
# Current Status and Physics Potential of the Hyper-Kamiokande Experiment

UNDER CONSTRUCTION UNDER CONSTRUCTION UNDER CONSTRUCTION


## HQL 2021

Sophie King

# The Hyper-K Detector

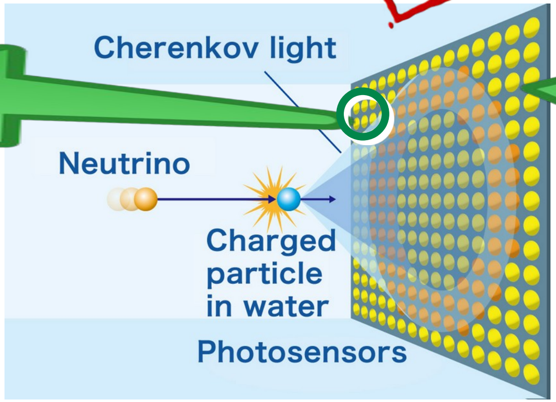
Hyper-Kamiokande

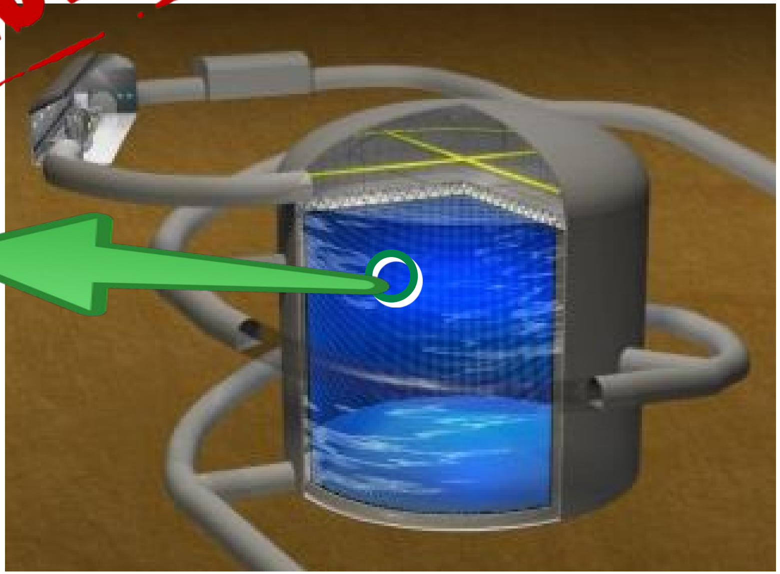
APPROVED

## Water Cherenkov detector

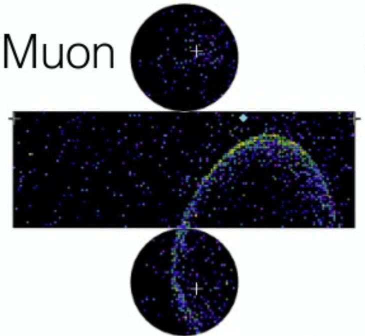
Photomultiplier tube

( PMT )

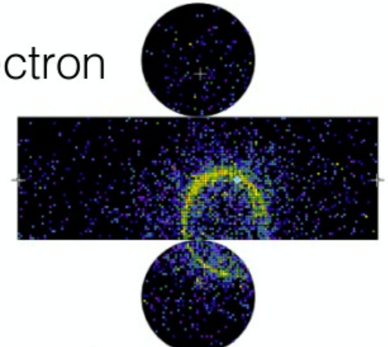


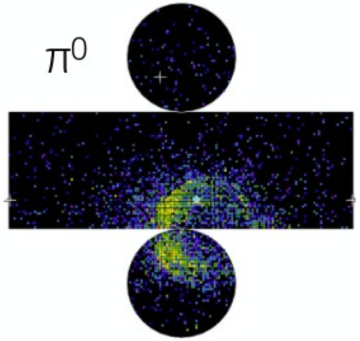
Muon



Electron



$\pi^0$



**Hyper-K will begin taking data in 2027**

# The Hyper-K Detector

**Inner detector (ID):**

* 216 kton

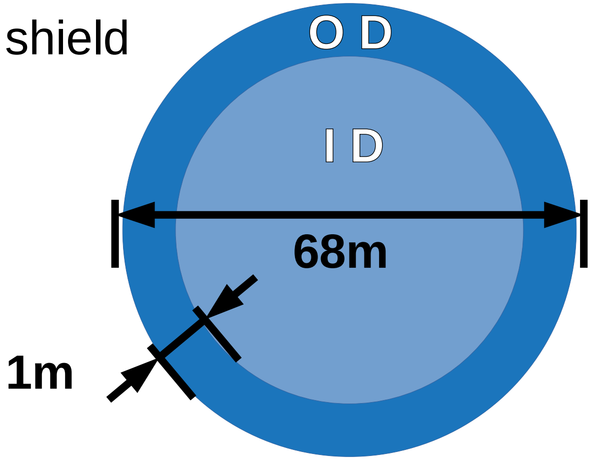
**Outer detector (OD):**

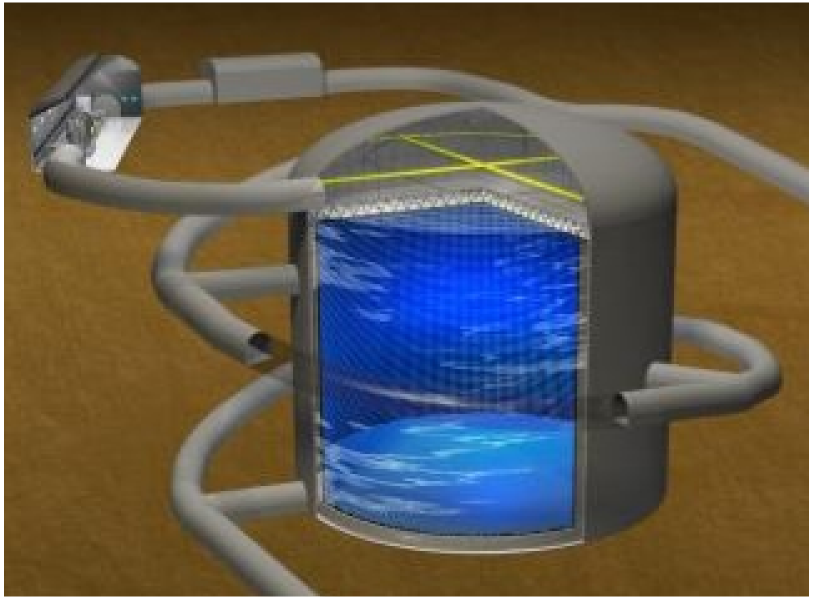
* 1m thick round the edge, 2m at top/bottom

* veto region  (incoming/outgoing particles)

* low energy background shield

ID / OD boundary
→ high reflectivity
(>90%) Tyvek



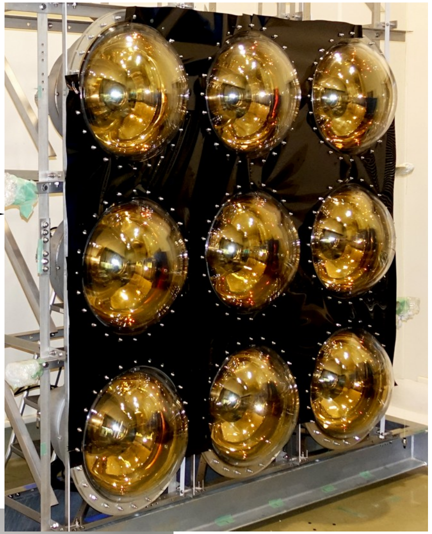



Height = 71m,    Diameter = 68m

Volume:  258kton

# PMT Photosensors

Hyper-Kamiokande



**50cm PMTs** (box and line dynode)

~ 1.5 ns timing resolution

Inner detector (ID)

20,000 * 50cm PMTs → 20% coverage

**8cm PMTs**

Outer detector (OD)

~10,000 * 8cm PMTs

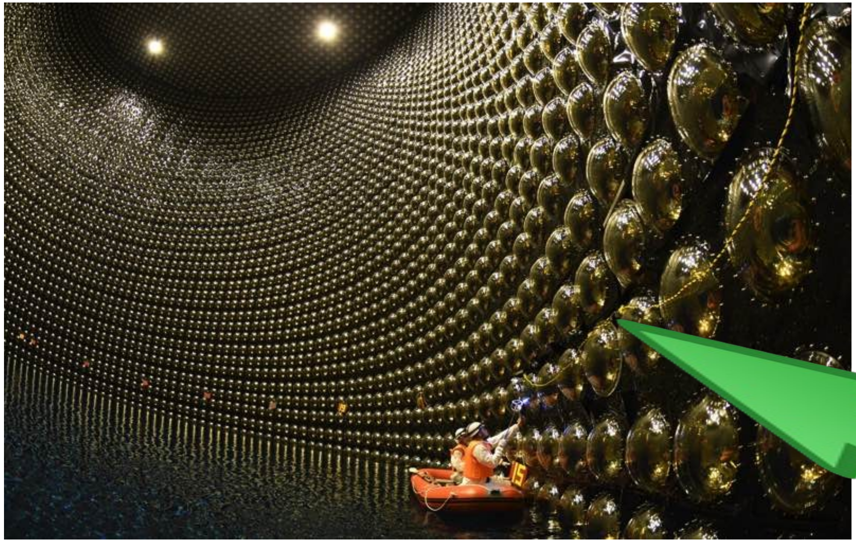
Multi-PMTs (mPMTs)

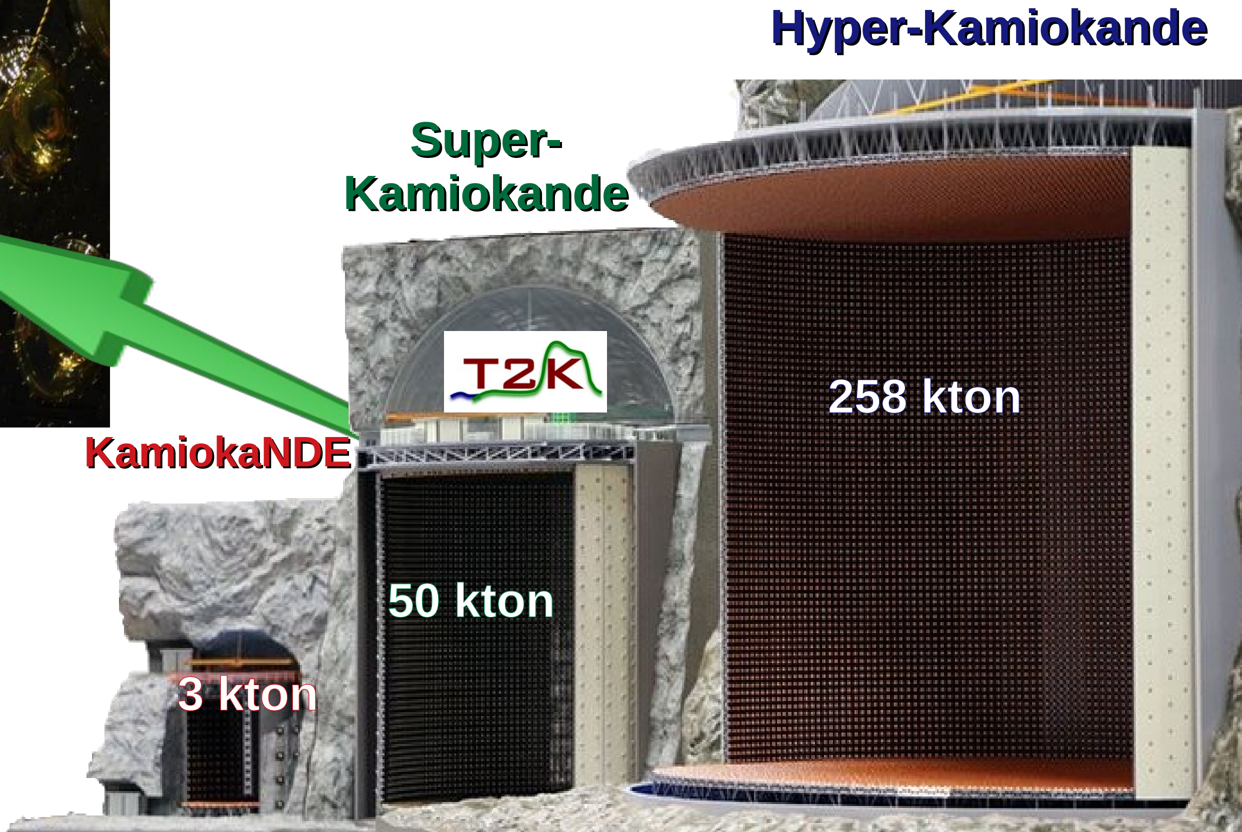
- 19 x 8cm PMTs inside single pressure vessel
- directional information and improved timing and spatial resolutions

Inner detector (ID)

~ few thousand mPMTs

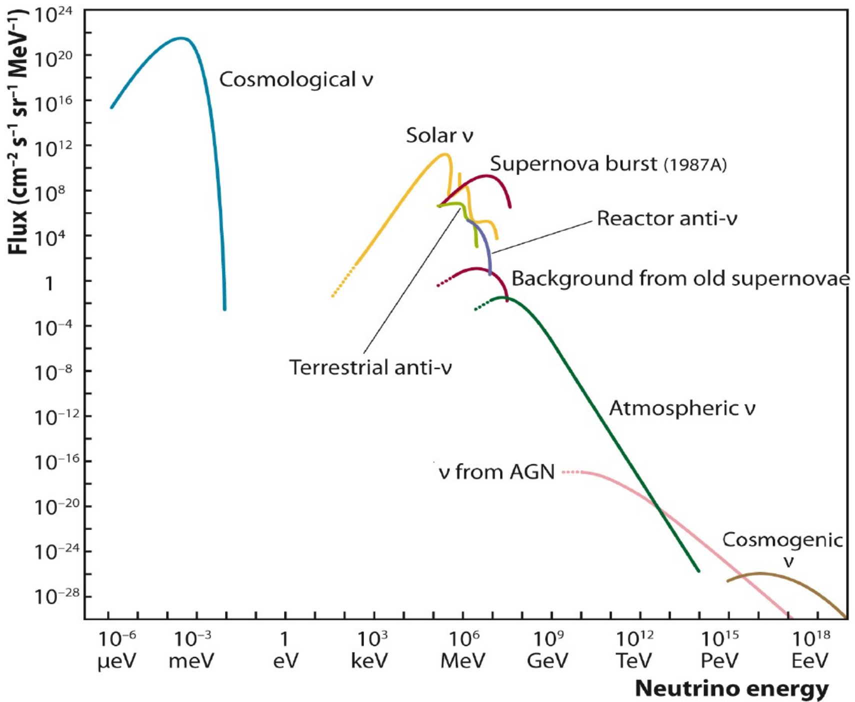
# The Kamiokande Series





# The Kamiokande Series

* Proton decay
* Solar, supernova and atmospheric neutrinos
* Accelerator beam neutrinos



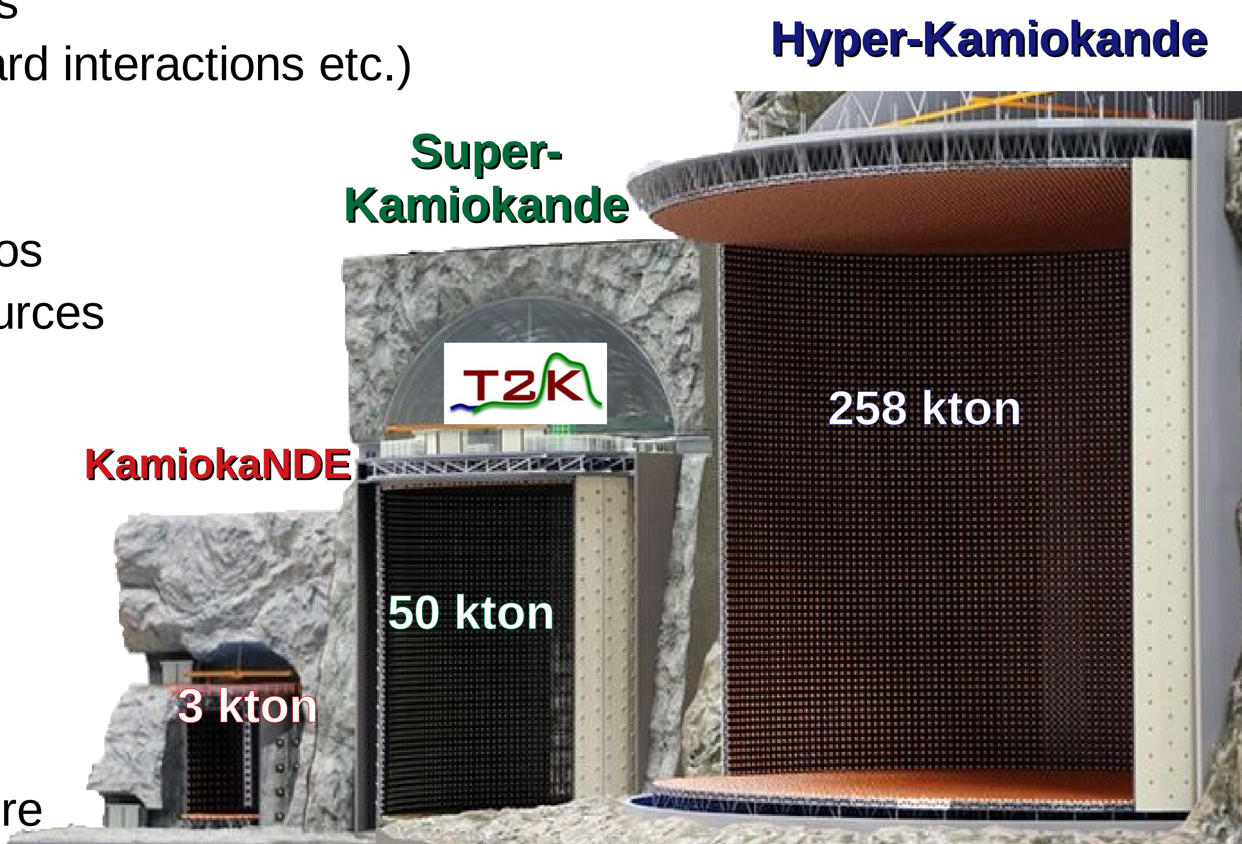

# Hyper-Kamiokande Physics

* Neutrino Oscillations
  - beam, atmospheric, solar neutrinos
  - BSM (sterile searches, non-standard interactions etc.)

* Astrophysics
  - solar neutrinos, supernova neutrinos
  - dark matter, gravitational-wave sources
  - gamma-ray sources

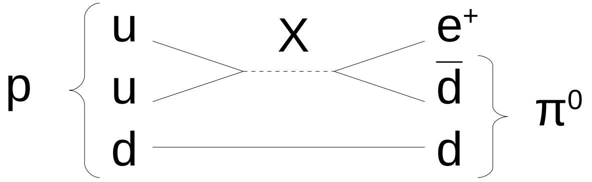
* Nuclear physics
  - neutrino interactions

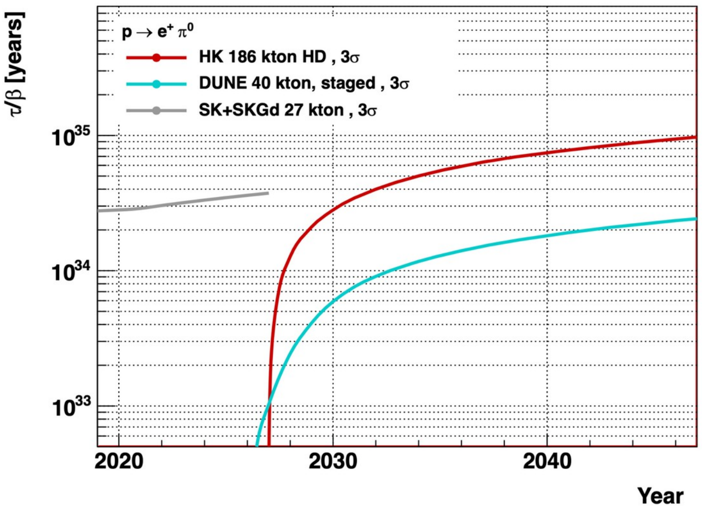
* Geophysics
  - matter effect on oscillations
  - electron density of Earths outer core



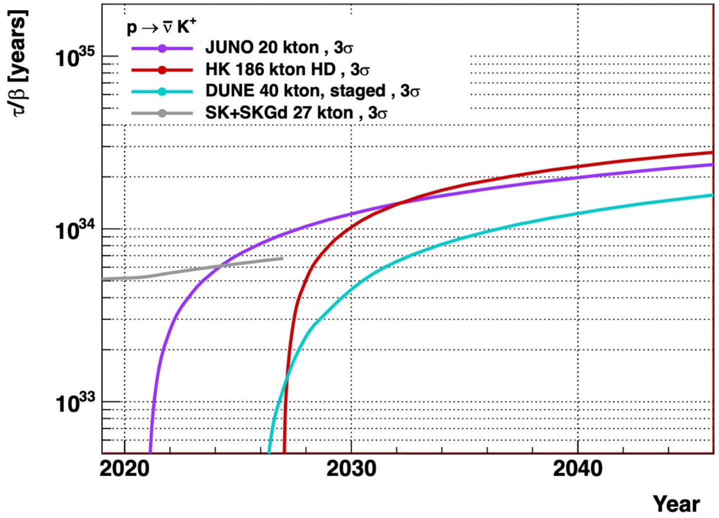
# Proton Decay

# Proton decay

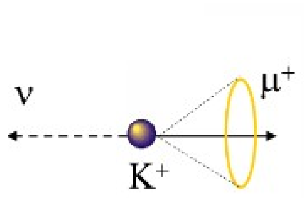



HK can improve the SK limit on this process from $10^{34}$ to $10^{35}$ years




HK also competitive for $p \to K^+ \nu$



# Neutrino Oscillations

# Neutrino Oscillations

Hyper-Kamiokande

* Mass and flavour states do not align
* Non-zero masses
→ neutrino osc. governed by PMNS matrix

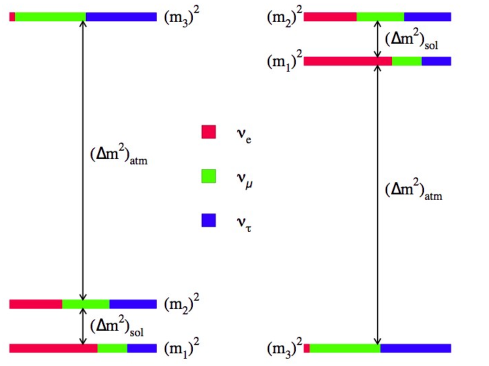
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Atmospheric and accelerator
$\theta_{23} \sim 50°$
$|\Delta m_{32}^2| \sim 2.5\text{x}10^{-3}$ eV$^2$

Reactor and accelerator
$\theta_{13} \sim 8°$
Accelerator only $\delta_{CP} = ??$

Solar and reactor
$\theta_{12} \sim 34°$
$\Delta m_{12}^2 \sim 7.5\text{x}10^{-5}$ eV$^2$

**1) Mass Ordering (NO or IO)**




Normal Ordering (NO) Inverted Ordering (IO)

**2) $\theta_{23}$ octant:**

$\theta_{23} > \pi/4$ or $\theta_{23} < \pi/4$

**3) CP violation ( $\delta_{cp} \neq 0, \pm\pi$ )**

$\theta_{13}$ precisely measured and not too small
→ opens the door for $\delta_{cp}$ measurements

If $\delta_{cp} \neq 0, \pm\pi$ → **CP violation**: $P(\nu_\mu \rightarrow \nu_e) \neq P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$

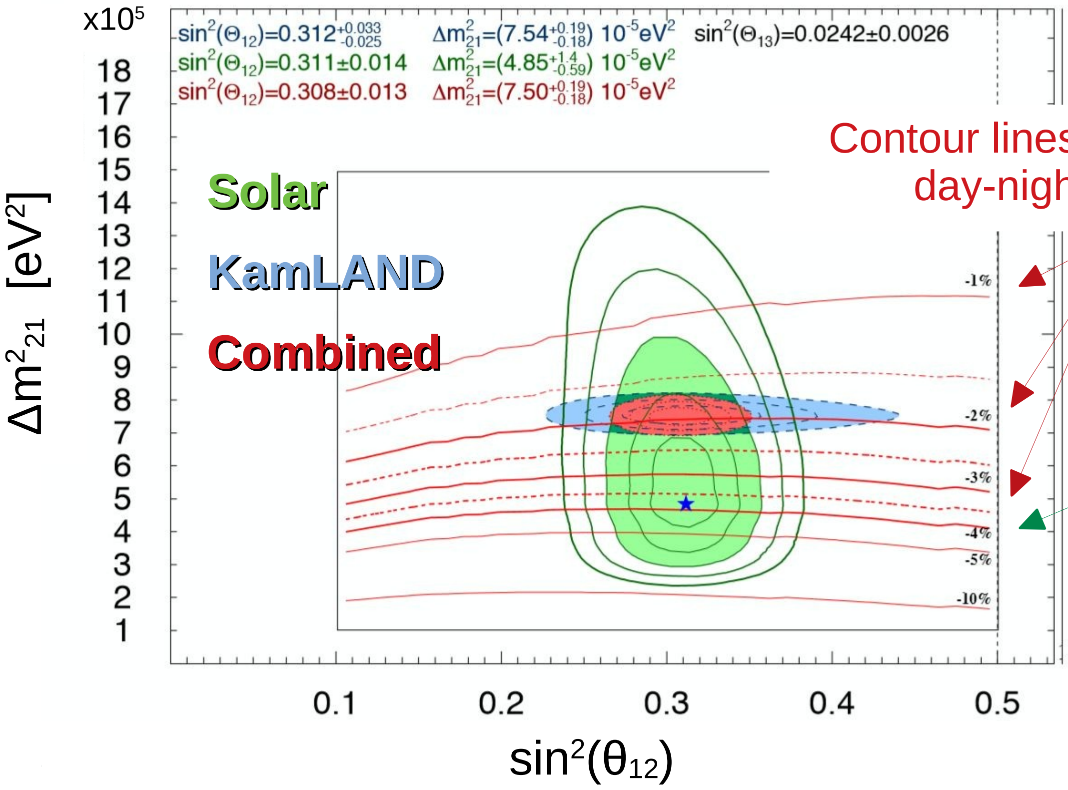
**Compare oscillation of ν and $\bar{\nu}$ to probe $\delta_{cp}$**

**Matter effects!** (electrons)
Difference in $\nu_e$ and $\bar{\nu}_e$ travelling through the earth ( similar effect as $\delta_{cp}$ )
→ allows for mass hierarchy determination

# Solar Neutrinos

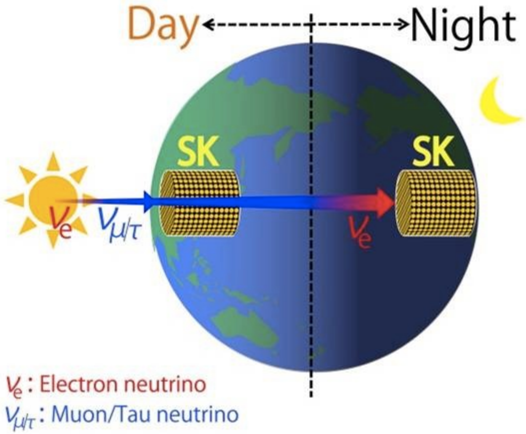
# Solar Neutrinos

~ 2σ tension in $\Delta m^2_{21}$ between solar & kamLAND (reactor)




Contour lines of constant day-night asym.

**SK best fit 4%**




$\nu_e$ flux differs between night and day

→ matter effects

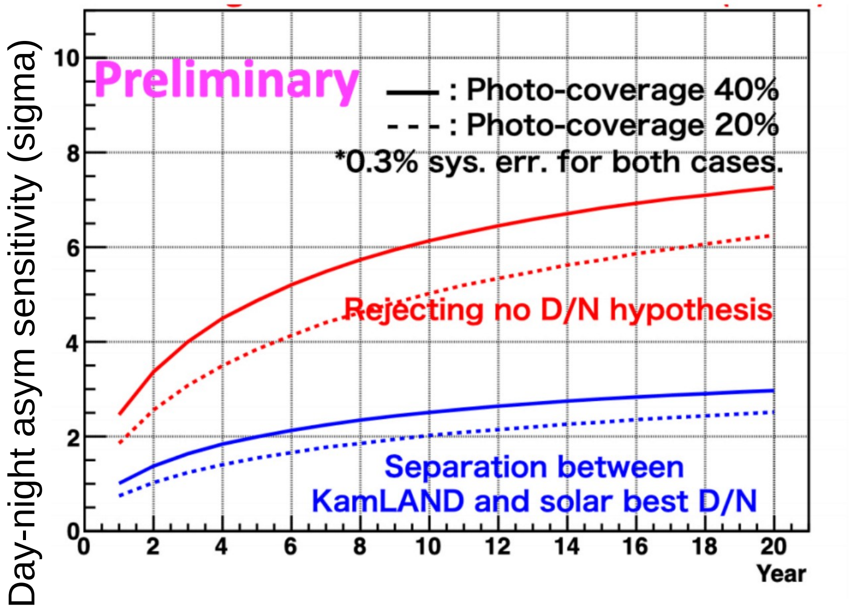
→ *day-night asymmetry*

Day-night asymmetry higher than expected from reactor constraint

→ contributes to the $\Delta m^2_{21}$ tension

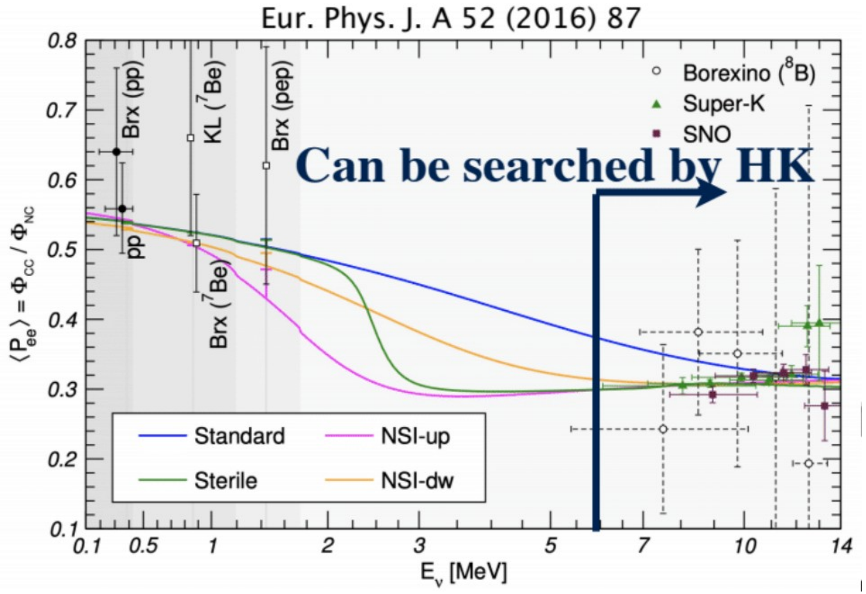
# Solar Neutrinos

Hyper-K can constrain the
**Day-Night Asymmetry**
(and improve **$\Delta m^2_{21}$ tension**)




For large D-N asymmetry, expect >5σ confirmation 10 years

Hyper-K can constrain the **'upturn'** in the vacuum-MSW transition region in the low energy solar neutrino **survival probability**

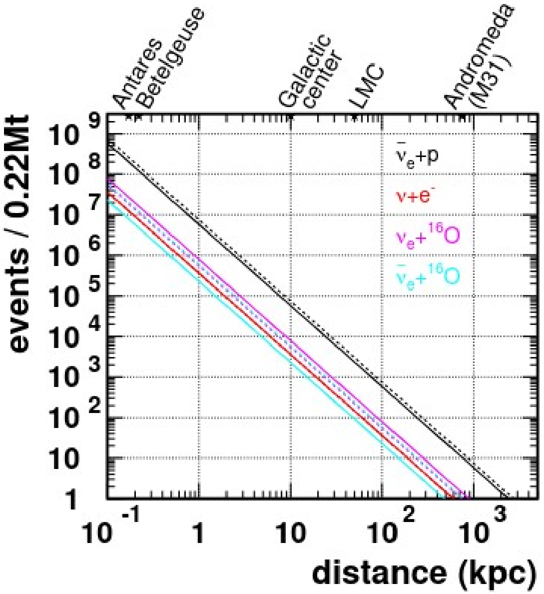



Expect 3-5σ for upturn discovery after 10 years

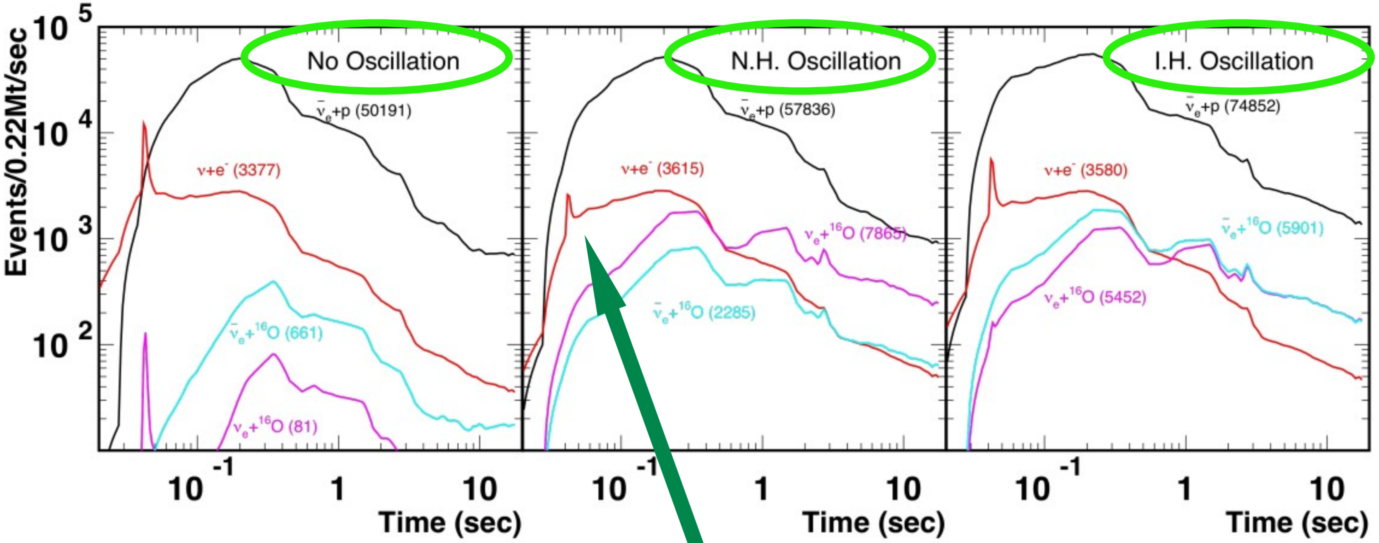
# Supernova Neutrinos

# Supernova Neutrinos

Expected number of events
as a function of
supernova distance




Expected time profile of a supernova at 10kpc
- numbers in brackets total interactions integrated over the 10s burst
- peak event rate of inverse beta decay events (black) reaches ~50 kHz




Neutronization peak
(sensitive to mass ordering)

Supernova Model Discrimination with Hyper-Kamiokande
**K. Abe et al 2021 ApJ916 15** https://arxiv.org/abs/2101.05269

# Supernova Neutrinos

Inverse beta decay dominates

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

Different models predict different electron antineutrino rates

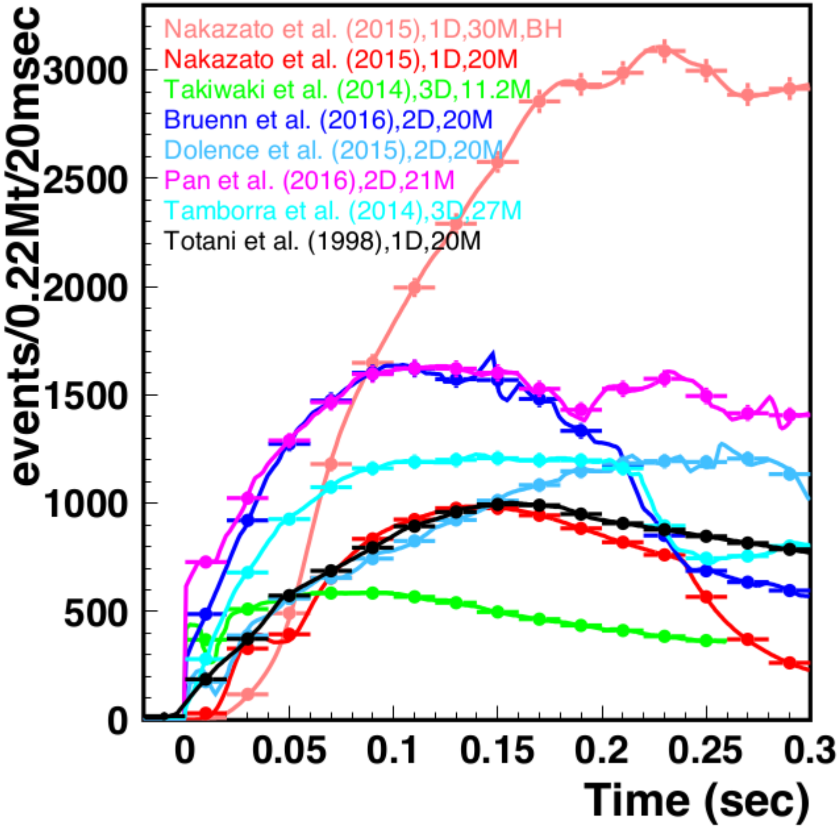
→ Hyper-K can constrain different models

* Stat error is much smaller than the difference between models

* Neutrino detection threshold of 3 MeV

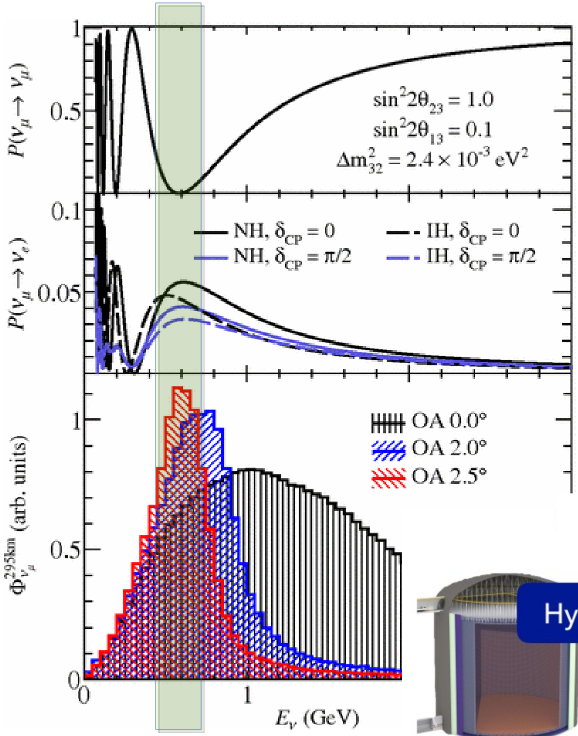
* Directional reconstruction allows for event-by-event measurement

Predicted inverse beta decay rates



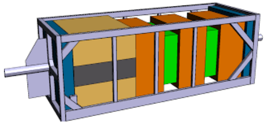
# Long-baseline neutrino oscillations (beam)

# Hyper-Kamiokande long-baseline



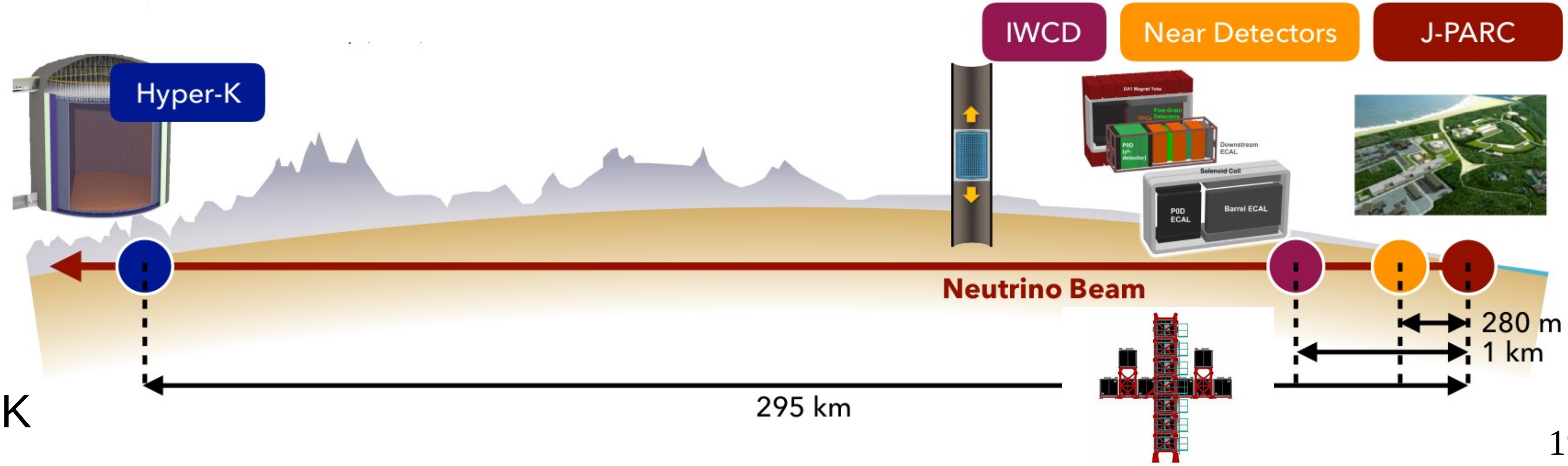

* Upgrade T2K beam to 1.3MW

* Upgraded ND280



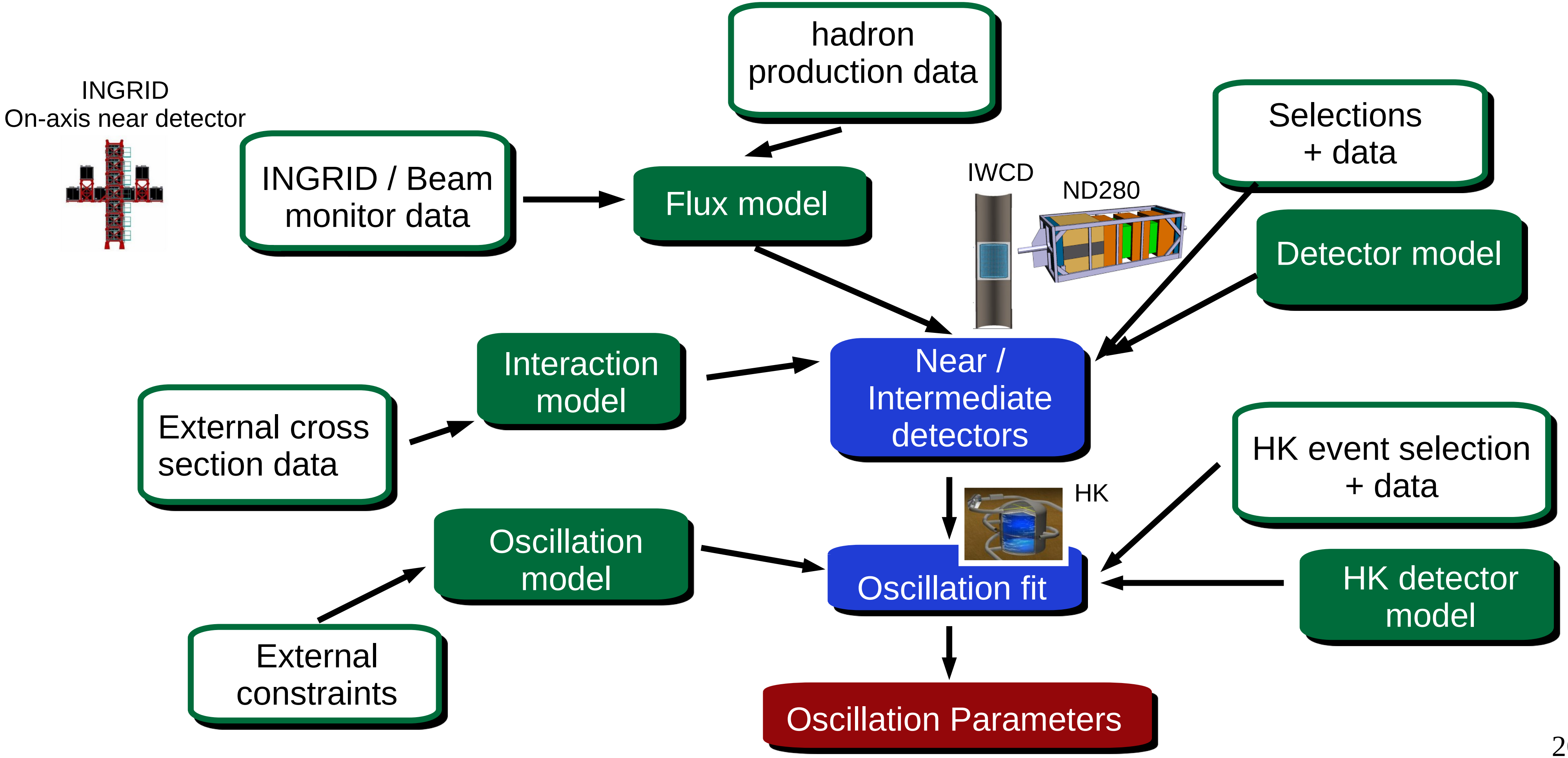
* New intermediate water Cherenkov detector (IWCD)

* Hyper-K far detector




HK at same distance and off-axis angle as SK

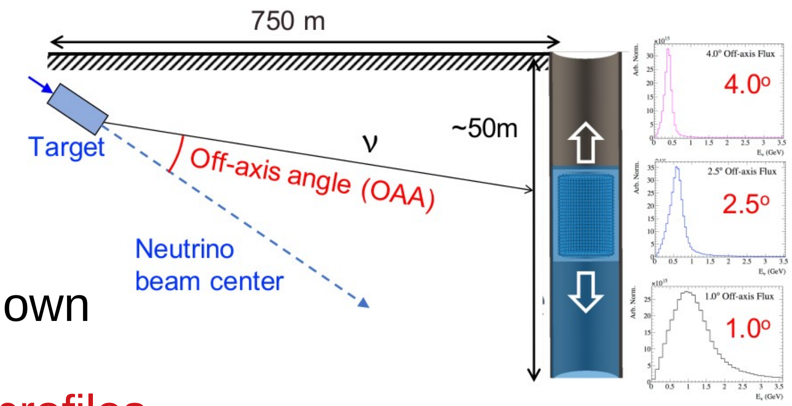
# Hyper-Kamiokande long-baseline



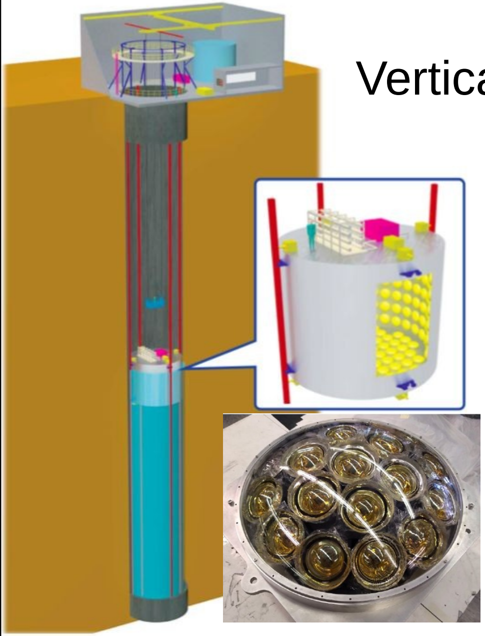
# Intermediate water Cherenkov detector (IWCD)

Constrain flux and neutrino interactions, with same target as far detector

Distance ~ 1km , Diameter ~8m, height ~6m
Size optimised to contain 1GeV muons,
while minimizing beam pile up events



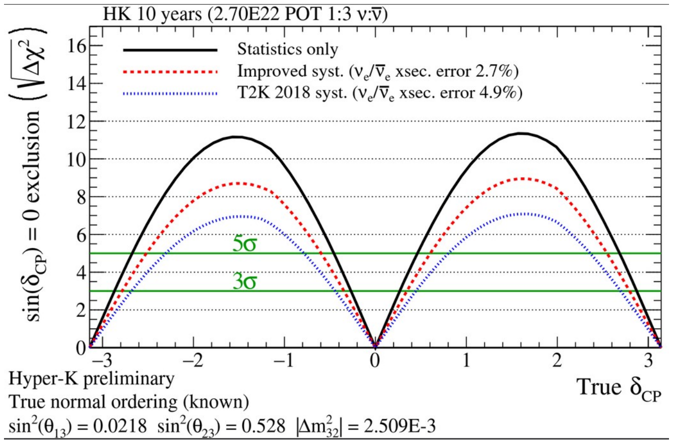

Vertical pit (50m), detector moves up and down
→ samples flux at different angles
→ sample flux at different energy profiles



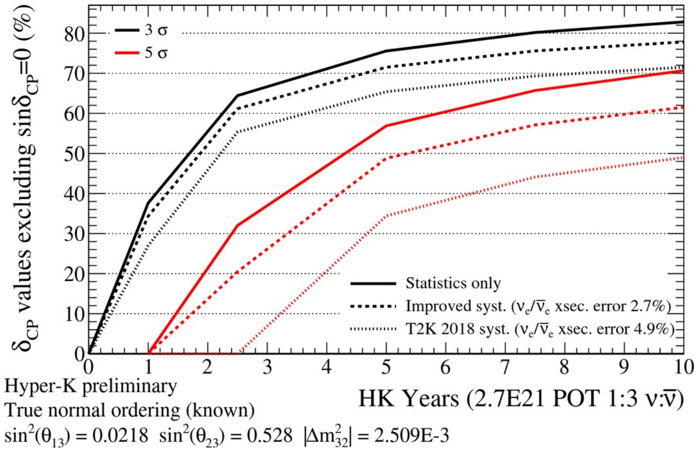
**Multi-PMTs:** better timing and spatial resolution than 1 large PMT
→ good reconstruction despite small detector

Plans to load with Gadolinium: 0.1% Gd
→ Neutron tagging

# Hyper-Kamiokande long-baseline




Sensitivity for excluding δCP=0 given different true values of δCP



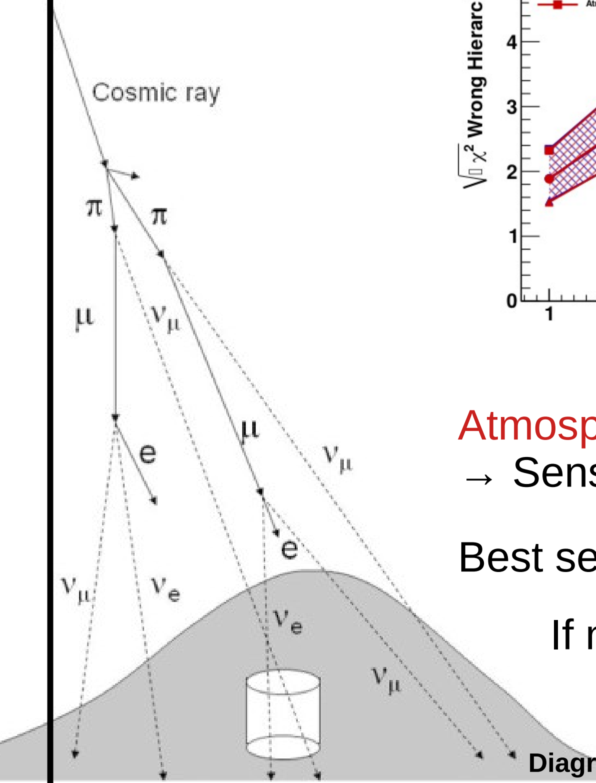

Percentage of true δCP values for which sin(δCP)=0 can be excluded, as a function of HK years.

* Solid line: Statistical errors
* Small dash: T2K systematic uncertainties
* large dash: Improved systematic for the $\nu_e$ / $\bar{\nu}_e$ cross section error

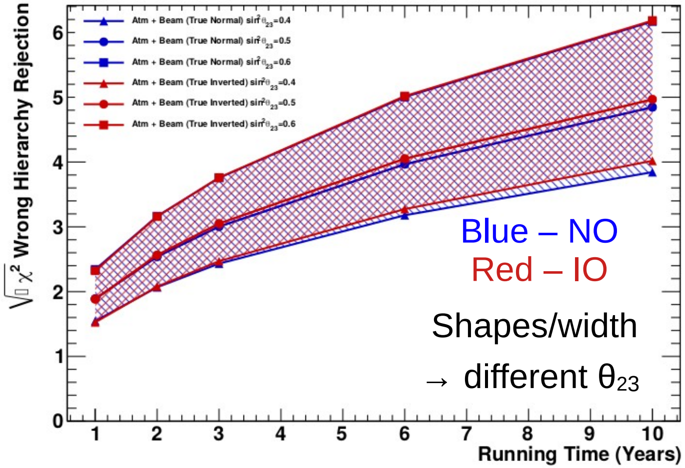
The systematic uncertainty on the $\nu_e$ / $\bar{\nu}_e$ cross section will have the largest impact on δCP
→ Near/intermediate detectors will play a vital role in constraining these errors

**5σ achieved for ~60% fraction of δCP values with 10years data taking**

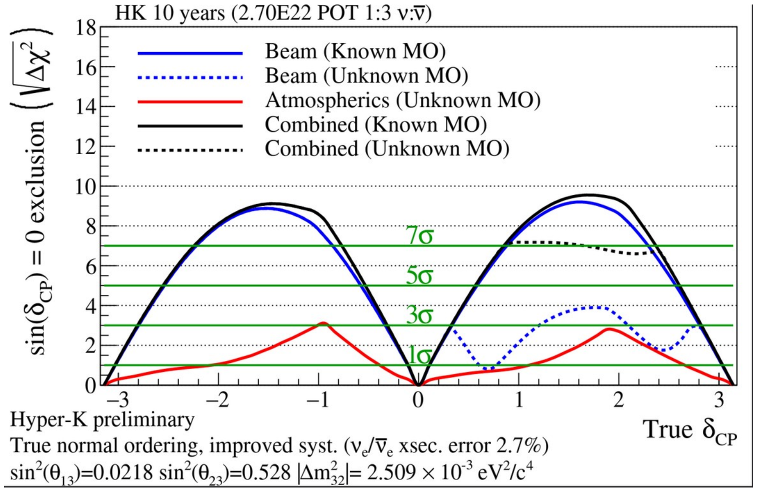
# Atmospheric neutrinos + beam




Sensitivity to mass ordering




Sensitivity to CP-violation




Atmospheric neutrinos sensitive to matter effects as they traverse the Earth
→ Sensitive to mass ordering, also helps with $\theta_{23}$ octant

Best sensitivity to mass ordering from **combined fit: atmospheric data + beam data**

If mass ordering unknown, atmospheric data improves beam sensitivity to $\delta_{CP}$

**Diagram: Kajita T. (10.2183/pjab.86.303)**

# Summary

# Construction has begun!

Hyper-Kamiokande

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# Summary

**The Hyper-Kamiokande is a next-generation neutrino experiment**

* Builds on the expertise and knowledge gained from the successful Super-K programe
  - Fiducial volume 8 times larger than SK
  - Improved photosensors
  - beam upgrade to 1.3 MW
  - New intermediate water Cherenkov detector and upgraded near detectors

**Wide range of physics**

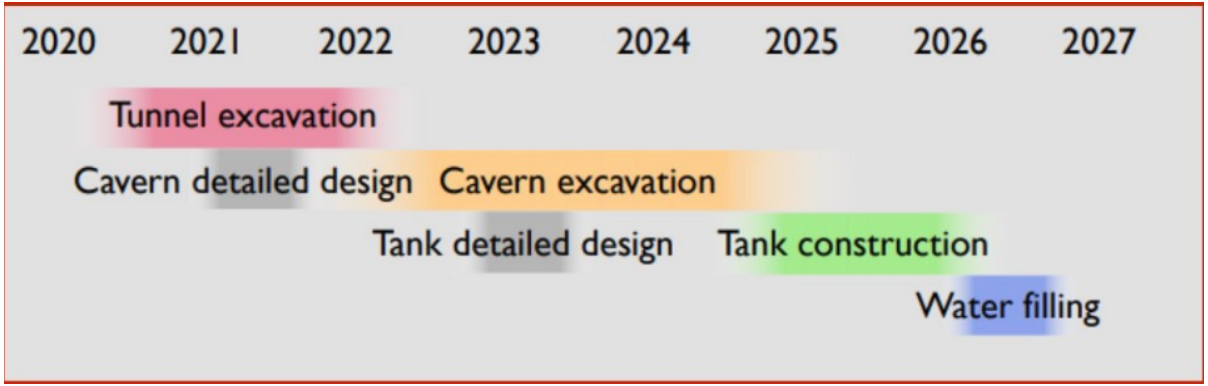
* CP violation in the lepton sector
* Nucleon decays
* Astrophysics
* Potential to discover new physics

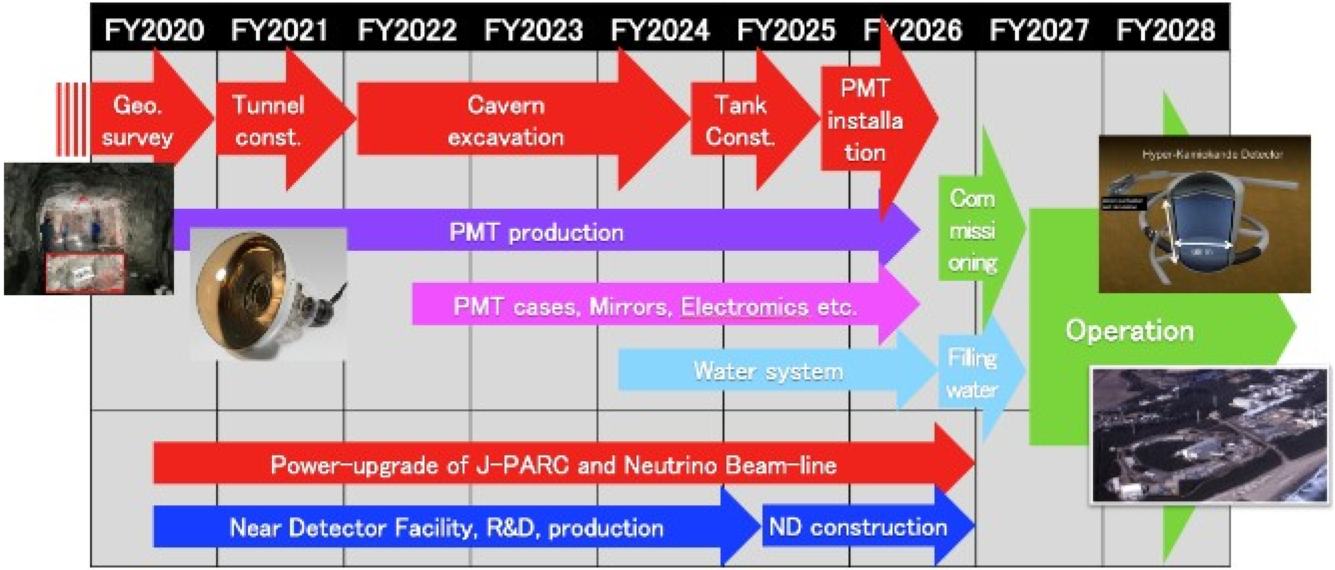


**New collaborators welcome!**

**Construction underway**
**Data taking in 2027**

# BACKUP

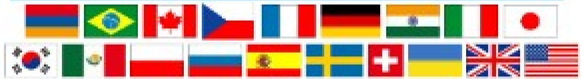

2020
2021
2022
2023
2024
2025
2026
2027
Tunnel excavation
Cavern detailed design
Cavern excavation
Tank detailed design
Tank construction
Water filling


FY2020
FY2021
FY2022
FY2023
FY2024
FY2025
FY2026
FY2027
FY2028
Geo. survey
Tunnel const.
Cavern excavation
Tank Const.
PMT installa tion
Com missi oning
PMT production
PMT cases, Mirrors, Electronics etc.
Water system
Filling water
Operation
Power-upgrade of J-PARC and Neutrino Beam-line
Near Detector Facility, R&D, production
ND construction

# HYPER-K COLLABORATION:

19 countries, 93 institutes, ~450 people as of May 2021, still growing

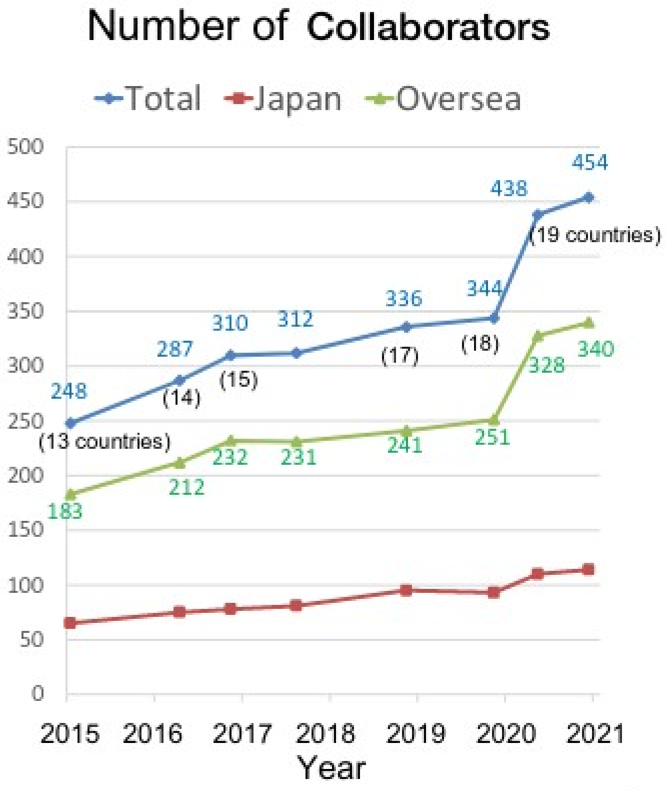
Collaborating Institutes



| Europe | 260 members |
|---|---|
| Armenia | 3 |
| Czech | 3 |
| France | 28 |
| Germany | 1 |
| Italy | 53 |
| Poland | 37 |
| Russia | 21 |
| Spain | 26 |
| Sweden | 5 |
| Switzerland | 5 |
| Ukraine | 4 |
| UK | 74 |

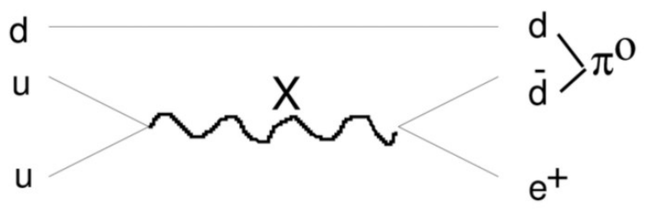
| Asia | 142 members |
|---|---|
| India | 10 |
| Korea | 18 |
| Japan | 114 |

| Americas | 52 members |
|---|---|
| Brazil | 3 |
| Canada | 29 |
| Mexico | 11 |
| USA | 9 |

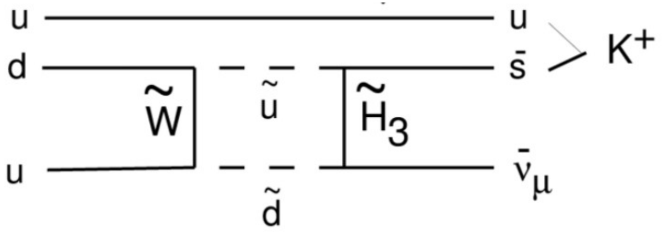


# Proton decay and neutrinos

$p \rightarrow e^{+}\pi^{0} > 1.9 \times 10^{34}$ years




$p \rightarrow \nu K^{+} > 0.8 \times 10^{34}$ years




Atmospheric nu still biggest background for kaon mode

Originally proposed by Sakharov to provide baryon number violation to explain the matter-antimatter asymmetry of the universe.

Many GUT predict proton decay

KamiokaNDE (Kamioka Nucleon Decay Experiment) I&II

→ Did not observe proton decay
→ ruled out many GUTs at the time

→ observed Supernova 1987a

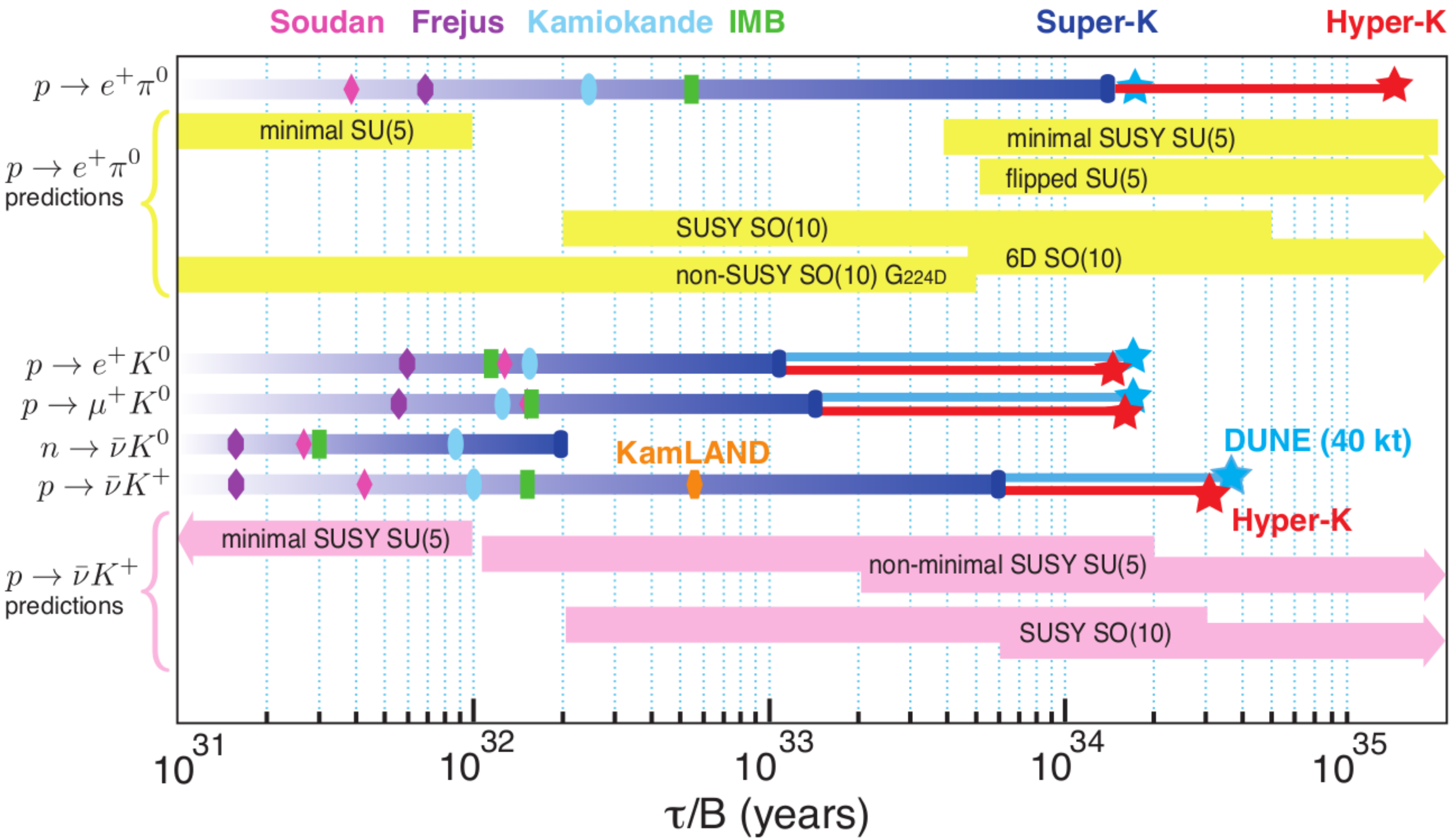
→ saw hints of neutrino oscillation

  → solar neutrinos

  → atmospheric neutrinos

Super-K limit on proton decay $> 10^{34}$ years

# Proton decay



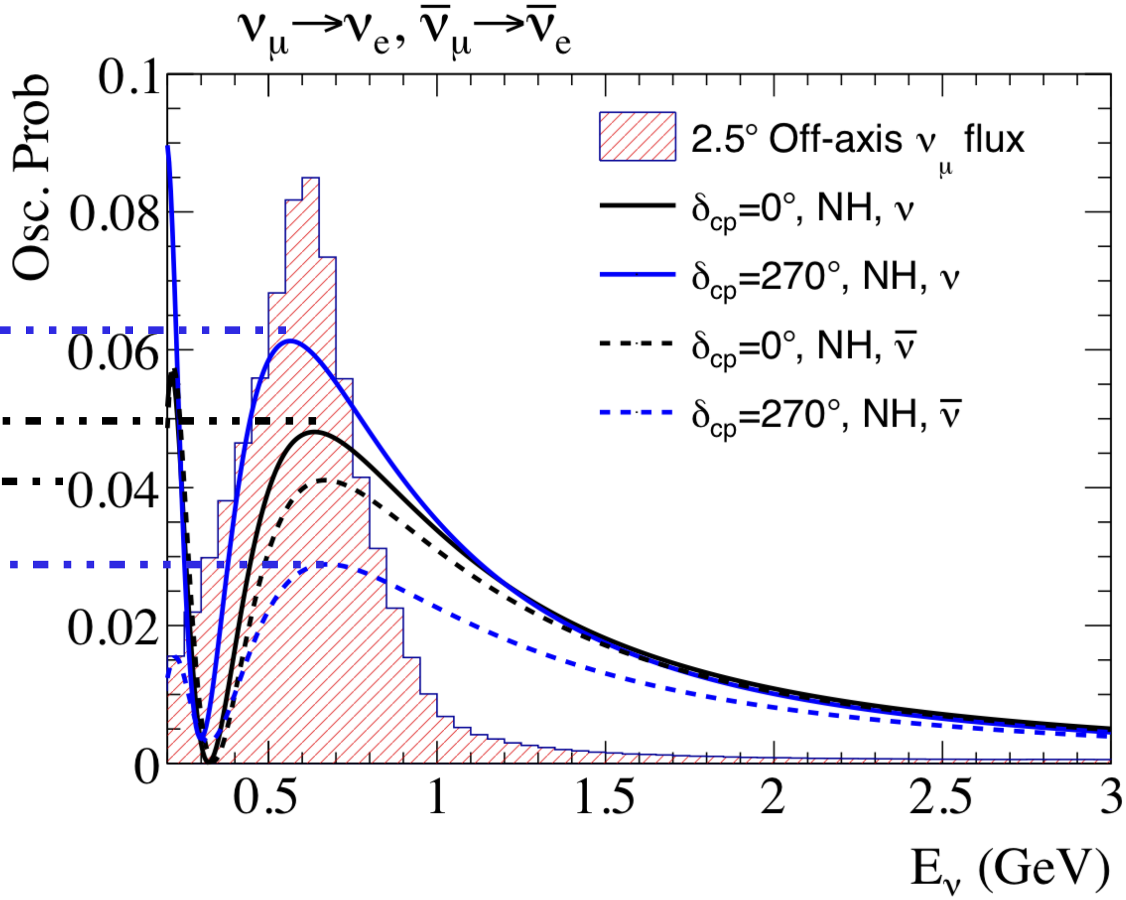
# $\nu_e$ ($\bar{\nu}_e$) appearance

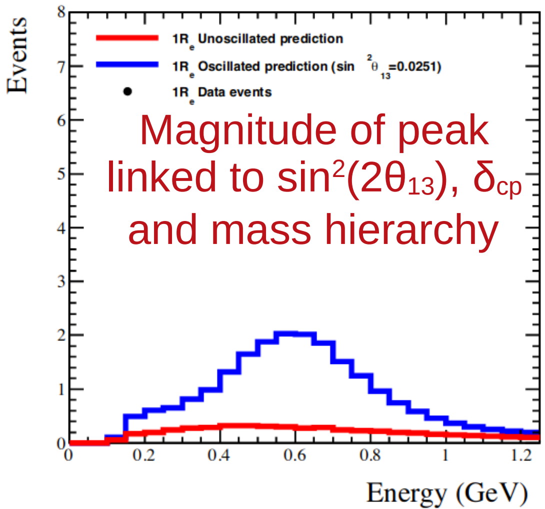
Oscillation peak causes peak in $\nu_e$ ($\bar{\nu}_e$) observed at SK

sensitive to $\theta_{23} < \pi/4$ or $\theta_{23} > \pi/4$

Maximum possible $\delta_{cp}$ effect ~30%

Matter effect

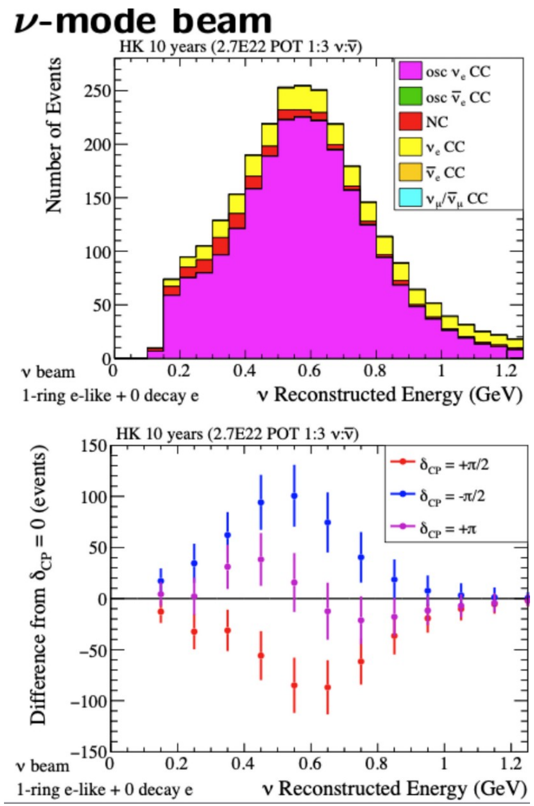


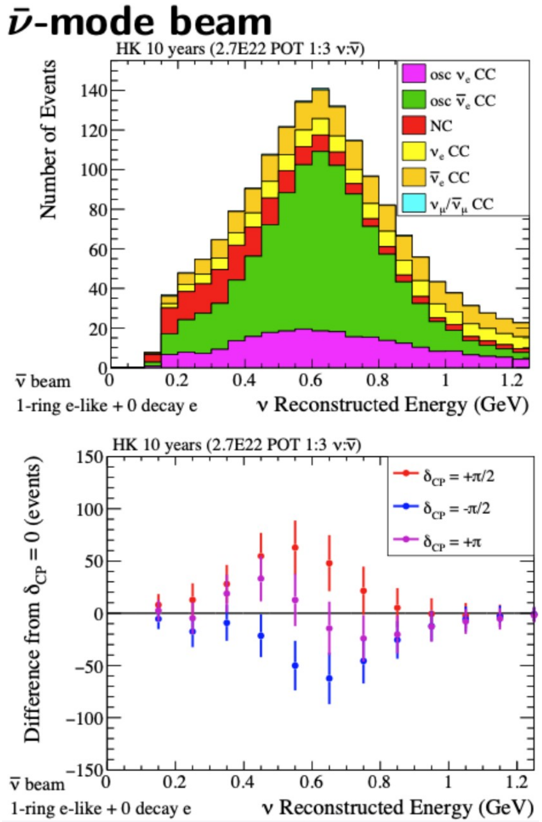




Magnitude of peak linked to $\sin^2(2\theta_{13})$, $\delta_{cp}$ and mass hierarchy

**Test CP symmetry**

# Hyper-Kamiokande long-baseline



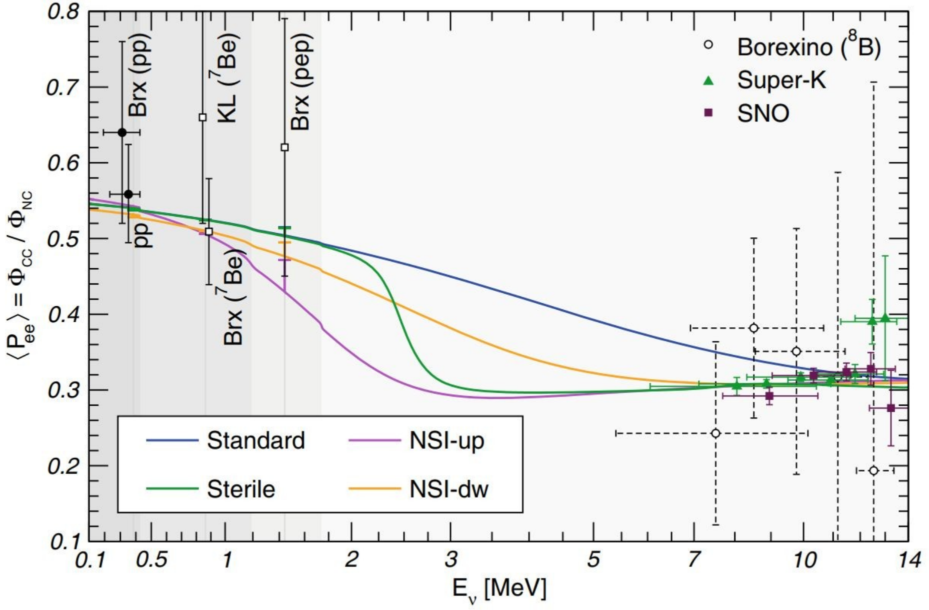

Predicted HK far detector event yields for 10 years of operation

$\nu : \bar{\nu} = 1 : 3$

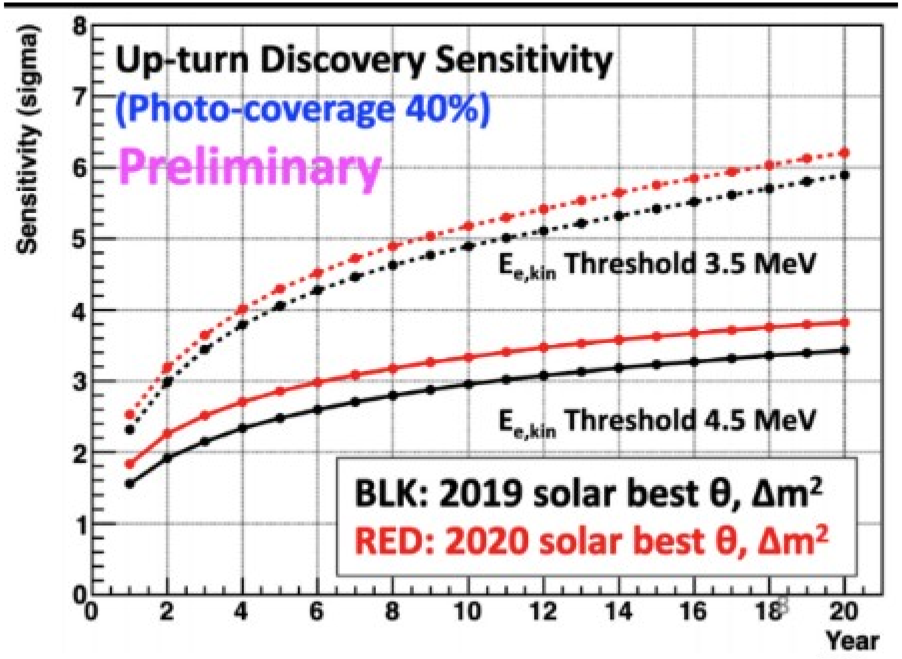
Run mode chosen to optimise deltaCP sensitivity

# Solar Neutrinos

‘Upturn’: increase in the solar neutrino survival probability at low energy
→ transition region between mater dominated and vacuum dominated oscillations




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

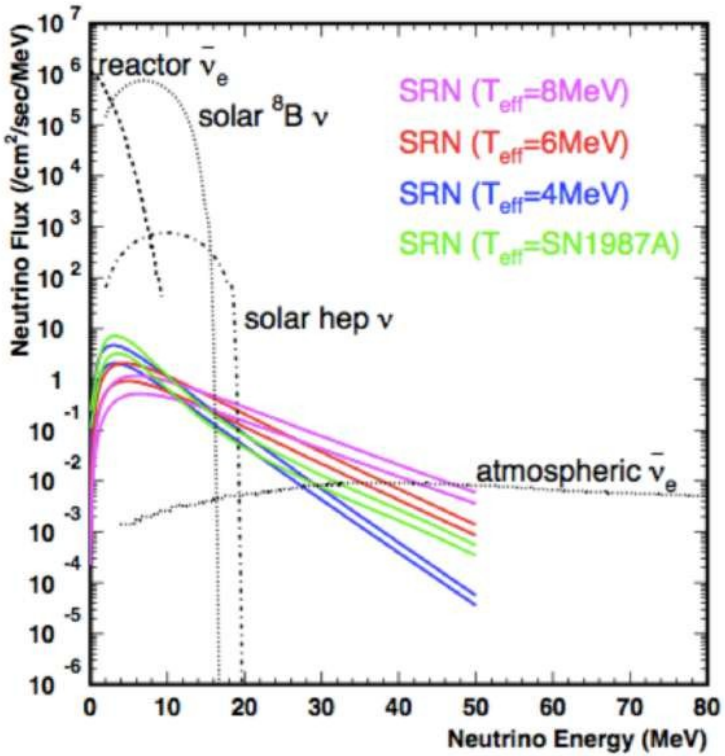



Significance of upturn detection at HK

# Supernova Relic Neutrinos

Hyper-Kamiokande

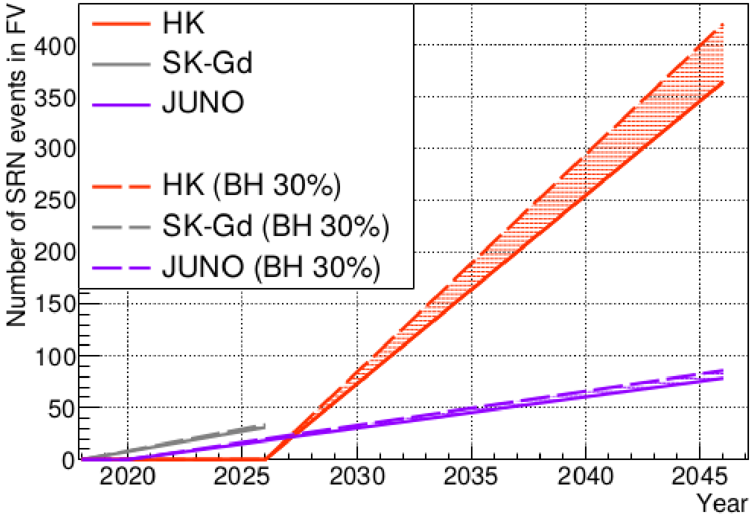
Predicted flux for different models




* Small flux
* Large backgrounds

→ No evidence of supernova relic neutrinos at SK yet

Predicted event numbers




Dashed line for case where 30% form black hole and emit higher energy neutrinos

# Supernova Neutrinos

M31 (Andromeda 6898 Galaxy)
~ 10 to 16 events expected at Hyper-K.

Large Magellanic Cloud (where SN1987A was located)
~ 2,200 to 3,600 events expected at Hyper-K

Betelgeuse (200pc)
~ 117.5 million – 180 million

# Supernova Neutrinos

Hyper-Kamiokande

* Blackhole formation can be observed as a sharp drop in neutrino flux

* Hyper-K can confirm/refute models relating to the dynamics of the explosion
( Standing Accretion Shock Instability )

* Supernova flux is  sensitive to mass ordering without too much model dependence
→ neutronization burst

# The Kamiokande Series

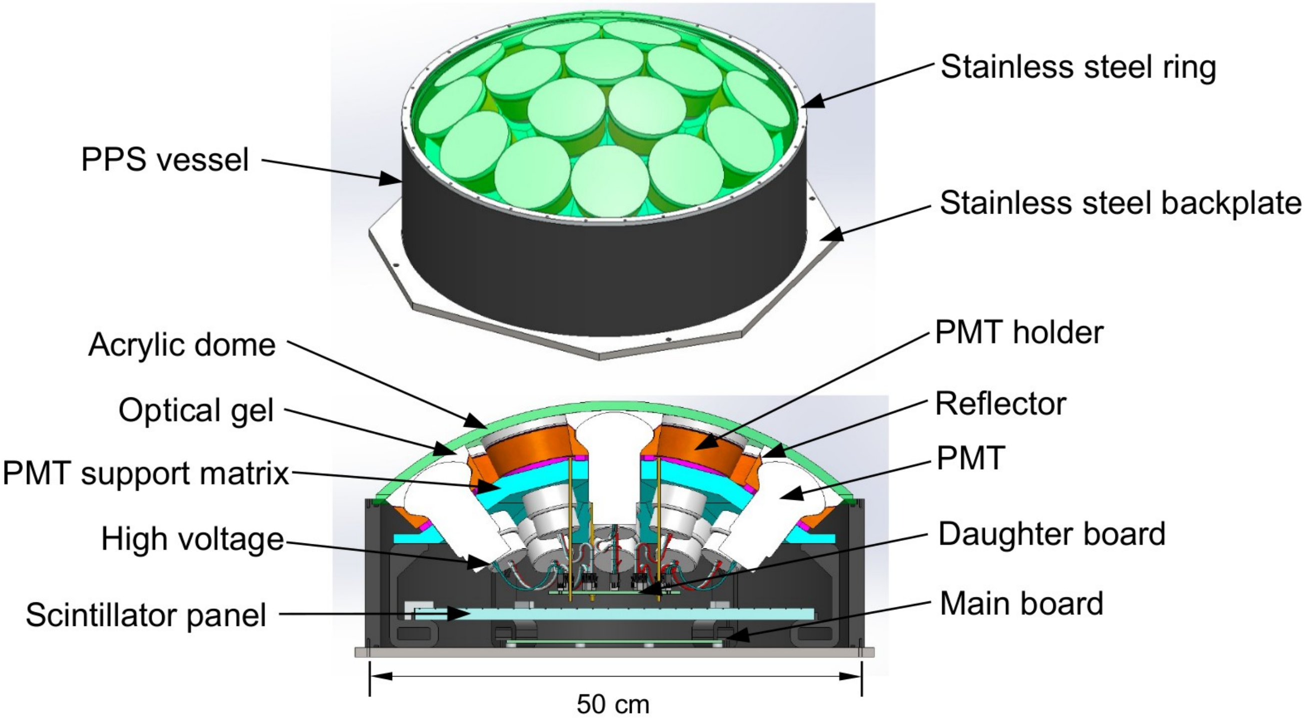
**Hyper-K: Height h = 71m, diameter d = 68m**
**Volume V = 258 kton, Fiducial Volume FV >= 187 kton**

**Super-K: h = 41.4m, d = 39.1m**
**V = 50kton, FV: 22.5 kton**

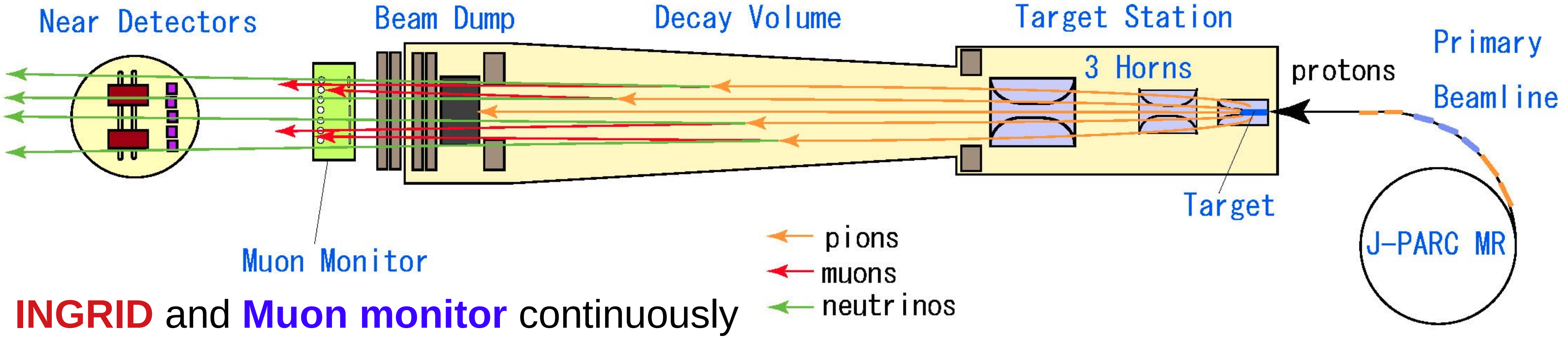
**Kamiokande**

**h = 16 m**
**d = 15.6 m**
**V = 3 kton**
**FV = 0.68 kton**

# Multi-PMT (mPMT)




# Neutrino beam




**INGRID** and **Muon monitor** continuously measure beam rate and direction

* **30GeV protons** → **graphite** target → charged **hadrons**
* **charge selection** and focusing of hadrons with **3 electromagnetic horns**
* **hadrons decay to $\nu$ or $\bar{\nu}$** (depending on charge of hadron)

**Dominant systematic error due to hadron interaction modelling**

→ Constrained using NA61/SHINE replica target measurements

→ In future flux uncertainty will be reduced by the EMPHATIC experiment

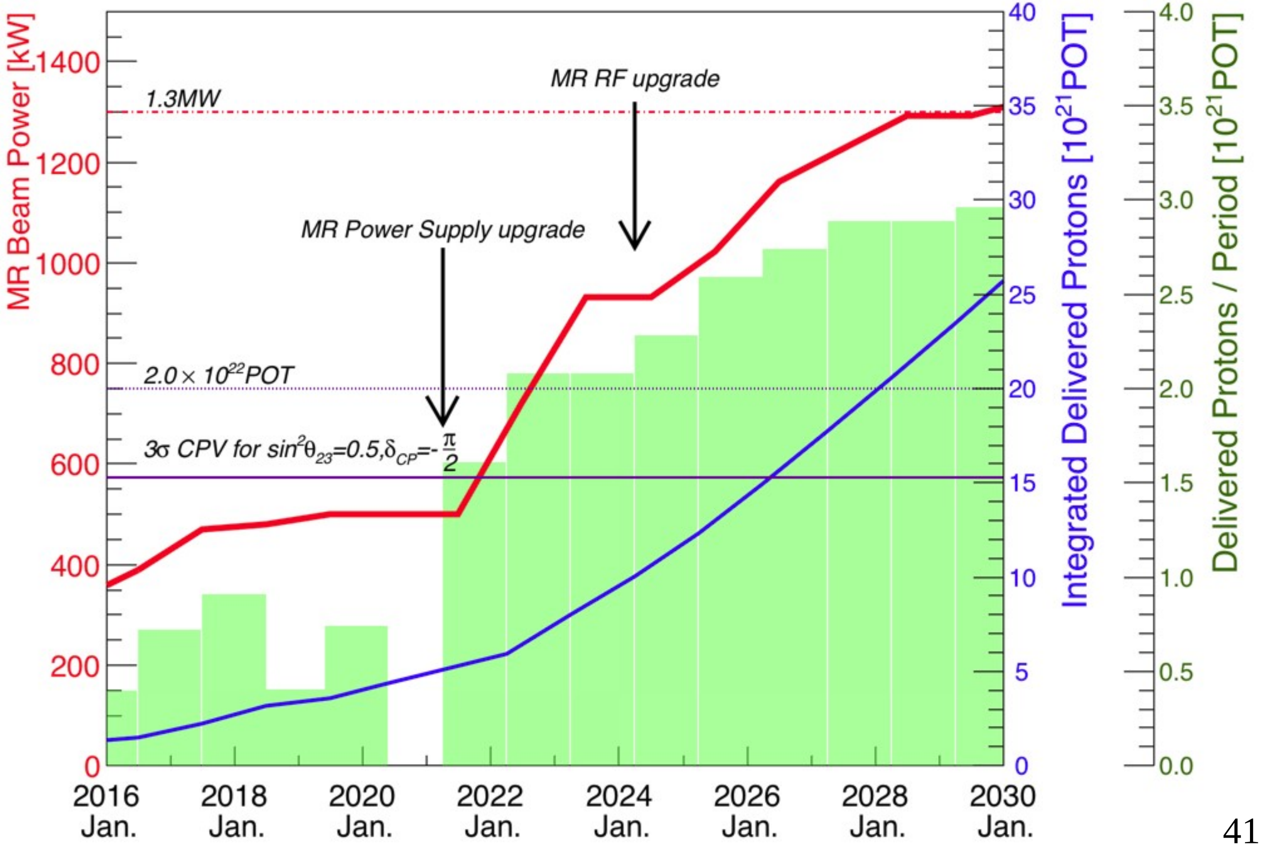
# T2K/HK  Beam upgrade

Hyper-Kamiokande

* Beam currently capable of 450-500kW stable running

* Beam line upgrade in 2021
  - Nd280 upgrade will happen at the same time

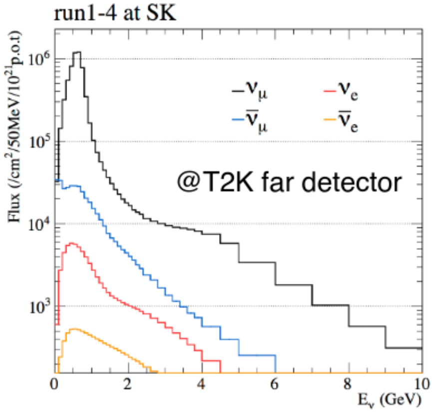
* target power:  1.3MW



# J-PARC neutrino beam flux and its error

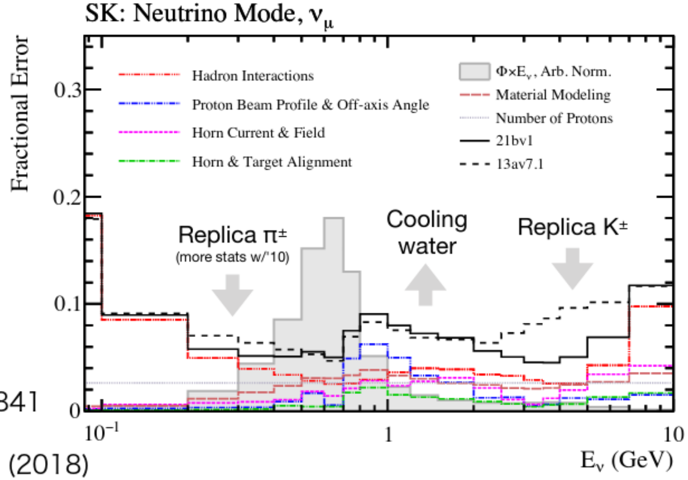
ν flux is predicted based on hadron production and in-situ proton beam measurements

- ❖ Recently flux error was improved with NA61/SHINE replica 2010 data : **~5% error**
- ❖ Further reduction of flux systematic errors, several activities are underway




*Hadron production is still largest error source*

**New measurements at NA61/SHINE, EMPHATIC are underway to reduce the remaining flux error**

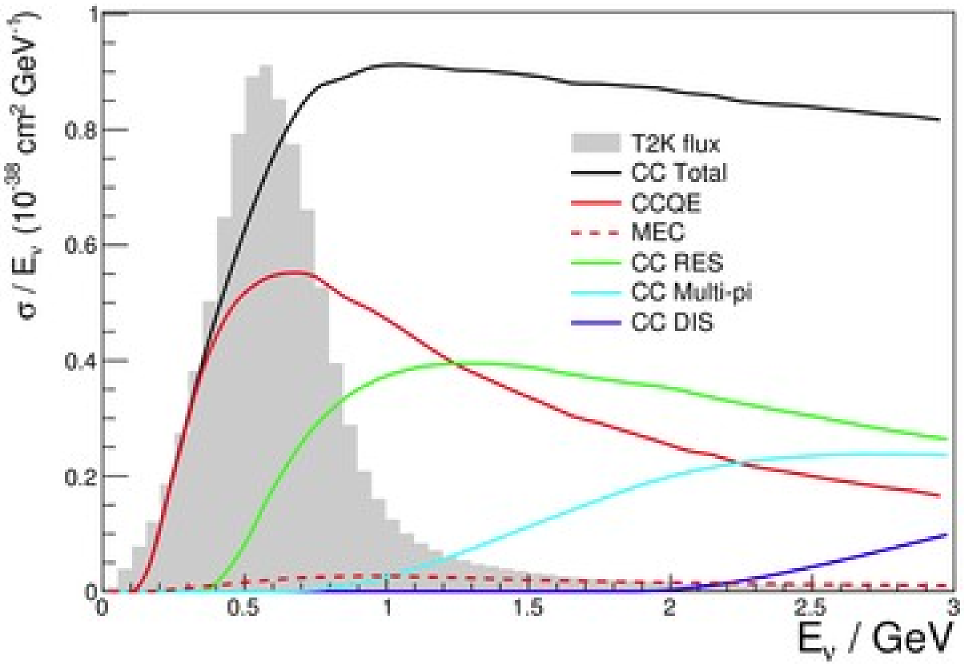



arXiv:1912.08841

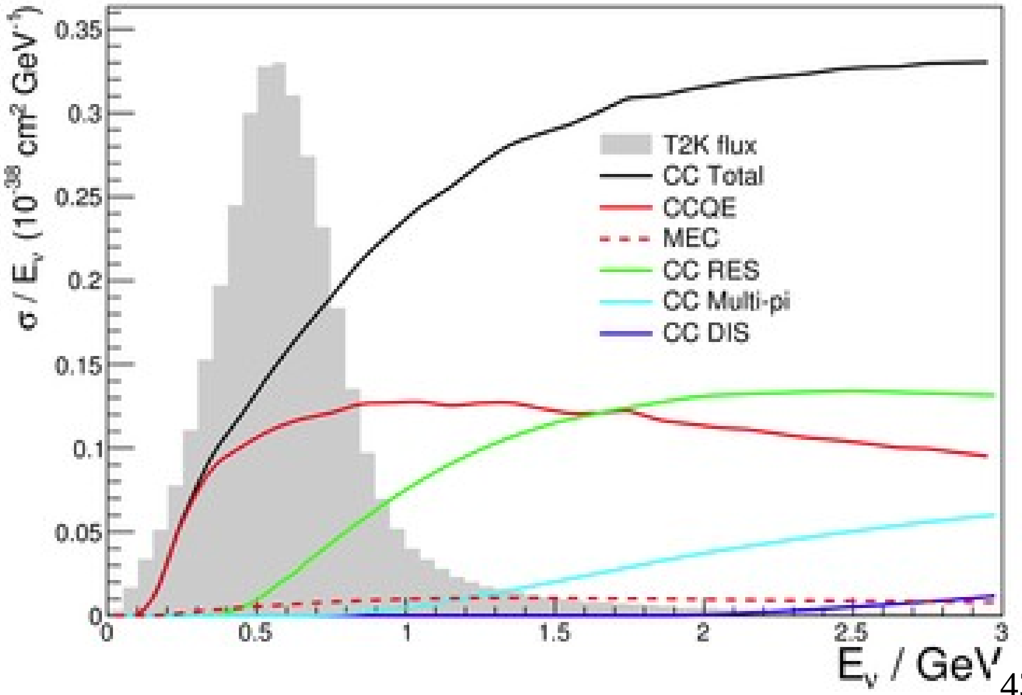
CERN-SPSC-2018-008, SPSC-P-330-ADD-10 (2018)

# Neutrino interaction cross sections and T2K/HK flux

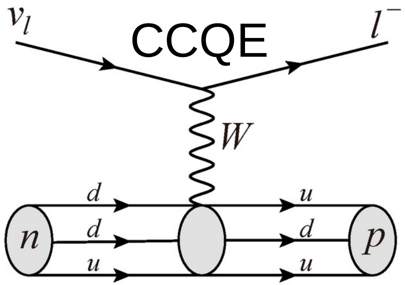
$\nu$

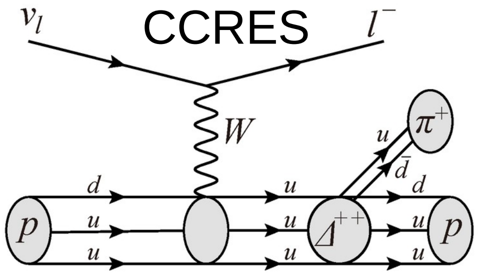


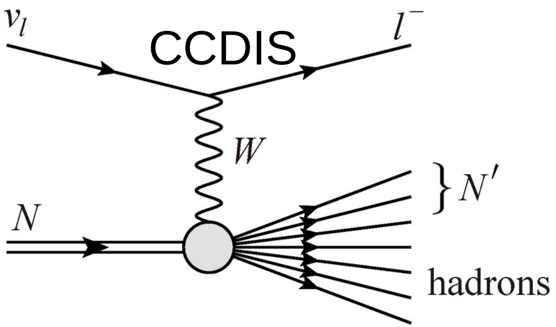

$\bar{\nu}$



# Neutrino interactions



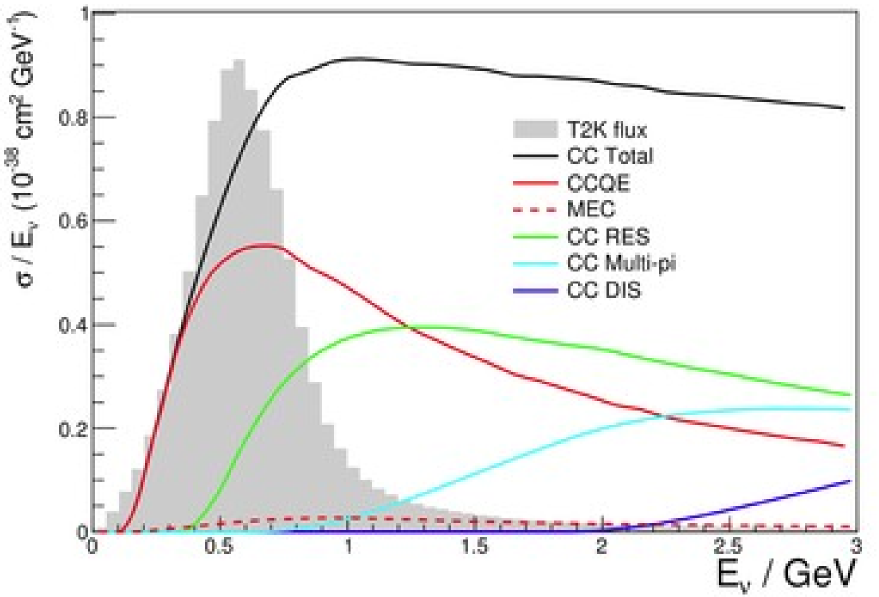




NC interactions also important

e.g. NC$\pi^0$, NC1γ

→ background




Interactions occur with nucleons bound inside a nucleus

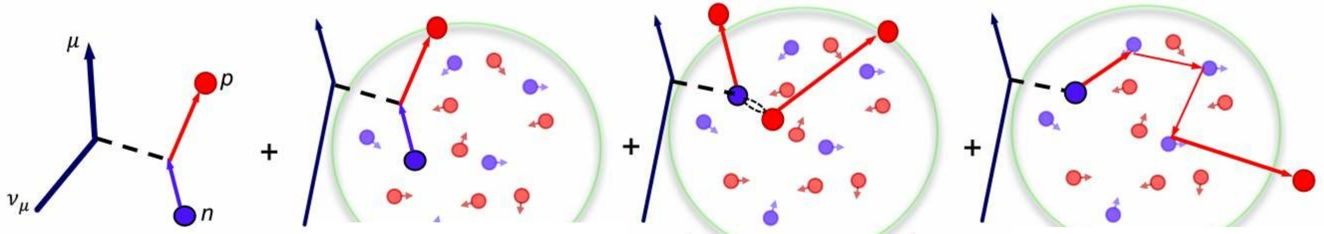
→ **Nuclear effects!!**

We only measure particles that exit the nucleus

→ lose information about the initial interaction

→ can create a bias in energy reconstruction

# Neutrino interactions



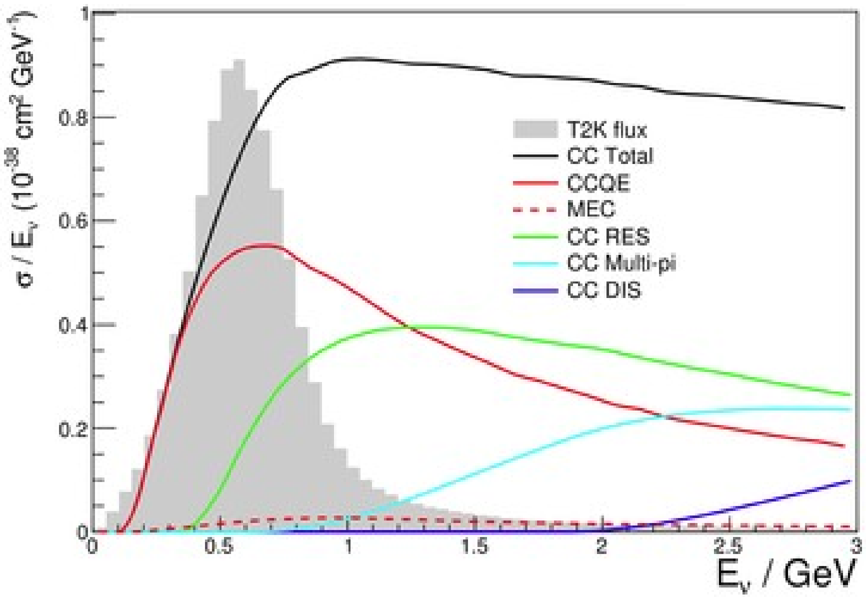

Free nucleon

Initial nuclear state

Extra nuclear effects

Final state interactions

Interaction modes and Nuclear models tuned to external data

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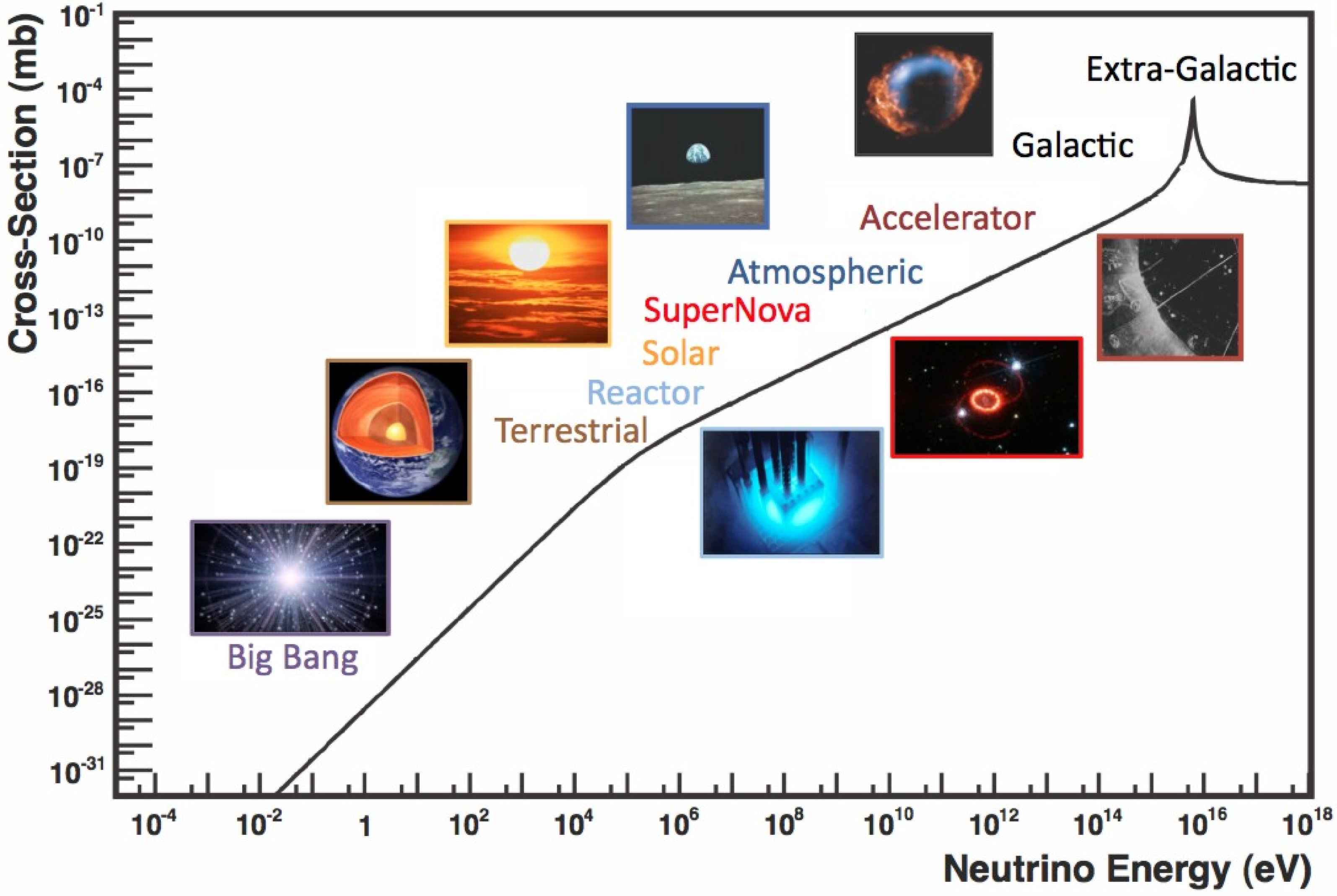
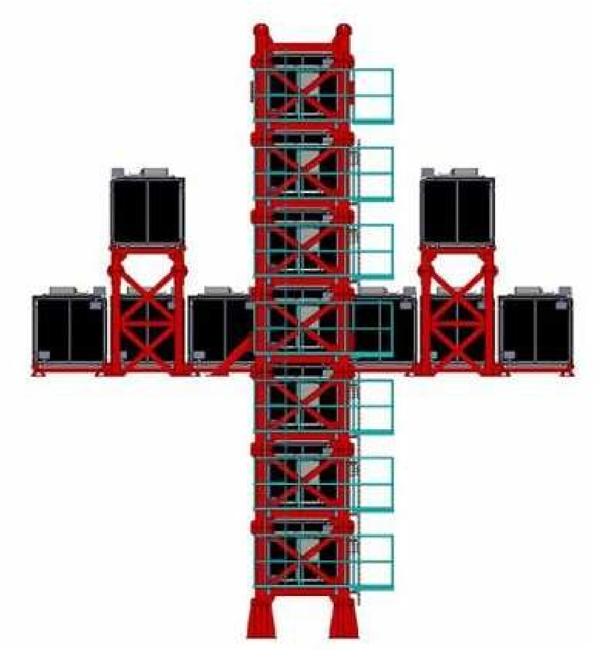

Cross-Section (mb)
10-1
10-4
10-7
10-10
10-13
10-16
10-19
10-22
10-25
10-28
10-31
Extra-Galactic
Galactic
Accelerator
Atmospheric
SuperNova
Solar
Reactor
Terrestrial
Big Bang
10-4
10-2
1
10^2
10^4
10^6
10^8
10^10
10^12
10^14
10^16
10^18
Neutrino Energy (eV)

# Near Detectors

280m from the $\nu$ ($\bar{\nu}$) source



**INGRID**

- On-axis, scintillator and iron
- monitors beam direction, intensity and stability

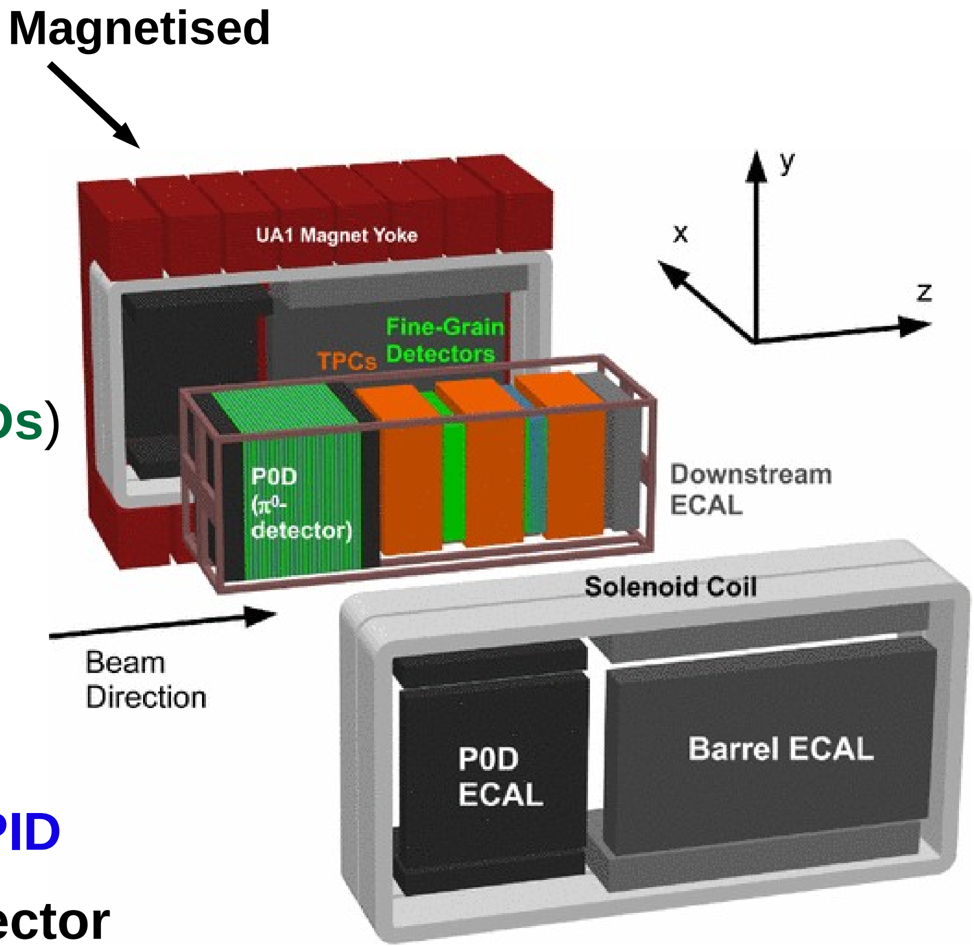
# Near Detectors

280m from the ν ($\bar{\nu}$) source

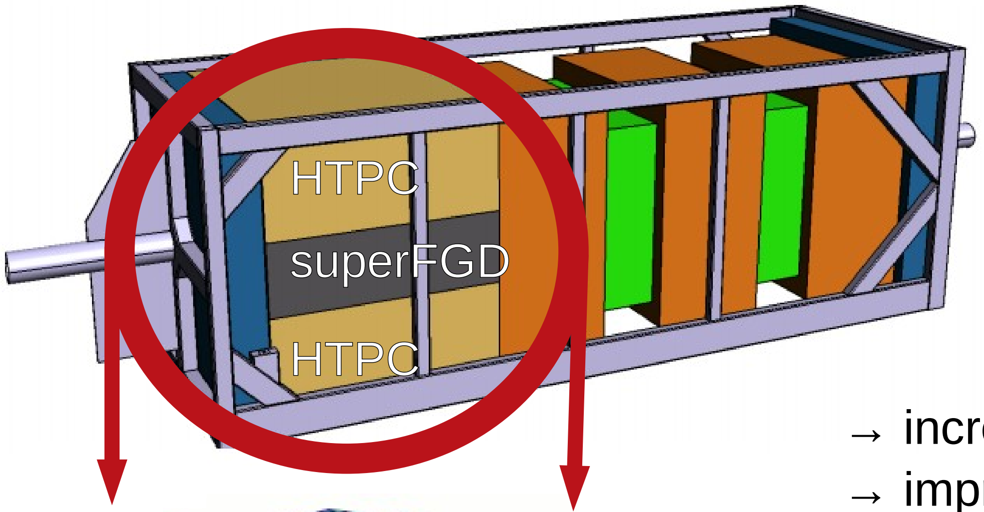
## ND280

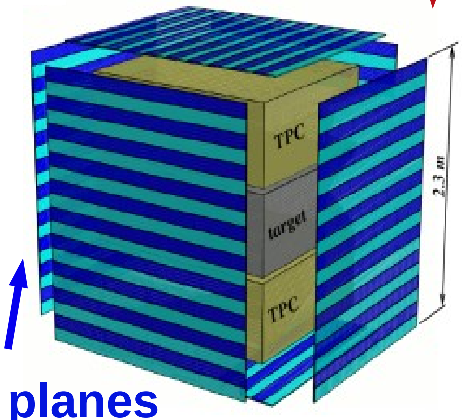
Same off-axis angle as SK

- Active target mass → 2 x scintilltors (**FGDs**)
  → vertex reconstruction
- 3 Time projection chambers (**TPC**)
  → **momentum** reconstruction
  → **charge** identification
  → Particle identification (**PID**)
- Electromagnetic calorimeters (**Ecal**) → **PID**
- **$\pi^0$ detector** and **side muon range detector**



# ND280 upgrade (2021)




**6 ToF planes**

**Pi0 detector is being replaced by**
*** SuperFGD**
- higher granularity, 3D readout

*** Horizontal TPCs (HTPCs)**
*** Time of Flight (ToF) planes**

→ increases active target **mass** for oscillation analysis
→ improved **angular acceptance**
→ able to reconstruct **low energy short tracks**
  → improved hadronic information
  → better $\gamma \rightarrow e^+ e^-$ identification

**Reduce systematic uncertainty to 4%**
→ 3σ exclusion of CP conservation for 36% of the $\delta_{cp}$ phase space (if mass hierarchy is known)

# The Beam

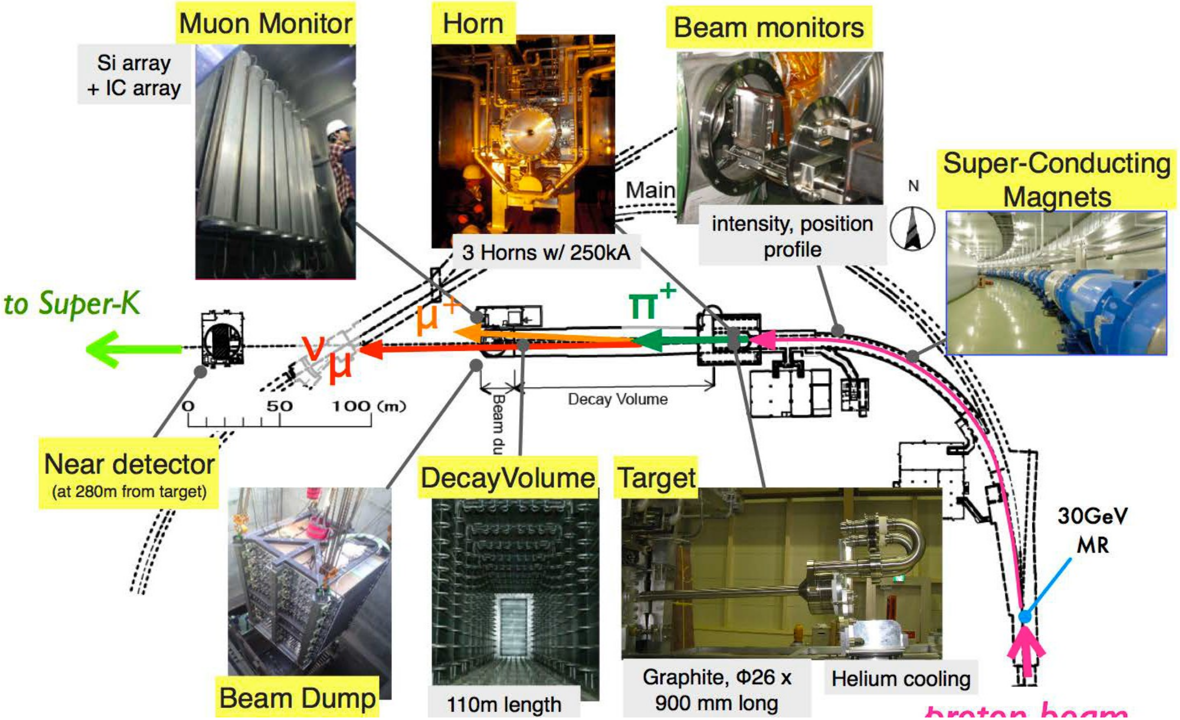
Major neutrino-producing decay modes in the decay volume:

For a neutrino beam

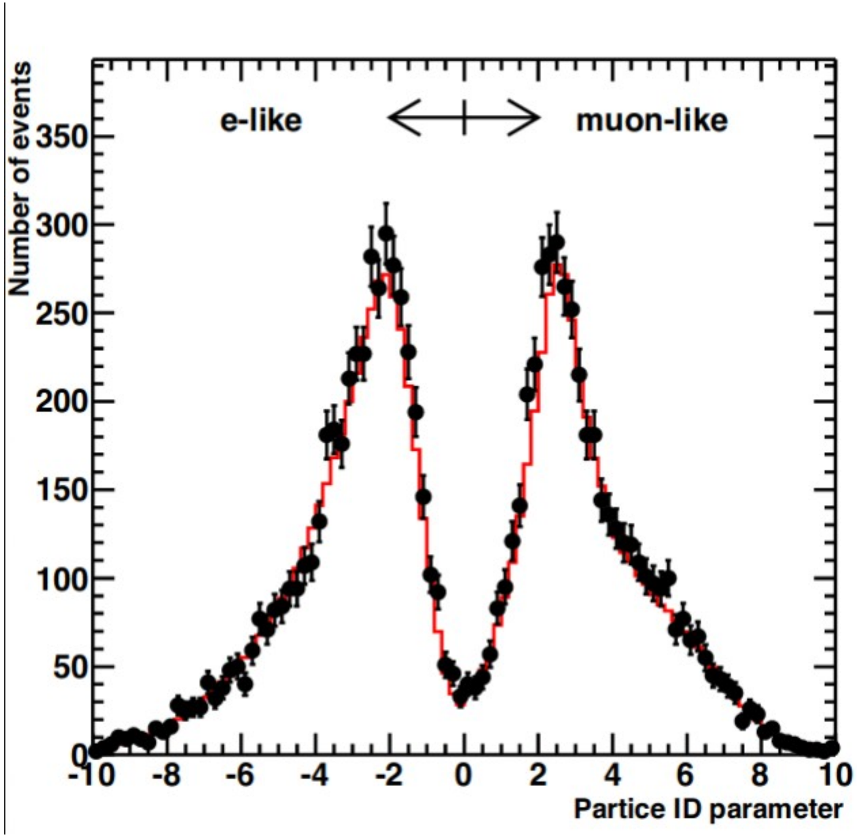
$\boldsymbol{\pi^+ \rightarrow \mu^+ + \nu_\mu}$
$\boldsymbol{K^+ \rightarrow \mu^+ + \nu_\mu}$
$\boldsymbol{K^+ \rightarrow \pi^0 + \mu^+ + \nu_\mu}$
$K^0 \rightarrow \pi^- + \mu^+ + \nu_\mu$
$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$

$\boldsymbol{K^+ \rightarrow \pi^0 + e^+ + \nu_e}$

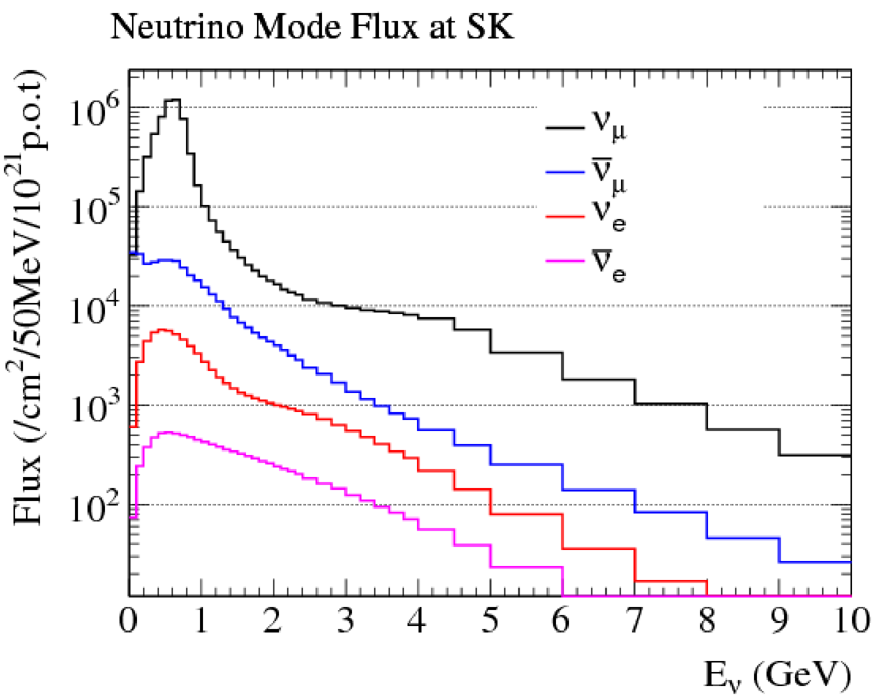
$\boldsymbol{\pi^+ \rightarrow e^+ + \nu_e}$
$K^0 \rightarrow \pi^- + \mu^+ + \bar{\nu}_\mu$
$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$

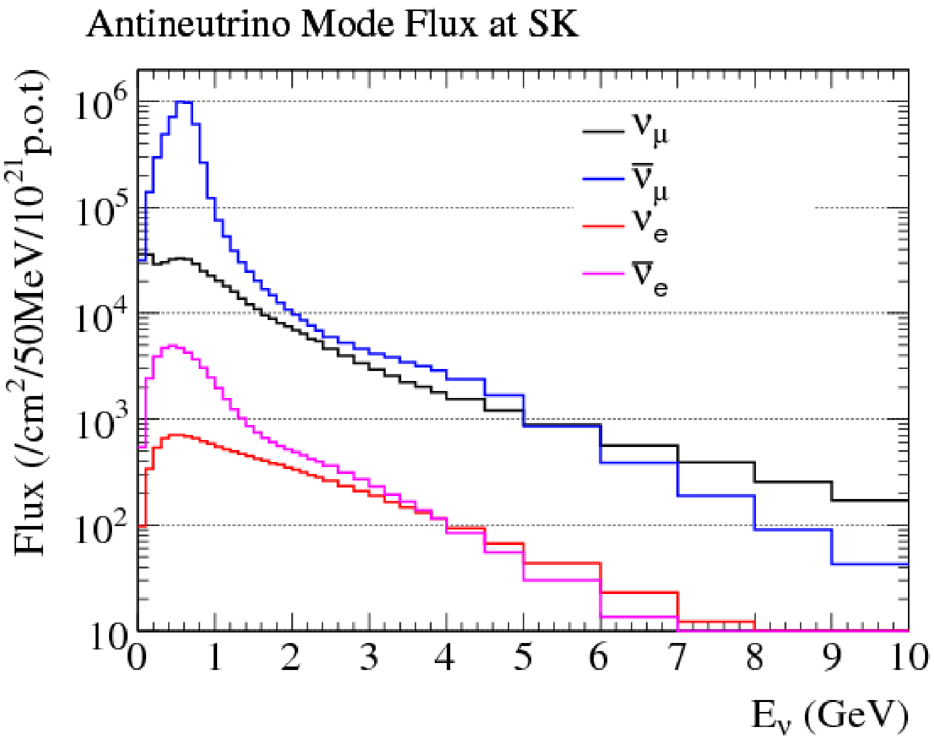


# SK particle identification



# Beam Flux


Neutrino Mode Flux at SK
Flux (/cm$^2$/50MeV/10$^{21}$p.o.t)
$10^6$
$10^5$
$10^4$
$10^3$
$10^2$
$\nu_\mu$
$\bar{\nu}_\mu$
$\nu_e$
$\bar{\nu}_e$
0 1 2 3 4 5 6 7 8 9 10
$E_\nu$ (GeV)

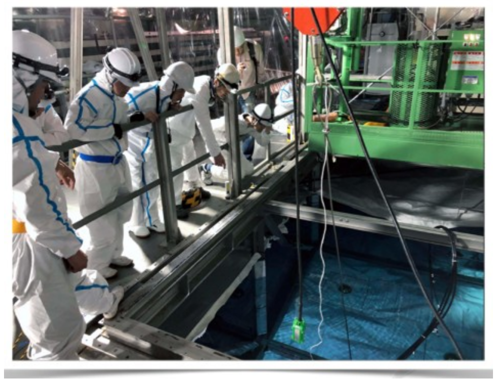

Antineutrino Mode Flux at SK
Flux (/cm$^2$/50MeV/10$^{21}$p.o.t)
$10^6$
$10^5$
$10^4$
$10^3$
$10^2$
10
$\nu_\mu$
$\bar{\nu}_\mu$
$\nu_e$
$\bar{\nu}_e$
0 1 2 3 4 5 6 7 8 9 10
$E_\nu$ (GeV)

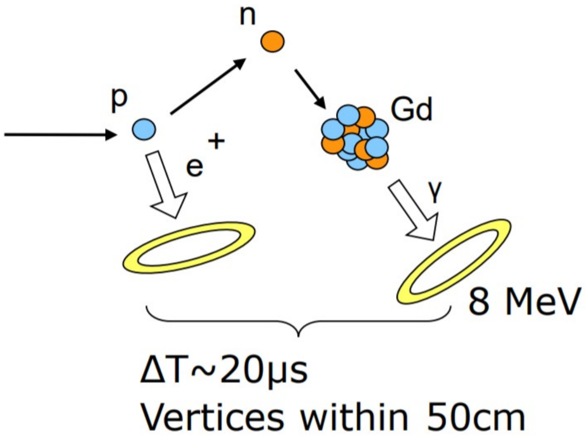
# T2K II:  SK upgrade

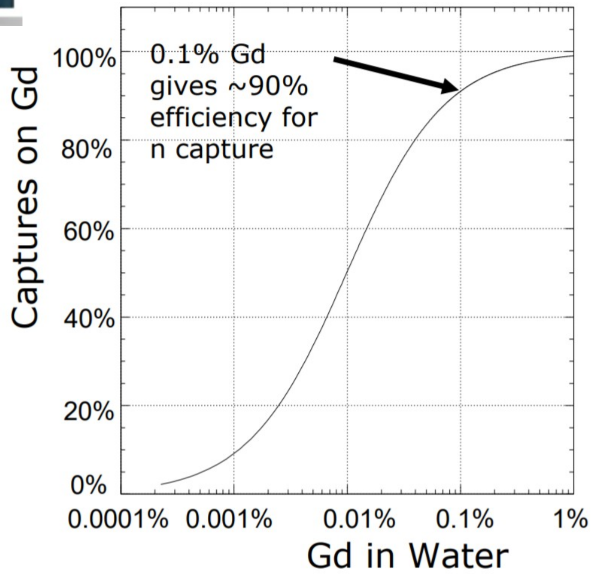
* SK repairs performed in 2018
  - detector drained and cleaned
  - reinforcement of water sealing
  - improved tank piping
  - PMTs replaced

* Plan to add **Gadolinium** to the water
  - 0.01% next year
  - increase to 0.1% eventually $\overline{\nu}_e$

→ **Better $\nu$ / $\overline{\nu}$ separation**





# Neutrino Oscillations

Hyper-Kamiokande

Flavour eigenstate: Interact
Mass eigenstate: Propagate

Neutrino oscillation
→ mass states do not align with flavour states
→ non-zero masses

Oscillations governed by PMNS flavour-mass mixing matrix, U

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i} |\nu_i\rangle$$

Flavour states    Mass states

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \underbrace{\begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}}_{\text{Atmospheric and accelerator}} \underbrace{\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta_{CP}}\\ 0 & 1 & 0\\ -s_{13}^{i\delta_{CP}} & 0 & c_{13}\end{pmatrix}}_{\text{Reactor and accelerator}} \underbrace{\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}}_{\text{Solar and reactor}} \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

Atmospheric and accelerator
$\theta_{23} \sim ∶ 45°$
$|\Delta m_{32}^2| \sim 2.5\text{x}10^{-3}$ eV$^2$

Reactor and accelerator
$\theta_{13} \sim 8°$
Accelerator only $\delta_{CP} = ??$

Solar and reactor
$\theta_{12} \sim 34°$
$\Delta m_{12}^2 \sim 7.5\text{x}10^{-5}$ eV$^2$

$c_{ij} = \cos(\theta_{ij})$ , $s_{ij} = \sin(\theta_{ij})$

$\Delta m^2_{ij} = m^2_i - m^2_j$

$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j} \underline{\Re(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})} \sin^2 \underline{\left(\Delta m^2_{ij}\frac{L}{4E}\right)} + 2\sum_{i>j} \underline{\Im(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})} \sin \underline{\left(\Delta m^2_{ij}\frac{L}{2E}\right)}$$

→ **Amplitude** of oscillation: **mixing angles and phase**

→ **Distance** of oscillation: **squared mass differences and Energy**

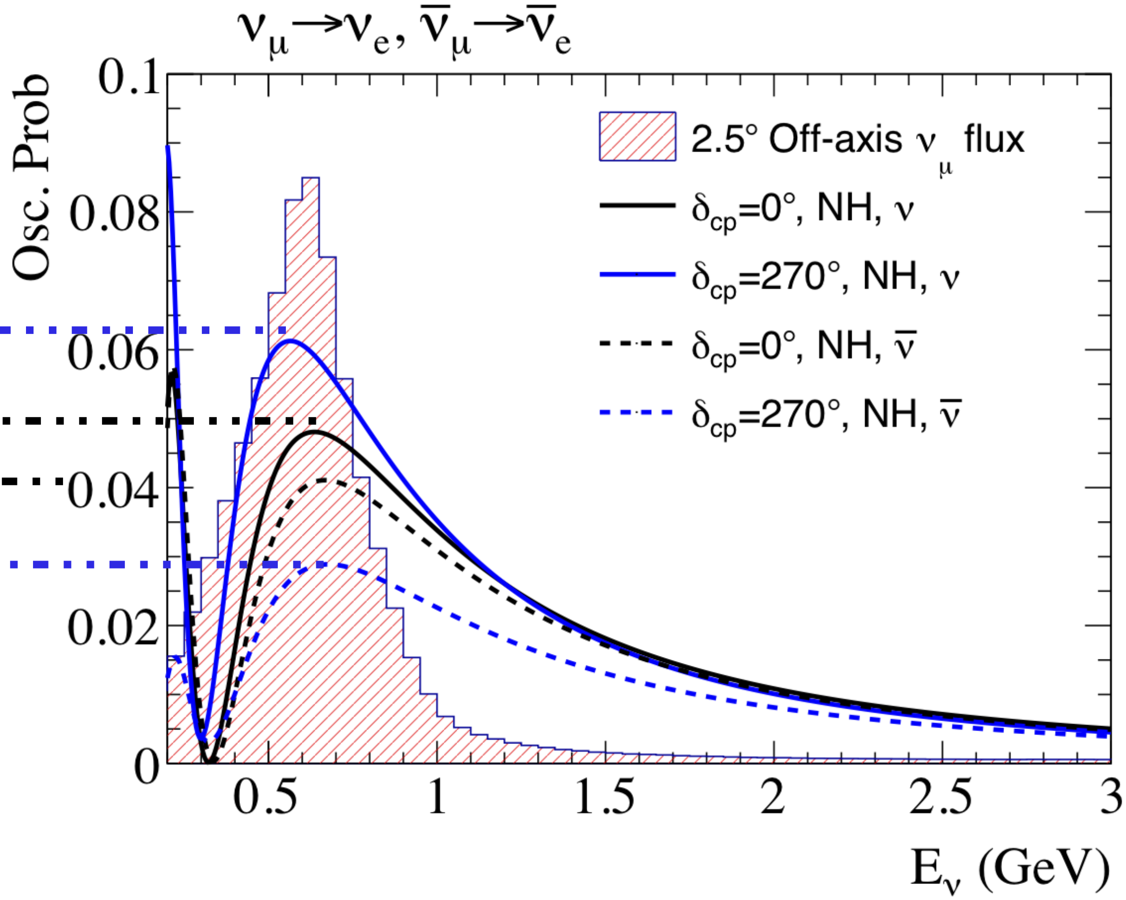
# $\nu_e$ ($\bar{\nu}_e$) appearance

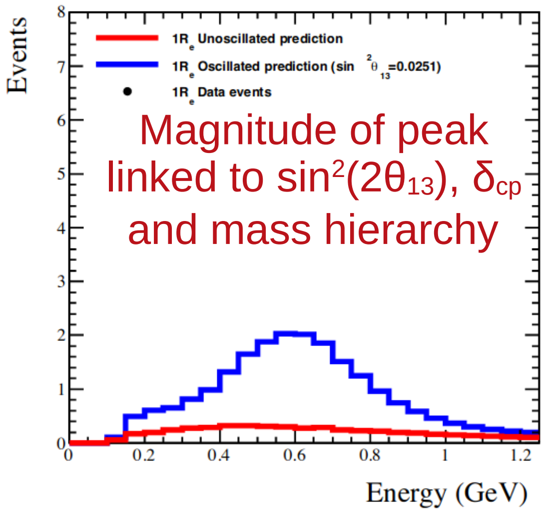
Oscillation peak causes peak in $\nu_e$ ($\bar{\nu}_e$) observed at SK

sensitive to $\theta_{23} < \pi/4$ or $\theta_{23} > \pi/4$

Maximum possible $\delta_{cp}$ effect ~30%

Matter effect




Magnitude of peak linked to $\sin^2(2\theta_{13})$, $\delta_{cp}$ and mass hierarchy

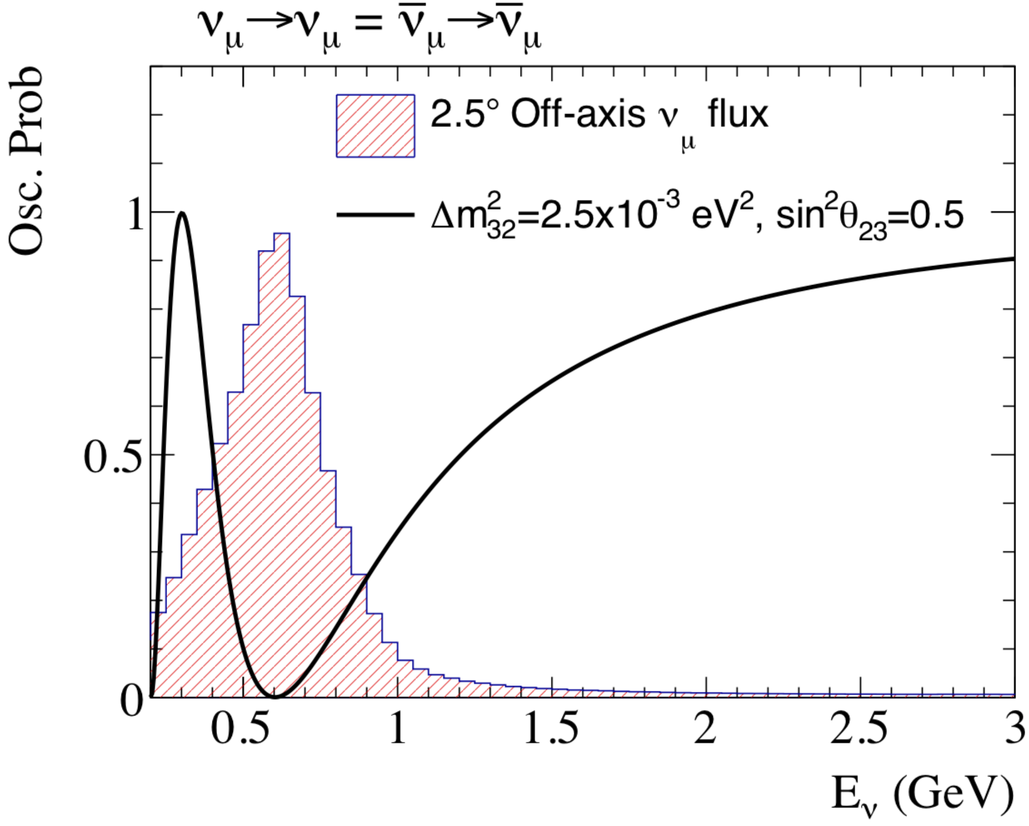
**Test CP symmetry**

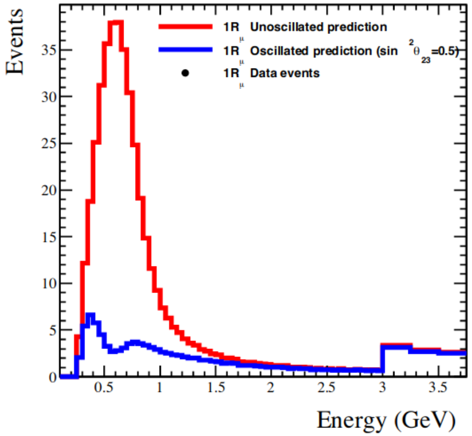
# $\nu_\mu$ ($\bar{\nu}_\mu$) disappearance

Probability minimum causes a dip in the number of $\nu_\mu$ observed at SK

Depth of dip – $\sin^2(\theta_{23})$
Energy of dip – $|\Delta m^2_{32}|$ ($|\Delta m^2_{13}|$)

Hard to distinguish mass ordering




**Test CPT symmetry**