PROBING FLAVOUR WITH NEUTRINOS

Concha Gonzalez-Garcia

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OUTLINE

Introduction:

The Parameters of the New Minimal Standard Model

Update on ν Masses and Mixing from Global 3 ν Mixing Analysis

Near Future Expectations and Far Future Challenges

And what about LSND?

Beyond Masses and Mixing

Flavour Tests of Fundamental Symmetries (LI, WEP, CPT), NSNI . . .

Summary

ν in the SM

- The SM is a gauge theory based on the symmetry group

$$SU(3)_C \times SU(2)_L \times U(1)_Y \Rightarrow SU(3)_C \times U(1)_{EM}$$

$(1,2)_{-\frac{1}{2}}$	$(3,2)_{\frac{1}{6}}$	$(1,1)_{-1}$	$(3,1)_{\frac{2}{3}}$	$(3,1)_{-\frac{1}{3}}$
$\begin{pmatrix} e \\ \nu_e \end{pmatrix}_L$	$\begin{pmatrix} u^i \\ d^i \end{pmatrix}_L$	e_R	u^i_R	d^i_R
$\begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix}_L$	$\begin{pmatrix} c^i \\ s^i \end{pmatrix}_L$	μ_R	c^i_R	s^i_R
$\begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}_L$	$\begin{pmatrix} t^i \\ b^i \end{pmatrix}_L$	τ_R	t^i_R	n^i_R

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$\Rightarrow$ Accidental global symmetry:

$B \times L_e \times L_\mu \times L_\tau$

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There is no ν_R

$\Rightarrow$ Accidental global symmetry: $B \times L_e \times L_\mu \times L_\tau$

$\Rightarrow$ ν *strictly* massless

- We have learned:

  $*$ Atmospheric ν_μ disappear ($> 15\sigma$) most likely to ν_τ

  $*$ K2K: accelerator ν_μ disappear at $L \sim 250$ Km with E-distortion (~ 2.5–4σ)

  $*$ MINOS: accelerator ν_μ disappear at $L \sim 735$ Km with E-distortion ($\sim 5\sigma$)

  $*$ Solar ν_e convert to ν_μ or ν_τ ($> 7\sigma$)

  $*$ KamLAND: reactor $\overline{\nu_e}$ disappear at $L \sim 200$ Km with E-distortion ($\gtrsim 3\sigma$ CL)

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- The *important* question:

What is the underlying physics?

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- The *important* question:

  What is the underlying physics?

- The *difficult* path:

  Detailed determination of the new LE parameters

Effects of ν Mass

- Minimal Extensions to give Mass to the Neutrino:

  * Introduce ν_R AND impose L conservation $\Rightarrow$ Dirac ν:

$$\mathcal{L} = \mathcal{L}_{SM} - M_\nu \overline{\nu_L} \nu_R + h.c.$$

  * NOT impose L conservation $\Rightarrow$ Majorana ν

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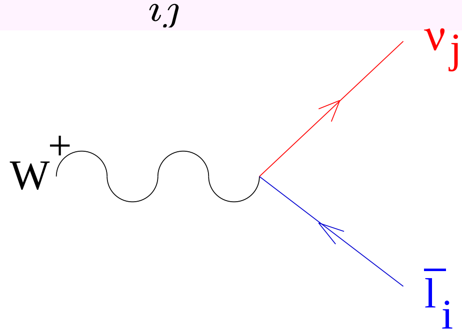
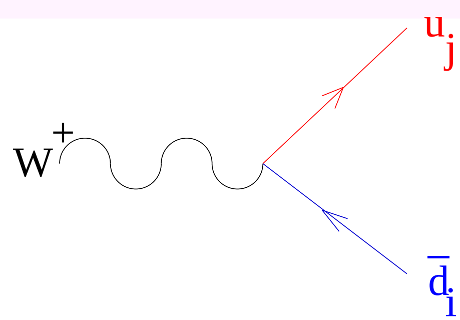
- The charged current interactions of leptons are not diagonal

$$\frac{g}{\sqrt{2}} W_\mu^+ \sum_{ij} \left(U_{LEP}^{ij} \, \overline{\ell^i} \, \gamma^\mu \, L \, \nu^j \; + \; U_{CKM}^{ij} \, \overline{U^i} \, \gamma^\mu \, L \, D^j \right) \; + \; h.c.$$





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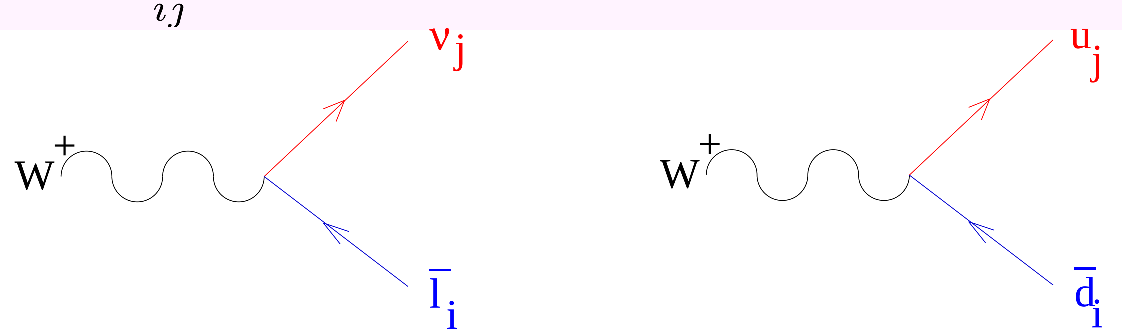

- In general for $N = 3 + m$ massive neutrinos U_{LEP} is $3 \times N$ matrix

$$U_{LEP} U_{LEP}^\dagger = I_{3\times 3} \qquad \text{but in general} \qquad U_{LEP}^\dagger U_{LEP} \neq I_{N\times N}$$

- U_{LEP}: $3(N-2)$ angles + $2N-5$ Dirac phases + $N-1$ Majorana phases

Effects of ν Mass: Oscillations

- If neutrinos have mass, a weak eigenstate $|\nu_\alpha\rangle$ produced in $l_\alpha + N \to \nu_\alpha + N'$

  is a linear combination of the mass eigenstates ($|\nu_i\rangle$) : $|\nu_\alpha\rangle = \sum_{i=1}^{n} U_{\alpha i} |\nu_i\rangle$

- After a distance L it can be detected with flavour β with probability

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4\sum_{j\neq i}^{n} \mathrm{Re}[U^\star_{\alpha i} U_{\beta i} U_{\alpha j} U^\star_{\beta j}] \sin^2\left(\frac{\Delta_{ij}}{2}\right) + 2\sum_{j\neq i} \mathrm{Im}[U^\star_{\alpha i} U_{\beta i} U_{\alpha j} U^\star_{\beta j}] \sin\left(\Delta_{ij}\right)$$

$$\frac{\Delta_{ij}}{2} = \frac{(E_i - E_j)L}{2} = 1.27 \frac{(m_i^2 - m_j^2)}{\mathrm{eV}^2} \frac{L/E}{\mathrm{Km/GeV}}$$

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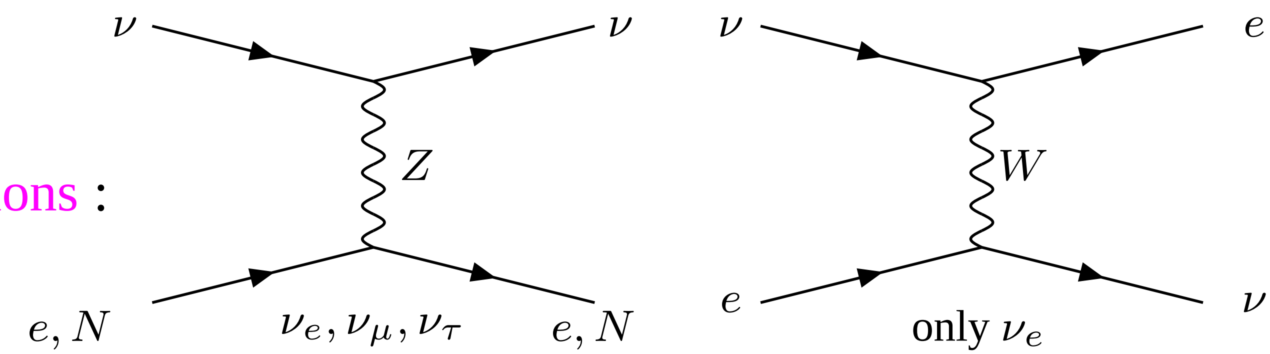
No information on mass scale nor Majorana versus Dirac ν nature

Matter Effects

- If ν cross matter regions (Sun, Earth...) it interacts *coherently*
  - But Different flavours have different interactions :



  - To include this effect: potential in the evolution equation: $V_e \neq V_\mu$

$\Rightarrow$ *Modification of mixing angle and oscillation wavelength*

- The mixing angle in matter

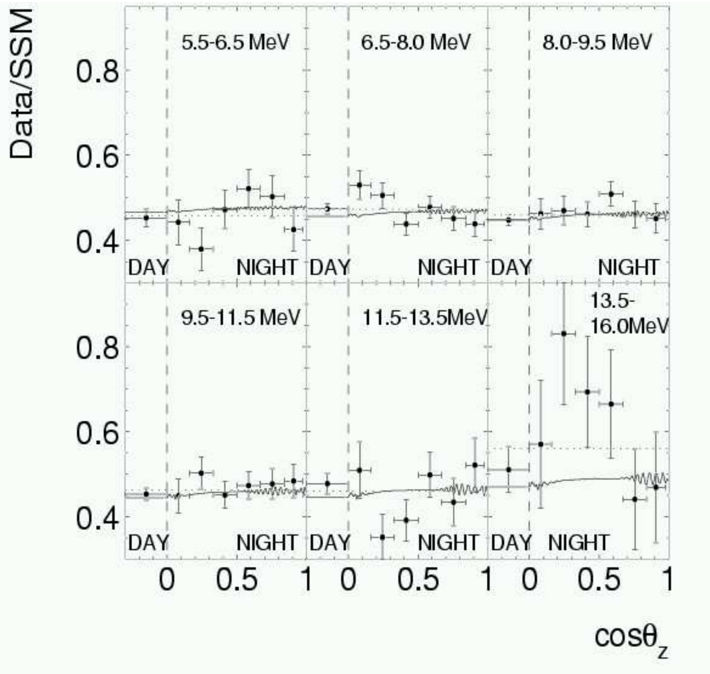
$$\sin(2\theta_m) = \frac{\Delta m^2 \sin(2\theta)}{\sqrt{(\Delta m^2 \cos(2\theta) - A)^2 + (\Delta m^2 \sin(2\theta))^2}} \qquad A = 2\,E\,(V_\alpha - V_\beta)$$

  - When $\Delta m^2 \cos(2\theta) \sim A \Rightarrow$ Enhancement of Oscillation (MSW Effect)

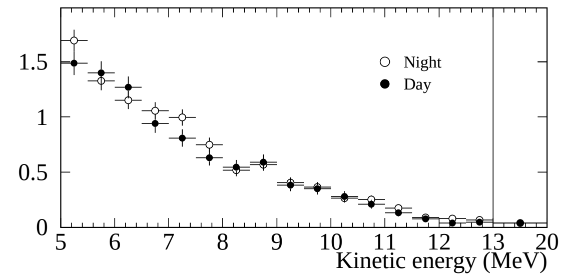
Global Fits: Solar Neutrinos

- $\Sigma(\mathrm{Cl}) = 2.56 \pm 0.23$ (SNU)
- $\Sigma(\mathrm{Ga}) = 68.1 \pm 3.75$ (SNU)

- SK Zenith spectrum (44 Data points)



- SNO Ph-I D-N Spectrum (34 Points)



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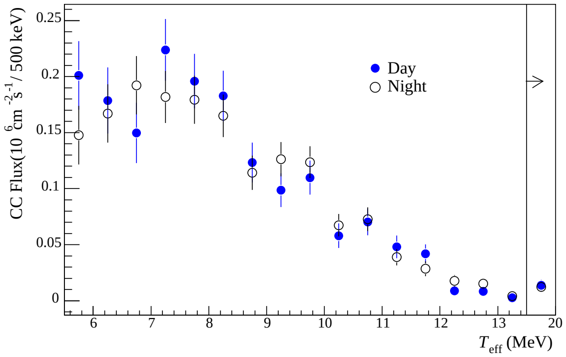

- SNO Ph-II ES, NC D&N Fluxes (4)

$$\phi^{\mathrm{SNO}}_{\mathrm{ES,D}} = 2.17 \pm 0.34 \pm 0.14$$
$$\phi^{\mathrm{SNO}}_{\mathrm{ES,N}} = 2.52 \pm 0.32 \pm 0.16$$
$$\phi^{\mathrm{SNO}}_{\mathrm{NC,D}} = 4.81 \pm 0.31 \pm 0.39$$
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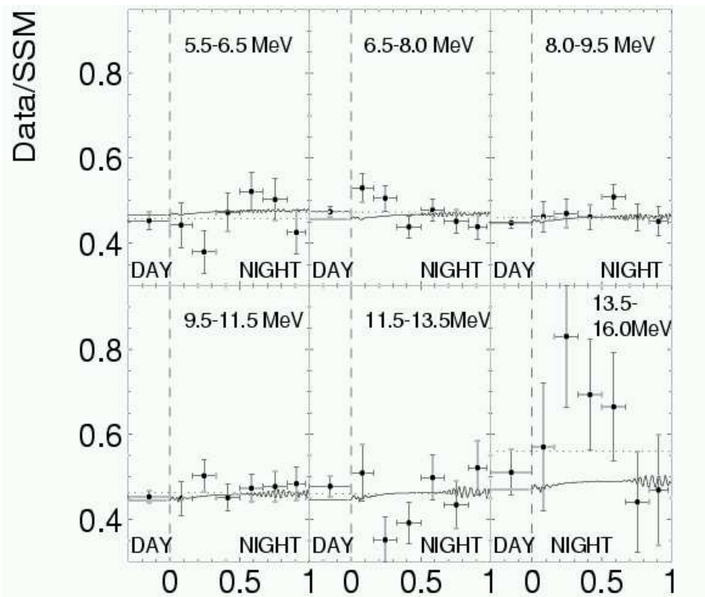

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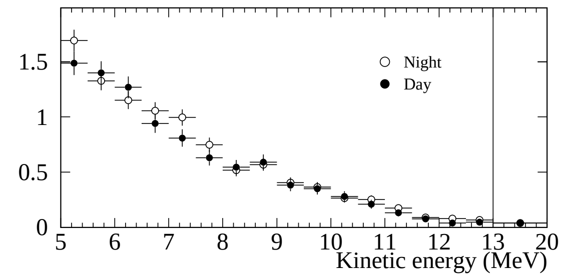

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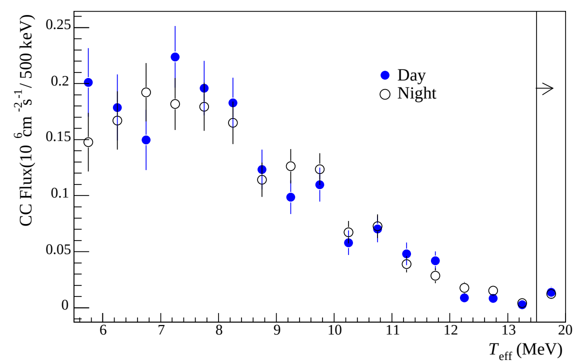

All experiments measuring mostly ν_e observed a deficit

Deficit is energy dependent for $E_\nu \lesssim 5 MeV$

Deficit disappears in NC

Seasonal Variation ⇒ Nothing beyond $1/R^2$

Very small Day-Night Variation ⇒ No Earth Matter Effect

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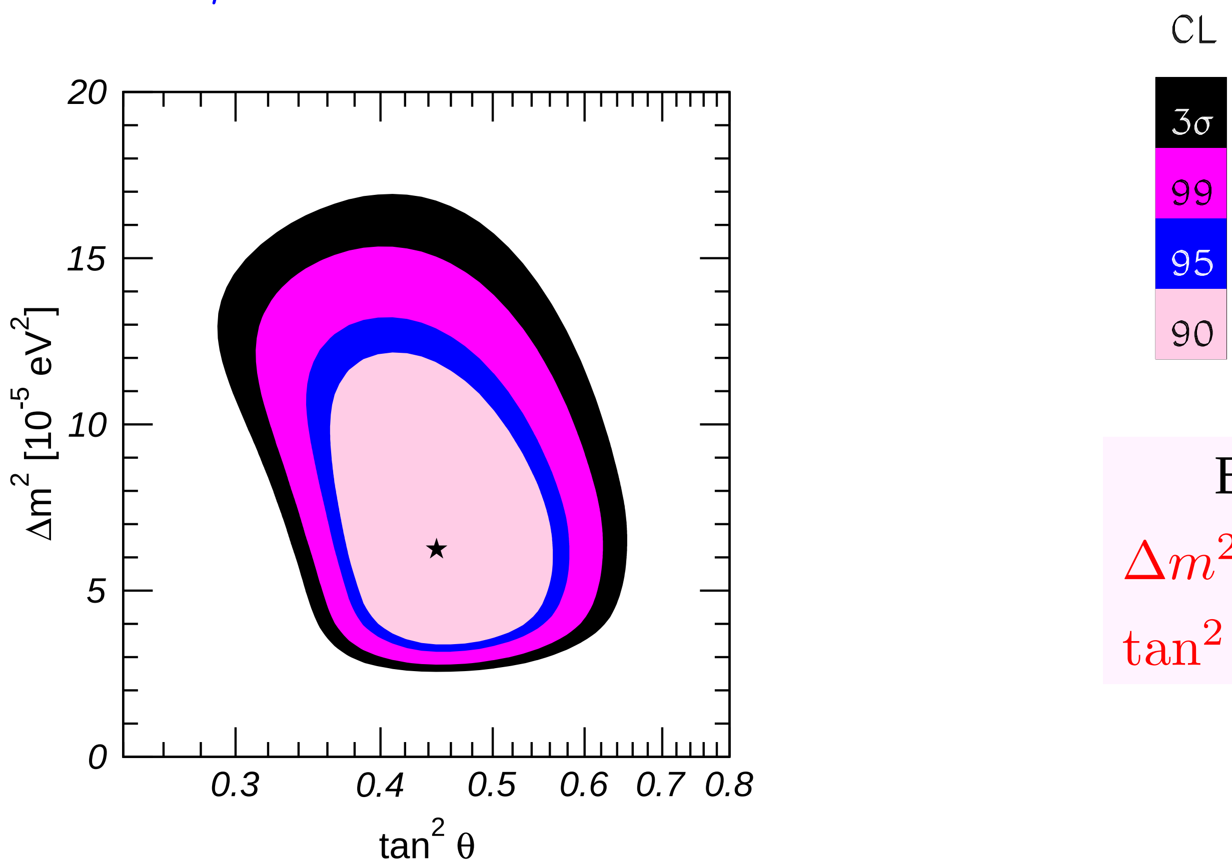
Solar Neutrinos: Oscillation Solutions

- $\nu_e \to \nu_\mu, \nu_\tau$:



Best fit

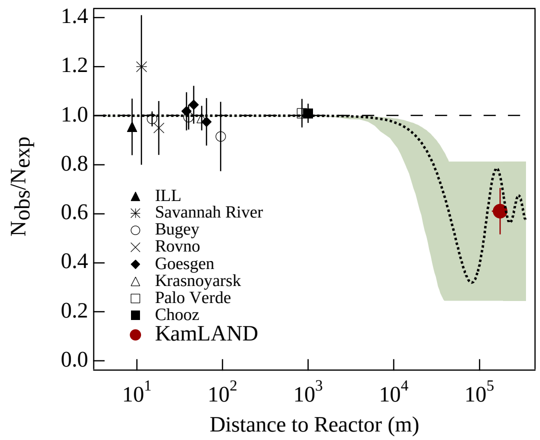
$\Delta m^2 = 6.3 \times 10^{-5}$ eV^2

$\tan^2\theta = 0.44$

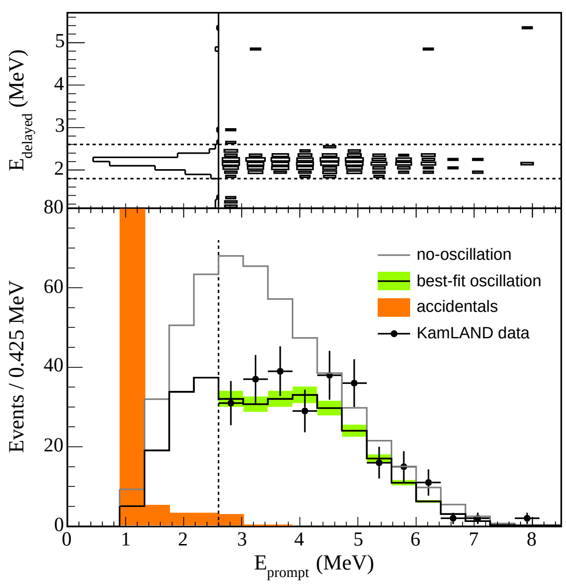
Terrestrial Test of LMA: KamLAND

- Search on $\overline{\nu_e}$ at L$\sim$ 180 km reactors, $E_{\overline{\nu}} \sim$ few MeV: $\bar{\nu}_e + p \to n + e^+$

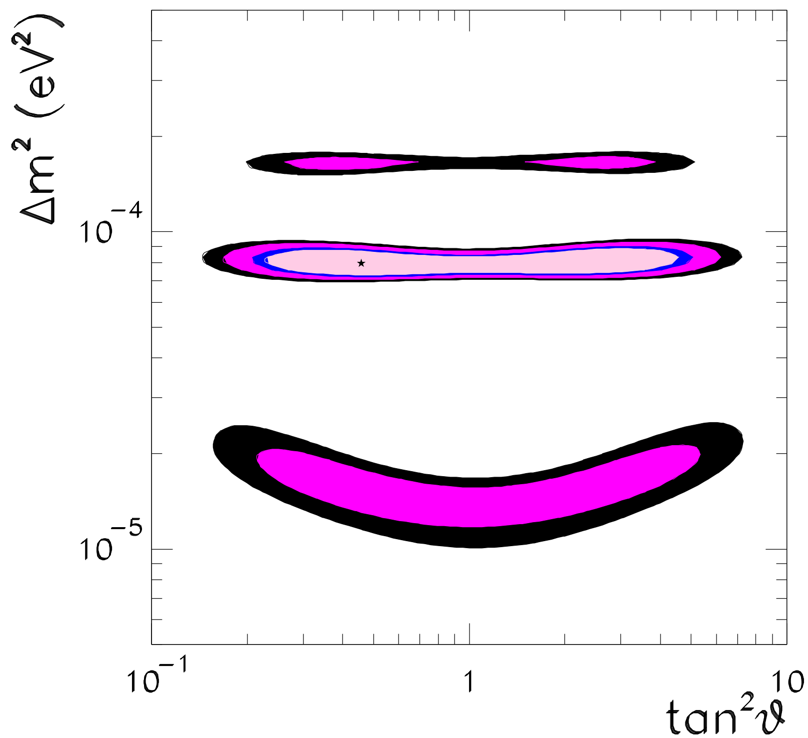
2002: Defi cit $R_{\rm KLAND} = 0.611 \pm 0.094$



2004: Signifi cant Energy Distortion



Oscillation Analysis



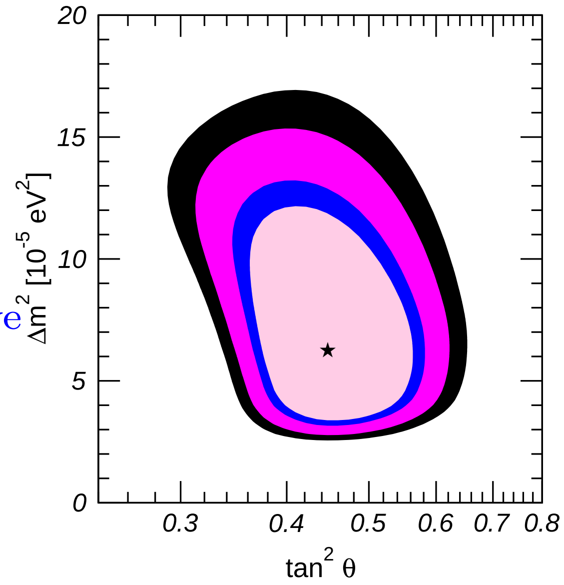
Best Fit

$\Delta m^2 = 7.9 \times 10^{-5}$ eV^2

$\tan^2\theta = 0.46 \quad (2.2)$

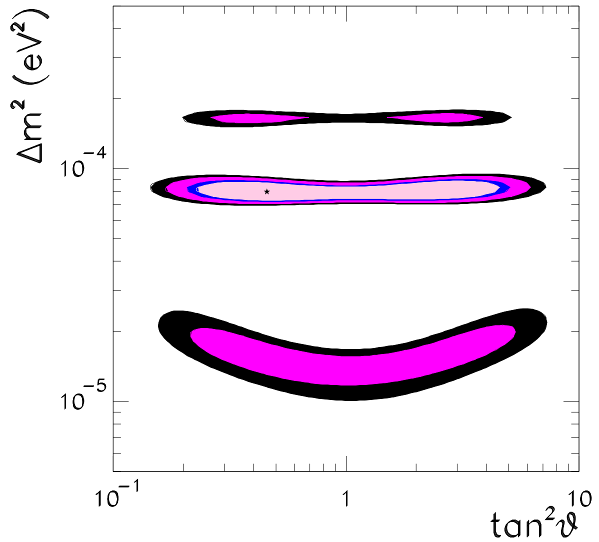
Solar

$\nu_e \longrightarrow \nu_{\rm active}$



+ KamLAND

$\bar\nu_e \not\rightarrow \bar\nu_e$



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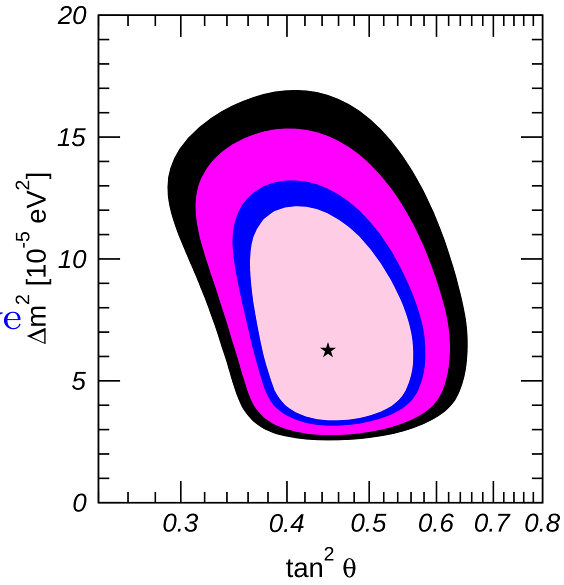

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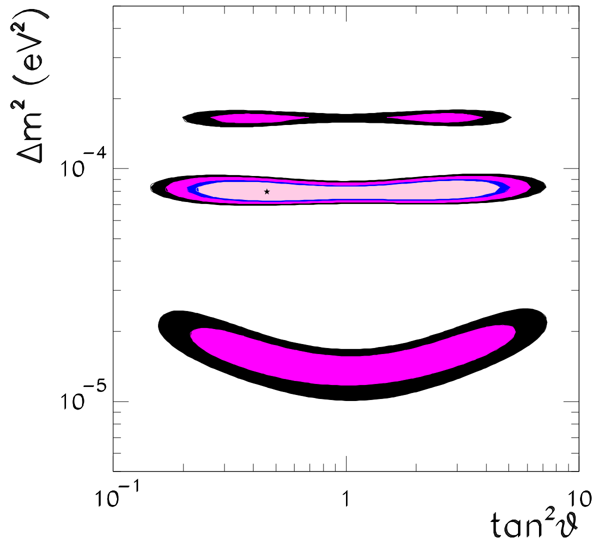
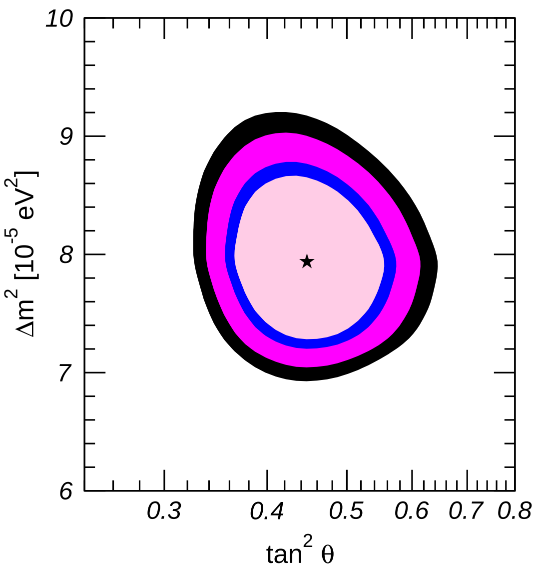


ν_e oscillation parameters compatible with $\overline{\nu}_e$: *Sensible* to assume CPT: $P_{ee} = P_{\bar{e}\bar{e}}$

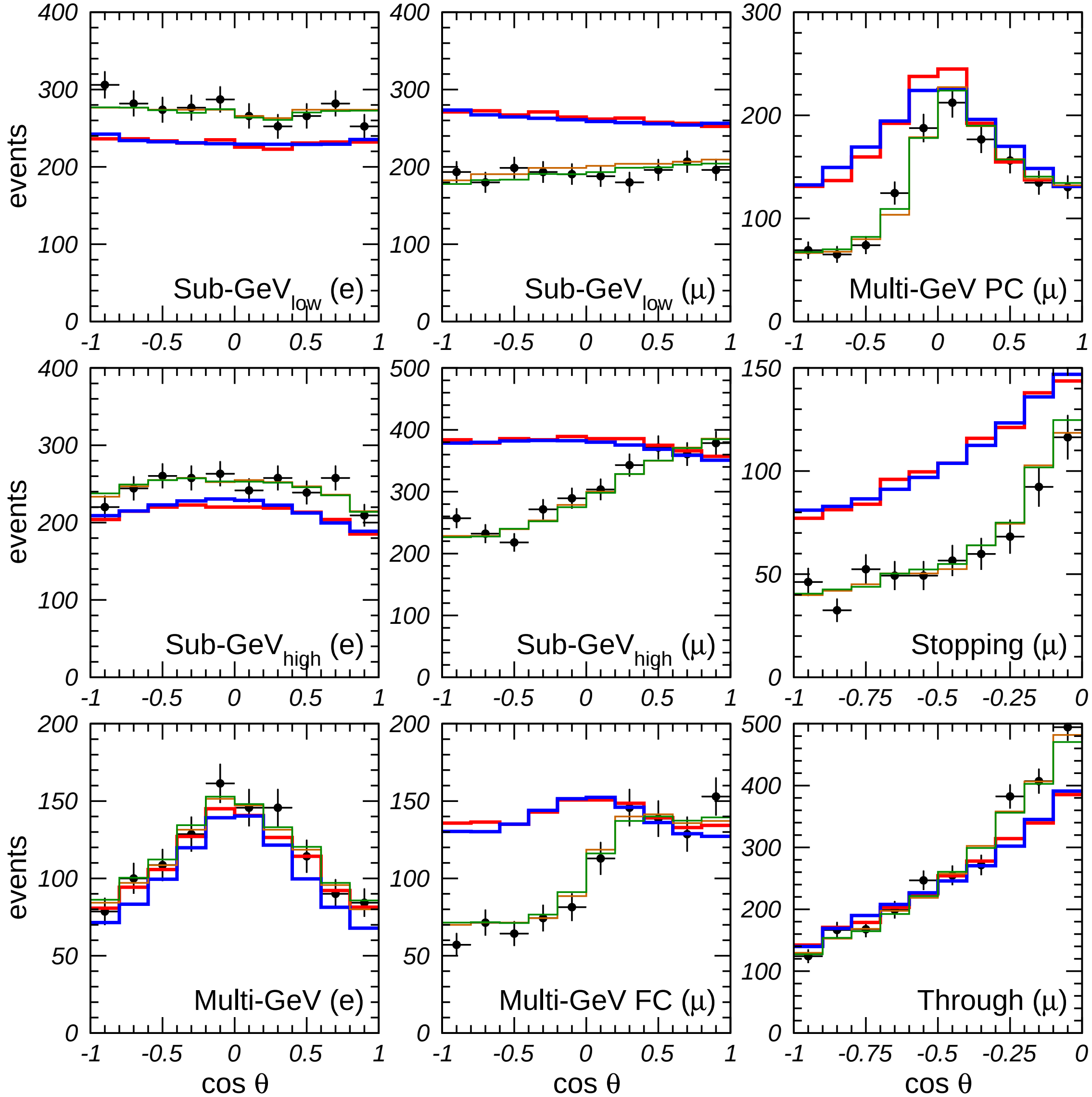


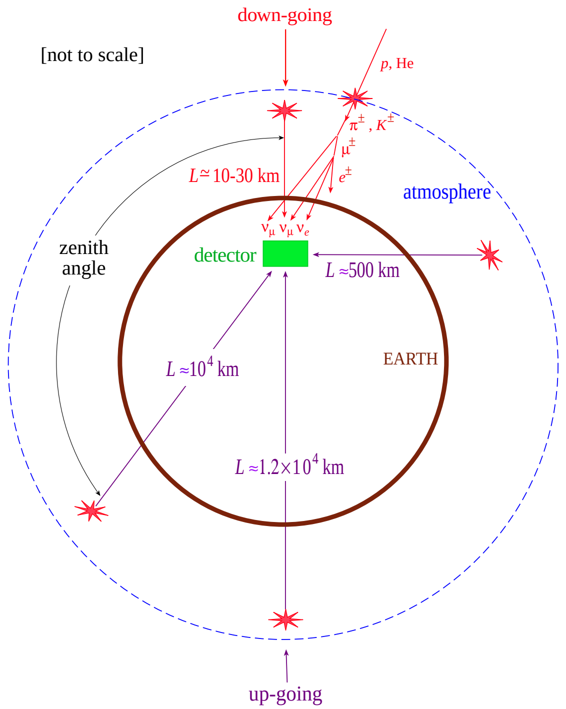
$$\Delta m^2 = \left(7.9^{+0.27}_{-0.28}\right) \times 10^{-5}\ \text{eV}^2 \quad (1\sigma)$$

$$\tan^2\theta = 0.44^{+0.045}_{-0.042}$$

Atmospheric Neutrinos

- Complete SKI+II data:

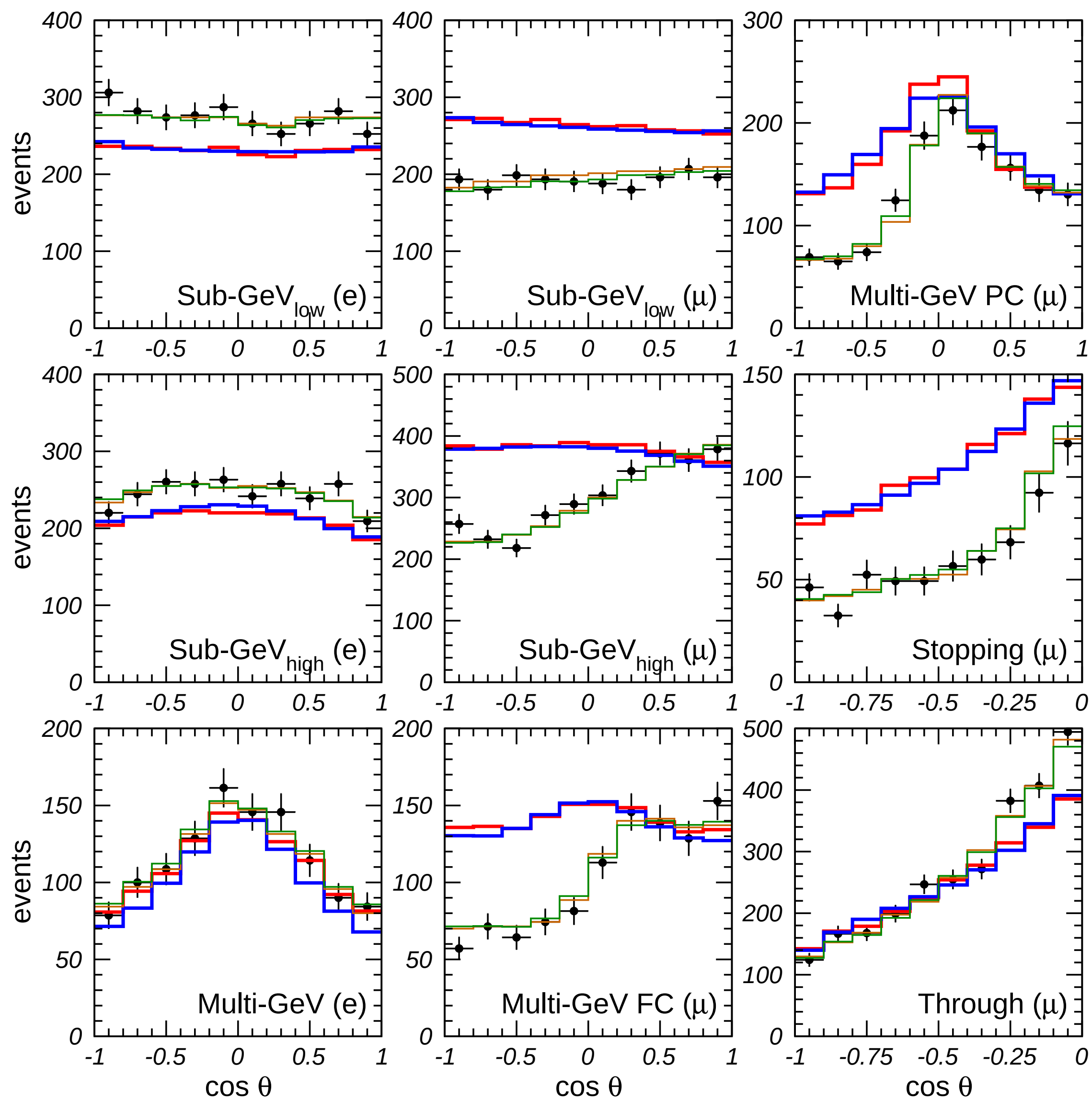


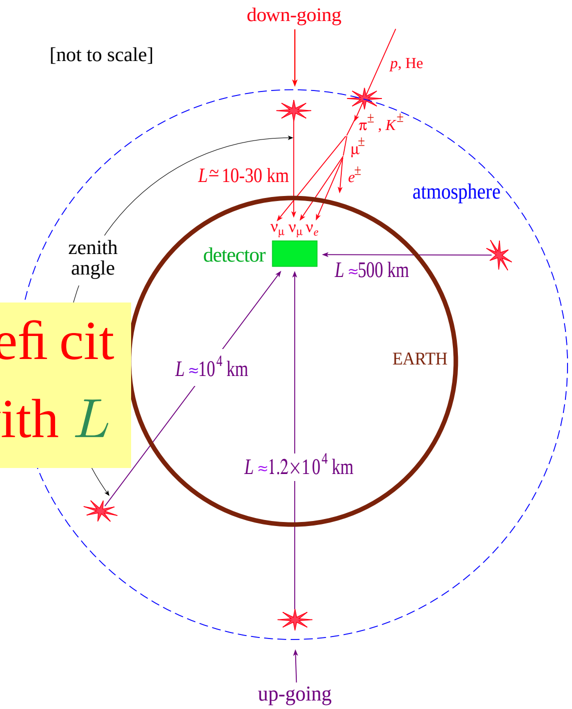


Atmospheric Neutrinos

- Complete SKI+II data:

ν_e in agreement with SM



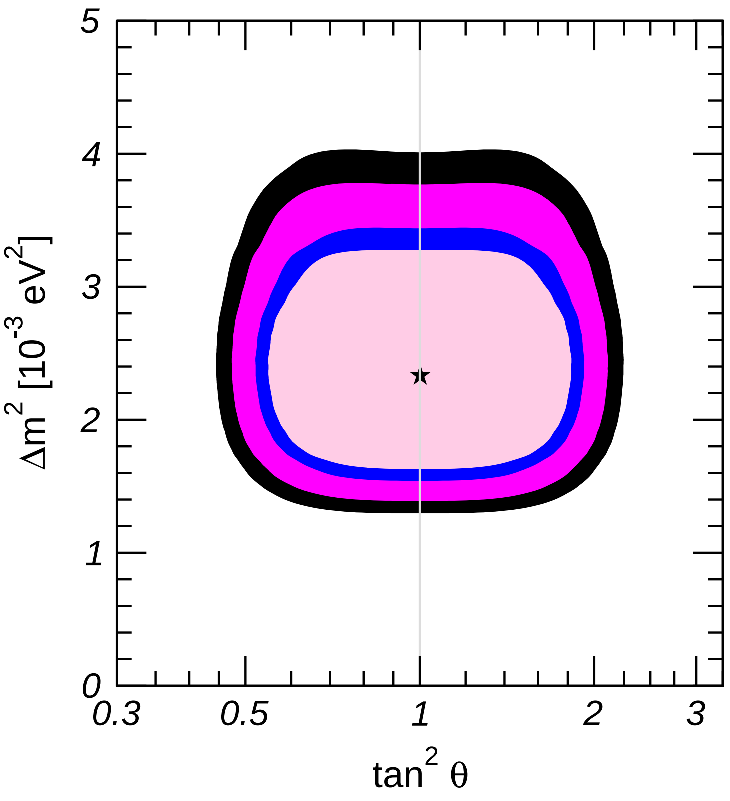


→ ν_μ Deficit grows with L

→ ν_μ Deficit decreases with E

Atmospheric Neutrinos: Oscillation Solutions

- $\nu_\mu \to \nu_\tau$: best channel



Best fit

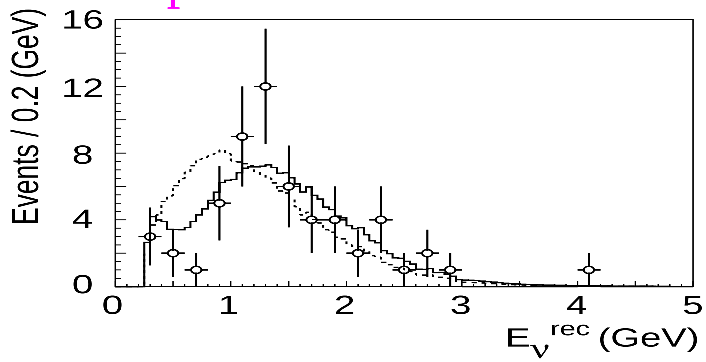
$\Delta m^2 = 2.15 \times 10^{-3}$ eV^2

$\tan^2\theta = 1$

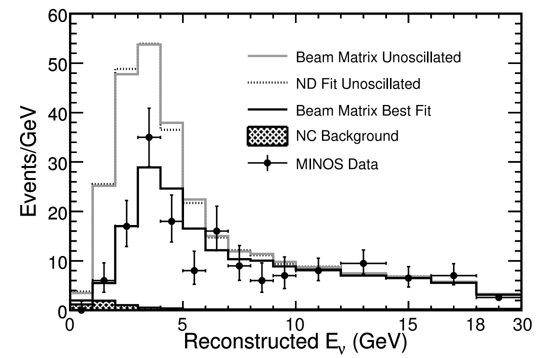
ATM Test at Long Baseline Experiments

K2K	ν_μ at KEK	SK	L=250 km
MINOS	ν_μ at Fermilab	Soundan	L=735 km
Opera	ν_μ at CERN	Gran Sasso	L=740 km

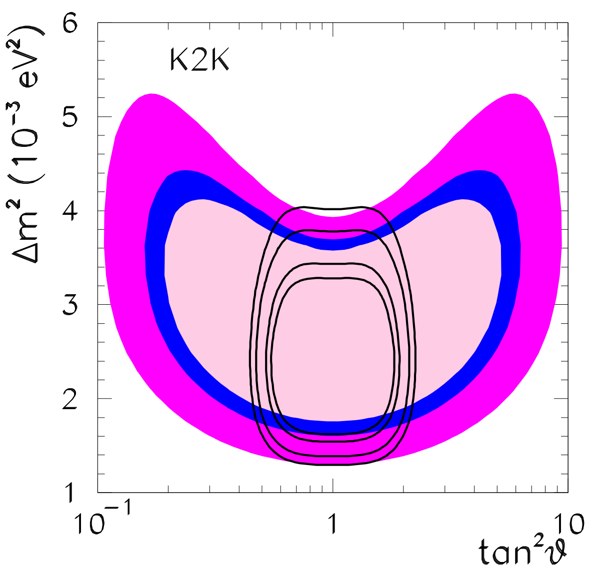
K2K 2004: spectral distortion



MINOS 2006: spectral distortion



Confi rmation of ATM oscillations



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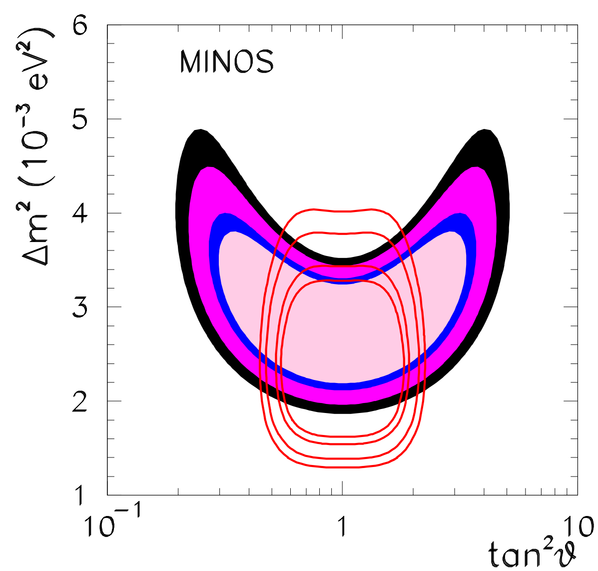
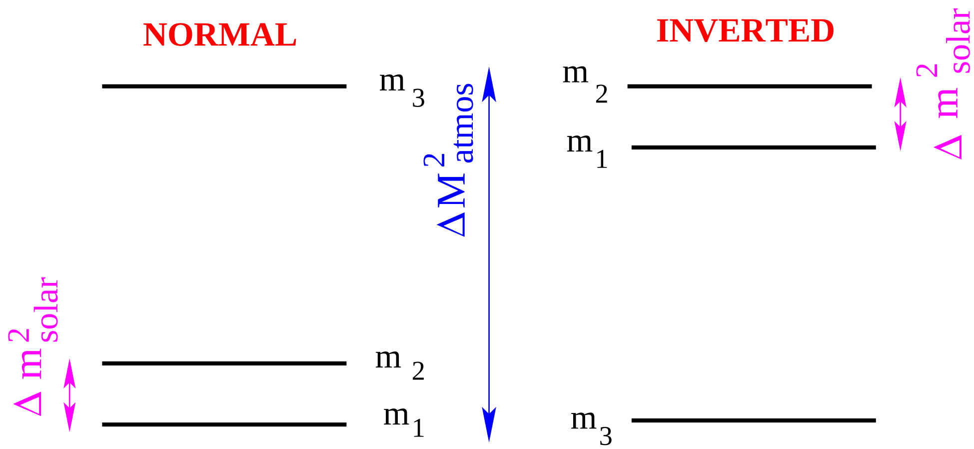


Solar+Atmospheric+Reactor+LBL 3ν Oscillations

U: 3 angles, 1 CP-phase
+ (2 Majorana phases)

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{21} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Two mass schemes



2ν oscillation analysis $\Rightarrow \Delta m^2_{21} = \Delta m^2_{\odot} \ll \Delta M^2_{atm} \simeq \pm\Delta m^2_{32} \simeq \pm\Delta m^2_{31}$

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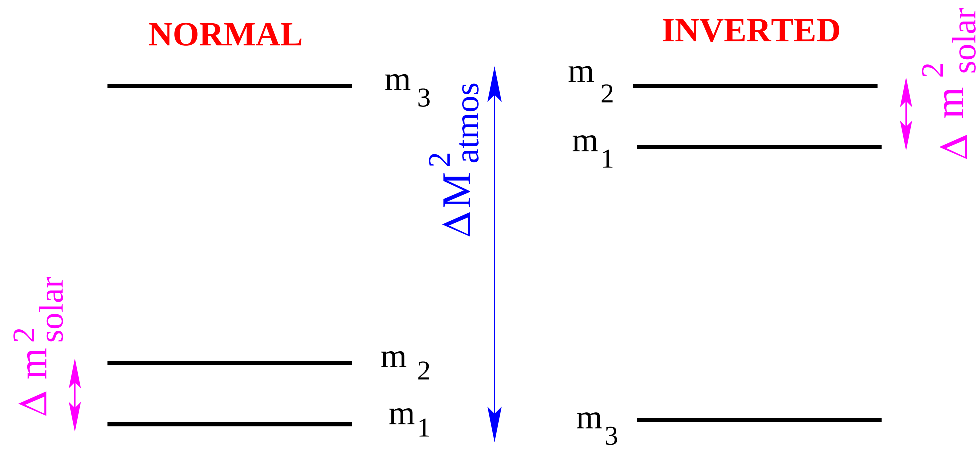
Two mass schemes



2ν oscillation analysis $\Rightarrow \Delta m^2_{21} = \Delta m^2_{\odot} \ll \Delta M^2_{atm} \simeq \pm\Delta m^2_{32} \simeq \pm\Delta m^2_{31}$

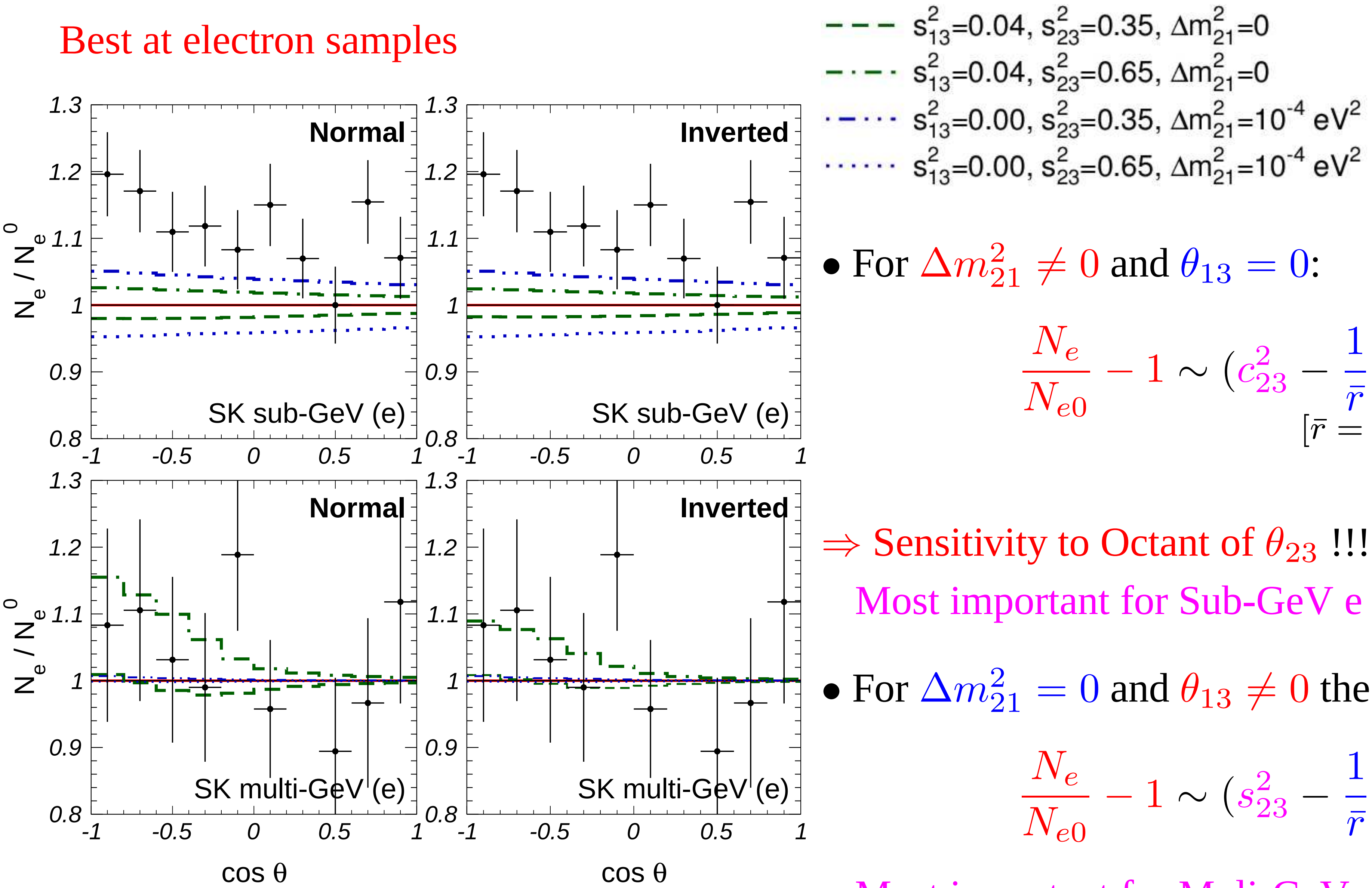
Generic 3ν mixing effects:

- Effects due to θ_{13}
- Difference between Inverted and Normal
- Interference of two wavelength oscillations
- CP violation due to phase δ

Beyond Hierarchical: Δm^2_{21} effects in ATM Data

Smirnov, Peres 99,01; Fogli, Lisi, Marrone 01; MC G-G, Maltoni 02; MCG-G, Maltoni, Smirnov 04

Best at electron samples



- For $\Delta m^2_{21} \neq 0$ and $\theta_{13} = 0$:

$$\frac{N_e}{N_{e0}} - 1 \sim (c^2_{23} - \frac{1}{\bar{r}})$$

$$[\bar{r} = \frac{N_{\mu 0}}{N_{e0}} \simeq 2]$$

$\Rightarrow$ Sensitivity to Octant of θ_{23} !!!

Most important for Sub-GeV e

- For $\Delta m^2_{21} = 0$ and $\theta_{13} \neq 0$ the opposite:

$$\frac{N_e}{N_{e0}} - 1 \sim (s^2_{23} - \frac{1}{\bar{r}})$$

Most important for Muli-GeV e

Beyond Hierarchical: Effect $\theta_{13} \times \Delta m^2_{21}$ in ATM

Smirnov, Peres 01,03, MC G-G, Maltoni 02

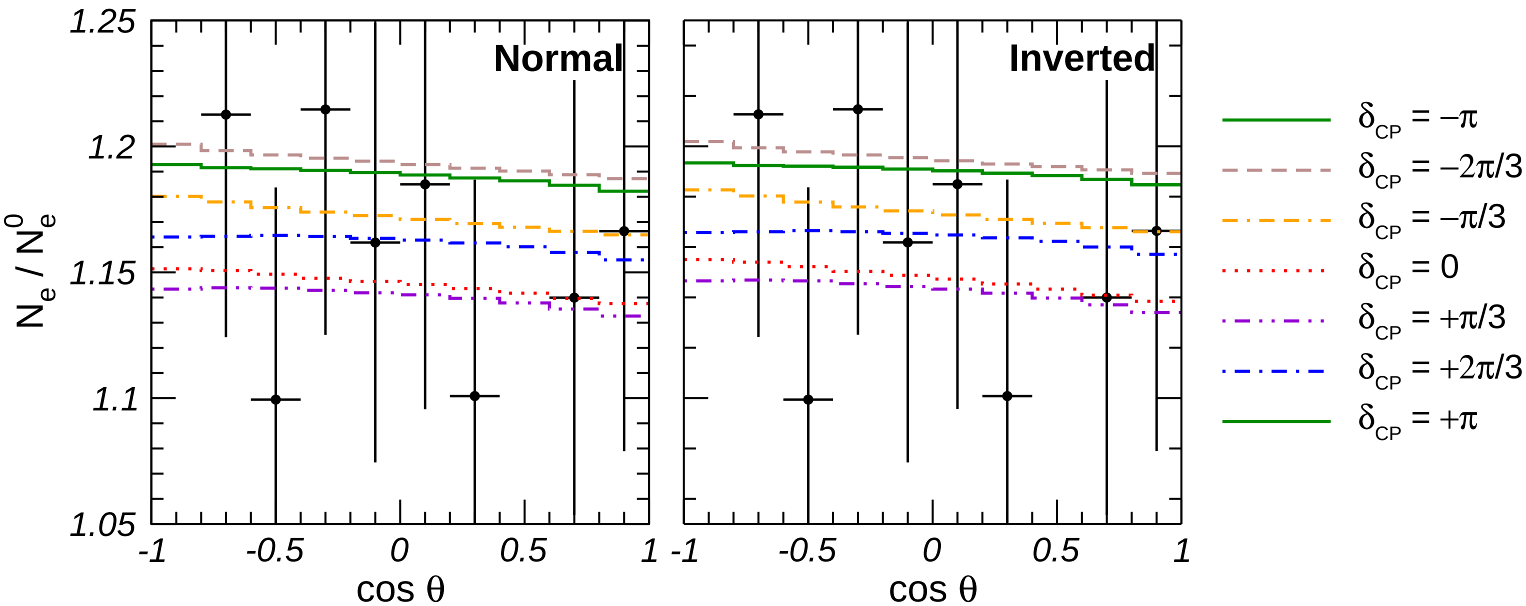
For sub-GeV energies

$$\frac{N_e}{N_e^0} - 1 \simeq \overline{P_{e2}}\,\bar{r}(c^2_{23} - \frac{1}{\bar{r}}) + 2\tilde{s}^2_{13}\bar{r}(s^2_{23} - \frac{1}{\bar{r}}) - \bar{r}\tilde{s}_{13}\tilde{c}^2_{13}\sin 2\theta_{23}(\cos\delta_{CP}\,\overline{R_2} - \sin\delta_{CP}\overline{I_2})$$

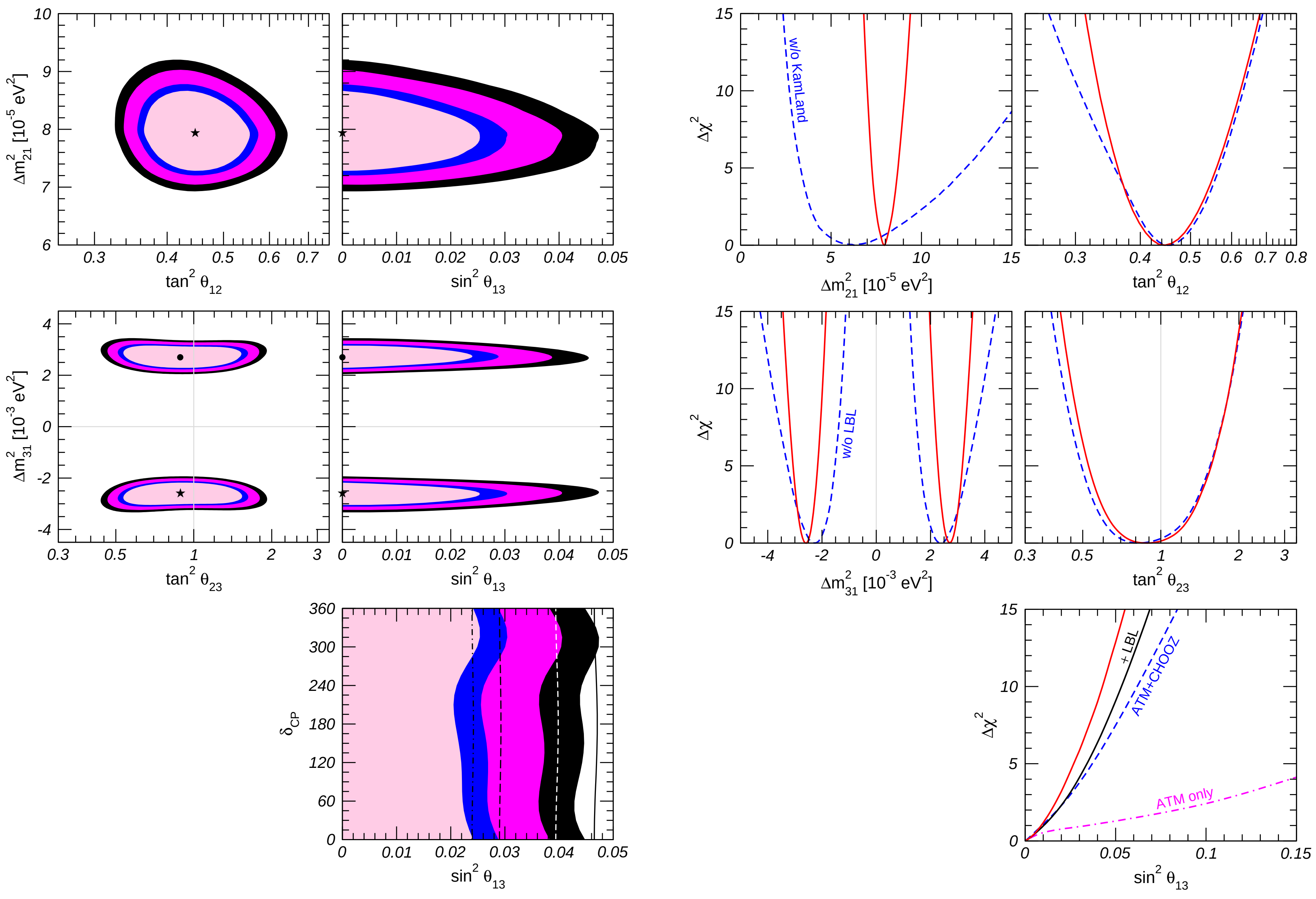
$$P_{e2} = \sin^2 2\theta_{12,m}\,\sin^2\frac{\phi_m}{2} \qquad \sin 2\theta_{12,m} = \frac{\sin 2\theta_{12}}{\sqrt{(\cos 2\theta_{12} \mp \frac{2E_\nu V_e}{\Delta m^2_{21}})^2 + \sin^2 2\theta_{12}}}$$

$$R_2 = -\sin 2\theta_{12,m}\cos 2\theta_{12,m}\,\sin^2\frac{\phi_m}{2} \qquad I_2 = -\frac{1}{2}\sin 2\theta_{12,m}\,\sin\phi_m$$

$$\tilde{\theta}_{13} \approx \theta_{13}\left(1 + \frac{2E_\nu V_e}{\Delta m^2_{31}}\right) \qquad \phi \approx (\Delta m^2_{31} + s^2_{12}\,\Delta m^2_{21})\frac{L}{2E_\nu}$$



Global Analysis: Three Neutrino Oscillations



Global Analysis: Three Neutrino Oscillations

The derived ranges for the six parameters at 1σ (3σ) are:

$$\Delta m^2_{21} = 7.9\,^{+0.27}_{-0.28}\,\left({}^{+1.1}_{-0.89}\right) \times 10^{-5}\ \mathrm{eV}^2 \qquad \left|\Delta m^2_{31}\right| = 2.6 \pm 0.2\,(0.6) \times 10^{-3}\ \mathrm{eV}^2$$

$$\theta_{12} = 33.7 \pm 1.3\ \left({}^{+4.3}_{-3.5}\right) \qquad \theta_{23} = 43.3\,^{+4.3}_{-3.8}\ \left({}^{+9.8}_{-8.8}\right)$$

$$\theta_{13} = 0\,^{+5.2}_{-0.0}\ \left({}^{+11.5}_{-0.0}\right) \qquad \delta_{\mathrm{CP}} \in [0,\ 360]$$

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

$$\sim \begin{pmatrix} \frac{1}{\sqrt{2}}(1+\lambda) & \frac{1}{\sqrt{2}}(1-\lambda) & \epsilon \\ \frac{1}{2}(1-\lambda+\Delta+\epsilon\cos\delta) & \frac{1}{2}(1+\lambda+\Delta-\epsilon\cos\delta) & \frac{1}{\sqrt{2}}(1-\Delta) \\ \frac{1}{2}(1-\lambda-\Delta-\epsilon\cos\delta) & \frac{1}{2}(1+\lambda-\Delta+\epsilon\cos\delta) & \frac{1}{\sqrt{2}}(1+\Delta) \end{pmatrix}$$

With $1\ \sigma$ ranges

$$\lambda \simeq 0.18 \pm 0.02 \quad \Delta \simeq 0.03 \pm 0.07 \quad \epsilon \leq 0.09 \quad -1 \leq \cos\delta \leq 1$$

Open Questions

We still ignore:

(1) Is $\theta_{13} \neq 0$? How small?

(2) Is $\theta_{23} = \frac{\pi}{4}$? If not, is it $>$ or $<$?

(3) Is there CP violation in the leptons (is $\delta \neq 0, \pi$)?

(4) What is the ordering of the neutrino states?

(5) Are neutrino masses:

hierarchical: $m_i - m_j \sim m_i + m_j$?

degenerated: $m_i - m_j \ll m_i + m_j$?

(6) Dirac or Majorana?

Neutrino Mass Scale: Tritium β Decay

• Fermi proposed a kinematic search of ν_e mass from beta spectra in ^3H beta decay

$$^3H \rightarrow ^3He + e + \overline{\nu}_e$$

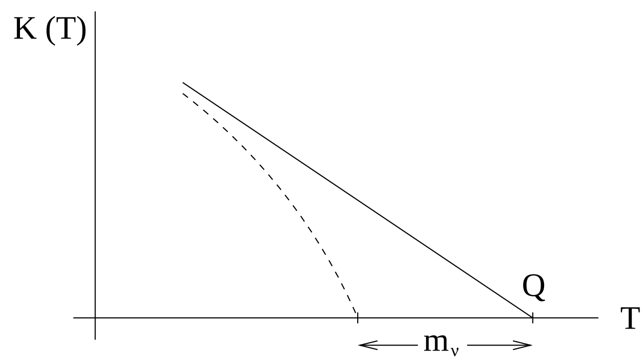
• For "allowed" nuclear transitions, the electron spectrum is given by phase space alone

$$K(T) \equiv \sqrt{\frac{dN}{dT}\frac{1}{Cp\,E\,F(E)}} \propto \sqrt{(Q-T)\sqrt{(Q-T)^2 - m_\nu^2}}$$

$T = E_e - m_e$, Q= maximum kinetic energy, (for ^3H beta decay $Q = 18.6$ KeV)

• $m_\nu \neq 0 \Rightarrow$ distortion from the straight-line at the end point of the spectrum

$$m_\nu = 0 \;\Rightarrow\; T_{\max} = Q$$
$$m_\nu \neq 0 \;\Rightarrow\; T_{\max} = Q - m_\nu$$



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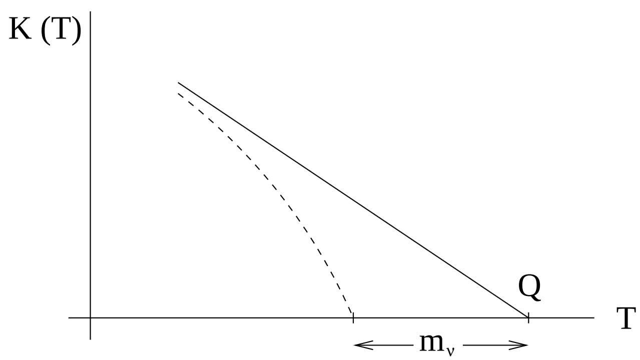


– At present only a bound: $m_{\nu_e}^{eff} \equiv \sqrt{\sum m_j^2 |U_{ej}|^2} < 2.2$ eV (at 95 % CL)
(Mainz & Troisk experiments)

– Katrin proposed to improve present sensitivity to $m_{eff}^{\beta} \sim 0.3\,\text{eV}$

m_ν "Near" Future: Katrin

KArlsruhe TRItium Neutrino experiment - KATRIN

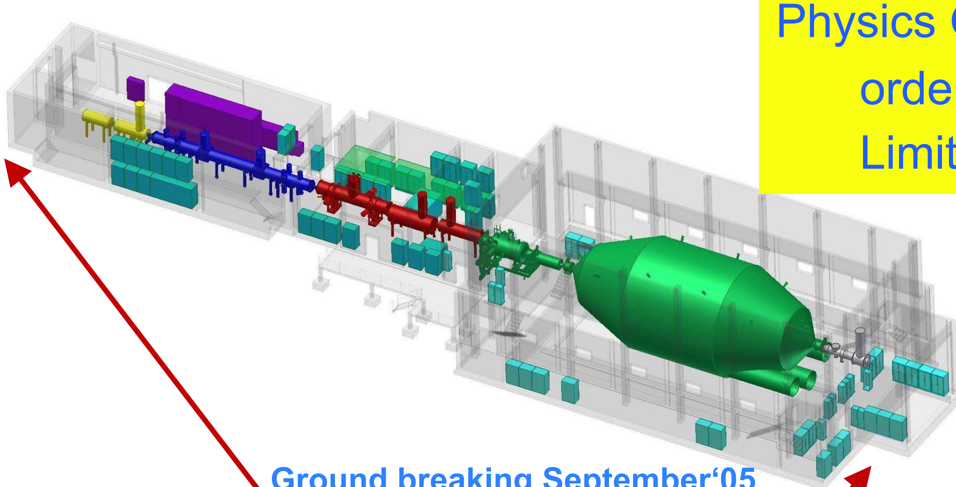
Physics Goal:

order of magnitude improvement in m_ν

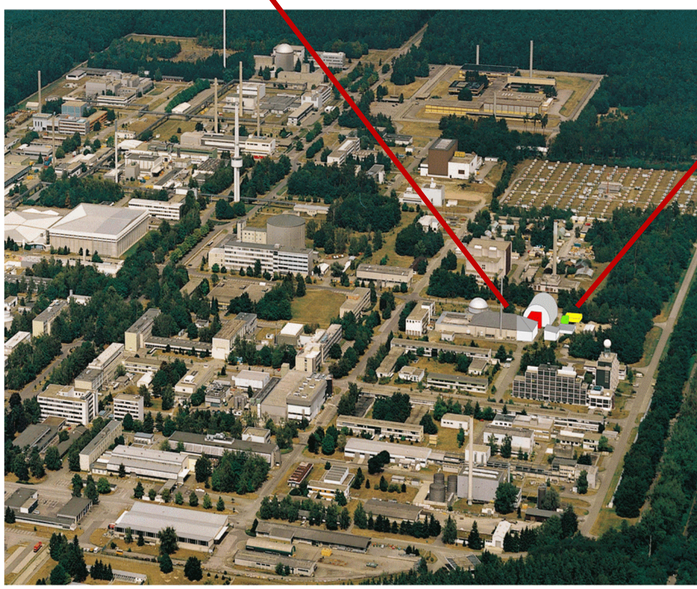
Limit m_ν 2.2 eV → 0.2 eV

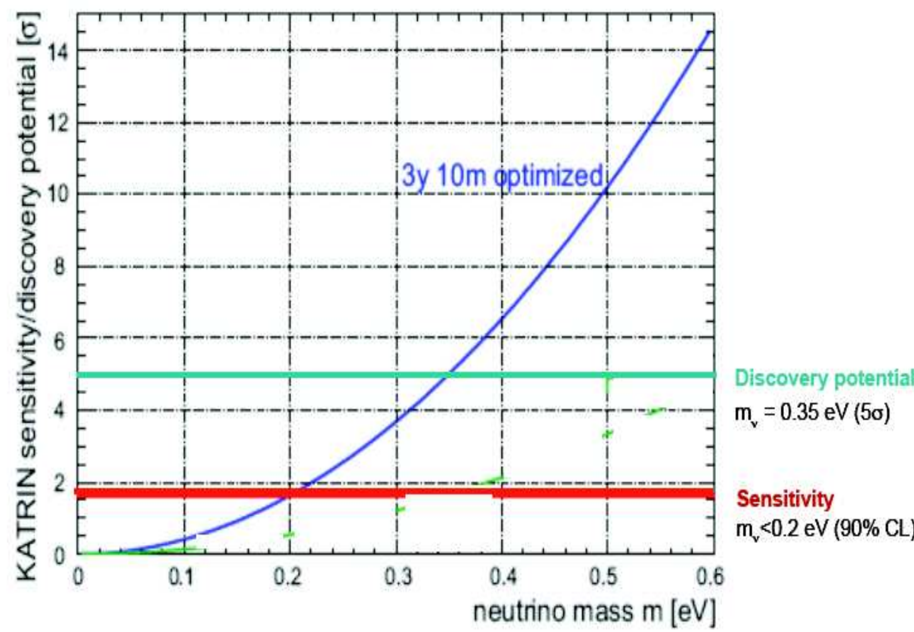
Expect after 3 full beam years $\sigma_{sys} \approx \sigma_{stat}$

(~ 5 calendar years)



Ground breaking September'05





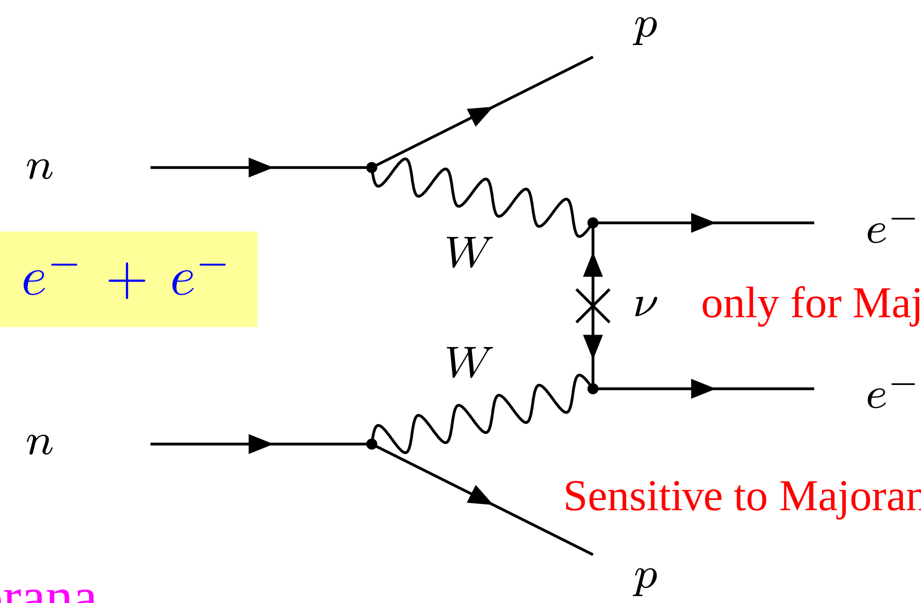
From P. Doe, Talk at $-\nu$2006

First data Fall 2009

Full sensitivity 2015

Neutrino Mass Scale: ν-less Double-β Decay

$$(A, Z) \to (A, Z+2) + e^- + e^-$$



only for Majorana ν's

Sensitive to Majorana CP phases

- ν-less-$\beta\beta \Leftrightarrow$ ν is Majorana
- But Majorana m_ν maybe not unique source of L breaking
- If only Majorana $m_\nu \Rightarrow (T^{0\mu}_{1/2})^{-1} = \frac{1}{m_e^2} G^{0\nu} |M^{0\nu}|^2 \langle m_{ee} \rangle^2$ with

$$\langle m_{ee} \rangle = |\sum U_{ej}^2 m_j|$$

Neutrino Mass Scale: ν-less Double-β Decay

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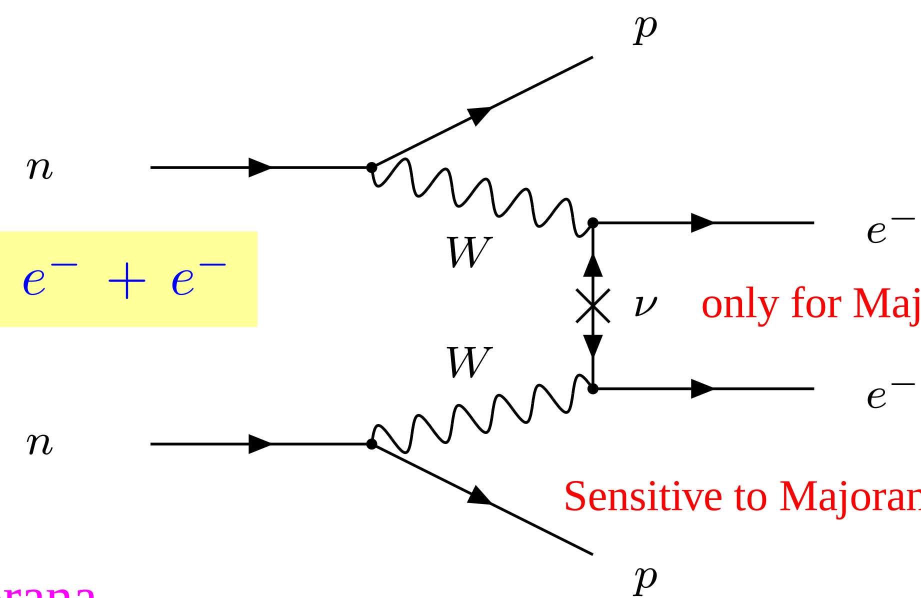

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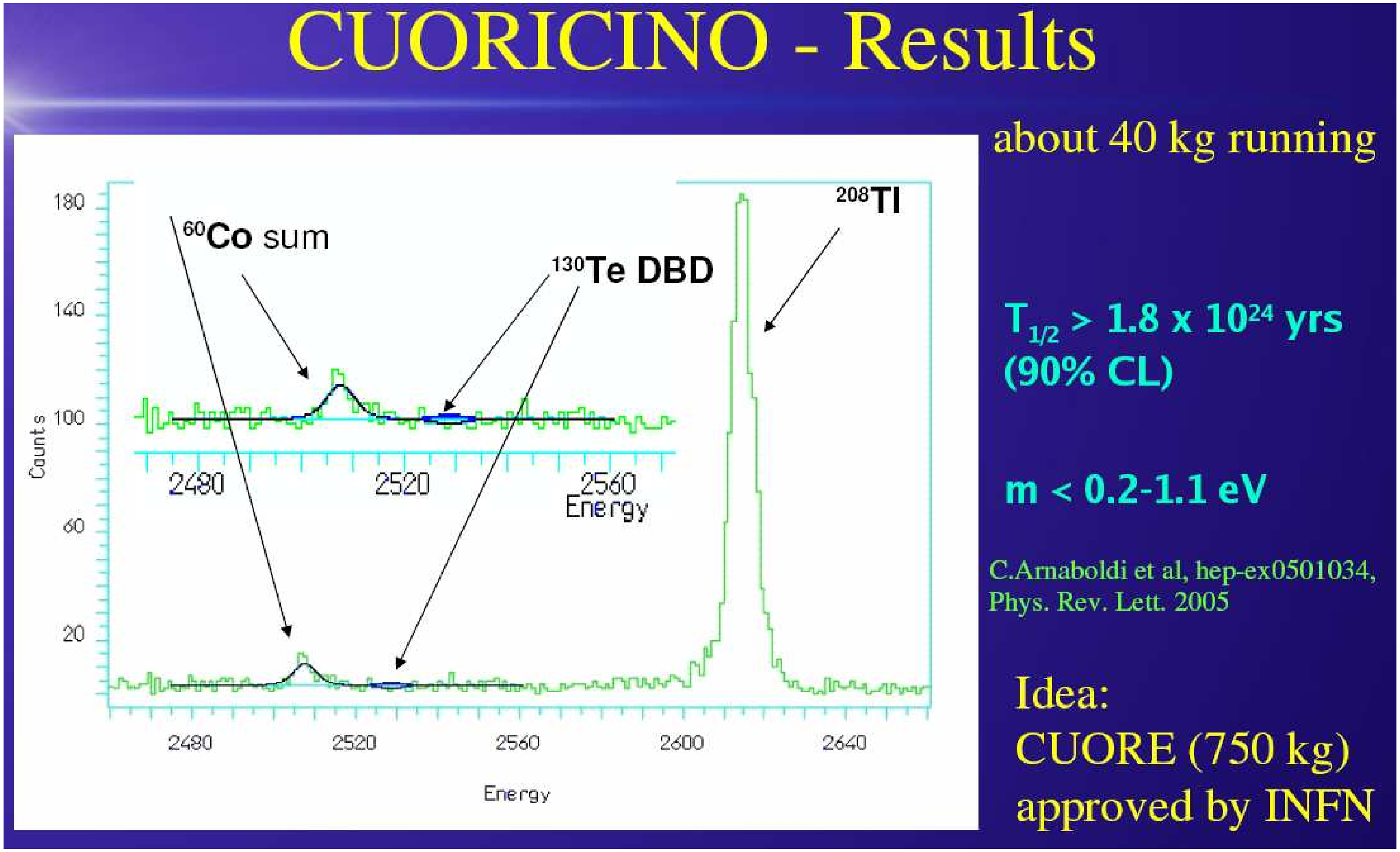
$$\langle m_{ee}\rangle = |\sum U_{ej}^2 m_j|$$

– Present bound: $|\langle m_{ee}\rangle| < 0.35$ eV +theor. uncert. < 1.05 eV (90% CL)

(Heidelberg-Moscow and IGEX experiments)

ν-less Double-β: Present

- Two experiments: Cuorecino and NemoIII running
- Less sensitive than present bounds
- But able to partially test masses in range of claimed evidence



Talk By K. Zuber at Epiphany Conf 06

ν-less Double-β: Present

- Two experiments: Cuorecino and NemoIII running
- Less sensitive than present bounds
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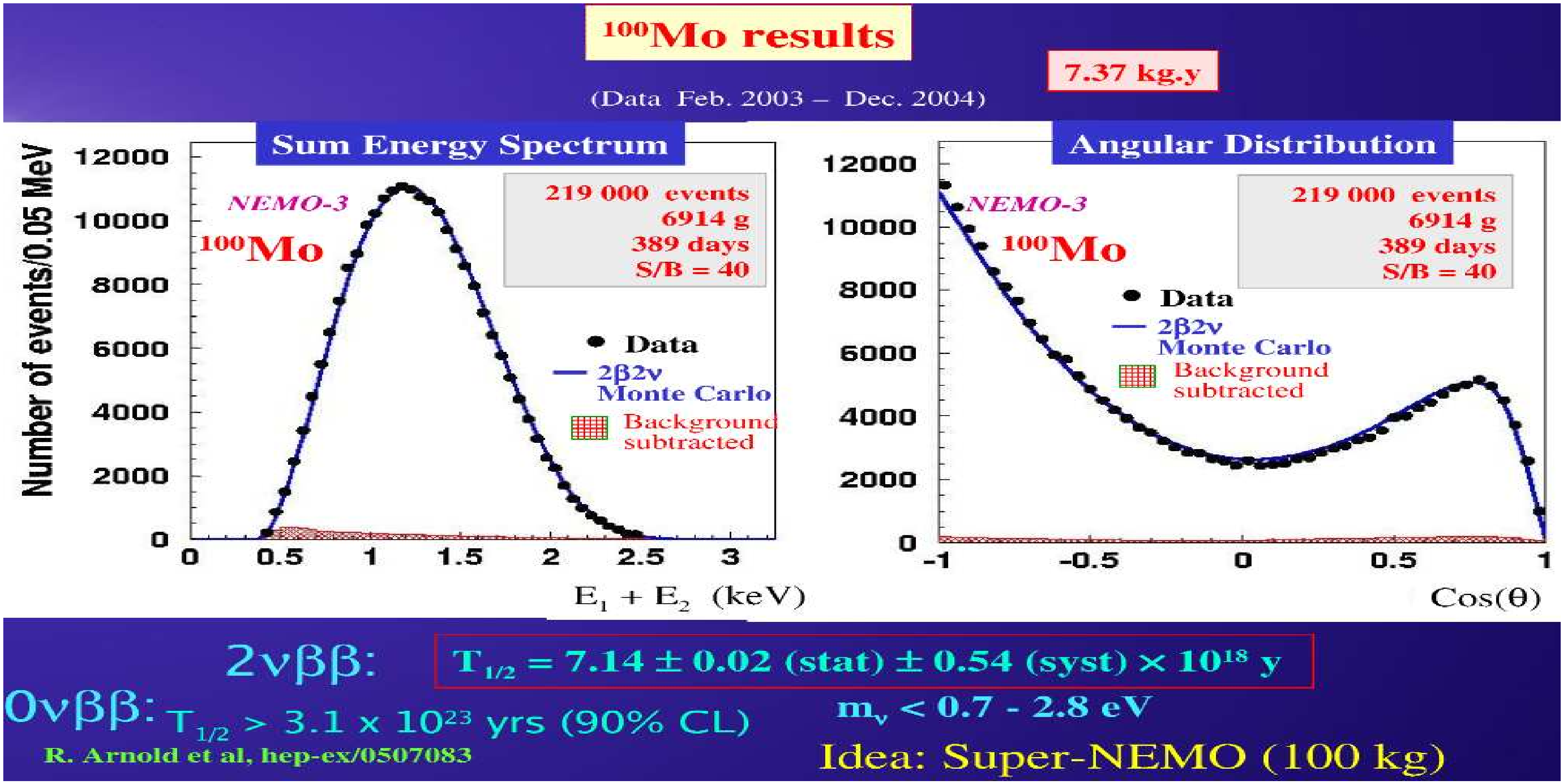


Talk By K. Zuber at Epiphany Conf 06

ν-less Double-β: Future

- Many Proposals to reach $m_{ee} \sim 0.05$ eV

CARVEL	Ca-48	100 kg $^{48}CaWO_4$ crystal scintillators
COBRA	Te-130	10 kg CdTe semiconductors
DCBA	Nd-150	20 kg Nd layers between tracking chambers
NEMO	Mo-100, Various	10 kg of ββ isotopes (7 kg of Mo), expand to superNEMO
CAMEO	Cd-114	1 t $CdWO_4$ crystals
CANDLES	Ca-48	Several tons CaF_2 crystals in liquid scint.
CUORE	Te-130	750 kg TeO_2 bolometers
EXO	Xe-136	1 ton Xe TPC (gas or liquid)
GEM	Ge-76	1 ton Ge diodes in liquid nitrogen
GENIUS	Ge-76	1 ton Ge diodes in liquid nitrogen
GERDA	Ge-76	~30-40 kg Ge diodes in LN, expand to larger masses
GSO	Gd-160	2 t Gd_2SiO_5:Ce crystal scint. in liquid scint.
Majorana	Ge-76	~180 kg Ge diodes, expand to larger masses
MOON	Mo-100	Mo sheets between plastic scint., or liq. scint.
Xe	Xe-136	1.56 t of Xe in liq. Scint.
XMASS	Xe-136	10 t of liquid Xe

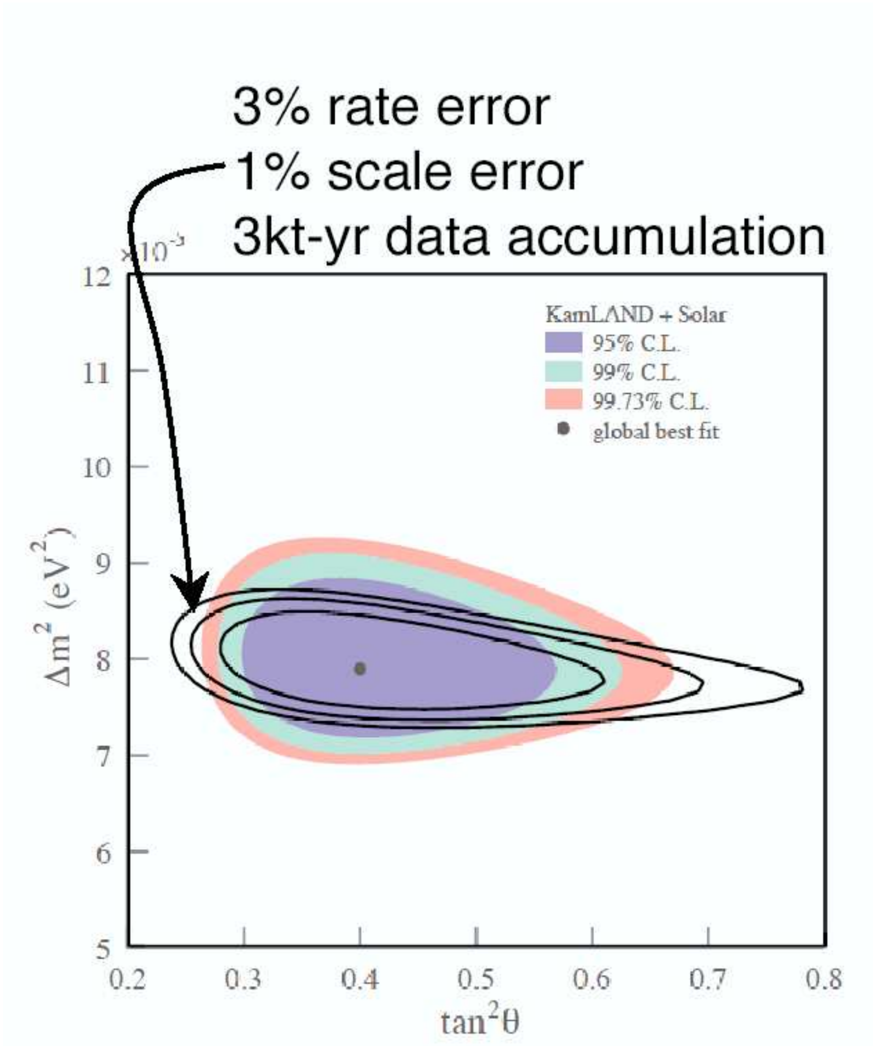
Talk By K. Zuber at Epiphany Conf 06

Present and Future of Neutrino Parameters

3-ν parameter	Present knowledge ($\sim 3\sigma$ C. L.)	Near and Not so Near Future
θ_{12}	$0.34 \leq \tan^2\theta_{12} \leq 0.61$	KamLAND, Future LE Solar
θ_{23}	$0.47 \leq \tan^2\theta_{23} \leq 1.8$	$P(\nu_\mu \to \nu_\mu)$ MINOS, OPERA
θ_{13}	$\sin^2\theta_{13} \leq 0.04$	$P(\bar\nu_e \to \bar\nu_e)$ Reactor, $P(\nu_\mu \to \nu_e)$ LBL
$\lvert\Delta m^2_{21}\rvert$	$7.0 \leq \Delta m^2_{21}/10^{-5}\text{eV}^2 \leq 9.0$	$P(\bar\nu_e \to \bar\nu_e)$ KamLAND
$\lvert\Delta m^2_{31}\rvert$	$2.4 \leq \lvert\Delta m^2_{31}\rvert/10^{-3}\text{eV}^2 \leq 3.2$	$P(\nu_\mu \to \nu_\mu)$ MINOS, OPERA LBL
$\text{sgn}(\Delta m^2_{31})$	unknown	$P(\nu_\mu \to \nu_e)$, $P(\bar\nu_\mu \to \bar\nu_e)$ LBL
δ	unknown	$P(\nu_\mu \to \nu_e)$ versus $P(\bar\nu_\mu \to \bar\nu_e)$ LBL
Majorana	unknown	$0\nu\beta\beta$
m_ν	$\sum m_\nu < \mathcal{O}(1)$ eV	β-decay, $0\nu\beta\beta$

12 Near Future: Expected KamLAND Sensitivity

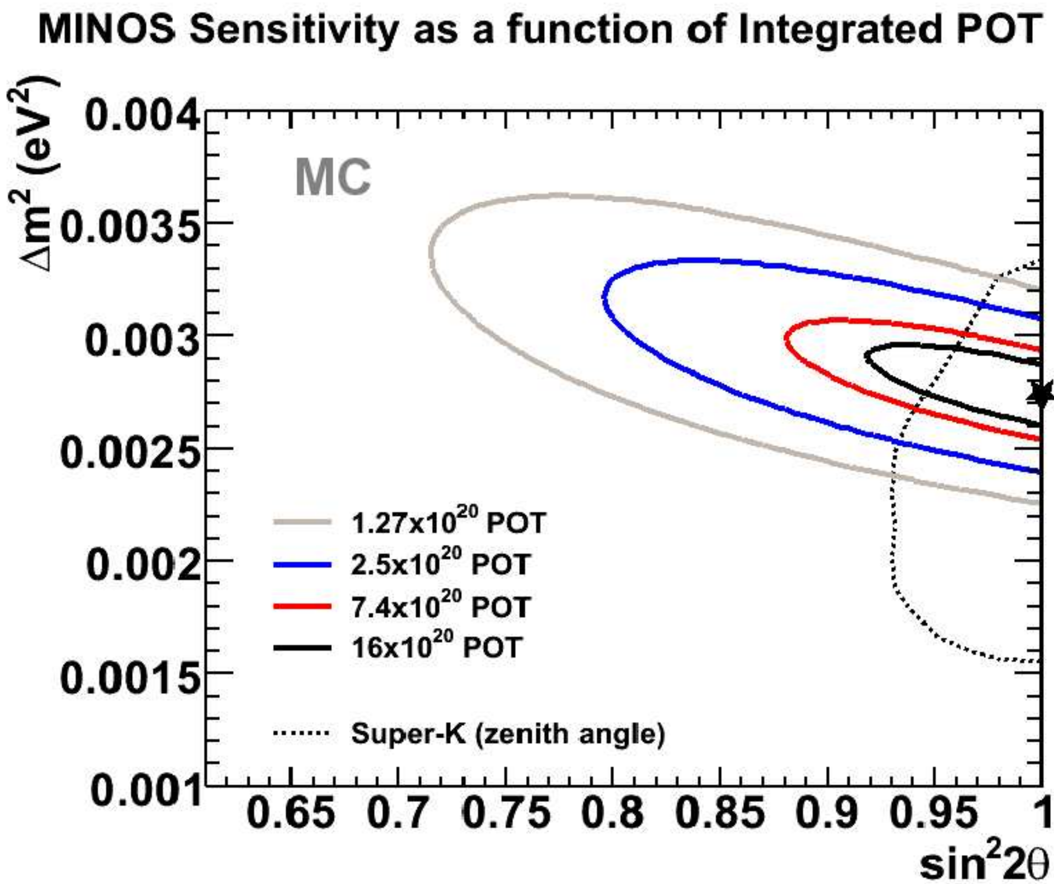
From T. Mitsui, Talk at $-\nu$2006



– No improvement on θ_{12}

– $\sigma(\Delta m^2_{21})/\Delta m^2_{21} \gtrsim \pm$ 3% (1dof)

23 Near Future: Expected Minos Sensitivity



Input parameters

$|\Delta m^2_{32}| = 2.74 \times 10^{-3} eV^2$

$\sin^2 2\theta_{23} = 1.00$

90% contours

Statistical errors only

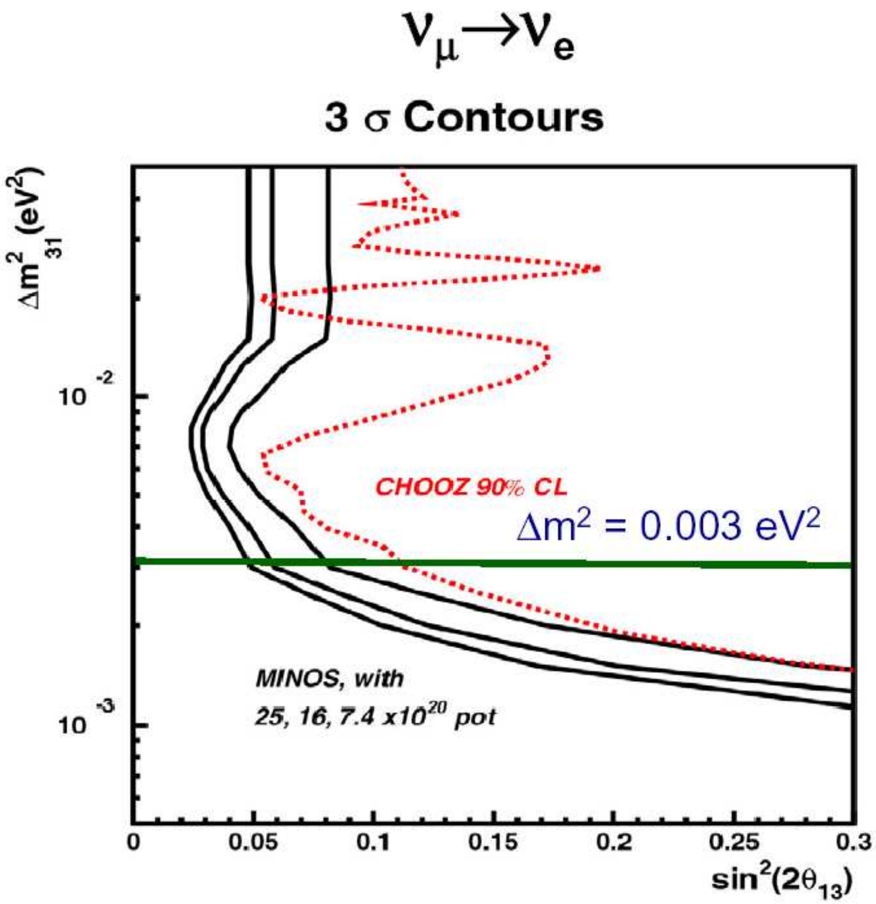
http://www-numi.fnal.gov

– No improvement on θ_{23}

– $\sigma(\Delta m^2_{31})/\Delta m^2_{31} \gtrsim \pm$ 5% (1dof)

θ_{13} Near Future: MINOS and OPERA

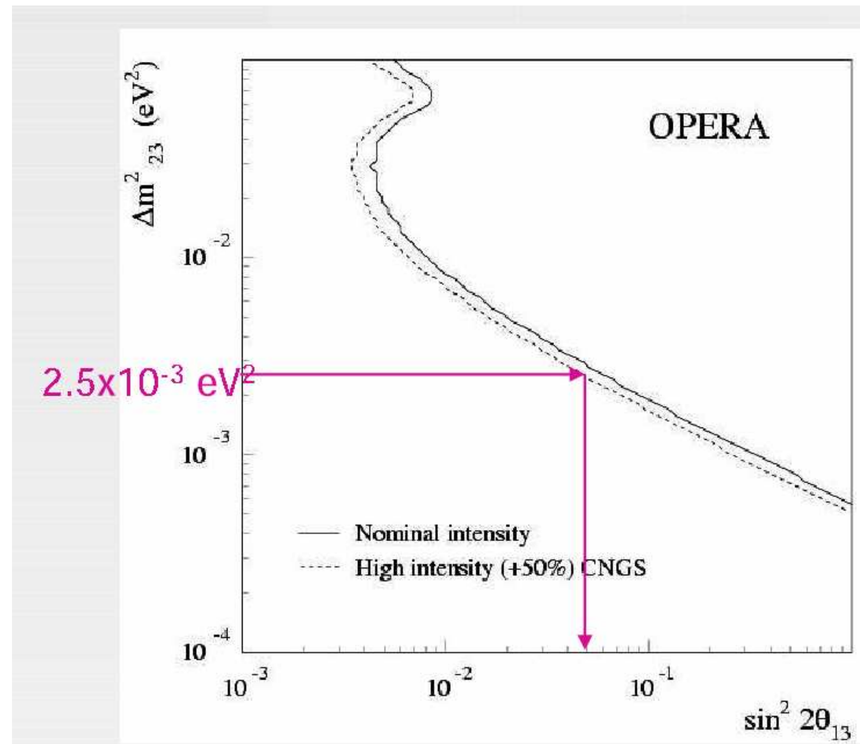
MINOS



http://www-numi.fnal.gov

OPERA 5 Years (2.2×10^{20} pot)

$\sin^2 2\theta_{13} \leq 0.06$ 90% CL



C. Sirignano, talk at ν-2006

Neutrino Parameters: Future Strategies

- Oscillation Probabilities in Earth: $\Delta_{ij} = \frac{\Delta m^2_{ij}}{2E_\nu}$ $B_\pm = \Delta_{31} \pm V_E$ ($V_E \sim 10^{-13}$ eV)
  $\tilde{J} = c_{13} \sin^2 2\theta_{13} \sin^2 2\theta_{23} \sin^2 2\theta_{12}$

$$
\begin{aligned}
P_{\nu_e\nu_\mu(\bar\nu_e\bar\nu_\mu)} &\simeq s^2_{23} \sin^2 2\theta_{13} \left(\frac{\Delta_{31}}{B_\mp}\right)^2 \sin^2\left(\frac{B_\mp L}{2}\right) \\
&+ \tilde{J} \frac{\Delta_{12}}{V_E} \frac{\Delta_{31}}{B_\mp} \sin\left(\frac{V_E L}{2}\right) \sin\left(\frac{B_\mp L}{2}\right) \cos\delta \cos\left(\frac{\Delta_{31} L}{2}\right) \\
&\pm \tilde{J} \frac{\Delta_{12}}{V_E} \frac{\Delta_{31}}{B_\mp} \sin\left(\frac{V_E L}{2}\right) \sin\left(\frac{B_\mp L}{2}\right) \sin\delta \sin\left(\frac{\Delta_{31} L}{2}\right) + \dots \\
P(\nu_\mu \to \nu_\mu) &\simeq 1 - c^2_{13} \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta_{31} L}{2}\right) + \mathcal{O}(\Delta_{12}, s^2_{13}) \\
P(\nu_e \to \nu_e) &\simeq 1 - \sin^2 2\theta_{31} \sin^2\left(\frac{\Delta_{31} L}{2}\right) - c^4_{31} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta_{21} L}{2}\right)
\end{aligned}
$$

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\end{aligned}
$$

– θ_{13}: Very intense ν_μ or ν_e beam + low background and/or small systematics

Neutrino Parameters: Future Strategies

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\end{aligned}$$

– θ_{13}: Very intense ν_μ or ν_e beam + low background and/or small systematics

– sgn(Δm^2_{31}): Need of matter effects $\Rightarrow$ very long L

Neutrino Parameters: Future Strategies

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$$

– θ_{13}: Very intense ν_μ or ν_e beam + low background and/or small systematics

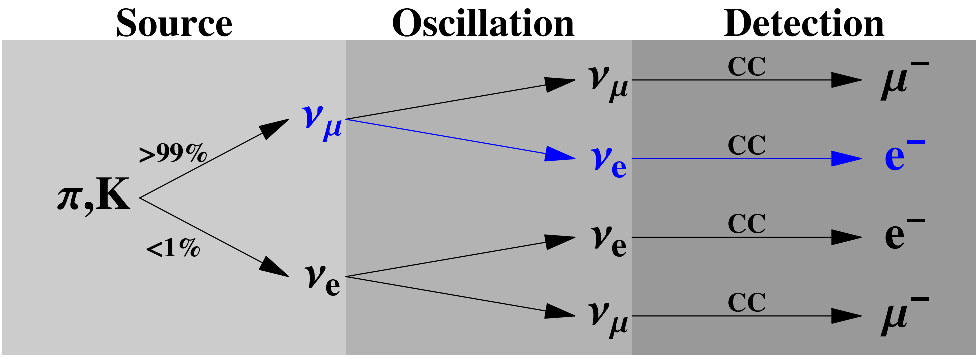
– sgn(Δm^2_{31}): Need of matter effects ⇒ very long L

– $\not{C}$P: All angles and Δm^2 non vanishing ⇒ θ_{13} not too small

Intense beams best with exchangeable initial state ($\nu/\bar\nu$)

Experimental Set-ups

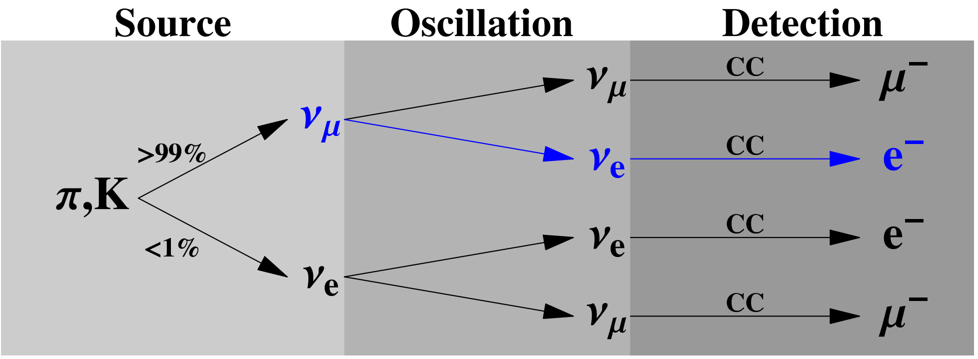
- Conventional (=from π decay) Superbeams



	Exp	L	$\langle E\rangle$
Off-Axis	T2K (Japan)	295 km	0.76 GeV
	Noνa (Fermilab)	812 km	2.22 GeV

Experimental Set-ups

- Conventional (=from π decay) Superbeams



	Exp	L	$\langle E \rangle$
Off-Axis	T2K (Japan)	295 km	0.76 GeV
Off-Axis	Noνa (Fermilab)	812 km	2.22 GeV

- Reactor Experiment with 2 Detectors [only θ_{13}]

$$P(\nu_e \to \nu_e) \simeq 1 - \sin^2 2\theta_{31} \sin^2\left(\frac{\Delta_{31} L}{2}\right)$$

CHOOZII (France), Many proposals

$\langle E \rangle \sim 4$ MeV $\qquad L \sim 1$–2 km

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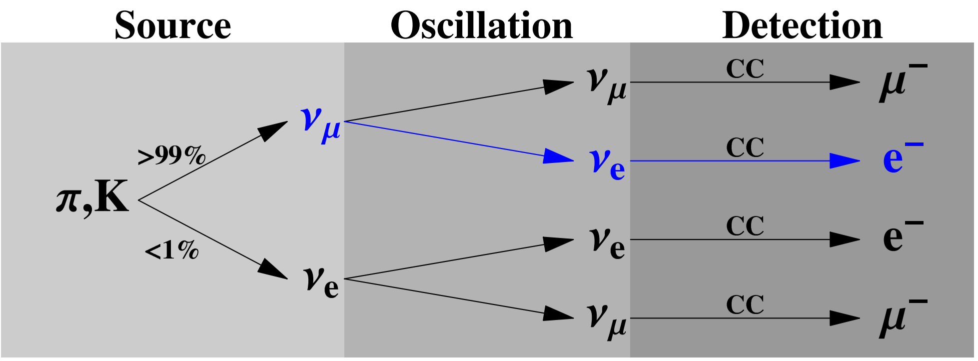

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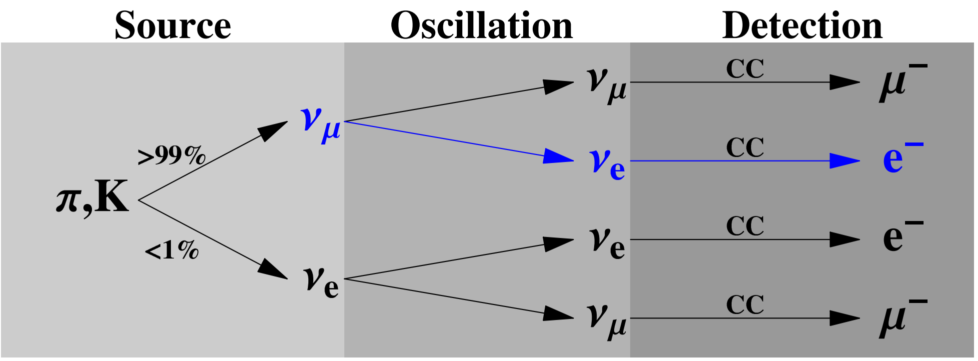

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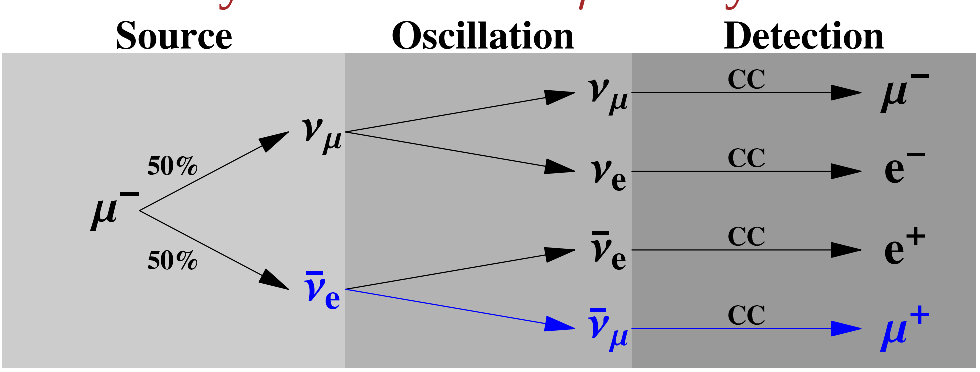
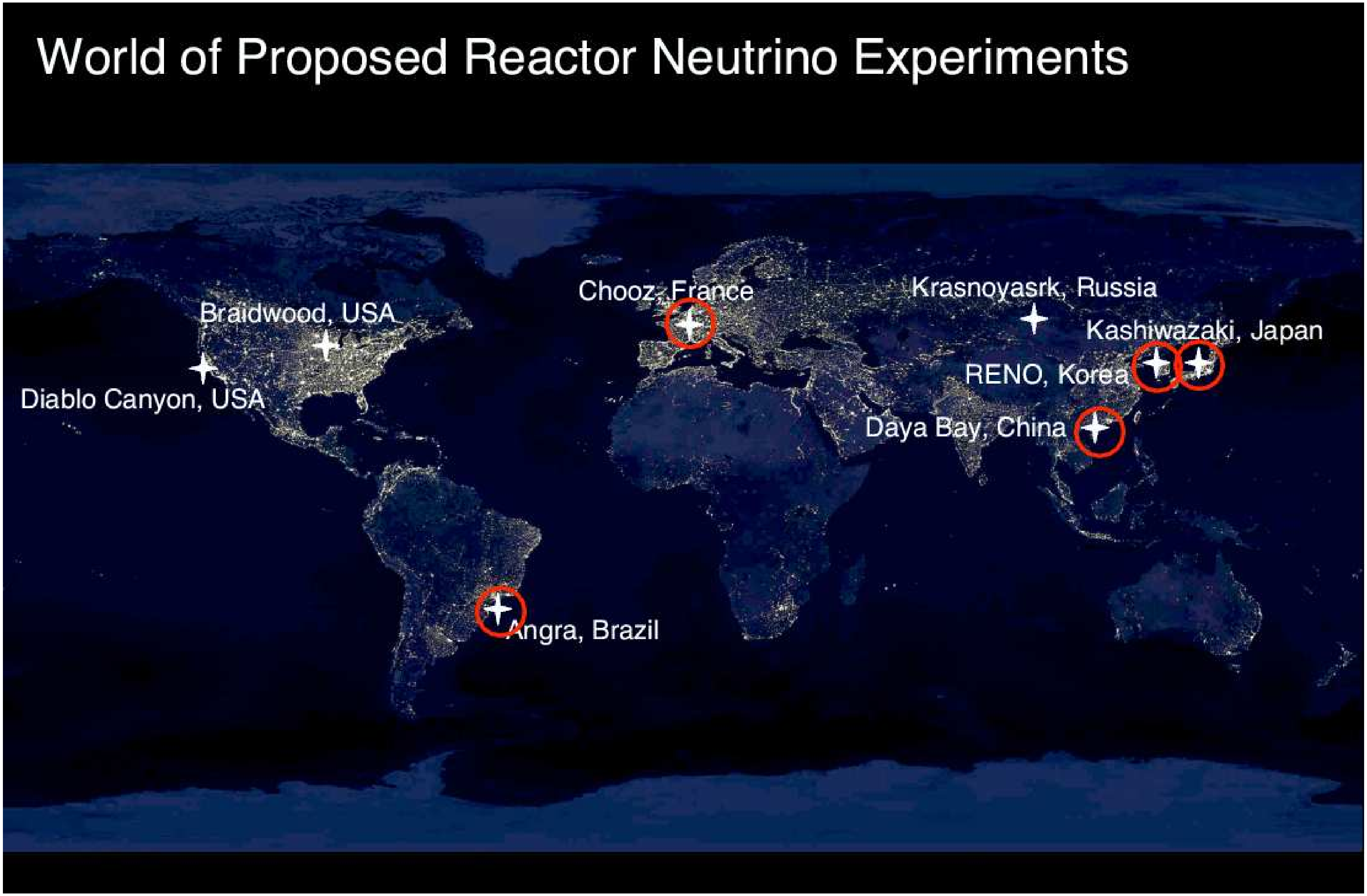
- ν-factory: ν beam from μ decay



$\langle E \rangle \sim$ 20–50 GeV

$L \sim$ 700–7000 km



From K. Heeger, Talk at $-\nu 2009$

Prospects for a Reactor Measurement of $\sin^2 2\theta_{13}$

Angra, Brazil $\sin^2 2\theta_{13} < 0.005$

- R&D on reactor monitoring. Proposal for θ_{13} measurement after Double Chooz.

Daya Bay, China $\sin^2 2\theta_{13} < 0.01$

- Approved by the Chinese Academy of Science for 50M RMB.
- Other Chinese agencies are expected to contribute ~100M RMB.
- US DOE has provided 0.8M$ for R&D for FY06. Working towards US project start in FY08.
- Plan to start near-mid data taking in 2009, and begin full operation in 2010.

Double-CHOOZ, France $\sin^2 2\theta_{13} < 0.03$

- Funding committment in France and Germany.
- Begin running far detector in 2008.
- Complete near detector in 2009.

RENO, Korea $\sin^2 2\theta_{13} < 0.02$

- Approved by Ministry of Science and Technology for US $9M. R&D program starting.
- Plan to begin data taking in 2009/2010.

KASKA, Japan $\sin^2 2\theta_{13} < 0.025$

- R&D program in progress. If funded, plan to begin data taking in 2009/2010.

Expectations at Double Chooz

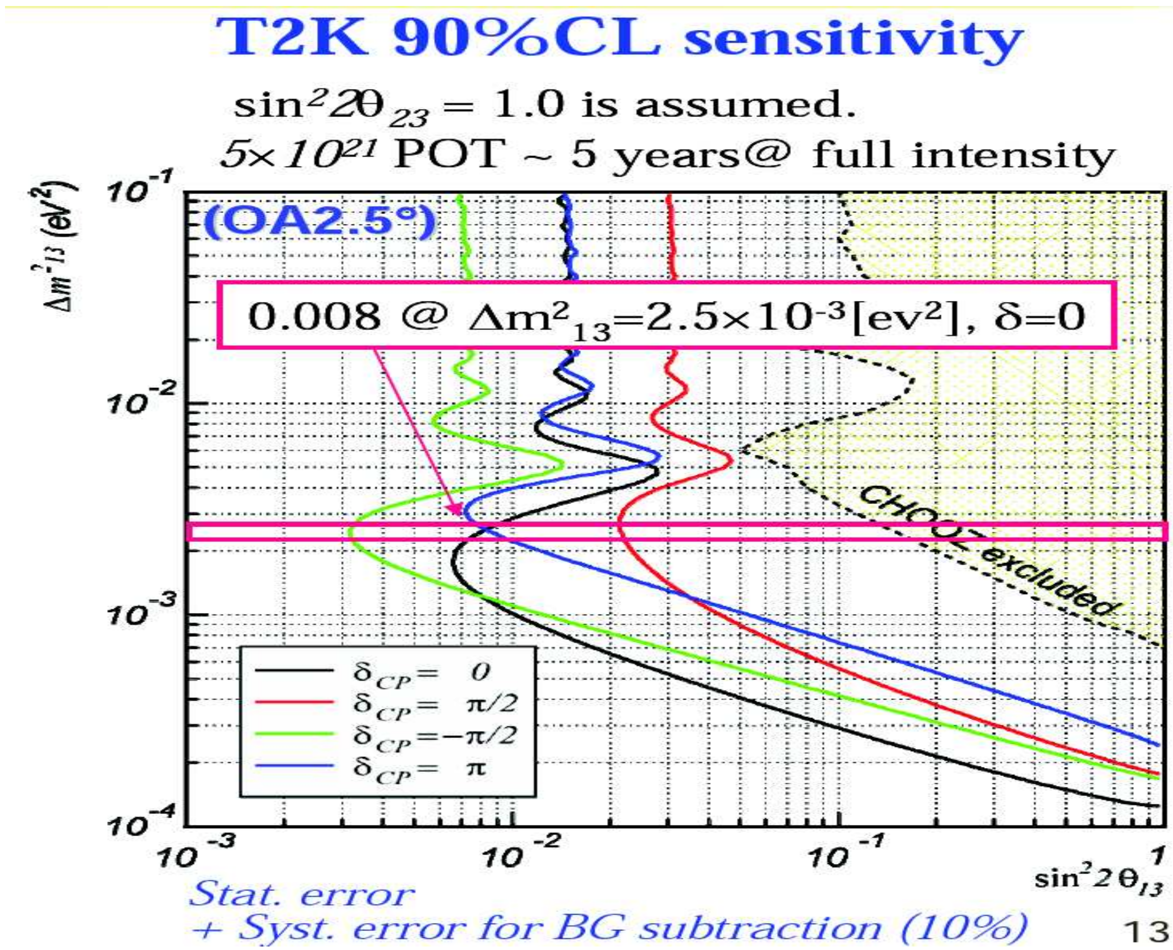
Expectations at T2K-I

- JPARK to SuperKamiokande:
  $L = 295$ Km, 10^{21} pot/yr, Off-Axis 2-2.5 deg, $\langle E \rangle \sim .75$ GeV
  Starting data taking 2009

- In $\nu_\mu \to \nu_\mu$: Goal $\delta(\sin^2 2\theta_{23}) \sim 0.01$ and $\delta(\Delta m^2_{31}) \sim 10^{-4}$ eV^2

- In $\nu_\mu \to \nu_e$:

Talk by T. Nakadaira at ν-2006



Challenges at Future LBL: Parameter Degeneracies

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P_{\nu_e\nu_\mu(\bar\nu_e\bar\nu_\mu)} &\simeq s_{23}^2 \sin^2 2\theta_{13} \left(\frac{\Delta_{31}}{B_\mp}\right)^2 \sin^2\left(\frac{B_\mp L}{2}\right) \\
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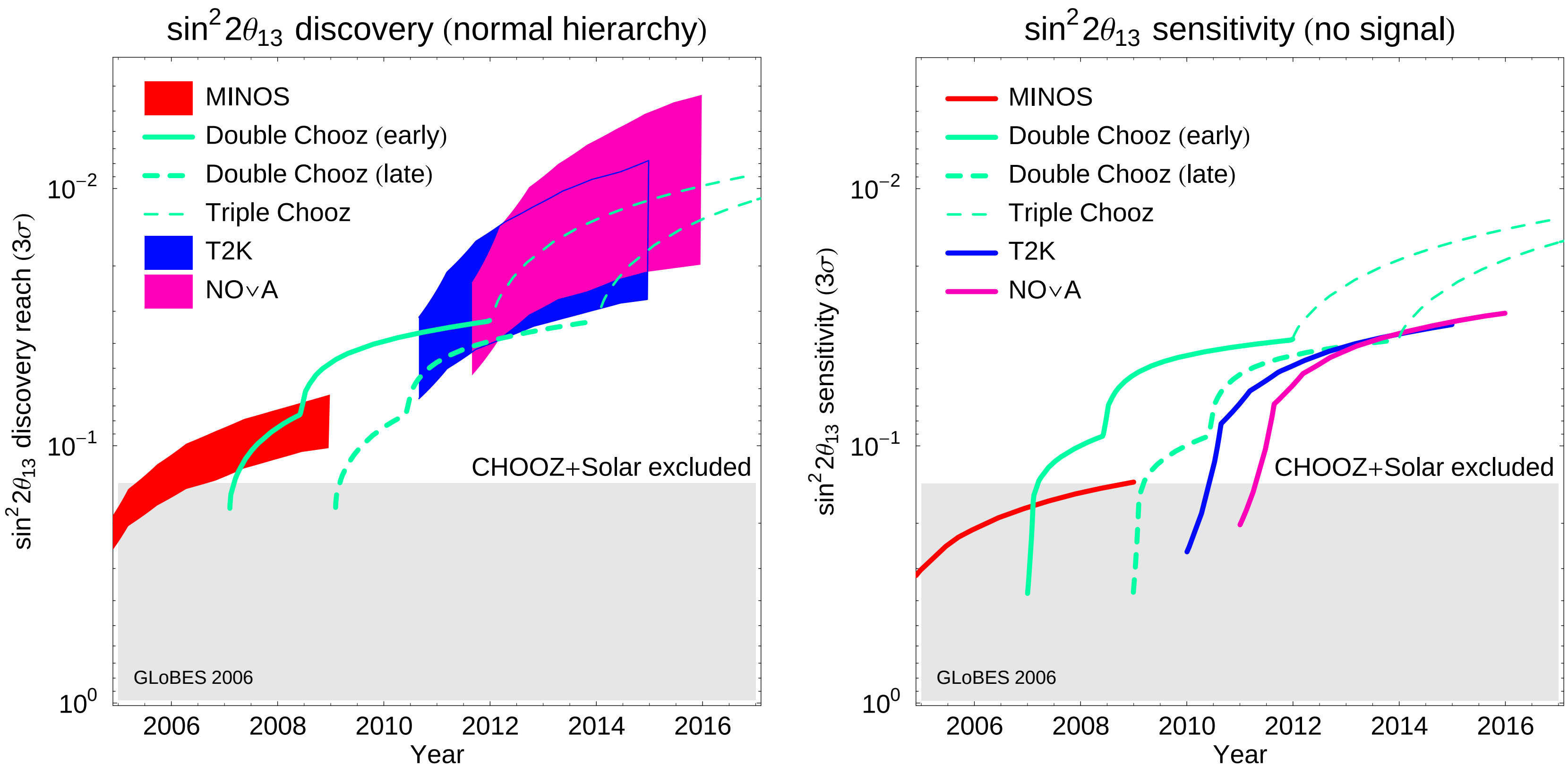
$$\Downarrow$$

If only total number of ν_e, ν_μ, $\overline{\nu}_e$ and $\overline{\nu}_\mu$ at given L are measured $\Rightarrow$ 8-fold degeneracy

Possible Time Scale in Sensitivity to θ_{13}



From Huber, Kopp, Lindner, Rolinec and Winter 06

Future LBL: Cures of Degeneracies

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- Go to *magic* baselines: Huber and Winter 03, Barger, Marfatia, Whisnant . . .

At $L = \frac{2\pi}{V_e} \sim 8000$ km $\Rightarrow$ Only first term survives

Unambiguous determination of θ_{13} but no sensitivity to CP violation (also a bit too long...)

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At $L = \frac{\pi}{4\Delta_{31}} \simeq 560\text{km}\frac{E}{\text{GeV}}\,\frac{2.2\times10^{-3}}{\Delta m^2_{31}}$ $\Rightarrow$ $\cos\delta$ term cancels out

(θ_{13}, δ) ambiguity broken but others remain

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- Combine measurements at different L and different E

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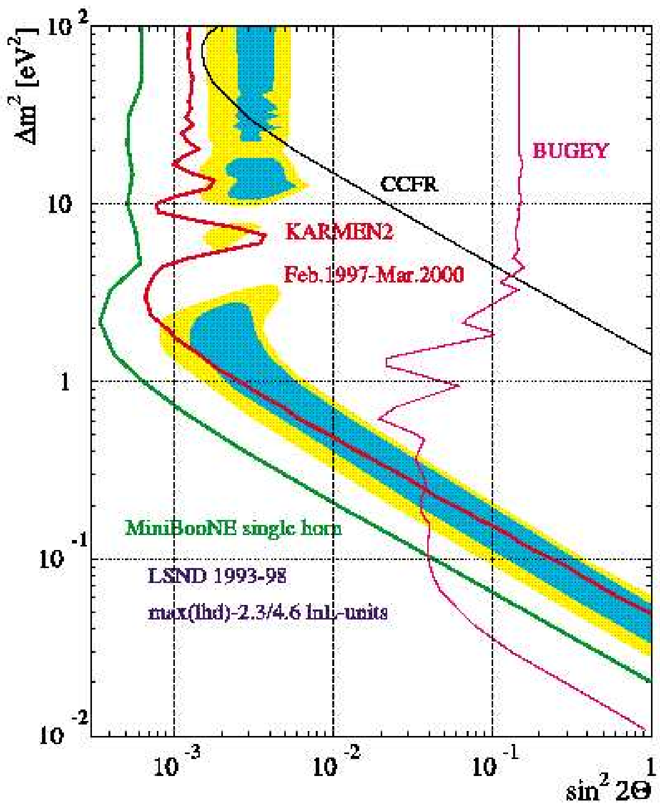
- Wide-band superbeam allowing for spectrum measurements $N_\nu(E_\nu)$

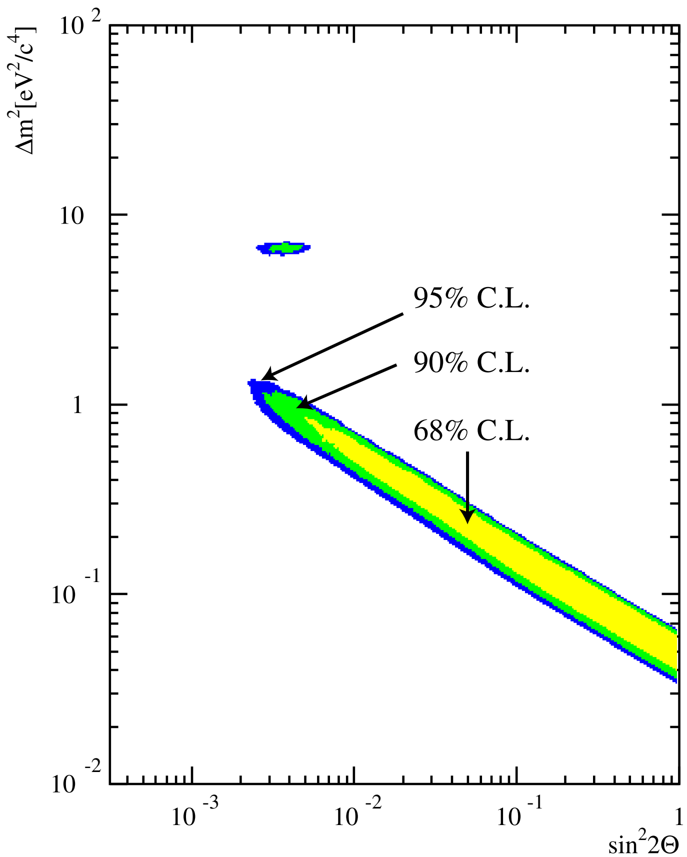
  M. Diwan *etal* 03

LSND

- The only short distance signal for oscillation: $L = 30$ m with $\langle E_\nu \rangle \sim 30$ MeV
- Observed $\overline{\nu_\mu} \to \overline{\nu_e}$ with probability $\langle P_{e\mu} \rangle = (0.26 \pm 0.07 \pm 0.05)\%$
- $Karmen$ searched for the same signal and did not observe oscillations



LSND+Karmen Combined Analysis



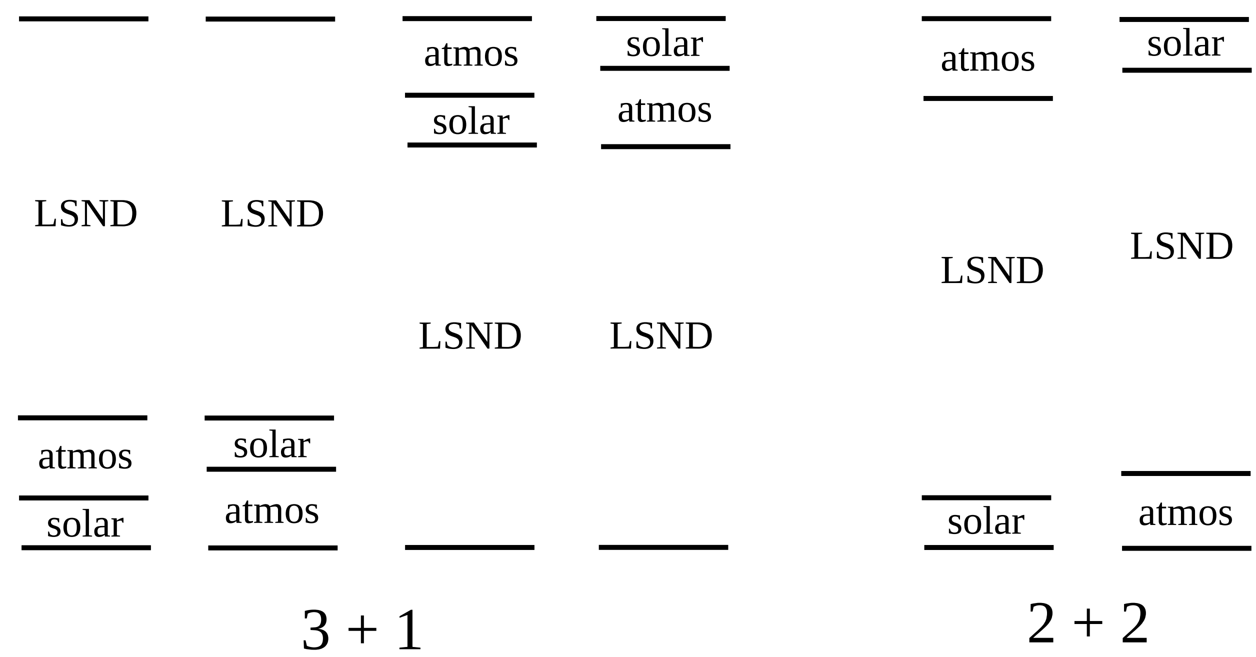
- $MiniBoone$ in Fermilab is expected to clarify this **SOON!!**.

LSND Try I: Sterile Neutrinos and 4ν Mixing

- Motivation: To explain LSND

$$\Delta m^2_{\rm LSND} \gg \Delta m^2_{atm} \gg \Delta m^2_{\odot}$$

- To fit solar, atmospheric and LSND $\Rightarrow$ 3 Δm^2 $\Rightarrow$ 4th sterile ν
- U: 6 mixing angles and 3 CP Dirac phases and 3 Majorana phases
- 6 mass spectra of two type:



LSND Try I: Sterile Neutrinos and 4ν Mixing

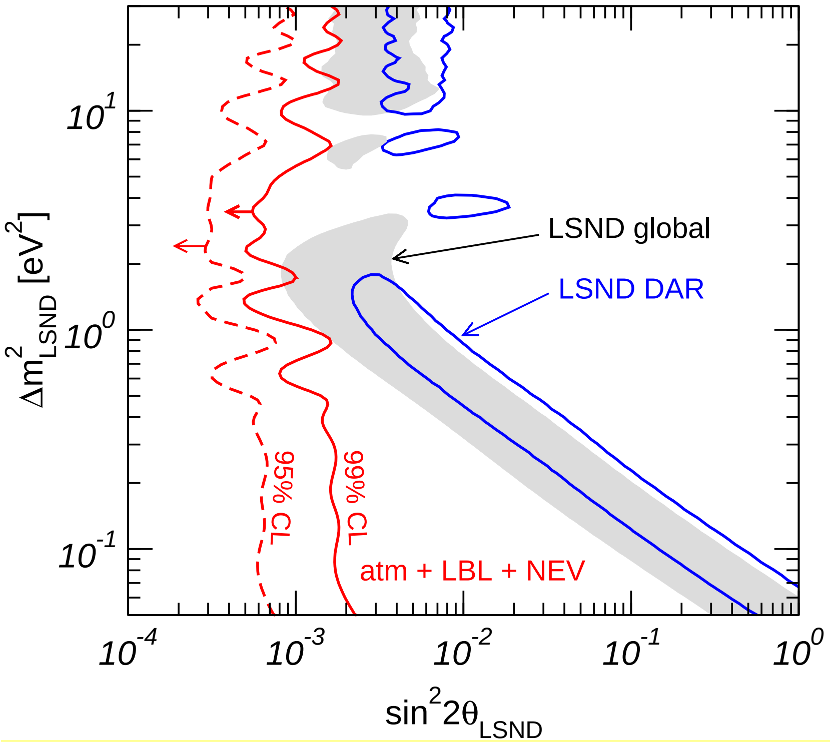
$\underline{3+1}$

$\sin^2 2\theta_{\rm LSND} = 4|U_{e4}|^2|U_{\mu4}|^2$

$|U_{e4}|^2$ constrained by Bugey

$|U_{\mu4}|^2$ constrained by CDHSW+ATM

Maltoni *et al* 05, Updated Maltoni, MCG-G 07



Only tiny regions at 99%CL

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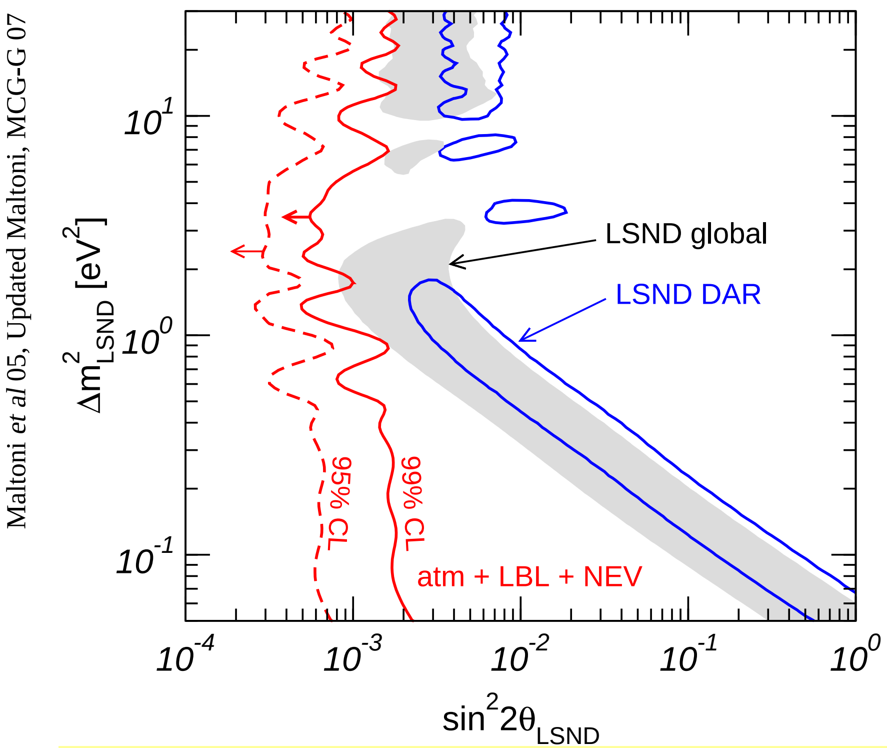


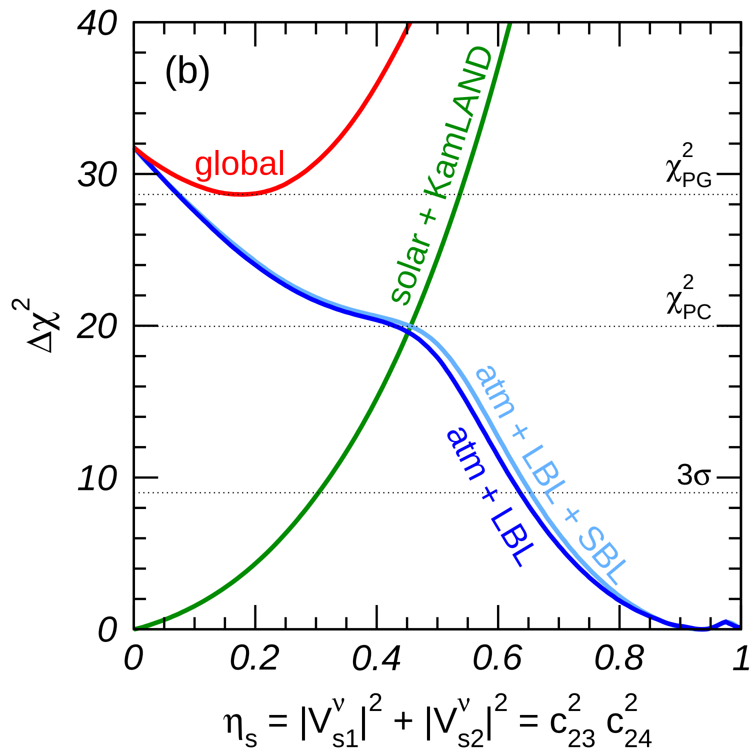
Only tiny regions at 99%CL

$2+2$

Mixed active-sterile oscillations

Naively: Solar: $\nu_e \to \cos\eta\,\nu_s + \sin\eta\,\nu_\tau$

Atm: $\nu_\mu \to \sin\eta\,\nu_s - \cos\eta\,\nu_\tau$



Disagreement at more than 4σ

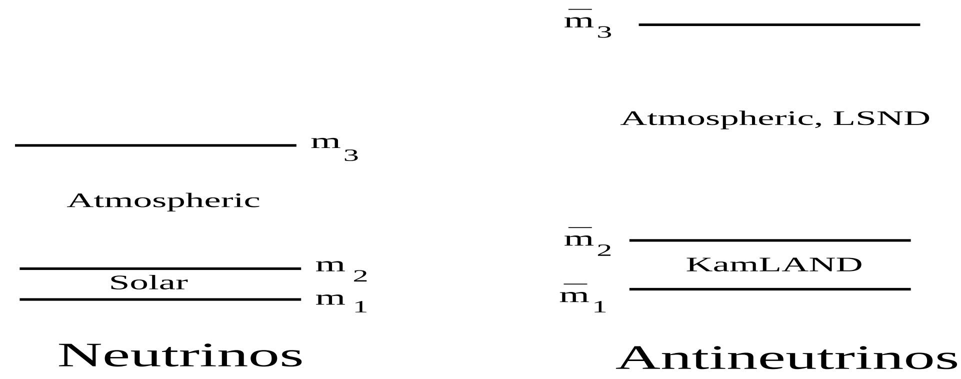
LSND Try II : CPT Violation

MCG-G, Maltoni,Schwetz 04, MCG-G, Maltoni 07

CPT violation:

⇒ ν's and $\bar{\nu}$'s can have different masses

⇒ Possibility of accommodating LSND?



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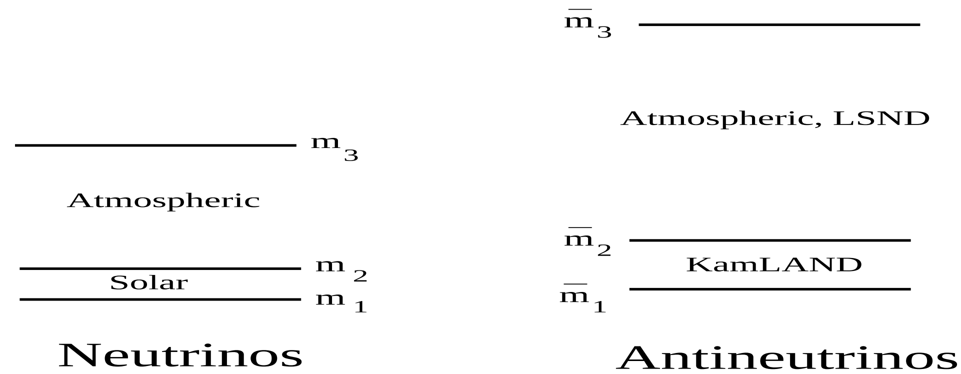
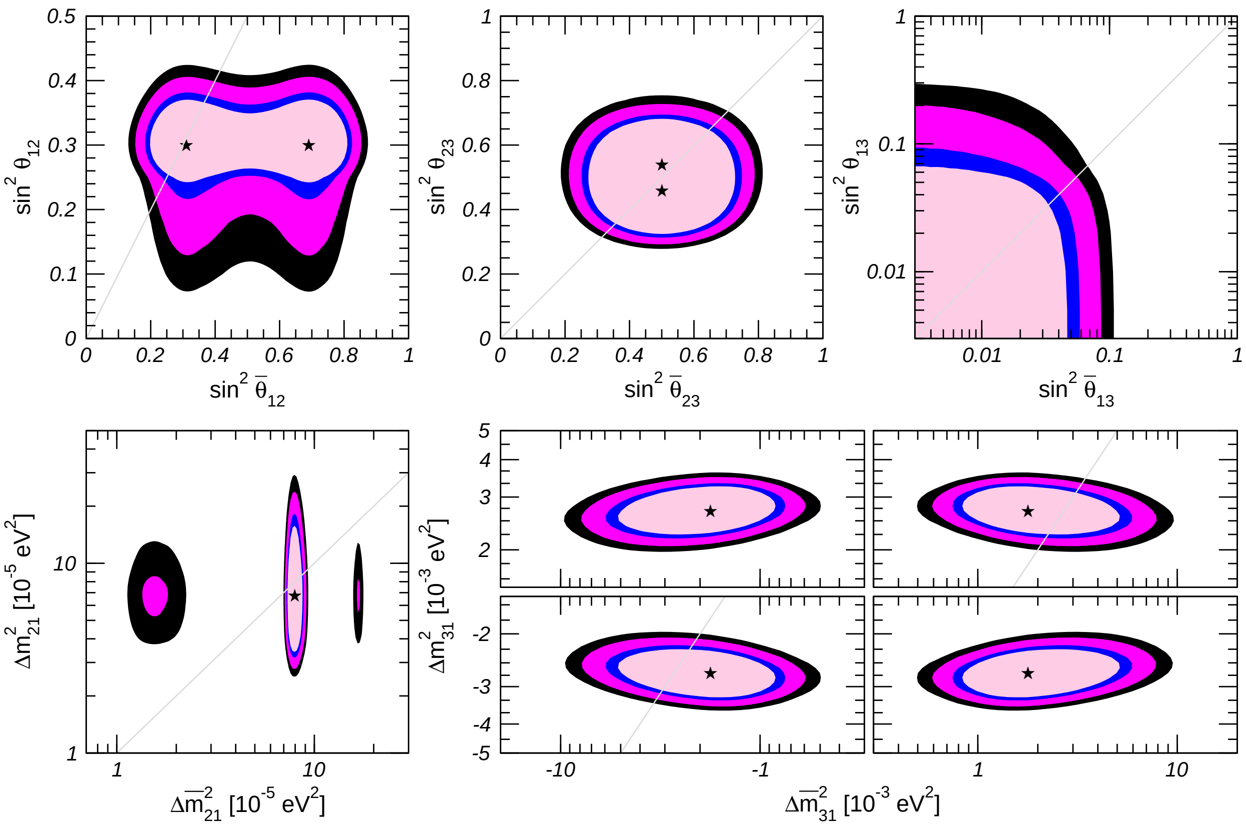


But Data does not support this:

ATM ⇒ ν_μ and $\bar{\nu}_\mu$'s similar wavelength

Solar ν_e and KamLAND $\bar{\nu}_e$ similar Δm^2



Best fit near CPT conservation

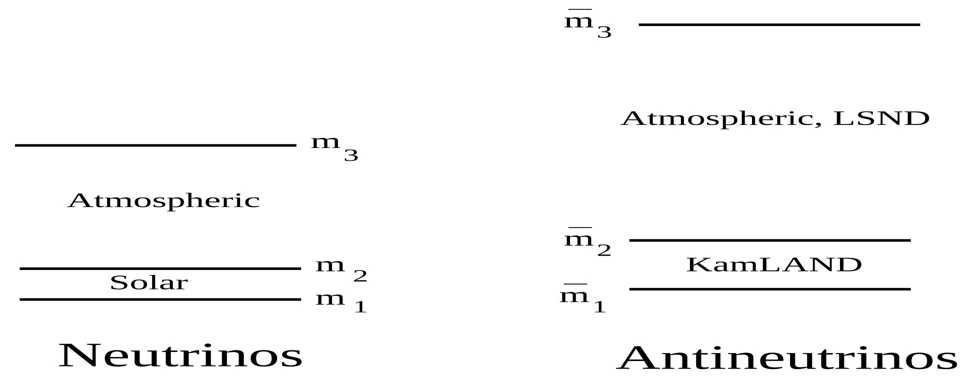
LSND Try II : CPT Violation

MCG-G, Maltoni,Schwetz 04, MCG-G, Maltoni 07

CPT violation:

$\Rightarrow$ ν's and $\bar{\nu}$'s can have different masses

$\Rightarrow$ Possibility of accommodating LSND?



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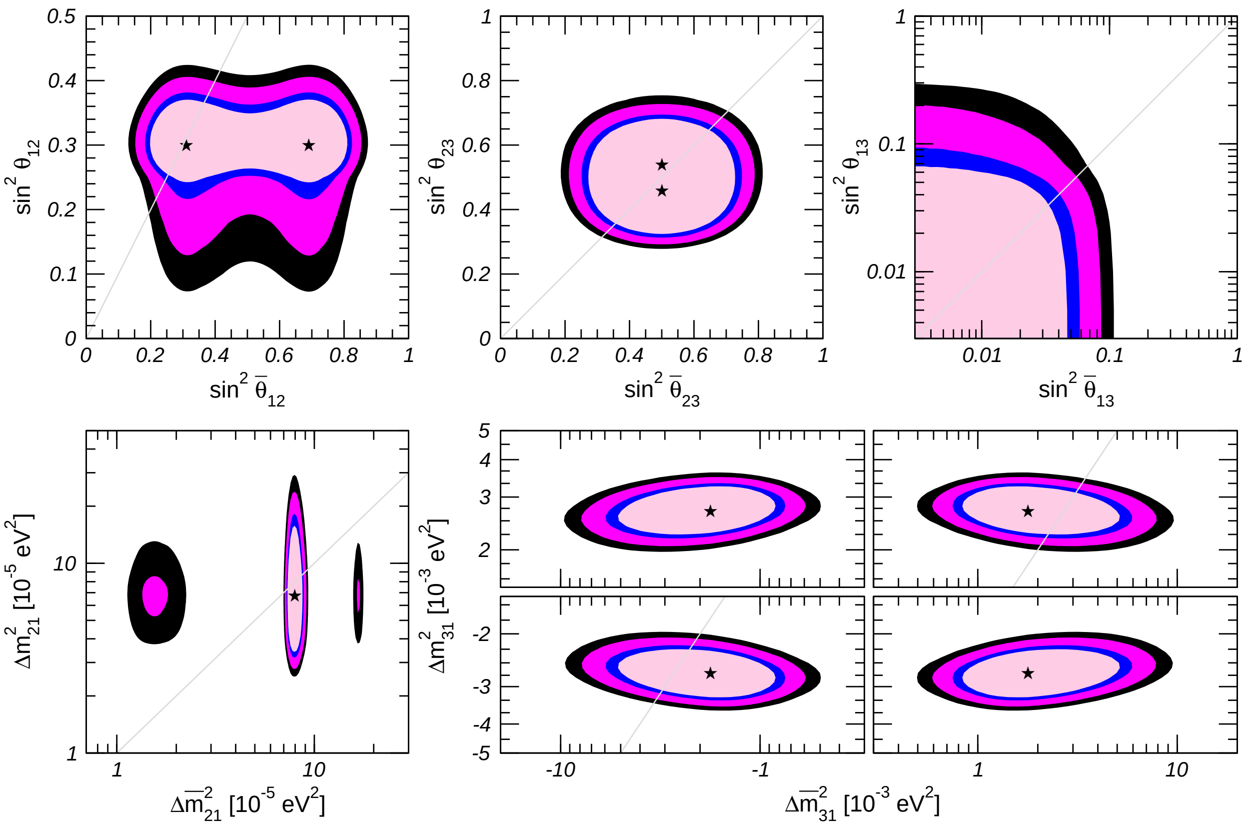


Best fi t near

CPT conservation

Ruled out at $\gtrsim 4\sigma$

LSND III: What it is Claimed to Work

- 3 active plus 2 light sterile neutrino mixing

  Sorel, Conrad and Shaevitz, hep-ph/0305255

- 3 active plus 1 light sterile neutrino mixing plus CPT violation

  Barger, Marfatia and Whisnant hep-ph/0308299

- 3 active plus 1 light sterile neutrino mixing plus MaVaN's interactions

  Barger, Marfatia and Whisnant hep-ph/0509163

- 3 active plus 1 light sterile neutrino mixing plus decay

  Ma, Rajasekaran and Stancu hep-ph/9908489

  Palomares-Ruis,Pascoli and Schewtz, hep-ph/0505216

- 3 active plus 1 light sterile neutrino with extra dimensions

  Pas, Pakvasa and Weiler, hep-ph/0504096

- 3 active plus quantum decoherence (and CPT violation)

  Baremboim,Mavromatos hep-ph/0404014

  Baremboim, Mavromatos, Sarkar and Waldron-Lauda, hep-ph/0603028

Some New Physics in ATM ν -Oscillations

- Oscillations are due to:
  - Misalignment between CC-int and propagation states: Mixing $\Rightarrow$ Amplitude
  - Difference phases of propagation states $\Rightarrow$ Wavelength.

For Δm^2-OSC $\lambda = \frac{4\pi E}{\Delta m^2}$

- ν masses are not the only mechanism for oscillations

Violation of Equivalence Principle (VEP): Gasperini 88, Halprin,Leung 01

Non universal coupling of neutrinos $\gamma_1 \neq \gamma_2$ *to gravitational potential* ϕ

$$\lambda = \frac{\pi}{E|\phi|\delta\gamma}$$

Violation of Lorentz Invariance (VLI): Coleman, Glashow 97

Non universal asymptotic velocity of neutrinos $c_1 \neq c_2 \Rightarrow E_i = \frac{m_i^2}{2p} + c_i p$

$$\lambda = \frac{2\pi}{E\Delta c}$$

Interactions with space-time torsion: Sabbata, Gasperini 81

Non universal couplings of neutrinos $k_1 \neq k_2$ *to torsion strength* Q

$$\lambda = \frac{2\pi}{Q\Delta k}$$

Violation of Lorentz Invariance (VLI) Colladay, Kostelecky 97; Coleman, Glashow 99

due to CPT violating terms: $\bar{\nu}_L^\alpha b_\mu^{\alpha\beta}\gamma_\mu\nu_L^\beta \Rightarrow E_i = \frac{m_i^2}{2p} \pm b_i$

$$\lambda = \pm\frac{2\pi}{\Delta b}$$

Non-standard ν interactions in matter: Wolfenstein 78

$$G_F \varepsilon_{\alpha\beta}(\overline{\nu_\alpha}\gamma^\mu\nu_\beta)(\overline{f}\gamma_\mu f)$$

$$\lambda = \frac{2\pi}{2\sqrt{2}G_f\ N_f\ \sqrt{\varepsilon_{\alpha\beta}^2 + (\varepsilon_{\alpha\alpha} - \varepsilon_{\beta\beta})^2/4}}$$

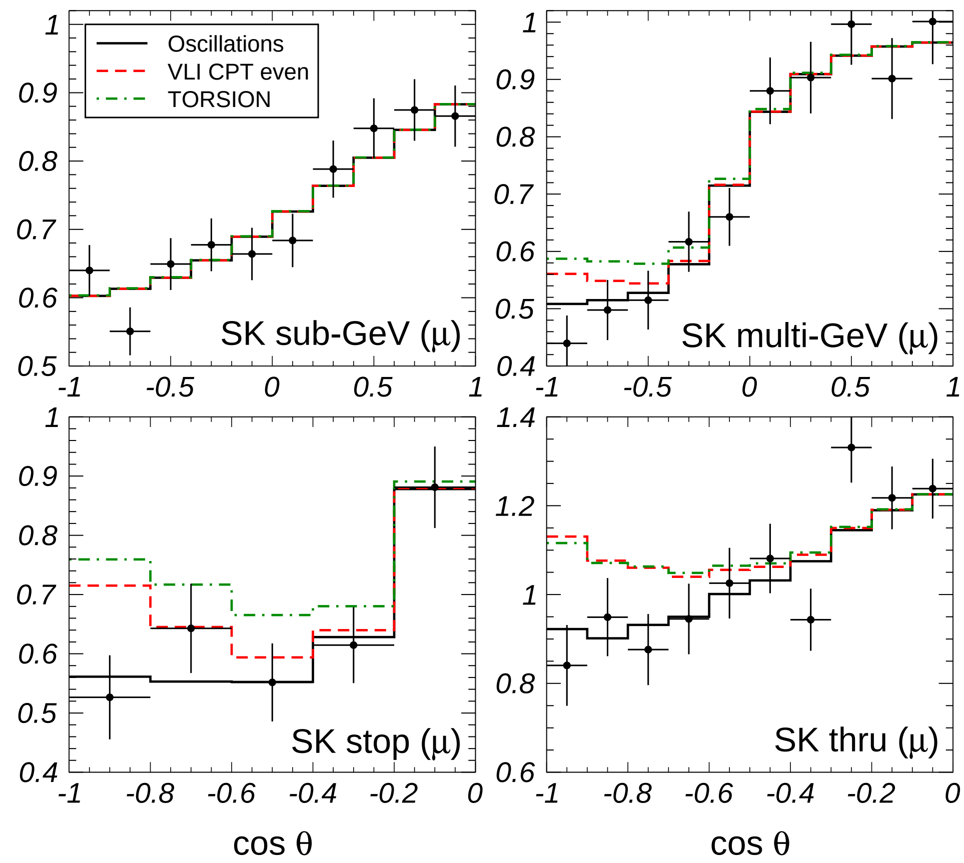
ATM ν's: Subdominant NP Effects

$$P_{\nu_\mu \to \nu_\mu} = 1 - \sin^2 2\Theta \, \sin^2\left(\frac{\Delta m^2 L}{4E}\,\mathcal{R}\right)$$

$$\mathcal{R}\cos 2\Theta = \cos 2\theta + \sum_n R_n \cos 2\xi_n$$

$$\mathcal{R}\sin 2\Theta = \sin 2\theta + \sum_n R_n \sin 2\xi_n \, e^{i\eta_n}$$

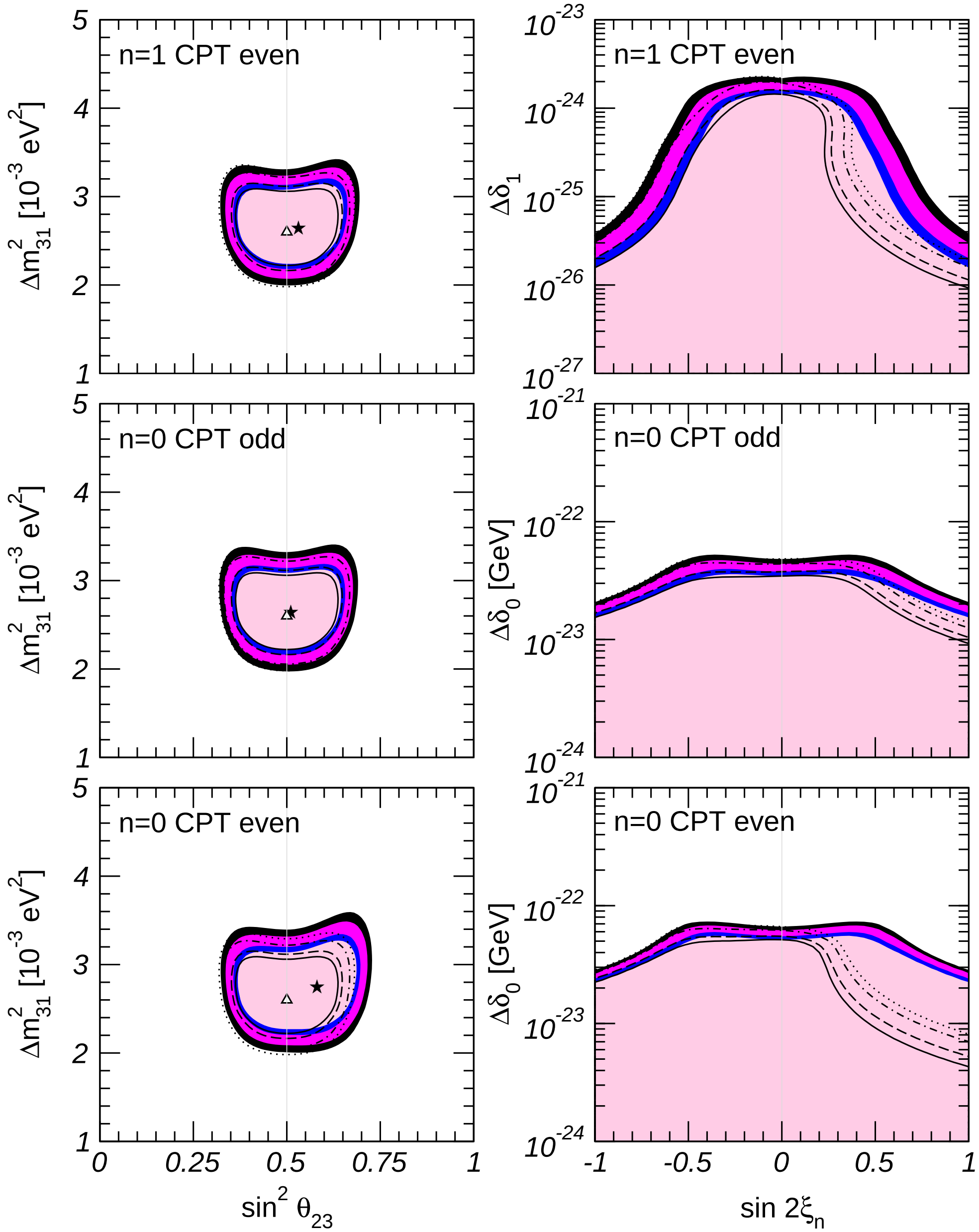
$$R_n = \sigma_n^+ \frac{\Delta\delta_n E^n}{2} \, \frac{4E}{\Delta m^2}$$

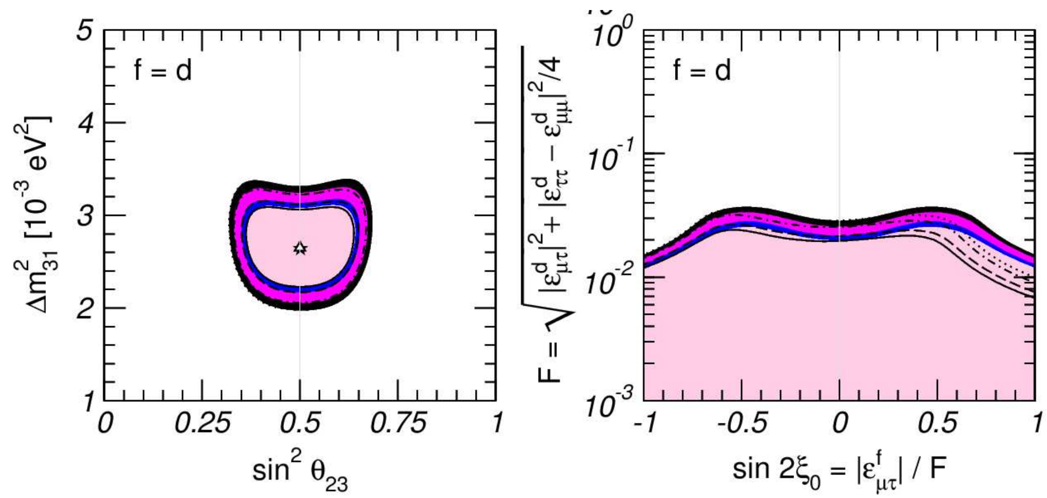


- Questions:
  - Do these effects affect our determination of oscillation parameters?
  - Can we limit these effects?

ATM ν's: Subdominant NP Effects

MCG-G, M. Maltoni 04,07





At 90% CL:

$$\frac{|\Delta c|}{c} \leq 1.2 \times 10^{-24}$$

$$|\phi\, \Delta\gamma| \leq 5.9 \times 10^{-25}$$

$$|\Delta b| \leq 3.0 \times 10^{-23}\ \mathrm{GeV}$$

$$|Q\, \Delta k| \leq 4.8 \times 10^{-23}\ \mathrm{GeV}$$

$$|\varepsilon^d_{\mu\mu} - \varepsilon^d_{\tau\tau}| \leq 0.012$$

$$|\varepsilon^d_{\mu\tau}| \leq 0.038$$

Future Bounds on New Physics: ν Telescopes

At ν Telescopes (Amanda, Antares, IceCube)

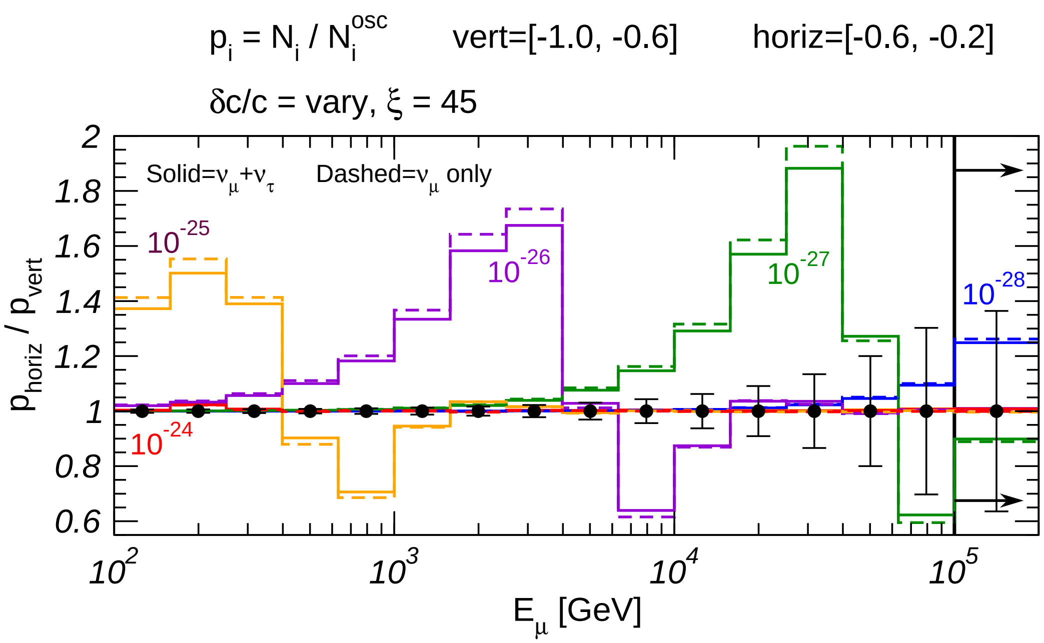
$E_{\nu,thres} \gtrsim 100$ GeV

Large # ATM $\nu' s$

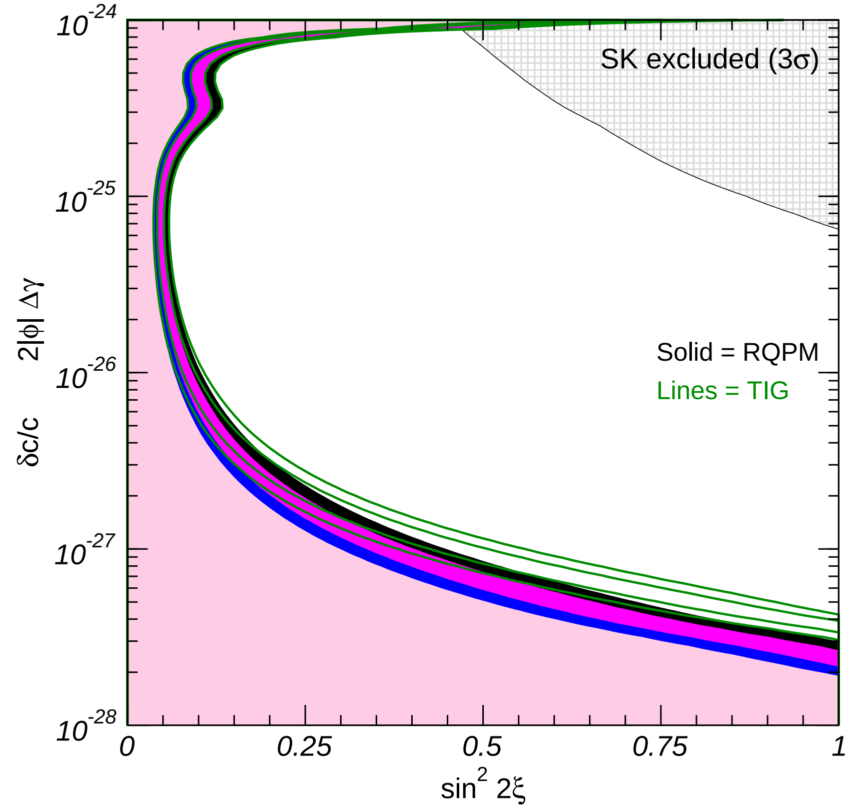
($\sim 10^5 \nu_\mu$ events/yr at ICECUBE)

$\Rightarrow$ Standard oscillations suppressed

$\Rightarrow$ Better sensitivity to Oscillations due to NP



Expected Sensitivity at IceCube



MCG-G, Halzen,Maltoni, 05

Summary

- Big experimental effort has been devoted to proof ν oscillations beyond doubt
- Solar and atmospheric signals are being confirmed with "man-made" neutrino beams from reactor and accelerators.
- Solar, Reactor, Atmospheric and LBL data: Perfect in 3ν-oscillations
- Ambitious experimental program and intense activity of phenomenologists to optimize the path to answer open questions:

  What is the value of θ_{13}?

  Is there CP violation in the leptons

  What is the ordering of the states

  The absolute scale of neutrino mass

  Are neutrinos Dirac or Majorana particles?
- Accommodating LSND: A problem
- ν oscillation data already provides interesting constraints on:

  Fundamental symmetries: LI, WEP, CPT

  ν models for Dark Energy

  Solar Physics . . .