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ICTP 40th Anniversary

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"VII School on Non-Accelerator Astroparticle Physics"

26 July - 6 August 2004

Towards the Complete Neutrino Mixing Matrix and CP-Violation

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Towards the Complete Neutrino Mixing Matrix and CP-Violation

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NEUTRINO 2004
Paris
June 16, 2004

2001– Remarkable progress in the studies of $\nu-$ mixing and oscillations

- **June, 2001: SNO CC data + SK data → $\nu_{\mu,\tau}$ and/or $\bar{\nu}_{\mu,\tau}$ in $\Phi_E(\nu_\odot)$**

- **April, 2002: SNO NC data → evidences for $\nu_{\mu,\tau}$ and/or $\bar{\nu}_{\mu,\tau}$ in $\Phi_E(\nu_\odot)$ strengthen**

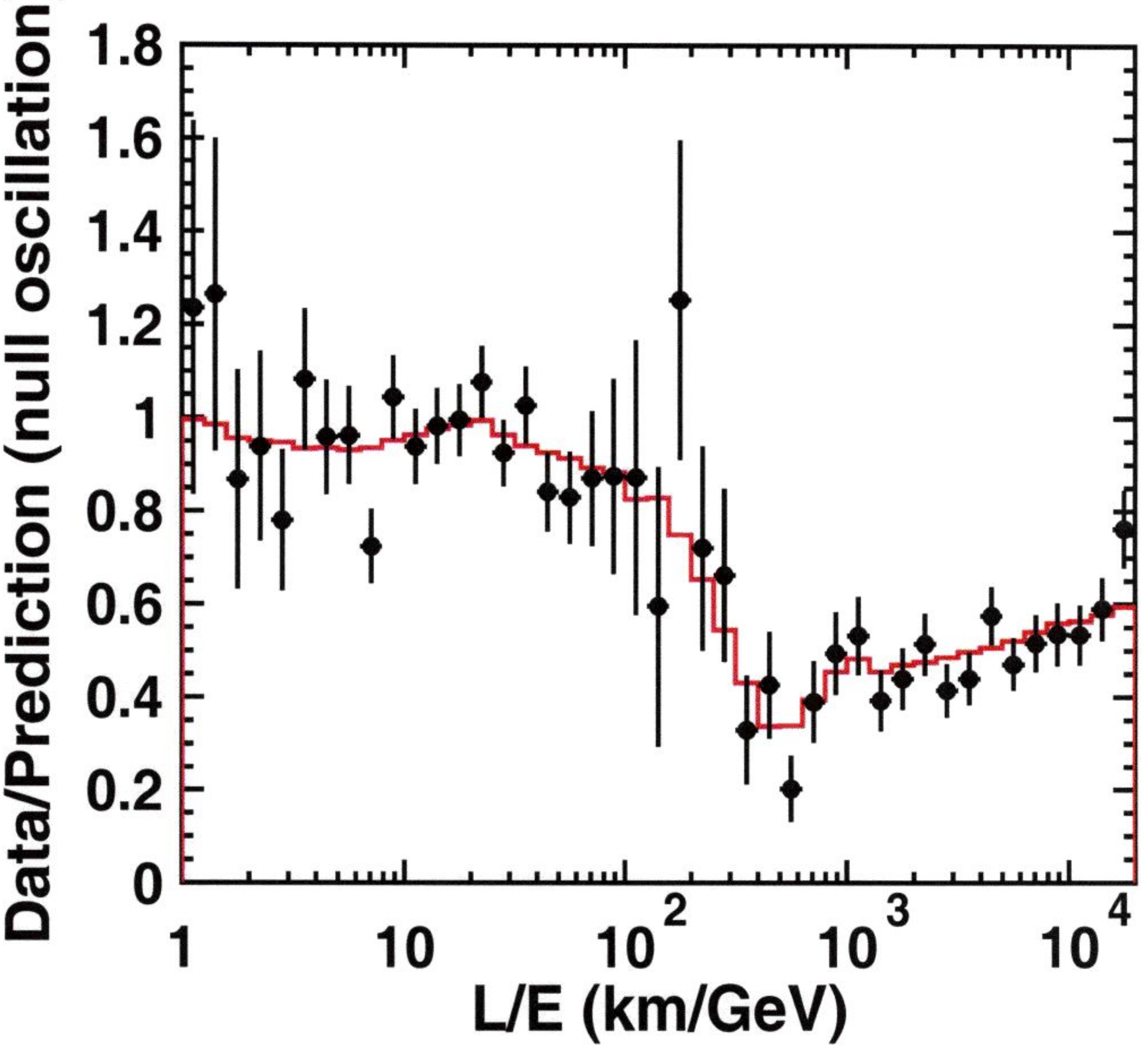
- **December, 2002: KamLAND**
  - First compelling evidence for $\nu-$oscillations in an experiment with terrestrial ν's
  - Evidence for ν_e-mixing in vacuum
  - $\nu_\odot$: LMA solution (CPT)
  - KamLAND "massacre":

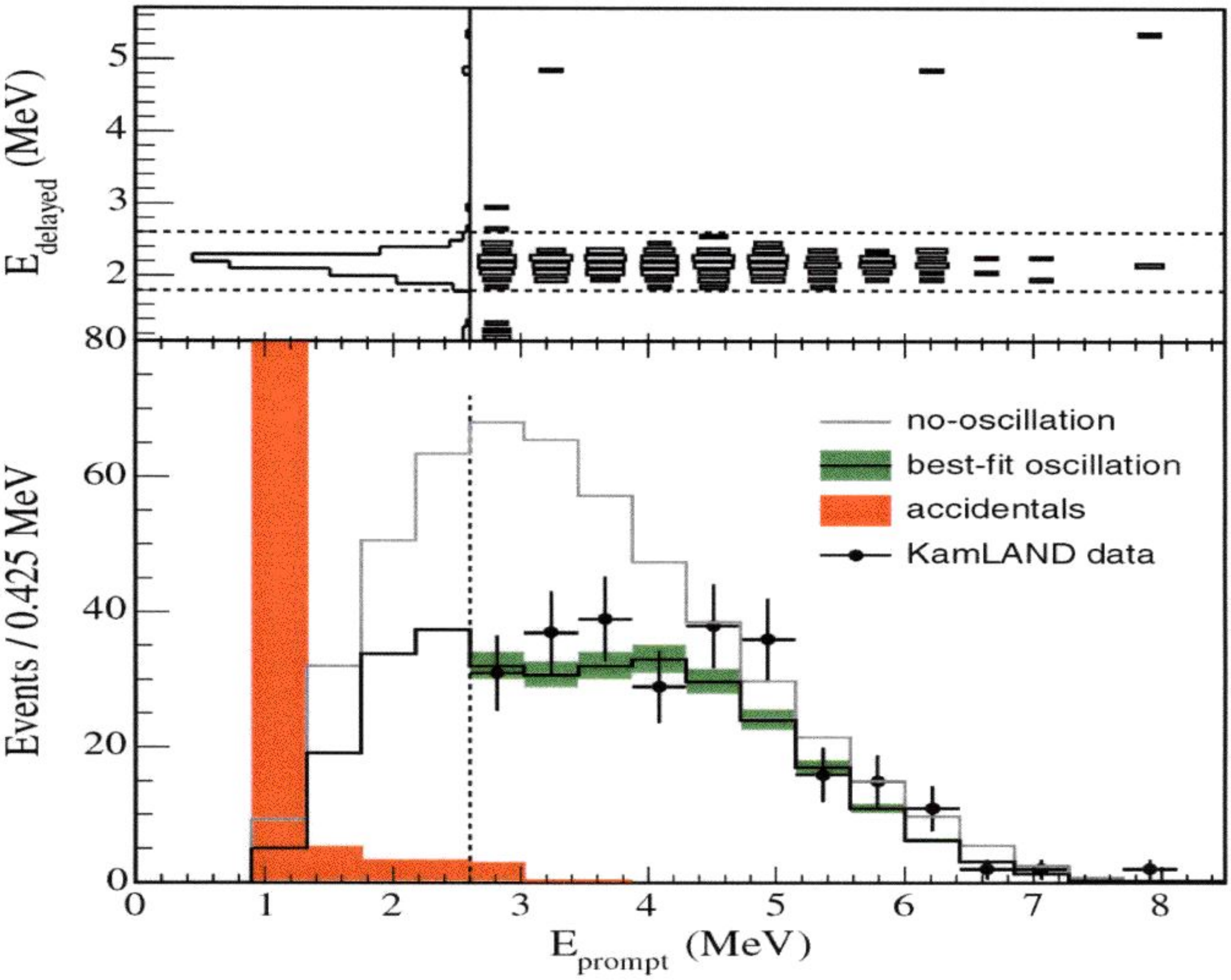
    VO, QVO, LOW, SMA MSW, RSFP, FCNC, WEPV, LIV,...

- **September, 2003: SNO salt phase data,**

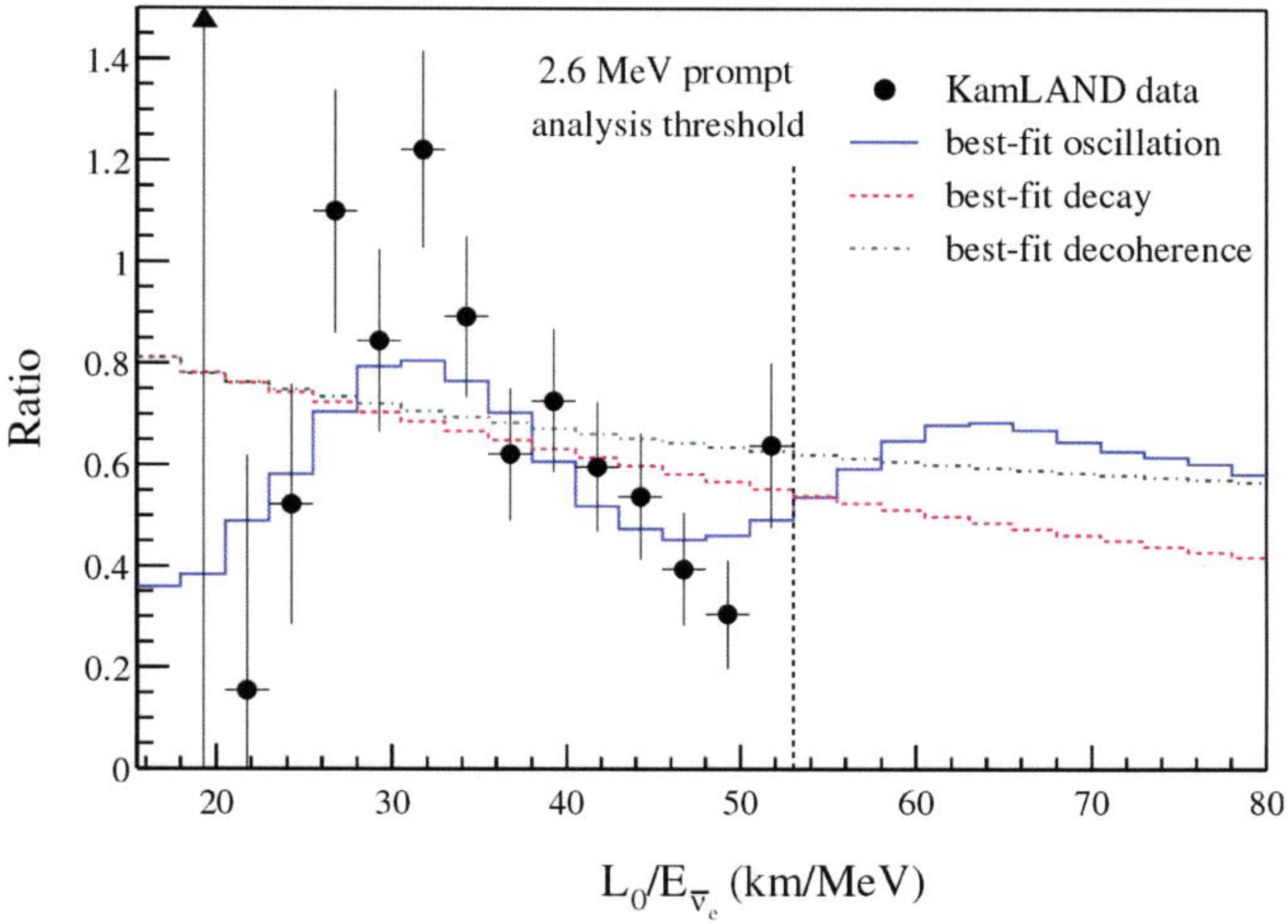
  higher precision measurement of $\Phi_B(\nu_\odot)$

SK: L/E Dependence, $\mu-$Like Events





KamLAND: e^+–Spectrum Deformation



KamLAND: e^+–Spectrum Deformation

K2K: Spectrum Deformation

Evidences for $\nu-$Oscillations

$-\nu_{\text{atm}}$: SK UP-DOWN ASYMMETRY

θ_Z-, $L/E-$ dependences of $\mu-$like events

Dominant $\nu_\mu \to \nu_\tau$ K2K; MINOS, CNGS

$-\nu_\odot$: Homestake, Kamiokande, SAGE, GALLEX/GNO
Super-Kamiokande, SNO; KamLAND

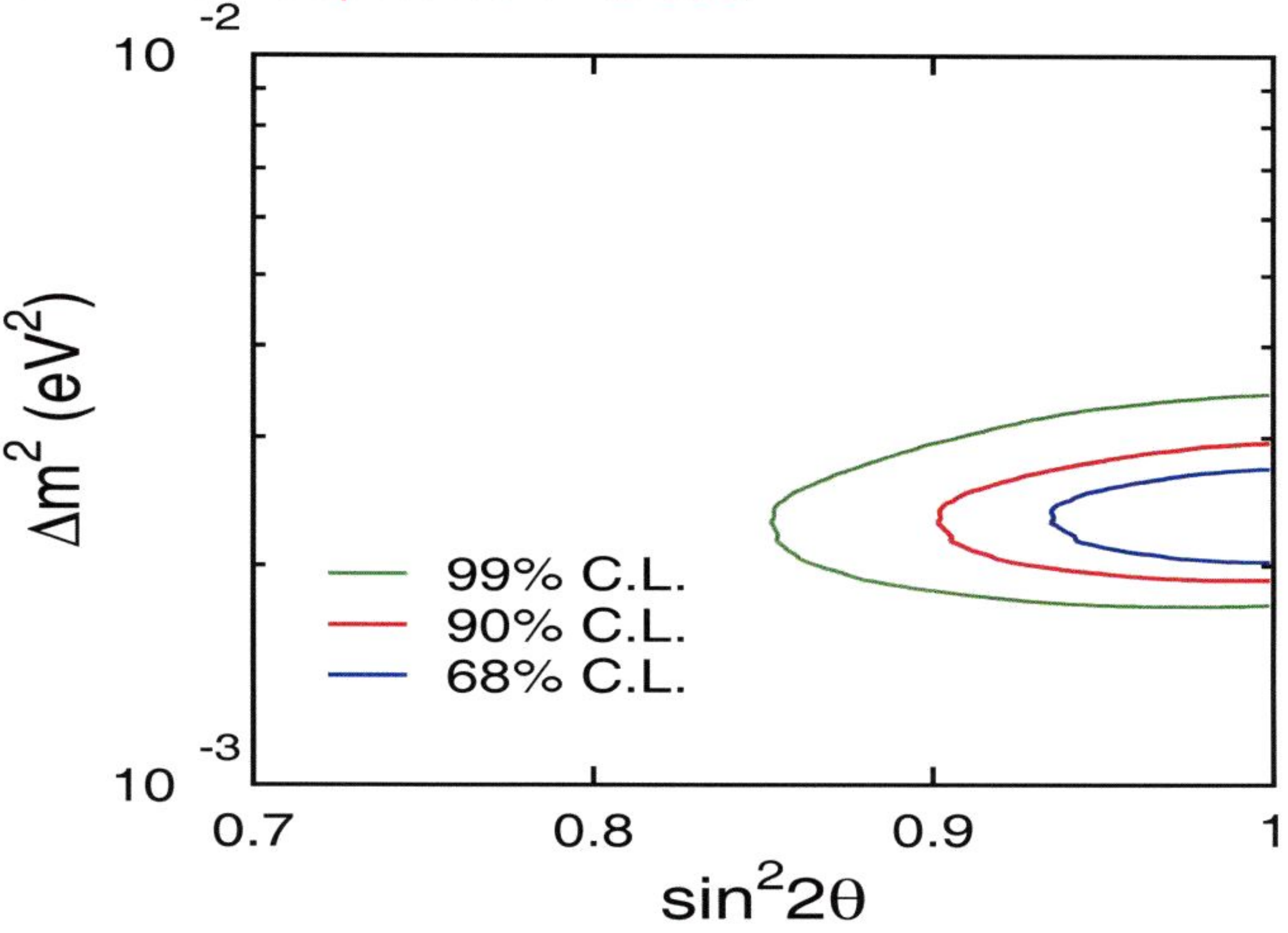
Dominant $\nu_e \to \nu_{\mu,\tau}$ BOREXINO,..., LowNu

– LSND

Dominant $\bar{\nu}_\mu \to \bar{\nu}_e$ MiniBOONE

$$\nu_{l\mathrm{L}} = \sum_{j=1} U_{lj}\,\nu_{j\mathrm{L}} \qquad l = e, \mu, \tau. \tag{1}$$

SK: Atmospheric ν Data



$$\Delta m^2_{\text{atm}} \equiv \Delta m^2_{31} = 2.1 \times 10^{-3} \text{ eV}^2, \ \sin^2\theta_{\text{atm}} \equiv \sin^2 2\theta_{23} = 1.0 \ ;$$

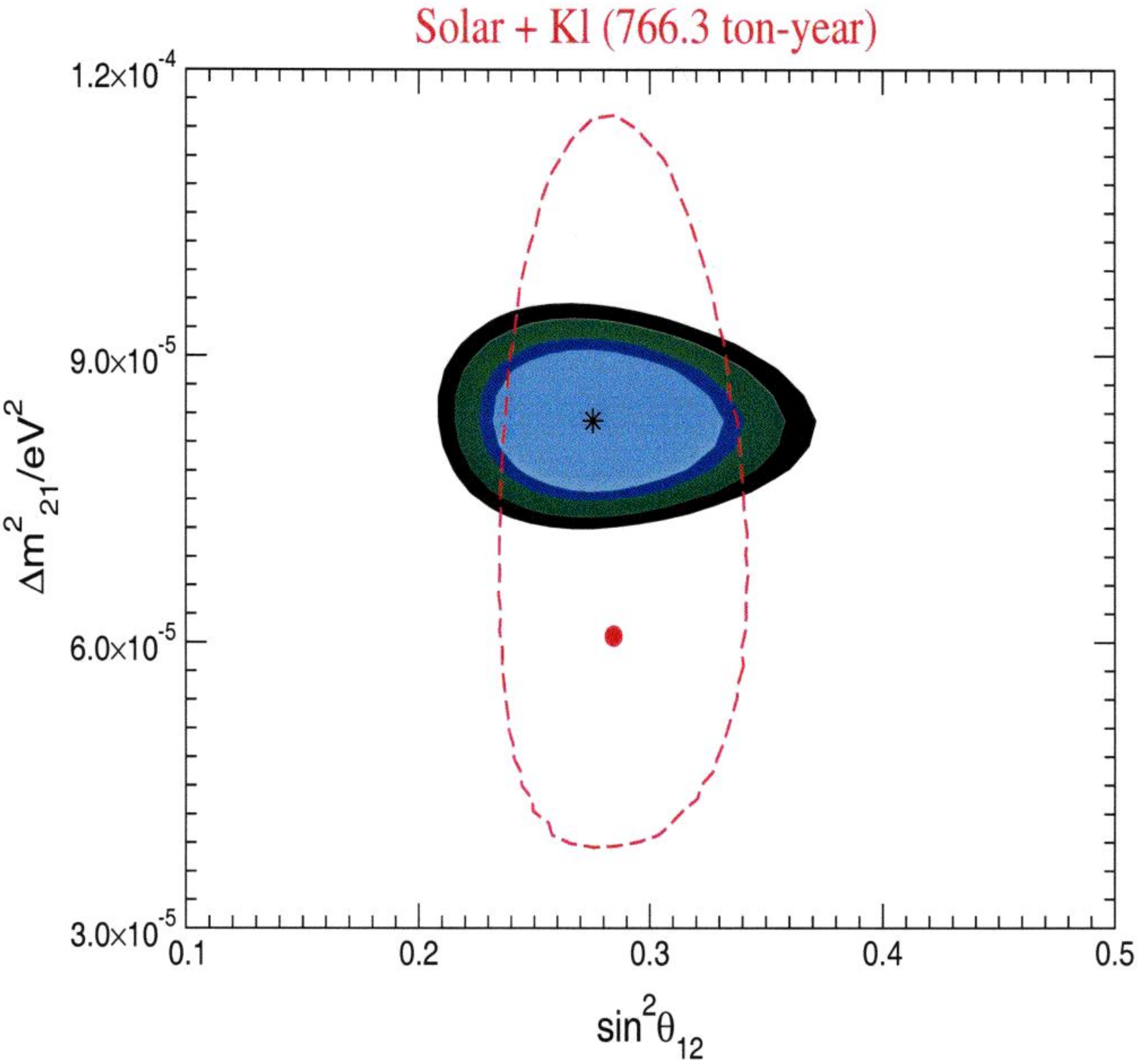
$$\Delta m^2_{31} = (1.5 - 3.4) \times 10^{-3} \text{ eV}^2, \ \sin^2 2\theta_{23} \geq 0.92, \quad 90\% \text{ C.L.}$$

- sign of Δm^2_{atm} not determined;

3-ν mixing: $\Delta m^2_{31} > 0$, $m_1 < m_2 < m_3$ (NH);

$\Delta m^2_{31} < 0$, $m_3 < m_1 < m_2$ (IH).

- If $\theta_{23} \neq \frac{\pi}{4}$: θ_{23}, $(\frac{\pi}{4} - \theta_{23})$ ambiguity.



$$\Delta m^2_\odot \equiv \Delta m^2_{21} = 8.3 \times 10^{-5}\ \text{eV}^2\ ,$$

$$\sin^2\theta_\odot \equiv \sin^2\theta_{12} = 0.27\ ;$$

$\cos 2\theta_{12} = 0.46$; $\cos 2\theta_{12} > 0.28$, 99% C.L.

- $\sin^2\theta_{12} = 0.50$ excluded at > 6 s.d.
- High-LMA excluded at > 3 s.d.

A. Bandyopadhyay et al, hep-ph/0406328

CHOOZ : $\bar{\nu}_e \rightarrow \bar{\nu}_e$

~ 1 km

$\bar{E}_\nu$ ~ 2 MeV

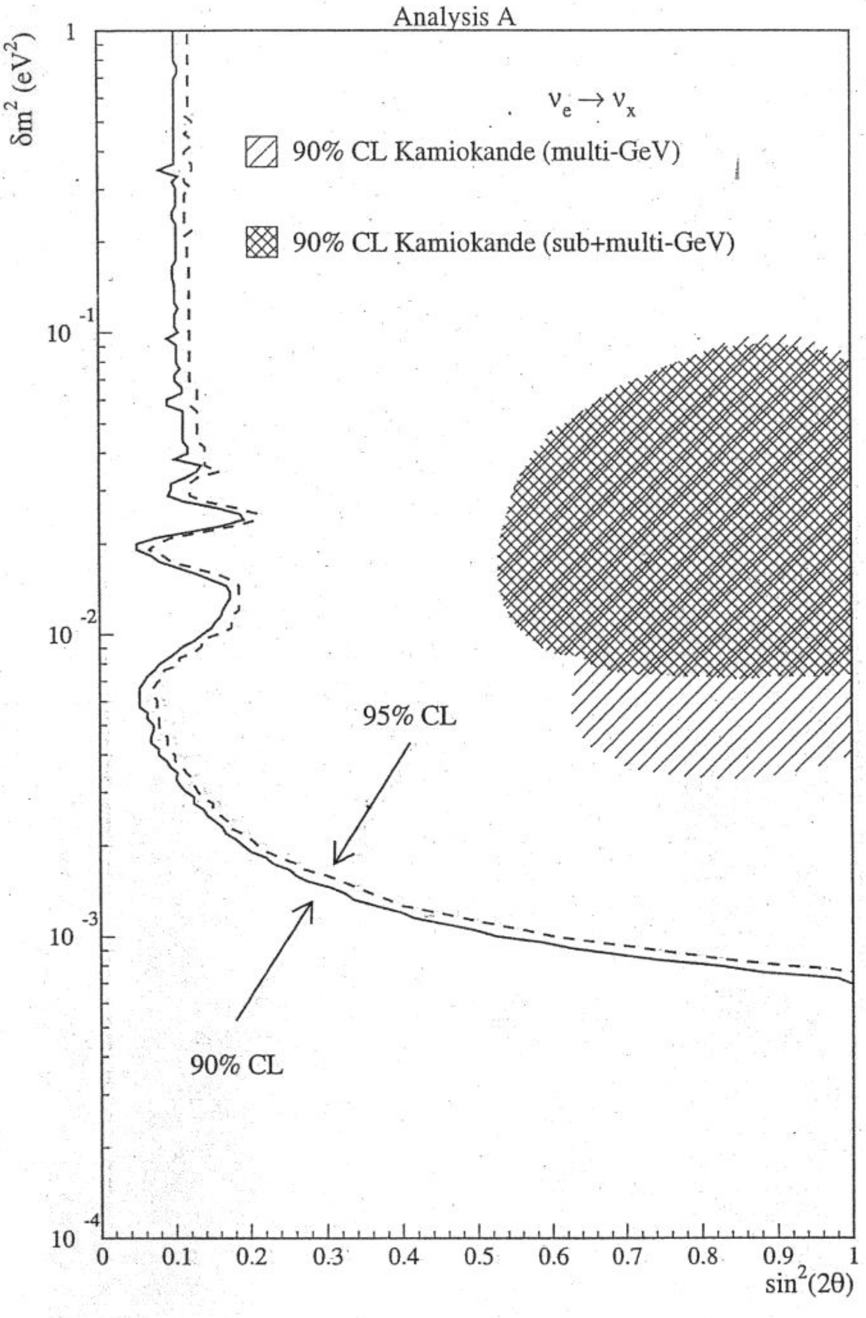
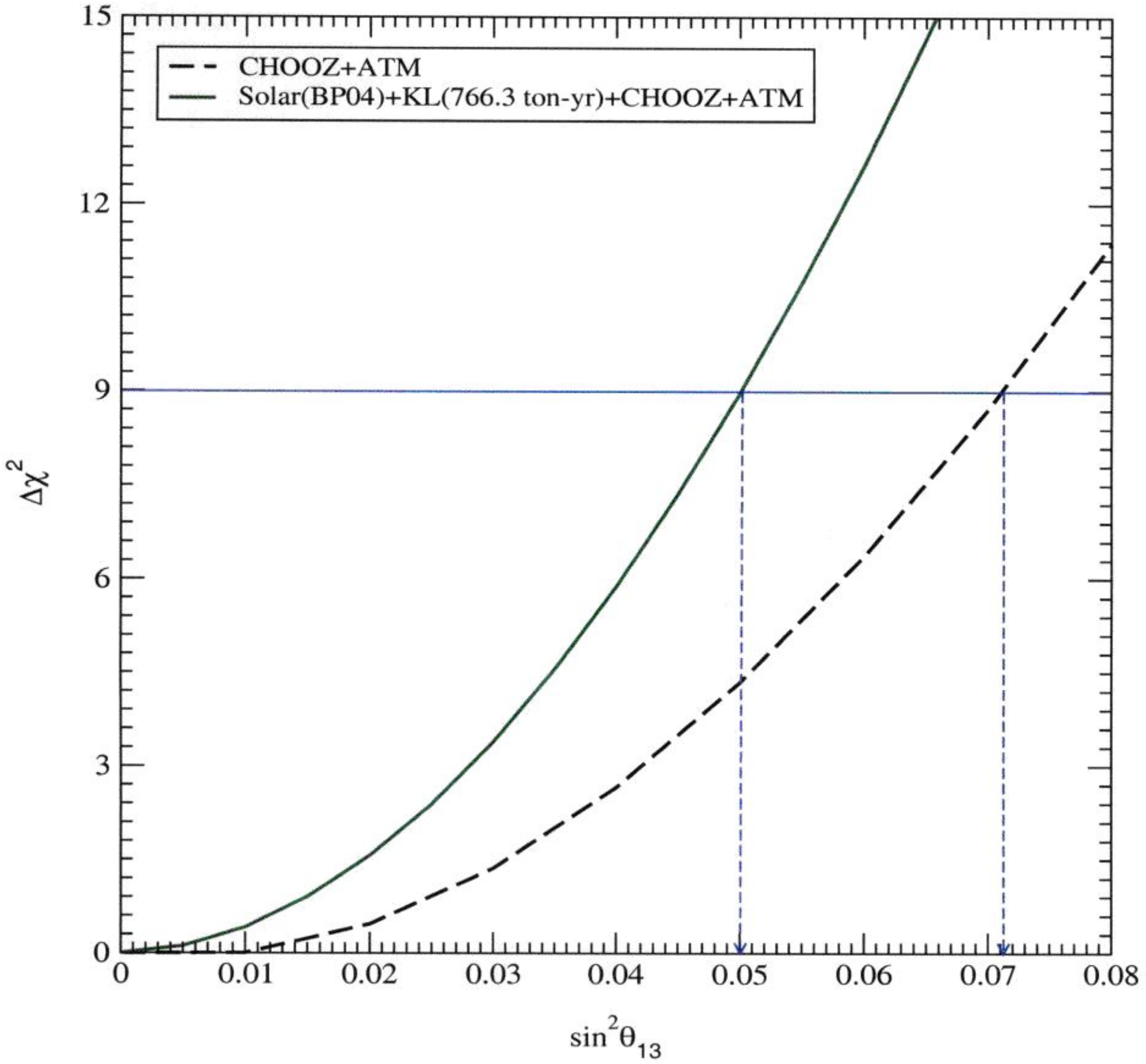


Figure 9: Exclusion plot for the oscillation parameters based on the absolute comparison of measured vs. expected positron yields.



$\Delta m^2_{\text{atm}} \equiv \Delta m^2_{31} = (1.3 - 4.2) \times 10^{-3}\ \text{eV}^2,\ 3\ s.d.$

SK: E. Kearns et al, talk given at Neutrino'04

- $\sin^2\theta_{13} < 0.05$ at 99.73% C.L.

A. Bandyopadhyay et al., hep-ph/0406328

Three Neutrino Mixing

$$\nu_{l\mathrm{L}} = \sum_{j=1}^{3} U_{lj}\, \nu_{j\mathrm{L}} \ . \tag{2}$$

U is the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) neutrino mixing matrix,

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \tag{3}$$

- U - $n \times n$ unitary:

	n	2	3	4
mixing angles:	$\frac{1}{2}n(n-1)$	1	3	6
CP-violating phases:				
• ν_j- Dirac:	$\frac{1}{2}(n-1)(n-2)$	0	1	3
• ν_j- Majorana:	$\frac{1}{2}n(n-1)$	1	3	6

$n = 3$: 1 Dirac and
2 additional CP-violating phases, Majorana phases

S.M. Bilenky, J. Hosek, S.T.P.,1980;
J. Schechter, J.W.F. Valle,1980;
M. Doi, T. Kotani, E. Takasugi,1981

Standard Parametrization

$$U = V \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\frac{\alpha_{21}}{2}} & 0 \\ 0 & 0 & e^{i\frac{\alpha_{31}}{2}} \end{pmatrix} \tag{4}$$

$$V = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13}e^{i\delta} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13}e^{i\delta} \end{pmatrix} \tag{5}$$

- $s_{ij} \equiv \sin\theta_{ij}$, $c_{ij} \equiv \cos\theta_{ij}$, $\theta_{ij} = [0, \frac{\pi}{2}]$,
- δ - Dirac CP-violation phase, $\delta = [0, 2\pi]$,
- α_{21}, α_{31} - the two Majorana CP-violation phases.
- If $\Delta m^2_{\odot} = \Delta m^2_{21} > 0$, $\Delta m^2_{\text{atm}} = \Delta m^2_{31}$,

then $\theta_{12} = \theta_{\odot}$, $\theta_{23} = \theta_{\text{atm}}$, $\theta_{13} = \theta$.

The angle θ is limited by the data from the CHOOZ and Palo Verde experiments.

- α_{21}, α_{31}:
  - $\nu_l \leftrightarrow \nu_{l'}$, $\bar{\nu}_l \leftrightarrow \bar{\nu}_{l'}$ not sensitive;

    S.M. Bilenky, J. Hosek, S.T.P.,1980;
    P. Langacker et al.,1987;
  - $|<m>|$ in $(\beta\beta)_{0\nu}$–decay depends on α_{21}, α_{31};
  - $\Gamma(\mu \to e + \gamma)$ etc. in SUSY theories depend on $\alpha_{21,31}$;
  - BAU, leptogenesis scenario: $\alpha_{21,31}$?

Neutrino Mixing Parameters

$\theta_{12}, \theta_{23}, \theta_{13}$

ν_j	Dirac	Majorana
	δ	$\delta, \alpha_{21}, \alpha_{31}$

$m_1, \quad m_2, \quad m_3$

m_2, m_3 - in terms of $\Delta m^2_\odot$, $\Delta m^2_{\rm atm}$ and m_1

Conventions

A. $m_1 < m_2 < m_3$ (NH) or $m_3 < m_1 < m_2$ (IH)

- $\Delta m^2_\odot = \Delta m^2_{21} > 0$
- $\Delta m^2_{\rm atm} = \Delta m^2_{31} > 0$ (NH), $\Delta m^2_{\rm atm} = \Delta m^2_{32} < 0$ (IH)
- $m_2 = \sqrt{m_1^2 + \Delta m^2_{21}}$, $m_3 = \sqrt{m_1^2 + \Delta m^2_{31}}$

B. $m_1 < m_2 < m_3$

- $\Delta m^2_{\rm atm} = \Delta m^2_{31} > 0$

Two possibilities:

$\Delta m^2_\odot = \Delta m^2_{21} > 0$, NH

$\Delta m^2_\odot = \Delta m^2_{32} > 0$, IH

"discrete" parameter

Future Progress

- High precision determination of $\Delta m^2_\odot$, $\theta_\odot$, $\Delta m^2_{\rm atm}$, θ_{atm}.

- Measurement of, or improving by at least a factor of (5 - 10) the existing upper limit on, $\sin^2\theta_{13}$.

- Determination of the type of the $\nu-$ mass spectrum

$$m_1 \ll m_2 \ll m_3, \qquad \text{NH},$$

$$m_1 \ll m_2 \cong m_3, \qquad \text{IH},$$

$$m_1 \cong m_2 \cong m_3,\ m^2_{1,2,3} >> \Delta m^2_{\rm atm},\ \text{QD};\ m_j \gtrsim 0.20 \text{ eV}.$$

- Determining or obtaining significant constraints on the absolute scale of neutrino masses, or on m_1.

- Determination of the nature - Dirac or Majorana, of ν_j .

- Status of the CP-symmetry in the lepton sector: violated due to δ (Dirac), and/or due to α_{21}, α_{31} (Majorana)?

- Searching for possible manifestations, other than ν_l-oscillations, of the non-conservation of L_l, $l = e, \mu, \tau$, such as $\mu \to e + \gamma$, $\tau \to \mu + \gamma$, etc. decays.

- Understanding at fundamental level the mechanism giving rise to the $\nu-$ masses and mixing and to the L_l-non-conservation, i.e., finding The Theory of $\nu-$mixing.

$\nu_\odot$, Δm^2_{atm}, CHOOZ Data:

- $\theta_{12} = \theta_\odot \cong \frac{\pi}{6}$, $\qquad \theta_{23} = \theta_{\text{atm}} \cong \frac{\pi}{4}$, $\qquad \theta_{13} < \frac{\pi}{12}$

$$U = \begin{pmatrix} \frac{\sqrt{3}}{2} & \frac{1}{2} & \epsilon \\ -\frac{1}{2\sqrt{2}} & \frac{\sqrt{3}}{2\sqrt{2}} & \frac{1}{\sqrt{2}} \\ \frac{1}{2\sqrt{2}} & -\frac{\sqrt{3}}{2\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix} \tag{6}$$

Very different from the CKM-matrix!

- $\cos\theta_{12} \cong \cos(\frac{\pi}{4} - \frac{\pi}{12}) = \frac{1}{\sqrt{2}}(1+\lambda)$, $\quad \sin\theta_{12} \cong \frac{1}{\sqrt{2}}(1-\lambda)$,
- $\lambda \cong (0.20 - 0.25)$: $\quad \theta_\odot + \theta_c = \pi/4$?

Natural Possibility:

$$U = U^\dagger_{\text{lep}}(\lambda)\; U_{\text{bimax}} \tag{7}$$

with

$$U_{\text{bimax}} = \begin{pmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & 0 \\ -\frac{1}{2} & \frac{1}{2} & \frac{1}{\sqrt{2}} \\ \frac{1}{2} & -\frac{1}{2} & \frac{1}{\sqrt{2}} \end{pmatrix} \tag{8}$$

- $U^\dagger_{\text{lep}}(\lambda)$ - from diagonalization of the l^- mass matrix,
- U_{bimax} - from diagonalization of the $\nu-$mass matrix

Further, $\Delta m^2_\odot \ll |\Delta m^2_{\text{atm}}|$.

- U_{bimax} can be associated with a symmetry:

$$L' = L_e - L_\mu - L_\tau$$

S.T.P., 1982

This symmetry cannot be exact.

HOW?

- $\nu_\odot-$, $\nu_{\text{atm}}-$ experiments

  SK (ν_{atm}), INO (ν_{atm})

  SNO

  GNO, SAGE

  BOREXINO

  LowNu (XMASS, LENS,...)
- Reactor Experiments $\sim (1 - 180)$ km
- Accelerator Experiments

K2K	250 km
MINOS (ν_{atm})	732 km
OPERA, ICARUS	732 km

- Super Beams

JHF (T2K), SK (HK)	295 km
NuMI (NOνA)	$\sim$800 km
SPL+$\beta-$beams, UNO (1 megaton): CERN-Frejus	$\sim$140 km
$\nu-$Factories	$\sim$ 3000, 7000 km

- $(\beta\beta)_{0\nu}-$Decay, ^{3}H $\beta-$Decay
- Astrophysics, Cosmology

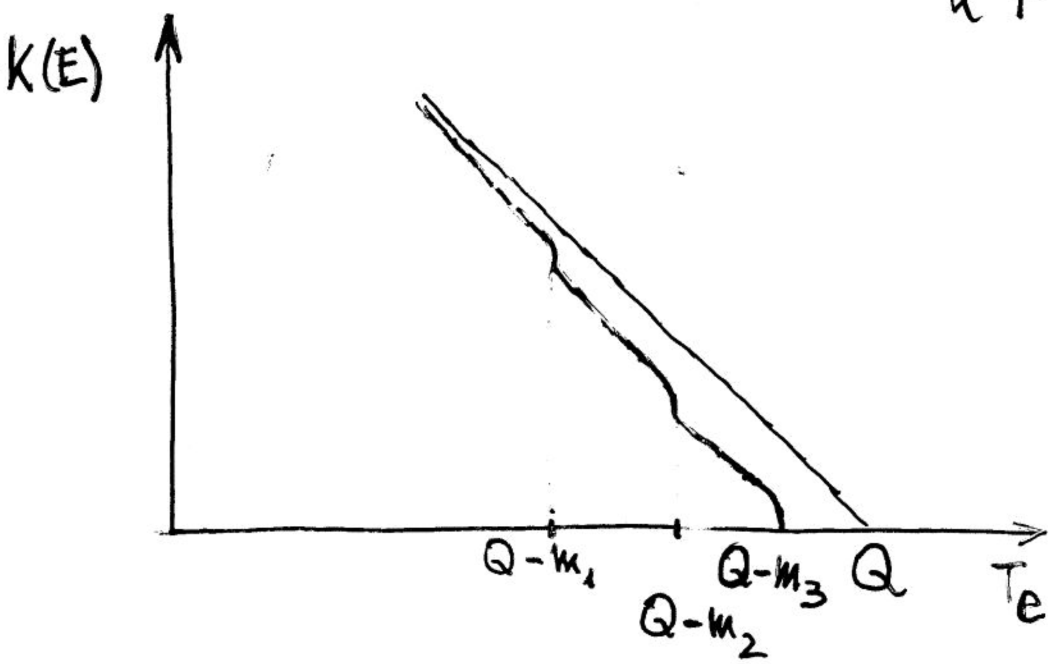
INFORMATION ABOUT ν-MASS SPECTRUM

$^3H \rightarrow {}^3He + e^- + \bar{\nu}_e$ FERMI 1934

e^- - SPECTRUM

$$\frac{dN_e}{dE} = \sum_{j=1} |U_{ej}|^2 \, W(E, m_j^2)$$

$$W(E, m_j^2) = c\, p_e E\, (Q - T_e) \sqrt{(Q-T_e)^2 - m_j^2} \times$$
$$\times F(E)$$



Absolute Neutrino Mass Measurements

The Troitzk and Mainz ^{3}H β-decay experiments

$$m_{\nu_e} < 2.2 \text{ eV} \qquad (95\% \text{ C.L.})$$

There are prospects to reach sensitivity

$$\text{KATRIN}: \qquad m_{\nu_e} \sim 0.2 \text{ eV}$$

Cosmological and astrophysical data: the WMAP result

$$\sum_j m_j < 0.70 \text{ eV} \quad (95\% \text{ C.L.}) \quad (X \sim 2)$$

The WMAP and future PLANCK experiments can be sensitive to

$$\sum_j m_j \cong 0.4 \text{ eV}$$

Data on weak lensing of galaxies by large scale structure, combined with data from the WMAP and PLANCK experiments may allow to determine

$$\sum_j m_j : \qquad \delta \cong 0.04 \text{ eV}.$$

$(\beta\beta)_{0\nu}$–Decay Experiments:

- Majorana nature of ν_j
- Type of ν–mass spectrum (NH, IH, QD)
- Absolute neutrino mass scale

^{3}H β-decay , cosmology: m_ν

- CPV due to Majorana CPV phases

$A(\beta\beta)_{0\nu} \sim <m>$ M, M – NME,

$|<m>| = \left|m_1|U_{e1}|^2 + m_2|U_{e2}|^2\, e^{i\alpha_{21}} + m_3|U_{e3}|^2\, e^{i\alpha_{31}}\right|$,

α_{21}, α_{31} - the two Majorana CPVP of the PMNS matrix.

Best sensitivity: Heidelberg-Moscow ^{76}Ge experiment.
Claim for a positive signal at $> 3\sigma$:
H. Klapdor-Kleingrothaus et al., PL B586 (2004),

$|<m>| = (0.1 - 0.9)$ eV (99.73% C.L.).

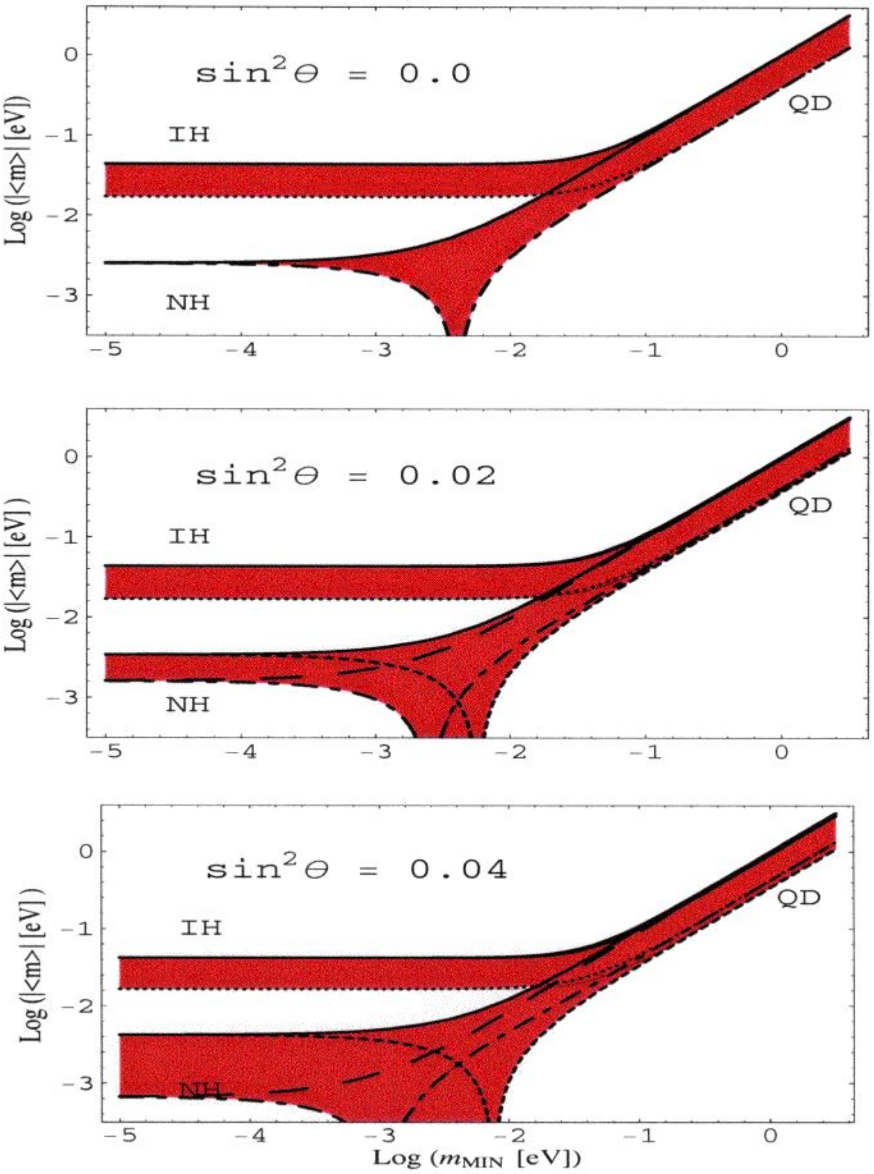
IGEX ^{76}Ge: $|<m>| < (0.33 - 1.35)$ eV (90% C.L.).

Taking data - NEMO3 (^{100}Mo), CUORICINO (^{130}Te):

$|<m>| \sim (0.2 - 0.3)$ eV

Large number of projects: $|<m>| \sim (0.01 - 0.05)$ eV

CUORE - ^{130}Te,
GENIUS - ^{76}Ge,
EXO - ^{136}Xe,
MAJORANA - ^{76}Ge,
MOON - ^{100}Mo,
CANDLES - ^{48}Ca,
XMASS - ^{136}Xe.



S. Pascoli, S.T.P., hep-ph/0310003

Highest Priority: θ_{13}

- Controls the sub-dominant $\nu_\mu \leftrightarrow \nu_e$ and $\bar{\nu}_\mu \leftrightarrow \bar{\nu}_e$ oscillations

  - of the atmospheric ν's

  - in LBL experiments MINOS, OPERA,...

  - in VLBL experiments at $\nu-$factories

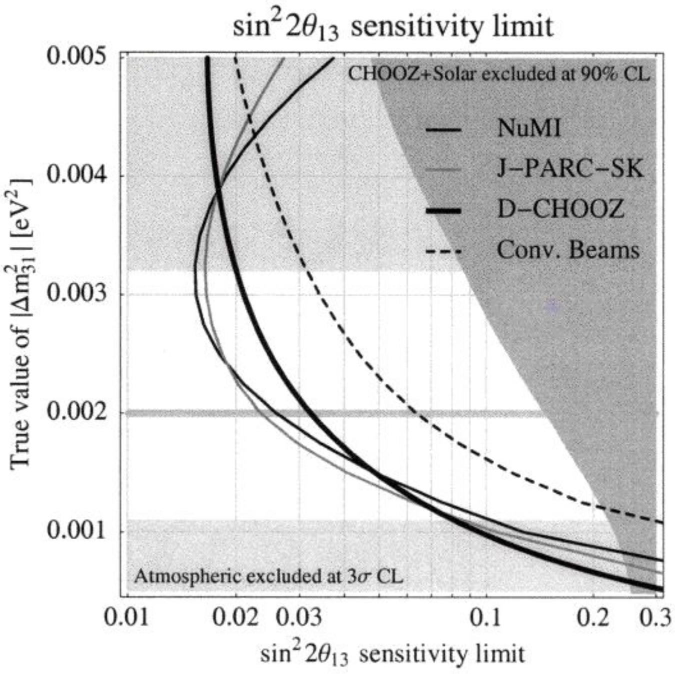
- Controls together with $\sin\delta$ the magnitude of CP- and T-violating effects in $\nu-$oscillations

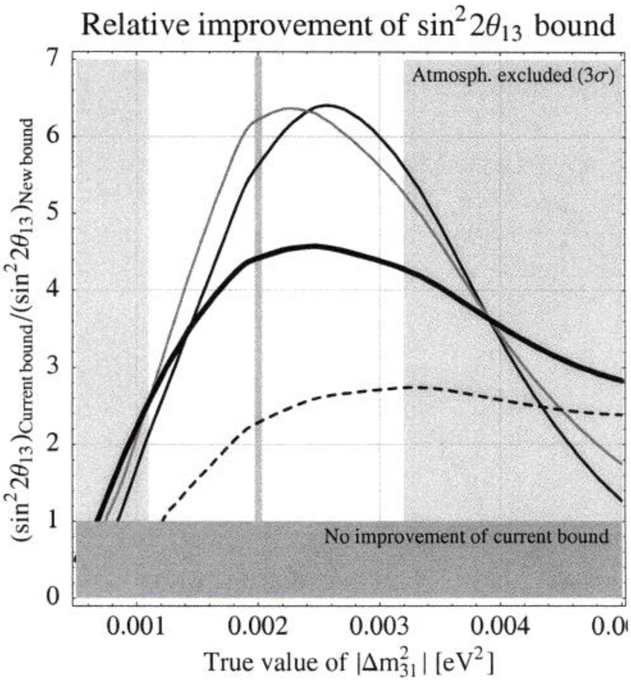
- $|\langle m \rangle|$ in $(\beta\beta)_{0\nu}$-decay for NH

- The knowledge of the value of θ_{13} is crucial for the searches for correct theory of $\nu-$masses and mixing

Sensitivity of future experiments to $\sin^2 2\theta_{13}$

Conventional beams: MINOS, ICARUS, OPERA
Reactor experiments: Double-CHOOZ
Super beam off-axis experiments: T2K, NOνA (NuMI)





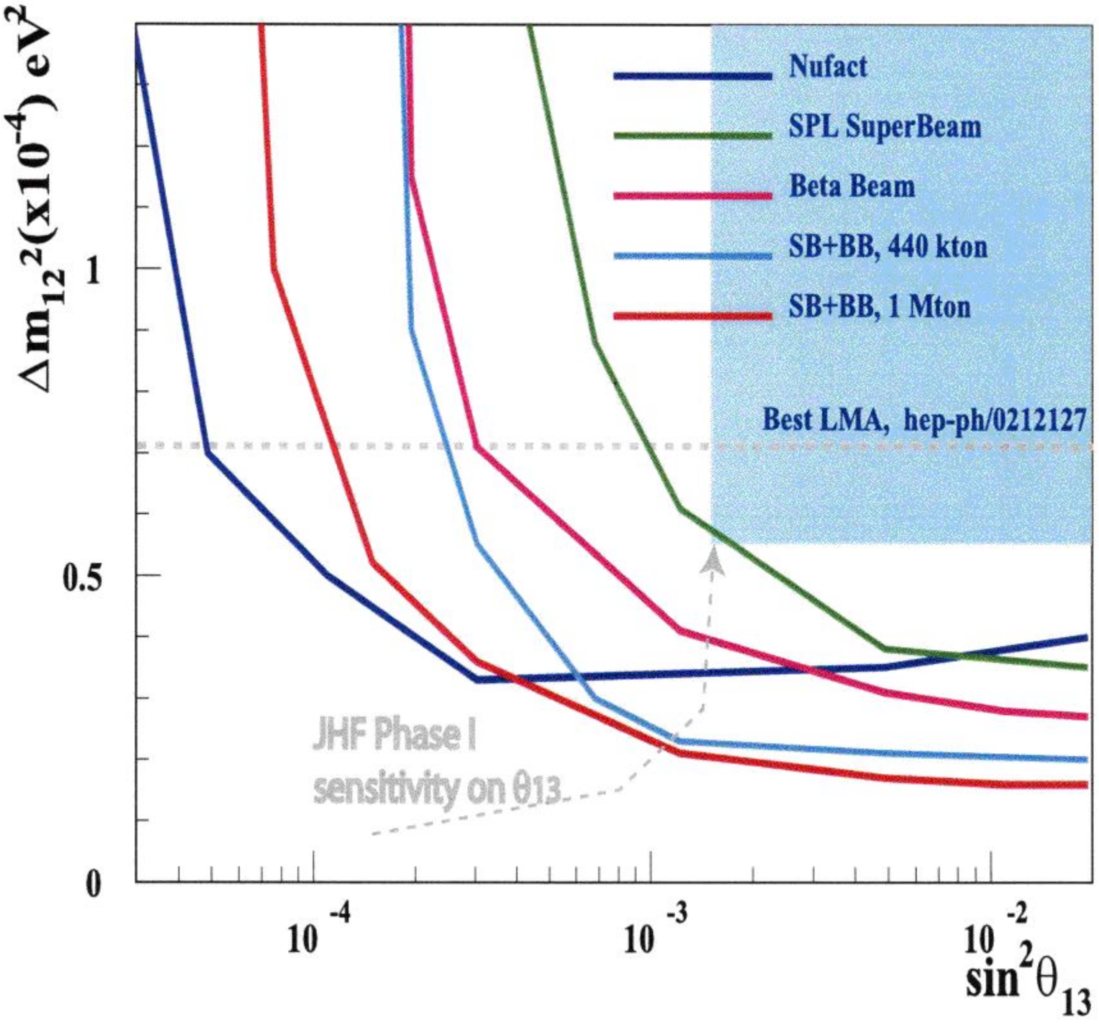
P.Huber et al., hep-ph/0403068

Proposals for reactor experiments: KASKA (Japan), U.S.A.

L.A. Mikhaelyan et al., hep-ex/9908047 and 0211070

H. Minakata et al., hep-ph/0211111

After Moriond, very preliminary



$$\Delta m^2_{\odot} = \Delta m^2_{21},\ \theta_{\odot} = \theta_{12}$$

Data from $\nu_{\odot}$- experiments

- **SNO**: $A_{\text{D-N}} < 6\%$

  would restrict further Δm^2_{21} from below

  $R_{\text{CC/NC}} = 0.306 \pm 0.035$, reducing the error

  would restrict further

  i) Δm^2_{21} from above, ii) the range of $\sin^2\theta_{12}$

- **BOREXINO**
- LowNu (pp neutrinos) - **LENS, XMASS**: $\sin^2 2\theta_{12}$

  (uncertainty due to $\sin^2\theta_{13}$)

Reactor Experiments

Future more precise KamLAND data

KamLAND: Low-LMA - Δm^2_{21} with high precision

$\sin^2\theta_{12}$ cannot be determined with a high precision

("wrong distance")

even with SHIGA-2 reactor to be operative in 2006

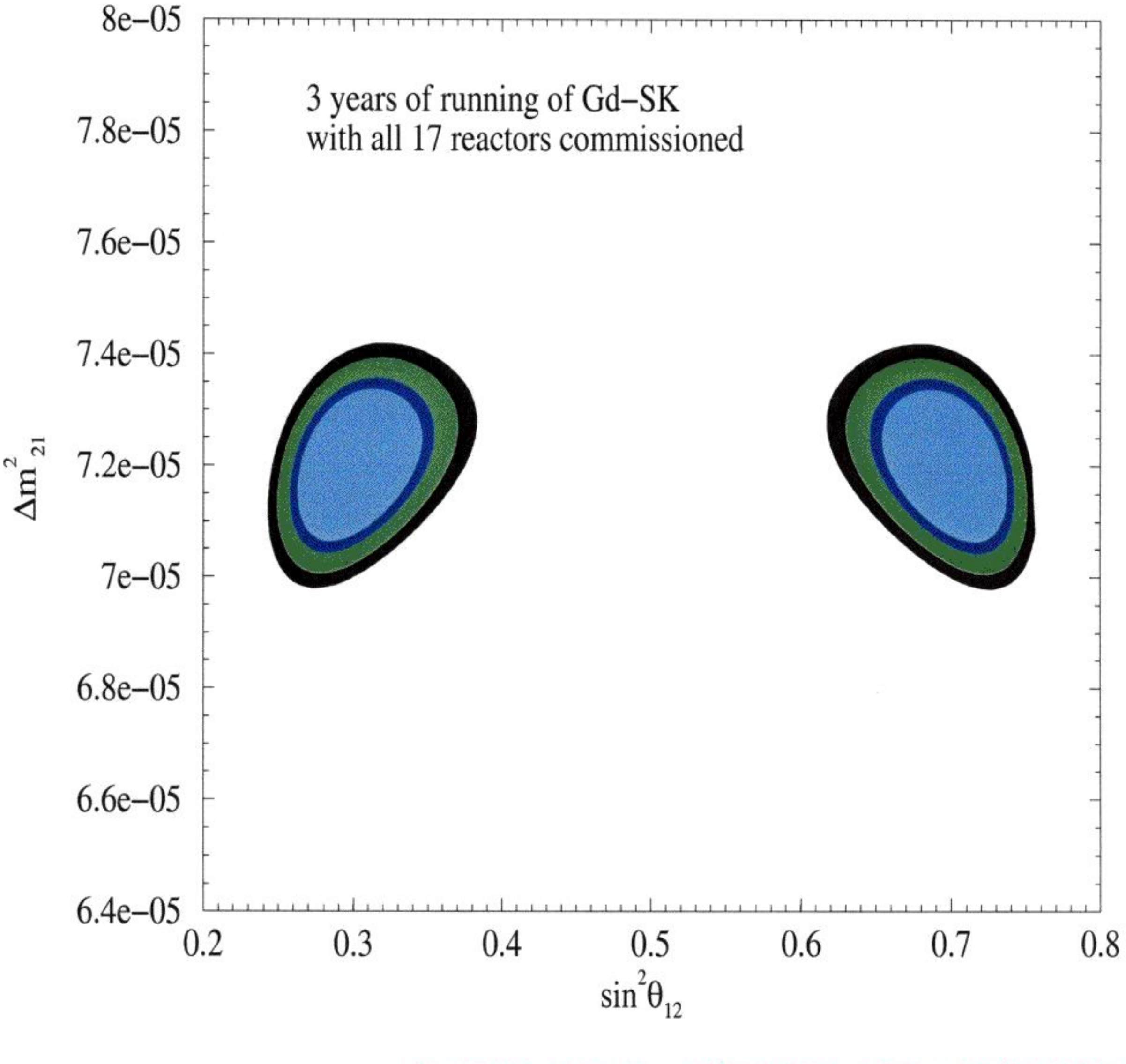
("right distance" but signal too weak)

Low-LMA: $L \sim 60$ km: $\sin^2 2\theta_{12}$

SK + 0.2% Gd

J.F. Beacom and M.R. Vagins, hep-ph/0309300

SK-Gd reactor $\bar{\nu}_e$ rate ~ 43 times KamLAND rate



S.T.P. and S. Choubey, hep-ph/0404103

Sensitivity to Δm^2_{21} and $\sin^2\theta_{12}$

$$\text{spread} = \frac{a_{max} - a_{min}}{a_{max} + a_{min}}, \quad p \equiv \Delta m^2_{21} \text{ or } \sin^2\theta_{12}$$

Data set used	99% CL range of $\Delta m^2_{21}\times$ 10^{-5}eV^2	99% CL spread of Δm^2_{21}	99% CL range of $\sin^2\theta_{12}$	99% CL spread in $\sin^2\theta_{12}$
only solar	3.2 - 14.9	65%	0.22 – 0.37	25%
solar+162 Ty KL	5.2 - 9.8	31%	0.22 – 0.37	25%
solar with future SNO	3.3 – 11.9	57%	2.2 – 0.34	21%
solar+1 kTy KL(low-LMA)	6.5 - 8.0	10%	0.23 – 0.37	23%
solar+2.6 kTy KL(low-LMA)	6.7 – 7.7	7%	0.23 – 0.36	22%
solar with future SNO+1.3 kTy KL(low-LMA)	6.7 – 7.8	8%	0.24 – 0.34	17%
3 yrs SK-Gd	7.0 - 7.4	2.7%	0.25 – 0.37	19%
5 yrs SK-Gd	7.05 – 7.35	2.1%	0.26 – 0.35	15%
solar+3 yrs SK-Gd(low-LMA)	7.0 – 7.4	3%	0.25 – 0.34	15%
solar+3 yrs SK-Gd(high-LMA)	14.5 – 15.4	3%	0.24 – 0.37	21%
solar with future SNO+3 yrs SK-Gd(low-LMA)	7.0 – 7.4	3%	0.25 – 0.335	14%
solar with future SNO+3 yrs SK-Gd(high-LMA)	14.5 – 15.4	3%	0.24 – 0.35	19%
3 yrs SK-Gd with Kashiwazaki "down"	6.8 – 7.6	6%	0.23 – 0.40	27%
7 yrs SK-Gd with *only* Shika-2 "up"	7.0 – 7.3	< 1%	0.28 – 0.32	6.7%

Table 1: The range of parameter values allowed at 99% C.L. and their corresponding spread.

$|\Delta m^2_{31}|$, sign(Δm^2_{31}), θ_{23}

MINOS: $|\Delta m^2_{31}|$ $\sim 10\%$

JHF (T2K), SK: $P(\nu_\mu \rightarrow \nu_\mu)$; $P(\nu_\mu \rightarrow \nu_e)$, $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ at maximum: $|\Delta m^2_{31}|\ L/(4E) = \pi/2$

- $|\Delta m^2_{31}|$, $\sin^2 2\theta_{23}$ high precision
- The sign(Δm^2_{31}) - a problem
- Exact $\delta \leftrightarrow (\pi - \delta)$ degeneracy
- If $\sin^2 2\theta_{23} < 1$: $\sin^2 \theta_{23} > 0.5$, $\sin^2 \theta_{23} < 0.5$ ambiguity

Lead to ambiguities in the measurements of $\sin^2 \theta_{13}$ and δ

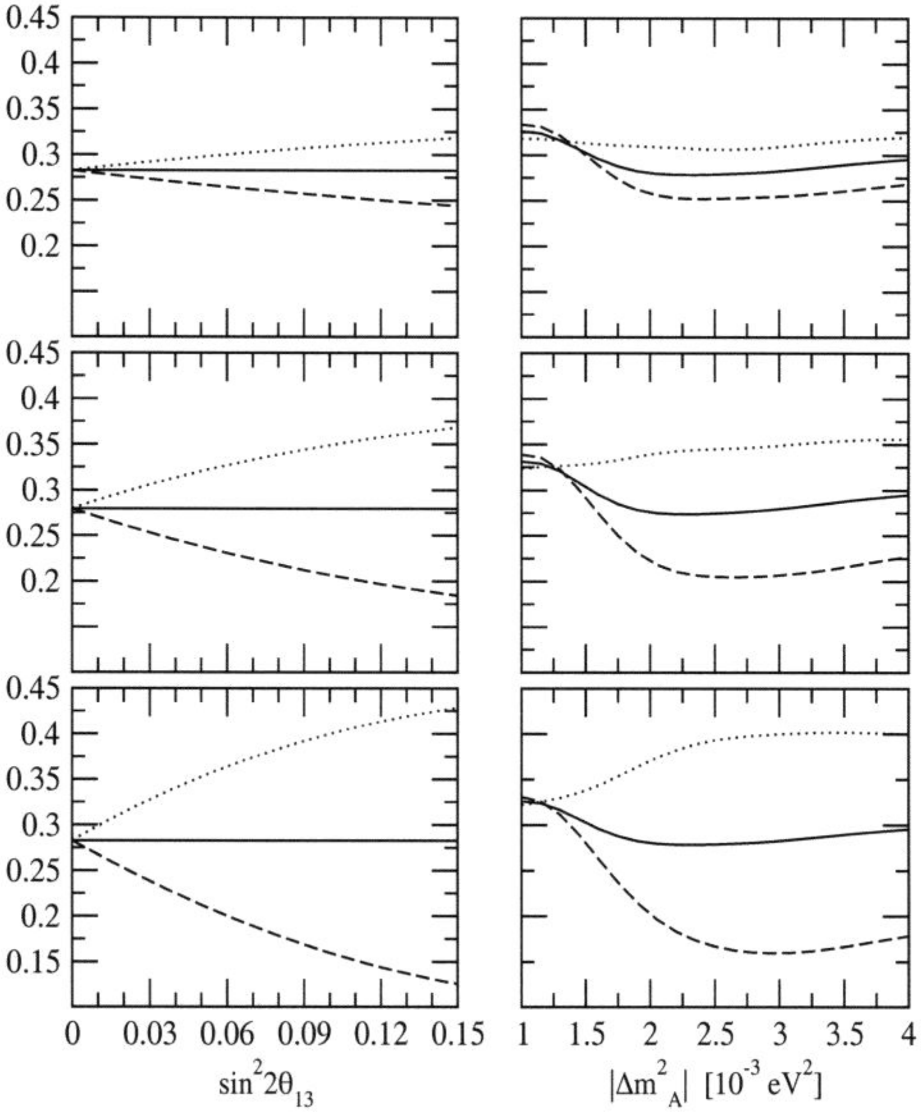
J. Burguet-Castell et al., hep-ph/0103258
V. Barger, D. Marfatia, K. Whisnant, hep-ph/0112119
H. Minakata, H. Nunokawa, S.J. Parke, hep-ph/0301210
P. Huber et al., hep-ph/0403068
O. Yasuda, hep-ph/0405005

Resolving the ambiguities may require data from

NuMI off-axis, and/or

new off-maximum JHF, and/or

SPL + $\beta-$beams experiment(s).



Iron Magnetized Detectors (MINOS, INO): multi-GeV μ^- and μ^+ event rates, N_{μ^-} and N_{μ^+}

$A \equiv \frac{U-D}{U+D}$ **in the θ_n- dependence of** $\frac{N_{\mu^-}}{N_{\mu^+}}$

- $|\Delta m^2_{31}| = 3 \times 10^{-3}$ eV^2, $\sin^2\theta_{23} =$**0.36, 0.50, 0.64**
- $\Delta m^2_{31} > 0$-**NH (dashed),** $\Delta m^2_{31} < 0$-**IH (dotted), 2**$-\nu$ **(solid)**

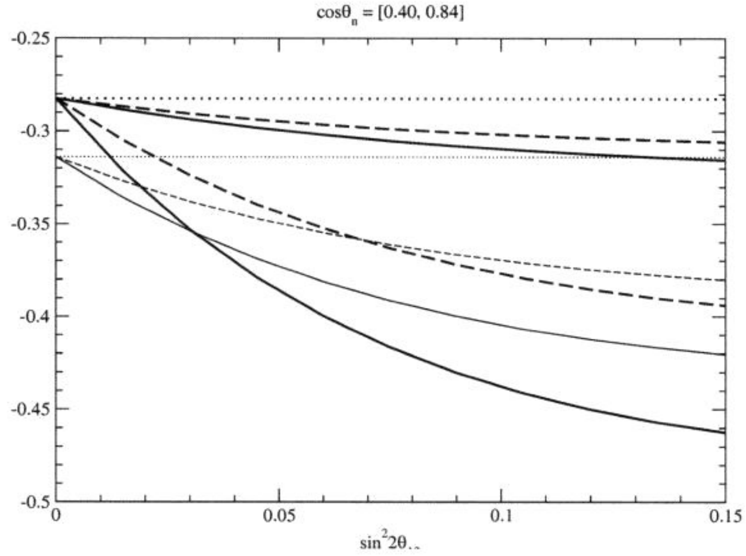
$\cos\theta_n = (0.30 - 0.84)$ **mantle bin, E = [5,20] GeV**

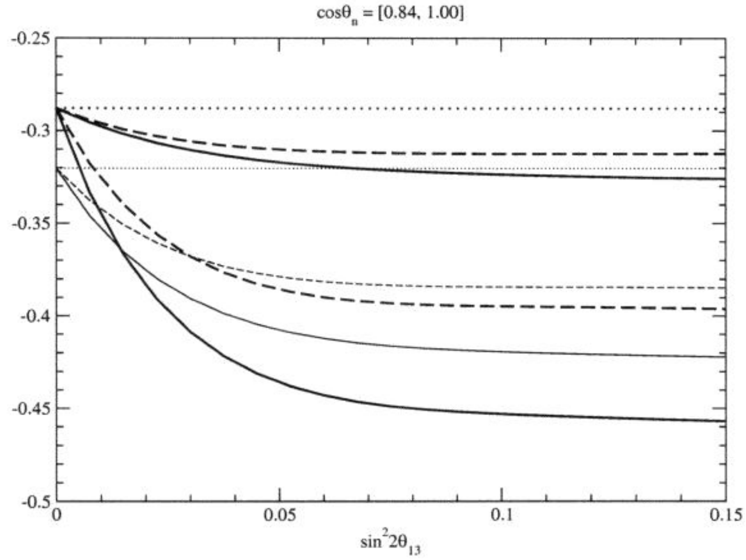
S.T.P., S. Palomares-Ruiz, hep-ph/0406

Water-Čerenkov Detectors (SK, etc.): multi-GeV $\mu-$like and $e-$like event rates, N_μ and N_e

$A \equiv \frac{U-D}{U+D}$ **in the** θ_n- **dependence of** $\frac{N_\mu}{N_e}$

- $|\Delta m^2_{31}| = 2 \times 10^{-3}$ eV^2, $\sin^2\theta_{23}$ =**0.36, 0.50, 0.64**
- $\Delta m^2_{\rm atm} > 0$-**NH (solid),** $\Delta m^2_{\rm atm} < 0$-**IH (dashed),** $2-\nu$ **(dotted)**





Instead of Conclusions

We are at the beginning of the Road...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磨針嶺
広重画
魚栄