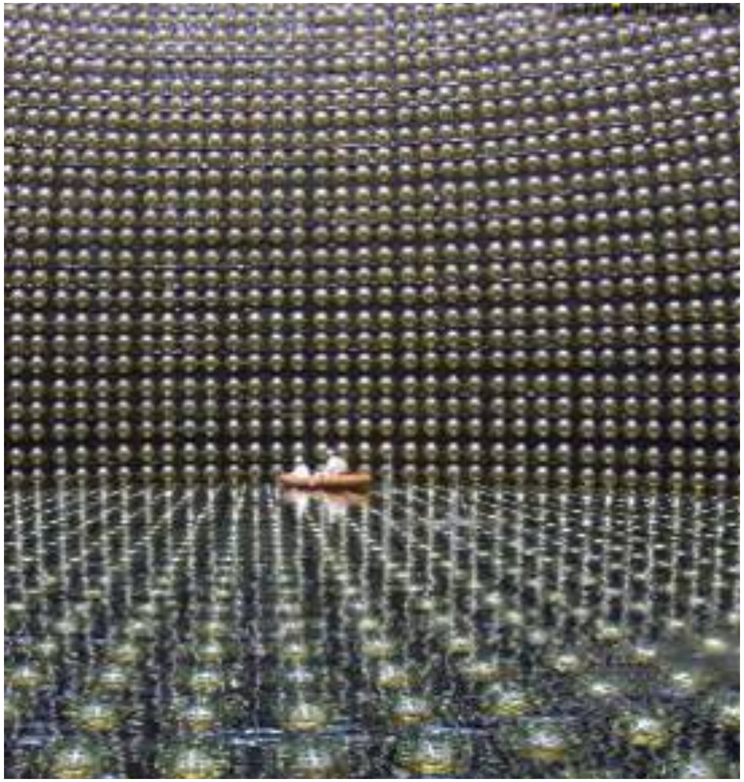
Super-Kamiokande

Recent neutrino oscillation studies

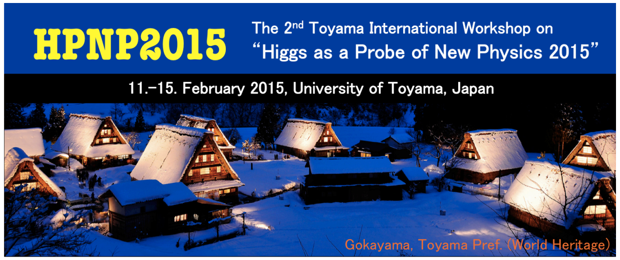


Shoei Nakayama

(Kamioka Observatory, ICRR)

February 13, 2015

HPNP2015 @ University of Toyama



Fundamental questions about neutrinos

ν?

- Why neutrino masses are so tiny?
- Why neutrino mixing is so strong?
- What the ordering of three neutrino masses is?
- Whether the three-neutrino mixing violates the matter-antimatter (CP) symmetry?
- Whether empirical relationships between neutrino-mixing parameters (or between neutrino- and quark-mixing parameters) can be established?
- Whether the three-neutrino mixing picture is the whole story?
- …

Neutrino experiments aim to answer these questions.

Neutrino experiments : Broad physics programs

- Oscillation studies
  - Atmospheric ν
  - Accelerator ν
  - Solar ν
  - Reactor ν
- Exotics searches
  - Sterile ν
  - Lorentz invariance violation
- Neutrino properties
  - kinematic ν mass
  - 0ν double β decay
- Neutrino-nucleus interaction measurements
- Neutrino astronomy
  - Supernovae burst ν
  - Relic ν (DSNB)
  - Very high-E cosmic ν
  - Indirect search for DM (WIMP annihilation)
  - Solar flare ν
  - Cosmological ν
- Neutrino geophysics

Unknowns in Neutrino Oscillation Parameters

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

CP phase

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

- θ_{12} = 33.9° ± 1.0° Solar ν, KamLAND
- θ_{23} = 45° ± 6° (90%CL) Atm. ν, Acc. ν

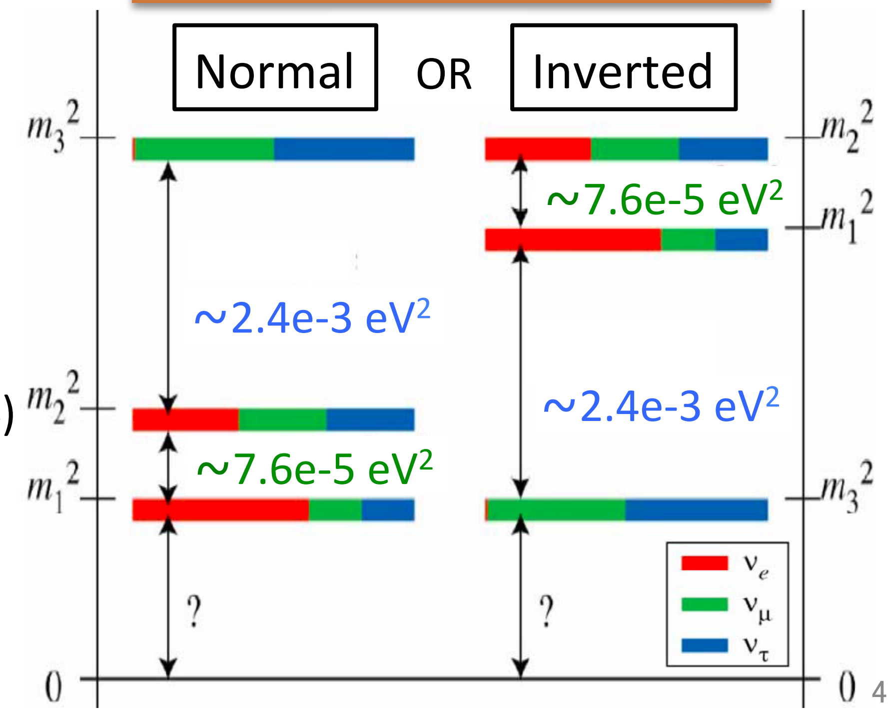
θ_{23} : How close to 45° ?
Octant? (<45°, >45° ?)

- θ_{13} = 9.0° ± 0.5° 8.7° ± 0.4° by Daya Bay PRD 90, 071101(R) (2014)

First indication of $\theta_{13} \neq 0$ by T2K (2011)

Precise measurements by reactor ν experiments (2012-)

Neutrino Mass Hierarchy

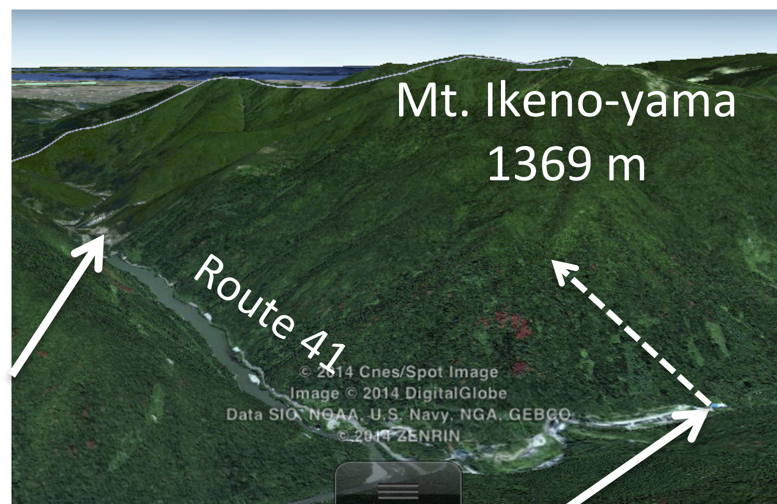


Kamioka Observatory (ICRR, University of Tokyo)

- Located in Hida-City, Gifu prefecture
- Established in 1995 to conduct the Super-Kamiokande experiment
- Other experiments (XMASS, etc.) also in the Kamioka Underground Lab.

We are here now

Kamioka Observatory

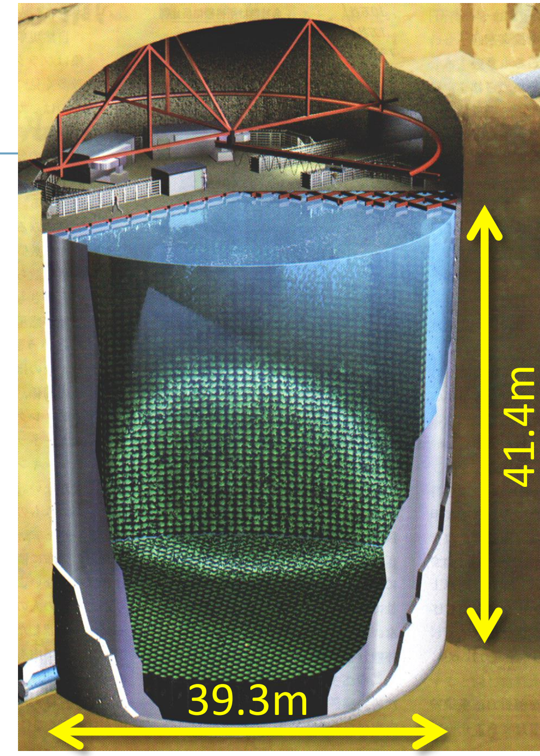


Research Building

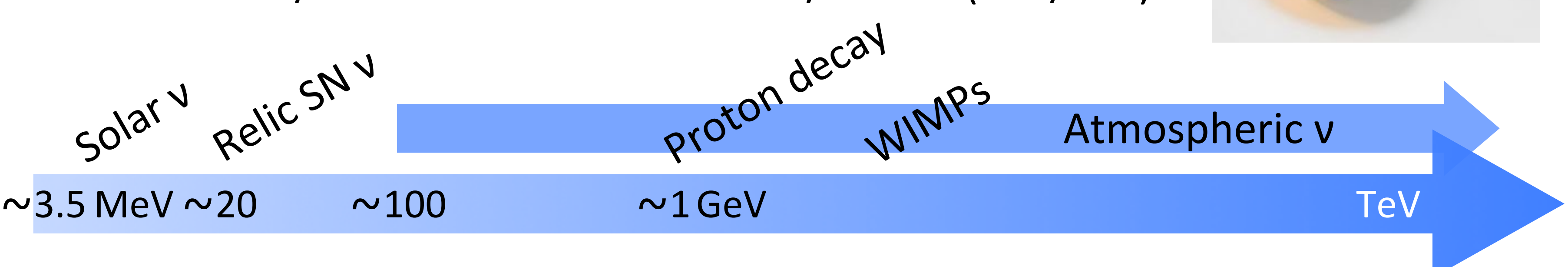
Entrance to the underground lab.

Super-Kamiokande

- 50 kton Water Cherenkov detector
  - 22.5 kton fiducial mass
- 1000 m (2700 m.w.e.) under the peak of Mt. Ikeno-yama
- Optically separated into
  - Inner detector : 11,146 50cmϕ PMTs
  - Outer detector : 1,885 20cmϕ PMTs
- Serves as the far detector for LBL experiments
  - 250/295 km from KEK-Tsukuba/J-PARC (K2K/T2K)



©Scientific American

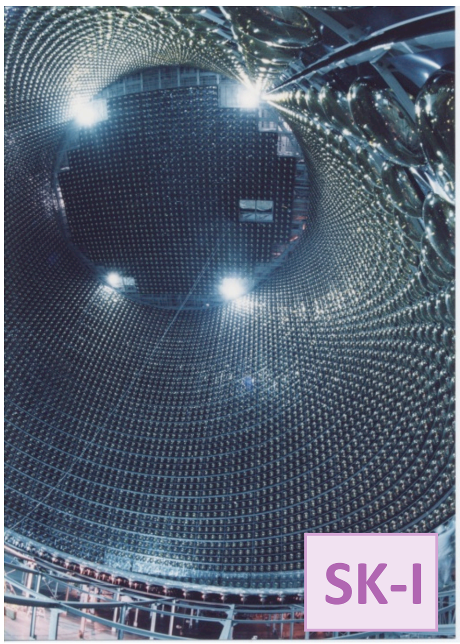


History of Super-K

>18 years of observation with continuous improvement

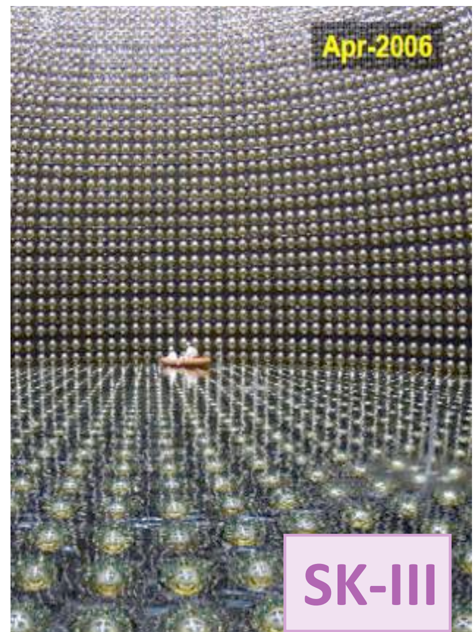
96	97	98	99	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15

SK-I SK-II SK-III SK-IV

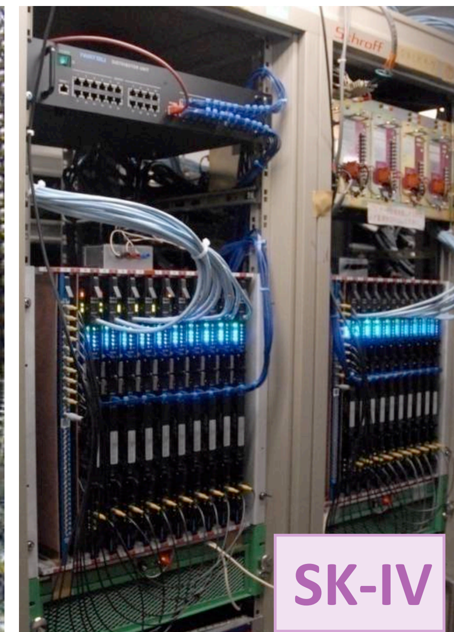


11146 ID PMTs
(40% coverage)

5182 ID PMTs
(19% coverage)

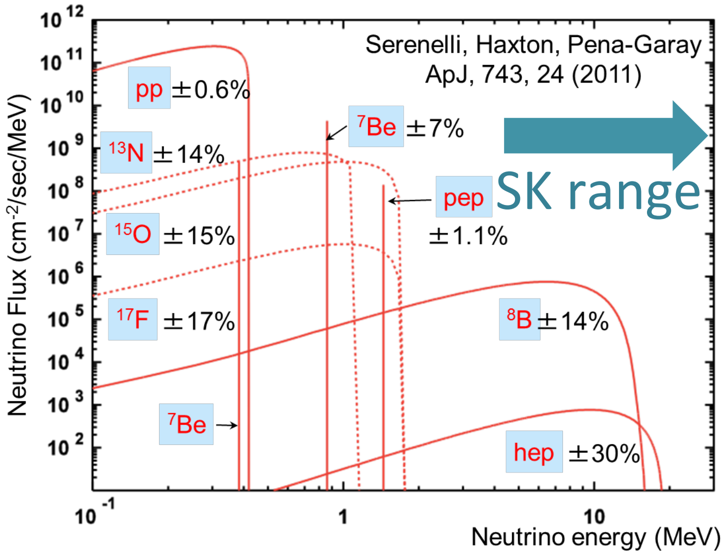


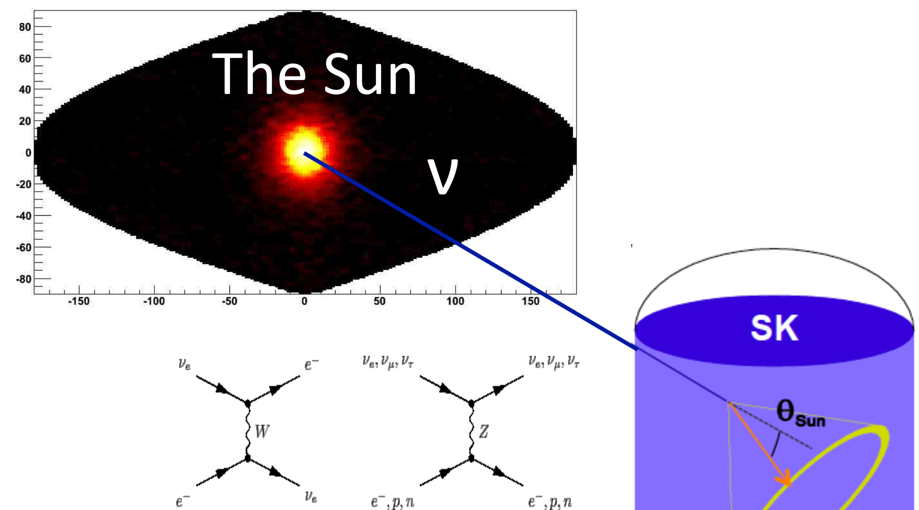
11129 ID PMTs
(40% coverage)



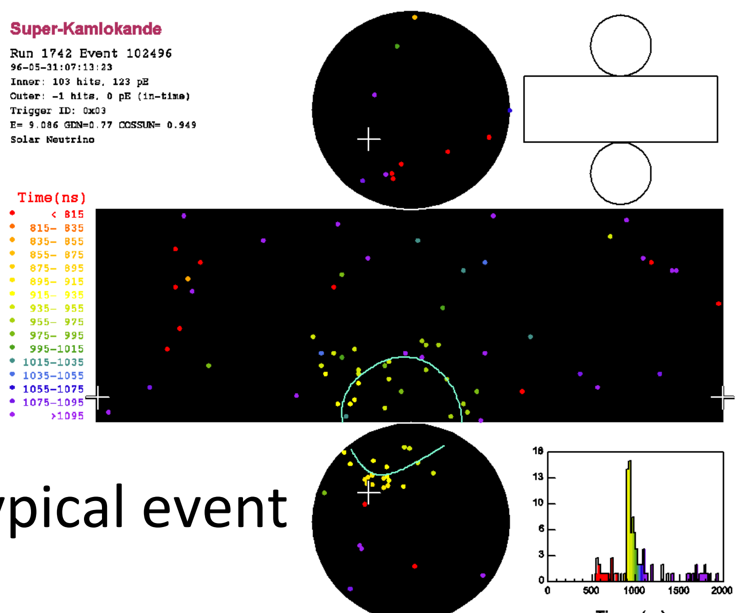
Electronics
Upgrade

Solar neutrino observation in Super-K





$$\nu + e^- \rightarrow \nu + e^-$$



Typical event

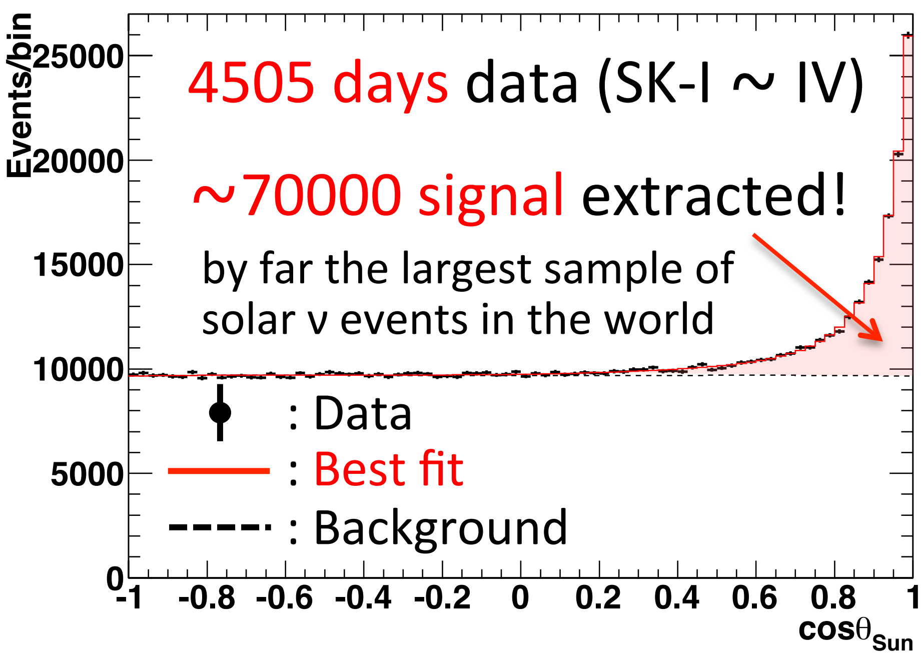
- Detects recoil electrons by neutrino-electron elastic scatterings
- Direction relative to the Sun
- Energy spectrum
- Realtime measurements
  - Day-Night flux difference
  - Seasonal flux variation

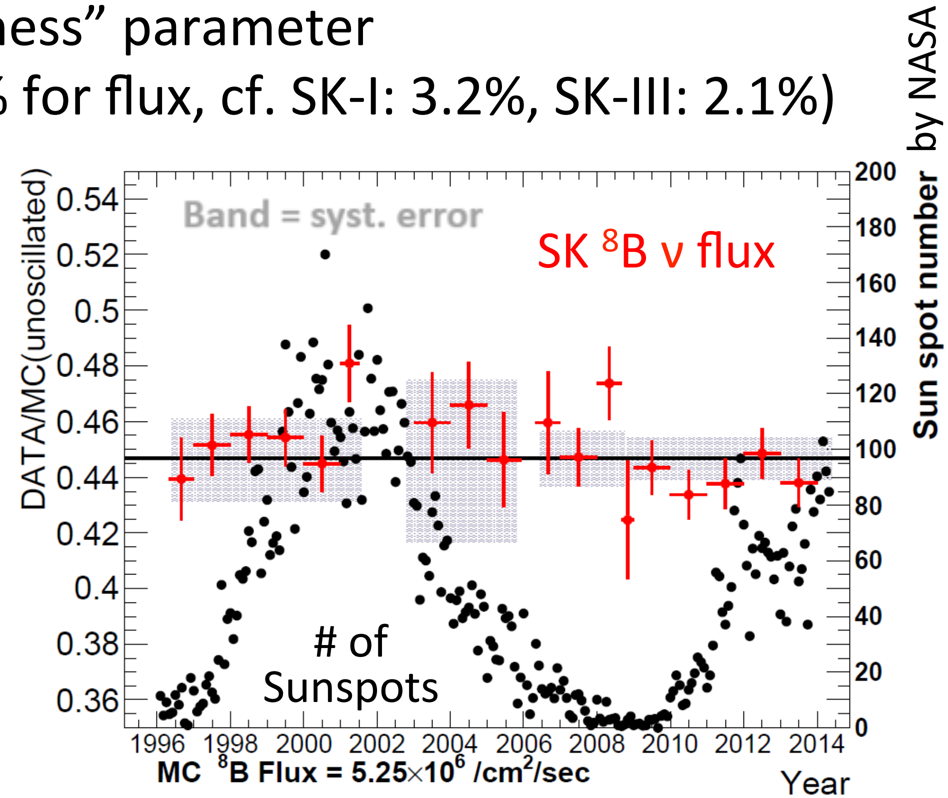
^{8}B solar ν flux measurement : Latest SK results

Preliminary

SK-IV improvements

- BG reduction by better water quality control
  → Achieved the 3.5 MeV (kin.) energy threshold !
- New multiple scattering "goodness" parameter
- Reduced systematic error (1.7% for flux, cf. SK-I: 3.2%, SK-III: 2.1%)





$\Phi^{SK}(^{8}B) = 2.344 \pm 0.034\ [10^{6}/cm^{2}/s]$

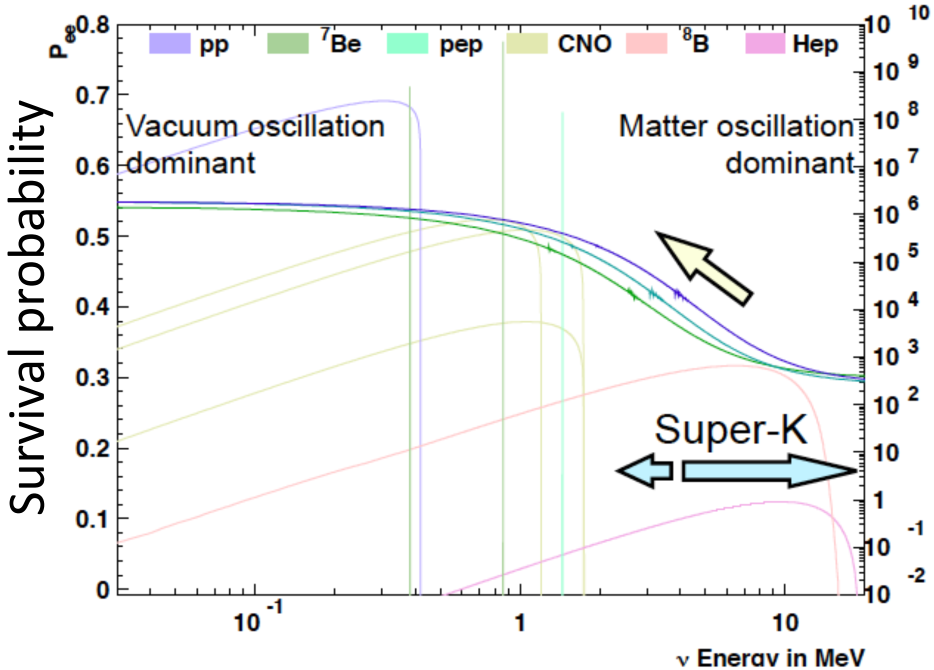
No correlation with solar activity

SK solar ν measurements : Current targets

Direct verification of matter (MSW) effects in neutrino oscillations

Solar matter effect

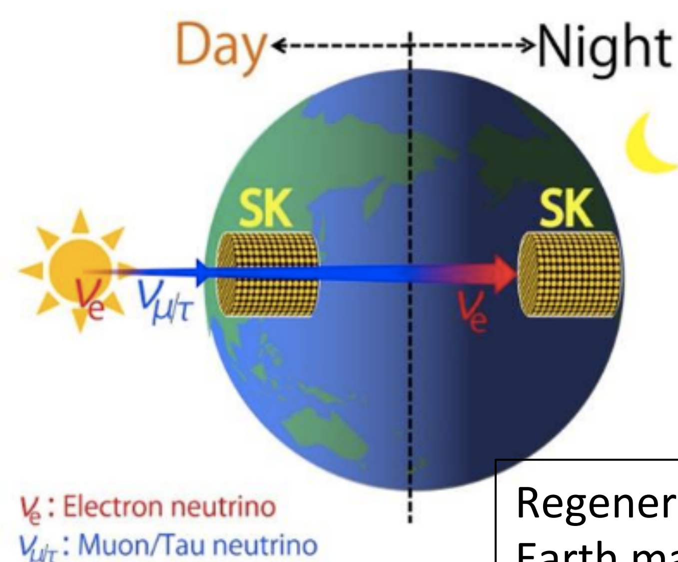
→ "Upturn" in energy spectrum



Test of some exotic models (FCNC, sterile νs, MaVaNs, ...)

Earth matter effect

→ Day-Night flux asymmetry

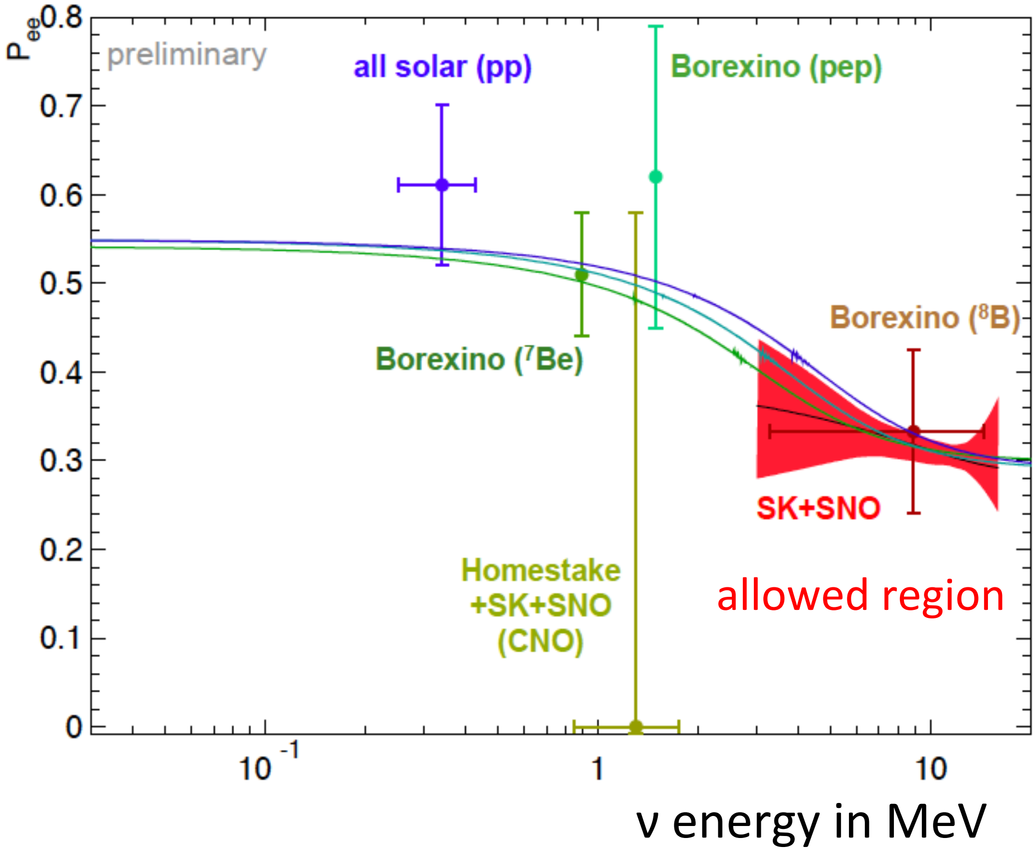


Regenerate ν_e by Earth matter effect

Solar matter effect

Preliminary

Solar ν_e survival probability : Latest SK results



- SK gives the strongest constraints on the shape of survival probability $P_{ee}(E_\nu)$ in the transition region (MSW→Vacuum)
- Slightly disfavor the MSW curves, but are consistent with MSW prediction w/ 1-1.7σ

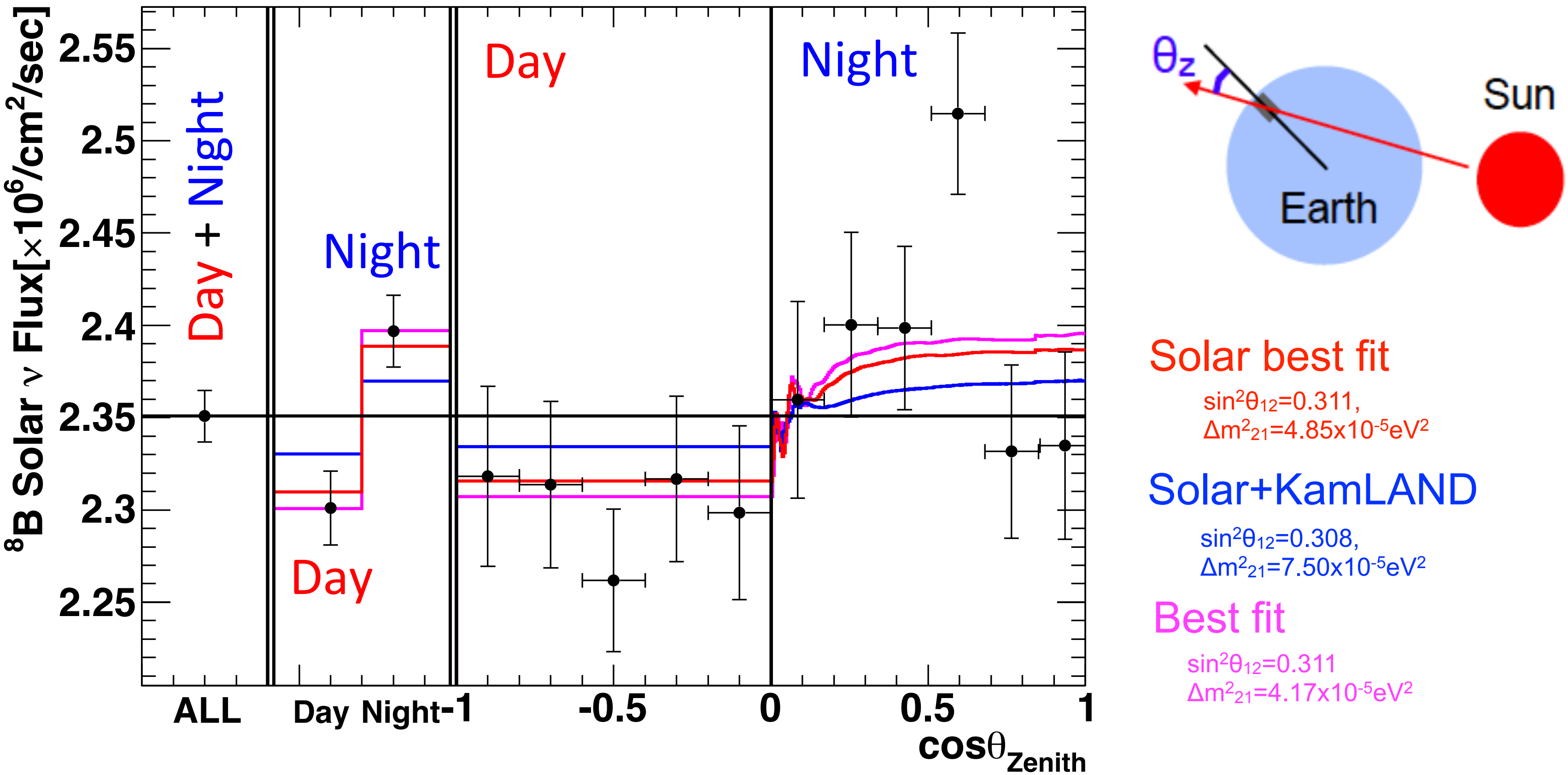
- To see the spectrum upturn clearly,
  - Trying to further reduce the BG and enlarge the FV
  - Installing an intelligent trigger w/ 100% efficiency for E_{kin}>2.5MeV

Earth matter effect

PRL 112, 091805 (2014)

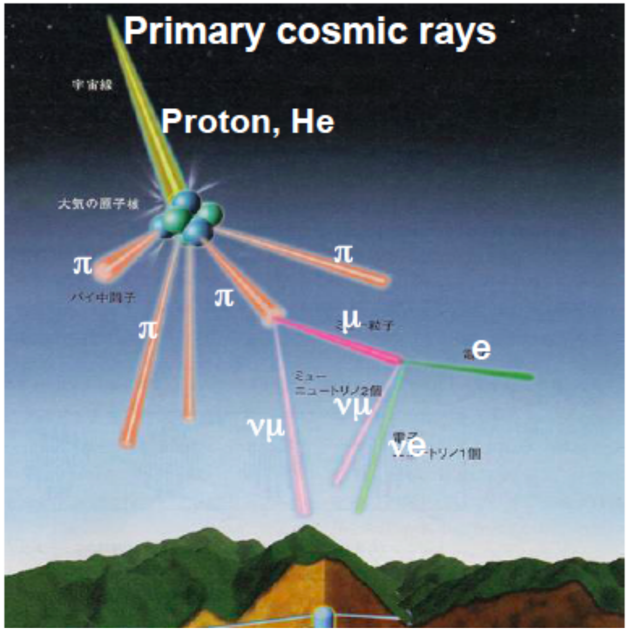
Day-Night ^8B ν flux asymmetry : Latest SK results

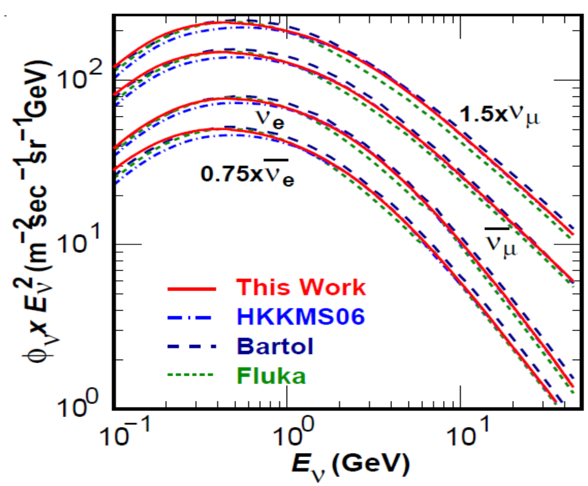
Zenith angle distribution of ^8B ν flux (SK-I ~ IV combined)



First direct indication (~3σ) of terrestrial matter effect

Atmospheric neutrino observation





$$p + A \rightarrow \pi^+ + X$$
$$\hookrightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

- Cosmic rays strike air nuclei and the decay of the out-going hadrons gives neutrinos

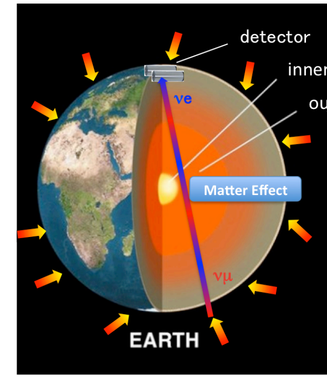
- νs travel 10-13,000 km before detection
- Flux spans many decades in energy : ~100 MeV – 10 TeV+
- Excellent tool for broad studies of ν osc.

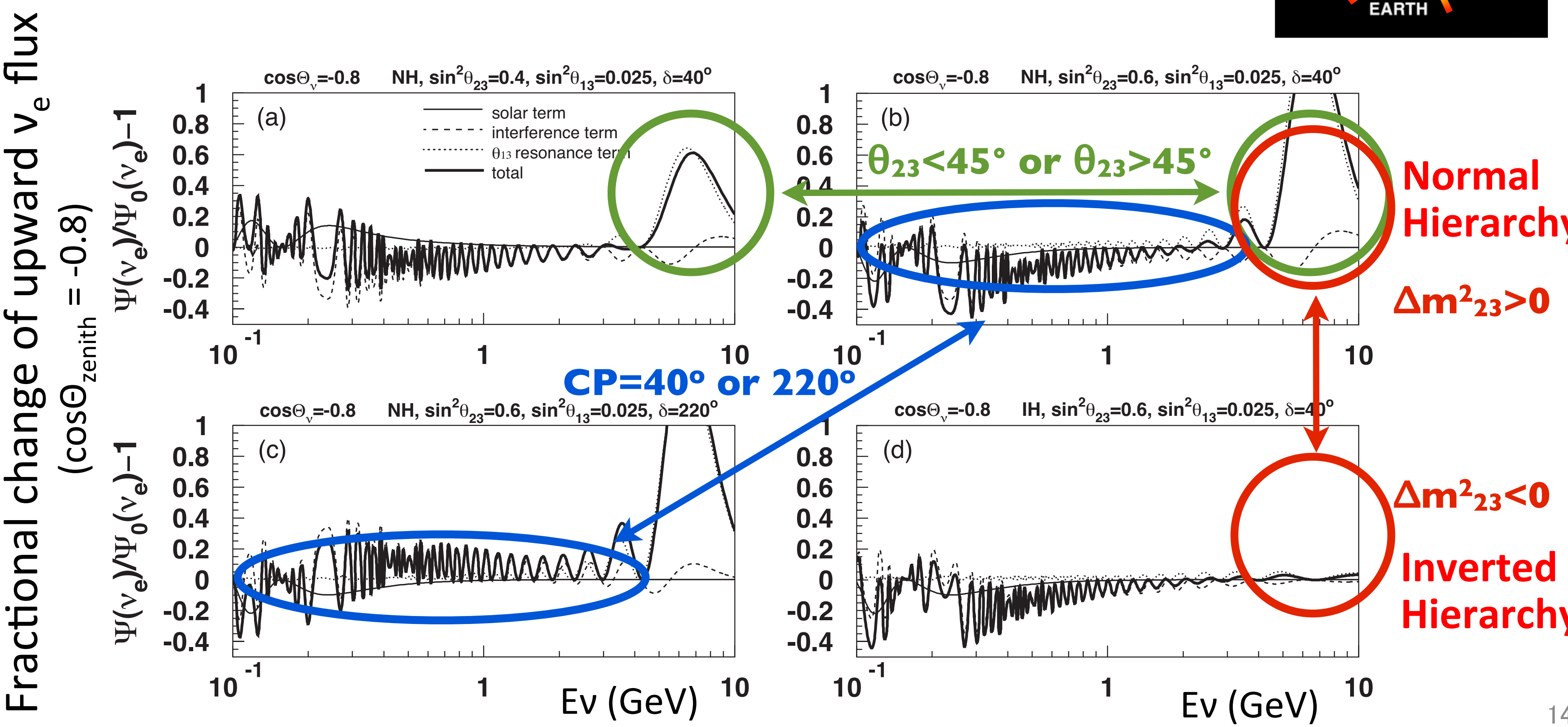
- Super-K : 4581 days of atm-ν data
  - 40,000 events
  - Access to sub-leading effects

Searching for three-flavor oscillation effects

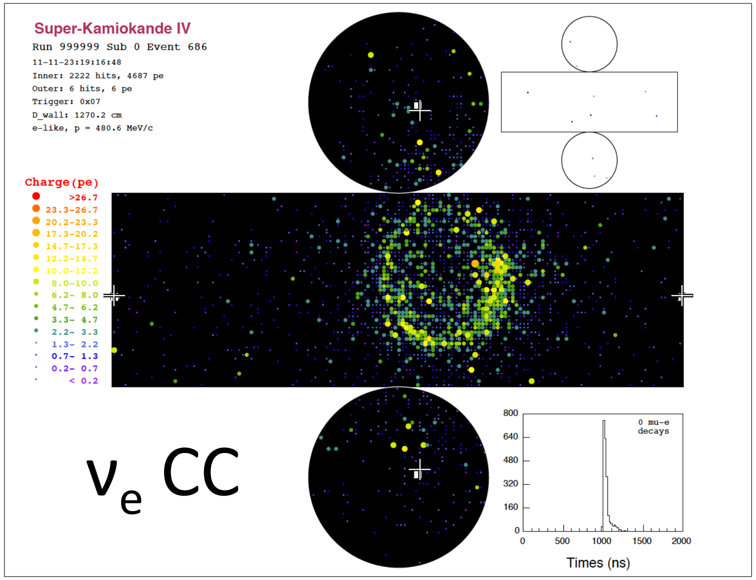
Sub-dominant oscillation effects sensitive to

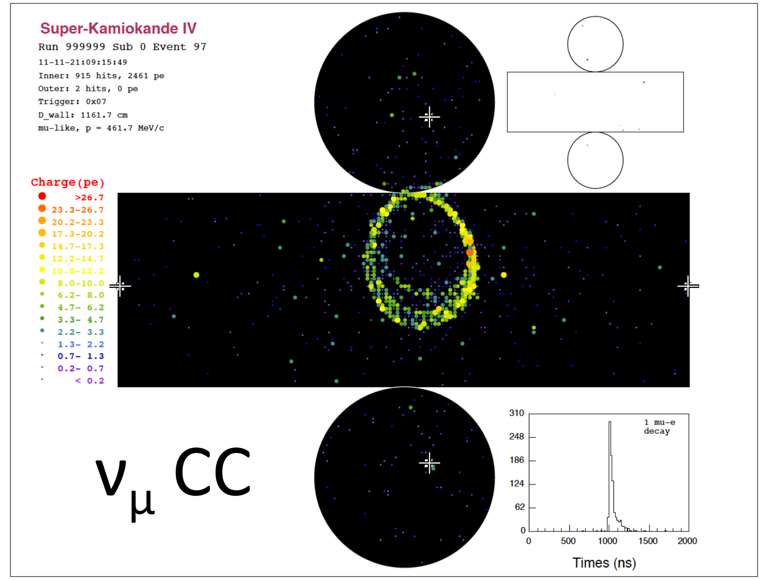
- Mass hierarchy : Resonance in multi-GeV ν_e or $\overline{\nu}_e$
- θ_{23} octant : Magnitude of the resonance
- CP δ : Two Δm^2 interference region

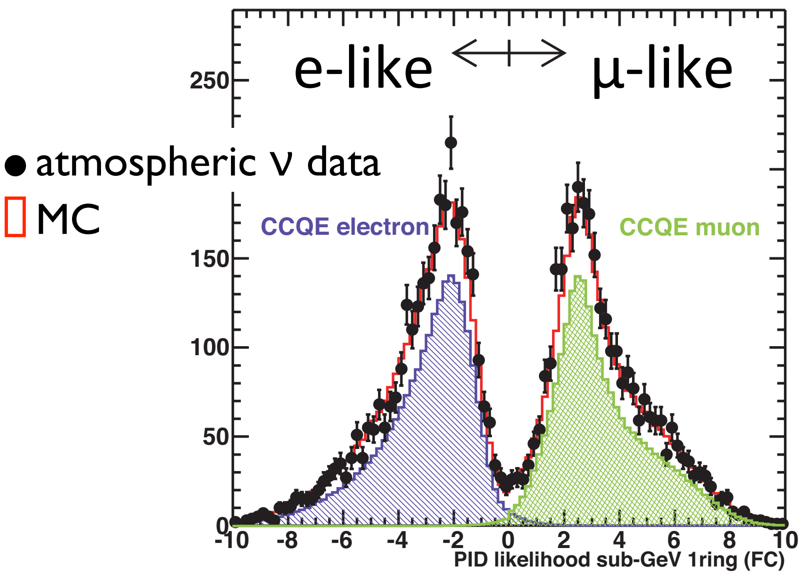




Particle identification (PID) in Super-K





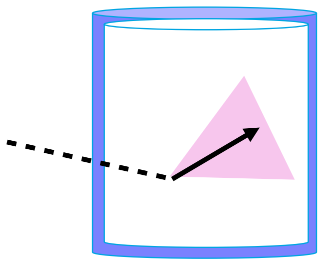


Excellent PID between showering (e-like) and non-showering (μ-like)

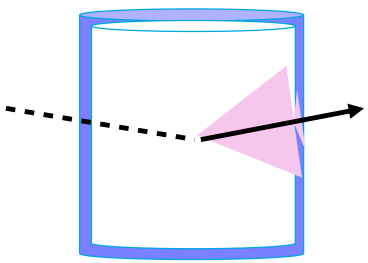
- Ring shape and opening angle
- < 1% mis-ID at 1 GeV

Super-K atmospheric ν analysis samples

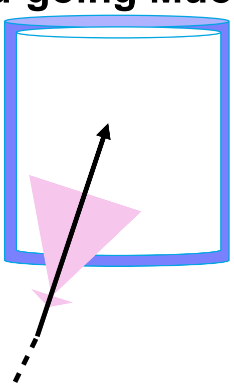
Fully Contained (FC)



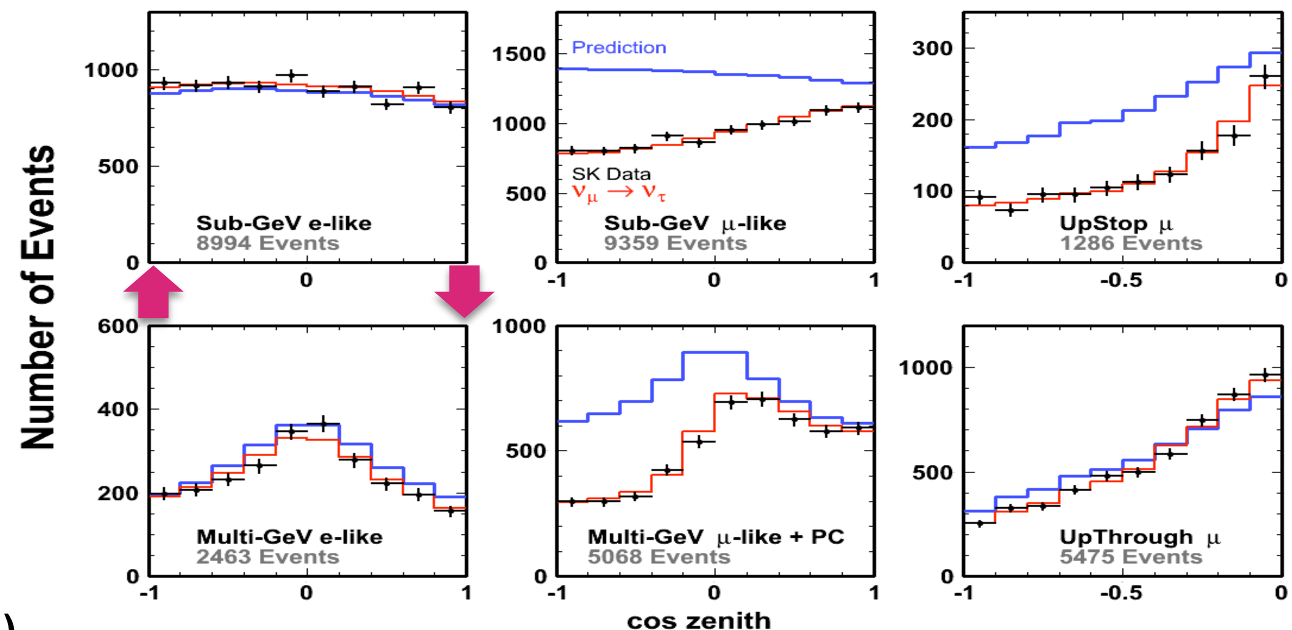
Partially Contained (PC)



Upward-going Muons (Up-μ)

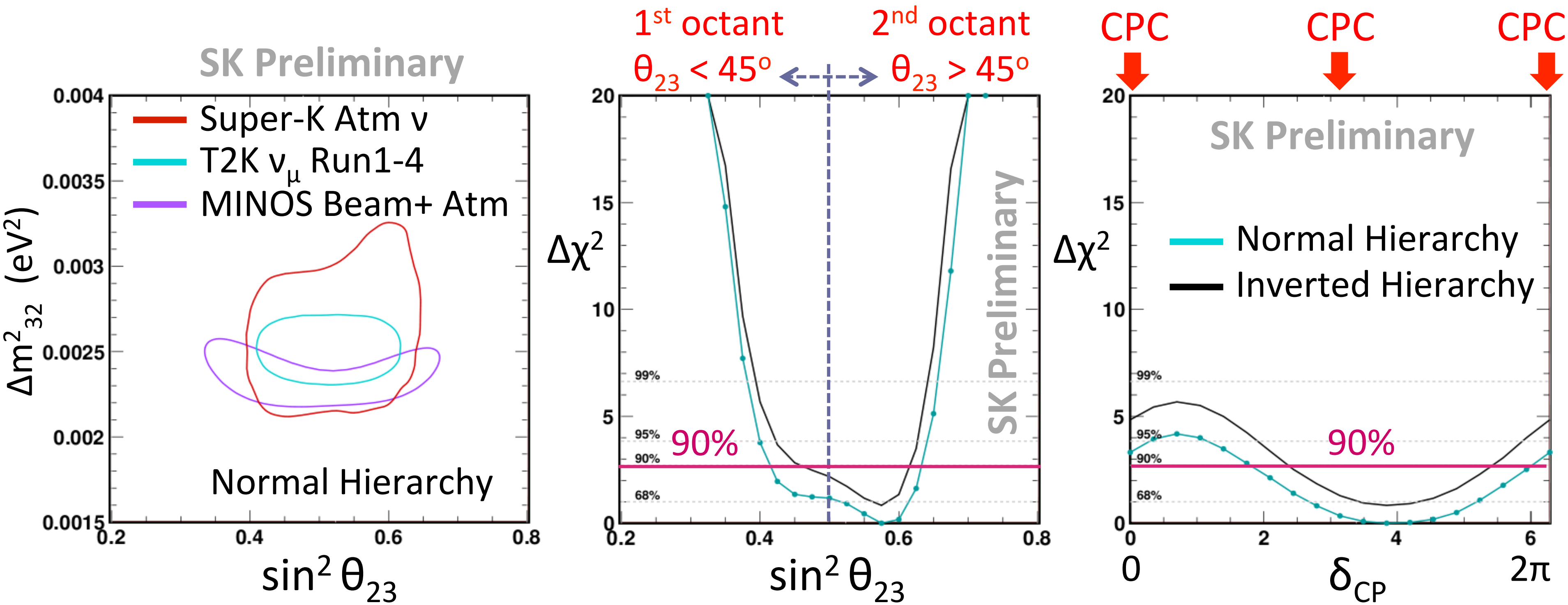


Zenith angle distribution of each sample



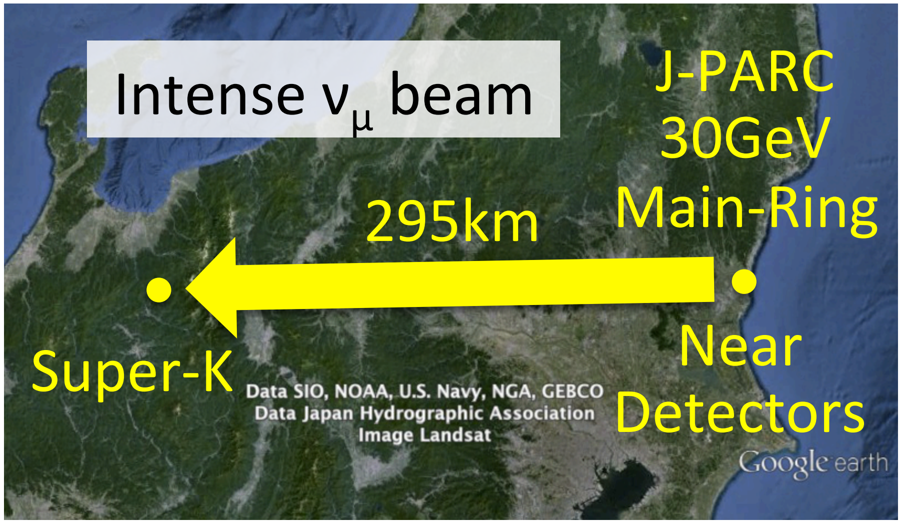
- In total 19 analysis samples (classified by ν flavors, event topologies, energies, …)
- Fit to the data in bins of $\cos\Theta_{zenith}$ and momentum
- Dominated by $\nu_\mu \rightarrow \nu_\tau$ oscillations
- Interested in sub-dominant contributions
  - Three-flavor effects, Sterile Neutrinos, LIV, …

SK three-flavor oscillation analysis results

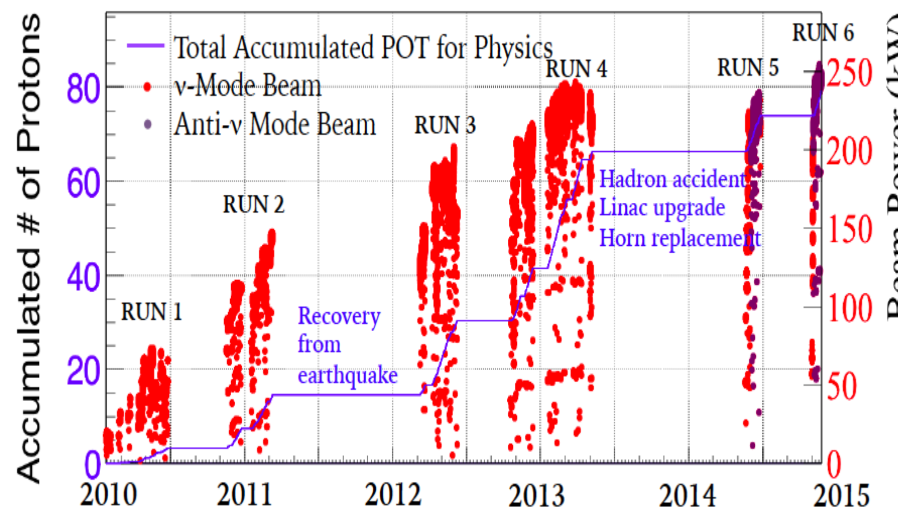


- Normal hierarchy is slightly preferred ($\chi^2_{IH} - \chi^2_{NH} = 0.9$)
- Best-fit $\sin^2\theta_{23}$ is ~0.6, but both the octants still allowed
- Best-fit δ_{CP} is ~$3\pi/2$, but CP conservation ($\sin\delta=0$) still allowed
- With constraints by T2K, the preference of NH and δ_{CP}~$3\pi/2$ is slightly strengthened, but not definitive.

T2K (Tokai-to-Kamioka) experiment



T2K beam accumulation history



Primary goals

- Discovery of ν_e appearance ($\nu_\mu \rightarrow \nu_e$ oscillations via non-zero θ_{13})

  Opens the possibility to probe the leptonic CP violation

  → Definitive observation at >7σ (2013)

- Precision measurement of ν_μ disappearance

  → θ_{23} measurement with the world-leading precision (2014)

Achieved w/ only 8% of approved beam statistics

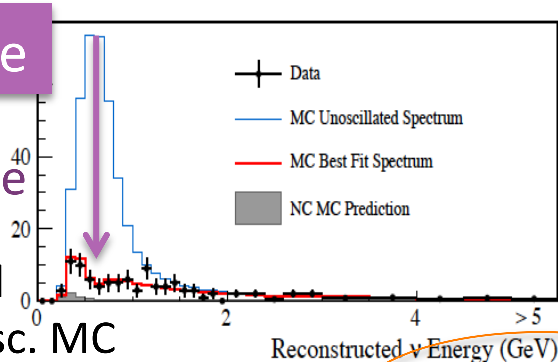
Latest T2K results : Joint $\nu_\mu + \nu_e$ analysis

ν_μ sample

Disappearance

120 observed

446±23 un-osc. MC



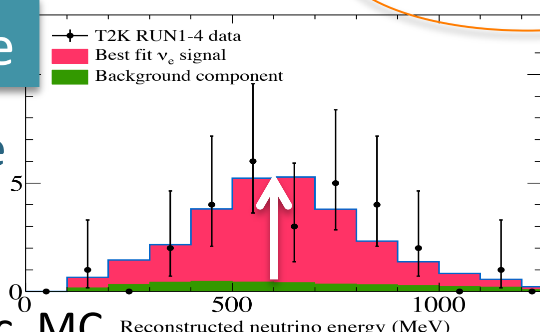
+ Combined fit

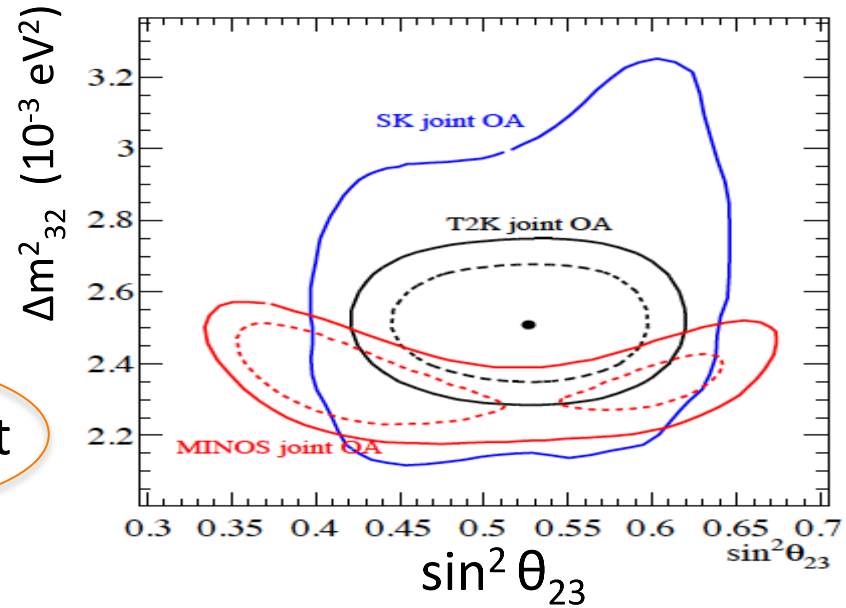
ν_e sample

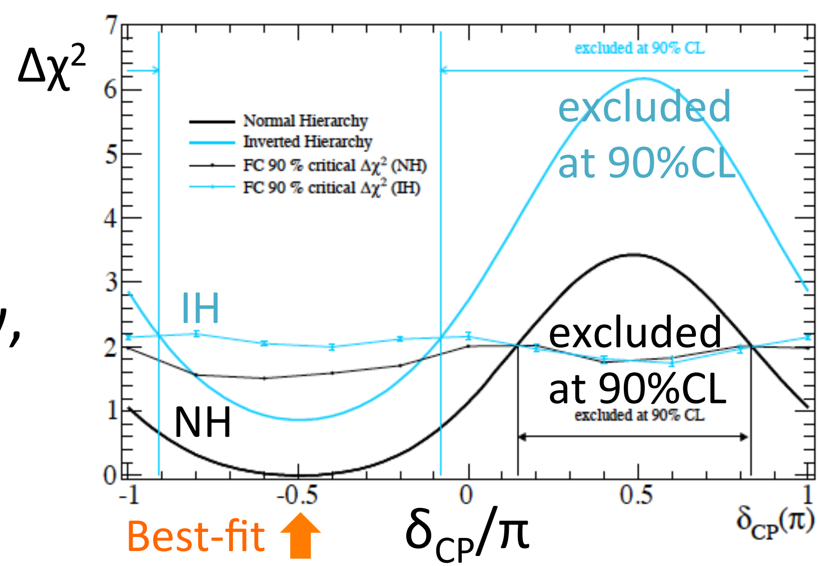
Appearance

28 observed

4.9±0.6 un-osc. MC



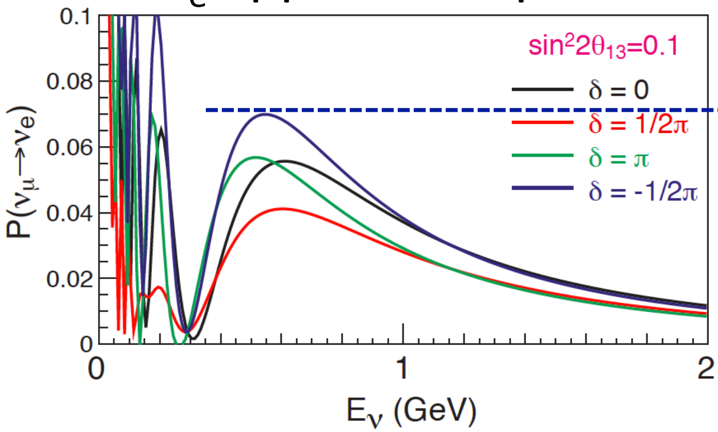




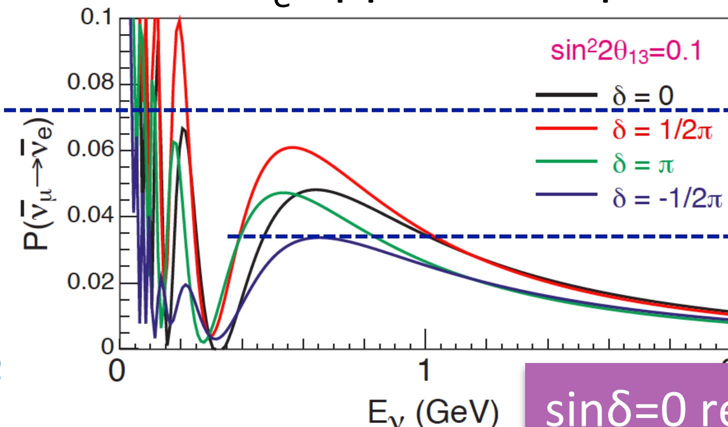
- With a constraint on θ_{13} by reactor ν, T2K data favors NH and δ_{CP}~-π/2.
- Some δ_{CP} regions excluded at 90%CL

T2K future prospects

ν_e appearance prob.

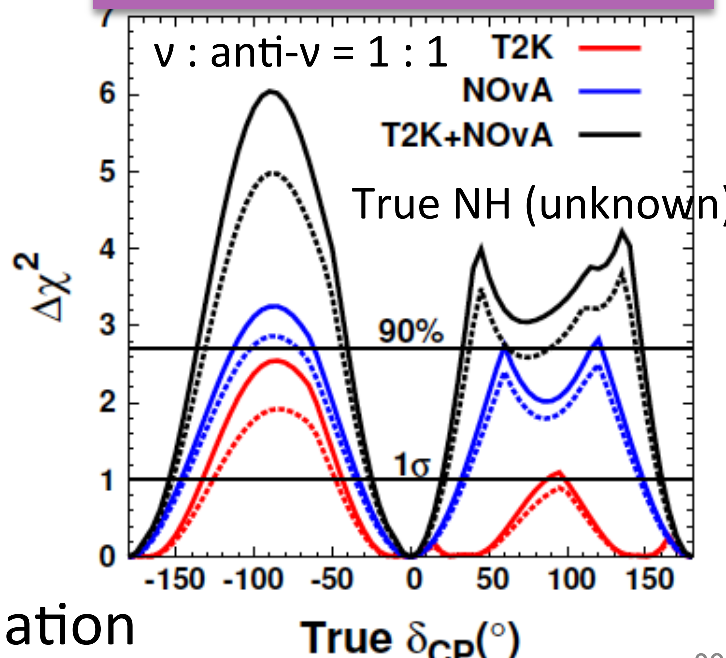


Anti-ν_e appearance prob.



as large as ±25% (from δ=0)

sinδ=0 rejection sensitivity



- Comparison btw ν and anti-ν modes enhances the sensitivity to δ_{CP}
- Plan: 50% ν + 50% anti-ν modes
  → now running with anti-ν mode

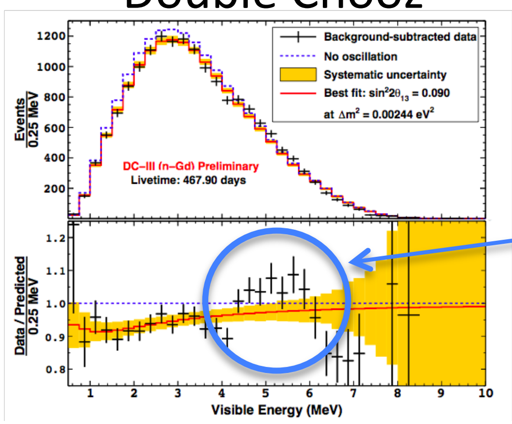
Main goals :

- Exploring leptonic CPV (aiming for >3σ)
- High precision ν_μ disapp. measurement
- Important contribution to MH determination

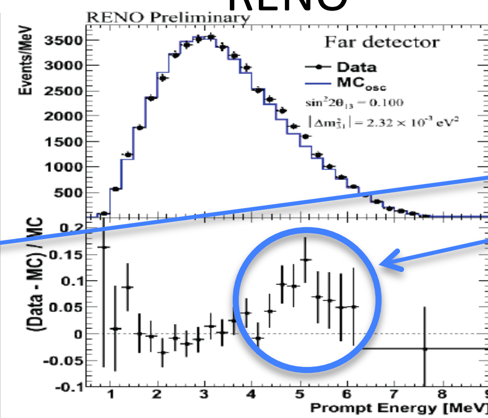
Other experiments : Many important results …

θ_{13} precision measurement by reactor experiments

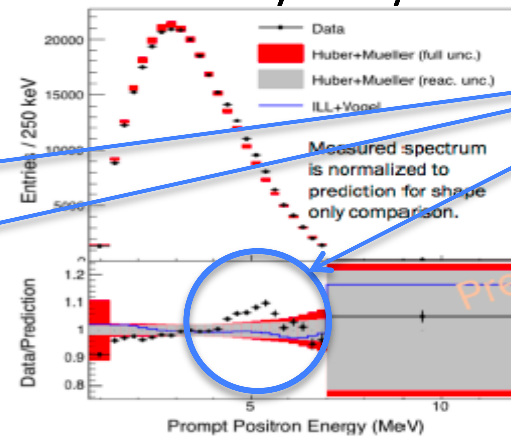
Double Chooz



RENO



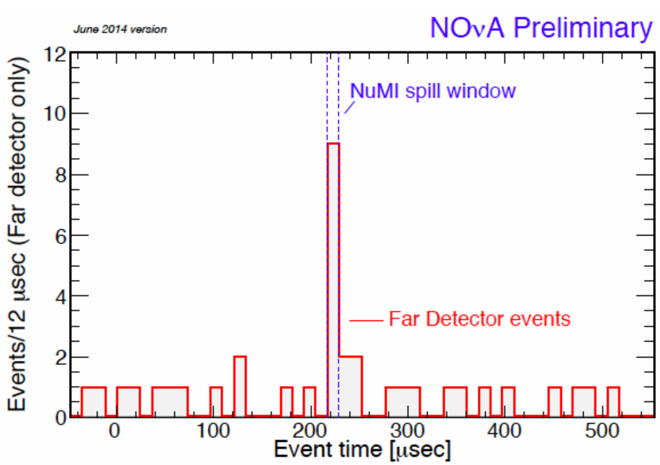
Daya Bay



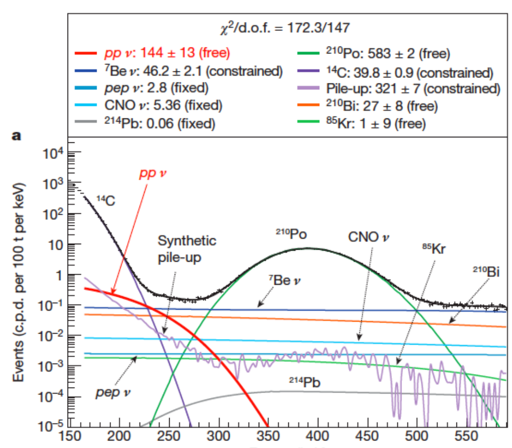
What is this ?

and more …

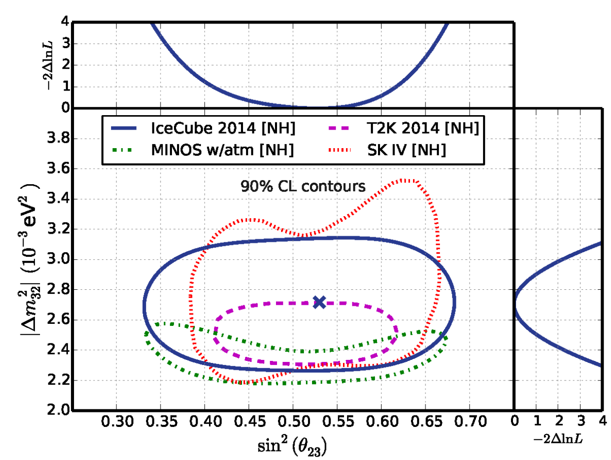
NOvA: Far detector time peak



Borexino: pp solar ν



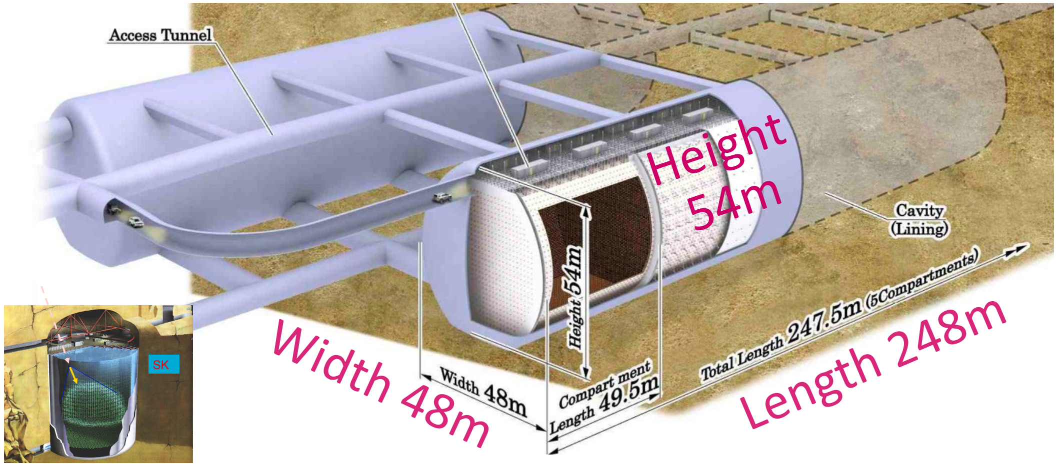
IceCube: atm-ν osc.



Hyper-Kamiokande

(Letter of Intent) arXiv:1109.3262
(LBL study) arXiv:1412.4673
http://www.hyper-k.org/

Next generation Mega-ton water Cherenkov detector



Total Mass : 0.99 Mton

Fiducial Mass : 0.56 Mton
(x 25 of Super-K)

Aiming to start observation in 2025
(3yrs for full survey & final designing
+ 7yrs for construction)

Wide physics program

- Proton decay search
- Full picture of neutrino oscillation (leptonic CP violation, …)
- Astrophysical neutrinos (solar ν, supernova ν, WIMP, …)
- Neutrino geophysics

Great potential to discover new physics !

Hyper-K project status

5th open meeting in Vancouver
(19-22 July 2014)

- 6 open meetings held semiannually
- 5 year grant for R&D and prototype detector from 2013 (Japan)
- Selected as one of top 27 large-scale projects in "Master Plan 2014" of the Science Council of Japan
- Funding requests in Canada, EU, Switzerland, and UK
  - Some already awarded
- R&D in progress by HK international WG
  - ~240 people from 13 countries
- Hyper-K proto-collaboration just formed
- MoU between KEK-IPNS and ICRR
- CDR to be prepared in a year

Summary

- Super-K solar neutrino observation
  - No clear signature of the spectrum "upturn" yet
  - 3σ day-night flux asymmetry

    → First direct indication of terrestrial matter effect

- Super-K atmospheric neutrino observation
  - Slightly favors normal hierarchy, 2nd octant θ_{23} , and $\delta_{CP}\sim-\pi/2$

- T2K oscillation analysis
  - Slightly favors NH and $\delta_{CP}\sim-\pi/2$. 90%CL exclude regions on δ_{CP}
  - Taking data with anti-ν mode to enhance the sensitivity to δ_{CP}

- Hyper-K international proto-collaboration is formed
  - Baseline design exists. CDR to be prepared in a year.

Supplement