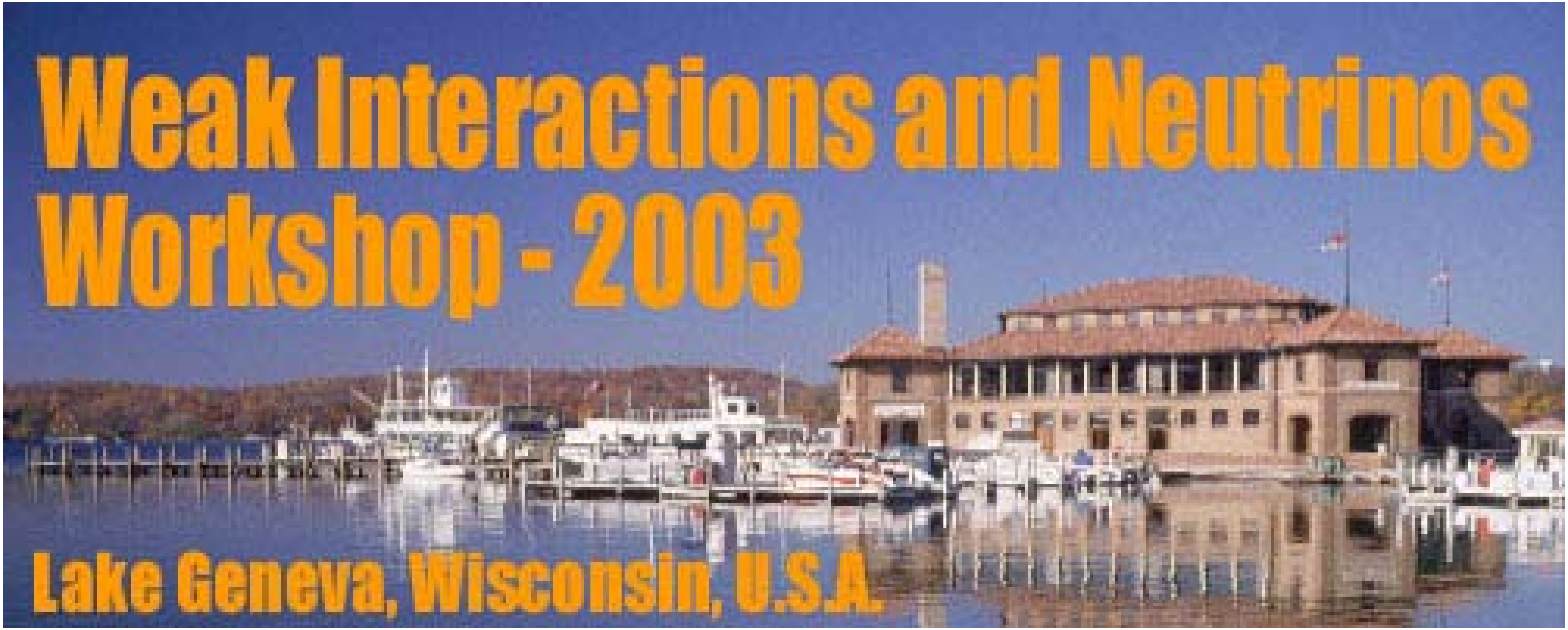


Neutrino physics: experimental status

Takaaki Kajita
Institute for Cosmic Ray Research, Univ. of Tokyo

Outline

- Introduction (very short)
- Solar neutrino experiments and KamLAND
- Atmospheric neutrino experiments
- K2K
- LSND and MiniBOONE (very short)
- Future neutrino oscillation experiments
- Summary

Sorry, but I will not discuss;

- Non-standard explanations of oscillation experiments
- Other types of experiments related to neutrino masses and mixings ($\beta\beta$, ^3H, …)
- Other neutrino experiments….

Introduction

Neutrino Mixing

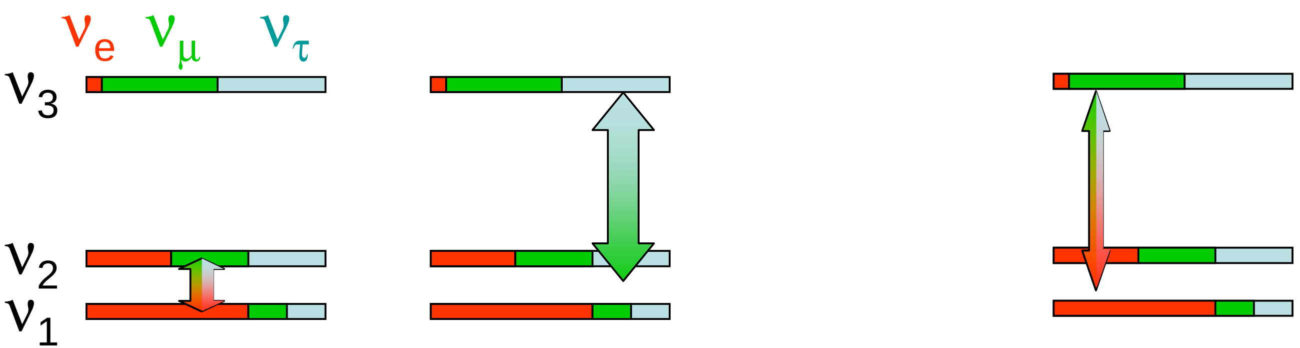
$$|\nu_l\rangle = \Sigma U_{li} |\nu_i\rangle$$

Weak eigenstates — Mass eigenstates

small

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{-i\delta} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & 1 & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix}$$

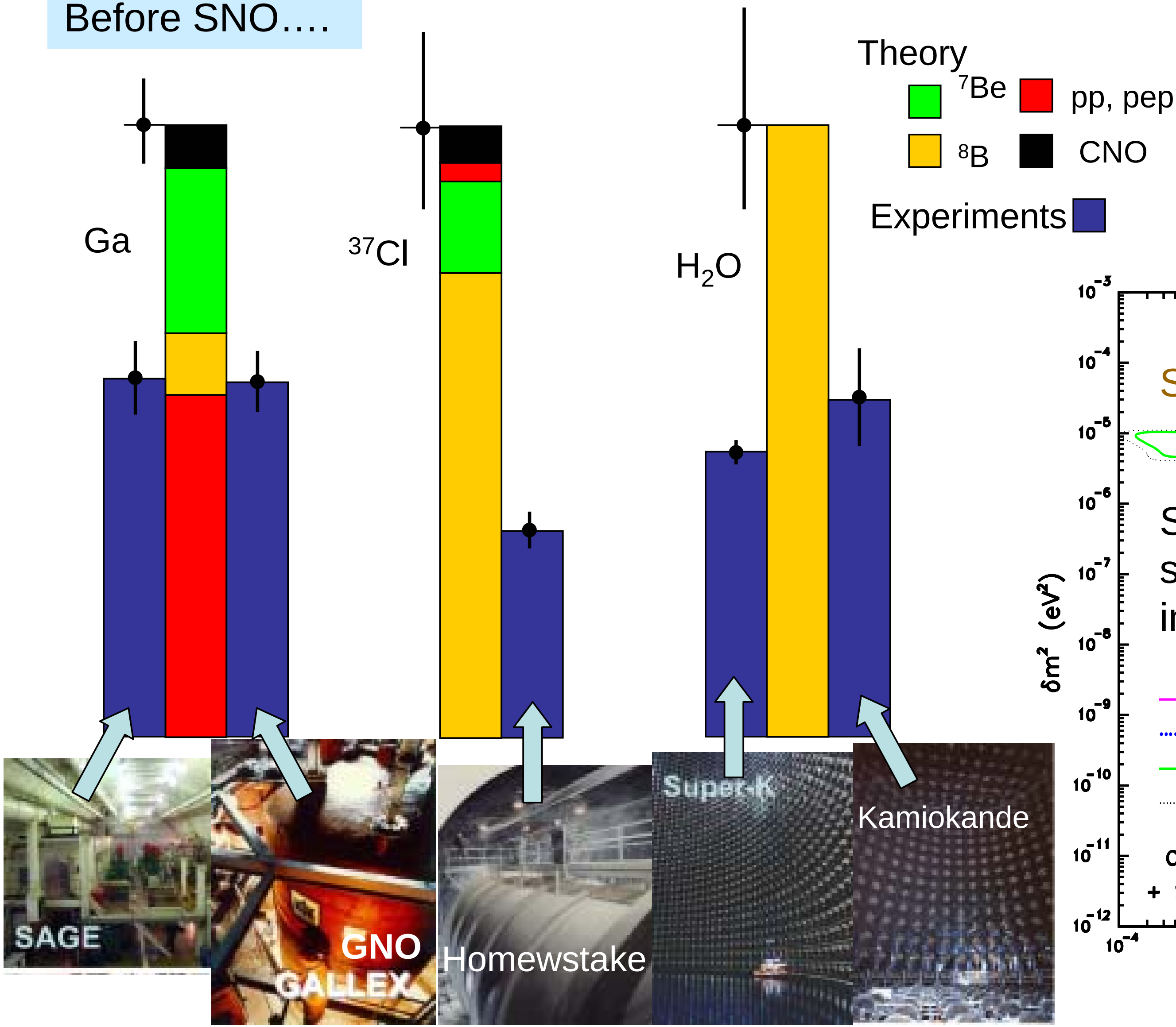
Normal mass hierarchy assumed:

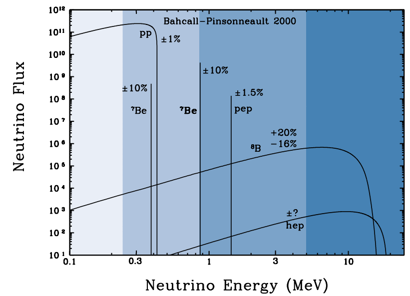


Solar, KamLAND	Atmospheric Long baseline	(future) Super-beam Neutrino factory	(future) LBL Reactor

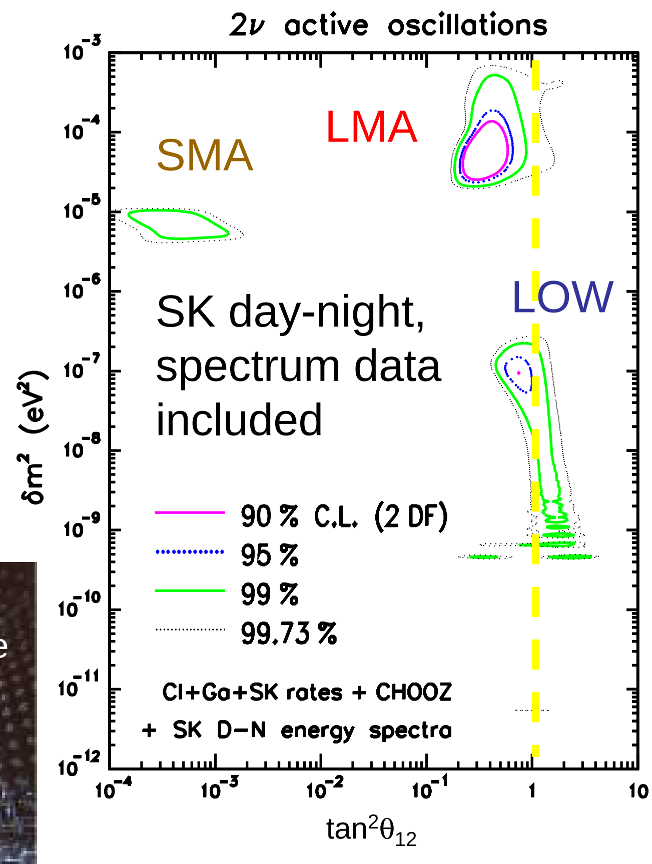
Solar neutrino experiments

Before SNO….

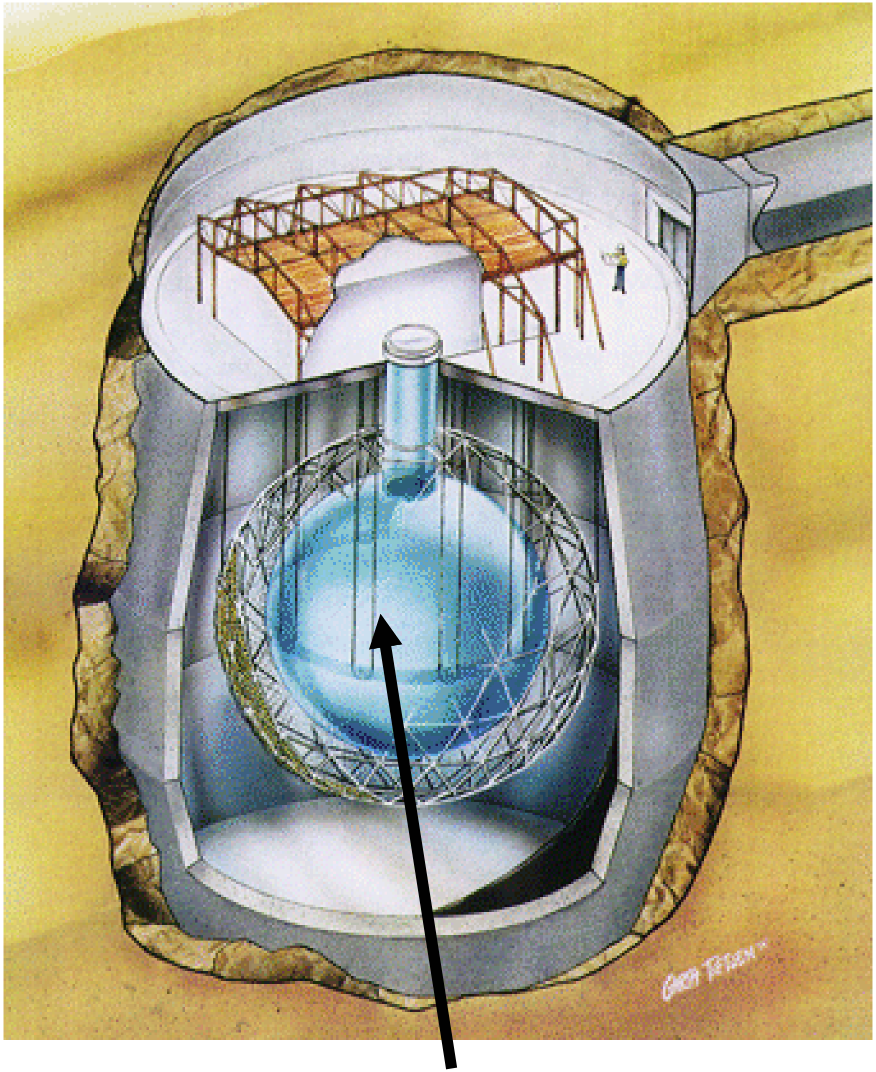




G.L.Fogli et al.



SNO



1,000ton D_2O

^8B ν Reactions in SNO

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

- ν_e **ONLY**

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

Mainly sensitive to ν_e, less to ν_μ and ν_τ

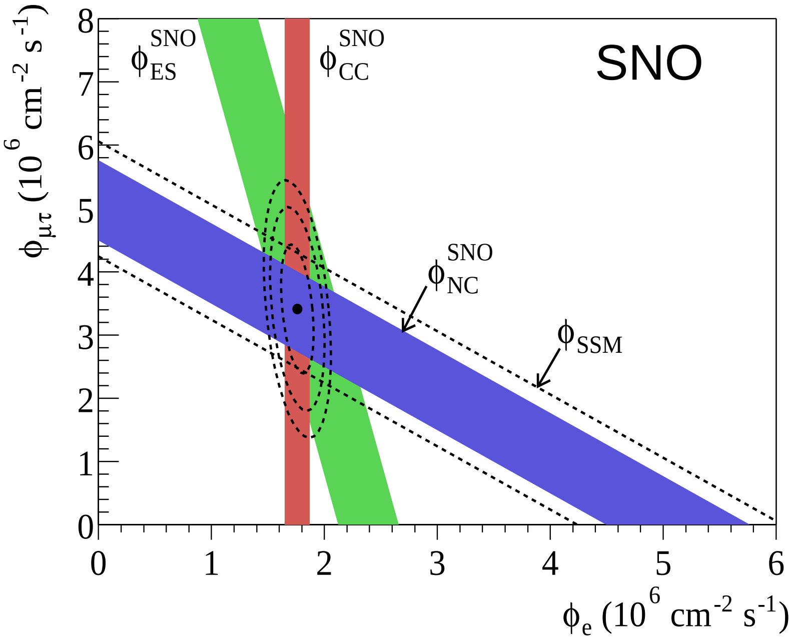
NC $\nu_x + d \rightarrow p + n + \nu_x$

$n + d \rightarrow t + \gamma$ (E_γ = 6.25 MeV)

(pure D_2O phase)

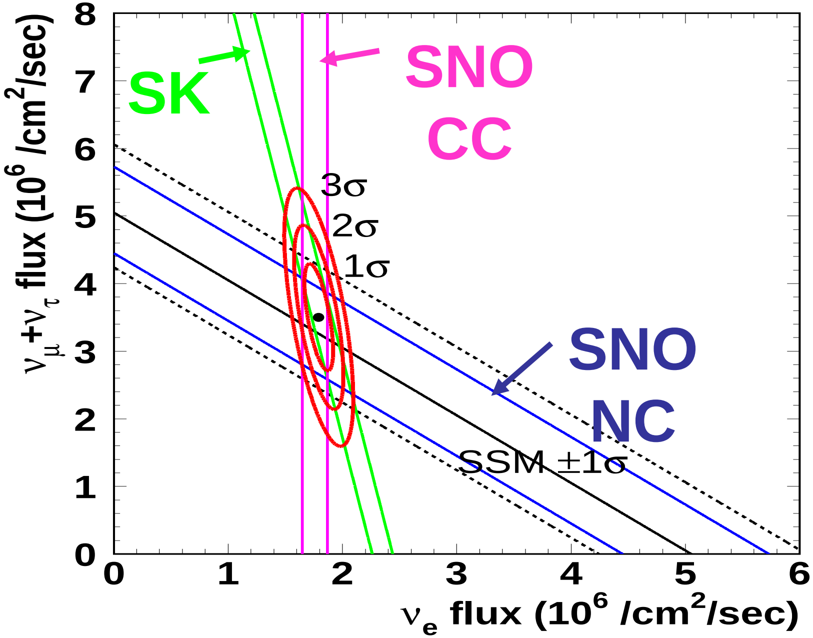
- Equal cross section for all ν types

SNO results in 2002



OR

If Super-K data (ES) are used:



$$\Phi_{\mu\tau} = 3.41^{+0.45}_{-0.45}(\text{stat.})\ ^{+0.48}_{-0.45}\ (\text{syst.})\ \text{x}10^6\ \text{cm}^{-2}\text{s}^{-1}$$

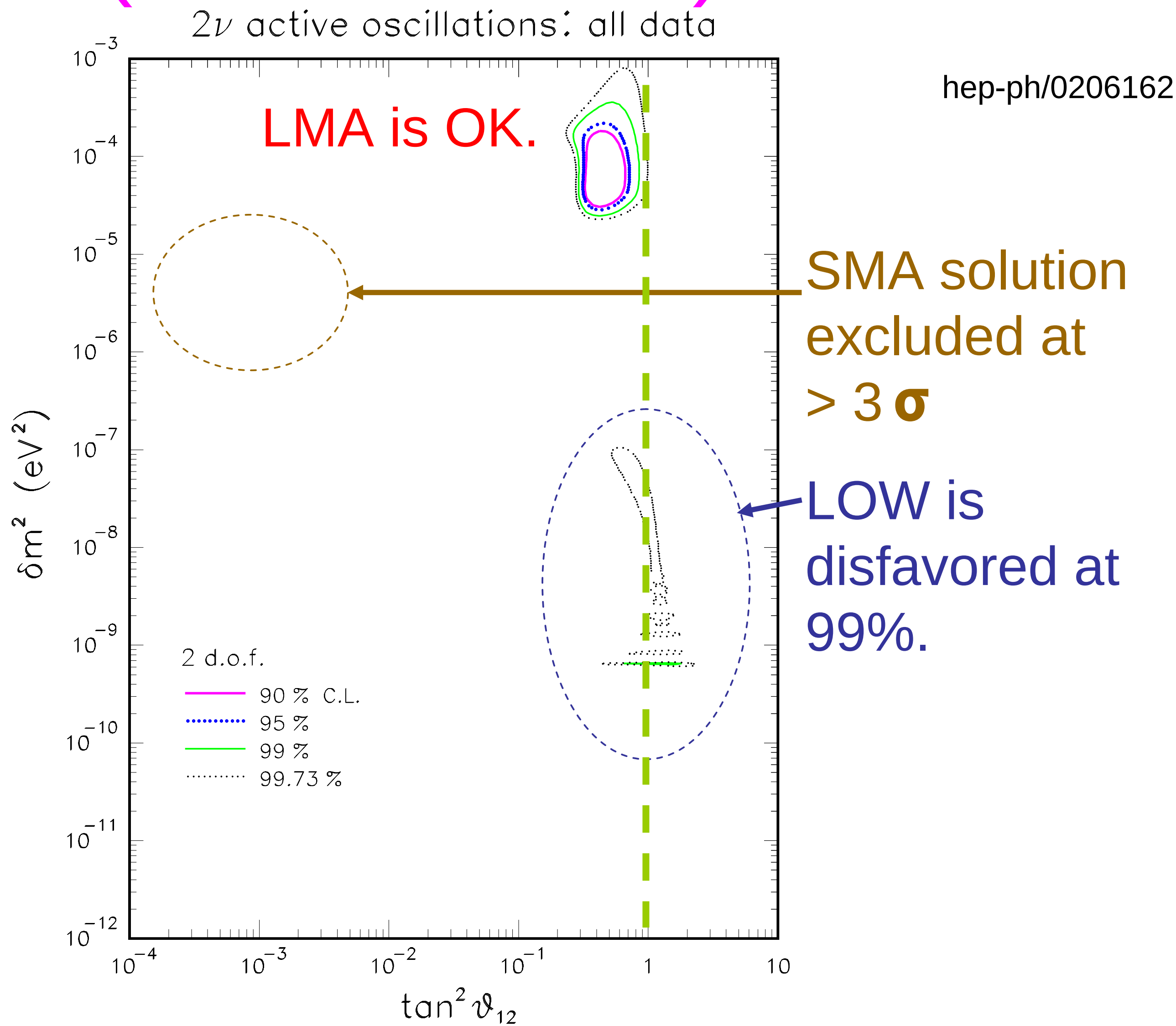
(5.3 **σ**)

$$\Phi_{\mu\tau} = 3.45^{+0.65}_{-0.62}\ \text{x}10^6\ \text{cm}^{-2}\text{s}^{-1}$$

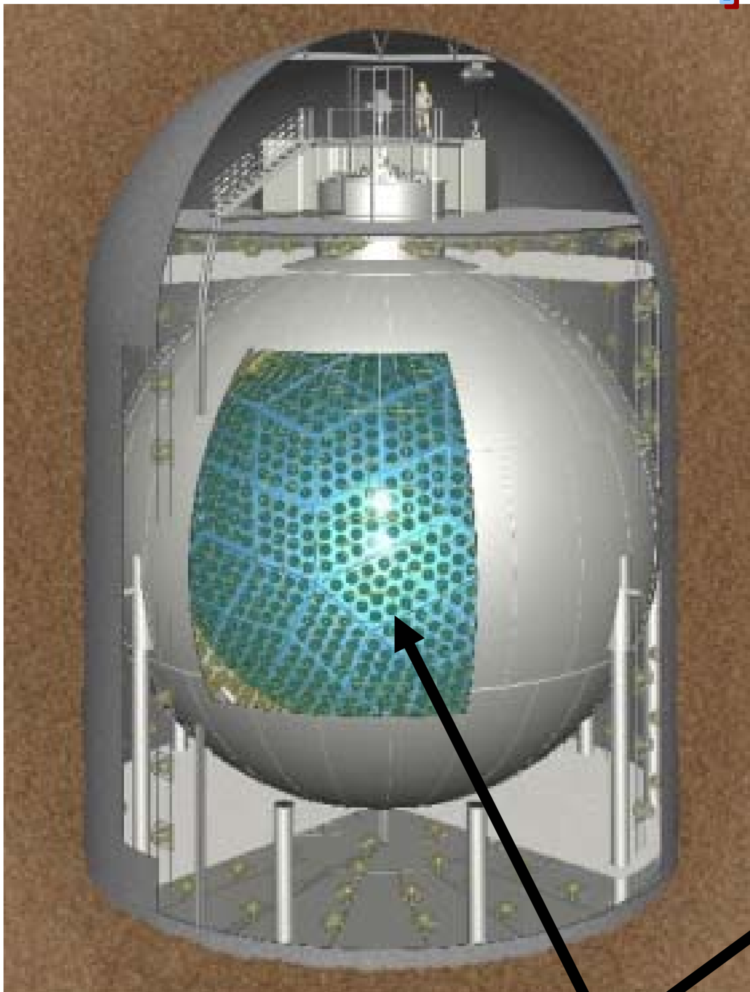
(5.5 **σ**)

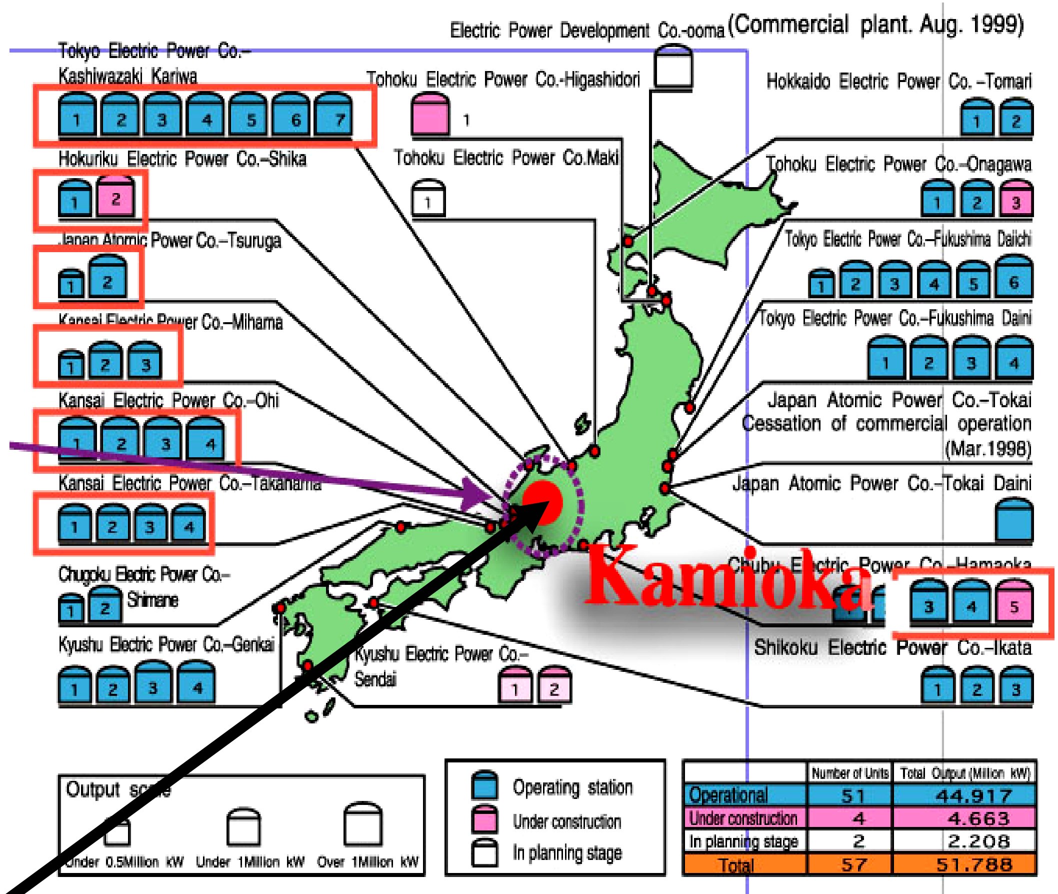
Evidence for ν_μ or ν_τ appearance

Neutrino oscillation parameters (summer 2002)



KamLAND





	Number of Units	Total Output (Million kW)
Operational	51	44.917
Under construction	4	4.663
In planning stage	2	2.208
Total	57	51.788

1,000ton liquid scintillator detector

Thermal power ~ 80GW

<E> ~ 3 MeV

<base line> ~ 180 km

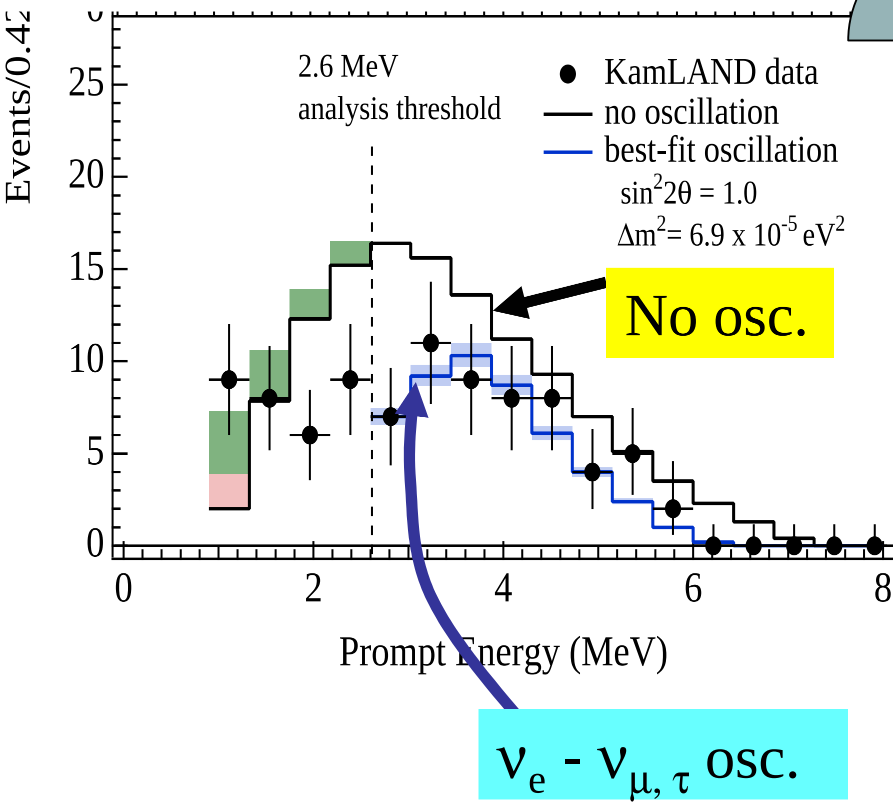
KamLAND results

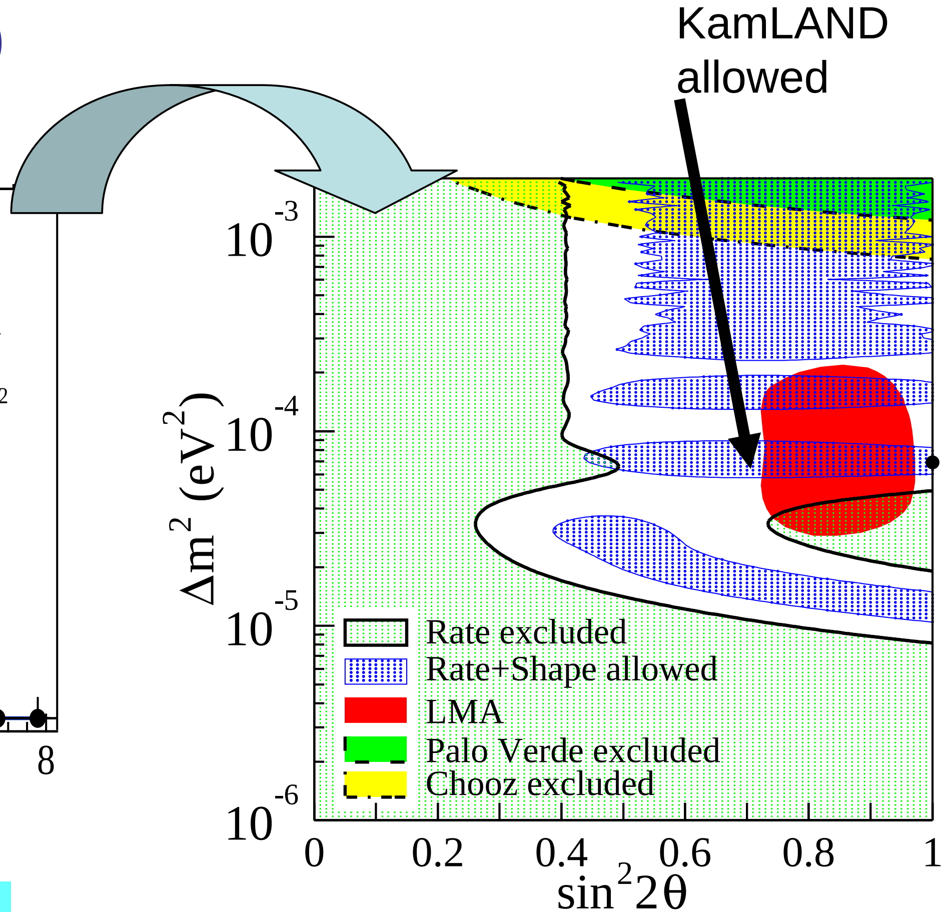
hep-ex/0212021

86.8±5.6 events expected

54 observed (0.95±0.99 BG)

(145 days)

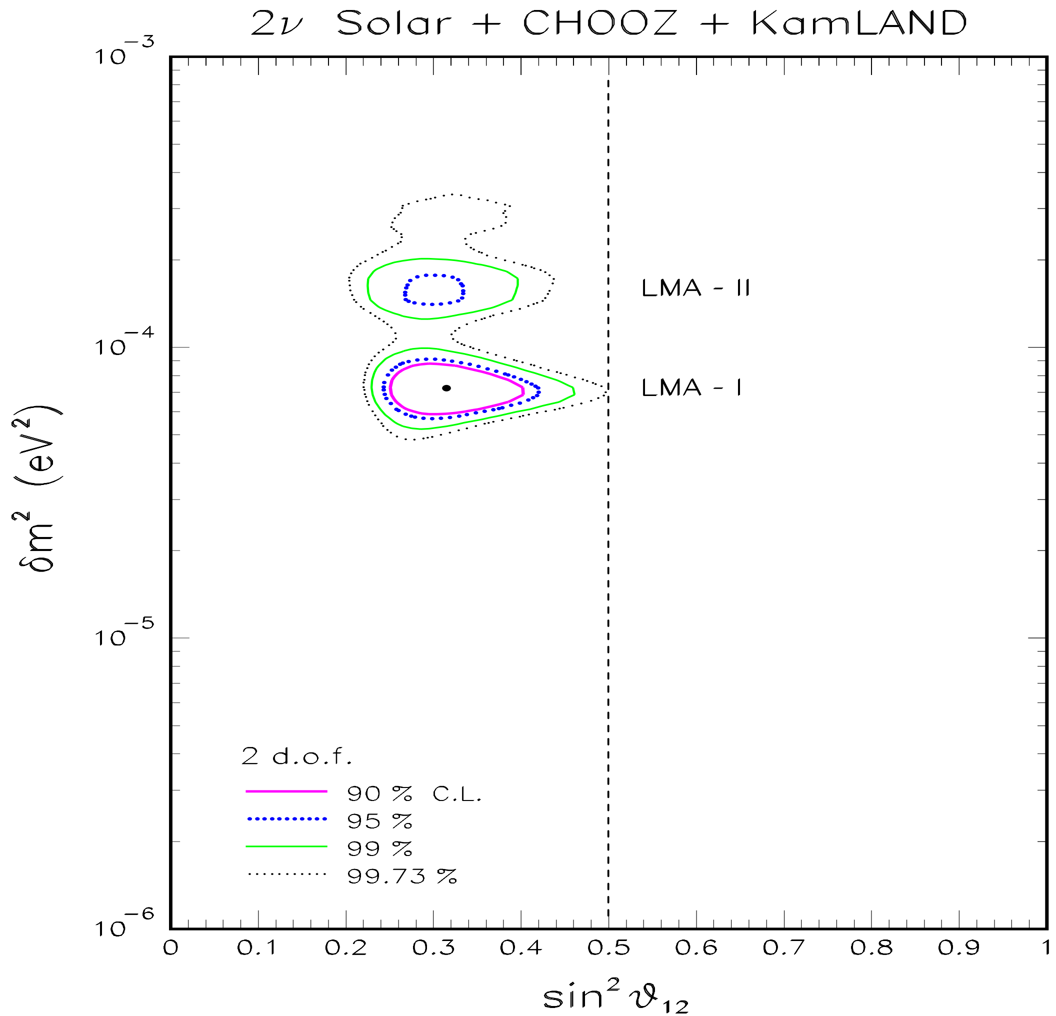




Confirmation of the LMA solution

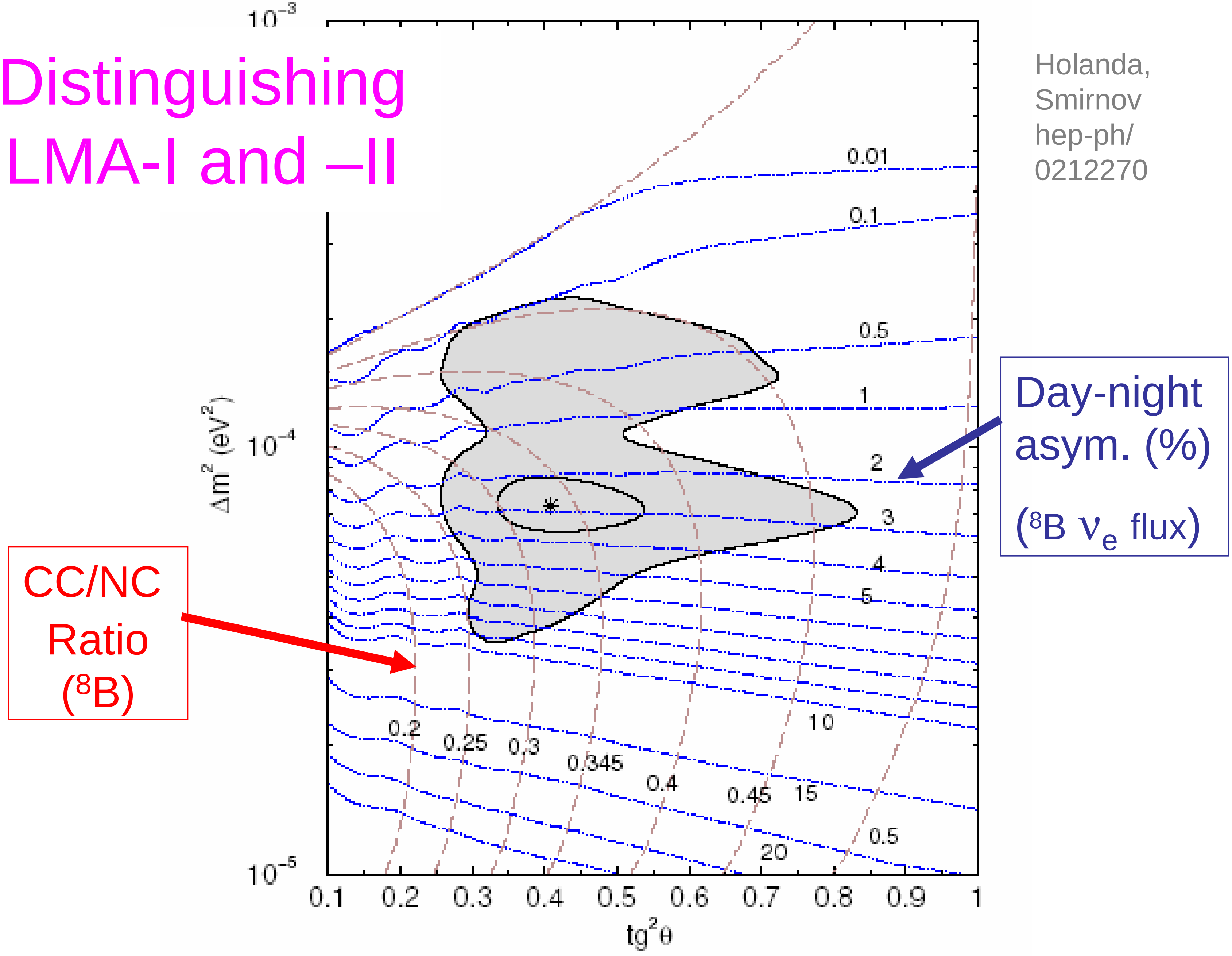
Neutrino oscillation parameters: Solar + KamLAND

G.L.Fogli et al.

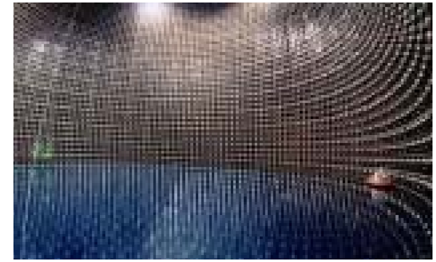


Distinguishing LMA-I and –II

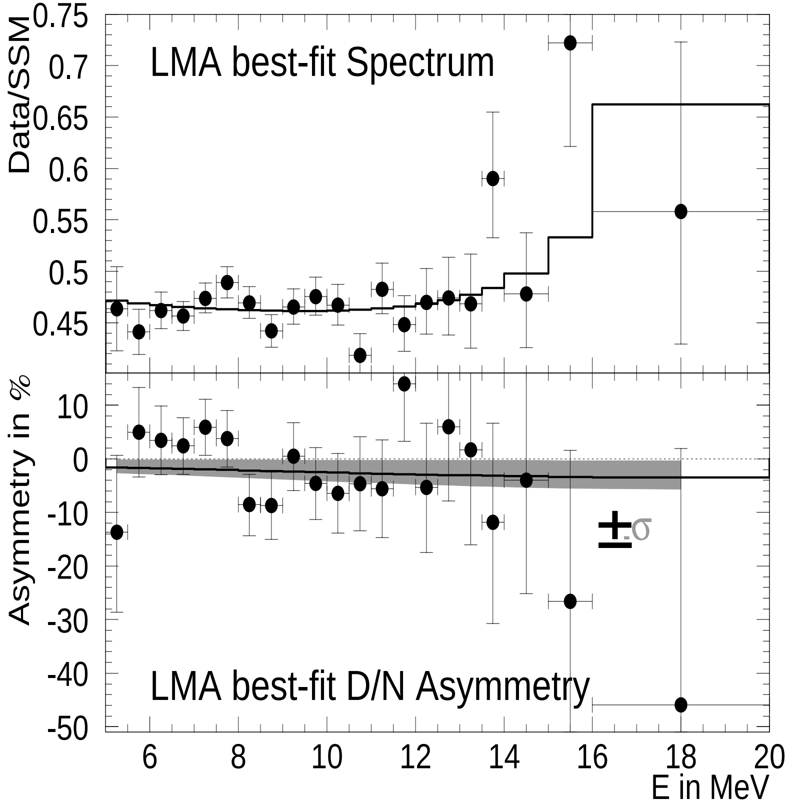
Holanda, Smirnov hep-ph/0212270



New analysis results from Super-Kamiokande



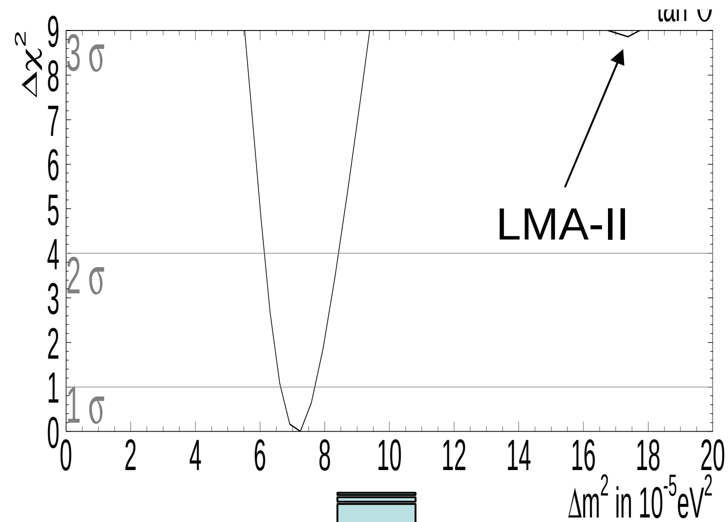
max. likelihood analysis (hep-ex/0309011)



$A_{DN} = -1.8 \pm 1.6 ^{+1.3}_{-1.2} \%$

25% smaller (@LMA-I)

SK-new analysis + solar + SNO(2002) + KamLAND



LMA-II is disfavored at about 99%CL (2 parameter region).

SNO salt phase

➔ WG discussion
J.Formaggio

2 tons of NaCl added into 1000 ton D_2O

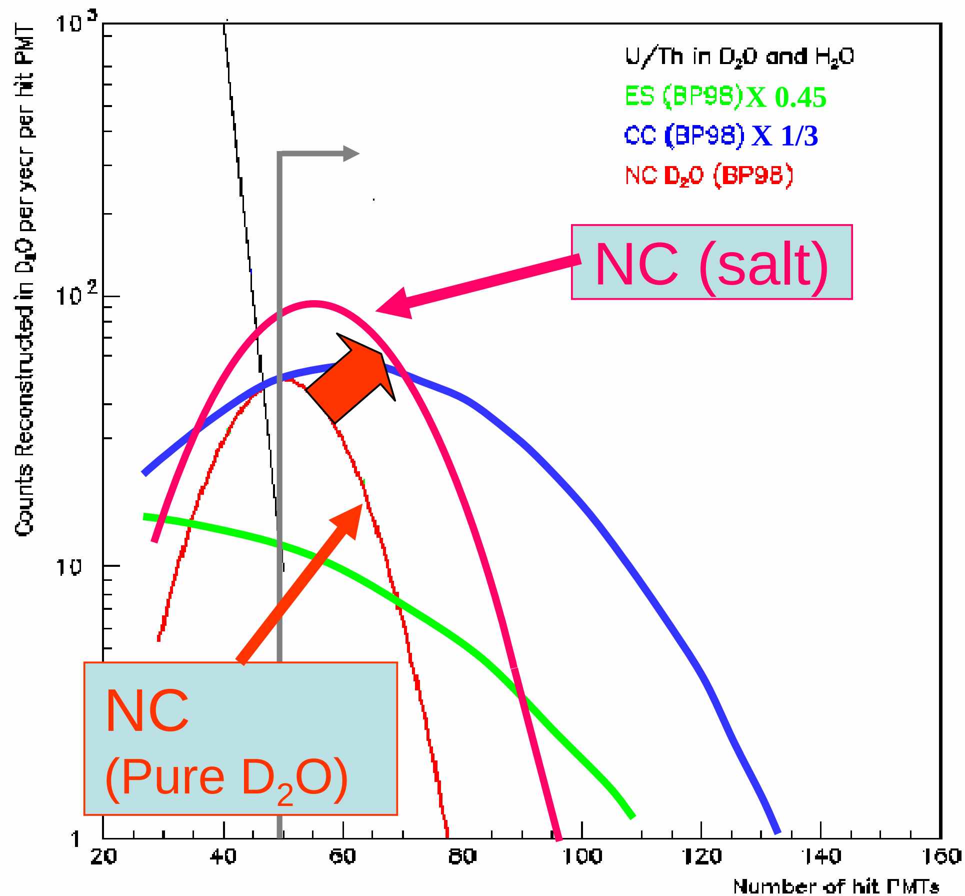
(Salt phase: 2001-2003)

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

$n + Cl \rightarrow Cl + \gamma$'s ($\Sigma E_\gamma = 8.6$ MeV)

- Equal cross section for all ν types

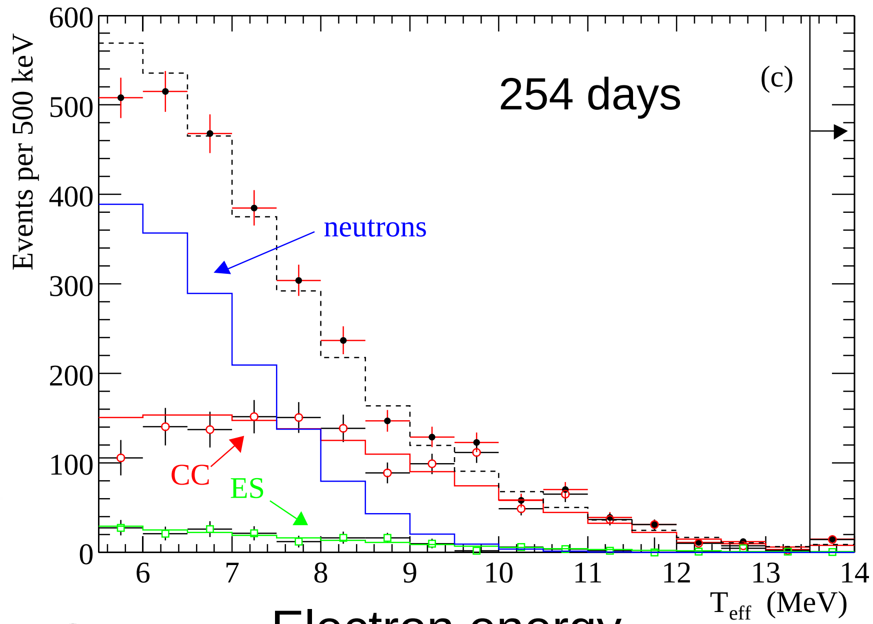
- Higher neutron capture rate
- Higher total energy release
- Isotropic signal (many gammas)



~ 9 NHIT/MEV

New results from SNO

Nucl-ex/0309004



Electron energy

$$\phi_{CC}^{SNO} = 1.59^{+0.08}_{-0.07}(\text{stat})^{+0.06}_{-0.08}(\text{syst})$$

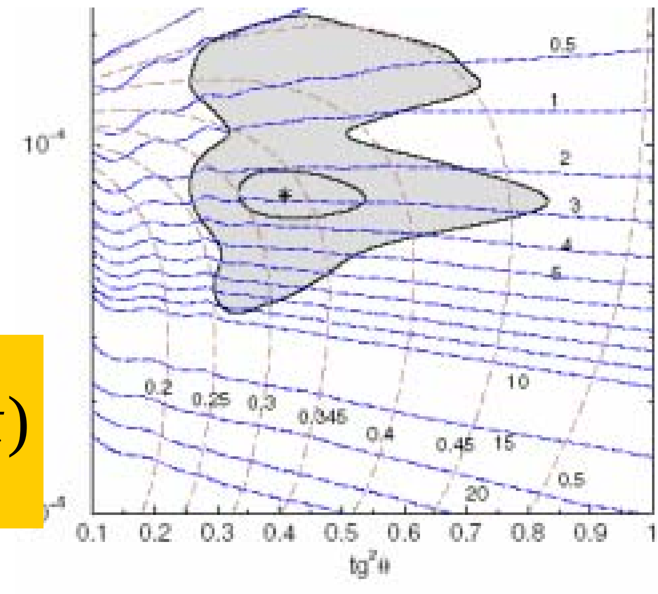
$$\phi_{ES}^{SNO} = 2.21^{+0.31}_{-0.26}(\text{stat}) \pm 0.10\,(\text{syst})$$

$$\phi_{NC}^{SNO} = 5.21 \pm \underline{0.27\,(\text{stat})} \pm \underline{0.38\,(\text{syst})}$$

×0.6 of Pure D_2O

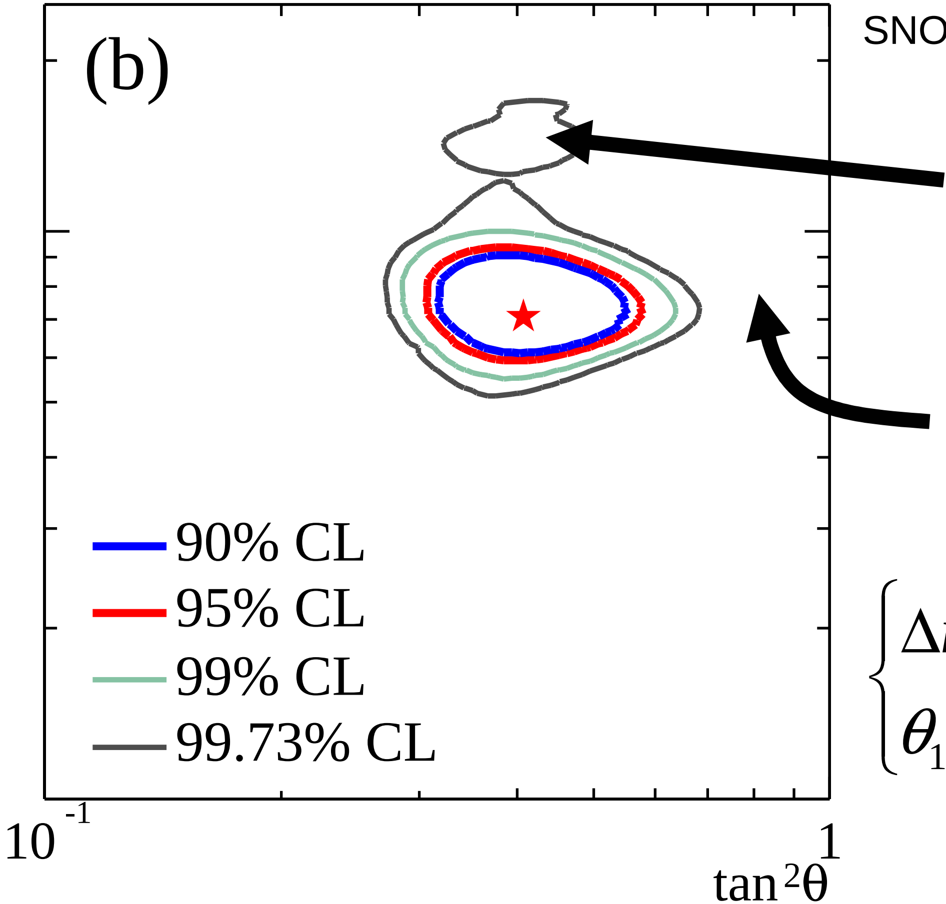
×0.85 of Pure D_2O

$$\frac{\phi_{CC}}{\phi_{NC}} = 0.306 \pm 0.026\,(stat) \pm 0.024\,(syst)$$



Oscillation analysis

SNO(2003)+KamLAND+solar (Sep.2003)



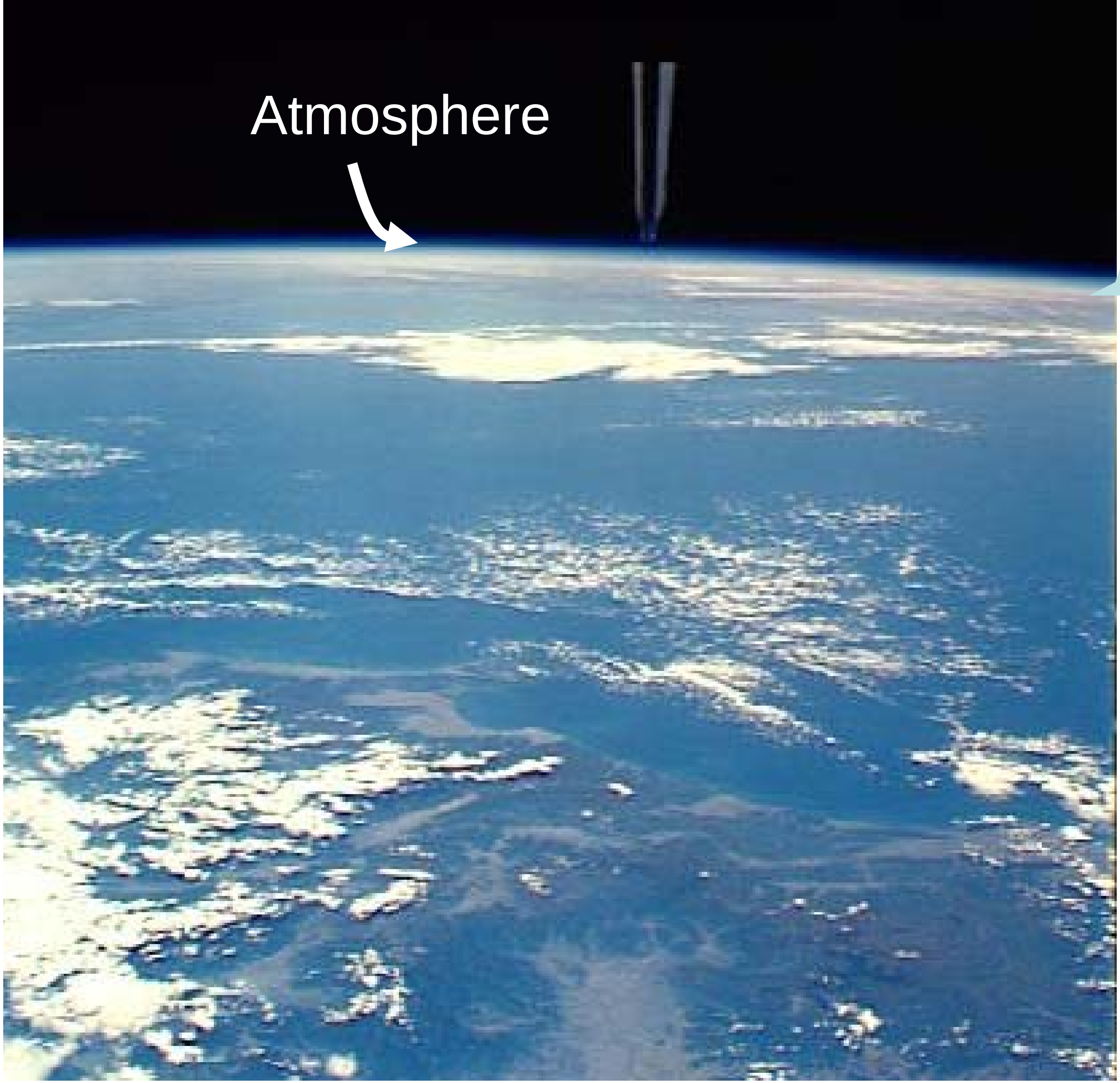
SNO nucl-ex/0309004

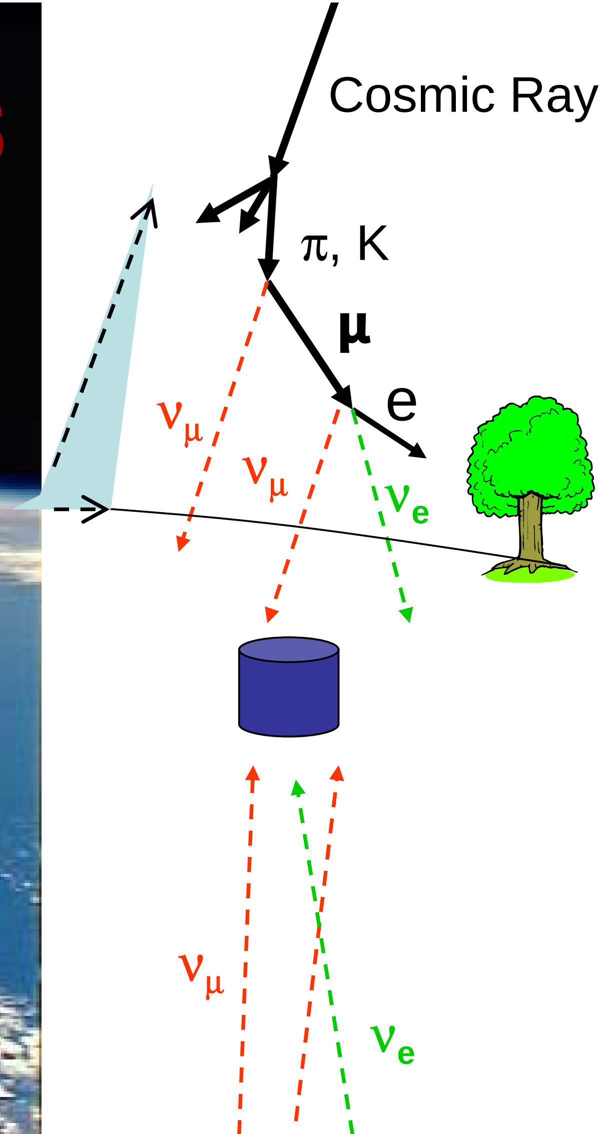
LMA-II disfavored at >99%CL

Full mixing for θ_{12} excluded at 5.4σ

$$\begin{cases} \Delta m^2_{12} = 7.1^{+1.2}_{-0.6}\, eV^2 \\ \theta_{12} = 32.5^{+2.5}_{-2.4} \end{cases} (68\%CL)$$

Atmospheric neutrinos



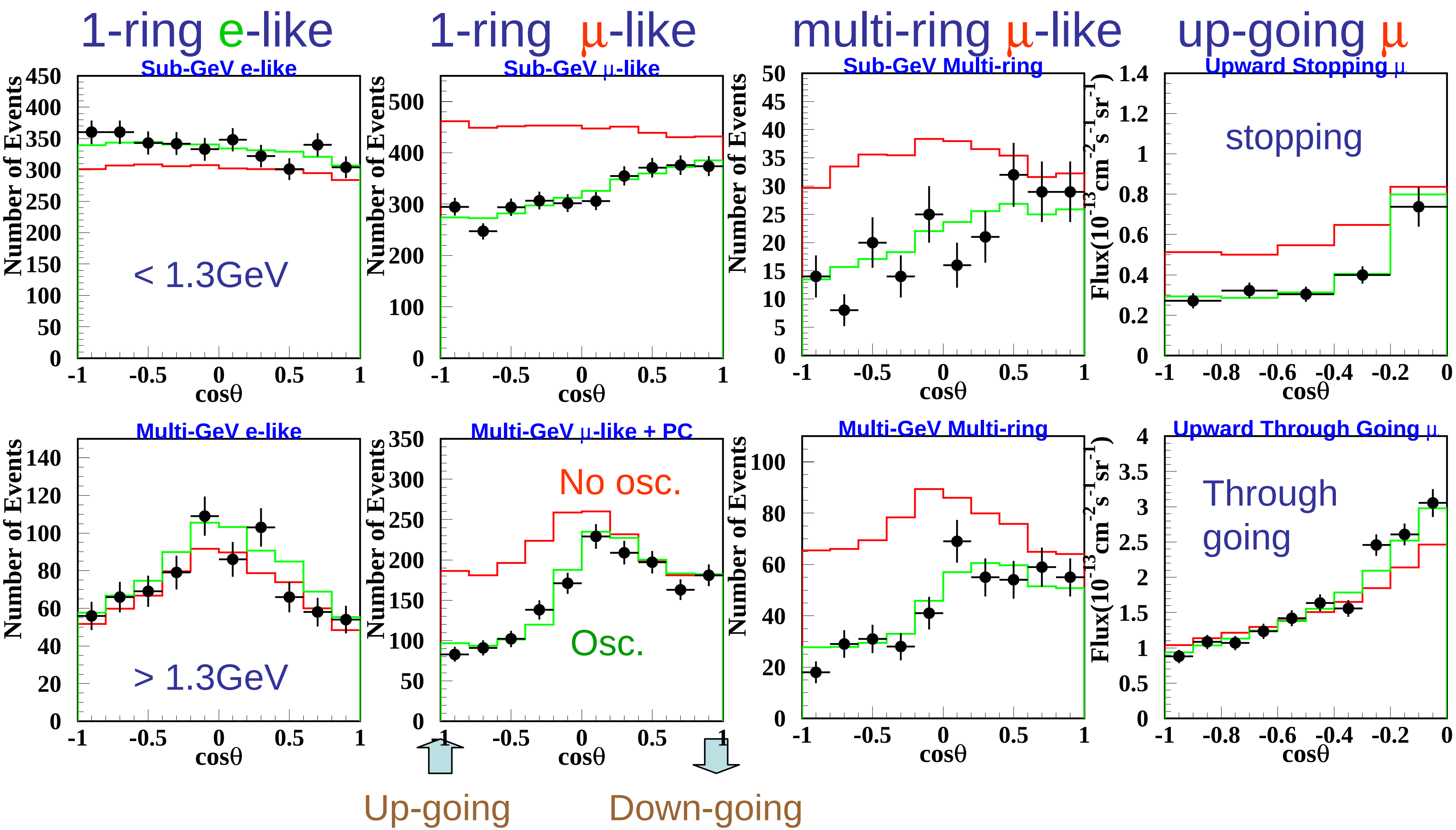


Neutrinos from the other side of the Earth.

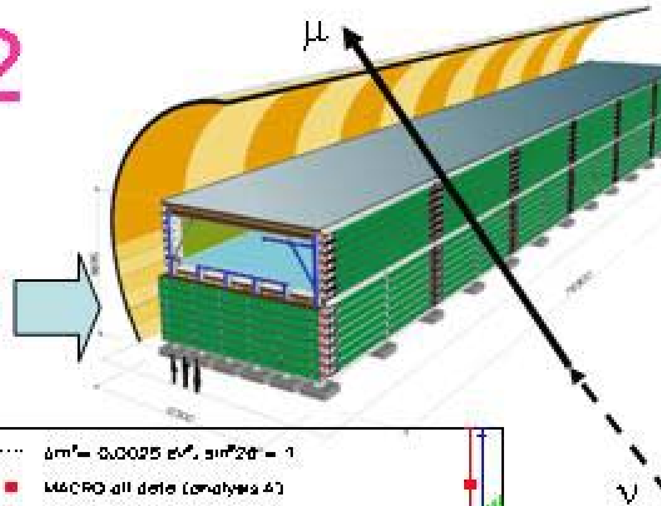
SK atmospheric neutrino data

(reanalyzed, still prelim.)

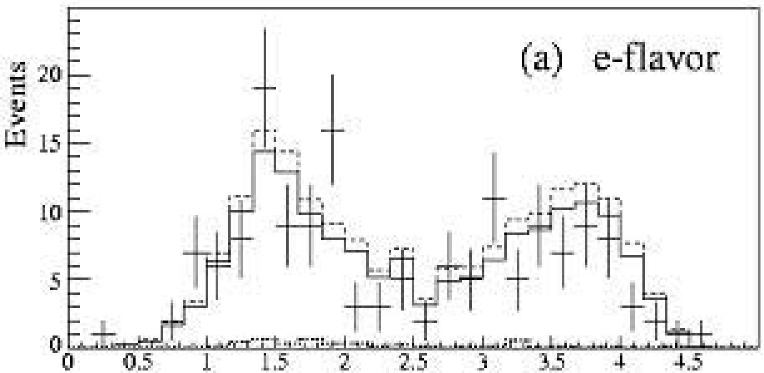
1489day FC+PC data + 1646day upward going muon data

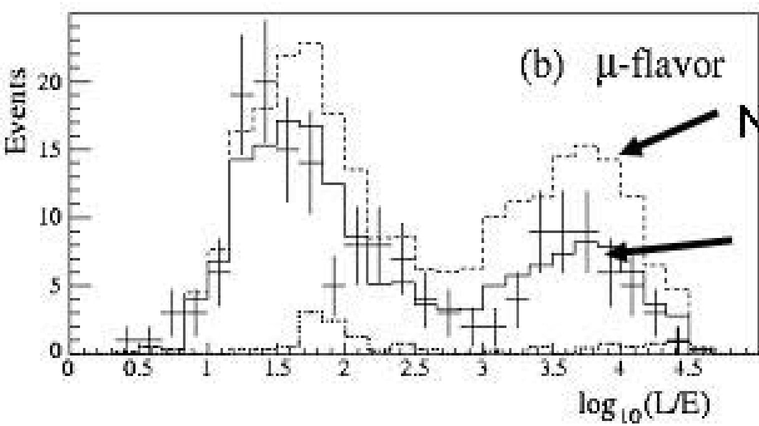


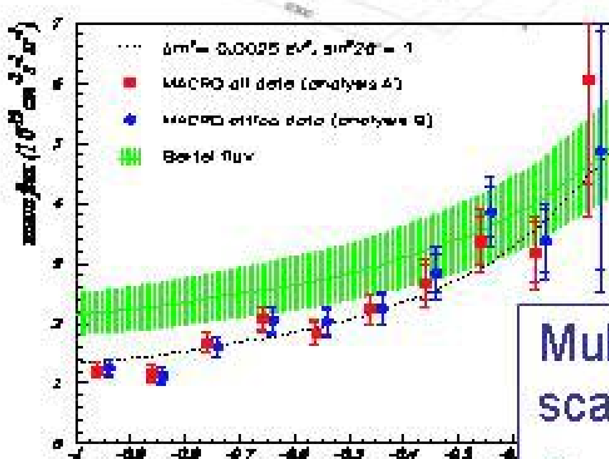
Soudan-2 and MACRO



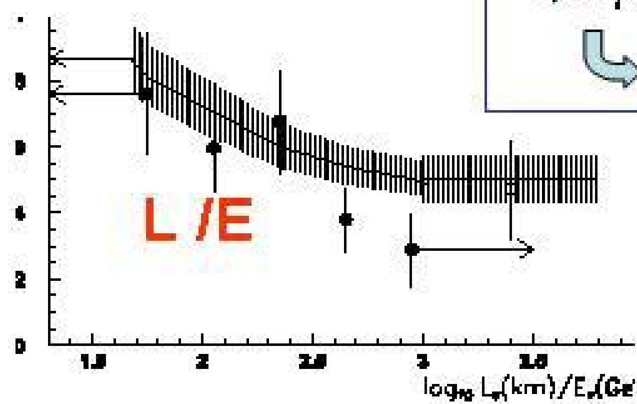
Zenith → L /E



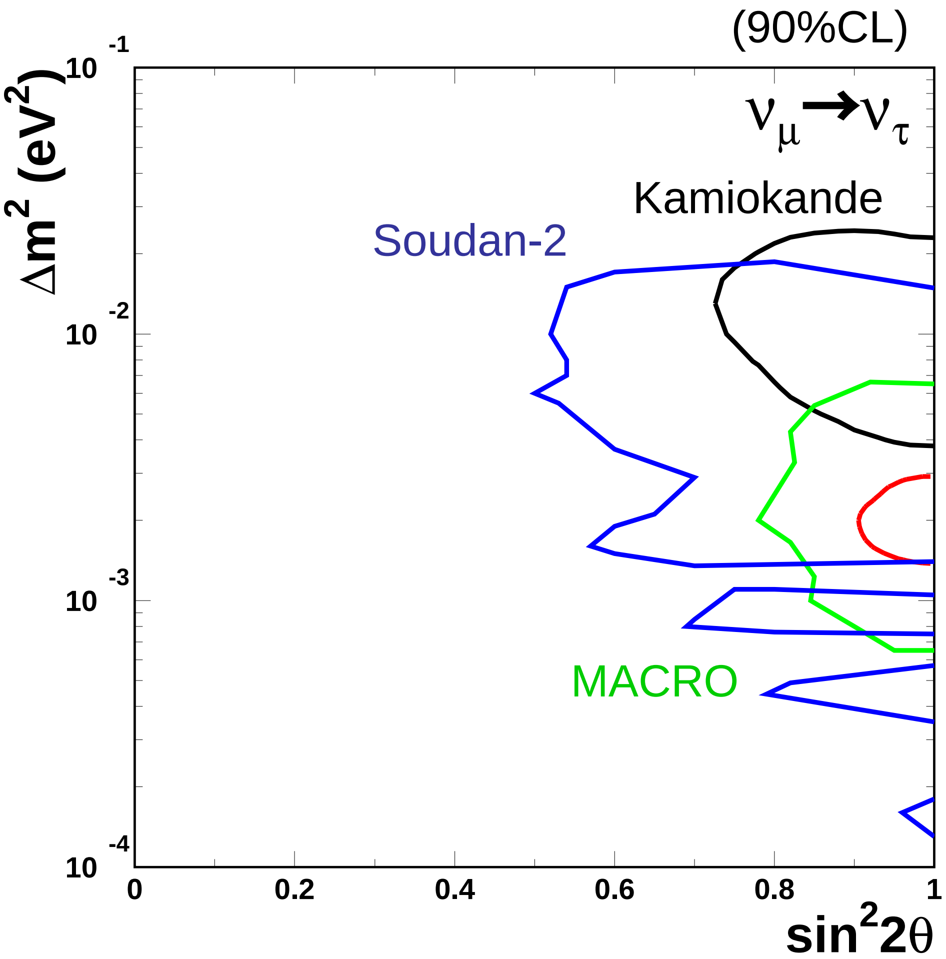




Multiple scattering
↳ Eμ
↳ Eν



Neutrino oscillation parameters



Super-K

$$\begin{cases} 1.3 < \Delta m^2 < 3.0 \times 10^{-3} (eV^2) \\ \sin^2 2\theta > 0.90 \end{cases}$$

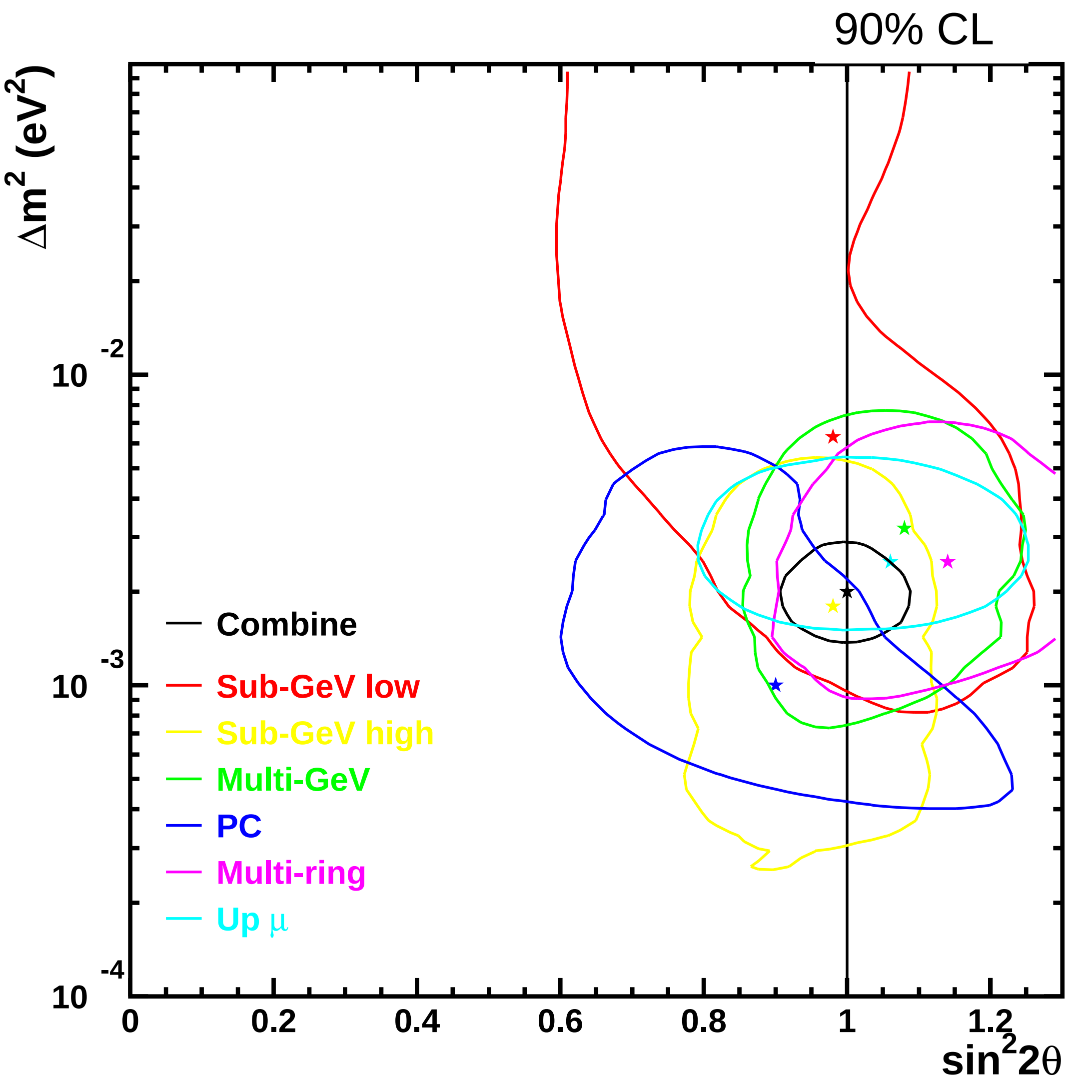
(90%CL)

Improvements and sub-sample consistency (SK)

Improvements

- ν flux
  (1dimensional ➔ 3d.)
- ν interaction models
  (based on K2K near data)
- Detector simulation
- Event reconstruction

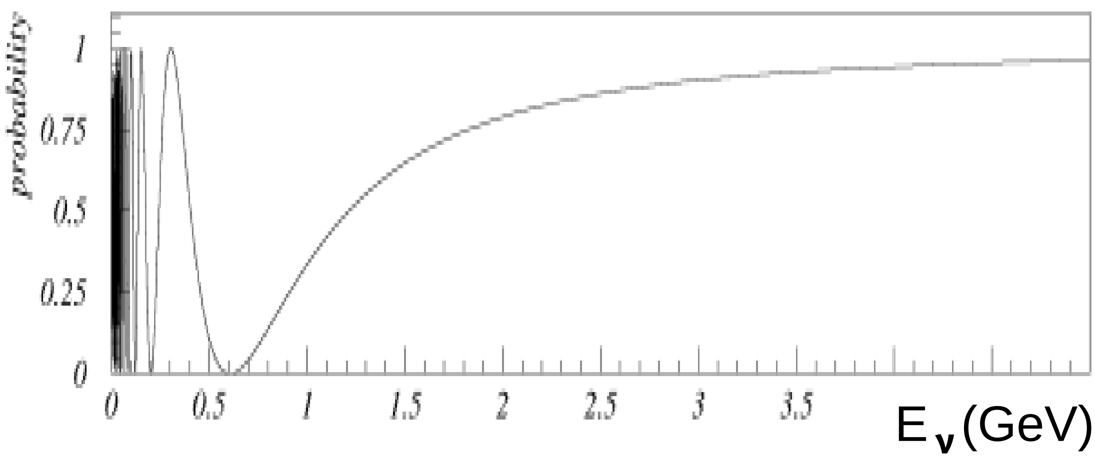
Each change contributes to the shift in the allowed (Δm^2) region.



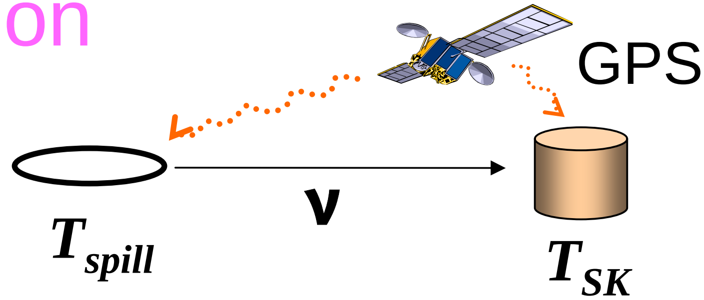
WG discussion (E.Kearns)

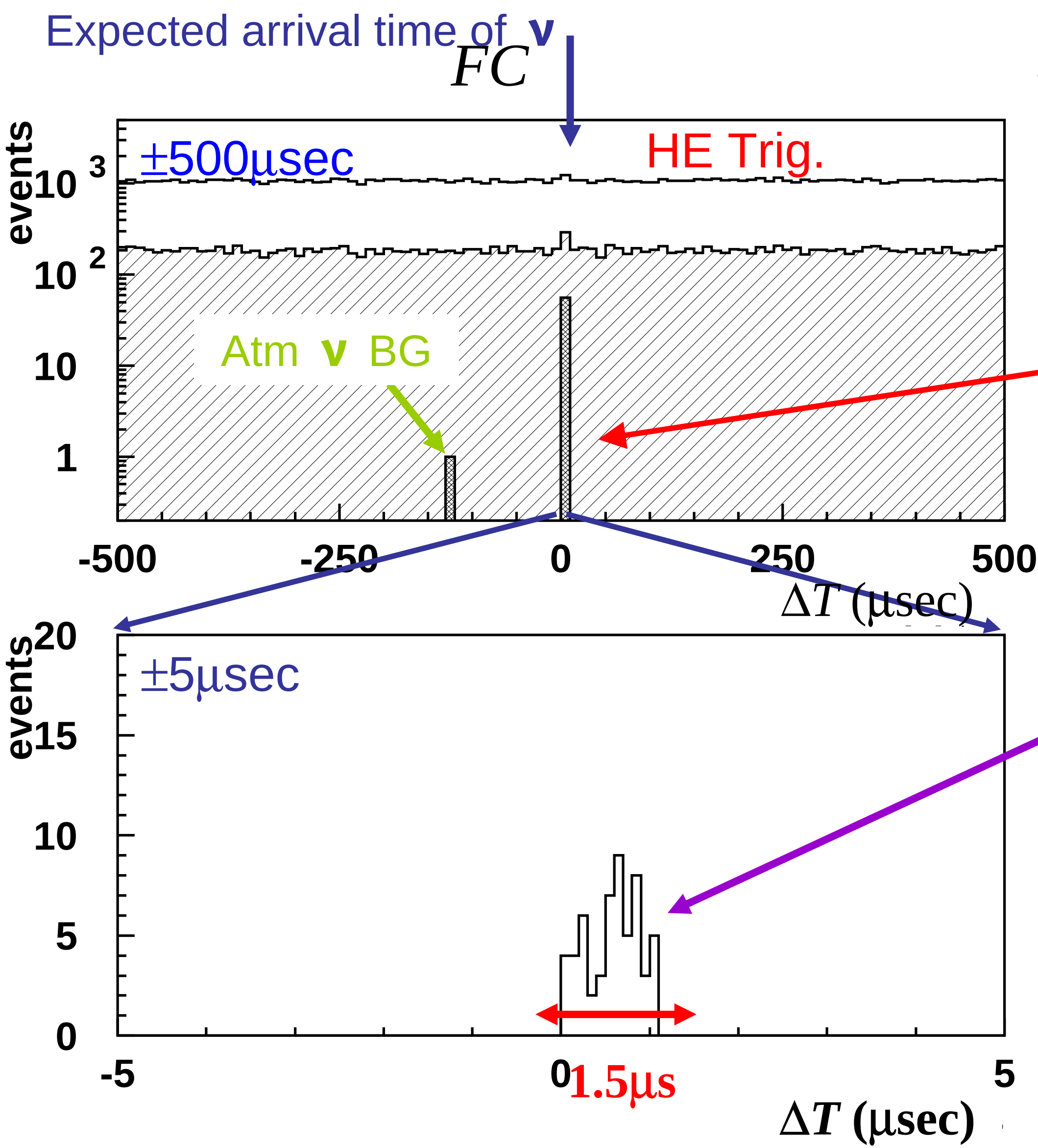
K2K

Neutrino oscillation probability for Δm^2=0.003eV^2 and at 250km.



Event selection





fully contained
22.5kt fiducial volume

number of events

56 observed

$80.1^{+6.2}_{-5.4}$ expected

null oscillation prob. 1.3%

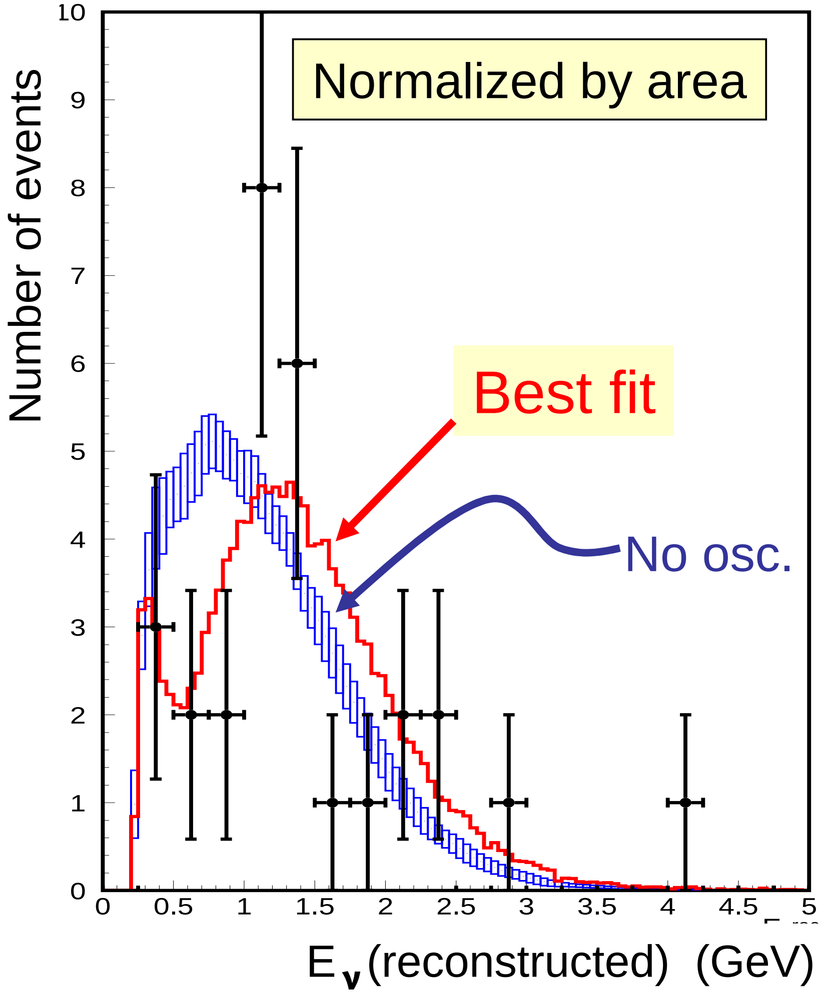
0.48×10^{19} p.o.t.

(1999-2001)

(1/2 of the proposal)

Oscillation vs. data

CC quasi elastic reaction ⇨ E_ν from (E_μ and θ_μ)



Best fit point ($\sin^2 2\theta$, Δm^2) = (1.0, $2.8\times10^{-3}eV^2$)

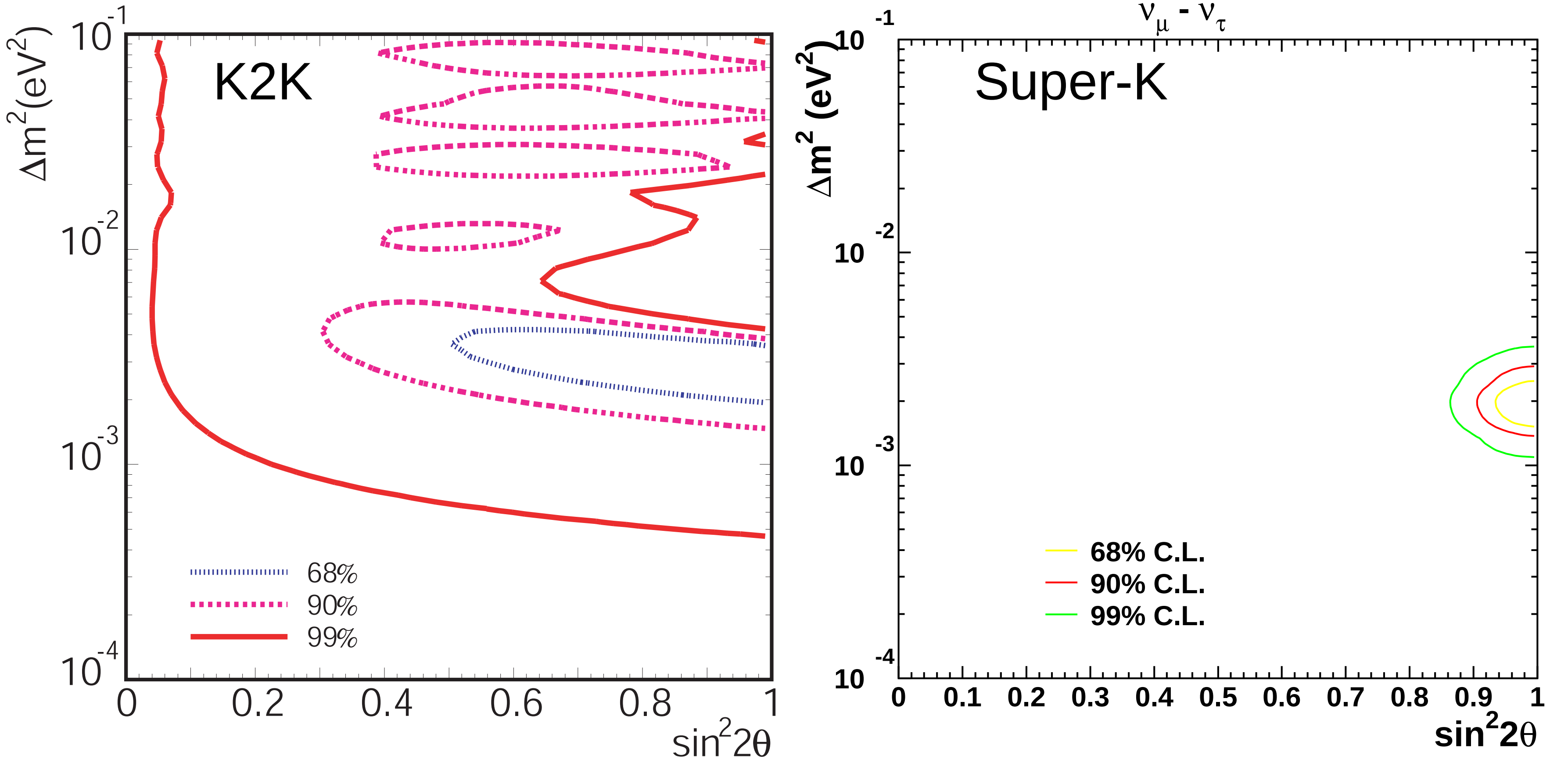
★KS test prob.(E_ν dist): 79%

★N_{SK}(expected by osc.)=54

N_{SK}(observed)=56

Both N_{SK} and E_ν-distribution are consistent with oscillations.

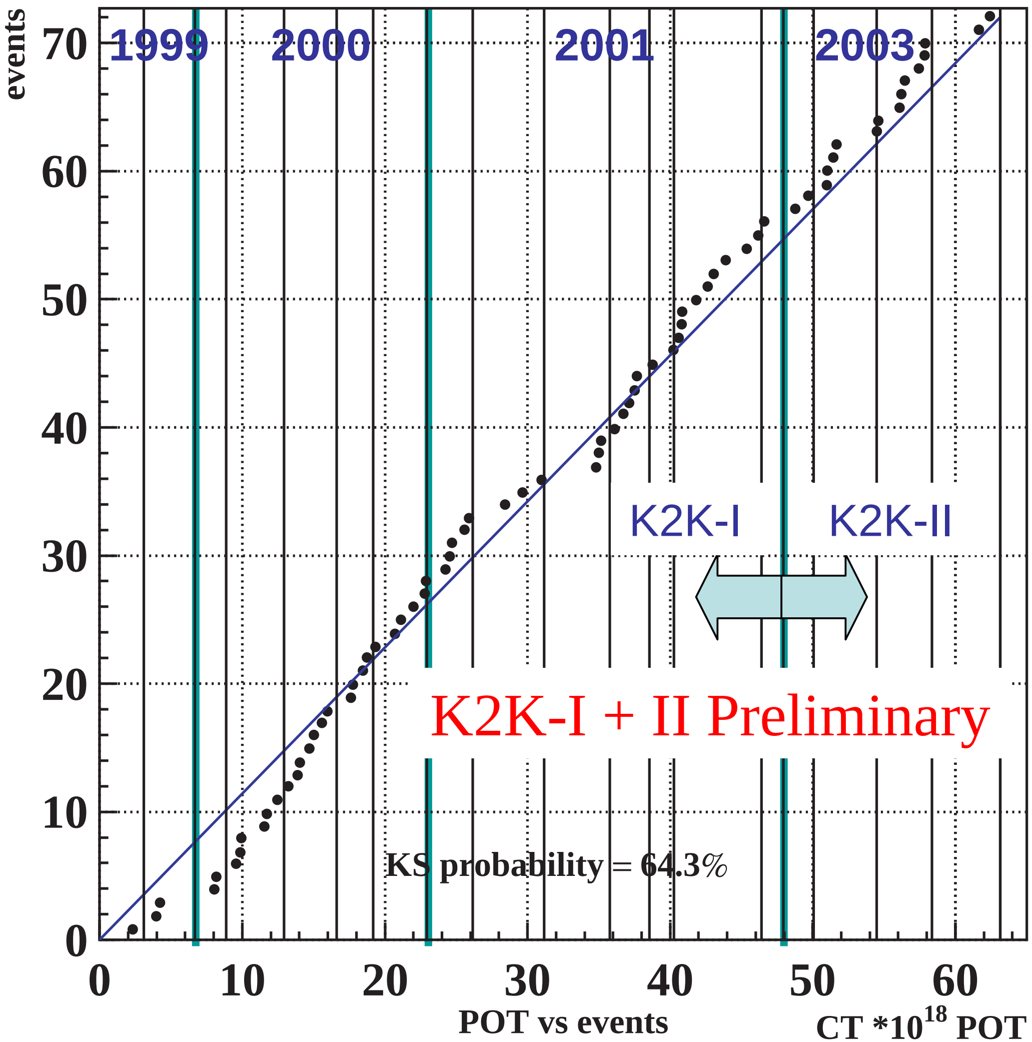
Allowed parameter region based on E_ν and N_{SK}



K2K and atmospheric neutrino data are consistent.

New K2K data after SK recovery

FC 22.5kt



K2K-I

$80.1^{+6.2}_{-5.4}$ expected

56 observed

obs/exp=**0.70±0.09**(stat)

K2K-II (until April 2003)

$26.4^{+2.3}_{-2.1}$ expected

16 observed

obs/exp=**0.61±0.15**(stat)

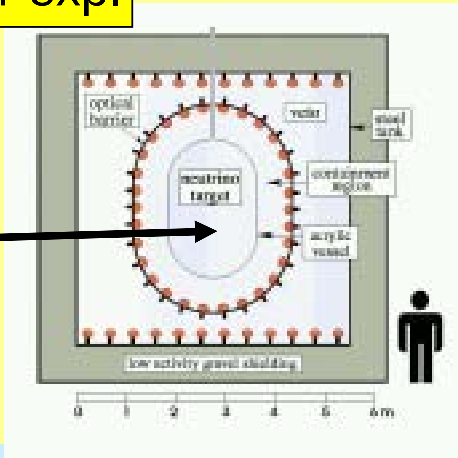
Event rates are consistent between K2K-I and -II

θ_{13} ?

Reactor exp.

$\overline{\nu}_e \rightarrow \overline{\nu}_X$

$\sim$ 1km



$\Delta m^2_{12}=0$ assumed

$P(\nu_e \rightarrow \nu_X)$

$$= \sin^2 2\theta_{13} \cdot \sin^2\left(\frac{1.27\Delta m^2 L}{E_\nu}\right)$$

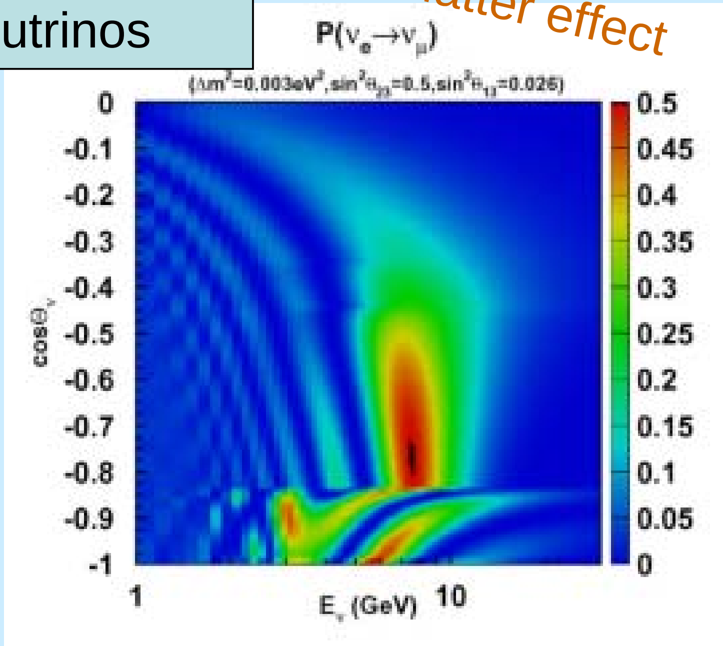
$P(\nu_\mu \rightarrow \nu_e)$

$$= \sin^2 \theta_{23} \cdot \sin^2 2\theta_{13} \cdot \sin^2\left(\frac{1.27\Delta m^2 L}{E_\nu}\right)$$

$=0.50 \pm 0.16$

Atmospheric neutrinos

Matter effect

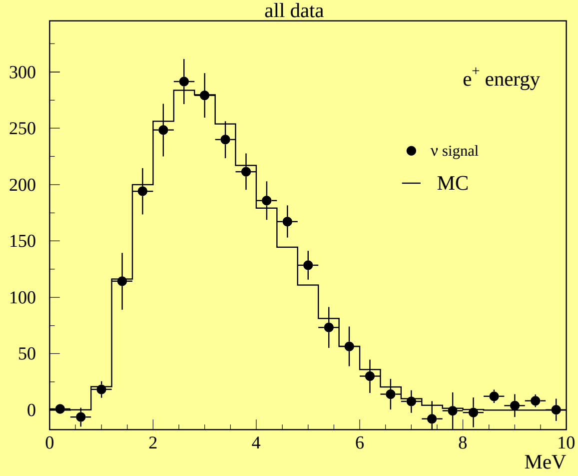


Long baseline exp.

$\nu_\mu \rightarrow \nu_e$

Data

CHOOZ ν_e disappearance

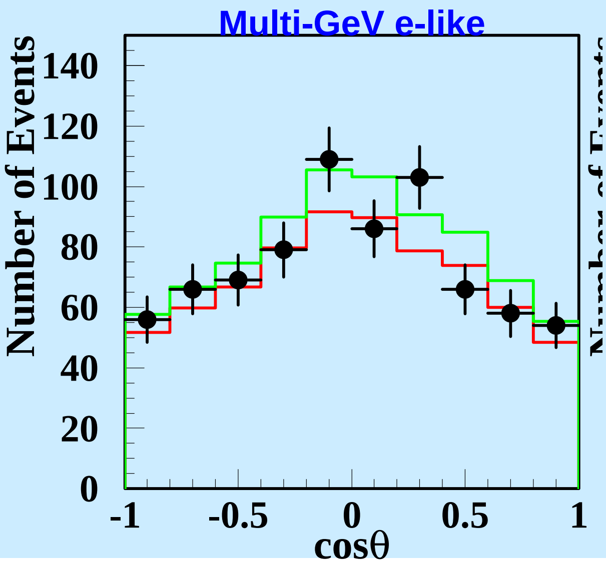


K2K electron appearance

Data	1
BG	2.4
ν_μ BG	2.0
ν_e BG	0.35

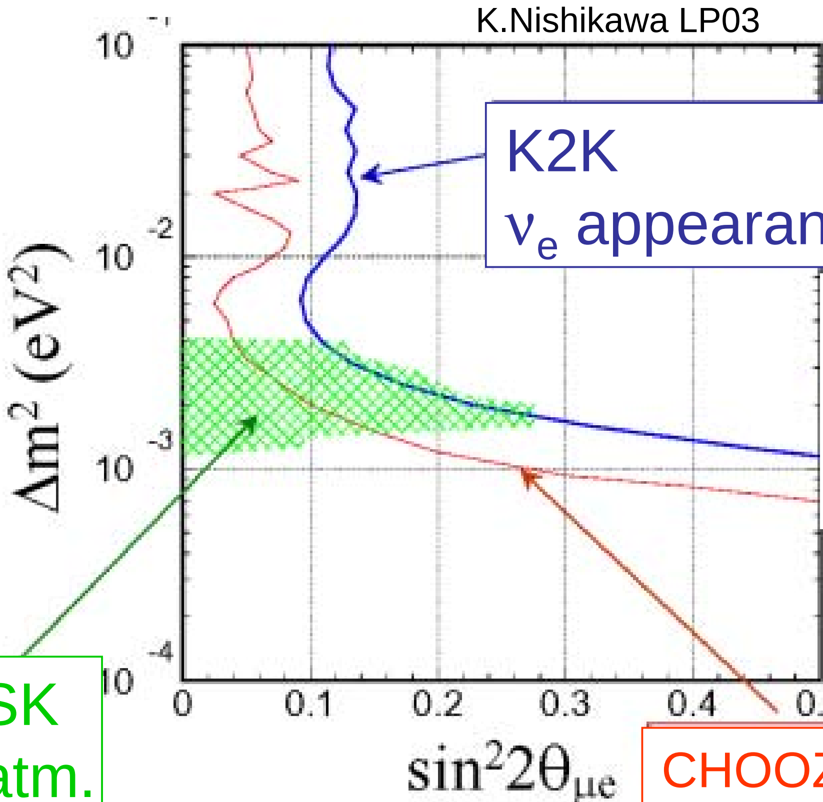
(ε=55%)

SK Atmospheric neutrinos



No evidence for non-zero θ_{13}

Constraints on θ_{13}



K2K ν_e appearance

SK atm. (old analysis)

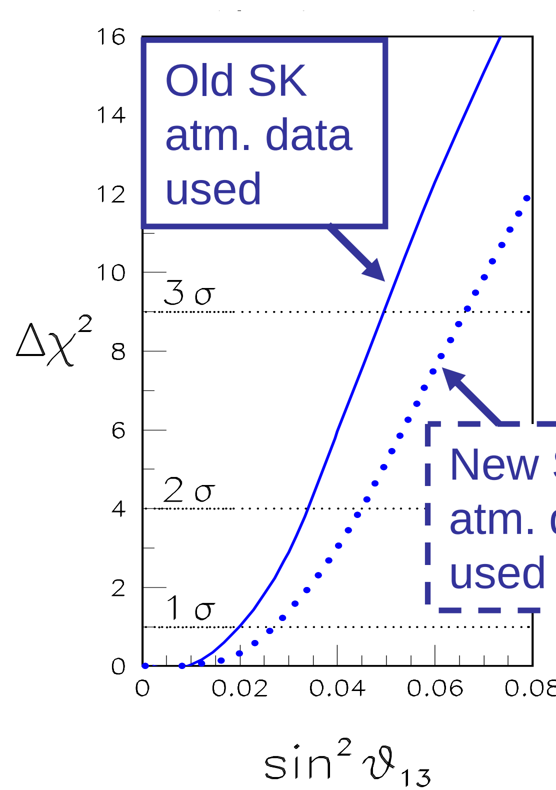
$= 0.5 \cdot \sin^2 2\theta_{13}$

CHOOZ ν_e disappearance

(Similar but slightly weaker constraint from Palo Verde)

Lower Δm^2 and global analysis

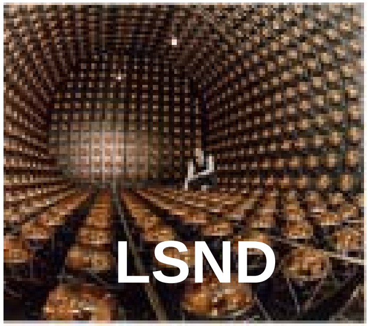
hep-ph/0308055

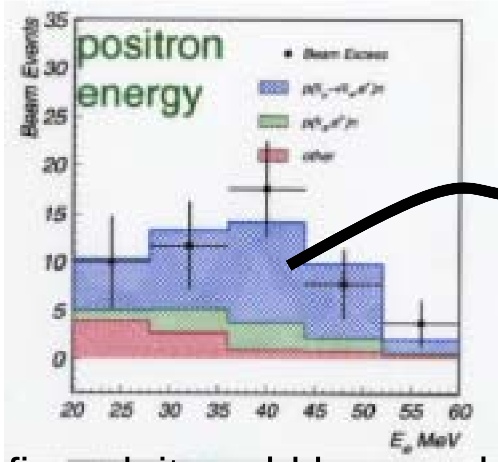


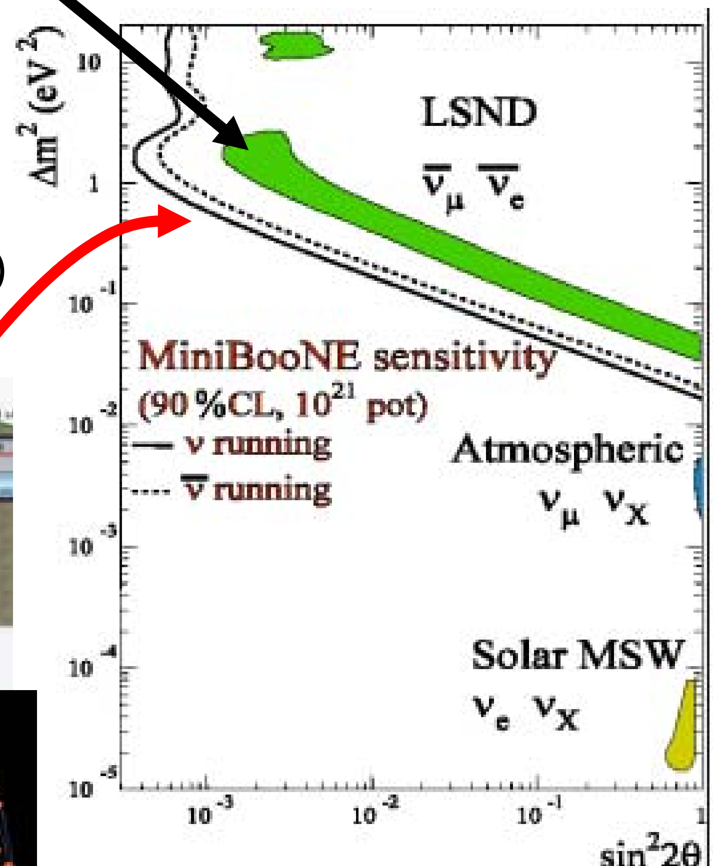
Old SK atm. data used

New SK atm. data used

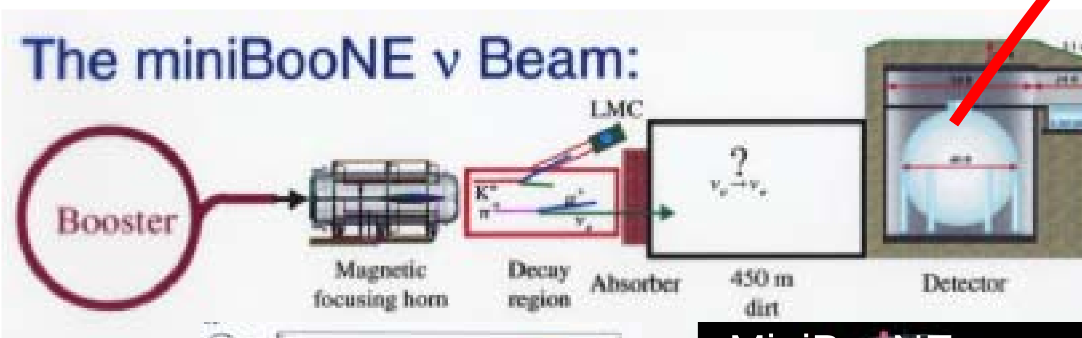
LSND and MiniBooNE



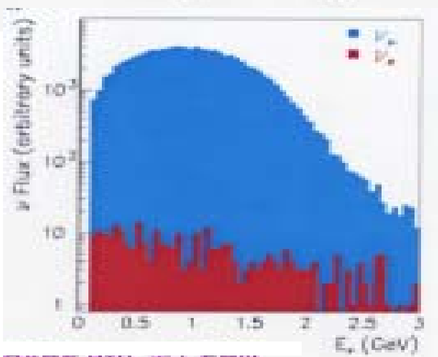




If LSND result is confirmed, it could be a real new physics. (No one can explain LSND within the presently known frame work of neutrino oscillations.)
➔ Very important to check the LSND results.



flux



MiniBooNE taking data since Aug.2002. (ν WG H.Tanaka)

Status

- Known;

  $\Delta m^2_{23(13)}$, θ_{23},

  Δm^2_{12}, θ_{12} and the sign of Δm^2_{12}

- Unknown;

  θ_{13} (known to be small),

  δ(CP phase),

  sign of $\Delta m^2_{23(13)}$

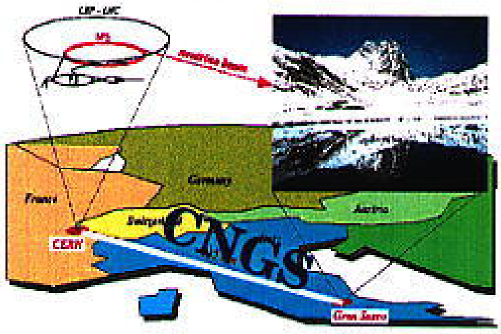
Need experimental confirmation;

Oscillation

τ appearance

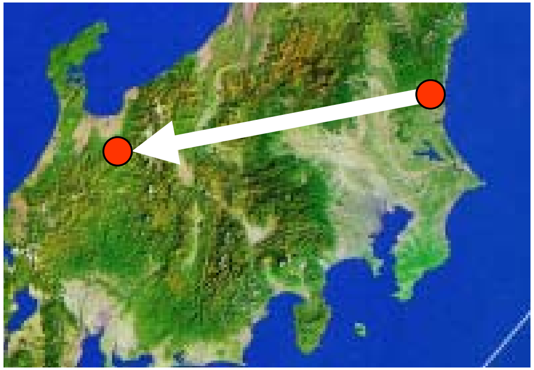
Future neutrino oscillation experiments

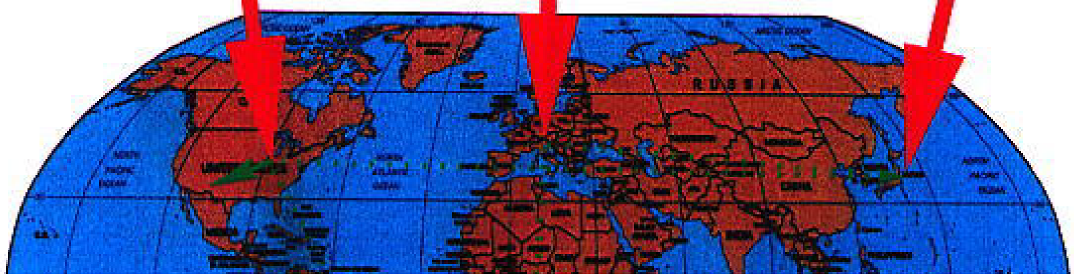
CERN to Gran Sasso Neutrino Beam



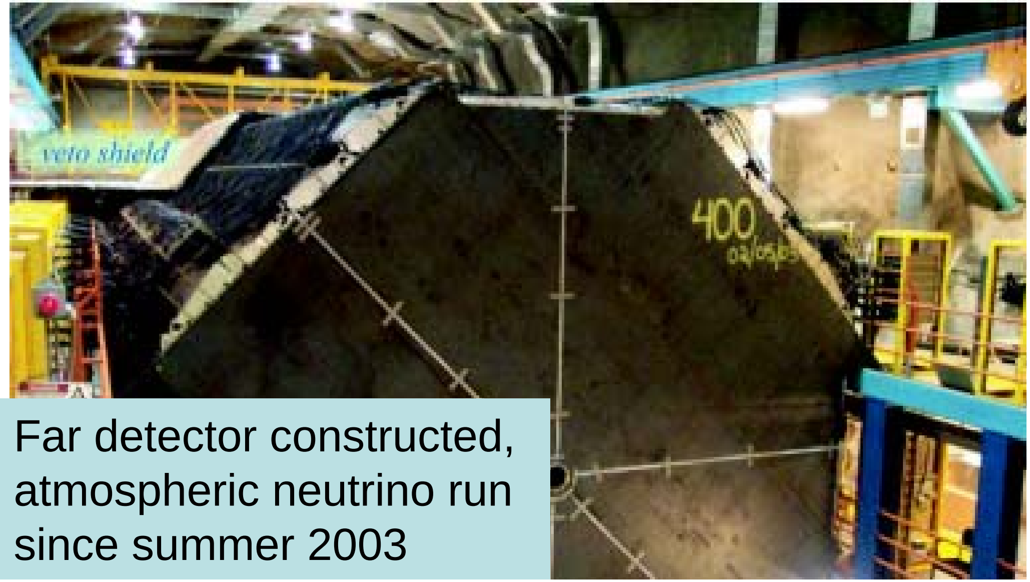
WG discussions

JPARC-nu

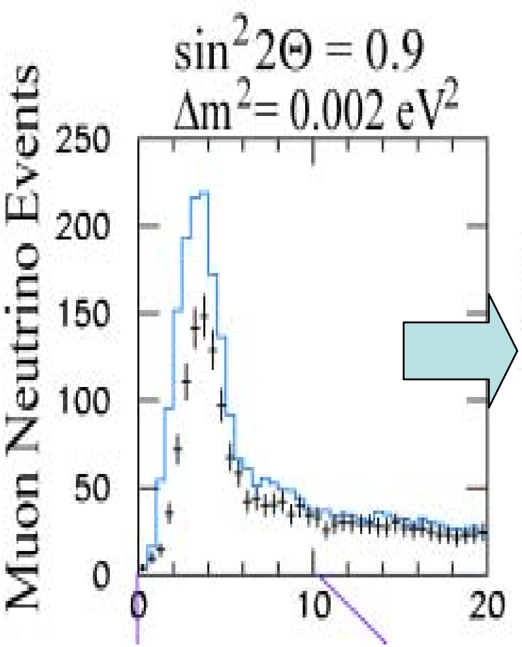


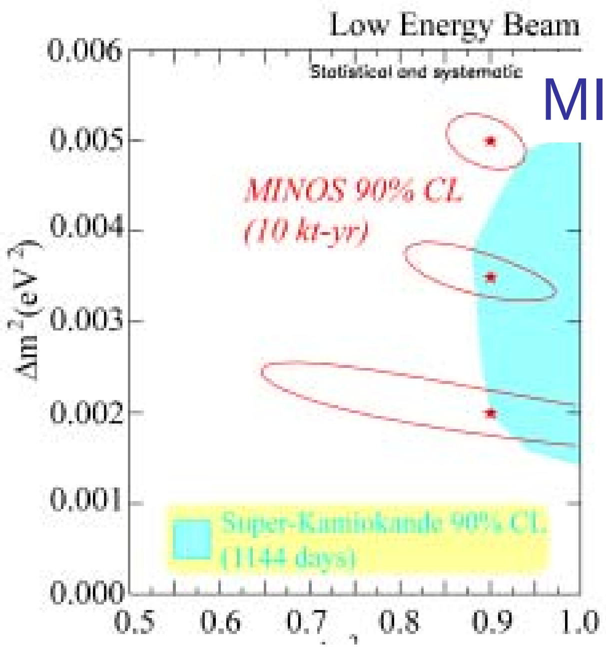


MINOS (start end 2004)

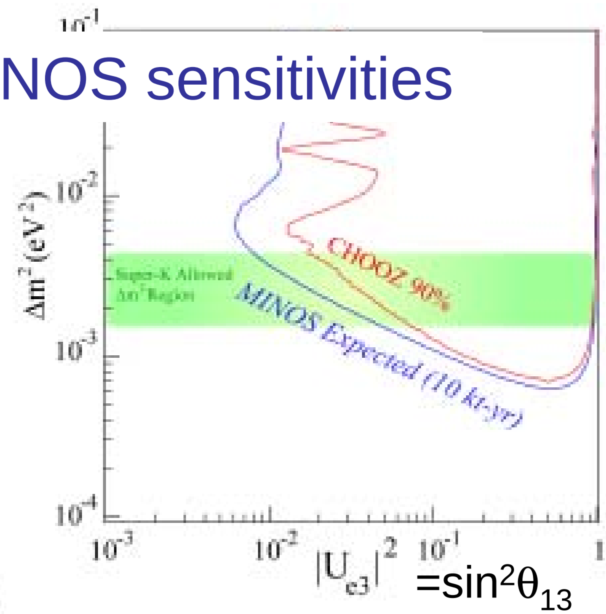


Far detector constructed, atmospheric neutrino run since summer 2003





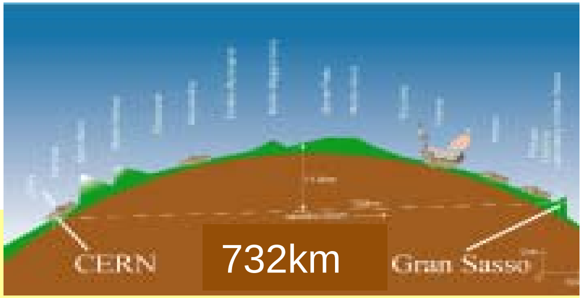
MINOS sensitivities



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

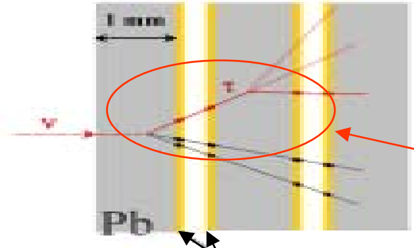
CNGS (start 2006)

Primary goal: detection of tau neutrinos



OPERA

Hybrid emulsion detector (1.7kton)



Observe τ decay

Emulsion layers

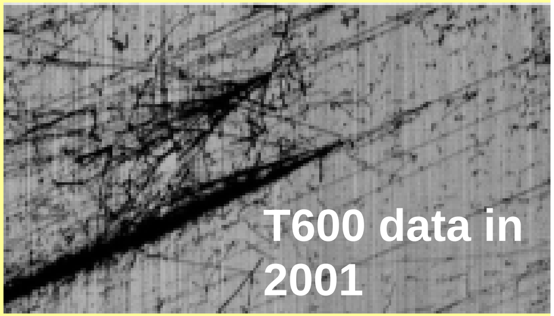
ICARUS

3.0 kton liq. argon detector

Bubble chamber like image

↓

Detailed kin. study of ν_τ events



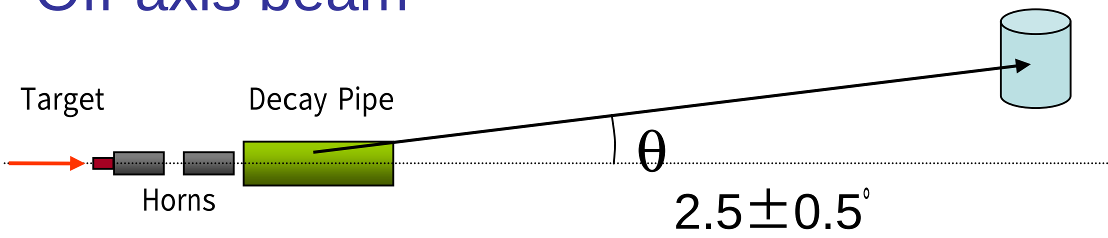
Expected number of τ events

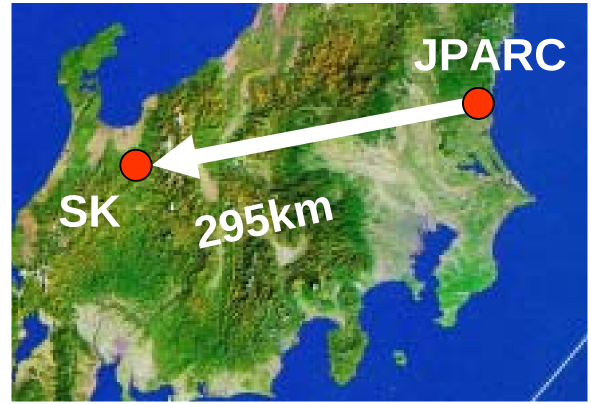
	$1.6 \cdot 10^{-3}$	$2.5 \cdot 10^{-3}$	$4.0 \cdot 10^{-3}$	background
OPERA	4.3	10.3	26.3	0.65
ICARUS	4.9	11.9	30.5	0.7

(5yrs)

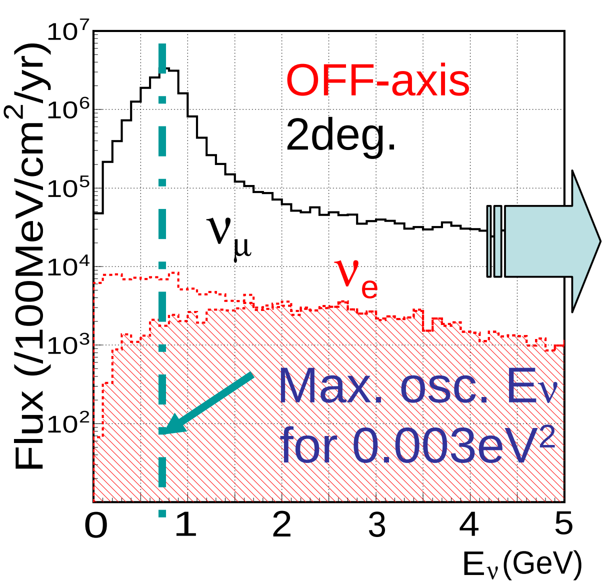
JPARC neutrino project (start 2008 or 9?)

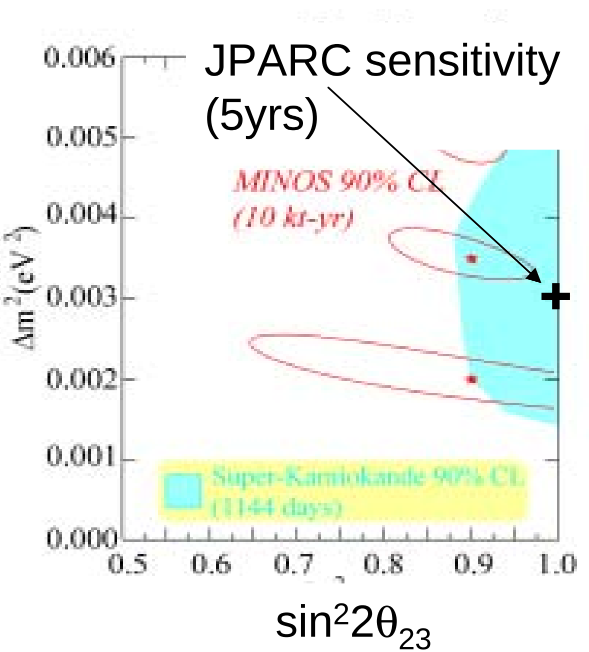
Off-axis beam

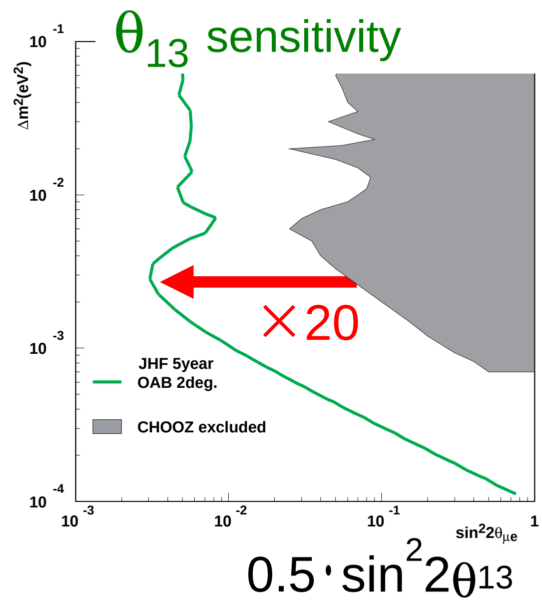




×100 more intensity than K2K, Eν < 1GeV



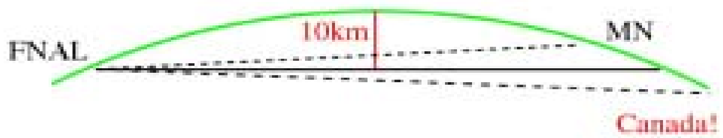




Status: waiting for decision (approval?) at the end of this year

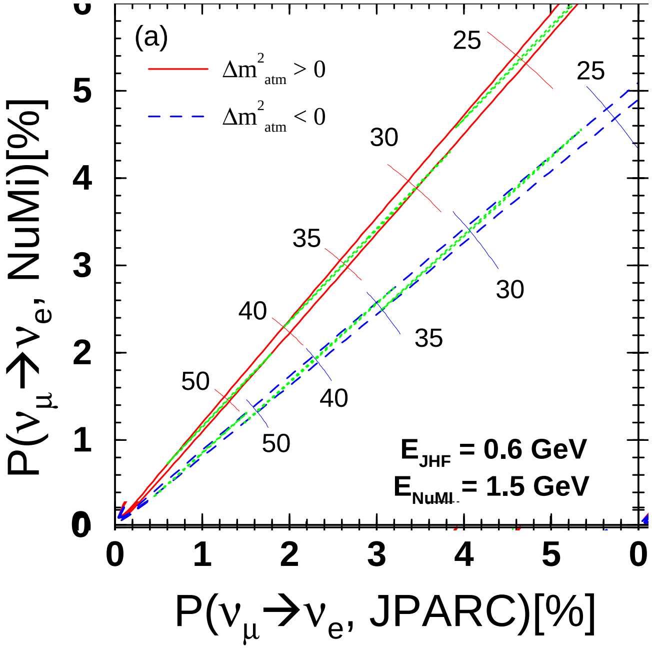
NuMi Off-axis (year ?)

Neutrino oscillation experiment with an Off-Axis detector (lower energy neutrinos)



Matter effect: MuNi-Off-axis > JPARC

hep-ph/0301210



Detector:
40kton fiducial mass
Low Z, high granularity detector

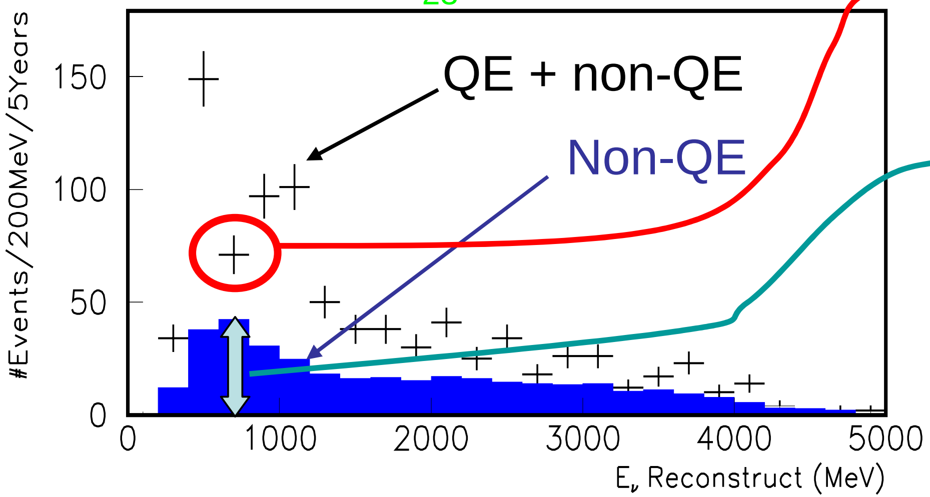
Determine the sign of Δm^2

Similar sensitivity as JPARC-ν

Importance of understanding of neutrino interactions

Example:

For $\sin^2 2\theta_{23}$=1.00 (JPARC)

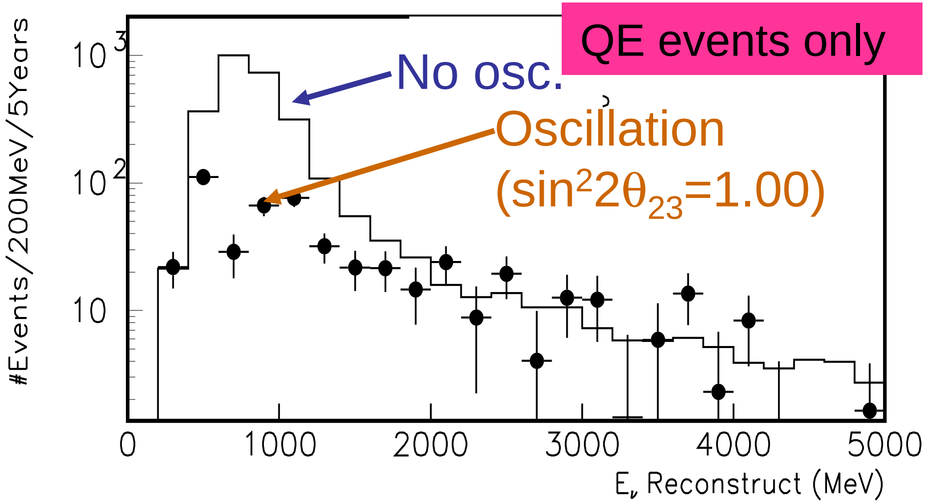


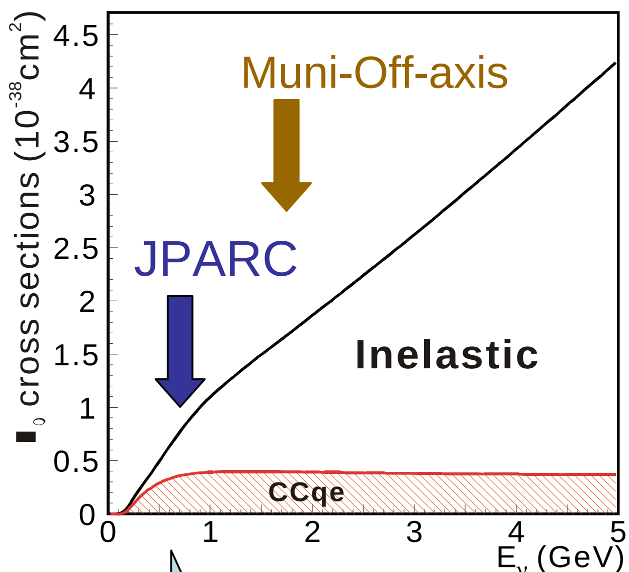
Stat. error: +/- 8.5

Non-QE BG: 43

20% syst. In non-QE/QE ratio = 8.5 events

⇒ Non-QE/QE ratio must be understood (much) better than 20%.





⇒ WG discussion

Reactor experiments for θ_{13}

(Do better than CHOOZ did)

Good: Relatively cheep(?),

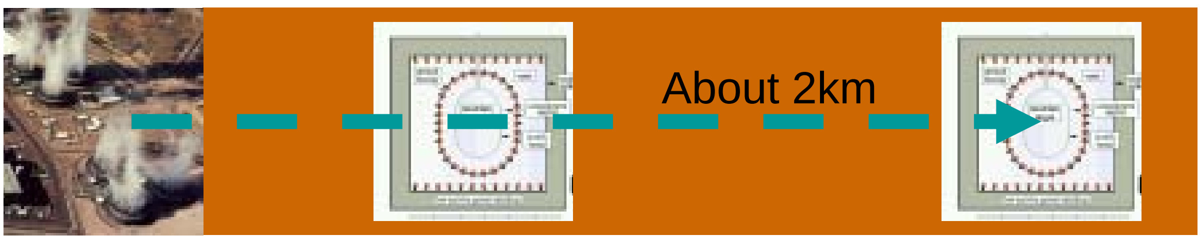
If measured, the measurement is really a measurement of θ_{13}

(No ambiguity from θ_{23}, sign of Δm^2, CP phase)

Challenge: disappearance (% range) ➔ control systematics <1%, higher stat.

2 (identical) detector system, ~50tons each

underground



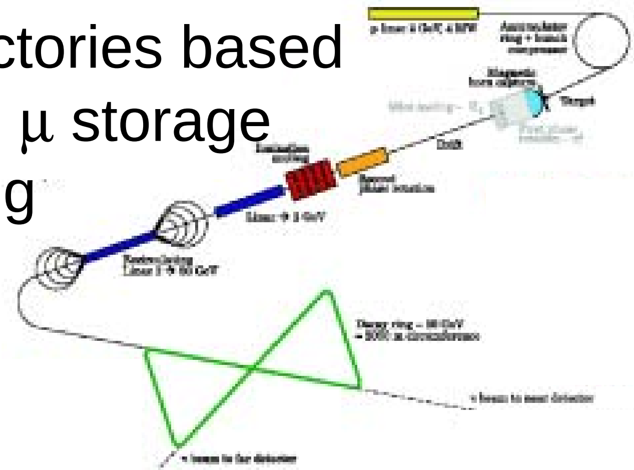
Serious discussions in Russia, USA, Europe and Japan

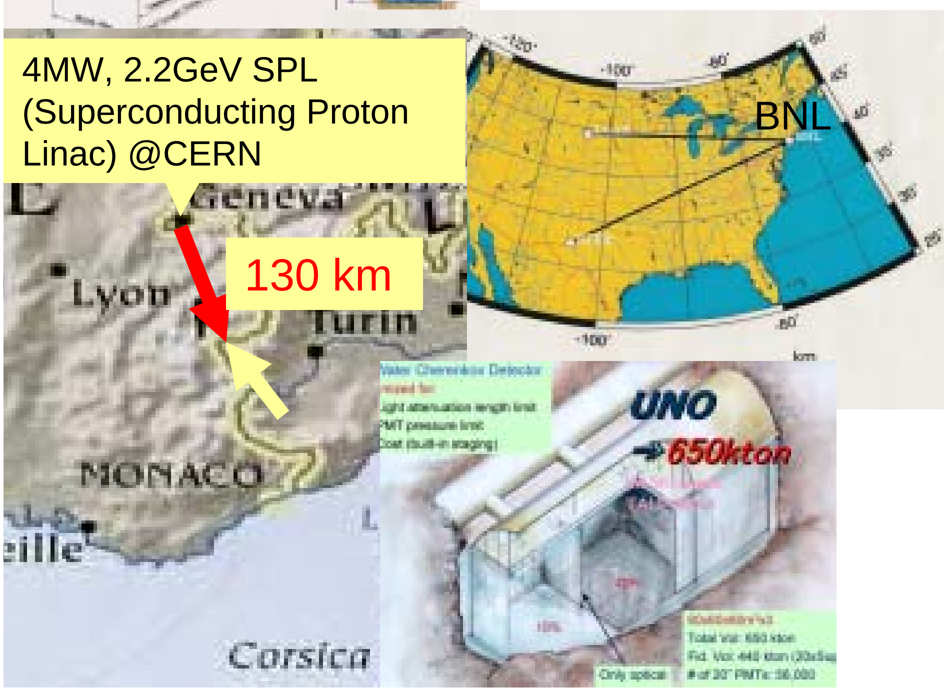
Factor 5-10 improvement seems possible

Toward the measurement of δ(CP phase)

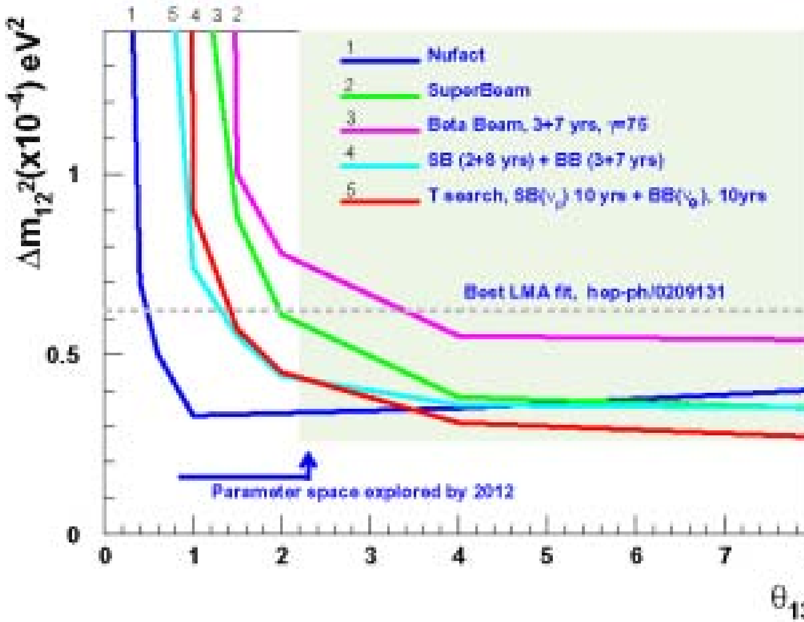
Super-beam experiments

Neutrino factories based on μ storage ring





Ability to see maximal CP violation



Summary

- In the past several years, we have learned a lot about the neutrino masses and mixings.
- We know $\Delta m^2_{23(13)}$, θ_{23}, Δm^2_{12}, θ_{12} and the sign of Δm^2_{12} .
- In the future neutrino oscillation experiments, yet unknown oscillation parameters (θ_{13}, δ, and sign of $\Delta m^2_{23(13)}$) can be measured.