

STATUS OF NEUTRINO FITS

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Atmospheric $\nu_\mu \rightarrow \nu_\tau$ (Super-K) \iff Accelerator ν_μ disappearance (K2K)

Solar $\nu_e \rightarrow \nu_\mu, \nu_\tau$ (SNO) \iff Reactor $\bar{\nu}_e$ disappearance (KamLAND)

Cosmology (CMB+LSS) $\implies \sum m_{\text{light neutrinos}} \lesssim 1 \text{ eV}$

XXXVIIIth Rencontres de Moriond, ElectroWeak Interactions and Unified Theories
Les Arcs 1800, March 2003

MAIN CHARACTERISTICS OF SOLAR ν DATA

Experiment	Reaction	E_{th} (MeV)	ν Flux Sensitivity	Operating Time	$\frac{R^{exp}}{R^{BP2000}}$
SAGE	$\nu_e + {}^{71}\text{Ga} \rightarrow {}^{71}\text{Ge} + e^-$	0.233	$pp, {}^7\text{Be}, {}^8\text{B},$ $pep, hep,$ ${}^{13}\text{N}, {}^{15}\text{O}, {}^{17}\text{F}$	1990 – 2001	0.55 ± 0.05
GALLEX				1991 – 1997	0.61 ± 0.06
GNO				1998 – 2000	0.51 ± 0.08
Homestake	$\nu_e + {}^{37}\text{Cl} \rightarrow {}^{37}\text{Ar} + e^-$	0.814	${}^7\text{Be}, {}^8\text{B},$ $pep, hep,$ ${}^{13}\text{N}, {}^{15}\text{O}, {}^{17}\text{F}$	1970 – 1994	0.34 ± 0.03
Kamiokande	$\nu + e^- \rightarrow \nu + e^-$	6.75	${}^8\text{B}$	1987 – 1995 2079 days	0.55 ± 0.08
Super-Kam.		4.75		1996 – 2001 1496 days	0.465 ± 0.015
SNO	$\nu_e + d \rightarrow p + p + e^-$	6.9	${}^8\text{B}$	1999 – 2002 306.4 days	0.35 ± 0.02
	$\nu + d \rightarrow p + n + \nu$	2.2			1.01 ± 0.13
	$\nu + e^- \rightarrow \nu + e^-$	5.2			0.47 ± 0.05

$$\Phi_{hep} < 7.9 \Phi_{hep}^{SSM} \quad (90\% \text{ C.L.})$$

[Smy (SK), Neutrino 2002]

SK & SNO \implies no spectral distortion

$$\mathcal{A}_{ND}^{SK} = 0.021 \pm 0.024$$

[SK, PLB 539 (2002) 179]

SK \implies no seasonal variation

$$\mathcal{A}_{ND}^{SNO} = 0.070 \pm 0.051$$

[SNO, PRL 89 (2002) 011302]

SK & SNO \implies very small night-day asymmetry

THE TRIUMPH OF SNO

Sudbury Neutrino Observatory, 1 kton of D₂O, $T_{\text{eff}} \geq 5 \text{ MeV} \Rightarrow \nu_{8B}$

CC $\nu_e + d \rightarrow p + p + e^-$ $E_{\nu}^{\text{th}} \simeq 6.9 \text{ MeV}$

NC $\nu + d \rightarrow p + n + \nu$ $E_{\nu}^{\text{th}} \simeq 2.2 \text{ MeV}$

ES $\nu + e^- \rightarrow \nu + e^-$ $E_{\nu}^{\text{th}} \simeq 5.2 \text{ MeV}$

assuming no spectral distortions

$$R_{\text{CC}}^{\text{SNO}} \equiv \Phi_{\text{CC}}^{\text{SNO}} / \Phi_{\nu_e}^{\text{SSM}} = 0.35 \pm 0.02$$

$$R_{\text{NC}}^{\text{SNO}} \equiv \Phi_{\text{NC}}^{\text{SNO}} / \Phi_{\nu_e}^{\text{SSM}} = 1.01 \pm 0.13$$

$$R_{\text{ES}}^{\text{SNO}} \equiv \Phi_{\text{ES}}^{\text{SNO}} / \Phi_{\nu_e}^{\text{SSM}} = 0.47 \pm 0.05$$

[SNO, PRL 89 (2002) 011301]

EVIDENCE OF $\nu_e \rightarrow \nu_{\mu}, \nu_{\tau} \Rightarrow$ MIXING!

$$\Phi_{\nu_e} = \Phi_{\text{CC}}^{\text{SNO}} = (1.76 \pm 0.11) \times 10^6 \text{ cm}^{-2} \text{ s}^{-1}$$

$$\begin{aligned} \Phi_{\nu_{\mu}, \nu_{\tau}} &= \Phi_{\text{NC}}^{\text{SNO}} - \Phi_{\text{CC}}^{\text{SNO}} \\ &= (3.33 \pm 0.65) \times 10^6 \text{ cm}^{-2} \text{ s}^{-1} \quad (5.1\sigma) \end{aligned}$$

APPEARANCE EXPERIMENT !

Super-Kamiokande

22.5 ktons of H₂O, $E_{\nu}^{\text{th}} \simeq 4.75 \text{ MeV} \Rightarrow \nu_{8B}$

$$R_{\text{ES}}^{\text{SK}} \equiv \Phi_{\text{ES}}^{\text{SK}} / \Phi_{\nu_e}^{\text{SSM}} = 0.465 \pm 0.015 \quad [\text{SK, PLB 539 (2002) 179}]$$

SNO SOLVED SOLAR NEUTRINO PROBLEM



NEUTRINO PHYSICS

OKKAM'S RAZOR



CONSIDER SIMPLEST HYPOTHESIS



$\nu_e \rightarrow \nu_\mu, \nu_\tau$ oscillations

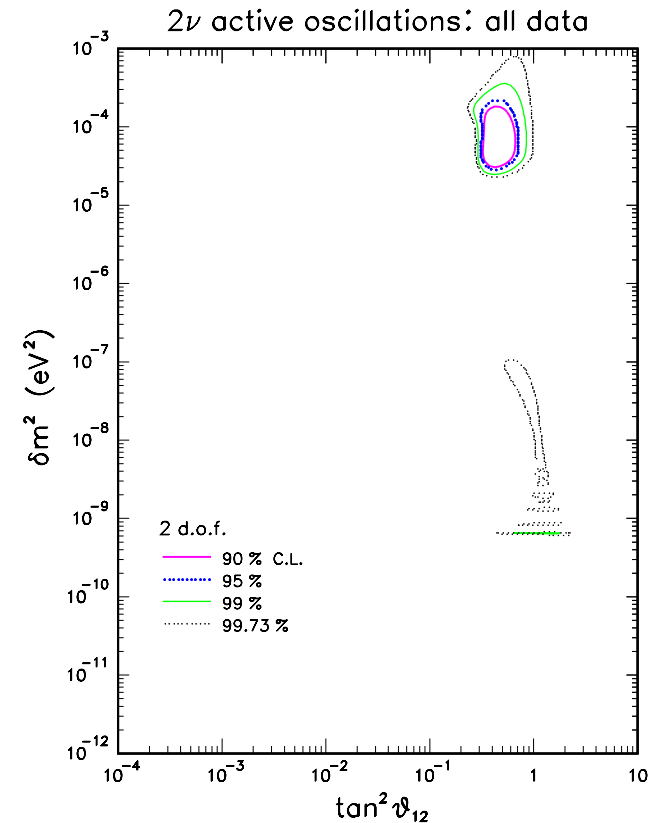


Large Mixing Angle solution

LMA

$$\Delta m^2 \simeq 5 \times 10^{-5} \text{ eV}^2$$

$$\tan^2 \vartheta \simeq 0.4$$



90%, 95%, 99%, 99.73% (3σ) C.L.

[Fogli, Lisi, Marrone, Montanino, Palazzo, PRD 66 (2002) 053010]

see also

[SNO, PRL 89 (2002) 011302]

[Barger, Marfatia, Whisnant, Wood, PLB 537 (2002) 179]

[Bahcall, Gonzalez-Garcia, Peña-Garay, JHEP 07 (2002) 054]

[SK, PLB 539 (2002) 179]

[de Holanda, Smirnov, PRD66 (2002) 113005]

[Aliani et al., PRD 67 (2003) 013006]

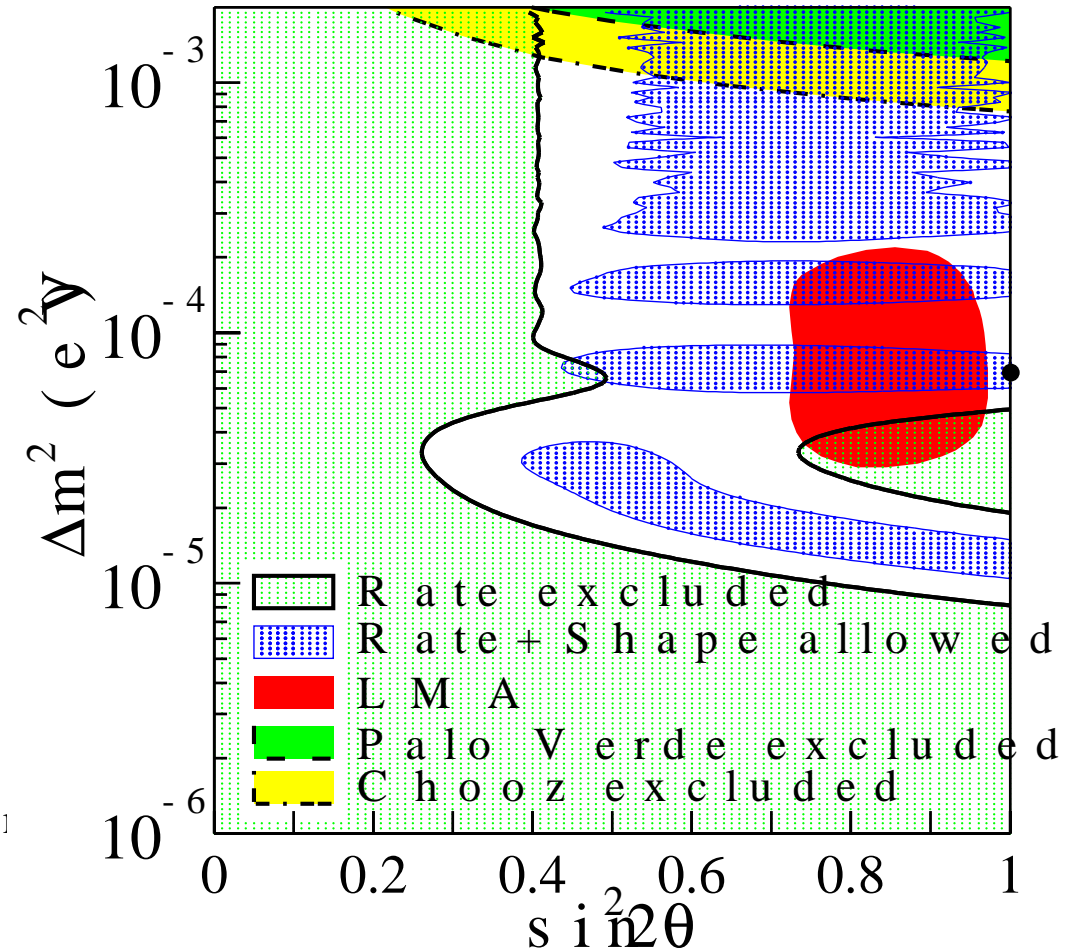
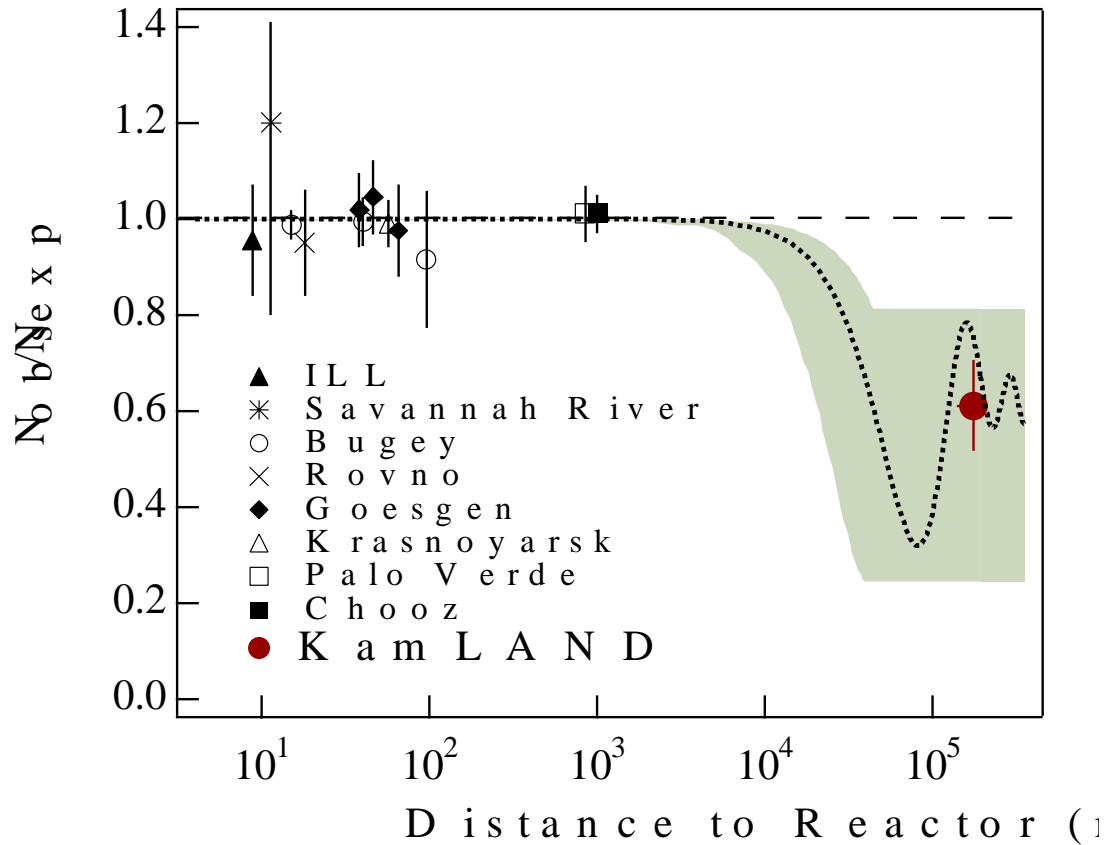
[Bandyopadhyay et al., PLB 540 (2002) 14]

[Creminelli, Signorelli, Strumia, hep-ph/0102234]

[Maltoni, Schwetz, Tortola, Valle, PRD 67 (2003) 013011]

KamLAND \Rightarrow spectacular confirmation of LMA

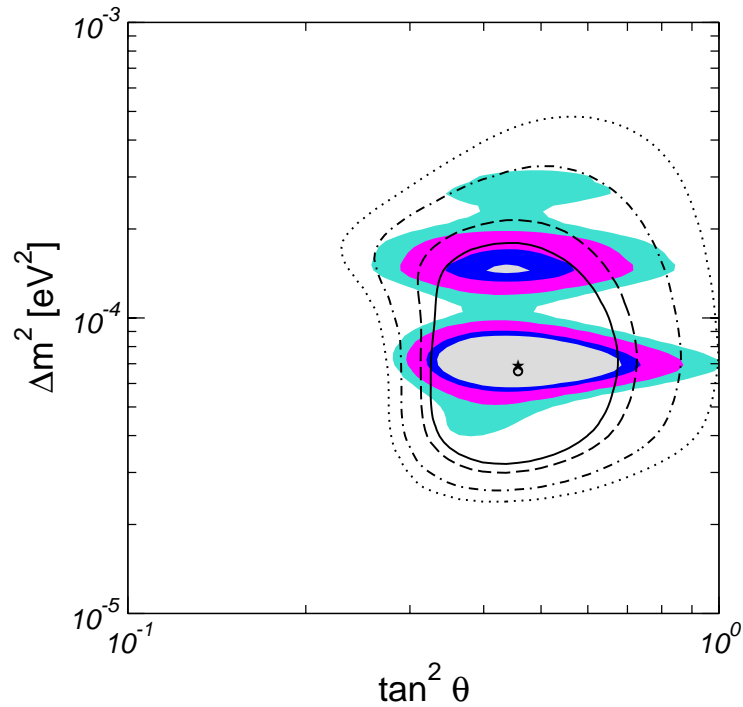
Kamioka Liquid scintillator Anti-Neutrino Detector, long-baseline reactor $\bar{\nu}_e$ experiment



95% C.L.

[KamLAND, PRL 90 (2003) 021802]

Fits of reactor + solar neutrino data



90%, 95%, 99%, 99.73% (3σ) C.L.

[Maltoni, Schwetz, Valle, hep-ph/0212129]

see also

[Barger, Marfatia, hep-ph/0212126]

[Fogli et al., hep-ph/0212127]

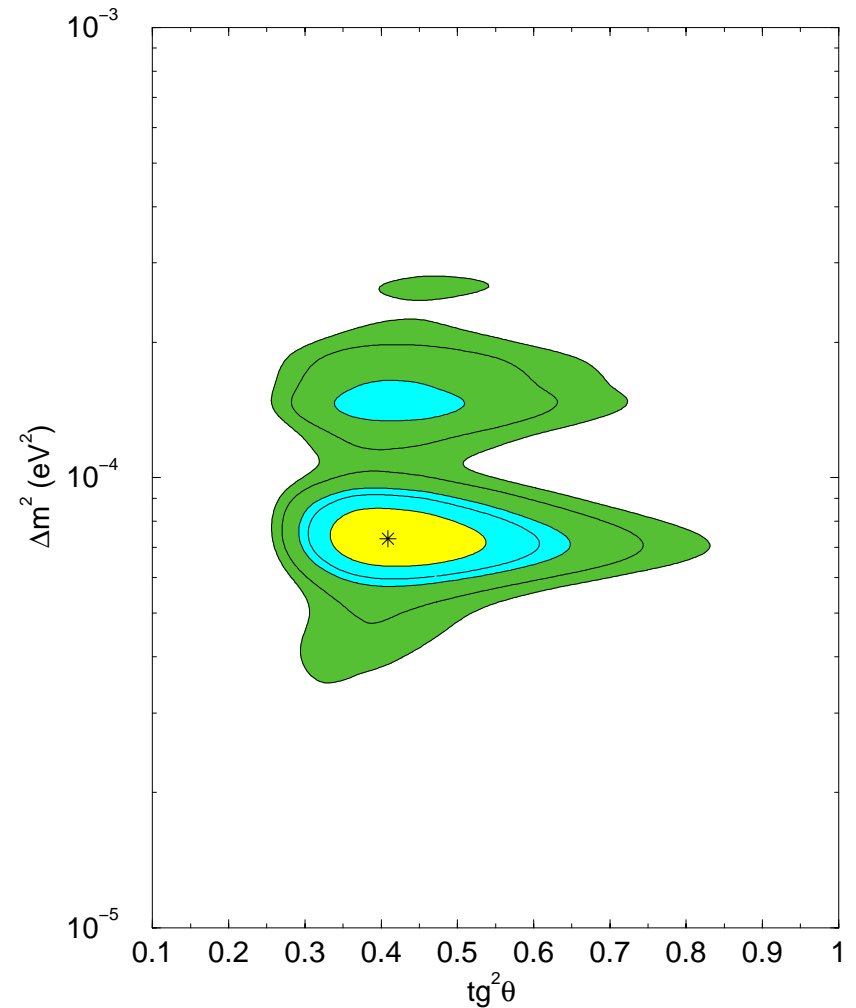
[Bandyopadhyay et al., hep-ph/0212146]

[Bahcall, Gonzalez-Garcia, Pena-Garay, hep-ph/0212147]

[Nunokawa, Teves, Zukanovich Funchal, hep-ph/0212202]

[Aliani, Antonelli, Picariello, Torrente-Lujan, hep-ph/0212212]

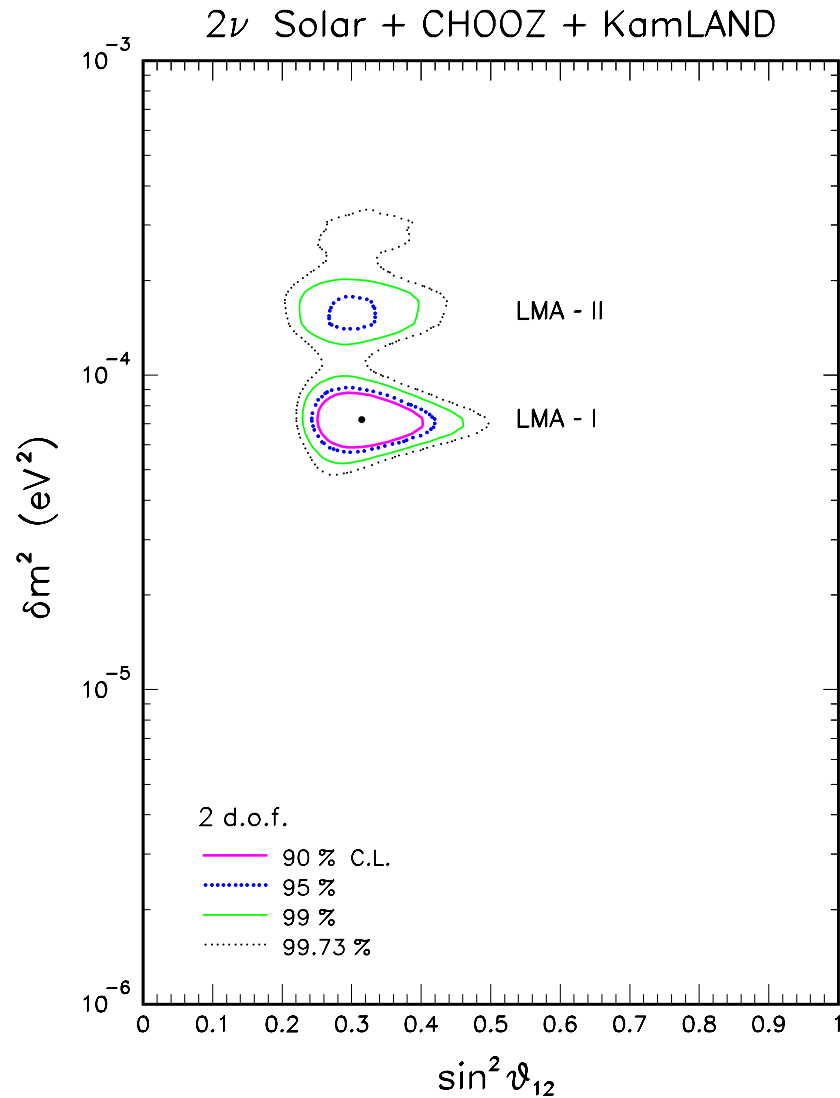
[Balantekin, Yuksel, hep-ph/0301072]



68.3% (1σ) 90%, 95%, 99%, 99.73% (3σ) C.L.

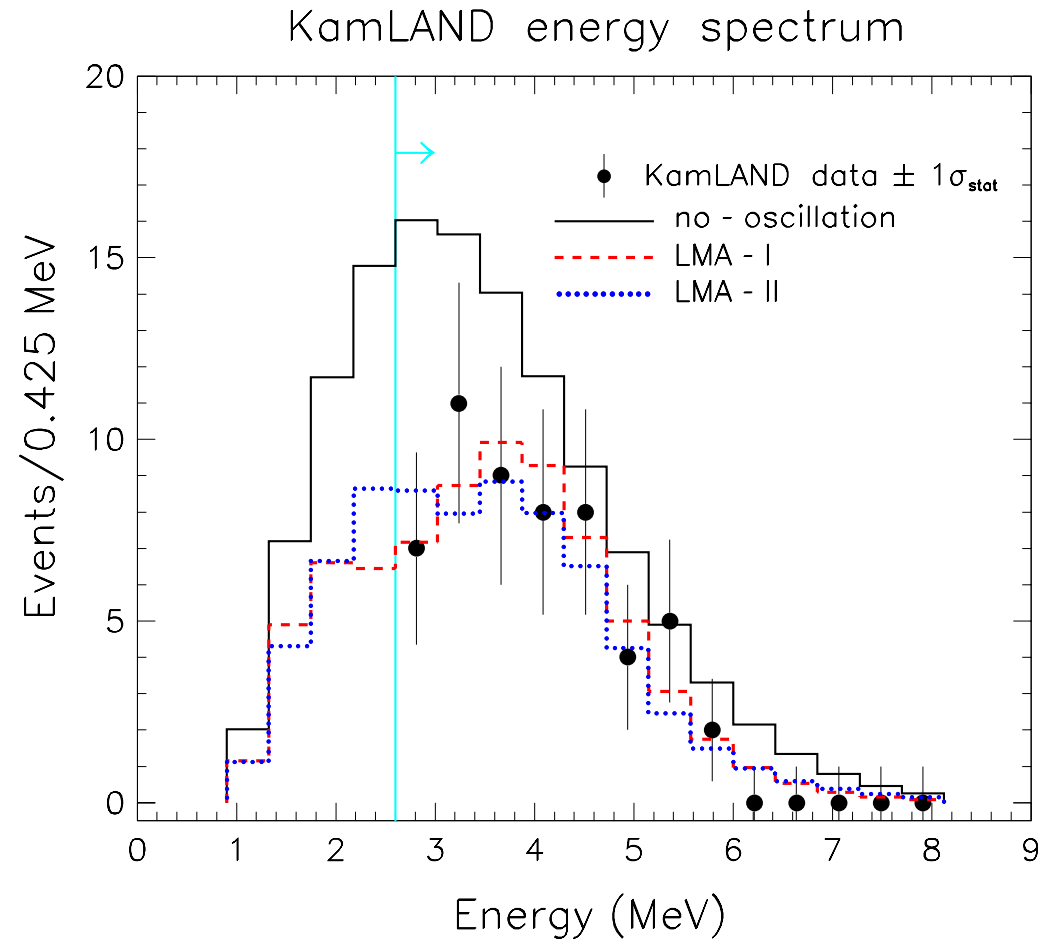
[de Holanda, Smirnov, hep-ph/0212270]

LMA-I or LMA-II?



90%, 95%, 99%, 99.73% (3σ) C.L.

[Fogli et al., hep-ph/0212127]



— different energy peak

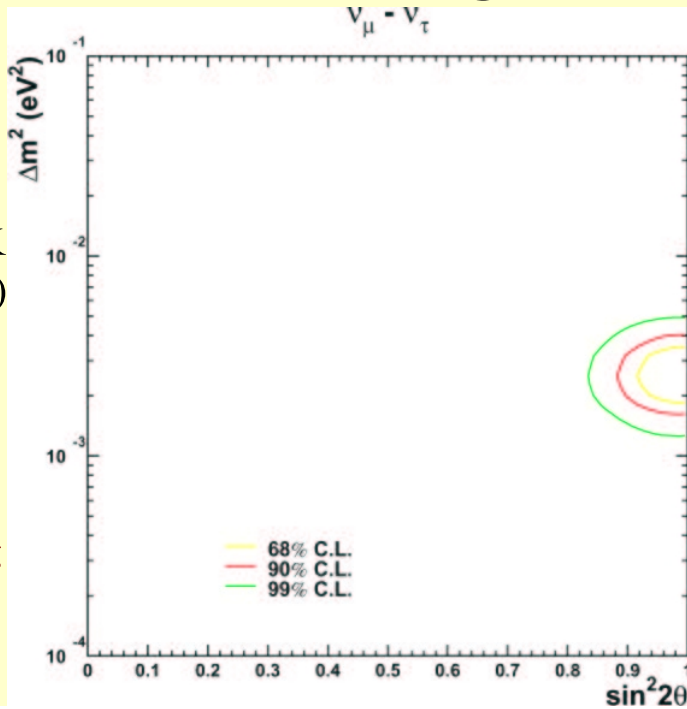
— bin at $E \simeq 2.4$ MeV

ATMOSPHERIC NEUTRINOS

Super-Kamiokande Up-Down asymmetry: $A_\mu = \left(\frac{U-D}{U+D} \right)_\mu = -0.311 \pm 0.043 \pm 0.01 \quad (7\sigma)$

Atmospheric Allowed Region

- Disappearance of μ -type, no appearance of e -type: $\nu_\mu \rightarrow \nu_\tau$
- Uses all Super-K data sets (1290d) FC, PC, up μ and multi-ring
- Very good χ^2 (175.0/190)
- Maximal mixing

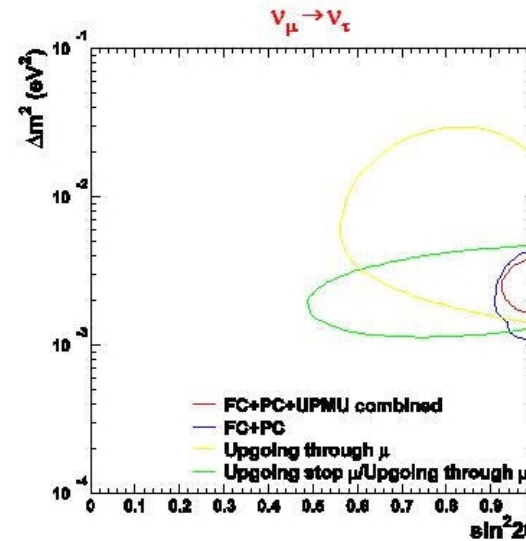


Michael Smy, UC Irvine

[Smy (SK), Moriond 2002]

Combined allowed regions

May-2002 Neutrino2002 @ Munich



$\nu_\mu \leftrightarrow \nu_\tau$ oscillations

Best fit ($\Delta m^2 = 2.5 \times 10^{-3}, \sin^2 2\theta = 1.0$)

$\chi^2_{\min} = 163.2/170$ d.o.f)

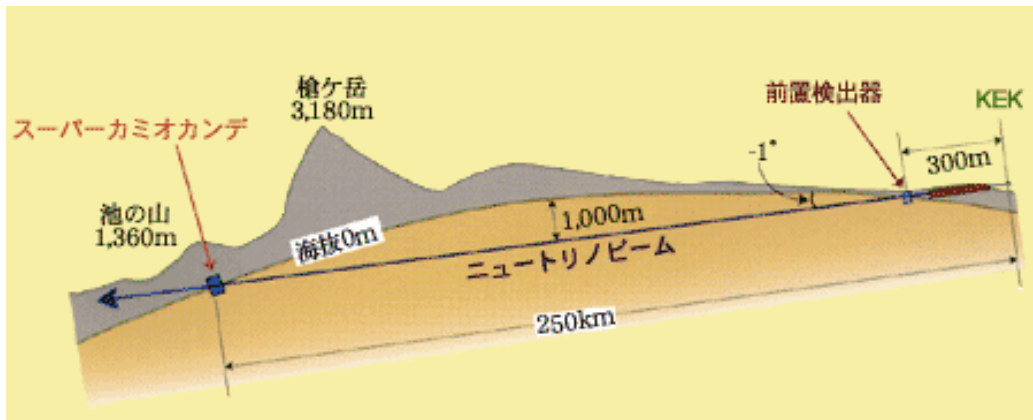
No oscillation

($\chi^2 = 456.5/172$ d.o.f)

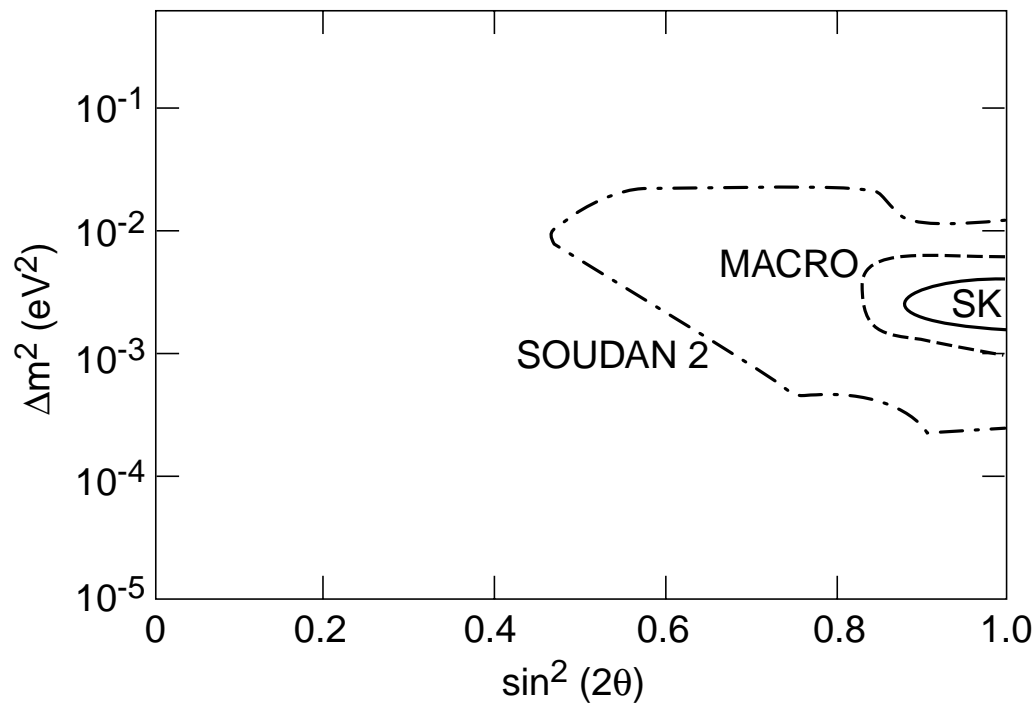
$\Delta m^2 = (1.6 \sim 3.9) \times 10^{-3} \text{eV}^2$

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

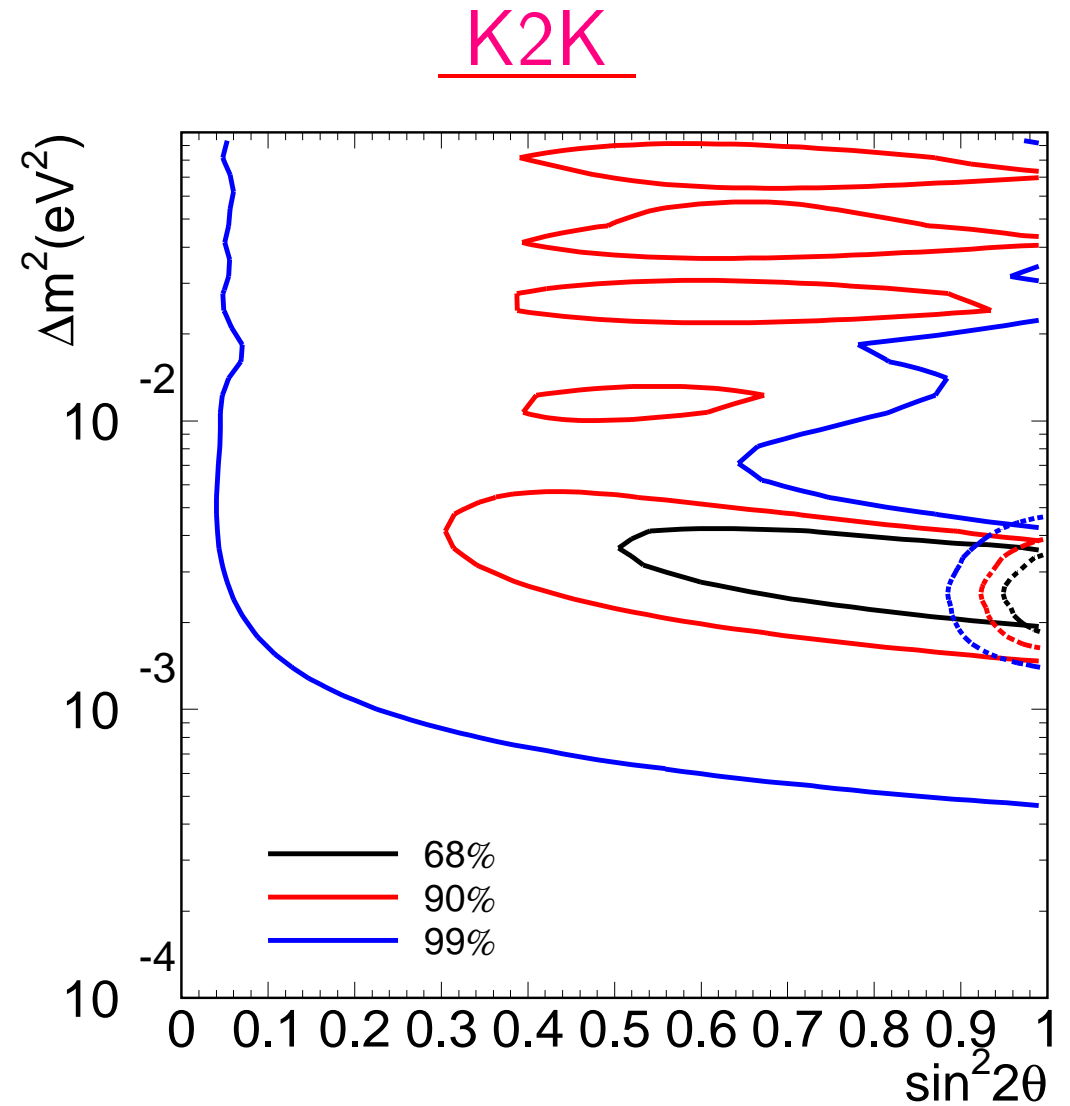
[Shiozawa (SK), Neutrino 2002]



[<http://neutrino.kek.jp/news/2002.06.12>]



[Giacomelli, Giorgini, Spurio, hep-ex/0201032]



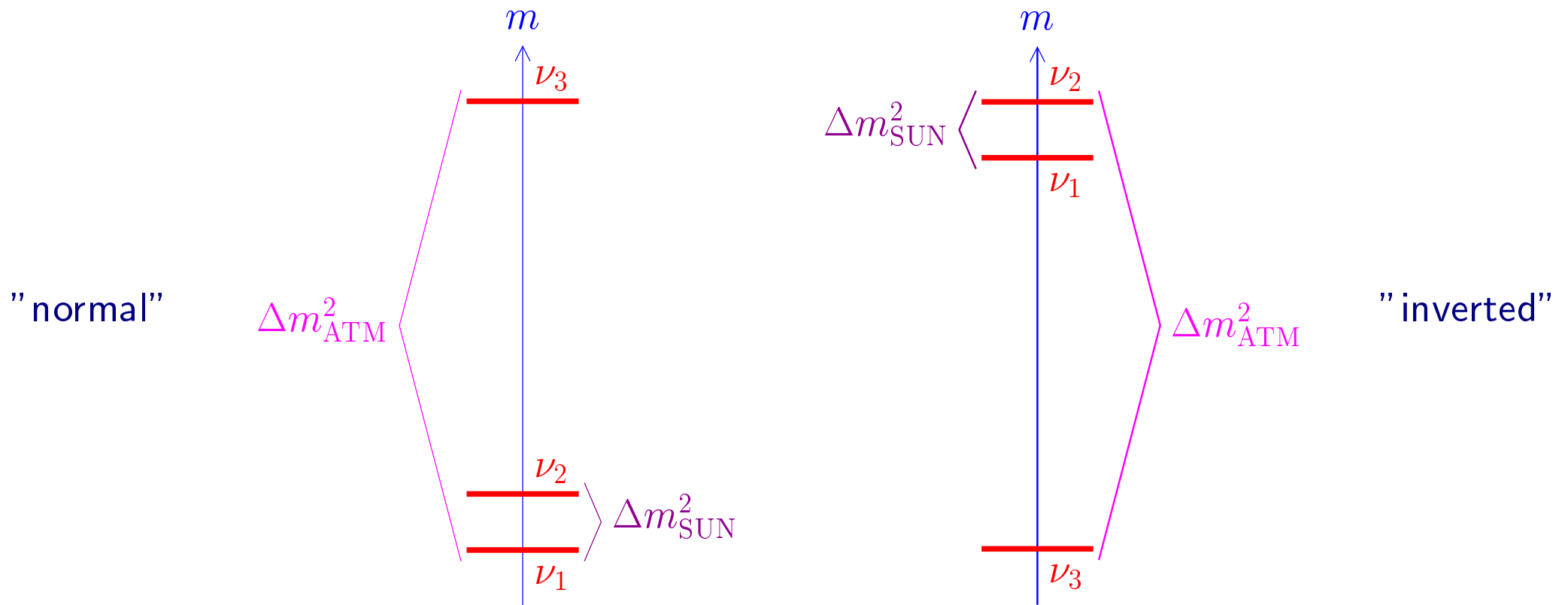
[Oyama, hep-ex/0210030]

see also [K2K, PRL 90 (2003) 041801]

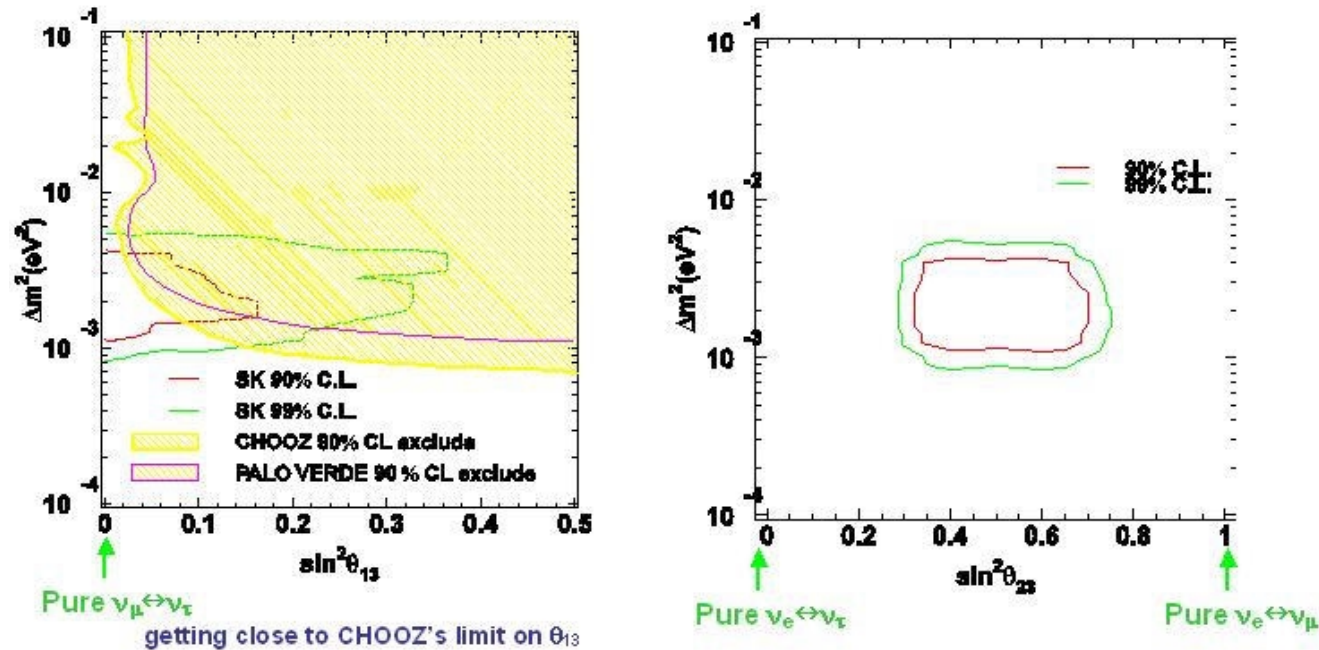
THREE-NEUTRINO MIXING

flavor fields ν_α , $\alpha = e, \mu, \tau$ $\nu_{\alpha L} = \sum_{k=1}^3 U_{\alpha k} \nu_{kL}$ massive fields $\nu_k \rightarrow m_k$

$\Delta m_{\text{SUN}}^2 = \Delta m_{21}^2 \sim 5 \times 10^{-5} \text{ eV}^2$ $\Delta m_{\text{ATM}}^2 \simeq |\Delta m_{31}^2| \sim 2.5 \times 10^{-3} \text{ eV}^2$



Allowed region for active 3-flavor oscillations



consistent with CHOOZ's excluded region

[Shiozawa (SK), Neutrino 2002]

FUTURE

MINOS: sensitivity $|U_{e3}|^2 \sim 10^{-2}$

JHF-Kamioka: sensitivity $|U_{e3}|^2 \sim 2 \times 10^{-3}$ ($|U_{e3}|^2 \sim 10^{-4}$ with Hyper-Kamiokande) [hep-ex/0106019]

Neutrino Factory: sensitivity $|U_{e3}|^2 \sim 10^{-5}$

$|U_{e3}| > 0 \Rightarrow$ normal or inverted scheme (Earth matter effects) and (maybe) CP violation

BILARGE MIXING

$$|U_{e3}|^2 \ll 1 \Rightarrow U \simeq \begin{pmatrix} c_{\vartheta_S} & s_{\vartheta_S} & 0 \\ -s_{\vartheta_S} c_{\vartheta_A} & c_{\vartheta_S} c_{\vartheta_A} & s_{\vartheta_A} \\ s_{\vartheta_S} s_{\vartheta_A} & -c_{\vartheta_S} s_{\vartheta_A} & c_{\vartheta_A} \end{pmatrix} \Rightarrow \begin{cases} \nu_e = c_{\vartheta_S} \nu_1 + s_{\vartheta_S} \nu_2 \\ \nu_a^{(S)} = -s_{\vartheta_S} \nu_1 + c_{\vartheta_S} \nu_2 \\ \phantom{\nu_a^{(S)}} = c_{\vartheta_A} \nu_\mu - s_{\vartheta_A} \nu_\tau \end{cases}$$

$$\sin^2 2\vartheta_A \simeq 1 \Rightarrow \vartheta_A \simeq \frac{\pi}{4} \Rightarrow U \simeq \begin{pmatrix} c_{\vartheta_S} & s_{\vartheta_S} & 0 \\ -s_{\vartheta_S}/\sqrt{2} & c_{\vartheta_S}/\sqrt{2} & 1/\sqrt{2} \\ s_{\vartheta_S}/\sqrt{2} & -c_{\vartheta_S}/\sqrt{2} & 1/\sqrt{2} \end{pmatrix}$$

$$\text{Solar } \nu_e \rightarrow \nu_a^{(S)} \simeq \frac{1}{\sqrt{2}} (\nu_\mu - \nu_\tau)$$

$$\frac{\Phi_{\text{CC}}^{\text{SNO}}}{\Phi_{\nu_e}^{\text{SSM}}} \simeq \frac{1}{3} \implies \Phi_{\nu_e} \simeq \Phi_{\nu_\mu} \simeq \Phi_{\nu_\tau} \text{ for } E \gtrsim 6 \text{ MeV}$$

$$\text{LMA} \Rightarrow \tan^2 \vartheta_S \simeq 0.4 \Rightarrow \vartheta_S \simeq \frac{\pi}{6} \Rightarrow U \simeq \begin{pmatrix} \frac{\sqrt{3}}{2} & \frac{1}{2} & 0 \\ -\frac{1}{2\sqrt{2}} & \frac{\sqrt{3}}{2\sqrt{2}} & \frac{1}{\sqrt{2}} \\ \frac{1}{2\sqrt{2}} & -\frac{\sqrt{3}}{2\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

CONSTRAINTS ON THE MIXING MATRIX

[Guo, Xing, hep-ph/0212142]

$$\left. \begin{aligned} \sin^2 2\vartheta_S &= 4|U_{e1}|^2|U_{e2}|^2 \\ \sin^2 2\vartheta_A &= 4|U_{\mu 3}|^2(1 - |U_{\mu 3}|^2) \\ \sin^2 2\vartheta_C &= 4|U_{e3}|^2(1 - |U_{e3}|^2) \end{aligned} \right\} \Leftrightarrow \left\{ \begin{aligned} |U_{e1}|^2 &= \frac{1}{2} \left[\cos^2 \vartheta_C + \sqrt{\cos^4 \vartheta_C - \sin^2 2\vartheta_S} \right] \\ |U_{e2}|^2 &= \frac{1}{2} \left[\cos^2 \vartheta_C - \sqrt{\cos^4 \vartheta_C - \sin^2 2\vartheta_S} \right] \\ |U_{e3}|^2 &= \sin^2 \vartheta_C \\ |U_{\mu 3}|^2 &= \sin^2 \vartheta_A \\ |U_{\tau 3}|^2 &= \cos^2 \vartheta_C - \sin^2 \vartheta_A \end{aligned} \right.$$

$$0.25 < \sin^2 \vartheta_S < 0.40 \text{ (90\% C.L.)} \quad [\text{Fogli et al., hep-ph/0212127}]$$

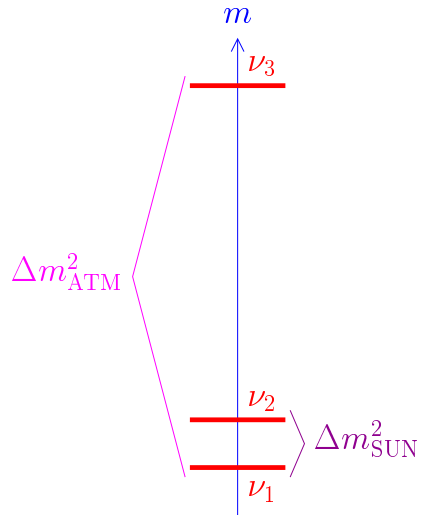
$$\sin^2 2\vartheta_A > 0.92 \text{ (90\% C.L.)} \quad [\text{Shiozawa (SK), Neutrino 2002}]$$

$$\sin^2 2\vartheta_C < 0.1 \text{ (90\% C.L.)} \quad [\text{CHOOZ, PLB 466 (1999) 415}]$$

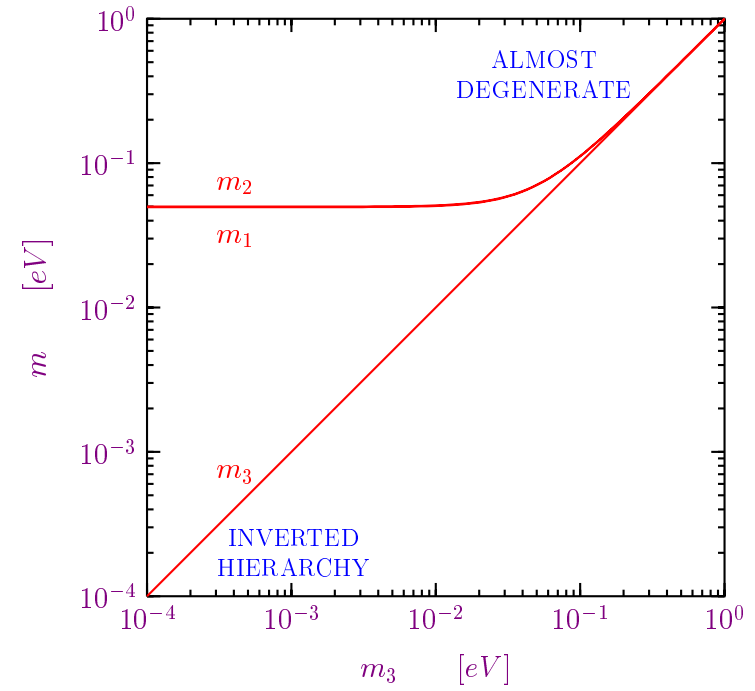
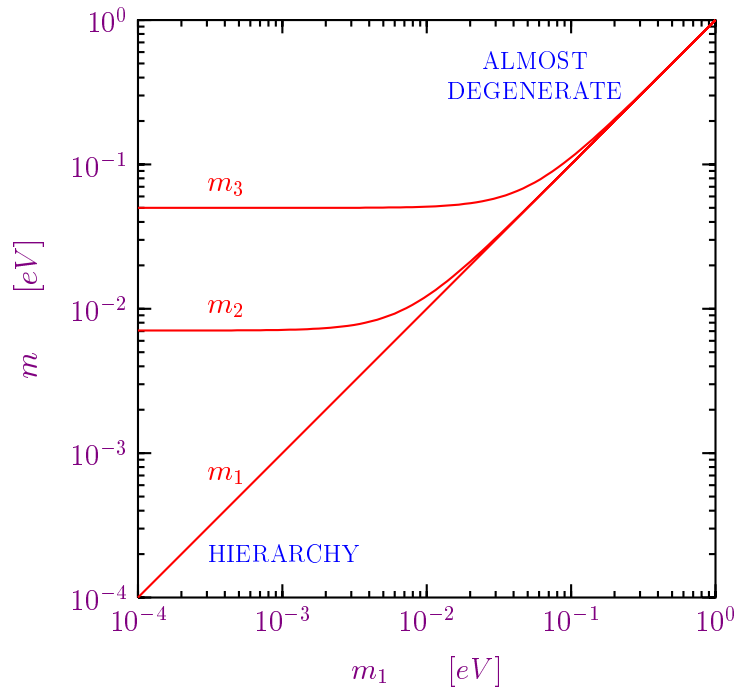
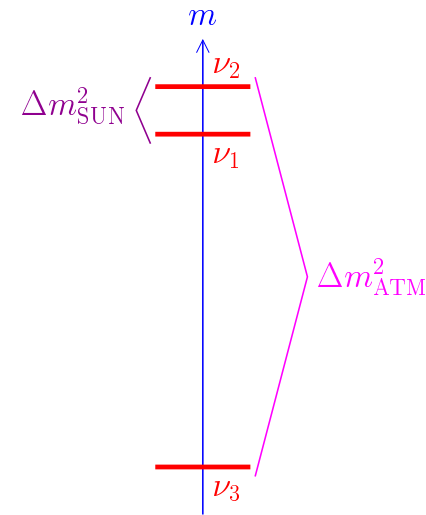
$$|U| \simeq \begin{pmatrix} 0.70 - 0.87 & 0.50 - 0.69 & 0.00 - 0.16 \\ 0.20 - 0.61 & 0.34 - 0.73 & 0.60 - 0.80 \\ 0.21 - 0.63 & 0.36 - 0.74 & 0.58 - 0.80 \end{pmatrix}$$

ABSOLUTE SCALE OF NEUTRINO MASSES

”normal”



”inverted”



laboratory constraint on the main massive component of ν_e

Tritium β -decay: $m_{\nu_e} < 2.2 \text{ eV}$ (95% C.L.)

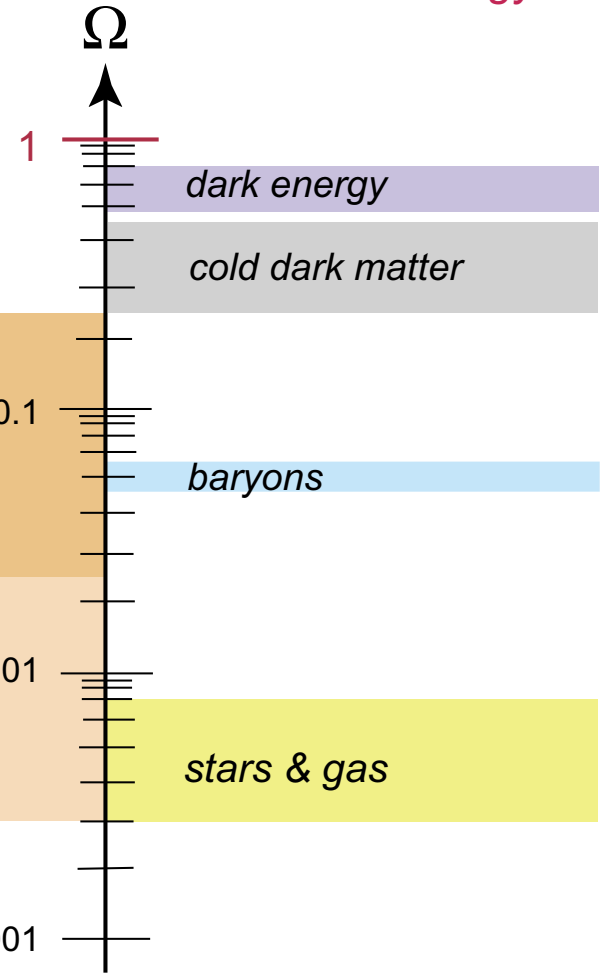
[Mainz, Troitsk, hep-ex/0210050]

neutrino HDM

matter & energy

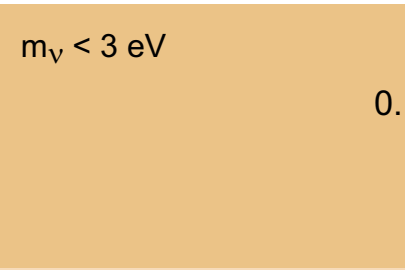
$$\Omega_\nu h^2 = \sum m_\nu / 92 \text{ eV}$$

Hubble Parameter $h = 0.65$ (65 km/s/Mpc)



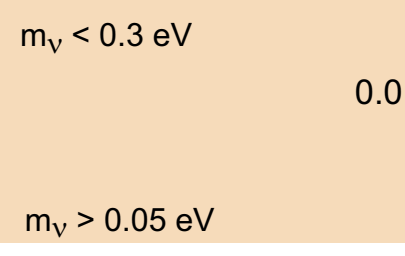
$$\Omega_\nu < 0.25$$

*structure formation
tritium experiments*



$$\Omega_\nu < 0.025$$

KATRIN



$$\Omega_\nu > 0.003$$

Super-Kamiokande



Future: KATRIN

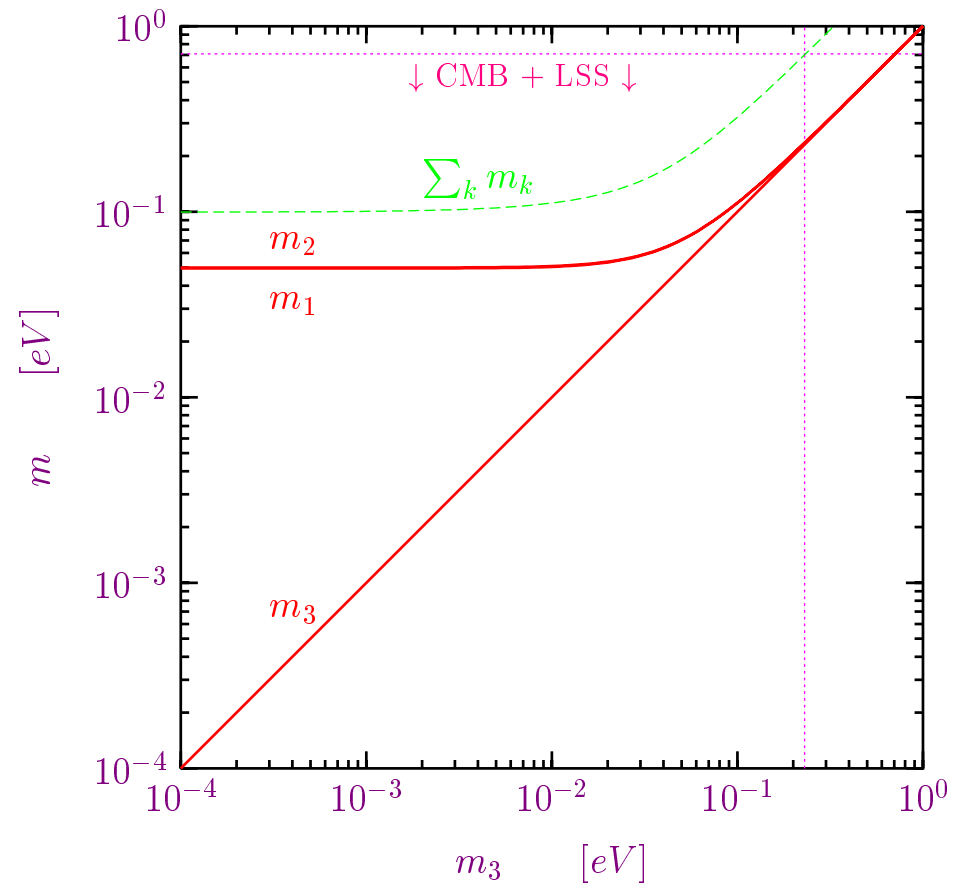
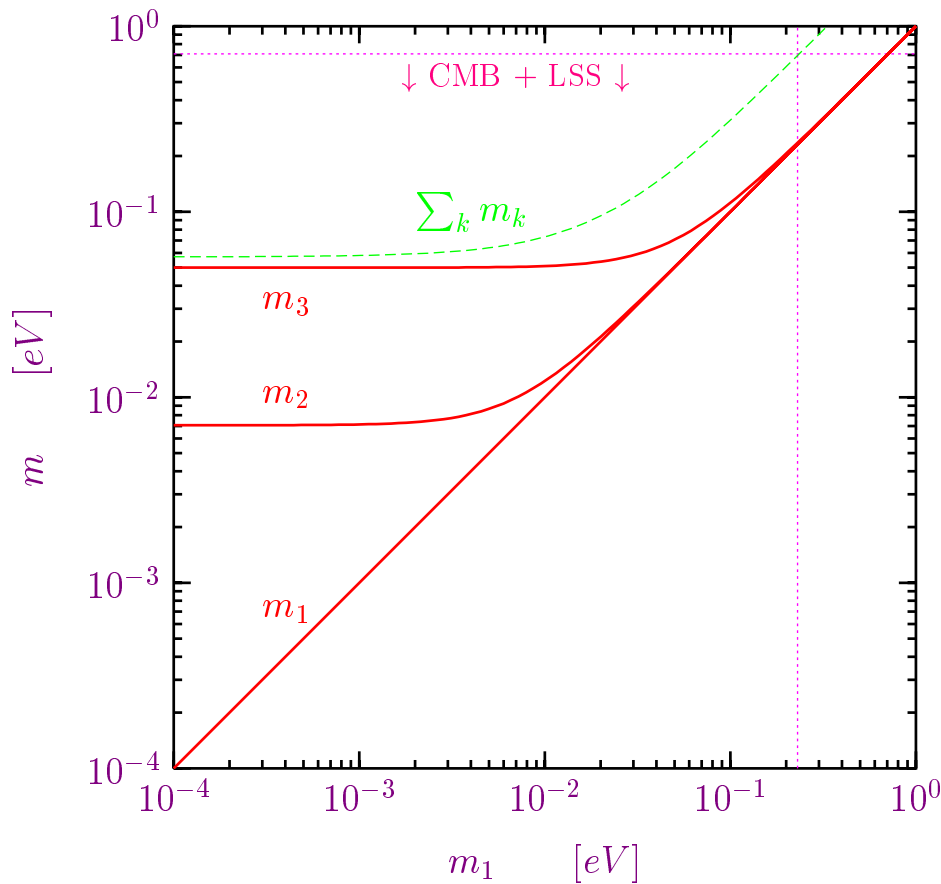
[KATRIN, hep-ex/0109033]

COSMOLOGICAL LIMIT ON NEUTRINO MASSES

CMB (WMAP, CBI, ACBAR) + LSS (2dFGRS) [WMAP, astro-ph/0302207, astro-ph/0302209]

Λ CDM: $h = 0.71_{-0.03}^{+0.04}$, $\Omega_{\text{tot}} = 1.02 \pm 0.02$, $\Omega_b h^2 = 0.0224 \pm 0.0009$, $\Omega_m h^2 = 0.135_{-0.009}^{+0.008}$

$$\Omega_\nu h^2 < 0.00076 \text{ (95\% confidence limit)} \implies \sum_k m_k < 0.71 \text{ eV} \implies m_k < 0.23 \text{ eV}$$



OPEN QUESTIONS

Absolute Scale of Neutrino Masses?

Nature of Neutrinos (Dirac or Majorana)?

Short-Baseline $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ (LSND)?

Active \rightarrow Sterile Transitions?

Number of Massive Neutrinos?

$$\left. \begin{aligned} \Delta m_{\text{SUN}}^2 &\simeq 5 \times 10^{-5} \text{ eV}^2 \\ \Delta m_{\text{ATM}}^2 &\simeq 2.5 \times 10^{-3} \text{ eV}^2 \\ \Delta m_{\text{LSND}}^2 &\sim 0.2 - 1 \text{ eV}^2 \end{aligned} \right\} \implies N_\nu > 3$$

no contradiction with

invisible width of Z boson ($Z \rightarrow \sum_\ell \nu_\ell \bar{\nu}_\ell$) $\implies N_{\text{light flavor neutrinos}} = 2.994 \pm 0.012$

[PDG, PRD 66 (2002) 010001, <http://pdg.lbl.gov>]

Sterile Neutrinos in Atmospheric Neutrino Flux?

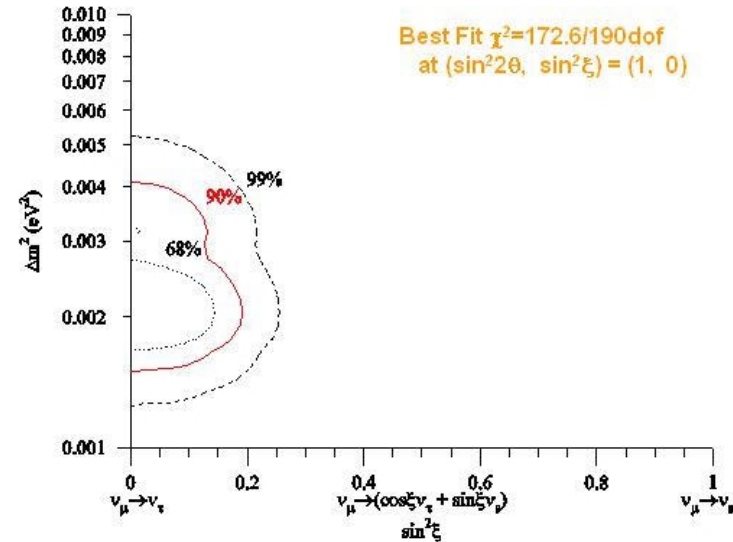
Nature of atmospheric Oscillation

Mode	Best fit	$\Delta\chi^2$	σ
$\nu_\mu - \nu_\tau$	$\sin^2 2\theta = 1.00$; $\Delta m^2 = 2.5 \times 10^{-3} \text{eV}^2$	0.0	0.0
$\nu_\mu - \nu_e$	$\sin^2 2\theta = 0.97$; $\Delta m^2 = 5.0 \times 10^{-3} \text{eV}^2$	79.3	8.9
$\nu_\mu - \nu_s$	$\sin^2 2\theta = 0.96$; $\Delta m^2 = 3.6 \times 10^{-3} \text{eV}^2$	19.0	4.4
LxE	$\sin^2 2\theta = 0.90$; $\alpha = 5.3 \times 10^{-4}$	67.1	8.2
ν_μ Decay	$\cos^2 \theta = 0.47$; $\alpha = 3.0 \times 10^{-3} \text{eV}^2$	81.1	9.0
ν_μ Decay to ν_s	$\cos^2 \theta = 0.33$; $\alpha = 1.1 \times 10^{-2} \text{eV}^2$	14.1	3.8

[Smy (SK), Moriond 2002]

limit on $\nu_\mu \leftrightarrow \nu_s$ admixture

May-2002 Neutrino2002 @ Munich



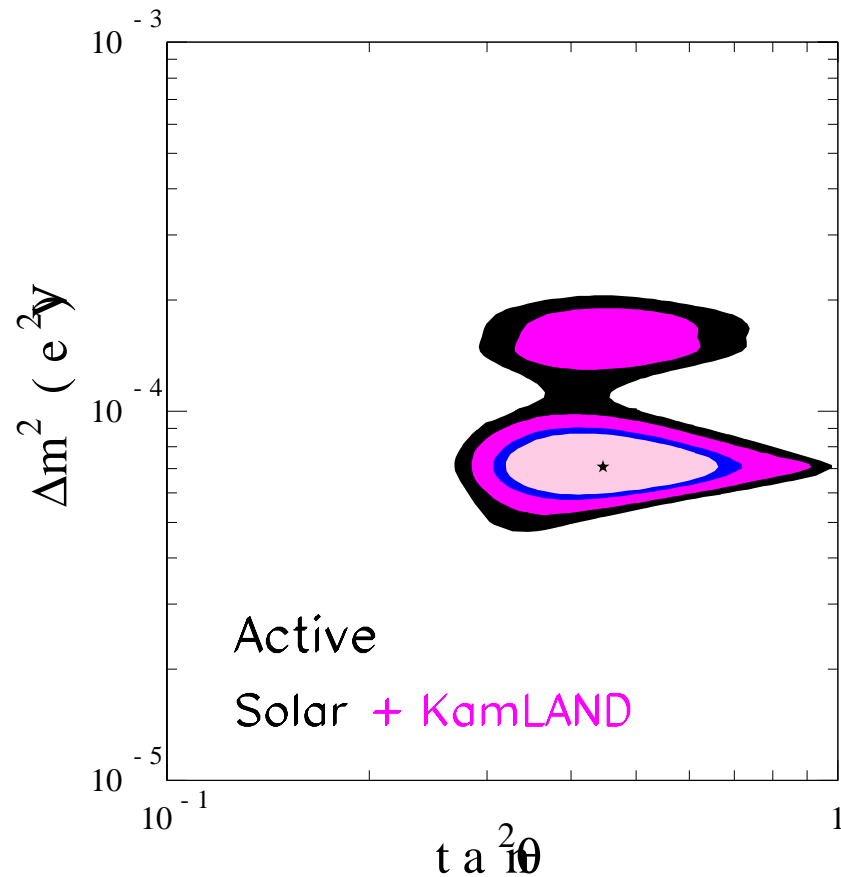
[Shiozawa (SK), Neutrino 2002]

FUTURE

MINOS: $\nu_\mu \rightarrow \nu_\mu, \nu_\mu \rightarrow \nu_e, \nu_\mu \rightarrow \nu_{e,\mu,\tau}$ (NC)

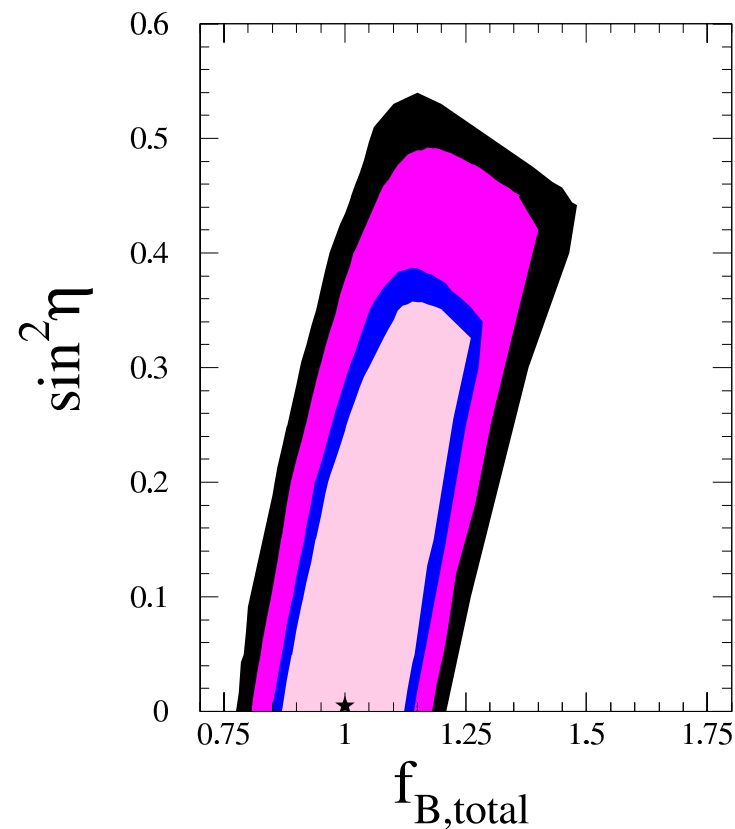
CNGS: ICARUS: $\nu_\mu \rightarrow \nu_e, \nu_\mu \rightarrow \nu_\tau$ OPERA: $\nu_\mu \rightarrow \nu_\tau$

Sterile Neutrinos in Solar Neutrino Flux?



90%, 95%, 99%, 99.73% (3σ) C.L.

[Bahcall, Gonzalez-Garcia, Pena-Garay, JHEP 0302 (2003) 009]



$$\nu_e \rightarrow \cos \eta \nu_a + \sin \eta \nu_s$$

$$\sin^2 \eta < 0.52 (3\sigma)$$

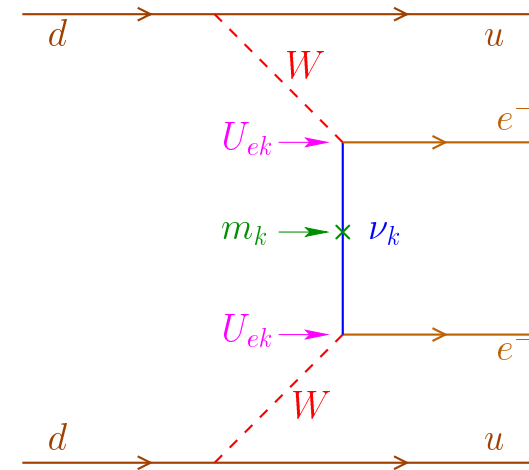
$$f_{B,\text{total}} = \frac{\Phi_{8B}}{\Phi_{8B}^{\text{SSM}}} = 1.00 \pm 0.06$$

MAJORANA NEUTRINOS? $\iff \beta\beta_{0\nu}$ decay

$$\mathcal{N}(A, Z) \rightarrow \mathcal{N}(A, Z + 2) + e^- + e^-$$

effective Majorana mass

$$|\langle m \rangle| = \left| \sum_k U_{ek}^2 m_k \right|$$



complex $U_{ek} \Rightarrow$ possible cancellations among m_1, m_2, m_3 contributions

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

conserved CP

$$\alpha_{21} = 0, \pi \quad \alpha_{31} = 0, \pi$$

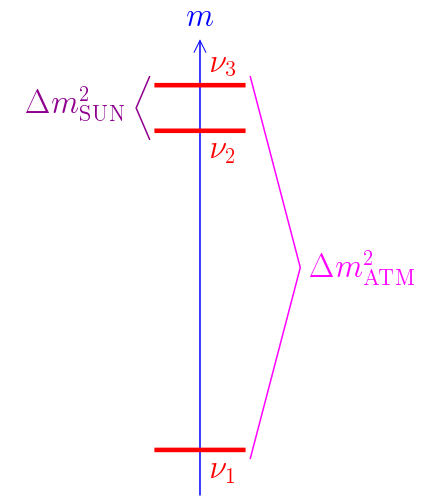
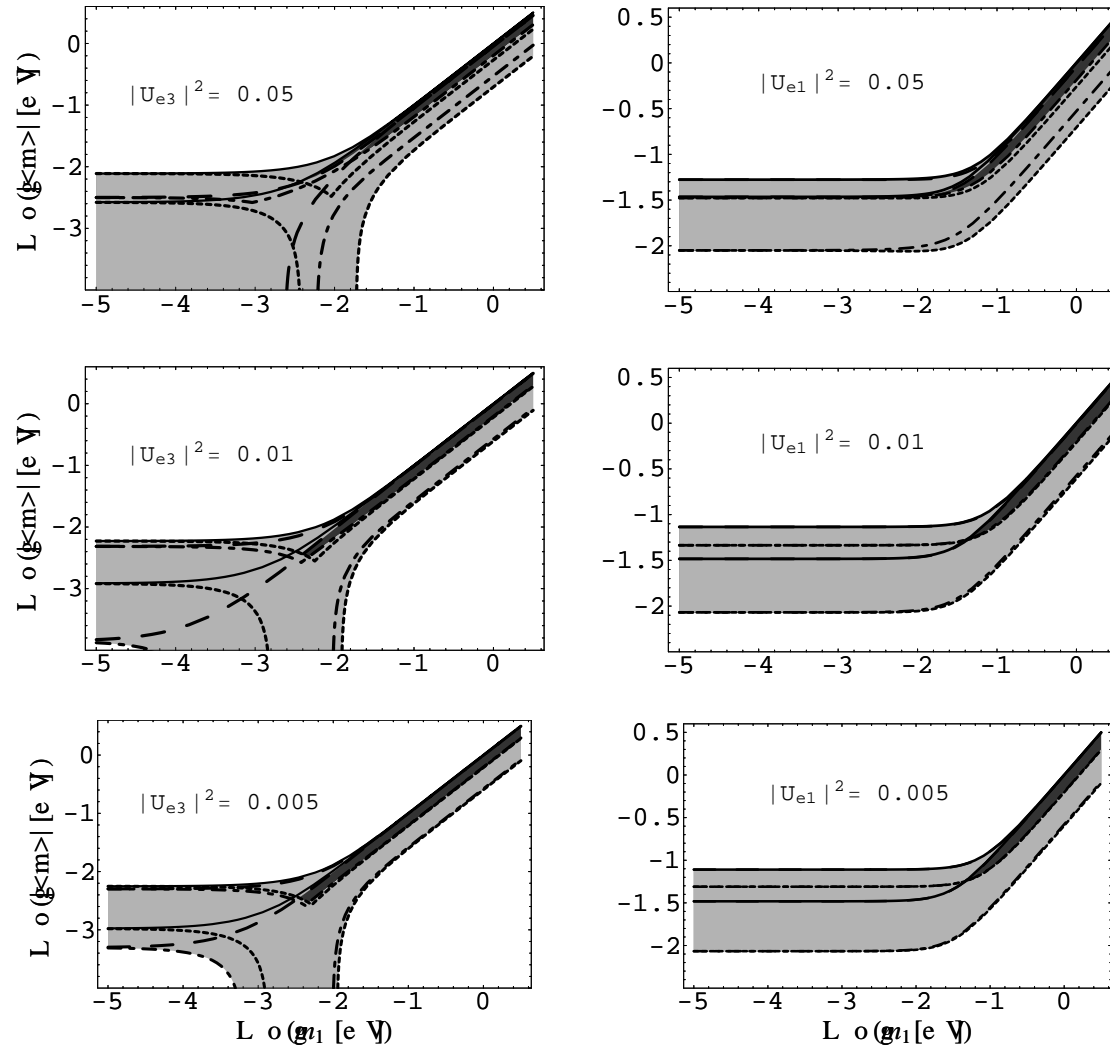
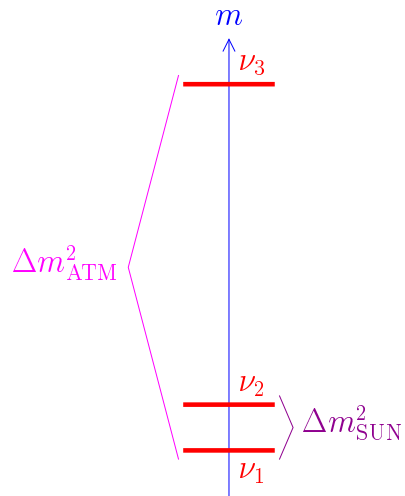
$$\eta_{kj} = e^{i\alpha_{kj}} \text{ relative CP parity}$$

Heidelberg-Moscow (^{76}Ge) $|\langle m \rangle|_{\text{exp}} < 0.35 \text{ eV (90\% C.L.)}$ [EPJA 12 (2001) 147]

IGEX (^{76}Ge) $|\langle m \rangle|_{\text{exp}} < 0.33 - 1.35 \text{ eV (90\% C.L.)}$ [PRD 65 (2002) 092007]

about factor 3 theoretical uncertainty on nuclear matrix element!

Neutrino Oscillations implications for $\beta\beta_{0\nu}$ decay



[Pascoli, Petcov, PLB 544 (2002) 239], see also [Feruglio, Strumia, Vissani, NPB 637 (2002) 345]

FUTURE: NEMO3, CAMEO, Majorana, CUORICINO, XMASS ($|\langle m \rangle| \sim 10^{-1}$ eV)
 GENIUS, CUORE, EXO, MOON, GEM ($|\langle m \rangle| \sim 10^{-2}$ eV)

CONCLUSIONS

$\nu_\mu \rightarrow \nu_\tau$ with $\Delta m_{\text{ATM}}^2 \simeq 2.5 \times 10^{-3} \text{ eV}^2$ (Super-K, K2K)

$\nu_e \rightarrow \nu_\mu, \nu_\tau$ with $\Delta m_{\text{SUN}}^2 \simeq 5 \times 10^{-5} \text{ eV}^2$ (SNO, KamLAND)

Cosmology (CMB+LSS) $\Rightarrow \sum m_{\text{light neutrinos}} \lesssim 1 \text{ eV}$ (WMAP, 2dFGRS)

3ν mixing \Rightarrow bilarge mixing with $|U_{e3}|^2 \ll 1$

theory: why $|U_{e3}|^2$ is so small?

future exp.: measure $|U_{e3}| > 0 \Rightarrow$ normal or inverted scheme and CP violation

data disfavor Active \rightarrow Sterile transitions

Short-Baseline $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ (LSND)? \Leftarrow MiniBooNE

Neutrino Unbound

<http://www.to.infn.it/~giunti/NU>

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