T2HKK/KNO, ESSnuSB, and THEIA

Hyunsoo Kim
Sejong University

Neutrino 2022 virtual Seoul

What is happening now?

Major issues in long baseline neutrino physics

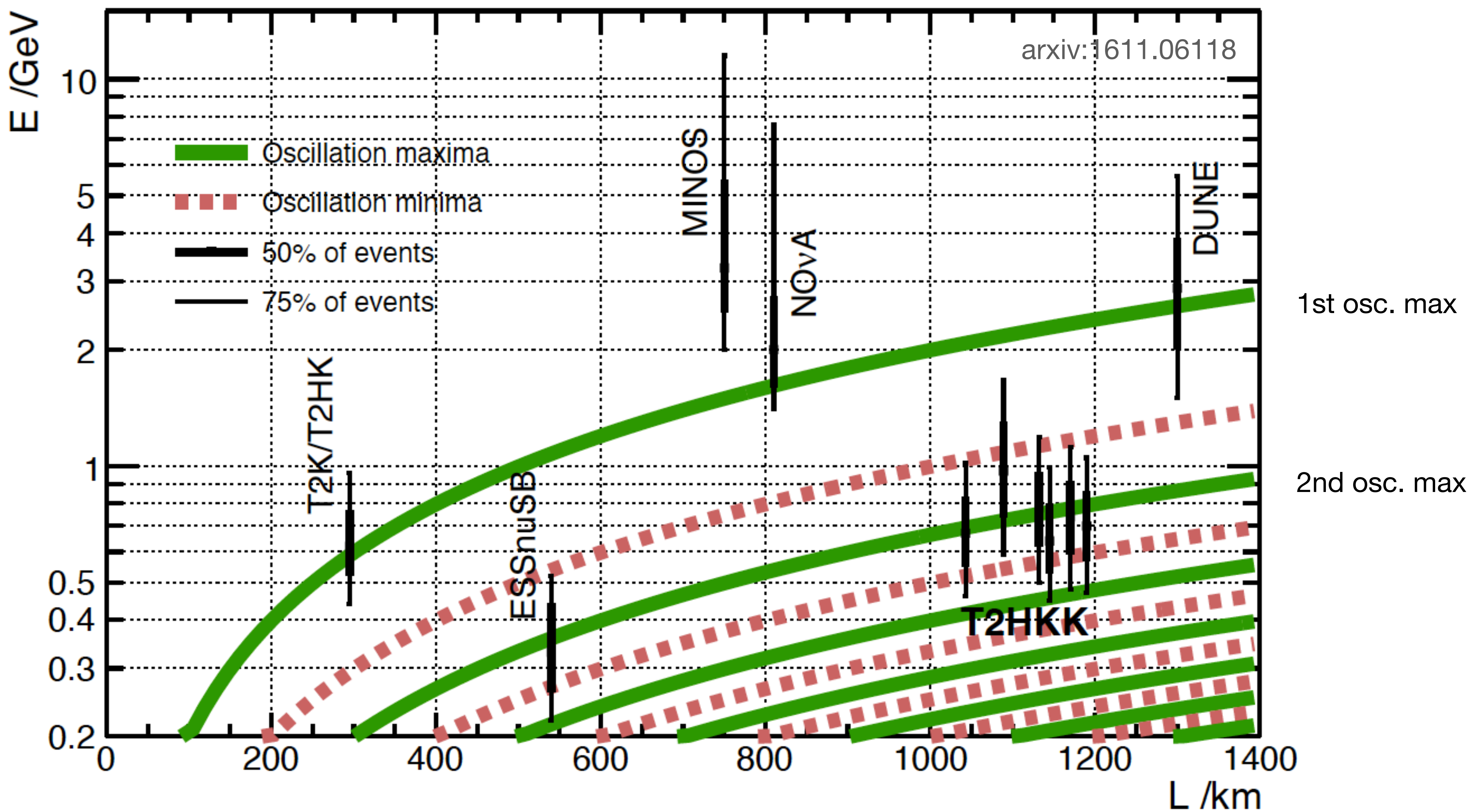
- Neutrino mass ordering
- CP violation in leptonic sector
- Sterile neutrinos?
- … and precision measurements of all oscillation parameters

Experimental environment

- T2K and NOvA experiments are taking data
- JUNO experiment starts soon
- DUNE and T2HK experiments are under construction

Future Neutrino Beam Experiments for $\delta_{\rm CP}$

- To obtain $\delta_{\rm CP}$, measure $P(\nu_\mu \to \nu_e)$ and $P(\bar{\nu}_\mu \to \bar{\nu}_e)$



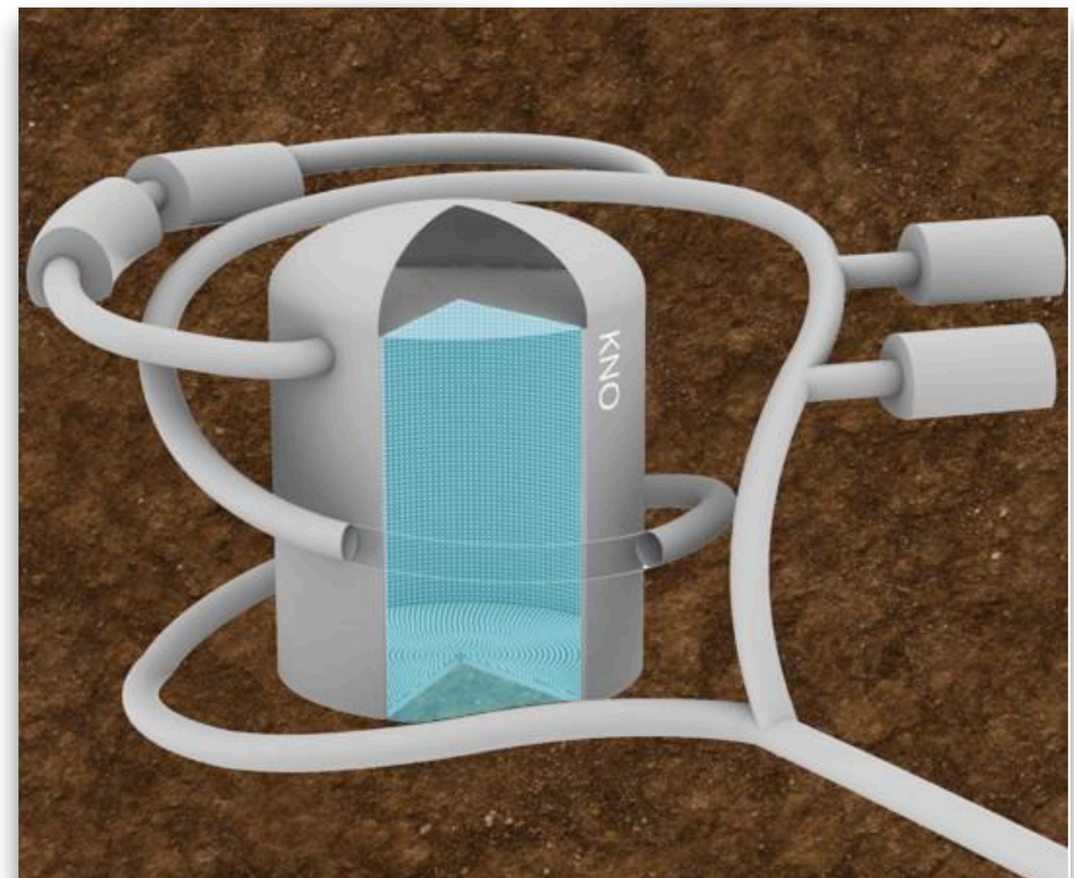
KNO (T2HKK)

Korean Neutrino Observatory
(Tokai to Hyper-K detector in Korea)

KNO Overview

KNO is a proposal to build a large scale neutrino detector in Korea to act as a neutrino telescope and second detector to T2HK

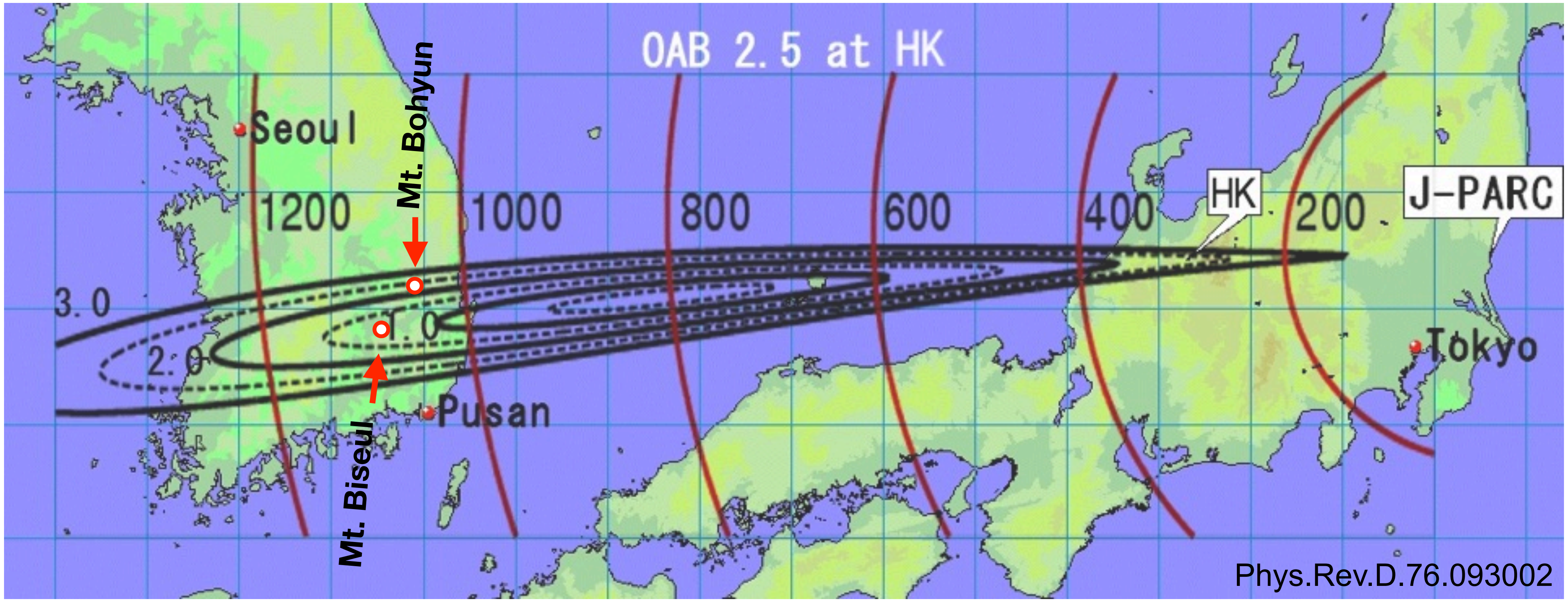
- Water Cherenkov detector
  - 260~500 kton
  - cylindrical shape
  - 40% photo sensor coverage
- Development of photosensors, water purification system, DAQ electronics, and event reconstruction software
- 60 collaborators from 10 institutions
- Main physics goals
  - Precision CP violation measurement
  - Proton decay search
  - Astrophysics



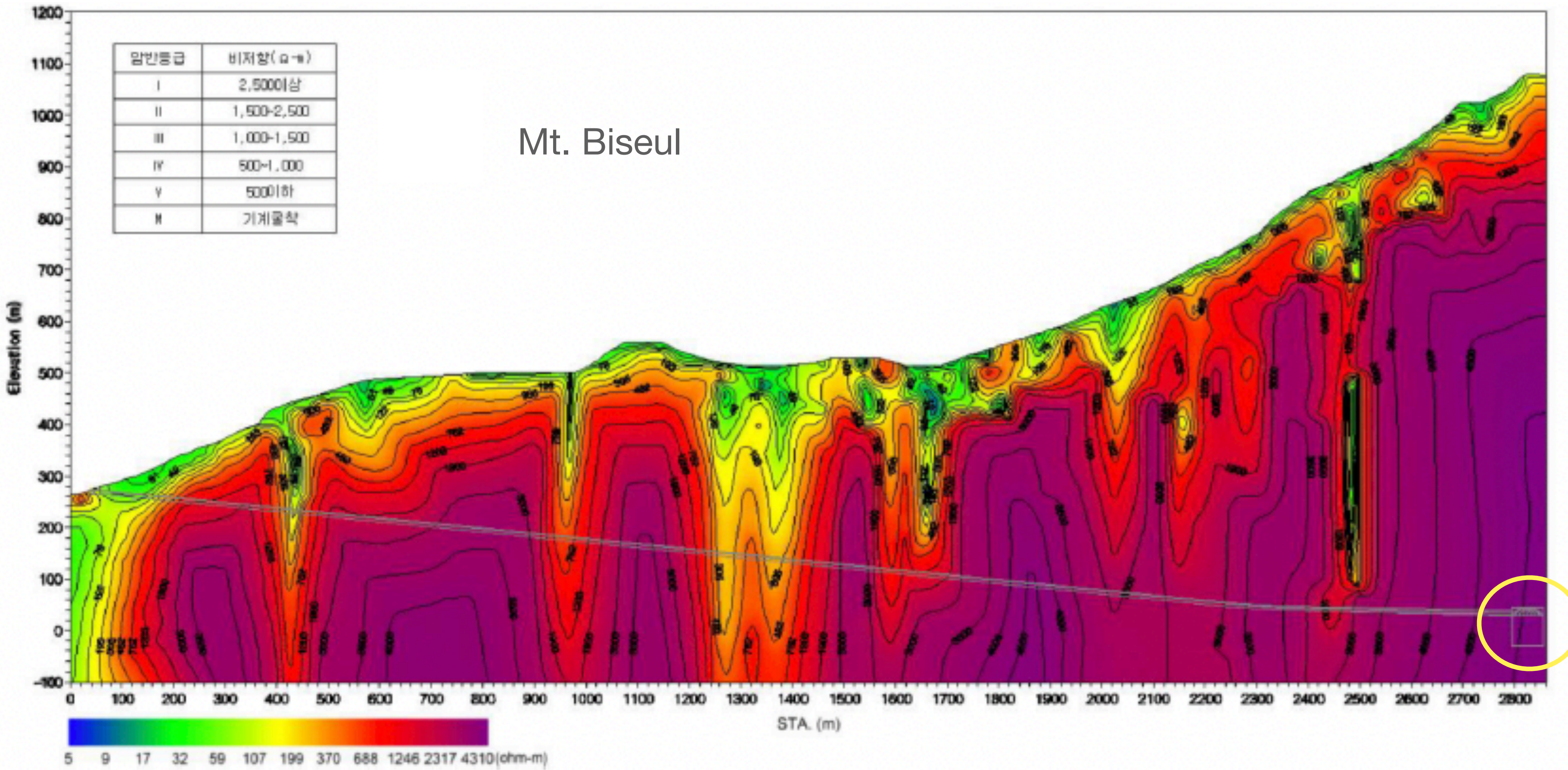
KNO Candidate Locations

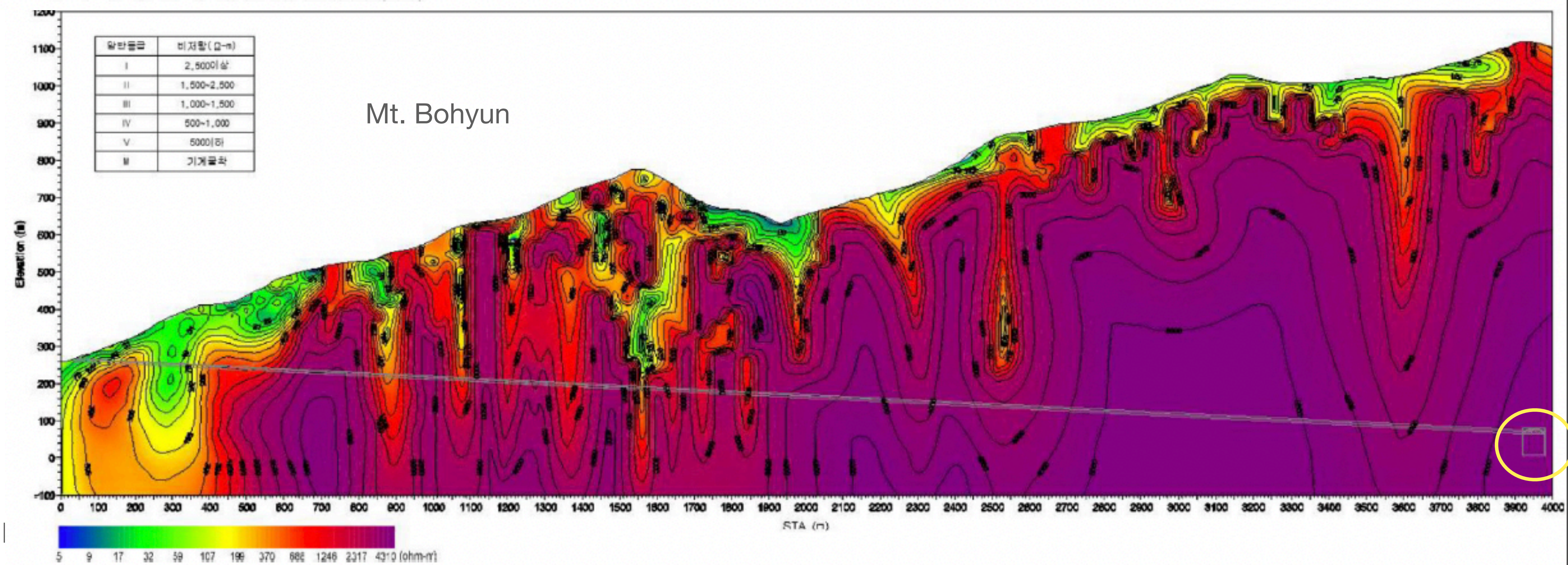
- Geological surveys done on six locations
- Two favoured candidate locations:

	Baseline (km)	Height (m)	Off-axis Angle	Rock Composition
Mt. Biseul	1088	1084	1.3^o	Granite porphyry, andesitic breccia
Mt. Bohyun	1042	1124	2.3^o	Granite, volcanic rocks, volcanic breccia



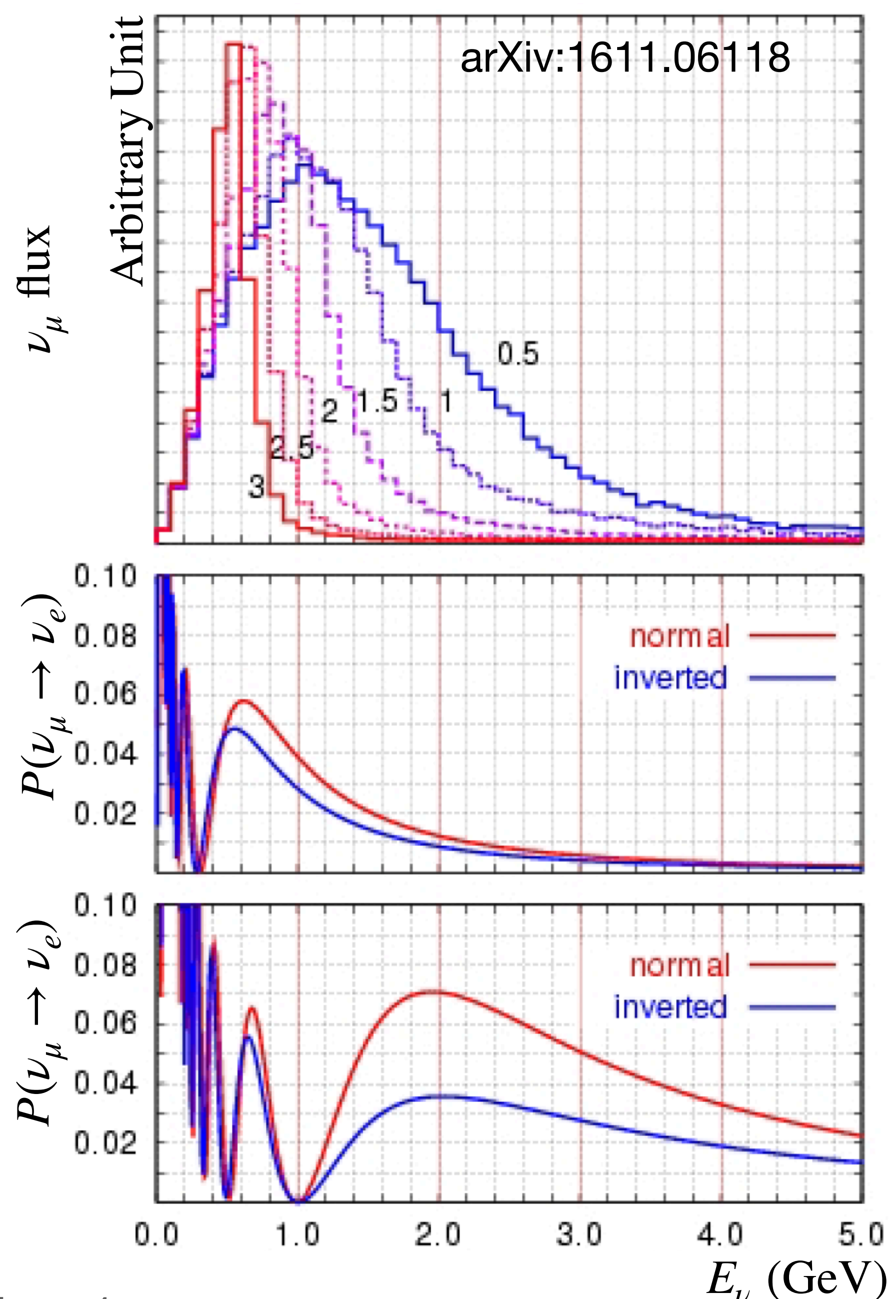
Survey of Candidate Sites





Neutrino Beam

- The J-PARC delivers neutrino beam to T2K
- The beam line will be upgraded over to 1.3MW beam power.
- HK is at a 2.5^{o} off axis from the beam centre.



Off-axis beam energy profile

@SK
L=300 km→1st oscillation max

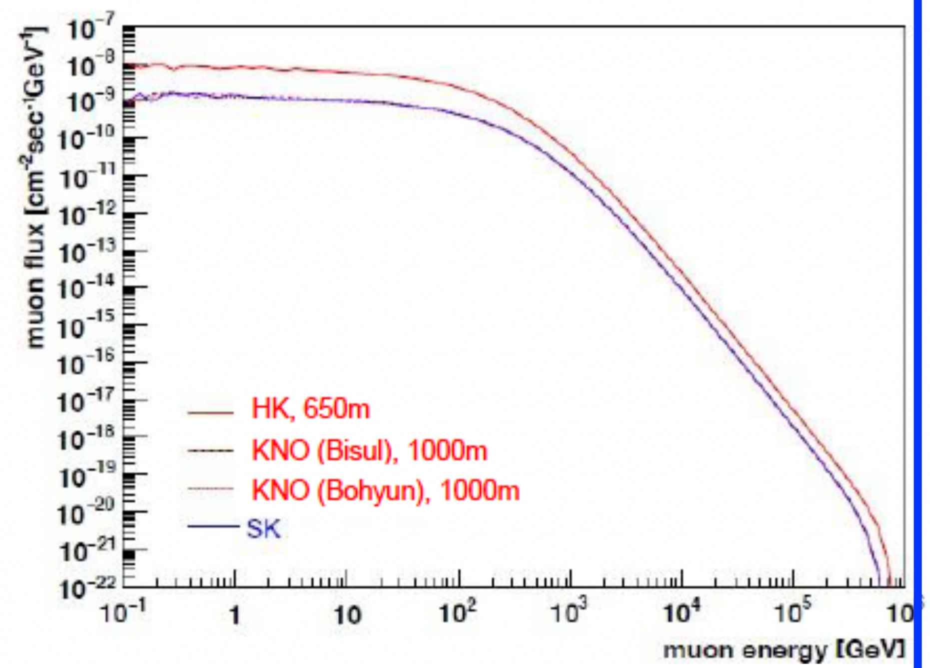
@Korean sites
L=1100 km→1st & 2nd oscillation max

Why a Detector in Korea?

The same physics programme as the Hyper-Kamiokande.

Pros

- Longer baseline (~1100 km) neutrino beam for KNO →1st and 2nd oscillation maxima
  - More sensitivity to leptonic CP violation (δ_{CP}) and mass ordering
  - Better for probing non-standard neutrino interaction
- Larger overburden than HK (~1000 m vs 650 m)
  - 5 times smaller muon flux
  - Smaller cosmogenic backgrounds
  - Better sensitivity to astrophysical neutrinos



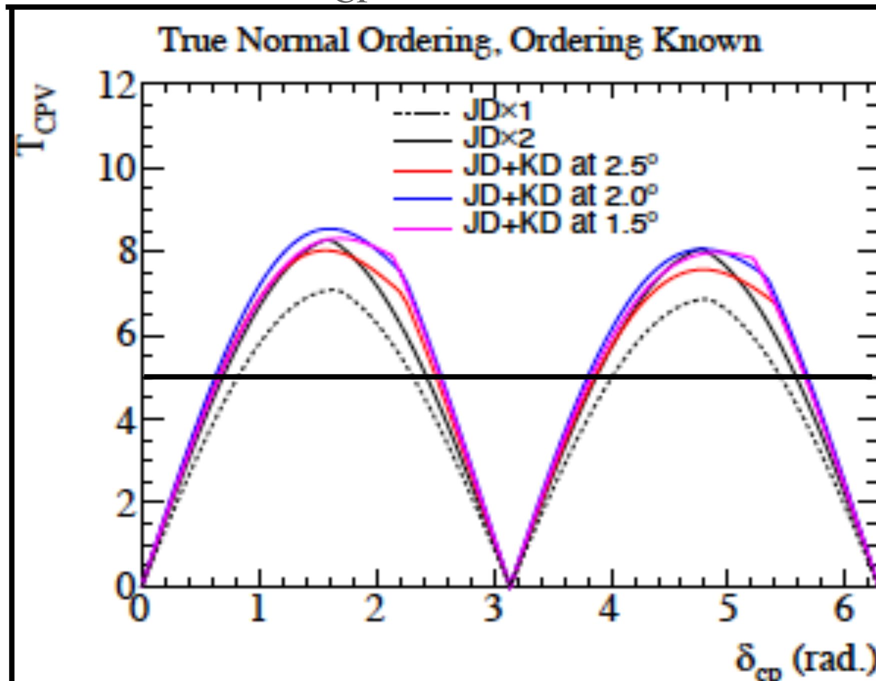
Cons

- 10 times lower neutrino beam flux than HK due to longer baseline

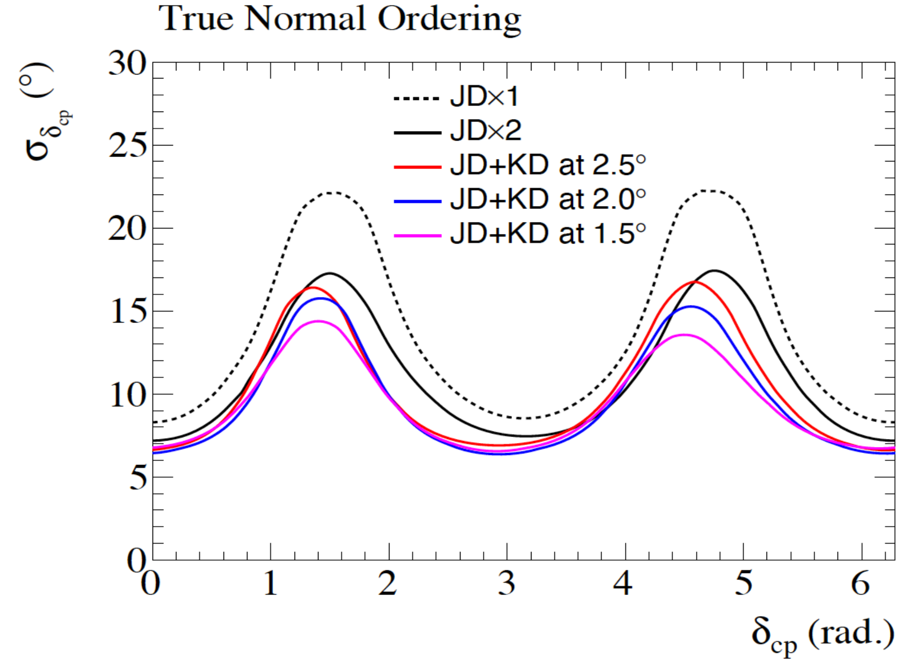
Sensitivities

Baseline 1100 km
Beam exposure 10 yrs
260 kton

δ_{CP} significance

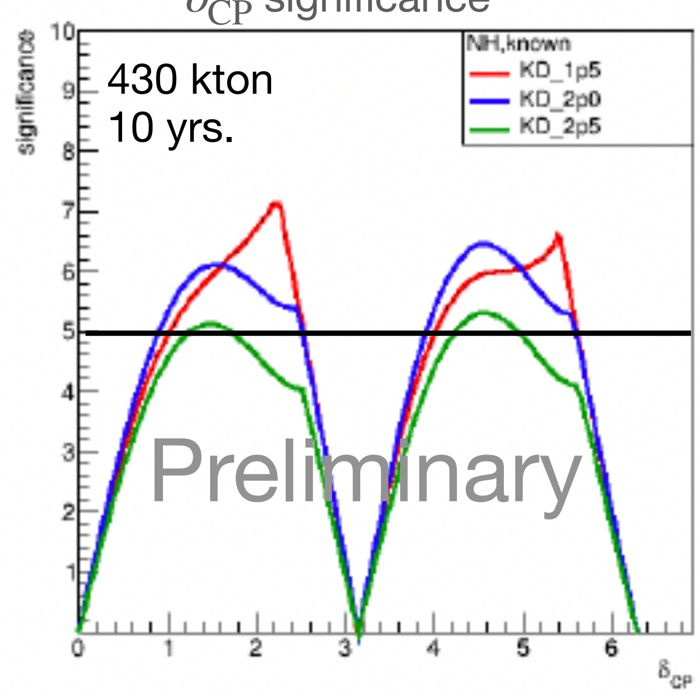


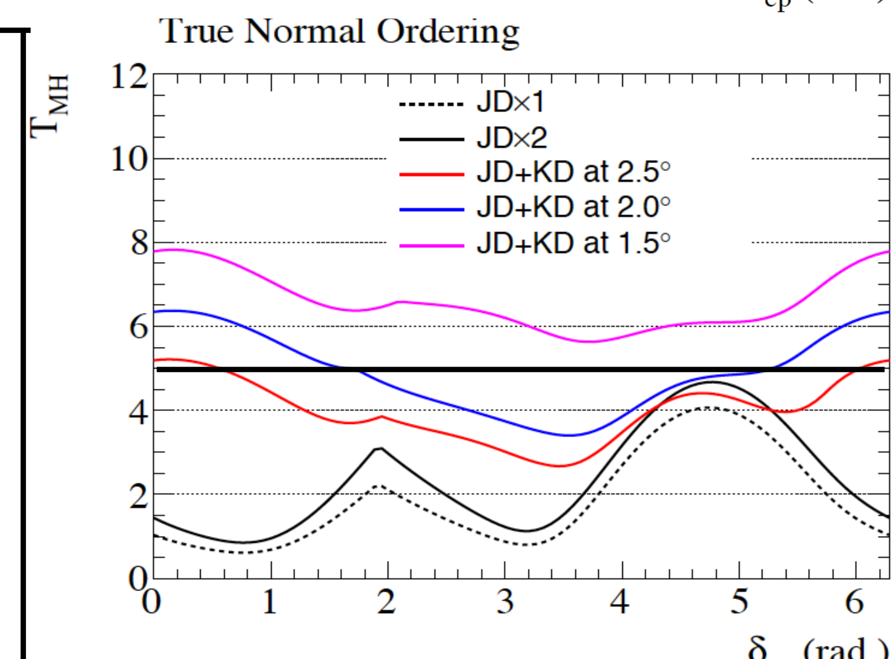
δ_{CP} precision



Very conservative systematics

δ_{CP} significance





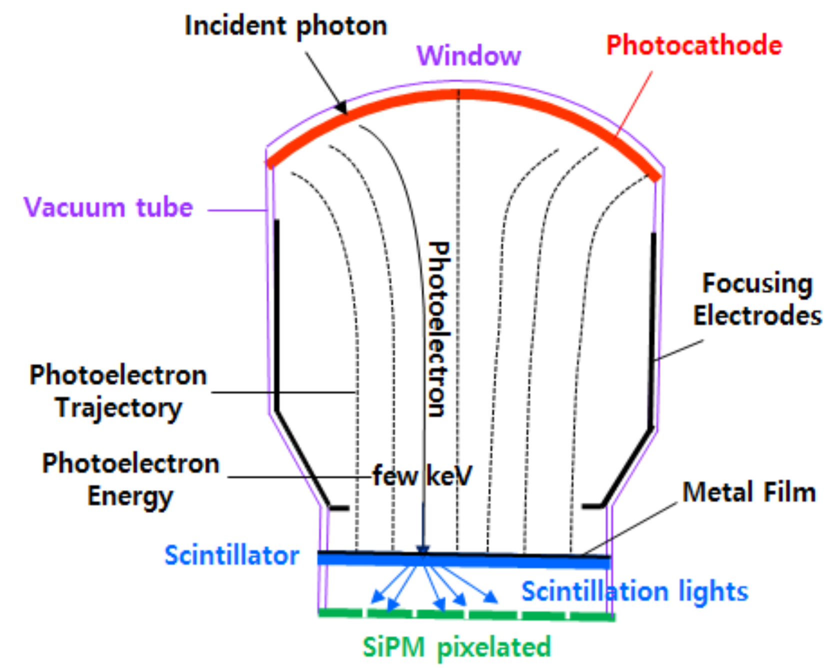
mass ordering significance

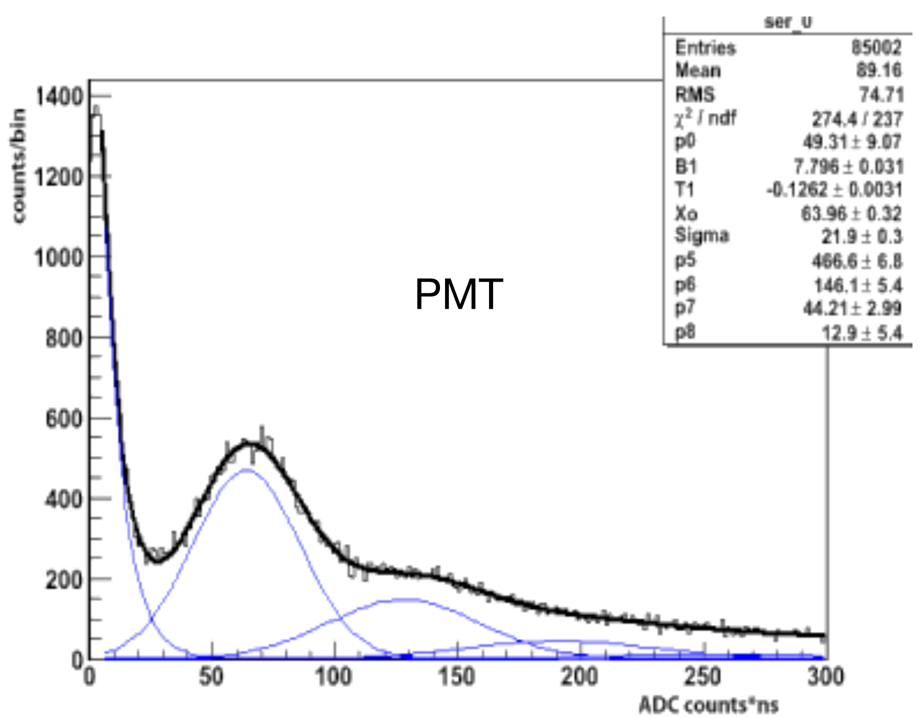
arxiv:1611.06118

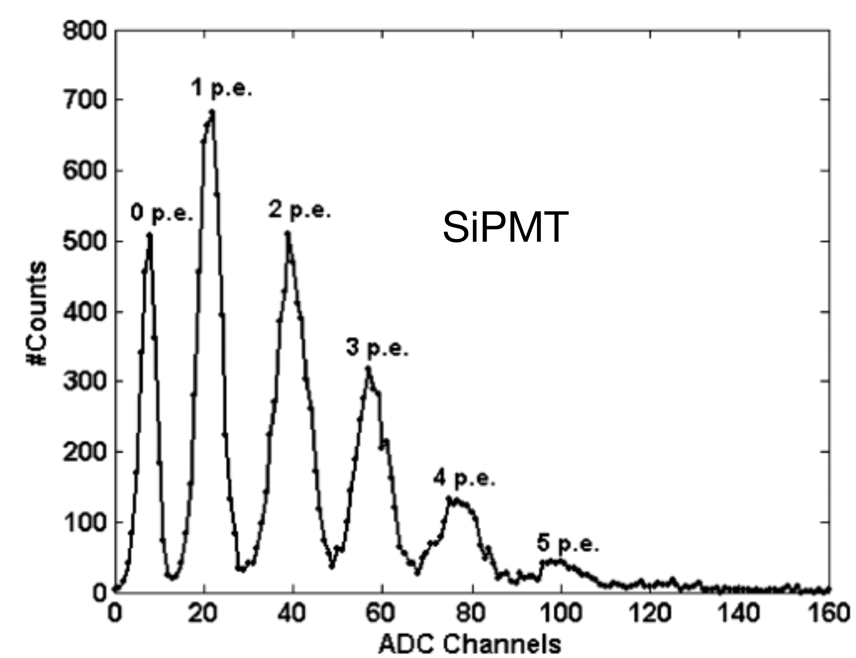
Hardware Development

Development of a new type of hybrid photodetector SiPMT: Photocathode+Scintillator+SiPM

- Total amplification: $\sim 2 \times 10^7$
- Fast response time: a few ns
- Simple internal structure (no dynodes): lower cost







ESSnuSB

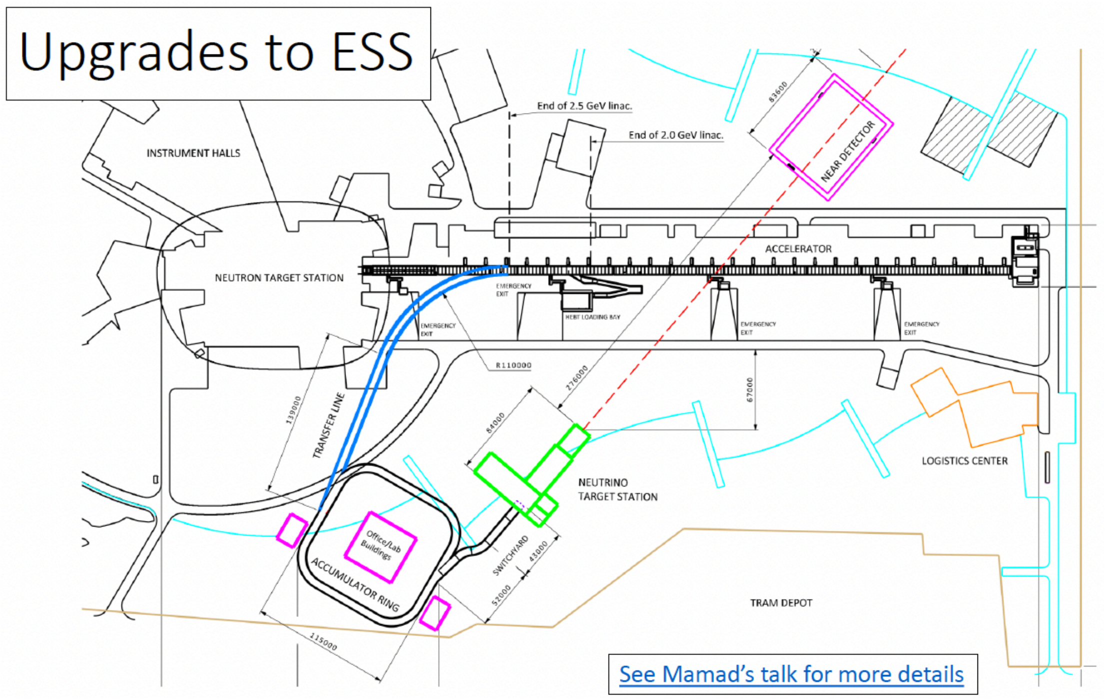
European Spallation Source Neutrino Super Beam

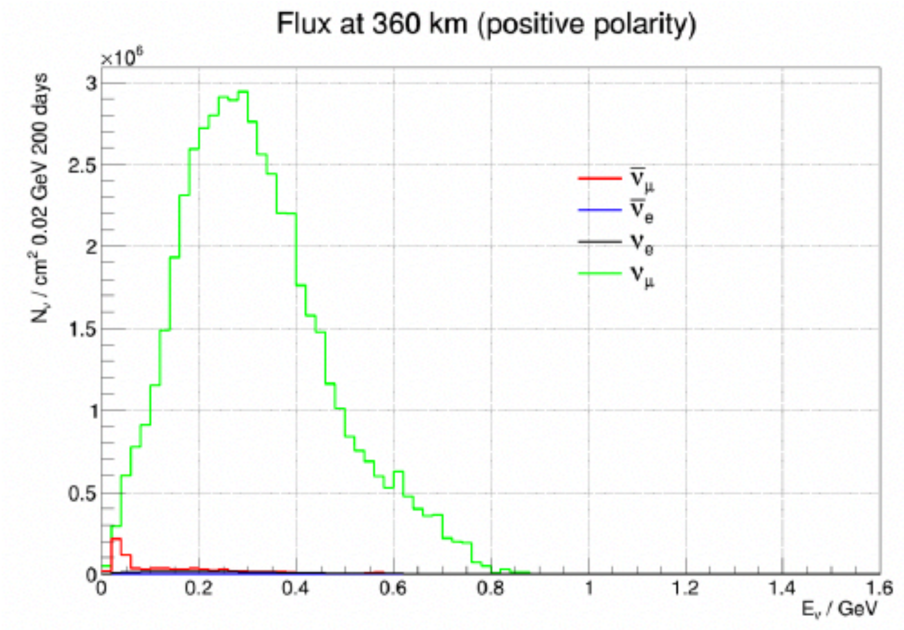
ESSnuSB Overview

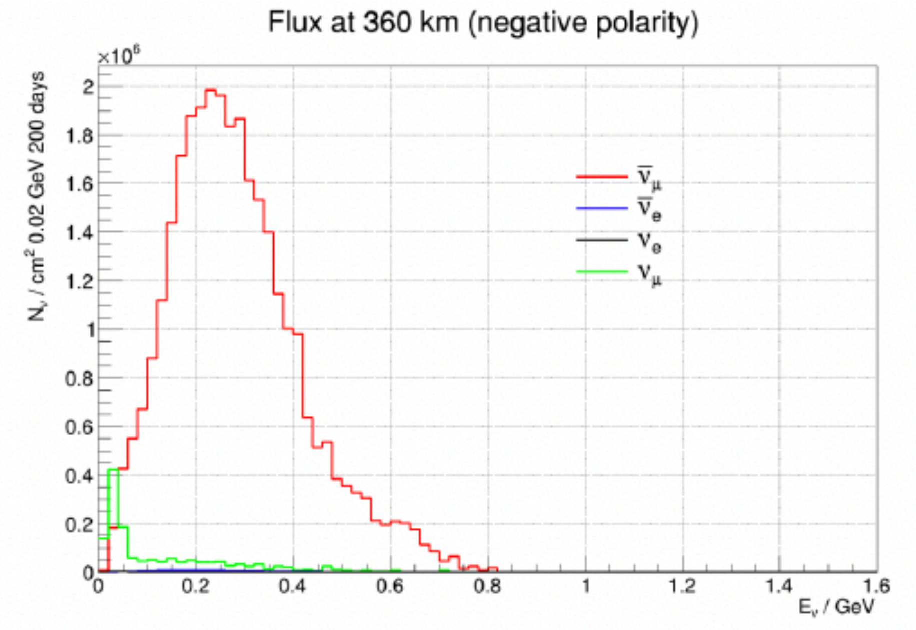
- ESSnuSB is a design study project financed by the European Commission for measuring δ_{CP} with high precision
- Take advantage of ESS neutron beam facility being constructed in Lund, Sweden.
- 55 collaborators from 15 institutions

ESSnuSB Neutrino Beam

- 5 MW average beam power
- Upgrade ESS
  - Upgrade the linac to accelerate H- instead of proton
  - Build an accumulator ring
  - ν-target station
- neutrino beam with mean energy of ~0.3 GeV







Far Detector Sites

Two favoured sites

- Zinkgruvan mine @360 km

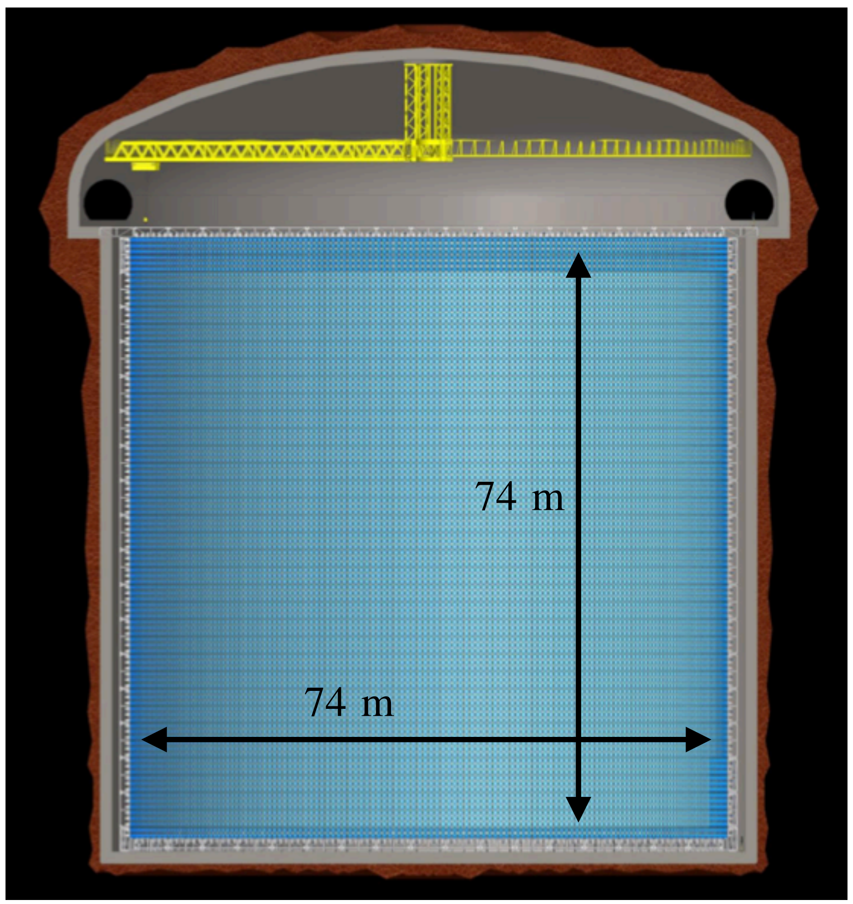
  Partly covering first and second osc. maxima

- Garpenberg mine@540 km

  Second osc. maximum

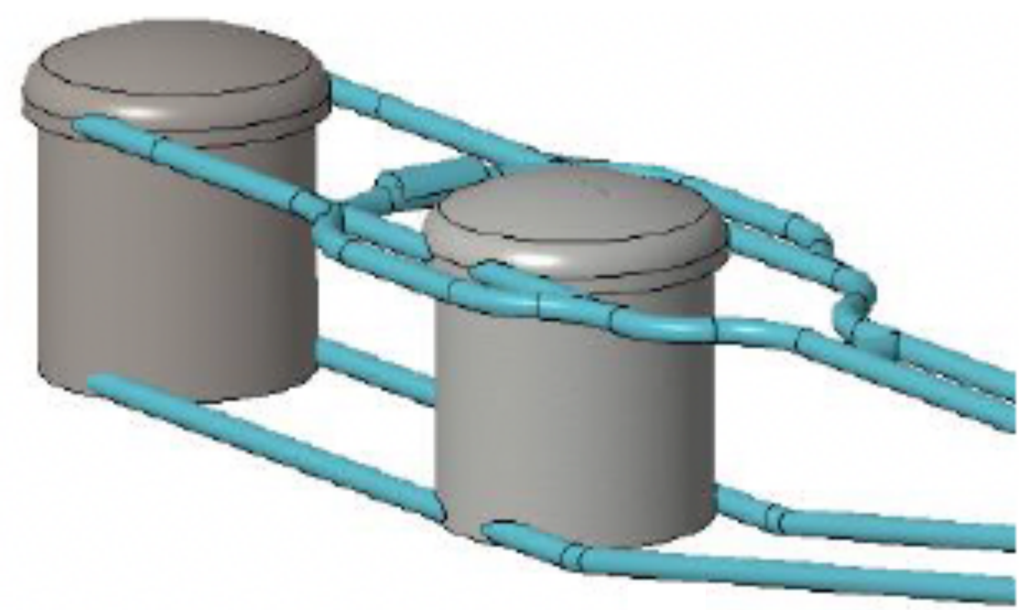
https://essnusb.eu/wp-content/uploads/2020/06/Visit-Zingruvan-Mine-March-2019-n3-optimised-768x1024.jpg

Far Detectors



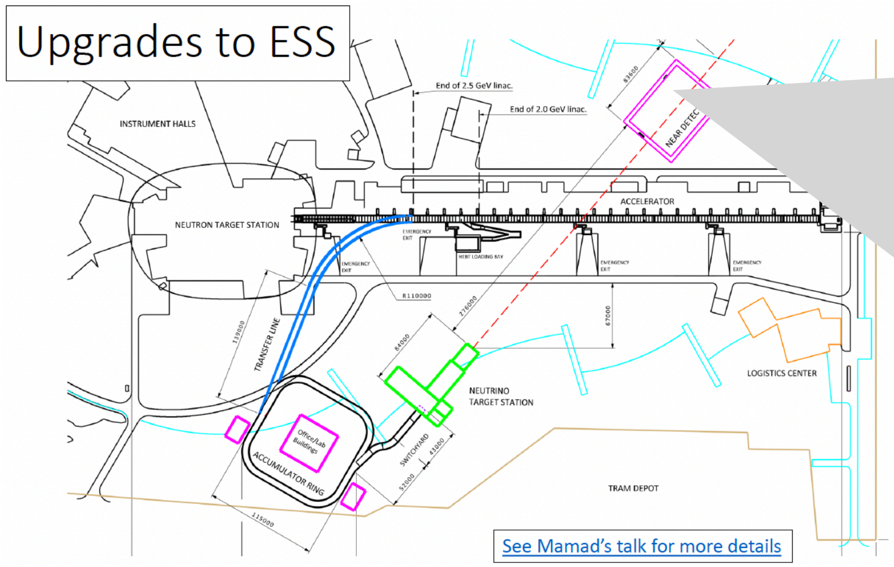
- Two identical cylindrical shape water Cherenkov detectors
- 2 x 320 kton ultra pure water

  (2 x 270 kton fiducial volume)
- 50k 20" PMTs per detector (40% optical coverage)
- 1500 m overburden

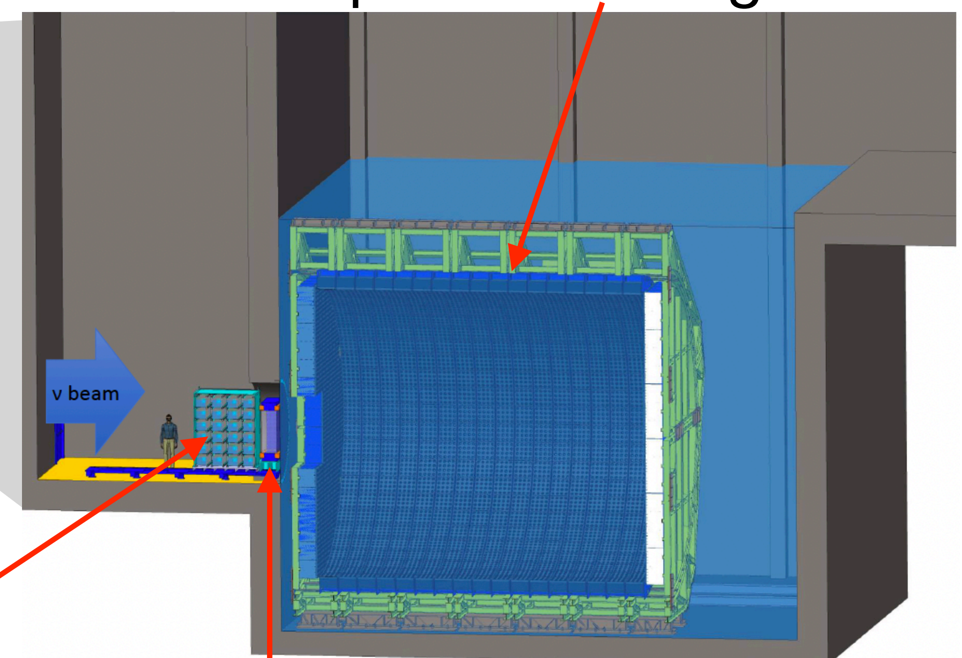


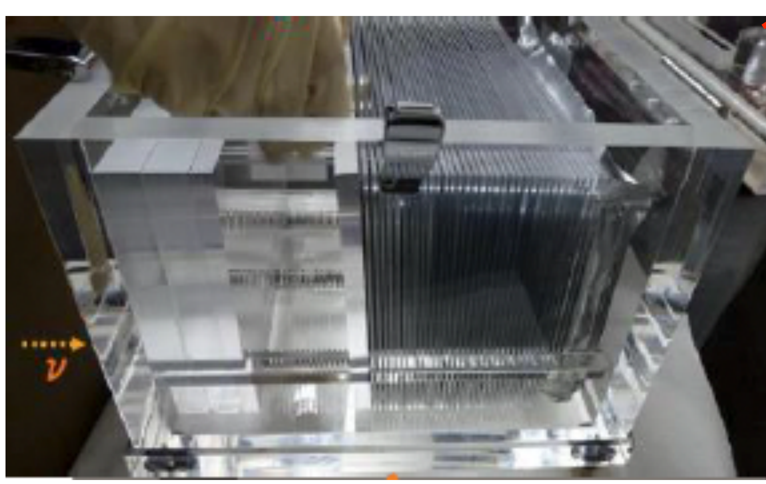
Near Detectors

- Near Detectors @250 m

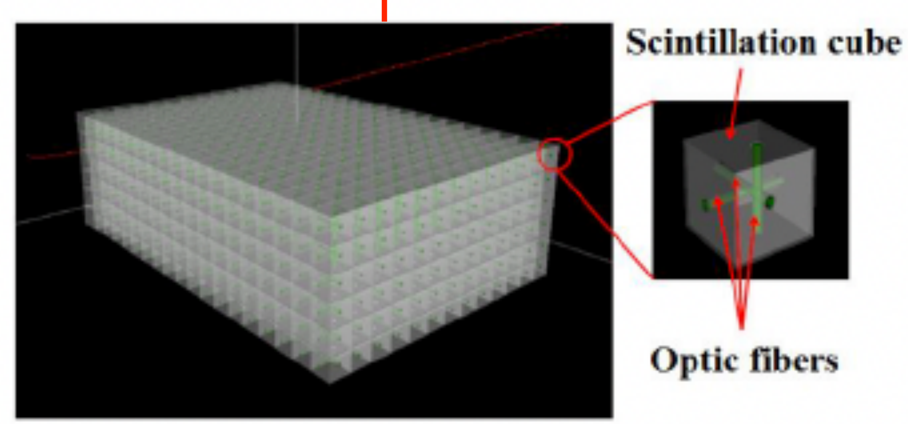


water Cherenkov detector:
0.77 kt fiducial volume: 30% photo coverage





water-emulsion detector
(1 ton fiducial volume)

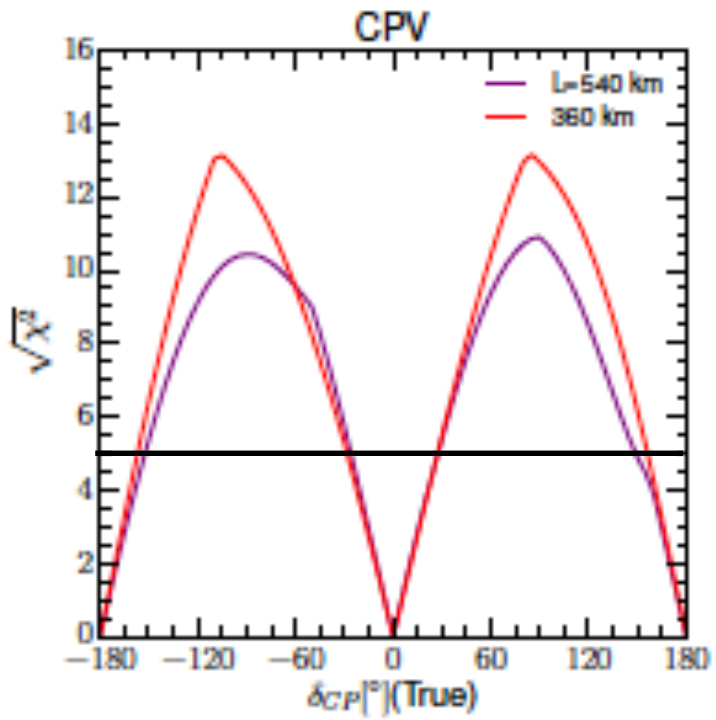


Scintillator tracker

Sensitivities

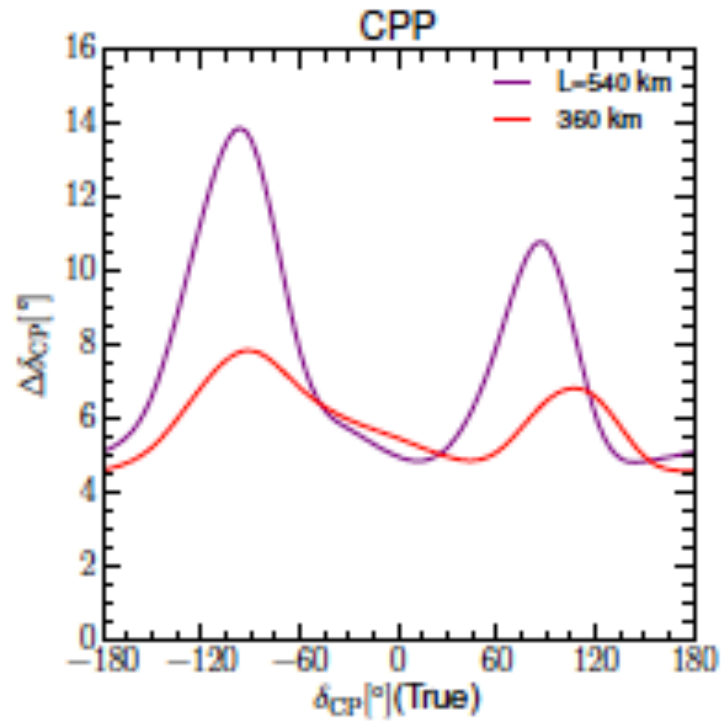
10 year beam exposure

δ_{CP} significance



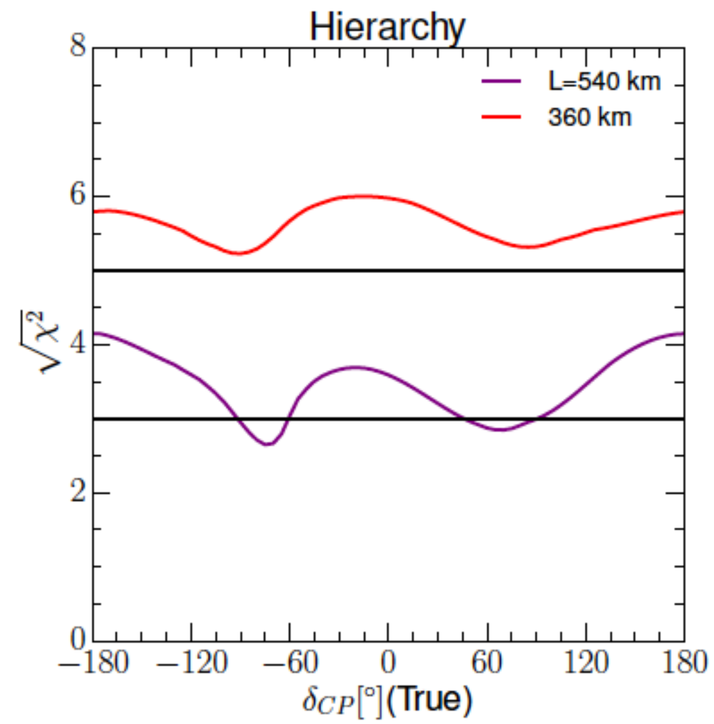
~70% region of δ_{CP} can be measured at 5σ

δ_{CP} precision



<8º (14º)

mass ordering significance



Eur.Phys.J.C81 (2021) 12, 1130

ESSnuSB Roadmap

2012: inception of the project

Nucl. Phys. B 885 (2014) 127

2016-2019: beginning of COST Action EuroNuNet

COST – EUROPEAN COOPERATION IN SCIENCE AND TECHNOLOGY

2018: beginning of ESSvSB Design Study (EU-H2020)

ESSνSB – ESS NEUTRINO SUPER BEAM

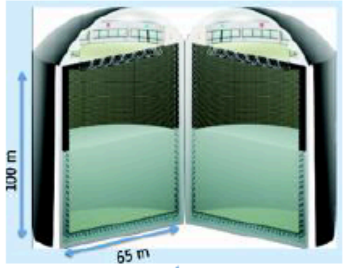
Eu. Phys. J. C 81, (2021) 1130

2021: End of ESSvSB Design Study, CDR and preliminary costing

ESFRI

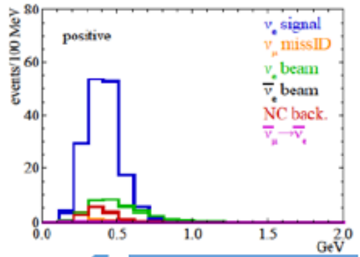
2022-2025: Preparatory Phase, TDR

2025-2028: Preconstruction Phase, International Agreement



EUROPEAN SPALLATION SOURCE

2028-2034: Construction of the facility and detectors, including commissioning



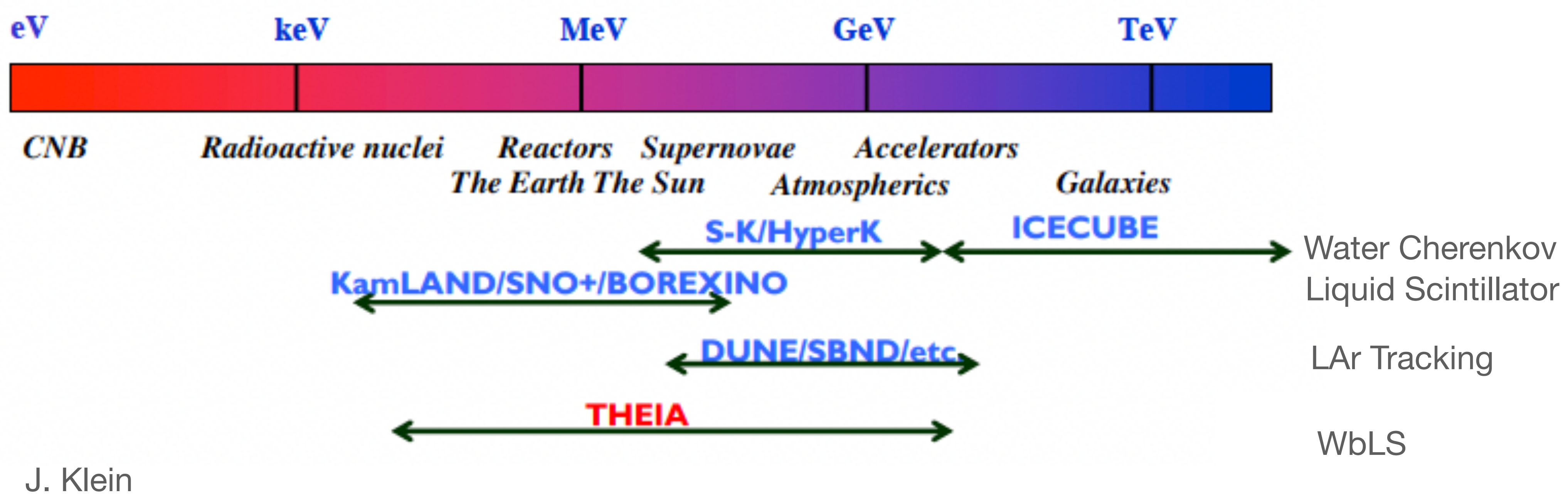
2035-: Data taking

Tamer Tolba @Lepton-Photon 2021

THEIA

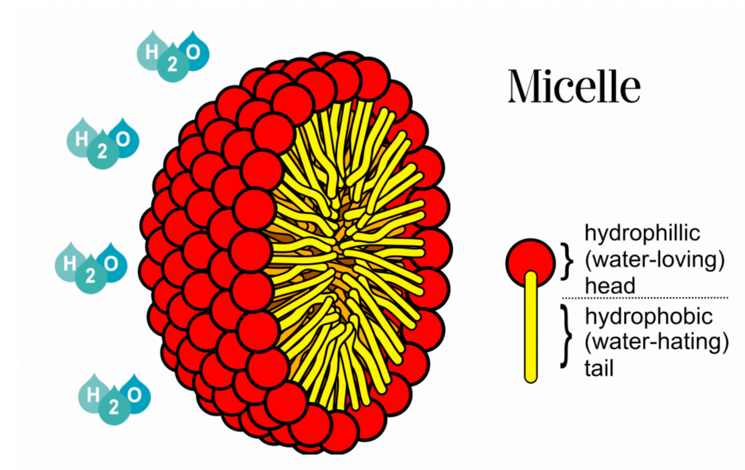
Overview

- THEIA is a proposed large scale Water-based Liquid Scintillator (WbLS) detector for broad range neutrino physics
- WbLS provides good energy resolution of scintillator detector and enables event direction reconstruction of Cherenkov detector
- Incorporates fast photon detector timing, high-efficiency photon detection, advanced reconstruction method, etc.
- 82 collaborators from 38 institutions



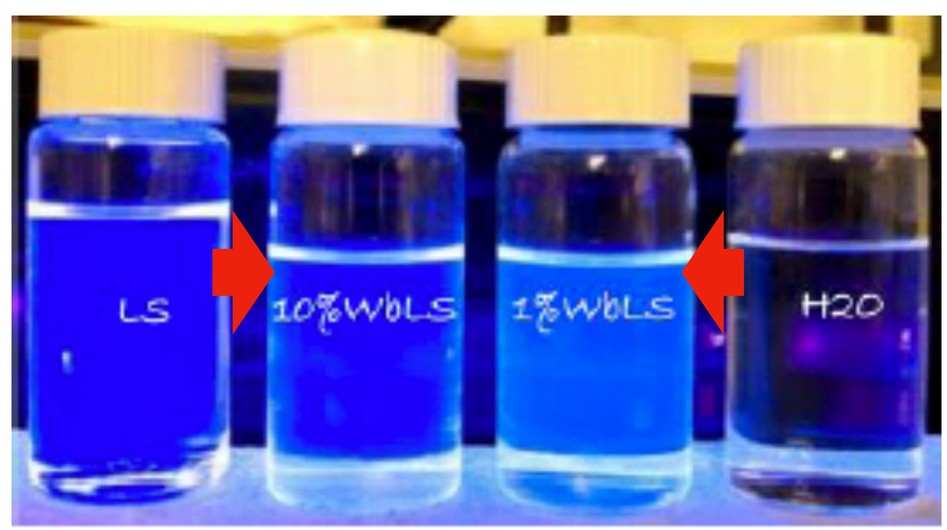
Water Based Liquid Scintillator

- Water-based liquid scintillator is a mixture of pure water and oil based liquid scintillator
- Mixture is possible using a surfactant to hold LS droplets in water
- Lower the LS concentrations
  - Reduces light yield
  - Increases transparency
- Successfully produced at BNL and JGU Mainz and BNL working on production of larger samples



https://svoboda.ucdavis.edu/application/files/3015/1639/8116/micelle.png

High Light Yield:
- good energy resolution
- low energy threshold

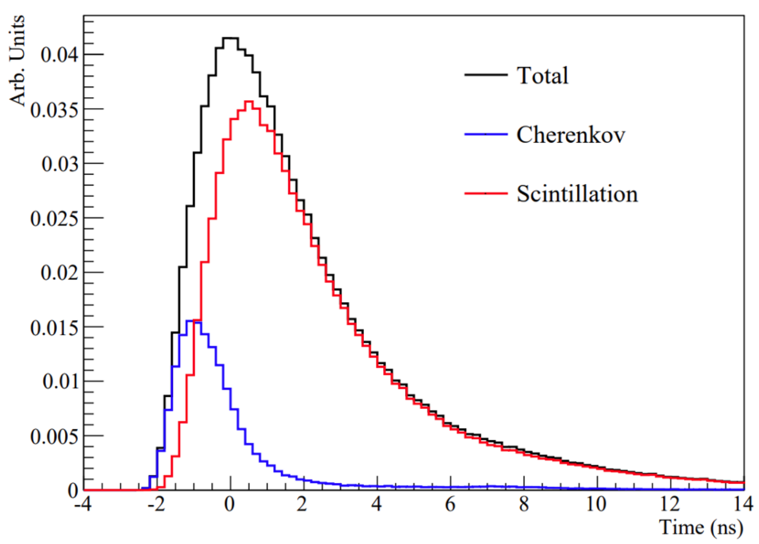


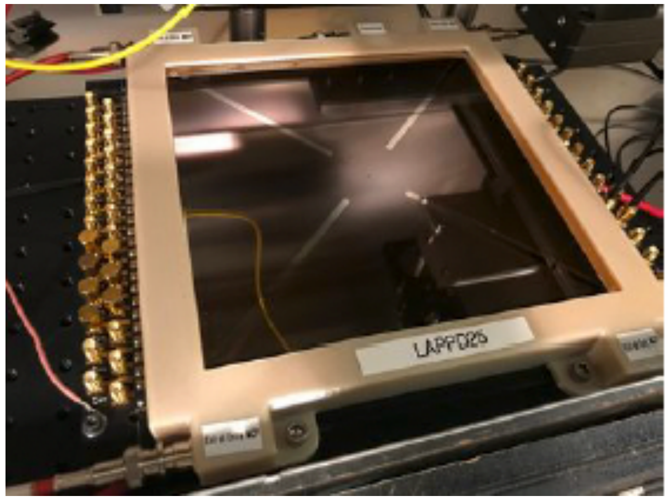
High transparency
Directionality
Particle ID

WbLS from Mifang Yeh (BNL)

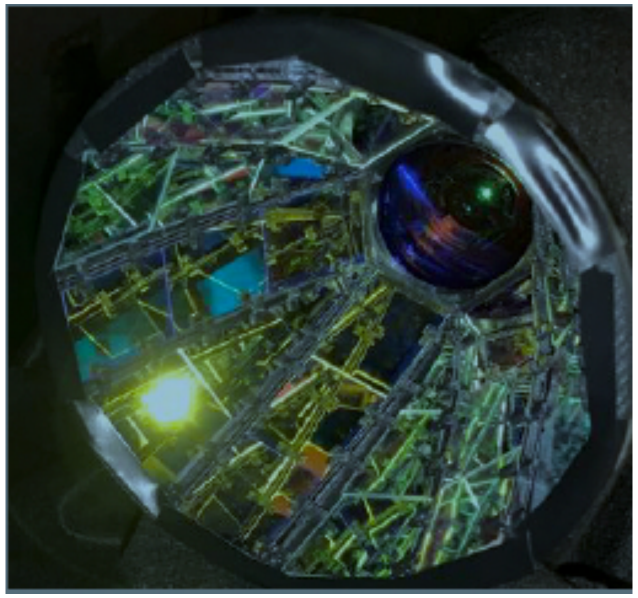
Separation of Cherenkov and Scintillation Photons

- To separate Cherenkov photons and scintillation photons
  - Fast sensors (PMT, LAPPD, SiPM)
  - Wavelength filter (dichroic filter)
  - Advanced reconstruction methods

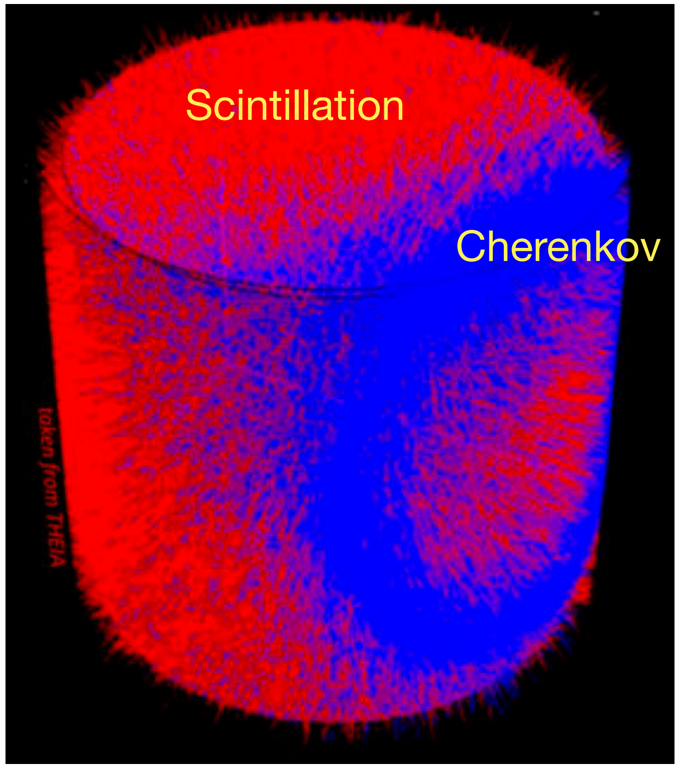




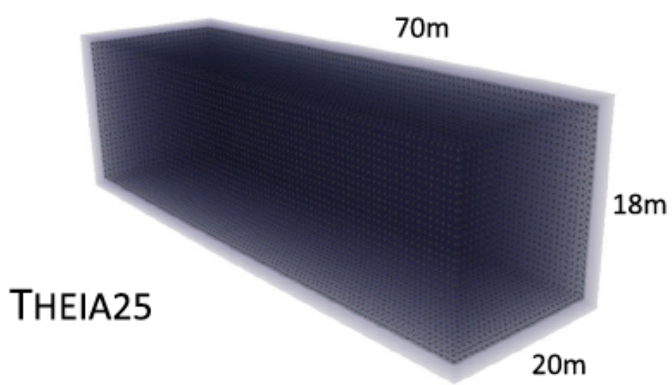
LAPPDs
(Large Area Picosecond
Photon Detectors)



Dichroicon



Detector Designs



- Baseline design: THEIA-25
  - 25 kton (17 kton FV)
  - 23k 10”PMTs and 700 8” LAPPDs
  - Designed to fit into DUNE detector caverns

- Ideal design: THEIA-100
  - 100 kton (70 kton FV)
- Size depends on physics and location, and maximum size limited by WbLS transparency

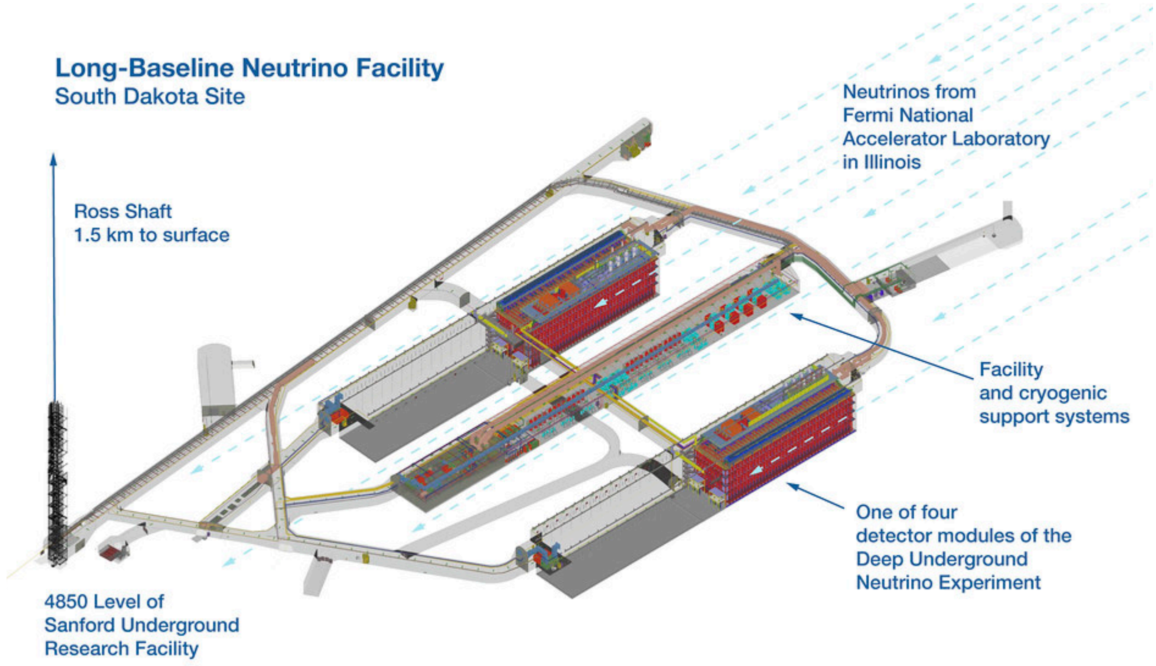
Eur. Phys. J. C (2020) 80:416

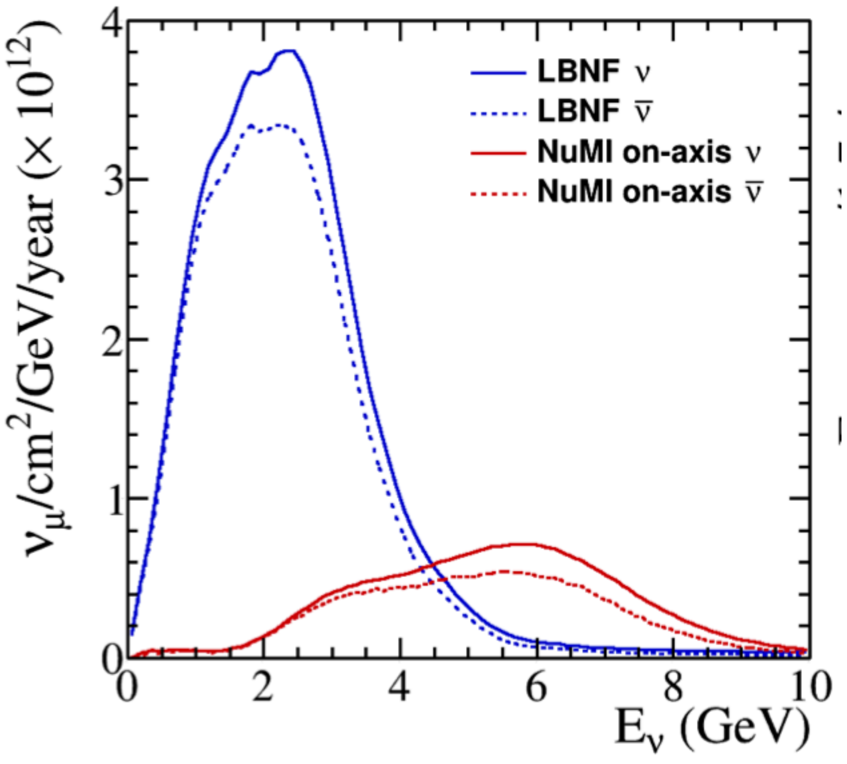
- Can be upgraded to a multi-ton scale $0\nu\beta\beta$ search with loaded LS in a suspended vessel

Location

- Any deep underground lab with neutrino beam
  - (Korea, SURF, etc)

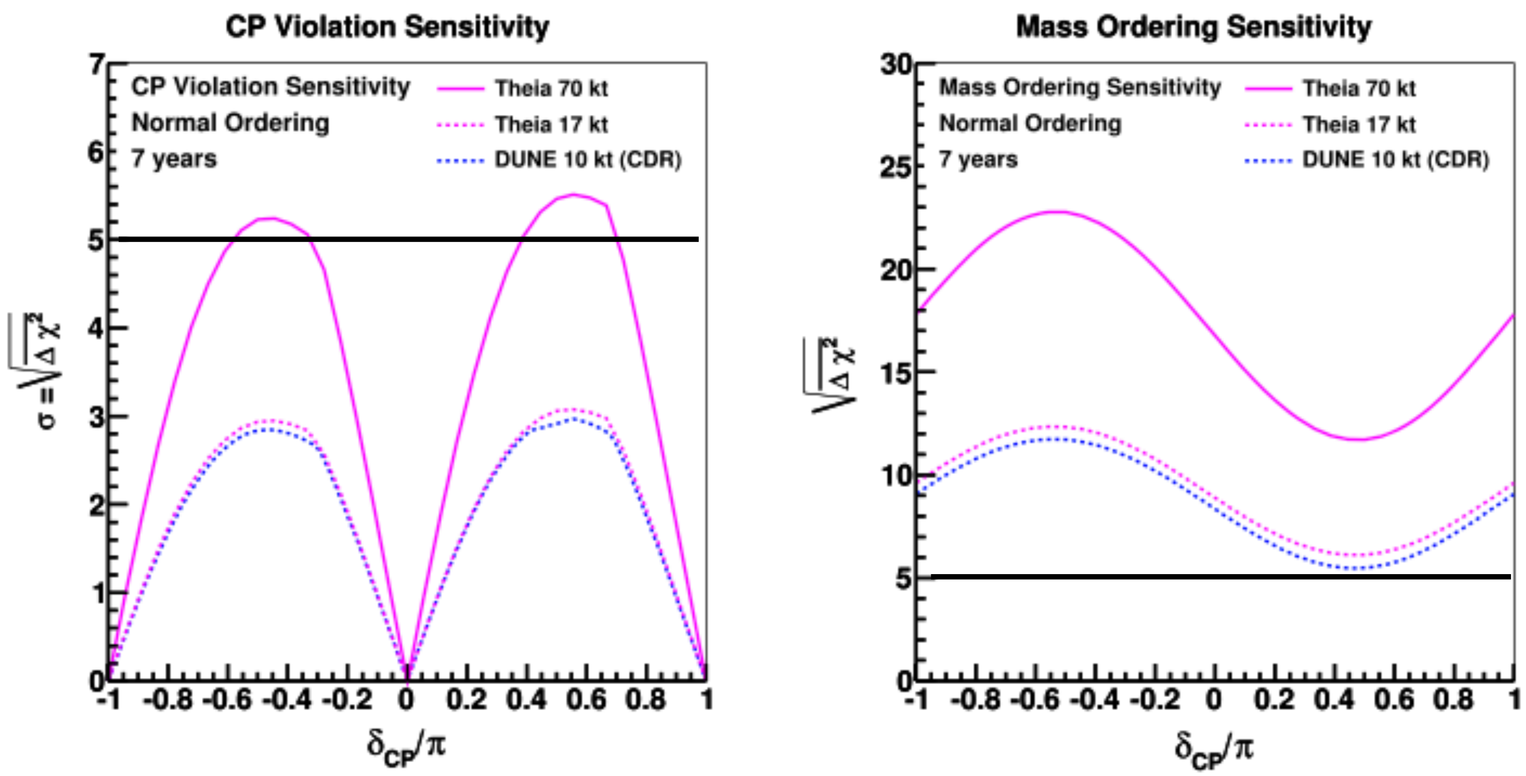
- Favoured site: SURF (DUNE)
  - Overburden 1500 m
  - Baseline 1300 km
- Beam source
  - LBNF
  - >1 MW
  - Neutrino peak at 2~3 GeV





Sensitivities

- Sensitivities calculated without the advantages of WbLS and fast timing.



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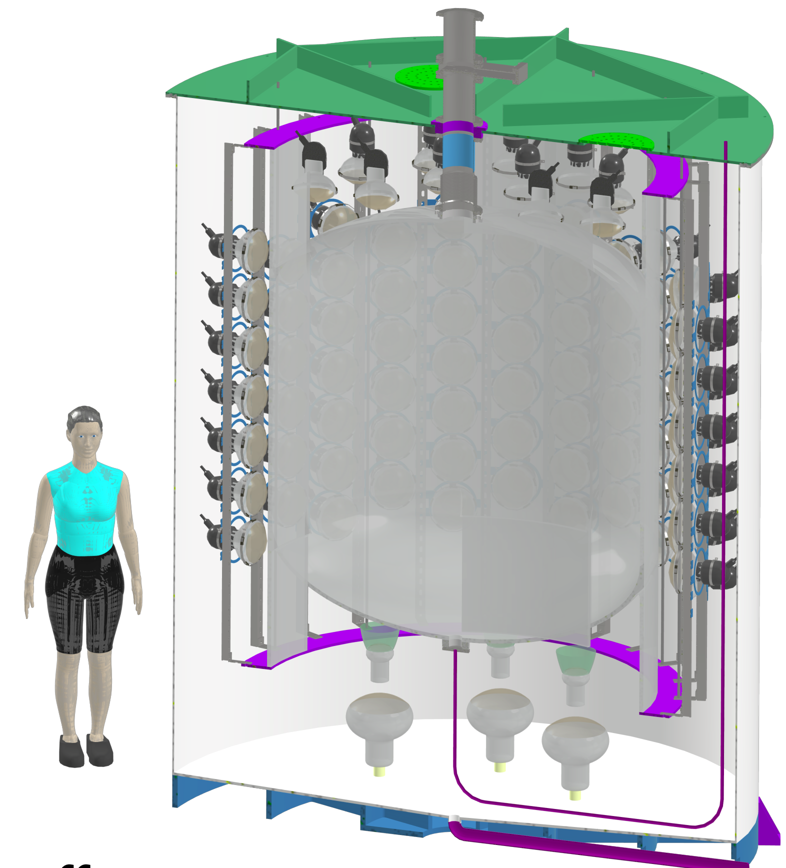
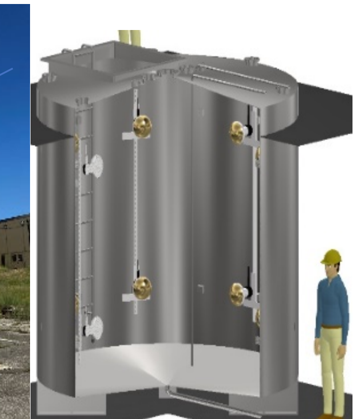
- THEIA-25 results are equivalent to one DUNE detector module
  - Different set of systematic uncertainties
  - Complementary to DUNE programme

THEIA Demonstrators

- Eos: To validate models to support large-scale detector performance predictions
- 4-ton target mass (water, WbLS, LS deployment)
- 200 8-” PMTs (R14688-100, 900ps FWHM)
- Dichroicon deployment for spectral sorting



- BNL-led effort to construct 30-ton tank for demonstration of WbLS production, transparency and stability



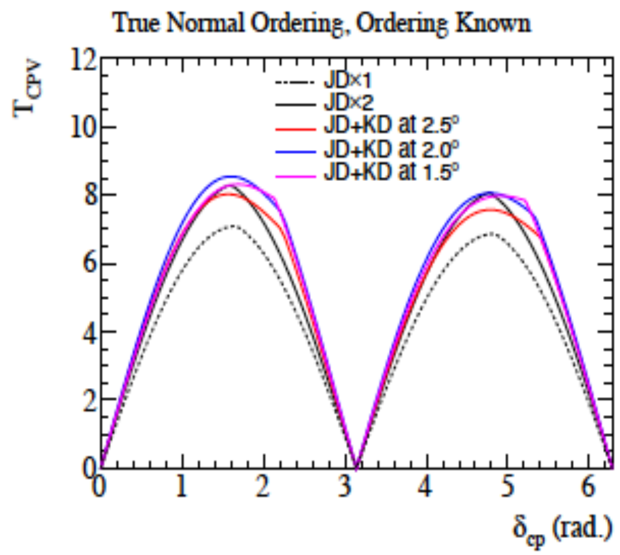
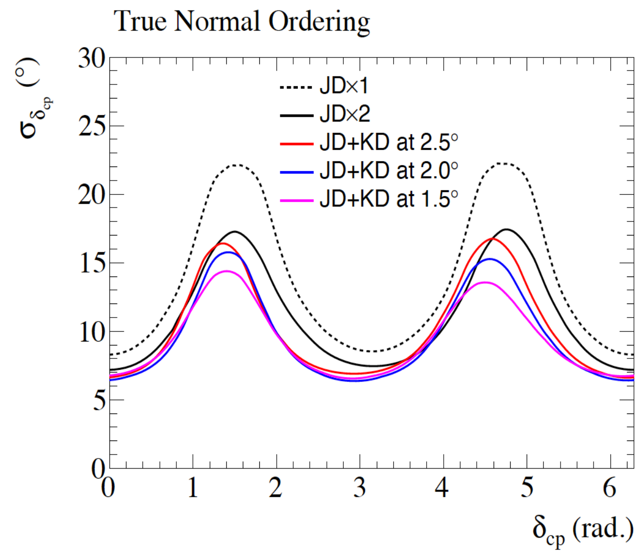
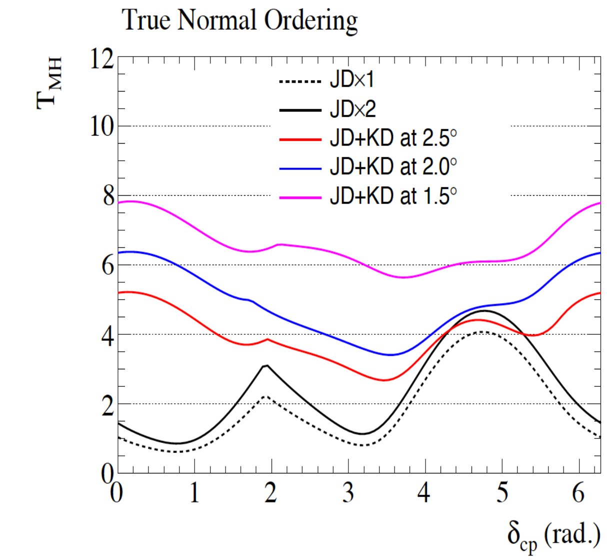
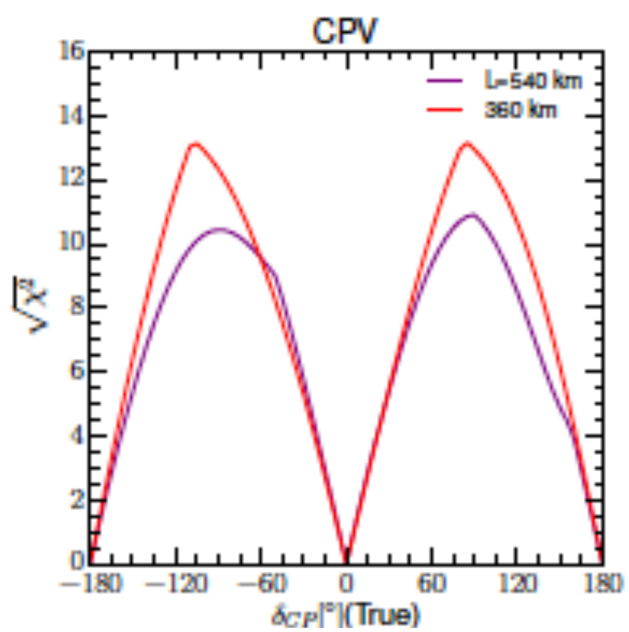
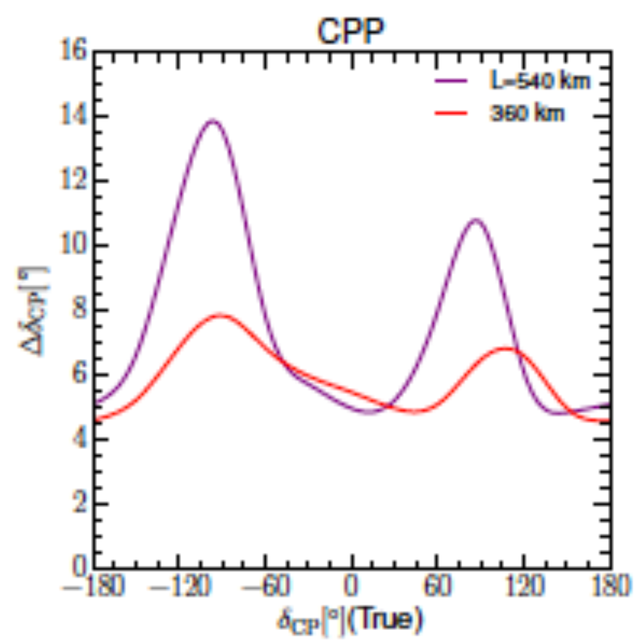
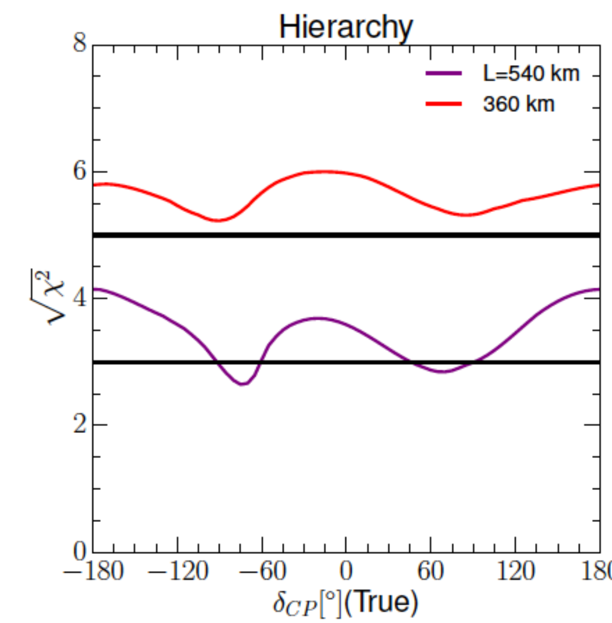
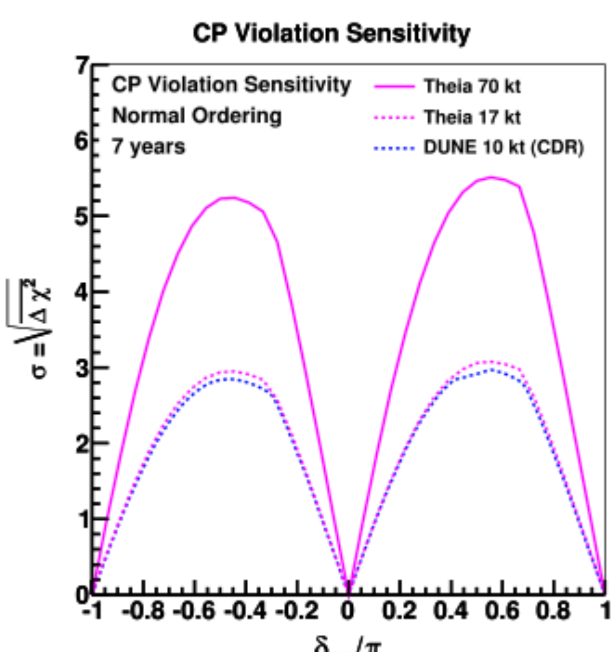
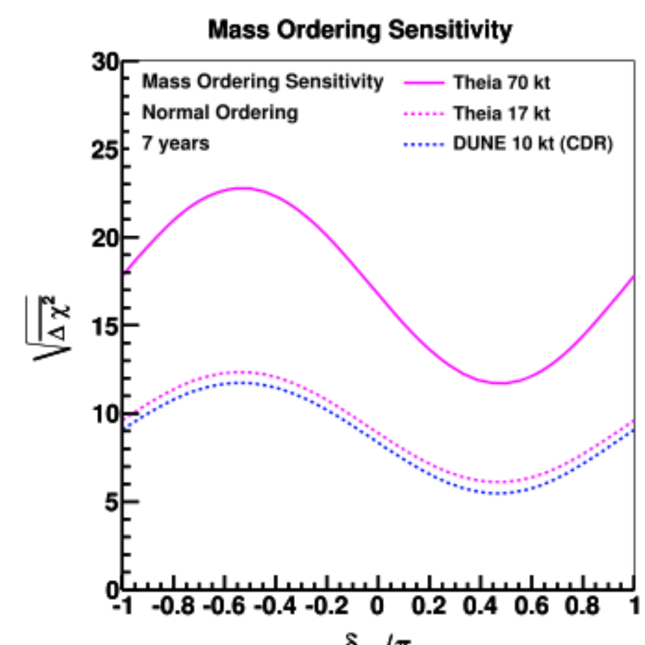
G.O.Gann

Summary

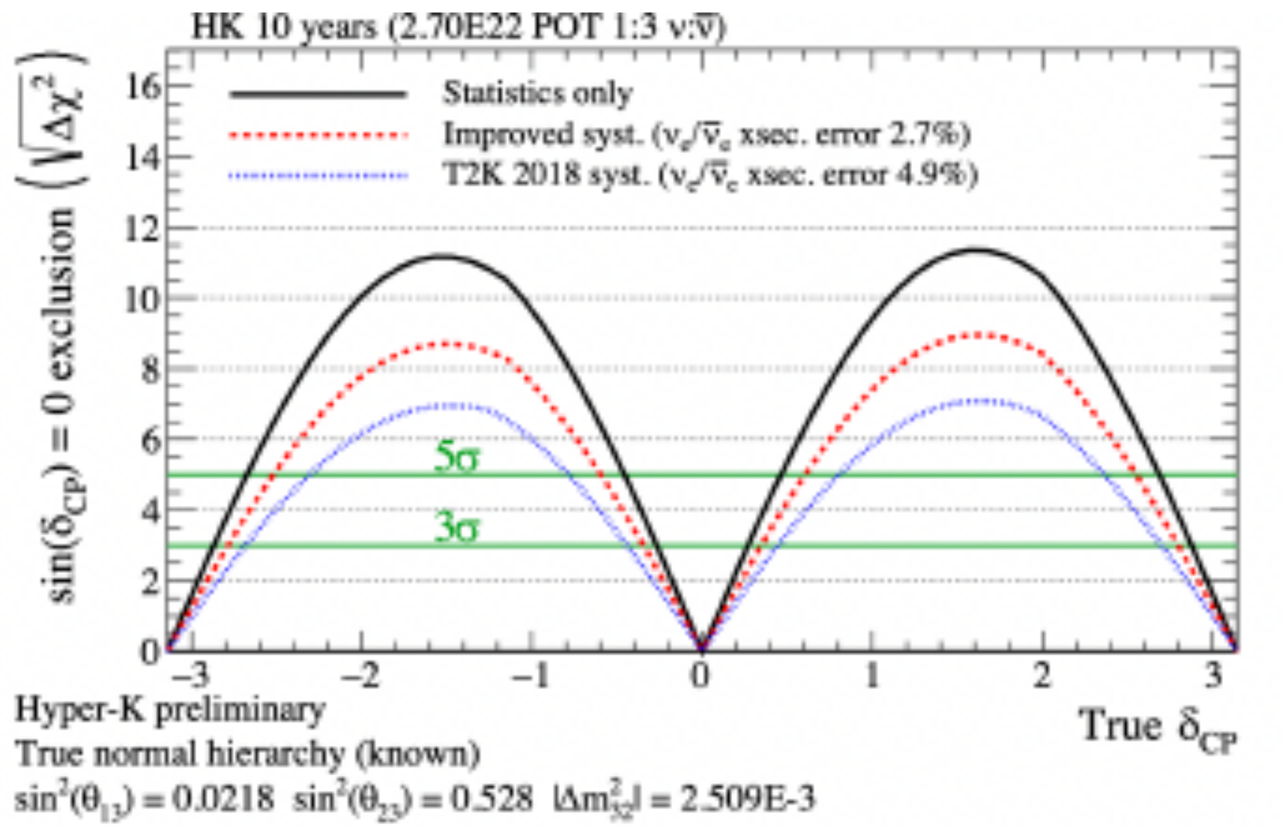
- Large scale long baseline neutrino beam experiments are proposed for precision δ_{CP} measurements
- If experiments are built, precision measurement of δ_{CP} is possible.

	Type	Far Detector Size	Baseline	overburden	Power	ν Peak Energy
KNO	WCD	250~500 kt	~1100 km	~1000 m	1.3 MW	0.6 GeV
ESSnuSB	WCD	2 x 360 kt	360/540 km	1500 m	5 MW	0.3 GeV
THEIA	WbLSD	25/100 kt	1300 km	1500 m	>1 MW	2 GeV

Backup Slides

	δ_{CP} significance	δ_{CP} precision	mass ordering significance
KNO 250 kt +HK 10 yrs			
ESSnuSB fid. volume 538 kt 10 yrs			
THEIA WCD 7 yrs			

Updated Estimate of HK δ_{CP} Sensitivity



J.R.Wilson, Journal of Physics: Conference Series 2156 (2022) 012153

KNO Project Timeline