Review of Neutrino Experiments in Korea

The 21st International Workshop on Neutrinos from Accelerators

(Satellite Workshop)

K.K. Joo
Chonnam National University

2019-08-25 The Grand Hotel, Deagu, Korea

Fundamental Questions on Neutrino

- Absolute neutrino masses? (Why so small?)
- Neutrino mass ordering? (Normal or inverted?)
- Dirac or Majorana? (Neutrinoless double beta decay?)
- Leptonic CP violating phase?
- 3 ν paradigm enough? (Sterile neutrino?)
- Why so large neutrino mixing angles?

1st domestic large neutrino experiment, RENO has started measuring

※ High precision measurement of neutrino oscillations

→ Precise values of mixing angles and mass difference are necessary for solving those fundamental problems

List of neutrino experiments in the world

(Wikipedia)

(out of date)

External links [edit]

- "Experiments". *Neutrino Unbound*. Istituto Nazionale di Fisica Nucleare. 24 February 2017. Retrieved 2017-02-28. Regularly updated index of neutrino physics research.

V · T · E	Neutrino detectors, experiments, and facilities [hide]	
Discoveries		Cowan–Reines (ν_e) · Lederman–Schwartz–Steinberger (ν_μ) · DONUT (ν_τ) · Neutrino oscillation · SN 1987 neutrino burst
Operating (divided by primary neutrino source)	Astronomical	ANITA · ANTARES · BDUNT · Borexino · BUST · HALO · IceCube · LVD · NEVOD · SAGE · Super-Kamiokande · SNEWS
	Reactor	Daya Bay · Double Chooz · KamLAND · RENO · STEREO NEOS
	Accelerator	ICARUS (Fermilab) · MicroBooNE · MINERvA · MiniBooNE · NA61/SHINE · NOvA · NuMI · T2K · COHERENT
	$0\nu\beta\beta$	AMoRE · COBRA · CUORE · EXO · GERDA · KamLAND-Zen · MAJORANA · NEXT · PandaX · XMASS AMoRE
	Other	KATRIN · WITCH
Construction		ANNIE · ARA · ARIANNA · BEST · DUNE · JUNO · KM3NeT · SNO+ · SuperNEMO
Retired		AMANDA · CDHS · Chooz · CNGS · Cuoricino · DONUT · ERPM · GALLEX · Gargamelle · GNO · Heidelberg-Moscow · Homestake · ICARUS · IGEX · IMB · K2K · Kamiokande · KARMEN · KGF · LSND · MACRO · MINOS · MINOS+ · NARC · NEMO · OPERA · RICE · SciBooNE · SNO · Soudan 2 · Utah
Proposed		CUPID · GRAND · Hyper-Kamiokande · INO · LAGUNA · LEGEND · LENA · Neutrino Factory · nEXO · Nucifer · SBND · UNO · JEM-EUSO · WATCHMAN KNO
Cancelled		DUMAND Project · Long Baseline Neutrino Experiment · NEMO Project · NESTOR Project · SOX · BOREX
See also		BNO · Kamioka Observatory · LNGS · SNOLAB · List of neutrino experiments

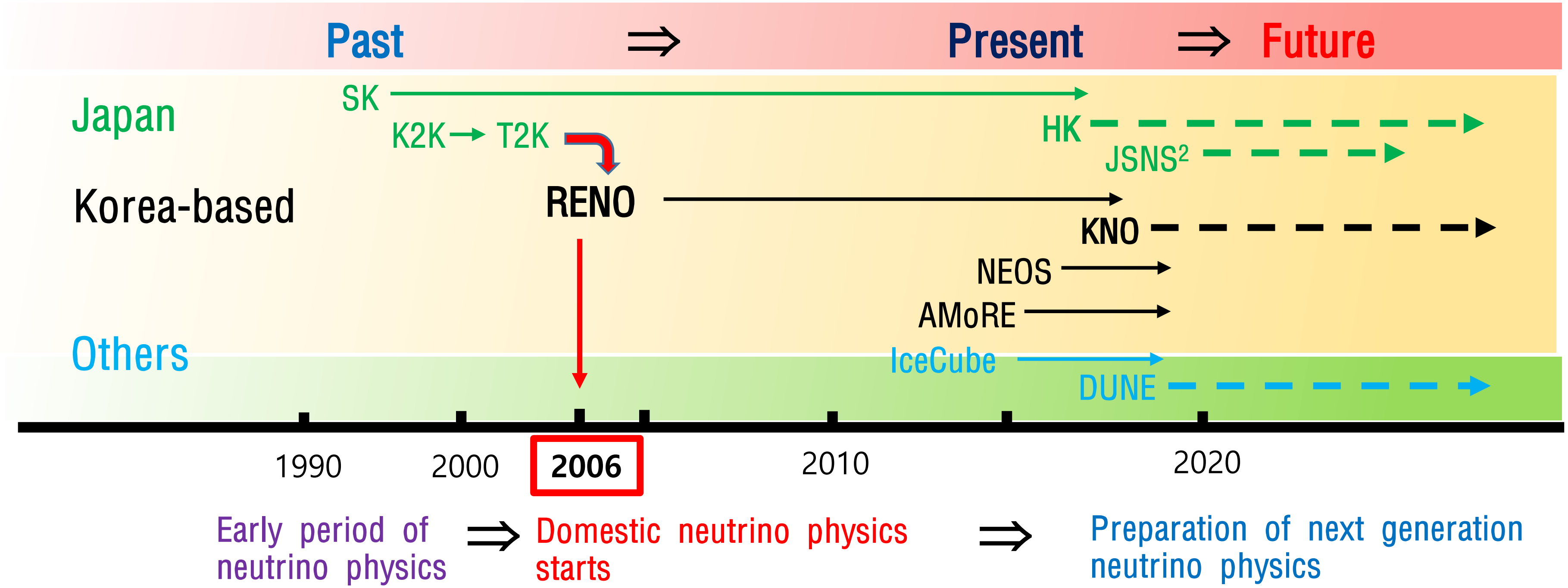
Present

Past

Future

Brief history of neutrino experiments (Korean group involved)

(Purely personal view)



- From mid 1990, Korean group have joined as international collaborator (SK, K2K, T2K)
- At 2006, pure domestic large neutrino experiment has started (RENO)
  - Using **reactor neutrino**, focus on measuring oscillation parameter
- Now, future experiments preparation is under way (KNO, DUNE, HK, etc)

➡ Important to have various experiments for a robust neutrino program

Google

korea neutrino

AAAS Become a Member

Science

LETTERS

Neutrino physics for Korean diplomacy

Rachel Carr[1,*], Jonathon Coleman[2], Giorgio Gratta[3], Karsten Heeger[4], Patrick Huber[5], YuenKeung Hor[6], Takeo Kawasaki[7], Soo-Bong Kim[8], Yeongduk Kim[9], John Learned[10], Manfred Lindner[11], Kyohei Nakajima[12], Seon-Hee Seo[9], Fumihiko Suekane[13], Antonin Vacheret[14], Wei Wang[6], Liang Zhan[15]

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They claimed that they can help monitoring North Korea reactor by neutrino detector technology

Edited by **Jennifer Sills**

Denuclearizing North Korea requires trust

In their Policy Forum "Denuclearizing North Korea: A verified, phased approach" (7 September, p. 981) A. Glaser and Z. Mian describe a pathway for verified denuclearization of North Korea. I agree that such an approach is necessary and, equally importantly, technically feasible. However, Glaser and Mian only highlight the disarmament side of the denuclearization agreement, without a plan to develop the mutual trust and the assurances on which such a deal depends. Incentivizing North Korea to reduce nuclear weapons and fissile materials will require confidence-building measures, ease of sanctions, and security guarantees. These elements are strongly related to the disarmament questions and must be regulated with similar precision.

Coordinating with the proposed phased approach, the involved parties could pair North Korea's freeze on weapon-related activities with a freeze of new nuclear-related sanctions or military exercises in the region. Such commitments would lay the foundation for an interim agreement, paving the way for long-term denuclearization. In a final step, the facilitation of humanitarian trade in areas such as health and nutrition would initiate the ease of sanctions and the establishment of credible security guarantees.

These measures need control and verification mechanisms, too. In case of nonfulfillment of such an agreement, it must be possible to swiftly reinstate the United Nations Security Council's sanctions. The structure of this contingency could be similar to the snapback mechanism in Article 37 of the Joint Comprehensive Plan of Action with Iran (*1*). Likewise, North Korea will insist on similar guarantees if it dismantles its nuclear weapons. It is always a challenge to create mechanisms that can credibly assure such guarantees for both parties, and this has become even more difficult after the U.S. withdrawal from the Iran nuclear agreement.

Tobias W. Langenegger
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REFERENCE

1. United Nations Security Council Resolution [illegible] (2015); https://undocs.org/S/RES/2231(2015).

10.1126/science.[illegible]4635

Neutrino physics for Korean diplomacy

Continued diplomatic progress with North Korea will be a journey of many steps, as A. Glaser and Z. Mian describe in their Policy Forum "Denuclearizing North Korea: A verified, phased approach" (7 September, p. 981). Leaders in North Korea, South Korea, and the United States agree that one step could be dismantlement or civilian repurposing of the nuclear reactors at Yongbyon. We propose a cooperative method for verifying reactor shutdown or conversion. The key tools are meter-scale, field-deployable detectors that track neutrino emissions from reactor cores.

Neutrino detectors can track power levels and fuel evolution in nuclear reactors, as experiments in South Korea, China, Russia, the United States, and Europe have demonstrated (*1*–*7*). At Yongbyon, neutrino detectors could be deployed to verify reactor shutdown or civilian operations without the need for operational records or access inside reactor buildings. Shutdown of North Korea's main plutonium production reactor could be verified with a detector in a standard freight container parked outside the reactor building.

Existing neutrino technology may be attractive to all parties in the ongoing talks. North Korea may value a tool for demonstrating treaty compliance while maintaining custody of the reactor buildings. Other parties may value the tamper resistance of the neutrino signal and resilience of neutrino detectors, which require minimal on-site access and can reconstruct reactor operational history even after a data-taking pause. Neutrino projects are also a natural opportunity to strengthen relations between North and South Korea and to build international scientific ties. South Korea has an active neutrino community and could choose to deploy a counterpart to a Yongbyon-based detector at one of its own reactors. Resulting scientific collaboration could benefit Korea and the world. We encourage policy-makers to consider neutrino detectors as one step toward stability and security on the Korean Peninsula.

A freeze in military exercises could help to establish trust during nuclear negotiations with North Korea.

Rachel Carr,[1]* Jonathon Coleman,[2] Giorgio Gratta,[3] Karsten Heeger,[4] Patrick Huber,[5] YuenKeung Hor,[6] Takeo Kawasaki,[7] Soo-Bong Kim,[8] Yeongduk Kim,[9] John

Published by AAAS

Neutrino Mixing Angles

Atmospheric Neutrino Oscillation — θ_{23}

~45° (1998)
Super-K; K2K

Solar Neutrino Oscillation — θ_{12}

34° (2001)
SNO, Super-K; KamLAND

Reactor Neutrino Oscillation — θ_{13}

9° (2012)
Daya Bay, RENO
Double Chooz

2015 Nobel Prize

"Neutrino has mass"

"Established three-flavor mixing framework"

JUNO
T2HKK/KNO

Past → Future of Reactor Experiments

2020~ ?

2011/2012 - The year of θ_{13}

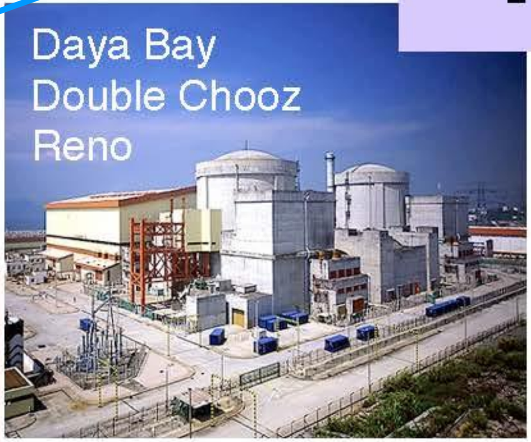
2008 - Precision measurement of Δm_{12}^2. Evidence for oscillation

2003 - First observation of reactor antineutrino disappearance

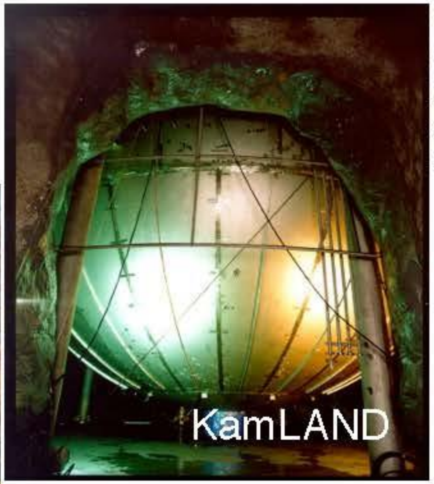
1995 - Nobel Prize to Fred Reines

1980s & 1990s - Reactor neutrino flux measurements in U.S. and Europe

1956 - First observation of (anti)neutrinos



Reactor neutrino exp

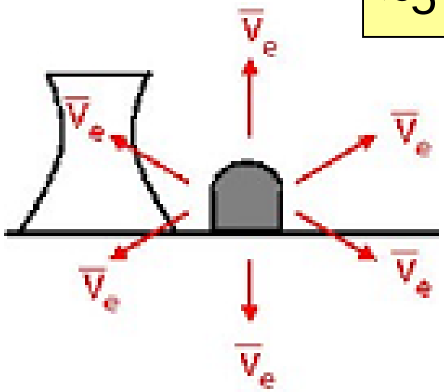


Karsten M. Heeger
University of Wisconsin

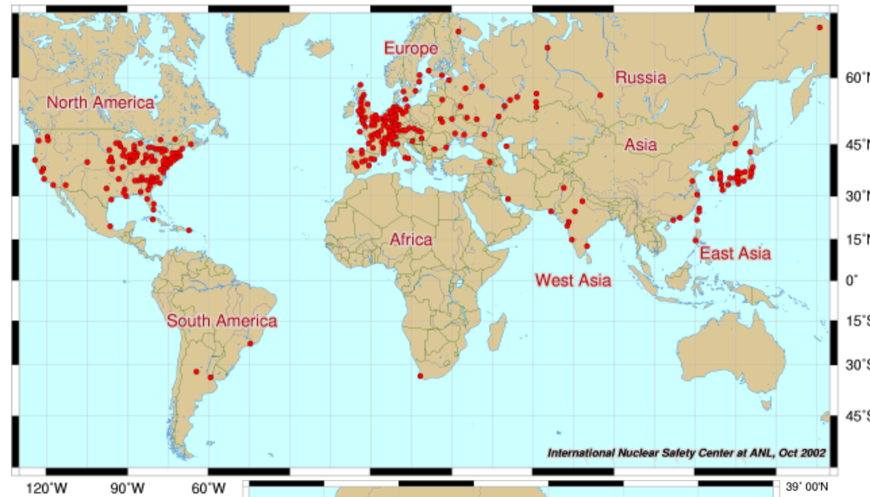
Reactor Neutrinos

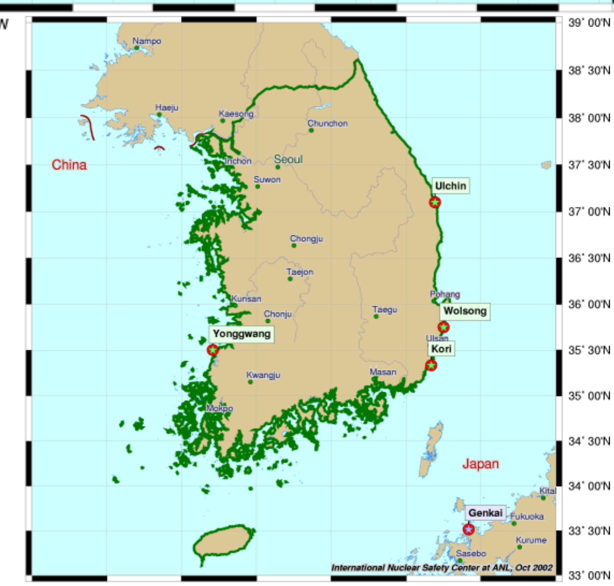
Reactor Neutrinos

~5×10[21] ν/sec



Nuclear Power Plants around the World





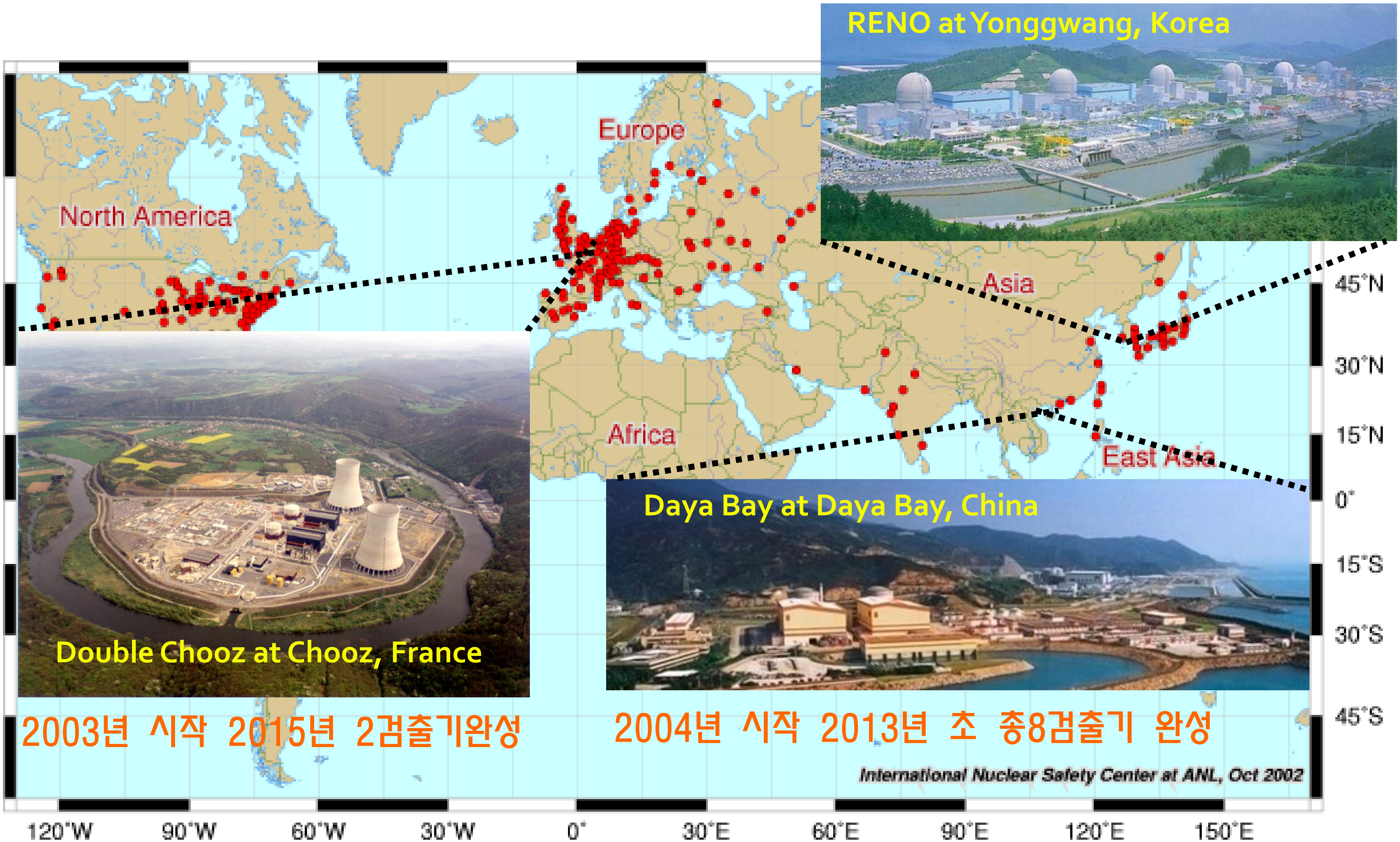
▪ Cost-free, intense, low-energy & well-known neutrino source !

▪ In Korea, 4 nuclear reactor sites

(Yonggwang, Uljin, Wolsung, Kori)

Reactor θ_{13} Experiments

2006년 후발 주자로 시작 2011년 1월 완성



RENO Collaboration

RENO ν θ_{13}

8 institutions and 35 physicists in Korea

- Chonnam National University
- Dongshin University
- GIST
- KAIST
- Kyungpook National University
- Seoul National University
- Seoyeong University
- Sungkyunkwan University

- **Total cost : $10M**
- Start of project : **2006**
- The first experiment running with both near & far detectors since **Aug. 2011**

YongGwang (靈光) :

New name: Hanbit

Reactor **E**xperiment for **N**eutrino **O**scillation

Candidate site

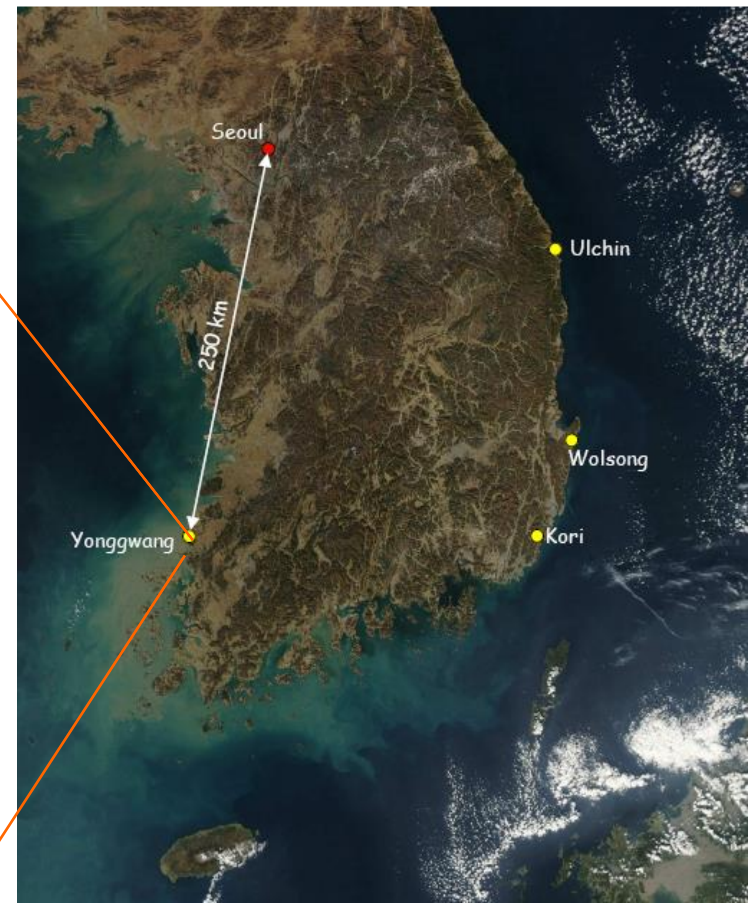
울진(UlChin)캠퍼스

©손동철 (2005.08)

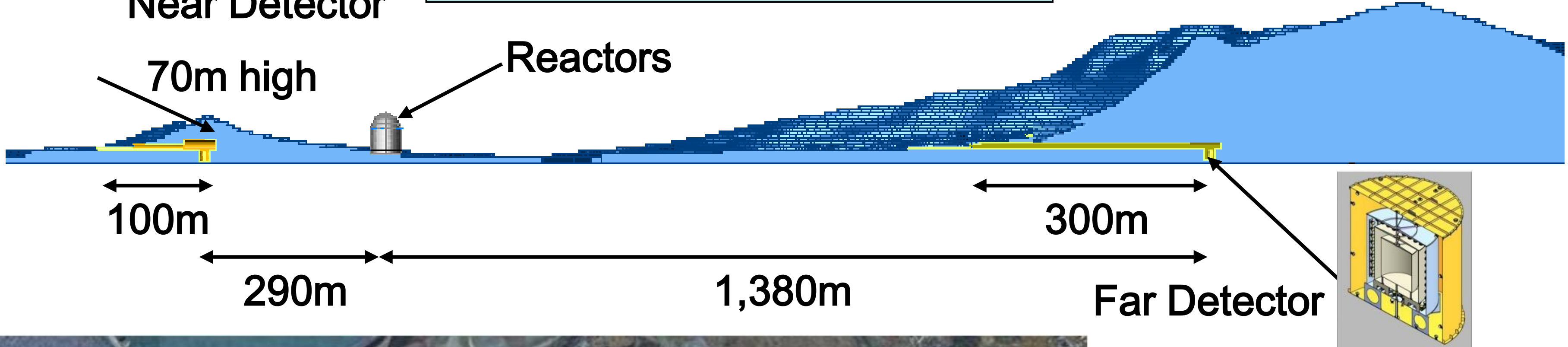
YongGwang Nuclear Power Plant

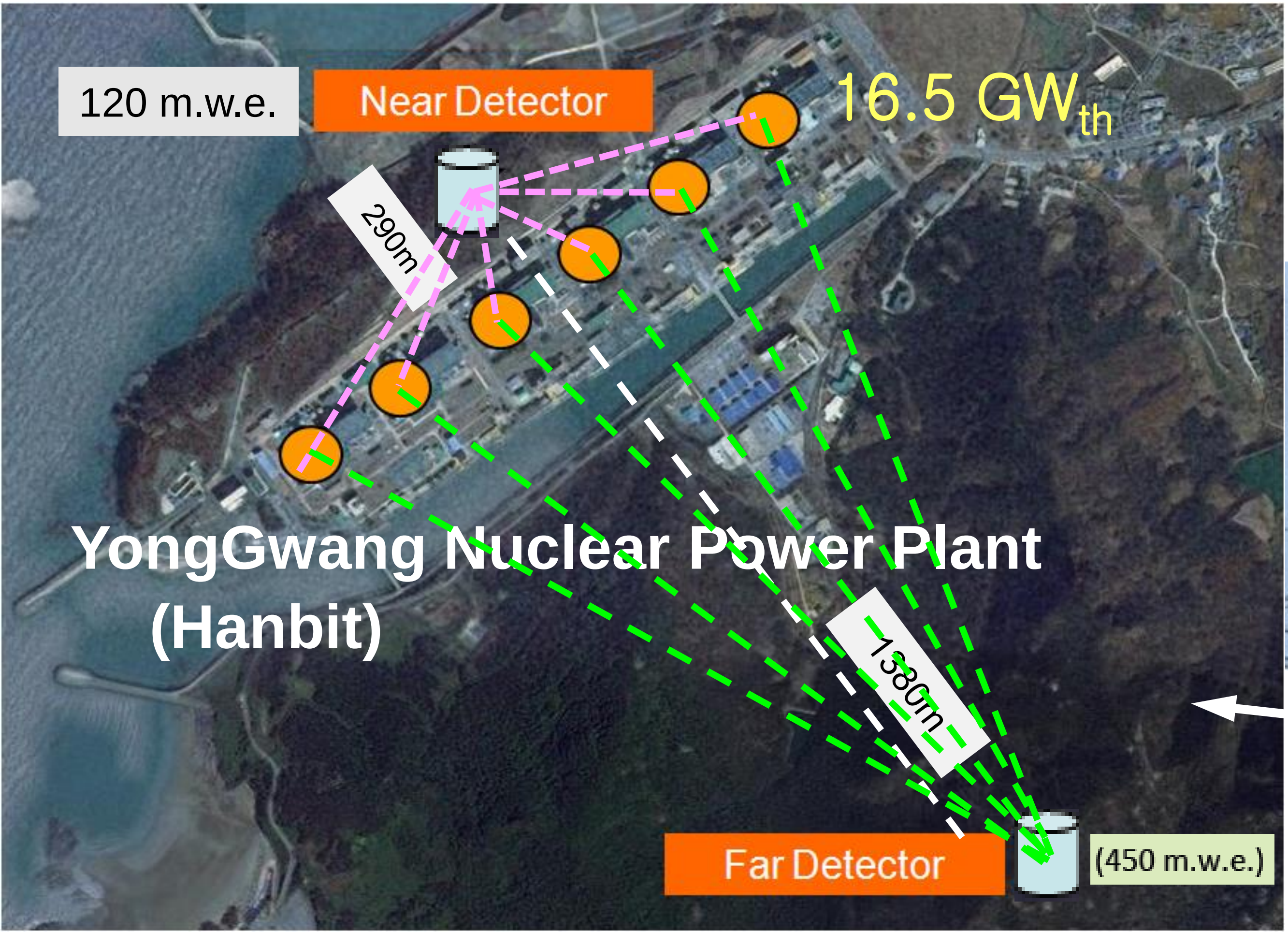
- ❐ Located in the west coast of southern part of Korea
- ❐ ~300 km from Seoul
- ❐ 6 reactors are lined up in roughly equal distances and span ~1.3 km
- ❐ Total average thermal output ~16.7GW$_{th}$ (one of powerful sources in the world)

YongGwang(靈光):
= glorious[splendid] light
(~spirited)
New name: Hanbit



Google Satellite View of Experimental Site





RENO ν θ_{13}

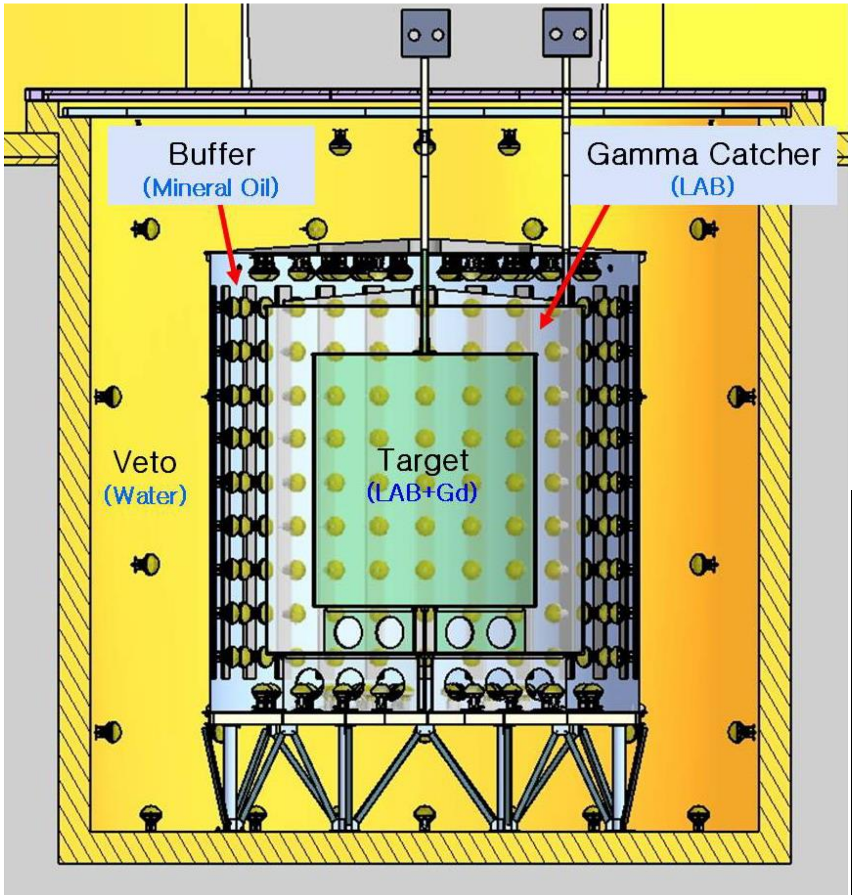
Near & far tunnels construction

(2008.6~2009.3)

by Daewoo Eng. Co. Korea

- 세계 최고 수준 (터널, 교량, 도로 건설 등)
  - (예) 원전 옆 폭약사용
- 현재: 관광명소 중 하나 (초기 반핵단체 극심한 반대 불구하고)

RENO Detector



	Thick (cm)	vessel	Material	Mass (tons)
Target	140	Acrylic (10mm)	Gd(0.1%) +LS	15.4
Gamma catcher	60	Acrylic (15mm)	LS	27.5
Buffer	70	SUS(5mm)	Mineral oil	59.2
Veto	150	Steel (15mm)	water	354.7

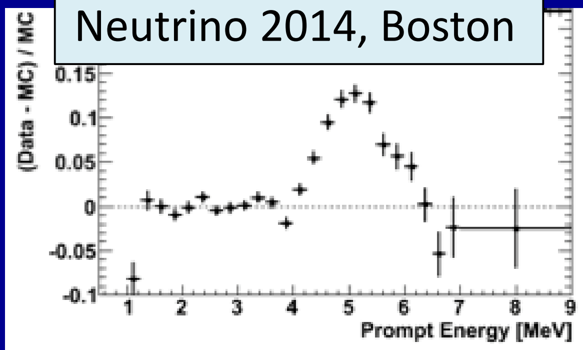
total ~460 tons

- **Inner PMTs: 354 10" PMTs**
  - solid angle coverage = ~14%
- **Outer PMTs: ~ 67 10" PMTs**

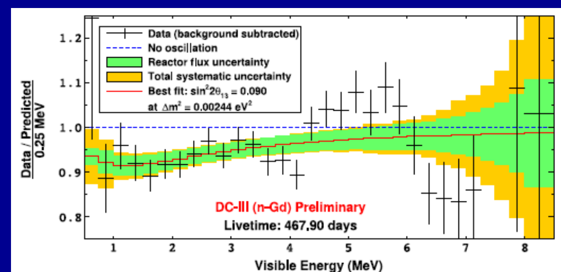
The 5 MeV Excess is there !

RENO

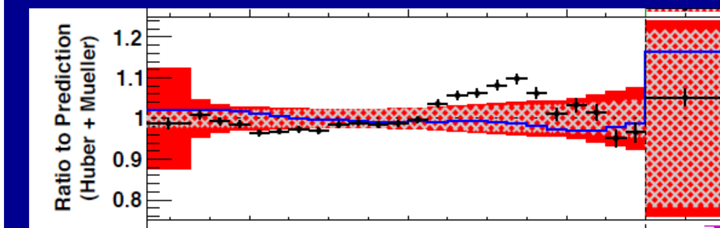
Neutrino 2014, Boston



Double Chooz



Daya Bay

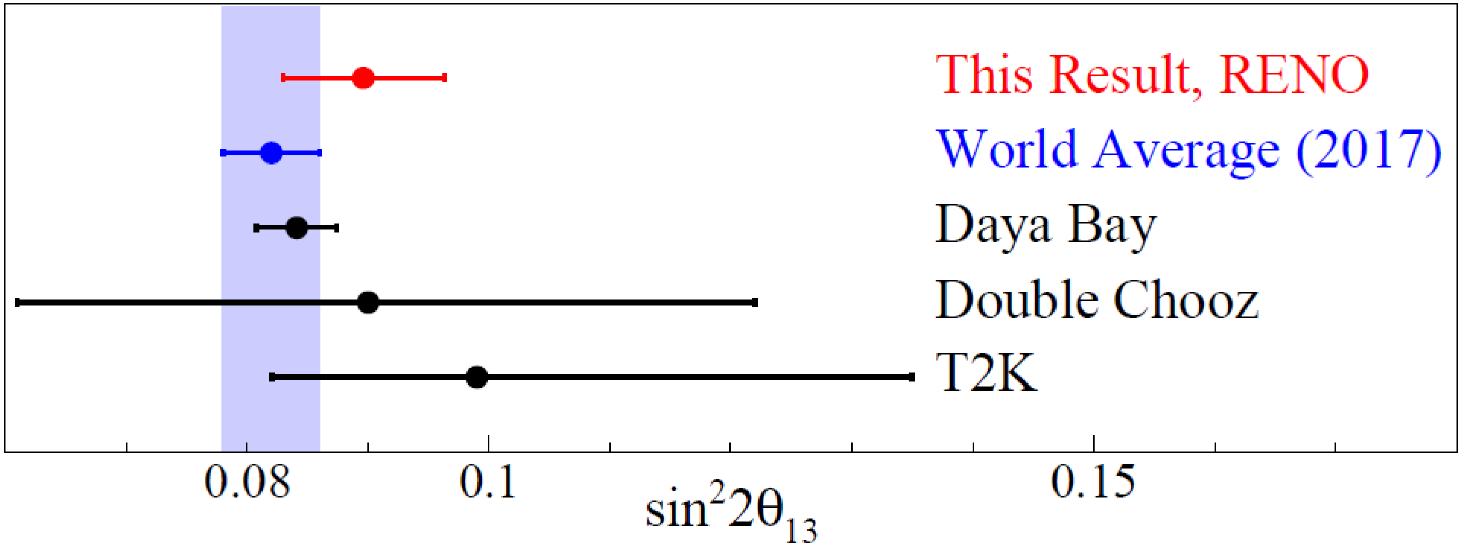


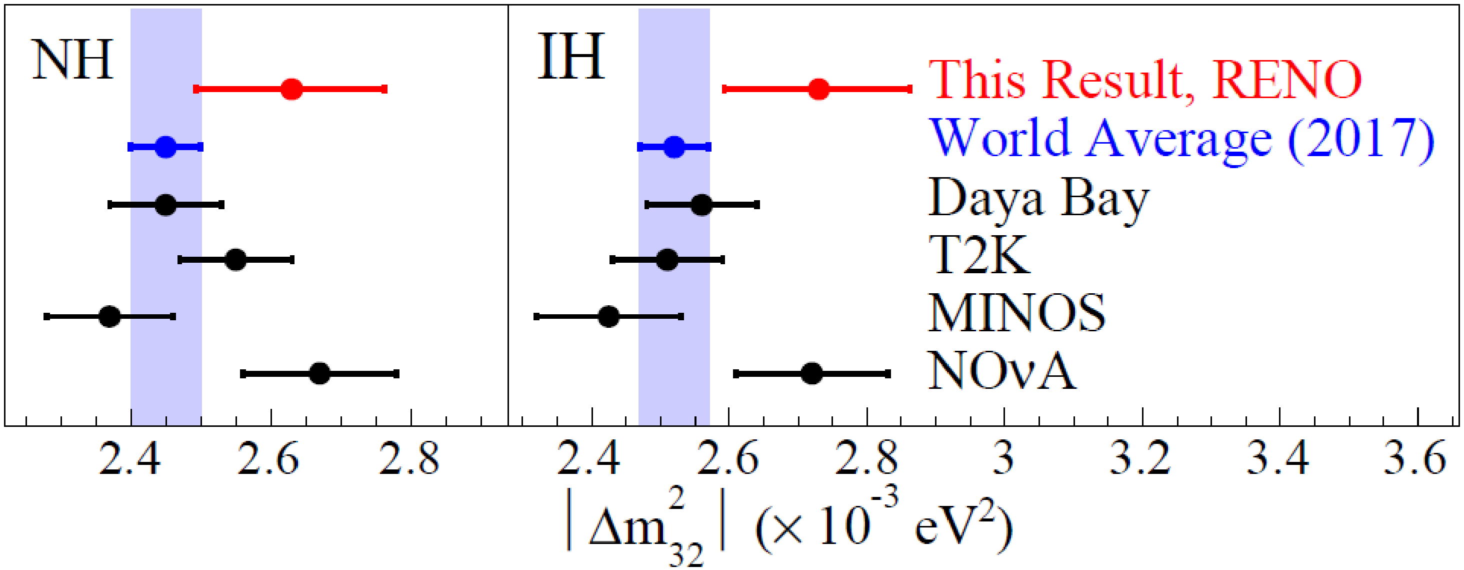
In 2014, RENO firstly showed that the 5 MeV excess is from reactor neutrinos @Boston

Since then, DC & DB also observed 5 MeV excess

Comparison of θ_{13} and $|\Delta m^2_{ee}|$

PRL 121.201801 (2018)





RENO : Plan and Prospects

Plan for RENO data taking

RENO data has taken for almost 9 for the analysis

Possible extension of additional 2~3 years

According to our recent study, the systematic error of $|\Delta m_{ee}^2|$ is smaller than the statistical error

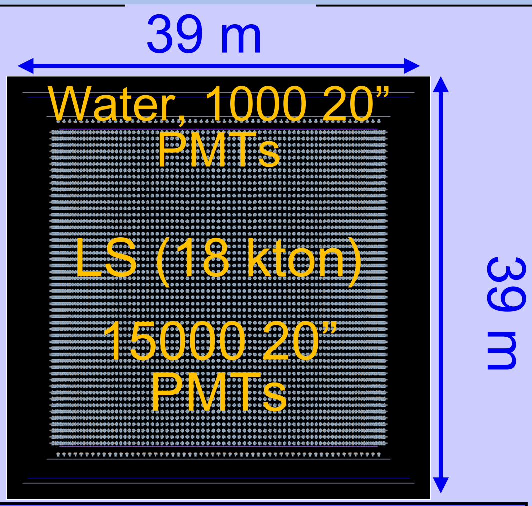
$\sin^2 2\theta_{13}$ and $|\Delta m_{ee}^2|$ will approach to **~6% precision** (our design goal)

	500 days Measured	1500 days Measured (preliminary)	~3500 days Expected
$\sin^2 2\theta_{13}$	12 %	9 %	6 ~ 7 %
$\lvert\Delta m_{ee}^2\rvert$	10 %	7 %	4 ~ 5 %

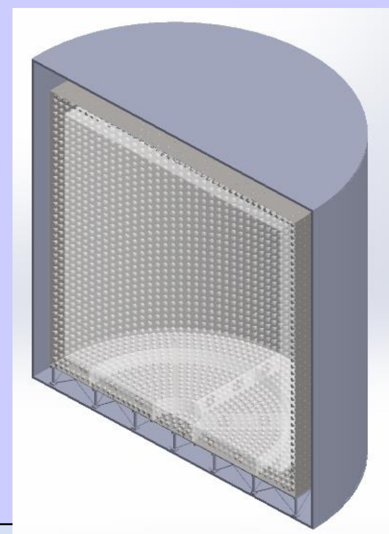
(Brief) Overview of RENO-50

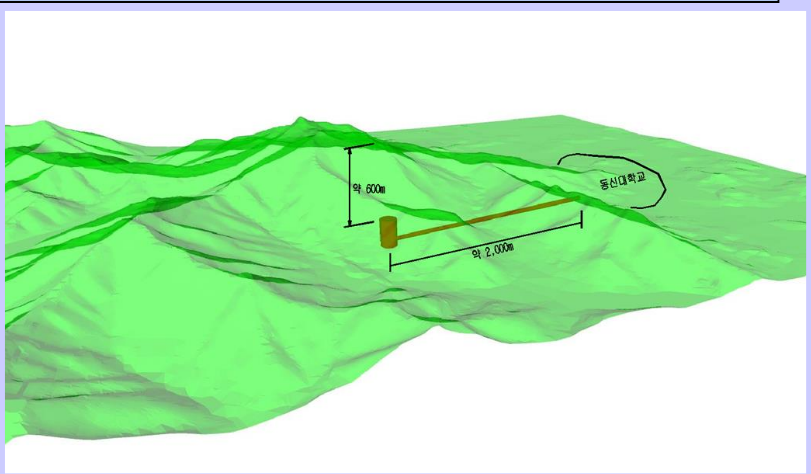
- **RENO-50** : An underground detector consisting of 18 kton ultra-low-radioactivity liquid scintillator & 15,000 20” PMTs, at 50 km away from the Hanbit (Yonggwang) nuclear power plant

- **Goals** : - Determination of neutrino mass hierarchy
  - High-precision measurement of θ_{12}, Δm^2_{21} and Δm^2_{ee}
  - Supernova neutrinos, Geo neutrinos, Sterile neutrino search, ….



RENO-50 detector (MC)





- **Scheduled** : 2013 ~ : Facility and detector construction, operation, etc

- **Unfortunately,** failed to get fund. In spite of much effort, disappearing into history

Particle Data Book

LEPTONS

Neutrino Mixing

$\sin^2(2\theta_{12}) = 0.857 \pm 0.024$ **($\pm$2.8%)**

$\Delta m^2_{21} = (7.50 \pm 0.20) \times 10^{-5}$ eV^2 **($\pm$2.7%)**

$\sin^2(2\theta_{23}) > 0.95$ [i] **($\pm$3.1%)**

$\Delta m^2_{32} = (2.32^{+0.12}_{-0.08}) \times 10^{-3}$ eV^2 [j] **(+5.2-3.4%)**

$\sin^2(2\theta_{13}) = 0.098 \pm 0.013$ **($\pm$13.3%)**

$\sin^2\theta_{12} = 0.312 \pm 0.017$ ($\pm$5.4%)

$\sin^2\theta_{23} = 0.42{+}0.08{-}0.03$ (+19.0 -7.1%)

$\Delta m_{21}^2 / |\Delta m_{31(32)}^2| \approx 0.03$

$\sin^2\theta_{13} = 0.0251 \pm 0.0034$ ($\pm$13.5%)

- Precise measurement of θ_{12}, Δm^2_{21} and Δm^2_{32}

$$\frac{\delta \sin^2\theta_{12}}{\sin^2\theta_{12}} < 1.0\%(1\sigma) \quad (\leftarrow 5.4\%)$$

$$\frac{\delta \Delta m^2_{21}}{\Delta m^2_{21}} < 1.0\%(1\sigma) \quad (\leftarrow 2.6\%)$$

$$\frac{\delta \Delta m^2_{32}}{\Delta m^2_{32}} < 1.0\%(1\sigma) \quad (\leftarrow 5.2\%)$$

International Workshop on RENO-50

Seoul, June 13-14, 2013

RENO-50 at Snowmass

Opportunities in ν Oscillations

Summary talk on Intensity Frontier by J. Hewett at Snowmass meeting (Aug. 2013)

Category	Experiment	Status	Osc params
accelerator	T2K	data-taking	MH/CP/octant
accelerator	NOνA	commissioning	MH/CP/octant
accelerator	RADAR	R&D	MH/CP/octant
accelerator	CHIPS	R&D	MH/CP/octant
accelerator	T2HK	design/ R&D	MH/CP/octant
accelerator	LBNE	design/ R&D	MH/CP/octant
accelerator	DAEδALUS	design/ R&D	CP
reactor	JUNO	design/R&D	MH
reactor	RENO-50	design/R&D	MH
atmospheric	Super-K	data-taking	MH/CP/octant
atmospheric	Hyper-K	design/R&D	MH/CP/octant
atmospheric	LBNE	design/R&D	MH/CP/octant
atmospheric	INO	design/R&D	MH/octant
atmospheric	PINGU	design/R&D	MH
atmospheric	ORCA	design/R&D	MH
supernova	existing	N/A	MH

T2HK plays an important role

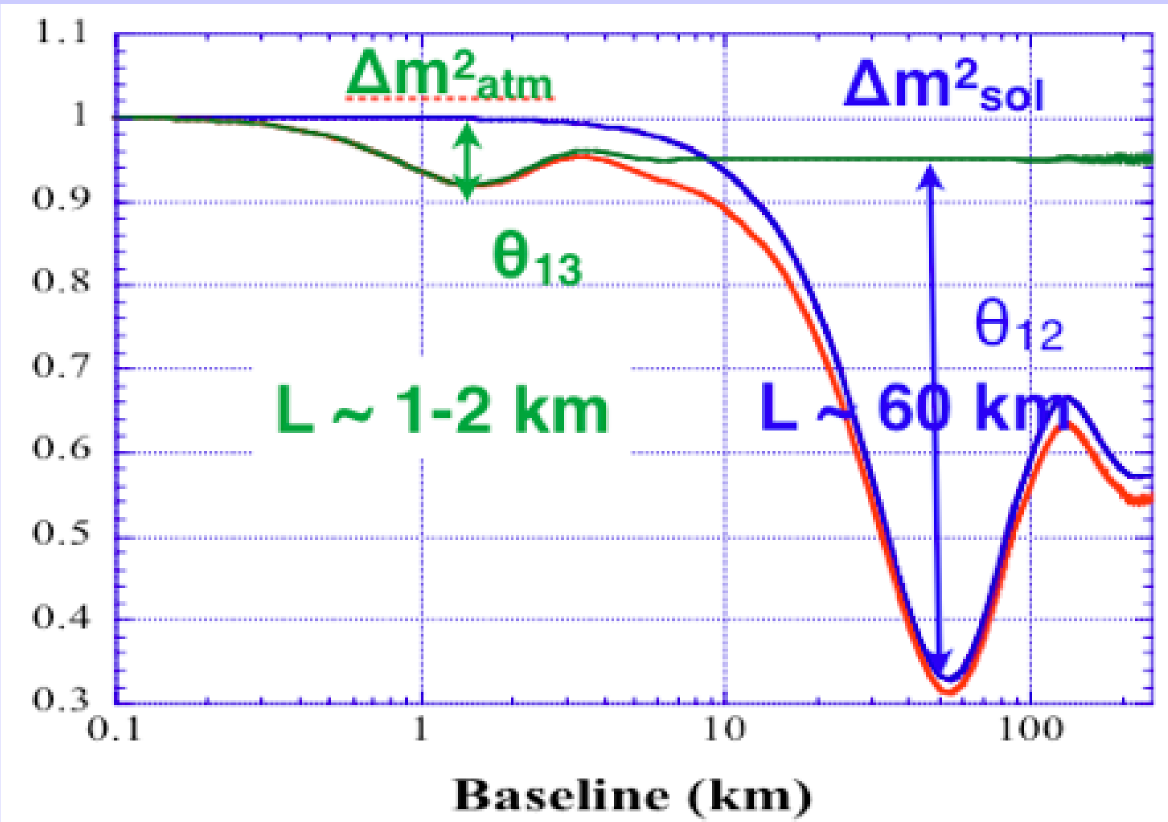
Reactor Neutrino Oscillations

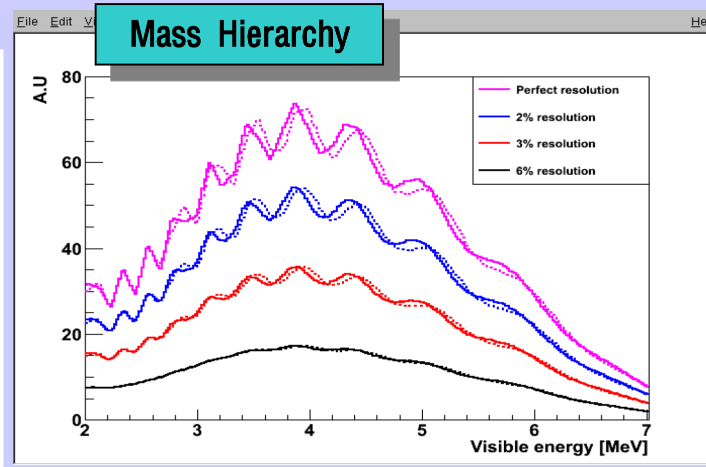
$$P(\nu_e \rightarrow \nu_e) \approx 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\left(\frac{1.27\Delta m^2_{12}L}{E_\nu}\right) - \sin^2 2\theta_{13}\sin^2\left(\frac{1.27\Delta m^2_{13}L}{E_\nu}\right)$$

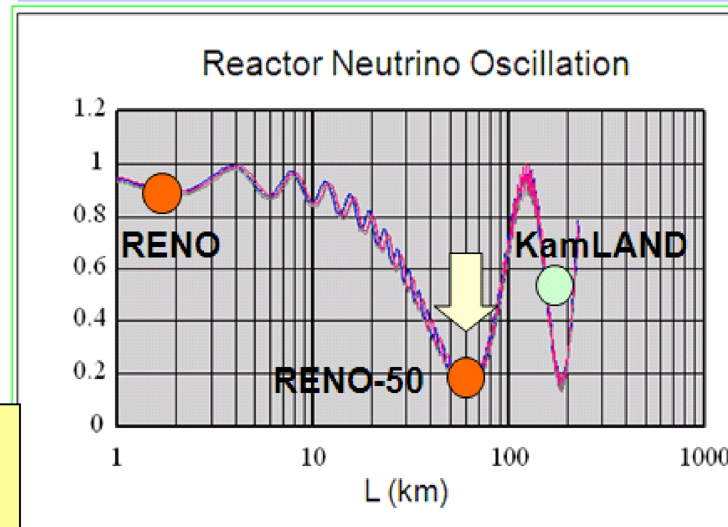
RENO-50

RENO

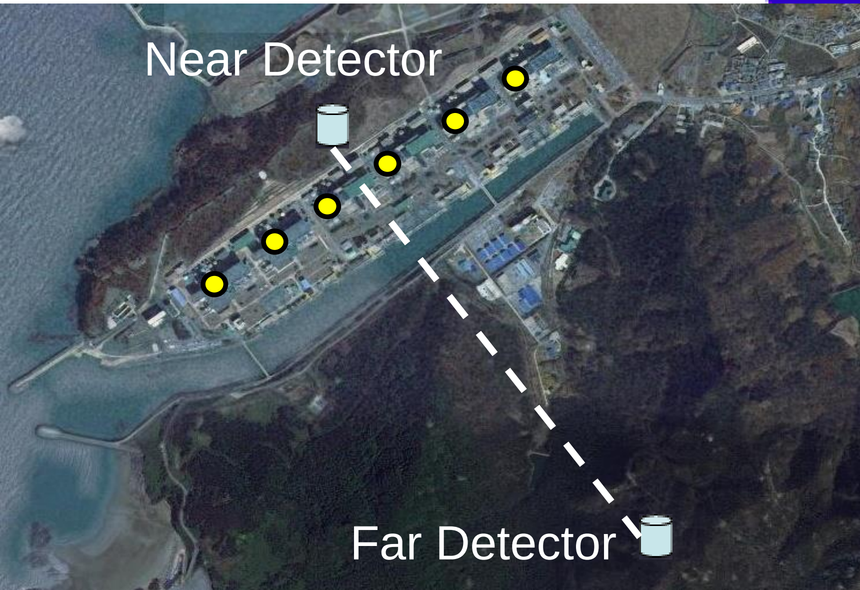
Very challenging, better than 3% energy resolution is required







- Large θ_{12} neutrino oscillation effect at 50km
  + 18kton liquid scintillator detector



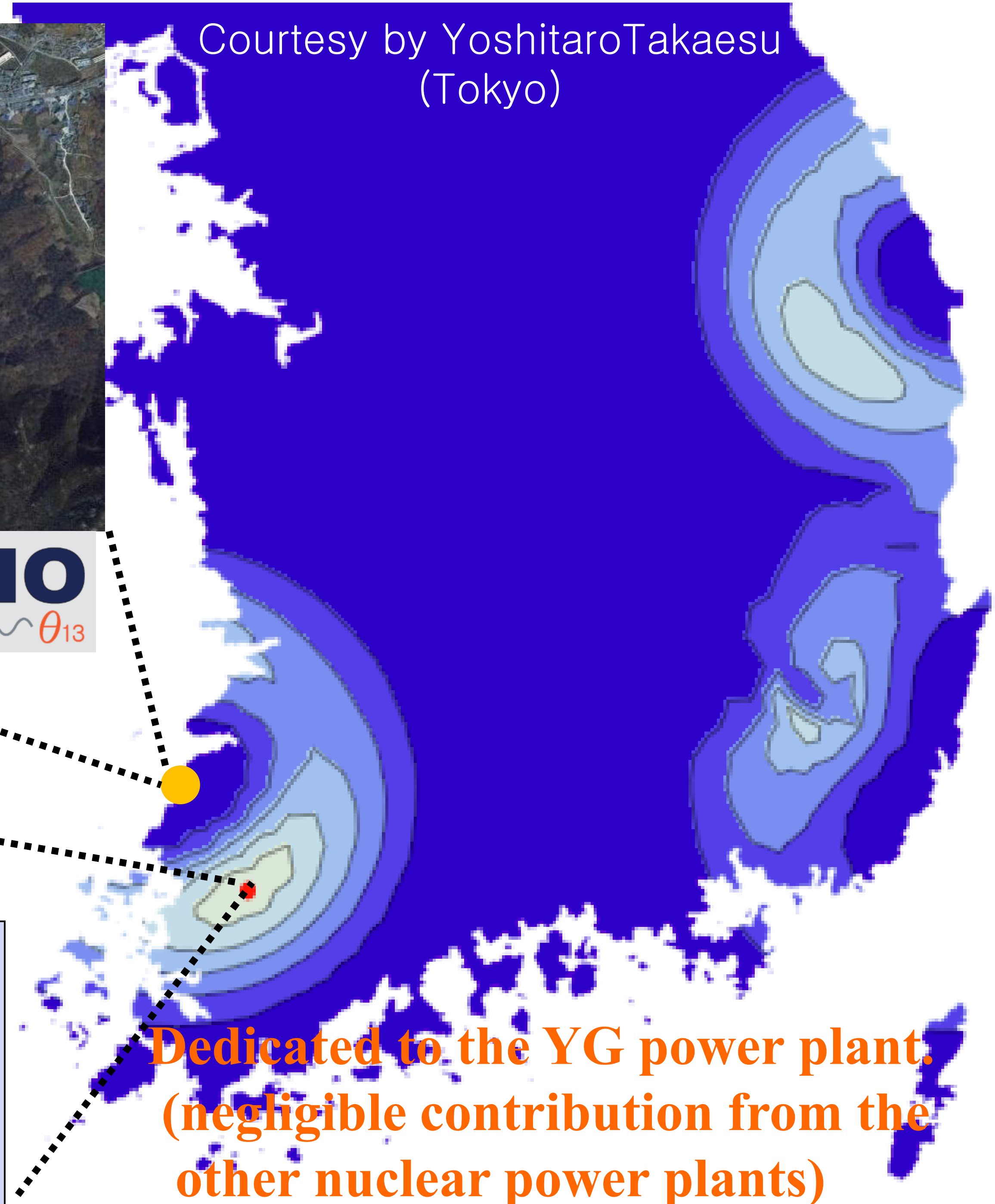
(NEAR Detector)

(FAR Detector)

RENO-50

18 kton LS Detector
~47 km from YG reactors

Mt. Guemseong (450 m)
~900 m.w.e. overburden



Dedicated to the YG power plant.
(negligible contribution from the other nuclear power plants)

RENO-50 Candidate Site

RENO-50 Candidate Site

Additional Physics with RENO-50

- Neutrino burst from a Supernova in our Galaxy
  - ~5,600 events (@8 kpc)
  - A long-term neutrino telescope

KNO inherited

- Geo-neutrinos : ~ 1,000 geo-neutrinos for 5 years
  - Study the heat generation mechanism inside the Earth

KNO inherited

- Solar neutrinos : with ultra low radioacitivity
  - MSW effect on neutrino oscillation
  - Probe the center of the Sun and test the solar models

KNO inherited

- Detection of J-PARC beam : ~100 events/year

KNO inherited

- Neutrinoless double beta decay search : possible modification like KamLAND-Zen

Institute of Basic Science (IBS)

CUP + • • •

CUP (Center for Underground Physics)

~$10M/year for next 10 years. Total ~$100M

ν program

Personnel

Total	65
Gender	49(Male), 16(Female)
Korean/ International	53(Korean), 12(International)

Searching for Dark Matter to understand the origin and structure of the universe

- Searching for Weakly Interacting Massive Particles (WIMPs) as dark matter candidates
- Searching for **neutrino-less double beta decay** and **sterile neutrinos**

- AMoRE (Advanced Mo-based Rare process Experiment)
  - Searching for neutrino-less double beta decay of ^{100}Mo using cryogenic $^{40}Ca^{100}MoO_4$ detectors

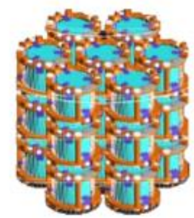
- 5 countries (Korea, Russia, Ukraine, China, Germany)
- 13 institutes, ~84 collaborators

AMoRE detector

$^{40}Ca^{100}MoO_4$

~ 1.5 kg

AMoRE Pilot



$^{40}Ca^{100}MoO_4$

~ 5 kg

AMoRE-I

$X^{100}MoO_4$

200 kg

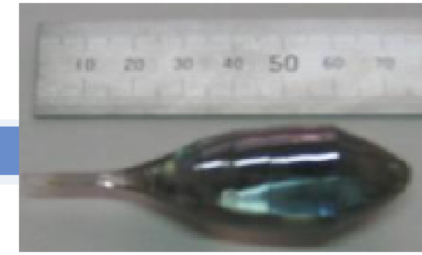
AMoRE-II

ckky : counts/ (keV kg year)

	AMoRE-Pilot	AMoRE-I	AMoRE-II
Crystal Mass (kg)	1.5	5	200
Backgrounds(ckky)	~ 10^{-2}	~ 10^{-3}	10^{-4}
$T_{1/2}$(year)	1.0×10^{24}	8.2×10^{24}	8.2×10^{26}
m_{bb} (meV)	380-719	130-250	13-25
Schedule	2017	2018	2020-2023

Weight ~300g

History of CaMoO4



1) 2002 : Idea and try to grow CMO in Korea
2) 2003 : Collaboration with V.Kornokov. Received CMO (better)
3) 2004 : CMO test and Conference presentation (VIETNAM2004), Extended idea of XMoO4, cryogenic detector of CMO
4) 2005-2007 : Large CMO with 1st ISTC project
5) 2006 : Collaboration with F. Danevich group (CMO by Lviv)
6) 2007 : CMO R&D in cryogenic temperature started.
7) 2008 : 2nd ISTC project : 1kg of $^{40}Ca^{100}MoO4$ crystal growing
8) 2009 : AMORE collaboration formed
9) 2010-11 : Characterization of $^{40}Ca^{100}MoO4$ & background study
10) 2012 : Russian group got funding for CMO production line
11) 2013 : AMoRE project funded (Under IBS CUP)

AMoRE group has a long history for developing detector & good experiences, technology, etc

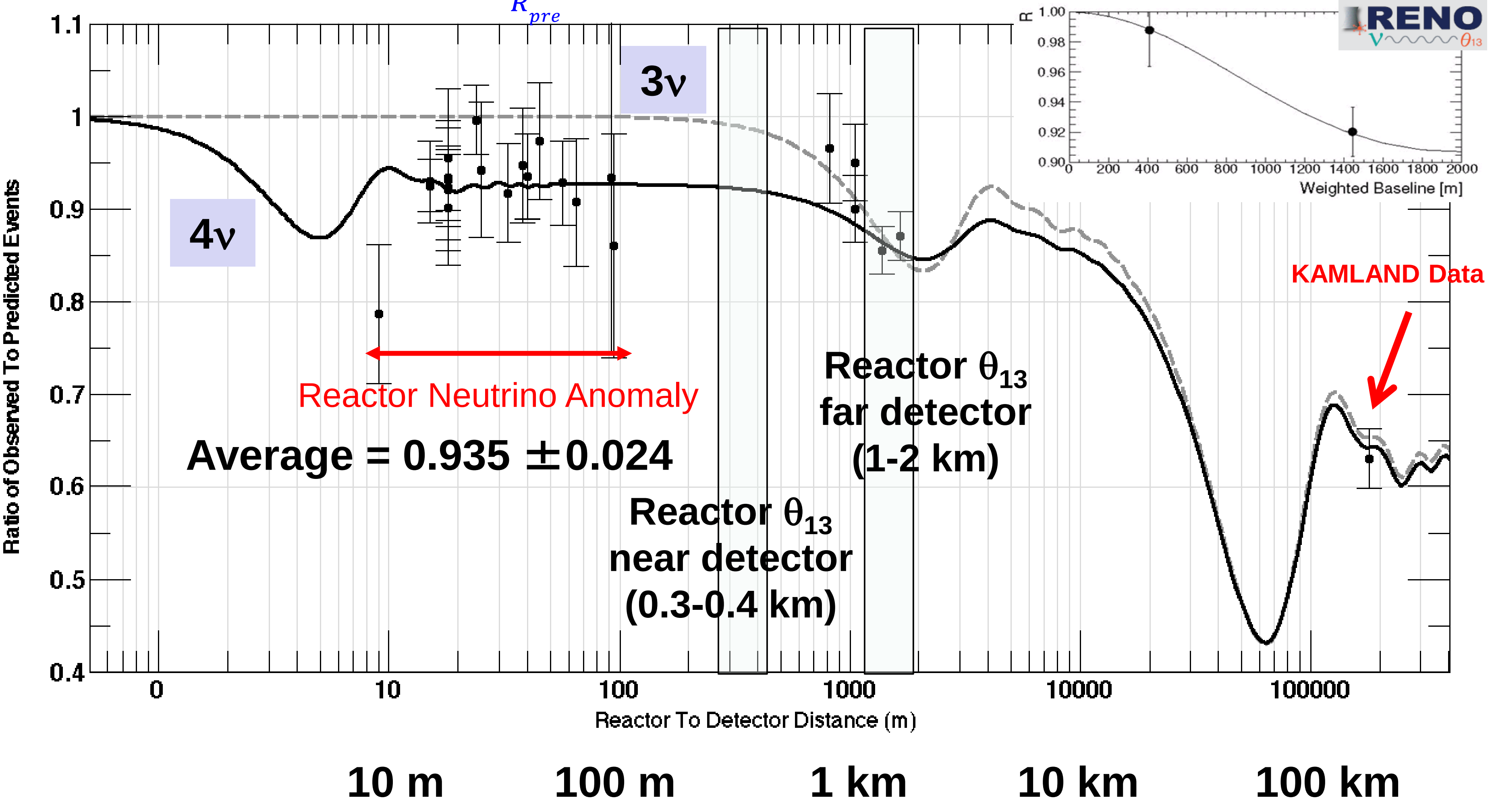
- *Proc. New View in Particle Physics (VIETNAM '2004) Aug. 2004, p.449*
- *IEEE Nucl. Sci. 52, 1131 (2005)*
- *NIMA 584, 334 (2008)*
- *IEEE Nucl. Sci. (2010,2012)*

Reactor Neutrino Anomaly ? (3ν vs. 4ν)

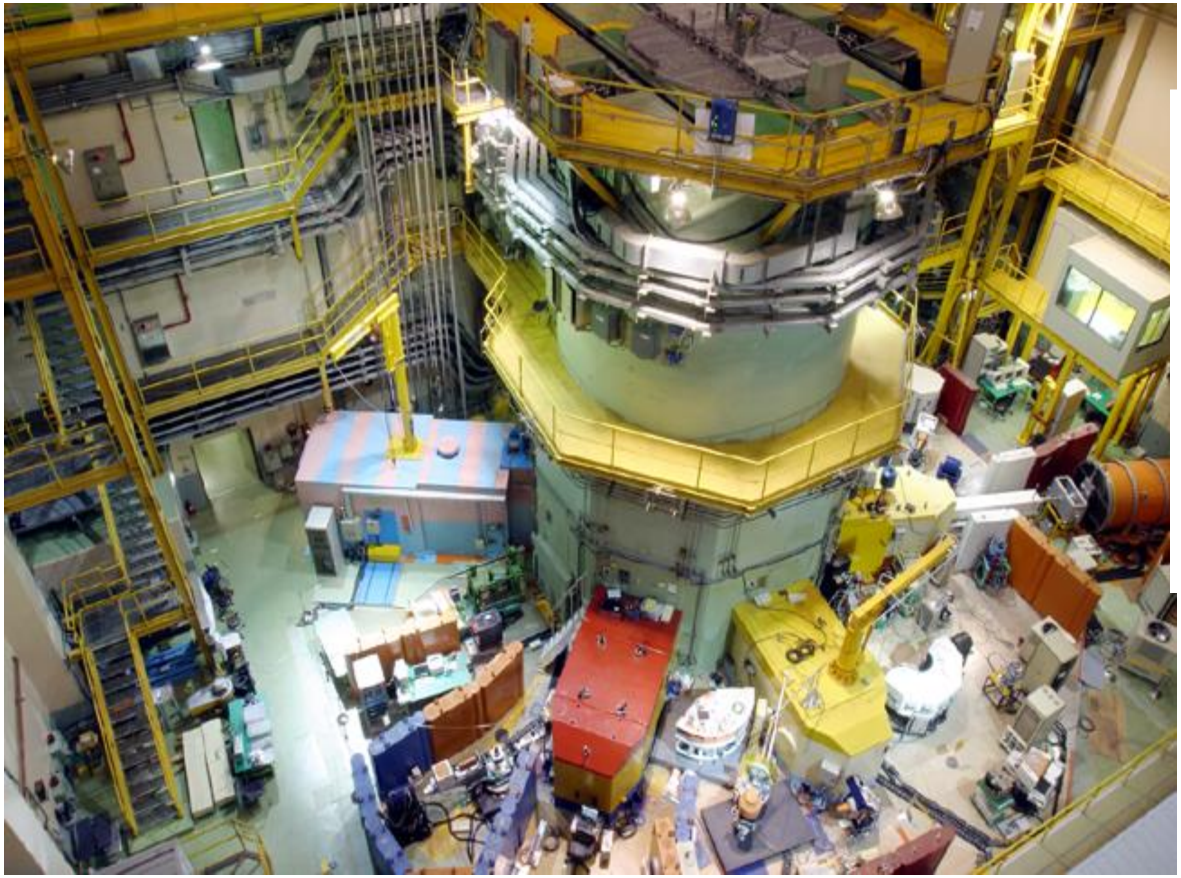
Reactor nuclear physics vs. new physics ?

adapted from Lasserre AAP 2012

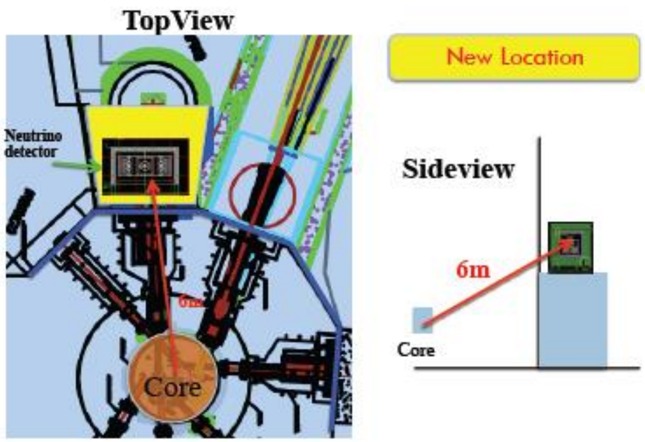
In 2009, reactor neutrino spectrum modified → previous data shows 6% deficit . R = $\frac{R_{obs}}{R_{pre}} < 1$



Hanaro Short Baseline (SBL) Neutrino Experiment in Korea



(2012~2015)



Baseline ~6m

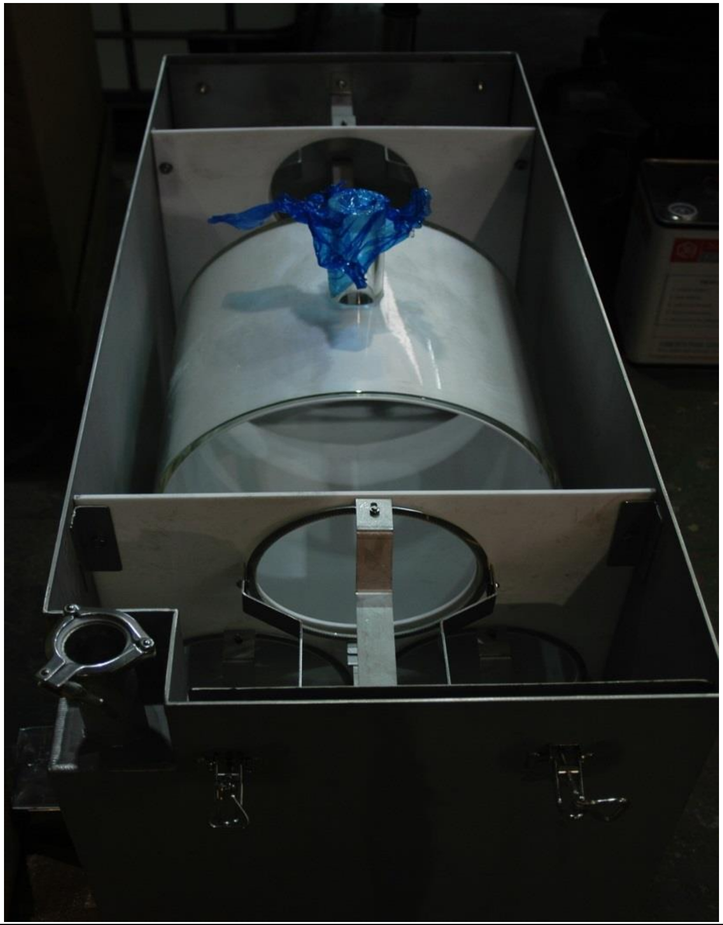
~100 neutrinos/day

Funded (~2M$) for 3 yrs

- 30MW Hanaro research reactor in KAERI, Daejeon, Korea is used to investigate a reactor neutrino anomaly
- Small core size: 20x40x60 cm^3
- 50L prototype detector and then 500L LS (GdLS, ^{6}LiLS) main detector

Hanaro SBL Prototype Detector

Target (50L)



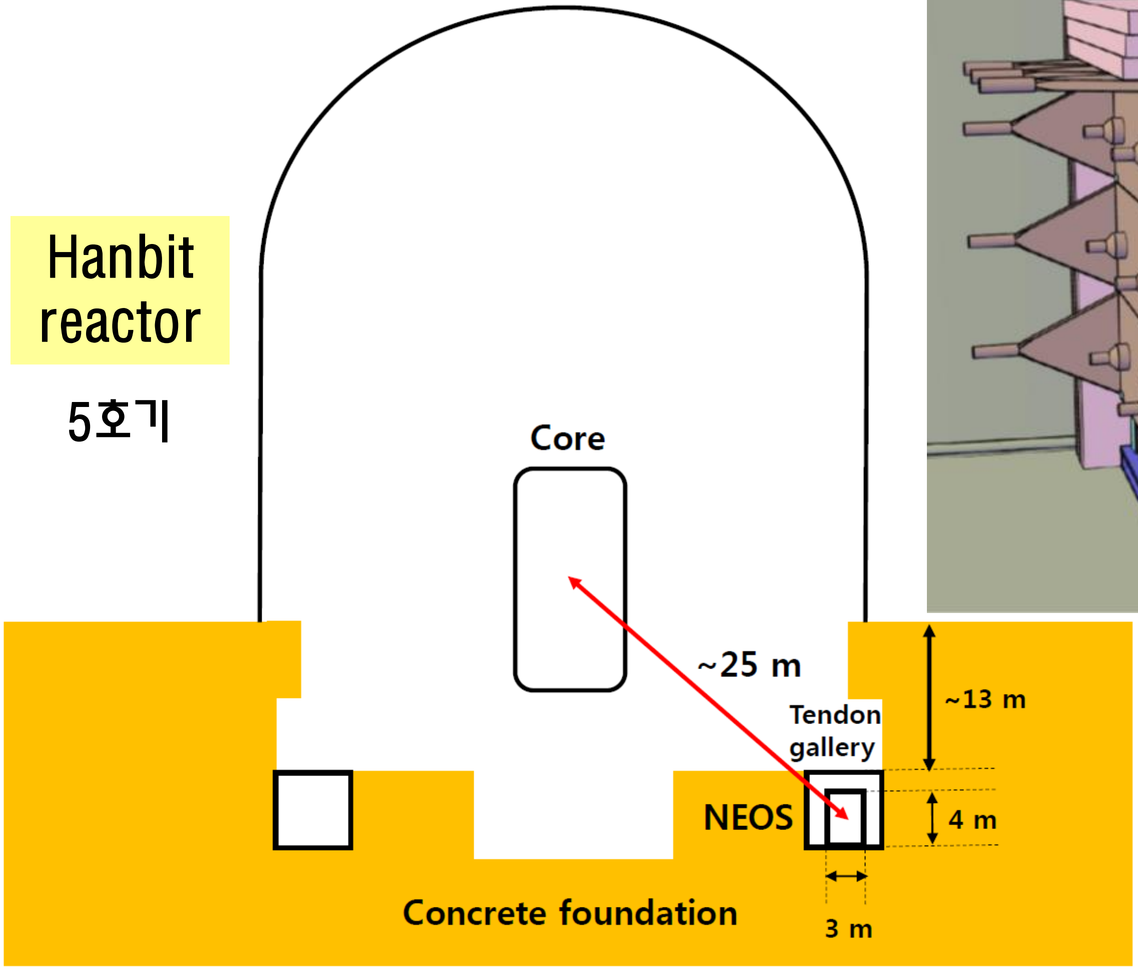
- Target (50L) of GdLS/^{6}LiLS
- PMT: 6 x 8” R5912 Hammatsu PMTs
- Passive shield (10 cm thickness Lead)
- 4π muon veto
- Background is studied at over ground LAB

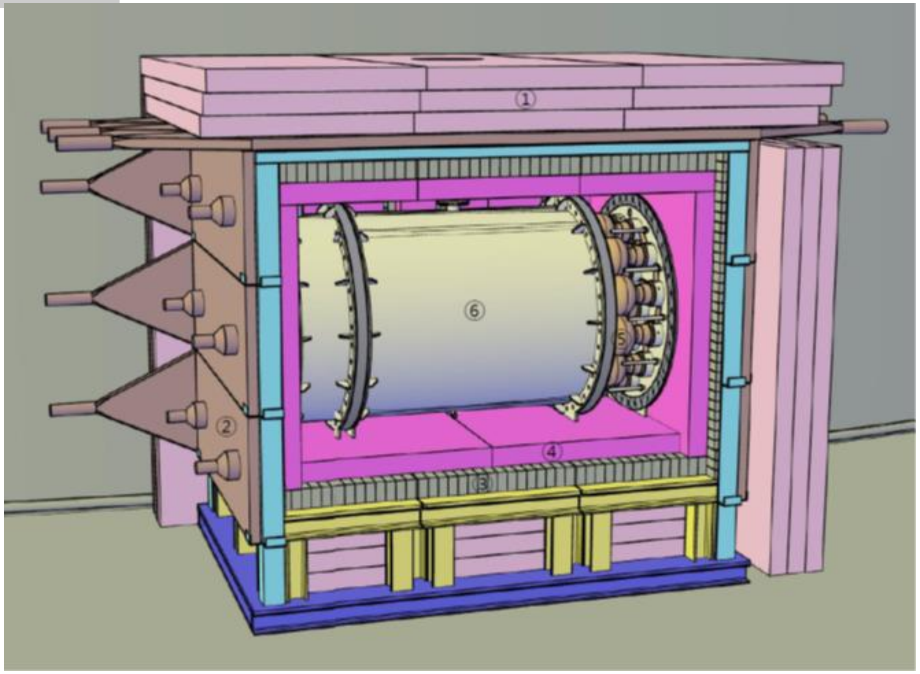
Deployment plan: Hanaro @6m, March 2014

NEOS (NEutrino Oscillation at Short-baseline) Experiment

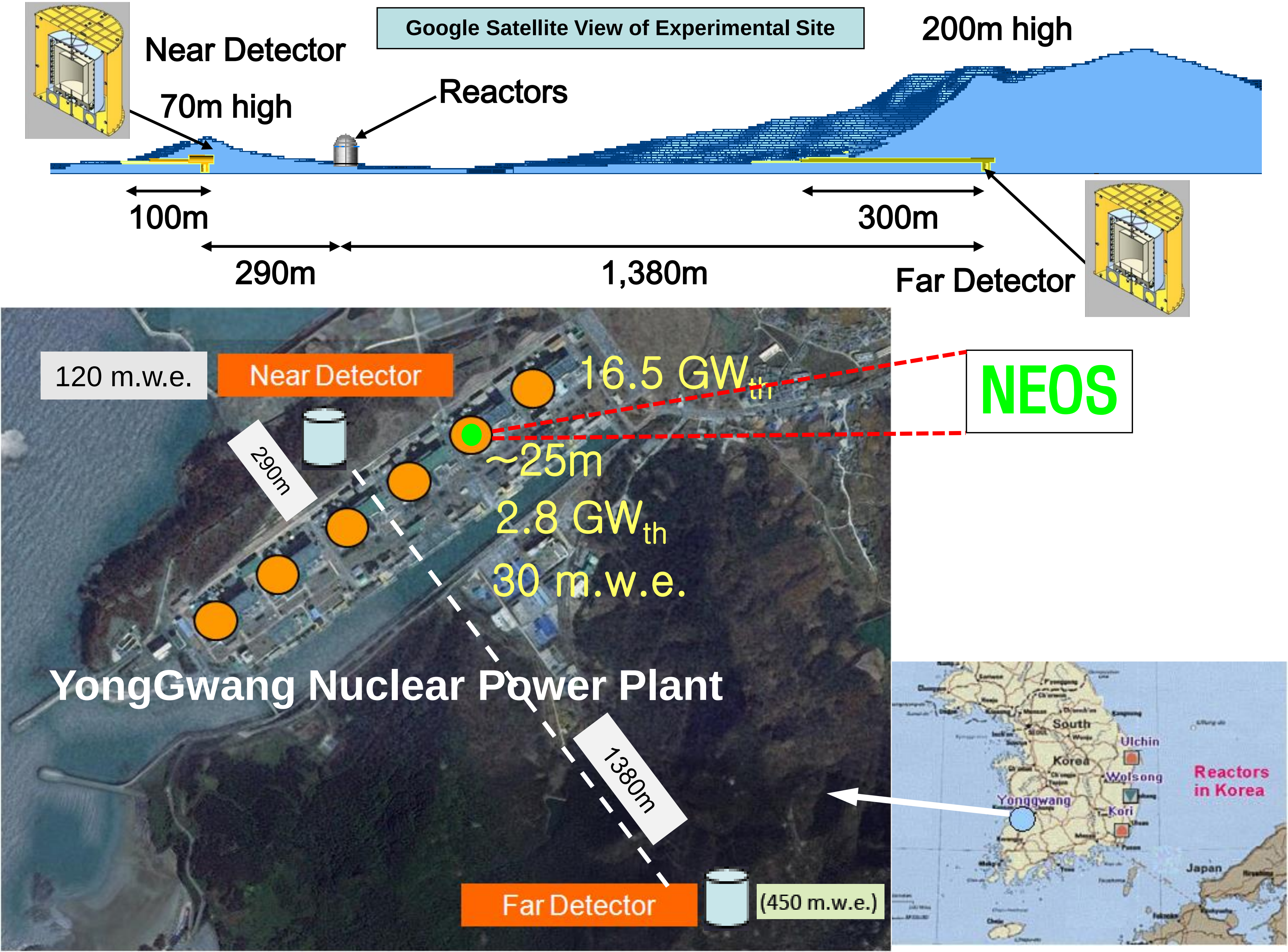
To investigate a reactor antineutrino anomaly

- NEOS I: taking data (2015.08 ~ 2016.05)
- NEOS II: 2018.09 ~ present

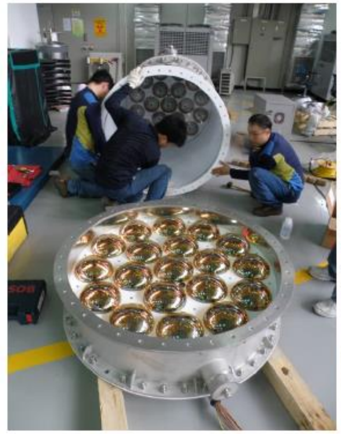


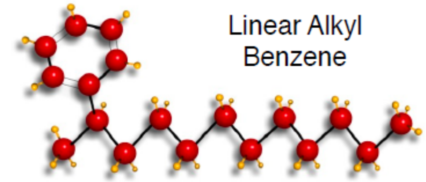


- 1-ton LAB-based LS
- ~0.5% Gd-loaded
- ~10% DIN added


Google Satellite View of Experimental Site
Near Detector
70m high
Reactors
200m high
100m
290m
1,380m
300m
Far Detector
120 m.w.e.
Near Detector
16.5 GW$_{th}$
NEOS
~25m
2.8 GW$_{th}$
30 m.w.e.
290m
YongGwang Nuclear Power Plant
1380m
Far Detector
(450 m.w.e.)
South
Korea
Ulchin
Wolsong
Yonggwang
Kori
Reactors in Korea
Japan

NEOS I



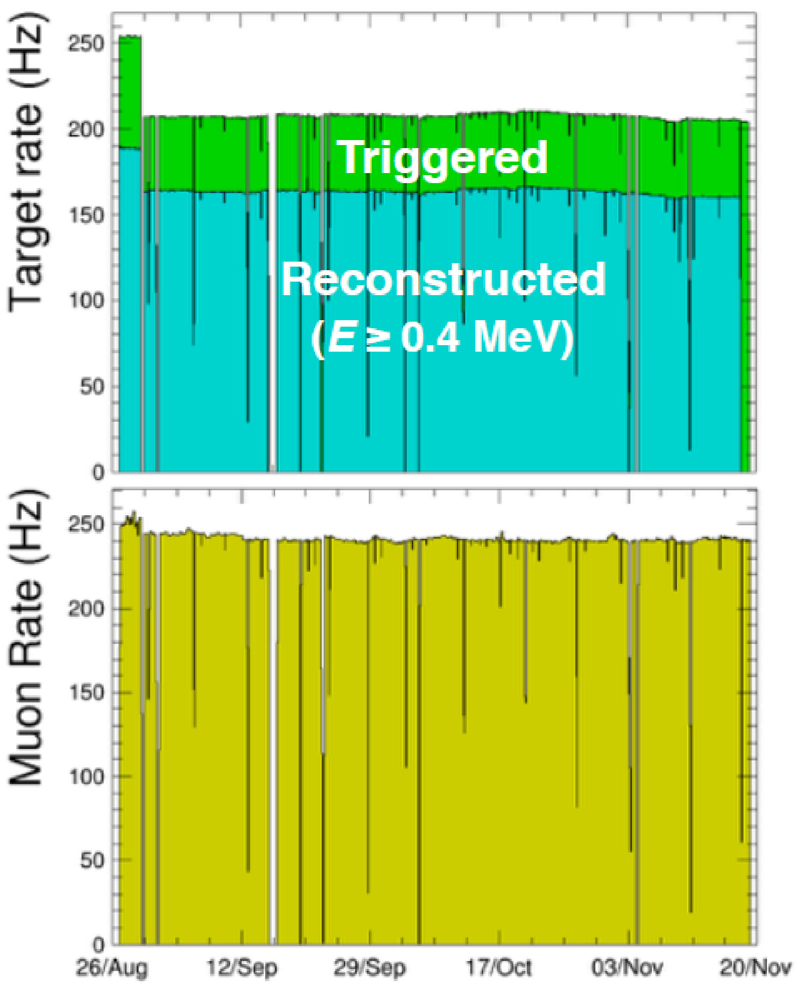
- Homogeneous LS target
  - 1008 L volume (R 51.5, L 121) cm
  - LAB+UG-F (9:1)
  - 0.5% Gd loaded for high neutron capture efficiency
  - 38 8″ PMT in mineral oil buffer
- Shieldings
  - 10 cm B-PE (n), 10 cm Pb (γ)
  - active muon counter
- Data AcQuisition
  - 500 MS/s FADC (waveform)
  - 62.5 MS/s ADC (μ veto)
- Source calibration through chimney

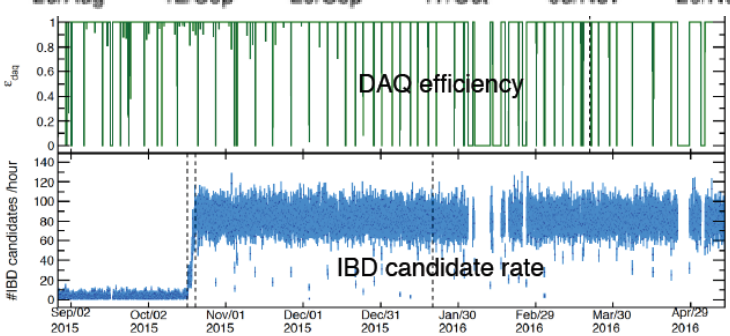


NEOS II

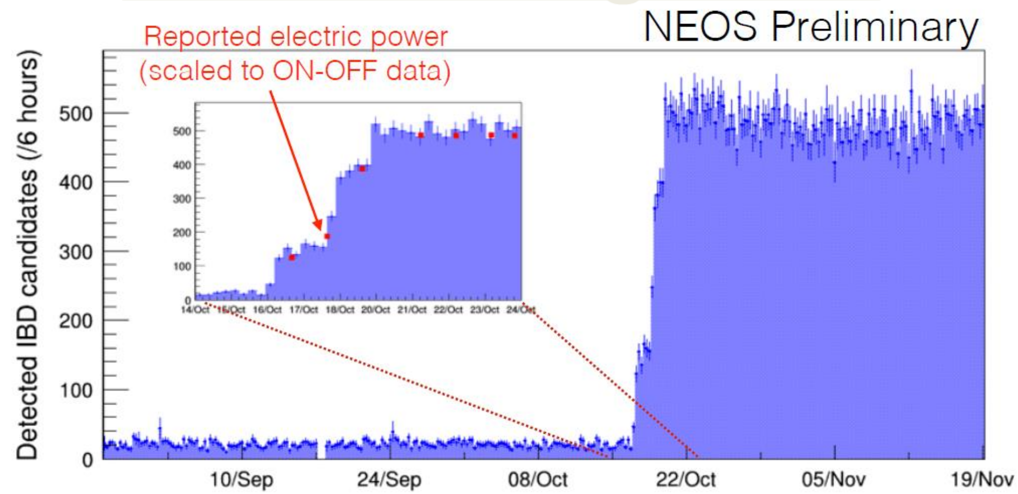
- LS is replaced
- No major change
 (minor change in detector structure)
- Evolution of reactor neutrino flux /spectrum will be studied according to the fuel component changes


NEOS Data-taking





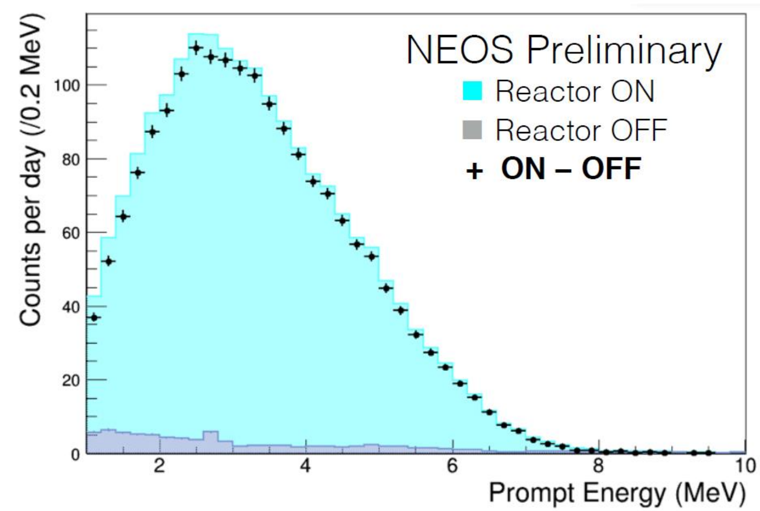
IBD Counting Rate



OFF: 84 ± 1; ON : 1946 ± 8 cpd

Signal / Background ~ 22

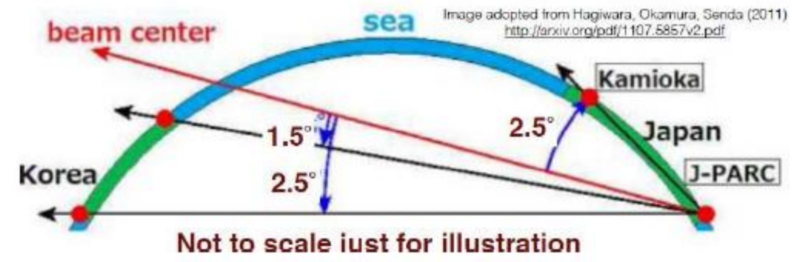
IBD Prompt Energy



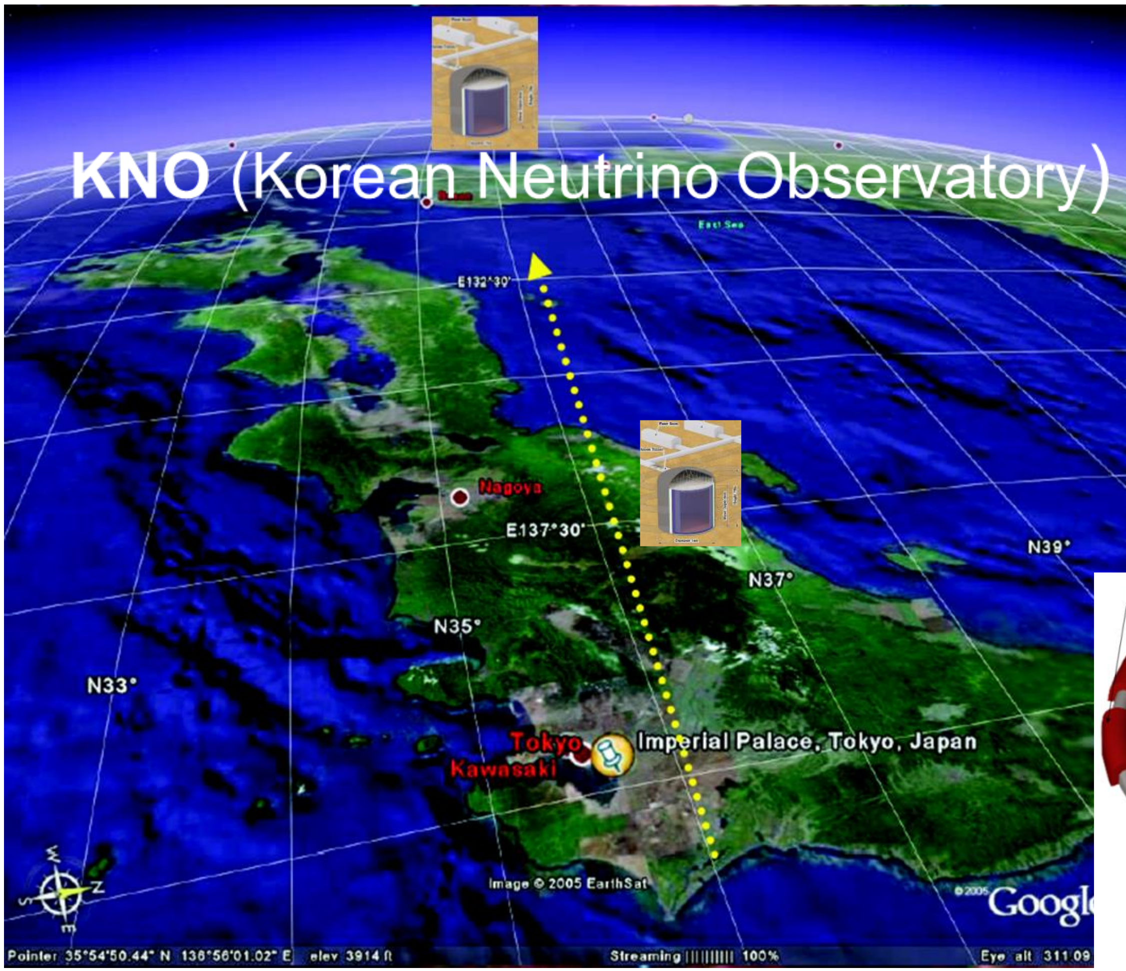
NEOS successfully measured spectral shape of IBD prompt energy **PRL118, 121802 (2017)**

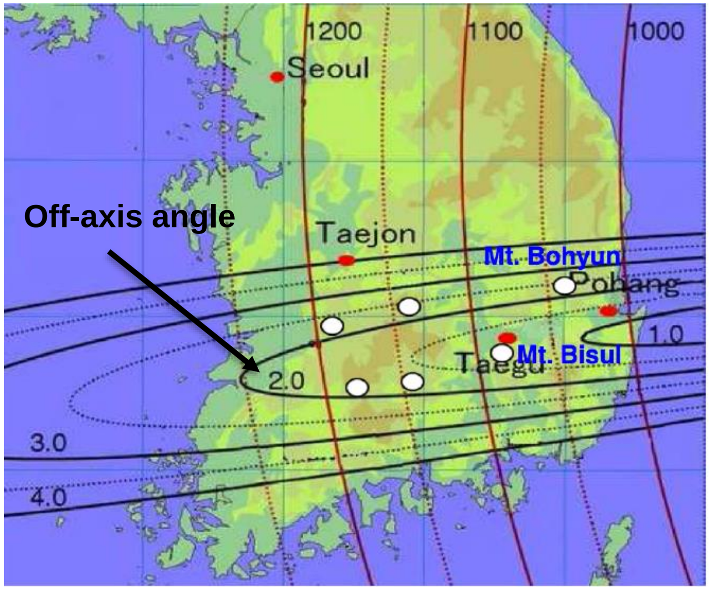
KNO

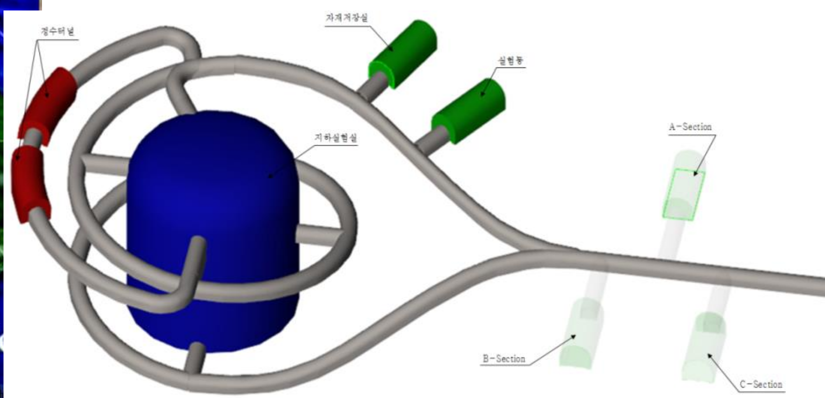
T2KK, T2HKK or **KNO**?
(played as a 2nd Hyper-K detector in Korea)



J-PARC off-axis neutrino beam comes to Korea





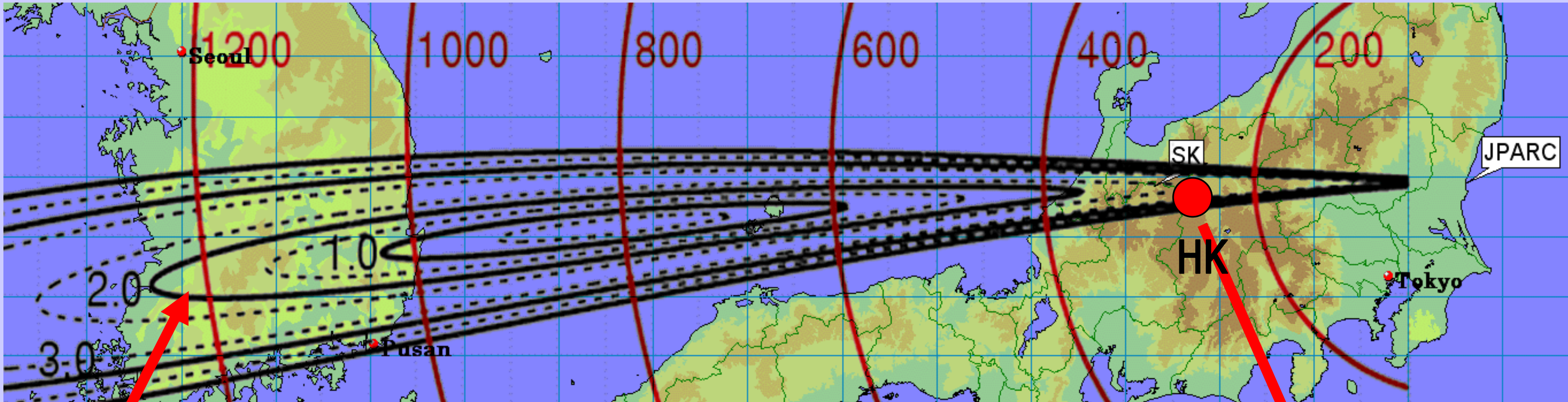


Baseline ~1100km: next oscillation maxima in Korea

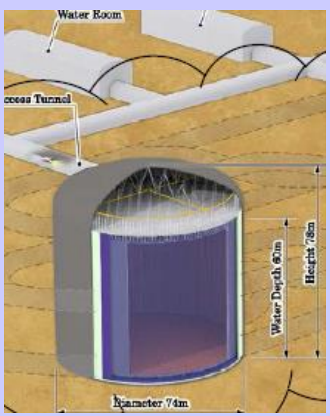
J-PARC neutrino beam

Dr. Okamura & Prof. Hagiwara (2005)

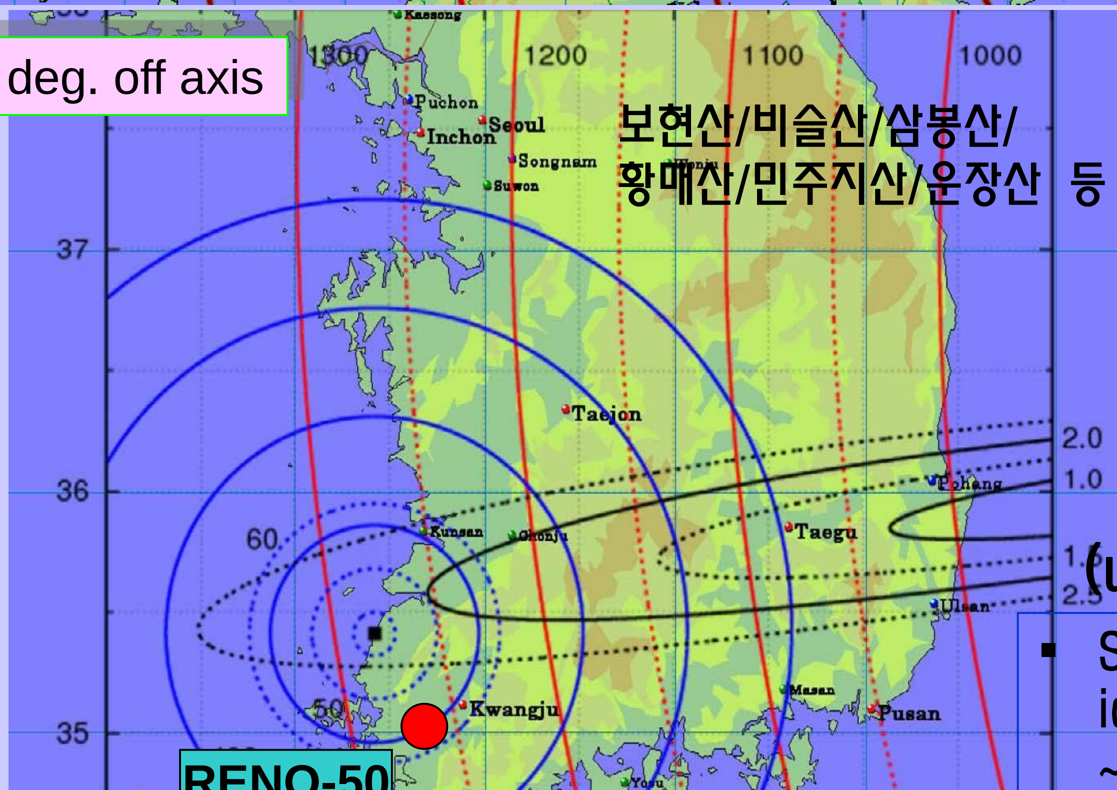
International Workshop on a Far Detector in Korea for the JPARC Neutrino Beam



2~3 deg. off axis

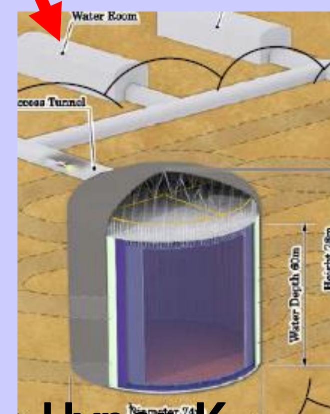


0.5Mton



RENO-50

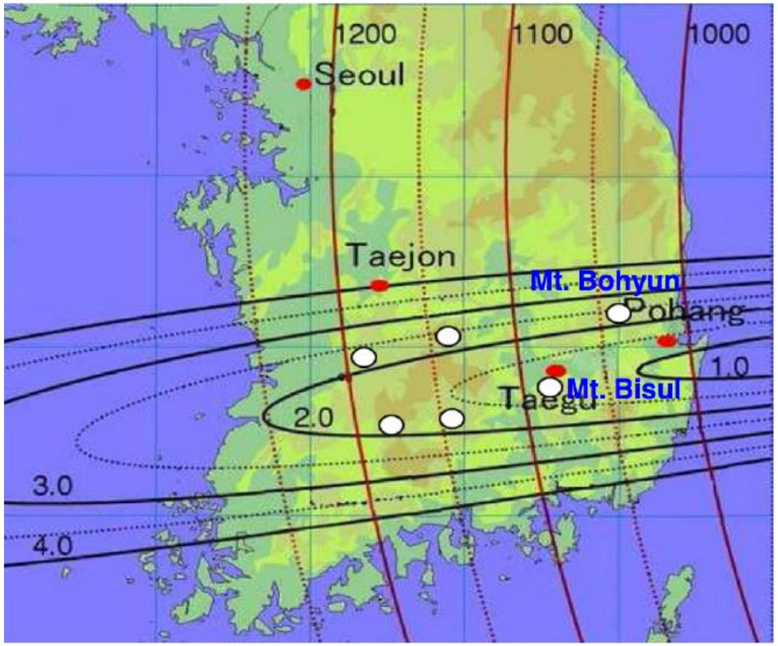
0.5Mton

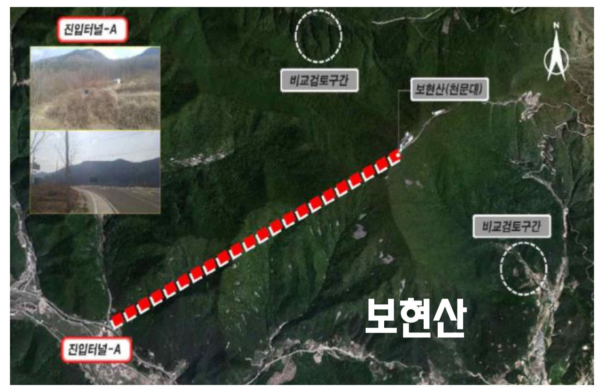


Hyper-K (under construction)

- Surprisingly, this idea was introduced ~15 yrs ago

KNO Candidate Sites

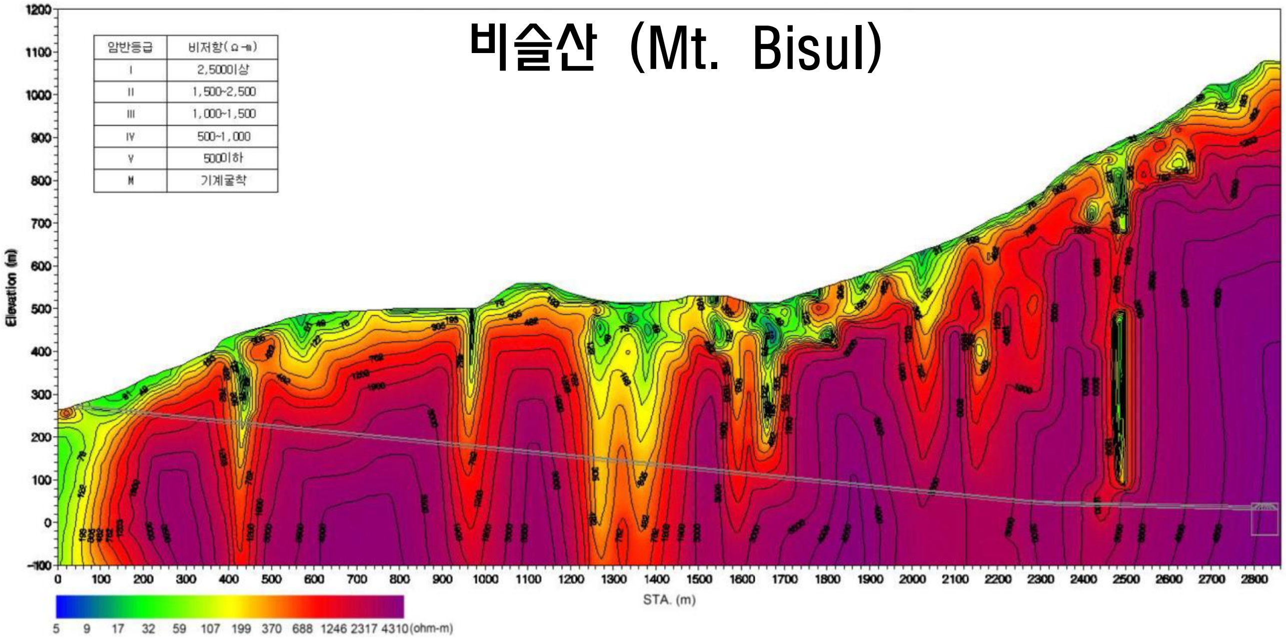


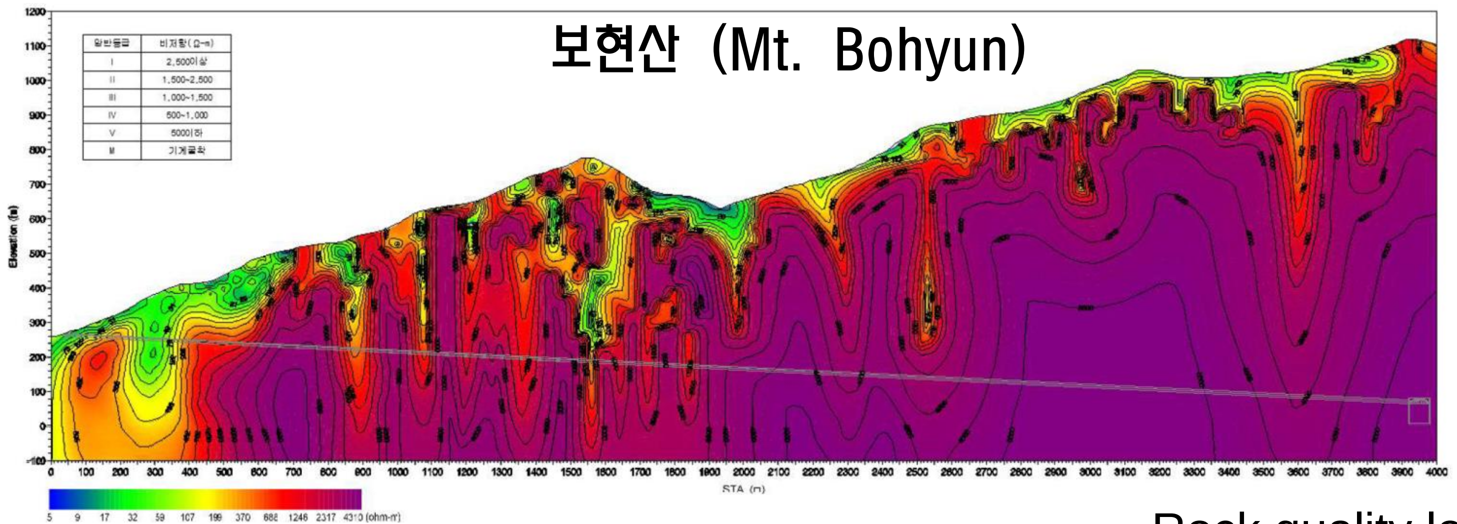


SEOYOUNG
서영엔지니어링

- Bidding process for geological survey/tunnel design company was done (May, 2017)
- Seo young engineering company surveyed surface and underground of Mt. Bisul & Mt. Bohyun (1.5억원, ~$0.15M) (June, 2017)
- Conceptual design and construction cost estimation through stress analysis was reported (July, 2017)

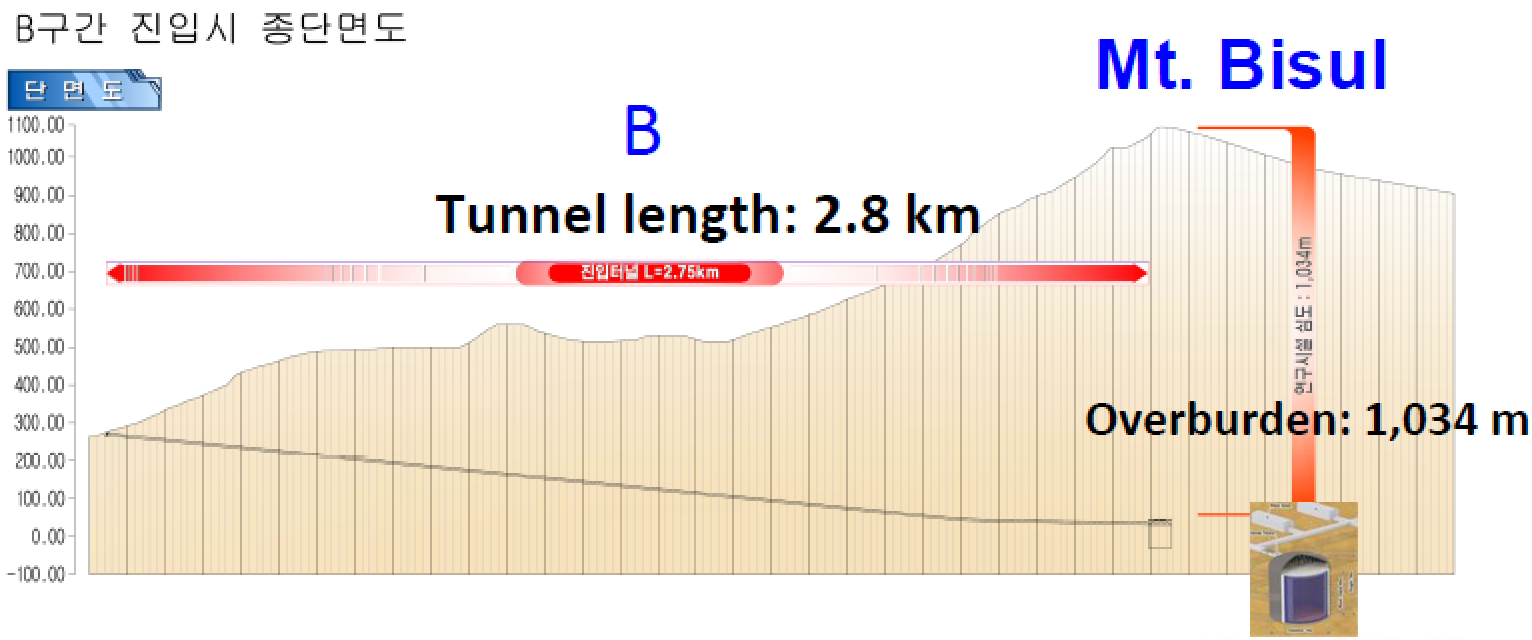
KNO Rock Strength of Underground

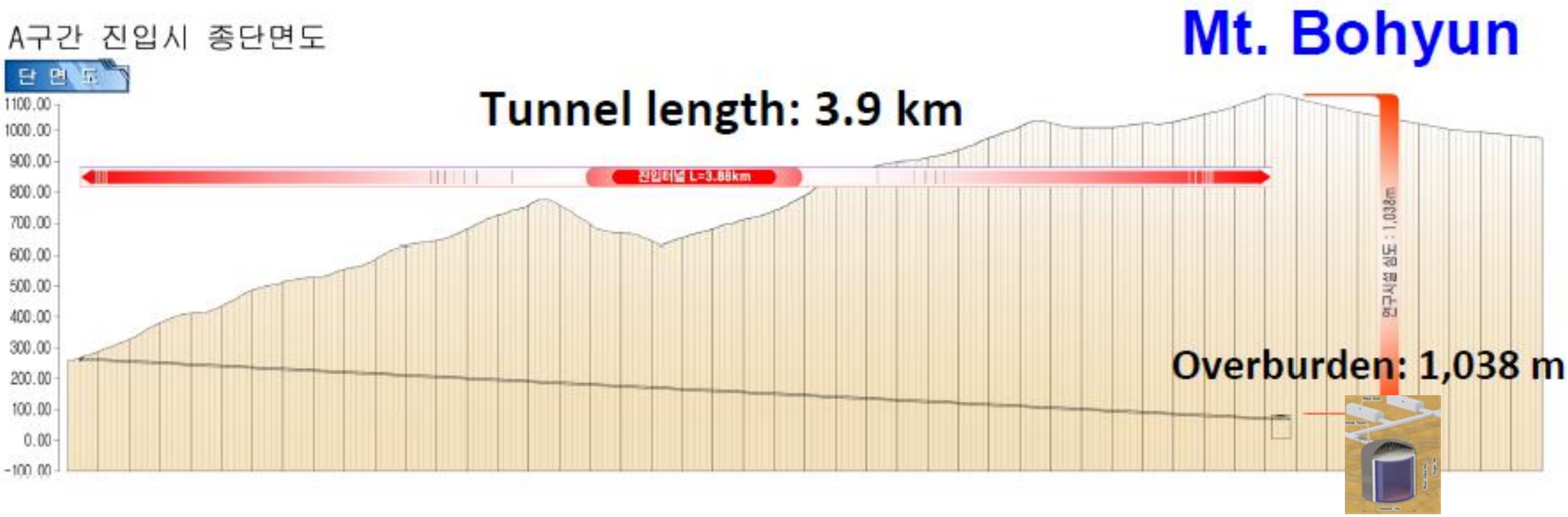




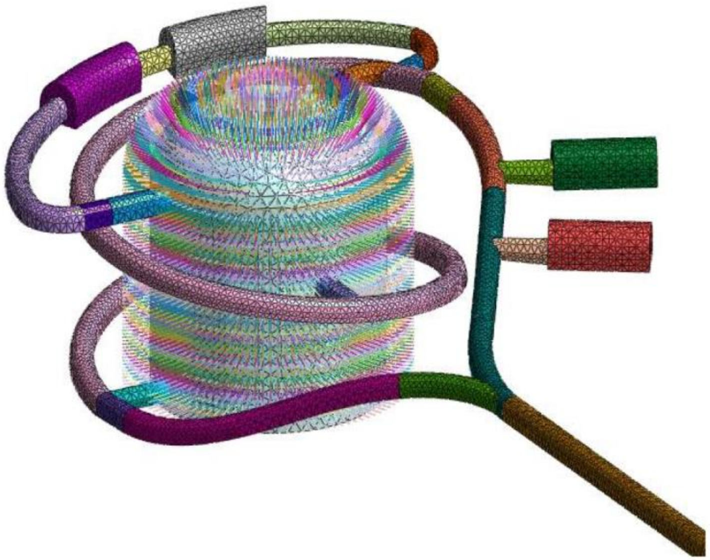
Rock quality looks good

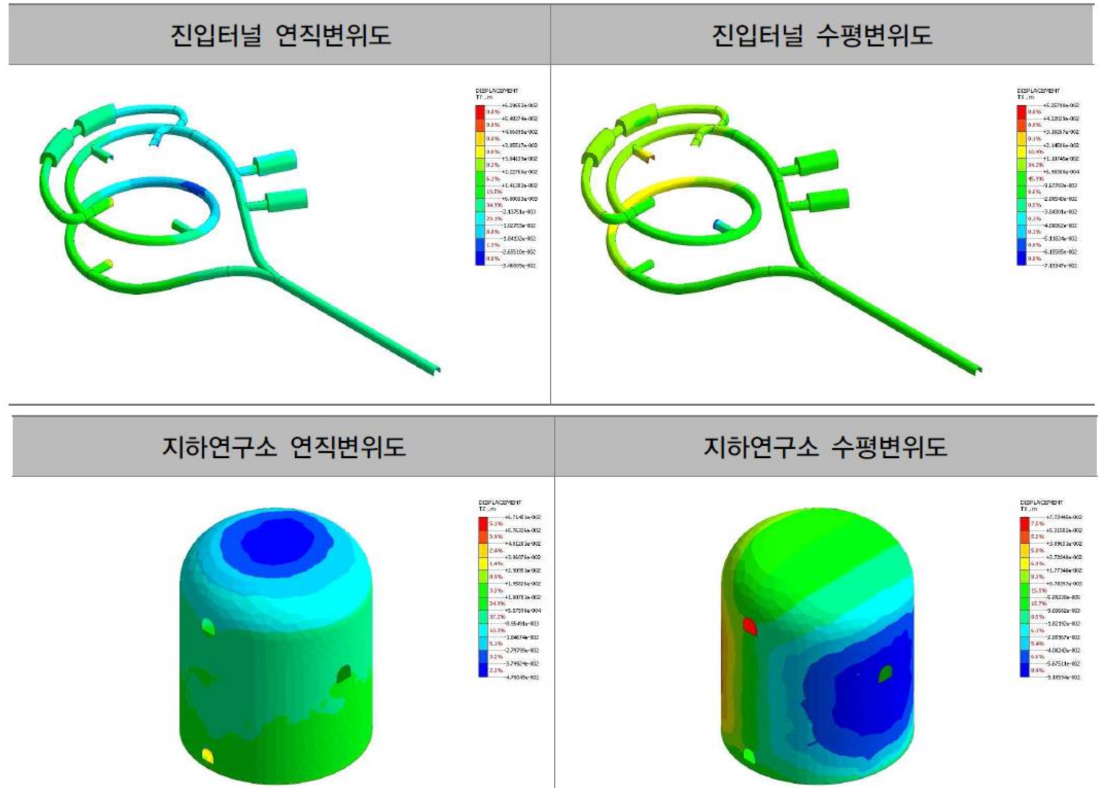
KNO Underground Facility

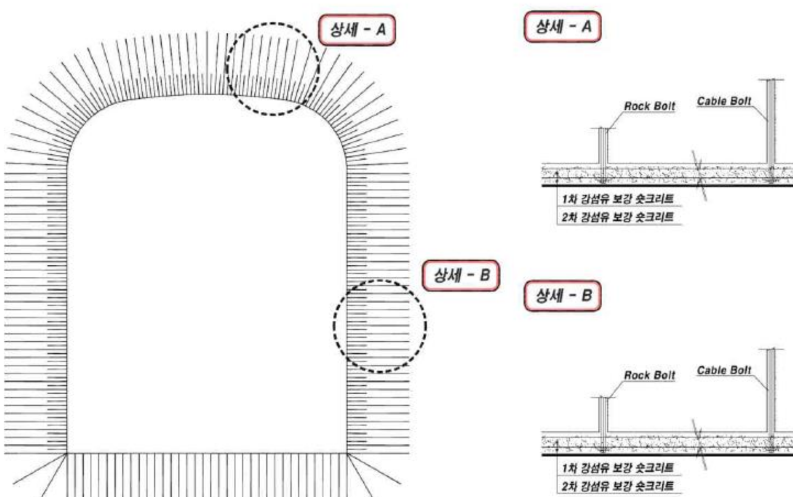




Stress Analysis for Tunnel Design







- **예상된 지하시설 구축 비용**: 600~700 억원

Estimated cost for tunnel: $60 ~ 70M

- Estimate quantity & quality of underground water

➡ All details for KNO, please see other slides in this satellite workshop

Closing Remarks

- Since last ~30 yrs, Korean group has joined various neutrino program and 1st domestic large collaboration started at 2006 (RENO collaboration)

- Korean reactors have used as an intense neutrino source to study the neutrino properties.

- The smallest mixing angle of θ_{13} is firmly (to ~7% precision) measured. RENO will have ~3 more yrs data taking scheduled. This is one of the most important achievements of Korean group in the world neutrino community

- Currently, several neutrino programs are on-going internally or outside (RENO, NEOSII, $JSNS^2$, IceCube, etc)

- Korean group are preparing for the next generation neutrino programs (KNO, DUNE, IBS-neutrino program, etc) & international collaborators are welcomed

θ_{13} from Reactor and Accelerator Experiments

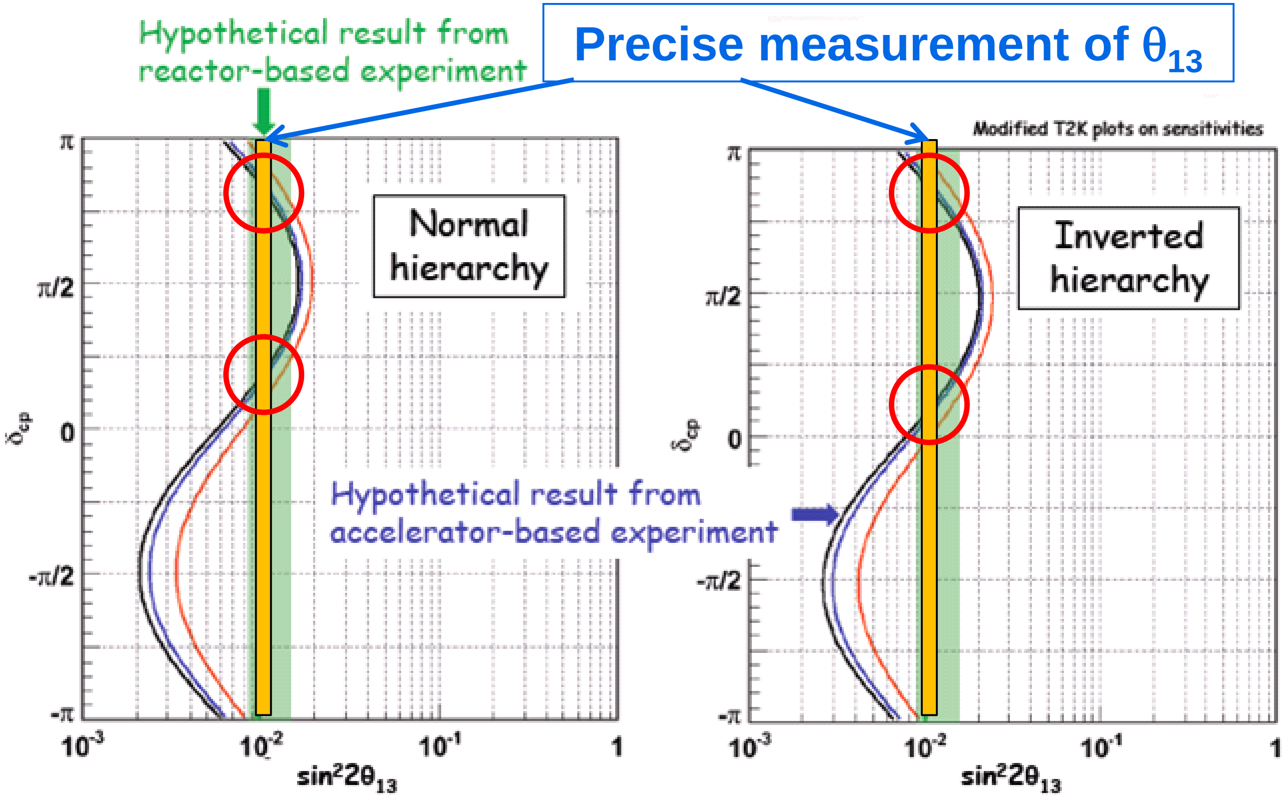
* Reactor

$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}{}^2 L}{4E_\nu}\right) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m_{21}{}^2 L}{4E_\nu}\right)$$

- Clean measurement of θ_{13} with no matter effects

* Accelerator

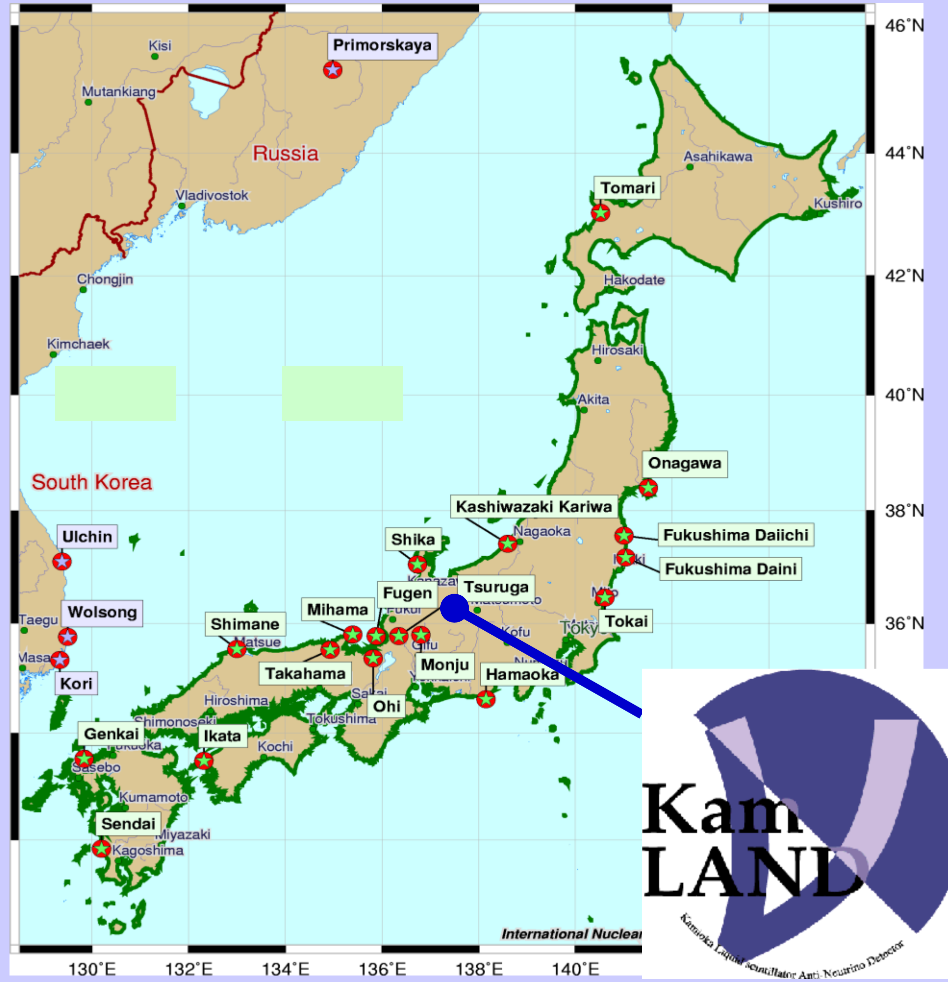
- mass hierarchy + CP violation + matter effects



- Complementary :

Combining results from accelerator and reactor based experiments could offer the first glimpse of δ_{CP}.

RENO-50 vs. KamLAND

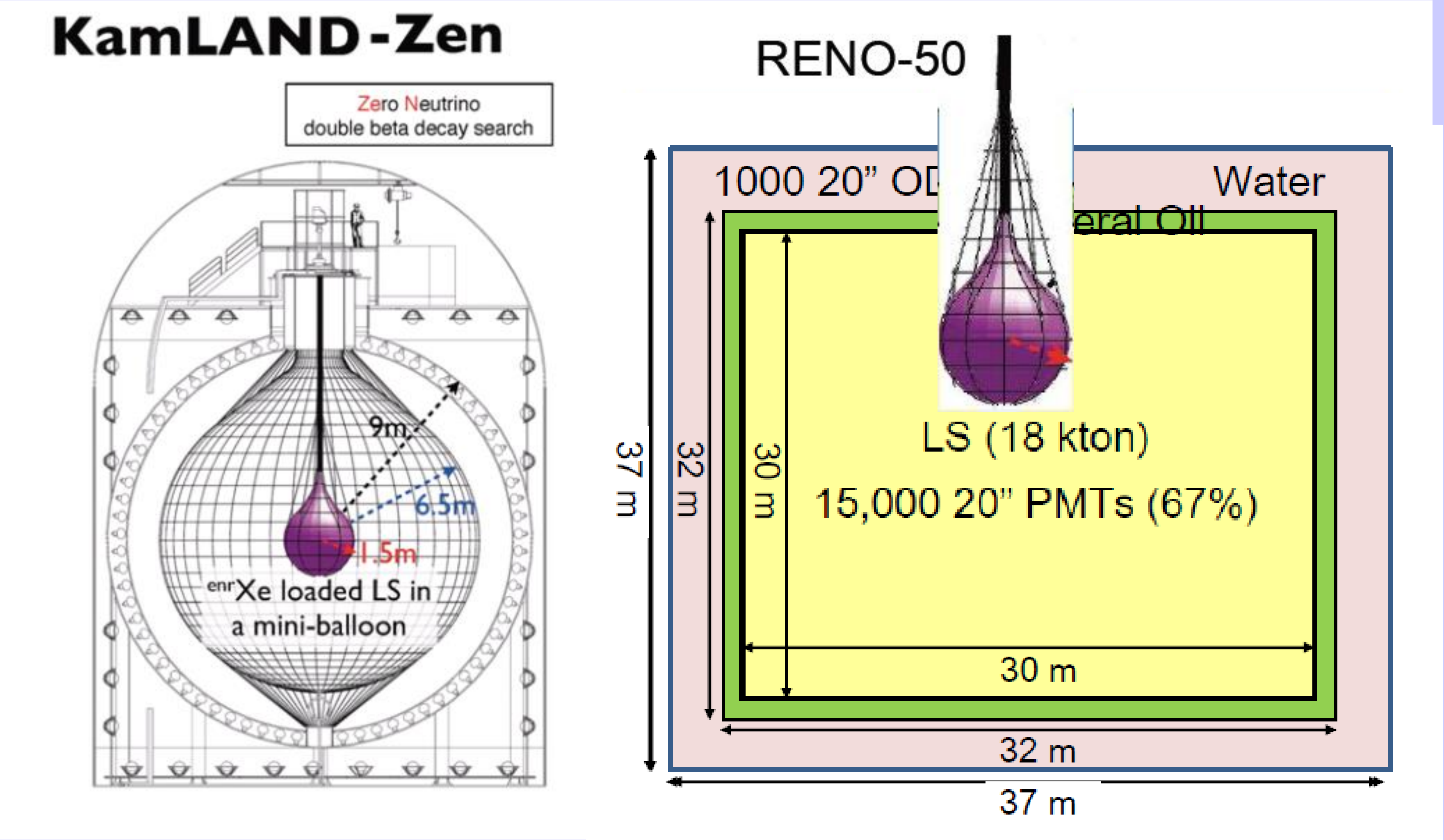


- RENO-50 is dedicated to the YG power plant. (negligible contribution from the other nuclear power plants)
- RENO can be used as near detectors.
- Precise reactor neutrino fluxes : systematic error from ~3% to ~0.1%

- KamLAND uses the entire Japanese nuclear power plants as a source.

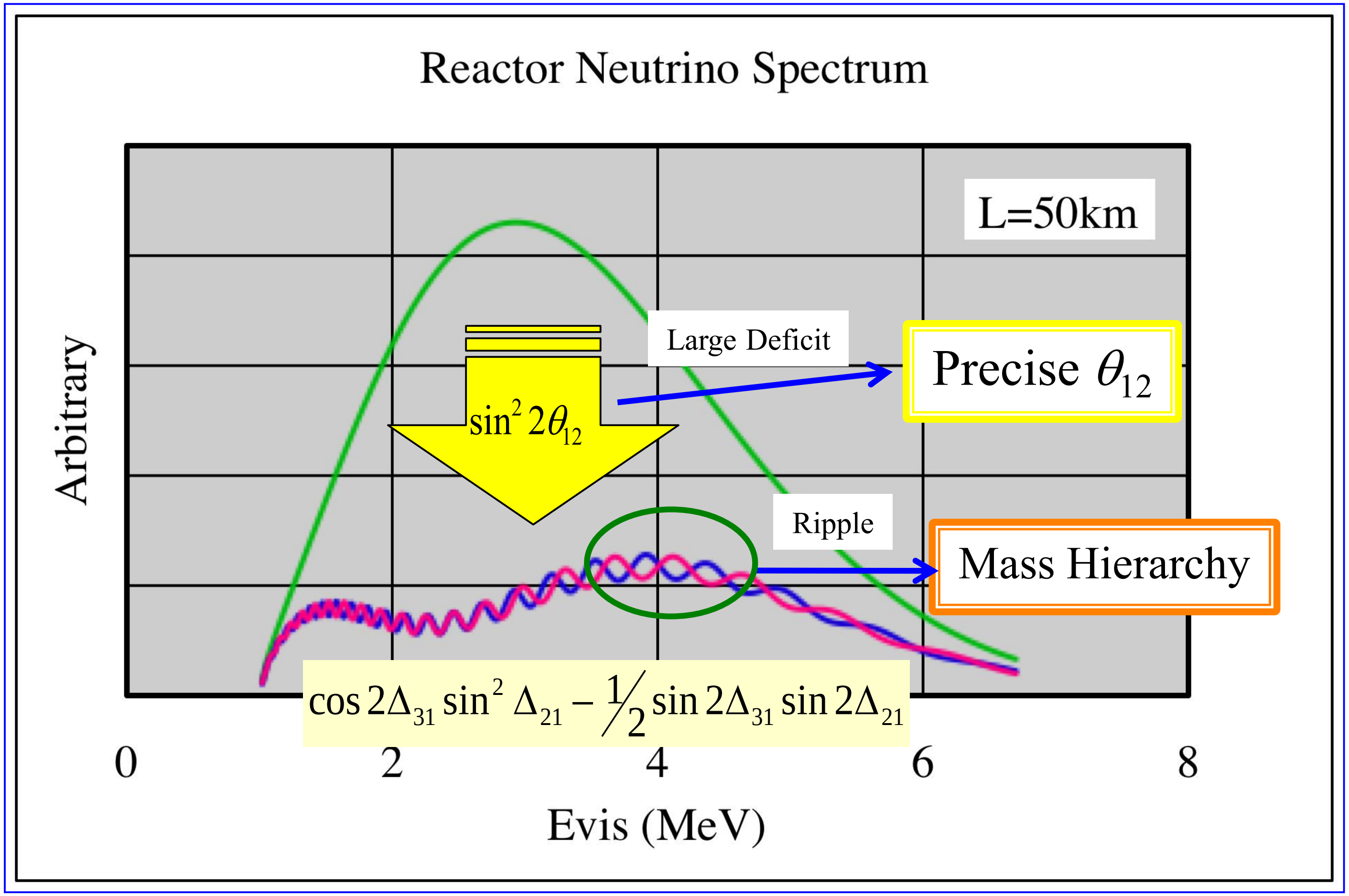
Physics with RENO-50

- Search for neutrinoless double beta decay



1^{st} Δm^2_{21} Maximum (L~50km) ;
mass hierarchy + precise value of θ_{12}, Δm^2_{21} & Δm^2_{31}

$$P_R(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \left\{ \begin{array}{l} \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21} \\ +\sin^2 2\theta_{13}\sin^2\theta_{12}\left(\cos 2\Delta_{31}\sin^2\Delta_{21} - \frac{1}{2}\sin 2\Delta_{31}\sin 2\Delta_{21}\right) \end{array} \right\}$$



Summary of Final Data Sample

(Prompt energy < 10 MeV)

Detector	Near	Far
Selected events	279787	30211
Total background rate (per day)	20.48± 2.13	4.89± 0.60
IBD rate after background subtraction (per day)	737.69± 2.58	70.13± 0.75
DAQ Live time (days)	369.03	402.69
Detection efficiency (ϵ)	62.0± 0.014	71.4± 0.014
Accidental rate (per day)	3.61± 0.05	0.60± 0.03
^{9}Li/^{8}He rate (per day)	13.73± 2.13	3.61± 0.60
Fast neutron rate (per day)	3.14± 0.09	0.68± 0.04

RENO ν θ_{13}

Analysis Results

Rate Only $\sin^2 2\theta_{13} = 0.087 \pm 0.009(\text{stat.}) \pm 0.007(\text{syst.})$ $\pm\ 0.011(\text{total})$

Rate + Shape (submitted in PRL)

$\left|\Delta m^2_{ee}\right| = 2.62^{+0.21}_{-0.23}(\text{stat.})^{+0.12}_{-0.13}(\text{syst.})\ (\times\ 10^{-3} eV^2)$ $\pm\ 0.26\ (\text{total})$ 10 % precision

$\sin^2 2\theta_{13} = 0.082 \pm 0.009(\text{stat.}) \pm 0.006(\text{syst.})$ $\pm\ 0.010(\text{total})$ 13 % precision

DC (latest) $\sin^2 2\theta_{13} = 0.111 \pm 0.018(\text{stat.} + \text{syst.})$