Future Neutrino Experiments

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Contents

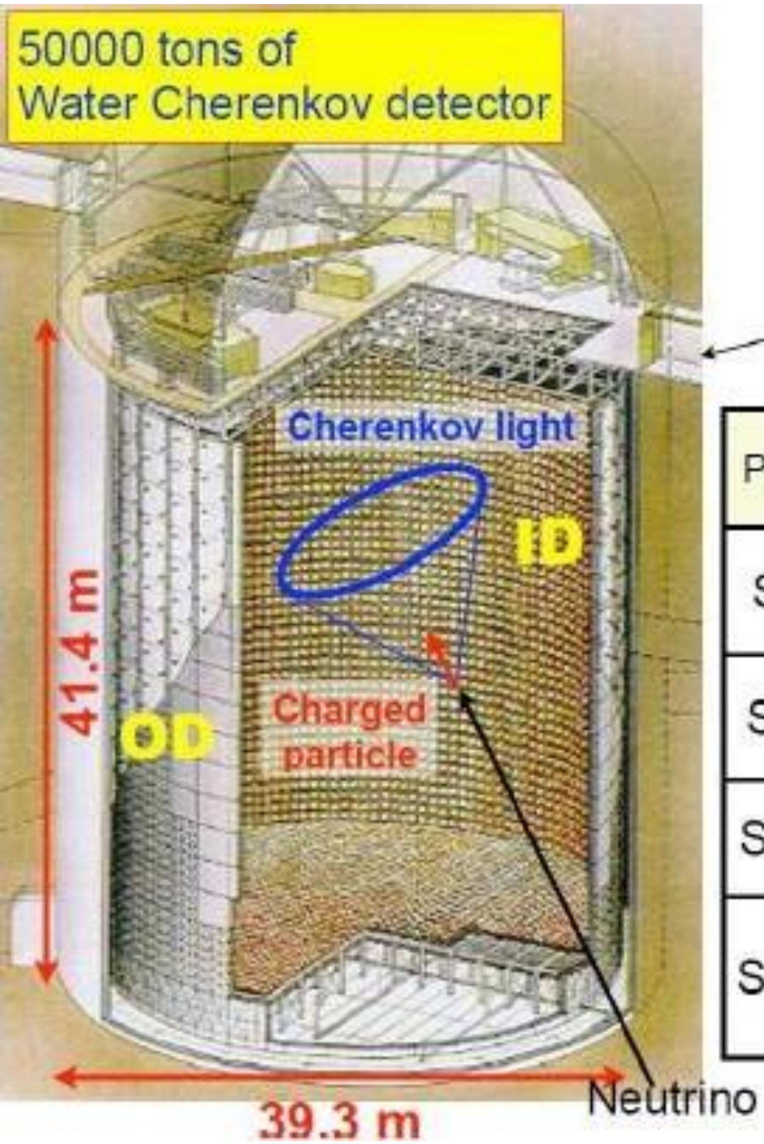
0. SK-Gd

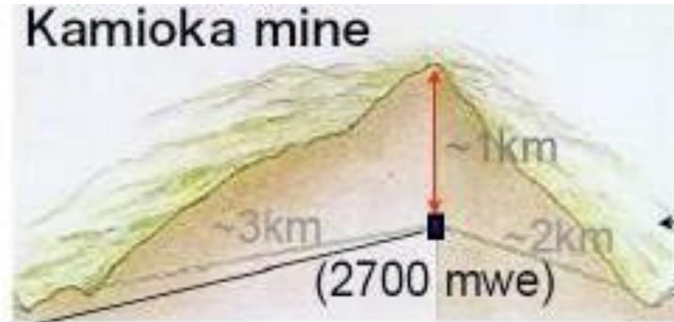
Super-Kamiokande Gadolinium Project

We dissolved Gadolinium ($Gd_2(SO_4)_3$) in the SK water in Aug. 2020 (0.01 %) in the first time and added more in 2022 (0.03 %) successfully.

Target Gd concentration is 0.1 % and fruitful results will be expected in near future.

Super-Kamiokande





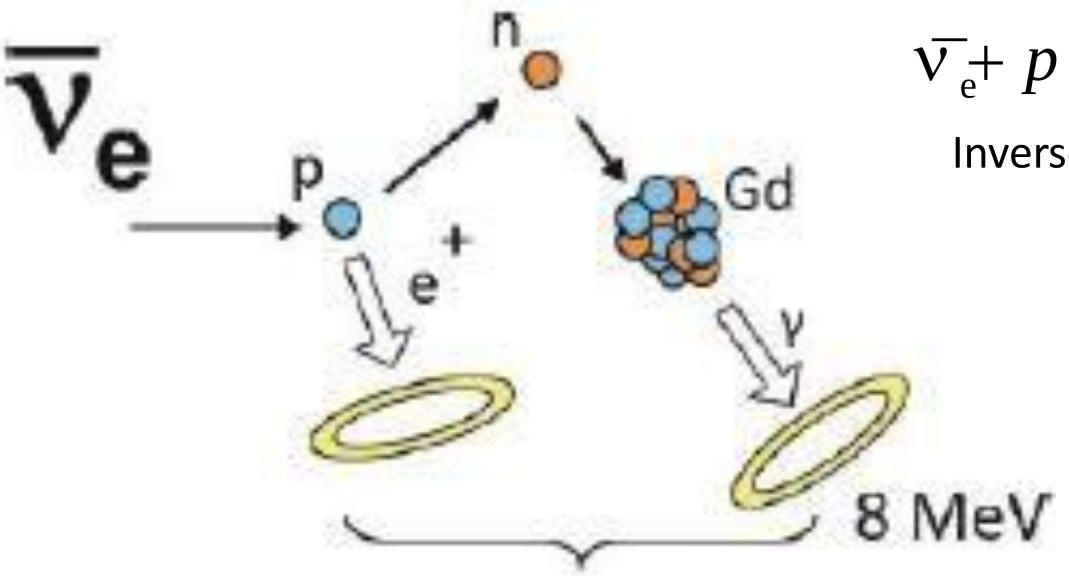
(For Solar neutrino analysis)

Phase	Period	Livetime (days)	Fiducial vol. (kton)	# of PMTs	Energy thr.(MeV)
SK-I	1996.4 ~ 2001.7	1496	22.5	11146 (40%)	4.5
SK-II	2002.10 ~ 2005.10	791		5182 (20%)	6.5
SK-III	2006.7 ~ 2008.8	548	22.5 (>5.5MeV) 13.3 (<5.5MeV)	11129 (40%)	4.5
SK-IV	2008.9 ~		22.5 (>5.5MeV) 13.3 (4.5<E<5.5) 8.8 (<4.5MeV)		3.5

(coverage) (Kinetic energy)

Why gadolinium?

- **Gd has the large cross section σ for thermal neutrons ($< \sigma_{Gd} >$= 49.7 kb >> σ_H = 0.33 b, 1 b = 10^{-24} cm^2).**
- **Neutrons captured by Gd emitt γ rays (E_{total} = 8 MeV)**
- **We can tag $\overline{\nu_e}$ by delayed coincidence technique in IBD:**



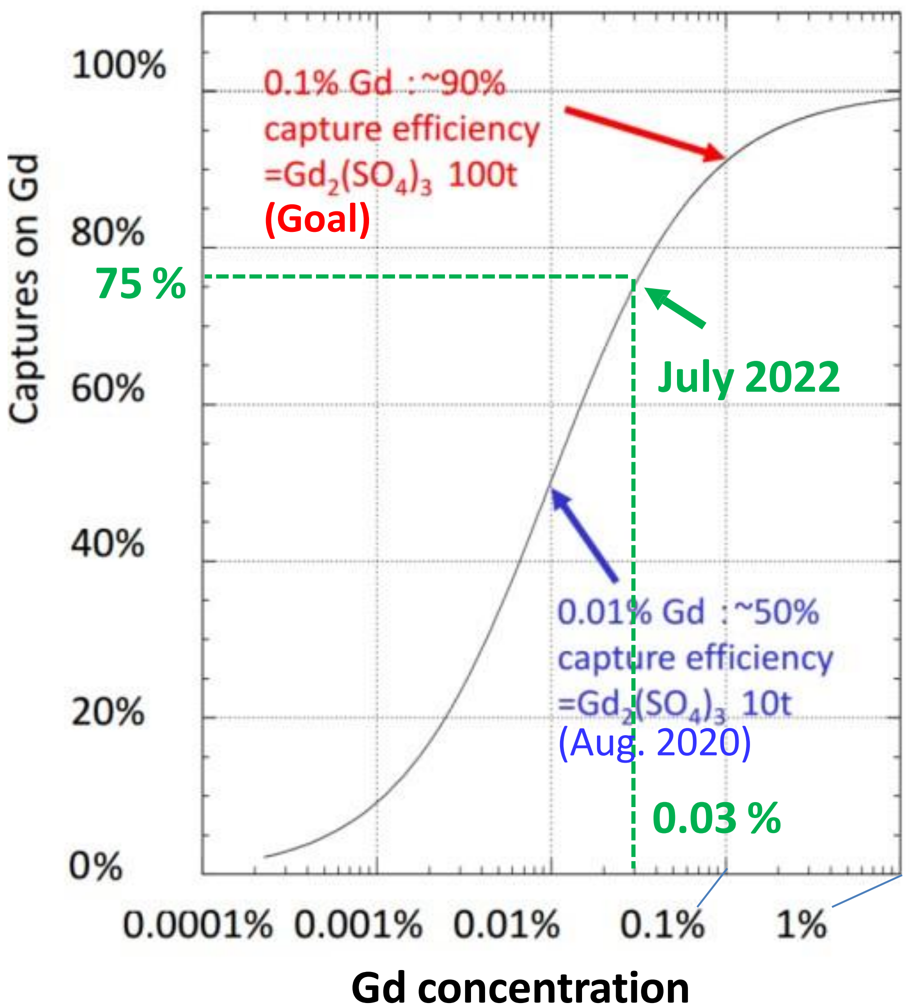
$$\overline{\nu}_e + p \rightarrow n + e^+$$

Inverse beta decay

$\Delta T \sim 30\,\mu s$

Vertices within 50 cm

Physics Targets



Physics targets:

*(1) Supernova relic neutrino (SRN)
(2) Improve pointing accuracy for galactic supernova
*(3) Precursor of nearby supernova by Si-burning neutrinos
(4) Reduce proton decay background
(5) Neutrino/anti-neutrino discrimination (Long-baseline and atm nu's)
(6) Reactor neutrinos

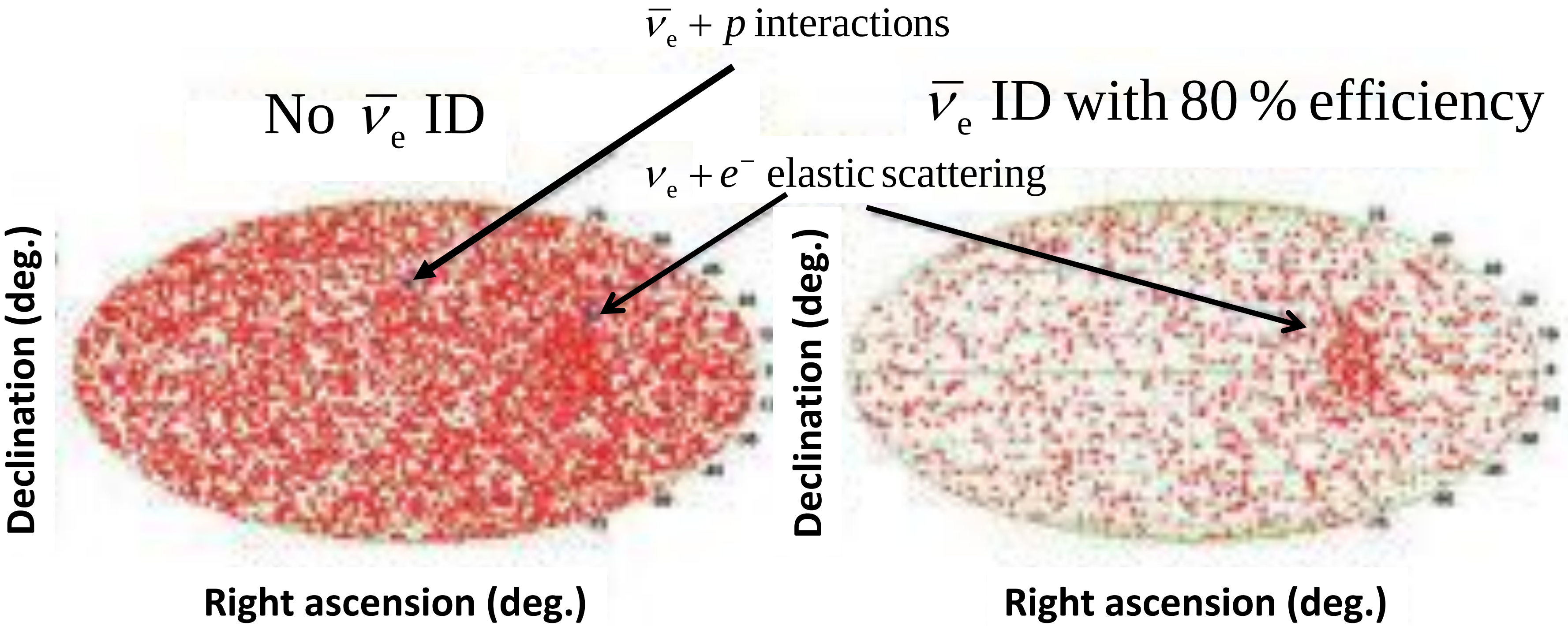
***(1) SRN: All the neutrinos which have ever been emitted by every supernova since the onset of stellar formation suffuse the universe.**

***(3) Approximately a week before exploding, the turn-on of silicon fusion in the core would raise the temperature of the star sufficiently and electron-positron annihilations within its volume would begin to produce $\bar{\nu}_e$ just above inverse beta threshold.**

Improvement of pointing accuracy for galactic SN

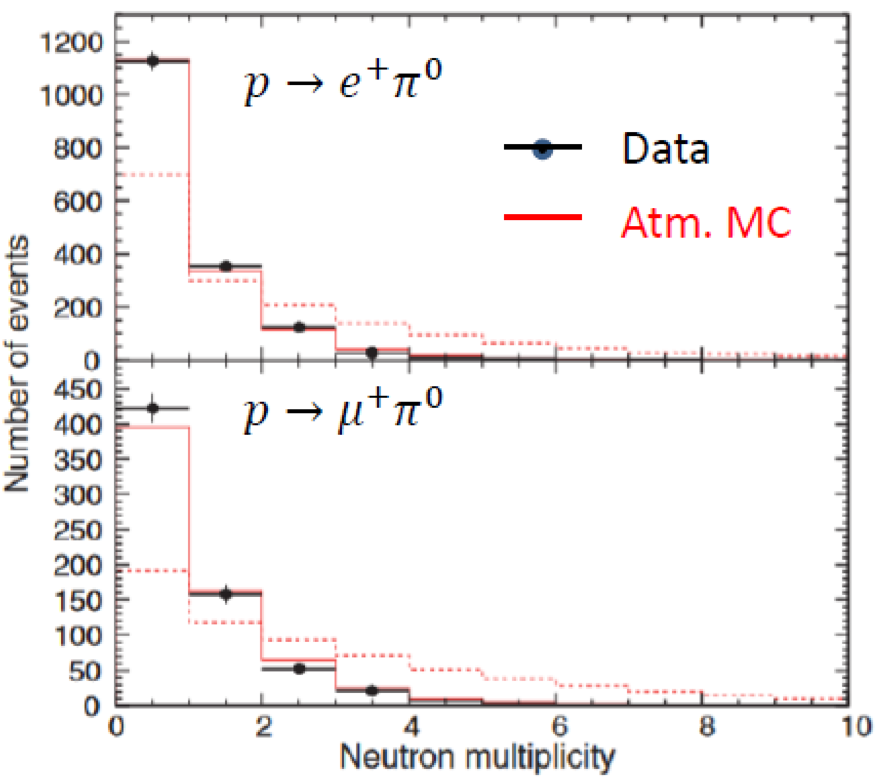
$\nu_e + e^- \longrightarrow \nu_e + \boxed{e^-}$ **: direction information**

$\bar{\nu}_e + p \longrightarrow n + \boxed{e^+}$ **: no direction information**



Direction distribution reconstructed by neutrinos from SN at 10 kpc distance (simulation)

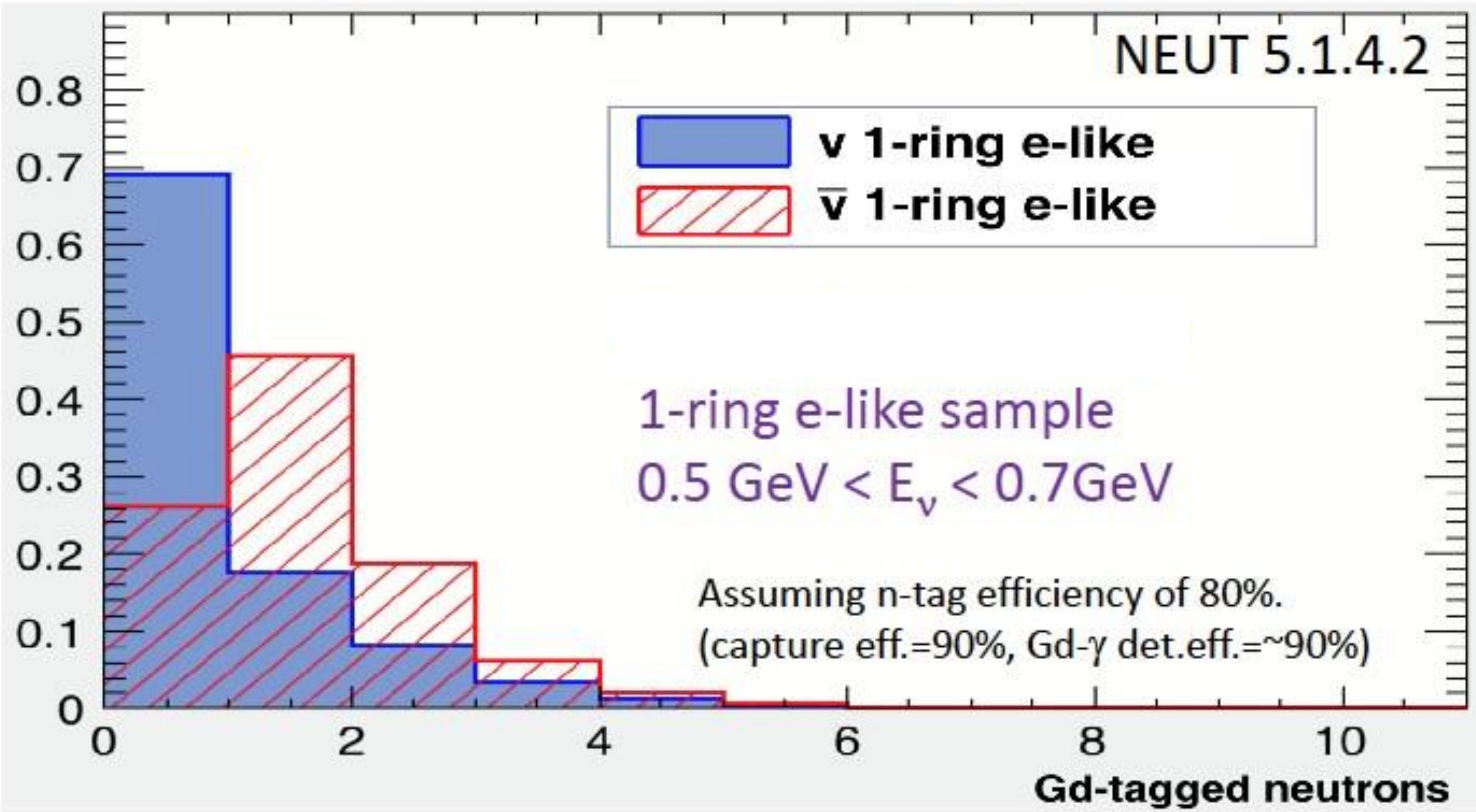
Improvement of proton decay



- ~ 50 % background events are rejected with neutron=0.
- ~ 7.5 % of $p \rightarrow e^+\pi^0$ are accompanied with neutron from deexcitation of nucleus.→ only a few % reduction of selection efficiency.

Improvement for T2K

Number of tagged neutrons in T2K energy range

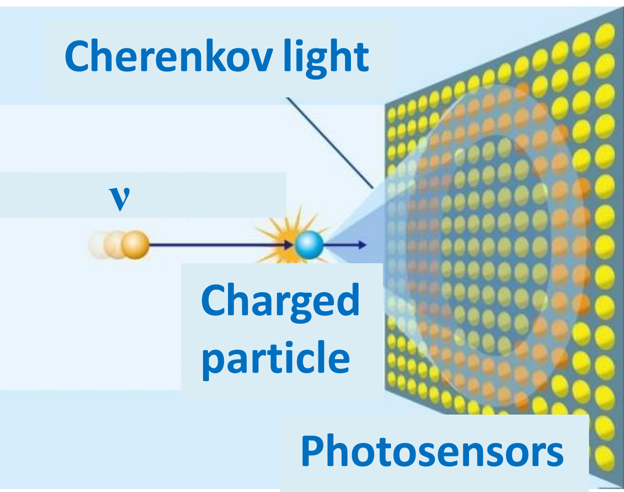


ν_e contamination in the $\bar{\nu}_e$ enhanced sample: 30 % → 13 %

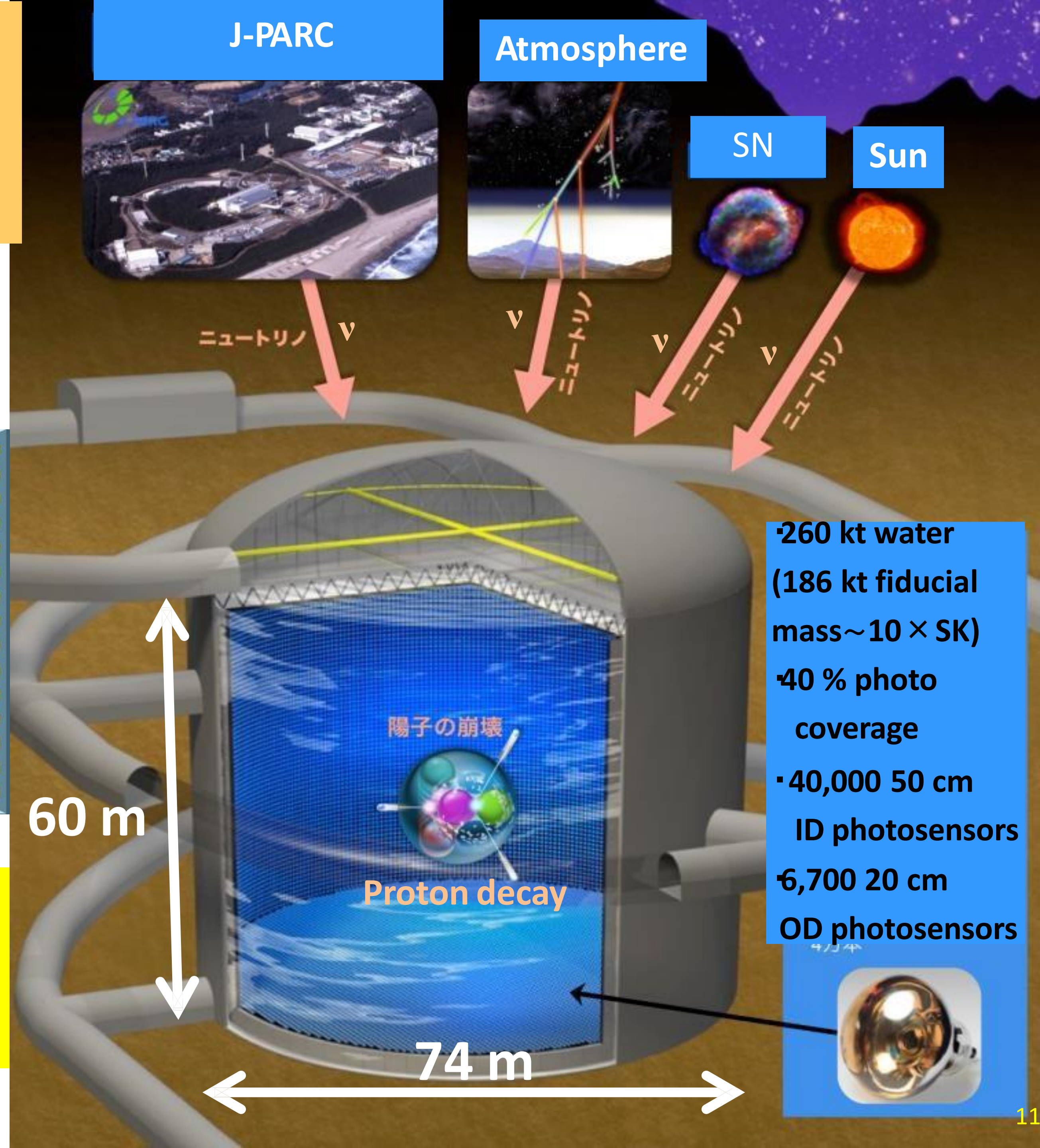
1-1. Hyper-Kamiokande(HK)

Hyper-Kamiokande

Large water Cherenkov detector

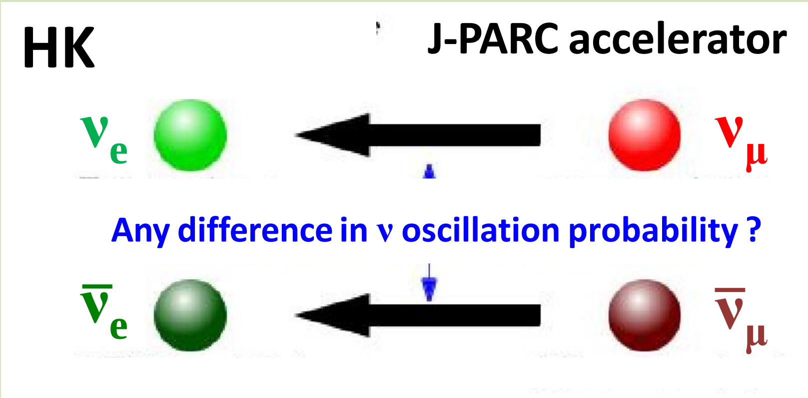


- Construction started in 2020
- Operation will start in 2027 (priority project by MEXT's roadmap)

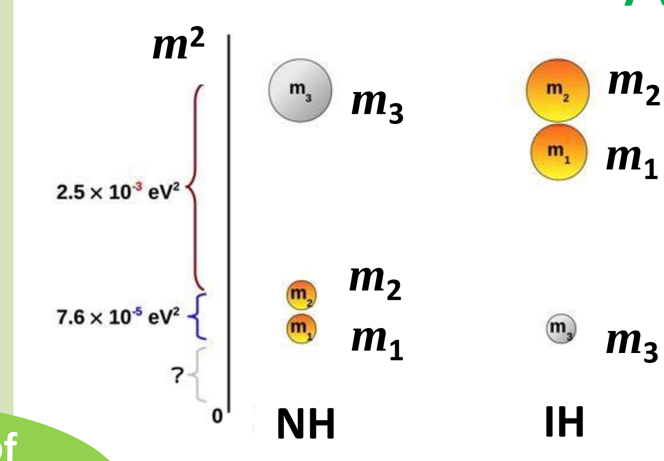


Physics goals

CPV measurement

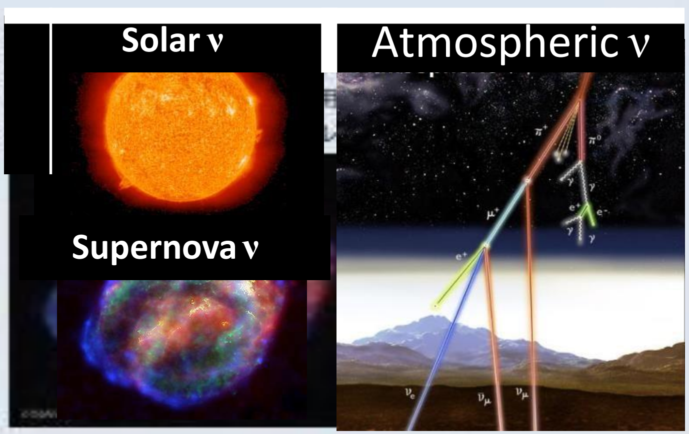


Determination of mass hierarchy (MH)



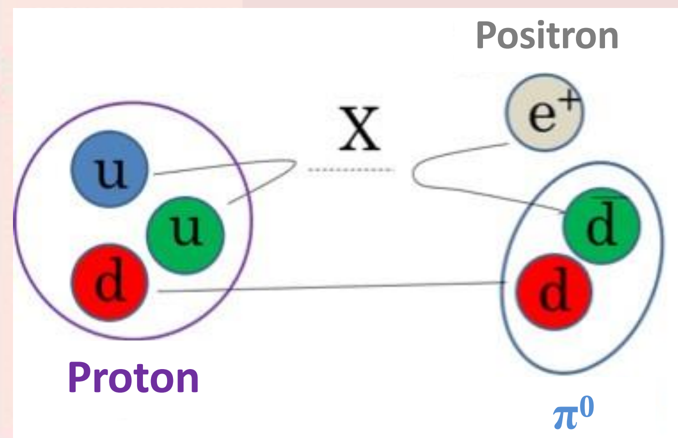
Elucidation of whole picture of ν oscillation

Cosmic neutrino observation



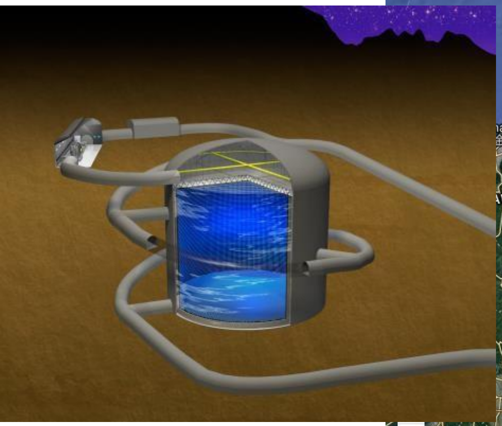
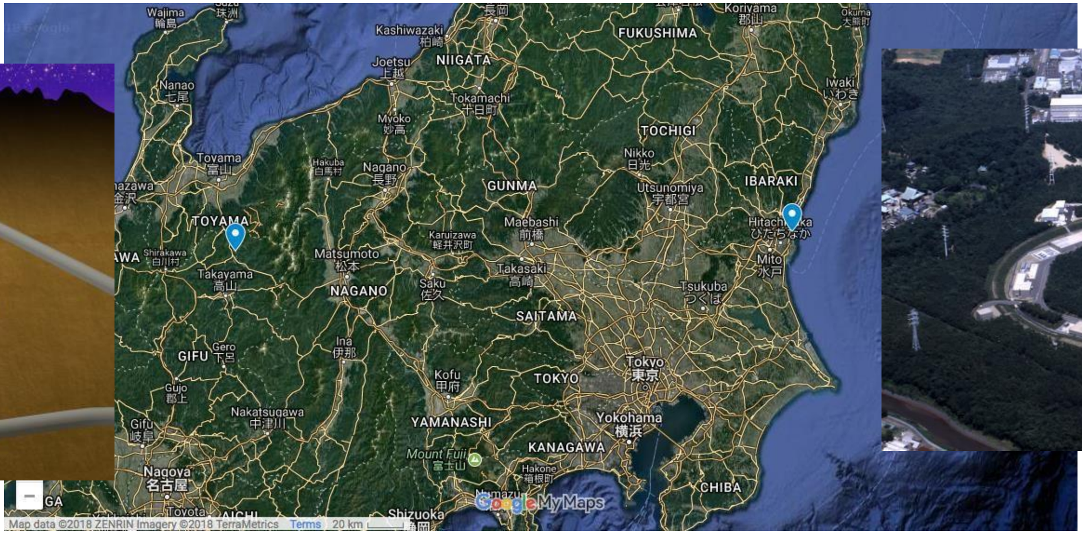
Elucidation of the origin and the history of the universe

Proton decay search

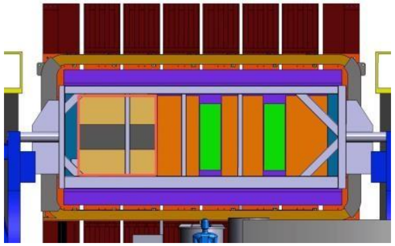


Investigation of GUT

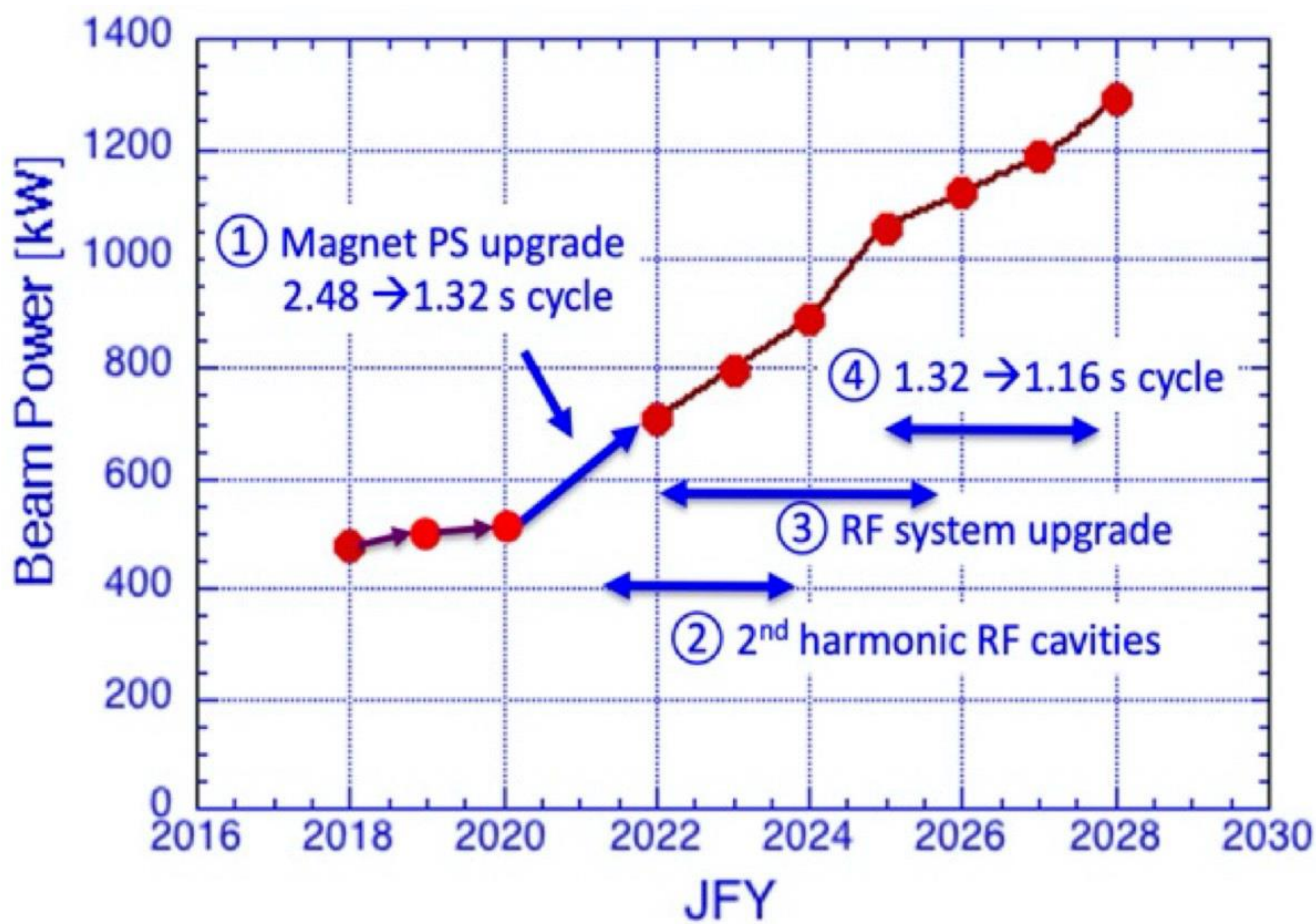
HK Long Baseline Project

- J-PARC ν beam: 500 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 w/ upgrades (SFGD & HA-TPC).
- FD:SK → HK will realize high statistic ν data
- Intermediate Water Cherenkov Detector (IWCD) will be newly constructed at ～1 km from the neutrino source.



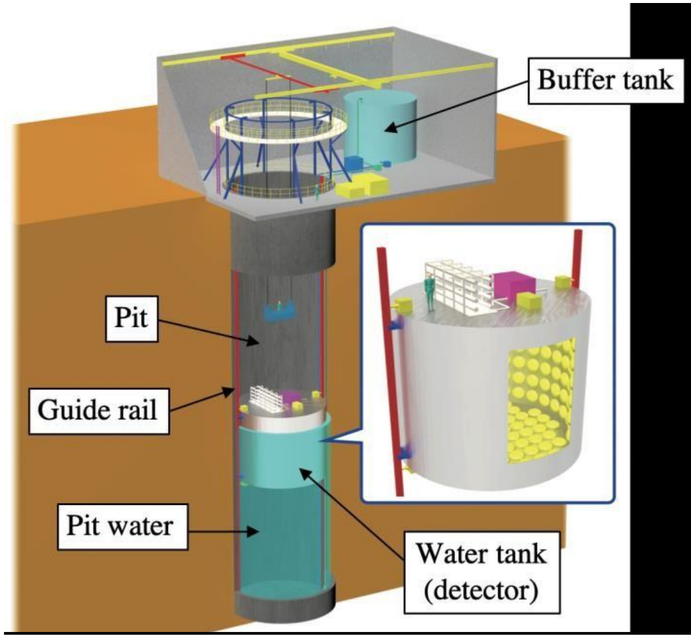

J-PARC beam power upgrade



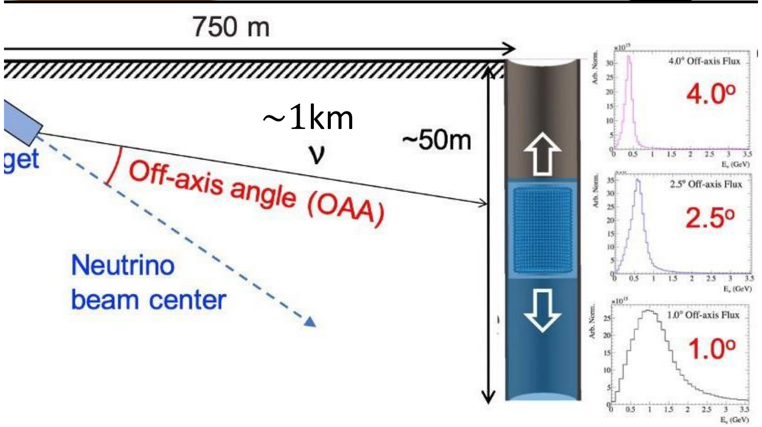
→ 1.3 MW (1.16 sec cycle)

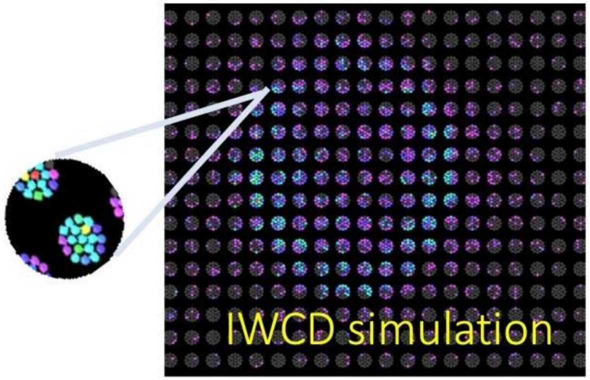
Trial for 1 MW-equivalent operation was successful !

IWCD

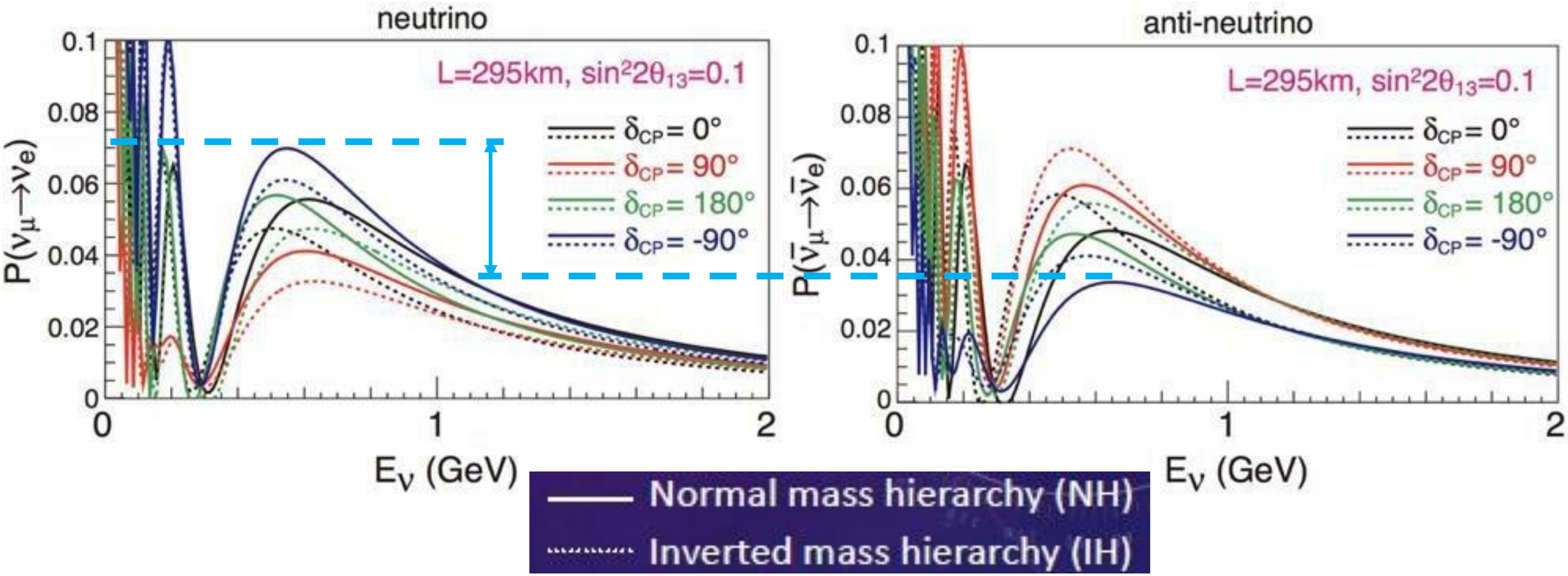


- ~600 t water Cherenkov detector located at ~1km from the neutrino source
- Moves vertically to measure energy spectrum at different off-axis between 1° and 4°.
- Potential to load with Gd to enhance neutron detection
- Multi-PMT units will be used. → good reconstruction despite small detector



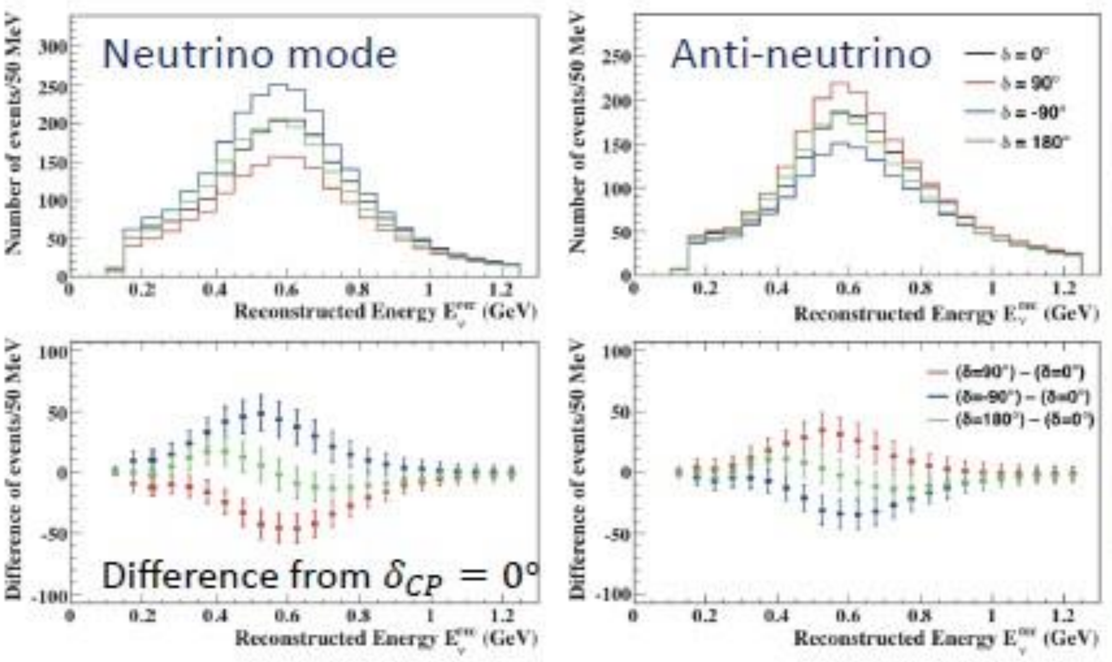


(1) Measurement of CP asymmetry



- 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 project



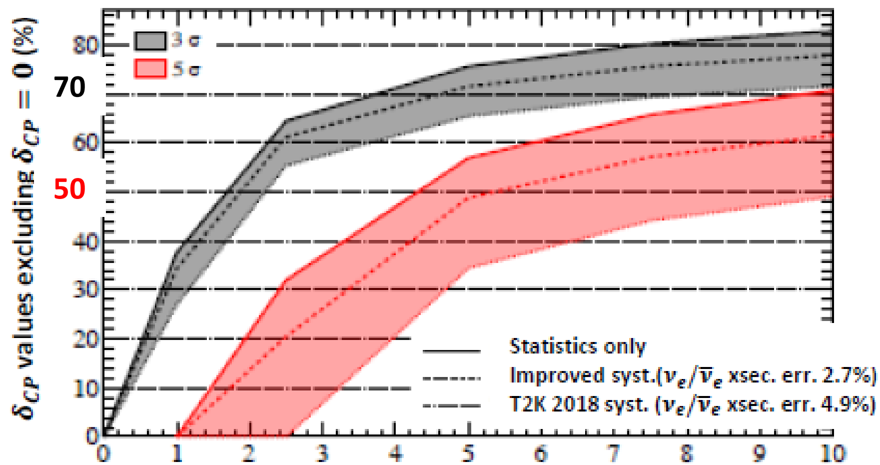
- A few % stat. uncertainties on $\nu_\mu \rightarrow \nu_e$ & $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ signals
- $E\nu$ is reconstructed from (p, θ) of e or μ
- Realistic estimates of wrong sign & NC BG contaminations are based on T2K

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

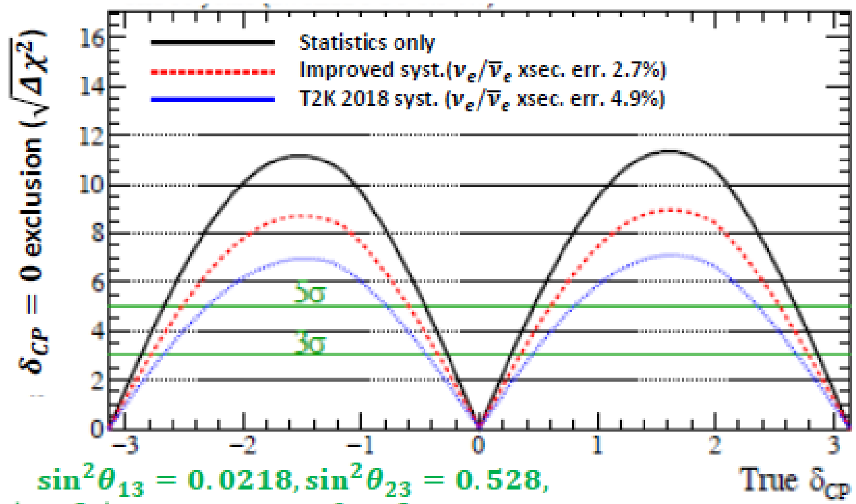


$\sin^2\theta_{13} = 0.0218, \sin^2\theta_{23} = 0.528$
$|\Delta m^2_{32}| = 2.509 \times 10^{-3}[\mathrm{eV}^2]$

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

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

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



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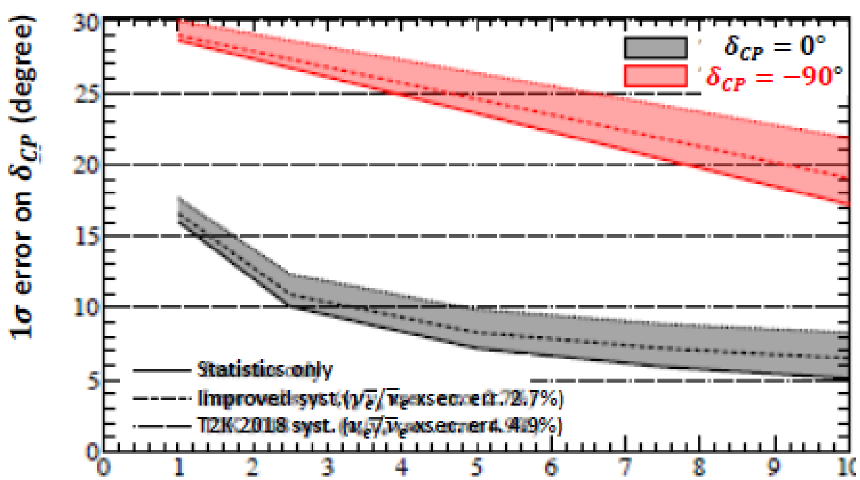

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$|\Delta m^2_{32}| = 2.509 \times 10^{-3}[\mathrm{eV}^2]$

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

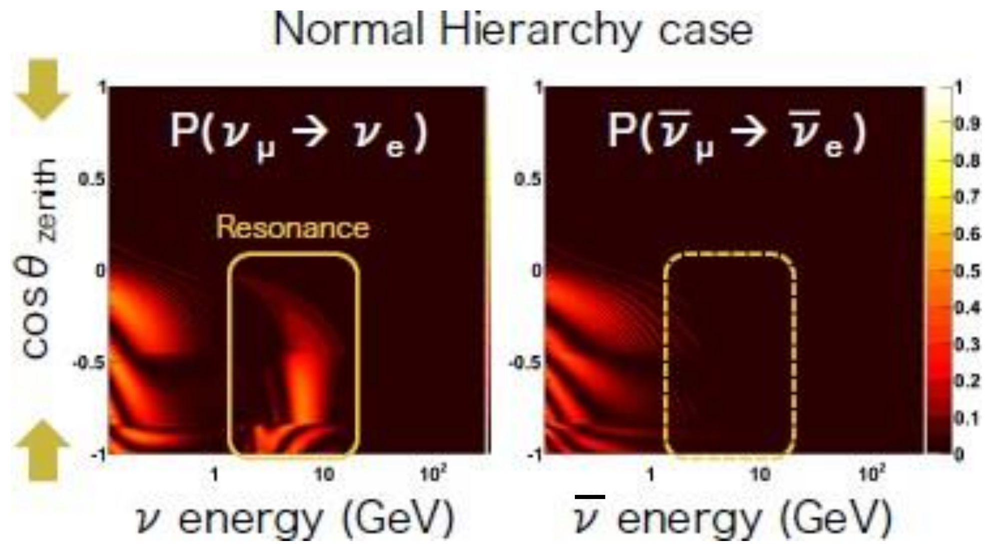
Significance to exclude $\delta_{CP} = 0$ (CP conservation)

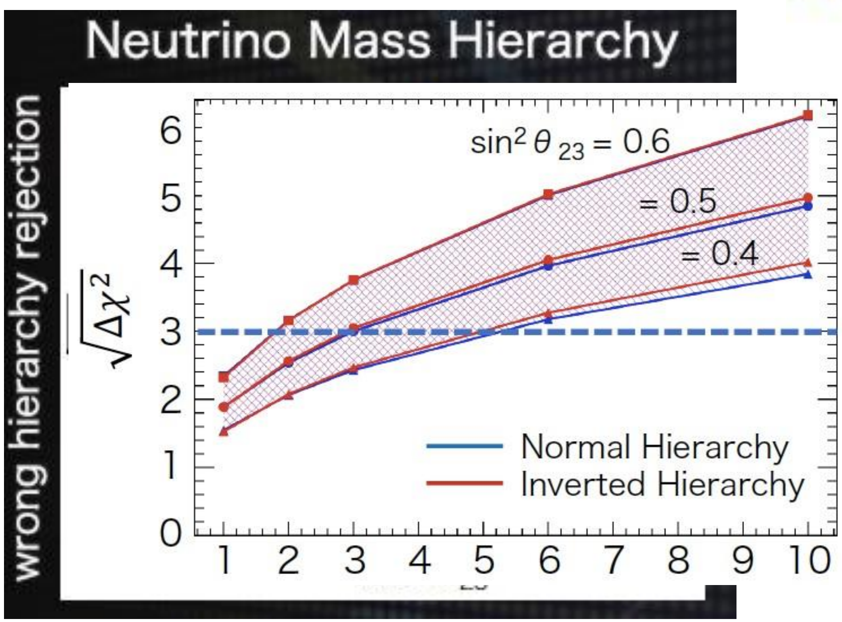
For $\sim 70\ (50)$ % region, CP conservation is excluded at $> 3\sigma(5\sigma)$

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

(2) Mass hierarchy determination

*See Miura-san's lecture in detail.



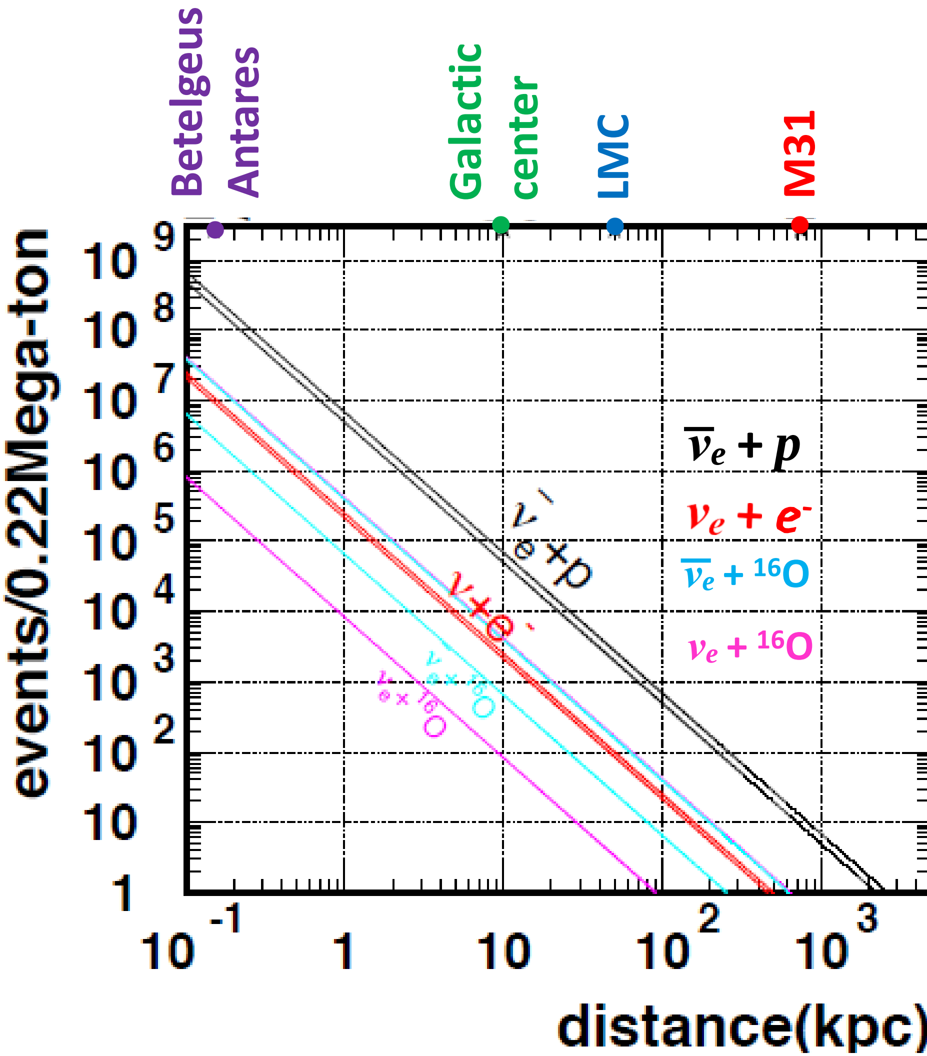


- The resonance appears for ν_e ($\bar{\nu}_e$) in NH (IH) case.
- Sensitivity enhanced by combining atm & beam ν data.→ **3σ determination within 2 ~ 5 years !**

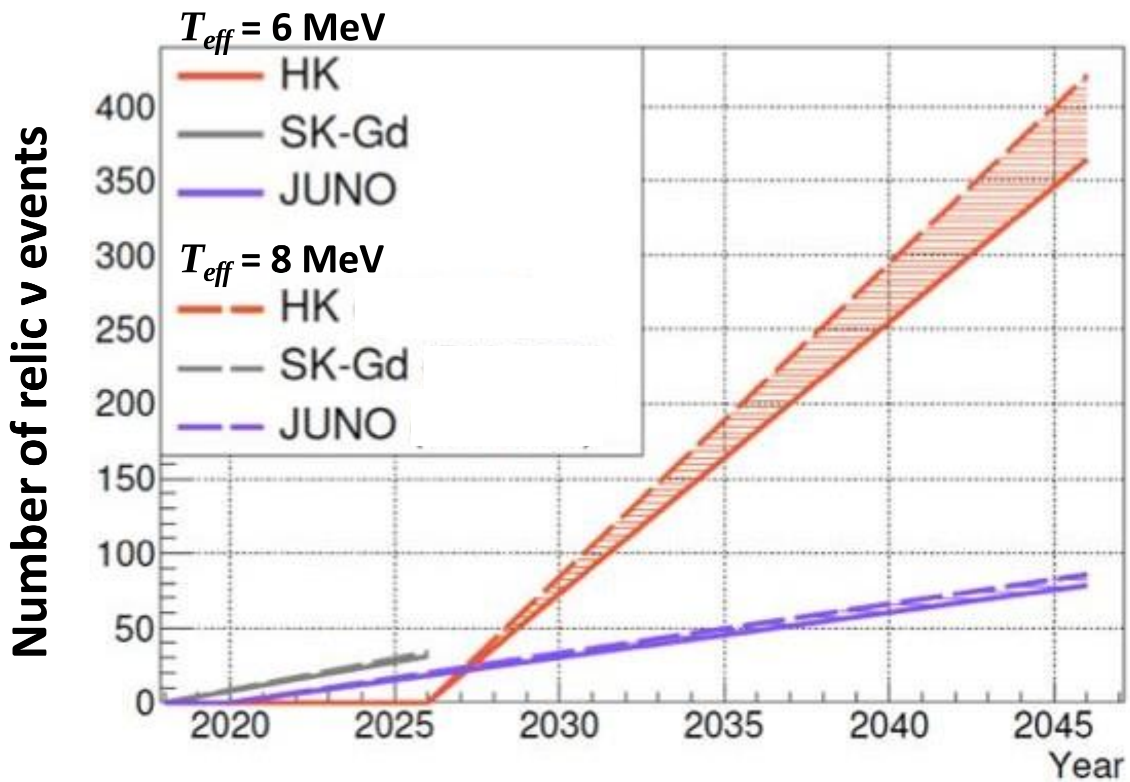
(3) Neutrino astrophysics

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.



(3) Neutrino astrophysics



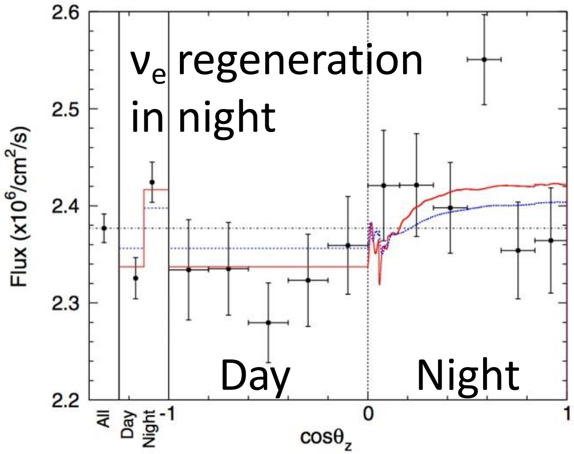
SN relic ν

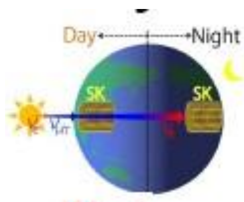
- 1st discovery by SK-Gd
- HK will measure the spectrum.

(3) Neutrino astrophysics-solar ν-

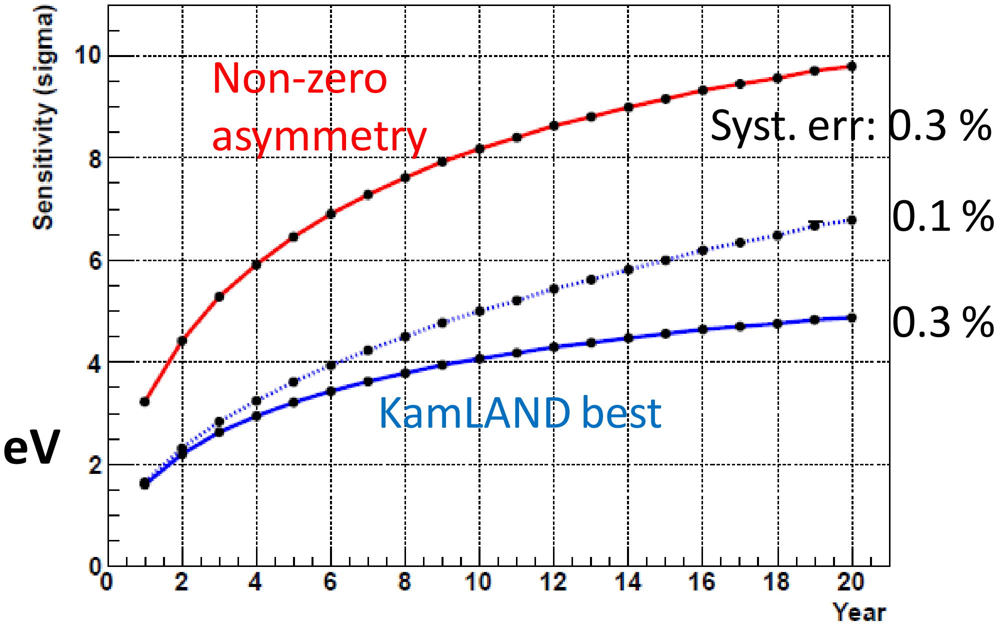
Day-night asymmetry observation

Sensitivity (See Oyama-san's lecture in detail)



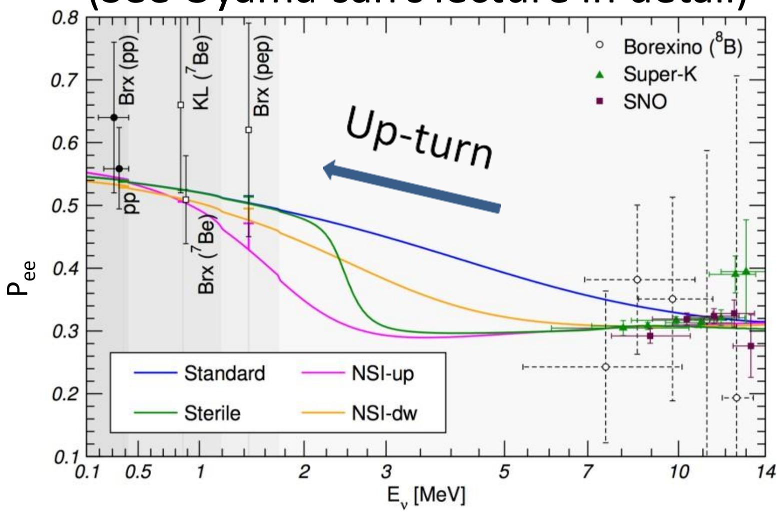


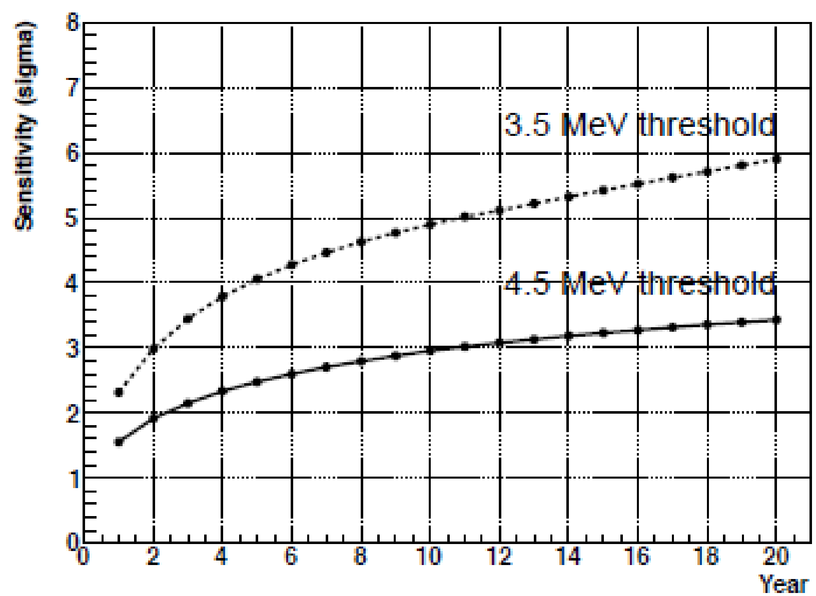
E_{thr} = 6.5 MeV



Energy spectrum up-turn

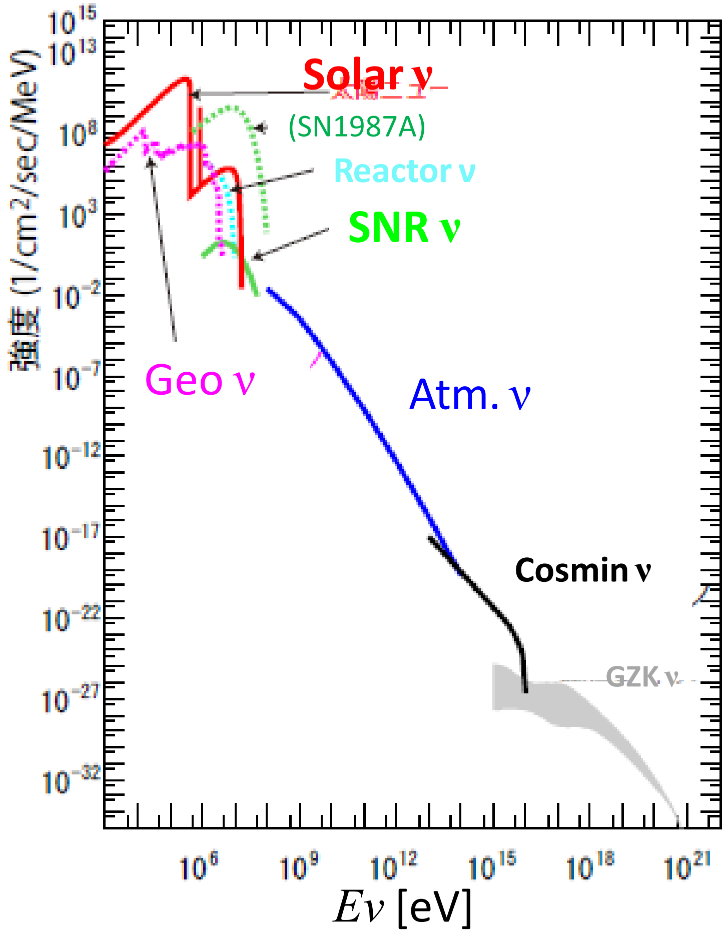
(See Oyama-san's lecture in detail)



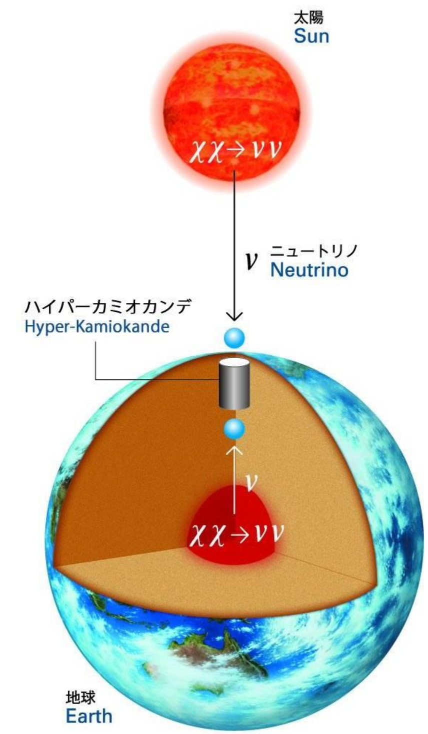


(3) Neutrino astrophysics

-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.

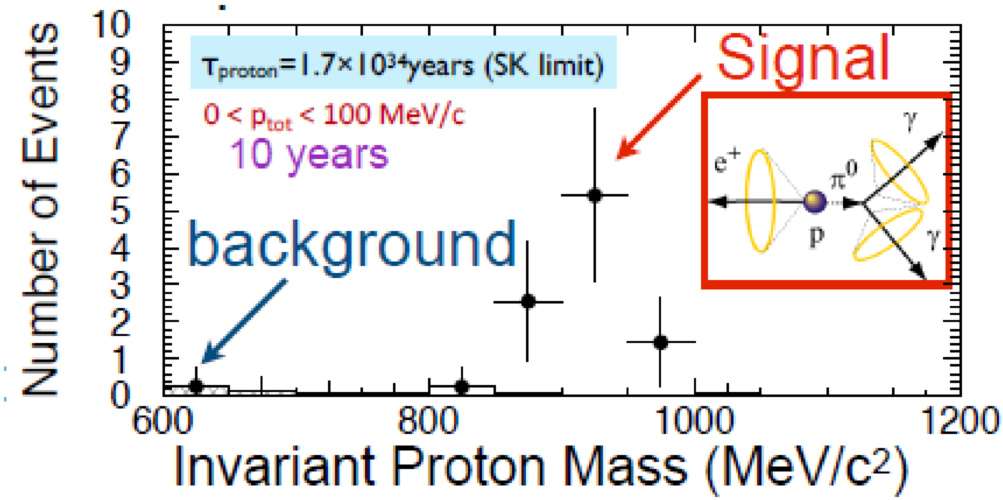


Indirect DM search: Hyper-Kamiokande detects the neutrinos generated by the interaction of dark matters in the Sun or the earth.

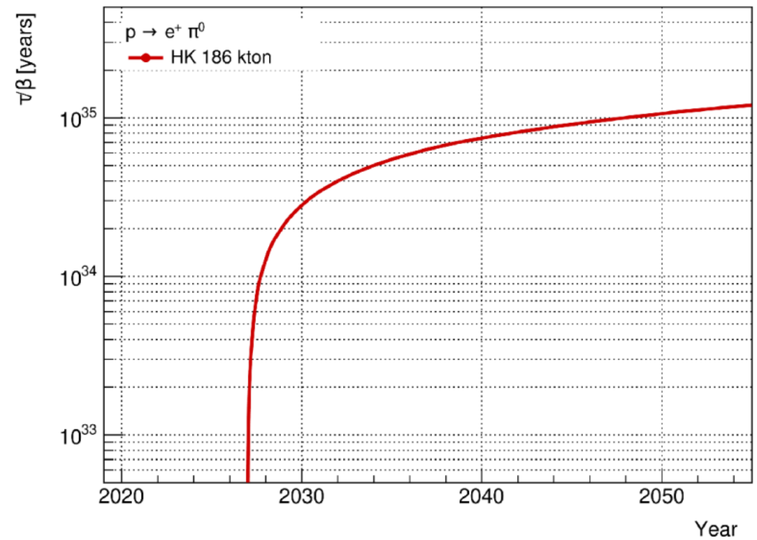
(4) Proton decay search

*See Miura-san's lecture

■ $p \rightarrow e^+\pi^0$ search



3σ discovery sensitivity



Almost BKG free measurement !

$0 < p_{tot} < 100$ MeV/c		$100 < p_{tot} < 250$ MeV/c	
ϵ_{sig} [%]	Bkg [/Mton·yr]	ϵ_{sig} [%]	Bkg [/Mton·yr]
18.7 ± 1.2	0.06 ± 0.02	19.4 ± 2.9	0.62 ± 0.20

(SK: 0.18) (SK: 1.1)

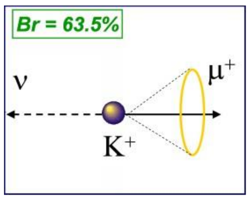
3σ discovery sensitivity :
$\tau_p/Br = 10^{35}$ years
for 20 year operation.

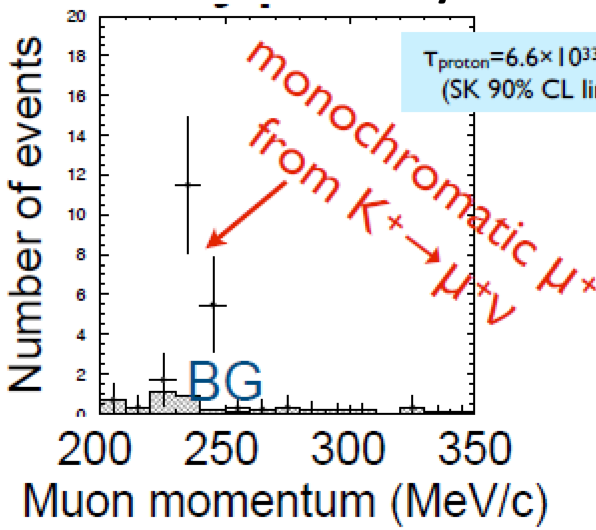
(4) Proton decay search

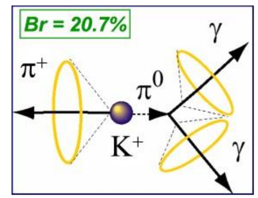
■$p \to \nu K^+$ search

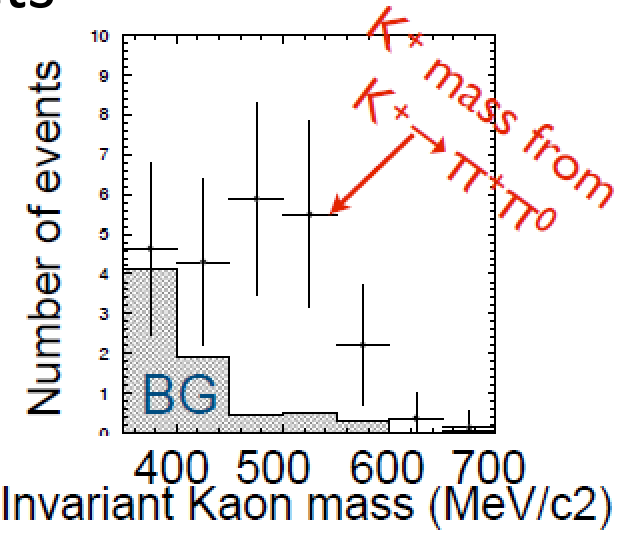
*See Miura-san's lecture

- K^+ is identified by its decay products

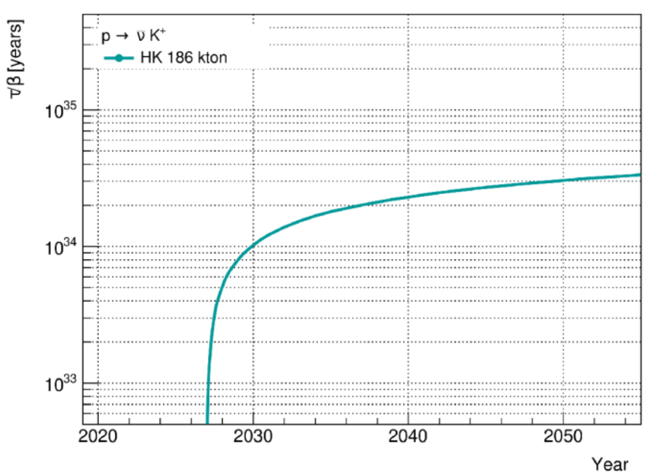








3σ discovery sensitivity



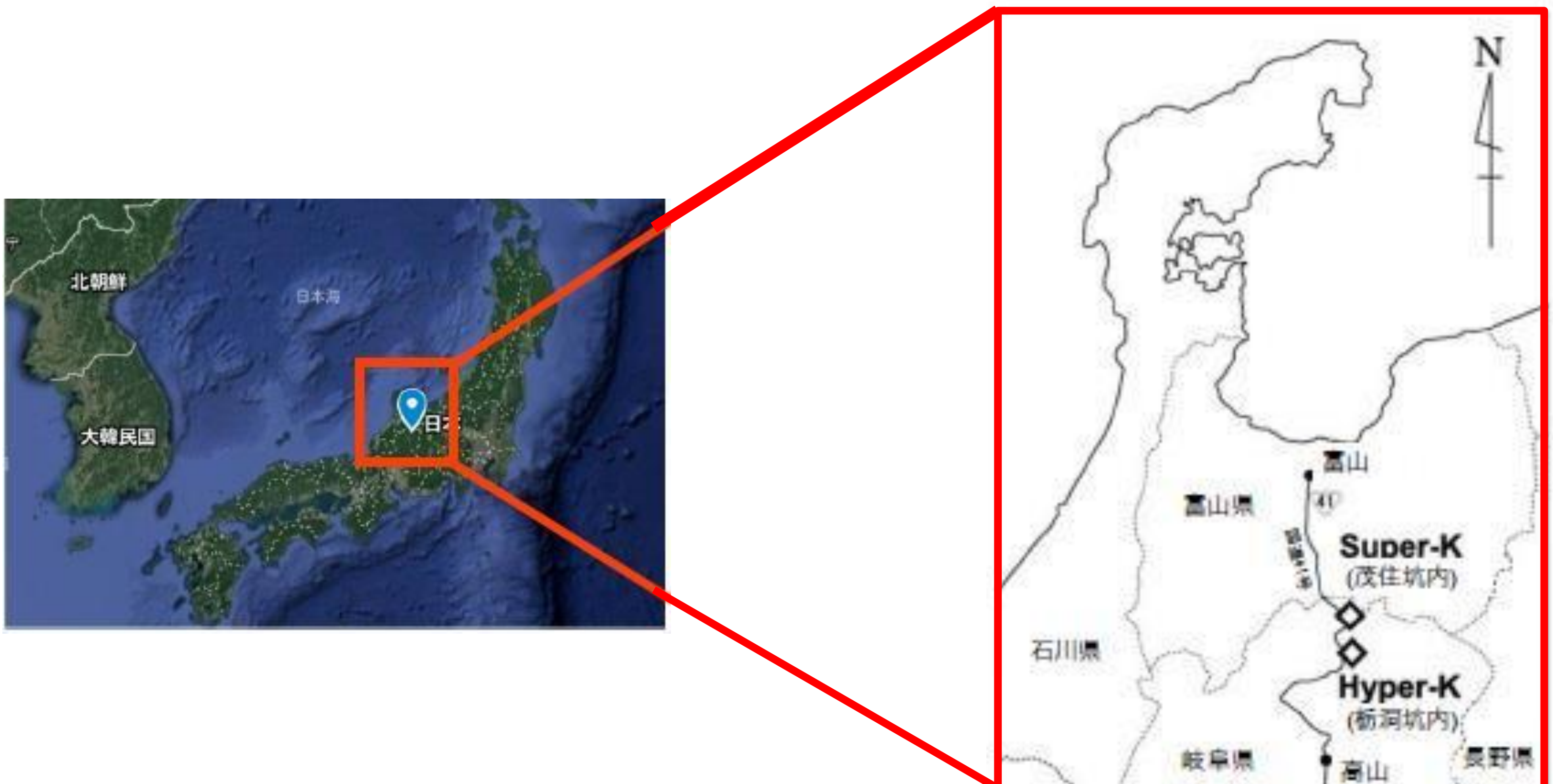
Prompt γ		$\pi^+\pi^0$		p_μ Spectrum		
ϵ_{sig} [%]	Bkg [/Mton·yr]	ϵ_{sig} [%]	Bkg [/Mton·yr]	ϵ_{sig} [%]	Bkg [/Mton·yr]	σ_{fit} [%]
12.7 ± 2.4	0.9 ± 0.2	10.8 ± 1.1	0.7 ± 0.2	31.0	1916.0	8.0

3σ discovery sensitivity :
$\tau_p/Br = 3 \times 10^{34}$ years
for 20 year operation.

Detector Location

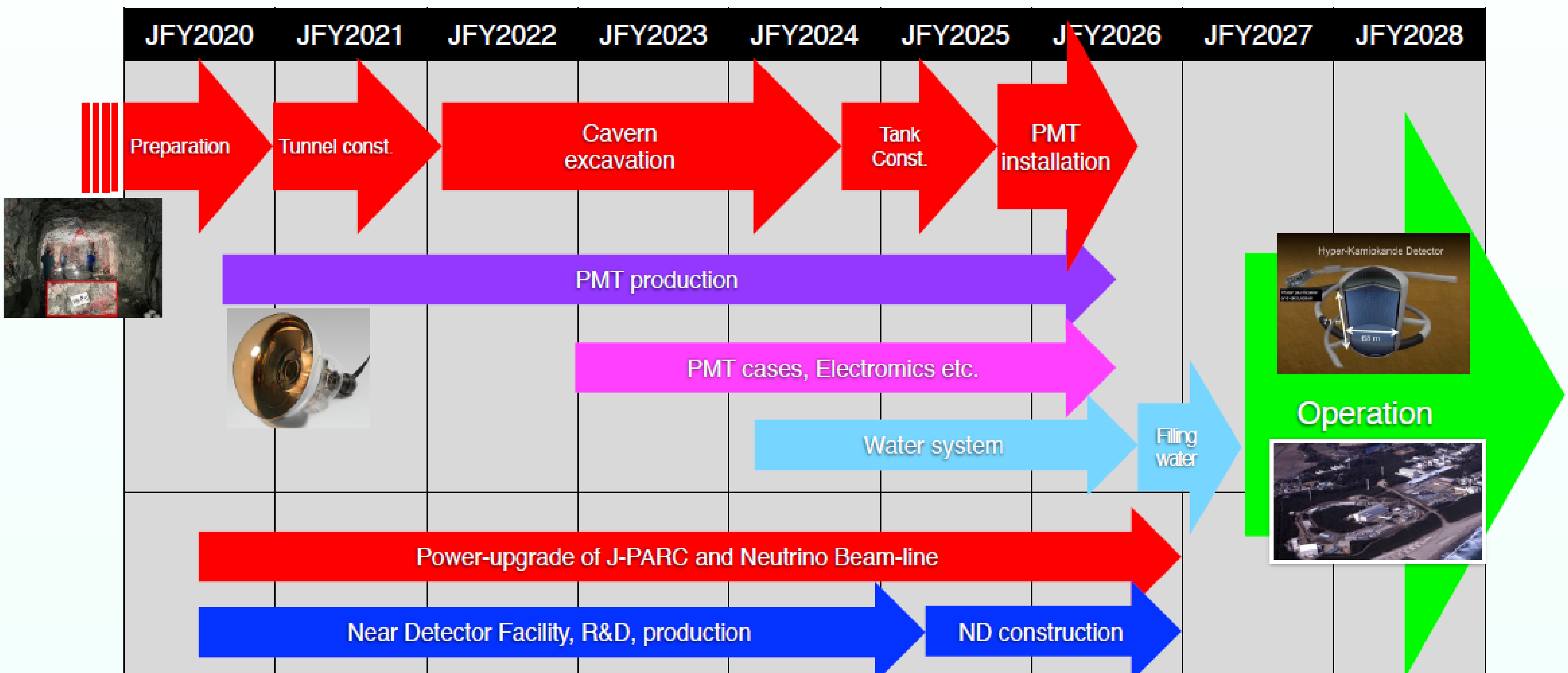
*See Miura-san's lecture

- 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



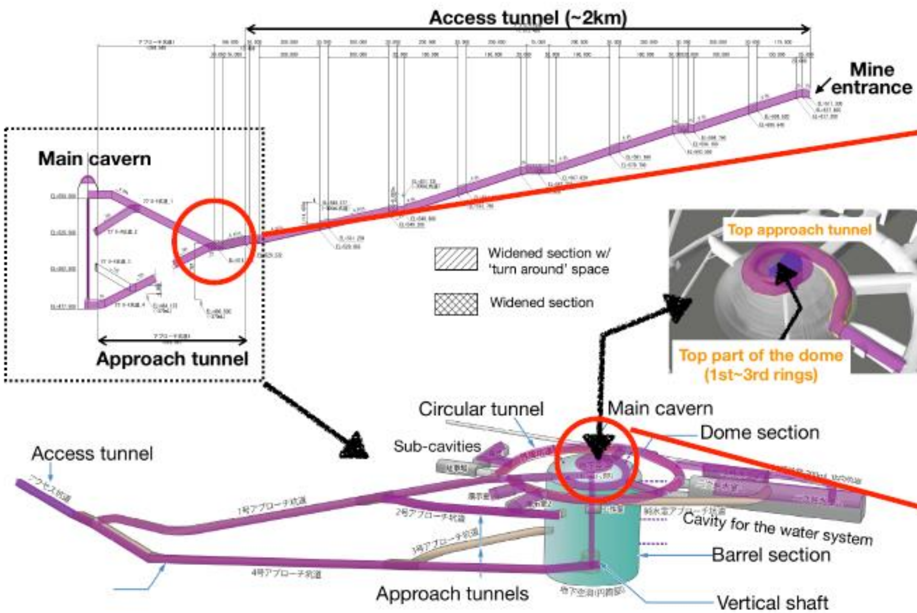
Timeline

- 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

Cavern excavation status



- Access tunnel (~2 km) completed in Feb. 2022
- Excavation of the main cavern started in fall 2022 and is proceeding as scheduled

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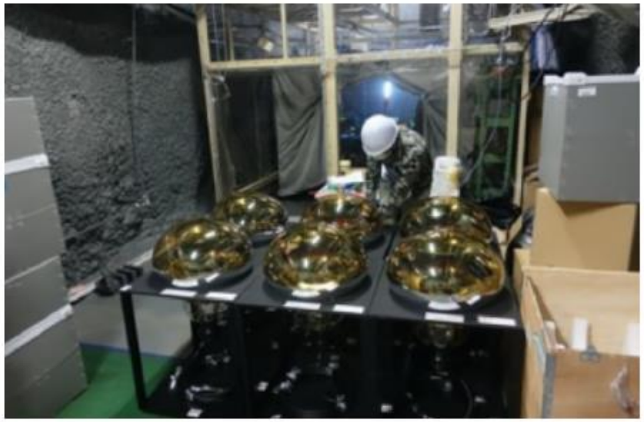
T. Nakaya, Neutrino workshop @ IFIRSE on July 27, 2023

Detector component (some production starting)

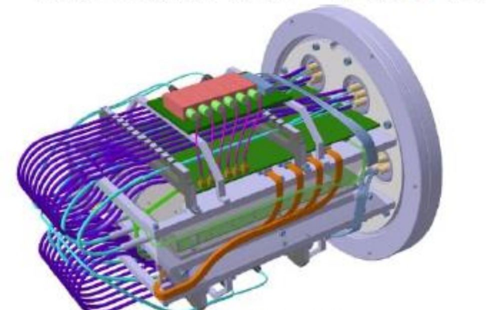
PMTs (**x 2** better photodetection eff.)



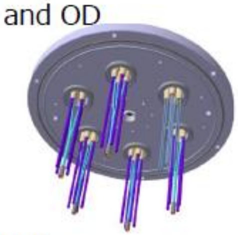
ID mockup

Underwater electronics:

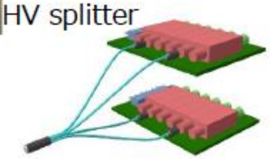
20 x 50 cm ID PMTs + 12 x OD PMTs



Feedthroughs for ID and OD



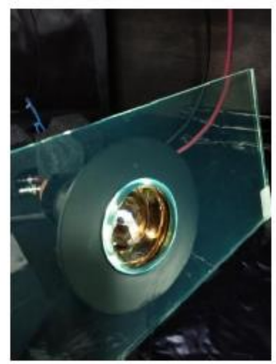
OD signal + HV splitter



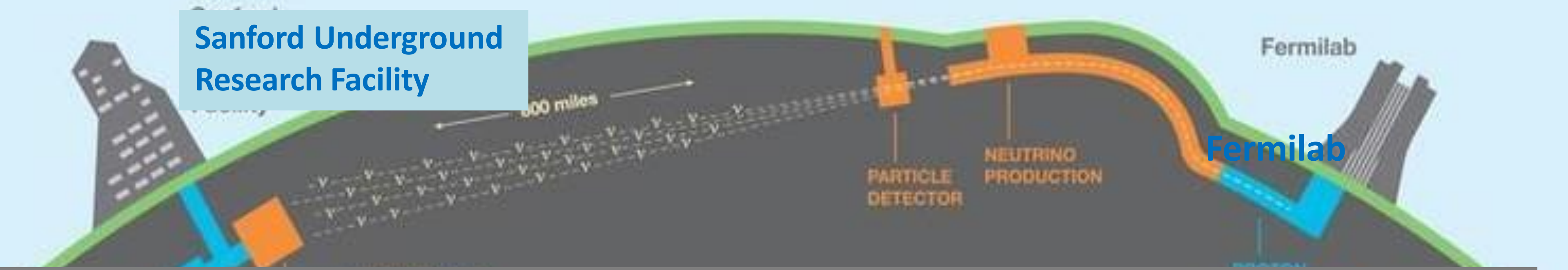
PMT cover

Multi-PMT module:

Outer detector: PMT+WLS plate

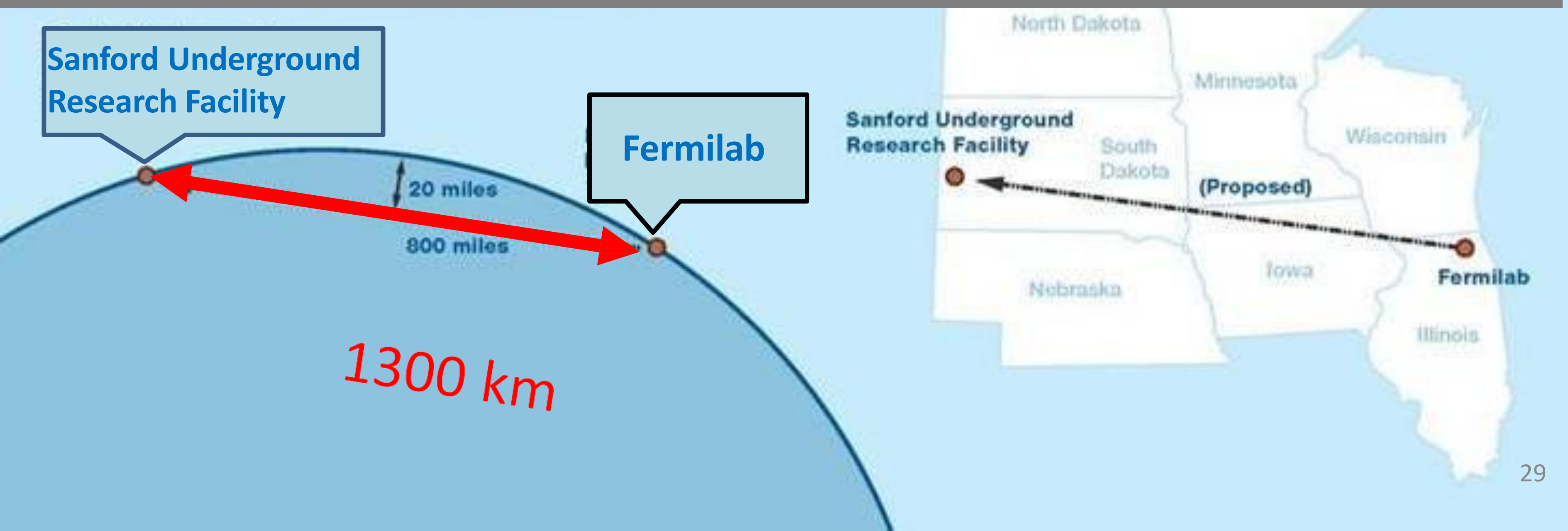


T. Nakaya, Neutrino workshop @ IFIRSE on July 27, 2023



1-2. DUNE

(Deep Underground Neutrino Experiment)



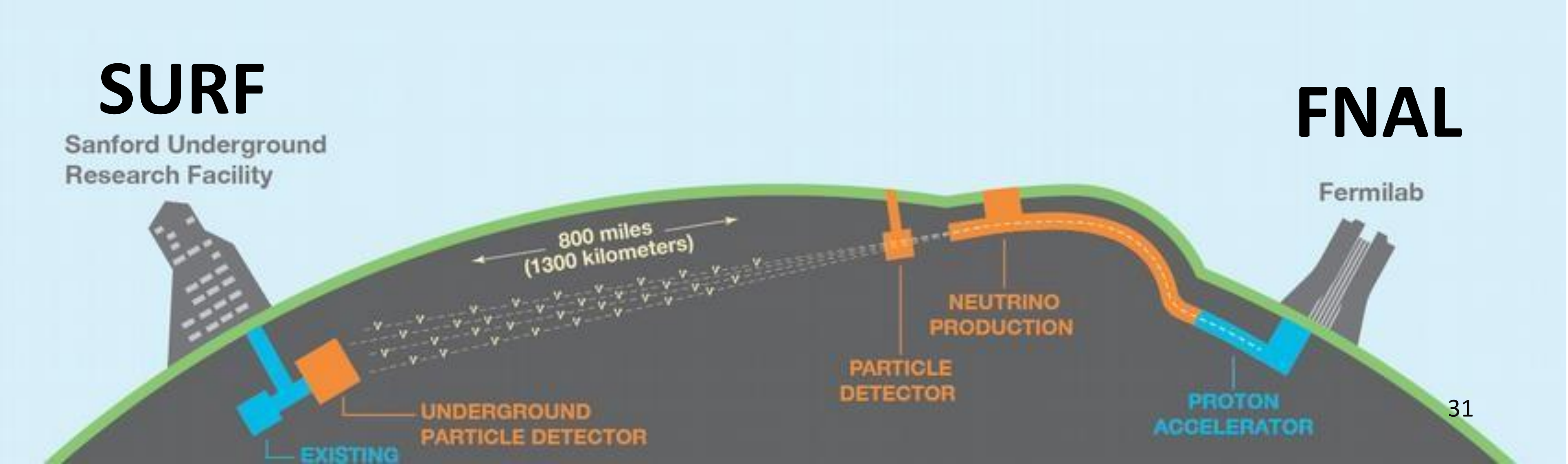
Introducing DUNE

- 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)

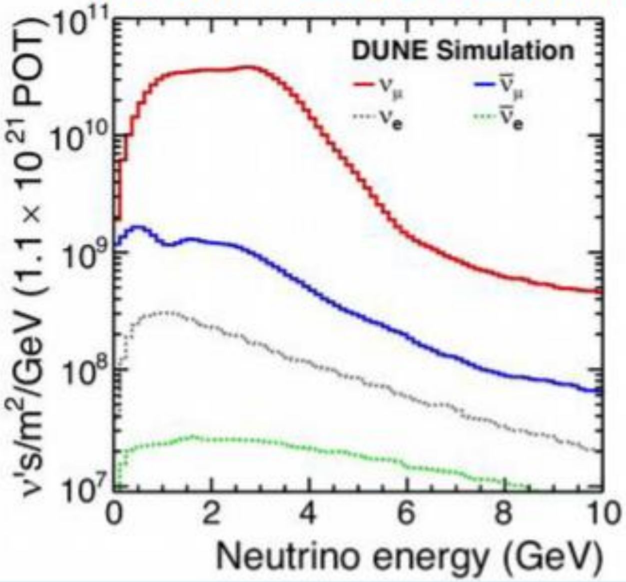
  (2) SN burst ν's and astrophysics

  (3) Proton decay

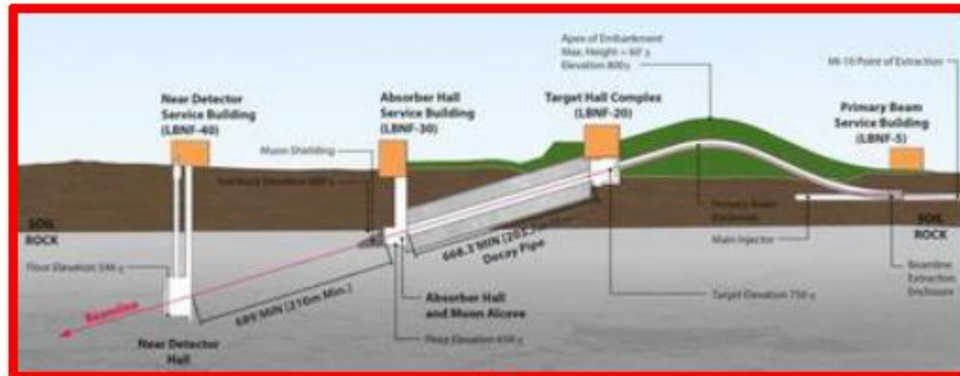


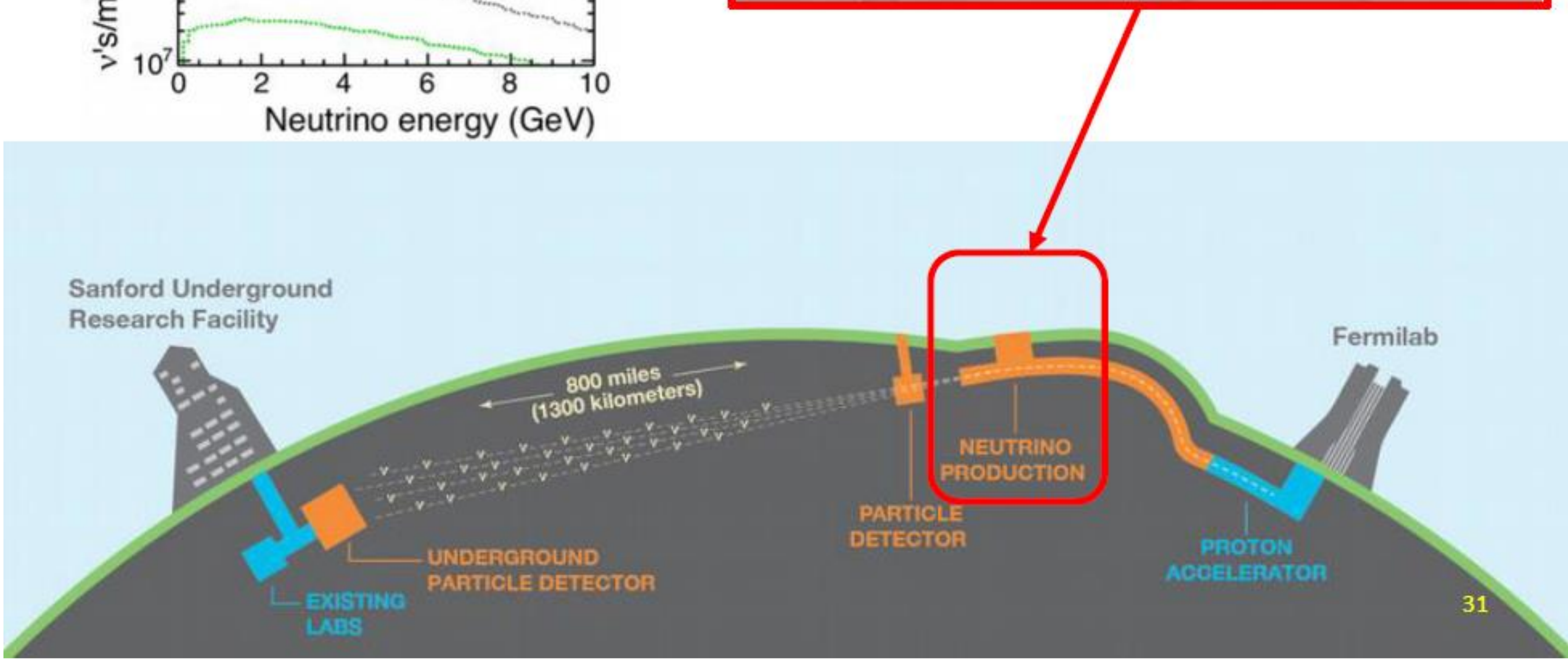
ν source

MW-scale wide band beam

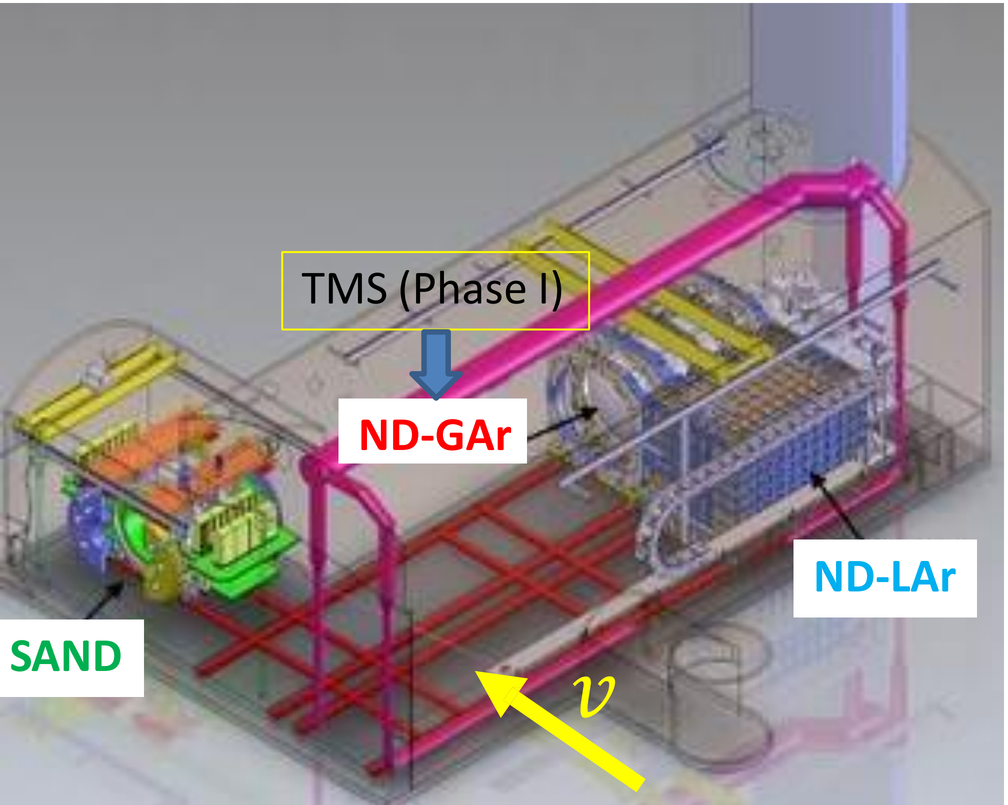


Long Baseline Neutrino Facility (LBNF)

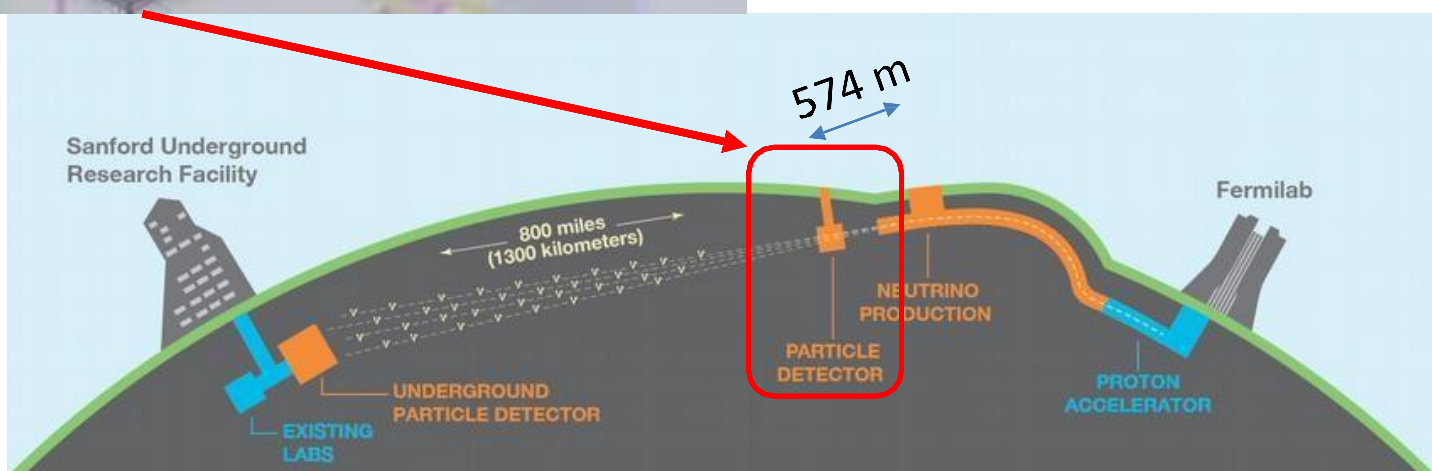




Near Detector (ND)

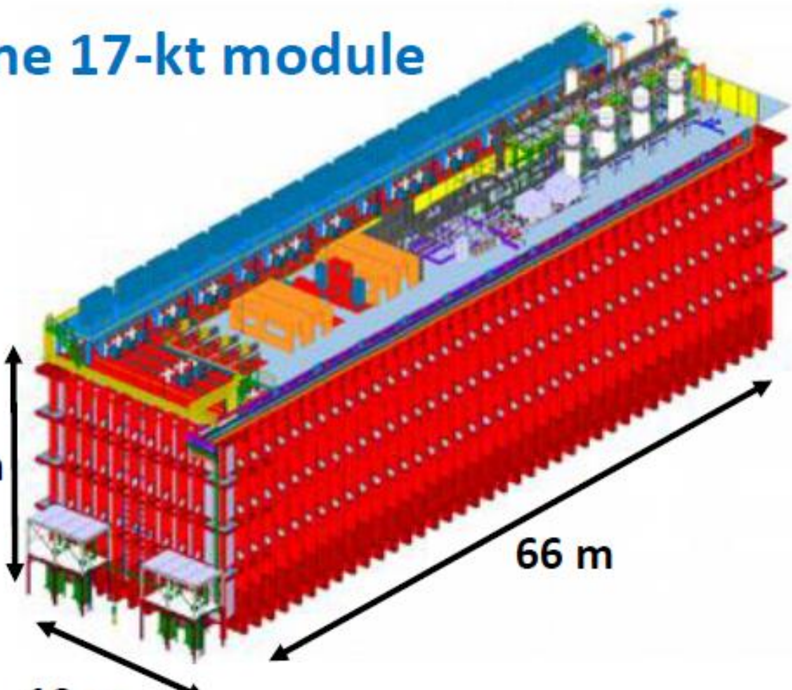


- **Located 574 m from the beam target**
- **ND-LAr: pixelated LArTPC**
- **ND-GAr (in Phase II): high-pressure GAr TPC surrounded by ECAL and 0.5 T magnet**
- **SAND** (System for on-Axis Neutrino Detection)**: tracker surrounded by ECAL and 0.6 T magnet**
- **ND-LAr/ND-GAr can move to off-axis up to 33m modifying the energy spectrum (DUNE-PRISM)**

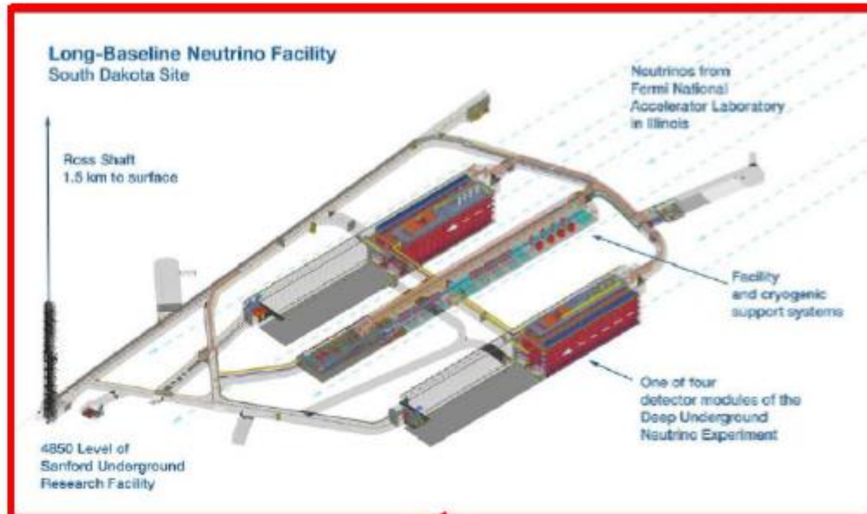


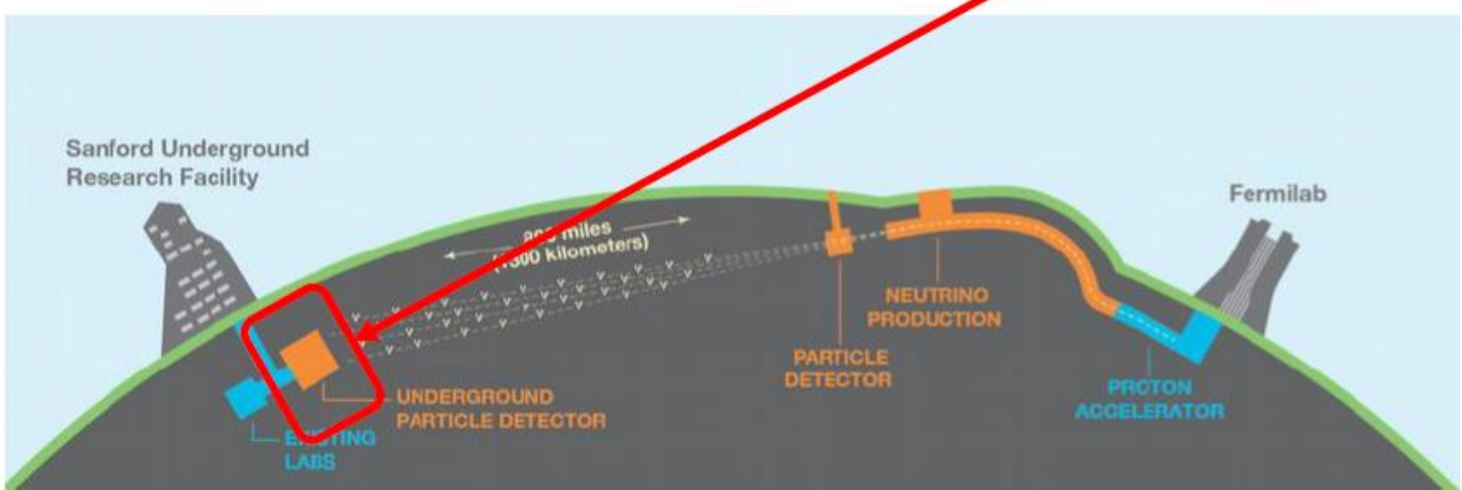
Far Detector (FD)

One 17-kt module

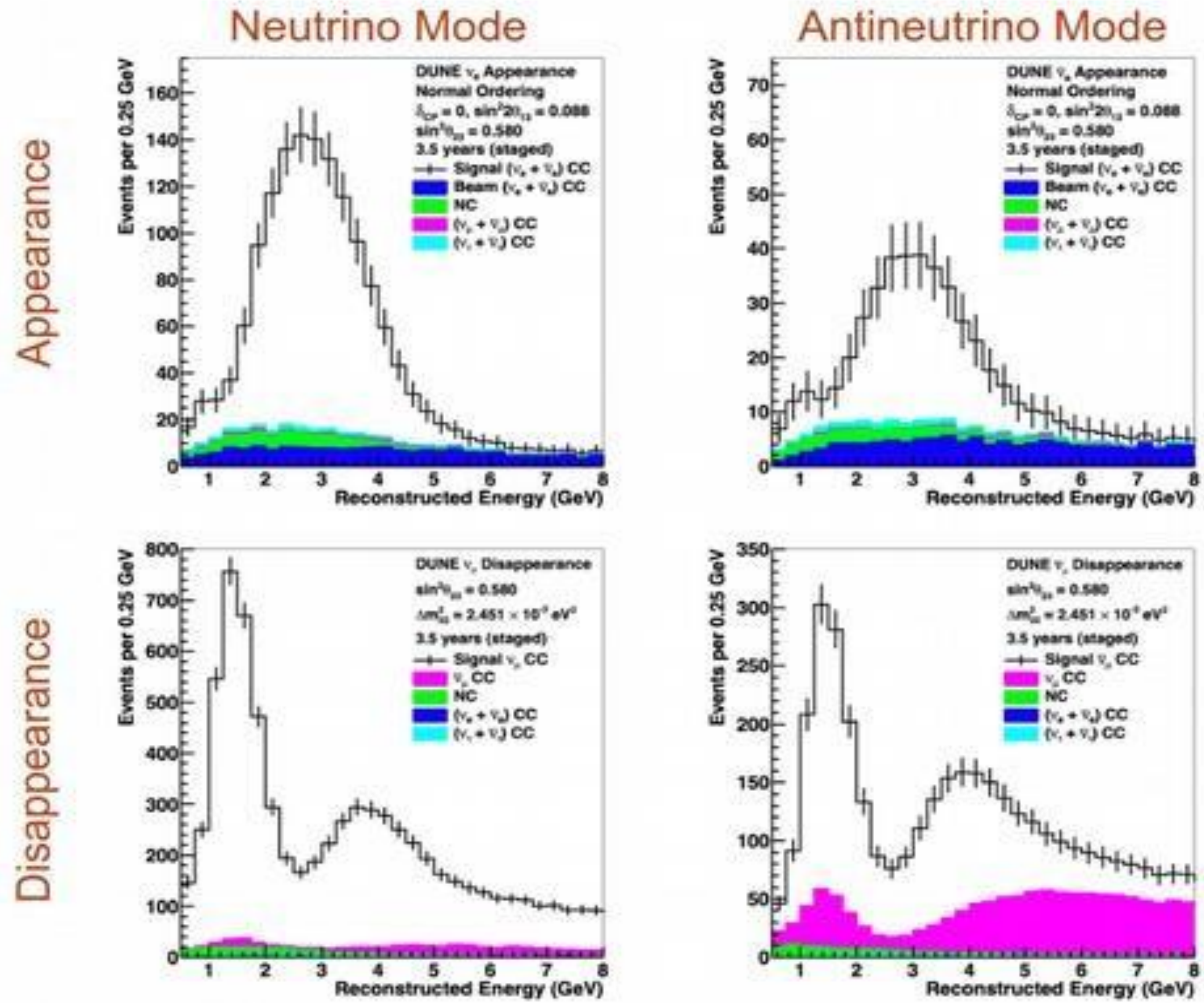


4 LArTPC detector modules





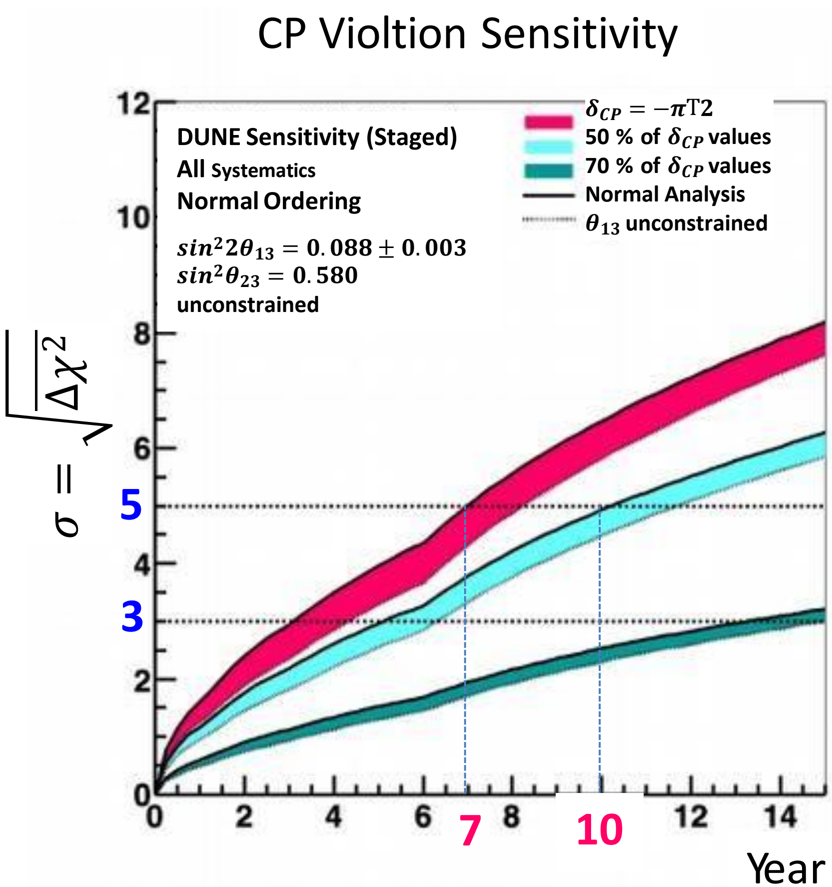
ν Oscillation Prospect

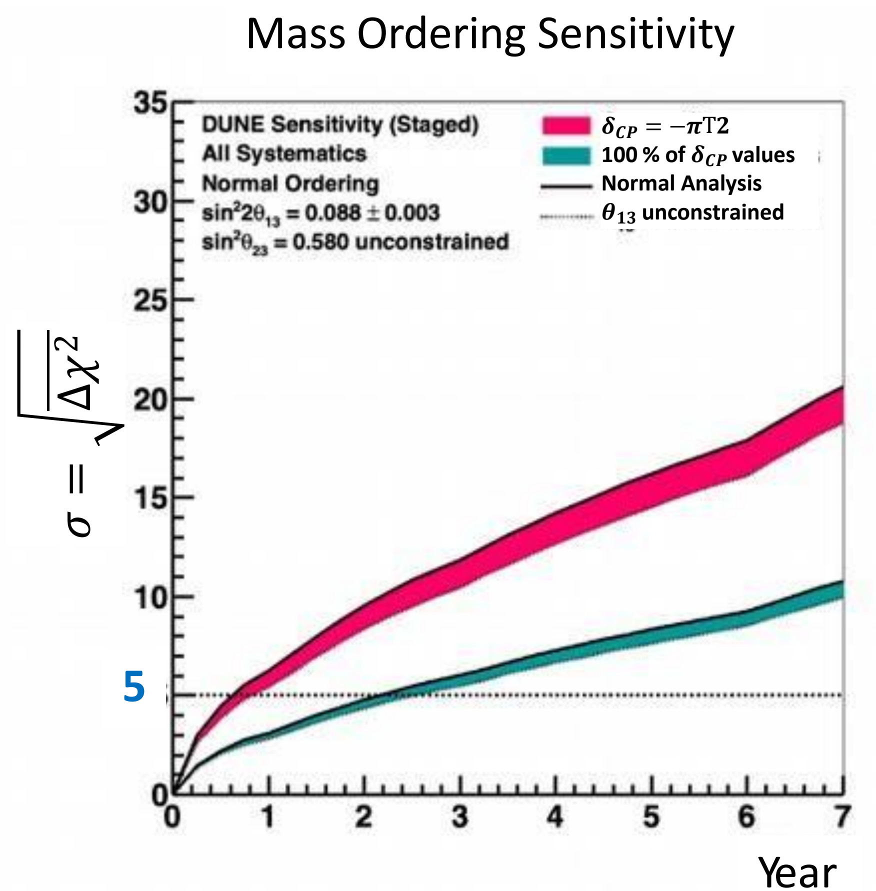


Order 1000 appearance events in 7 years

Order 10,000 disappearance events in 7 years

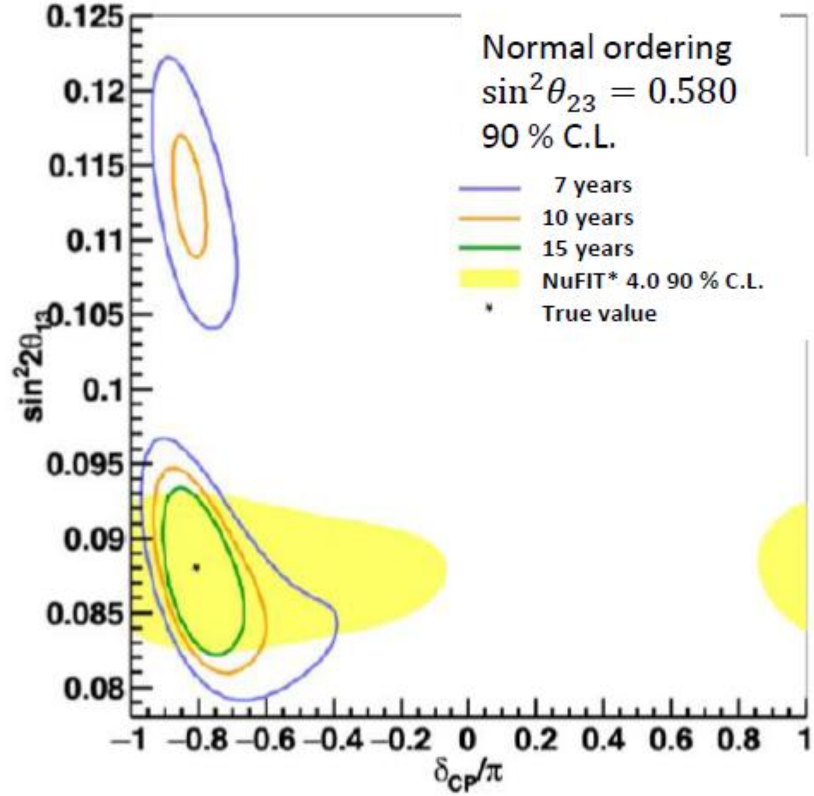
Sensitivity Over Time

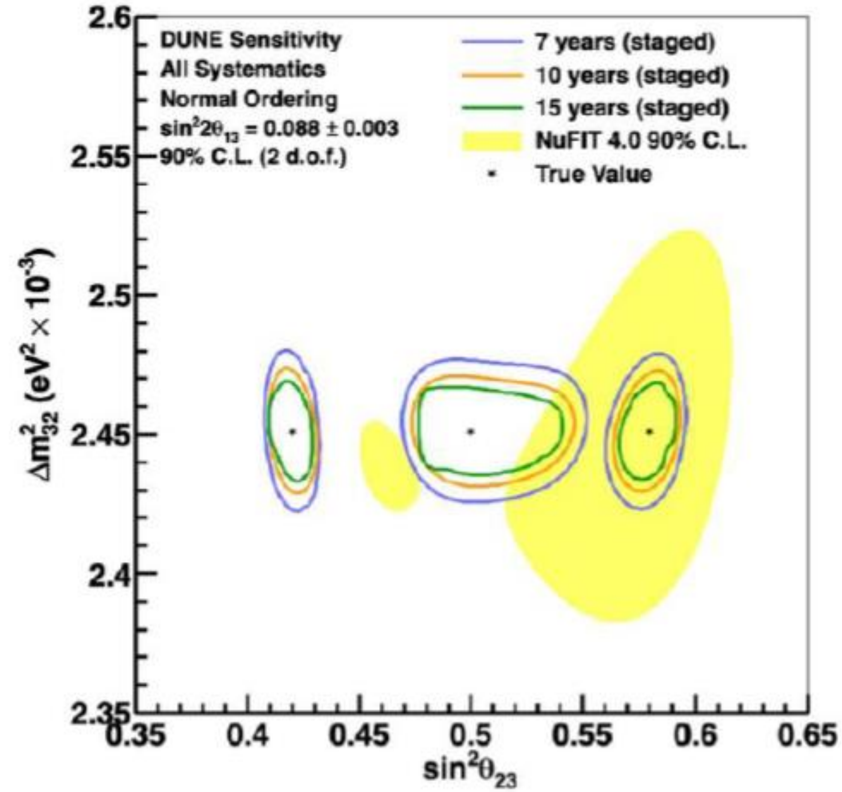




- **CPV discovery if true $\delta_{CP} = -\pi/2$ in $\sim$7 years**
- **CPV discovery for 50 % of true δ_{CP} values in $\sim$10 years**
- **In 2 years, mass ordering will be determined w/ 5σ regardless δ_{CP}**

Other mixing parameter measurements





- **θ_{13} measurement will be comparable with reactor experiments after ∼15 years.**
- **Significant improvement in precision measurement of atmospheric parameters.**

* NuFIT provides:

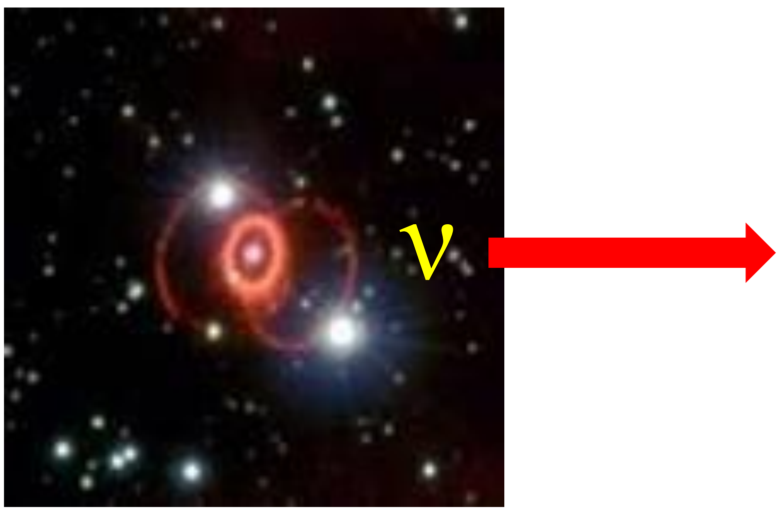
•An updated global analysis of neutrino oscillation measurements determining the leptonic mixing matrix and the neutrino masses in the framework of the Standard Model with 3 massive neutrinos and some of its extensions.

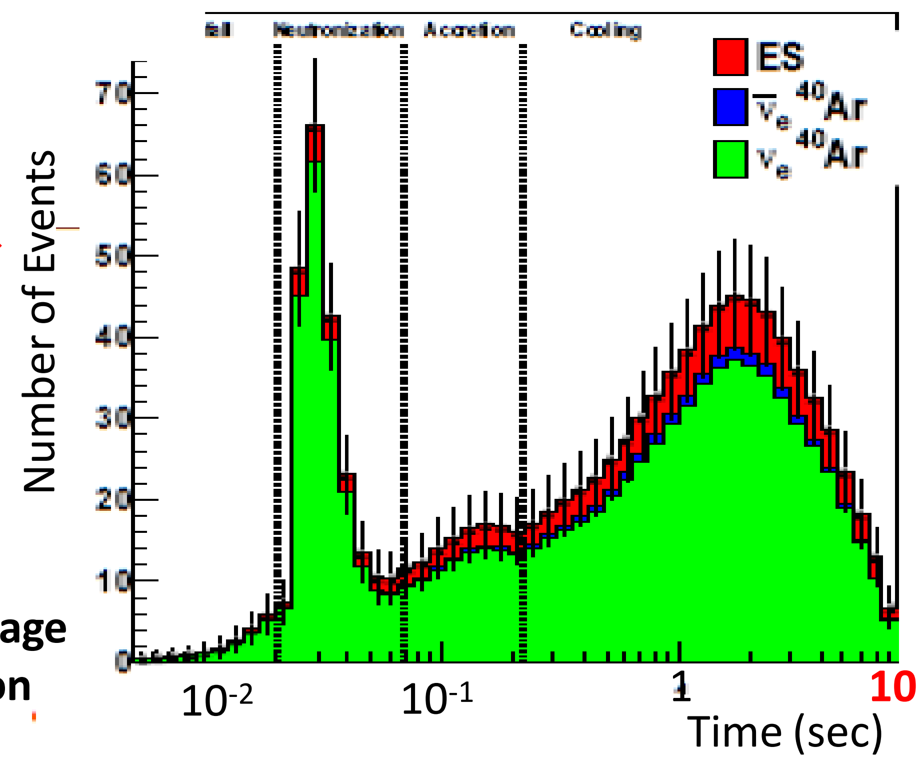
•Graphical and numerical bounds on the parameters.

Supernova ν's

- **A core collapse SN produces an intense burst of neutrinos**
- ∼10000 neutrinos from a SN in our galaxy over a period of 10 seconds.
- In argon (uniquely), the largest sensitivity is

$$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$$





Highlights include:

Possibility to "see" neutron star formation stage

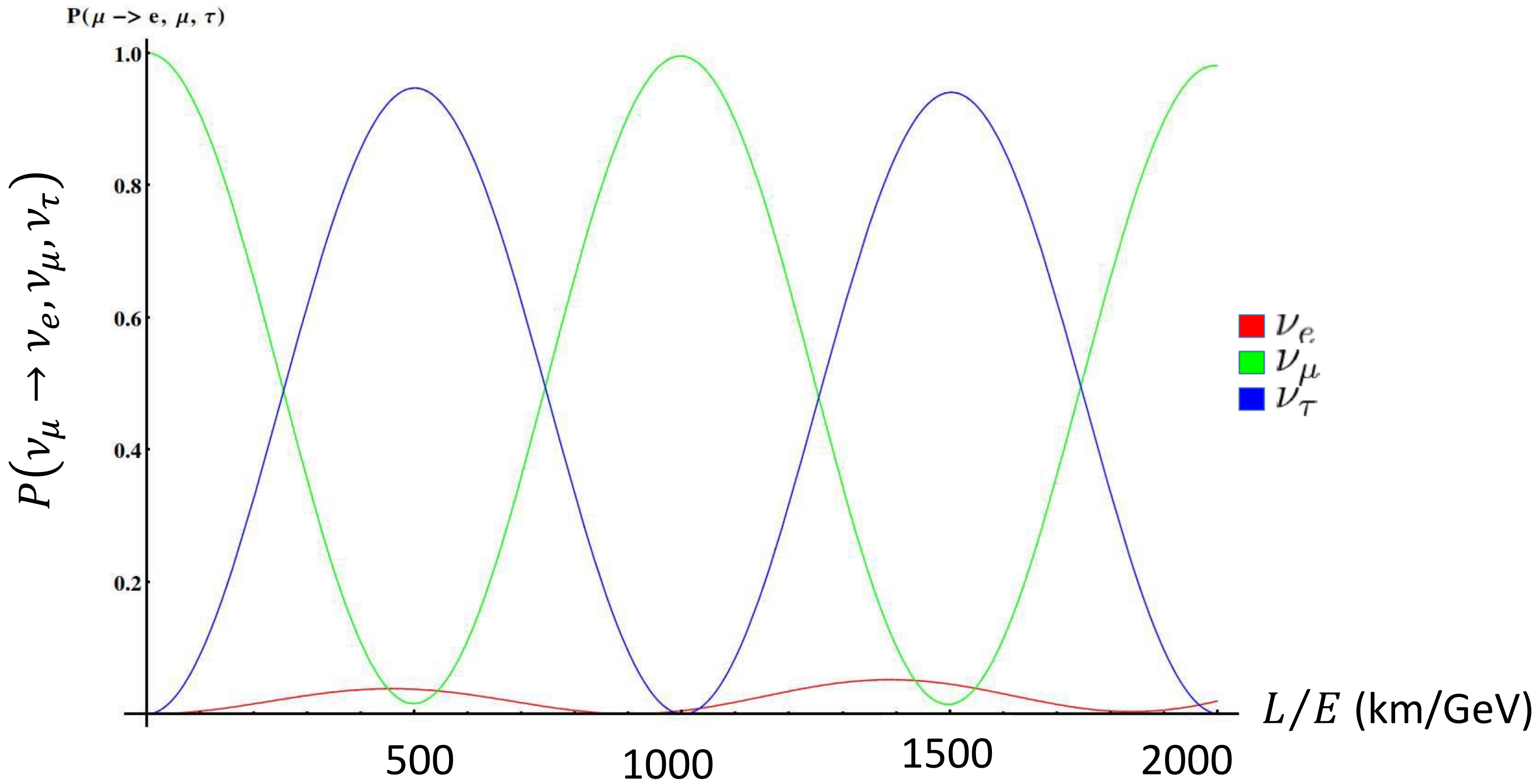
Even the potential to see black hole formation

DUNE: Schedule & Plans

- **Far site construction is underway.**
- **Near site preparation is also in progress.**
- **Physics should begin this decade.**

1-3. ESSnuSB
(European Spallation Source neutrino super-beam)

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



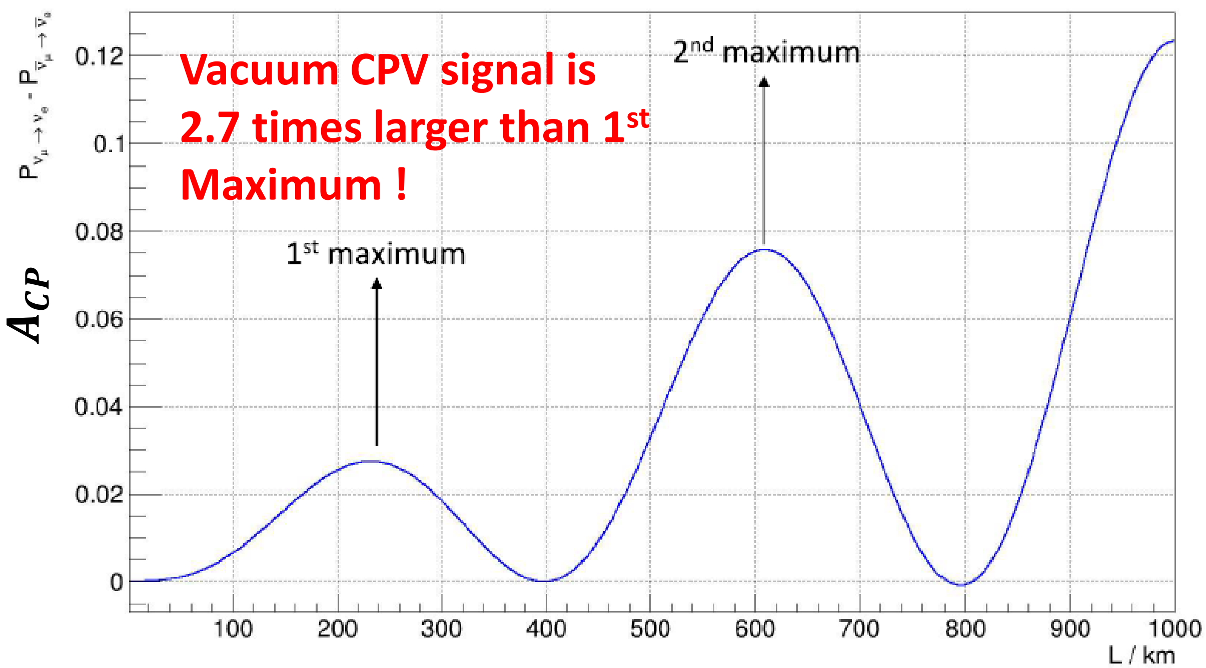
Why 2nd maximum ? (1)

CP violation in ESSnuSB

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

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

E = 400 MeV



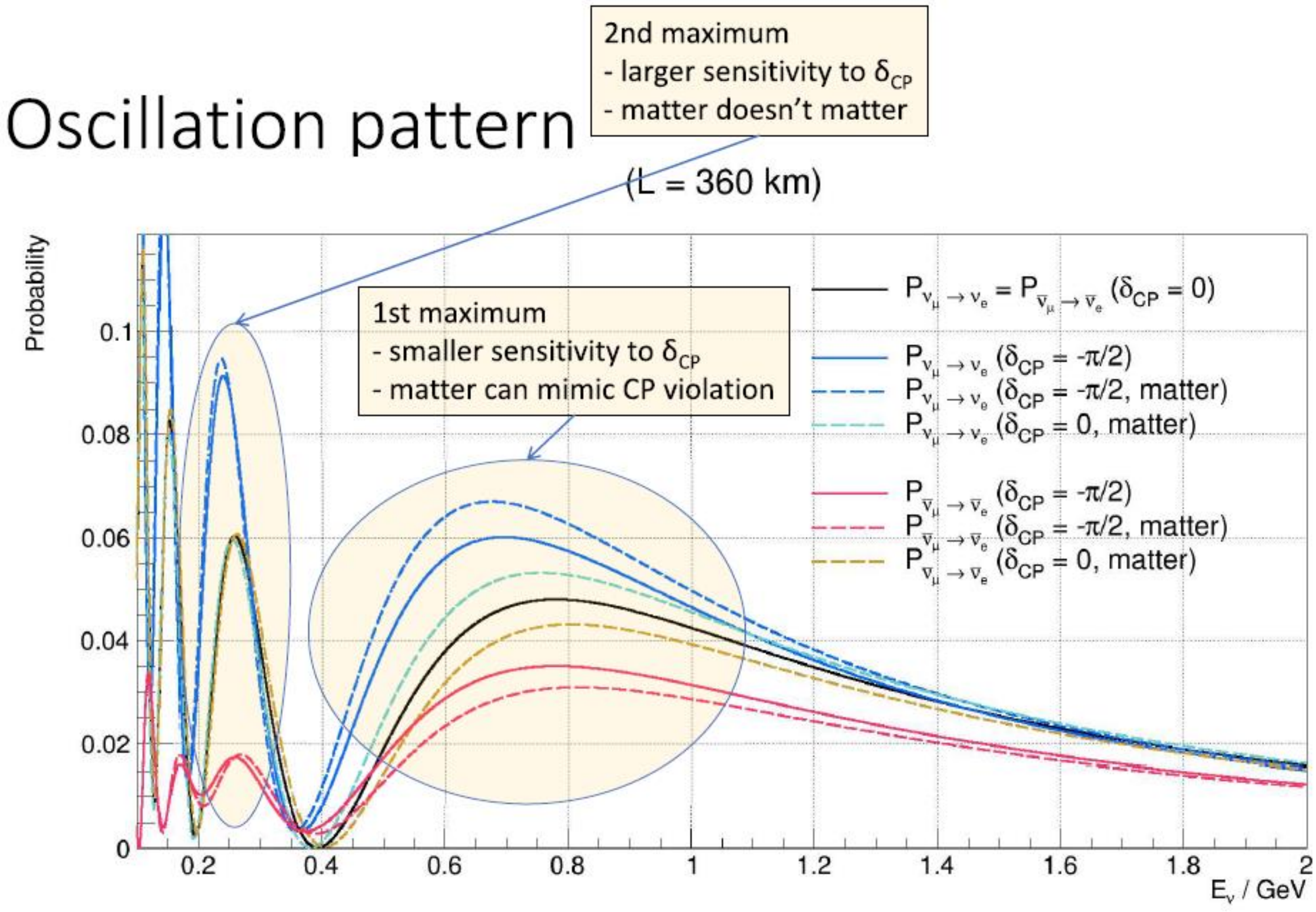
$$\frac{A_{CP}\ @\ \text{2nd max}}{A_{CP}\ @\ \text{1st max}} \sim 2.7$$

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

Vacuum

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}	$(7.42 \pm 0.21) \times 10^{-5}\ \text{eV}^2$
Δm^2_{31}	$(2.510 \pm 0.027) \times 10^{-3}\ \text{eV}^2$

Why 2^{nd} maximum ? (2)

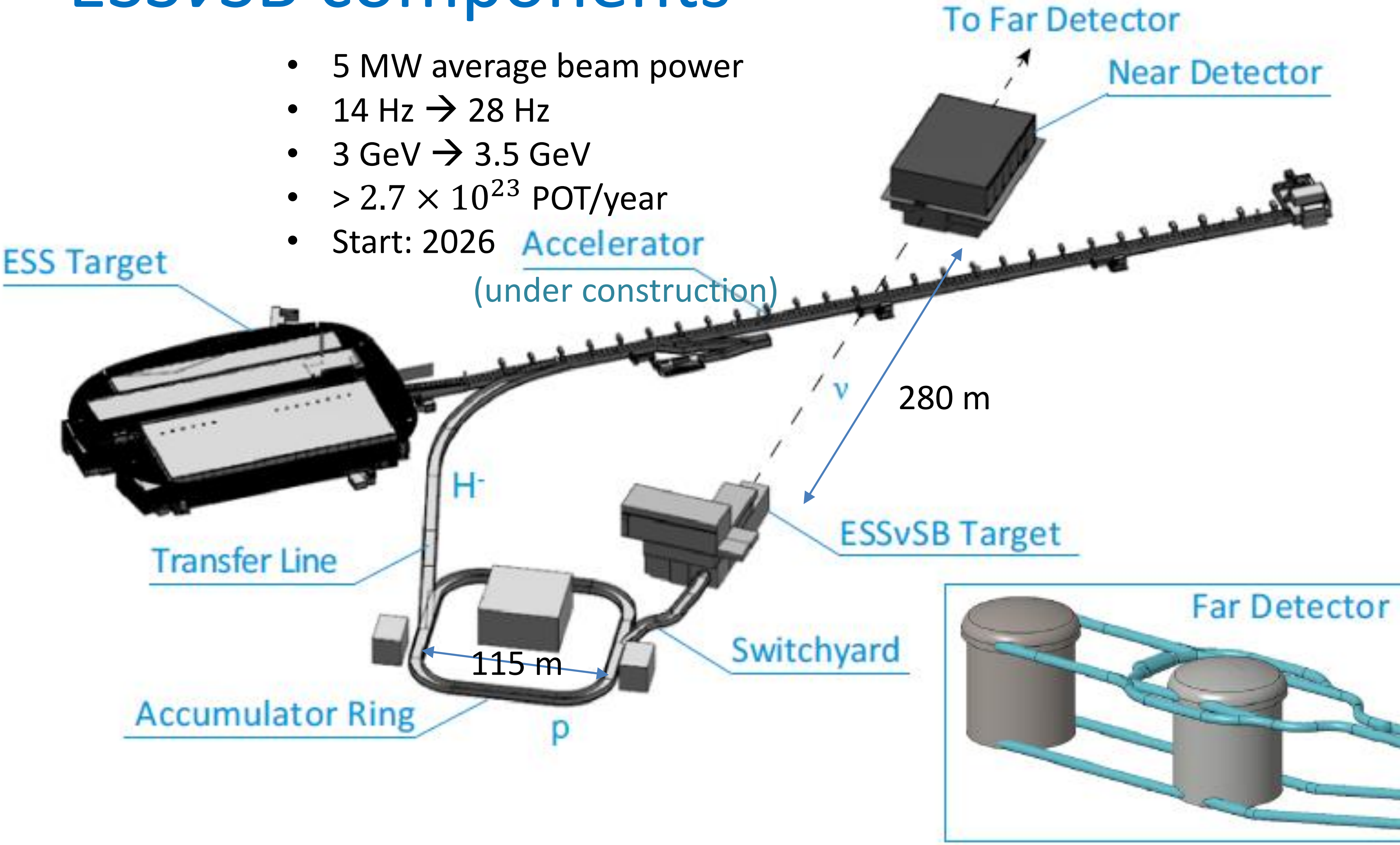


ESSnuSB neutrino baseline

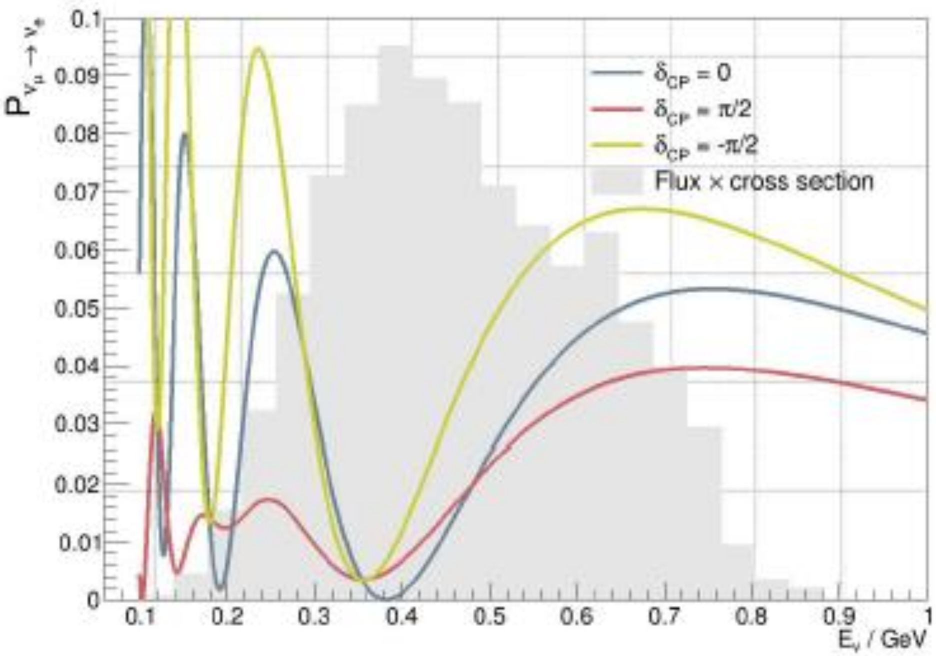
Zinkgruvan mine, 360 km from the source, partly covernig 1[st] and 2[nd] maximum

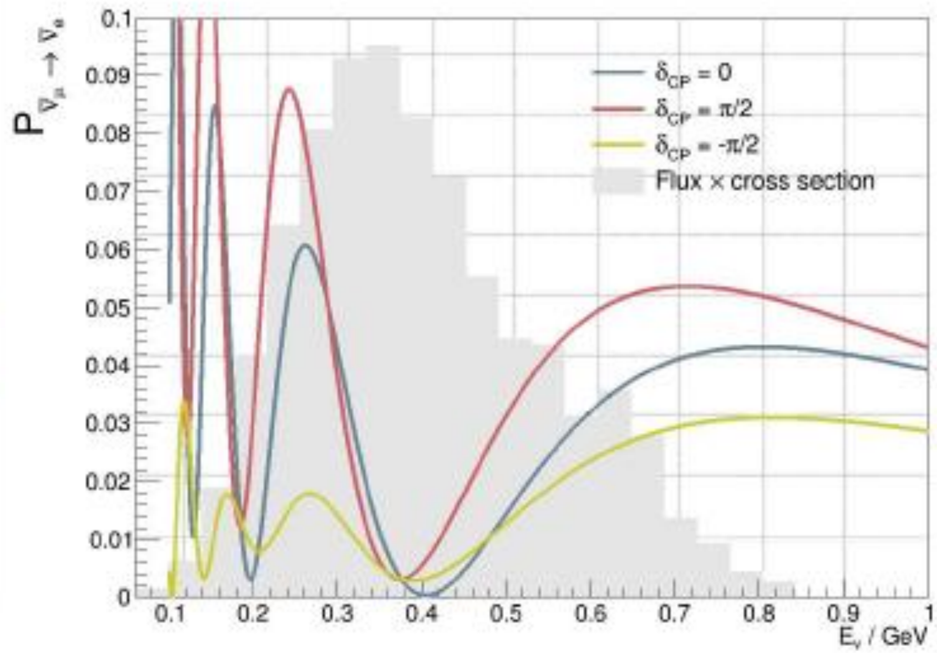
Layout of the ESSνSB components

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

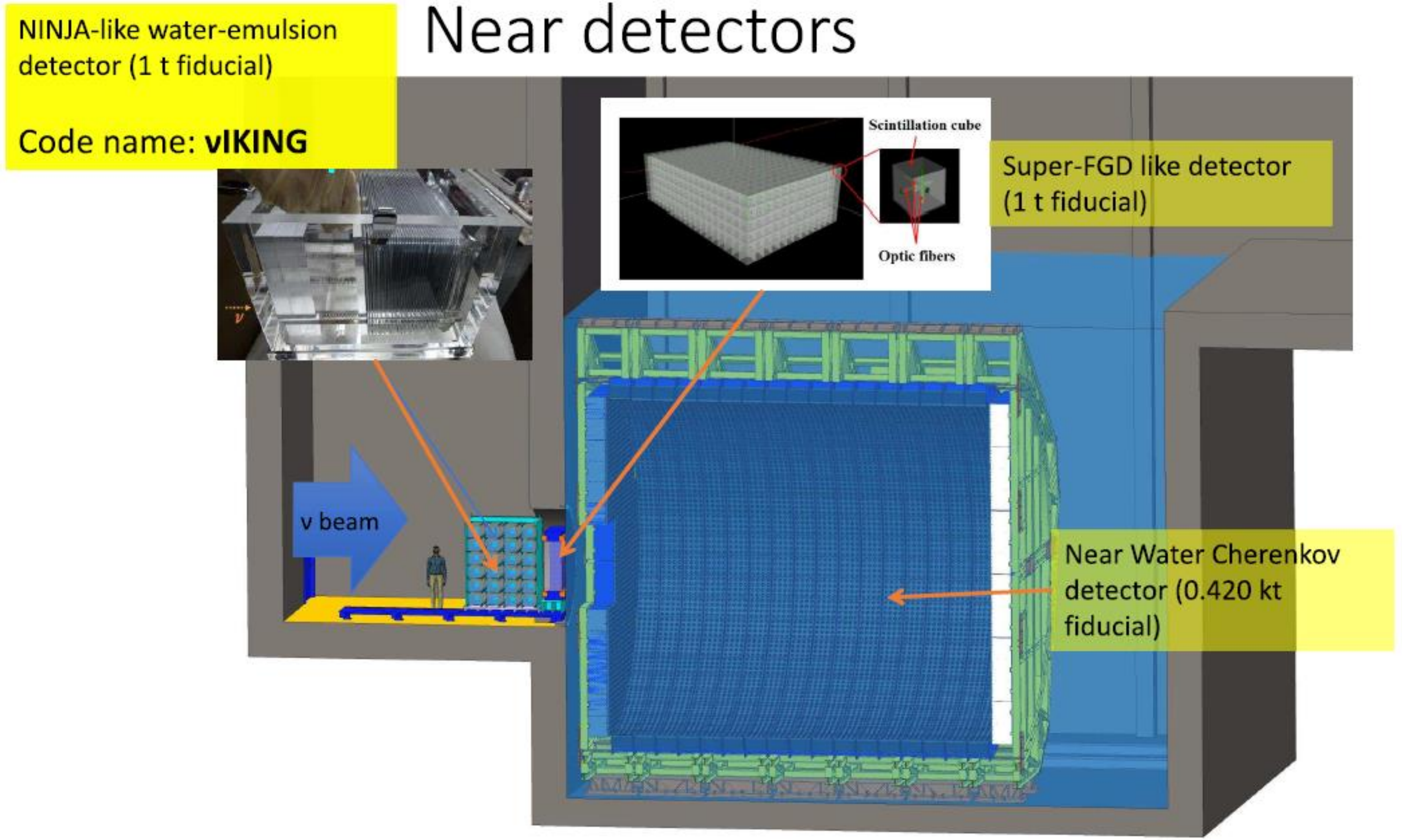


Oscillation coverage

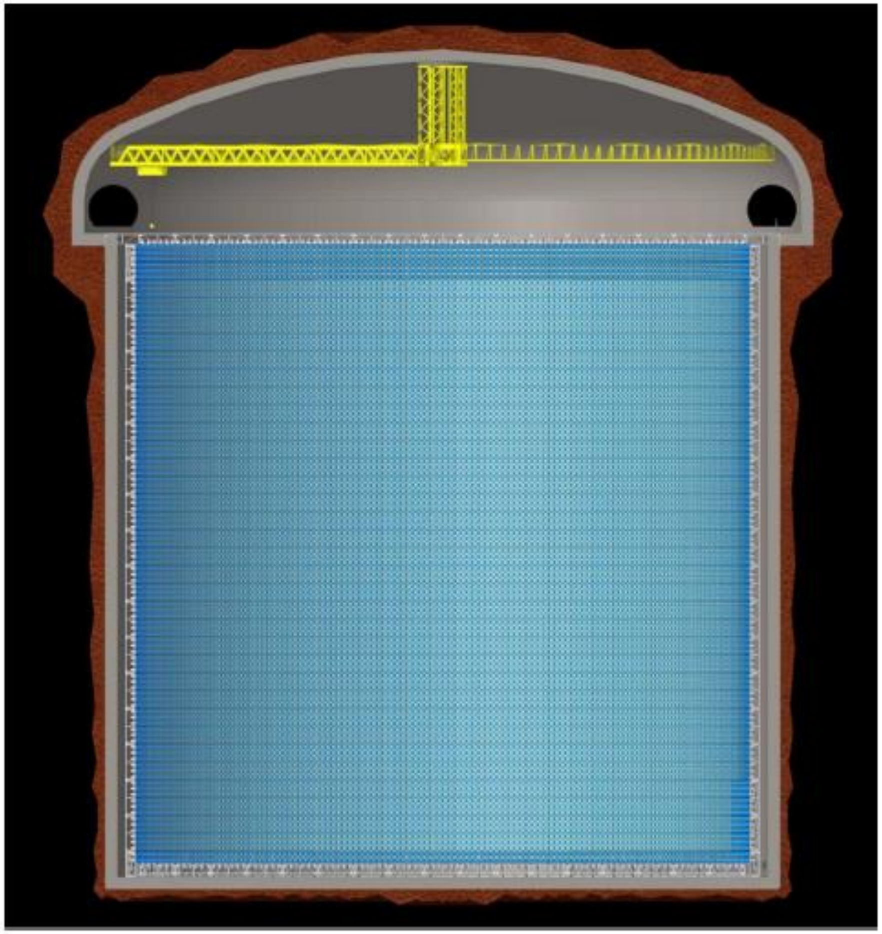




Near detectors



Far detectors



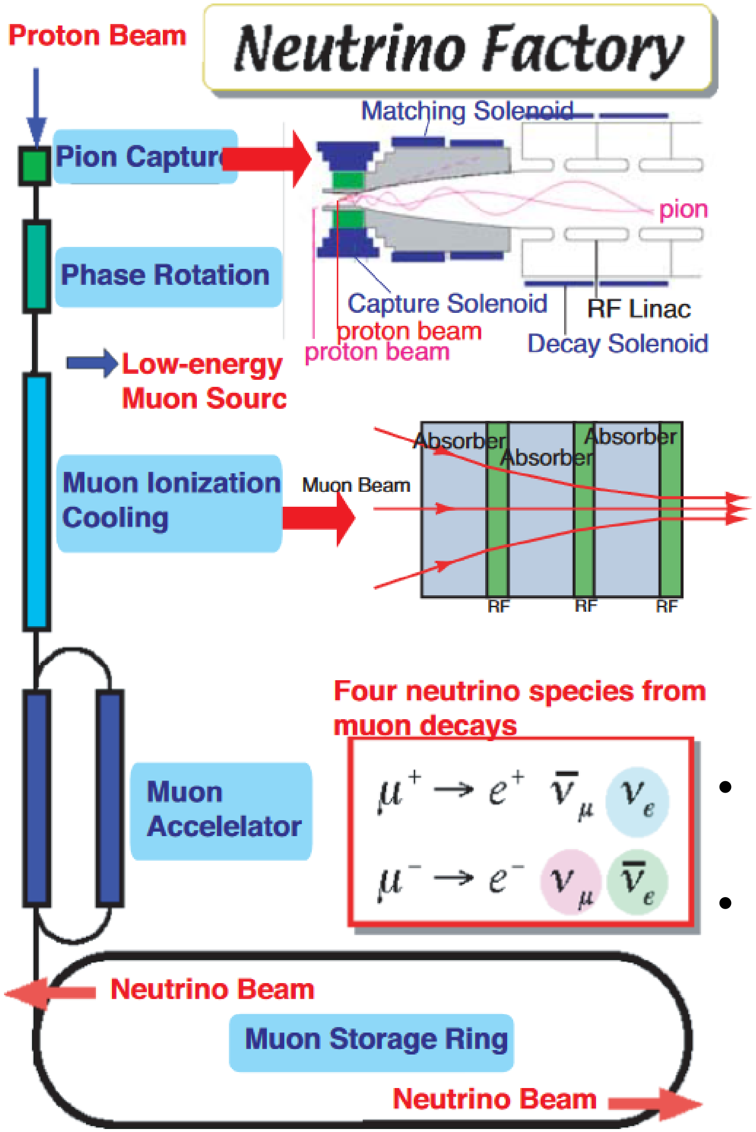
Design
- 2 x 270 kt fiducial volume (~2x HyperK)
- Readout: 2 x 38k 20” PMTs
- 30% optical coverage
  - design here for 40% with an option that ¼ PMTs will not be installed

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



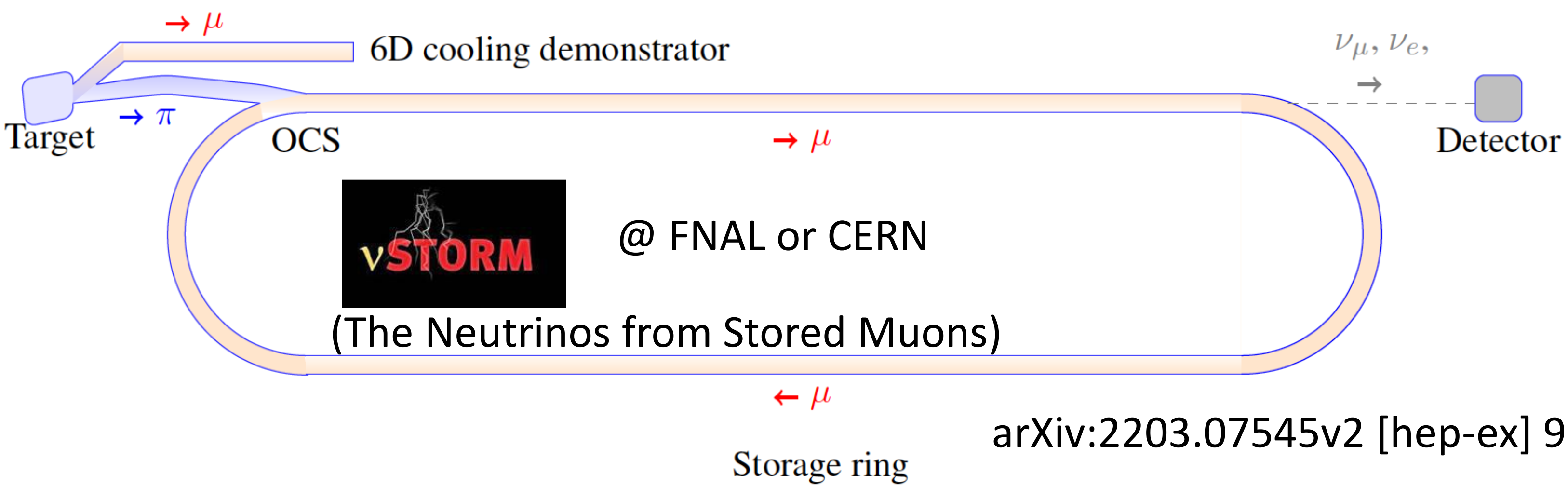
Pion capture by high magnetic field solenoid.

Suppression of transverse momentum of pions

- Deceleration by absorbers
- Acceleration by RF

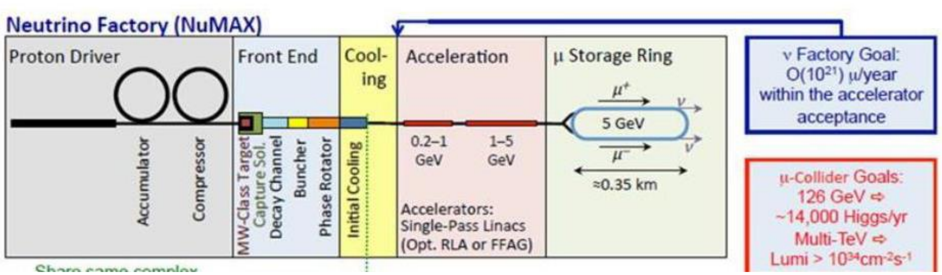
- Immediate acceleration by a muon accelerator with high repetition (~50 Hz)
- High intensity & energy ν_μ $(\bar{\nu}_\mu)$ & $\bar{\nu}_e$ (ν_e) beams simultaneously from the straight part of the muon storage ring

Some future plans



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

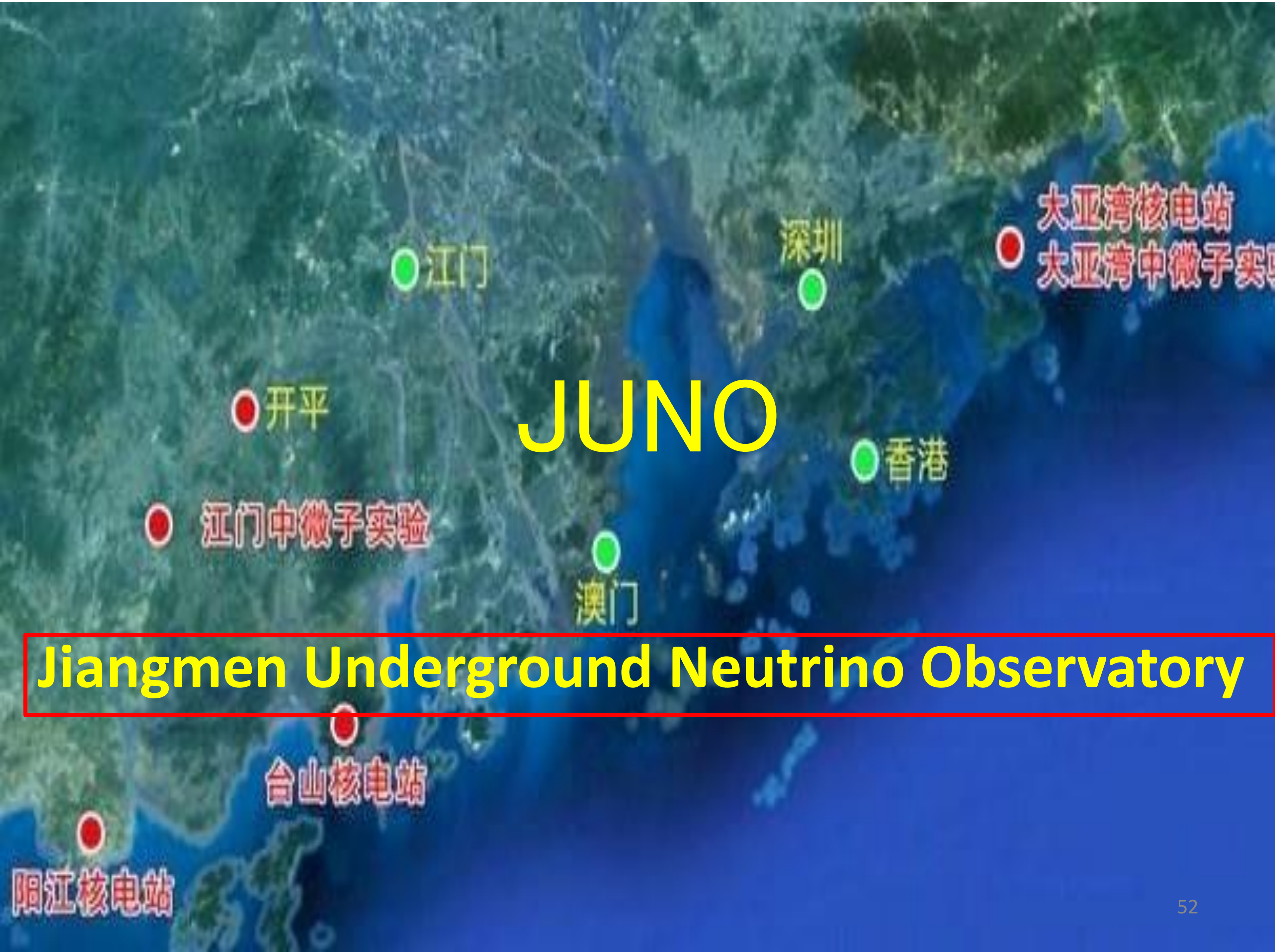
NuMAX (**Ne**utrino from **M**uon **A**ccelerator comple**x) @**FNAL site



BNL-205756-2018-JAAM

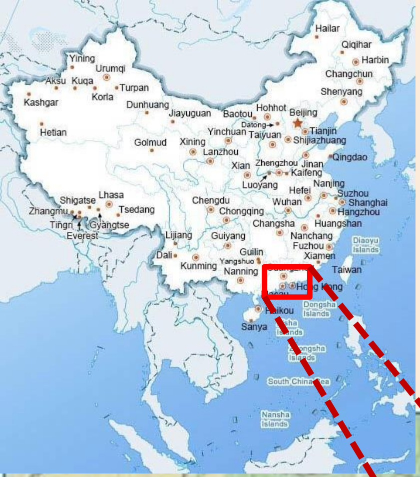
2. Reactor Neutrino Experiment (JUNO)

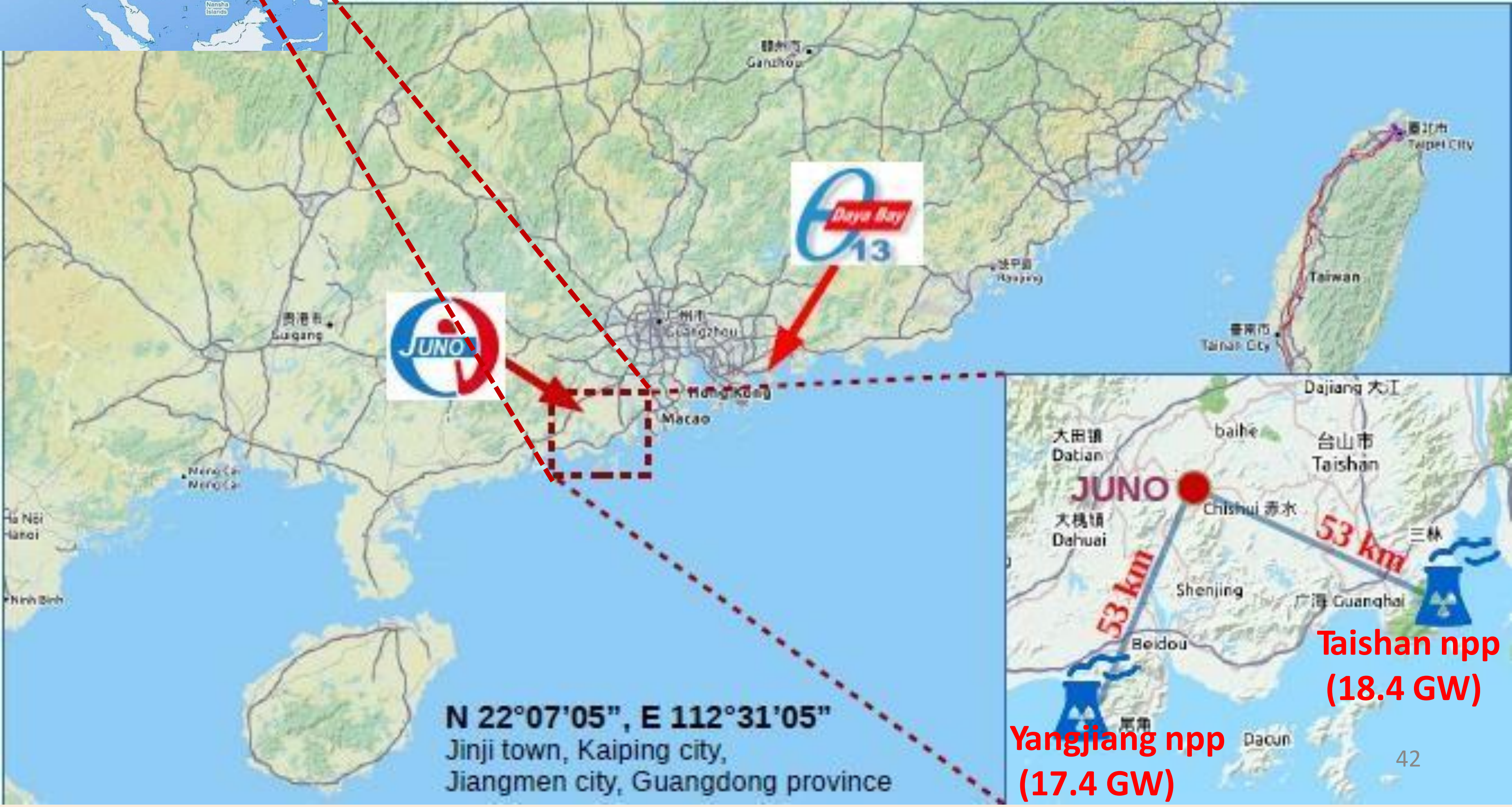
*See Huang-san's lecture



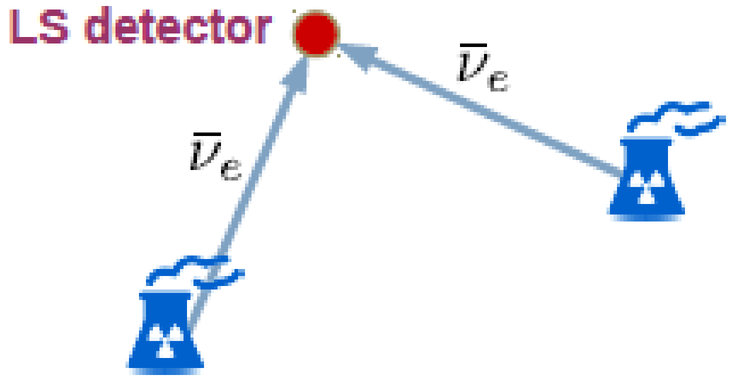
JUNO
Jiangmen Underground Neutrino Observatory
江门
深圳
大亚湾核电站
大亚湾中微子实
开平
香港
江门中微子实验
澳门
台山核电站
阳江核电站

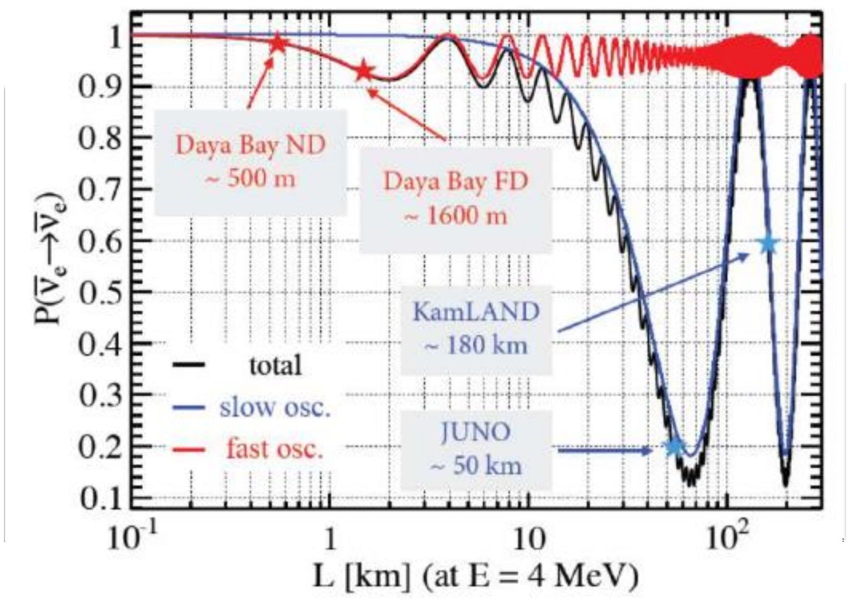
Location




Ganzhou
Taipei City
Taiwan
Tainan City
Guangzhou
Hong Kong
Macao
Daya Bay
JUNO
Dajiang 大江
baihe
台山市
Taishan
Datian
JUNO
Chishui 赤水
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



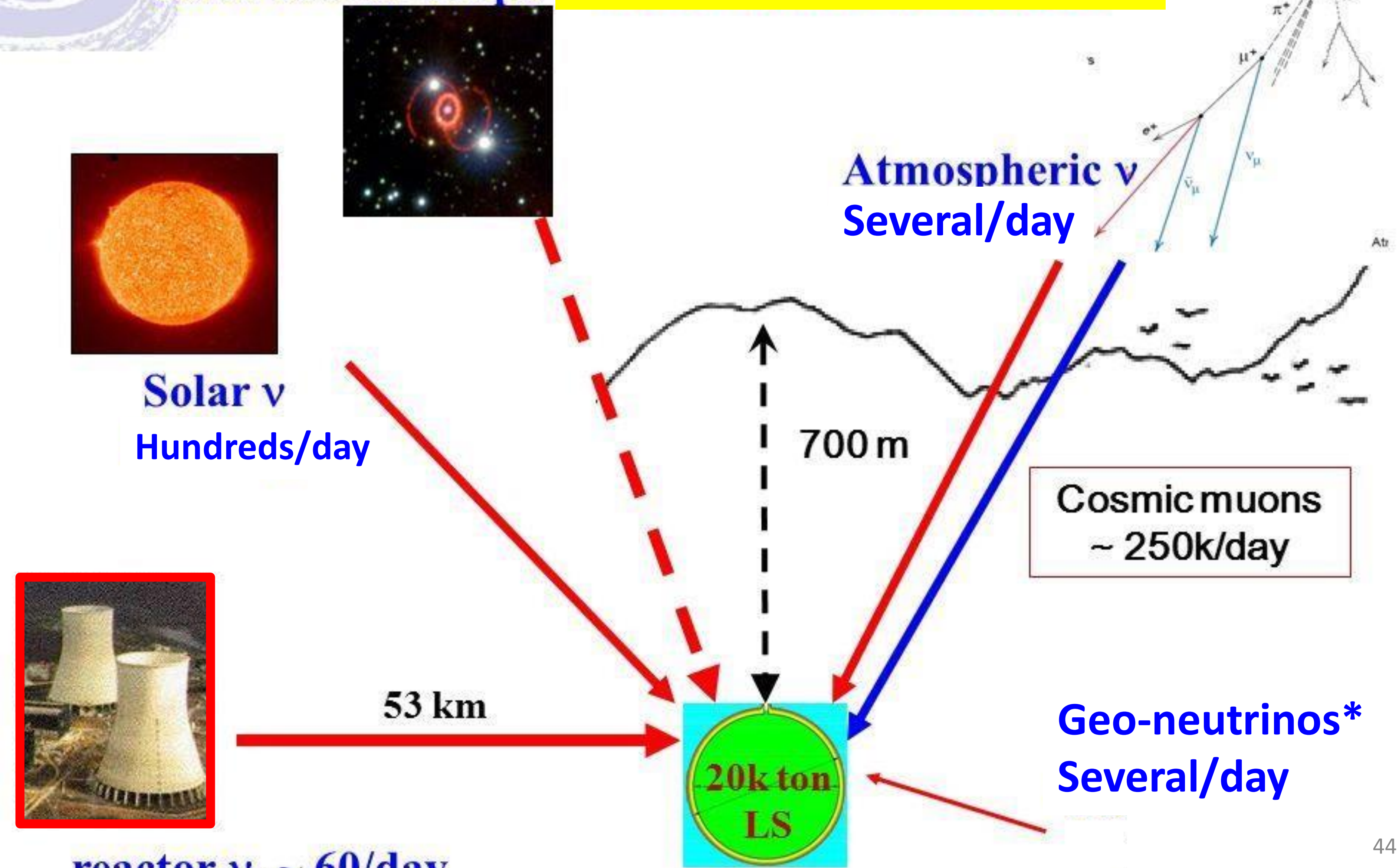


- **Source: 6+2 reactors**
  (Yangjiang and Taishan NPP)
- **Baseline: 53 km**
- **Detection channel: inverse β-decay**

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

- **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

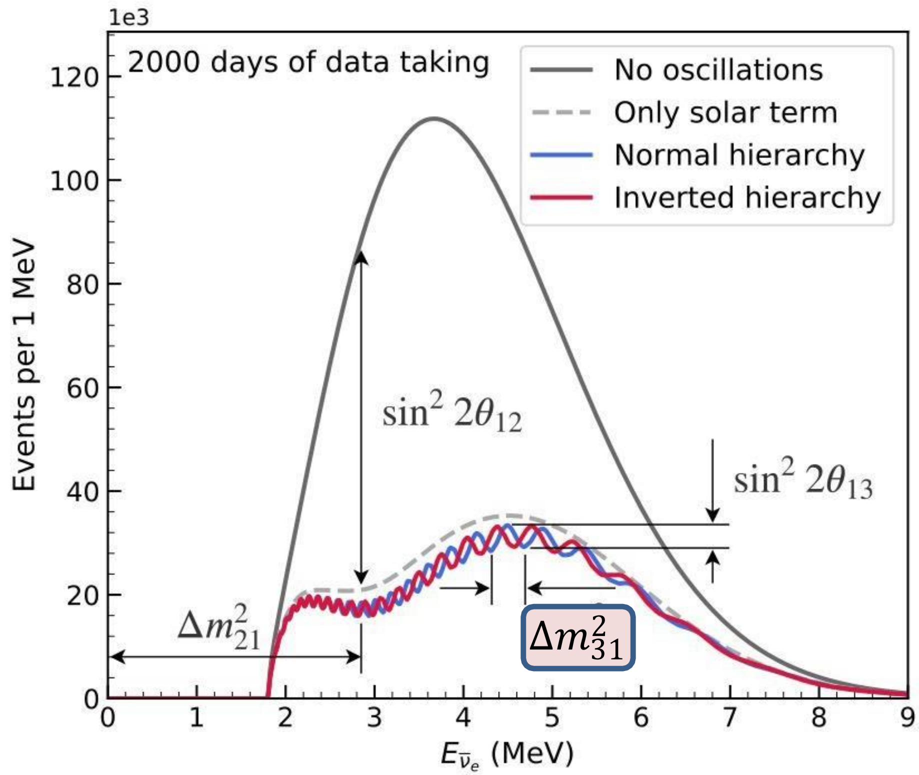


*a neutrino or antineutrino emitted in decay of radionuclide naturally occurring in the Earth

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

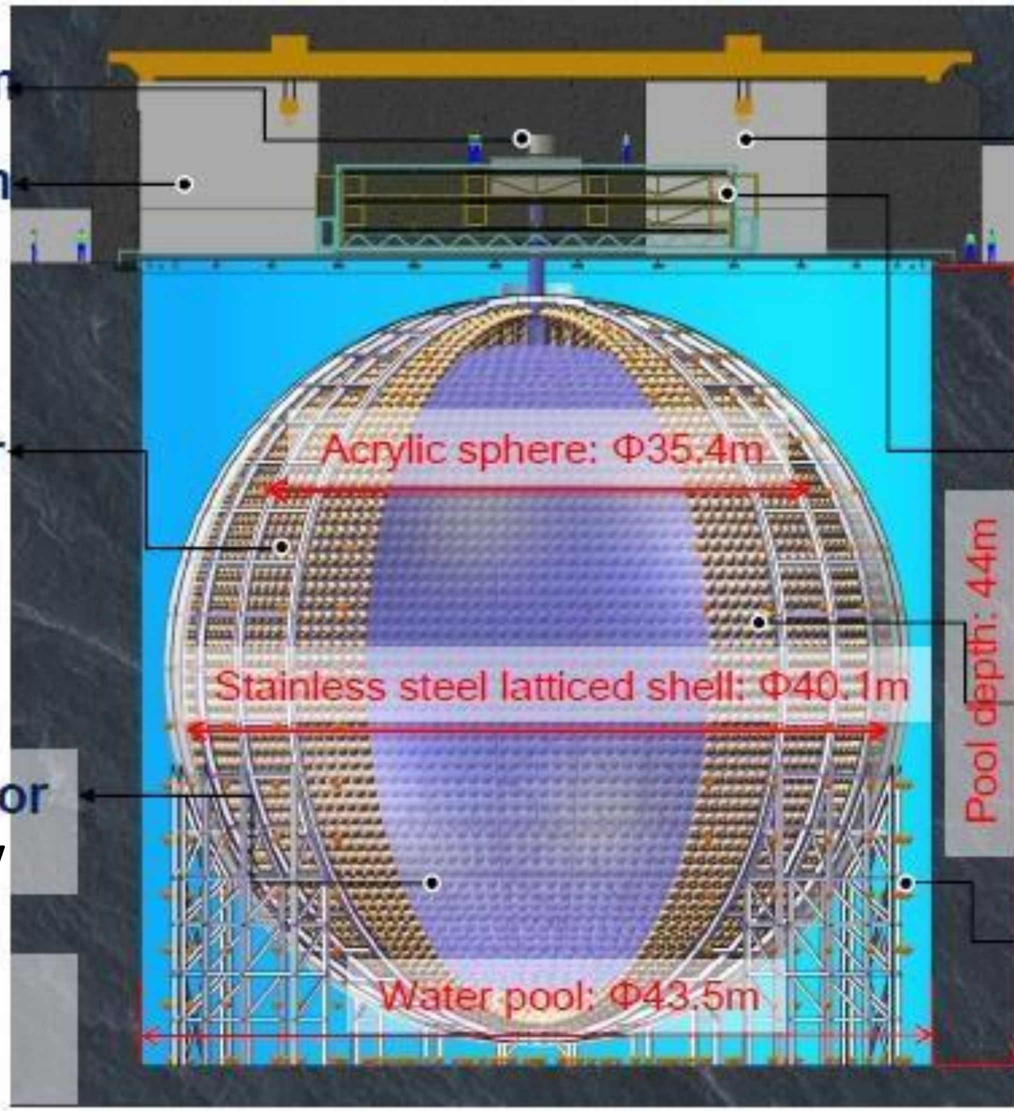
- Sub-% accuracy for $\theta_{12}, \Delta m^2_{21}, \& \Delta m^2_{31}$

* 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

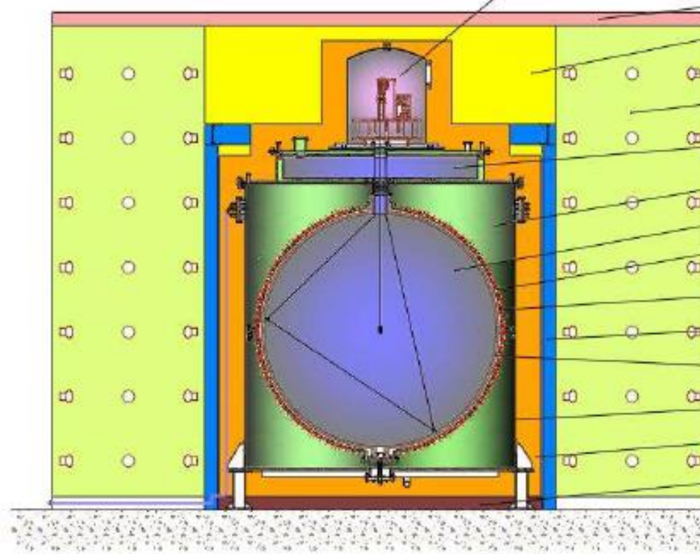
Taishan Antineutrino Observatory (TAO)

Physics potential

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

arXiv: 2005.08745

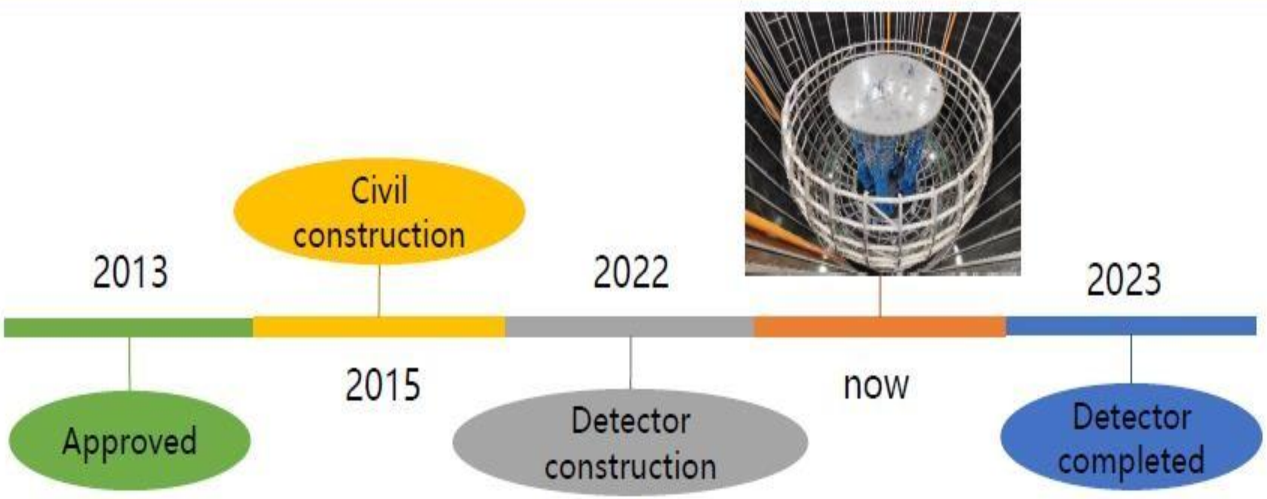
2.8 ton GdLS detector	
Baseline	~30 m
Reactor Thermal Power	4.6 GW
Light Collection	SiPM
Photon Detection Efficiency	>50%
Working Temperature	-50 °C
Dark Count Rate [Hz/mm^2]	~100
Coverage	~94%
Detected Light Level [PE/MeV]	4500
Energy resolution	< 2% @ 1 MeV



- ✓ 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

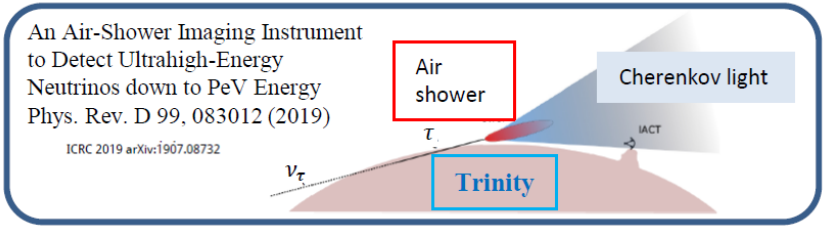
Physics	Sensitivity
Neutrino Mass Ordering	3σ (~1σ) in 6 yrs by reactor (atmospheric) $\bar{\nu}_e$
Neutrino Oscillation Parameters	Precision of $\sin^2\theta_{12}$, Δm^2_{21}, $\lvert\Delta m^2_{32}\rvert$ < 0.5% in 6 yrs
Supernova Burst (10 kpc)	~5000 IBD, ~300 eES and ~2000 pES of all-flavor neutrinos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

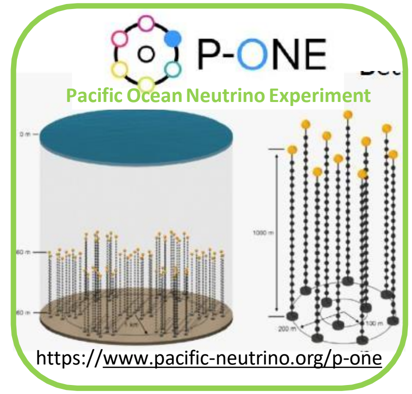


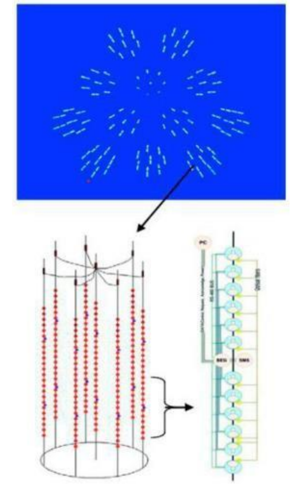
3. Atmospheric & Astrophysical Neutrino Measurements

Future Plans

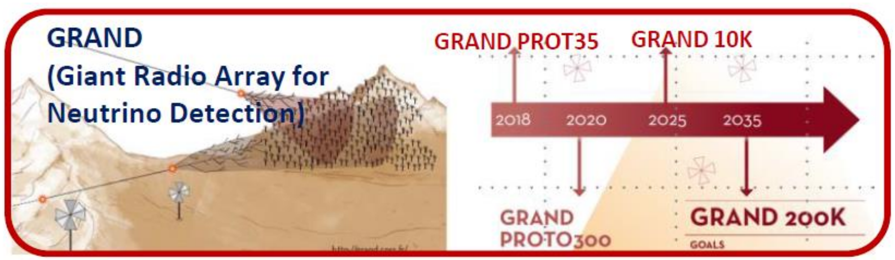
- **Optical Detection of Cherenkov Radiation**
  - **IceCube -Upgrade & Gen 2- @ South Pole**
  - **P-ONE @ Pacific Ocean**
  - **Trinity** (candidate site:not decided yet)
  - **Baikal GVD @ Lake Baikal**





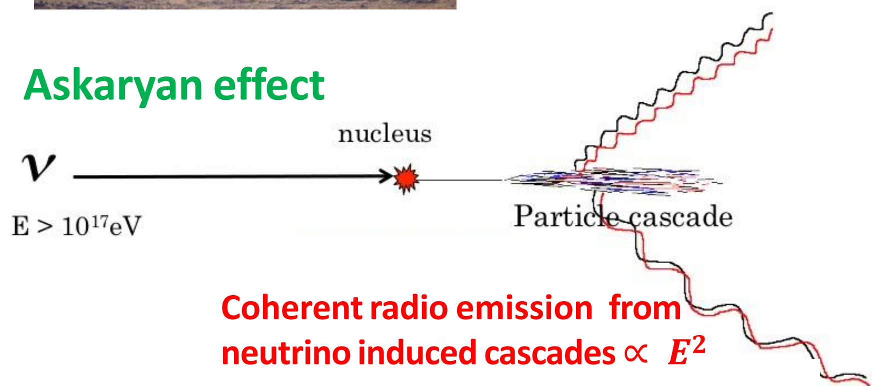


- **Radio Technique (Askaryan effect)**



  - **RNO-G (Greenland)**

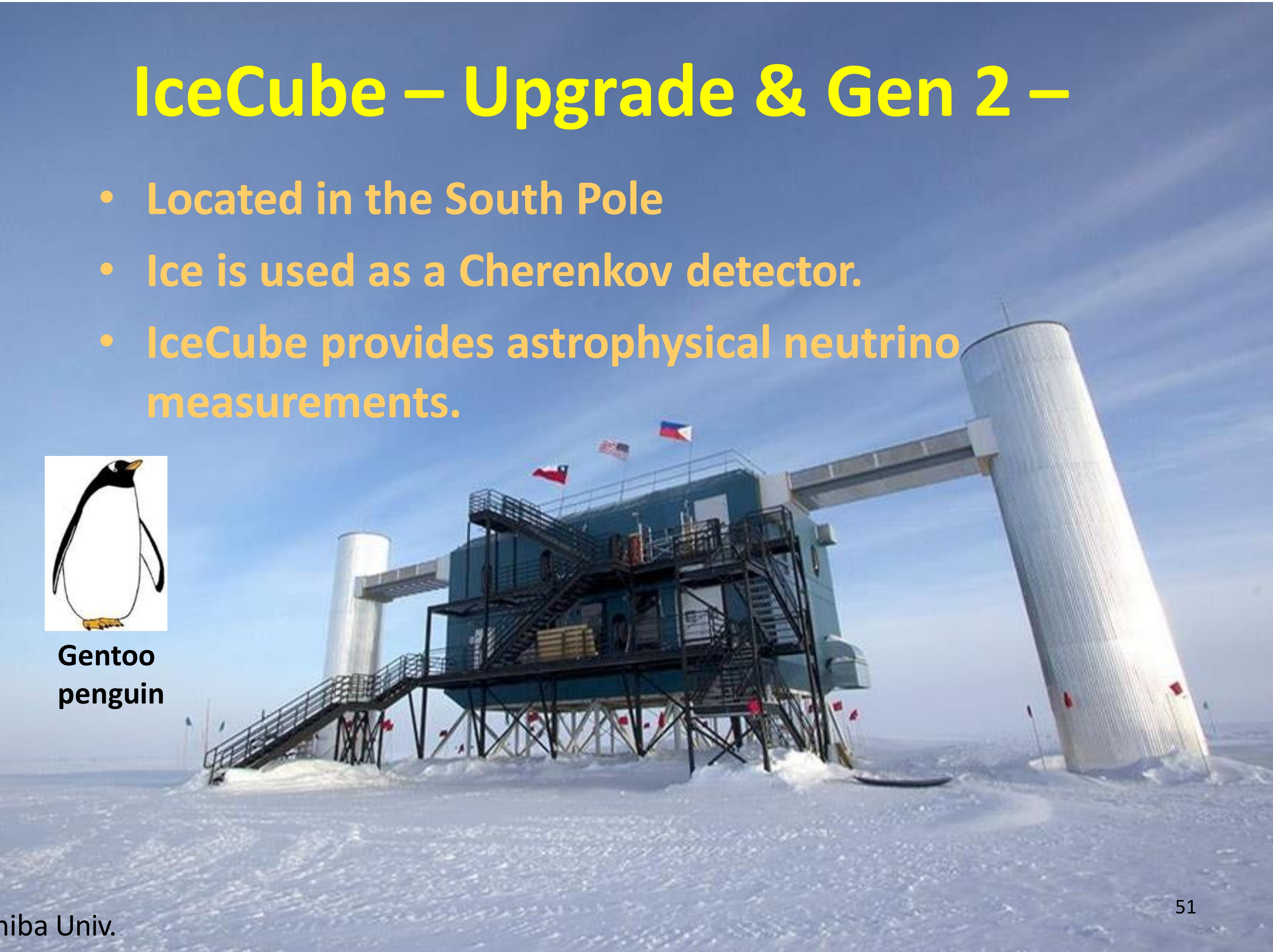
Askaryan effect



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

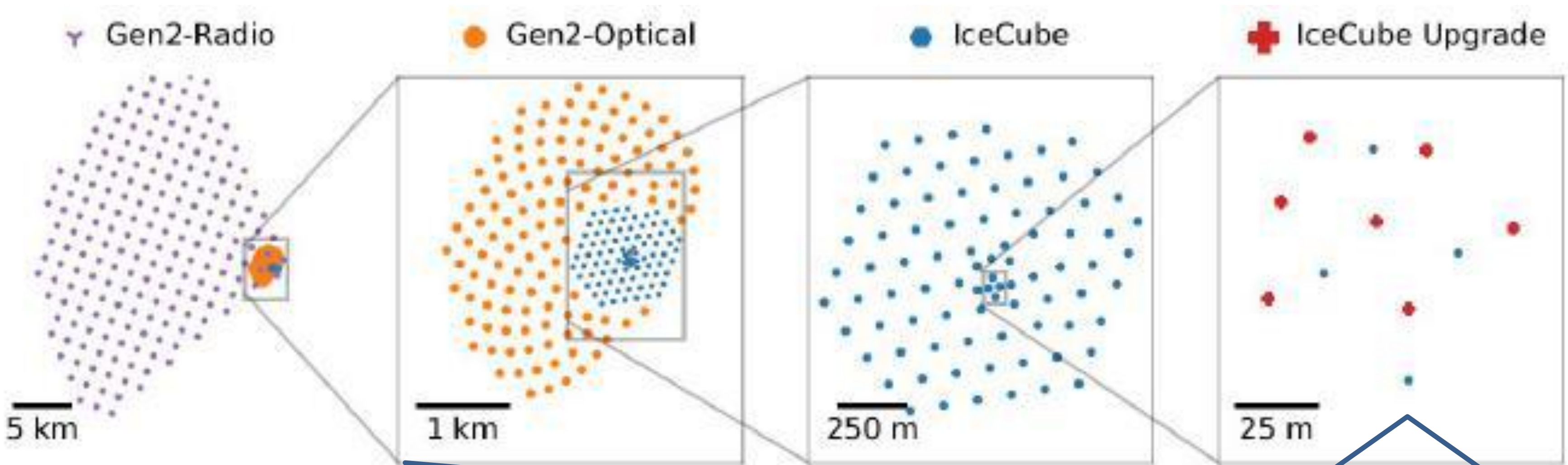
IceCube – Upgrade & Gen 2 –

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

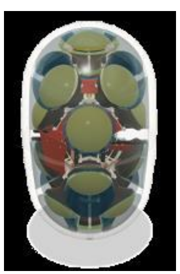


Gentoo penguin

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

Testbed for new sensor types →

D-Egg

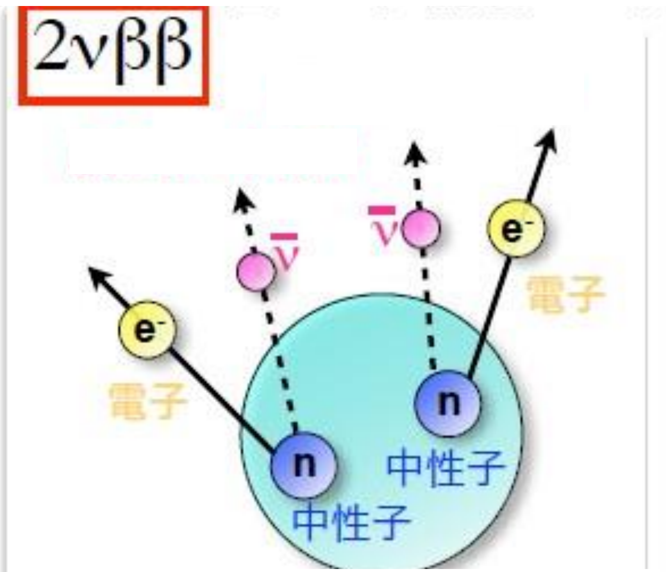
mDOM

・Improved detector calibration/ ice model characterization

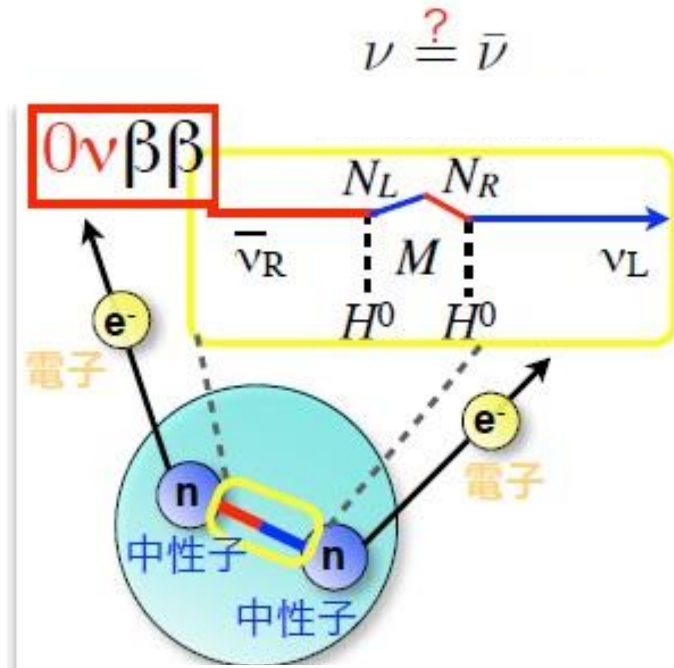
4. 0νββ Decay Experiments

*See Huang-san's lecture in detail

Double beta decay



2 neutrons decay in a nuclei.



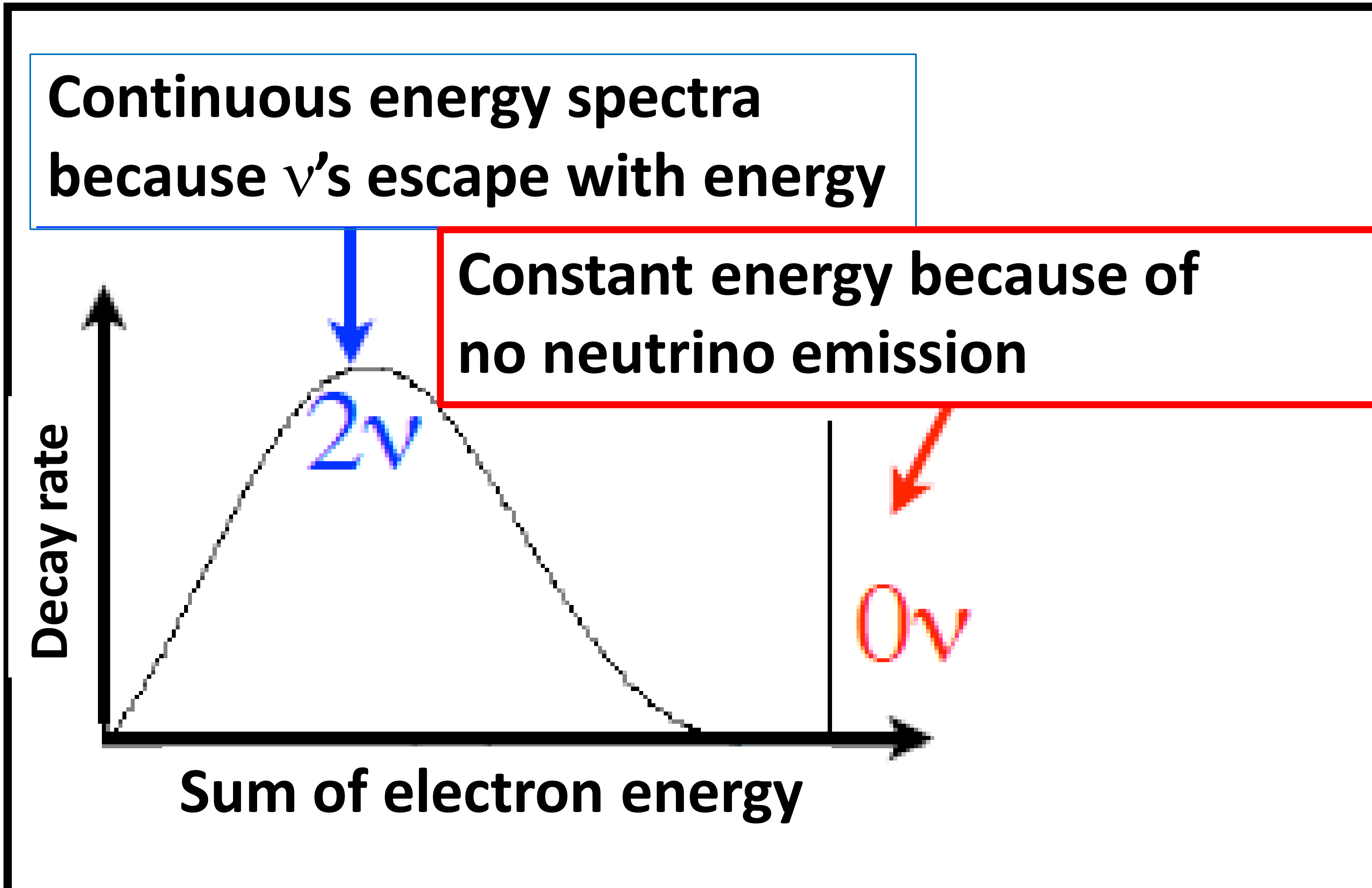
No ν is emitted.

Possible in SM
Lifetimes are measured for ~10 nucleus

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

How to detect

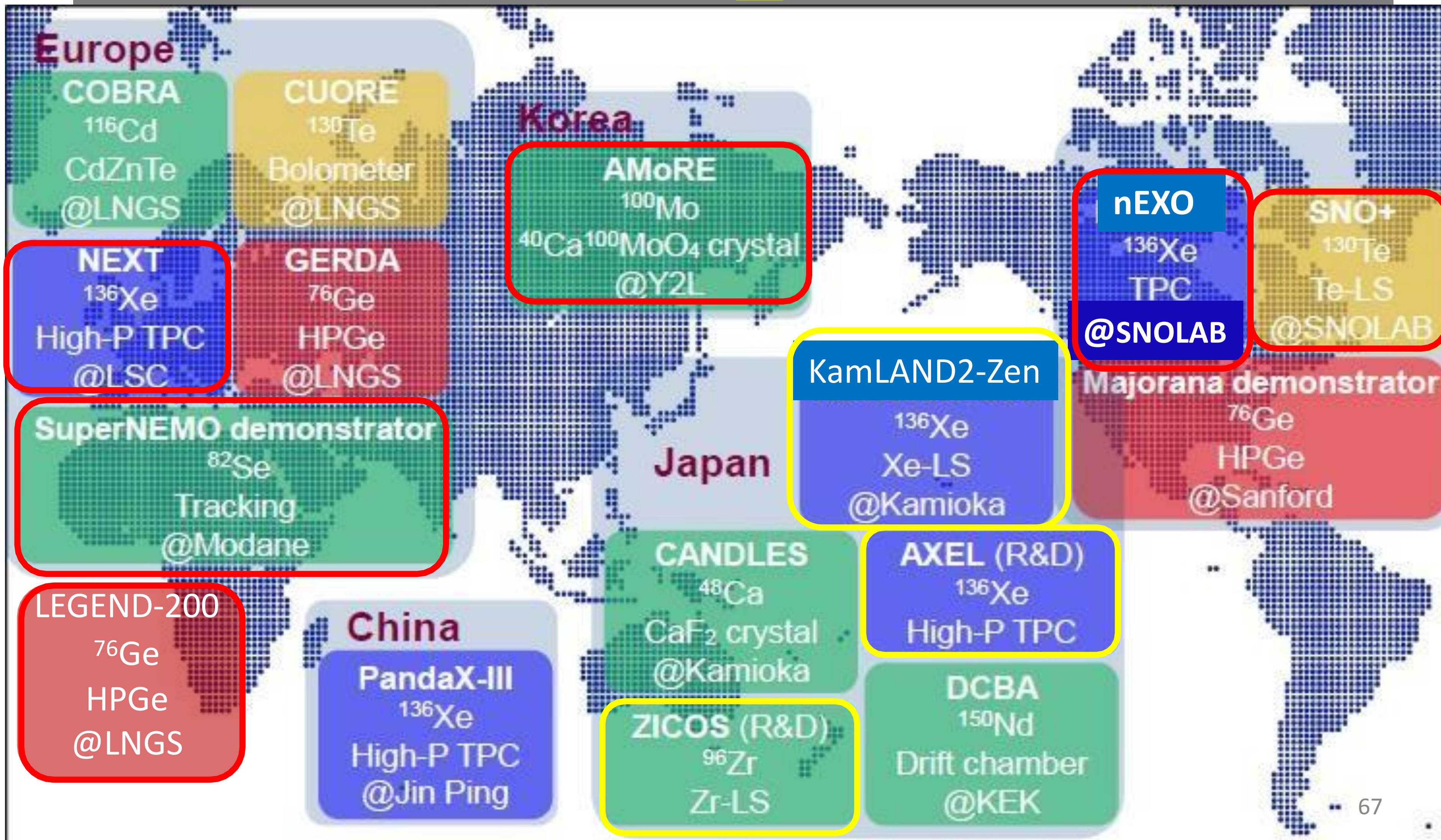
- Catch 1 electron pair emitted !



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

Plan

R&D



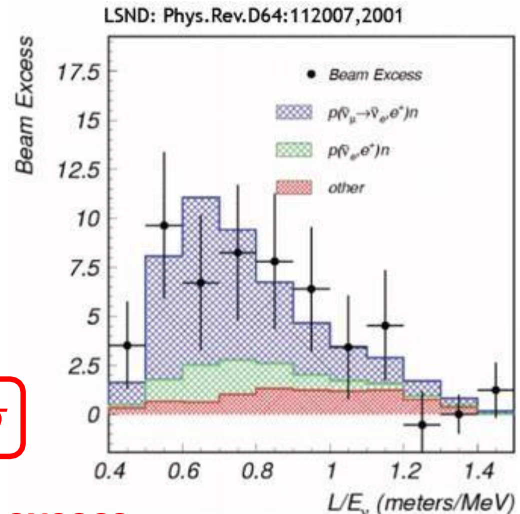
5. Sterile Neutrino Experiments

- **JSNS^2 II**
- **PROSPECT-II**
- **IsoDAR**

Why sterile neutrino ?

Do 3-neutrino oscillations explain all experimental results?

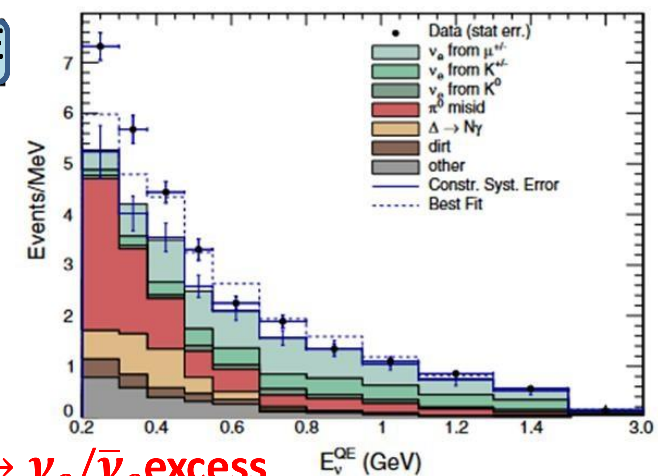
LSND



3.8σ

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

MiniBooNE



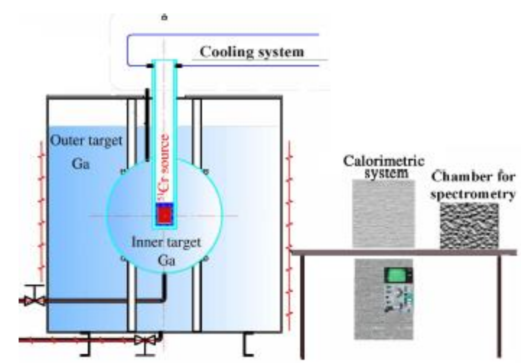
4.8σ

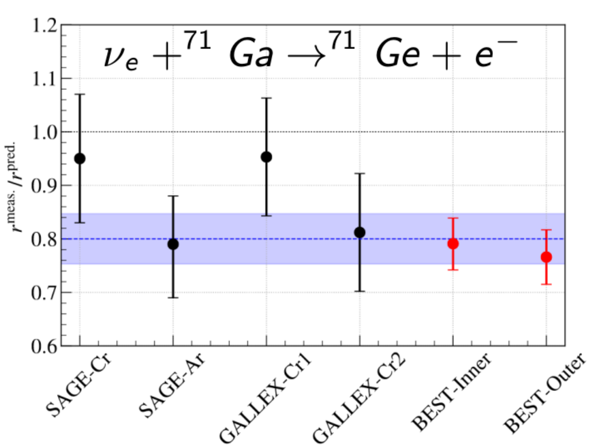
$\nu_\mu/\bar{\nu}_\mu \to \nu_e/\bar{\nu}_e$**excess**

Possible common explanation:

Additional squared mass difference

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





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

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

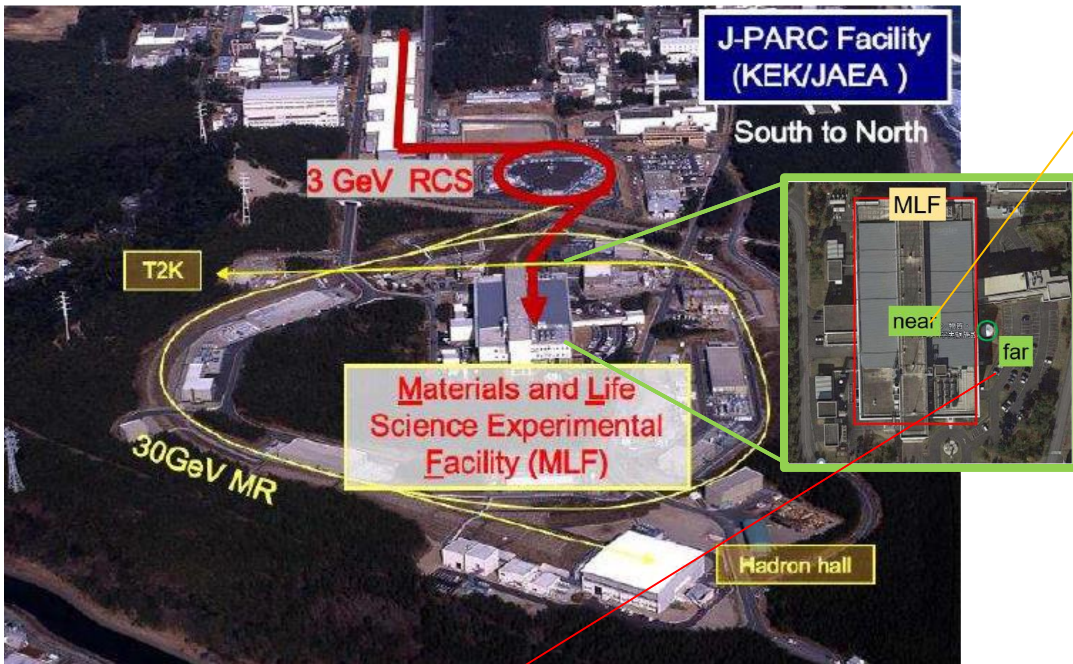
- **Recently confirmed by BEST**

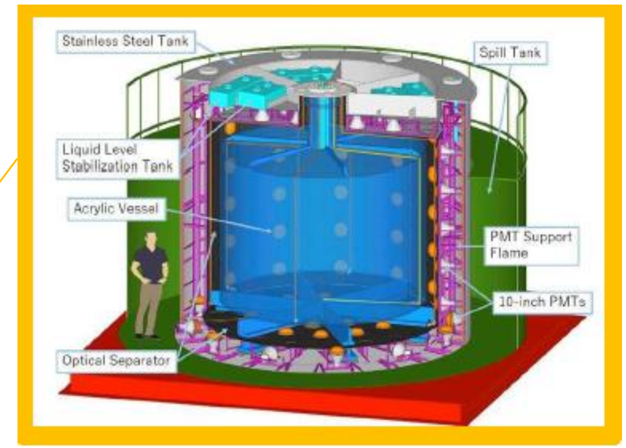
  (Baksan Experiment on Sterile Transitions)

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

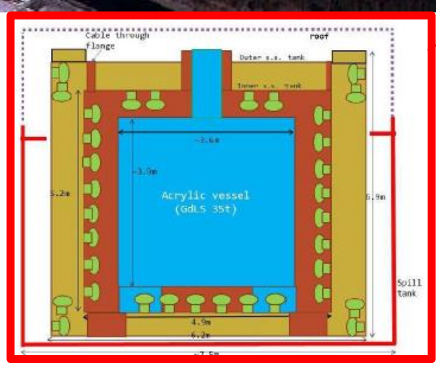
JSNS^2 II

(J-PARC Sterile Neutrino Search at J-PARC Spallation Neutron Source)





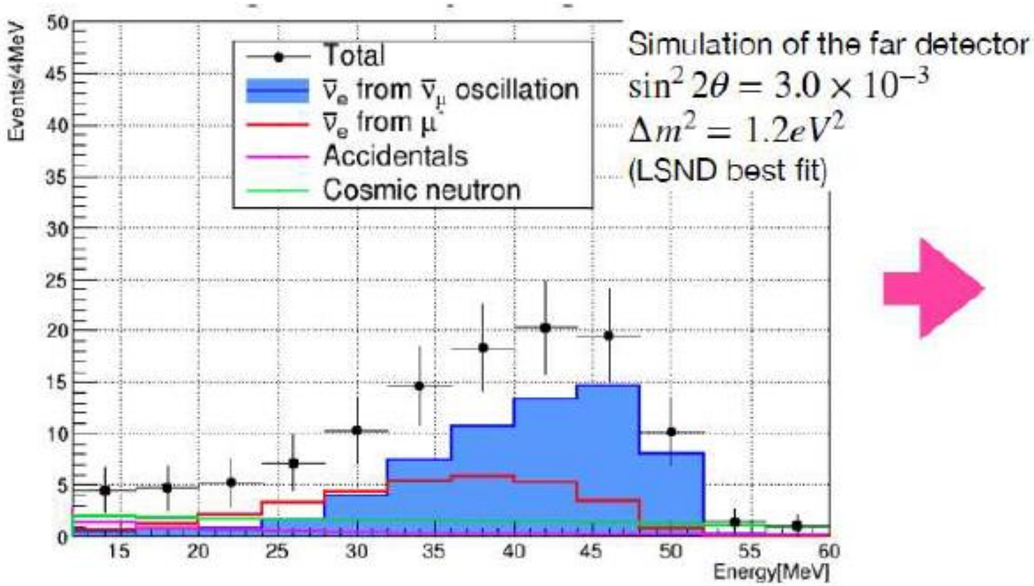
- **24 m from the Hg target.**
- **17 t GdLS**
- **96, 10" PMTs for ID & 24, 10" PMTs for OD**

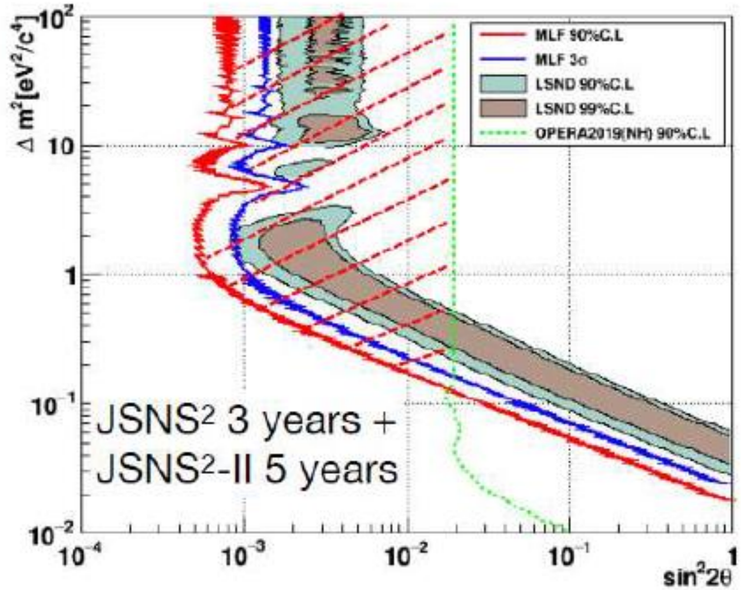


- **48 m from the Hg target**
- **32 t GdLS**
- **228 PMTs**
- **Under construction**

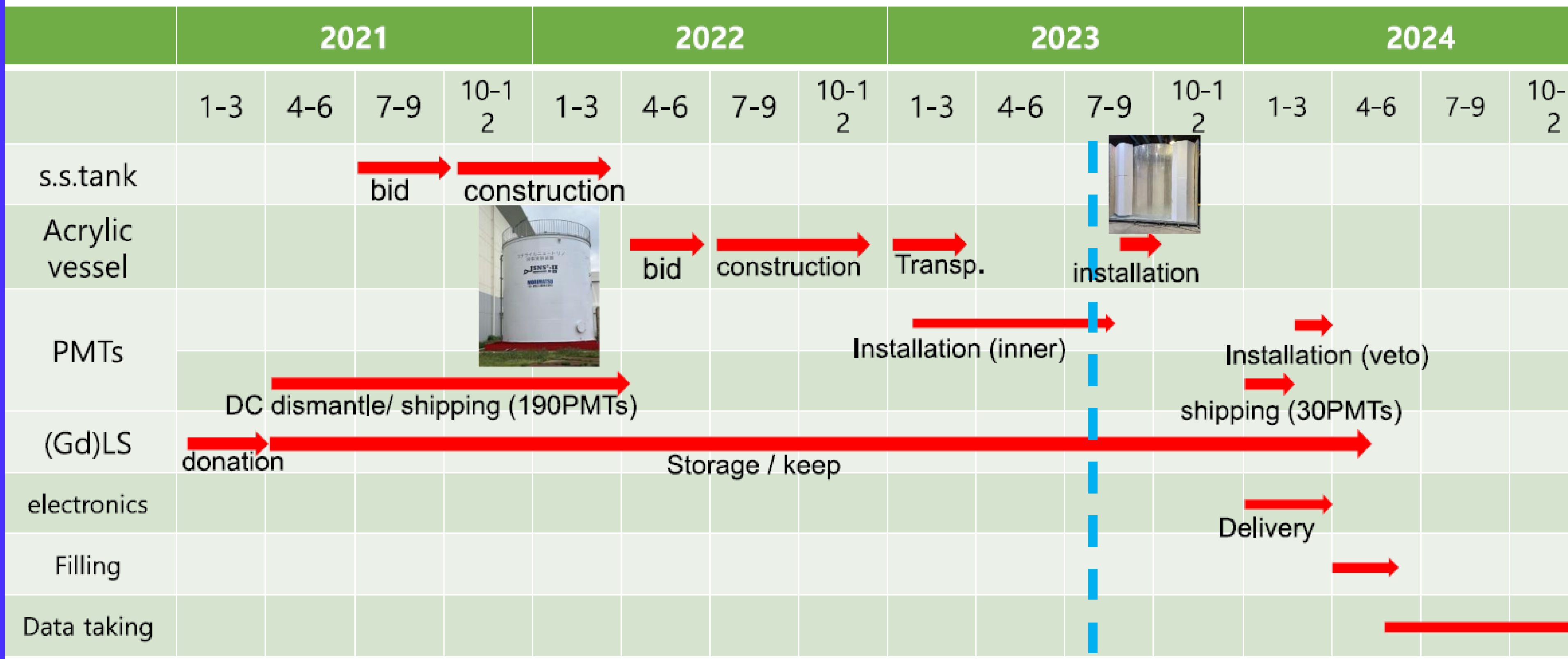
Sensitivity of JSNS^2-II

- Each background simulation was done based on the JSNS^2 data.
- The sensitivity becomes better in the low Δm^2 region.



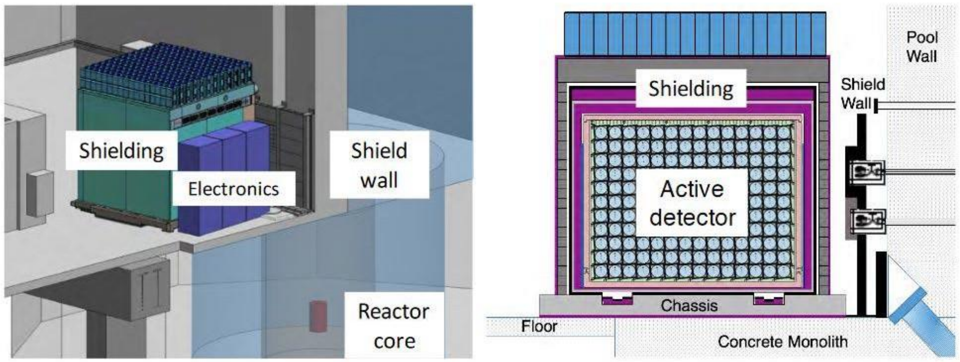


Construction schedule of JSNS^2-II



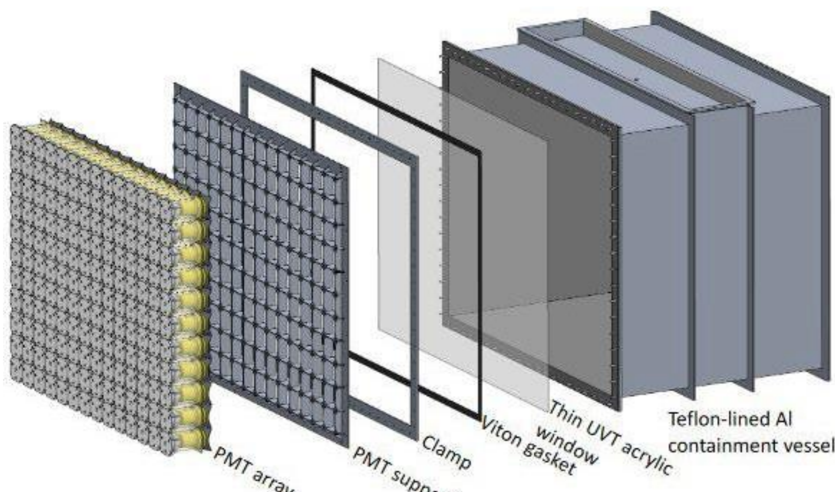
PROSPECT-II

Original PROSPECT Design



https://arxiv.org/abs/2107.03934

PROSPECT II Design



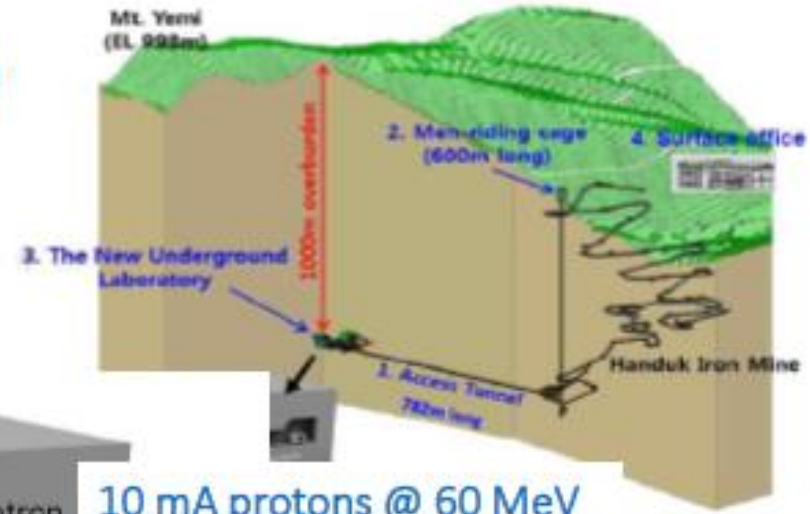
https://arxiv.org/abs/2107.03934

- 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

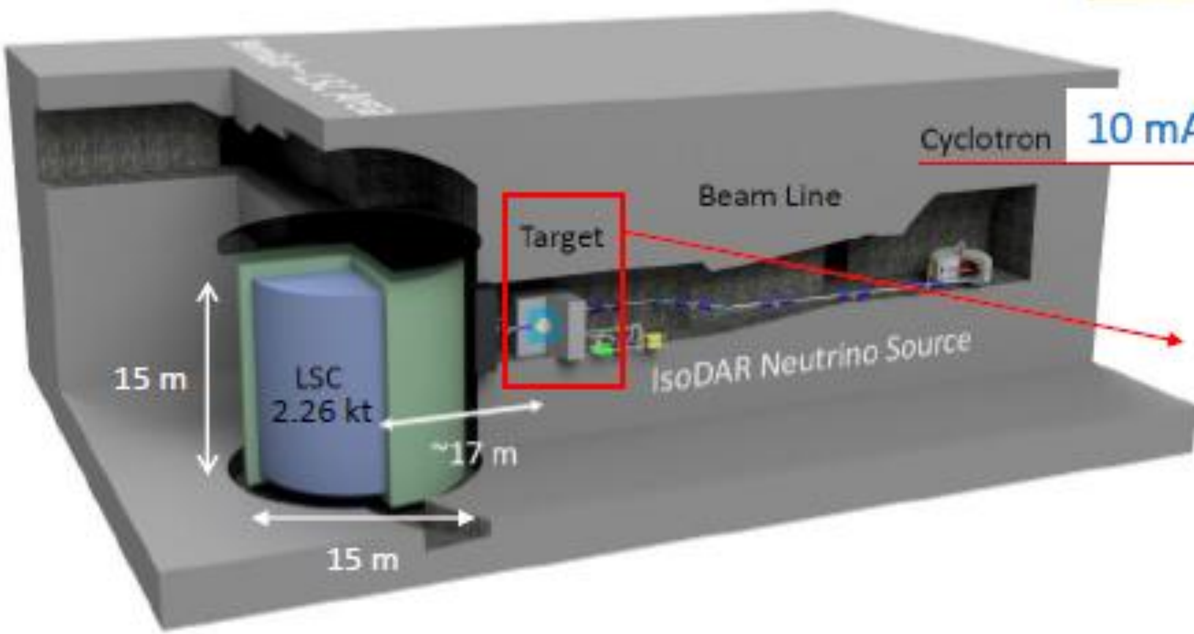
IsoDAR

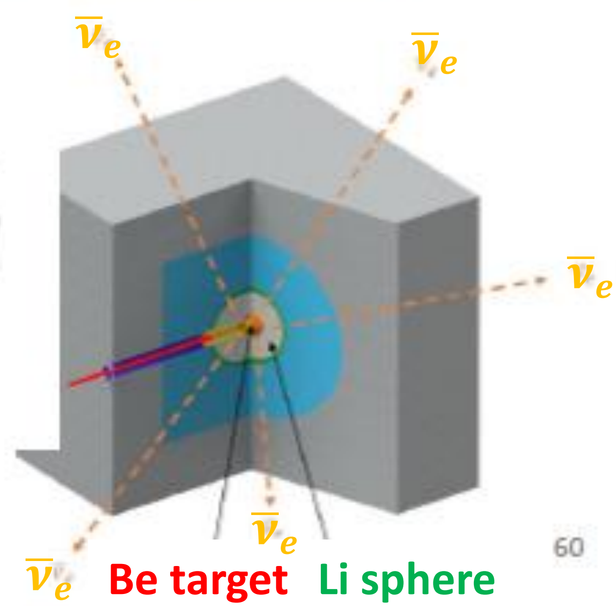
(Isotope Decay At Rest)

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

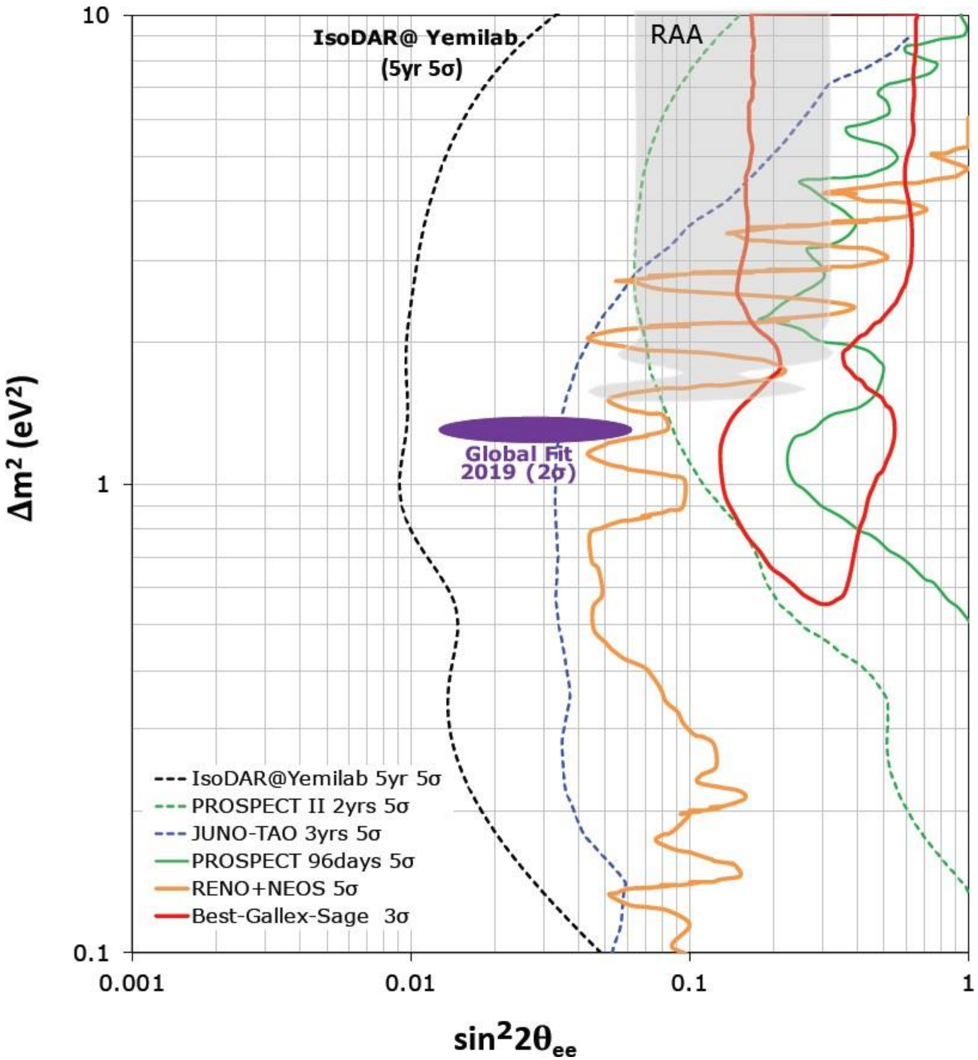


10 mA protons @ 60 MeV





Sensitivities



- 2y: PROSPECT-II → high Δm^2
- (3y: JUNO-TAO → low Δm^2)
- 5y: IsoDAR@Yemilab → full coverage

NEUTRINO 2022
XXX International Conference on Neutrino Physics and Astrophysics
Virtual Seoul May 30 (Mon) - June 4 (Sat), 2022

Joshua Spitz, Daniel Winklener

3+1 oscillations assumed

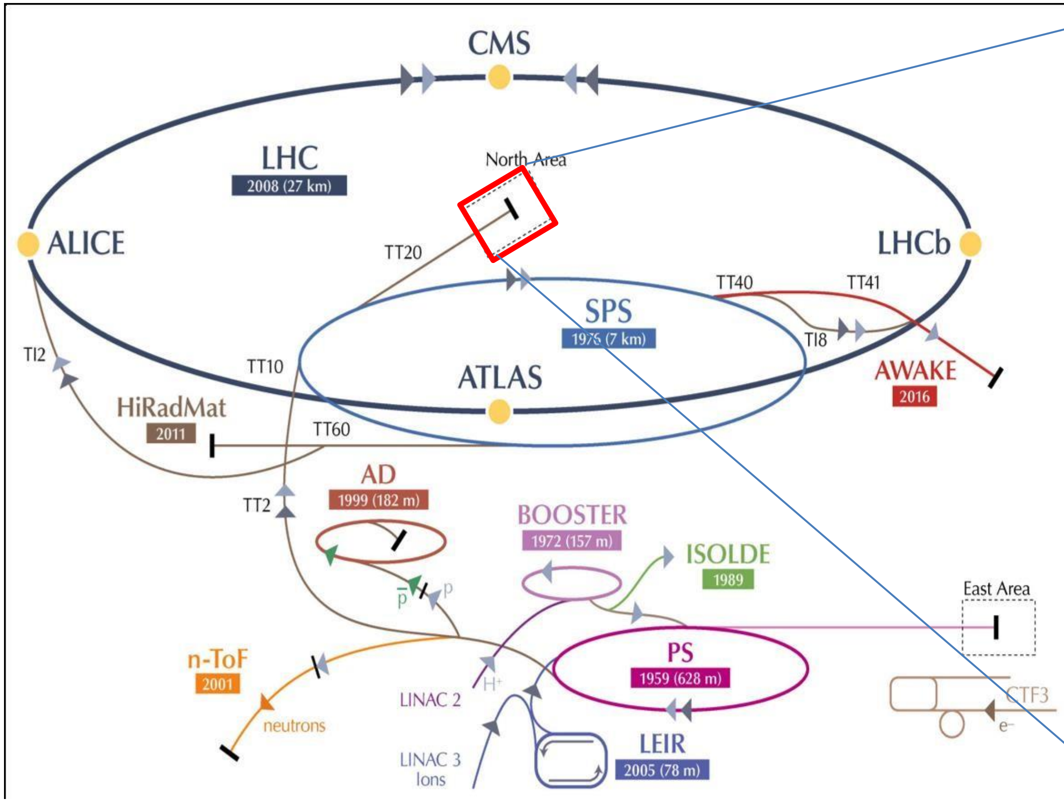
$$P_{ee} = 1 - \sin^2 2\theta \sin^2\left(1.27\frac{\Delta m^2[\mathrm{eV}^2]L[m]}{E_\nu[\mathrm{MeV}]}\right)$$

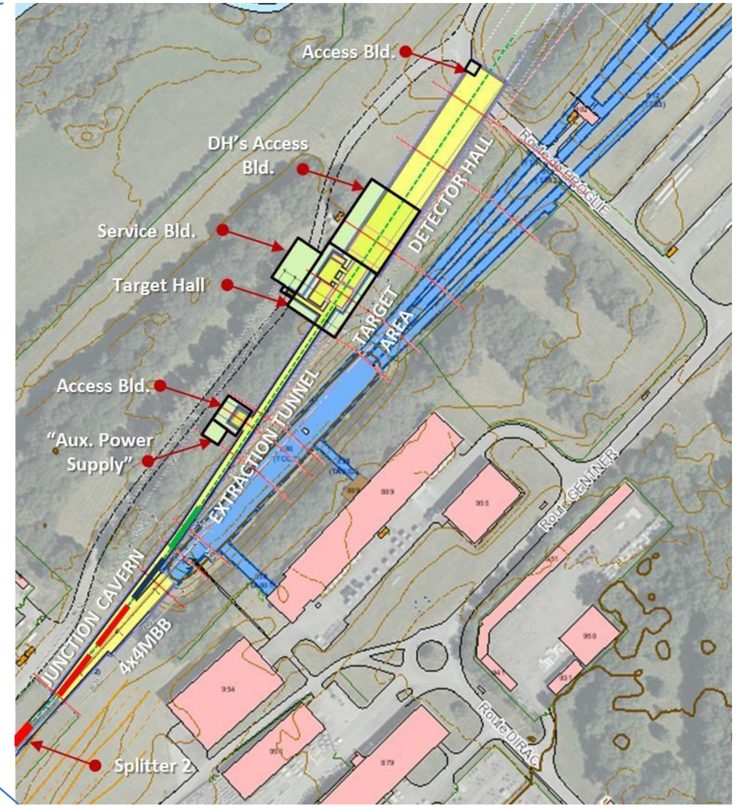
6. High statistic ν_τ Experiment (SHiP)

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.

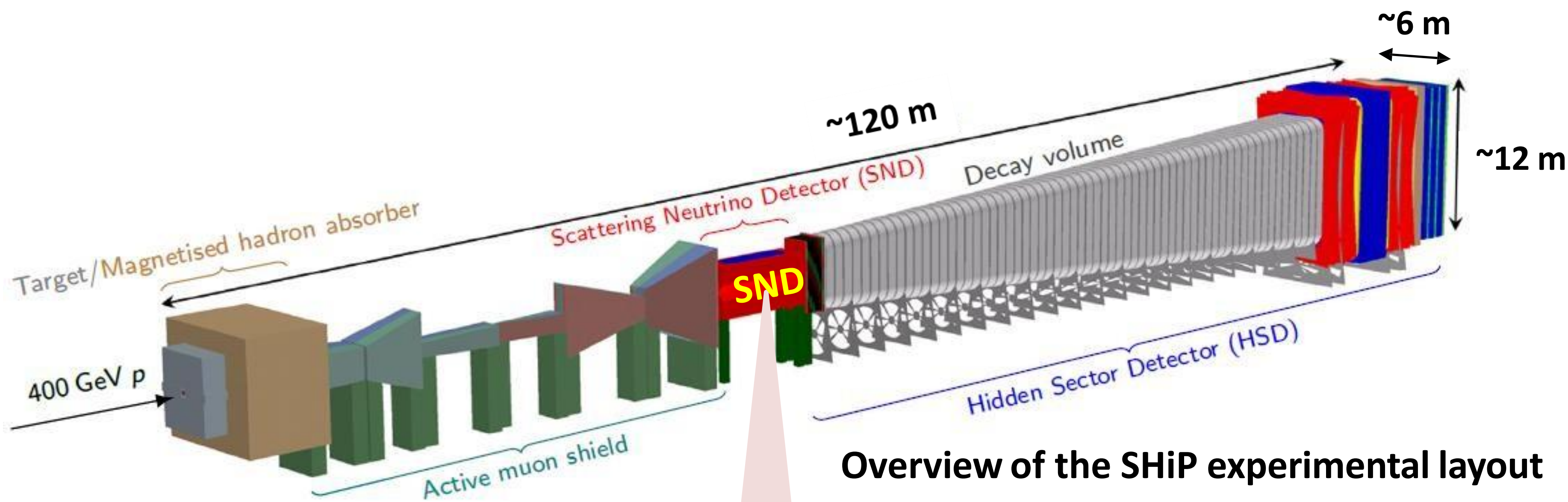
SHiP: experimental site



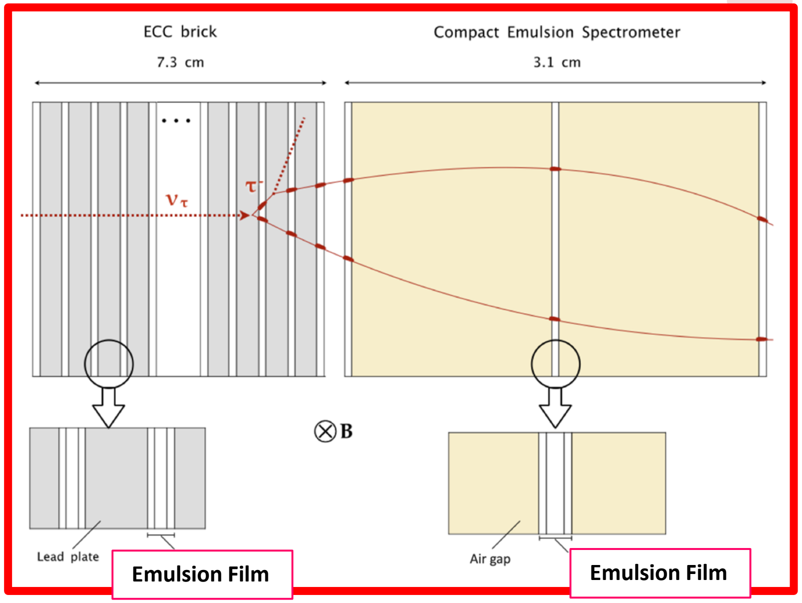


- Fixed target facility @ CERN SPS
- 400 GeV protons
- 4×10^{13} POT/spill in every 7 sec → 2×10^{20} POT in 5 years

SHiP detector



Overview of the SHiP experimental layout



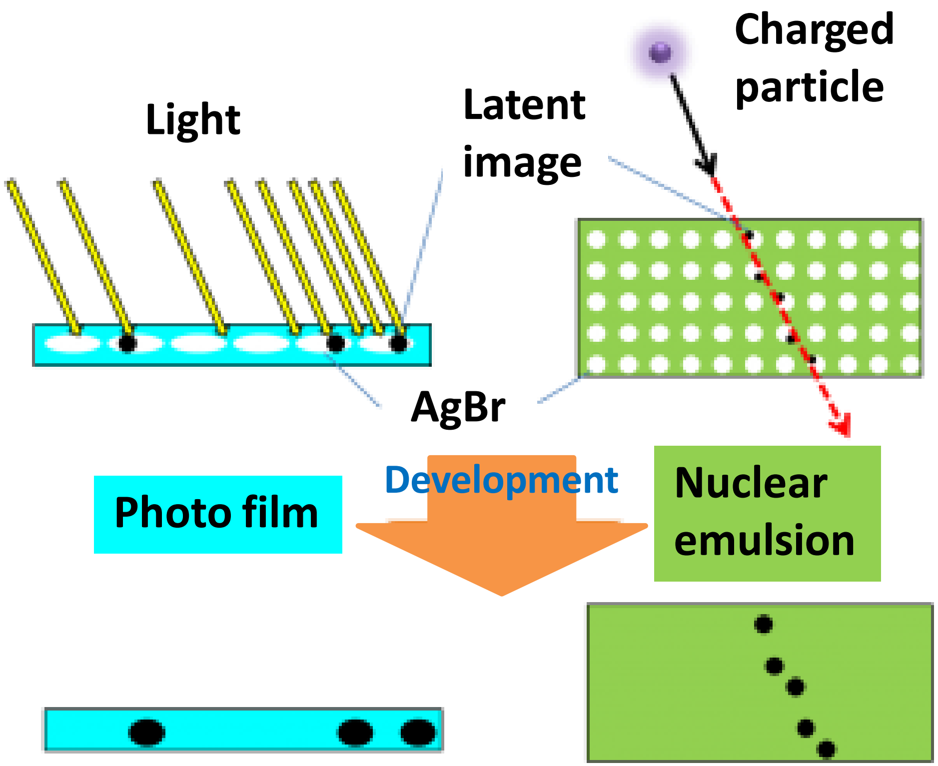
Basic unit of the SND & the ECC brick

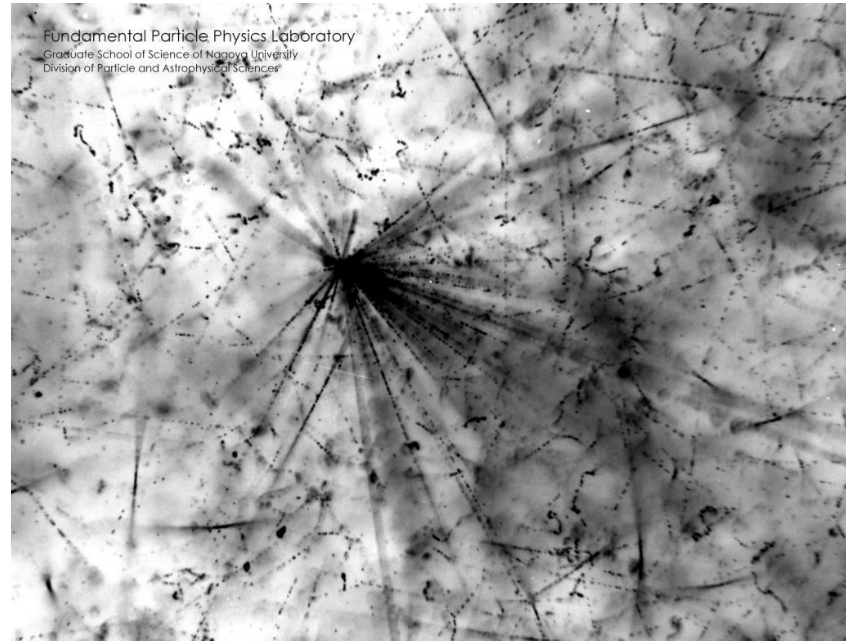
In the SND, the *Emulsion Cloud Chamber (ECC) is used as tracking detector and the Compact Emulsion Spectrometer (CES) is used for charge measurement.

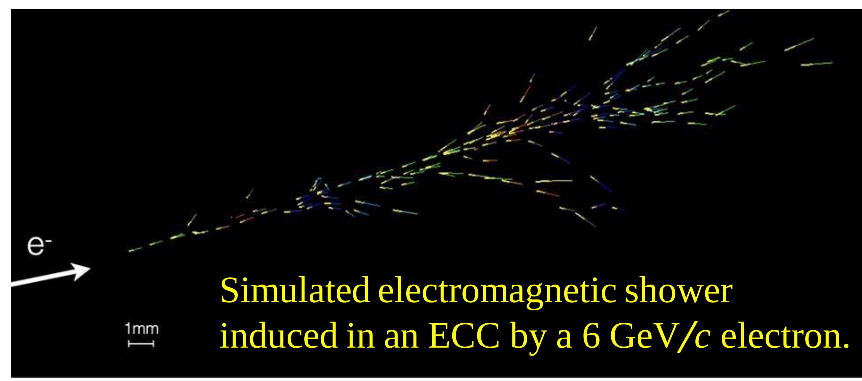
* Nuclear emulsion has the best position resolution of ~1μm. The emulsion technique has been highly developed in Japan.

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

Nuclear emulsion







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

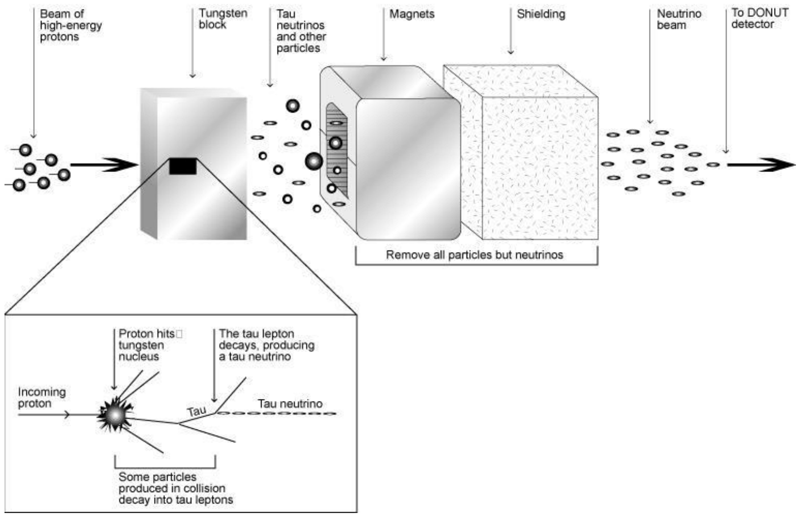
- Kind of photo film.
- Contains small grains of AgBr.
- Ag grains are remained after charged particle pass.
- We can detect the track after the development.
- Position resolution is $\sim 1 \mu$m (still the best in all detectors).

Discovery of ν_τ

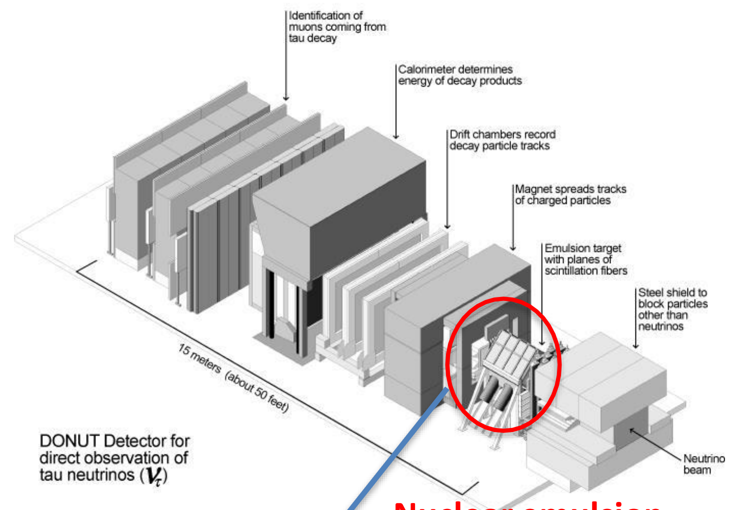
DONUT experiment, 2000（Direct Observation of NeUtrino Tau ,Fermilab. E872）

Nagoya Univ., Kobe Univ., et al

Creating a Tau Neutrino Beam

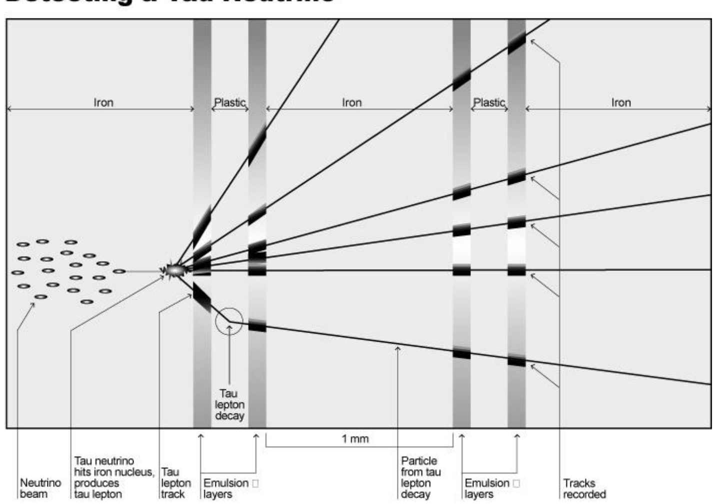


DONUT Detector



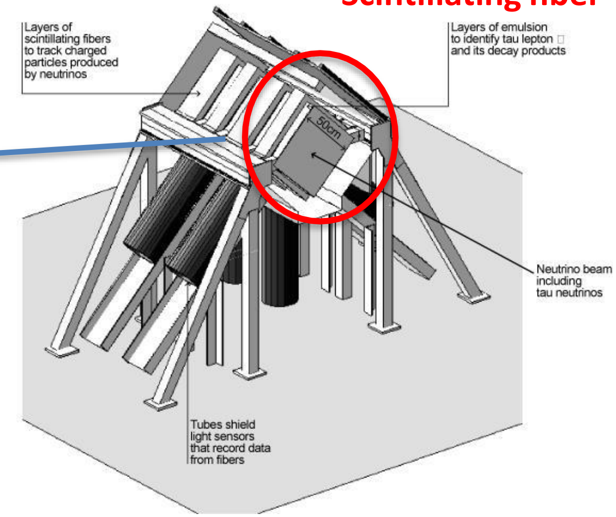
Nuclear emulsion
＋
Scintillating fiber

Detecting a Tau Neutrino



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 $\overline{\nu_r}$ properties (ex. Cross sections, etc)
  - Test lepton flavor universality by comparing ν_μ to ν_τ interactions
  - ν_e study in high energy range.

	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

(SK-Gd,) HK, DUNE, ESSnuSB, ν-factory, JUNO, IceCube Gen 2 & atmospheric ν experiments, 0νββ experiments, sterile ν experiments, and SHiP.


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

Thank you !