Neutrino Oscillations

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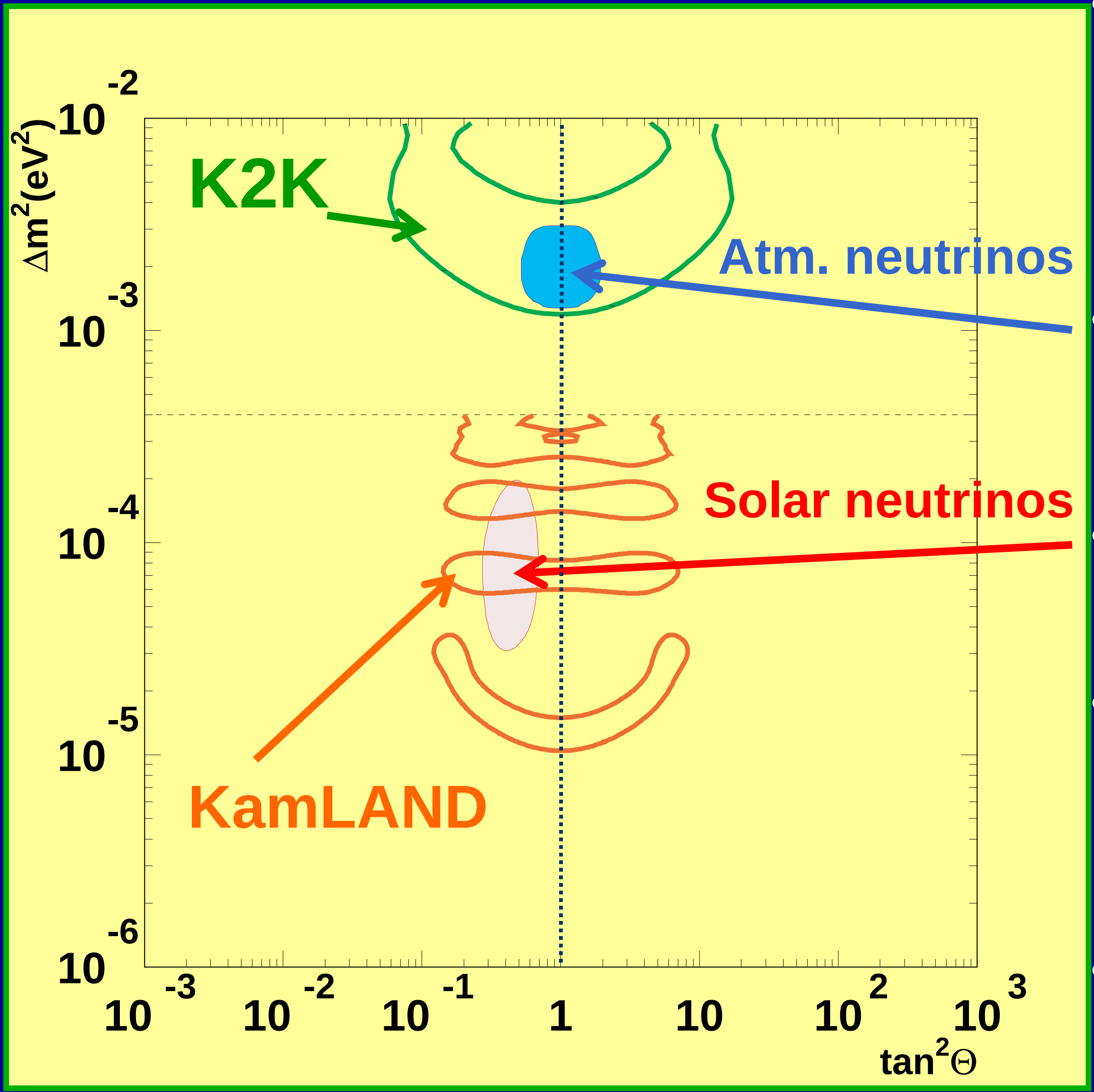
What we know

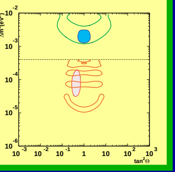
Remaining problems

Solar neutrinos / Reactor experiments
Atmospheric neutrinos / Accelerator experiments
and
their futures

`Standard Solution`



- Neutrino oscillation has been established as a leading effect of the solar-atmospheric neutrino flavor conversion
- Atmospheric neutrino oscillation is mostly due to $\nu_\mu \rightarrow \nu_\tau$
- Solar neutrino oscillation is mostly due to $\nu_e \rightarrow \nu_\mu; \nu_\tau$
- Both atmospheric and solar neutrino oscillations have been confirmed by the terrestrial experiments.
- Small sub-leading effects may lead us to the physics beyond the Standard Solution of the neutrino oscillations



Three generation neutrino mixing

mixing:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Flavor eigenstates (↑ ν_e, ν_μ, ν_τ)

Mass eigenstates (↑ ν_1, ν_2, ν_3)

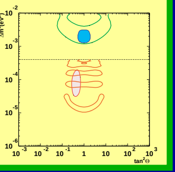
Atmospheric **Solar**

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$\approx \begin{pmatrix} c_{12} & s_{12} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} & c_{23}c_{12} & s_{23} \\ s_{23}s_{12} & -s_{23}c_{12} & c_{23} \end{pmatrix} \qquad for \begin{pmatrix} s_{13} = \sin\theta_{13} \ : small \\ c_{13} = \cos\theta_{13} \to 1 \end{pmatrix}$$

$$|U_{e1}| \approx \cos\theta_{12}^{(solar)}; |U_{e2}| \approx \sin\theta_{12}^{(solar)}$$

$$|U_{\mu3}| \approx \cos\theta_{23}^{(atm)}; |U_{\tau3}| \approx \sin\theta_{23}^{(atm)}$$



Neutrino Oscillation

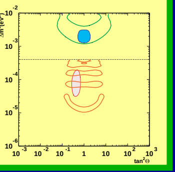
Time evolution:

$$|\nu_\alpha>_t = \sum_{K=1}^{3} U^*_{\alpha k} e^{-iE_k t} |\nu_k>$$

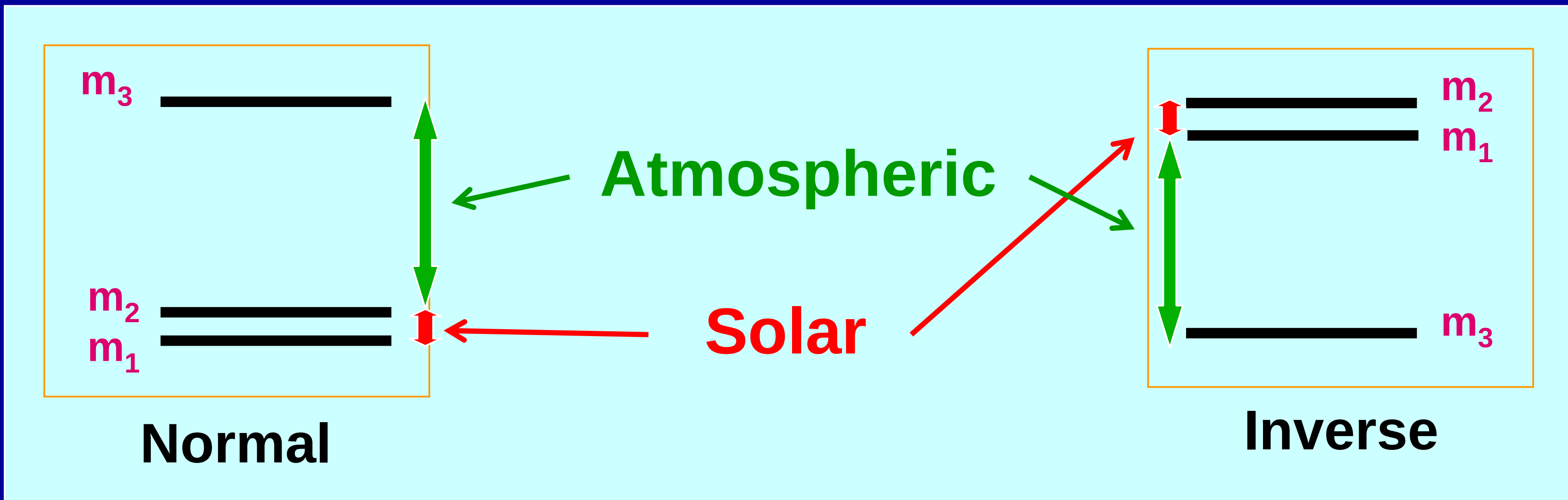
$$= \sum_{\beta} \sum_{K=1}^{3} U_{\beta k} e^{-iE_k t} U^*_{\alpha k} |\nu_\beta>$$

$$P_{\nu_\alpha \rightarrow \nu_\beta} = \left| \delta_{\alpha\beta} + \sum_{K=2}^{3} U_{\beta k} U^*_{\alpha k} [\exp(-i\Delta m_{k1}^2/2E) - 1] \right|^2$$

Parameters: Δm_{12}^2, Δm_{13}^2, θ_{12}, θ_{23}, θ_{13}, δ



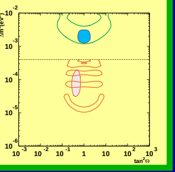
Mass Hierarchy



$\Delta m_{23}^2 \sim \Delta m_{13}^2 \sim \Delta m_{atm}^2 \quad \sim O(10^{-3})\ eV^2$

$\Delta m_{12}^2 \sim \Delta m_{sol}^2 \quad \lesssim O(10^{-4})\ eV^2$

$$\Delta m_{sol}^2 << \Delta m_{atm}^2$$



Atmospheric, Accel. long baseline, Reactor (short baseline)

$\lambda_{osc} = 4\pi E/\Delta m^2$

Δm_{atm}	Energy	baseline	$\lambda/2$ for Δm_{sol}^2 (5×10^{-5}eV^2)	$\lambda/2$ for Δm_{atm}^2 (2.5×10^{-3}eV^2)
Reactor	(5MeV)	1 km	~~125 km~~	2.5 km
Accelerator	(1GeV)	250 km	~~25,000 km~~	500 km
Atmospheric	(1GeV)	20~13,000 km	25,000 km	500 km
Atmospheric	(10GeV)	20~13,000 km	~~250,000 km~~	5,000 km

$\Delta m_{sol}^2 << \Delta m_{atm}^2$

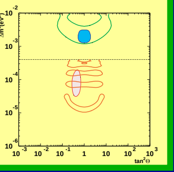
Similar to the `two neutrino` oscillation formula

$$P^{(atm,acc)}_{\nu_\mu \to \nu_{\tau(e)}} = \frac{1}{2} 4 |U_{\mu 3}|^2 |U_{\tau(e)3}|^2 \left(1 - \cos\frac{\Delta m_{13}^2 L}{2E}\right)$$

$$P^{(reacter;SBL)}_{\nu_e \to \nu_e} = 1 - \frac{1}{2} 4 |U_{e3}|^2 \left(1 - |U_{e3}|^2\right)\left(1 - \cos\frac{\Delta m_{13}^2 L}{2E}\right)$$

$$|U_{\mu 3}| \approx \cos\theta_{23}^{(atm)};\ |U_{\tau 3}| \approx \sin\theta_{23}^{(atm)} \quad \textit{for} \quad \sin\theta_{13} = |U_{e3}| << |U_{\mu 3}|, |U_{\tau 3}|$$

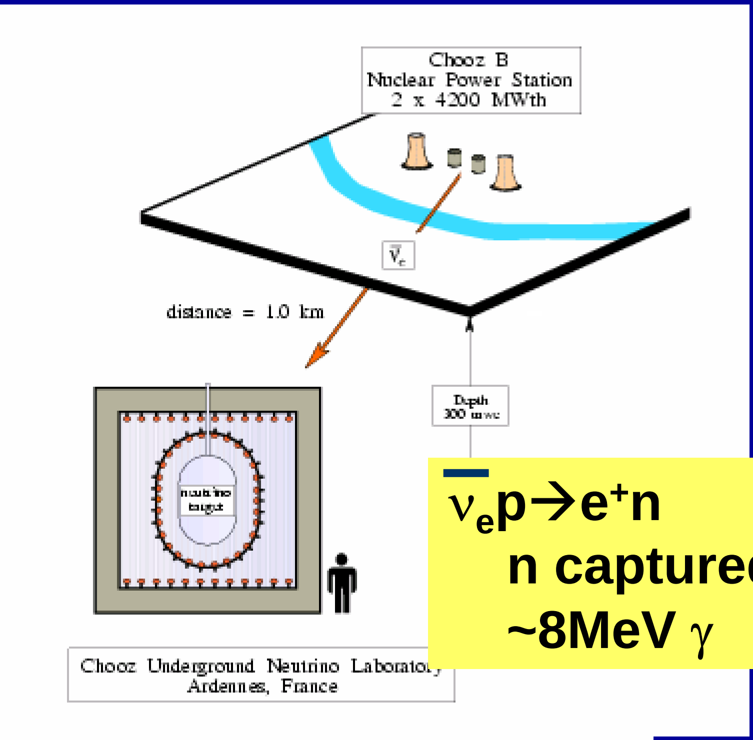
Parameters: Δm_{13}^2, θ_{23}, θ_{13}, (δ)



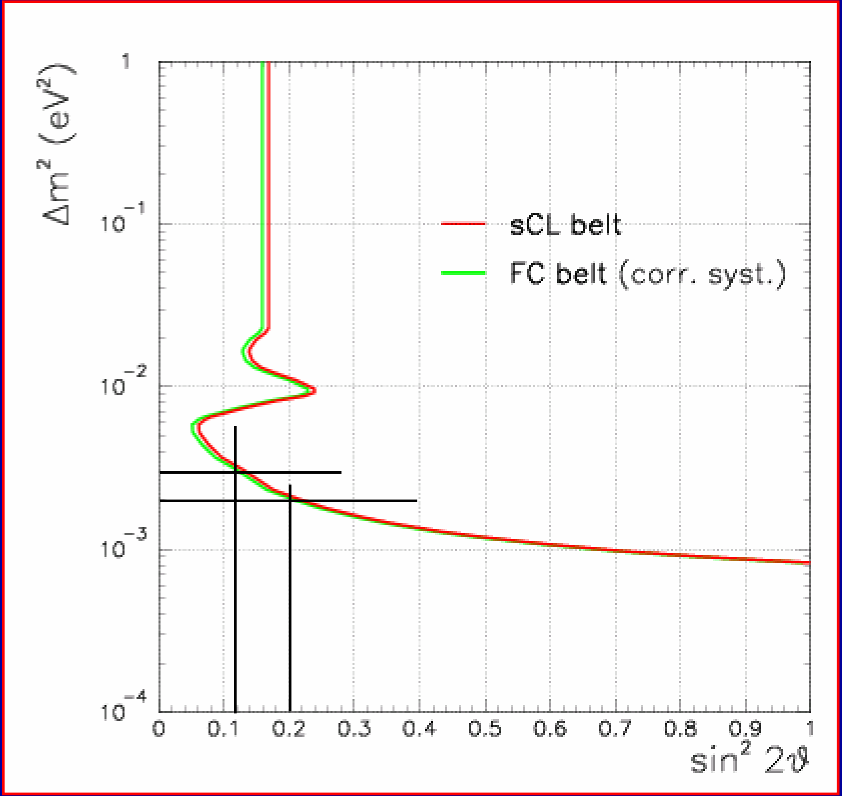
Upper limit on θ_{13}: CHOOZ

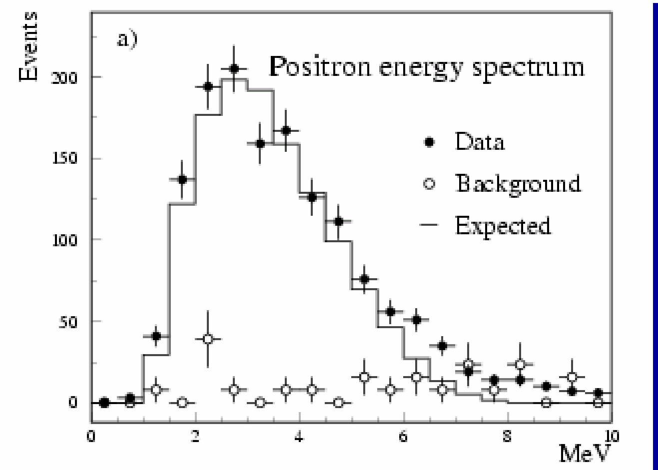
Reactor experiment (1km baseline)

measures $\bar{\nu}_e$ disappearance



$\bar{\nu}_e p \to e^+ n$
n captured on Gd
~8MeV γ

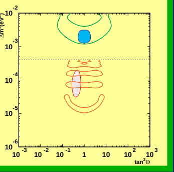




$\sin^2 2\theta_{13} < 0.12$ for 3×10^{-3} eV^2

$\sin^2 2\theta_{13} < 0.2$ for 2×10^{-3} eV^2

($\sin^2\theta_{13} = |U_{e3}|^2 < 0.05$)



Solar and the long baseline reactor experiment

Δm_{sol}	Energy	baseline	$\lambda/2$ for Δm_{sol}^2 ($5\times10^{-5}eV^2$)	$\lambda/2$ for Δm_{atm}^2 ($2.5\times10^{-3}eV^2$)
Solar ν	(0.5MeV)	1.5×10^8 km	12.5 km	0.25 km
Solar ν	(5MeV)	1.5×10^8 km	125 km	2.5 km
Reactor	(5MeV)	180 km	125 km	2.5 km

- Effect from Δm_{atm}^2 → averaged (no phase)

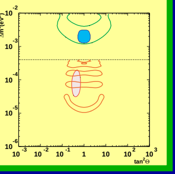
$$P^{(solar)}_{\nu_e\to\nu_e} = \left(1-|U_{e3}|^2\right)^2 P^{(12)}_{\nu_e\to\nu_e} + |U_{e3}|^4$$

$$P^{(12)}_{\nu_e\to\nu_e} = 1 - \frac{1}{2}4\frac{|U_{e1}|^2|U_{e2}|^2}{1-|U_{e3}|^2}\left(1-\cos\frac{\Delta m_{12}L}{2E}\right)$$

Good also for the matter oscillation

Negligible: $|U_{e3}|^2 < 0.00025$ (at most)

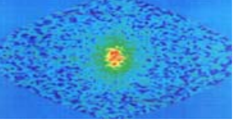
Parameters: Δm_{12}^2, θ_{12}

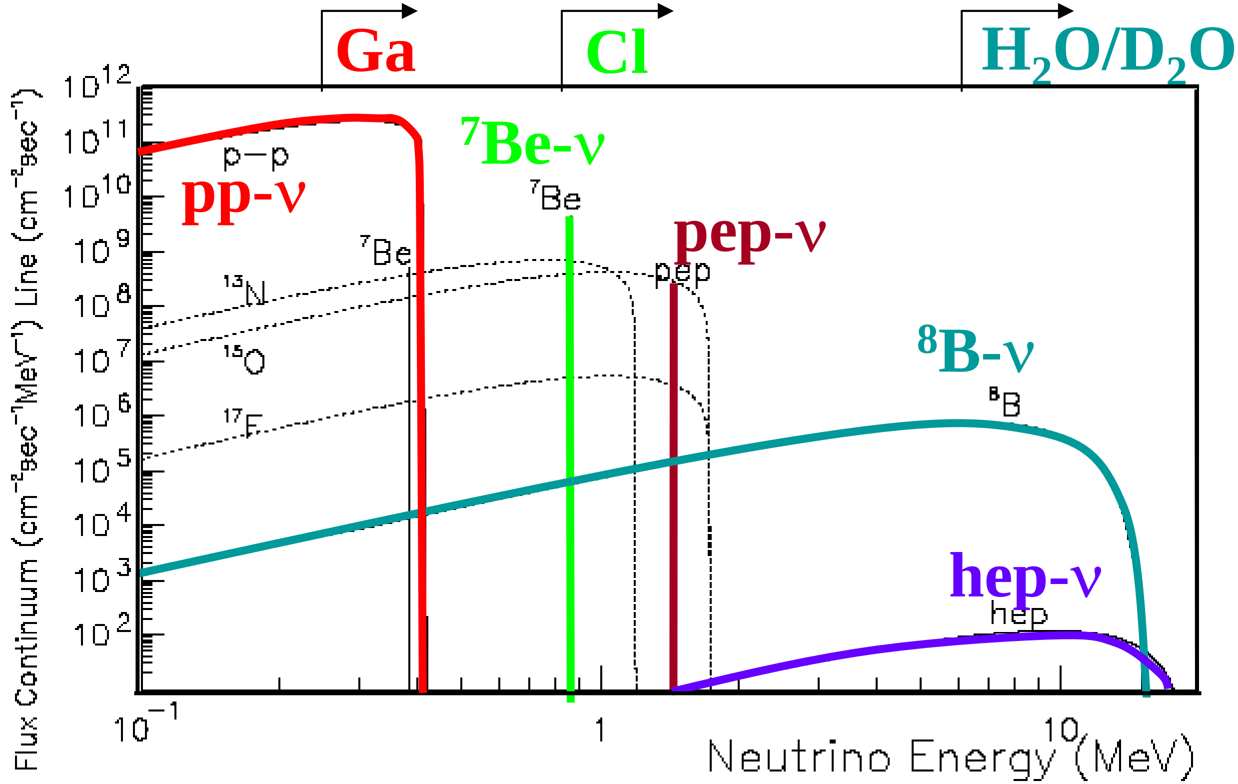


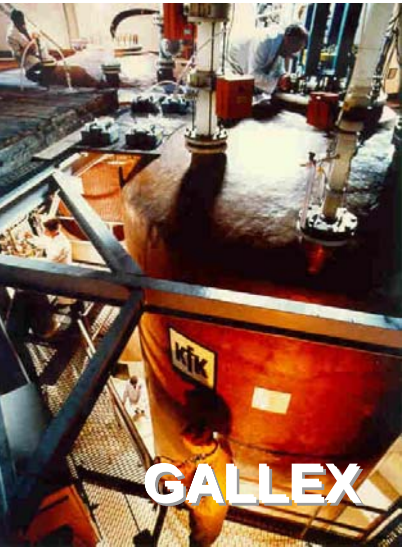
Note

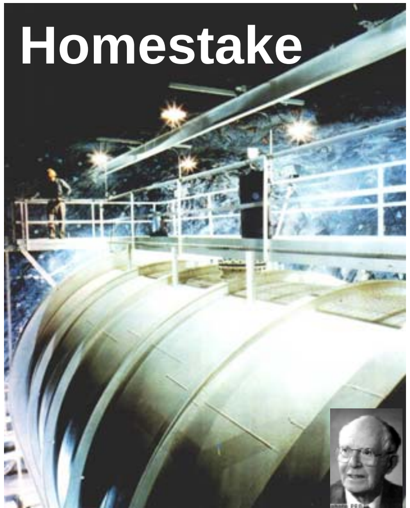
- Due to the mass hierarchy and the smallness of the $\sin\theta_{13}$, the atmospheric and solar neutrino oscillations can be treated independently, although the atmospheric neutrinos may have a small effect from Δm_{12}

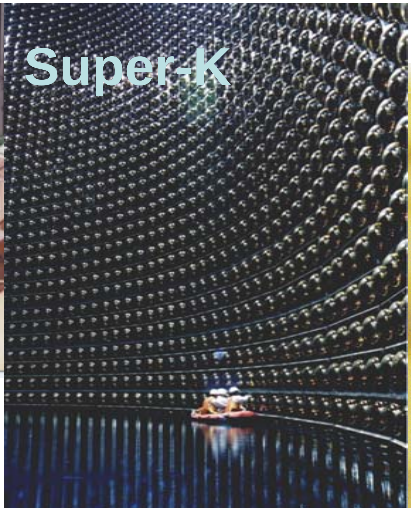
Solar neutrinos

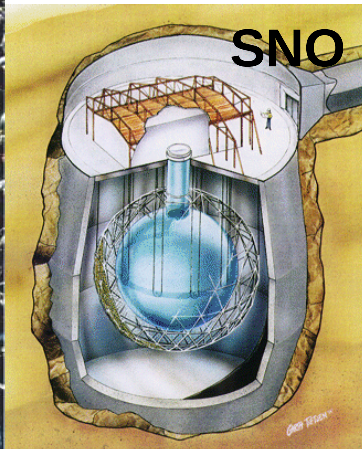




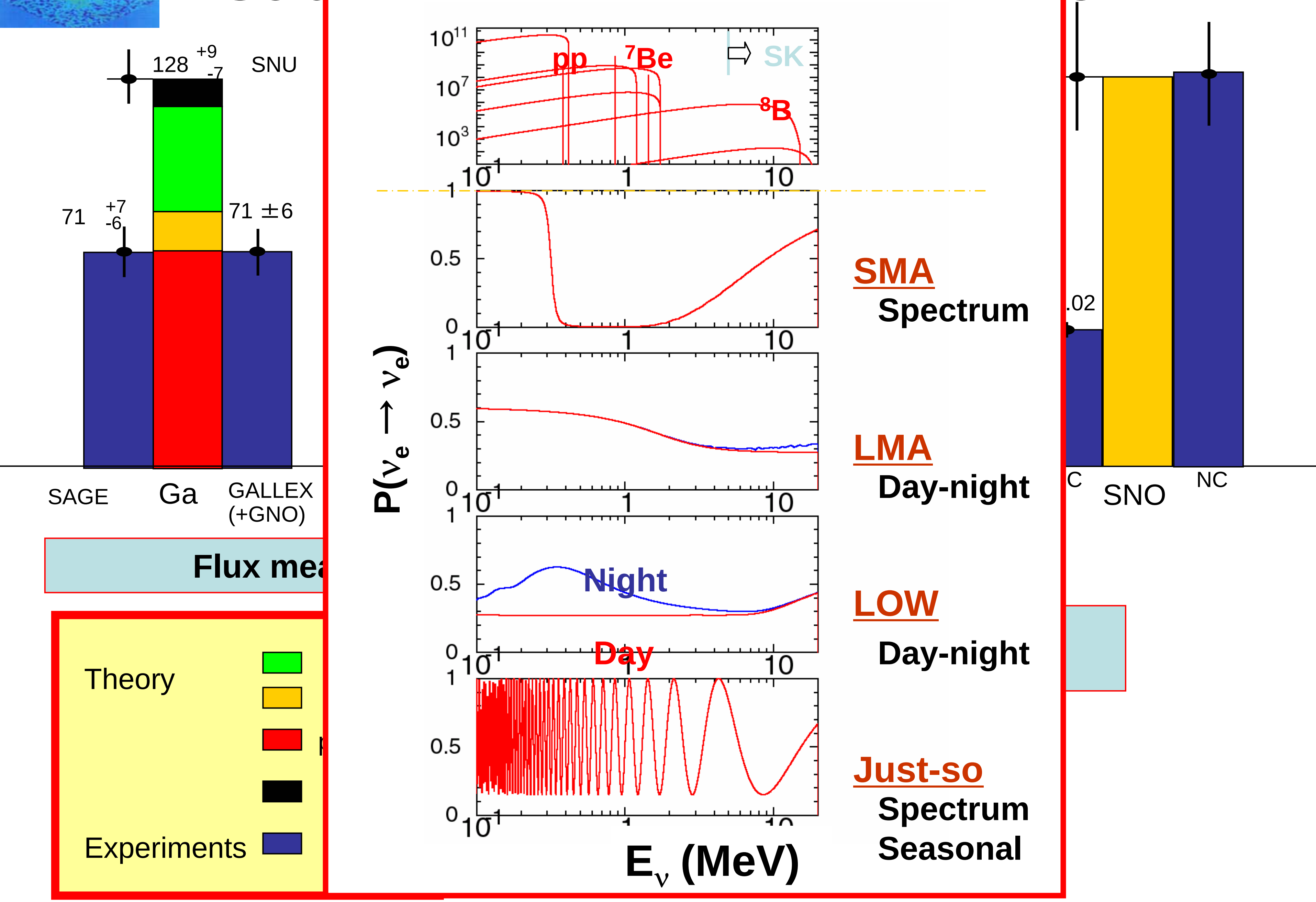


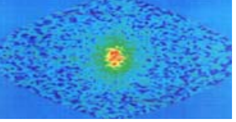




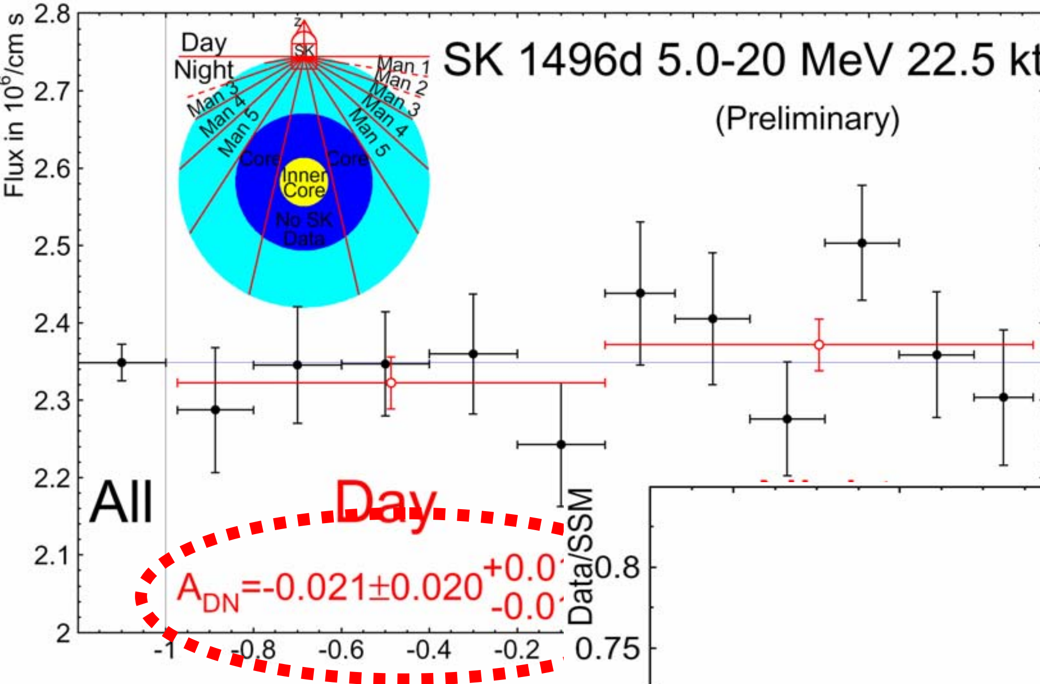


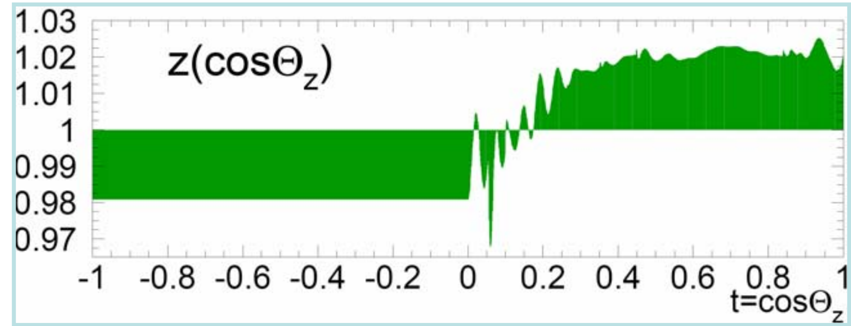
Solar neutrino flux measurements

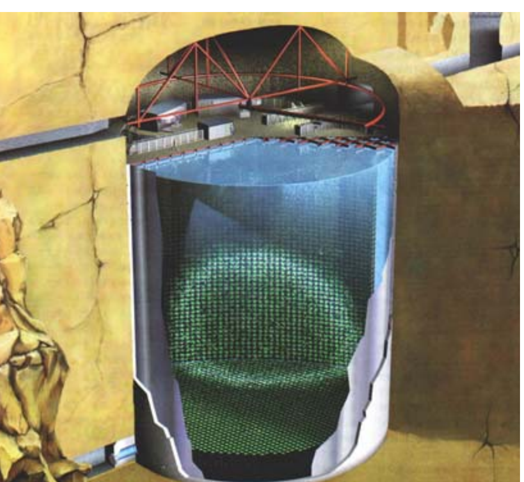


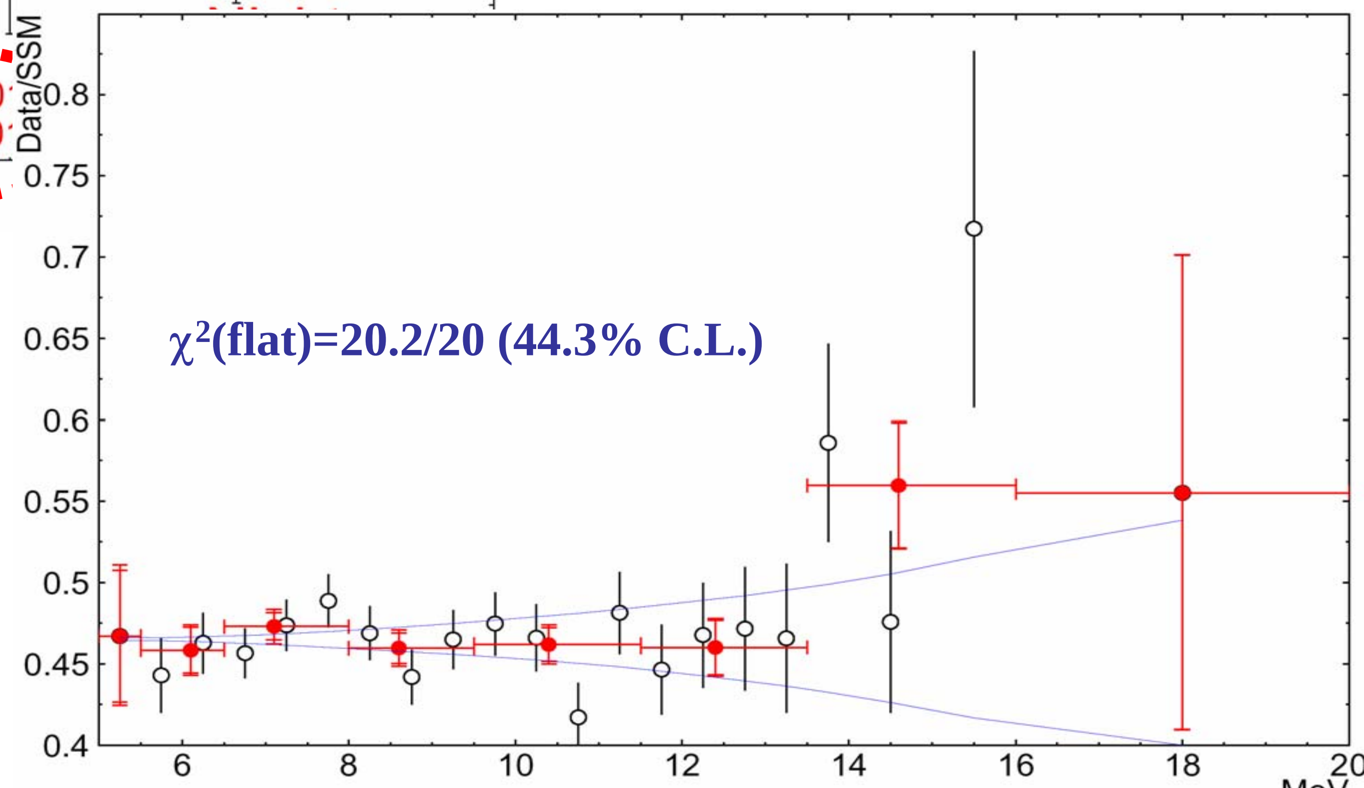


Super-Kamiokande Data

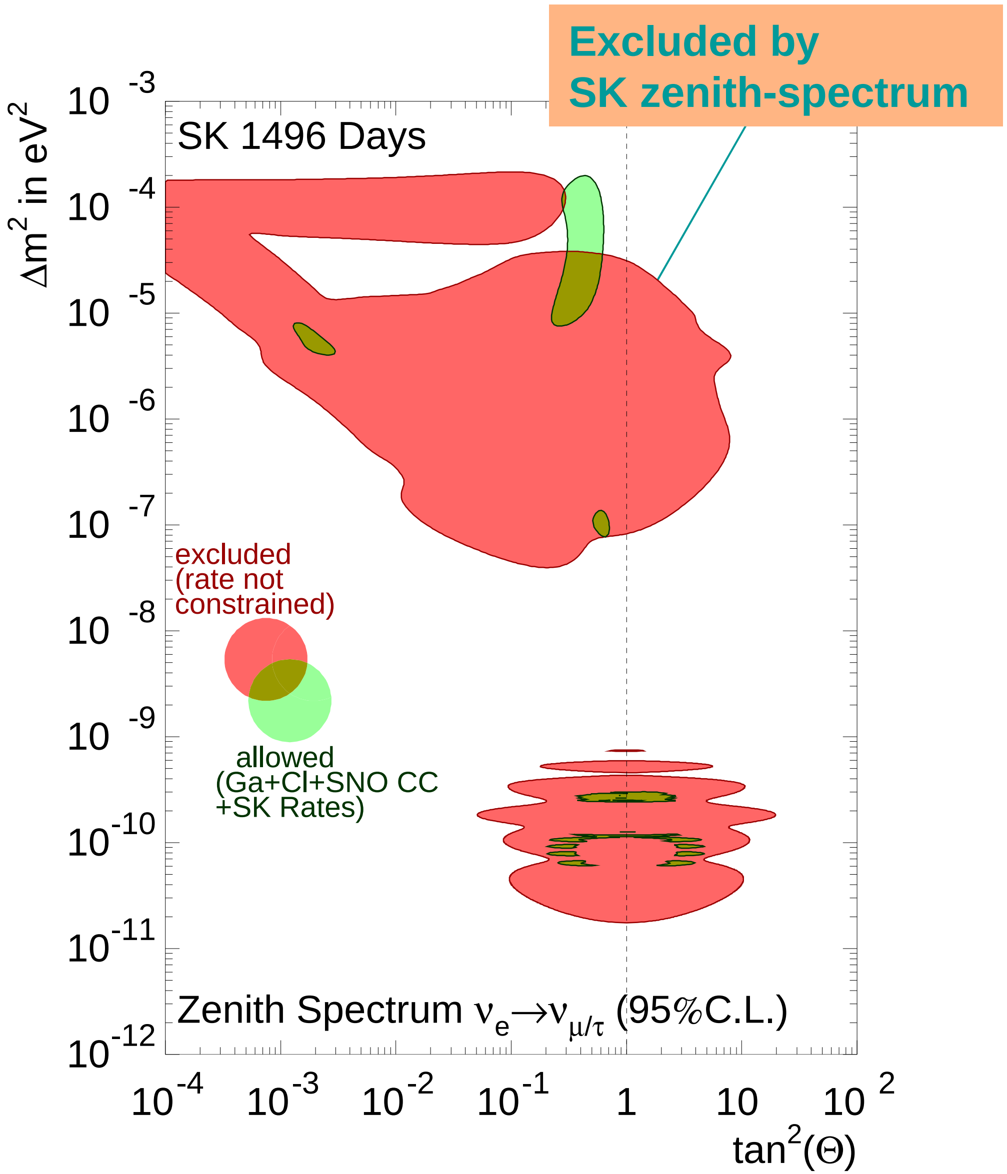


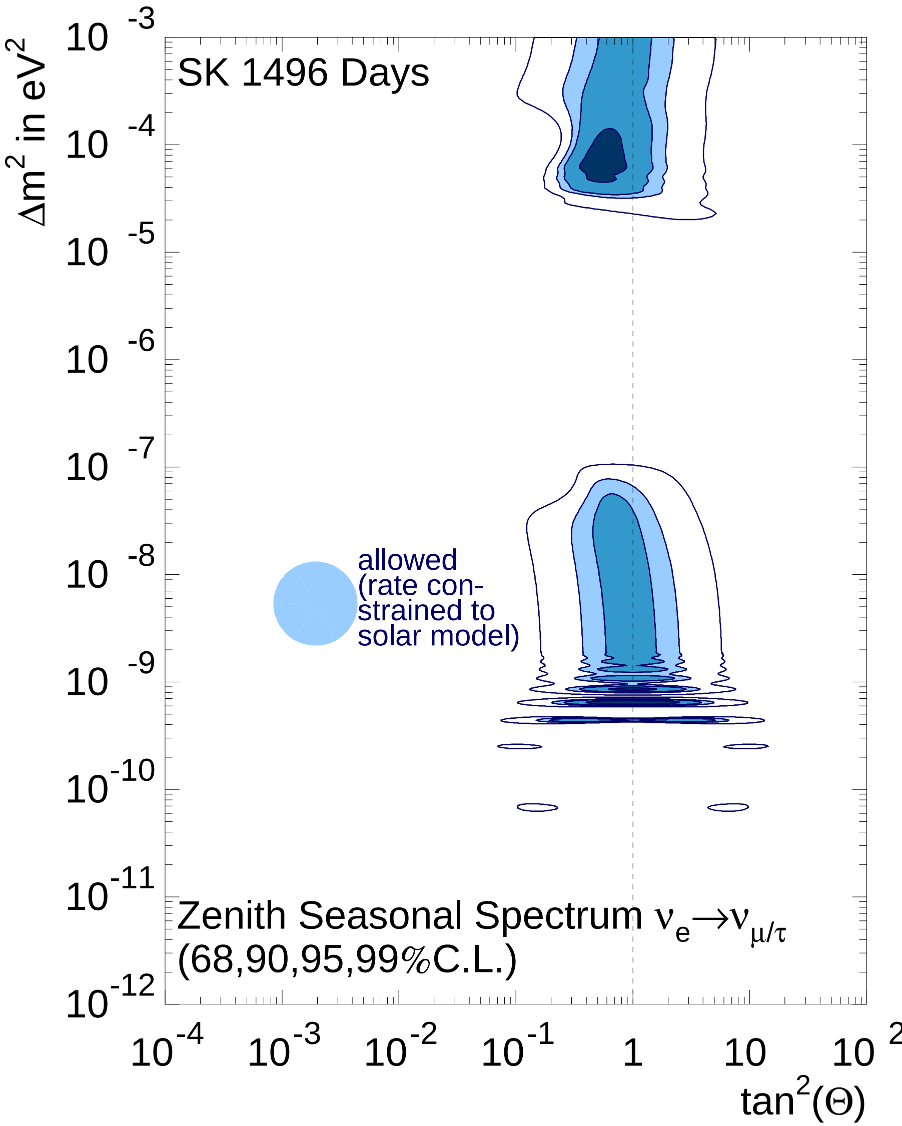




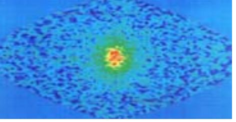


SK Results

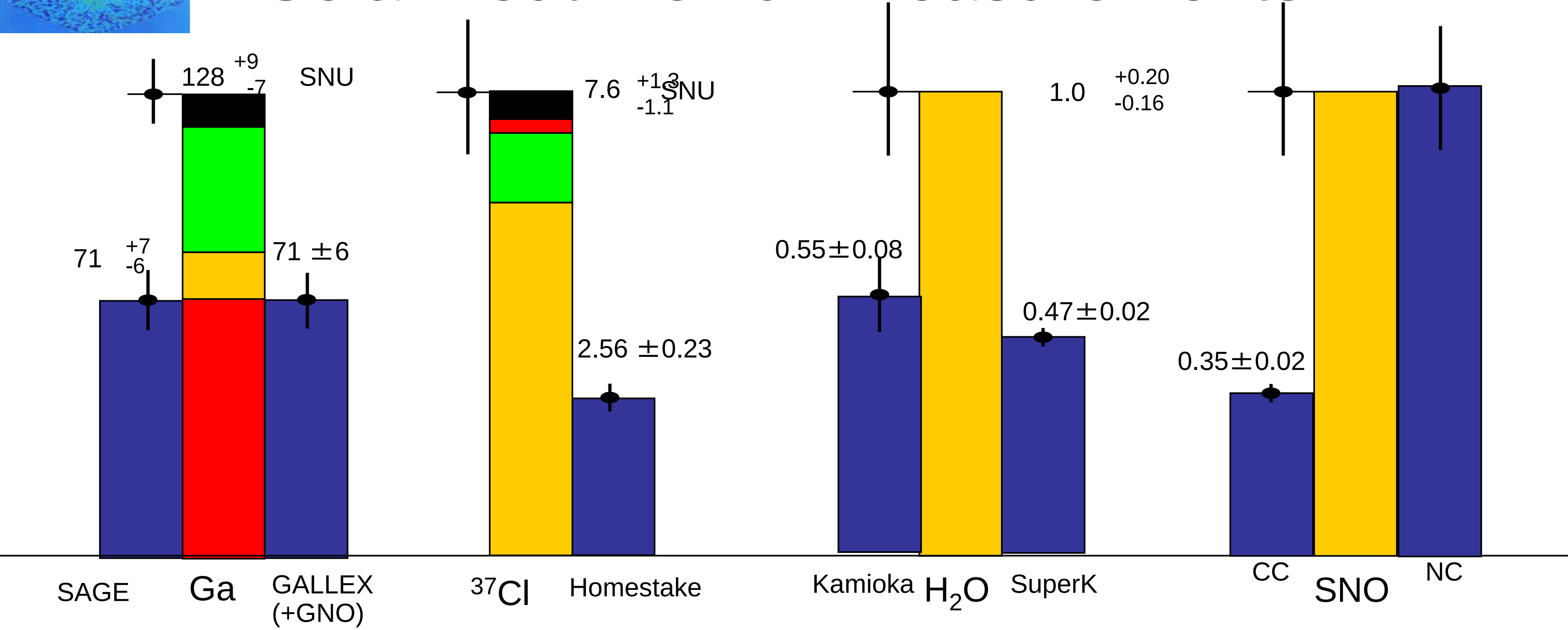




Strong indication for the large mixing solutions in 2000



Solar neutrino flux measurements



Flux measurement + SSM Calculation

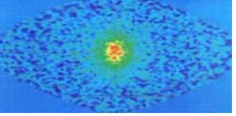
Theory
- ^7Be
- ^8B
- pp, pep
- CNO

Experiments

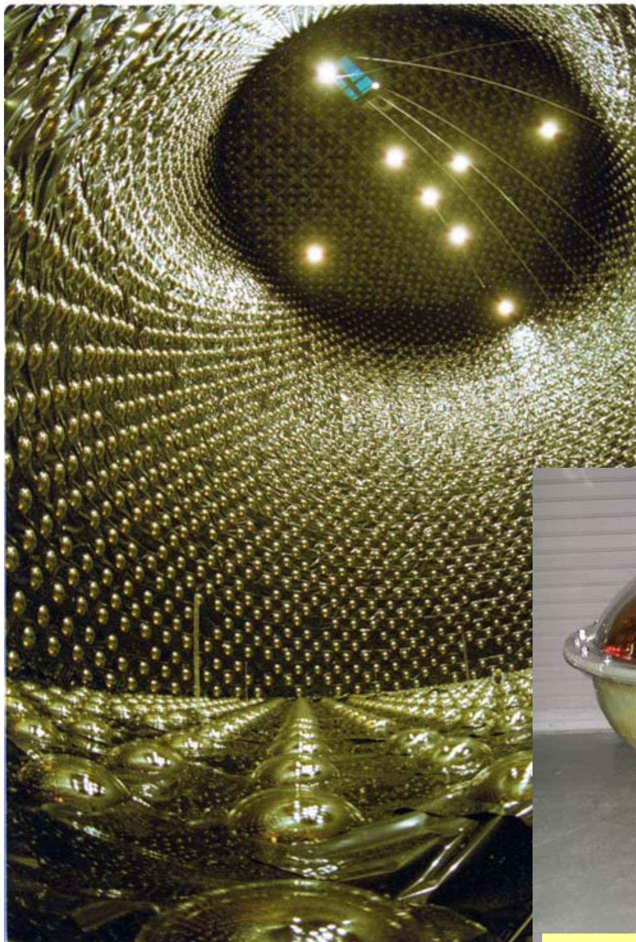
Spectrum distortion
Day/Night effect

ES vs CC (^8B only)
Flux independent

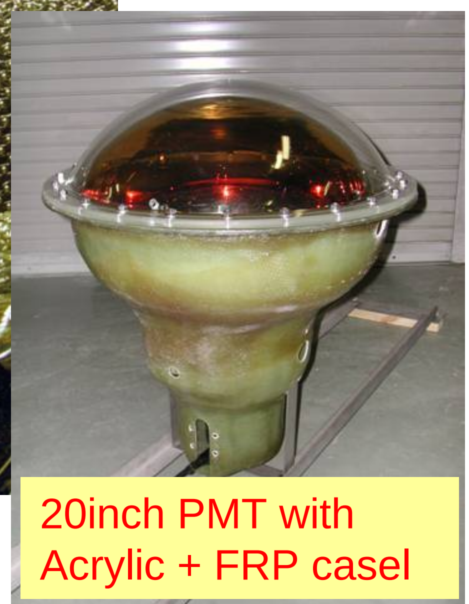
CC vs NC
Flux independent



Super Kamiokande-II

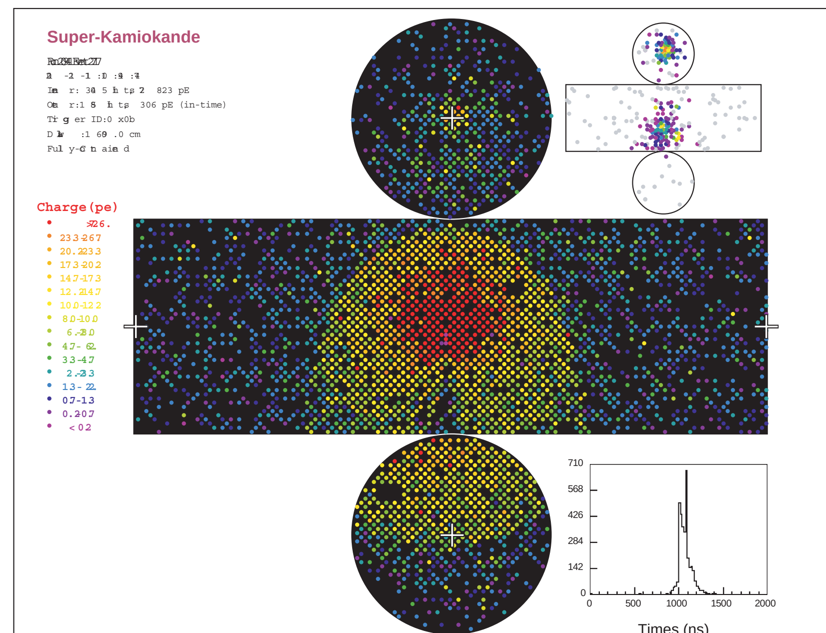


We have rebuilt the detector
and
resumed data taking in Oct. 2002.



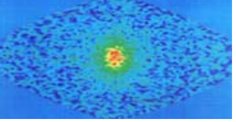
20inch PMT with
Acrylic + FRP casel

SK-II Cosmic ray muon

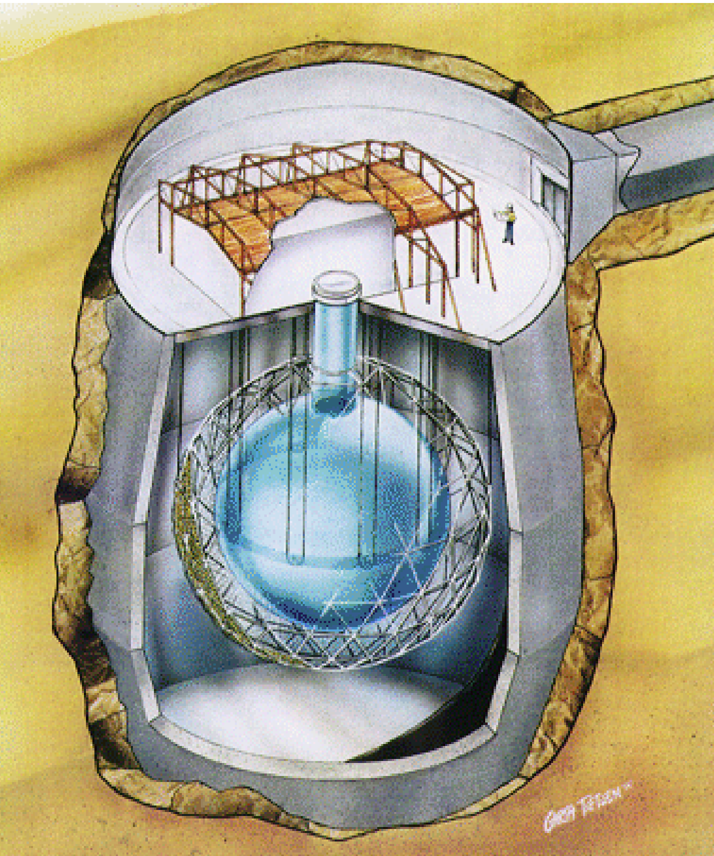


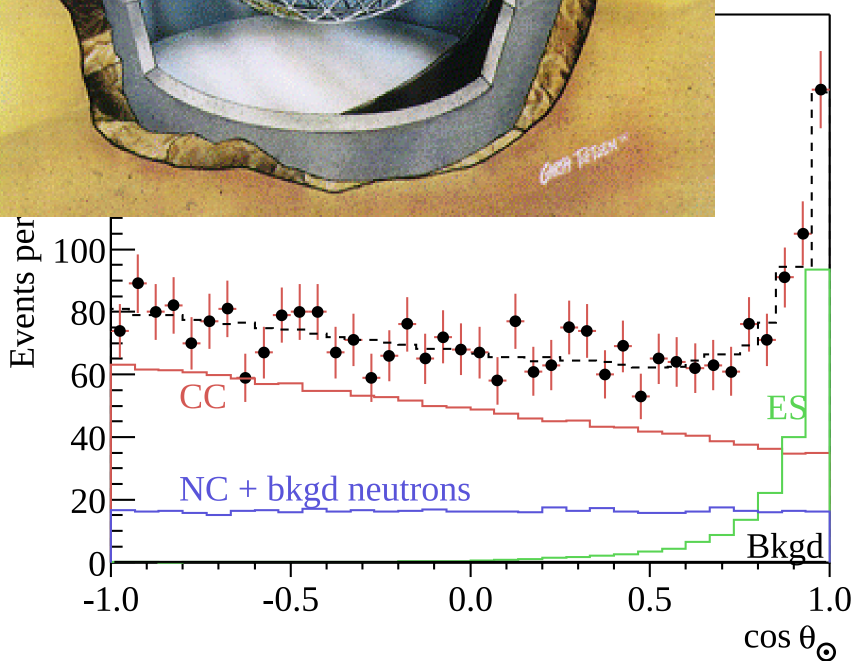
Inner detector
→ ~5200 20inch PMTs

Outer detector
→ 1885 8inch PMTs



SNO (Sudbury Neutrino Observatory)





- ***Electron scattering***

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

  ν_e and $(\nu_\mu、\nu_\tau)$x~0.15

- ***Charged Current (CC)***

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

  sensitive only to ν_e

- ***Neutral current interaction***

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

  1) $\nu + d \rightarrow T + 6.25$ MeV γ

  2) $\nu + {}^{35}Cl \rightarrow {}^{36}Cl + 8.6$MeV $\Sigma\gamma$

  3) $\nu + {}^{3}He$ counter

  sensitive to all neutrinos

$$\phi_{CC} = 1.76\,^{+0.06}_{-0.05}\,(\text{stat.}) \pm 0.09(\text{syst.})$$

$$\phi_{ES} = 2.39\,^{+0.24}_{-0.23}\,(\text{stat.}) \pm 0.12(\text{syst.})$$

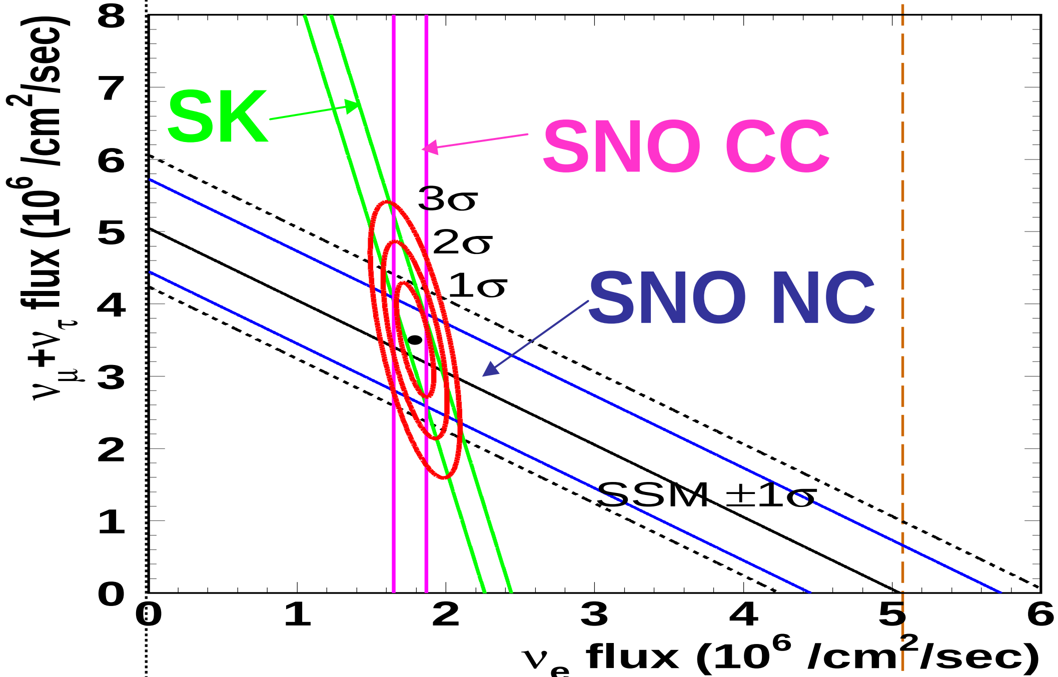
$$\phi_{NC} = 5.09\,^{+0.44}_{-0.43}\,(\text{stat.})\,^{+0.46}_{-0.43}\,(\text{syst.})$$

$[\times 10^6/cm^2/s]$

Discovery of Solar Neutrino Oscillation

- **SK (ES) +SNO（CC) in June 2001**

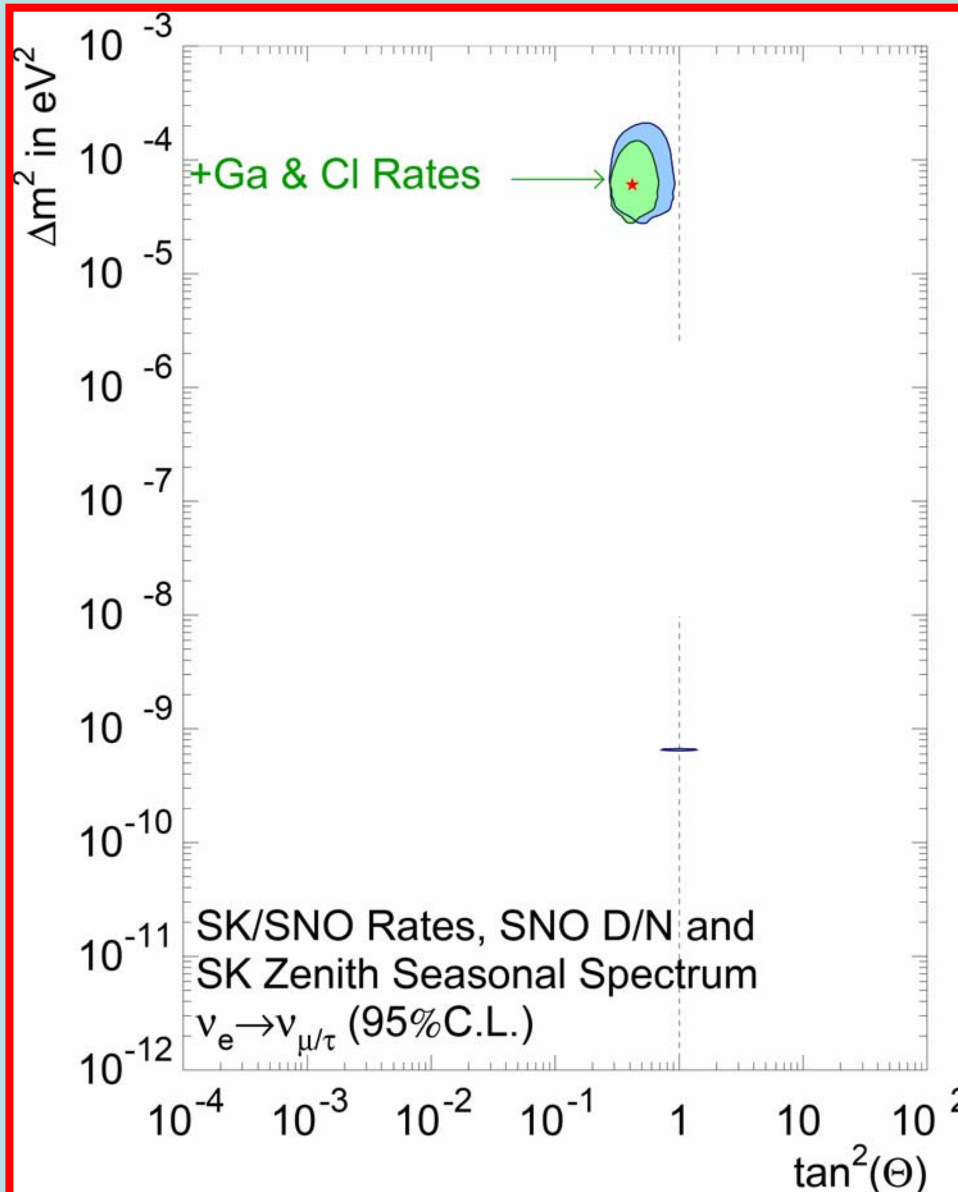
ν_e produced in the sun		**Prediction from SSM**
SK	46.5 %	**ν_e + (ν_μ,ν_τ)x0.15**
SNO CC	35 %	
SK break down	35% from ν_e,remaining from ν_μ,ν_τ	
Total ν flux	5.7±0.9 [x10^6/cm^2/s]	

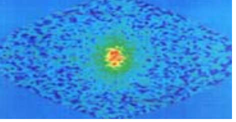


(in 2002) SNO NC 5.1±0.6 [x10^6/cm^2/s]

Global Best Fit Solutions: Parameter Pull

Global Solution	Large Mixing Angle(LMA)
Δm^2 [eV^2]	6.0×10^{-5}
$\tan^2\theta$	0.42
χ^2 (24 dof, p_{χ^2})	**21.2 (62.8%)**
$\Delta\chi^2$(2 dof; $p_{\Delta\chi^2}$)	**0.0 (100%)**
$\Delta\chi^2_{SK\text{-}Spec}$ ($p_{\Delta\chi^2}$)	**3.3 (1.3σ)**
$\Delta\log\mathcal{L}_{SKV}$($p_{\Delta\log\mathcal{L}}$)	**-0.8 (0.8σ)**
$\Delta\chi^2_{SNO\text{-}DN}$ ($p_{\Delta\chi^2}$)	**0.4 (+0.6σ)**
Ga Rate [SNU]	**69.7 (-0.2σ)**
Cl Rate [SNU]	
SK Rate [%]	**46.0 (-0.4σ)**
SNO CC [%]	**34.4 (-0.2σ)**
SNO NC [%]	**104 (+0.2σ)**
$\phi_{^8B}$ [10^6/cm^{2}s]	**5.25 (+0.2σ)**
ϕ_{hep} [10^3/cm^{2}s]	
^{8}B Spectrum	**-0.2σ**
SK E-sc/resol.	**-0.3σ /-0.1σ**





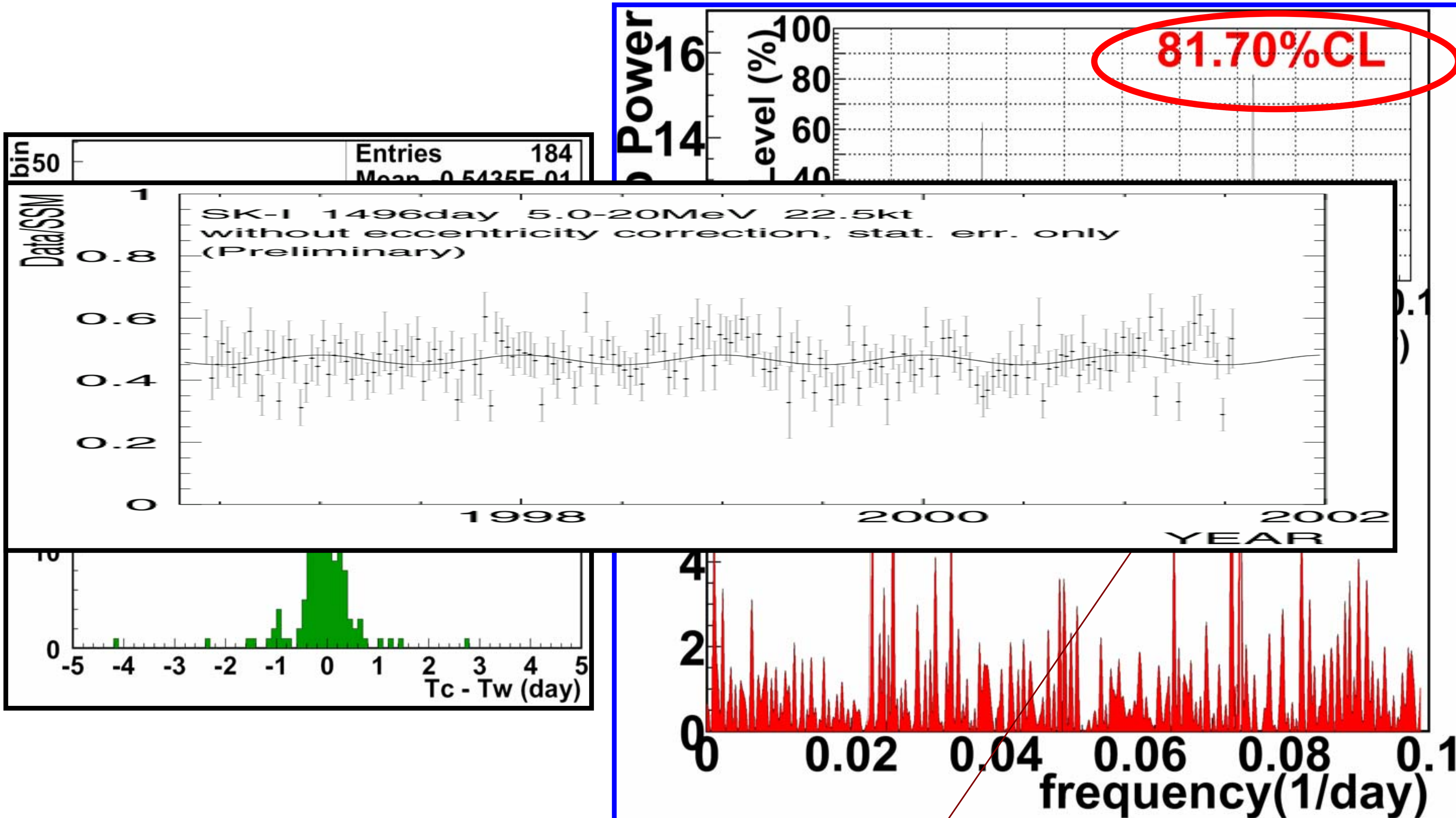
Troubles or Hints?

- **Homestake (Cl) data: 2 σ lower**
- **Hep-ν flux： Higher value is required**

  (> 4 x SSM)

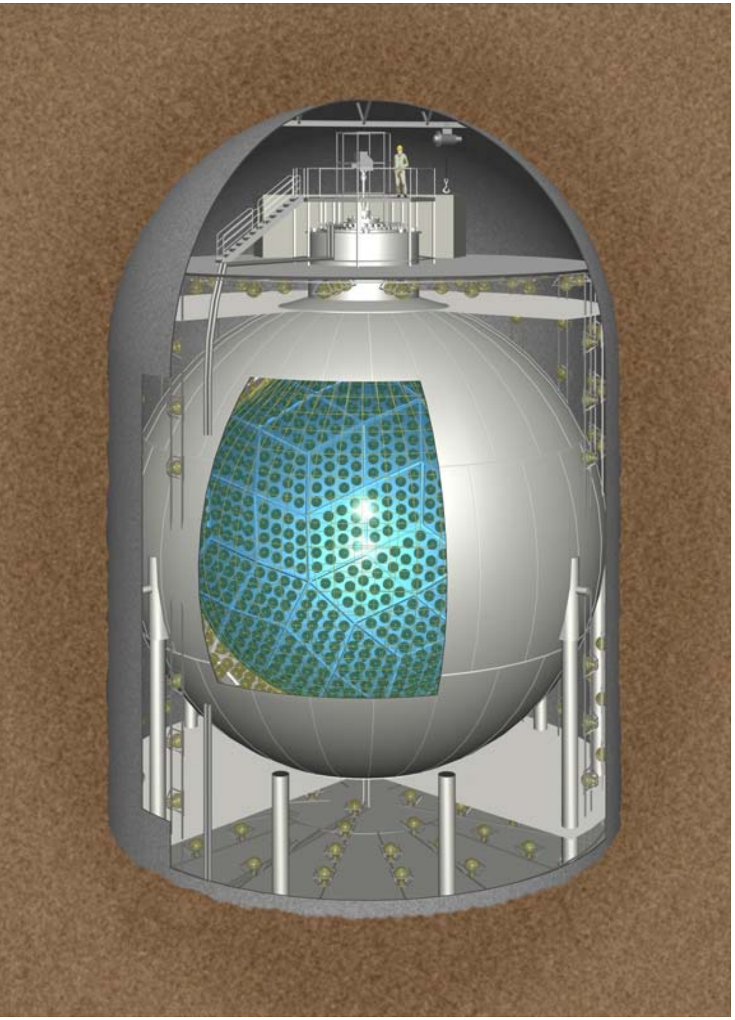
- **Time Variation ?**

Periodicity in the SK solar neutrino data?



Lomb Power decreases, if Correct bin-time is used!!

KamLAND



Long Baseline Reactor Experiment
hosted by Tohoku University

1,200 m^3 liq. scint.

1,280 17" PMTs 20% coverage

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

$\hookrightarrow + p \rightarrow \gamma$ (2.2MeV)

$E_{th} = 1.8$ MeV

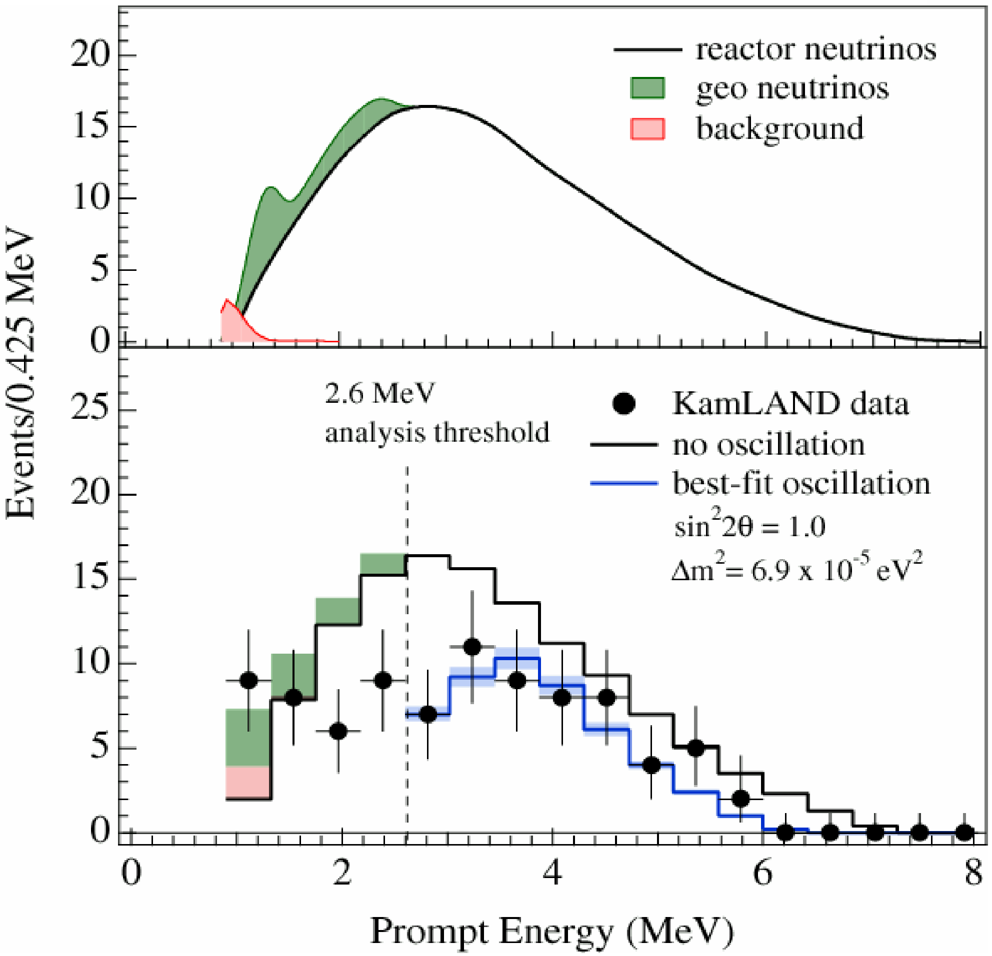
Commercial power reactor

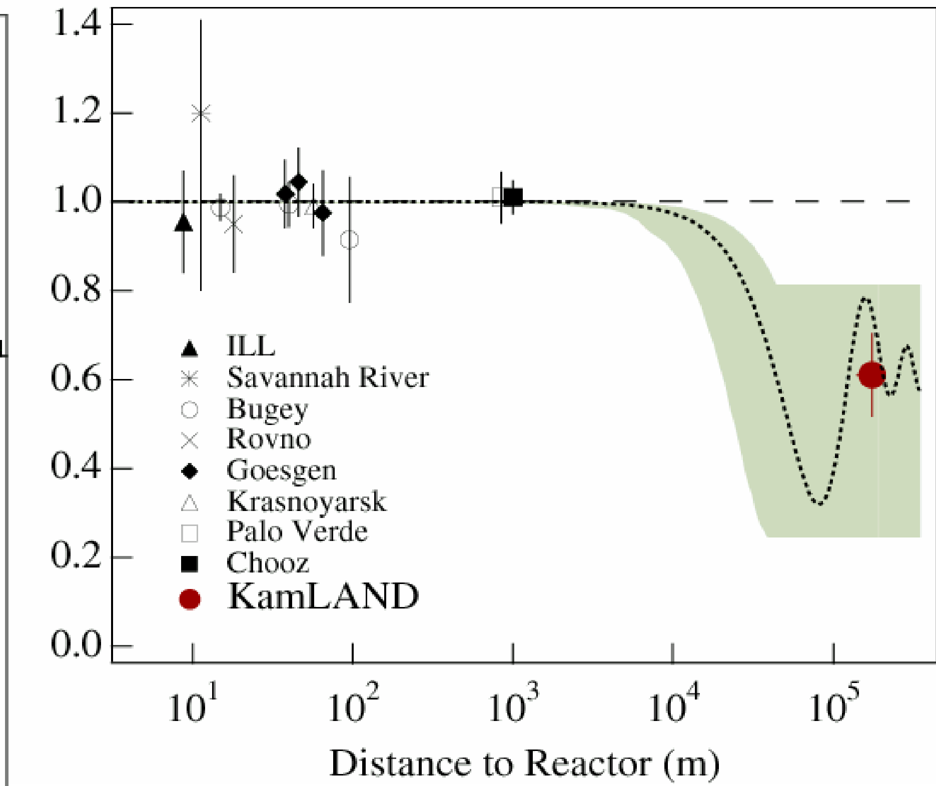
$\langle L \rangle \sim 180$km

$\langle E\nu \rangle \sim 5$ MeV

$\Rightarrow \Delta m^2 > 3\text{x}10^{-5}\text{eV}^2$
(sensitivity)

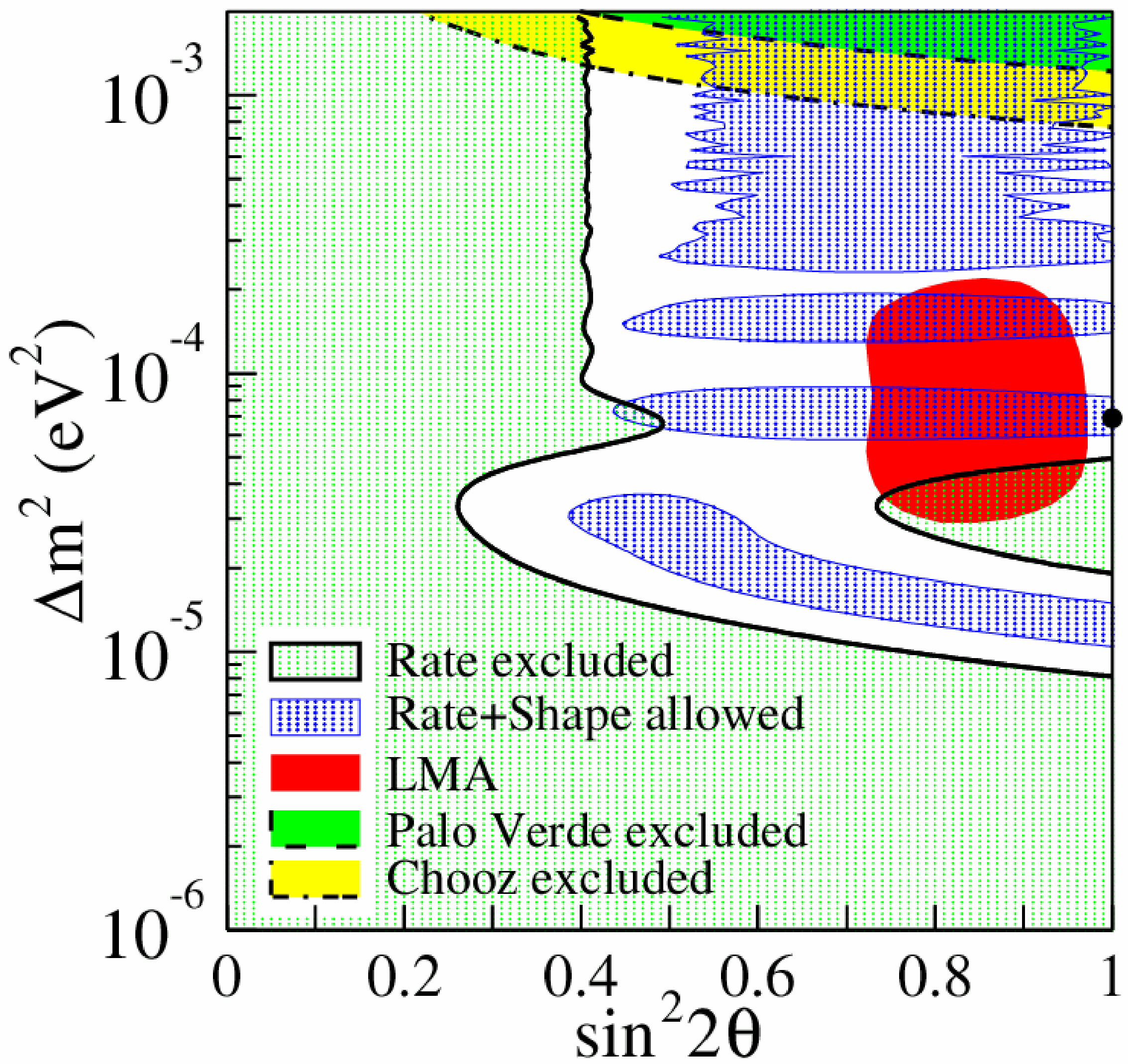
KamLAND Results





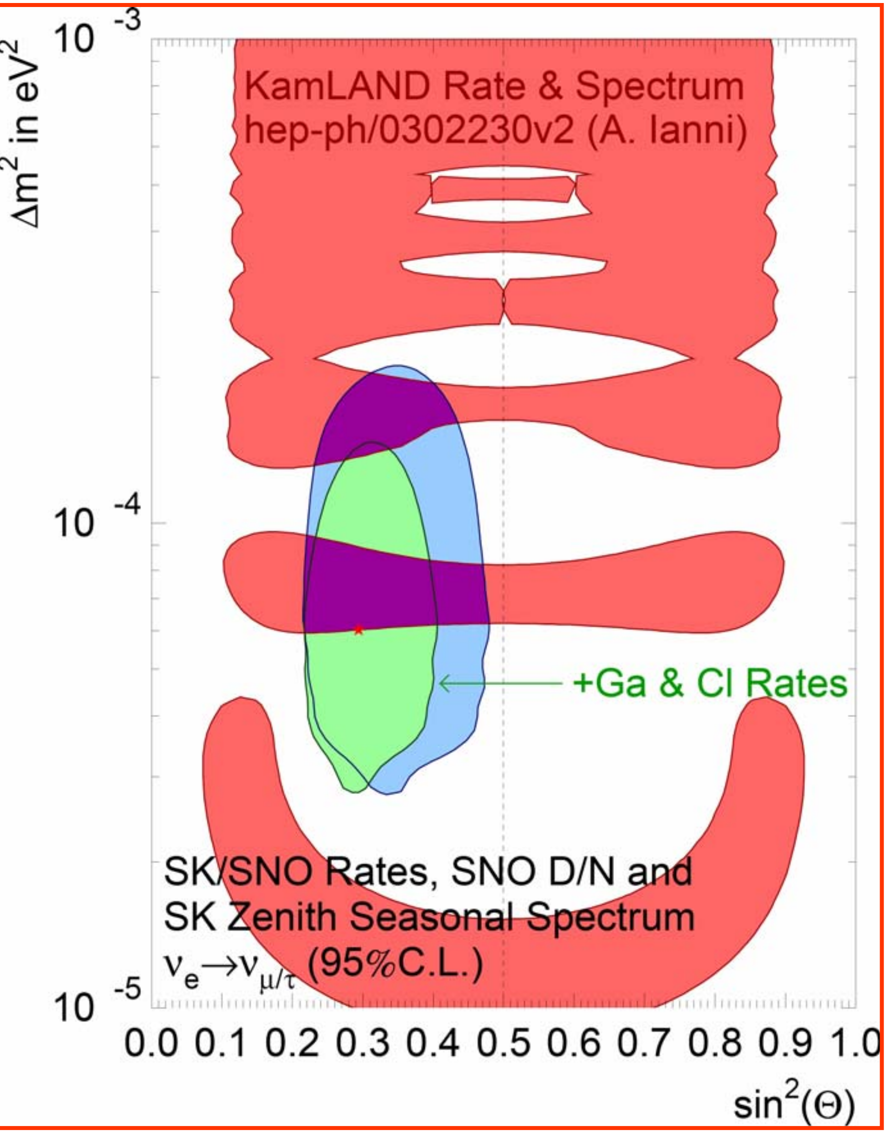
141.1 days
Observe 54 events
Expects 86.8 ±5.6 events

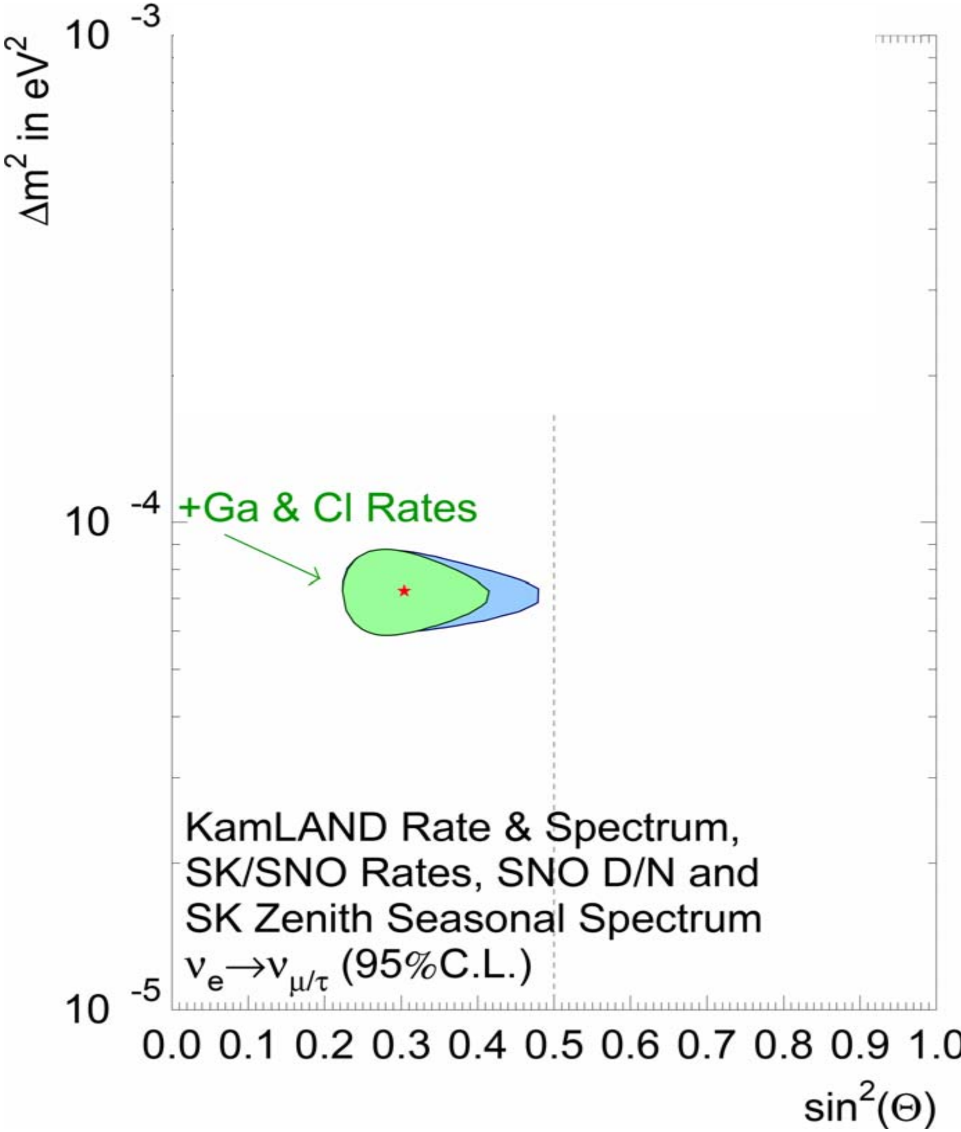
Ratio = 0.661±0.085 ±0.041



KamLAND confirmed the LMA solution and made the allowed Δm^2 region smaller.

Solar+KamLAND Combined Analysis





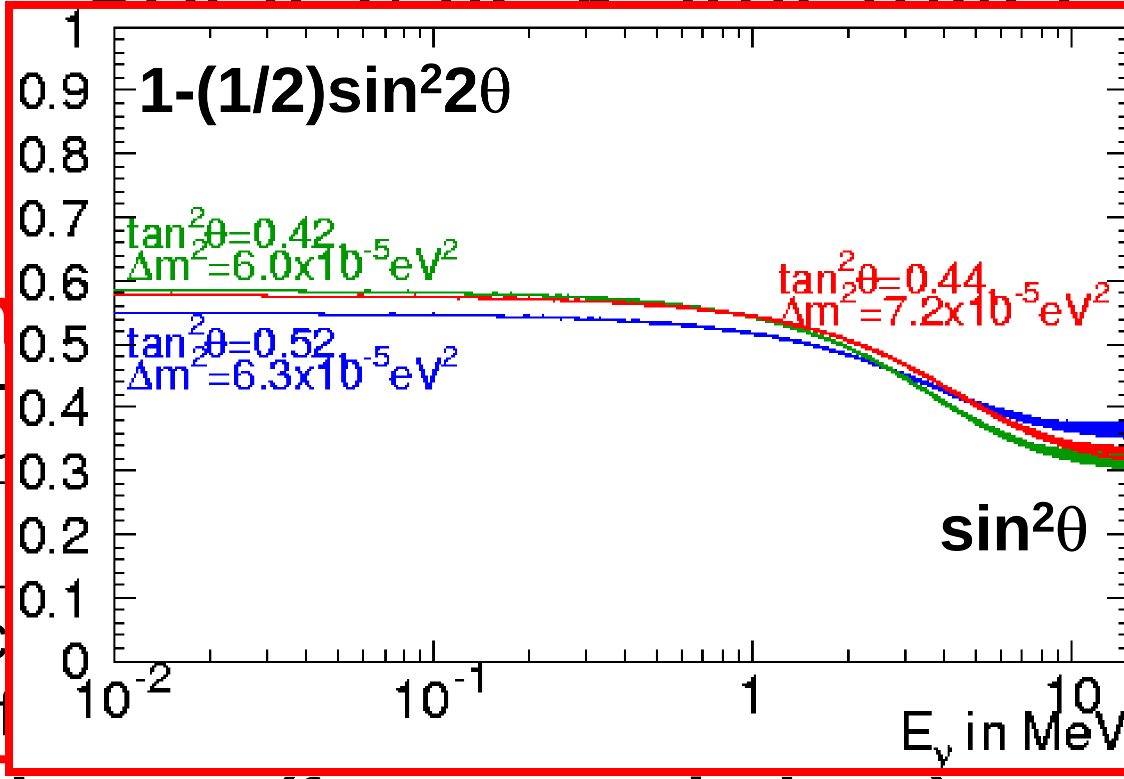
LMA Solutions

Parameter Fits	SK/SNO	All Solar	SK/SNO+ KamLAND	All Solar+ KamLAND
$\tan^2\theta$	0.48	0.42	0.48	0.44
Δm^2 in eV^2	$6.0\text{x}10^{-5}$	$6.0\text{x}10^{-5}$	$7.2\text{x}10^{-5}$	$7.2\text{x}10^{-5}$
$\Delta\chi^2$/CL [%]	5.1/7.8 (qVAC)	9.5/0.9 (LOW)	7.0/3.1 (HLMA)	9.1/1.1 (HLMA)
$\phi_{8B}/\phi_{hep}[10^6/cm^2s]$	5.04/0.034	5.25/0.037	4.96/0.035	5.06/0.033
SK/SNO A_{DN}[%]	-2.3/-3.7	-2.3/-3.8	-1.6/-2.6	-1.6/-2.6

Solar ν vs KamLAND

- **Caution**

Solar neu	
ν_e	CPT?
Adiabatic matter eff	
~	
Ve	ay ?
N	
St in	?



- **In the sun (for LMA solutions)**
  - **Low energy ν below ~1 MeV, never pass the resonance:**
    - $\theta_m \rightarrow \theta_V$ **(E <1 MeV)** ➔ ***$P=1-(1/2)\sin^2 2\theta$***
  - **E_ν > 1 MeV: adiabatic**
    $P=\cos^2\theta\cos^2\theta_m+\sin^2\theta\sin^2\theta_m$:
    - $\theta_m \rightarrow \pi/2$ ➔ ***$P=\sin^2\theta$***

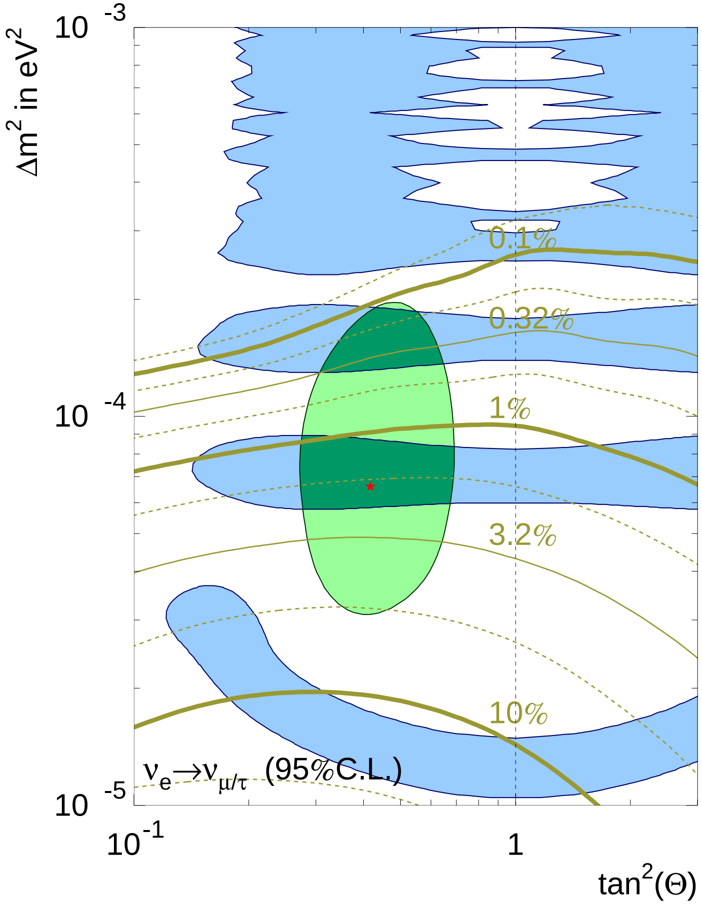
Need more precise measurements
of both solar neutrinos and KamLAND,
which may provide a further confirmation
and
may lead us to the sub-leading phenomena
beyond the standard scenario of LMA.

Sterile mixture
Non-standard interactions
CPTV
Decay
SFP

Day-Night Effect must be observed

1~3 %

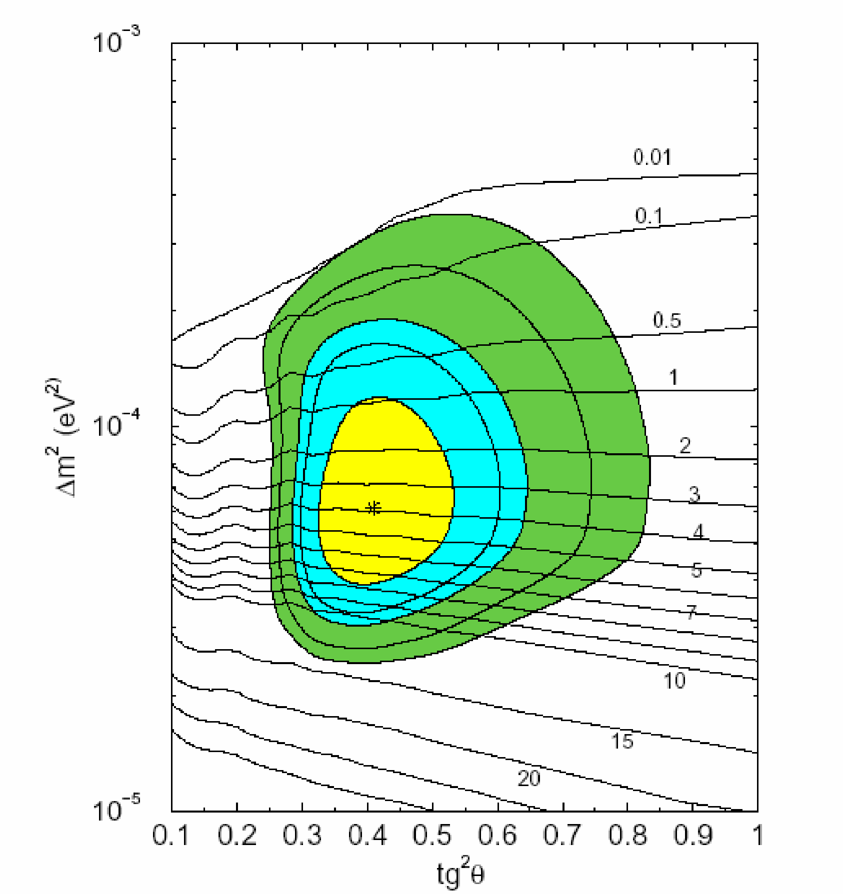
Super-Kamiokande



$$-0.021 \pm 0.020^{+0.013}_{-0.012}$$

2~5 %

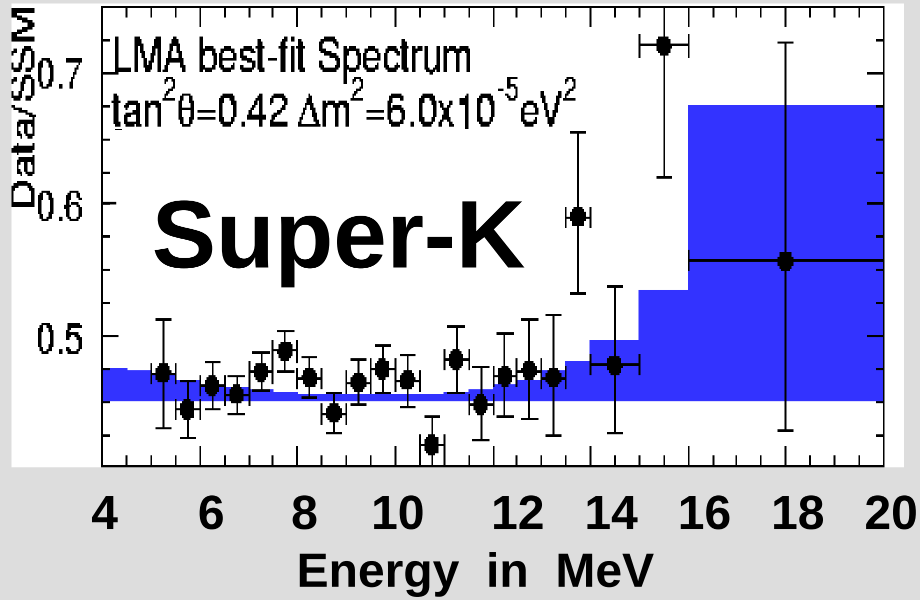
SNO

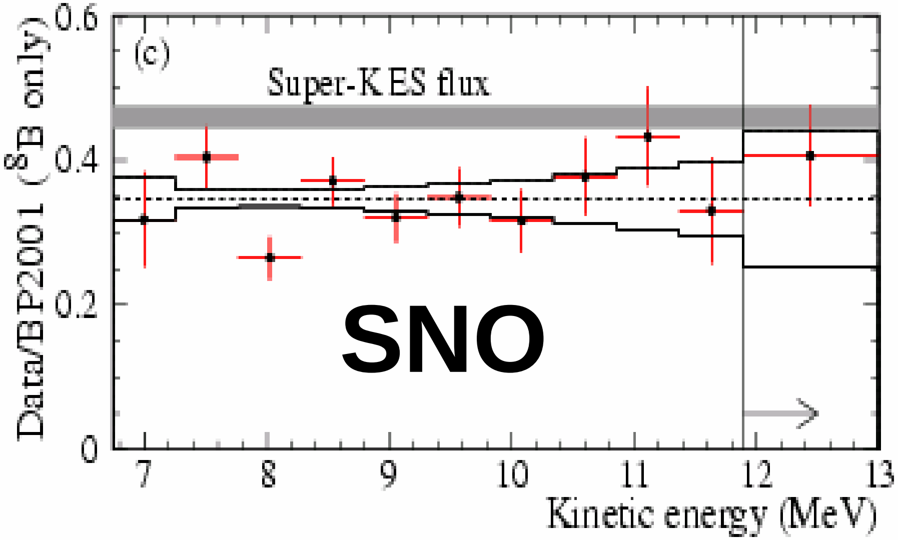


$$-0.07 \pm 0.049^{+0.013}_{-0.012}$$

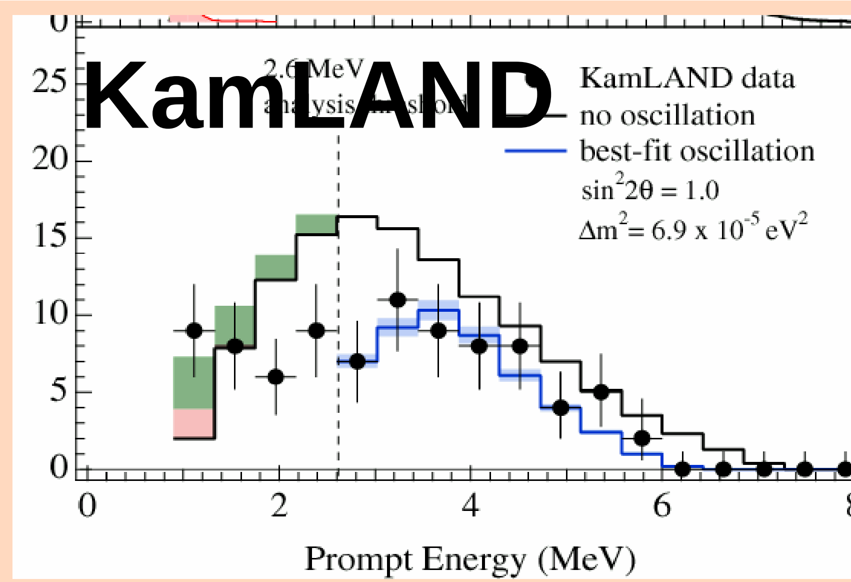
Spectrum Distortion must be observed
-- no significant distortions observed yet --

Systematics Limited
→ **Extend to low energy**

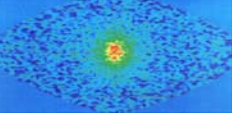




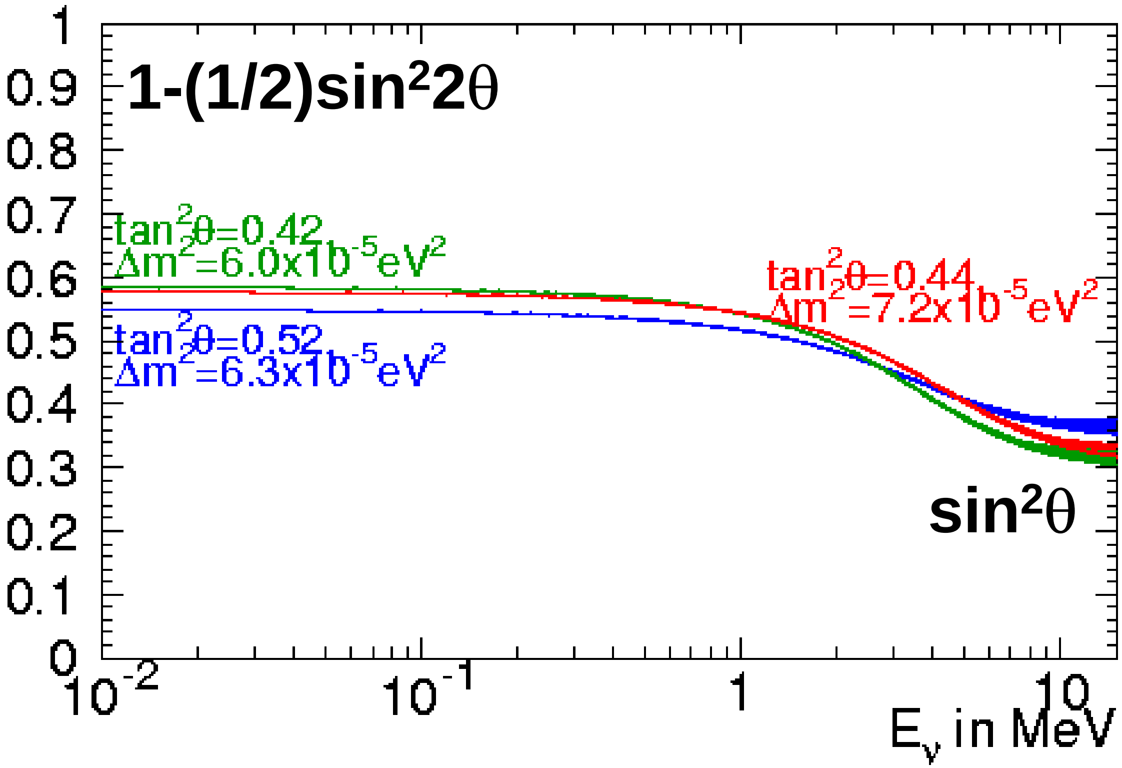
Systematics are large
Statistics→ Need time



Distortion only in a low energy
→ **Need time**



Expectation for pp and ^{7}Be flux



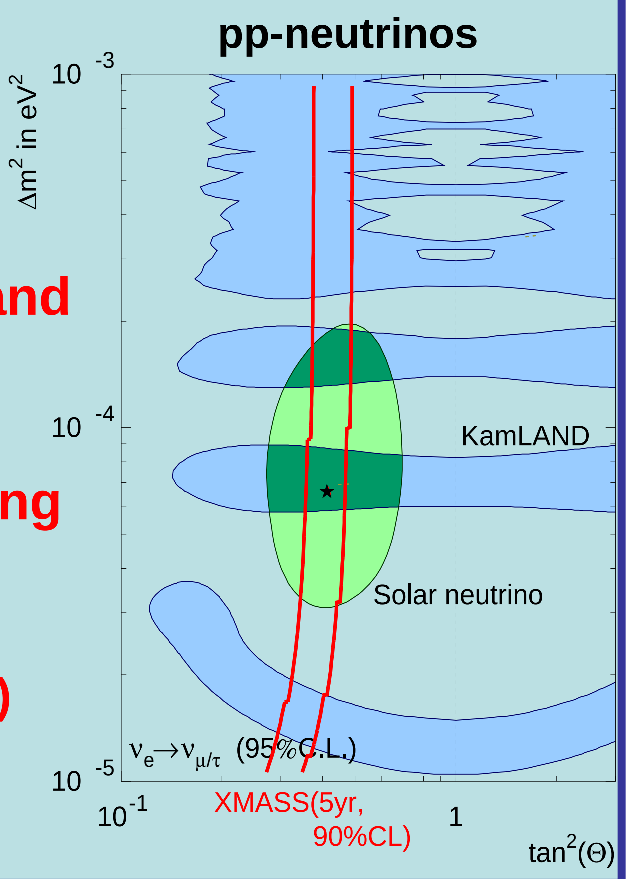
- **pp-neutrinos**
  - **~55~58%**
- **^{7}Be-neutrinos**
  - **~52~54%**

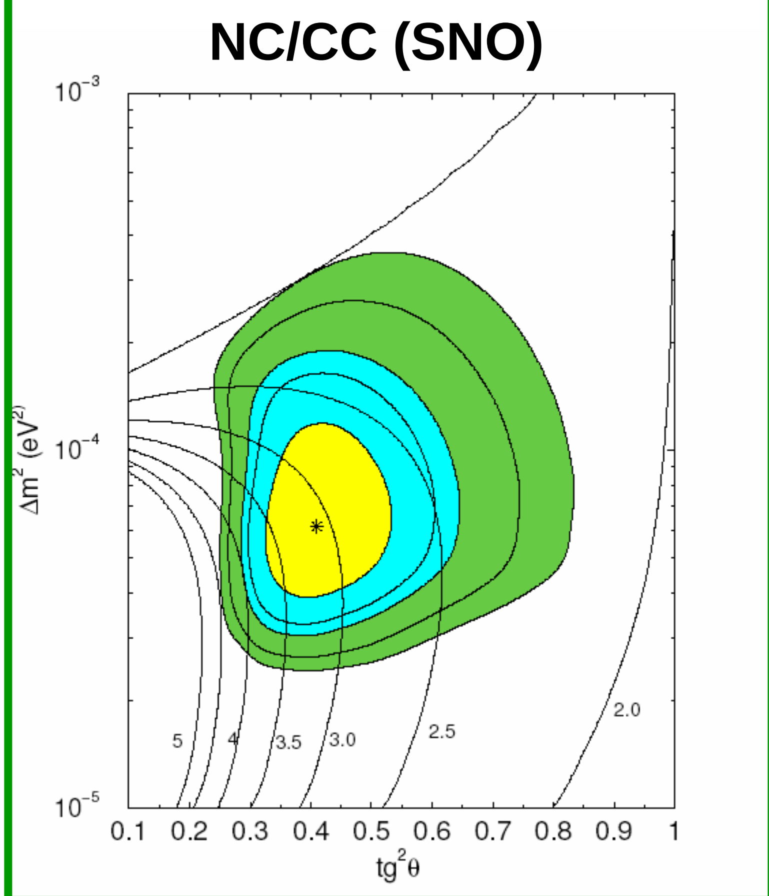
- **Confirmation of the solutions**
  - **Cl-problem?**
- **Understanding of the oscillation mechanism**
  - **Vacuum vs Matter**
  - **Vacuum-Matter transition**

$\tan\theta_{12}$ improvement

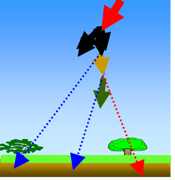
- NC/CC
- pp-neutrinos

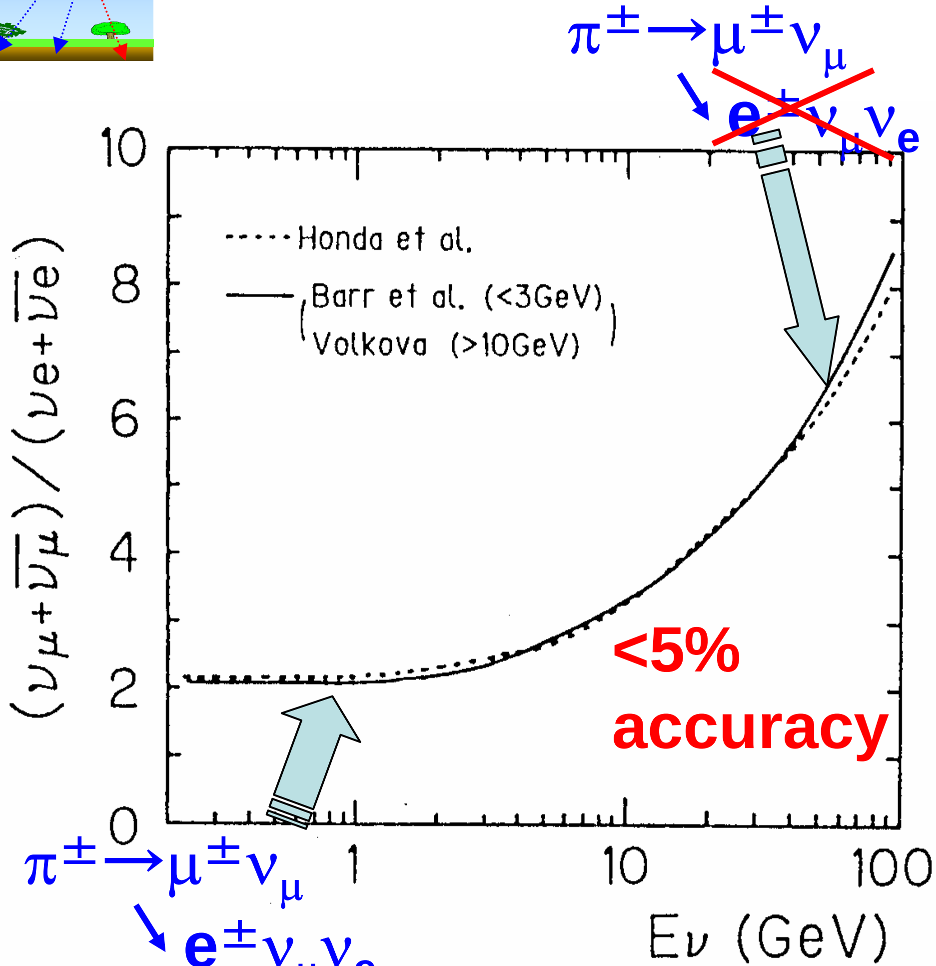
- **Statistical error and SSM prediction error (1%)**
- **Accuracy of mixing angle:**
  - **$\sin^2 2\theta = 0.77 \pm 0.03$(stat.+SSM)**

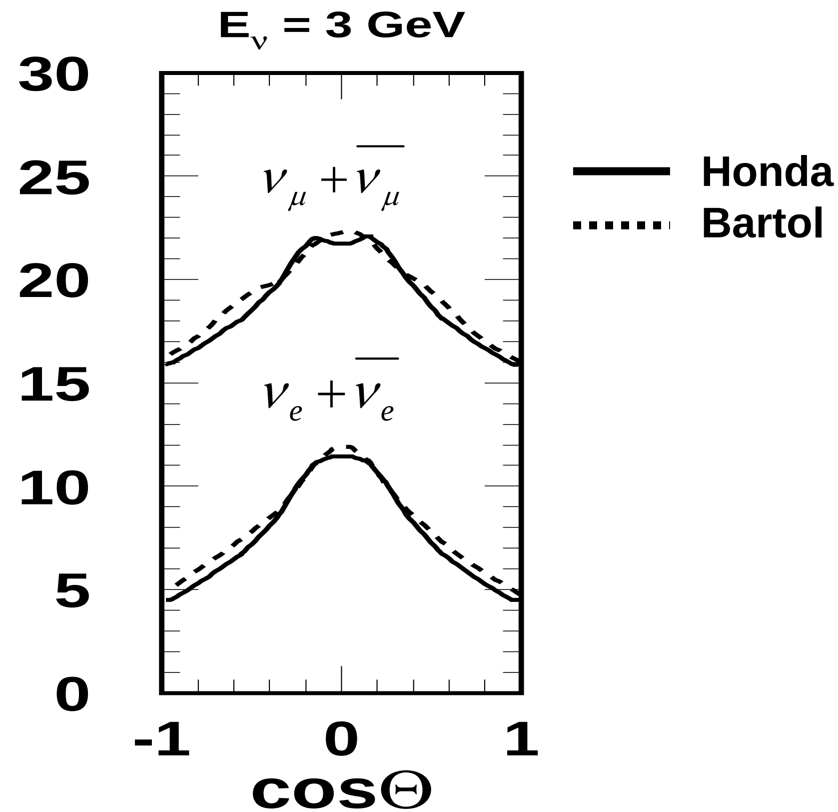




Atmospheric neutrinos







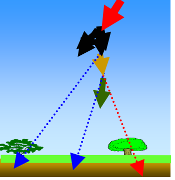
up-down symmetric for both ν_μ and ν_e (above a few GeV).

Neutrino oscillations :

$$\left(\frac{\nu_\mu+\overline{\nu}_\mu}{\nu_e+\overline{\nu}_e}\right)_{data} \Big/ \left(\frac{\nu_\mu+\overline{\nu}_\mu}{\nu_e+\overline{\nu}_e}\right)_{MC} \neq 1$$

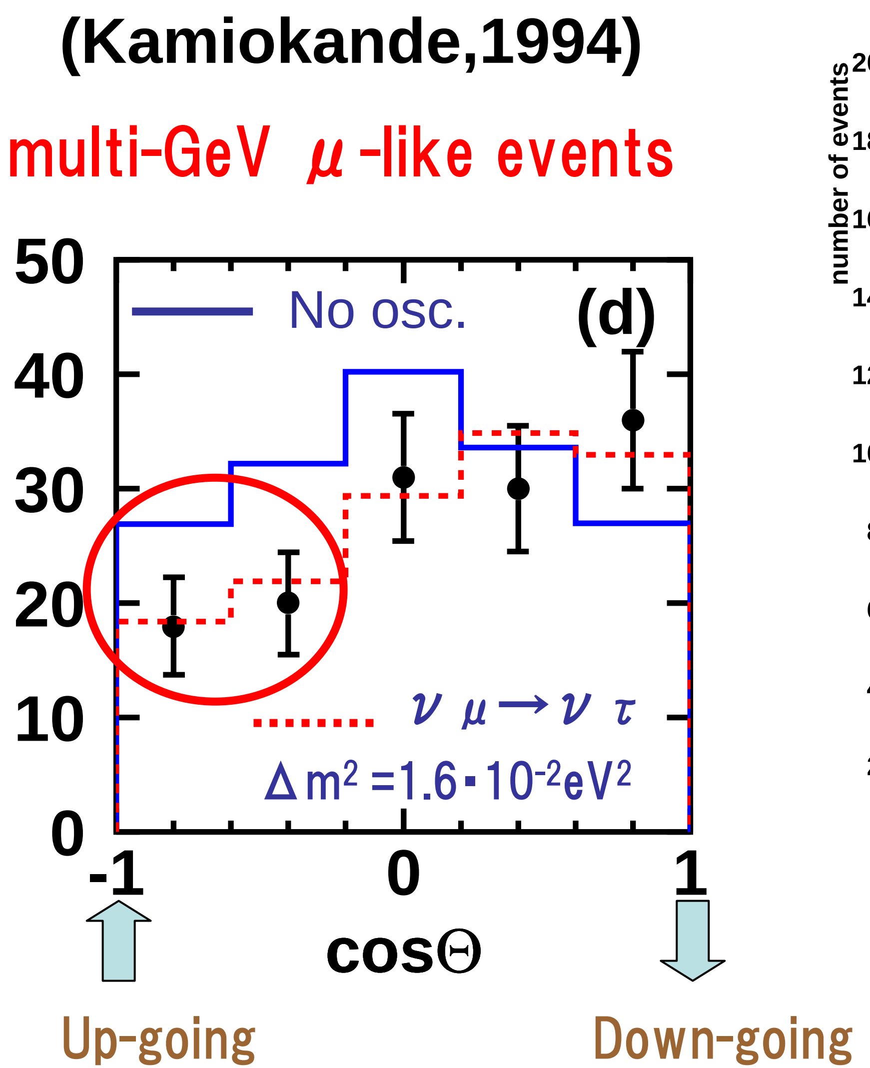
and/or

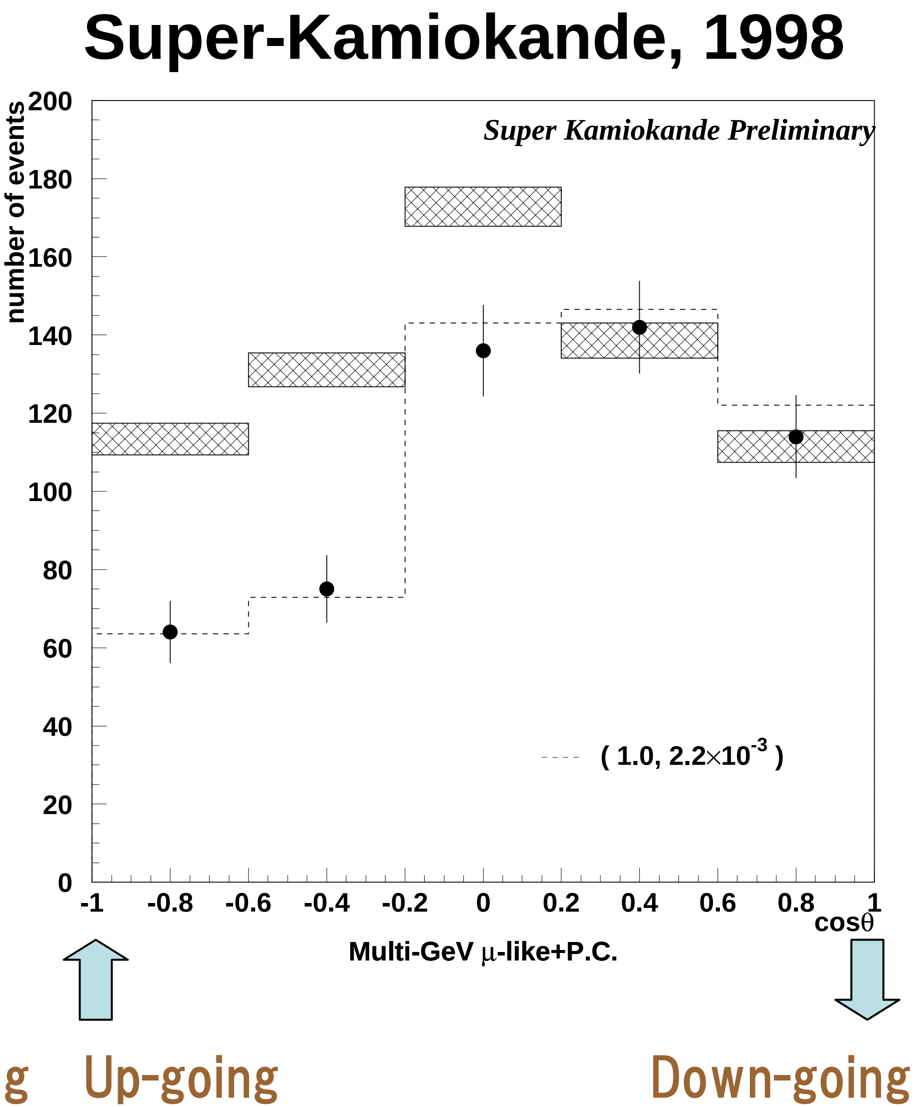
Up-down asymmetry (L dependency)

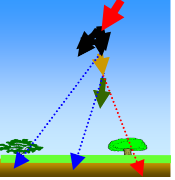


Kamiokande & Super-K

- **Discovery of Atmospheric Neutrino Oscillation by Super-Kamiokande in 1998**





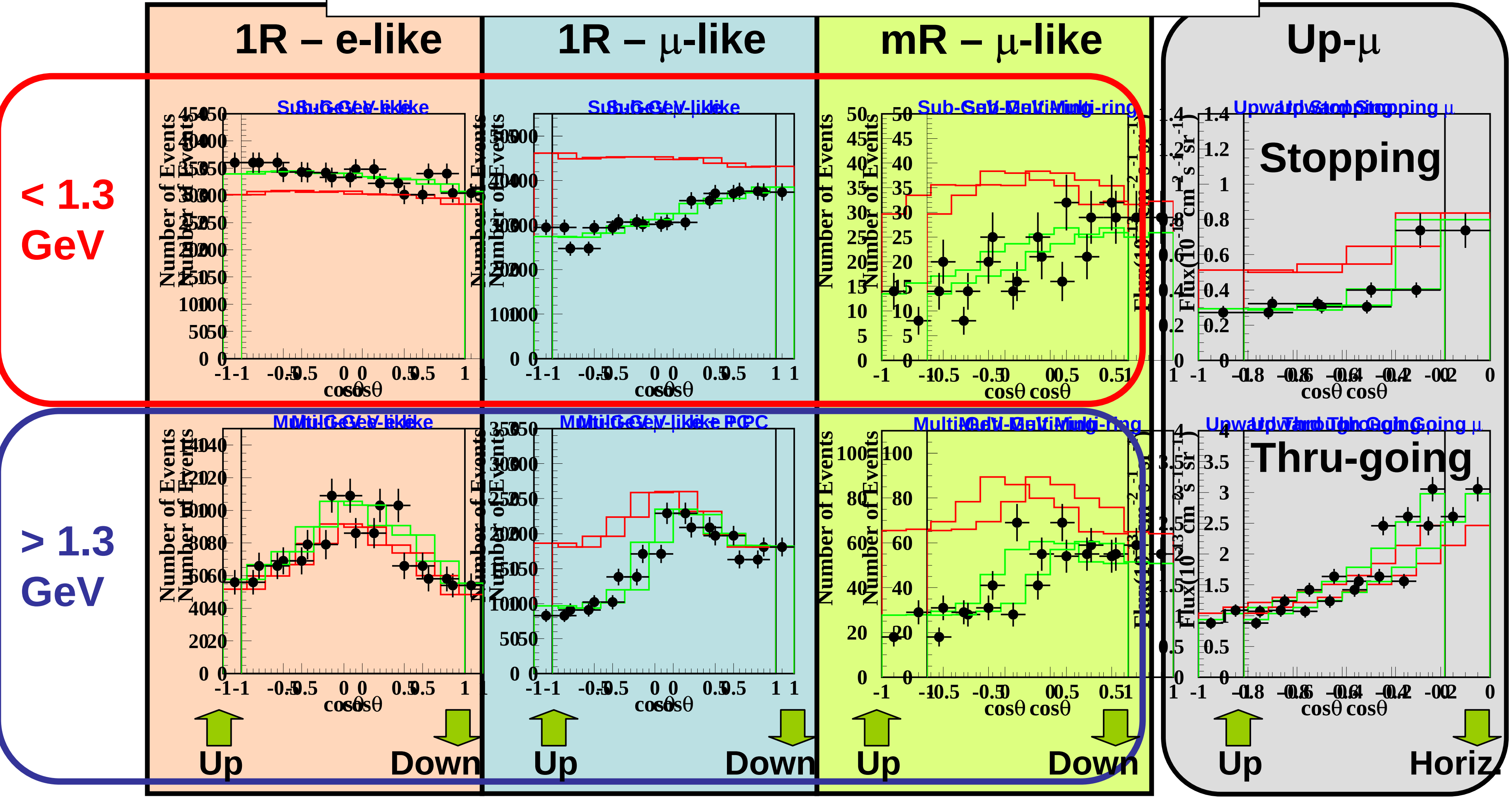


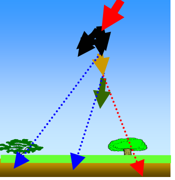
Super Kamiokande

1489d … evised)

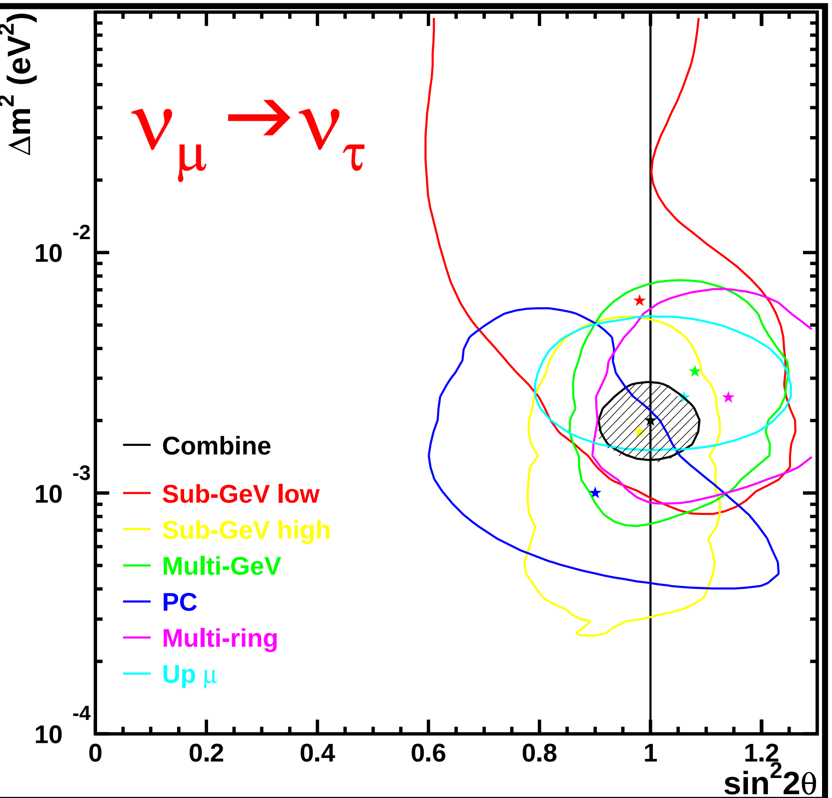
Best fit:
$\Delta m^2 = 2.0 \times 10^{-3} eV^2$, $\sin^2 2\theta = 1.0$

Null Oscillation:





Combined allowed regions (revised)



Best fit (in previous figures):

$\Delta m^2 = 2.0\times10^{-3}$ eV^2, $\sin^2 2\theta = 1.0$

$\chi^2_{min} = 170.8/170$ d.o.f

Null Oscillation:

$\chi^2_{min} = 445.2/172$ d.o.f

Oscillation significance

$\Delta\chi^2 = 274$

Ratio: $\dfrac{(\mu/e)_{data}}{(\mu/e)_{MC}}$

$0.649 \pm^{0.016}_{0.016} \pm 0.051$ (sub-GeV (1R))

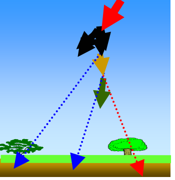
$0.698 \pm^{0.032}_{0.030} \pm 0.083$ (multi-GeV (1R))

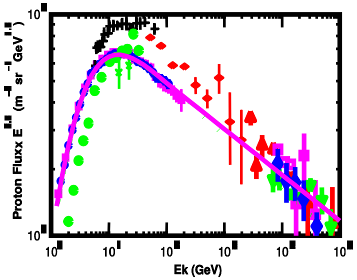
$\Delta m^2 = (1.3\sim3.0)\times10^{-3}$ eV^2

$\sin^2 2\theta > 0.90$

@ 90%CL

Comparison of old and new analysis results

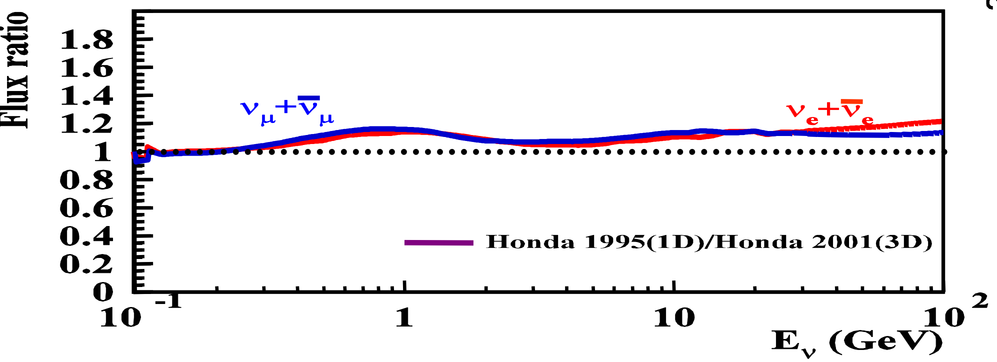


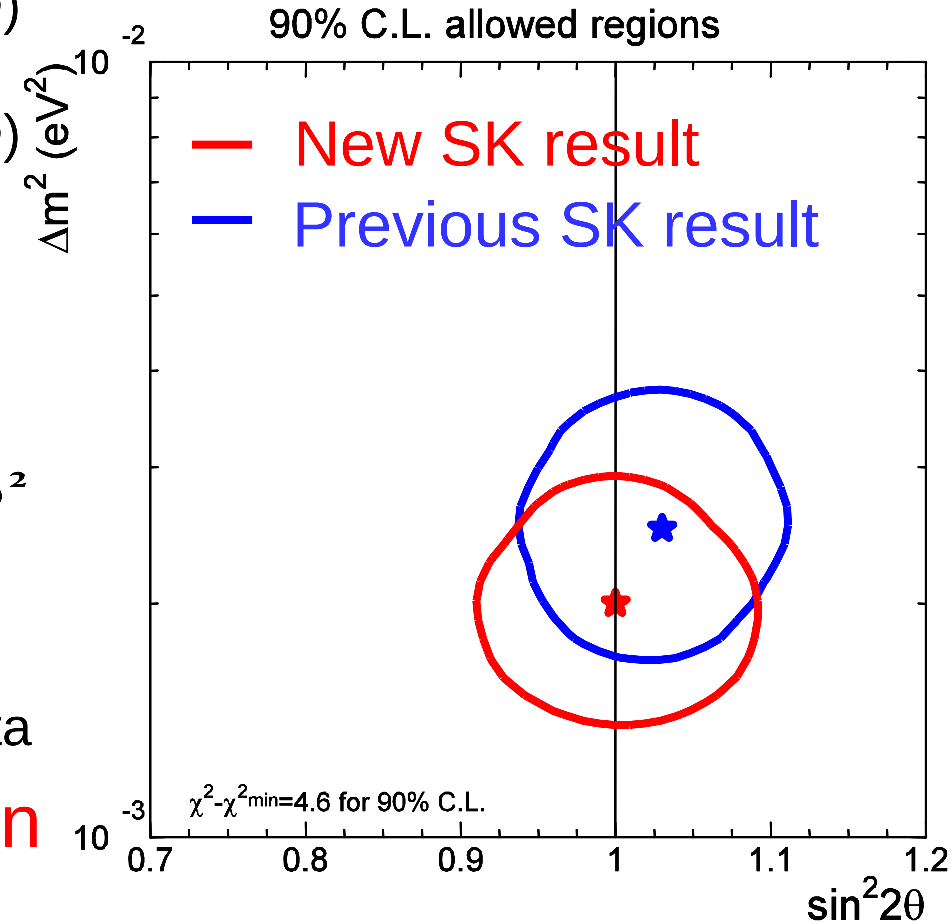


- Neutrino flux

Honda 1995(1D)

Honda 2001(3D)





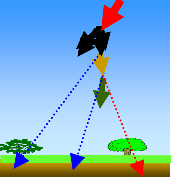
- Neutrino interaction model

several improvements:

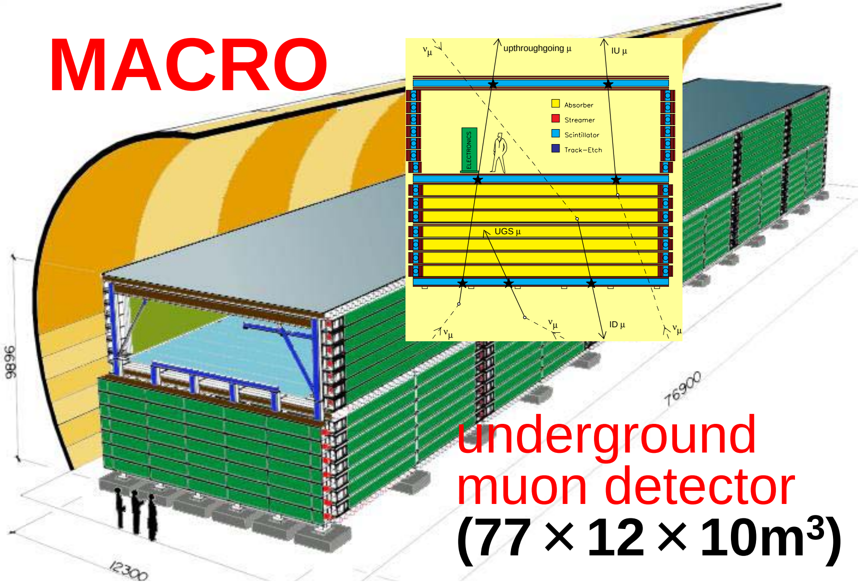
agree better with K2K near-detector data

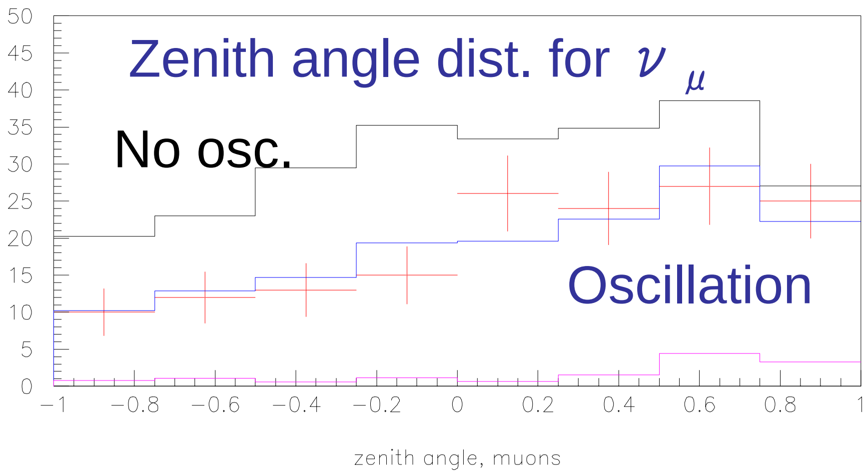
- Improved detector simulation
- Improved event reconstruction

Each change contributes to the shift in the allowed Δm^2 region.

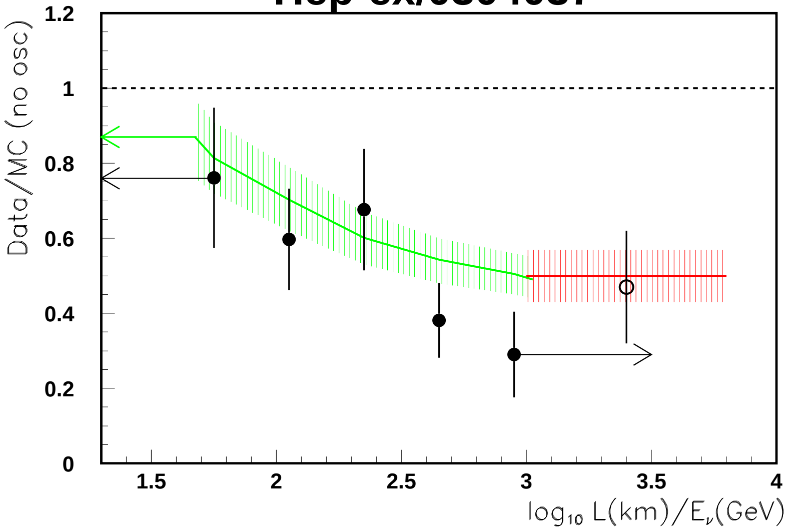


Other atmospheric neutrino experiments



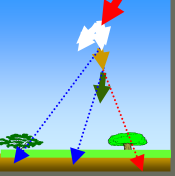


Hep-ex/0304037

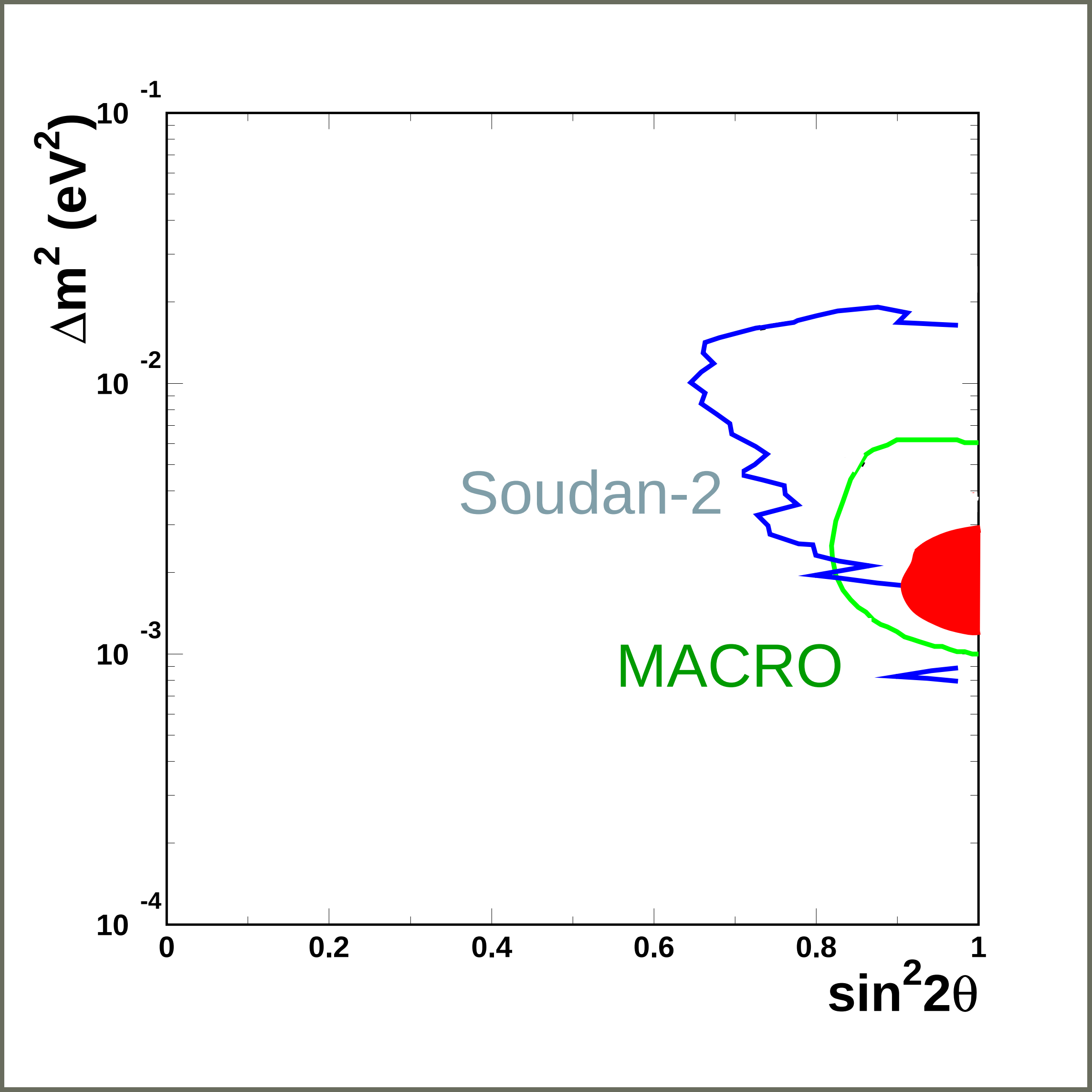


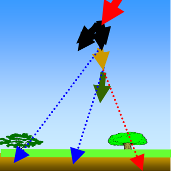
● Black points : upthroughgoing μ data

○ Open point : Internal Up (IU) μ data



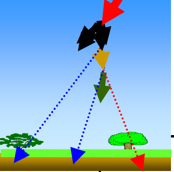
Other atmospheric neutrino experiments



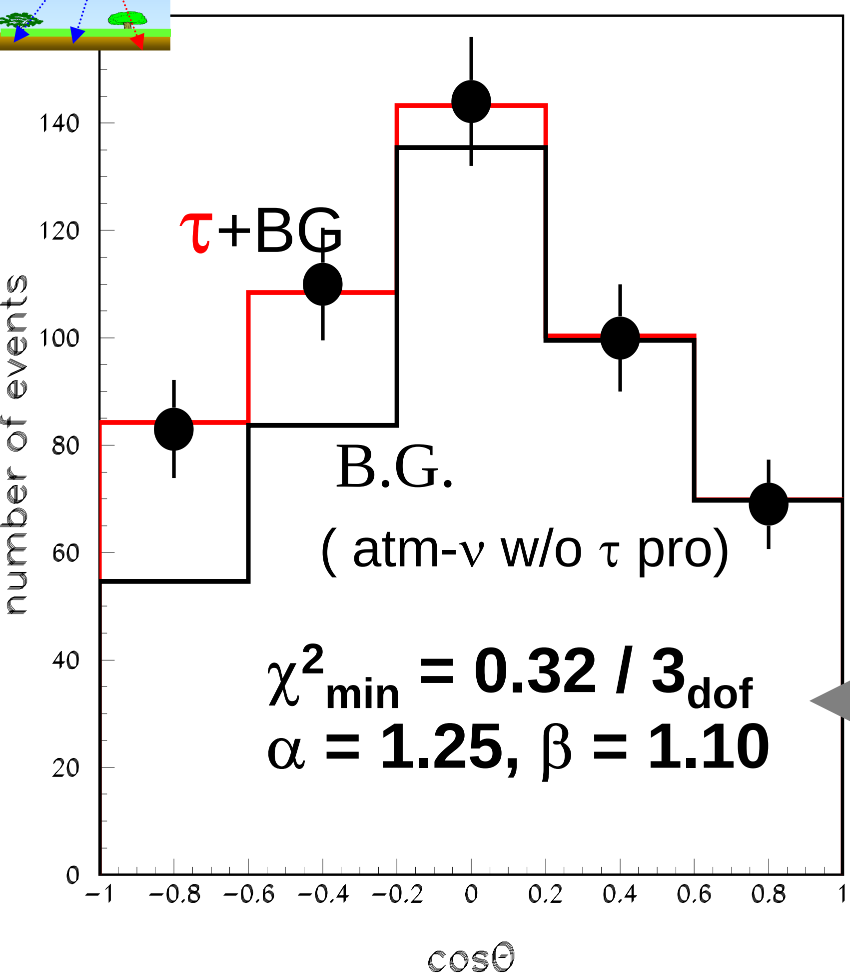


Search for τ production in atmospheric ν

- **τ events cannot be identified by event-by-event basis**
- **Need statistical analysis**
- Adopted three different analyses:
  1) Energy flow
  2) Neural Network
  3) Likelihood Method
     - **Selection Criteria**
       - **multi-GeV, multi-ring**
       - **most energetic ring is e-like**
     - **Calculate Likelihood and cut events to enhance τ**



zenith angle dist. of τ-like events



$$\chi^2 = \sum_{\cos\Theta}^{5} \left(\frac{N_{data} - \left(\alpha N^{\tau}_{MC} + \beta N^{BG}_{MC}\right)}{\sigma} \right)^2$$

$N_\tau = 48 \, {}^{+19}_{-20}$ events

$N^{FC}_{\tau} = N_{\tau} / eff(\tau)$

$= 105 \, {}^{+42}_{-45} \, {}^{+12}_{-17}$ events

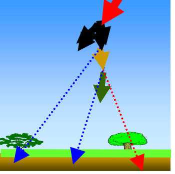
Expected: 86 for 1489 days

consistent with $\nu_\mu \leftrightarrow \nu_\tau$

Other analyses give similar results:

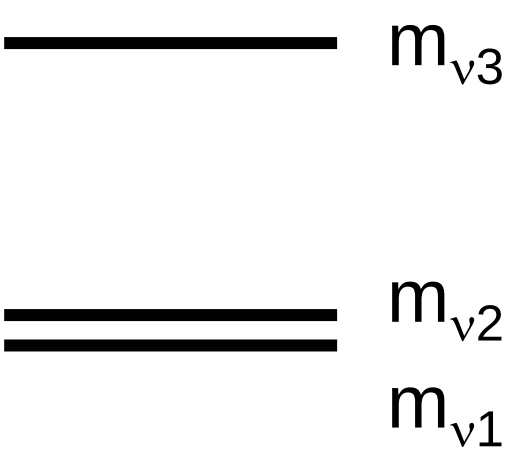
Neural Network $= 92 \pm^{35}_{35} \pm^{21}_{16}$ events

Energy Flow $= 79 \pm^{44}_{40}$ events



3 flavor analysis

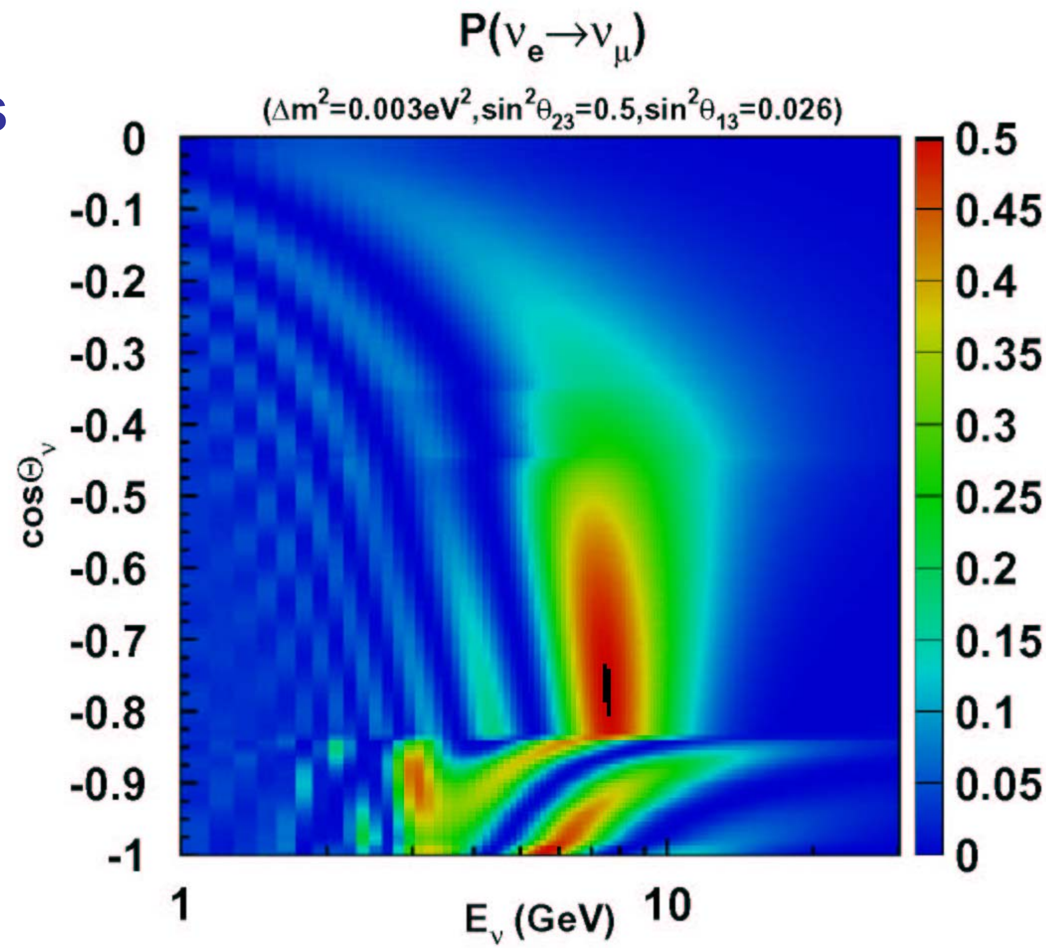
Assumption in SK analysis



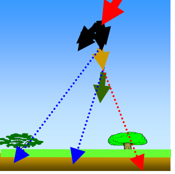
$\Delta m_{12}=0$

$\Delta m_{13}= \Delta m_{23}$

$\Delta m_{13}^2, \theta_{23}, \theta_{13}$



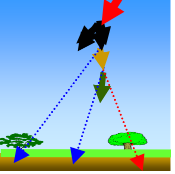
Matter effect through those parameters



Note for the effect from Δm_{sol}^2 on the atmospheric oscillation

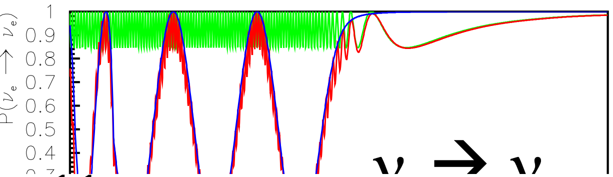
- **Electron appearance in `Low Energy`**
- **But was negligible**
  - **Cancellation (ν_μ : ν_e = 2 : 1 & full mixing of θ_{23})**

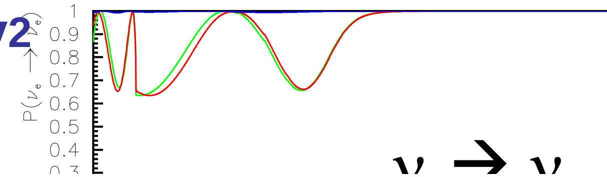
- **Now we know Δm_{12}^2 is relatively large**
- **Re-examination**
  - **Matter effect**
  - **Interfere from the transitions through Δm_{12} & Δm_{13} (no cancellation)**



effect from Δm_{sol}^2 on the atmospheric oscillation

100 MeV **3 GeV**

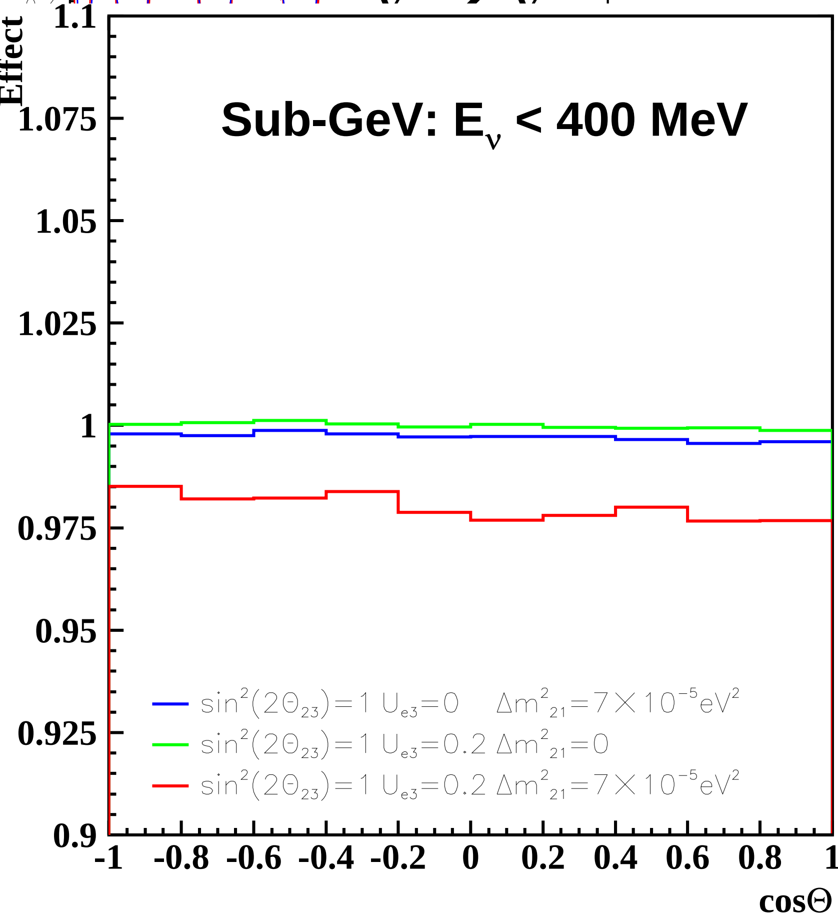


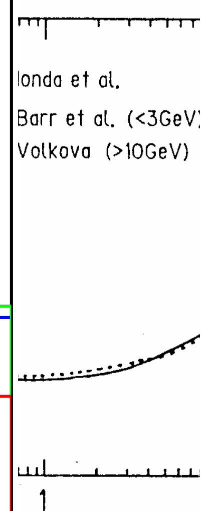


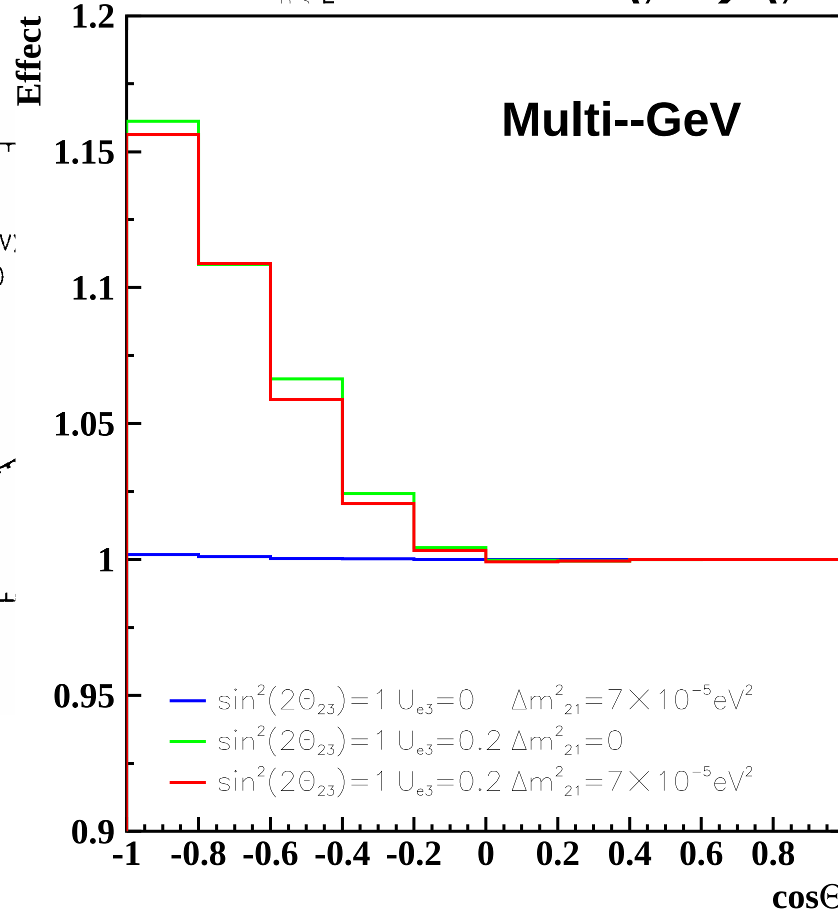
$|U_{e3}|=0.2$ (green)

$\Delta m_{12}^2=7\times10^{-5}eV^2$ (blue)

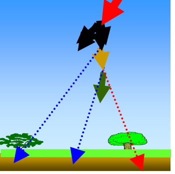
Interference (red)



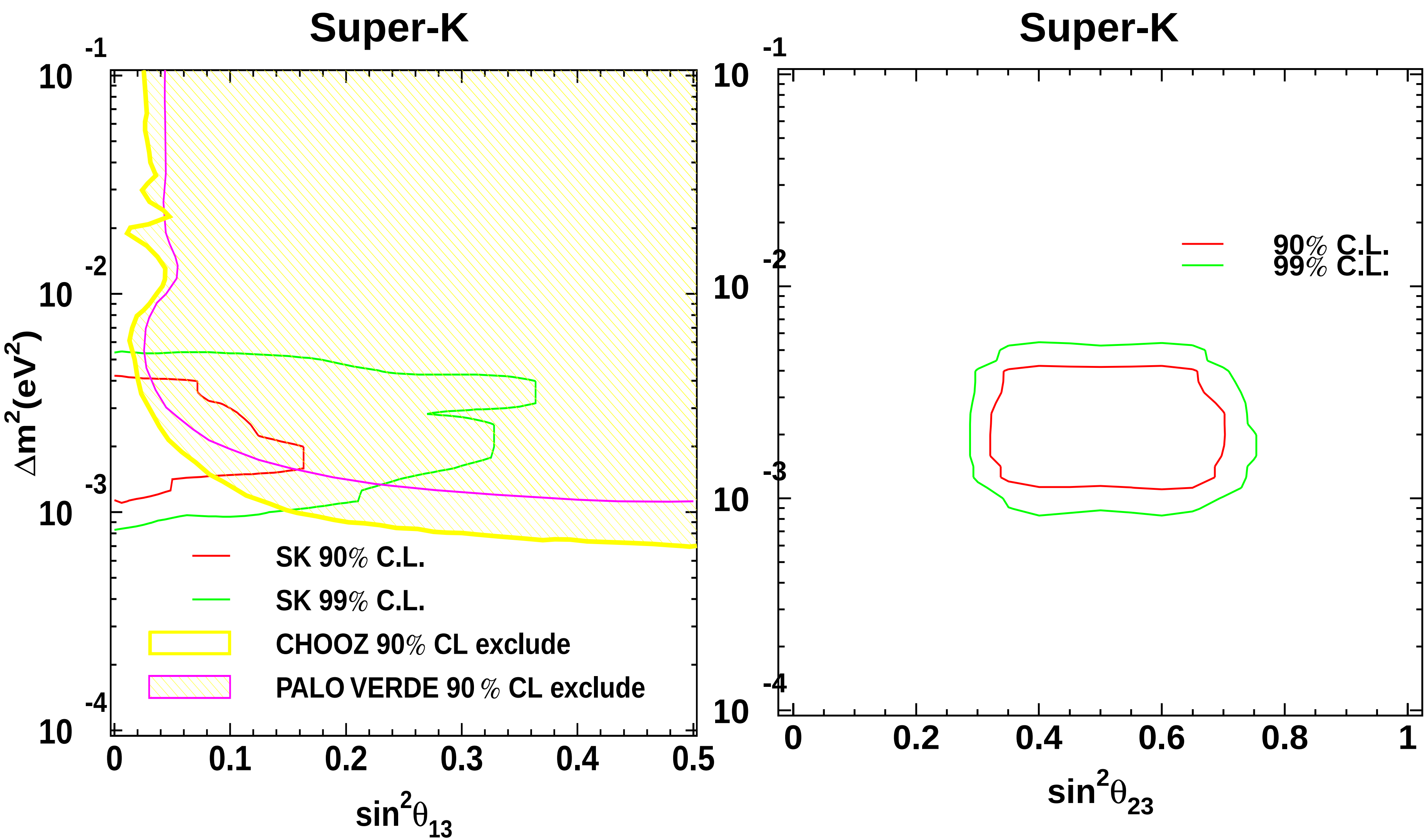




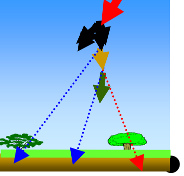
SK assumption, $\Delta m_{12}=0$ is still OK.



Allowed region for active 3-flavor oscillations including θ_{13}, but not Δm_{12}



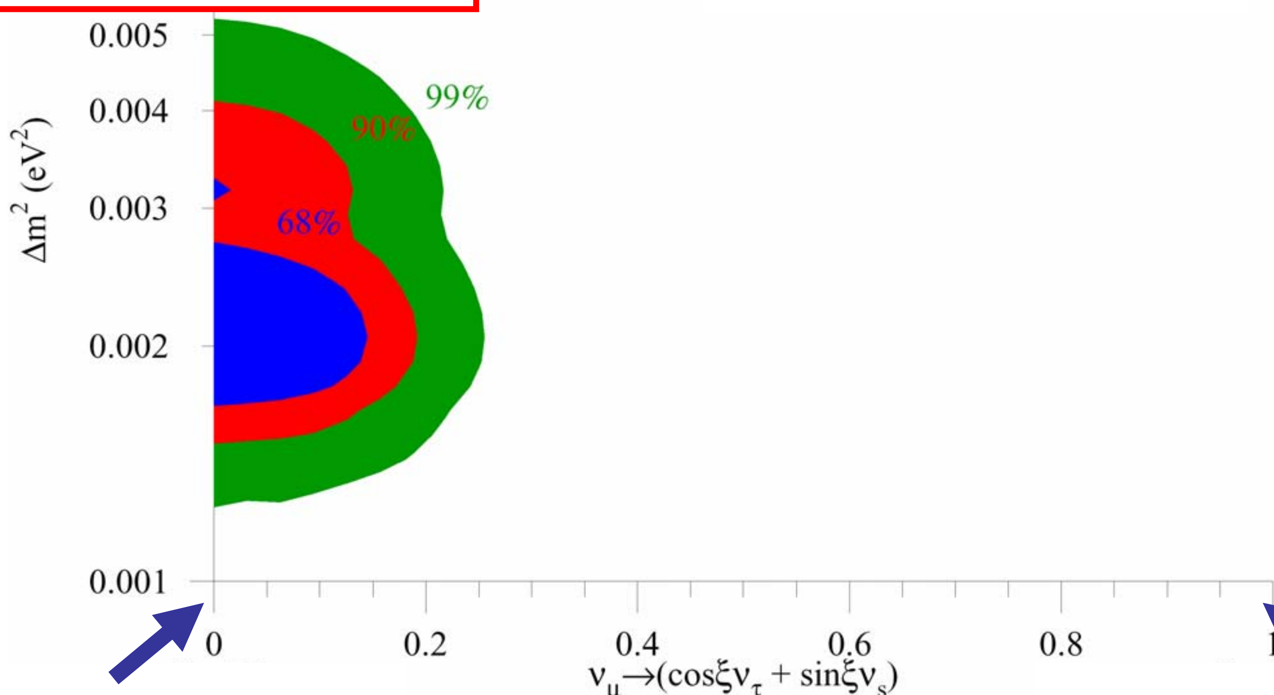
Getting closer to the CHOOZ's limit on θ_{13}



Oscillation to sterile neutrinos?

- Use NC deficit or Matter effect to discriminate
- Use all the SK data
  (including NC, up-through-going-muons and High-E PC)
  ➔
- 100% transition to the sterile state have been rejected
  (>99%C.L.)

$\nu_\mu \rightarrow \cos\xi\nu_\tau + \sin\xi\nu_s$



pure $\nu_\mu \rightarrow \nu_\tau$

$\sin^2\xi$

pure $\nu_\mu \rightarrow \nu_s$

K2K Long baseline neutrino oscillation experiment

Far detector: SK

ν_μ disappearance
spectrum distortion

Beam monitors
Near detectors

ν_μ flux
spectrum

$$prob. = \sin^2 2\theta \cdot \sin^2\left(\frac{1.27\Delta m^2 \ L}{E_\nu}\right)$$

L=250km (fixed), <Eν> ~ 1.3GeV

$\Delta m^2 = 2.5\text{x } 10^{-3}$ eV^2, $\sin^2 2\theta = 1$ → **~ 0.3**

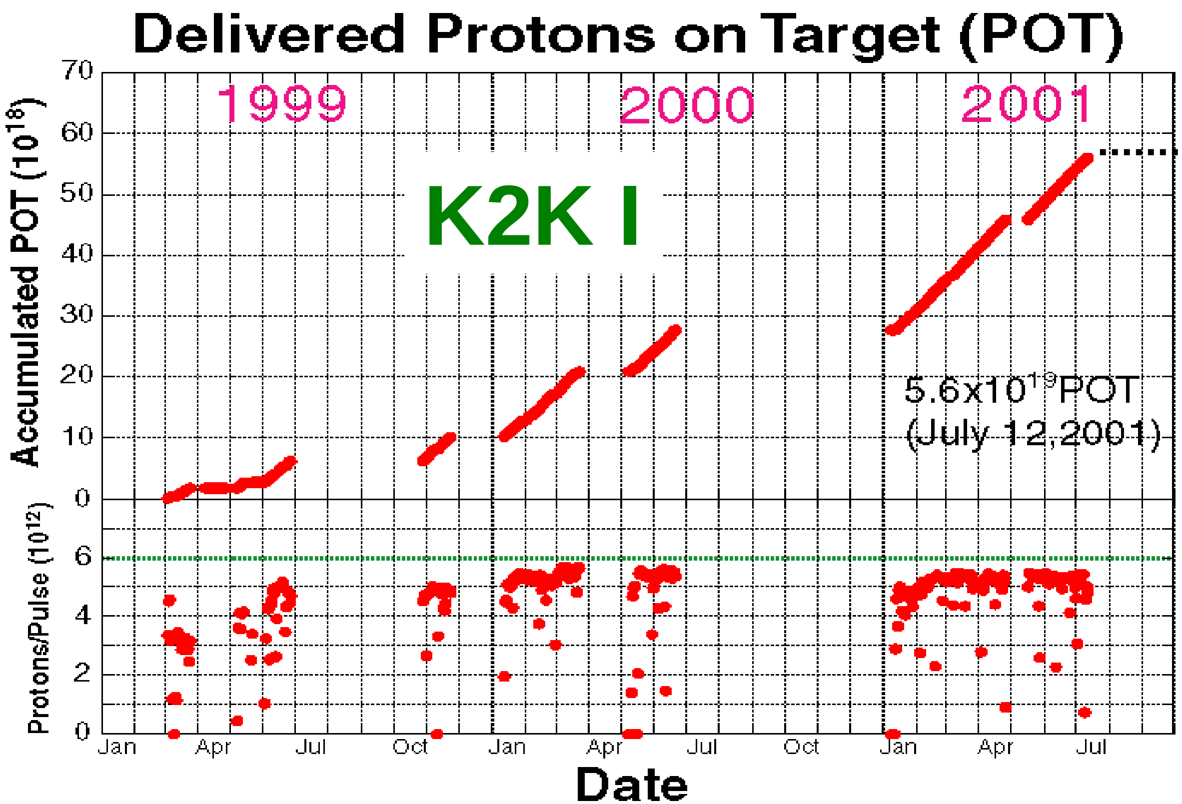
Expect ~70% survival prob.

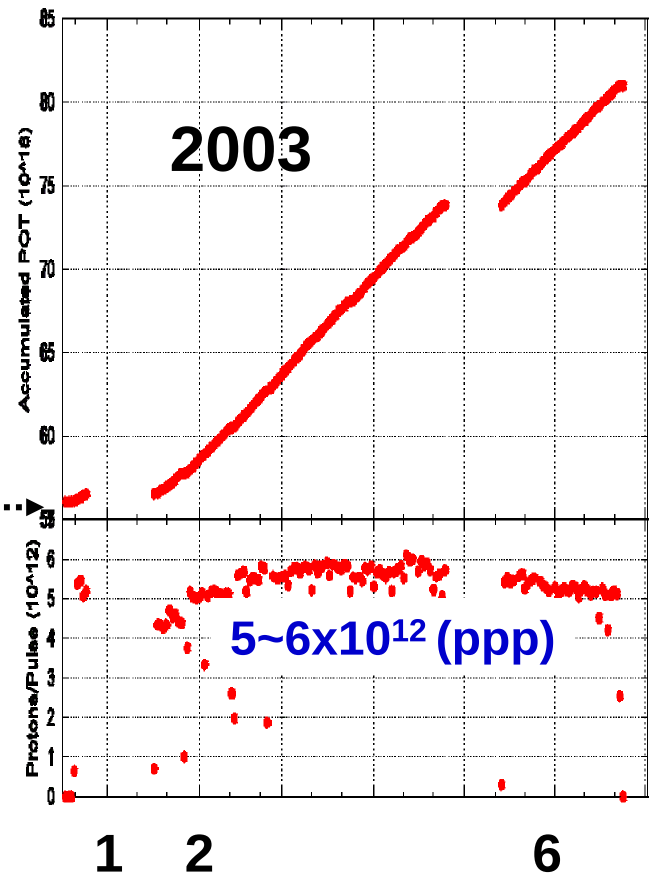
Delivered Beam for K2K

	Delivered P.O.T.	Usable P.O.T.
June '99-July '01	~5.6×10^{19}	4.8×10^{19}
Dec. '02-Apr. '03	~1.7×10^{19}	Analysis in progress
May '03-Jun. '03	~0.8×10^{19}	Analysis in progress

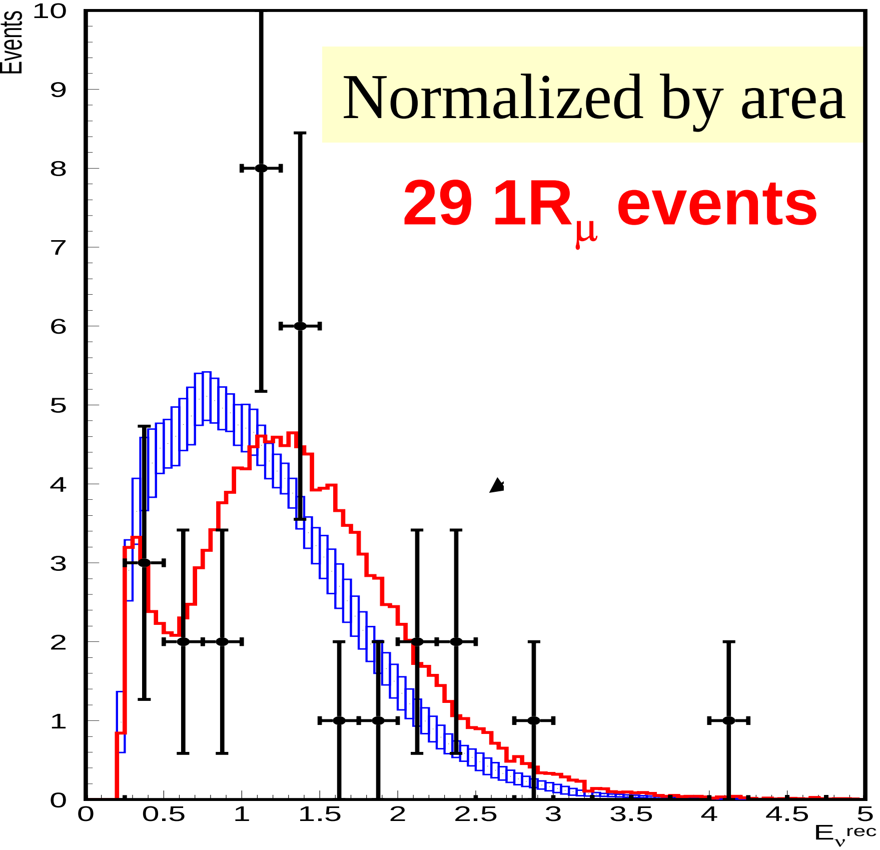
K2K II

from Dec. 21, 2002





K2K-I Result



Reconstructed Energy (GeV)

Observation : 56 events

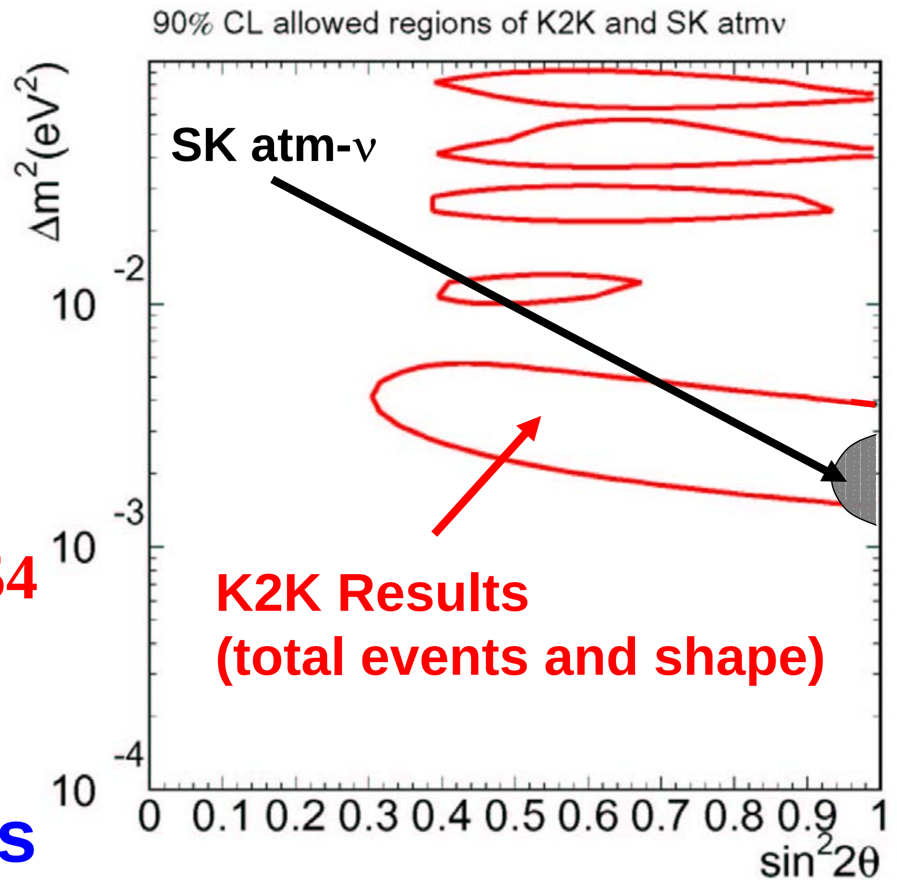
Expected Events (w/o oscillation)

$80.6 \pm 0.3(\text{stat.}) \pm ^{7.3}_{8.0} (\text{syst.})$

Null oscillation probability is less than 1%.

$\sin^2 2\theta = 1.0$
$\Delta m^2 = 2.8\times10^{-3} eV^2$
(1.5~3.9)

⇒ $N_{SK} = 54$



consistent with
SK atmospheric ν results

K2K-II events at SK-II

SK II: Running stably since Oct.2002!

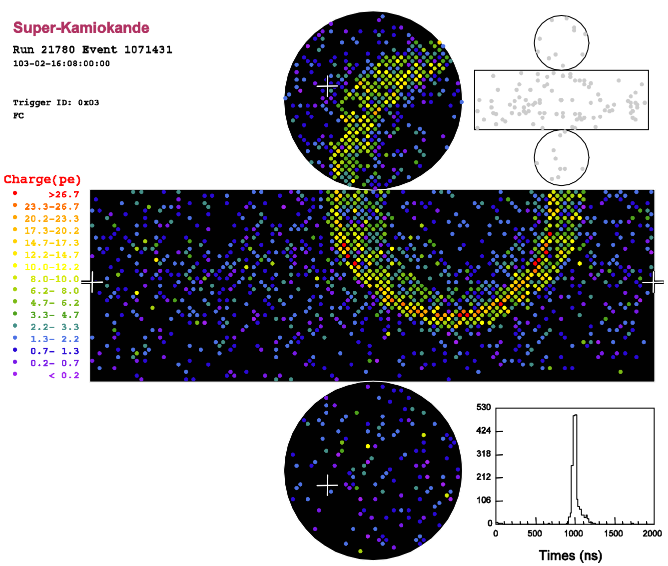
Data taken as for K2K-I

4.8×10^{19}POT

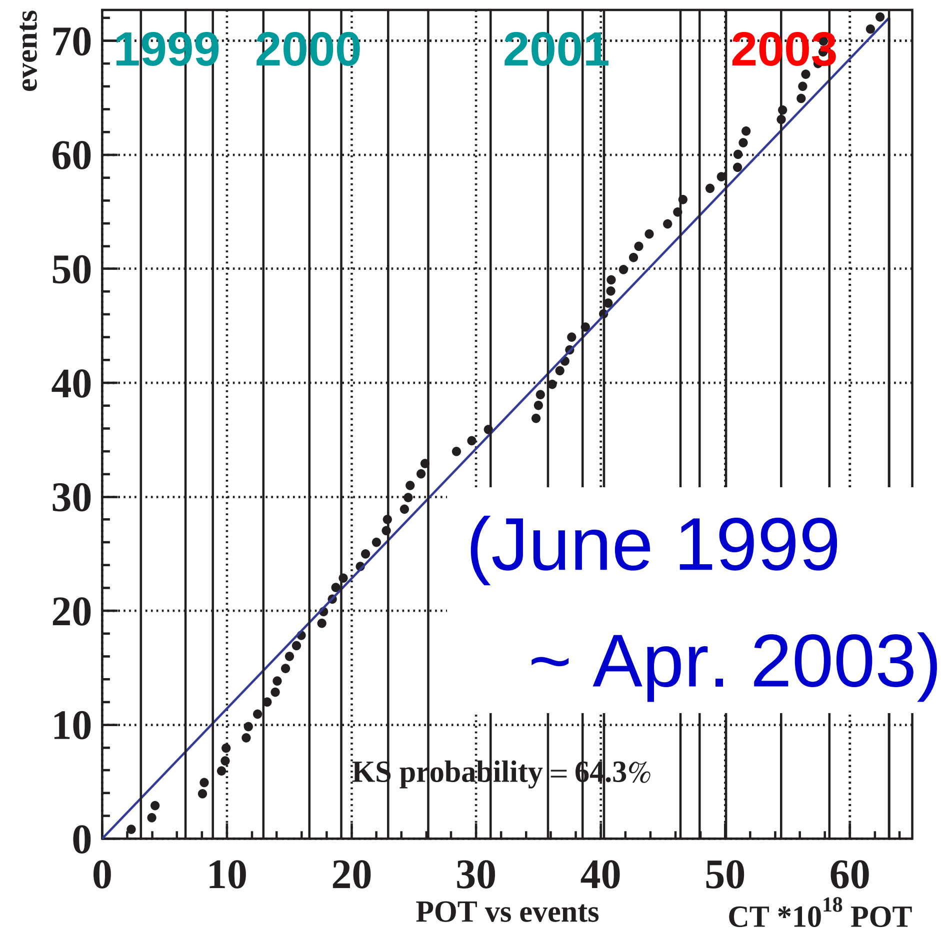
Proposal:

1.0×10^{20}POT

➔ Will run until 2006



K2K-II neutrino candidate event



Event rate for K2K-II

consistent with K2K-I

Further confirmation and future (Atmospheric & LBL)

- **Missing**
  - **L/E oscillatory pattern (atmospheric)**
  - **Tau appearance (atmospheric; accelerator)**
  - **Energy spectrum distortion (K2K)**

- **Notes on the differences (atm-ν vs K2K/LBL)**
  - $\nu_\mu + \bar{\nu}_\mu + \nu_e + \bar{\nu}_e$ **(atm-ν) vs ν_μ (K2K)**
  - **Wider energy range (atm-ν) vs limited energy range (K2K)**
    - **Experiment at different energy and distance (LBL)**
    - $\bar{\nu}_\mu$ **disappearance (LBL)**

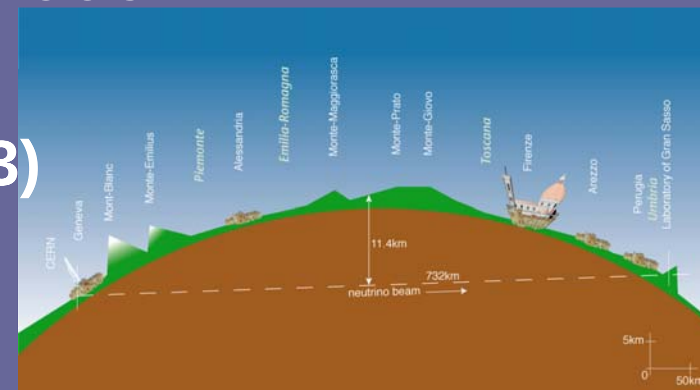
- **Study sub-leading effects**
  - **Electron appearance through θ_{13}**
  - **Beyond θ_{13} → CPV**

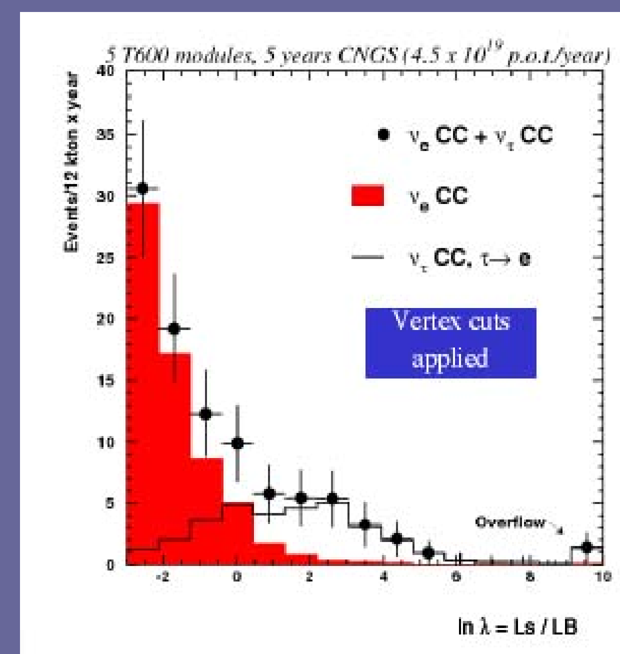
Studies in future by accelerator experiments

Beyond K2K

CERN Neutrinos to Gran Sasso (CNGS)

- **Aim: tau appearance (L=730km)**
- **CNGS commission in summer 2006**
- **ICARUS: Liq-Ar. TPC 3000 tons**
  - **300T success; 600T@LNGS(>2003)**
- **OPERA**
  - **Hybrid Emulsion Experiment**
- **Event rate (*OPERA*) (# of expected tau events)**
  - **4.3 for 1.6 x 10^{-3} eV^2** ?
  - **10.3 for 2.5 x 10^{-3} eV^2**
  - **26.3 for 4.0 x 10^{-3} eV^2**
  - **BG = 0.64 events**
  - **5 years@4.5x10^{19}POT/yr**

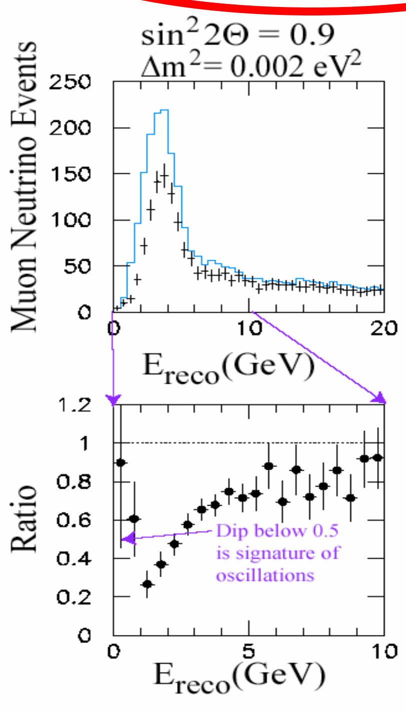


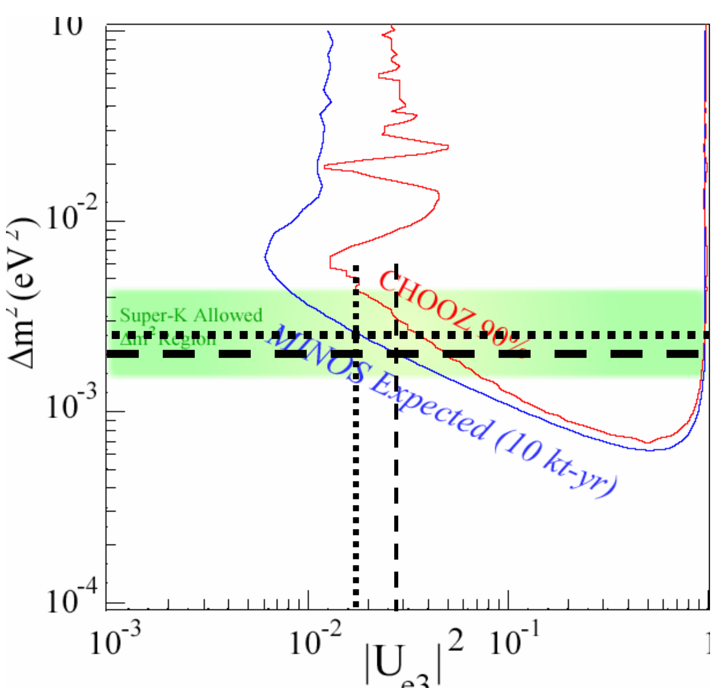


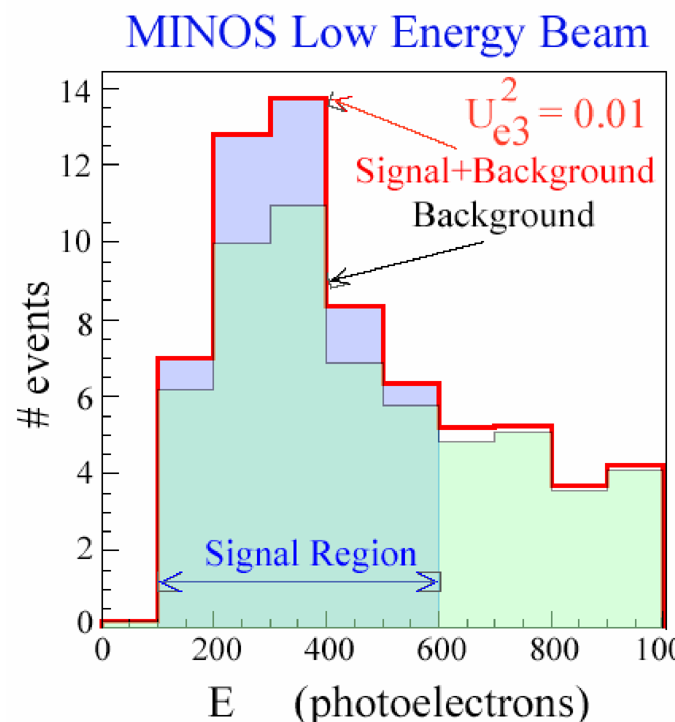
NuMI-MINOS (Fermi → Soudan mine)

- NuMI
  - Dec-2004
- Far Detector (L= 735km)
  - Completed
- Near Detector
  - Plan completed
- Physics run
  - in 2005 for 5 yr

- May see oscillation dip
  if $\Delta m_{23}^2 > 2\text{x}10^{-3}\ eV^2$
- $\delta\Delta m_{23}^2 \sim 1\text{x}10^{-3}\ eV^2$
- Electron appearance
  - 8 $\nu_\mu \rightarrow \nu_e$
  - BG(26NC, 5beamν_e, 4ν_m, 3ν_τ)
  - U_{e3}^2=0.01 for Δm^2=0.003eV^2
  - 10ktyr (2yr x 3.8x10^{20}POT/yr)







J-PARC-ν (100xK2K)

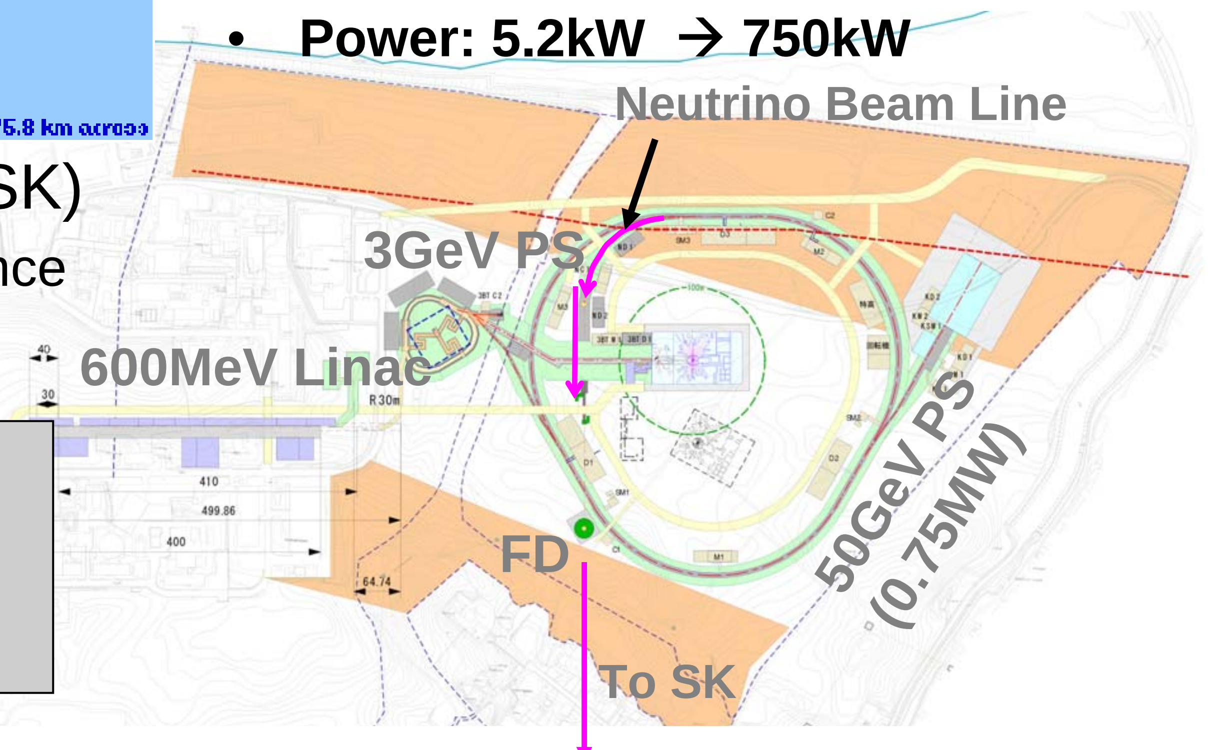
JAERI@Tokai-mura (60km N.E. of KEK)

- **50 GeV PS Construction:**
  - **2001 ~ 2006 JFY**
- **Neutrino Program: not yet approv.**
- ν_μ **beam ~ 1GeV to be adjusted for the oscillation maximum**

KEK-PS → J-PARC-PS

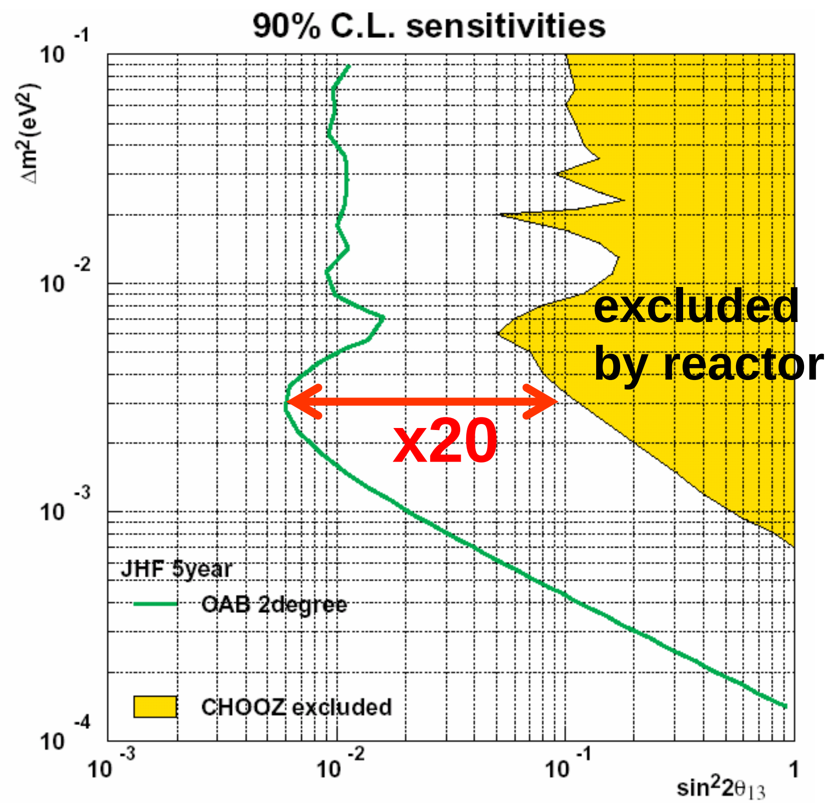
- **Beam: 6 x10^{12}ppp → 330 x10^{12}ppp**
- **Rate: 0.45 Hz → 0.275 Hz**
- **Power: 5.2kW → 750kW**

- Phase 1 (0.75MW + SK)
  - $\nu_\mu \rightarrow \nu_x$ disappearance
  - $\nu_\mu \rightarrow \nu_e$ appearance

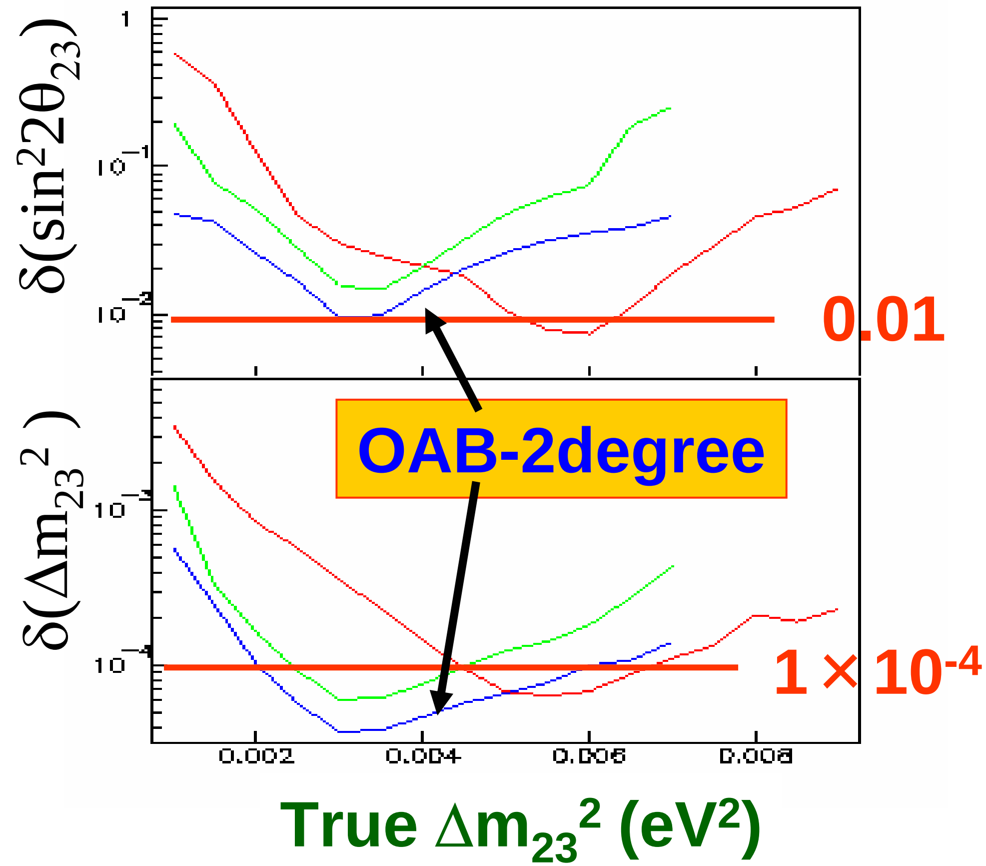


Sensitivities in first phase(5yrs)

Search for ν_e appearance



ν_μ disappearance

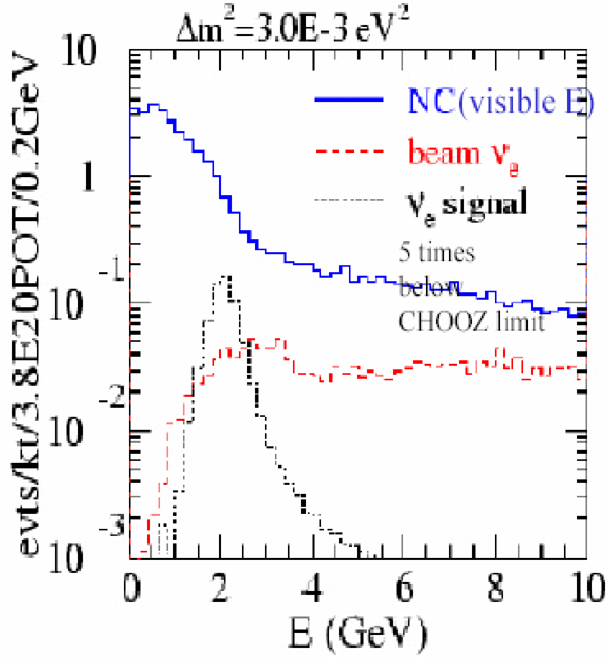


$\sin^2 2\theta_{13}$>0.006~0.008 (90%)
$|U_{e3}|^2$>0.0015~0.002

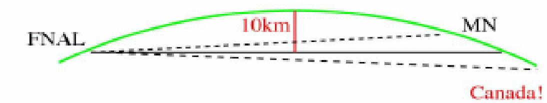
$d(\sin^2 2\theta)$~0.01
$d(\Delta m^2)$ ~<1×10^{-4}
in 5 years

NuMI-Off axis

Note: J-PARC-ν: ~2^o-off axis



- low energy narrow band (~2GeV)
  - Lower NC backgrounds
  - Below tau threshold
- Simultaneous operation with MINOS
- L=700~900km, medium energy NuMI
- 50kt detector with low Z, high granularity
- Rate:
  - 20kt fid, 3.7x10^{20} POT/yr x 5yr
    - 400 oscillated ν_e for $|U_{e3}|^2$=0.025 (~CHOOZ)
    - 15 events for $|U_{e3}|^2$=0.0025
- Sensitivity
  - 90% C.L. down to $|U_{e3}|^2$=0.0007 (statistics only
- Schedule
  - Proposal to Fermilab PAC in late 2003
  - Hope to start in late 2007

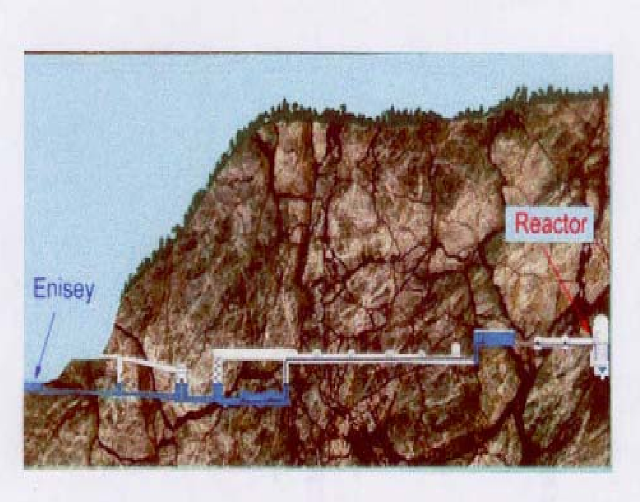


Reactor experiments for θ_{13}

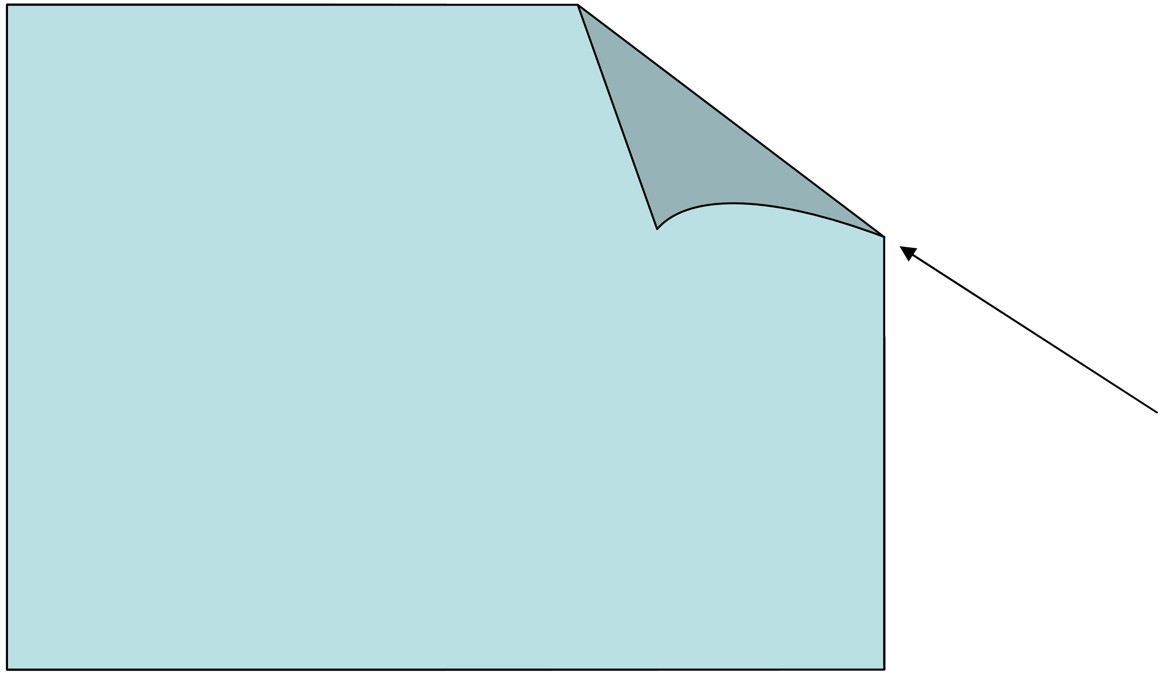
- $P_{\bar{\nu}e \rightarrow \bar{\nu}e} = 1 - \sin^2 2\theta_{13} \sin^2(\Delta m_{13}^2 L/4E)$
  - Direct θ_{13} measurement: no uncertainty due to s_{23}^2 in like LBL Acc. Experiments
  - No matter effects & no CPV effects
  - Difficulty: Disappearance
    - small effect in a large number
  - Aim: $\sin^2 2\theta < 0.01$
    - 50tons (CHOOZx10): statistics
    - Larger power reactor
    - 2 detector (syst. 3% → < 1%)
    - Deeper: reduce BG

Experiments considered

- Kr2Det: 2 detector experiment @ Krasnoyarsk
  - 46 tons (15m $ 1000m); 600mwe
  - 20,000 ev (S/B ~ 10)
- Diablo Canyon @California coast
  - 600mwe (3.1+3.1 GW)
- Kashiwazaki-Kariwa inJapan
  - Need underground shaft to be built
  - 7 Nucl. Power Stations: largest PS in the world



Beyond θ_{13}

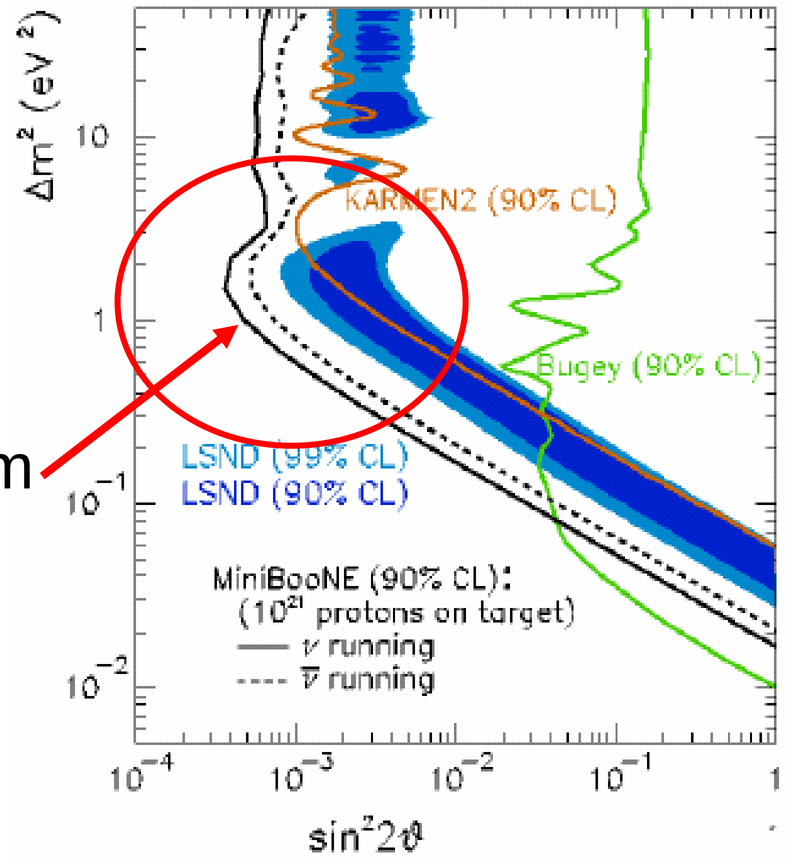


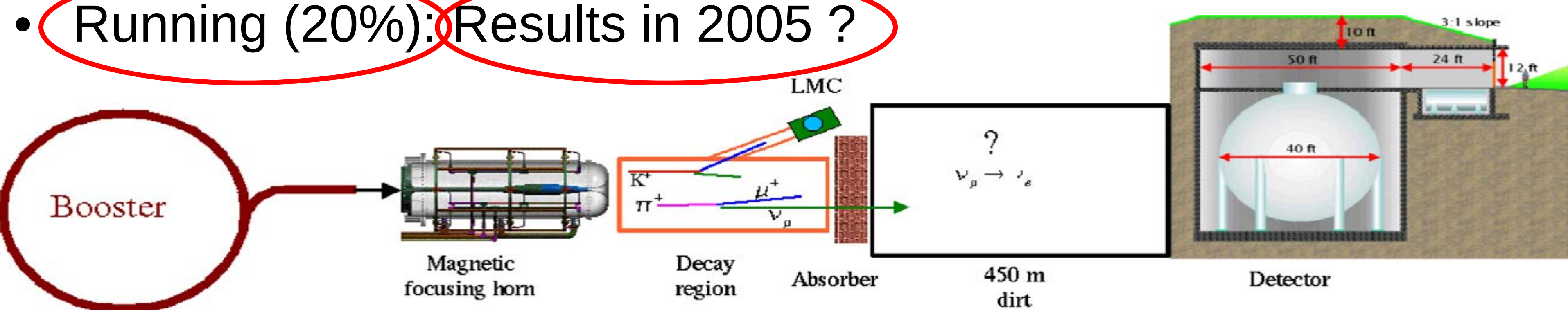
$\sin^2 2\theta_{13} > 0.01$ must be required

- **experimentally**
- **politically**

LSND/KARMEN/mini-BOONE

- Remaining problem (LSND)
  - $\nu_\mu \rightarrow \nu_e$: $\Delta m^2 \sim 1eV^2$, $\sin^2 2\theta \sim 3x10^{-3}$
    - **Non-standard int.: $\mu^+ \rightarrow e^+\nu_e\nu_i$**
    - **Sterile ν (2+2 or 3+1 or 3+2)**
    - **CPT violation**
- Mini-BOONE will resolve the problem
  - 800(450) tons of mineral oil
  - 1280 8" PMTs
  - Booster 8 GeV (5x10^{20} POT/yr)
  - L=0.5km, <Eν> ~ 1GeV
  - $\nu_e/\nu_\mu \sim 3 \times 10^{-3}$
- Running (20%): Results in 2005 ?





Conclusions

- Neutrino oscillation is established as a leading effect of the solar-atmospheric flavor conversion
- Precise measurement of the oscillation phenomena will provide us further confirmations, and may also provide a hint to the physics beyond the standard scenario