# Neutrino Oscillation study with Hyper-Kamioande

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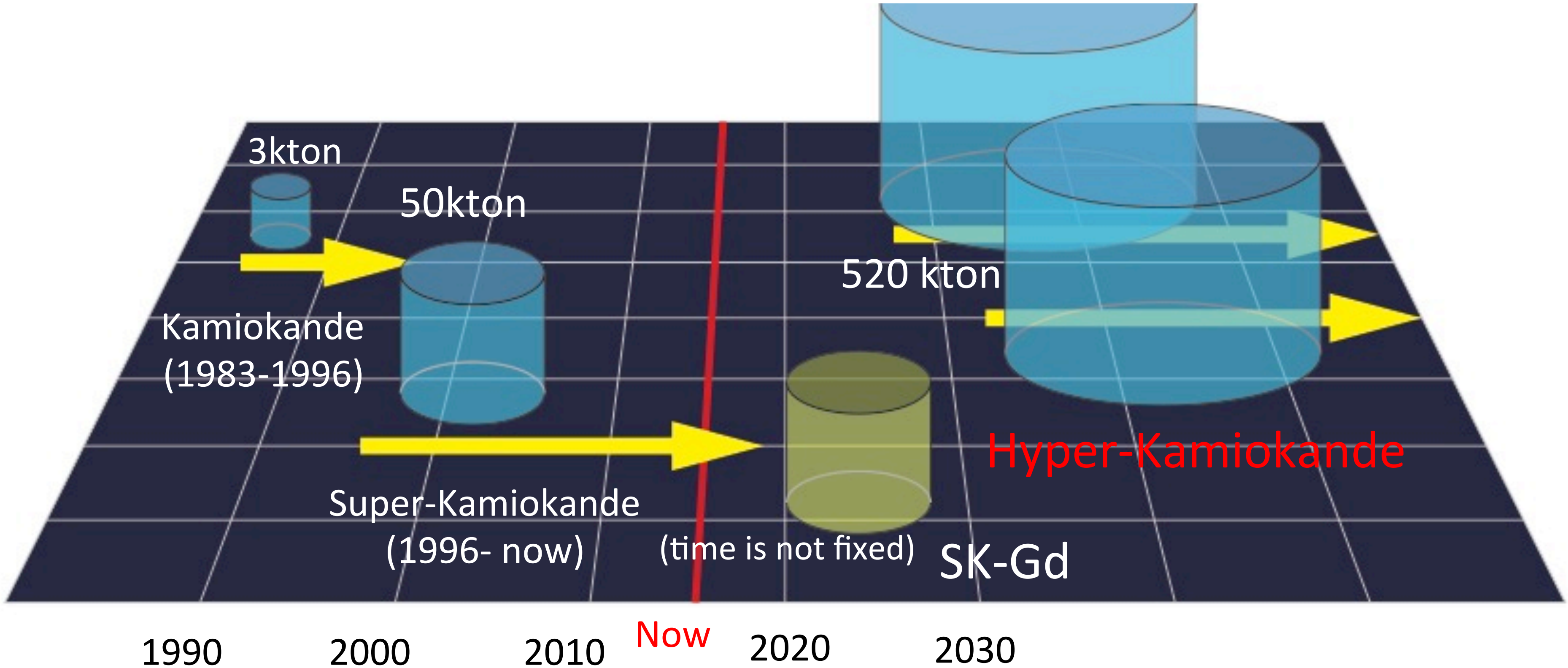
**for Hyper-Kamiokande proto-collaboration**

**Nov.10th, 2016**

# Outline

- Introduction of Next Generation Project: Hyper-Kamiokande
- Physics potentials (limited topics)
  - Neutrino oscillation with atmospheric neutrinos
  - Long-baseline experiment with $\nu$ beam
  - Nucleon decay (not neutrino oscillation)
- Summary

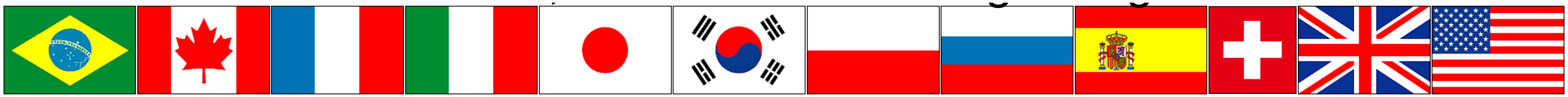
# Evolution of Water Cherenkov Detectors in Kamioka



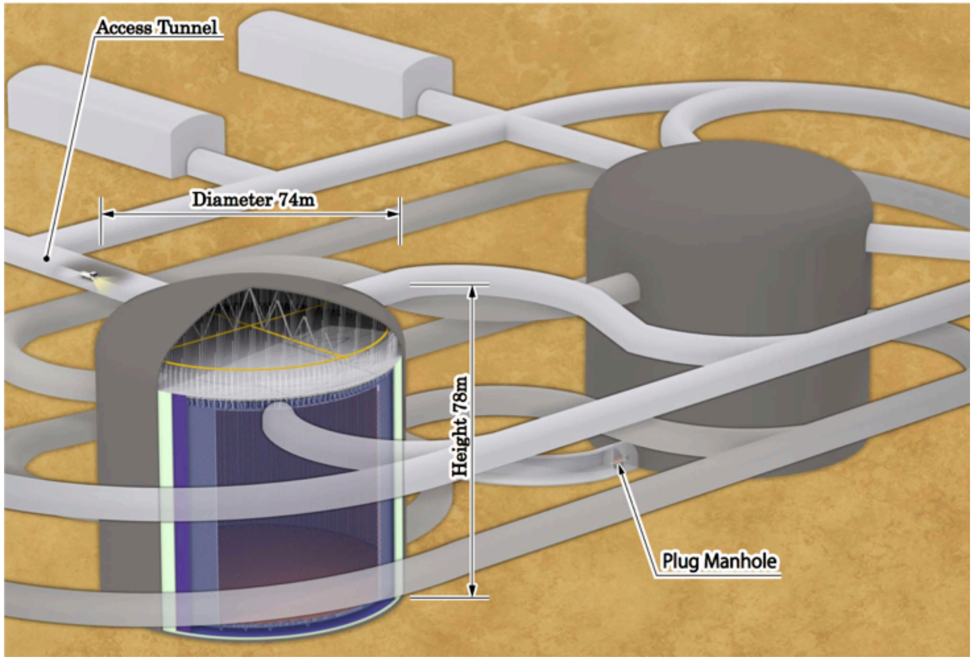

- Above 30 years continuous experiments with Water Cherenkov detectors in Kamioka. Many experiences, established method.
- New steps from Super-Kamokande
  - Bigger (with improvement) → Hyper-Kamkokande
  - Gadlinimum in water → SK-Gd project

# Hyper-Kamiokande proto-collaboration

- Proto-collaboration was formed January 2015
- 12 countries, ~300 members



# Hyper-Kamiokande

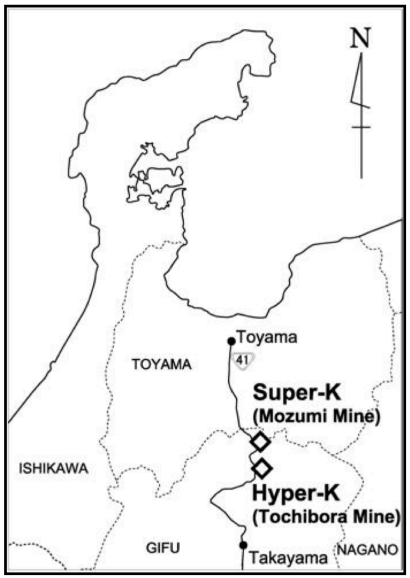



- Huge water C detectors (H60m×ϕ74mx2 water vol., 0.38Mton fid.vol.)
- Two tanks in staging approach:
  - Second will be on stages from six year after first one.
- 40% Photo-coverage with newly developed High QE PMTs.

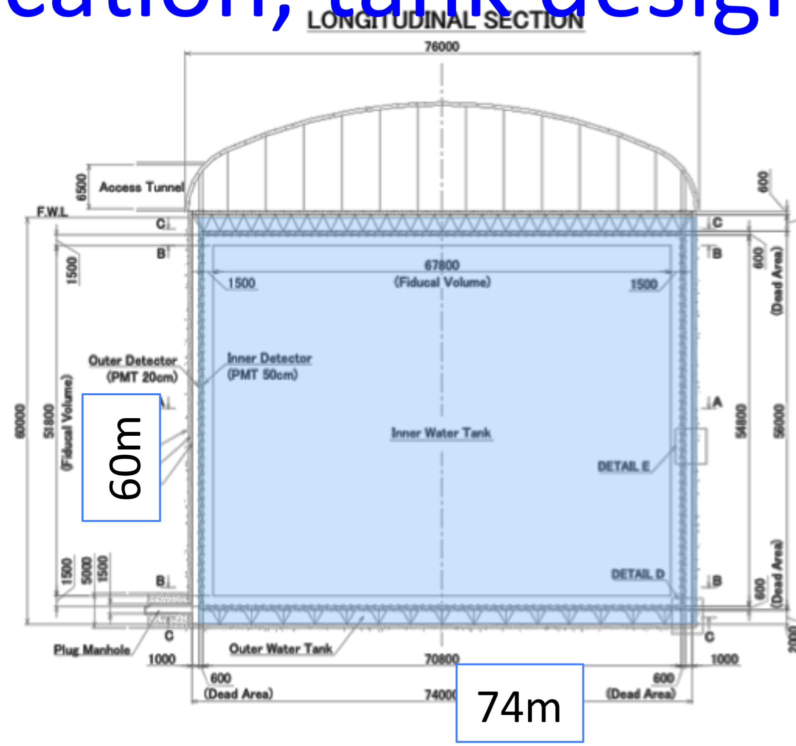
Broad Scientific targets:

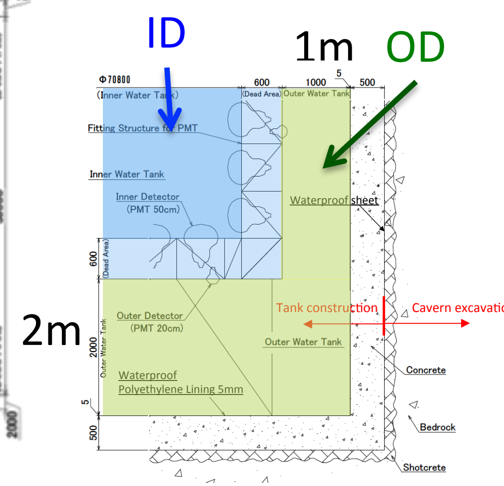
- Comprehensive study of neutrino oscillation
  - CP violation
  - Mass hierarchy
  - Precise measurement of parameters ($\theta_{23}$, $\Delta m^2_{32}$,..)
  - Non-standard $\nu$ oscillation.
- Astrophysics (Supernova, solar)
- Study Grand Unified Theories (nucleon decays)
- Geophysics (Neutrino Tomography)

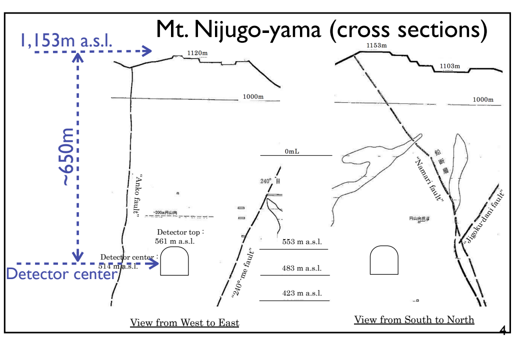
# Location, tank design




~8km from SK site



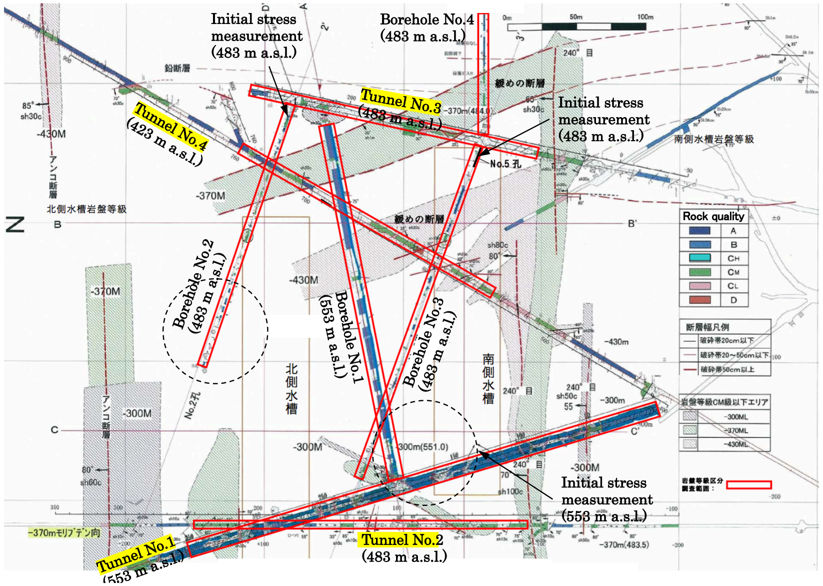



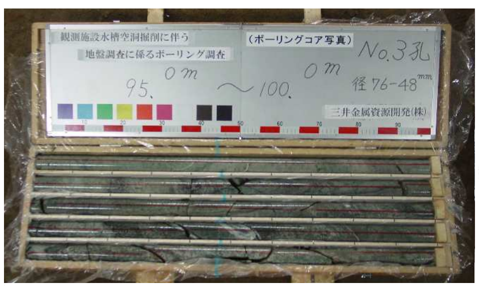

- 60m×70m cylindrical shape water tanks.
- Concentric cylinders
  - Inner Detector (ID) : ~40,000 50cm PMTs /Tank
  - Outer detector(OD): ~6,700 20cm PMTs /Tank
- The candidate site is Location survey is on-going, a candidate is Mt. ‘Niju-Go Yama’, ~8km south from Super-K. ~650m overburden.

Conceptual Design report submitted to KEK Preprint2016-21, ICRR-Report-701-2016-1

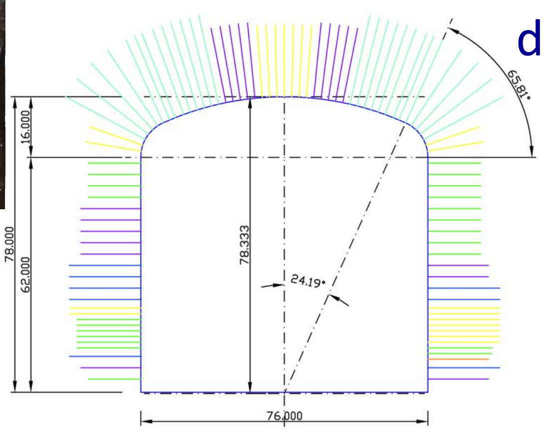
# Cavern excavation




- Detailed geophysical survey at the site candidate is done.
- Confirmed bedrock condition is suitable for a large cavern construction.
- Cavern stability analysis with simulation is carried out with the survey information.
- Hyper-K cavern can be constructed with existing technology.
- Other items are also investigated & discussed.
  - Access tunnel, excavation strategy, ..



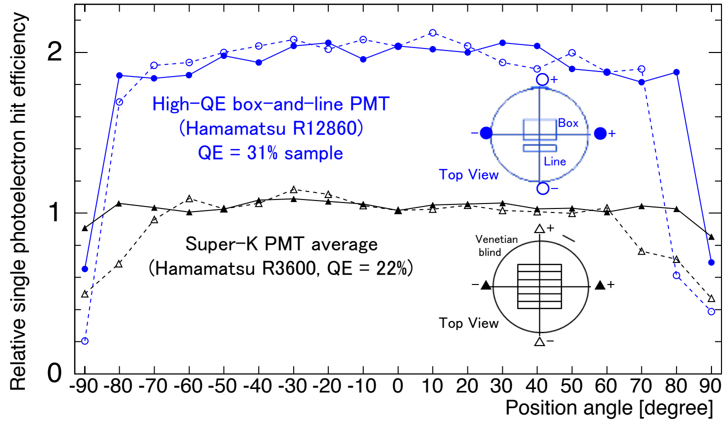

Rock samples



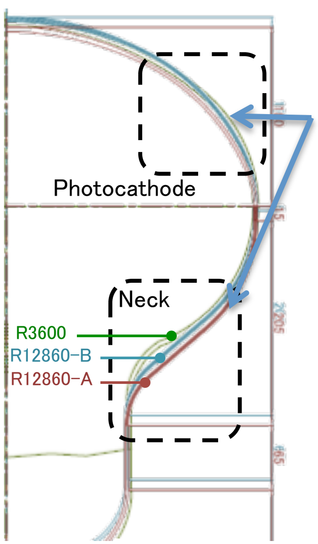
# Photo Sensor R&D

**Super-K** PMT

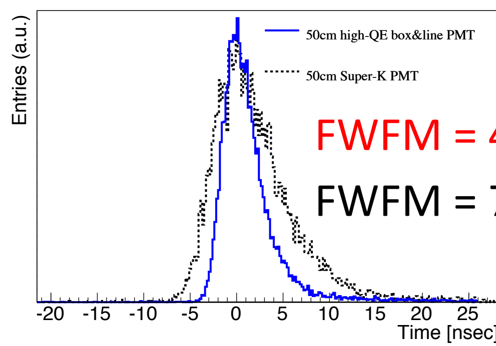
50 cm HQE Box&Line PMT

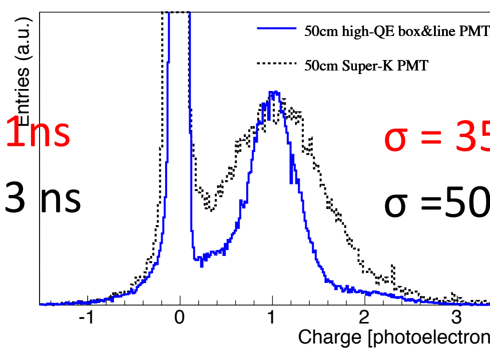



x2 Detection Efficiency



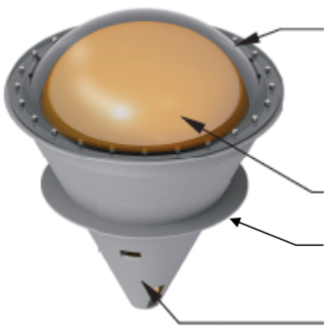

Improved Bulb for higher pressure

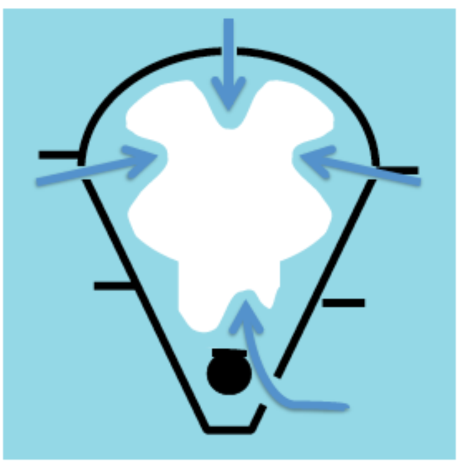



- A 50cm PMT with improved photo-cathode & dynode is developed with HAMAMATSUPhotonics K.K.
  → Better timing resolution , photoelectron resolution, high QE.
- Improved design for higher pressure, and tested by hydrostatic pressure test.
- Other international activities: mPMT, OD, ..

# Anti chain-implosion of PMTs



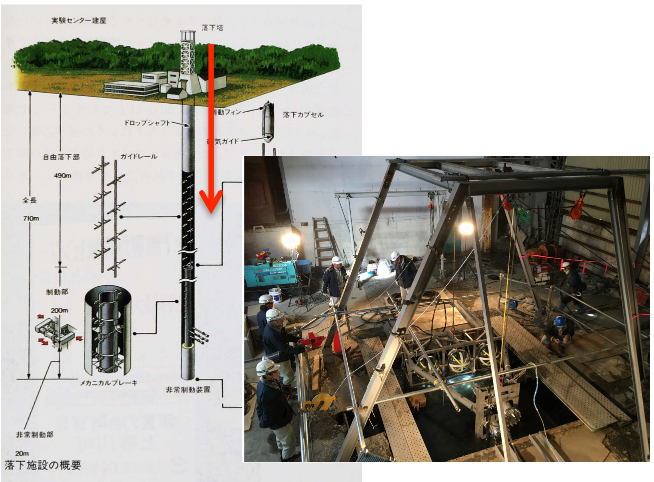
Milder water flow into cover to prevent shockwave

- PMT implosion in deep water generates shockwave by the rush of the water to the space.
  → Chain implosion of PMTs
- It is one of a key issue of big water (liquid) Cherenkov detector.
- Super-K employs a cover:
  - Milder water flow & prevent shockwave generation
- Hyper-K needs such system for deeper water.

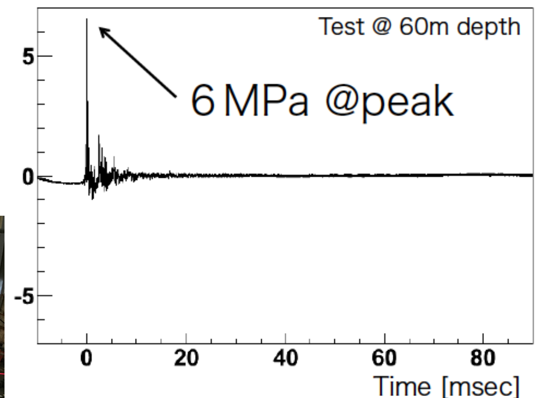
- Prototype is designed and tested:
  - Hydrostatic test
  →1.1MPa (100m depth equiv.)
  - Prevent of chain reaction.
  →OK at 80m (next page)

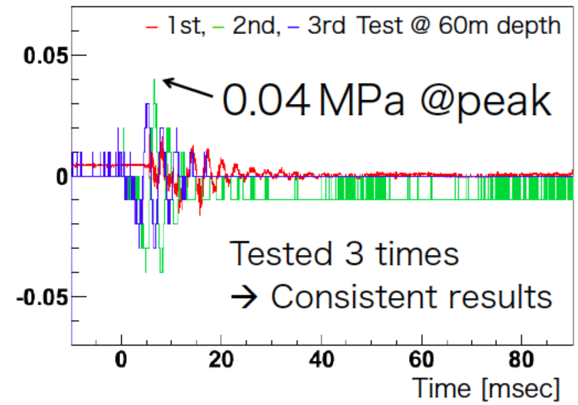
# Proof test of the cover

Put 3x3 Array of PMTs
in 60m/80m depth.



Pressure @70cm ahead [Mpa]

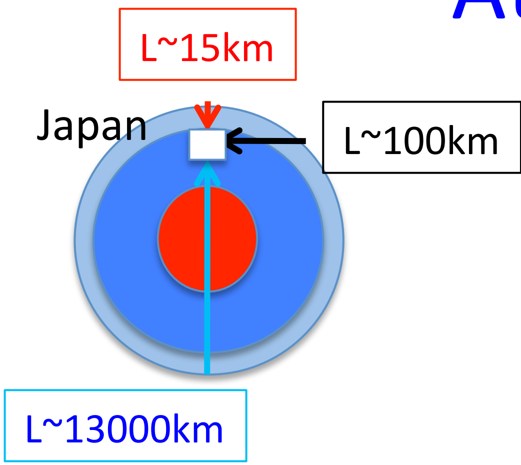



- March 2016, we did chain reaction test in deep water at Hokkaido, JPN.
- We proved proto-type.
  - No damage of PMT cover.
  - No damage of neighboring PMTs.
- Shockwave is very weak.
- Several types are under R&D.

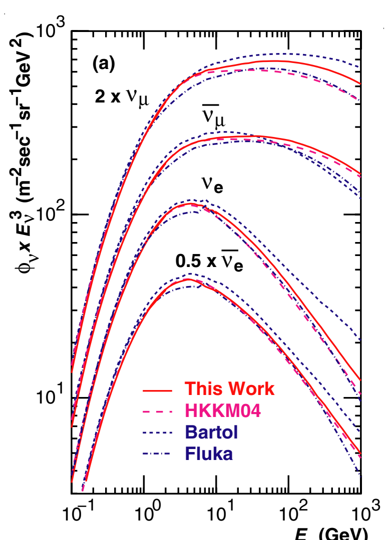
# Physics potential
# (limited topics)

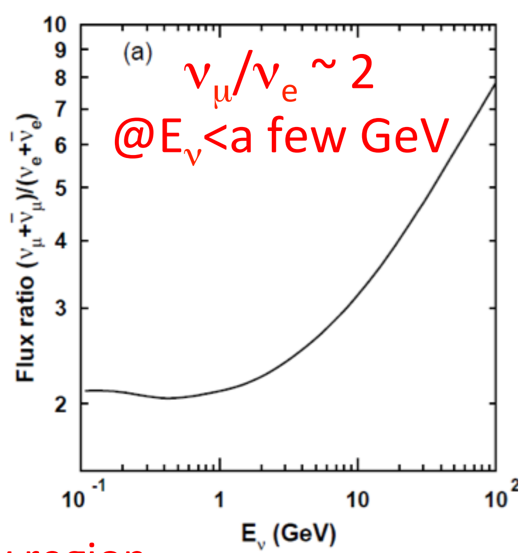
# Atmospheric neutrinos

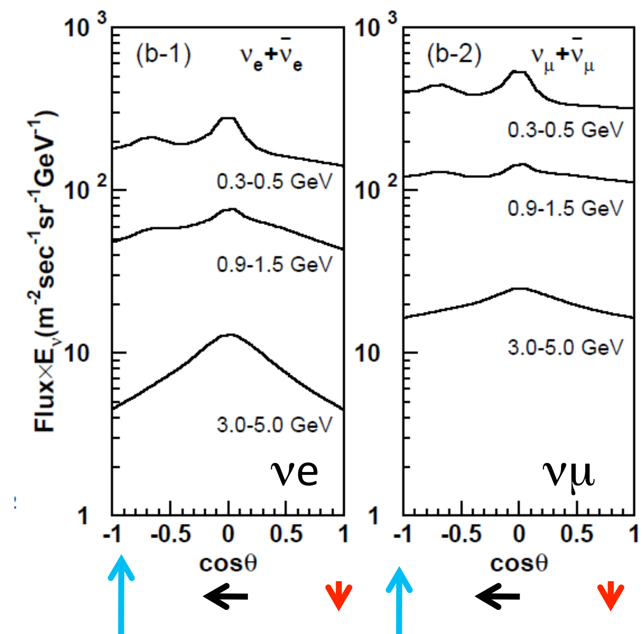



- Wide energy range, wide range of flight length.
- Passing through dense matter inside the Earth.
- Mixture of $\nu_\mu$, $\nu_e$, and their anti-neutrinos.
- Up/Down symmetric (> a few GeV)
- DC-like continuous beam, FREE!

→ Good opportunity to test $\nu$ oscillation physics.



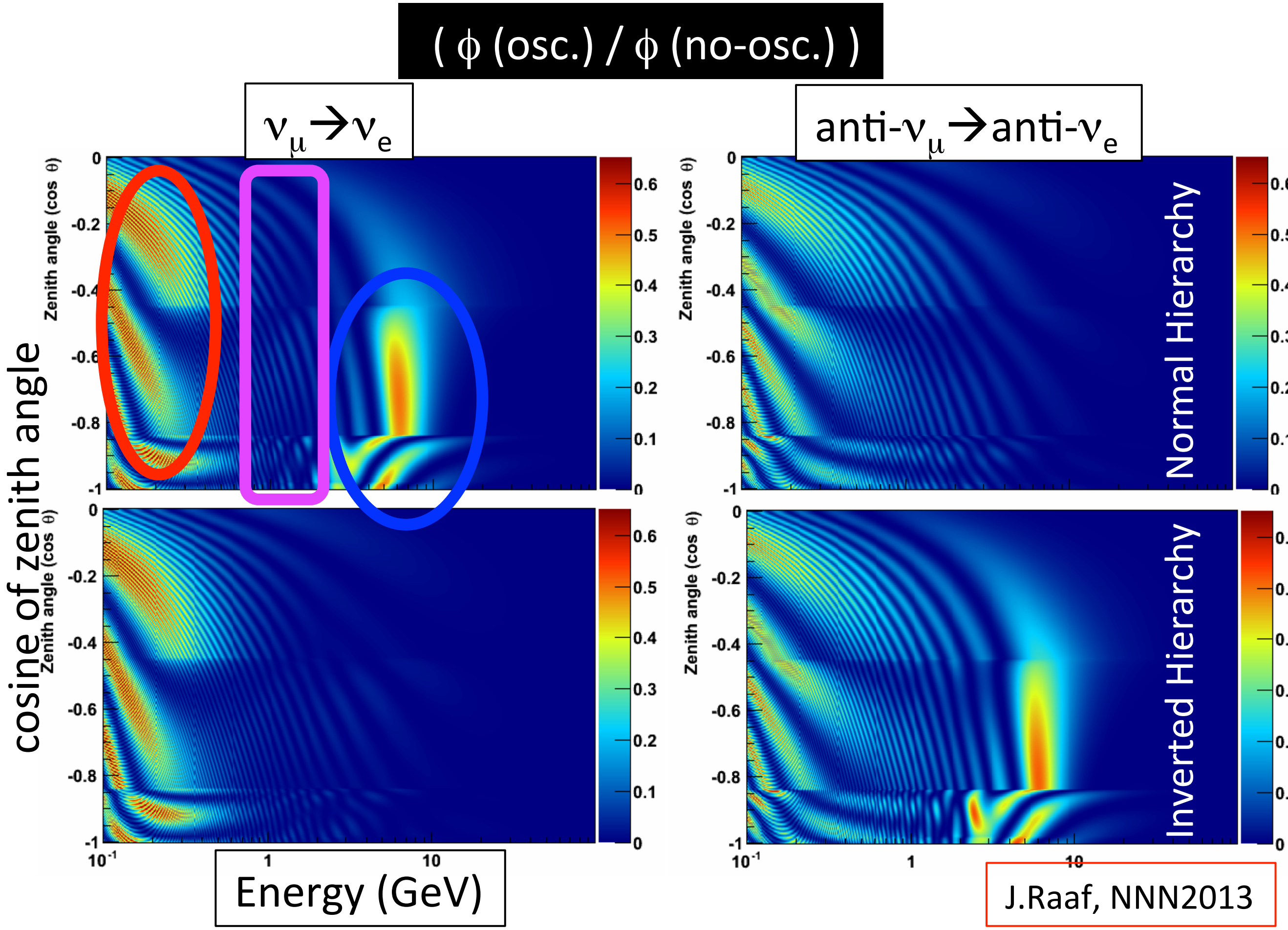




Flux ~ $E^{-2.71}$ at high energy region
<10% uncertainty @1GeV region

Symmetric for $E_\nu$ > a few GeV

# Neutrino oscillation in atmospheric $\nu$




- "Solar term" → $\sin^2\theta_{23}$ octant
- Interference term → CP violation phase
- Resonance term → mass hierarchy

Resonance on $\nu$ or anti-$\nu$ depending on mass hierarchy.

$$\frac{\Psi(\nu_e)}{\Psi_0(\nu_e)} - 1 \cong \underbrace{P_2(r\cdot\cos^2\theta_{23}-1)}_{\text{"Solar Term"}}$$

$$\underbrace{-\, r\cdot\sin^2\tilde{\theta}_{13}\cdot\cos^2\tilde{\theta}_{13}\cdot\sin 2\theta_{23}(\cos\delta_{CP}\cdot R_2-\sin\delta_{CP}\cdot I_2)}_{\text{Interference}}$$

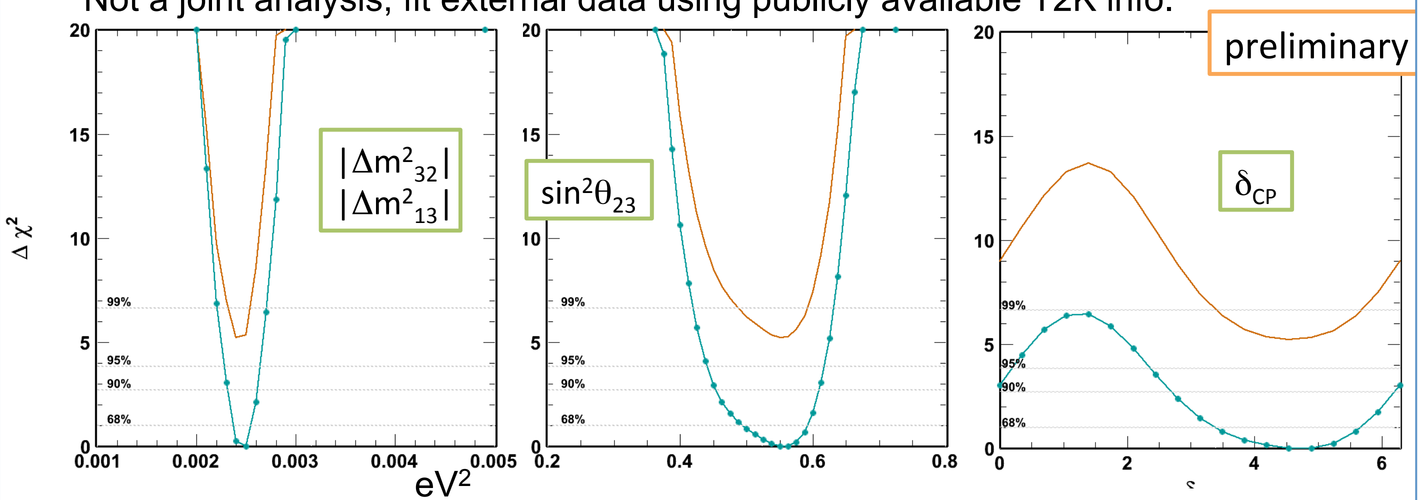
$$\underbrace{+\,2\sin^2\tilde{\theta}_{13}(r\cdot\sin^2\theta_{23}-1)}_{\text{Resonance}}$$

P2: Osc. prob. driven by 12 sector
r: $\nu_\mu/\nu_e$ flux ratio
R2, I2: osc. prob driven by 12sector

# Current Mass hierarchy constraint from atmospheric neutrinos.

## SK+T2K $\nu_\mu$, $\nu_e$ parameter determination

Not a joint analysis, fit external data using publicly available T2K info.




| Fit (585 dof) | $\chi^2$ | $\sin^2\theta_{13}$ | $\delta_{CP}$ | $\sin^2\theta_{23}$ | $\|\Delta m^2_{32}\|$ eV$^2$ |
|---|---|---|---|---|---|
| SK+T2K (IH) | 644.82 | 0.0219 (fix) | 4.538 | 0.55 | $2.5\text{x}10^{-3}$ |
| SK+T2K (NH) | 639.61 | 0.0219 (fix) | 4.887 | 0.55 | $2.4\text{x}10^{-3}$ |

- SK+T2K ($\theta_{13}$ fixed): $\Delta\chi^2 = \chi^2_{NH}-\chi^2_{IH} = -5.2$
  (-3.8 exp. for SK best, -3.1 for combined best)
- Under IH hypothesis, the probability to obtain $\Delta\chi^2$ of -5.2 or less is 0.024 ($\sin^2\theta_{23}$=0.6) and 0.001 ($\sin^2\theta_{23}$=0.4). NH: 0.43 ($\sin^2\theta_{23}$=0.6)

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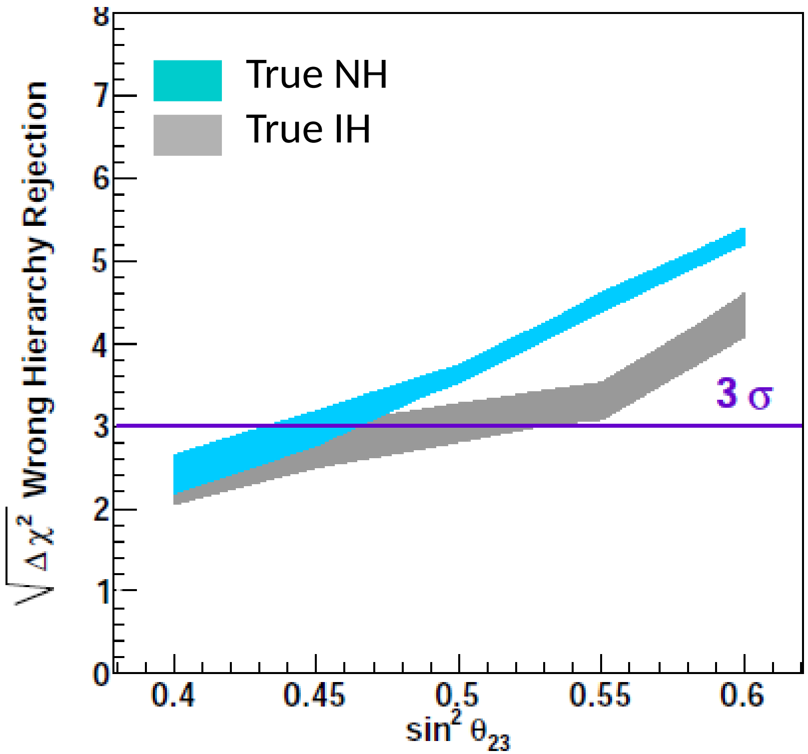
Shown by Prof. Moriyama for **Super-Kamiokande collaboration**, NEUTRINO 2016

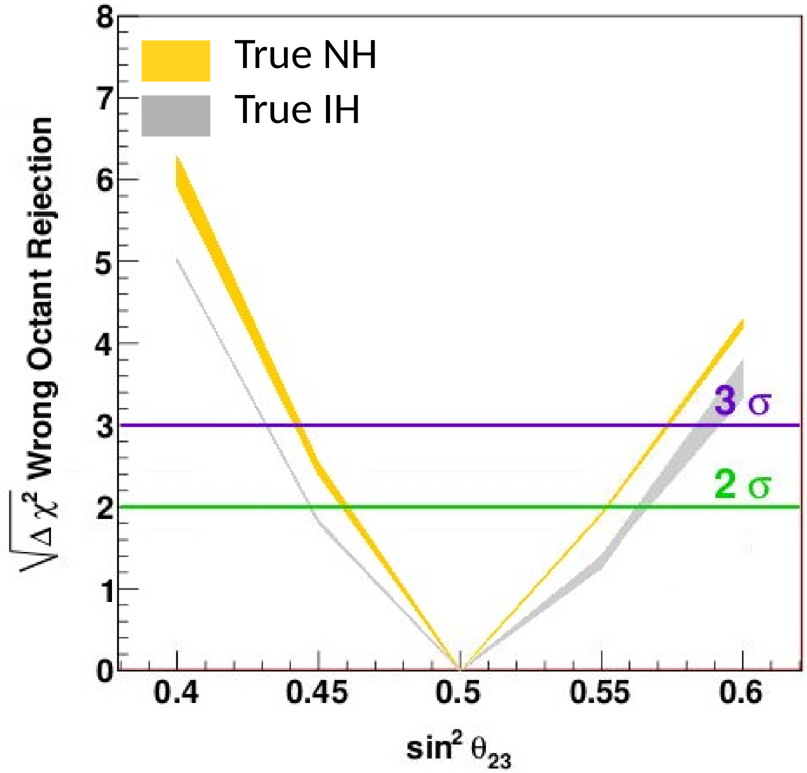
Normal Mass hierarch is favored currently.

# Atmospheric neutrino analysis in HK

Basically similar analyses in SK is assume.

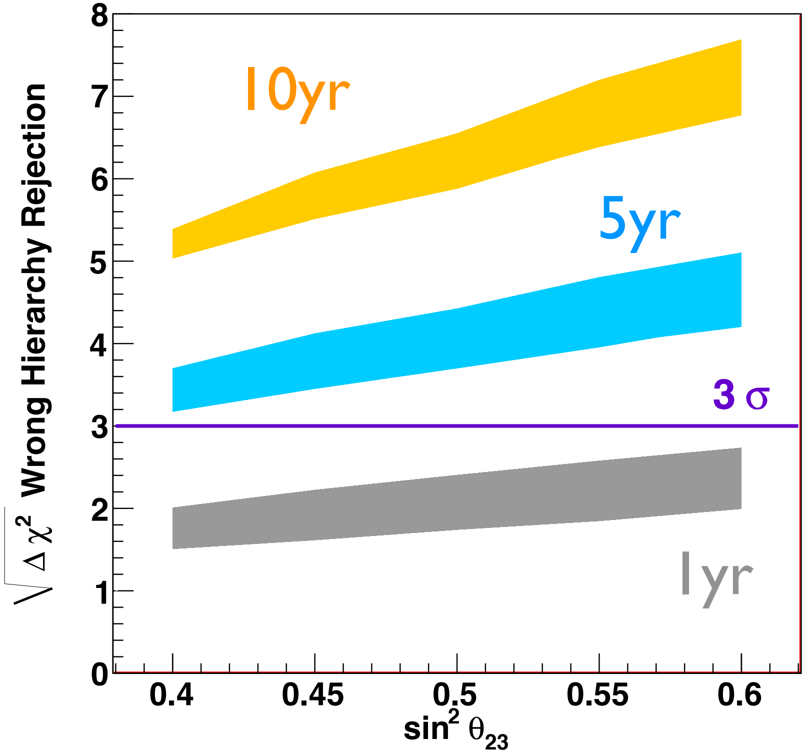
HK 10yr expectation

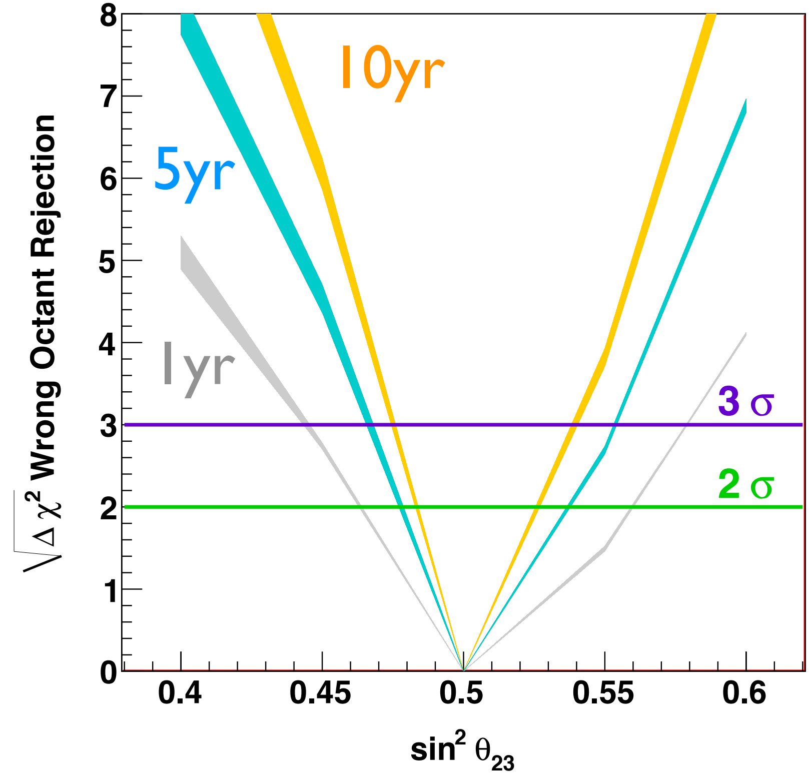



- Expect ~3σ sensitivity with 10yr running for mass hierarchy.
- Octant of $\theta_{23}$ can be solved for $|\theta_{23}-45°|>8°$.

# Atmospheric ν + beam ν

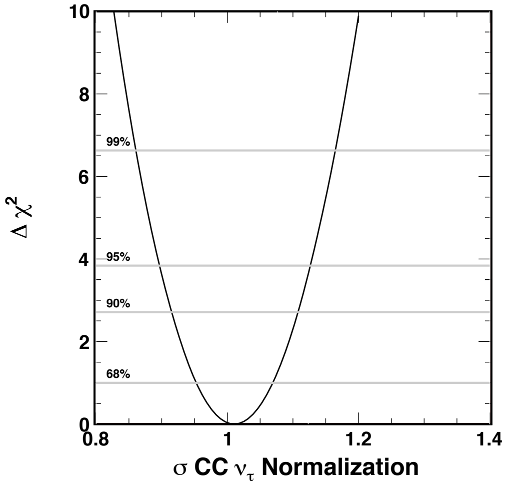


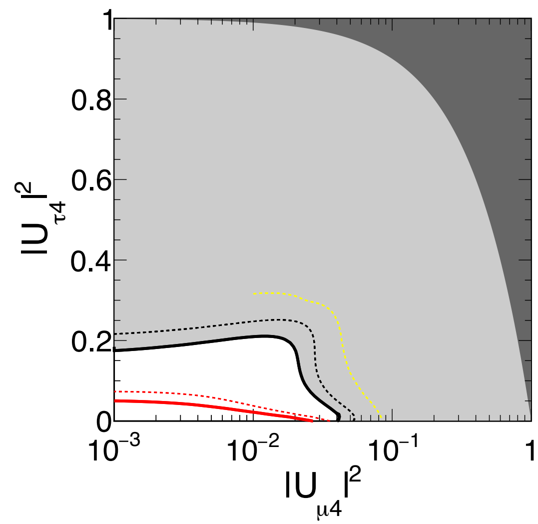



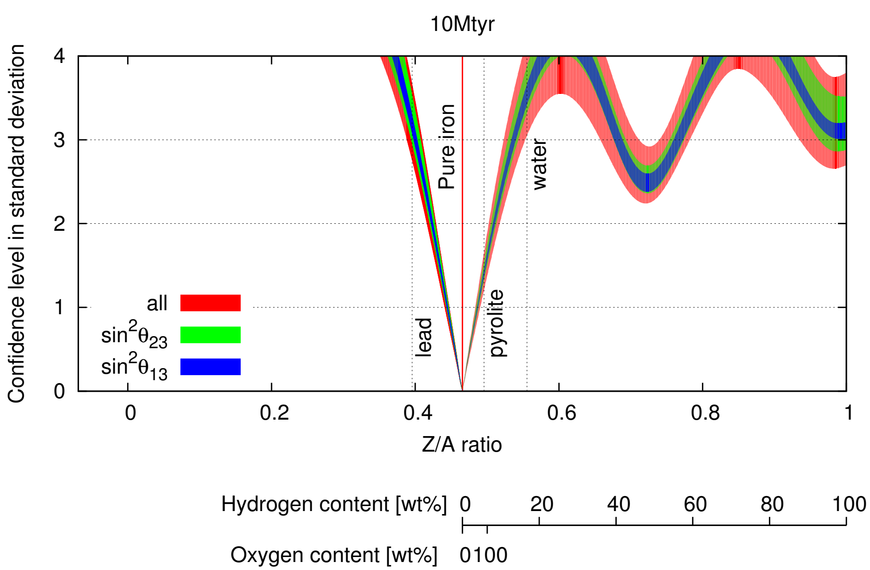

- Enhanced sensitivity by beam ν measurement.
- Better octant separation by Beam ν results.

# Other science with atm.$\nu$

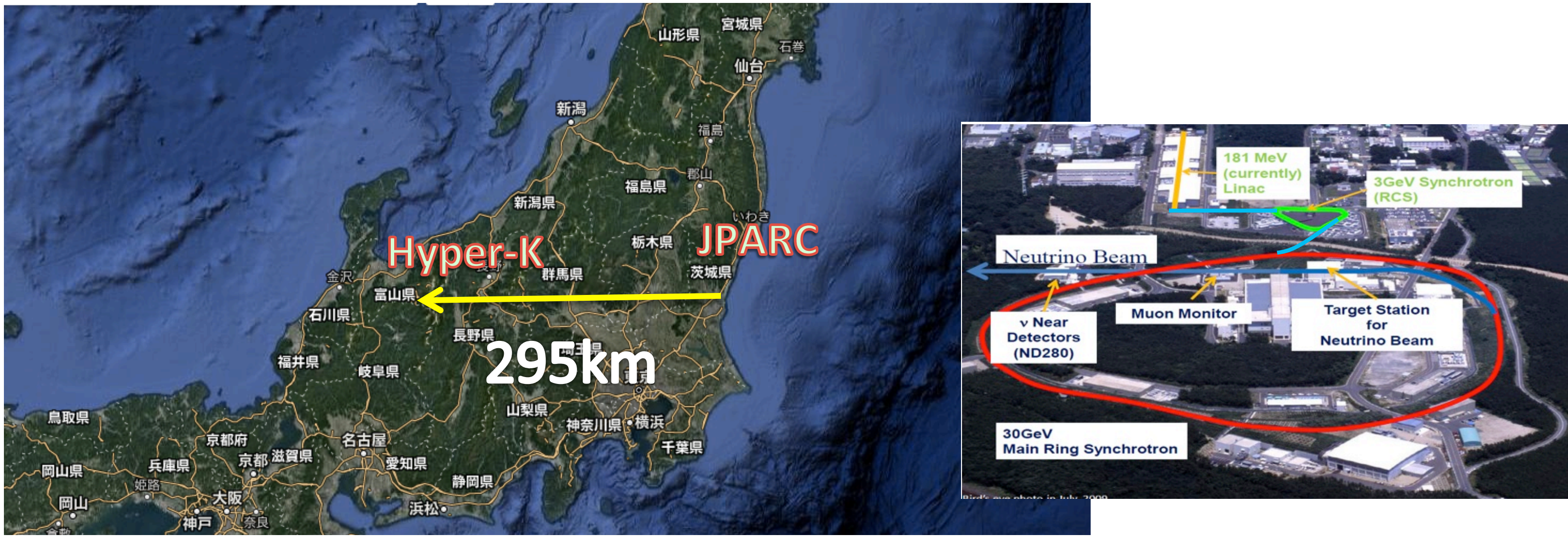
- Sterile neutrino
  - $4^{th}$ generation of neutrino?
- Cross section of $\nu_\tau$
- Matter information inside Earth's core via matter effect



# Beam ν based Long-baseline experiment

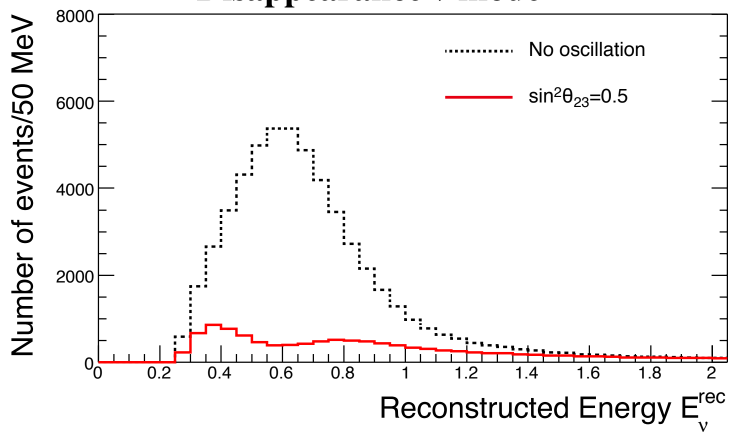



- Utilize JPARC neutrino beam from JPARC. (Currently T2K experiment utilize the beam).
- Same baseline (295km), same Off-Axis angle (2.5deg.)
- Beam upgrade to 1.3MW.
- Staged upgrade of JPARC ν beam is planned and upgrade to 750kW is approved.
- Upgrades of Near Detectors/intermediate detectors.

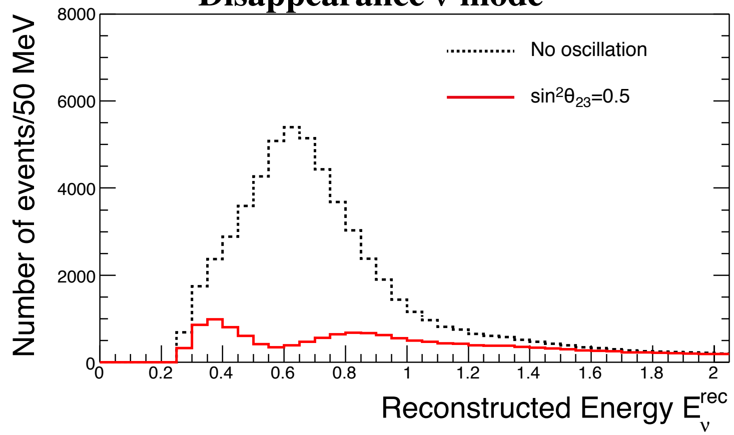
# Expected signal (10yr running)

Beam running time for $\nu_\mu$/anti-$\nu_\mu$ 1:3

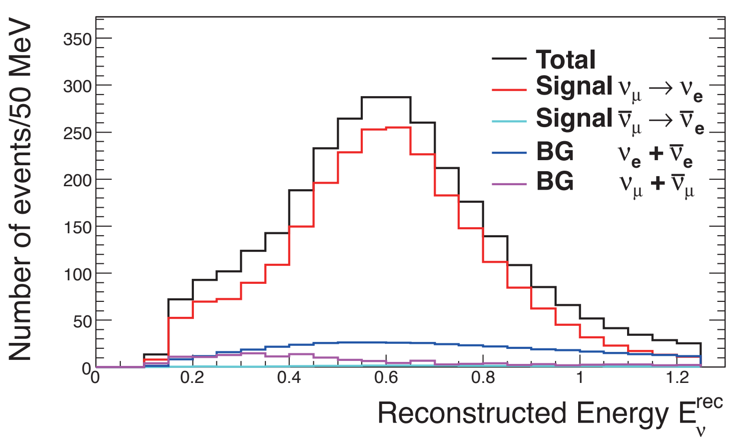
**Disappearance $\nu$ mode**



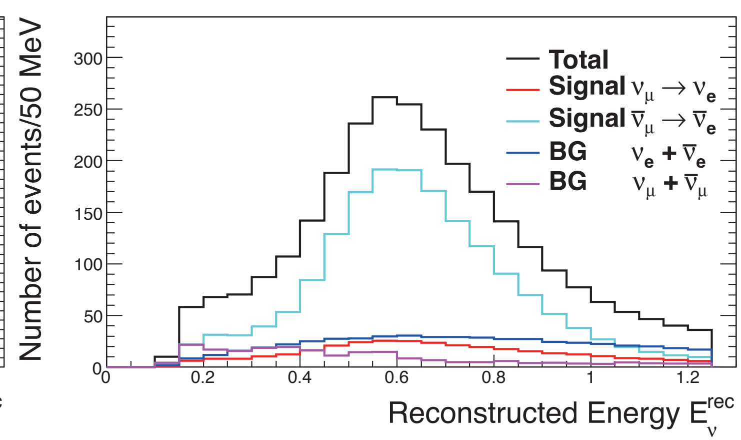

**Disappearance $\bar{\nu}$ mode**



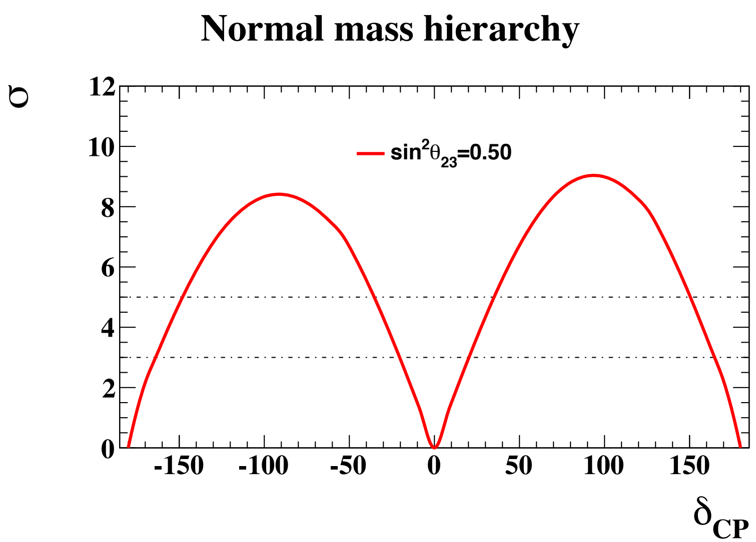

**Appearance $\nu$ mode**

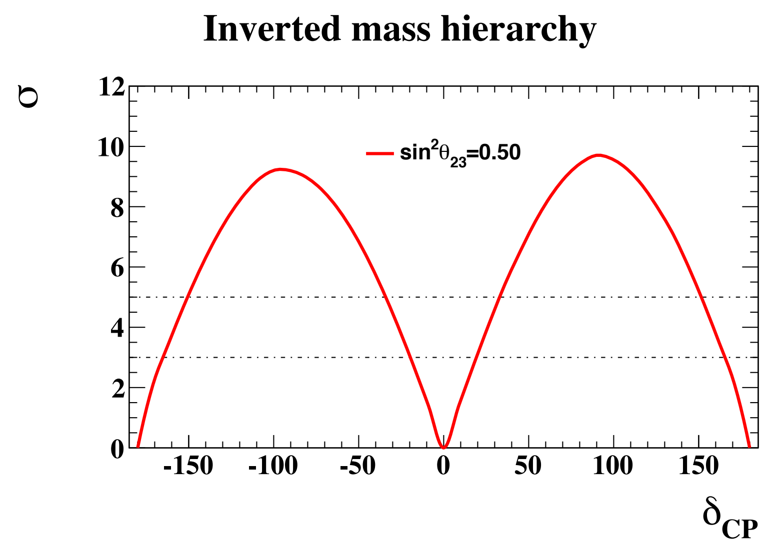


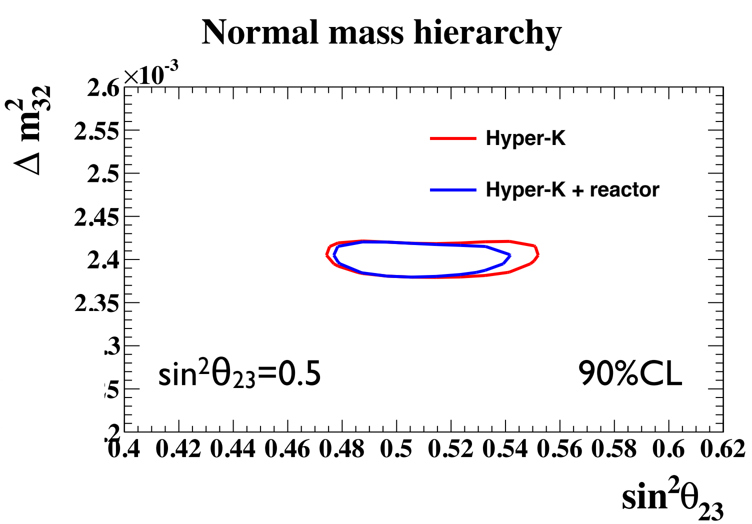

**Appearance $\bar{\nu}$ mode**



# Sensitivity for CPV, $\Delta m^2_{32}/\theta_{23}$




Exclusion of δcp=0

>57% (76%) of δcp with 5σ (3σ)

$\delta(\Delta m^2_{32}) = 1.4\times10^{-5}\ \mathrm{eV}^2$

$\delta(\sin^2\theta_{23}) = 0.015$ (for $\sin^2\theta_{23} = 0.5$)

$= 0.006$ (for $\sin^2\theta_{23} = 0.45$)

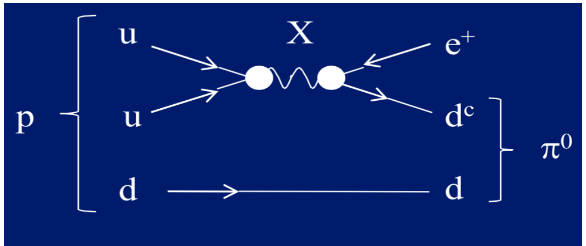
# Nucleon decay searches

A simple question:

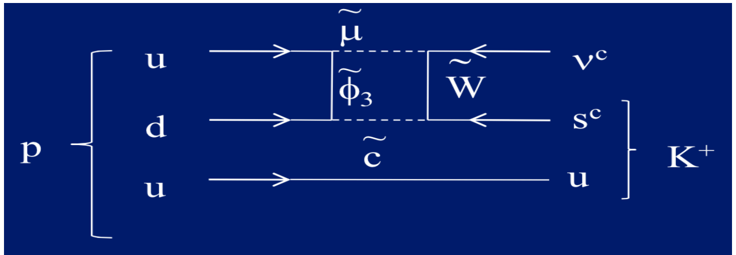
Why (usual) matters are electrically neutral?

= Why electric charge of quarks and electron are in integral ratio? ($|Q_d|$, $|Q_u|$, $|Q_e|$ = 1:2:3)

Grand Unified Theories (GUTs) give a natural explanation, and, consequently predict nucleon instability due to change of quark to lepton = Nucleon Decay



Minimal SU(5) model

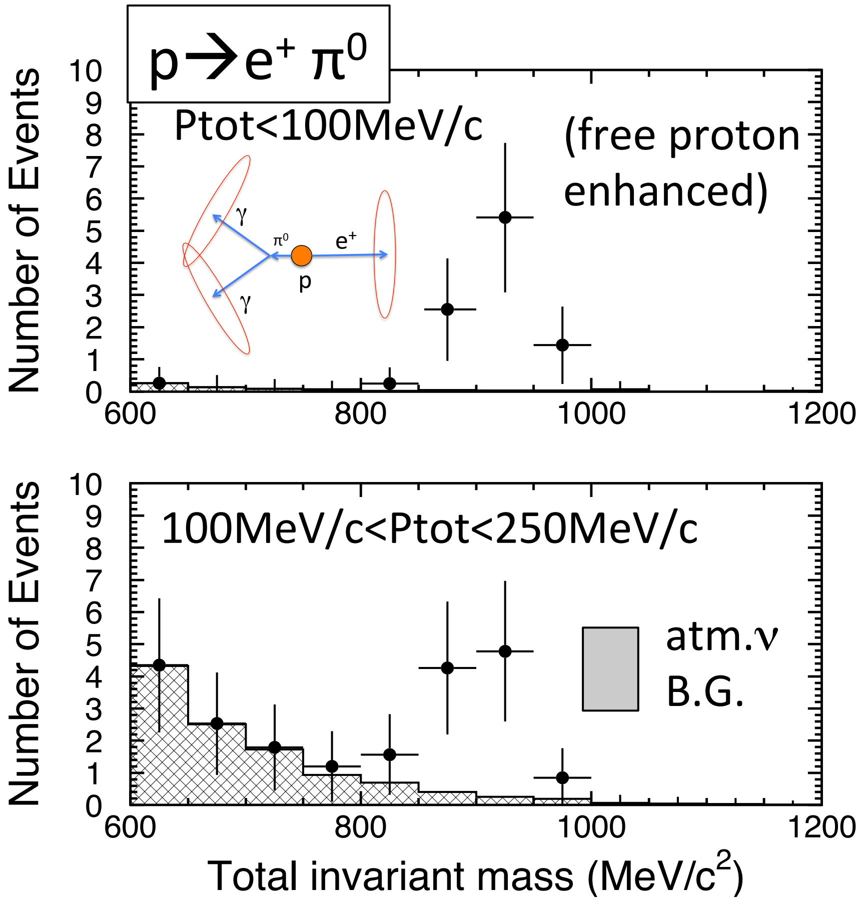


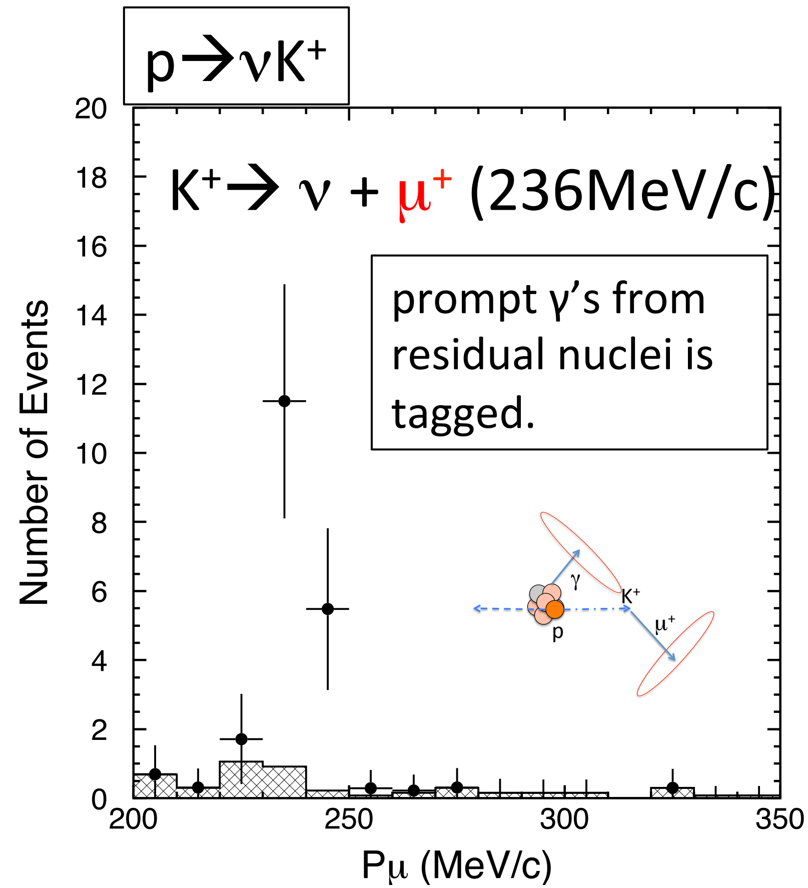
SUSY SU(5) model

GUTs predict many decay modes including $|\Delta B|$=1 and 2
(Di-nucleon decay processes, NN→l+X)

# Expected signals in Hyper-Kamiokande

Assume SK limit, HK 10yr exposure



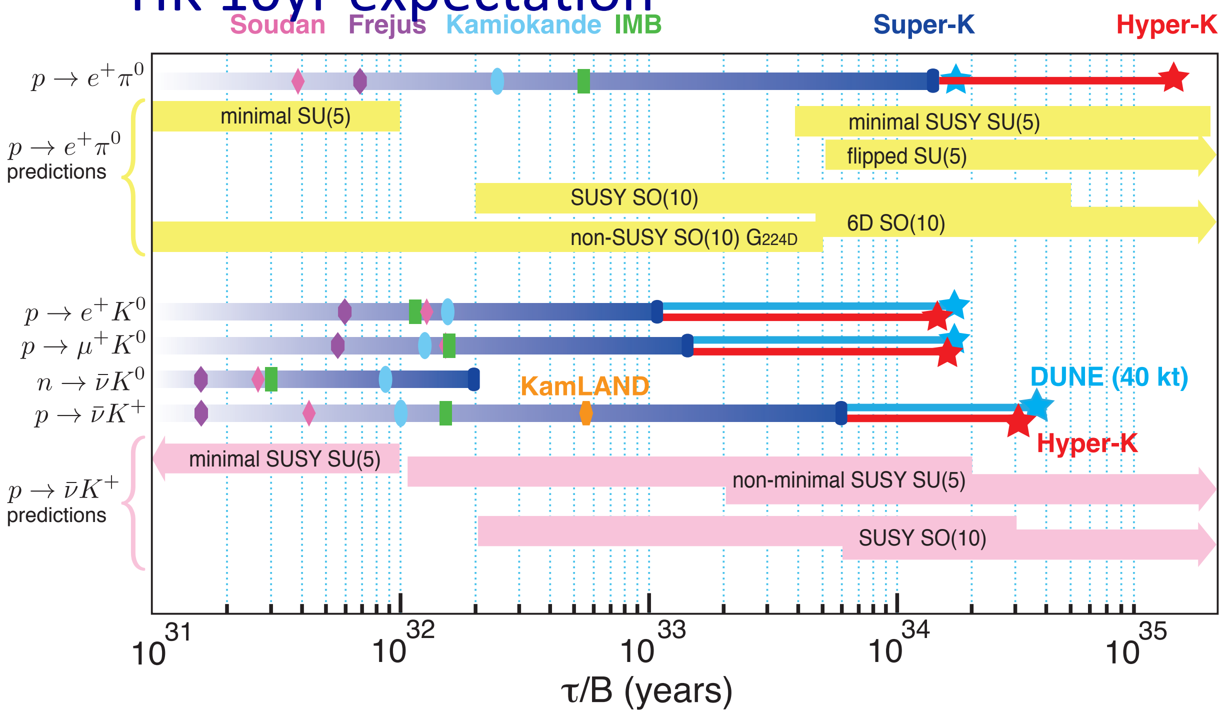




Clear signal & background free, due to high QE PMTs and high photo-coverage:

- Efficient neutron tagging reduces B.G. by atm.ν. (γ from n capture on free-proton)
- Efficient tagging of prompt γ from de-excitation of residual nuclei.

# Hyper-Kamiokande potential on nucleon decay search

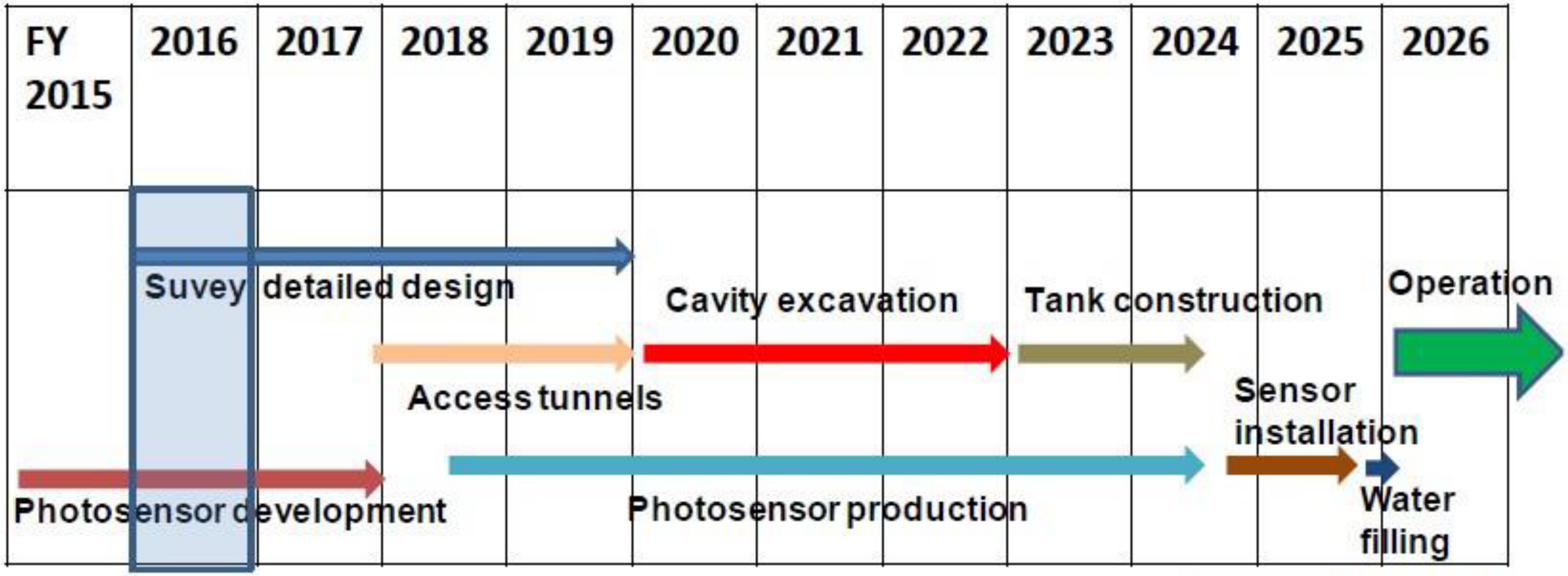
## HK 10yr expectation




| | 3σ discovery ($10^{34}$yr) | Lower limit ($10^{34}$yr) |
|---|---|---|
| $p \to e\pi^0$ | 8.0 | 1.6 |
| $p \to \nu K^+$ | 2.5 | 0.66 |
| $p \to \mu\pi^0$ | 8.7 | 0.77 |
| $p \to e\eta$ | 4.0 | 1.0 |
| $p \to \mu\eta$ | 4.3 | 0.47 |
| $n \to e^+\pi^-$ | 1.7 | 0.53 |
| $n \to \mu^+\pi^-$ | 1.1 | 0.35 |

- Many GUTs predictions are covered by Hyper-K.
- Multi mode can be tested, sensitivity is ~one order of magnitude or more higher than current limits.

# Possible schedule




(shown by Obayashi, Aug. 24th this workshop)

Assuming HK project is approved before the end of JFY 2017.

- Detailed conceptual Design Report is reviewed by Hyper-K Advisory committee, submitted to KEK preprint & ICRR report.
- Hyper-K project proposal was submitted to Science Council of Japan.

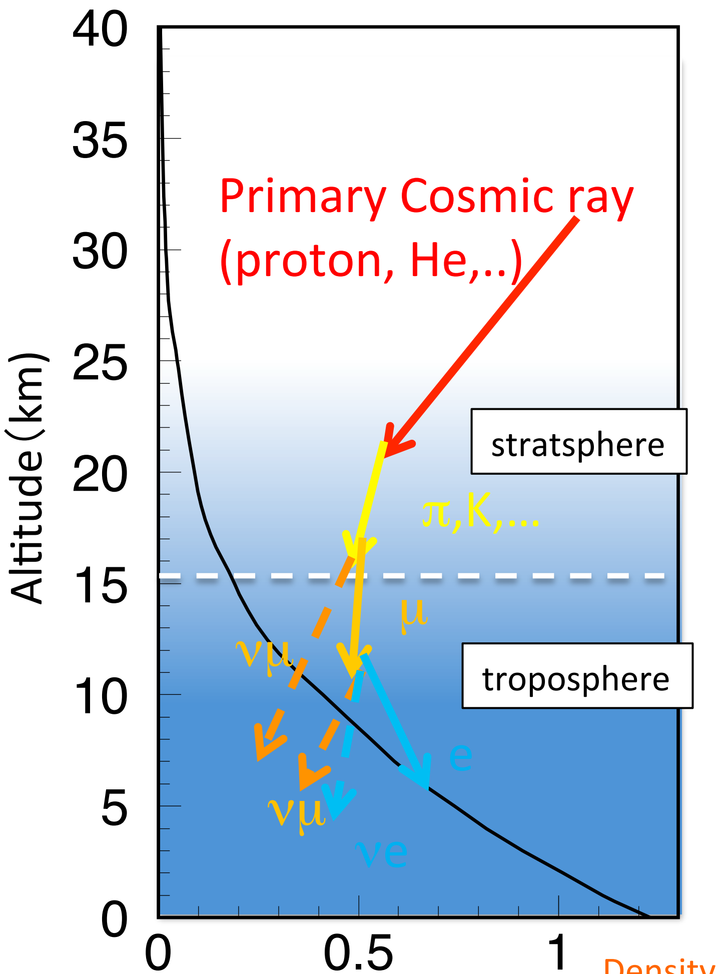
# Summary

- Hyper-Kamiokande
  - Next generation Water C detector.
  - Wide science with ~×10 large volume and improved PMTs.
    - Determination of neutrino mass hierarchy with > 3σ with 10yr data.
    - B.G. free search for nucleon decays.
  - Launched from 2026, if approved by the fiscal year 2017.

# Supplements

# Atmospheric neutrinos

## = Secondary products of primary cosmic rays in the atmosphere

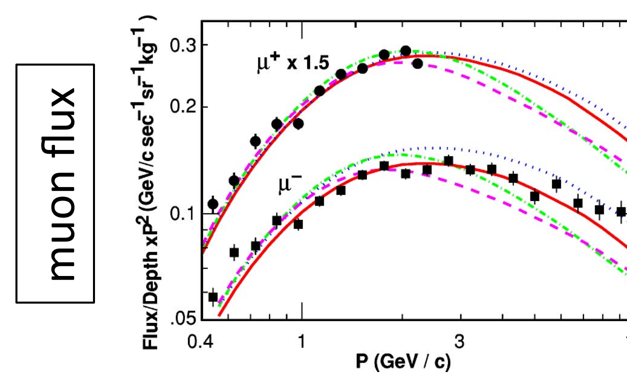



$\lambda$~40g/cm$^2$ for proton
→L~15km

p + A → π's, …. $\pi^{\pm} \to \mu^{\pm} + \boxed{\nu_{\mu}}(\bar{\nu}_{\mu})$

$$\to e^{\pm} + \boxed{\nu_{e}}(\bar{\nu}_{e}) + \boxed{\bar{\nu}_{\mu}}(\nu_{\mu})$$

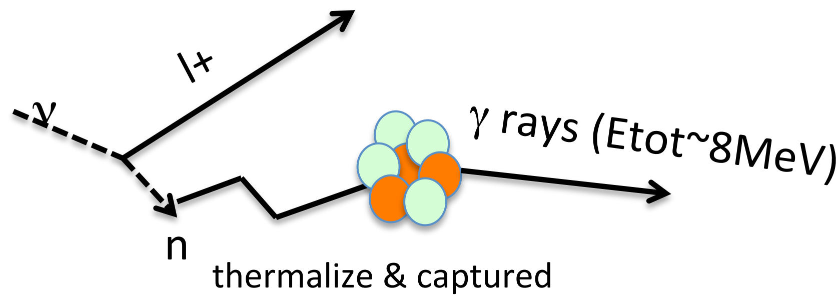
- First observation in 1965 in two deep underground experiments.
- Several Flux calculations on the market:
  - Primary CR fluxes, p+A cross sections,
  - π's production, Geo-magnetic field, ..
- Calculated fluxes are well tested (calibrated) by Cosmic Ray muons.



# Super-K-Gd project

=Water Cherenkov detector with Gd dissolved water as neutron absorber

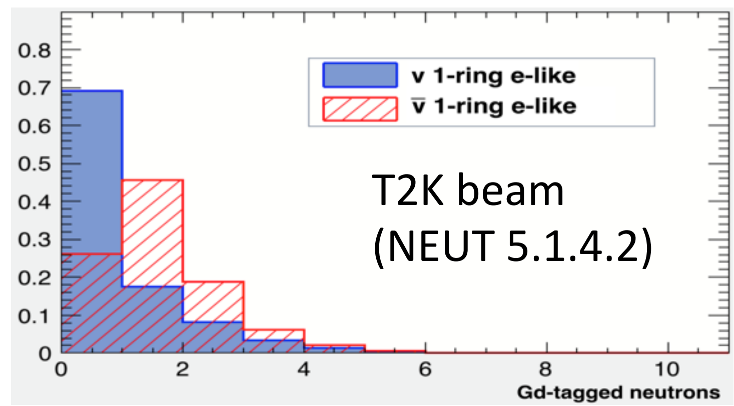
- High efficient neutron tagging using 0.2% $Gd_2(SO_4)_3$ dissolved water.
- Delayed coincidence of $\gamma$-ray signal from thermal neutron capture on Gd.




Physics targets:

- Supernova relic neutrino (SRN)
- Reduce proton decay background
- Neutrino/anti-neutrino discrimination (Long-baseline and atm nu's)

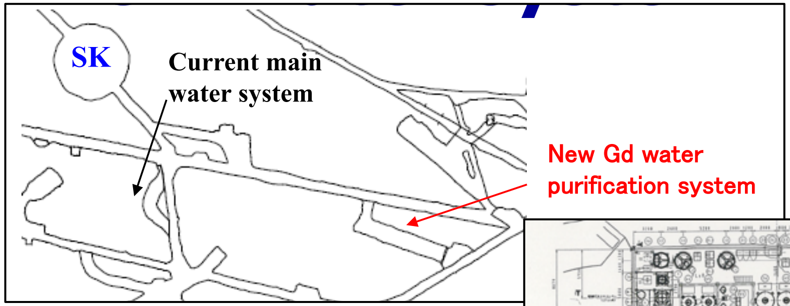
and more..



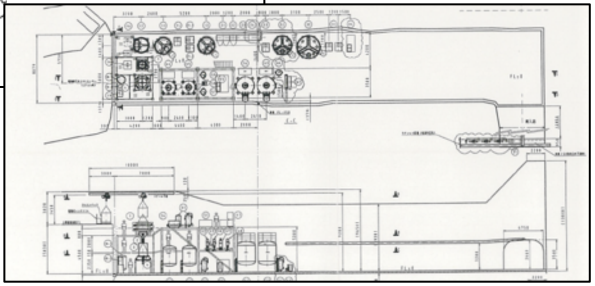

- Five year evaluation experiment (EGADS) tests water quality, materials, basic techniques, and so on.
- On June 27, 2015, the Super-Kamiokande collaboration approved the Super-K-Gd project.

# Progresses toward SK-Gd

- New Water System is in construction.


Water system

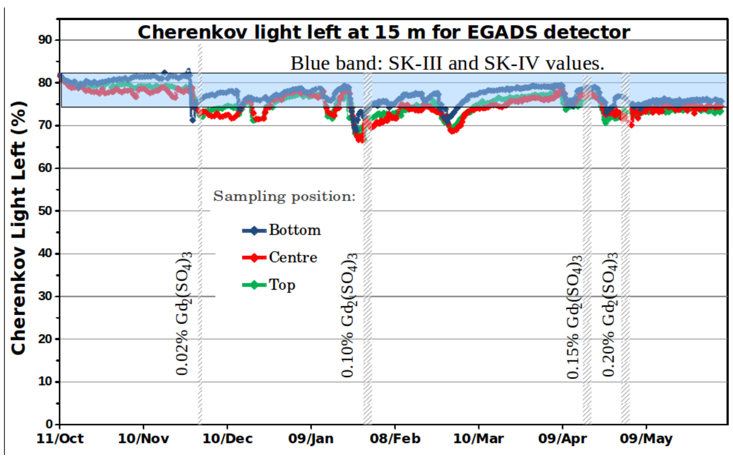


- Seal water leak(s) in SK
  - We know (small but) water leak somewhere in SK outer wall.
  - Sealing method is almost settled. Sealing melding lines of the tank with a good sealing material (low B.G., mechanically strong).
- etc..

Schedule and plan of refurbishment of SK is under discussion. Expected from 2018. (closely related to T2K beam upgrade).

After ~5yr Technical Evaluation experiment (EGADS) , we proved that basic techinique is

☑Gd water transparency must be similar to SK water
☑Effect of Gd to detector materials
☑Effect of Gd water quality to physics analysis
☑How to stop leak of SK detector
(But still exploring improved methods)
☐Reduction of radioactive backgrounds in Gd powder
(only affects Lowe analysis)
☑ : done, ☐ : under study




"Mini" Super-K : same materials used

Measured Water quality → MC study for Physics

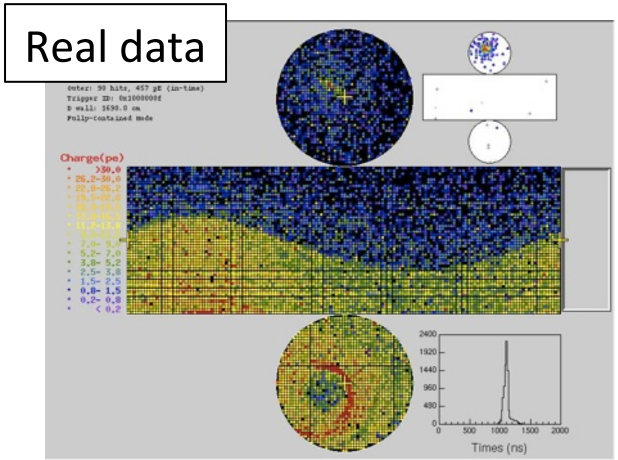
- On June 27, 2015, the Super-Kamiokande collaboration approved the Super-K-Gd project.
- Actual schedule including refurbishment of the tank, Gd loading time will be determined soon taking into account the T2K schedule.

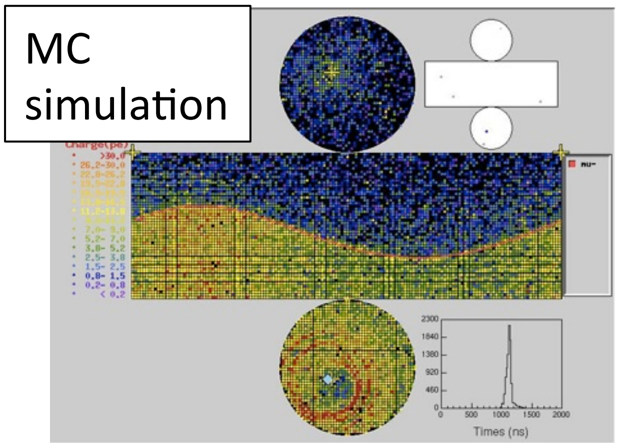
# Official statement from Super-K collaboration

On June 27, 2015, the Super-Kamiokande collaboration approved the SuperK-Gd project which will enhance anti-neutrino detectability by dissolving gadolinium to the Super-K water.

The actual schedule of the project including refurbishment of the tank and Gd-loading time will be determined soon taking into account the T2K schedule.

# Calibration of the detector



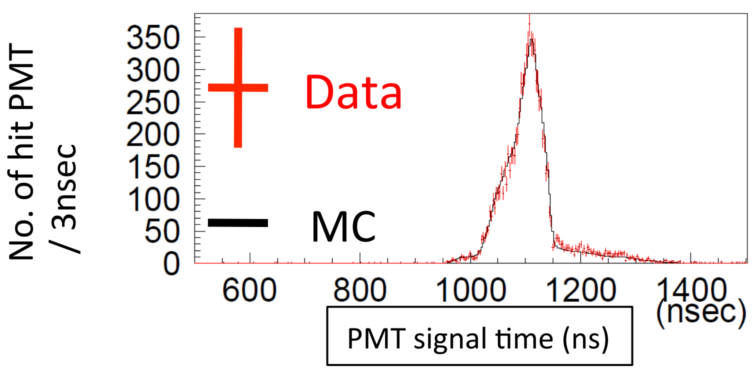




Detailed Calibration works has been done intensively with in-situ & ex-situ sources: (pulse laser, CRμ, electron LINAC, ..)

- Timing response of PMTs
- Gain of PMTs
- Water transparency measurement
- Detector Uniformity …

Well test the event reconstruction performance

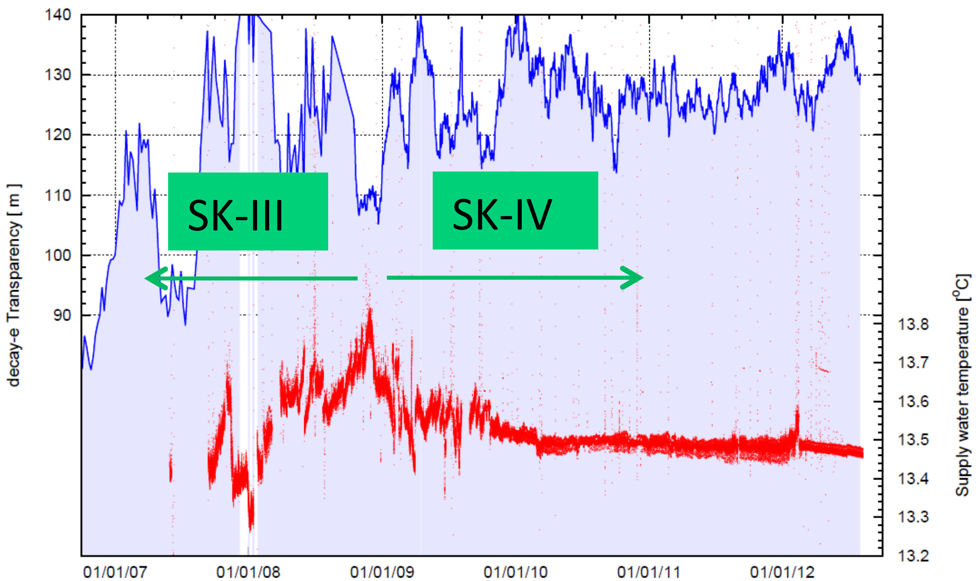
- Vertex, direction
- Particle identification
- Energy reconstruction, …

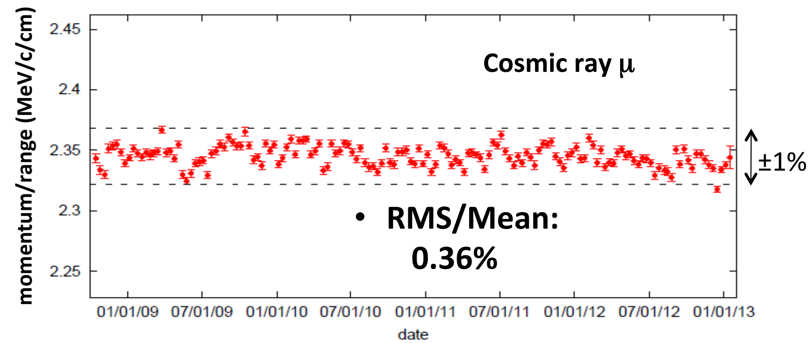


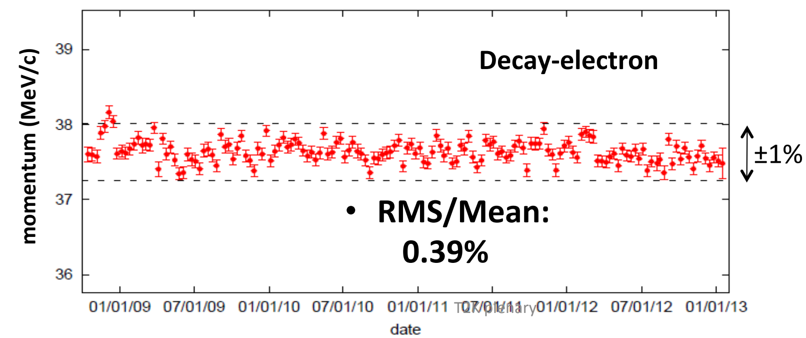

Full Monte Carlo (MC) simulation has been developed based on measurements of fundamental parameters & available models.

# Stability

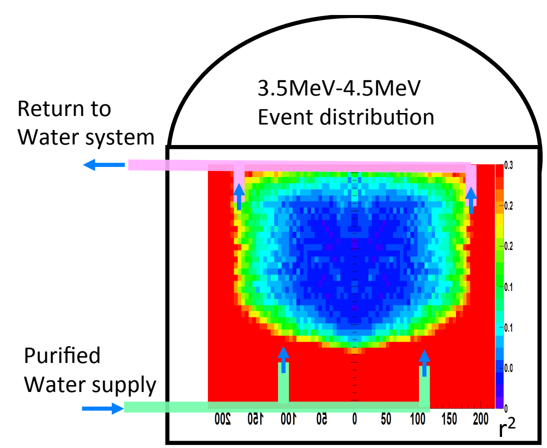
## Key issue is a water quality.



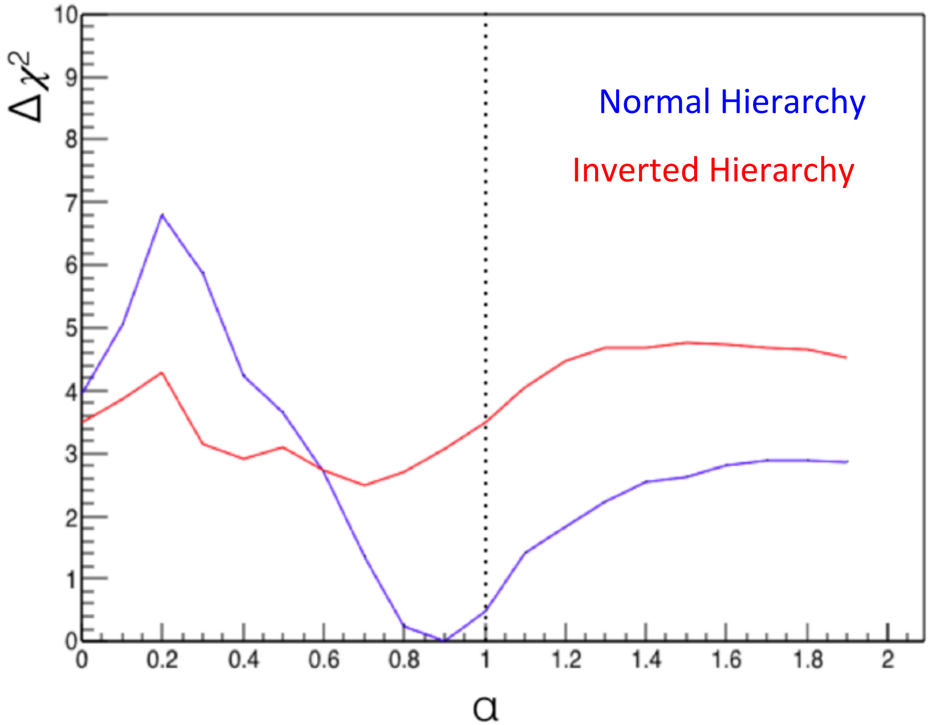




- Keep water quality by continuous purification of the water.
- Carefully control the flow inside Super-K
- Water transparency is continuously monitored and taken into account in event reconstruction.
- 1% level stability of energy estimation.



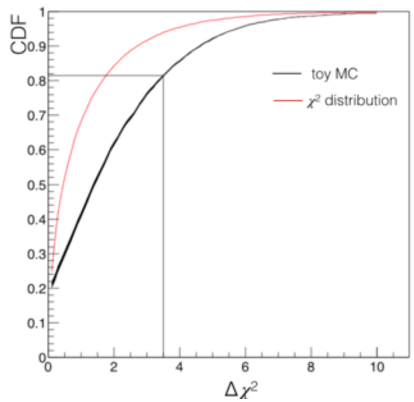
# Test of Matter effect




- Atmospheric neutrino data in SK prefer the matter effect hypothesis or not?
- Introduce a phenomenological scaling factor α to electron potential:

$$H = UMU^{\dagger} + \alpha \cdot V_e$$

and carried out 3-flavor ν oscillation analysis.




- Best fit is at α = 0.9 for NH.
- $\Delta\chi^2$ = 3.5 (vacuum), 0.5(α=1.0)
- Based on Toy MC, vacuum case (α=0) excluded at 82% confidence. Weakly prefer existence of matter effect.

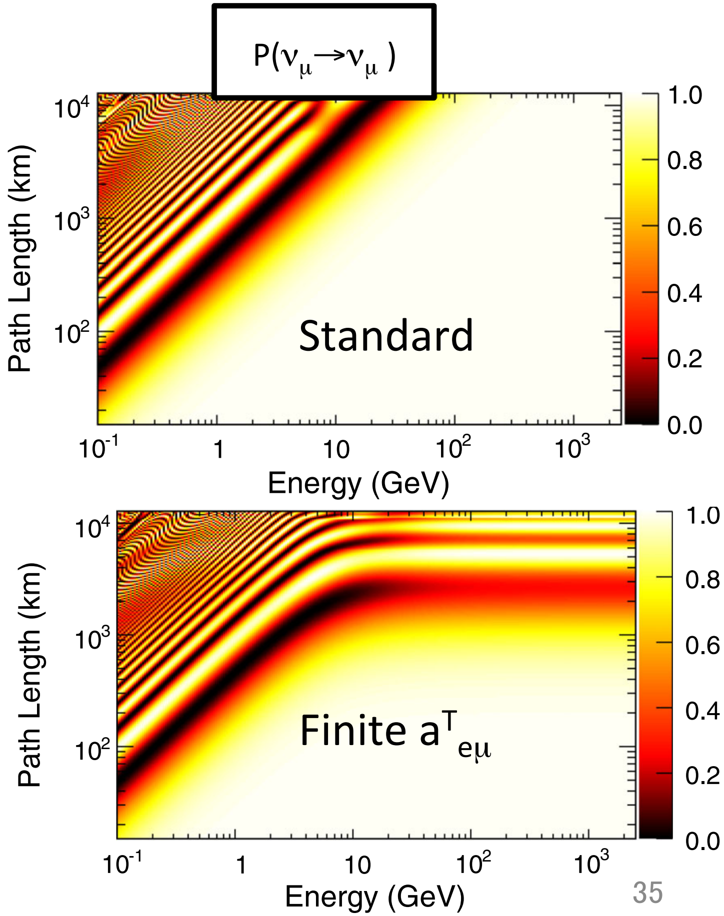
# Tests of Lorentz Invariance

PHY. REV.D 91, 052003 (2015)

- Non-standard terms from Lorentz invariance violating (LIV) effect is tested.

$$H = U \begin{pmatrix} 0 & 0 & 0 \\ 0 & \frac{\Delta m^2_{21}}{2E} & 0 \\ 0 & 0 & \frac{\Delta m^2_{31}}{2E} \end{pmatrix} U^\dagger \pm \sqrt{2} G_F \begin{pmatrix} N_e & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \pm \begin{pmatrix} 0 & a^T_{e\mu} & a^T_{e\tau} \\ (a^T_{e\mu})^* & 0 & a^T_{\mu\tau} \\ (a^T_{e\tau})^* & (a^T_{\mu\tau})^* & 0 \end{pmatrix} - E \begin{pmatrix} 0 & c^{TT}_{e\mu} & c^{TT}_{e\tau} \\ (c^{TT}_{e\mu})^* & 0 & c^{TT}_{\mu\tau} \\ (c^{TT}_{e\tau})^* & (c^{TT}_{\mu\tau})^* & 0 \end{pmatrix}$$

- In addition to Standard L/E dependence, L or L・E dependences are introduced.
- Spacially isotropic case is tested (sensitive to sidereal effects as well...)




Results

Most Stringent limit, (O(3)~O(7) improved

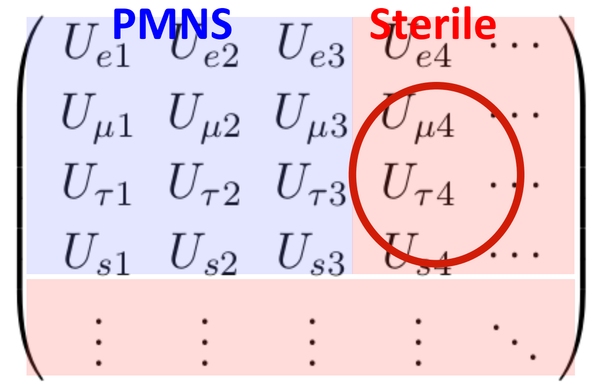
| Re($a^T$) | | | Im($a^T$) | | |
|---|---|---|---|---|---|
| eμ | eτ | μτ | eμ | eτ | μτ |
| $2\times10^{-23}$ | $4\times10^{-23}$ | $8\times10^{-24}$ | $2\times10^{-23}$ | $2\times10^{-23}$ | $4\times10^{-24}$ |

| Re($c^{TT}$) | | | Im($c^{TT}$) | | |
|---|---|---|---|---|---|
| eμ | eτ | μτ | eμ | eτ | μτ |
| $4\times10^{-26}$ | $2\times10^{-24}$ | $2\times10^{-26}$ | $4\times10^{-26}$ | $2\times10^{-24}$ | $2\times10^{-26}$ |

# Sterile Neutrino Oscillations in Atmospheric Neutrinos

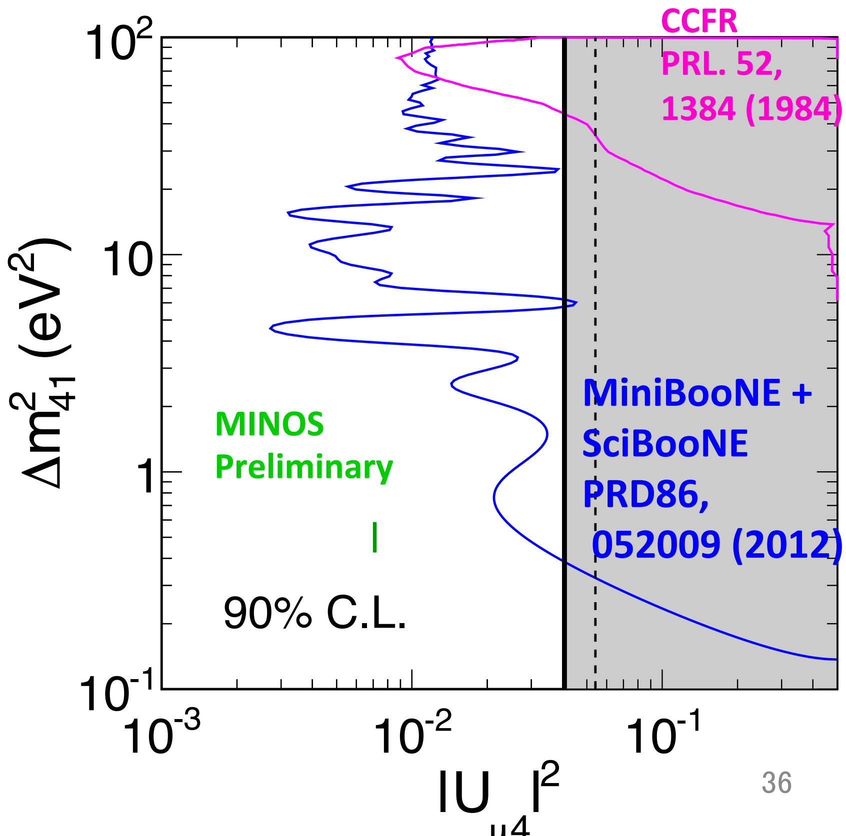
PHYS. REV.D 91, 052019 (2015)

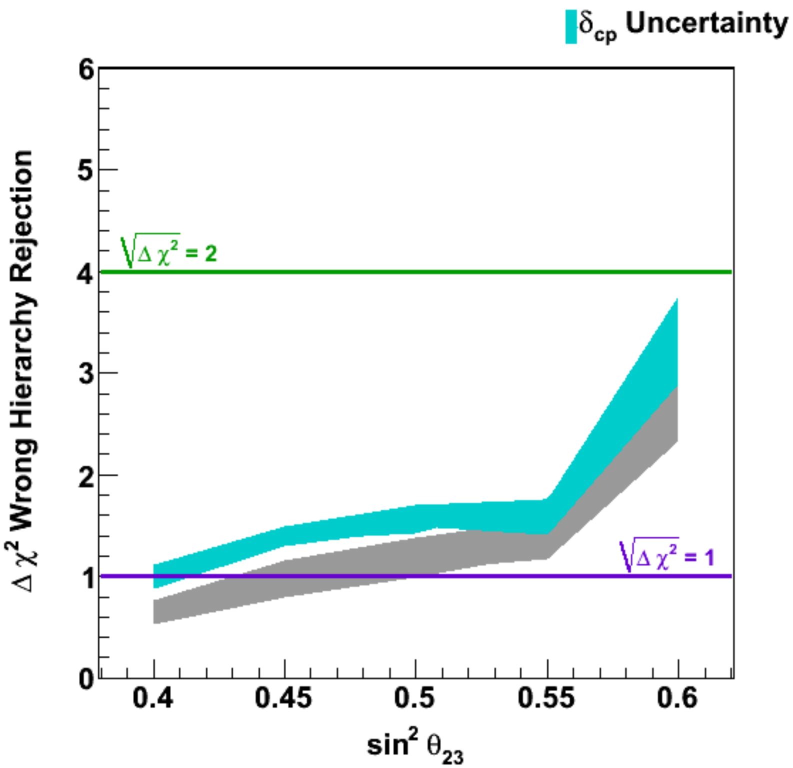
- (Standard neutrinos + sterile neutrinos) is tested for large $\Delta m^2_{41}$ region ($>0.01\text{eV}^2$) .
- Two cases are investigated
  - $U_{e4}$ is assumed to be 0.
  - No matter effect from NC potent on sterile neutrinos.



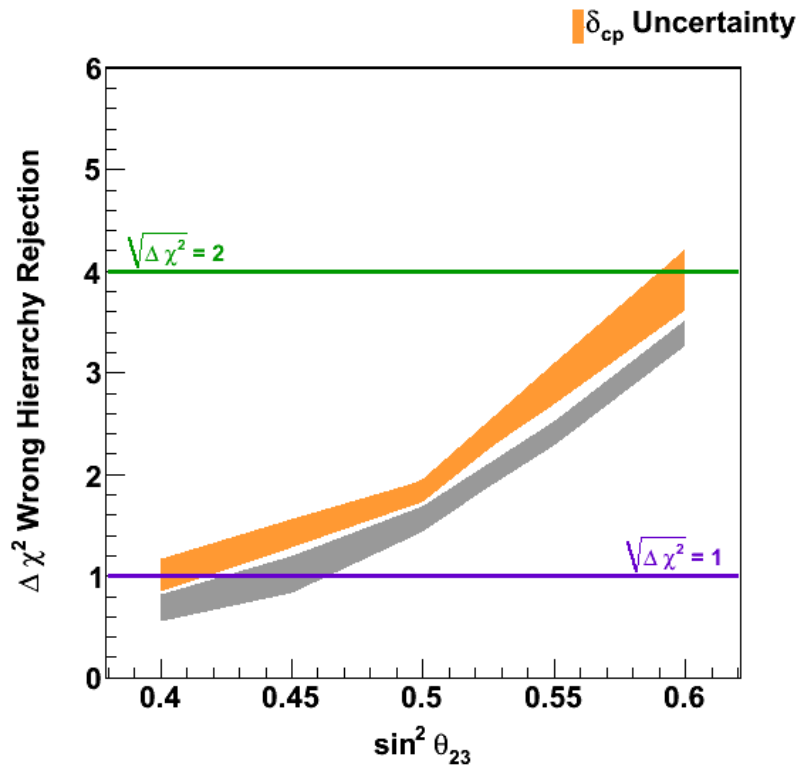

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} & \cdots \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} & \cdots \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} & \cdots \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} & \cdots \\ \vdots & \vdots & \vdots & \vdots & \ddots \end{pmatrix}$$

- Turning off sterile matter effects while preserving standard three-flavor oscillations provides a pure measurement of $|U_{\mu 4}|^2$
- As with similar experiments, no strong sterile-driven $\nu_\mu$ disappearance
- $|U_{\mu 4}|^2 < 0.041$ at 90% C.L.





$\delta_{cp}$ Uncertainty
$\Delta\chi^2$ Wrong Hierarchy Rejection
$\sqrt{\Delta\chi^2} = 2$
$\sqrt{\Delta\chi^2} = 1$
0
1
2
3
4
5
6
0.4
0.45
0.5
0.55
0.6
$\sin^2\theta_{23}$

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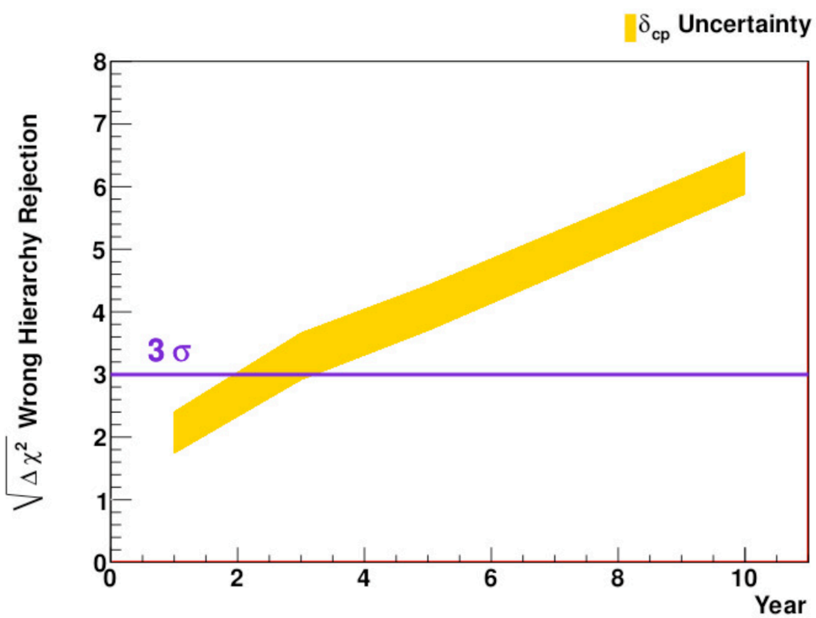
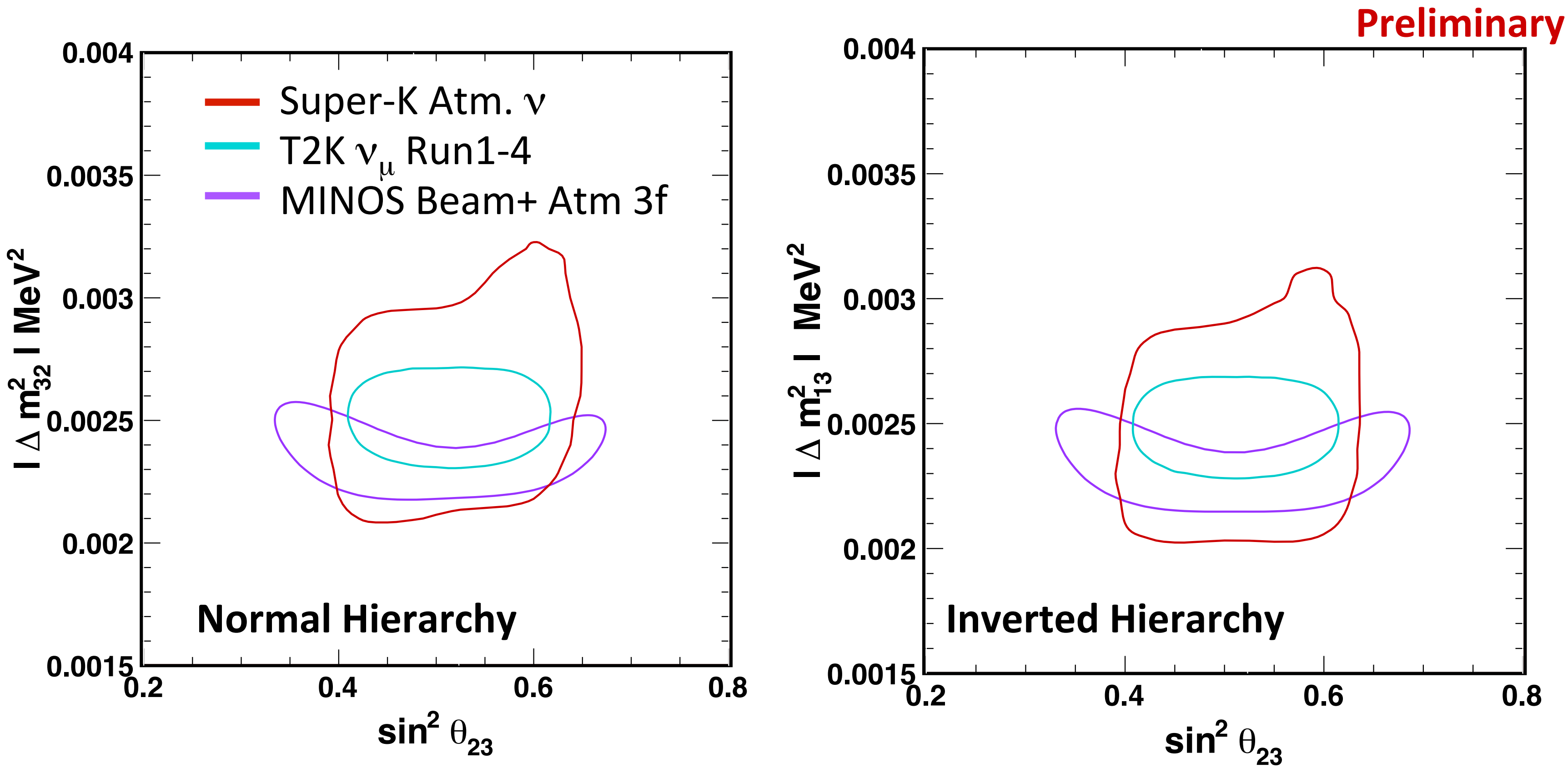


$\delta_{cp}$ Uncertainty
$\sqrt{\Delta\chi^2}$ Wrong Hierarchy Rejection
3 σ
Year
0
1
2
3
4
5
6
7
8
0
2
4
6
8
10

# Allowed region on ($\sin^2\theta_{23}$, $\Delta m^2_{32}$ or $\Delta m^2_{13}$)




- Consistent with long-baseline measurements.
- Atmospheric neutrinos allow wider parameter space,

# Neutrino flavor oscillation (PMNS matrix)

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{\alpha i} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \cdot \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \cdot \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

**Flavor eigenstates**

**Mass eigenstates**

Atmospheric ν,
Accelerator ν experiments
(K2K, MINOS, T2K..)

$\theta_{23} \sim 45°$
$\Delta m^2_{23} \sim 2.5\text{x}10^{-3}(\text{eV}^2)$

Reactor ν,
Accelerator ν,
Atm. ν

$\sin^2 2\theta_{13} \sim 0.1$

Solar ν,
Reactor ν

$\theta_{12} \sim 34°$
$\Delta m^2_{12} \sim 8\text{x}10^{-5}(\text{eV}^2)$

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

- Three frequency driven by $\Delta m^2_{ij}$, amplitudes by mixing angles.
- Appearance ($\alpha \rightarrow \beta$) is a window to observe $\delta_{cp}$.
- Mass hierarchy (sign of $\Delta m^2_{ij}$), phase of $\delta_{cp}$ is still open questions