CURRENT STATUS OF NEUTRINO MASSES AND MIXINGS

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FACTS

- Solar $\nu_e \to \nu_\mu, \nu_\tau$
- Atmospheric $\nu_\mu \to \nu_\tau$
- Atmospheric and Long-Baseline ν_e Oscillations are Suppressed
- Suppressed Short-Baseline ν_e and ν_μ Oscillations
- $m_{\text{light neutrinos}} \lesssim$ few eV

MYSTERIES

- Absolute Scale of Neutrino Masses?
- Nature of Neutrinos (Dirac or Majorana)?
- LSND $\bar{\nu}_\mu \to \bar{\nu}_e$?
- Active $\to$ Sterile Transitions?
- Number of Massive Neutrinos?

ICHEP 2002, Amsterdam, 24-31 July 2002

MAIN CHARACTERISTICS OF SOLAR ν DATA

Experiment	Reaction	E_{th} (MeV)	Operating Time	$\frac{R^{\text{exp}}}{R^{\text{BP2000}}}$
SAGE	$\nu_e + {}^{71}\text{Ga} \to {}^{71}\text{Ge} + e^-$	0.233	1990 – 2001	0.54 ± 0.05
GALLEX			1991 – 1997	0.61 ± 0.06
GNO			1998 – 2000	0.51 ± 0.08
Homestake	$\nu_e + {}^{37}\text{Cl} \to {}^{37}\text{Ar} + e^-$	0.814	1970 – 1994	0.34 ± 0.03
Kamiokande	$\nu_e + e^- \to \nu_e + e^-$	6.75	1987 – 1995 2079 days	0.55 ± 0.08
Super-Kam.		4.75	1996 – 2001 1496 days	0.465 ± 0.015
SNO	$\nu_e + d \to p + p + e^-$	6.9	1999 – 2002 306.4 days	0.35 ± 0.02
	$\nu + d \to p + n + e^-$	2.2		1.27 ± 0.55 (1.01 ± 0.13)
	$\nu + e^- \to \nu + e^-$	5.2		0.47 ± 0.05

$\Phi_{hep} < 7.9\,\Phi_{hep}^{\text{SSM}}$ (90% CL)

[Smy (SK), Neutrino 2002]

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

[SK, PLB 539 (2002) 179]

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

[SNO, PRL 89 (2002) 011302]

SK & SNO $\Longrightarrow$ no spectral distortion

SK $\Longrightarrow$ no seasonal variation

SK & SNO $\Longrightarrow$ very small night-day asymmetry

THE TRIUMPH OF SNO

Sudbury Neutrino Observatory, 1 kton of D_2O, $T_{\text{eff}} \geq 5\,\text{MeV} \Rightarrow \nu_{^8\text{B}}$

C $\nu_e + d \to p + p + e^-$ $E_\nu^{\text{th}} \simeq 6.9\,\text{MeV}$

C $\nu + d \to p + n + \nu$ $E_\nu^{\text{th}} \simeq 2.2\,\text{MeV}$

S $\nu + e^- \to \nu + e^-$ $E_\nu^{\text{th}} \simeq 5.2\,\text{MeV}$

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 $\nu_e \to \nu_\mu, \nu_\tau \Longrightarrow$ MIXING!

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

$$\Phi_{\nu_\mu, \nu_\tau} = \Phi_{\text{NC}}^{\text{SNO}} - \Phi_{\text{CC}}^{\text{SNO}}$$

$$= (3.33 \pm 0.65) \times 10^6\,\text{cm}^{-2}\,\text{s}^{-1} \quad (5.1\sigma)$$

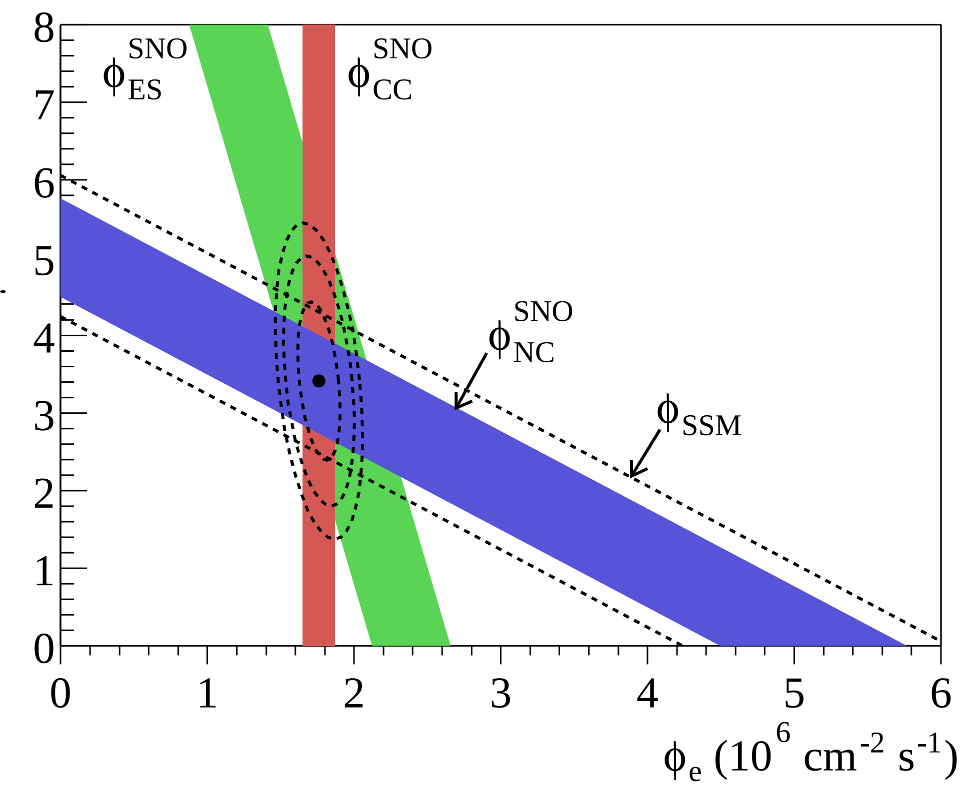
APPEARANCE EXPERIMENT !

Super-Kamiokande

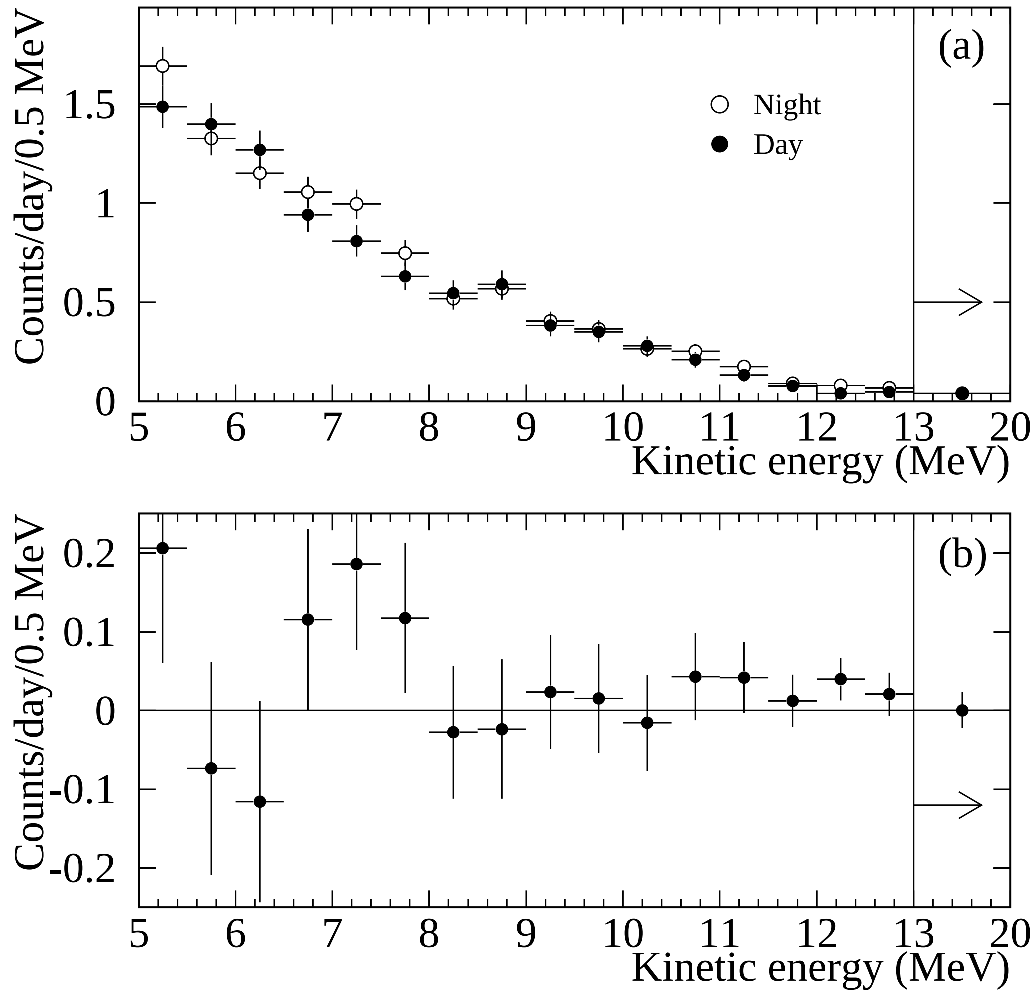
22.5 ktons of H_2O, $E_\nu^{\text{th}} \simeq 4.75\,\text{MeV} \Rightarrow \nu_{^8\text{B}}$

$$R_{\text{ES}}^{\text{SK}} \equiv \Phi_{\text{ES}}^{\text{SK}} / \Phi_{\nu_e}^{\text{SSM}} = 0.465 \pm 0.015$$

[SK, PLB 539 (2002) 179]



[SNO, PRL 89 (2002) 011301]



[SNO, PRL 89 (2002) 011302]

$$\Phi_{\nu_e} = (1.76 \pm 0.11) \times 10^6 \, \mathrm{cm}^{-2} \, \mathrm{s}^{-1} \qquad \Phi_{\nu_\mu,\nu_\tau} = (3.41 \pm 0.65) \times 10^6 \, \mathrm{cm}^{-2} \, \mathrm{s}^{-1}$$

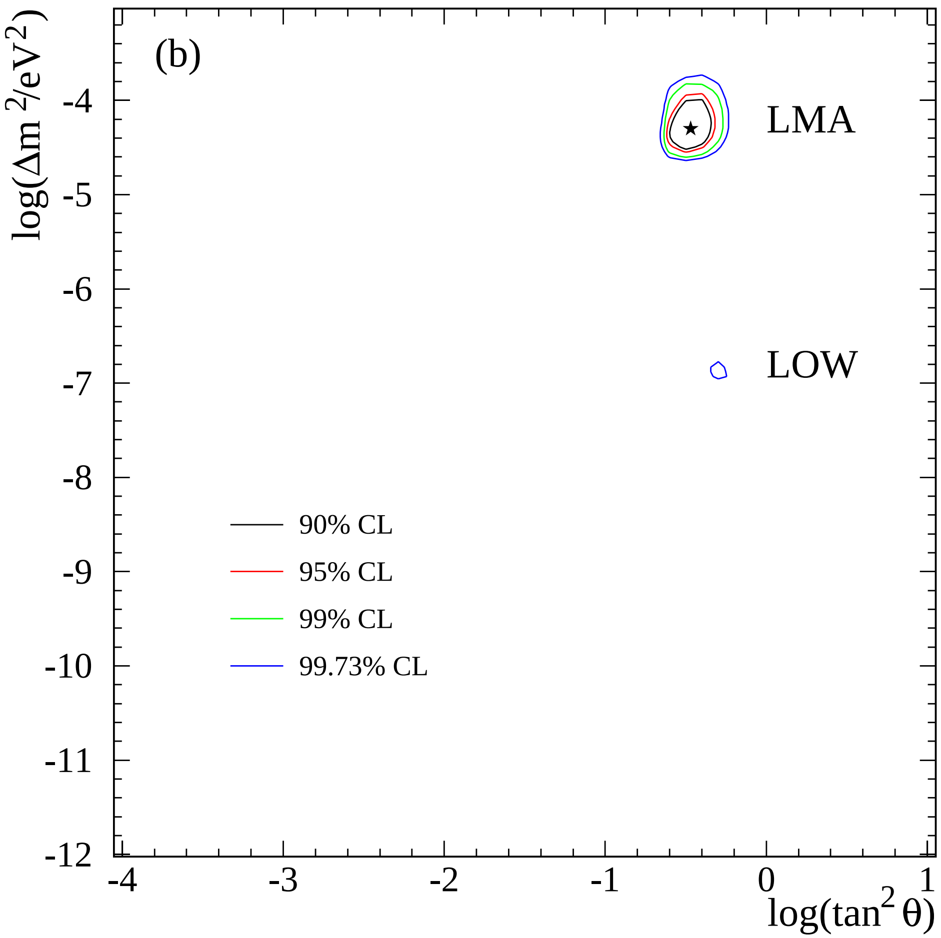
$$\Phi_{\nu_e,\nu_\mu,\nu_\tau} = (5.09 \pm 0.64) \times 10^6 \, \mathrm{cm}^{-2} \, \mathrm{s}^{-1} \qquad \Phi^{\mathrm{SSM}}_{^8\mathrm{B}} = \left(5.05^{+1.01}_{-0.81}\right) \times 10^6 \, \mathrm{cm}^{-2} \, \mathrm{s}^{-1}$$

SO SOLVED SOLAR NEUTRINO PROBLEM

(if no future surprises!)

⇓

NEUTRINO PHYSICS



OKKAM'S RAZOR

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CONSIDER SIMPLEST HYPOTHESIS

⇓

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

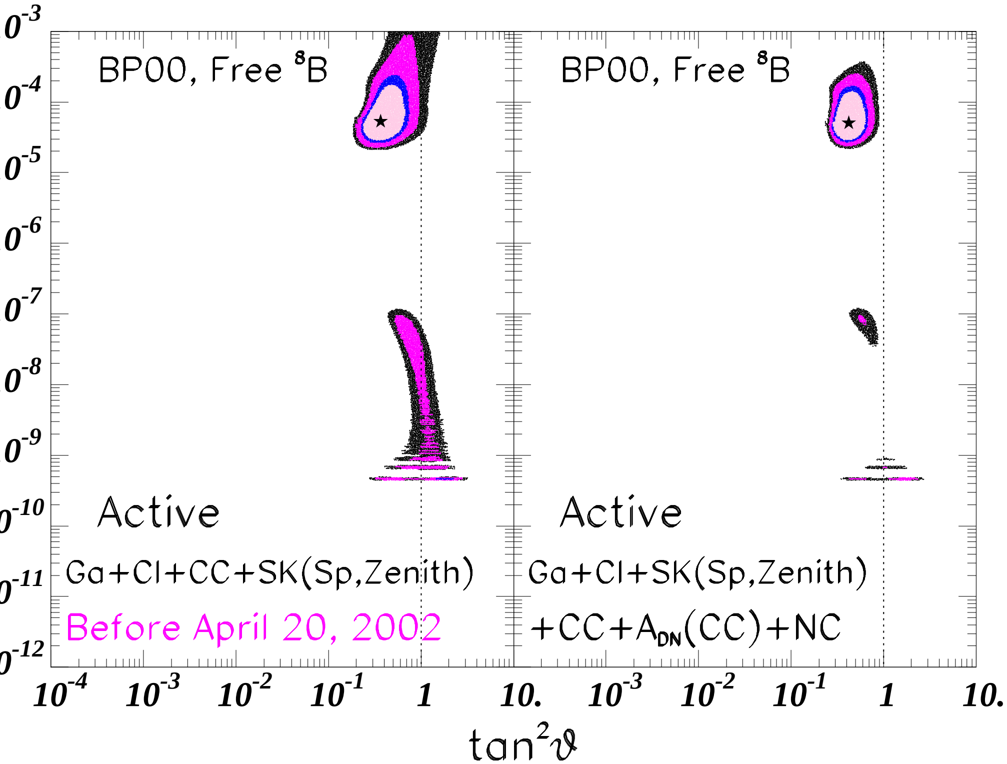
Large Mixing Angle solution

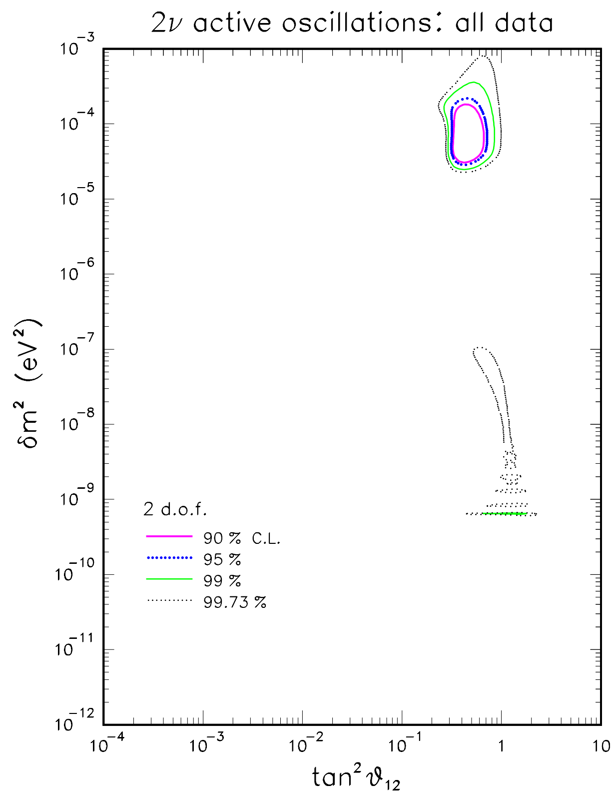
LMA

$$\Delta m^2 \simeq 5.0 \times 10^{-5}\,\mathrm{eV}^2$$

$$\tan^2\vartheta \simeq 0.34$$

[SNO, PRL 89 (2002) 011302]





[Bahcall, Gonzalez-Garcia, Peña-Garay, hep-ph/0204314]

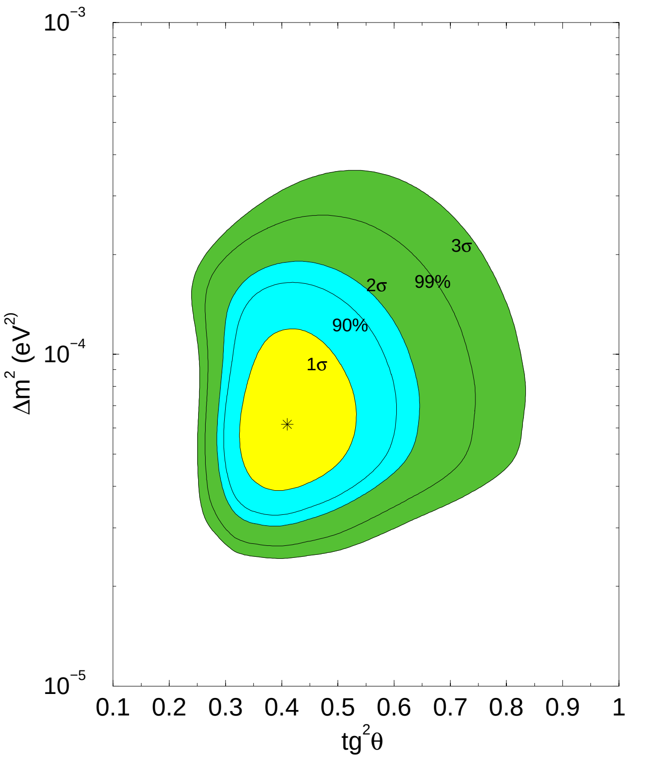
[Fogli, Lisi, Marrone, Montanino, Palazzo, hep-ph/0206162]

LARGE MIXING BUT MAXIMAL MIXING IS DISFAVORED!

LMA	$0.24 < \tan^2\vartheta < 0.89$	$2.3 \times 10^{-5} < \Delta m^2 < 3.7 \times 10^{-4}$	99.73% CL
LOW	$0.43 < \tan^2\vartheta < 0.86$	$3.5 \times 10^{-8} < \Delta m^2 < 1.2 \times 10^{-7}$	

[Bahcall, Gonzalez-Garcia, Peña-Garay, hep-ph/0204314]

FUTURE: KamLAND (LMA), BOREXINO (LOW), ...



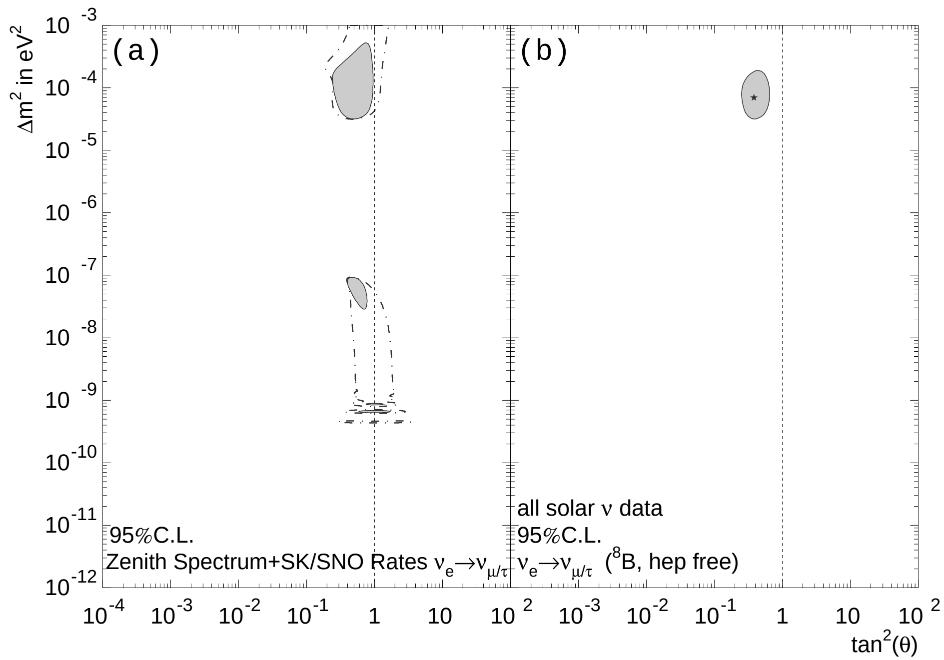
$$0.2 < \tan^2\vartheta < 0.84$$

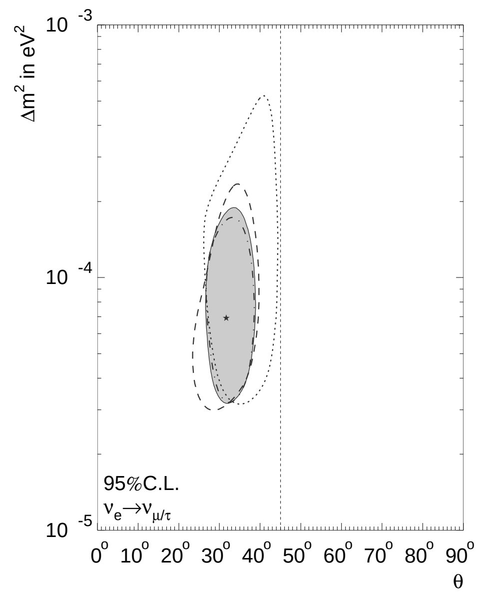
$$2.3 \times 10^{-5} < \Delta m^2 < 3.6 \times 10^{-4}$$

99.73% CL

[de Holanda, Smirnov, hep-ph/0205241]

see also
[Barger, Marfatia, Whisnant, Wood, PLB 537 (2002) 179]
[Bandyopadhyay et al., hep-ph/0204286]
[Aliani et al., hep-ph/0205053]
[Creminelli, Signorelli, Strumia, hep-ph/0102234]
[Maltoni, Schwetz, Tortóla, Valle, hep-ph/0207227]





[SK, PLB 539 (2002) 179]

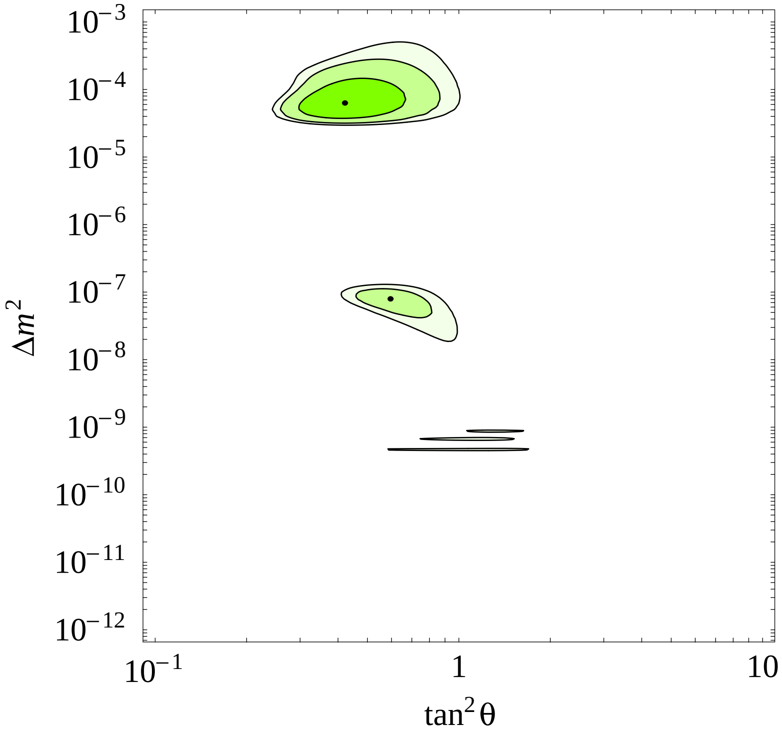
worry: LOW is disfavored because LMA fit is too good!

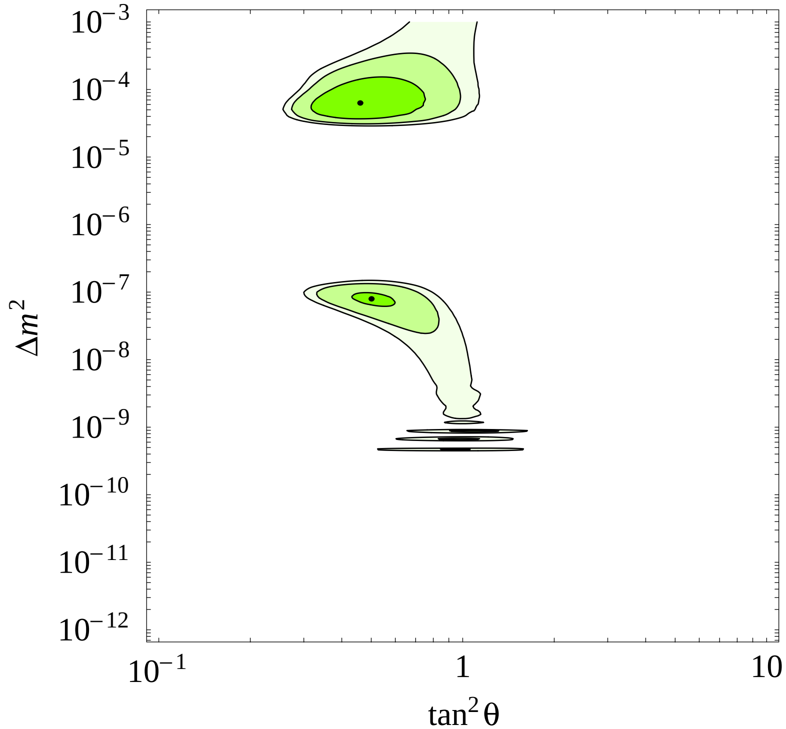
dof $= 72 = 17+17$(SNO) $+$ $19+19$(SK) $+$ 3(HOM+GAL+SAG) $-$ $3(\Delta m^2 + \tan^2\vartheta + \Phi_{^8\mathrm{B}})$

LMA $\chi^2_{\min} = 57.0$ $\Delta m^2 = 5.0 \times 10^{-5}\,\mathrm{eV}^2,\ \tan^2\vartheta = 0.34$

LOW $\chi^2_{\min} = 67.7$ $\Delta m^2 = 1.3 \times 10^{-7}\,\mathrm{eV}^2,\ \tan^2\vartheta = 0.55$

[SNO, PRL 89 (2002) 011302]





$R^{\mathrm{exp}}_{\mathrm{Ga}} = 70.8 \pm 4.4\,\mathrm{SNU}$ (1990-2001)

$R^{\mathrm{exp}}_{\mathrm{Ga}} = 66.1 \pm 5.3\,\mathrm{SNU}$ (1998-2001)

90%, 99%, 99.73% CL

[Strumia, Cattadori, Ferrari, Vissani, hep-ph/0205261]

ATMOSPHERIC NEUTRINOS

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

Atmospheric Allowed Region

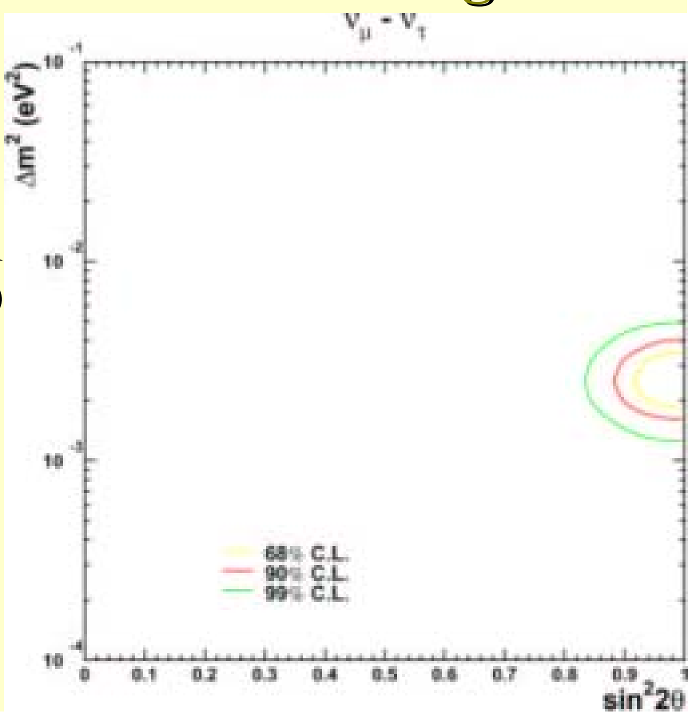
Disappearance of μ-type, no appearance of e-type: $\nu_\mu - \nu_\tau$

Uses all Super-K data sets (1290d) FC, PC, up μ and multi-ring

Very good χ^2 (175.0/190)

Maximal mixing

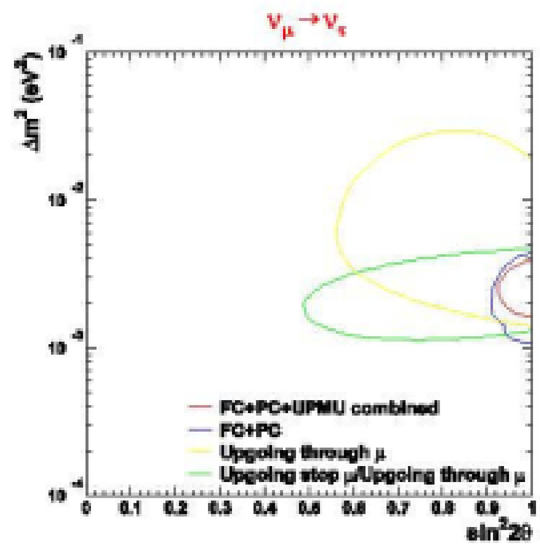
Smy, UC Irvine



[Smy (SK), Moriond 2002]

May-2002 Neutrino2002 @ Munich

Combined allowed regions



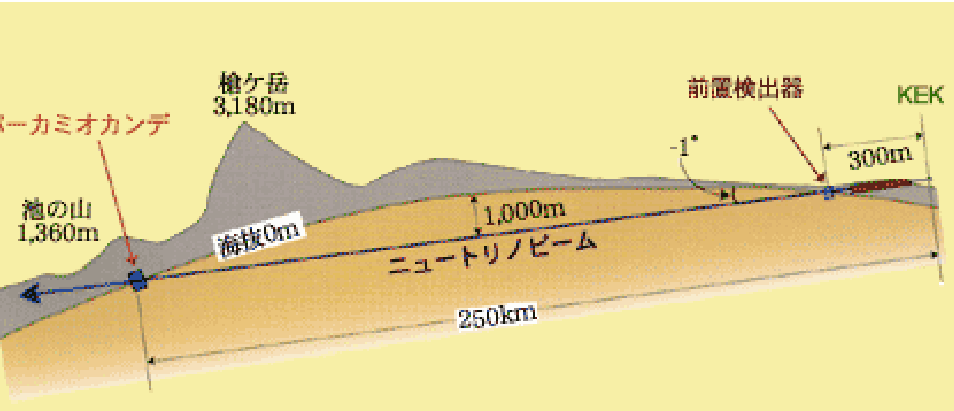
$\nu_\mu \leftrightarrow \nu_\tau$ oscillations

Best fit($\Delta m^2 = 2.5\times10^{-3}$, $\sin^2 2\theta = 1.0$
$\chi^2_{min} = 163.2/170$ d.o.f)

No oscillation
(χ^2 =456.5/172 d.o.f)

$\Delta m^2 = (1.6\sim3.9)\times10^{-3}$ eV^2
$\sin^2 2\theta > 0.92$ @ 90%CL

[Shiozawa (SK), Neutrino 2002]



← K2K [http://neutrino.kek.jp/news/2002.06.12]

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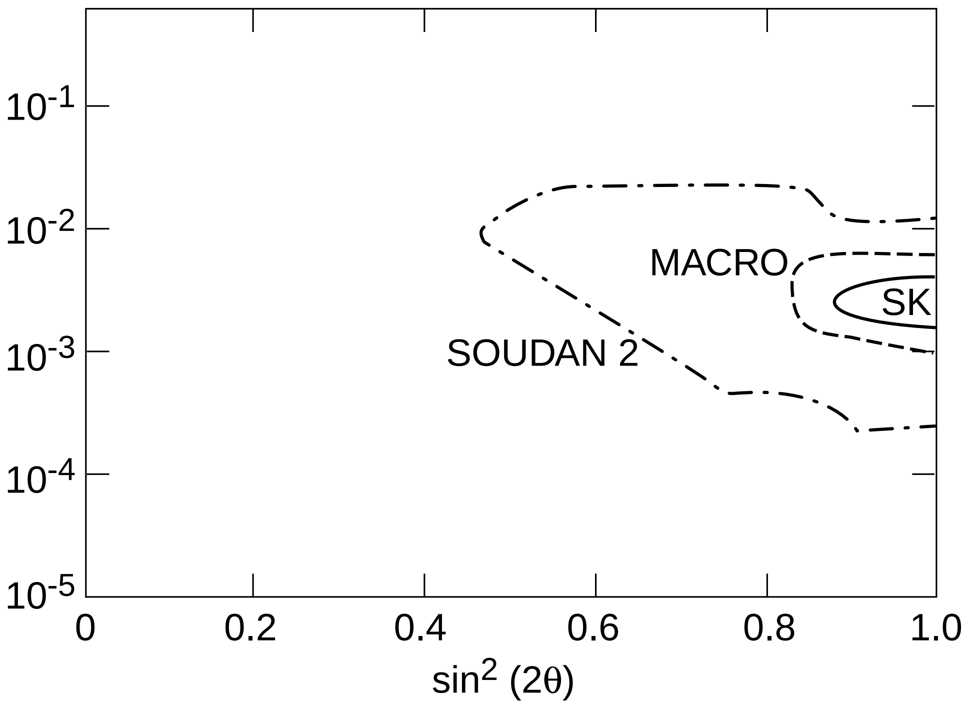
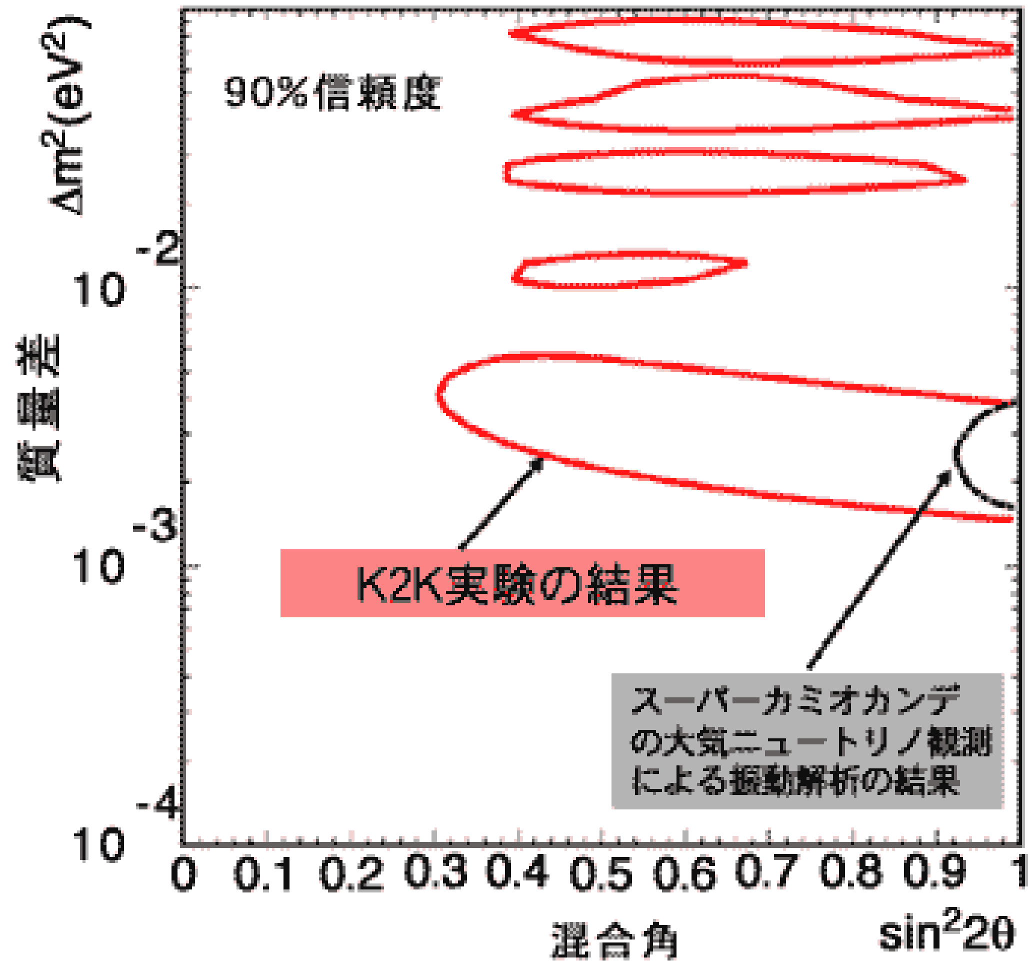


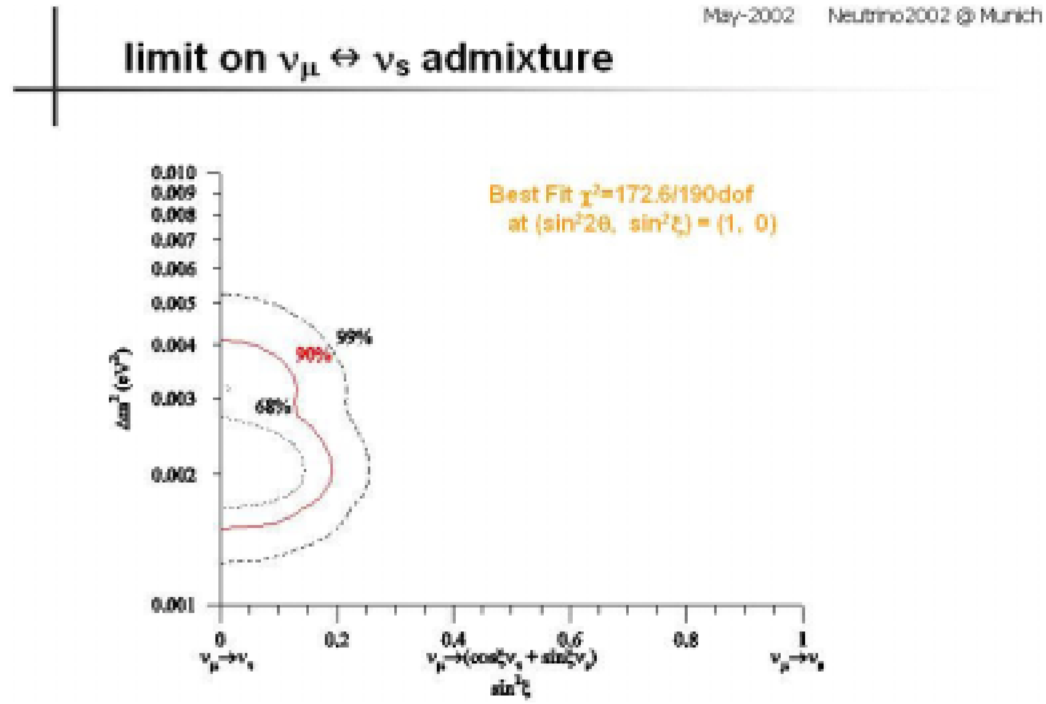
[Giacomelli, Giorgini, Spurio, hep-ex/0201032]



Nature of atmospheric Oscillation

ode	Best fit	$\Delta\chi 2$	σ
-ν_τ	$\sin^2 2\theta$=1.00; Δm^2=2.5x10^{-3}eV^2	0.0	0.0
-ν_e	$\sin^2 2\theta$=0.97; Δm^2=5.0x10^{-3}eV^2	79.3	8.9
-ν_s	$\sin^2 2\theta$=0.96; Δm^2=3.6x10^{-3}eV^2	19.0	4.4
E	$\sin^2 2\theta$=0.90; α=5.3x10^{-4}	67.1	8.2
Decay	$\cos^2\theta$=0.47; α=3.0x10^{-3}eV^2	81.1	9.0
Decay to ν_s	$\cos^2\theta$=0.33; α=1.1x10^{-2}eV^2	14.1	3.8

[Smy (SK), Moriond 2002]



[Shiozawa (SK), Neutrino 2002]

FUTURE

K2K: $\nu_\mu \to \nu_\mu$

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

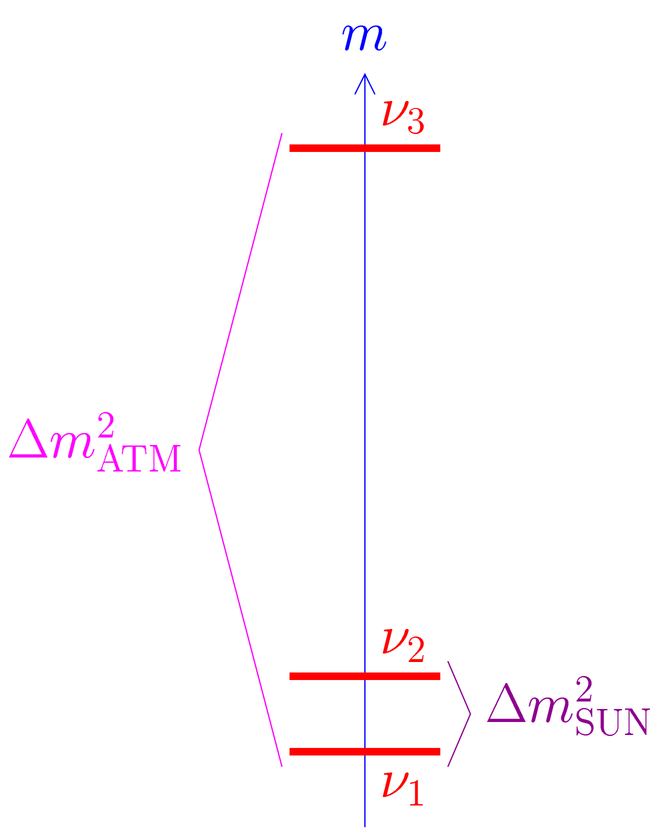
CNGS: ICARUS: $\nu_\mu \to \nu_e$, $\nu_\mu \to \nu_\tau$ OPERA: $\nu_\mu \to \nu_\tau$

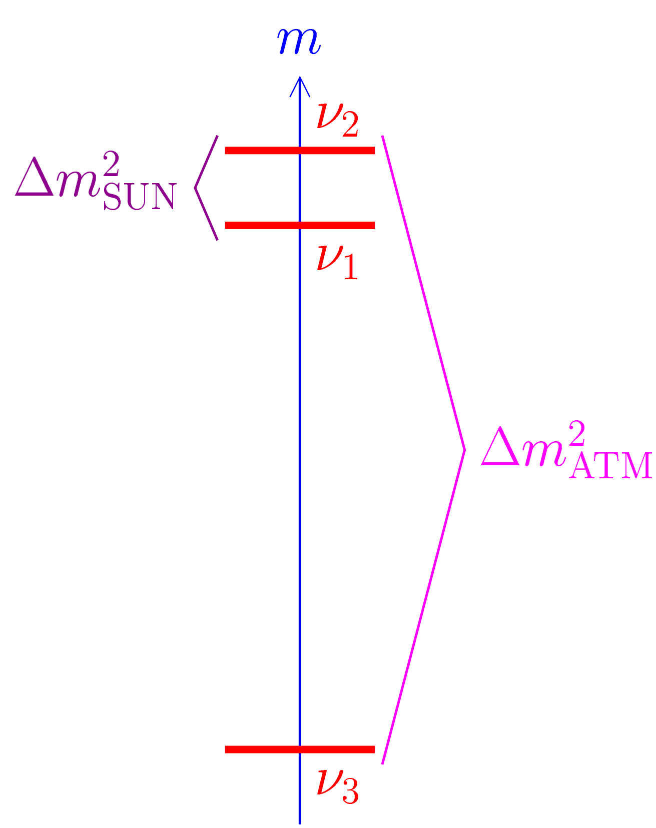
THREE-NEUTRINO MIXING

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

$\Delta m^2_{\mathrm{SUN}} = \Delta m^2_{21} \sim 5 \times 10^{-5}\,\mathrm{eV}^2 \qquad \Delta m^2_{\mathrm{ATM}} \simeq |\Delta m^2_{31}| \sim 2.5 \times 10^{-3}\,\mathrm{eV}^2$

"normal"





"inverted"

SUN → $U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$ ← ATM

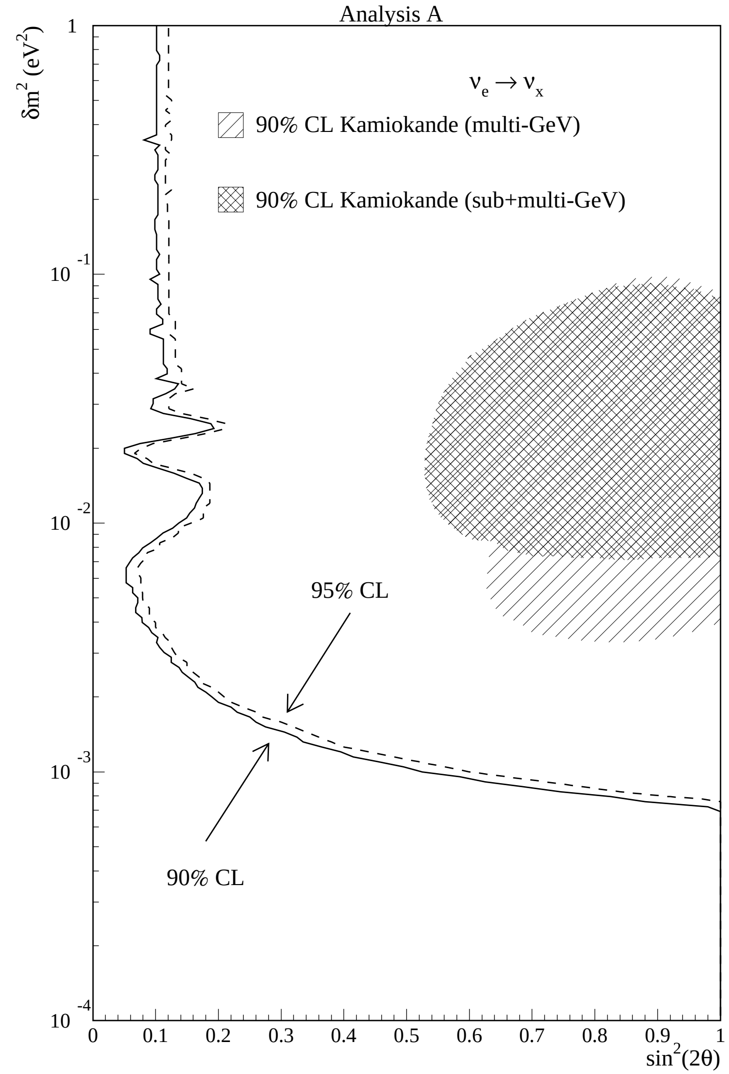
$$\Delta m^2_{21} \ll |\Delta m^2_{31}|$$

CHOZ: $\begin{cases} \Delta m^2_{\text{CHOOZ}} = \Delta m^2_{31} = \Delta m^2_{\text{ATM}} \\ \sin^2 2\vartheta_{\text{CHOOZ}} = 4|U_{e3}|^2(1 - |U_{e3}|^2) \end{cases}$

$\Downarrow$

$|U_{e3}|^2 \lesssim 4 \times 10^{-2}$ for $\Delta m^2_{\text{ATM}} \simeq 2.5 \times 10^{-3}\,\text{eV}^2$

confirmed by Palo Verde [PRD 64 (2001) 112001]



[CHOOZ, PLB 466 (1999) 415]

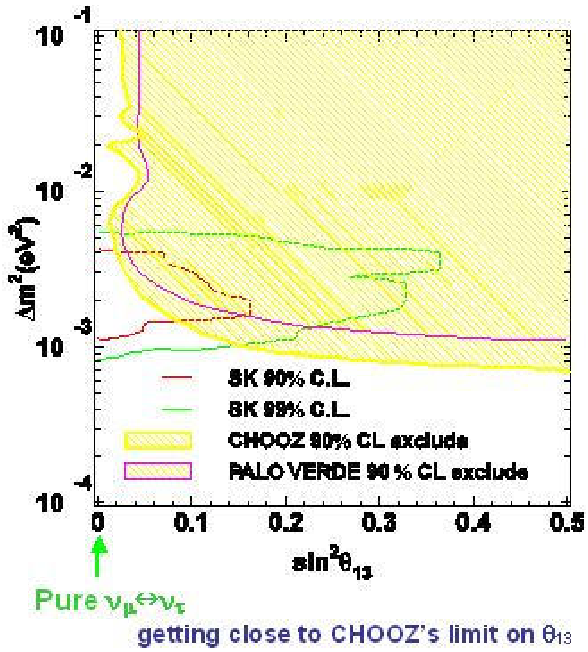
SOLAR AND ATMOSPHERIC ν OSCILLATIONS
ARE PRACTICALLY DECOUPLED!

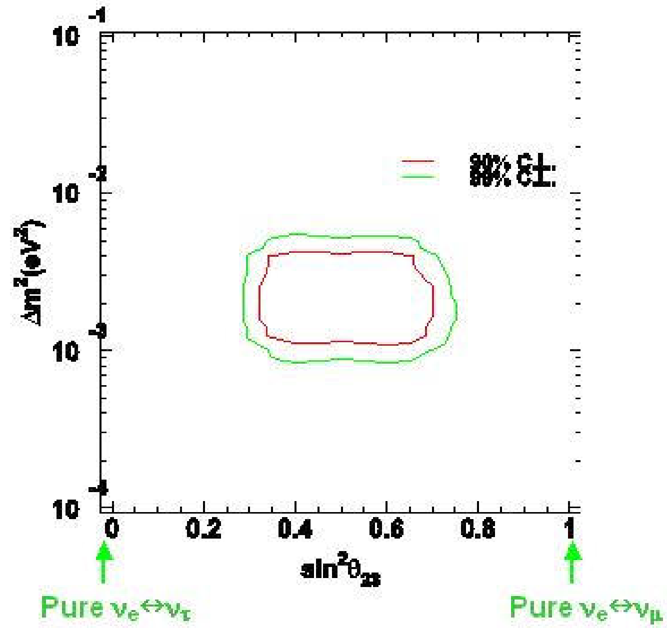
TWO-NEUTRINO SOLAR and ATMOSPHERIC ν OSCILLATIONS ARE OK!

$\sin^2\vartheta_{\text{SUN}} = \frac{|U_{e2}|^2}{1-|U_{e3}|^2} \simeq |U_{e2}|^2 \quad \sin^2\vartheta_{\text{ATM}} = \frac{|U_{\mu 3}|^2}{1-|U_{e3}|^2} \simeq |U_{\mu 3}|^2$ [Bilenky, Giunti, PLB 444 (1998) 379]

May-2002 Neutrino2002 @ Munich

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 $|U_{e3}|^2 \sim 10^{-5}$

$|U_{e3}| > 0 \Rightarrow$ sign of Δm^2_{31} (Earth matter effects) and (maybe) CP violation

ALMOST BIMAXIMAL MIXING (BILARGE)

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

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

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

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

$$\text{LMA} \Rightarrow \tan^2 \vartheta_{\rm S} \simeq 0.34 \Rightarrow \vartheta_{\rm S} \simeq \frac{\pi}{6} \Rightarrow U \simeq \begin{pmatrix} \frac{\sqrt{3}}{2} & \frac{1}{2} & 0 \\ -\frac{1}{2\sqrt{2}} & \frac{\sqrt{3}}{2\sqrt{2}} & \frac{1}{\sqrt{2}} \\ \frac{1}{2\sqrt{2}} & -\frac{\sqrt{3}}{2\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

DEPARTURE FROM BIMAXIMAL MIXING: EXAMPLE

$$j_\rho^{\mathrm{CC}\dagger} = 2 \sum_{\alpha'=e',\mu',\tau'} \overline{\ell_{\alpha' L}} \gamma_\rho \nu_{\alpha' L} \qquad \ell_{\alpha' L} = \sum_{\alpha=e,\mu,\tau} V^{(\ell)}_{\alpha'\alpha} \ell_{\alpha L} \qquad \nu_{\alpha' L} = \sum_{k=1}^{3} V^{(\nu)}_{\alpha' k} \nu_{kL}$$

$$j_\rho^{\mathrm{CC}\dagger} = 2 \sum_{\alpha,k} \overline{\ell_{\alpha L}} \gamma_\rho \left(\sum_{\alpha'} V^{(\ell)\,*}_{\alpha'\alpha} V^{(\nu)}_{\alpha' k} \right) \nu_{kL} = 2 \sum_{\alpha,k} \overline{\ell_{\alpha L}} \gamma_\rho U_{\alpha k} \nu_{kL}$$

$U = V^{(\ell)\dagger} V^{(\nu)}$ bimaximal $V^{(\nu)} = \begin{pmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & 0 \\ -\frac{1}{2} & \frac{1}{2} & \frac{1}{\sqrt{2}} \\ \frac{1}{2} & -\frac{1}{2} & \frac{1}{\sqrt{2}} \end{pmatrix}$ hierarchical $V^{(\ell)}$ like U_{CKM}

bilarge mixing with $\vartheta_{\mathrm{SUN}} < \pi/4$, $\vartheta_{\mathrm{ATM}} \simeq \pi/4$, $U_{e3} \neq 0$

LMA $\Rightarrow 10^{-3} \lesssim |U_{e3}|^2 \lesssim 4 \times 10^{-2}$ measurable in JHF-Kamioka

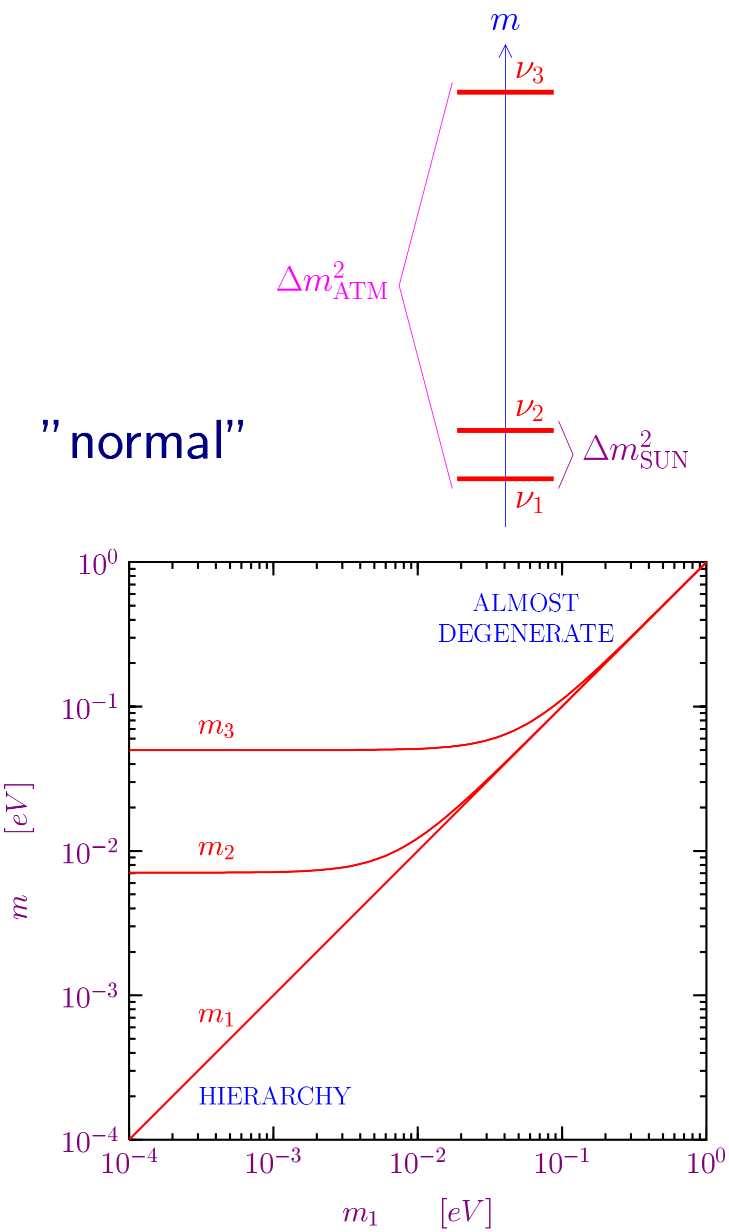
$$V^{(\ell)} \simeq U_{\mathrm{CKM}} \Rightarrow |U| \simeq \begin{pmatrix} 0.80 & 0.58 & 0.15 \\ 0.35 & 0.66 & 0.66 \\ 0.48 & 0.48 & 0.74 \end{pmatrix} \Rightarrow \tan^2 \vartheta_{\mathrm{S}} \simeq 0.45, \ \sin^2 2\vartheta_{\mathrm{A}} \simeq 0.99,$$

unfortunately small CP violation: $J \lesssim 4 \times 10^{-3}$ $\left(J_{\mathrm{max}} = \frac{1}{6\sqrt{3}} = 9.6 \times 10^{-2}, \ J_{\mathrm{max}}^{(\mathrm{quasi-bimax})} \simeq 5 \times 10^{-2} \right)$

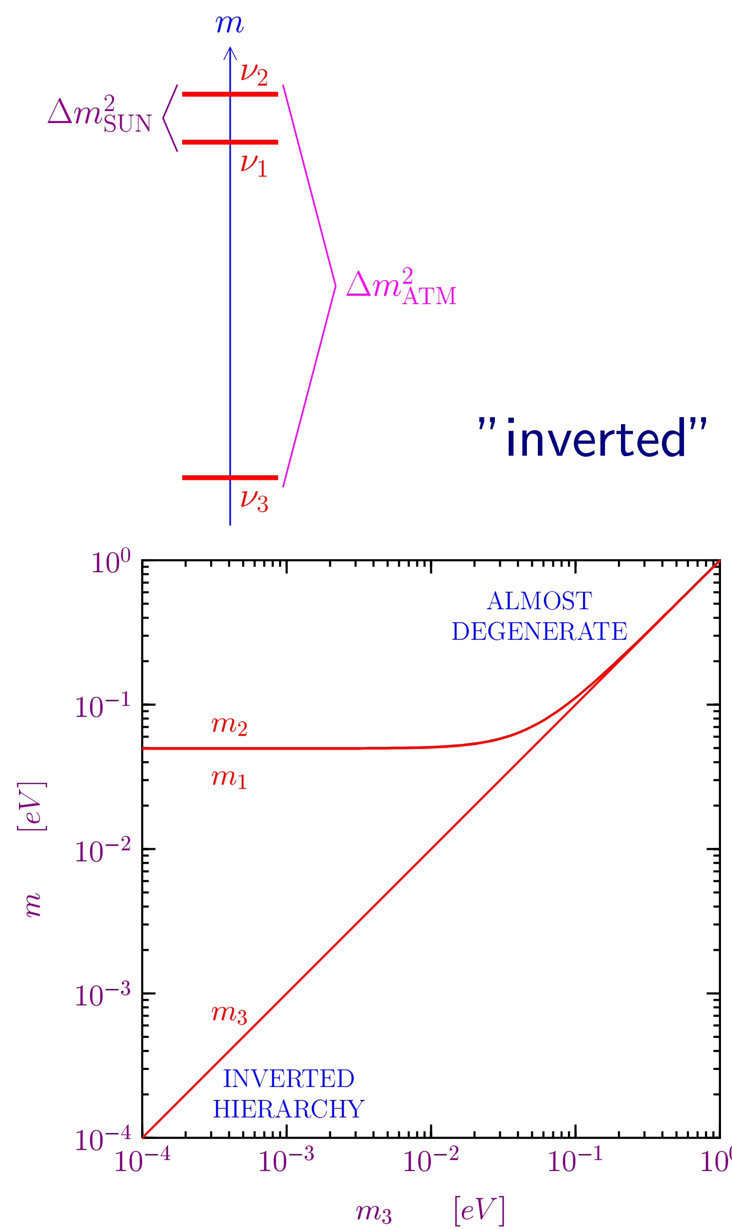
[Giunti, Tanimoto, hep-ph/0207096]

ABSOLUTE SCALE OF NEUTRINO MASSES

"normal"



"inverted"



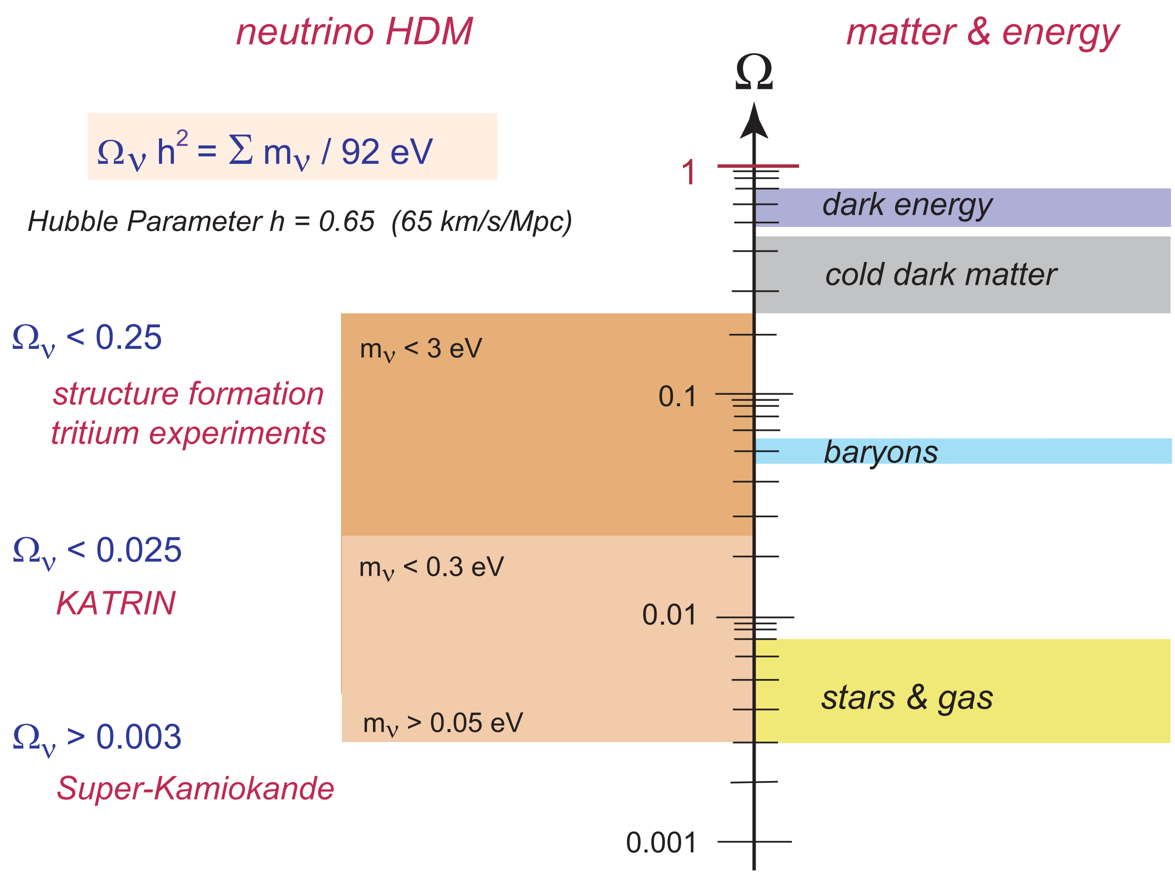
constraints on the main massive components of active flavor ν_e, ν_μ, ν_τ

Tritium β-decay: $m_{\nu_e} \lesssim 2 - 3\,\mathrm{eV}$ (95% CL) [Mainz, Troitsk]

Cosmology: $\sum_{\text{light } \nu} m_\nu \lesssim 2 - 3\,\mathrm{eV}$ (95% CL) [2dFGRS team, astro-ph/0204152] [Hannestad, astro-ph/0205223]

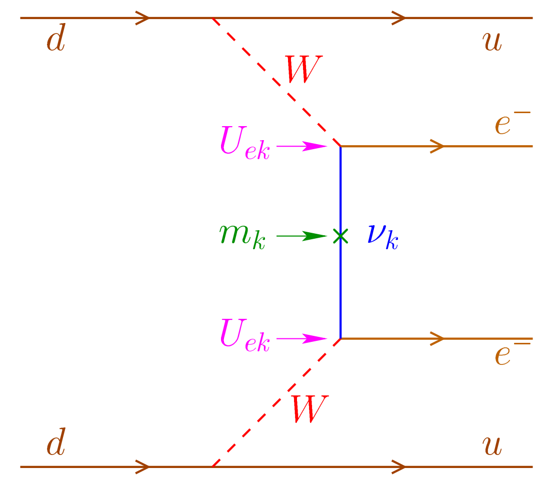
Future: KATRIN

[hep-ex/0109033]



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

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



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

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

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

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

---

eidelberg-Moscow (^{76}Ge) $\quad |\langle m \rangle|_{\text{exp}} < 0.35\,\text{eV}$ (90% CL) $\quad$ [EPJA 12 (2001) 147]

GEX (^{76}Ge) $\quad |\langle m \rangle|_{\text{exp}} < 0.33 - 1.35\,\text{eV}$ (90% CL) $\quad$ [PRD 65 (2002) 092007]

about factor 3 theoretical uncertainty on nuclear matrix element!

NEUTRINO OSCILLATIONS $\Longleftrightarrow$ $\beta\beta_{0\nu}$ decay

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

ss hierarchy without fine-tuned cancellations among

[Giunti, PRD 61 (2000) 036002]

, m_2, m_3 contributions

$$|\langle m \rangle| \simeq \max_k |\langle m \rangle|_k \qquad |\langle m \rangle|_k \equiv |U_{ek}|^2 m_k$$

$$|U_{e2}|^2 \simeq \sin^2\vartheta_{\text{SUN}},\ m_2 \simeq \sqrt{\Delta m^2_{\text{SUN}}} \qquad |U_{e3}|^2 \simeq \sin^2\vartheta_{\text{CHOOZ}},\ m_3 \simeq \sqrt{\Delta m^2_{\text{ATM}}}$$

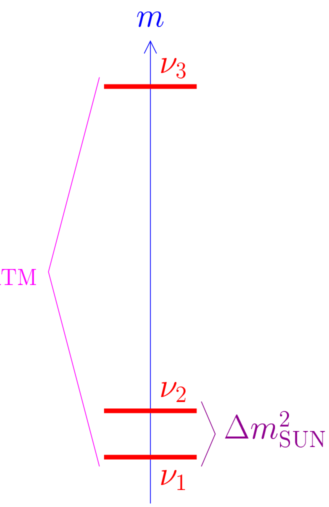
LMA (99.73% CL)

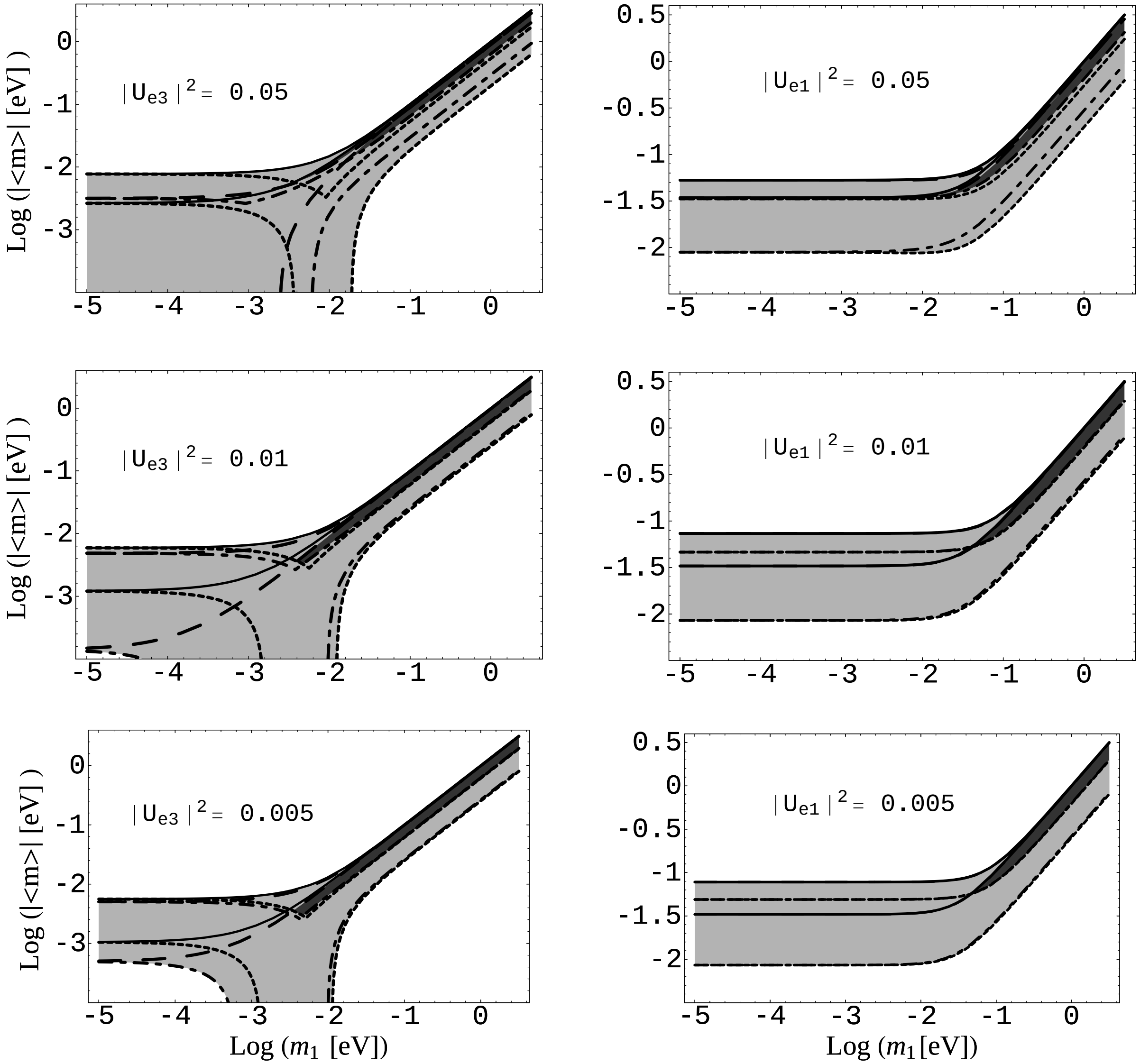
$$0.24 < \tan^2\vartheta_{\text{SUN}} < 0.89$$
$$2.3 \times 10^{-5} < \Delta m^2_{\text{SUN}} < 3.7 \times 10^{-4} \quad \Rightarrow \quad 9 \times 10^{-4} \lesssim |\langle m \rangle|_2 \lesssim 9 \times 10^{-3}$$

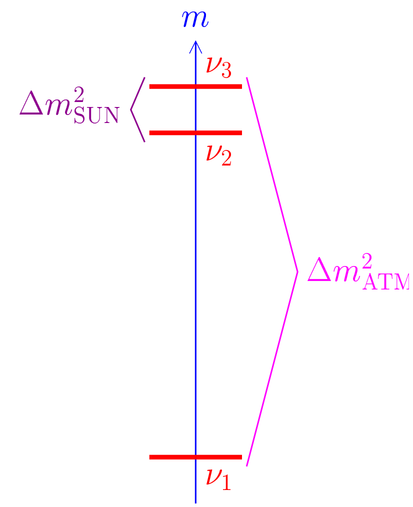
[Bahcall, Gonzalez-Garcia, Peña-Garay, hep-ph/0204314]

$$|U_{e3}|^2 \lesssim 4 \times 10^{-2}$$
$$\Delta m^2_{\text{ATM}} \simeq 2.5 \times 10^{-3} \quad \Rightarrow \quad |\langle m \rangle|_3 \lesssim 2 \times 10^{-3}$$

m_2 contribution $|\langle m \rangle|_2$ may be dominant! (lower limit for $|\langle m \rangle|$)





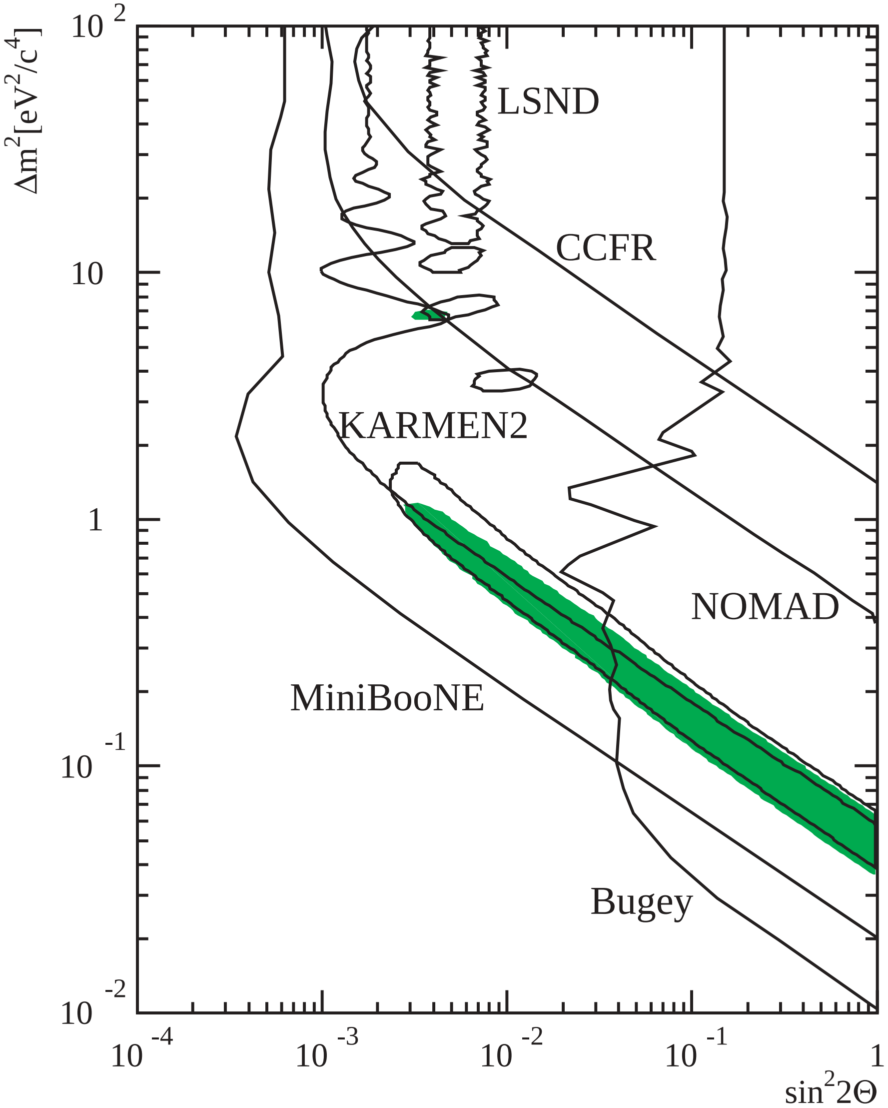


[Pascoli, Petcov, hep-ph/0205022]

see also [Feruglio, Strumia, Vissani, hep-ph/0201291]

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)

LSND $\Rightarrow N_\nu > 3$



[Church, Eitel, Mills, Steidl, PRD66 (2002) 013001]

$$\Delta m^2_{\mathrm{LSND}} \sim 0.2 - 1\,\mathrm{eV}^2$$

$$\Delta m^2_{\mathrm{ATM}} \sim 10^{-3} - 10^{-2}\,\mathrm{eV}^2$$

$$\Delta m^2_{\mathrm{SUN}} \lesssim 10^{-4}\,\mathrm{eV}^2$$

$$\Downarrow$$

$$N_\nu > 3$$

see
[Giunti, hep-ph/0012236]

OKKAM'S RAZOR

$$\Downarrow$$

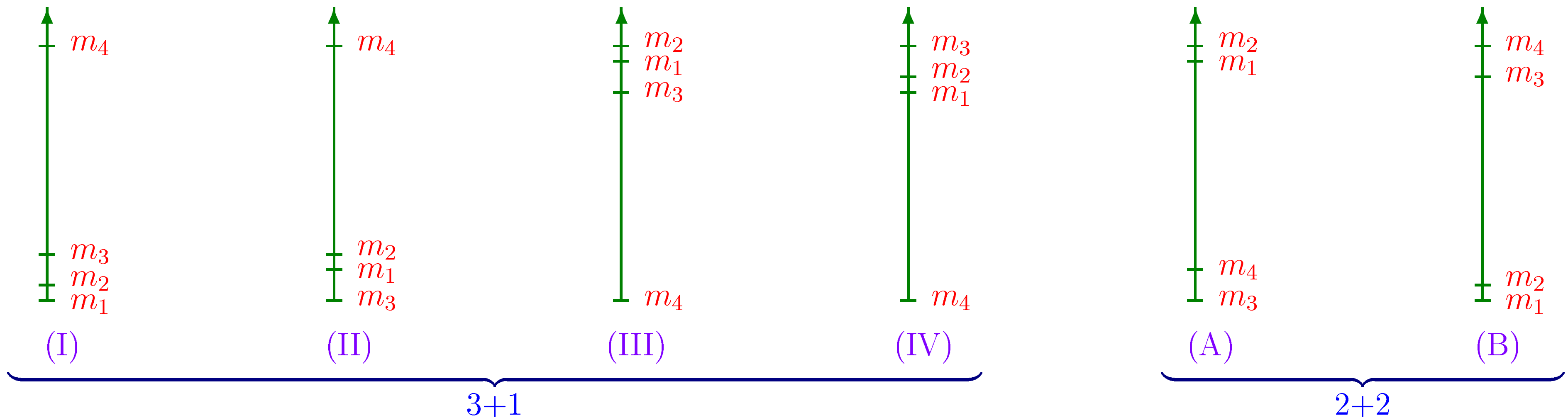
$$N_\nu = 4$$

$$\Downarrow$$

light sterile ν_s

FOUR-NEUTRINO MIXING

$\Delta m^2_{\rm LSND} \sim 1\,{\rm eV}^2$ $\Delta m^2_{\rm ATM} \sim 3 \times 10^{-3}\,{\rm eV}^2$ $\Delta m^2_{\rm SUN} \lesssim 10^{-4}\,{\rm eV}^2$



3+1 schemes disfavored by short-baseline ν oscillation experiments

[Bilenky, Giunti, Grimus, EPJC 1 (1998) 247] [Bilenky, Giunti, Grimus, Schwetz, PRD 60 (1999) 073007]

2+2 schemes need ν_s in SUN or ATM $(\eta_s^{\rm SUN} + \eta_s^{\rm ATM} \simeq 1)$

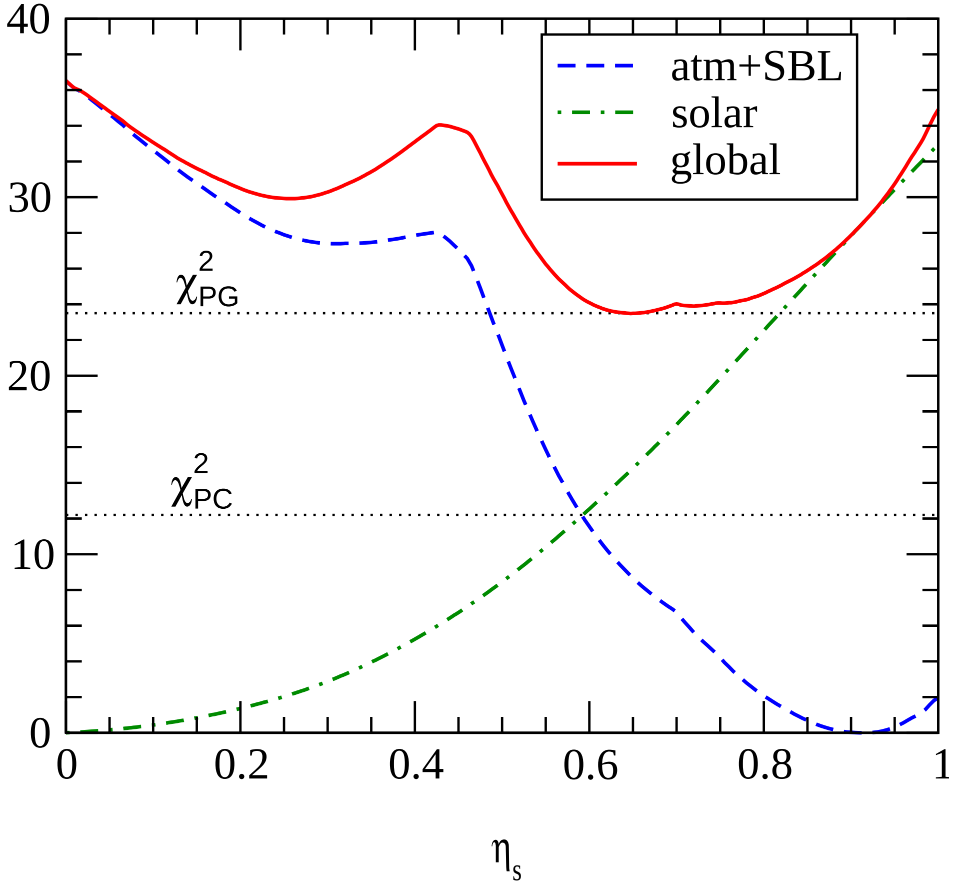
[Peres, Smirnov, NPB 599 (2001) 3]

2+2 FOUR-NEUTRINO SCHEMES

pure $\nu_\mu \to \nu_s$ is strongly disfavored in ATM (SK)

pure $\nu_e \to \nu_s$ is practically excluded in SUN (SNO & SNO+SK)

partial $\nu_e \to \nu_s$ in SUN and $\nu_\mu \to \nu_s$ in ATM is disfavored



$\eta_S \equiv$ fraction of ν_s in solar osc.

G.o.F. $= 1.3 \times 10^{-6}$

[Maltoni, Schwetz, Tortóla, Valle, hep-ph/0207157]

see also

[Dooling, Giunti, Kim, Kang, PRD 61 (2000) 073011]

[Giunti, Gonzalez-Garcia, Peña-Garay, PRD 62 (2000) 013005]

[Yasuda, hep-ph/0006319]

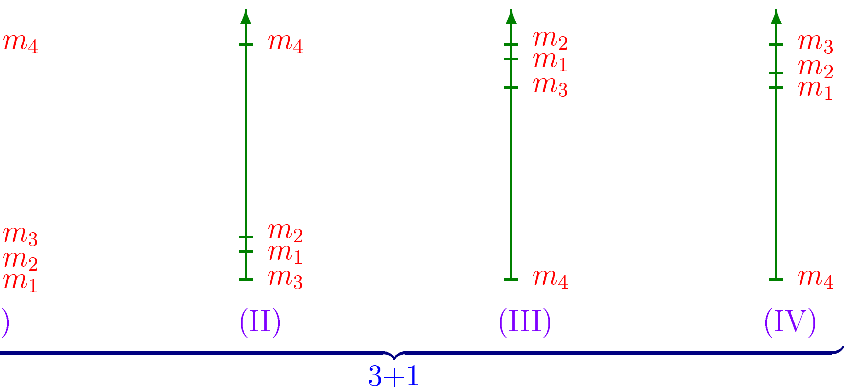
[Fogli, Lisi, Marrone, PRD 63 (2001) 053008]

[Gonzalez-Garcia, Maltoni, Peña-Garay, PRD 64 (2001) 093001]

[Bahcall, Gonzalez-Garcia, Peña-Garay, hep-ph/0204194]

[Maltoni, Schwetz, Tortóla, Valle, hep-ph/0207227]

3+1 FOUR-NEUTRINO SCHEMES



short-baseline experiments

$$A(\nu_e \to \nu_e) = 4|U_{e4}|^2 \left(1 - |U_{e4}|^2\right)$$

$$A(\nu_\mu \to \nu_\mu) = 4|U_{\mu 4}|^2 \left(1 - |U_{\mu 4}|^2\right)$$

$$A(\nu_\mu \to \nu_e) = 4|U_{\mu 4}|^2 |U_{e4}|^2$$

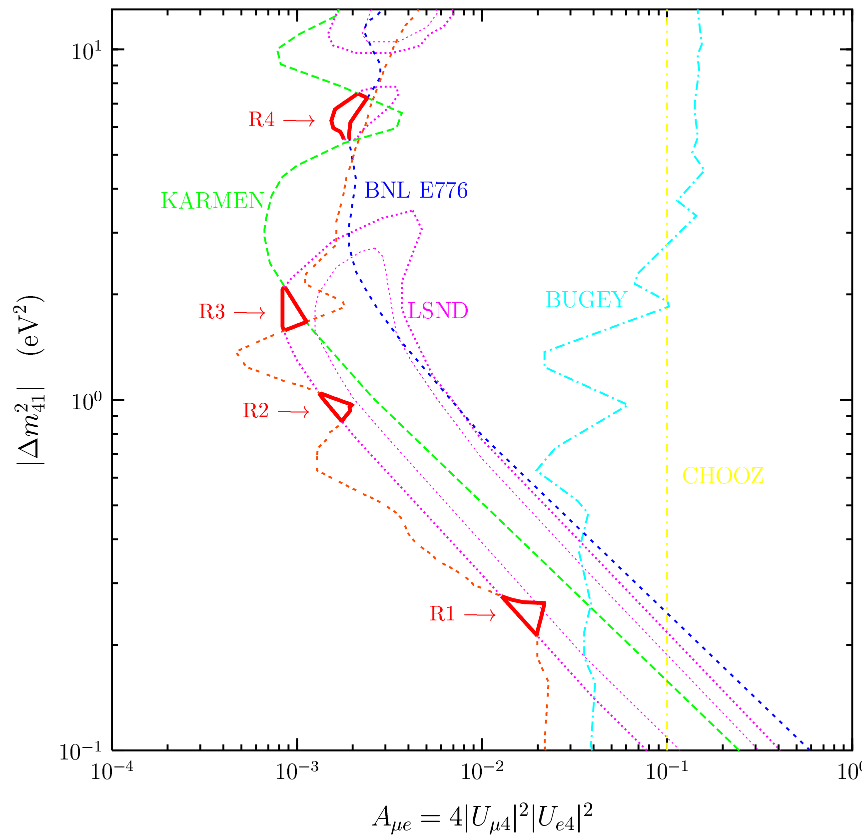
[Bilenky, Giunti, Grimus, EPJC 1 (1998) 247]

see also

[Barger, Weiler, Whisnant, PLB 427 (1998) 97]

[Barger, Pakvasa, Weiler, Whisnant, PRD 58 (1998) 093016]

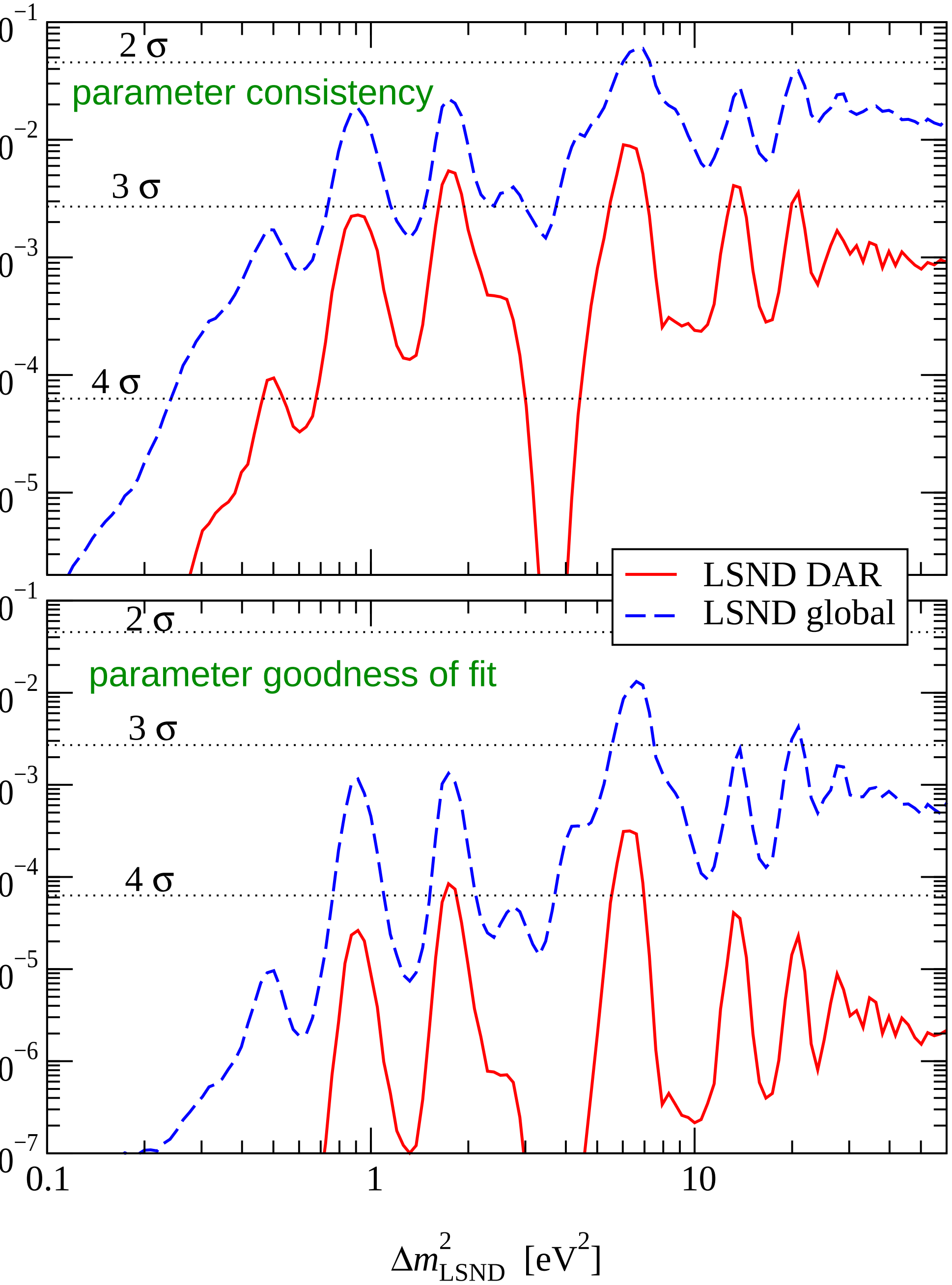
[Bilenky, Giunti, Grimus, PPNP 43 (1999) 1]



[Giunti, Laveder, JHEP 02 (2001) 001]

see also

[Barger, Kayser, Learned, Weiler, Whisnant , PLB 489 (2000) 345]



[Maltoni, Schwetz, Tortóla, Valle, hep-ph/0207157]

see also

[Peres, Smirnov, NPB 599 (2001) 3]

[Grimus, Schwetz, EPJC 20 (2001) 1]

[Maltoni, Schwetz, Valle, PLB 518 (2001) 252]

[Maltoni, Schwetz, Valle, PRD 65 (2002) 093004]

[Strumia, PLB 539 (2002) 91]

CONCLUSIONS

SNO and SNO+SK smoking gun evidence of solar flavor transitions

all solar ν experiments $\Rightarrow$ LMA $\nu_e \to \nu_\mu, \nu_\tau$ transitions

3ν mixing (SUN+ATM) $\Rightarrow$ almost bimaximal mixing with $|U_{e3}|^2 \ll 1$

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

future exp.: measure $|U_{e3}| > 0 \Rightarrow$ sign of Δm^2_{31} and CP violation

4ν mixing is disfavored

SBL experiments disfavor 3+1 schemes

SUN+ATM experiments disfavor 2+2 schemes

adding more sterile neutrinos (e.g. extra-dim.) does not help!

if MiniBooNE will confirm LSND $\Rightarrow$ real puzzle

Neutrino Unbound

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

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