Status and Prospects of Water Cherenkov Detector

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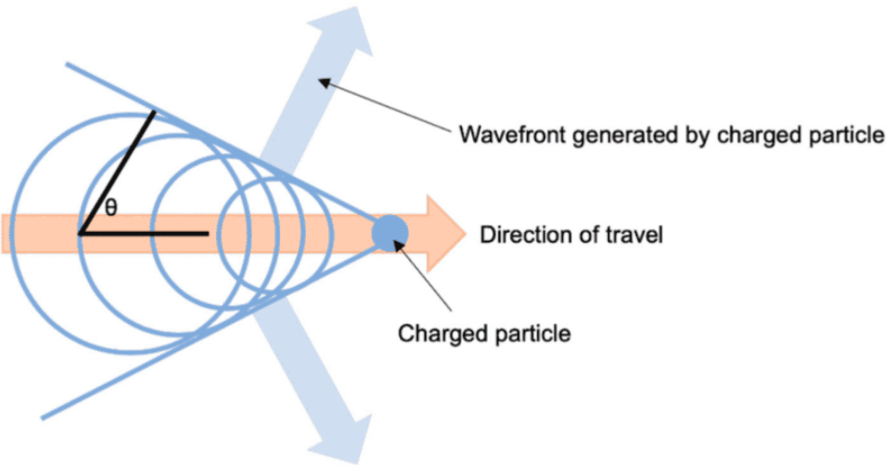
Principle of Cherenkov Radiation



Cherenkov angle $\theta = \cos^{-1}(c/nv)$

$\theta_{max} = \cos^{-1}(1/n)$

n : refractive index of medium

- Cherenkov radiation is generated by charged particles moving with $v > c/n$ in medium
- Particles generating Cherenkov radiations : electrons, muons, charged hadrons,

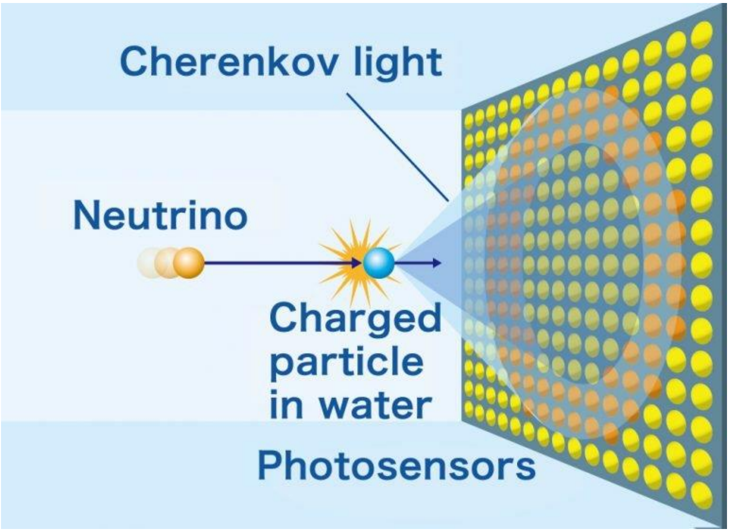
  γ through EM showers, π^0 through $\pi^0 \rightarrow \gamma\gamma$ decays
- Medium used for Cherenkov detectors (transparent to Cherenkov radiations)

  gases : N_2, He, CF_4,..

  liquid : **water (ice)**, liquid argon, mineral oil,..

  solid : quartz, lead fluoride,...

Water Cherenkov Detector



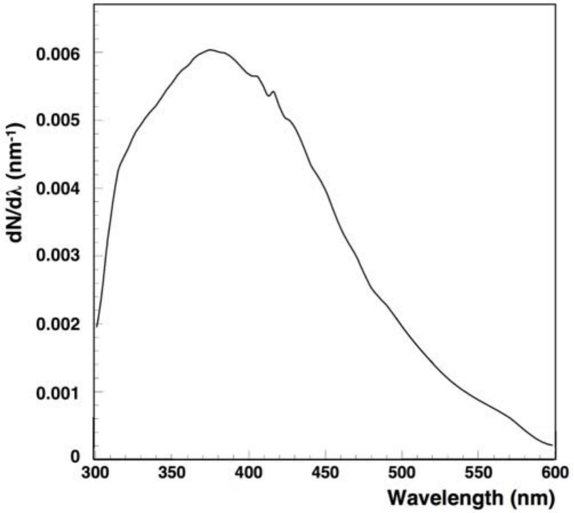
- refractive index of water = 1.33

  θ_{max} = $\cos^{-1}$ (1/n) = 41.2°

- Threshold energy $E_{th} = \frac{mc^2}{\sqrt{1-\frac{1}{n^2}}}$

  Electron : E_{th} ~ 0.77 MeV in water

  Muon : E_{th} ~ 160 MeV in water



- Cherenkov radiations in water: mostly UV lights
- Cherenkov radiations are detected by photosensors (typically PMTs)
- Cherenkov radiation energy loss δE

$$\frac{dE}{dx} = 2\pi\alpha q^2 \int_{\lambda_{\min}}^{\lambda_{\max}} \frac{1}{\lambda^2}\left(1 - \frac{1}{\beta^2 n^2(\lambda)}\right) d\lambda$$

δE ∝ dE/dx X Δx = E

Δx : track length in medium

- Detection of Cherenkov photons leads to the measurement of energy and direction of charged particles

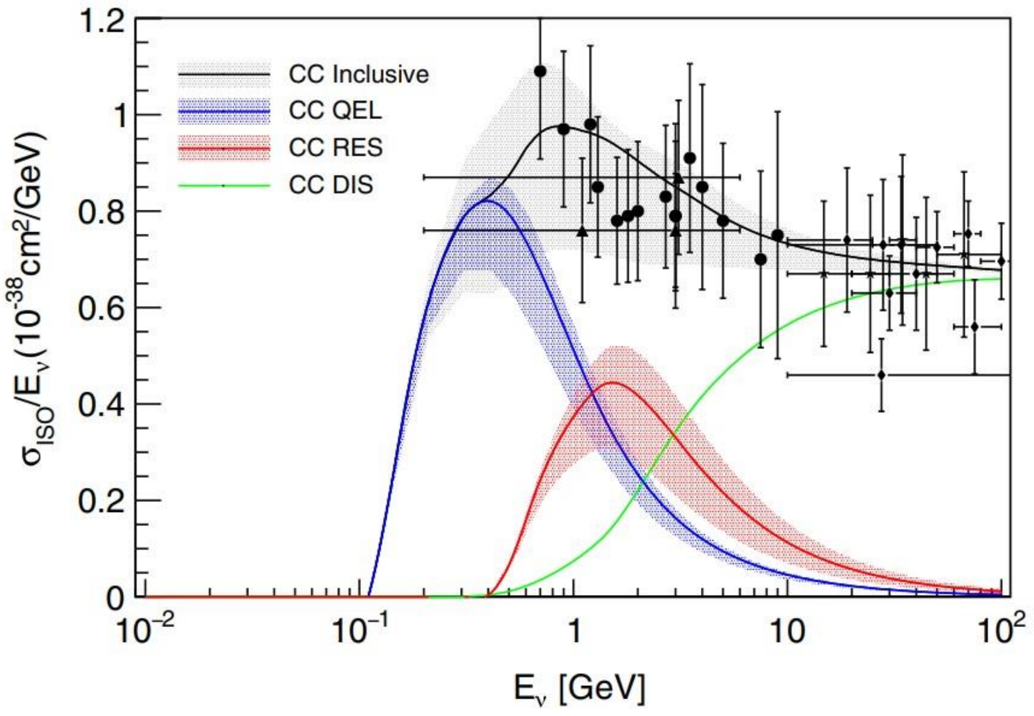
Neutrino Detection in Water Cherenkov Detector

- Interactions of neutrinos with water producing energetic charged particles (muons, electrons)

  $\nu_l + N \rightarrow l + X$: charged current (CC) weak interactions

  $\nu + e^- \rightarrow \nu + e^-$: neutral current (NC) weak interactions

- NC cross sections are much smaller than CC cross sections



- The energy of neutrino can be reconstructed using the energy of a charged particle if the neutrino direction is known

$$E_\nu \approx \frac{E_l \cdot m_n}{m_n - E_l(1 - \cos\theta)}$$

- neutrino energy resolution

  ~10% : O(10) MeV ~2% : O(1) GeV

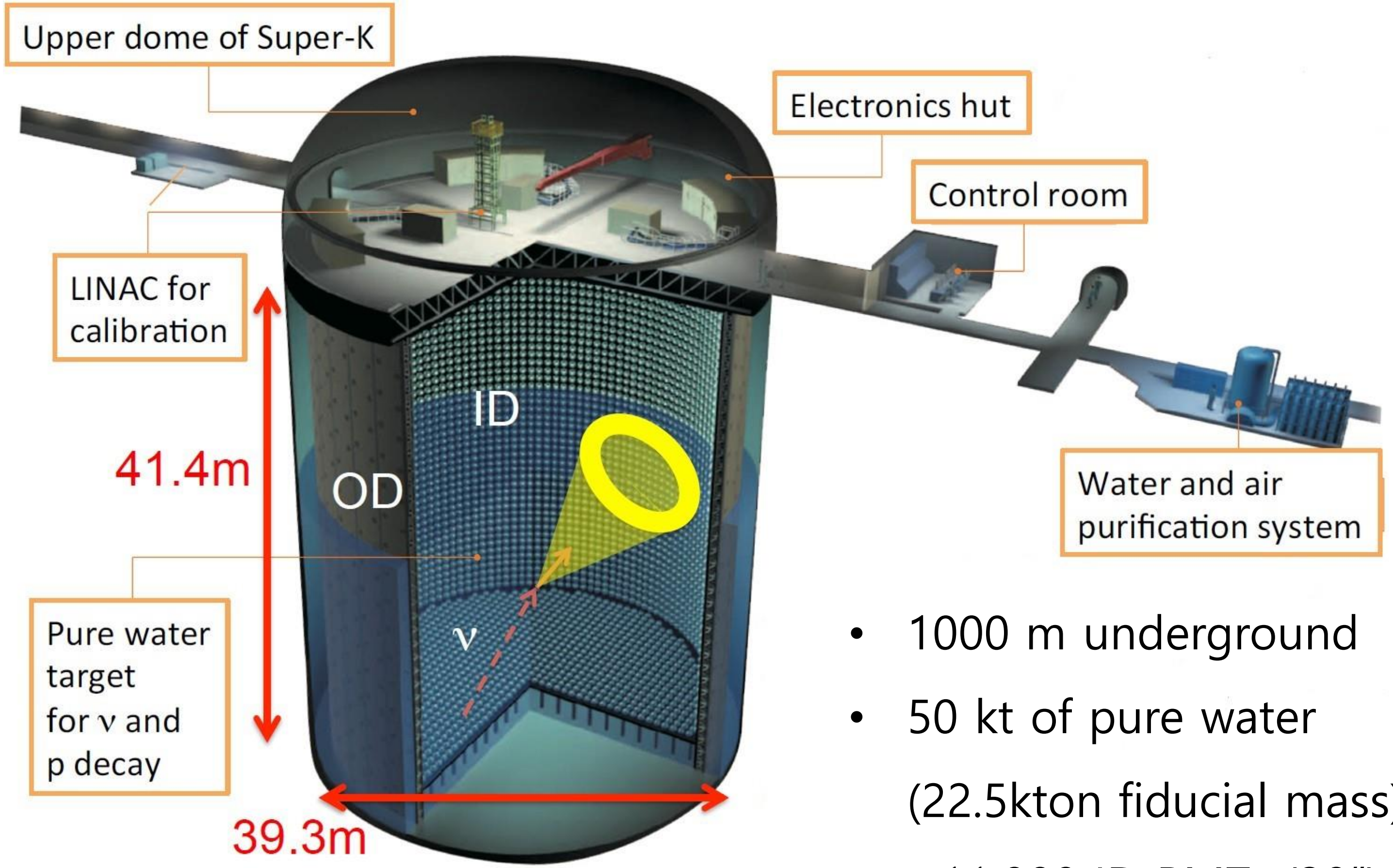
- neutrino angular resolution

  20~25° : O(10) MeV 1~3° : O(10) GeV

Water Cherenkov Neutrino Experiments

- Super-Kamiokande
- Hyper-Kamiokande
- IceCube
- KM3NeT
- TRIDENT
- P-ONE (Pacific Ocean)
- ESSnuSB
- KNO (Korea Neutrino Observatory)

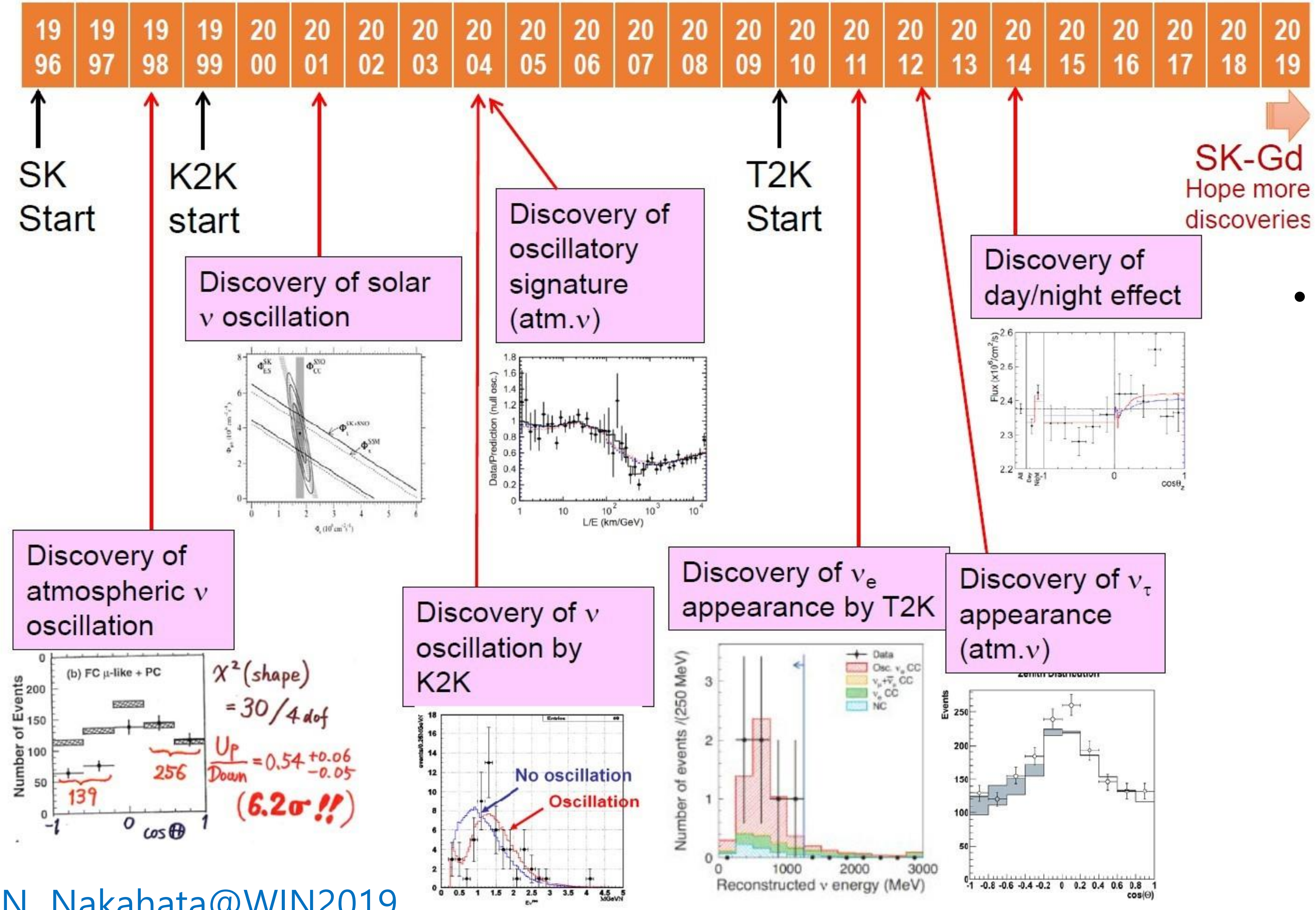
Super-Kamiokande (SK)



- 1000 m underground
- 50 kt of pure water
  (22.5kton fiducial mass)
- ~11,000 ID PMTs (20")
  ~1,900 OD PMTs (8")

- Solar neutrinos
  3.5~20 MeV
  ~15 events/day
- Supernova neutrinos
  3.5~20 MeV
  ~8000 events for 10kpc
- Atmospheric neutrinos
  100 MeV~10 GeV
  ~10 events/day
- Beam neutrinos (T2K)
  100 MeV~5GeV
  ~0.3 events/day

Discoveries at Super-Kamiokande



- Physics at SK/T2K

  Neutrino Oscillations

  Solar Neutrinos

  Atmospheric Neutrinos

  Supernova Neutrinos

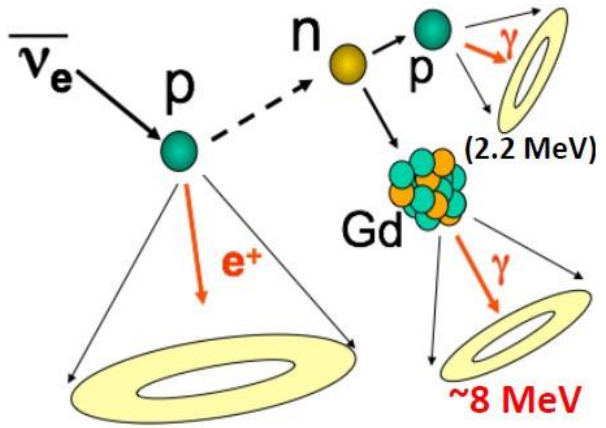
  Proton Decay Searches

  Dark Matter Searches

N. Nakahata@WIN2019

Gd loading at Super-Kamiokande

Inverse beta decay



- SK started its Gd-loading run in 2020
- By adding Gd to water, we can enhance neutron tagging efficiency and reduce backgrounds

- Gd-loading was done in 2 stages

  1st stage (2020~2022) : Gd concentration (0.011%), neutron capture efficiency (~50%)

  2nd stage (2022~) : Gd concentration (0.033%), neutron capture efficiency (~75%)

- Physics targets

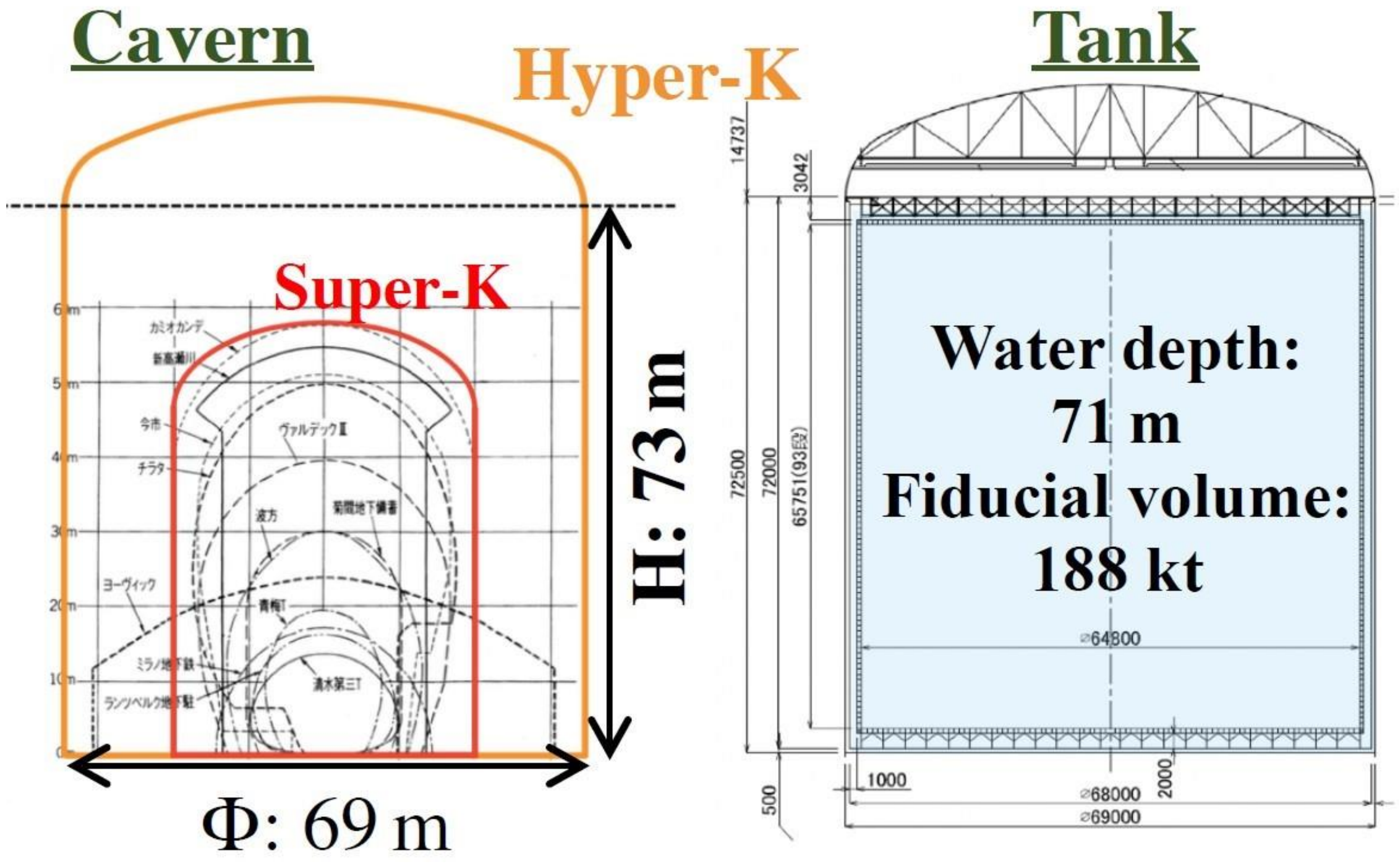
  detection of supernova relic neutrinos by reducing muon spallation backgrounds by 10^{-4}

  enhancement of ν_e and $\bar{\nu_e}$ discrimination

  reduction of backgrounds in proton decay search

Hyper-Kamiokande (HK)

- Next generation water Cherenkov neutrino detector
- HK plans to start its operation in 2028



- 650 m underground
- 260 kt of pure water (188 kt fiducial mass)
- ~20,000 ID PMTs (20") ~1,000 ID mPMTs ~3,600 OD PMTs (3")

Physics at Hyper-Kamiokande

LBL (1.3MW×10years)	δ precision	7°-22°
	CPV coverage (3/5σ)	76%/58%
	$\sin^2\theta_{23}$ error (for 0.5)	±0.017
ATM+LBL (10 years)	MH determination	>3.8σ
	Octant determination (3σ)	$\lvert\theta_{23}$-45°$\rvert$>2°
Proton Decay (20 years)	$e^+\pi^0$ (3σ)	1×10^{35}
	$\bar{\nu}K$ (3σ)	3×10^{34}
Solar (10 years)	Day/Night (from 0/from KL)	8σ/4σ
	Upturn	>3σ
Supernova	Burst (10kpc)	54k-90k
	Relic	70ν's / 10 years

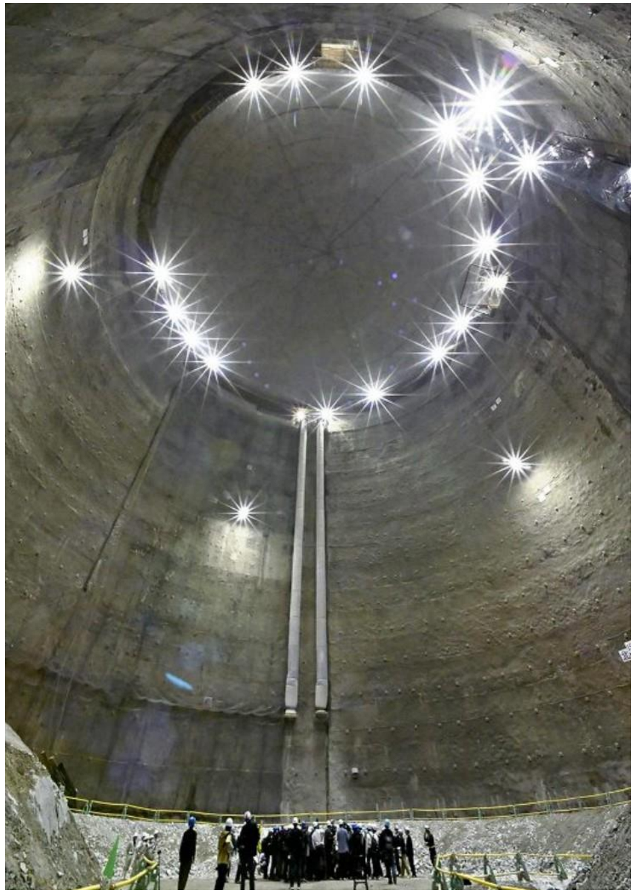
- J-PARC neutrino beam for LBL physics

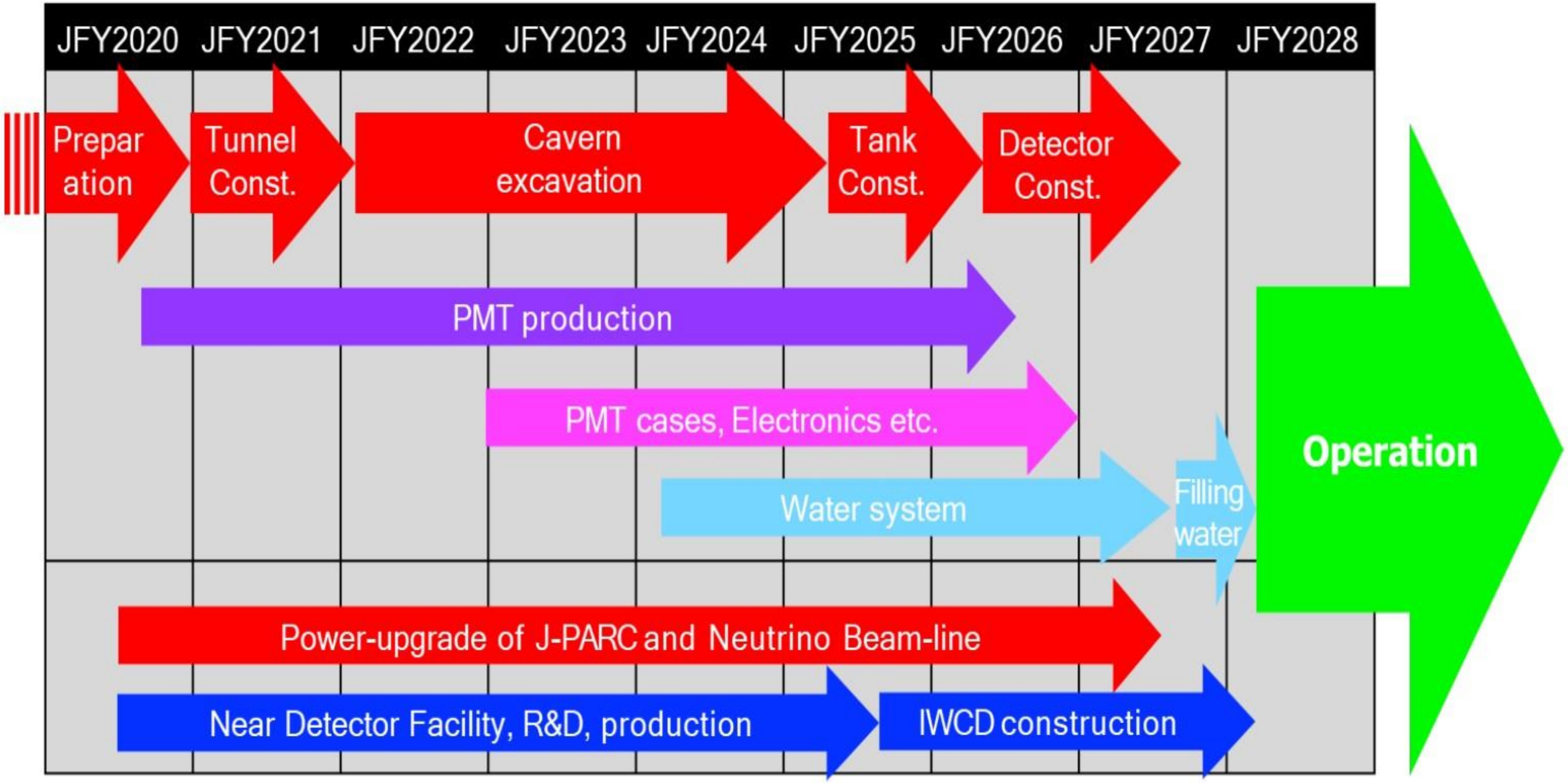
  beam power: 1.3 MW

  2.2 X 10^{21} POT/year

Status of Hyper-Kamiokande

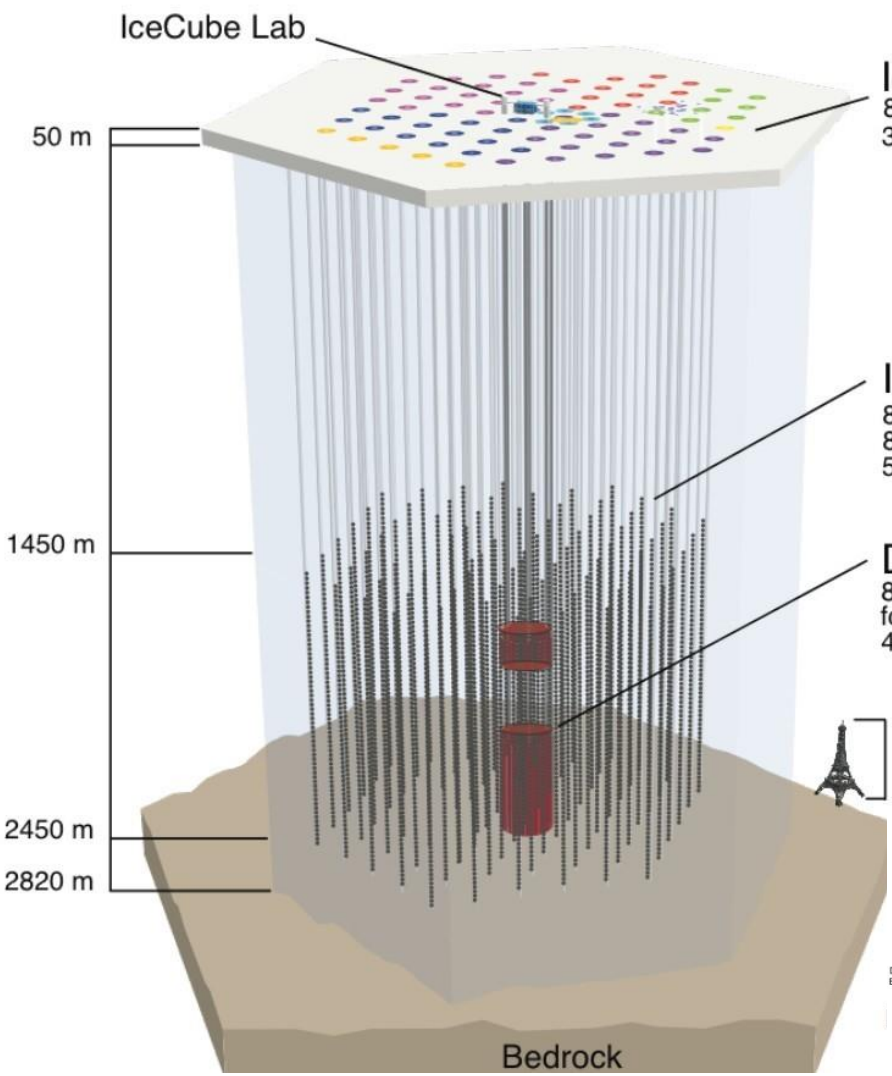
- HK operation will start with 1.3 MW neutrino beam in 2028
- Site excavation was completed in June 2025
- PMT production will be completed in 2026

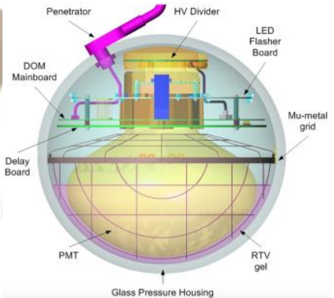




IceCube

- Ice Cherenkov neutrino detector as a neutrino telescope (10 GeV ~ 10 PeV)





- 1450~2450 m underground in south pole
- 1 km^3 of ice
- 86 strings X 60 DOMs = 5,160 DOMs

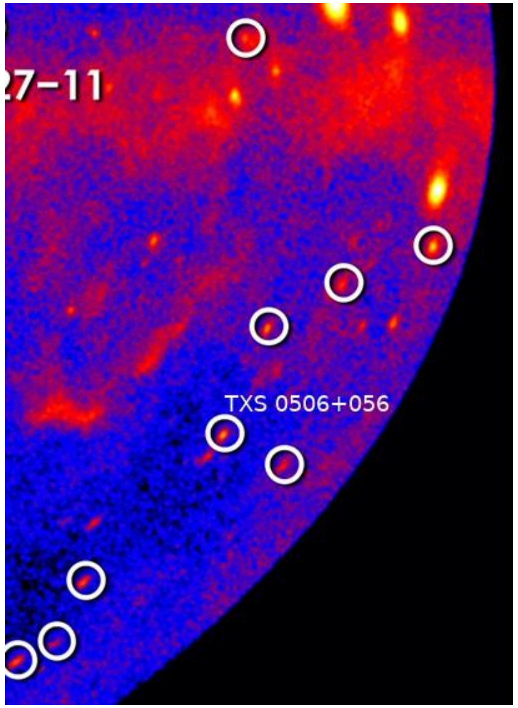
  8 strings X 60 DOMs = 480 DOMs (Deep Core) for measurement of neutrinos down to 10 GeV

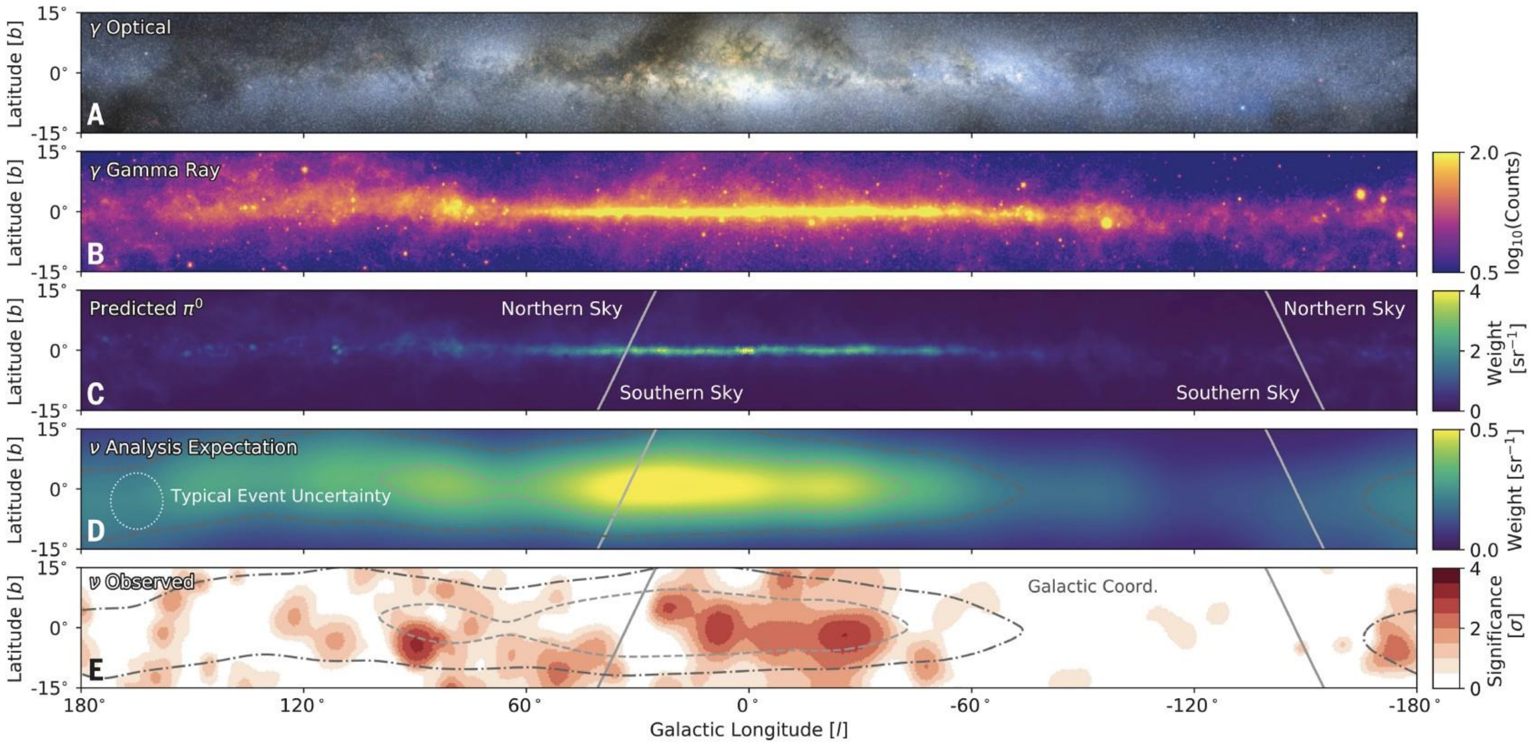
- DOM (digital optical module)

  10″ PMT + main board

Physics at IceCube

- IceCube opened a new window to multi-messenger astronomy by observing high energy neutrinos from blazars (2017~) and galactic plane (2023)

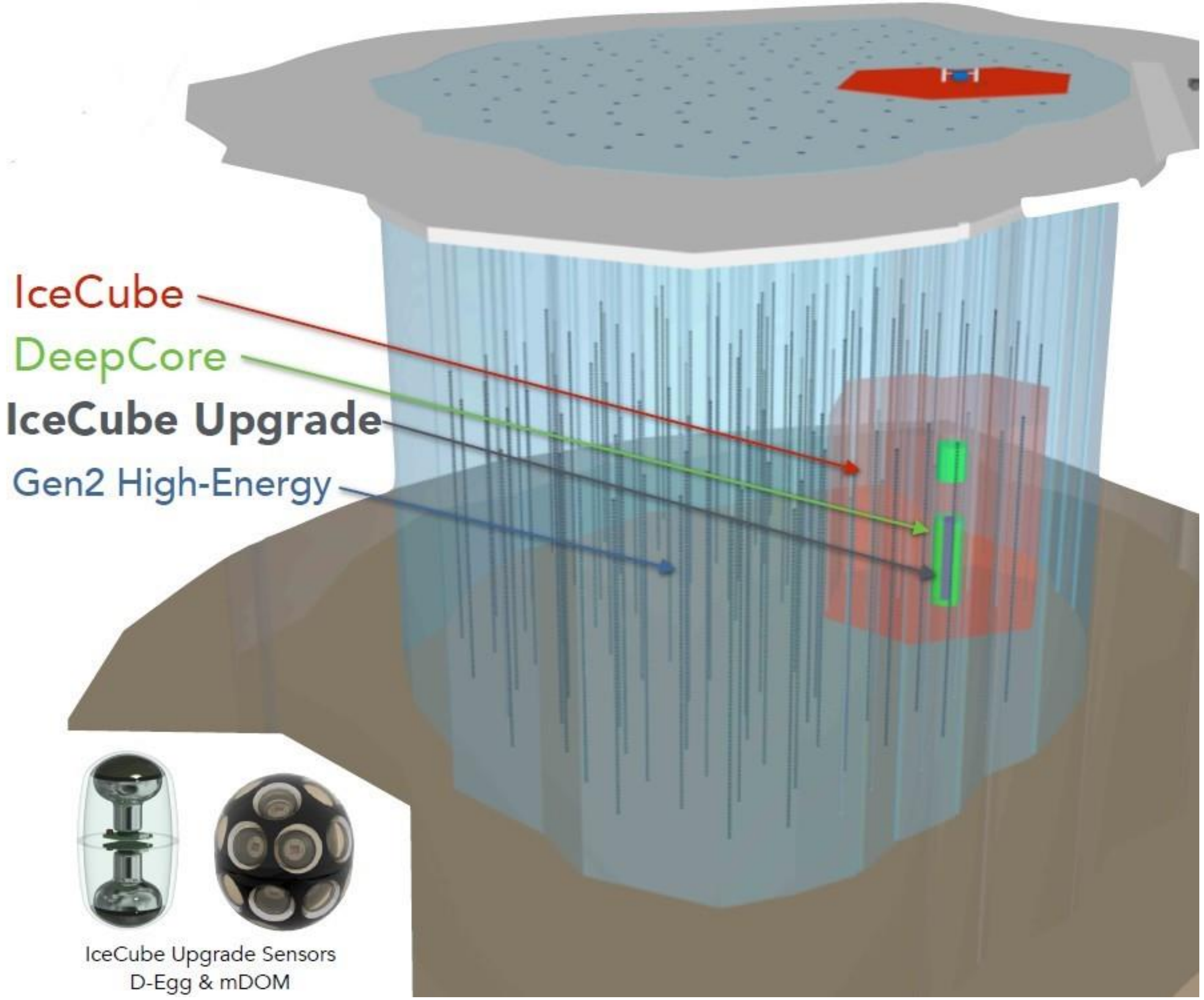




- Physics program of IceCube

All-Sky searches for ultra high energy neutrinos, Neutrino Oscillations, Sterile Neutrino Search, Dark Matter Searches, ..

Future of IceCube



- IceCube Upgrade

  7 new strings in 2 Mt core

  ~ 700 upgraded photosensors

  down to 1 GeV

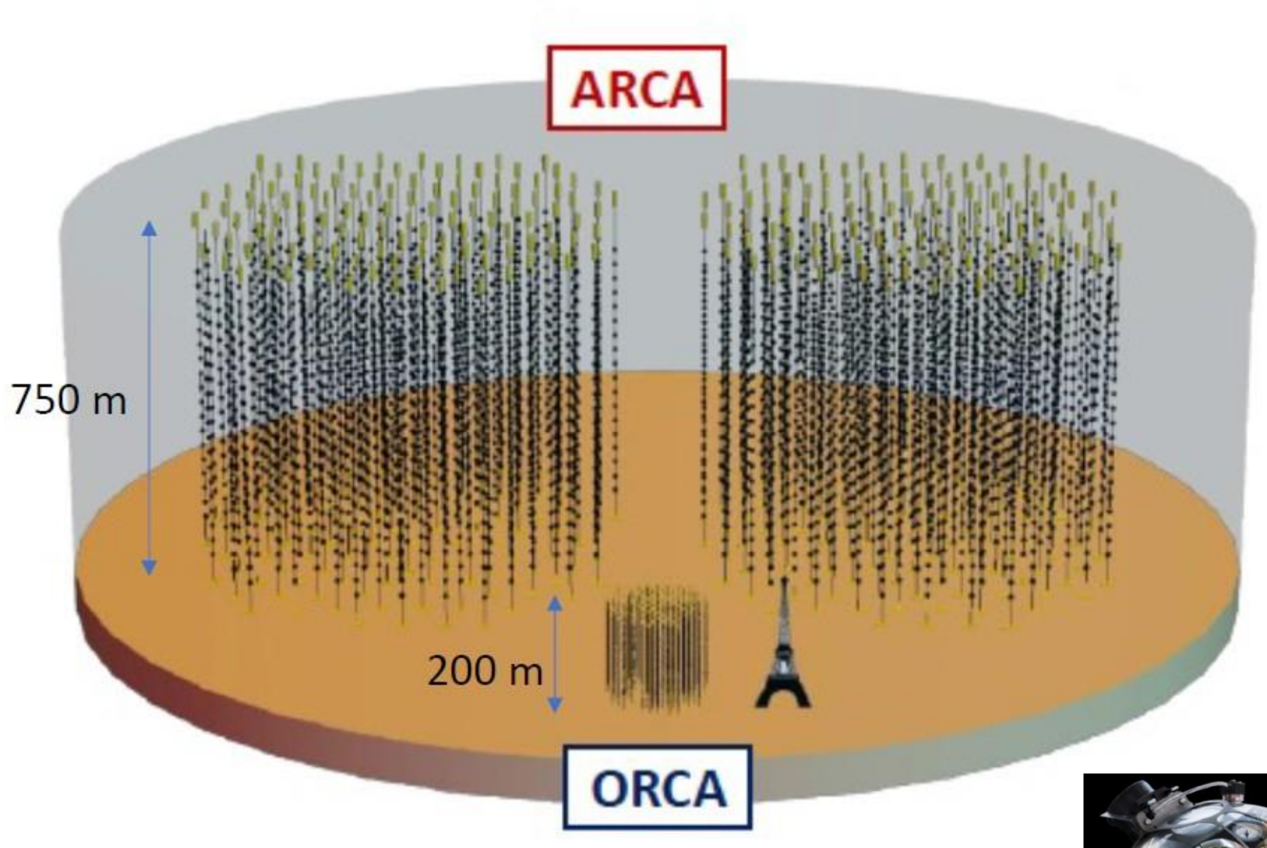
- IceCube Gen 2

  add 120 new strings

  8 km^3 of ice

KM3Net

- Deep underwater Cherenkov neutrino detector consisting of two neutrino telescopes



- ARCA

  3500 m underwater

  1 km^3 of water

  ~230 (57) strings X 18 DOMs

  1 TeV ~ 100 PeV

- ORCA

  2500 m underwater

  7 Mt of water

  ~115 (33) strings X 18 DOMs

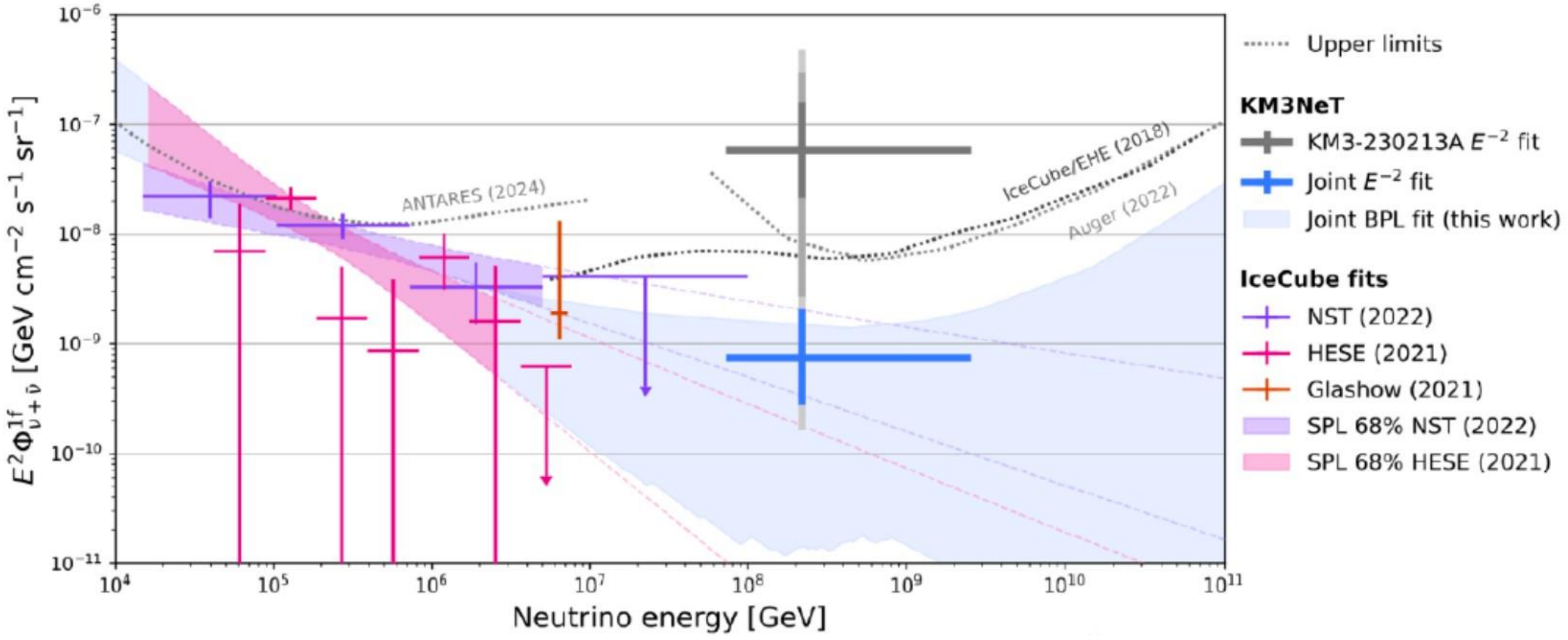
  1 GeV ~ 100 GeV

- DOM (digital optical module)

  consisting of 31 3″ PMT

Physics at KM3Net

- The most energetic neutrino (~120 PeV) was discovered by ARCA (2023)



- Tension (~2σ) with IceCube/Auger Limits

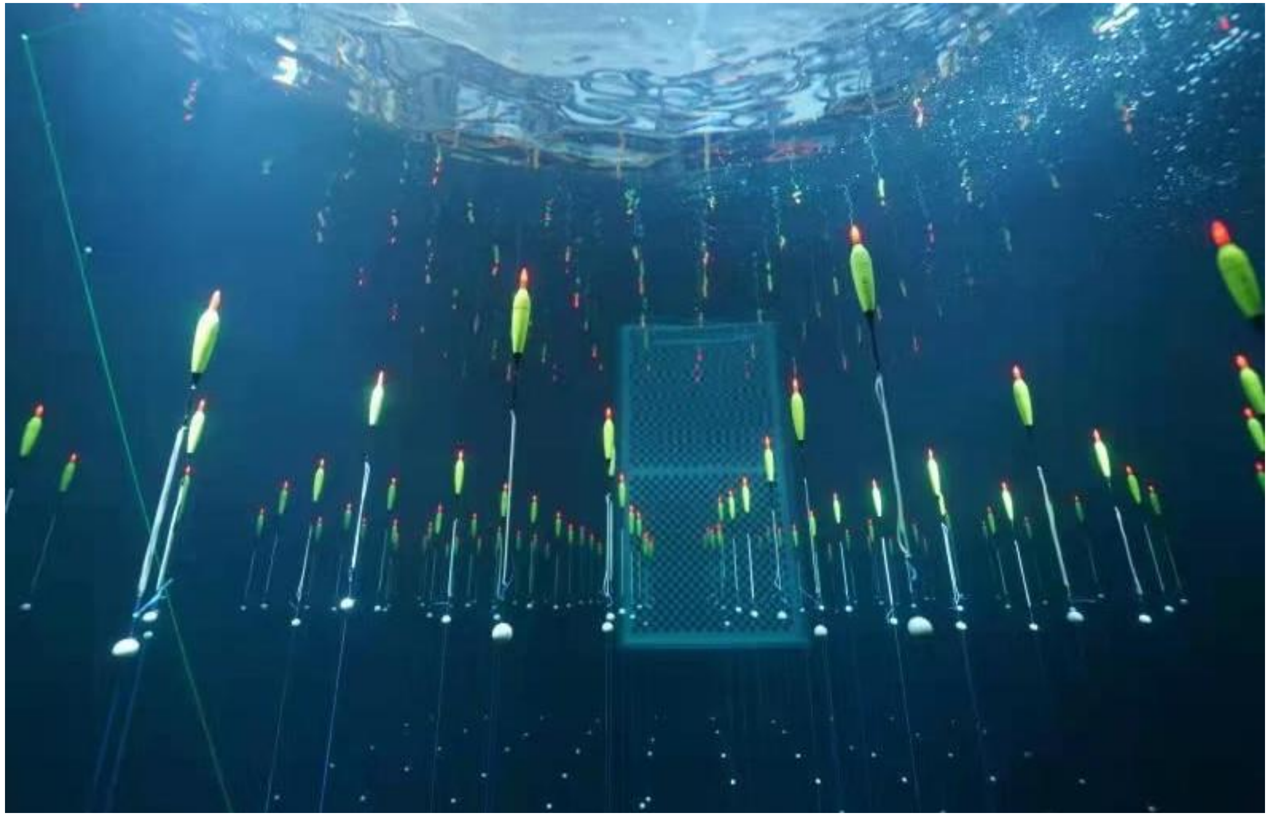
- Source not identified yet

- Physics program of KM3Net

All-Sky searches for ultra high energy neutrinos, Neutrino Oscillations, Neutrino Mass Ordering, Sterile Neutrino Searches, ..

TRIDENT

- Largest deep underwater Cherenkov neutrino telescope located near the equator



- 3500 m underwater in south China sea
- 7.5 km^3 of water
- 1211 strings X 20 hDOMs

  = 24,220 hDOMs
- 1 TeV ~ 1 EeV

- hDOM

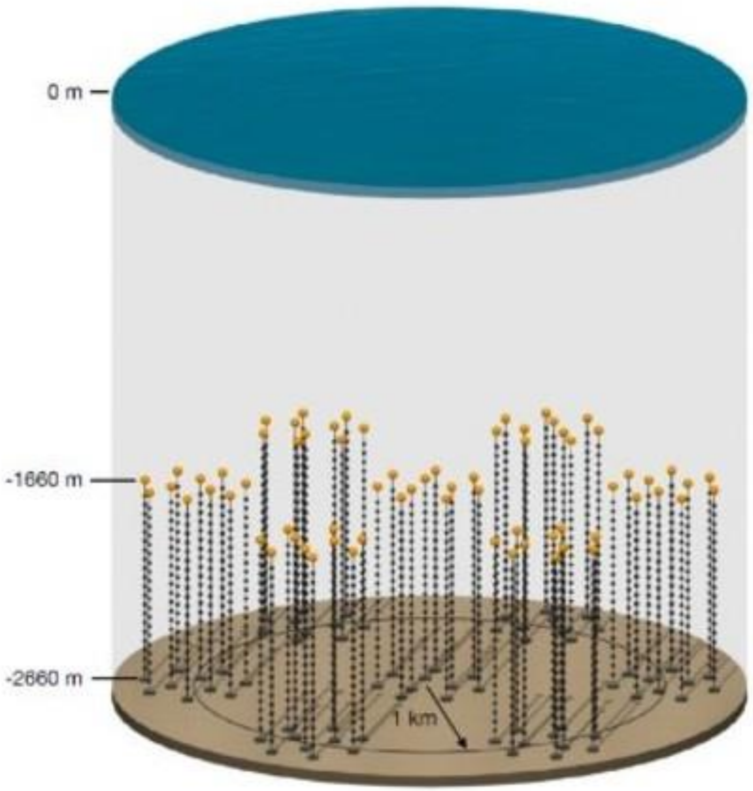
  hybrid digital optical module

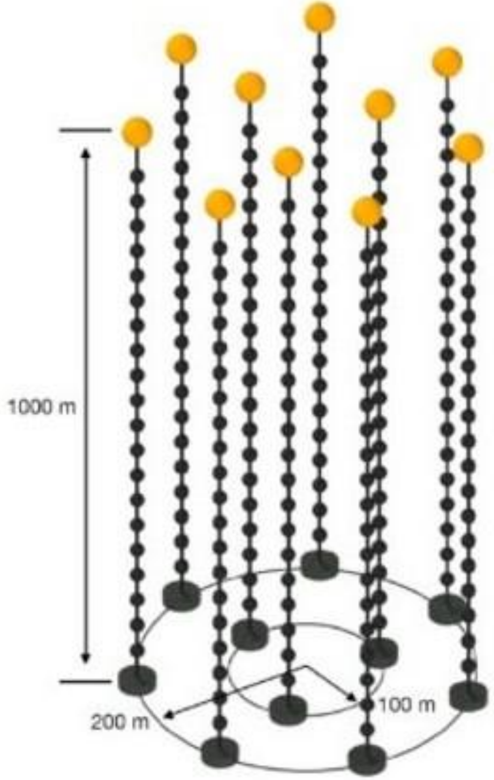
  31 3″ PMTs + 20 SiPMs

- Phase 1 (2026) : deploy first 10 strings

P-ONE

- New deep underwater Cherenkov neutrino telescope in northern hemisphere





- 2600 m underwater in the coast of Canada
- 1 km^3 of water
- 70 strings X 20 POMs

  = 1,400 POMs
- 1 TeV ~ 10 PeV
- Plug in existing NEPTUNE power grid

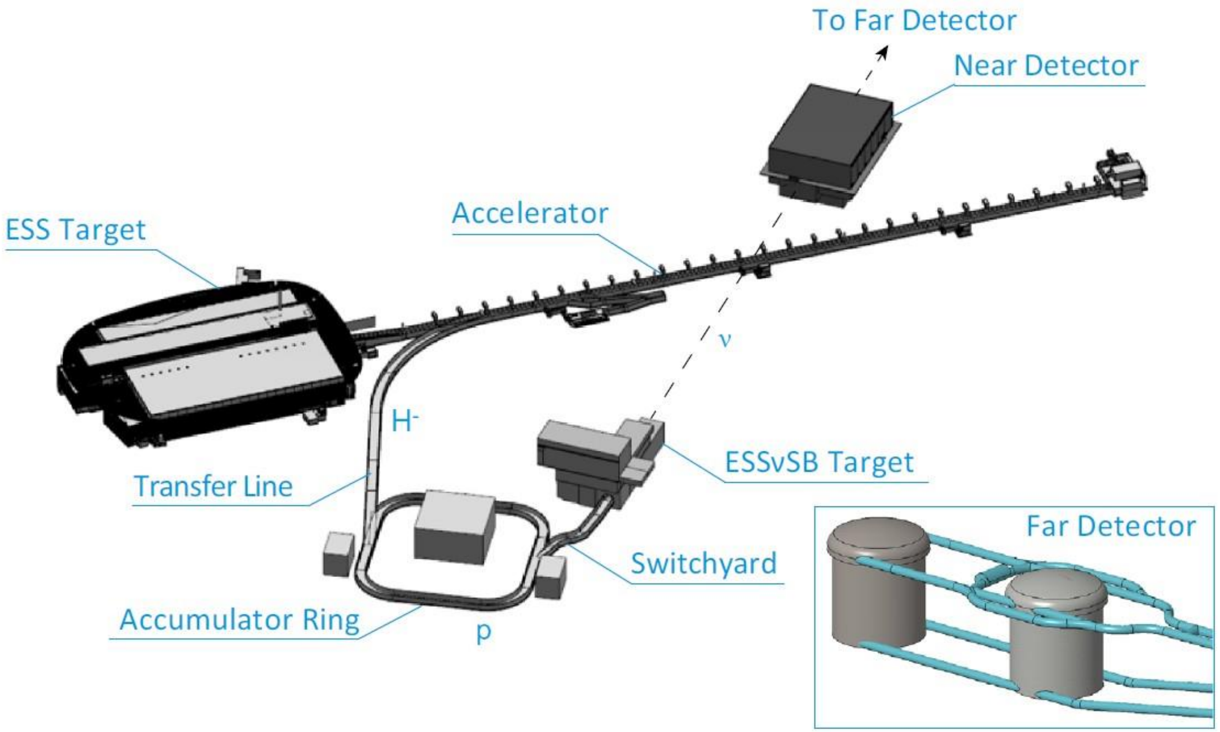
- POM

  16 3″ PMTs

- Phase 1 (2027) : complete the first cluster consisting of 10 strings

ESSnuSB

- Water Cherenkov neutrino detector project at ESS (European Spallation Source) facility



- 5 MW beam power

  Upgrade to 10 MW is proposed

- Far detector

  360 km baseline

  1000 m underground

  2 X 270 kt water Cherenkov detectors

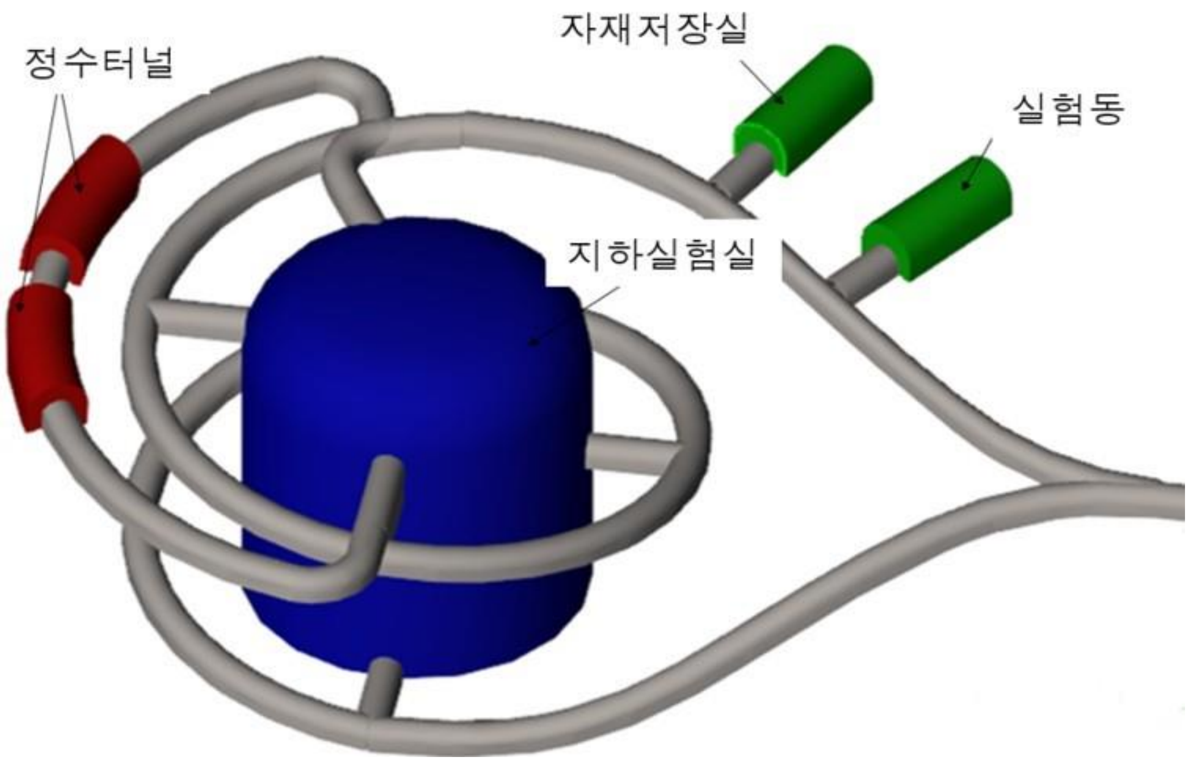
- Main goal : precision measurement of leptonic CP violation

  utilize 2nd oscillation maxima

- CDR (2022) → Finalize ESSnuSB studies (2026) (not approved yet)

KNO

- First water Cherenkov neutrino detector project in Korea



- Very Far detector to J-PARC neutrino beam

  ~1000 km baseline

  1000 m underground

  500 kt water Cherenkov detector

- Physics Goals

  precision measurement of leptonic CP violation

  proton decay searches

  supernova neutrinos

- KNO 기획보고서 (2024) → 대형연구개발사업 지원계획 (2026) (not approved yet)

Summary

- Water Cherenkov detector is a proven technology which can be used to measure the energy, direction, type of particles

- Water Cherenkov detectors are widely used as neutrino detectors and cosmic ray detectors

- Water Cherenkov neutrino detectors have made many fundamental discoveries such as supernova neutrinos, neutrino oscillations, and ultra high energy cosmic neutrinos

- New water Cherenkov neutrino detector projects are in progress and they are expected to open a new era of neutrino physics

- KNO will be the first domestic water Cherenkov neutrino project and a leading neutrino experiment worldwide over next decades if approved