Future Neutrino Experiments

Atsumu Suzuki
Kobe University

9th Vietnam School on Neutrino (VSoN9)
2025/July/24

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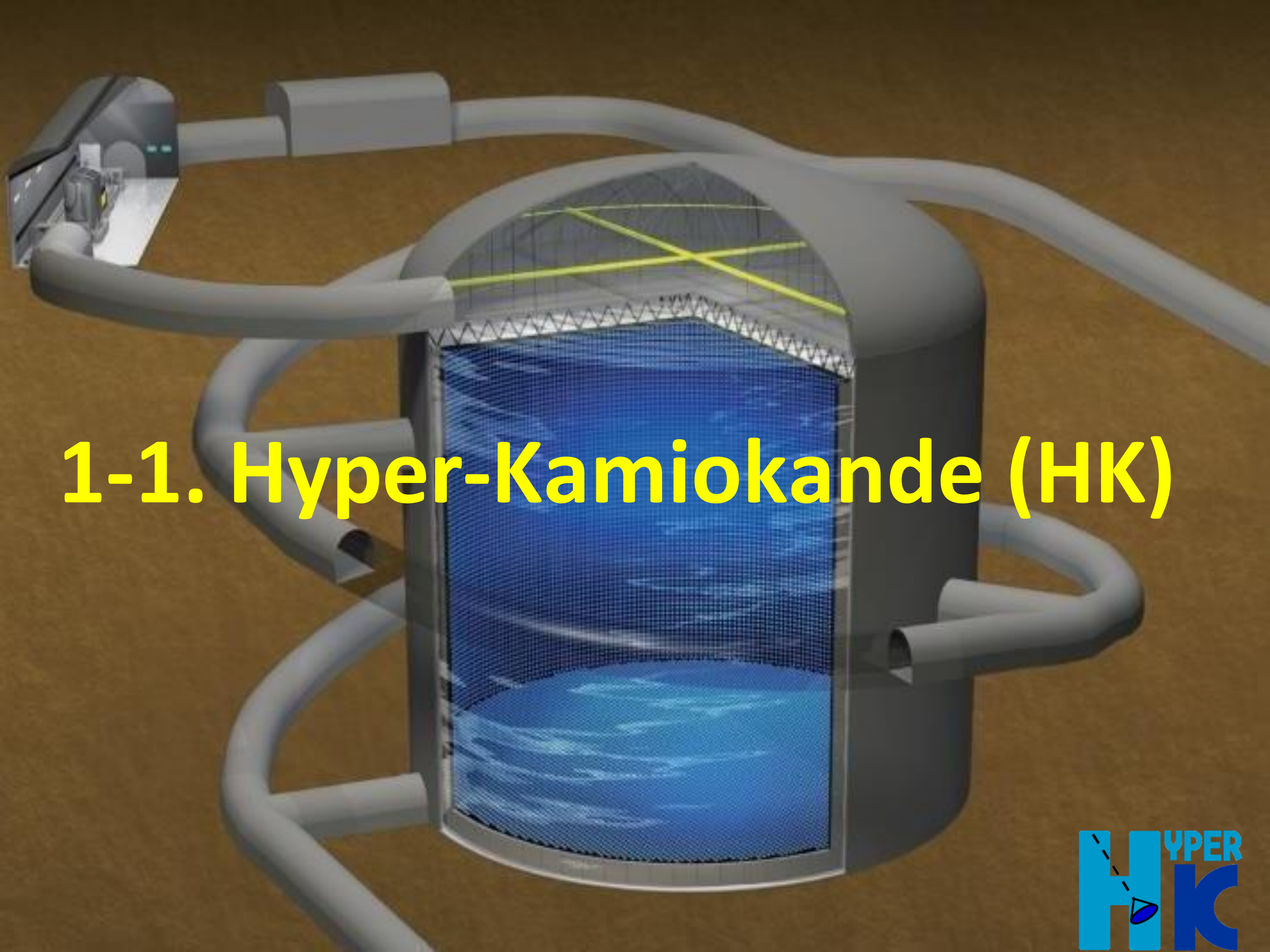
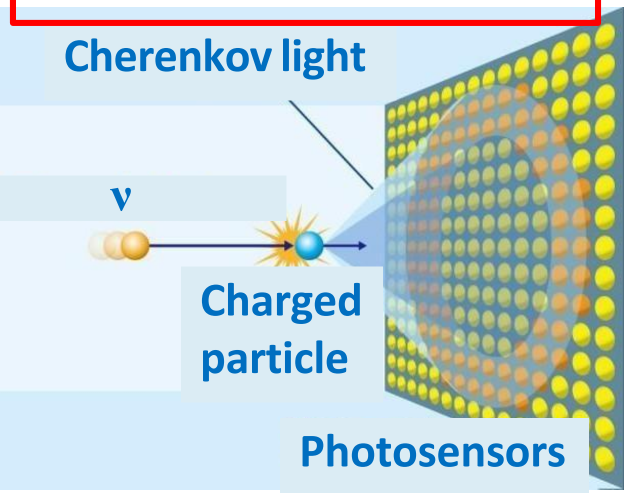
1-1. Hyper-Kamiokande (HK)

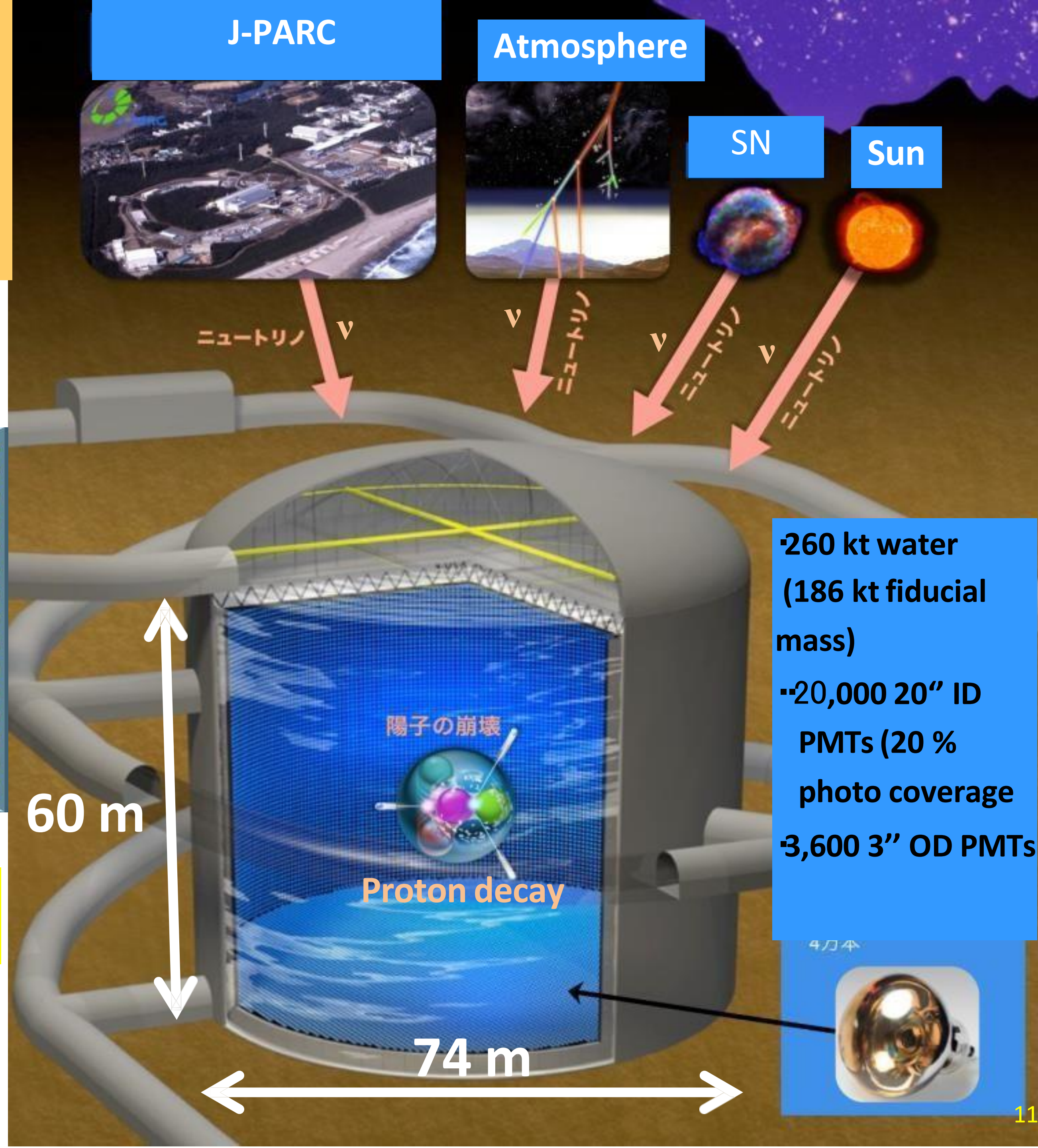


Hyper-Kamiokande Detector

Large water Cherenkov detector



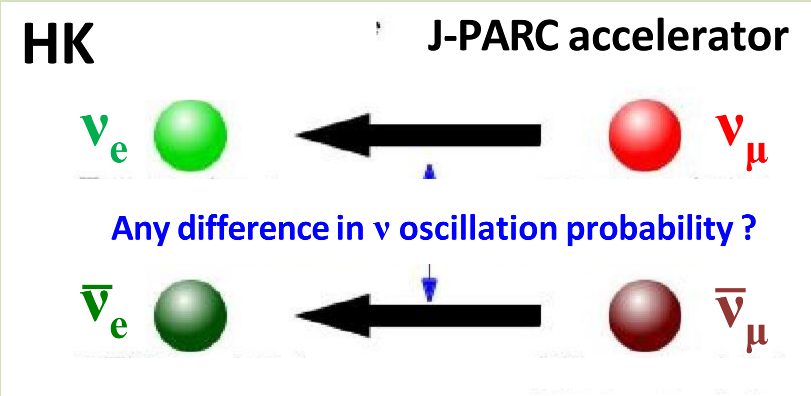
- Construction started in 2020
- Operation will start in 2028



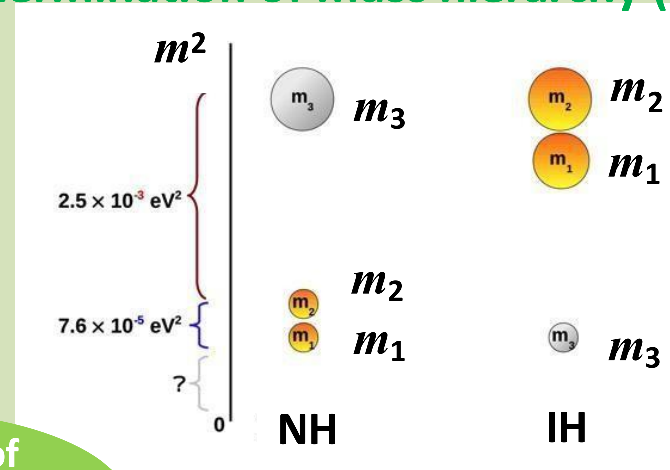
- 260 kt water (186 kt fiducial mass)
- 20,000 20” ID PMTs (20 % photo coverage
- 3,600 3’’ OD PMTs

Physics goals

CPV measurement

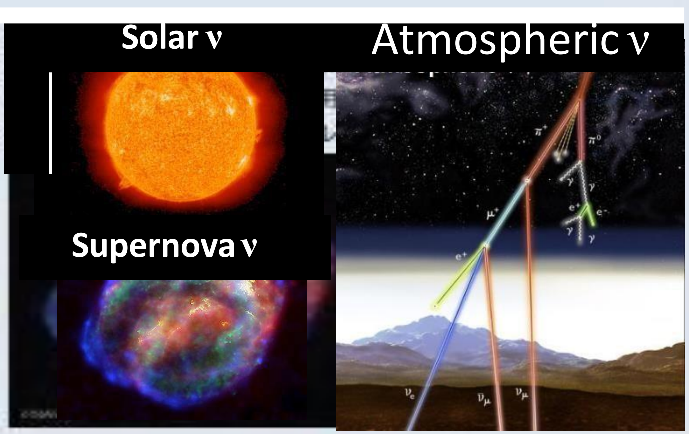


Determination of mass hierarchy (MH)



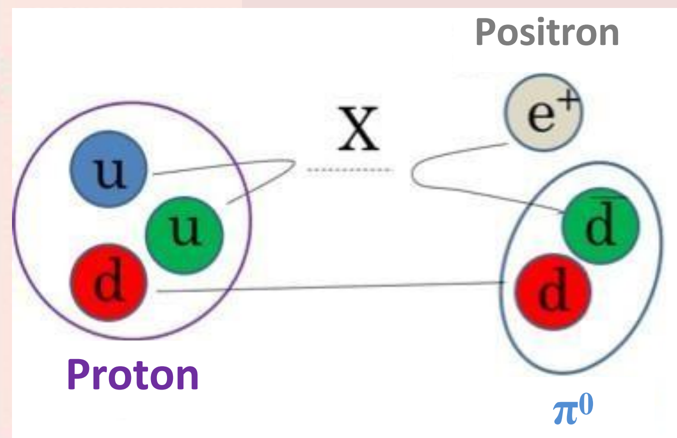
Elucidation of whole picture of ν oscillation

Cosmic neutrino observation



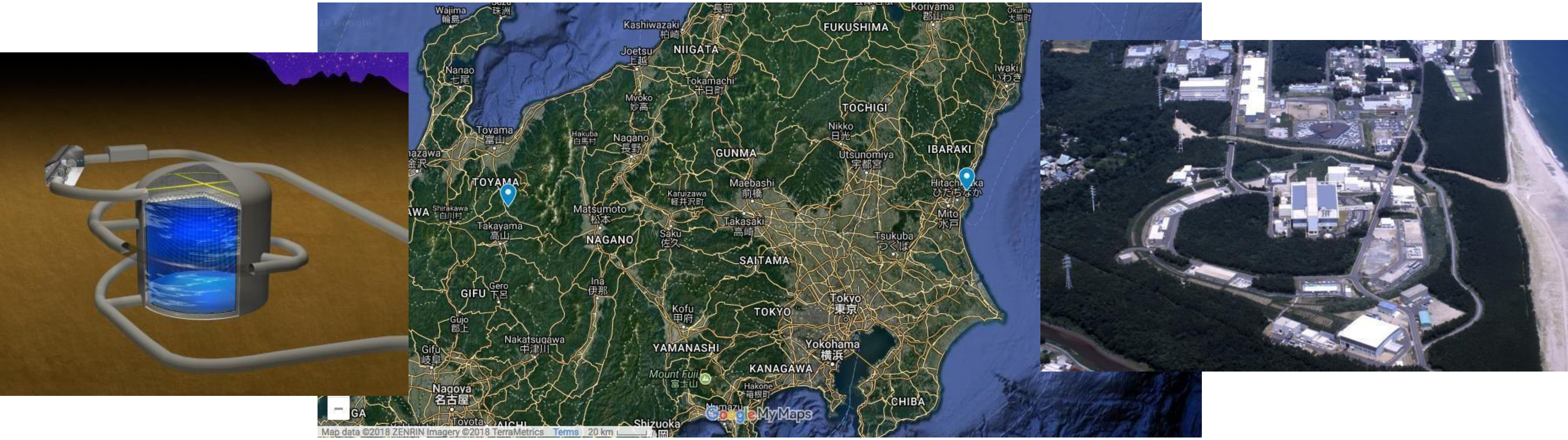
Elucidation of the origin and the history of the universe

Proton decay search

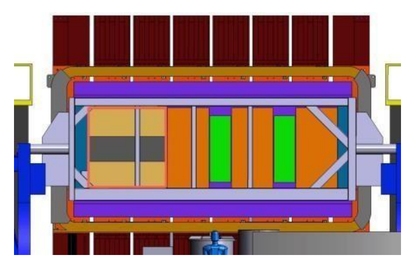


Investigation of GUT

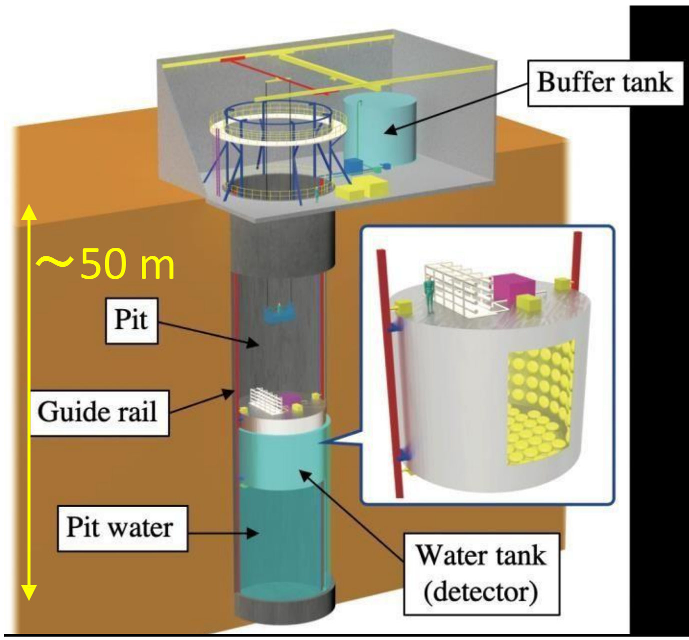
HK Long Baseline Experiment

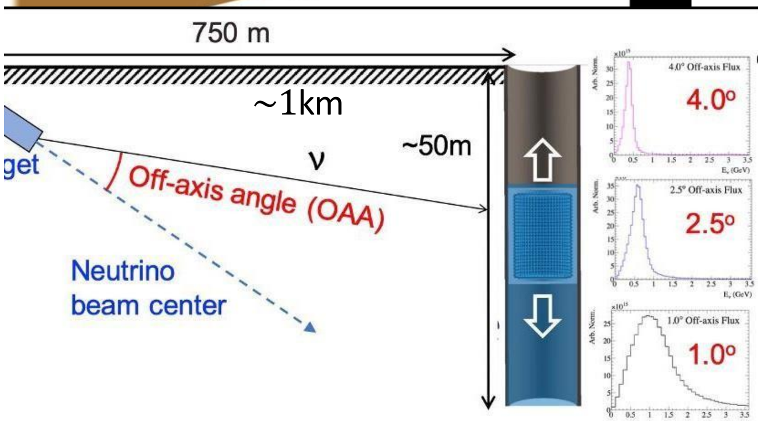


- J-PARC ν beam: 800 kW → 1.3 MW
  2.5° off-axis, peak energy @～600 MeV (oscillation maximum)
  → narrow band beam suppresses NC-π^0 and CC-nQE contamination
- ND280 should continue its operation for HK.
- FD:SK → HK will realize high statistic ν data
- Intermediate Water Cherenkov Detector (IWCD) will be newly constructed at ～800 m from the neutrino source.

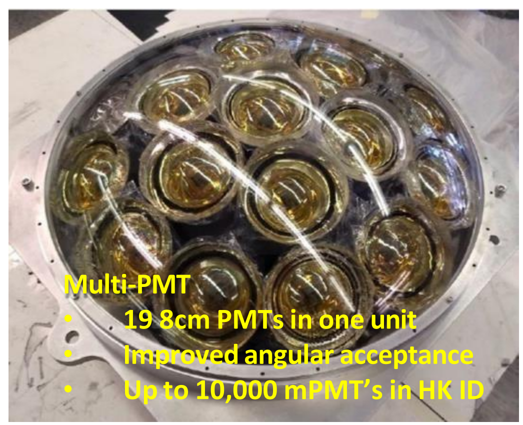


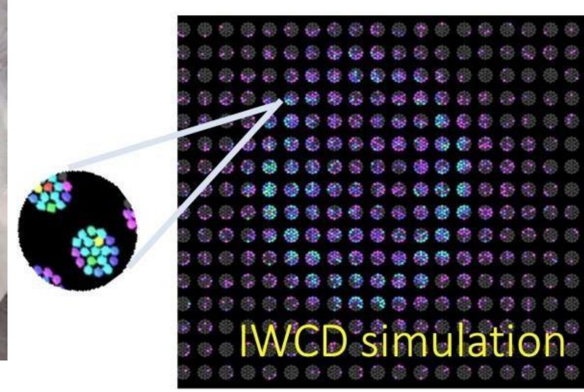
Intermediate Water Cherenkov Detector (IWCD)



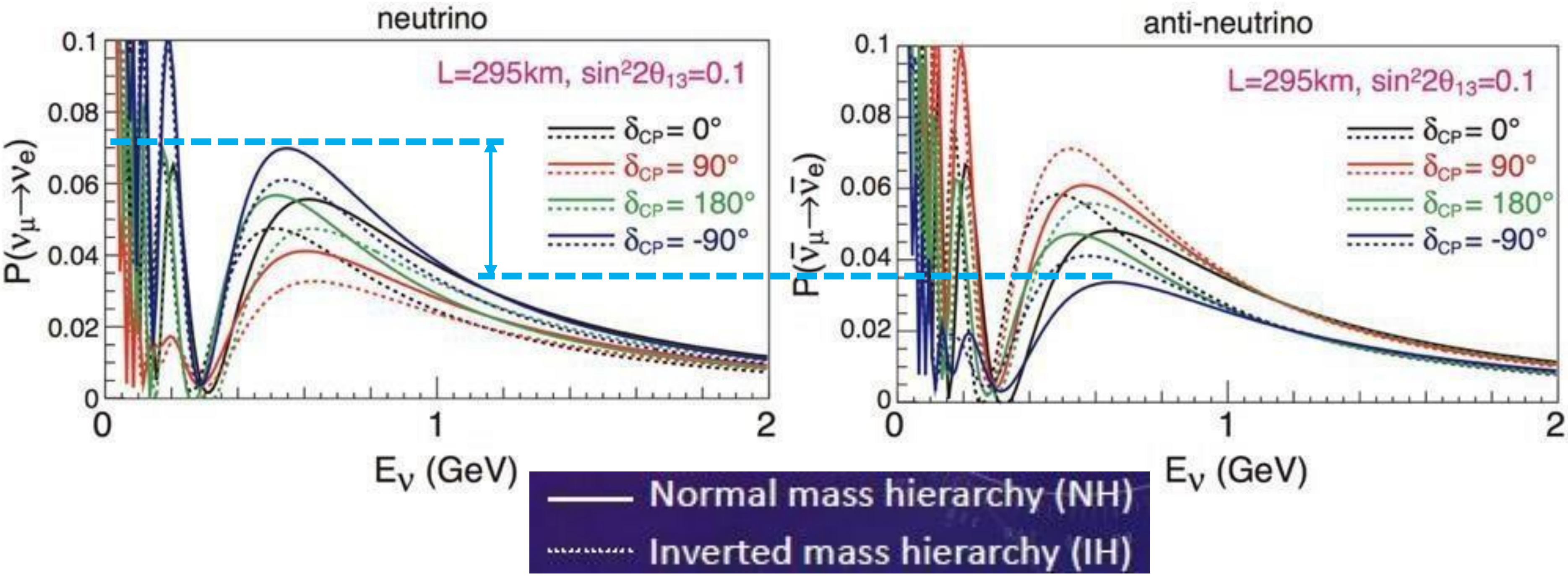


- $\sim$600 t water Cherenkov detector located at $\sim$900 m from the neutrino source
- Moves es vertically to measure energy spectrum at different off-axis between 1° and 4°.
- $R \equiv \frac{\sigma(\nu_e)/\sigma(\nu_e)}{\sigma(\overline{\nu}_e)/\sigma(\overline{\nu}_e)}$, $\Delta R/R$: 5 % → ≤ 2.7 %
- Multi-PMT units will be used. → good event reconstruction despite small detector



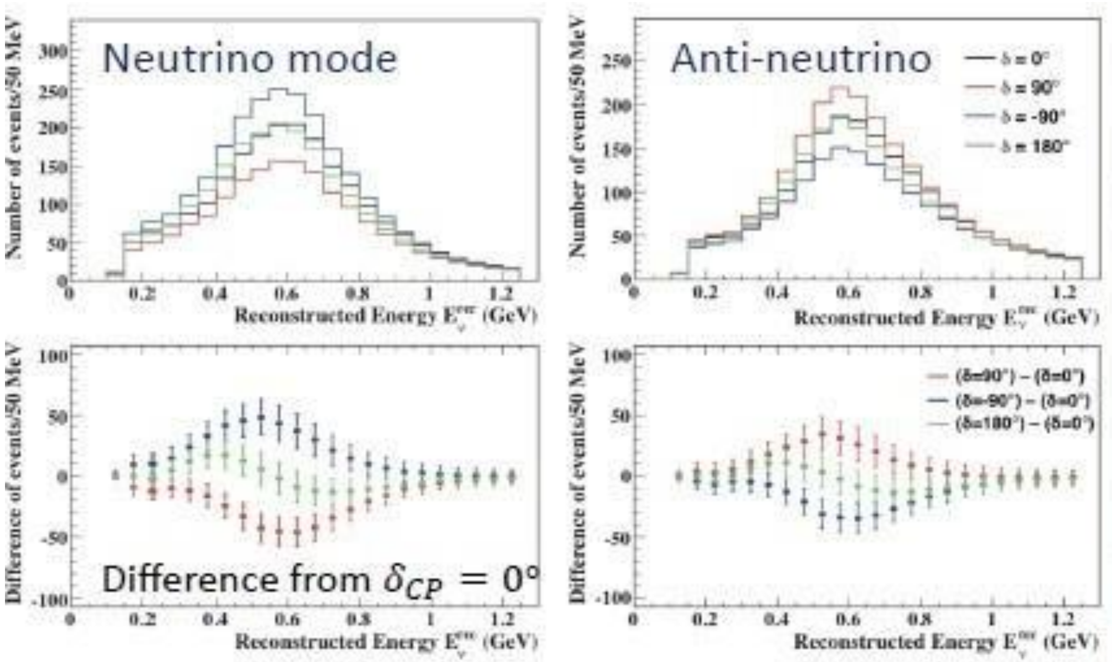


Measurement of *CP* asymmetry



- Comparison between the probabilities: $P(\nu_\mu \to \nu_e)$ vs $P(\bar{\nu}_\mu \to \bar{\nu}_e)$
- Up to ～±30 % variation at δ_{CP} = -90° in NH (or 90° in IH) wrt $\sin\delta_{CP}$=0

Expected events in HK LBL experiment



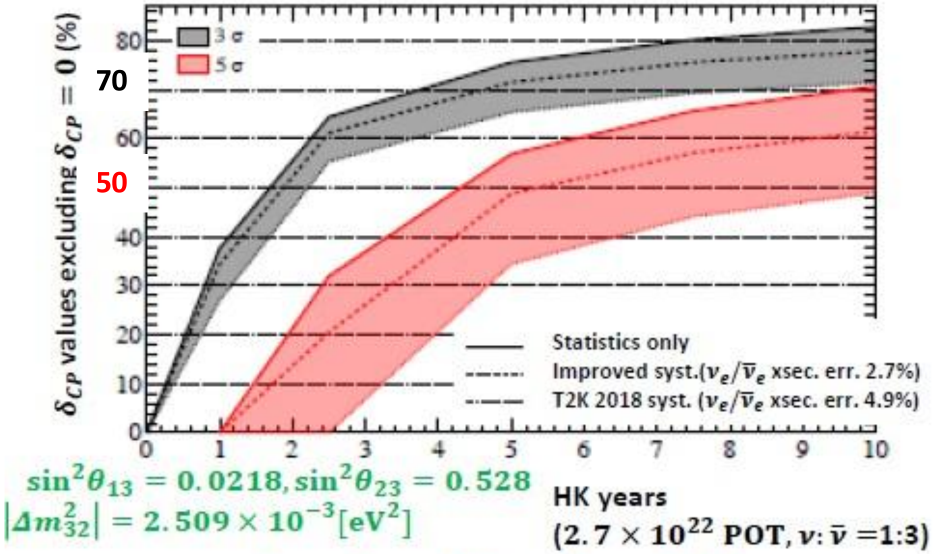
- A few % stat. uncertainties on $\nu_\mu \rightarrow \nu_e$ & $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ signals
- $E\nu$ is reconstructed from (p, θ) of e or μ
- Realistic estimates of wrong sign & NC BG contaminations are based on T2K

Expected signals & BG's : 10 years (1.3 MW × 10^8 s), 1 tank, $\sin^2 2\theta_{13}$ = 0.1, δ_{CP} = 0, & $\nu : \overline{\nu} = 1 : 3$

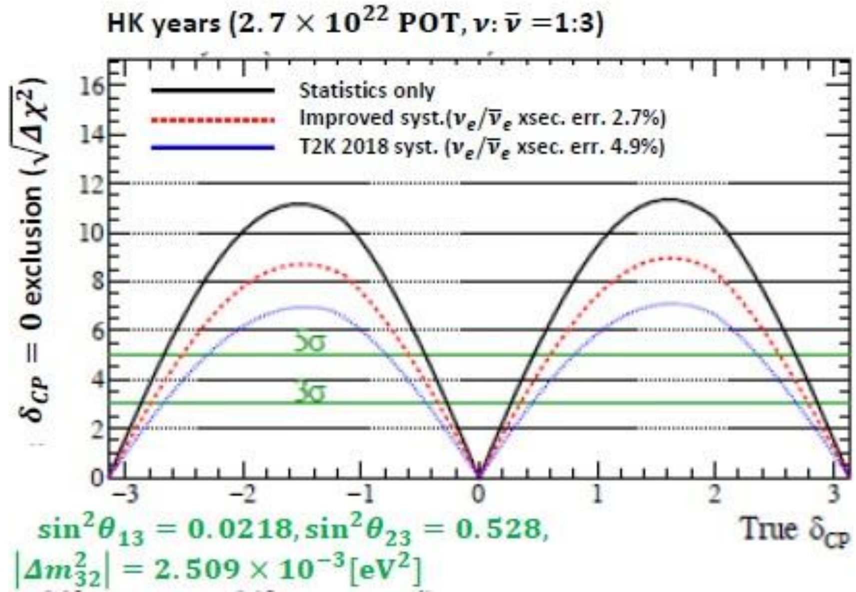
for $\delta_{CP} = 0$	Signal $\nu_\mu \rightarrow \nu_e$ CC	Wrong sign appearance	$\nu_\mu / \overline{\nu}_\mu$ CC	Beam $\nu_e / \overline{\nu}_e$ contamination	NC
ν beam	1,643	15	7	259	134
$\overline{\nu}$ beam	1,183	206	4	317	196

δ_{CP} sensitivity

- NH is assumed.
- Preliminary

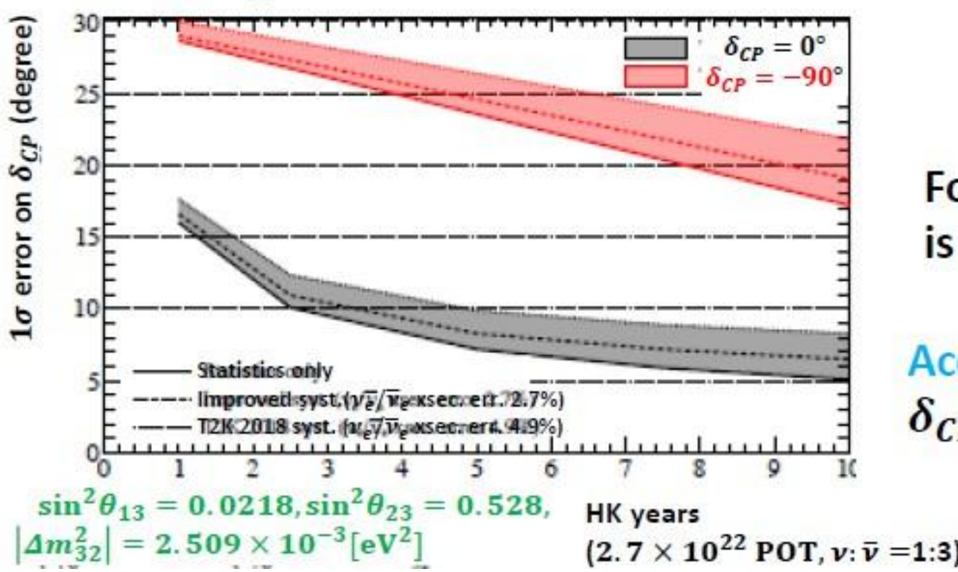


Fraction of δ_{CP} for which $\delta_{CP} = 0$ can be exclude



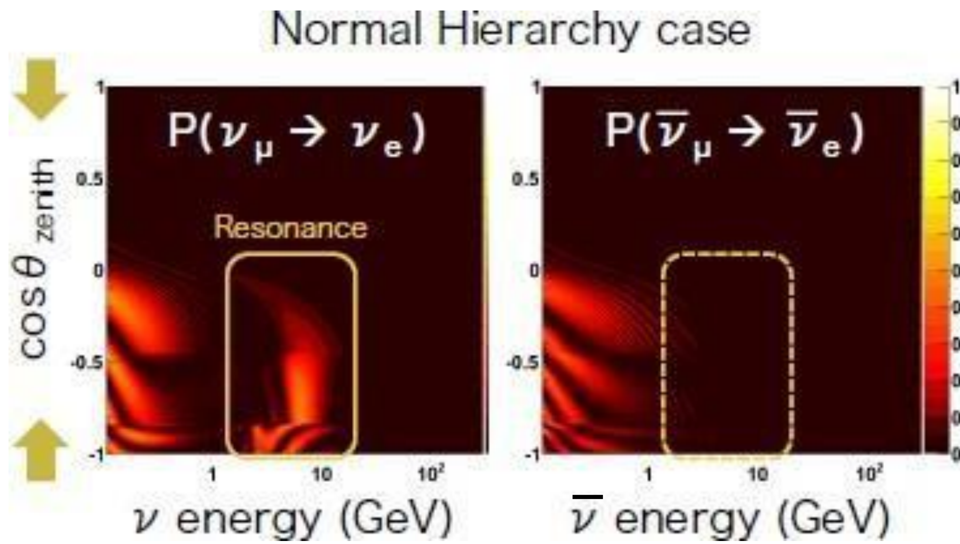
Significance to exclude $\delta_{CP} = 0$ (CP conservation)

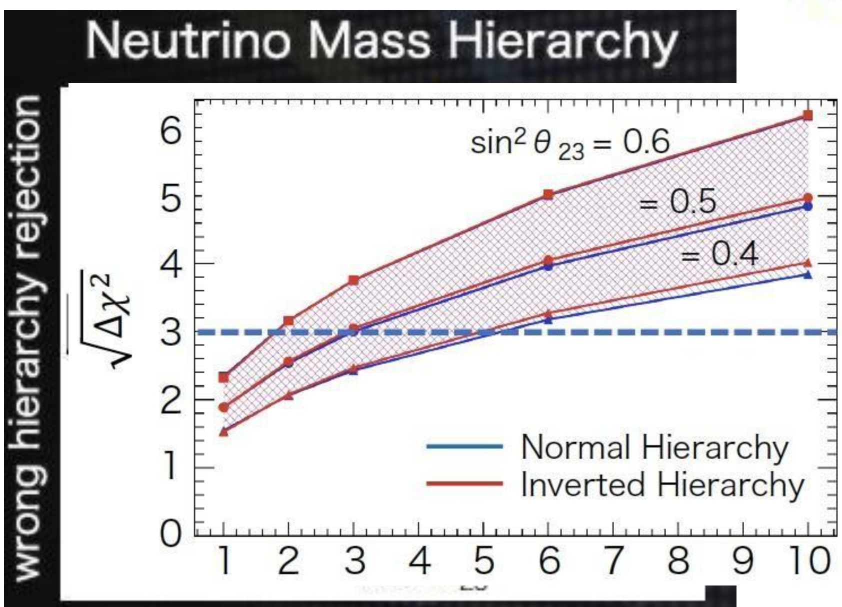
For ~$70\ (50)\ \%$ region, CP conservation is excluded at $> 3\sigma (5\sigma)$



Accuracy on measurement for $\delta_{CP} = 0°$ and $-90°$

Mass hierarchy determination



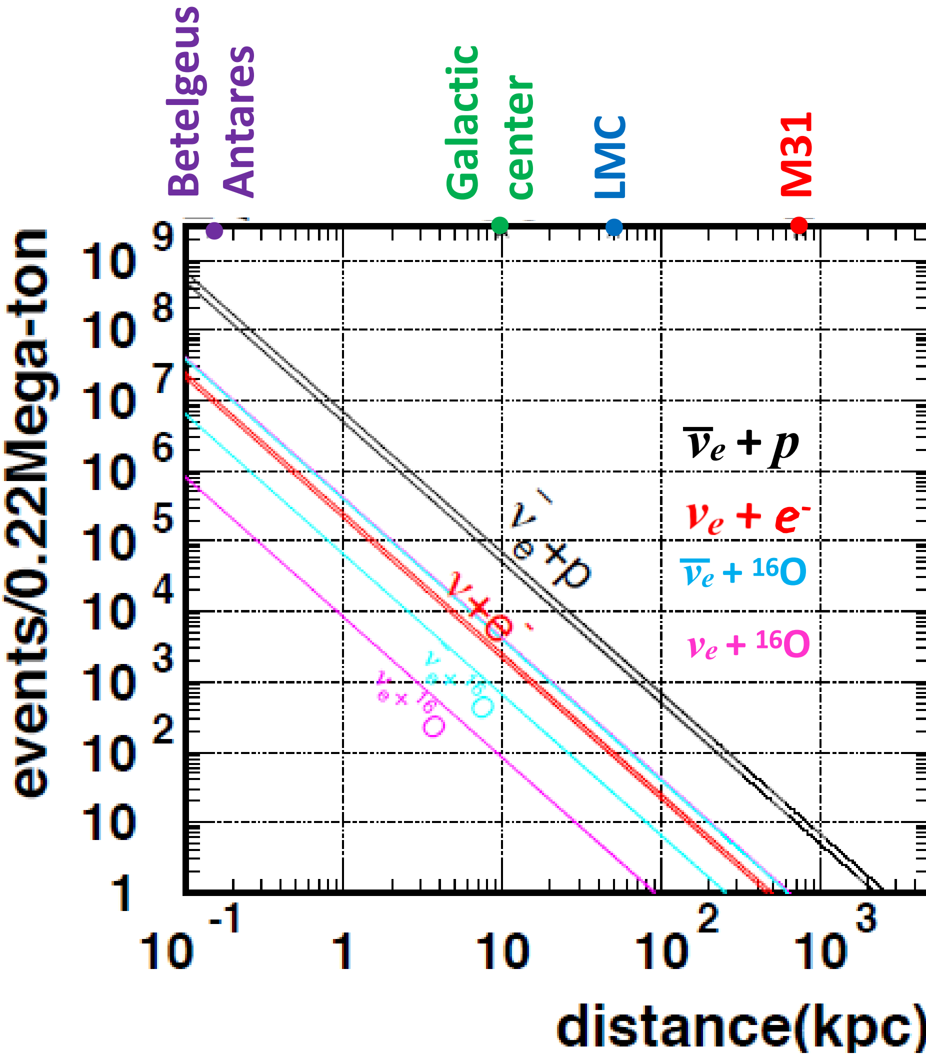


- The resonance appears for ν_e ($\overline{\nu_e}$) in NH (IH) case.
- Sensitivity enhanced by combining atm & beam ν data.→ **3σ determination within 2 ~ 5 years !**

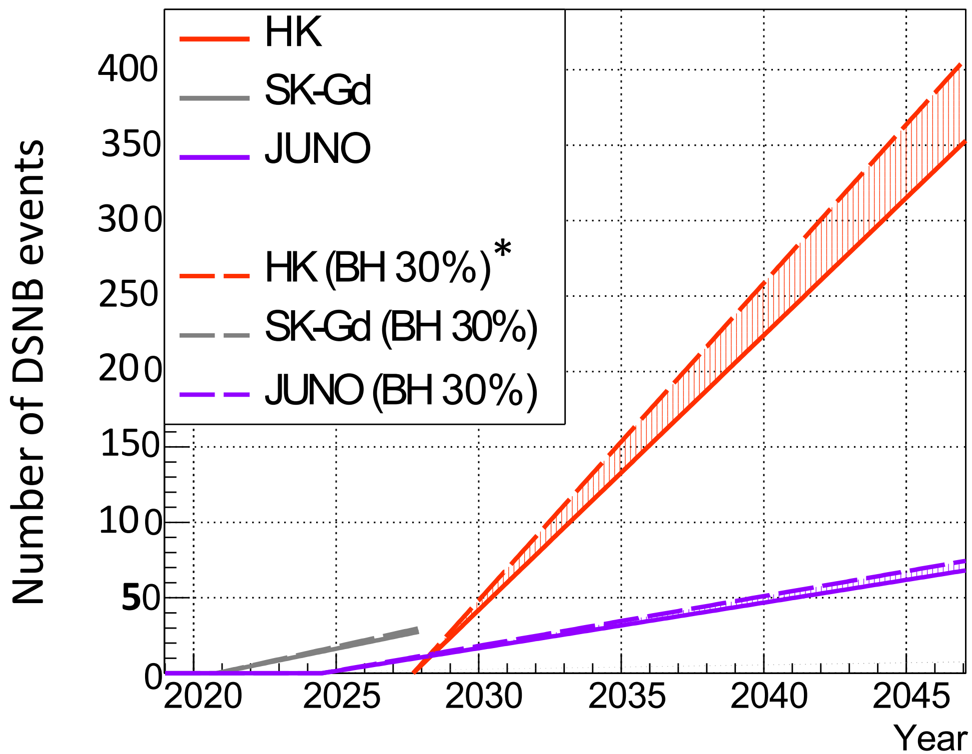
Neutrino astrophysics

SN burst

- ~9 – 13 events for M31 (Andromeda)
- 50 – 80 k events/SN @ 10 kpc
- Time & energy profiles with high statistics
  → Dynamics of SN central engine, explosion mechanism, NS/BH formation
- 1° pointing for SN @ 10 kpc
  → Multi-messenger measurement with optical, GW, etc.



Neutrino astrophysics



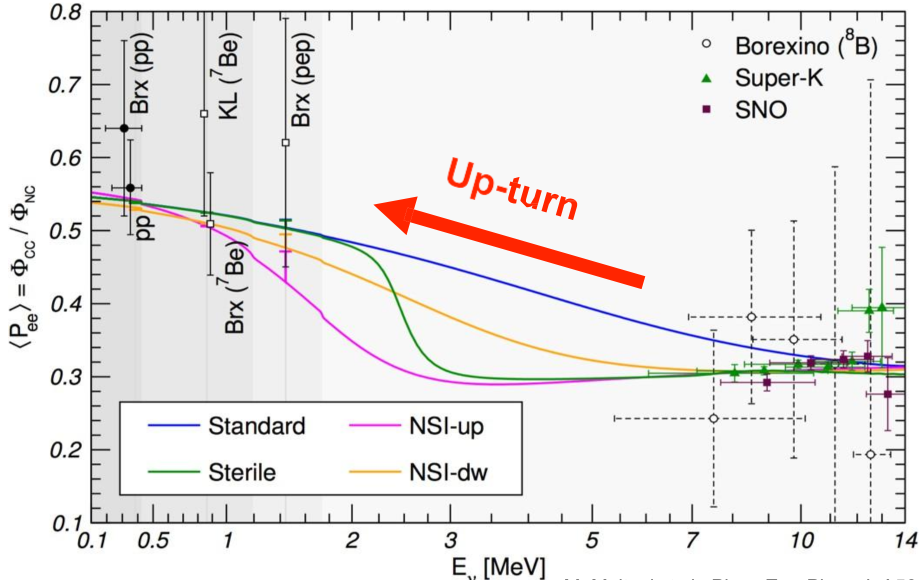
BH 30 % :30% of the supernovae form black hole and emits higher energy Neutrinos.

Defused Supernova Neutrino Background (DSNB)

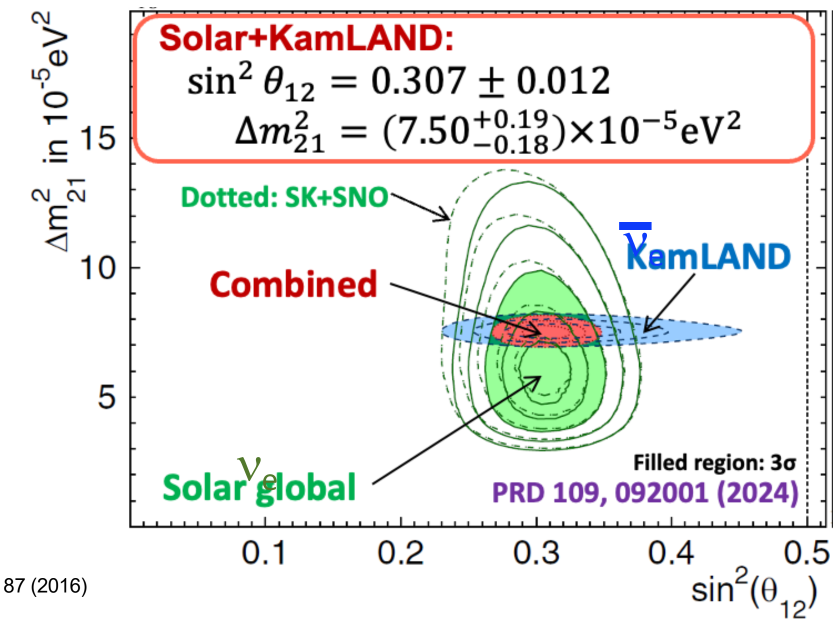
- 1st discovery by SK-Gd
- HK will measure the spectrum.

Solar ν spectrum & possible differences in $\nu_e/\bar{\nu}_e$ oscillation

- Confirmation of MSW effect by observing spectrum distortion "up-turn"
- Comparison of $\nu_e/\bar{\nu}_e$ oscillation (currently ~1.5σ tension in solar/reactor ν)

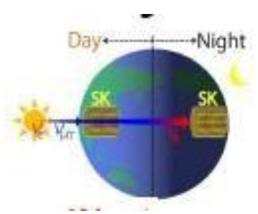


M. Maltoni et al., Phys. Eur. Phys. J. A52, 87 (2016)



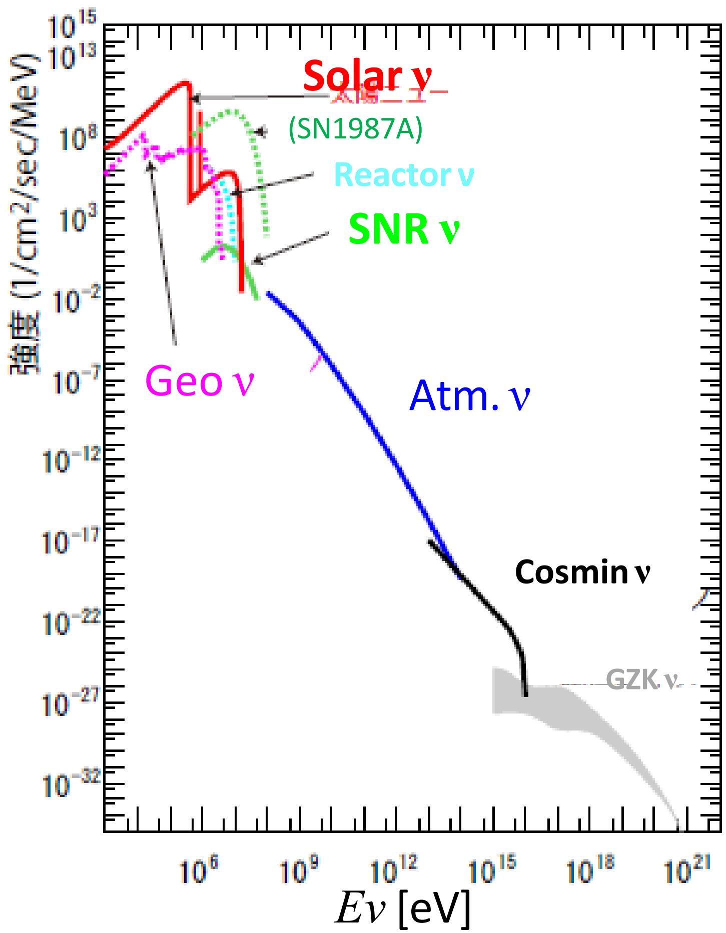
<u>~130 events/day</u>

- > 3σ sensitivity for the spectrum up-turn in 10 yrs (E_{th}=4.5 MeV).
- ~2σ day/night sensitivity expected for the difference in $\nu_e/\bar{\nu}_e$ osc. in 20 yrs.

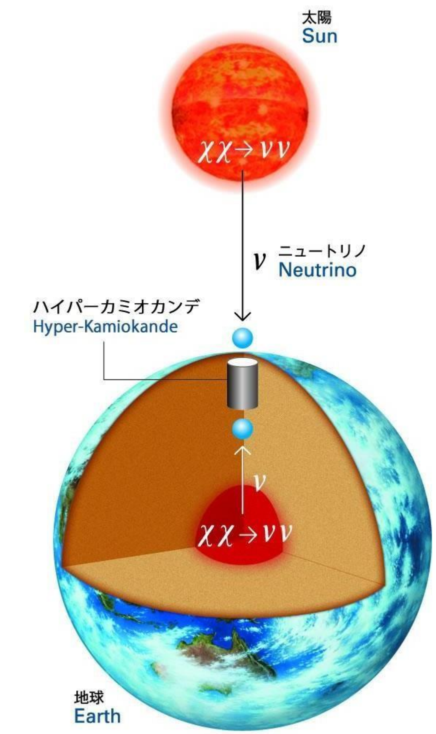


Neutrino astrophysics

-Cosmic ν Observation-



Neutrino fluxes at Kamioka as a function of neutrino energy. Precision measurements for solar, SN(R), and atmospheric neutrinos can be done with high statistics.

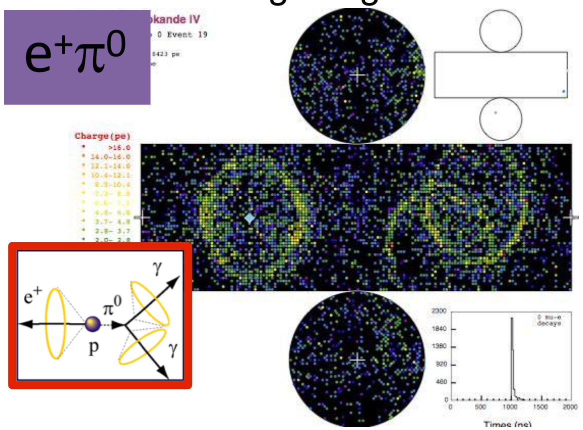


Indirect DM search: Hyper-Kamiokande detects the neutrinos generated by the interaction of dark matters in the Sun or the earth.

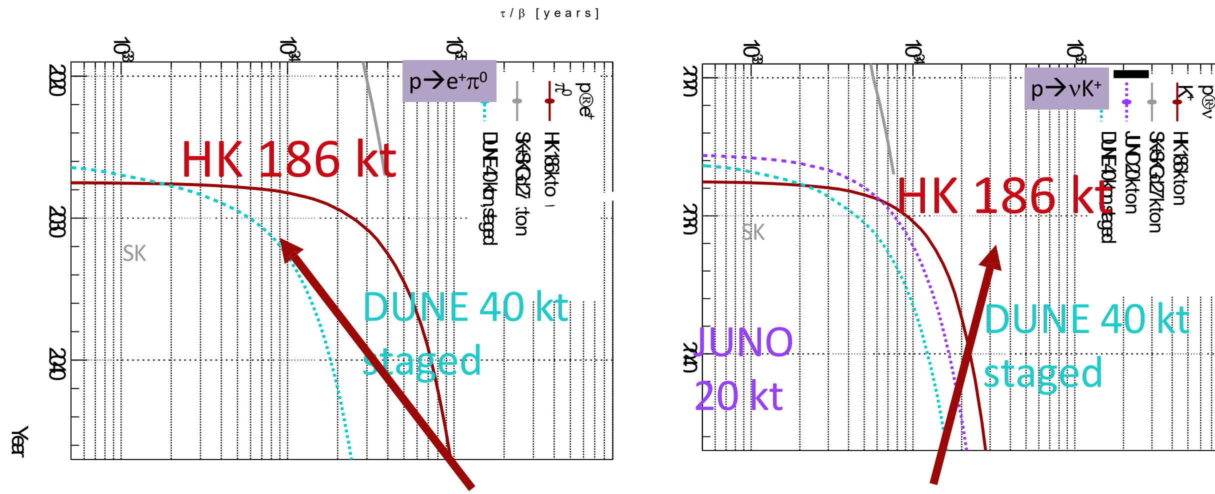
Proton decay searches (note: FV ~8 x Super-K)

→ See and remember Miura-san's lecture

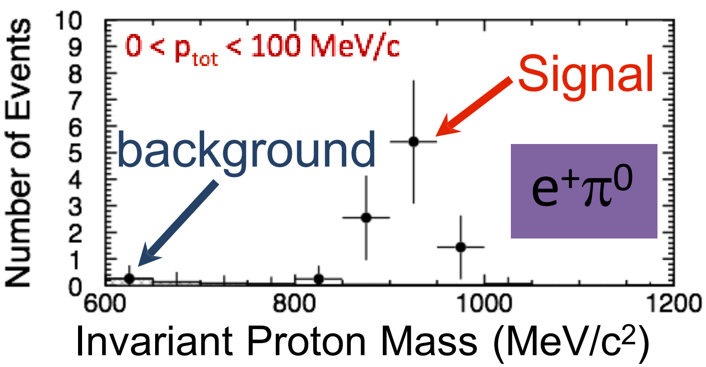
Cherenkov ring image $e^+\pi^0$ in SK



Hyper-K 10 years operation assuming $\tau_{proton}=1.7\times10^{34}$ years (~Super-K limit)



3σ discovery potential



HK 10 years

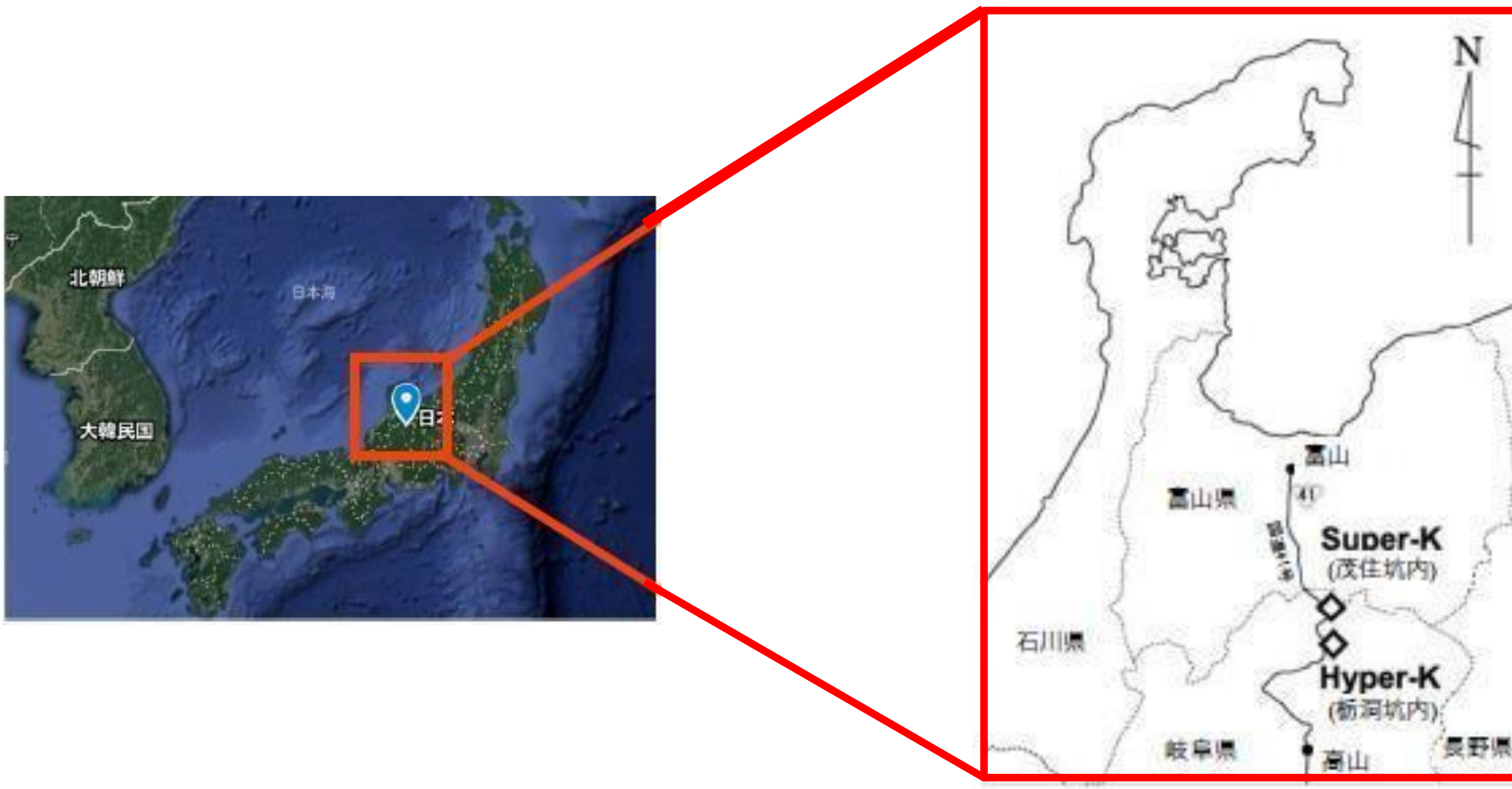
- p→$e^+\pi^0$: ~6×10^{34} yrs
- p→νK^+: ~2×10^{34} yrs
- …

Hyper-K will play a leading role in the next-generation proton decay search

Detector Location

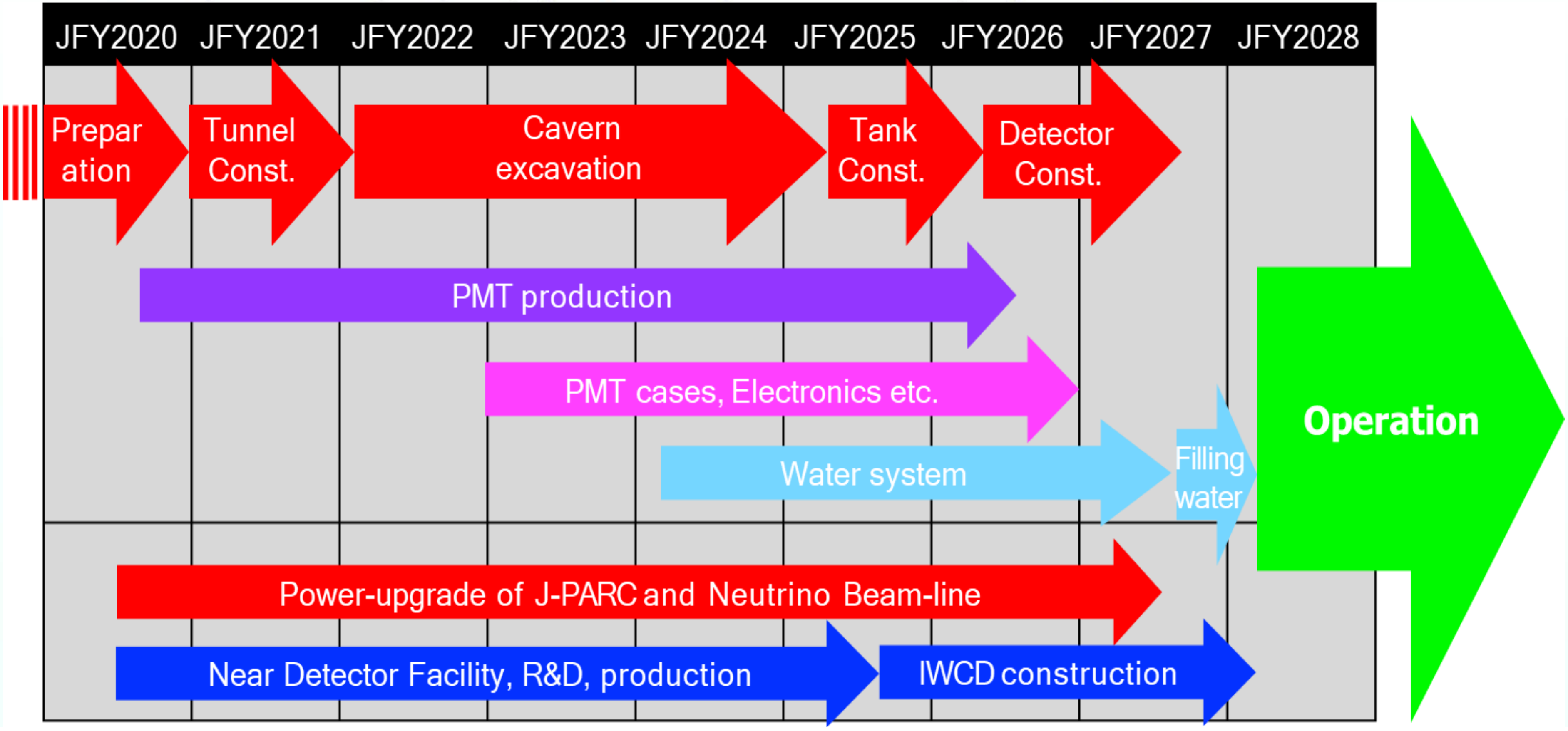
*See Miura-san's lecture

- Under Mt. Nijugo(25)-yama (mountain)
- ～8km south from SK
- Overburden ～650m (～1755m w.e.)
- Identical baseline (295 km) and off-axis angle (2.5°) to T2K



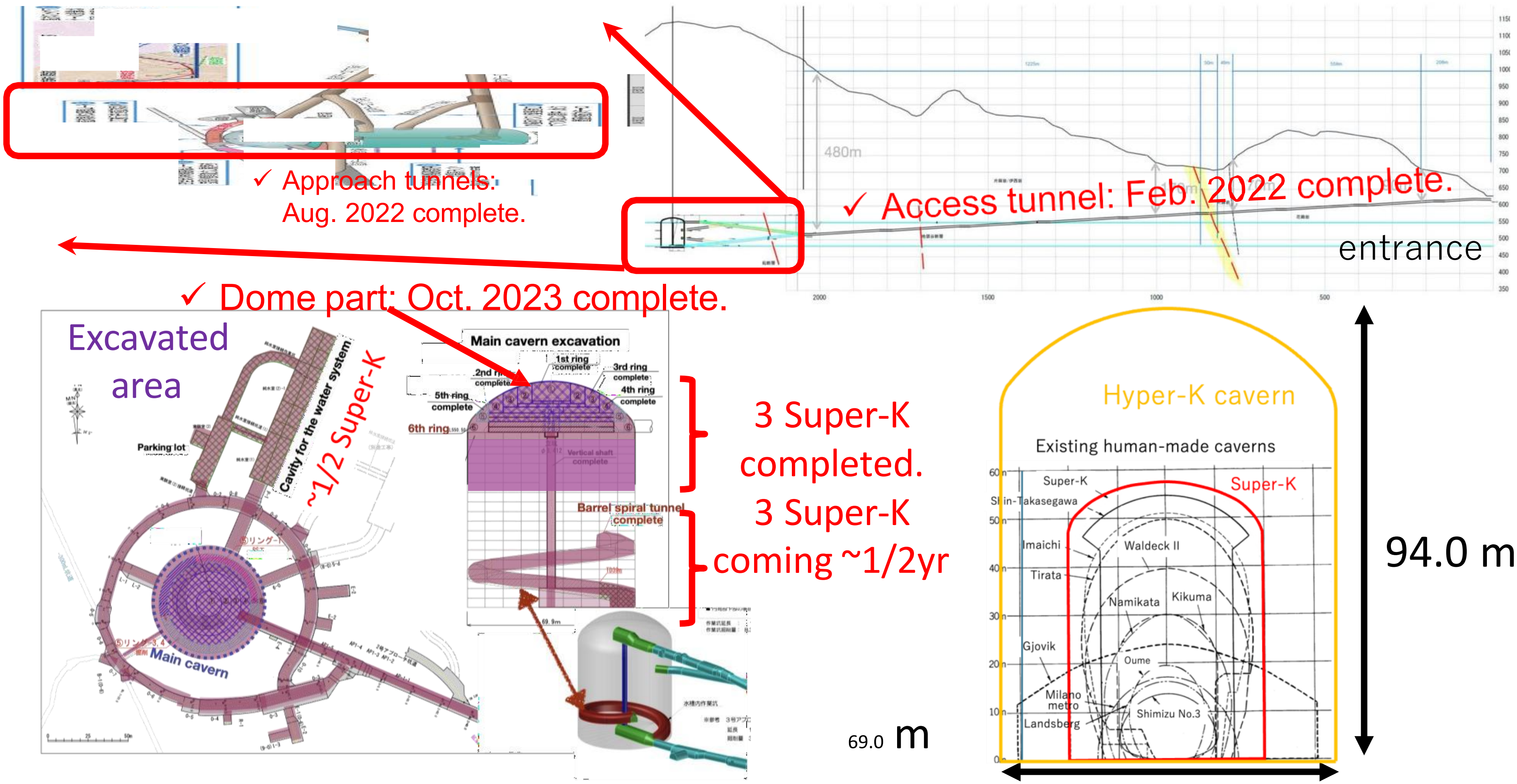
Timeline

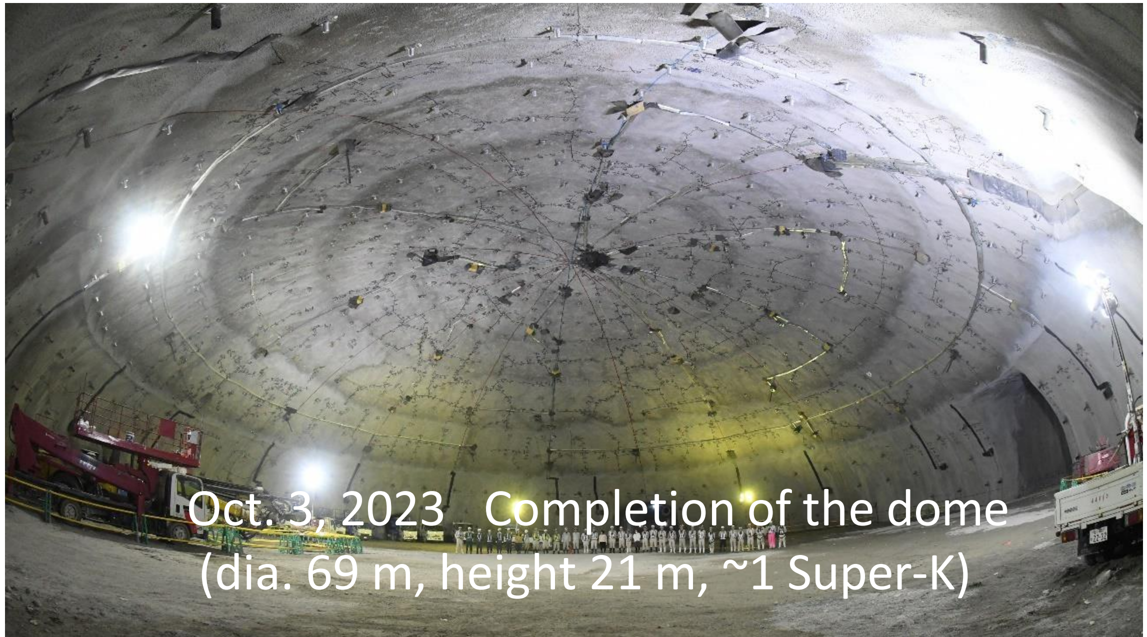
2022-2028 : Construction, 2028- : Operation



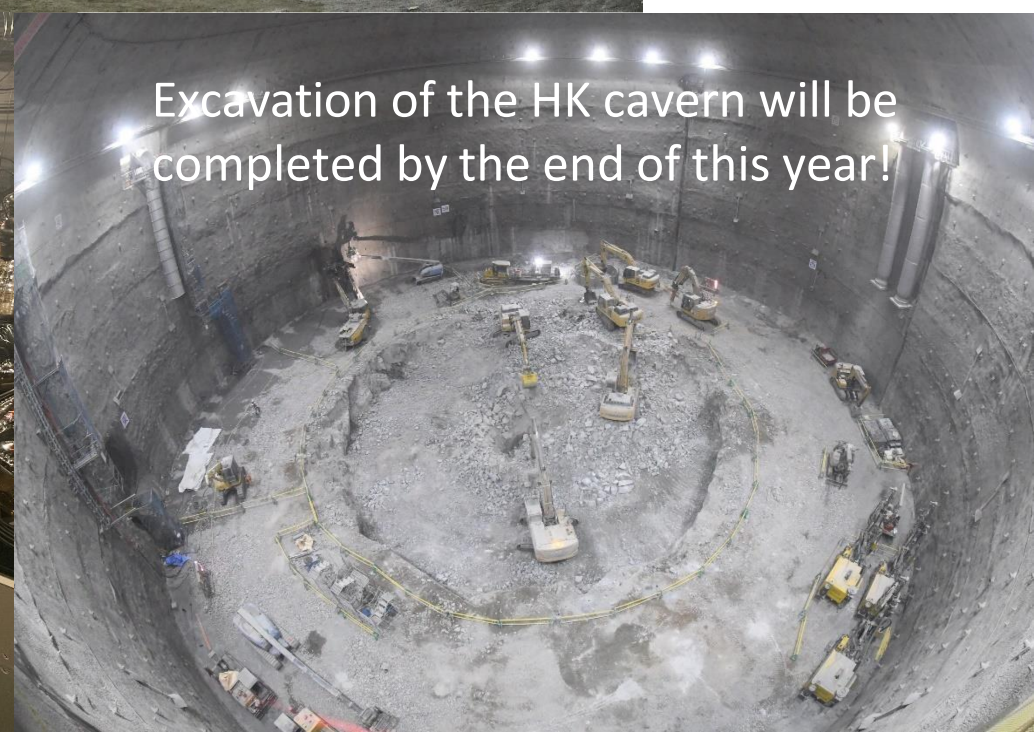
T. Nakaya, Neutrino workshop @ IFIRSE on July 27, 2023

Excavating the world's largest human-made cavern




Oct. 3, 2023   Completion of the dome
(dia. 69 m, height 21 m, ~1 Super-K)

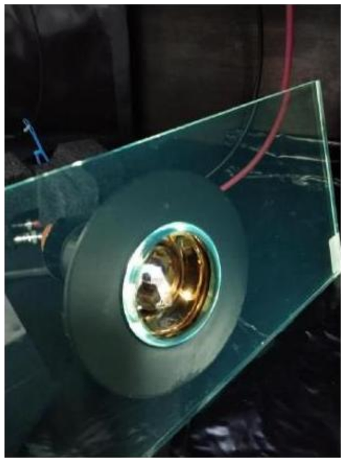

• PMT production ongoing, >10,000 delivered.
• Screening both at Hamamatsu and Kamioka

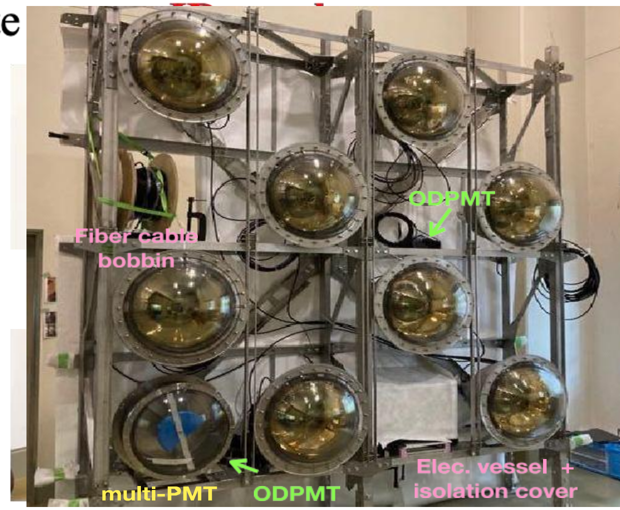

Excavation of the HK cavern will be completed by the end of this year!

Photosensors and underwater electronics

Photosensors/elec. mockup

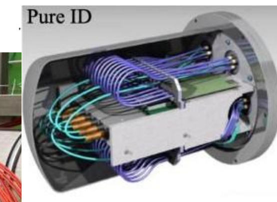
Outer detector: PMT+WLS plate

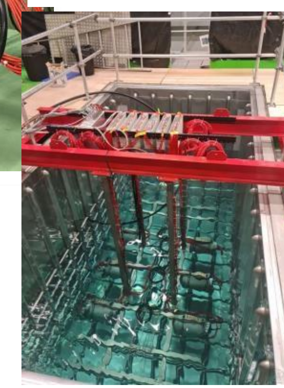




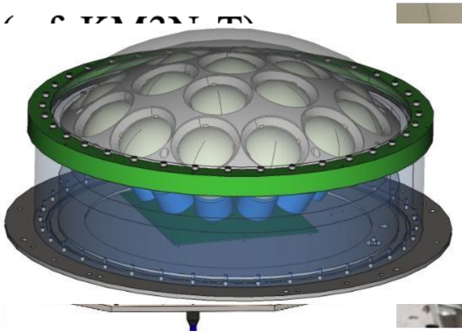
Underwater electronics:

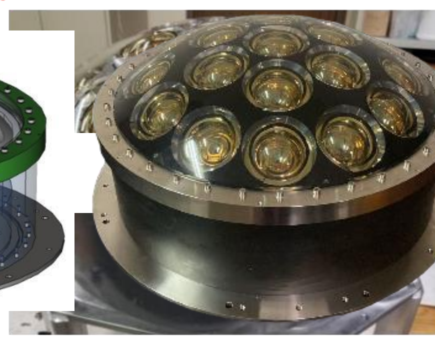
Case design and feedthrough



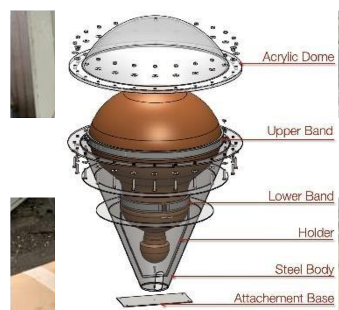


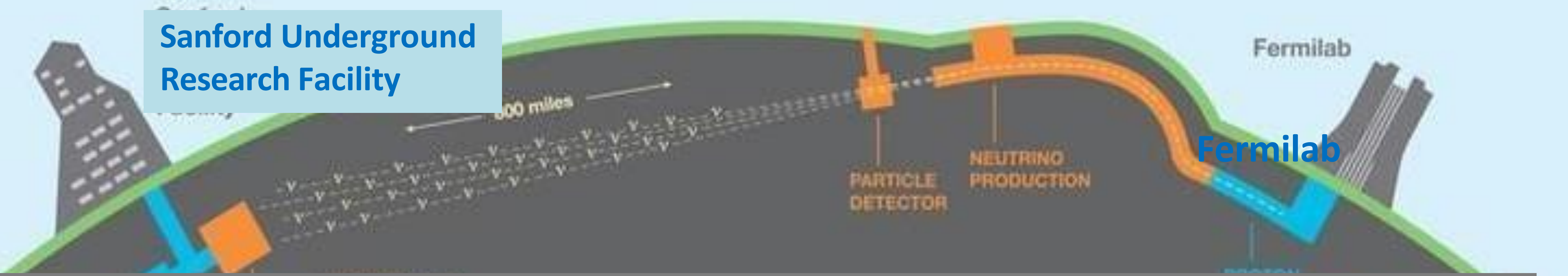
Multi-PMT module:





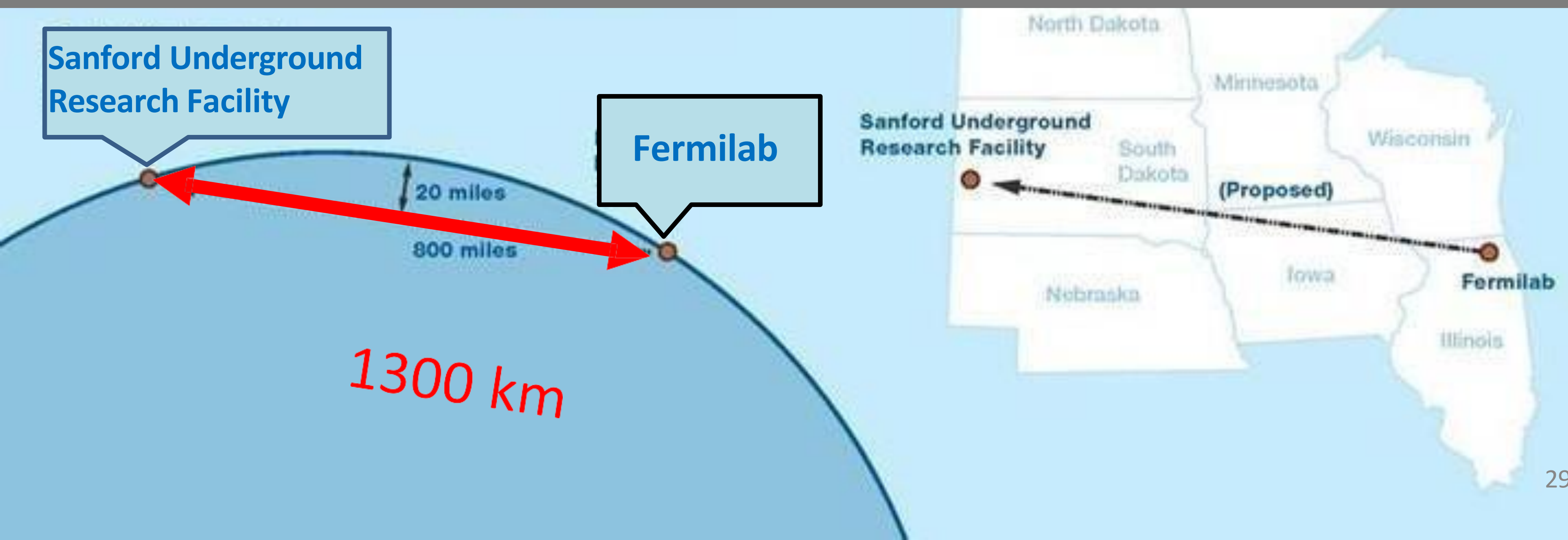
PMT cover





1-2. DUNE

(Deep Underground Neutrino Experiment)



DUNE Science Program

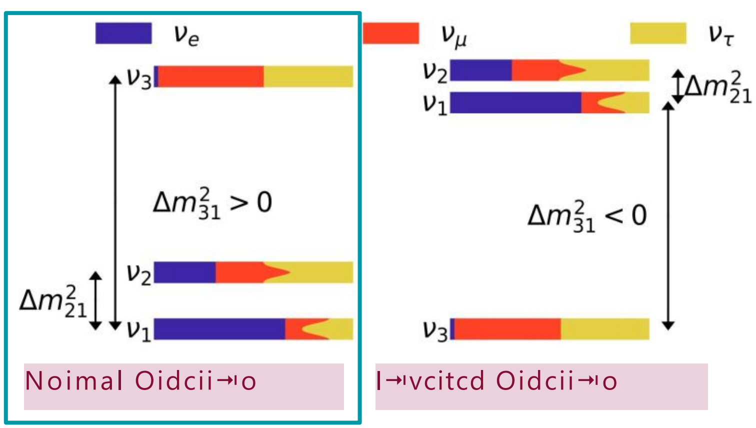
BEAM

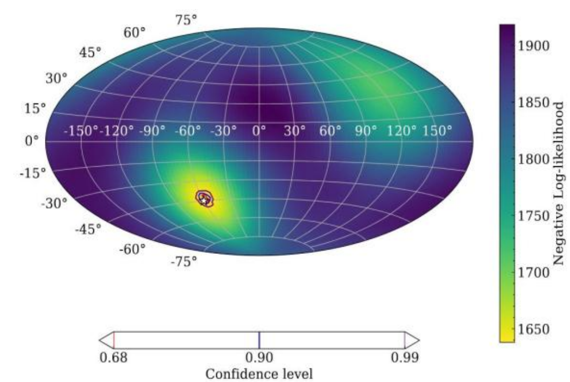
Taking advantage of the **long-baseline,** DUNE will perform **precision** measurements on:

- Leptonic **CP violation**
- **Three neutrino mixing parameters**
- Neutrino **mass ordering** (5σ)

NON-BEAM

- Searches for physics beyond the Standard Model (BSM)
  - Proton Decay search ($p \rightarrow K^{+} \bar{\nu}$)
- Atmospherics neutrinos
- **Low energy neutrino astrophysics:**
  - Solar neutrinos
  - Core-collapse supernovae

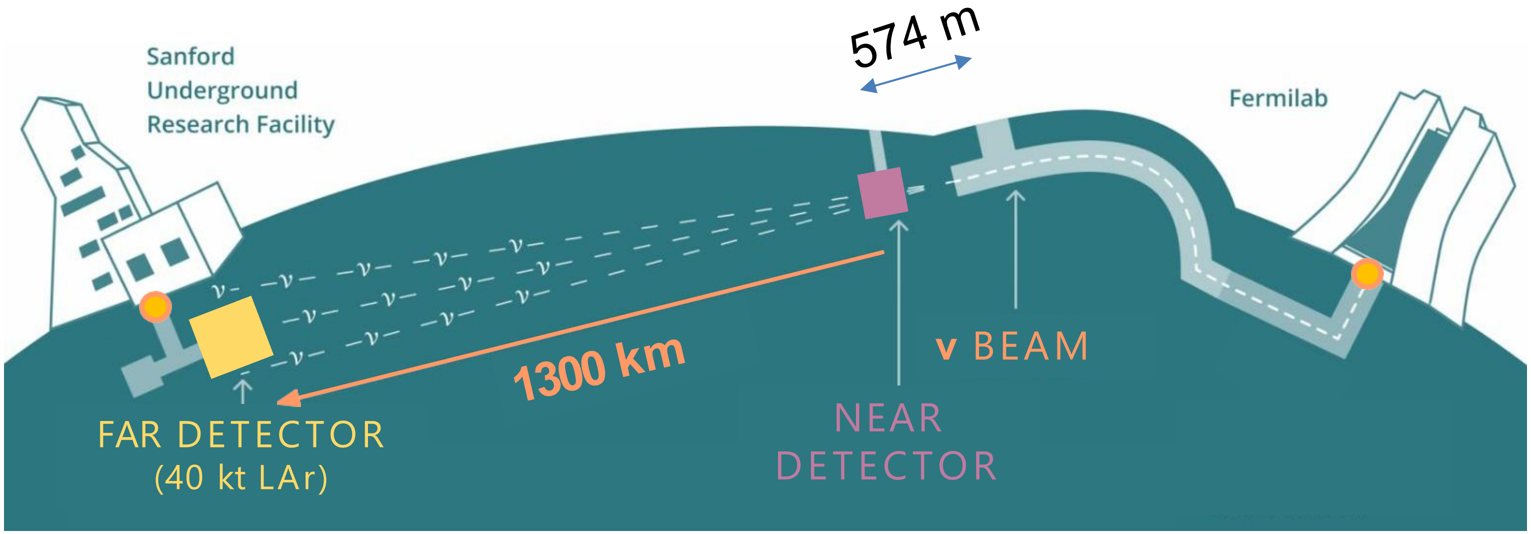




Deep Underground Neutrino Experiment

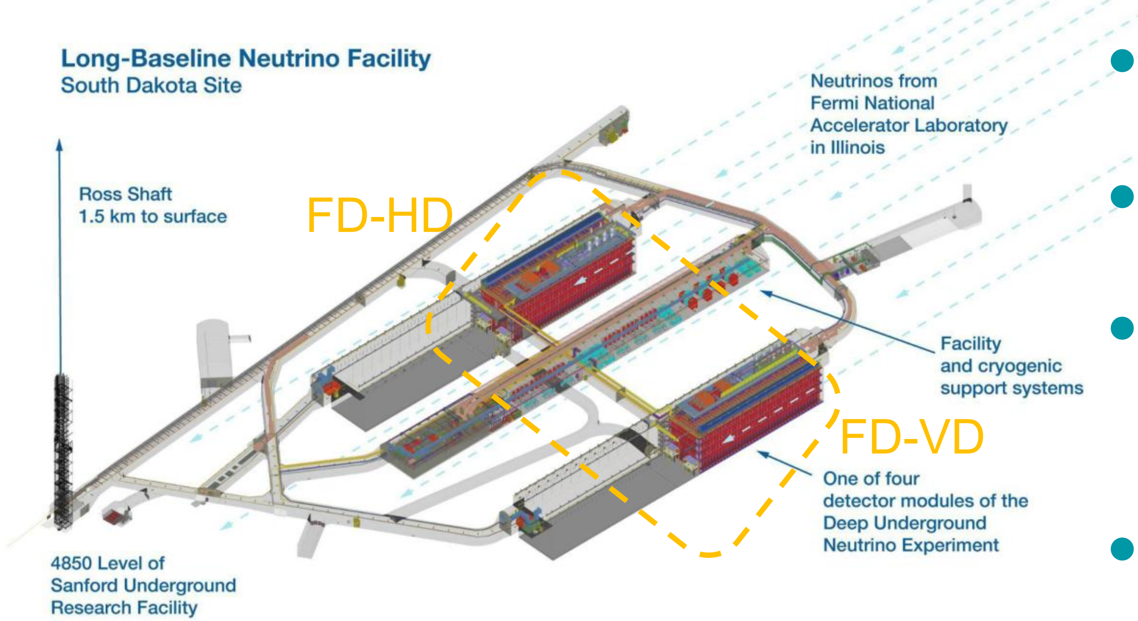
Next-generation long-baseline **1300 km**) oscillation experiment **between Fermilab** (Illinois) and the
Sanford Underground Research Facility (South Dakota, **1.5 km to surface**) consisting of:

1. **Muon neutrino beam: 1.2 MW neutrino beamline** (LBNF)
2. **Near Detector (ND):** 574 m from the beam for **monitoring** the unoscillated flux
3. **Far Detector (FD):** measurement of oscillated neutrinos with four 17-kT LArTPC modules



Phase Approach

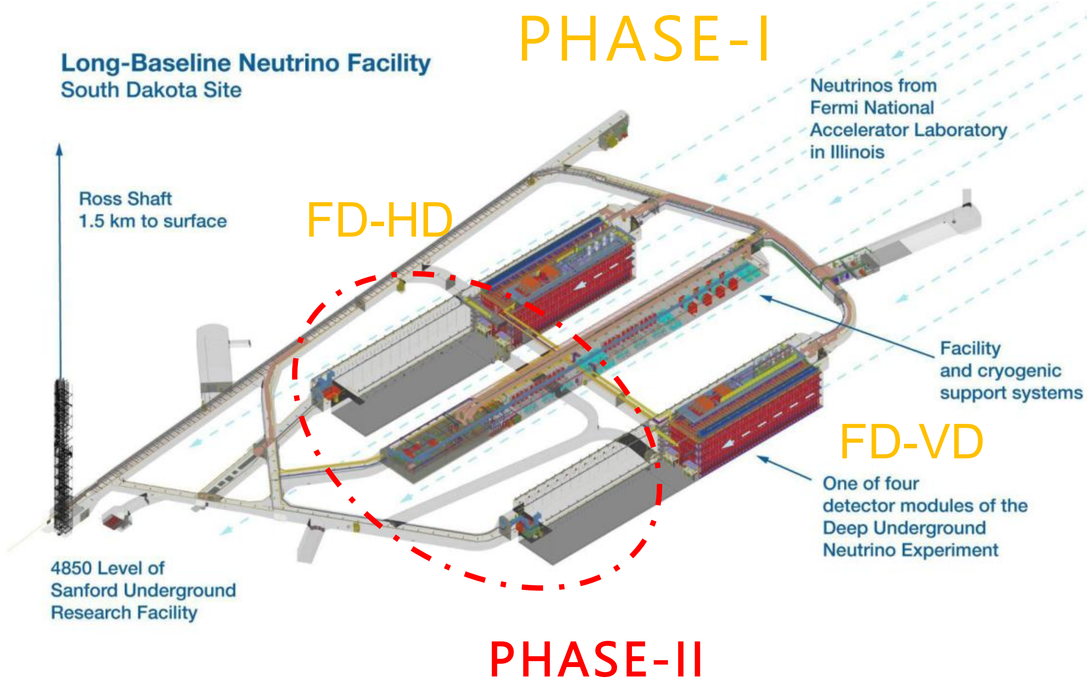
PHASE-I



PHASE-I

- **Full** Near and Far site facilities
- 1.2 MW **upgradable** neutrino beamline
- Far Detector (FD): **two** LArTPCs modules (17 kt each)
- Near Detector (ND): **three** detectors including a LArTPC and a temporary muon spectrometer

Phase Approach



PHASE-II

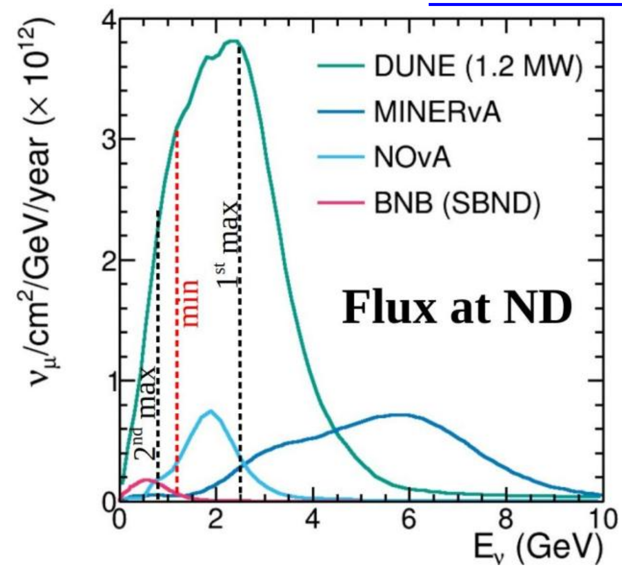
- Beamline upgrade to **> 2MW**
- **Two additional** FD modules (four in total for 40 kt of active volume)
- A more capable ND

DUNE beam and oscillation probability

Precision measurements of the oscillation parameters from P($\nu_\mu \rightarrow \nu_e$) and P($\bar{\nu}_\mu \rightarrow \bar{\nu}_e$)

- Neutrino and Anti-neutrino mode
- **World-leading intensity:** 1.2 MW → 2.4 MW
- Very high flux peaked at **2.5 GeV** neutrino energy
- The oscillation probability has a strong dependence on both δ_{CP} and **mass ordering** for L=1300 km
- **Wide band beam:** coverage of first and second oscillation maximum will be crucial to resolve the degeneracy

DUNE collaboration. Neutrino 2024



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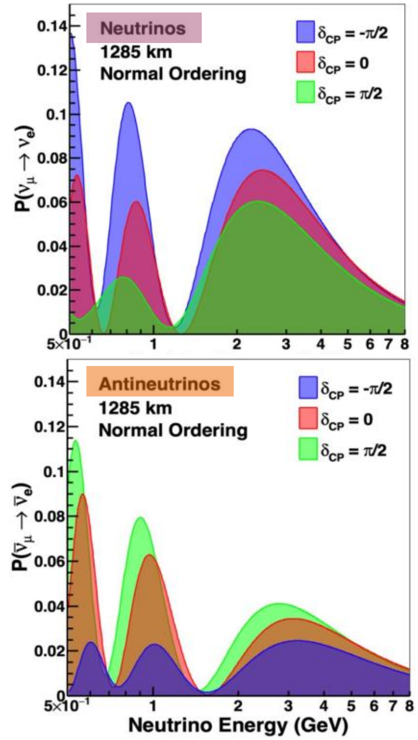
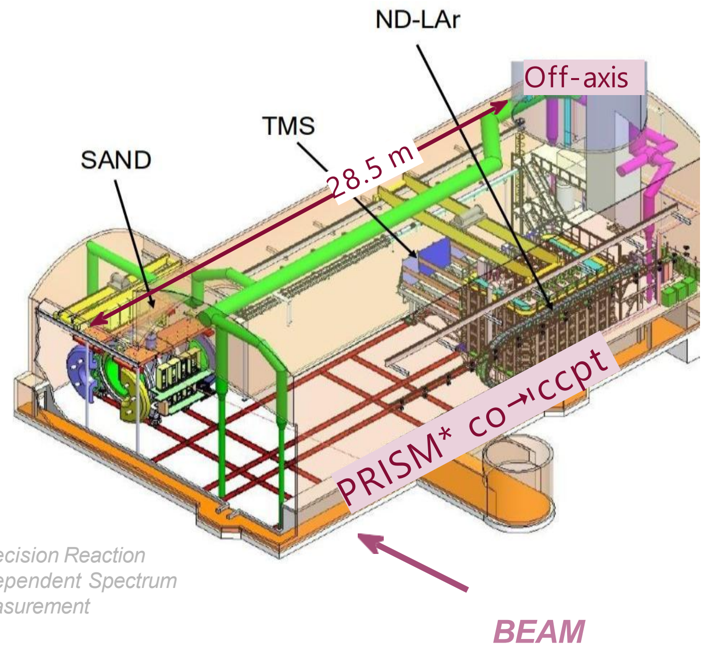


DUNE collaboration. EPJC (2020) 80:978

DUNE Near Detector (ND) - Phase I

Constrain uncertainties for oscillation measurements
- → Monitor unoscillated neutrino flux
- → Measure ν-Ar cross section
- → **Prediction on neutrino spectra at FD**



**Precision Reaction Independent Spectrum Measurement*

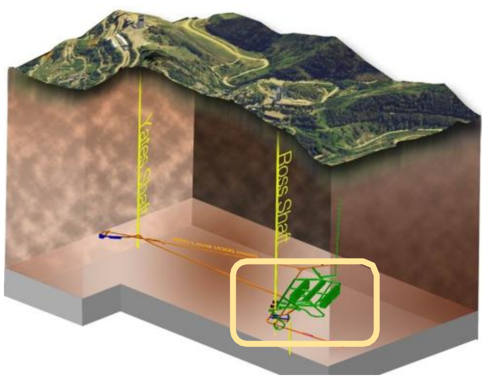
DUNE collaboration. [Instruments 5 (2021) 4, 31]

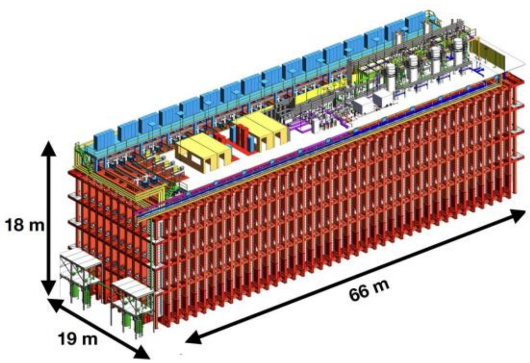
Located 574 m from the beam & 60 m underground

1. **ND-LAr: 50t fiducial volume detector**
   - Primary target, FD technology + pixelated readout
2. **The muon spectrometer (TMS)**
   - Measure μ's escaping the first detector
3. **SAND (tracker surrounded by an electromagnetic calorimeter and magnet)**
   - Monitor the neutrino beam

DUNE Far Detector (FD)

A massive 70 kt detector deployed in 4 modules





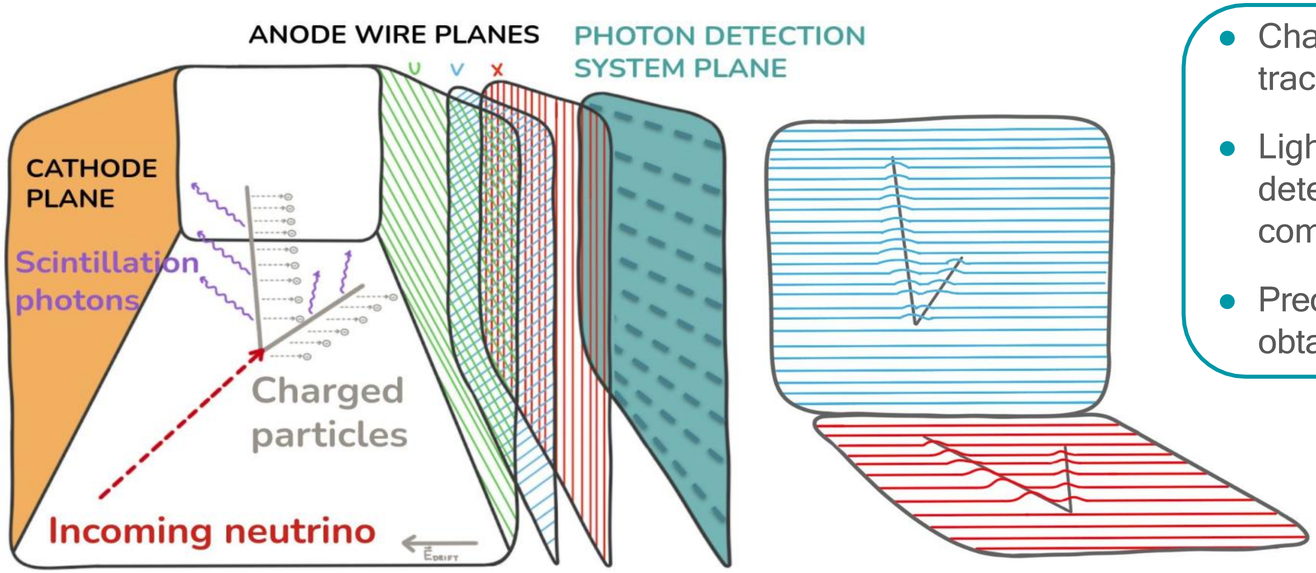
- Sanford Underground Research Facility (SURF)
- 1300 km apart from ND (Baseline)
- 1500 m underground (Background)
- 4 modules in two different caverns
  - Modules 1, 2 and 3 → LArTPCs
  - Module 4 → Module of Opportunity

The phase approach allows to:
- ➔ Consider different technologies for the fourth module
- ➔ Improvements can be applied in the second phase

LArTPC technology

Interaction in LAr

- Ionization electrons (~27k e^-/MeV) → drifted & collected by **anodes planes**
- Scintillation photons (~24k γ/MeV) → detected by the **photon collectors**

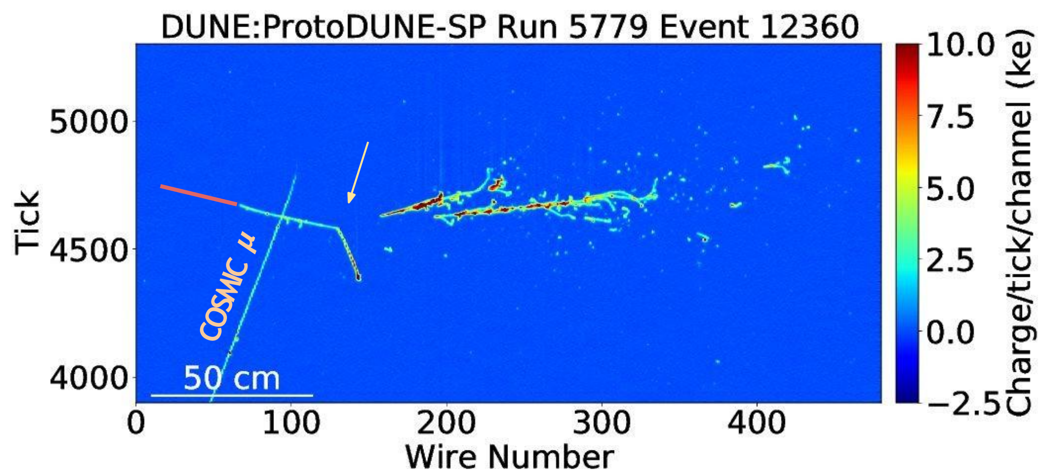


- Charge provide a precise tracking and calorimetry
- Light is crucial for t_0 determination and can complement calorimetry
- Precise **images** can be obtained

LArTPC images

- ➔ 60% of interactions at DUNE energy have final state pions
  - ◆ Measuring them will constrain DUNE interaction models!
- ➔ LArTPC enables precise hadron reconstruction
- ➔ Excelent e/μ and e/γ separation
- ➔ High quality **particle ID** and **energy reconstruction**
- ➔ Spatial resolution ~mm

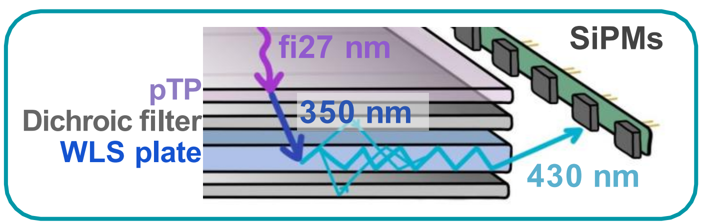
1st ProtoDUNE run - Beam Event Example

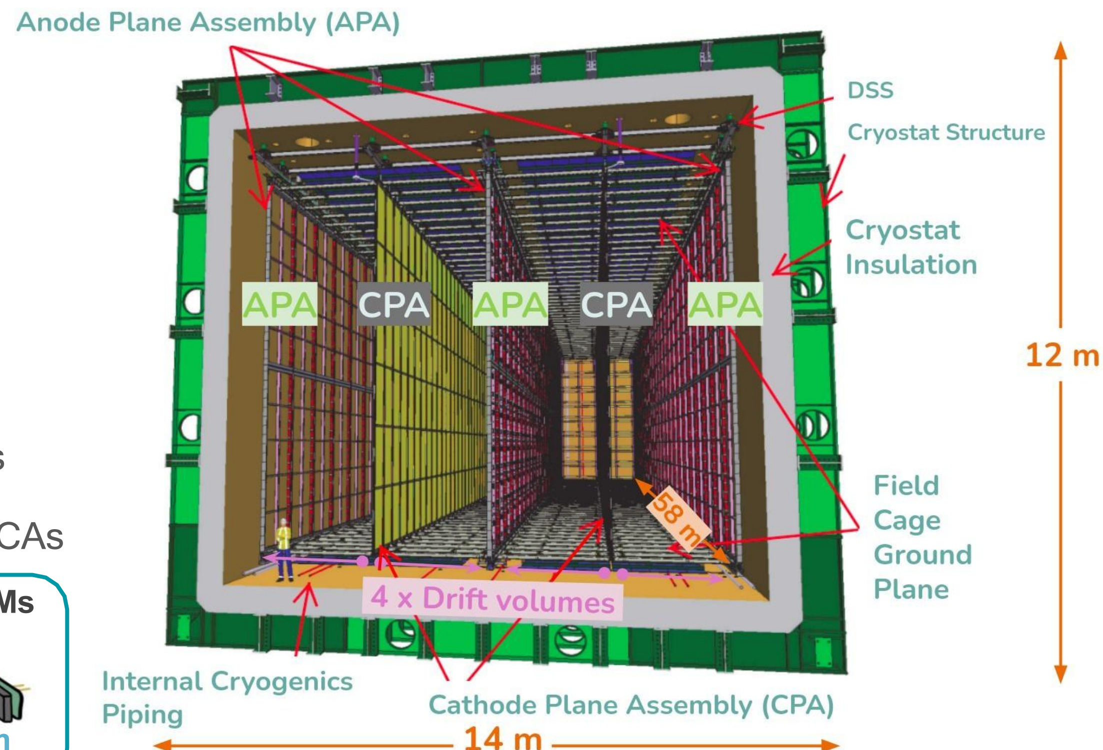


ProtoDUNE-SP. [JINST 15 (2020) P12004]

Far Detector Horizontal Drift (FD-HD)

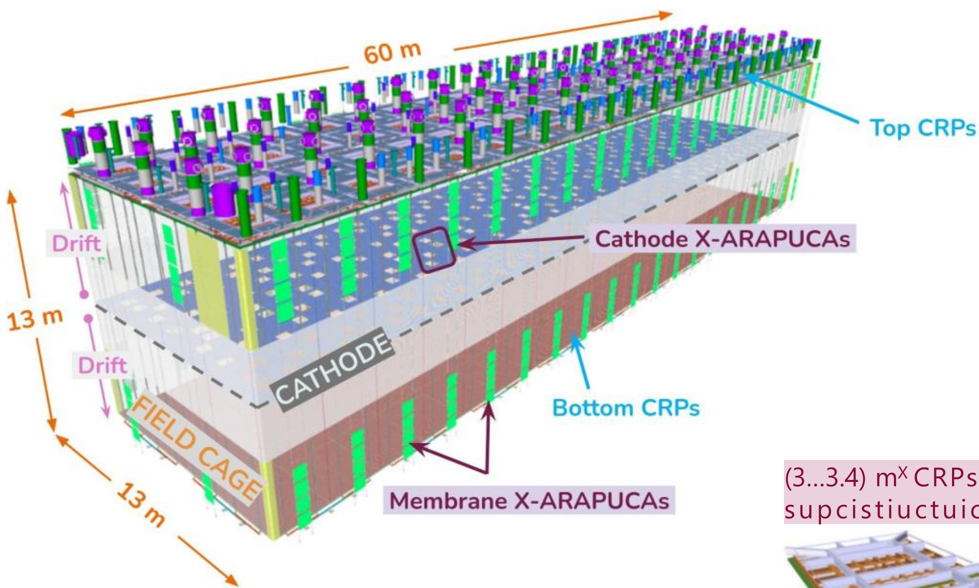
- Established and validated technology
- TPC size: $(12x14x58.2)\ m^3$
- 4 horizontal drift regions (3.5 m)
- Drift Voltage 500 V/cm
- Vertical cathode and anode planes
- Photon detectors on the anode planes
- Photon detection based on X-ARAPUCAs





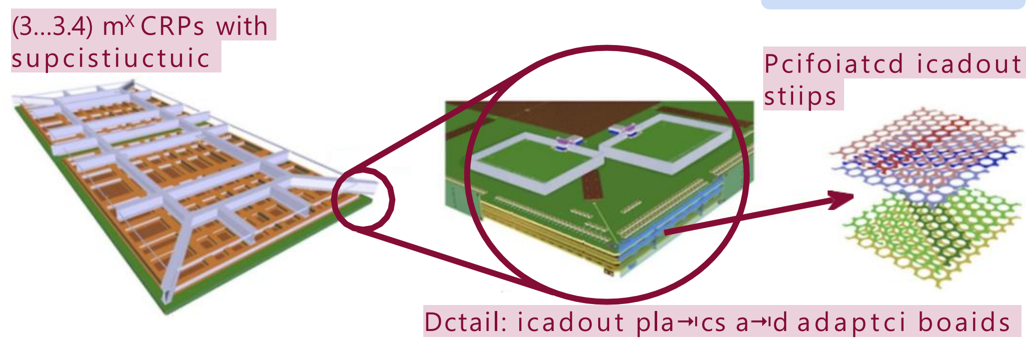
DUNE collaboration. [JINST 15 (2020) T08010]

Far Detector Vertical Drift (FD-VD)



- Simpler construction
- 2 volumes separated by a cathode
- 6.5 m drift distance (drift field 450 V/cm)
- 2 anode planes (top & bottom)
- X-ARAPUCAs on the cathode plane and membrane walls
- PCB-based charge readout

see F. Boran's talk



Baseline design for modules 3 and 4

DUNE collaboration. [*JINST 19 (2024) 08 T08004*]

ProtoDUNEs at CERN (HD & VD)

- 750 t LAr total (1/20 of one FD module)
- **Real-size** readout elements (APA, PDS, CRP)
- Successful phase-I (2018 - 2020)
- ProtoDUNE-HD campaign in 2024
  - Test upgraded components in **their final design** and take more beam data
- ProtoDUNE-VD campaign in 2025
  - Test the VD concept for the first time at large scale

Building DUNE: schedule

2025

Building & Site Infrastructure

2026

Cryostat installation

2027

FD Installation

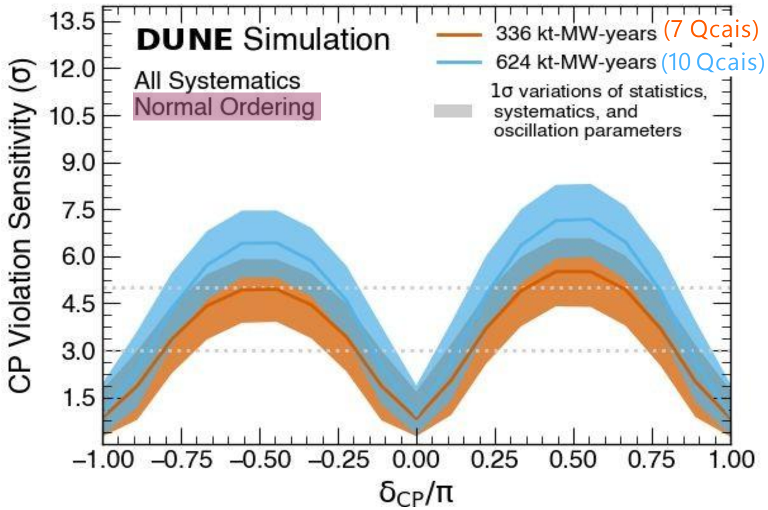
2030

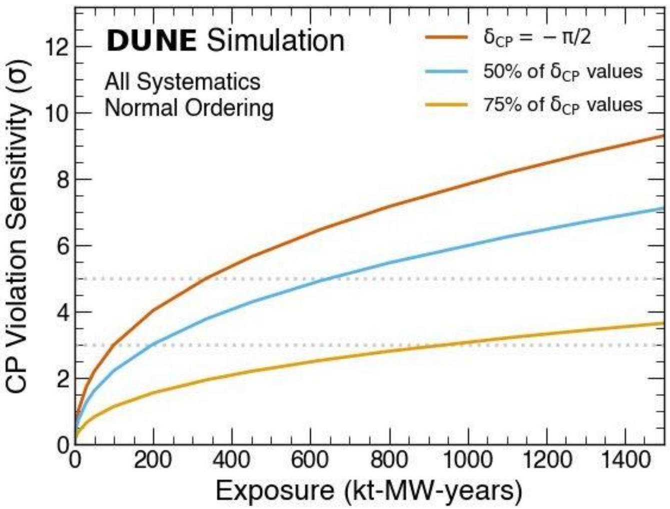
PHYSICS

- Solar, atmospheric and astrophysics
- Full beam physics

CP Sensitivity

- After **10 years** exposure there is significant CP violation ($\delta_{CP} \neq 0, \pi$) discover potential across true values of δ_{CP} and for both hierarchies
- DUNE can establish CPV **over 75% of δ_{CP} values** at >3σ ***(worst case scenario)***
- DUNE can establish CPV **over 50% of δ_{CP} values** at >5σ



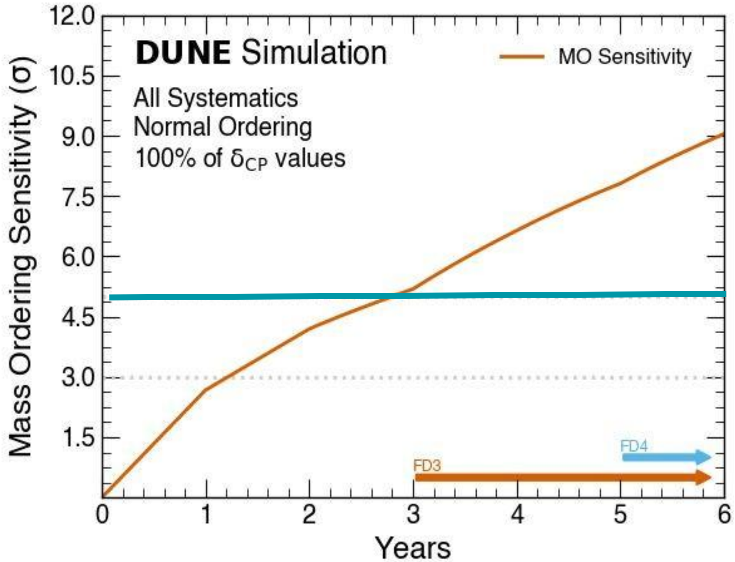


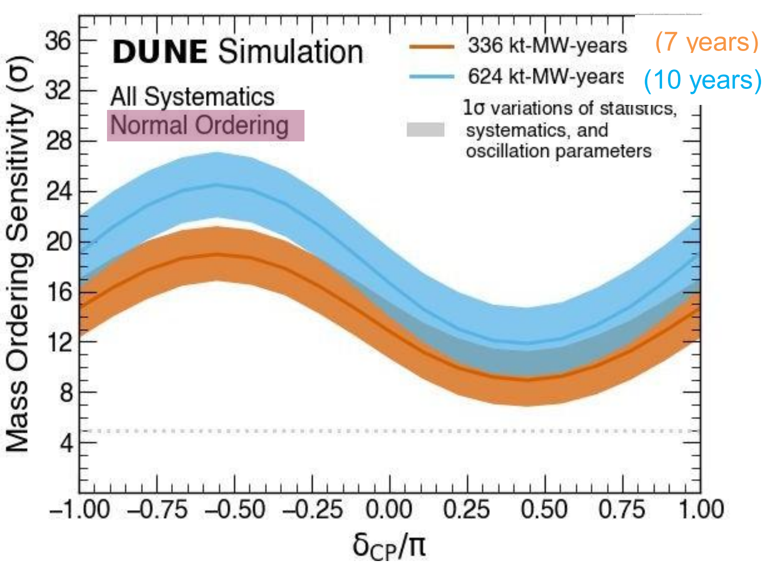
DUNE collaboration. [EPJC (2020) 80:978](#) & [Neutrino 2024](#)

Mass Ordering Sensitivity

Regardless of the values of the other oscillation parameters:

- DUNE can establish mass ordering at > 5σ in **3 years** (worst case scenario)
- Obtain a definitive answer for the mass hierarchy within **7 years**



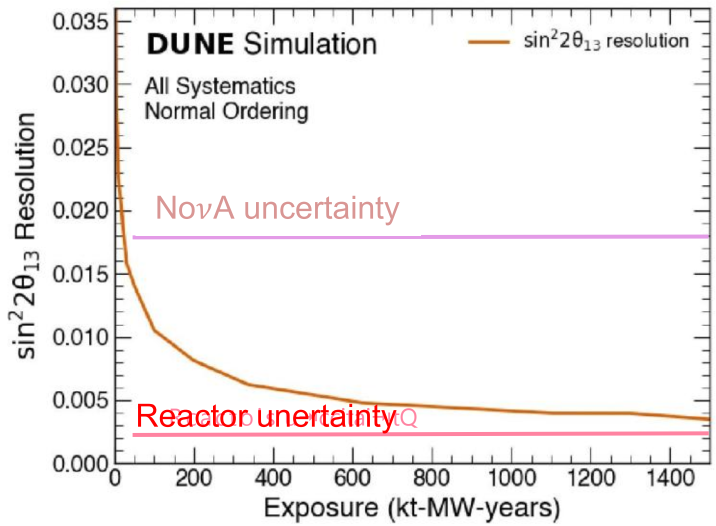


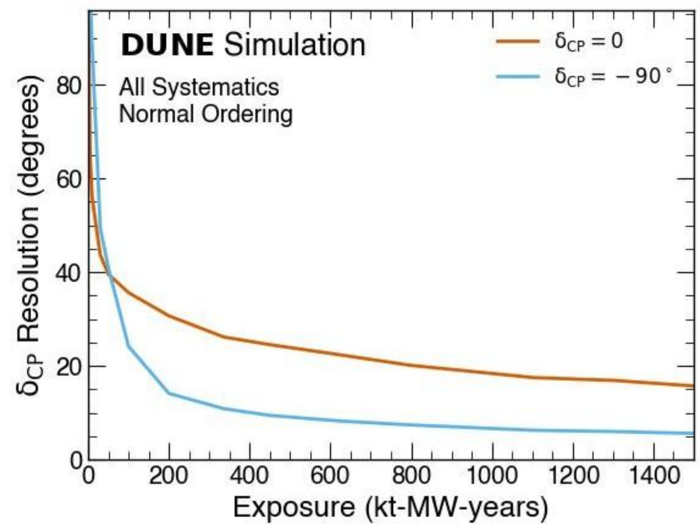
DUNE collaboration. [*EPJC (2020) 80:978*] *&* [*Neutrino 2024*]

European Physical Society (Marseille) - 8th July 2025

Resolution to oscillation parameters

- **World-leading precision** (for long-baseline experiment) in θ_{13} and Δm^2
  $\rightarrow$ comparisons with reactor measurements are sensitive to new physics
- Ultimate precision 6°-16° in δ_{CP}



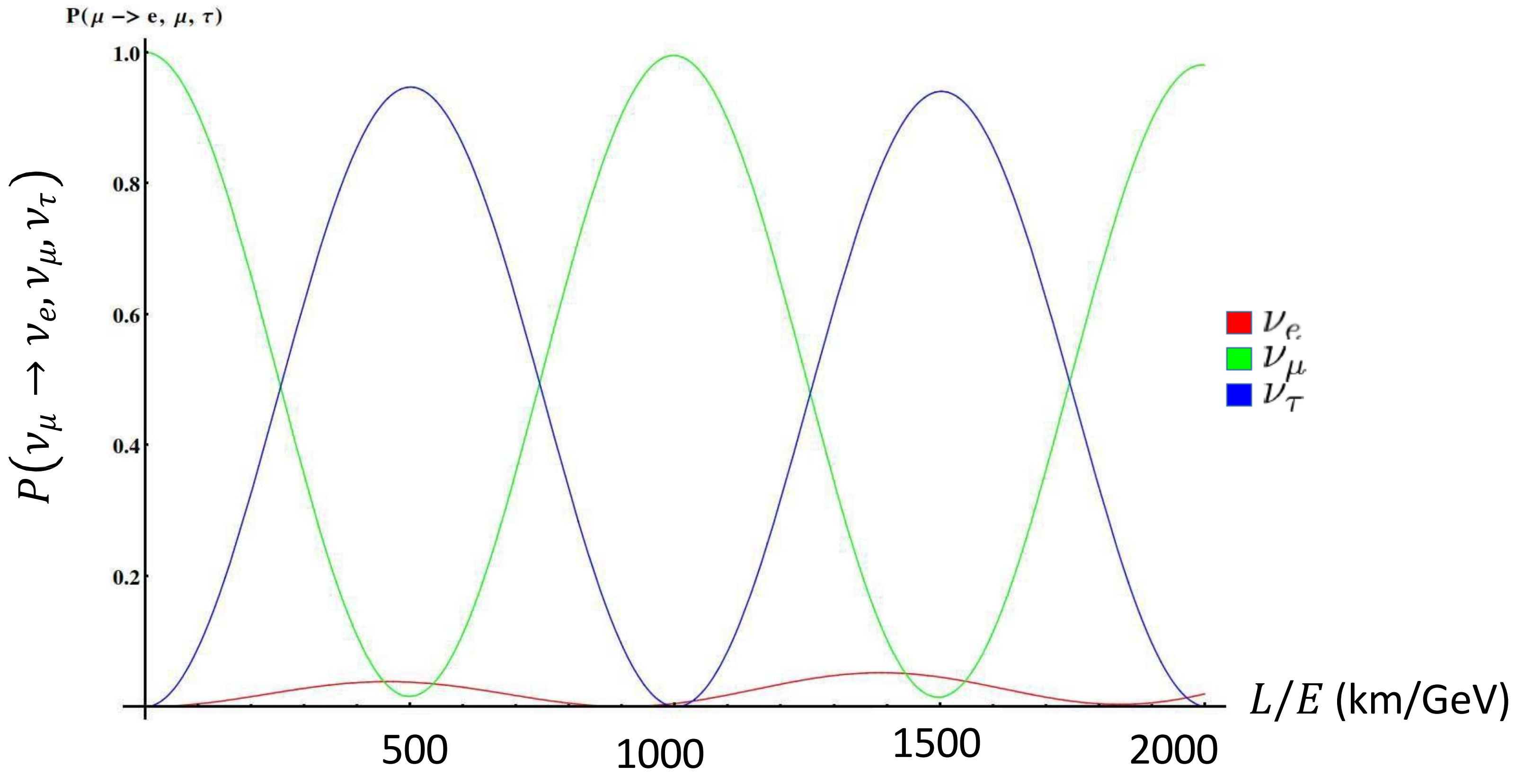


DUNE collaboration. [*EPJC (2020) 80:978*]() *&* [*Neutrino 2024*]()

1-3. ESSnuSB

(European Spallation Source neutrino super-beam)

Next-to-next CPV precision measurement experiment at the 2nd oscillation maximum



Why 2nd maximum ?

$$A_{CP} \equiv P_{\nu_\mu \to \nu_e} - P_{\overline{\nu}_\mu \to \overline{\nu}_e} = -16J \sin\frac{\Delta m^2_{31}L}{4E} \sin\frac{\Delta m^2_{32}L}{4E} \sin\frac{\Delta m^2_{21}L}{4E}$$

$$A_{CP}(1st\ Osci.max) = \mathbf{0.03} \cdot sin\delta_{CP}$$

$$A_{CP}(2nd\ Osci.max) = \mathbf{0.075} \cdot sin\delta_{CP}$$

$s_{ij} \equiv \sin\theta_{ij}$

$c_{ij} \equiv \cos\theta_{ij}$

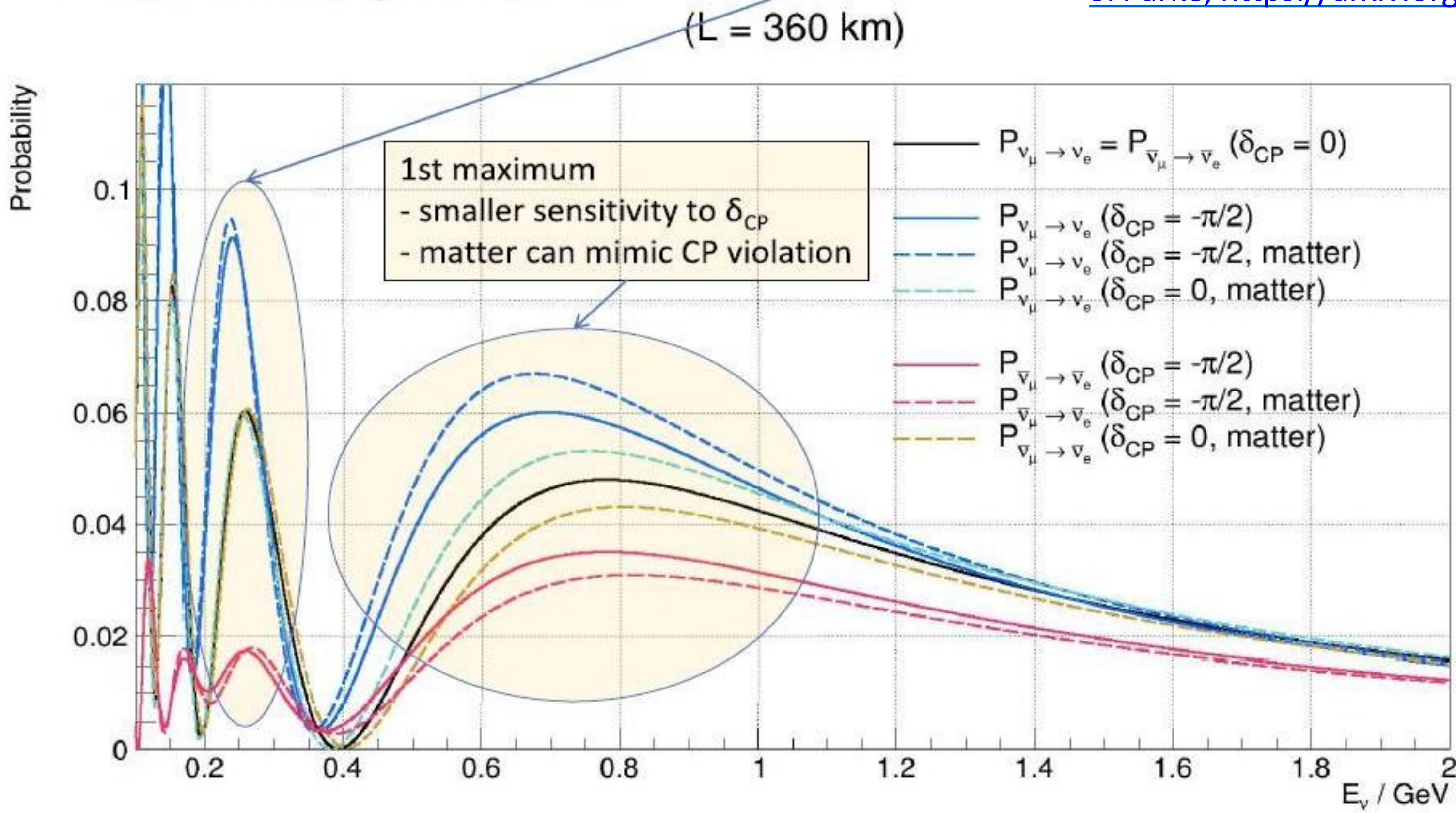
$\Delta m^2_{ij} \equiv m^2_{\nu_i} - m^2_{\nu_j}$ $\quad J = s_{12}c_{12}s_{13}c_{13}s_{23}c_{23}c_{13}\sin\delta_{CP}$

$$\frac{A_{CP}@\ 2nd\ max.}{A_{CP}@\ 1nd\ max.} \sim 2.5$$

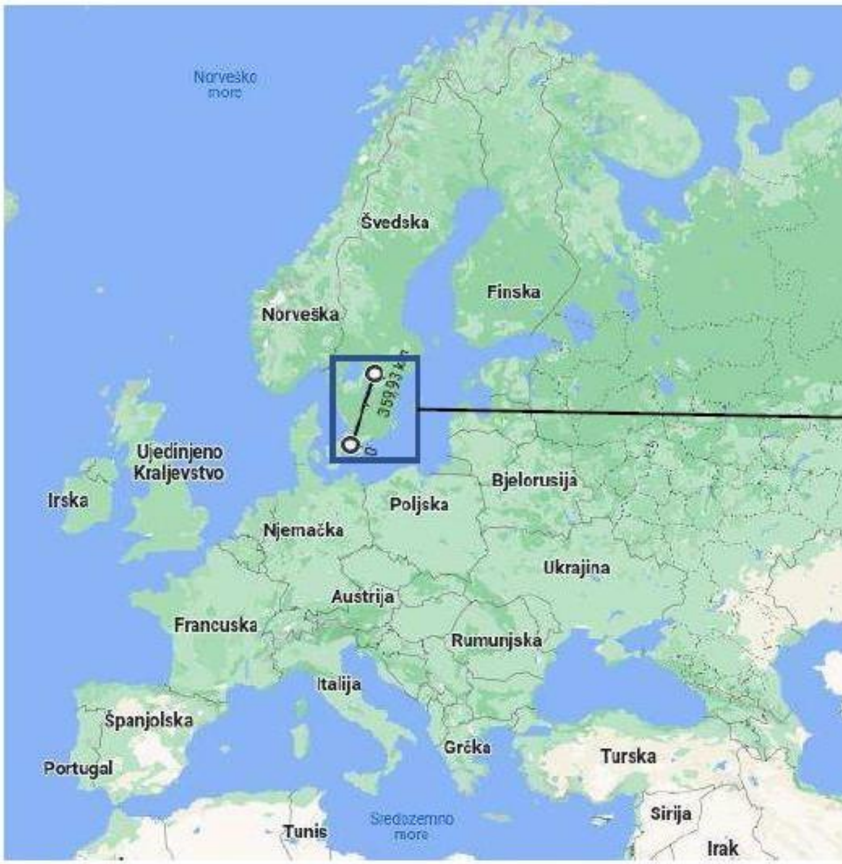
S. Parke, https://arxiv.org/pdf/1310.5992

2nd maximum
- larger sensitivity to δ_{CP}
- matter doesn't matter

Oscillation pattern



ESSnuSB neutrino baseline



Zinkgruvan mine, 360 km from the source, partly covernig 1st and 2nd maximum

The European Spallation Source (ESS)

- The ESS facility is under construction in Lund, Sweden. First beam expected in 2026.
- Using a powerful proton linear accelerator,

  designed for $E_{kinetic}$ = 2 GeV and 5 MW power.
- to produce the world's most powerful

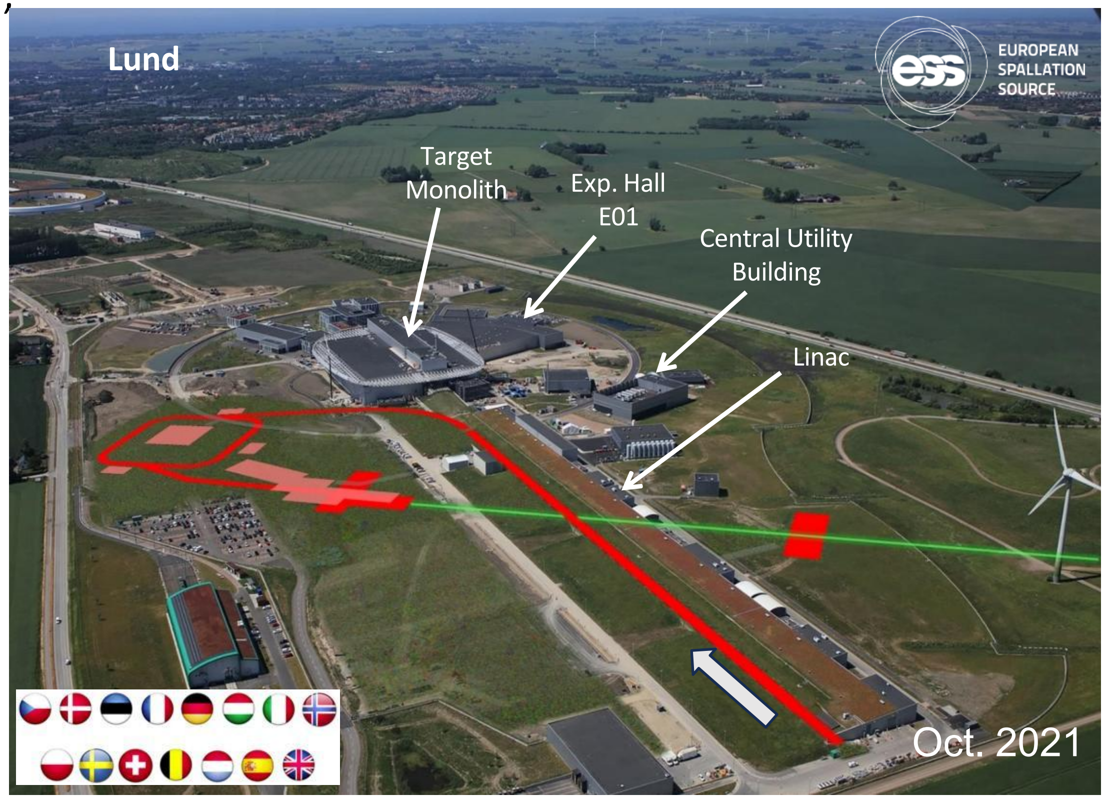
  neutron source.
- 14 Hz repetition rate (2.86 ms pulse

  duration, 10^{15} protons).→ 28 Hz
- up to 3.5 GeV with linac upgrades,

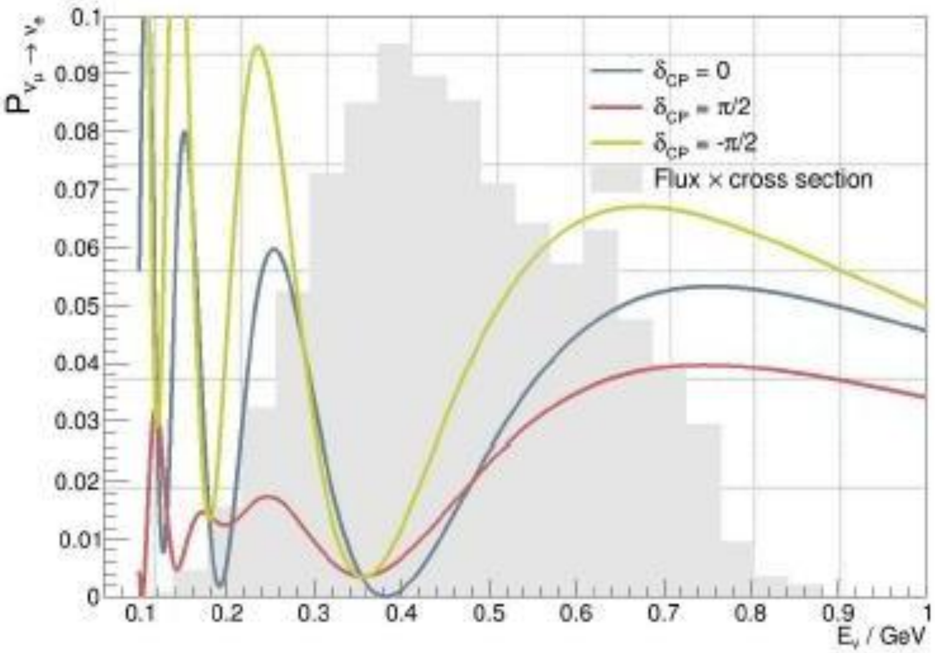
  > 2.7x10^{23} p.o.t/year.

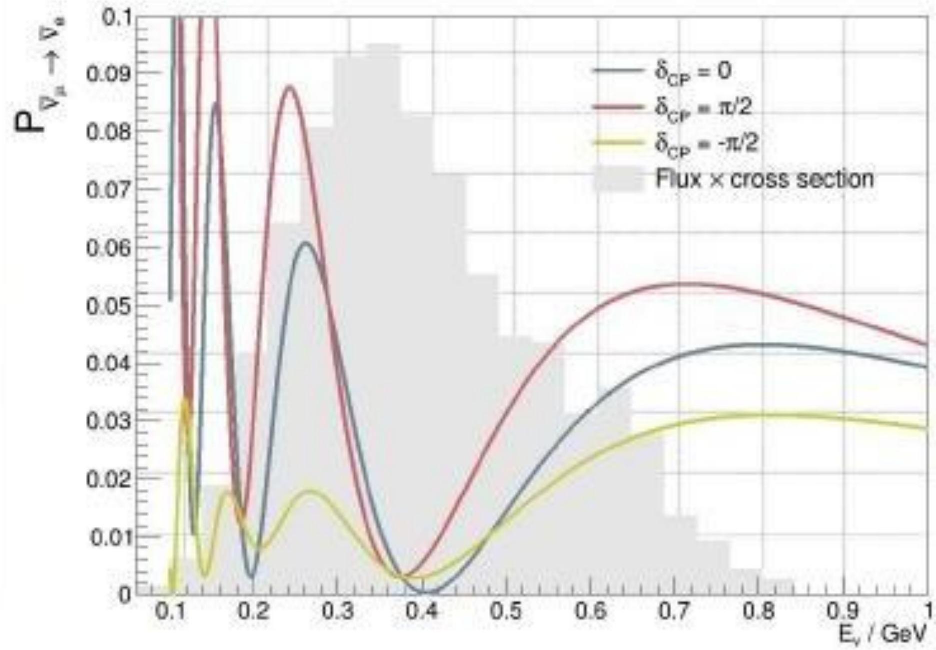
Using this powerful accelerator, we can produce a high intensity neutrino super beam!

The European Spallation Source Neutrino Super Beam (ESSνSB)

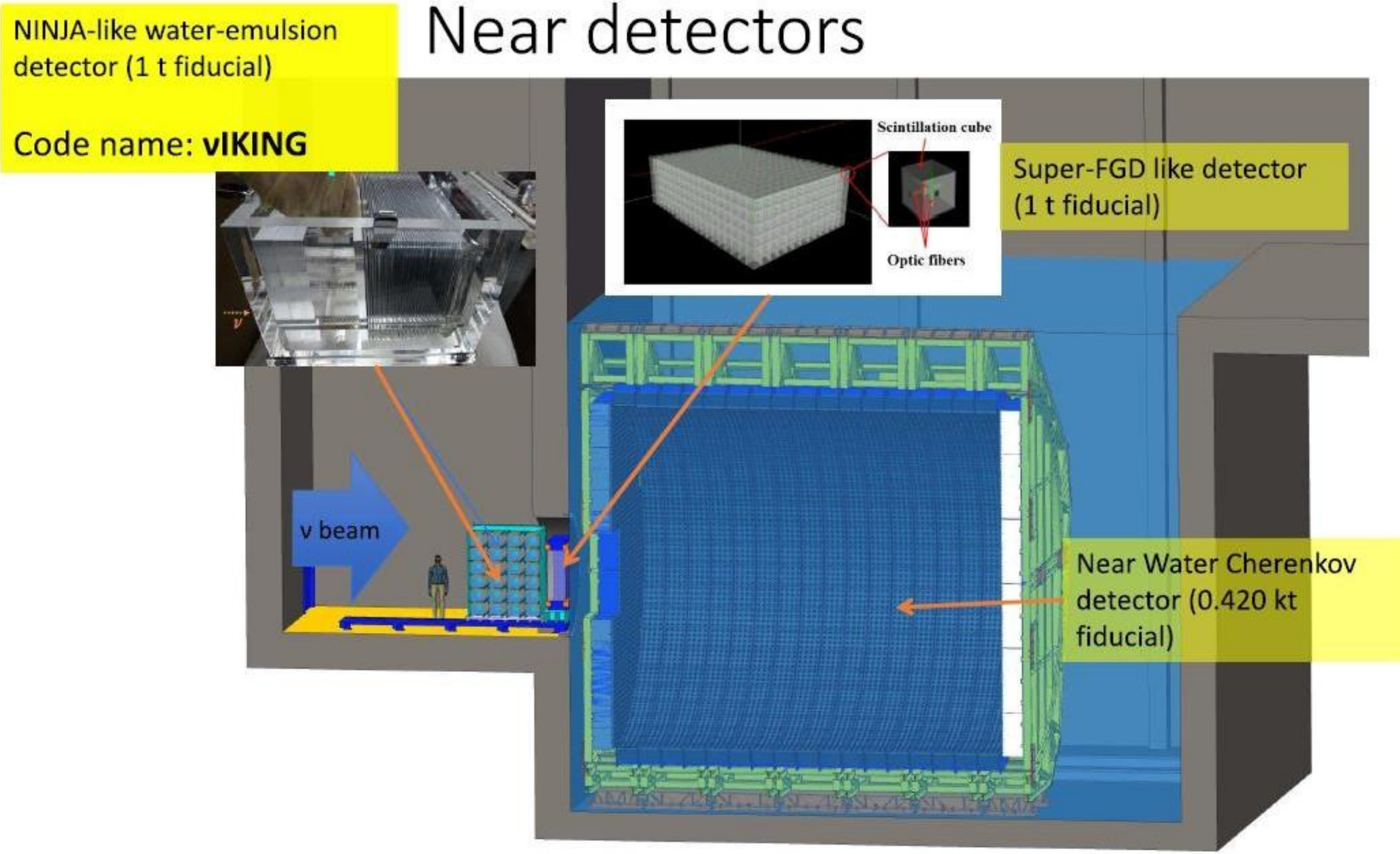


Oscillation coverage

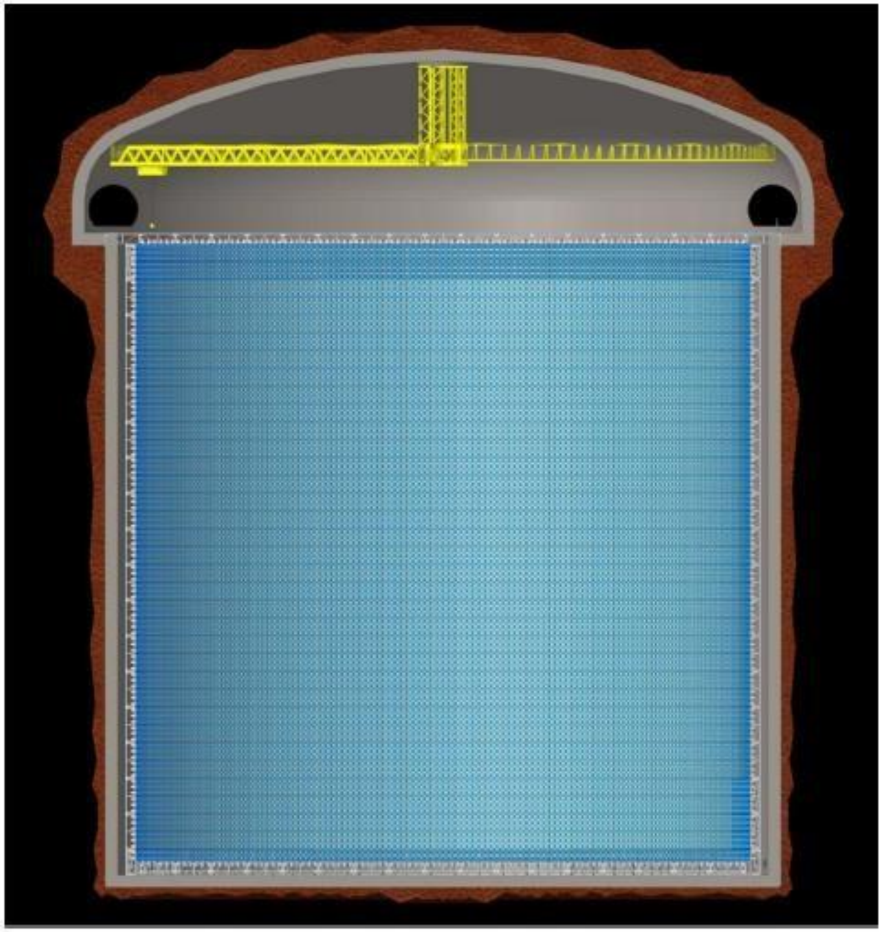




Near detectors



Far detectors



Design

- 2 x 270 kt fiducial volume (~2x HyperK)
- Readout: 2 x 38k 20" PMTs
- 30% optical coverage
    - design here for 40% with an option that ¼ PMTs will not be installed

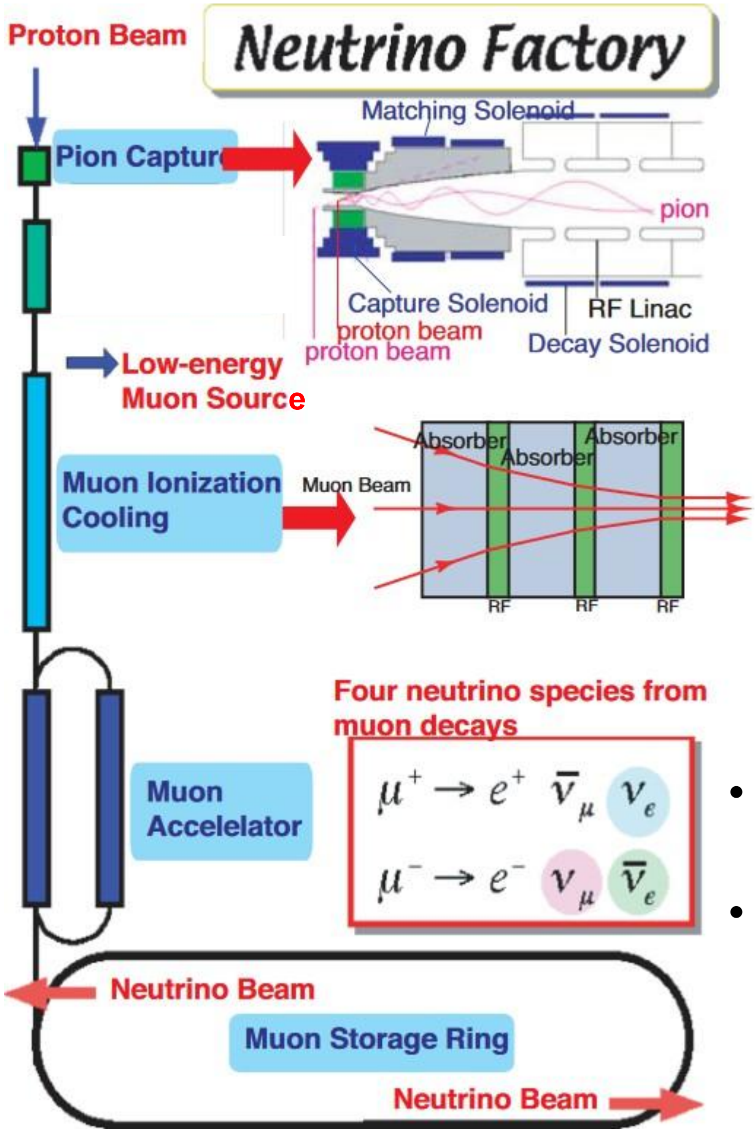
Can also be used for other purposes:

- Proton decay
- Astroparticles
- Galactic SN ν
- Diffuse supernova neutrino background
- Solar Neutrinos
- Atmospheric Neutrinos

1-4. Neutrino Factory

Neutrino Factory serves high luminosity, in particular also at high energies, both muon and electron flavor content, well known neutrino energy spectra and very well determined beam intensity.

Composition of ν Factory



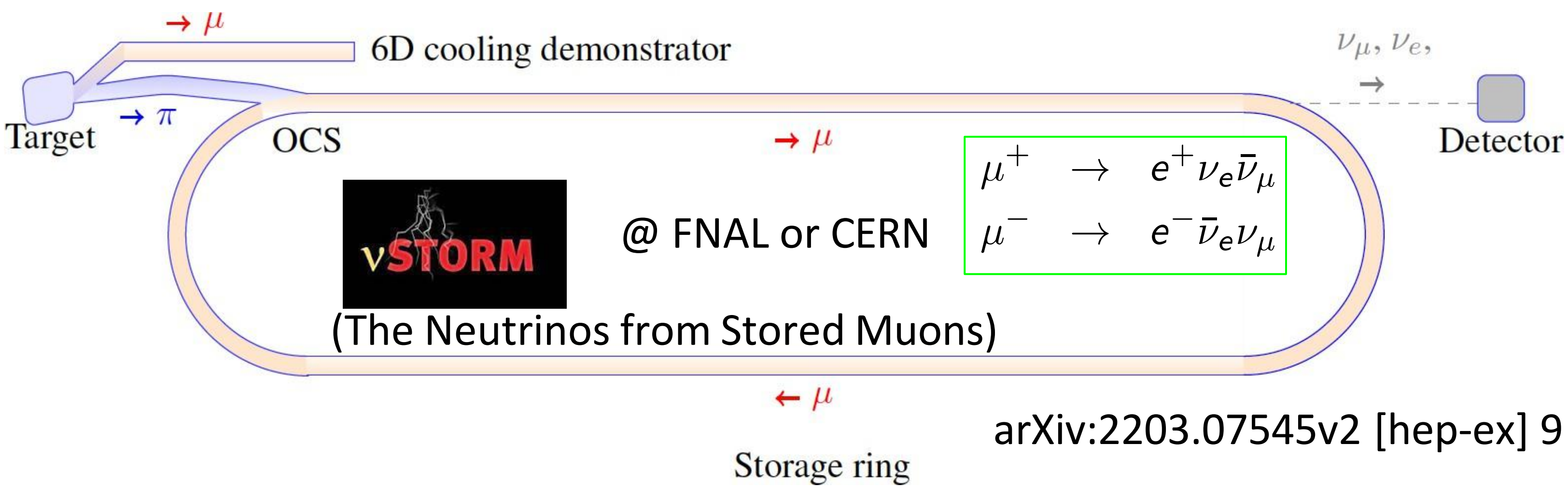
Pion capture by high magnetic field solenoid.

Suppression of transverse momentum of muons

- Deceleration by absorbers
- Acceleration by RF

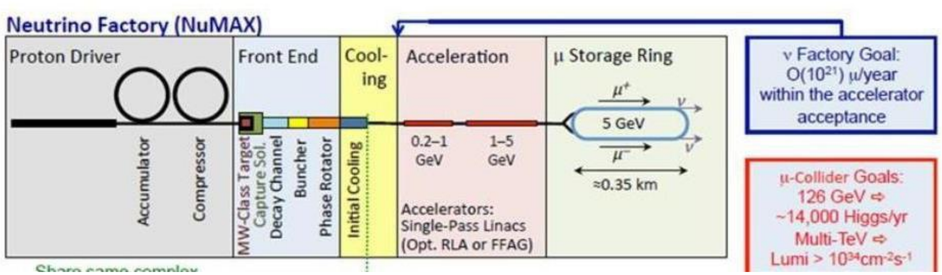
- Immediate acceleration by a muon accelerator with high repetition (~50 Hz)
- High intensity & energy ν_μ $(\bar{\nu}_\mu)$& ν_e $(\bar{\nu}_e)$ beams simultaneously from the straight part of the muon storage ring

Some future plans



arXiv:2203.07545v2 [hep-ex] 9 Aug 2022

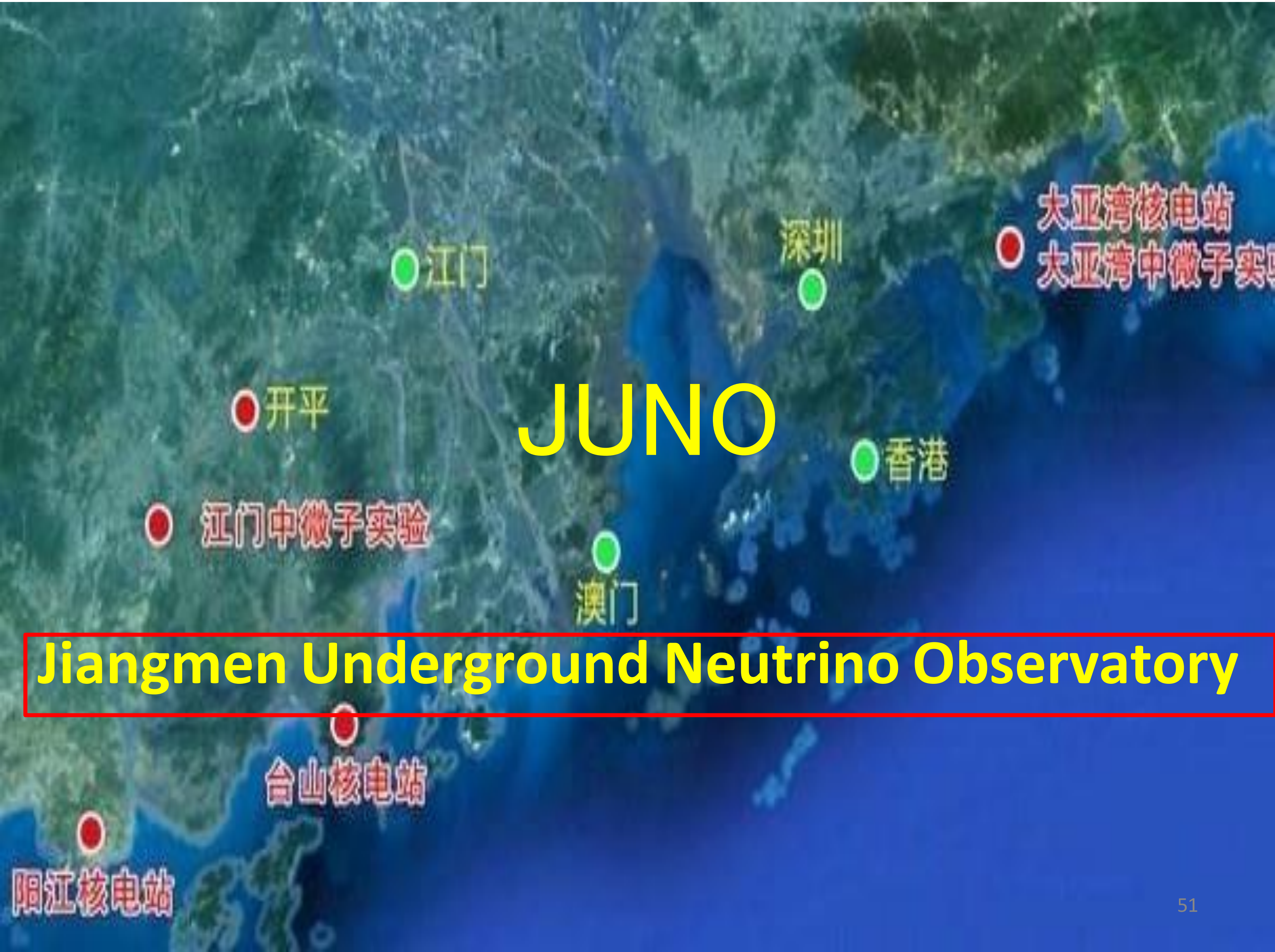
NuMAX (**Ne**u**trino from **M**uon **A**ccelerator comple**x) @**FNAL site



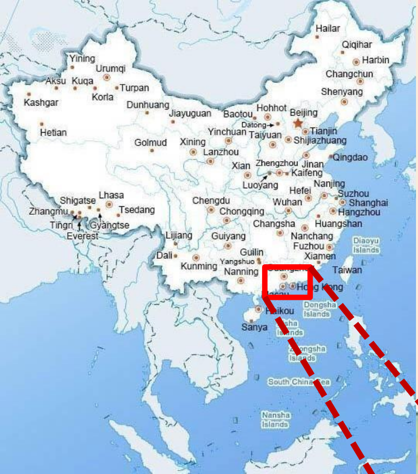
BNL-205756-2018-JAAM

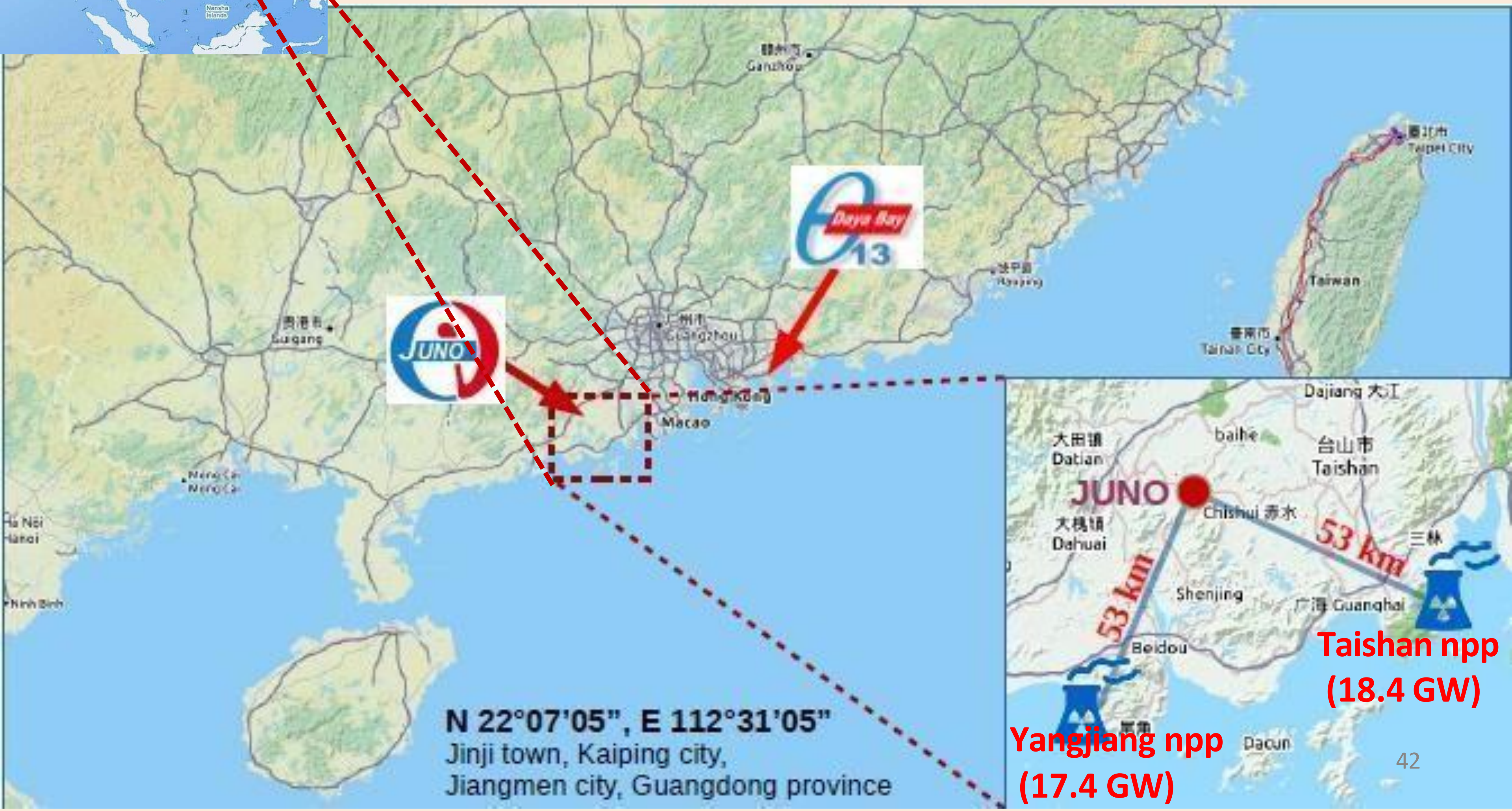
2. Reactor Neutrino Experiment (JUNO)

* Iwan Morton-Blake-san’s lecture

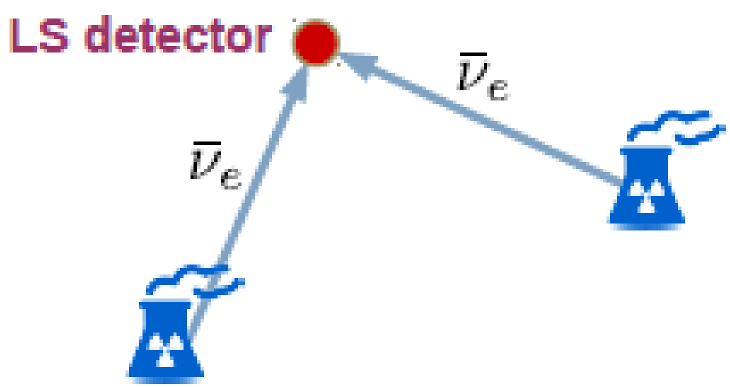

大亚湾核电站
大亚湾中微子实
深圳
江门
开平
JUNO
香港
江门中微子实验
澳门
Jiangmen Underground Neutrino Observatory
台山核电站
阳江核电站

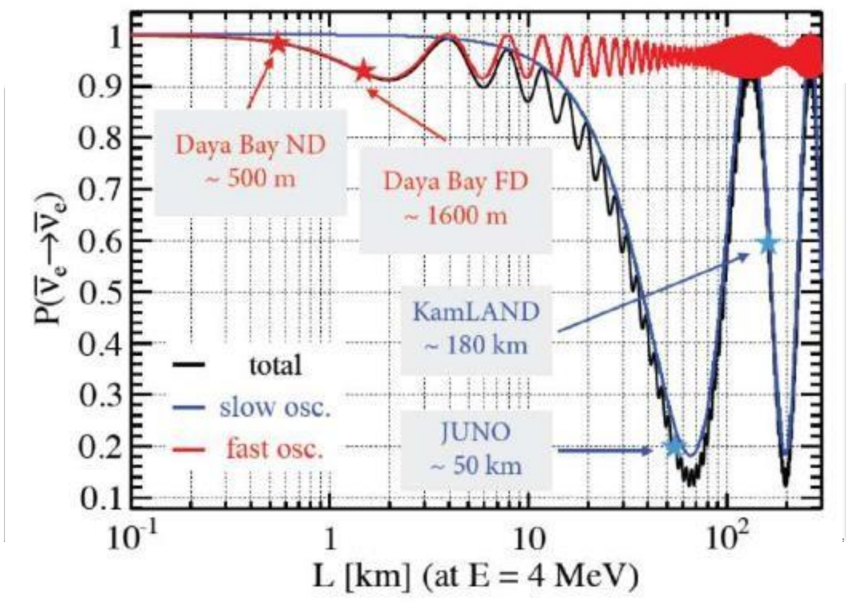
Location




Daya Bay
13
JUNO
Hong Kong
Macao
Taiwan
Dajiang 大江
baihe
台山市
Taishan
Datian
JUNO
Chishui 赤水
Dahuai
53 km
53 km
Shenjing
Guanghai
Beidou
Taishan npp
(18.4 GW)
Yangjiang npp
(17.4 GW)
Dacun
N 22°07'05", E 112°31'05"
Jinji town, Kaiping city,
Jiangmen city, Guangdong province

JUNO Layout



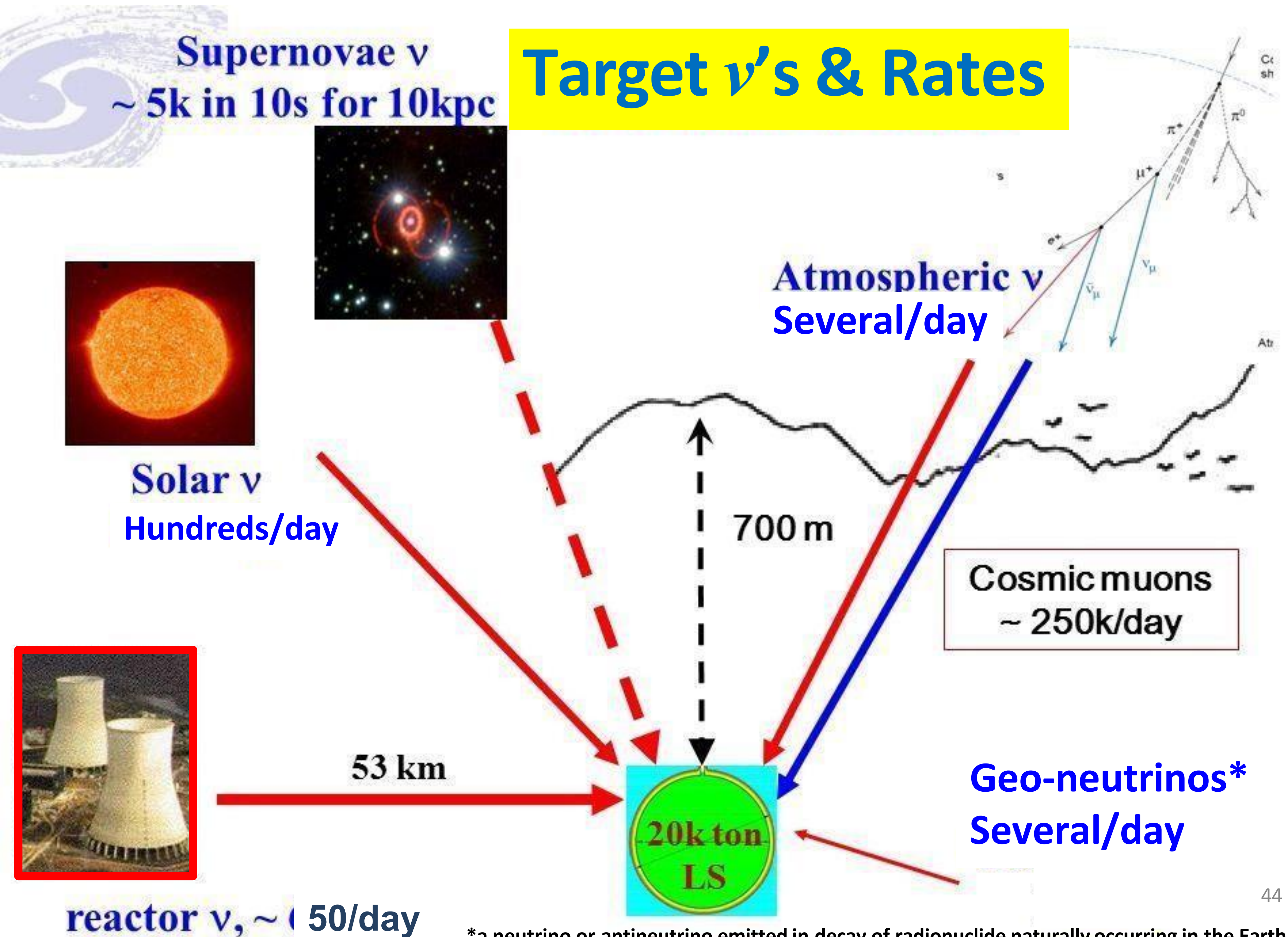


- **Source: 6+2 reactors**
  (Yangjiang and Taishan NPP)
- **Baseline: 53 km**
- **Detection channel: inverse β-decay**

$$\overline{\nu}_e + p \to e^+ + n$$

- **Target:** single volume 20-kt liquid scintillator
- **Detection technique:** system of photomultiplier tubes (18k 20'' PMTs + 25k 3" PMTs)
- **Overburden:** 700 m

Target ν's & Rates

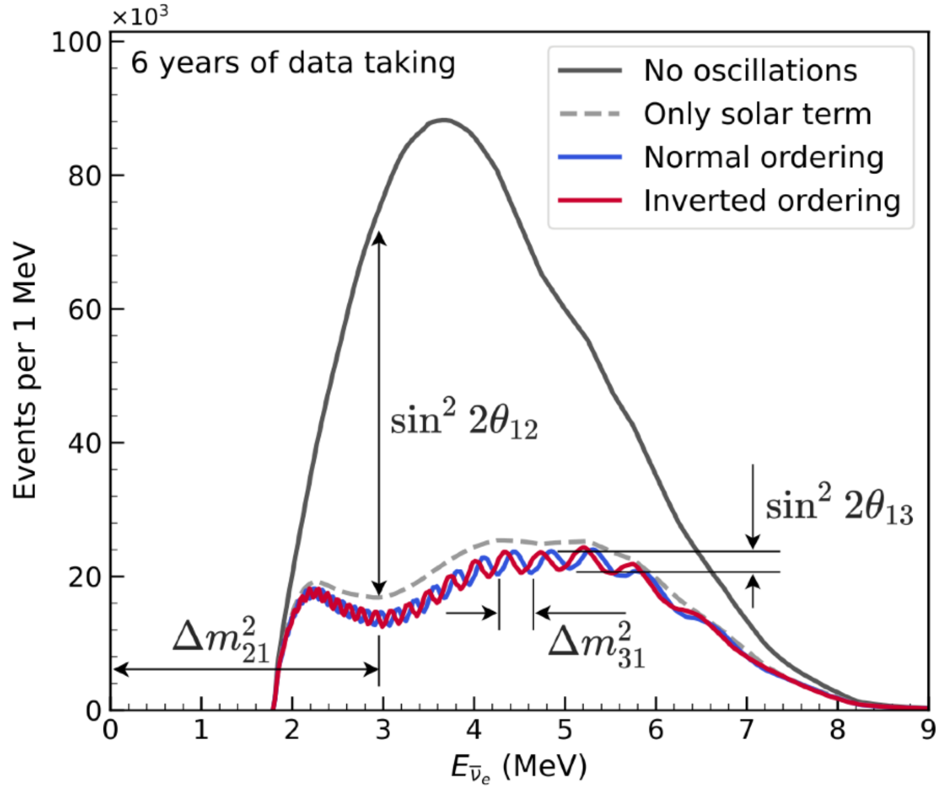


*a neutrino or antineutrino emitted in decay of radionuclide naturally occurring in the Earth

Physics goals

$\bar{\nu}_e$ survival probability in vacuum

$$P_{\bar{\nu}_e\to\bar{\nu}_e} = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\frac{\Delta m^2_{12}L}{4E} - \sin^2 2\theta_{13}\left(\cos^2\theta_{12}\sin^2\frac{\Delta m^2_{31}L}{4E} + \sin^2\theta_{12}\sin^2\frac{\Delta m^2_{32}L}{4E}\right)$$



Mass ordering (main goal)

- The energy resolution is one of the key factors for determining neutrino mass ordering.
- 3σ MO sensitivity within 6 years with only JUNO data

Oscillation parameters

- Sub-% accuracy for θ_{12}, Δm^2_{21} & Δm^2_{31}

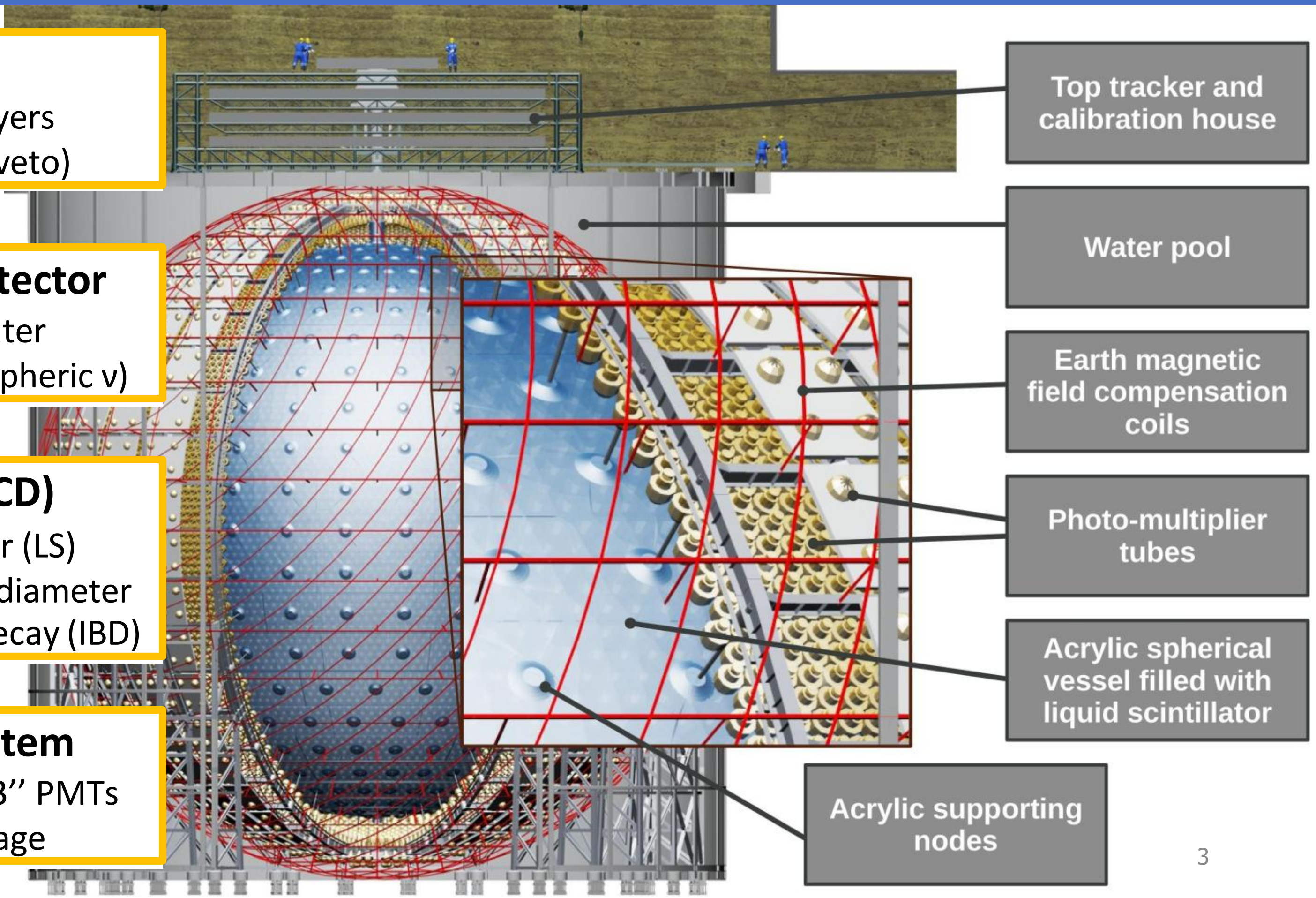
A Multi-purpose Underground Liquid Scintillator Experiment

Top Tracker
3 plastic scintillator layers
Precise muon tagging (veto)

Water Cherenkov Detector
35 kton ultra-pure water
>2500 PMTs (veto & atmospheric ν)

Central Detector (CD)
20 kton liquid scintillator (LS)
Acrylic sphere with 35.4 m diameter
Detect ν's via inverse beta decay (IBD)

Light Detection System
17596 20'' PMTs + 25600 3'' PMTs
78% geometric coverage



"Status of the JUNO Detector", **Runze Zhao, EPS-HEP 2025**

Key Design Features of JUNO

- Primary goal: to determine **Neutrino Mass Ordering** (NMO)

- Requirements:
  - High statistics (~10^5 IBD events in 6 years)
  - Excellent energy resolution (3% at 1 MeV)
  - Well controlled energy response systematics
  - Low background, both internal & external

- How?
  - Huge LS mass with high light yield & transparency
  - High PMT coverage and efficiency
  - Good PMT performance
  - Complementary calibration systems

Characteristics	KamLAND	JUNO (goal)	Relative Gain	
Energy Resolution	**6% @ 1 MeV**	**3% @ 1 MeV**	**2**	**target**
Light Yield	**250 p.e. / MeV**	**>1200 p.e. / MeV**	**~5**	**target**
Geometric coverage	34%	~78%	~2	**> 40000 PMTs**
PPO content	1.5 g/L PPO	2.5 g/L PPO	~1.5	**optimized LS**
Attenuation length / D	15/16 m	20/35 m	~0.8	**optimized LS**
PMT QExCE	20%x60% ~ 12%	~30%	~2	**more efficient PMTs**

use **KamLAND** as a reference

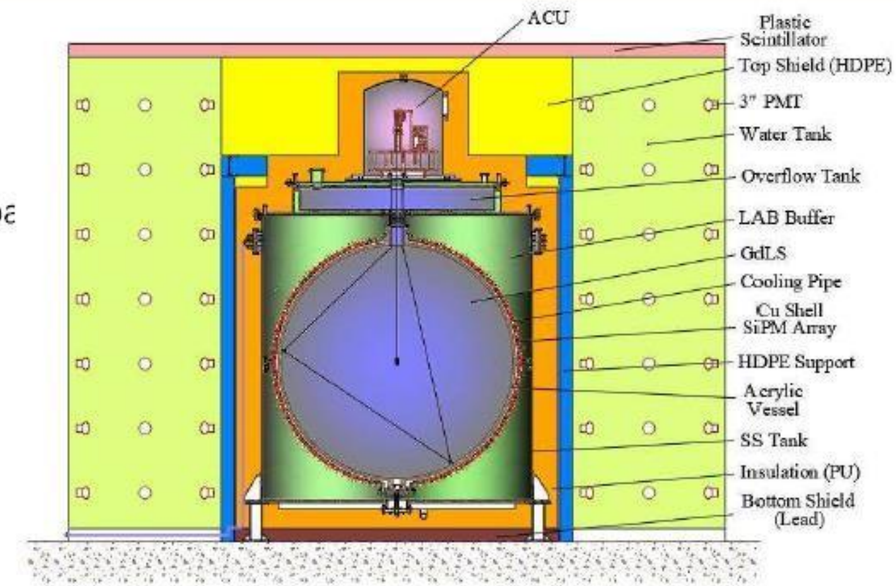
Taishan Antineutrino Observatory (TAO)

Physics potential

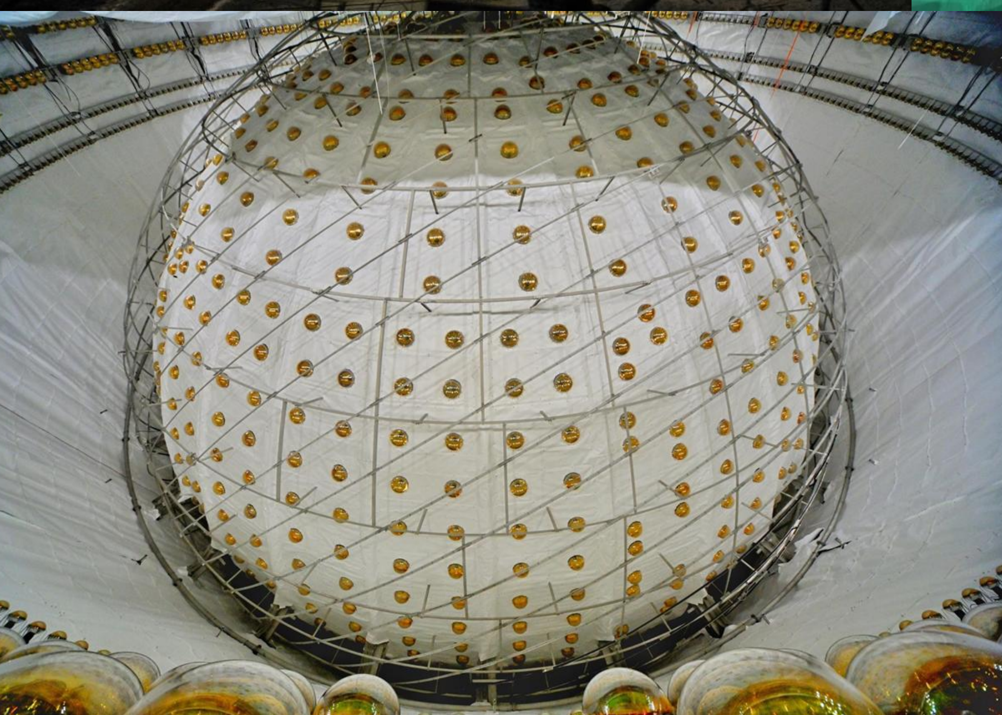
- ✓ Precise measurement of antineutrino spectra
- ✓ Sterile neutrino searches
- ✓ Provide a reference spectrum for JUNO, nuclear databa
- ✓ etc.

arXiv: 2005.08745

2.8 ton GdLS detector	
Baseline	~30 m
Reactor Thermal Power	4.6 GW
Light Collection	SiPM
Photon Detection Efficiency	>50%
Working Temperature	-50 ℃
Dark Count Rate [Hz/mm²]	~100
Coverage	~94%
Detected Light Level [PE/MeV]	4500
Energy resolution	< 2% @ 1 MeV



- ✓ 10 m^2 SiPM is used to achieve high light yield with ~94% coverage
  → 4500 PEs/MeV & energy resolution < 2% @ 1 MeV
- ✓ Gd-LS works at -50℃ to lower the dark noise of SiPM

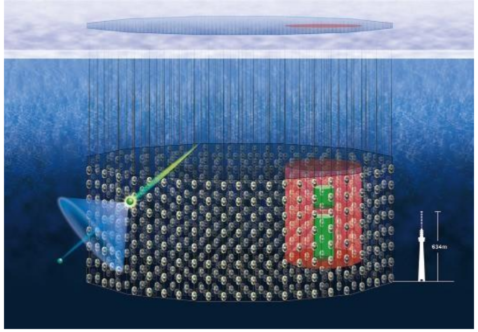


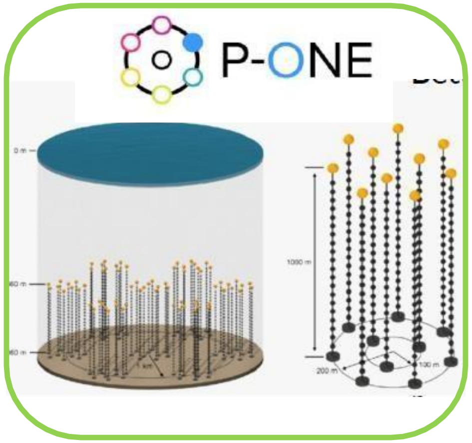
- The construction of the detector is completed
- Water filling phase is finished
- Currently under liquid scintillator filling phase
  - Taking commissioning data: good performance so far
  - **Expect physics data-taking in beginning of summer 2025**

3. Atmospheric & Astrophysical Neutrino Measurements

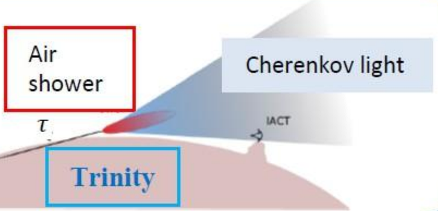
Future Plans

- **Optical Detection of Cherenkov Radiation**
  - **IceCube -Upgrade & Gen 2- @ South Pole**
  - **P-ONE @ Pacific Ocean → Targeting 2030**
  - **Trinity** (candidate site:not decided yet)

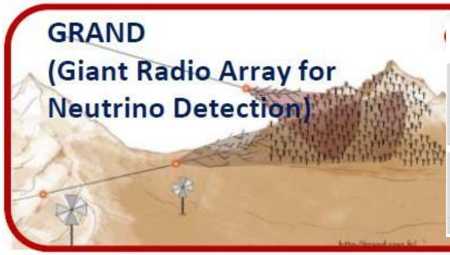




An Air-Shower Imaging Instrument to Detect Ultrahigh-Energy Neutrinos down to PeV Energy
Phys. Rev. D 99, 083012 (2019)
ICRC 2019 arXiv:1907.08732



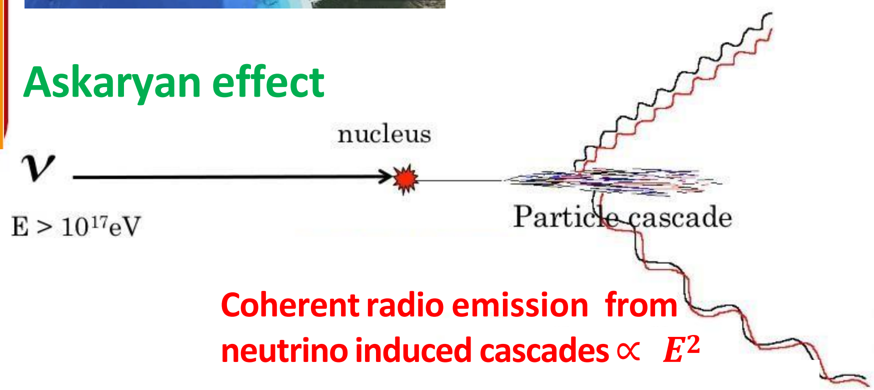
- **Radio Technique (Askaryan effect)**



	Prototyping	GRAND10k	GRAND200k
	2022	2025	203X
Goals	**autonomous** radio detection of **very inclined** air-showers **cosmic rays $10^{16.5-18}$ eV** • Galactic/extragalactic transition • muon problem • radio transients	**1st GRAND sub-array** • **discovery of EeV neutrinos** for optimistic fluxes • radio transients (FRBs!)	sensitive **all-sky** detector **1st EeV neutrino detection and/or neutrino astronomy!**
Setup	• **GRAND@Nançay**: 4 antennas for trigger testing • **GRAND@Auger**: 10 antennas for cross-calibration • **GRANDProto300**: 300 HorizonAntennas over 200 km²	• 10,000 radio antennas over 10,000 km²	• 200,000 antennas over 200,000 km² • 20 sub-arrays of 10k antennas • on different continents

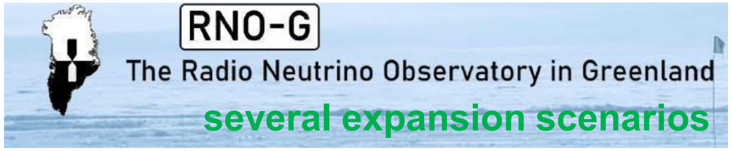
https://grand.cnrs.fr/

Askaryan effect



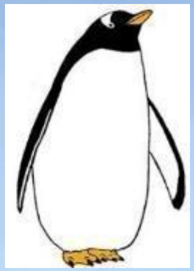
Coherent radio emission from neutrino induced cascades $\propto E^2$

  - **RNO-G (Greenland)**



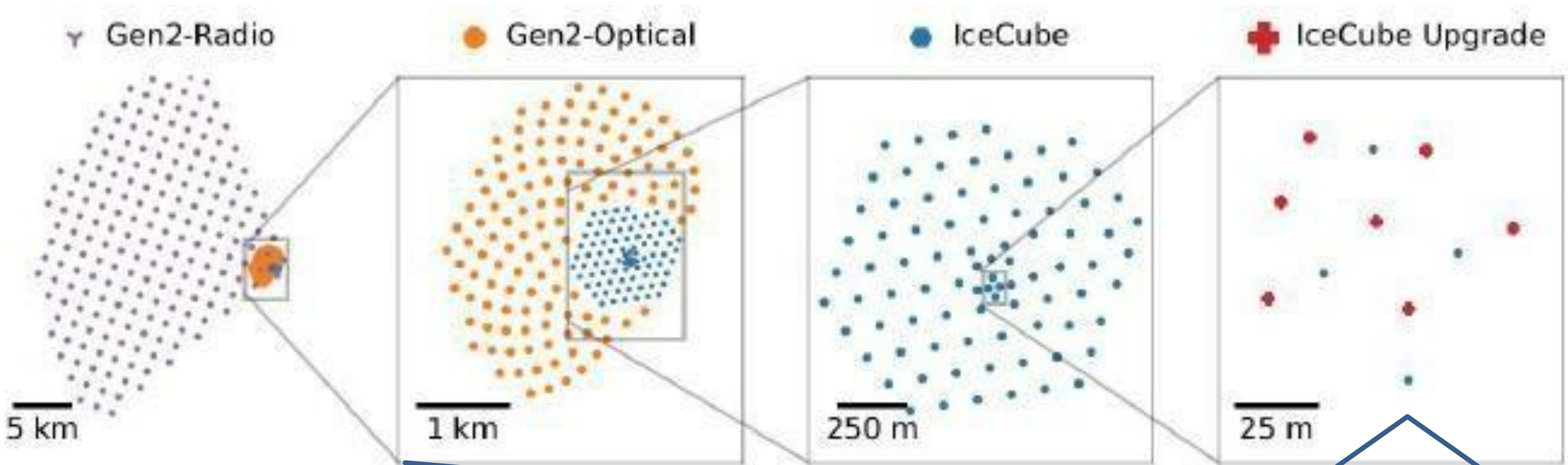
IceCube – Upgrade & Gen 2 –

- Located in the South Pole
- Ice is used as a Cherenkov detector.
- IceCube provides astrophysical neutrino measurements.

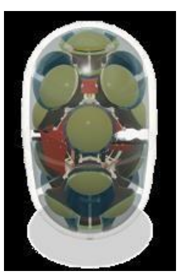


Gentoo penguin

IceCube : Upgrade & Gen2



IceCubeGen 2 (design phase)



- Optical array ~8 × Gen 1
- New sensor (Gen 2 LOM) will be used.
- Increase statistics around the PeVregion

Gen 2 LOM (= D-Egg+mDOM)

IceCubeUpgrade

2025:
Construction start

Testbed for new sensor types →

D-Egg

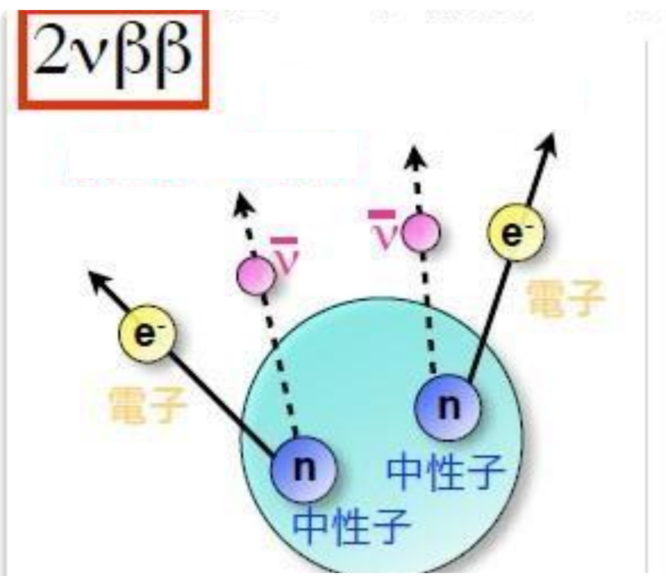
mDOM

・Improved detector calibration/ ice model characterization

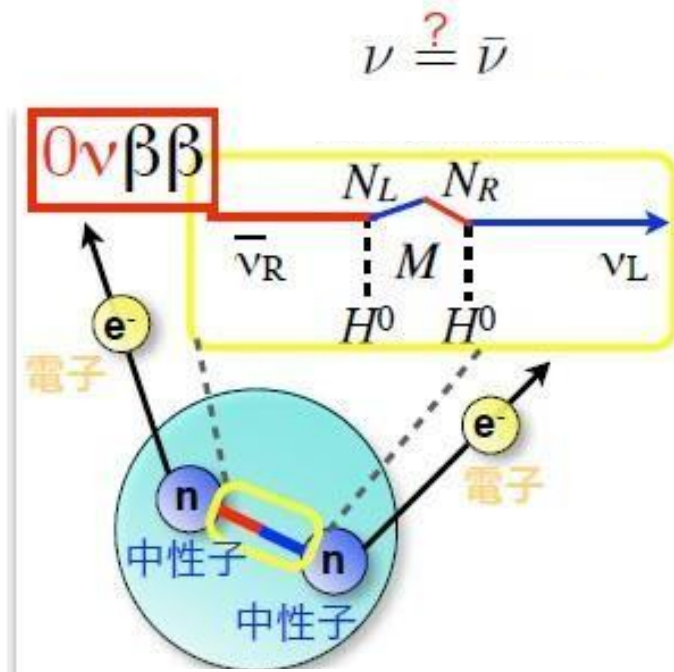
4. 0νββ Decay Experiments

* See & remember Surukuchi-san's lecture in detail

Double beta decay



2 neutrons decay in a nuclei.



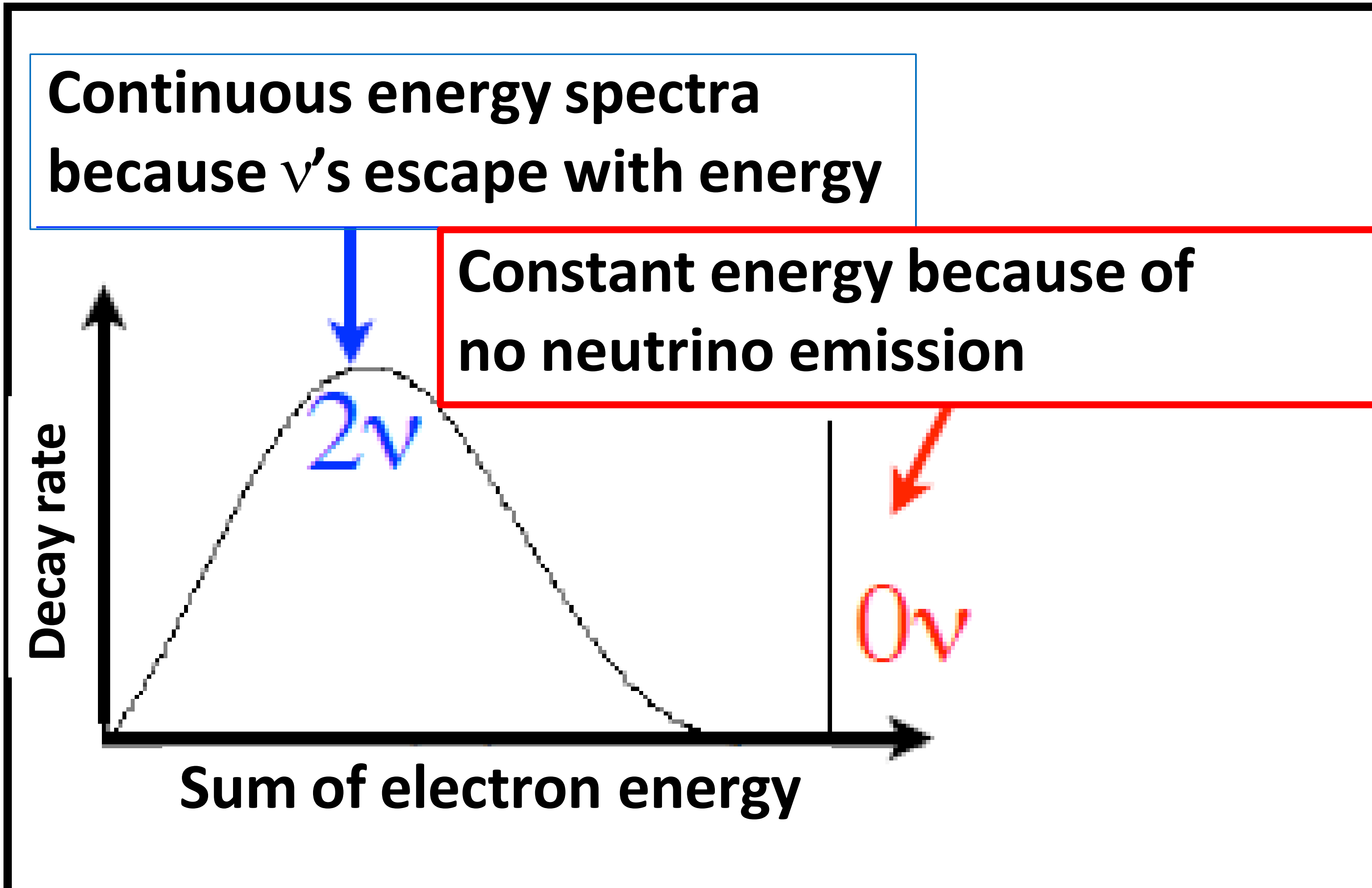
No ν is emitted.

Possible in SM
Lifetimes are measured for ~10 nucleus

Forbidden in SM
(Lepton number violation)
Possible if ν is Majonara

How to detect

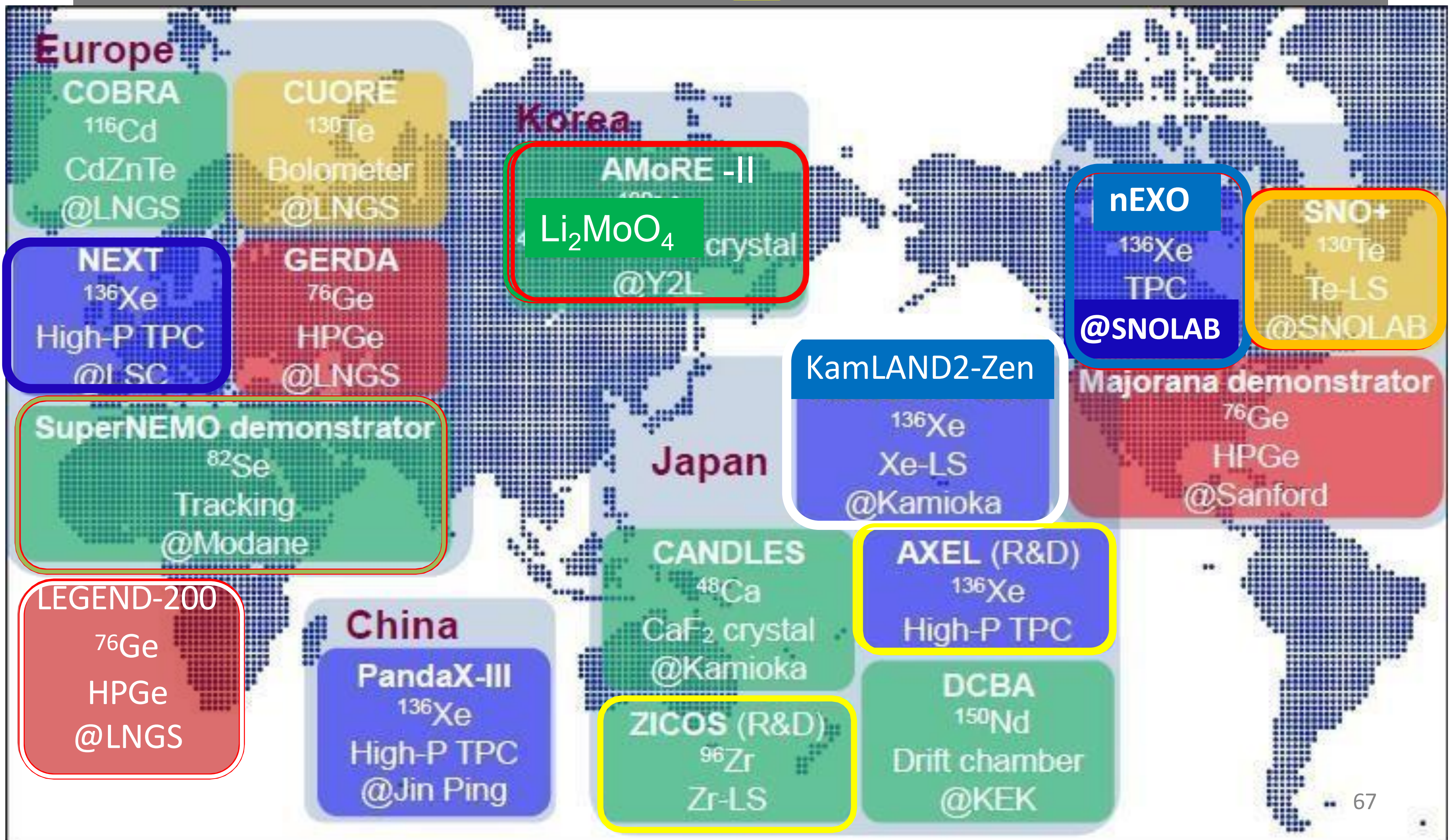
- Catch 1 electron pair emitted !



0νββ experiments now & future (using ^{136}Xe, ^{76}Ge, ^{130}Te, etc)

Plan

R&D



5. Sterile Neutrino Experiments

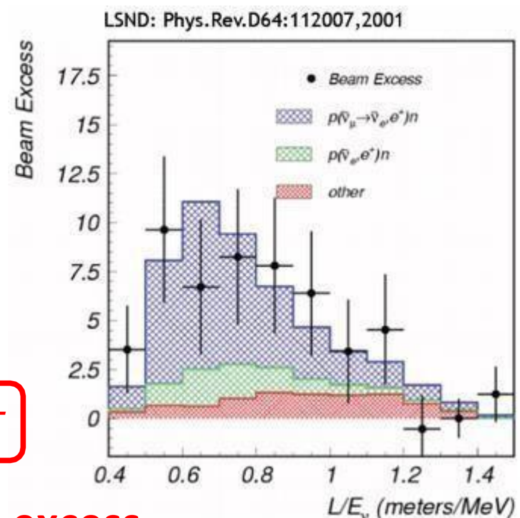
See and remember Erin-san's lecture.

- **PROSPECT-II**
- **IsoDAR**

Why sterile neutrino ?

Do 3-neutrino oscillations explain all experimental results?

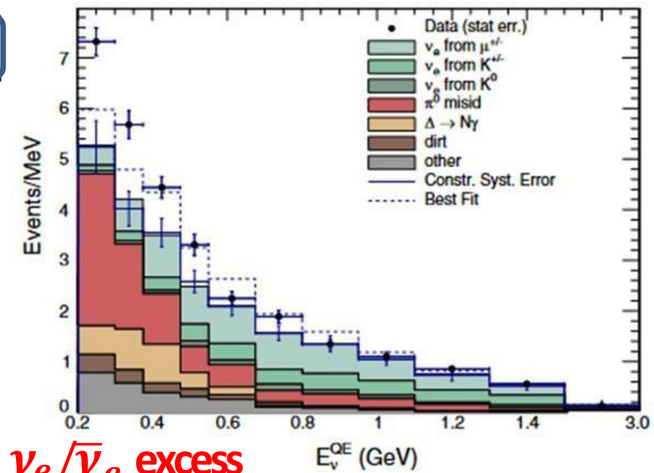
LSND



3.8σ

$\bar{\nu}_\mu \to \bar{\nu}_e$ excess

MiniBooNE



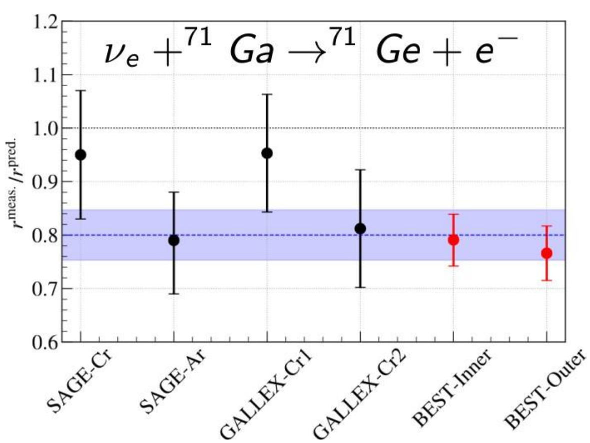
4.8σ

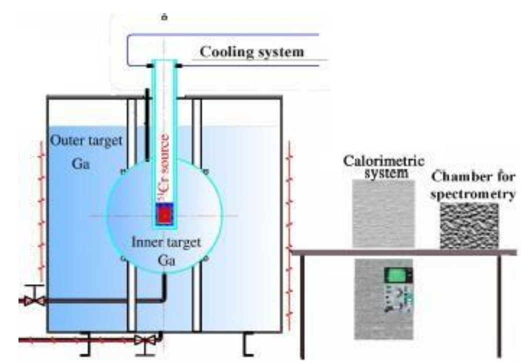
$\nu_\mu/\bar{\nu}_\mu \to \nu_e/\bar{\nu}_e$ excess

Possible common explanation:

Additional squared mass difference

$$\Delta m^2_{\text{SBL}} \simeq 1\ \text{eV}^2$$





- **Experiments with intense radioactive sources**
- **Neutrino detection via**

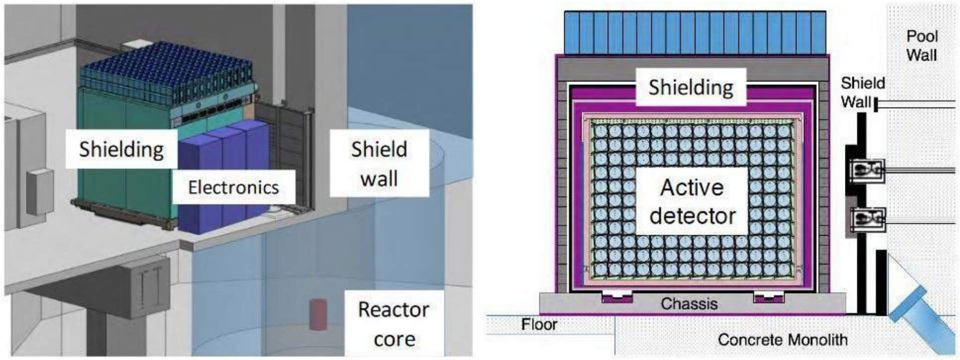
$$^{71}\text{Ga} + \nu_e \to {}^{71}\text{Ge} + e^-$$

- **Recently confirmed by BEST**
  (Baksan Experiment on Sterile Transitions)

$$R = \left(\frac{measured}{predicted}\right) = 0.803 \pm 0.035 \geq 5\sigma$$

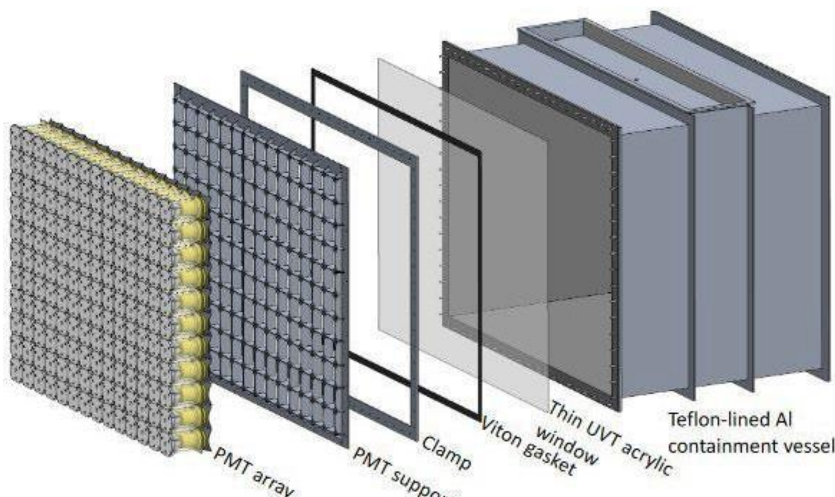
PROSPECT-II

Original PROSPECT Design



https://arxiv.org/abs/2107.03934

PROSPECT II Design



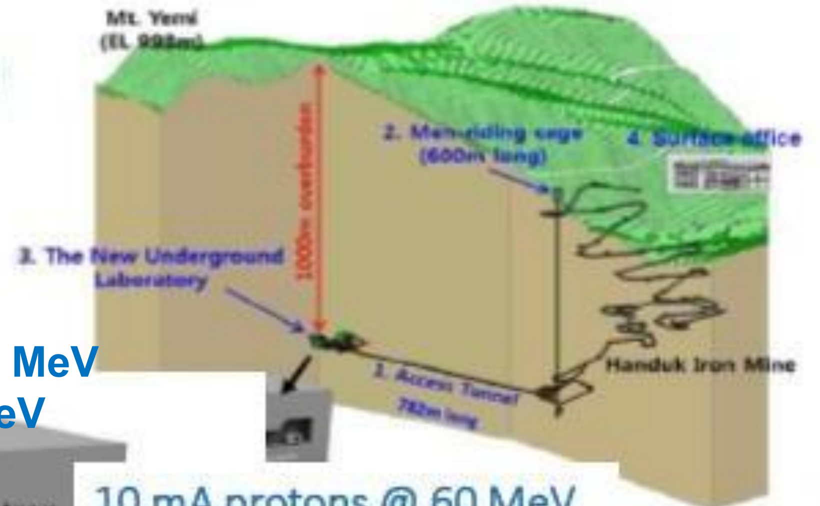
https://arxiv.org/abs/2107.03934

- High Flux Isotope Reactor (HFIR) at Oak Ridge National Laboratory
- Segmented ^{6}Li-doped liquid scintillator
- IBD detection of protons on LS, 1.8 MeV threshold
- Prompt (positron annihilation, 1-8 MeV) + delayed (n + ^{6}Li→ α + t + 4.8 MeV)
- Slightly higher ^{6}Li loading (0.08 % → 0.1% by mass)
- Larger segment length 118 cm → 145 cm → IBD rate increases to roughly 1150/day

IsoDAR

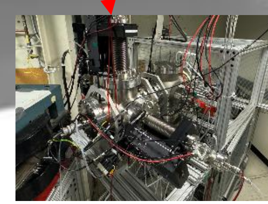
(Isotope Decay At Rest)

- Underground facility at Mt. Yemi in Korea
- > 1000 m overburden (cosmic ray shielding)
- 60 MeV proton cyclotron
- p^{+} + Be → spallation neutrons
- $n + {}^{7}\mathrm{Li} \rightarrow {}^{8}\mathrm{Li}^{*} \rightarrow {}^{8}\mathrm{Be} + e^{-} + \bar{\nu}_e$

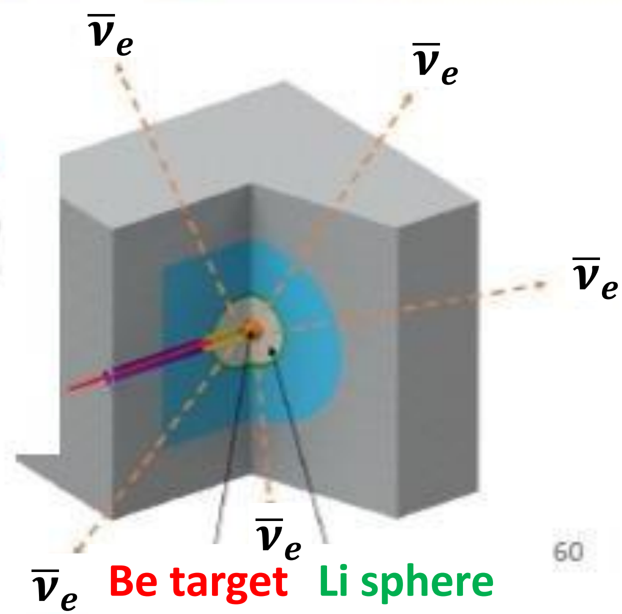


$E_{meam} = 6.4$ MeV
$E_{max} \sim 15$ MeV

Target hall



IsoDAR's work-in-progress ion source



6. High statistic ν_τ Experiment (SHiP)

SHiP
(Search for Hidden Particles)

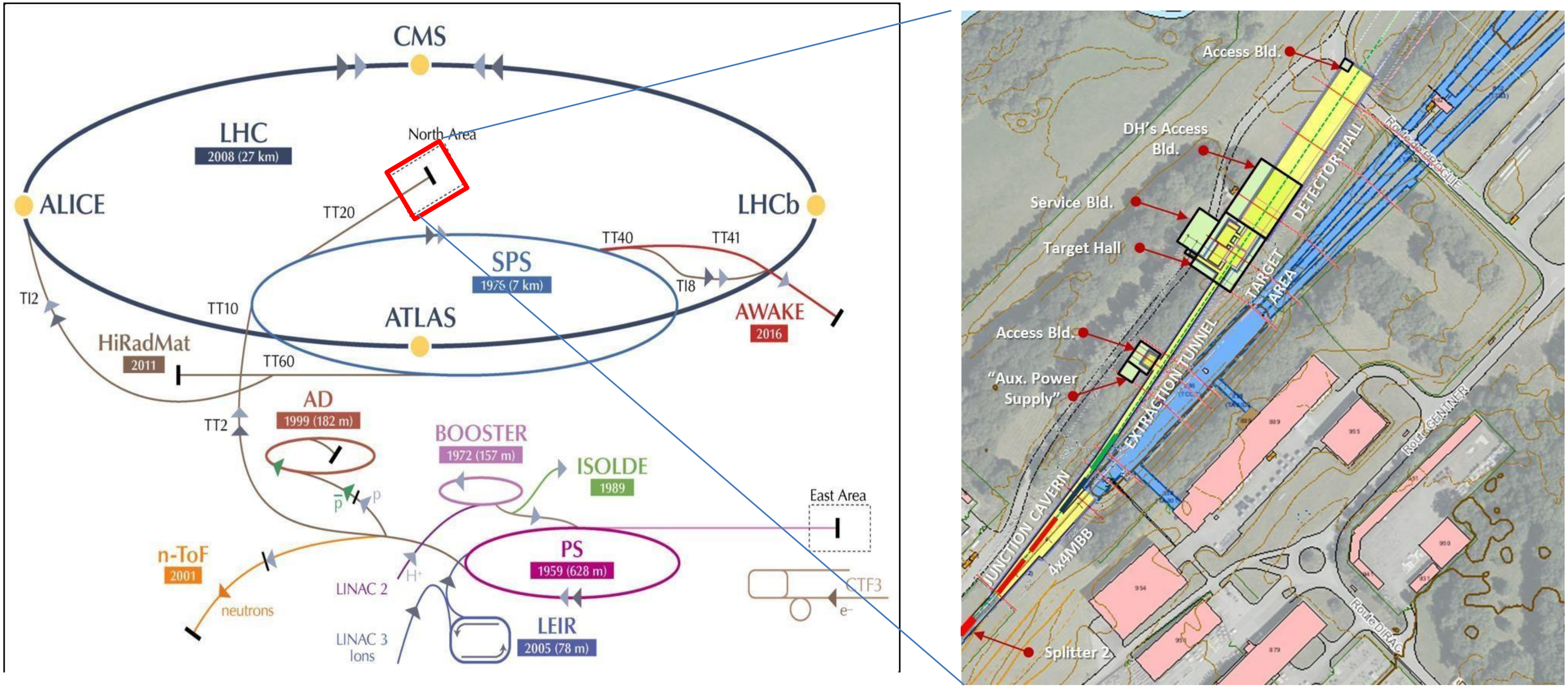
- to explore the domain of hidden particles, such as Heavy Neutral Leptons (HNL), dark photons, light scalars, supersymmetric particles, axions etc., with masses below O(10) GeV

  → Original purpose

- Large amount of ν's, especially ν_τ's with three orders of magnitude more statistics than available in previous experiments combined.

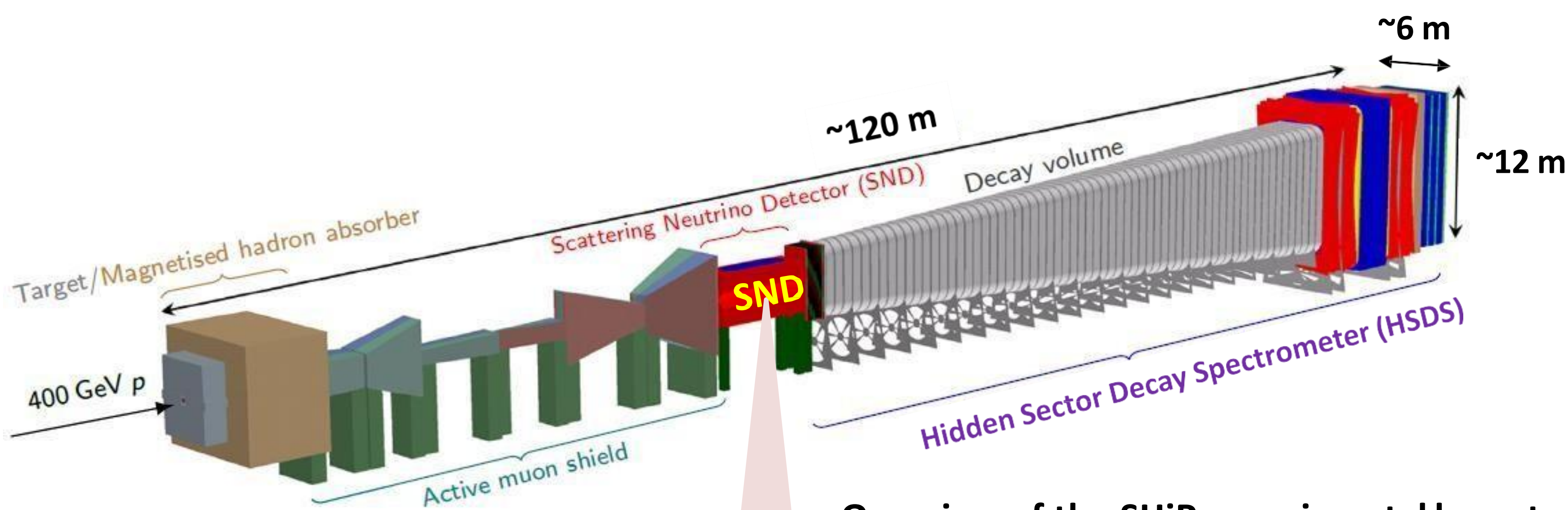
  → I would like to introduce as high statistic ν_τ experiment using the nuclear emulsion technology, which has been highly developed in Japan.

SHiP: experimental site

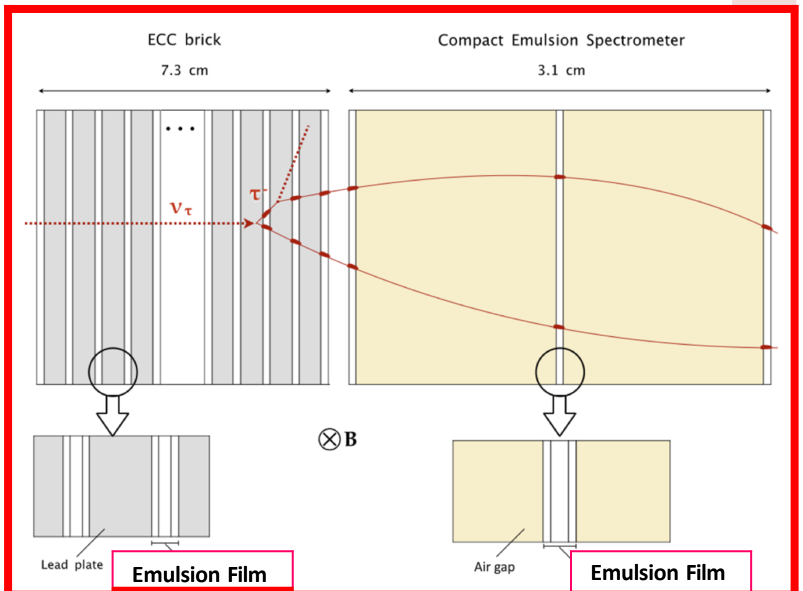


- Fixed target facility @ CERN SPS
- 400 GeV protons
- 4×10^{13} POT/spill in every 7 sec → 2×10^{20} POT in 5 years

SHiP detector



Overview of the SHiP experimental layout



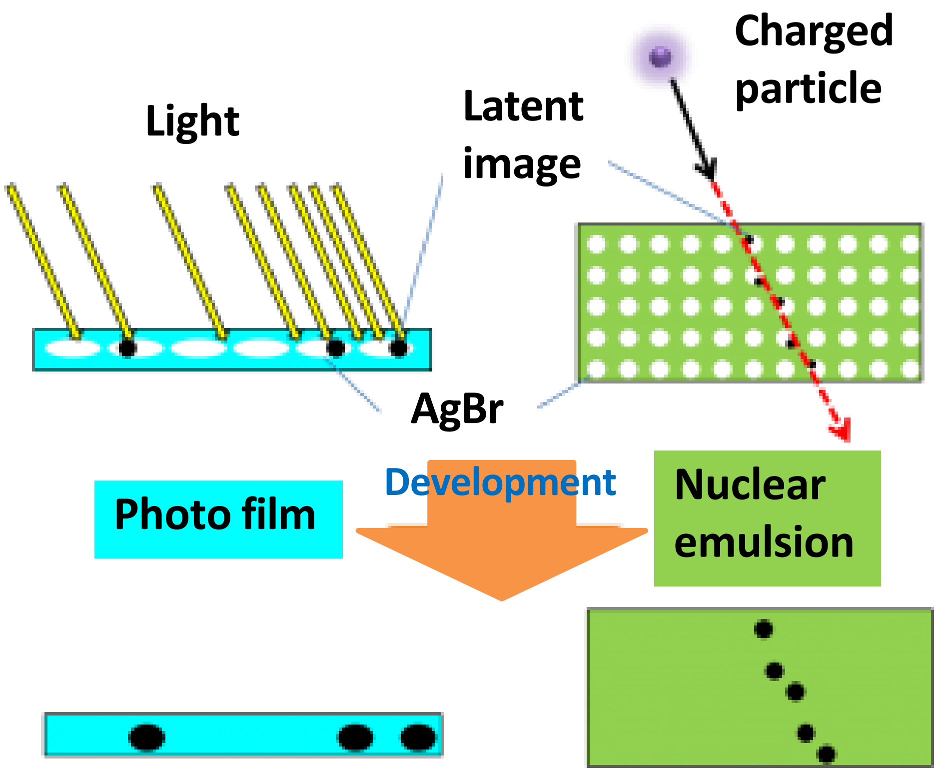
Basic unit of the SND & the ECC brick

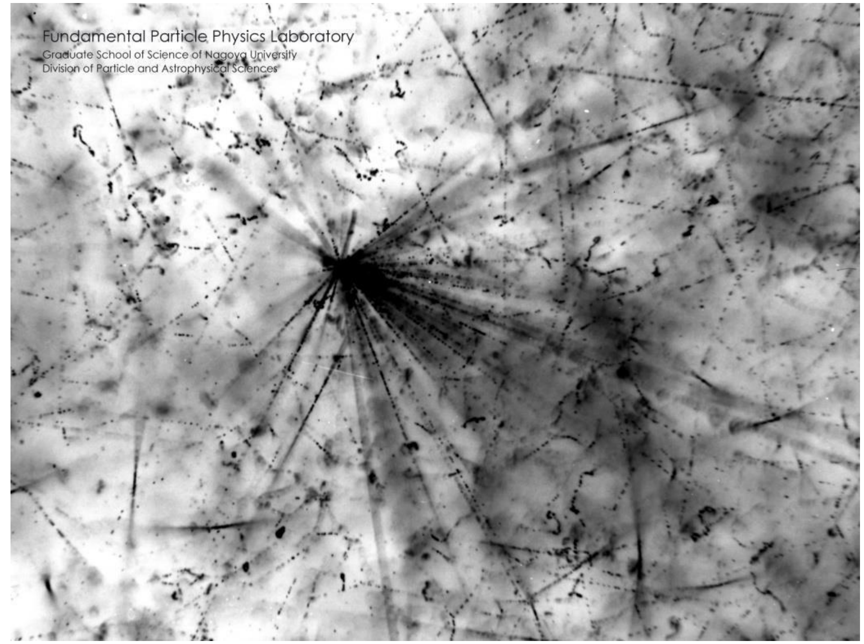
In the Scattering Neutrino detector (SND), the *Emulsion Cloud Chamber (ECC) is used as tracking detector and the Compact Emulsion Spectrometer (CES) is used for charge measurement.

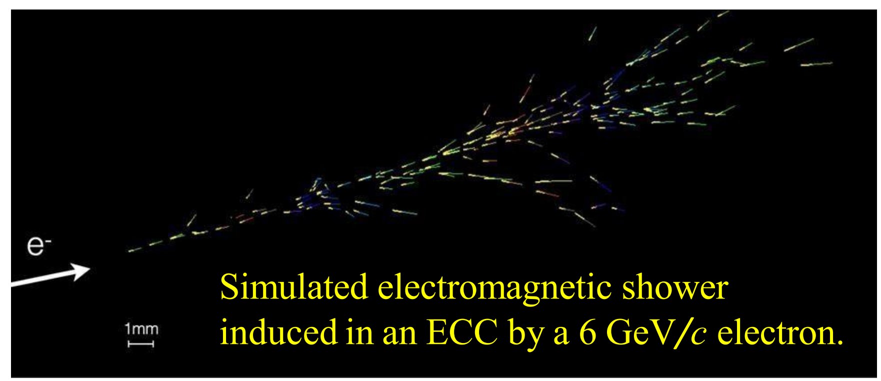
* Nuclear emulsion has the best position resolution of $\sim 1\mu m$. The emulsion technique has been highly developed in Japan.

https://doi.org/10.1007/JHEP04(2021)199

Nuclear emulsion







Simulated electromagnetic shower induced in an ECC by a 6 GeV/c electron.

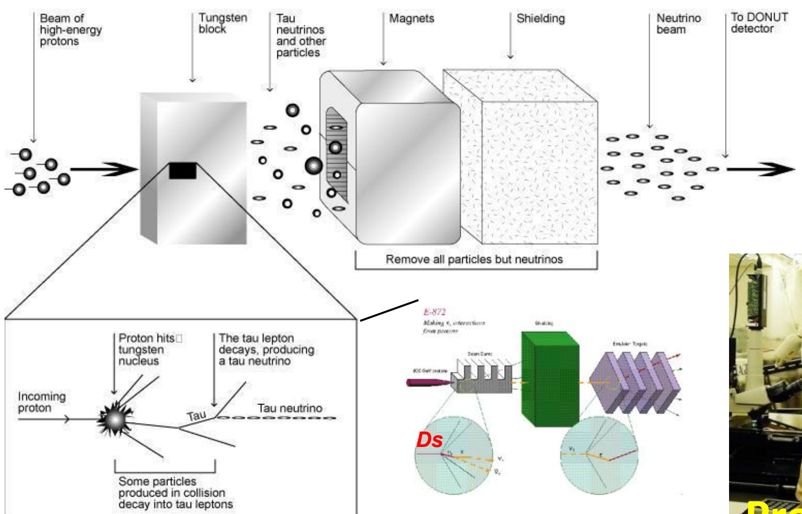
- Kind of photo film.
- Contains small grains of AgBr.
- Ag grains are remained after charged particle pass.
- We can detect the track after the development.
- Position resolution is $\sim 1\mu$m (still the best in all detectors).

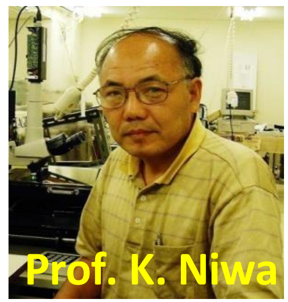
Discovery of ν_τ

DONUT experiment, 2000 (Direct Observation of NeUtrino Tau, Fermilab. E872)

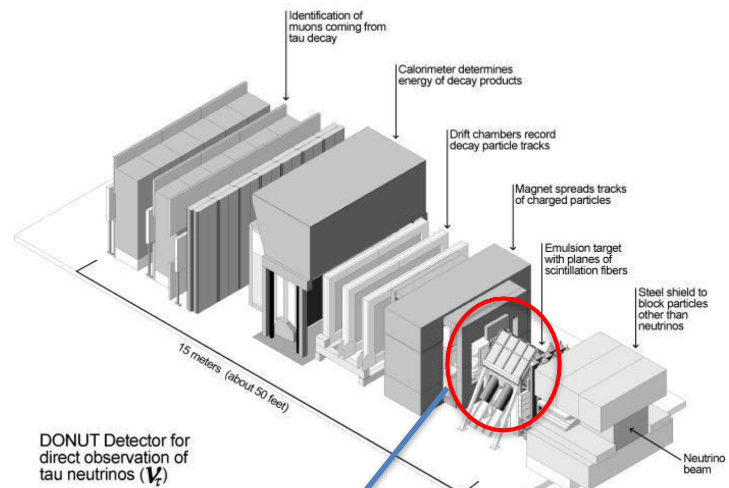
Nagoya Univ., Kobe Univ., et al

Creating a Tau Neutrino Beam



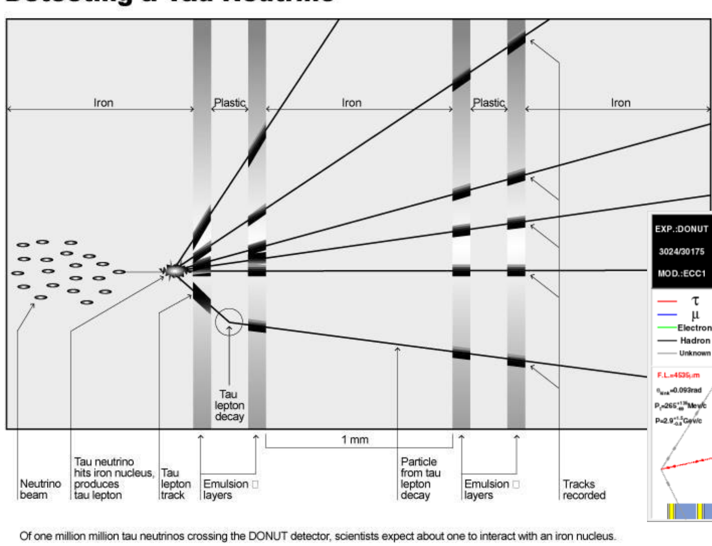


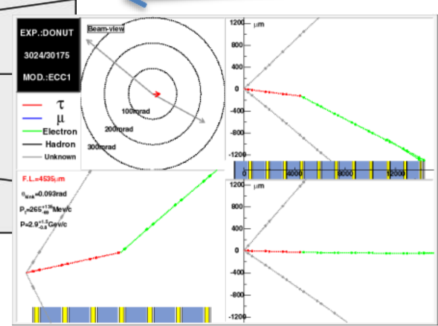
DONUT Detector



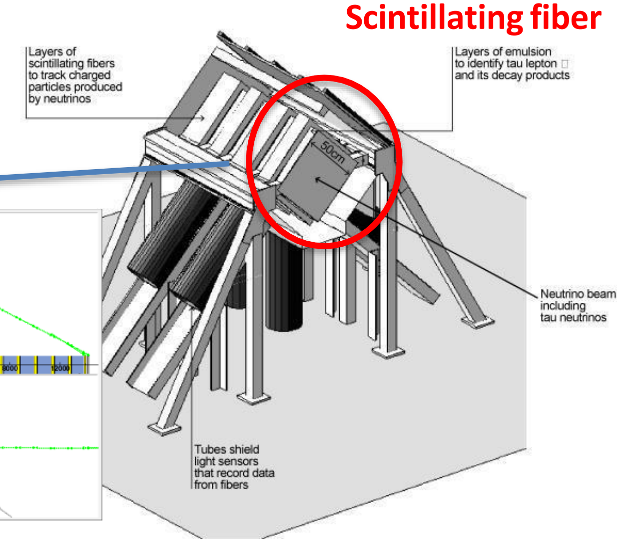
Nuclear emulsion + Scintillating fiber

Detecting a Tau Neutrino





DONUT Target Station



ν physics @ SHiP

- **Production of large amounts of neutrinos**
  - **Study ν_τ and $\bar{\nu}_\tau$ properties (ex. Cross sections, etc)**
  - **Test lepton flavor universality by comparing ν_μ to ν_τ interactions**
  - **ν_e study in high energy range.**
  - **Start in 2031-2035 ?**

	CC DIS interactions
N_{ν_e}	8.6×10^5
N_{ν_μ}	2.4×10^6
N_{ν_τ}	2.8×10^4
$N_{\overline{\nu}_e}$	1.9×10^5
$N_{\overline{\nu}_\mu}$	5.5×10^5
$N_{\overline{\nu}_\tau}$	1.9×10^4

Expected CC DIS interactions in the SND assuming 2×10^{20} protons on target

Summary

- There are many interesting and fascinating future ν experiments.
- Introduced today are

HK, DUNE, ESSnuSB, ν-factory, (JUNO,) IceCube Gen 2 & atmospheric ν experiments, (0$\nu\beta\beta$ experiments,) sterile ν experiments, and SHiP.


Prof. Takaaki Kajita
Atsumu Suzuki (me)
Join us !

Thank you !