# Hyper-Kamiokande Project
# Status and Plans

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**and for Yury Kudenko**

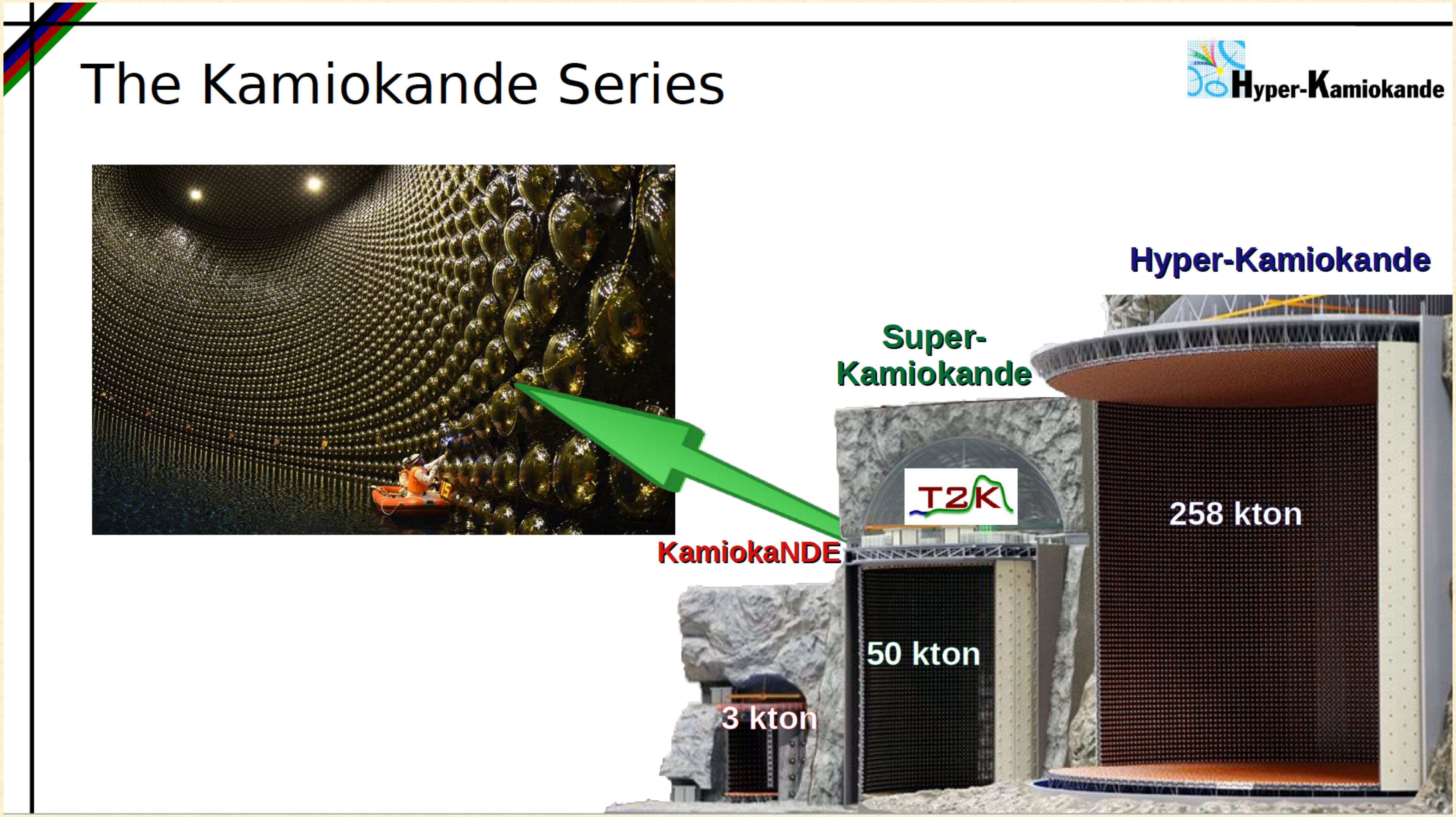
**October 5, 2021**

# Future neutrino projects

- Despite a huge success of the past and current neutrino experiments in fulfilling the neutrino puzzle a range of question exists that requires further efforts
- Neutrino mass ordering, CP-violation in neutrino (lepton) sector, θ23 - angle (octant, any new symmetries?), sterile neutrinos?, non-standard interactions?, heavy neutral leptons?
- A new generation of experiments is needed is needed to provide definitive determinations of neutrino properties
  - And accelerator based neutrino beams will continue their one of the leading roles
- Here we enter **Hyper-Kamiokande** and DUNE era

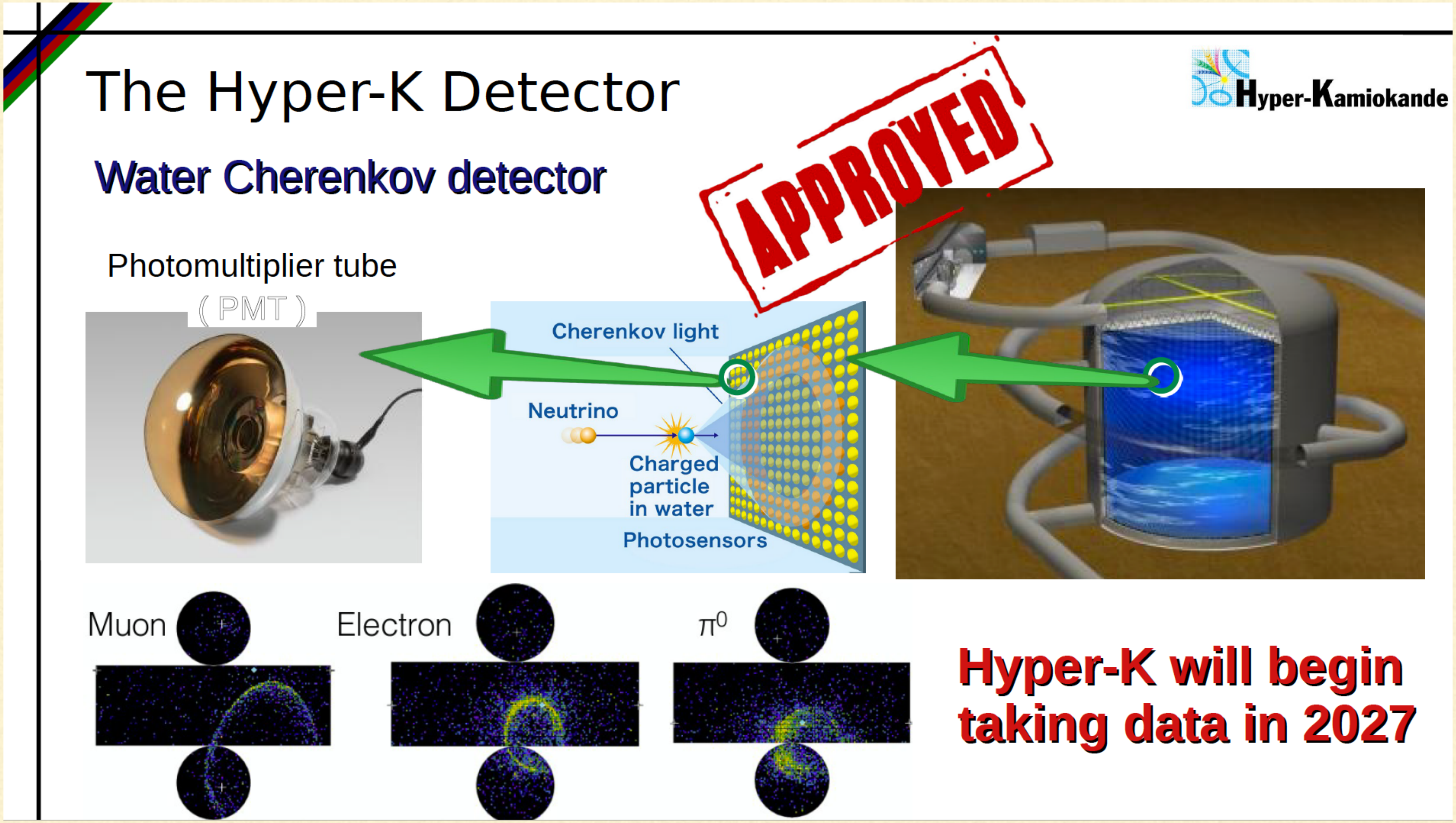
# Hyper-Kamiokande detector

- Further superb iterations of the Kamiokande physics



# Hyper-Kamiokande detector

- The main idea is to build the new unique large-scale water Cherenkov detector



# Hyper-Kamiokande detector design

- Inner and outer detectors

## The Hyper-K Detector

Hyper-Kamiokande

**Inner detector (ID):**

* 216 kton

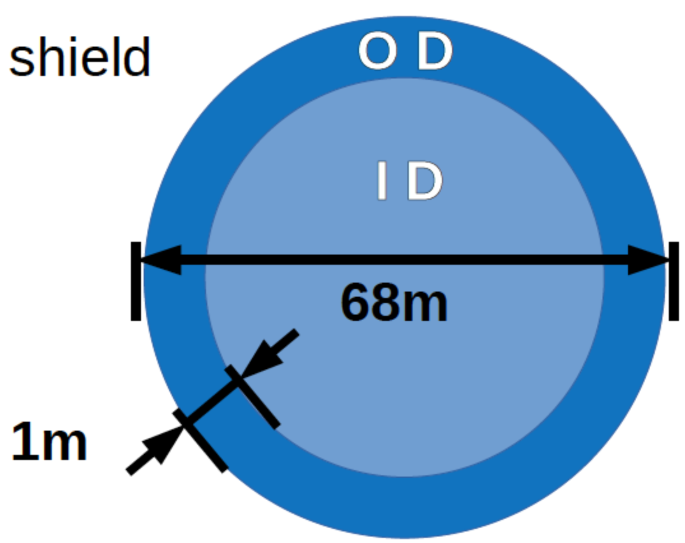
**Outer detector (OD):**

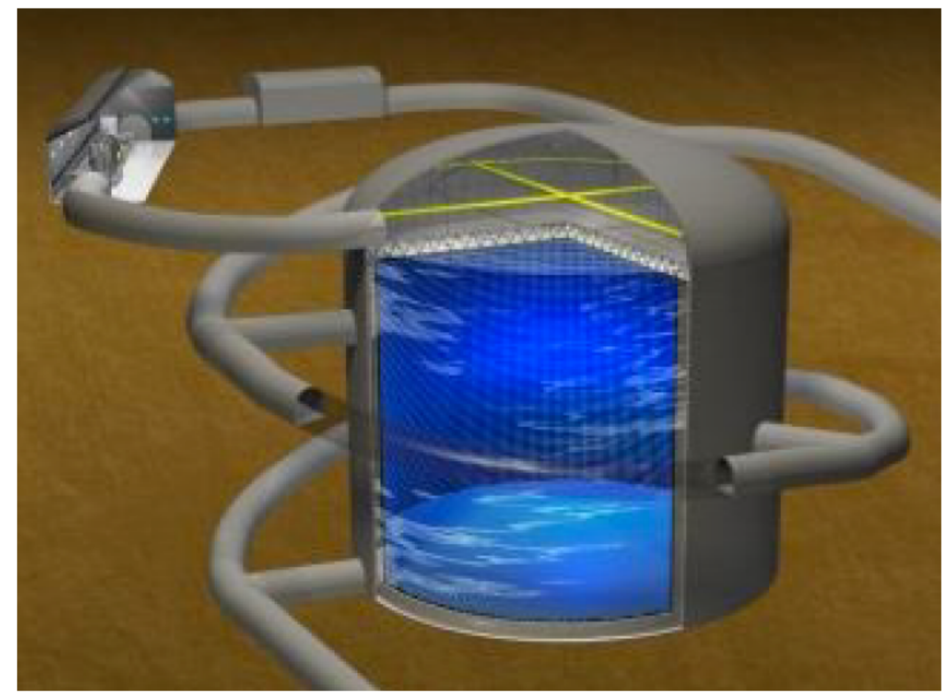
* 1m thick round the edge, 2m at top/bottom

* veto region  (incoming/outgoing particles)

* low energy background shield

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



Height = 71m,    Diameter = 68m

Volume:  258kton

# Hyper-Kamiokande detector design

- PMTs

## PMT Photosensors

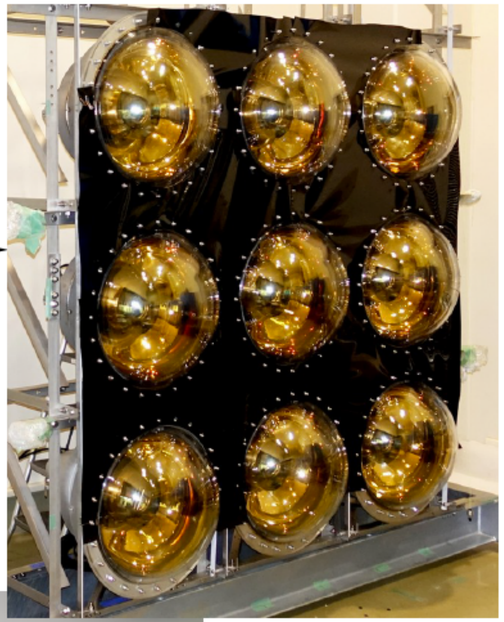
Hyper-Kamiokande

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

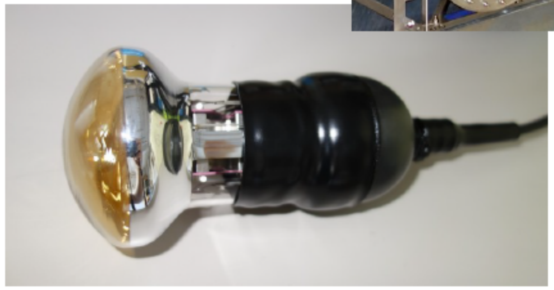
~ 1.5 ns timing resolution

Inner detector (ID)

20,000 * 50cm PMTs → 20% coverage



**8cm PMTs**



Outer detector (OD)

~10,000 * 8cm PMTs

Multi-PMTs (mPMTs)

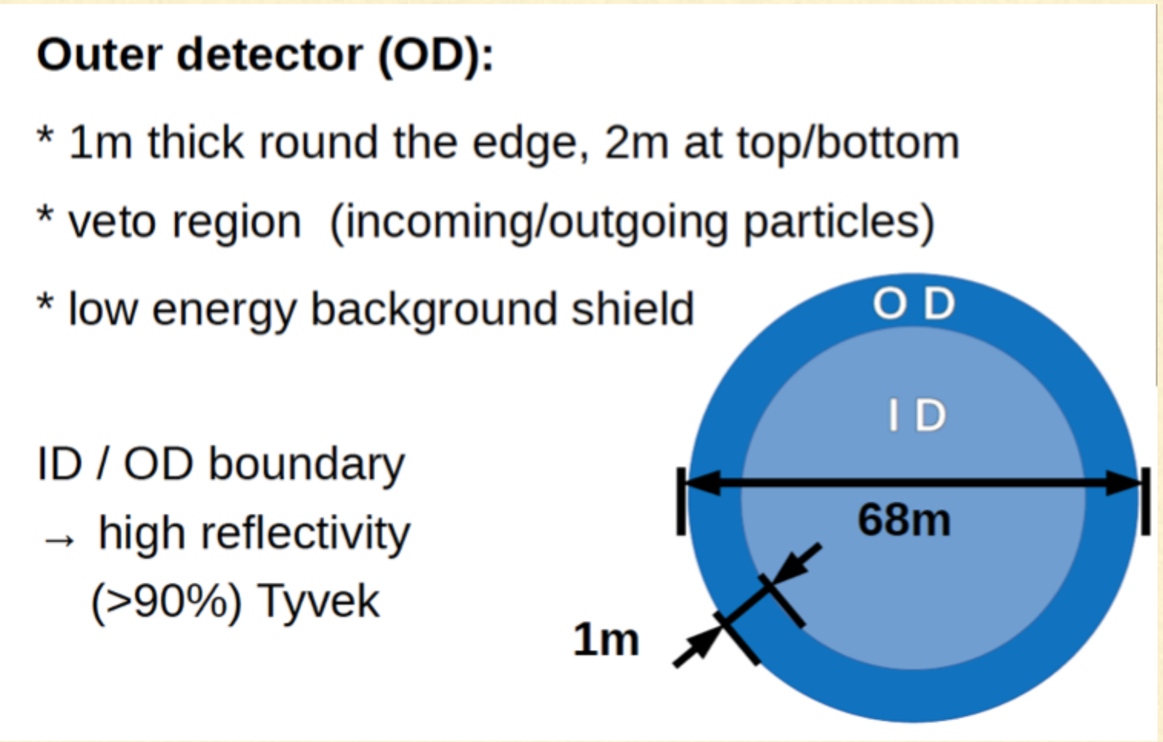
- 19 x 8cm PMTs inside single pressure vessel
- directional information and improved timing and spatial resolutions

Inner detector (ID)

~ few thousand mPMTs

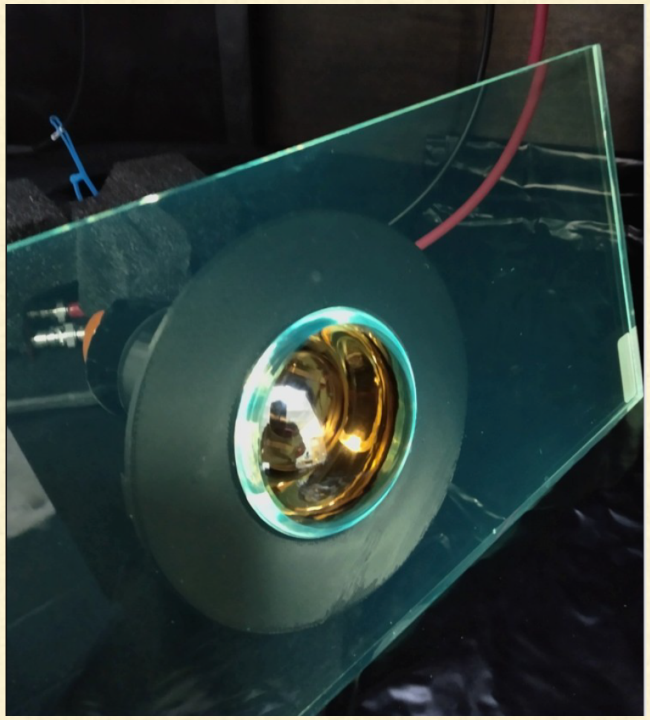
# Hyper-Kamiokande Outer Detector INR RAS Efforts

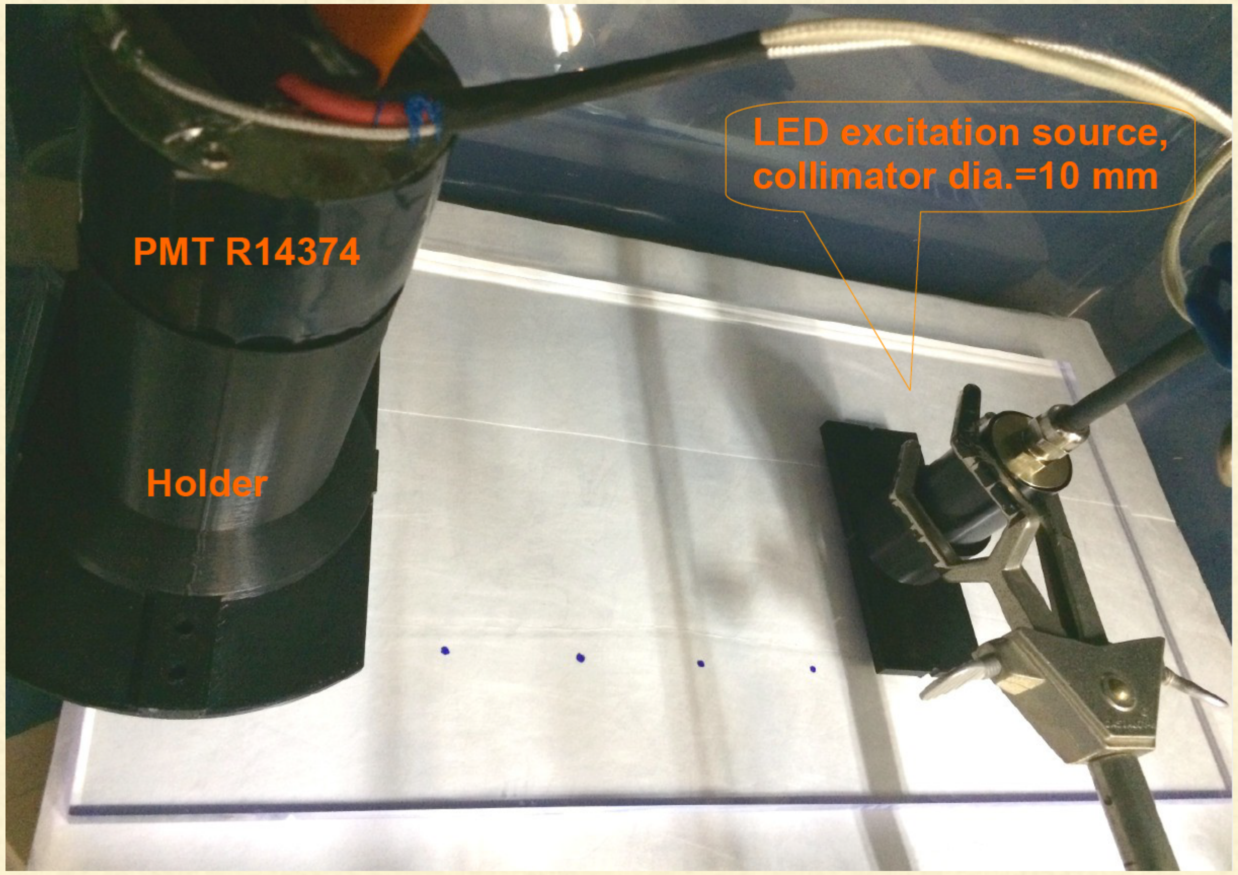
- Relatively thin volume of OD (vs 2.6-2.7 m in SuperK)
- Need high-detection efficiency to achieve and improve physics capabilities
- Need efficient light-collection
- Super-Kamiokande: acrylic bis-MSB doped WS plates with a hole to mount a PMT
  - Absorbing UV light and re-irradiating photons in the blue–green, better matching PMTs spectral sensitivity
- Reviewing and testing the approach for HyperK

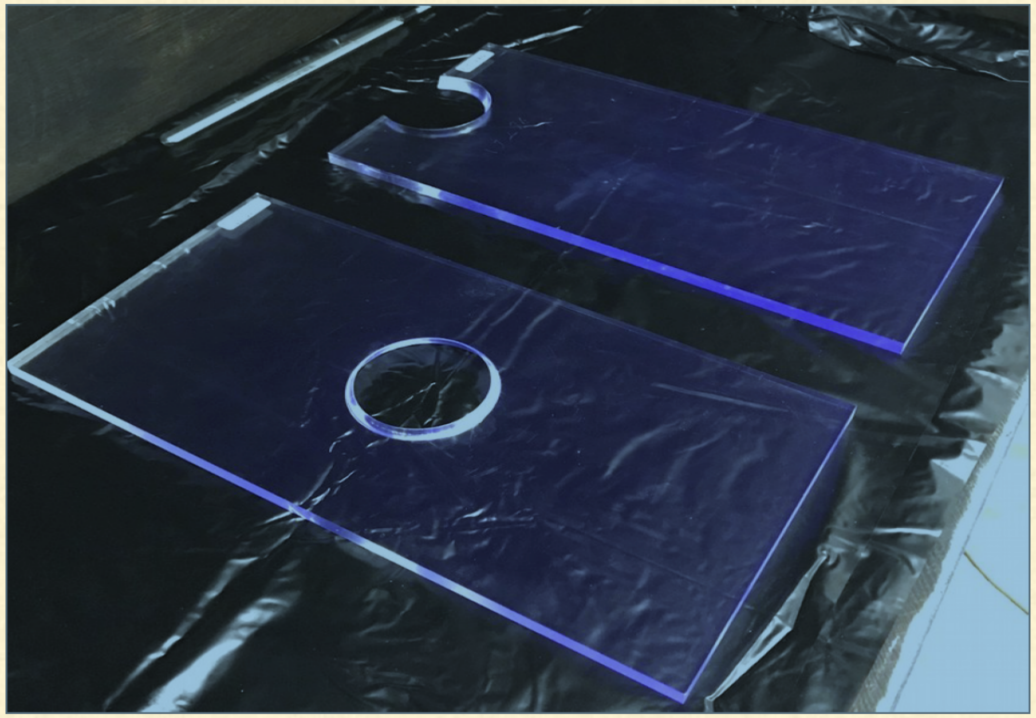


# Hyper-Kamiokande Outer Detector PMMA Plates, INR RAS Efforts

- Collaboration with НИИ Полимеров, Dzerjinsk, Russia
- Test different plate compositions and configurations on the light-collecting efficiency

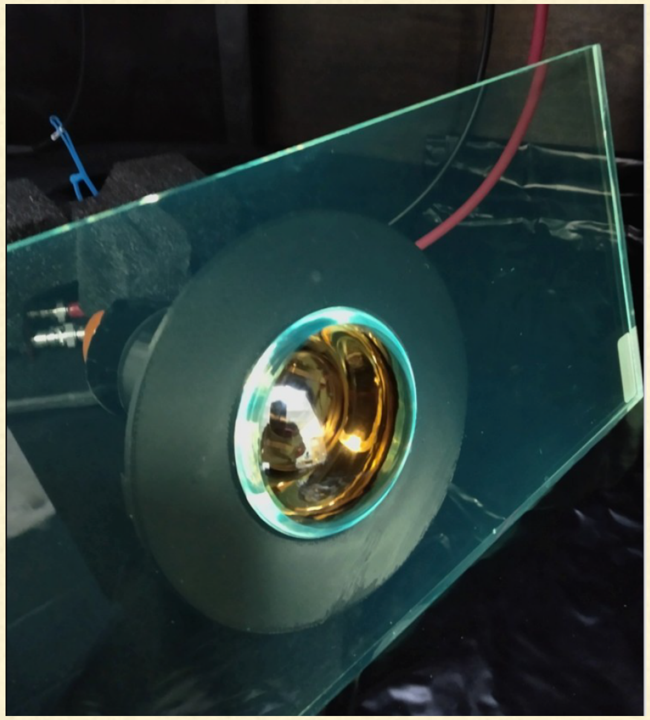


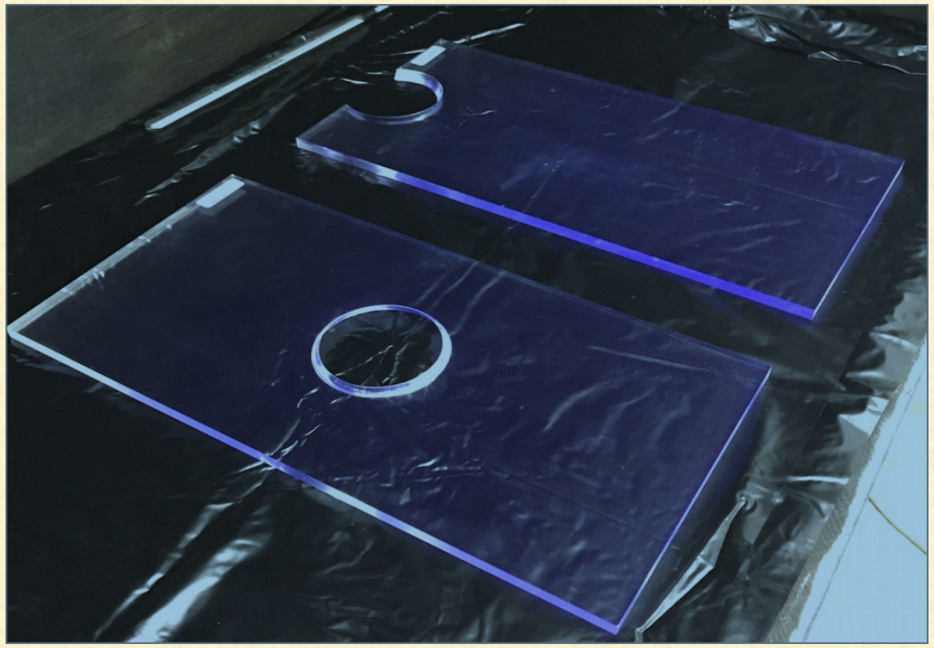


# Hyper-Kamiokande Outer Detector PMMA Plates, INR RAS Efforts

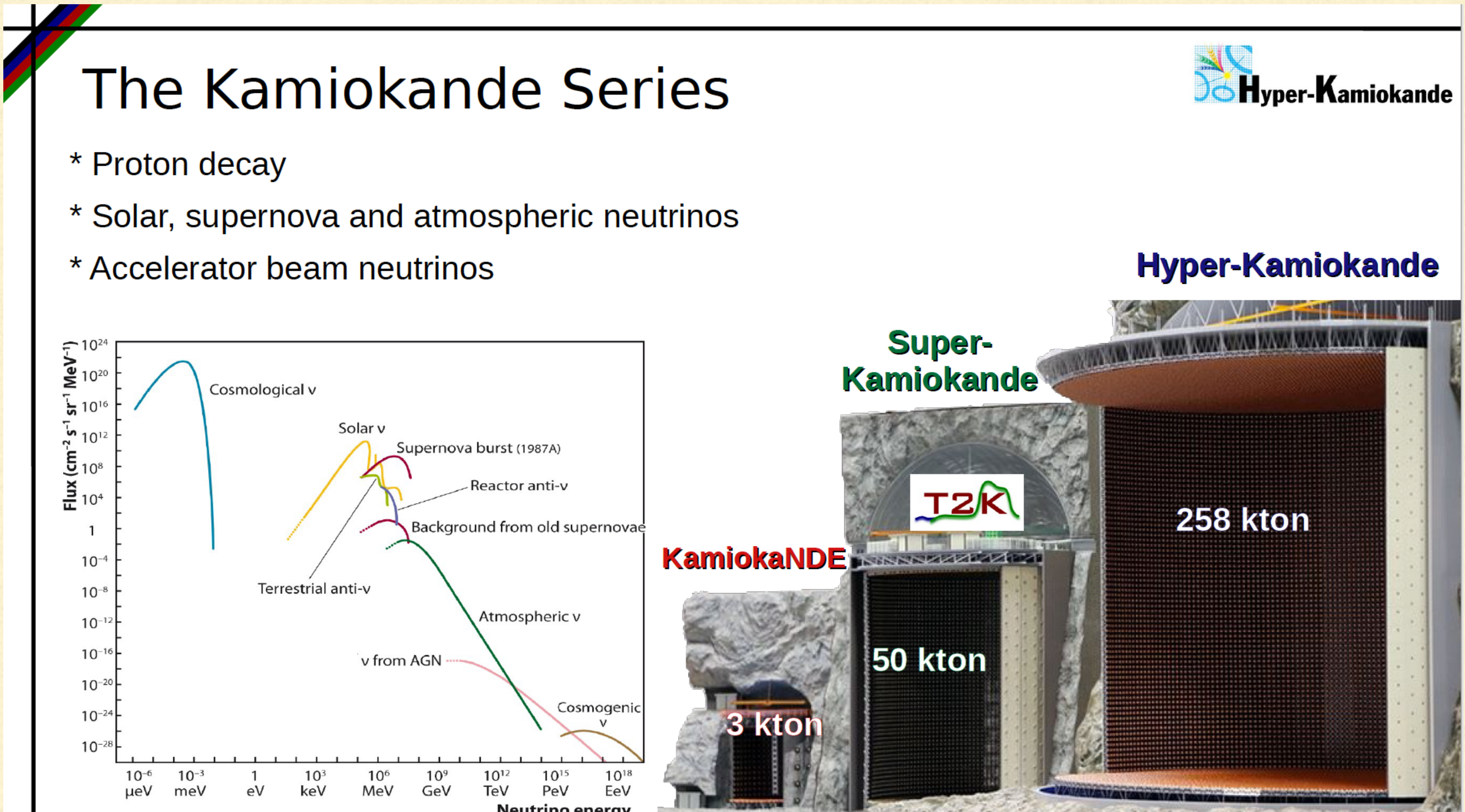
- Collaboration with НИИ Полимеров, Dzerjinsk, Russia
- Test different plate compositions and configurations on the light-collecting efficiency
- POPOP(200) doped PMMA plates tested with an INR test-bench
- Up-to 75% increase in light collection efficiency gained with the WLS plates
  - More tests on-going





# Hyper-Kamiokande physics program

- Wide opportunities for studies



# Hyper-Kamiokande physics program

- Wide opportunities for studies

## Hyper-Kamiokande Physics

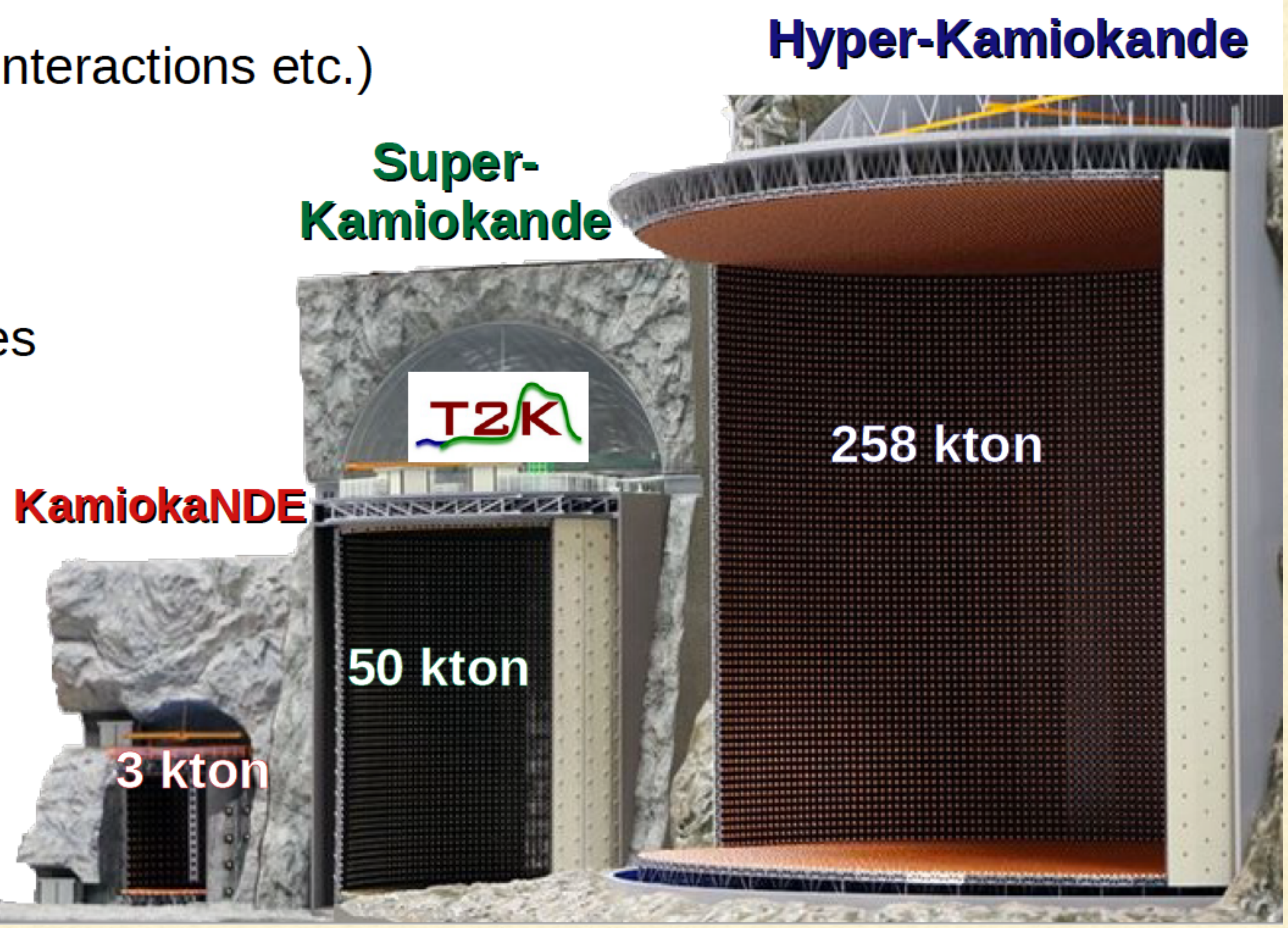
Hyper-Kamiokande

* 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

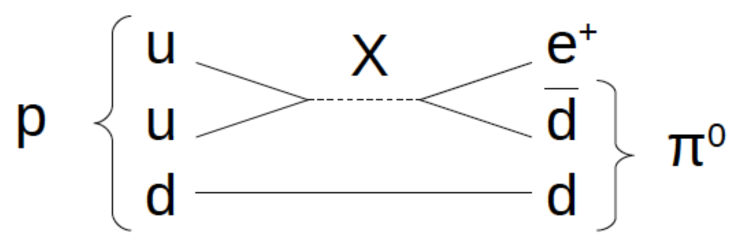
* Geophysics
- matter effect on oscillations
- electron density of Earths outer core



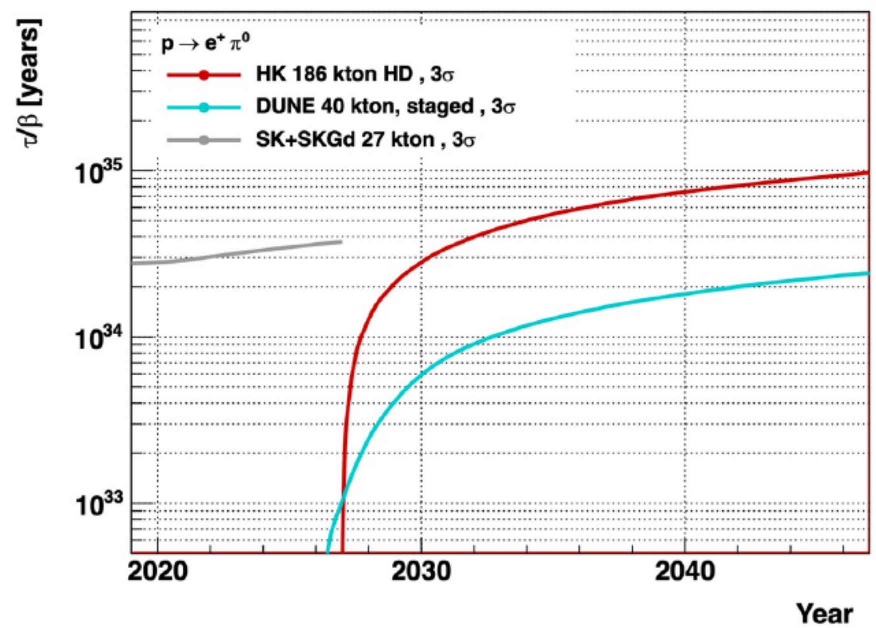
# Hyper-Kamikande: Proton Decay

## Proton decay

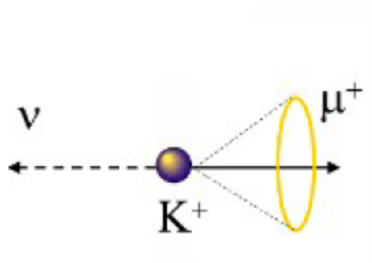
Hyper-Kamiokande

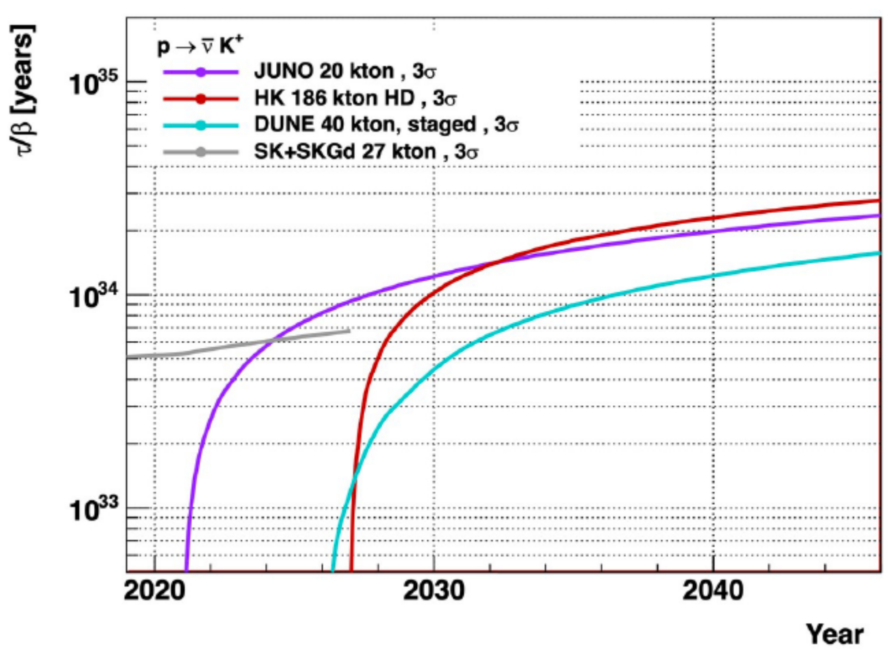



HK can improve the SK limit on this process from $10^{34}$ to $10^{35}$ years




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



# Hyper-Kamikande: Neutrino Oscillations

## Neutrino Oscillations

Hyper-Kamiokande

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

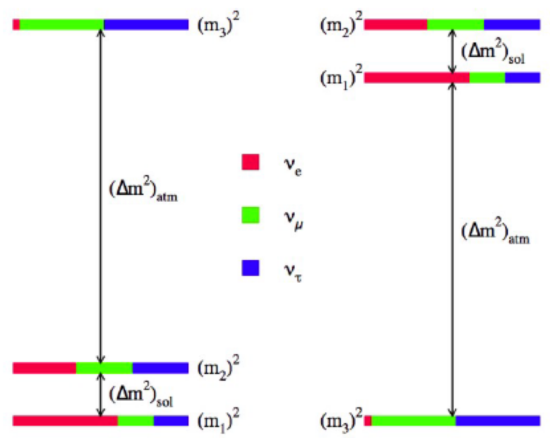
$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta_{CP}}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12}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

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**: $P(\nu_\mu \to \nu_e) \neq P(\bar{\nu}_\mu \to \bar{\nu}_e)$

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

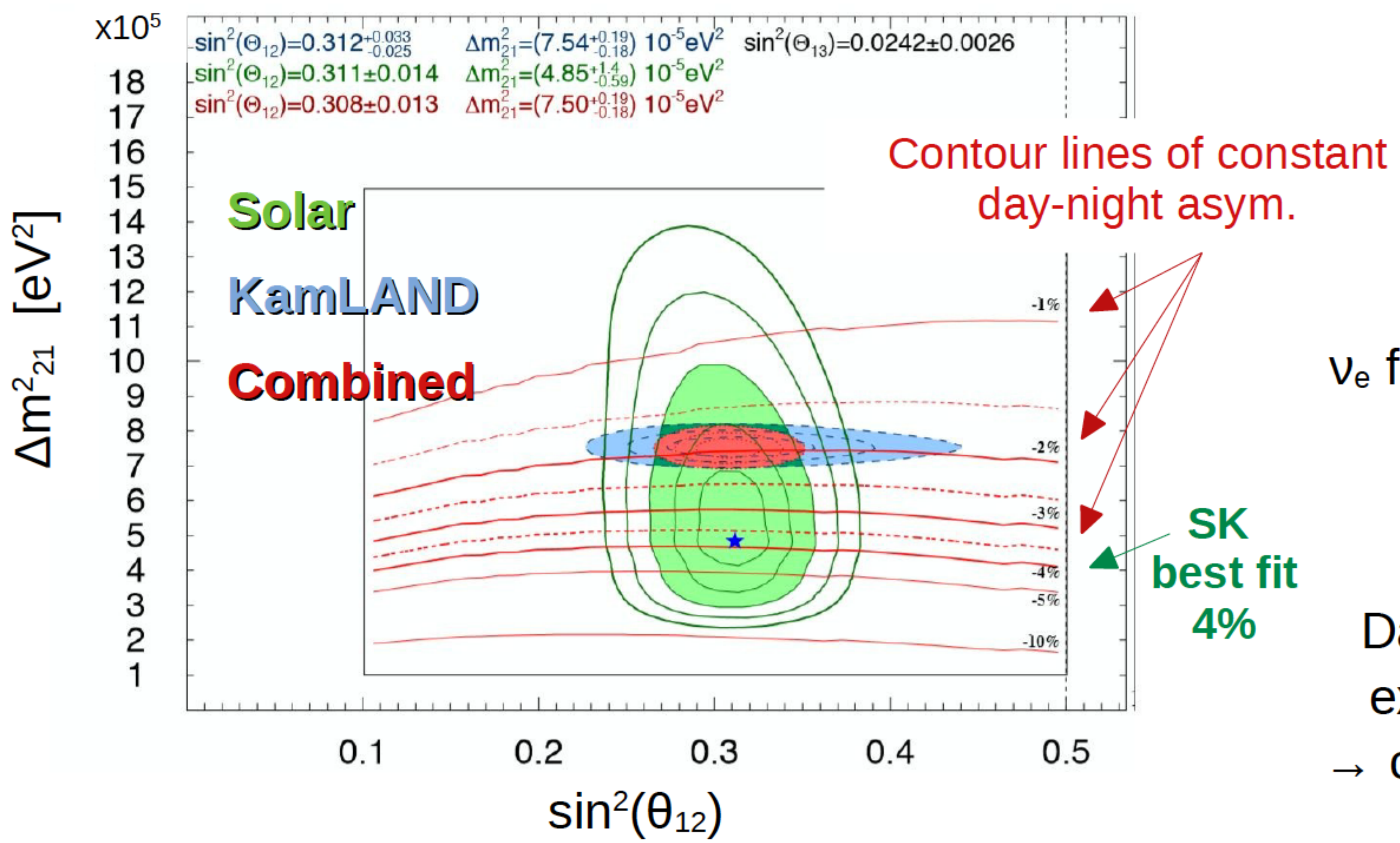
**Matter effects!** (electrons)
Difference in $\nu_e$ and $\bar{\nu}_e$ travelling through the earth ( similar effect as $\delta_{cp}$ )
→ allows for mass hierarchy determination

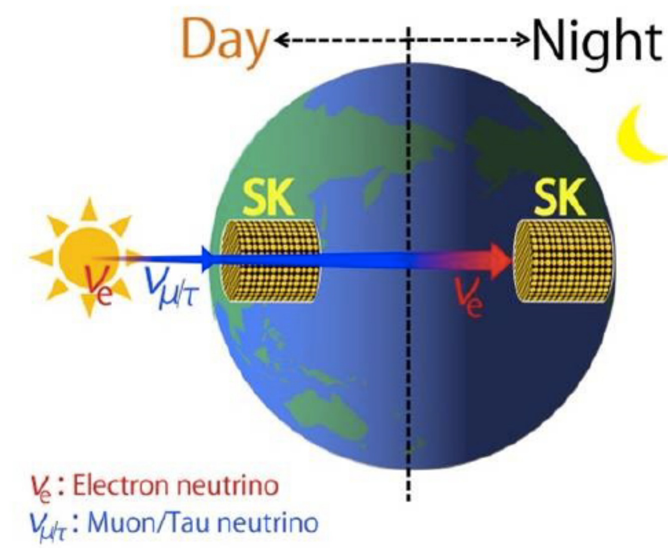
# Hyper-Kamikande: Solar Neutrinos

## Solar Neutrinos

Hyper-Kamiokande

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




$\nu_e$ flux differs between night and day
→ matter effects
→ *day-night asymmetry*

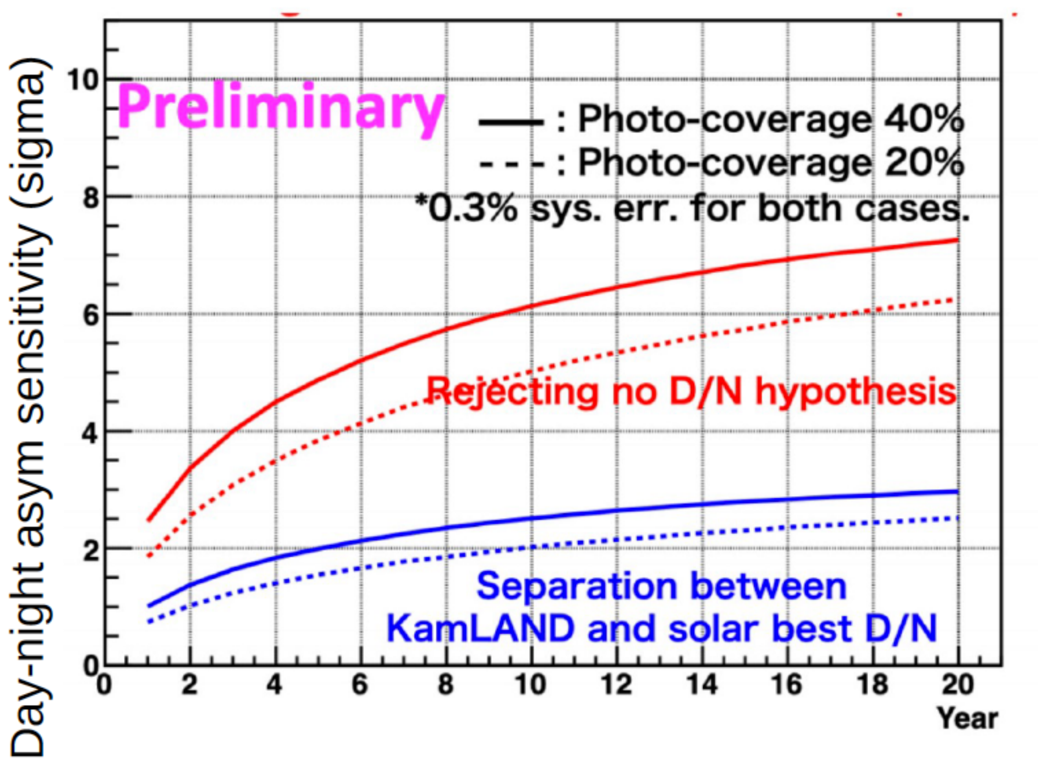
Day-night asymmetry higher than expected from reactor constraint
→ contributes to the $\Delta m^2_{21}$ tension

# Hyper-Kamikande: Solar Neutrinos

## Solar Neutrinos

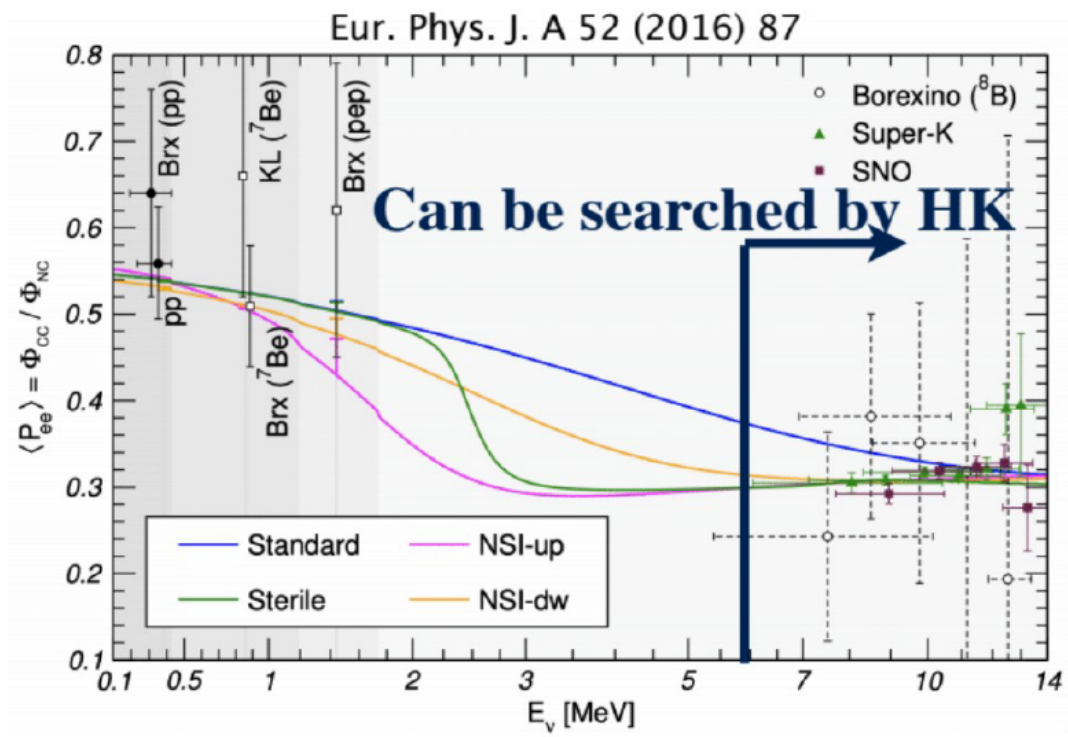
Hyper-Kamiokande

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**



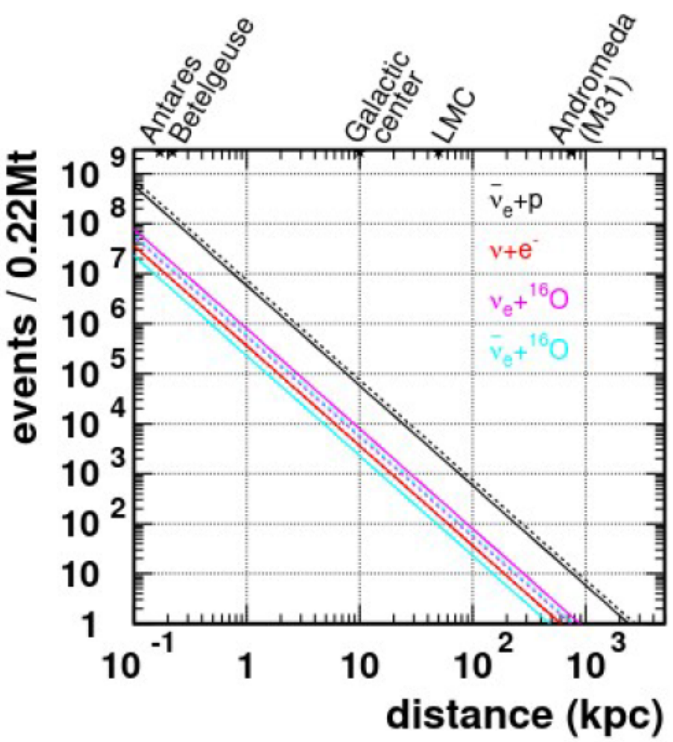

Expect 3-5σ for upturn discovery after 10 years

# Hyper-Kamikande: Supernova Neutrinos

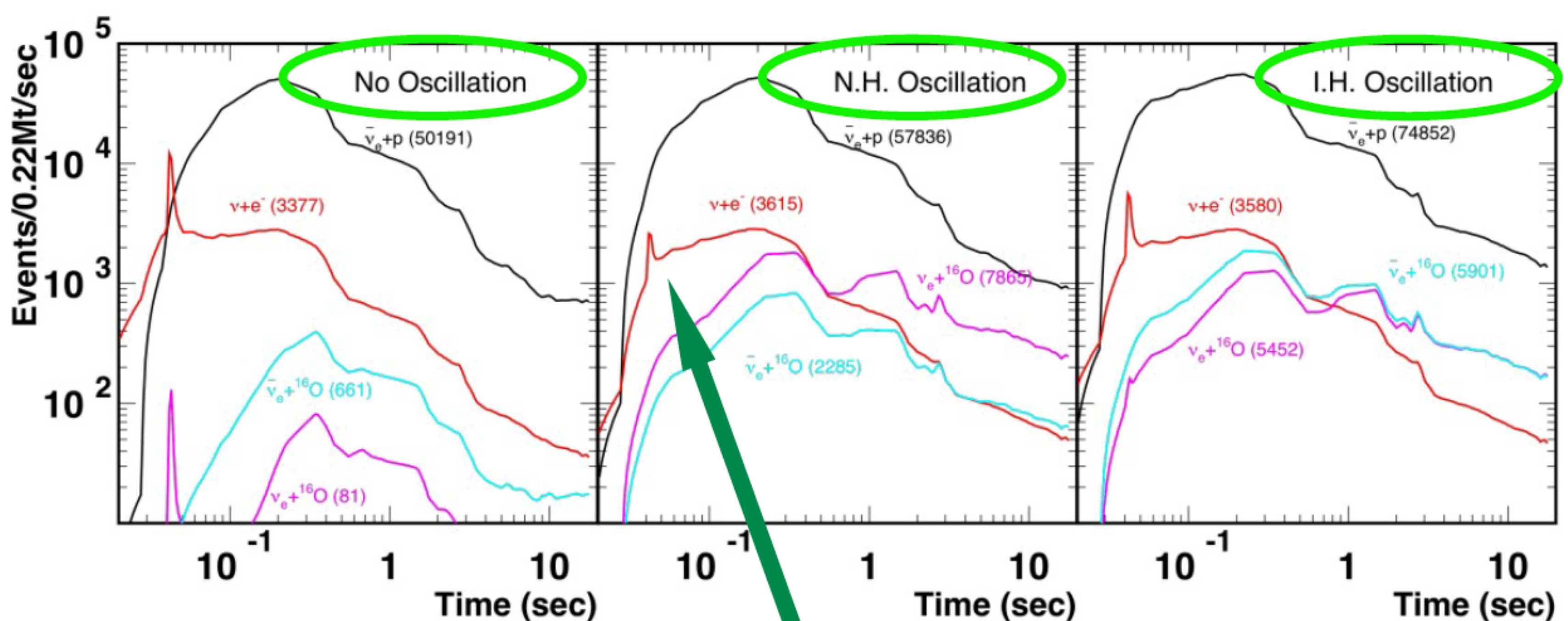
## Supernova Neutrinos

Hyper-Kamiokande

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

# Hyper-Kamikande: Supernova Neutrinos

## Supernova Neutrinos

Hyper-Kamiokande

Inverse beta decay dominates

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

Different models predict different electron antineutrino rates

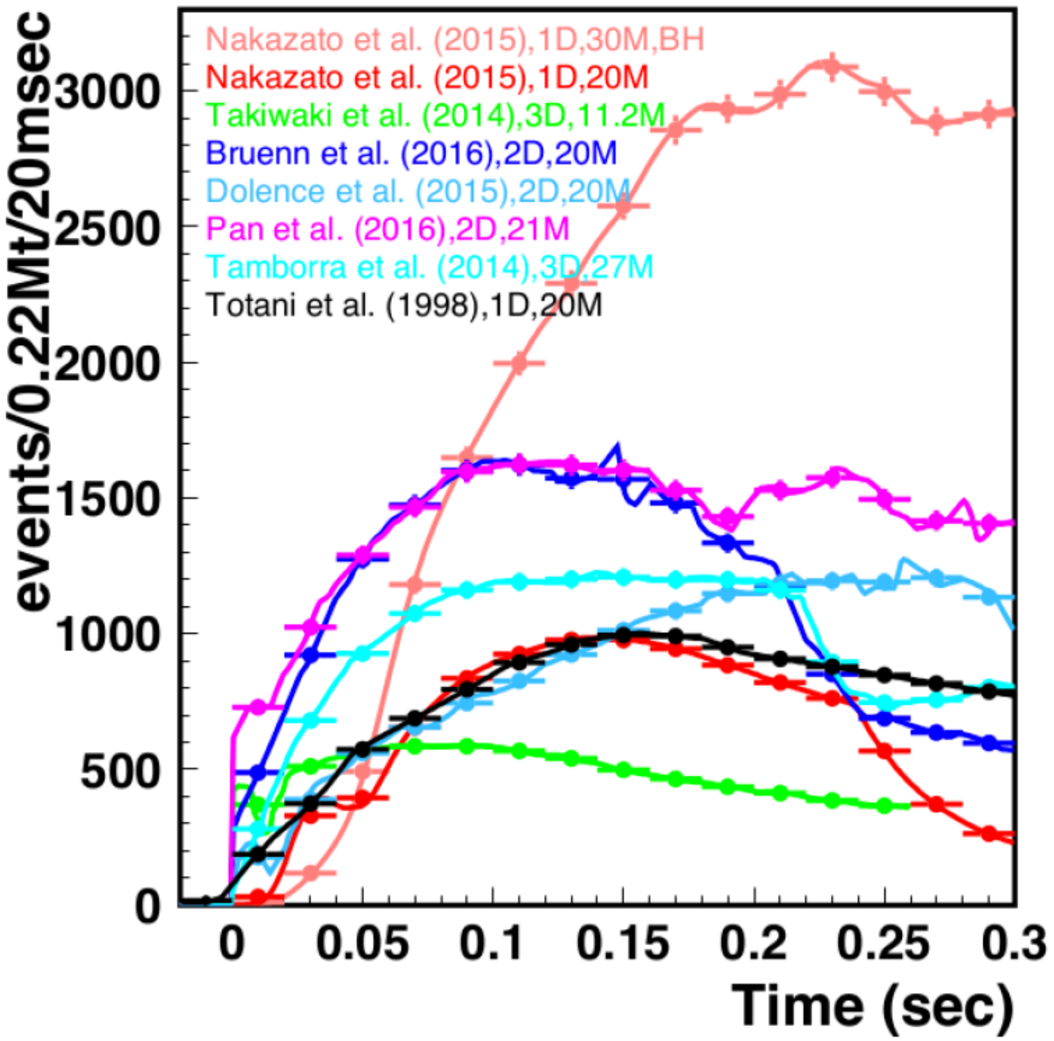
→ Hyper-K can constrain different models

* Stat error is much smaller than the difference between models

* Neutrino detection threshold of 3 MeV

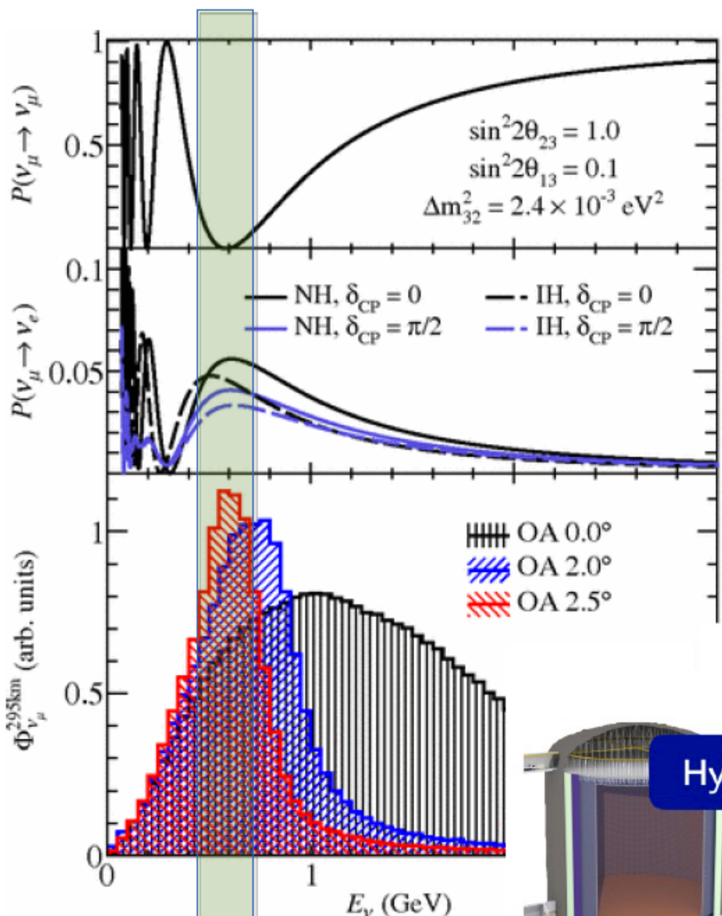
* Directional reconstruction allows for event-by-event measurement

Predicted inverse beta decay rates



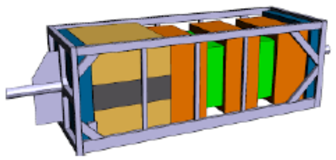
# Hyper-Kamikande: Long-baseline neutrino interactions (beam)

## Hyper-Kamiokande long-baseline



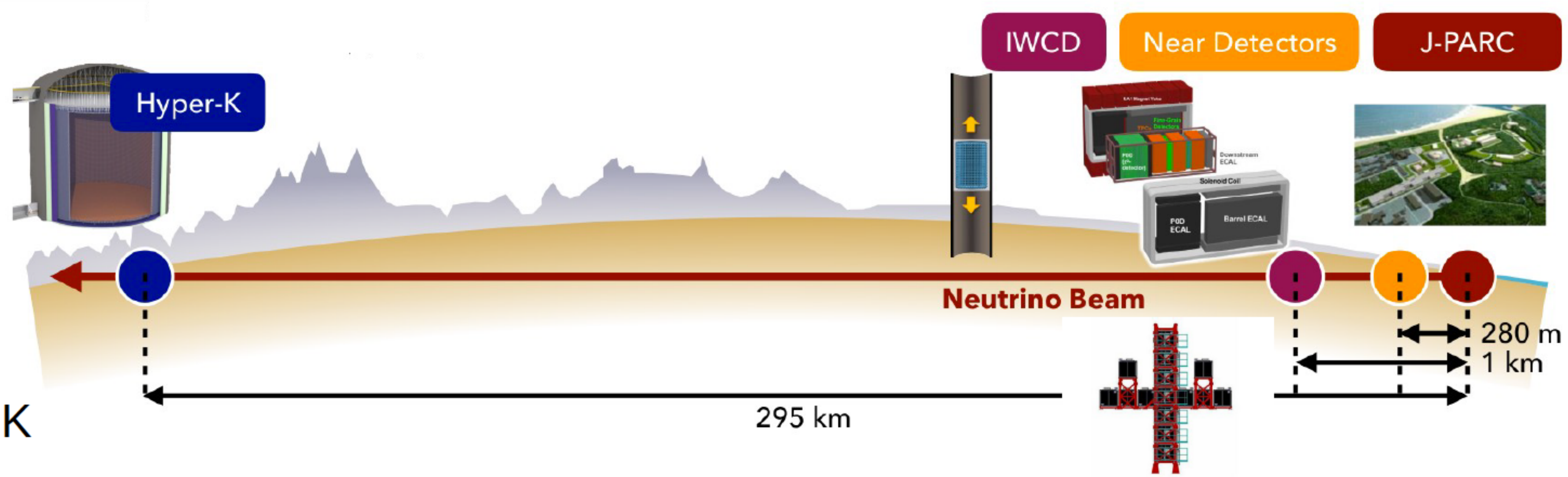

* Upgrade T2K beam to 1.3MW

* Upgraded ND280



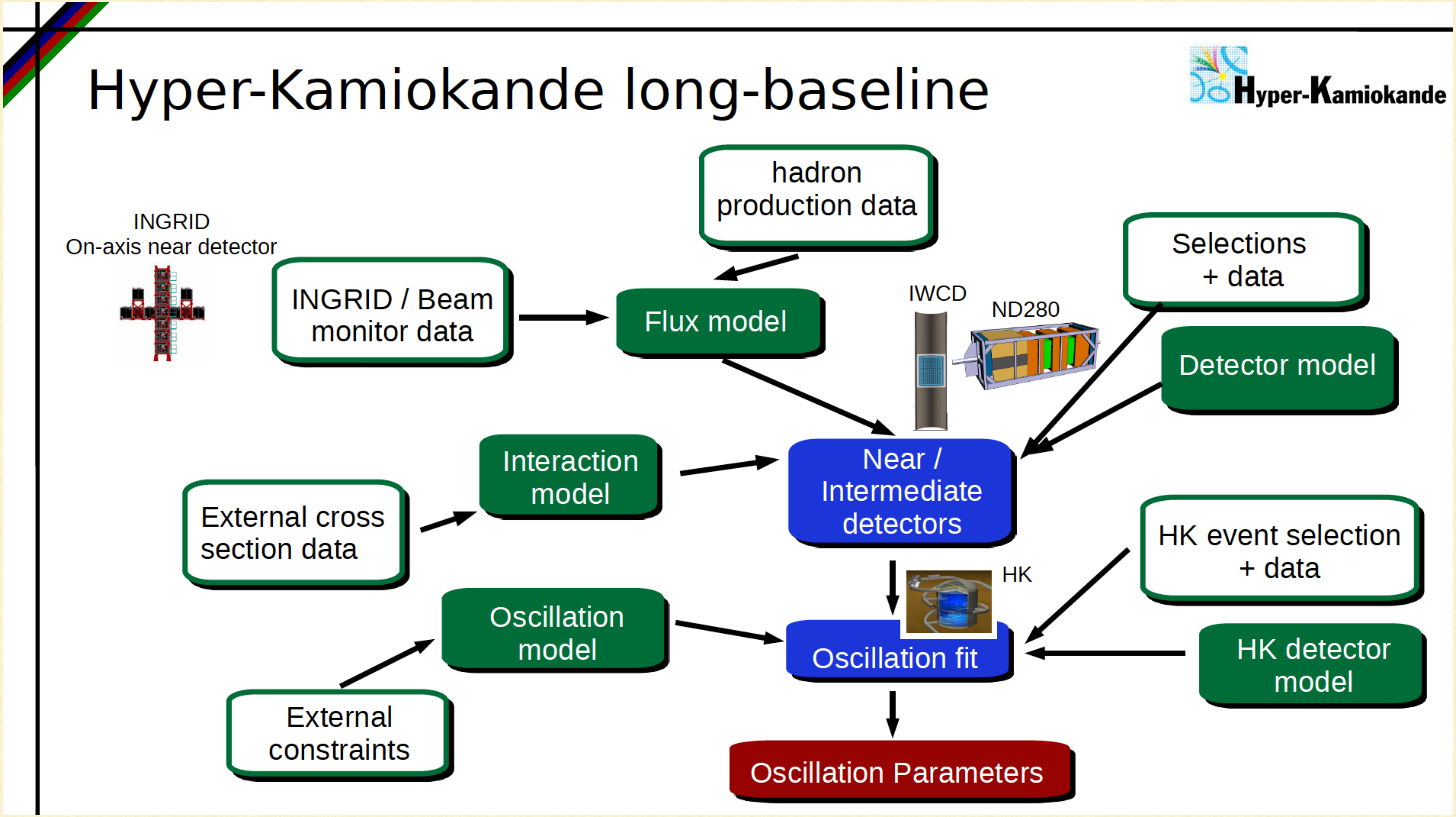
* New intermediate water Cherenkov detector (IWCD)

* Hyper-K far detector




HK at same distance and off-axis angle as SK

# Hyper-Kamikande: Long-baseline neutrino interactions (beam)



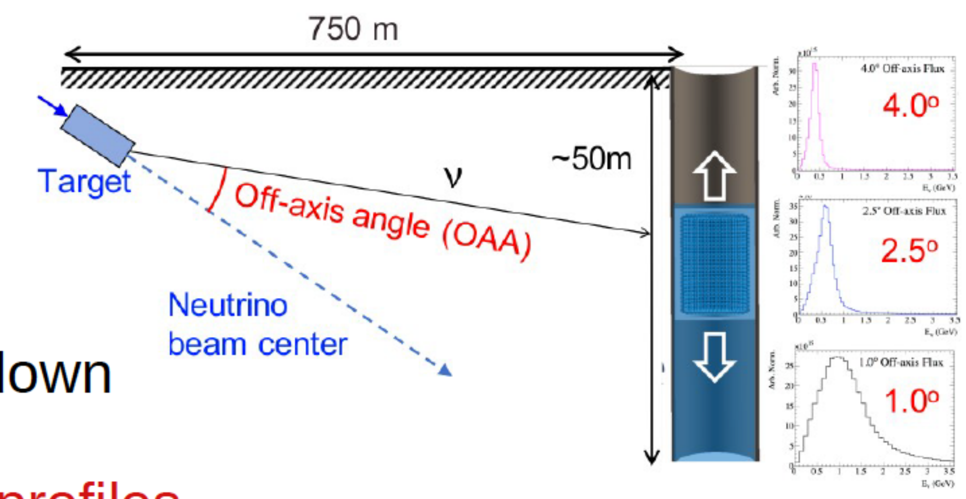
# Hyper-Kamikande: Long-baseline neutrino interactions (beam)

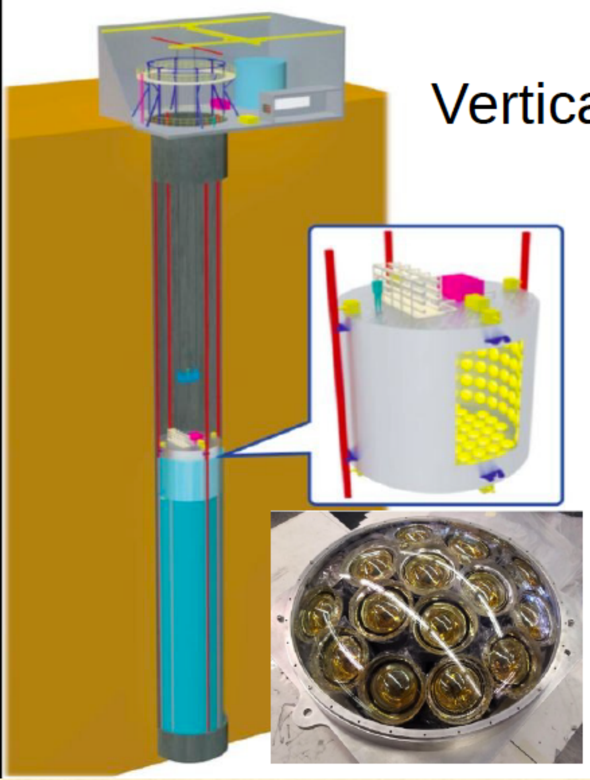
## Intermediate water Cherenkov detector (IWCD)

Hyper-Kamiokande

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



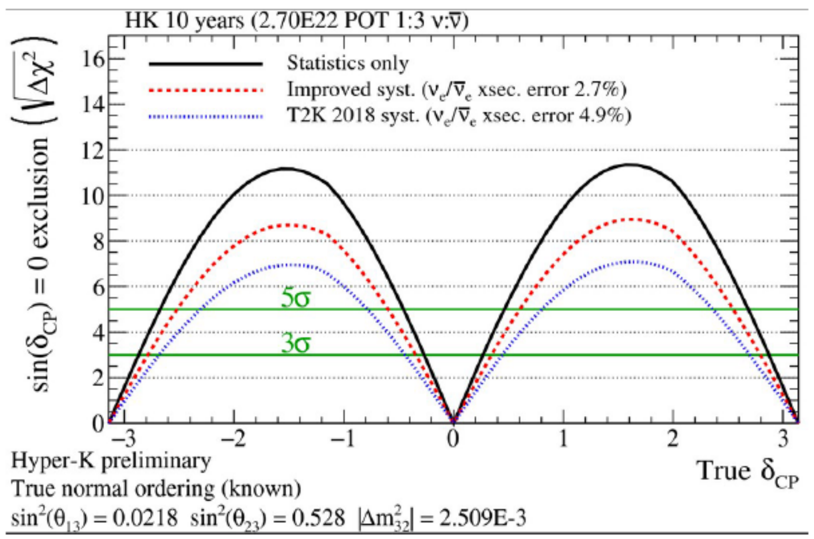
Vertical pit (50m), detector moves up and down
→ samples flux at different angles
→ sample flux at different energy profiles

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

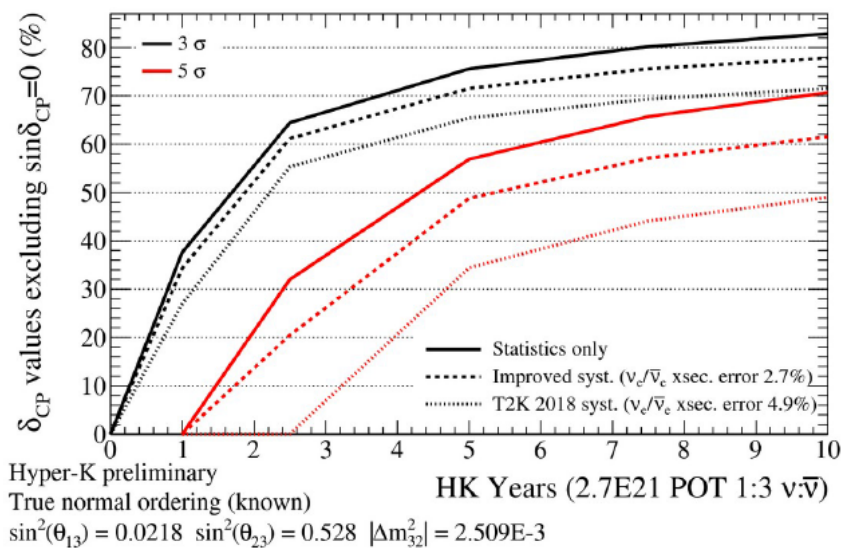
Plans to load with Gadolinium: 0.1% Gd
→ Neutron tagging

# Hyper-Kamikande: Long-baseline neutrino interactions (beam)

## 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

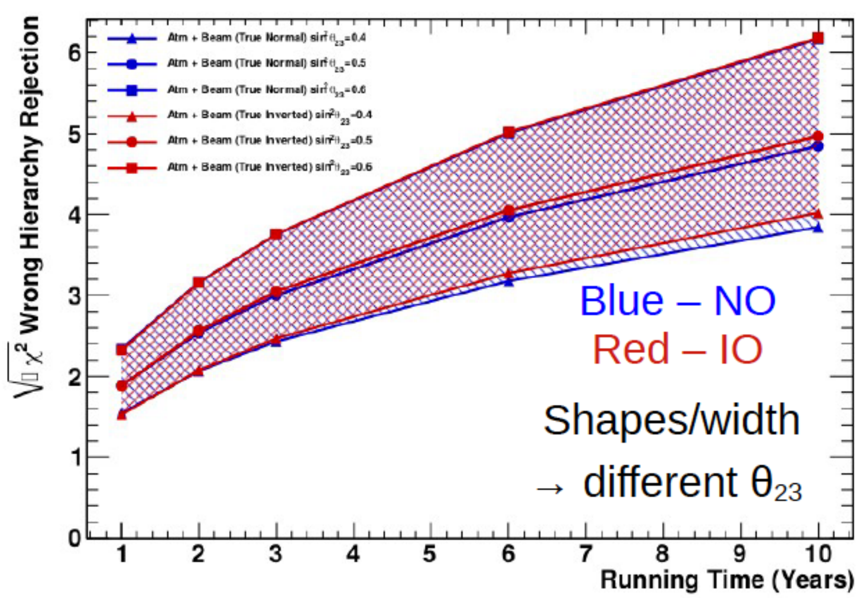
**5σ achieved for ~60% fraction of δCP values with 10years data taking**

# Hyper-Kamikande: Long-baseline neutrino interactions, beam + atmospheric

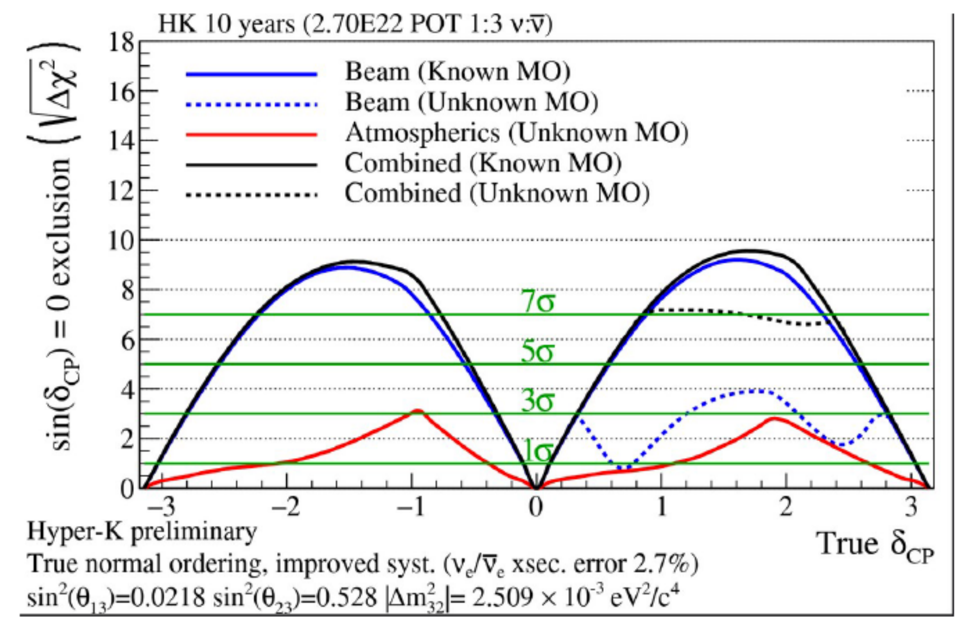
## Atmospheric neutrinos + beam

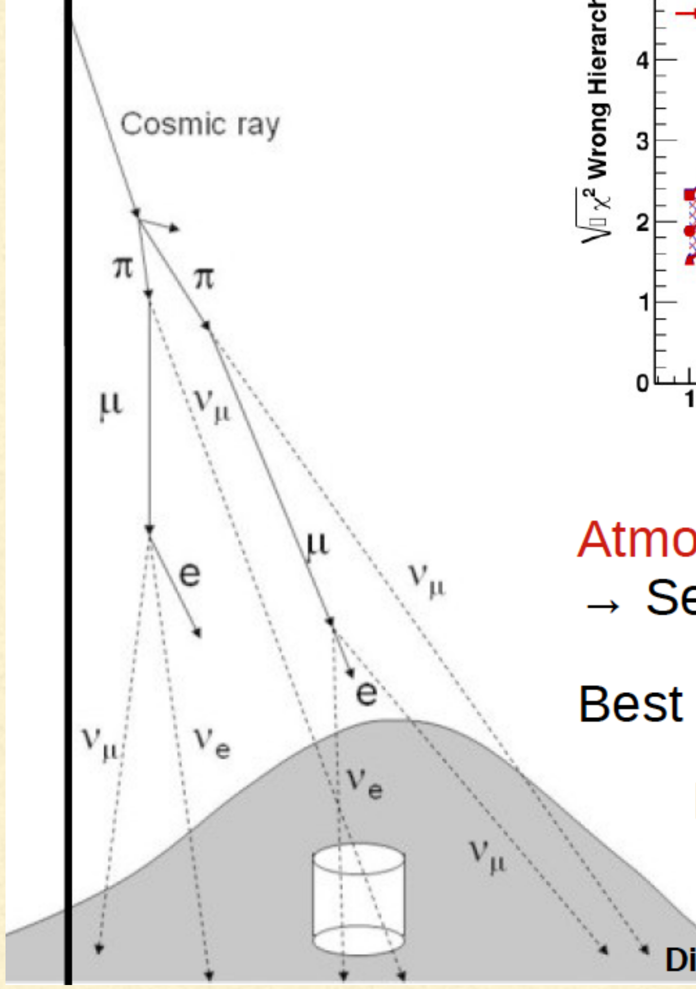
Hyper-Kamiokande

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**

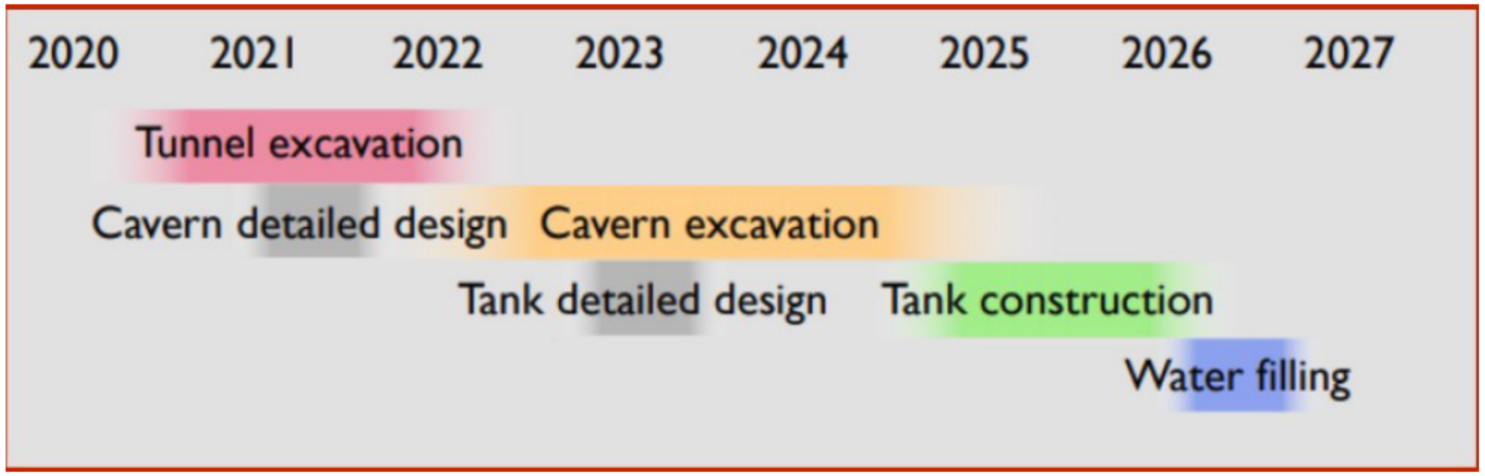
If mass ordering unknown, atmospheric data improves beam sensitivity to δCP

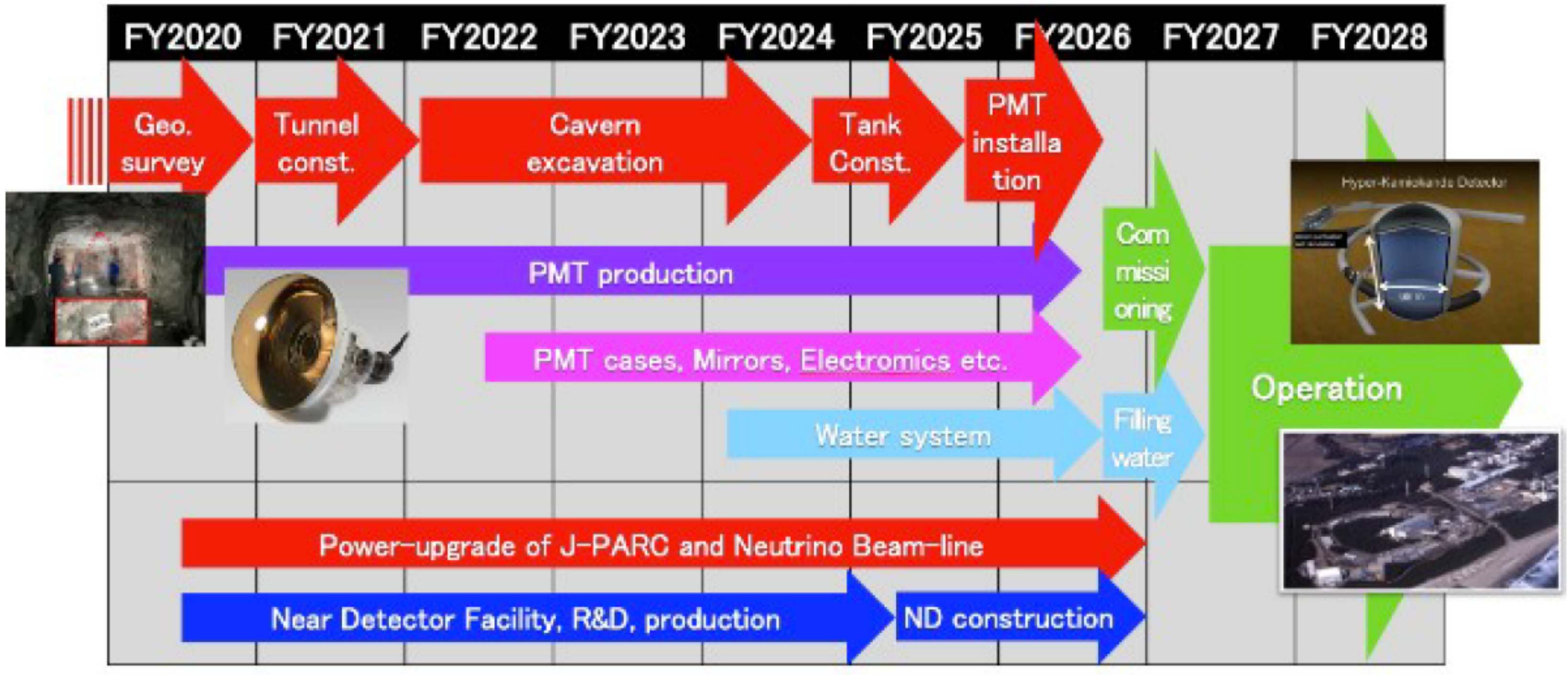
Diagram: Kajita T. (10.2183/pjab.86.303)

# Hyper-Kamiokande, stay tuned!

# Hyper-Kamiokande, stay tuned!

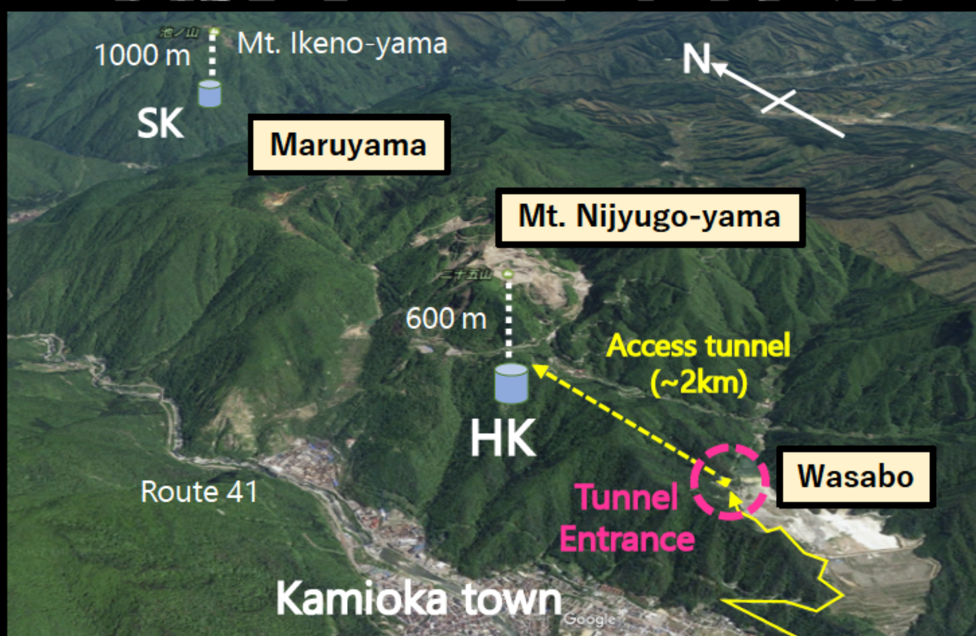
Hyper-Kamiokande



# Hyper-Kamiokande, stay tuned!

## *Entrance Yard Construction*





- Construction of entrance yard in Wasabo is completed.
- Construction of the waste water treatment facility at the entrance yard.

# Hyper-Kamiokande, stay tuned!

# Summary

## Summary

Hyper-Kamiokande

**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!**

APPROVED


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

# BACKUP SLIDES

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## HYPER-K COLLABORATION:

Hyper-Kamiokande

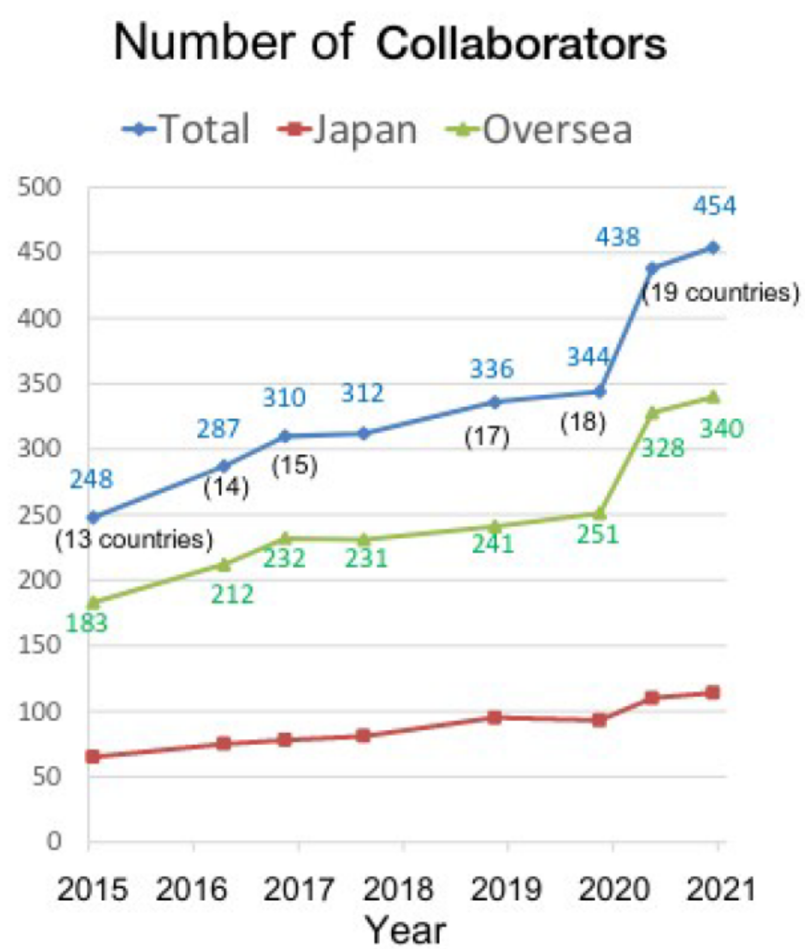
19 countries, 93 institutes, ~450 people as of May 2021, still growing

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 |

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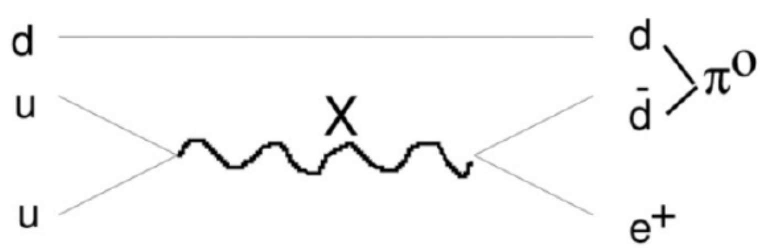
# BACKUP SLIDES

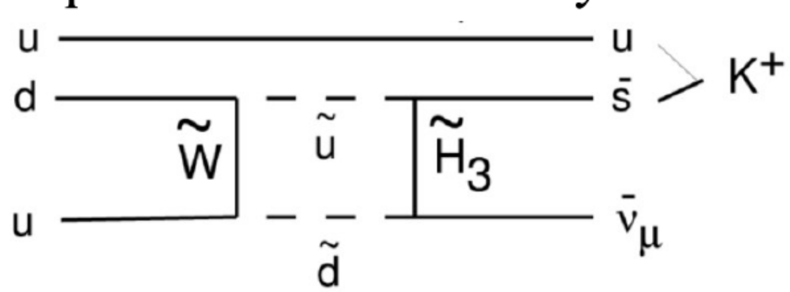
## Proton decay and neutrinos

Hyper-Kamiokande

$p \rightarrow e^+\pi^0 > 1.9\times10^{34}$ years




$p \rightarrow \nu K^+ > 0.8\times10^{34}$ 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.

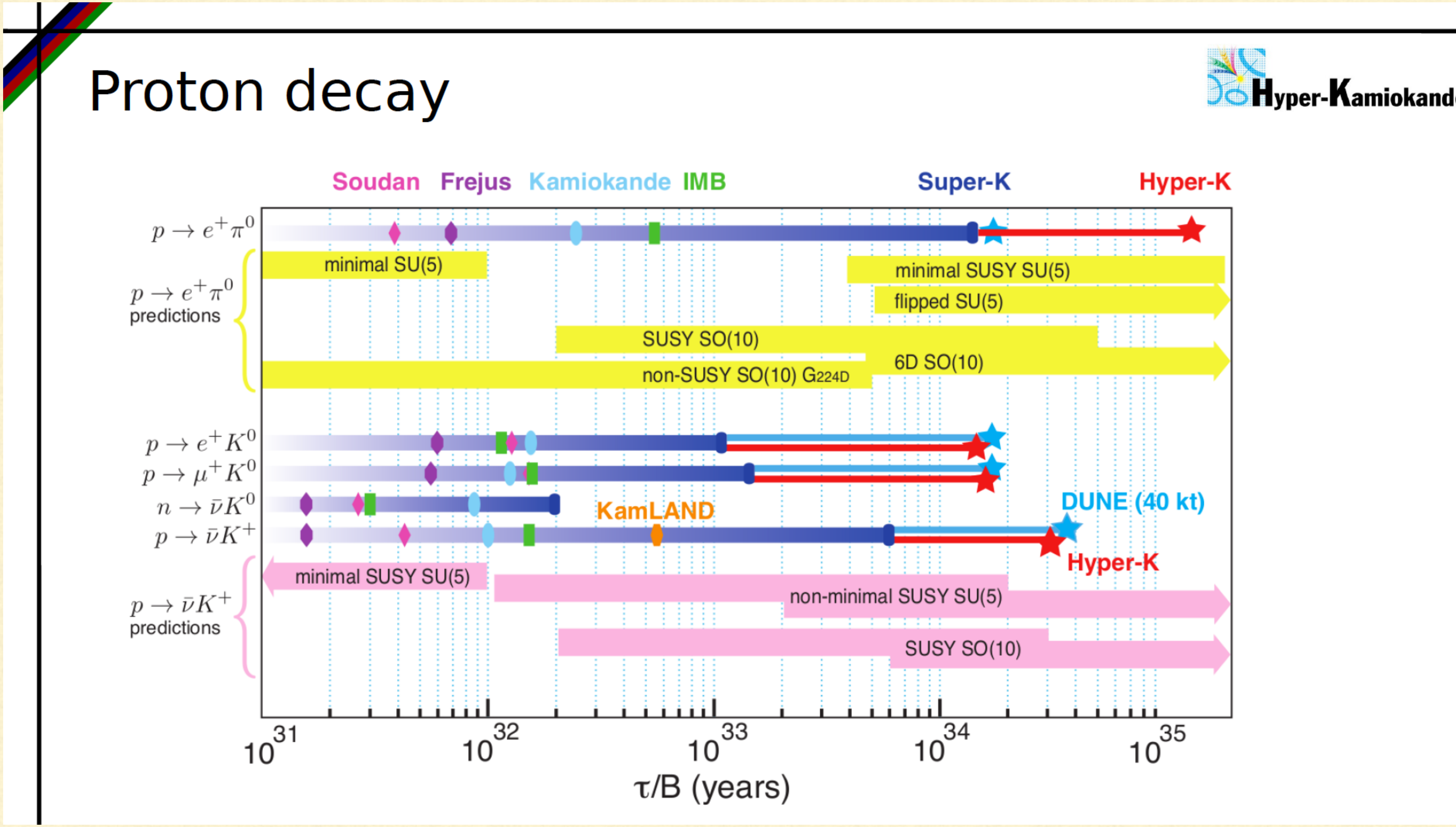
Many GUT predict proton decay

KamiokaNDE (Kamioka Nucleon Decay Experiment) I&II

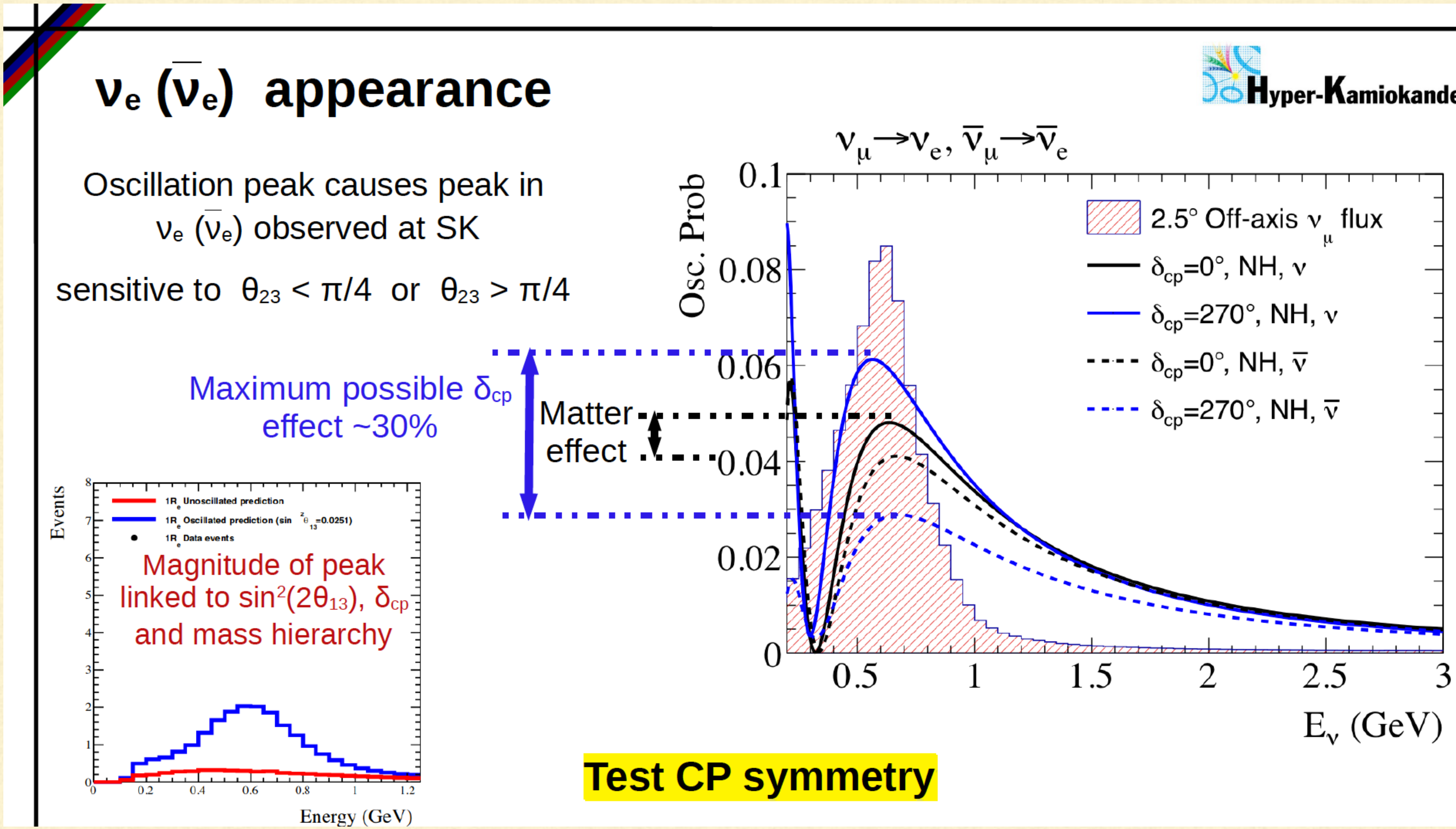
→ Did not observe proton decay
→ ruled out many GUTs at the time
→ observed Supernova 1987a
→ saw hints of neutrino oscillation
  → solar neutrinos
  → atmospheric neutrinos

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

# BACKUP SLIDES



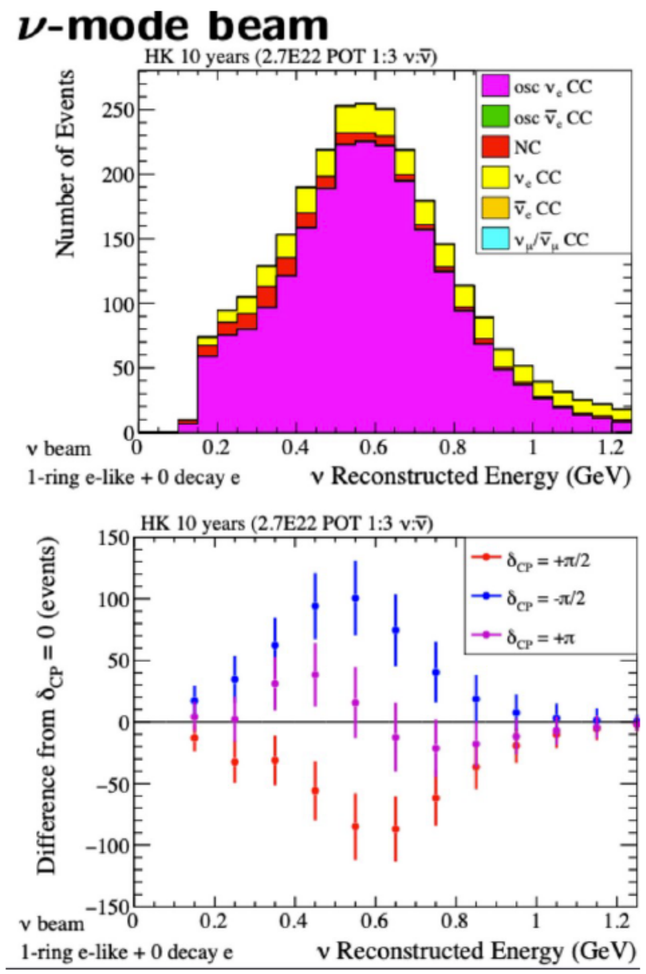
# BACKUP SLIDES

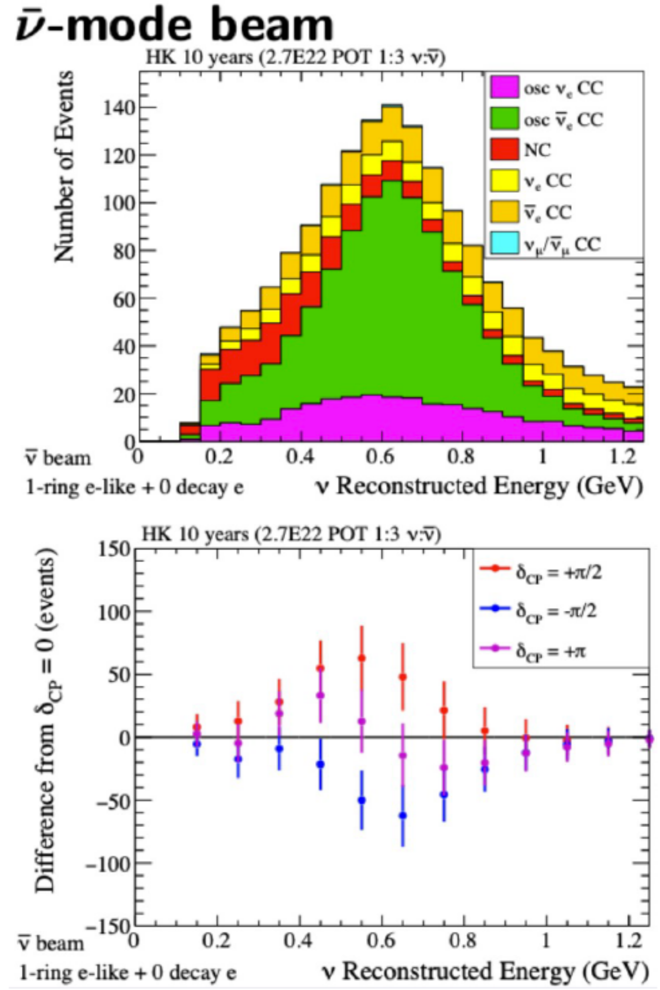


# BACKUP SLIDES

## Hyper-Kamiokande long-baseline

Hyper-Kamiokande




Predicted HK far detector event yields for 10 years of operation

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

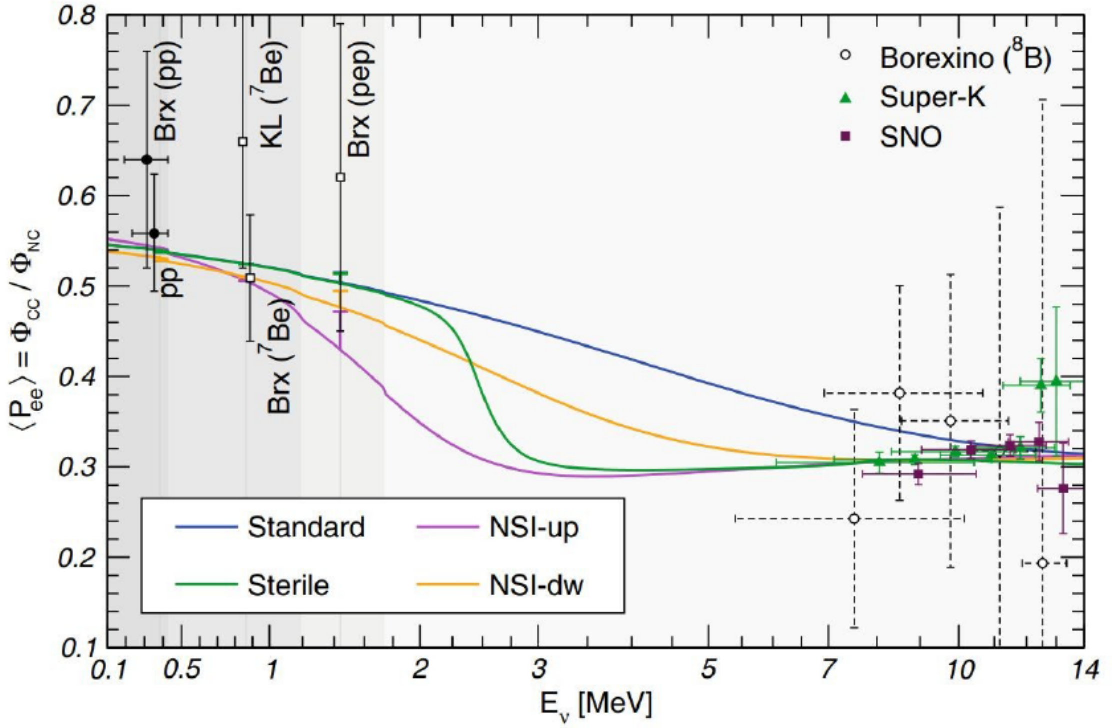
Run mode chosen to optimise deltaCP sensitivity

# BACKUP SLIDES

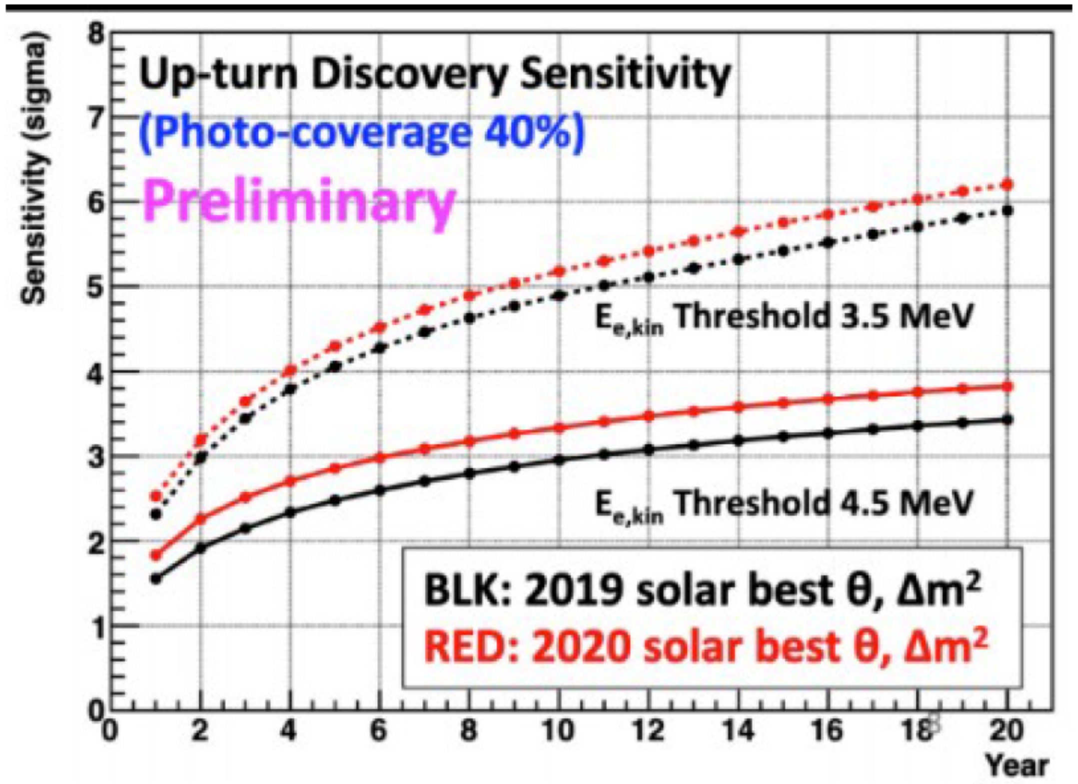
## Solar Neutrinos

Hyper-Kamiokande

'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)



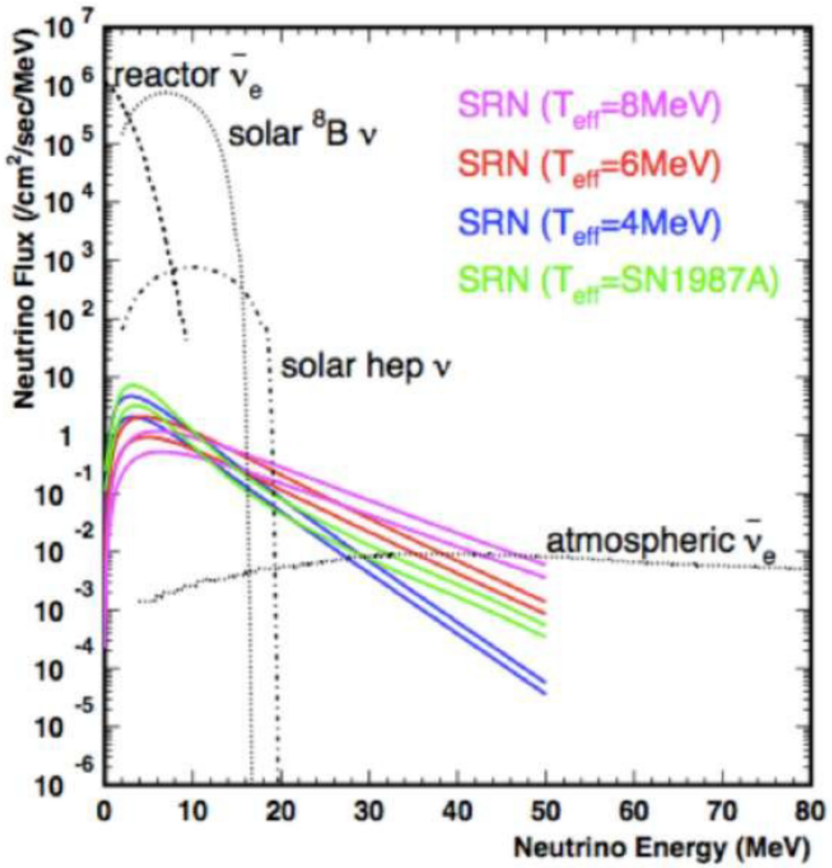

Significance of upturn detection at HK

# BACKUP SLIDES

## Supernova Relic Neutrinos

Hyper-Kamiokande

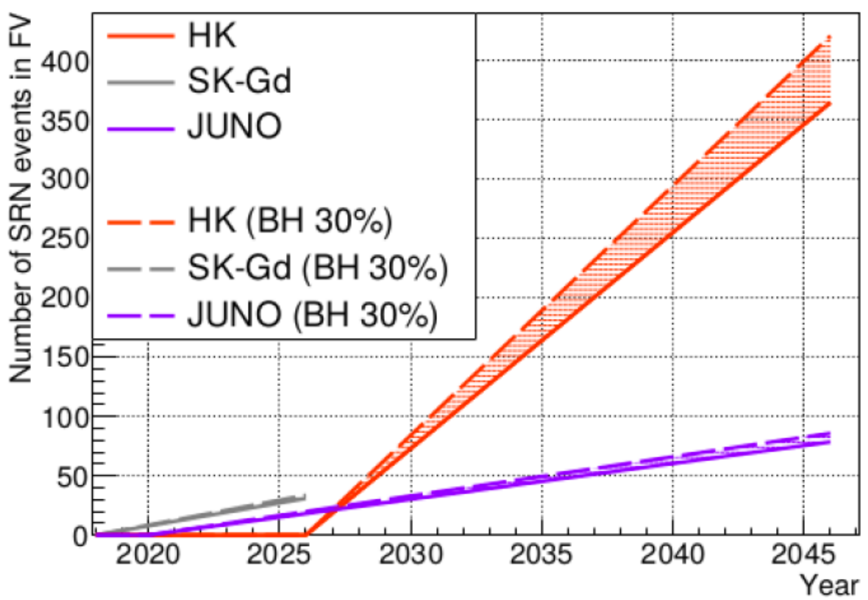
Predicted flux for different models




* 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

# BACKUP SLIDES

## Supernova Neutrinos

Hyper-Kamiokande

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

# BACKUP SLIDES

## 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

# BACKUP SLIDES

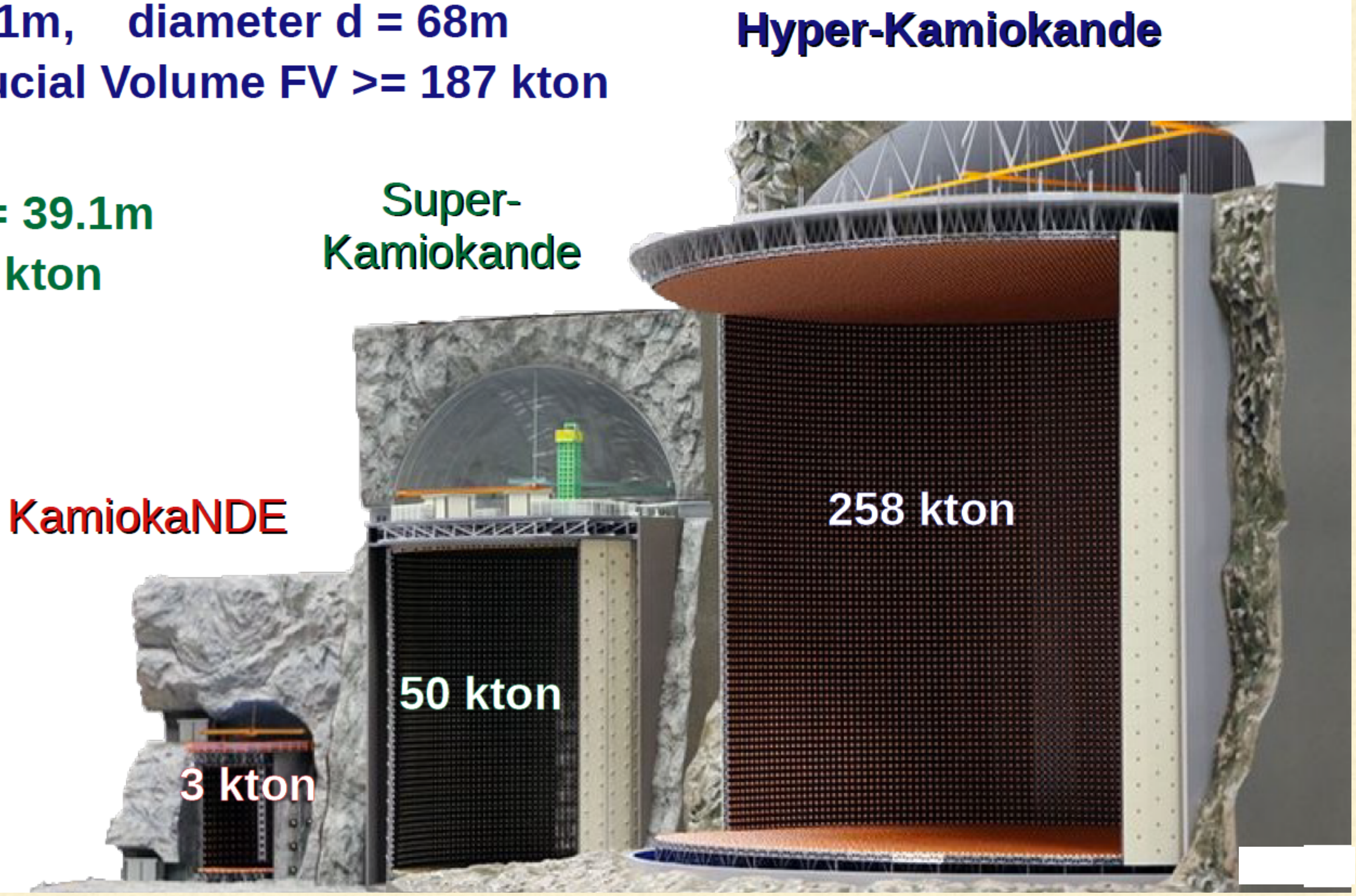
## The Kamiokande Series

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

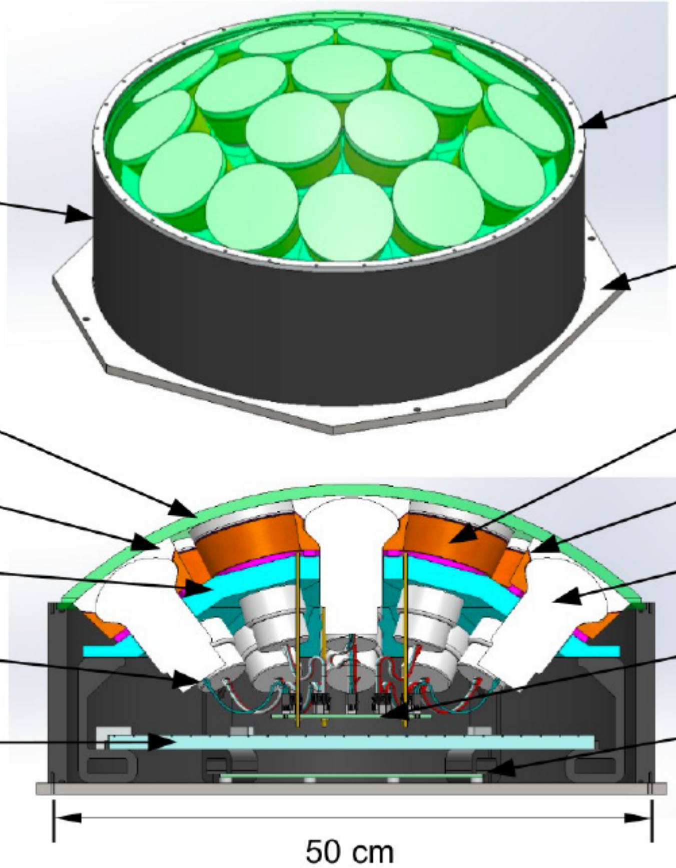
h = 16 m
d = 15.6 m
V = 3 kton
FV = 0.68 kton



# BACKUP SLIDES

## Multi-PMT (mPMT)

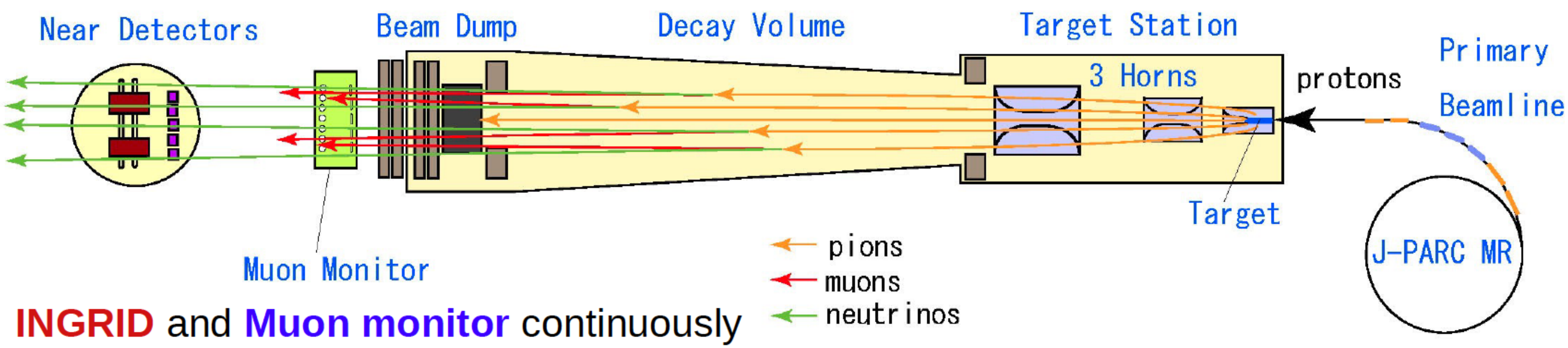
Hyper-Kamiokande




# BACKUP SLIDES

## Neutrino beam

Hyper-Kamiokande




**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

# BACKUP SLIDES

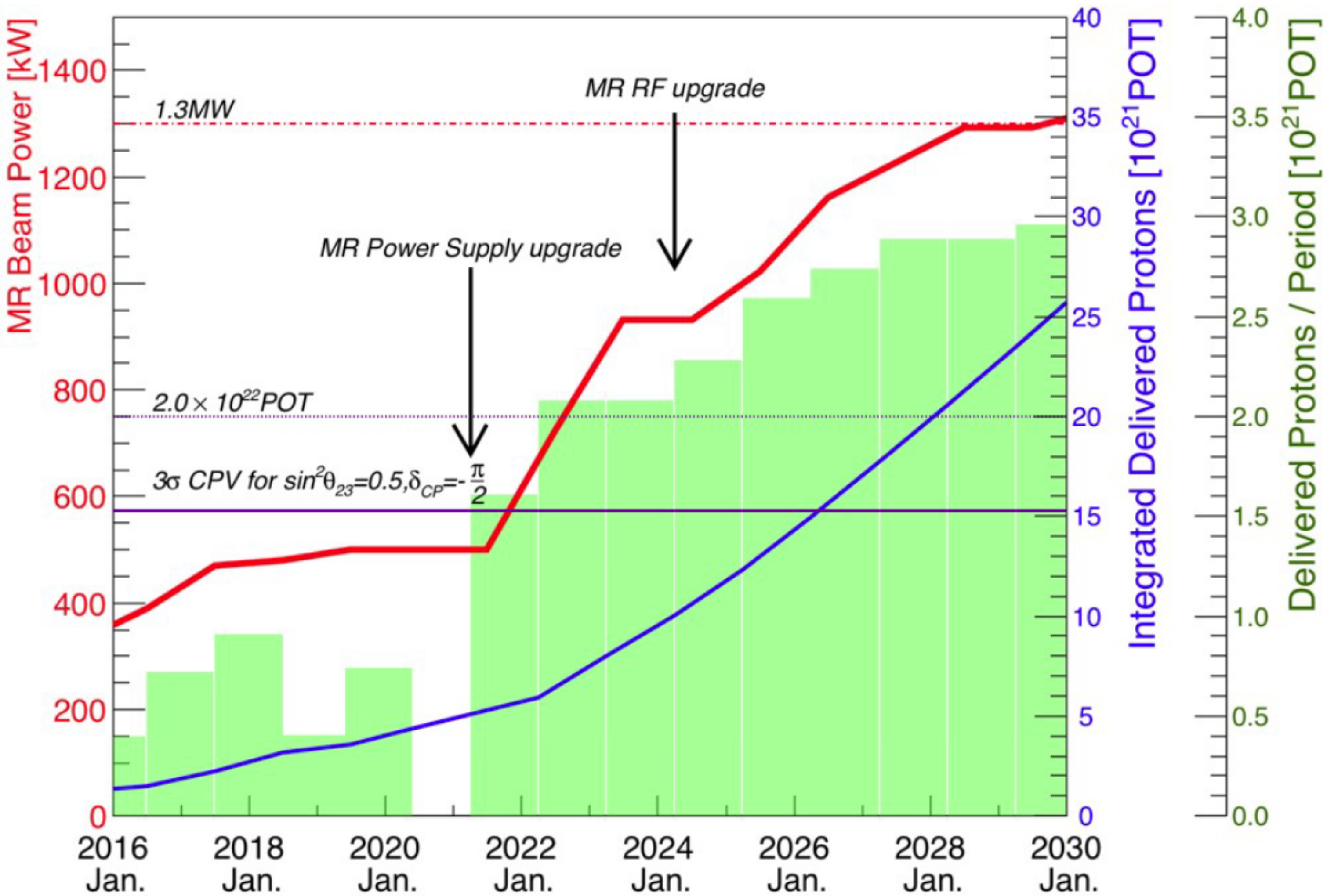
## T2K/HK Beam upgrade

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



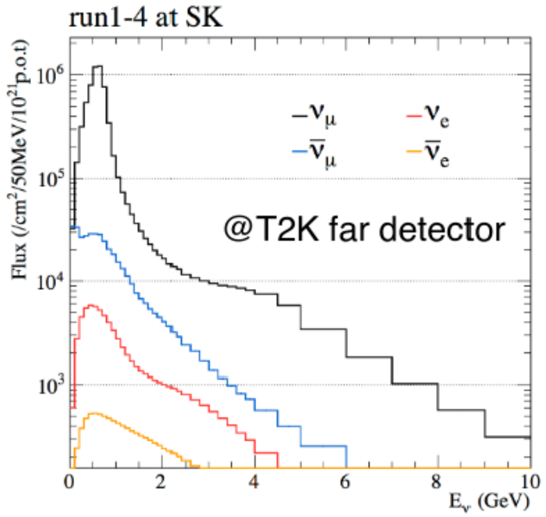
# BACKUP SLIDES

Hyper-Kamiokande

## J-PARC neutrino beam flux and its error

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

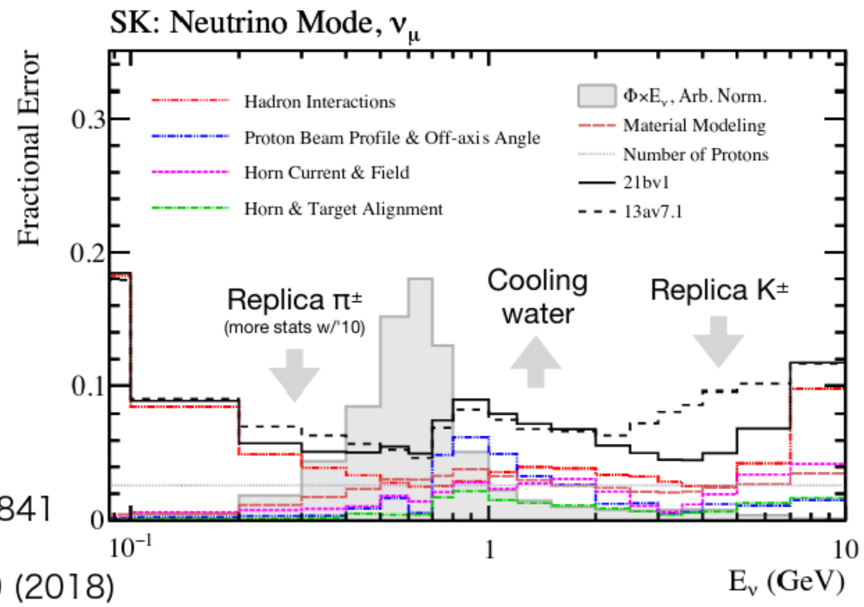
- ❖ Recently flux error was improved with NA61/SHINE replica 2010 data : **~5% error**
- ❖ Further reduction of flux systematic errors, several activities are underway




*Hadron production is still largest error source*

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

SHINE EMPHATIC




arXiv:1912.08841

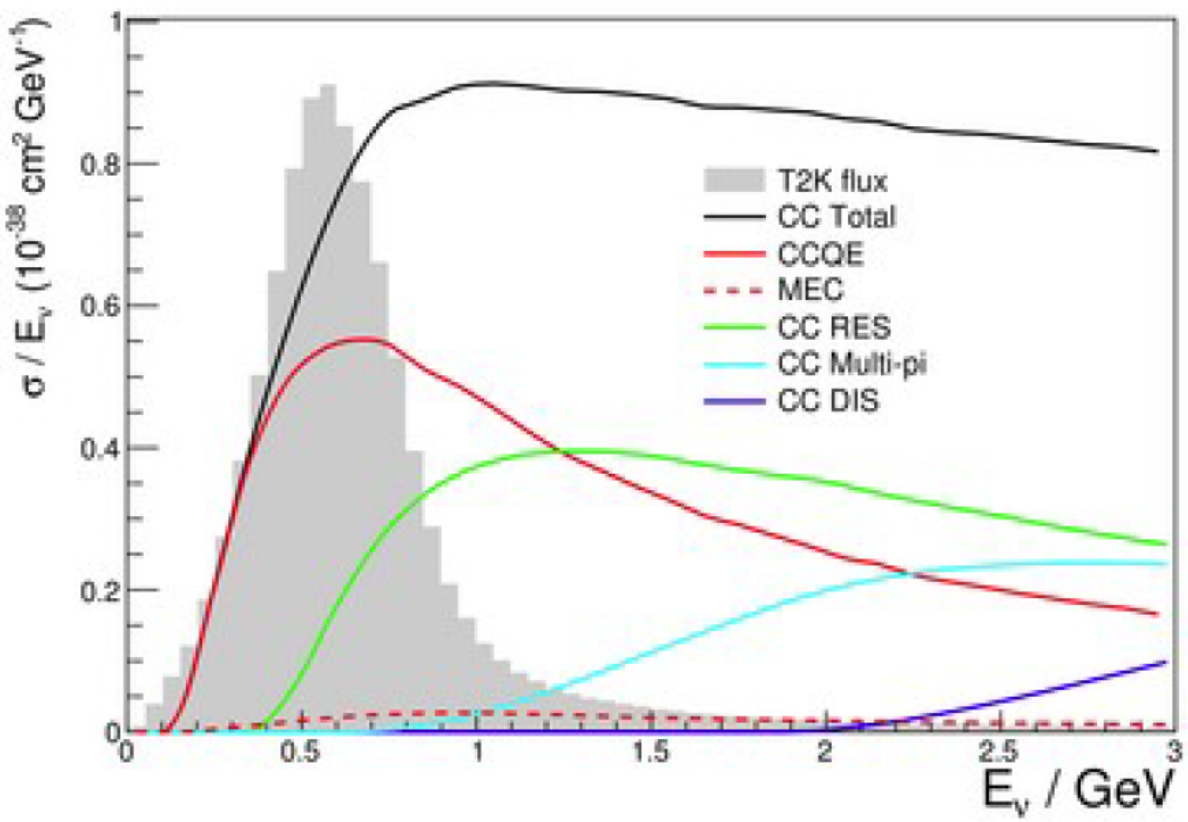
CERN-SPSC-2018-008, SPSC-P-330-ADD-10 (2018)

# BACKUP SLIDES

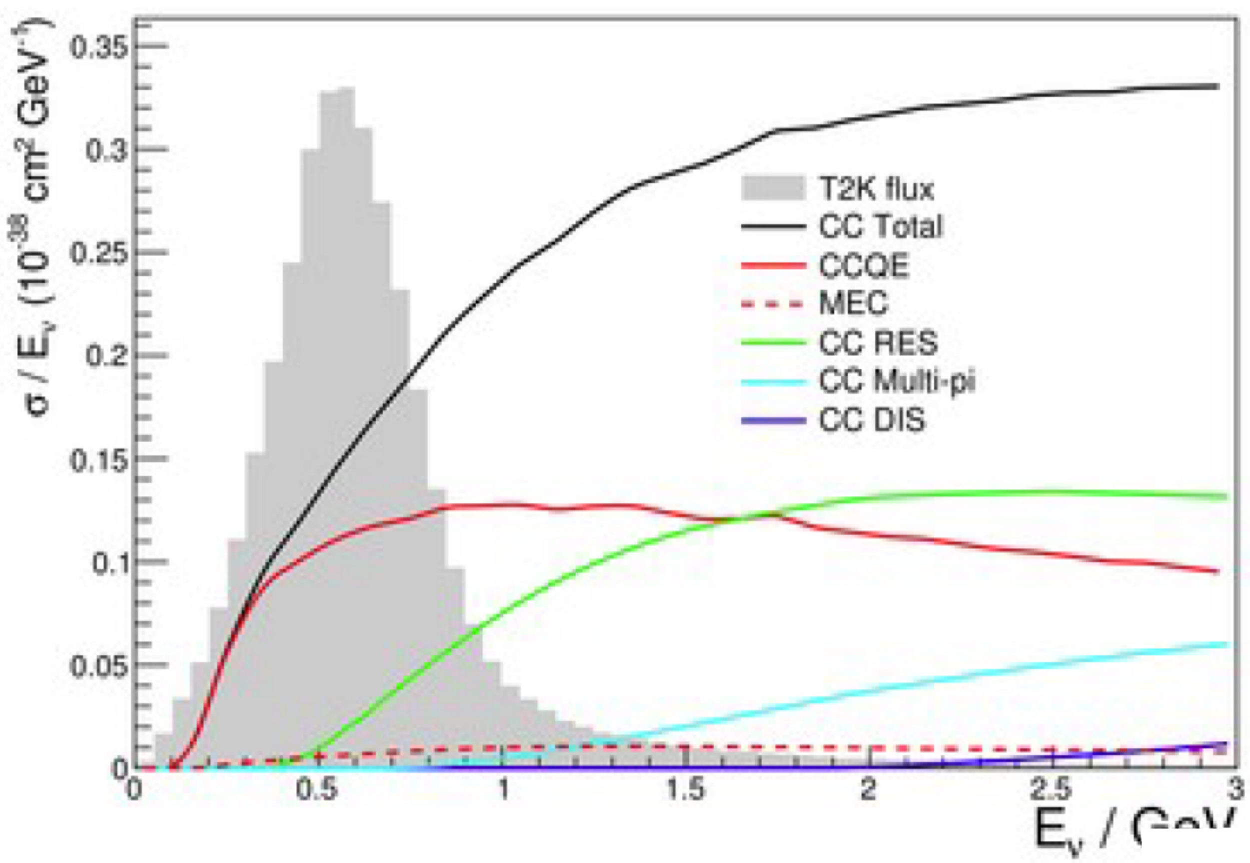
## Neutrino interaction cross sections and T2K/HK flux

Hyper-Kamiokande

$\nu$



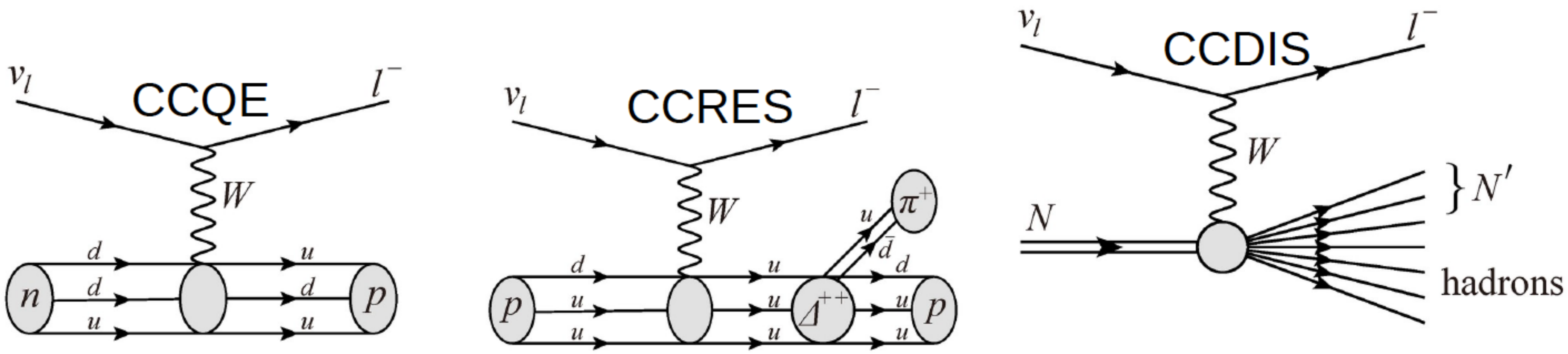

$\bar{\nu}$



# BACKUP SLIDES

## Neutrino interactions

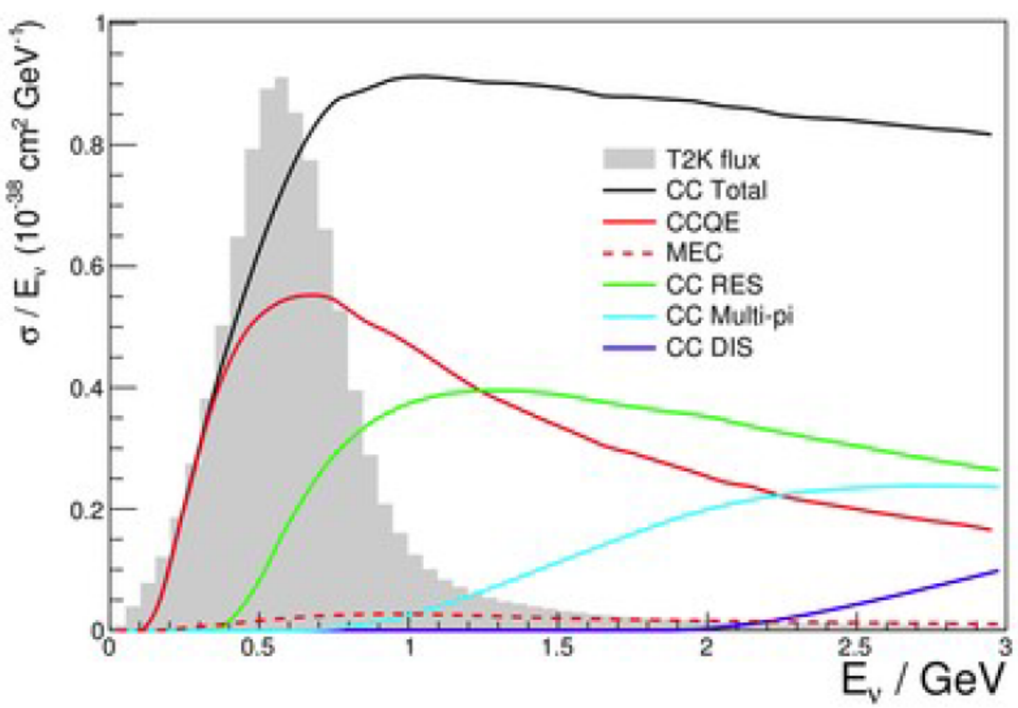
Hyper-Kamiokande




NC interactions also important

e.g. NCπ$^0$, NC1γ

→ background




Interactions occur with nucleons bound inside a nucleus

→ **Nuclear effects!!**

We only measure particles that exit the nucleus

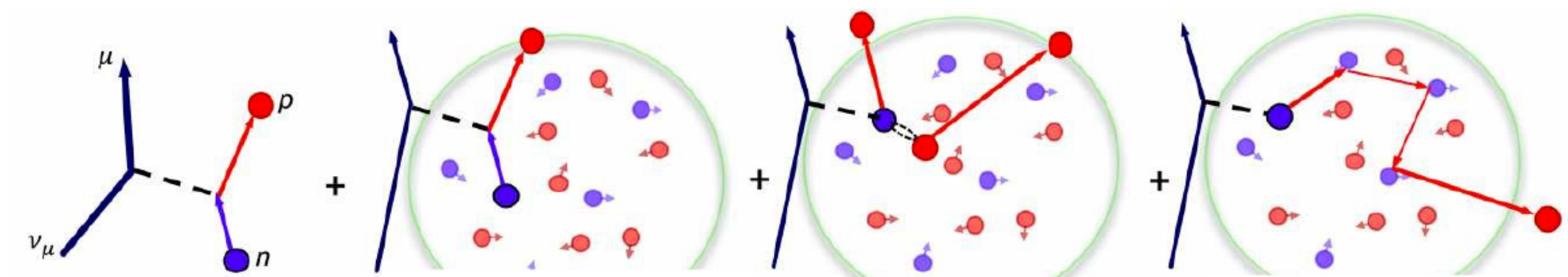
→ lose information about the initial interaction

→ can create a bias in energy reconstruction

# BACKUP SLIDES

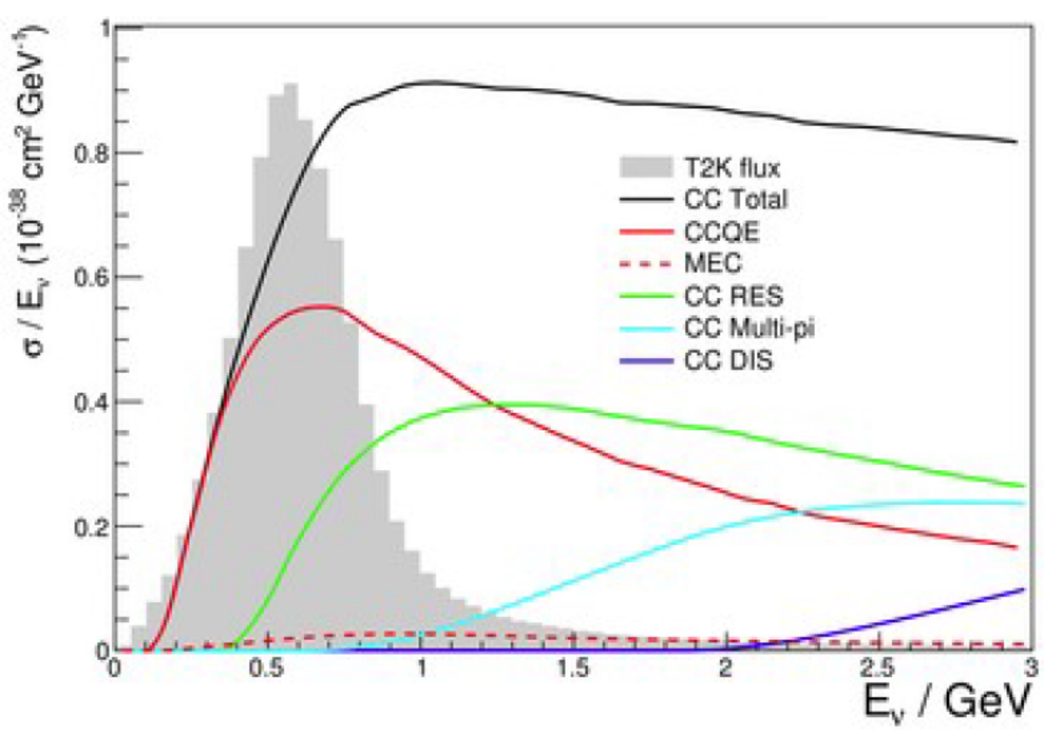
## Neutrino interactions

Hyper-Kamiokande




Free nucleon | Initial nuclear state | Extra nuclear effects | Final state interactions

Interaction modes and Nuclear models tuned to external data

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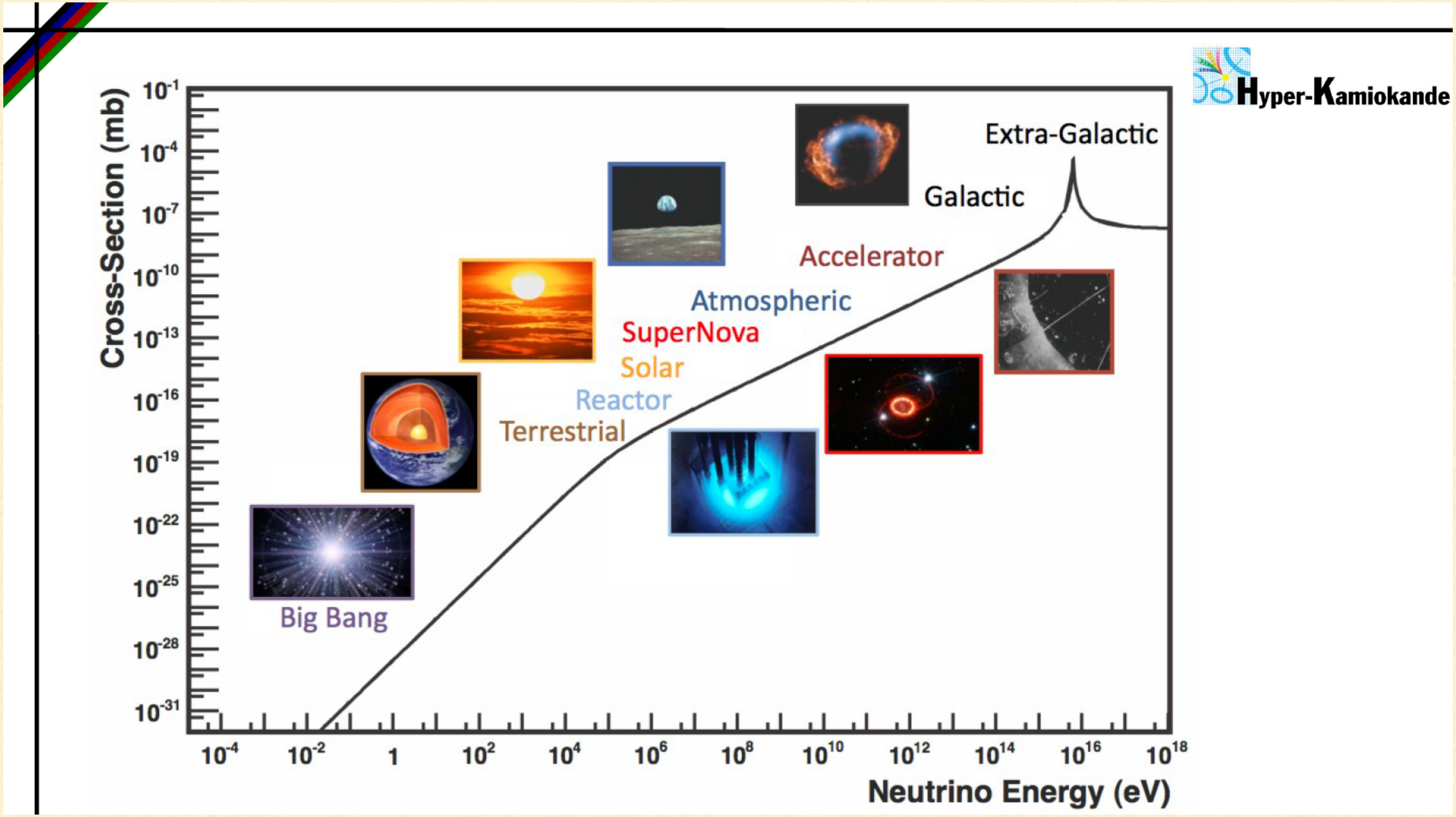
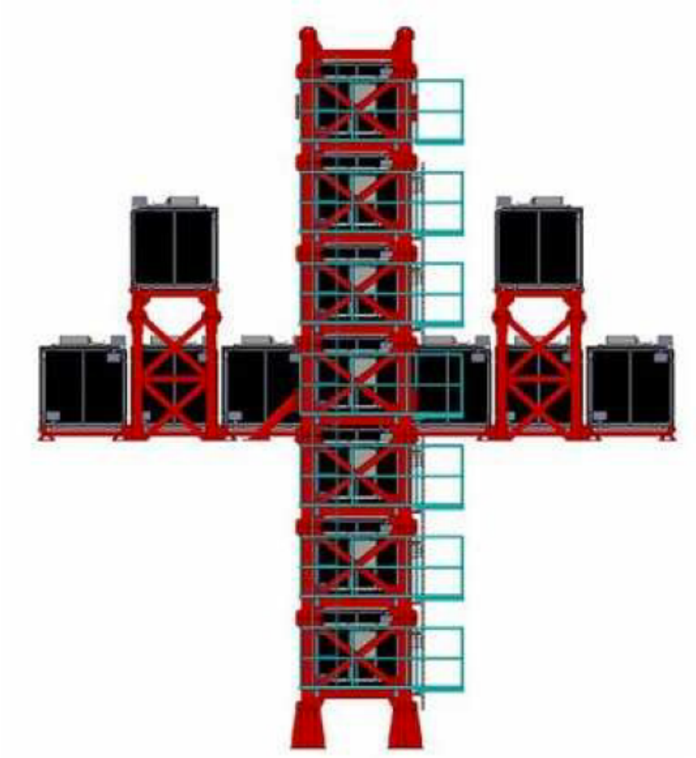
# BACKUP SLIDES



# BACKUP SLIDES

## Near Detectors

280m from the ν ($\bar{\nu}$) source



**INGRID**

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

# BACKUP SLIDES

Hyper-Kamiokande

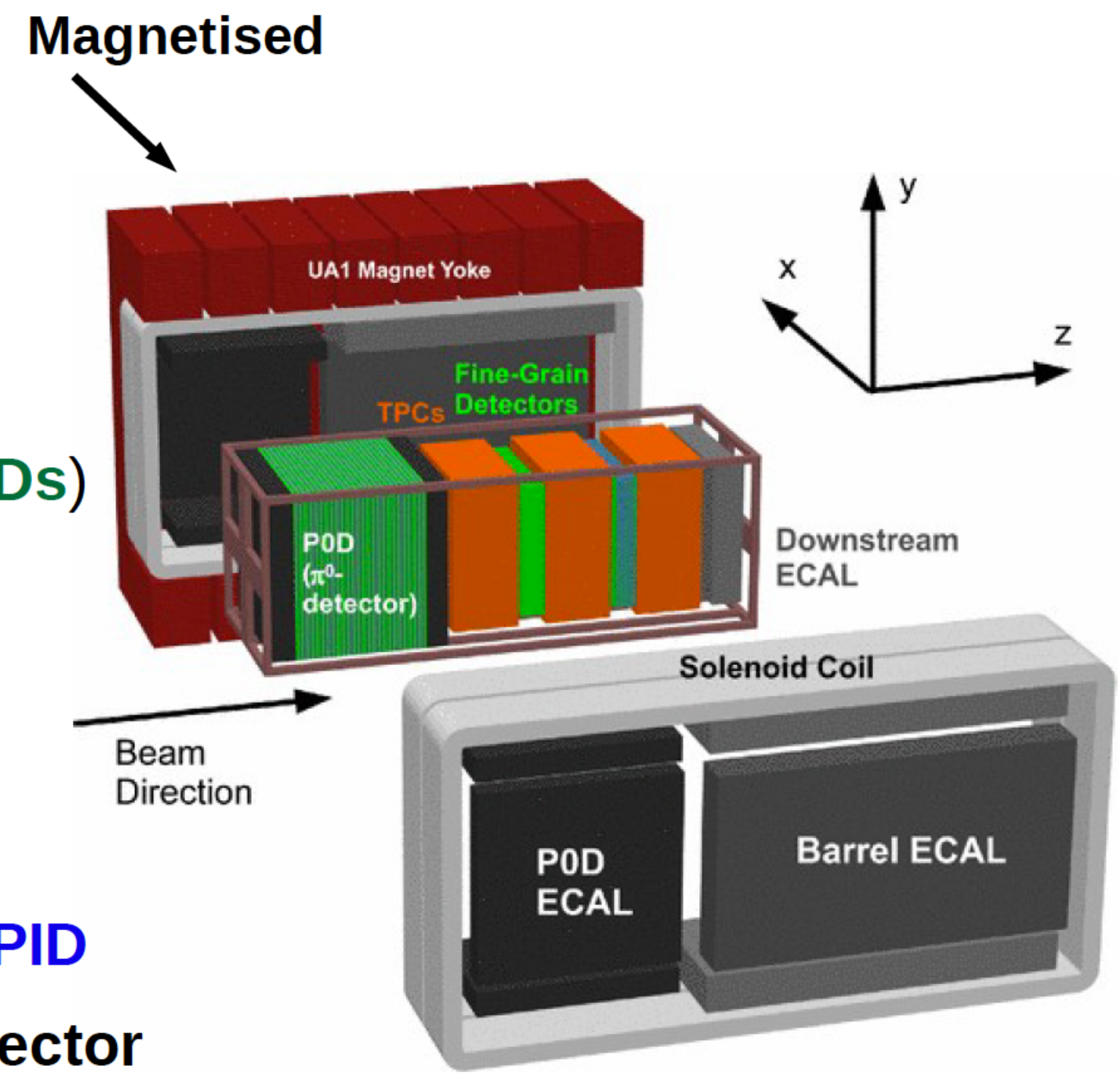
## Near Detectors

280m from the ν ($\bar{\nu}$) source

**ND280**

Same off-axis angle as SK

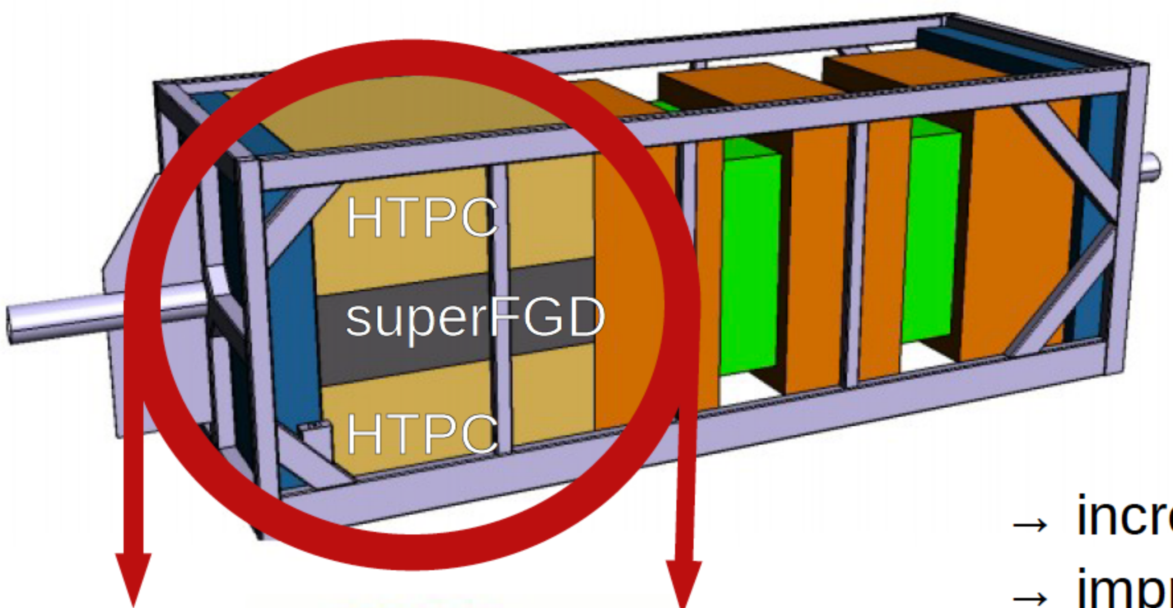
- Active target mass → 2 x scintilltors (**FGDs**)
  → vertex reconstruction
- 3 Time projection chambers (**TPC**)
  → **momentum** reconstruction
  → **charge** identification
  → Particle identification (**PID**)
- Electromagnetic calorimeters (**Ecal**) → **PID**
- **$\pi^0$ detector** and **side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

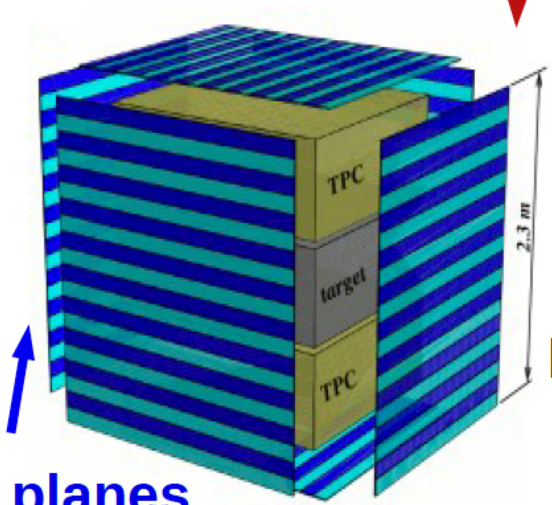


# BACKUP SLIDES

## ND280 upgrade (2021)

Hyper-Kamiokande




**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)

# BACKUP SLIDES

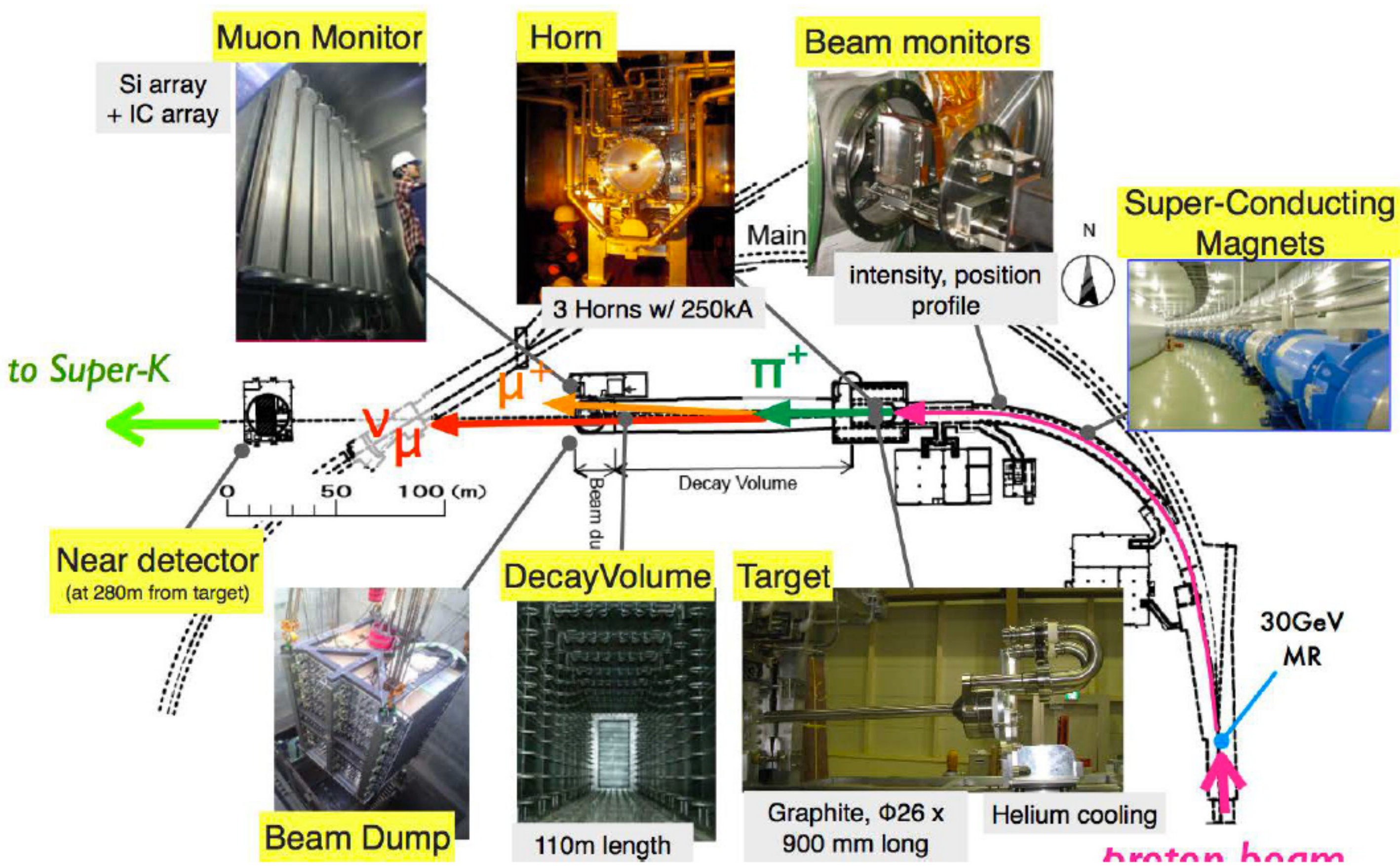
## The Beam

Major neutrino-producing decay modes in the decay volume:

For a neutrino beam

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

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

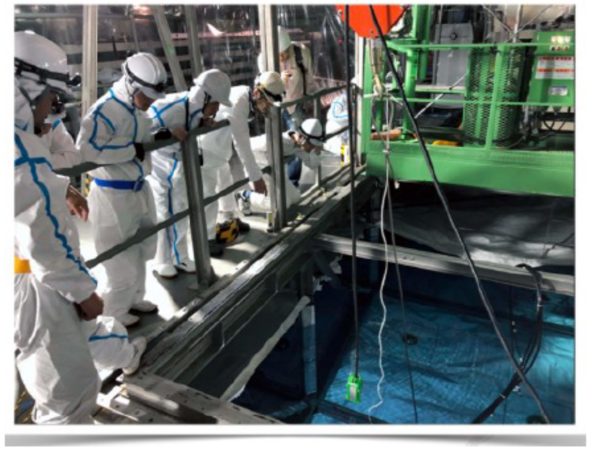


# BACKUP SLIDES

## T2K II: SK upgrade

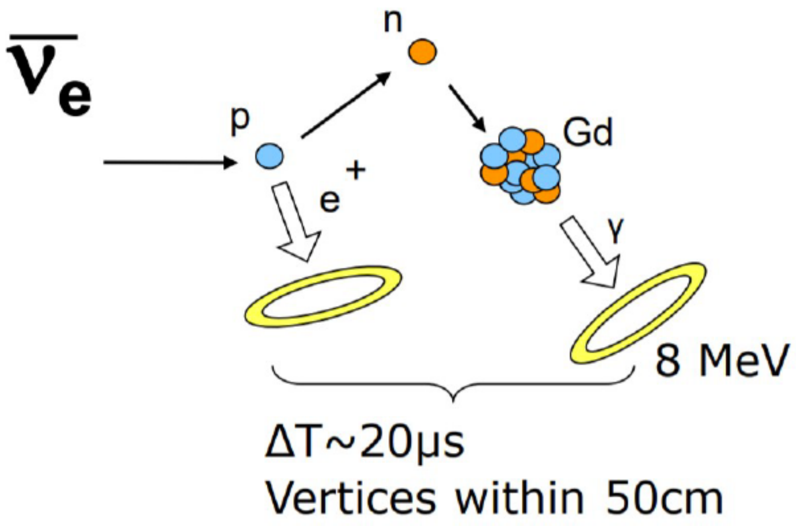
Hyper-Kamiokande

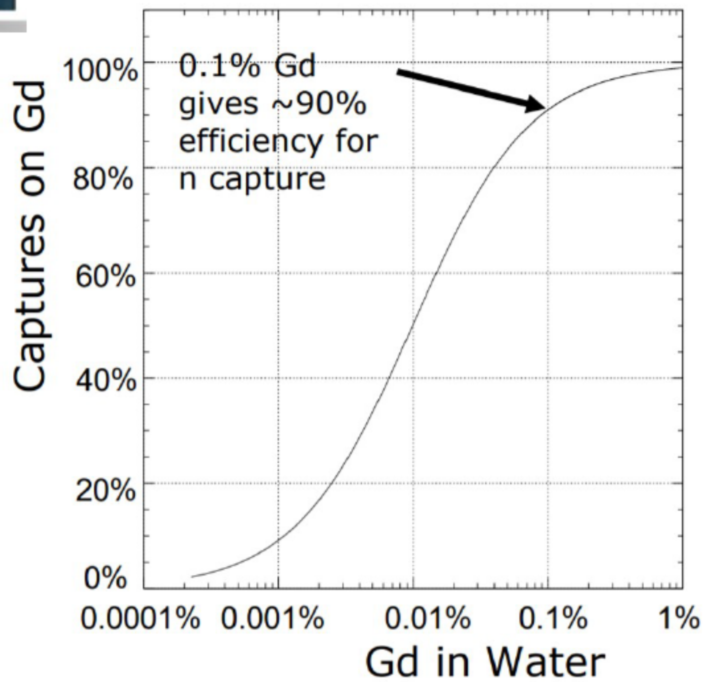
* SK repairs performed in 2018
  - detector drained and cleaned
  - reinforcement of water sealing
  - improved tank piping
  - PMTs replaced



* Plan to add **Gadolinium** to the water
  - 0.01% next year
  - increase to 0.1% eventually

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



# BACKUP SLIDES

## 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

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

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

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

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 $\delta_{CP}$ = ??

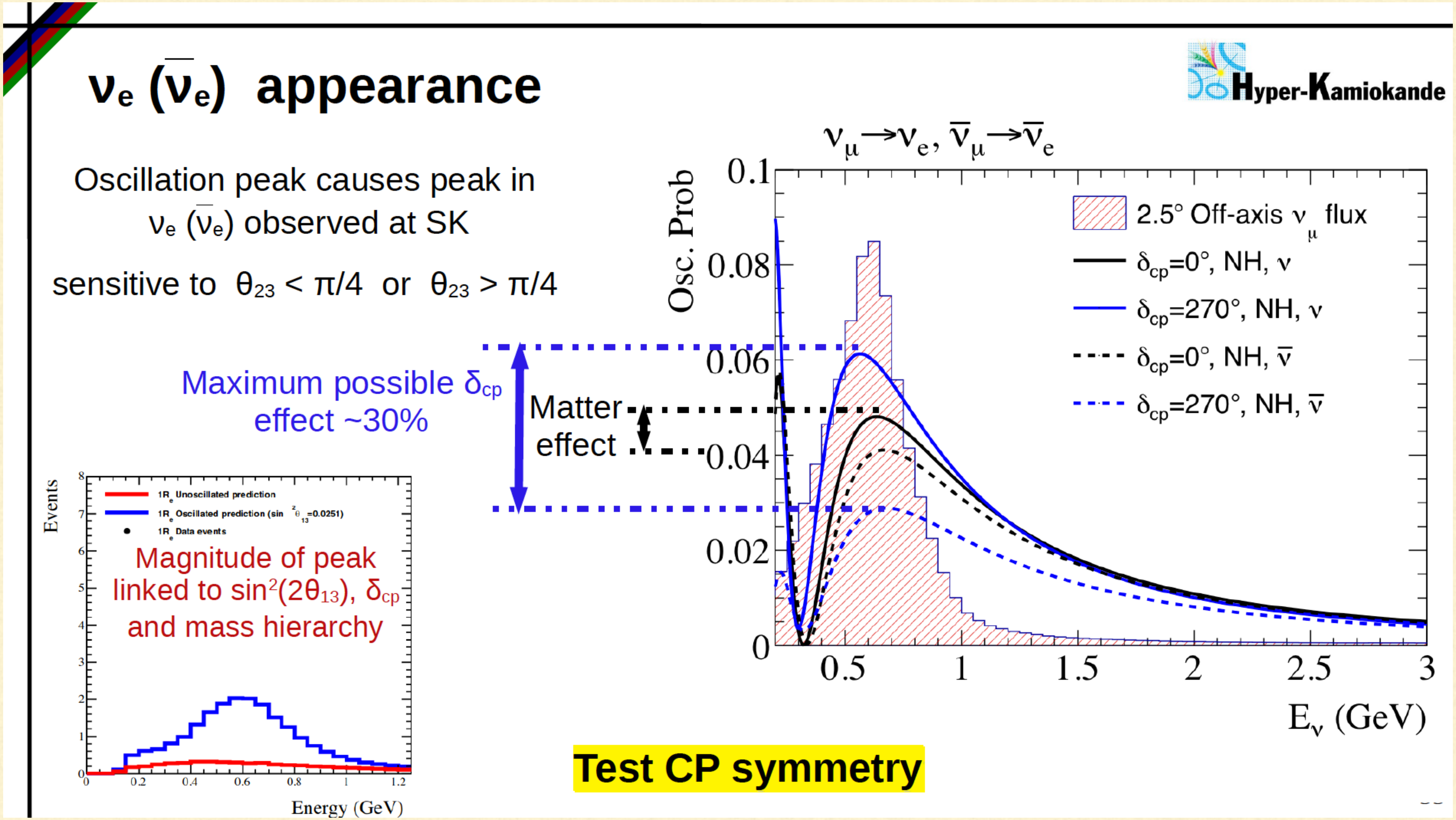
Solar and reactor
$\theta_{12} \sim 34°$
$\Delta m_{12}^2 \sim 7.5\text{x}10^{-5}$ eV$^2$

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

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

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

# BACKUP SLIDES



# BACKUP SLIDES

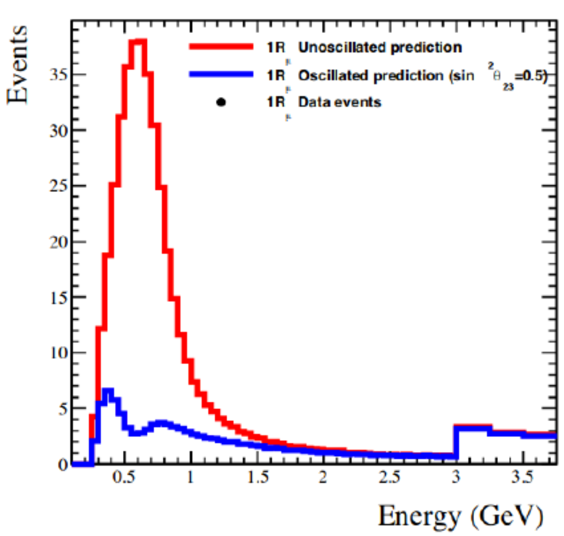
## $\nu_\mu$ ($\bar{\nu}_\mu$) disappearance

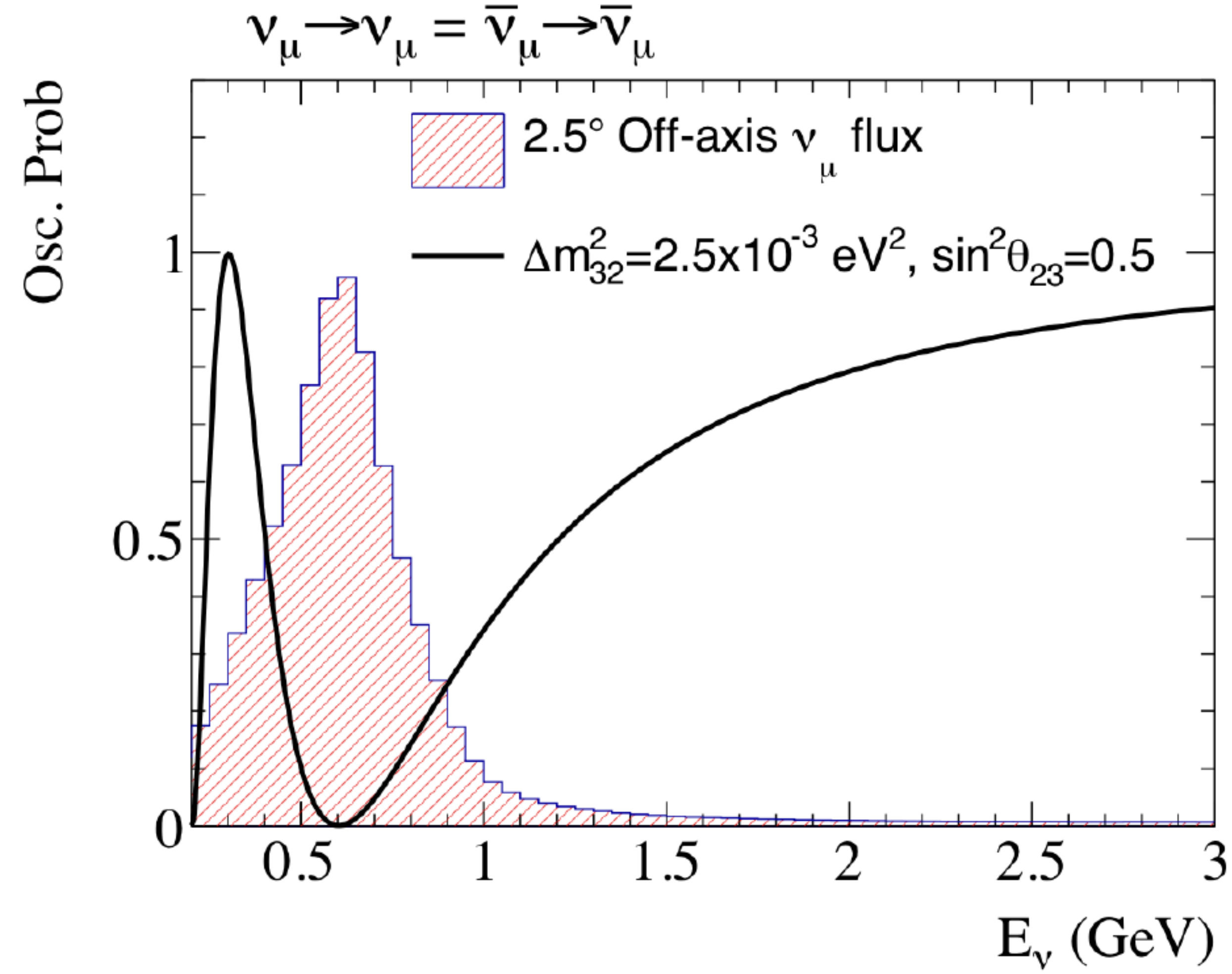
Hyper-Kamiokande

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**