NEUTRINO MASSES AND MIXING ...

and Beyond

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Introduction:

The Parameters of the New Minimal Standard Model

Global 3 ν Mixing Analysis

Update of Leptonic Mixing

Learning about the Fluxes

Constraints on Some Extensions of the NMSM:

Tests of Symmetries: LI, WEP, CPT ...

Mass Varying $\nu's$ in the Sun

And What About LSND?

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

There is no ν_R

$\Rightarrow$ Accidental global symmetry:

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

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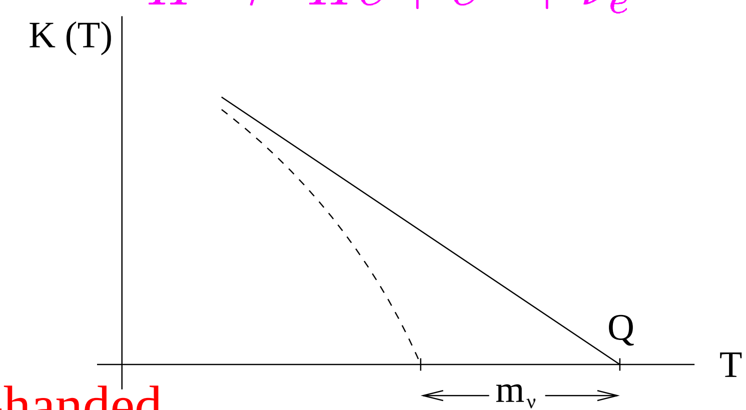
$\Rightarrow$ Accidental global symmetry: $B \times L_e \times L_\mu \times L_\tau$

$\Rightarrow$ **ν *strictly* massless**

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



- When SM was built upper bounds on m_ν

$m_{\nu_e} < 2.2$ eV

$m_{\nu_\mu} < 190$ KeV $\quad (\pi \rightarrow \mu\nu_\mu)$

$m_{\nu_\tau} < 18.2$ MeV $\quad (\tau \rightarrow n\pi\nu_\tau)$

- Neutrinos are conjured to be massless and left-handed

- 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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- Minimal Extensions to give Mass to the Neutrino:

  $*$ Introduce ν_R AND impose L conservation $\Rightarrow$ Dirac ν : ($\nu \neq \nu^C$)

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

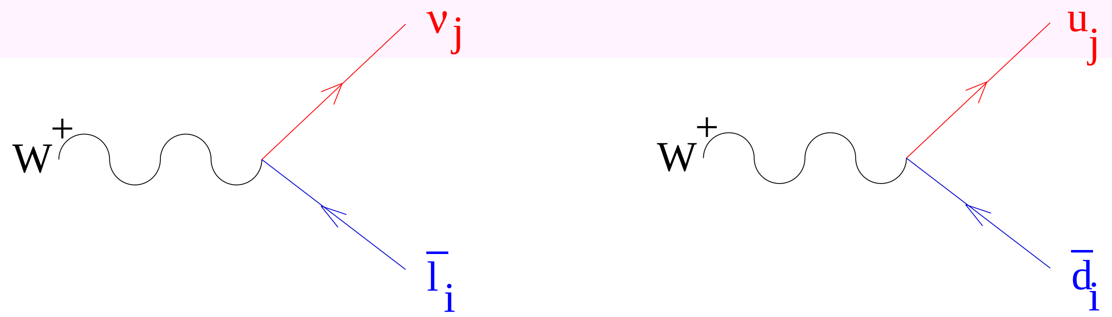
  $*$ NOT impose L conservation $\Rightarrow$ Majorana ν ($\nu = \nu^C$)

$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{2} M_\nu \overline{\nu_L} \nu_L^C + h.c.$$

Effects of ν Mass

- Neutrino masses must have kinematic effects at some level
- The charged current interactions of leptons are not diagonal (same as quarks)

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



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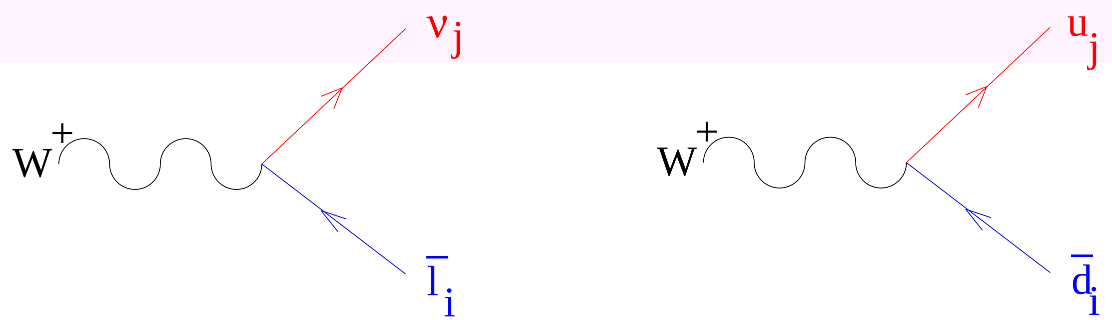


- For example for 3 ν's : 3 Mixing angles + 1 Dirac Phase + +Majorana Phases

$$U_{\rm LEP} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13} e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{21} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\phi_2} & 0 \\ 0 & 0 & e^{i\phi_3} \end{pmatrix}$$

- SM gauge invariance *does not imply* $U(1)_{L_e} \times U(1)_{L_\mu} \times U(1)_{L_\tau}$ symmetry
- Total lepton number $U(1)_L = U(1)_{Le+L_\mu+L_\tau}$ can be or cannot be still a symmetry depending on whether neutrinos are Dirac or Majorana

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

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

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

- $P_{\alpha\beta}$ depends on Theoretical Parameters
  - $\Delta m^2_{ij} = m_i^2 - m_j^2$ The mass differences
  - $U_{\alpha j}$ The mixing angles (and Dirac phases)

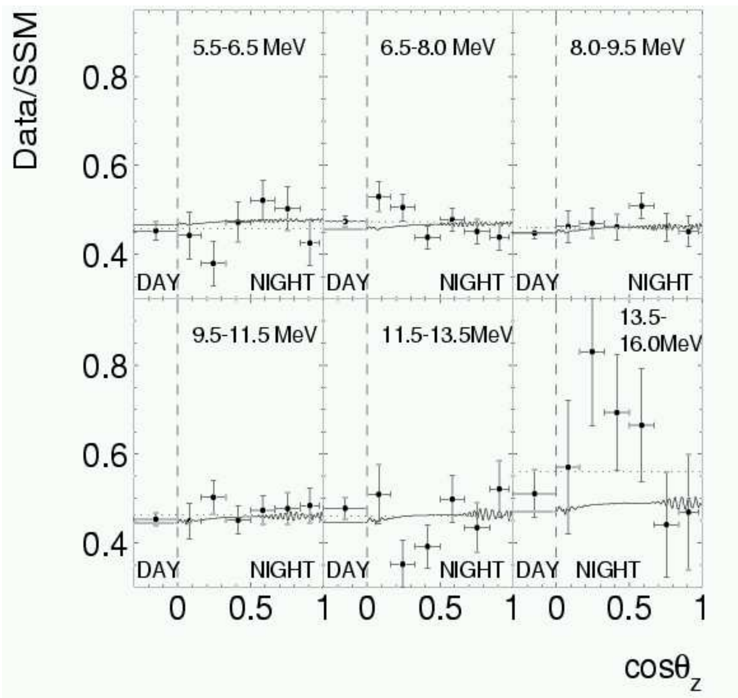
  and on Two *Experimental* Parameters:
  - E The neutrino energy
  - L Distance ν source to detector

No information on mass scale nor Majorana versus Dirac ν nature

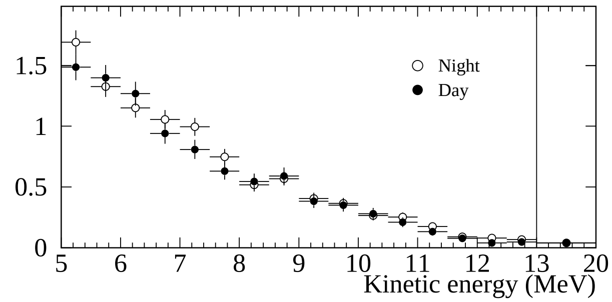
Global Fits: Solar Neutrinos

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

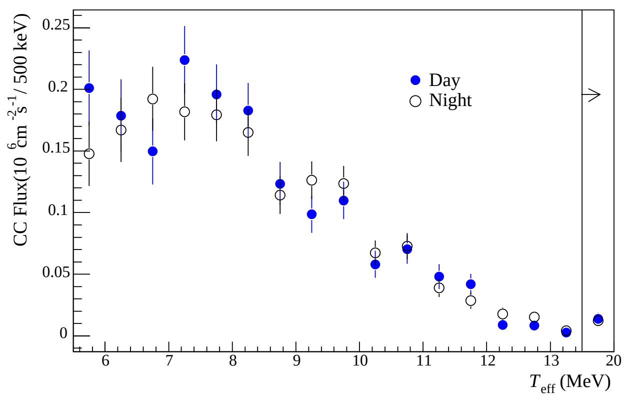
* SK Zenith spectrum (44 Data points)



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



* SNO Ph-II CC D-N Spec (34 Points)



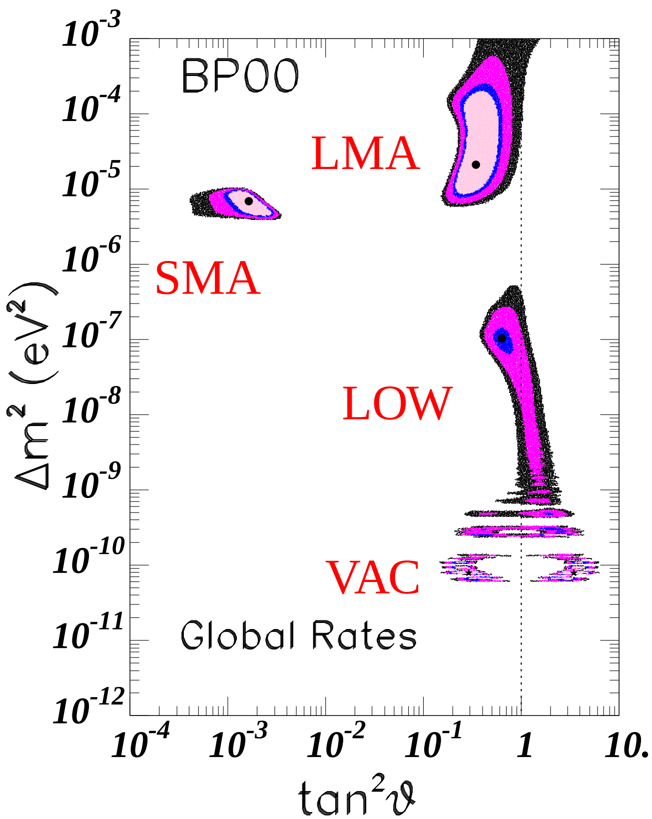
* SNO Ph-II ES, NC D&N Fluxes (4)

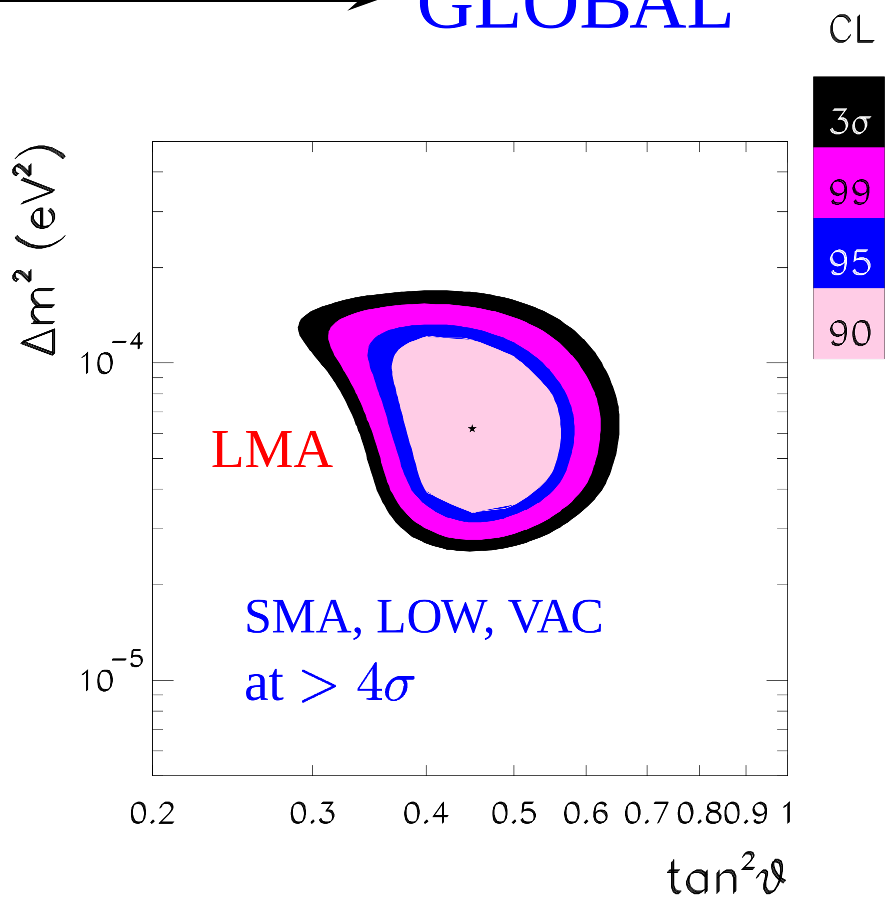
$$\phi^{\rm SNO}_{\rm ES,D} = 2.17 \pm 0.34 \pm 0.14 \qquad \phi^{\rm SNO}_{\rm ES,N} = 2.52 \pm 0.32 \pm 0.16$$

$$\phi^{\rm SNO}_{\rm NC,D} = 4.81 \pm 0.31 \pm 0.39 \qquad \phi^{\rm SNO}_{\rm NC,N} = 5.02 \pm 0.29 \pm 0.16$$

Solar Neutrinos: Oscillation Solutions

RATES ONLY —SK and SNO E and t dependence→ GLOBAL





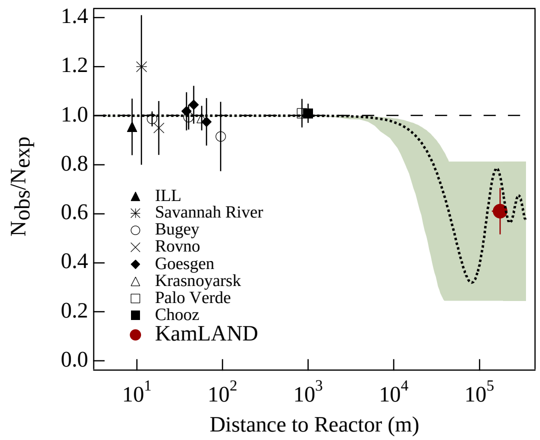
$$\Delta m^2 = \left(6.3^{+2.3}_{-1.9}\right) \times 10^{-5}\ \mathrm{eV}^2\ (1\sigma)$$

$$\tan^2\theta = 0.45^{+0.05}_{-0.04}$$

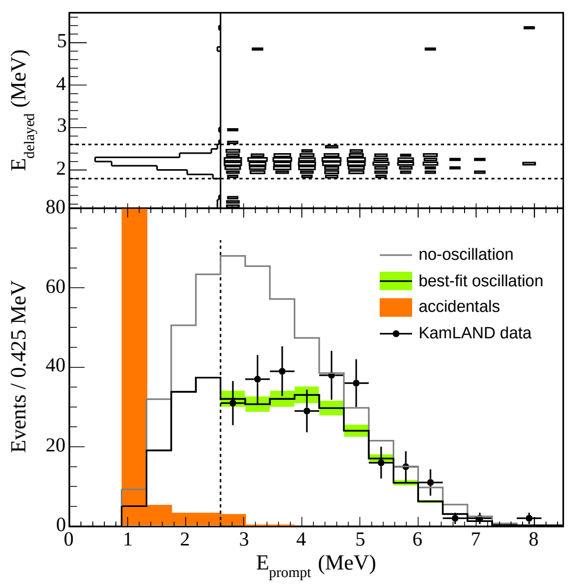
Terrestrial Test of LMA: KamLAND

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

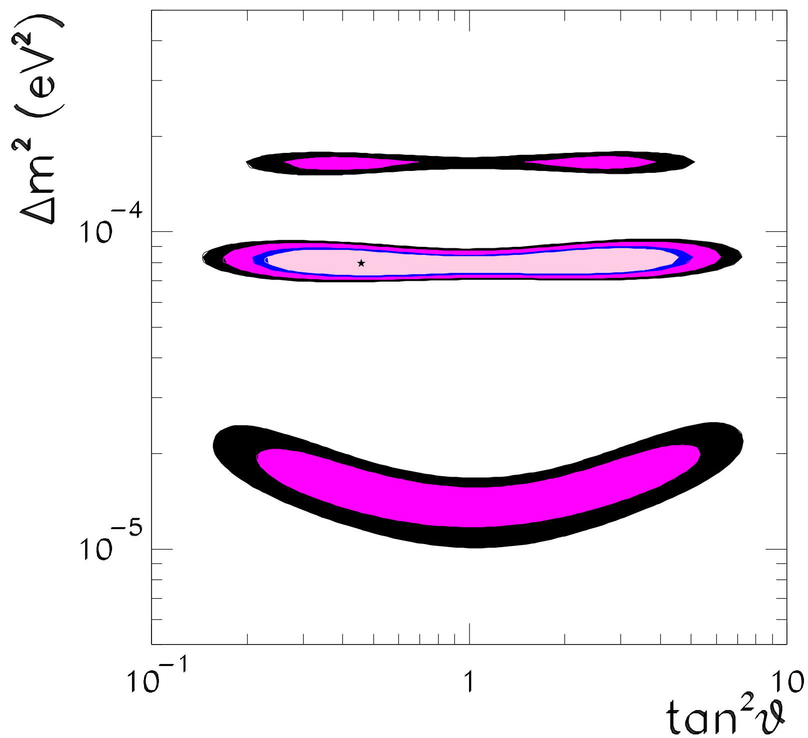
2002: Deficit $R_{\rm KLAND} = 0.611 \pm 0.094$



2004: Significant Energy Distortion



Oscillation Analysis

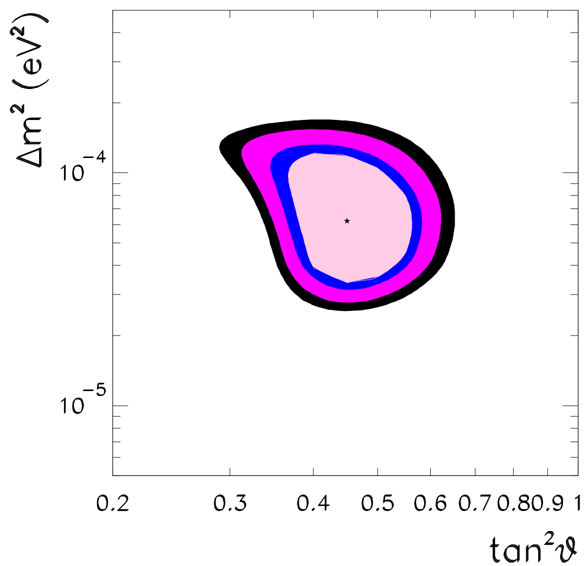


$$\Delta m^2 = (7.9^{+0.4}_{-0.3}) \times 10^{-5}\ {\rm eV}^2\ (1\sigma)$$

$$\tan^2\theta = 0.46^{+0.20}_{-0.15} \quad (2.2^{+1.0}_{-0.6})$$

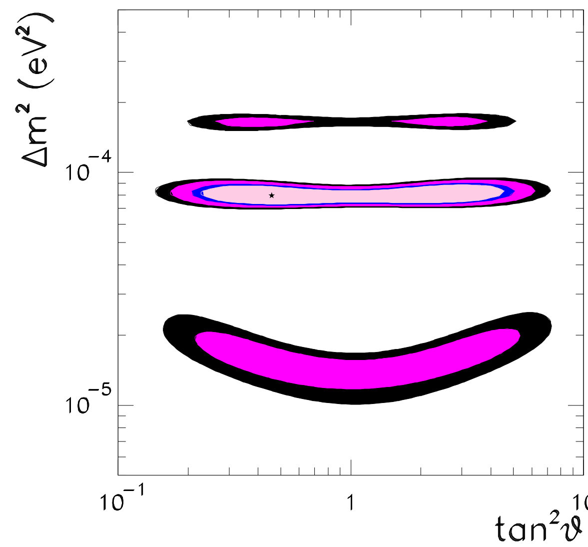
Solar

$\nu_e \to \nu_{\mathrm{active}}$



+ KamLAND

$\bar{\nu}_e \not\to \bar{\nu}_e$



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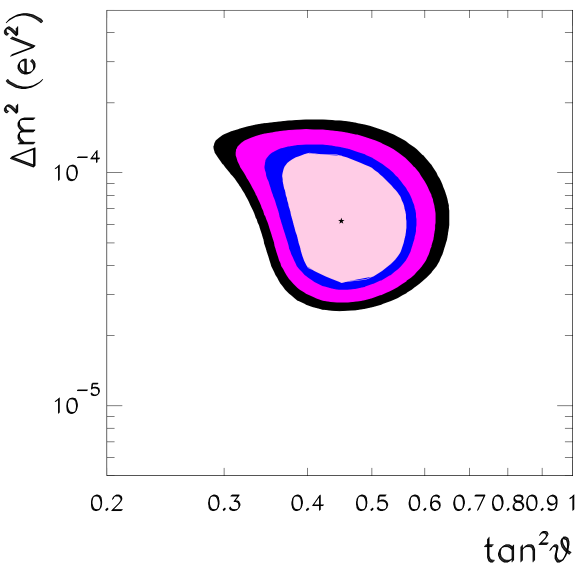

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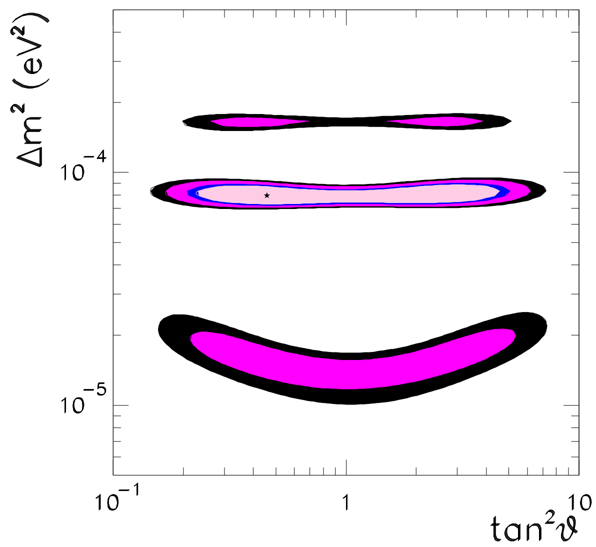
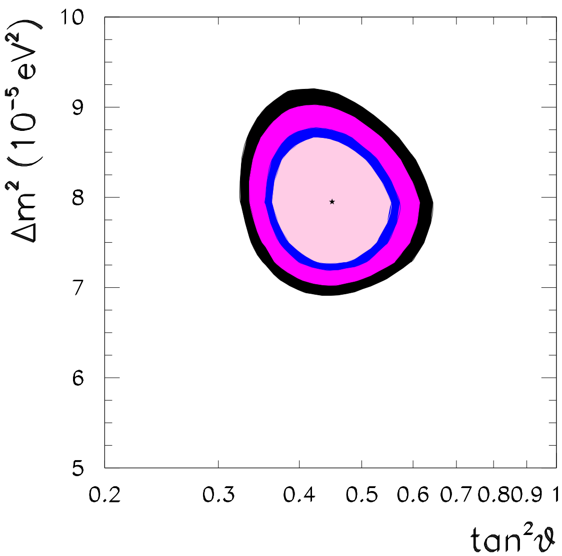


ν_e oscillation parameters compatible with $\overline{\nu}_e$: *Sensible* to assume CPT: $P_{ee} = P_{\bar{e}\bar{e}}$



$$\Delta m^2_\odot = \left(8^{+0.4}_{-0.5}\right) \times 10^{-5}\ \text{eV}^2 \quad (1\sigma)$$
$$\tan^2\theta_\odot = 0.45^{+0.05}_{-0.05}$$

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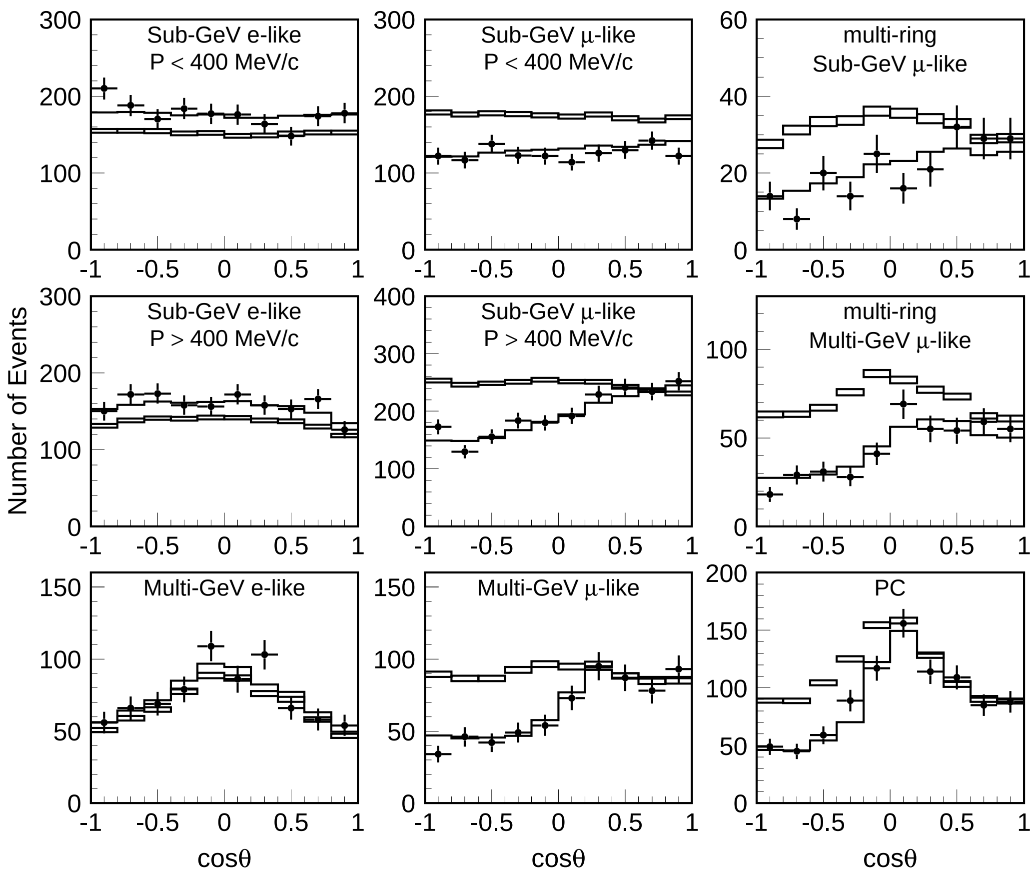
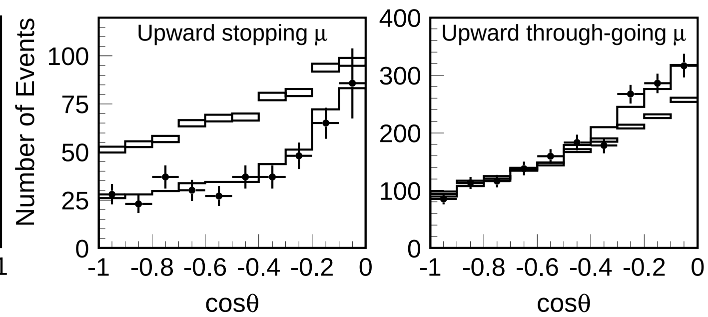
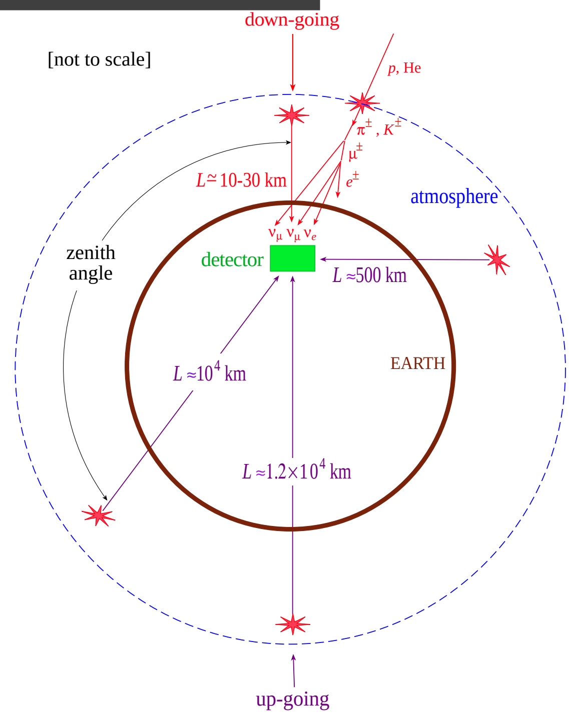
Atmospheric Neutrinos

- Complete SKI data:

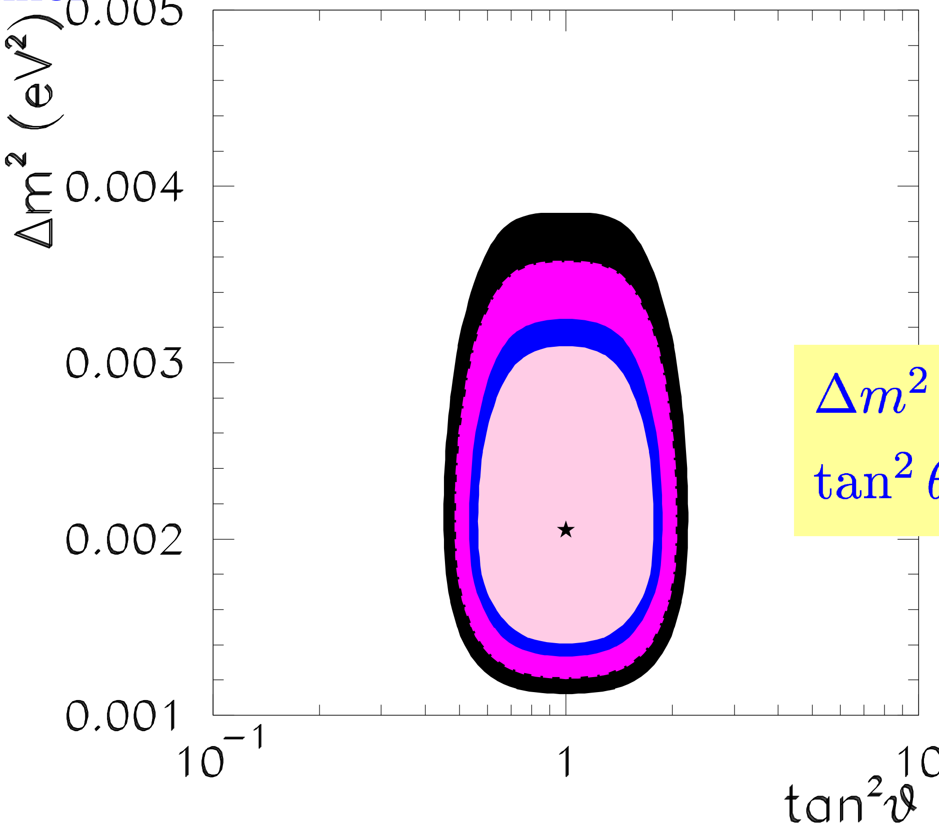






Atmospheric Neutrinos: Oscillation Solutions

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



$$\Delta m^2 = \left(2.05^{+0.4}_{-0.4}\right) \times 10^{-3}\, \mathrm{eV}^2$$

$$\tan^2\theta = 1^{+0.38}_{-0.27}$$

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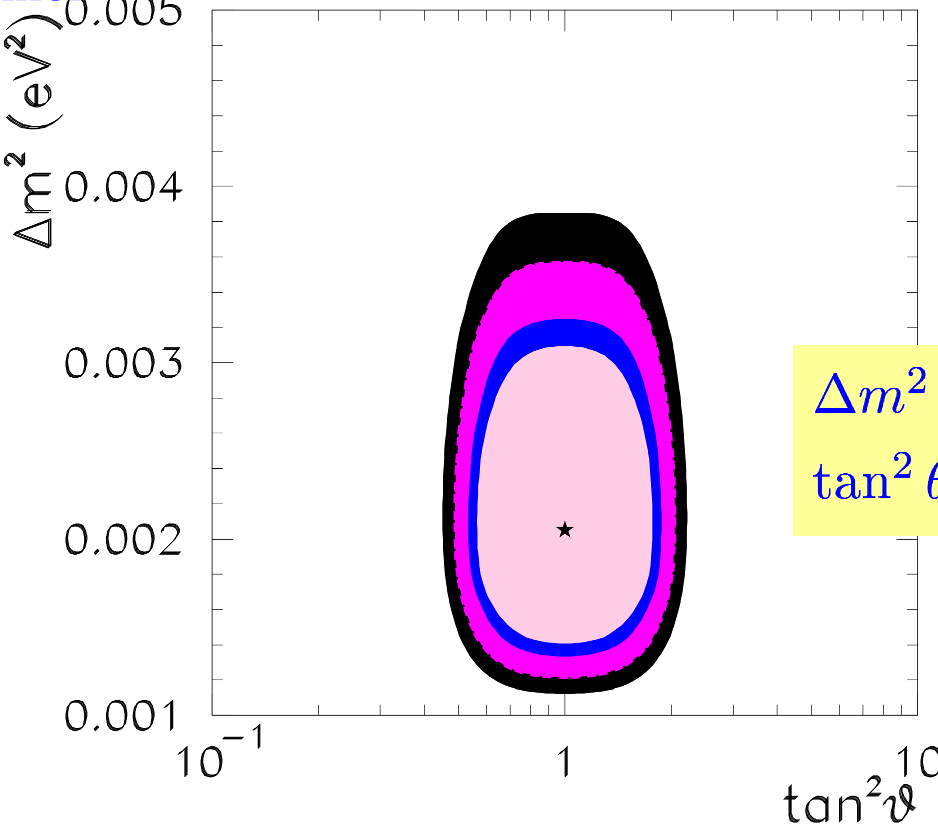

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$$\tan^2\theta = 1^{+0.38}_{-0.27}$$

- $\nu_\mu \to \nu_{\rm e}$: Excluded at $\gtrsim 5\sigma$ (Bad fit to observed SM like ν_e distributions)

  Strongly limited subdominant contribution in 3ν mixing because of CHOOZ

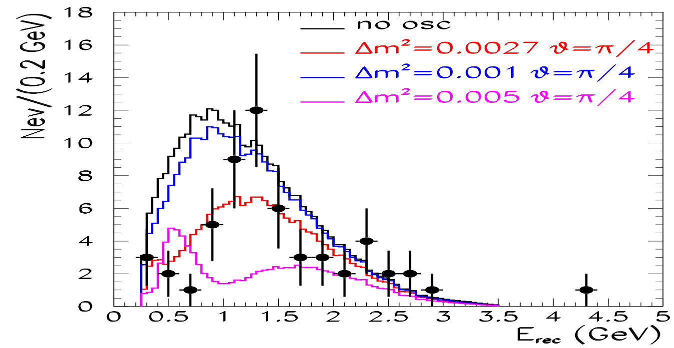
- $\nu_\mu \to \nu_{\rm sterile}$: Disfavoured at $\gtrsim 3\sigma$ (Matter effects $\Rightarrow$ Flatter upgoing-μ distribution)

  Limited subdominant contribution in 4ν mixing

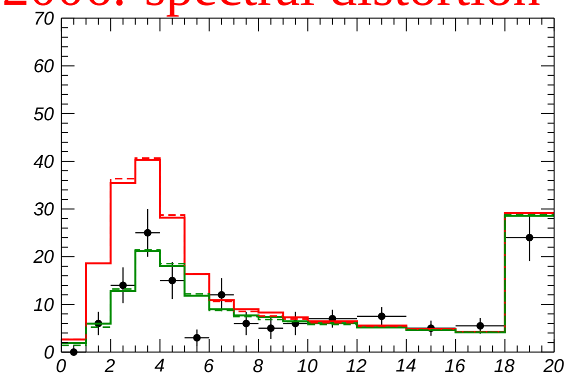
ATM Test at Long Baseline Experiments

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

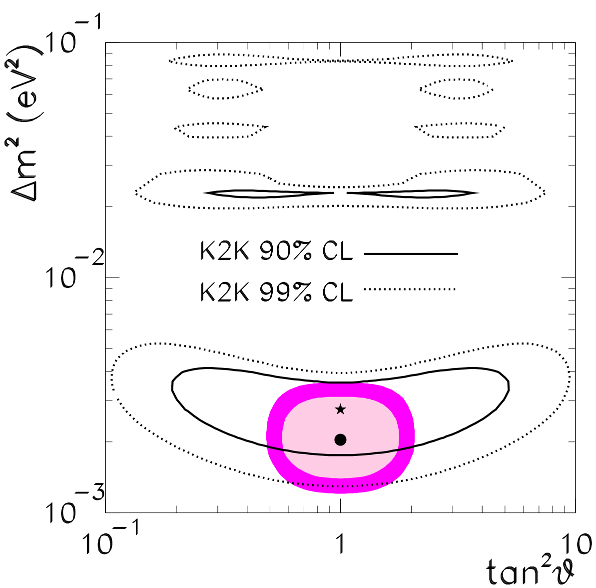
K2K 2004: spectral distortion



MINOS 2006: spectral distortion



Confirmation of ATM oscillations



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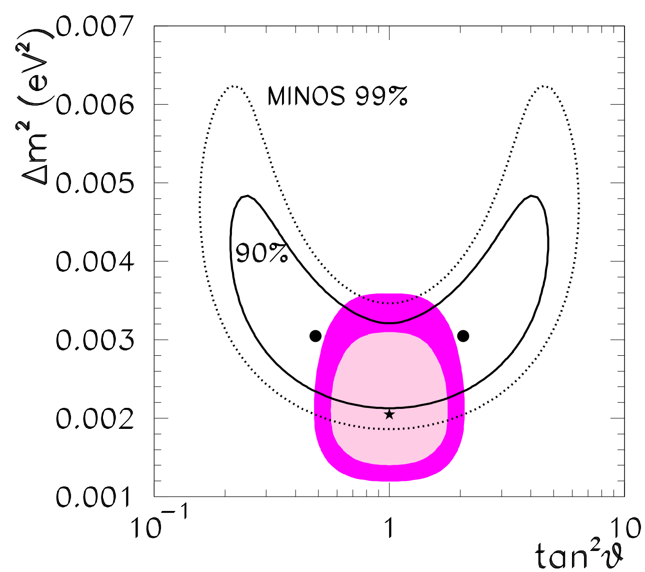
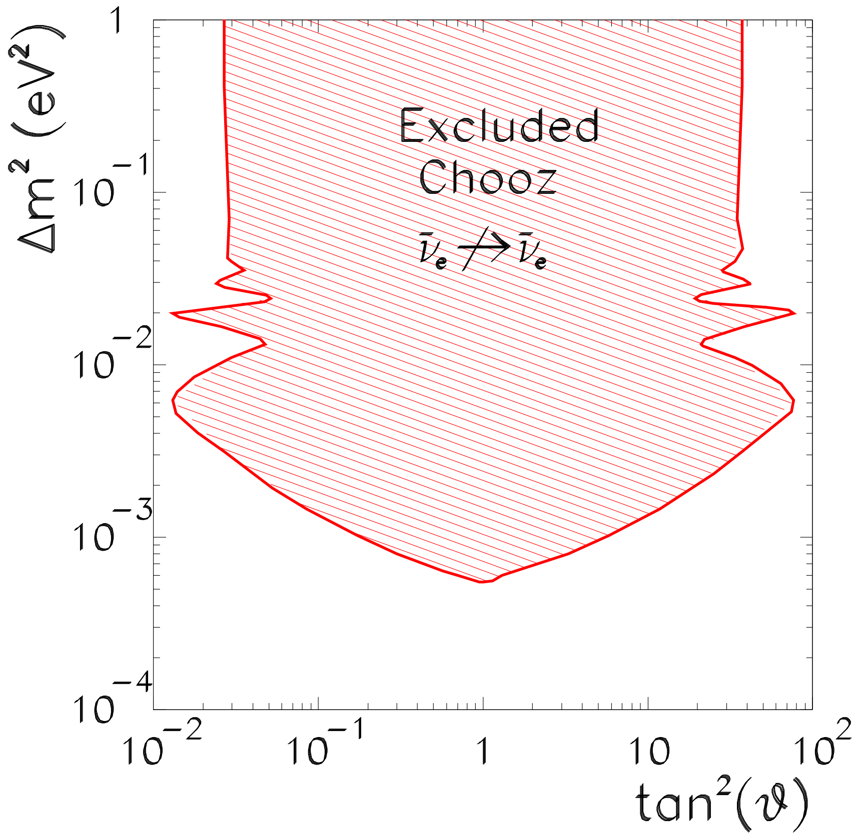


CHOOZ

Negative search with $\overline{\nu_e}$ source: Nuclear Reactor at $L \sim 1$ km

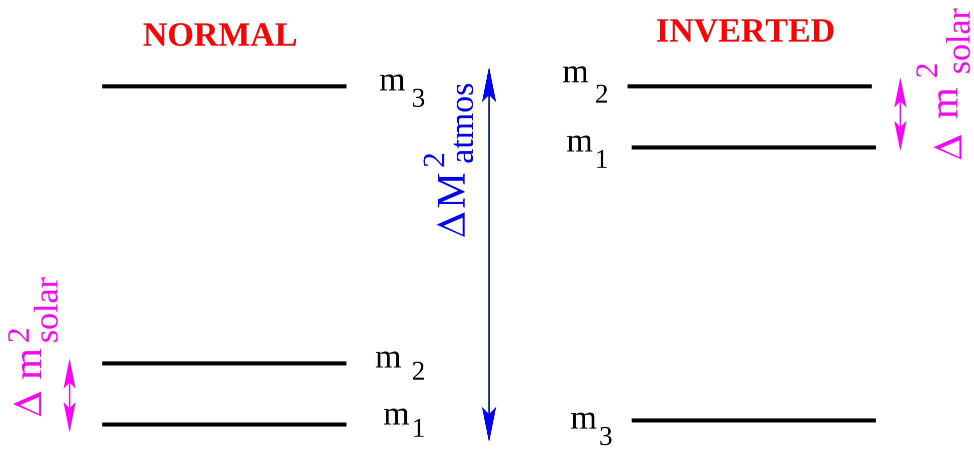


Solar+Atmospheric+Reactor+LBL 3ν Oscillations

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

- In the Hierarchical approximation $\Delta m^2_\odot \ll \Delta M^2_{atm}$

∗ For $\theta_{13} = 0$ solar and atmospheric oscillations decouple $\Rightarrow$ Normal$\equiv$ Inverted

  – Solar and KamLAND $\rightarrow \Delta m^2_{21} = \Delta m^2_\odot \quad \theta_{12} = \theta_\odot$

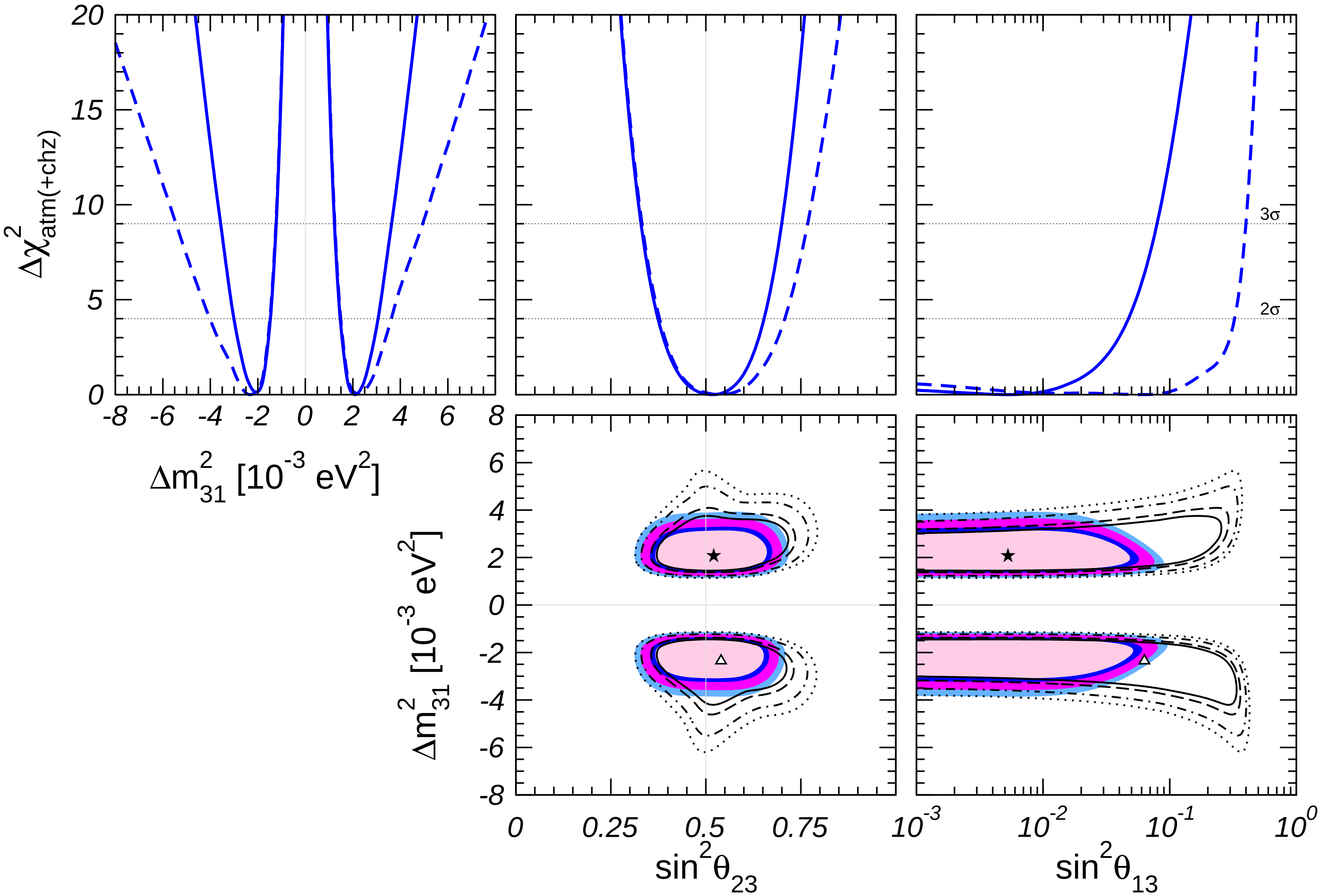
  – Atmospheric and K2K $\rightarrow \Delta m^2_{31} = \Delta M^2_{atm} \quad \theta_{23} = \theta_{atm}$

$*$ For $\theta_{13} \neq 0$

– CHOOZ: $P_{ee}^{CH} \simeq 1 - 4c_{13}^2 s_{13}^2 \sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right)$ $|\Delta m_{31}^2| \gtrsim 8 \times 10^{-4}$ eV^2 $\Rightarrow$ limit on θ_{13}

– Atmos : Independent of θ_{12}, Δm_{21}^2. $\theta_{13} \Rightarrow$ some $\nu_\mu \to \nu_e \Rightarrow$ Limit on θ_{13}

Thanks to Michele Maltoni



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– Atmos & K2K

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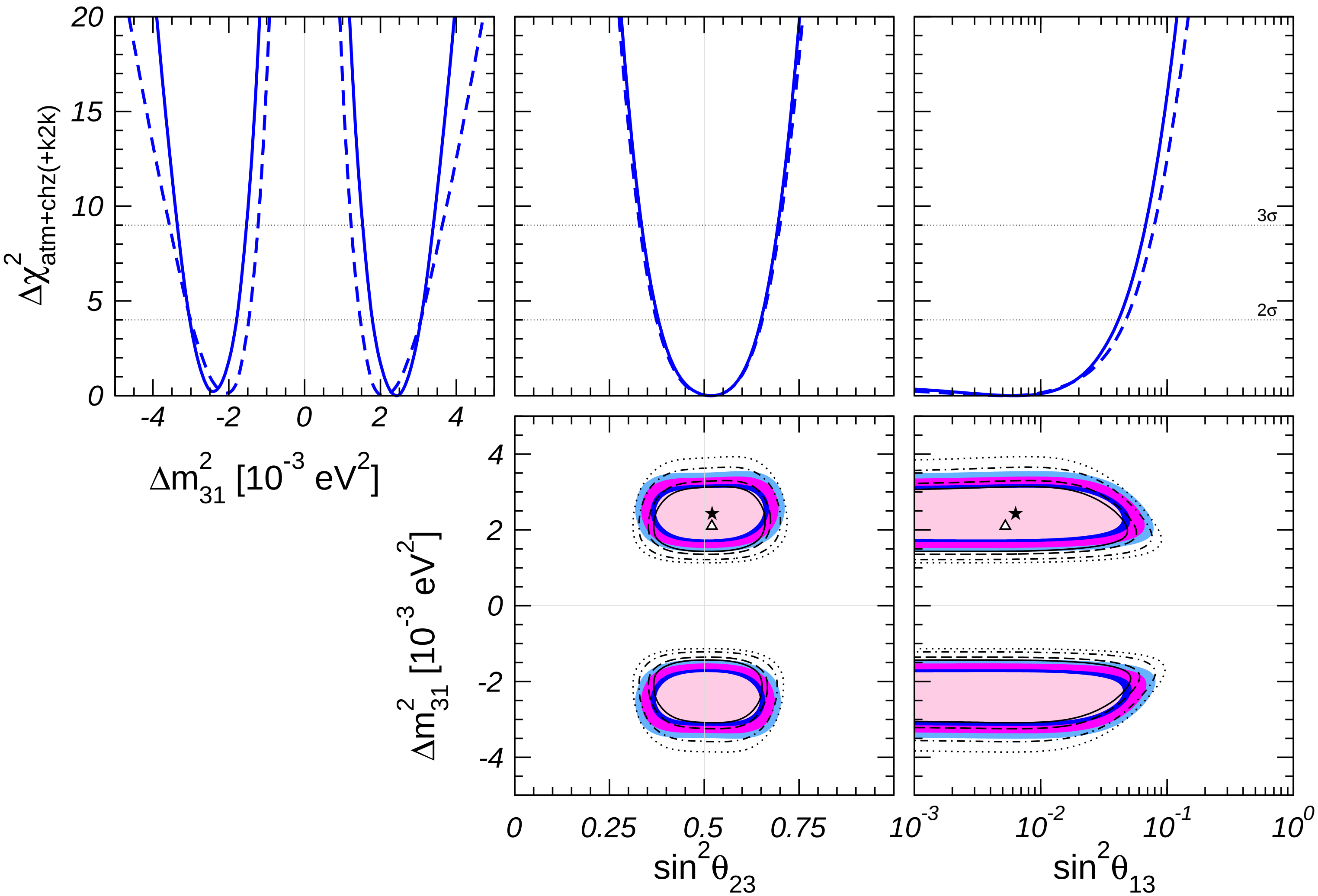
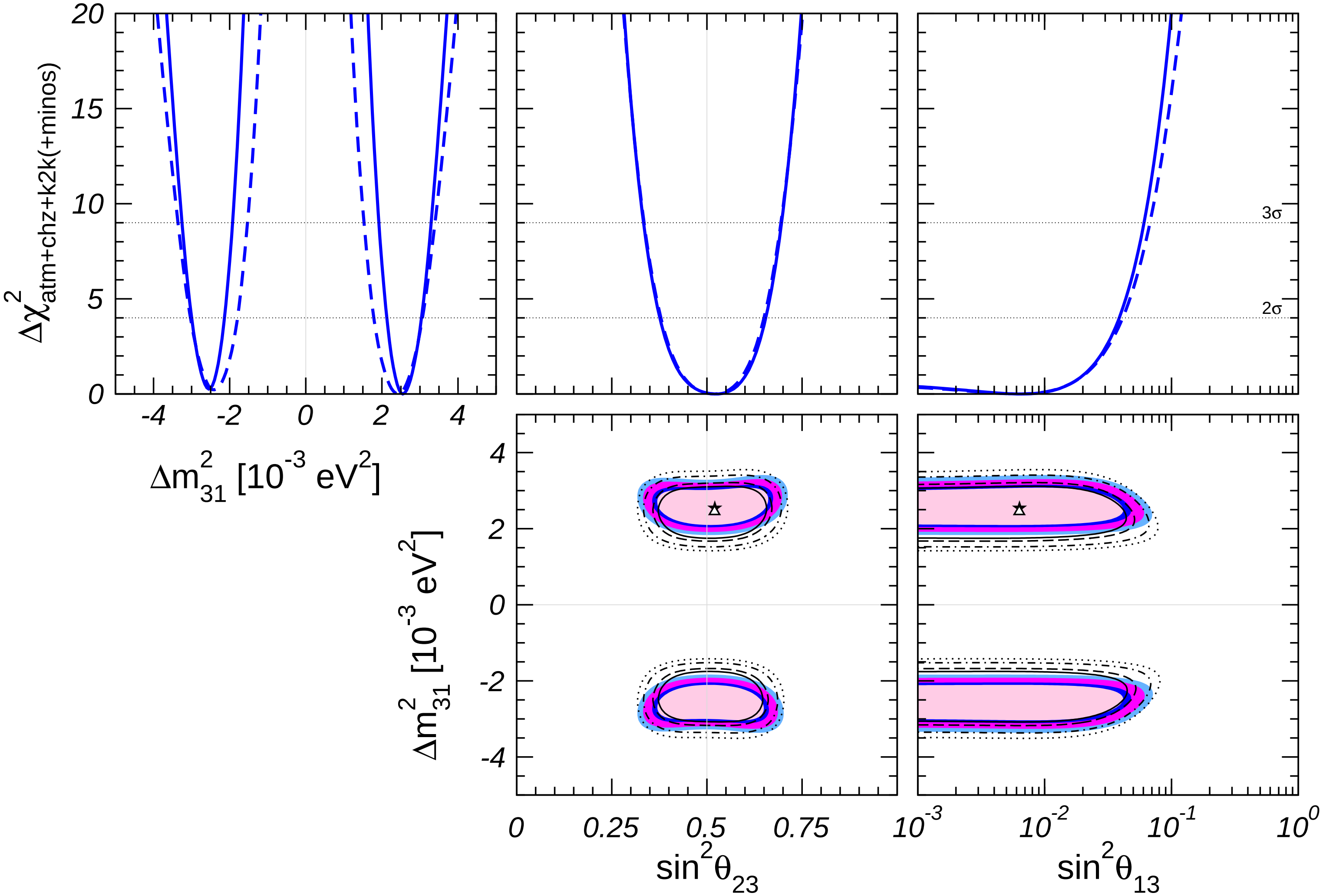


$*$ For $\theta_{13} \neq 0$

– CHOOZ: $P_{ee}^{CH} \simeq 1 - 4 c_{13}^2 s_{13}^2 \sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right)$ $|\Delta m_{31}^2| \gtrsim 8 \times 10^{-4}$ eV^2 $\Rightarrow$ limit on θ_{13}

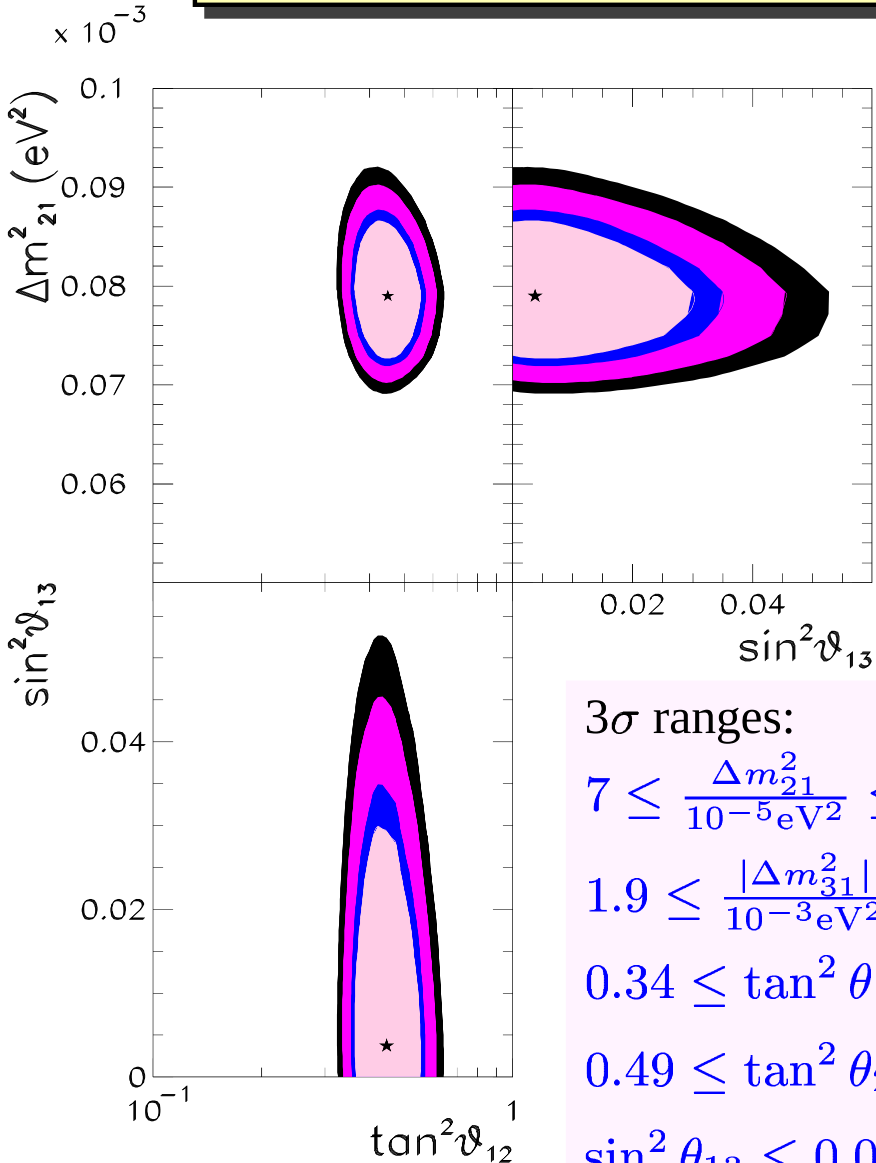
– Atmos & K2K &MINOS: some $\nu_\mu \to \nu_e \Rightarrow$ Limit on θ_{13}

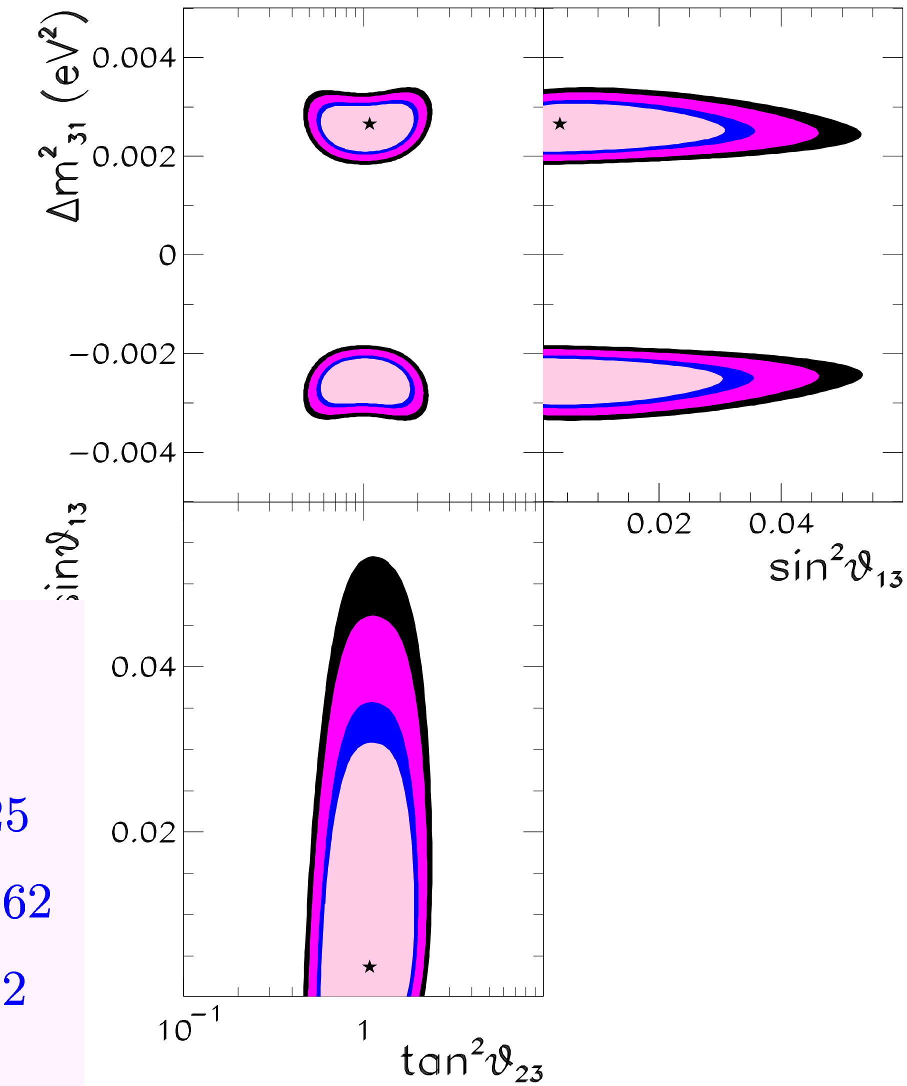
Thanks to Michele Maltoni



– Solar and KamLAND: $P_{ee}^{3\nu} = c_{13}^4 P_{ee}^{2\nu}(\Delta m_{12}^2, \theta_{12}) + s_{13}^4 \Rightarrow$ Further limit on θ_{13}

Global Analysis: Three Neutrino Oscillations





3σ ranges:

$$7 \leq \frac{\Delta m^2_{21}}{10^{-5}\mathrm{eV}^2} \leq 9.1$$

$$1.9 \leq \frac{|\Delta m^2_{31}|}{10^{-3}\mathrm{eV}^2} \leq 3.25$$

$$0.34 \leq \tan^2\theta_{12} \leq 0.62$$

$$0.49 \leq \tan^2\theta_{23} \leq 2.2$$

$$\sin^2\theta_{13} \leq 0.045$$

$$|U_{\mathrm{LEP}}| = \begin{pmatrix} 0.79-0.86 & 0.50-0.61 & <0.20 \\ 0.19-0.53 & 0.39-0.72 & 0.58-0.82 \\ 0.22-0.55 & 0.43-0.74 & 0.55-0.81 \end{pmatrix}$$

Global Analysis: Three Neutrino Oscillations

At 3σ

$$|U_{\rm LEP}| = \begin{pmatrix} 0.79-0.86 & 0.50-0.61 & <0.20 \\ 0.19-0.53 & 0.39-0.72 & 0.58-0.82 \\ 0.22-0.55 & 0.43-0.74 & 0.55-0.81 \end{pmatrix}$$

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

At 1 σ

$$\lambda = \mathcal{O}(0.2)(1\pm 10\%) \quad \Delta = \mathcal{O}(0)\pm 10\% \quad \epsilon \leq 0.12 \quad -1 \leq \cos\delta \leq 1$$

Learning How the Sun Shines

– Solar ν experiments measure a convolution $Obs_\odot = P^{\rm sun}_{eX} \otimes$ Sun Properties

– KamLAND determines independently $P^{\rm vac}_{eX}(\text{osc param}) \Rightarrow P^{\rm sun}_{eX}(\text{osc param})$

$\Rightarrow$ Back to study Sun Properties from $Obs_\odot$

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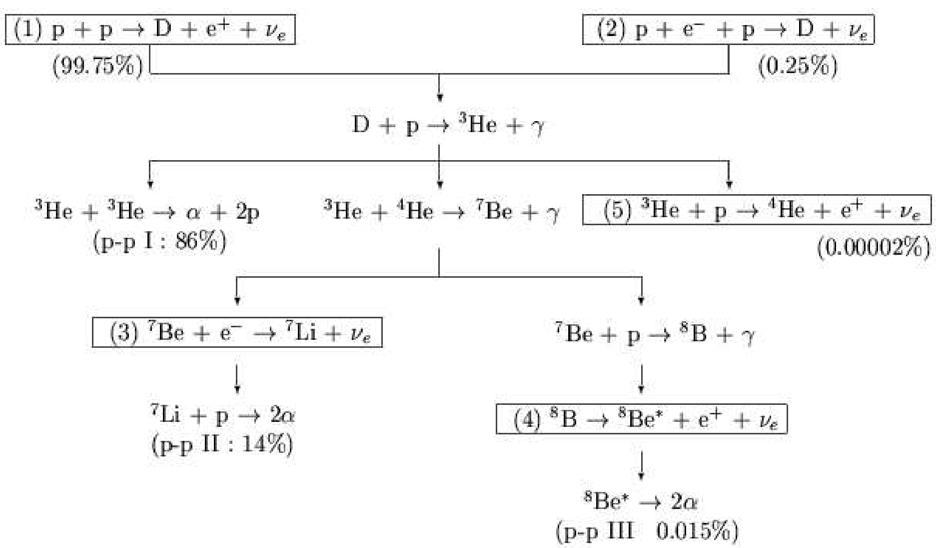
$\Rightarrow$ Back to study Sun Properties from $Obs_{\odot}$

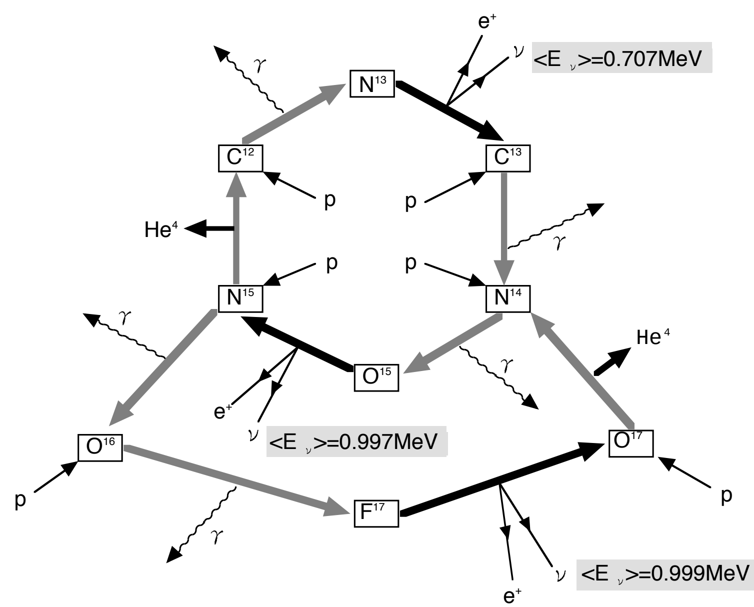
- The Sun shines converting protons into α, e^+ and $\nu' s$

$$4\,p \;\rightarrow\; {}^4He \;+\; 2\,e^+ \;+\; 2\,\nu_e \;+\; \gamma$$

$4m_p - m_{^4He} - 2m_e \simeq 26$ MeV Thermal energy mostly in γ

pp chain: CNO cycle:



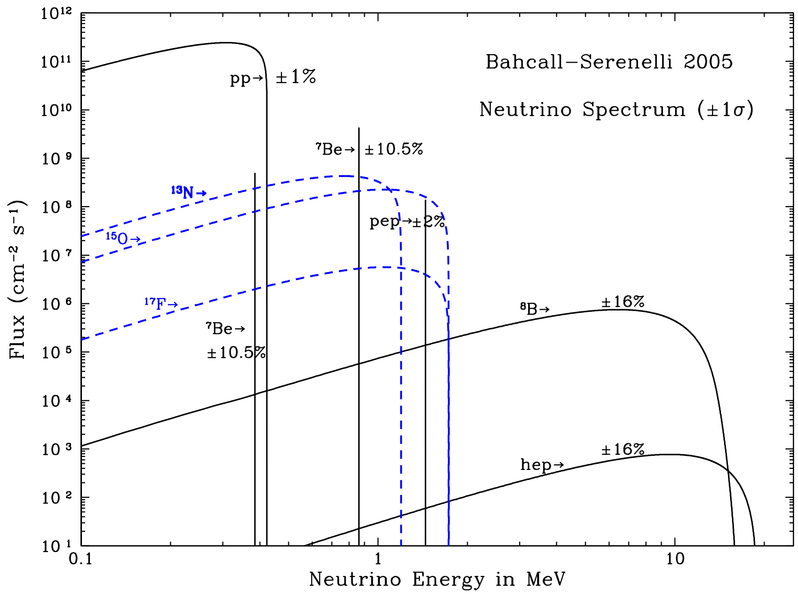


- First proposal by Bethe (1939) was that CNO dominated

" It is shown that the most important source of energy in ordinary stars is the reactions of carbon and nitrogen with protons."

- Improved Solar Model& nuclear reaction data $\Rightarrow$ Sun shines primarily by p-p

- SSM Fluxes



$$\frac{L_{CNO}}{L_\odot} = 1.5\%$$

$$\frac{L_{p-p}}{L_\odot} = 98.5\%$$

- Can this be tested experimentally?

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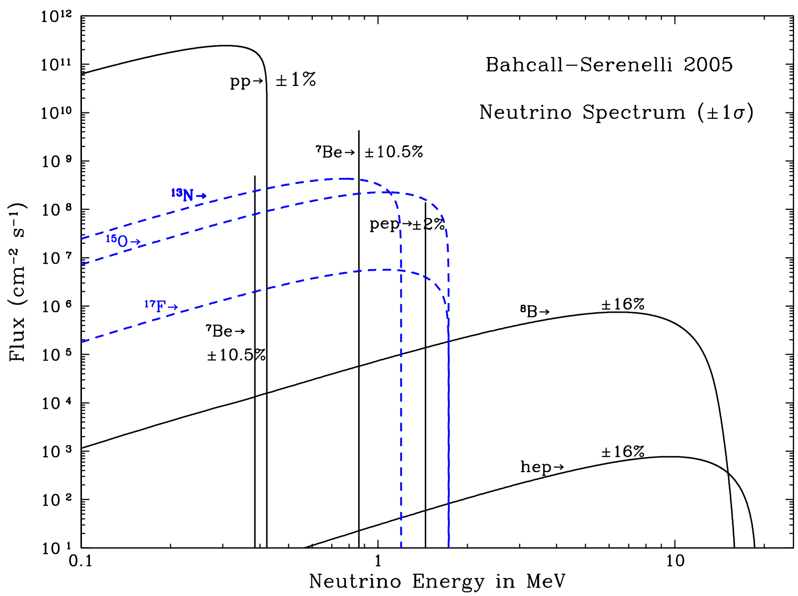

$$\frac{L_{CNO}}{L_\odot} = 1.5\%$$

$$\frac{L_{p-p}}{L_\odot} = 98.5\%$$

- Can this be tested experimentally? Difficult

– Radiochemical experiments sensitive to CNO fluxes

But do not measure $E \Rightarrow$ only integrated flux above E_{th}

– Oscillations modify the E dependence of detected fluxes

$\Rightarrow$ Possible suppression of CNO fluxes $\Rightarrow$ TILL RECENTLY, ANSWER: No limit

How the Sun Shines? Present Answer

Bahcall, MCG-G, Peña-Garay, astro-ph/0212331

- Fit solar (and KamLAND) data for:
  - 2ν oscillations Δm^2, $\tan^2\theta$ + 8 free solar ν fluxes under Luminosity constraint

$$\frac{L_\odot}{4\pi(A.U.)^2} = \sum_{i=1}^{8} \alpha_i \Phi_i \qquad \alpha_i \equiv \text{Energy released in reaction i}$$

- Study the quality of fit as a function of: $$L_{CNO} = \sum_{i=N,O,F} \alpha_i \Phi_i$$

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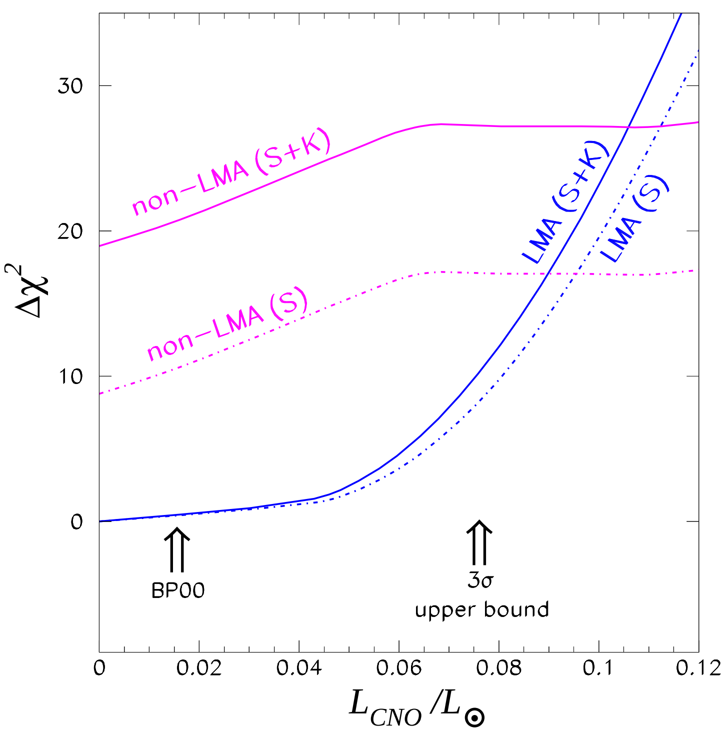

Resulting Limit:

$$\frac{L_{\rm CNO}}{L_\odot} < 7.3\%$$

Testing the Solar Luminosity with Neutrinos

$$\frac{L_\odot(\nu - \text{inferred})}{L_\odot} = 1.4^{+0.2}_{-0.3}\left({}^{+0.7}_{-0.6}\right)$$

Concha Gonzalez-Garcia

Learning About ATM Fluxes

In ATM analysis one uses that the expected number of ATM ν events

$$N_\beta = n_t T \sum_\alpha \int \frac{d^2\Phi_\alpha}{dE_\nu d\cos\theta_\nu} \kappa_\alpha(h) \frac{d\sigma}{dE_{l,beta}} \varepsilon(E_\nu, E_{l,\beta}) dE_\nu dE_{l,\beta} P_{\alpha\beta}(E_\nu, \cos\theta)) d\cos\theta_\nu dh$$

$\Phi_\alpha \equiv \text{Neutrino Flux}$

$\frac{d\sigma}{dE_{l,\beta}} \equiv \text{Neutrino Interaction Cross Section}$

$P_{\alpha\beta}(E_\nu, \cos\theta)) \equiv \text{Oscillation Probability}$

$\kappa_\alpha \equiv \nu \text{ Production Point Distribution}$

$\varepsilon(E_\nu, E_{l,\beta}) \equiv \text{Detection Efficiency}$

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The ATM fluxes are inputs given by several groups. Schematically:

Bartol Group: Barr, Gaisser, Lipari, Robbins Stanev
Honda Group: Honda, Kajita, Kasahara, Midorikawa

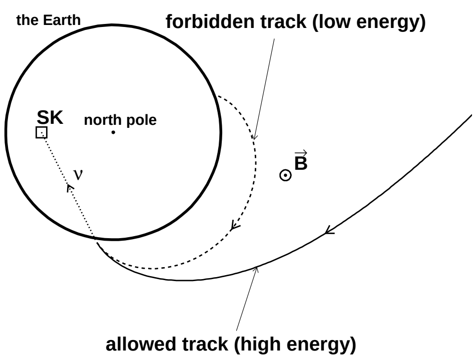
$$\Phi_\nu = \sum_A \Phi_A \otimes R_A \otimes Y_{A\to\nu}$$

$\Phi_A \equiv$ Cosmic ray spectrum

$R_A \equiv$ Geomagnetic Cutoff

$Y_{A\to\nu} \equiv$ Cross Section for

$$A + A_{atmos} \to \nu + X$$



Learning About ATM Fluxes

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- Question? Can we Extract ($\equiv$ *Deconvolute*) Φ_α from ATM ν data?
  - ∗ Answer : You need:
    - – Independent knowledge of oscillation parameters (OK)
    - – General enough analytical parametrization of fluxes (MISSING)

Learning About ATM Fluxes

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  - $*$ Answer : You need:
    - – Independent knowledge of oscillation parameters (OK)
    - – General enough analytical parametrization of fluxes (MISSING)

      Or Neural Network parametrization of fluxes (J. Rojo, M. Maltoni, MCG-G, in preparation)

- Our First Attempt: Extract only E dependence using SK data

$$\Rightarrow \Phi_{\alpha,net}(E_\nu, \cos\theta) = F_{net}(E_\nu)\Phi_{\alpha,calc}(E_\nu, \cos\theta)$$

Procedure:

(1) Generate N_R Replicas of Data according to all uncertainties:
Statistical, Systematic, Theo from Cross Section . . .

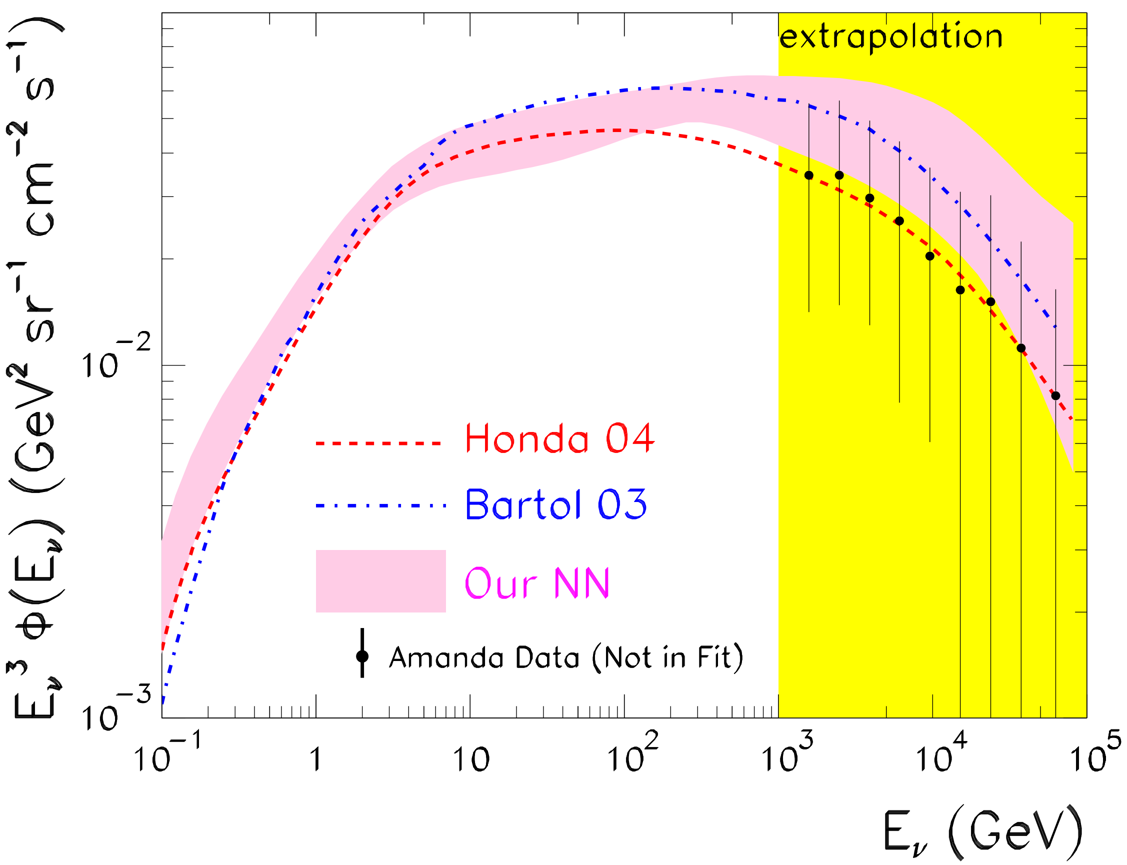
(2) Train Network to each Replica k to get best fit flux $\Phi_\alpha^{(\mathrm{net})(k)}(E_\nu, \cos\theta)$
$\Rightarrow$ Chose some statistical criterion to define "best fit" avoiding *overlearning*

(3) Define average and range of fluxes:

$$\left\langle \Phi_\alpha^{(\mathrm{net})} \right\rangle_{\mathrm{rep}} (E_\nu, \cos\theta) = \frac{1}{N_{\mathrm{rep}}} \sum_{k=1}^{N_{\mathrm{rep}}} \Phi_\alpha^{(\mathrm{net})(k)} \qquad \sigma_\Phi^2 = \frac{1}{N_{\mathrm{rep}}} \sum_{k=1}^{N_{\mathrm{rep}}} \Phi^{(\mathrm{net})(k)\,2} - \left\langle \Phi^{(\mathrm{net})} \right\rangle_{\mathrm{rep}}^2$$

Extracted ATM Fluxes from SK Data

(J. Rojo, M. Maltoni, MCG-G, preliminary)



Some New Physics in ATM ν -Oscillations

- Oscillations are due to:
  - Missalignment between CC-int and propagation states: Mixing $\Rightarrow$ Amplitude
  - Difference phases of propagation states $\Rightarrow$ Wavelength. For Δm^2-OSC $\lambda = \frac{4\pi E}{\Delta m^2}$

Some New Physics in ATM ν -Oscillations

- Oscillations are due to:
  - Missalignment 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 graviational 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

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

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

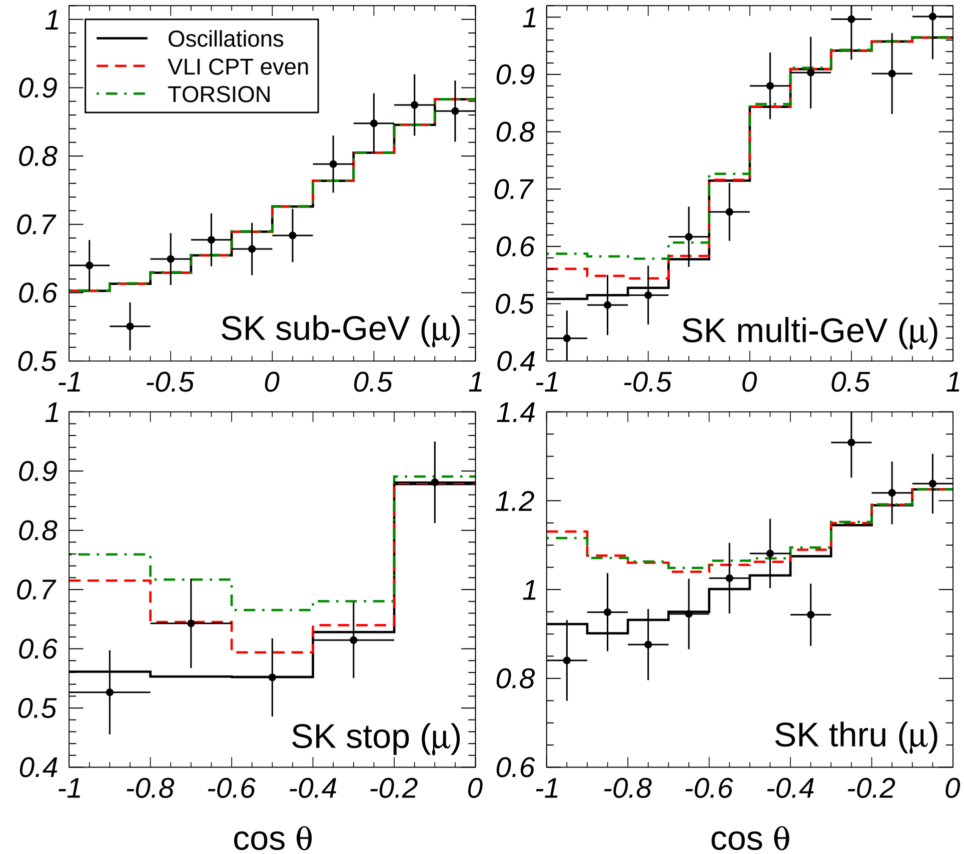
ATM ν's: Subdominant NP Effects

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

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

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

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



MCG-G, M. Maltoni hep-ph/0404085

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

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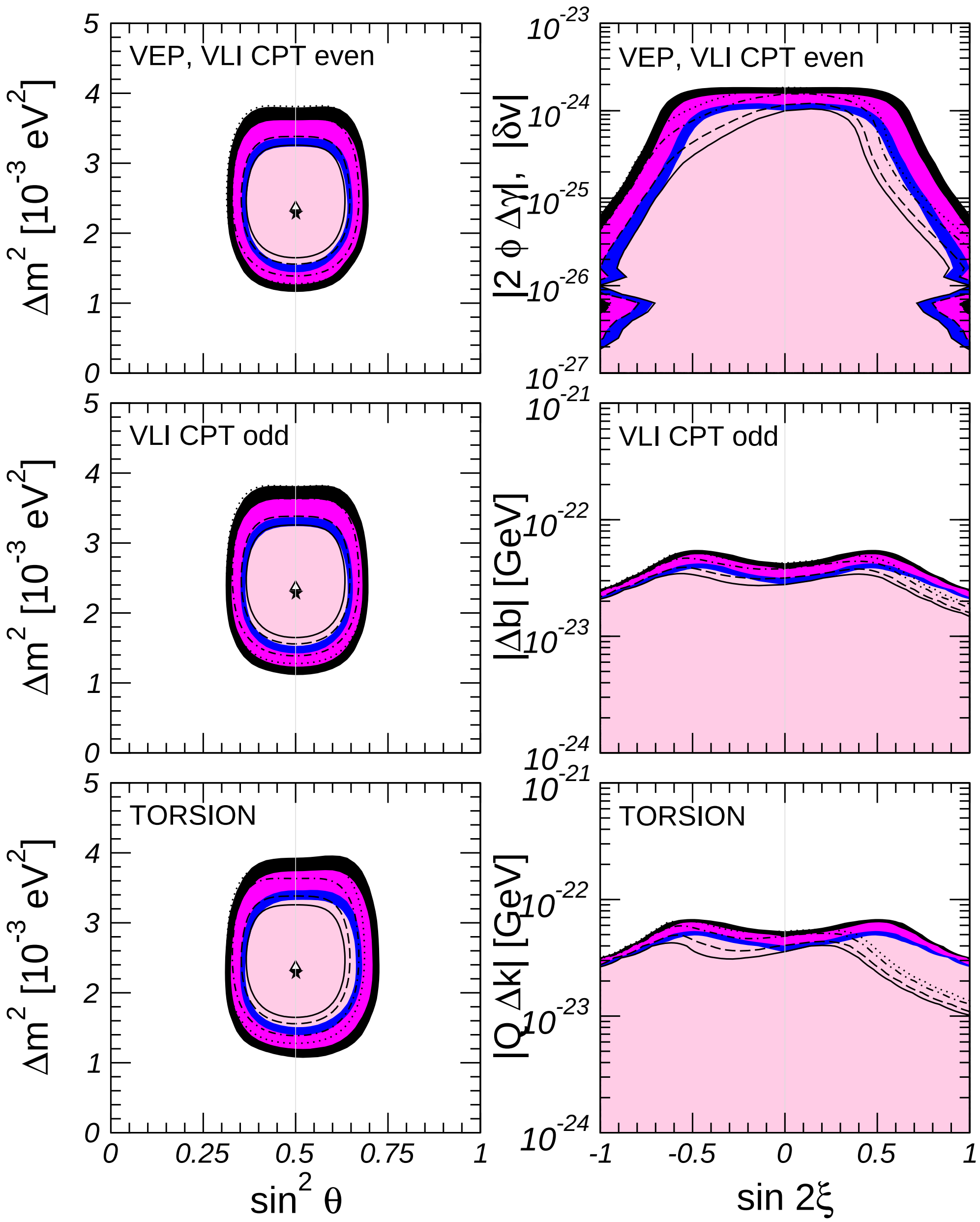
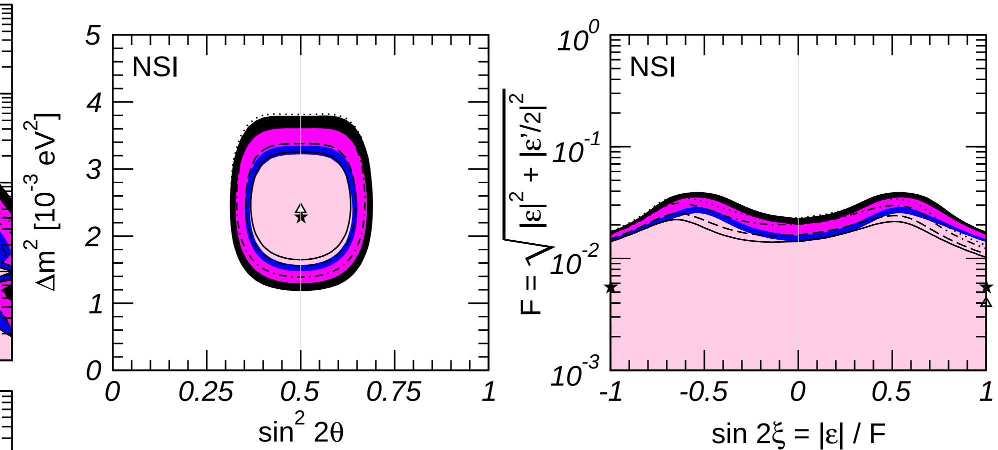
ATM ν's: Subdominant NP Effects

MCG-G, M. Maltoni hep-ph/0404085





At 90% CL:

$$\frac{|\Delta c|}{c} \leq 8.1 \times 10^{-25}$$

$$|\phi\,\Delta\gamma| \leq 4.0 \times 10^{-25}$$

$$|\Delta b| \leq 3.2 \times 10^{-23}\ \text{GeV}$$

$$|Q\,\Delta k| \leq 4.0 \times 10^{-23}\ \text{GeV}$$

$$|\varepsilon_{\mu\mu} - \varepsilon_{\tau\tau}| \leq 0.013$$

$$|\varepsilon_{\mu\tau}| \leq 0.034$$

Future Bounds on New Physics: ν Telescopes

At ν Telescopes (Amanda, Antares, IceCube)

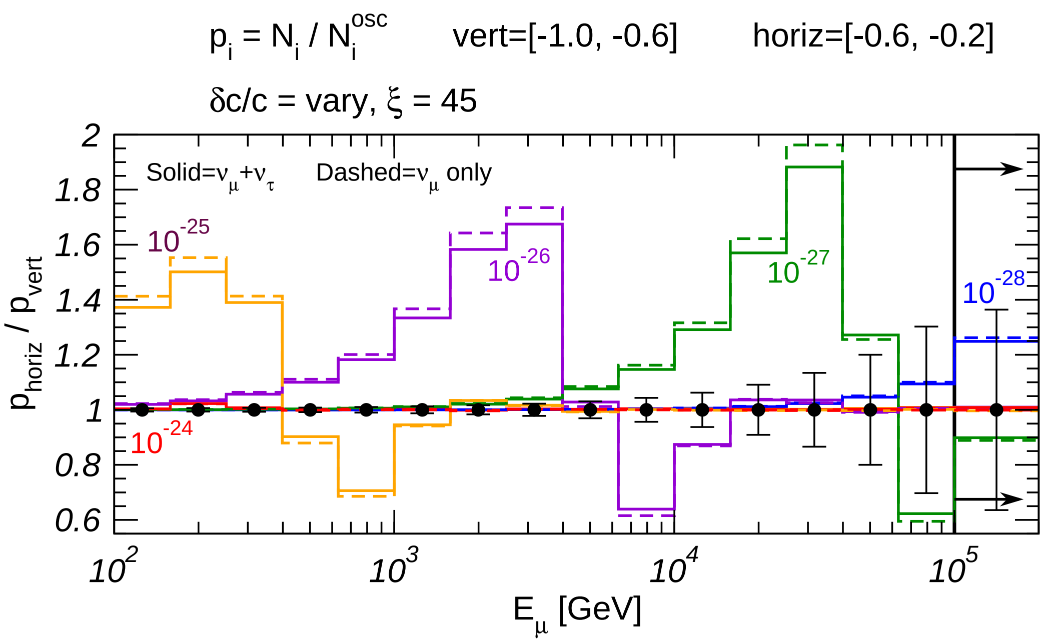
$E_{\nu,thres} \gtrsim$ 100 GeV

Large # ATM $\nu's$

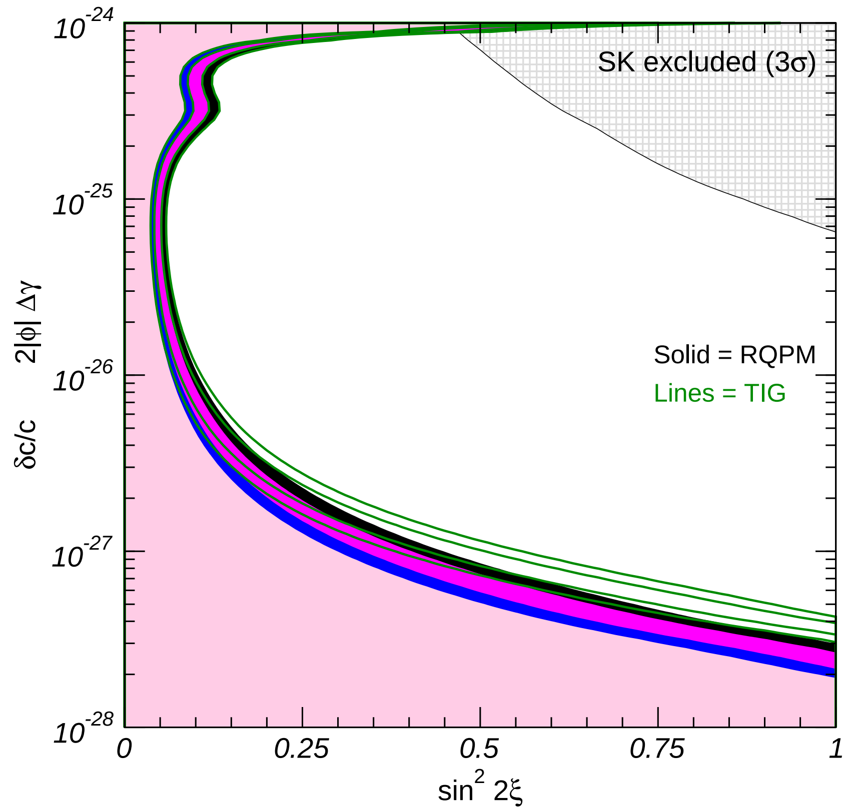
(~ $10^5 \nu_\mu$ events/yr at ICECUBE)

⇒ Standard oscillations suppressed

⇒ Better sensitivity to Oscillations due to NP

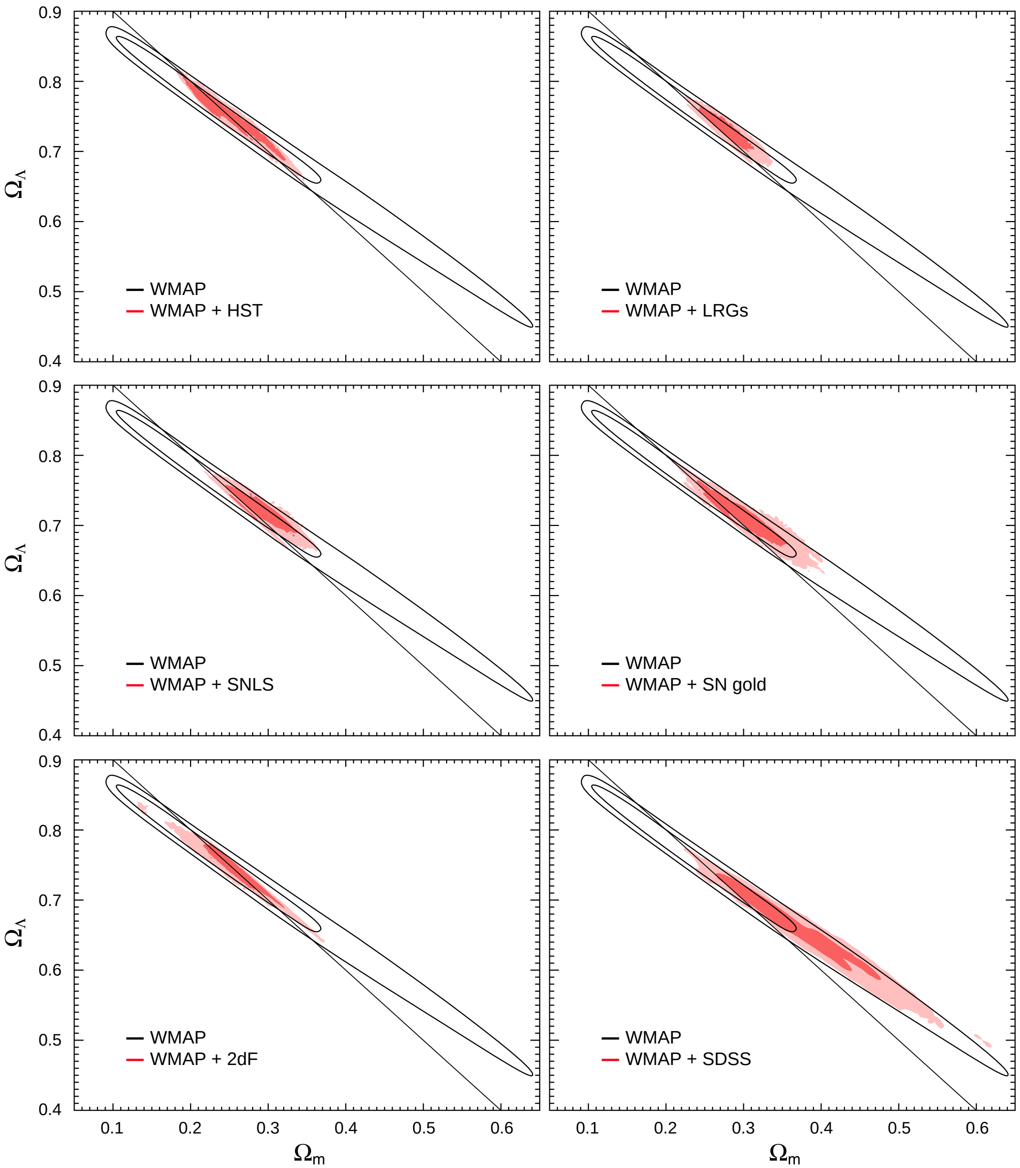


Expected Sensitivity at IceCube



The Dark Energy Problem – ν Connection

Including latest WMAP results



$$\Omega_\Lambda = 0.74 \pm 0.02$$

$$\Omega_m = 0.26^{+0.01}_{-0.03}$$

$$\Omega_b = 0.047 \pm 0.004$$

$$\Omega_\nu = 0.0081^{+0.0032}_{-0.0081}$$

- Big Question: What is Λ?

  We do not know

- Next Question: Why now $\Omega_\Lambda \sim \Omega_m$?

  We do not know

- Next Question: Why now $\Omega_\Lambda \sim \Omega_\nu$?

  (within factor 10^3)

  May be Ω_Λ and Ω_ν are related and "track" each other

(Fardon, Nelson and Weiner, astro-ph/0309800)

Mass Varying Neutrinos: Framework

Gonzalez-Garcia

- Ingredients: neutrinos ν and a scalar field the acceleron $\mathcal{A}$

$$\mathcal{L} = m_\nu(\mathcal{A})\nu\nu + V_{tot}(\mathcal{A})$$

- In presence of a ν background:

$$\begin{aligned}
V_{tot}(\mathcal{A}) &\equiv V_{tot}(m_\nu(\mathcal{A})) \\
&= V_{de}(m_\nu(\mathcal{A})) + V_\nu(m_\nu(\mathcal{A})) \\
V_{de}(m_\nu) &= \Lambda^4 f\left(\frac{m_\nu}{\mu}\right) \quad (\Lambda \sim 10^{-3}\ \text{eV}) \\
V_\nu(m_\nu) &= \int \frac{d^3k}{(2\pi)^3}\sqrt{k^2 + m_\nu^2}\, f_\nu(k)
\end{aligned}$$

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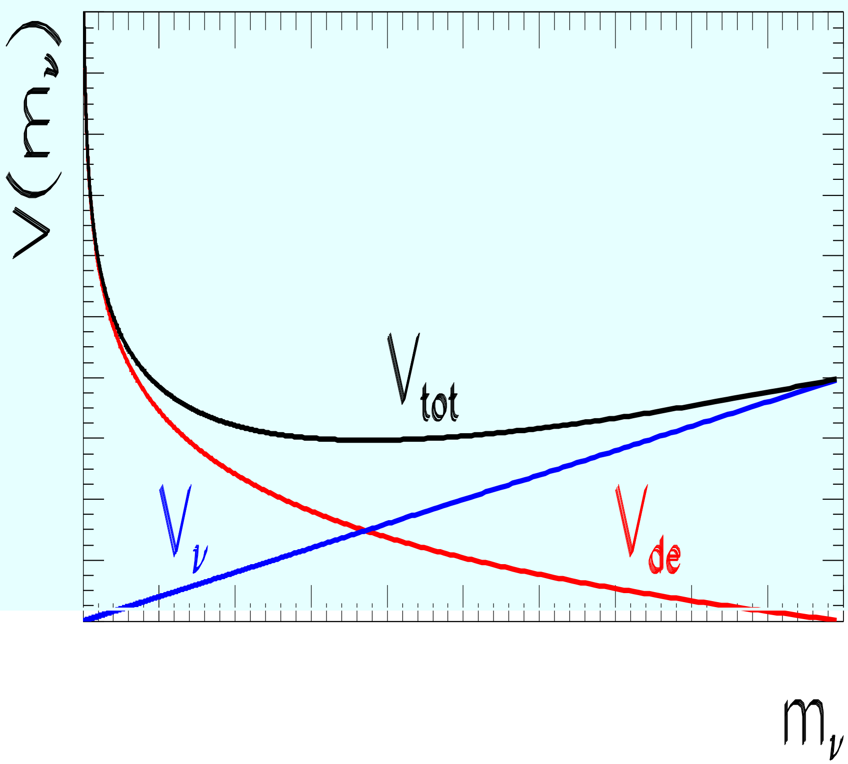
- In cosmic ν background ($n^{C\nu B} \simeq 112\ \text{cm}^{-3}$)

$$V_\nu(m_\nu) = m_\nu n^{C\nu B}$$

- Both $\rho_{DE} \equiv V_{tot,min}$ and $m_\nu \equiv m_\nu^0$ fixed by the minimum condition

$$V'_{de}(m_\nu^0) + n^{C\nu B} = 0$$



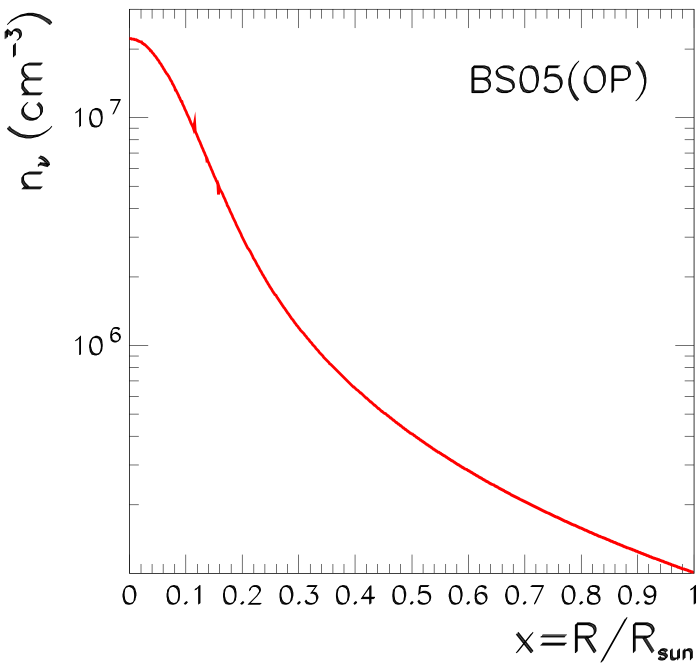
Mass Varying Neutrinos in the Sun

Gonzalez-Garcia

M. Cirelli, M.C.G-G, C. Peña-Garay hep-ph/0503028

In the cosmic ν background ($n^{C\nu B} \simeq 112$ cm^{-3}) $m_\nu \equiv m_\nu^0$ with $V'_{dc}(m_\nu^0) + n^{C\nu B} = 0$

In the Sun



$$V_\nu(m_\nu) = m_\nu \, n^{C\nu B} + V_{\nu,\mathrm{Sun}}(m_\nu)$$

$$\Downarrow$$

$$m_{\nu,\mathrm{Sun}}(x) - m_\nu^0 \sim A(x)(m_\nu^0)^2$$

$$\Downarrow$$

$$\Delta m^2_{21,\mathrm{kin}}(x) \simeq \Delta m^2_{21,0}\left[1 - 3\sin^2\theta^0_{12} A(x)_{\nu_e,\mathrm{Sun}} m_{0,1}\right] + \dots$$

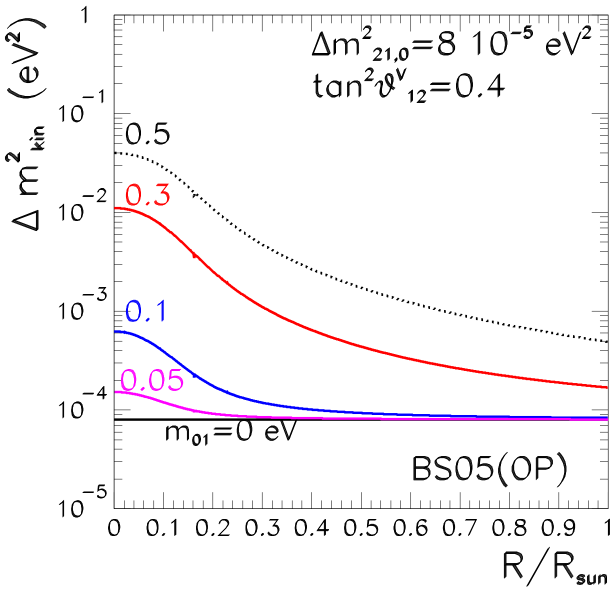
$$\left[A(x)_{\nu_e,\mathrm{Sun}} \sim \frac{n_{\nu,\mathrm{Sun}}(x)}{n^{C\nu B}\langle E_{\nu_e,\mathrm{Sun}}\rangle}\right]$$

Effective mass difference depends on neutrino mass scale $m_{0,1}$

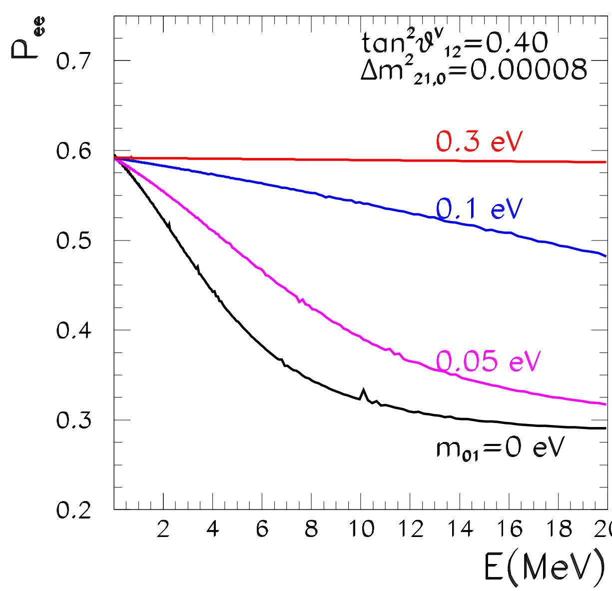
Mass Varying Neutrinos in the Sun

Gonzalez-Garcia

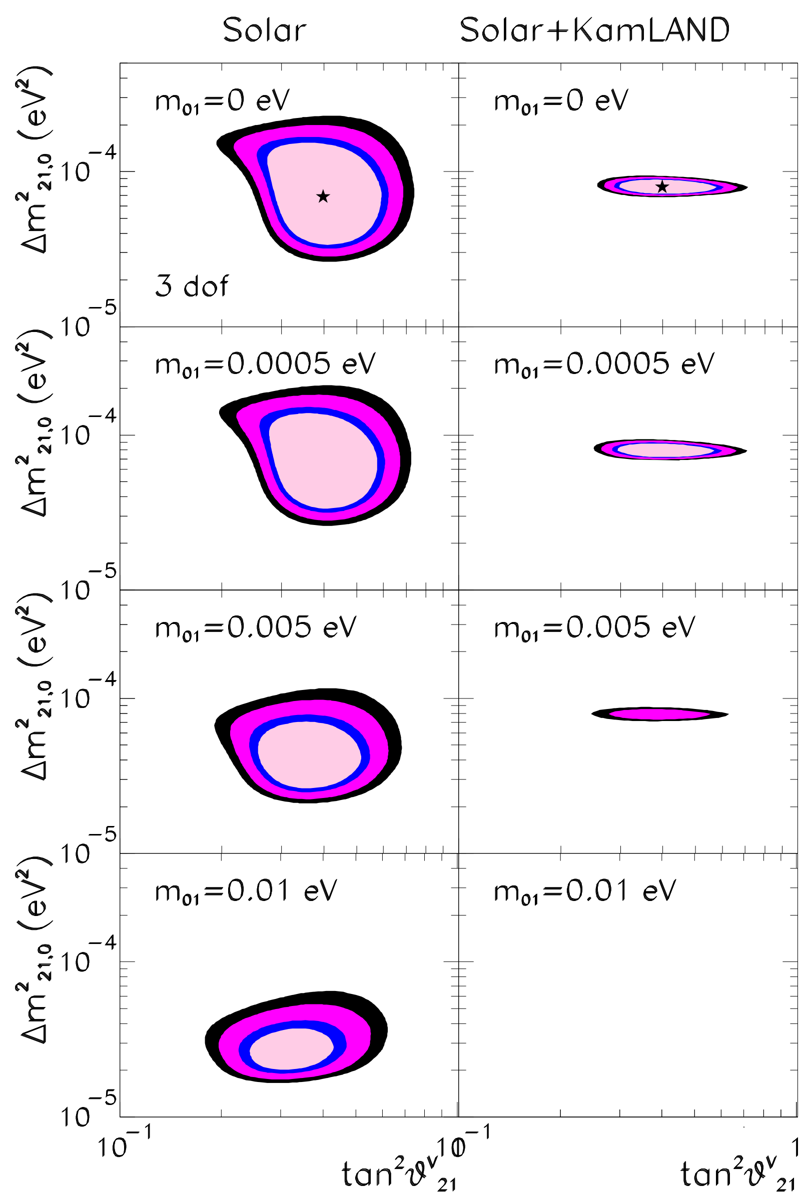
Effective mass difference



Survival Probability



Fit worsens for degenerate ν's



$m_{0,1} < 0.01$

(3σ)

Mass Varying Neutrinos in the Sun (II)

Kaplan, Nelson and Weiner hep/ph0401099

If acceleron $\mathcal{A}$ also couples to matter fields f

$$\mathcal{L} = \sum_{ij} \lambda^{\nu}_{ij} \bar{\nu}_i \nu_j \mathcal{A} + \sum_f \lambda^f \bar{f} f \mathcal{A} + V_{de}(\mathcal{A})$$

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Kaplan, Nelson and Weiner hep/ph0401099

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Neutrino mass also depends on the background matter densities $n_f(r)$

$$\begin{aligned} m^{\nu}_{ij}(r) &= m^0_{\nu,i} \delta_{ij} - M^{\nu}_{ij}(r), \\ M^{\nu}_{ij}(r) &= \frac{\lambda^{\nu}_{ij}}{m^2_{\mathcal{A}}} \sum_f \lambda^f n_f(r) \sim \alpha_{ij} \left[\frac{\rho(r)}{(\mathrm{gr/cm^3})} \right] \end{aligned}$$

$$\alpha \sim 4.8 \times 10^{23} \, \lambda^{\nu} \, \lambda^{N} \left(\frac{10^{-7}\mathrm{eV}}{m_{\mathcal{A}}} \right)^2 \mathrm{eV}$$

(Tests of gravitational inverse square law $\Rightarrow \lambda^n, \lambda^p \lesssim 10^{-21}$ for $m_{\mathcal{A}} \gtrsim 10^{-11}$ eV)

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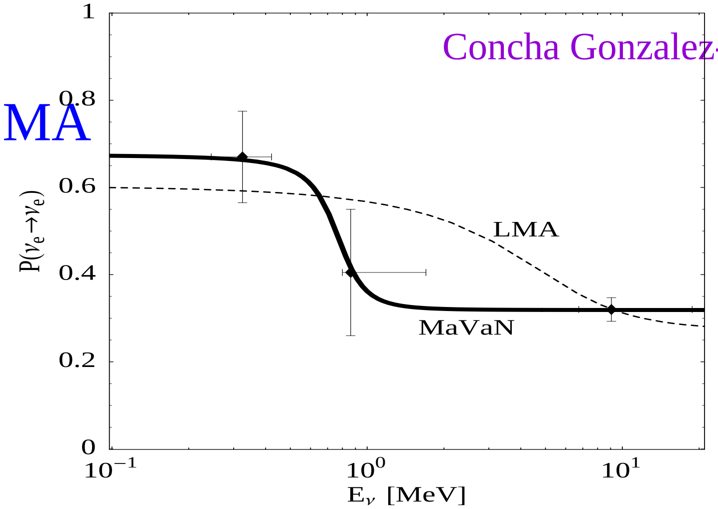
This new matter density dependence affects solar neutrino evolution

Concha Gonzalez-Garcia

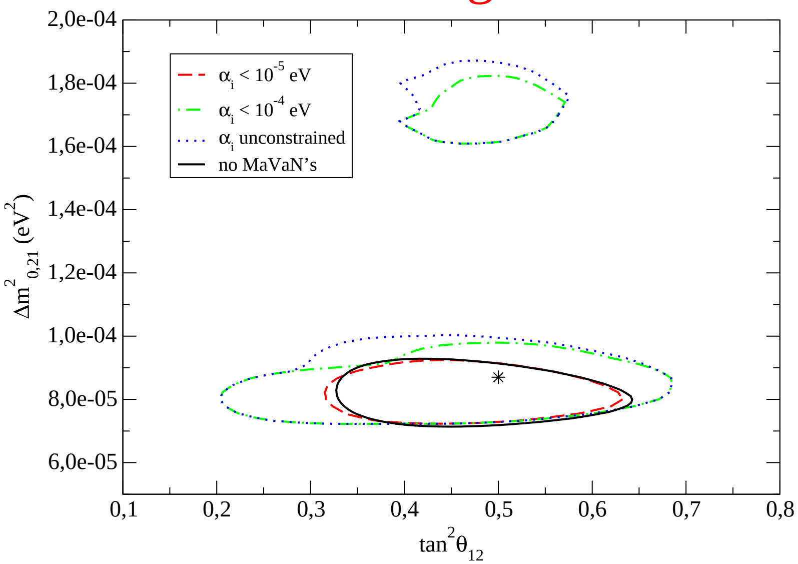
(1) For some values $\alpha's$ ⇒ Slight better fit for LMA

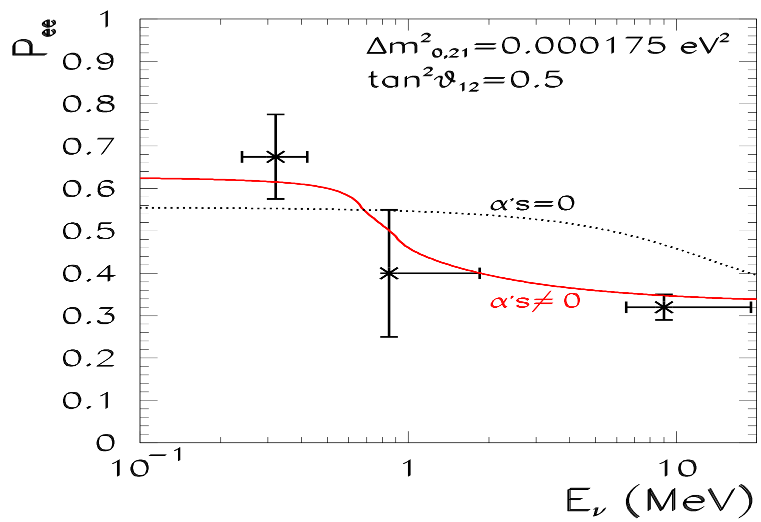
Barger, Huber, Marfatia hep-ph/0502196



(2) For some values $\alpha's \sim 10^{-4}$–10^{-5}

⇒ New Allowed Region at 99% CL





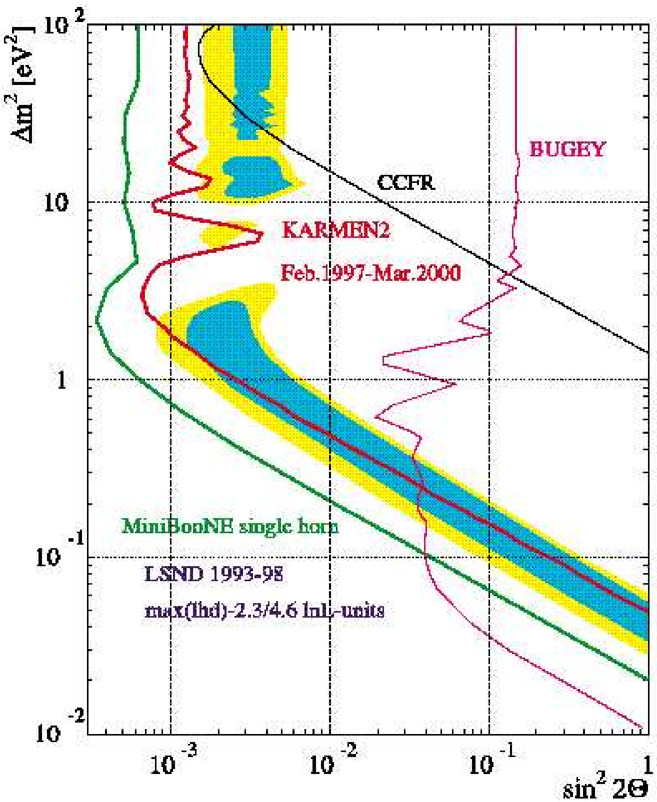
MCG-G, de Holanda, Zukanovich hep-ph/0511093

(3) Fit worsens for large α's ⇒ bound on acceleron couplings

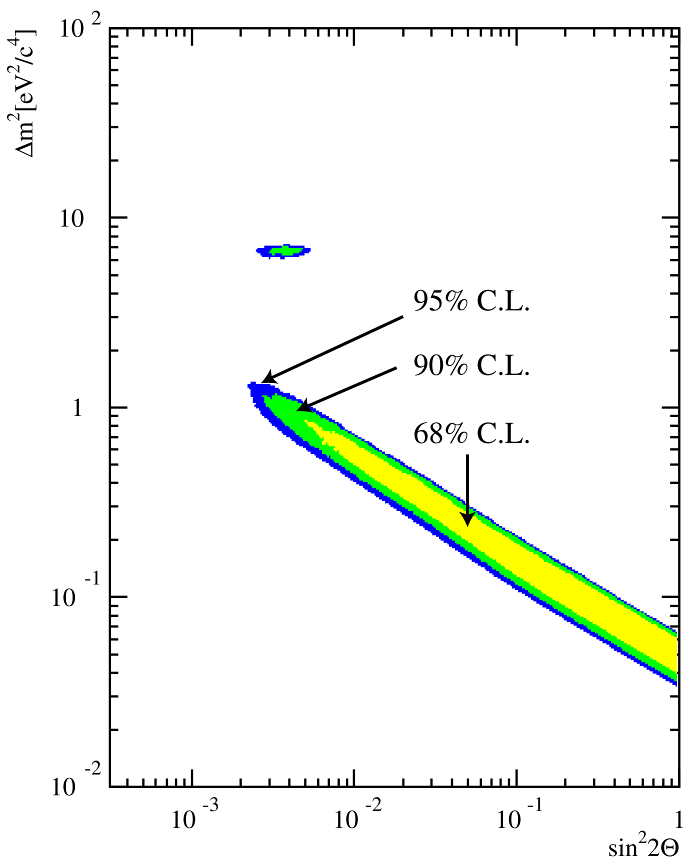
$$|\lambda^\nu \, \lambda^N| \left(\frac{10^{-7}\,\text{eV}}{m_{\mathcal{A}}}\right)^2 \leq 3.0 \times 10^{-28} \quad (90\% CL)$$

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

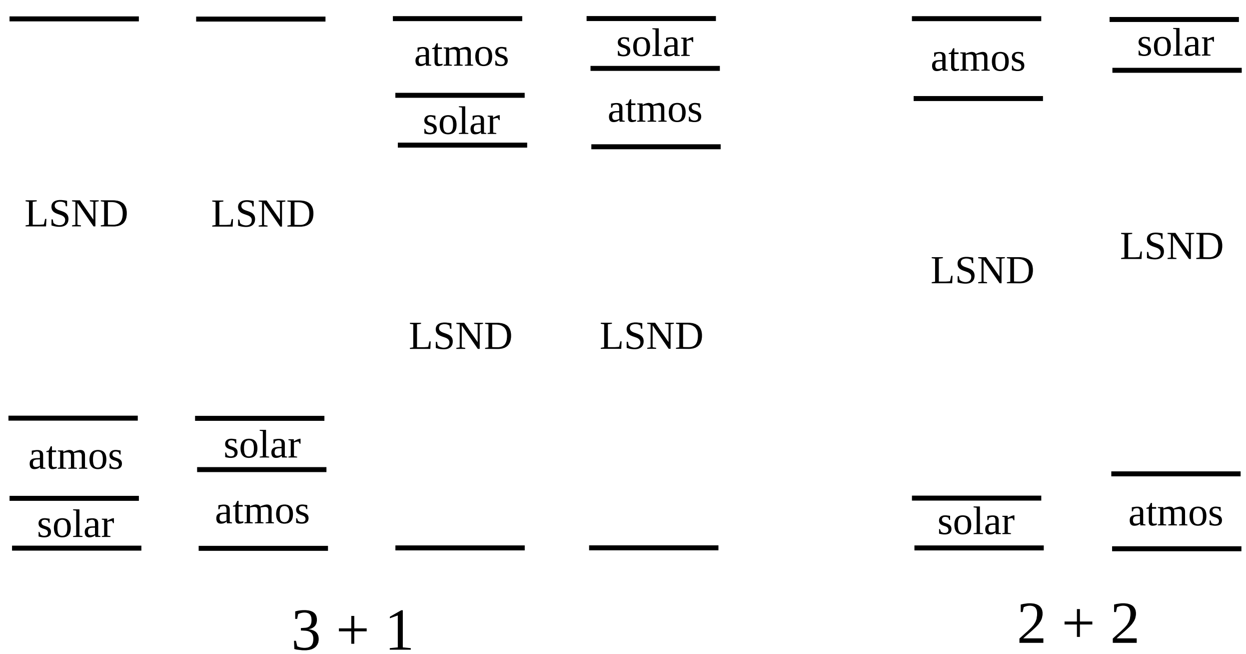


LSND Try I: Sterile Neutrinos and 4ν Mixing

- 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 $\Delta m^2 \Rightarrow$ 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

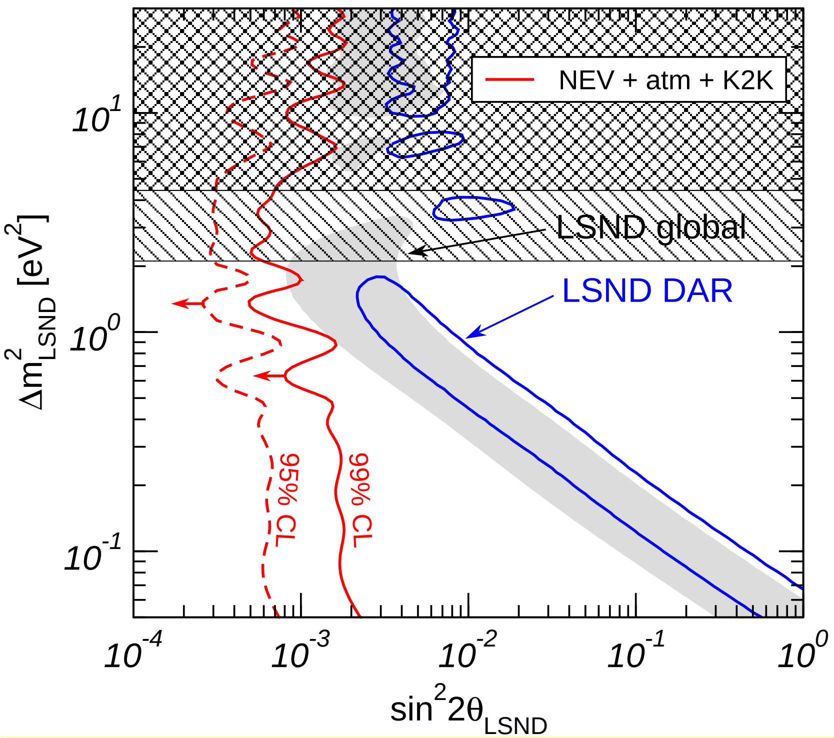
$3+1$

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

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

$|U_{\mu 4}|^2$ constrained by CDHSW+ATM

Maltoni *et al* hep-ph/0107150



Only tiny regions at 99%CL

Also constrained by cosmo bound on $\sum m_{\nu_i}$

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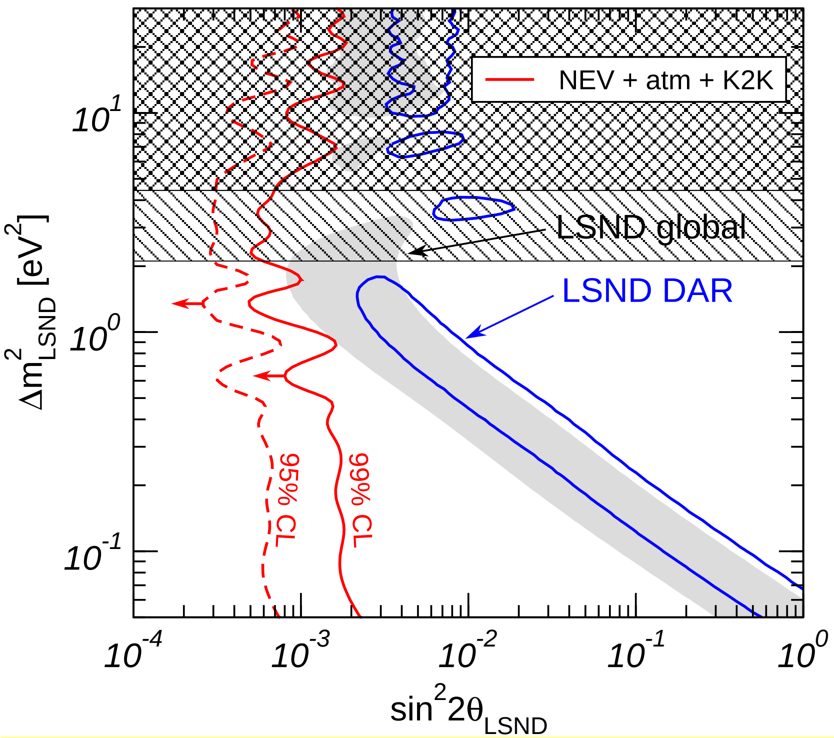

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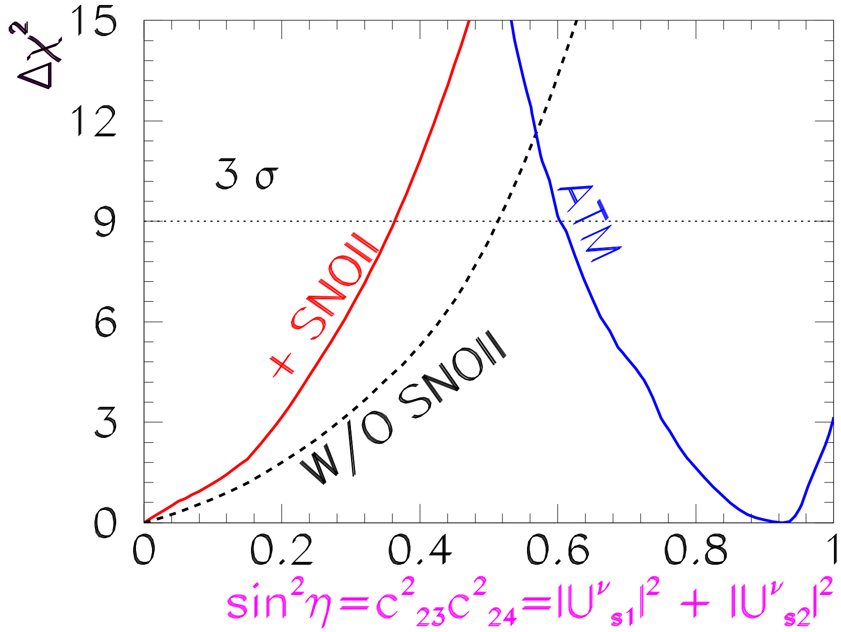
$2+2$

Mixed active-sterile oscillations

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

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



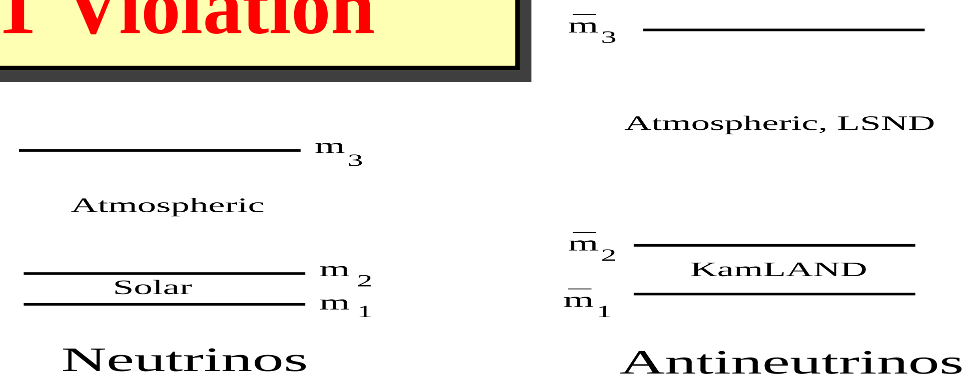
Disagreement at more than 4σ

LSND Try II : CPT Violation

CPT violation:

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

⇒ Possibility of accommodating LSND?



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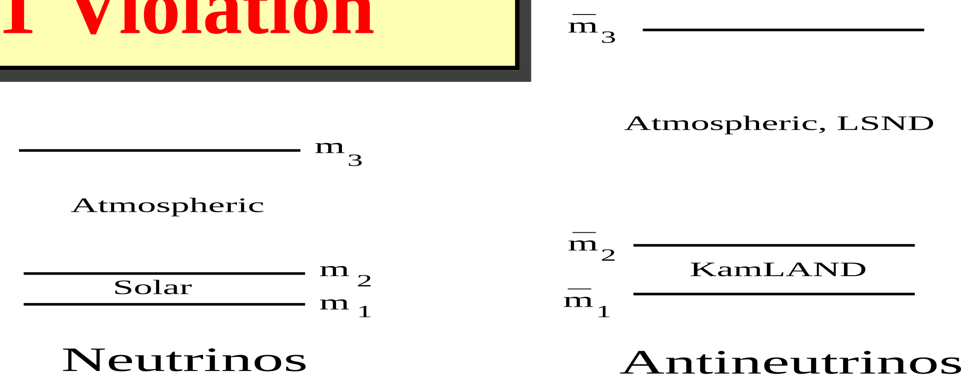


CPT violation:

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

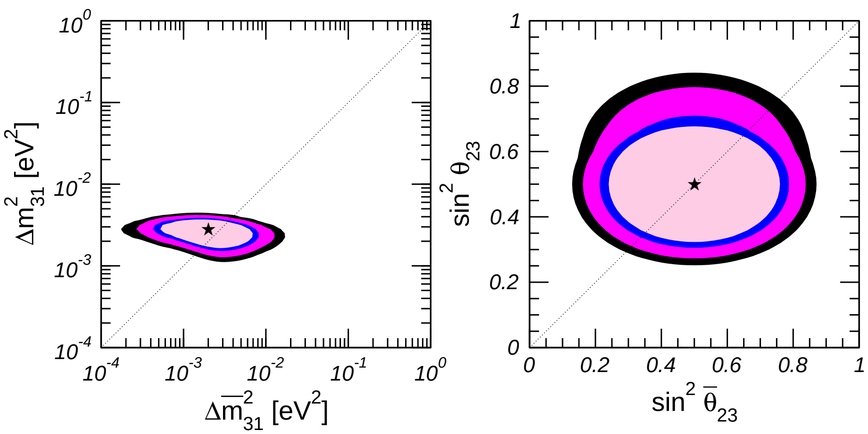
⇒ Possibility of accommodating LSND?

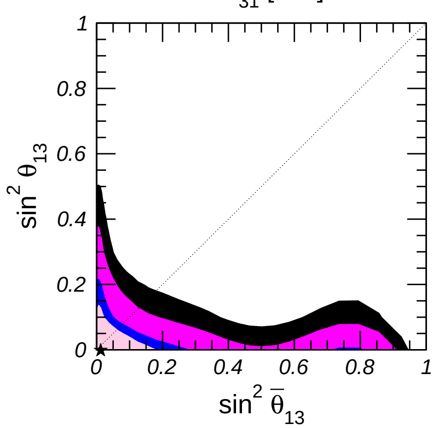
But Data does not support this:

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

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

MCG-G, Maltoni, Schewtz, 04



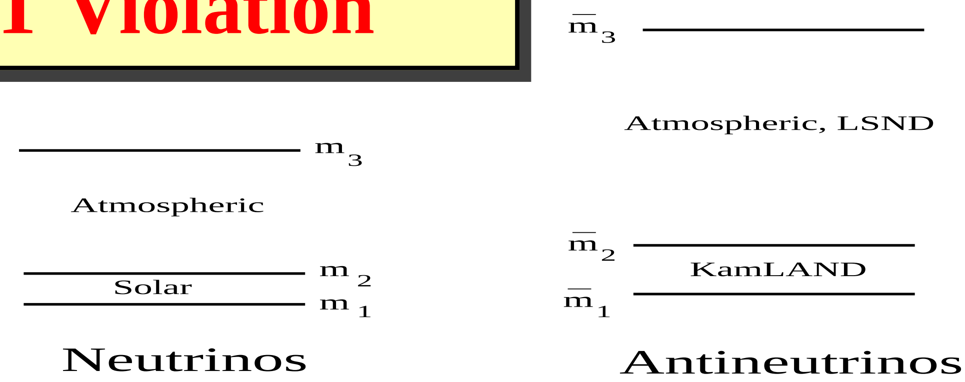


Best fit near

CPT conservation

Concha Gonzalez-Garcia

LSND Try II : CPT Violation



CPT violation:

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

$\Rightarrow$ Possibility of accommodating LSND?

But Data does not support this:

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

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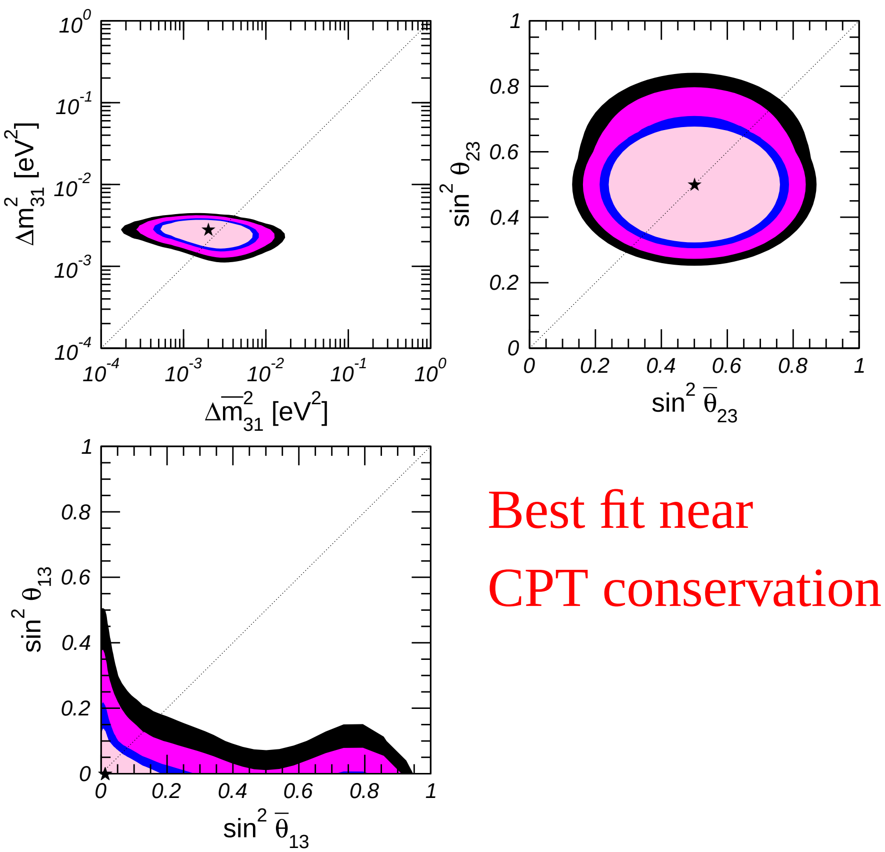
All-But-LSND and LSND regions incompatible at $\gtrsim 3\sigma$

MCG-G, Maltoni, Schewtz, 04



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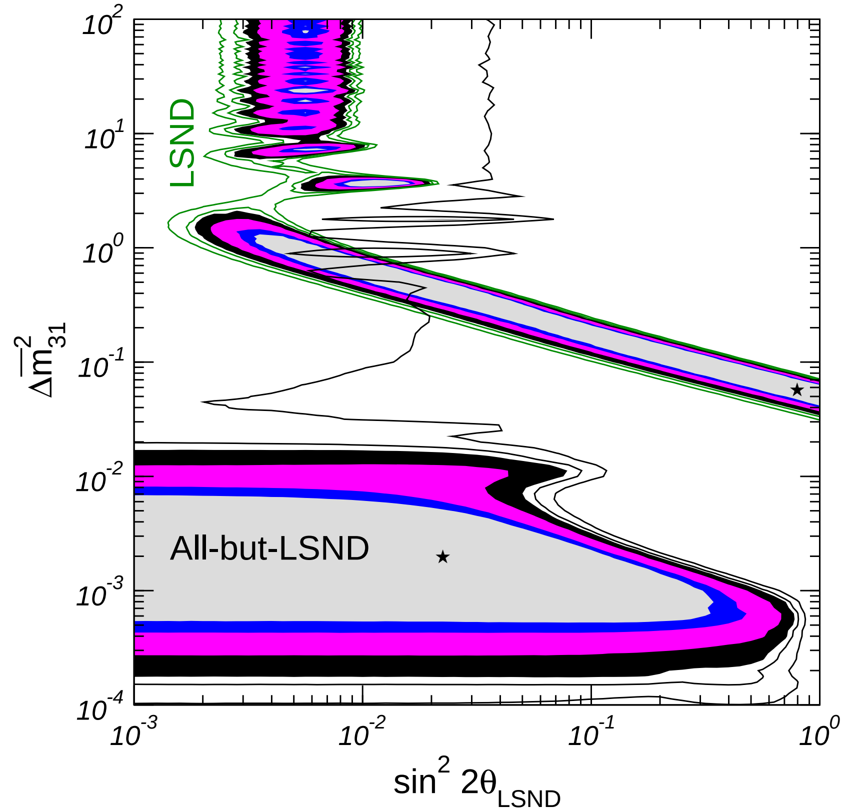

LSND III: What it is Claimed to Work

- 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-Ruiz,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

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

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
- After all existing experiments still many open questions:

  What is the value of θ_{13}?

  Is there CP violation in the leptons

  The absolute scale of neutrino mass

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

  Solar Physics

  Atmospheric Fluxes

  Fundamental symmetries: LI, WEP, CPT

  ν models for Dark Energy ...
- Accommodating LSND: A problem