Future Neutrino Experiments

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8th Vietnam School on Neutrino (VSoN8)
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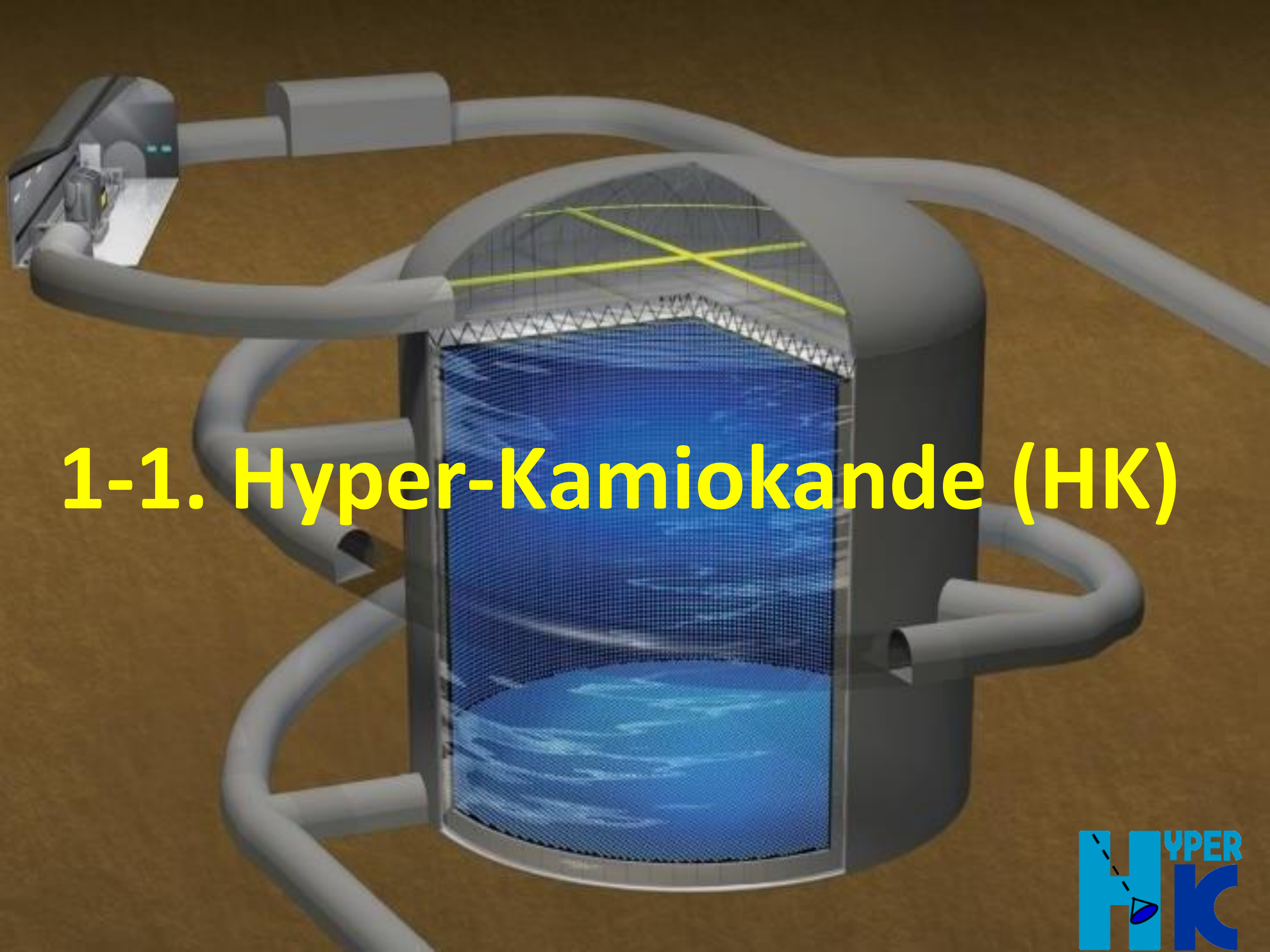
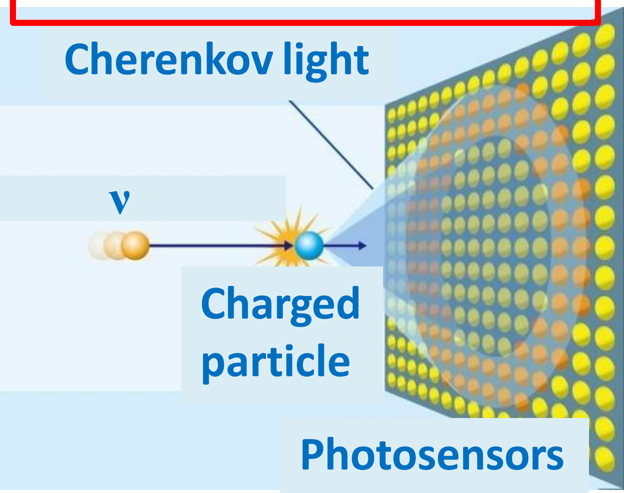
1-1. Hyper-Kamiokande (HK)

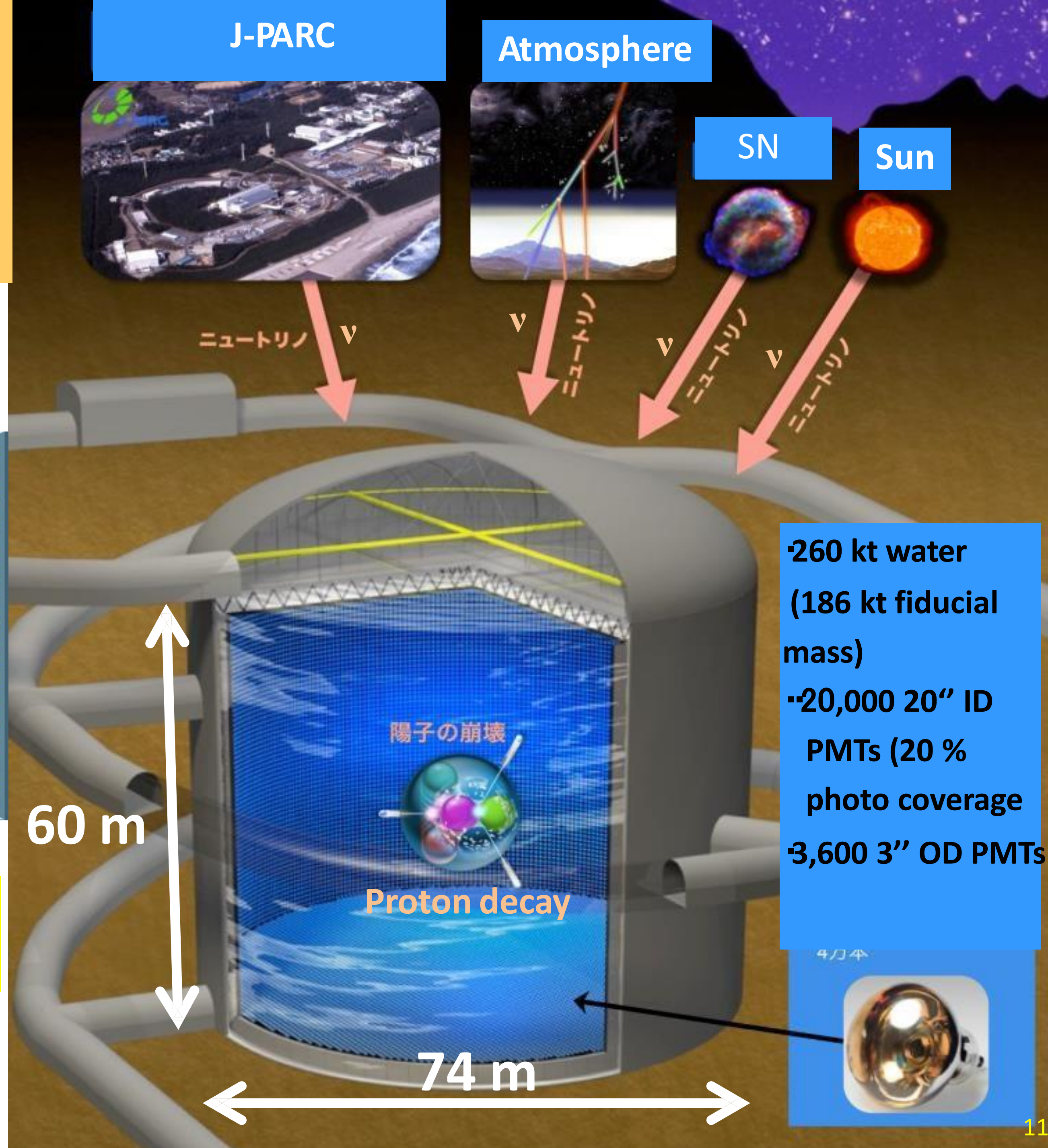


Hyper-Kamiokande Detector

Large water Cherenkov detector

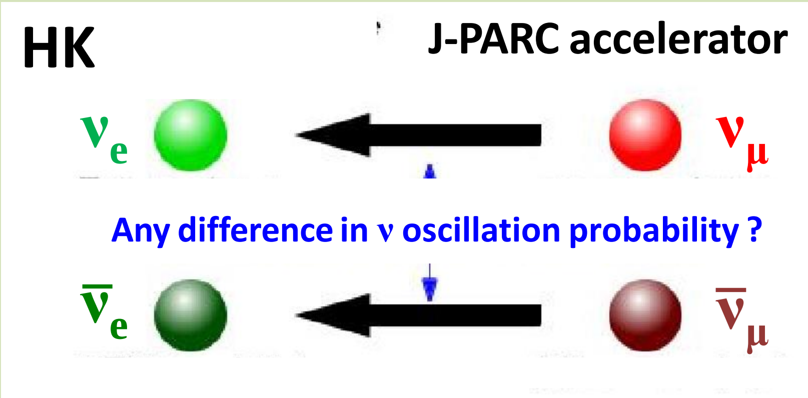


- Construction started in 2020
- Operation will start in 2027

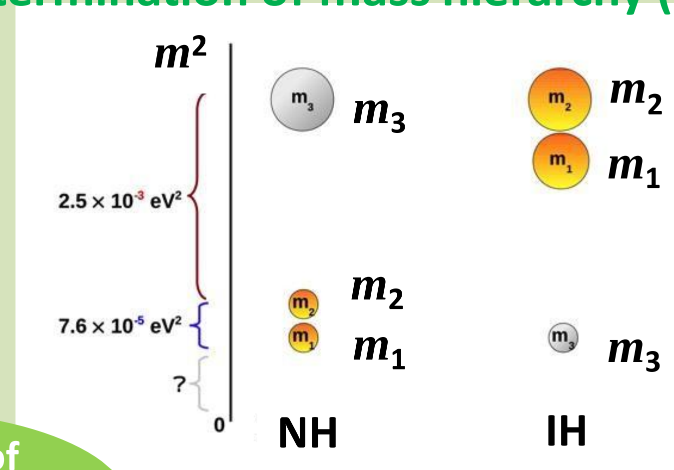


Physics goals

CPV measurement

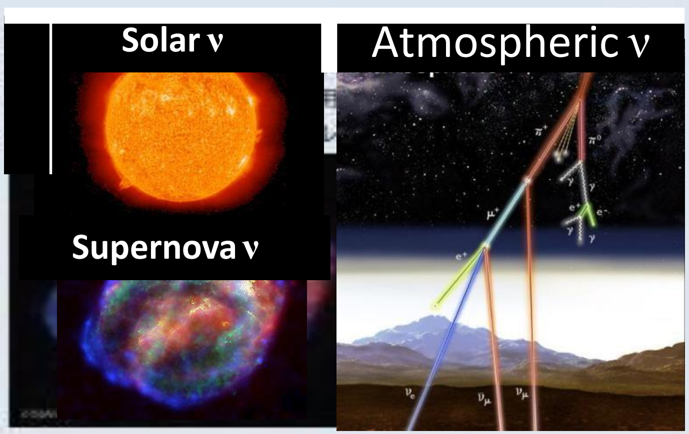


Determination of mass hierarchy (MH)



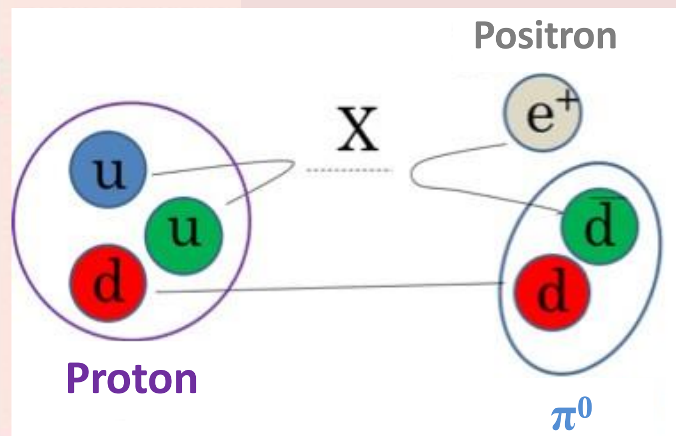
Elucidation of whole picture of ν oscillation

Cosmic neutrino observation



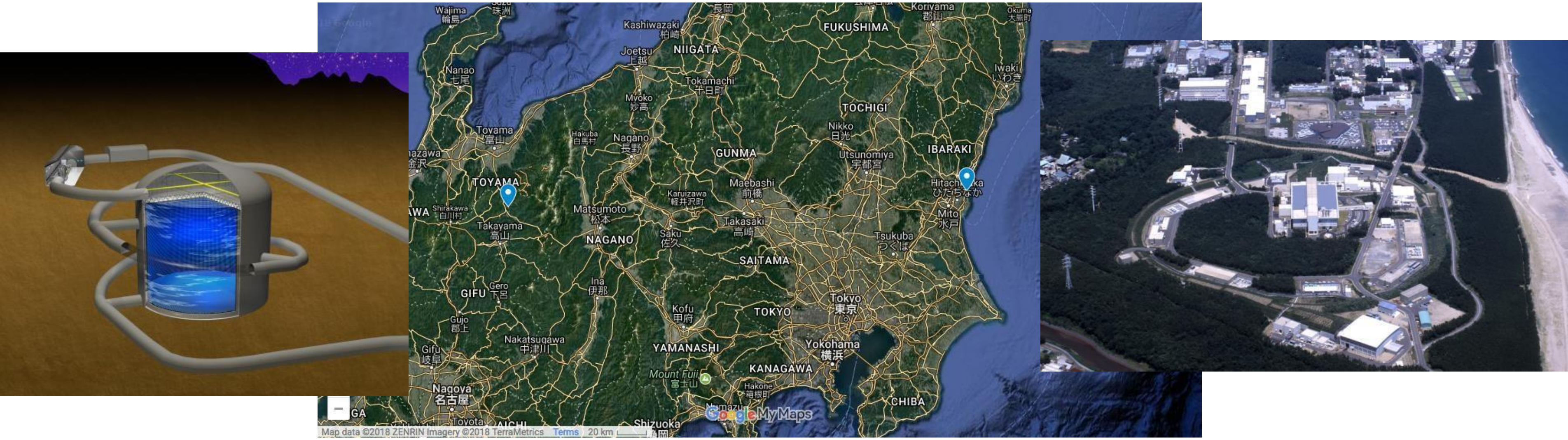
Elucidation of the origin and the history of the universe

Proton decay search



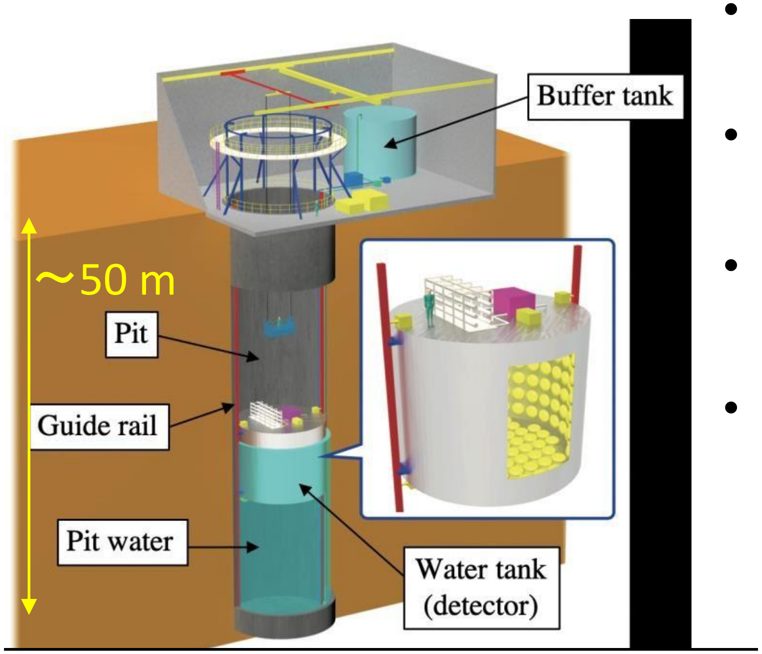
Investigation of GUT

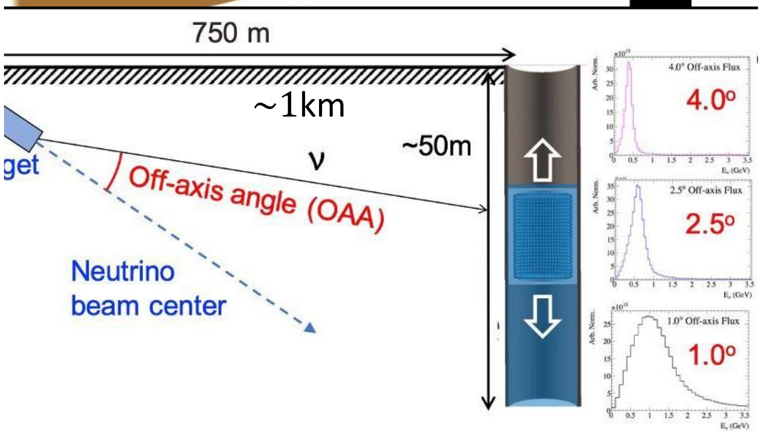
HK Long Baseline Experiment



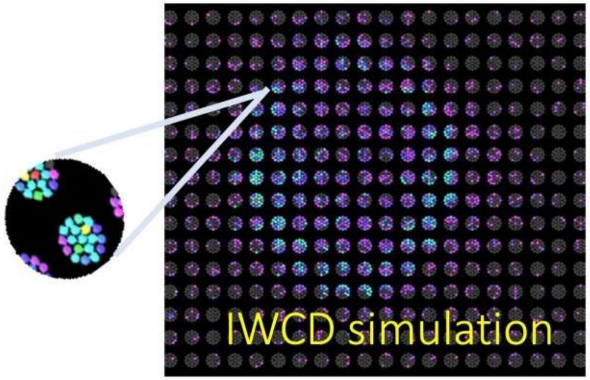
- J-PARC ν beam: 800 kW → 1.3 MW
  2.5° off-axis, peak energy @～600 MeV (oscillation maximum)
  → narrow band beam suppresses NC-π^0 and CC-nQE contamination
- ND280 should continue its operation for HK.
- FD:SK → HK will realize high statistic ν data
- Intermediate Water Cherenkov Detector (IWCD) will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

Intermediate Water Cherenkov Detector (IWCD)

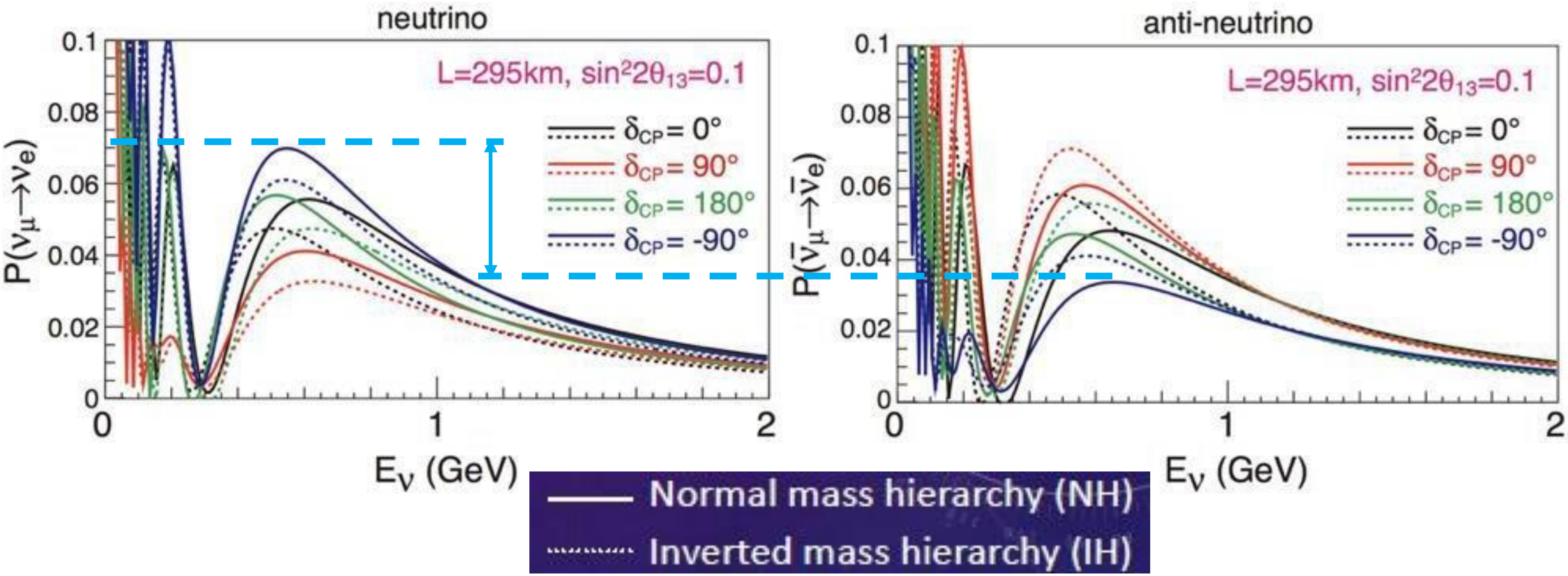




- ~600 t water Cherenkov detector located at ~800 m from the neutrino source
- Moves es vertically to measure energy spectrum at different off-axis between 1° and 4°.
- $\sigma(\nu_e)/\sigma(\nu_\mu), \sigma(\nu_e)/\sigma(\nu_\mu)$
  - 3-4% accuracy at 600 MeV (work in progress)
- Multi-PMT units will be used. → good reconstruction despite small detector

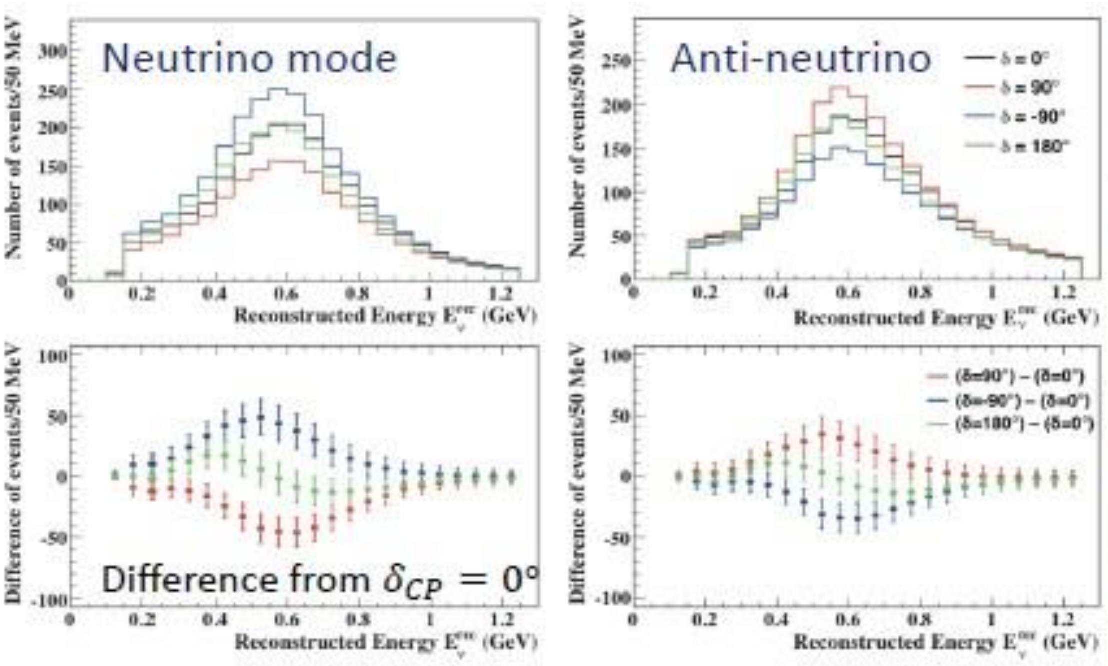


Measurement of CP asymmetry



- Comparison between the probabilities: $P(\nu_\mu \rightarrow \nu_e)$ vs $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$
- 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



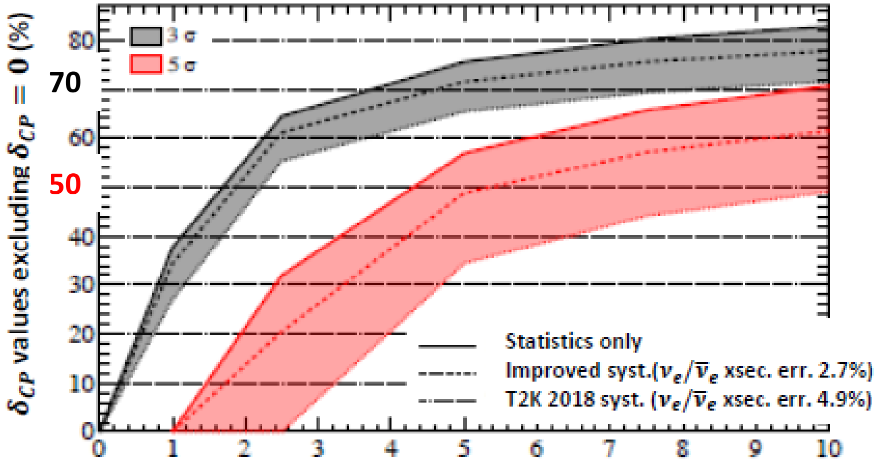
- A few % stat. uncertainties on $\nu_\mu \rightarrow \nu_e$ & $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ signals
- $E\nu$ is reconstructed from (p, θ) of e or μ
- Realistic estimates of wrong sign & NC BG contaminations are based on T2K

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

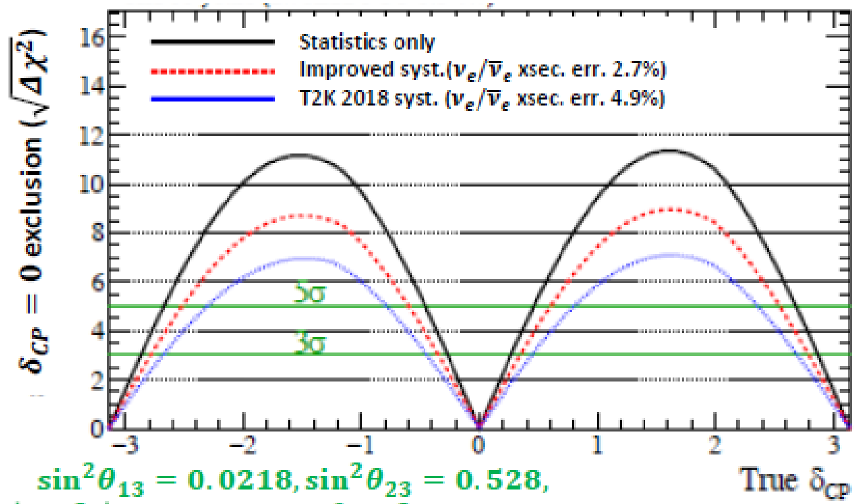


$\sin^2\theta_{13} = 0.0218, \sin^2\theta_{23} = 0.528$
$|\Delta m^2_{32}| = 2.509 \times 10^{-3}[\mathrm{eV}^2]$

HK years
(2.7×10^{22} POT, $\nu : \overline{\nu}$ =1:3)

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

HK years (2.7×10^{22} POT, $\nu : \overline{\nu}$ =1:3)



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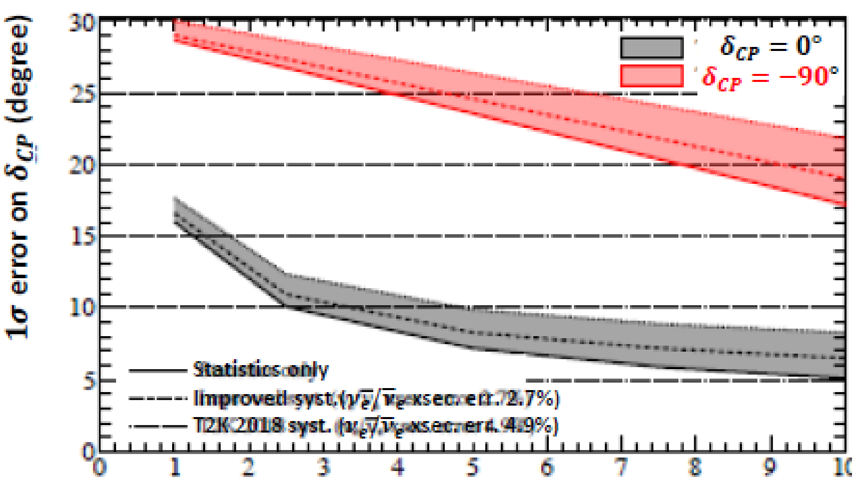

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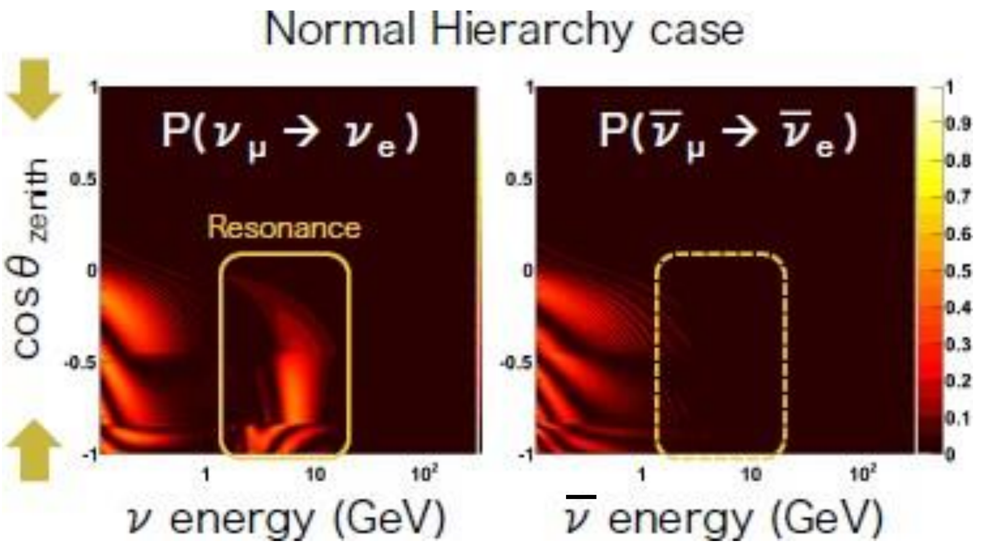
HK years
(2.7×10^{22} POT, $\nu : \overline{\nu}$ =1:3)

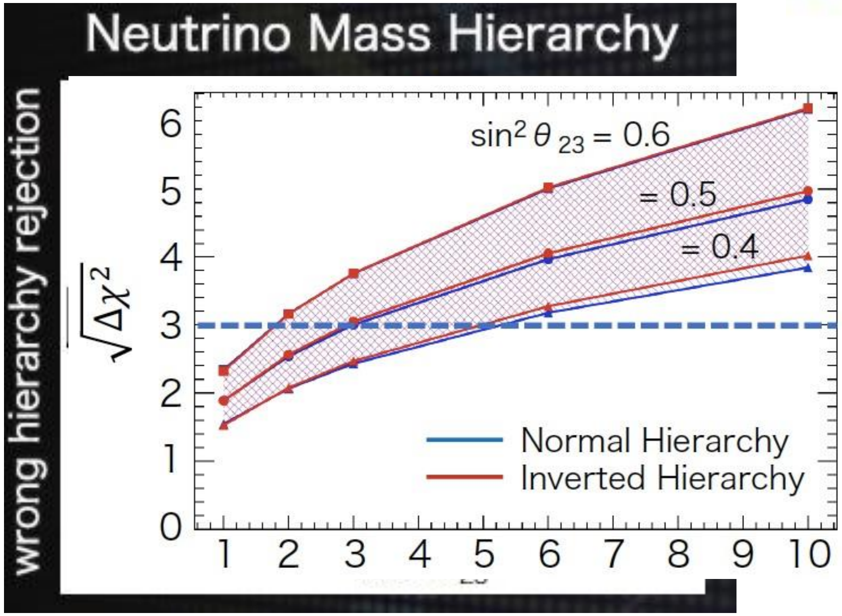
Significance to exclude
$\delta_{CP} = 0$ (CP conservation)

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

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

Mass hierarchy determination



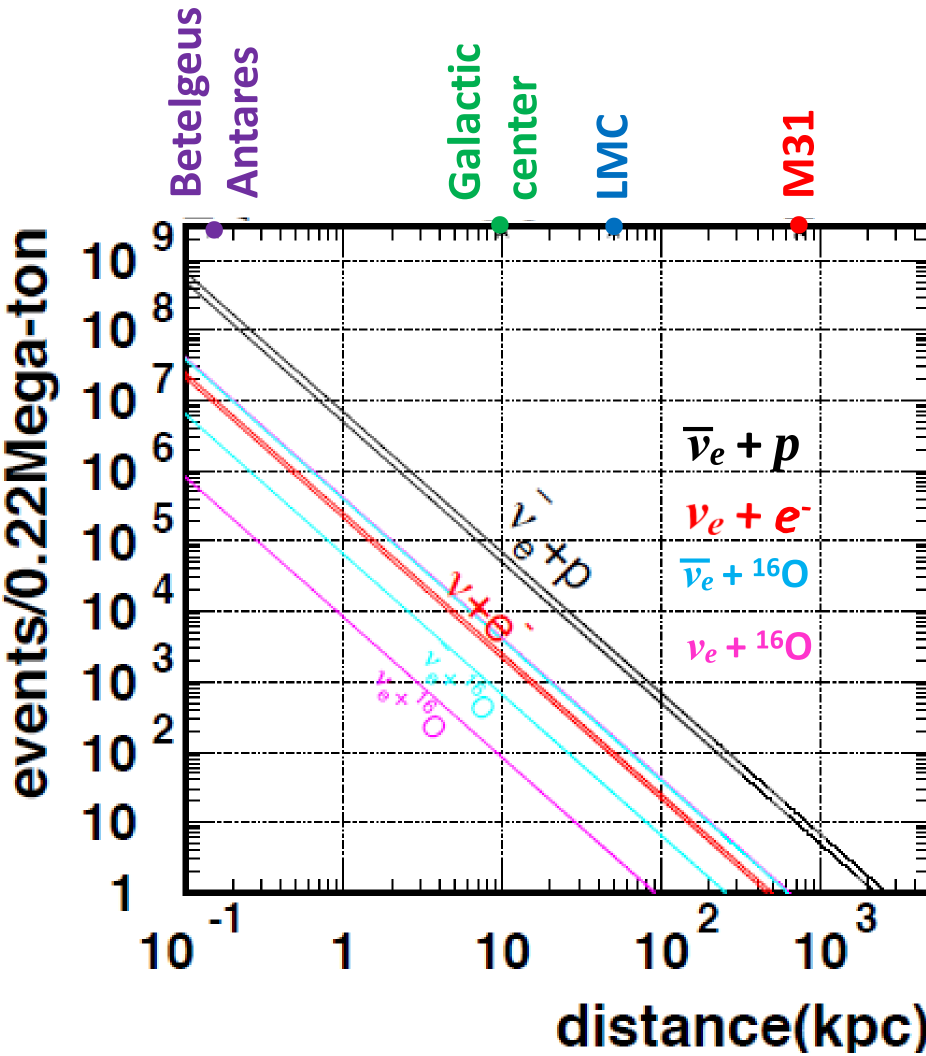


- The resonance appears for ν_e ($\bar{\nu}_e$) in NH (IH) case.
- Sensitivity enhanced by combining atm & beam ν data.→ **3σ determination within 2 ~ 5 years !**

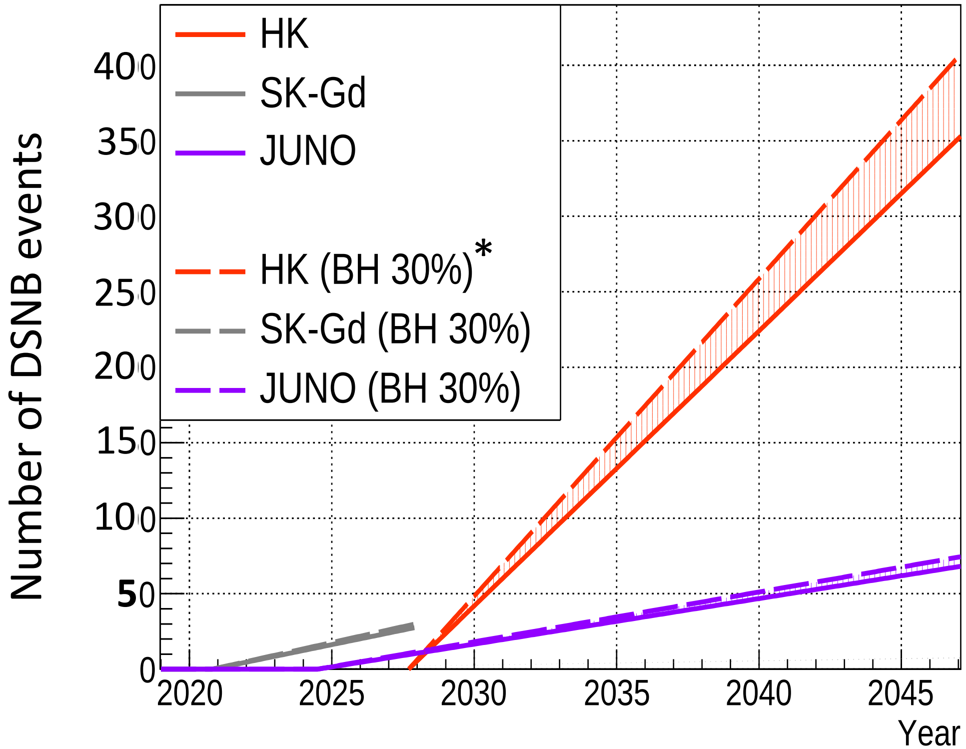
Neutrino astrophysics

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



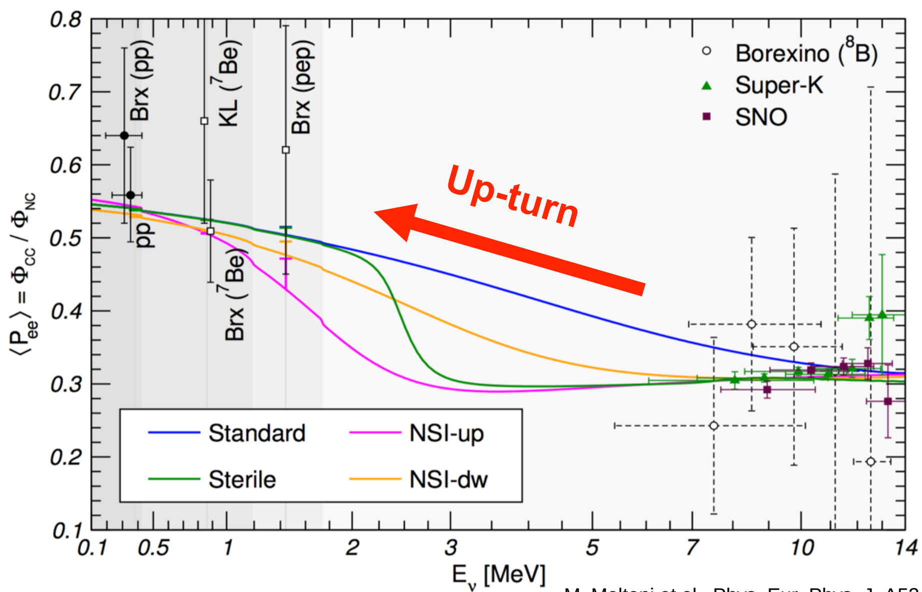
BH 30 % :30% of the supernovae form black hole and emits higher energy Neutrinos.

Defused Supernova Neutrino Background (DSNB)

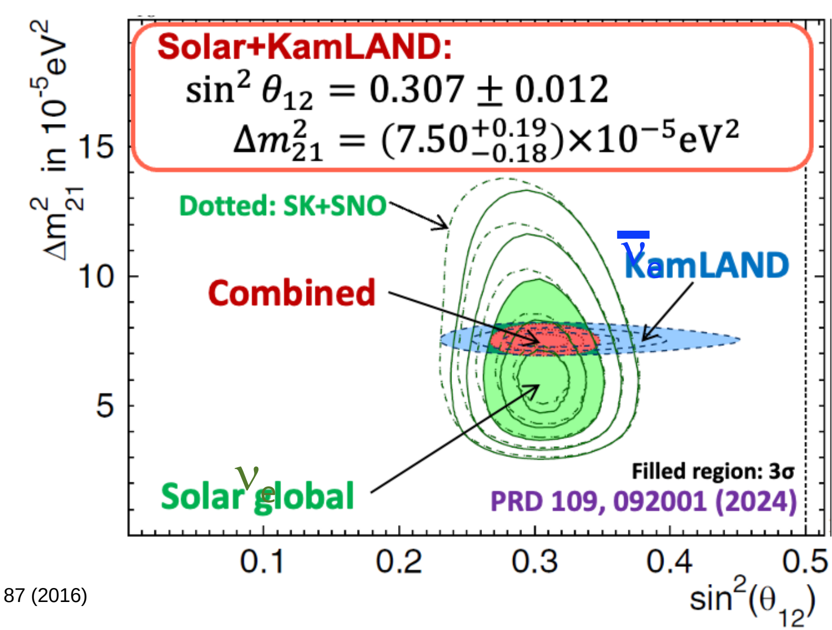
- 1st discovery by SK-Gd
- HK will measure the spectrum.

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

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

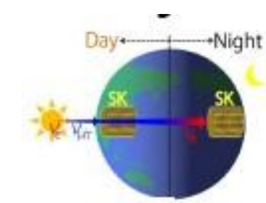


M. Maltoni et al., Phys. Eur. Phys. J. A52, 87 (2016)



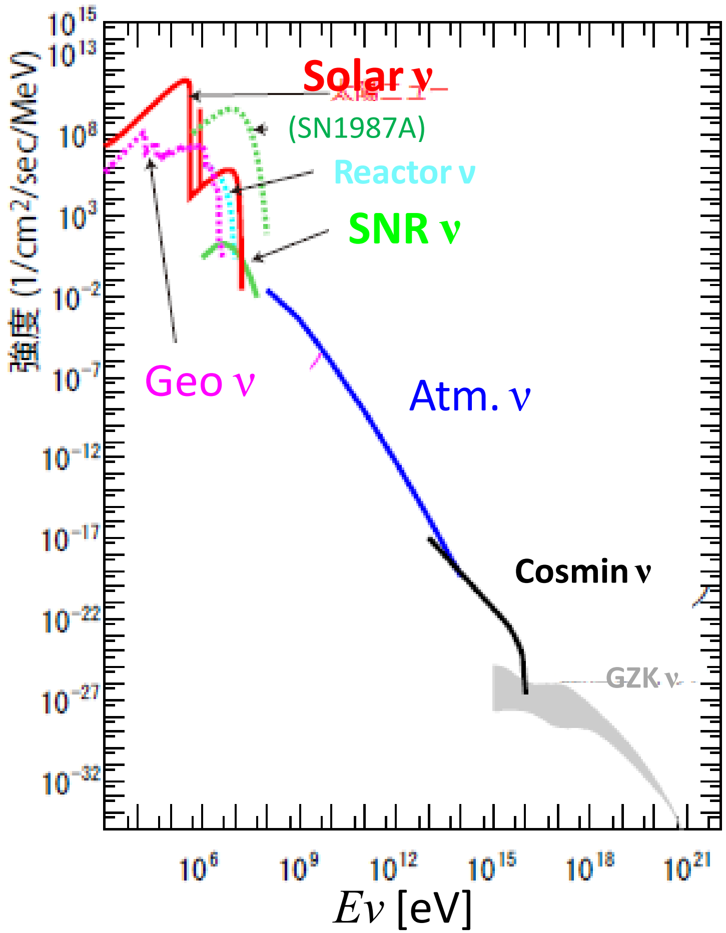
<u>~130 events/day</u>

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

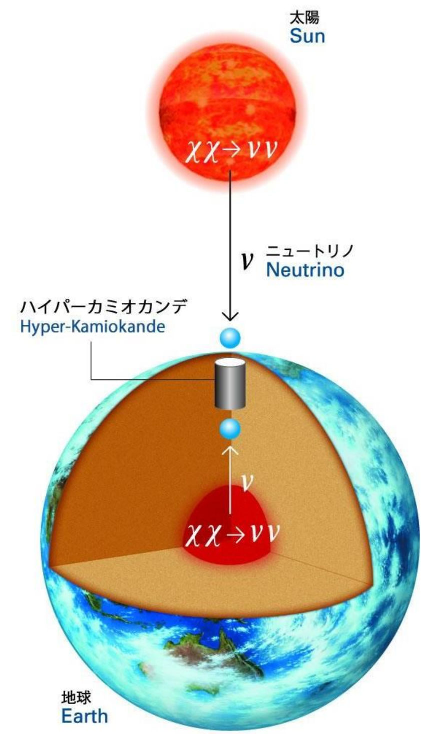


Neutrino astrophysics

-Cosmic ν Observation-



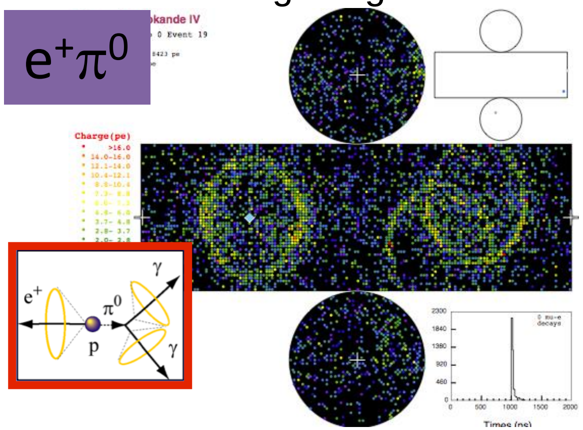
Neutrino fluxes at Kamioka as a function of neutrino energy. Precision measurements for solar, SN(R), and atmospheric neutrinos can be done with high statistics.



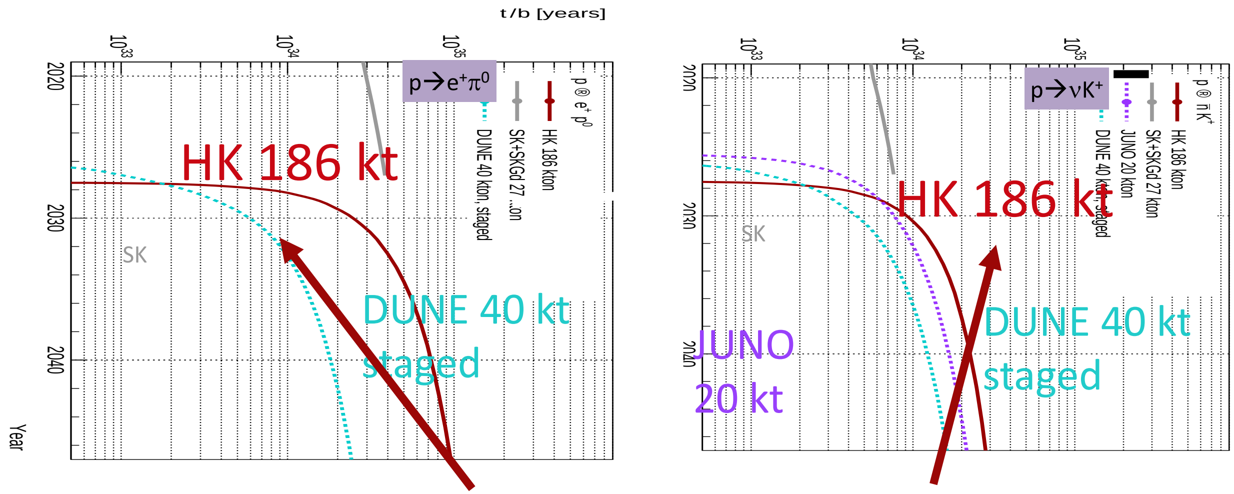
Indirect DM search: Hyper-Kamiokande detects the neutrinos generated by the interaction of dark matters in the Sun or the earth.

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

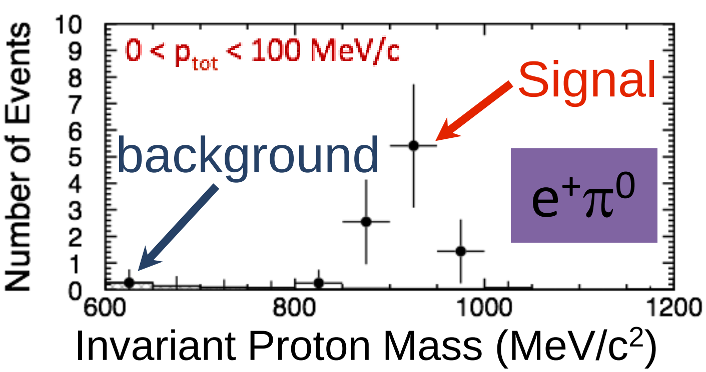
Cherenkov ring image $e^+\pi^0$ in SK



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



3σ discovery potential



HK 10 years

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

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

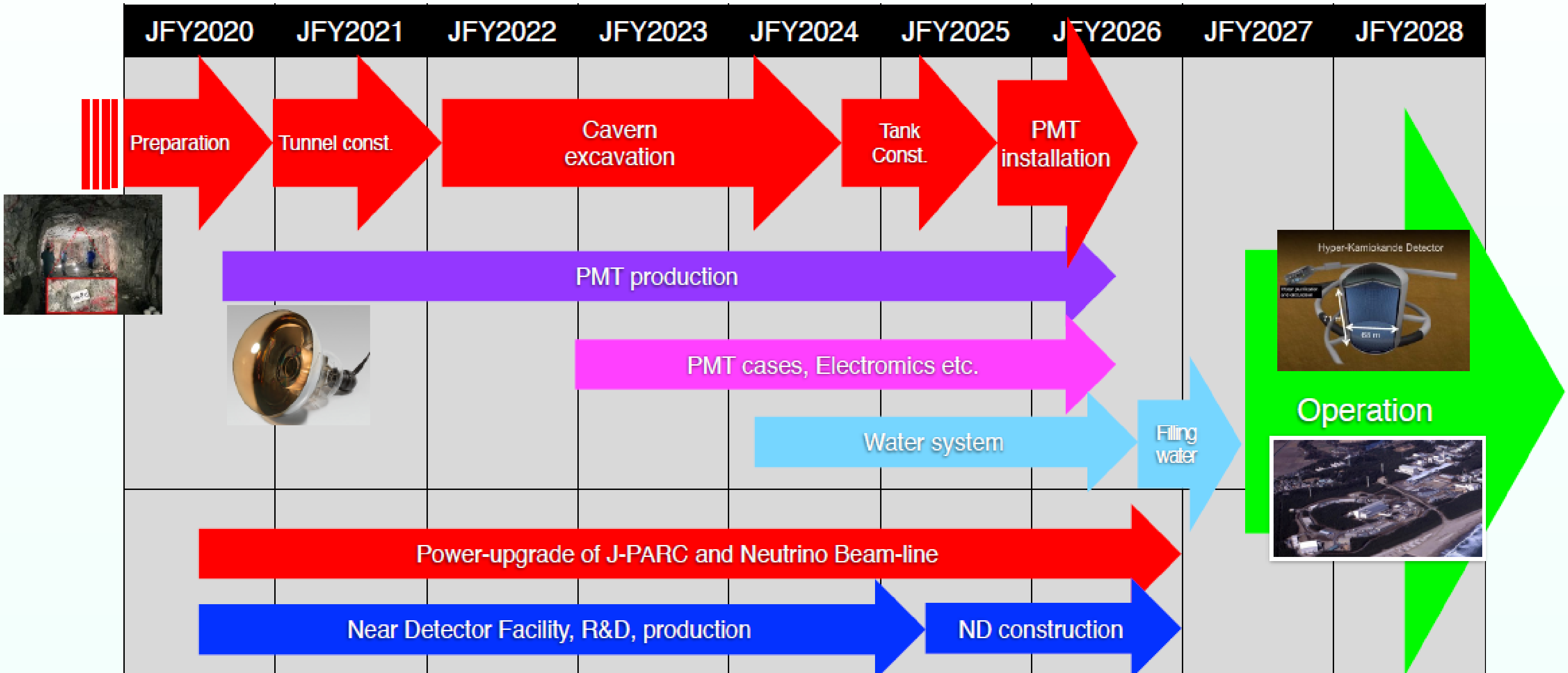
Detector Location

*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

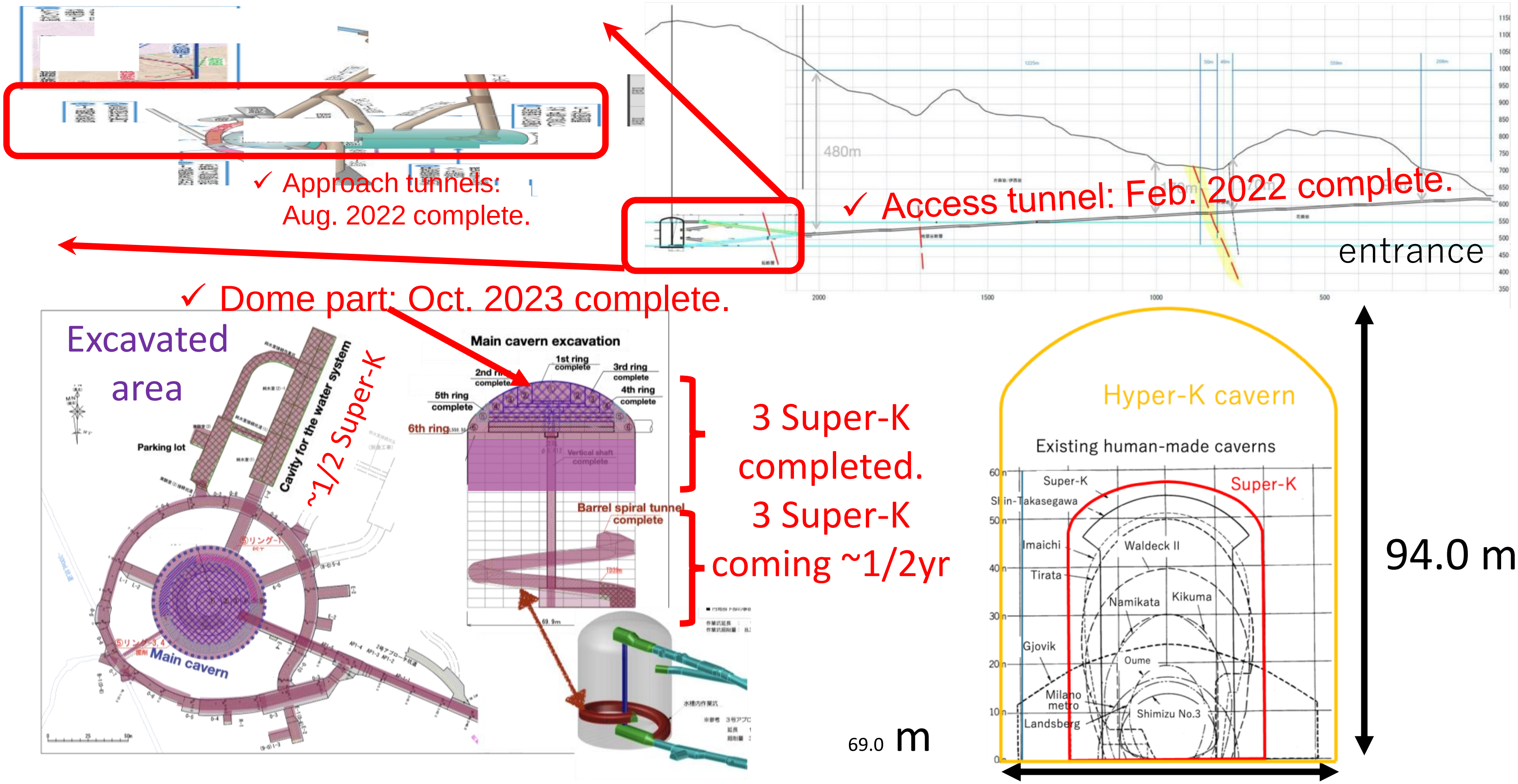
Timeline

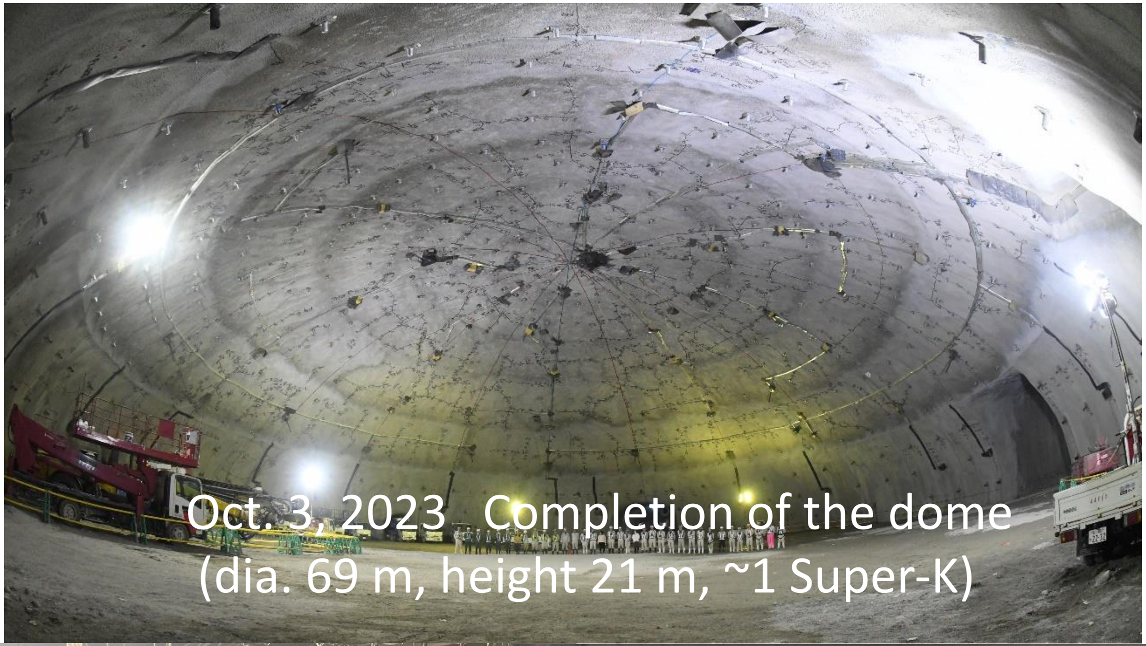
- 2022-2027: Construction, 2027- : Operation
  - No change of schedule since the approval of project in 2020



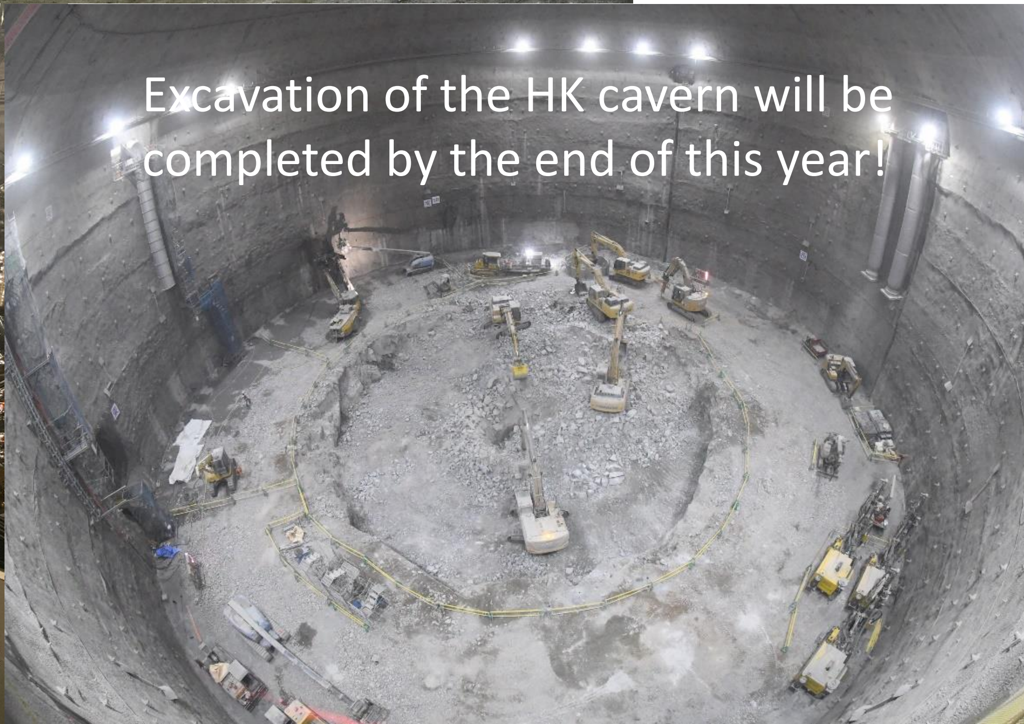
T. Nakaya, Neutrino workshop @ IFIRSE on July 27, 2023

Excavating the world's largest human-made cavern




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

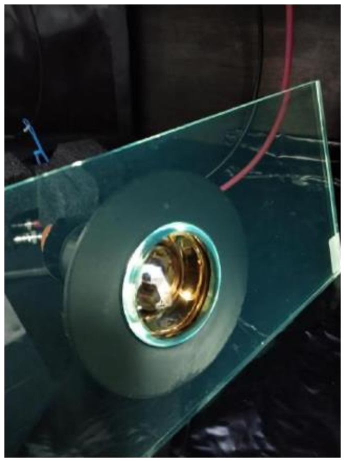

• PMT production ongoing, >10,000 delivered.
• Screening both at Hamamatsu and Kamioka

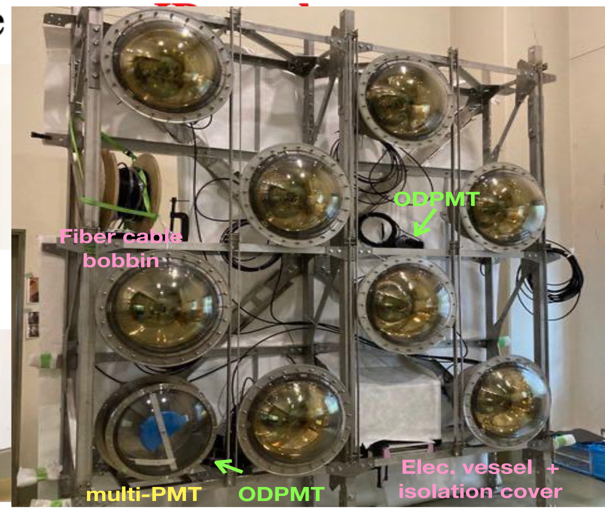

Excavation of the HK cavern will be completed by the end of this year!

Photosensors and underwater electronics

Photosensors/elec. mockup

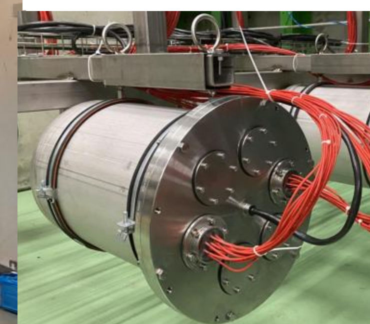
Outer detector: PMT+WLS plate

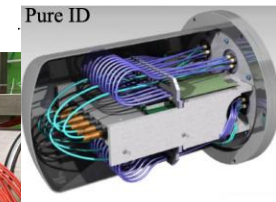


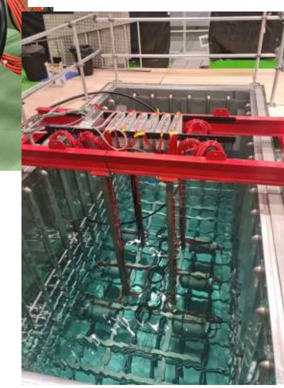


Underwater electronics:

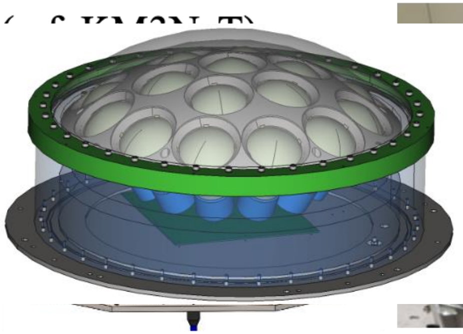
Case design and feedthrough

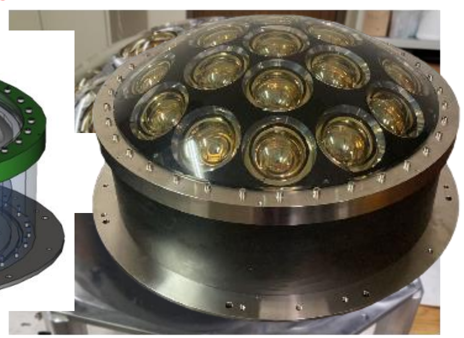




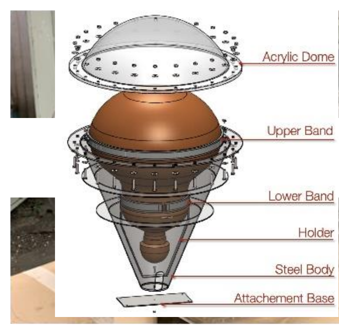


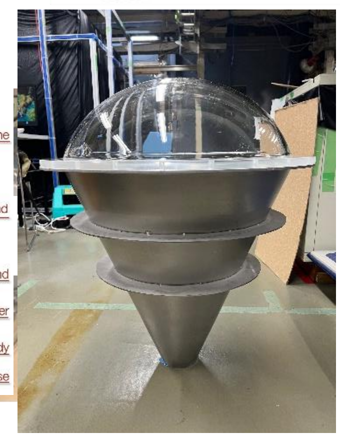
Multi-PMT module:

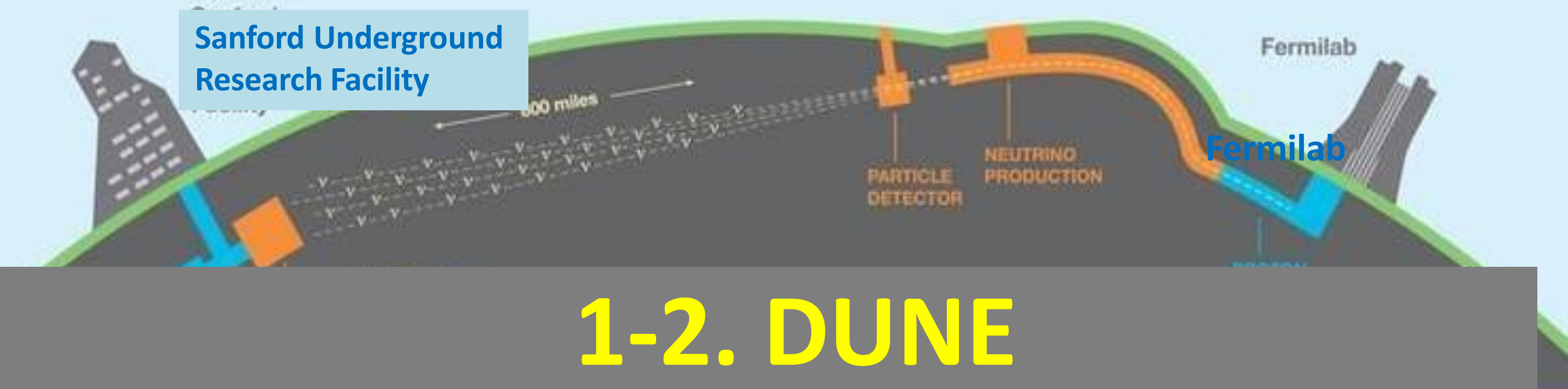




PMT cover







1-2. DUNE

(Deep Underground Neutrino Experiment)

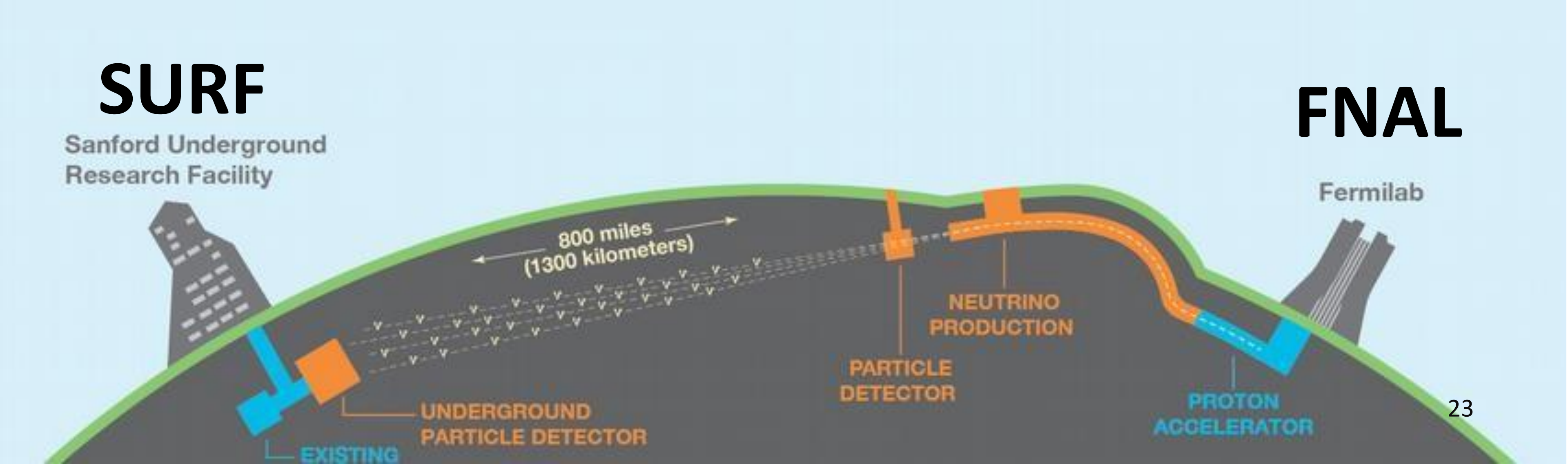
Introducing DUNE

- 1,300 km beamline
- 70 kt LArTPC far detector 1.5 km underground
- Primary physics goals:

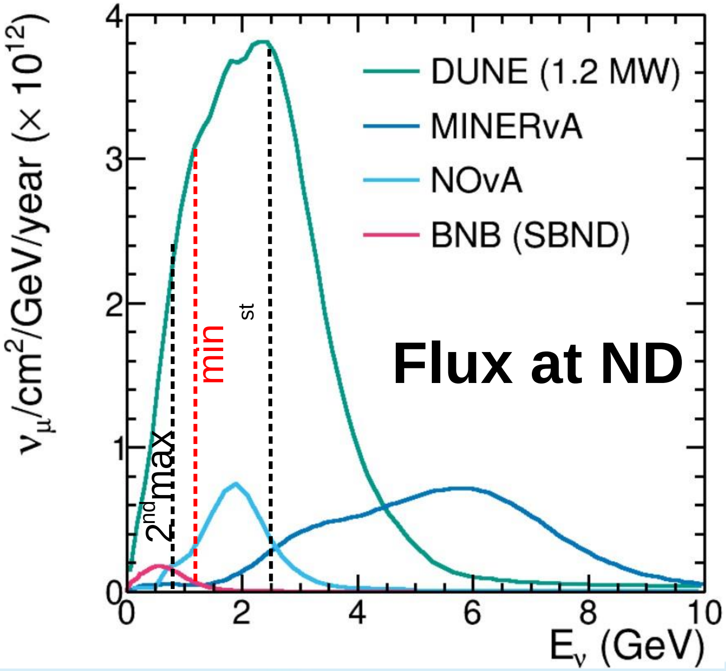
  (1) ν oscillations ($\delta_{CP}, \theta_{23}, \theta_{13}$, mass ordering)

  (2) SN burst ν's and astrophysics

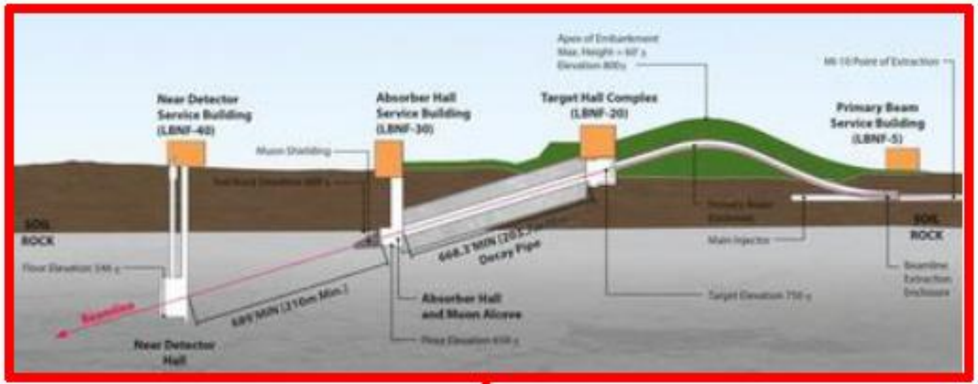
  (3) Proton decay

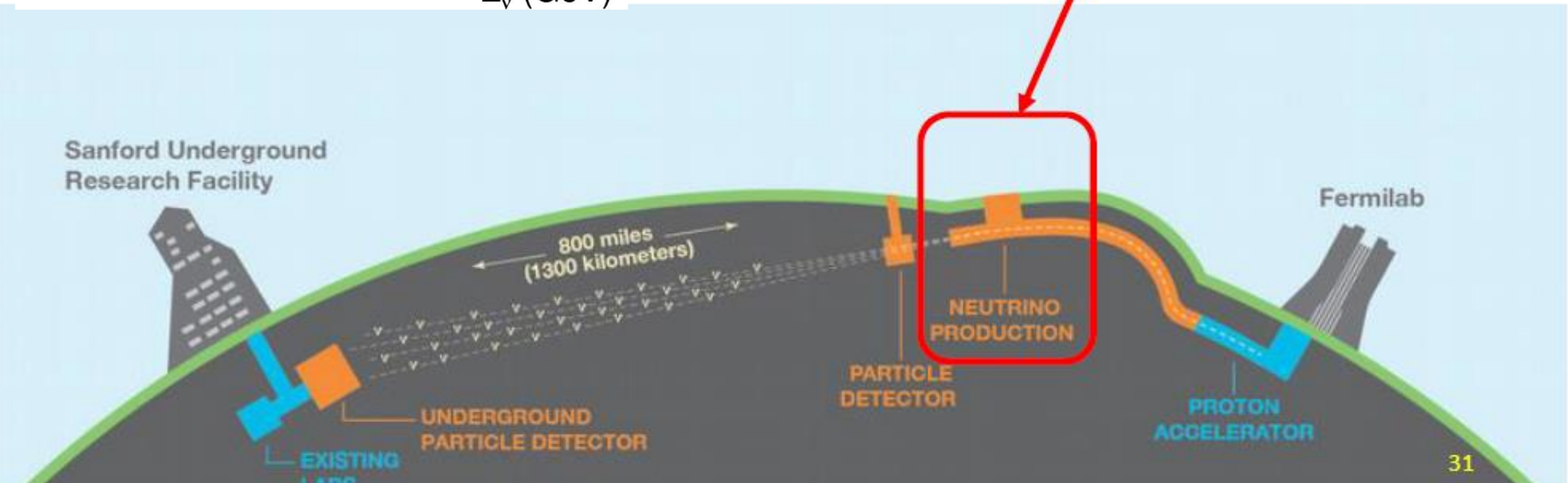


ν source

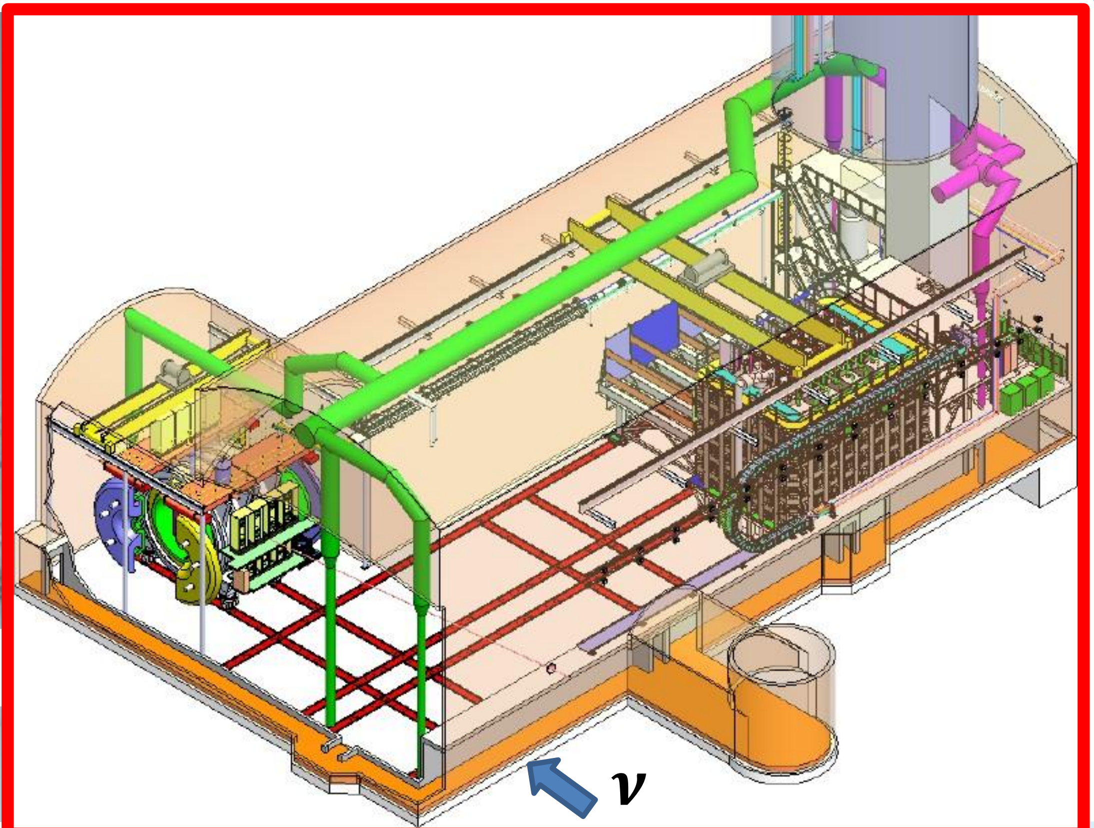


Long Baseline Neutrino Facility (LBNF)

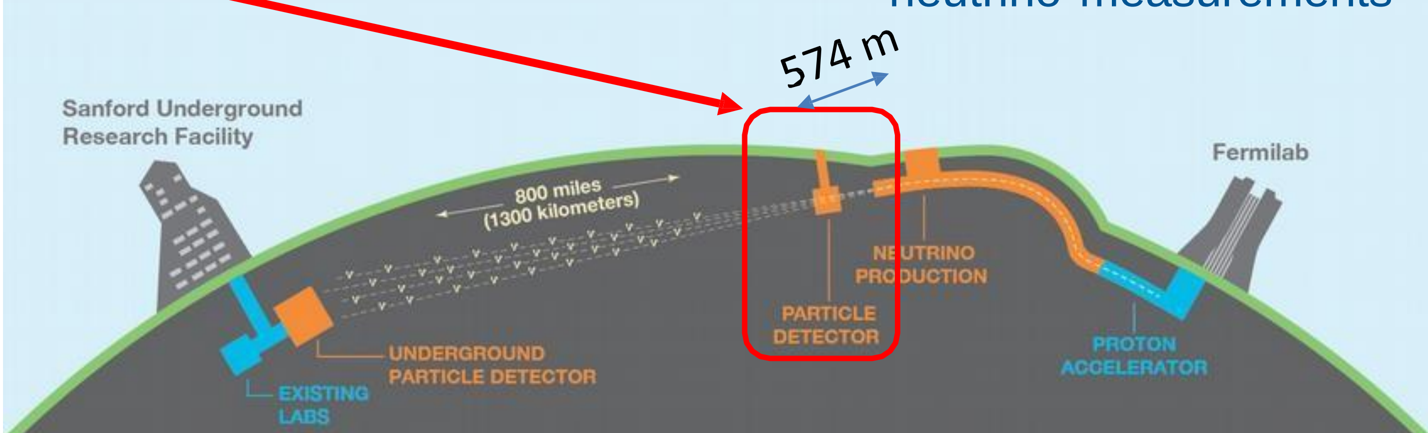




Near Detector Complex



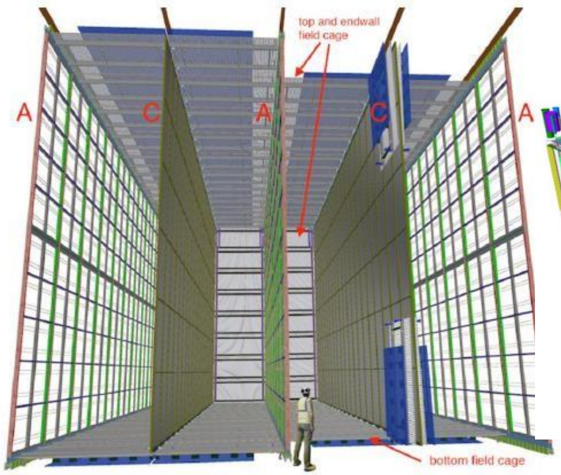
- Main purpose: prediction of Far Detector reconstructed spectra
- Movable detector system: LArTPC (ND-LAr) with muon spectrometer (TMS)
- Off-axis data in different neutrino fluxes constrains energy dependence of neutrino cross sections
- Same target, same technology → inform predictions of reconstructed E_ν in Far Detector On-axis magnetized detector (SAND) for beam monitoring and neutrino measurements

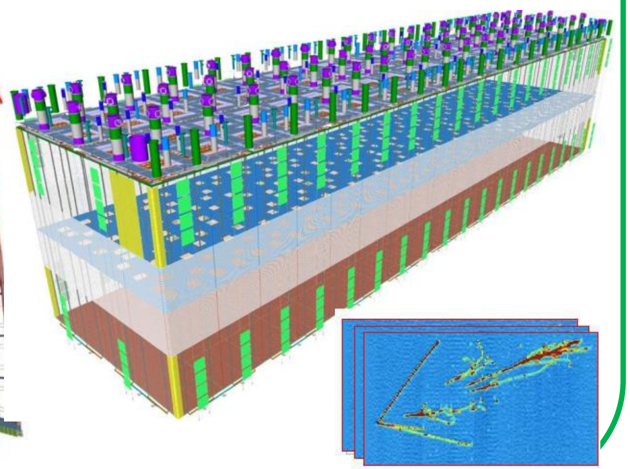


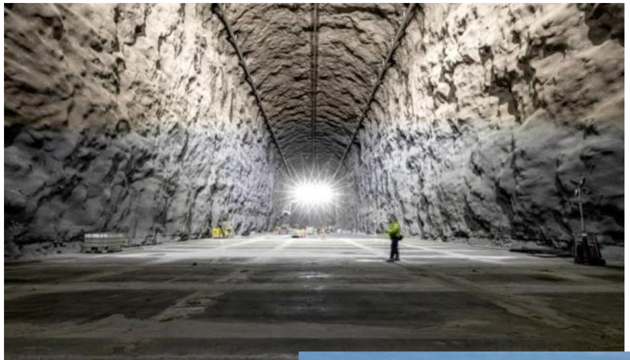
Far Detector Technologies

LiAr TPC module

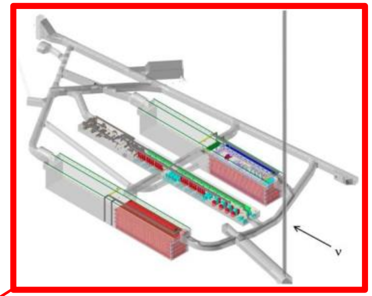
***FD-HD**: JINST 15 T08010 (2020)* ***FD-VD**: arXiv:2312.03130 (2023)*

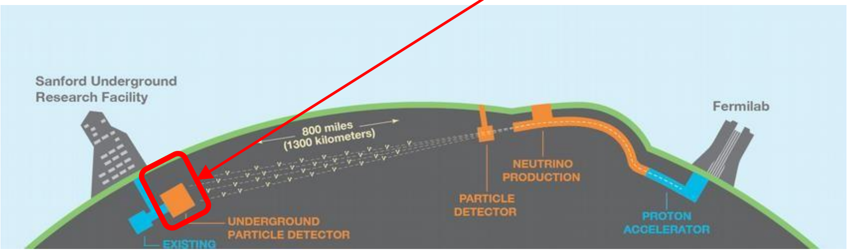






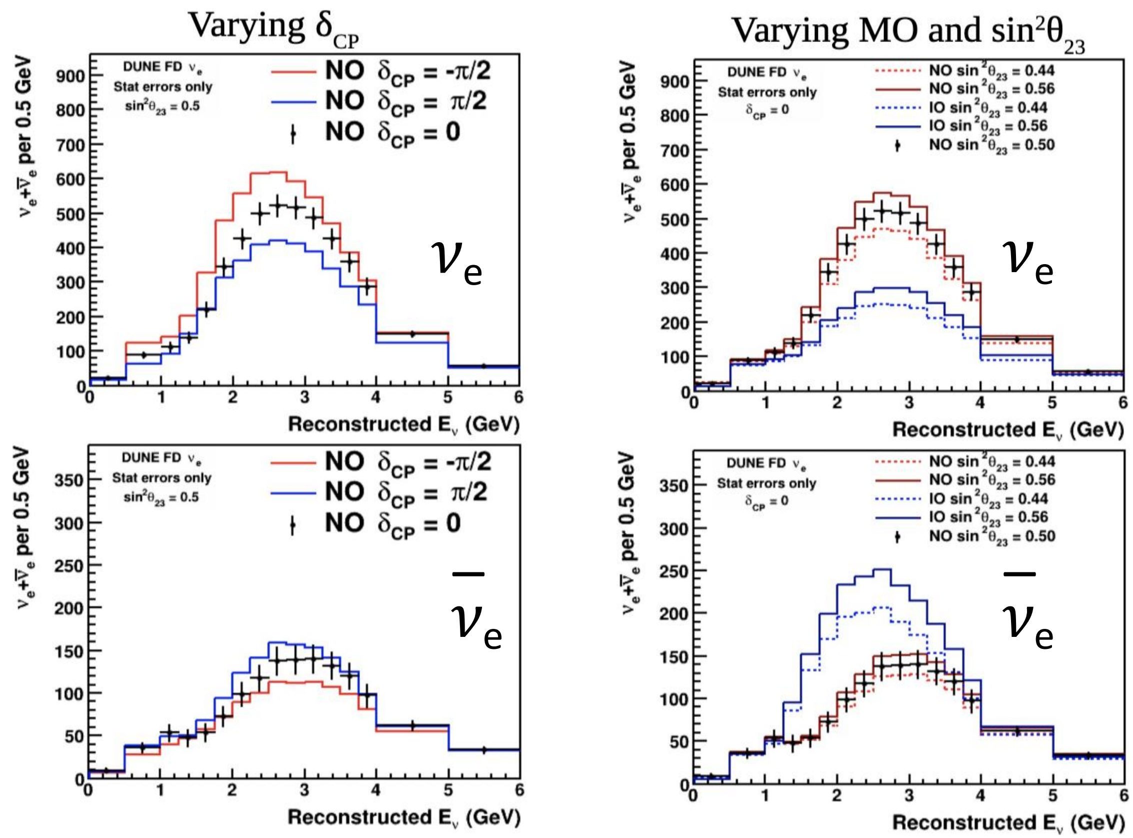
- Horizontal drift (FD-HD) using wire readout planes, four drift regions (3.6m)
- Vertical drift (FD-VD) using two 6.25m drift regions and central cathode
  - Simpler to install → first DUNE FD module will use vertical drift
  - VD is baseline design for FD modules 3 and 4





Neutrino energy spectra at the Far Detector

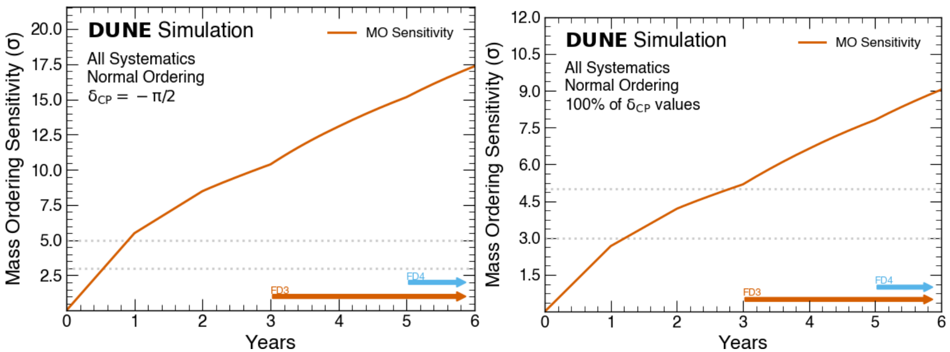
- Sensitivity to $\boldsymbol{\delta_{CP}}$
  - If $\delta_{CP} \sim -\pi/2$, DUNE will measure an enhancement in electron neutrino appearance, and a reduction in electron antineutrino appearance
- Sensitivity to mass ordering (**MO**)
  - If MO is normal, DUNE will measure a <u>much larger</u> enhancement in electron neutrino appearance, and a reduction in electron antineutrino appearance
- MO, δ_{CP}, and θ_{23} all affect spectra with different shape



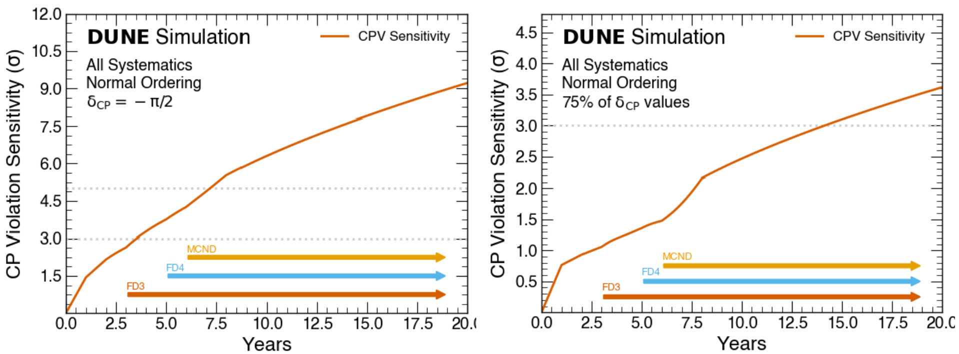
DUNE sensitivity

Neutrino mass ordering

Eur. Phys. J. C 80, 978 (2020)



CP violation sensitivity

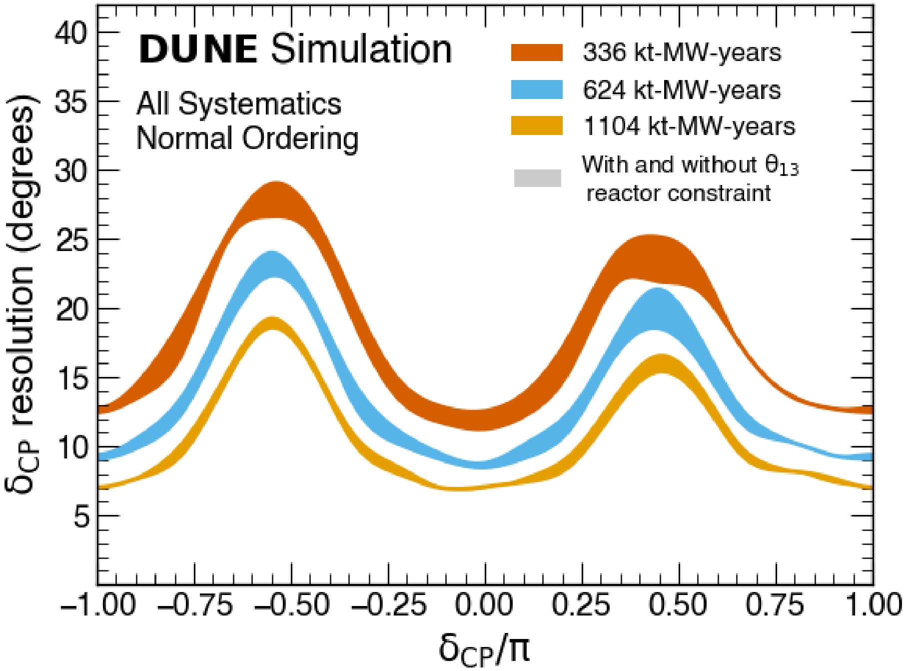


- For <u>best-case</u> oscillation scenarios, DUNE has
  - $> 5\sigma$ mass ordering sensitivity in 1 year
  - $> 3\sigma$ CPV sensitivity in 3.5 years
- For <u>worst-case</u> oscillation scenarios, DUNE has $> 5\sigma$ mass ordering sensitivity in 3 years
- In <u>long term</u>, DUNE can establish CPV over 75% of δ_{CP} values at $>3\sigma$

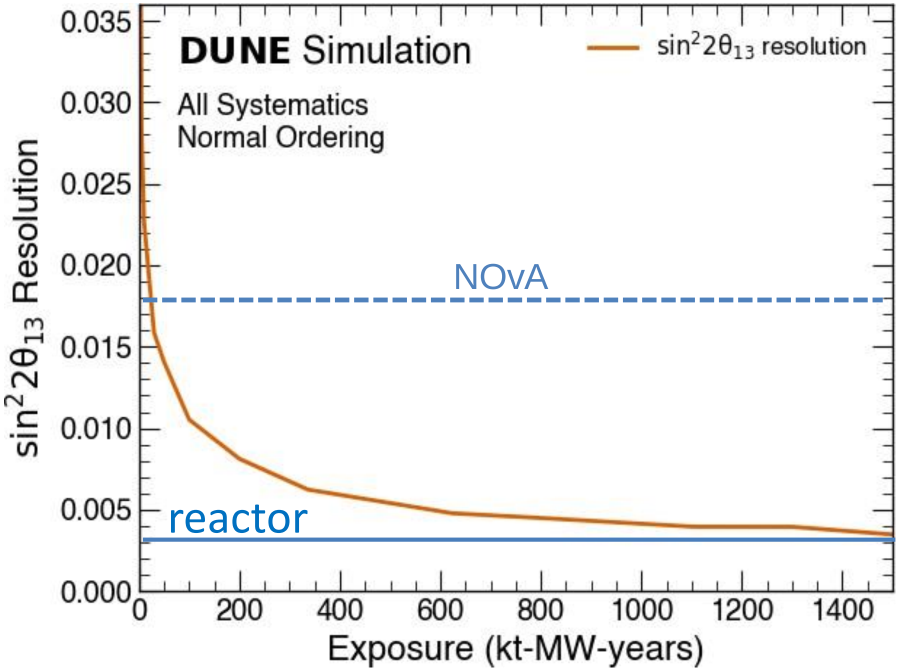
DUNE precise measurements

- Ultimate precision 6-16° in $\boldsymbol{\delta_{CP}}$
- World-leading precision (for long-baseline experiment) in $\boldsymbol{\theta_{13}}$ → comparisons with reactor measurements are sensitive to new physic

$\boldsymbol{\delta_{CP}}$



$\boldsymbol{\theta_{13}}$

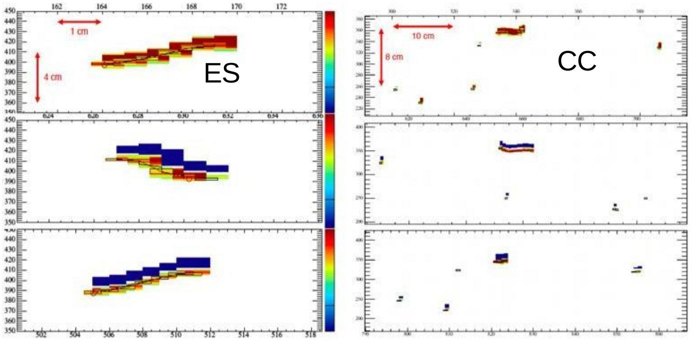


Astrophysical neutrinos in DUNE

Unique sensitivity to MeV electron neutrinos:

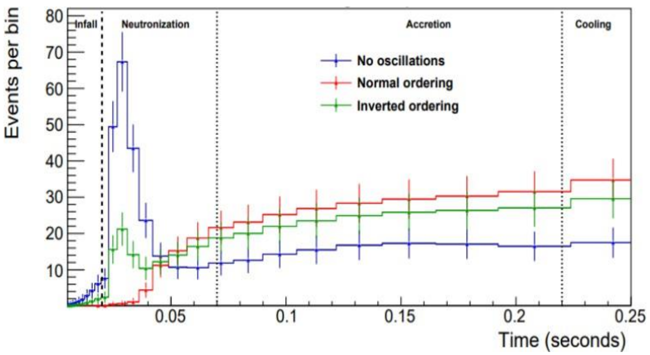
CC $\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$ *(main channel)*

ES $\nu_x + e^- \rightarrow \nu_x + e^-$ *(pointing)*

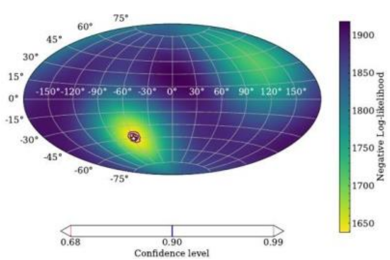


Neutrinos from core-collapse supernovae

- **Neutronization** burst measurements → mass ordering measurement *Eur. Phys. J. C 81 (2021) 5, 423* *Phys.Rev.D 107 (2023) 11, 112012*

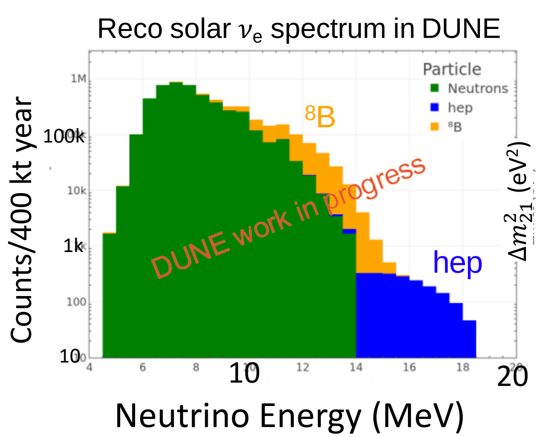


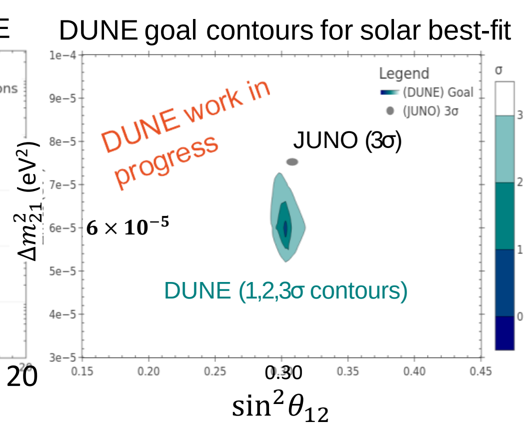
- **Pointing** capabilities: ES channel ~5° pointing resolution (40 kt, 10 kpc)



Neutrinos from the Sun

- DUNE has excellent sensitivity to **^{8}B solar neutrinos** above ~10 MeV, and discovery sensitivity to the **hep solar flux**
- DUNE can improve upon existing solar oscillation measurements via **day-night asymmetry** induced by matter effects → comparison with JUNO

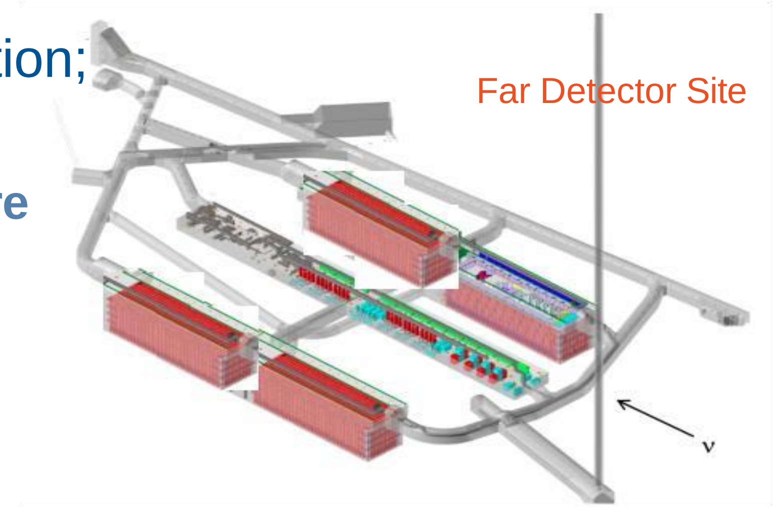




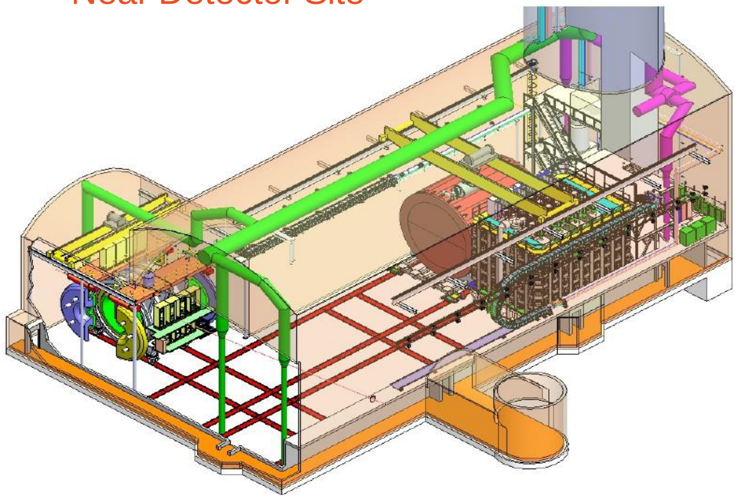
DUNE Phases

- **DUNE Phase I** (2026 start detector installation; 2029 physics; 2031 beam + ND)
  - **Full near + far site facility and infrastructure**
  - **Two 17 kt LArTPC modules**
  - **Upgradeable 1.2 MW neutrino beamline**
  - **Movable LArTPC near detector with muon catcher**
  - **On-axis near detector**

Far Detector Site



Near Detector Site



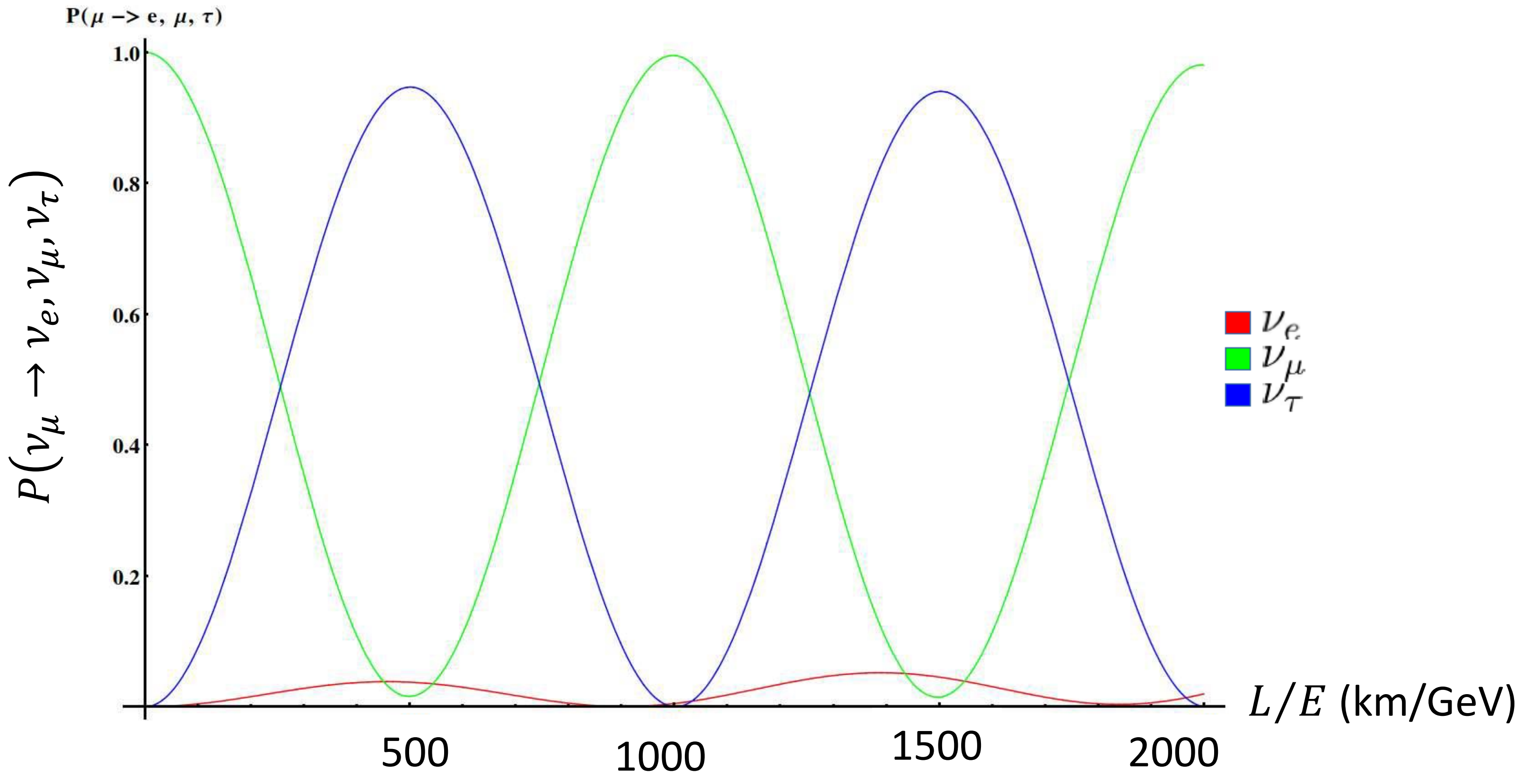
- **DUNE Phase II**:
  - **Two additional FD modules (≥40 kt fiducial in total)**
  - **Beamline upgrade to >2 MW**
  - **More capable Near Detector (ND-GAr)**

P5 report endorses FD3, ACE-MIRT, and MCND in the next decade, and R&D toward FD4

1-3. ESSnuSB

(European Spallation Source neutrino super-beam)

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



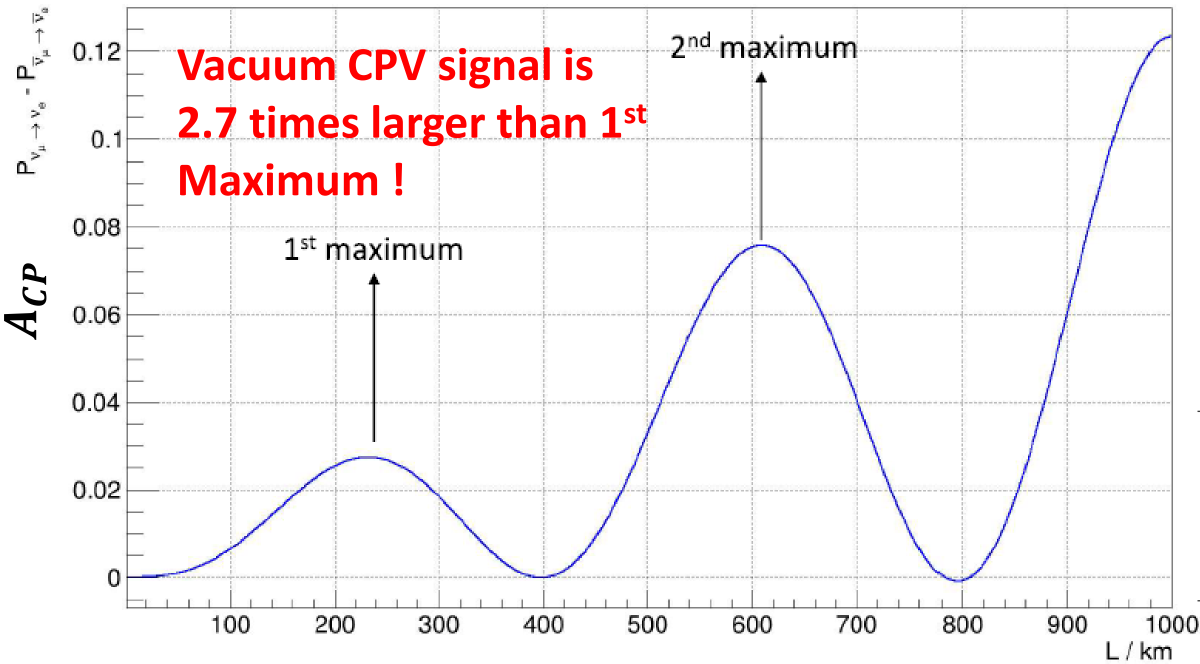
Why 2nd maximum ? (1)

CP violation in ESSnuSB

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

$$s_{ij} \equiv \sin\theta_{ij}$$
$$c_{ij} \equiv \cos\theta_{ij}$$
$$\Delta m^2_{ij} \equiv m^2_i - m^2_j$$
$$A^{\alpha\beta}_{ij} \equiv U^*_{\alpha i} U_{\alpha j} U_{\beta i} U^*_{\beta j}$$
$$J = s_{12} c_{12} s_{13} c_{13} s_{23} c_{23} c_{13} \sin\delta_{\mathrm{CP}}$$

E = 400 MeV

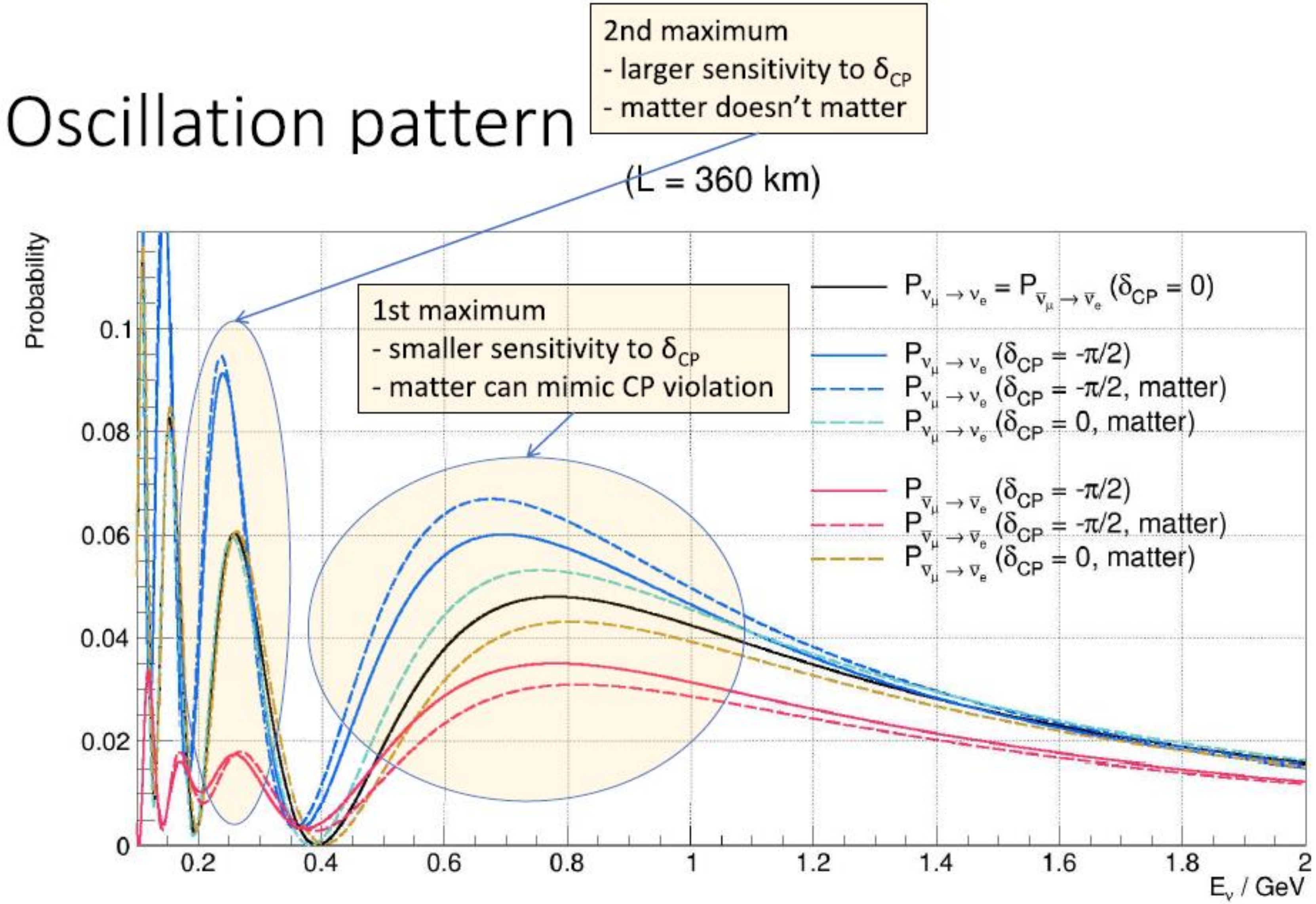


$$\frac{A_{CP} \text{ @ 2nd max}}{A_{CP} \text{ @ 1st max}} \sim 2.7$$

- Does not depend on *J*, i.e. PMNS matrix elements
- Depends only on mass splittings

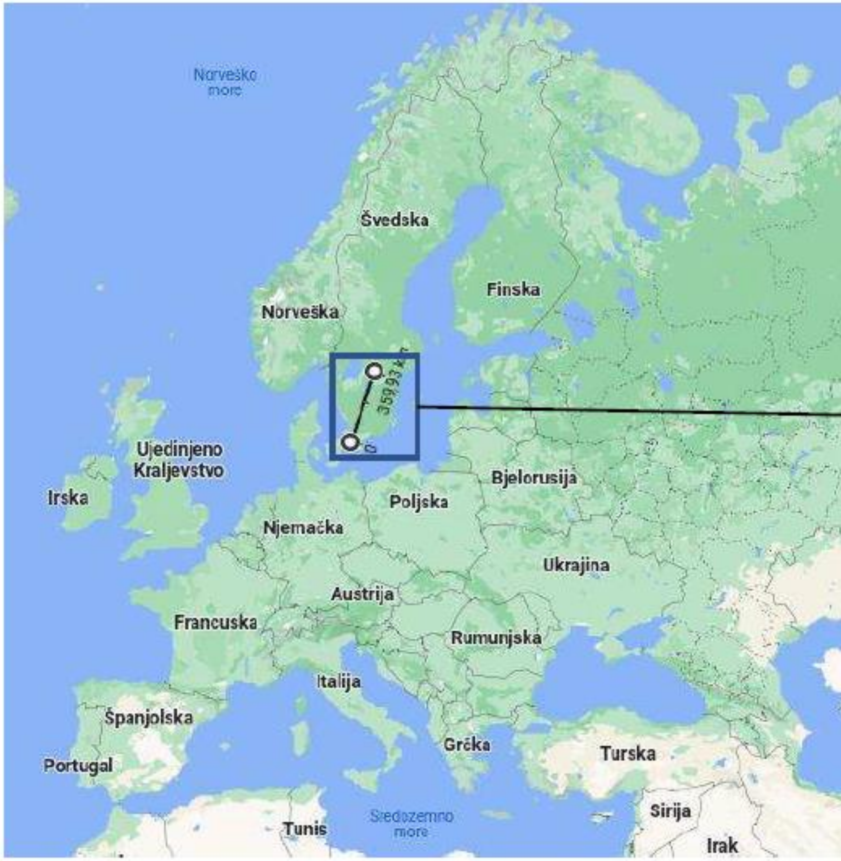
Parameter	Best-fit value $\pm 1\sigma$ range
$\sin^2\theta_{12}$	0.304 ± 0.012
$\sin^2\theta_{13}$	0.02246 ± 0.00062
$\sin^2 2\theta_{23}$	0.9898 ± 0.0077
Δm^2_{21}	$(7.42 \pm 0.21) \times 10^{-5}$ eV^2
Δm^2_{31}	$(2.510 \pm 0.027) \times 10^{-3}$ eV^2

Why 2nd maximum ? (2)



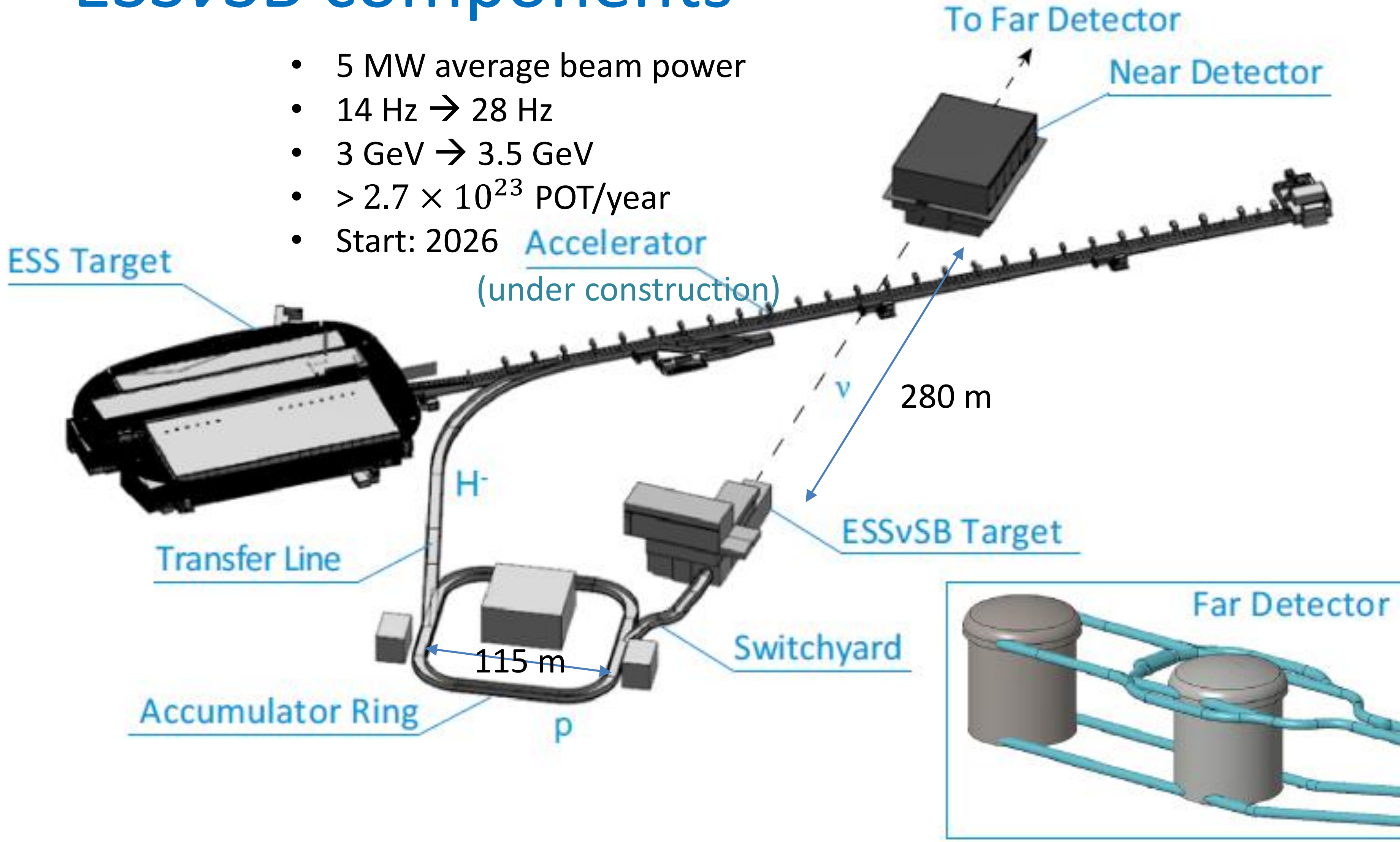
ESSnuSB neutrino baseline

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

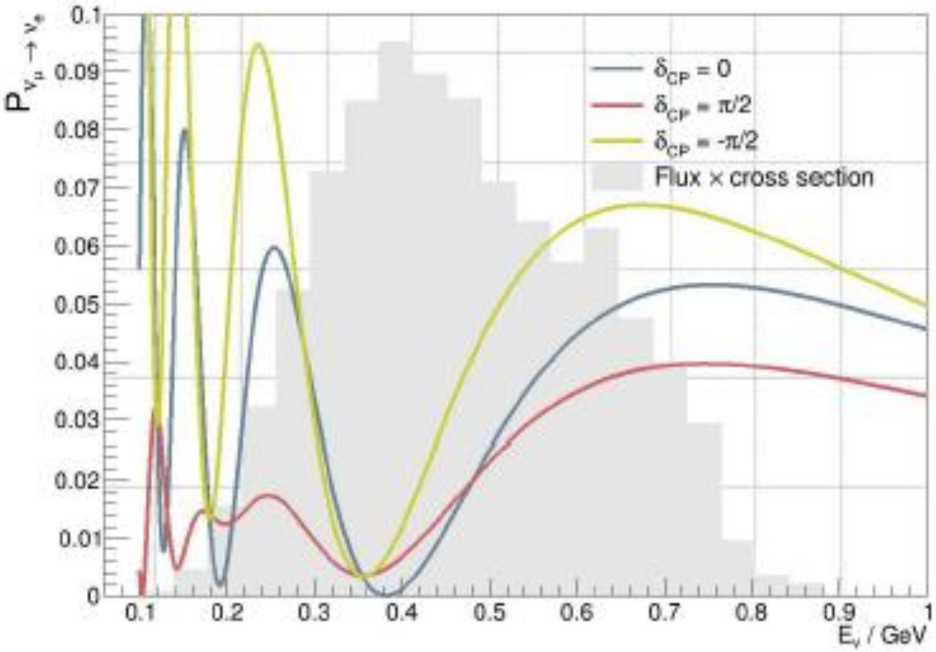


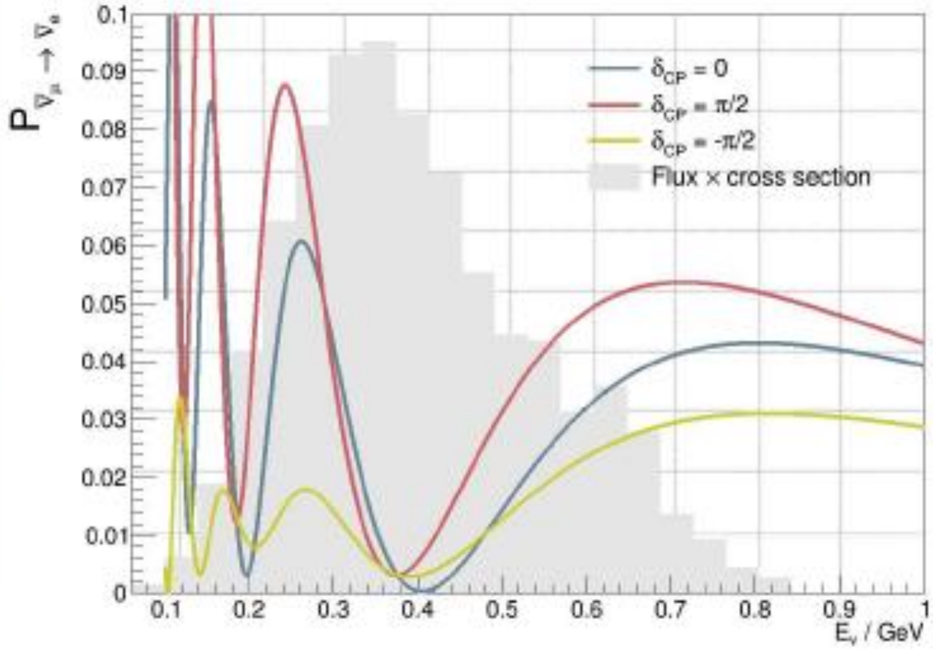
Layout of the ESSνSB components

- 5 MW average beam power
- 14 Hz → 28 Hz
- 3 GeV → 3.5 GeV
- $> 2.7 \times 10^{23}$ POT/year
- Start: 2026

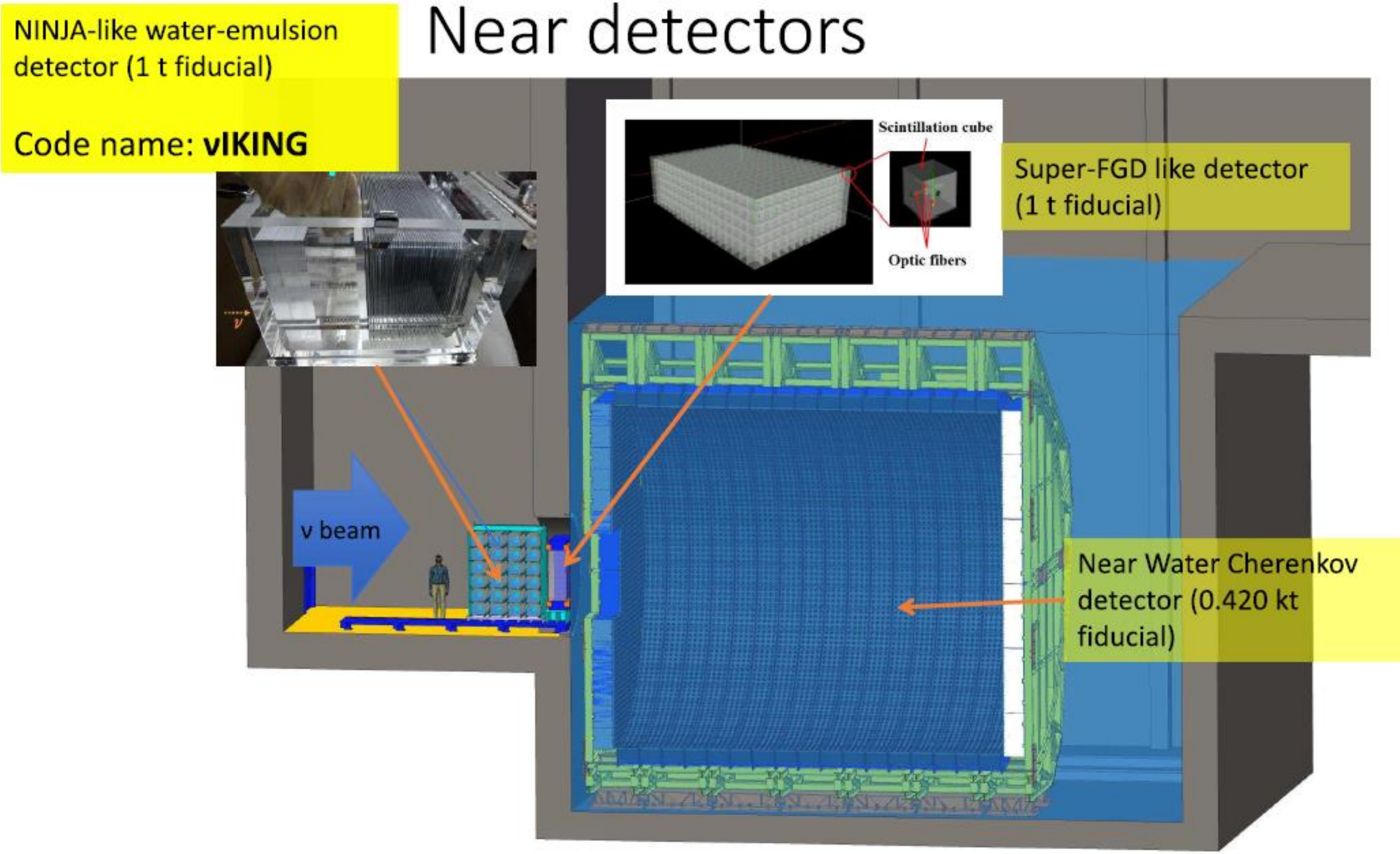


Oscillation coverage

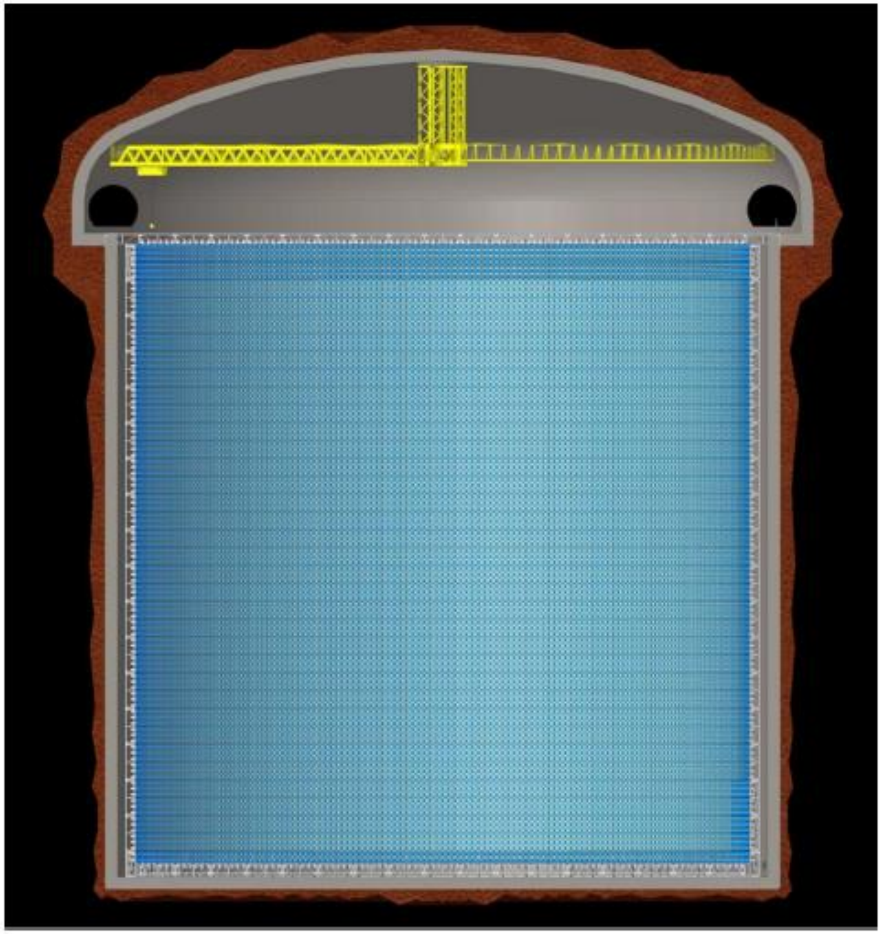




Near detectors



Far detectors



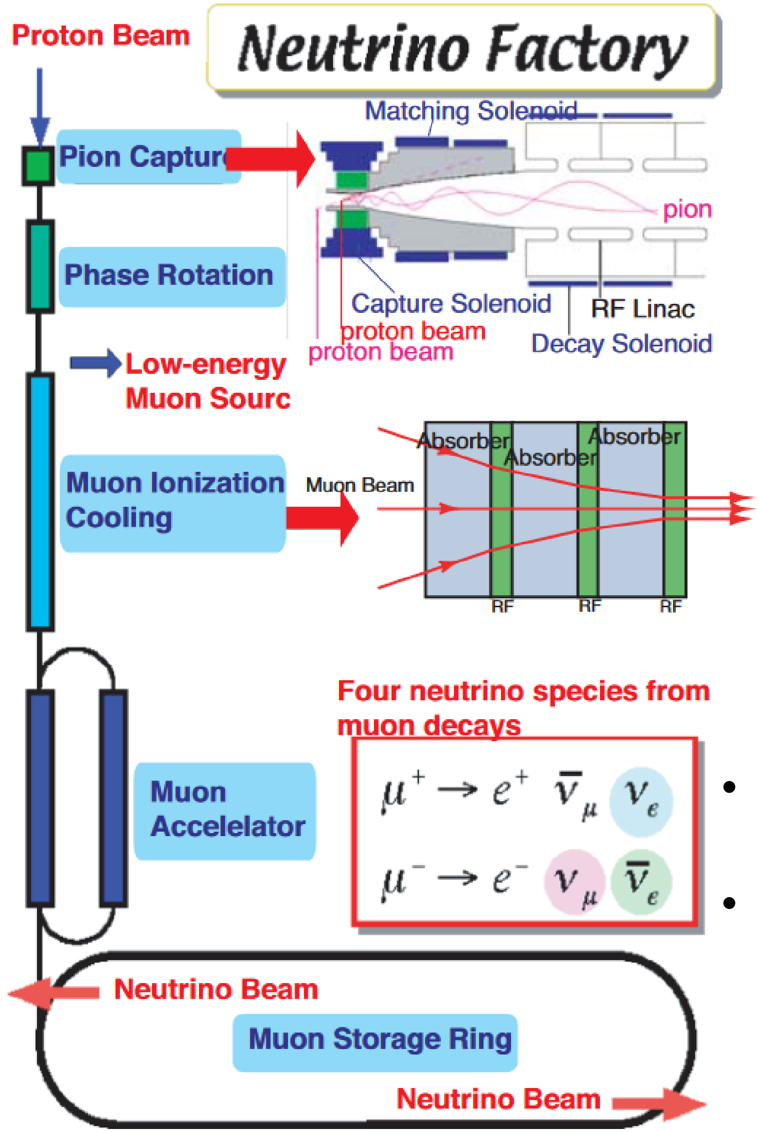
Design
- 2 x 270 kt fiducial volume (~2x HyperK)
- Readout: 2 x 38k 20" PMTs
- 30% optical coverage
  - design here for 40% with an option that ¼ PMTs will not be installed

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



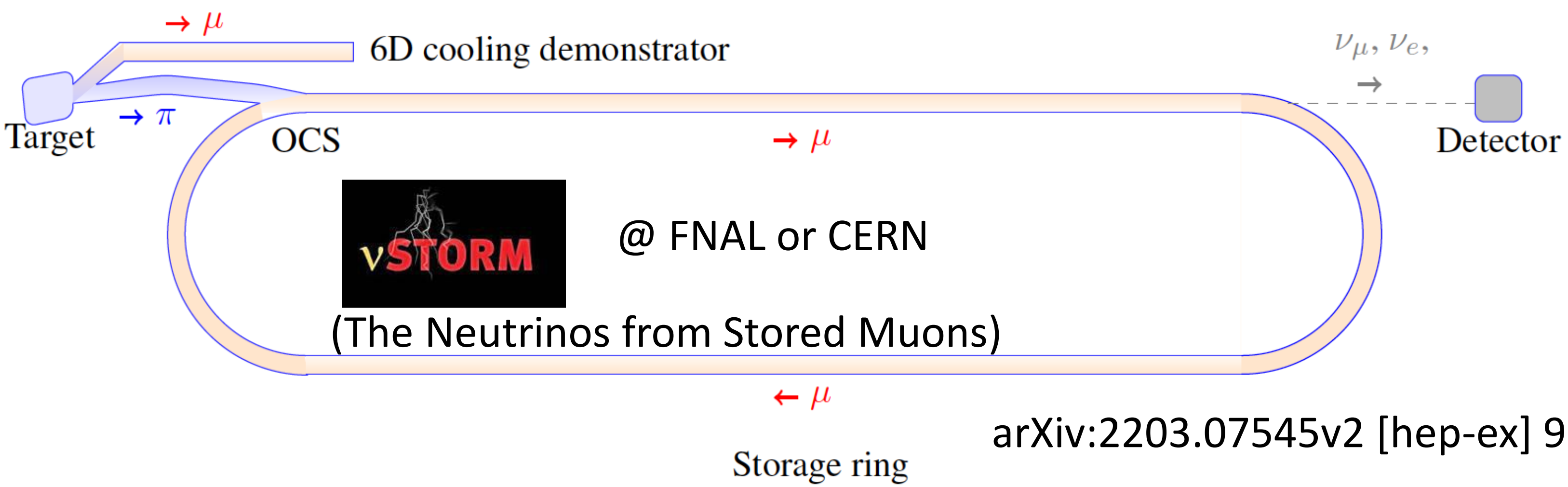
Pion capture by high magnetic field solenoid.

Suppression of transverse momentum of pions

- **Deceleration by absorbers**
- **Acceleration by RF**

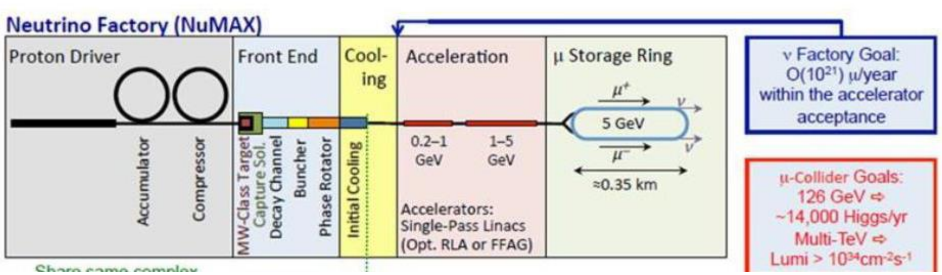
- **Immediate acceleration by a muon accelerator with high repetition (~50 Hz)**
- **High intensity & energy ν_μ ($\bar{\nu}_\mu$) & $\bar{\nu}_e$ (ν_e) beams simultaneously from the straight part of the muon storage ring**

Some future plans



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

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



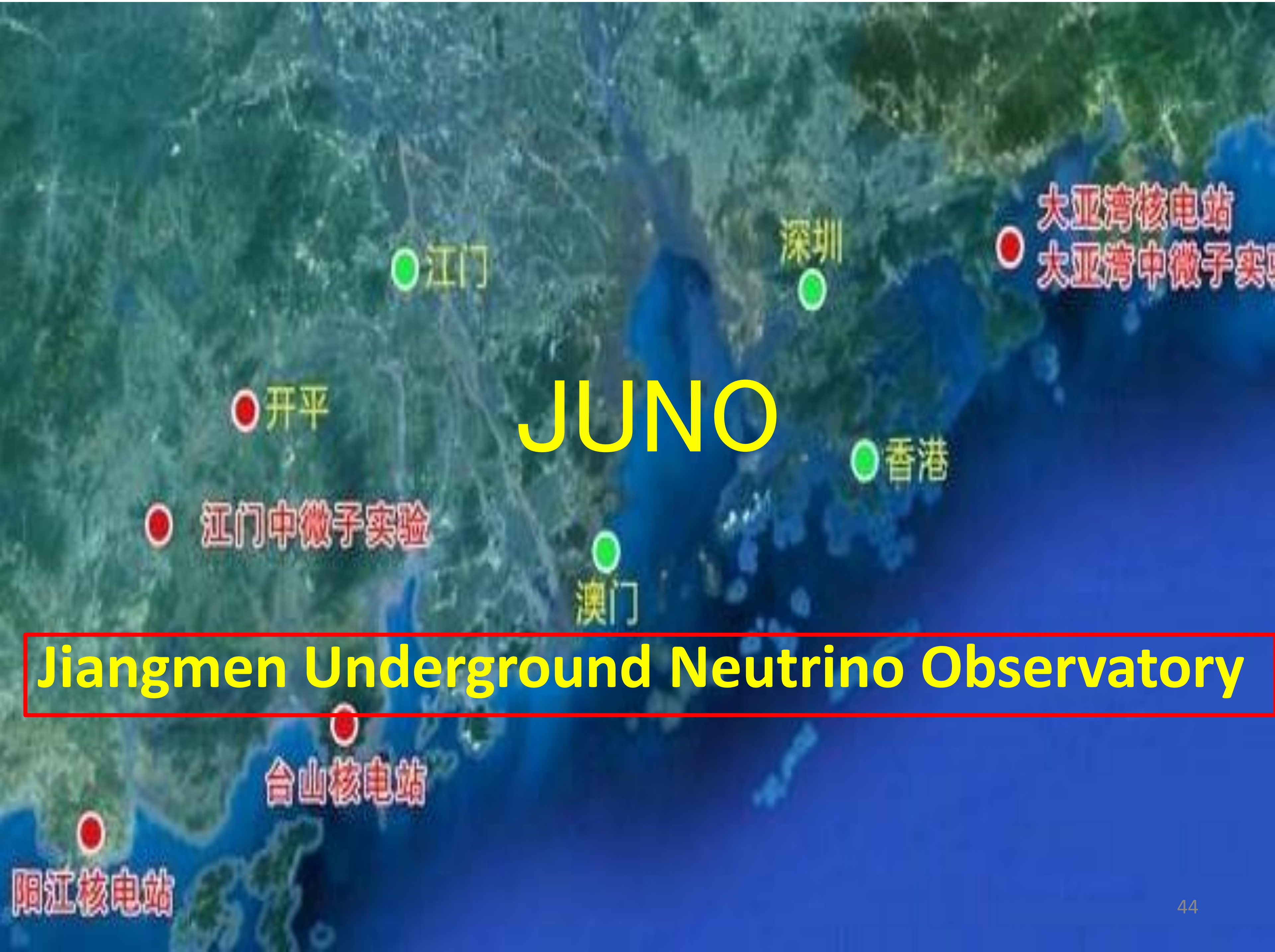
BNL-205756-2018-JAAM

2. Reactor Neutrino Experiment (JUNO)

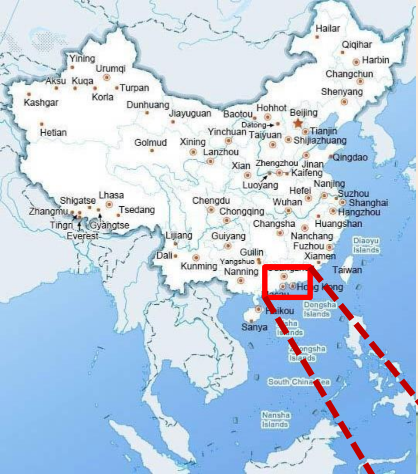
*See Huang-san's lecture

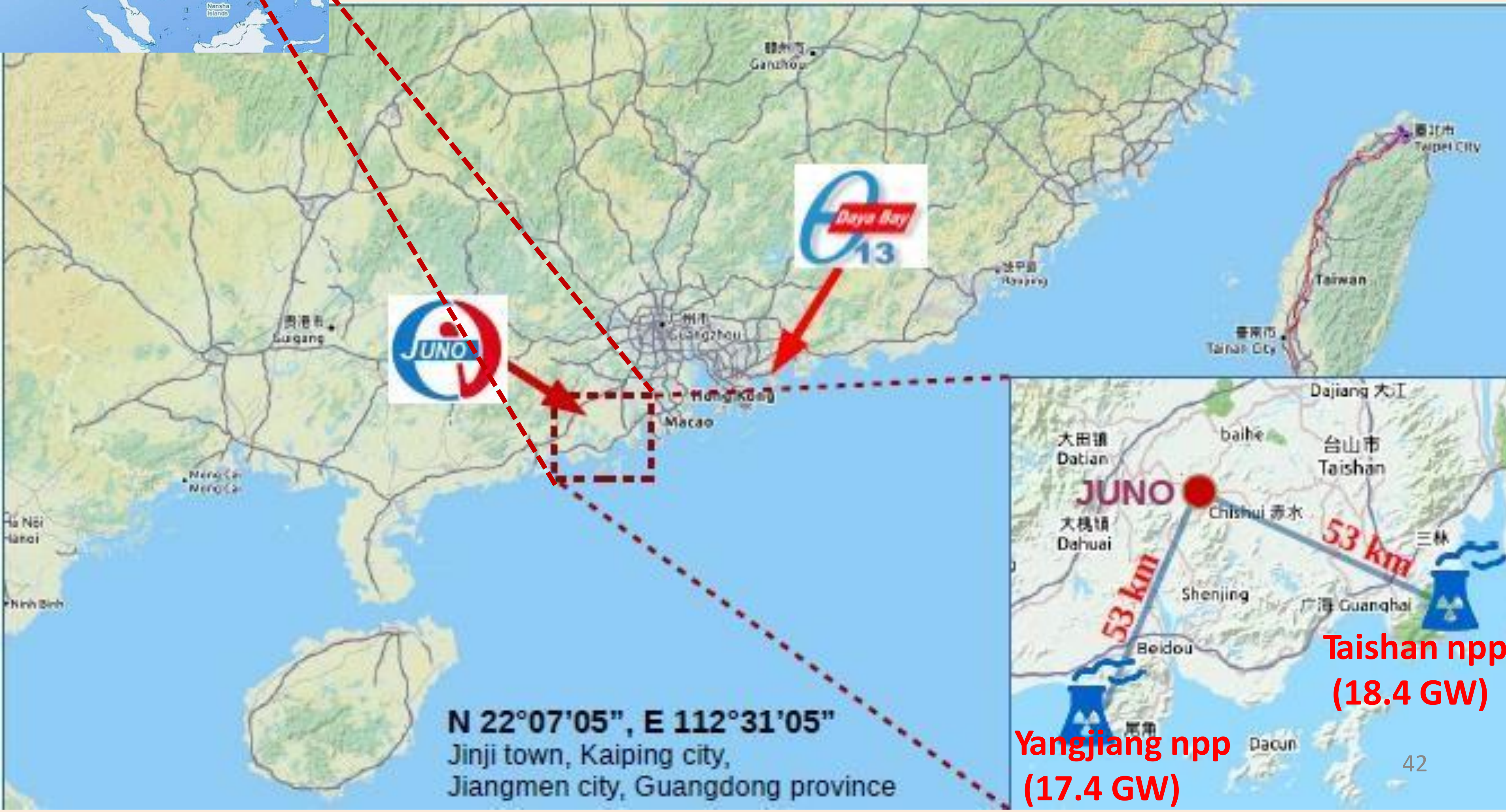
JUNO

Jiangmen Underground Neutrino Observatory



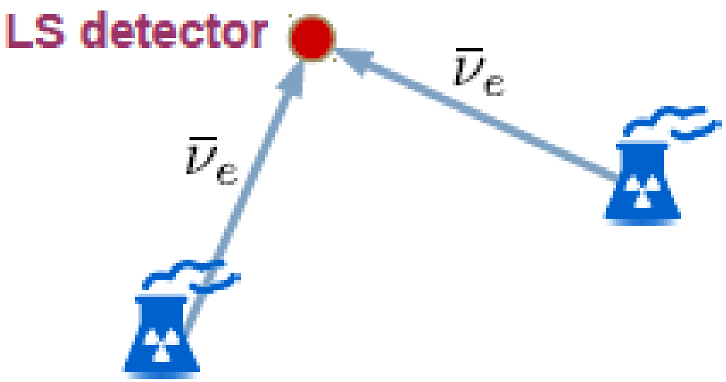
Location

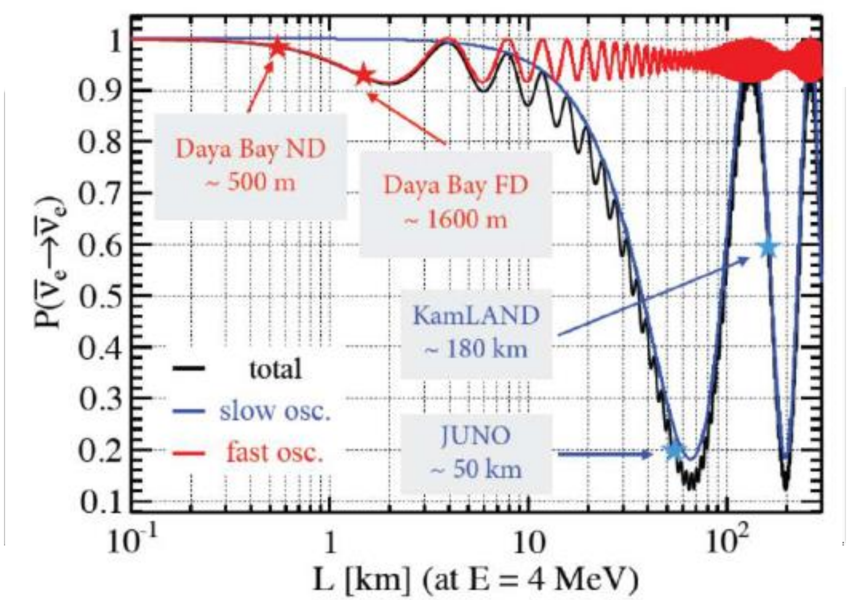




JUNO
Daya Bay
13
Guangzhou
Hong Kong
Macao
Taipei City
Taiwan
Dajiang 大江
baihe
台山市
Taishan
大田镇
Datian
JUNO
Chishui 赤水
大槐镇
Dahuai
53 km
53 km
Shenjing
Guanghai
Beidou
Dacun
Taishan npp
(18.4 GW)
Yangjiang npp
(17.4 GW)
N 22°07'05", E 112°31'05"
Jinji town, Kaiping city,
Jiangmen city, Guangdong province

JUNO Layout



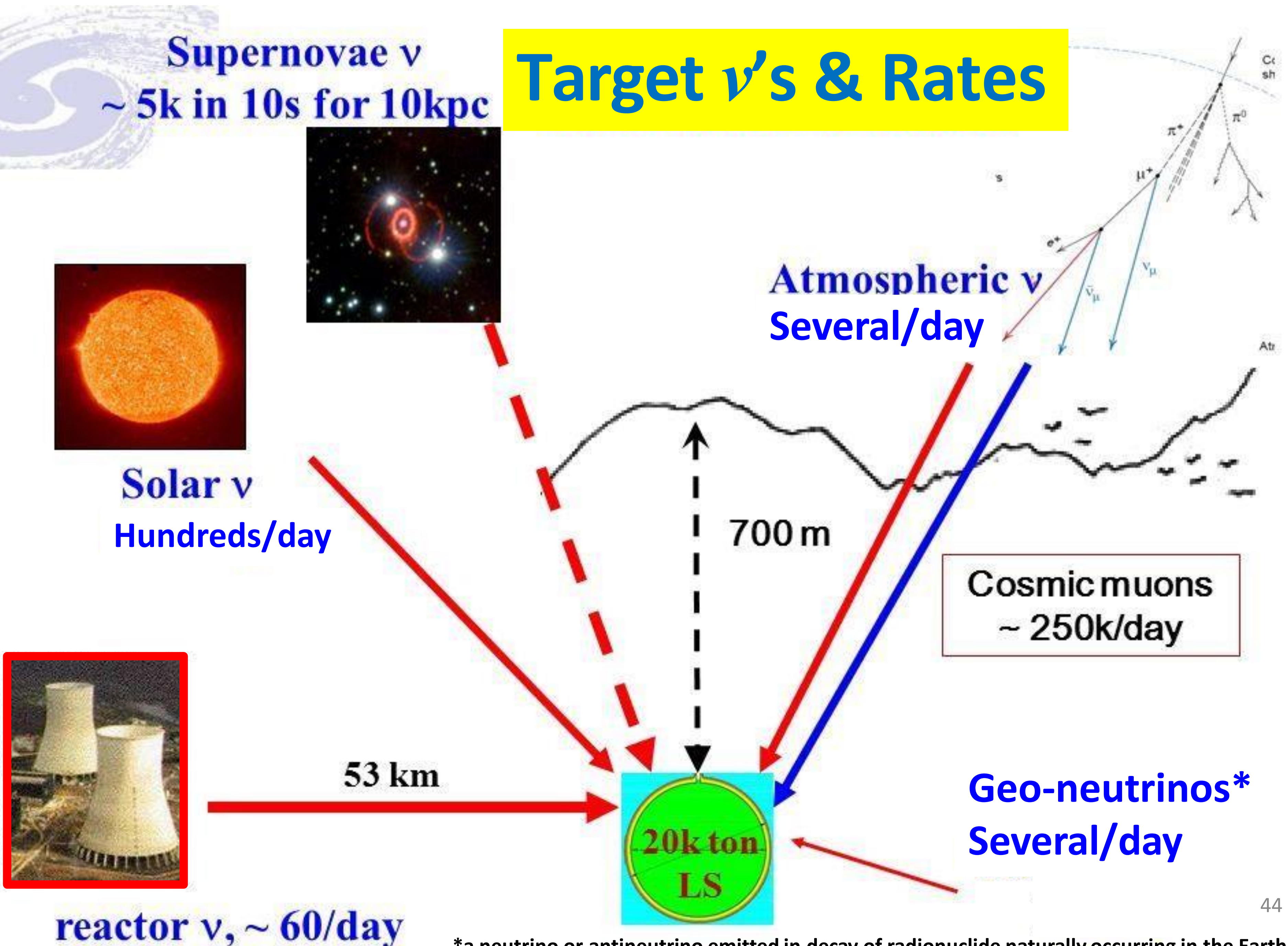


- **Source: 6+2 reactors**
  (Yangjiang and Taishan NPP)
- **Baseline: 53 km**
- **Detection channel: inverse β-decay**

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

- **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

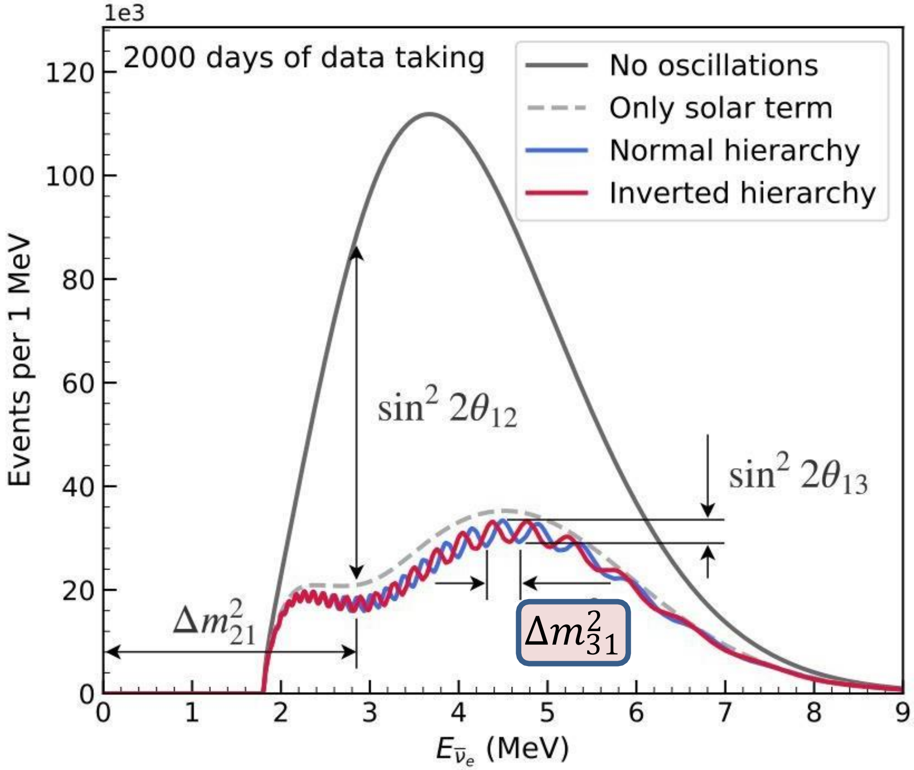


*a neutrino or antineutrino emitted in decay of radionuclide naturally occurring in the Earth

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 $\theta_{12}, \Delta m^2_{21}, \& \Delta m^2_{31}$

* Oscillation in matter with effective oscillation parameters (j.physletb.2020.135354).

JUNO Detector

Calibration room

Pure water room

LS Filling room

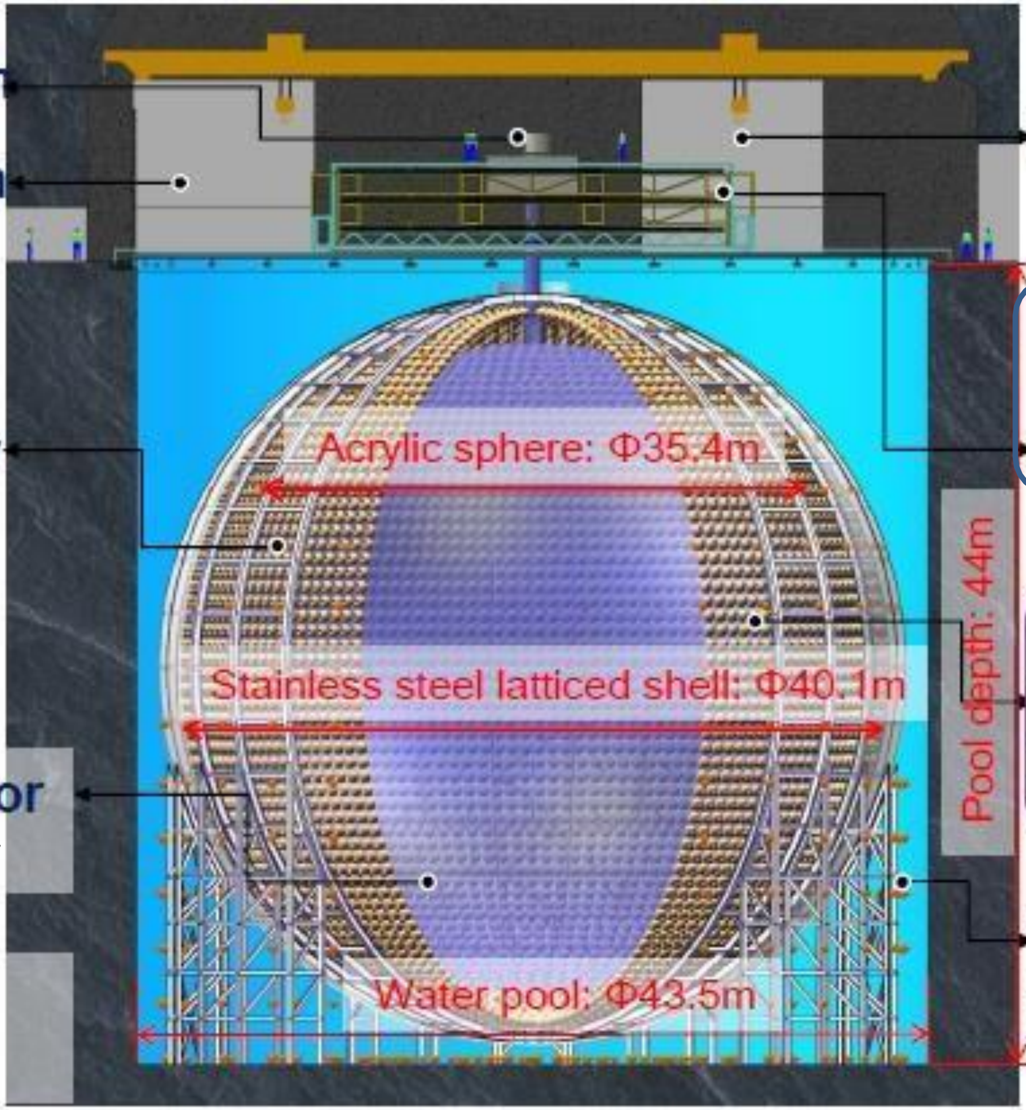
- Precision muon tracking
- 3 plastic scintillator layers
- Covering half of the top area

Top Tracker

Central detector

SS latticed shell

Acrylic sphere



Double calorimetry

PMT

~18,000 20" PMTs +

~25,000 3" PMTs:

coverage :78 %

Liquid scintillator

20 kton, high purity

(> 20 m att. Length)

700m underground

Water Cherenkov

35 kton pure water

2,000 20" veto PMTs

$\Delta E/E$ = 3% @ 1 MeV

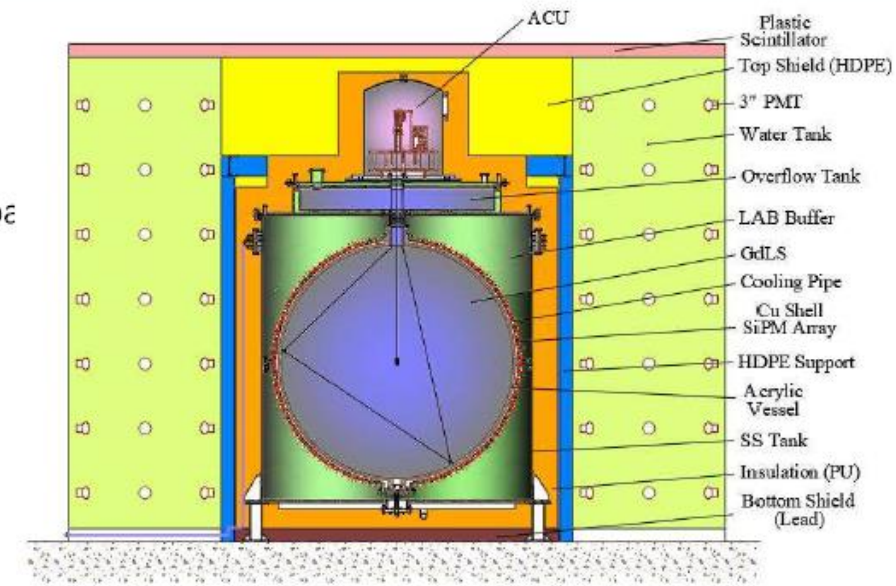
Taishan Antineutrino Observatory (TAO)

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/mm^2]	~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

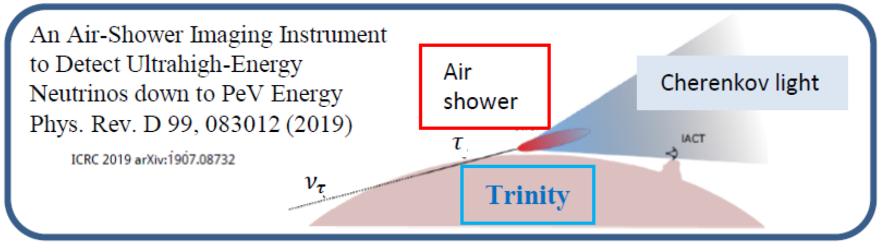
Outlook

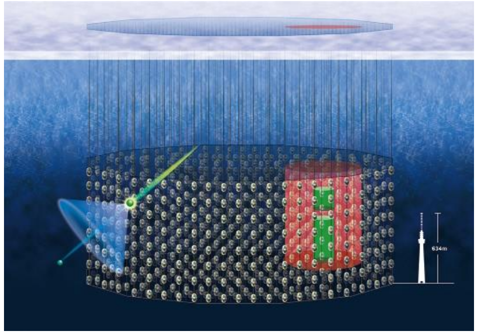
Physics	Sensitivity
Neutrino Mass Ordering	3σ (~1σ) in 6 yrs by reactor (atmospheric) $\bar{\nu}_e$
Neutrino Oscillation Parameters	Precision of $\sin^2\theta_{12}$, Δm^2_{21}, $\lvert\Delta m^2_{32}\rvert$ < 0.5% in 6 yrs
Supernova Burst (10 kpc)	~5000 IBD, ~300 eES and ~2000 pES of all-flavor neutrinos
DSNB	3σ in 3 yrs
Solar neutrino	Measure Be7, pep, CNO simultaneously, measure B8 flux independently
Nucleon decays ($p \rightarrow \bar{\nu}K^+$)	8.3×10^{33} years (90% C.L.) in 10 yrs
Geo-neutrino	~400 per year, 5% measurement in 10 yrs

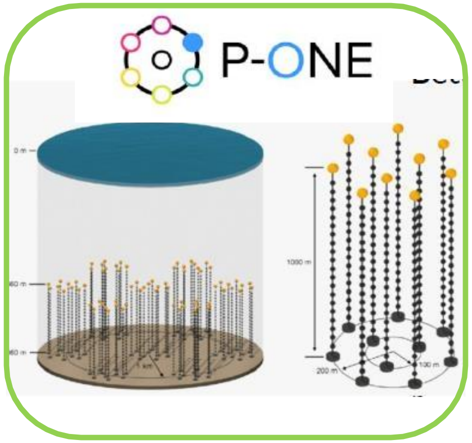
3. Atmospheric & Astrophysical Neutrino Measurements

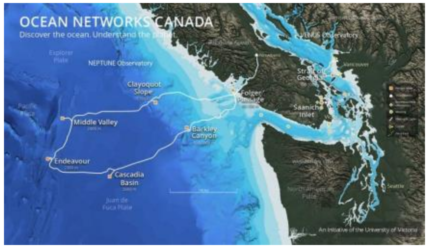
Future Plans

- **Optical Detection of Cherenkov Radiation**
  - **IceCube -Upgrade & Gen 2- @ South Pole**
  - **P-ONE @ Pacific Ocean → late 2020s: full detector construction**
  - **Trinity** (candidate site:not decided yet)

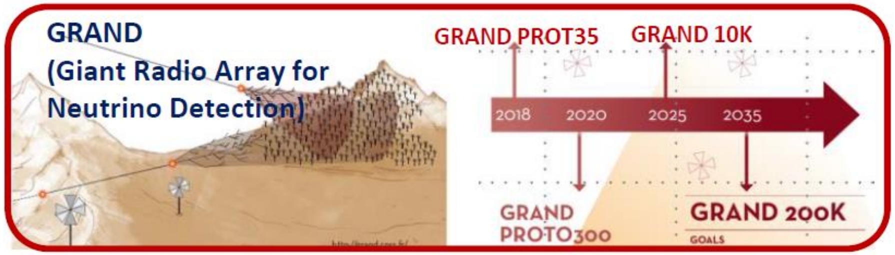






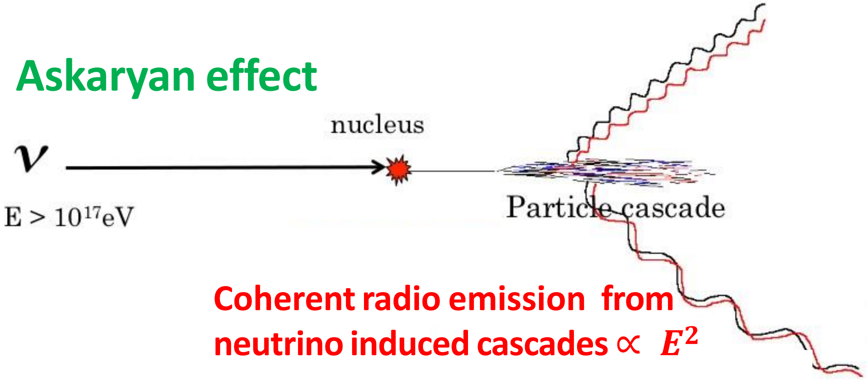


- **Radio Technique (Askaryan effect)**



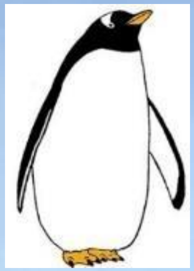
  - **RNO-G (Greenland)**

Askaryan effect

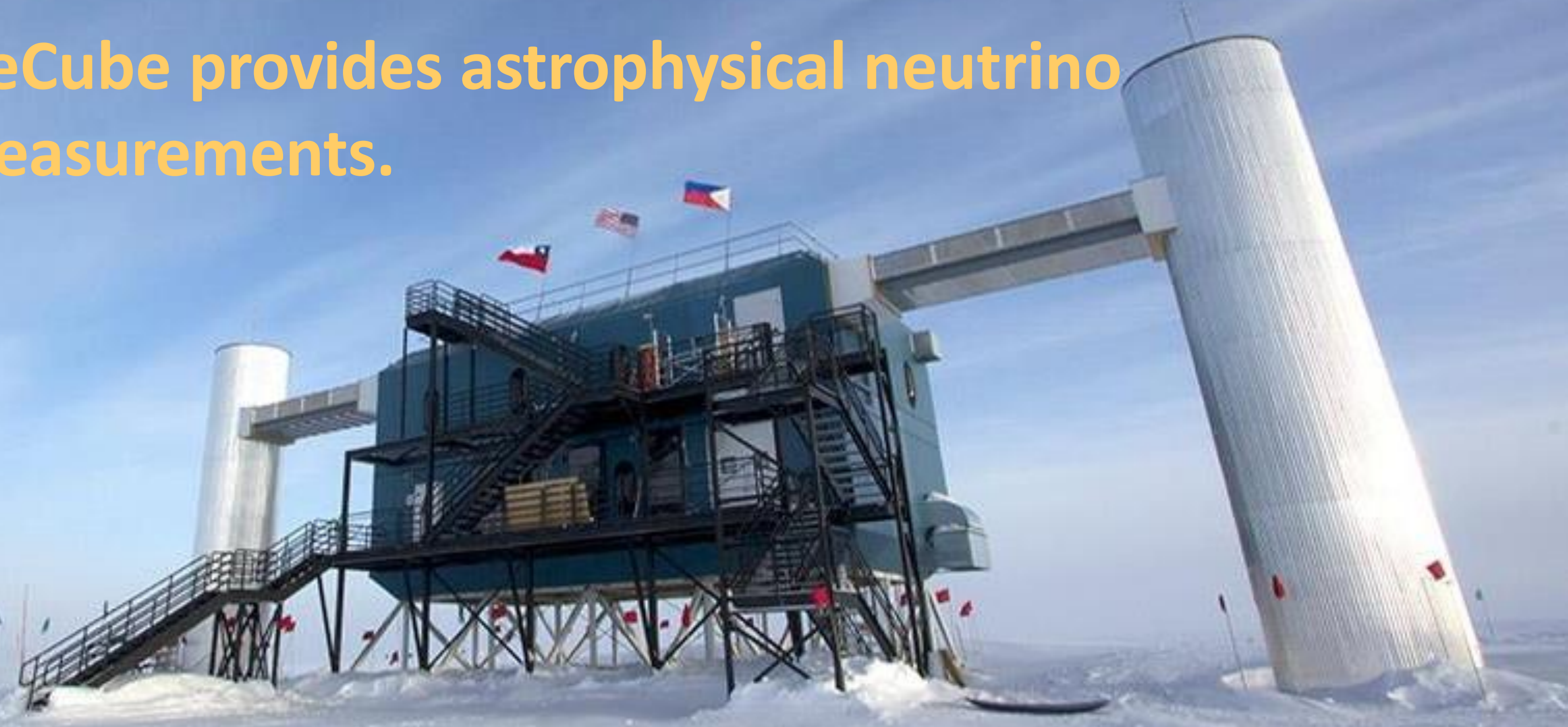


IceCube – Upgrade & Gen 2 –

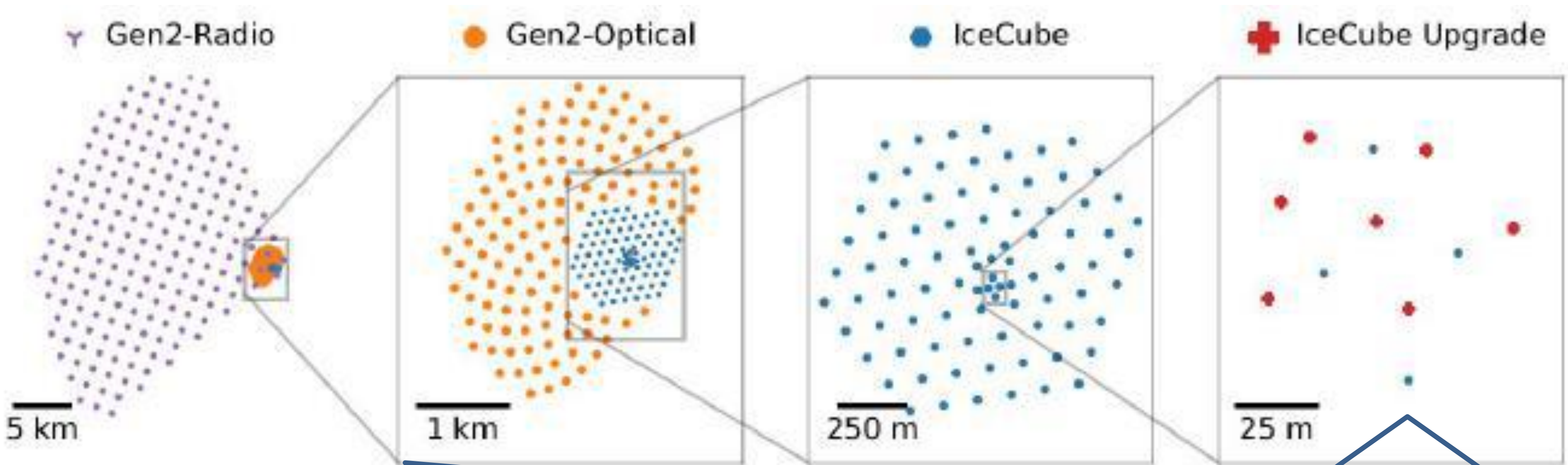
- Located in the South Pole
- Ice is used as a Cherenkov detector.
- IceCube provides astrophysical neutrino measurements.



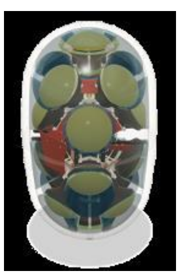
Gentoo penguin



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

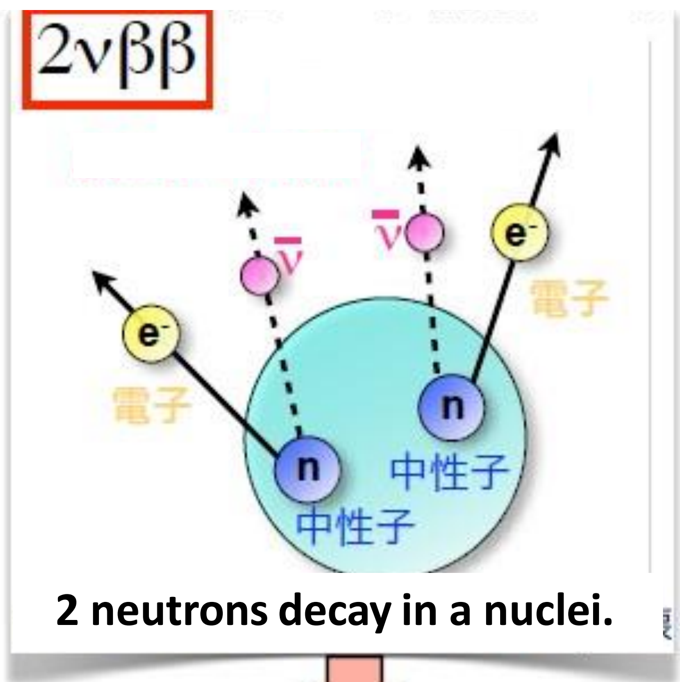
mDOM

- **Improved detector calibration/ ice model characterization**

4. 0νββ Decay Experiments

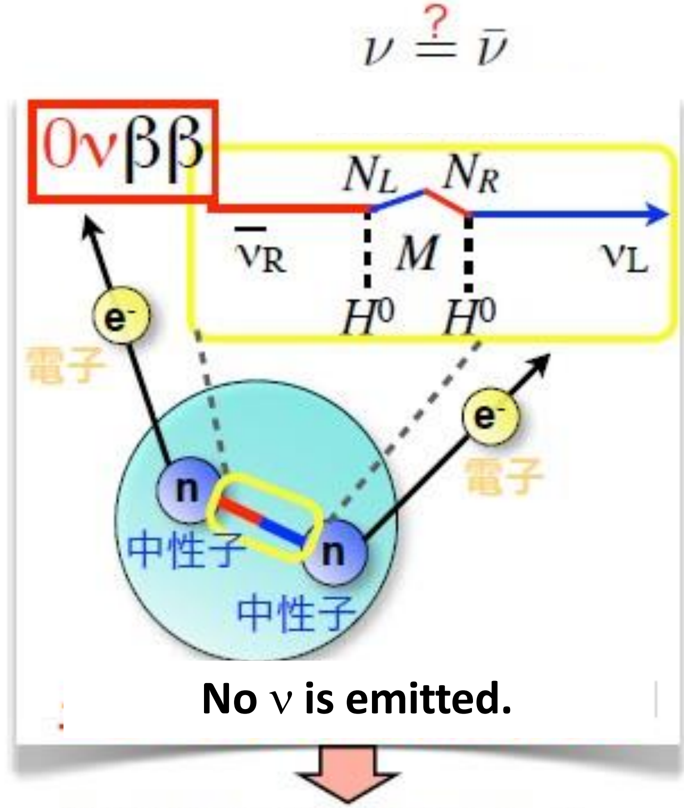
*See Huang-san's lecture in detail

Double beta decay



2 neutrons decay in a nuclei.

Possible in SM
Lifetimes are measured for ~10 nucleus

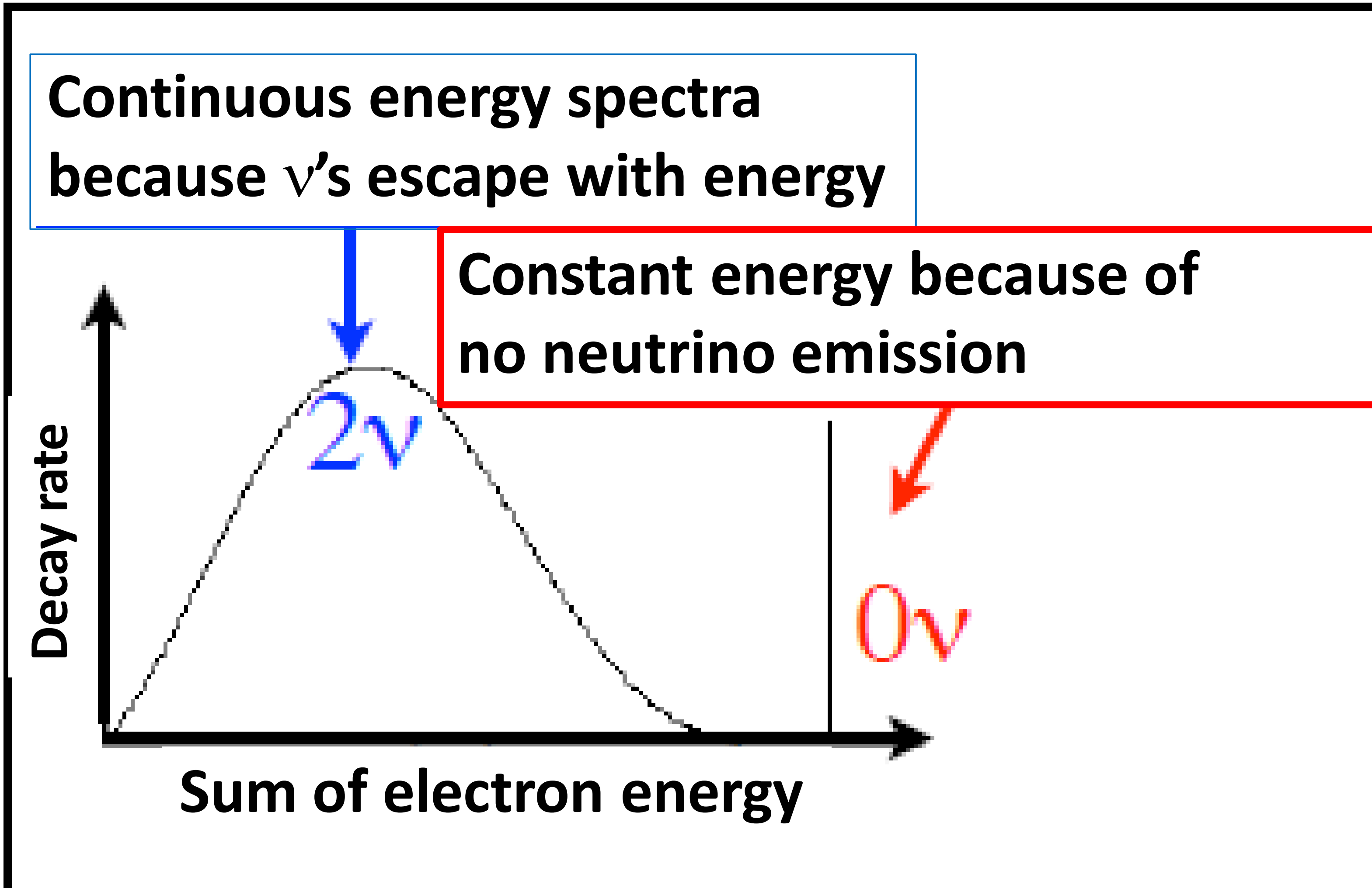


No ν is emitted.

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

How to detect

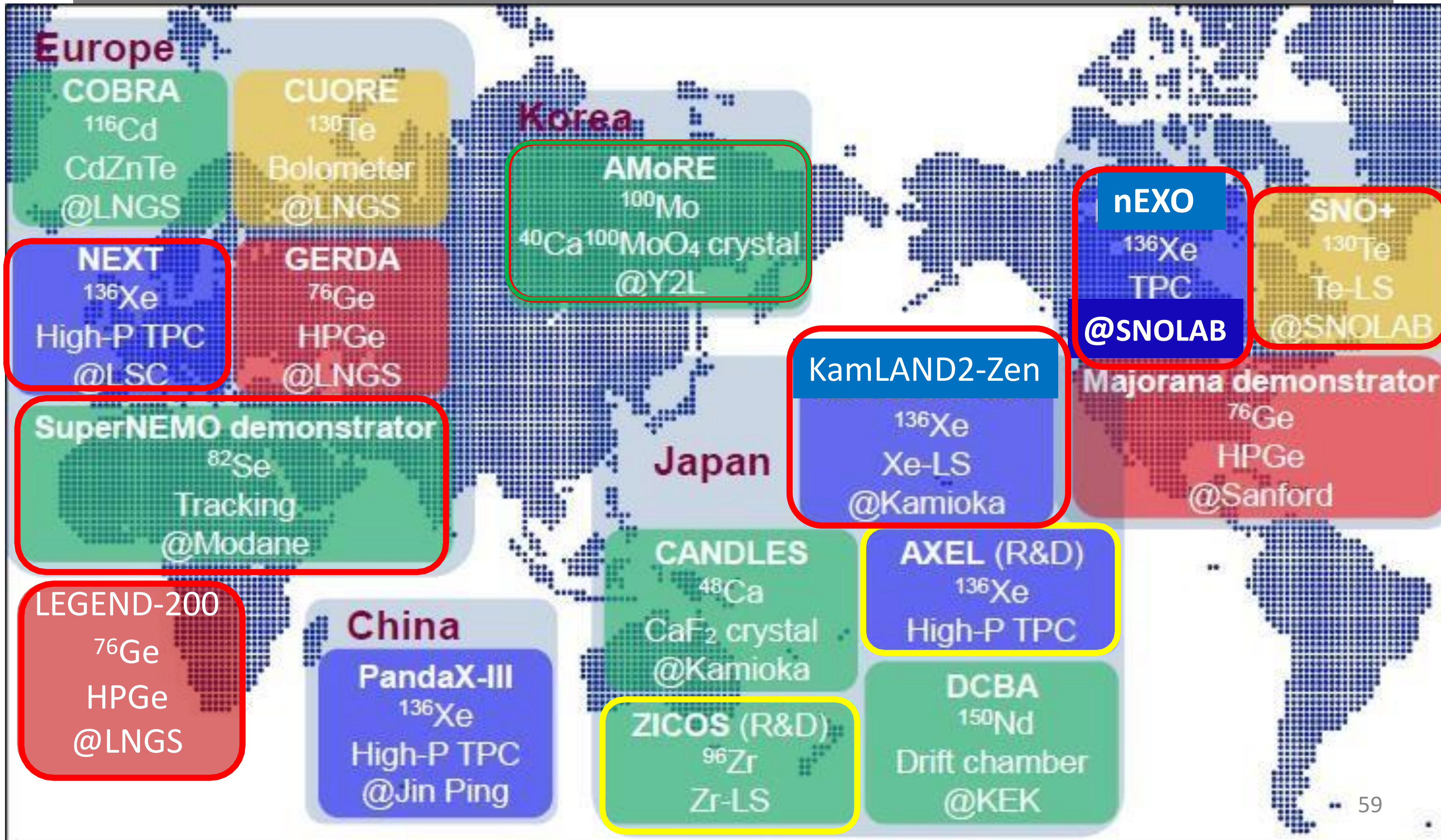
- Catch 1 electron pair emitted !



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

Plan

R&D



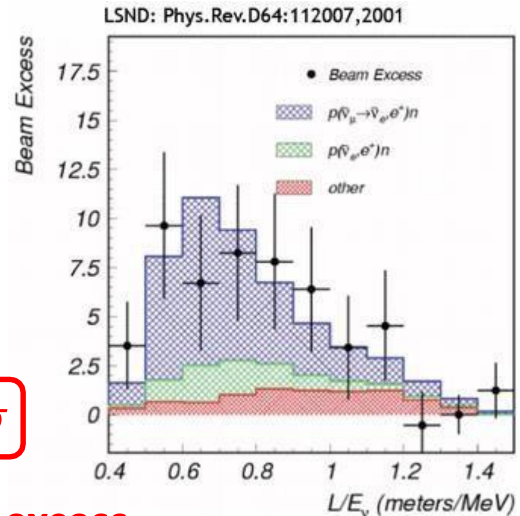
5. Sterile Neutrino Experiments

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

Why sterile neutrino ?

Do 3-neutrino oscillations explain all experimental results?

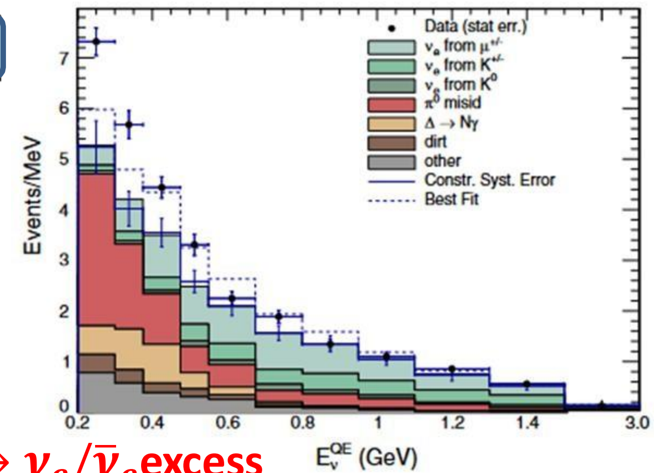
LSND



3.8σ

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

MiniBooNE

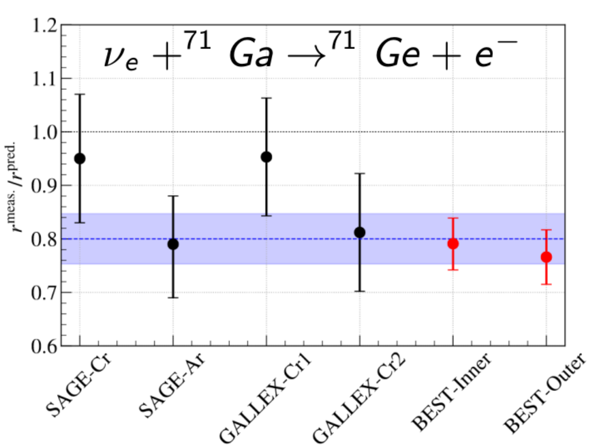


4.8σ

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

Possible common explanation:

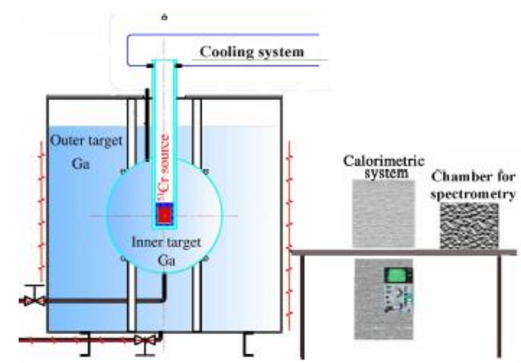
Additional squared mass difference
$\Delta m^2_{\text{SBL}} \simeq 1\ \text{eV}^2$



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

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

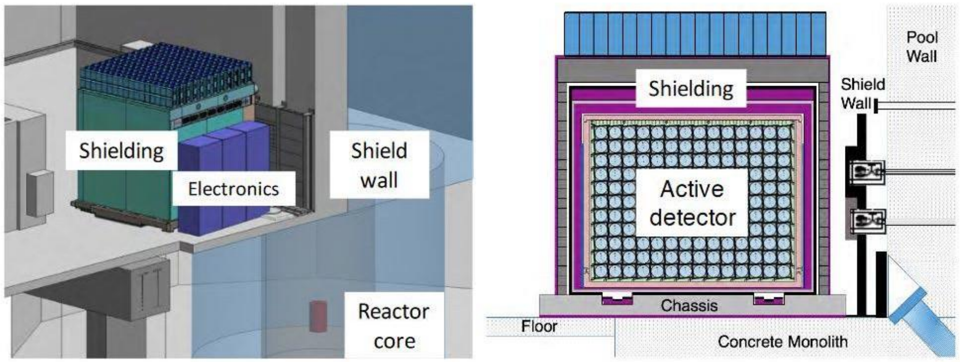
- **Recently confirmed by BEST**
  (Baksan Experiment on Sterile Transitions)



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

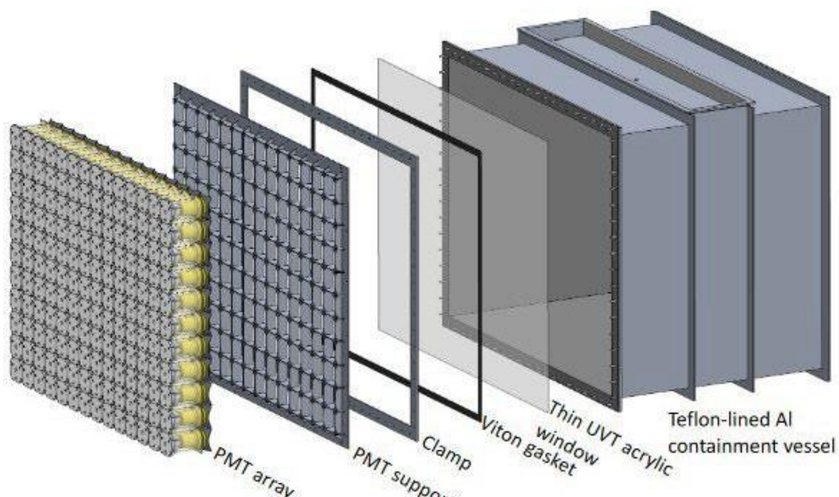
PROSPECT-II

Original PROSPECT Design



https://arxiv.org/abs/2107.03934

PROSPECT II Design



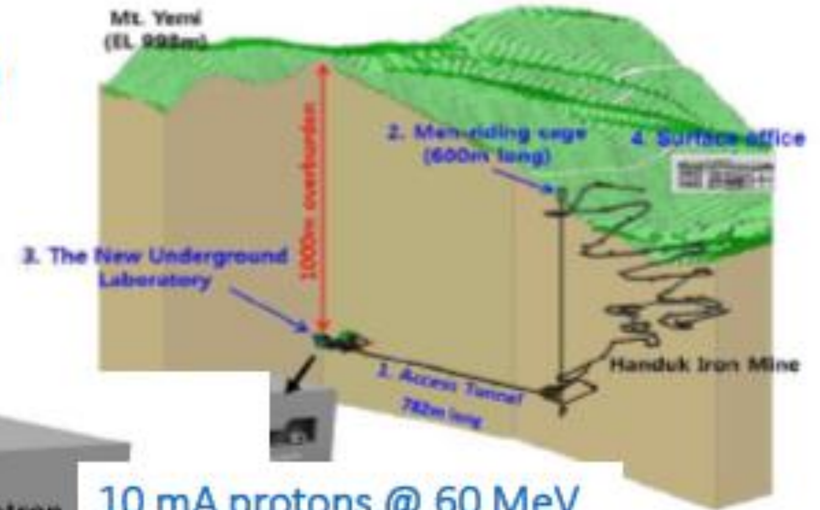
https://arxiv.org/abs/2107.03934

- 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

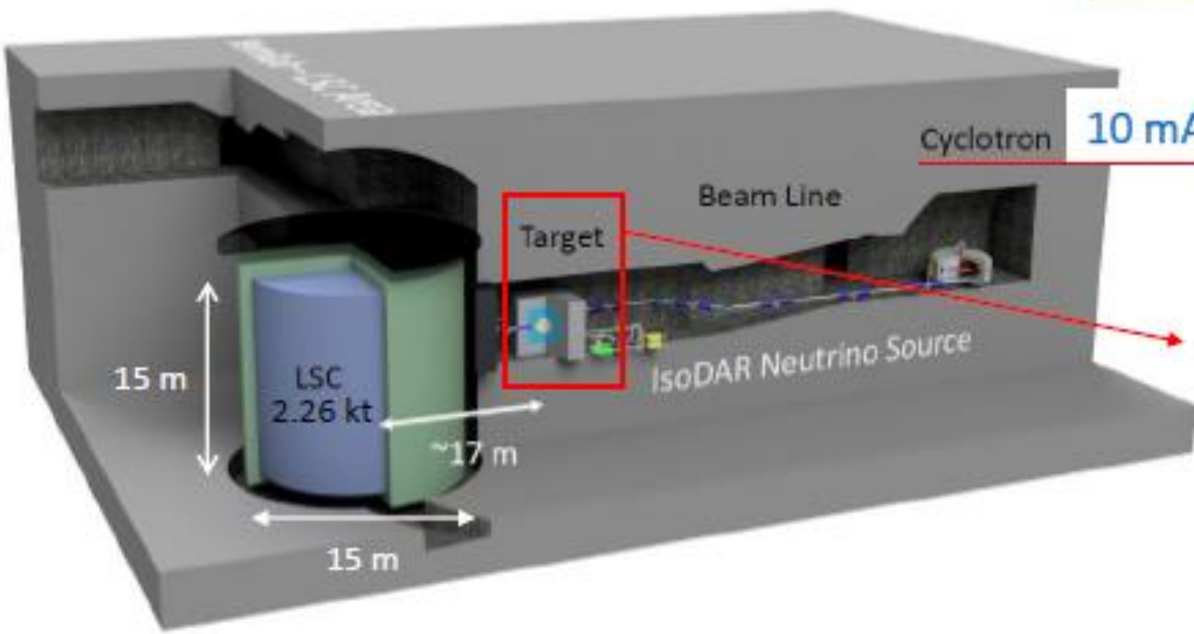
IsoDAR

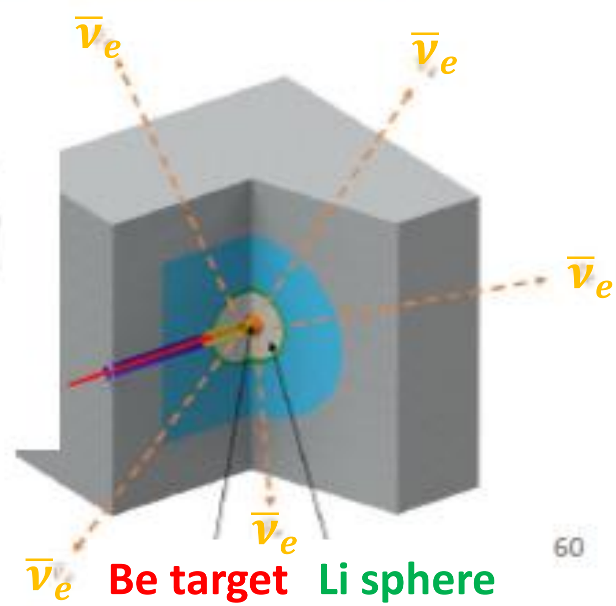
(Isotope Decay At Rest)

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



10 mA protons @ 60 MeV



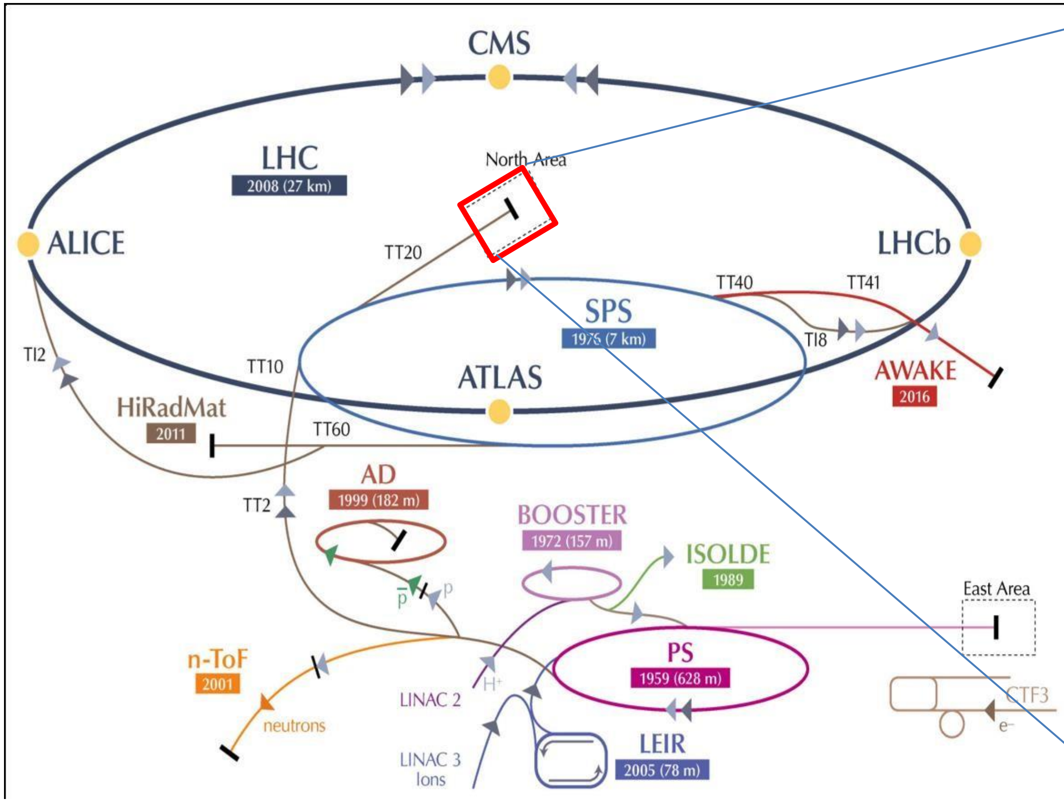


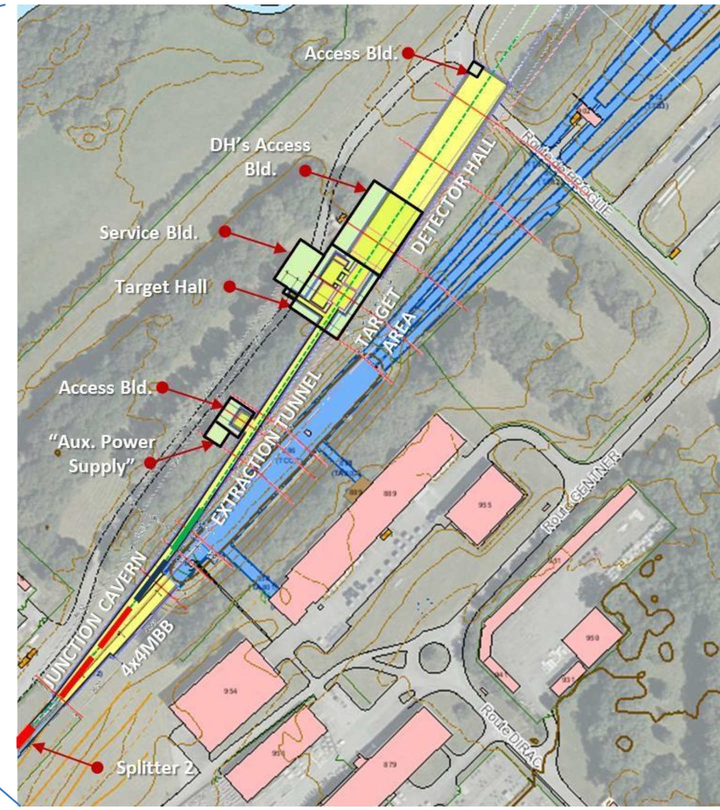
6. High statistic ν_τ Experiment (SHiP)

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

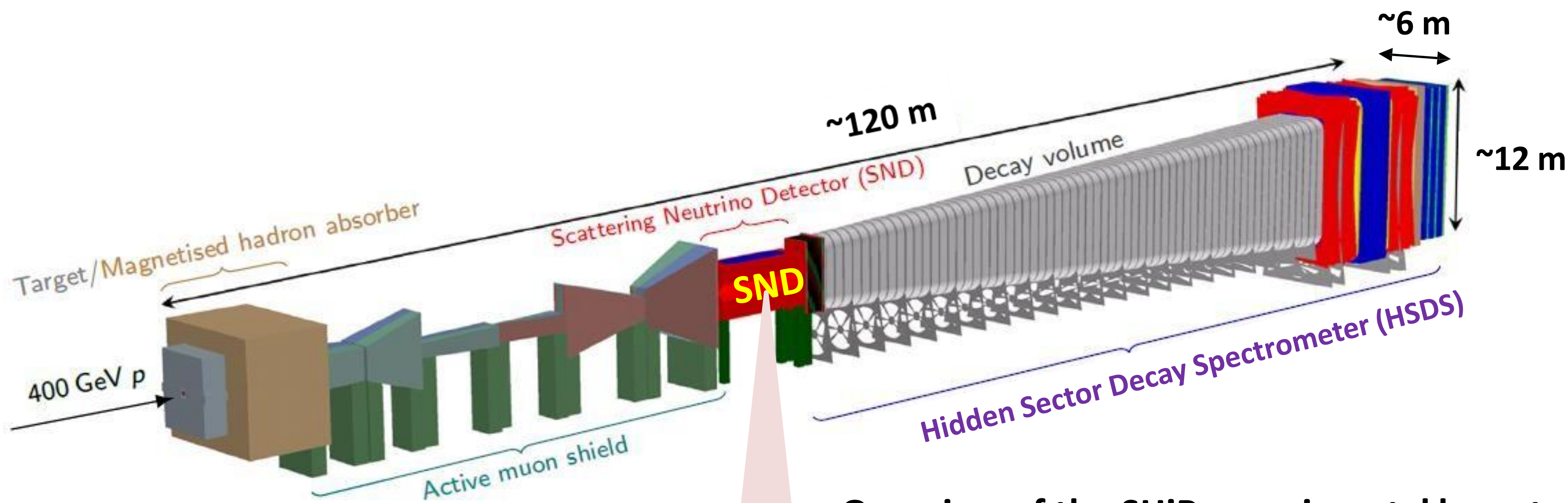
SHiP: experimental site



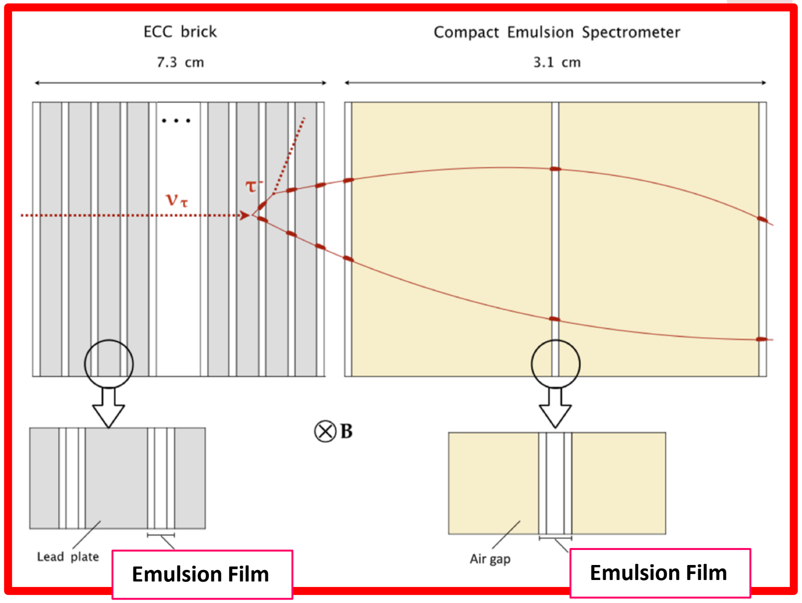


- Fixed target facility @ CERN SPS
- 400 GeV protons
- 4×10^{13} POT/spill in every 7 sec → 2×10^{20} POT in 5 years

SHiP detector



Overview of the SHiP experimental layout



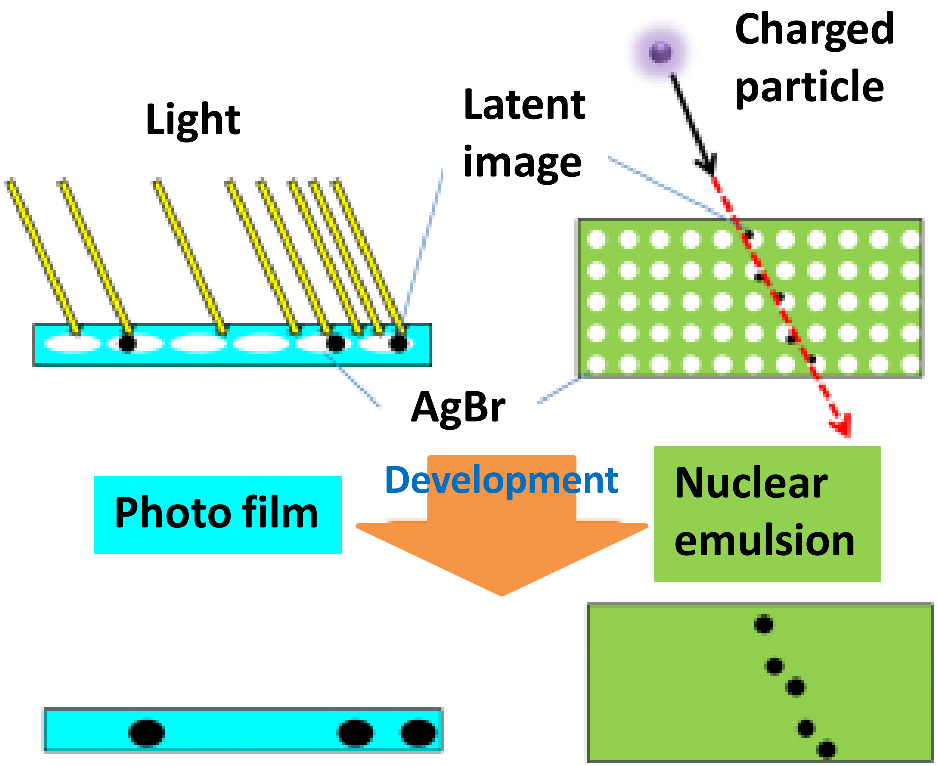
Basic unit of the SND & the ECC brick

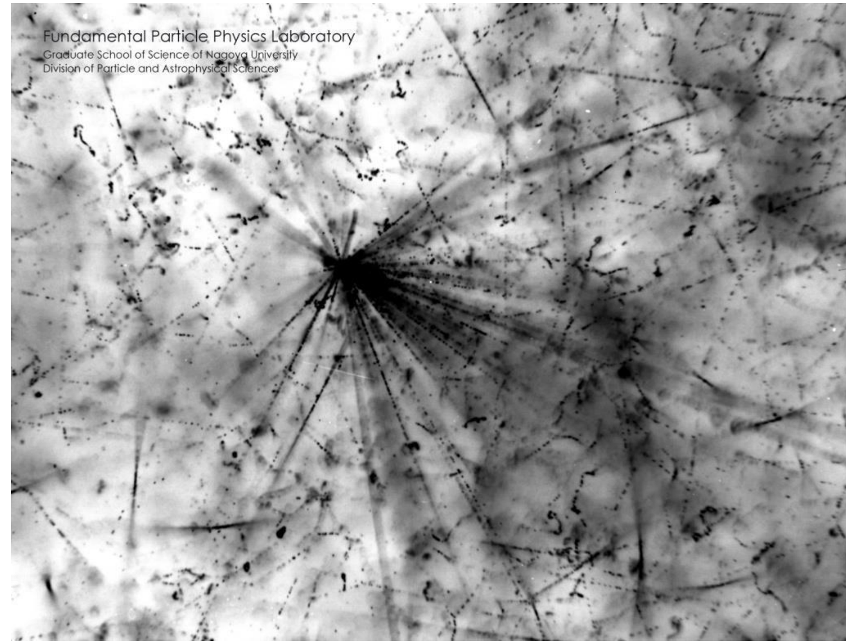
In the SND, the *Emulsion Cloud Chamber (ECC) is used as tracking detector and the Compact Emulsion Spectrometer (CES) is used for charge measurement.

* 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.

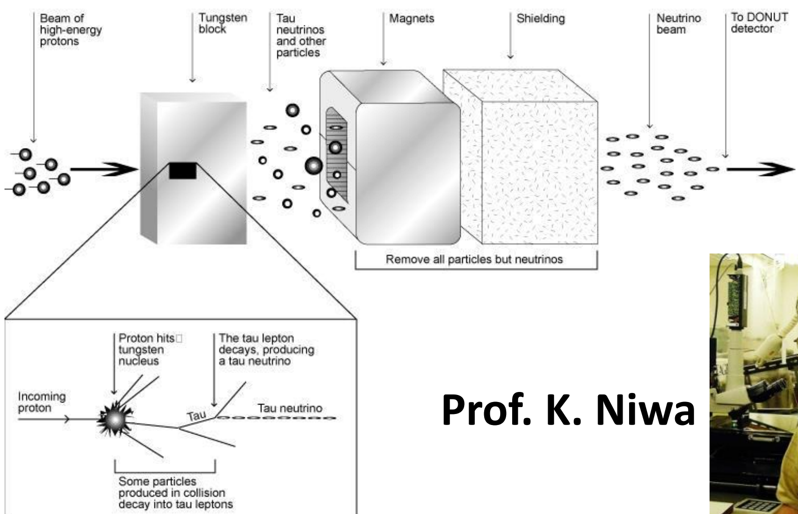
- Kind of photo film.
- Contains small grains of AgBr.
- Ag grains are remained after charged particle pass.
- We can detect the track after the development.
- Position resolution is $\sim 1\mu$m (still the best in all detectors).

Discovery of ν_τ

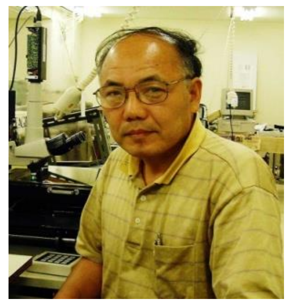
DONUT experiment, 2000（Direct Observation of NeUtrino Tau ,Fermilab. E872）

Nagoya Univ., Kobe Univ., et al

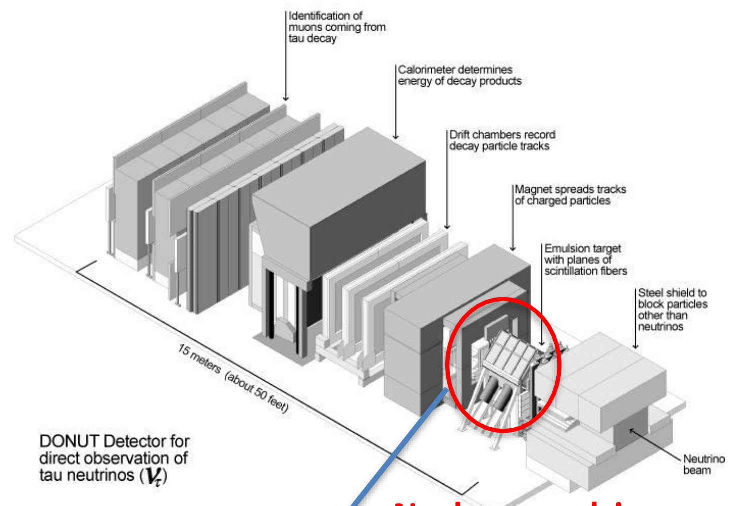
Creating a Tau Neutrino Beam



Prof. K. Niwa



DONUT Detector



Nuclear emulsion

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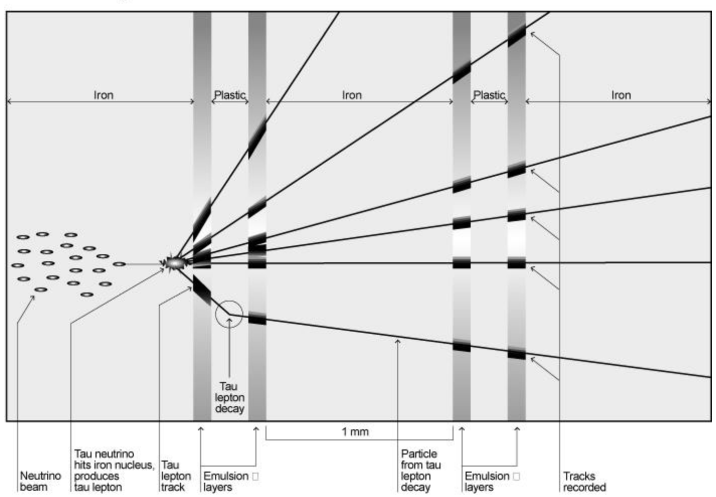
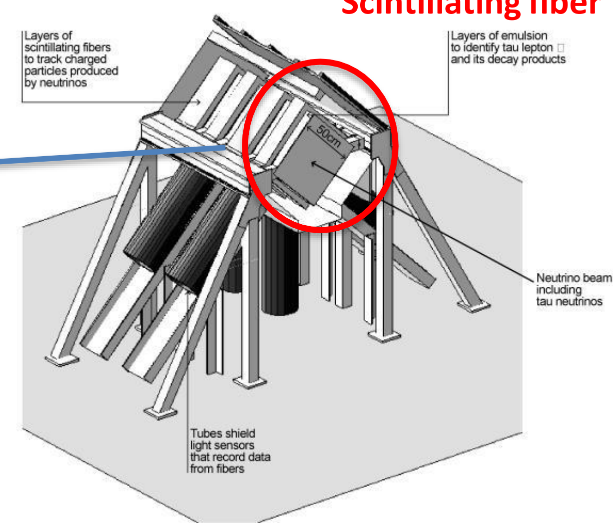
Scintillating fiber

Detecting a Tau Neutrino



Of one million million tau neutrinos crossing the DONUT detector, scientists expect about one to interact with an iron nucleus.

DONUT Target Station



ν physics @ SHiP

- **Production of large amounts of neutrinos**
  - **Study ν_τ and $\underline{\nu_\tau}$ 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 ?**

	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 !