Current Status and Physics Potential of the

Hyper-Kamiokande Experiment

UNDER CONSTRUCTION UNDER CONSTRUCTION UNDER CONSTRUCTION

Lake Louise 2023

KING'S College LONDON

Sophie King

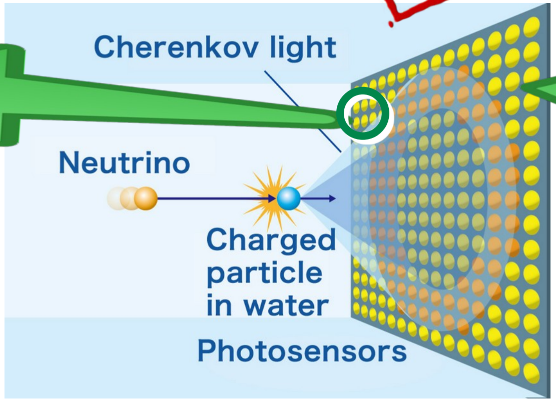
The Hyper-K Detector

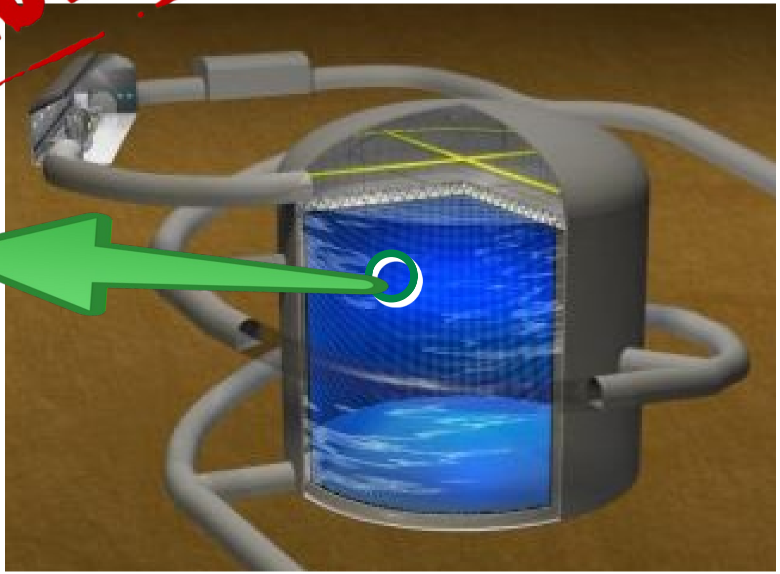
Hyper-Kamiokande

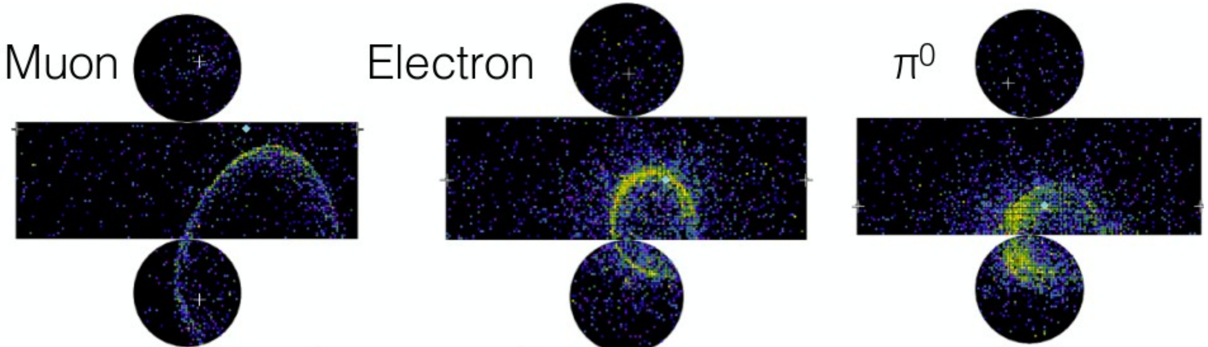
Water Cherenkov detector

Photomultiplier tube

(PMT)







Hyper-K will begin taking data in 2027

The Hyper-K Detector

Inner detector (ID):

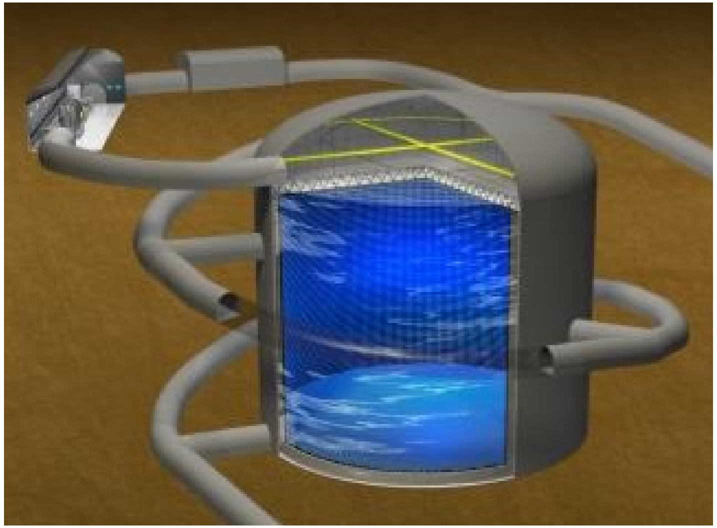
* 216 kton

Outer detector (OD):

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

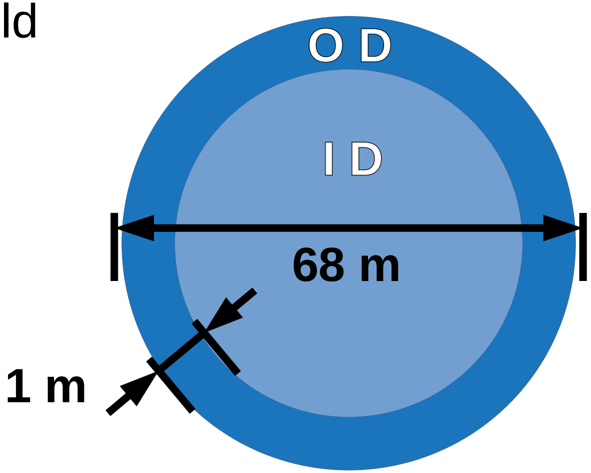
* veto region (incoming/outgoing particles)

* low energy background shield



* High reflectivity (>90%)
Tyvek facing OD

* Black sheet facing ID



Height = 71 m,   Diameter = 68 m

Volume: 258 kton

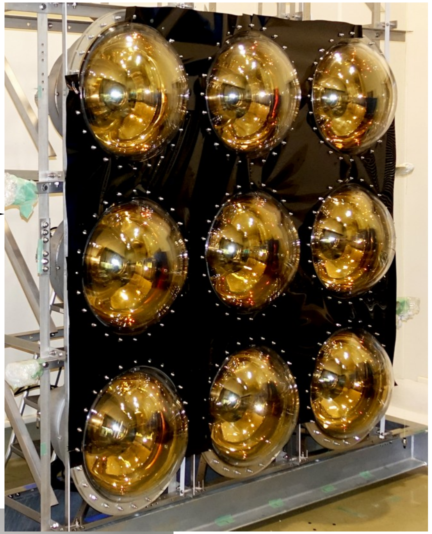
FV > 180 kton

PMT Photosensors

Hyper-Kamiokande

50 cm PMTs (box and line dynode)

~ 1.5 ns timing resolution



Inner detector (ID)

20,000 * 50 cm PMTs → 20% coverage

8cm PMTs

Outer detector (OD)

~ few thousand * 8 cm PMTs

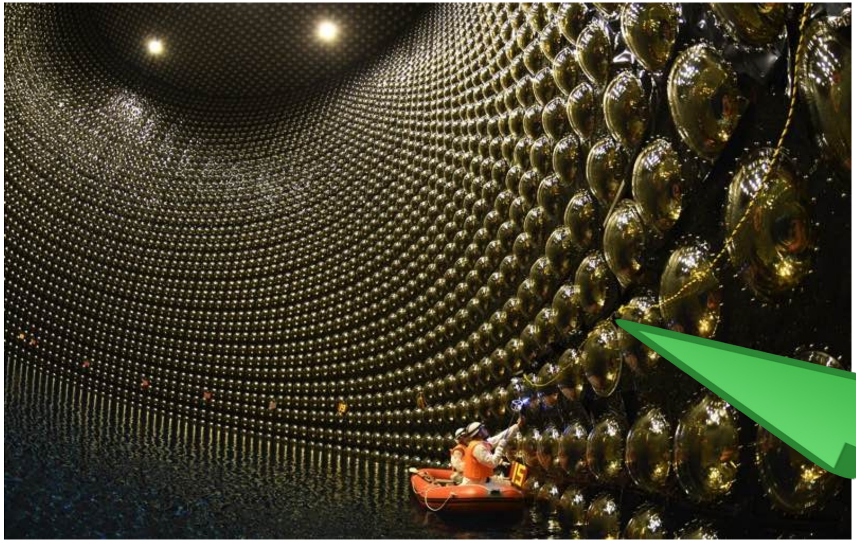
Multi-PMTs (mPMTs)

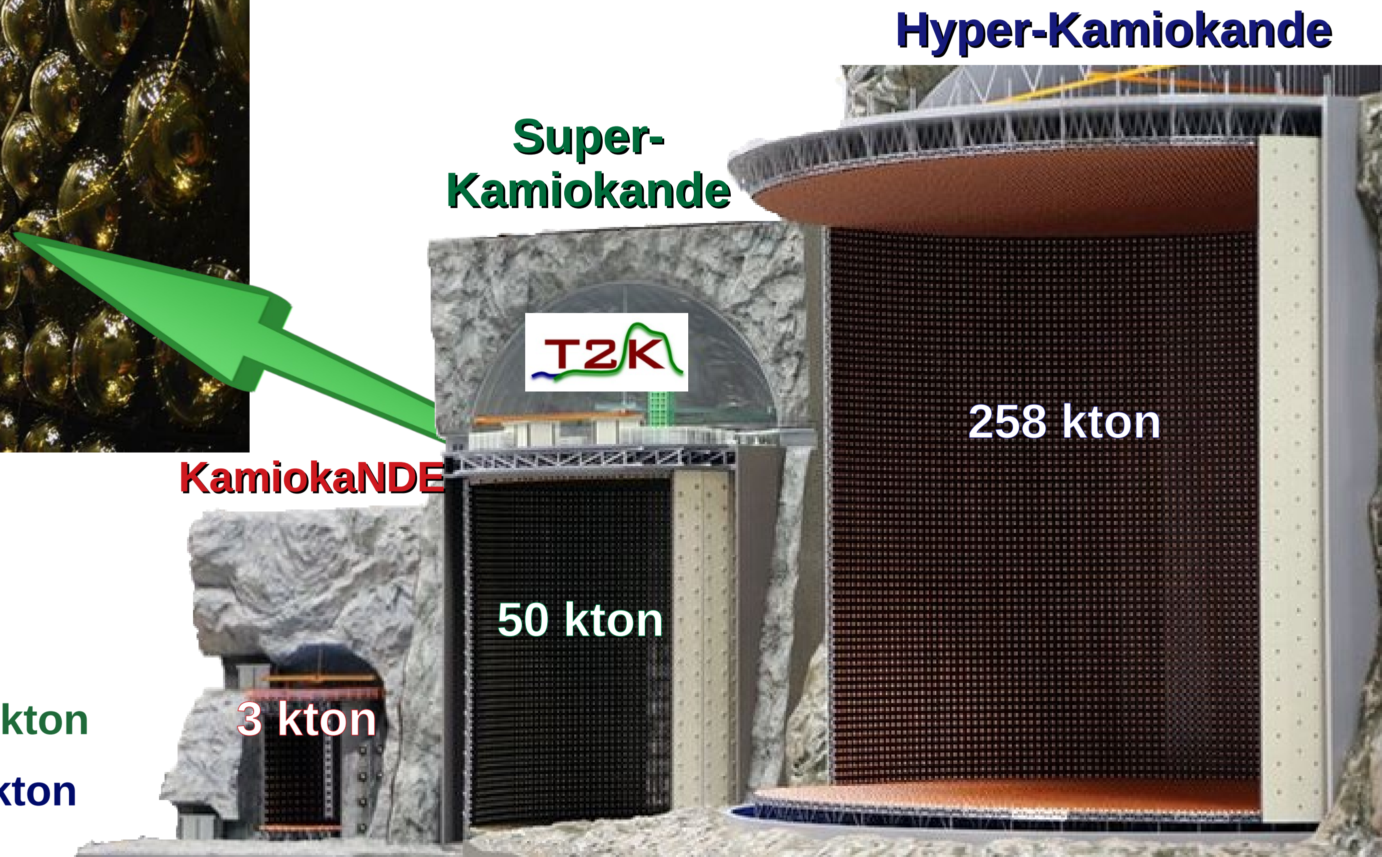
- 19 x 8 cm PMTs inside single pressure vessel
- directional information and improved timing and spatial resolutions

Inner detector (ID)

~ few thousand mPMTs

The Kamiokande Series





Fiducial volume (FV):

Kamiokande: FV = 0.7 kton

Super-Kamiokande: FV >= 22.5 kton

Hyper-Kamiokande: FV >= 180 kton

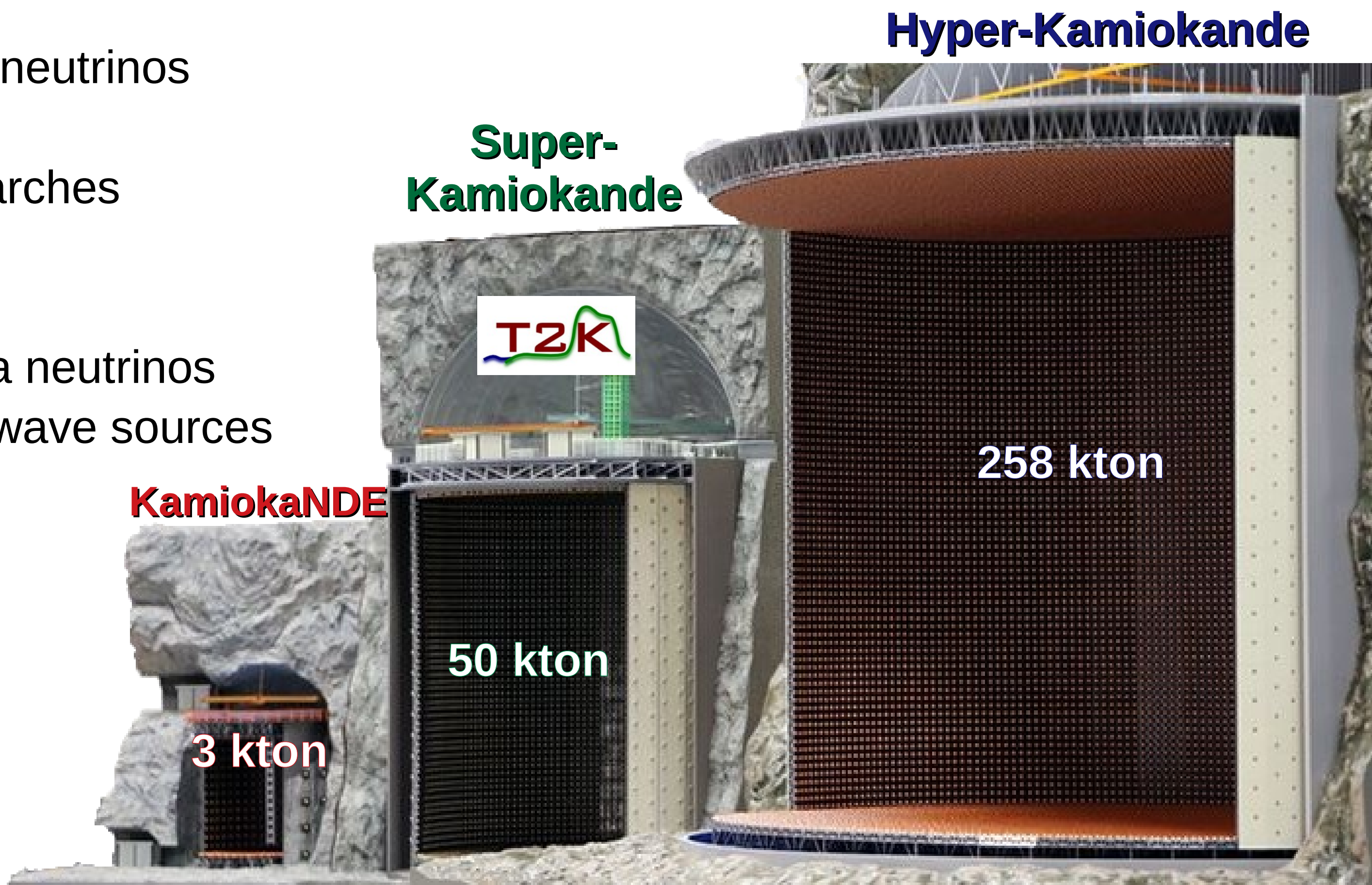
Hyper-Kamiokande Physics

* Neutrino Oscillations
  - beam, atmospheric, solar neutrinos

* Proton decay and BSM searches

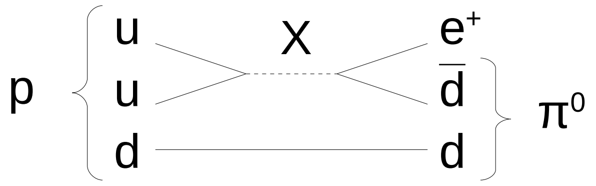
* Astrophysics
  - solar neutrinos, supernova neutrinos
  - dark matter, gravitational-wave sources
  - gamma-ray sources

* Nuclear physics
  - neutrino interactions



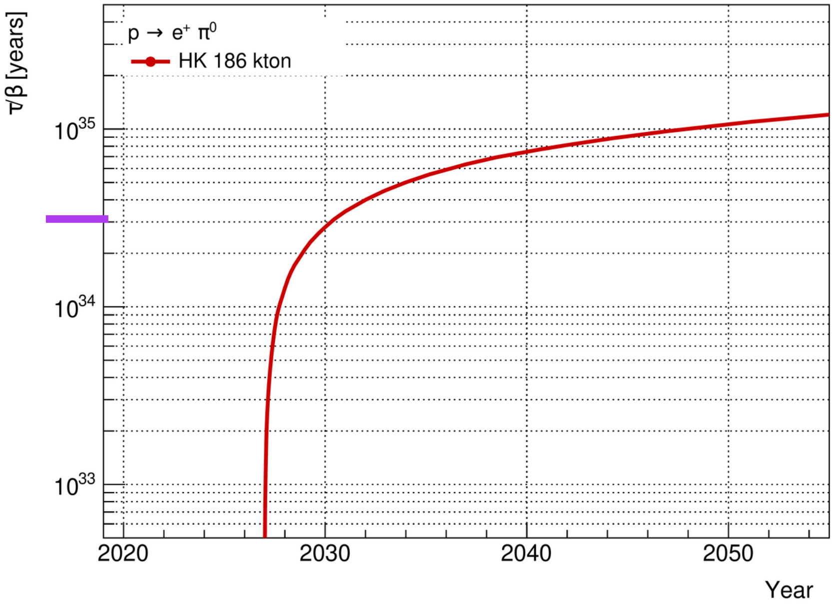
Proton Decay

Proton decay



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

$\tau > 2.4 \times 10^{34}$ years
(SK, PRD 102, (2020) 112011)



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

Neutrino Oscillations

Neutrino Oscillations

Hyper-Kamiokande

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

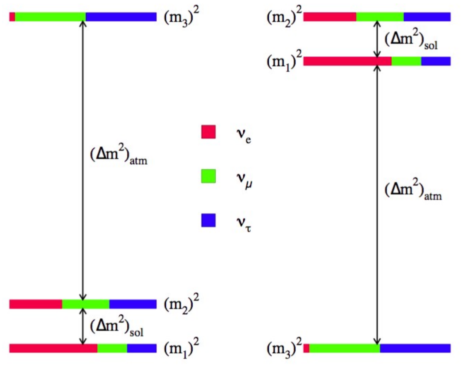
$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1&0&0\\0&c_{23}&s_{23}\\0&-s_{23}&c_{23}\end{pmatrix}\begin{pmatrix}c_{13}&0&s_{13}e^{-i\delta_{CP}}\\0&1&0\\-s_{13}e^{i\delta_{CP}}&0&c_{13}\end{pmatrix}\begin{pmatrix}c_{12}&s_{12}&0\\-s_{12}&c_{12}&0\\0&0&1\end{pmatrix}\begin{pmatrix}\nu_1\\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

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

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

Solar and reactor
$\theta_{12} \sim 34°$
$\Delta m_{21}^2 \sim 7.5\text{x}10^{-5}\ \text{eV}^2$

1) Mass Ordering (NO or IO)



Normal Ordering (NO) Inverted Ordering (IO)

2) θ_{23} octant:

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

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

θ_{13} precisely measured and not too small
→ opens the door for δ_{cp} measurements

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

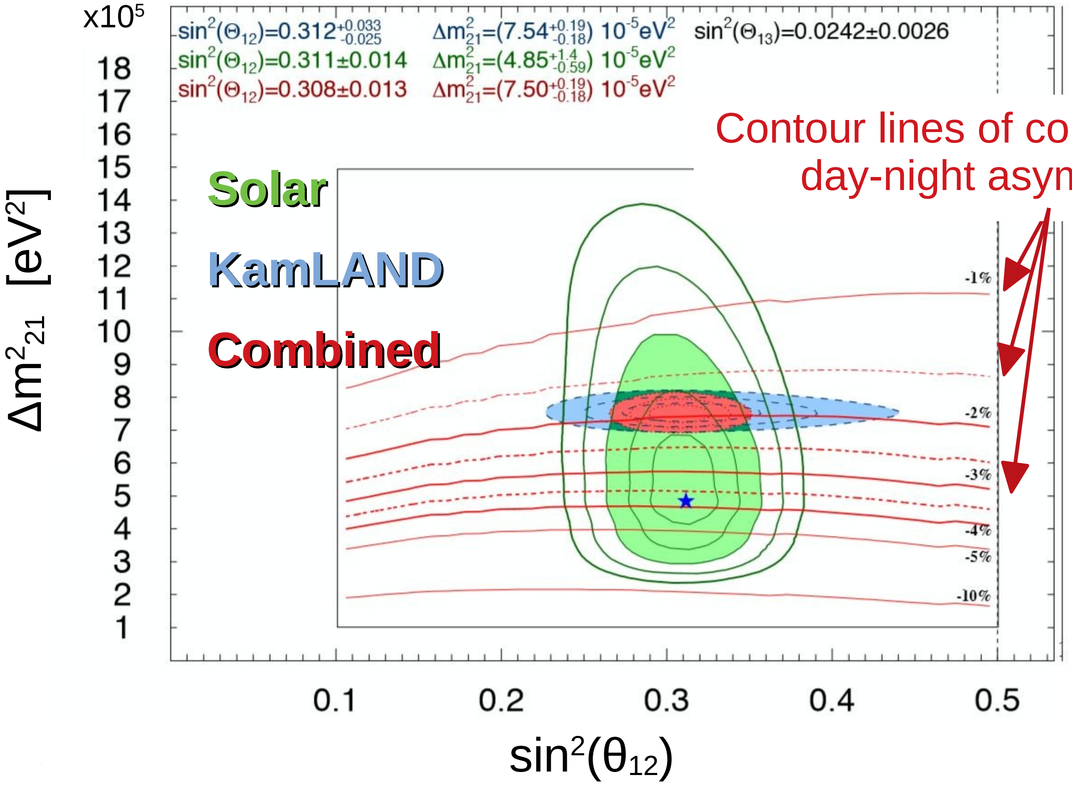
Compare oscillation of ν and $\bar{\nu}$ to probe δ_{cp}

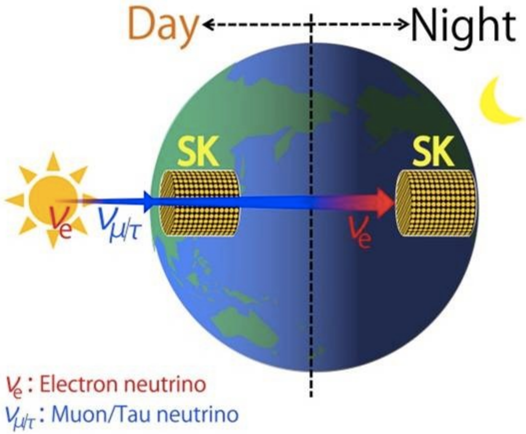
Matter effects! (electrons)
Difference in ν_e and $\bar{\nu}_e$ travelling through the earth (similar effect as δ_{cp})
→ allows for mass hierarchy determination

Solar Neutrinos

Solar Neutrinos

~ 1.5σ tension in Δm^2_{21} between solar & kamLAND (reactor)



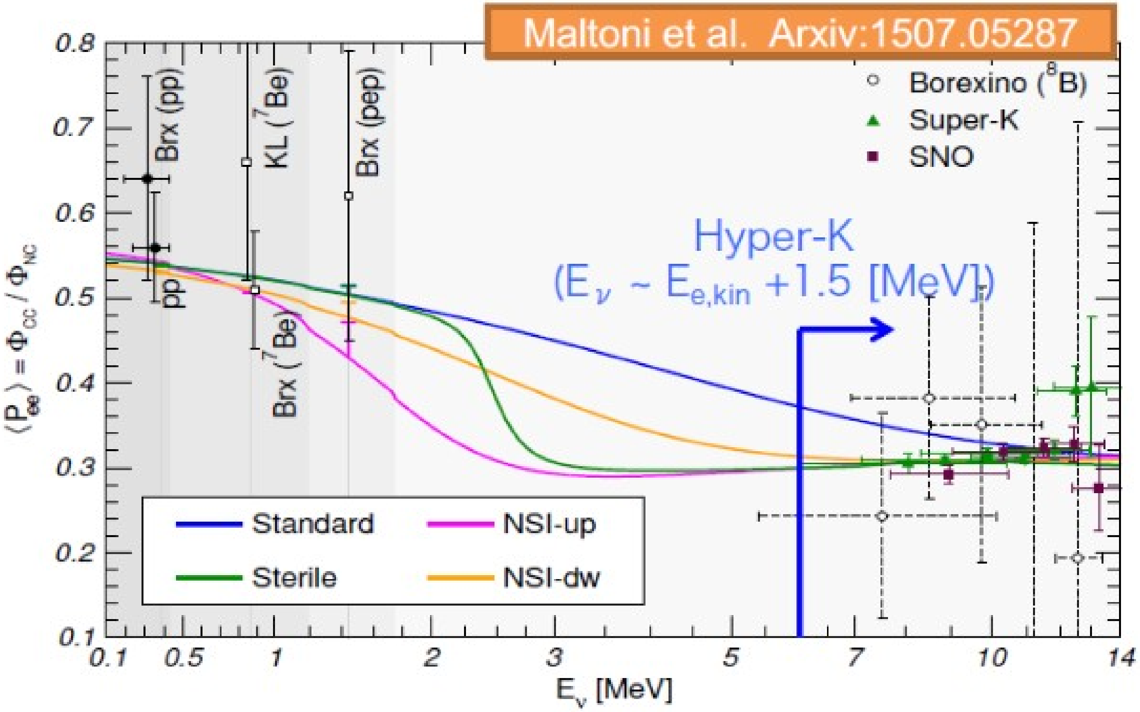


ν_e flux differs between night and day
→ matter effects
→ *day-night asymmetry*

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

Hyper-K can reject no D/S assym >5σ confirmation with 10 years of Hyper-k
And can investigate this tension with increased stats

Solar Neutrinos



Vacuum dominated region

Matter dominated region

Low energy solar neutrino survival probability

Hyper-K can constrain the **‘upturn’** in the vacuum-MSW transition region

Sensitivity depends on analysis energy threshold

Electron kinetic energy equivalent threshold 3.5-4.5 MeV

→ Sensitivity of 3-5σ for upturn discovery after Hyper-k 10 years

Supernova Neutrinos

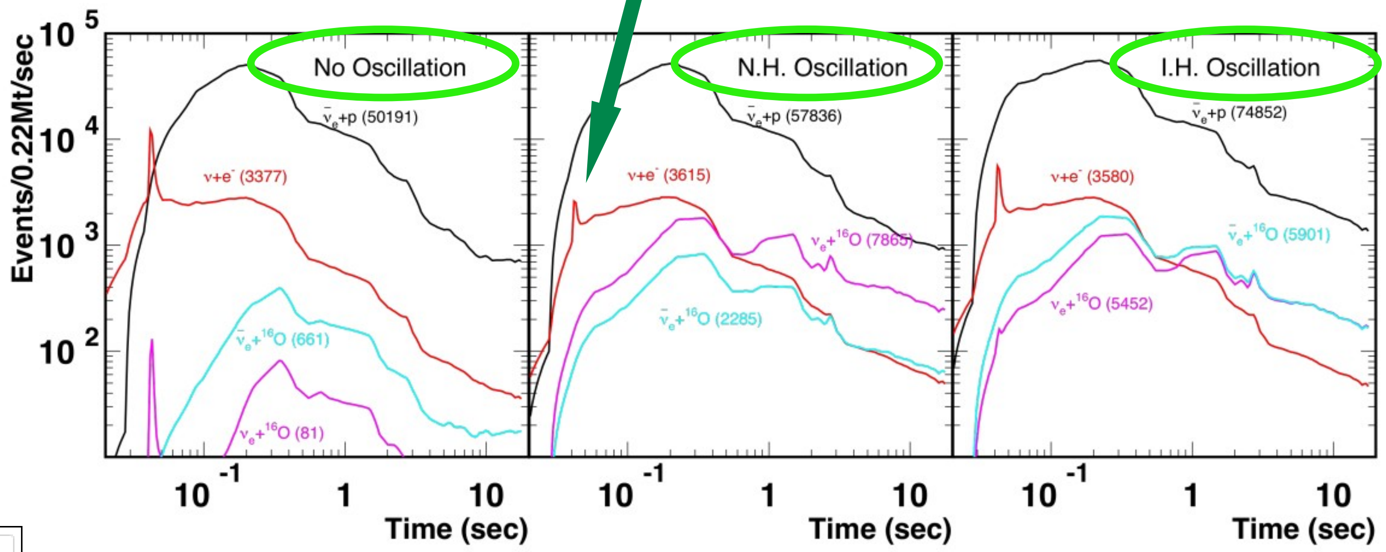
Supernova Neutrinos

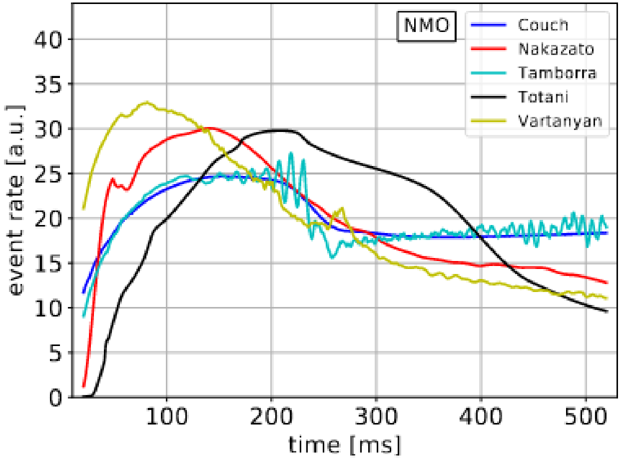
Neutronization peak
(sensitive to mass ordering)

Hyper-Kamiokande

Expected time profile of a supernova at 10kpc ➡

* numbers in brackets total interactions integrated over the 10s burst





⬅ **Event rate predicted by different SN models**

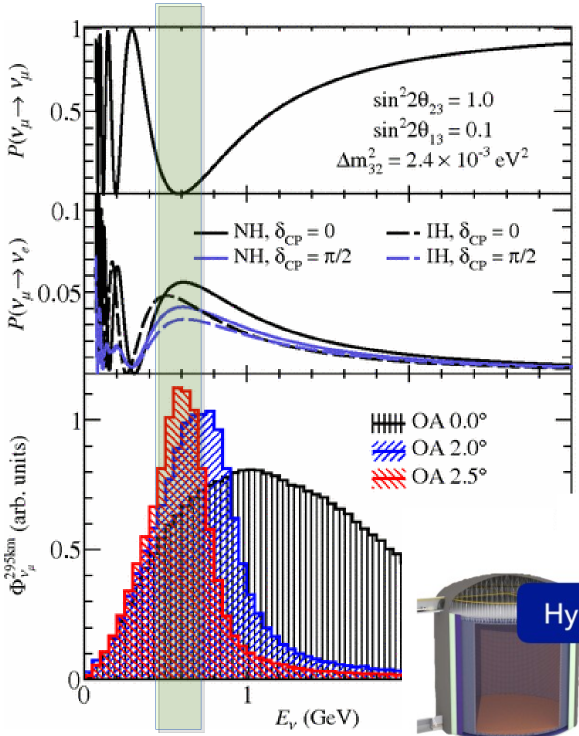
(normalised to total event rate, for unknown distance)

→ **Hyper-K can build discriminators to constrain SN models**

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

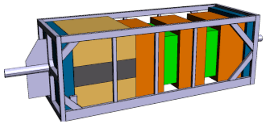
Long-baseline neutrino oscillations
(beam)

Hyper-Kamiokande long-baseline



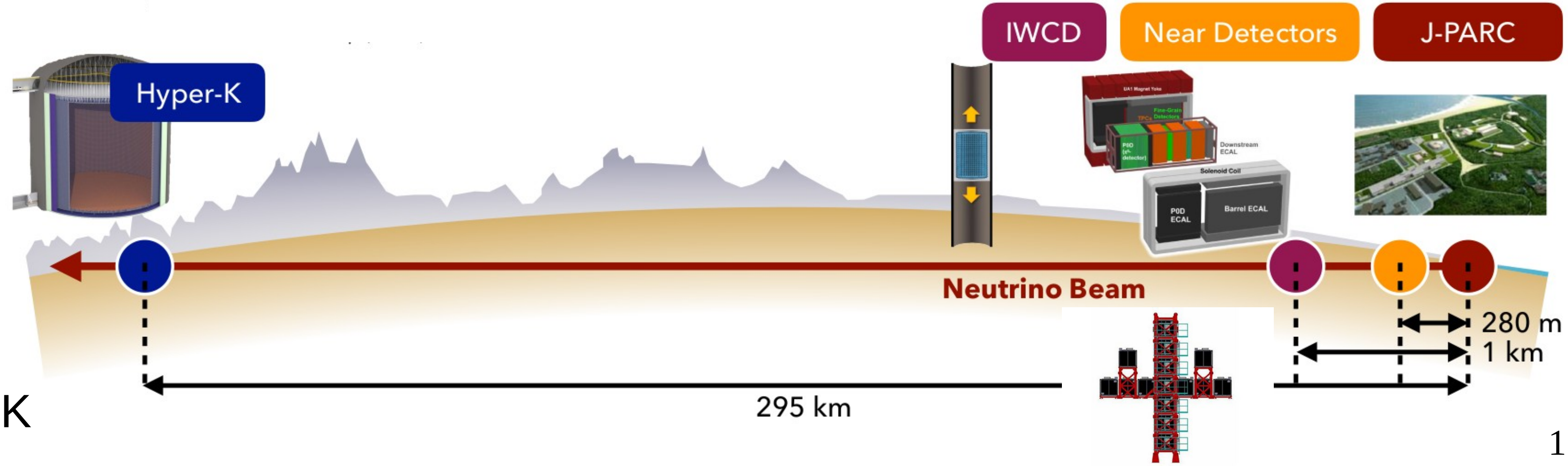
* Upgrade T2K beam to 1.3MW

* Upgraded ND280



* New intermediate water Cherenkov detector (IWCD)

* Hyper-K far detector

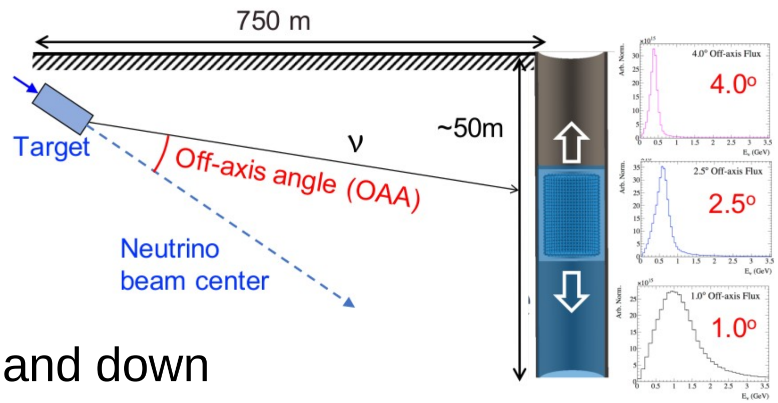


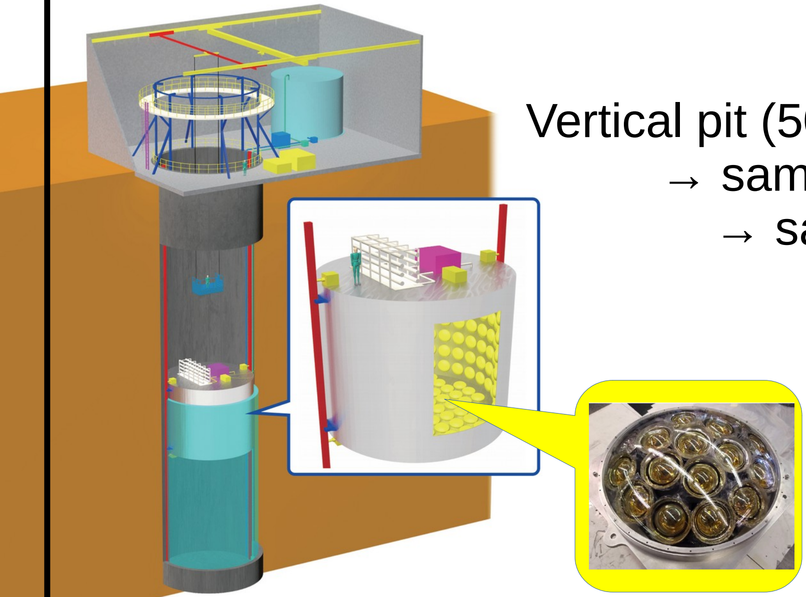
HK at same distance and off-axis angle as SK

Intermediate water Cherenkov detector (IWCD)

Constrains flux and neutrino interactions with same target as far detector

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



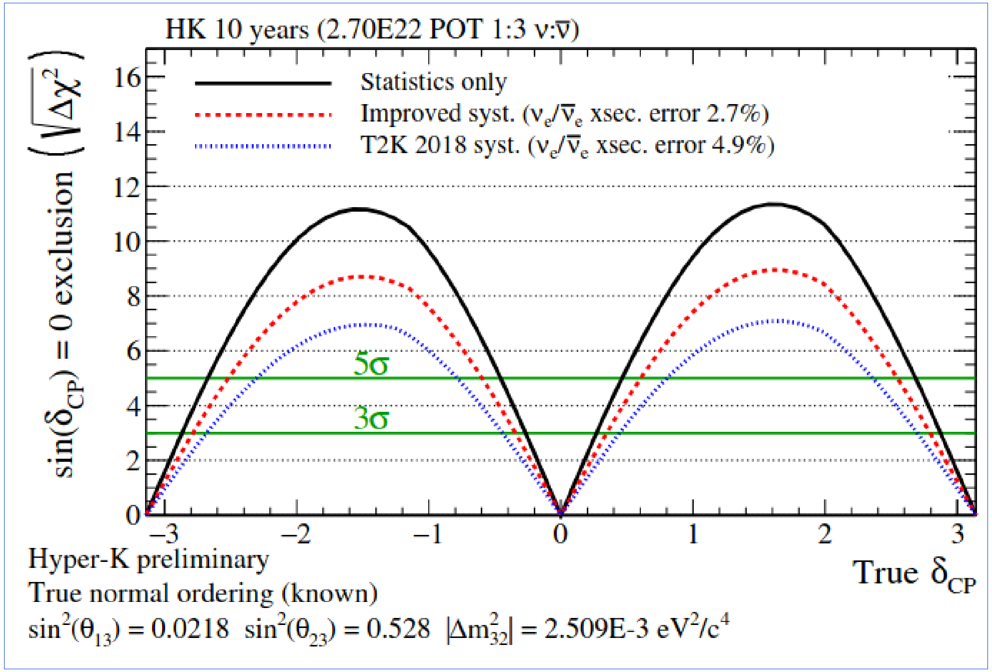


Vertical pit (50 m), detector moves up and down
→ samples flux at different angles
→ sample flux at different energy profiles

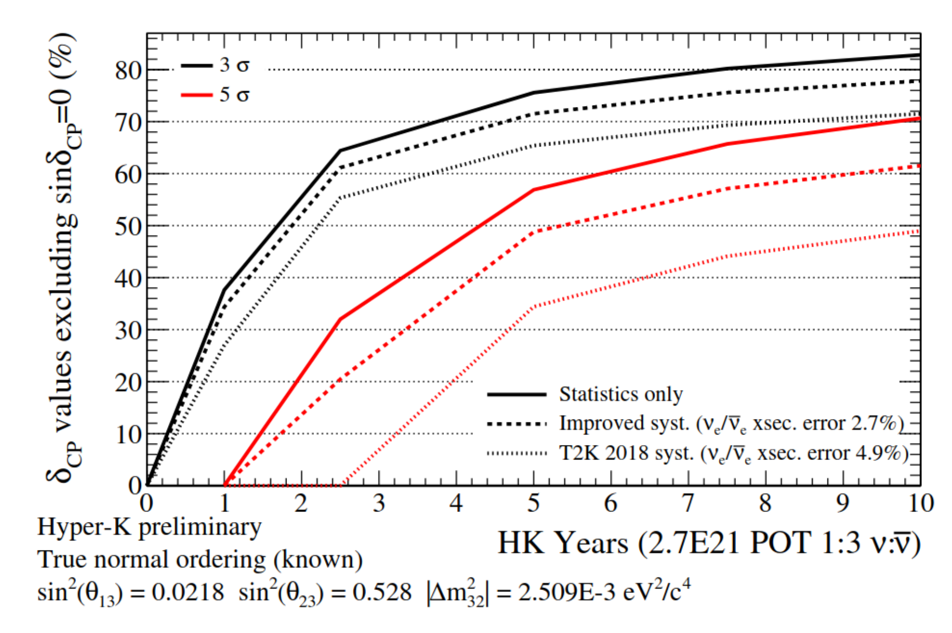
Multi-PMTs: better timing and spatial resolution than 1 large PMT
→ good reconstruction despite small detector

Talk Today
18.30
Deepak Tiwari

Hyper-Kamiokande long-baseline



Sensitivity to exclude $\delta_{CP} = 0$ given different true values of δ_{CP}



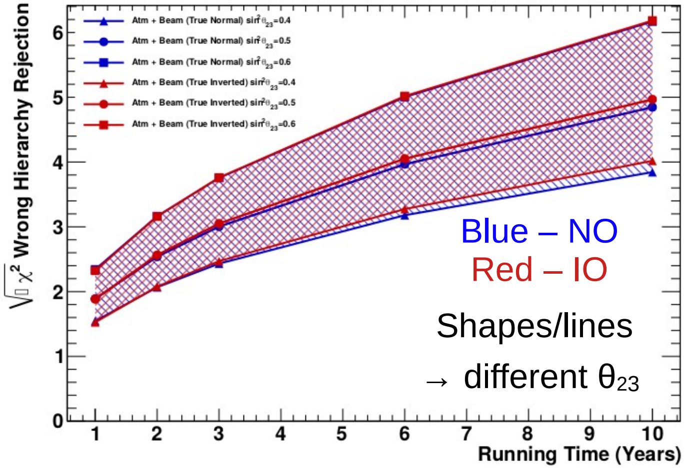
Percentage of true δ_{CP} values for which $\sin(\delta_{CP})=0$ can be excluded, as a function of HK years.

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

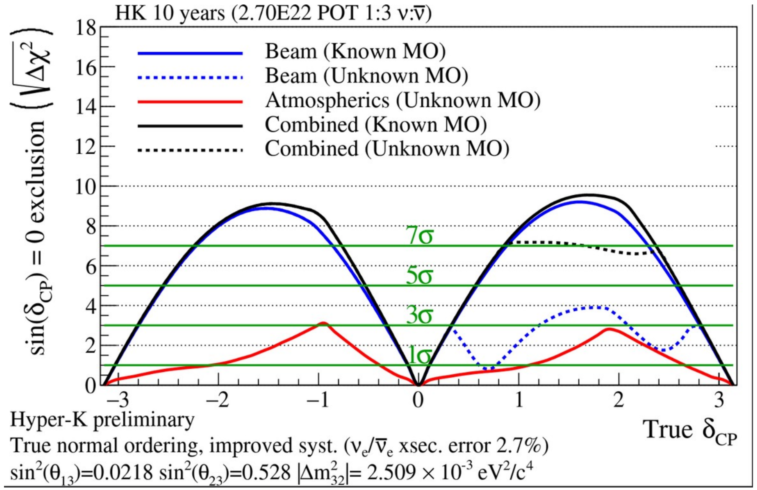
5σ achieved for ~60% fraction of δ_{CP} values with 10years data taking

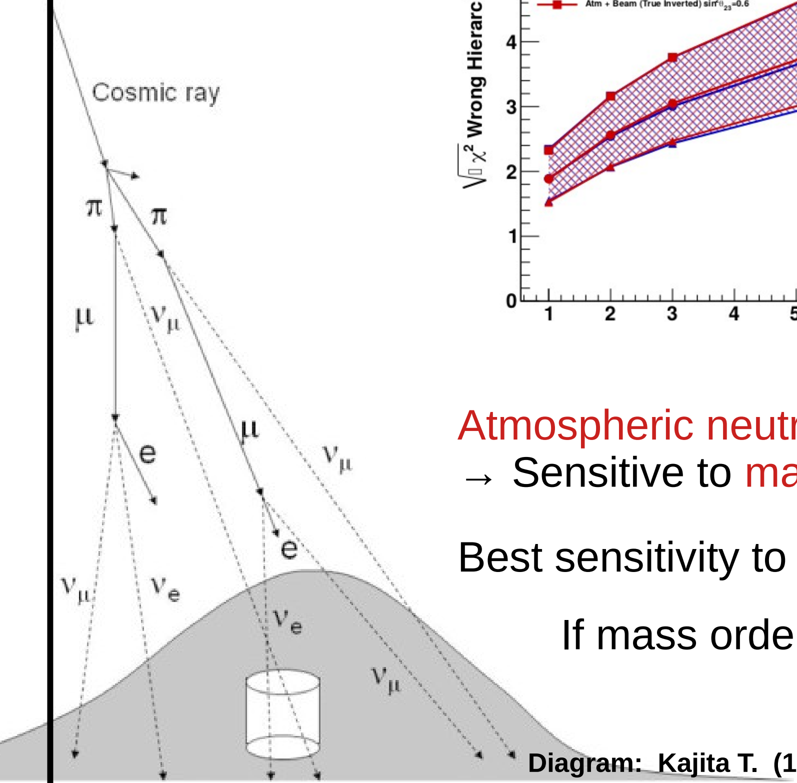
Atmospheric neutrinos + beam

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 θ_{23} octant

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

If mass ordering unknown, atmospheric data improves beam sensitivity to δ_{CP}

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

Construction and Outlook

Construction began in 2021!

Hyper-Kamiokande

UNDER CONSTRUCTION UNDER CONSTRUCTION UNDER CONSTRUCTION

UNDER CONSTRUCTION UNDER CONSTRUCTION UNDER CONSTRUCTION

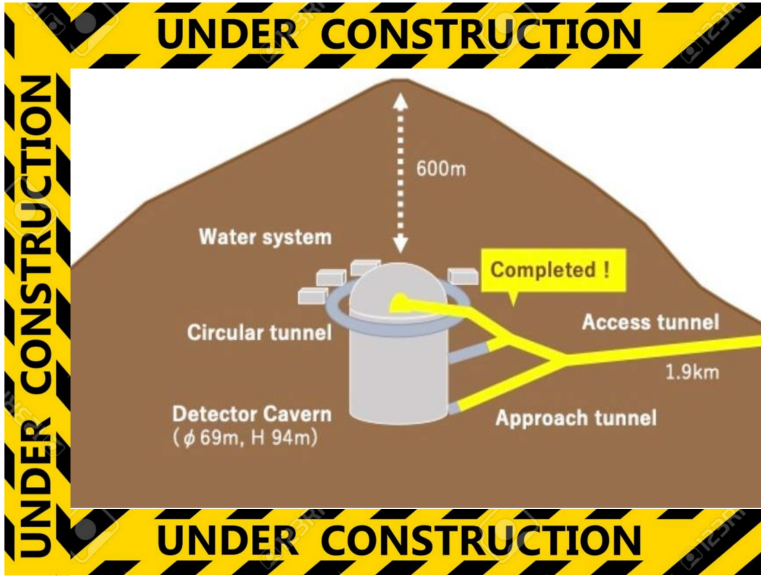
Excavation reached the centre of the cavern dome in June 2022

Hyper-Kamiokande

Summary

The Hyper-Kamiokande is a next-generation neutrino experiment

* Builds on the expertise and knowledge gained from the successful Super-K programme
  - 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!

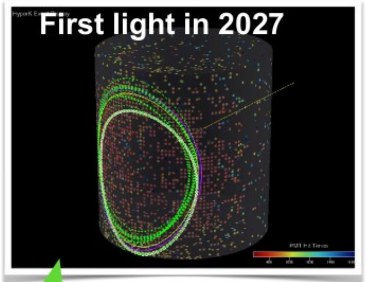
Construction underway

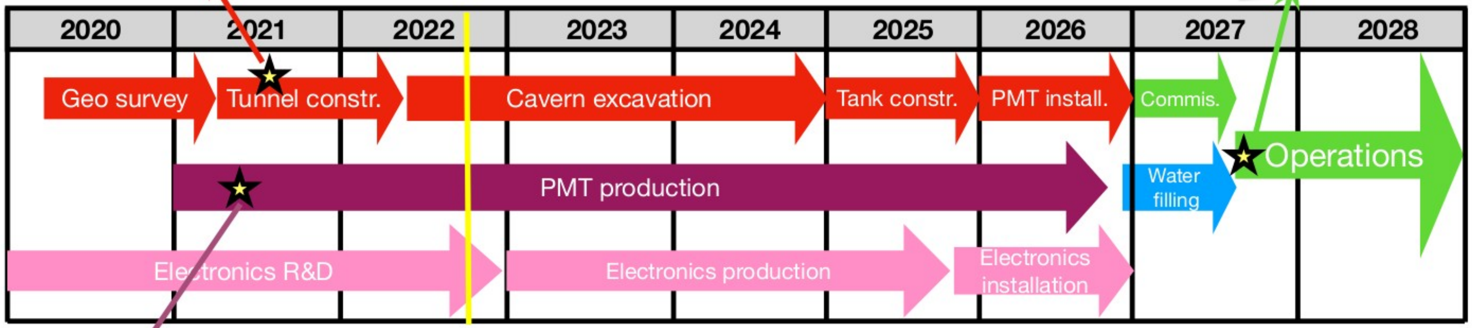
Data taking in 2027

BACKUP

Hyper-Kamiokande

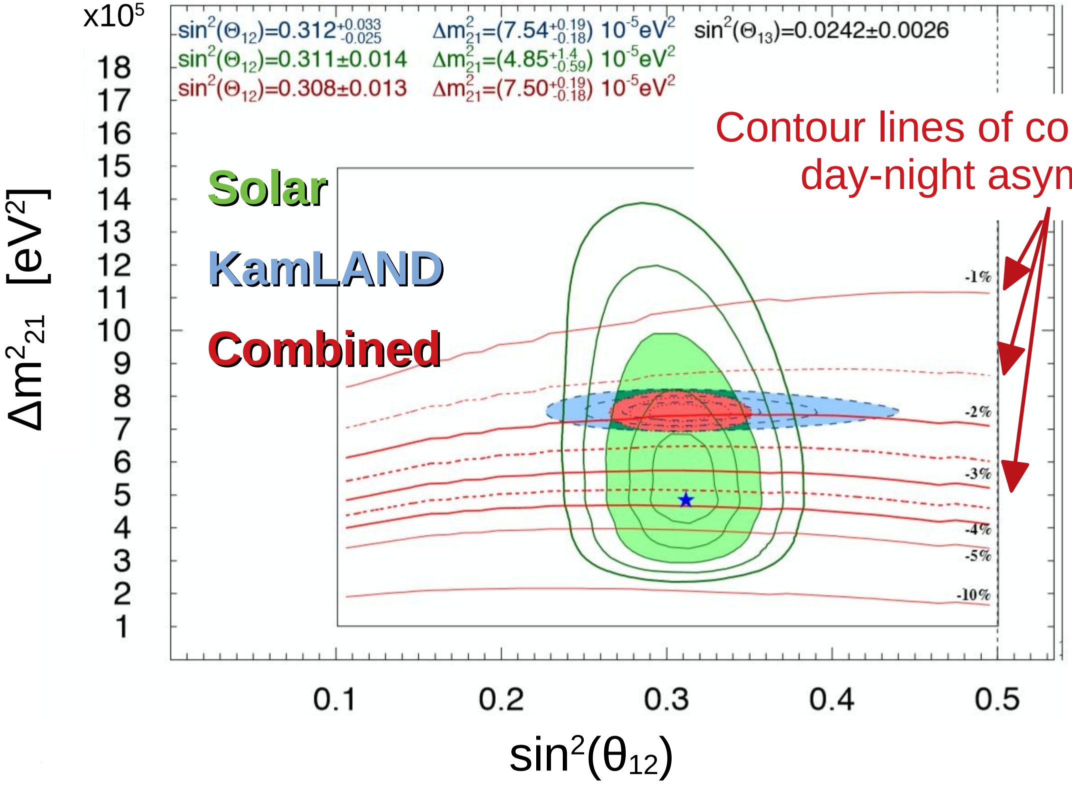
HK schedule



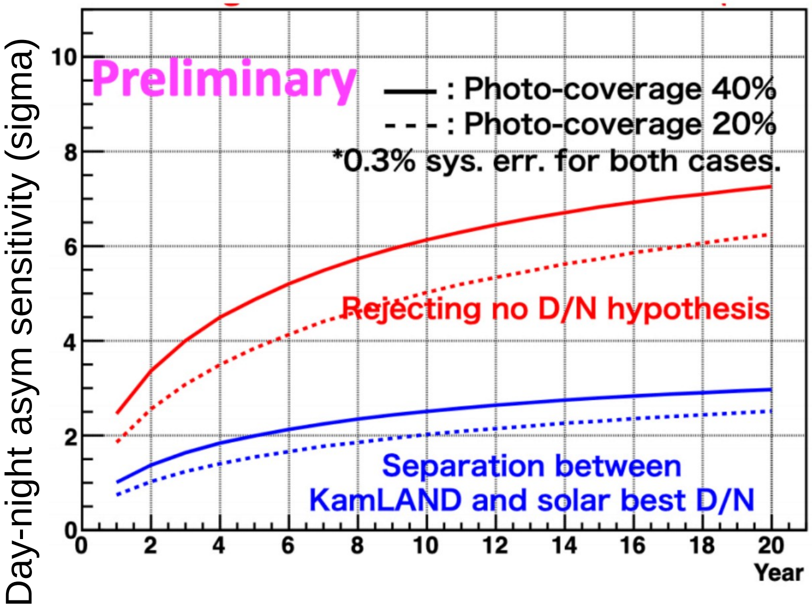


Solar Neutrinos

~ 2σ tension in Δm^2_{21} between solar & kamLAND (reactor)



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

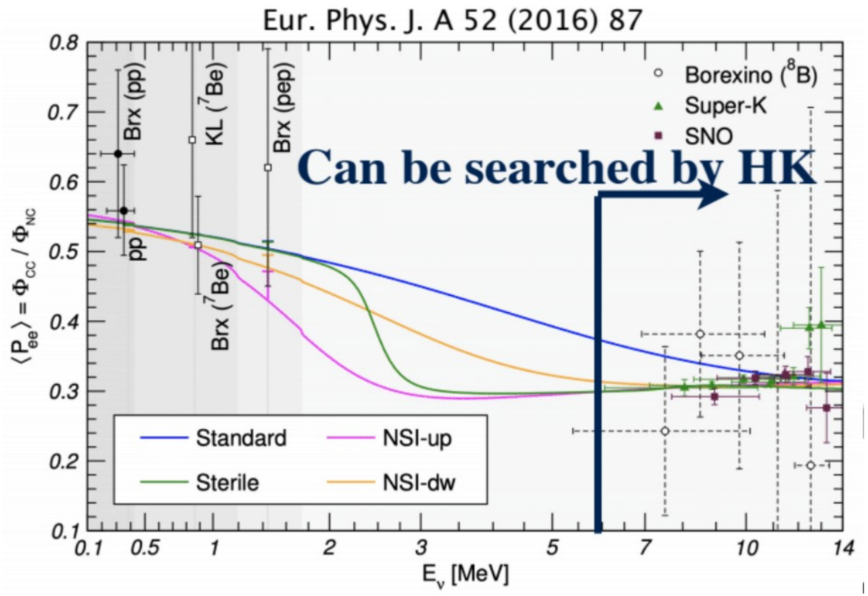


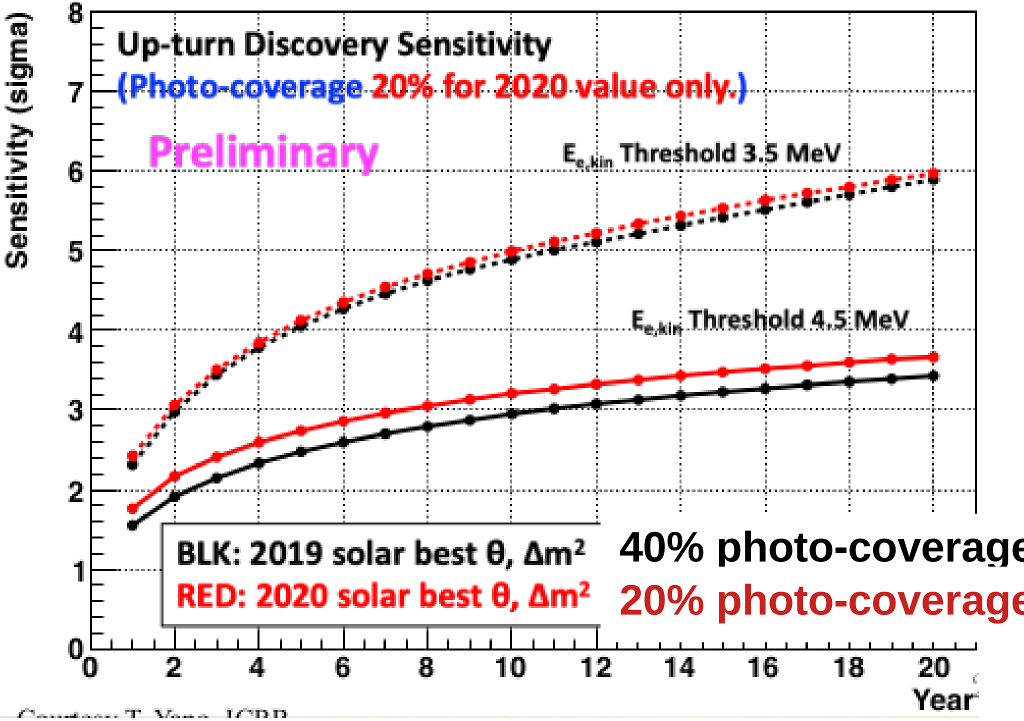
For large D-N asymmetry, expect >5σ confirmation 10 years

Solar Neutrinos

Hyper-K

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

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

Betelgeuse (200pc)
~ 117.5 million – 180 million events

* 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)

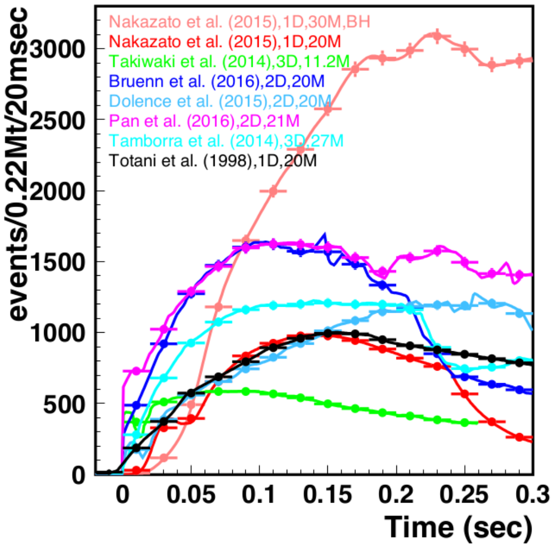
* Supernova flux is sensitive to mass ordering without too much model dependence
→ neutronization burst

Supernova Neutrinos

Inverse beta decay dominates

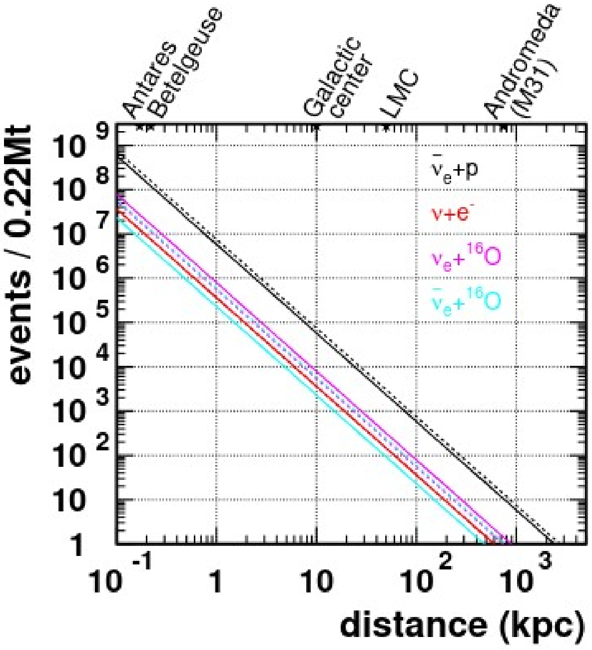
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

* Different models predict different electron antineutrino rates
* Stat error is much smaller than the difference between models



Predicted inverse beta decay rates

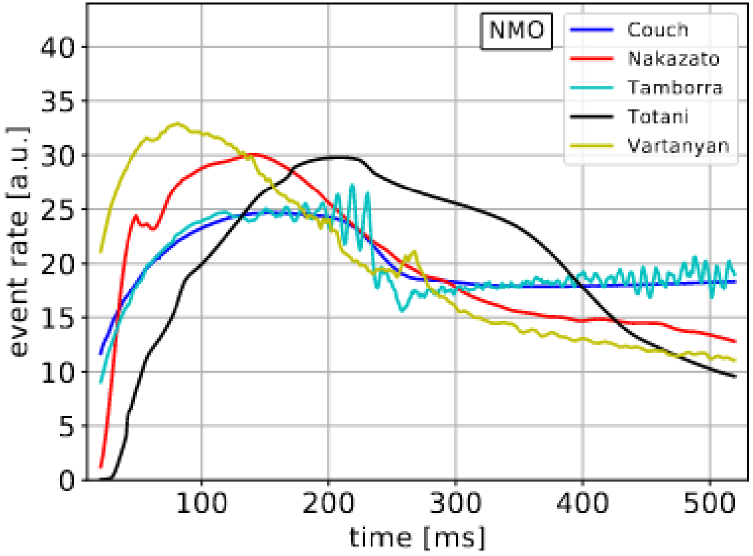
Expected number of events as a function of supernova distance



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

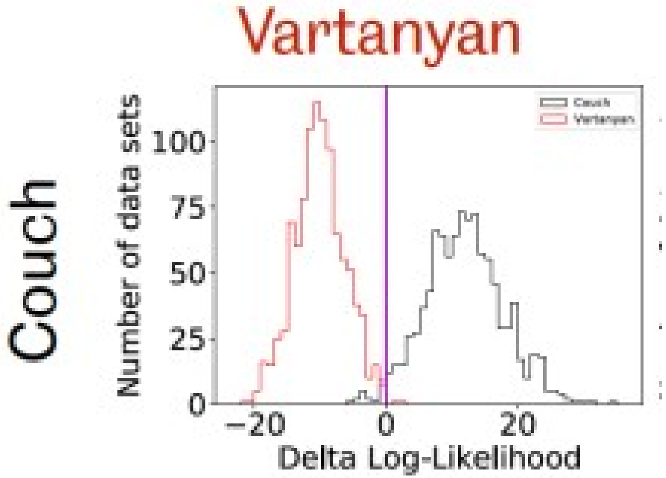
Supernova Neutrinos

Hyper-Kamiokande



The event rate is normalized to produce the same total number of events for each model, reflecting the assumption that the distance of the supernova is unknown.

Model discrimination example

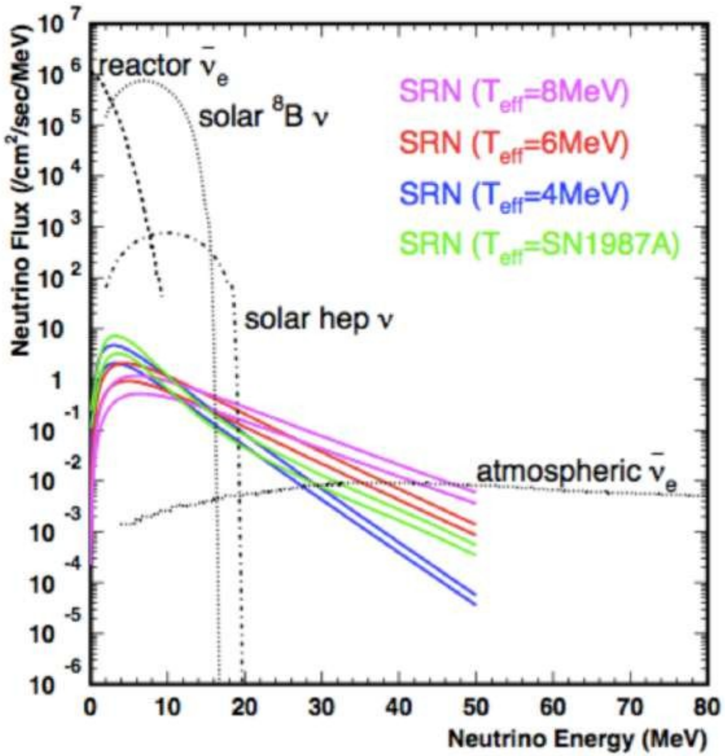


→ **Hyper-K can constrain different models**

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

Supernova Relic Neutrinos

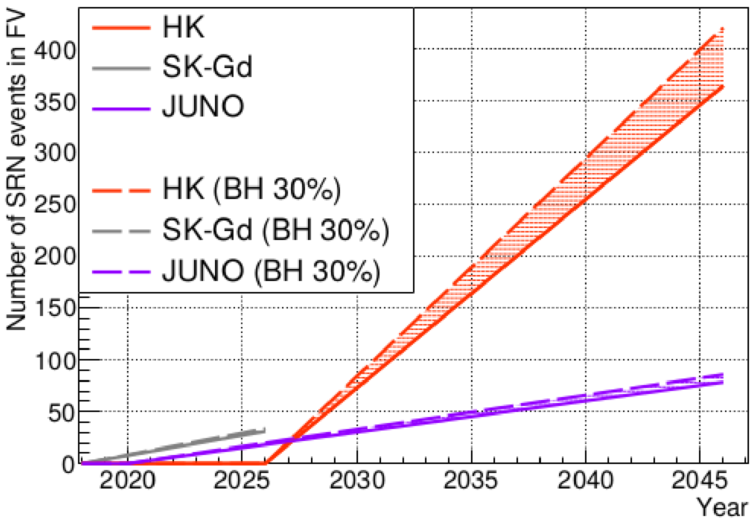
Predicted flux for different models



* Small flux, large backgrounds
→ No evidence of supernova relic neutrinos at SK yet

By HK detector:

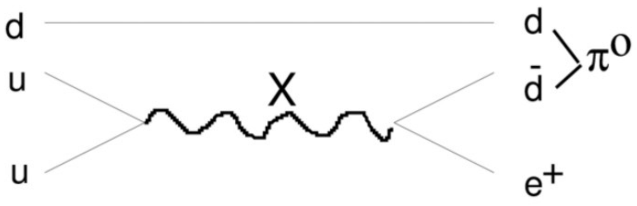
- SRN can be observed in 10y with ~70±17 events and > 4σ non-zero significance (photo-coverage 40%).
- ~40±13 events and 3σ with a 20% photo-coverage



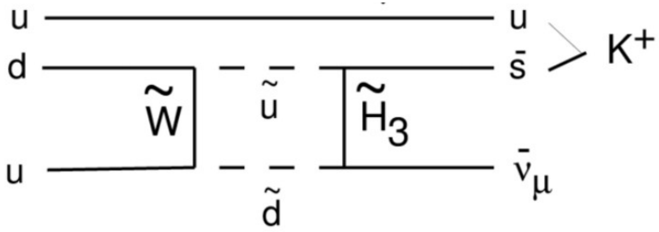
Dashed line for case where 30% form black hole and emit higher energy neutrinos

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

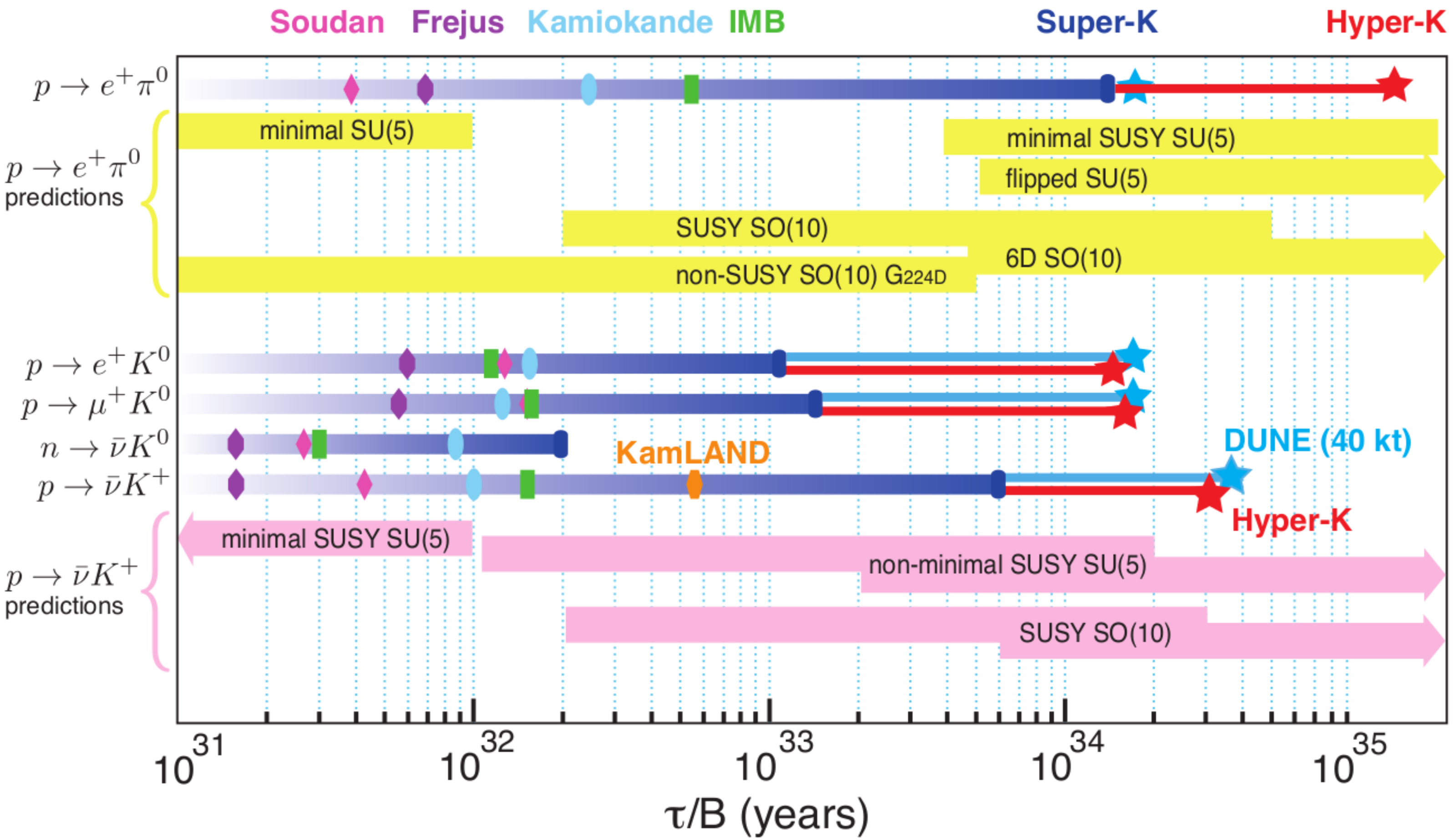
  → solar neutrinos

  → atmospheric neutrinos

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

Proton decay

Hyper-Kamiokande



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

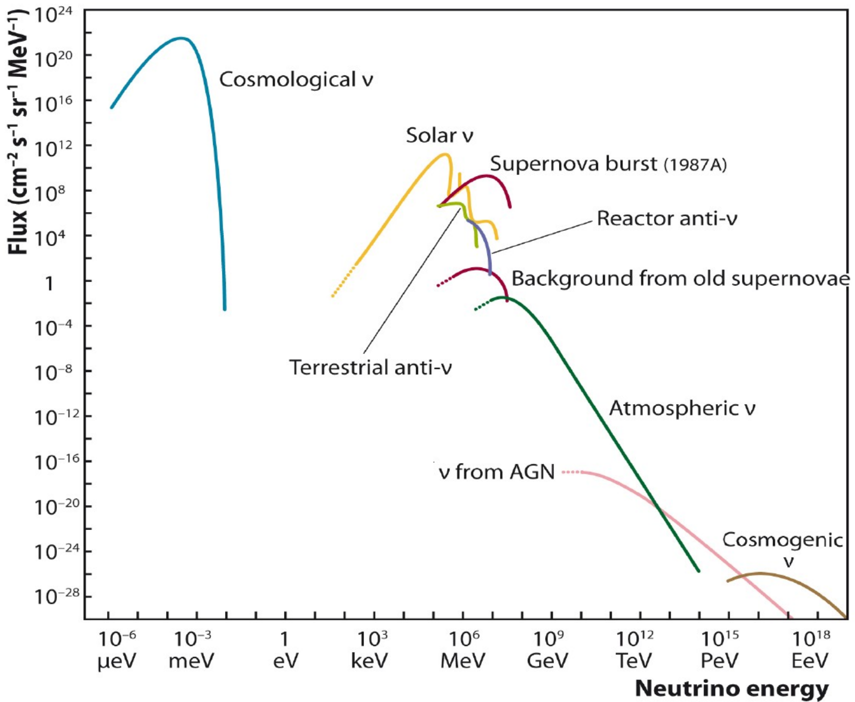
Kamiokande

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

The Kamiokande Series

Hyper-Kamiokande

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



PMTs

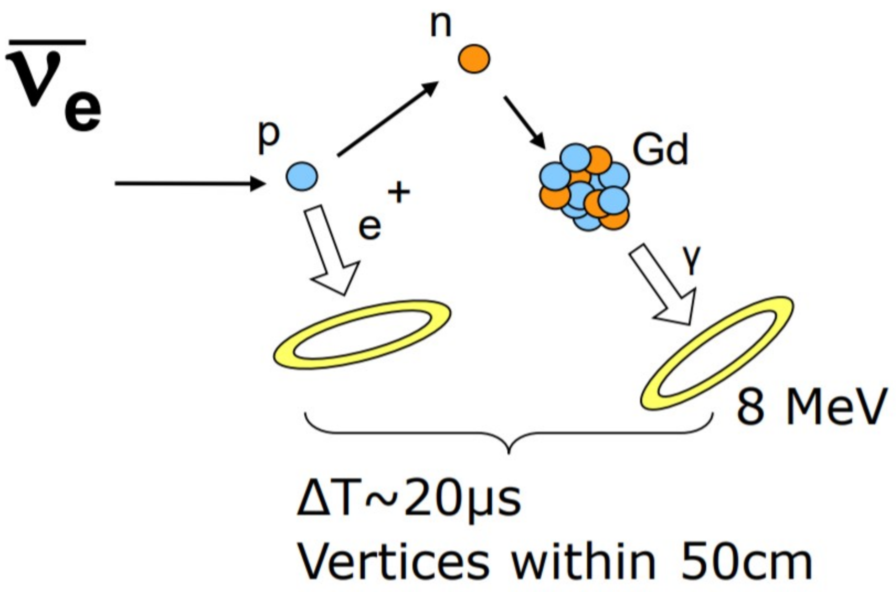
	Super-K	Hyper-K
	11,129 20” PMTs	20,000 20” PMTs (JPN) (+addition PDs) (Overseas))
photo-coverage	40%	20%
single photon efficiency/PMT	~12%	~24%
dark noise	~5kHz (typical)	4kHz (average)
time resolution (one p.e)	~3ns	~1.5ns

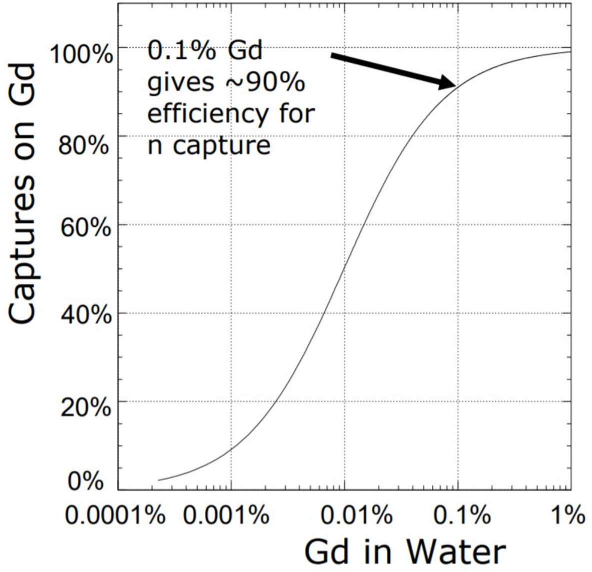
	mPMT: 19 x 3” PMTs	20” ‘B&L’ PMT
photo-cathode area	870 cm^2	2000 cm^2
effective light yield	~ 1 hit/MeV/5,000 mPMTs	~6 hits/MeV/20,000 PMTs
dark noise	19 x 200-300 Hz	~4kHz (typical)
transit time spread	1.3ns	2.7ns
comments	• granularity • directionality • better time resolution	• performance confirmed • high photon detection efficiency

Adding Gadolinium to IWCD

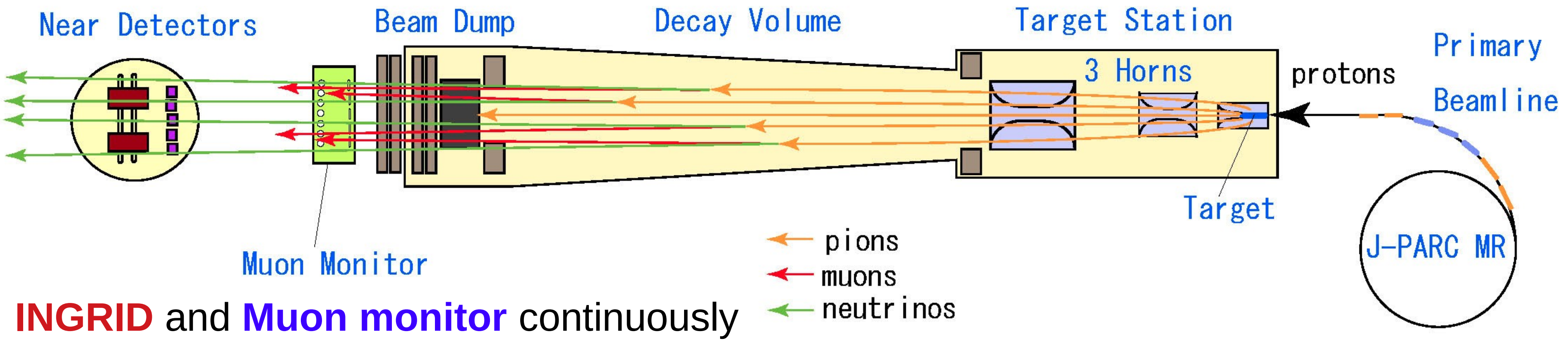
Adding Gadolinium to the water allows for neutron capture
→ **Better ν / $\bar{\nu}$ separation**

Potential to load IWCD with Gadolinium: 0.1% Gd
→ Neutron tagging





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 ν or $\bar{\nu}$** (depending on charge of hadron)

Dominant systematic error due to hadron interaction modelling

→ Constrained using NA61/SHINE replica target measurements

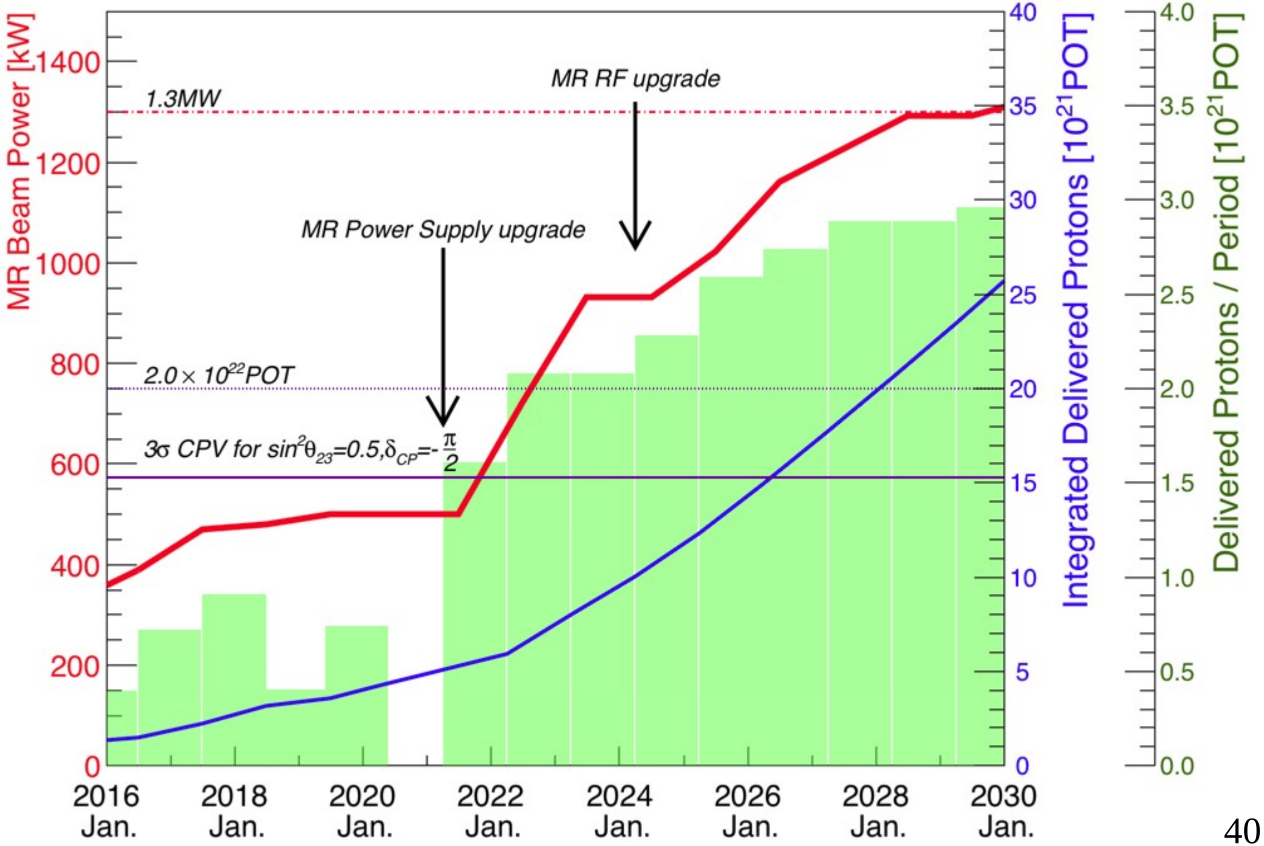
→ In future flux uncertainty will be reduced by the EMPHATIC experiment

T2K/HK Beam upgrade

* Beam currently capable of 450-500kW stable running

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

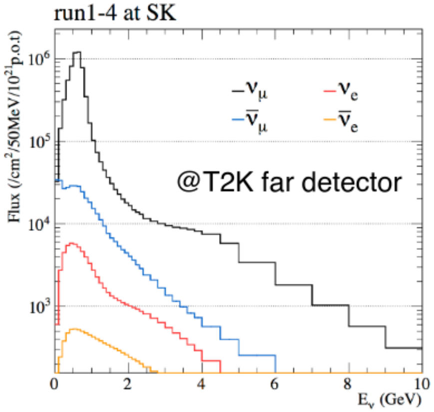
* target power: 1.3MW



J-PARC neutrino beam flux and its error

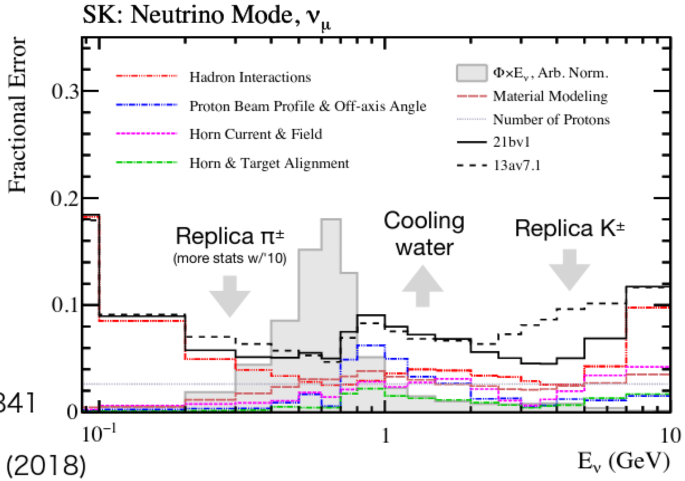
ν flux is predicted based on hadron production and in-situ proton beam measurements

- 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

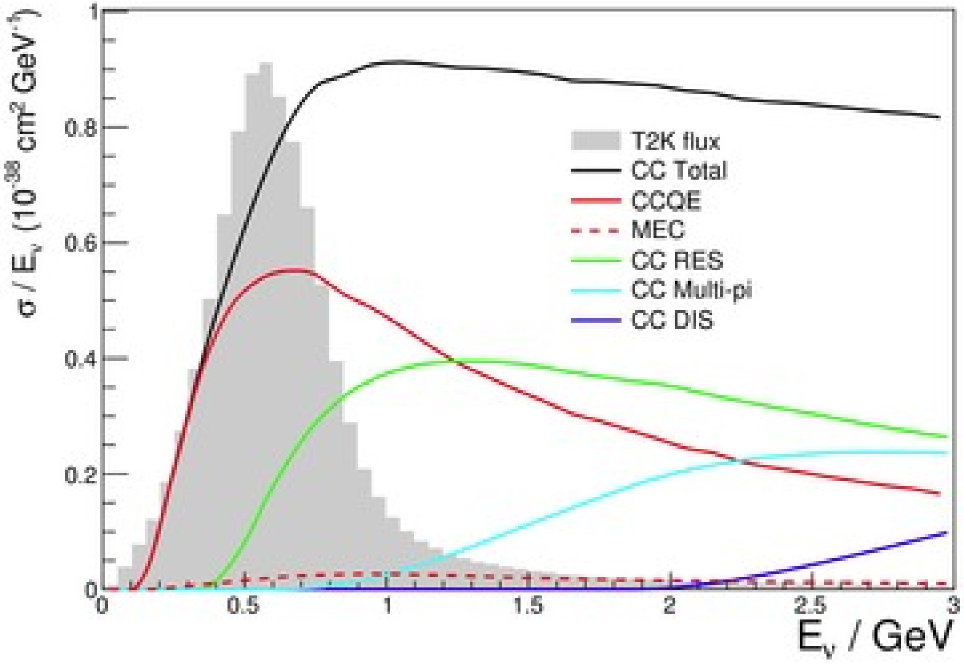


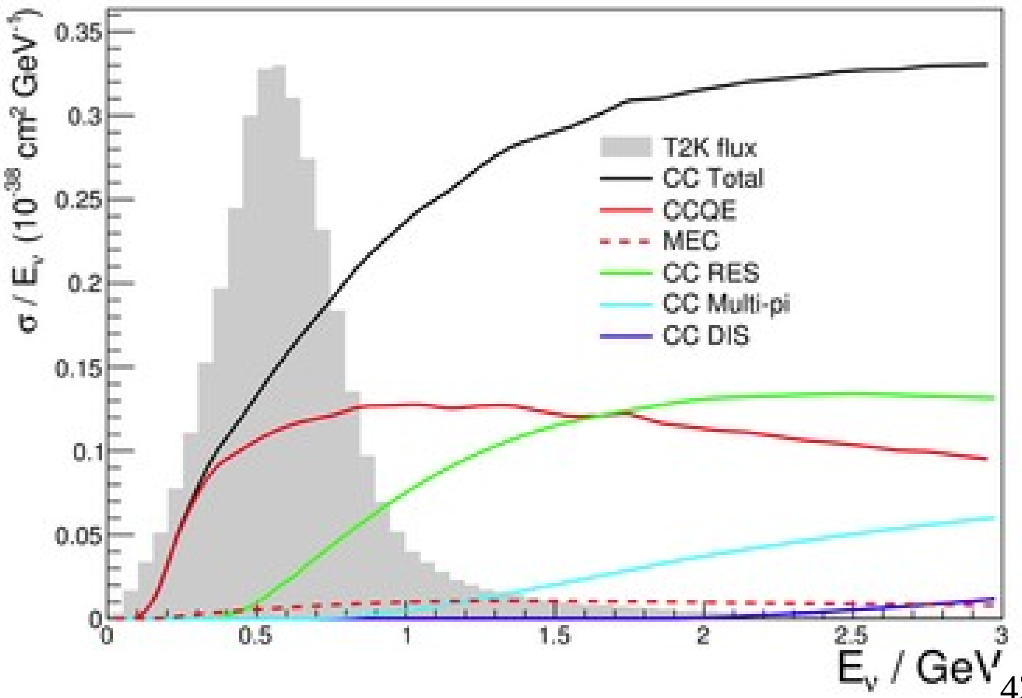
arXiv:1912.08841

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

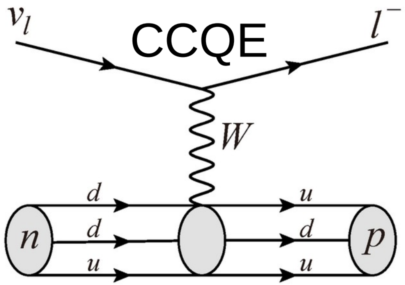
Neutrino interaction cross sections and T2K/HK flux

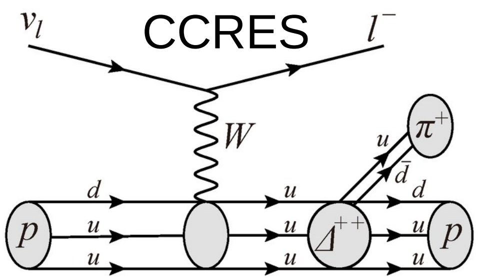
ν $\bar{\nu}$

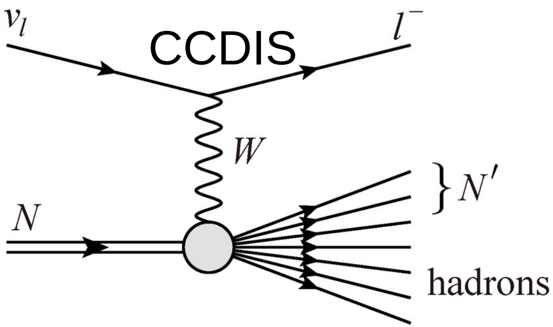




Neutrino interactions



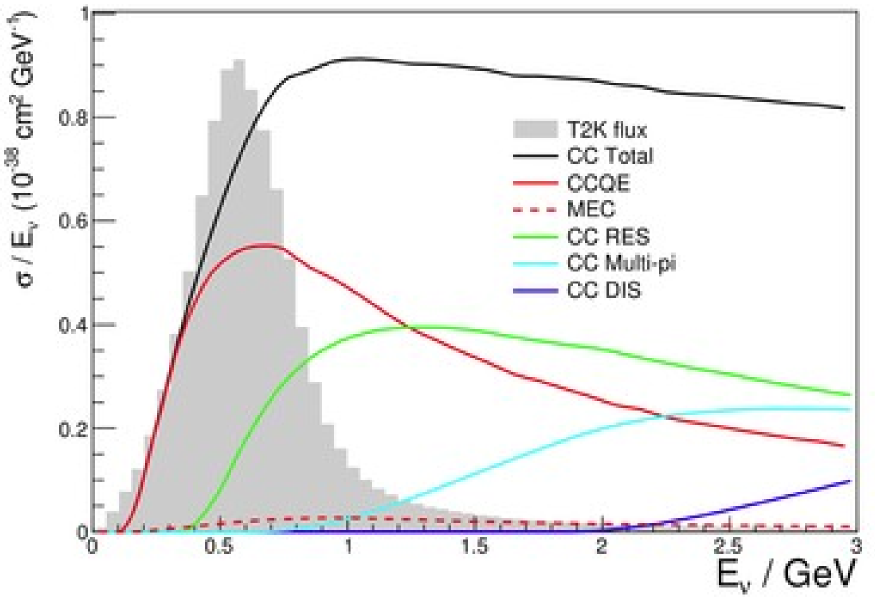




NC interactions also important

e.g. NCπ^0, NC1γ

→ background



Interactions occur with nucleons bound inside a nucleus

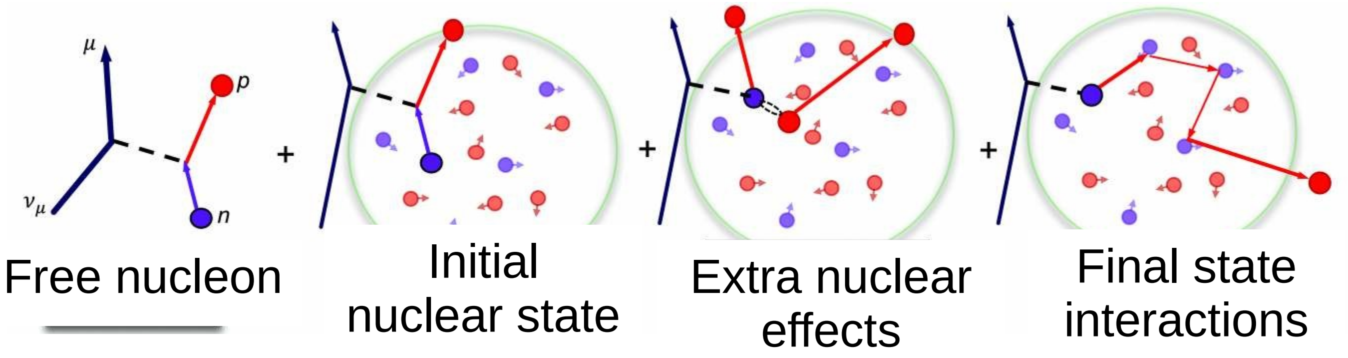
→ **Nuclear effects!!**

We only measure particles that exit the nucleus

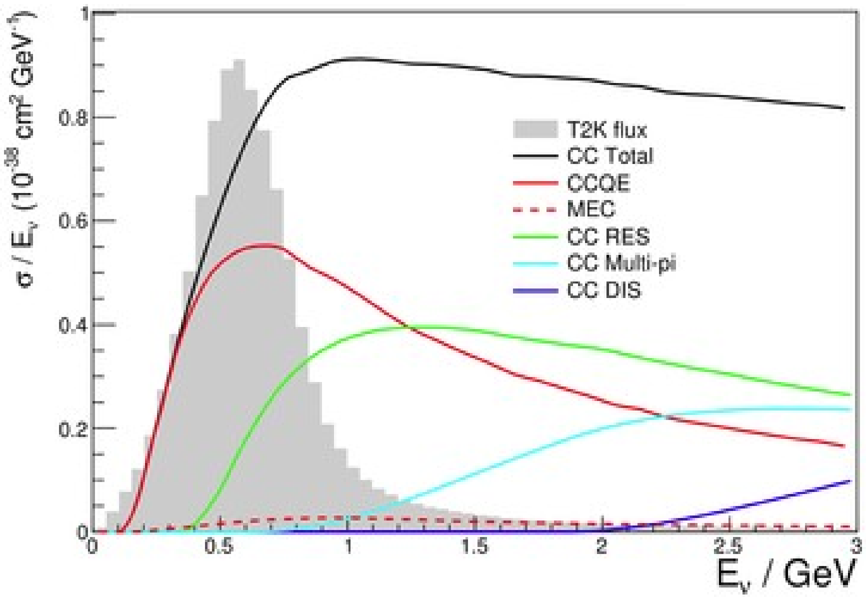
→ lose information about the initial interaction

→ can create a bias in energy reconstruction

Neutrino interactions



Interaction modes and Nuclear models tuned to external data



Interactions occur with nucleons bound inside a nucleus

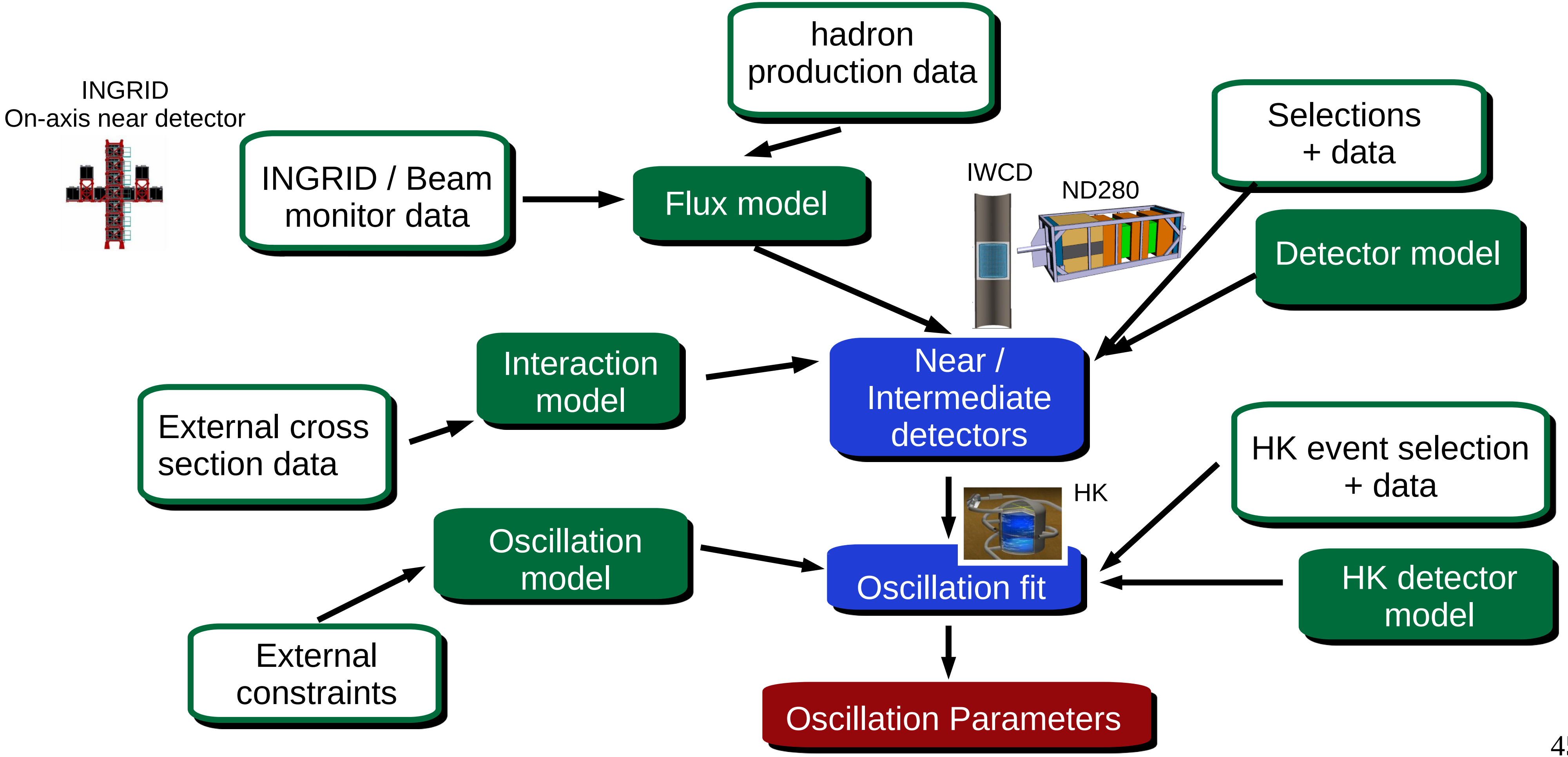
→ **Nuclear effects!!**

We only measure particles that exit the nucleus

→ lose information about the initial interaction

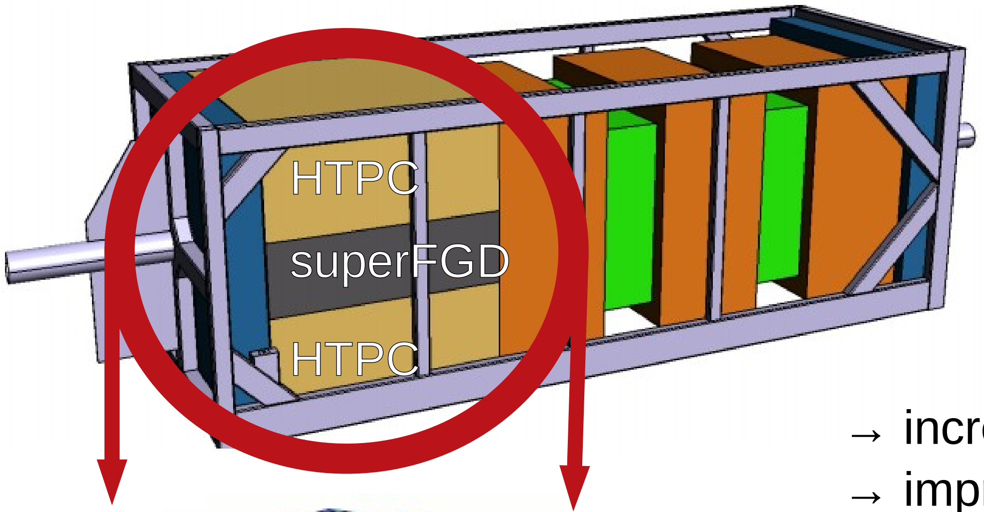
→ can create a bias in energy reconstruction

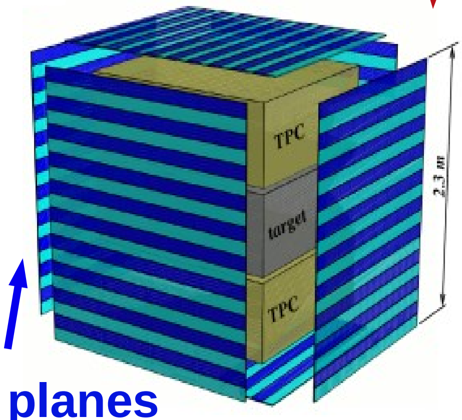
Hyper-Kamiokande long-baseline



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

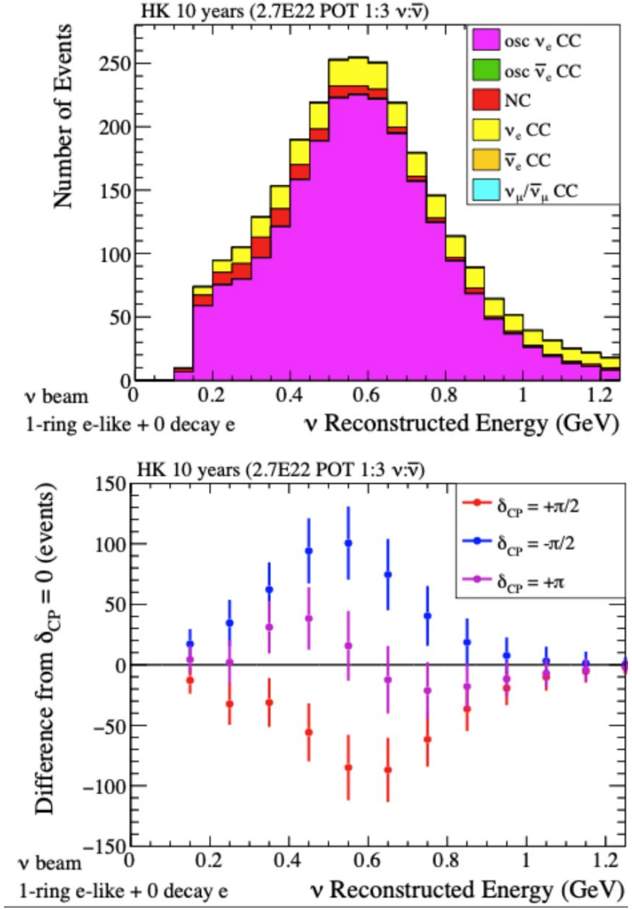
Reduce systematic uncertainty to 4%

→ 3σ exclusion of CP conservation for 36% of the δ_{cp} phase space (if mass hierarchy is known)

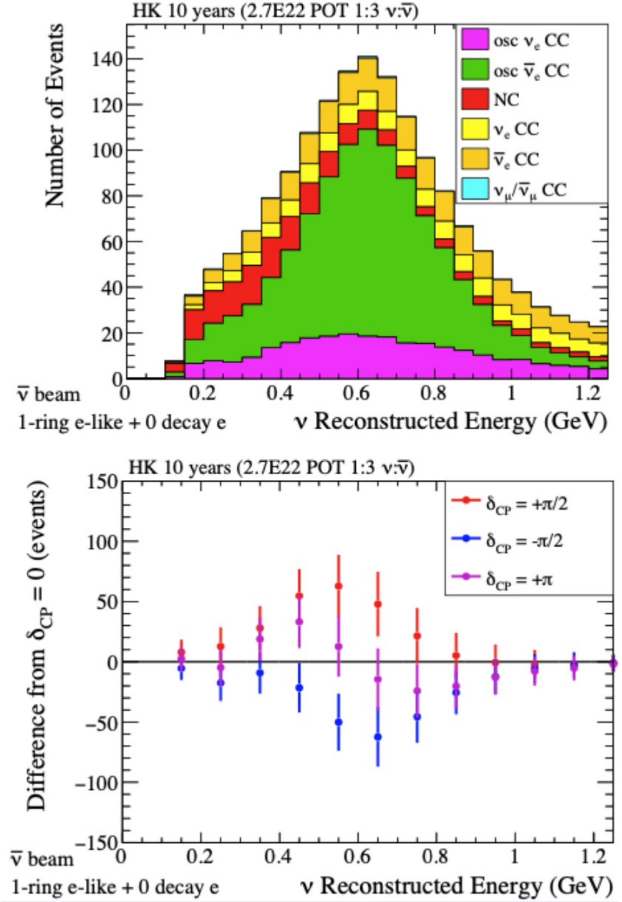
Hyper-Kamiokande long-baseline

Hyper-Kamiokande

ν-mode beam



$\bar{\nu}$-mode beam



Predicted HK far detector event yields for 10 years of operation

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