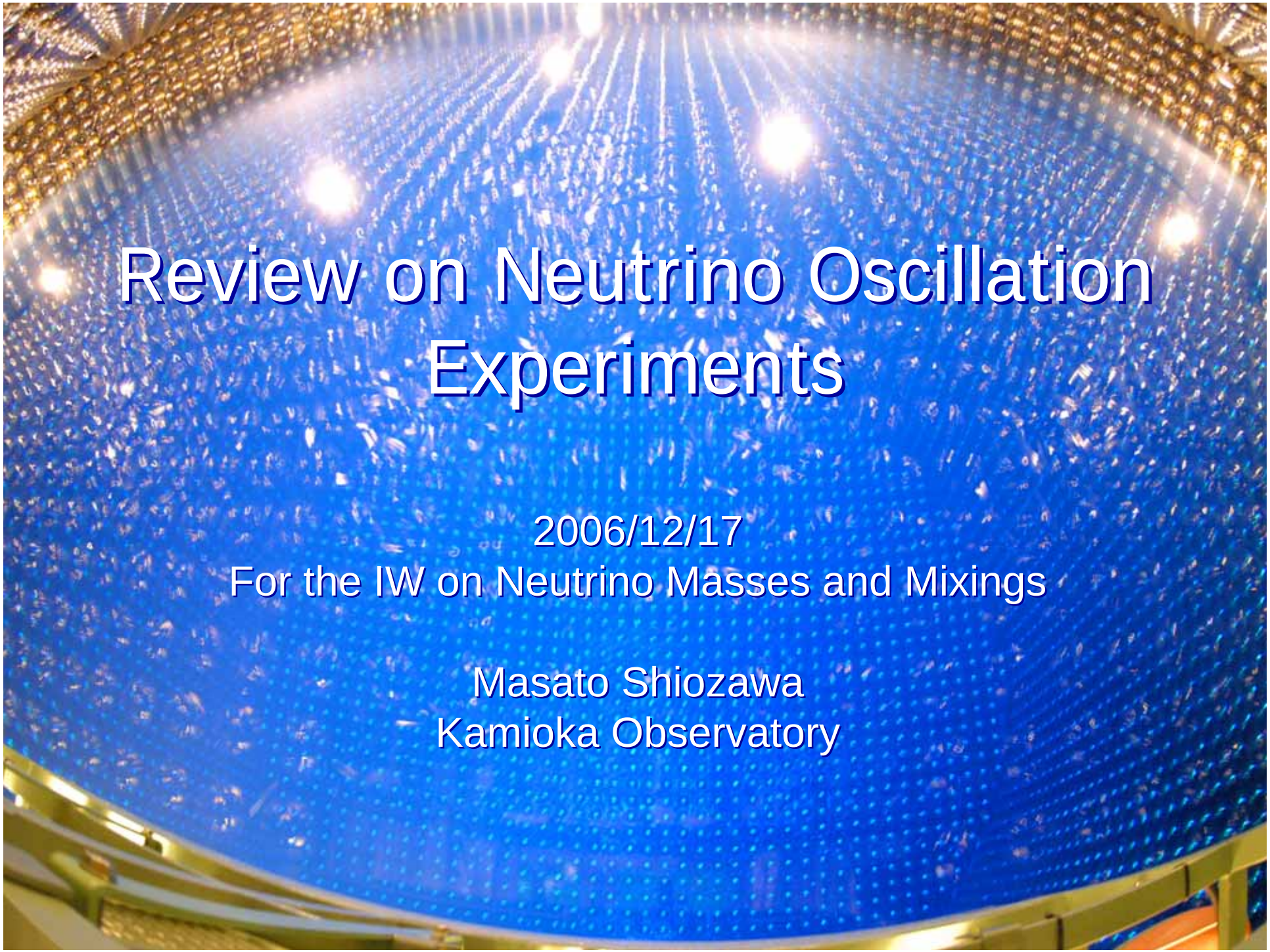


Review on Neutrino Oscillation Experiments

2006/12/17
For the IW on Neutrino Masses and Mixings

Masato Shiozawa
Kamioka Observatory

Outline

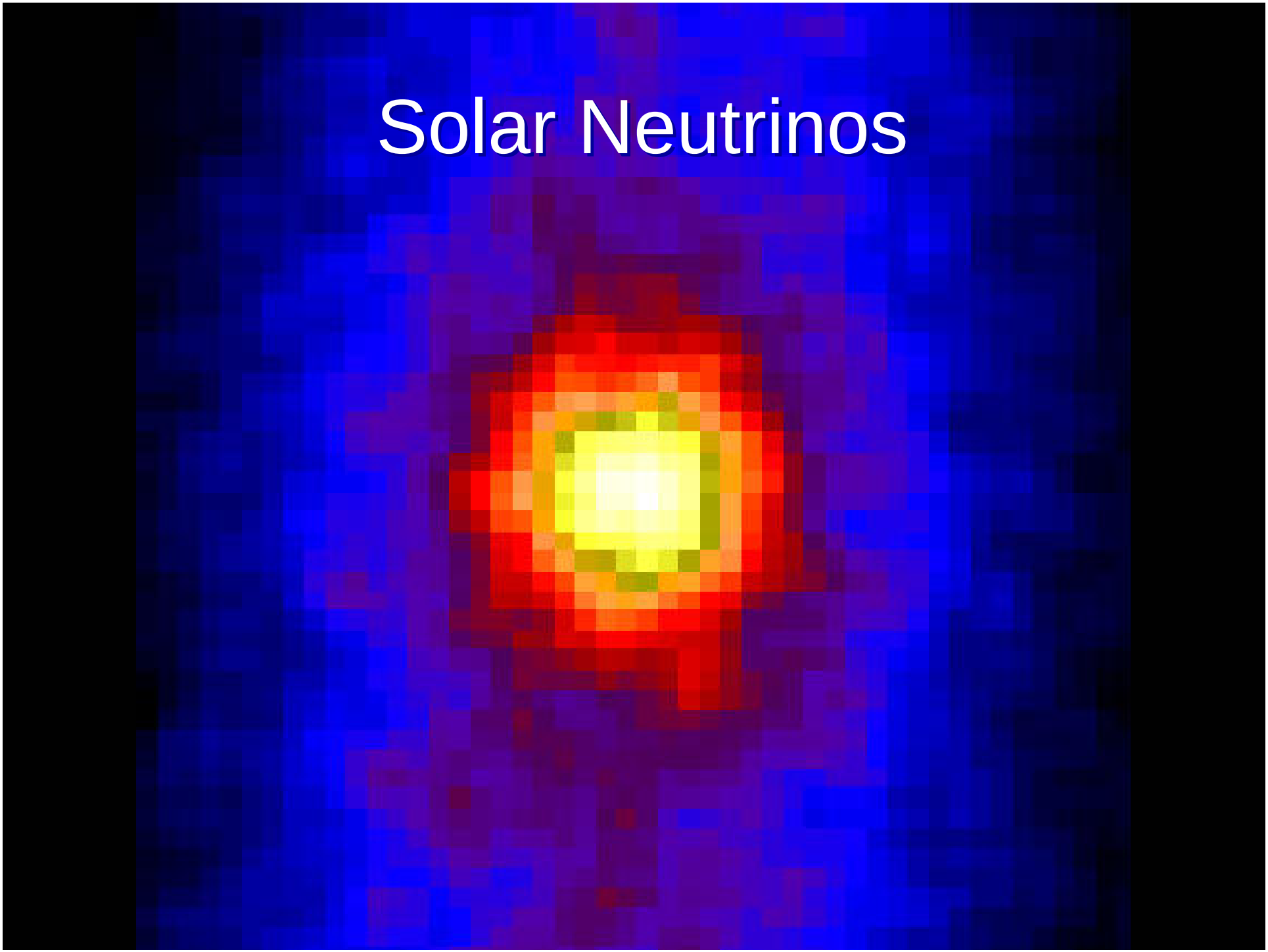
- reliability of each experimental results → (some) details of experiments
- accuracies of the parameters; especially θ_{23} and Δm^2_{23} → current results and future prospects

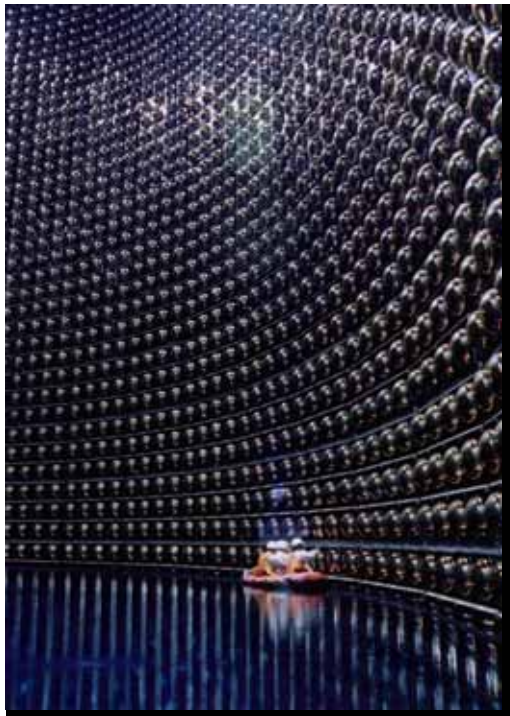
Outline (cont.)

- Solar neutrinos
  - θ_{12} and Δm^2_{12}
- Atmospheric Neutrinos
  - θ_{23} and Δm^2_{23}
- Accelerator Neutrinos (and Reactor)
  - θ_{23} and Δm^2_{23}
  - search for non-zero θ_{13}
  - CP phase

Thank you to the organizer for giving me so many topics to be covered.

Solar Neutrinos



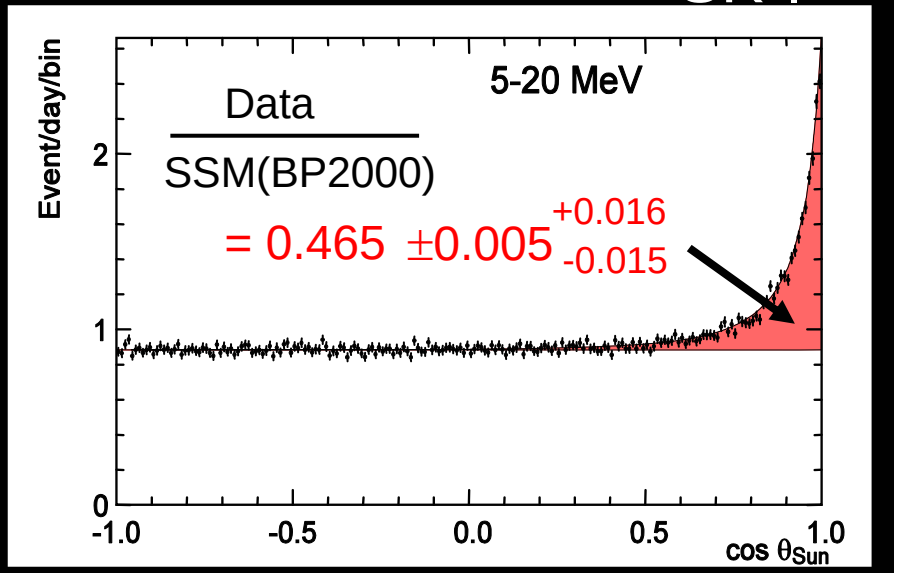


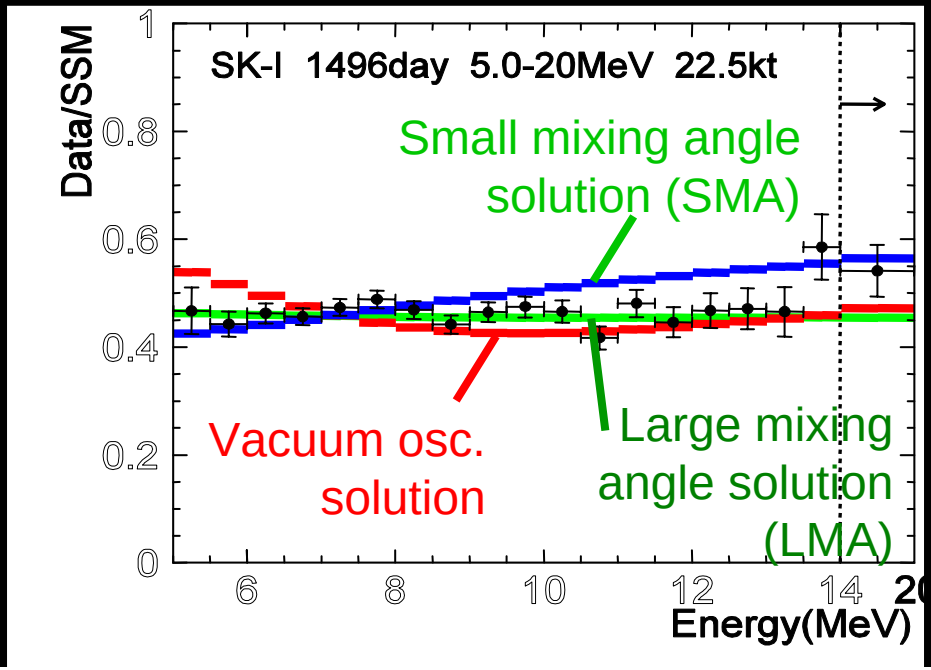
Super-Kamiokande

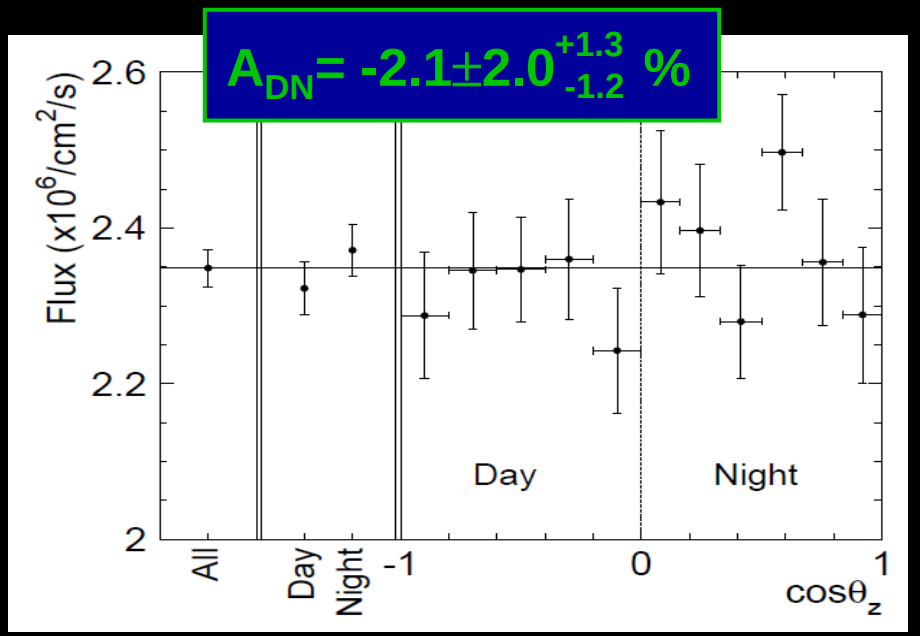
Phys.Rev.D73: 112001(2006)

SK-I

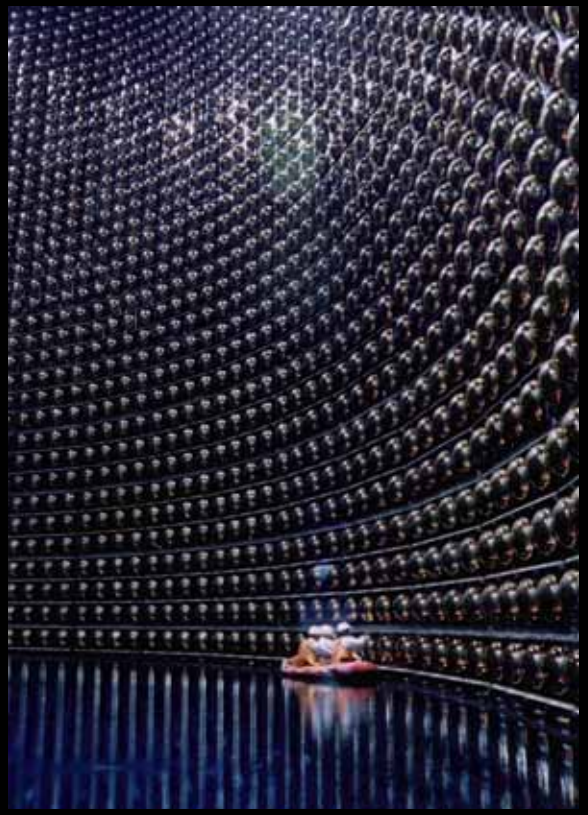
Detect solar neutrinos via: $\nu e \rightarrow \nu e$

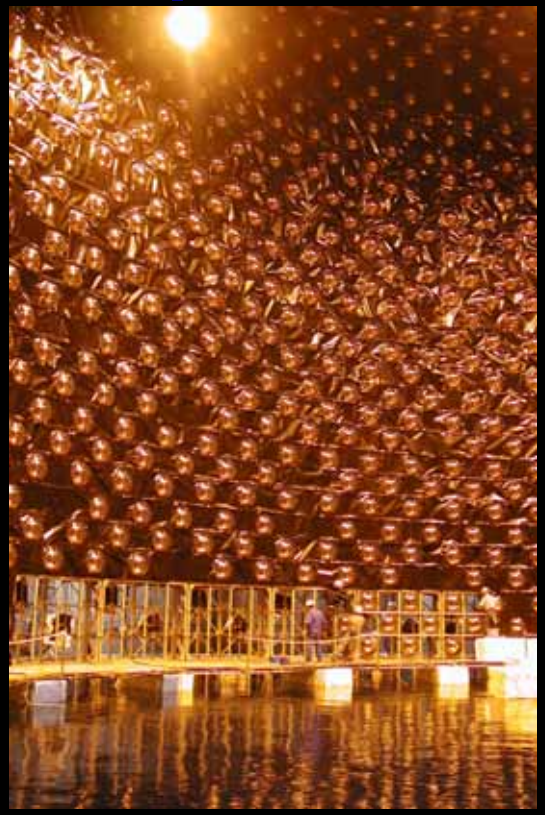


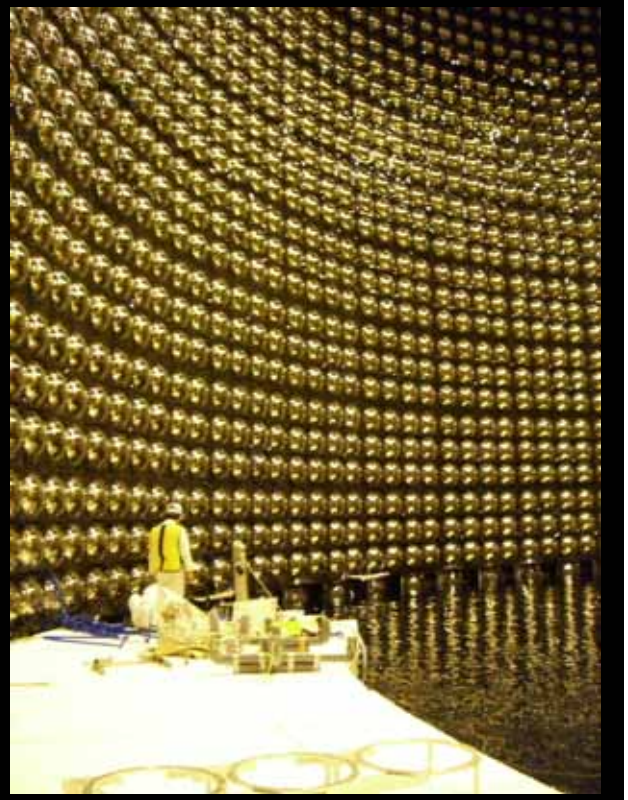




Status of Super-Kamiokande







SK-I: 1996-2001

SK-II: 2003-2005

SK-III started data taking in July 2006

Eth=5MeV

Eth=7MeV

Eth=~4MeV

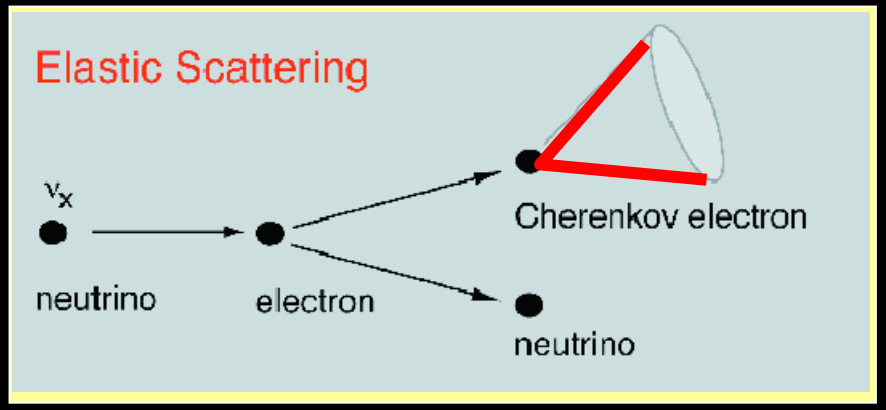
up-turn of $p(\nu_e \rightarrow \nu_e)$ at low E..

Solar ν Signatures in SNO (D_2O)

Elastic Scattering (ES)

$\nu_x + e^- \rightarrow \nu_x + e^-$

ν_x, but enhanced for ν_e

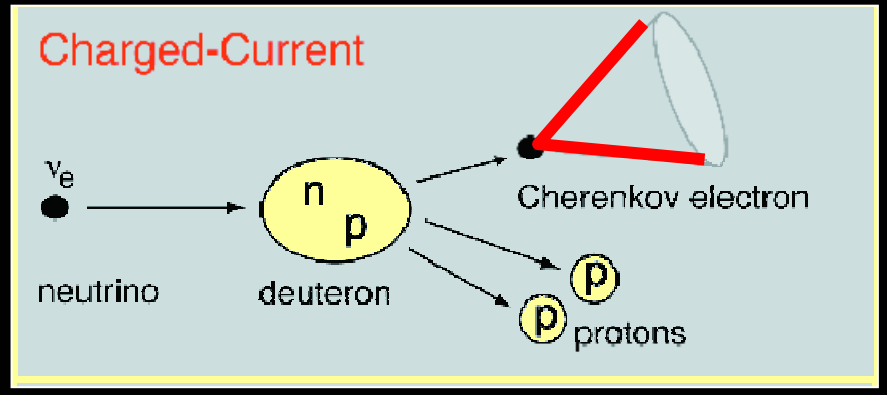


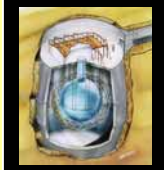
Charged-Current (CC)

$\nu_e + d \rightarrow e^- + p + p$

$E_{thresh} = 1.4$ MeV

ν_e only



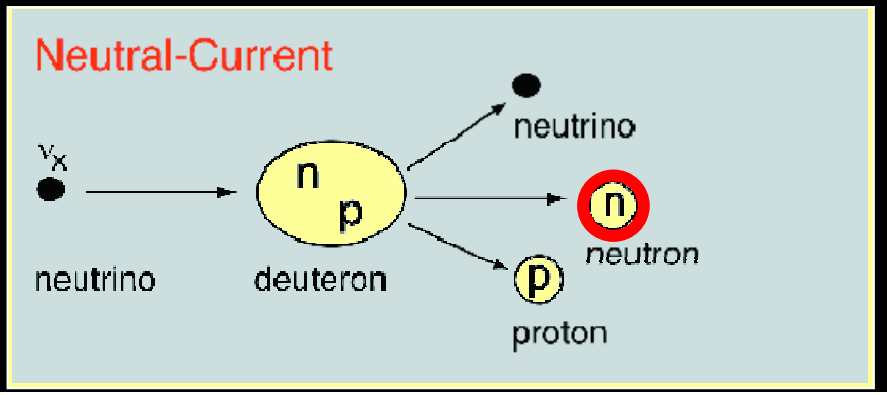


Neutral-Current (NC)

$\nu_x + d \rightarrow \nu_x + n + p$

$E_{thresh} = 2.2$ MeV

Equally sensitive to ν_e ν_μ ν_τ

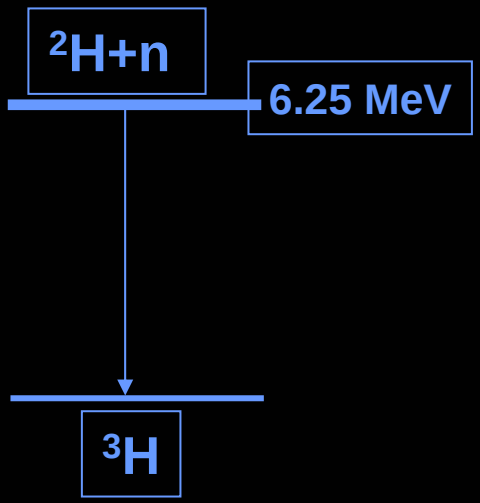


3 tagging methods

3 neutron (NC) detection methods

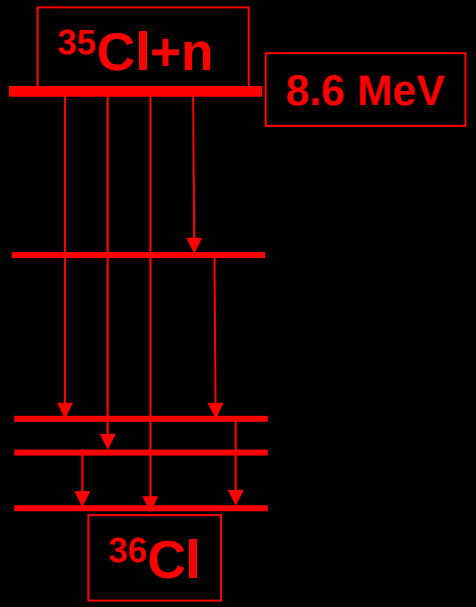
Phase I (D_2O)
Nov. 99 - May 01

n captures on
$^2H(n, \gamma)^3H$
Effc. ~14.4%
NC and CC separation by energy, radial, and directional distributions



Phase II (salt)
July 01 - Sep. 03

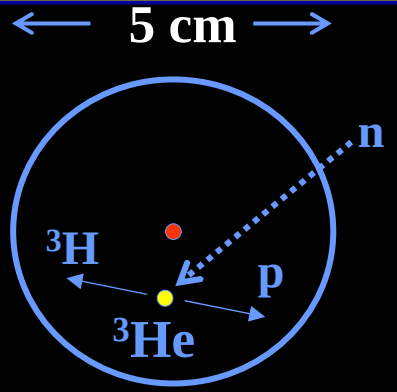
2 t NaCl. n captures on
$^{35}Cl(n, \gamma)^{36}Cl$
Effc. ~40%
NC and CC separation by event isotropy



Higher efficiency
Higher energy

Phase III (^3He)
Nov. 04-Nov. 06

40 proportional counters
$^3He(n, p)^3H$
Effc. ~ 30% capture
Measure NC rate with entirely different detection system.

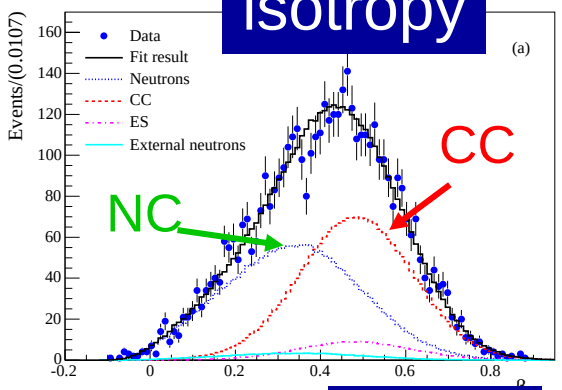


$n + {}^3He \rightarrow p + {}^3H$

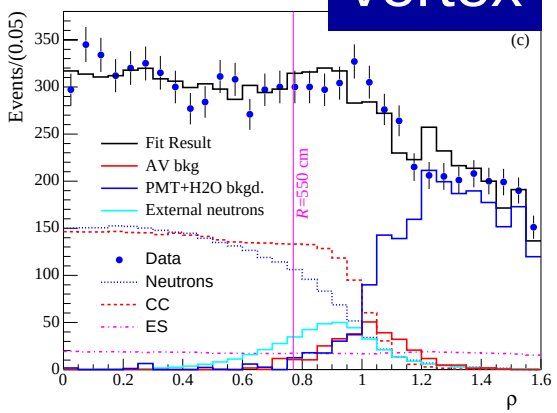
Extraction of ES, CC, and NC signal

(SNO 391days salt data, Phys.Rev.C72, 055502 (2005))

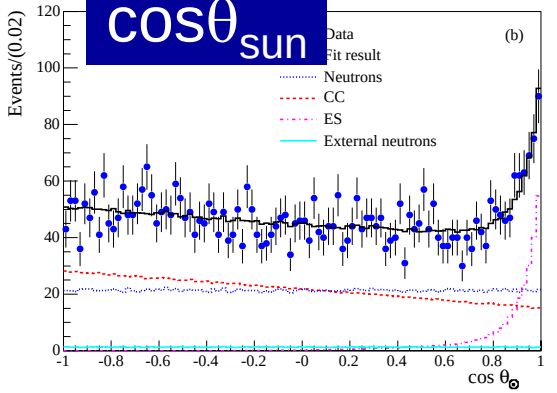
isotropy

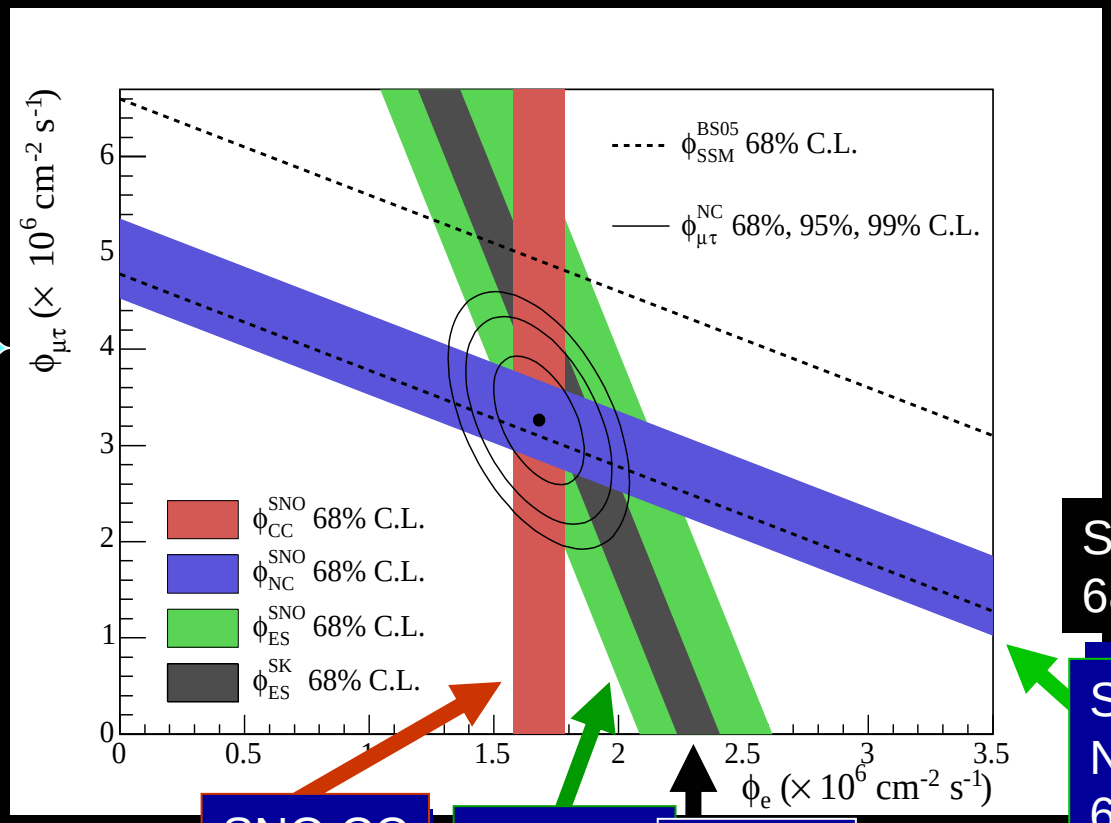


vertex



$\cos\theta_{sun}$





SSM 68%CL

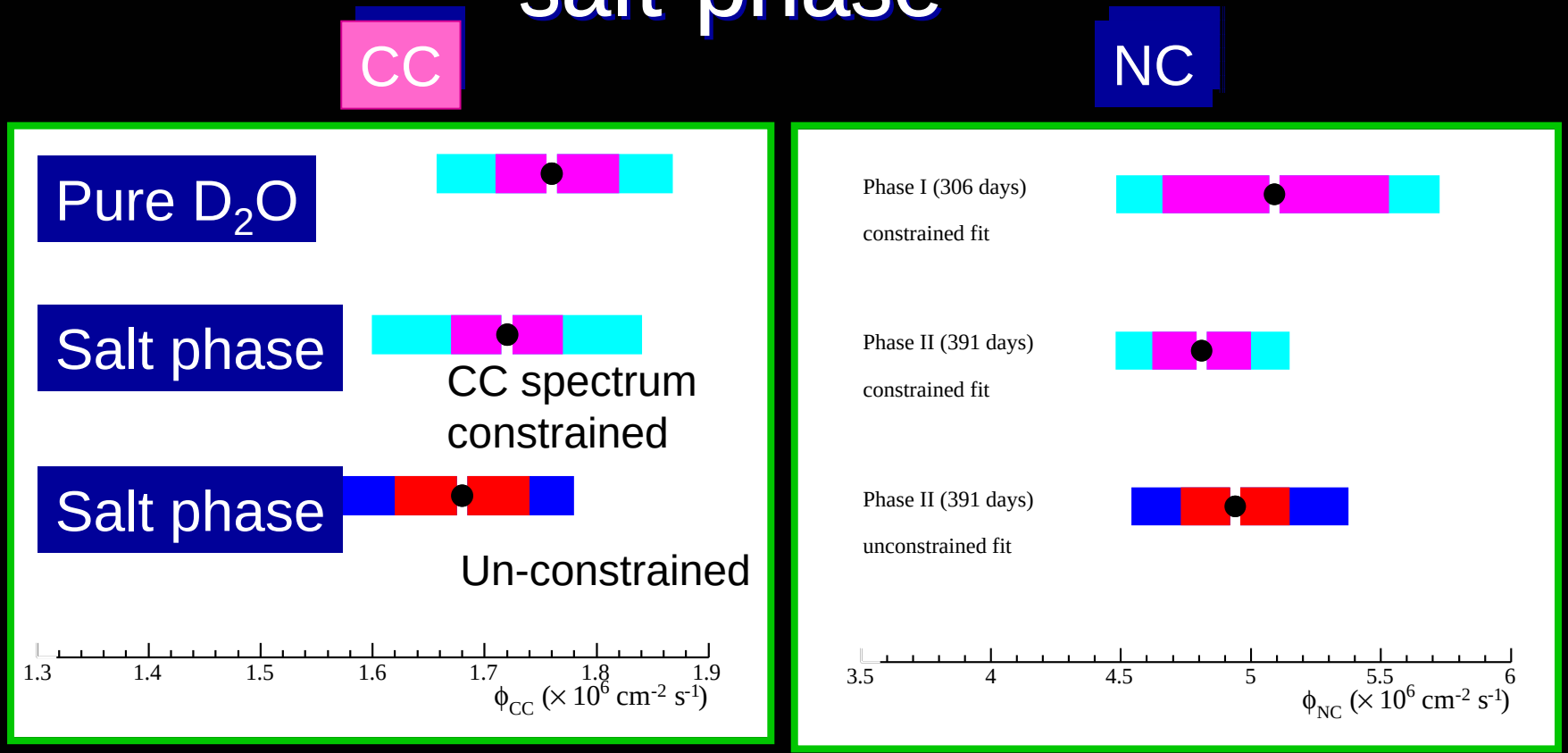
SNO NC 68%CL

SNO CC 68%CL

SNO ES 68%CL

SK ES 68%CL

Comparison of pure D_2O phase and salt phase



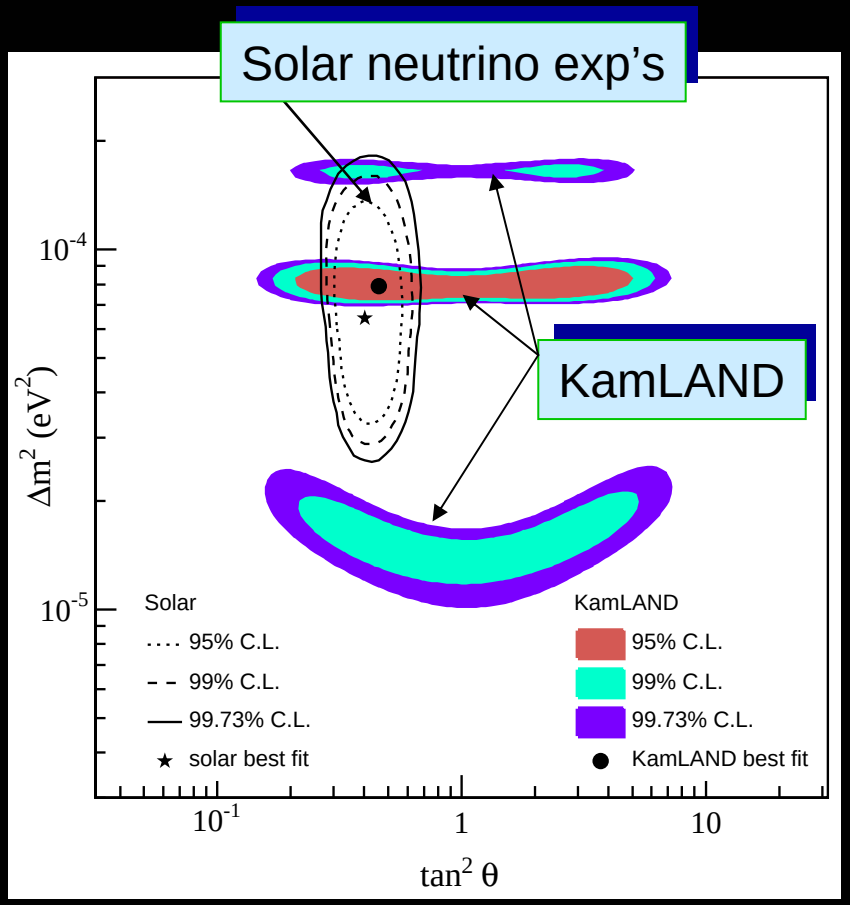
$$\phi_{CC} = 1.68\ ^{+0.06}_{-0.06}(\text{stat.})^{+0.08}_{-0.09}(\text{syst.})$$

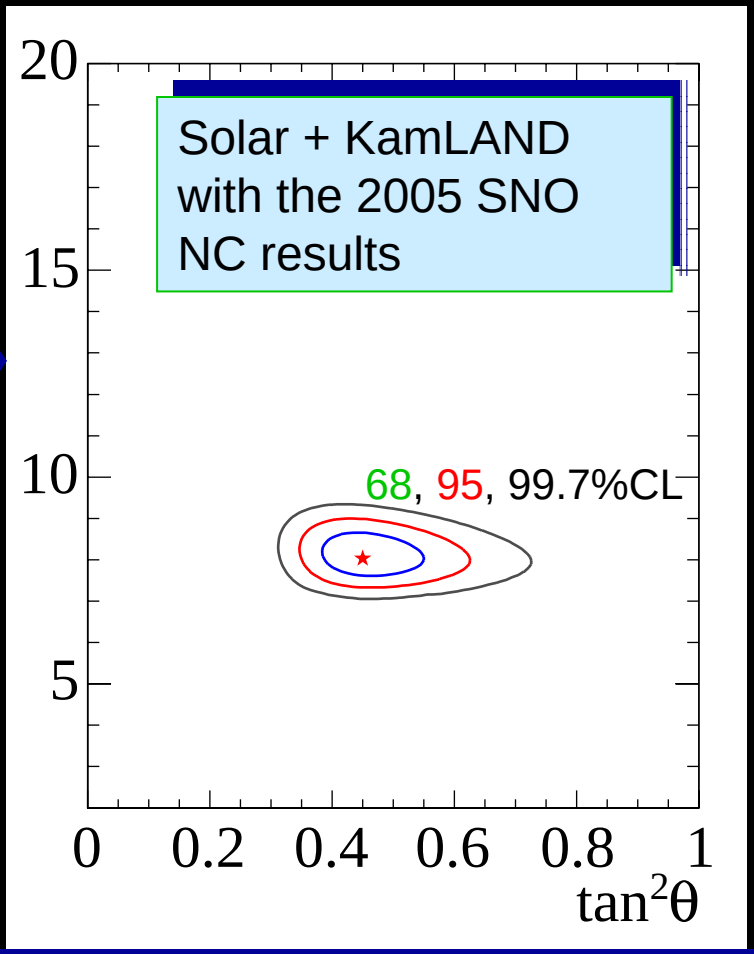
$$\phi_{NC} = 4.94\ ^{+0.21}_{-0.21}(\text{stat.})^{+0.38}_{-0.34}(\text{syst.})$$

$$\phi_{ES} = 2.35\ ^{+0.22}_{-0.22}(\text{stat.})^{+0.15}_{-0.15}(\text{syst.})$$

$$\frac{\phi_{CC}}{\phi_{NC}} = 0.34 \pm 0.023(\text{stat.})^{+0.029}_{-0.031} = \cos^4\theta_{13}\sin^2\theta_{12}$$

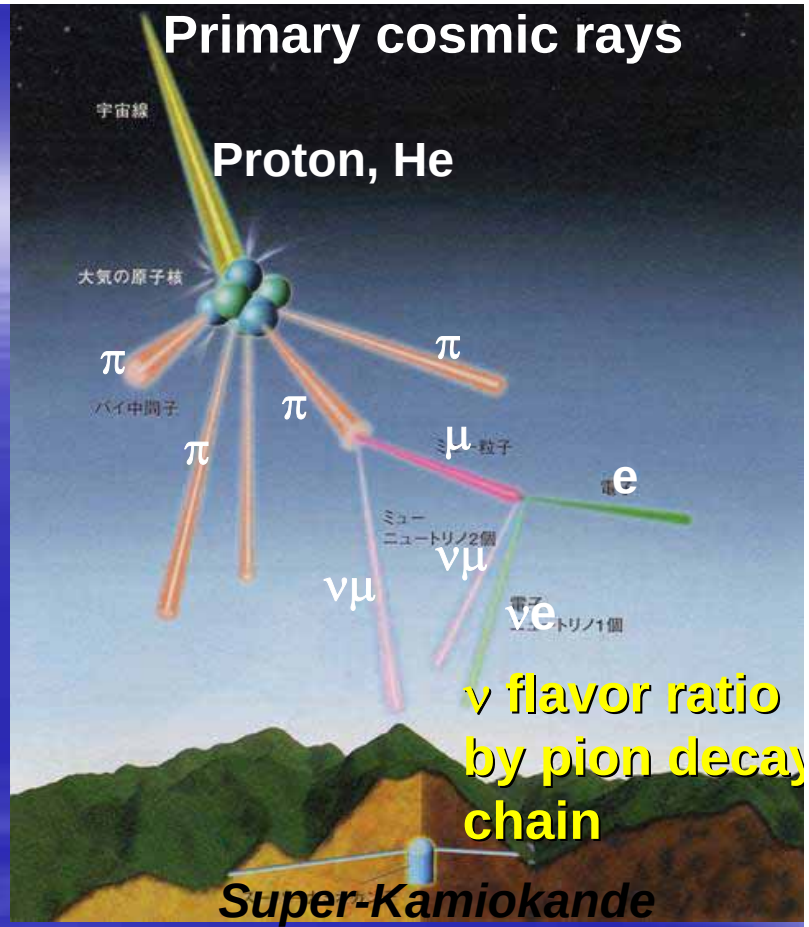
Allowed (θ_{12},Δm^2_{12}) region

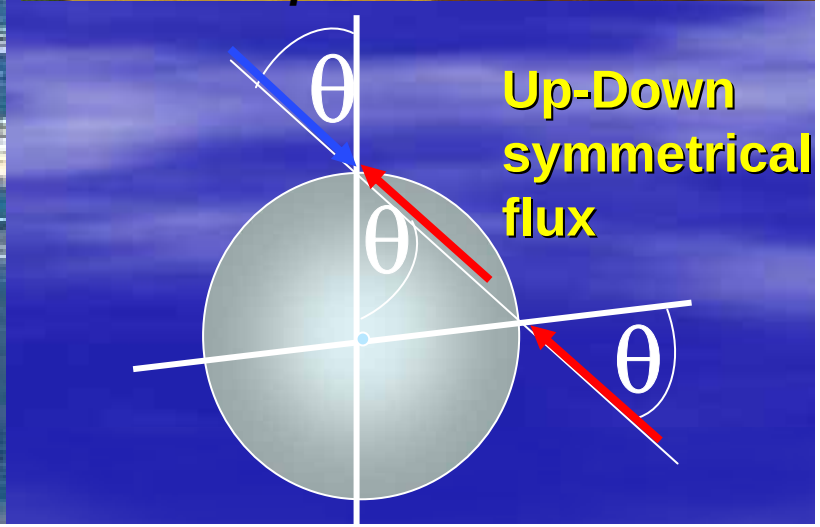




$\Delta m_{12}^2 = 8.0^{+0.6}_{-0.4} \times 10^{-5}\text{eV}^2$,
$\theta_{12} = 33.9^{+2.4}_{-2.2}$ degrees (68%CL)

Atmospheric ν's

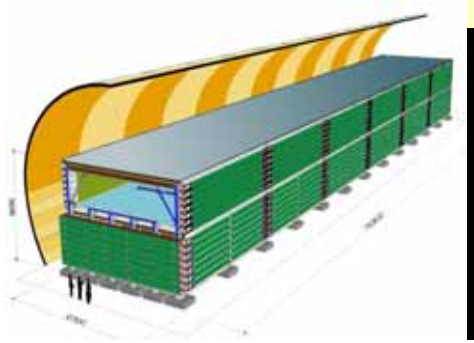


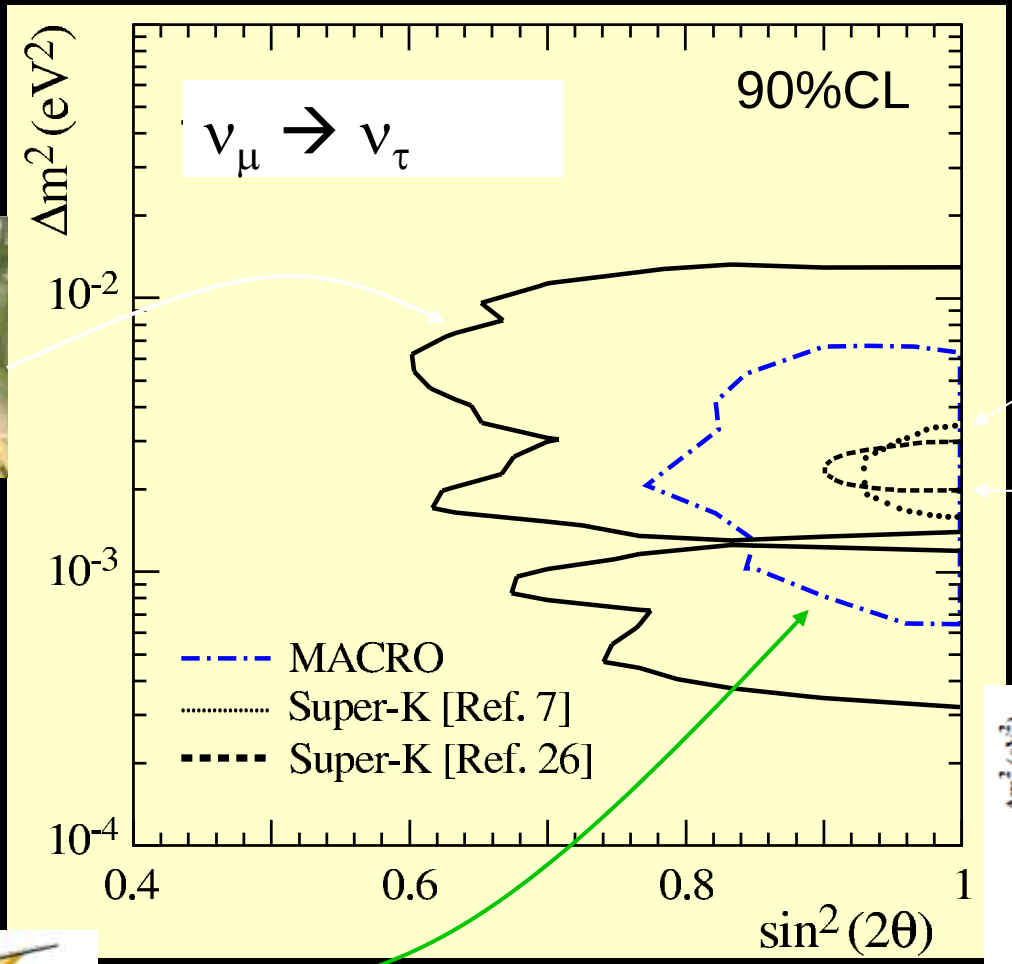


Allowed (θ_{23},Δm^2_{23}) regions

Soudan-2

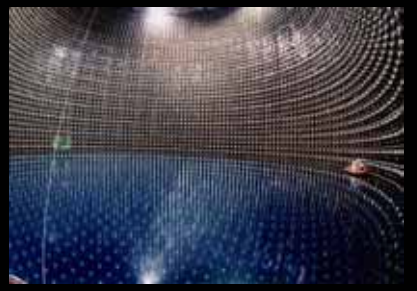
MACRO





MINOS

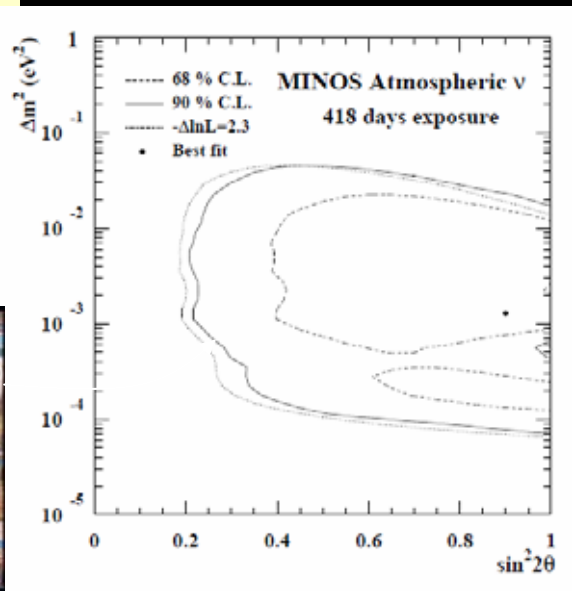
hep-ph/0507068



SK zenith-angle

SK L/E

MINOS atmospheric result (Phys.Rev.D73:072002,2006) is also consistent.



SK-I+II atmospheric neutrino data

SK-I: Phys.Rev.D71:112005,2005
+ SK-II 804 days

SK-I: 92 kton·yr
SK-II: 49 kton·yr
Total: 141 kton·yr

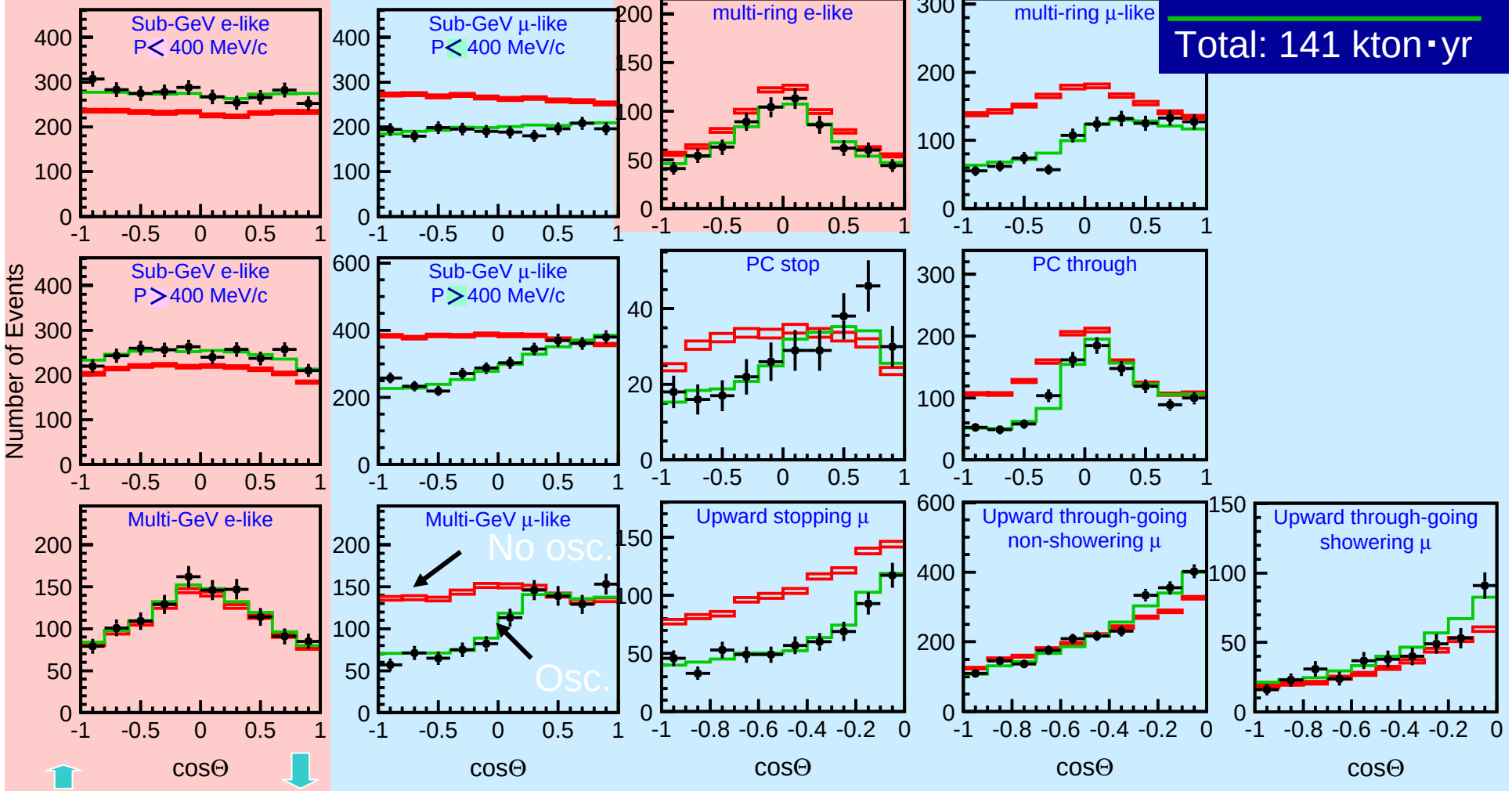
CC ν_e

CC ν_μ

SK-I + SK-II

SK-I + SK-II

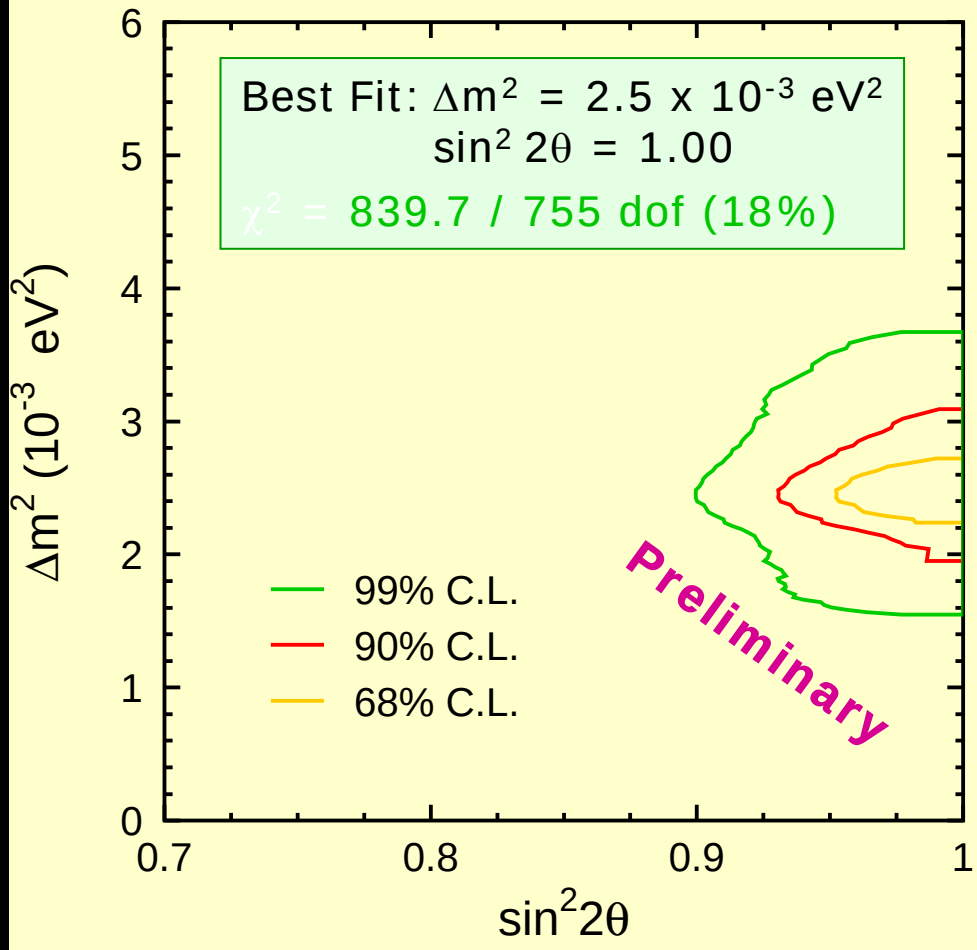
SK-II



$\nu_\mu \rightarrow \nu_\tau$ 2 flavor analysis

SK-I + SK-II

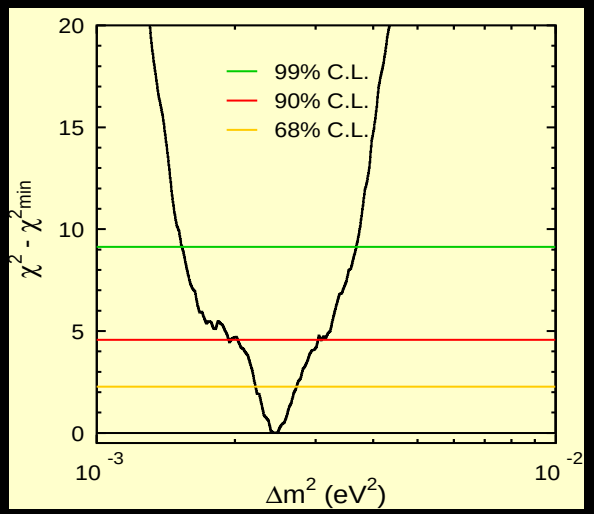
1489 days (SK-1)+ 804 days (SK-II)

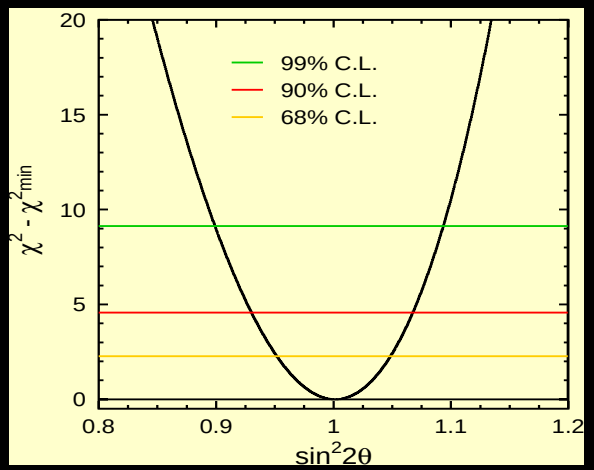


1.9×10^{-3} eV^2 < Δm^2 < 3.1×10^{-3} eV^2

$\sin^2 2\theta > 0.93$ at 90% CL

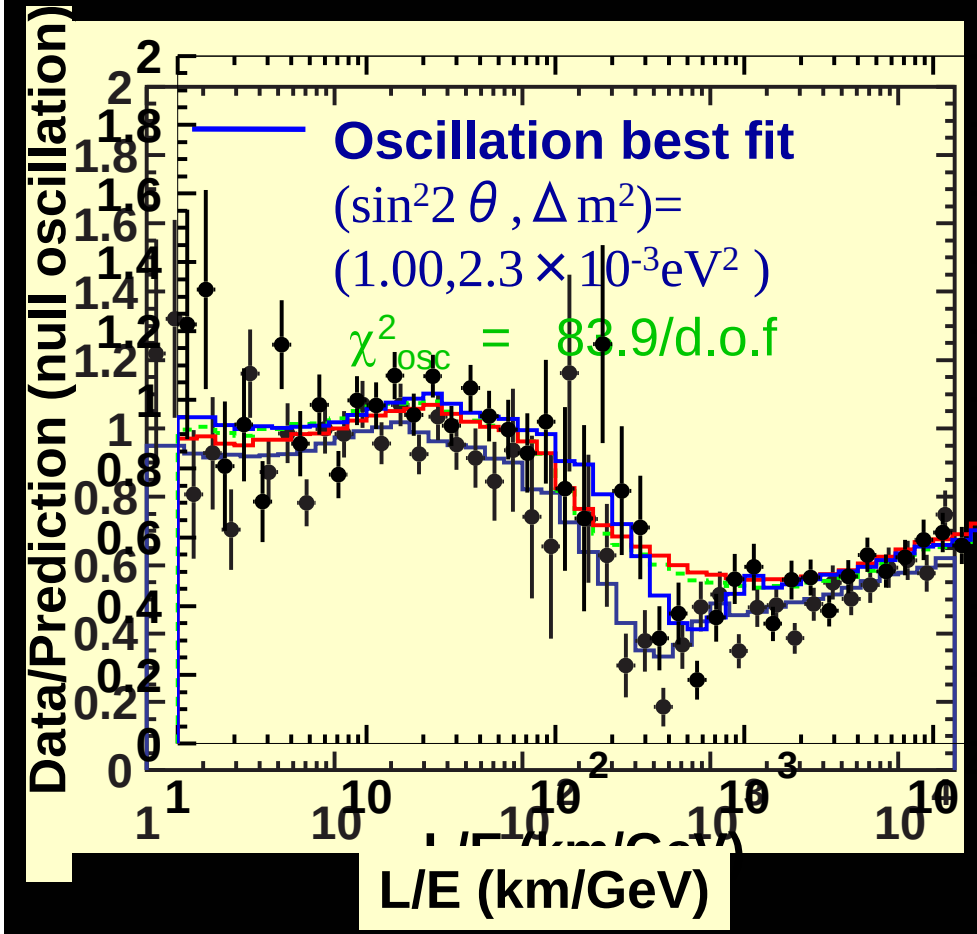
$\Delta\chi^2$ distributions

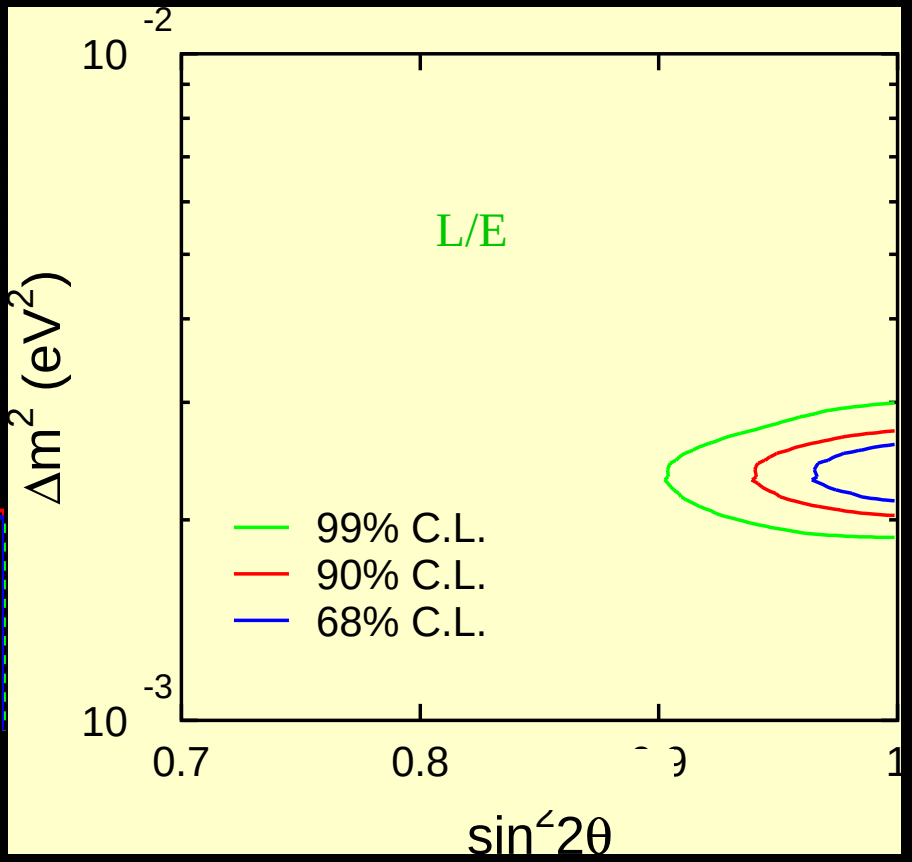




High resolution L/E sample

Update from Phys. Rev. Lett. 93,101801(2004)





$2.0 < \Delta m^2 < 2.9 \times 10^{-3} eV^2$

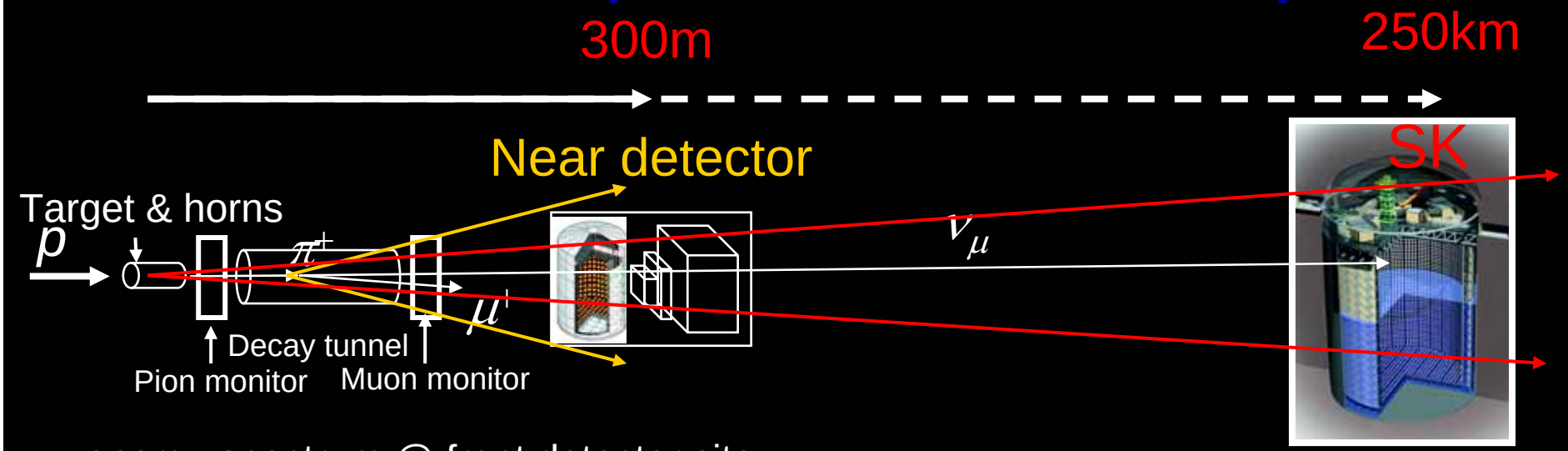
$\sin^2 2\theta > 0.92$ at 90 % CL

From zenith analysis: 1.9×10^{-3} eV² $< \Delta m^2 < 3.1 \times 10^{-3}$ eV²

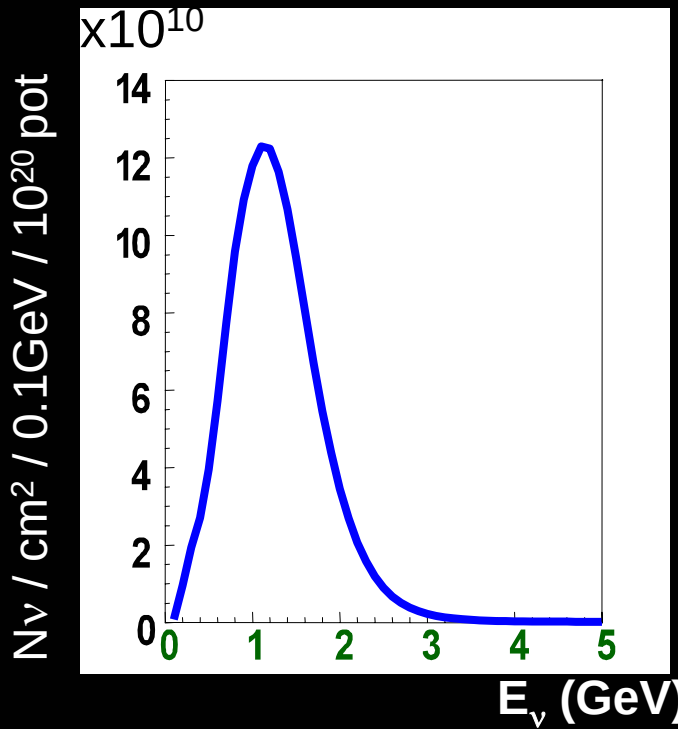
$\sin^2 2\theta > 0.93$ at 90 % CL

Accelerator Neutrinos
(Long Baseline experiment)

K2K experimental setup

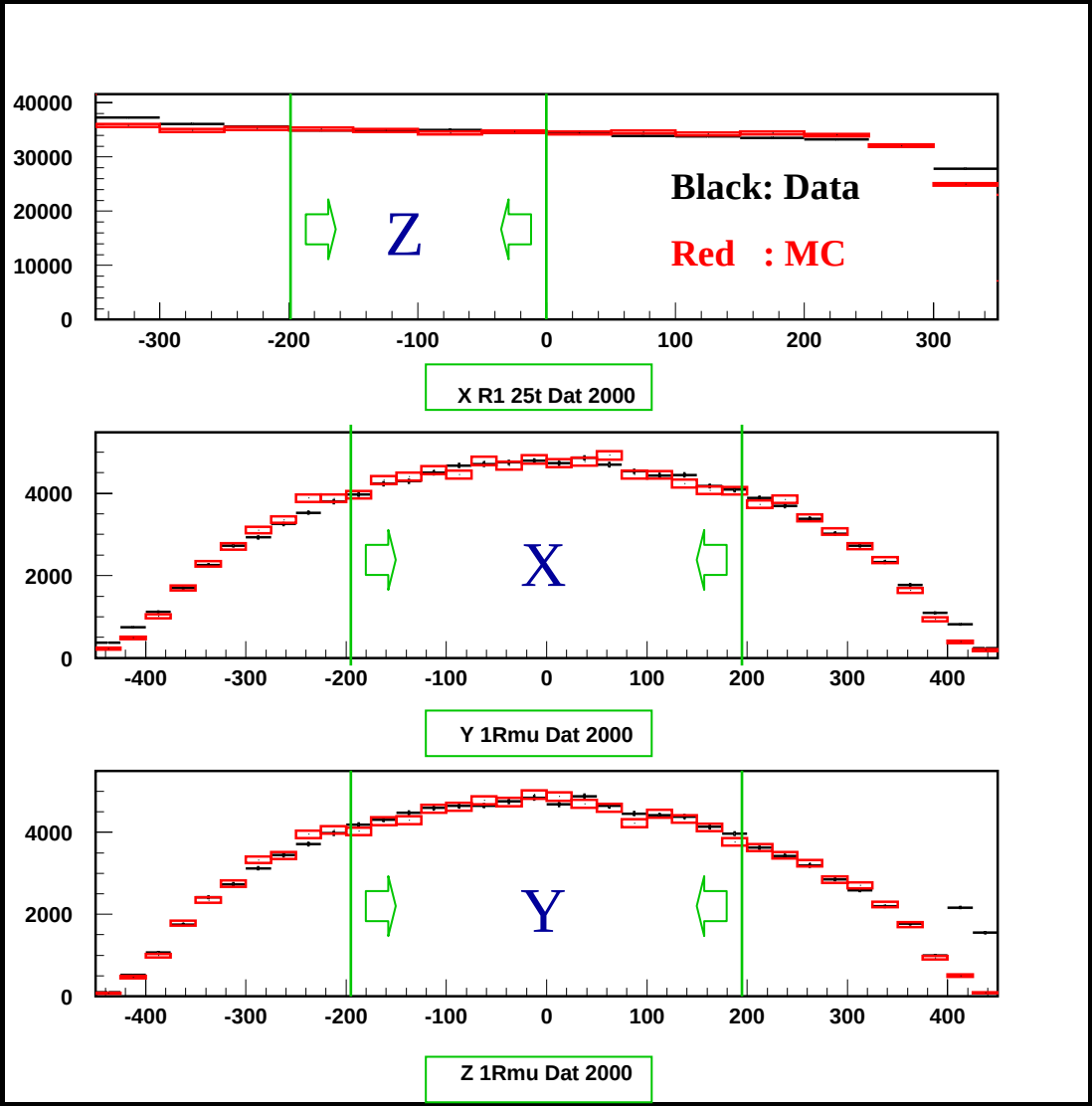


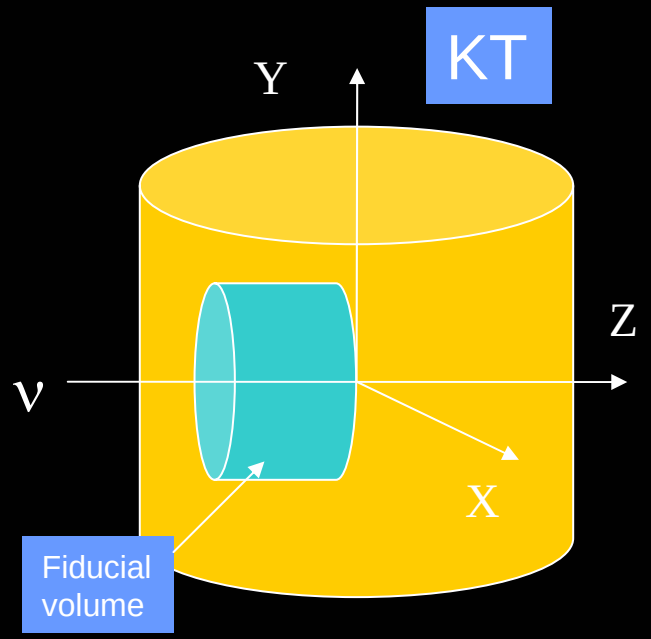
ν_μ energy spectrum @ front detector site



- almost pure ν_μ beam (~98%)
- Eν ~ 1.3 GeV

ν norm. determined by near detector



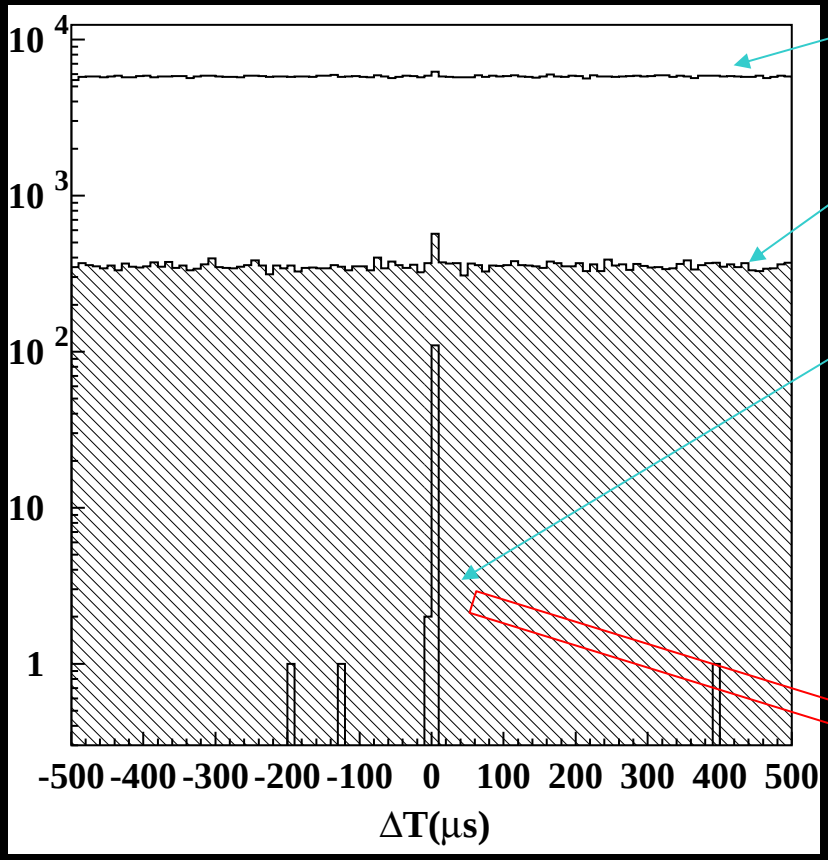


Very good agreement btw data and MC.

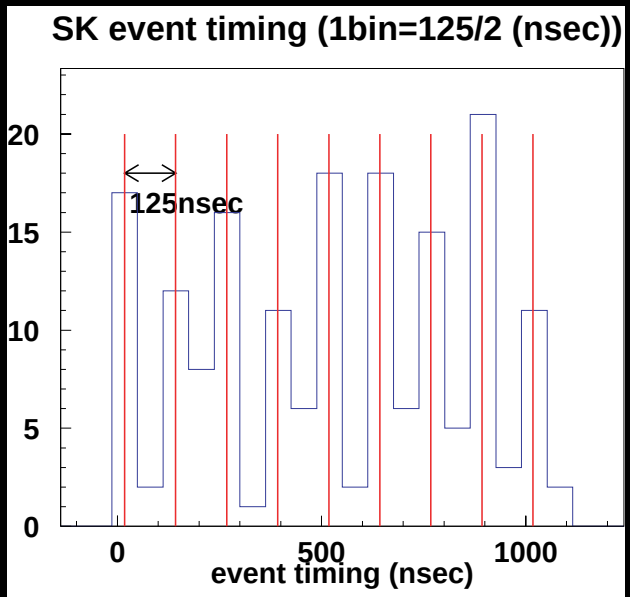
$$N_{KT}^{\text{int}} \rightarrow N_{SK} = 158.1^{+9.2}_{-8.6} \text{ events expected}$$

K2K Event selection @ far (SK)

TOF (0.83m sec) cut using GPS



Selection criteria	# of events
|ΔT|<500μsec, no pre-activity (Decay-e cut)	578k
Total q within 300n sec >200(K2K-I), 94(K2K-II) (~20MeV)	53k
No OD activity (FC), Evis>30MeV, Fiducial volume(Dwall>2m)	115
|ΔT|=-0.2 ~ +1.3μsec	112



112 on-timing fully contained events in fiducial volume are observed.

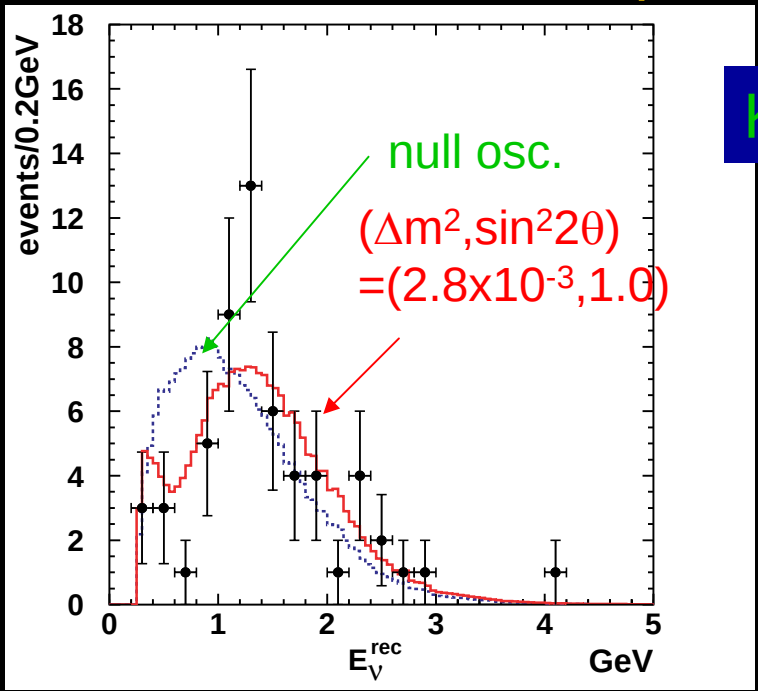
ν_μ disappearance analysis

Number of FC events

Obs. 112

Expected. $158.1^{+9.2}_{-8.6}$ (null osc.)

Reconstructed Eν spectrum



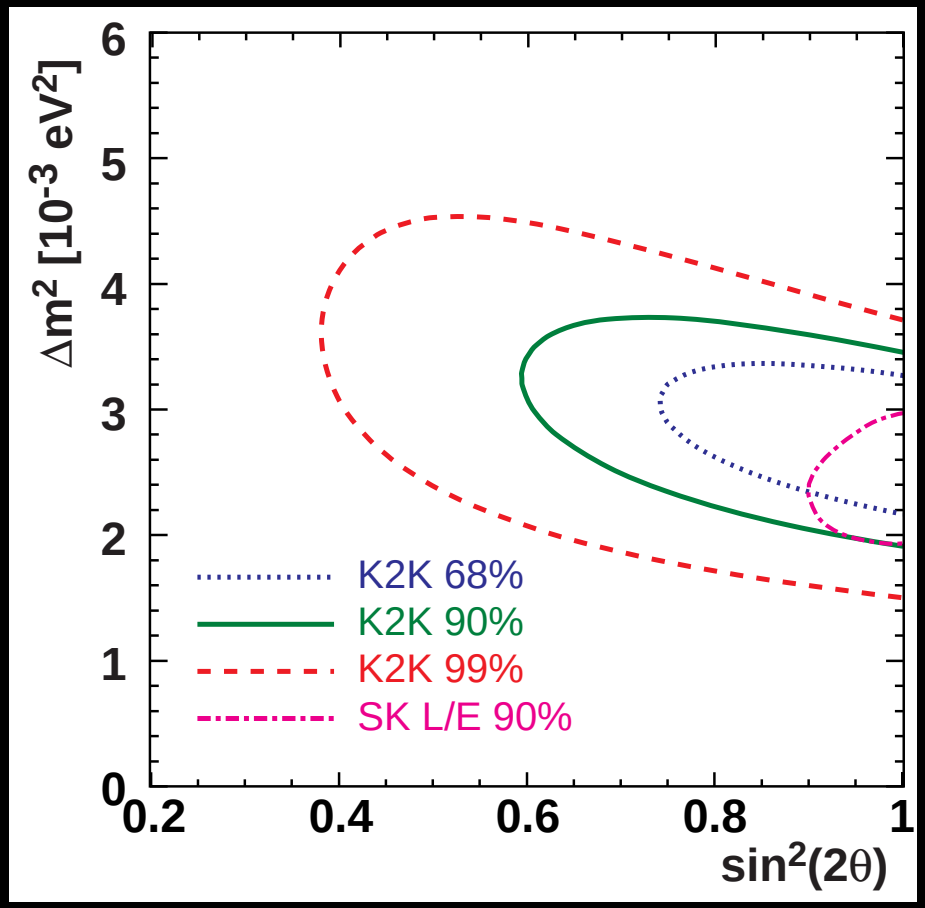
KS test probability for spectrum shape

Data-best fit $(2.8\times10^{-3},1.0)$	37%
Data-null osc.	0.07%

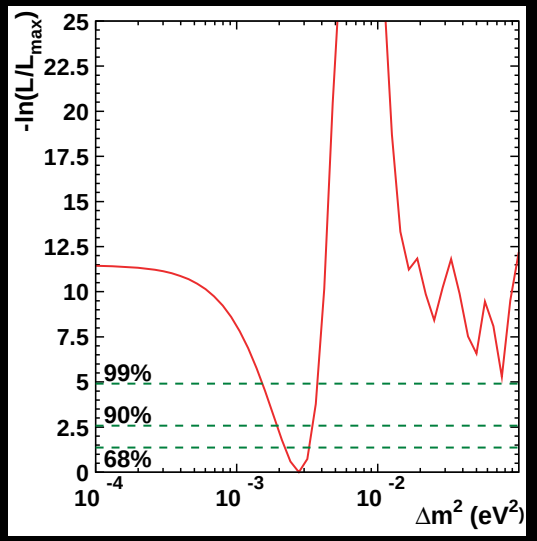
Null oscillation probability

	K2K	
Norm.	0.06%	(3.4σ)
Shape	0.42%	(2.9σ)
Shape+Norm.	0.0015%	(4.3σ)

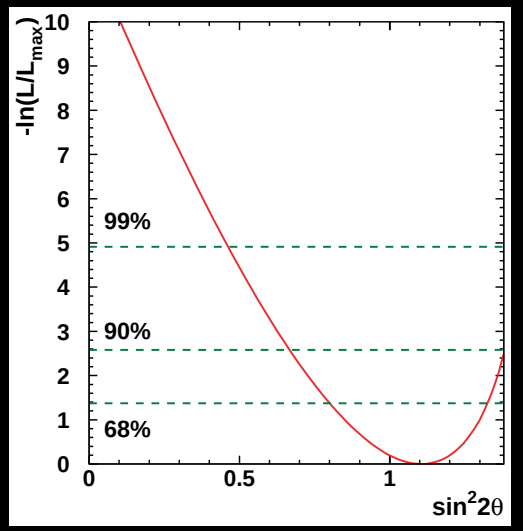
ν_μ disappearance allowed region



Δlikelihood @ $\sin^2 2\theta$=1.0



Δlikelihood @ Δm^2=2.8x10^{-3}



Best fit : (Δm^2,$\sin^2 2\theta$)

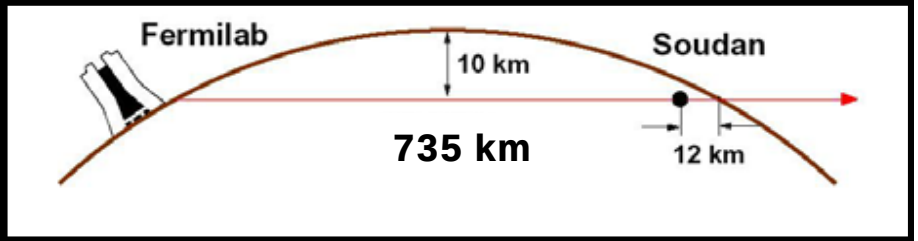
(2.55x10^{-3}, 1.19) (all region)

(2.75x10^{-3}, 1.0) (physical)

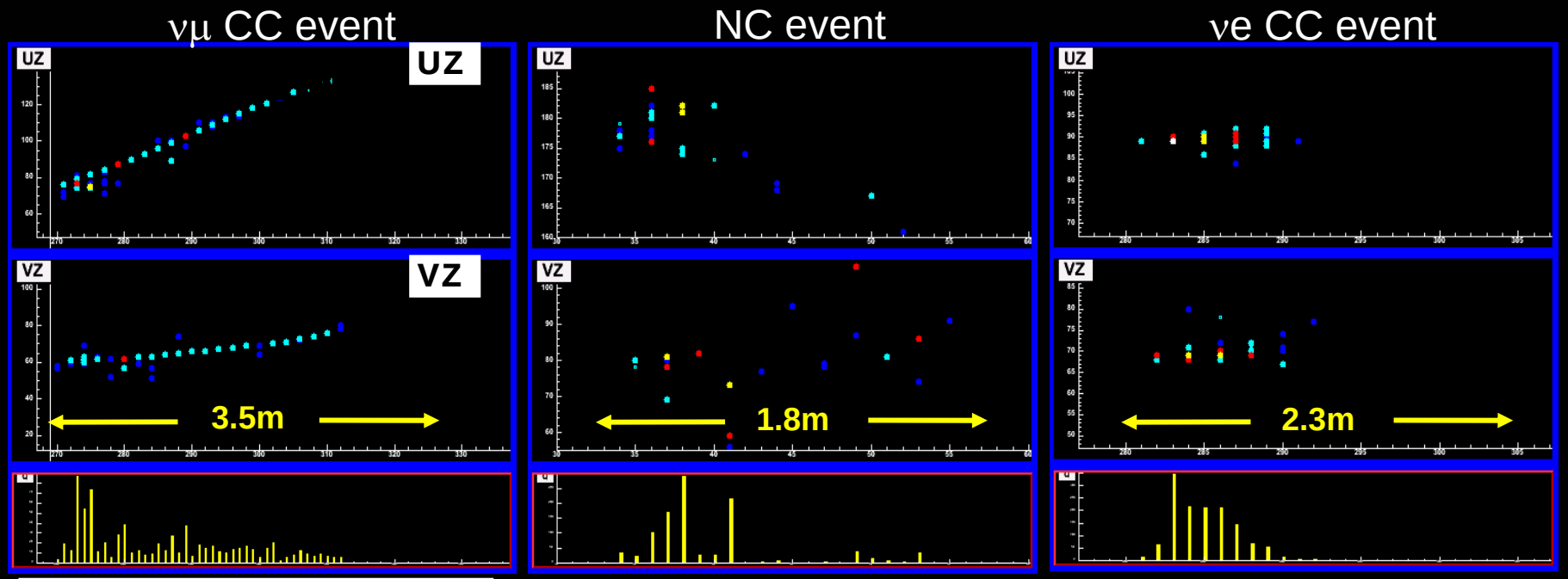
Atmnu confirmed by completely different method.

MINOS Experiment

- Main Injector Neutrino Oscillation Search
- High power ν_μ beam produced by 120 GeV protons from the Main Injector at FNAL
- Near detector (ND) at Fermilab to measure the beam composition and energy spectrum
- Far Detector (FD), 735km away, in the Soudan Mine, Minnesota
- LE-10 event composition: 92.9% ν_μ, 5.8% ν_μ, 1.3% ν_e / ν_e



MC Event Topologies



- Long muon track + hadronic activity at vertex
- Short showering event, often diffuse
- Short event with typical EM shower profile

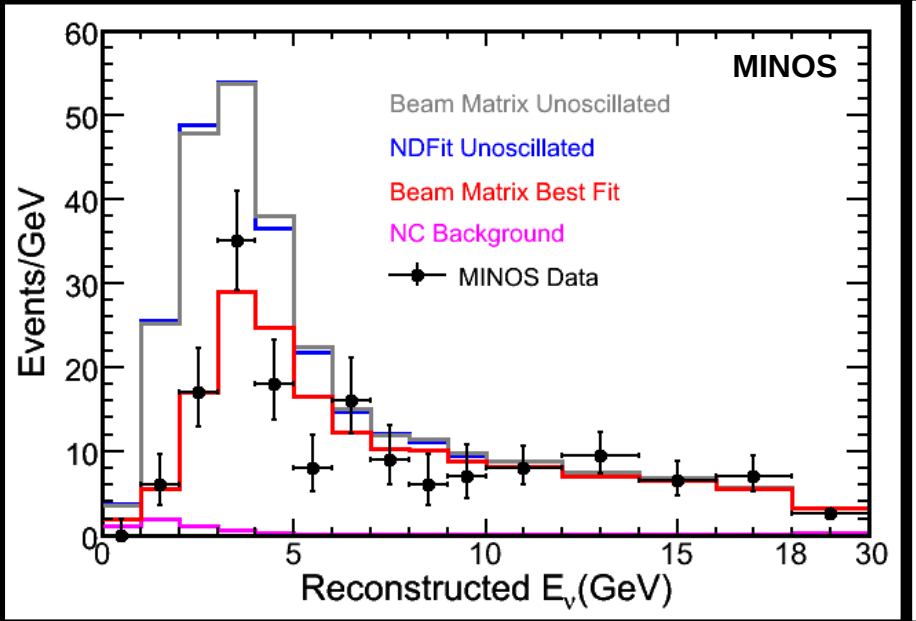
ν_μ CC is selected by;

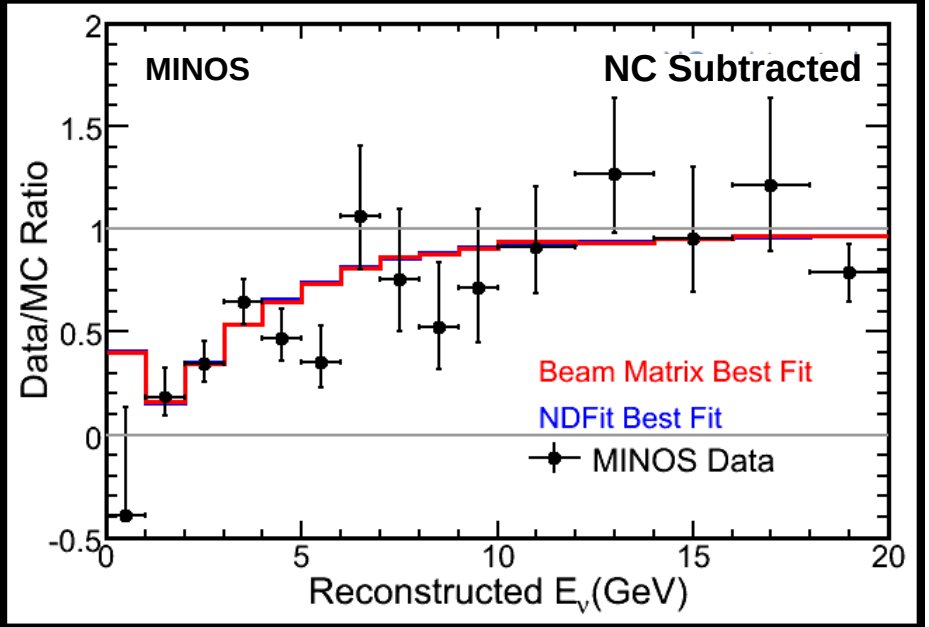
- >=1 track
- Negative charge (curvature)
- Likelihood based on
  - Track length
  - Fraction of pulse height in a track
  - dE/dx

MINOS Best-Fit Spectrum

PRL 97, 191801 (2006)

- Best-fit spectrum for 1.27×10^{20} POT





$$\left|\Delta m^2_{32}\right| = 2.74^{+0.44}_{-0.26}\ (\text{stat} + \text{syst}) \times 10^{-3}\ \text{eV}^2$$

$$\sin^2 2\theta_{23} = 1.00_{-0.13}\ (\text{stat} + \text{syst})$$

$$\text{Normalization} = 0.98$$

Measurement errors are 1σ, 1 DOF

$$\chi^2 = \sum_{i=1}^{nbins}\left[2(e_i - o_i) + 2o_i \ln(o_i/e_i)\right] + \sum_{j=1}^{nsys} \Delta s_j^2 / \sigma_{s_j}^2$$

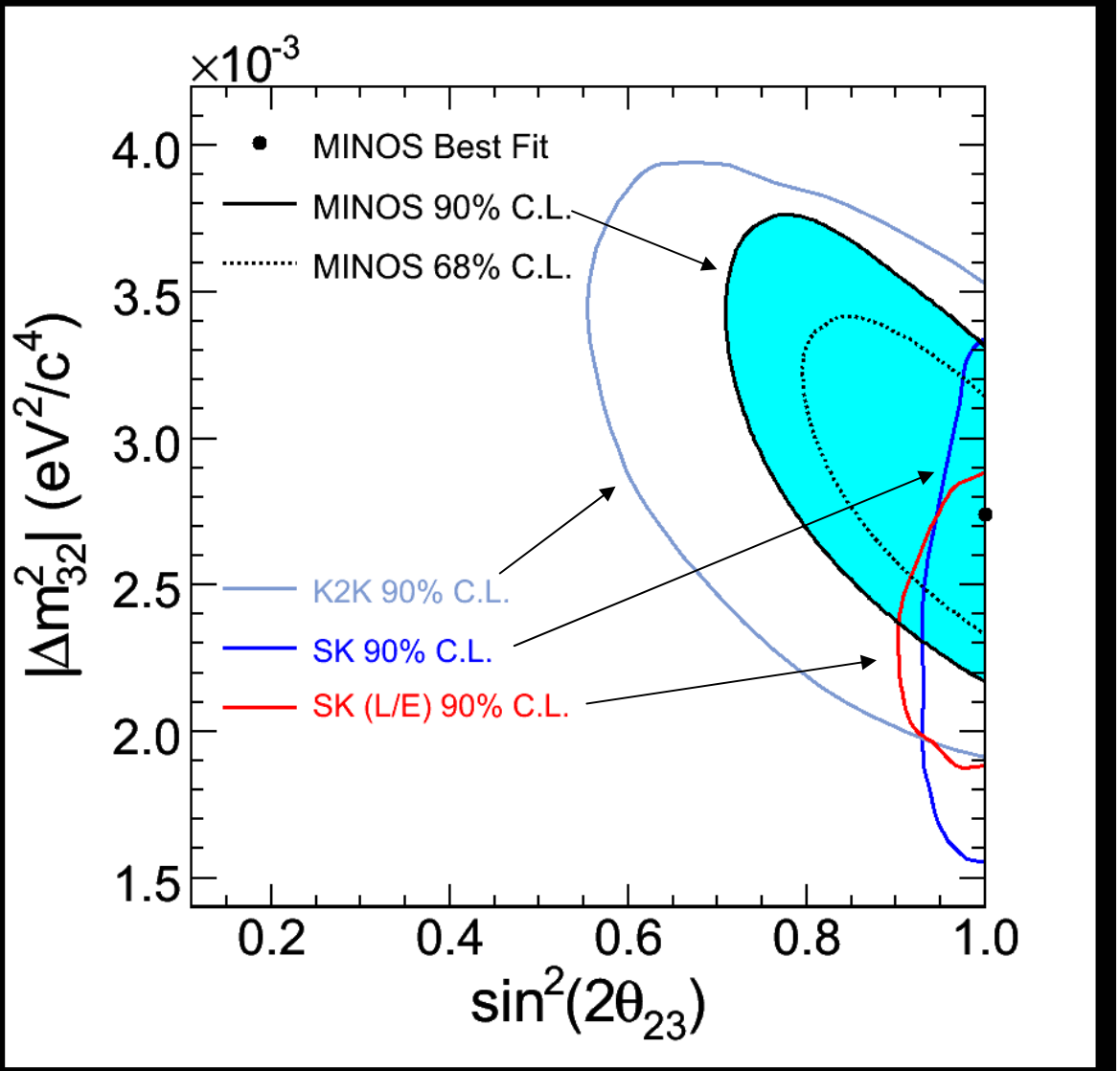
Allowed Region from MINOS

PRL 97, 191801 (2006)

- Fit includes penalty terms for three main systematic uncertainties
- Fit is constrained to physical region: $\sin^2(2\theta_{23}) \leq 1$

$$\left|\Delta m^2_{32}\right| = 2.74^{+0.44}_{-0.26} \times 10^{-3}\ \mathrm{eV}^2$$

$$\sin^2 2\theta_{23} = 1.00_{-0.13}$$

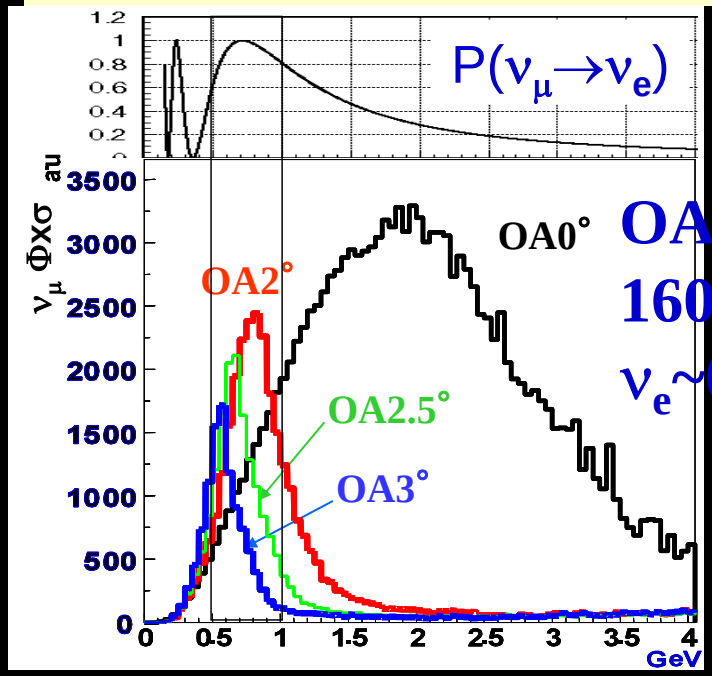


Future prospect of θ_{23}, Δm^2_{23}

T2K: Tokai-to(2)-Kamioka (~100×K2K)

- **T2K (approved in 2003)**
  - **Construction:2004~2008**
  - **Experiment: 2009 ~**

Off-axis beam: Narrow & Intense



OA2.5°:
1600ν_μCC/yr
ν_e~0.5% (peak)

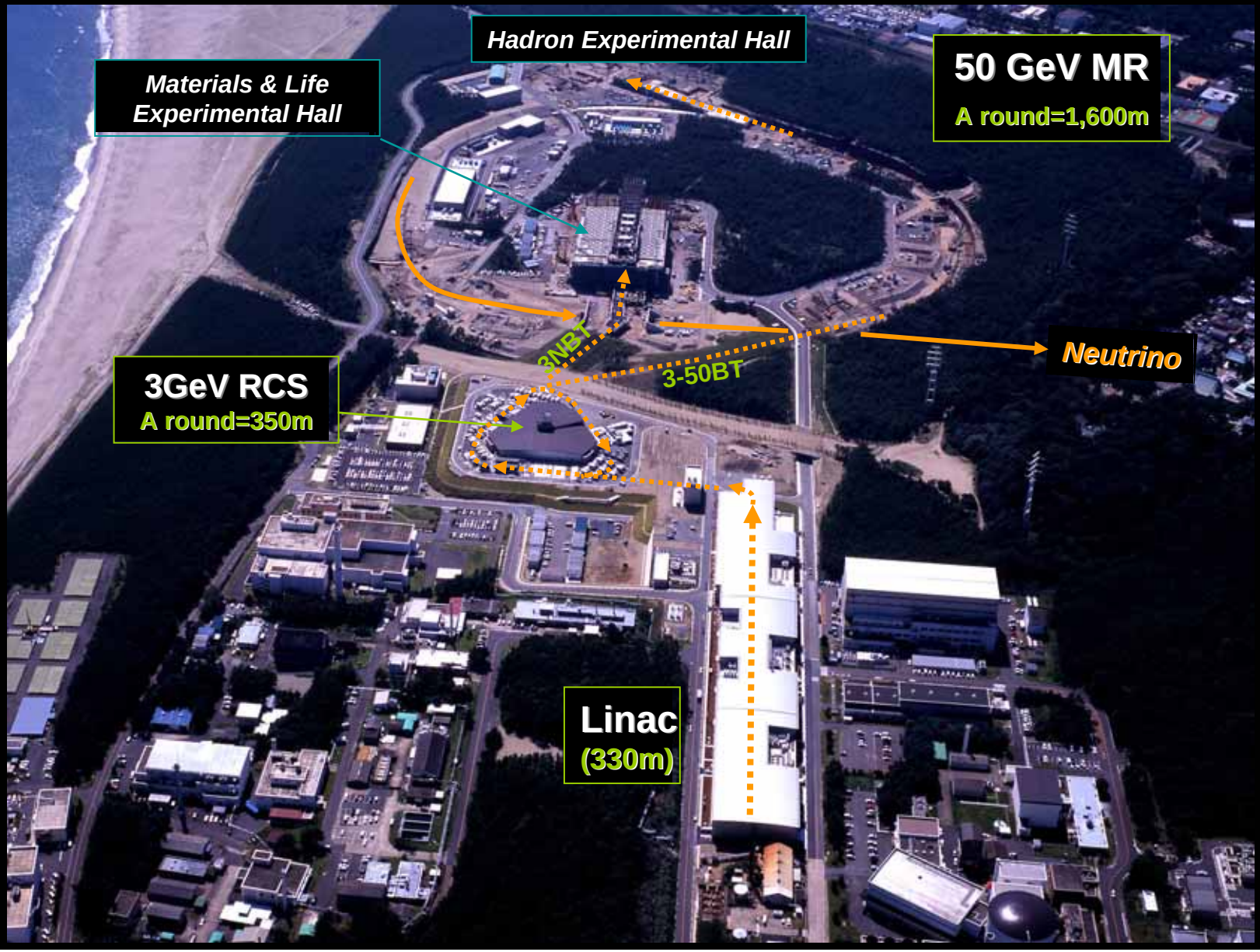
E_ν(GeV)

T2K-I (0.75MW + SK)

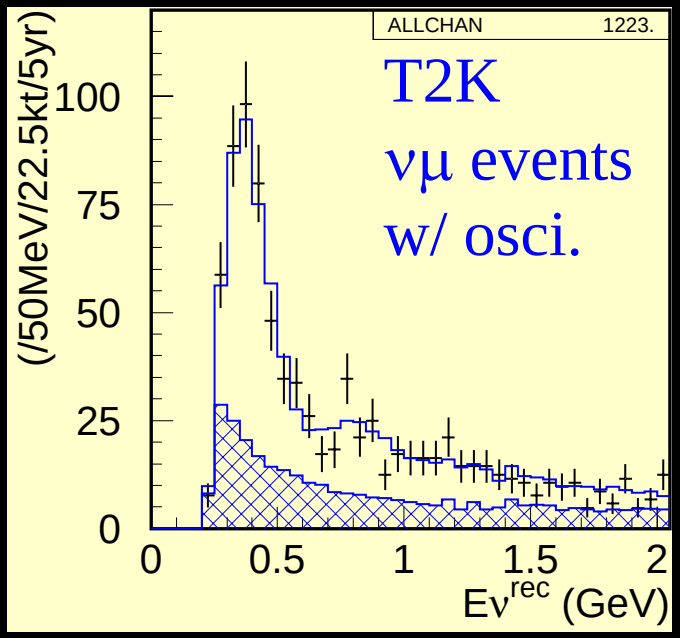
- $\nu_\mu \rightarrow \nu_e$ appearance
  - Aim to discover θ_{13}
- $\nu_\mu \rightarrow \nu_x$ disappearance
  - Precise Δm_{23}^2 $\sin^2 2\theta_{23}$

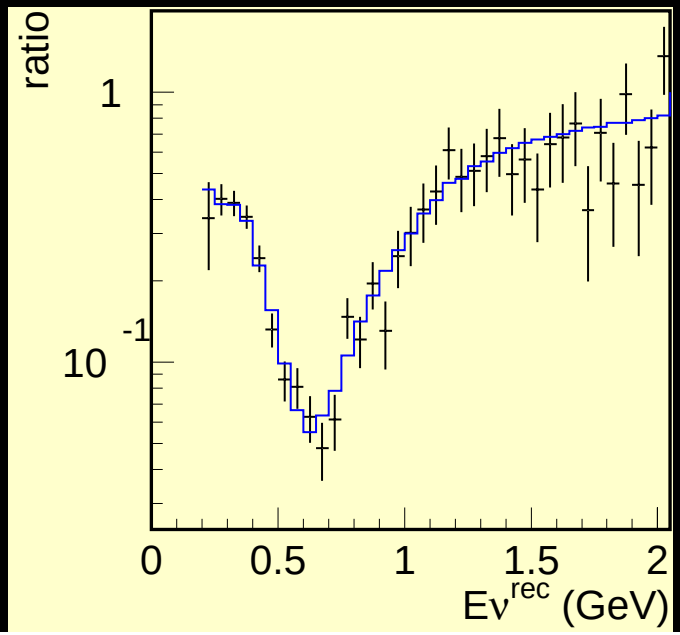
Phase II → 4MW, Mton, CPV

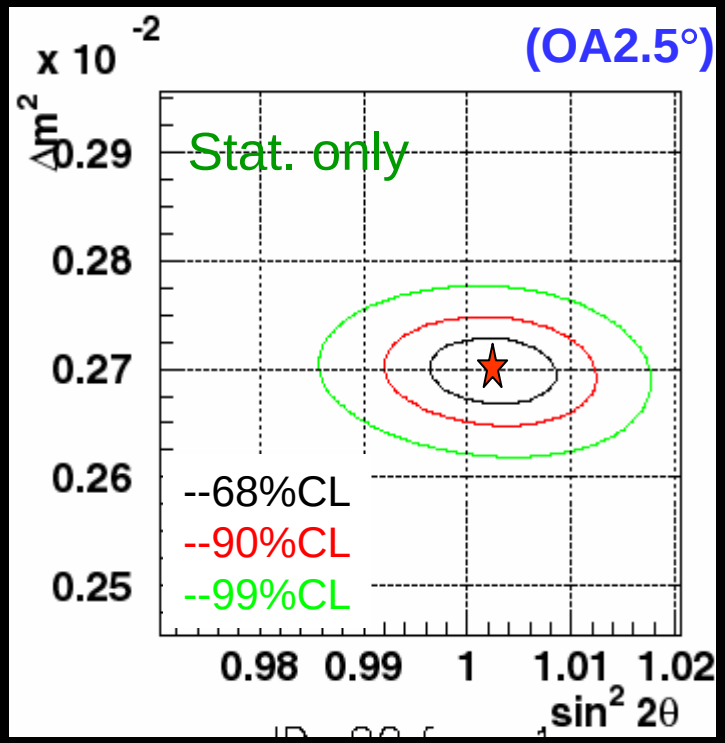
Bird's-Eye View (Feb. 2006)



T2K Sensitivity in $\nu_\mu \rightarrow \nu_\mu$ disappearance





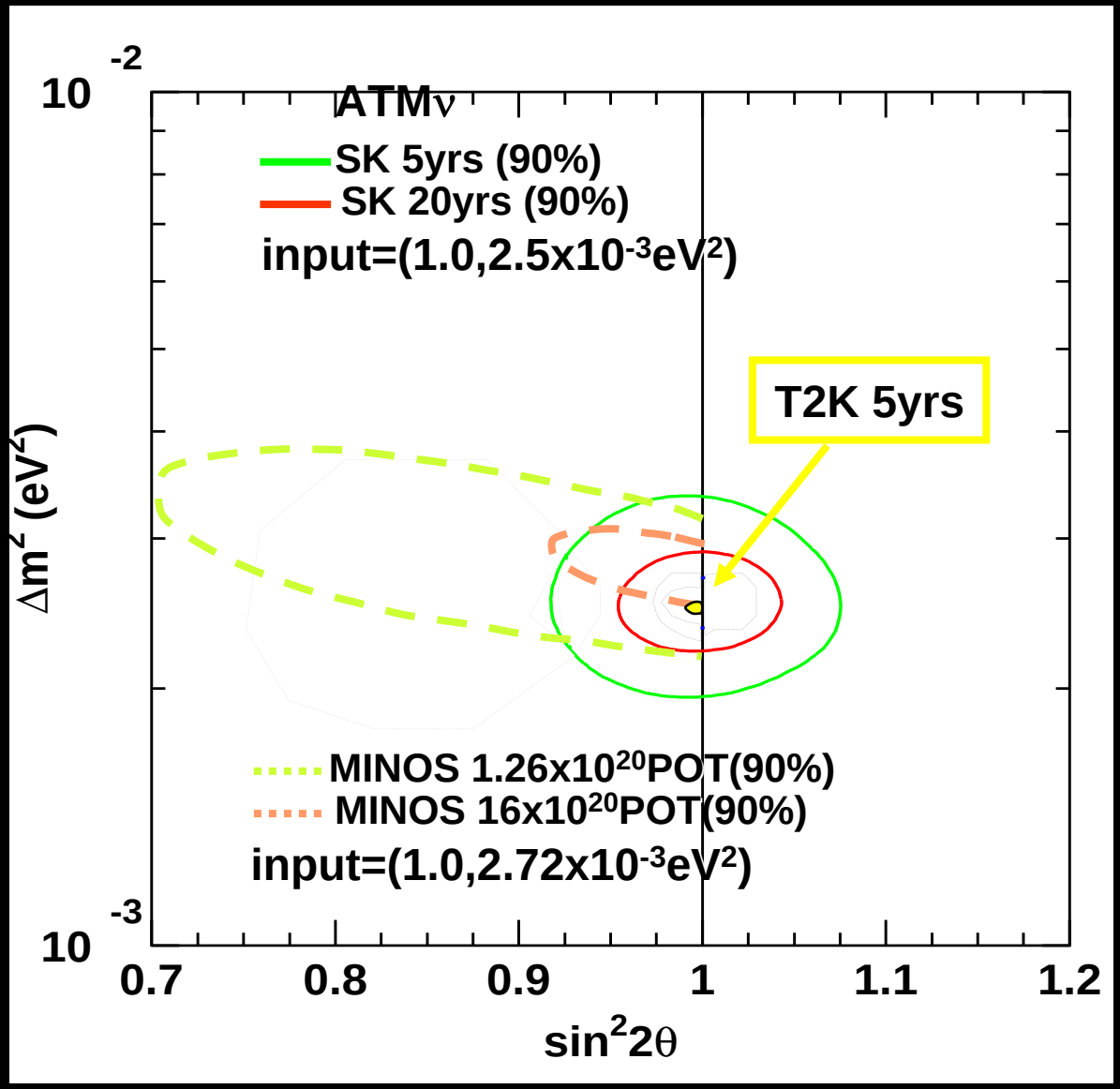


Goal

$\delta(\sin^2 2\theta_{23}) \sim 0.01$

$\delta(\Delta m_{23}^2) \sim < 1 \times 10^{-4}$

Future sensitivity study by fake data(MC)



T2K will give stringent limit.

SK atmnu, MINOS

- $\delta(\sin^2 2\theta) \propto$ 1/sqrt(stat.)
- $\delta(\Delta m^2) \propto$ 1/sqrt(stat.)
- will be compared with T2K

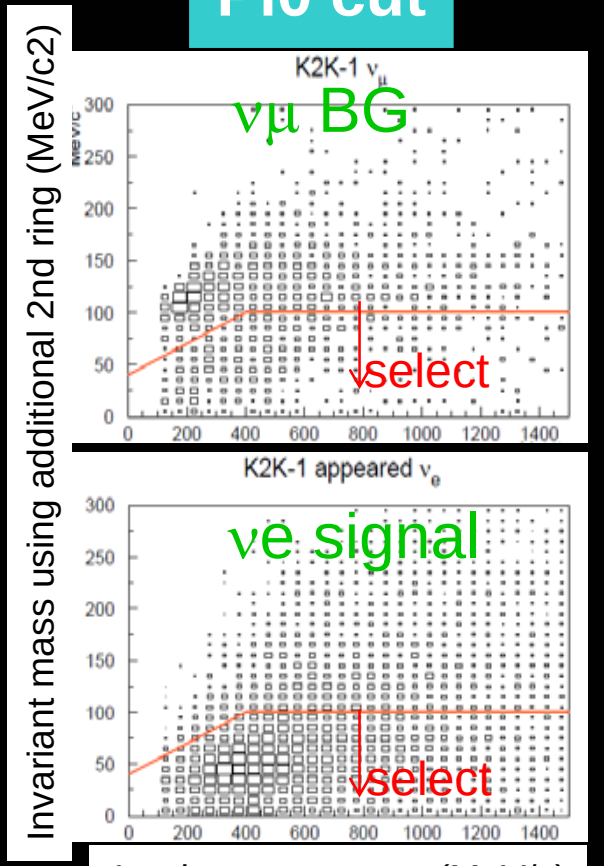
Search for non-zero θ_{13}

K2K ν_e appearance search

—K2K-1—	νμ MC	beam νe	Data
FCFV	81.1	0.81	55
Single ring	50.92	0.47	33
Tight e-like cut	2.66	0.40	3
Evis > 100 MeV	2.47	0.40	2
No decay-e	1.90	0.35	1
Pi0 cut	0.58	0.17	0

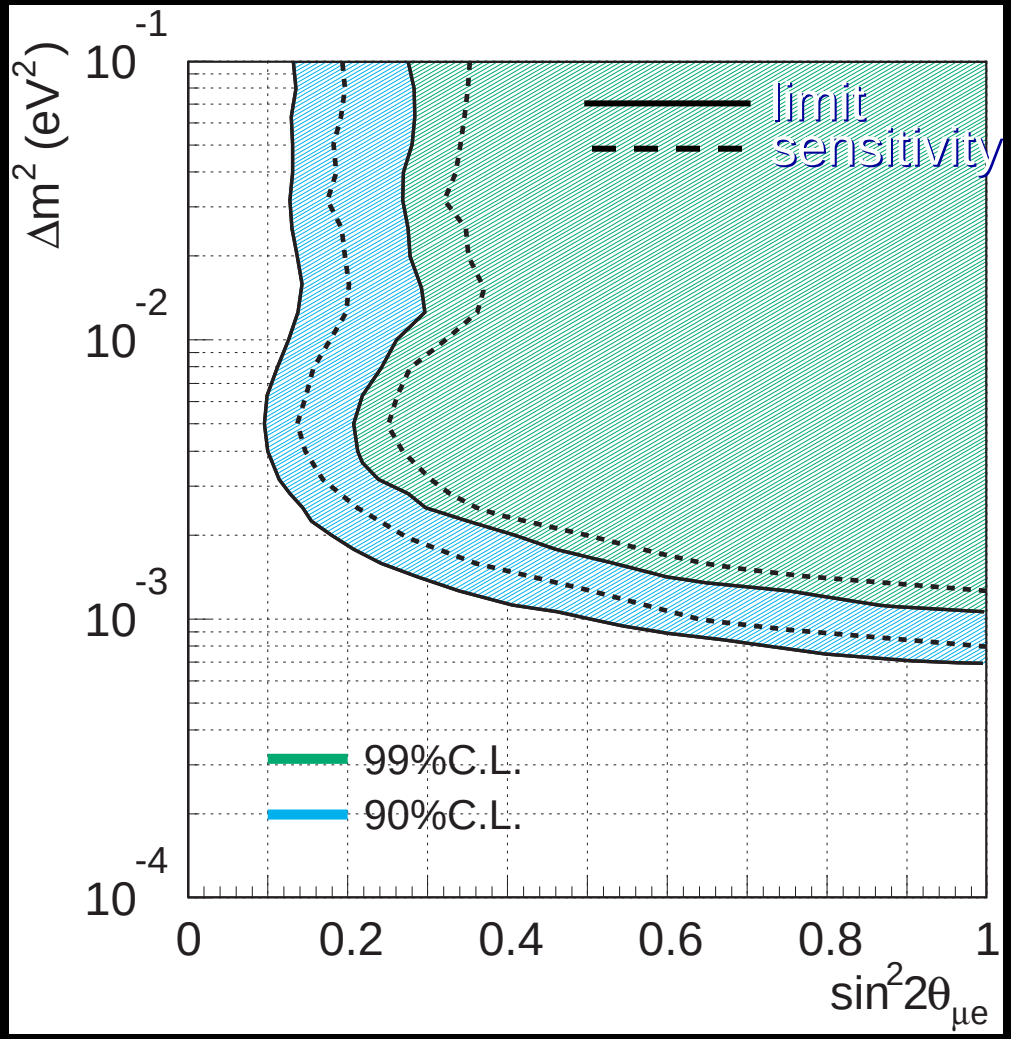
—K2K-2—	νμ MC	beam νe	Data
FCFV	77.4	0.86	57
Single ring	49.41	0.52	34
Tight e-like cut	3.21	0.44	5
Evis > 100 MeV	2.93	0.44	5
No decay-e	2.17	0.39	4
Pi0 cut	0.74	0.21	1

Pi0 cut



In total,
#expected BG = 1.70
#observed = 1

Exclude region for ν_e appearance search



upper limit (90% CL)

$\sin^2 2\theta_{\mu e} < 0.13$ @2.8×10^{-3} eV^2

K2K

$\sin^2\theta_{13} < \sim 0.06$ @2.8×10^{-3}eV^2

(assuming $\sin^2 2\theta_{23} = 1.0$)

Consistent result

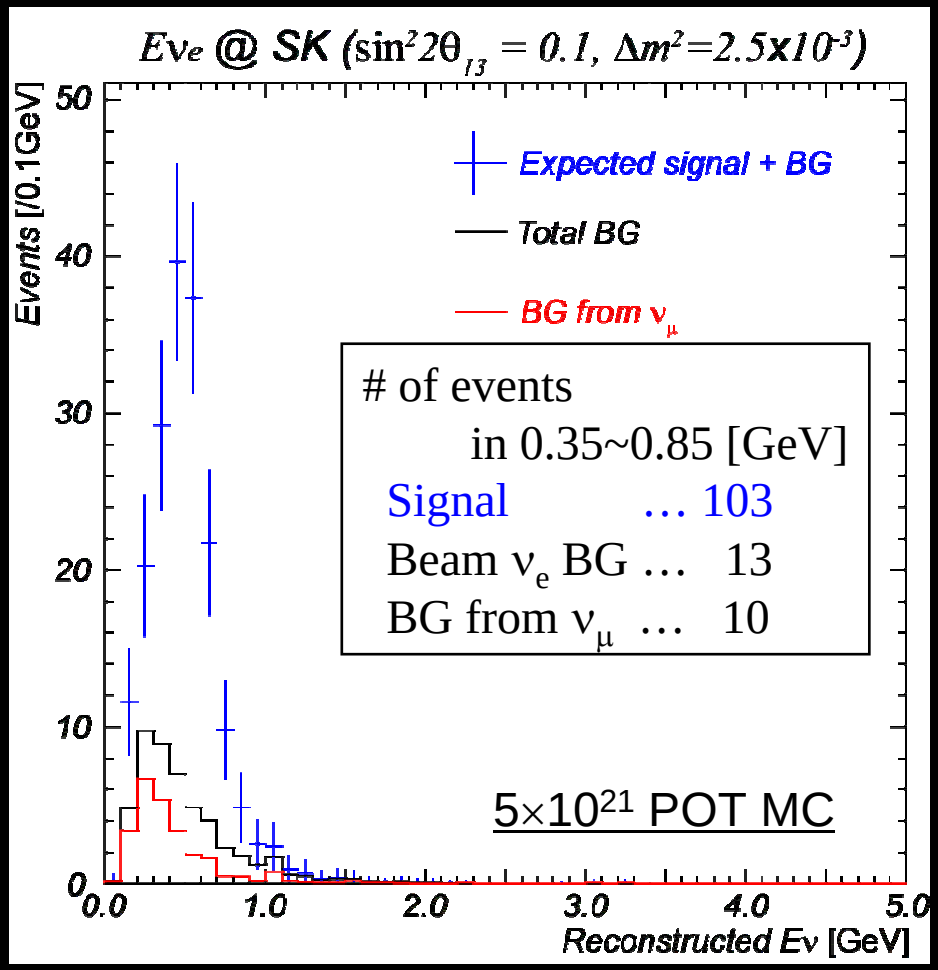
CHOOZ(reactor)

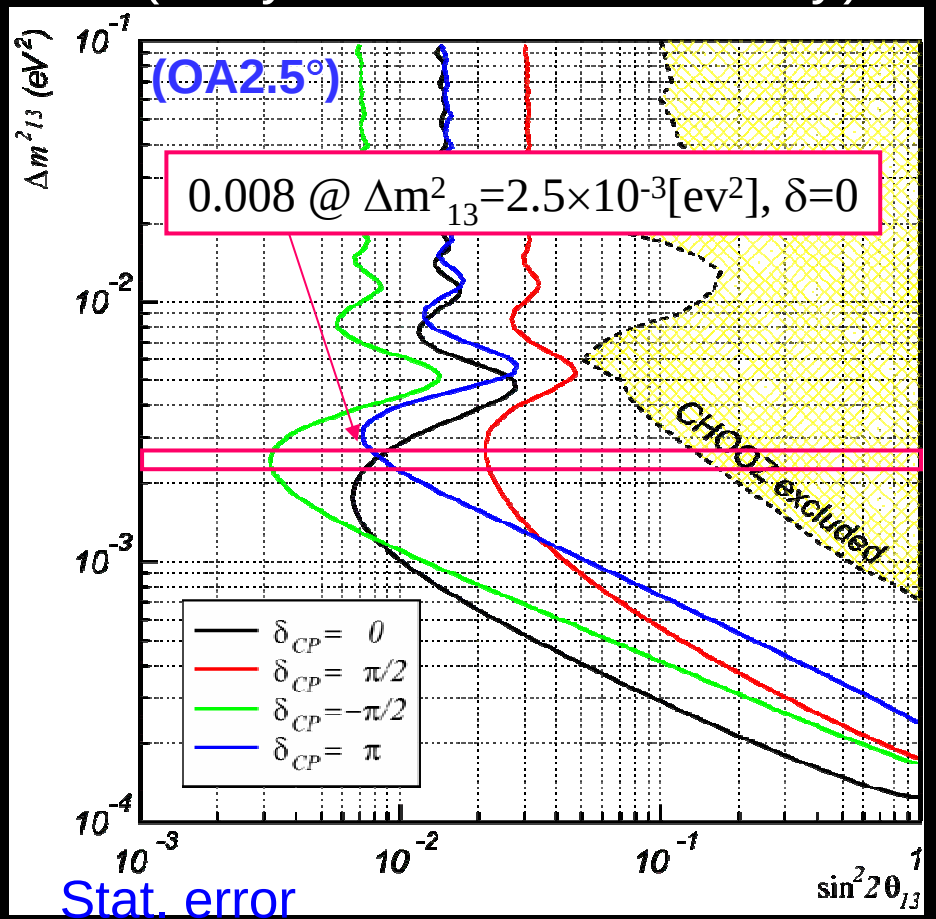
$\sin^2\theta_{13} < \sim 0.03$ @2.8×10^{-3}eV^2

T2K Sensitivity to θ_{13}

ν_e appearance

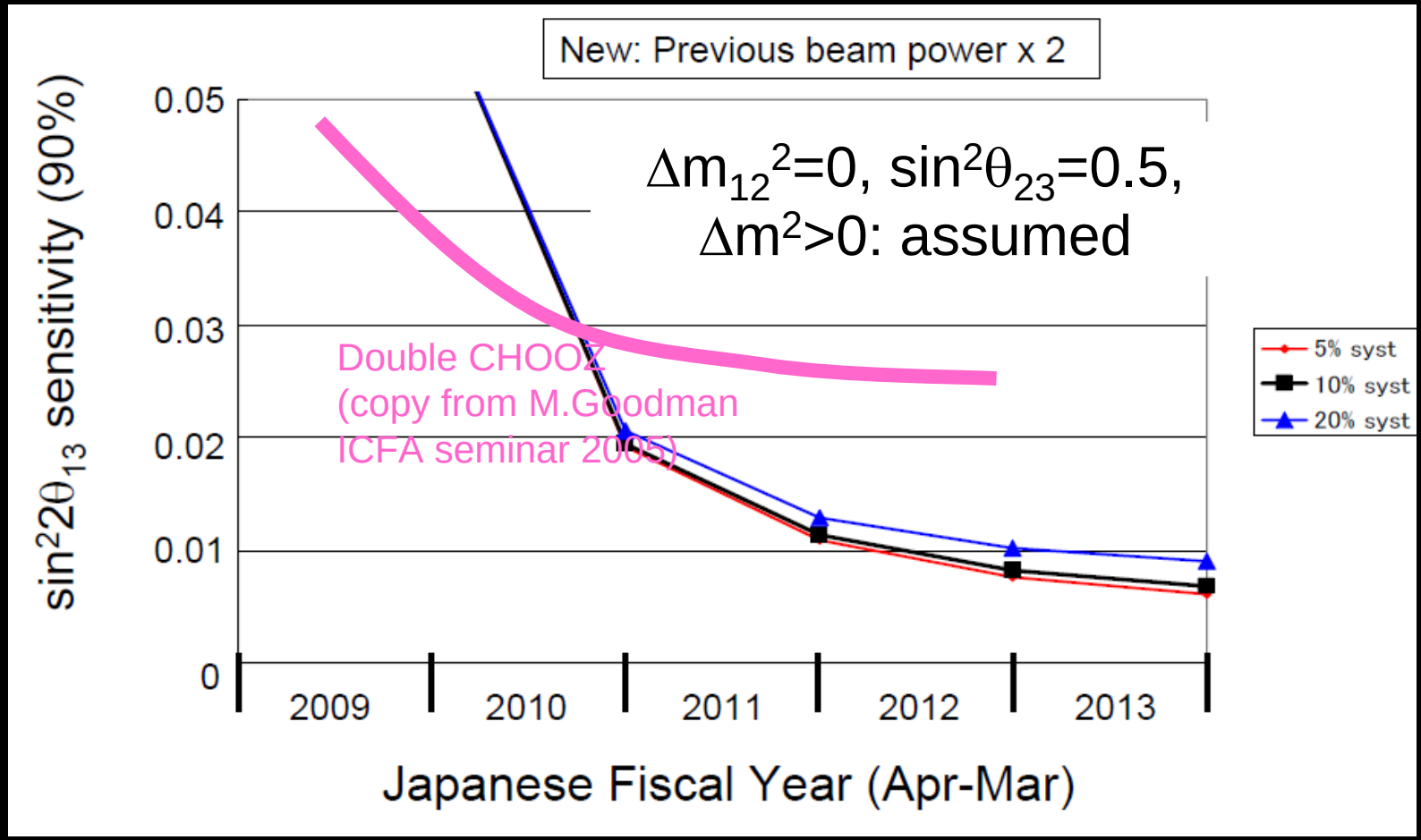
$\sin^2 2\theta_{23}$ = 1.0 is assumed.
5×10^{21} POT
(~5 years w/ full intensity)



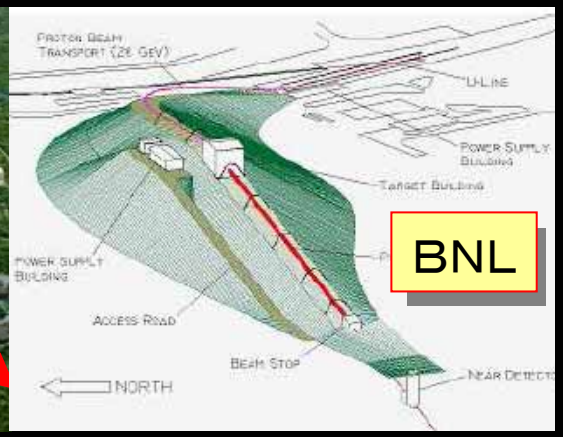


Stat. error
+ Sys. error for BG subtraction (10%)

θ_{13} sensitivity versus year

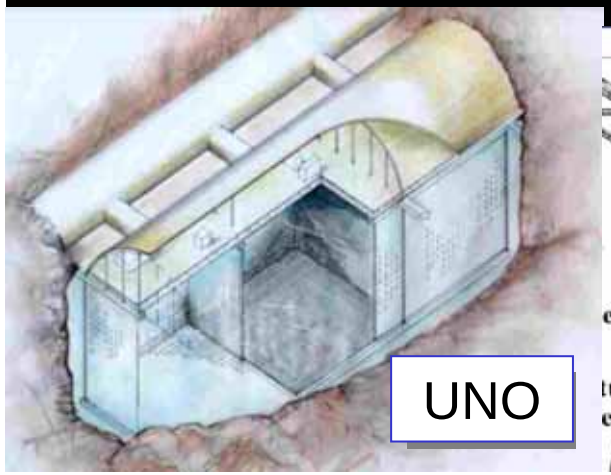


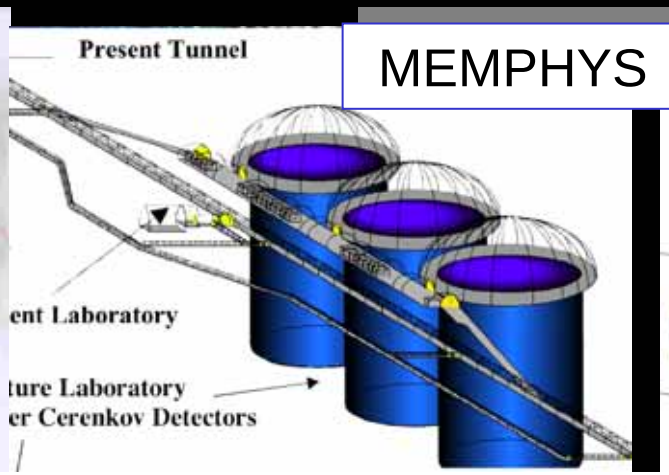
Beyond θ_{13}
(assuming $\sin^2 2\theta_{13}$ is larger than 0.01)

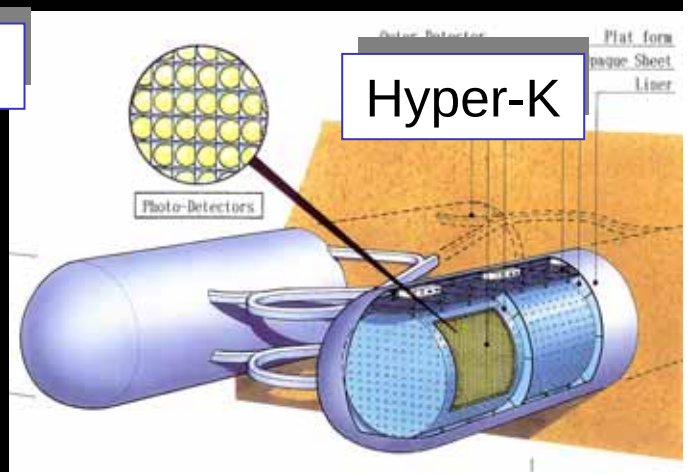


Megawatt class super (or β)-beam
+
Megaton class water detector

Hierarchy,
CP, ….



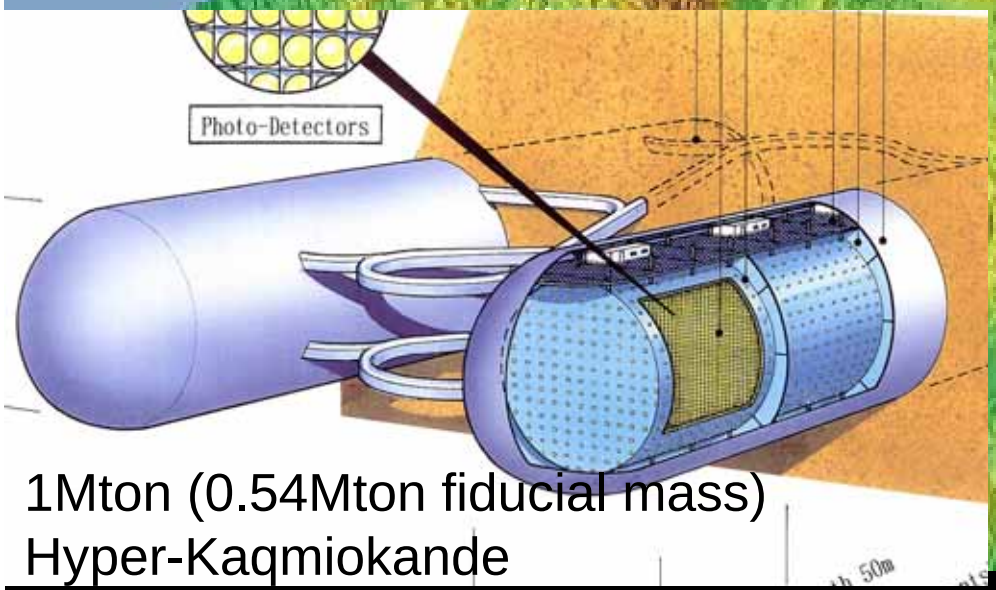




T2K phase-II: (baseline design)

295 km

KEK



1Mton (0.54Mton fiducial mass)
Hyper-Kaqmiokande

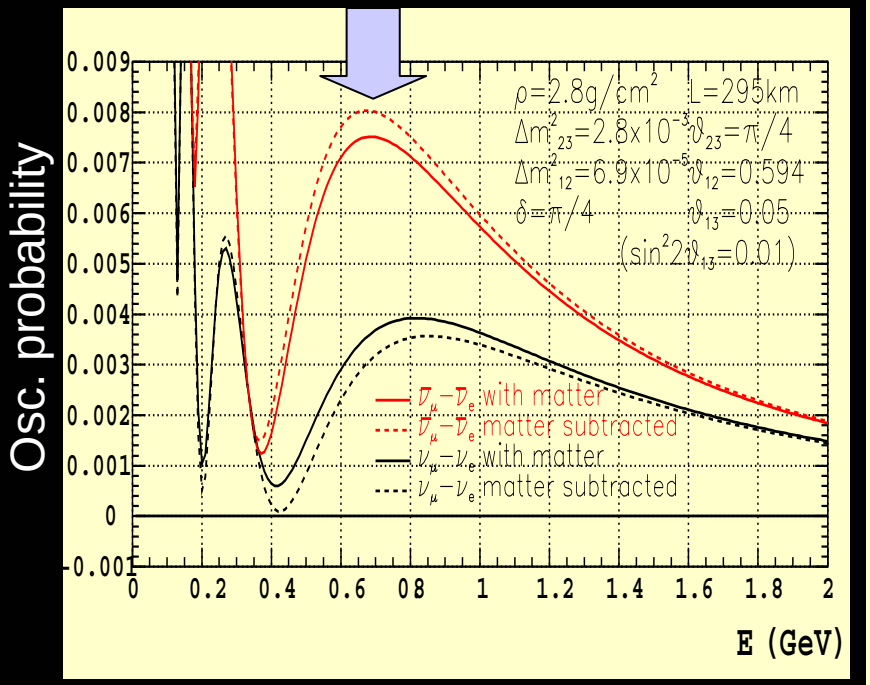
2years of ν run + 6 years of anti-ν run ➔
O(10^6) events for both runs

Oscillation probabilities and the expected signal

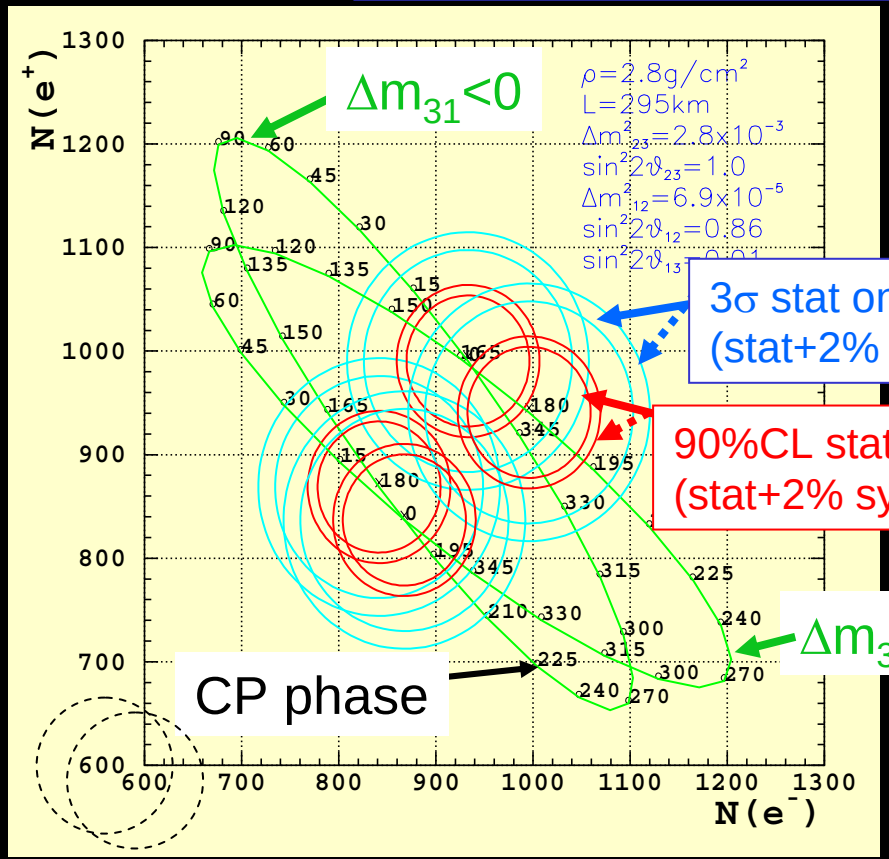
$$\sin^2 2\theta_{13} = 0.01$$

Neutrino run=2years,
anti-neutrino run=6.8years,
4MW, 0.54Mton fid. Vol.

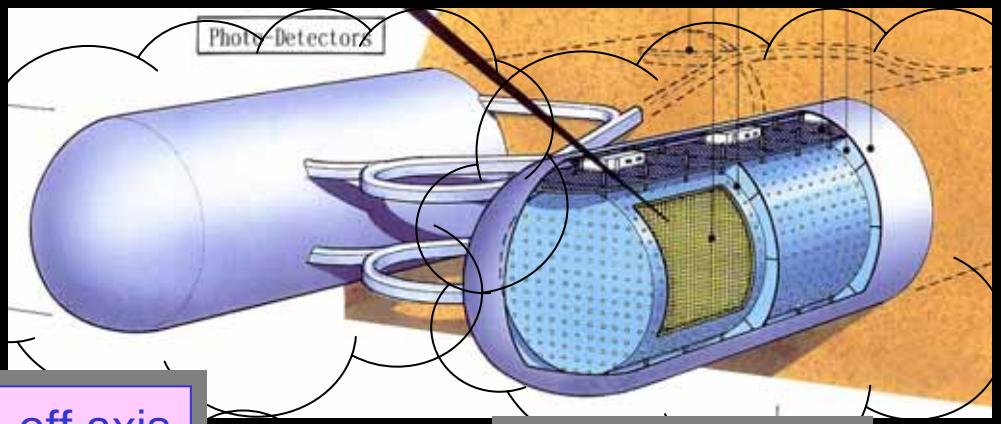
Peak energy of the T2K beam



Solid line: w/ matter
Dashed line: w/o matter



T2K Phase-II: other option

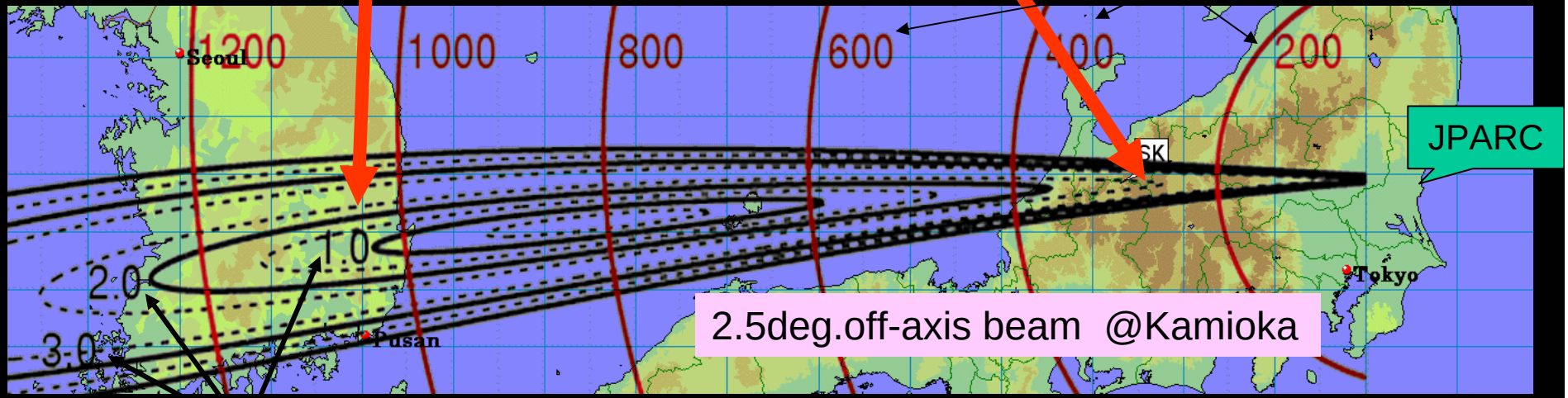


2.5 deg. off axis

2.5 deg. off axis

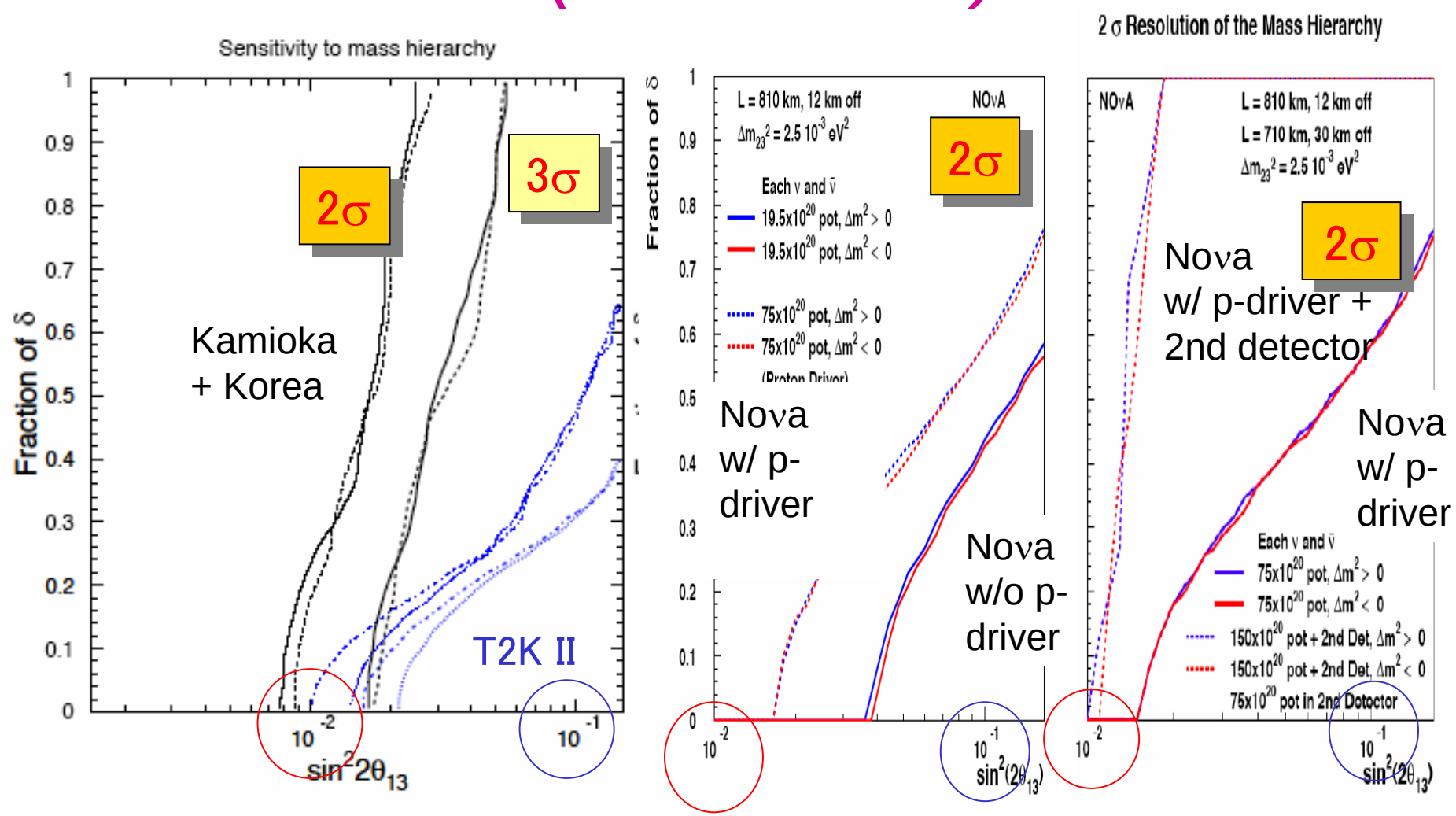
Total cost must be similar to the baseline design.

Distance from the target (km)

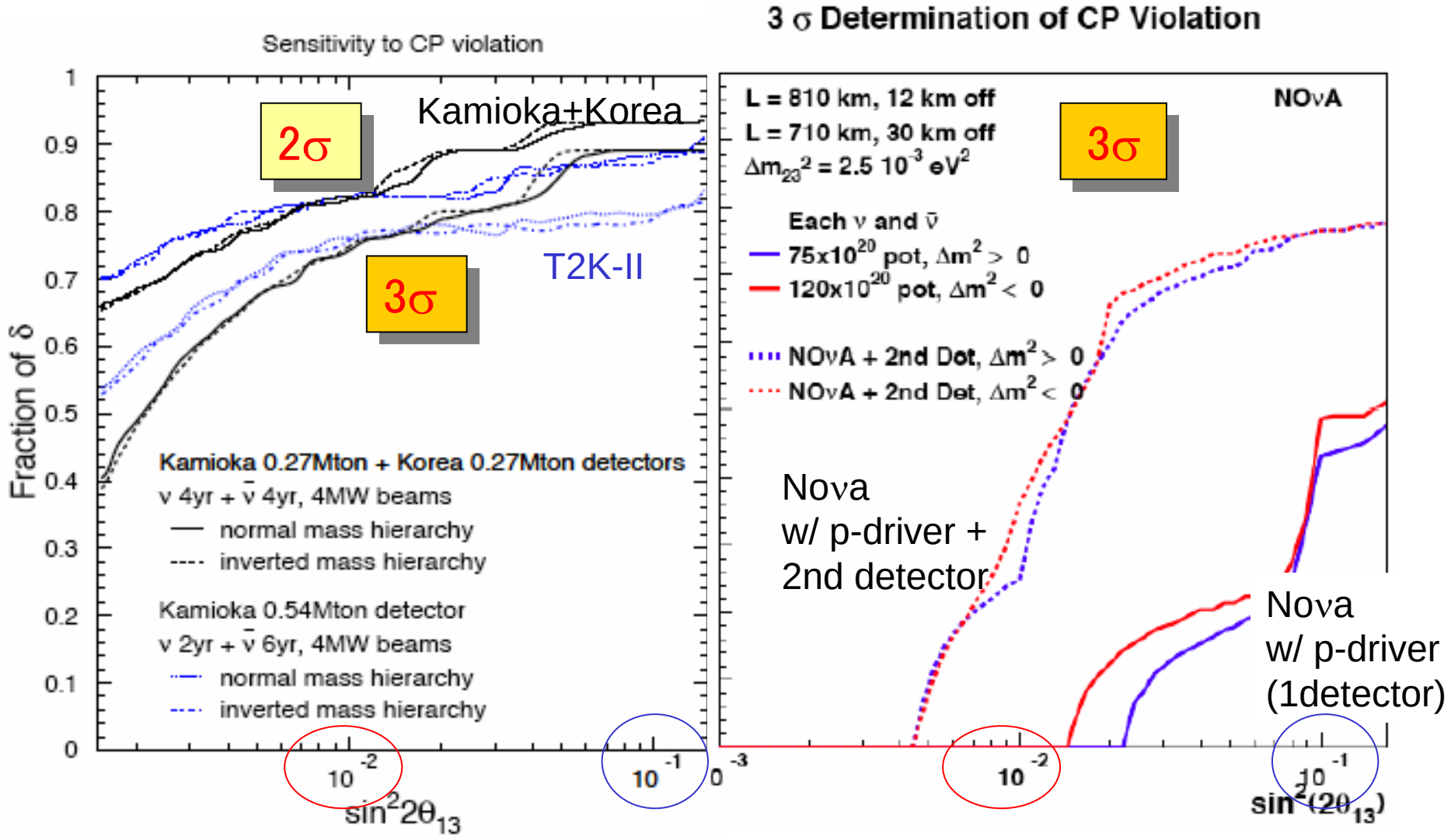


Based on; M.Ishitsuka et al., PRD 72, 033003 (2005), hep-ph/0504026
(see also, K. Hagiwara et al., hep-ph/0504061)

Sensitivity to mass hierarchy: T2K-II vs. (Kam+Korea) vs. Nova



Sensitivity to CP: T2K-II vs. (Kam+Korea) vs. Nona



Conclusion

- Neutrino flavor transition phenomena and some of related parameters have been experimentally established.
  - Solar and KamLAND+CPT
  - Atmospheric, K2K, MINOS
  - T2K aims to $\delta(\sin^2 2\theta_{23})<1\%$, $\delta(\Delta m^2_{23})<10^{-4}\mathrm{eV}^2$
- Next step is search for non-zero θ_{13}
  - reactor, T2K; sensitivity of $\sin^2 2\theta_{13}\sim 1\%$
  - Key to measure CP phase
- Next next step; δ
  - High intensity beam and Mton-scale far detector
  - R&D and discussions