Neutrino physics
- from Super-K to Hyper-K -

Masato Shiozawa
Kamioka Observatory, Institute for Cosmic Ray Research, U of Tokyo, and
Kamioka Satellite, Kavli Institute for the Physics and Mathematics of the Universe (WPI), U of Tokyo

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3-flavor oscillation scheme

Flavor eigenstate Mass eigenstate

$$^{t}(\nu_e,\nu_\mu,\nu_\tau) = U_{\alpha i}^{MNS}\,{}^{t}(\nu_1,\nu_2,\nu_3)$$

U^{MNS}: Maki-Nakagawa-Sakata Matrix

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

$$P(\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\beta) = \delta_{\alpha\beta} - 4\sum_{j>i}\mathrm{Re}(U_{\alpha i}^{*}U_{\beta i}U_{\alpha i}^{*}U_{\beta j})\sin^2\frac{(m_j^2-m_i^2)L}{4E_\nu}$$

$$(\mp)2\sum_{j>i}\mathrm{Im}(U_{\alpha i}^{*}U_{\beta i}U_{\alpha i}^{*}U_{\beta j})\sin\frac{(m_j^2-m_i^2)L}{2E_\nu}$$

Parameterized by 4 (mixing matrix) and 2 (difference of squared masses)

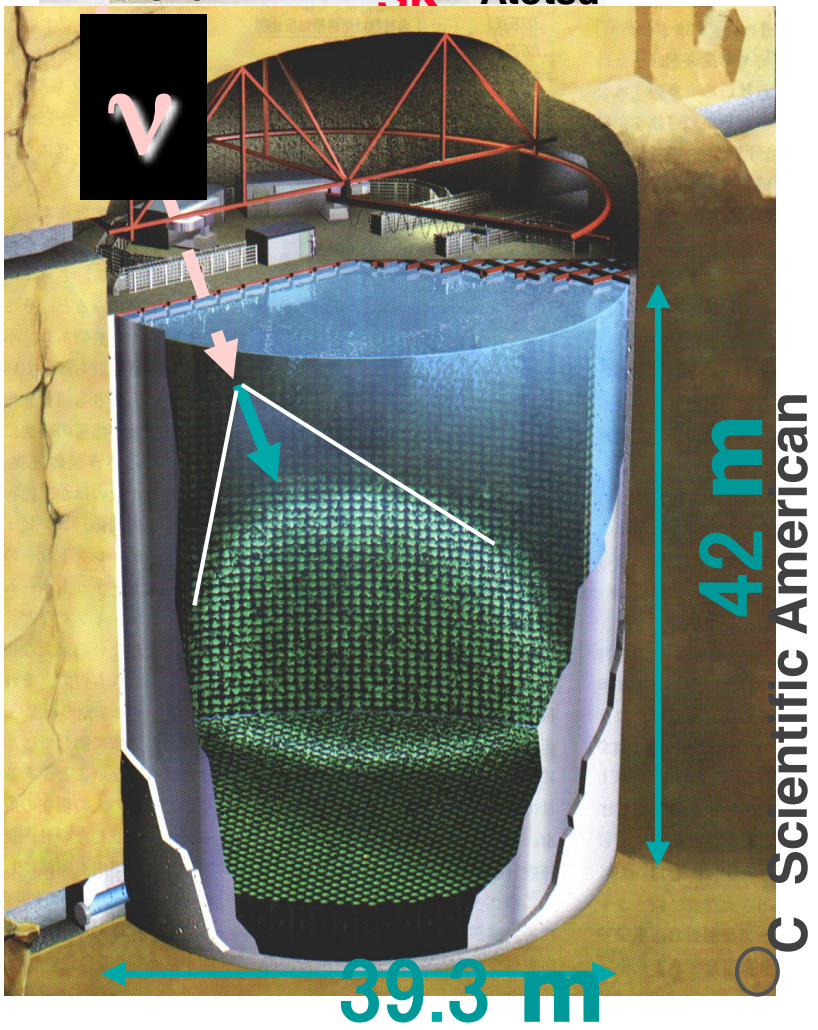
$\theta_{23}\sim45\pm5^\circ$ $\Delta m^2_{23}=2.4\times10^{-3}\mathrm{eV}^2$	$\theta_{12}\sim34\pm3^\circ$ $\Delta m^2_{21}=7.6\times10^{-5}\mathrm{eV}^2$	$\theta_{13}\sim9^\circ$	δ=unknown
Atmospheric ν, Accelerator ν	Solar ν, Reactor ν	Accelerator ν, Reactor ν	Accelerator ν, Atmospheric ν

$\Delta m^2_{32}=m^2_3-m^2_2>0$ (Normal mass hierarchy) or $\Delta m^2_{32}<0$ (Inverted mass hierarchy) is also unknown

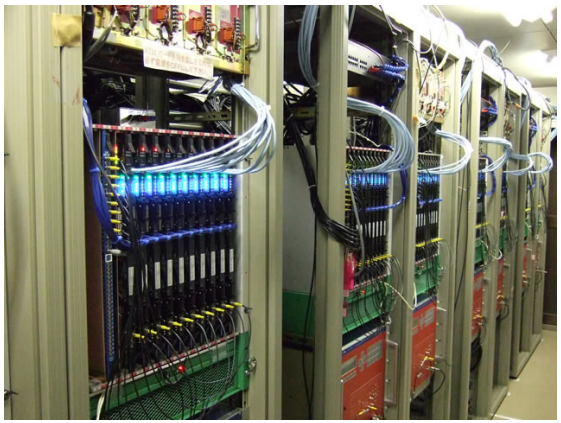
(key parameter for ν less ββ decay searches)

Majorana nature is also unknown

Super-K detector

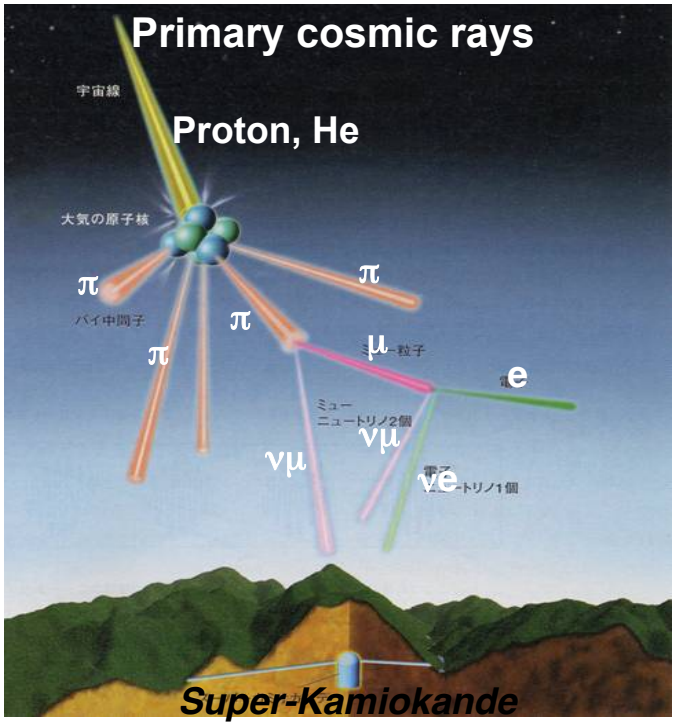


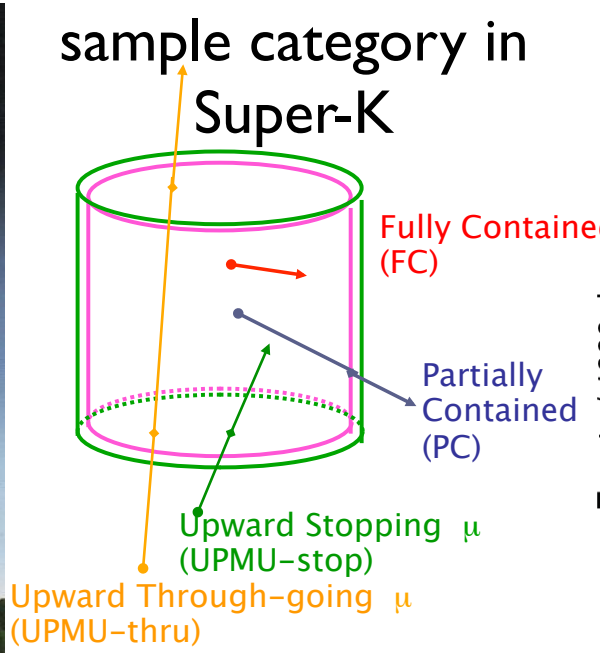
- Ring-imaging water Cherenkov detector
  - Fiducial volume 22kton (Total volume 50 kton)
  - Photon yield ~10p.e. / MeV
  - Atmospheric ν ~10 events/day
  - Solar ν ~15 events/day
  - Accelerator ν ~1 events/day (depends on the accelerator power)
  - always ready for Supernova ν and nucleon decays
- Observables
  - Direction of recoiled charged particles (leptons, pions, γ) by neutrinos
  - Particle spices (neutrino flavor)
  - Energy
  - Time

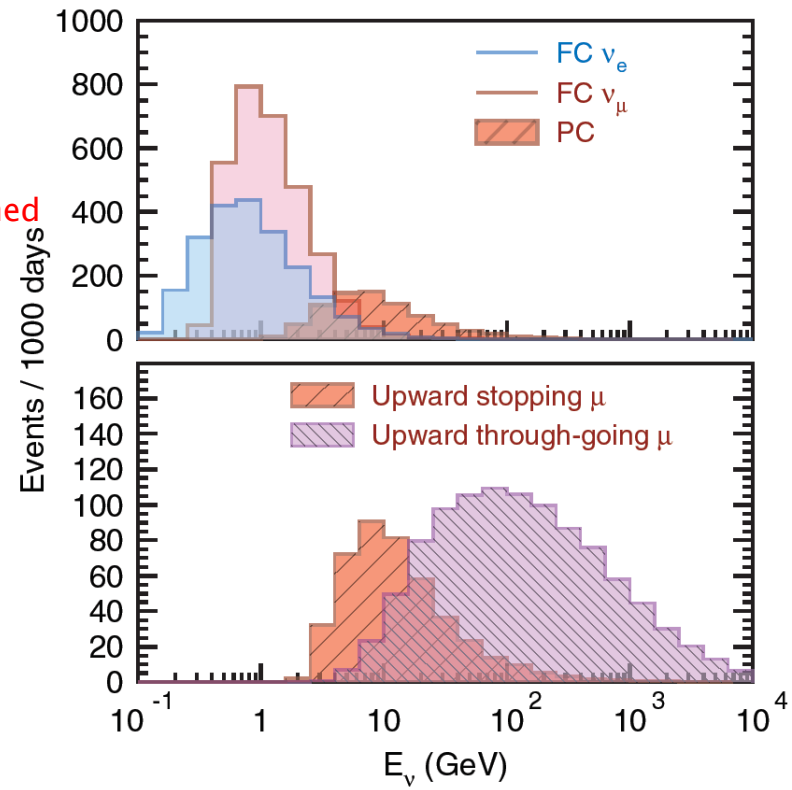


11,129 x 20inch PMTs (inner detector, ID)

Atmospheric Neutrinos in Super-K

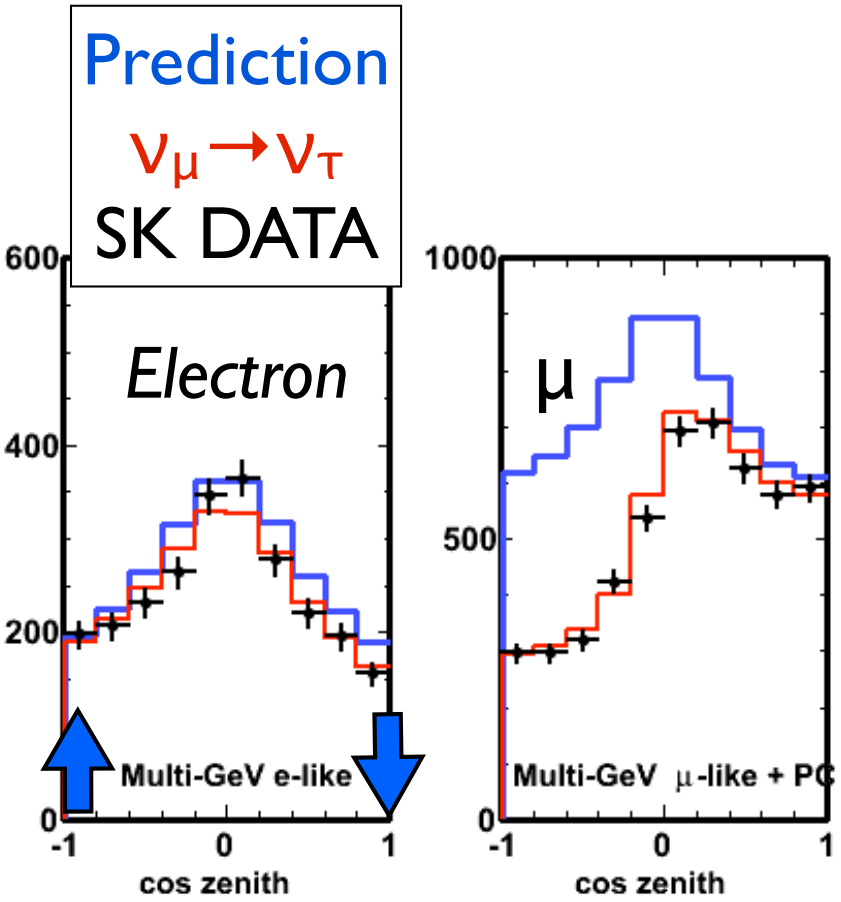


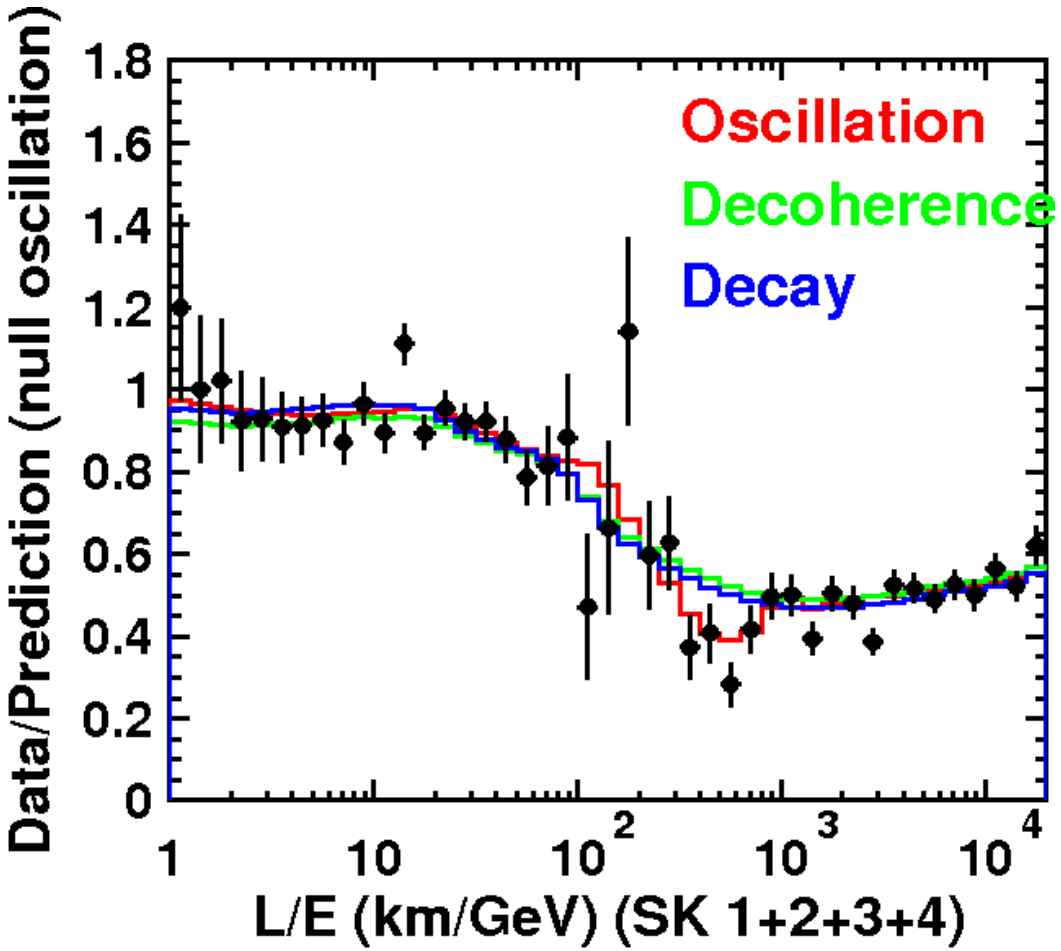




- Unique and complemental studies to solar/reactor/accelerator ν experiments
  - High statistical data (>40,000 events in Super-K)
  - Wide range of ν energy (0.1GeV ~ 10^4GeV)
  - Wide range of ν baseline (10km downward ~ 13,000km upward)
  - ν_μ:ν_e ~ 2:1 at production
  - ν oscillation study by all three flavors (ν_e, ν_μ, ν_τ)
  - test of ν's exotic property (4th ν, Lorentz violation, etc)

Early history of atmν's oscillations





- Dominant effect is ν_μ disappearance **(discovered in 1998)**
- Oscillatory signature **(evidence in 2004)**

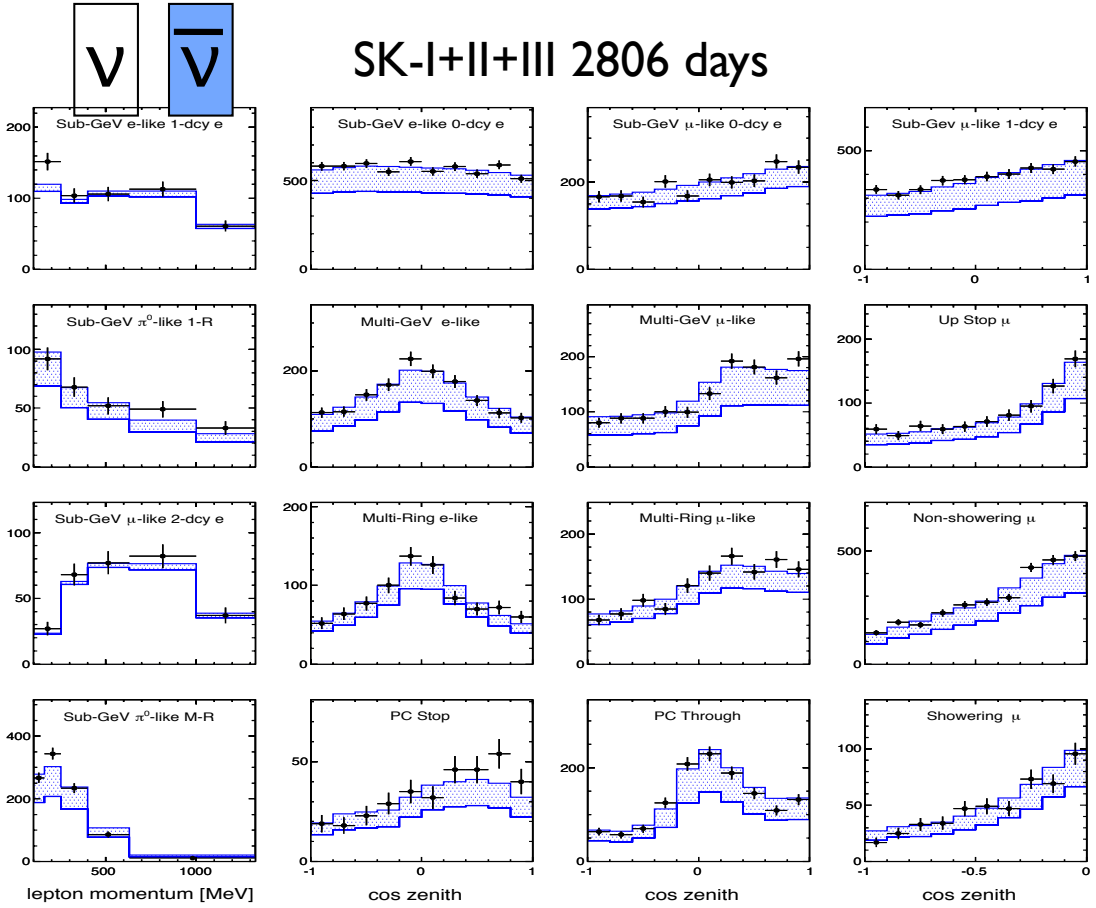
$\bar{\nu}_\mu$ oscillation study

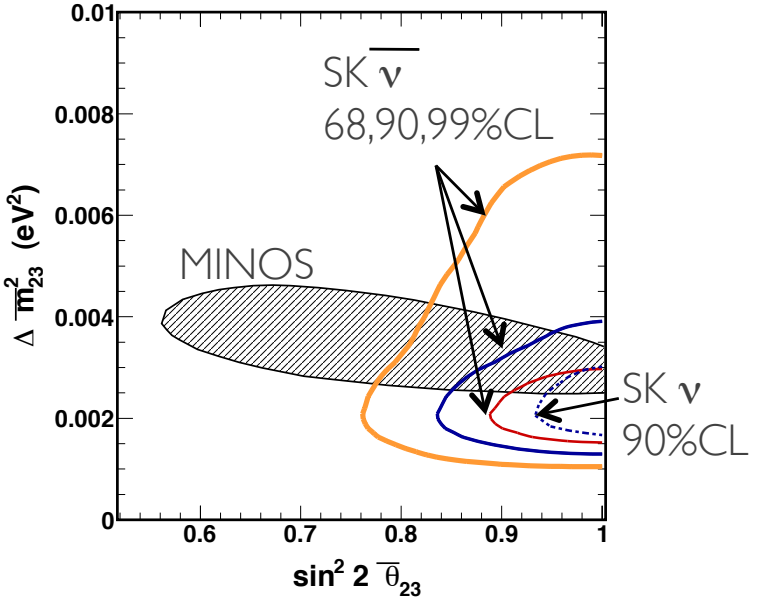
PRL 107, 241801 (2011)

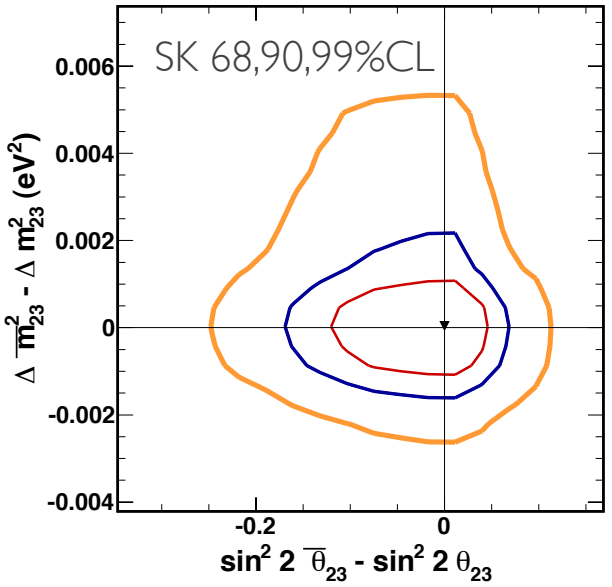
$$P(\nu_\mu \to \nu_\tau) = 1 - \sin^2 2\vartheta \sin\left(\frac{\Delta m^2 L}{E}\right)$$

$$P(\bar{\nu}_\mu \to \bar{\nu}_\tau) = 1 - \sin^2 2\bar{\vartheta} \sin\left(\frac{\Delta \bar{m}^2 L}{E}\right)$$

ν and ν-bar differ
- cross sections
- flux
- event topology

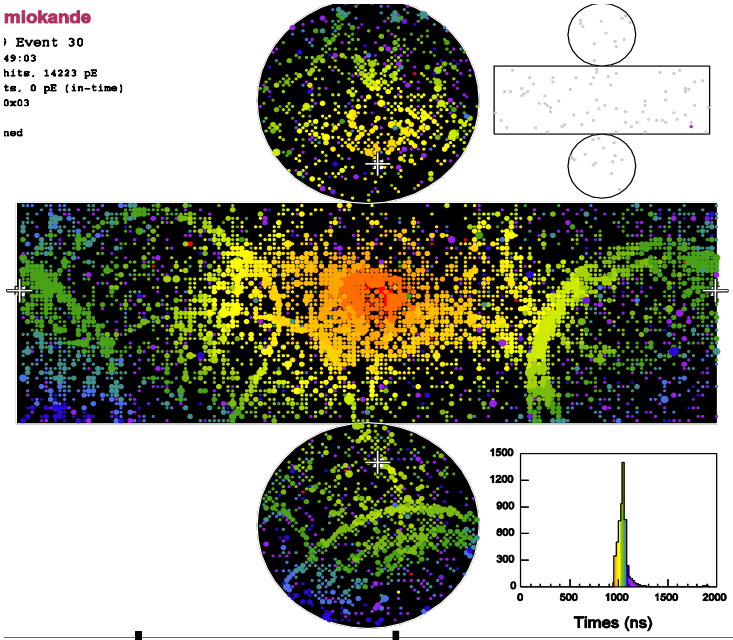






Good constraints on anti-neutrino parameters.
Data is consistent with CPT conservation.

Evidence for τ neutrino appearance

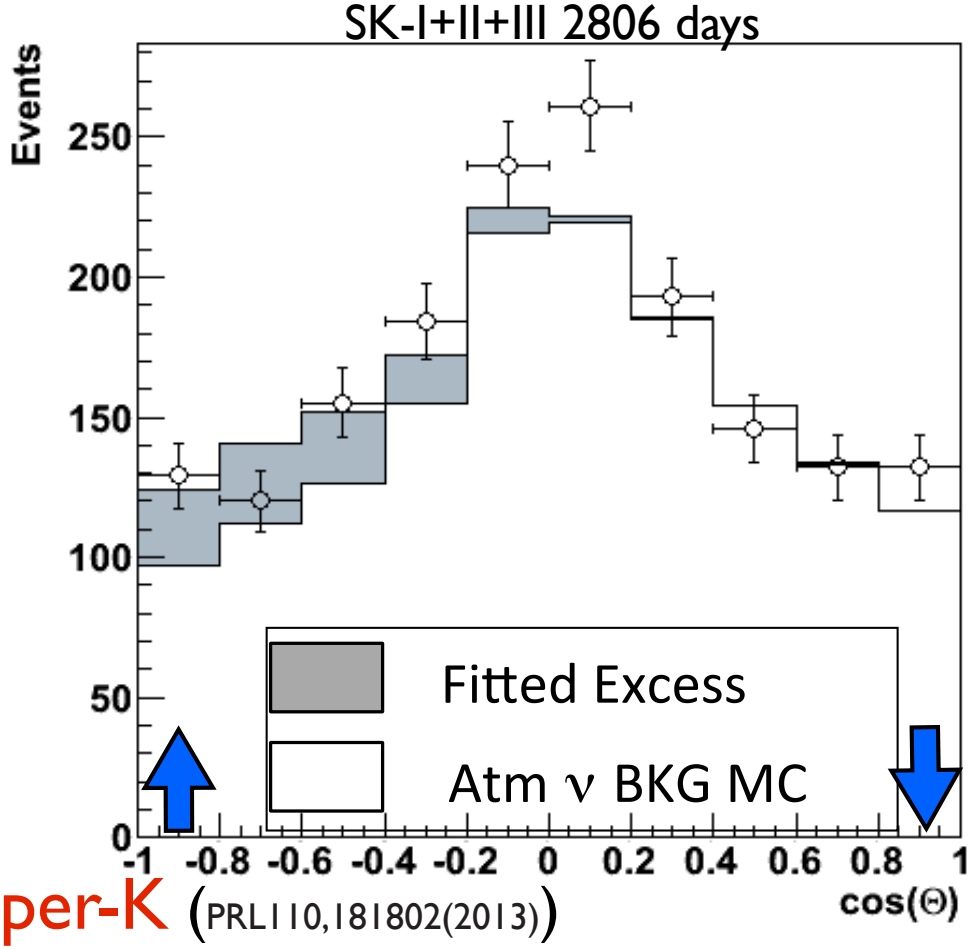


Neural network to enhance events consistent with hadronic decays of τ

$N_\tau^{DATA}/N_\tau^{exp}$
$=1.42\pm0.35(stat)+^{0.14}_{-0.12}(syst)$

PRL 110, 181802 (2013)

Zenith Distribution of τ-like events

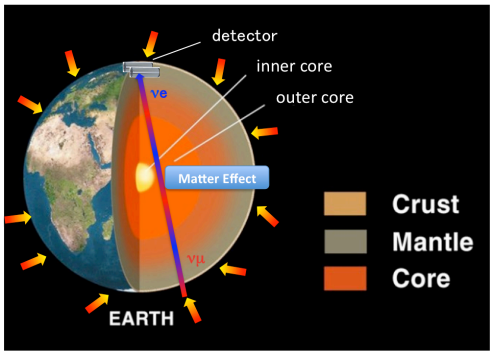


Evidence(3.8σ significance)@Super-K (PRL110,181802(2013))

5 τ observation (>5σ) @ OPERA (PRL115,121802(2015))

Atmospheric ν anomaly (problem) is finally concluded.
More precise measurement will be conducted in future.

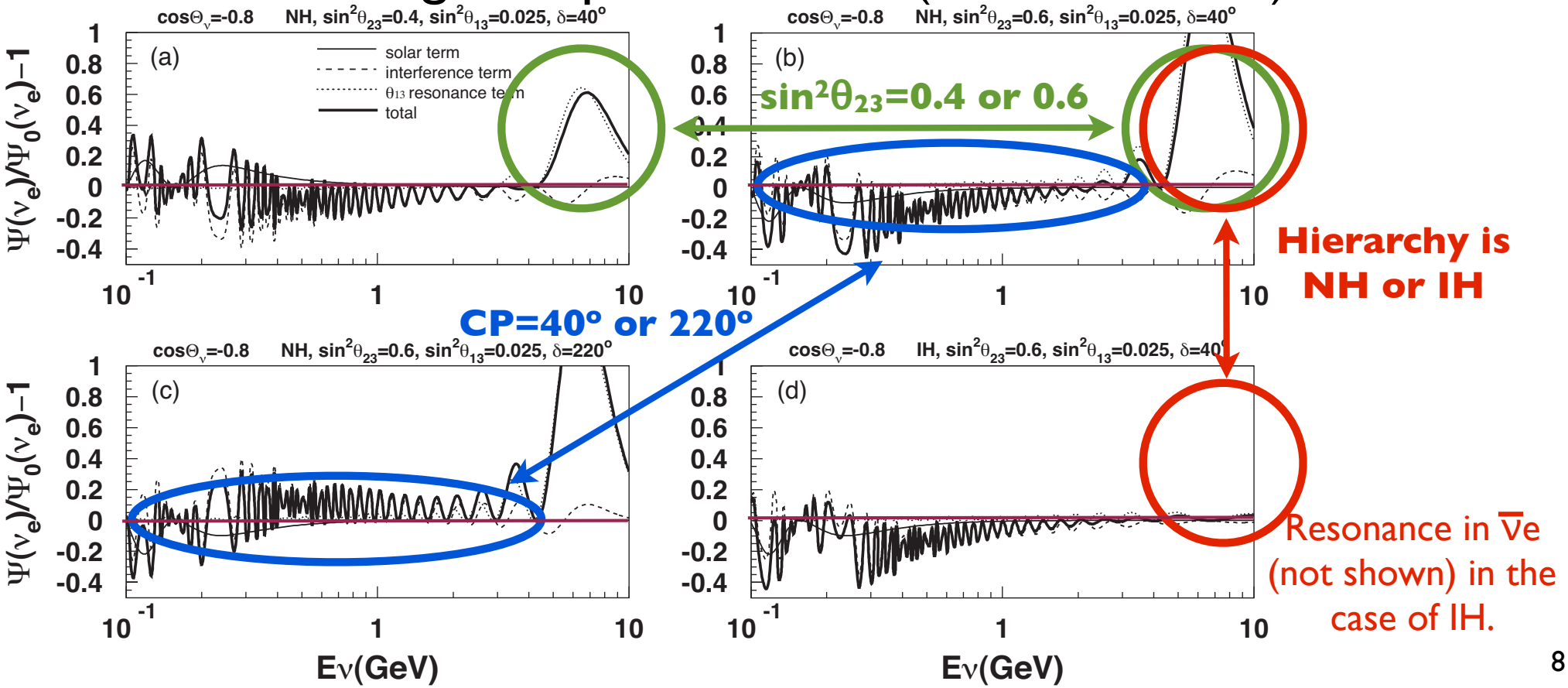
Atmospheric ν_e oscillation



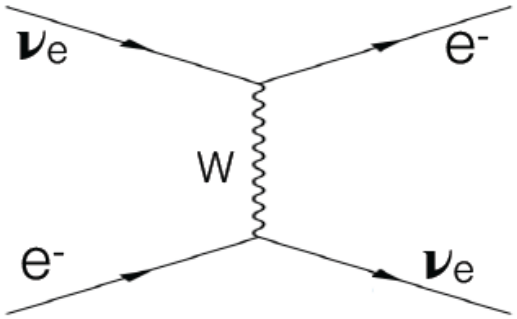
Through the matter effect in the Earth, we study on

- Mass hierarchy : resonance in multi-GeV $\bar{\nu}e$ or νe
- CP δ : interference btw two Δm^2 driven oscill.
- θ_{23} octant : magnitude of the resonance

"Fractional change of upward ν_e flux ($\cos\Theta_{zenith}$=-0.8)"



Test of Earth's matter effect

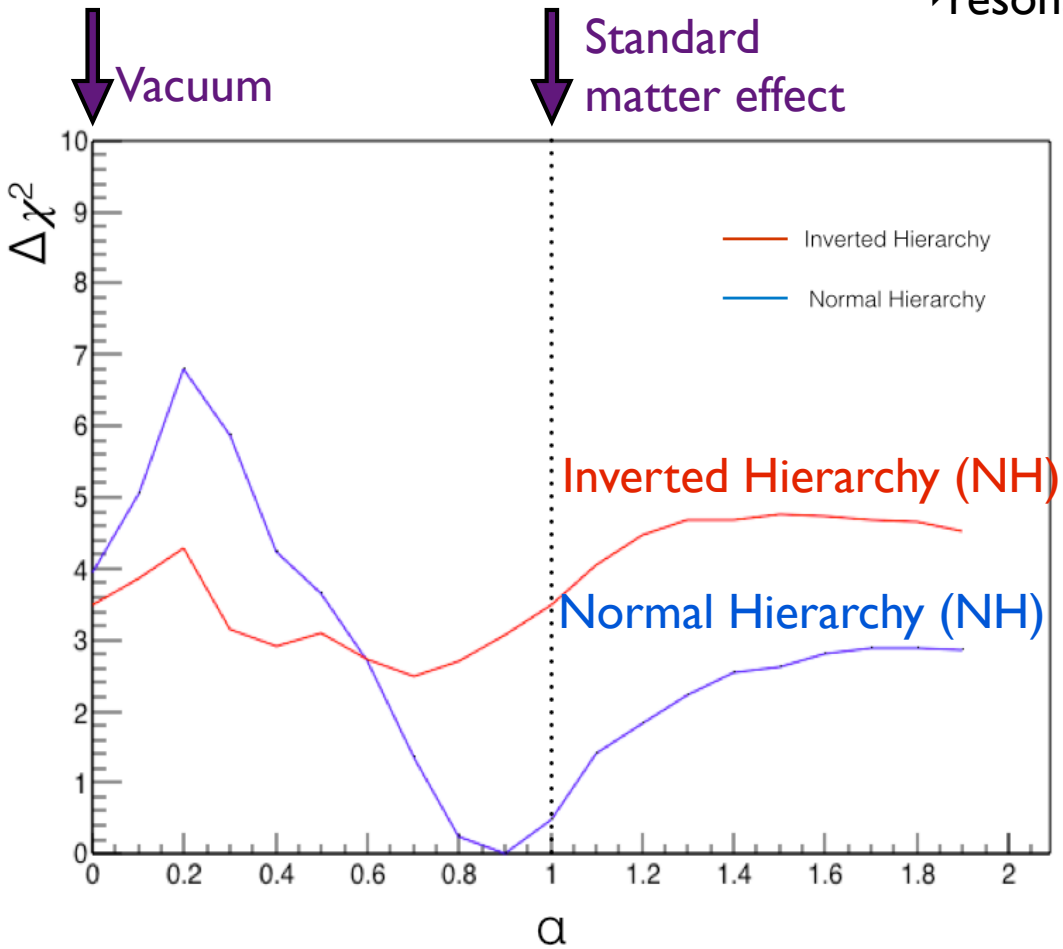


$$V_{cc}^{\nu_e} = \pm\sqrt{2}G_F N_e = \pm 7.56 \times 10^{-14}\left(\frac{\rho}{g/cm^3}\right) Y_e eV$$

(V>0 for ν, V<0 for anti-ν)

$$\sin 2\theta_m = \frac{\sin 2\theta}{\sqrt{\sin^2 2\theta + \left(\cos 2\theta - \frac{2EV}{\Delta m^2}\right)^2}}$$

- Δm^2_{32}>0 for Normal Mass Hierarchy (NH)
  →resonant oscillation in ν(V>0)
- Δm^2_{32}<0 for Inverted Mass Hierarchy (IH)
  →resonant oscillation in anti-ν(V<0)



α:scaling factor of the matter effect
(α=1: standard, α=0: vacuum)

χ^2 minimum at α=0.9

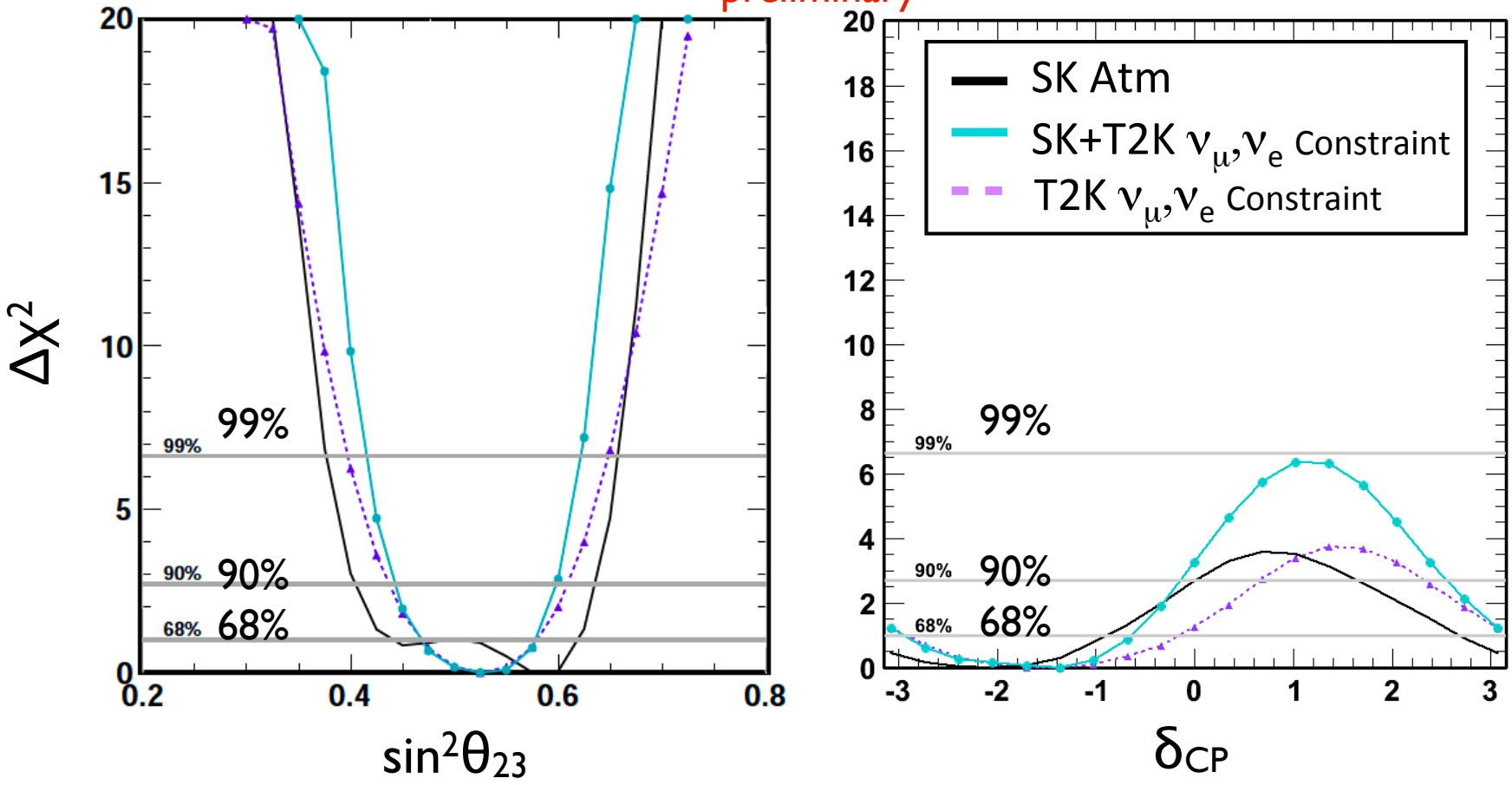
$\Delta\chi^2_{vac} = 3.5$

$\Delta\chi^2$ "standard" matter $= 0.5$

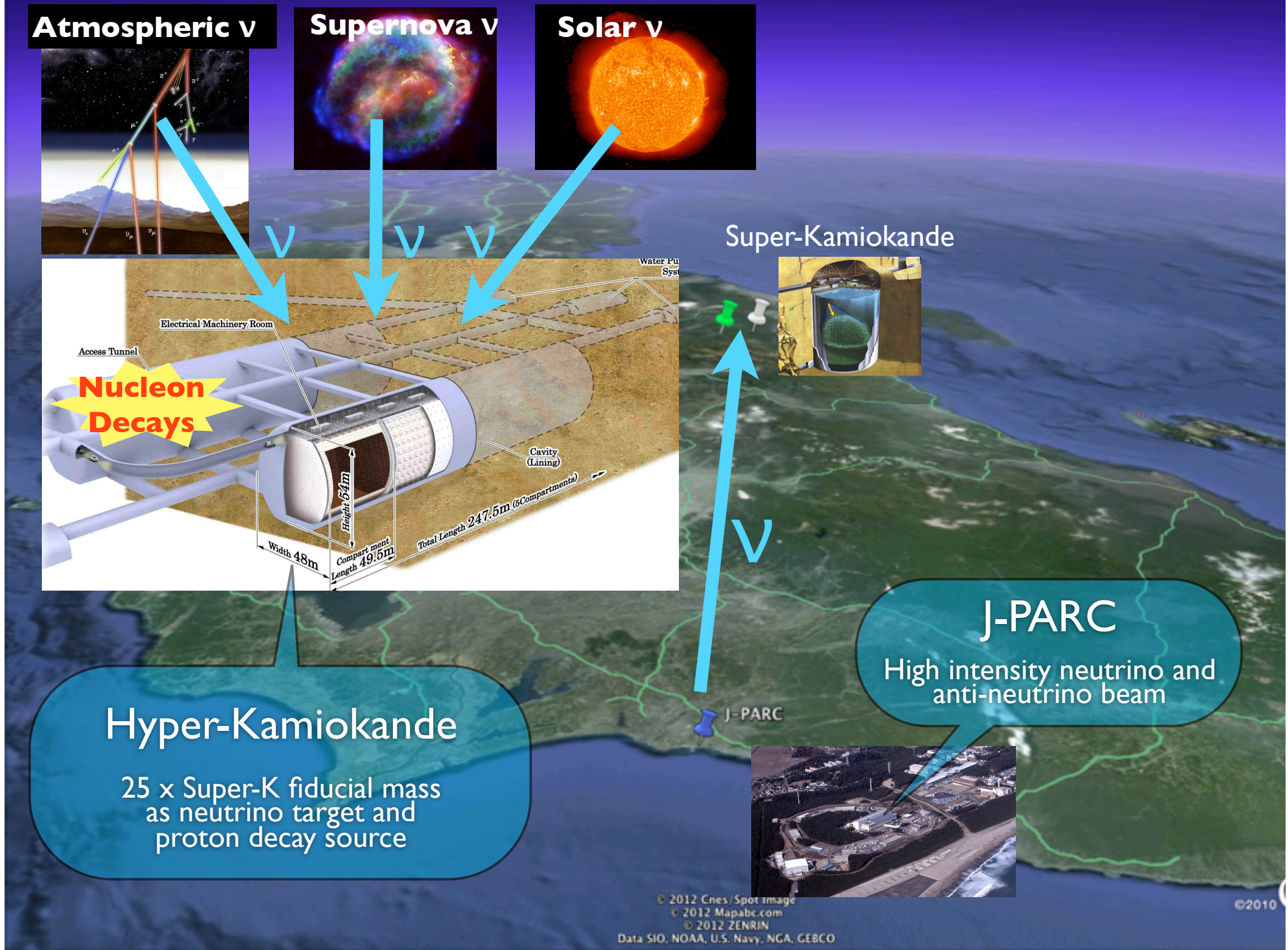
χ^2_{IH}-χ^2_{NH}=3 (α=1fixed)
Normal Hierarchy is favored.
More data is necessary, analysis improvement is also going on.

Results w/ T2K's constraints

preliminary



- Preference of normal hierarchy is slightly strengthened, $\chi^2_{IH}-\chi^2_{NH}=3.2$ (3.0 for SK only)
- T2K/SK are getting constraint on CP δ
  - Preference of δ_{CP} near $-\pi/2$ is strengthened by T2K
  - CP conservation ($\sin\delta_{CP}=0$) is still allowed at 90% CL

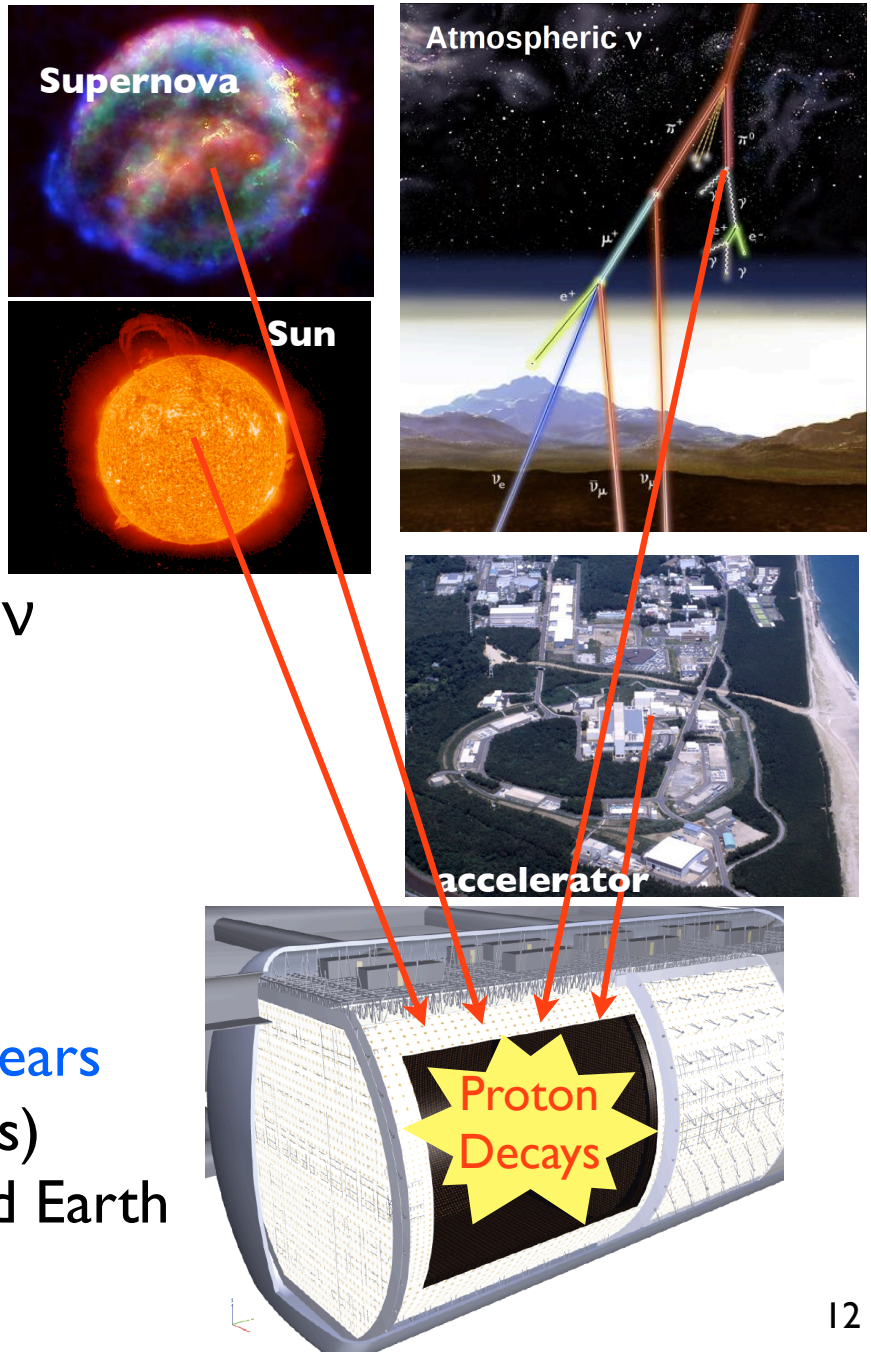

Atmospheric ν
Supernova ν
Solar ν
ν
ν
ν
Super-Kamiokande
Electrical Machinery Room
Access Tunnel
Nucleon Decays
Cavity (Lining)
Height 54m
Width 48m
Compartment Length 49.5m
Total Length 247.5m (5Compartments)
ν
J-PARC
Hyper-Kamiokande
25 x Super-K fiducial mass as neutrino target and proton decay source
J-PARC
High intensity neutrino and anti-neutrino beam
© 2012 Cnes/Spot Image
© 2012 Mapabc.com
© 2012 ZENRIN
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
©2010

Multi-purpose detector, Hyper-K

Letter of Intent, Hyper-K WG, arXiv:1109.3262 [hep-ex]

LBL study, Hyper-K WG, arXiv:1502.05199 and published in PTEP

- Proton decay 3σ discovery potential
  - 5×10^{34} years for $p\rightarrow e^+\pi^0$
  - 1×10^{34} years for $p\rightarrow \nu K^+$
- Comprehensive study on ν oscillations
  - CPV (76% of δ space at 3σ), <20° precision
  - MH determination for all δ by J-PARC/Atm ν
  - θ_{23} octant: $\sin^2\theta_{23}<0.47$ or $\sin^2\theta_{23}>0.53$
  - <1% precision of Δm^2_{32}
  - test of exotic scenarios by J-PARC/Atm ν
- Astrophysical neutrino observatory
  - Supernova up to 2Mpc distance, ~1SN /10 years
  - Supernova relic ν signal (~200ν events/10yrs)
  - Dark matter neutrinos from Sun, Galaxy, and Earth
  - Solar neutrino ~200ν events/day



Hyper-K proto-collaboration w/ cooperation of KEK-IPNS and UTokyo-ICRR

Inaugural Symposium on 1/31, 2015

Hyper-K Proto-Collaboration has been formed

MoU signing by KEK/ICRR

- **KEK-IPNS** and **Tokyo-ICRR** signed the **MOU** of the cooperation in promoting the Hyper-Kamiokande.

What's next?: Design Report

- **Design Report** to be prepared in 2015
  - Optimum design, Construction cost/period, Beam&Near detectors, International responsibility

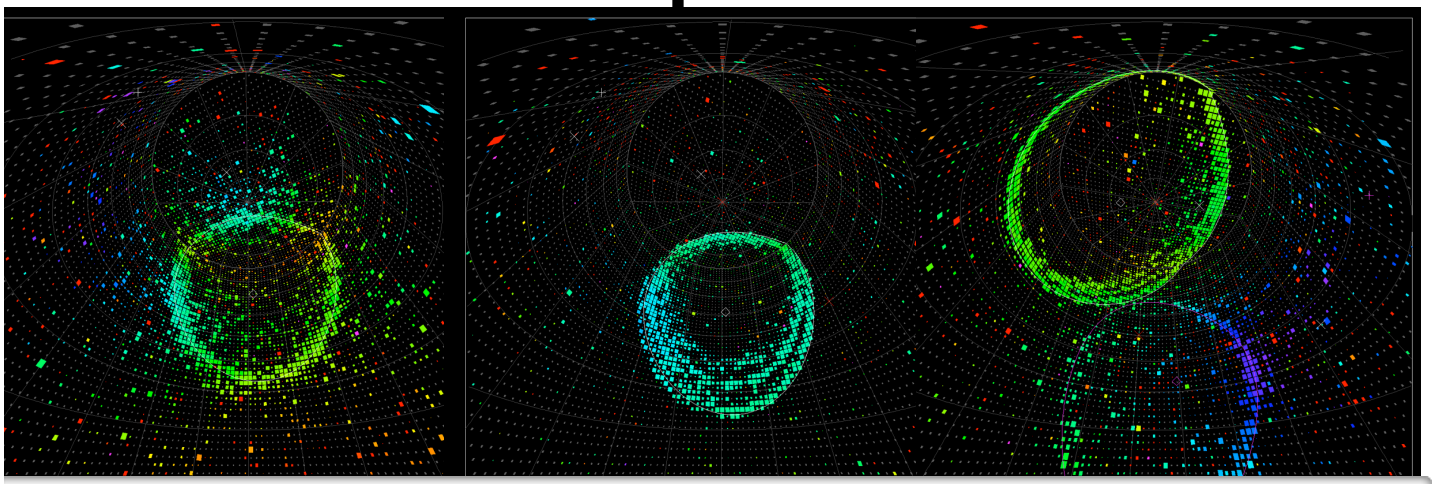
- **International Advisory Committee** under **KEK-IPNS/ICRR** to develop the project

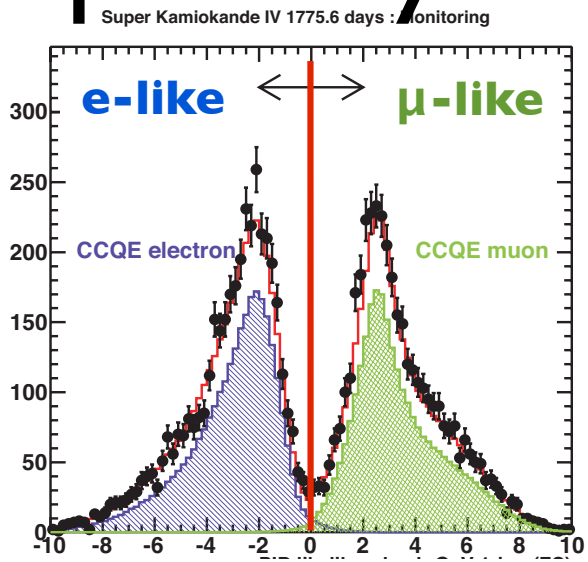
- Start **budget request**, and **Start construction** in 2018
  → start operation in ~2025

It is critical period to promote the project

Still open for new collaborators

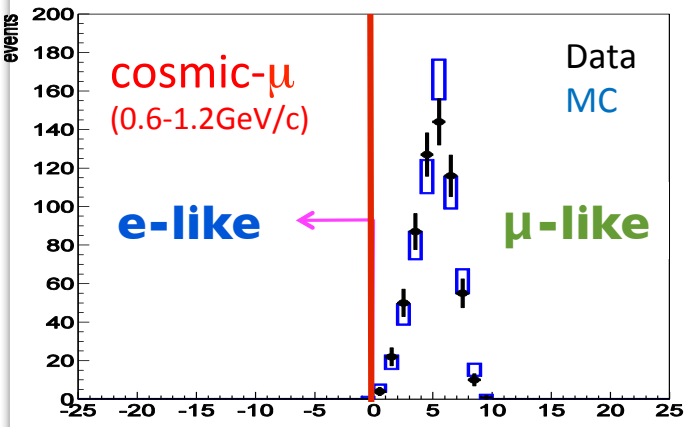
Detector performance for p-decays





PID likelihood (atmν)

- High mass (1Mton scale, 20×Super-K)
- Good ring-imaging capability at ~1GeV
  - atmospheric ν, proton decays, accelerator ν
- Excellent particle ID (e or μ) capability > 99%
- Energy resolution for e and μ ~3%
- opportunity to improve more
- for proton decay search via $p \rightarrow e^{+}\pi^{0}$
  - good ~5% invariant proton mass resolution
  - high 40% signal efficiency
  - 99.998% atmospheric ν BG rejection

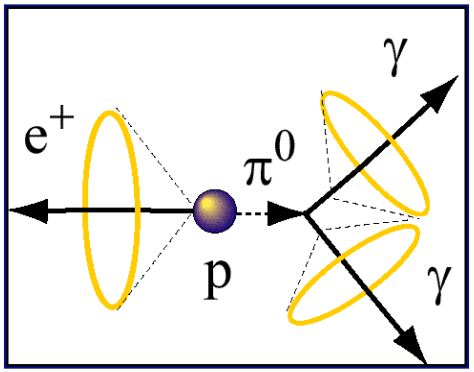


PID likelihood (CRμ)

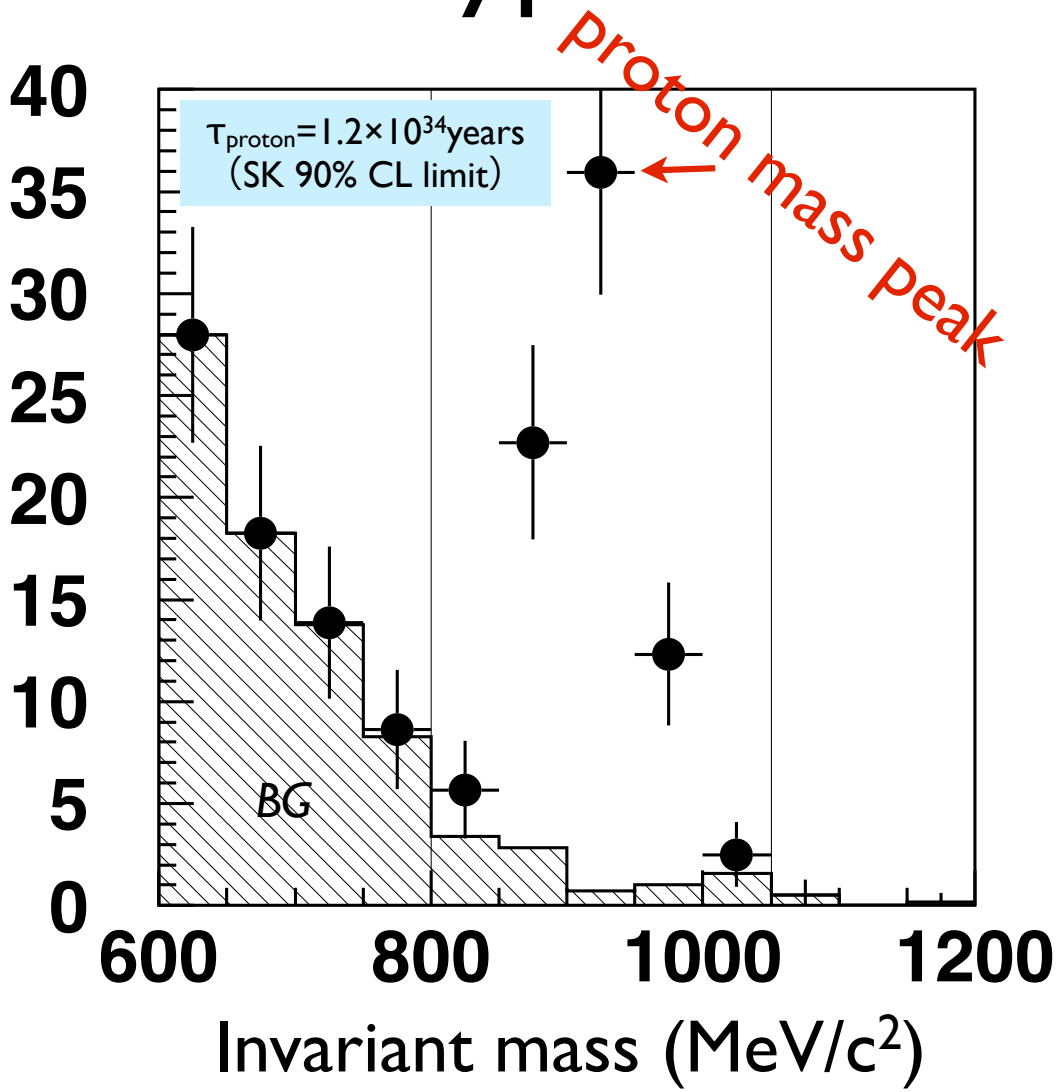
mis-PID:
Data: 0.00±0.16(stat.)%
MC : 0.10±0.10(stat.)%

Discovery potential in Hyper-K

$p \rightarrow e^+\pi^0$



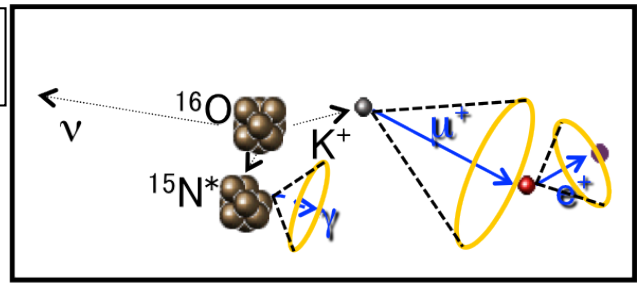
- Discovery reach (3σ)
  - $\tau(p \rightarrow e^+\pi^0) \sim 5\times10^{34}$years (HK 10yrs)
- Limit (90%CL)
  - $\tau(p \rightarrow e^+\pi^0) > 1\times10^{35}$years (HK 10yrs)



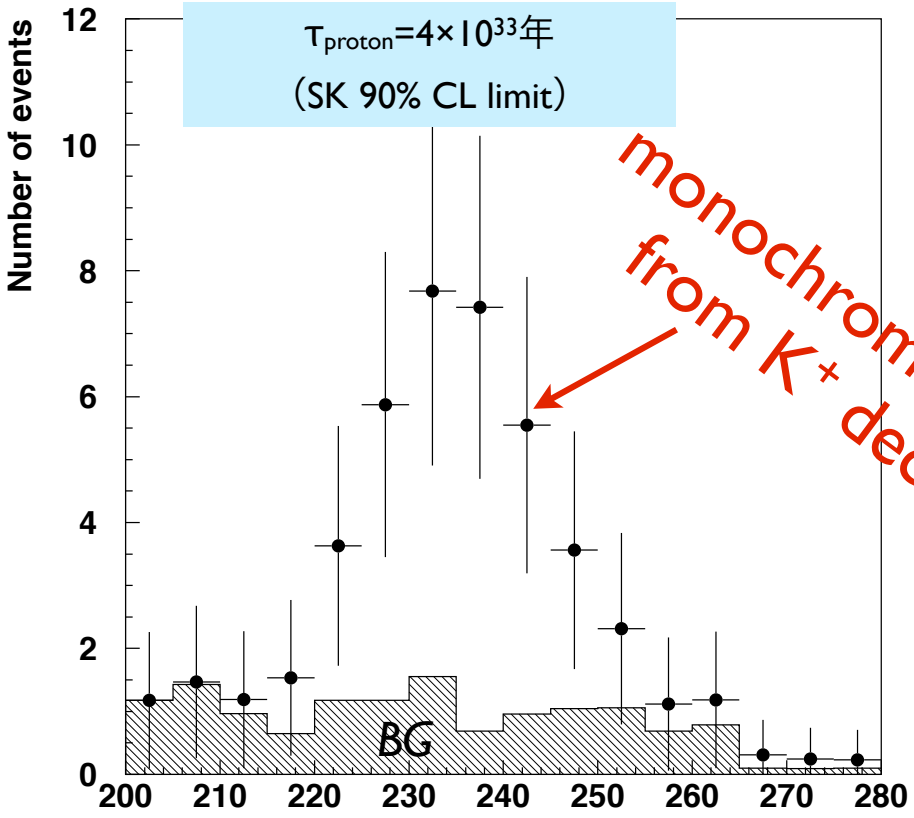
Only realistic proposal to reach the lifetime of 10^{35} years for $p \rightarrow e^+\pi^0$

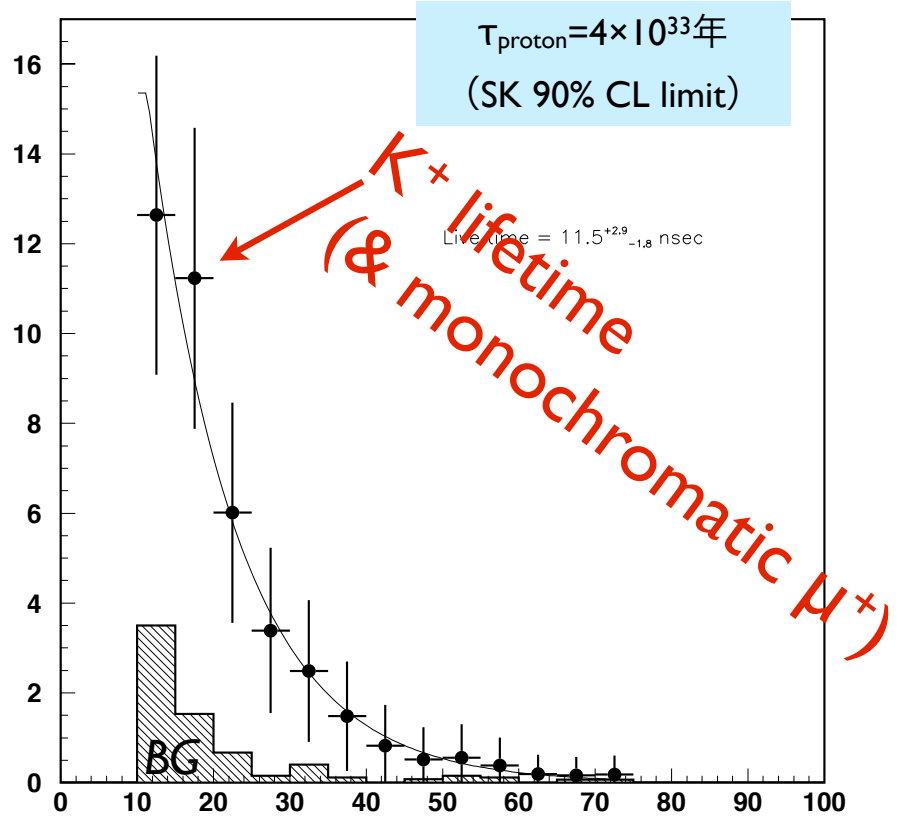
Discovery potential (2)

$p \rightarrow \nu K^+$



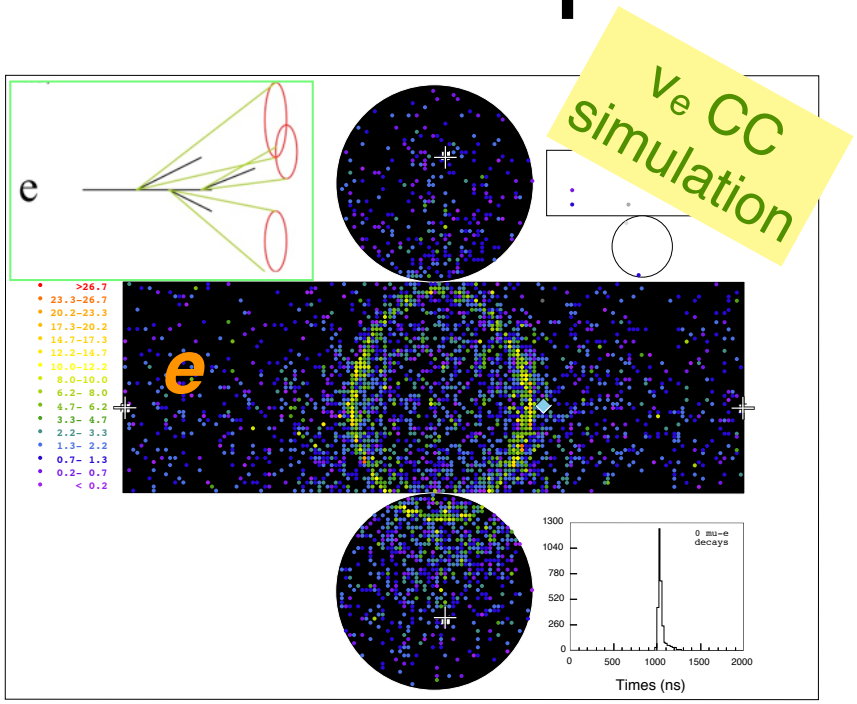
- Discovery reach (3σ)
  - $\tau(p \rightarrow \nu K^+) \sim 1 \times 10^{34}$years （HK 10yrs）
- Limit (90%CL)
  - $\tau(p \rightarrow \nu K^+) > 3 \times 10^{34}$years （HK 10yrs）

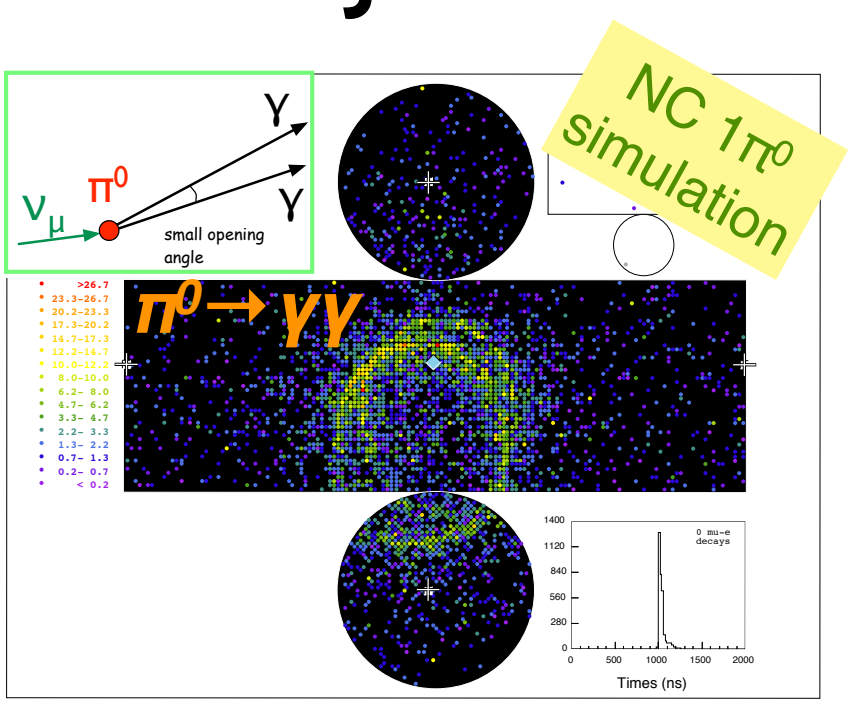




Experimental test on Supersymmetry

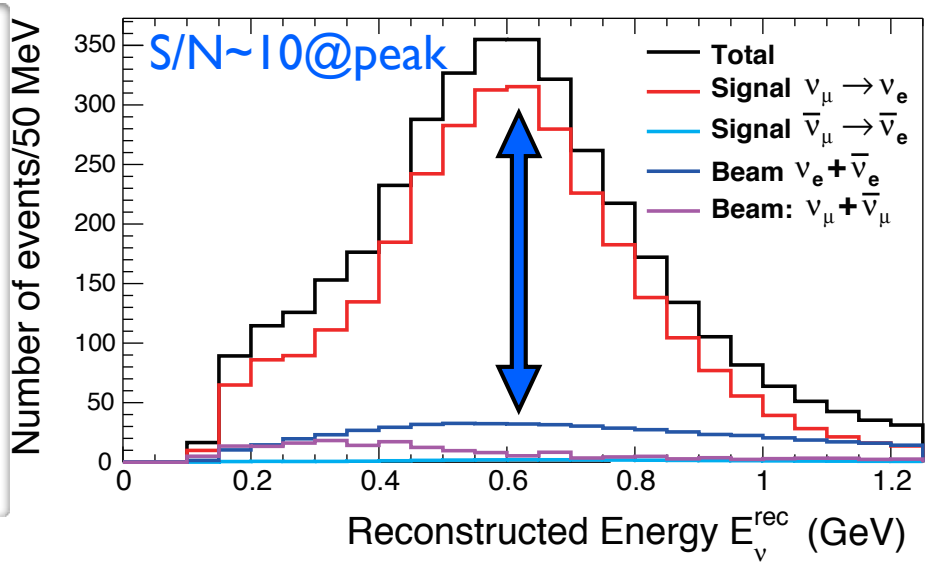
Detector performance for J-PARCν





Appearance ν mode

- For νe appearance in J-PARC ν_μ beam
  - high 60% νe signal efficiency
  - >99.9% ν_μCC rejection, 99% NC π^0 rejection
  - opportunity to improve more



δ_{CP} dependence of observables

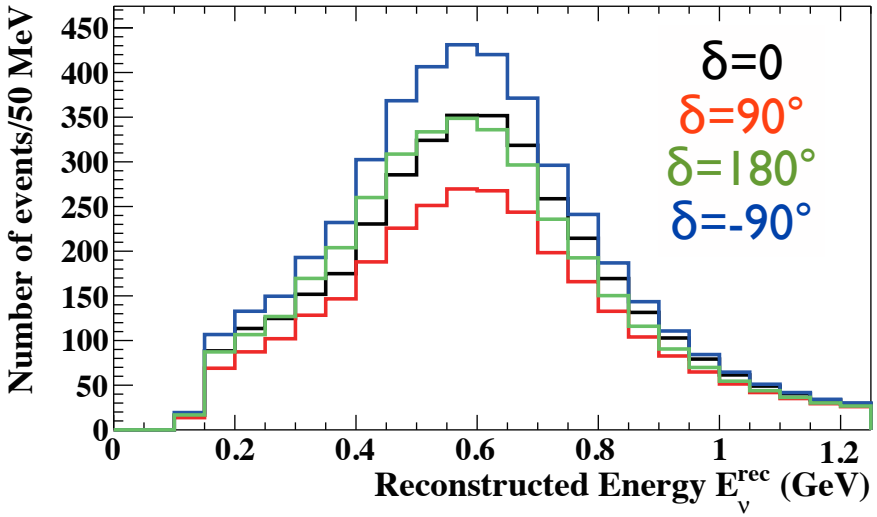
7.5MW×10^7s (1.56×10^{22} POT)

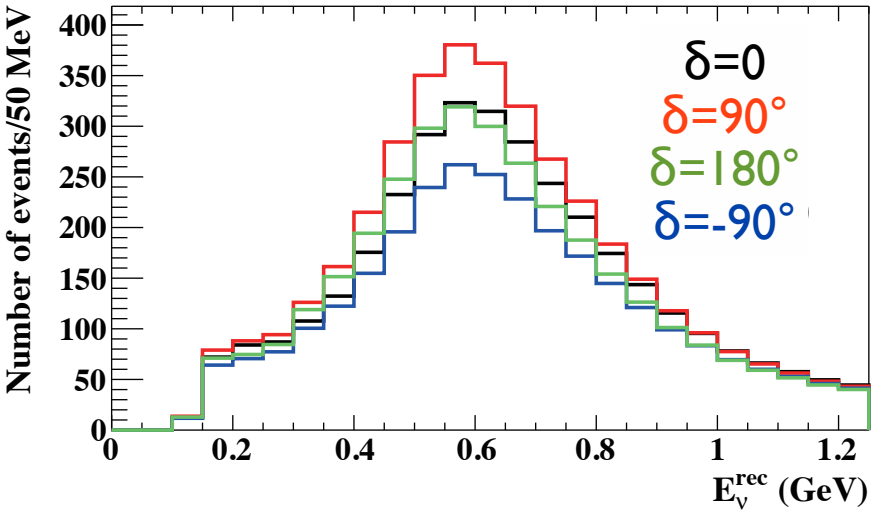
Neutrino mode: Appearance

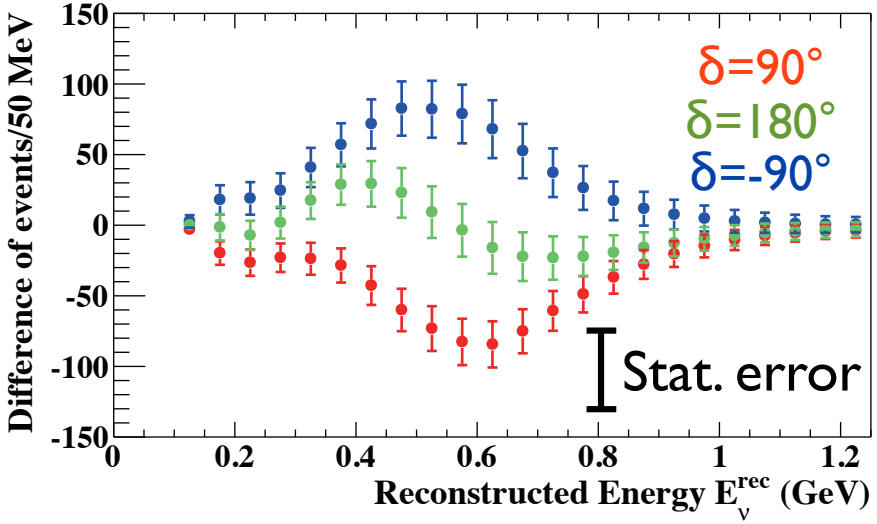
Antineutrino mode: Appearance

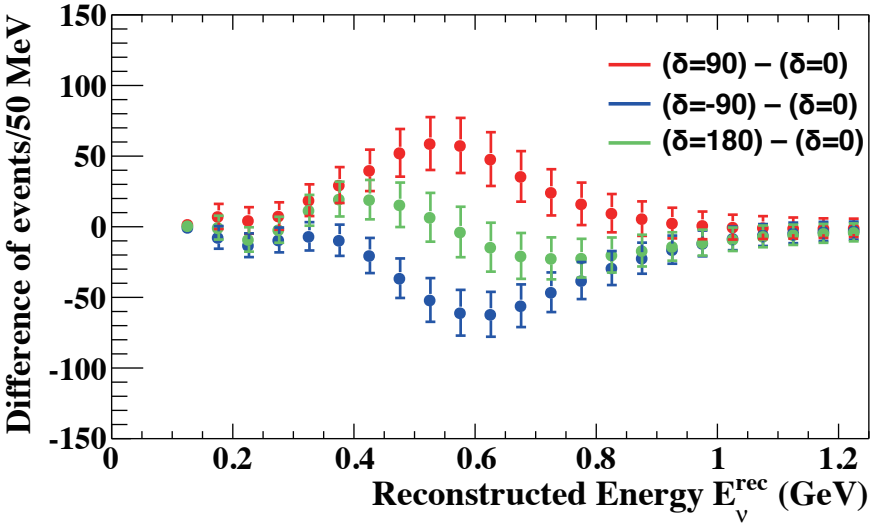
ve candidates

Difference from δ=0







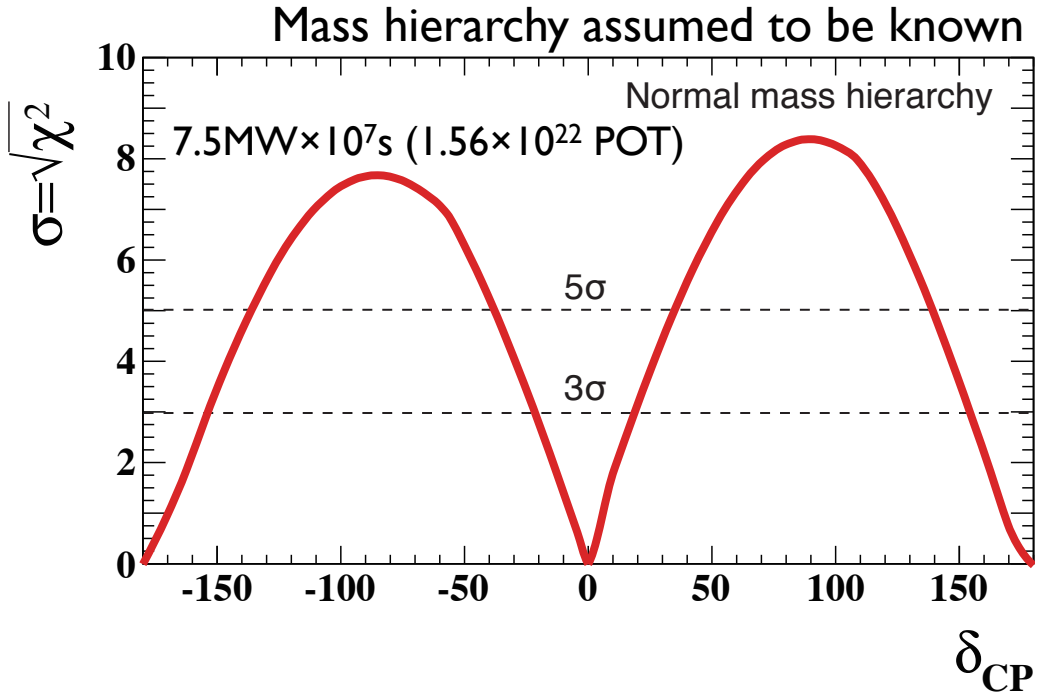


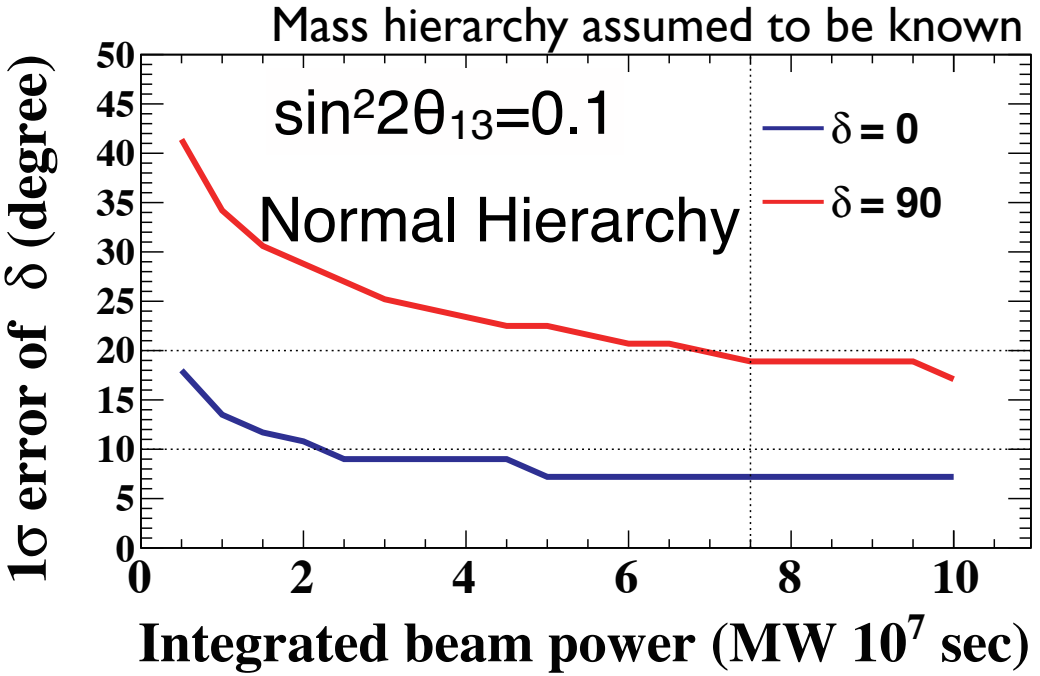
Sensitive to all values of δ with numbers + shape

Sensitivity to CP violation

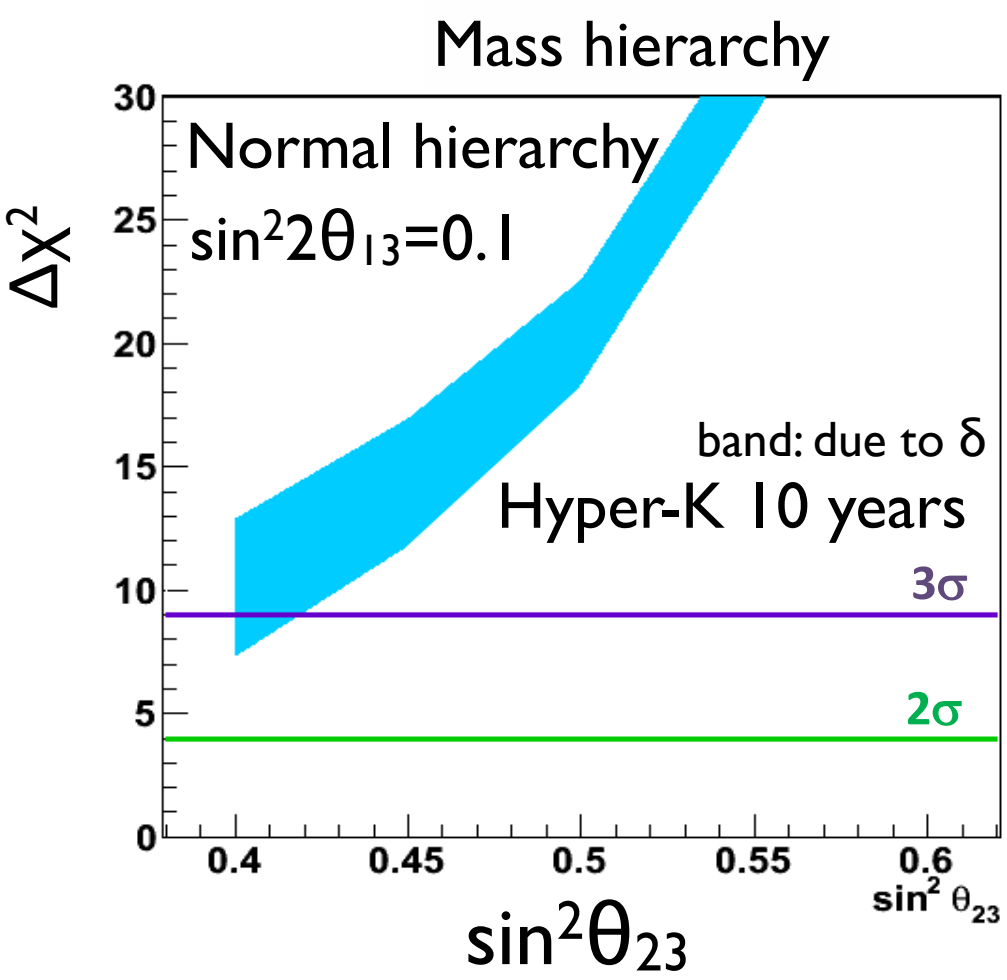
arXiv:1502.05199 and published in PTEP

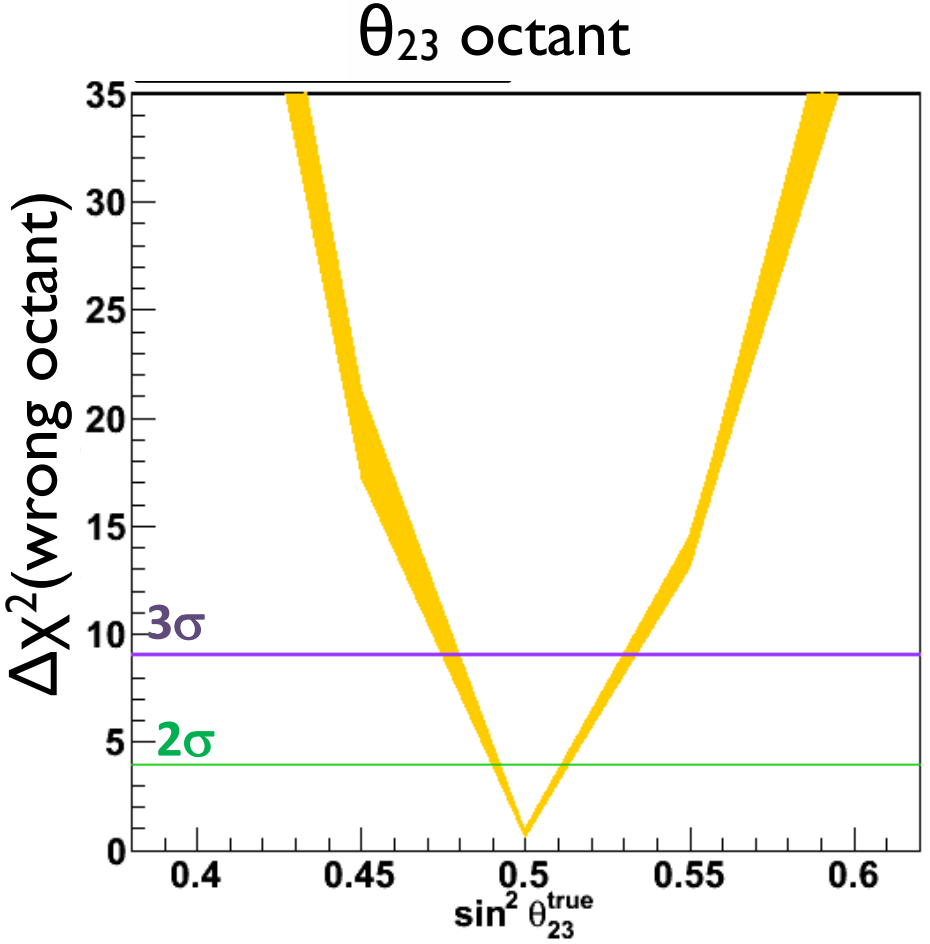
- Exclusion of sinδ=0
  - >3σ for 76% of δ
  - >5σ for 58% of δ
- 8°-19° precision depending on the true value of δ





Atmospheric ν

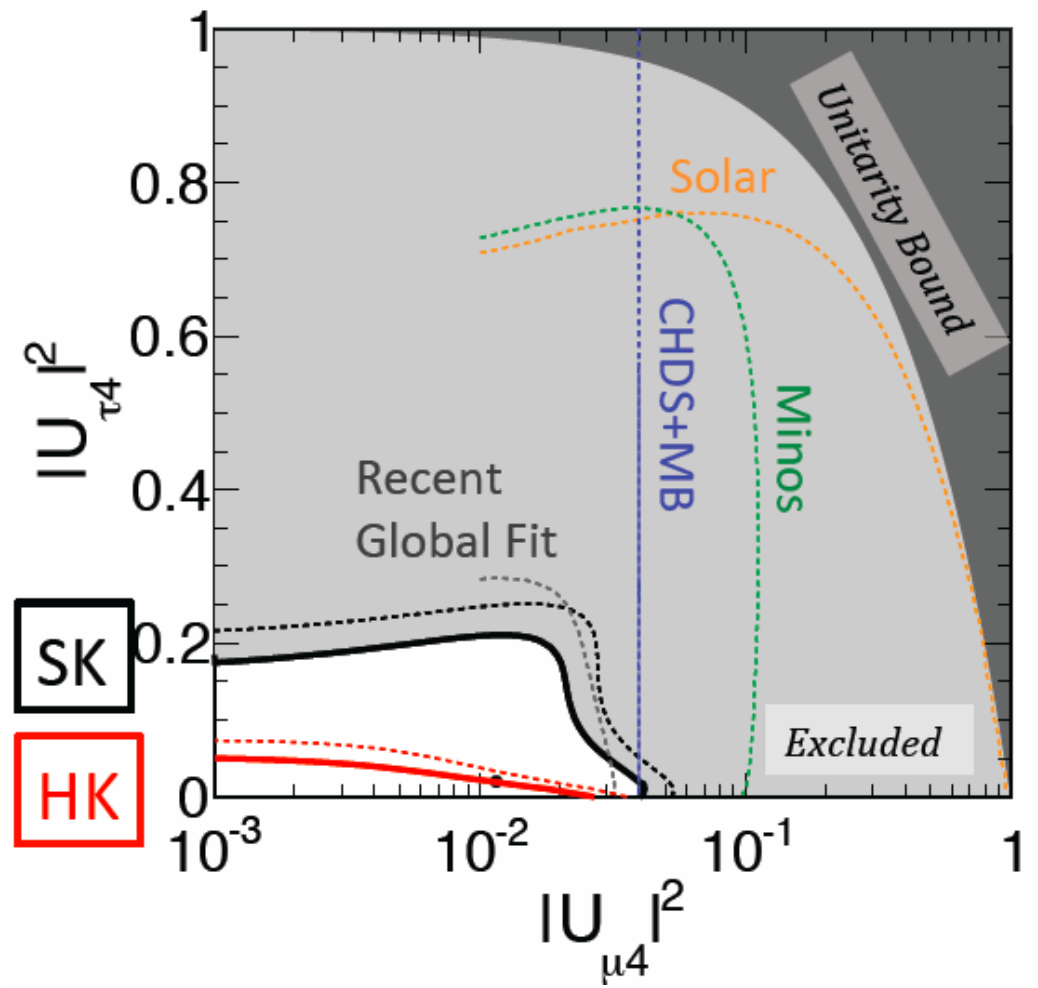


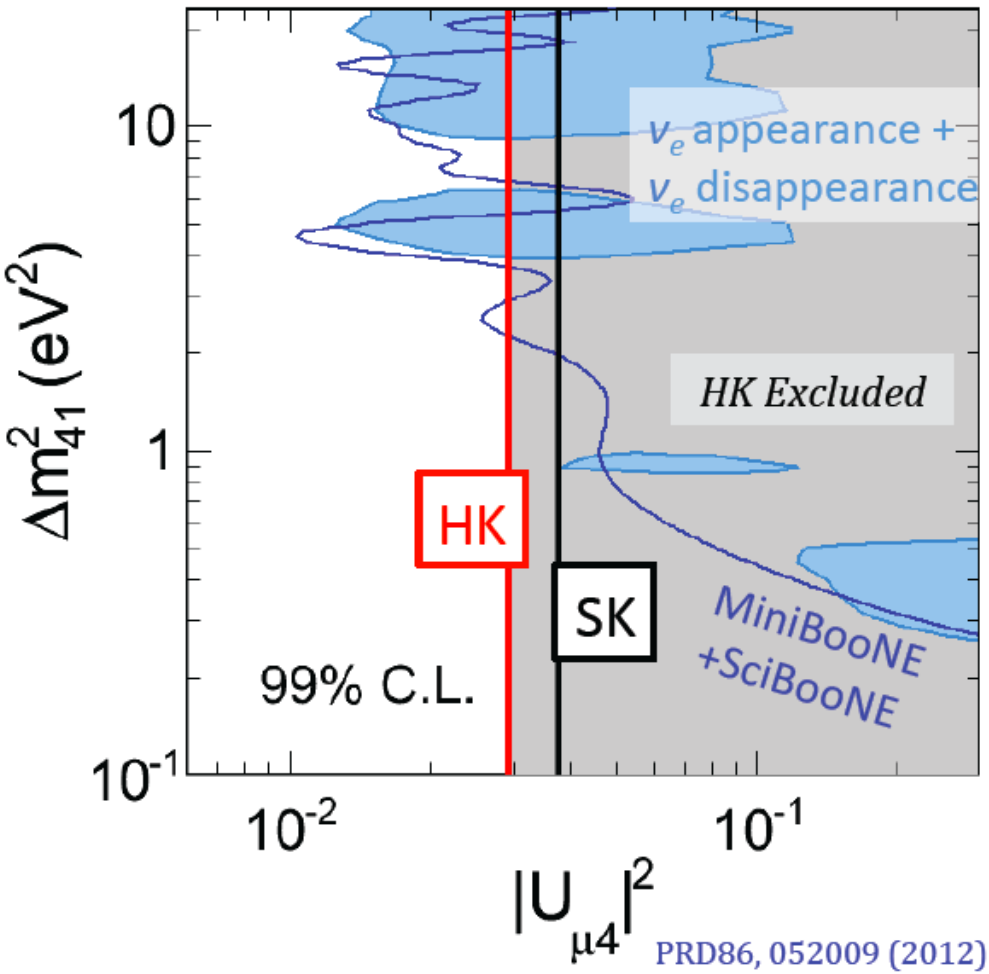


Complementary measurements to accelerator ν
Combined analysis of acc + atm ν will enhance capability

Test of Sterile ν by atmospheric ν

Look for **extra overall muon deficit** or **shape distortion**



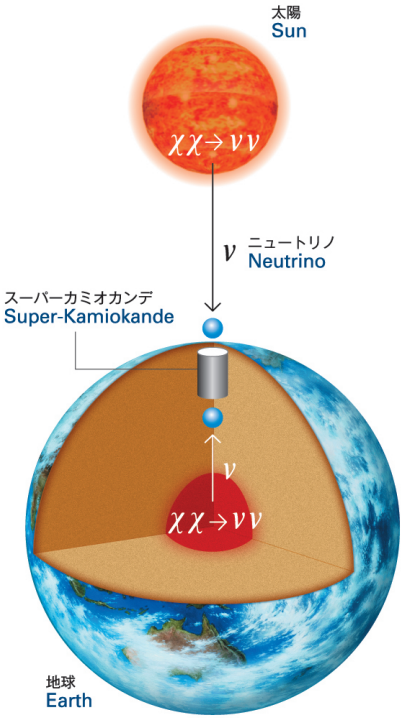


PRD86, 052009 (2012)
JHEP 1305 (2013) 050

$|U_{\tau 4}|^2$<0.066 @99%CL
(0.164 in Super-K)

$|U_{\mu 4}|^2$<0.029 @99%CL
(0.038 in Super-K)

Complementary to other experiments

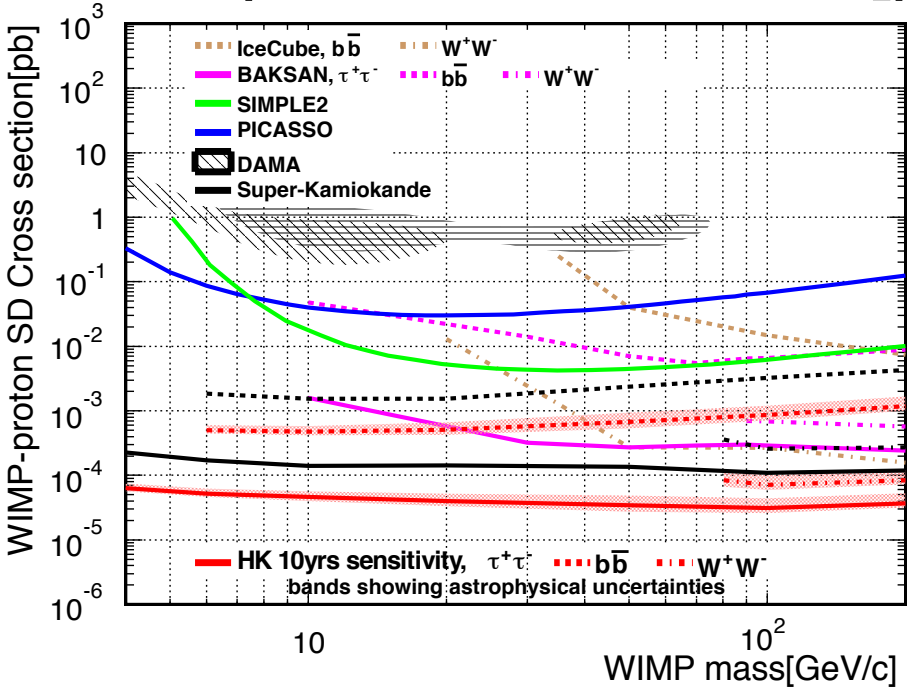


Search for ν's induced by dark matters

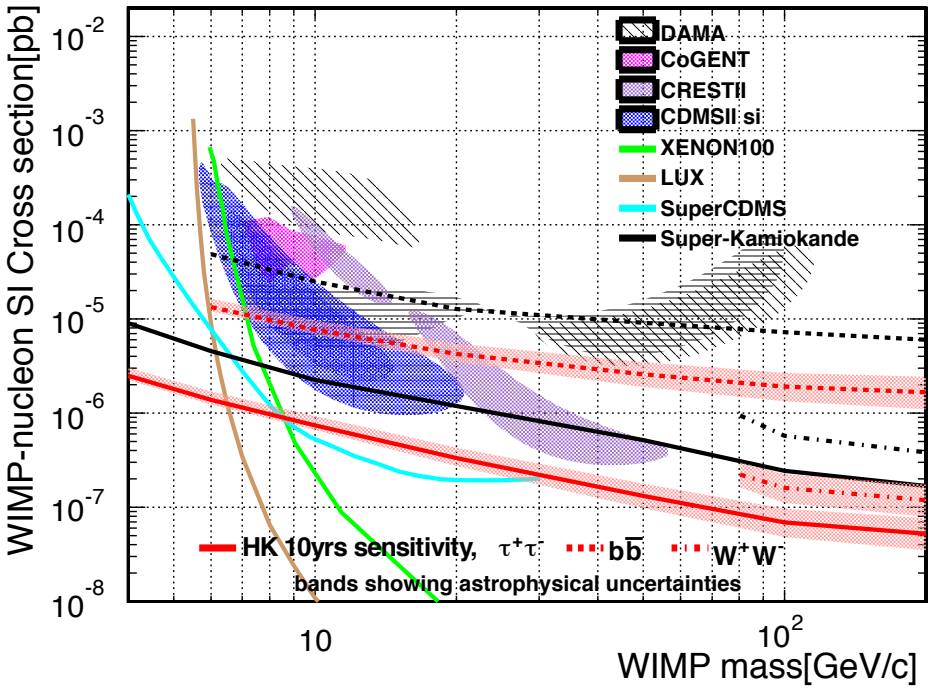
- provide complemental information w/ direct detection experiments
- Sensitive to low mass (GeV/c^2) WIMPs

Expected sensitivity for Solar WIMPs

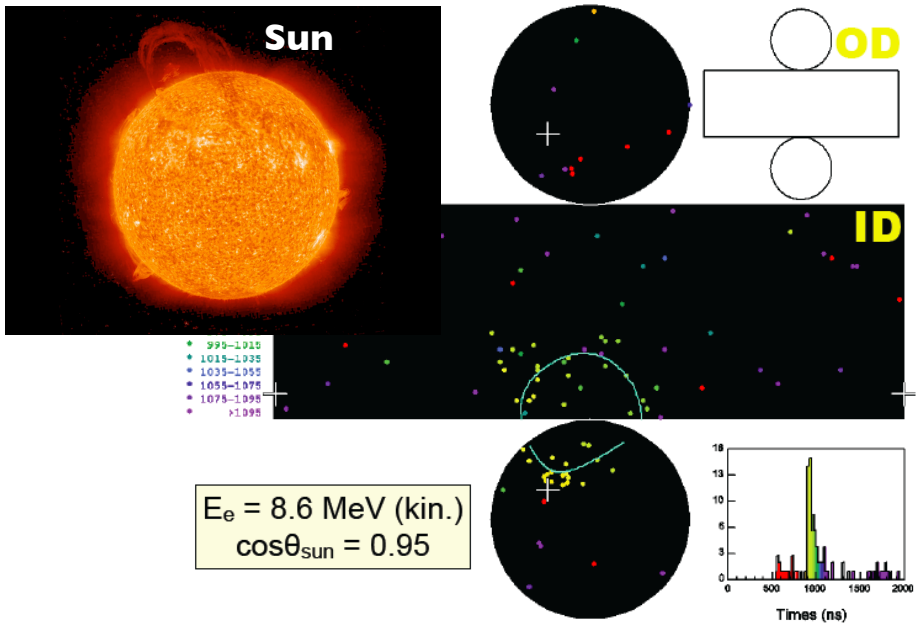
WIMP-proton cross section[pb]

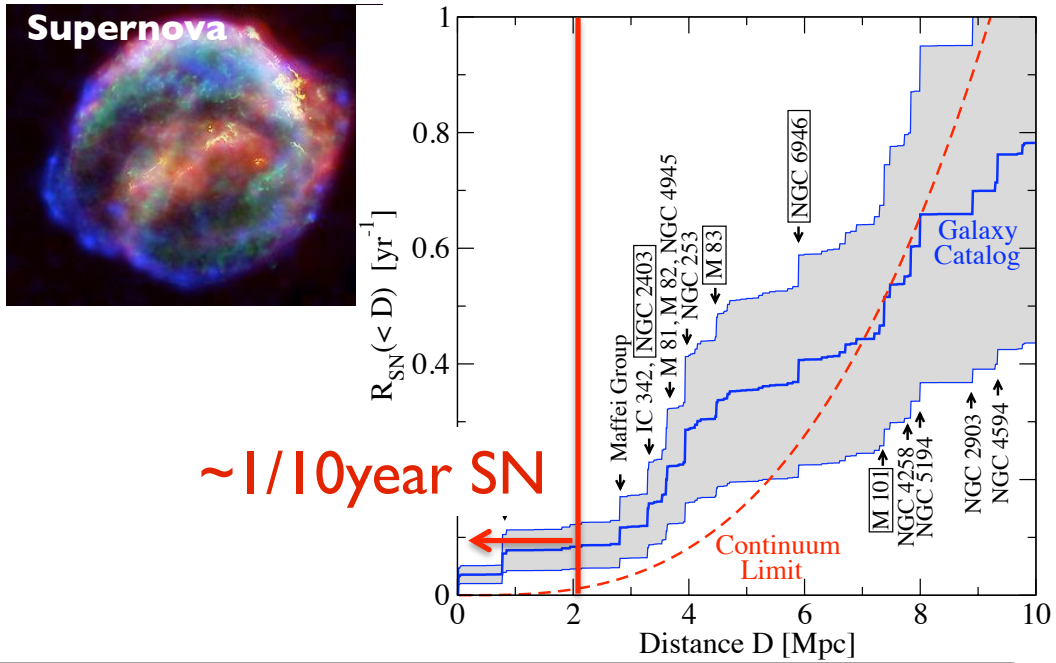


WIMP-nucleon cross section[pb]



Det. performance for astrophysical ν





- Astrophysical neutrinos such as **galactic supernova, supernova in nearby galaxies, relic SN νs**, solar νs
  - Energy threshold ~5MeV by established techniques of water purification, triggering system, analysis algorithms
  - tagging capability of μ→eνν and nuclear de-excitation γ in p→νK+

- energy scale stability ~1%
- stable operation (small <1% deadtime for Supernova observation)

Summary

- **Neutrinos play critical roles in various physics field**
  - Particle physics, Cosmology, Astroparticle physics
  - Challenges are being made for mass hierarchy, δ_{CP}, θ_{23} octant

- **Hyper-K would have wide physics topics, many discovery potentials**
  - Proton decay discovery
  - CPV (76% of δ space at 3σ), δ precision of $<20^{\circ}$
  - SN bursts, relic SN ν, WIMP annihilation ν ...

- **Boost promoting the project**
  - International proto-collaboration has been formed
  - Cooperation with KEK-IPNS/ICRR to develop the project
  - Design Report to be prepared in 2015