Future Neutrino Experiments

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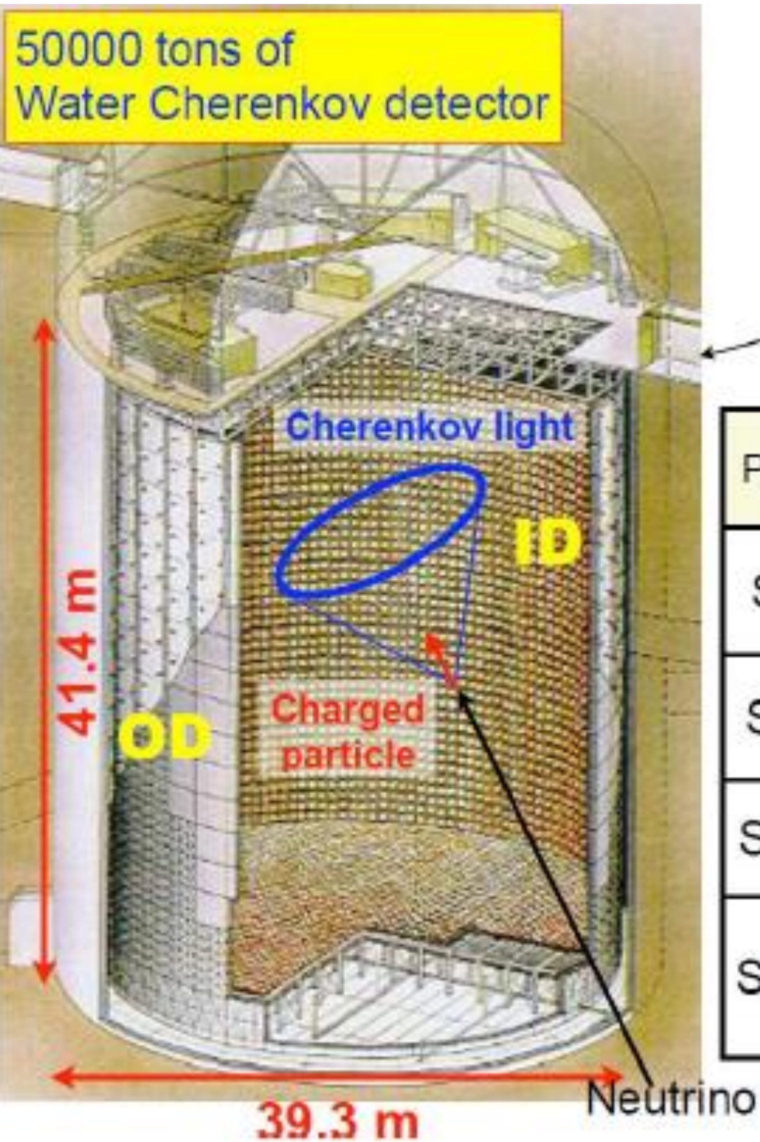
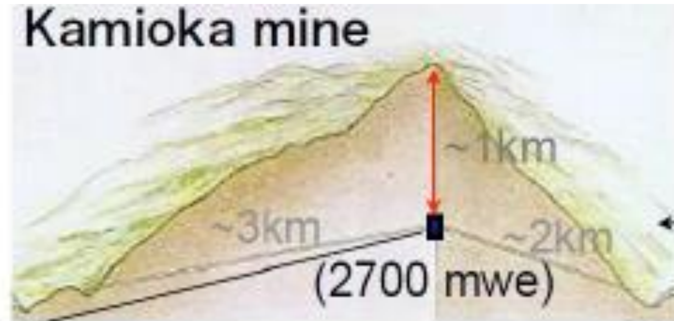
0. SK-Gd
Super-Kamiokande Gadolinium Project

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.

Fruitful results will be expected in near future.

Super-Kamiokande





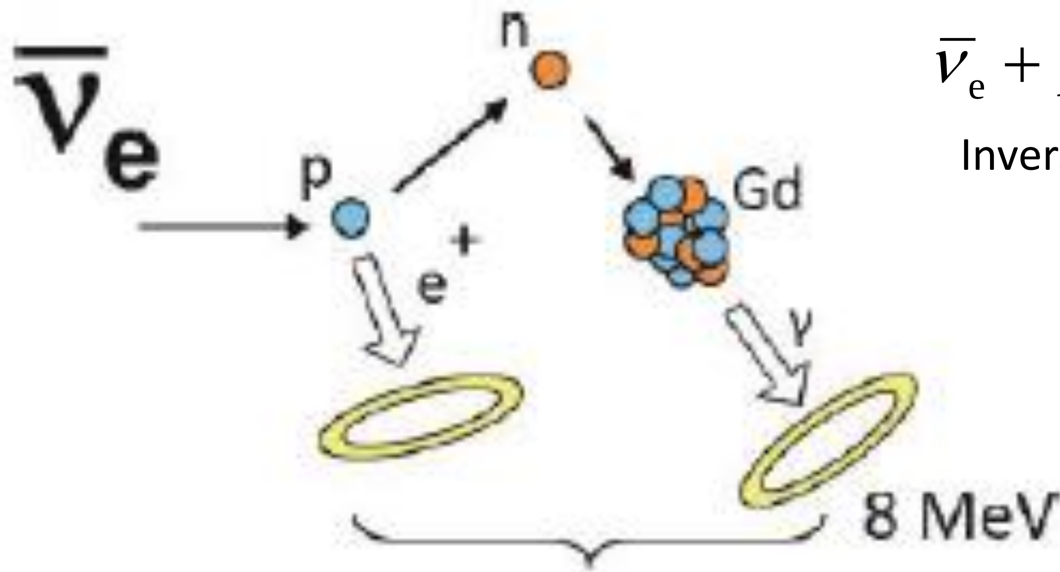
(For Solar neutrino analysis)

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 $>> \sigma_H = 0.33$ 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:



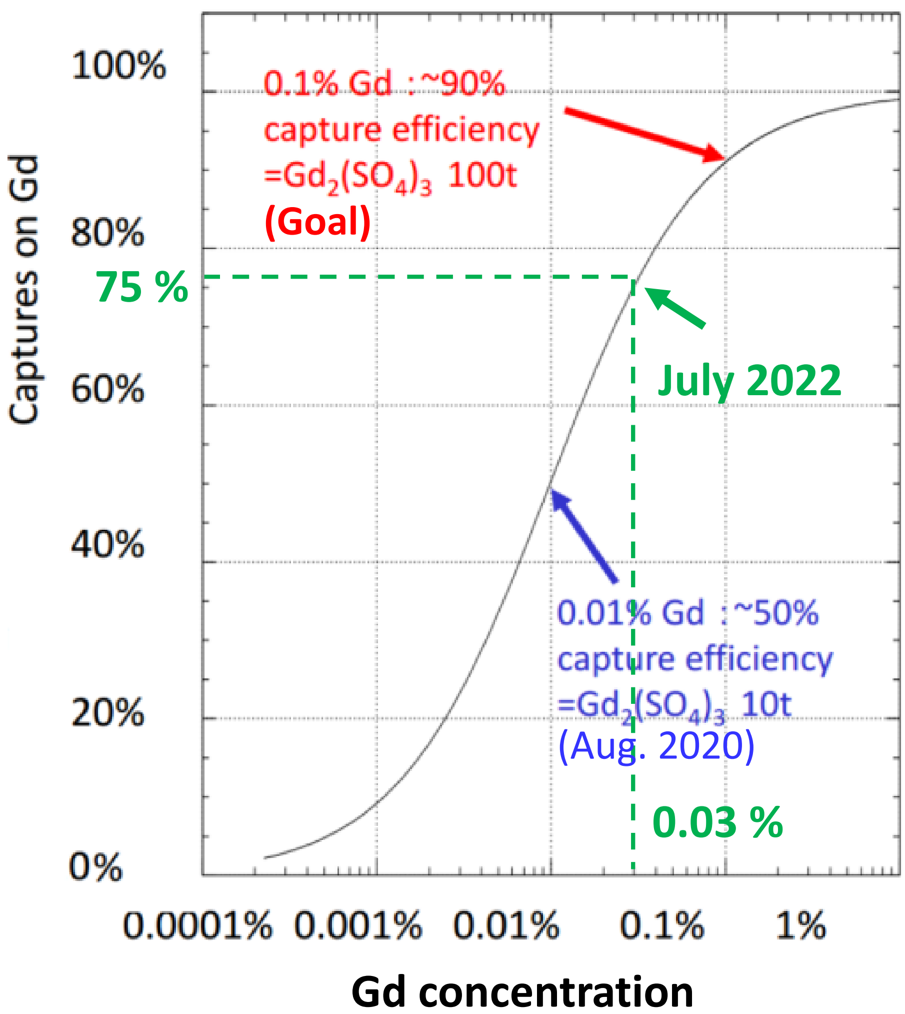
$$\bar{\nu}_e + p \rightarrow n + e^+$$

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

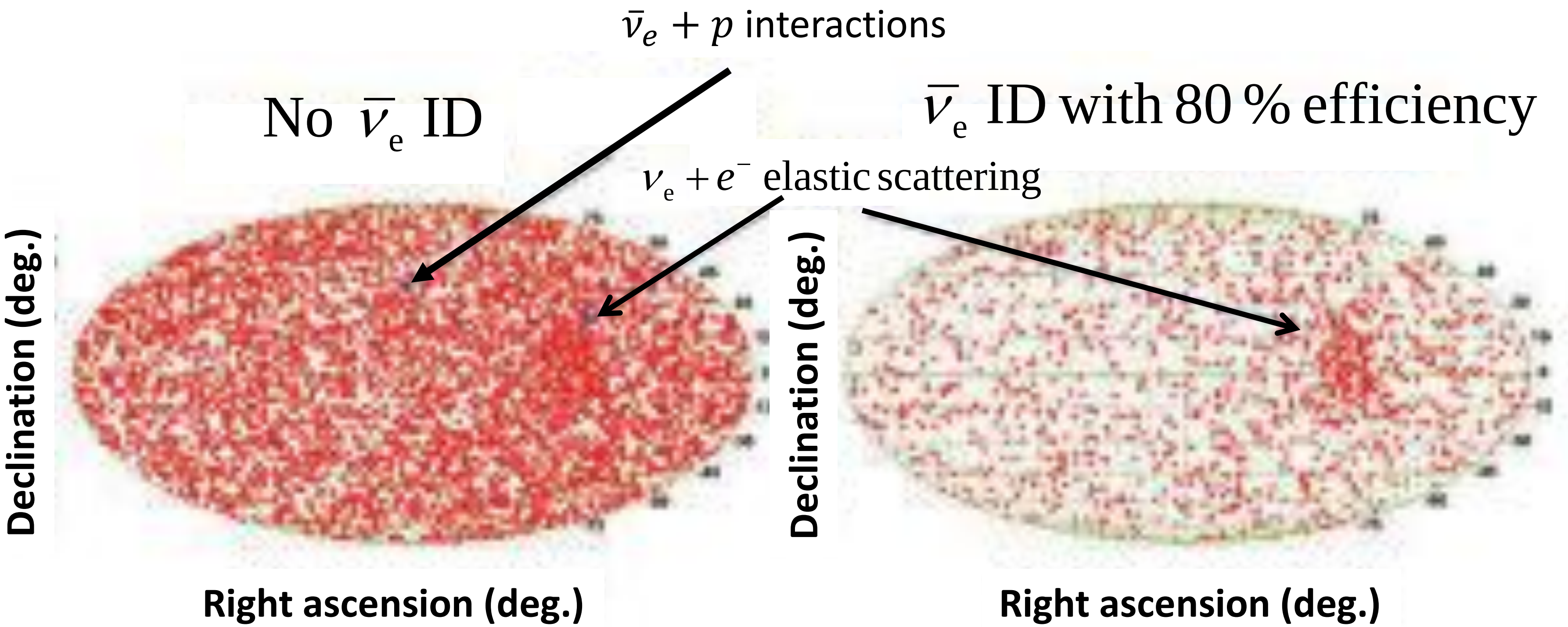
***(1) SRN: All the neutrinos which have ever been emitted by every supernova since the onset of stellar formation suffuse the universe.**

***(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

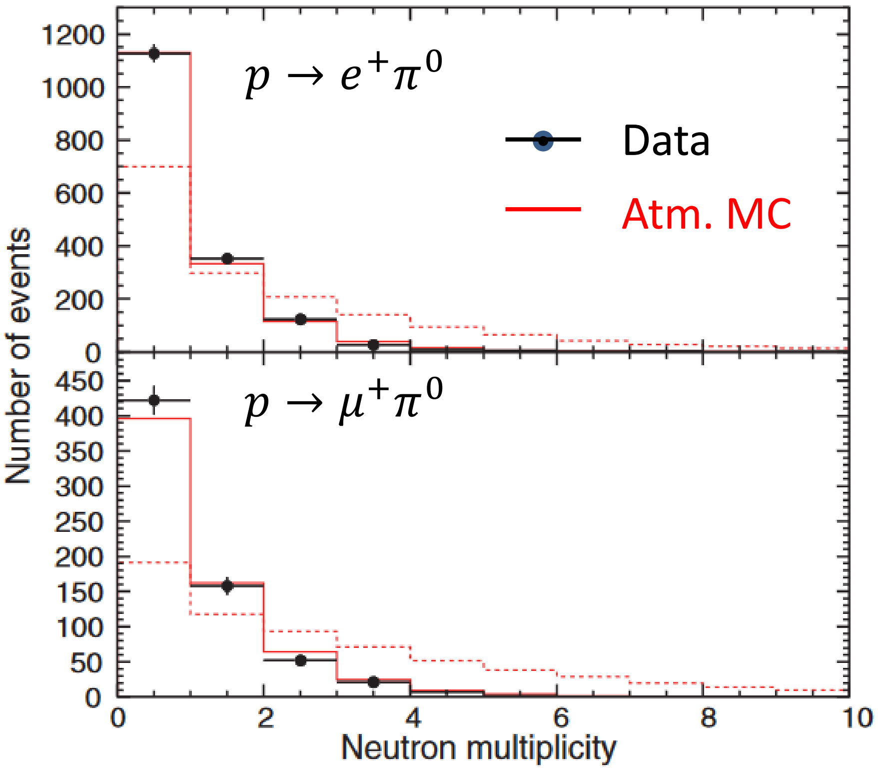
$\nu_e + e^- \longrightarrow \nu_e + \boxed{e^-}$ **: direction information**

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



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

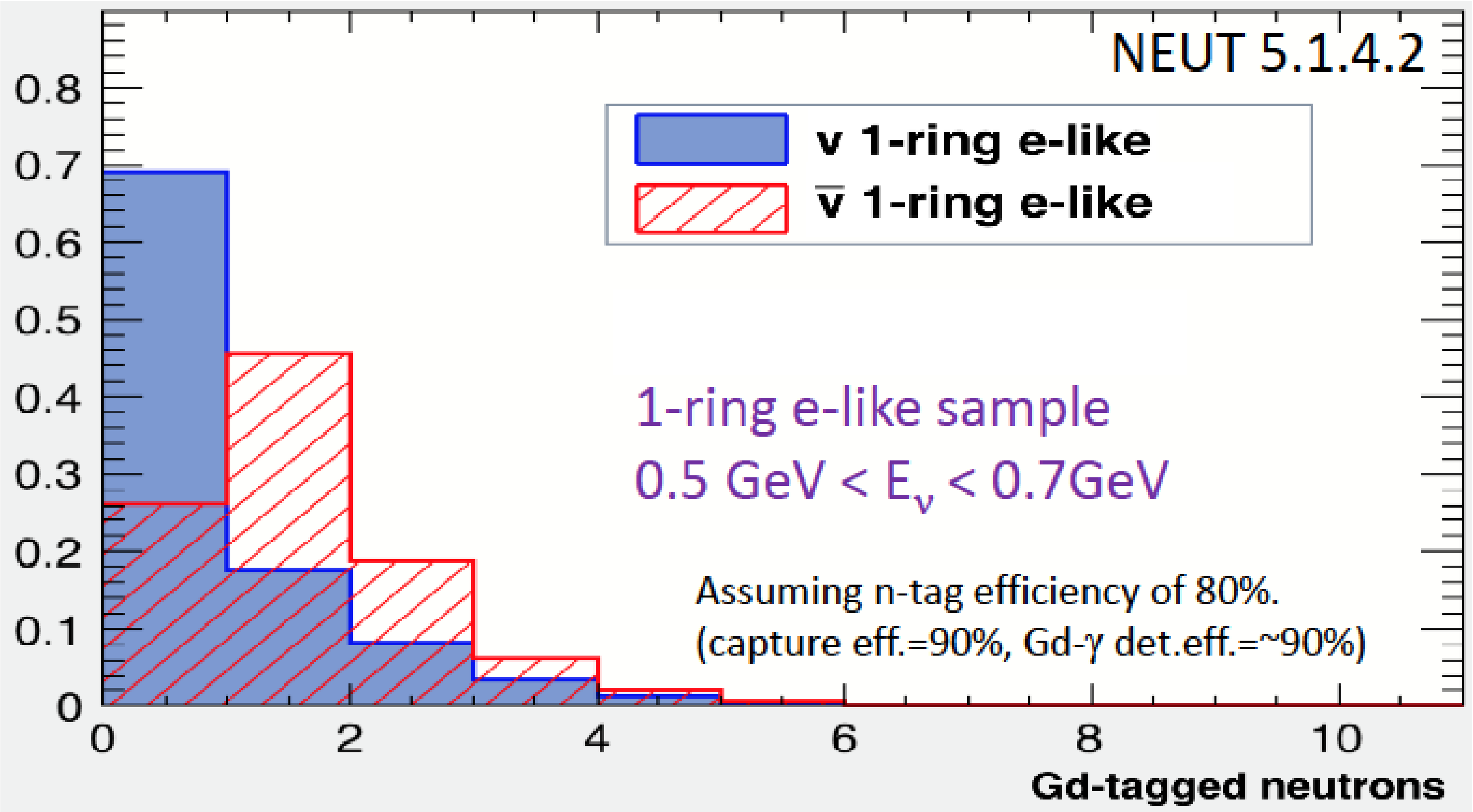
Improvement of proton decay



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

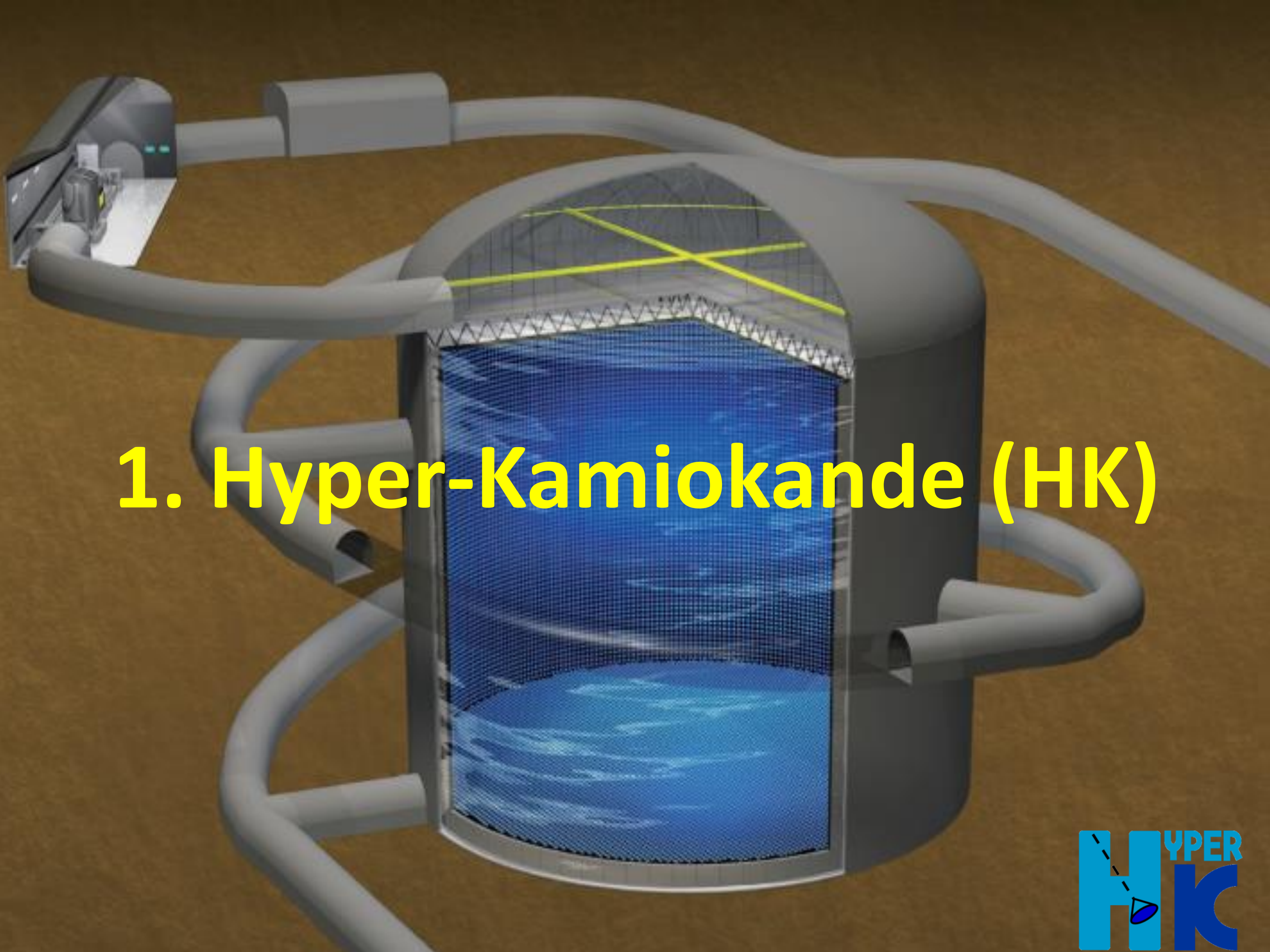
Improvement for T2K

Number of tagged neutrons in T2K energy range



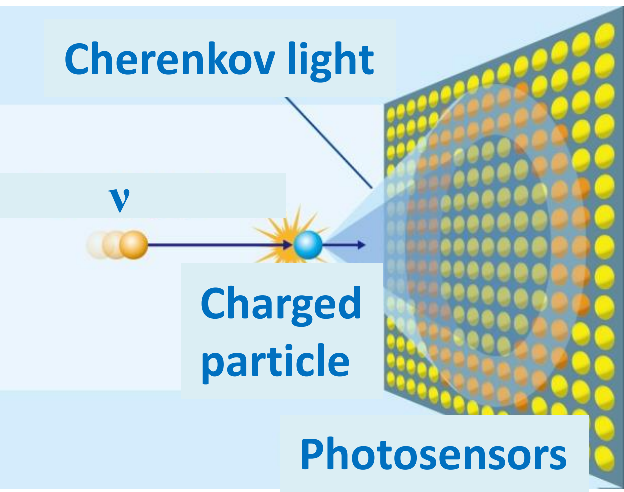
ν_e contamination in the $\bar{\nu}_e$ enhanced sample: 30 % → 13 %

1. Hyper-Kamiokande (HK)

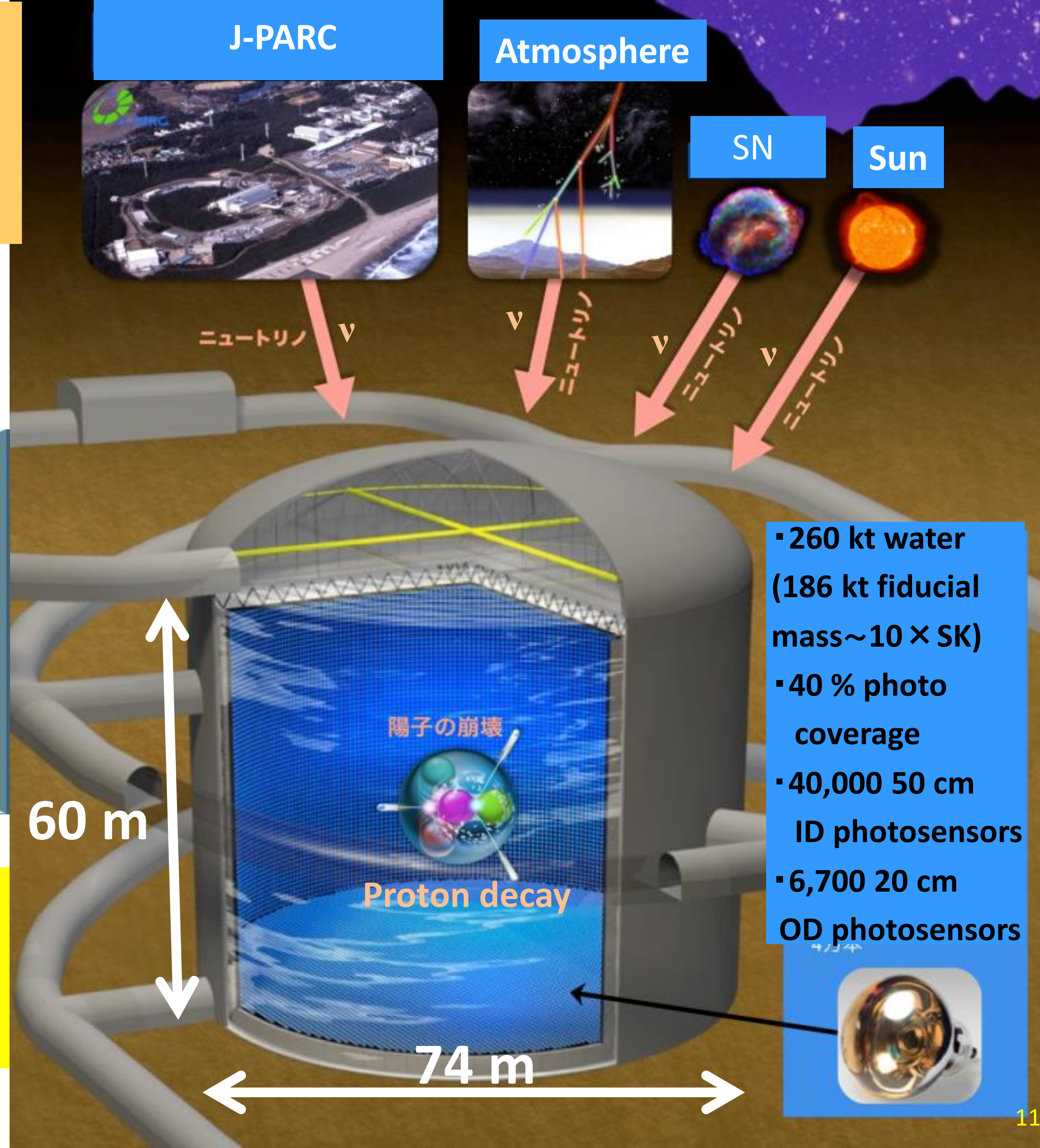


Hyper-Kamiokande

Large water Cherenkov detector



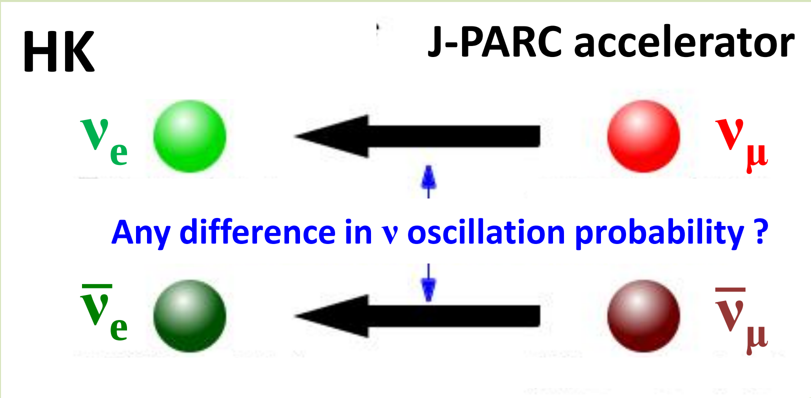
- Construction started in 2020
- Operation will start in 2027 (priority project by MEXT's roadmap)



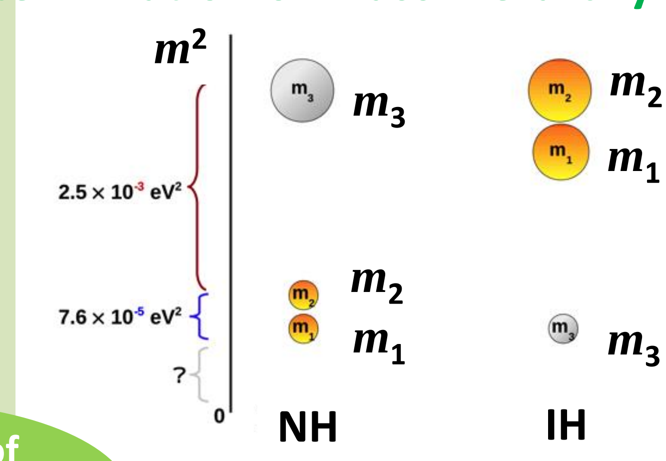
- 260 kt water (186 kt fiducial mass～10×SK)
- 40 % photo coverage
- 40,000 50 cm ID photosensors
- 6,700 20 cm OD photosensors

Physics goals

CPV measurement

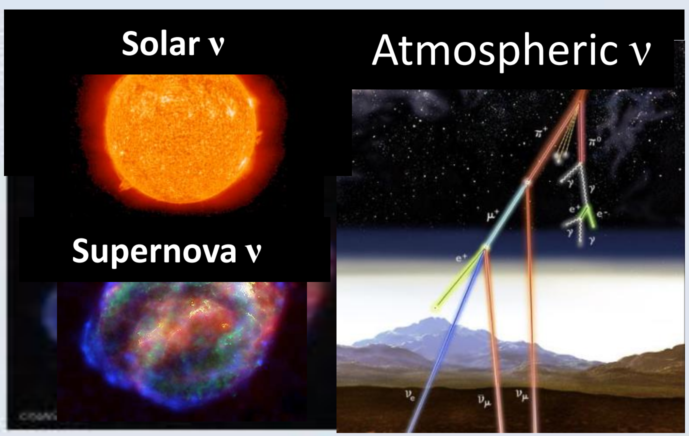


Determination of mass hierarchy (MH)

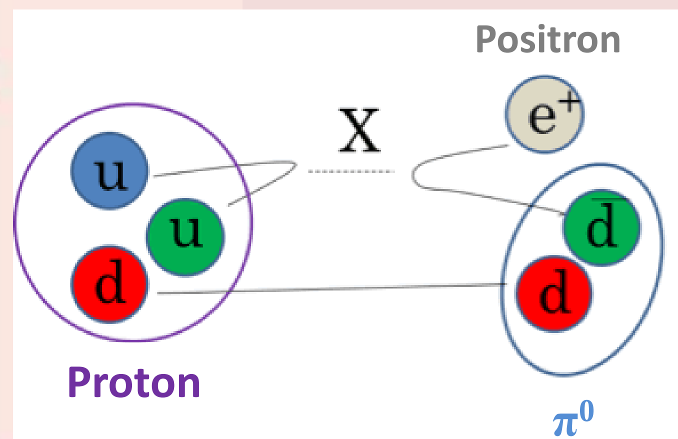


Elucidation of whole picture of ν oscillation

Cosmic neutrino observation



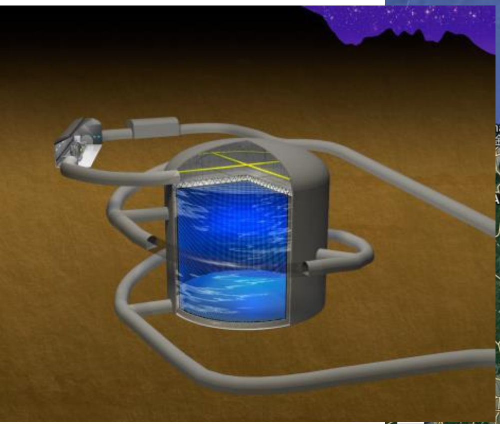
Proton decay search

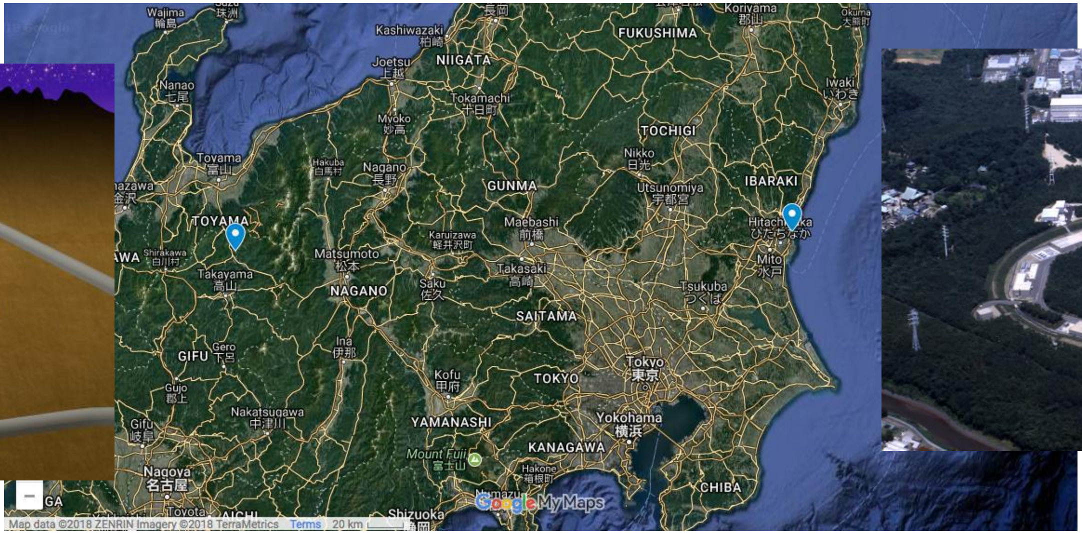


Elucidation of the origin and the history of the universe

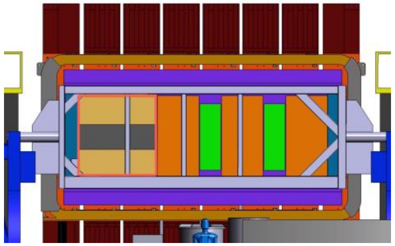
Investigation of GUT

HK Long Baseline Project

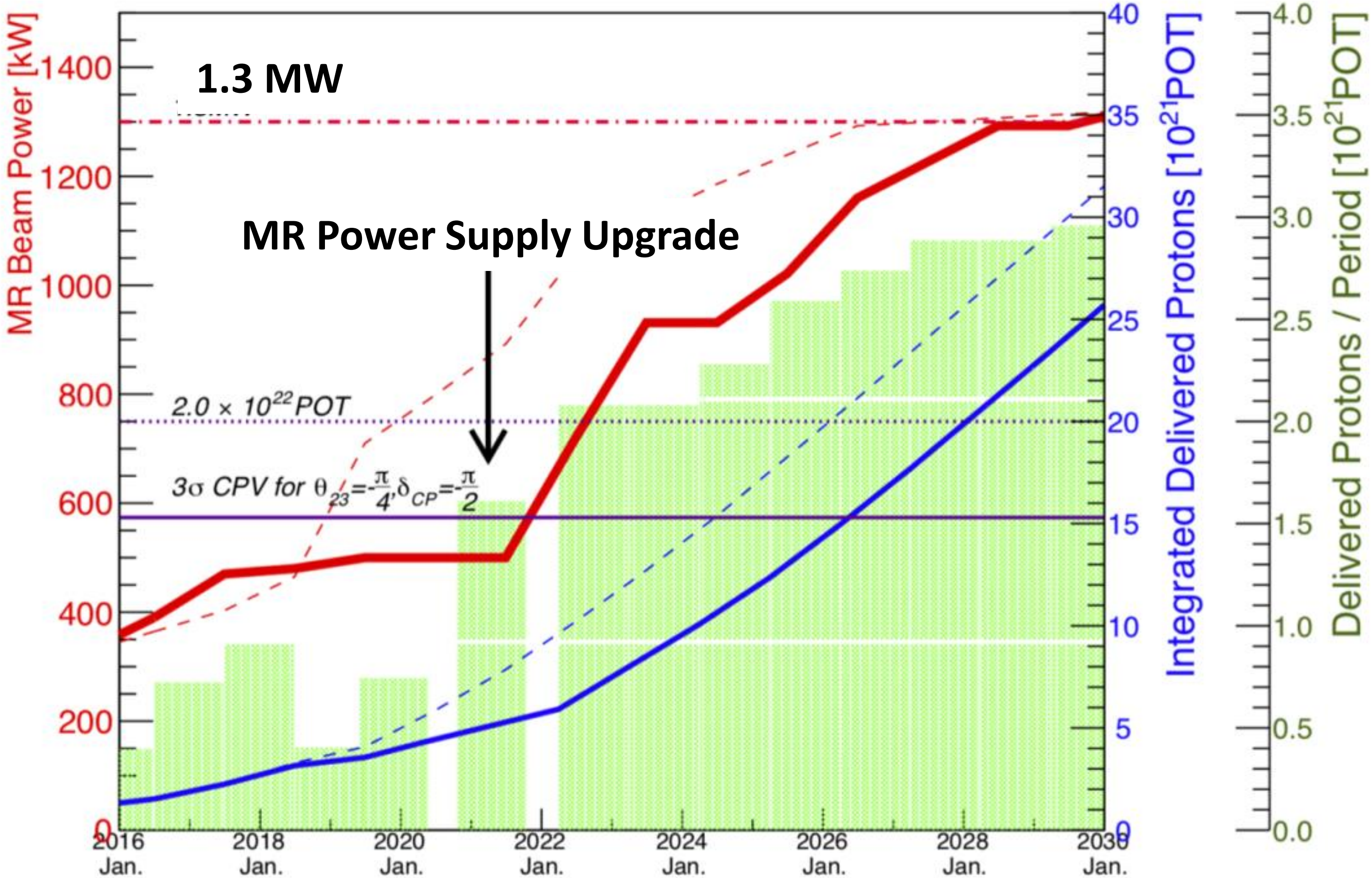




- J-PARC ν beam: 500 kW → 1.3 MW
  2.5° off-axis, peak energy @～600 MeV (oscillation maximum)
  → narrow band beam suppresses NC-π^0 and CC-nQE contamination
- ND280 should continue its operation for HK w/ potential upgrades (SFGD & HA-TPC).
- FD:SK → HK will realize high statistic ν data
- Intermediate Water Cherenkov Detector (IWCD) will be newly constructed at ～1 km from the neutrino source.



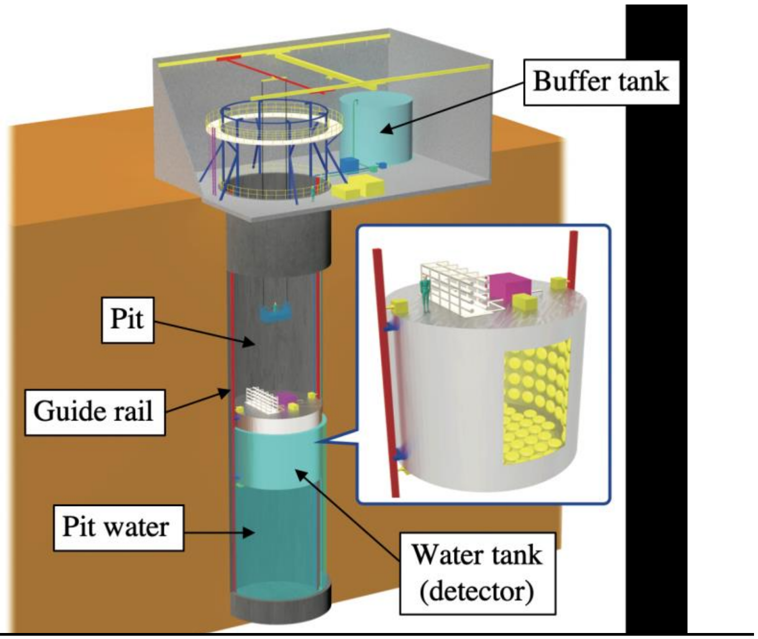
J-PARC beam power upgrade



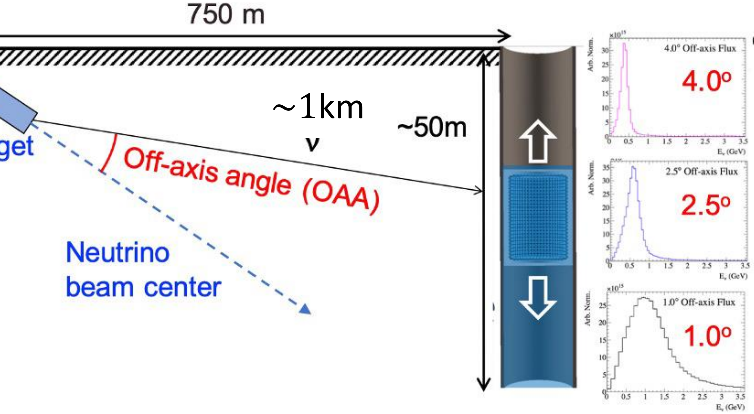
→ **1.3 MW (1.16 sec cycle)**

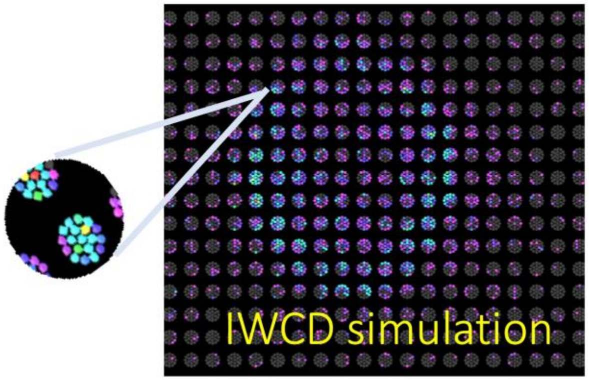
Trial for 1 MW-equivalent operation was successful !

IWCD

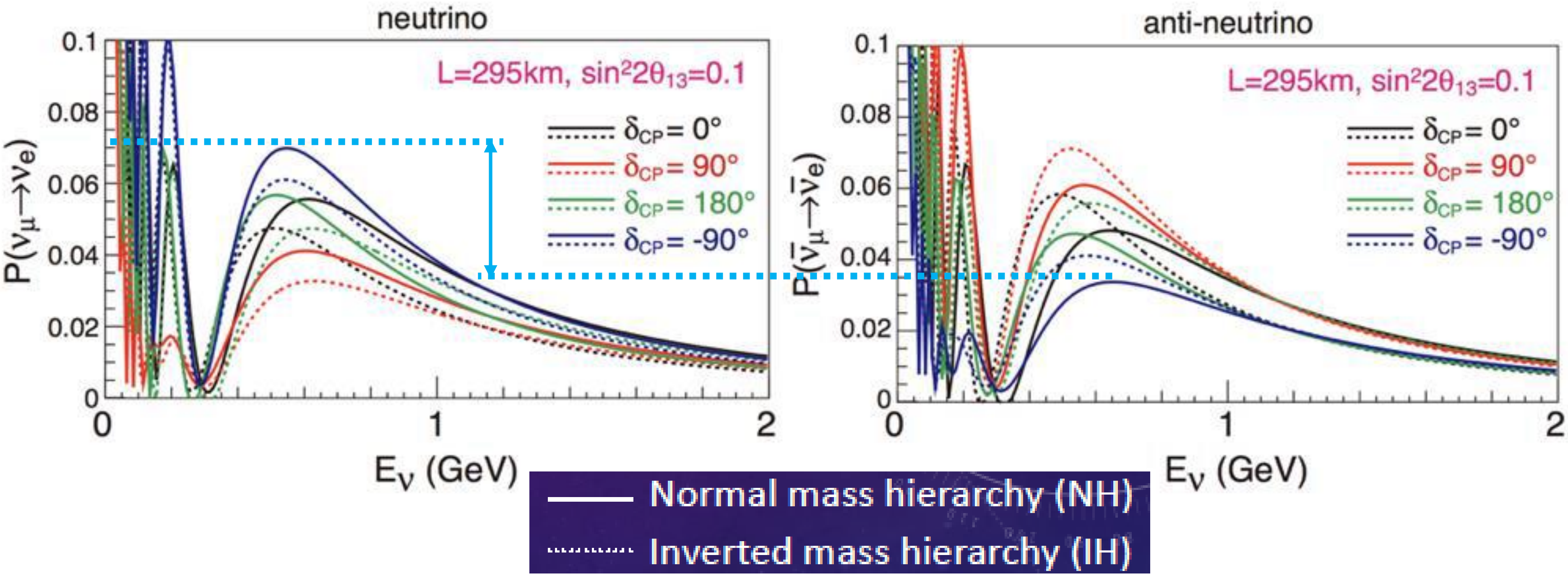


- $\sim$600t water Cherenkov detector located at $\sim$1km from the neutrino source
- Moves vertically to measure energy spectrum at different off-axis between 1° and 4°.
- Potential to load with Gd to enhance neutron detection
- Multi-PMT units will be used. → good reconstruction despite small detector



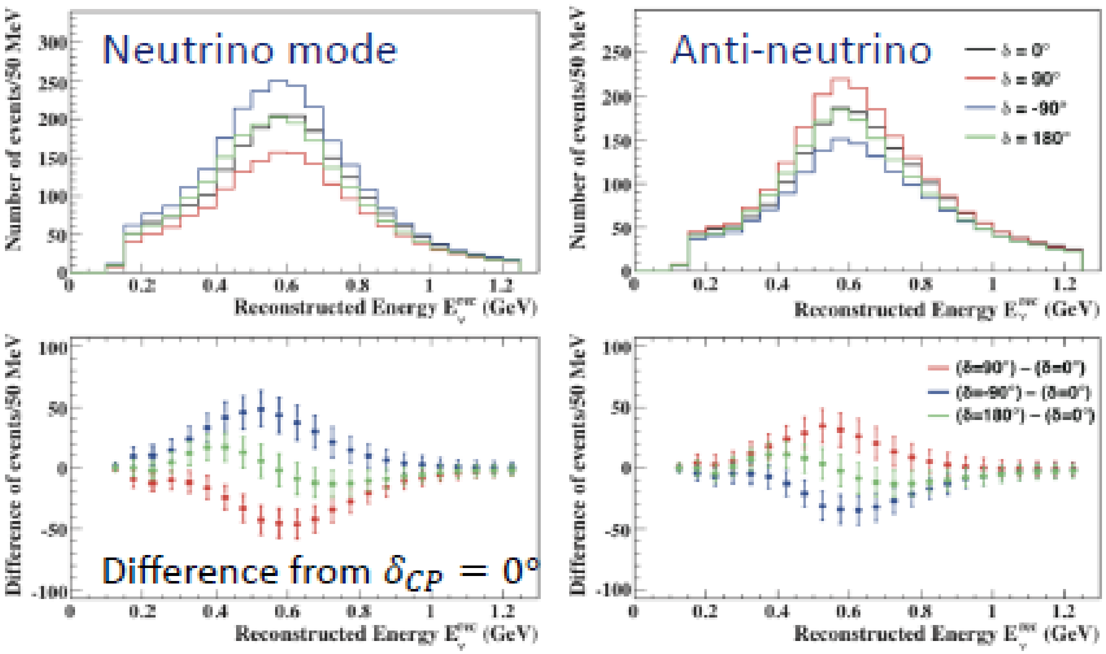


(1) Measurement of CP asymmetry



- 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



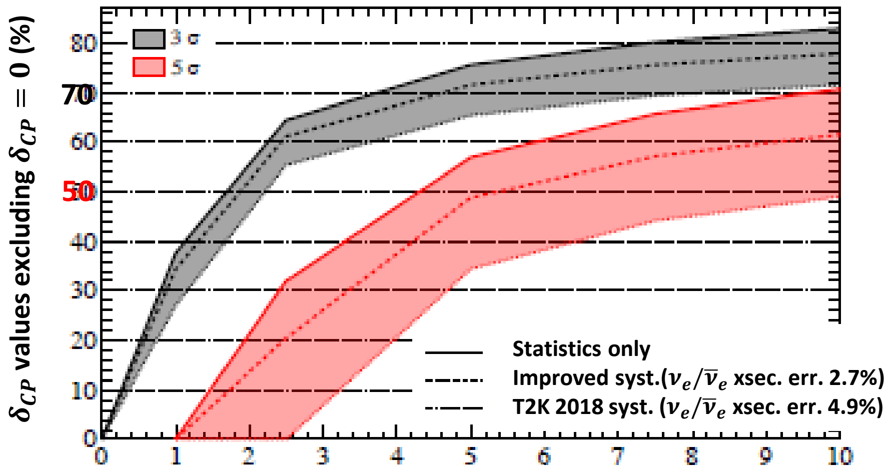
- A few % stat. uncertainties on $\nu_\mu \rightarrow \nu_e$ & $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ signals
- $E\nu$ is reconstructed from (p, θ) of e or μ
- Realistic estimates of wrong sign & NC BG contaminations are based on T2K

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

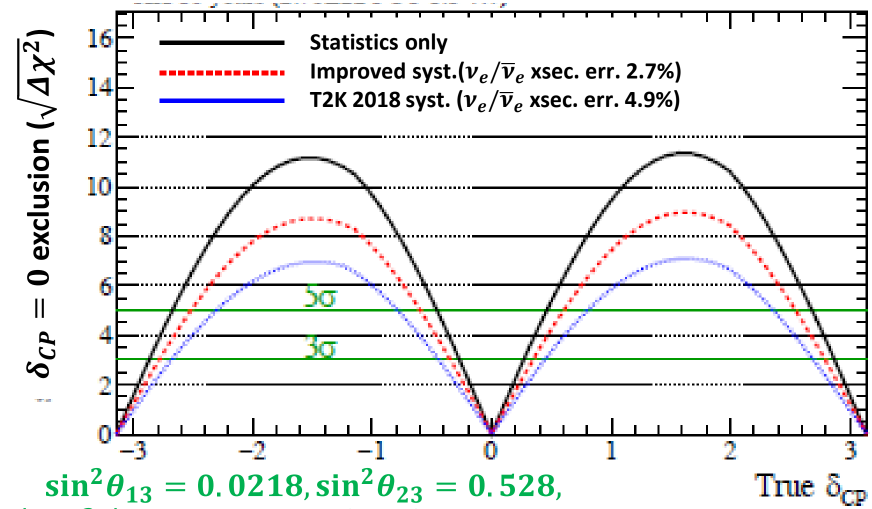


$\sin^2\theta_{13} = 0.0218, \sin^2\theta_{23} = 0.528,$
$|\Delta m^2_{32}| = 2.509 \times 10^{-3} [\mathrm{eV}^2]$

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

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

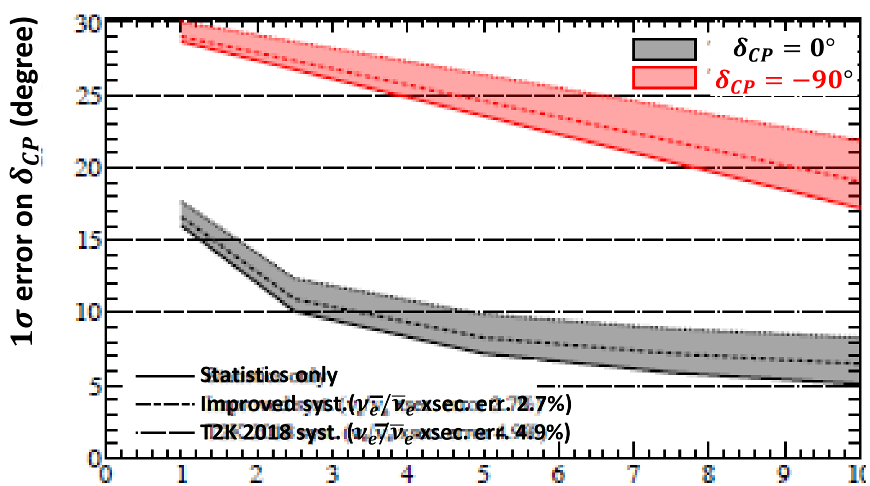
HK years (2.7×10^{22} POT, $\nu:\bar{\nu}$ =1:3)



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

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

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



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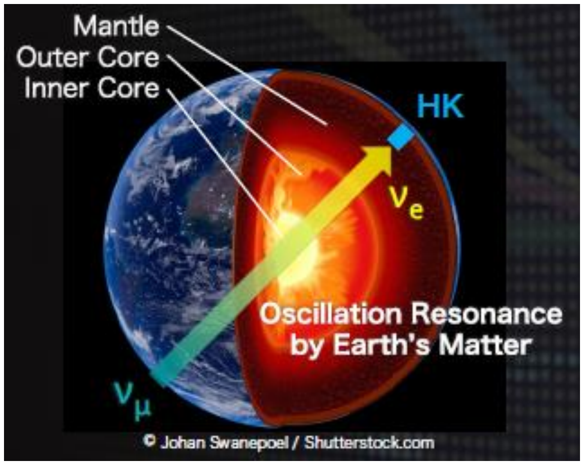
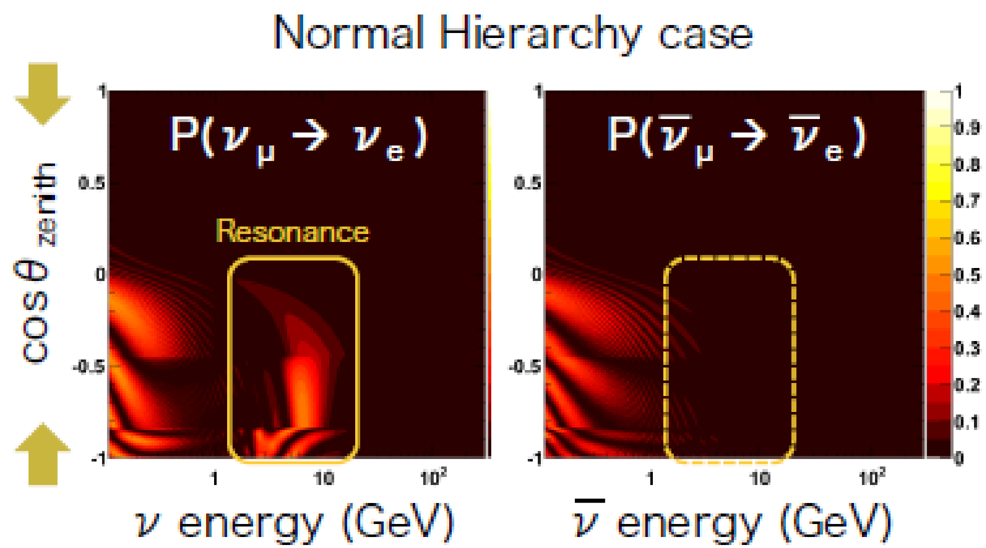
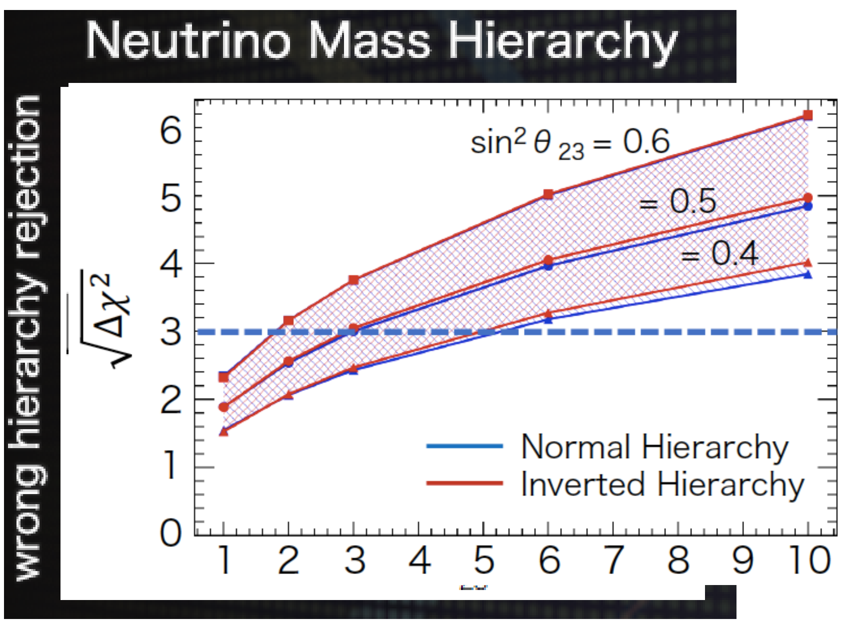
HK years
(2.7×10^{22} POT, $\nu:\bar{\nu}$ =1:3)

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

(2) Mass hierarchy determination





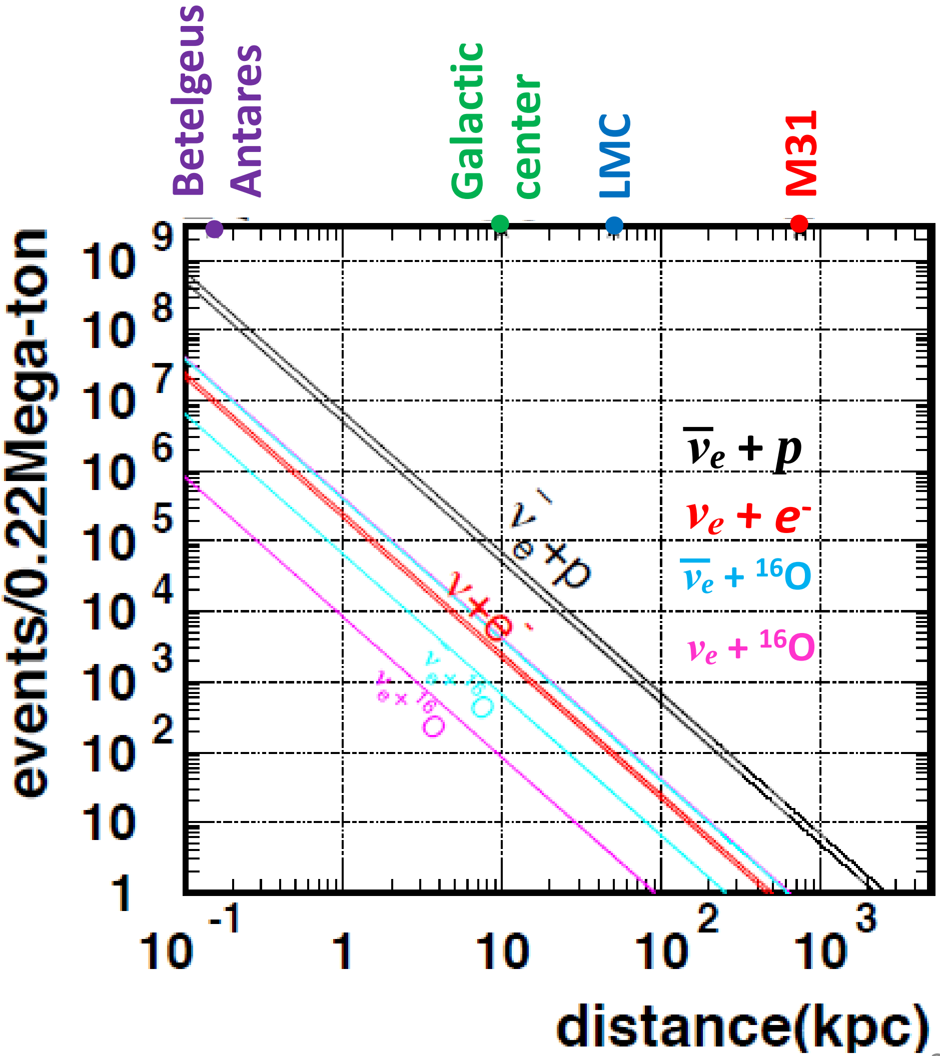


- The resonance appears for ν_e ($\bar{\nu}_e$) in NH (IH) case.
- Sensitivity enhanced by combining atm & beam ν data.→ **3σ determination within 2 ~ 5 years !**

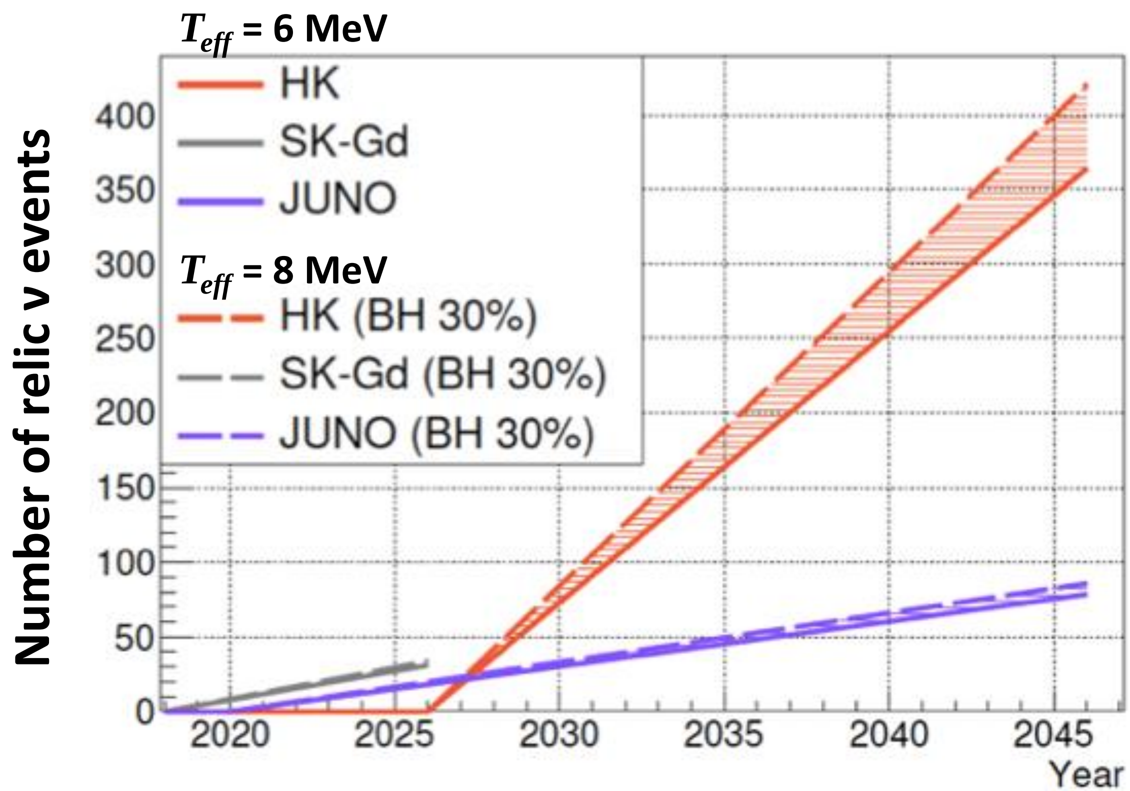
(3) Neutrino astrophysics

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



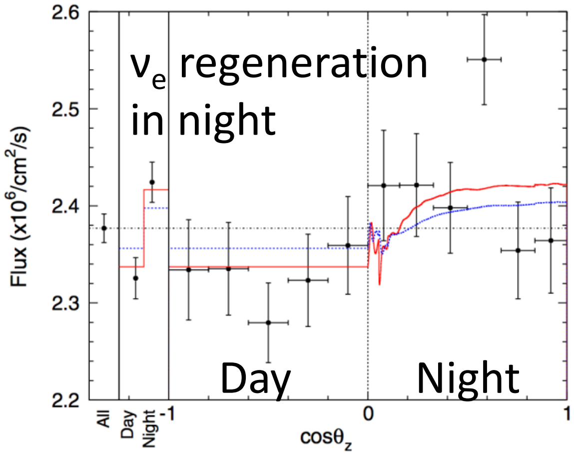
SN relic *ν*

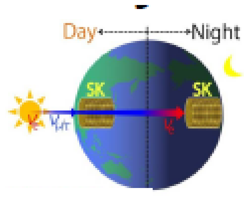
- 1st discovery by SK-Gd
- HK will measure the spectrum.

(3) Neutrino astrophysics-solar ν-

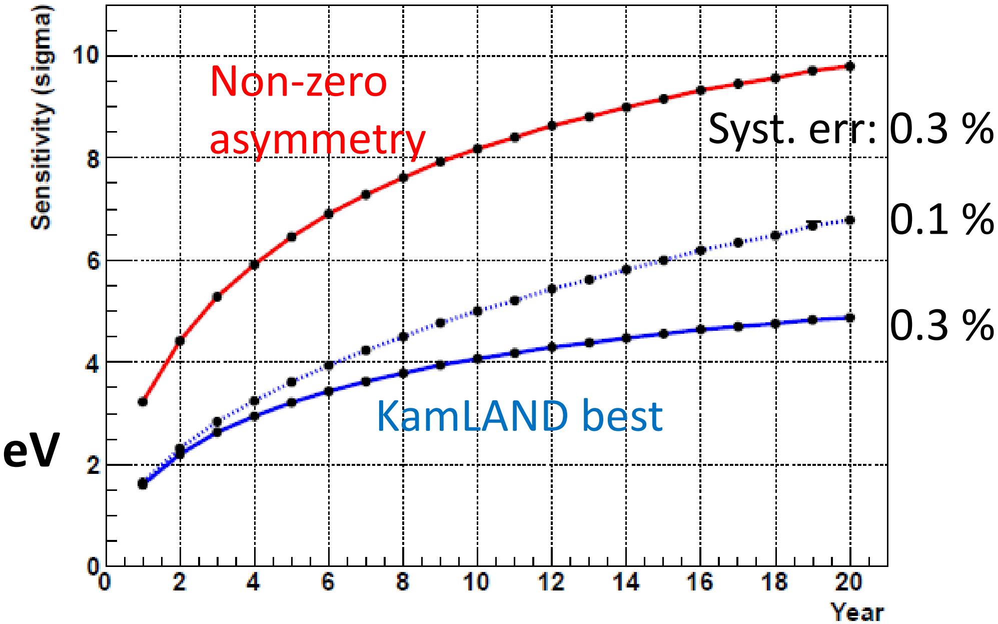
Day-night asymmetry observation

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



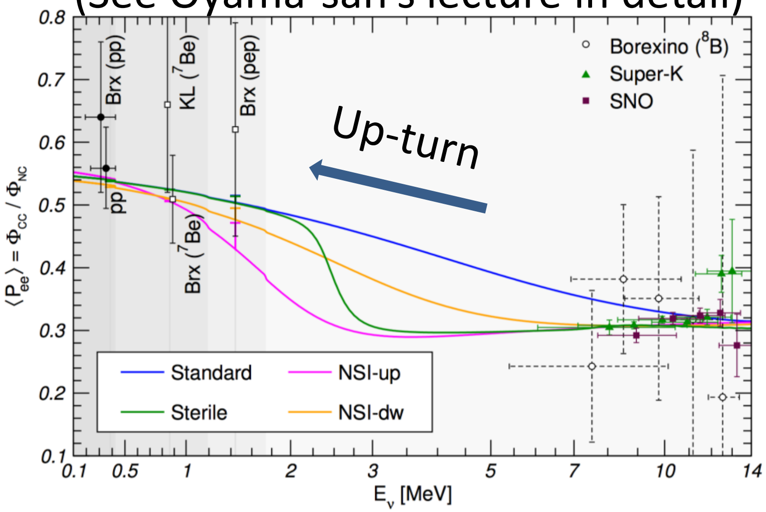


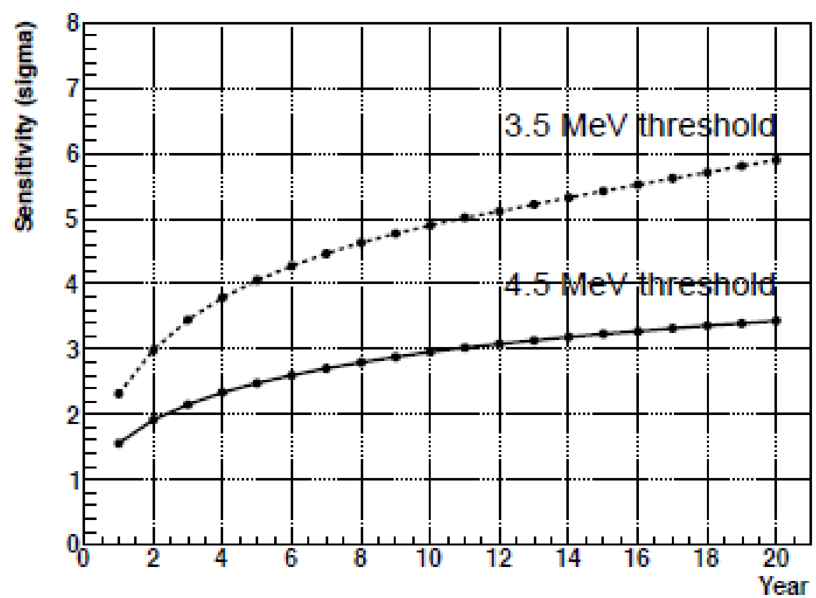
E_{thr} = 6.5 MeV



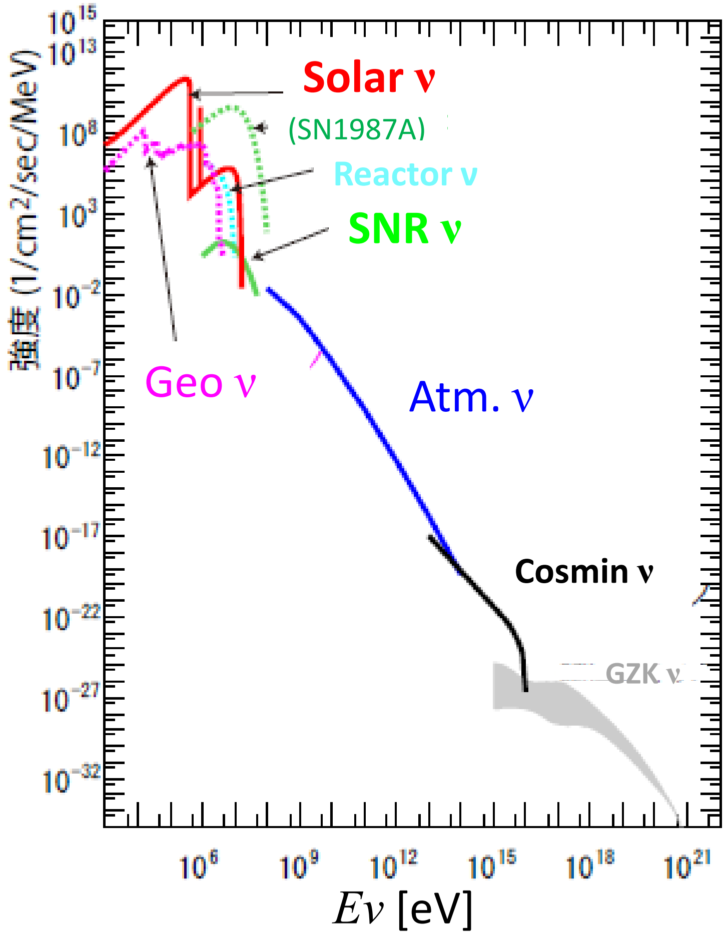
Energy spectrum up-turn

(See Oyama-san's lecture in detail)

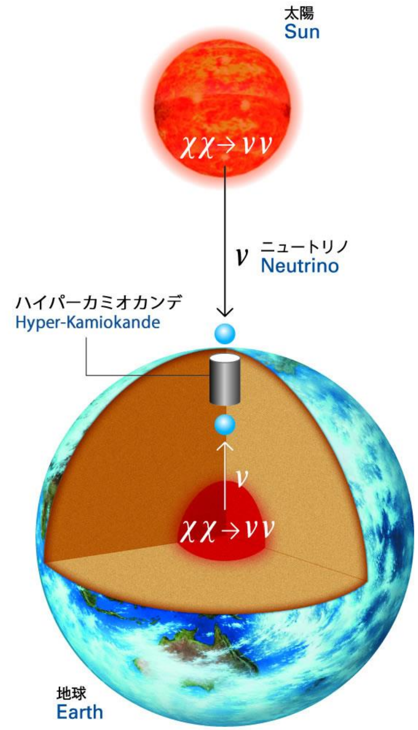




Cosmic ν Observation



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.

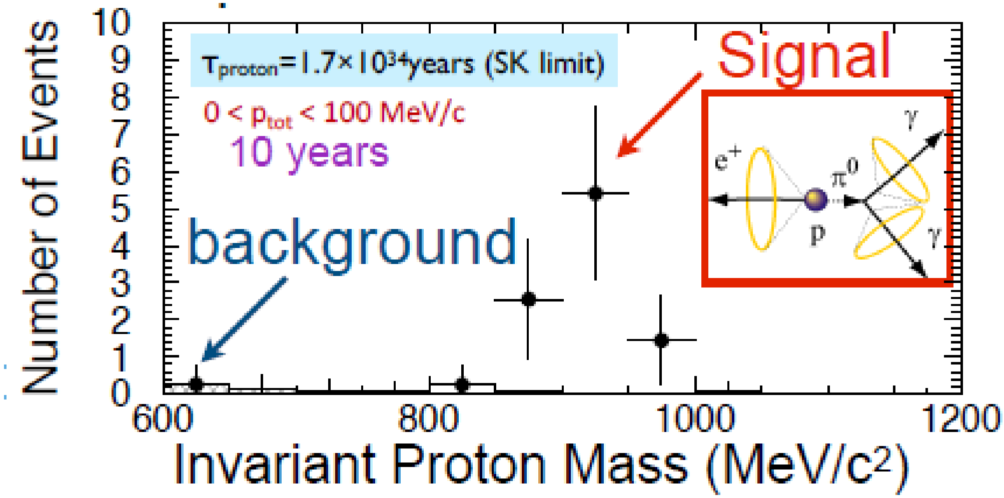


Indirect DM search:
Hyper-Kamiokande detects the neutrinos generated by the interaction of dark matters in the Sun or the earth.

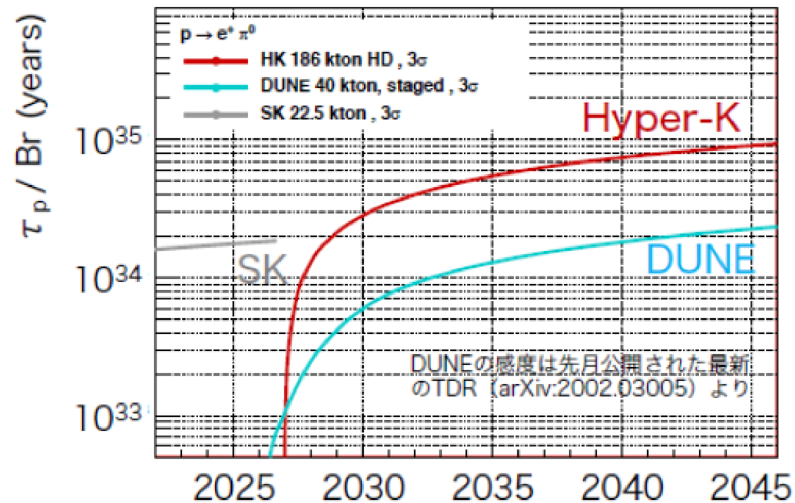
(4) Proton decay search

*See Miura-san's lecture

■$p \to e^+\pi^0$ search



3σ discovery sensitivity



20 years

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)

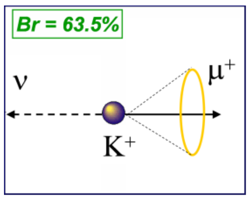
3σ discovery sensitivity : τ_p/Br = 10^{35} years for 20 year operation.

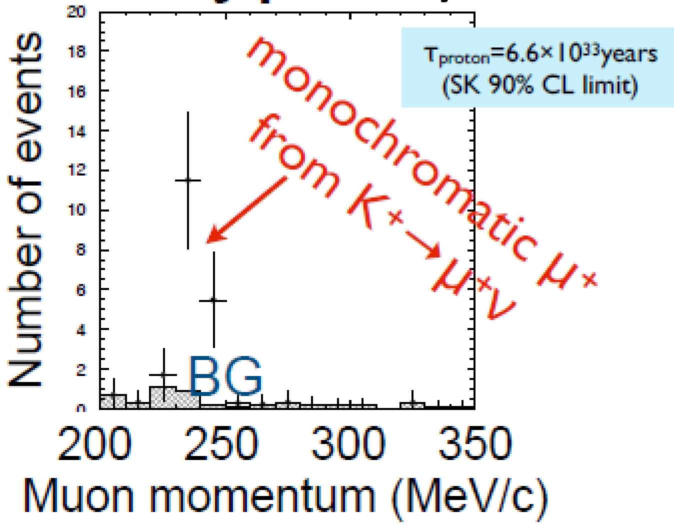
(4) Proton decay search

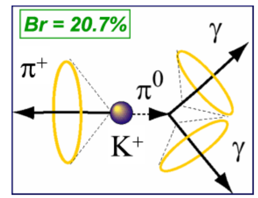
■$p \rightarrow \nu K^{+}$ search

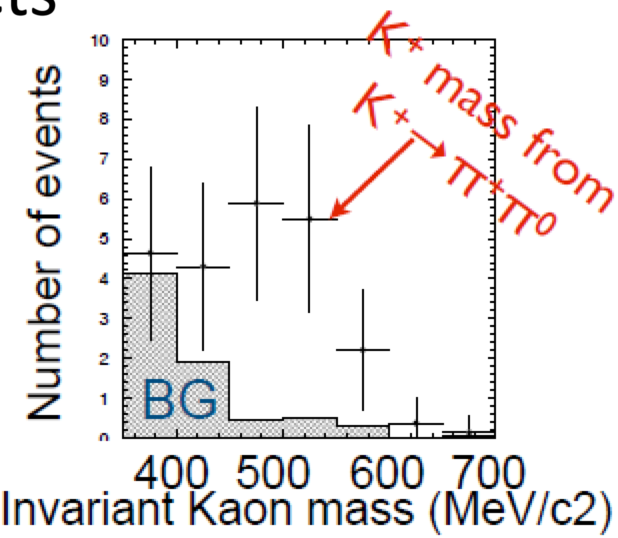
*See Miura-san's lecture

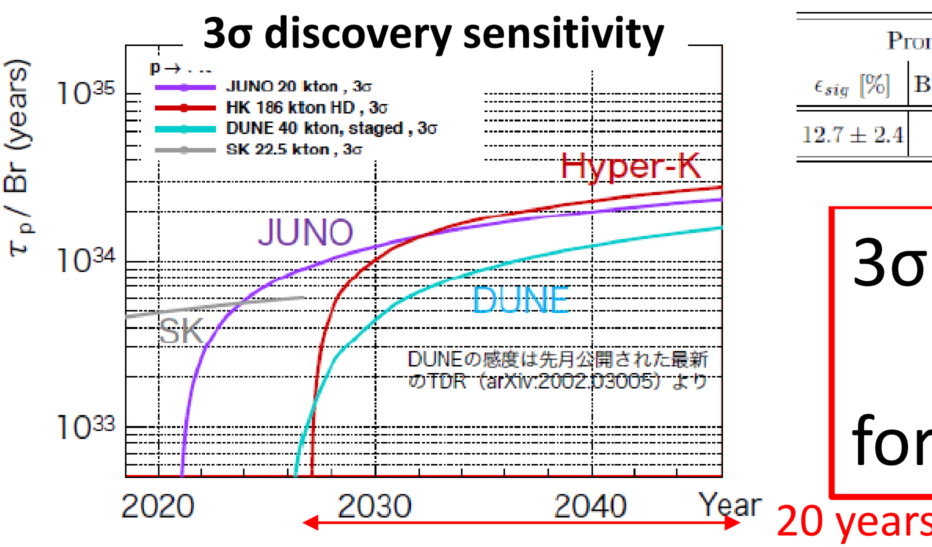
- K^{+} is identified by its decay products









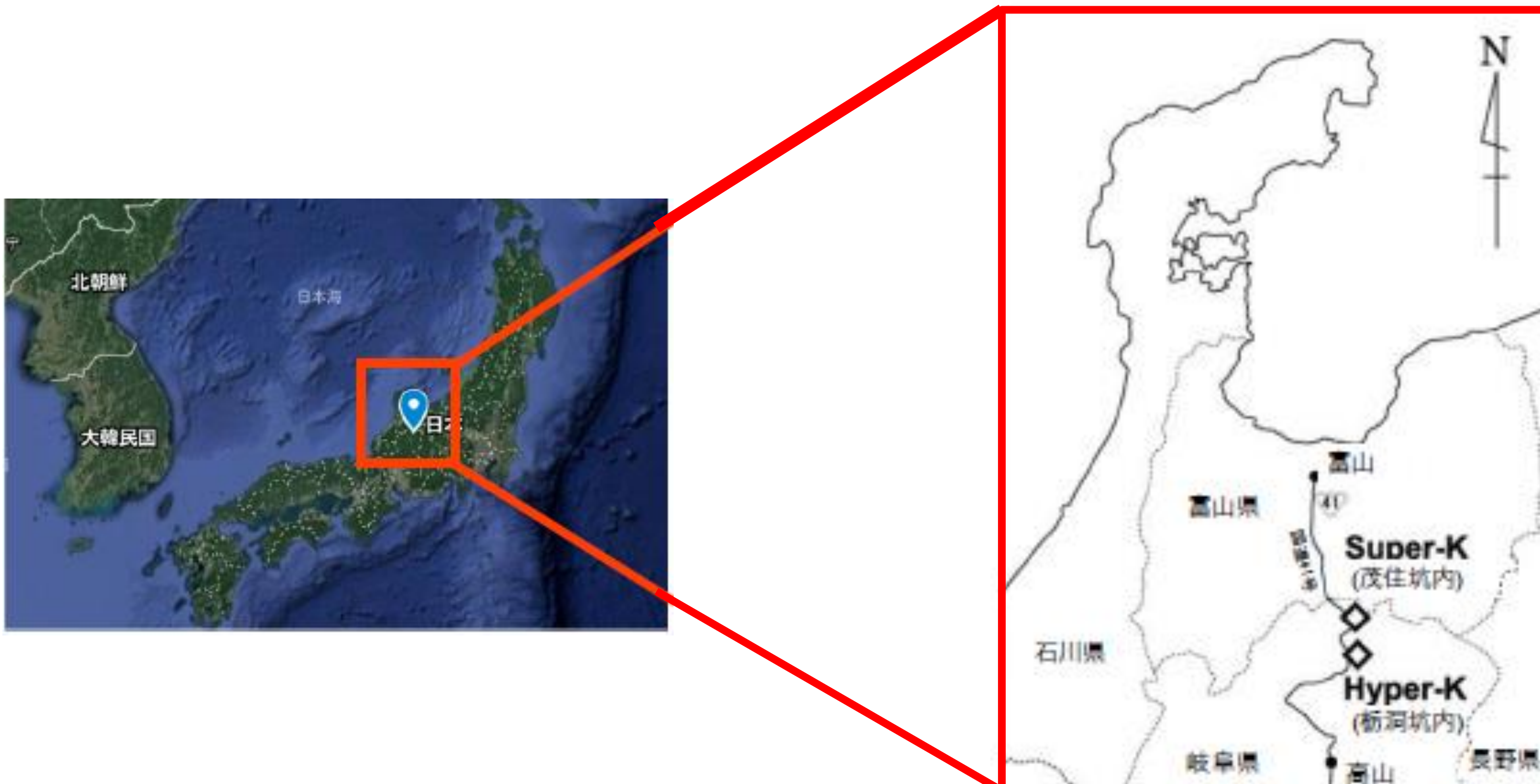


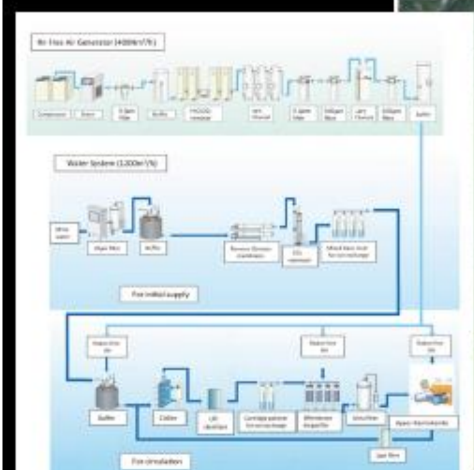
Prompt γ		$\pi^{+}\pi^{0}$		p_{μ} Spectrum		
ϵ_{sig} [%]	Bkg [/Mton·yr]	ϵ_{sig} [%]	Bkg [/Mton·yr]	ϵ_{sig} [%]	Bkg [/Mton·yr]	σ_{fit} [%]
12.7 ± 2.4	0.9 ± 0.2	10.8 ± 1.1	0.7 ± 0.2	31.0	1916.0	8.0

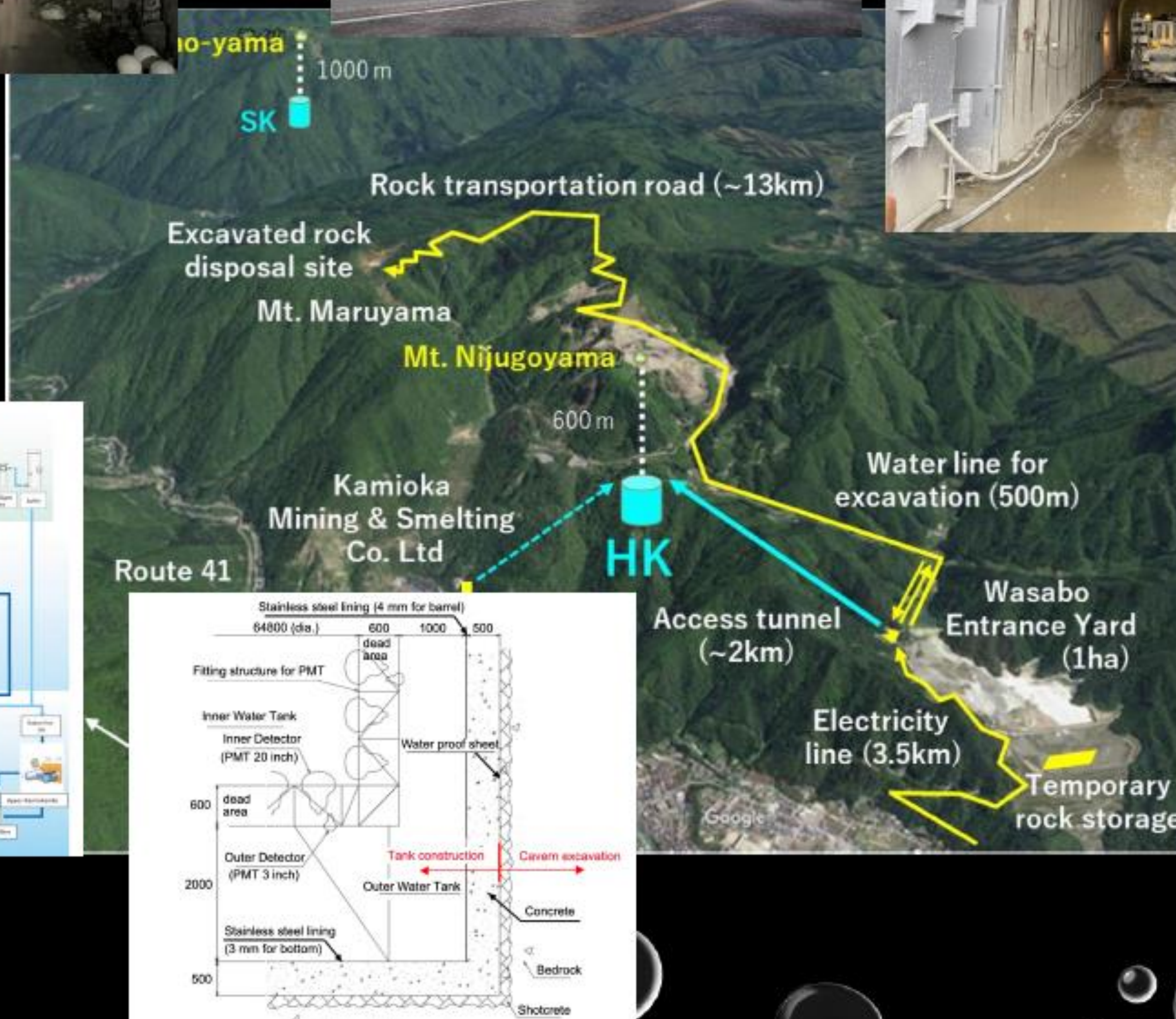
3σ discovery sensitivity :
$\tau_p/Br = 3 \times 10^{34}$ years
for 20 year operation.

Detector Location

- 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

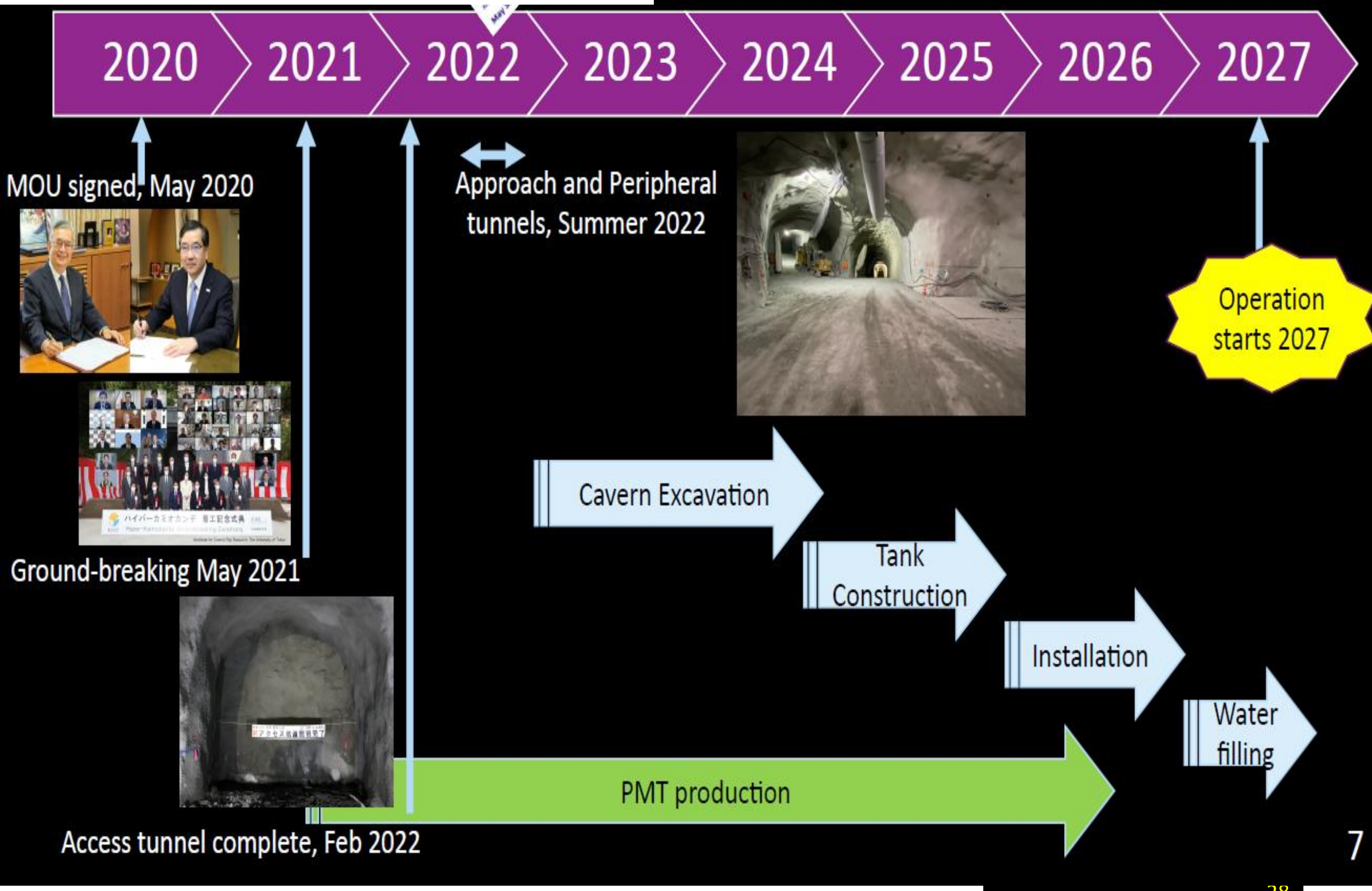


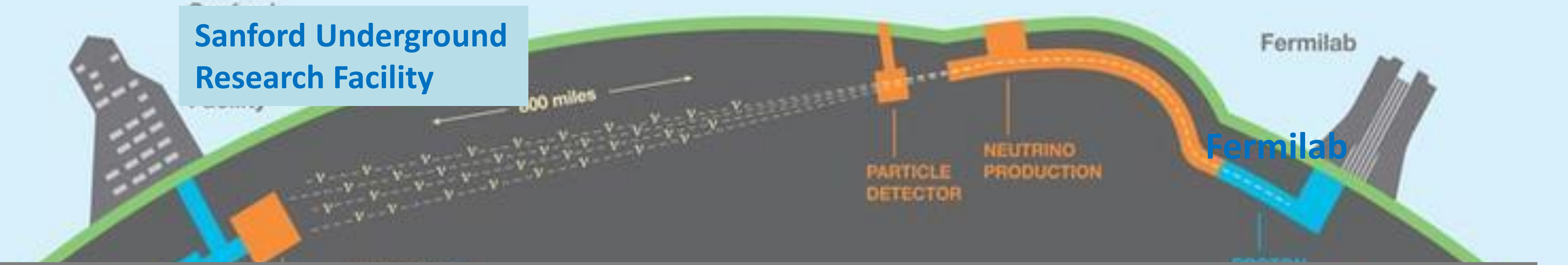




1000 m
SK
Rock transportation road (~13km)
Excavated rock disposal site
Mt. Maruyama
Mt. Nijugoyama
600 m
Kamioka Mining & Smelting Co. Ltd
Route 41
HK
Water line for excavation (500m)
Wasabo Entrance Yard (1ha)
Access tunnel (~2km)
Electricity line (3.5km)
Temporary rock storage
Google
Stainless steel lining (4 mm for barrel)
64800 (dia.)
600
1000
500
dead area
Fitting structure for PMT
Inner Water Tank
Inner Detector (PMT 20 inch)
Water proof sheet
600
dead area
Tank construction
Cavern excavation
Outer Detector (PMT 3 inch)
2000
Outer Water Tank
Concrete
Stainless steel lining (3 mm for bottom)
Bedrock
500
Shotcrete

Project Status





2. DUNE

(Deep Underground Neutrino Experiment)

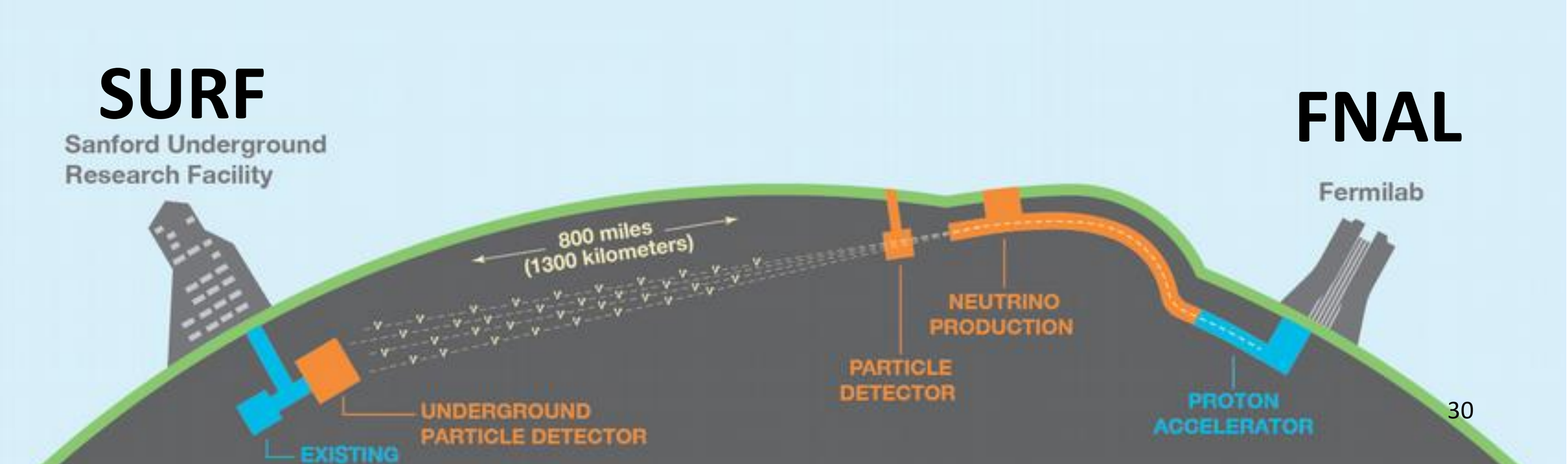
Introducing DUNE

- 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)

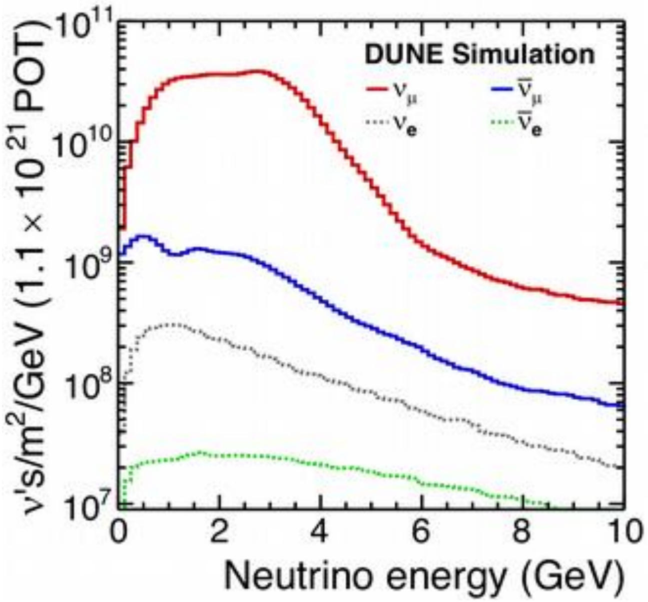
  (2) SN burst ν's and astrophysics

  (3) Proton decay

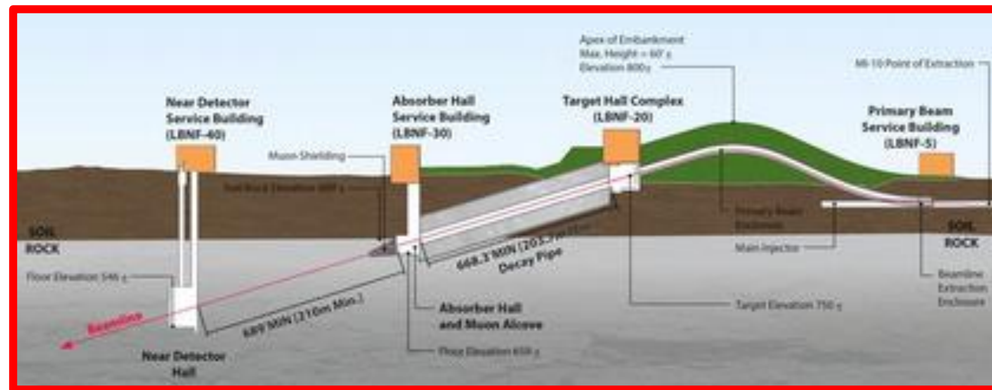


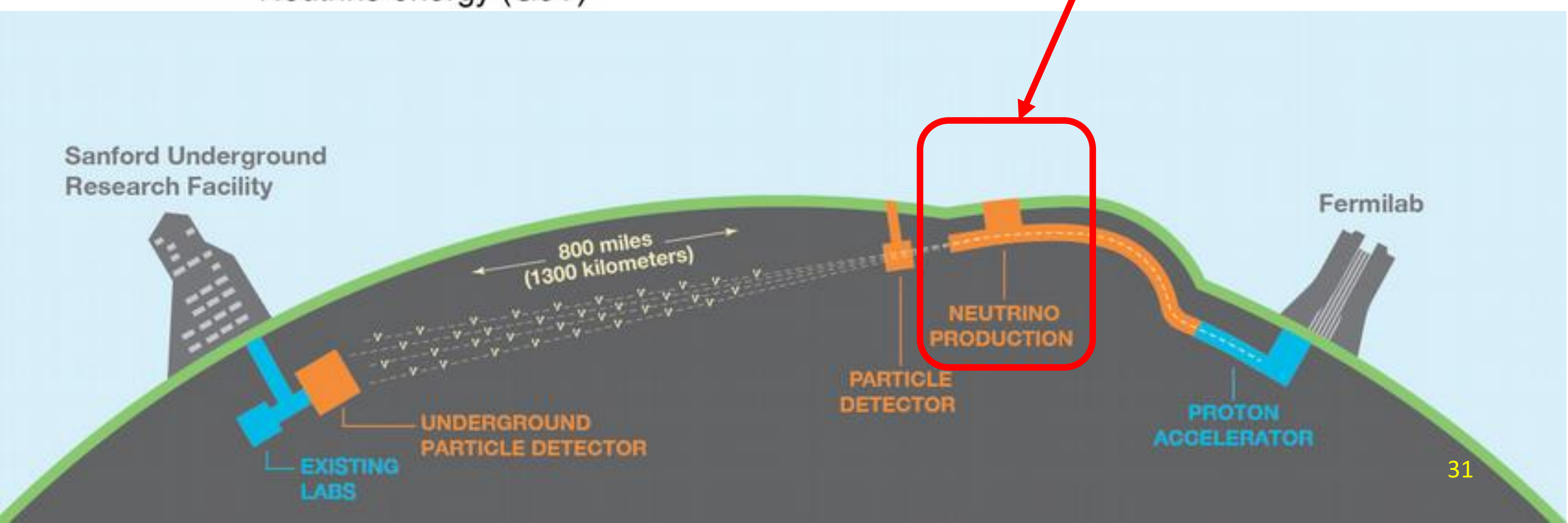
ν source

MW-scale wide band beam

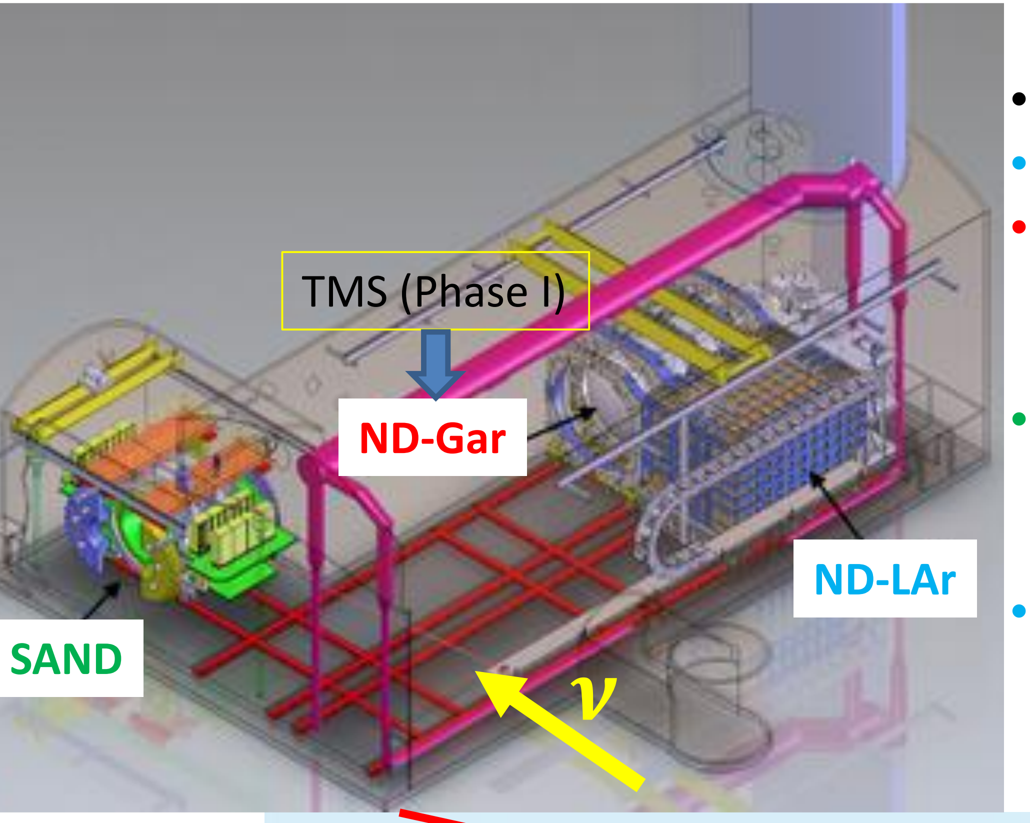


Long Baseline Neutrino Facility (LBNF)

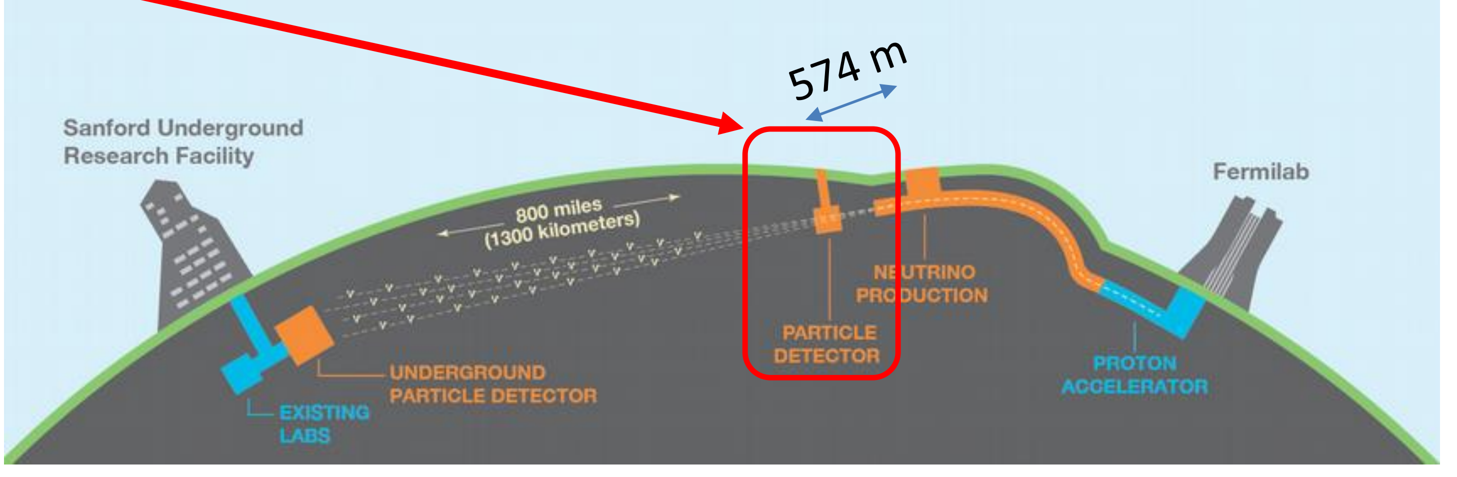




Near Detector (ND)

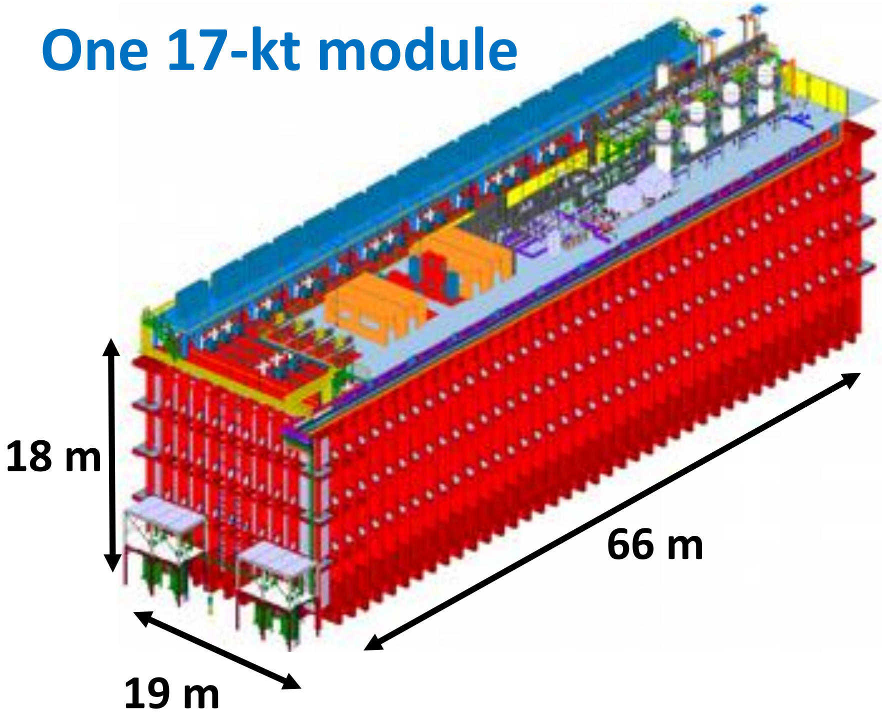


- Located 574 m from the beam target
- ND-LAr: pixelated LArTPC
- ND-Gar (in Phase II): high-pressure GAr TPC surrounded by ECAL and 0.5 T magnet
- **SAND** (System for on-Axis Neutrino Detection): **tracker surrounded by ECAL and 0.6 T magnet**
- ND-LAr/ND-GAr can move to off-axis up to 33m modifying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

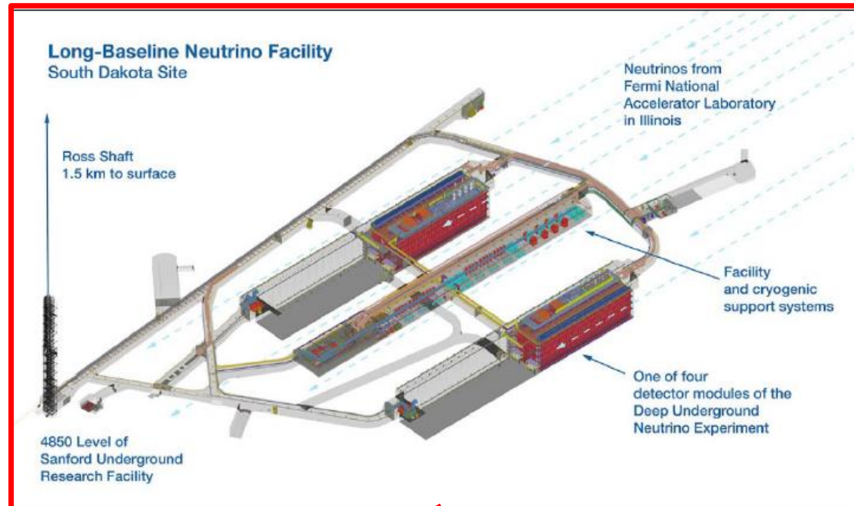


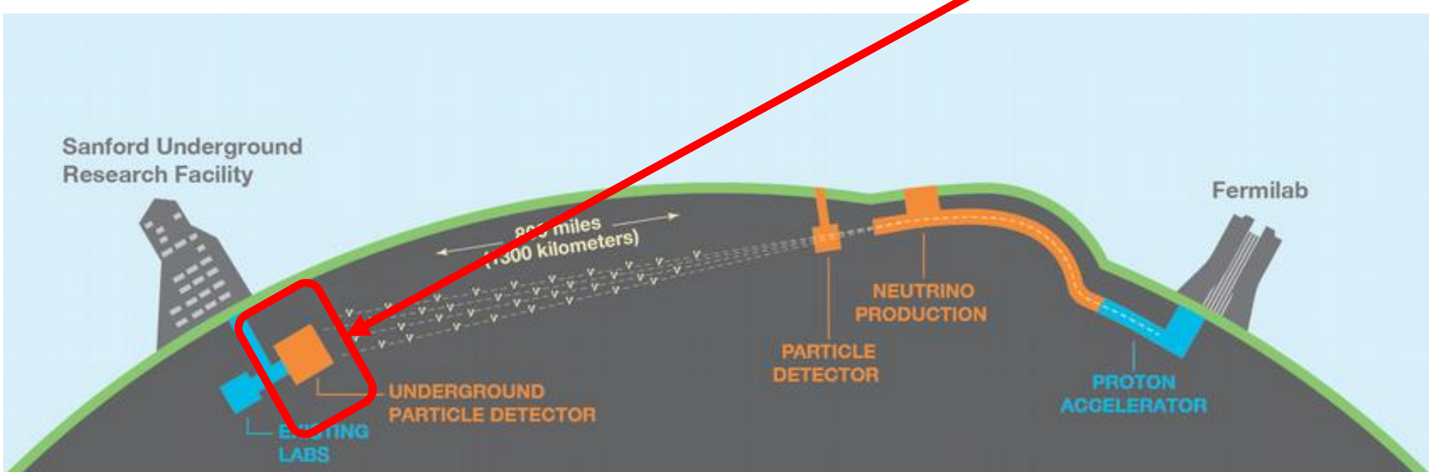
Far Detector (FD)

One 17-kt module

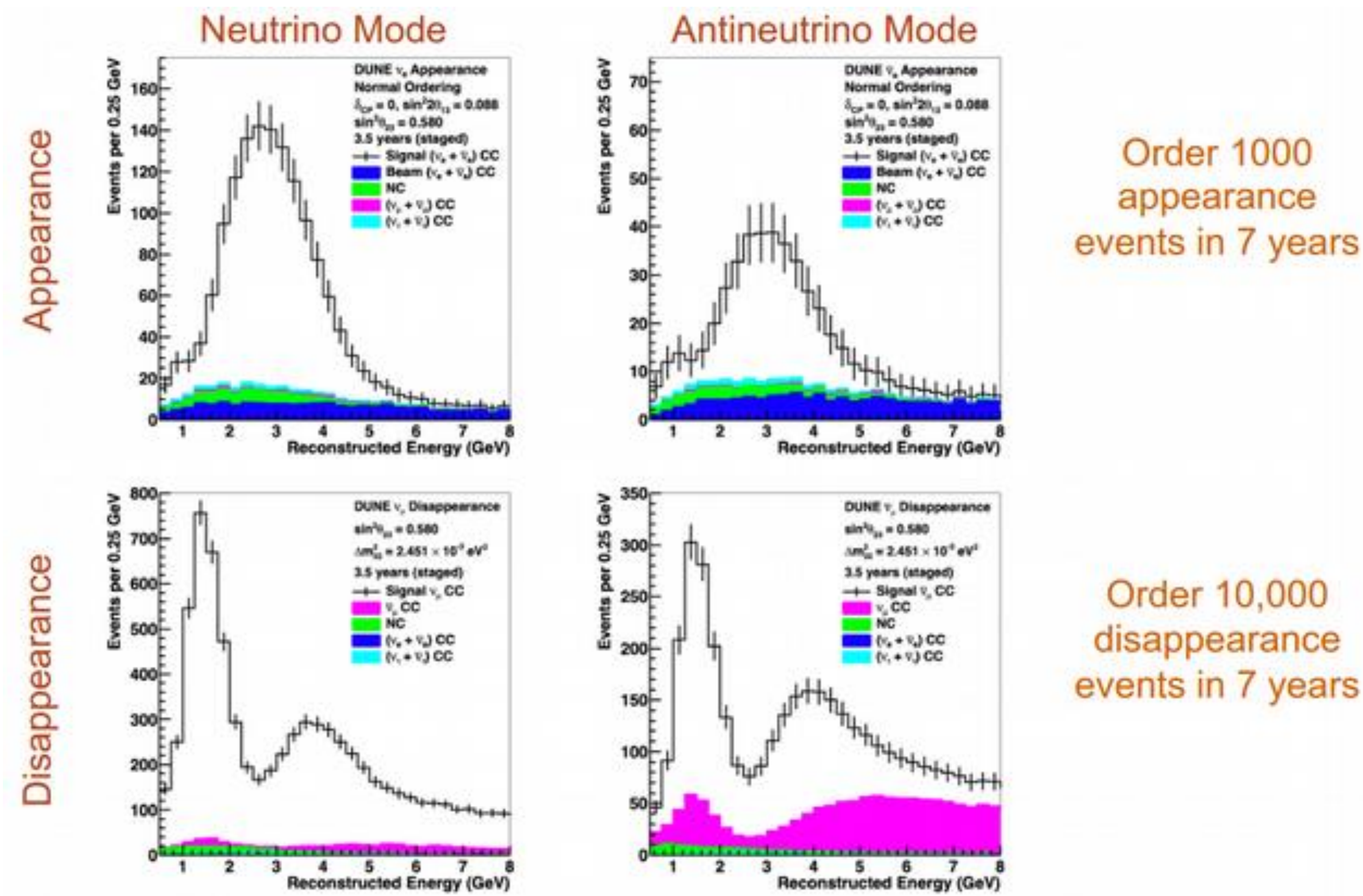


4 LArTPC detector modules

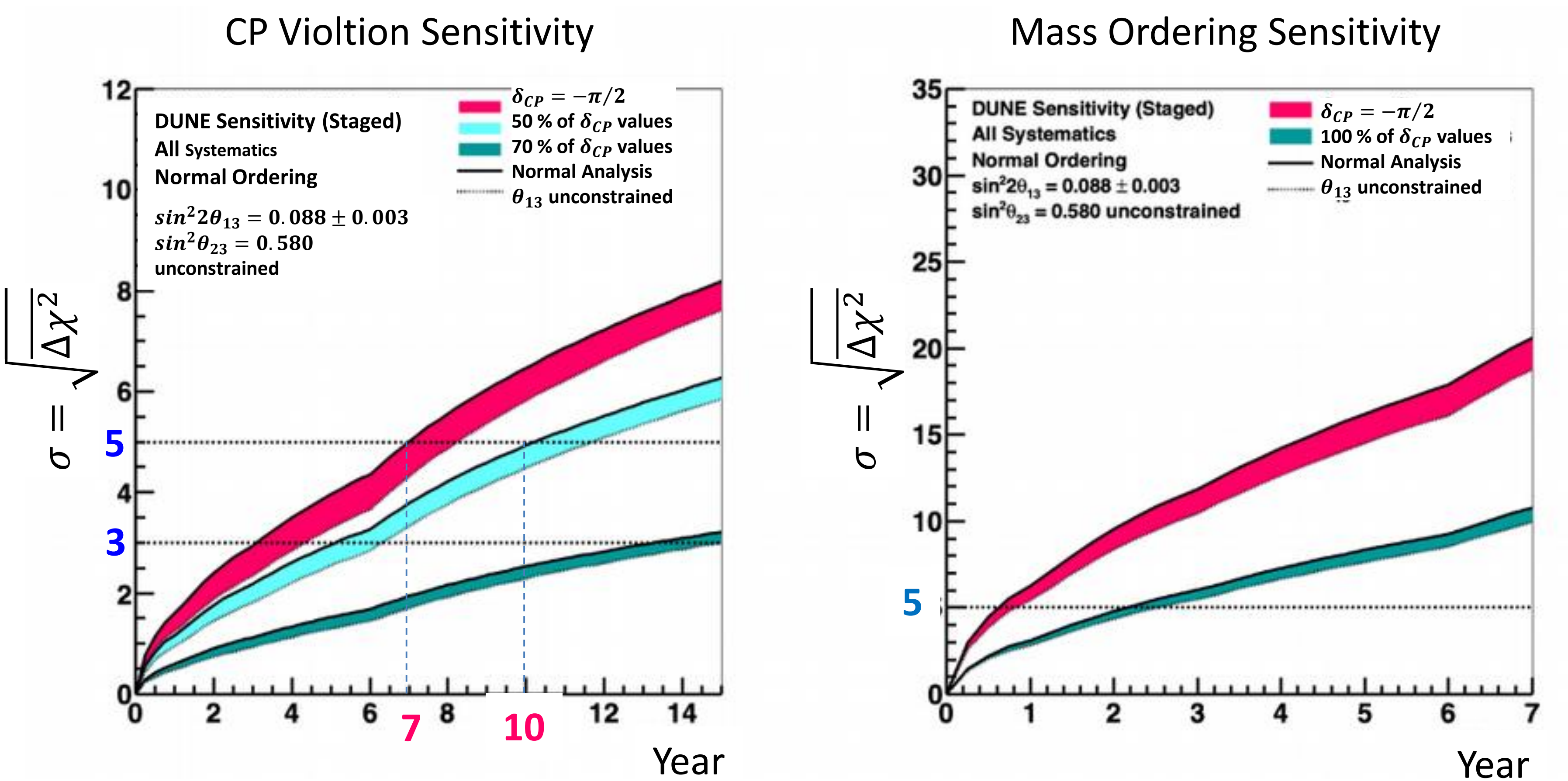




ν Oscillation Prospect

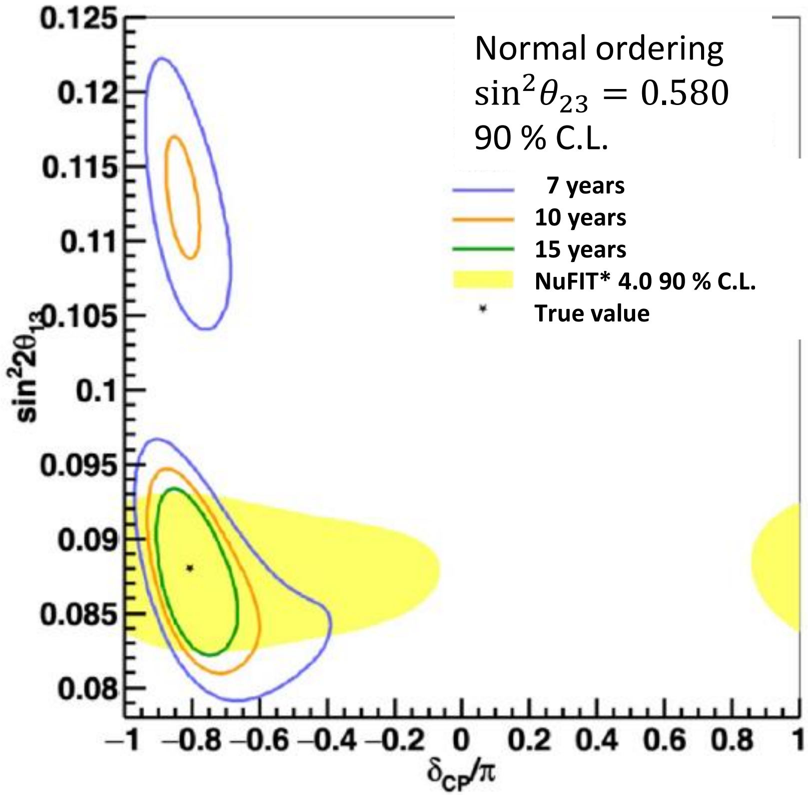


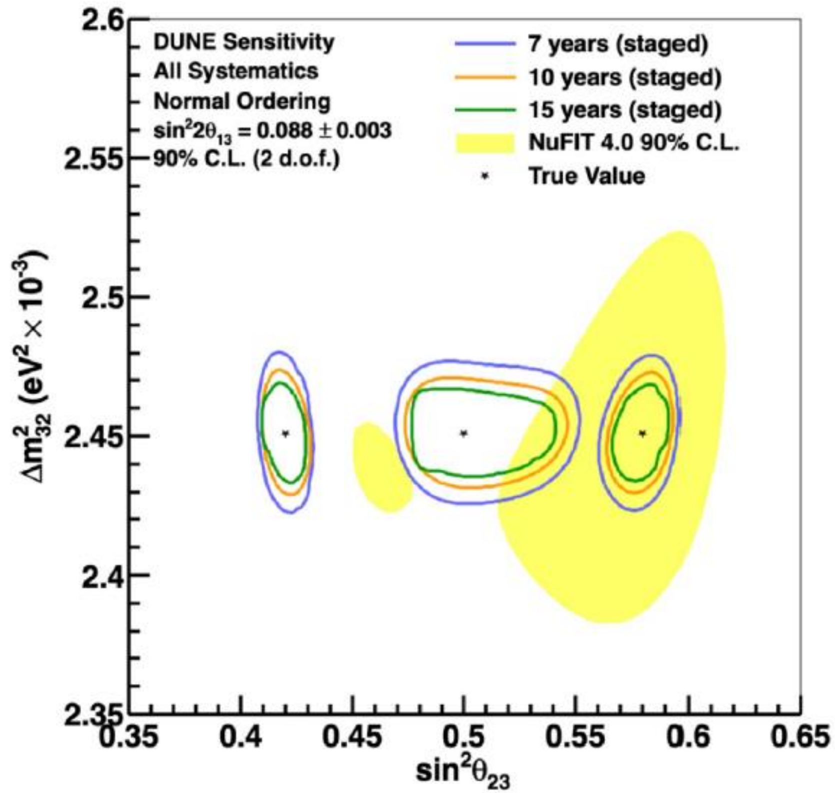
Sensitivity Over Time



- **CPV discovery if true $\delta_{CP} = -\pi/2$ in ∼7 years**
- **CPV discovery for 50 % of true δ_{CP} values in ∼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:

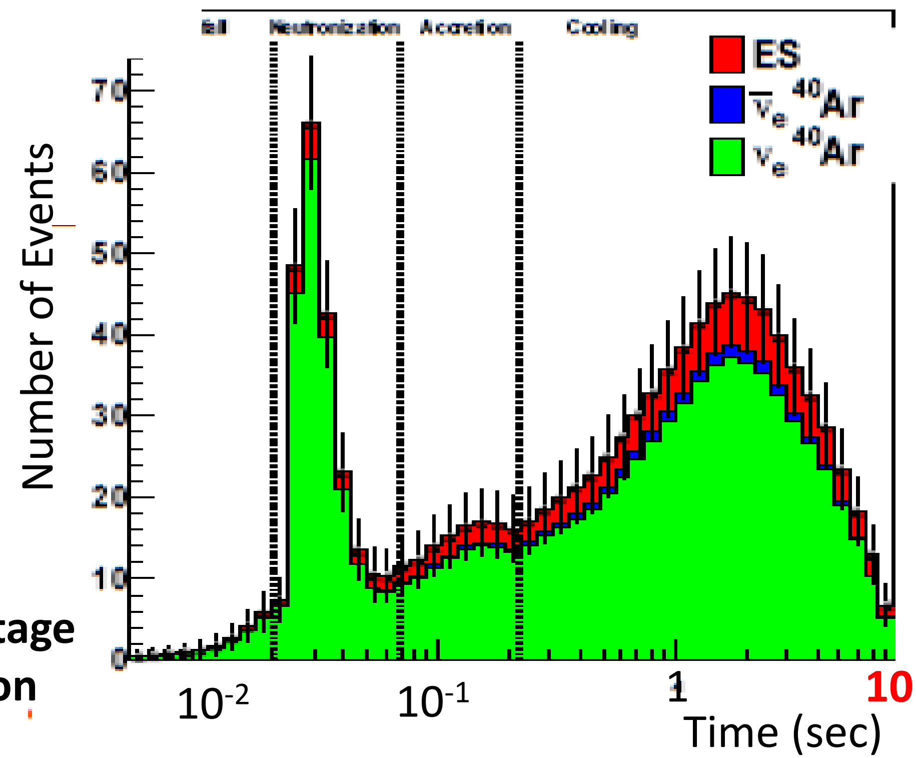
•An updated global analysis of neutrino oscillation measurements determining the leptonic mixing matrix and the neutrino masses in the framework of the Standard Model with 3 massive neutrinos and some of its extensions.

•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

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



Highlights include:

Possibility to "see" neutron star formation stage

Even the potential to see black hole formation

Proton Decay

- Watch many protons with the capability to see a single decay in a liquid argon TPC
- For example, look for kaons from p-decay modes such as

$$p \rightarrow K^{+} + \bar{\nu}$$

- Clean signature with very low BG

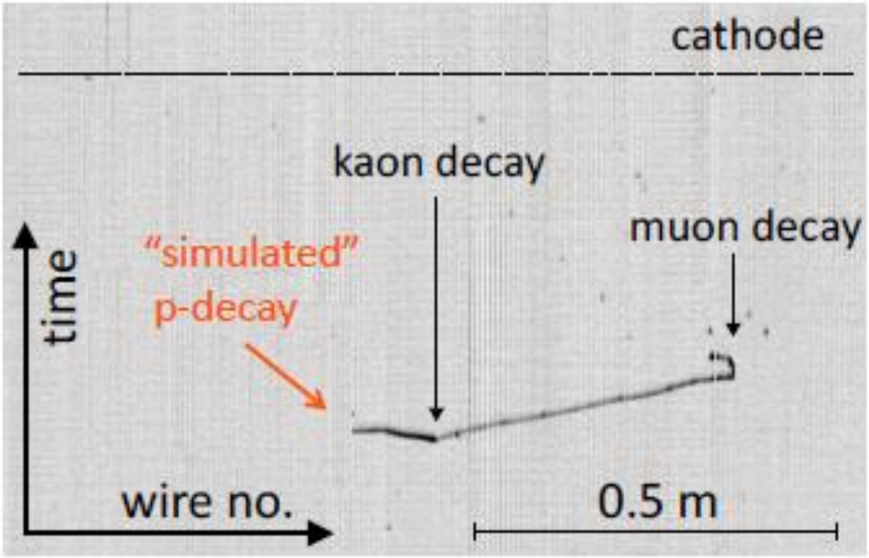


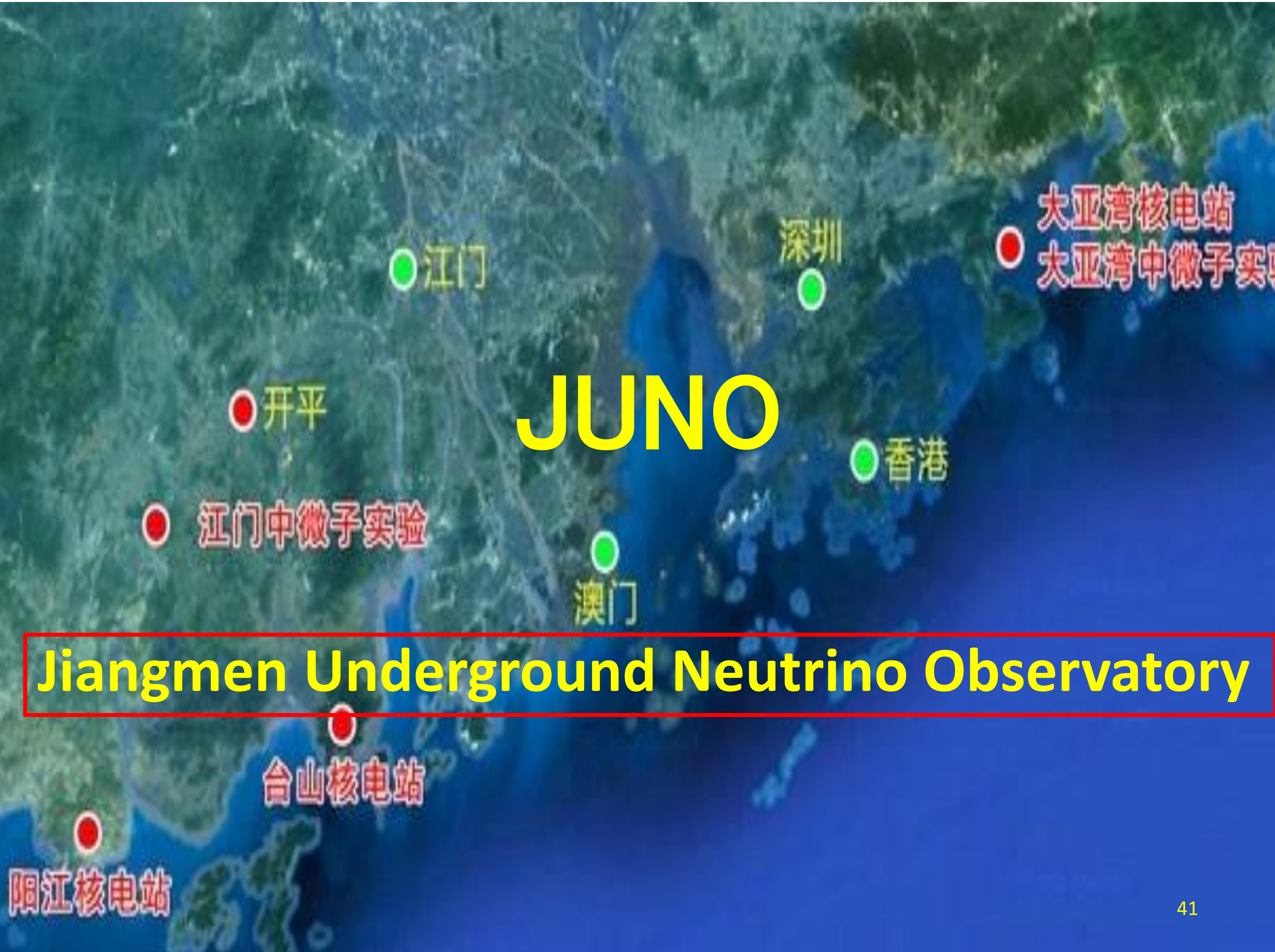
Image in a LAr TPC

DUNE: Schedule & Plans

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

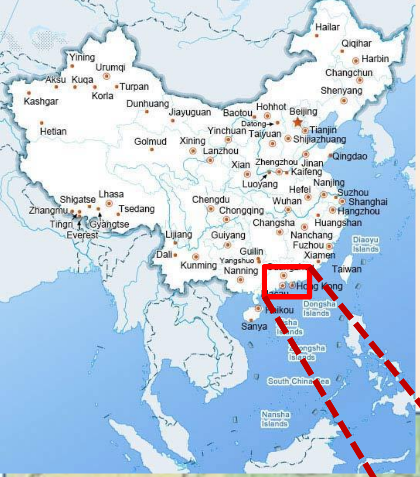
3. Reactor Neutrino Experiment

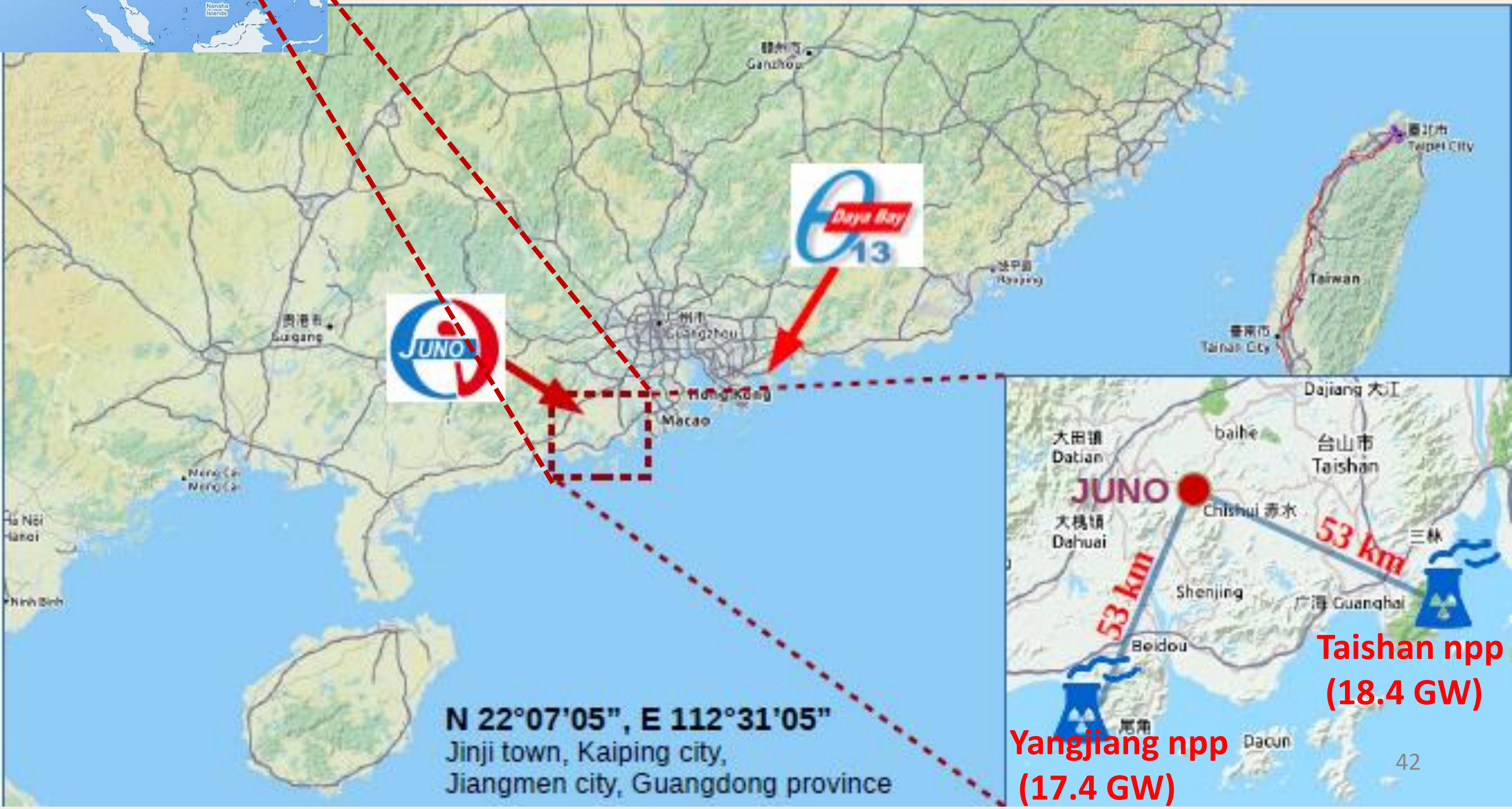
JUNO



Jiangmen Underground Neutrino Observatory

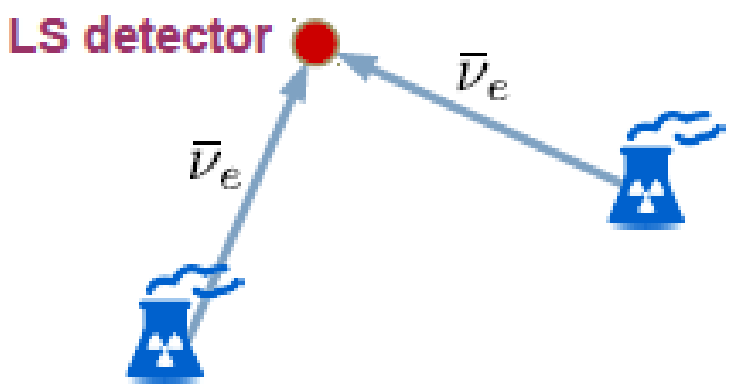
Location

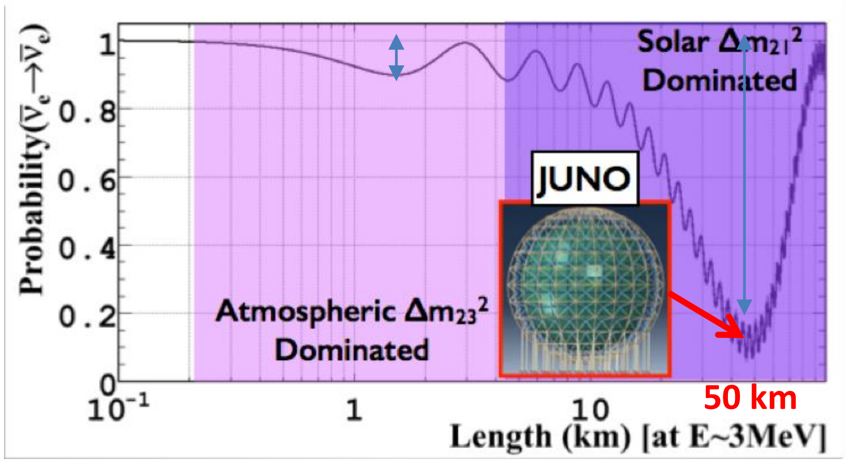




Daya Bay
13
JUNO
Hong Kong
Macao
Taipei City
Taiwan
Dajiang 大江
baihe
台山市
Taishan
大田镇
Datian
JUNO
Chishui 赤水
大槐镇
Dahuai
53 km
53 km
Shenjing
广海 Guanghai
Beidou
Dacun
Taishan npp
(18.4 GW)
Yangjiang npp
(17.4 GW)
N 22°07'05", E 112°31'05"
Jinji town, Kaiping city,
Jiangmen city, Guangdong province

JUNO Layout



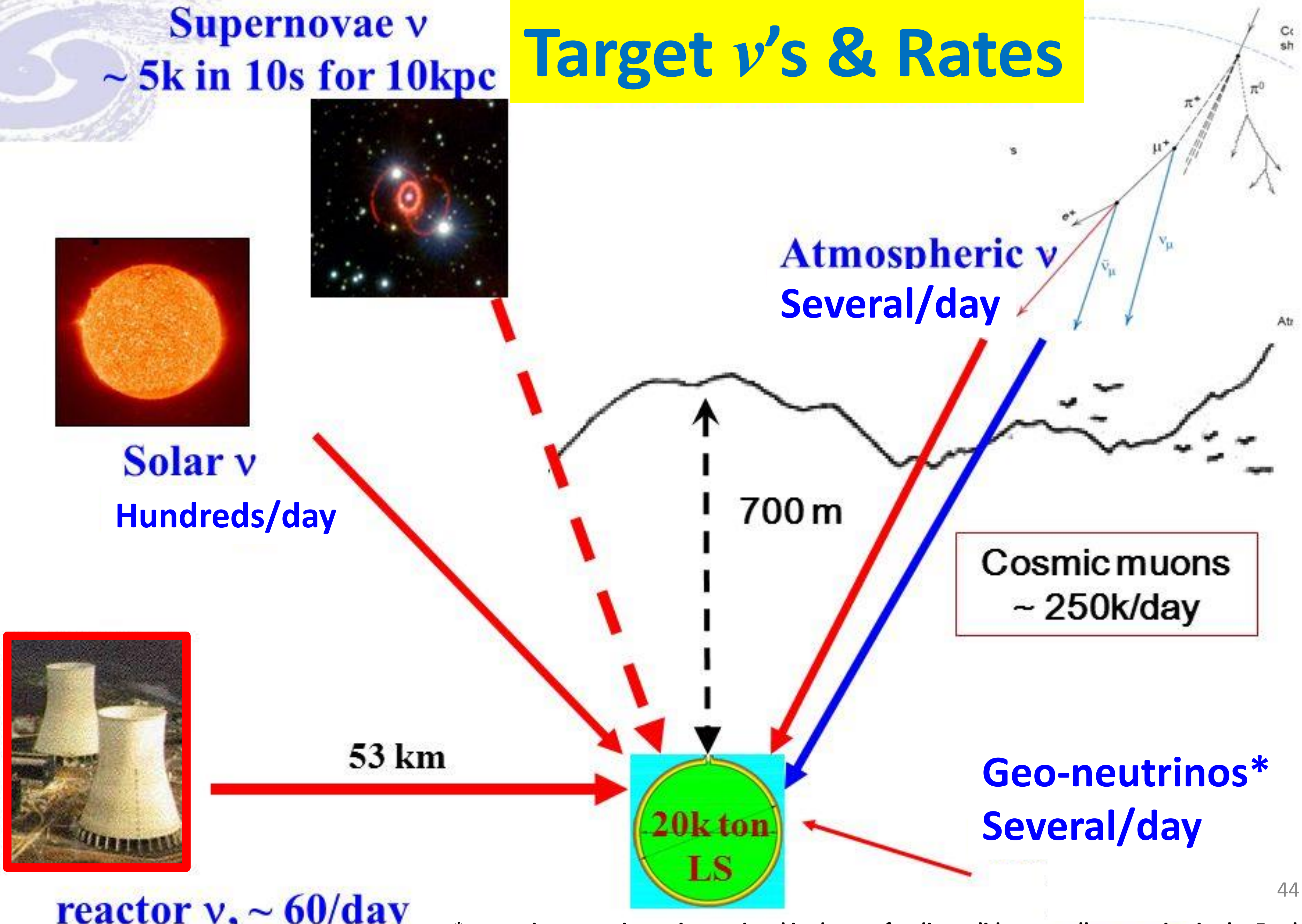


- **Source: 6+4 reactors** (Yangjiang and Taishan NPP)
- **Baseline: 53 km**
- **Detection channel: inverse β-decay**

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

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

Target ν's & Rates

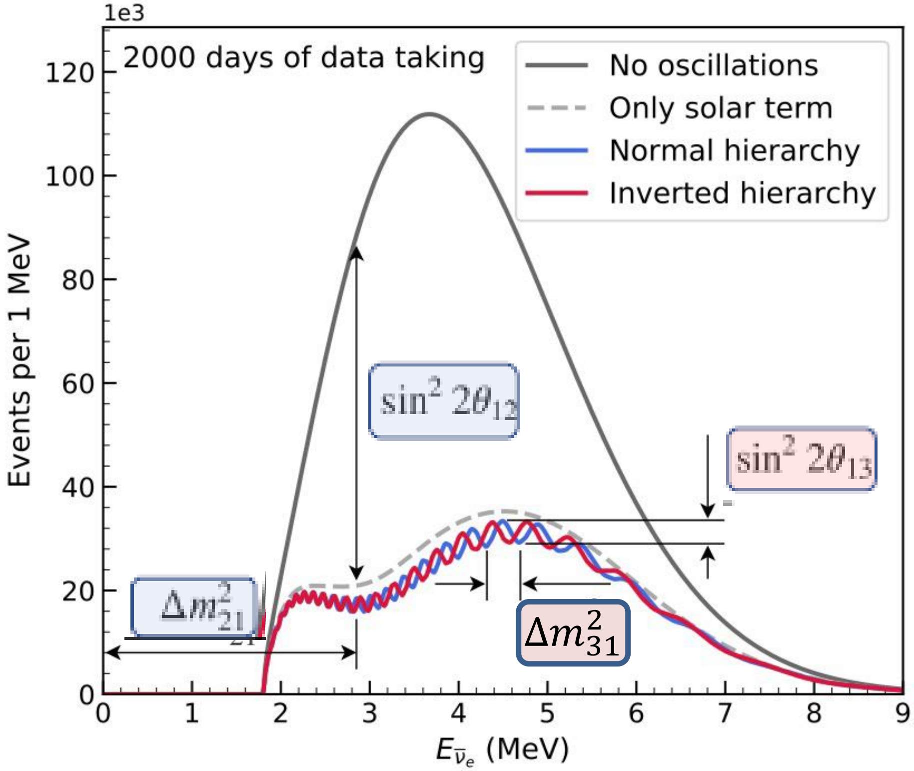


*a neutrino or antineutrino emitted in decay of radionuclide naturally occurring in the Earth

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)

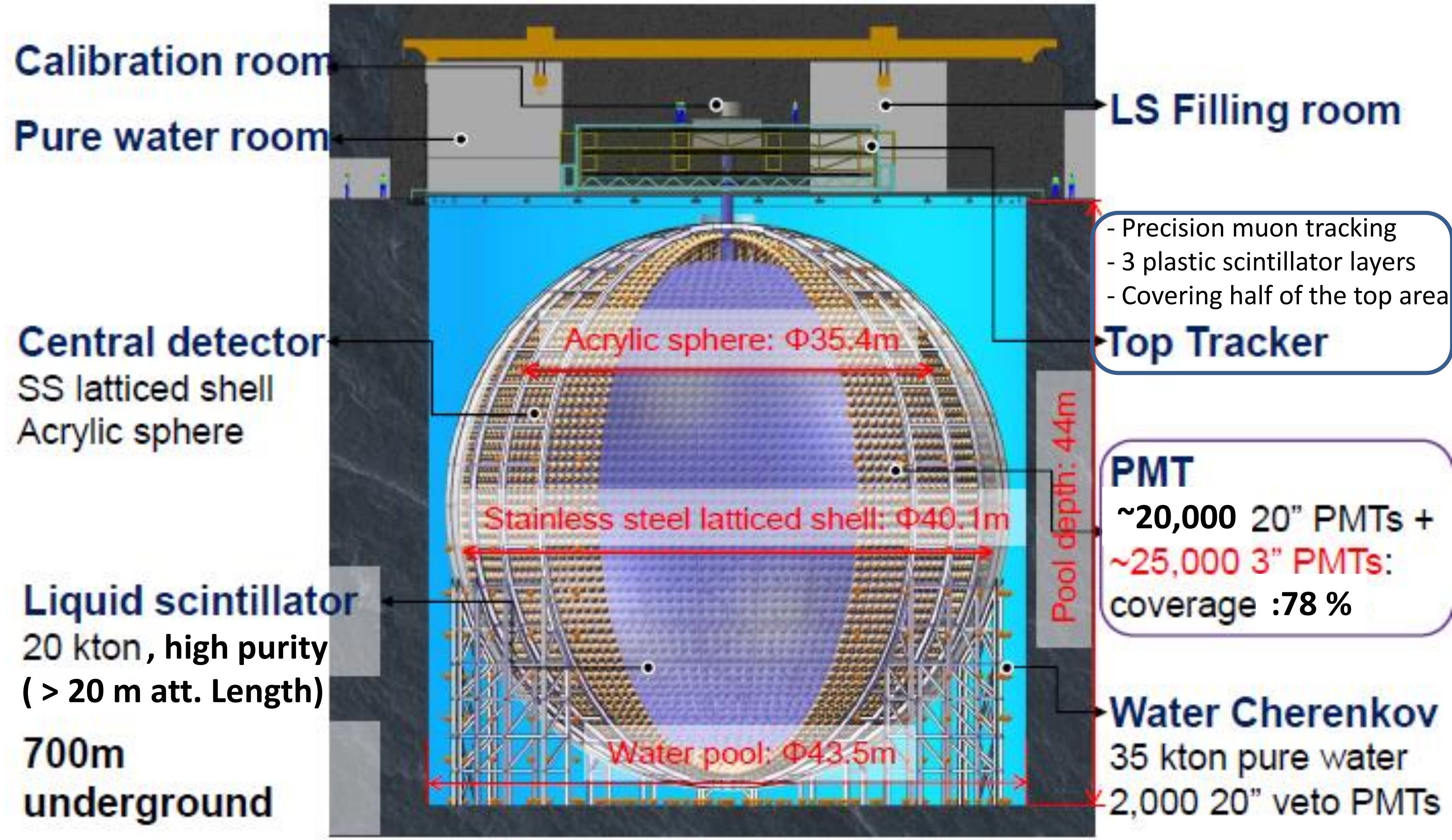
- The energy resolution is one of the key factors for determining neutrino mass ordering.
- 3σ MO sensitivity within 6 years with only JUNO data

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

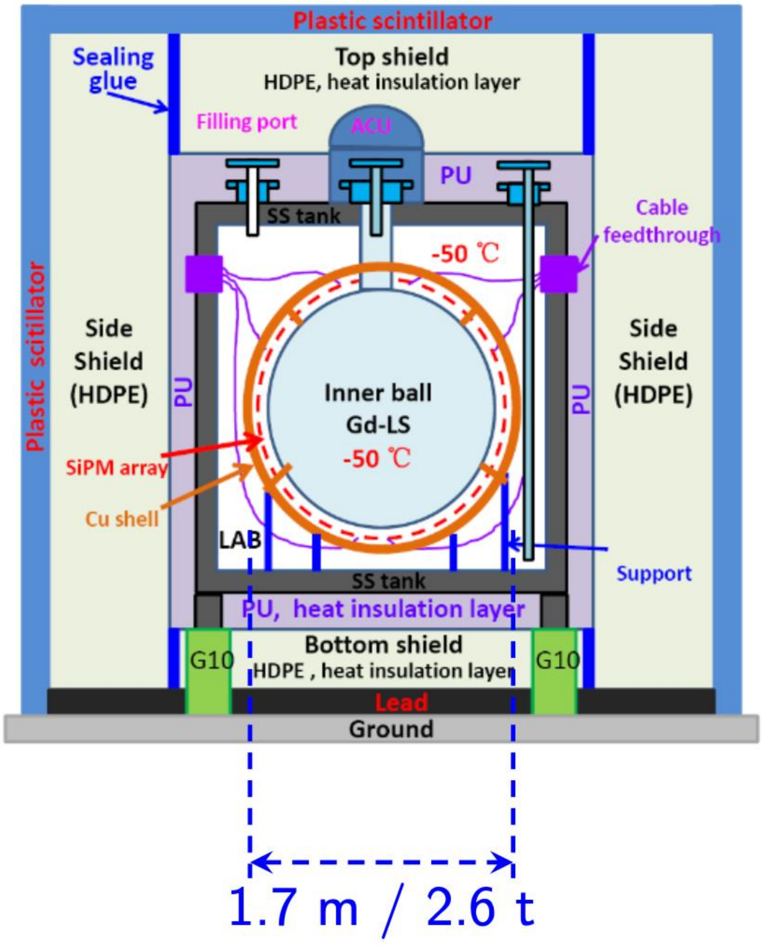


$\Delta E/E$ = 3% @ 1 MeV

JUNO-TAO
(Taishan Antineutrino Obsevatory)

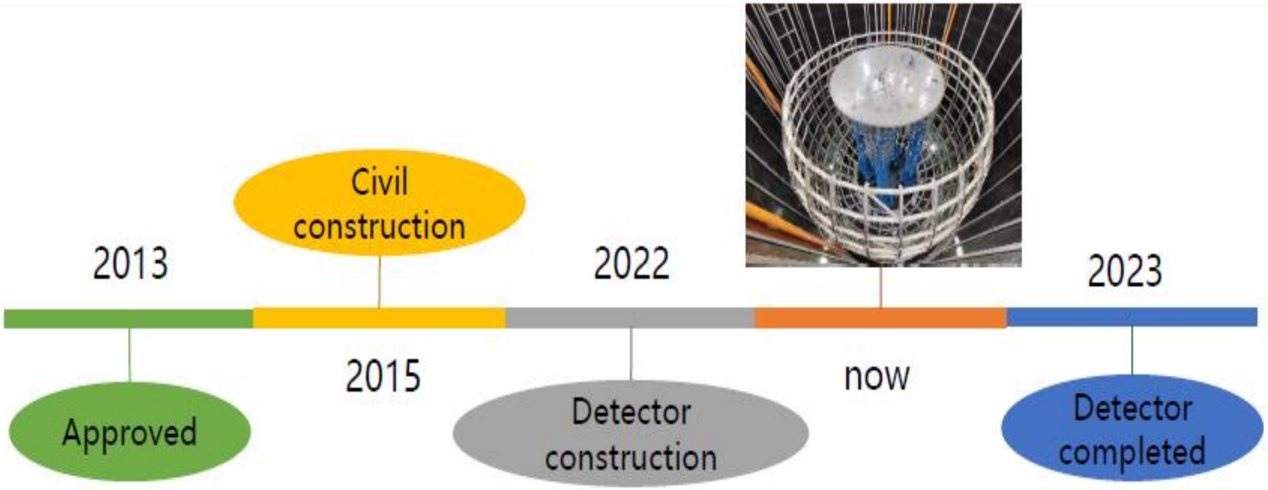
- Precision measurement of the reactor $\overline{\nu_e}$ spectrum.
- Provide a model independent reference spectrum for JUNO
- Reactor monitoring and safeguard.
- Detector:
  - 30 -35 m from a Taishan reactor core
  - 1t FV Gd-LS at -50 ℃
  - 10 m^2 SiPM of > 50% Photon Detection Efficiency & ~ 94 % coverage
  - <2% energy resolution@1 MeV

Prototype will be built in summer.



Outlook

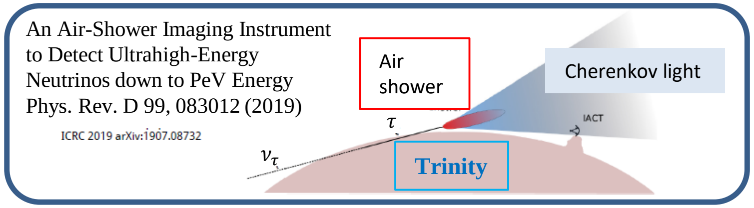
Physics	Sensitivity
Neutrino Mass Ordering	3σ (~1σ) in 6 yrs by reactor (atmospheric) $\bar{\nu}_e$
Neutrino Oscillation Parameters	Precision of $\sin^2\theta_{12}$, Δm^2_{21}, $\lvert\Delta m^2_{32}\rvert$ < 0.5% in 6 yrs
Supernova Burst (10 kpc)	~5000 IBD, ~300 eES and ~2000 pES of all-flavor neutrinos
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

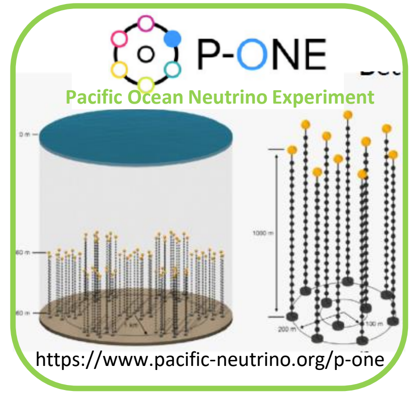


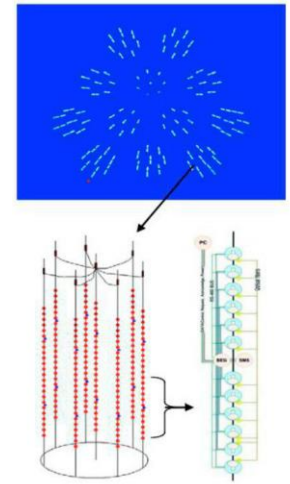
4. Atmospheric & Astrophysical Neutrino Measurements

Future Plans

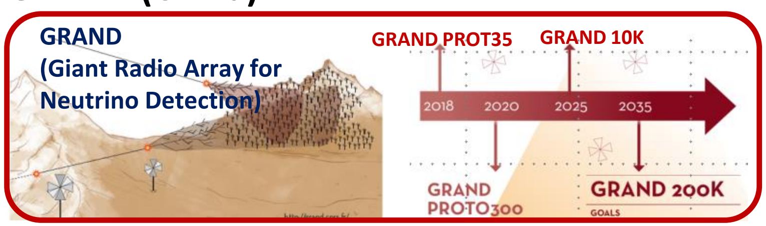
- **Optical Detection of Cherenkov Radiation**
  - IceCube -Upgrade & Gen 2- @ South Pole
  - P-ONE @ Pacific Ocean
  - Trinity
  - Baikal GVD @ Lake Baikal





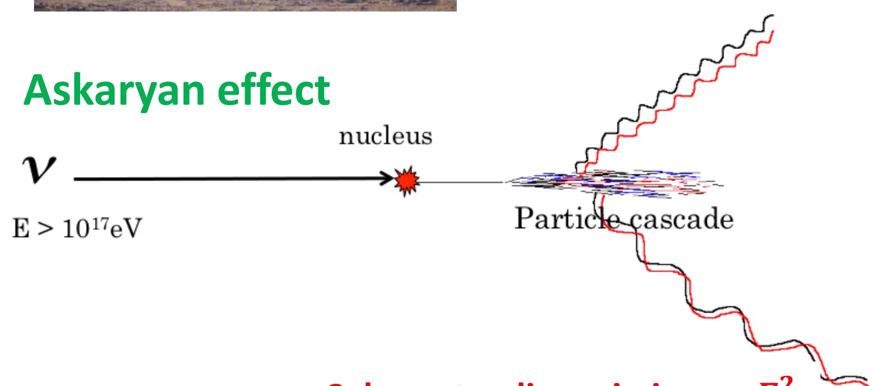


- **Radio Technique (Askaryan effect)**
  - IceCube-Gen 2-Radio
  - GRAND (China)



  - RNO-G (Greenland)

Askaryan effect



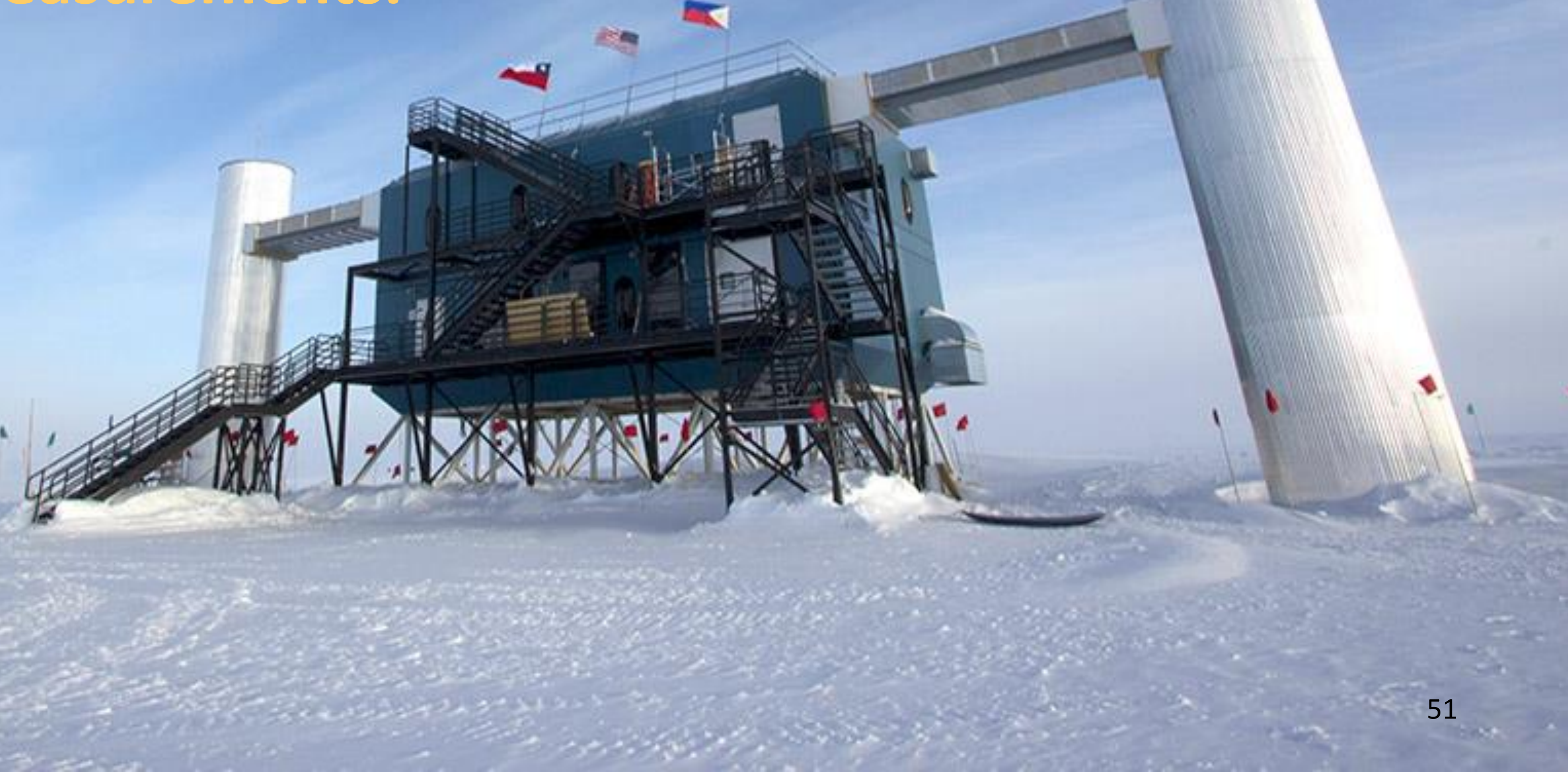
Coherent radio emission $\propto E^2$

IceCube – Upgrade & Gen 2 –

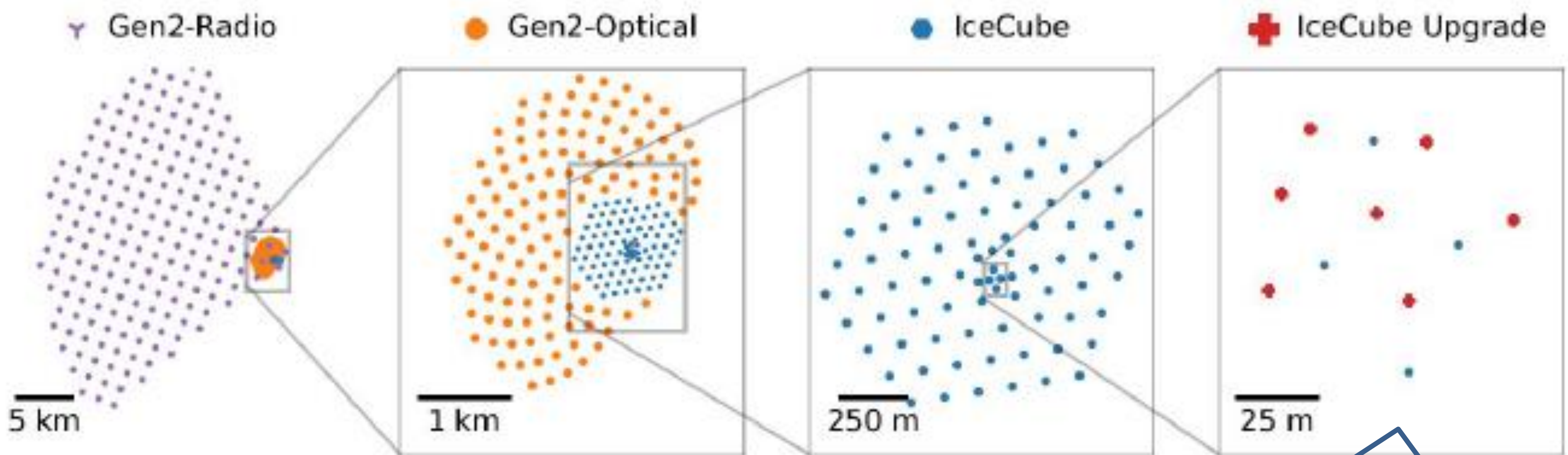
*See Meier-san's lecture

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

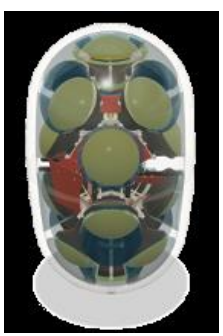
Gentoo penguin



IceCube : Upgrade & Gen2



IceCube Gen 2 (design phase)



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

Gen 2 LOM (= D-Egg+mDOM)

IceCube Upgrade

- Testbed for new sensor types →

D-Egg

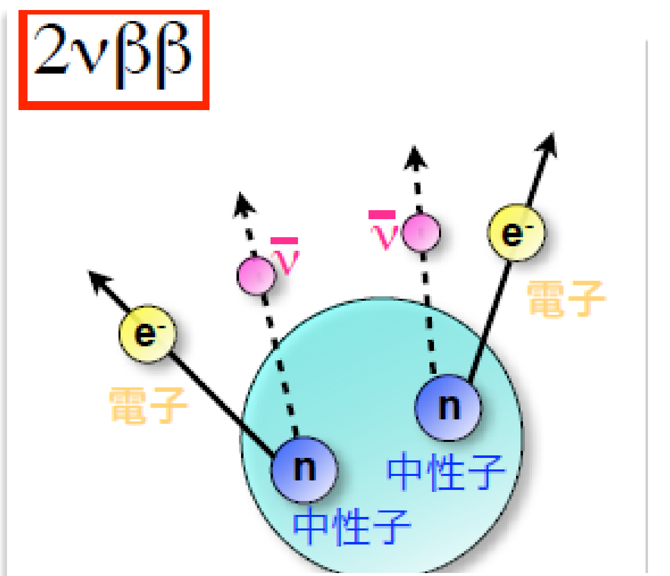
mDOM

- Improved detector calibration/ ice model characterization

5. 0νββ Decay Experiments

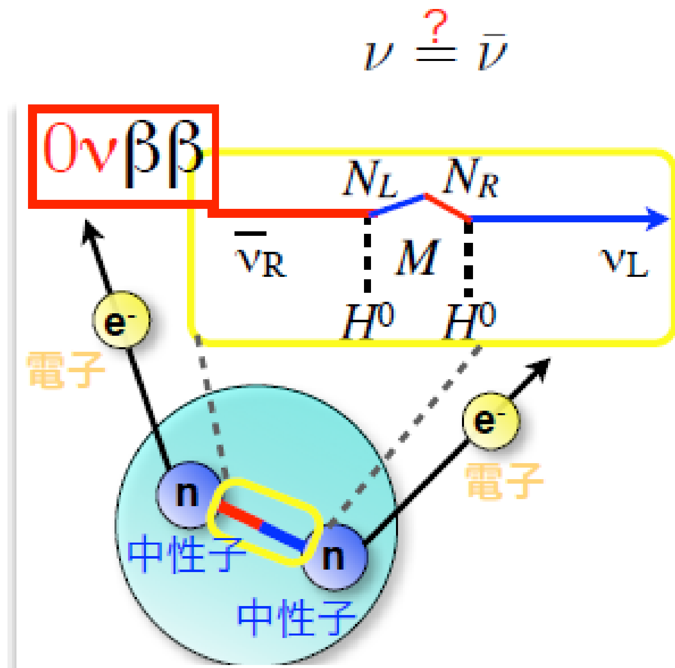
*See Iida-san’s lecture in detail

Double beta decay



2 neutrons decay in a nuclei.

Possible in SM
Lifetimes are measured for ~10 nucleus

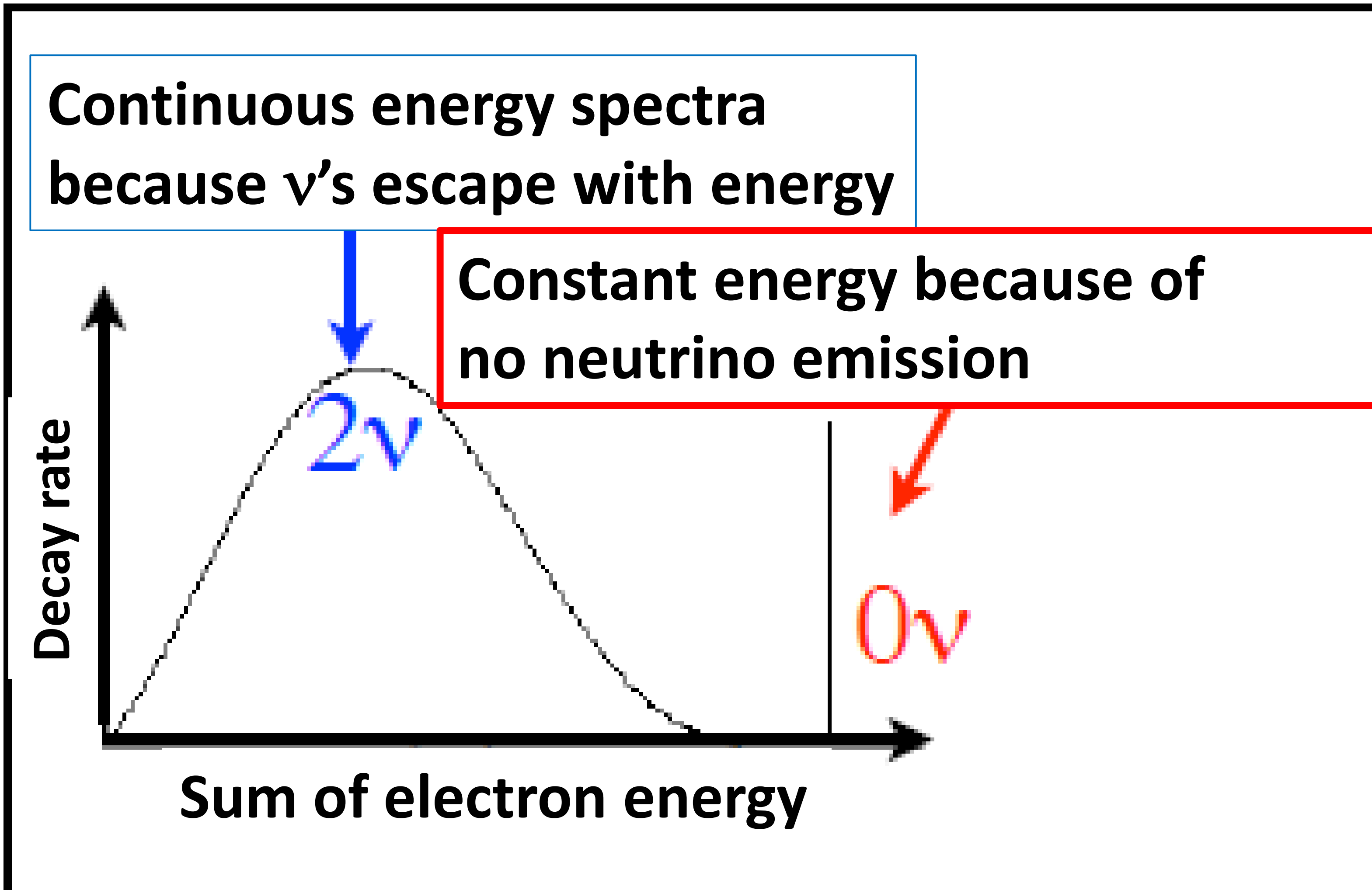


No ν is emitted.

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

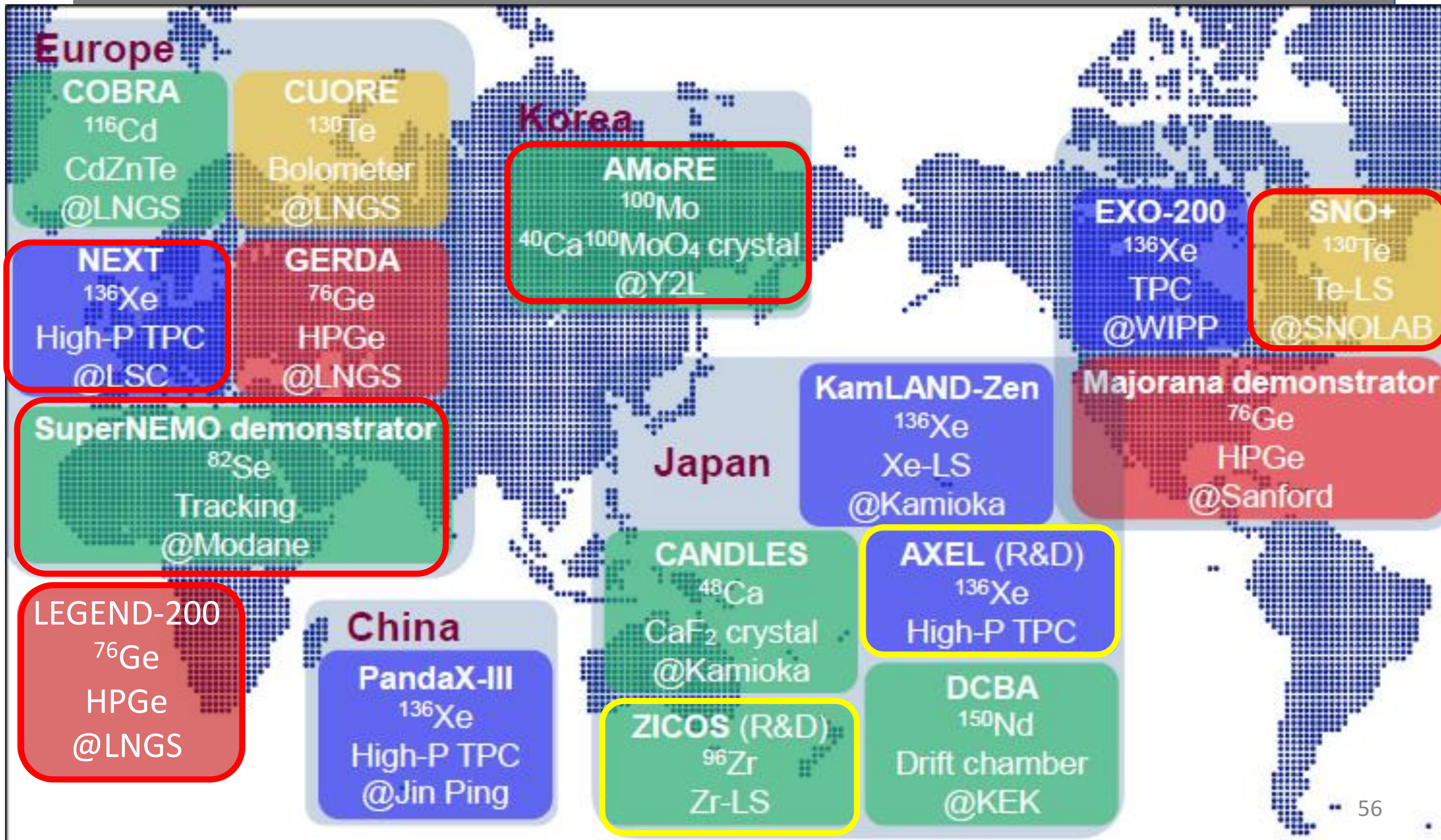
How to detect

- Catch 1 electron pair emitted !



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

Construction R&D



6. Sterile Neutrino Experiments

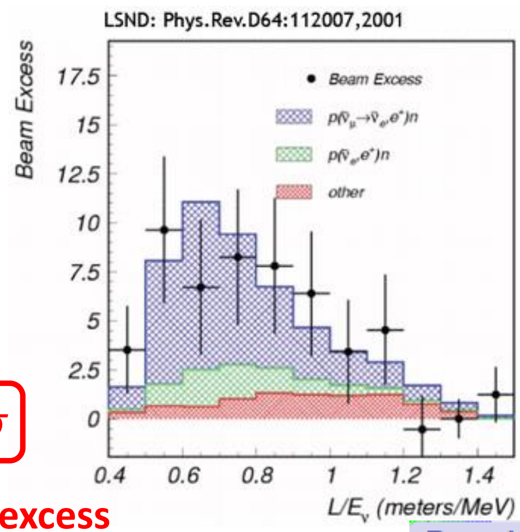
$\bar{\nu}_e$ disappearance experiments

- PROSPECT-II
- IsoDAR

Why sterile neutrino ?

Do 3-neutrino oscillations explain all experimental results?

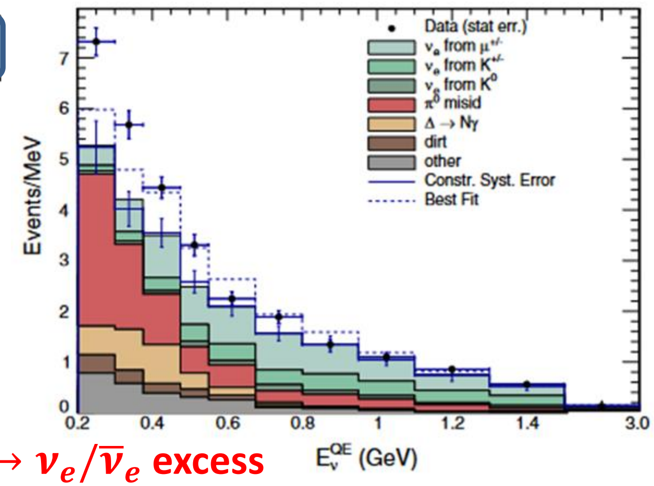
LSND



3.8σ

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

MiniBooNE



4.8σ

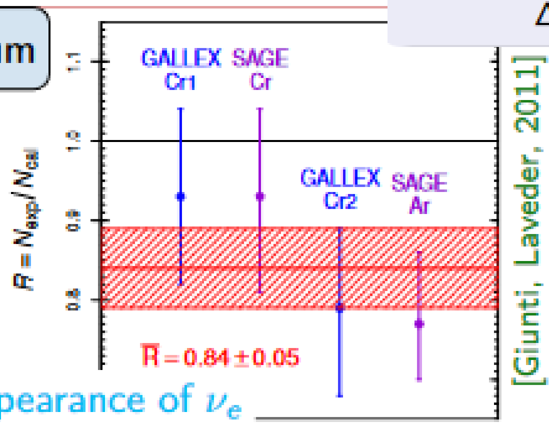
$\nu_\mu/\bar{\nu}_\mu \to \nu_e/\bar{\nu}_e$ **excess**

Possible common explanation:

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

*See Duffy-san's lecture

Gallium



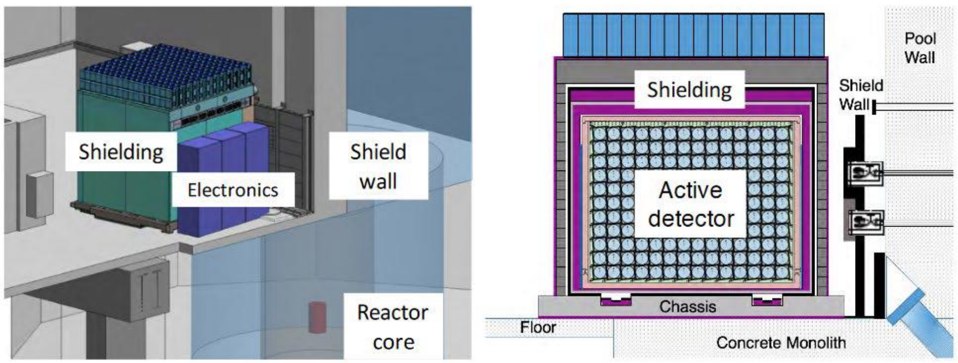
2.7σ

disappearance of ν_e

- **Experiments with intense radioactive sources**
- **Neutrino detection via**
  $$^{71}\text{Ga} + \nu_e \to {}^{71}\text{Ge} + e^-$$
- **Recently confirmed by BEST**
  (Baksan Experiment on Sterile Transitions)
  ~4σ

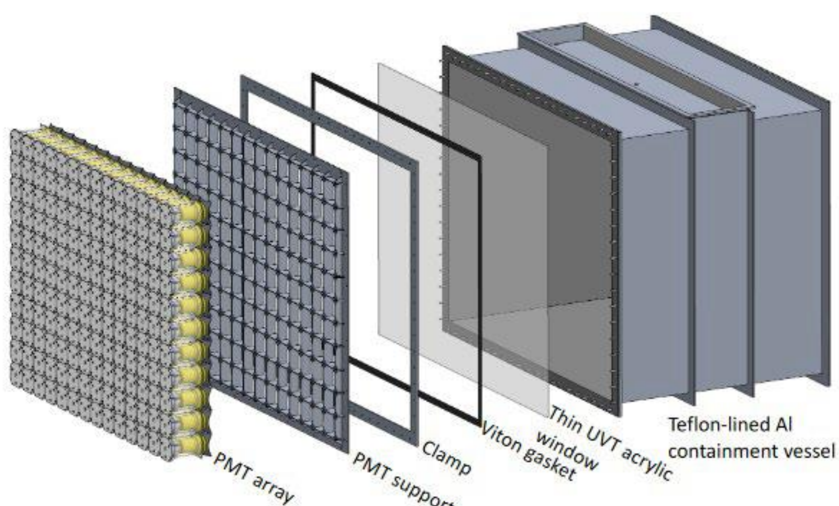
PROSPECT-II

Original PROSPECT Design



https://arxiv.org/abs/2107.03934

PROSPECT II Design

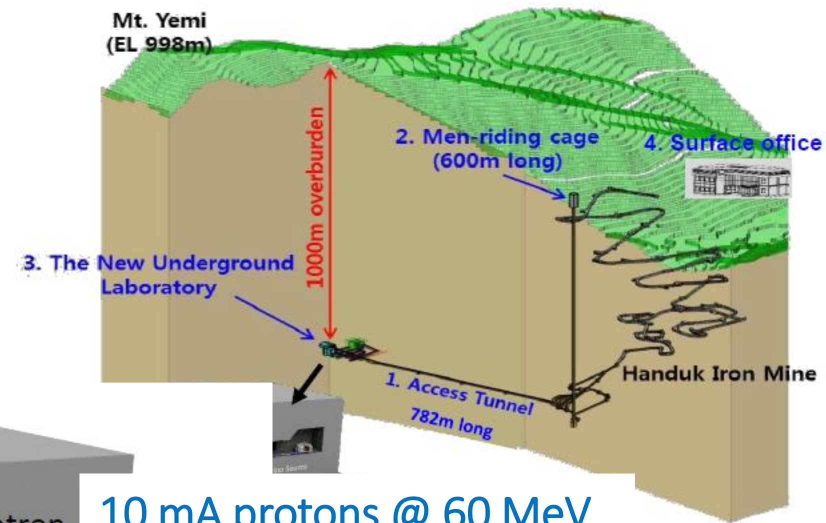


https://arxiv.org/abs/2107.03934

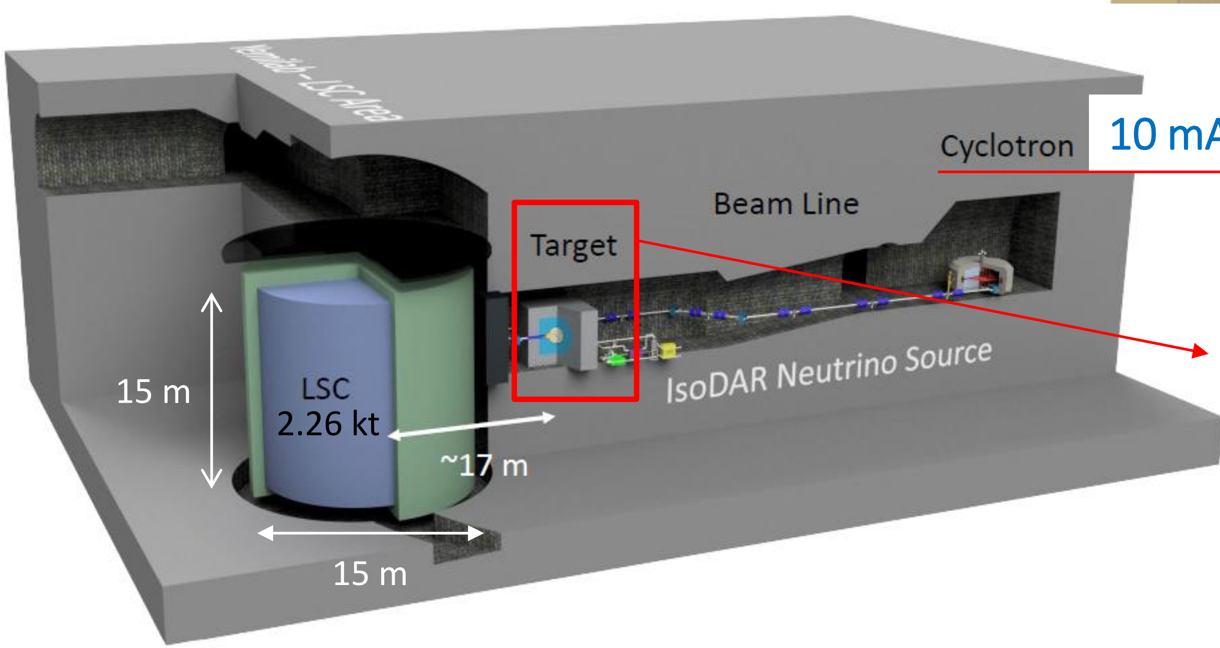
- High Flux Isotope Reactor (HFIR) at Oak Ridge National Laboratory
- Segmented ^{6}Li-doped liquid scintillator
- IBD detection of protons on LS, 1.8 MeV threshold
- Prompt (positron annihilation, 1-8 MeV) + delayed (n + ^{6}Li→ α + t + 4.8 MeV)
- Slightly higher ^{6}Li loading (0.08 % → 0.1% by mass)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

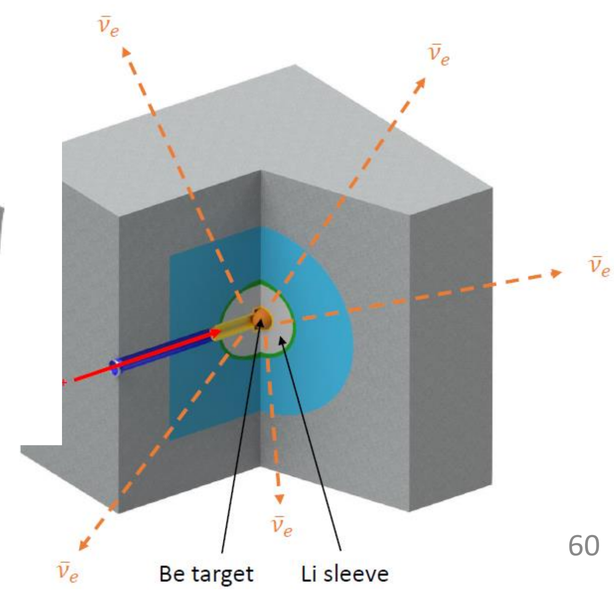
IsoDAR

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

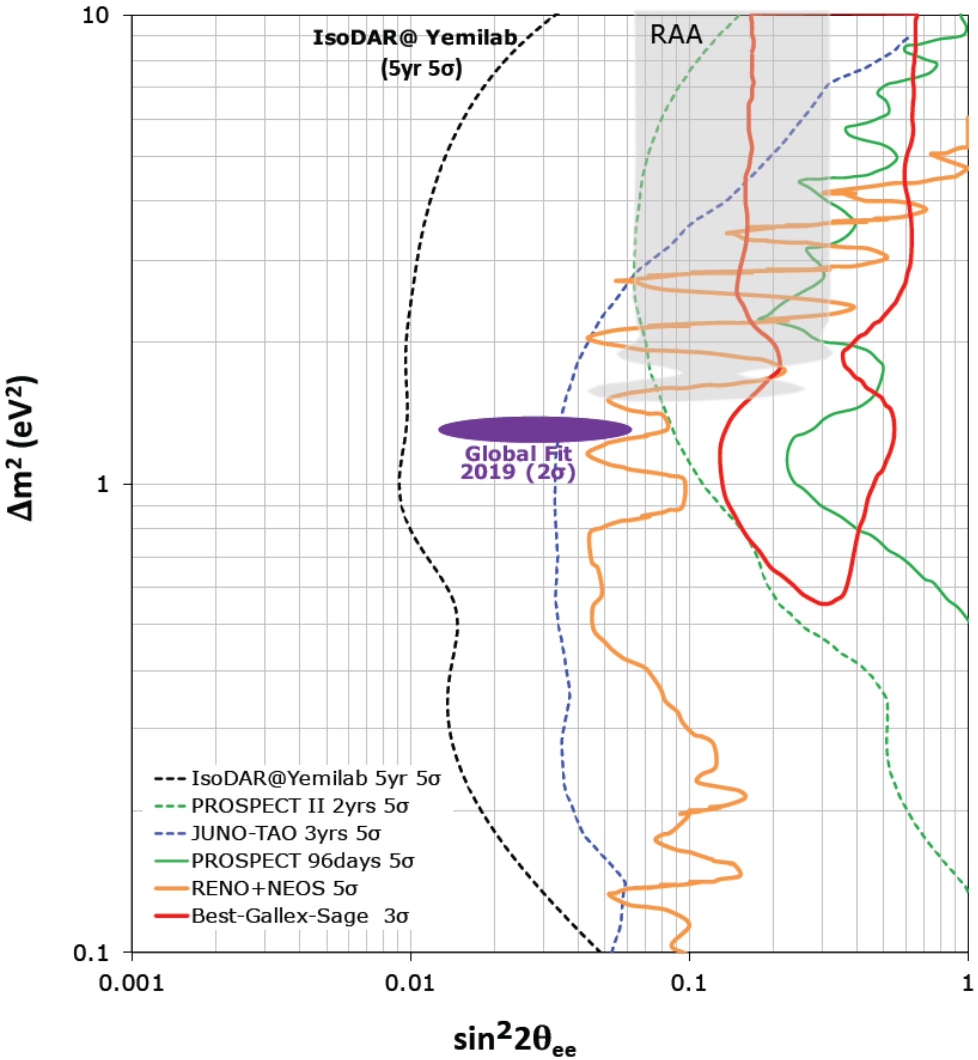


10 mA protons @ 60 MeV





Sensitivities



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

NEUTRINO 2022

Joshua Spitz, Daniel Winklener

3+1 oscillations assumed

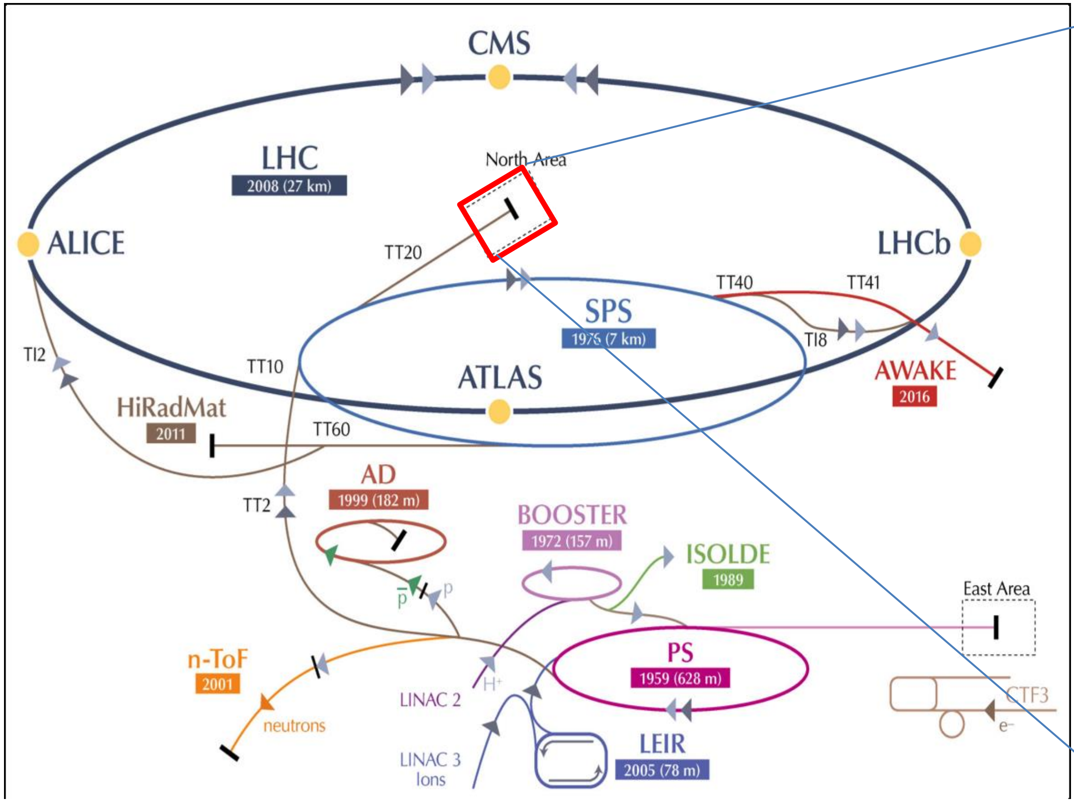
$$P_{ee} = 1 - \sin^2 2\theta \, \sin^2\left(1.27 \frac{\Delta m^2[\mathrm{eV}^2] L[m]}{E_\nu[\mathrm{MeV}]}\right)$$

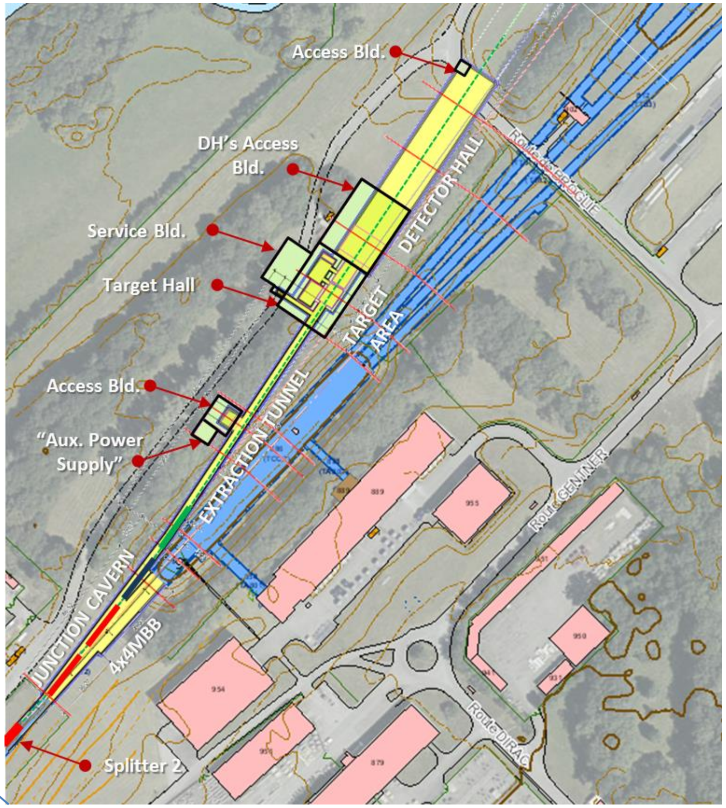
7. High statistic ν_τ Experiment (SHiP)

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.

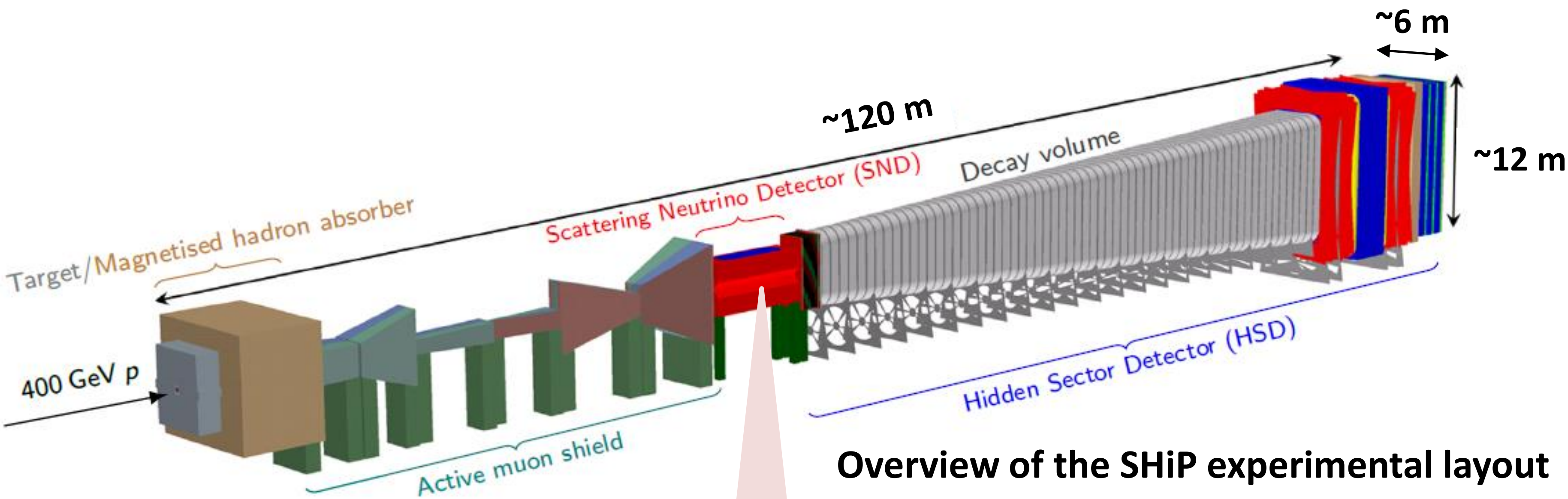
SHiP: experimental site



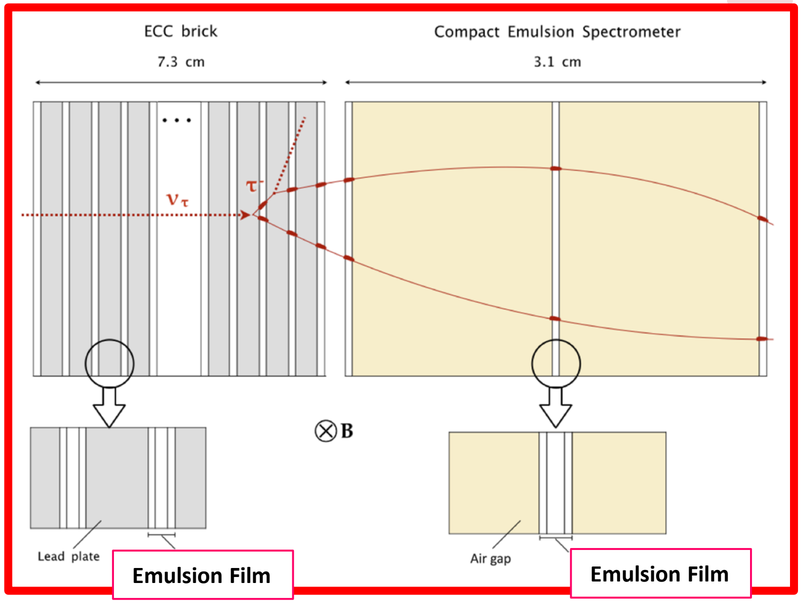


- Fixed target facility @ CERN SPS
- 400 GeV protons
- 4×10^{13} POT/spill in every 7 sec → 2×10^{20} POT in 5 years

SHiP detector



Overview of the SHiP experimental layout



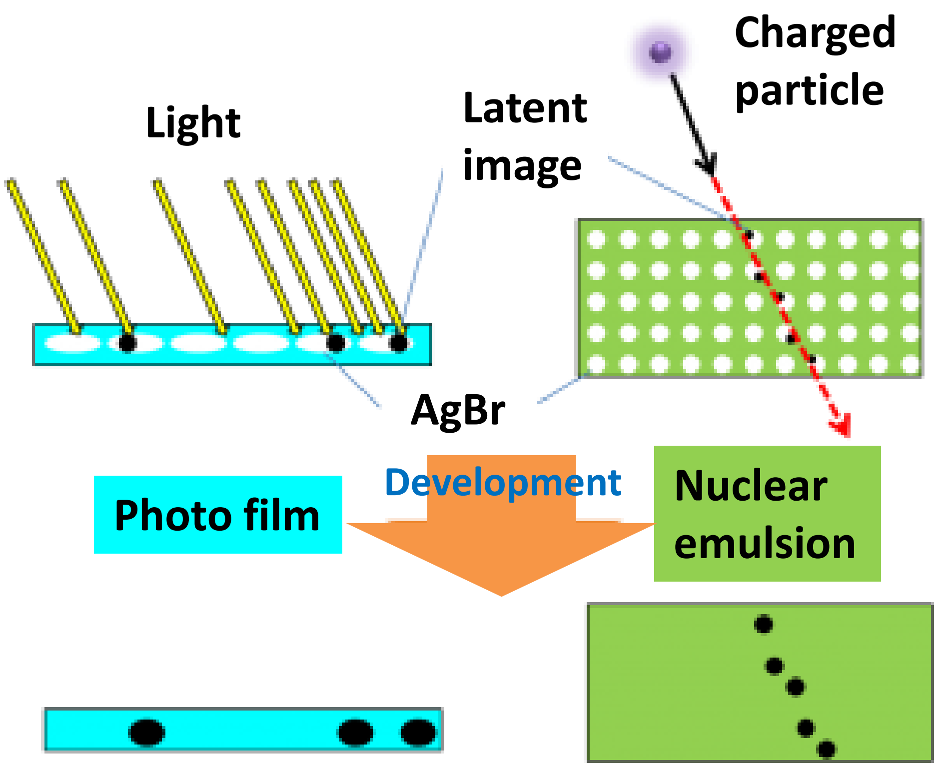
Basic unit of the SND & the ECC brick

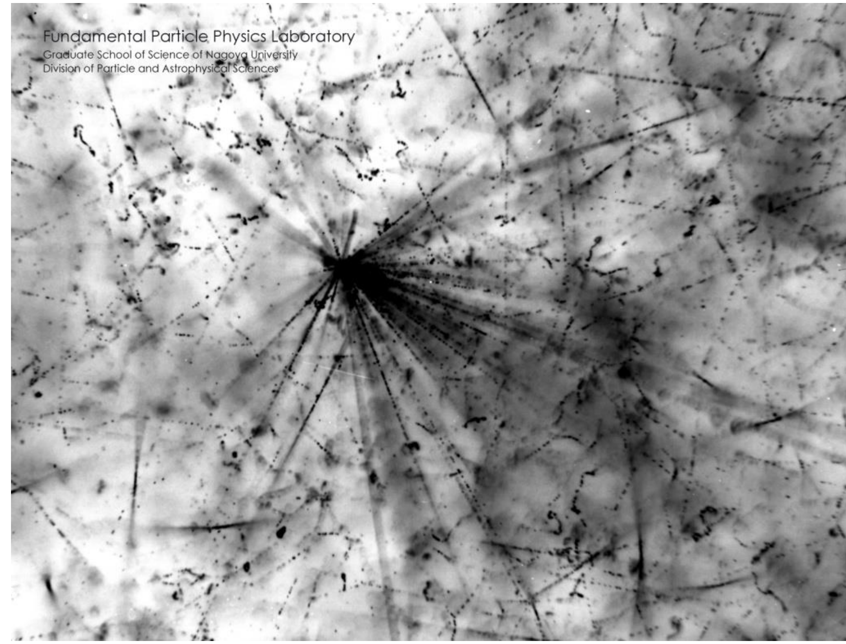
In the SND, the Emulsion* Cloud Chamber (ECC) is used as tracking detector and the Compact Emulsion Spectrometer (CES) is used for charge measurement.

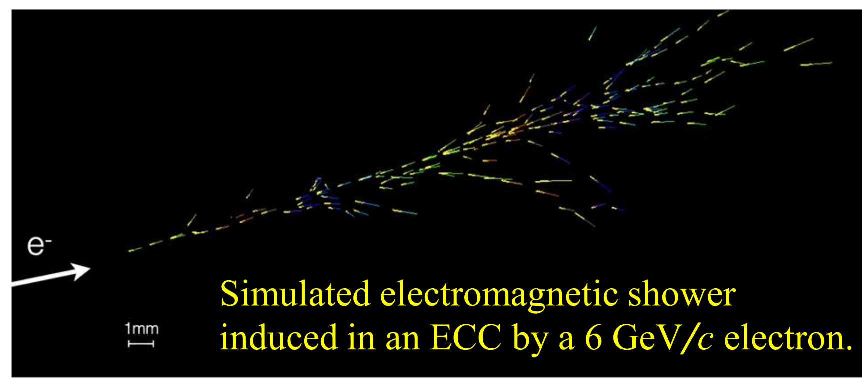
* Nuclear emulsion has the best position resolution of $\sim 1\mu m$. The emulsion technique has been highly developed in Japan.

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

Nuclear emulsion







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

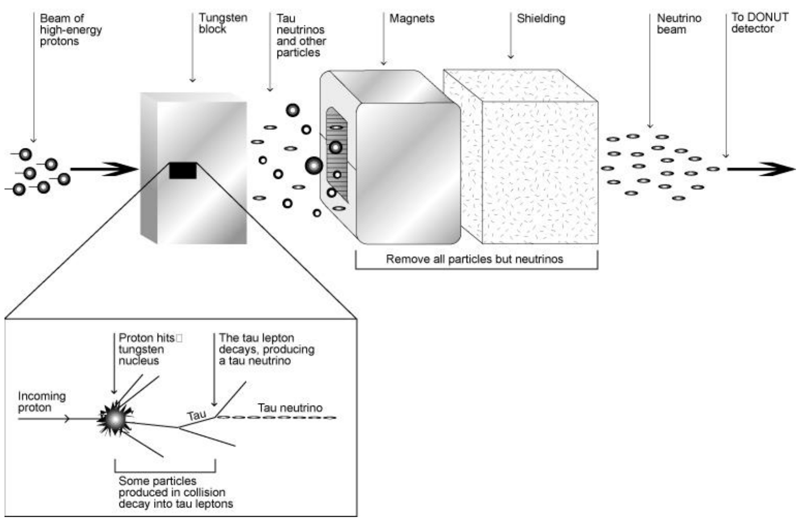
- Kind of photo film.
- Contains small grains of AgBr.
- Ag grains are remained after charged particle pass.
- We can detect the track after the development.
- Position resolution is $\sim 1 \mu$m (still the best in all detectors).

Discovery of ν_τ

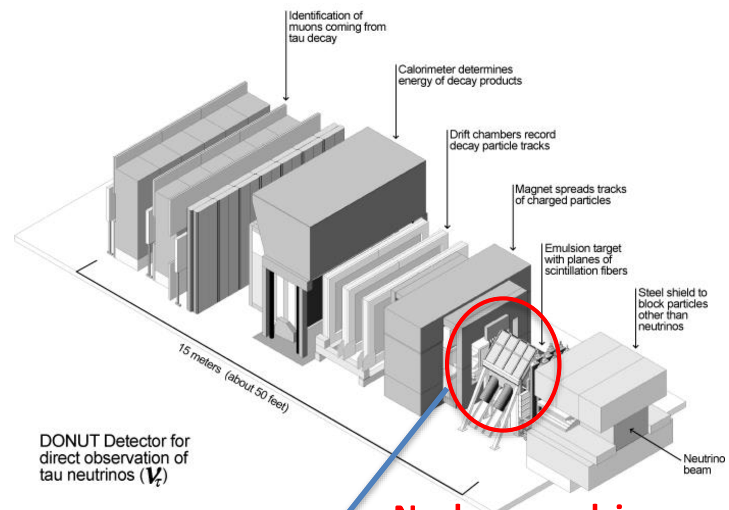
DONUT experiment, 2000 (Direct Observation of NeUtrino Tau ,Fermilab. E872)

Nagoya Univ., Kobe Univ., et al

Creating a Tau Neutrino Beam

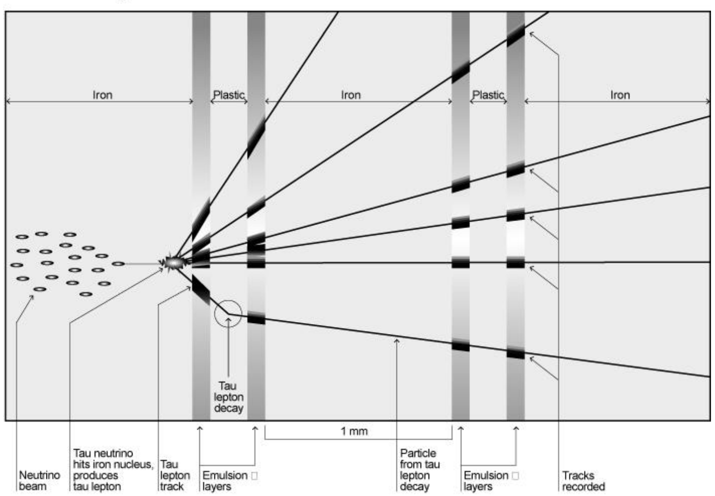


DONUT Detector



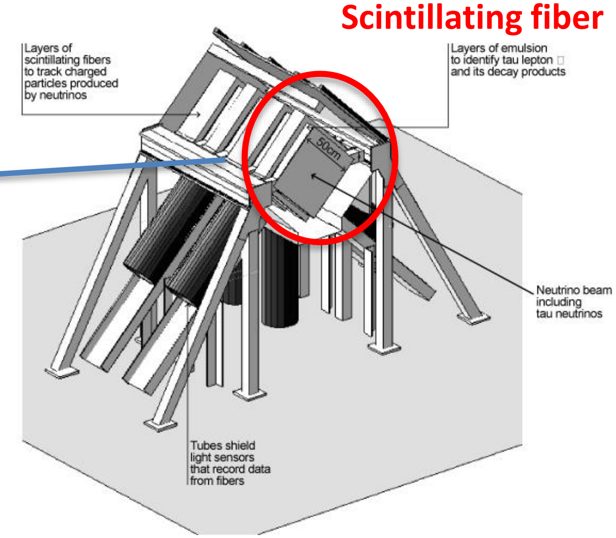
Nuclear emulsion
+
Scintillating fiber

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

	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

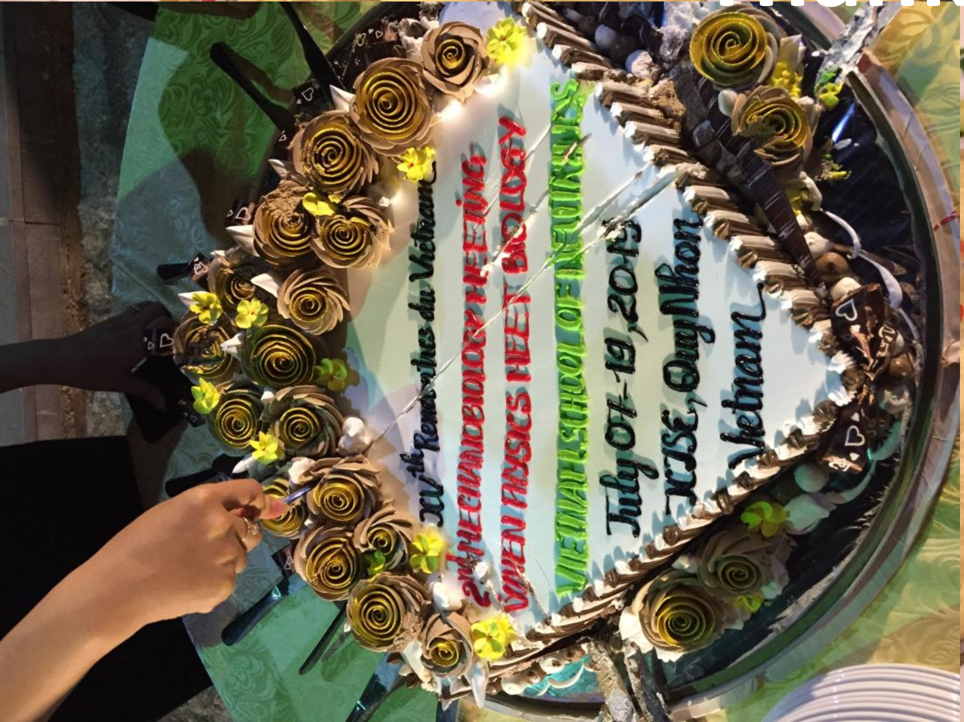
Summary

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

(SK-Gd,) HK, **DUNE, JUNO, IceCube Gen 2, 0$\nu\beta\beta$, sterile ν experiments, and SHiP**.


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

Thank you !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