

# Phenomenological Status of Neutrino Mixing

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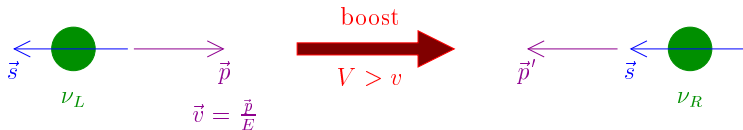
Neutrino Unbound: <http://www.nu.to.infn.it>

SIF, XCIII Congresso Nazionale, Pisa, 25 Settembre 2007

# Outline

- Brief Introduction on Neutrino Masses
- Solar Neutrinos and KamLAND
- Atmospheric Neutrinos, K2K and MINOS
- Three-Neutrino Mixing
- Absolute Scale of Neutrino Masses
- Tritium Beta-Decay
- Neutrinoless Double-Beta Decay
- Cosmology
- LSND and MiniBooNE
- Conclusions

# Standard Model: Massless Neutrinos



Standard Model:  $\nu_L, \nu_L^c = (\nu^c)_R \implies$  no Dirac mass term  
 $\mathcal{L}^D \sim m^D \overline{\nu}_L \nu_R$  (no  $\nu_R, (\nu^c)_L$ )

Majorana Neutrino:  $\nu \equiv \nu^c$   
 $(\nu^c)_R \equiv \nu_R \implies$  Majorana mass term  
 $\mathcal{L}^M \sim m^M \overline{\nu}_L \nu_L^c = m^M \overline{\nu}_L (\nu^c)_R$

Standard Model: Majorana mass term **not** allowed by  $SU(2)_L \times U(1)_Y$   
 (no Higgs triplet)

# Extension of the SM: Massive Neutrinos

Standard Model can be extended with  $\nu_R$  ( $e_L, e_R; u_L, u_R; d_L, d_R; \dots$ )

$\nu_L + \nu_R \Rightarrow$  Dirac neutrino mass term  $\mathcal{L}^D \sim m^D \overline{\nu}_L \nu_R \Rightarrow m^D \lesssim 100 \text{ GeV}$

surprise: Majorana neutrino mass for  $\nu_R$  is allowed!  $\mathcal{L}_R^M \sim m_R^M \overline{(\nu^c)_L} \nu_R$

total neutrino mass term  $\mathcal{L}^{D+M} \sim \begin{pmatrix} \overline{\nu}_L & \overline{(\nu^c)_L} \end{pmatrix} \begin{pmatrix} 0 & m^D \\ m^D & m_R^M \end{pmatrix} \begin{pmatrix} (\nu^c)_R \\ \nu_R \end{pmatrix}$

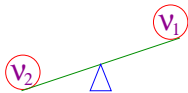
$m_R^M$  can be arbitrarily large (not protected by SM symmetries)

$m_R^M \sim$  scale of new physics beyond Standard Model  $\Rightarrow m_R^M \gg m^D$

diagonalization of  $\begin{pmatrix} 0 & m^D \\ m^D & m_R^M \end{pmatrix} \Rightarrow m_1 \simeq \frac{(m^D)^2}{m_R^M}, \quad m_2 \simeq m_R^M$

natural explanation of  
smallness of neutrino masses

massive neutrinos are Majorana!



see-saw mechanism

[Minkowski, PLB 67 (1977) 42]

[Yanagida (1979); Gell-Mann, Ramond, Slansky (1979); Mohapatra, Senjanovic, PRL 44 (1980) 912]

# Lepton Numbers

Standard Model:

Lepton numbers are conserved

	$L_e$	$L_\mu$	$L_\tau$		$L_e$	$L_\mu$	$L_\tau$
$(\nu_e, e^-)$	+1	0	0	$((\nu^c)_e, e^+)$	-1	0	0
$(\nu_\mu, \mu^-)$	0	+1	0	$((\nu^c)_\mu, \mu^+)$	0	-1	0
$(\nu_\tau, \tau^-)$	0	0	+1	$((\nu^c)_\tau, \tau^+)$	0	0	-1

$$L = L_e + L_\mu + L_\tau$$

Dirac mass term  $m^D \overline{\nu}_L \nu_R \rightarrow (\overline{\nu}_{eL} \quad \overline{\nu}_{\mu L} \quad \overline{\nu}_{\tau L}) \begin{pmatrix} m_{ee}^D & m_{e\mu}^D & m_{e\tau}^D \\ m_{\mu e}^D & m_{\mu\mu}^D & m_{\mu\tau}^D \\ m_{\tau e}^D & m_{\tau\mu}^D & m_{\tau\tau}^D \end{pmatrix} \begin{pmatrix} \nu_{eR} \\ \nu_{\mu R} \\ \nu_{\tau R} \end{pmatrix}$

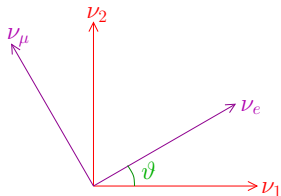
$L_e, L_\mu, L_\tau$  are not conserved, but  $L$  is conserved  $L(\nu_{\alpha R}) = L(\nu_{\beta L}) \Rightarrow |\Delta L| = 0$

Majorana mass term  $m^M \overline{\nu}_L (\nu^c)_R \rightarrow (\overline{\nu}_{eL} \quad \overline{\nu}_{\mu L} \quad \overline{\nu}_{\tau L}) \begin{pmatrix} m_{ee}^M & m_{e\mu}^M & m_{e\tau}^M \\ m_{\mu e}^M & m_{\mu\mu}^M & m_{\mu\tau}^M \\ m_{\tau e}^M & m_{\tau\mu}^M & m_{\tau\tau}^M \end{pmatrix} \begin{pmatrix} (\nu_e^c)_R \\ (\nu_\mu^c)_R \\ (\nu_\tau^c)_R \end{pmatrix}$

$L, L_e, L_\mu, L_\tau$  are not conserved  $L(\nu_\alpha^c) = -L(\nu_\beta) \Rightarrow |\Delta L| = 2$

# Two-Neutrino Mixing and Oscillations

$$|\nu_\alpha\rangle = \sum_{k=1}^2 U_{\alpha k} |\nu_k\rangle \quad (\alpha = e, \mu)$$



$$U = \begin{pmatrix} \cos\vartheta & \sin\vartheta \\ -\sin\vartheta & \cos\vartheta \end{pmatrix}$$

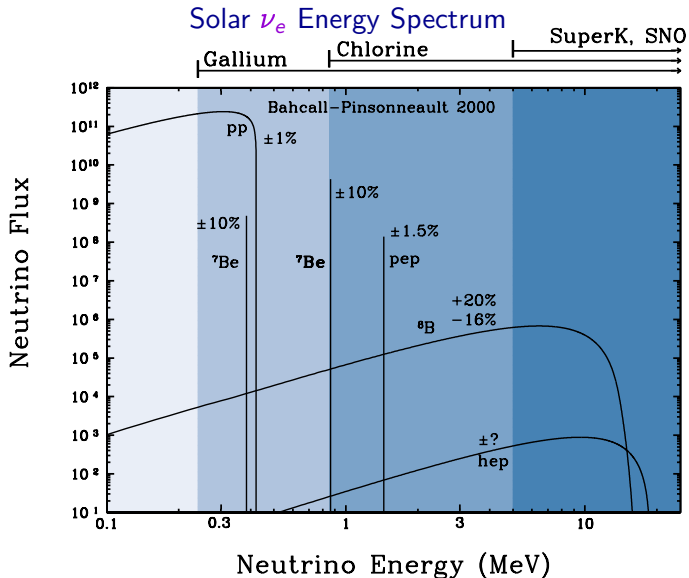
$$\begin{aligned} |\nu_e\rangle &= \cos\vartheta |\nu_1\rangle + \sin\vartheta |\nu_2\rangle \\ |\nu_\mu\rangle &= -\sin\vartheta |\nu_1\rangle + \cos\vartheta |\nu_2\rangle \end{aligned}$$

$$\Delta m^2 \equiv \Delta m_{21}^2 \equiv m_2^2 - m_1^2$$

Transition Probability:  $P_{\nu_e \rightarrow \nu_\mu} = P_{\nu_\mu \rightarrow \nu_e} = \sin^2 2\vartheta \sin^2 \left( \frac{\Delta m^2 L}{4E} \right)$

Survival Probabilities:  $P_{\nu_e \rightarrow \nu_e} = P_{\nu_\mu \rightarrow \nu_\mu} = 1 - P_{\nu_e \rightarrow \nu_\mu}$

# Solar Neutrinos



[J.N. Bahcall, <http://www.sns.ias.edu/~jnb>]

# Homestake+Kam.+GALLEX+SAGE+Super-K+SNO

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

$$\Phi_{\nu_e, \nu_\mu, \nu_\tau}^{\text{SNO}} = 5.09 \pm 0.66 \times 10^6 \text{ cm}^{-2} \text{ s}^{-1}$$

SNO solved  
solar neutrino problem



Neutrino Physics  
(April 2002)

[SNO, PRL 89 (2002) 011301, nucl-ex/0204008]

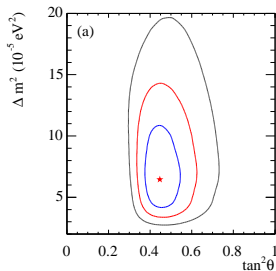
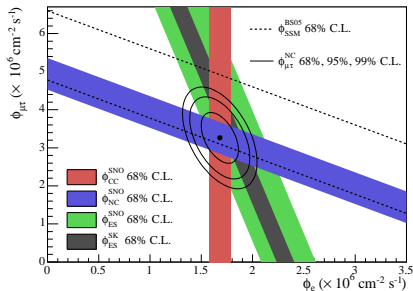
$\nu_e \rightarrow \nu_\mu, \nu_\tau$  oscillations



LMA: Large Mixing Angle solution

$$\Delta m^2 \simeq 6.5_{-2.3}^{+4.4} \times 10^{-5} \text{ eV}^2$$

$$\tan^2 \vartheta \simeq 0.45_{-0.08}^{+0.09}$$



[SNO, PRC 72 (2005) 055502, nucl-ex/0502021]

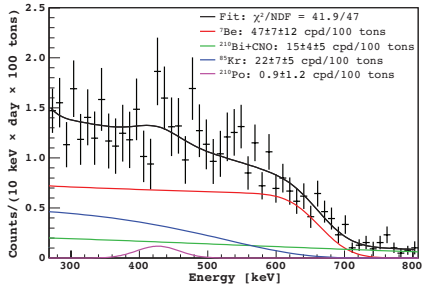
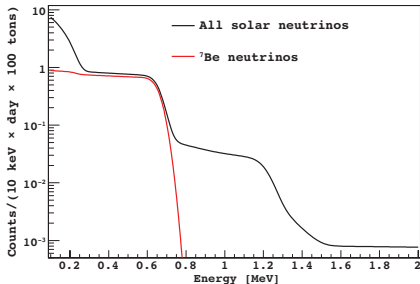


# BOREXino

[BOREXino, arXiv:0708.2251]

Real-time measurement of  ${}^7\text{Be}$  solar neutrinos (0.862 MeV)

$$\nu + e \rightarrow \nu + e \quad E = 0.862 \text{ MeV} \quad \Rightarrow \quad \sigma_{\nu e} \simeq 5.5 \sigma_{\nu\mu, \nu\tau}$$



$$n_{\text{the}}^{\text{no-osc}} = 75 \pm 4 \text{ day}^{-1} (100 \text{ tons})^{-1} \quad n_{\text{exp}} = 47 \pm 7 \pm 12 \text{ day}^{-1} (100 \text{ tons})^{-1}$$

$$n_{\text{the}}^{\text{osc}} = 49 \pm 4 \text{ day}^{-1} (100 \text{ tons})^{-1} \quad (n_{\text{the}}^{\text{no-osc}} - n_{\text{exp}}) / \Delta n \simeq 1.9$$

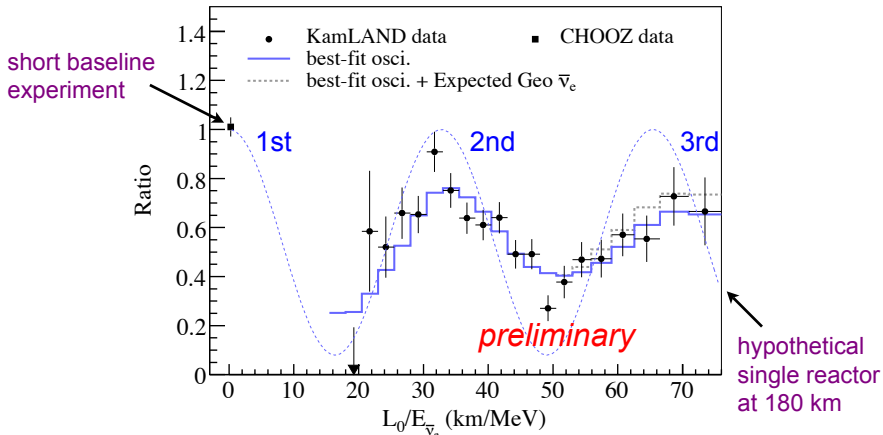
# KamLAND

Reactor  $\bar{\nu}_e \rightarrow \bar{\nu}_e$  confirmation of LMA (December 2002)

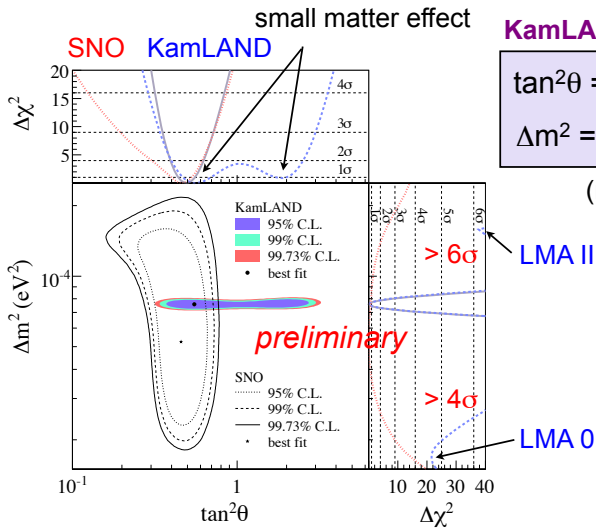
53 nuclear power reactors in Japan and Korea  $\rightarrow$  Kamioka Mine

$\langle L \rangle \simeq 180$  km

$\langle E \rangle \simeq 4$  MeV



[I. Shimizu (KamLAND), TAUP 2007]

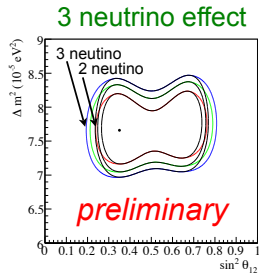


**KamLAND only**

$$\tan^2\theta = 0.56^{+0.14}_{-0.09}$$

$$\Delta m^2 = 7.58^{+0.21}_{-0.20} \times 10^{-5} \text{ eV}^2$$

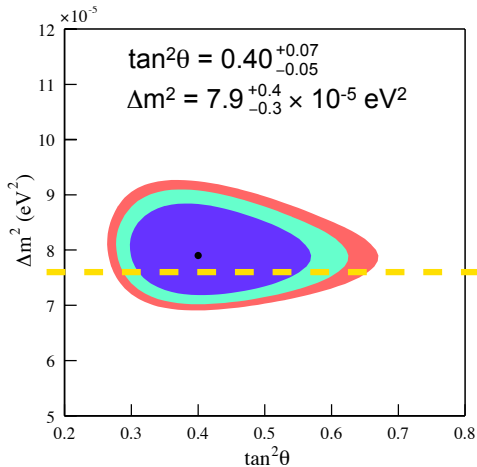
(marginalized error)



same result for  $\Delta m^2$

[I. Shimizu (KamLAND), TAUP 2007]

## KamLAND 2004

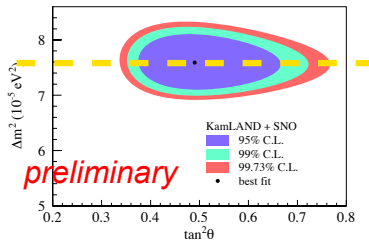


## This result

## KamLAND + SNO

$$\tan^2\theta = 0.49^{+0.07}_{-0.05}$$
$$\Delta m^2 = 7.59^{+0.20}_{-0.21} \times 10^{-5} \text{ eV}^2$$

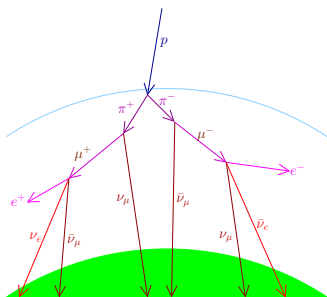
$\Delta m^2$ : systematic uncertainty 2.0%  
dominated by linear energy scale uncertainty



**$\Delta m^2$  is measured at 2.8% precision by KamLAND**

[I. Shimizu (KamLAND), TAUP 2007]

# Atmospheric Neutrinos



$$\frac{N(\nu_\mu + \bar{\nu}_\mu)}{N(\nu_e + \bar{\nu}_e)} \simeq 2 \quad \text{at } E \lesssim 1 \text{ GeV}$$

uncertainty on ratios:  $\sim 5\%$

uncertainty on fluxes:  $\sim 30\%$

ratio of ratios

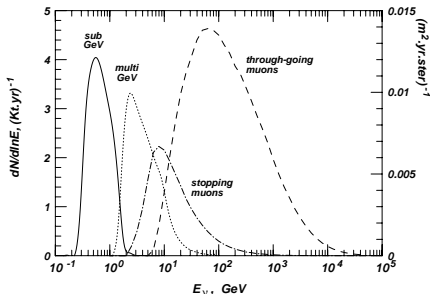
$$R \equiv \frac{[N(\nu_\mu + \bar{\nu}_\mu)/N(\nu_e + \bar{\nu}_e)]_{\text{data}}}{[N(\nu_\mu + \bar{\nu}_\mu)/N(\nu_e + \bar{\nu}_e)]_{\text{MC}}}$$

$$R_{\text{sub-GeV}}^{\text{K}} = 0.60 \pm 0.07 \pm 0.05$$

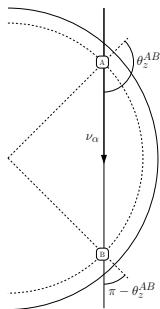
[Kamiokande, PLB 280 (1992) 146]

$$R_{\text{multi-GeV}}^{\text{K}} = 0.57 \pm 0.08 \pm 0.07$$

[Kamiokande, PLB 335 (1994) 237]



# Super-Kamiokande Up-Down Asymmetry



$E_\nu \gtrsim 1 \text{ GeV} \Rightarrow$  isotropic flux of cosmic rays

$$\phi_{\nu_\alpha}^{(A)}(\theta_z^{AB}) = \phi_{\nu_\alpha}^{(B)}(\pi - \theta_z^{AB}) \quad \phi_{\nu_\alpha}^{(A)}(\theta_z^{AB}) = \phi_{\nu_\alpha}^{(B)}(\theta_z^{AB})$$

$$\Downarrow$$
$$\phi_{\nu_\alpha}^{(A)}(\theta_z) = \phi_{\nu_\alpha}^{(A)}(\pi - \theta_z)$$

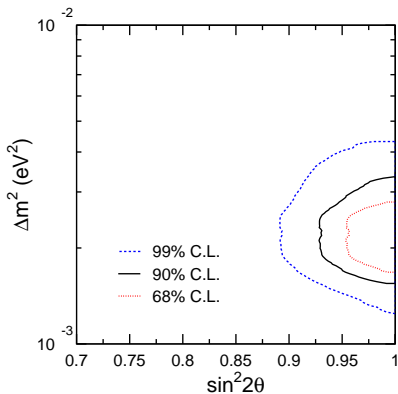
(December 1998)

$$A_{\nu_\mu}^{\text{up-down}}(\text{SK}) = \left( \frac{N_{\nu_\mu}^{\text{up}} - N_{\nu_\mu}^{\text{down}}}{N_{\nu_\mu}^{\text{up}} + N_{\nu_\mu}^{\text{down}}} \right) = -0.296 \pm 0.048 \pm 0.01$$

[Super-Kamiokande, Phys. Rev. Lett. 81 (1998) 1562, hep-ex/9807003]

$6\sigma$  MODEL INDEPENDENT EVIDENCE OF  $\nu_\mu$  DISAPPEARANCE!

# Fit of Super-Kamiokande Atmospheric Data



Best Fit:  $\left\{ \begin{array}{l} \nu_{\mu} \rightarrow \nu_{\tau} \\ \Delta m^2 = 2.1 \times 10^{-3} \text{ eV}^2 \\ \sin^2 2\theta = 1.0 \end{array} \right.$

1489.2 live-days (Apr 1996 – Jul 2001)

[Super-Kamiokande, PRD 71 (2005) 112005, hep-ex/0501064]

Measure of  $\nu_{\tau}$  CC Int. is Difficult:

- ▶  $E_{\text{th}} = 3.5 \text{ GeV} \Rightarrow \sim 20 \text{ events/yr}$
- ▶  $\tau$ -Decay  $\Rightarrow$  Many Final States

$\nu_{\tau}$ -Enriched Sample

$$N_{\nu_{\tau}}^{\text{the}} = 78 \pm 26 @ \Delta m^2 = 2.4 \times 10^{-3} \text{ eV}^2$$

$$N_{\nu_{\tau}}^{\text{exp}} = 138^{+50}_{-58}$$

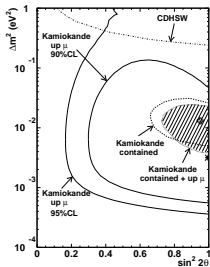
$$N_{\nu_{\tau}} > 0 @ 2.4\sigma$$

[Super-Kamiokande, PRL 97(2006) 171801, hep-ex/0607059]

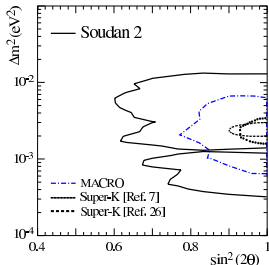
Future Check: OPERA ( $\nu_{\mu} \rightarrow \nu_{\tau}$ )  
 CERN to Gran Sasso (CNGS)  
 $L \simeq 732 \text{ km}$      $\langle E \rangle \simeq 18 \text{ GeV}$

[NJP 8 (2006) 303, hep-ex/0611023]

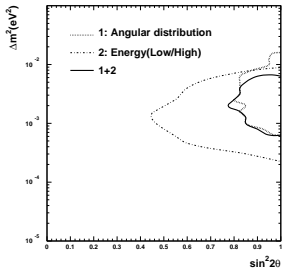
# Kamiokande, Soudan-2, MACRO and MINOS



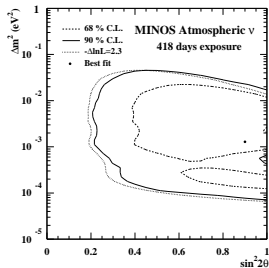
[Kamiokande, PRL 81 (1998) 2016, hep-ex/9806038]



[Soudan 2, PRD 72 (2005) 052005, hep-ex/0507068]



[MACRO, PLB 566 (2003) 35, hep-ex/0304037]



[MINOS, PRD 73 (2006) 072002, hep-ex/0512036]



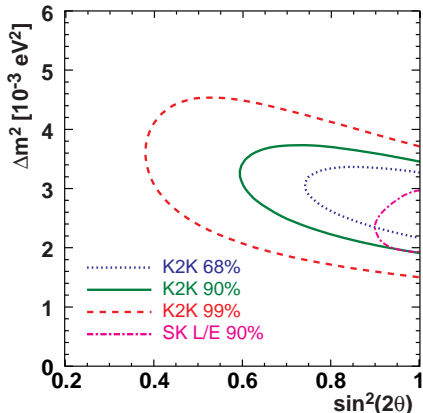
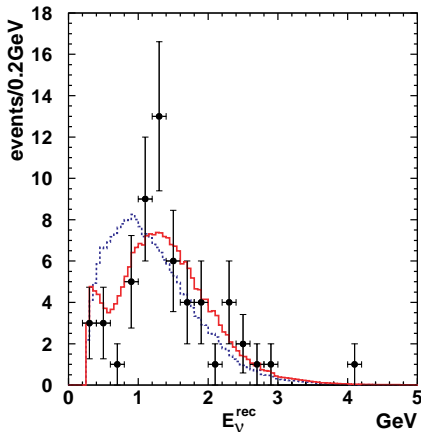
# K2K

KEK to Kamioka (Super-Kamiokande)

$\nu_\mu \rightarrow \nu_\mu$

$L \simeq 250$  km     $\langle E \rangle \simeq 1.3$  GeV

confirmation of atmospheric allowed region (June 2002)



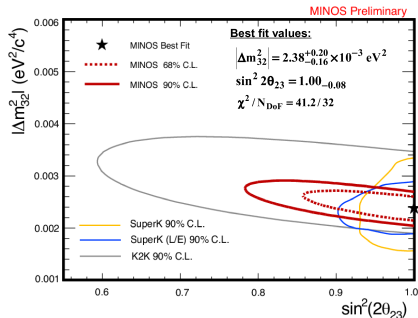
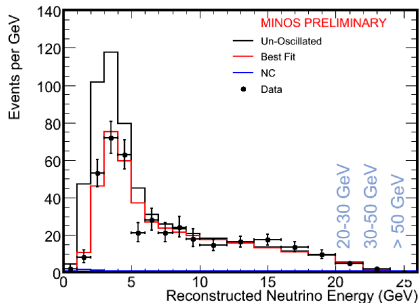
best fit:  $\Delta m^2 = 2.75 \times 10^{-3} \text{ eV}^2$      $\sin^2 2\vartheta = 1.00$

[K2K, PRD 74 (2006) 072003, hep-ex/0606032]

# MINOS

Fermilab to Soudan Mine (Minnesota)  $\nu_\mu \rightarrow \nu_\mu$

$L \simeq 730$  km  $\langle E \rangle \simeq 3.5$  GeV



[MINOS, TAUP 2007]

# Experimental Evidences of Neutrino Oscillations

<p>Solar <math>\nu_e \rightarrow \nu_\mu, \nu_\tau</math></p>	$\left( \begin{array}{c} \text{Homestake} \\ \text{Kamiokande/Super-K} \\ \text{GALLEX/GNO} \\ \text{SAGE} \\ \text{Super-Kamiokande} \\ \text{SNO} \\ \text{BOREXino} \\ \text{(KamLAND)} \end{array} \right)$	$\left. \vphantom{\left( \begin{array}{c} \text{Homestake} \\ \text{Kamiokande/Super-K} \\ \text{GALLEX/GNO} \\ \text{SAGE} \\ \text{Super-Kamiokande} \\ \text{SNO} \\ \text{BOREXino} \\ \text{(KamLAND)} \end{array} \right)} \right\} \xrightarrow{2\sigma}$	$\left\{ \begin{array}{l} \Delta m_{\text{SUN}}^2 = 7.59 (1 \pm 0.03) \times 10^{-5} \text{ eV}^2 \\ \sin^2 \vartheta_{\text{SUN}} = 0.49 (1_{-0.10}^{+0.14}) \\ \text{[I. Shimizu (KamLAND), TAUP 2007]} \end{array} \right.$
<p>Reactor <math>\bar{\nu}_e</math> disappearance</p>			
<p>Atmospheric <math>\nu_\mu \rightarrow \nu_\tau</math></p>	$\left( \begin{array}{c} \text{Kamiokande} \\ \text{IMB} \\ \text{Super-Kamiokande} \\ \text{MACRO} \\ \text{Soudan-2} \\ \text{(K2K \& MINOS)} \end{array} \right)$	$\left. \vphantom{\left( \begin{array}{c} \text{Kamiokande} \\ \text{IMB} \\ \text{Super-Kamiokande} \\ \text{MACRO} \\ \text{Soudan-2} \\ \text{(K2K \& MINOS)} \end{array} \right)} \right\} \xrightarrow{2\sigma}$	$\left\{ \begin{array}{l} \Delta m_{\text{ATM}}^2 = 2.6 (1_{-0.15}^{+0.14}) \times 10^{-3} \text{ eV}^2 \\ \sin^2 \vartheta_{\text{ATM}} = 0.45 (1_{-0.20}^{+0.35}) \\ \text{[Fogli et al, PRD 75 (2007) 053001, hep-ph/0608060]} \end{array} \right.$
<p>Accelerator <math>\nu_\mu</math> disappearance</p>			

# Three-Neutrino Mixing

$$\nu_{\alpha L} = \sum_{k=1}^3 U_{\alpha k} \nu_{kL} \quad (\alpha = e, \mu, \tau)$$

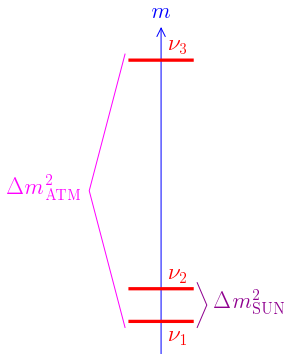
three flavor fields  $\nu_e, \nu_\mu, \nu_\tau$

three massive fields  $\nu_1, \nu_2, \nu_3$

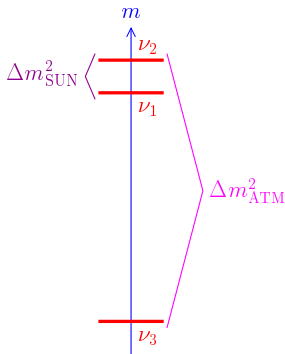
$$\Delta m_{\text{SUN}}^2 = \Delta m_{21}^2 \simeq 7.6 \times 10^{-5} \text{ eV}^2$$

$$\Delta m_{\text{ATM}}^2 \simeq |\Delta m_{31}^2| \simeq |\Delta m_{32}^2| \simeq 2.5 \times 10^{-3} \text{ eV}^2$$

# Allowed Three-Neutrino Schemes



"normal"



"inverted"

different signs of  $\Delta m_{31}^2 \simeq \Delta m_{32}^2$

absolute scale is not determined by neutrino oscillation data

# Mixing Matrix

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

SUN →
↑
ATM

$$\Delta m_{21}^2 \ll |\Delta m_{31}^2|$$

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

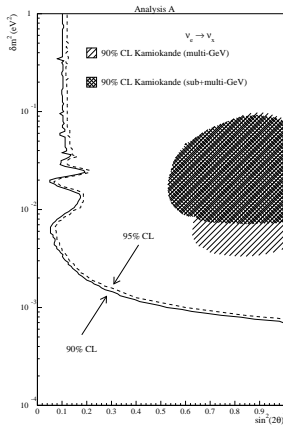


$$|U_{e3}|^2 \lesssim 5 \times 10^{-2} \text{ for } \Delta m^2 \gtrsim 2 \times 10^{-2} \text{ eV}^2$$

SOLAR AND ATMOSPHERIC  $\nu$  OSCILLATIONS ARE PRACTICALLY DECOUPLED!

TWO-NEUTRINO SOLAR and ATMOSPHERIC  $\nu$  OSCILLATIONS ARE OK!

$$\sin^2 \vartheta_{\text{SUN}} = \frac{|U_{e2}|^2}{1 - |U_{e3}|^2} \simeq |U_{e2}|^2 \quad \sin^2 \vartheta_{\text{ATM}} = |U_{\mu 3}|^2$$



[CHOOZ, PLB 466 (1999) 415]

see also [Palo Verde, PRD 64 (2001) 112001]

[Bilenky, C.G, PLB 444 (1998) 379]

[Guo, Xing, PRD 67 (2003) 053002]

# Standard Parameterization of Mixing Matrix

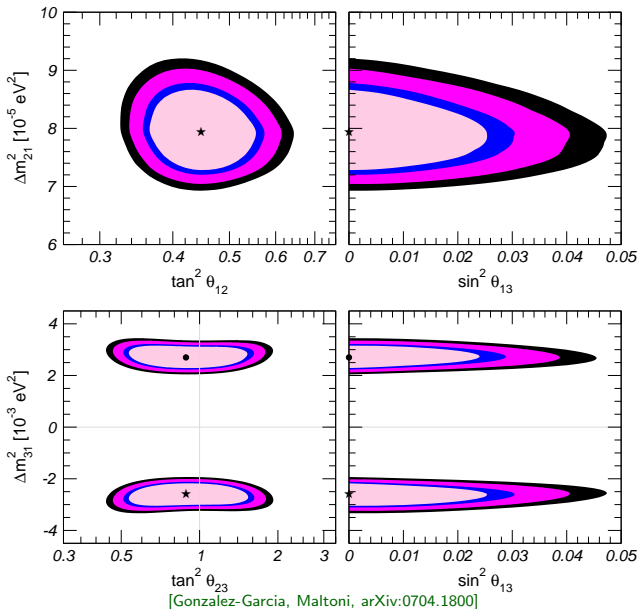
$$\begin{pmatrix} \nu_{eL} \\ \nu_{\mu L} \\ \nu_{\tau L} \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_{1L} \\ \nu_{2L} \\ \nu_{3L} \end{pmatrix}$$

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{13}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{13}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\lambda_2} & 0 \\ 0 & 0 & e^{i\lambda_3} \end{pmatrix}$$

$\vartheta_{23} \simeq \vartheta_{\text{ATM}}$                        $\vartheta_{13} = \vartheta_{\text{CHOOZ}}$                        $\vartheta_{12} \simeq \vartheta_{\text{SUN}}$                        $\beta\beta_{0\nu}$

$$= \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{13}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{13}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{13}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{13}} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\lambda_2} & 0 \\ 0 & 0 & e^{i\lambda_3} \end{pmatrix}$$

# Global Fit of Oscillation Data: Bilarge Mixing





$$\Delta m_{21}^2 = 7.9_{-0.28}^{+0.27} \begin{pmatrix} +1.1 \\ -0.89 \end{pmatrix} \times 10^{-5} \text{ eV}^2$$

$$|\Delta m_{31}^2| = 2.6 \pm 0.2 (0.6) \times 10^{-3} \text{ eV}^2$$

$$\theta_{12} = 33.7 \pm 1.3 \begin{pmatrix} +4.3 \\ -3.5 \end{pmatrix}$$

$$\theta_{23} = 43.3_{-3.8}^{+4.3} \begin{pmatrix} +9.8 \\ -8.8 \end{pmatrix}$$

$$\theta_{13} = 0_{-0.0}^{+5.2} \begin{pmatrix} +11.5 \\ -0.0 \end{pmatrix}$$

$$|U|_{90\%} = \begin{pmatrix} 0.81 - 0.85 & 0.53 - 0.58 & 0.00 - 0.12 \\ 0.32 - 0.49 & 0.52 - 0.69 & 0.60 - 0.76 \\ 0.27 - 0.46 & 0.47 - 0.64 & 0.65 - 0.80 \end{pmatrix}$$

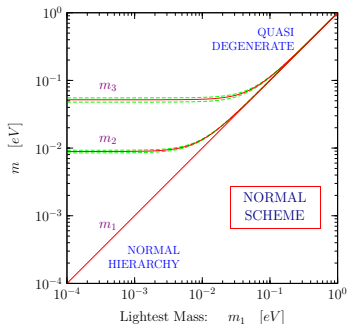
$$|U|_{3\sigma} = \begin{pmatrix} 0.79 - 0.86 & 0.50 - 0.61 & 0.00 - 0.20 \\ 0.25 - 0.53 & 0.47 - 0.73 & 0.56 - 0.79 \\ 0.21 - 0.51 & 0.42 - 0.69 & 0.61 - 0.83 \end{pmatrix}$$

[Gonzalez-Garcia, Maltoni, arXiv:0704.1800]

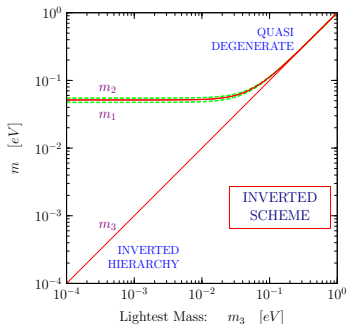
future: measure  $\vartheta_{13} \neq 0 \implies$  CP violation, matter effects, mass hierarchy

# Absolute Scale of Neutrino Masses

normal scheme



inverted scheme



$$m_2^2 = m_1^2 + \Delta m_{21}^2 = m_1^2 + \Delta m_{\text{SUN}}^2$$

$$m_3^2 = m_1^2 + \Delta m_{31}^2 = m_1^2 + \Delta m_{\text{ATM}}^2$$

$$m_1^2 = m_3^2 - \Delta m_{31}^2 = m_3^2 + \Delta m_{\text{ATM}}^2$$

$$m_2^2 = m_1^2 + \Delta m_{21}^2 \simeq m_3^2 + \Delta m_{\text{ATM}}^2$$

Quasi-Degenerate for  $m_1 \simeq m_2 \simeq m_3 \simeq m_\nu \gg \sqrt{\Delta m_{\text{ATM}}^2} \simeq 5 \times 10^{-2} \text{ eV}$

# Tritium Beta-Decay



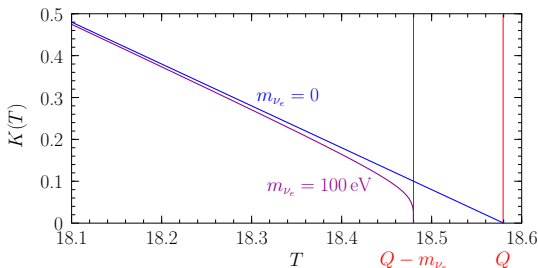
$$\frac{d\Gamma}{dT} = \frac{(\cos\vartheta_C G_F)^2}{2\pi^3} |\mathcal{M}|^2 F(E) p E (Q - T) \sqrt{(Q - T)^2 - m_{\nu_e}^2}$$

$$Q = M_{{}^3\text{H}} - M_{{}^3\text{He}} - m_e = 18.58 \text{ keV}$$

$$m_{\nu_e}^2 = m_\beta^2 = \sum_k |U_{ek}|^2 m_k^2$$

Kurie plot

$$K(T) = \sqrt{\frac{d\Gamma/dT}{\frac{(\cos\vartheta_C G_F)^2}{2\pi^3} |\mathcal{M}|^2 F(E) p E}} = \left[ (Q - T) \sqrt{(Q - T)^2 - m_{\nu_e}^2} \right]^{1/2}$$



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

Mainz & Troitsk

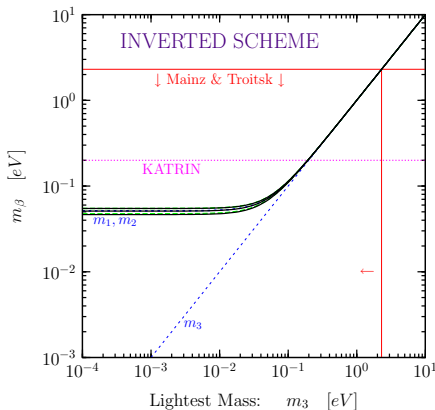
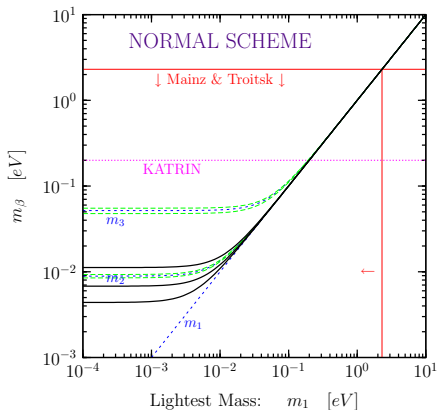
[Weinheimer, hep-ex/0210050]

future: KATRIN (start 2010)

[hep-ex/0109033] [hep-ex/0309007]

sensitivity:  $m_{\nu_e} \simeq 0.2 \text{ eV}$

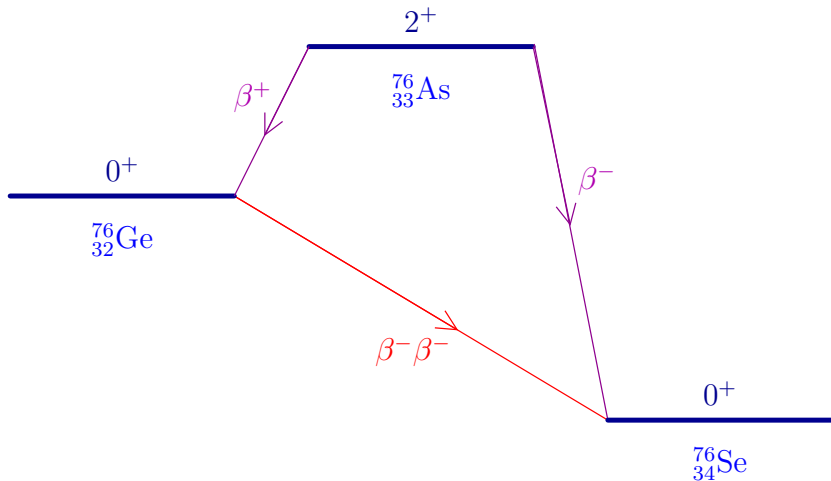
$$m_{\nu_e}^2 = m_\beta^2 = |U_{e1}|^2 m_1^2 + |U_{e2}|^2 m_2^2 + |U_{e3}|^2 m_3^2$$



Quasi-Degenerate:  $m_1 \simeq m_2 \simeq m_3 \simeq m_\nu \implies m_\beta^2 \simeq m_\nu^2 \sum_k |U_{ek}|^2 = m_\nu^2$

FUTURE: IF  $m_\beta \lesssim 4 \times 10^{-2} \text{ eV} \implies$  NORMAL HIERARCHY

# Neutrinoless Double-Beta Decay

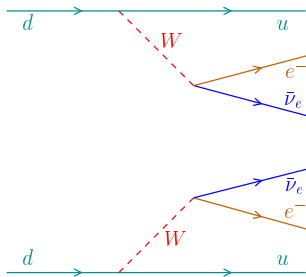


## Two-Neutrino Double- $\beta$ Decay: $\Delta L = 0$

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

$$(T_{1/2}^{2\nu})^{-1} = G_{2\nu} |\mathcal{M}_{2\nu}|^2$$

second order weak interaction process  
in the Standard Model



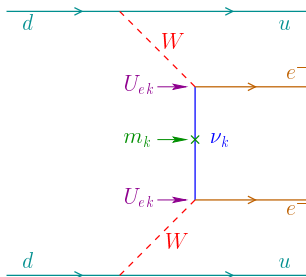
## Neutrinoless Double- $\beta$ Decay: $\Delta L = 2$

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

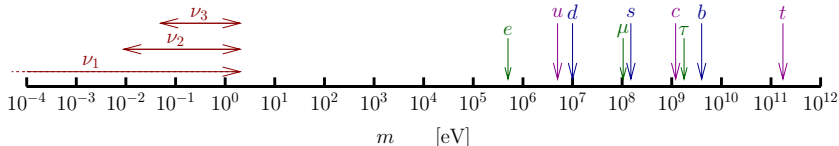
$$(T_{1/2}^{0\nu})^{-1} = G_{0\nu} |\mathcal{M}_{0\nu}|^2 |m_{\beta\beta}|^2$$

effective  
Majorana  
mass

$$m_{\beta\beta} = \sum_k U_{ek}^2 m_k$$



# Majorana Neutrino Mass?



known natural explanation of smallness of  $\nu$  masses

New High Energy Scale  $\mathcal{M} \Rightarrow \left\{ \begin{array}{l} \text{See-Saw Mechanism (if } \nu_R \text{'s exist)} \\ \text{5-D Non-Renormaliz. Eff. Operator} \end{array} \right.$

both imply  $\left\{ \begin{array}{l} \text{Majorana } \nu \text{ masses} \iff |\Delta L| = 2 \iff \beta\beta_{0\nu} \text{ decay} \\ \text{see-saw type relation } m_\nu \sim \frac{\mathcal{M}_{EW}^2}{\mathcal{M}} \end{array} \right.$

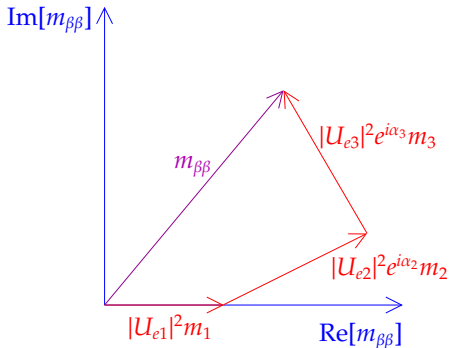
Majorana neutrino masses provide the most accessible window on New Physics Beyond the Standard Model

# Effective Majorana Neutrino Mass

$$m_{\beta\beta} = \sum_k U_{ek}^2 m_k \quad \text{complex } U_{ek} \Rightarrow \text{possible cancellations}$$

$$m_{\beta\beta} = |U_{e1}|^2 m_1 + |U_{e2}|^2 e^{i\alpha_2} m_2 + |U_{e3}|^2 e^{i\alpha_3} m_3$$

$$\alpha_2 = 2\lambda_2 \quad \alpha_3 = 2(\lambda_3 - \delta_{13})$$





# Experimental Bounds

Heidelberg-Moscow ( $^{76}\text{Ge}$ ) [EPJA 12 (2001) 147]

$$T_{1/2}^{0\nu} > 1.9 \times 10^{25} \text{ y} \quad (90\% \text{ C.L.}) \implies |m_{\beta\beta}| \lesssim 0.32 - 1.0 \text{ eV}$$

IGEX ( $^{76}\text{Ge}$ ) [PRD 65 (2002) 092007]

$$T_{1/2}^{0\nu} > 1.57 \times 10^{25} \text{ y} \quad (90\% \text{ C.L.}) \implies |m_{\beta\beta}| \lesssim 0.33 - 1.35 \text{ eV}$$

CUORICINO ( $^{130}\text{Te}$ ) [PRL 95 (2005) 142501]

$$T_{1/2}^{0\nu} > 1.8 \times 10^{24} \text{ y} \quad (90\% \text{ C.L.}) \implies |m_{\beta\beta}| \lesssim 0.2 - 1.1 \text{ eV}$$

NEMO 3 ( $^{100}\text{Mo}$ ) [PRL 95 (2005) 182302]

$$T_{1/2}^{0\nu} > 4.6 \times 10^{23} \text{ y} \quad (90\% \text{ C.L.}) \implies |m_{\beta\beta}| \lesssim 0.7 - 2.8 \text{ eV}$$

## FUTURE EXPERIMENTS

CAMEO, CANDLES, COBRA, EXO, Majorana, XMASS

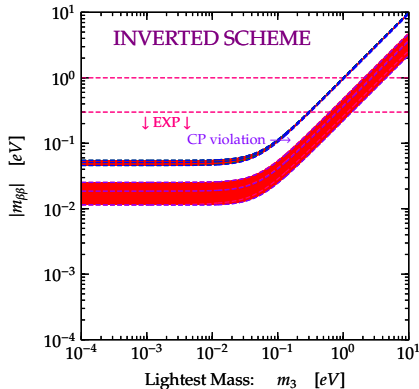
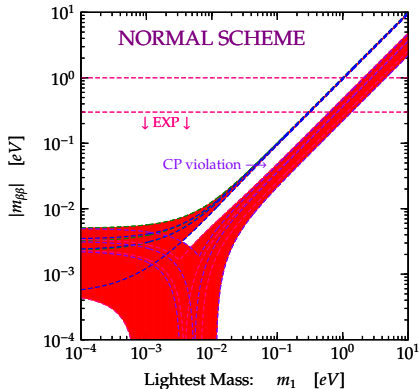
$$|m_{\beta\beta}| \sim \text{few } 10^{-1} \text{ eV}$$

CUORE, MOON, GEM, GERDA, SNO++, Super-NEMO

$$|m_{\beta\beta}| \sim \text{few } 10^{-2} \text{ eV}$$

# Bounds from Neutrino Oscillations

$$m_{\beta\beta} = |U_{e1}|^2 m_1 + |U_{e2}|^2 e^{i\alpha_2} m_2 + |U_{e3}|^2 e^{i\alpha_3} m_3$$



FUTURE: IF  $|m_{\beta\beta}| \lesssim 10^{-2} \text{ eV} \implies$  NORMAL HIERARCHY

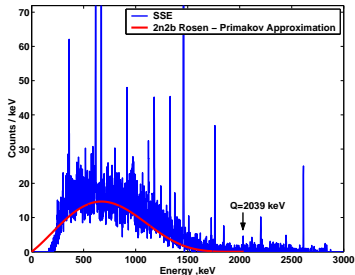
# Experimental Positive Indication

[Klapdor et al., MPLA 16 (2001) 2409]

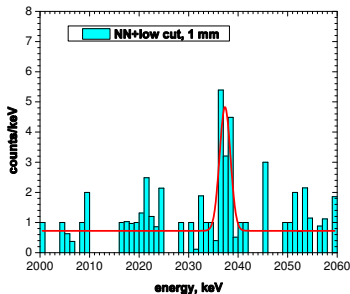
$$T_{1/2}^{0\nu} = (2.23_{-0.31}^{+0.44}) \times 10^{25} \text{ y}$$

6.5 $\sigma$  evidence

[MPLA 21 (2006) 1547]



[PLB 586 (2004) 198]



[MPLA 21 (2006) 1547]

the indication must be checked by other experiments

$$|m_{\beta\beta}| = 0.32 \pm 0.03 \text{ eV}$$

[MPLA 21 (2006) 1547]

if confirmed, very exciting (Majorana  $\nu$  and large mass scale)

# Cosmology

$H_0$  (Hubble Space Telescope Key Project)

CMBR (COBE, WMAP, Boomerang, DASI, MAXIMA, VSA, CBI, ACBAR)

LSS (2dFGRS, SDSS)

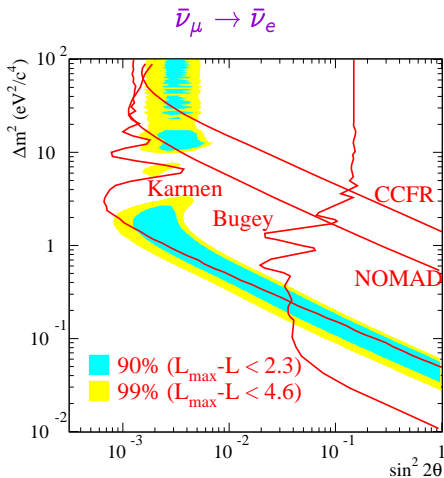
SNIa (High-z SN Search Team, Supernova Cosmology Project)

$\Lambda$ CDM



$$\sum_{k=1}^3 m_k \lesssim 0.2 - 0.7 \text{ eV}$$

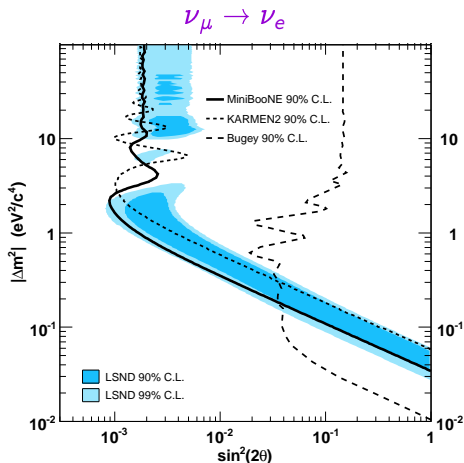
# LSND and MiniBooNE



[LSND, PRD 64 (2001) 112007, hep-ex/0104049]

$$\Delta m_{\text{LSND}}^2 \gtrsim 0.1 \text{ eV}^2$$

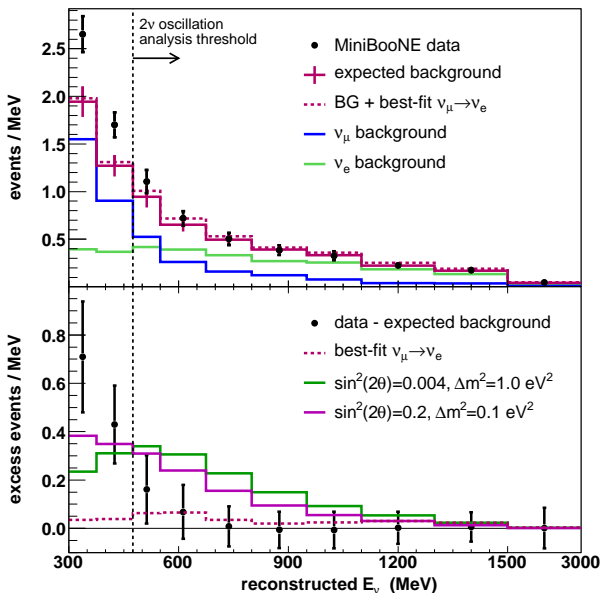
$$\Delta m_{\text{LSND}}^2 \gg \Delta m_{\text{ATM}}^2 \gg \Delta m_{\text{SUN}}^2$$



[MiniBooNE, PRL 98 (2007) 231801, arXiv:0704.1500]

$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$  is running

# MiniBooNE Low-Energy Anomaly



[MiniBooNE, PRL 98 (2007) 231801, arXiv:0704.1500]

## Conclusions

$\nu_e \rightarrow \nu_\mu, \nu_\tau$  with  $\Delta m_{\text{SUN}}^2 \simeq 7.6 \times 10^{-5} \text{ eV}^2$  (solar  $\nu$ , KamLAND)

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

Bilarge  $3\nu$ -Mixing with  $|U_{e3}|^2 \ll 1$  (CHOOZ)

$\beta$  Decay, Cosmology,  $\beta\beta_{0\nu}$  Decay  $\implies m_\nu \lesssim 1 \text{ eV}$

### FUTURE

**Theory:** Why lepton mixing  $\neq$  quark mixing?

Why only  $|U_{e3}|^2 \ll 1$ ?

Improve calculation of  $\mathcal{M}_{0\nu}$ !

LSND and MiniBooNE Low-Energy Anomaly?

**Exp.:** Measure  $|U_{e3}| > 0 \implies$  CP violation, matter eff., mass hierarchy

Check  $\beta\beta_{0\nu}$  signal at Quasi-Degenerate mass scale

Improve  $\beta$  Decay, Cosmology,  $\beta\beta_{0\nu}$  Decay measurements

LSND and MiniBooNE Low-Energy Anomaly?