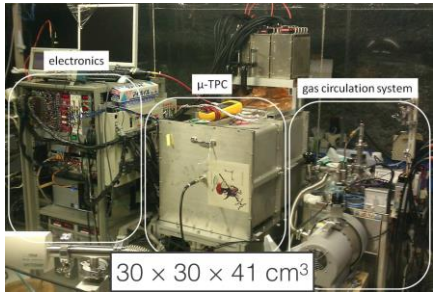
XMASS-I: single-phase LXe detector

- 832 kg total (~100 kg in fiducial)
- 642 low-BG PMTs
- Water Cherenkov veto detector
- Data taking was completed in 2019
- Result from full data set (1590.9 live days) was published in 2023

XMASS-I

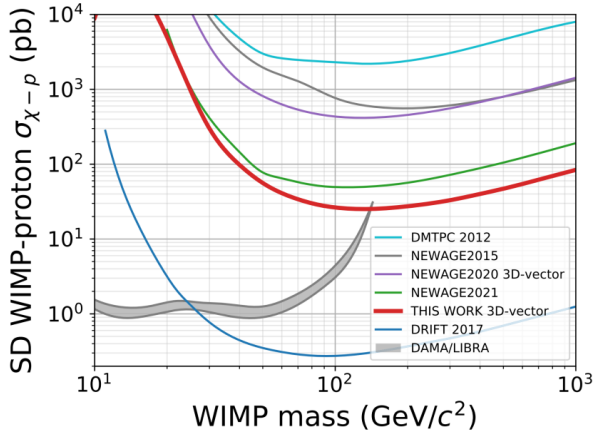
Phys. Rev. D 108, 083022 (2023)





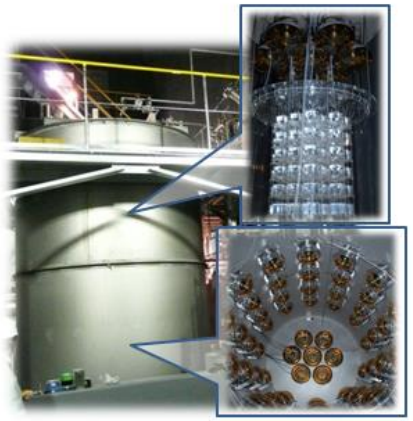
NEWAGE: directional DM search

- NEWAGE-0.3b'': Micro pattern gas detector (MPGD)-based micro TPC
- $30 \times 30 \times 40$ cm^3
- Low-pressure (0.1 atm) CF_4 gas
- Readout pitch: 400 μm



NEWAGE

PTEP 2023, 103F01 (2023)

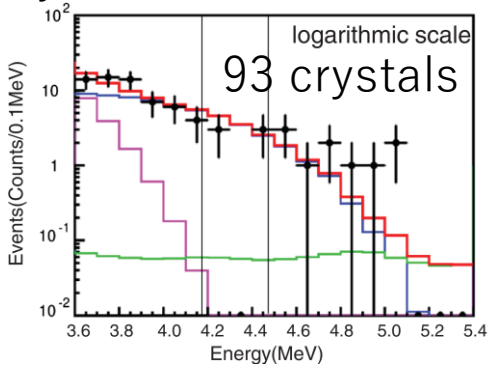


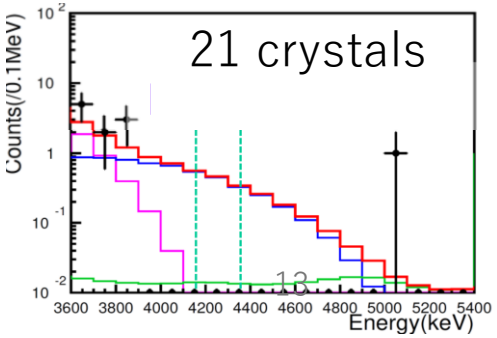
CANDLES: ^{48}Ca $0\nu\beta\beta$ search

- $Q_{\beta\beta} = 4.27$ MeV
- 300 kg CaF_2 crystals in liquid scintillator
- 130.4 days data
- Half life of ^{48}Ca $> 5.6 \times 10^{22}$ years

Phys. Rev. D103, (2021), 092008

CANDLES





Radioassay in Kamioka

- **HPGe**
  - Several HPGe detectors.
  - Recently, two ultra-low background HPGe detectors in Lab-C were developed.

They were used for development of ultra-pure gadolinium sulfate for SK-Gd project.

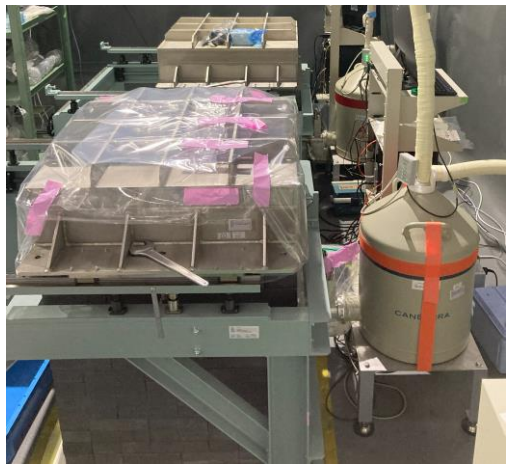
H. Ito et al., PTEP 2017, 113H01
K. Hosokawa et al., PTEP 2023, 013H01

→ ***K. Hosokawa, poster-64***

- **ICP-MS (Agilent7900)**
  - The auto-sampler is fully covered by the class 100 clean booth
- **Water Rn detectors (electrostatic)**
  - Rn concentration in SK-Gd is continuously monitored with 1 mBq/m^3 sensitivity.
- **α detector (Ultra-Lo1800)**

Three HPGe in Lab-I

Two HPGe in Lab-C



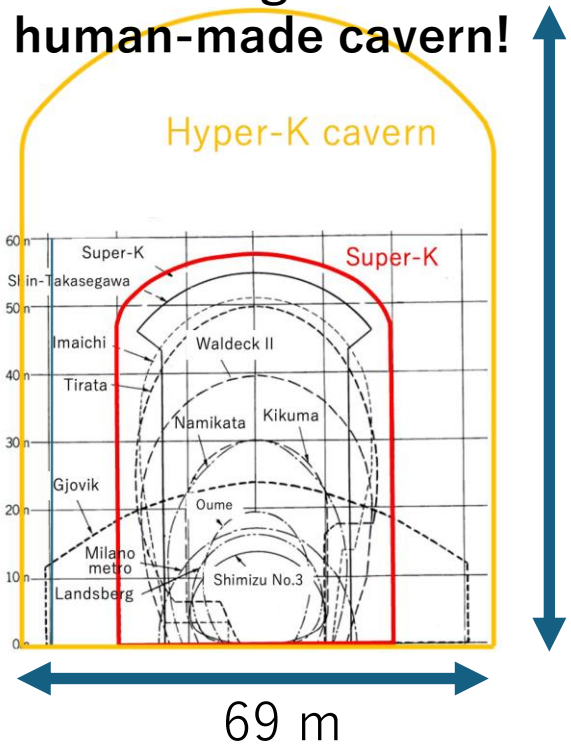
ICP-MS (Agilent7900)

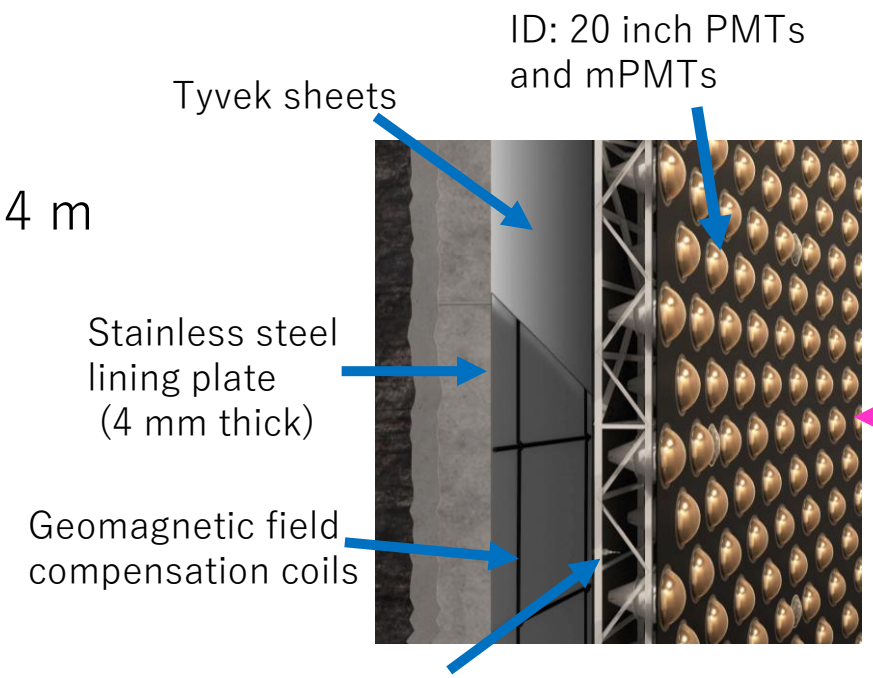
Water Rn detectors

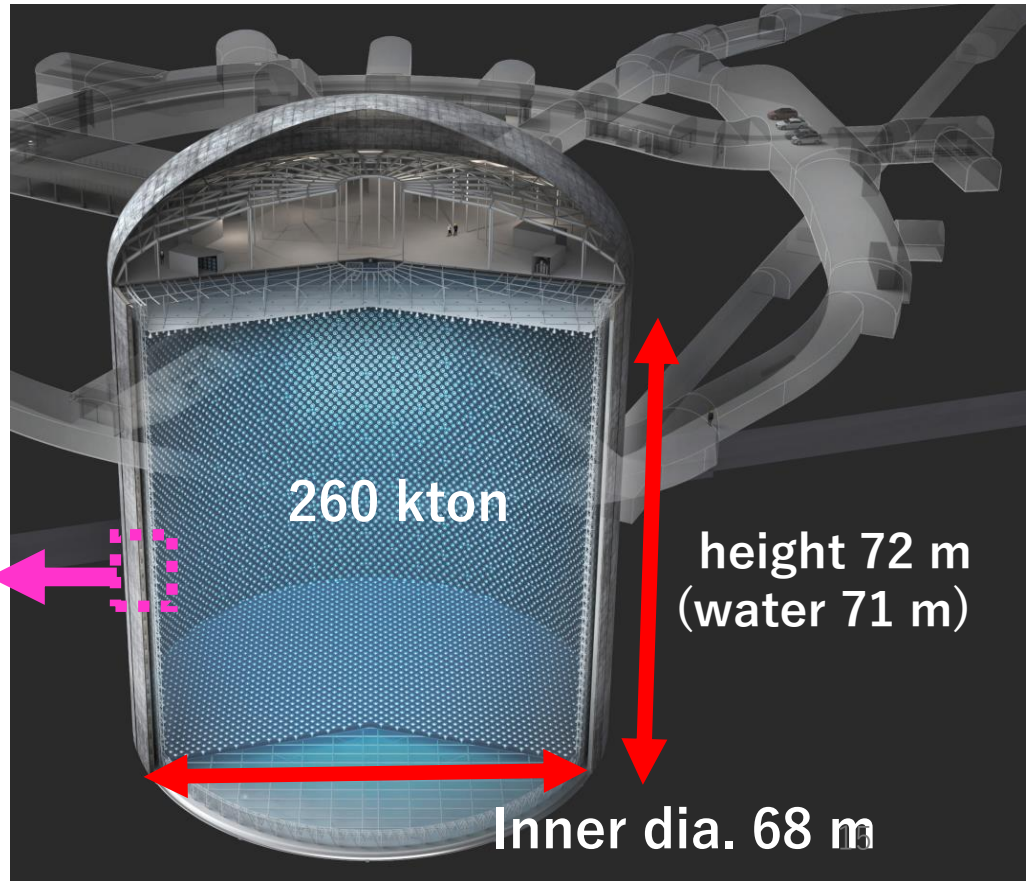
Hyper-Kamiokande

- The world's largest human-made cavern currently under excavation.
- Excavation of dome part was completed in Oct. 2023, and more than half of the barrel part has been excavated. It is scheduled to be completed in Jan. 2025, after that the water tank construction will begin.
- Aiming at operation start in 2027.

World's largest human-made cavern!





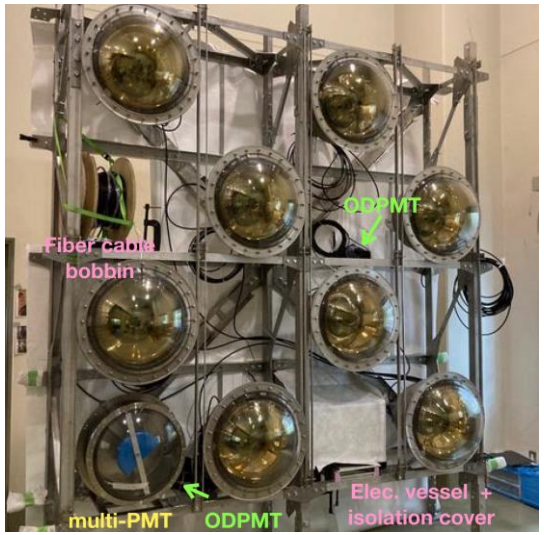


Current status of Hyper-Kamiokande

Oct. 3, 2023: Completion of the dome part

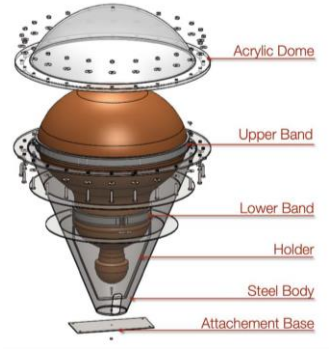
Now, barrel part is being excavated

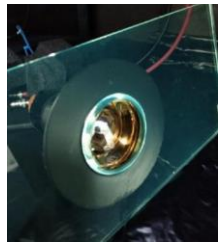
Detector components are being prepared at surface



ID PMTs being checked

PMT cover

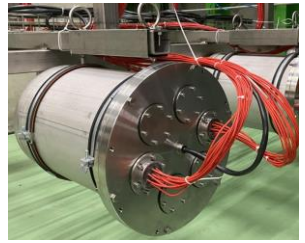


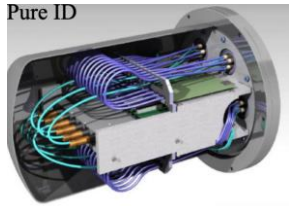


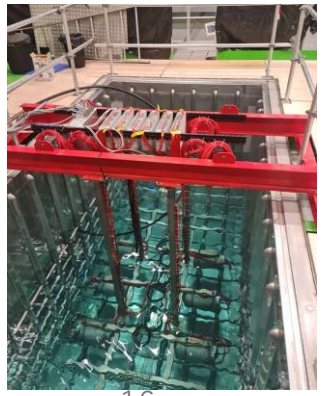
OD PMT + WLS plate

mPMT

Underwater electronics

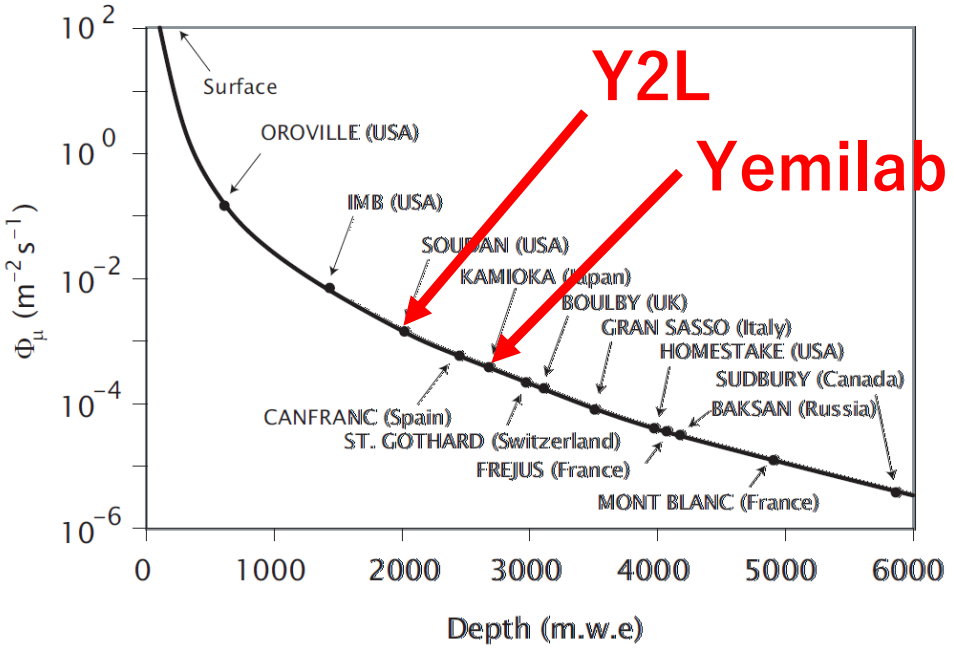






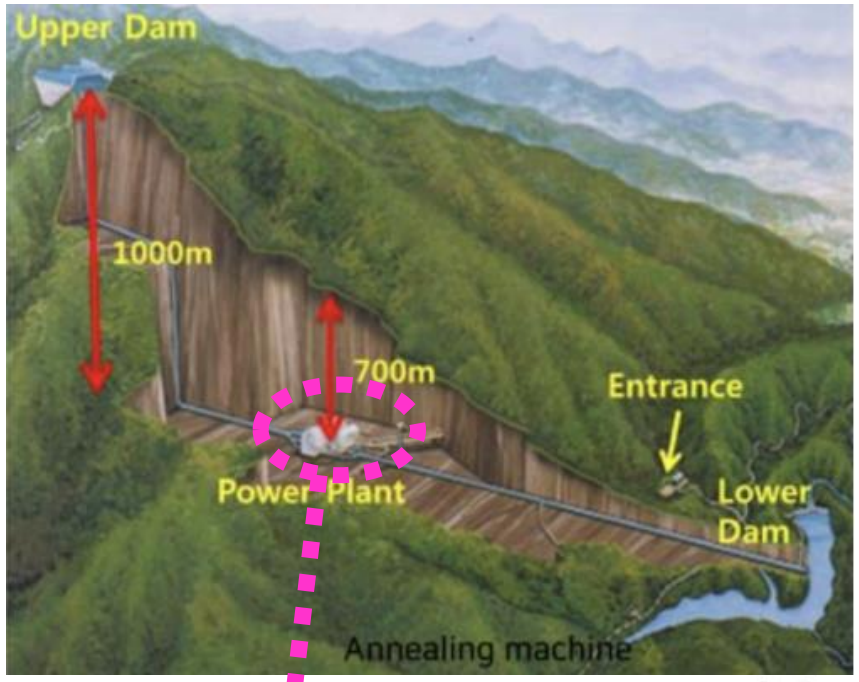
Underground labs in Korea

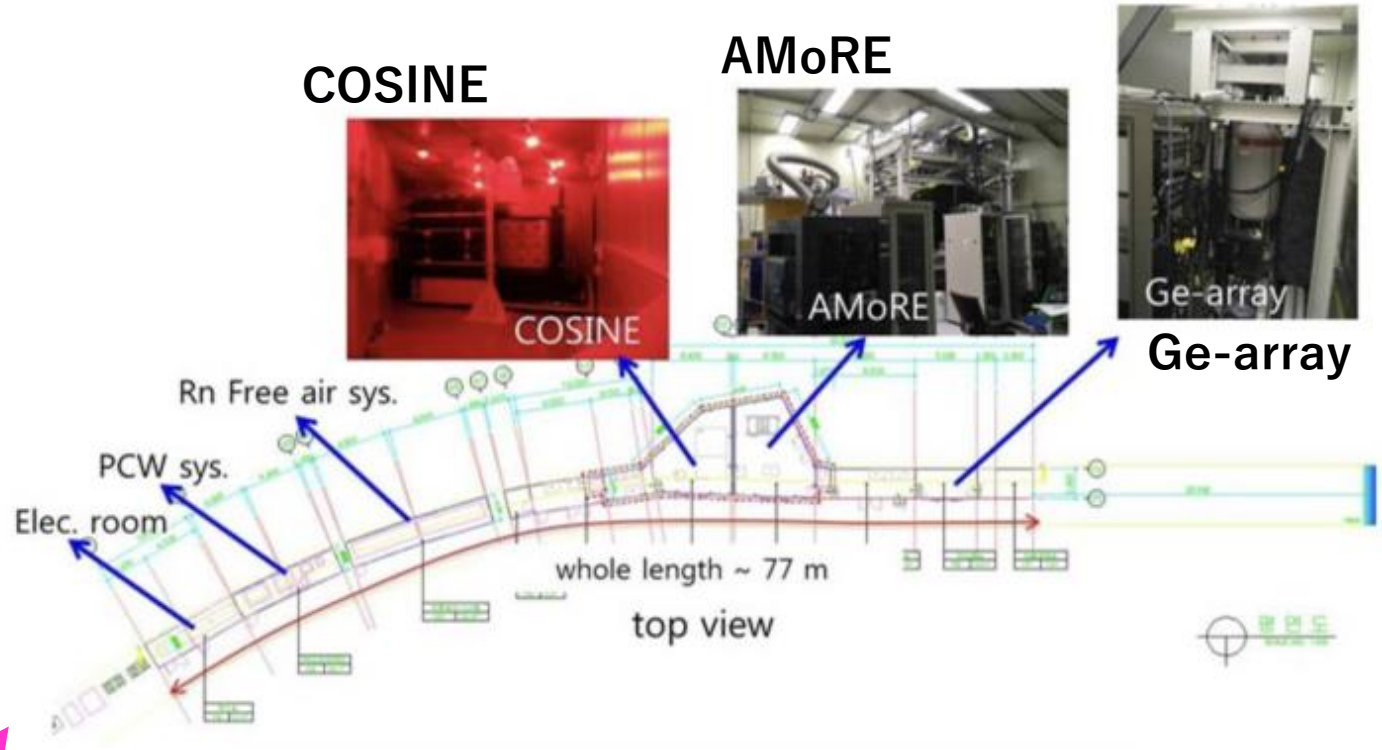
- **Yangyang Underground Laboratory (Y2L):**
  - Yangyang Pumped Storage Power plant
  - 700 m overburden
  - ~150 km from Seoul
- **Yemilab:**
  - Handeok mine
  - 1,000 m overburden
  - ~150 km from IBS-HQ

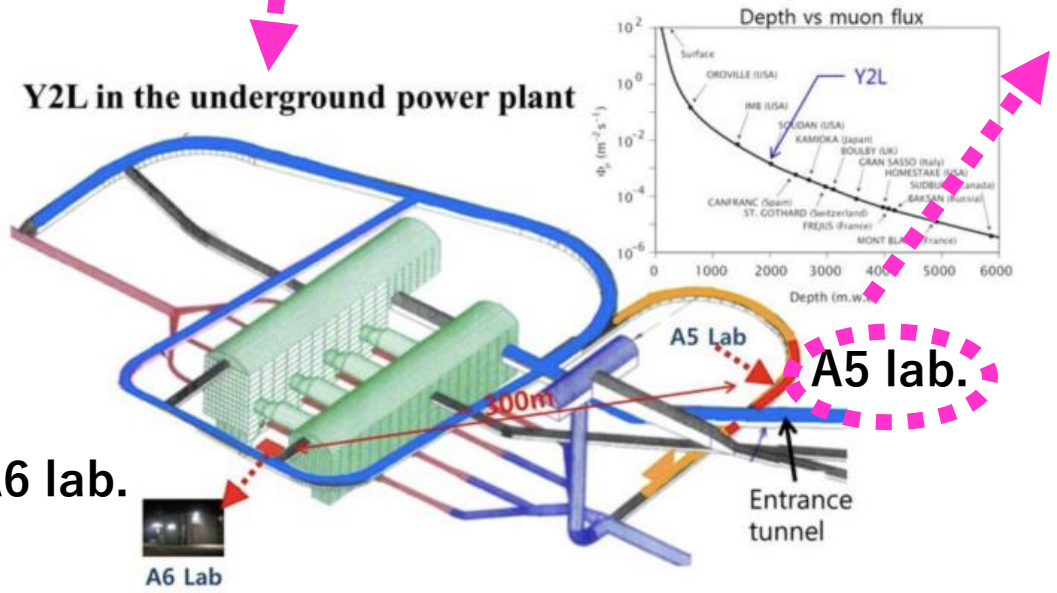


Mu-on flux

Yangyang Underground Laboratory (Y2L)



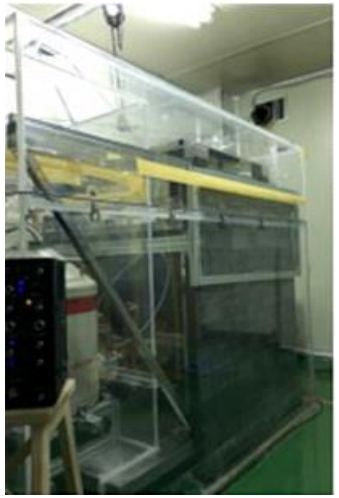




- **A5 lab (since 2014)**
  - AMoRE R&D (pilot/phase-I): ^{100}Mo 0νββ search
  - COSINE: NaI dark matter search
  - 14 element HPGe Array
- **A6 lab (since 2003)**
  - KIMS: CsI dark matter search
  - 2 HPGe detectors

Assay resource at Y2L

CC1

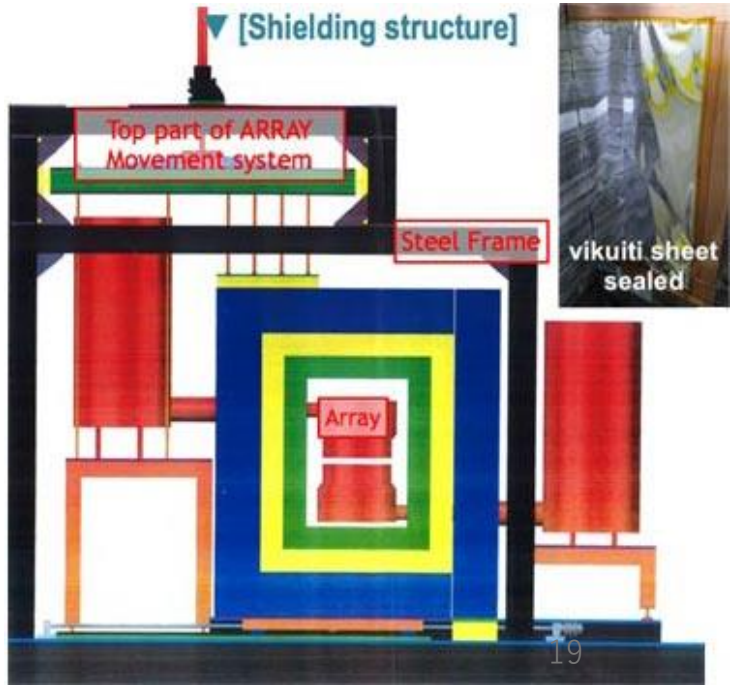


CC2

- **Two 100% HPGe detectors:** CC1 and CC2 at Y2L-A6
- **CUP Array of Germanium (CAGe)**: 14 detectors, 70% relative efficiency each at Y2L-A5.
  D. Leonard et al., NIM A 989 (2021) 164954.
- **XIA ULtraLo-1800**: alpha counter, 1800 cm^2 area.

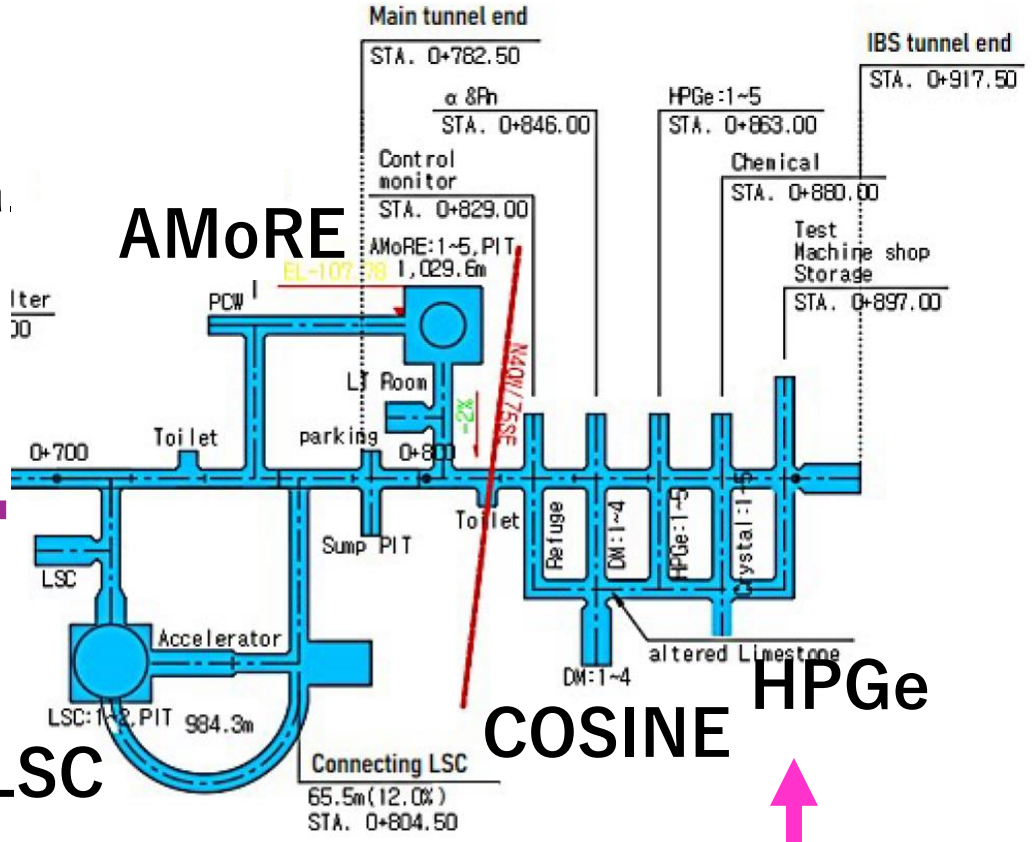
XIA ULtraLo-1800 α counter

CAGe

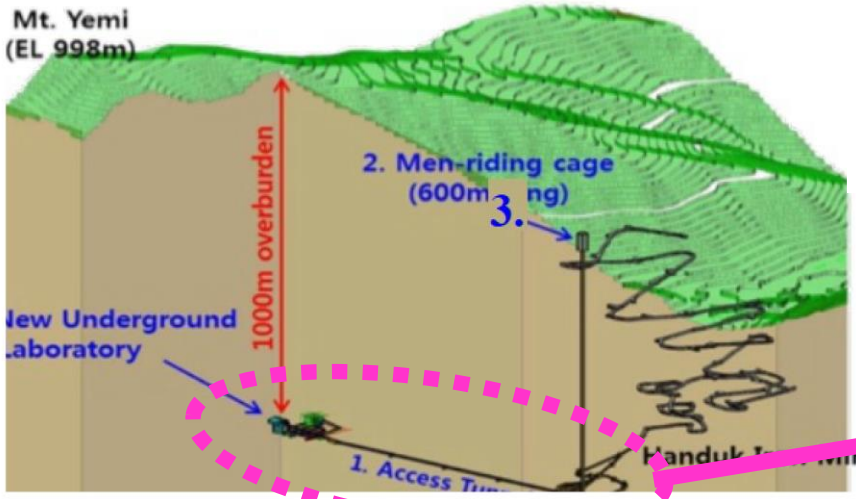


Yemilab

- Completed in September 2022.
- 1,000 m depth and 3,000 m^3 exclusive experimental area.
- Y2L facilities are being relocated to YemiLab.
- Large halls for **AMoRE-II**, LSC w/cyclotron/accelerator and purification.
- Ladder halls for **COSINE**, HPGe/Alpha, Refuge, etc.



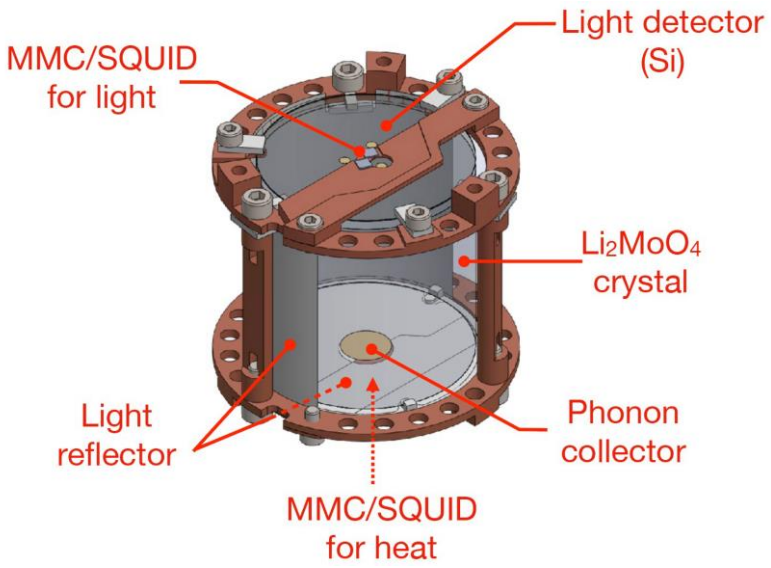
To entrance



Figures are taken from arXiv:2402.13708

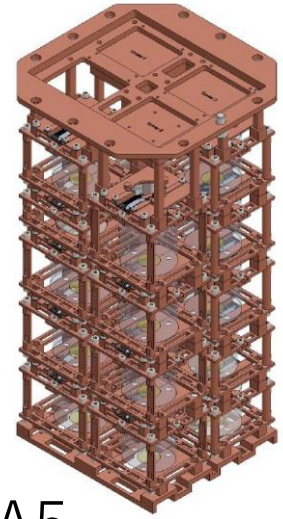
AMoRE experiments

- Cryogenic $X^{100}MoO_N$ detector for $0\nu\beta\beta$ search. (X=Ca, Li_2, Na_2, etc.)
- Metallic Magnetic Calorimeter (MMC) detectors.
- **^{100}Mo** (NA=9.7%): $Q_{\beta\beta}$ = 3034 keV > ^{208}Tl line (2615 keV), $T_{1/2}(2\nu) = 7.1 \times 10^{18}$ y
- **AMoRE-I:** $^{40}Ca^{100}MoO_4$, enriched ^{100}Mo and depleted ^{48}Ca, T_D=446 K, large scintillation yield.
- **AMoRE-II**: $Li_2{}^{100}MoO_4$, T_D=316 K, hygroscopic, low scintillation yield.



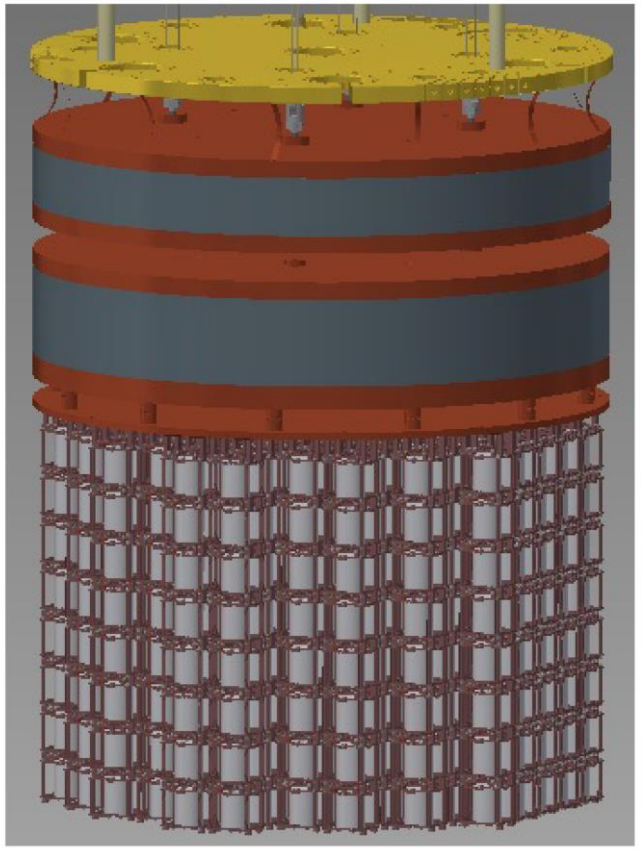
AMoRE Pilot 1.9 kg

AMoRE-I 6 kg



@Y2L-A5

AMoRE-II 157 kg (2024～)



@Yemilab

AMoRE-II @Yamilab

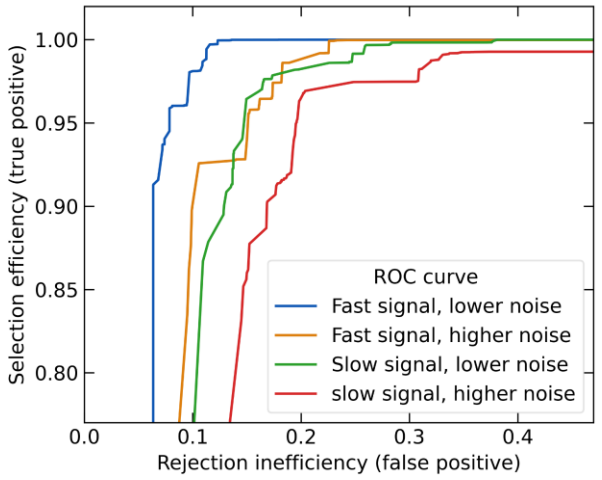
AMoRE-II hall

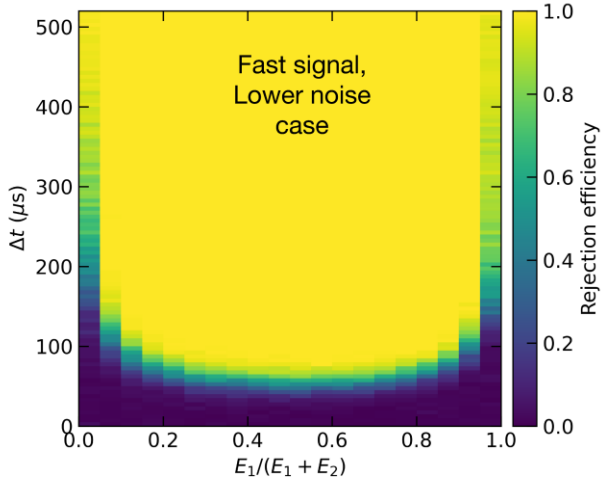
- Preparation of AMoRE-II (157 kg Li_2MoO_4) was mostly completed and will start data taking soon.
  - Energy resolution: ~10 keV FWHM at $Q_{\beta\beta}$=3034 keV.
  - BG level << 2×10^{-4} count/keV/kg/year (ckky)

Shielding Pb and PE installation

Yoomin Oh, “Pile-up rejection for AMoRE-II”, Neutrino2024, 2024/Jun./18

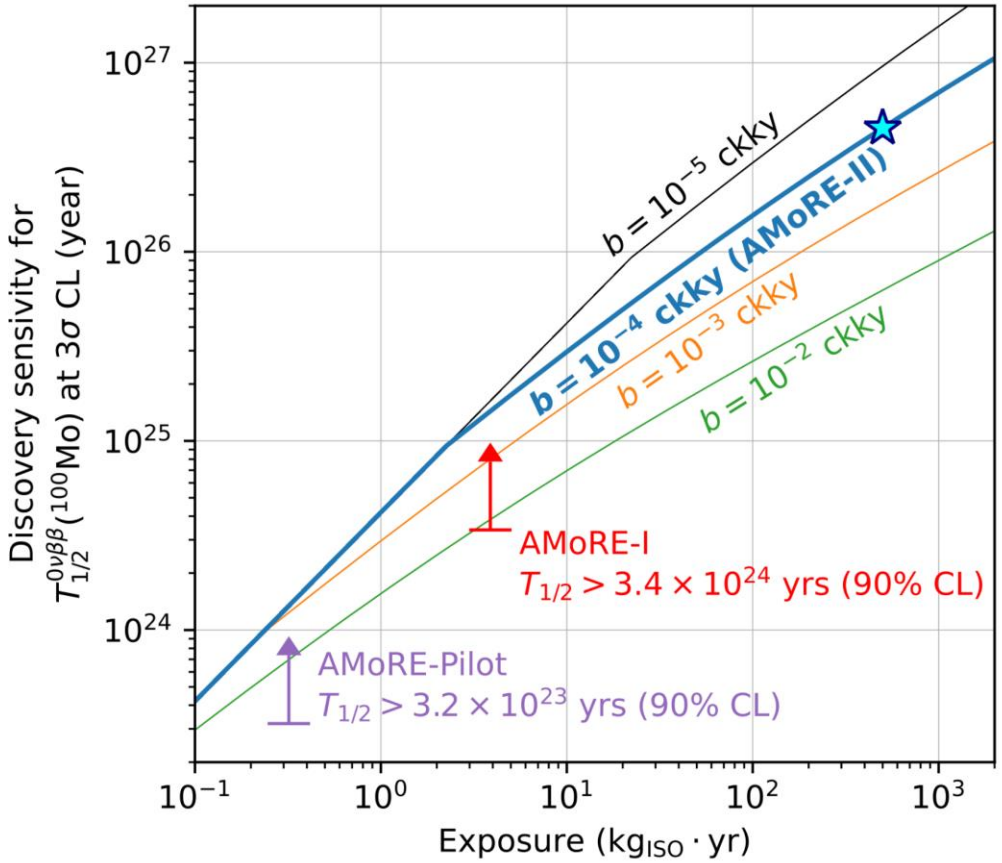
- It was found that pile-up rejection efficiency at ROI in 500 μs is better than 90% with faster signals on lower noise baselines.
- Pile-up rate by 2νββ can be suppressed down to (2-4) × 10^{-5} ckky.

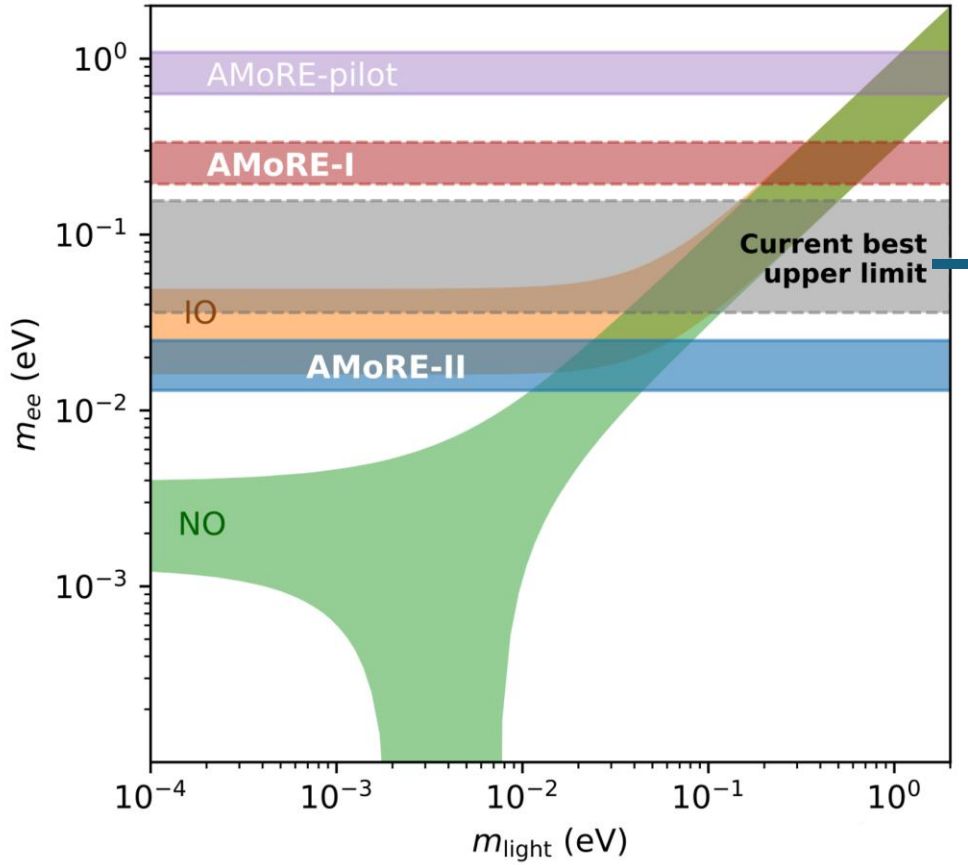




AMoRE status and goals

☆ **AMoRE-II** for $T_{1/2} > \sim 5 \times 10^{26}$ yrs by 100 kg of ^{100}Mo $\times 5$ yrs running assuming BG of 10^{-4} counts/keV/kg/yr.





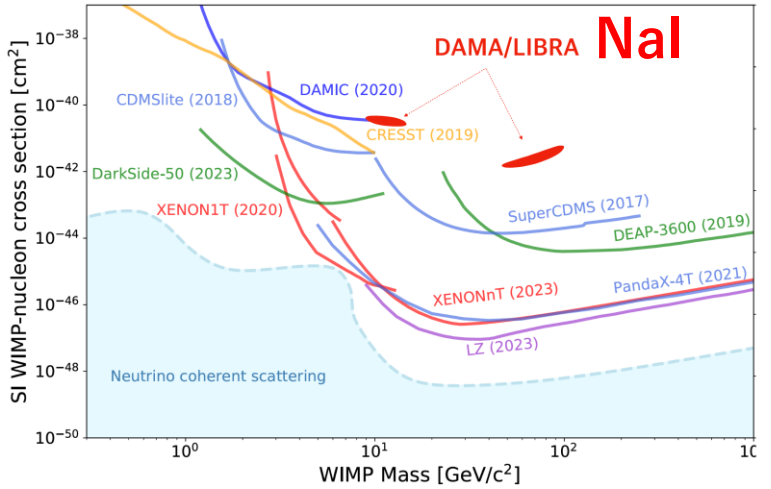
→ Set by KamLAND-Zen Phys. Rev. Lett. 130 (2023) 051801

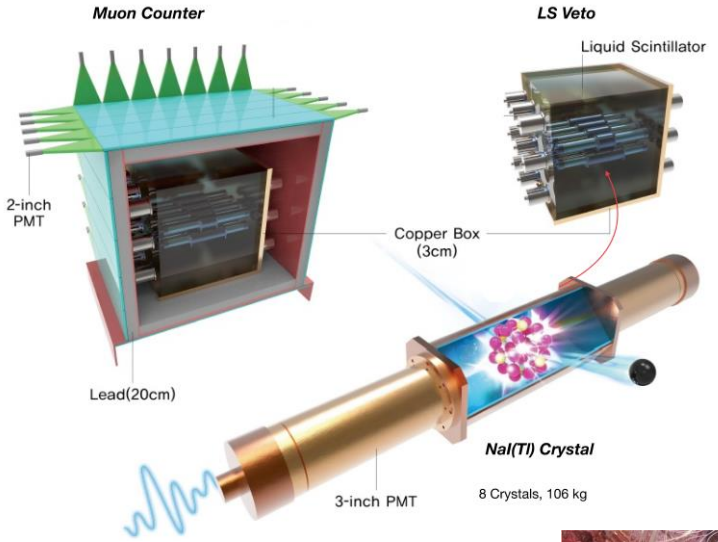
AMoRE-pilot: $T_{1/2} > 3.2 \times 10^{23}$ yrs (90% C.L.)
AMoRE-I: $T_{1/2} > 3.4 \times 10^{24}$ yrs (90% C.L.)

COSINE experiments

- Direct test of DAMA/LIBRA with NaI(Tl) target.
- **COSINE-100** (2016~2023) @Y2L-A5
  - Eight NaI(Tl) crystals (106 kg) with period of six years.
  - DAMA modulation was disfavored.
- **COSINE-100U** (2024~) @Yemilab
  - Setup of COSINE-100 was relocated to Yemilab.
  - Several improvements to explore new parameter space for DM search.

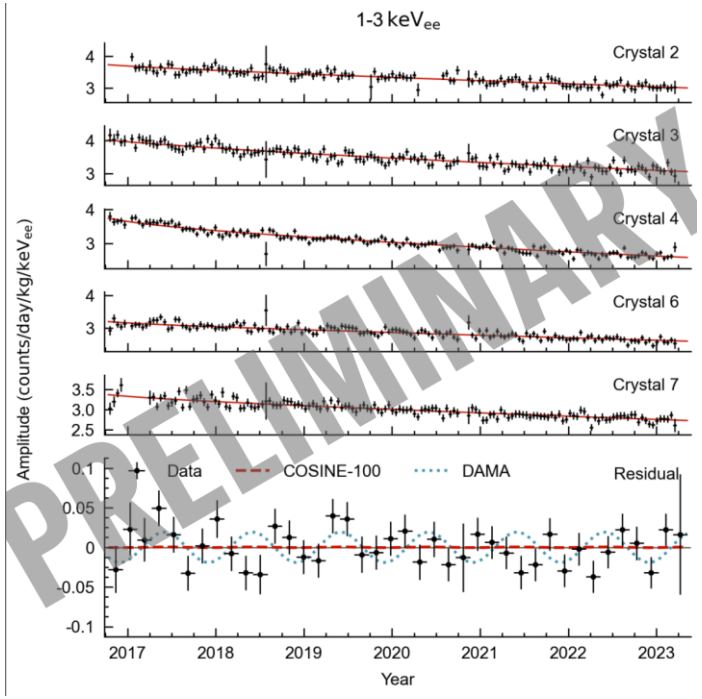
Particle Data Group: Review of Particle Physics (2024)

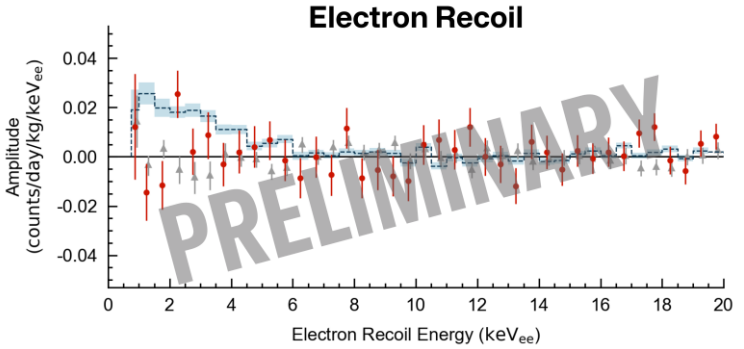


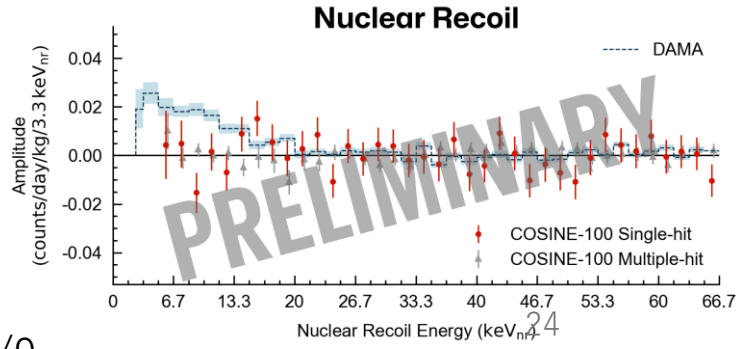


COSINE-100 @Y2L-A5

Results from six cycles: No modulation and disfavors DAMA (> 3σ)



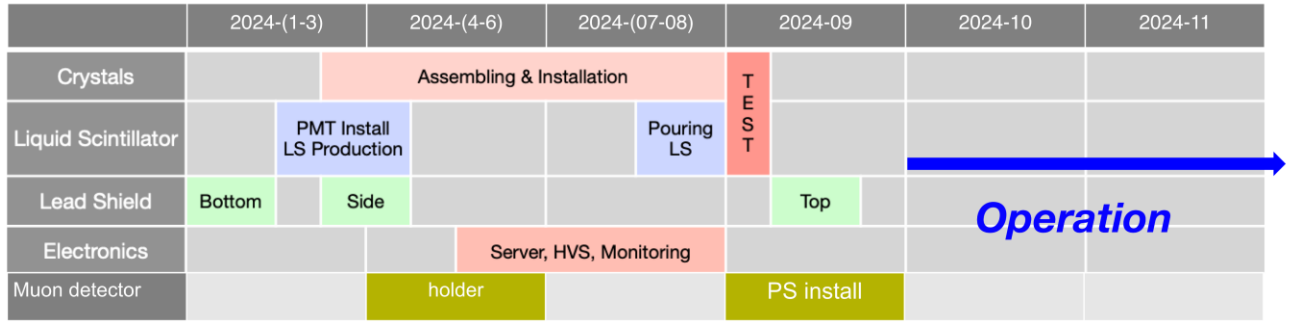




COSINE-100U @Yemilab

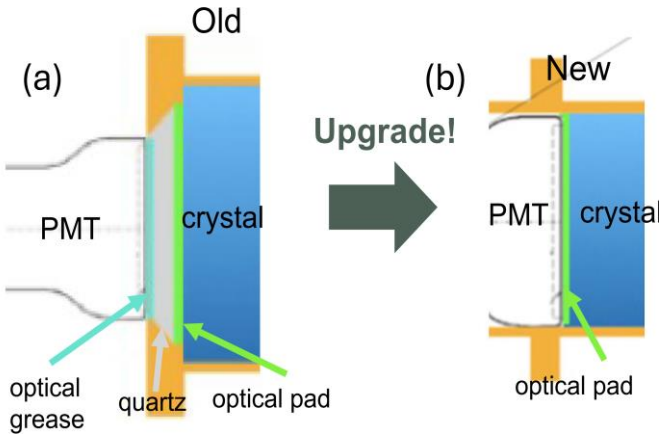
Gyunho Yu, 19th PATRAS Workshop, 2024/Sep./17

- Main upgrade for COSINE-100U
  - Operation at -35°C: ~5% increased light yield (Astropart. Phys. 141102709 (2022))
  - Minimum encapsulation: ~40% increased light yield (NIM A 981, 164556 (2020))
- Lowest limit sensitivity in low-mass SD channel is expected.
- Ultra-pure crystals for COSINE-200 are now being prepared.

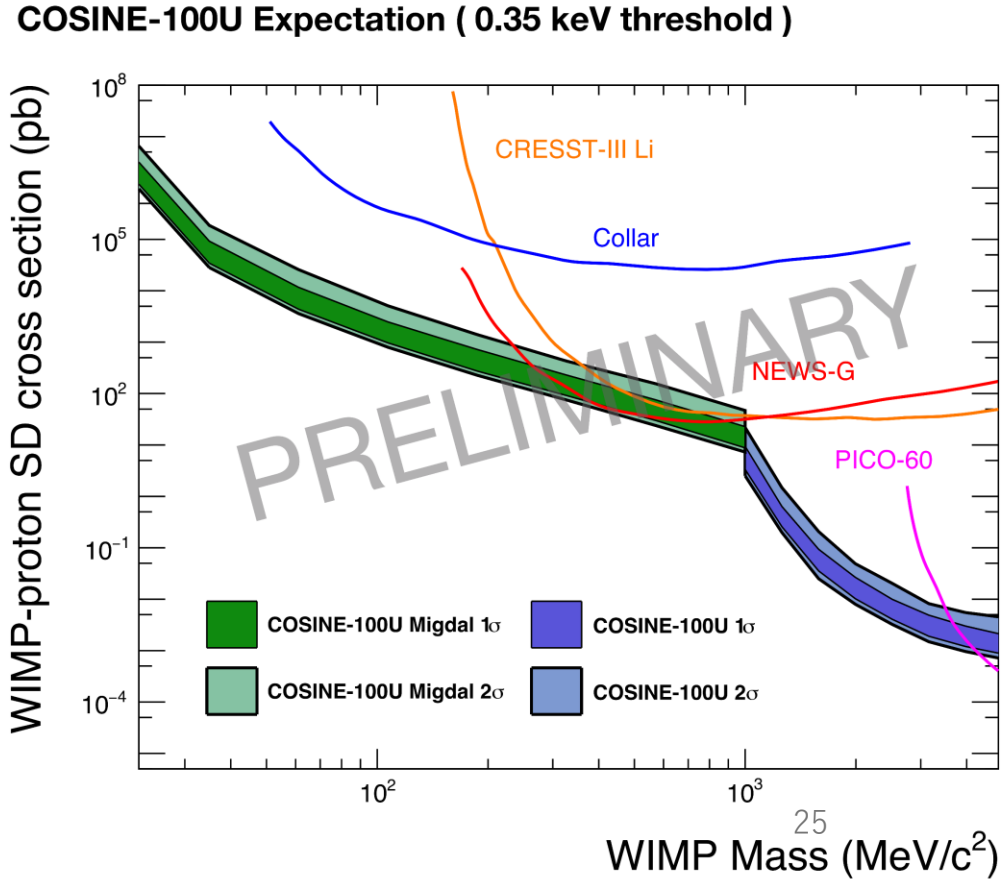


Fridge room (-35°C)

Minimum encapsulation



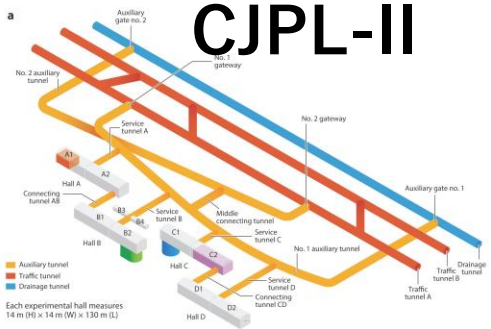
No quartz light guide



Summary

- Asian underground labs continue to expand
  - CJPL-II and JUNO in China
  - Hyper-K site in Japan
  - Yemilab in Korea
- Several new experiments are in preparation or have begun
- Also, new low background facilities and techniques are being developed
- Efforts of background reduction must keep up with the evolution of experimental projects.

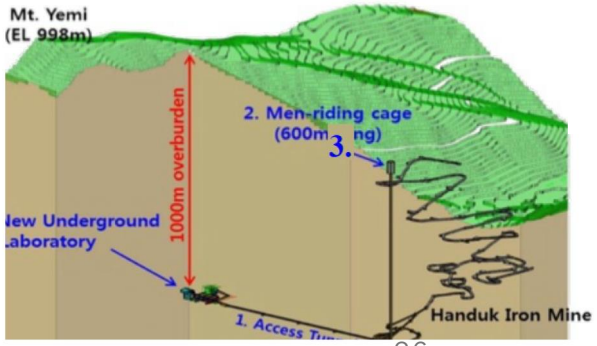
CJPL-II



JUNO

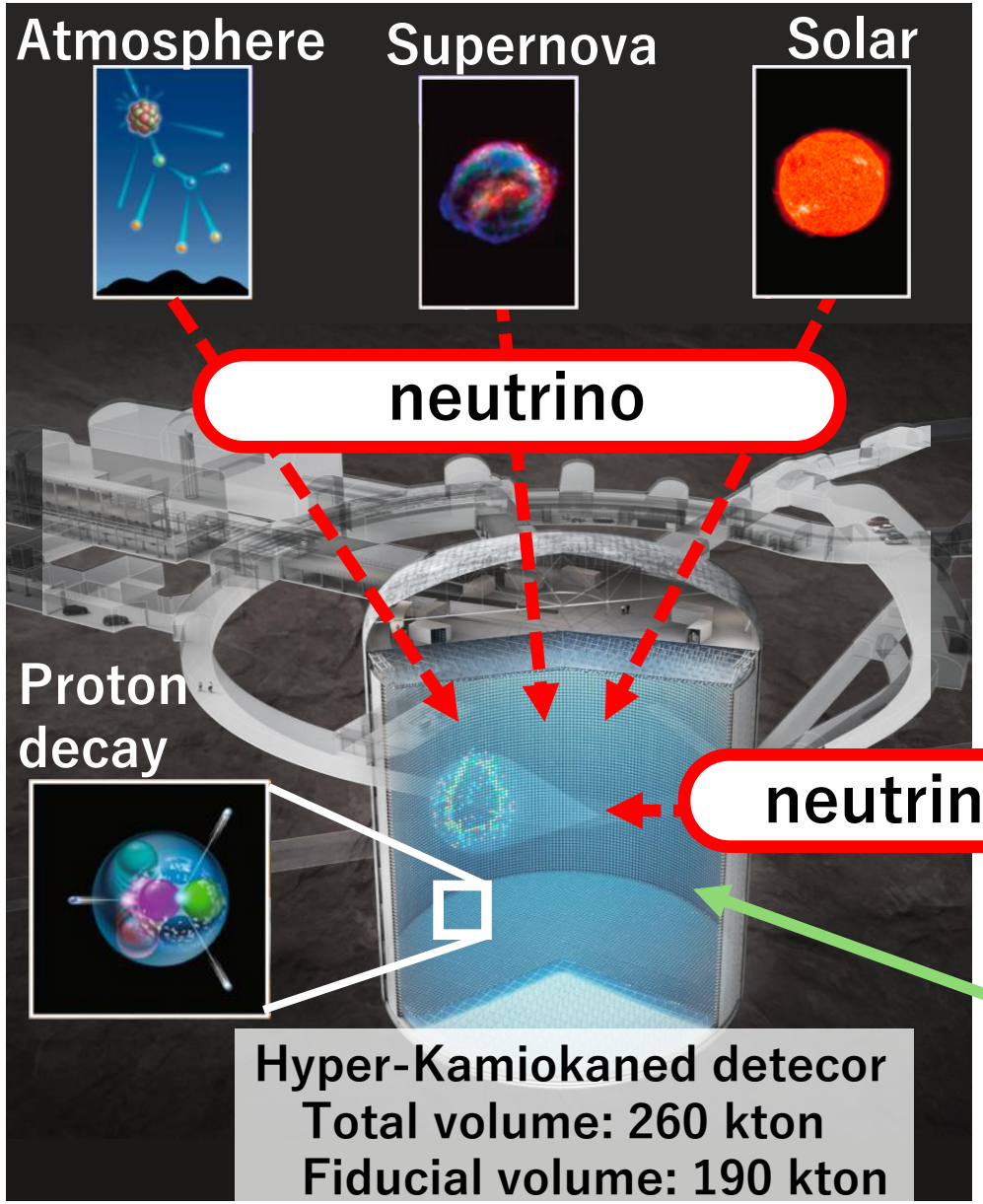
Hyper-K

Yemilab



Backup

Hyper-Kamiokande project



- **Hyper-kamiokande detector**
  - ×8 fiducial volume
  - ×2 sensitive PMTs
- **J-PARC high intensity neutrino beam**
  - ×3 intensity

- δCP measurement
- Supernova bust and DSNB
- Proton decay searches
- Precise measurement of neutrino oscillations
- Indirect dark matter searches

Newly developed PMTs (×2 sensitivity)

295 km

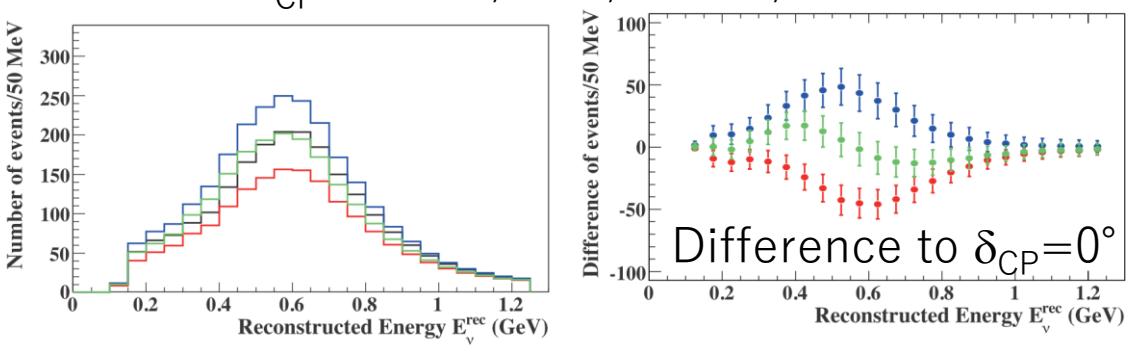
High intensity neutrino beam from J-PARC

写真提供: JAEA/KEK J-PARCセンター

HK Performance

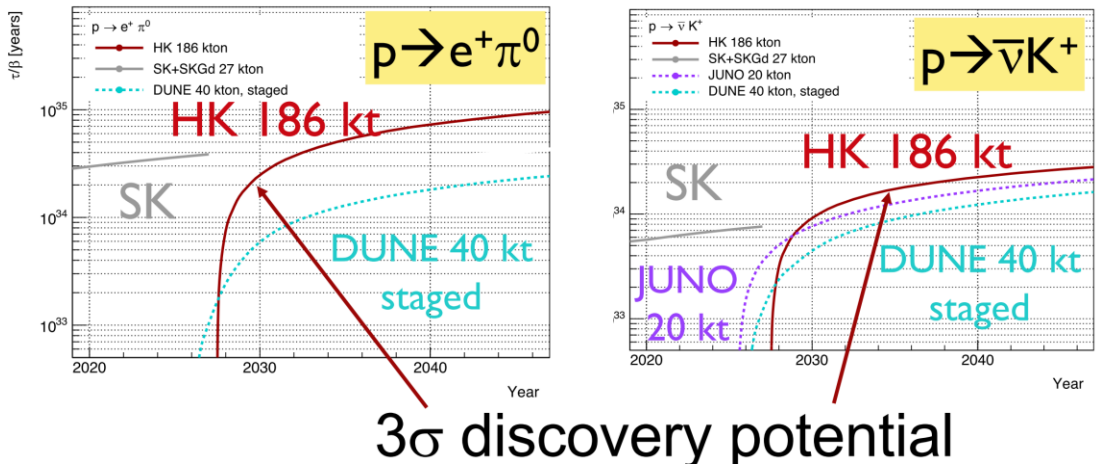
- Effect of CP violation on the e-like event sample (HK 10 yr, 2.7×10^{22} POT)

δ_{CP}= **-90°** , **0°** , **+90°** , **180°**



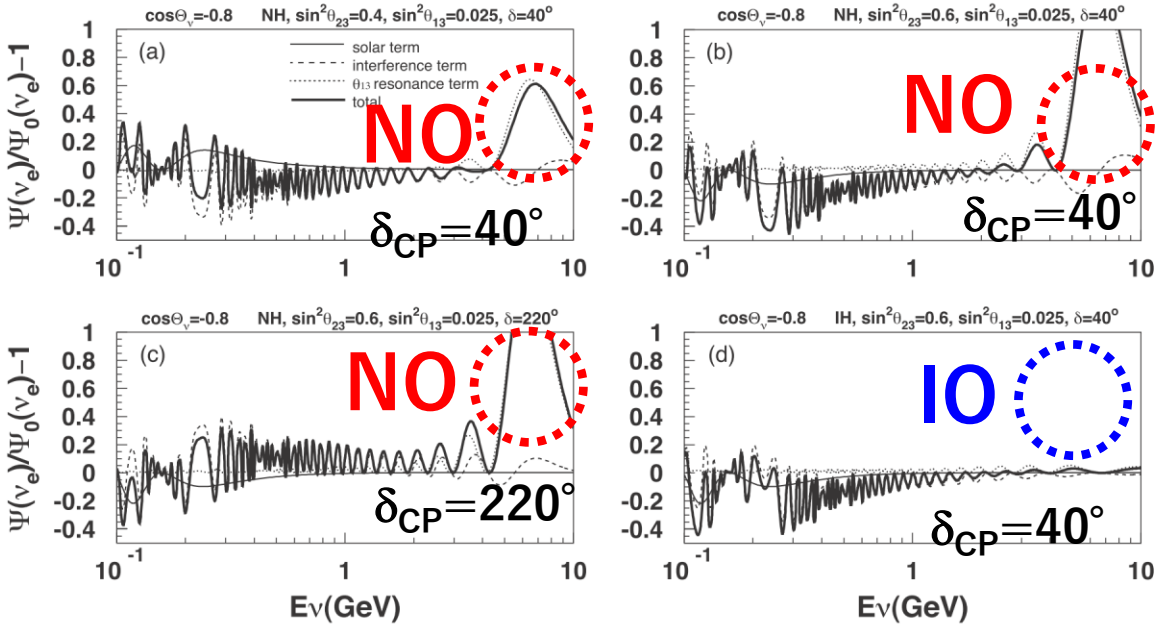
Reconstructed neutrino energy distribution

- 3σ discovery potential for proton decay



3σ discovery potential

- Effect of mass ordering (MO) and δ_{CP} on ν_e flux.



The ratio of oscillated to non-oscillated ne flux for zenith angle cosΘν = -0.8. High-energy resonance is only present in **NO**.

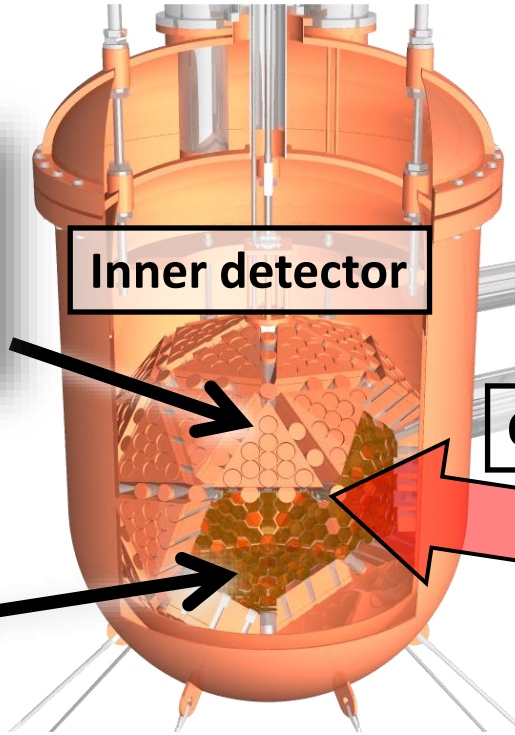
HK 10 years

- $p \to e + \pi^0$: $\sim 6 \times 10^{34}$ yrs
- $p \to \nu K^+$: $\sim 2 \times 10^{34}$ yrs

XMASS-I detector

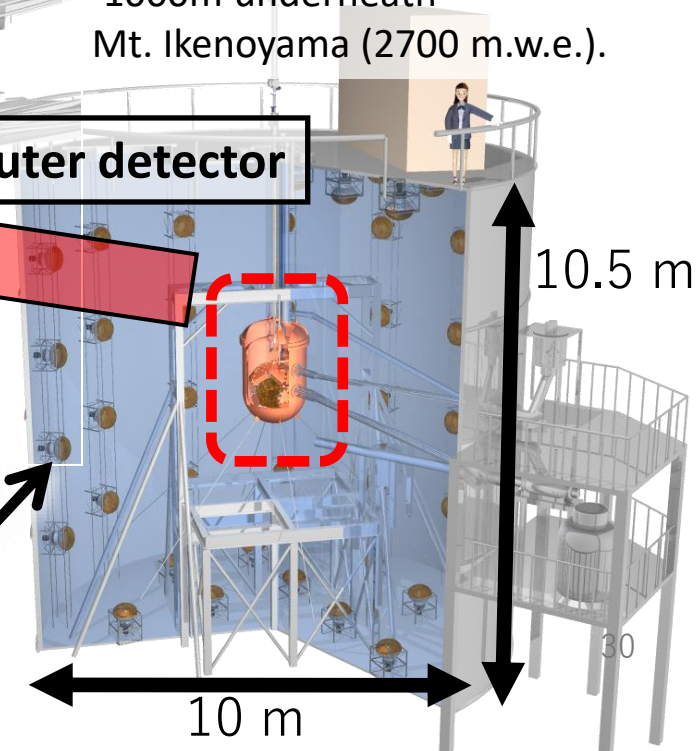
- **Inner detector**
  - Single phase liquid xenon detector. (832 kg xenon for sensitive region)
  - 642 low background PMTs. (2 inch, HAMAMATSU R10789)
    → each PMT signal is recorded by 10-bit 1GS/s waveform digitizers.
  - High light yield: ~14 PE/keV.
- **Outer detector**
  - 10 m x 10.5 m water tank with 72 PMTs (20 inch) for active muon veto and passive radiation shield.

642 PMTs
(R10789)



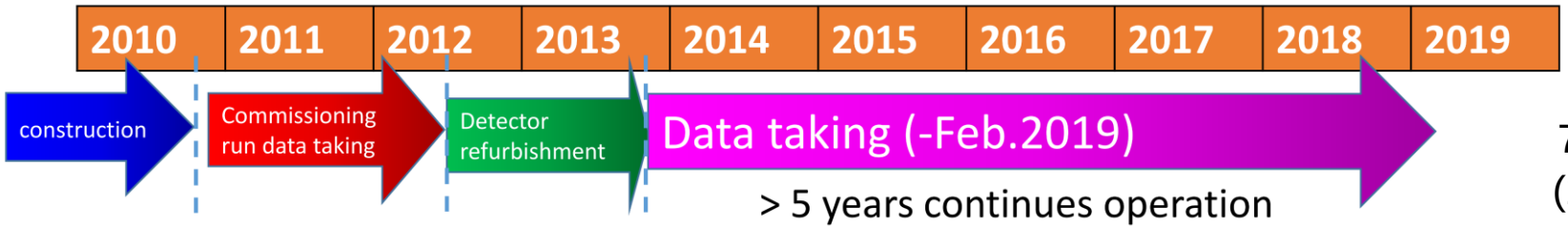
832kg
liquid xenon

~1000m underneath
Mt. Ikenoyama (2700 m.w.e.).



72 PMTs
(20 inch)

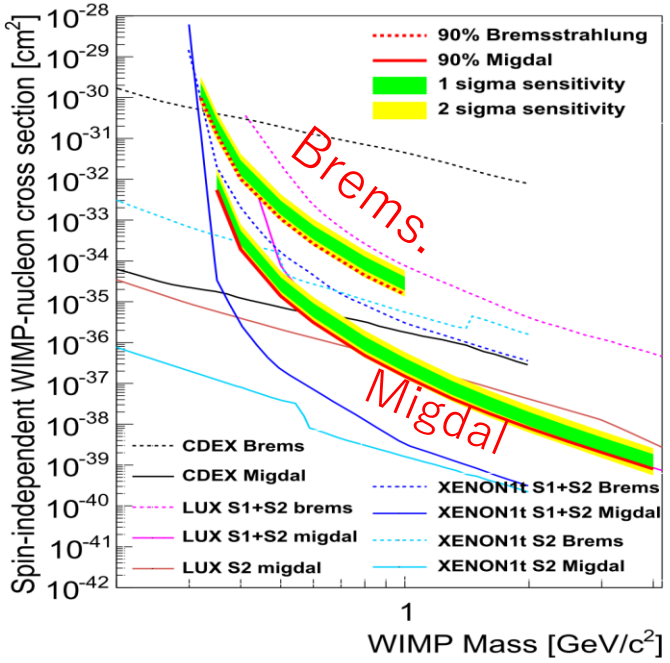
- **Long stable observation period**
  - 2013/11~2019/2 (> 5 years)
- **Variety of rare events search**
  - Dark matter, modulation, low mass, inelastic, and hidden photon
  - Solar axion, 2νECEC, GW and exotic neutrino interaction

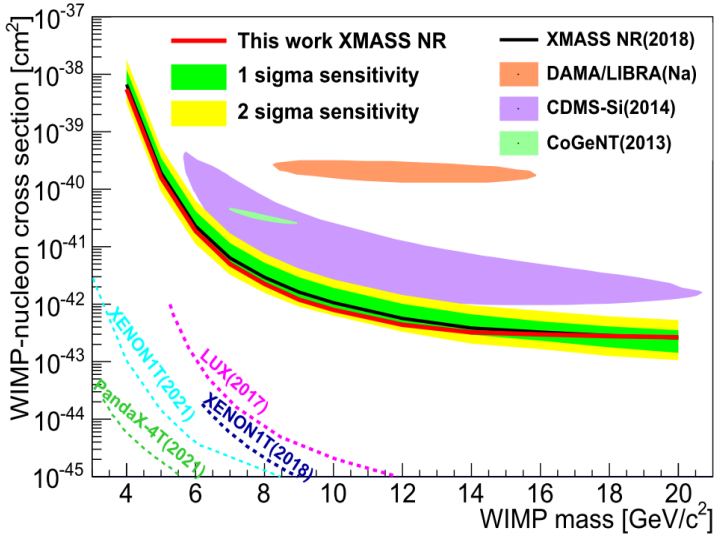


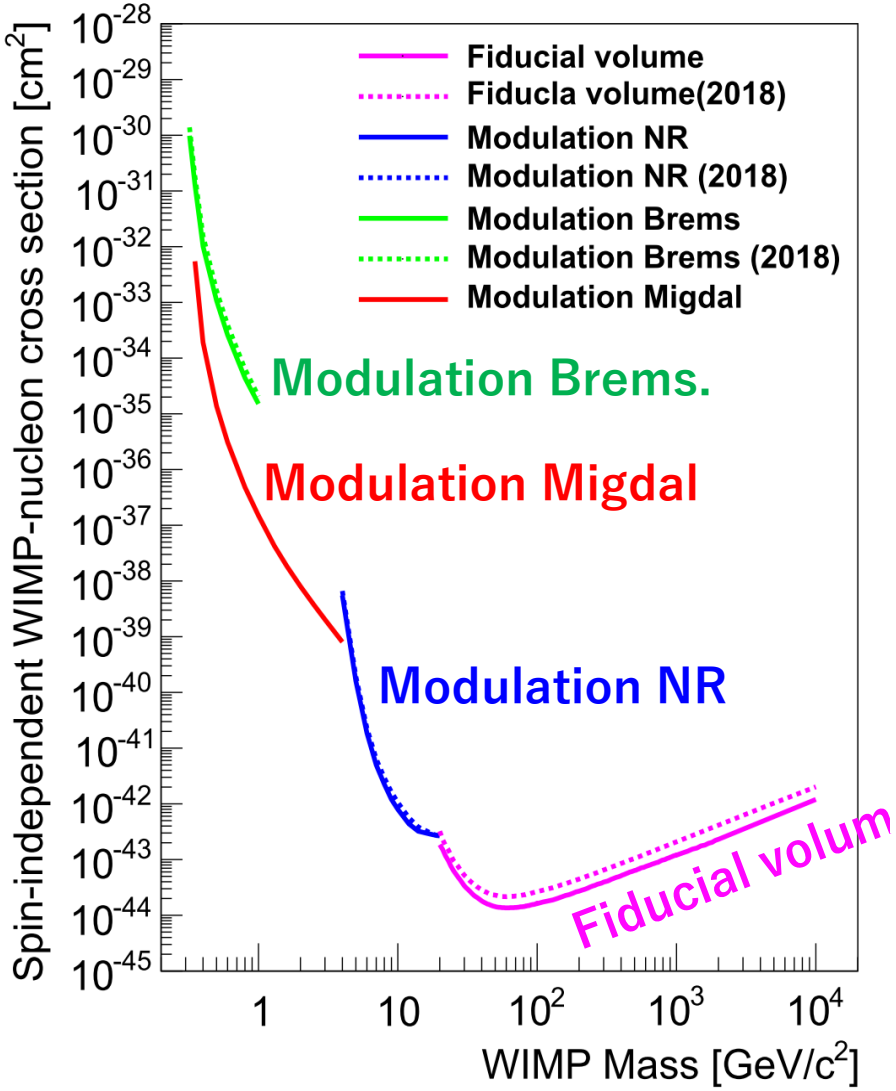
> 5 years continues operation

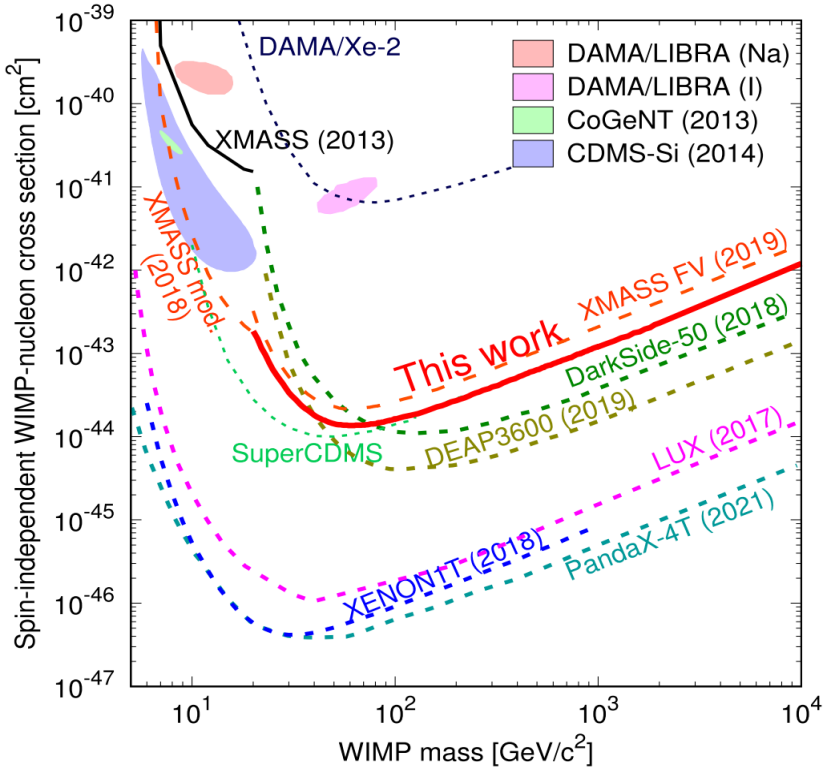
Results from XMASS full data-set

Phys. Rev. D 108, 083022 (2023)





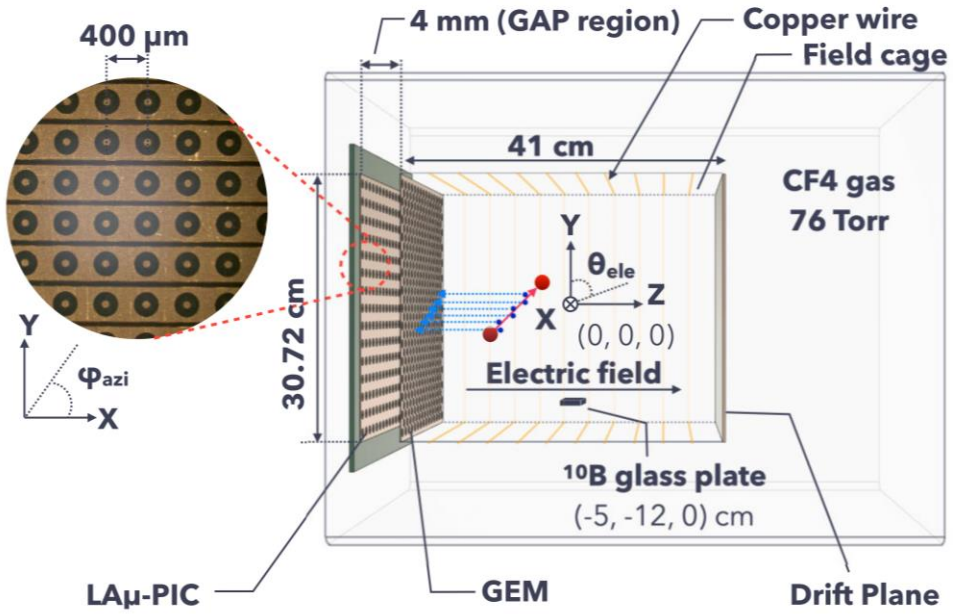




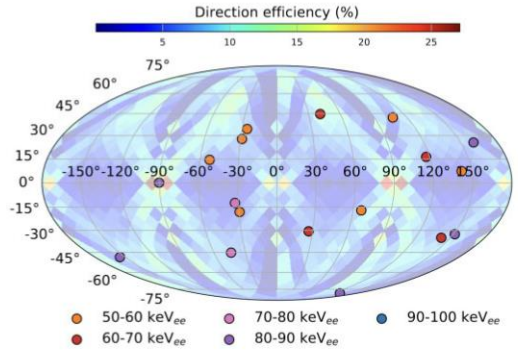
NEWAGE

- Direction-sensitive WIMP searches by using micro pattern gas detector (MPGD)-based micro TPC.
- The best direction-sensitive limit was obtained.

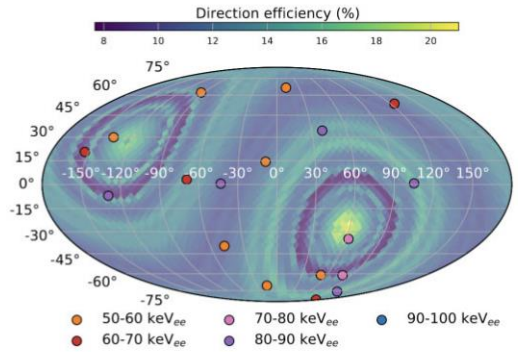
PTEP 2023, 103F01 (2023)



Schematic drawings of the NEWAGE-0.3b''



(a) Nuclear-recoil directions in the detector coordinate



(b) Nuclear-recoil directions in the galaxy coordinate