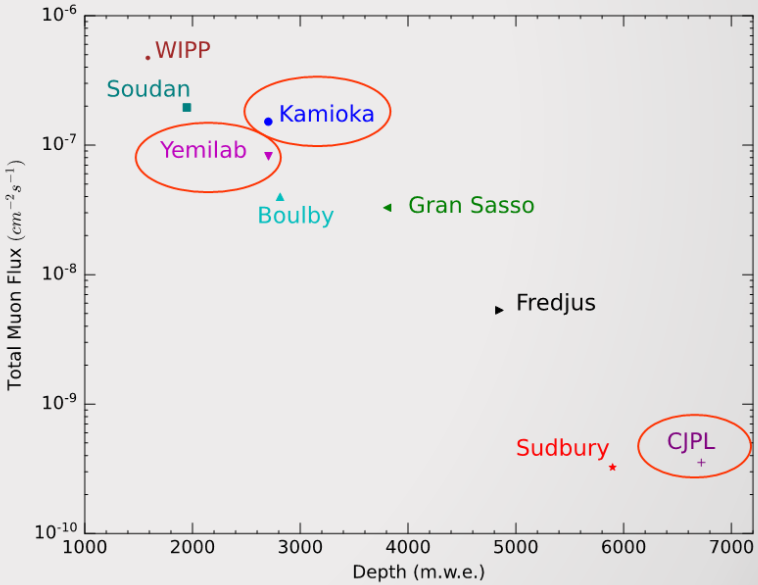
Status of Asian Underground Labs

Douglas Leonard

LRT2022

Rapid City, SD USA

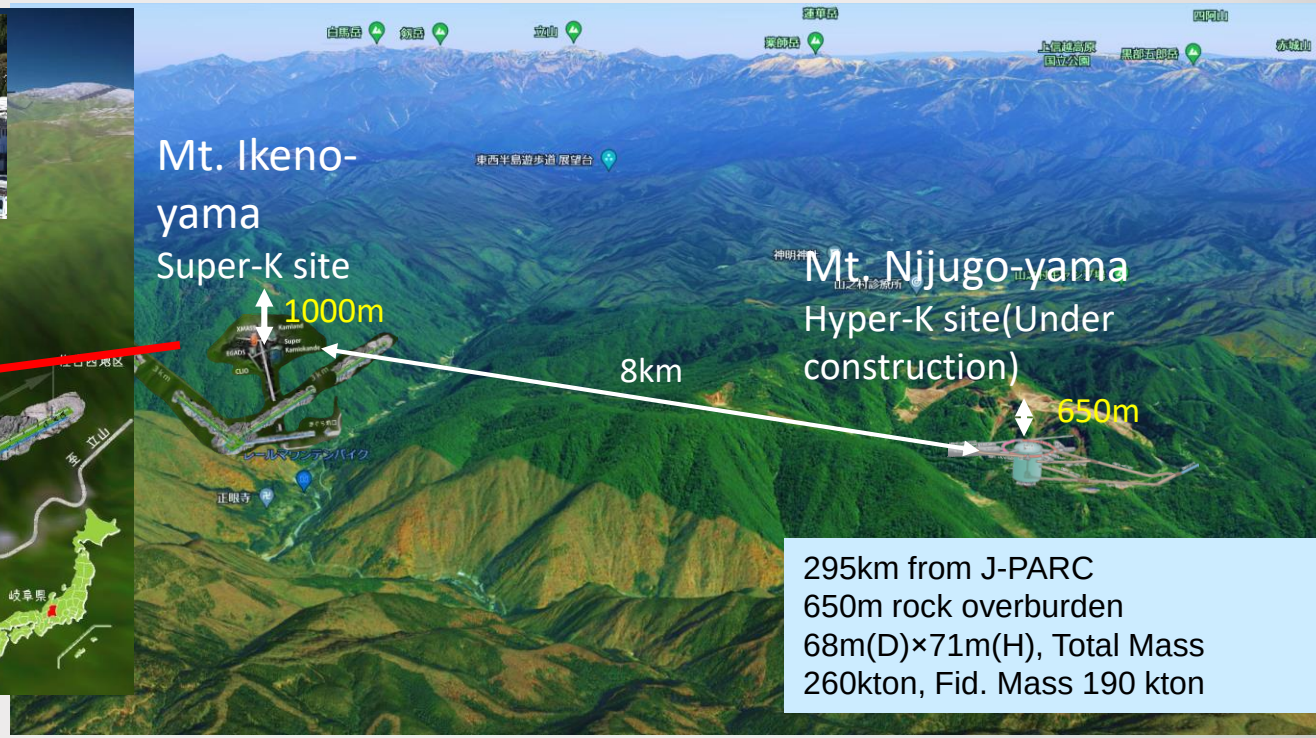


Kamioka underground facilities (Mt. Nijugo-yama)

Following SK slides collected by Hiroyuki Sekiya
(slightly modified)

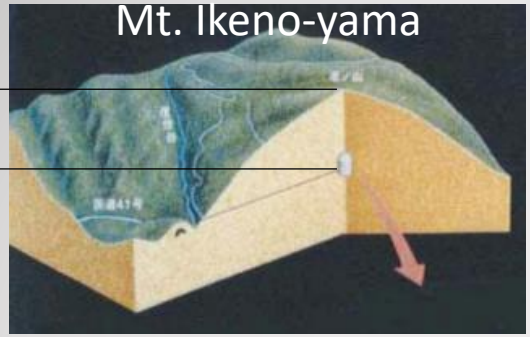
Hyper-Kamiokande is under construction in Mt. Nijugo-yama 8km south from Super-K

KAGRA
3 km L-shaped laser interferometric gravitational-wave telescope with a cryogenic sapphire mirror system.



295km from J-PARC
650m rock overburden
68m(D)×71m(H), Total Mass 260kton, Fid. Mass 190 kton

Kamioka underground facilities (Mt. Ikeno-yama)



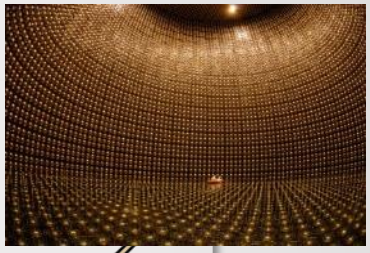
1000m

KamLAND (Tohoku Univ.)

1000ton liquid scintillator detector
Reactor, geo, low-energy astrophysical neutrinos. ^{136}Xe double beta decay

Super-Kamiokande

50,000m^3 Gd-water Cherenkov detector. Atmospheric, solar, supernova neutrinos, DSNB, proton decay, indirect dark matter search. Far detector for T2K.



CANDLES

CaF_2 scintillation detectors for ^{48}Ca double beta decay

KamLAND

Lab.A

Super-K dome

clean room

Lab.E/IMPU

Lab.2

IMPU

Lab.1

water system

Lab.G

100m

Atotsu entrance

Space	L x W x H (m) constrained
1) Hyper-Kamiokande	φ68 x 71
2) Super-Kamiokande	φ39.3 x 41.4
3) Lab-C	20 x 15 x 15
4) Lab-D	14 x 7 x 11
5) Lab-E	15(L) x 10(W) x 9(Hmax)
6) Lab-G	50(L) x 8(W) x 7(H)

XMASS

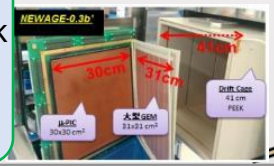
Direct dark matter search experiment using 1 ton of single-phase liquid xenon. Data taking was completed.

EGADS

200t Gd test tank

NEWAGE

Direction-sensitive direct dark matter search experiment with a low pressure TPC and MPGD readout.



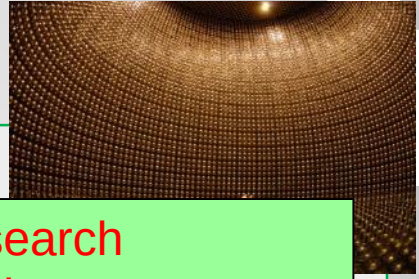
Gravitational-wave

CLIO 100m x 100m prototype

Geophysics 100m x 100m

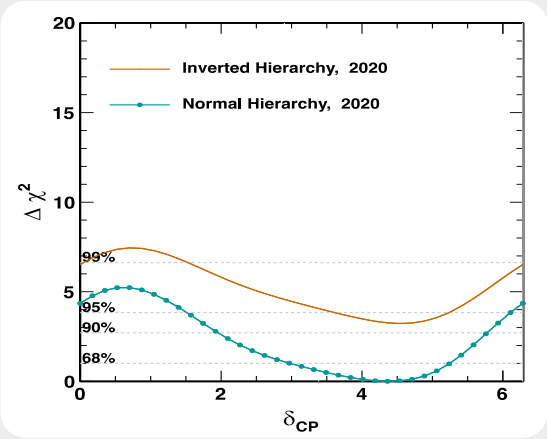
Laser strain meter

Super-Kamiokande

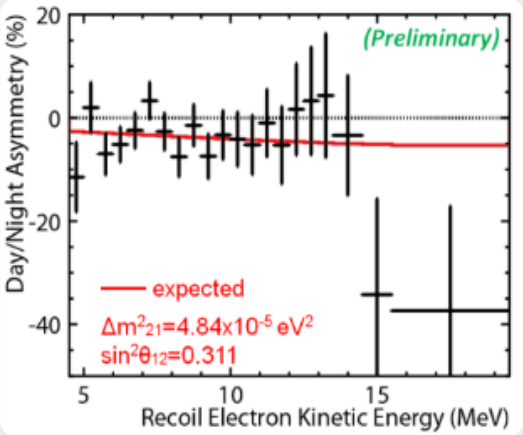


Recent progress

Mass hierarchy and CP (IH disfavored with 71.4 -90.3% by atm. ν)

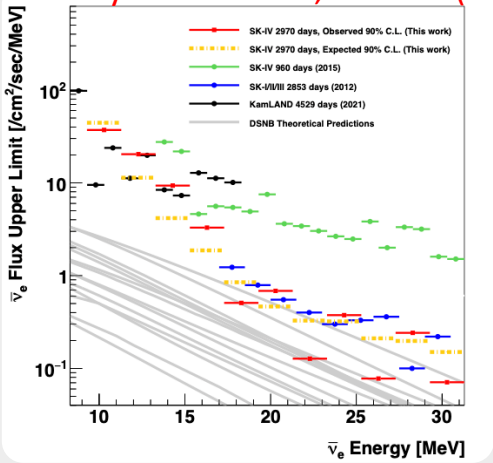


3σ day/night asymmetry (solar ν)



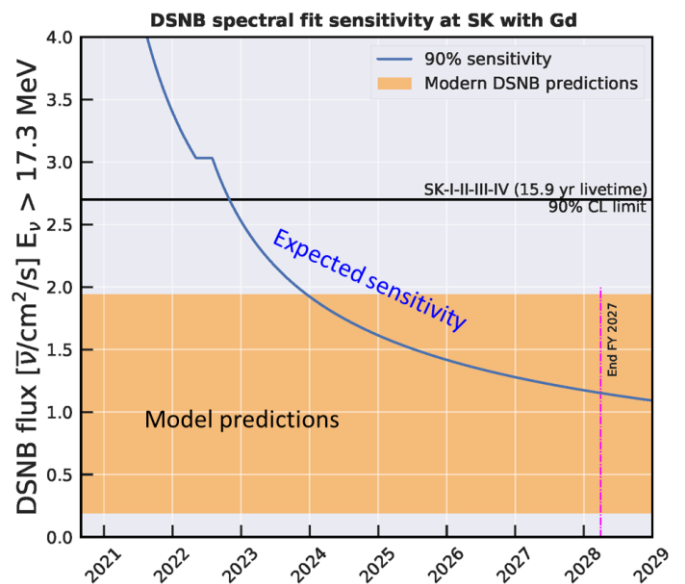
DSNB search
Best limits > 17MeV

Phys. Rev. D 104, 122002 (2021)



Prospects

- Gd concentration is being increased up to 0.03%(Jun.-July 2022)
  - Enhance anti-neutrino detectability, especially for diffuse supernova relic neutrino background.
- Continue ν oscillation studies (atm, solar) and nucleon decay searches.



Also see Neutrino 2022 talk, L. Wan, includes Boosted DM search.

T2K experiment

Recent progress

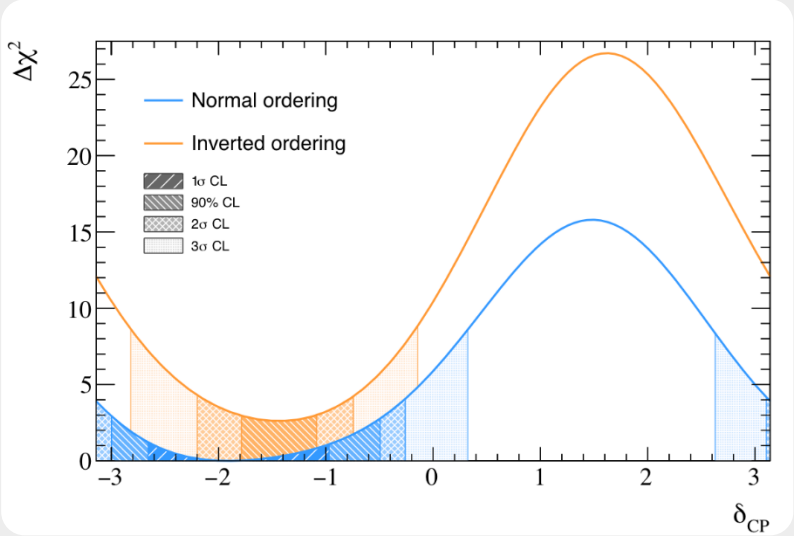
δCP measurement

ν_μ 19.7x10^{20} POT → ν_e 108 events

$\bar{\nu}_\mu$ 16.3x10^{20} POT → $\bar{\nu}_e$ 16 events

Nature 580 (2020) 339

Feldman-Cousins critical values using θ_{13} from reactor experiments suggest a value around -δCP =1/2π



δ_{CP} = [-π, -0.26] U[3.11,π](NH) @2σ CL

Prospects

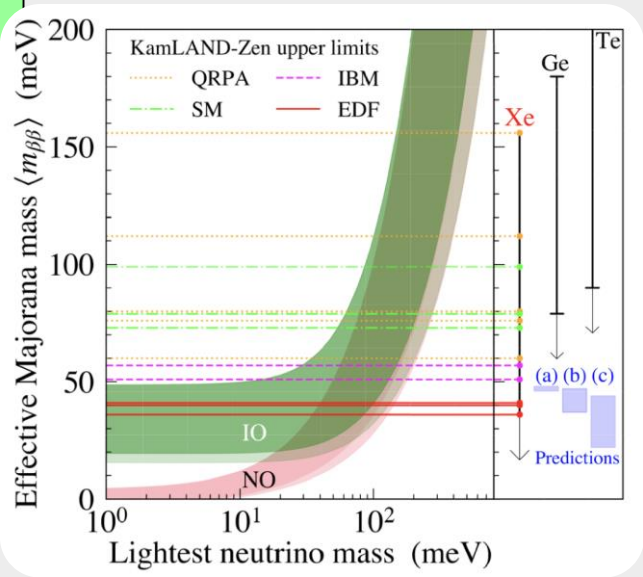
- T2K collaboration is aiming to accumulate 200 x 10^{20} POT.
- With much more statistics, search for CP asymmetry will be performed.
- Precise measurement of neutrino cross section at the near detector.

KamLAND

Recent progress

Improved Majorana Mass limit with Zen 800 data (750 kg Xe),
< 36-156 meV @90% C.L. (double β decay), entering the inverted ordering region

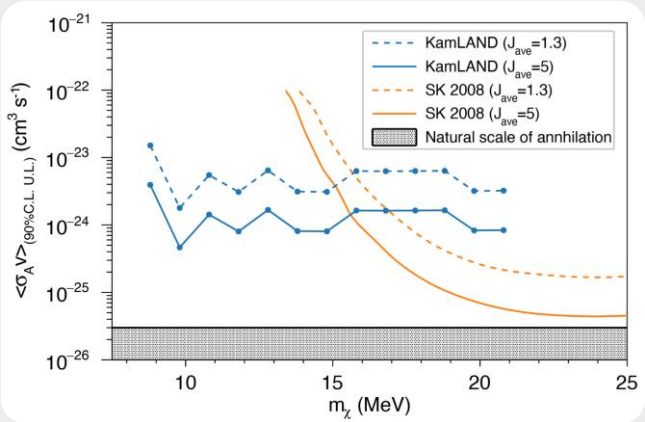
Also see Neutrino 2022 talk by Asuza Gando



arXiv:2203.02139

Improved sensitivity for low energy astronomical neutrinos including light dark matter annihilation

Astrophysical Journal 925 (2022) 14



Prospects

- New muon bundle reconstruction and particle identification using machine learning will further improve the sensitivity on the Majorana neutrino mass.
- Geo-neutrino data will be released soon with increased low reactor period.
- Studies on neutral current interaction called T2KL are going on with the J-PARC neutrino beam.

XMASS/Generation three consortium

- XMASS-I: single-phase LXe detector
  - 832 kg total (~100 kg in fiducial)
  - 642 low-BG PMTs
  - Self-shielding external gamma-rays
  - Water Cherenkov veto detector
  - Data-taking completed in 2019
  - DM search with 5 yrs data on going

Low background PMT, R13111

3'' convex-shape PMT for LXe det.

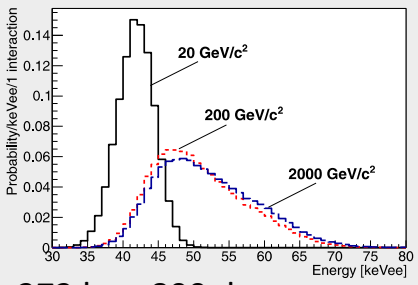
- ^{39}K enriched PC (less Cherenkov)
- Synthesized glass bead for feedthrough
- Purest grade Al for the seal

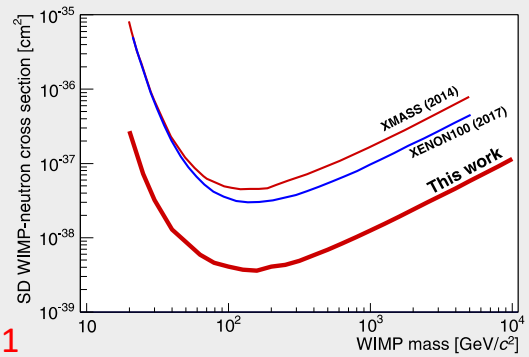
0.4 mBq ^{226}Ra, < 2 mBq ^{228}U

0.3 mBq ^{228}Ra, 2 mBq ^{40}K, 0.2 mBq ^{60}Co

JINST 15, P09027 (2020)

WIMP-^{129}Xe inelastic scattering with particle ID

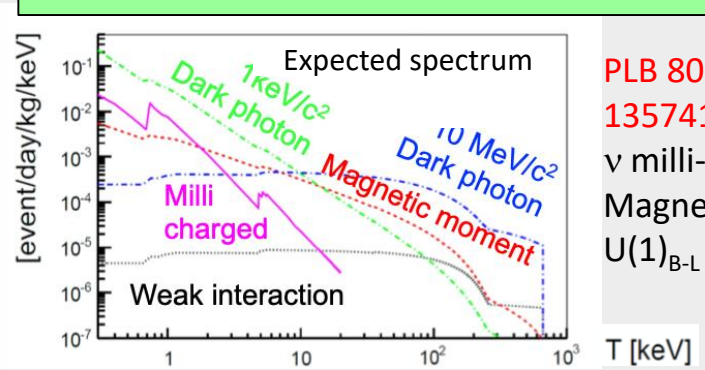




372 kg x 800 days exposure

Astropart. Phys. 110 (2019) 1

Exotic interaction of solar neutrinos



PLB 809 (2020) 135741

ν milli-charge

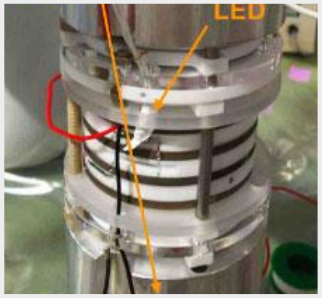
Magnetic mom.

$U(1)_{B-L}$ dark photon

- Generation three consortium (G3C)
  - Aiming at developing high sensitive DM det.
  - Sharing experimental equipment of XMASS among several groups in G3C
  - Target material other than LXe

Low noise photosensors (SiPM), directional sensitive crystals, infrared emission from LXe...

Dual-phase LXe TPC with a quartz chamber



PTEP 2020, 113H02

Dual-phase LXe TPC for reducing ^{222}Rn and electronegative impurities

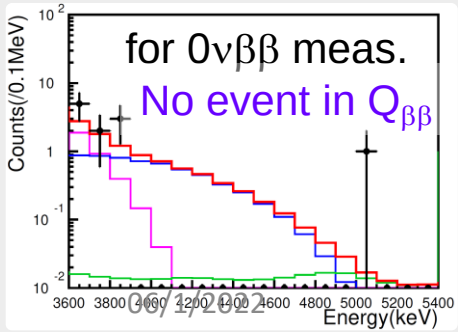
48 mm phi x 58 mm volume

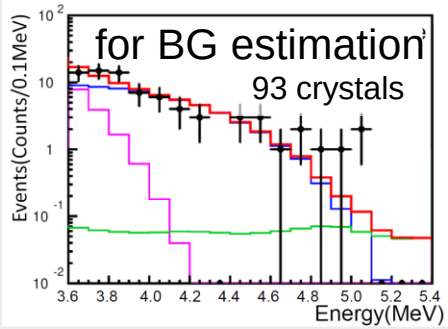
Proof of principle of TPCs incorporating a quartz chamber.

CANDLES

- ^{48}Ca 0νββ search
  - $Q_{\beta\beta}$=4.27MeV
  - 300kg CaF_2 crystals immerged in LS
  - 130.4 days data
  - BG event rate
    10^{-3} events/keV/yr/(kg of ^{nat}Ca)!
  - Lower limit 5.6 x 10^{22}years
    Physical Review D 103(2021)092008
  - New analyses for 778 days data
    Likelihood analysis and CNN
    will improve rejection effi. for ^{208}Tl
  - Future prospect
    ^{48}Ca enrichment
    $^{48}CaF_2$ bolometer

Results from 21 crystals





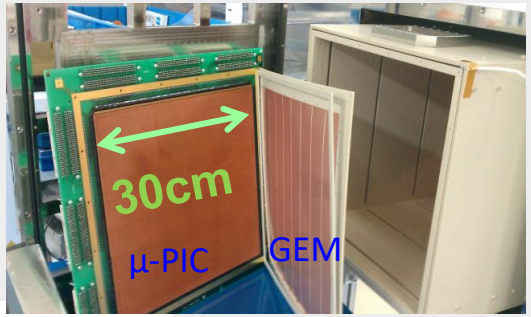
Including high contaminated crystals

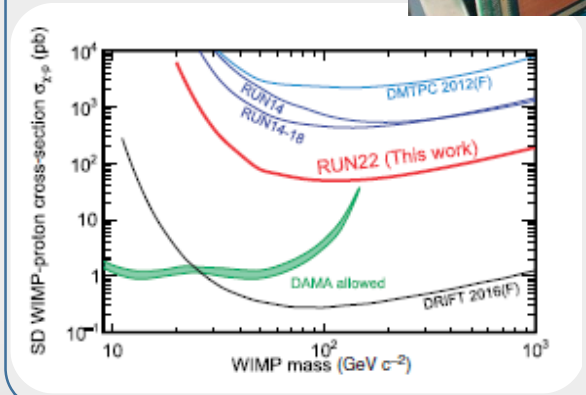
NEWAGE

- Directional DM search
  - NEWAGE-0.3b'': MPGD (micro pattern-gas detector)-based (micro-TPC)
  - 30 × 30 × 40cm^3
  - 3D nuclear tracks
  - low pressure (0.1 atm) CF4 gas
  - readout pitch: 400μm pitch
  - low-α μ-PIC ((2.1 ± 0.5) × 10^{-4} α/cm^2/s)
    NIMA 977 (2020) 164285

NEWAGE-0.3b"

MPGDs (μPIC+GEM)



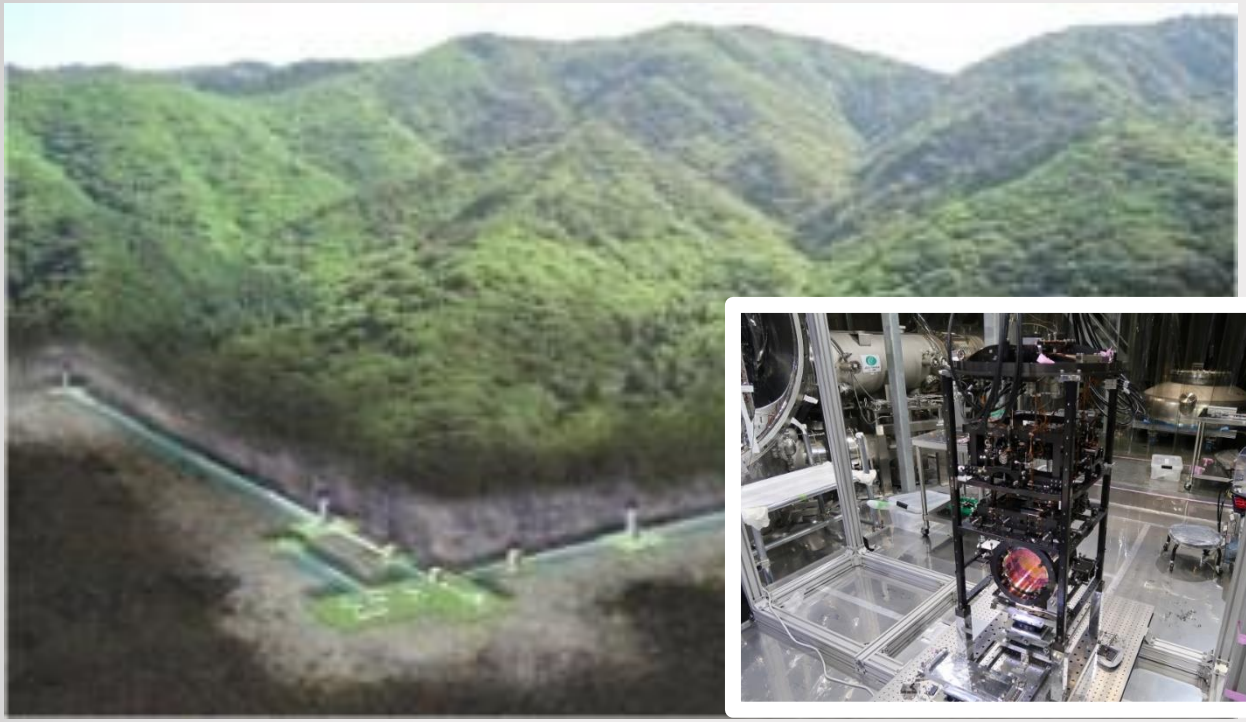


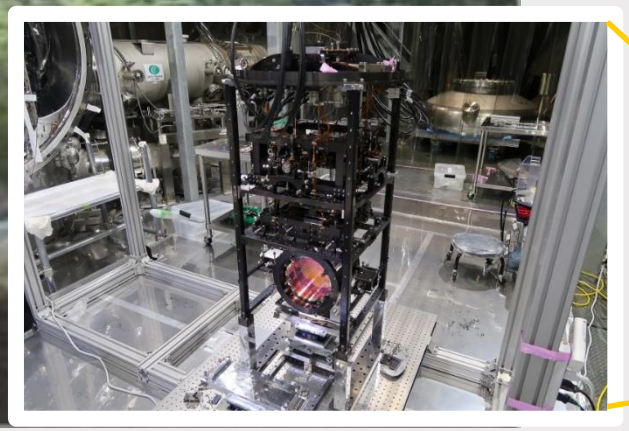
Directional DM search

PTEP 2021, 063F01
Updated directional DM search limits

KAGRA Gravitational-wave Telescope

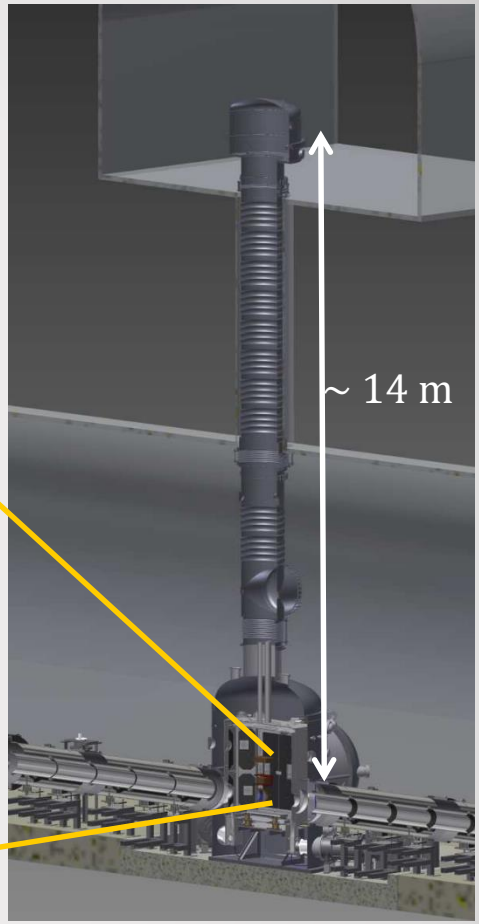
First km-scale GW detector built underground, and first with mirrors at cryogenic temperatures.





Cryogenic Sapphire Mirror

Vibration Isolation Tower



- MoA was concluded with LIGO and Virgo in October 2019 for the network GW observation.
- Gravitational wave observation with GEO600 in April 2020 (O3GK) was done.
- KAGRA, LIGO and Virgo have a plan to start the 4th GW network observation (O4) from December 2022.

Hyper-Kamiokande

arXiv:1805.04163

260,000 tonnes H2O
40,000 PMTs
68m D x 71m H

The center of HK dorm

50cm PMTs being produced
in Hamamatsu
and checked in Kamioka
Credit: Hamamatsu Photonics K.K

Access tunnel

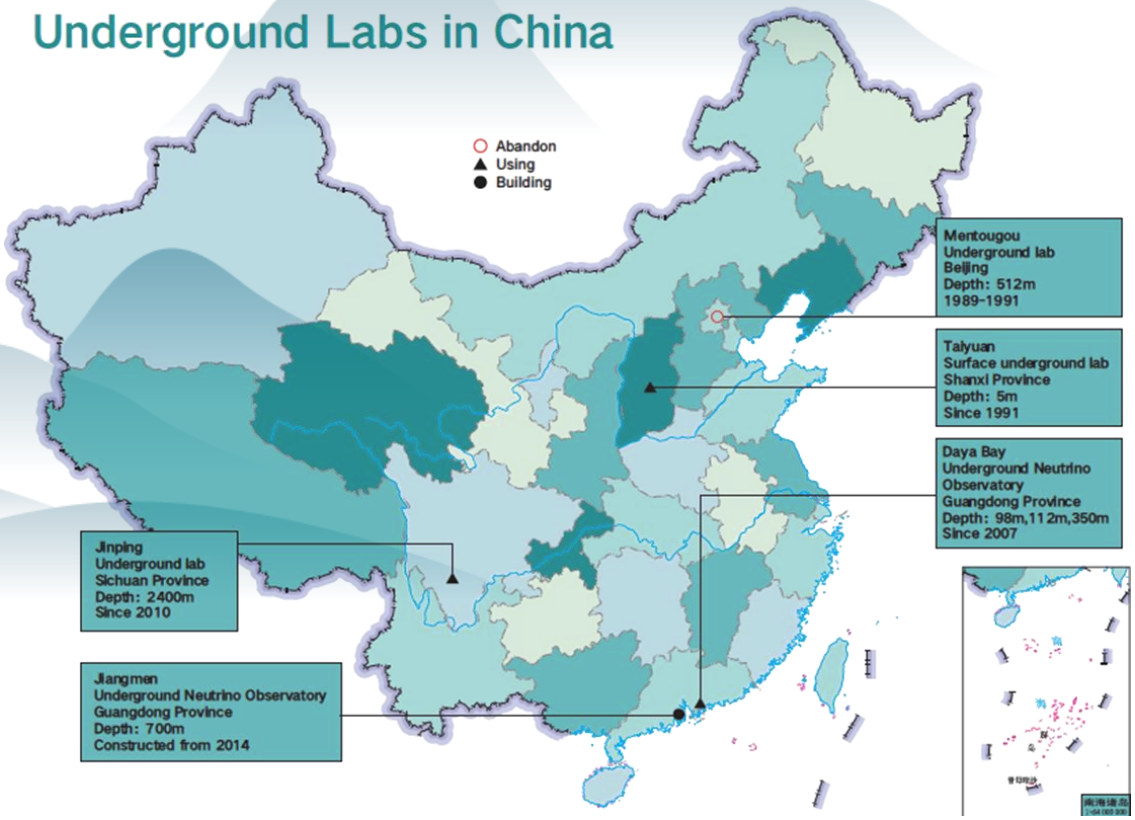
- Completion of 2km access tunnel excavation in Feb.2022
- Detector cavern excavation scheduled in 2022-2024
- Start operation in 2027

The China Jinping Underground Laboratory

Content of following slides mostly from Zhi ZENG

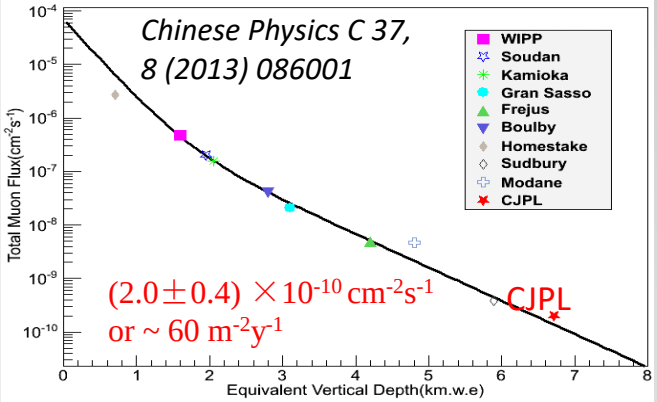
on behalf of the CJPL team

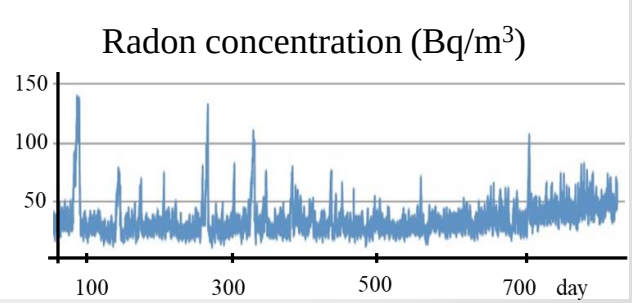
Tsinghua University

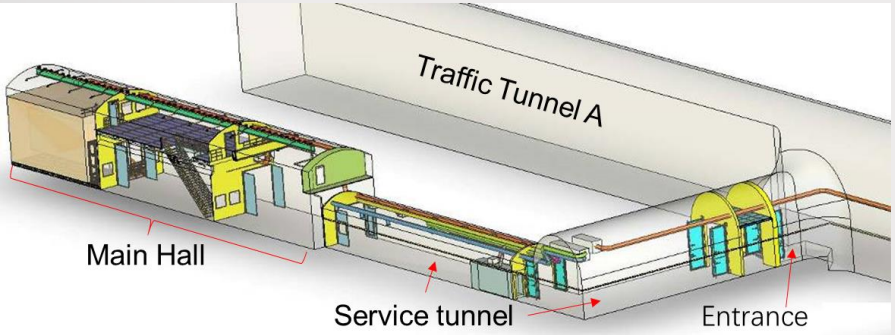


CJPL Features

- Deepest underground laboratory with a rock overburden of 2400m.
- Open on Dec. 12, 2010, extended from hydro-power facility.
- Total space: ~4000 m^3.
- Main Hall: 6.5m(W) × 6.5m(H) × 42m(L).
- Low Muon flux and environmental background.





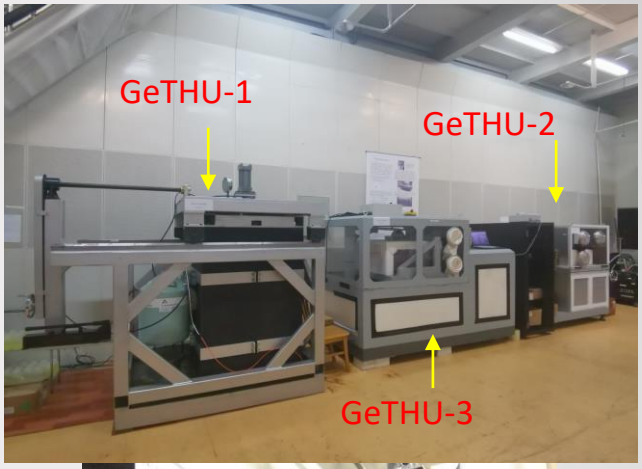


Rock sample(Marble) measurement by Germanium

(Unit : Bq/kg)	K-40	Ra-226 (609keV)	Th-232 (911keV)
Rock Sample	< 1.1	1.8±0.2	< 0.27
Ground Level(Beijing)	~600	~25	~50

GeTHU γ Spectrometers in CJPL-I

- GeTHU-1
  - N type, Rel. Eff. 40%
  - Crystal: ϕ59.9x59.8 mm (~900 g)
  - MDA: ~0.1 mBq/kg
- GeTHU-2/3
  - BEGe, Rel. Eff. 67%
  - Crystal: ϕ91.5x31.6mm (~1.1 kg)
  - FWHM: 1.67keV @1332keV
  - MDA: ~1mBq/kg
- GeTHU-4
  - P type, Rel. Eff. 120%
  - Crystal: ϕ84x84 mm (~2.5 kg)
  - MDA: <0.1 mBq/kg



CJPL-II Project

- Construction of CJPL-II started on Nov. 25, 2014
- Dec. 2015: The rock excavation of all exp. halls completed.
- May 2016: Expansion of two exp. pits finished.
- Dec. 2016: Installation of ventilation system started.
- Total volume: 300k m^3 with 4 main halls of 14x14x130 m (4000m^3 of CJPL-I) containing 2 large caverns/pits.

Exp. Hall excavation

Exp. Pit

Ventilation tubes

PHYSICS

China supersizes its underground physics lab

Planned expansion could pave way for "ultimate dark matter experiment"

The world's deepest physics laboratory is about to become one of its largest. Early next year, workers will start ca… ha… Mo… ince. On… Undergr… as well, … physics," says Nigel Smith, director of the underground SNOLAB in Sudbury, Canada.

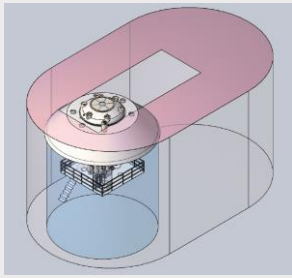
The world's **deepest** physics laboratory is about to become one of its **largest**.

Science, Nov. 30, 2014

DURF Project

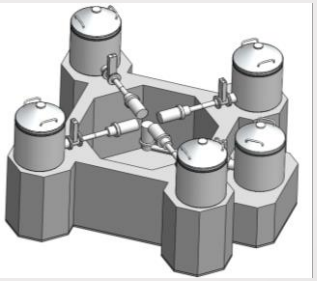
- **Deep Underground and ultra-low Radiation background Facility for frontier physics experiments(DURF)** is one of the 10 prior projects of ***National Major Science &Technology infrastructure***.
- CJPL-II was selected to build DURF, and the proposal approved in the Dec.13 , 2018, ~177 million euros.

- A large pure water vessel in hall B2
  - 27x15x13m (10m dia water tank)
  - Shielding from environmental radioactivity
- A large LN_2 tank in hall C1
  - Φ13x13 m, ~1700m^3 LN_2
  - Shielding from environmental radioactivity
  - Cryogen for low-temperature experiments
- A Low-background counting facility in C2
  - ARGUS spectrometer: ~10 μBq/kg
  - 15x Low Bkg spectrometers: ~0.1 mBq/kg

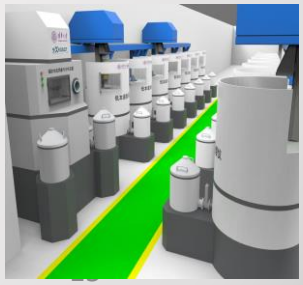


Water vessel

LN_2 tank



ARGUS

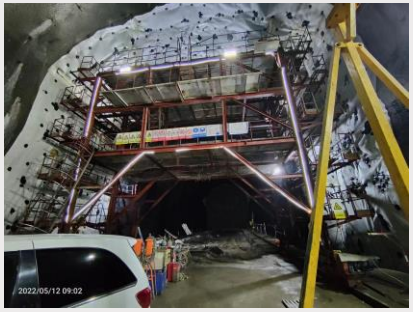


15 HPGe spectrometers

DURF Project

- Jun. 2019, preliminary design permissioned by MOE；
- Feb. 2020, investment budgetary approved by National Development and Reform Commission;
- Dec. 2020, engineering construction of DURF started;
- Jun. 2022, electromechanical equipment installation started;
- Dec. 2024 in planning, trial operation started and DURF prepared for acceptance;

Radioactivity screening by GeTHU during construction



current construction in hall C

Science at CJPL

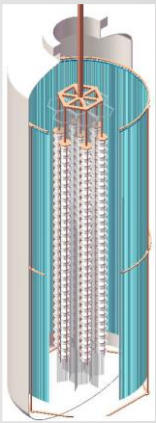
Hao Ma *et al* 2021 *J. Phys.: Conf. Ser.* **2156** 012170

CJPL-I

- CDEX-1 p-type Ge WIMP search in PE room. Excludes DAMA/LIBRA region.
- CDEX-10 Ge in LN2. WIMP and dark photon search
- PANDAX-II 580kg Xe TPC.

CJPL-II

- CDEX-50 (DM-search), WIMP-nucleon SI coupling cross section goal: 10^{-44} cm^2 at WIMP mass <10 GeV/c^2 .
- CDEX-300v 0νββ with p-type point contact (PPC) ^{76}Ge in purified LAr in LN2 tank, half-life goal > 10^{27} years.
- PandaX-4T: 3.7-tonne of liquid Xenon, in B2 hall (water tank), SI DM CS limit results: 3.8×10^{-47}cm^2 at 30 GeV/c2. Yue Meng et al., Phys. Rev. Lett. **127**, 261802
- JUNA in A1 hall, accelerator-based nuclear astrophysics, accelerator installed in 2020, with some early results. Liu, W.P., Li, Z.H., He, J.J. *et al. Few-Body Syst* **63,** 43 (2022)
- Full commissioning of CJPL-II → March 2023.



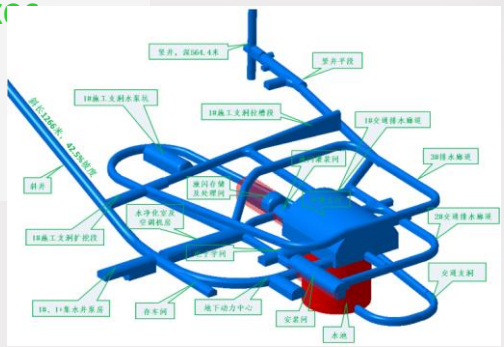
Qian Yue's CDEX-300v talk, TAUP 2021.

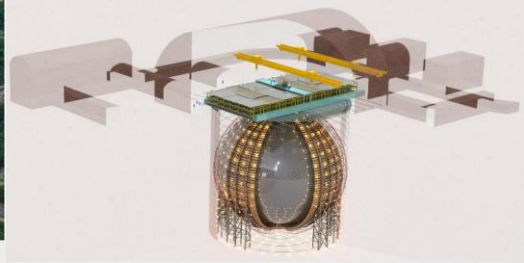
Jiangmen Underground Neutrino Observatory (JUNO)

Slide from Jun Cao

A 20k ton liquid scintillator detector for reactor, solar, atmospheric, supernova, and geo-neutrinos

- 700 meter underground
- 53 km from Taishan and from Yangjiang reactor complexes
- Detector submerged in a 44.5 X 44 m water pool
- Muon flux 0.004 Hz/m^2
- Excavation completed in 2020; detector ready in 2023





April 2022

JUNO Radioactivity Control

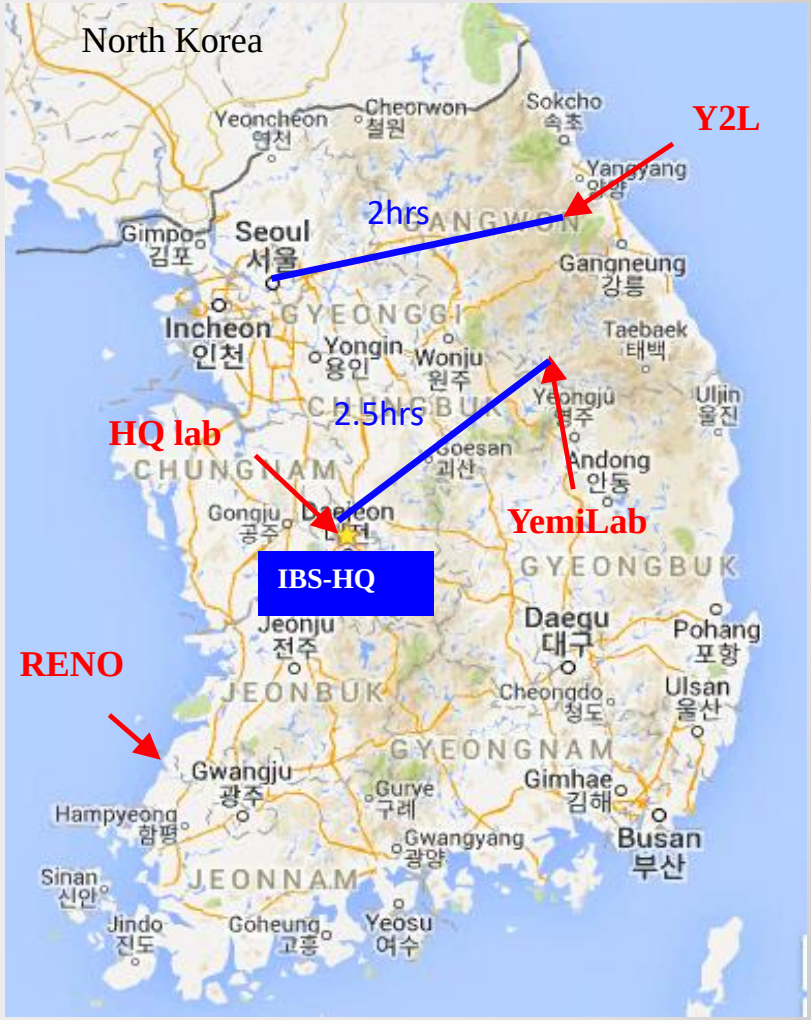
The JUNO collaboration., Abusleme, A., Adam, T. *et al.* *J. High Energ. Phys.* **2021,** 102 (2021)

Mostly through collaborative offsite resources:

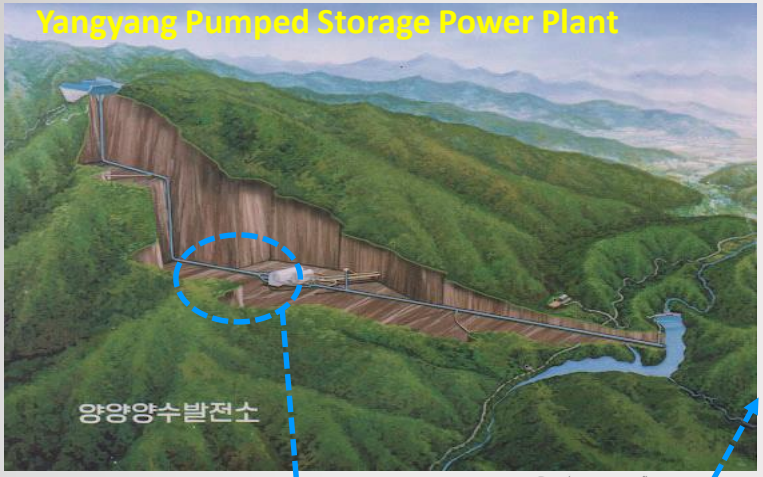
- HPGe, collaboration based resources at Jinping, Modane, LNGS, etc..
- ICP-MS at IHEP.
- Rn measurements via work at IHEP, CENBG, CPPM, etc.
- NAA via TRIGA Mark II reactor at University of Pavia and HPGe at Milano-Bicocca University.

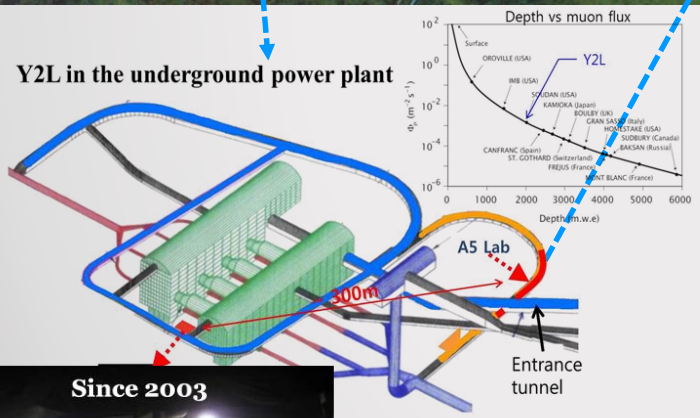
… not an exhaustive list.

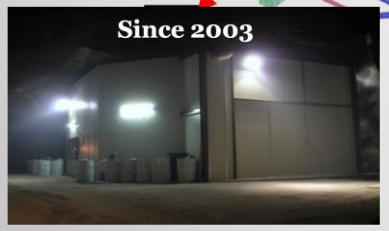
Underground Labs in Korea

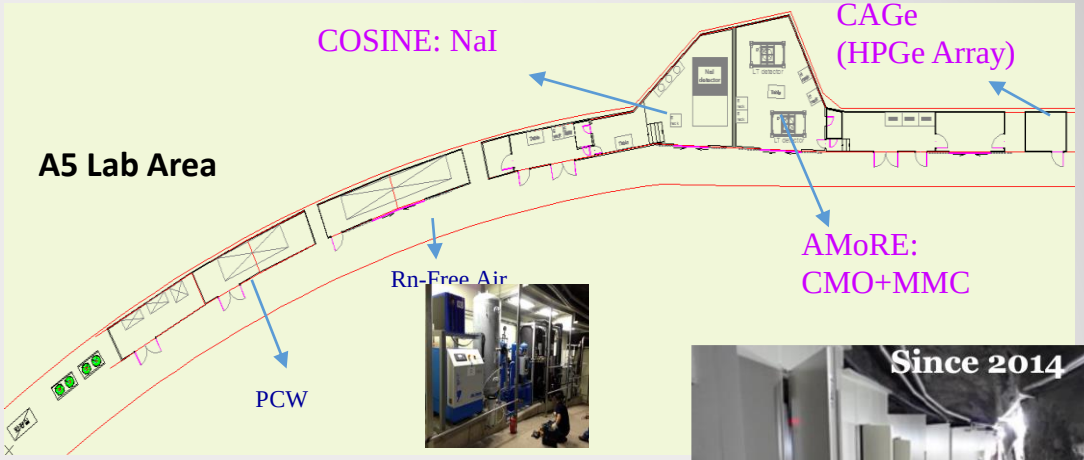


Yangyang Underground Laboratory (Y2L)









Minimum vertical depth : 700 m
Drive-in access: around 2 km

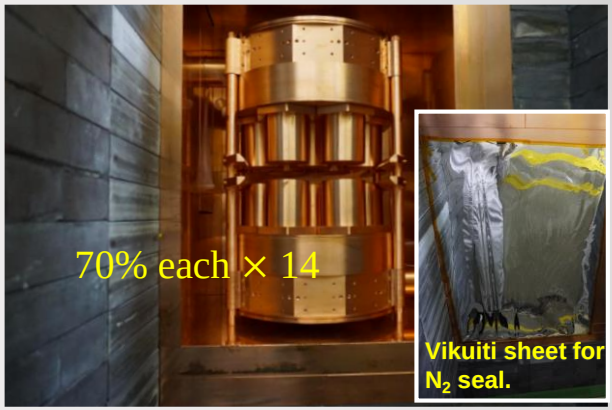
A5 lab space:
AMoRE-pilot/AMoRE-phase I 100Mo DBD experiment.
Cosine NaI dark matter search
14 element HPGe Array

A6 lab space:
Home to prior KIMS CsI DM experiment
Houses two 100% HPGe detectors

Assay Resources at Y2L

- Two 100% HPGe detectors underground at Y2L A6 site CC1 and CC2, N2 purged for Rn removal.
- XIA ULtraLo-1800 alpha counter, 1800 cm^2 area.
- CAGe array: 14 Detectors, 70% rel eff each @ Y2L A5 site.
- Compliments ICP-MS facilities in Daejeon.

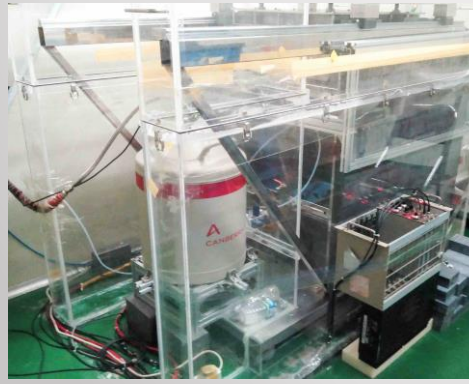
CAGe

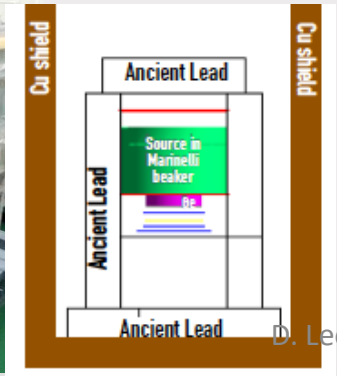


D. Leonard et al., "Development of an array of fourteen HPGe detecotors...," NIM A 989 (2021) 164954;

XIA UltraLo-1800 Alpha Counter

CC1

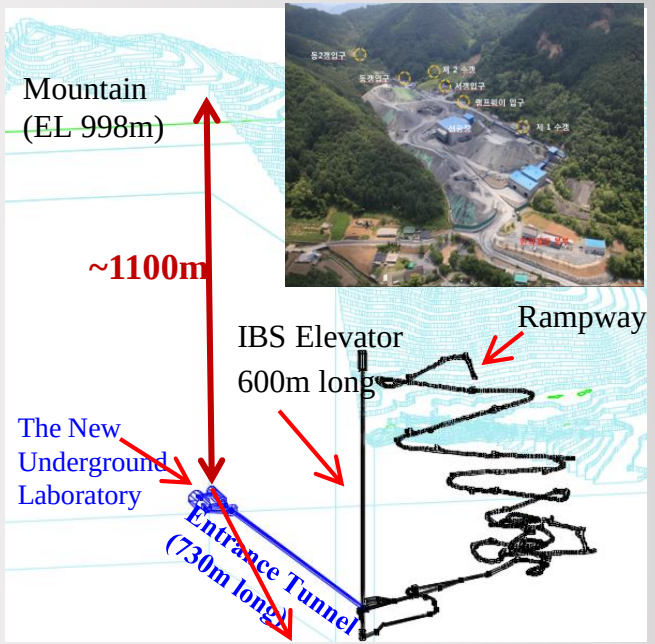


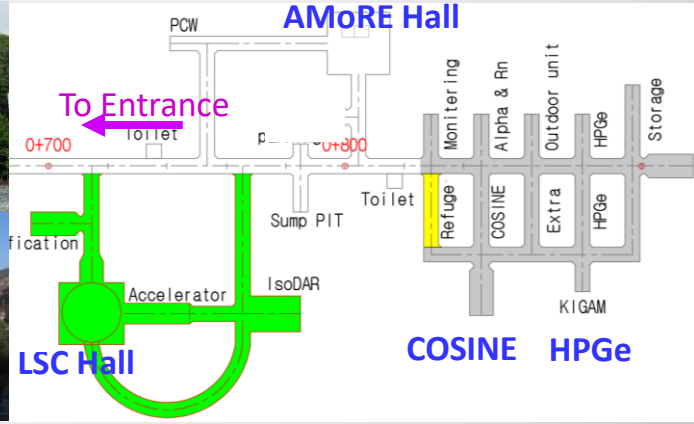


CC2

New YemiLab

- At Handeok Iron Mine (active), Jeongseon, Korea.
- Drive-in (large equipment), and vertical (default) access.
- 1100m deep, 2700 m^2 lab space, 6th largest in world.
- Large halls for AMoRE-II, LSC w/cyclotron/accelerator & purification
- "Ladder" halls for COSINE, HPGe/Alpha, Refuge, etc.
- Ground offices and residence.
- Completion Summer 2022.



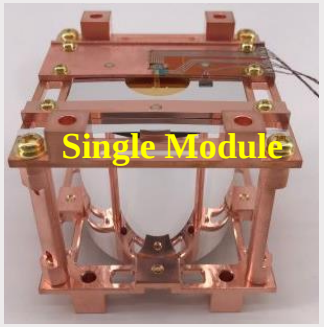


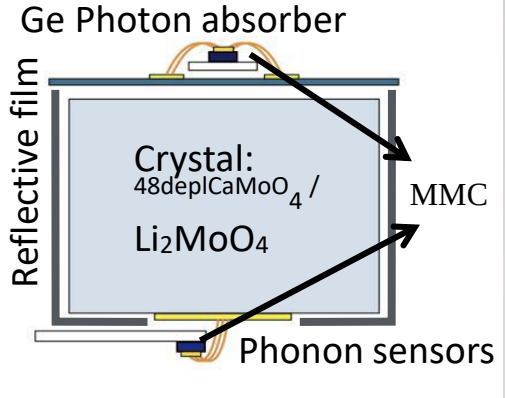
AMoRE Experiments

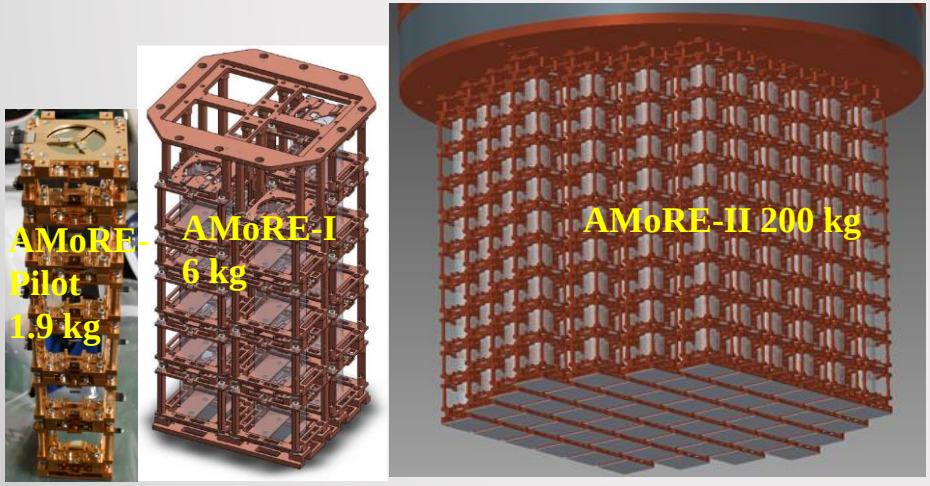
- 0νββ search with cryogenic $X^{100}MoO_N$ detectors. (X=Ca, Li_2, Na_2, etc..)
- MMC (Metallic Magnetic Calorimeter) detects heat by change in magnetization in current loop.
- "In-house" purification and crystal growing.
- Pilot ran from 2018 with 1.9kg $Ca^{100}MoO_4$

$T_{1/2} > 9.5 \times 10^{22}$ Alenkov, V. *et al.* *Eur. Phys. J. C* **79,** 791 (2019)

CUP grown $CaMoO_4$





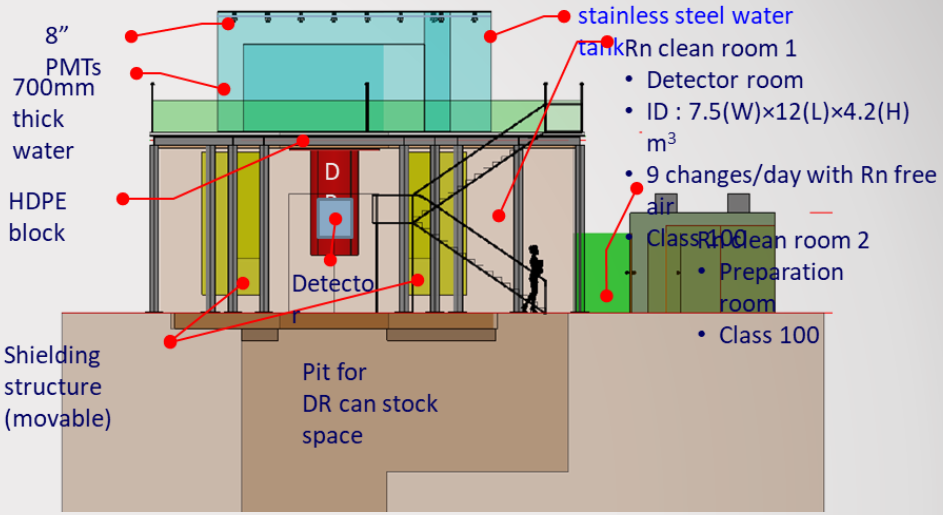


	Phase I	Phase II
Mass	~6 kg	~40 (200) kg
MMC Channel	36	1000
Required bkgd (ckky)	0.0015	0.0001
Sensitivity($T_{1/2}$) (year)	~10^{25}	~5×10^{26}
Sensitivity($m_{\beta\beta}$) (meV)	120-200	17-29
Location	Y2L	Yemilab
Schedule	2020 ~	2023 ~

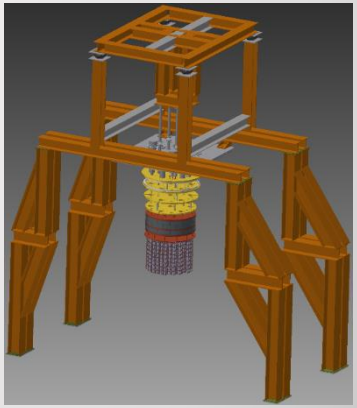
AMoRE II at Yemilab

AMoRE-II Hall

Shielding Pb and PE installation

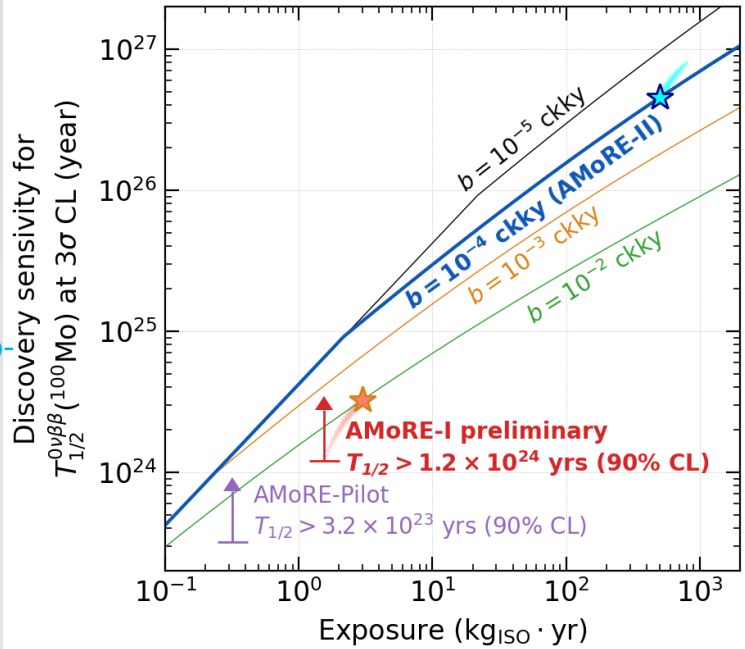


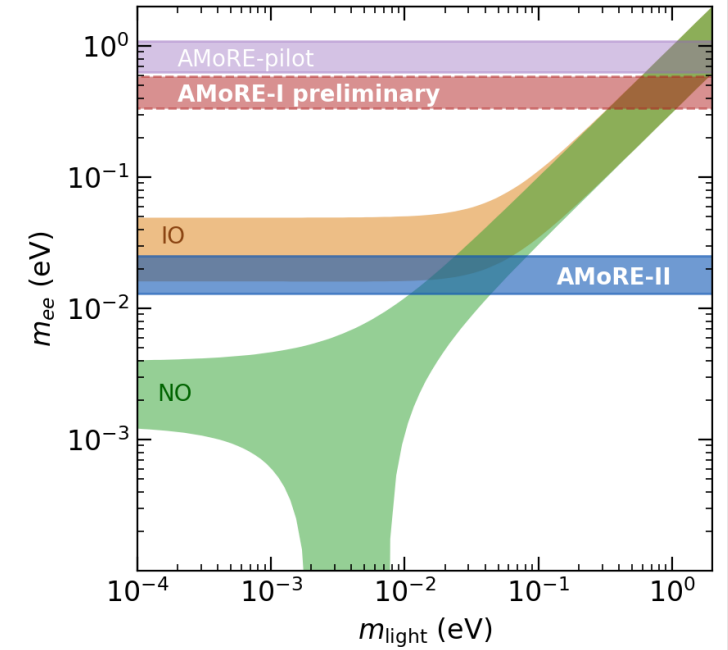
- AMoRE-II construction is underway at Yemlib.
- Commissioning next year.

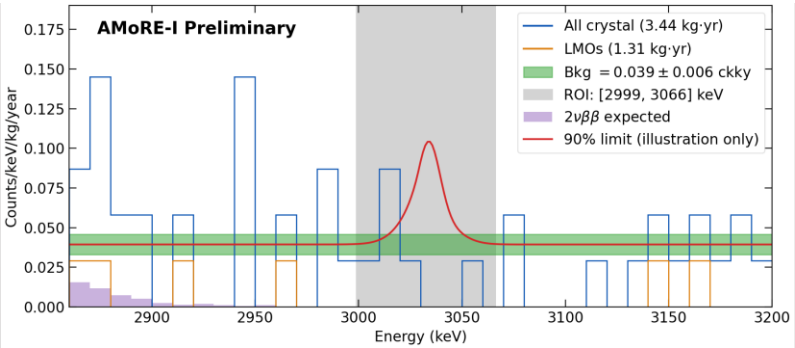


AMoRE Status

Yoomin Oh Neutrino-2022





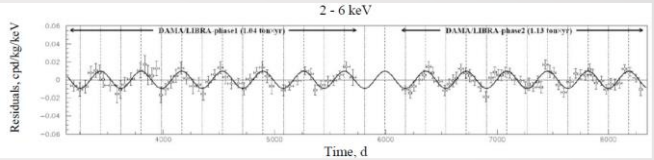


- AMoRE-I still taking data (~2 × more left)..

  Prelim: : $T_{1/2}^{0\nu} > 1.2 \times 10^{24}$, ~ 0.04 counts/kev/kg/yr @ROI.
- AMoRE-II plan: $T_{1/2}^{0\nu}$ >~5 × 10^{25} yr, 100 kg Mo-100 × 5 years.
- Reduction of background level down below 10^{-4} ckky.

COSINE-100

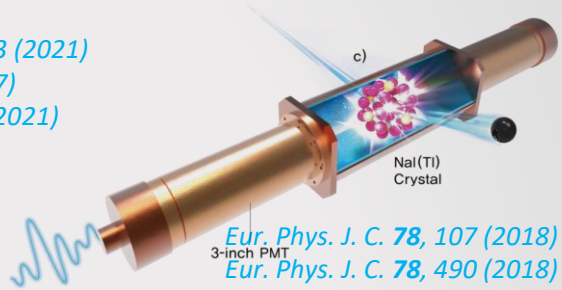
DAMA/LIBRA observation



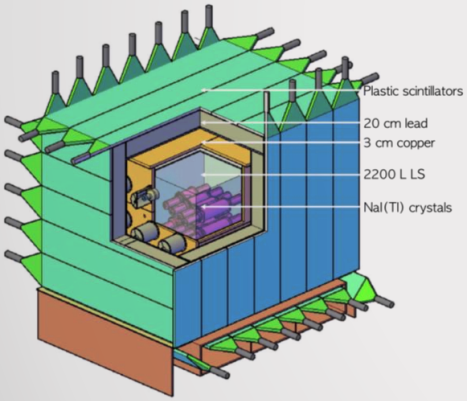
Nucl. Phys. At. Energy 19, 307-325 (2018)

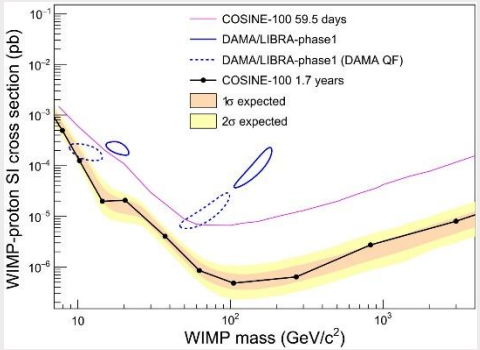
- NaI(Tl) detector modules.
- 4π PS and LS veto counters.
- Testing DAMA/LIBRA oscillation with same material.
- Stable since 9/30/2016

*JINST **13**, T02007 (2018), JCAP **02**, 013 (2021)*
*Nucl. Instrum. Meth. A **851**, 103 (2017)*
*Nucl. Instrum. Meth. A **106**, 165431 (2021)*

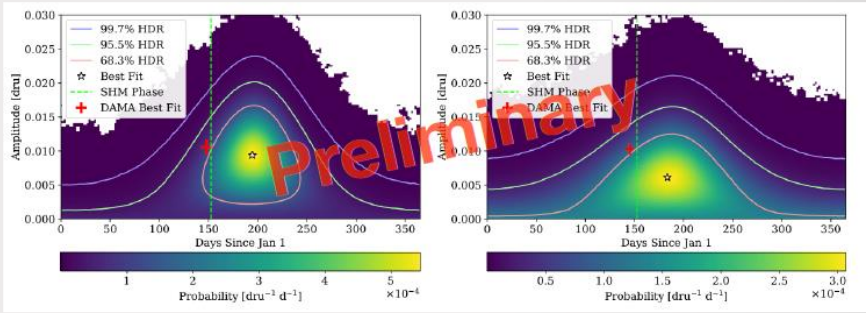


*Eur. Phys. J. C. **78**, 107 (2018)*
*Eur. Phys. J. C. **78**, 490 (2018)*





SCIENCE ADVANCES 10 Vol 7, Issue 46 (2021)



arXiv:211.08863v1

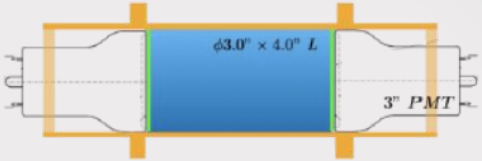
- Strong constraints on DAMA/LIBRA even with different Q factor.
- Can't rule out DAMA/LIBRA with model independent modulation search.

COSINE-200 plans at Yemilab

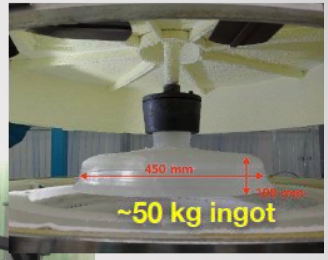
- In house purification and growing.

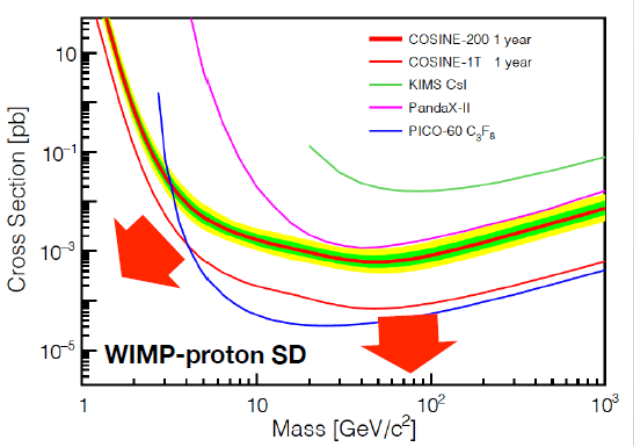
  => reduced bkgd, 0.2~0.3 cpd/kg/kev
- New direct-coupled encapsulation

  => 50% more light yield ~23 p.e./kev.
- 200kg NaI.
- Lower threshold.
- Possible low temperature.



New design

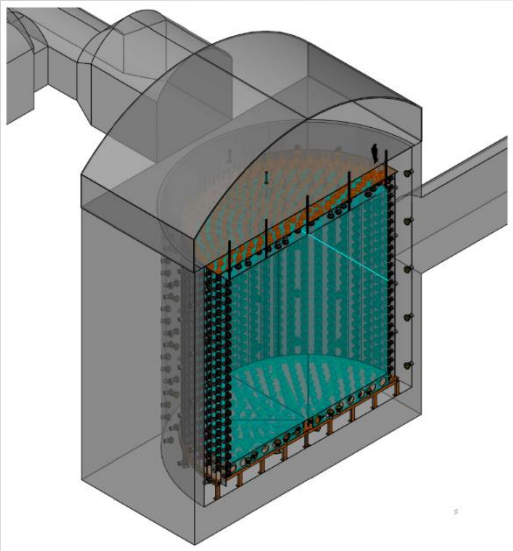




Y.J Ko, Blois 2022

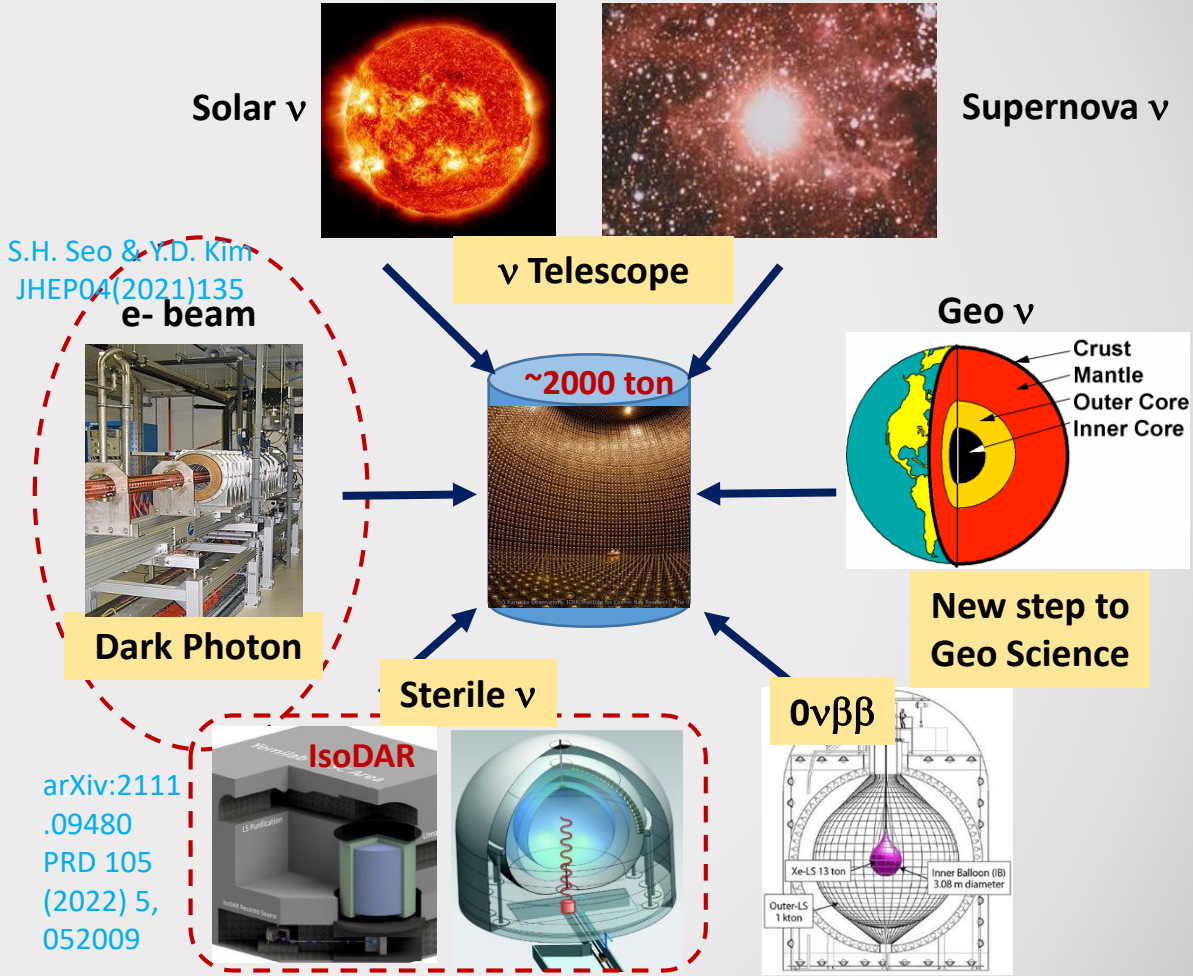
LSC Detector & Broad Physics Program

Slides from S.H. Seo, CUP, IBS



Target: **2.26 kton LS**
Buffer: 1.14 kton mineral oil
Veto: 2.41 kton water

1200(1800,2400) x 20 inch PMTs
= 20% (30, 40)% coverage



LSC Quick Summary

- In Yemilab, **new caverns** for ν detector & cyclotron room are constructed in early 2022.

- Constructing a ~2 kton LS detector would be the best physics case.

  Multi-purpose detector: **sterile ν, solar ν, direct dark photon, SN ν,** geo ν, etc.

- IsoDAR@Yemilab: world leading in sterile ν search in $P(\bar{\nu}_e \rightarrow \bar{\nu}_e)$ channel; definite conclusion on (3+1) ν or not; other interesting BSM physics searches

- 1 year operation of 100 MeV e^- beam (100 kW):

  best "direct" dark photon search sensitivity

  in O(1 eV) < M_ϕ < 30 MeV (assuming 10^3 bkg events/year)

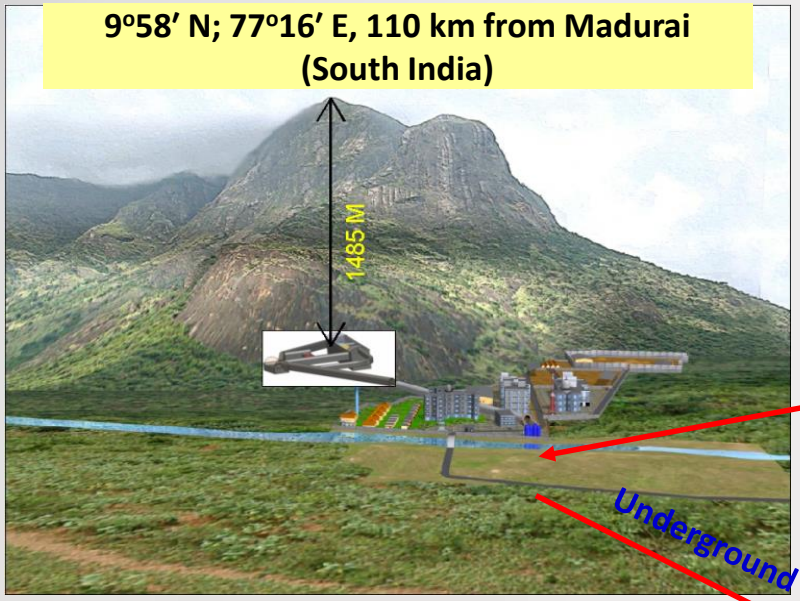
- **Funding** proposal for detector, Promoting more collaborators, and writing White paper, R&D studies are currently underway.

Plan to take data in ~2027

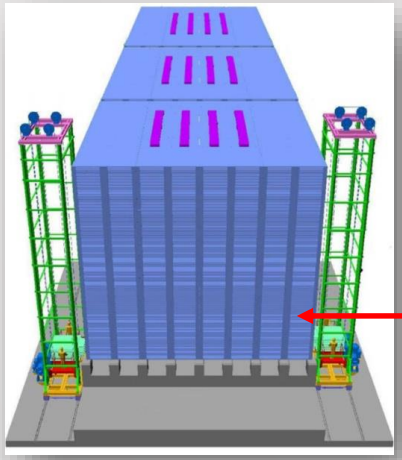
Underground Labs in India

Content provided by Gobinda Majumder

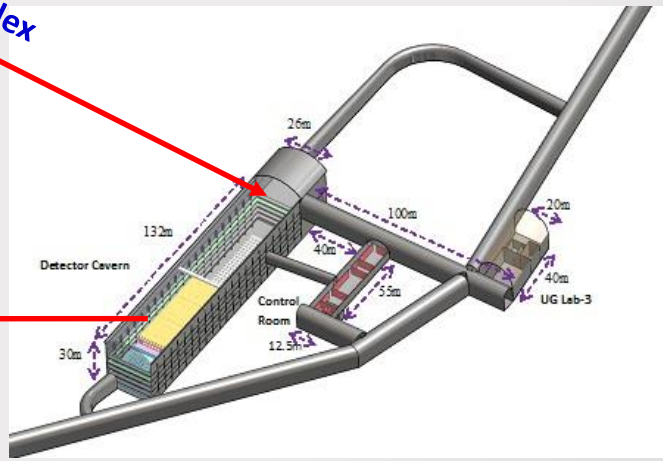
India-based Neutrino Observatory, Theni, India



Underground complex



50Kton ICAL
neutrino Detector

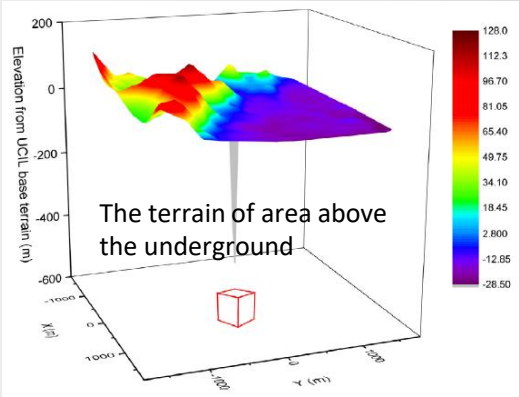


India-based Neutrino Observatory

https://doi.org/10.1007/s12043-017-1373-4

- Physics Programmes
  - 51-kt magnetized Iron CALorimeter (ICAL) for measurements on atmospheric neutrinos and mass hierarchy.
  - Cryogenic bolometer of tin (^{124}Sn) (TIN.TIN) to search for neutrino-less double beta decay.
  - Cryogenic Scintillator based dark matter experiment @INO (DINO).
  - Facility for other studies in physics, biology, geology, material research etc
- Approvals and Status
  - Environmental Clearance obtained second time in March 2018.
  - Wildlife Clearance from Central Government awaited.
  - Building and final construction Clearances awaited from Tamil Nadu State Government.

555m deep underground at Jadugura Mine, India



- Operating temperature of SLD (superheated liquid detector):
  24.3 ^{0}C ± 0.5 ^{0}C (Lab temperature).
- Backgrounds are an issue at JUSL.
- Expected background of energy threshold 1 MeV [JINST 16 (2021) 06, P06022]
  - Radiogenic: $(\mathbf{5.75 \pm 0.58}) \times \mathbf{10^{-6} cm^{-2}\ s^{-1}}$
  - Cosmogenic: $(\mathbf{7.25 \pm 0.65}) \times \mathbf{10^{-9} cm^{-2}\ s^{-1}}$
  - R&D with WIMP/DM search

Ongoing/ Future studies at JUSL :

- **Background measurements**
- **Cosmic muons studies**
- **Dark matter search using SLD**
- **Nuclear Physics related studies**

Publications from JUSL :

- **NIMA994 (2021) 165083**
- **PLB 823 (2021) 136760**
- **NIMA 1008 (2021) 165450**
- **Astro Phys. 139 (2022)102700**

Concluding Thoughts

- Underground labs continue to expand.
- New experiments.
- New results continue to push limits of knowledge.
- New background facilities.
- Emerging proposals for more sensitive results.
- Background efforts must keep up with evolving generations of projects.

Random Backup Slides

Experiments in Kamioka

Kamioka Observatory (Univ. of Tokyo)

- Super-Kamiokande
  - Precise oscillation studies by atmospheric and solar neutrinos.
  - Search for CP violation by T2K ν beam
  - Gd doped for anti-neutrino (astro)physics
- Hyper-Kamiokande
- XMASS/G3C
  - Direct dark matter search
  - Search for new physics with electron recoil events
  - Single phase Liq. Xe (XMASS) and R&Ds for the 3rd generation experiment (G3C)
- CANDLES
  - Search for $0\nu\beta\beta$ of ^{48}Ca with CaF_2
- NEWAGE
  - R&D for a directional dark matter detector
- CLIO (prototype of KAGRA)
- 100m laser strain meter for geophysics

KAGRA Observatory (Univ. of Tokyo)

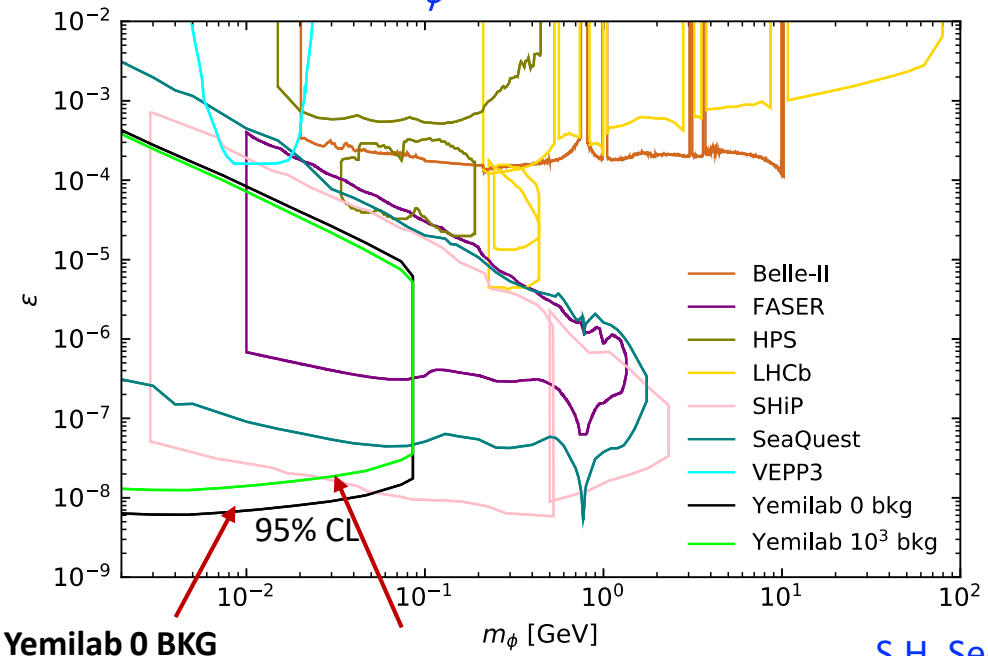
- KAGRA (Large-scale Cryogenic Gravitational-wave Telescope)
  - GW detection with LIGO and Virgo.
- 1.5km laser strain meter for geophysics

Neutrino Science Center (Tohoku Univ.)

- KamLAND
- KamLAND-ZEN (double beta decay of ^{136}Xe)

Dark Photon Search Sensitivities

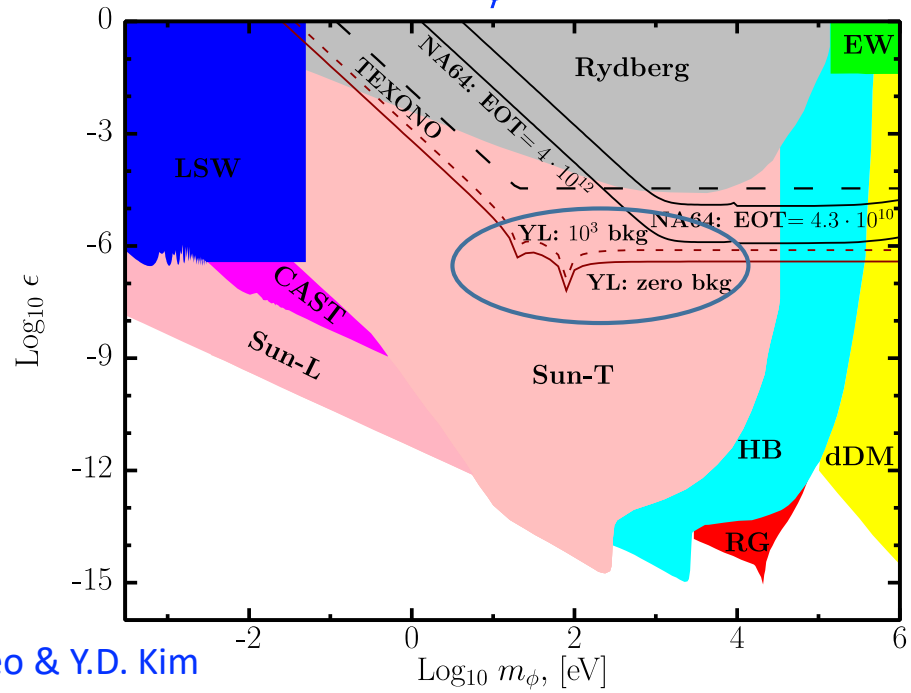
m_ϕ > 1 MeV



Yemilab 0 BKG

Yemilab 10^3 BKG

m_ϕ < 1 MeV



S.H. Seo & Y.D. Kim
JHEP04(2021)135

- Best "direct" DP search sensitivity in M_ϕ < 30 MeV (10^3 BKG)

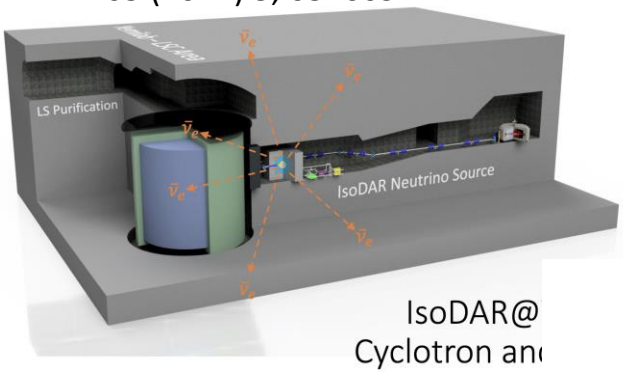
- Best "direct" DP search sensitivity in sub-MeV region

Sterile neutrino search Sensitivity w/ IsoDAR

arXiv:2111.09480
PRD 105 (2022) 5, 052009

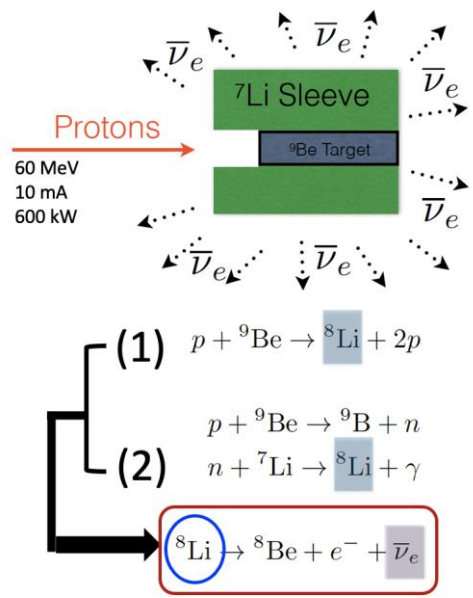
IsoDAR @Yemilab $P(\bar{\nu}_e \rightarrow \bar{\nu}_e)$

- World leading result
- Definite conclusion on (3+1) ν or not

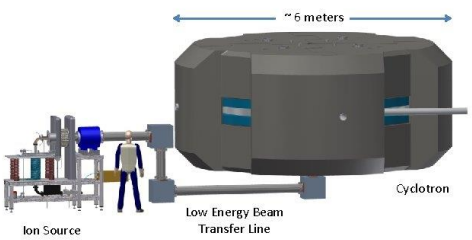


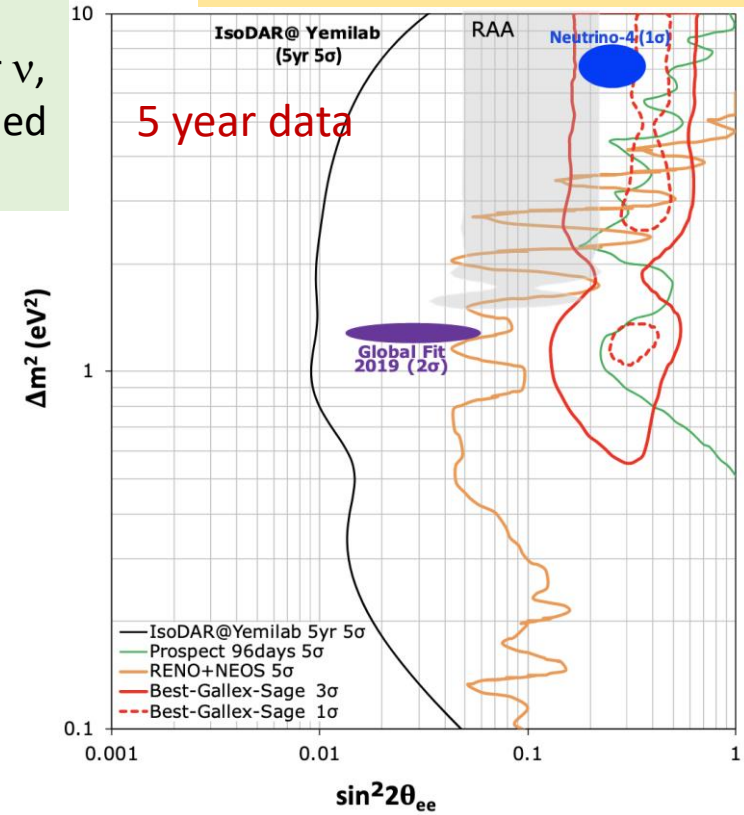
IsoDAR@
Cyclotron an

Advantage:
Unlike reactor/accelerator ν, IsoDAR has very well defined ν flux and shape.

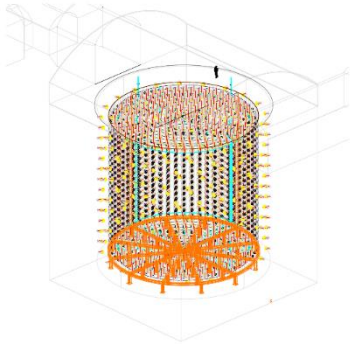


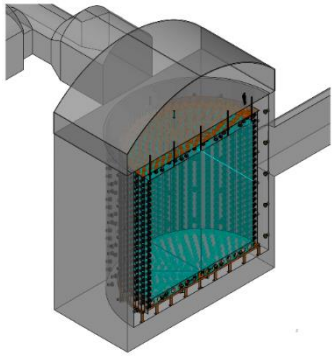
The IsoDAR Cyclotron and Ion Source

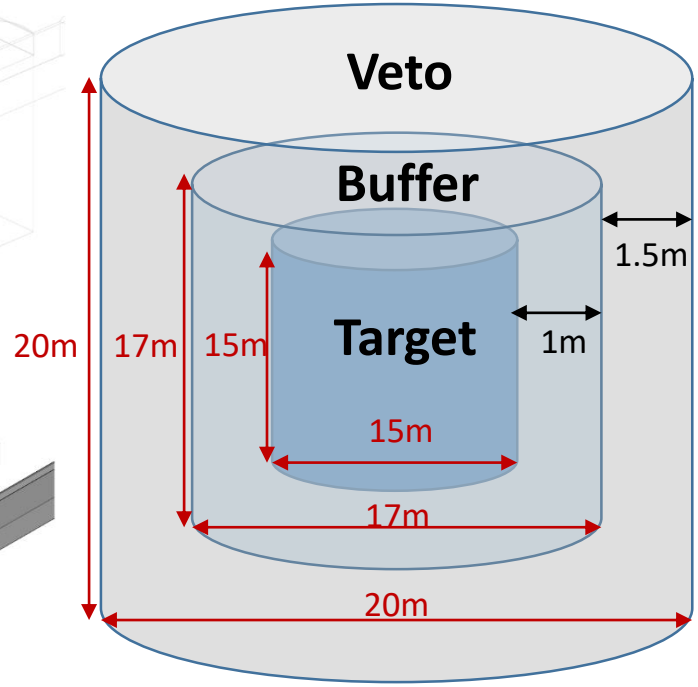




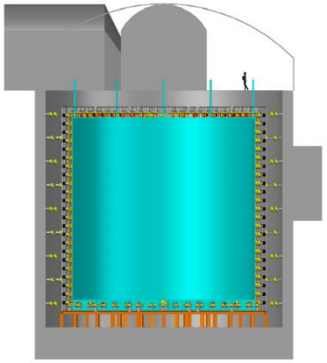
Candidate Detector Design





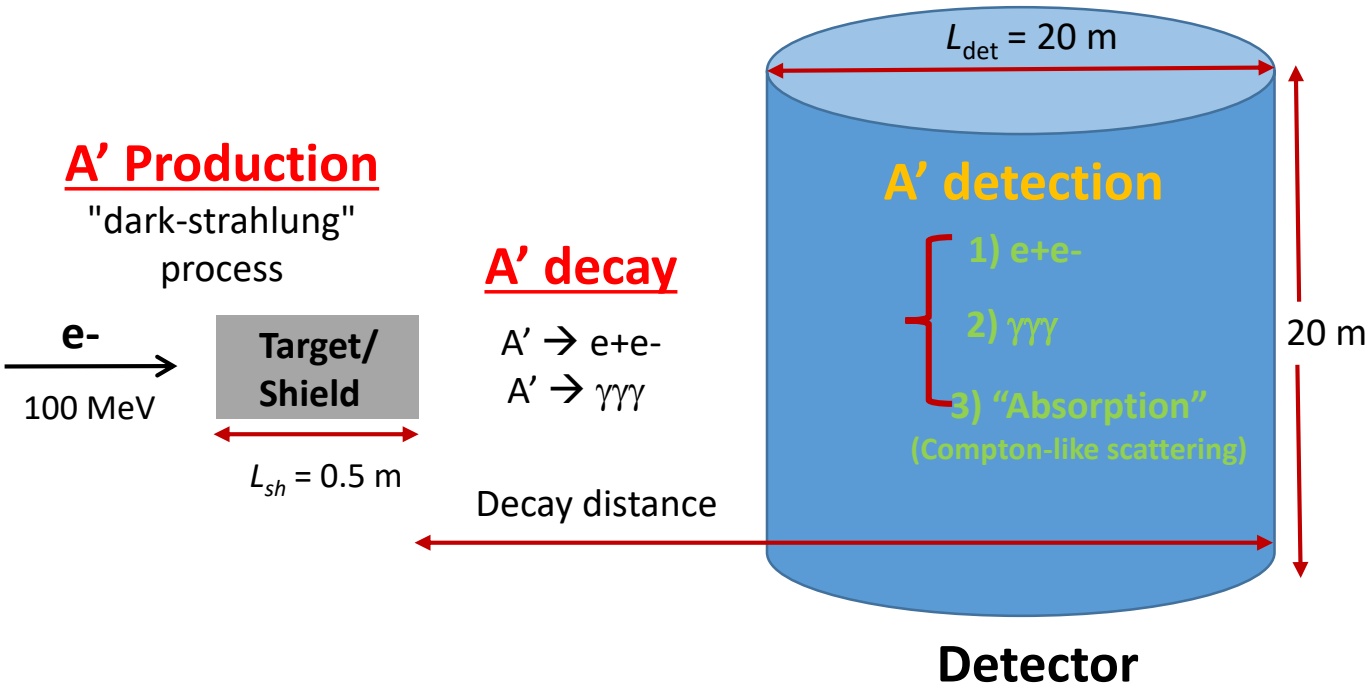


Target: **2.26 kton**
Buffer: 1.14 kton
Veto: 2.41 kton



1200(1800,2400) x 20 inch PMTs = 20% (30, 40)% coverage

Dark Photon Search Scheme

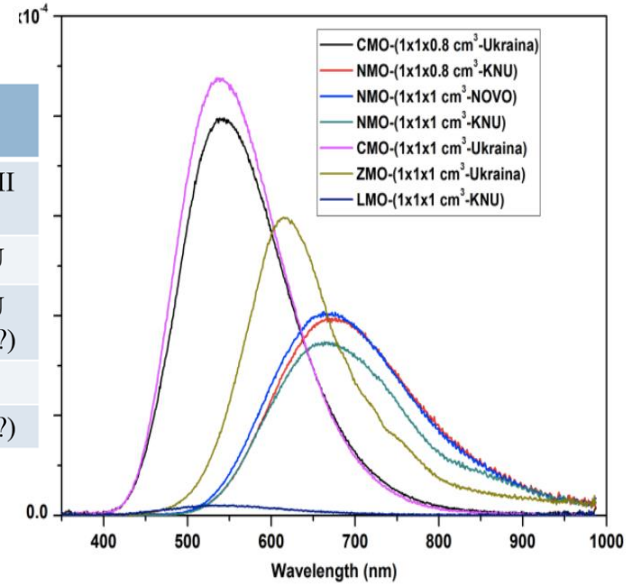


Crystals for AMoRE-II

- ✓ We search for other Mo containing crystals for AMoRE-II instead of $CaMoO_4$

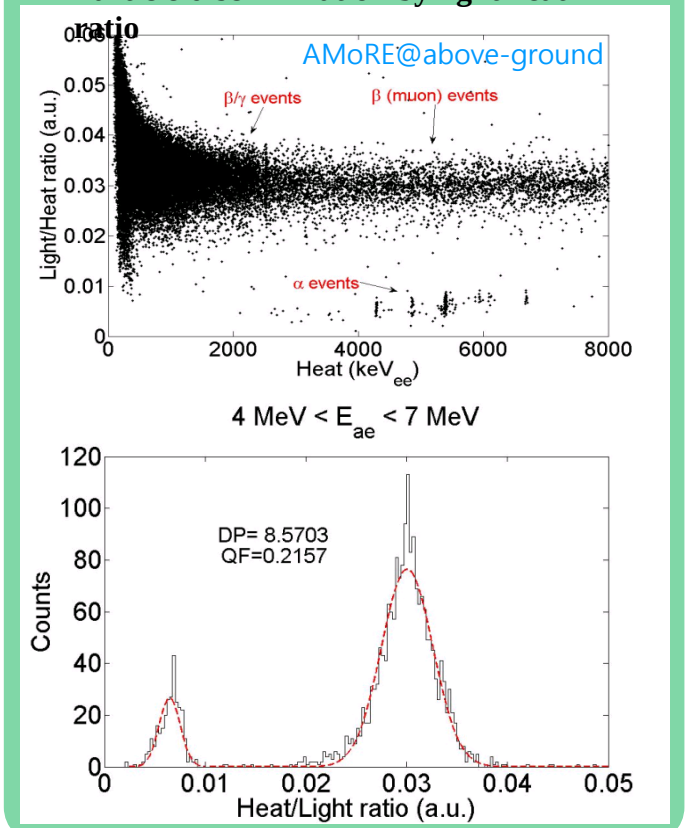
Crystal	Emission (nm)	LightYield @ 10K	density	Mo Fraction	Exp
$CaMoO_4$	538	100	4.34	0.49	AMoRE-1, II (?)
$ZnMoO_4$	614	20-50	4.37	0.436	LUMINEU
Li_2MoO_4	533	5	3.03	0.562	LUMINEU AMoRE-II(?)
$PbMoO_4$	490	~10	6.95	0.269	
$Na_2Mo_2O_7$	663	~40	3.62	0.558	AMoRE-II(?)

<From KNU>
measured under uv. excitation

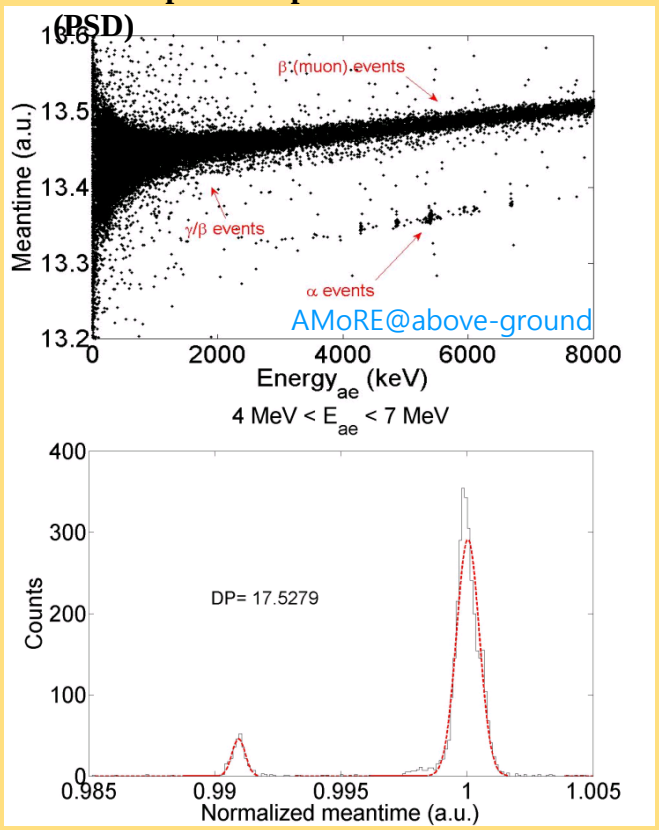


Particle discrimination

Particle discrimination by light heat ratio

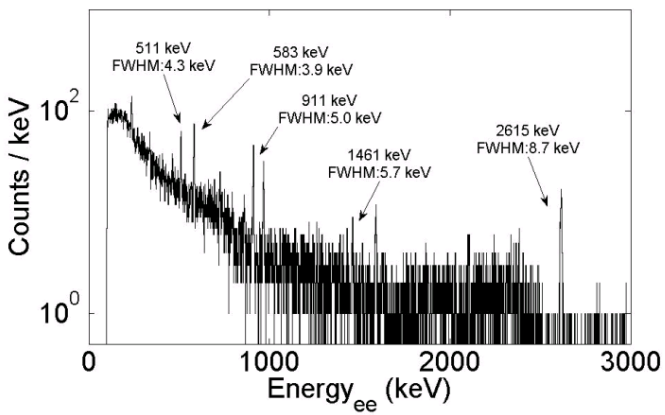


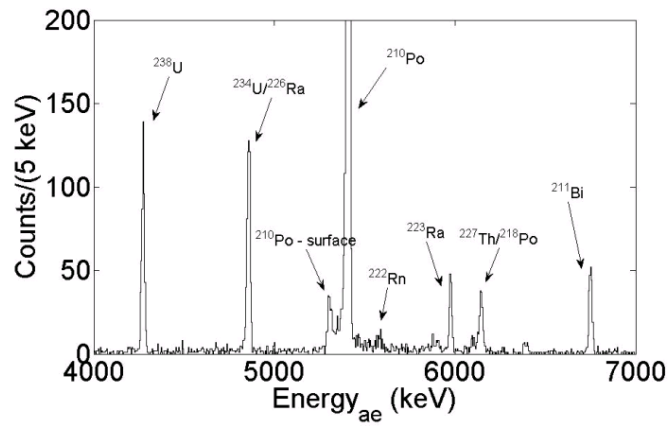
Phonon pulse shape discrimination (PSD)



Energy spectrum (above-ground)

Electron and alpha events can be efficiently identified.

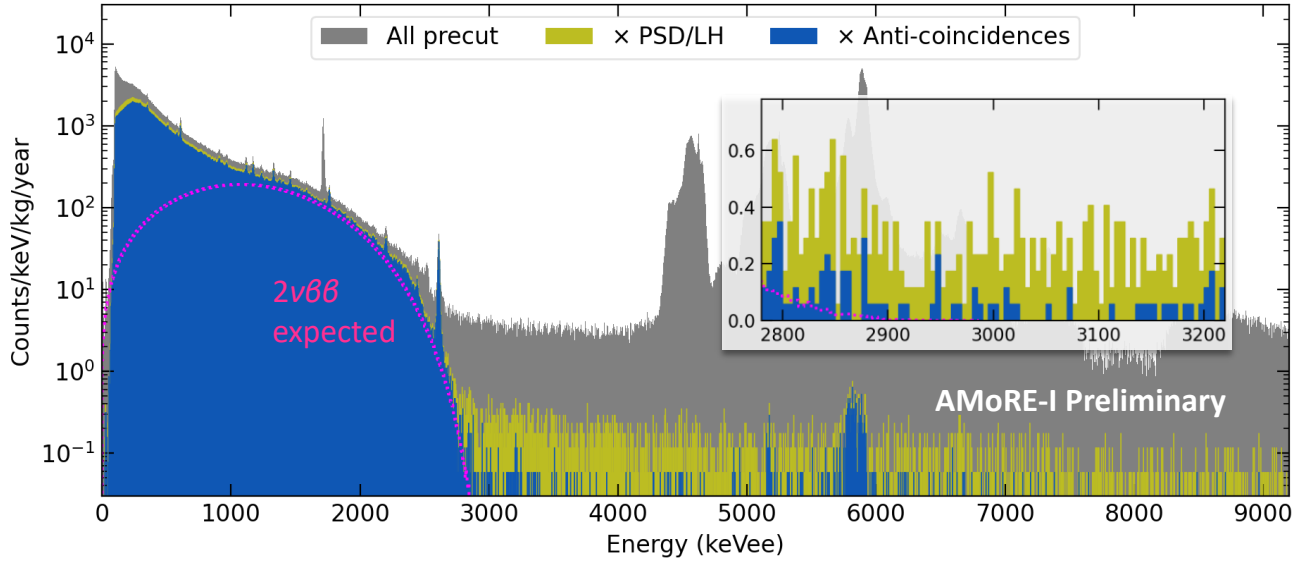




- Better than 9 keV energy resolution was obtained at 10 mK temperature.
- Internal alpha background levels of each isotopes were calculated successfully.

Background spectrum

Yoomin Oh Neutrino-2022



- All crystal excluding 1 LMO for very poor β/α discrimination power:
  - 13 CMO + 4 LMO: exposure = 3.44 kg_{XMO} ▪ yr = 1.67 kg_{ISO} ▪ yr.
- Anti-coincidence cuts reject events:
  - coincident at multiple crystals within 2 ms (ε ~ 99%),
  - within 10 ms after a muon counter event (ε ~ 99.7%),
  - within 20 minutes after a ^{212}Bi α-decay event candidate (ε ~ 98%).

Background budget for AMoRE-II