NEUTRINO MASSES AND MIXING:

PROGRESS REPORT & ARISEN ISSUES

(OR LIVING IN THE *data squeezing* TIMES)

Concha Gonzalez-Garcia

(ICREA-U Barcelona & YITP-Stony Brook)

NOW 2010

The New Minimal Standard Model

- 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

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

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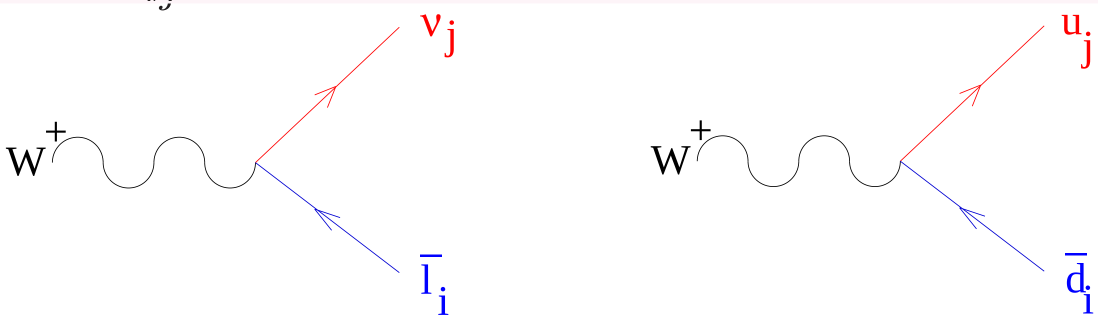
- The charged current interactions of leptons are not diagonal (same as quarks)

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



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- To fully determine the lepton flavour sector we want to know:

  * How many, N, massive ν_i and their masses m_i

  * Their mixing and CP properties (angles and phases in $U_{\rm LEP}$)

  * Their *nature*: Dirac neutrino $\Rightarrow$ If L is conserved

    Majorana neutrino $\Rightarrow$ If L is violated (and extra phases)

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

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

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

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- For example for 3 ν's : 3 Mixing angles + 1 Dirac Phase + 2 Majorana Phases

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

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

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

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

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No information on ν mass scale nor Majorana versus Dirac

Solar+Atmospheric+Reactor+LBL 3ν Oscillations

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

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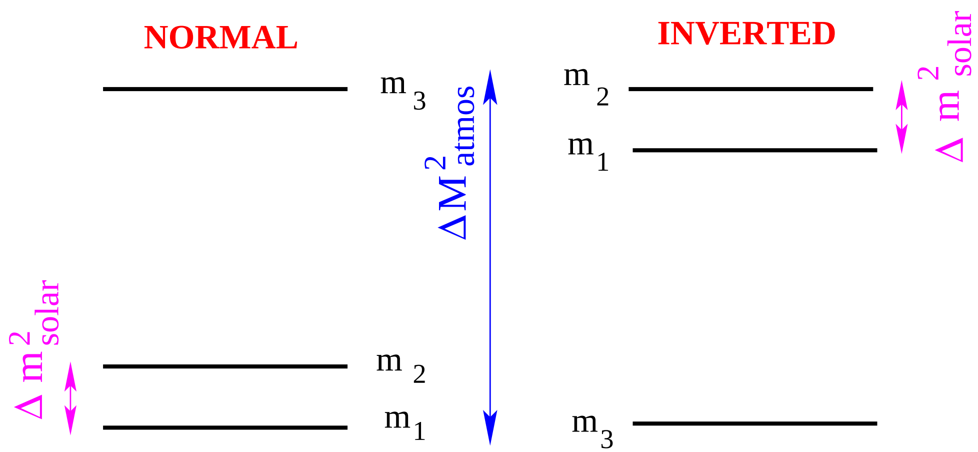
- **Two mass schemes**



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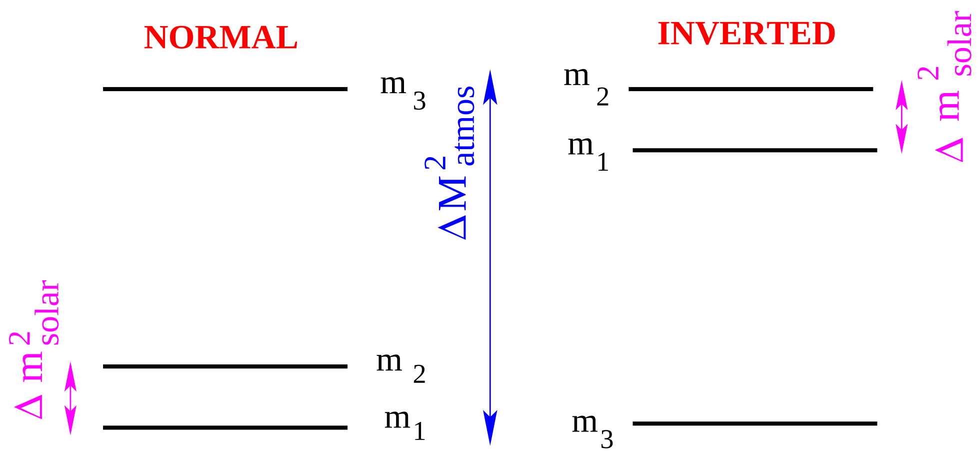

- **Dominant oscillations:**
  - Solar and KamLAND ($\nu_e \to \nu_{\mu,\tau}$): $\Delta m^2_{\rm solar} \simeq \Delta m^2_{21}$ and θ_{12}
  - ATM and Acc LBL ($\nu_\mu \to \nu_\tau$): $\Delta M^2_{\rm atmos} \simeq |\Delta m^2_{31}| \simeq |\Delta m^2_{32}| \gg \Delta m^2_{21}$ and θ_{23}
  - SBL Reactors (CHOOZ): $\sin^2\theta_{13} \lesssim 0.05$

Solar+Atmospheric+Reactor+LBL 3ν Oscillations

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

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

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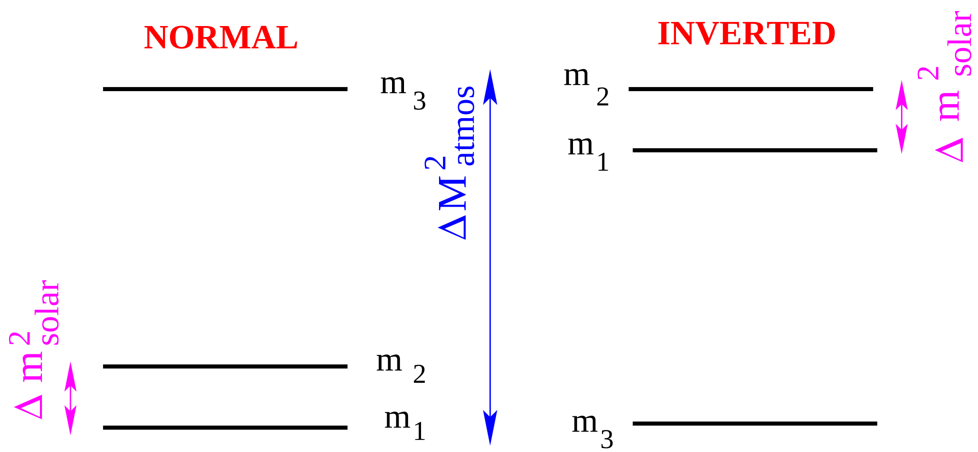
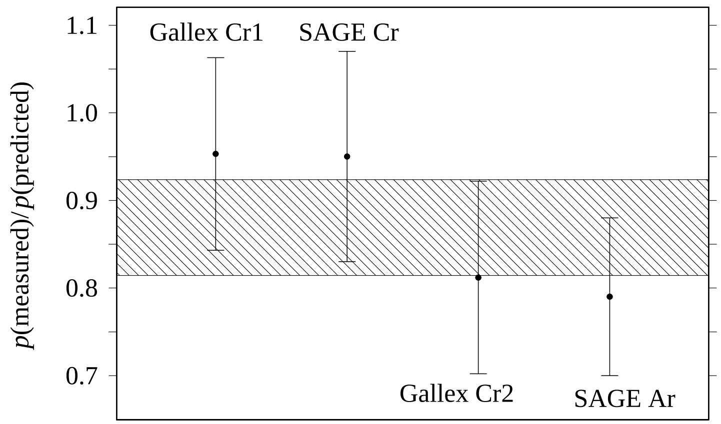


- **Subdominant 3ν mixing effects:**
  – Effects due to θ_{13}
  – Difference between Inverted and Normal
  – Interference of two wavelength oscillations and CP violation due to phase δ

Comments on Solar Neutrino Analysis

- Radiochemical Experiments:
  - $\Sigma(\mathrm{Cl}) = 2.56 \pm 0.16 \pm 0.16$ (SNU)
  - $\Sigma(\mathrm{Gallex}) = 68.1 \pm 6.05 \pm 3.9$ (SNU) Reanalisis in Kaeter *etal* arXiv:1001.2731
  - $\Sigma(\mathrm{GNO}) = 62.9 \pm 5.4 \pm 2.5$ (SNU)
  - $\Sigma(\mathrm{SAGE}) = 65.4^{+3.1+2.6}_{-3.0-2.8}$ (SNU) 2002-2007 Sage Coll arXiv:0901.2200 (before $66.2^{+3.3+3.5}_{-3.2-3.2}$)

- Callibration of Gallium Experiments with ^{51}Cr and ^{37}Ar Sources:



p(predicted) using ν capture cross section in ^{71}Ge

from Bahcall hep-ph/97100491

– Low rates in new callibrations

– Proposed *lower ν capture CS* removing capture in two lower ^{71}Ge excited states

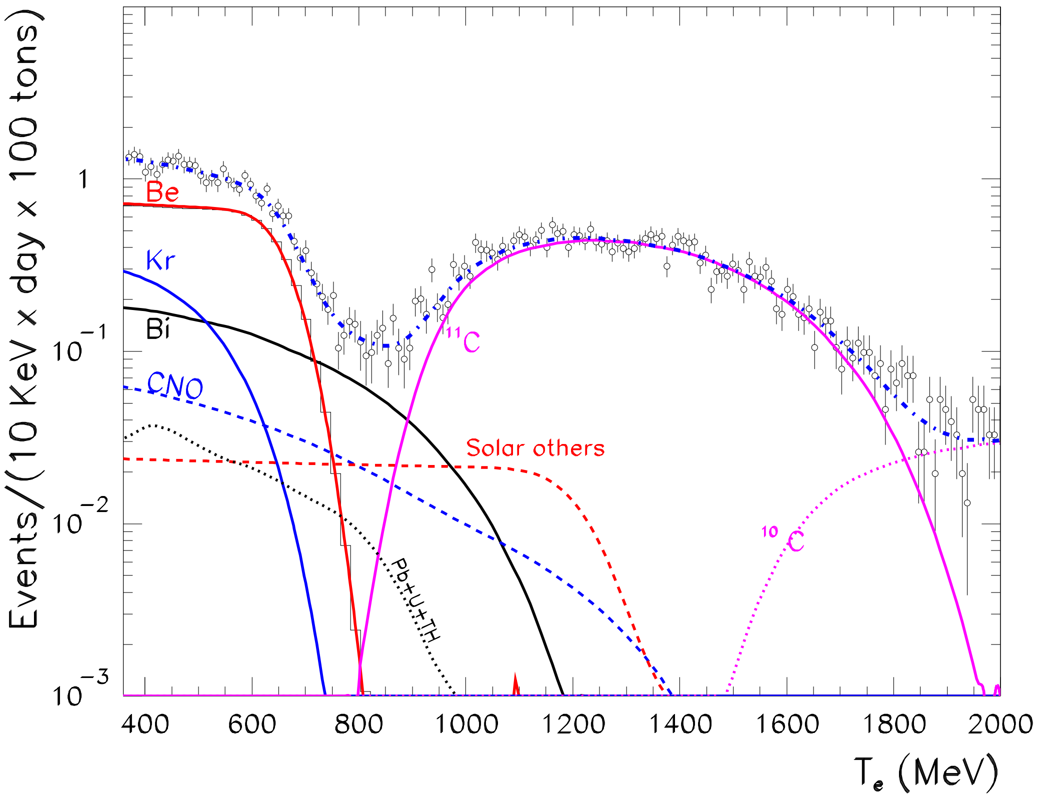
Sage Coll. arXiv:0901.2200, Haxton nucl-th/9804011

For alternatives talk by C. Giunti

Comments on Solar Neutrino Analysis

- Getting the most of Borexino Spectrum Borexino Coll. arXiv:0805.3943, Talk by M. Pallavicini

– Not using the total rate $R_{^7Be} = 49 \pm 3 \pm 4$ events



– But extraction of solar ν contribution (with oscillations) from fit to Borexino spectrum

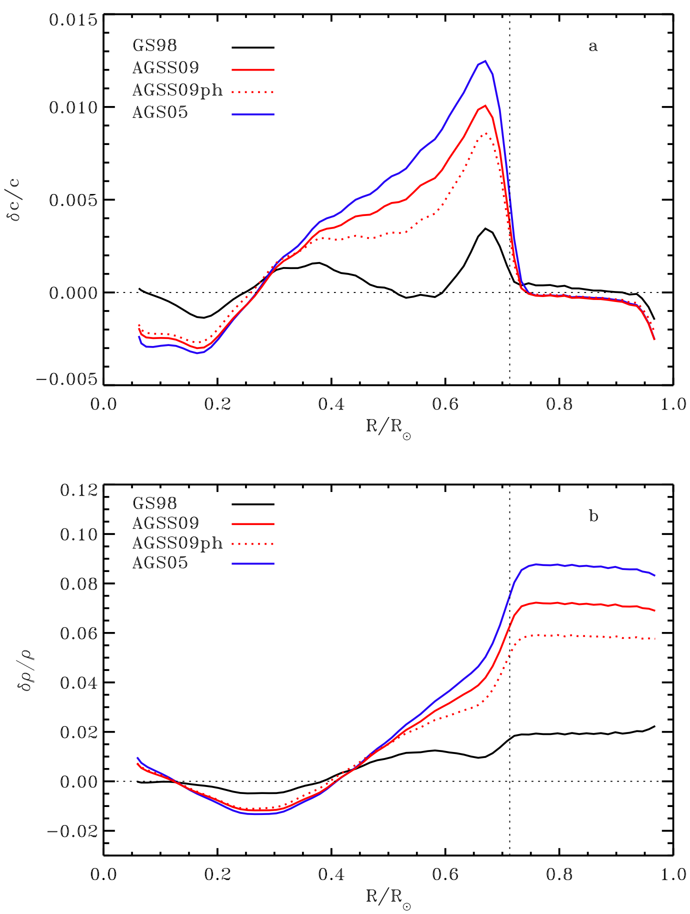
(Overall normalization of ^{11}C, ^{14}C, ^{210}Bi, ^{85}Kr backgrounds fitted to data)

MCG-G, M Maltoni, J Salvado arXiv:0910.4584

Comments on Solar Neutrino Analysis: Fluxes

– Newer determination of abundance of heavy elements in solar surface give lower values

– Solar Models with these lower metalicities fail in reproducing helioseismology data



– Two sets of SSM:

Starting from Bahcall *etal* 05,now Serenelli *etal* 0909.2

GS98 uses older metalicities

AGSXX uses newer metalicities

Flux $cm^{-2}\ s^{-1}$	GS98	AGSS09
$pp/10^{10}$	$5.97\ (1 \pm 0.006)$	$6.03\ (1 \pm 0.005)$
$pep/10^{8}$	$1.41\ (1 \pm 0.011)$	$1.44\ (1 \pm 0.010)$
$hep/10^{3}$	$7.91(1 \pm 0.15)$	$8.18\ (1 \pm 0.15)$
$^{7}Be/10^{9}$	$5.08\ (1 \pm 0.06)$	$4.64\ (1 \pm 0.06)$
$^{8}B/10^{6}$	$5.88\ (1 \pm 0.11)$	$4.85\ (1 \pm 0.12)$
$^{13}N/10^{8}$	$2.82\ (1 \pm 0.14)$	$2.07(1^{+0.14}_{-0.13})$
$^{15}O/10^{8}$	$2.09\ (1^{+0.16}_{-0.15})$	$1.47\ (1^{+0.16}_{-0.15})$
$^{17}F/10^{16}$	$5.65\ (1^{+0.17}_{-0.16})$	$3.48\ (1^{+0.17}_{-0.16})$

– Which one does the data favours?

Talk by F. Villante

Comments on Solar Neutrino Analysis: Fluxes

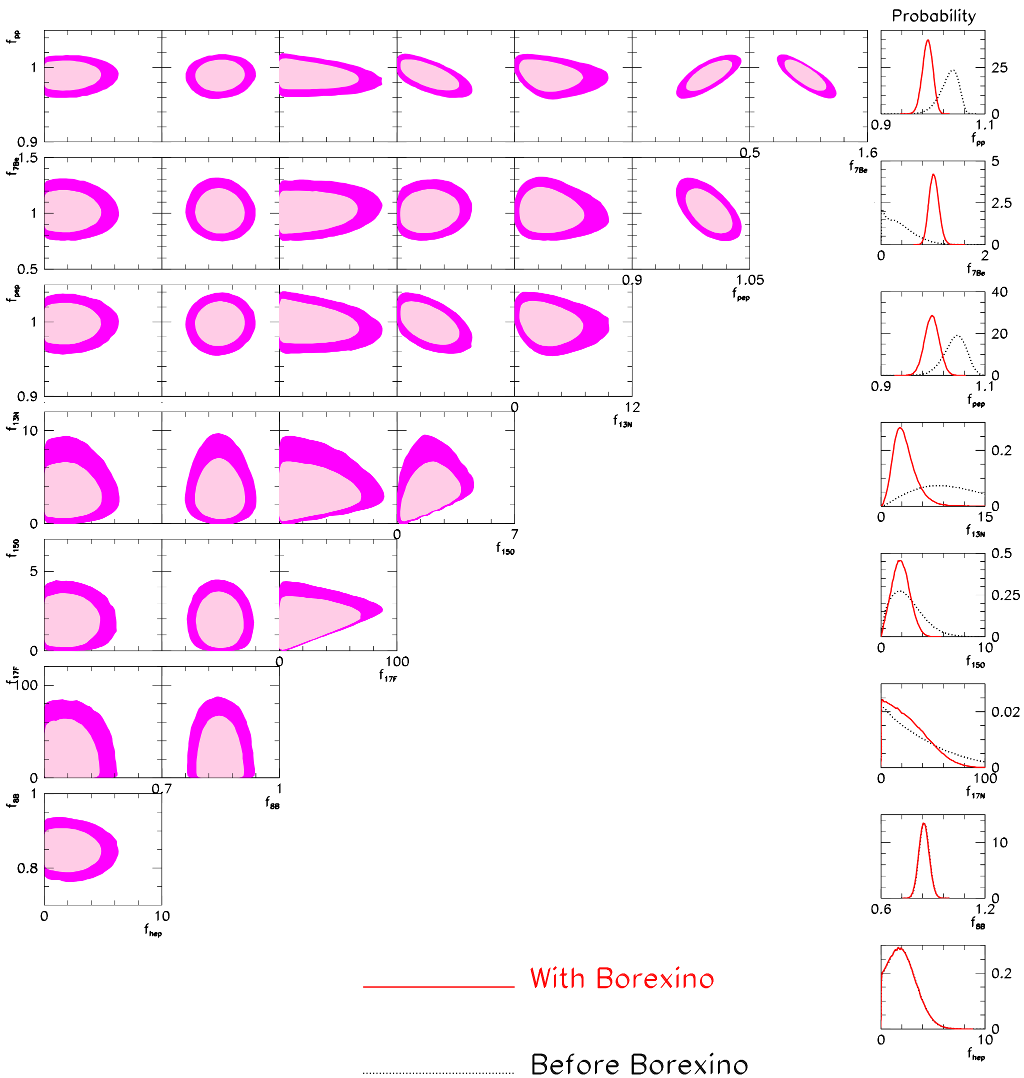
3ν oscillation fit with solar fluxes free:

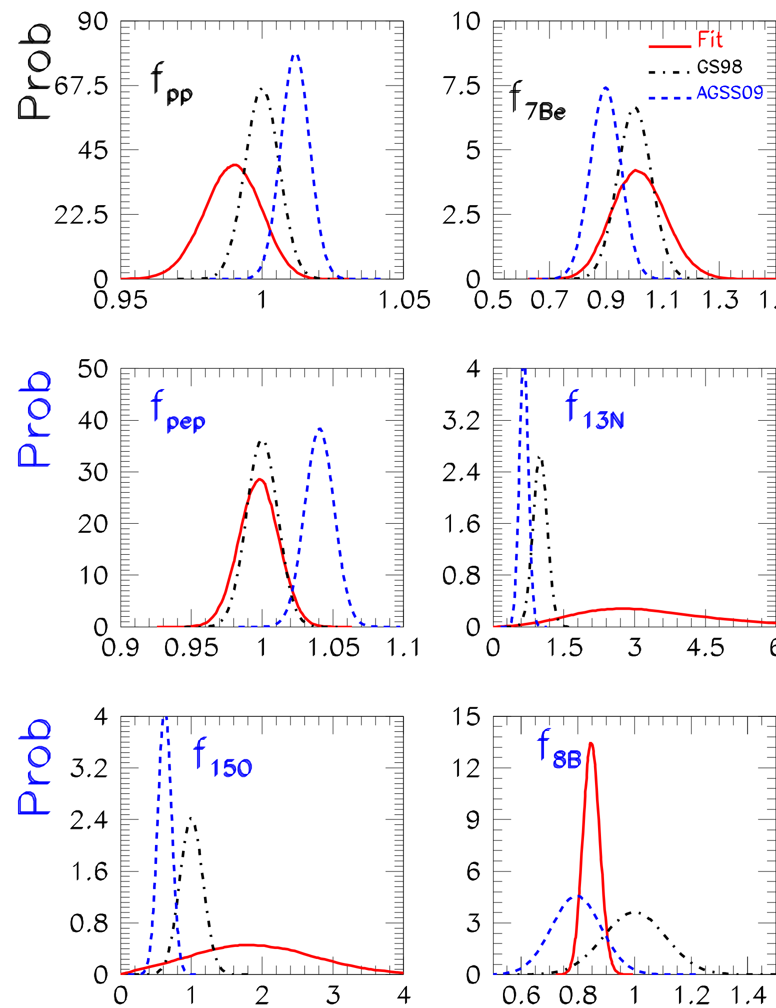
(within luminosity and minimum nuclear physics constraints)

– Two sets of SSM

– Which one does the data favours?

Both models statistically equally probable





MCG-G,Maltoni,Salvado arXiv:0910.4584

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Comments on Solar Neutrino Analysis

- Inclusion of Low Energy Threshold ($T_{\rm eff} > 3.5$ MeV) Analysis SNO Phase I+II

SNO Coll. arXiv:0910.2984, Talk N. Tolich

– Data reduced to an effective $P_{ee}(E_\nu)$
(5 “data” points+ $\Phi_{^8B}$)

$$A(E_\nu) = a_0 + a_1(E_\nu - 10\ \text{MeV})$$

$$P_{ee}^{\rm day}(E_\nu) = c_0 + c_1(E_\nu - 10\ \text{MeV}) + c_2(E_\nu - 10\ \text{MeV})^2$$

$$P_{ee}^{\rm night}(E_\nu) = P_{ee}^{\rm day} \times \frac{1 + A(E_\nu)/2}{1 - A(E_\nu)/2}$$

– Assumes unitarity in 3 flavours

– Not usable for scenarios with sterile neutrinos

– Not usable for scenarios with other functional dependences of $P_{ee}(E_\nu)$

Data

Parameter	Value	Stat	Syst
$\Phi_{^8\rm B}$	5.046	$^{+0.159}_{-0.152}$	$^{+0.107}_{-0.123}$
a_0	0.0325	$^{+0.0366}_{-0.0360}$	$^{+0.0059}_{-0.0092}$
a_1	−0.0311	$^{+0.0279}_{-0.0292}$	$^{+0.0104}_{-0.0056}$
c_0	0.3435	$^{+0.0205}_{-0.0197}$	$^{+0.0111}_{-0.0066}$
c_1	0.00795	$^{+0.00780}_{-0.00745}$	$^{+0.00308}_{-0.00335}$
c_2	−0.00206	$^{+0.00302}_{-0.00311}$	$^{+0.00148}_{-0.00128}$

Correlation

	$\Phi_{^8\rm B}$	a_0	a_1	c_0	c_1	c_2
$\Phi_{^8\rm B}$	1.000	−0.166	0.051	−0.408	0.103	−0.246
a_0	−0.166	1.000	−0.109	−0.263	0.019	−0.123
a_1	0.051	−0.109	1.000	−0.005	−0.499	−0.031
c_0	−0.408	−0.263	−0.005	1.000	−0.101	−0.321
c_1	0.103	0.019	−0.499	−0.101	1.000	−0.067
c_2	−0.246	−0.123	−0.031	−0.321	−0.067	1.000

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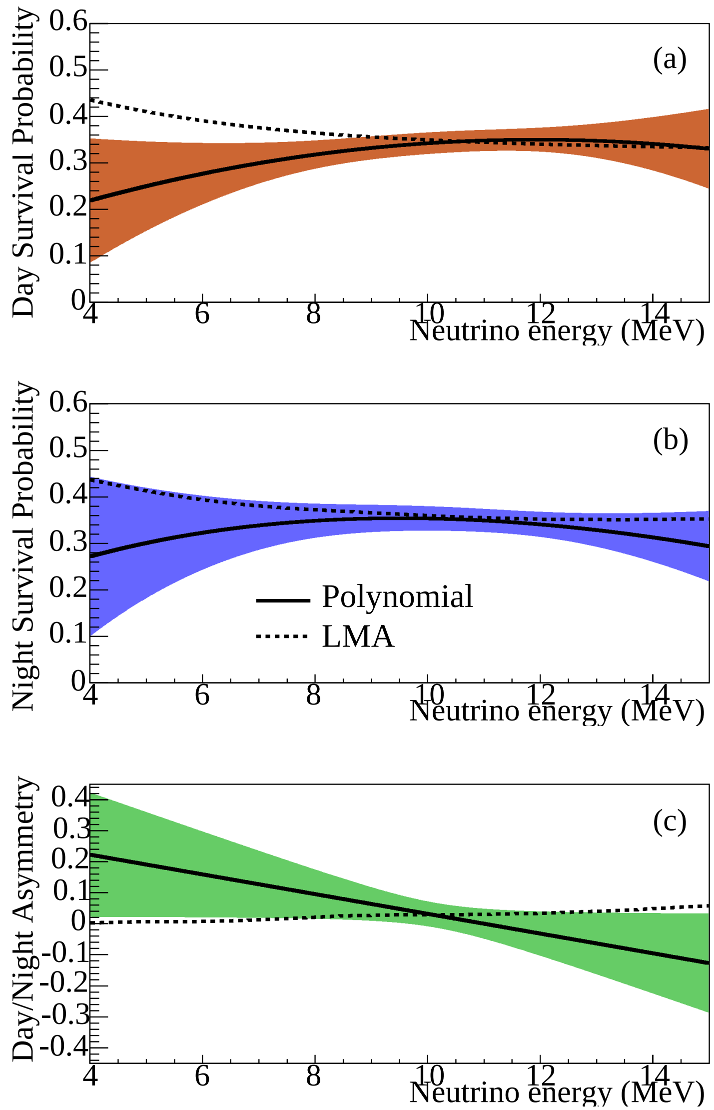

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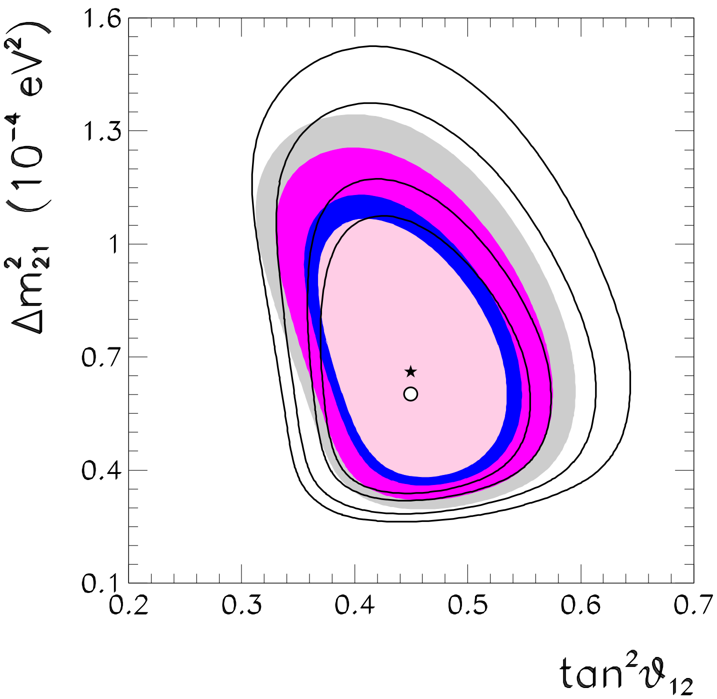
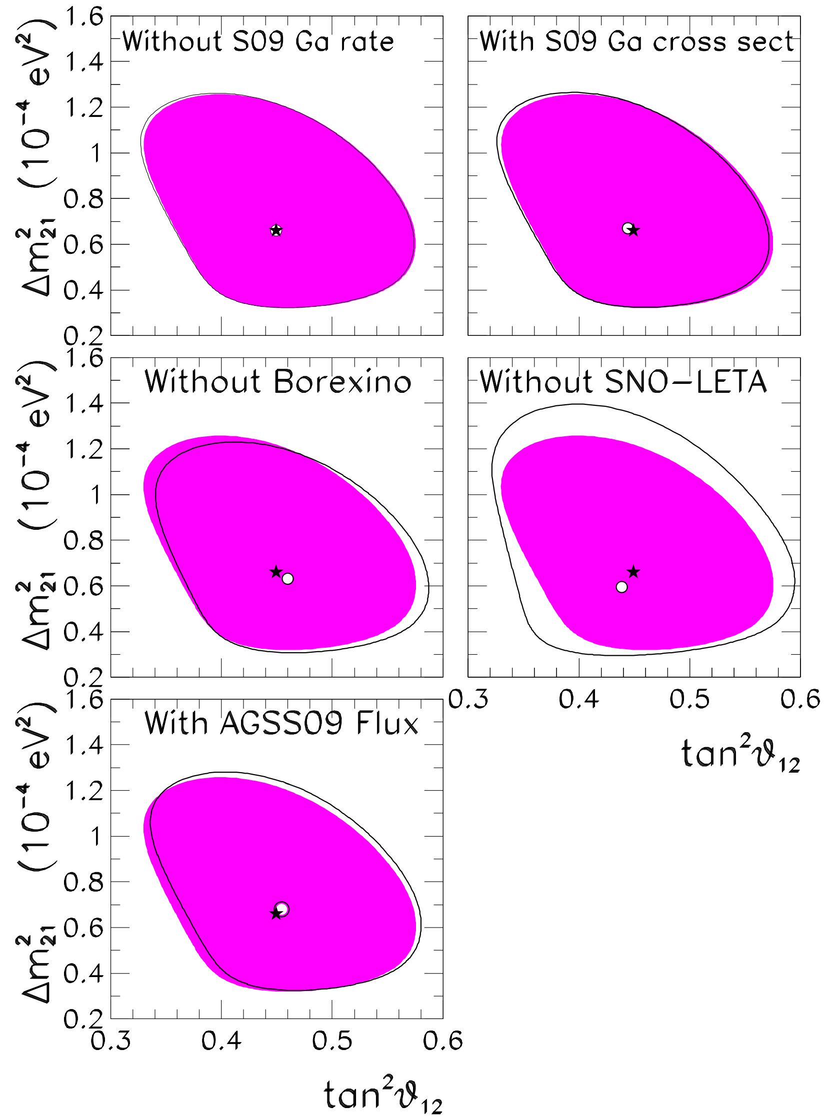
Solar Neutrinos: Leading Oscillations





MCGG, Maltoni, Salvado arXiv:1001.4552

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Solar Neutrino Oscillations: θ_{13}

For solar neutrinos

$$P^{3\nu}_{ee} = \sin^4\theta_{13} + \cos^4\theta_{13} P^{2\nu}_{ee}(\Delta m^2_{21}, \theta_{12})$$

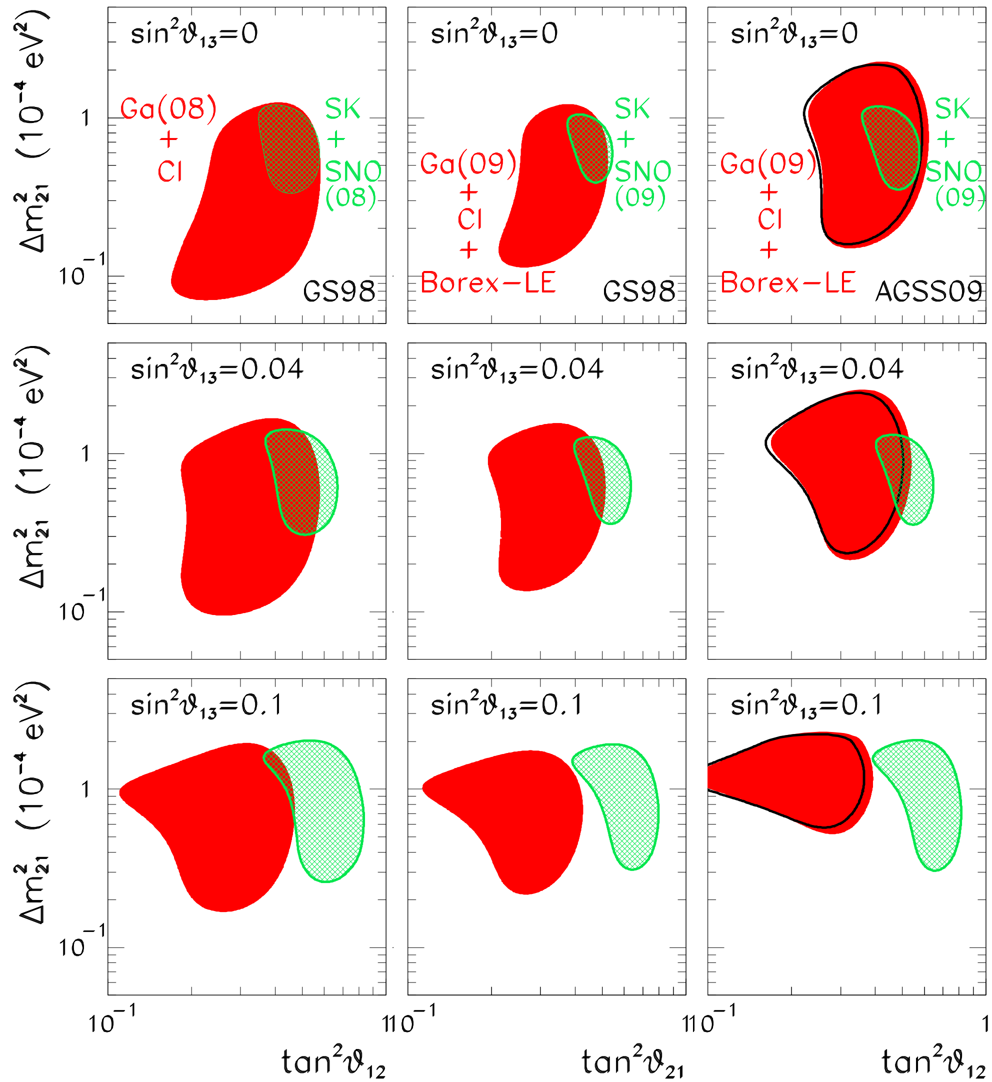
For $E_\nu \lesssim$ few $\times$ 100 KeV

$$P^{2\nu}_{ee}(\Delta m^2_{21}, \theta_{12}) \simeq 1 - \frac{1}{2}\sin^2(2\theta_{12})$$

For $E_\nu \gtrsim$ few $\times$ 1 MeV

$$P^{2\nu}_{ee}(\Delta m^2_{21}, \theta_{12}) \simeq \sin^2(\theta_{12})$$

Goswami and Smirnov, hep-ph/0411359



MCGG, Maltoni, Salvado arXiv:1001.4552

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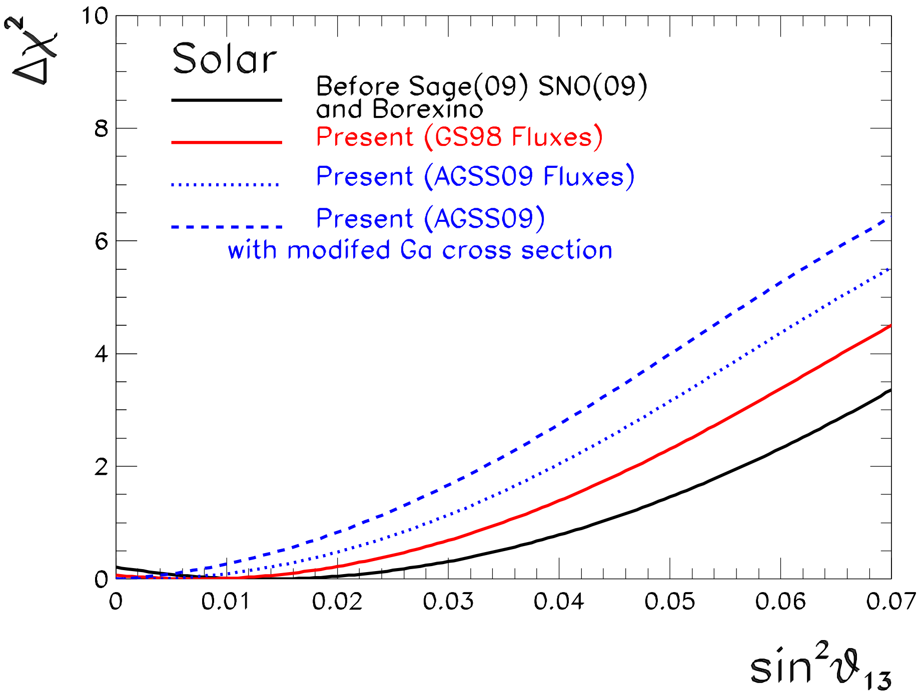
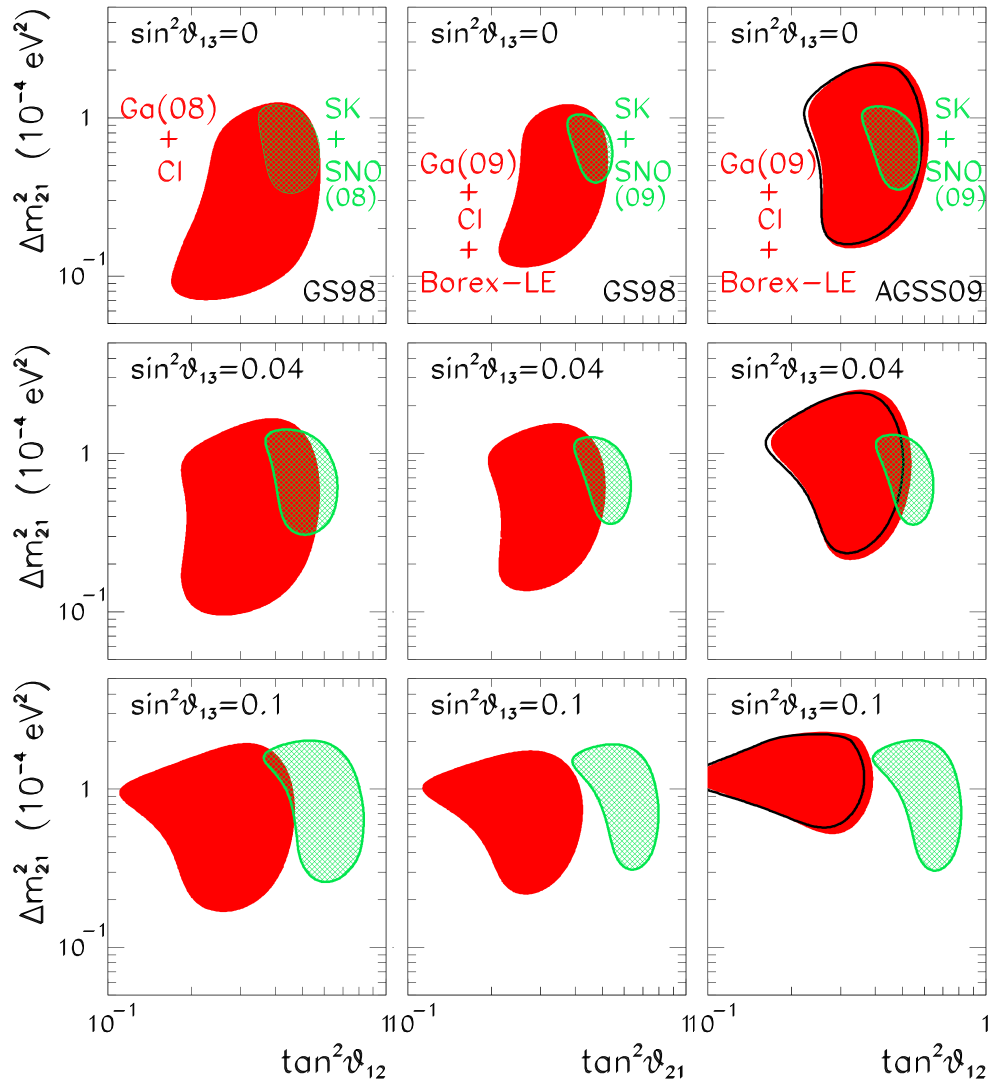
Solar Neutrino Oscillations: θ_{13}

$\theta_{13} = 0$ Best fit





MCGG, Maltoni, Salvado arXiv:1001.4552

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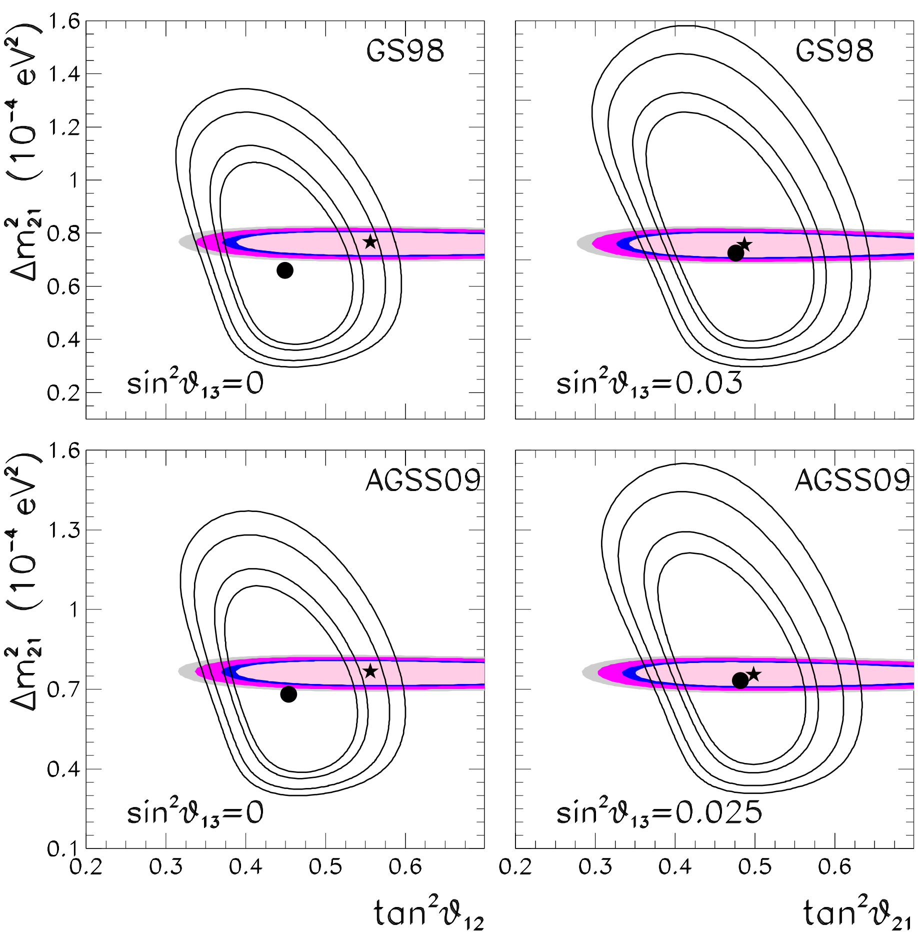
Solar + KamLAND and θ_{13}

After Fogli *etal* arXiv:0806.2649

For KamLAND also $P_{ee}^{3\nu} = \sin^4\theta_{13} + \cos^4\theta_{13} P_{ee}^{2\nu}(\Delta m^2_{21}, \theta_{12})$

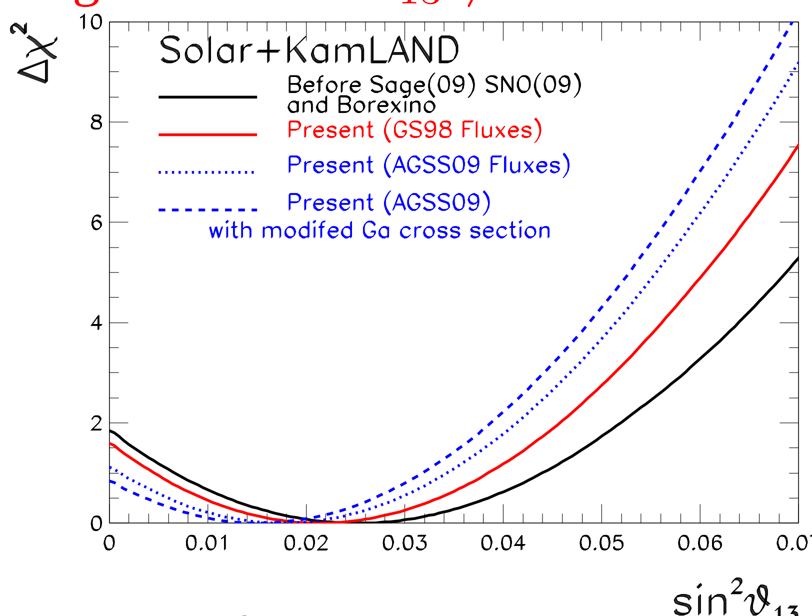
With $P_{ee}^{2\nu,\text{kam}} = 1 - \frac{1}{2}\sin^2(2\theta_{12})\sin^2\frac{\Delta m^2_{21} L}{2E}$

Better Agreement with $\theta_{13} \neq 0$



MCGG, Maltoni, Salvado arXiv:1001.4552

But significance of $\theta_{13} \neq 0$ decreased

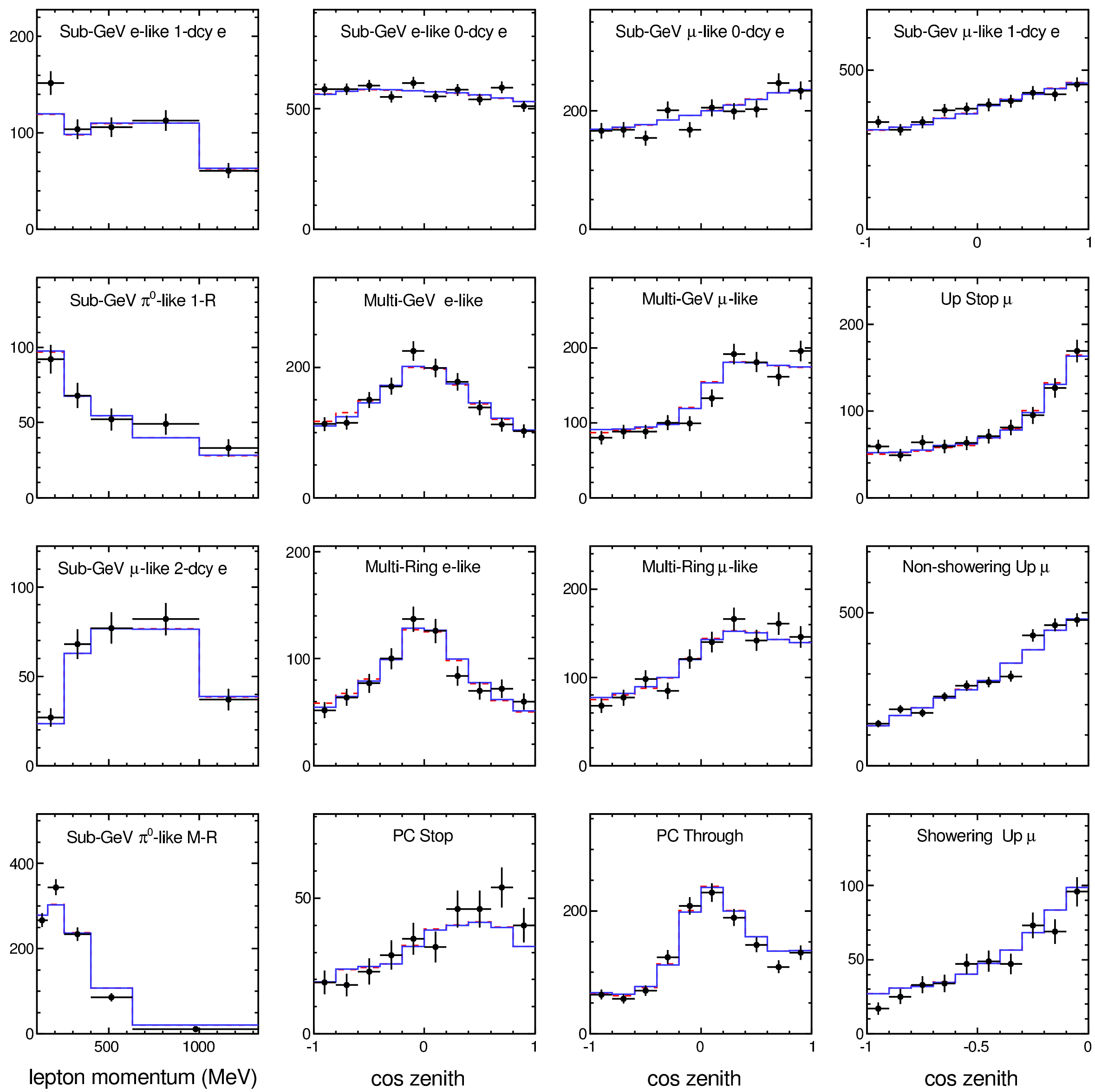


From: $\sin^2\theta_{13} = 0.025 \pm 0.018$

To:
$$\sin^2\theta_{13} = \begin{cases} 0.021 \pm 0.017 & \text{for GS98} \\ 0.017 \pm 0.017 & \text{for AGSS09} \\ 0.015 \pm 0.017 & \text{for AGSS09 with modified Ga CS} \end{cases}$$

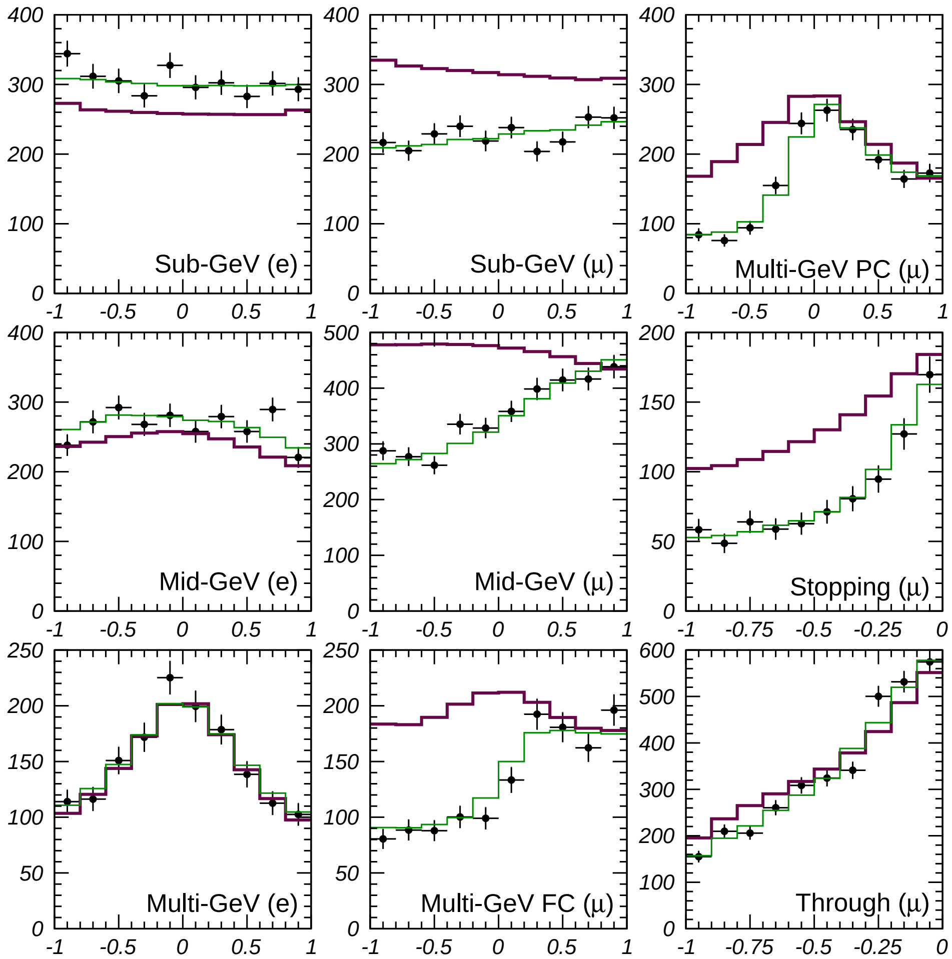
Atmospheric Neutrinos

- Complete SKI+II+III data: SuperKamiokande Coll. arXIv:1002.3471, Talk by T, Kajita



Atmospheric Neutrinos

- Our Analysis of SKI+II+III data: MCGG, Maltoni, Salvado arXiv:1001.4552



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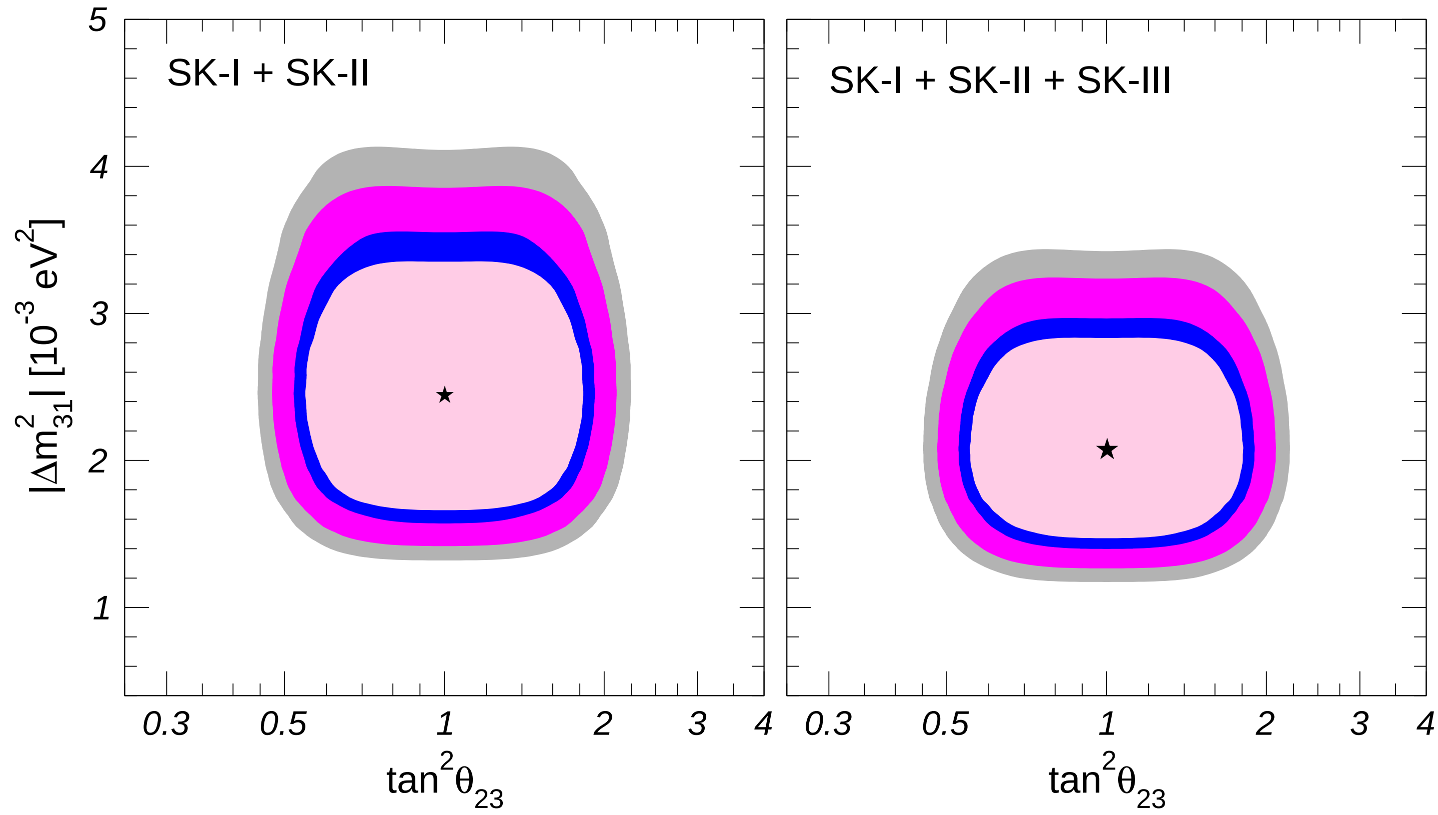
Atmospheric Neutrinos: Leading Oscillations



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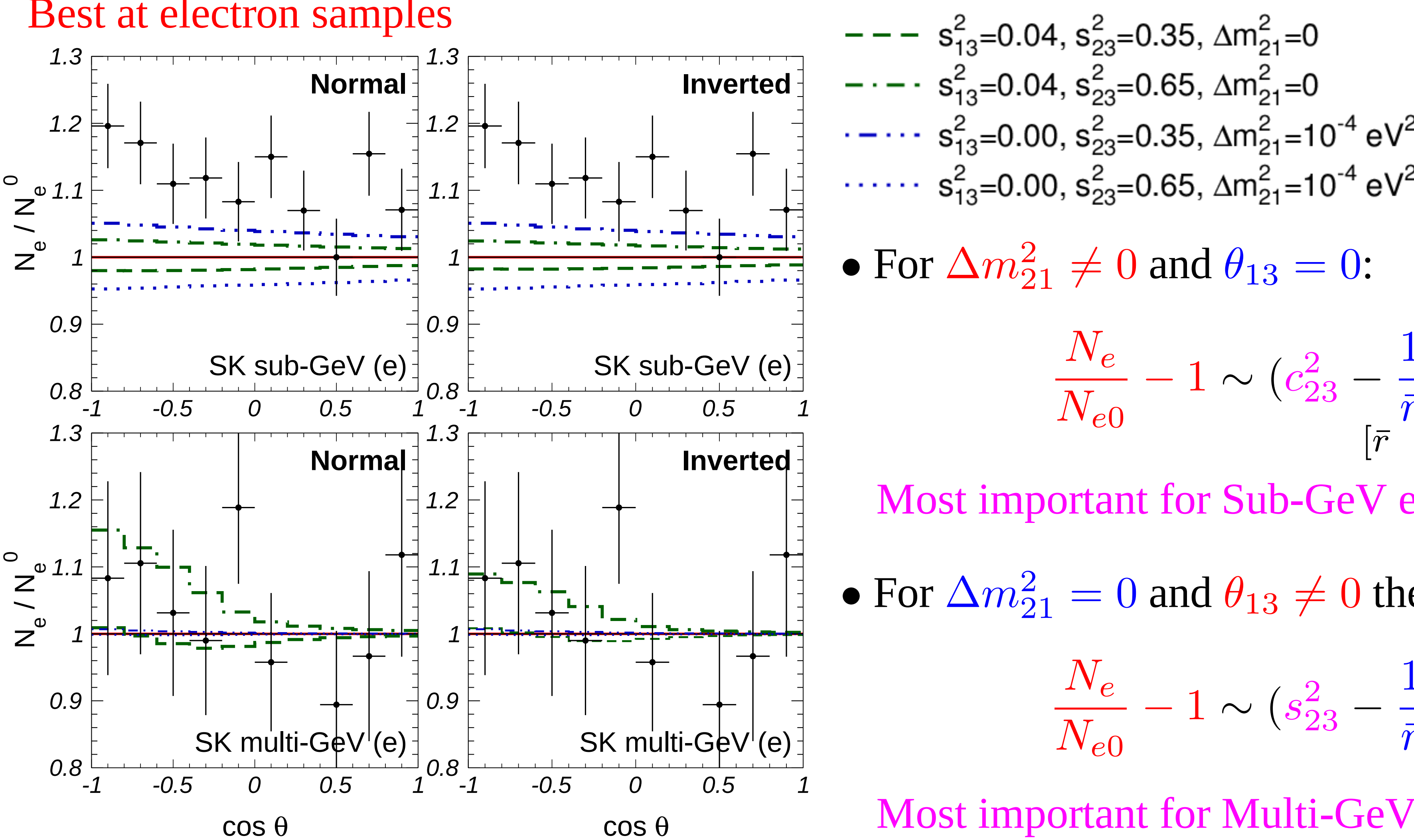
Atmospheric Neutrinos: θ_{13}, Δm^2_{21} and δ effects

Smirnov, Peres 99,01; Fogli, Lisi, Marrone 01; MC G-G, Maltoni 02; MCG-G, Maltoni, Smirnov 04,Smirnov, Peres 01,03

Best at electron samples



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

$$\frac{N_e}{N_{e0}} - 1 \sim (c^2_{23} - \frac{1}{\bar{r}}) \quad [\bar{r} = \frac{N_{\mu 0}}{N_{e0}} \simeq 2]$$

Most important for Sub-GeV e

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

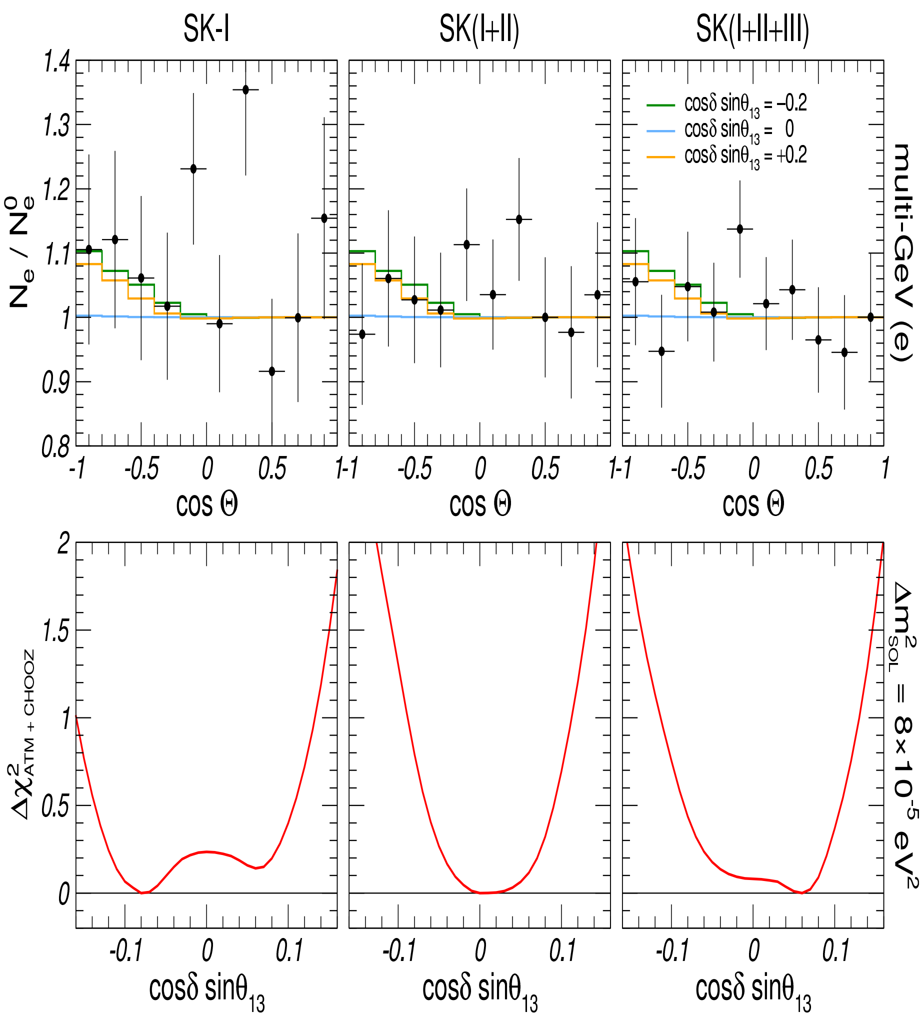
$$\frac{N_e}{N_{e0}} - 1 \sim (s^2_{23} - \frac{1}{\bar{r}})$$

Most important for Multi-GeV e

- For $\Delta m^2_{21} \neq 0$ and $\theta_{13} \neq 0$ sensitivity to δ_{CP} Most important for Sub-GeV e

Atmospheric Neutrinos: Status of θ_{13}

- Excess of multi-GeV e?



* Small ν_e excess SKI $\Rightarrow$ “hint’ of $\theta_{13} \neq 0$

Fogli *etal* arXiv:0806.2649

* Due mainly to two bins in Multi-GeV ν_e
Disappeared in SKI+II

Maltoni Schwetz arXiv:0812.3161

* Less significant in SKI+II+III

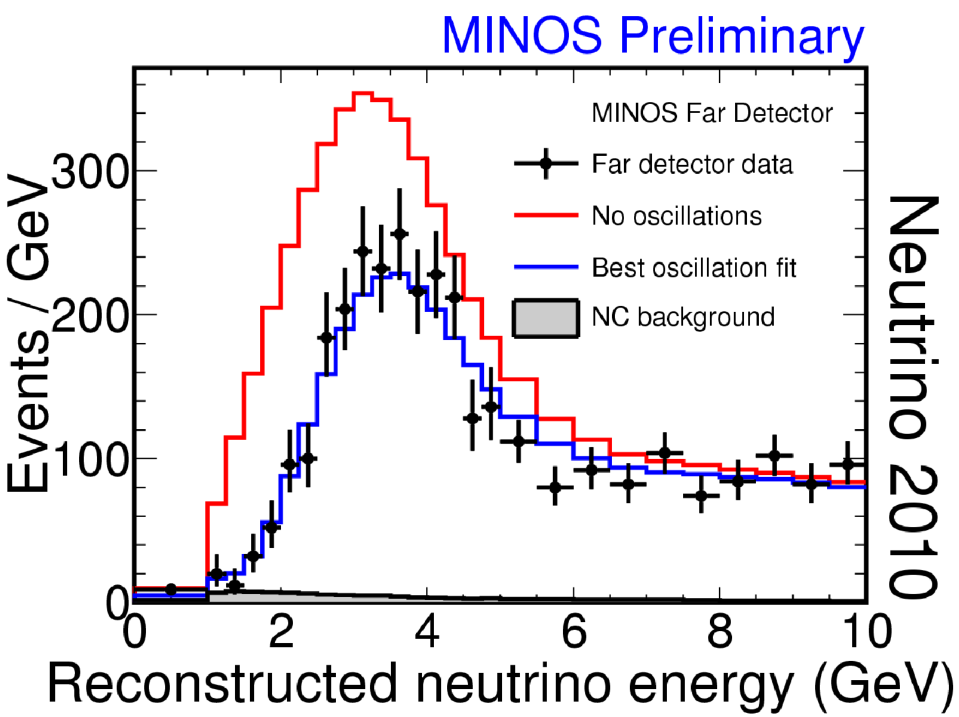
MCGG, Maltoni, Salvado arXiv:1001.4

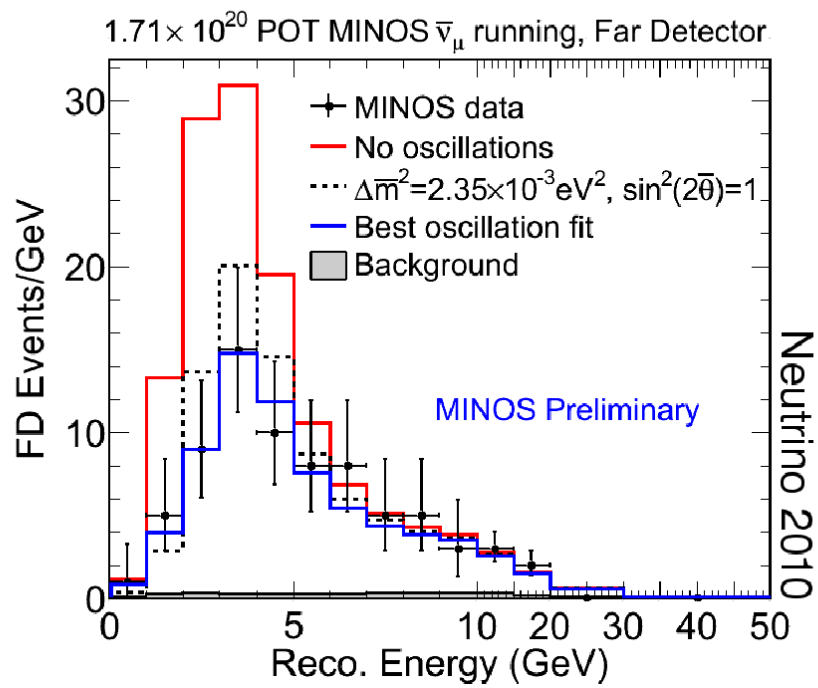
MINOS Disappearance

New Results Presented in ν2010:

$\nu_\mu \to \nu_\mu$ 7.2×10^{20} POT

$\overline{\nu}_\mu \to \overline{\nu}_\mu$ 1.7×10^{20} POT



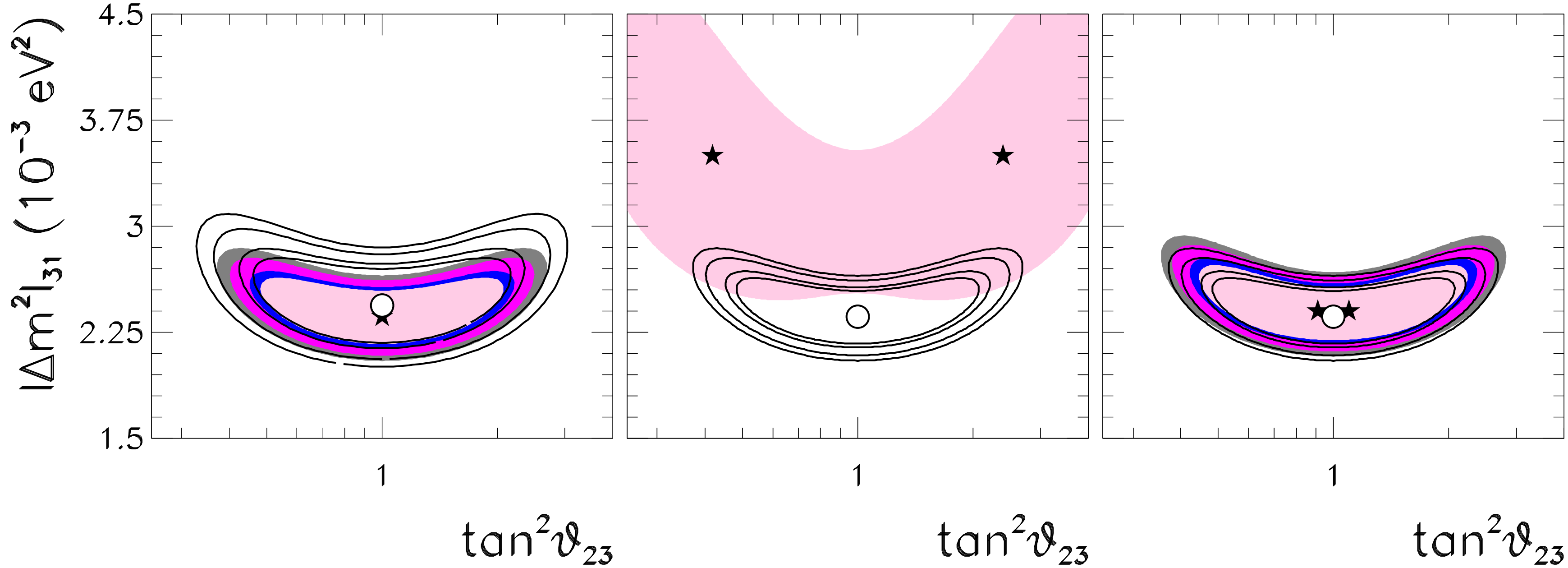


MINOS Disappearance: Leading Oscillations

$\nu_\mu \to \nu_\mu$ 3.4×10^{20} POT versus $\nu_\mu \to \nu_\mu$ 7.2×10^{20} POT

$\nu_\mu \to \nu_\mu$ 7.2×10^{20} POT versus $\overline{\nu}_\mu \to \overline{\nu}_\mu$ 1.77×10^{20} POT

$\nu_\mu \to \nu_\mu$ 7.2×10^{20} POT versus $\nu_\mu \to \nu_\mu + \overline{\nu}_\mu \to \overline{\nu}_\mu$



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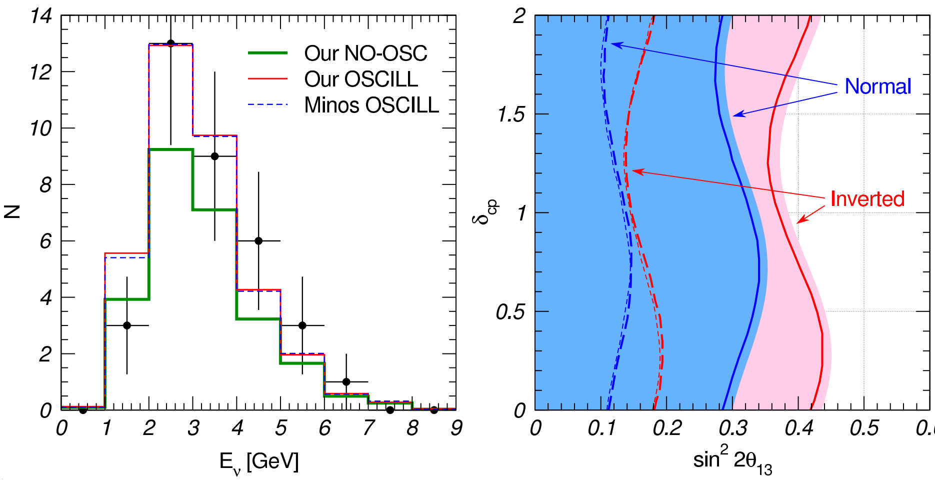
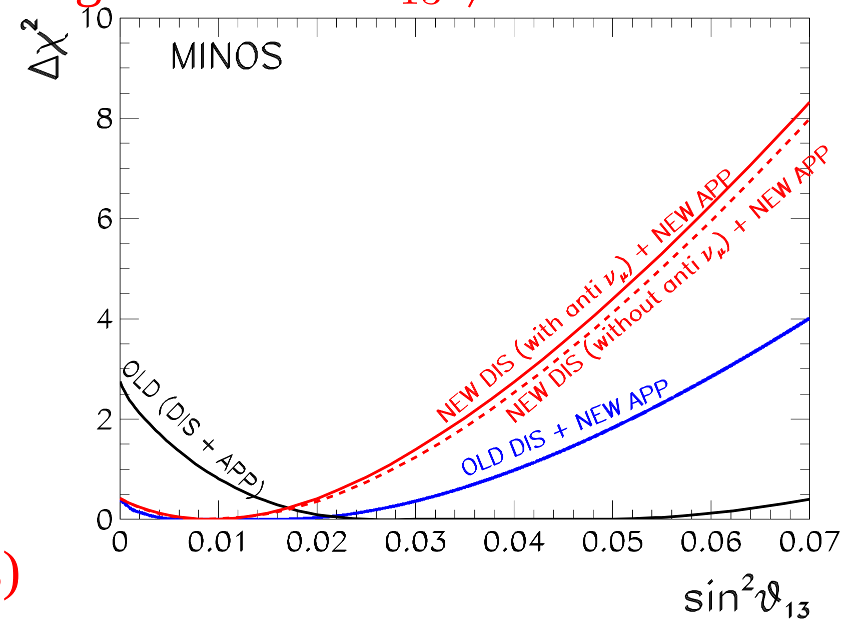
MINOS Appearance: θ_{13}

With 3.15×10^{20} POT: arXiv:0909.4996

35 events for $27 \pm 5 \pm 2$ bckg (1.5 σ excess)

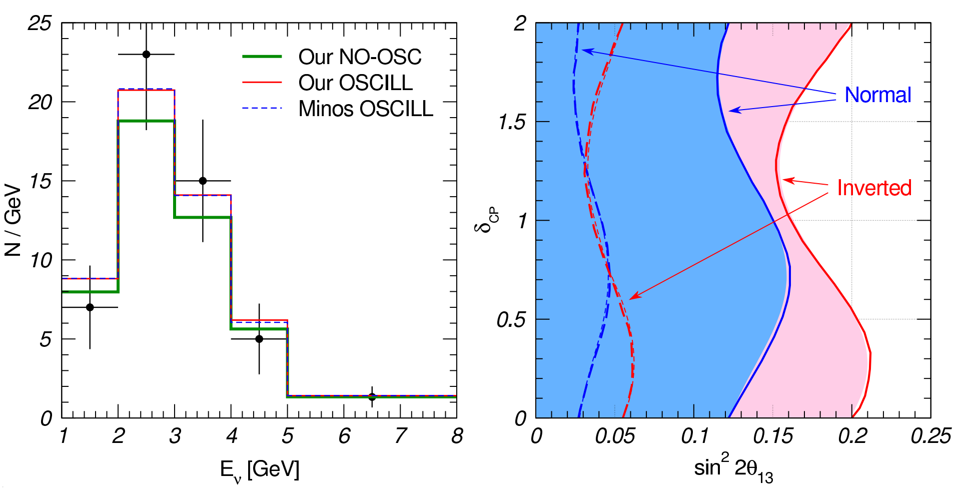


Significance of $\theta_{13} \neq 0$ decreased



With 7×10^{20} POT: April 2010

54 events for $49.1 \pm 7 \pm 2.7$ bckg (0.7 σ excess)



MCGG, Maltoni, Salvado arXiv:1001.4552

GLOBAL ANALYSIS

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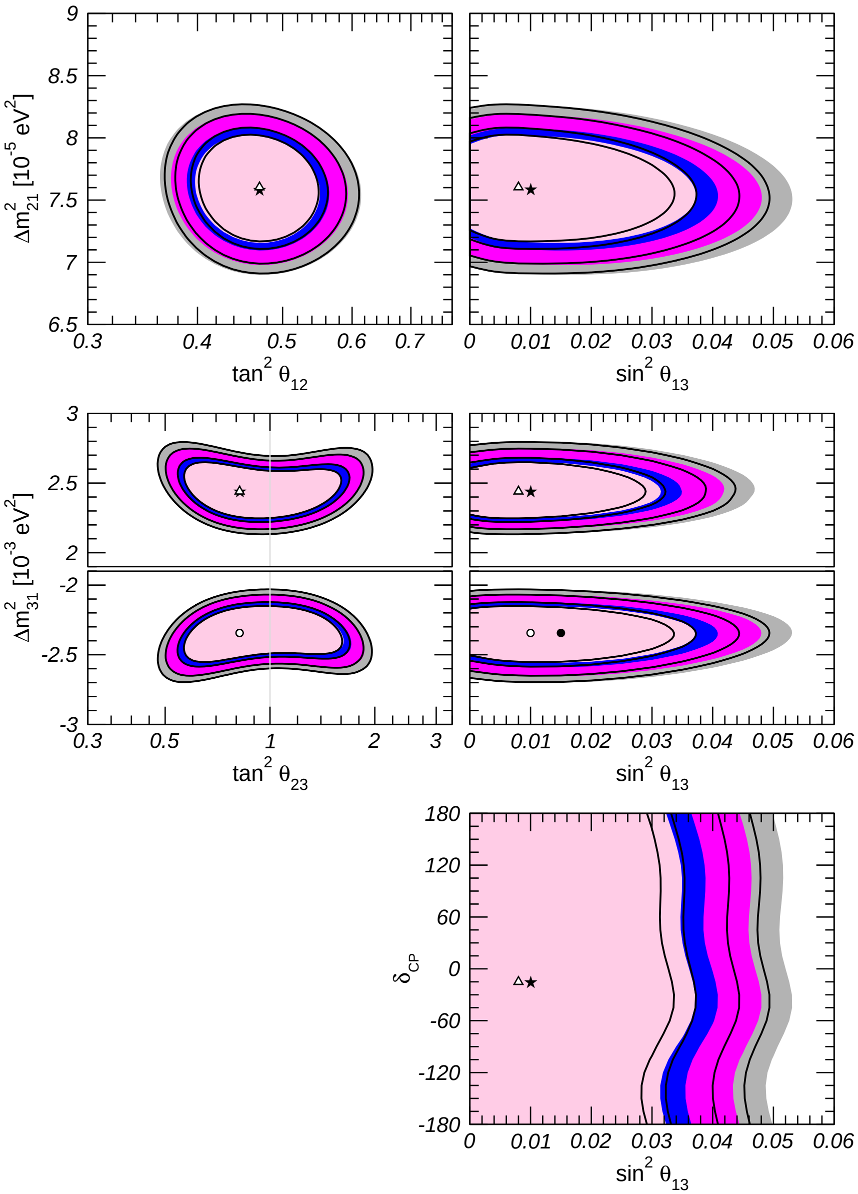
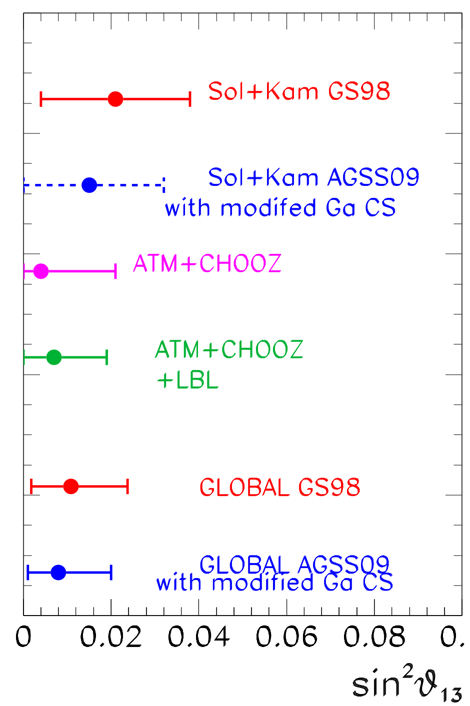
GS98 (full) or AGSS09' (lines)





	GS98	AGSS09 with modified Ga CS
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$= 7.59 \pm 0.20 \ \left({}^{+0.61}_{-0.69}\right)$	Same
$\frac{\Delta m^2_{31}}{10^{-3}\ \mathrm{eV}^2}$	$= \begin{cases} -2.41 \pm 0.09 \ \left({}^{+0.30}_{-0.27}\right) \\ +2.44 \pm 0.09 \ \left({}^{+0.30}_{-0.27}\right) \end{cases}$	Same
θ_{12}	$= 34.4 \pm 1.0 \ \left({}^{+3.2}_{-2.9}\right)^\circ$	$34.5 \pm 1.0 \ \left({}^{+3.2}_{-2.8}\right)^\circ$
θ_{23}	$= 42.3\ {}^{+5.2}_{-2.8} \ \left({}^{+11.3}_{-7.0}\right)^\circ$	Same
θ_{13}	$= 5.9\ {}^{+2.9}_{-2.7} \ (\leq 12.6)^\circ$	$5.1\ {}^{+3.0}_{-3.3} \ (\leq 12.1)^\circ$
$[\sin^2\theta_{13}$	$= 0.0108\ {}^{+0.013}_{-0.009} \ (\leq 0.048)]$	$[0.008\ {}^{+0.012}_{-0.007} \ (\leq 0.044$
δ_{CP}	$\in [0,\ 360]$	Same

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Neutrino Mass Scale

$^3H \to ^3He + e + \overline{\nu}_e$: for both Dirac or Majorana ν's

$$m_{\nu_e} = \sum m_j |U_{ej}|^2 = \sum_i m_i^2 |U_{ei}|^2 = c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2 < 2.2 \text{ eV}$$ (95 % C

Katrin, Talk by E. Ferri

ν-less Double-β decay: $(A, Z) \to (A, Z+2) + e^- + e^-$ for majorana $\nu' s$

$$m_{ee} = |\sum U_{ej}^2 m_j| = \left| c_{13}^2 c_{12}^2 m_1 \, e^{i\eta_1} + c_{13}^2 s_{12}^2 m_1 \, e^{i\eta_2} + s_{13}^2 \, e^{-i\delta_{CP}} \, , \right| \quad < \text{few } \; 0.1 \text{ eV}$$

+theor. uncert. $< ?$

Talks by F. Iacello and A. Giullani

COSMO:CMB, LSS, Type I-SN ... : for both Dirac or Majorana ν's

$$\sum m_i = m_1 + m_2 + m_3$$

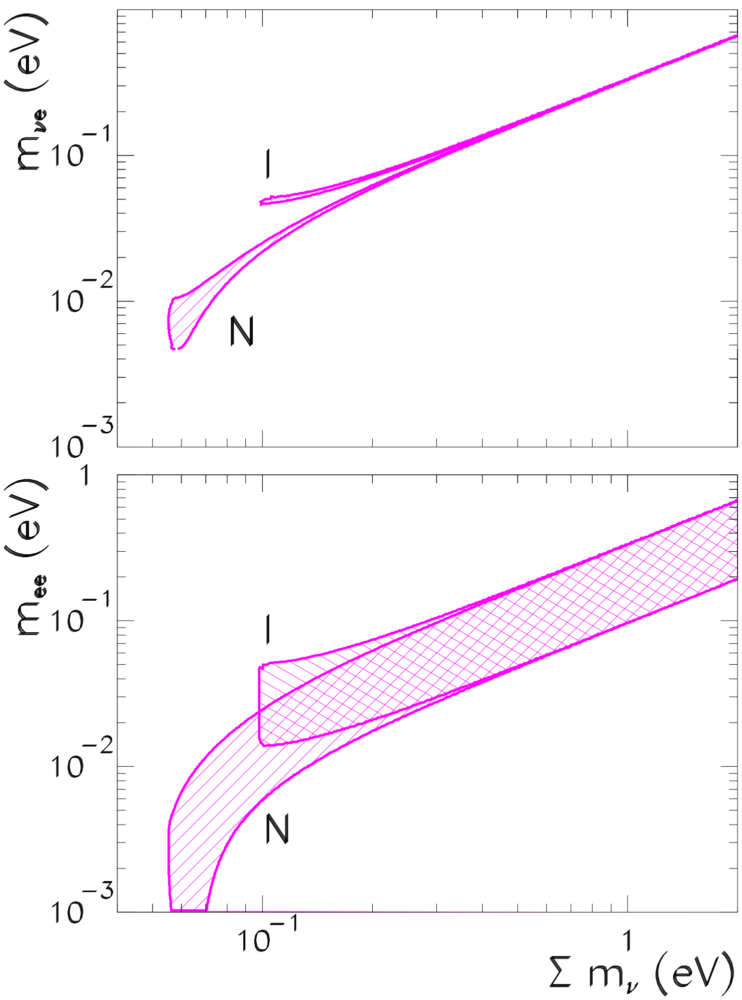
Talk by A. Cooray

Neutrino Mass Scale: The Cosmo-Lab Connection

Global oscillation analysis

⇒ Correlated ranges for m_{ν_e}, m_{ee} and $\sum m_\nu$
(Fogli *et al* hep-ph/0408045)

From Update MMG-G,Maltoni, Salvado at 95% CL



Neutrino Mass Scale: The Cosmo-Lab Connection

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$\Rightarrow$ Correlated ranges for m_{ν_e}, m_{ee} and $\sum m_\nu$

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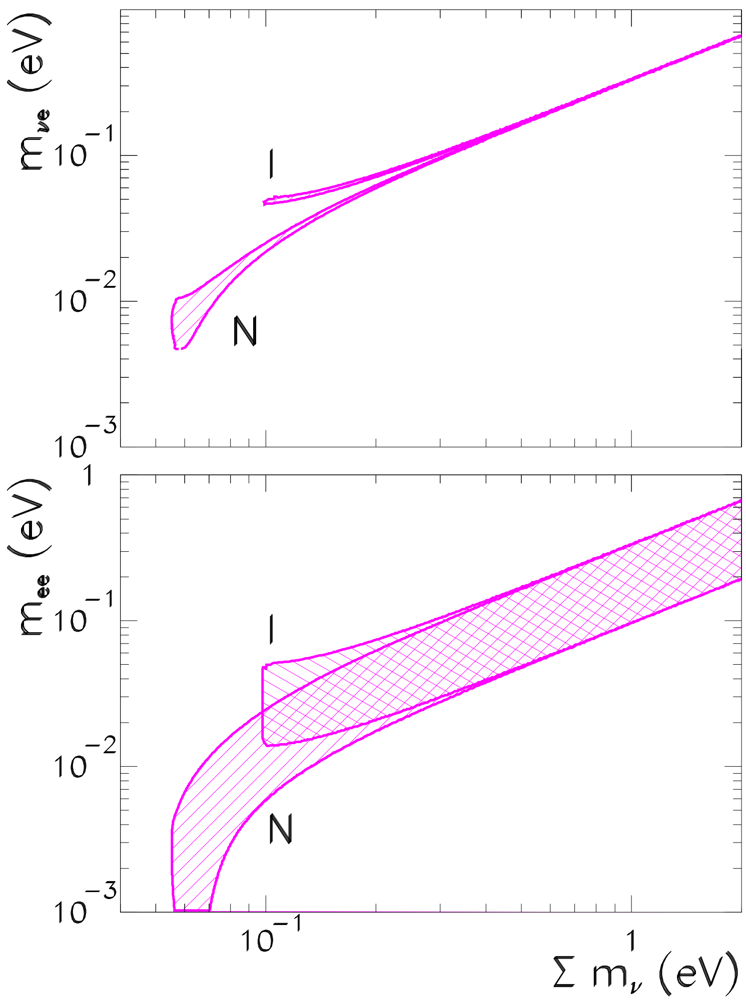


Analysis of Comological data

$\Rightarrow$ Constraint on $\sum m_\nu$. But careful

Neutrino Mass Scale: The Cosmo-Lab Connection

Bound depends on Cosmological model (and on Cosmo observables considered)

For example from Analisys beyond ΛCDM with:

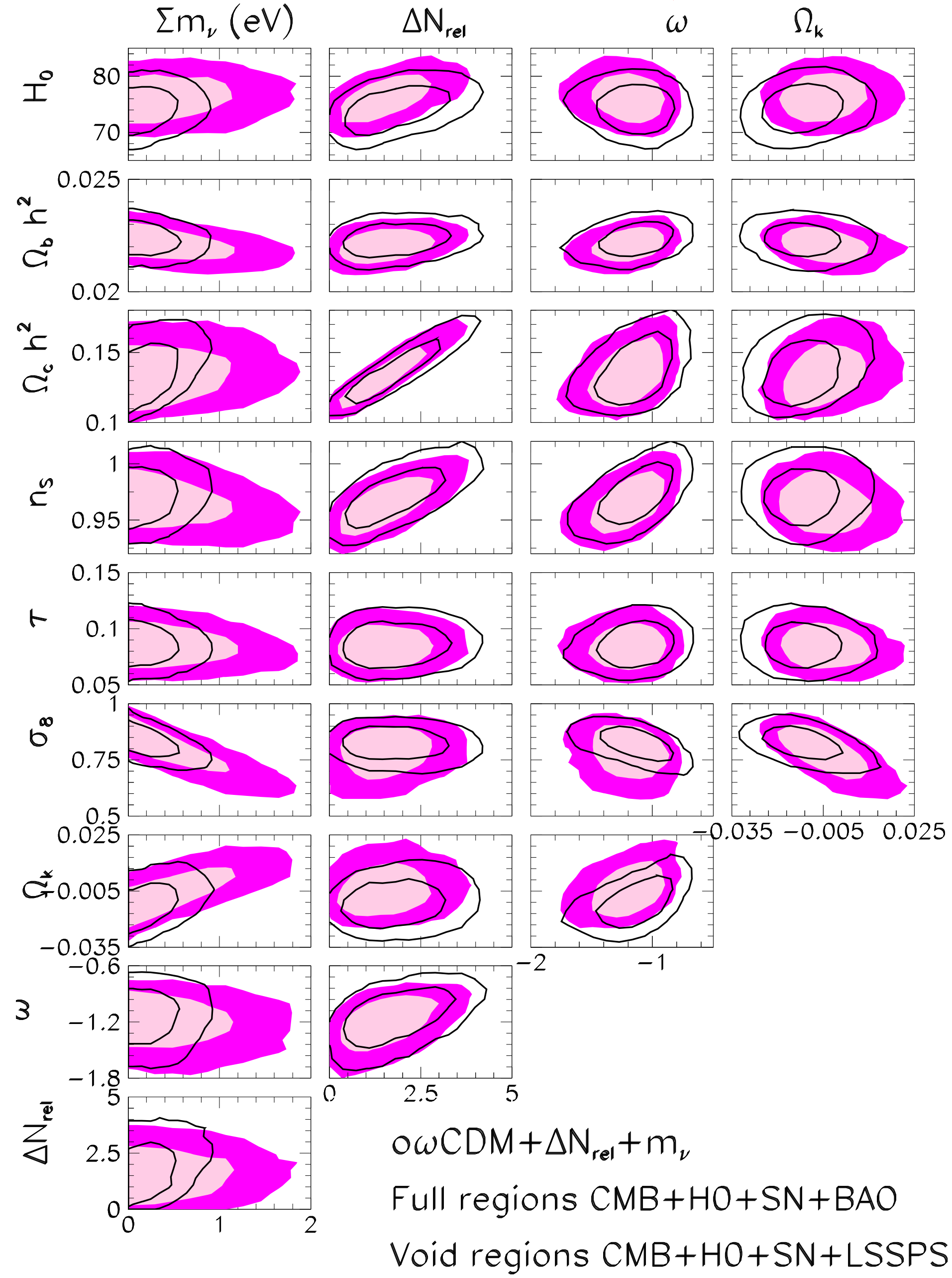
– m_ν

– Equation of state of DE $\omega \neq -1$

– Extra radiation ($\Delta N_{\rm eff}$)

– Non-flatness ($\Omega_k \neq 0$)

MCG-G,Maltoni, Salvado arXiv 1006.3795



Neutrino Mass Scale: The Cosmo-Lab Connection

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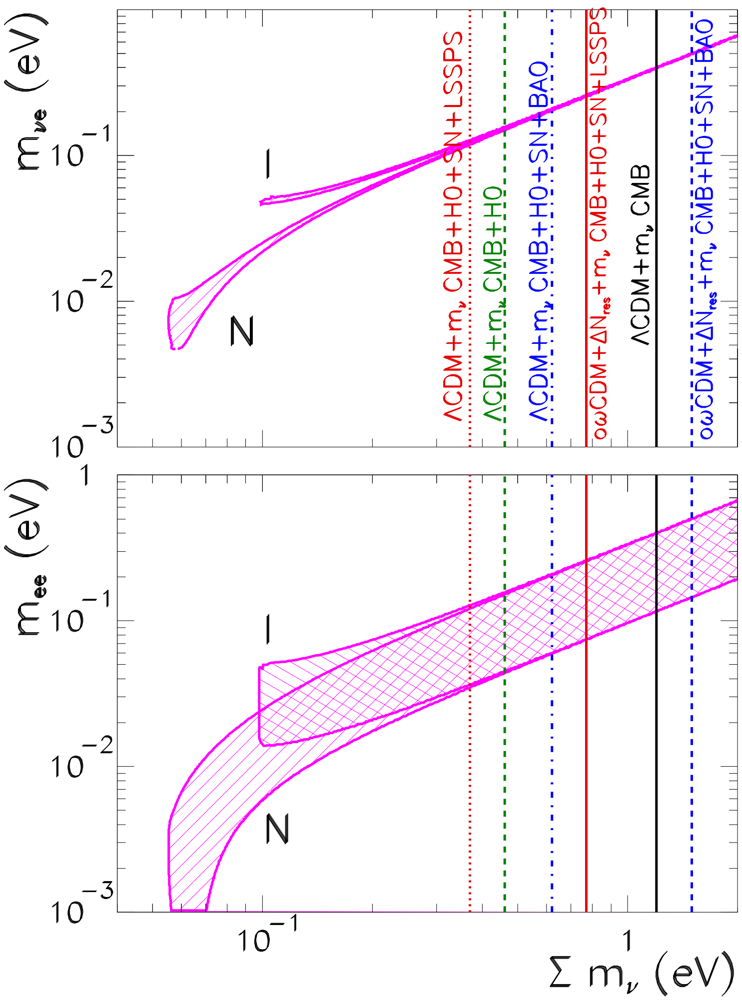


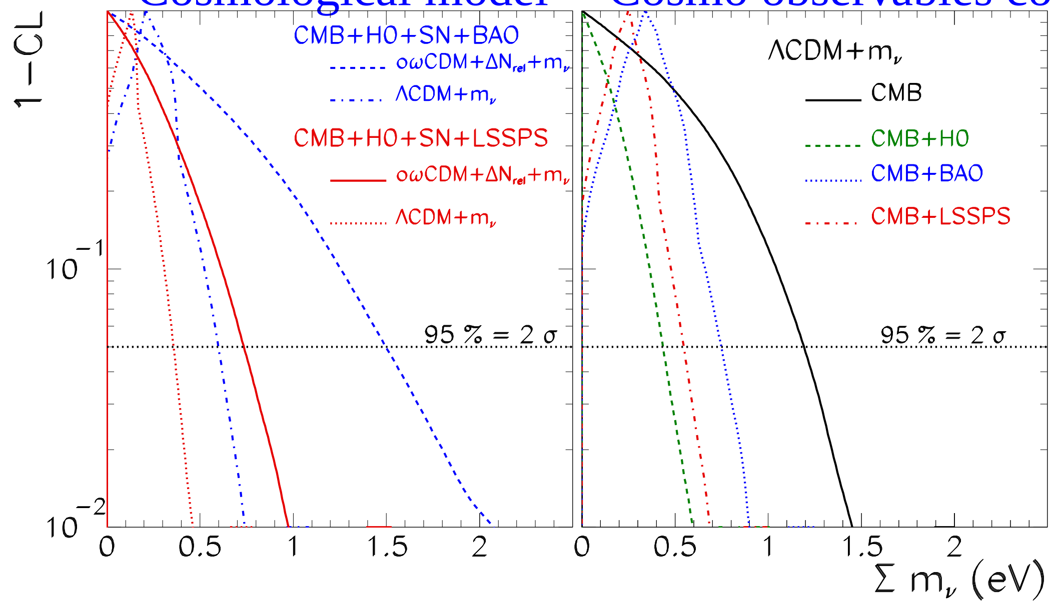
Analysis of Comological data

$\Rightarrow$ Constraint on $\sum m_\nu$

But bound depends on:

Cosmological model

Cosmo observables conside



Model	Observables	Σm_ν (eV) 95% Bound
$o\omega\text{CDM} + \Delta N_{\text{rel}} + m_\nu$	CMB+HO+SN+BAO	≤ 1.5
$o\omega\text{CDM} + \Delta N_{\text{rel}} + m_\nu$	CMB+HO+SN+LSSPS	≤ 0.76
$\Lambda\text{CDM} + m_\nu$	CMB+H0+SN+BAO	≤ 0.61
$\Lambda\text{CDM} + m_\nu$	CMB+H0+SN+LSSPS	≤ 0.36
$\Lambda\text{CDM} + m_\nu$	CMB (+SN)	≤ 1.2
$\Lambda\text{CDM} + m_\nu$	CMB+BAO	≤ 0.75
$\Lambda\text{CDM} + m_\nu$	CMB+LSSPS	≤ 0.55
$\Lambda\text{CDM} + m_\nu$	CMB+H0	≤ 0.45

From MCG-G,Maltoni, Salvado arXiv 1006.3795

Neutrino Mass Scale: The Cosmo-Lab Connection

		Cosmo+Oscillations 95% Ranges		
Model	Observables	m_{ν_e} (eV)	m_{ee} (eV)	Σm_ν (eV)
$o\omega$CDM $+\Delta N_{\rm rel} + m_\nu$	CMB+HO+SN+BAO	N $[0.0047 - 0.51]$ I $[0.047 - 0.51]$	N $[0.00 - 0.51]$ I $[0.014 - 0.51]$	N $[0.0056 - 1.5]$ I $[0.0098 - 1.5]$
$o\omega$CDM $+\Delta N_{\rm rel} + m_\nu$	CMB+HO+SN+LSSPS	N $[0.0047 - 0.27]$ I $[0.047 - 0.27]$	N $[0.00 - 0.25]$ I $[0.014 - 0.25]$	N $[0.0056 - 0.75]$ I $[0.0098 - 0.76]$
ΛCDM $+ m_\nu$	CMB+H0+SN+BAO	N $[0.0047 - 0.20]$ I $[0.048 - 0.21]$	N $[0.00 - 0.20]$ I $[0.014 - 0.21]$	N $[0.0056 - 0.61]$ I $[0.0097 - 0.61]$
ΛCDM $+ m_\nu$	CMB+H0+SN+LSSSP	N $[0.0047 - 0.12]$ I $[0.047 - 0.12]$	N $[0.00 - 0.12]$ I $[0.014 - 0.12]$	N $[0.0056 - 0.36]$ I $[0.0098 - 0.36]$
ΛCDM $+ m_\nu$	CMB (+SN)	N $[0.0047 - 0.40]$ I $[0.047 - 0.40]$	N $[0.00 - 0.40]$ I $[0.014 - 0.41]$	N $[0.0056 - 1.2]$ I $[0.0098 - 1.2]$
ΛCDM $+ m_\nu$	CMB+BAO	N $[0.0052 - 0.25]$ I $[0.047 - 0.25]$	N $[0.00 - 0.25]$ I $[0.014 - 0.25]$	N $[0.0056 - 0.75]$ I $[0.0099 - 0.75]$
ΛCDM $+ m_\nu$	CMB+LSSPS	N $[0.0047 - 0.18]$ I $[0.048 - 0.19]$	N $[0.00 - 0.18]$ I $[0.014 - 0.19]$	N $[0.0056 - 0.55]$ I $[0.0099 - 0.55]$
ΛCDM $+ m_\nu$	CMB+H0	N $[0.0047 - 0.14]$ I $[0.047 - 0.16]$	N $[0.00 - 0.14]$ I $[0.014 - 0.16]$	N $[0.0056 - 0.44]$ I $[0.0097 - 0.45]$

From MCG-G,Maltoni, Salvado arXiv 1006.3795

And MiniBooNE?

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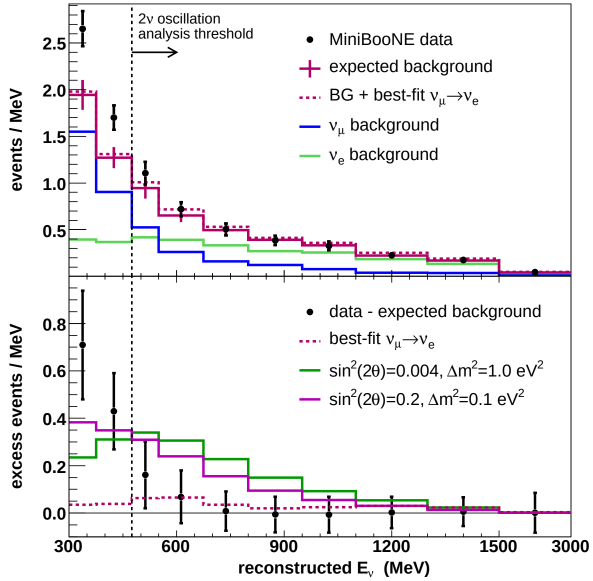
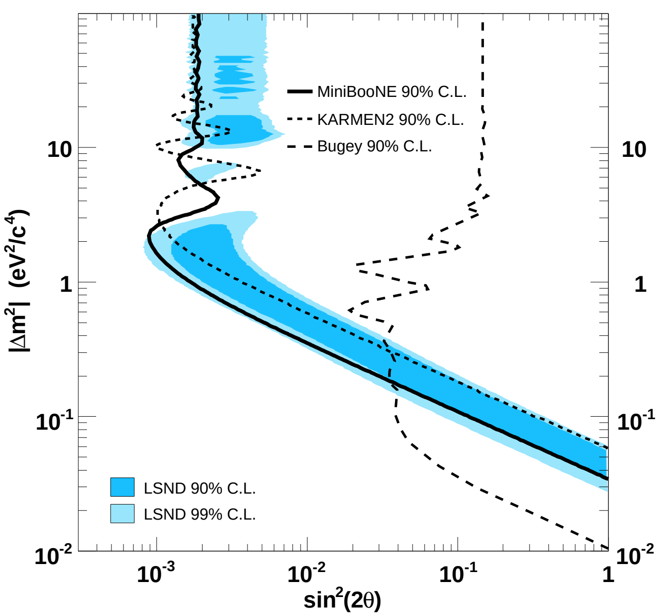
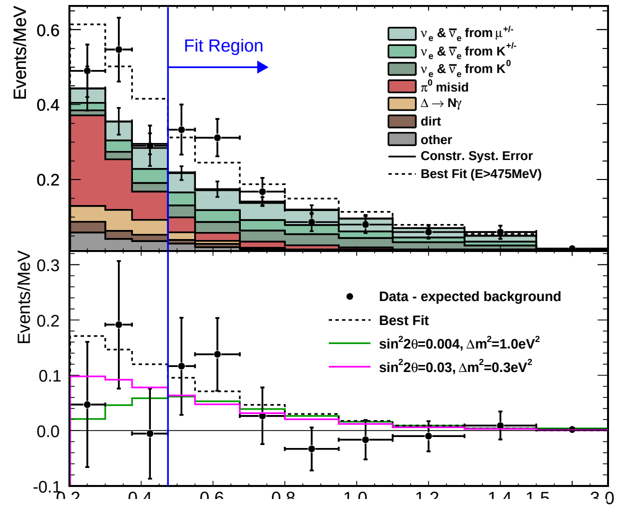
Talk by C. Polly

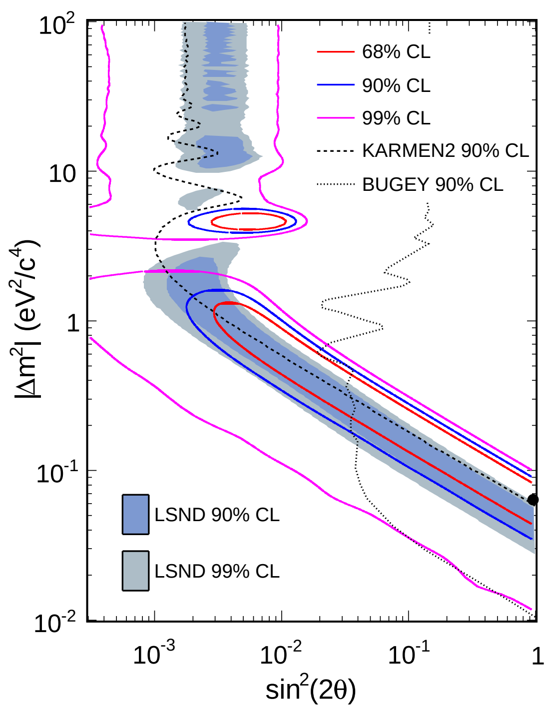
Neutrino Results (2007): No Signal, Bound





Antieutrino Results (2010): Signal

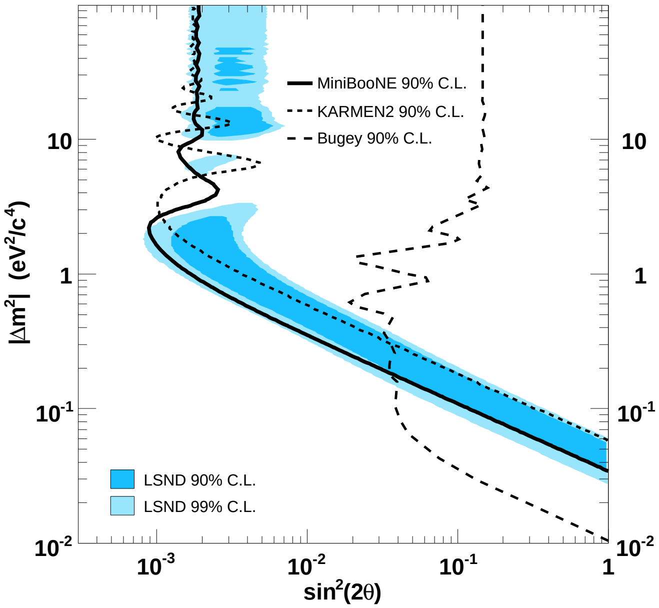




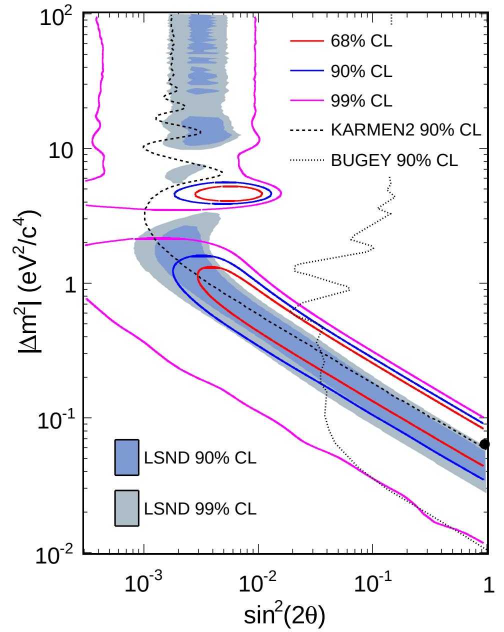
MiniBooNE versus LSND: A Comment

nzalez-Garcia

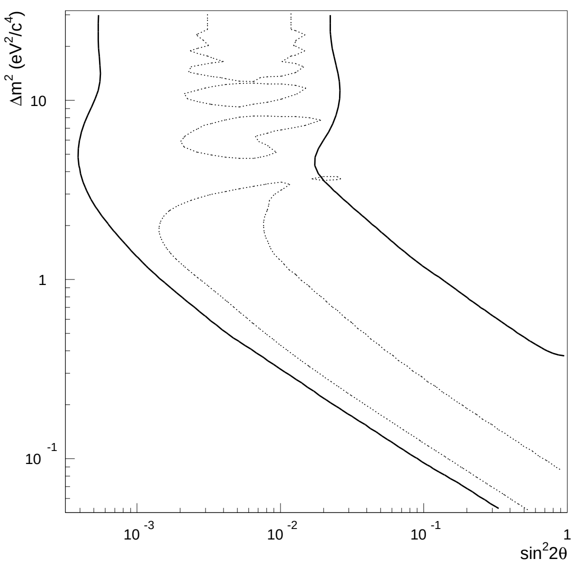
Neutrino Results (2007): No Signal, Bound



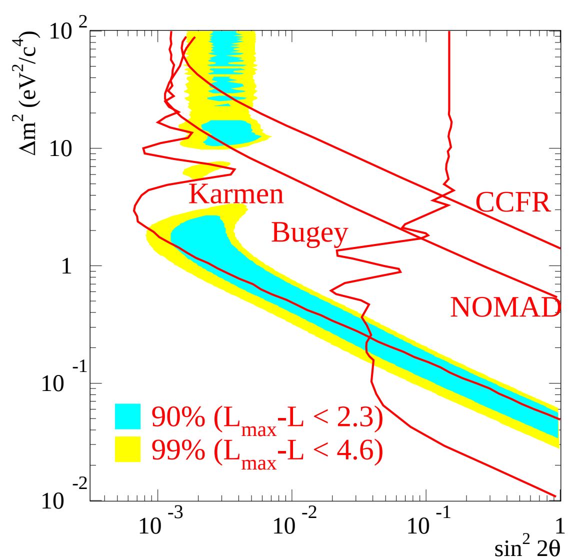
Antieutrino Results (2010): Signal



LSND: hep-ex/9709006 Signal



LSND hep-ex/0104049 Signal



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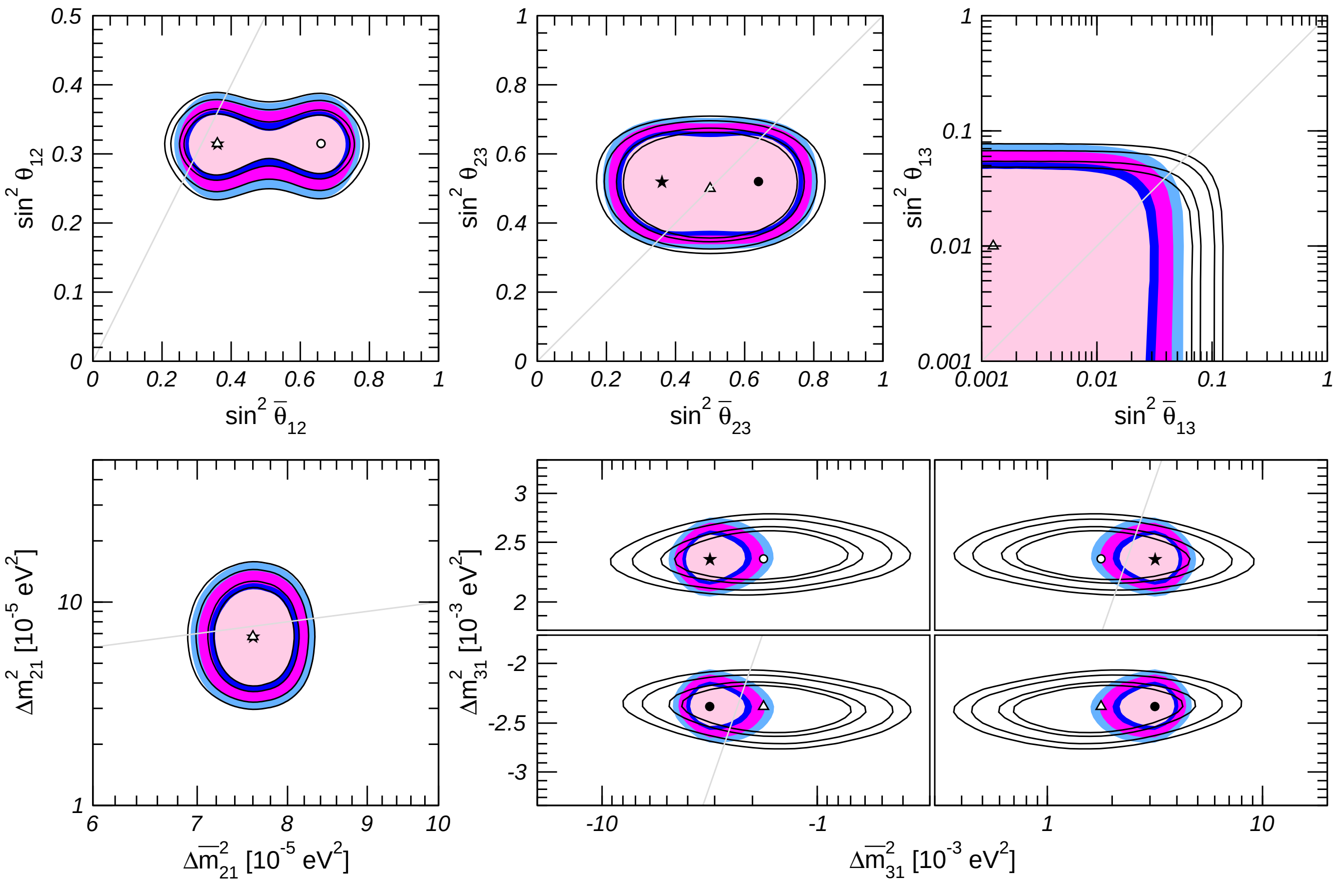
Status of CPT Violation

From Global Fit to Solar+ATM+Reactor+MINOS with 3ν and $3\overline{\nu}$ and C$\not{P}$T

Update by M. Maltoni



$\chi^{2,CPT}_{min} - \chi^{2,C\not{P}T}_{min} = 4.5$

Driven Mostly By MINOS

But $\Delta\overline{m}^2_{31} \leq 3 \times 10^{-3}$

Not possible to explain

MiniBooNE only with CPT

More (sterile) states

+ new CP or CPT violation?

Akhmedov,Schwetz 1007.4171

Talk by Akhmedov

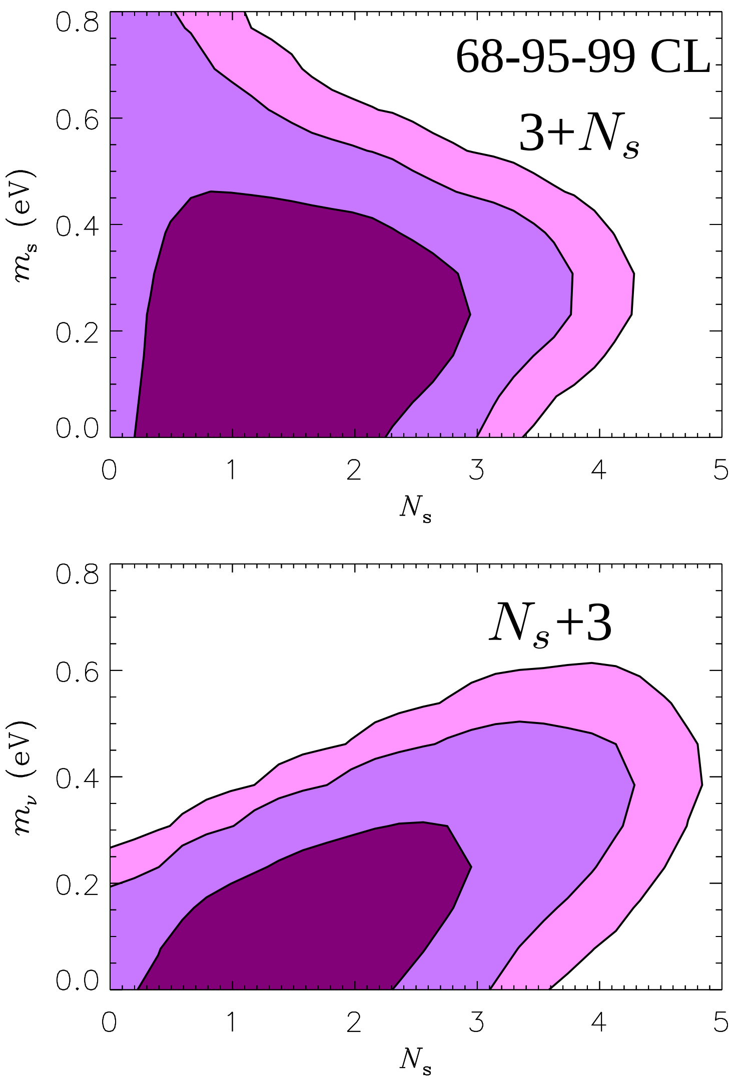
Barger,Marfatia (2003)…

Steriles in Cosmology

Comology Fits Favours Extra Radiation

Analysis in ΛCDM with massive neutrinos

Hamann *etal* arXiv:1006.5276

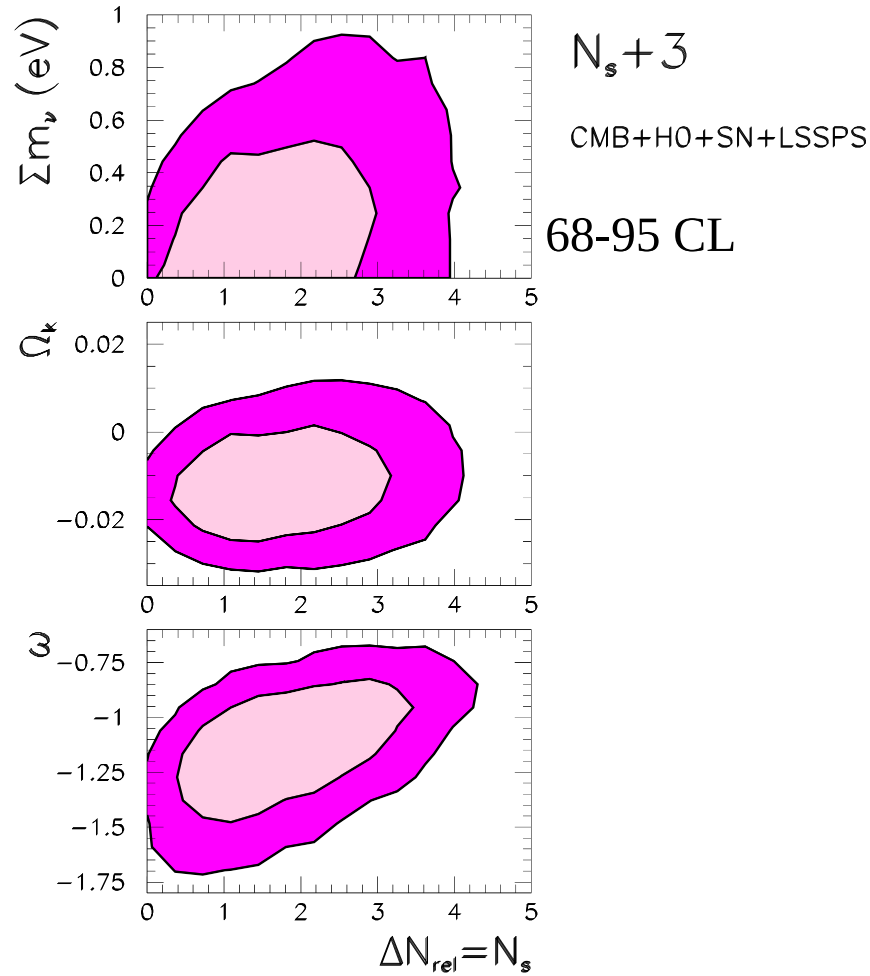


Found also in More General Cosmologies

With Dynamical Dark Energy $\omega \neq -1$

Without Assuming Flatness $\Omega_k \neq 0$

MCG-G, Maltoni, Salvado arXiv:1006.3795



Summary

- Progress in Determining Neutrino Parameters has *slowed down* (hopefully for short)

- Largest improvement in *leading* oscillation parameters:

  Δm^2_{21} and θ_{12} from SNO LETA

  $|\Delta m^2_{31}|$ from MINOS

  keep an eye on $|\overline{\Delta m^2}_{31}|$ from MINOS

- Significance of $\theta_{13} \neq 0$ decreased to 1-1.2 σ level

- Subdominant effects: Normal versus Inverted or $\theta_{23} \neq \frac{\pi}{4}$ not significant

- Cosmological Mass Bound is model dependent.

  For example it is relaxed to 1.5 eV within $o\omega\mathrm{CDM} + \Delta N_{\rm rel} + m_\nu$ cosmologies

- MiniBooNE/LSND remains an open problem