EXTRACTING OSCILLATION PARAMETERS FROM NEUTRINO DATA

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Outline of the course

Introduction

Lecture I: Solar Neutrinos (θ_{12}, Δm^2_{12})

Lecture II: Atmospheric Neutrinos (θ_{23}, Δm^2_{23})

Lecture III: Bounds on θ_{13} and δ

Lecture IV: Sterile Neutrinos

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Lecture II: Atmospheric Neutrinos (θ_{23}, Δm^2_{23})

Lecture III: Bounds on θ_{13} and δ; sterile neutrinos

Lecture IV: Future facilities?

BOUNDS ON Θ_{13} AND δ

Outline

- Direct searches
- Global three-families fits (0806.2649!?)
- LSND results and sterile neutrinos

The PMNS matrix

The Pontecorvo-Maki-Nakagawa-Sakata (PMNS) mixing matrix is the leptonic analogous of the CKM matrix

"Atmospheric" oscillation

"Solar" oscillation

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_1} & 0 \\ 0 & 0 & e^{i\alpha_2} \end{pmatrix}$$

$\theta_{23} = 39^o$–48^o

$\theta_{13} < 11^o$

$\theta_{12} = 32^o$–35^o

Majorana phases

Gonzalez-García and Maltoni '07

The PMNS matrix

Solar parameters:

$$\Delta m^2_{21} = 7.67\,^{+0.22}_{-0.21}\,\left(^{+0.67}_{-0.61}\right) \times 10^{-5}\ \mathrm{eV}^2$$

$$\theta_{12} = 34.5 \pm 1.4\,\left(^{+4.8}_{-4.0}\right)$$

Atmospheric parameters:

$$\Delta m^2_{31} = \begin{cases} -2.37 \pm 0.15\,\left(^{+0.43}_{-0.46}\right) \times 10^{-3}\ \mathrm{eV}^2 & \text{(inverted hierarchy)}, \\ +2.46 \pm 0.15\,\left(^{+0.47}_{-0.42}\right) \times 10^{-3}\ \mathrm{eV}^2 & \text{(normal hierarchy)}, \end{cases}$$

$$\theta_{23} = 42.3\,^{+5.1}_{-3.3}\,\left(^{+11.3}_{-7.7}\right),$$

Gonzalez-García and Maltoni '08

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Dirac CP-violating phase δ

Sign of Δm^2_{13}

θ_{23}-octant

DIRECT SEARCHES OF Θ_{13}

Direct searches of θ_{13}

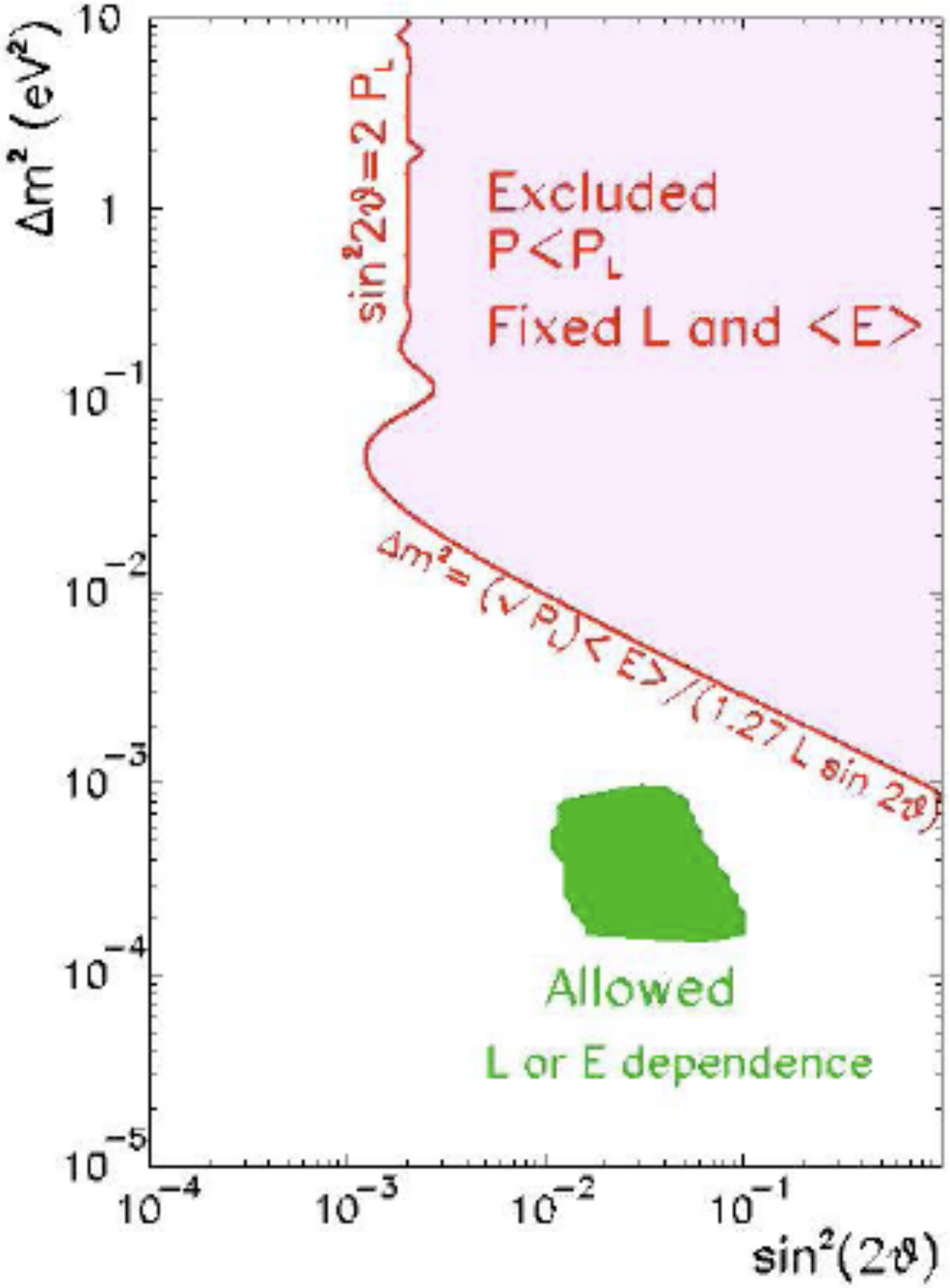
- This is a tale of exclusion plots.
- The angle θ_{13} can be directly tested using ν_e disappearance or the $\nu_\mu \rightarrow \nu_e$ appearance (indirectly through ν_μ disappearance)
- Accelerator and reactor experiments have been looking for it.

We must work in the three-family framework

Some useful approximations:

★ Hierarchical mass differences ($\Delta m^2_{sol} \ll \Delta m^2_{atm}$);

★ Small mixing between solar and atmospheric oscillations ($\theta_{13} \ll 1$);



The plotted mass difference is always one of the two (ATM or SOL) 3FAM mass differences,

the plotted 2FAM mixing angle is a combination of more than one 3FAM mixing angle.

Three-families analysis

The current data on neutrino oscillation suggest that we have (at least) three flavour neutrinos. A detailed discussion involves 6 parameters (3 angles, 2 mass differences and 1 CP phase). A simplified approach consist in making the (reasonable) assumption:

$$\Delta m^2_{sol} \equiv \Delta m^2_{12} \ll \Delta m^2_{atm} \equiv \Delta m^2_{23}$$

In this framework the $P(\nu_e \to \nu_x)$ approximated for atmospheric L/E ratios reads:

$$P(\nu_e \to \nu_x) \;=\; \sin^2 2\theta_{13} \sin^2\left(1.27\,\frac{\Delta m^2_{atm} L}{E}\right) \quad + \quad \mathcal{O}\left(\sin\theta_{13}\sin\delta(\frac{\Delta m^2_{sol} L}{E}), (\frac{\Delta m^2_{sol} L}{E})^2\right)$$

Caution: subleading effects can no longer be neglected.

Accelerator and reactor experiments

Neutrino Oscillations have been searched also in LABORATORY EXPERIMENTS with man-made neutrino fluxes. Two COMPLEMENTARY typologies of laboratory neutrino experiments:

- **Accelerator Neutrino Experiments:** with neutrino beam produced from a primary proton beam on fixed target. One can produce COLLIMATED $\overset{(-)}{\nu}_e$ and $\overset{(-)}{\nu}_\mu$ beams. The produced neutrino have a typical energy of $\mathcal{O}(\mathrm{GeV})$. These experiments can limit and/or test oscillation parameters in the ATMOSPHERIC RANGE (i.e. $\Delta m^2_{acc} \approx 10^{-3}$) while sensitivity to parameters in the SOLAR RANGE is not achievable (needs $L \geq 10^5$ km !!);

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- **Reactor Neutrino Experiments:** use the NON-COLLIMATED antineutrino flux (specifically $\bar{\nu}_e$) produced in the β decay of neutron-rich fission fragments. The produced neutrino have a typical energy of $\mathcal{O}$(MeV). Due to the low neutrino energy reactor experiment can only look at the $\bar{\nu}_e$ DISAPPEARANCE channel. These experiments can limit/test oscillation parameters in the ATMOSPHERIC and SOLAR RANGE (i.e. $\Delta m^2_{reac} \approx 10^{-3} \div 10^{-5}$ eV^2).

Sensitivity bounds by LBL accelerator experiments

EXP	θ_{13}	$\sin^2(2\theta_{13})$	$\sin^2\theta_{13}$
Global Fit	10.8°	0.135	0.035
BEAMS			
K2K	?	?	?
MINOS	6°	0.04	0.01
	$\to 8^\circ$	$\to 0.08$	$\to 0.02$
CNGS	5°	0.03	0.008
	$\to 7^\circ$	$\to 0.06$	$\to 0.015$

$$P_{\mu\mu} \simeq 1 - \sin^2(2\theta_{23})\sin^2\left[\frac{\Delta_{atm}L}{2}\right] + \mathcal{O}\left[\left(\frac{\Delta_{sol}}{\Delta_{atm}}\right)\sin\theta_{13}\cos\delta\right]$$

Sensitivity loss due to $(\theta_{13} - \delta)$-correlations

Reactor experiments

Neutrino oscillations are also searched using neutrino beams from nuclear reactors. Nuclear reactor produce $\bar{\nu}_e$ beams with typical $E_{\bar{\nu}_e}$ of $\mathcal{O}$(MeV). Due to the low neutrino energy electrons are the only charged leptons which can be produced in the neutrino CC interaction:

$$\bar{\nu}_e + p \rightarrow e^+ + n \qquad (E_{th} = 1.8 \text{ MeV})$$

If $\bar{\nu}_e$ oscillates to another flavour (for example ν_μ) its CC current cannot be observed as the neutrino has not enough energy to produce a lepton (for example a μ) and the NC reactions of the "oscillated" $\bar{\nu}_\mu$ or $\bar{\nu}_\tau$ have too low cross-section:

★ Neutrino Reactor experiments are sensitive only to $\bar{\nu}_e$ DISAPPEARANCE channels;

★ Due to very LOW E_ν are sensitive to SMALL $\Delta m^2 \approx \mathcal{O}(10^{-3} \div 10^{-5} \text{ eV}^2)$;

★ Having a NON-COLLIMATED neutrino source they have usually LOW LUMINOSITY.

★ Due also to UNCERTAINTIES on flux normalization they are NOT sensitive to very SMALL $\sin^2 2\theta$;

Reactor experiments

Reactor experiment can be divided in SHORT BASELINE (Bugey, CHOOZ, PaloVerde) and LONG BASELINE (KamLAND) experiments.

SHORT BASELINE experiments have been built with the specific purpose of TESTING the ATMOSPHERIC parameter range. The main differences between Bugey and CHOOZ/PaloVerde are the baseline and the reactor (power $\times$ detector) mass product

- Bugey reactor experiment:
  - Baseline of $\mathcal{O}(0.1$ km), reactor power 1 GW and detector mass 1 ton;
- CHOOZ and PaloVerde experiments have:
  - Baseline is $\mathcal{O}(1$ km), reactor power of respectively 8.5 and 11.6 GW and detector mass of respectively 5 and 12 tons;

Reactor experiments

So CHOOZ and PaloVerde are sensitive to smaller mass difference, while for larger mass difference

Bugey is sensitive to smaller mixing angle

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- Bugey best sensitivity is for $\Delta m^2 \approx \mathcal{O}(1\ \mathrm{eV}^2)$. So Bugey cannot be sensitive so SK ATM parameter region while it can help in excluding the large mixing angle region of the LSND signal

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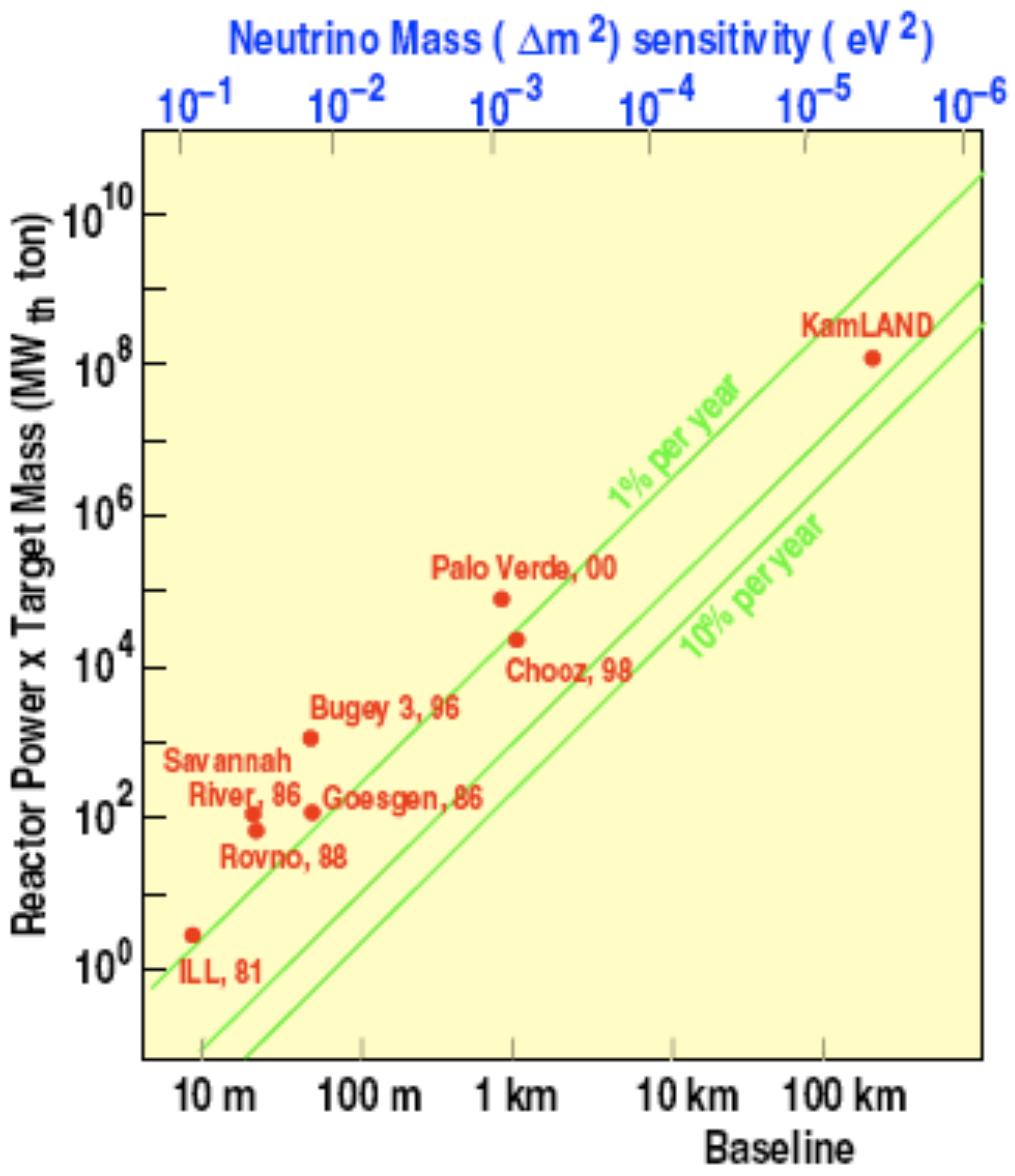
- CHOOZ and PaloVerde sensitivity to Δm^2 goes down to $\mathcal{O}(10^{-3}\ \mathrm{eV}^2)$. So they are sensitive to SK ATM parameter region. Note however that they are looking only to $\bar{\nu}_e$ disappearance channel (while SK to the ν_μ disappearance channel);

IF NO SIGNAL of $\bar{\nu}_e$ DEFICIT is SEEN at CHOOZ-PaloVerde

$\Downarrow$

ν_e ($\bar{\nu}_e$) NOT OSCILLATING in the ATM parameter RANGE

Reactor experiments



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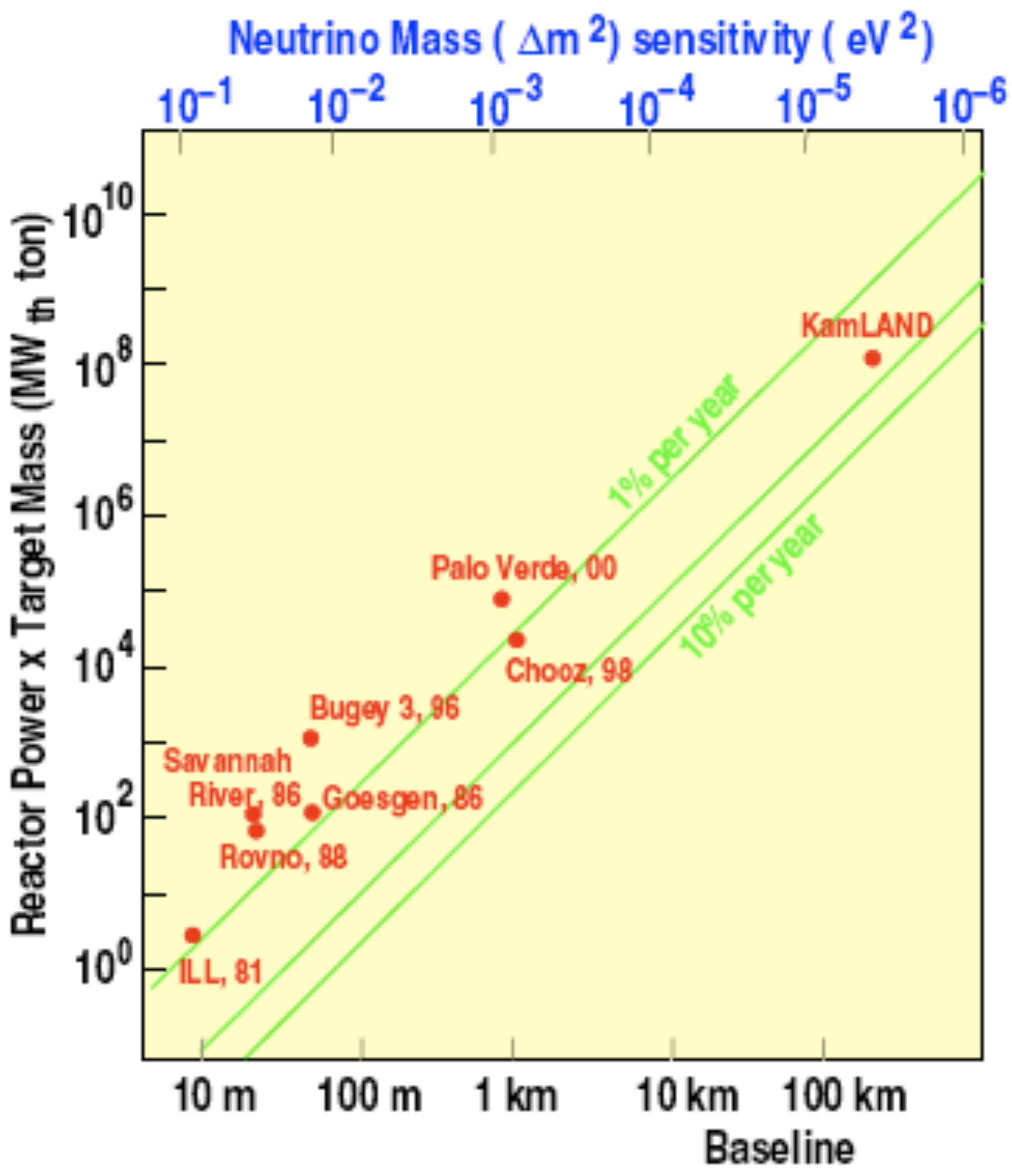

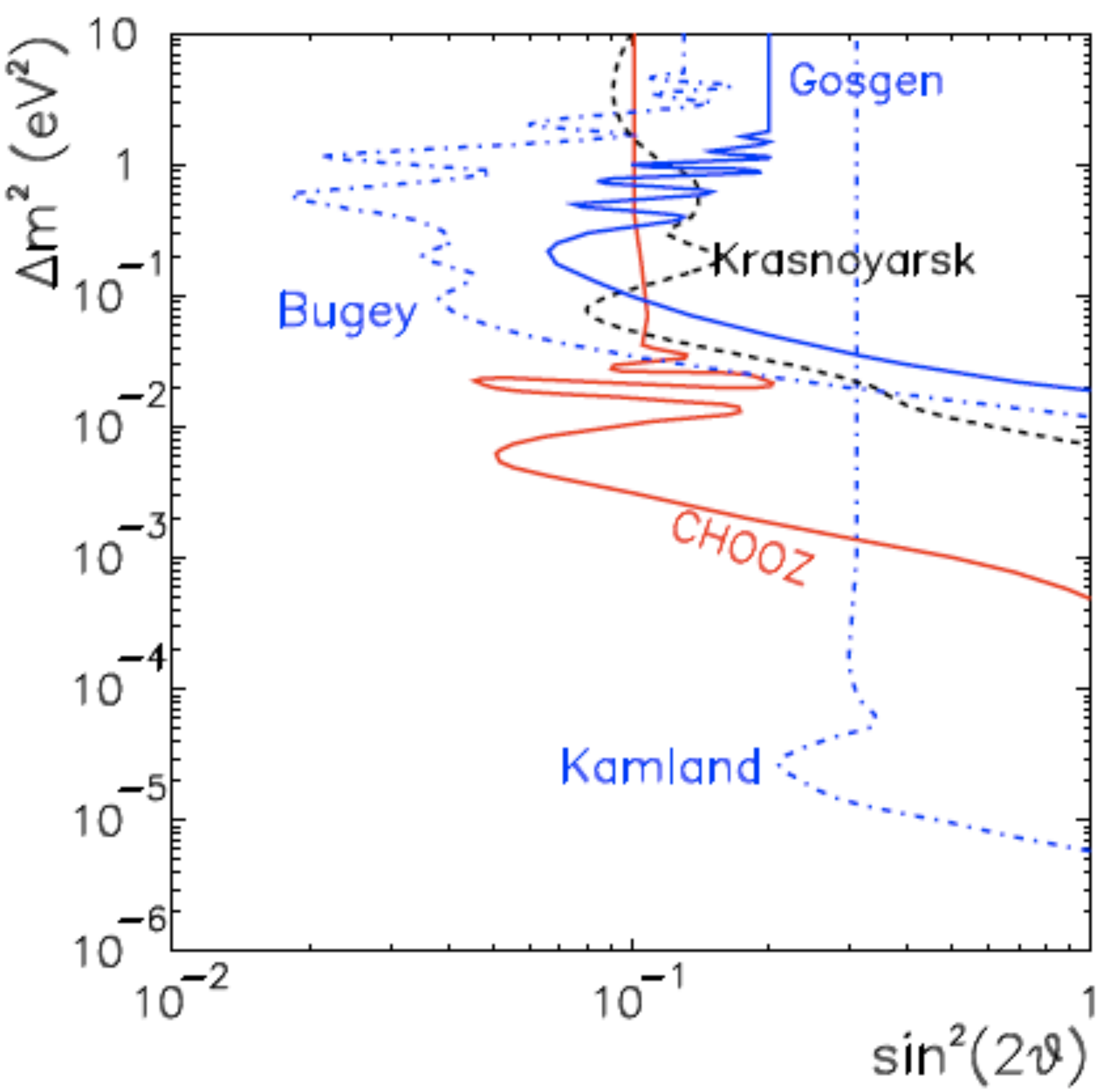

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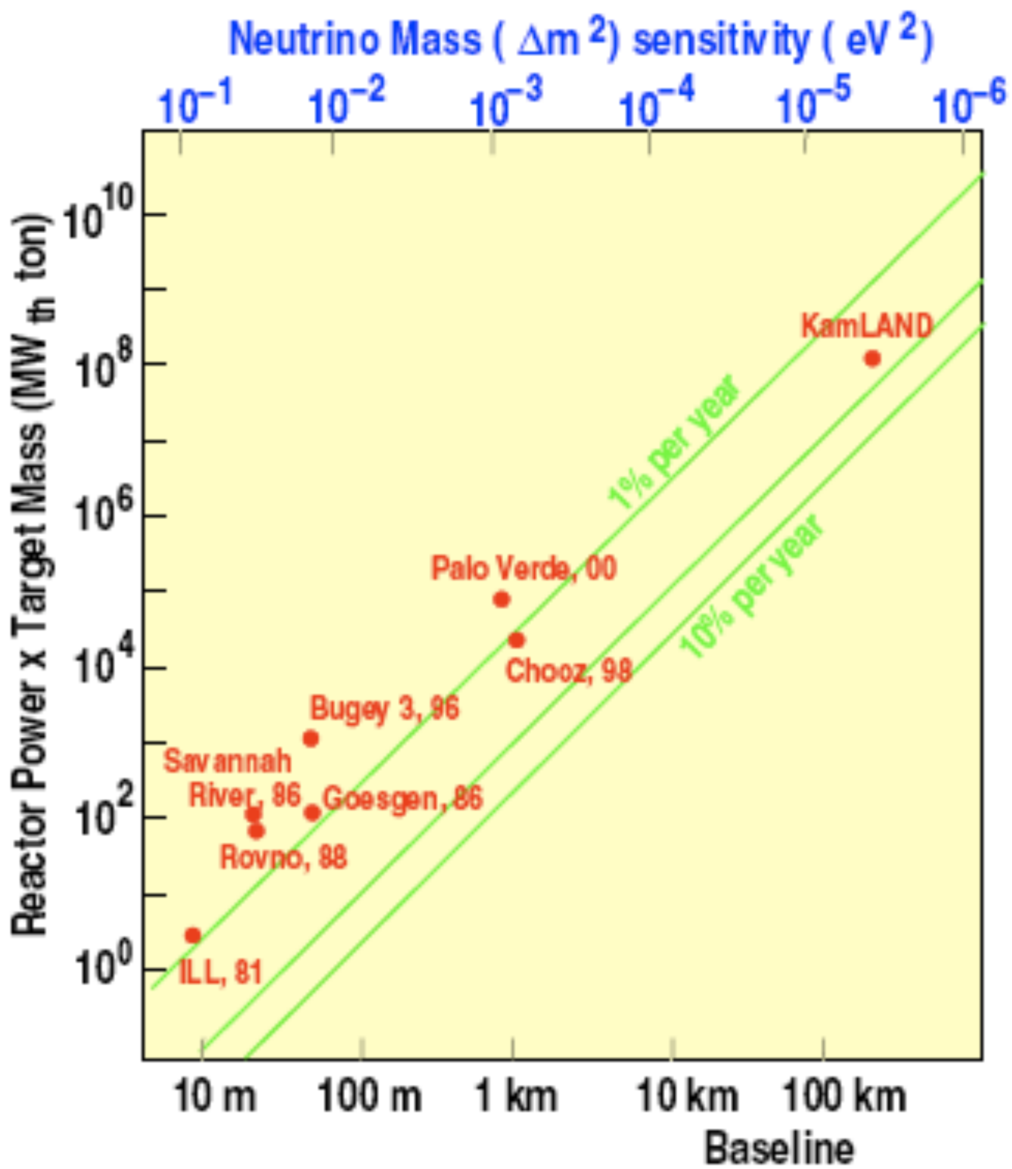
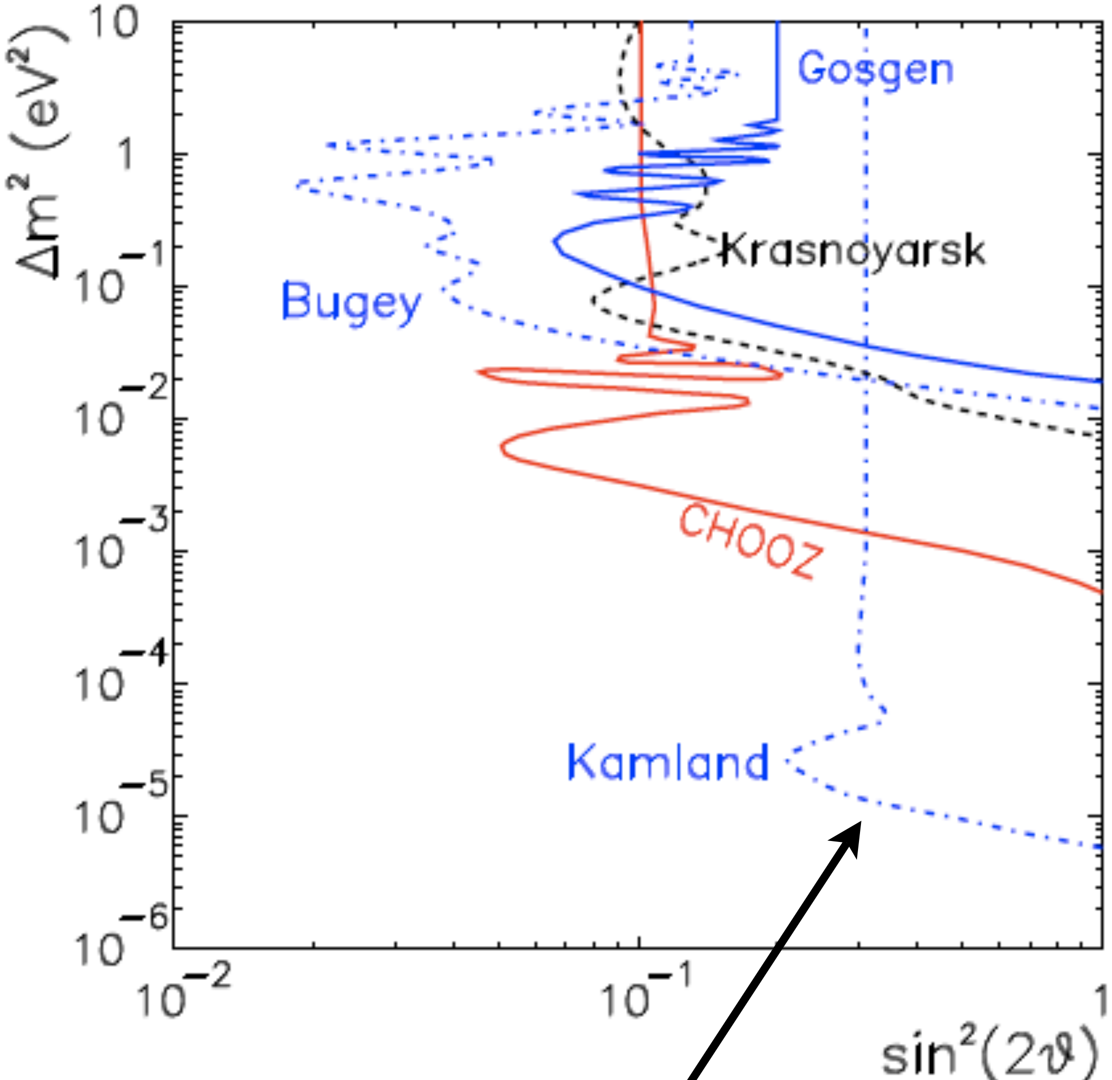




Caveat: KamLAND has a signal.....

Reactor experiments: Chooz

The CHOOZ experiment searches for disappearance of $\bar{\nu}_e$ produced by two reactors with a total thermal power of 8.5 GW. CHOOZ detector consisted of 5 tons of liquid scintillator placed at 1 km. The detector were shielded against cosmic ray radiation by 100 m of rock (300 mwe).

The $\bar{\nu}_e$ were detected through the inverse β-decay reaction:

$$\bar{\nu}_e + p \rightarrow n + e^+ \qquad (E_{th} = 1.8 \text{ MeV})$$

The reaction signature is the delayed coincidence between the prompt e^+ signal and the photon emission of the neutron capture. Gadolinium was introduced into the liquid scintillator for increasing the energy released (8 MeV compared to 2.2 MeV) and having a faster neutron capture.

- The reactor was built after the detector (VERY IMPORTANT). CHOOZ had the unique opportunity to measure the background with NO REACTOR and to calibrate with the slow RAMP-UP of power → GOOD BACKGROUND SUBTRACTION

Reactor experiments: Palo Verde

PaloVerde experiment has very similar configuration. It searches for disappearance of $\bar{\nu}_e$ produced by three reactors with a total thermal power of 11.6 GW. PaloVerde detector consisted of 12 tons of liquid scintillator placed at 0.9 km. The detector were shielded against cosmic ray radiation by 12 m of rock (32 mwe).

- This helps only in eliminating the hadronic component of the cosmic radiation. The rather large remaining component of CR radiation (muons) produce a substantial quantity of secondary neutrons → LARGE CR BACKGROUND;
- Moreover PaloVerde started taking data when the reactors were already functioning so it has worse calibration;

The same (as CHOOZ) inverse β-decay reaction were used for detecting $\bar{\nu}_e$ neutrinos. Also PaloVerde added Gadolinium for enhancing the neutron capture.

Reactor experiments: Chooz and Palo Verde

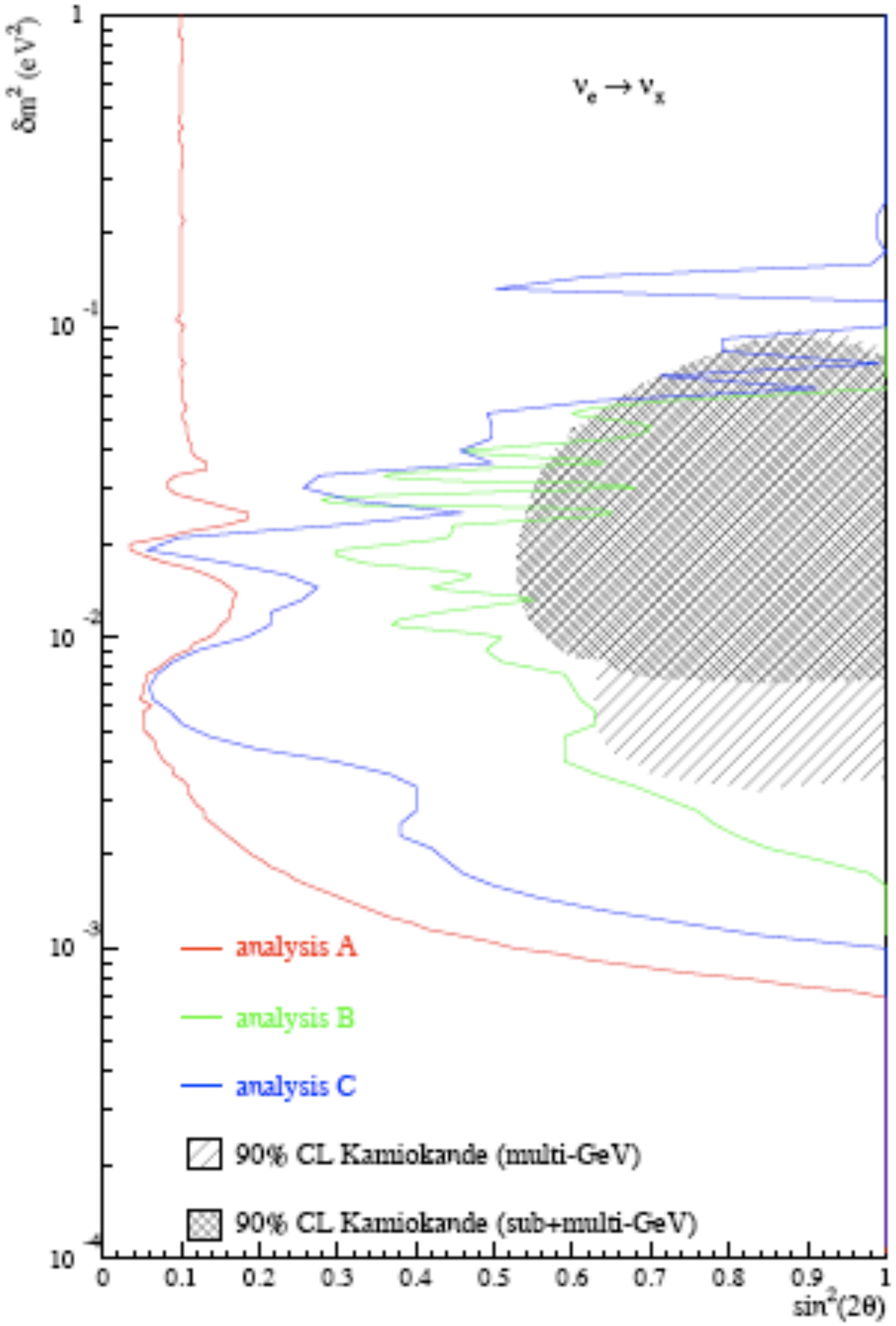
CHOOZ and PaloVerde reported the following ratio between measured and expected fluxes averaged over the neutrino energy spectrum (Note the larger systematic error of PaloVerde due to fact that were not able to calibrate the detector background with POWER OFF conditions):

$$\begin{cases} R = \dfrac{N_{exp}}{N_{th}} = 1.010 \pm 0.028\ \text{(stat)}\ \pm 0.027\text{(syst)} & \text{(CHOOZ)} \\ R = \dfrac{N_{exp}}{N_{th}} = 1.010 \pm 0.024\ \text{(stat)}\ \pm 0.053\text{(syst)} & \text{(PaloVerde)} \end{cases}$$

NO EVIDENCE of DEFICIT in the $\bar{\nu}_e$ FLUX in the SK ATM region

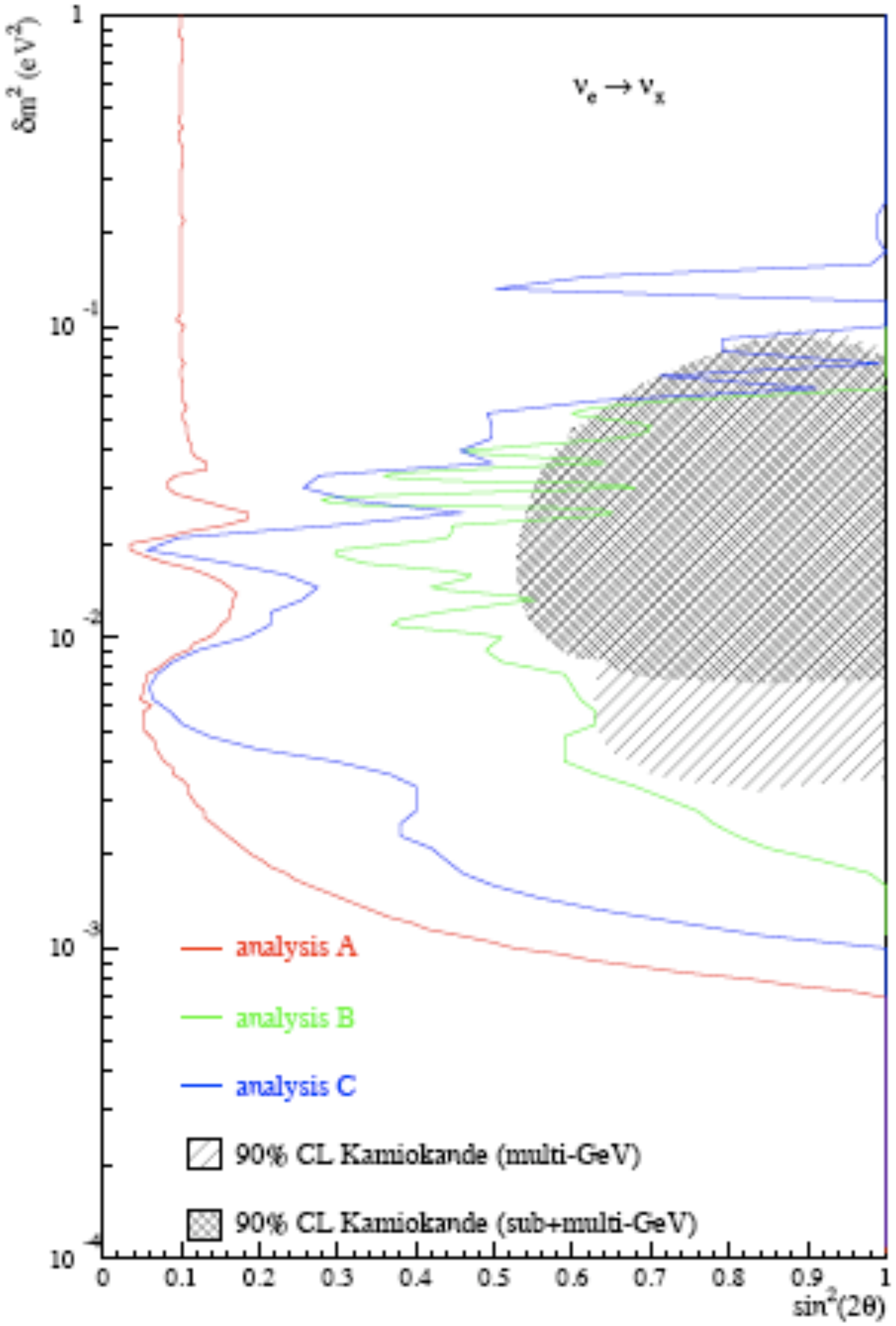
- CHOOZ and PaloVerde excluded the upper part of the LMA (SOLAR) solution;
- They ruled out the possibility that the $\nu_\mu \to \nu_e$ oscillation could be the (DOMINANT) explanation of the ATM ν_μ deficit (confirming SK no deficit in the ATM ν_e flux measurement);

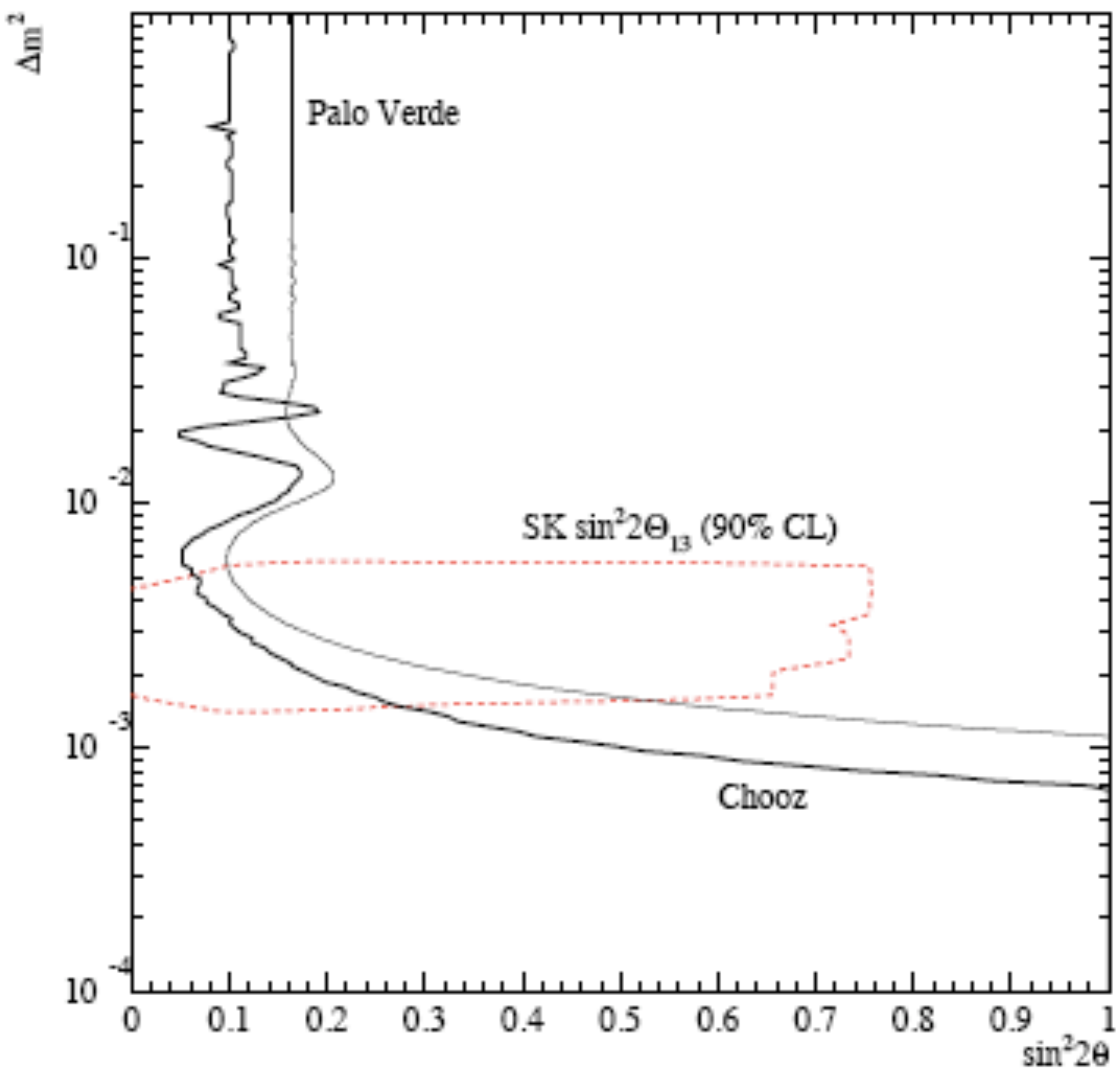
Reactor experiments: Chooz and Palo Verde



Atmo osc are not $\nu_\mu \to \nu_e$

Reactor experiments: Chooz and Palo Verde

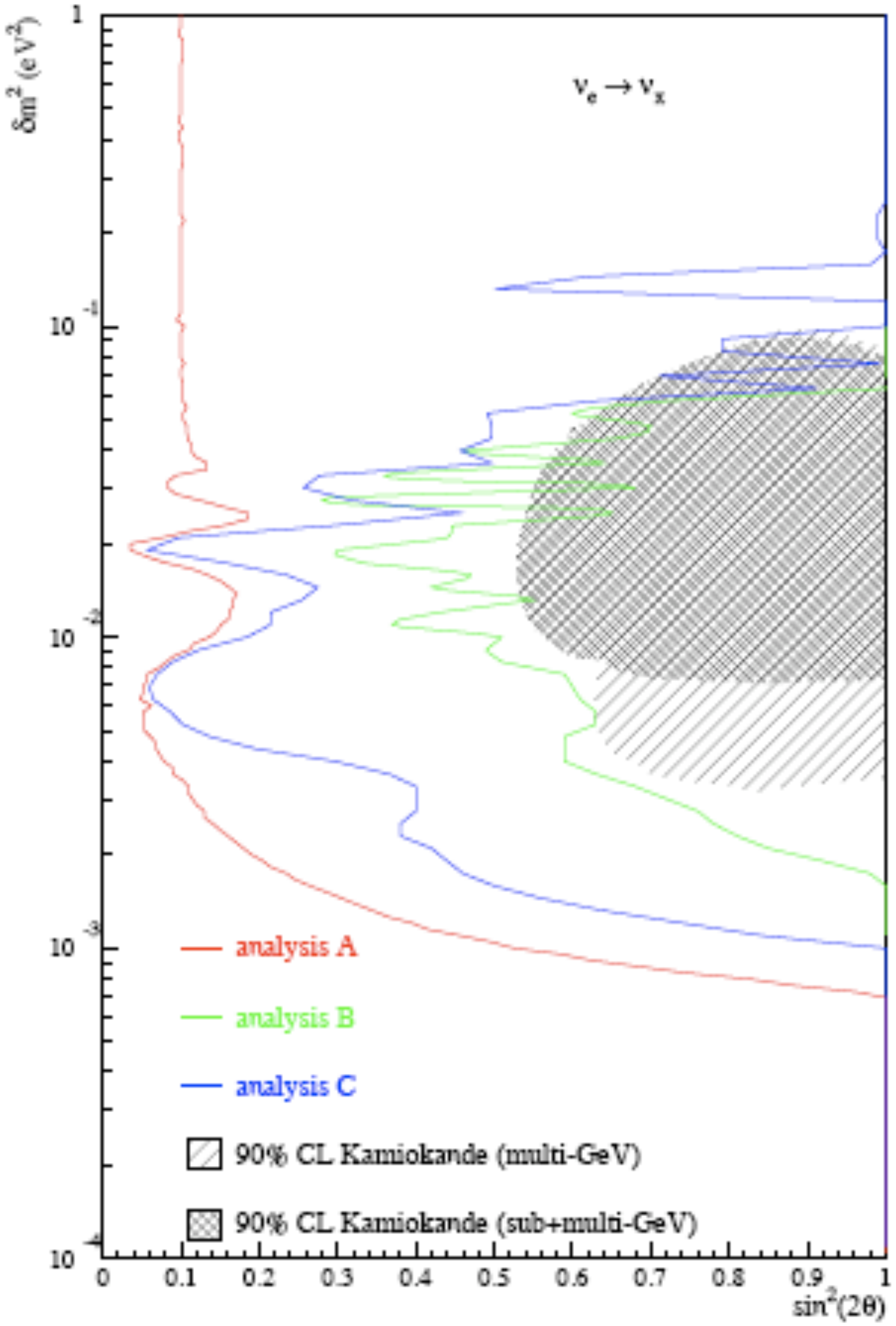


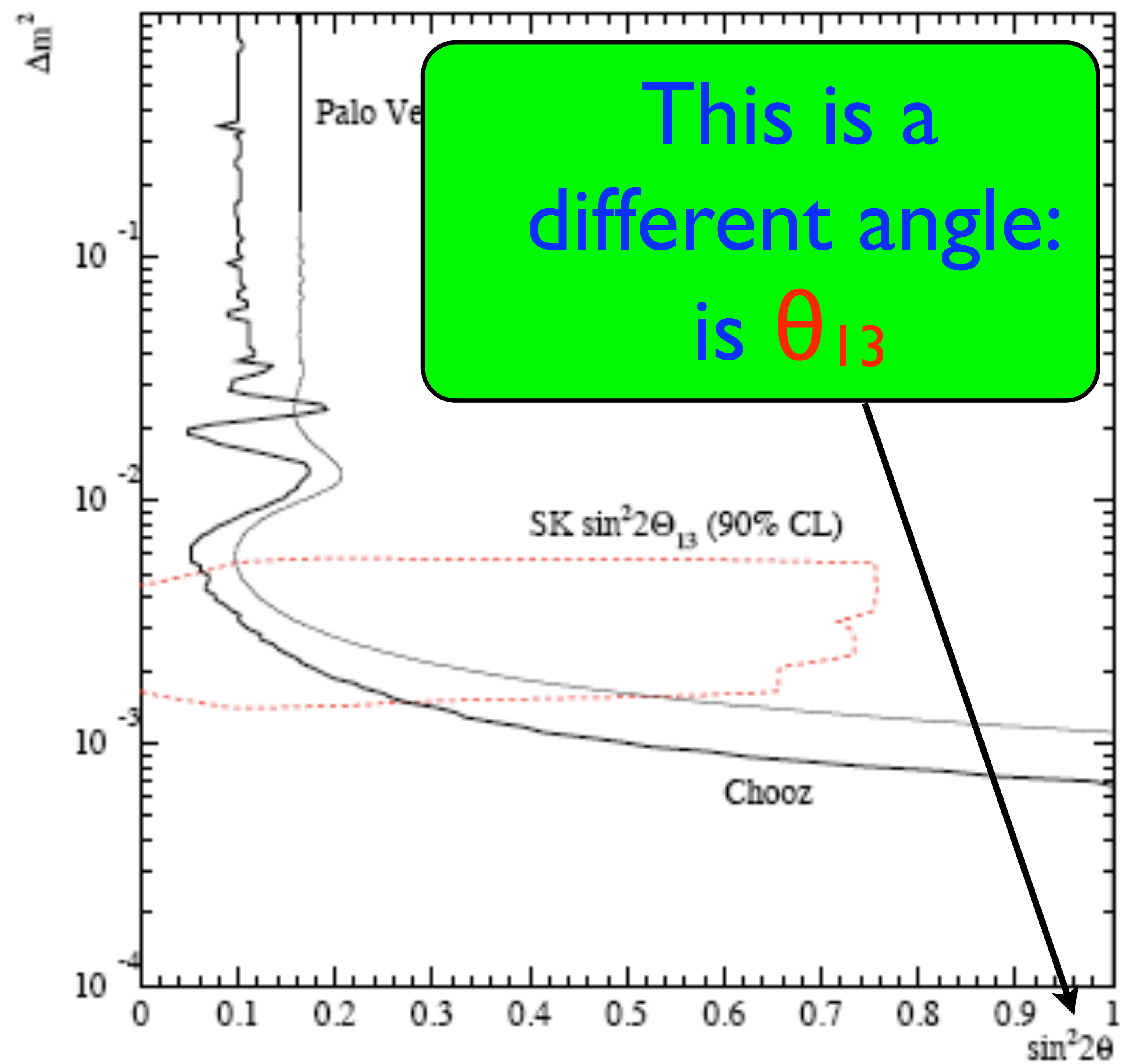


Atmo osc are not $\nu_\mu \rightarrow \nu_e$

$\theta_{13} \leq 11°$

Reactor experiments: Chooz and Palo Verde





This is a different angle: is θ_{13}

Atmo osc are not $\nu_\mu \to \nu_e$

$\theta_{13} \leq 11°$

Sensitivity bounds by future reactor experiments

EXP	θ_{13}	$\sin^2(2\theta_{13})$	$\sin^2\theta_{13}$
Global Fit	$10.8°$	0.135	0.035
REACT.			
Japan	$4.5°$	0.025	0.006
USA	$3.5°$	0.015	0.004
EU (D-CHOOZ)	$5°$	0.030	0.008

$$P_{ee} \simeq 1 - \sin^2(2\theta_{13})\sin^2\left[\frac{\Delta_{atm}L}{2}\right] + \mathcal{O}\left[\left(\frac{\Delta_{sol}}{\Delta_{atm}}\right)^2\right]$$

no sensitivity loss due to $(\theta_{13} - \delta)$-correlations

SYSTEMATIC DOMINATED!

THREE-FAMILY FIT TO DATA

Three-family analysis

$$P_{\mu\mu}^{\text{K2K, MINOS}} = 1 - 4\left(s_{23}^4 s_{13}^2 c_{13}^2 + c_{13}^2 s_{23}^2 c_{23}^2\right)\sin^2\left(\frac{\Delta m_{31}^2}{4E}L\right)$$
$$\simeq s_{13}^2 \frac{\cos 2\theta_{23}}{c_{23}^2} + \left(1 - s_{13}^2 \frac{\cos 2\theta_{23}}{c_{23}^2}\right) P_{\mu\mu}^{\text{K2K},2\nu}(\Delta m_{31}^2, \theta_{23}) + \mathcal{O}(s_{13}^4)\,.$$

$$P_{ee}^{\text{CHOOZ}} = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\left(\frac{\Delta m_{21}^2 L}{4E}\right)$$
$$- \sin^2 2\theta_{13}\left[\cos^2\theta_{12}\sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right) + \sin^2\theta_{12}\sin^2\left(\frac{\Delta m_{32}^2 L}{4E}\right)\right]$$
$$\simeq 1 - \sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right)\,,$$

Three-family analysis in atmospheric data

$$N_{\text{bin}}(\vec{\omega}) = n_t T \sum_{\alpha,\beta,\pm} \int_0^{\infty} dh \int_{-1}^{+1} dc_\nu \int_{E_{\text{min}}}^{\infty} dE_\nu \int_{E_{\text{min}}}^{E_\nu} dE_l \int_{-1}^{+1} dc_a \int_0^{2\pi} d\varphi_a$$
$$\frac{d^3\Phi^{\pm}_{\alpha}}{dE_\nu\, dc_\nu\, dh}(E_\nu, c_\nu, h)\, P^{\pm}_{\alpha\to\beta}(E_\nu, c_\nu, h\,|\,\vec{\omega})\, \frac{d^2\sigma^{\pm}_{\beta}}{dE_l\, dc_a}(E_\nu, E_l, c_a)\, \varepsilon^{\text{bin}}_{\beta}(E_l, c_l(c_\nu, c_a, \varphi_a))$$

- Atmospheric ν data are a convolution of neutrino fluxes, oscillation parameters $\vec{\omega}$, Earth matter density profile, cross-sections and details of the detector;
- we want to extract information on the oscillation parameters $\vec{\omega}$;
- ν fluxes, Earth profile, cross-sections and the detector are **source of uncertainties**.

Good

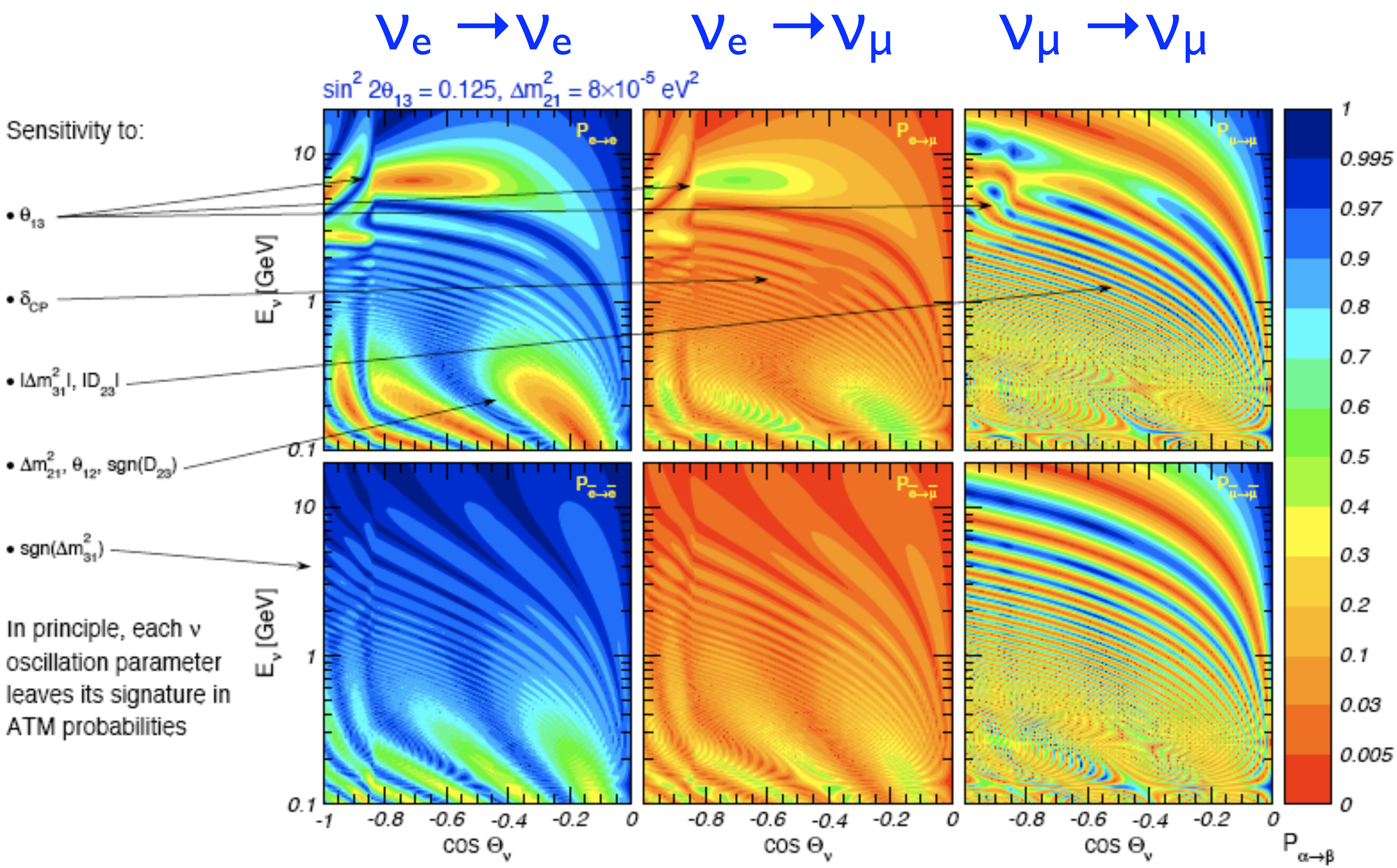
- baseline: $10 \to 10^4$ km;
- energy: $0.1 \to 10^4$ GeV;
- *huge statistics* and *large matter effects*.

Bad

- no "front detector" $\Rightarrow$ *huge systematics*;
- poor accuracy in ν *energy and direction*;
- only $\nu + \bar{\nu}$ without magnetized detector.

M. Maltoni, BENE meeting '06

Three-family analysis in atmospheric data



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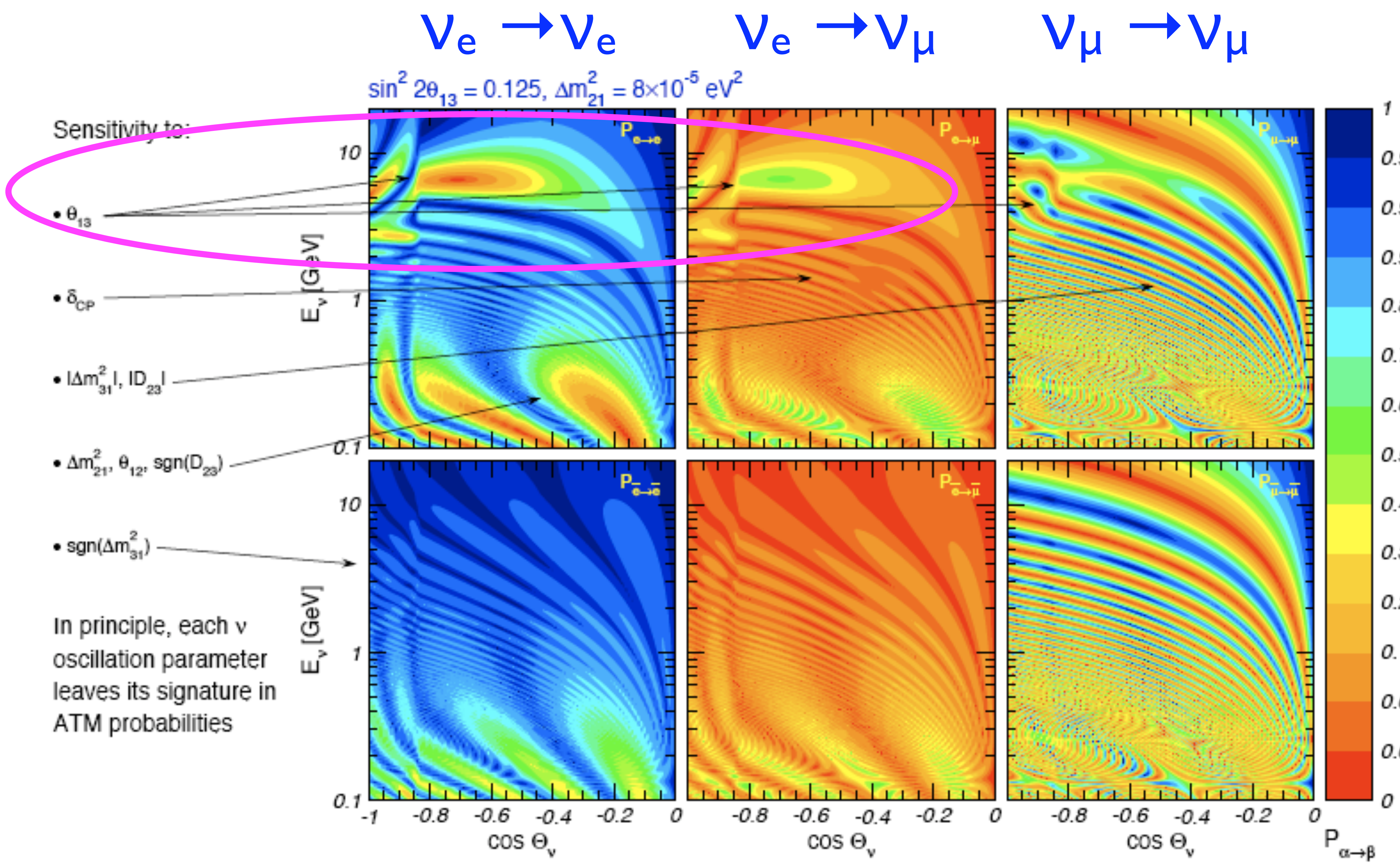

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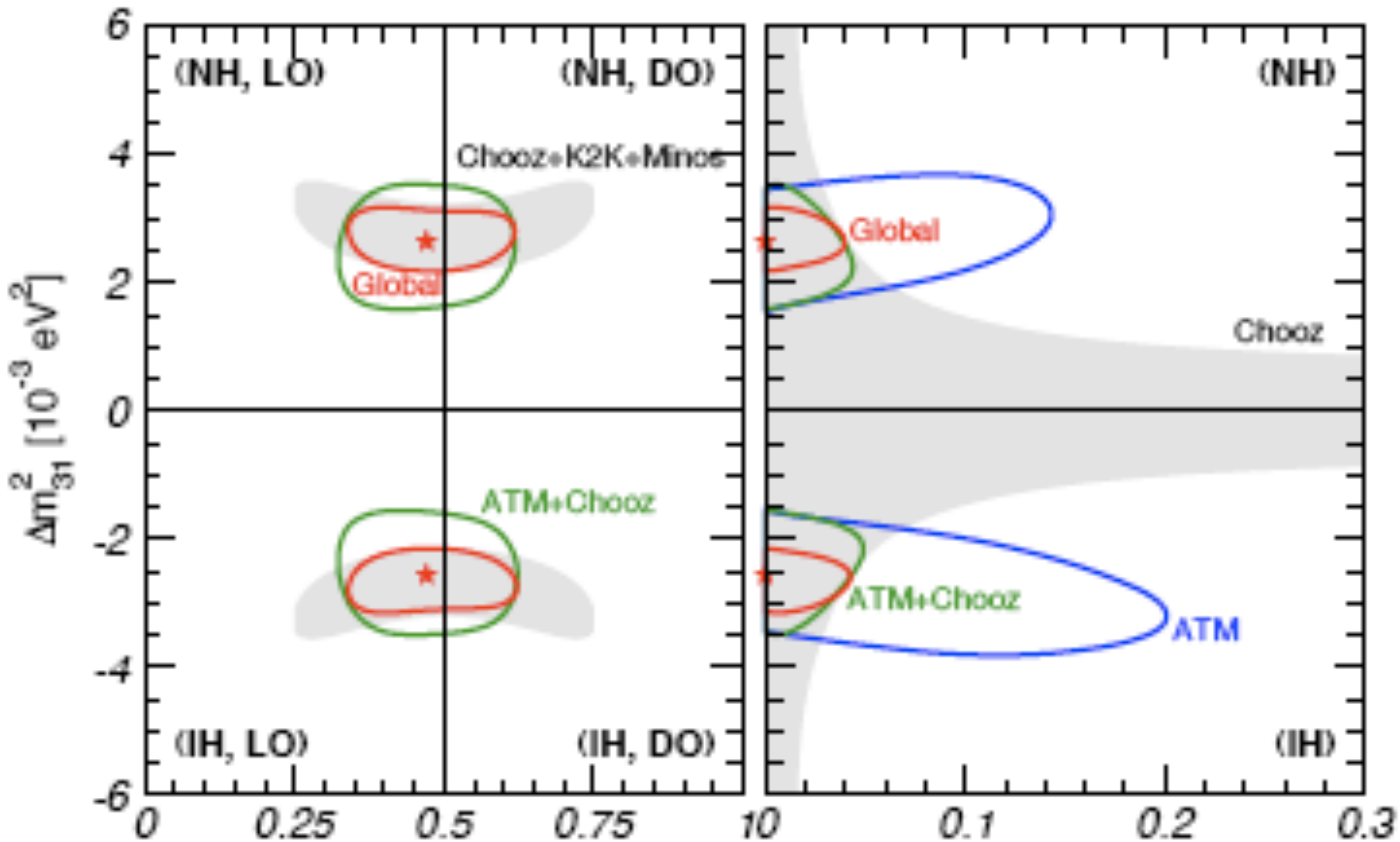
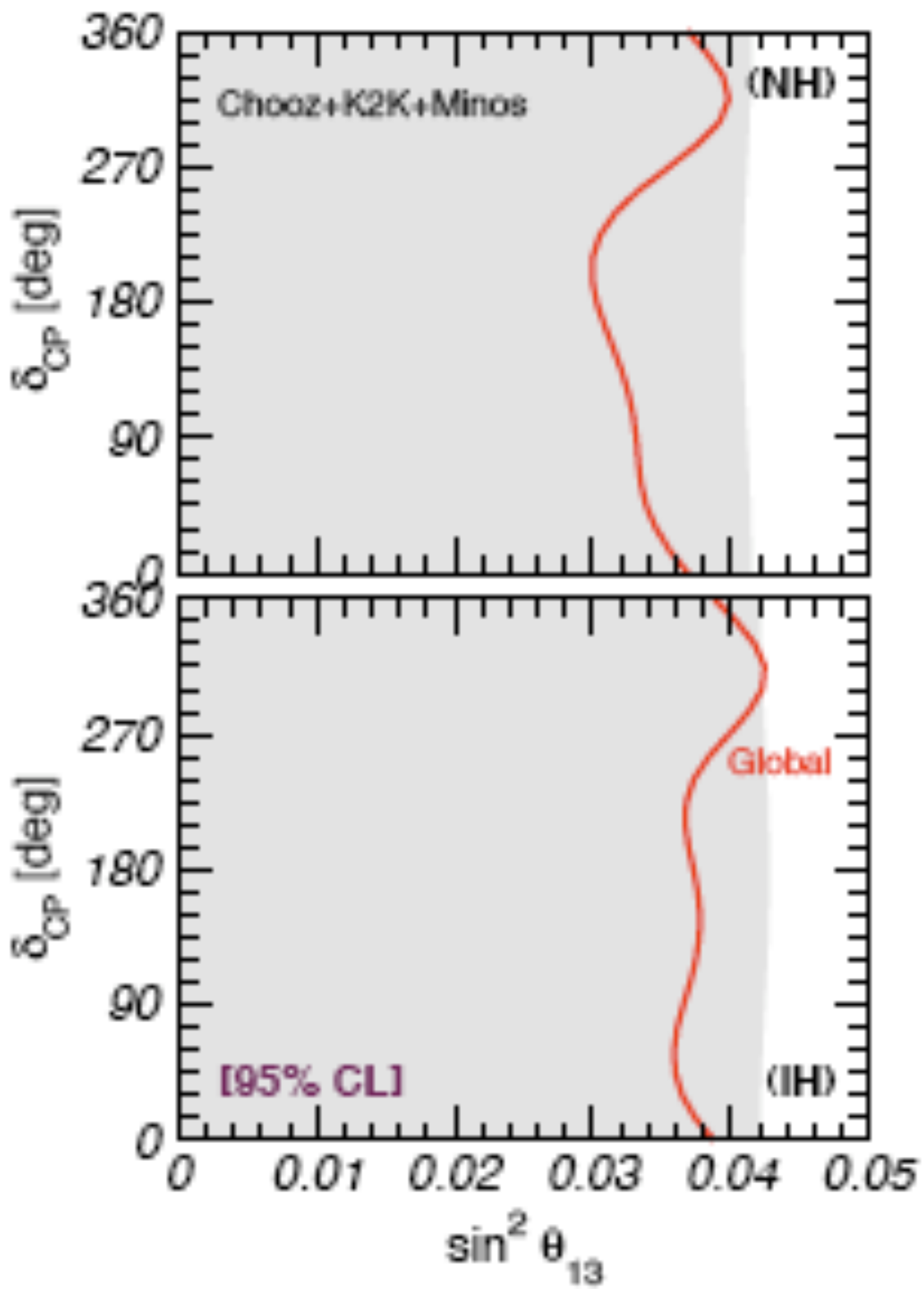


- LBL (grey regions) dominate the determination of θ_{13} and $|\Delta m^2_{31}|$ but are insensitive to **octant** and **hierarchy**;

Three-family analysis in atmospheric data

The atmospheric data sensitivity to θ_{13} depends on the CP-violating phase δ

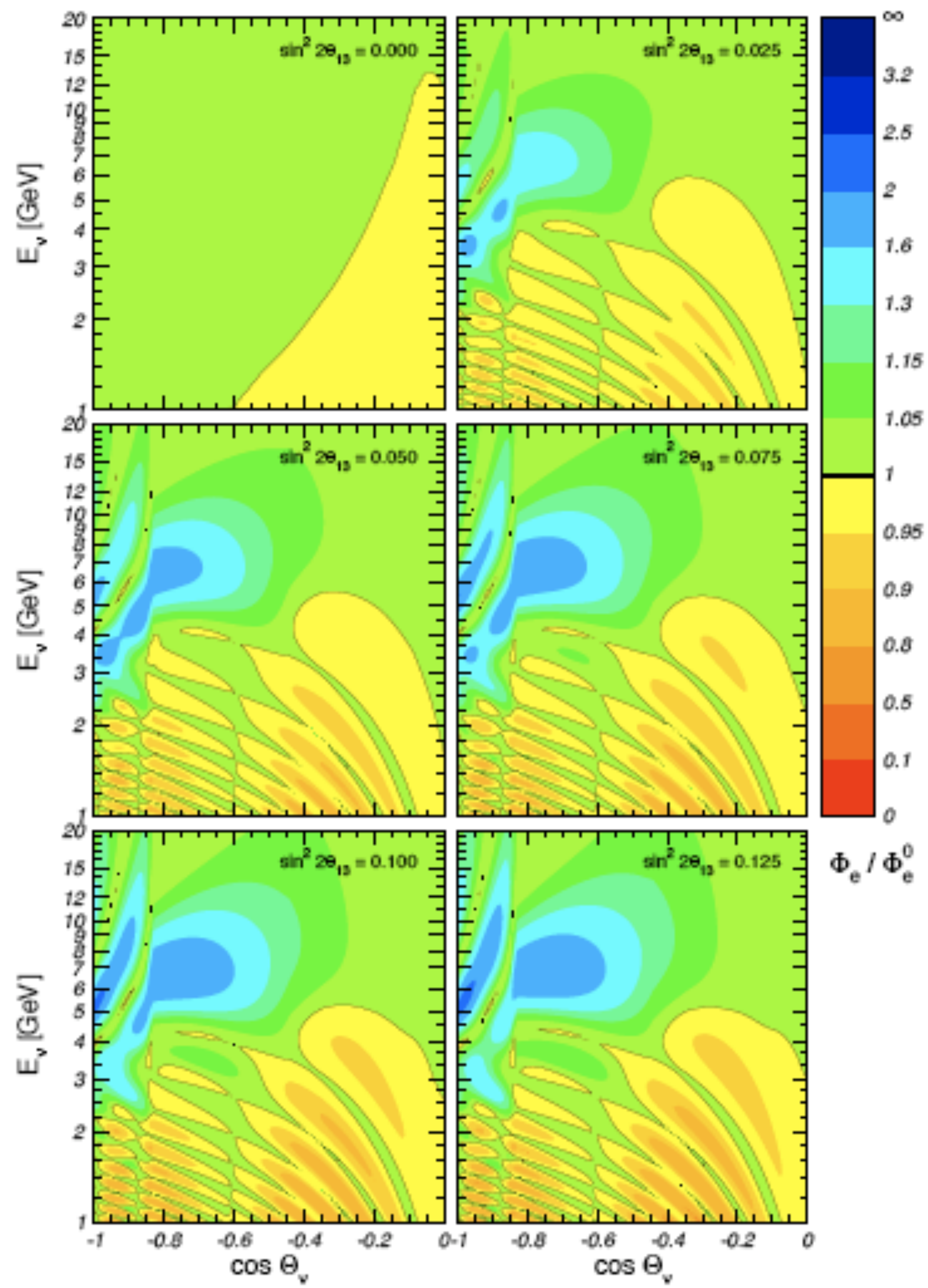


Three-family analysis in atmospheric data

Sensitivity to θ_{13}

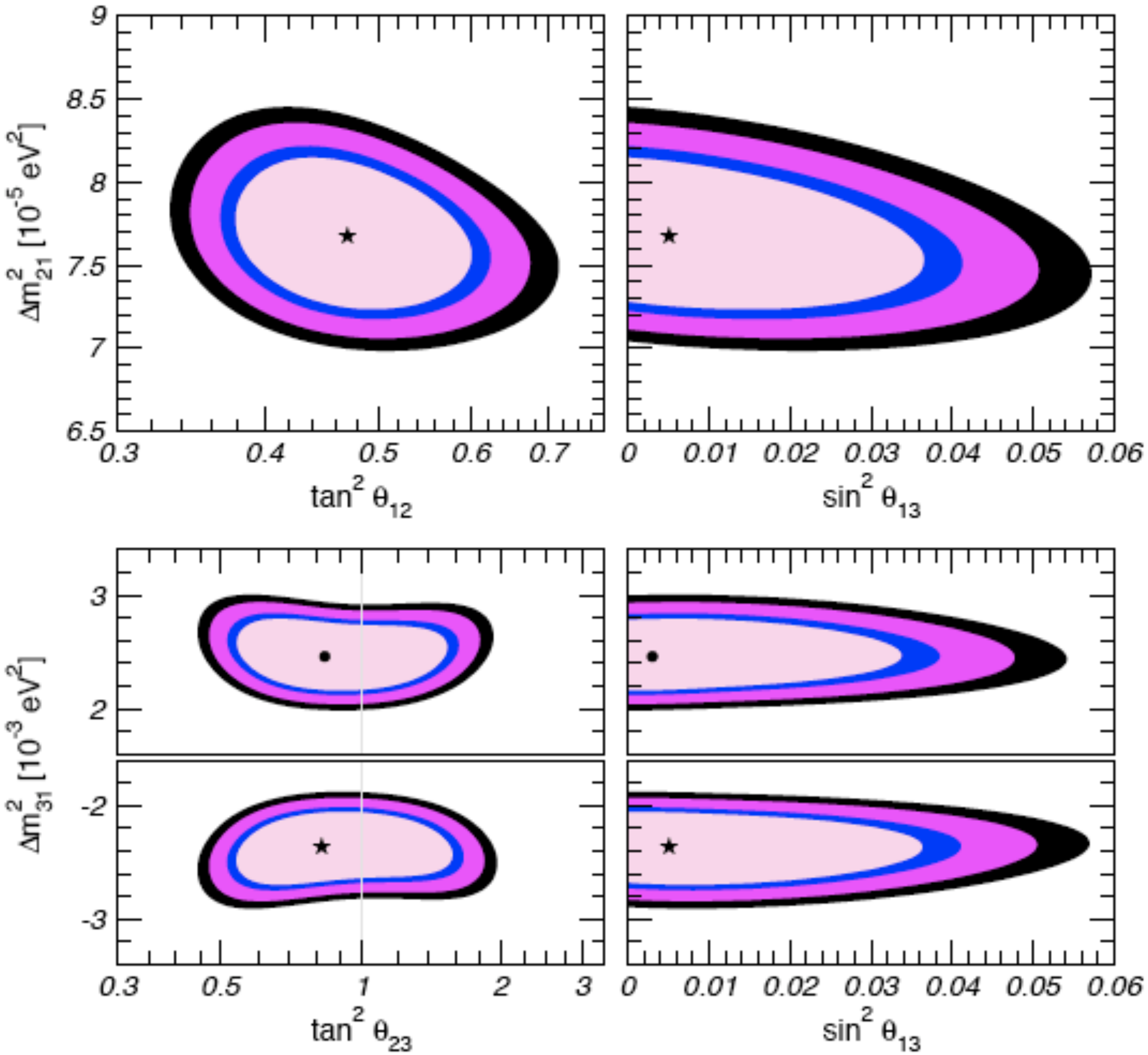
- <u>In principle</u>, θ_{13} can be measured by observing the MSW & parametric resonances;
- <u>in practice</u>, the sensitivity is limited by:
  - *statistics*: at $E_\nu \sim 6$ GeV the ATM flux is already suppressed;
  - *background*: the $\nu_e \to \nu_e$ events strongly dilute the $\nu_\mu \to \nu_e$ signal; also resonance occur only for ν **OR** $\bar{\nu}$, not both;
  - *resolution*: need **precise determination** of resonance peak to measure θ_{13}, but E_ν reconstruction is usually very poor;

$\Rightarrow$ sensitivity to θ_{13} will **not** be competitive with dedicated LBL experiments.



M. Maltoni, BENE meeting ‘06

Global three-family analysis



Gonzalez-García and Maltoni, '08

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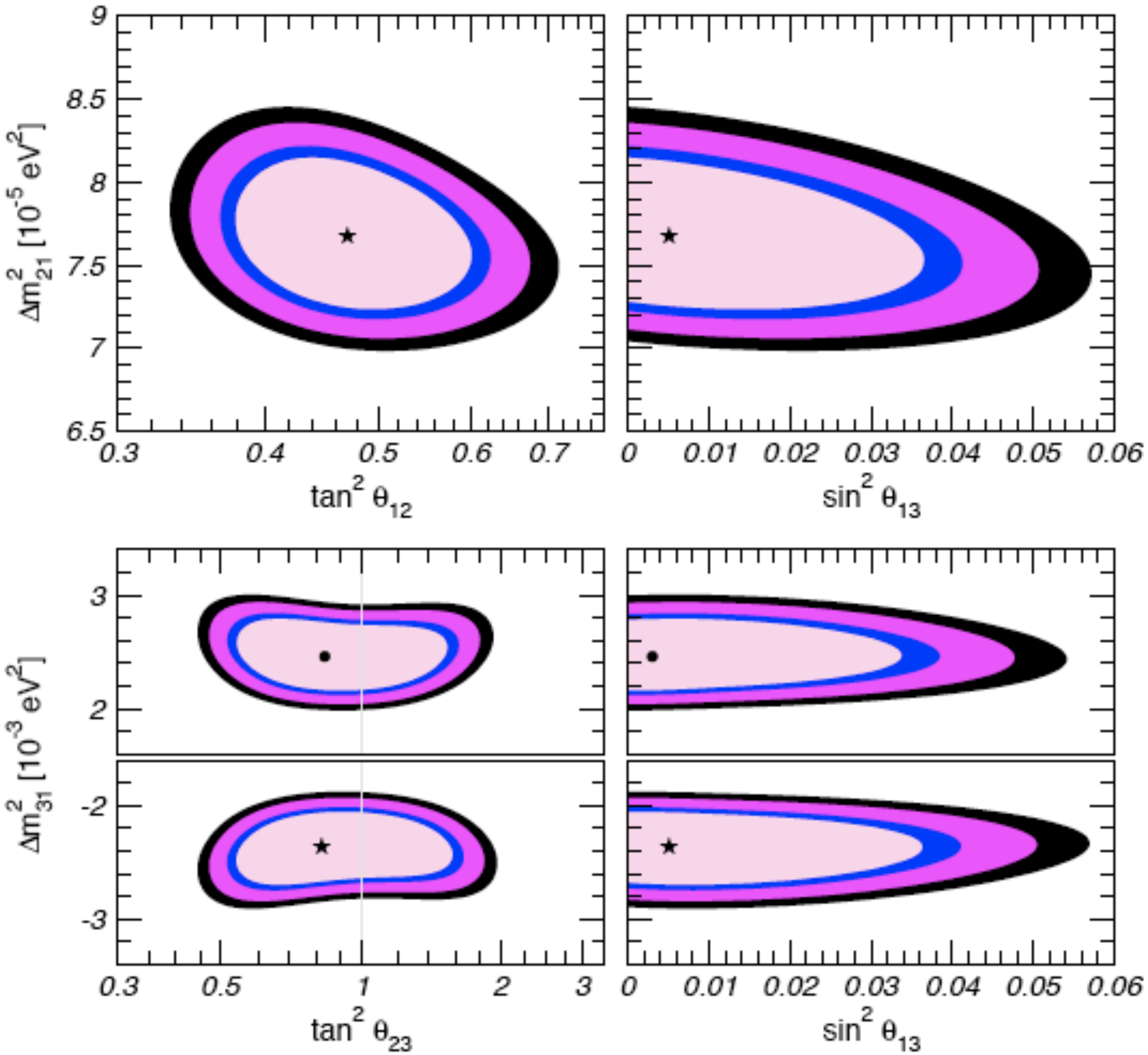

$$\theta_{13} = 0.0\,^{+7.9}_{-0.0}\ \left({}^{+12.9}_{-0.0}\right)$$

$$\delta_{\rm CP} \in [0,\ 360]\,.$$

Gonzalez-García and Maltoni, ‘08

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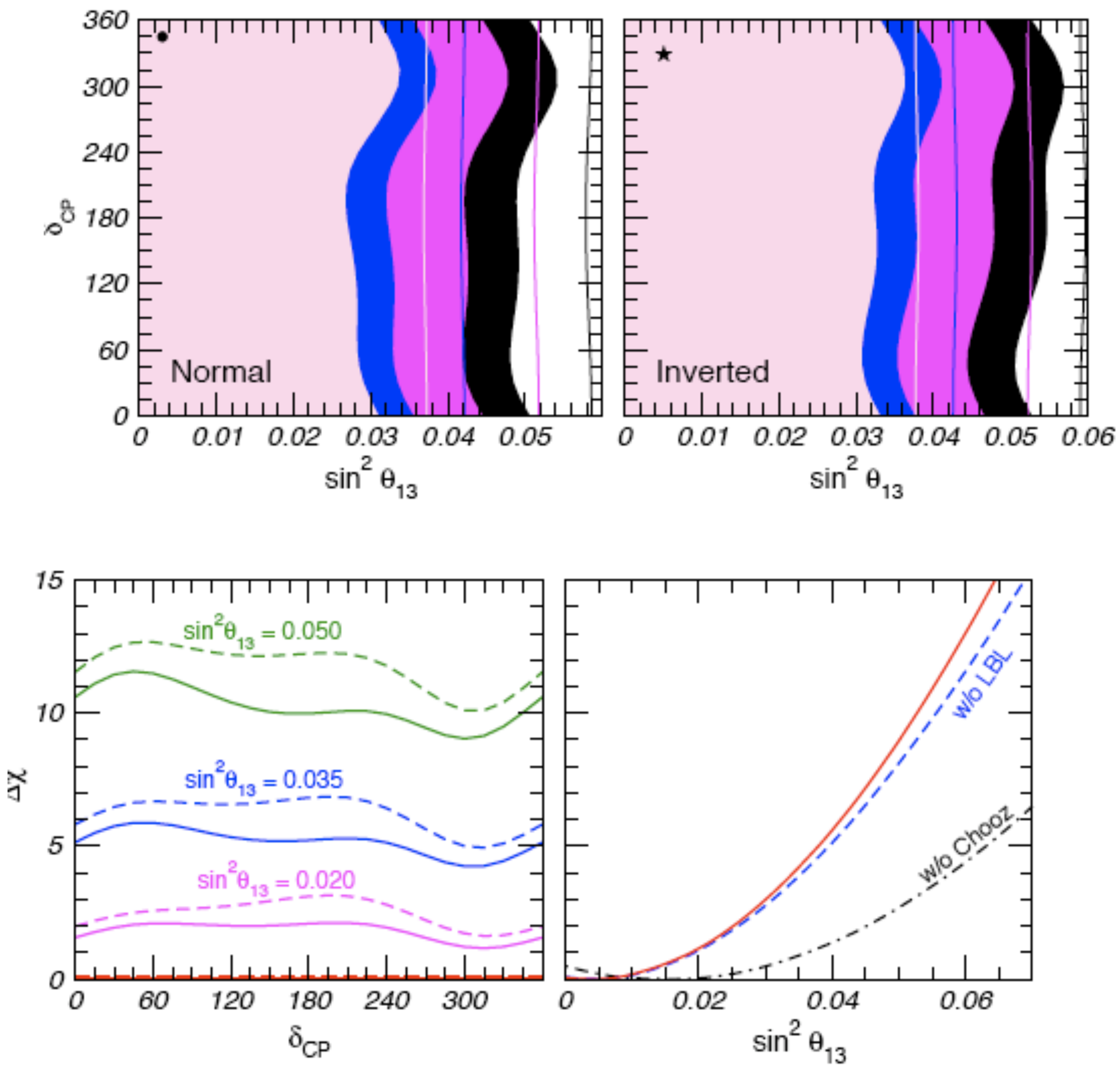

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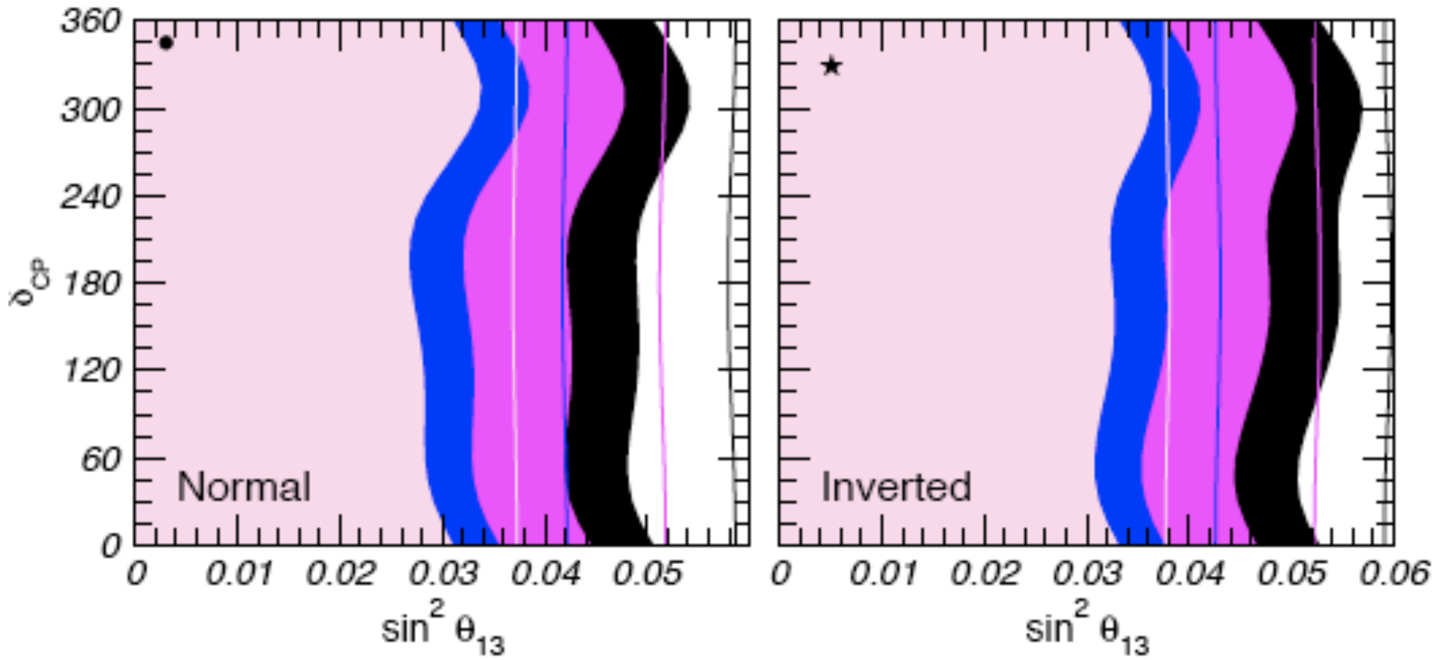
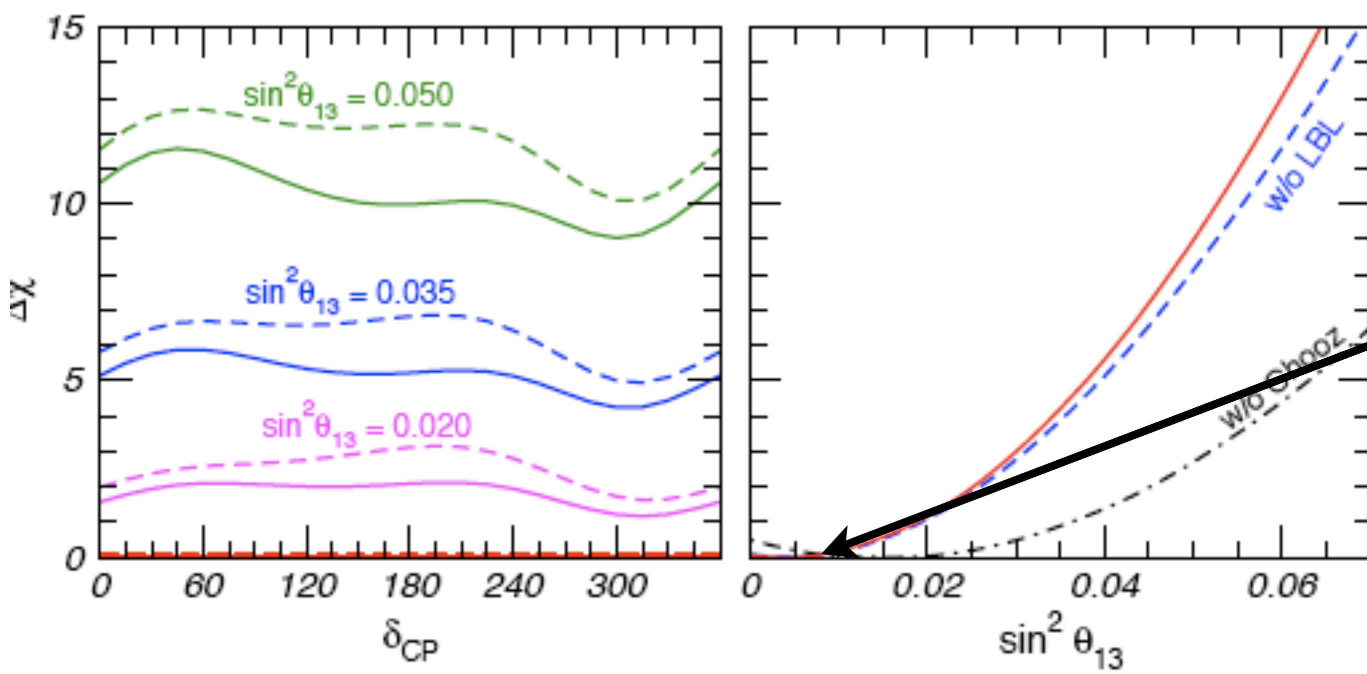


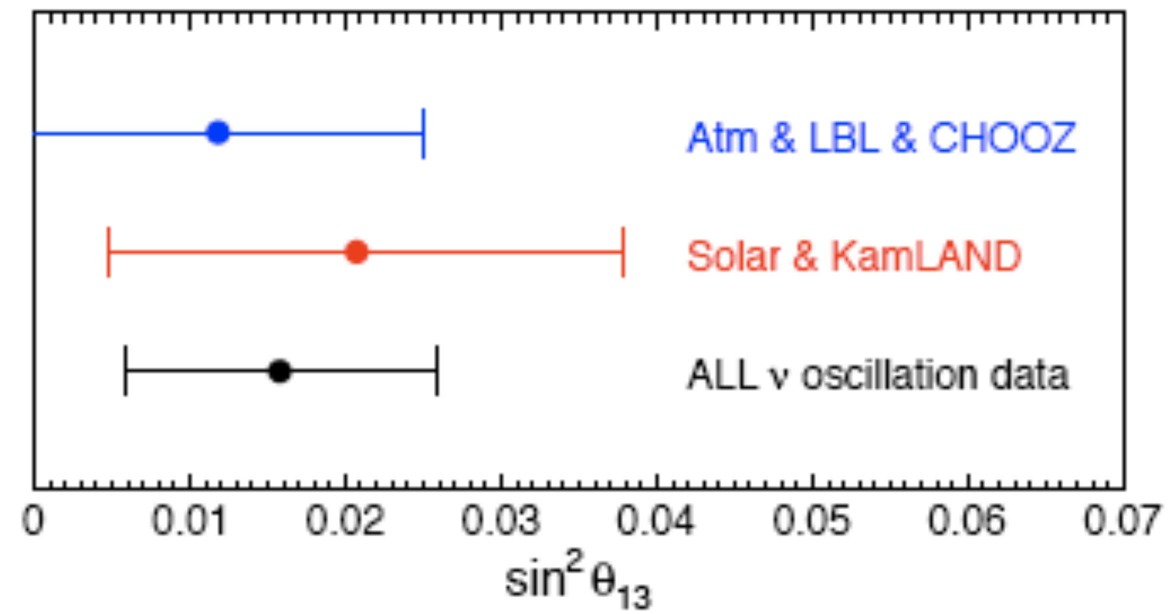


Hints of a non-vanishing θ_{13}?

Gonzalez-García and Maltoni, '08

Monday global three-family analysis

However.....
new SNO
and KamLAND
data



Fogli et al, 16/06/08

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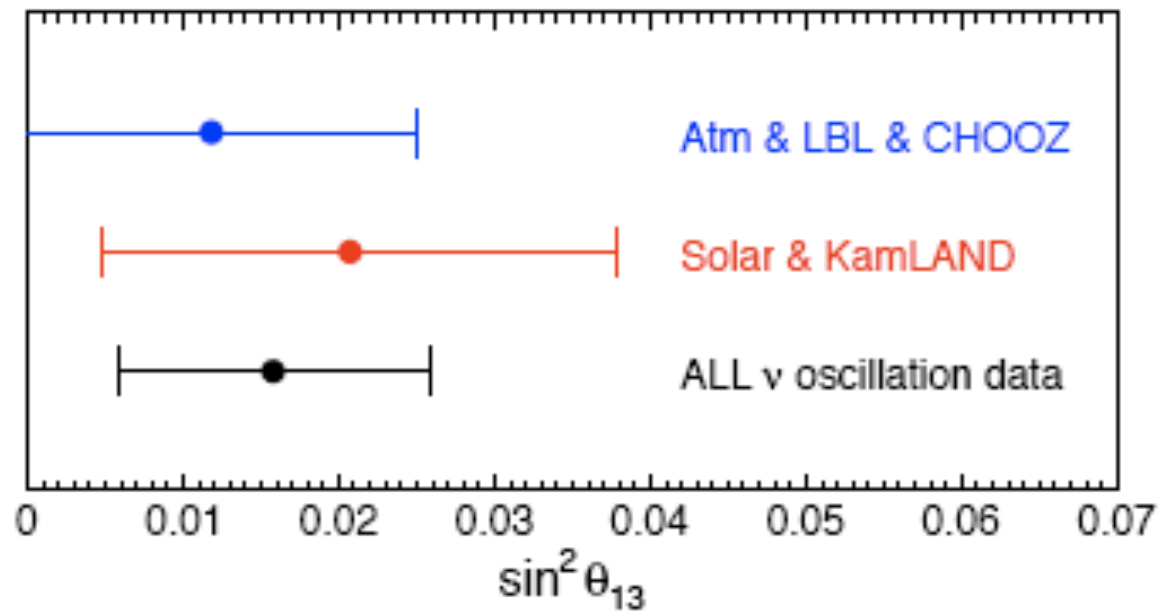

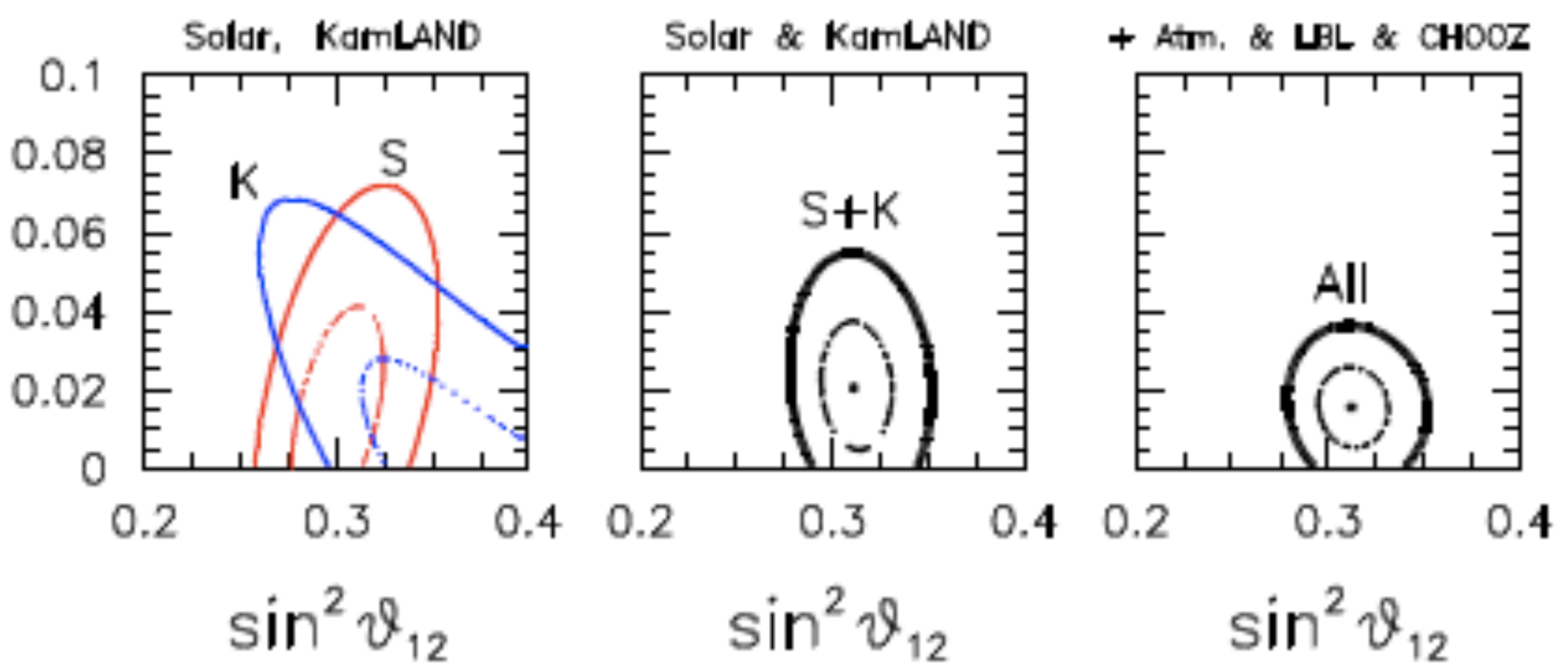

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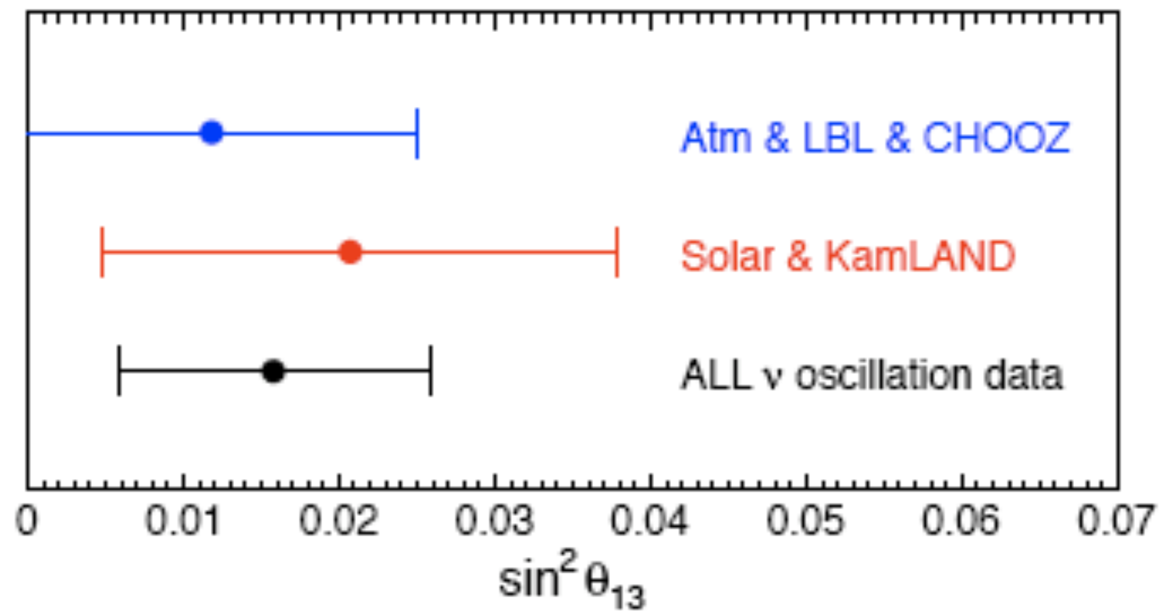
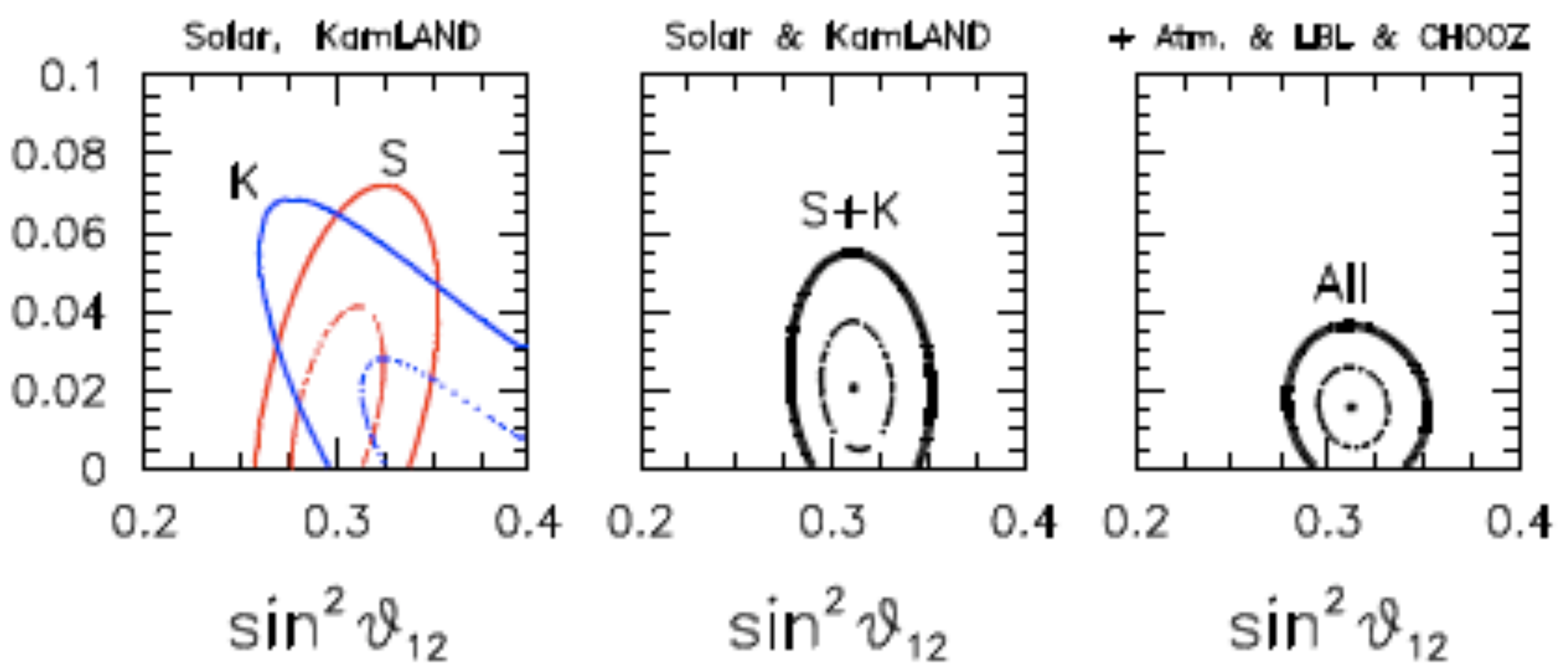




$\theta_{13} = 7° \pm 6°$

$\sin^2 \theta_{13} = 0.016 \pm 0.010$

Fogli et al, 16/06/08

STERILE NEUTRINOS

Short Baseline accelerator experiments

Many (all the older) neutrino experiments were performed with a typical baseline of $\mathcal{O}(0.1\text{ km})$. They are called SHORT BASELINE (SBL) accelerator neutrino experiment. As the typical energy of the neutrino beams $\mathcal{O}(1\text{ GeV})$ they are sensitive to mass differences:

$$\Delta m^2_{SBL} \approx \frac{E\text{ (GeV)}}{L\text{ (km)}} \approx 1\text{ eV}^2$$

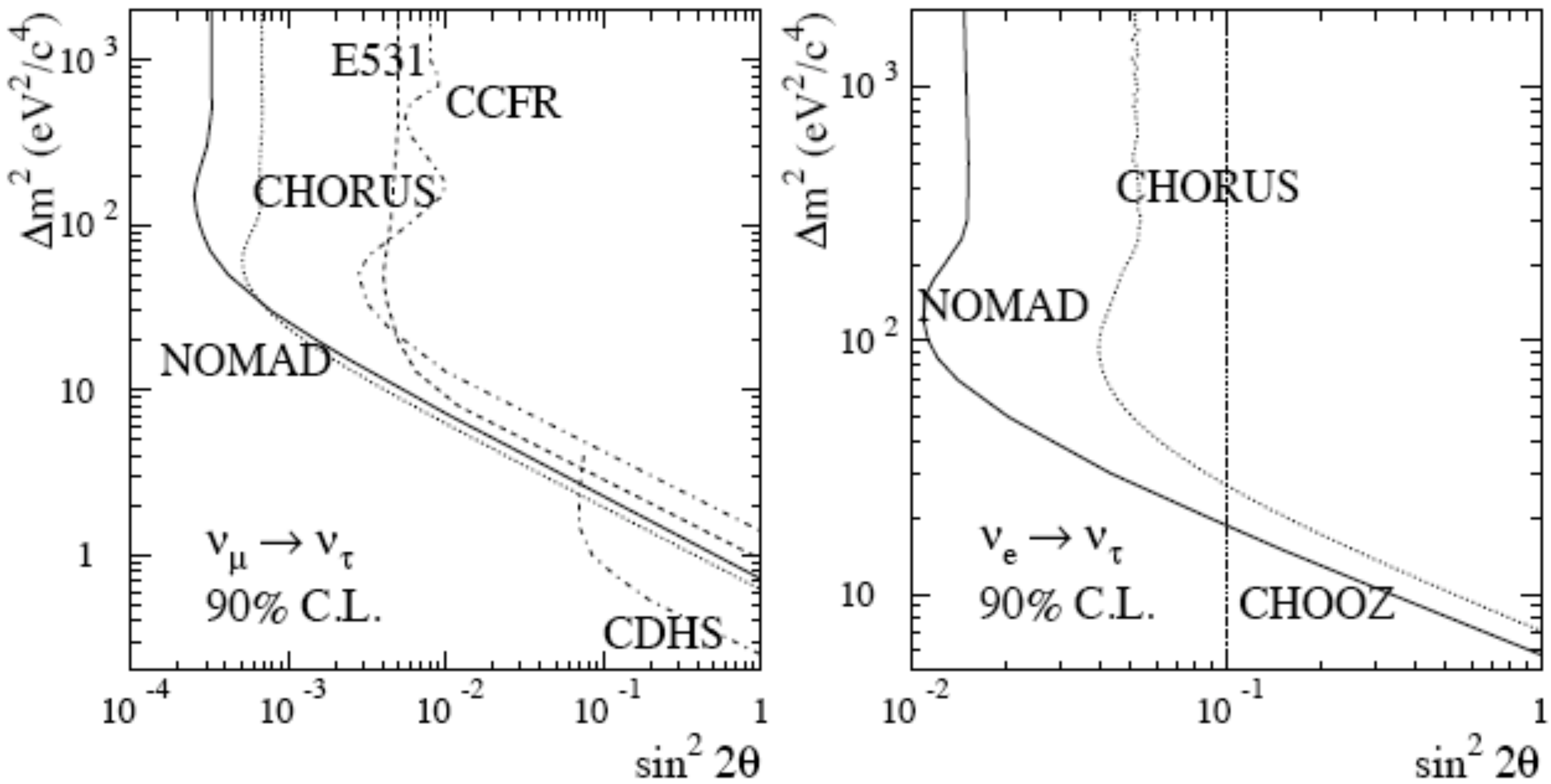
All the SBL accelerator experiment except LSND (see below) reported negative searches. Their results exclude typically the region of mass difference above 1 eV^2 (see Fig. 2):

- Mixing angle $\sin^2\theta \geq 10^{-2} - 10^{-3}$ (channel dependent) are excluded for $\Delta m^2 \geq 10^2\text{ eV}^2$(see for example CHORUS and NOMAD results in Fig. 2);
- For large mixing angle SBL are sensitive to $\Delta m^2 \geq 1(10)\text{ eV}^2$ (depending on the channel);

NOT RELEVANT for ATMOSPHERIC and SOLAR OSCILLATIONS

Important for sterile neutrino searches!

Short Baseline accelerator experiments



The problem: LSND

LSND is a low-energy "neutrino factory":

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In the DAR sample, an excess of 87.9 ± 22.4 ± 6.0 events over the background has been observed

Aguilar et al, hep-ex/0104049

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$\pi^+ \to \mu^+ \nu_\mu$ → $\nu_\mu \to \nu_e$

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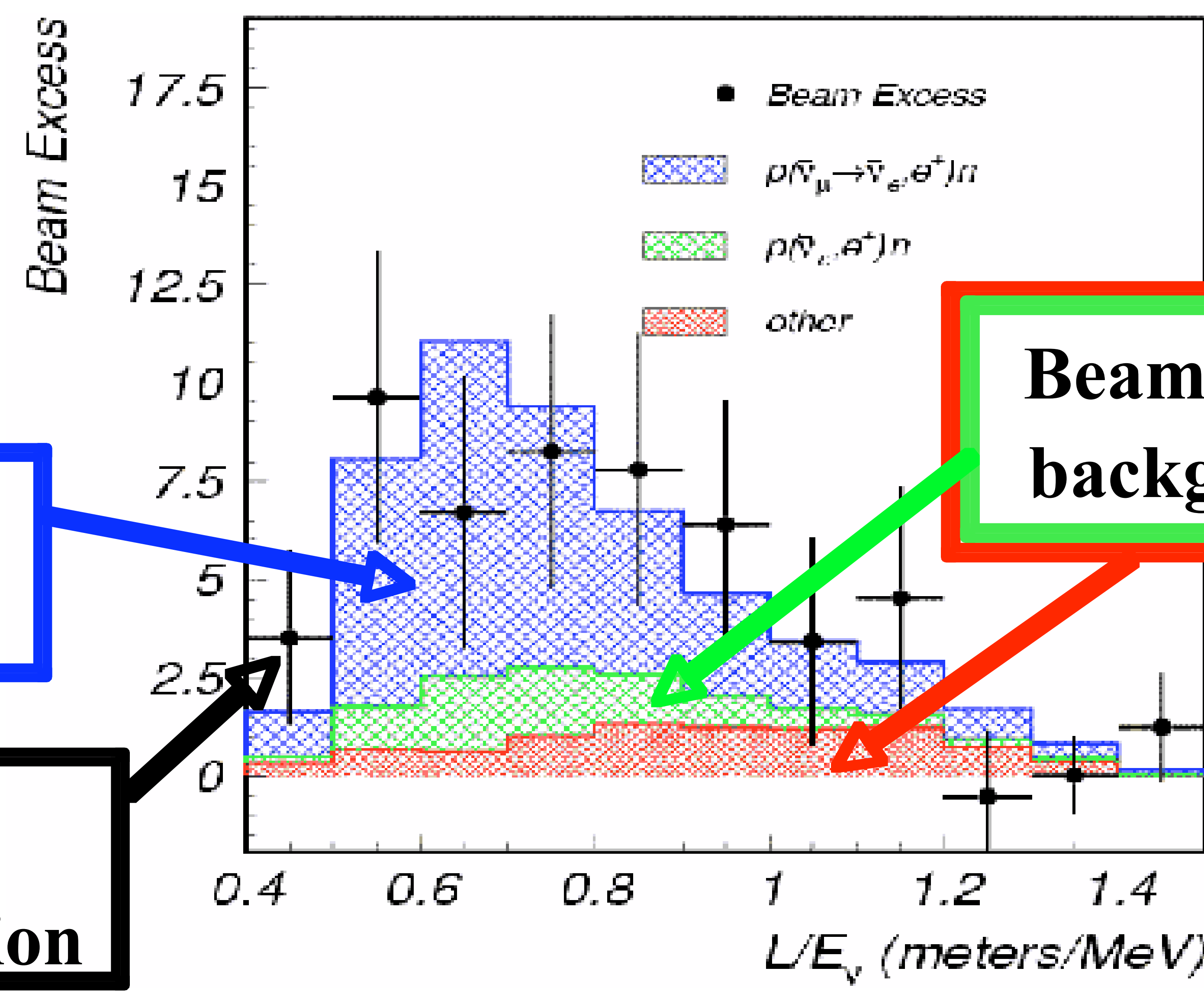
An excess of 8.1 ± 12.2 ± 7.0 events has been observed in the $\nu_\mu \to \nu_e$ channel

Aguilar et al, hep-ex/0104049

The problem: LSND (2)

Excess of events:

87.9 ± 22.4 ± 6.0



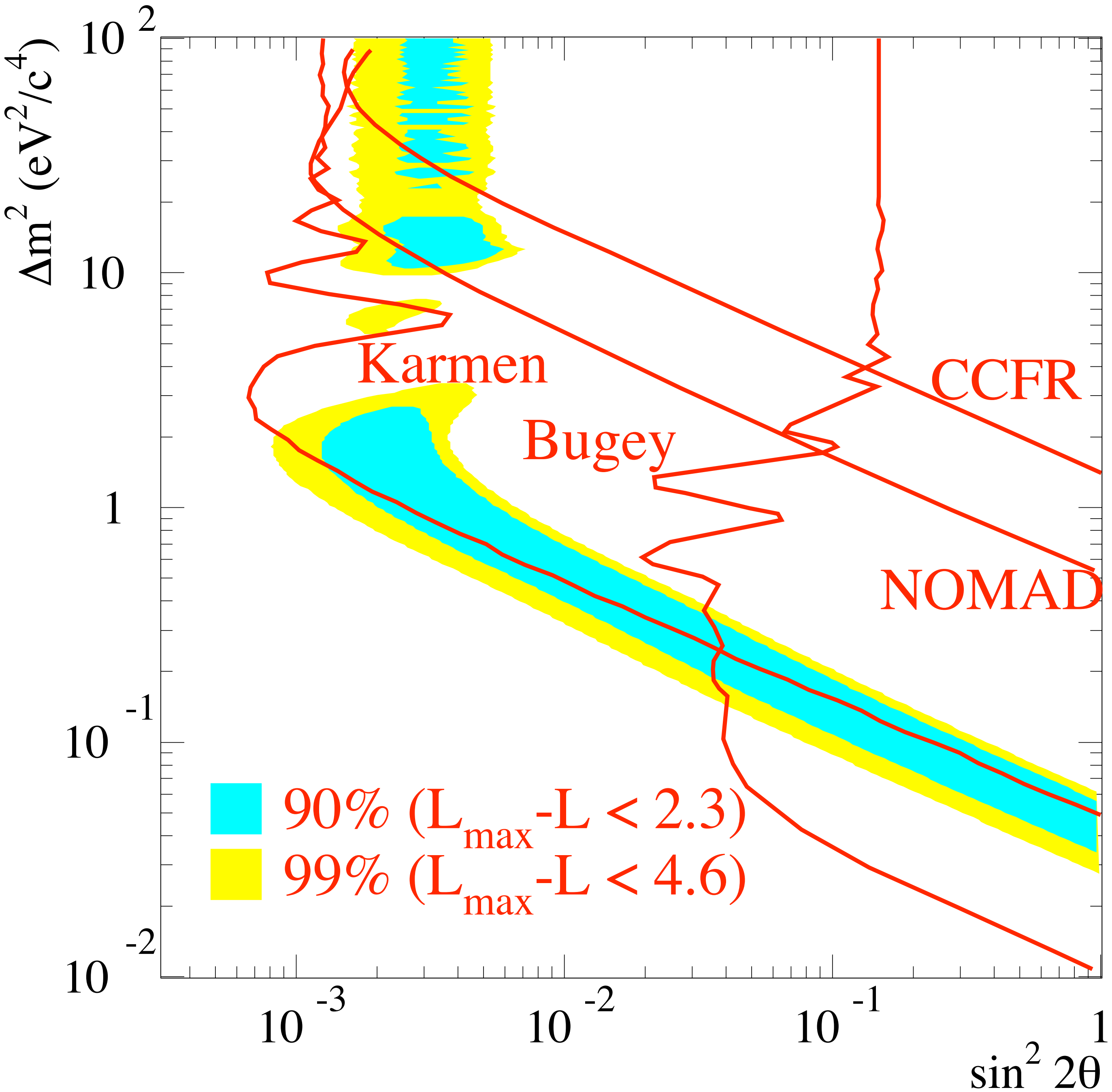
Expectation for oscillations

Data points after background subtraction

Beam related backgrounds

Aguilar et al, hep-ex/0104049

LSND analysis (2001)



Oscillation probability

$$P_{\mu e} = (0.264 \pm 0.067 \pm 0.045)\%$$

Effective two-family analysis

$$\Delta m^2_{LSND} = 0.2 - 10\,\mathrm{eV}^2$$

$$\sin^2 2\theta_{\mu e} = 10^{-3} - 10^{-1}$$

Aguilar et al, hep-ex/0104049

Sterile neutrinos

Easiest possibility to solve the LSND puzzle:

add one or more singlet fermion states to the SM

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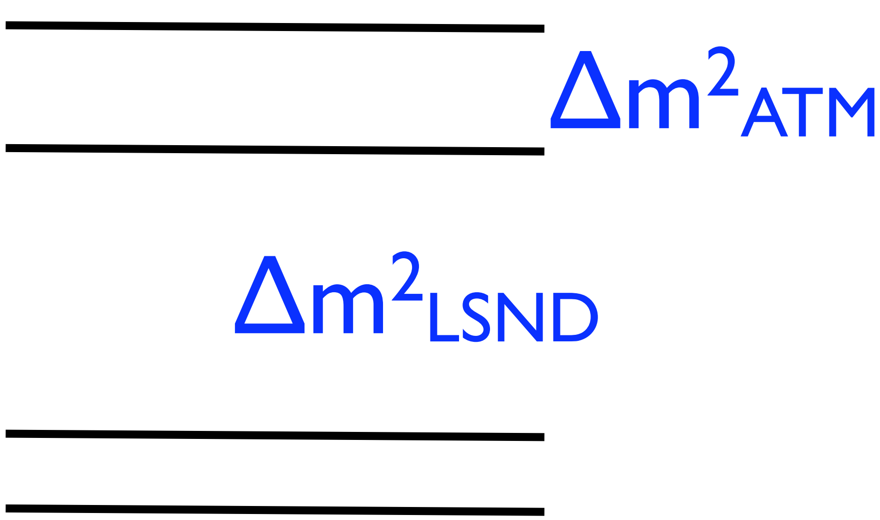

2+2

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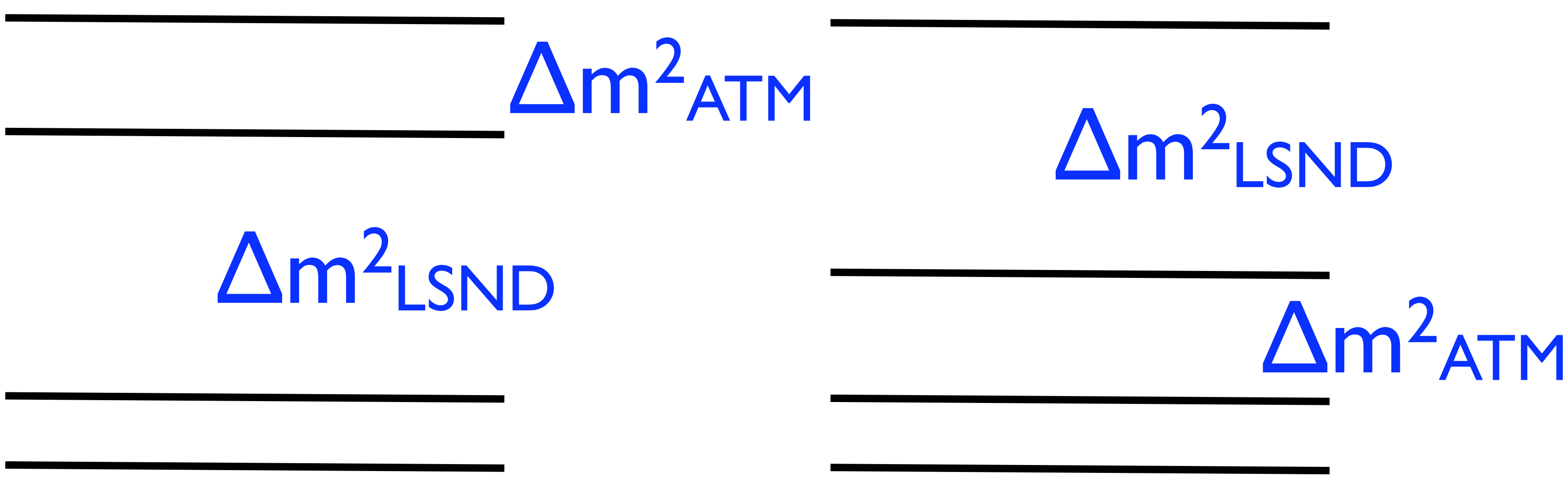

2+2 3+1

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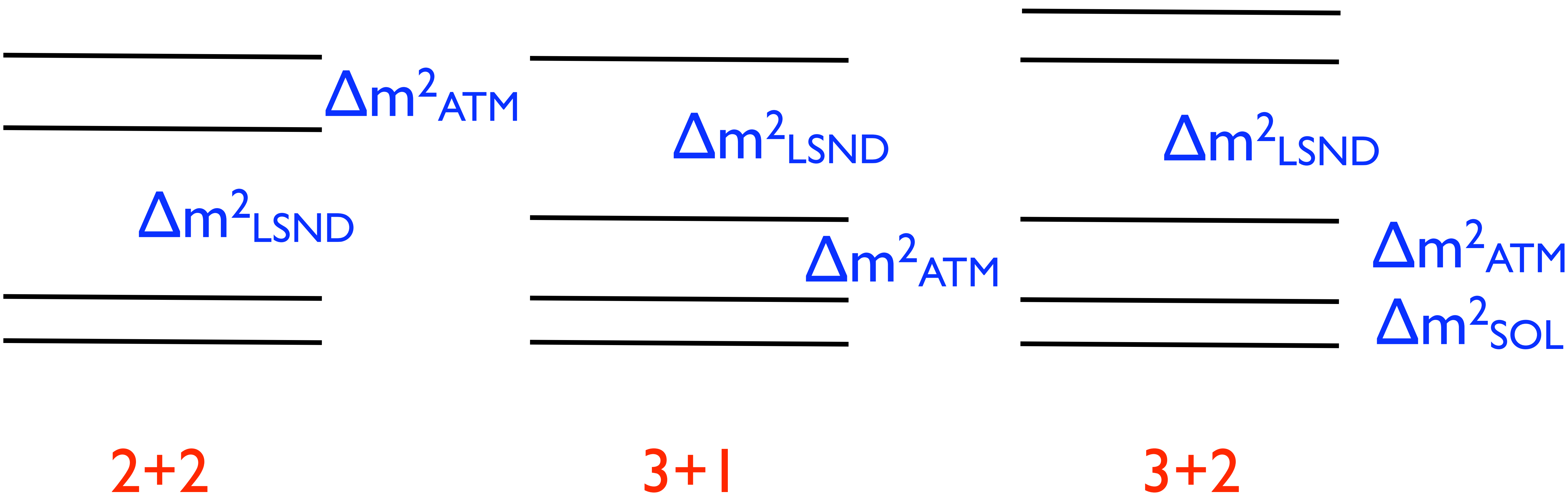
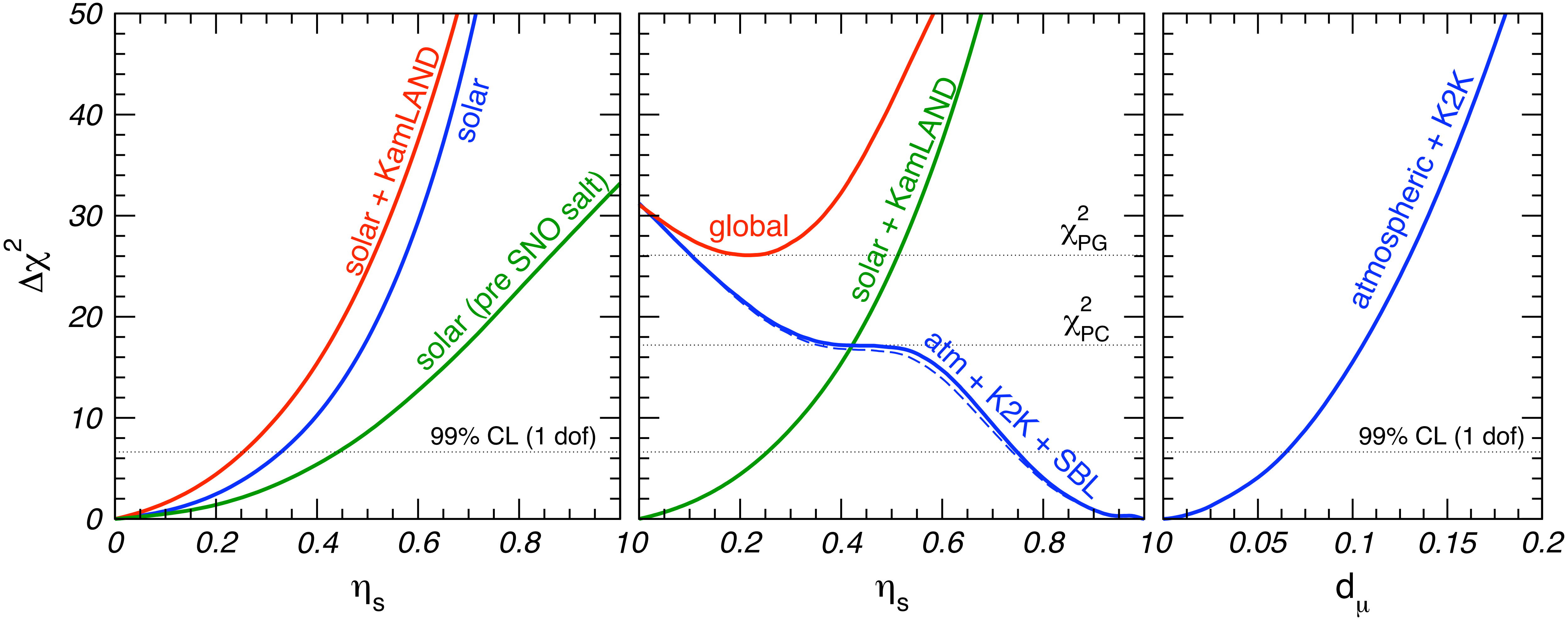


Sorel, Conrad and Schaevitz, hep-ph/0305255

Pre-MiniBooNE

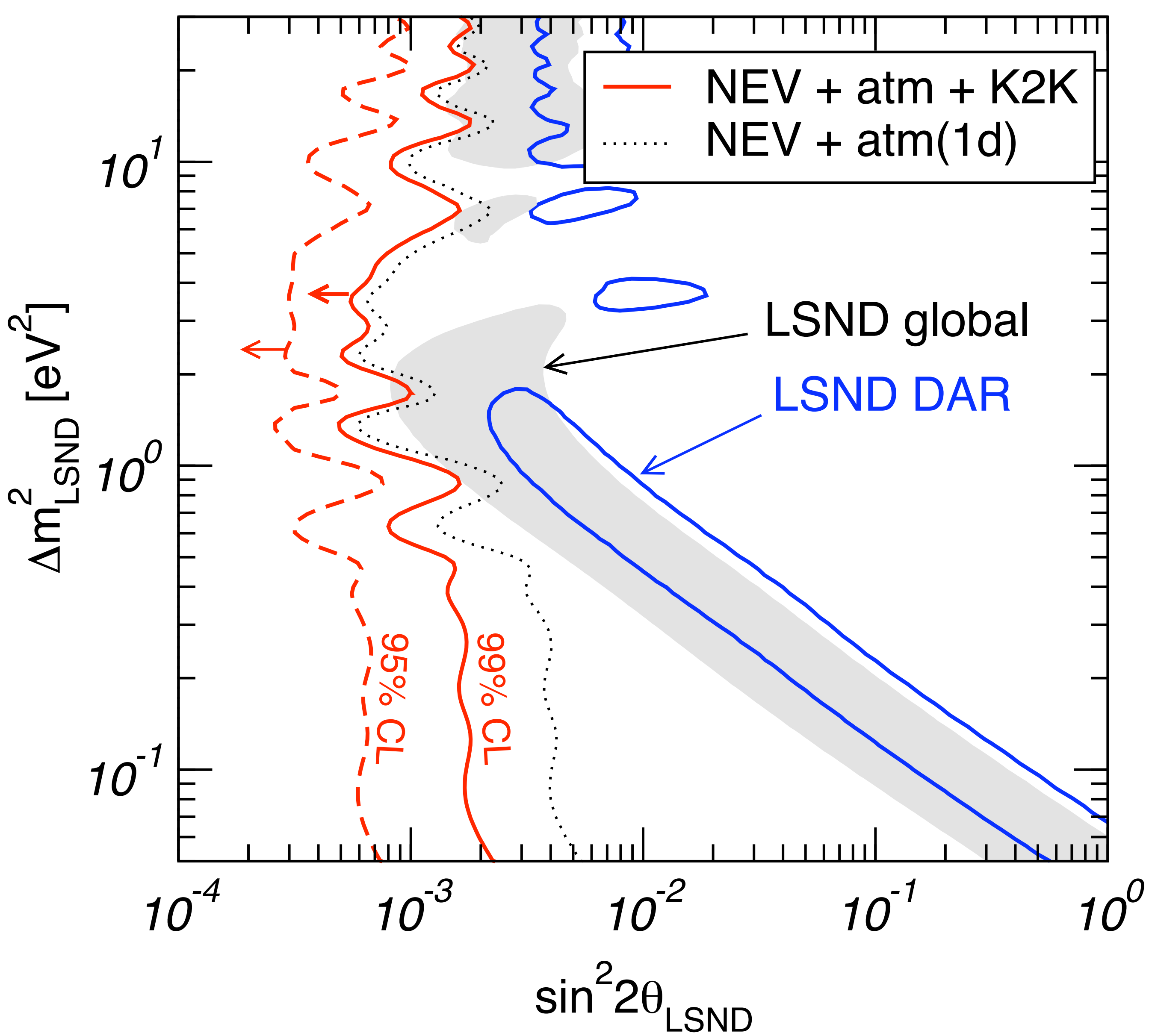
The 2+2 model is ruled out by solar and atmospheric neutrino data



$$\eta_\alpha = \sum_{i \in solar} |U_{\alpha i}|^2 \qquad d_\alpha = 1 - \sum_{i \in atmo} |U_{\alpha i}|^2$$

Maltoni, Schwetz, Tórtola and Valle, hep-ph/0405172

Pre-MiniBooNE (2)



The 3+1 model was also in a bad shape

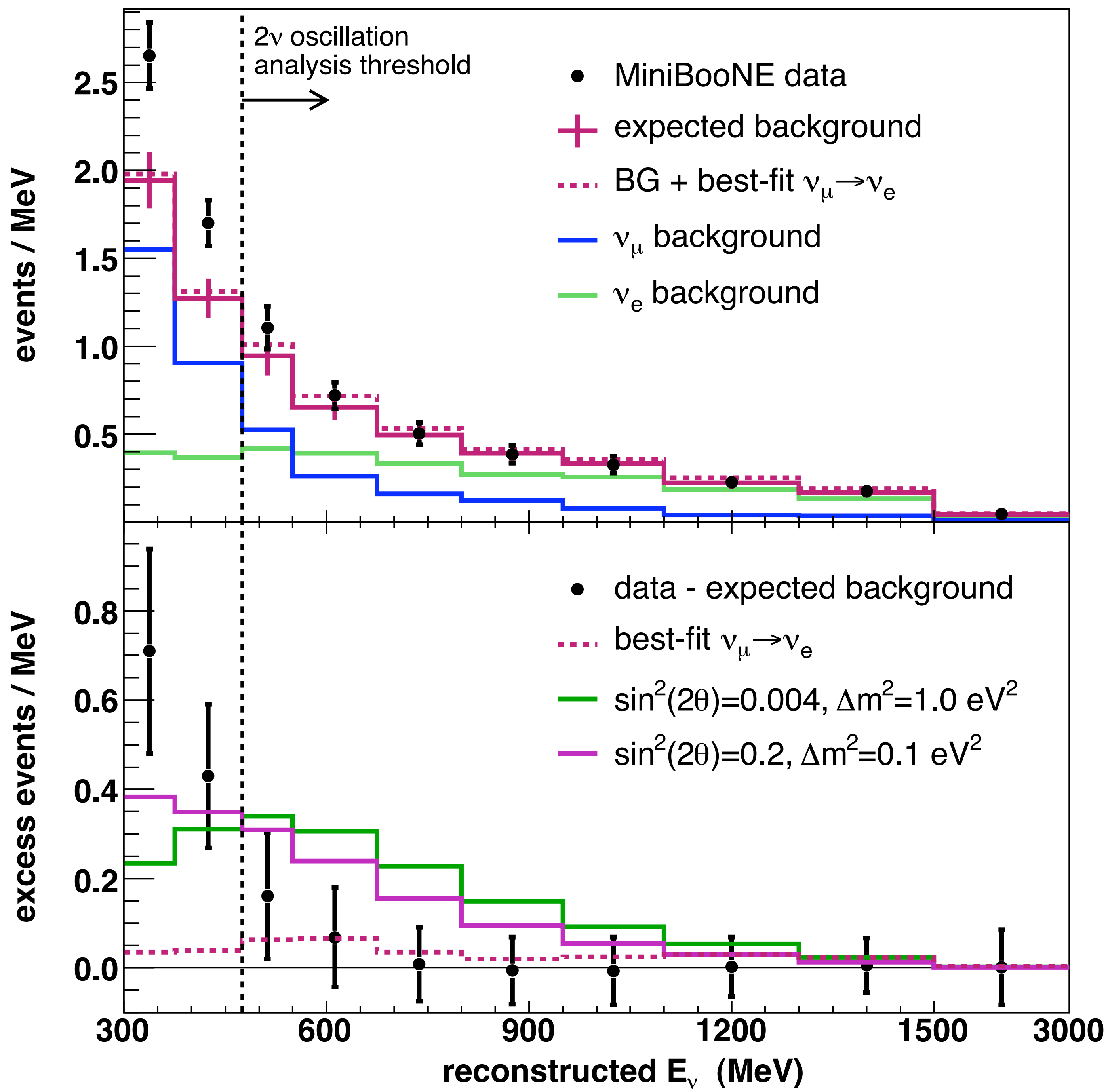
$d_e \sim |U_{e4}|^2 < 0.053$ Bugey

$d_\mu \sim |U_{\mu 4}|^2 < 0.063$ CDHS + atmospherics

$$\sin^2 2\theta_{\mu e} = 4 d_e d_\mu < 3 \times 10^{-3}$$

Maltoni, Schwetz, Tórtola and Valle, hep-ph/0405172

MiniBooNE results



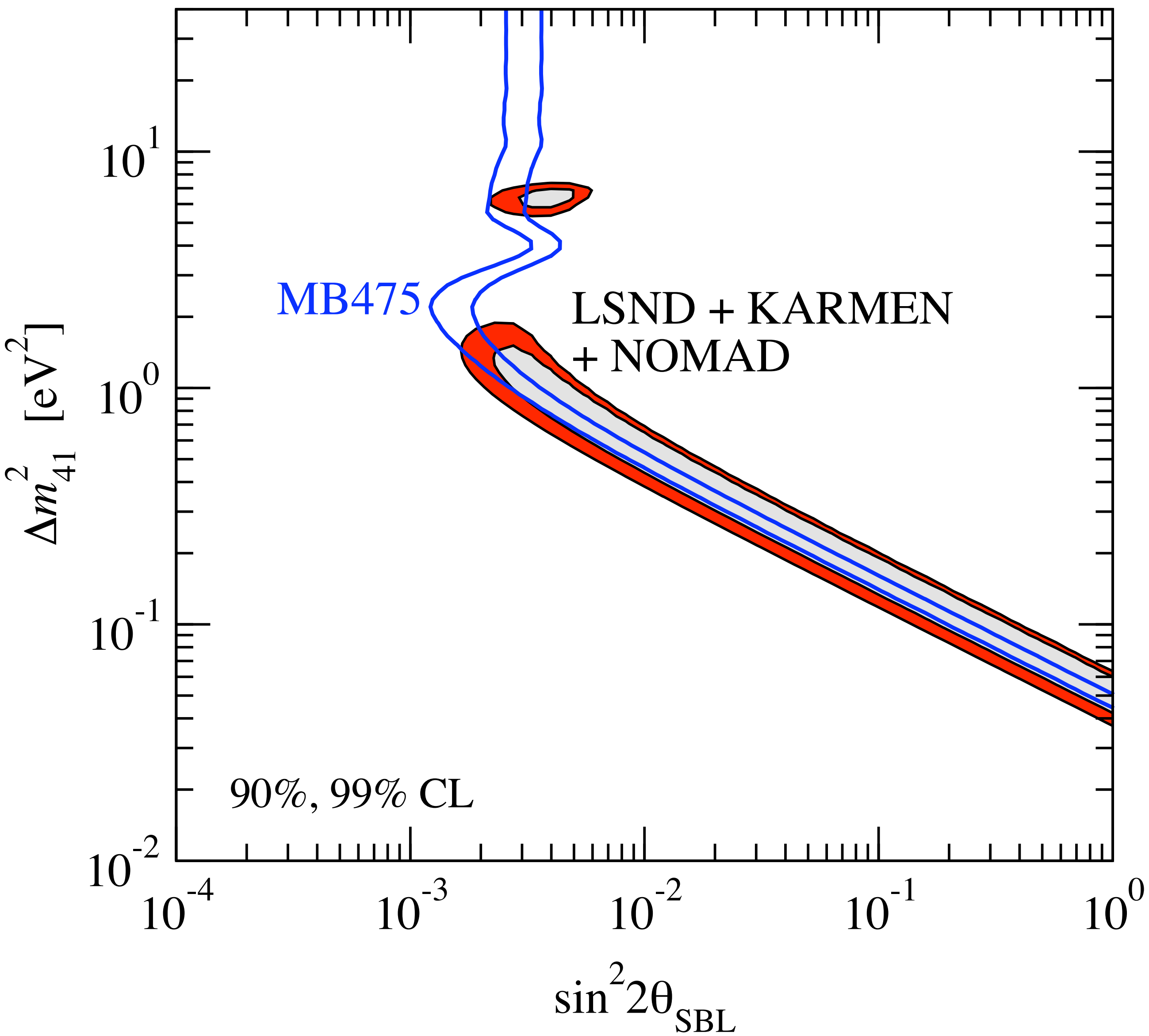
No event excess observed above 475 MeV

However, unexplained event excess observed in the range [300-475] MeV

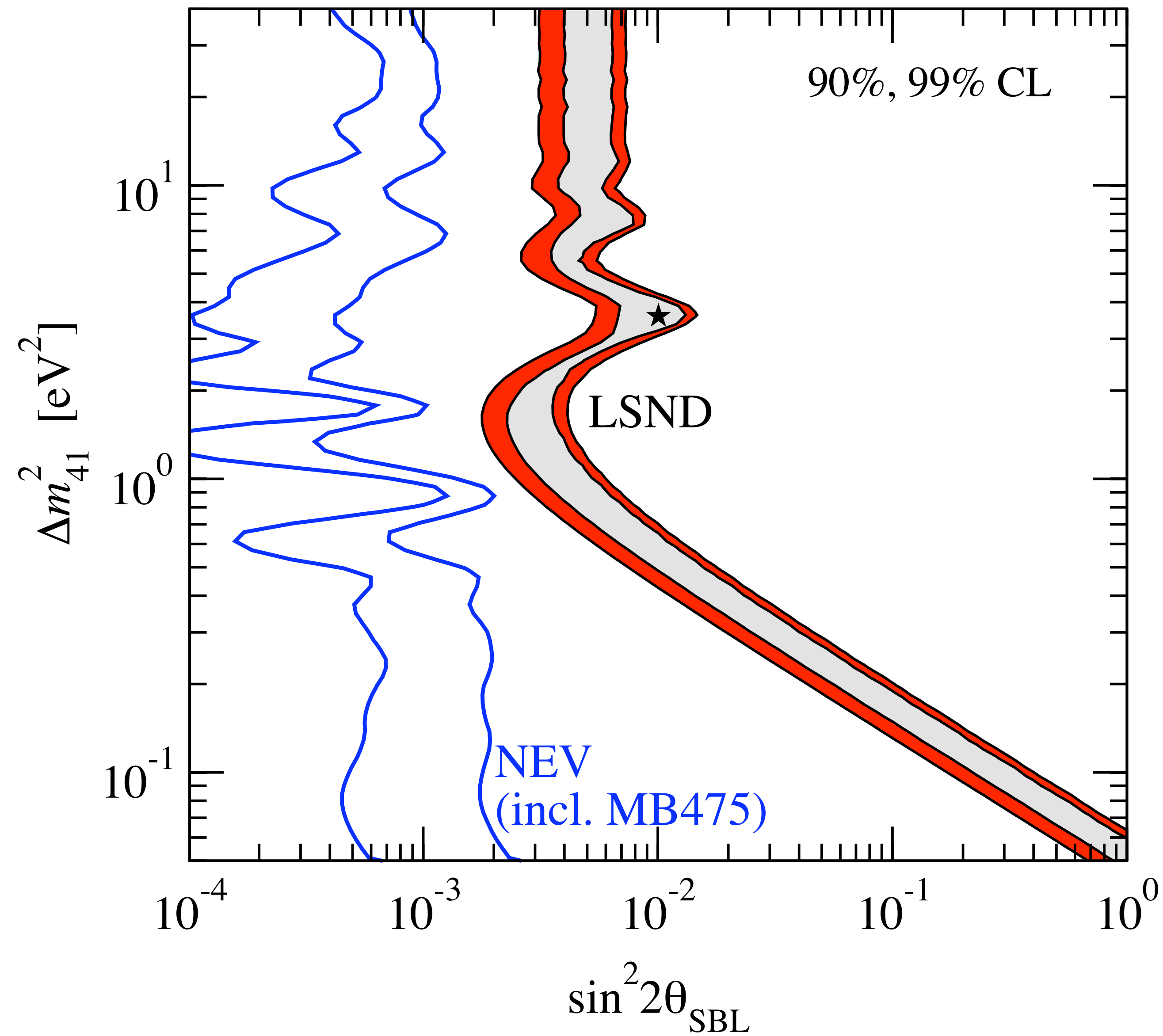
Aguilar et al, 0704.1500 [hep-ex]

3+1 after MiniBooNE

Only appearance



Everything



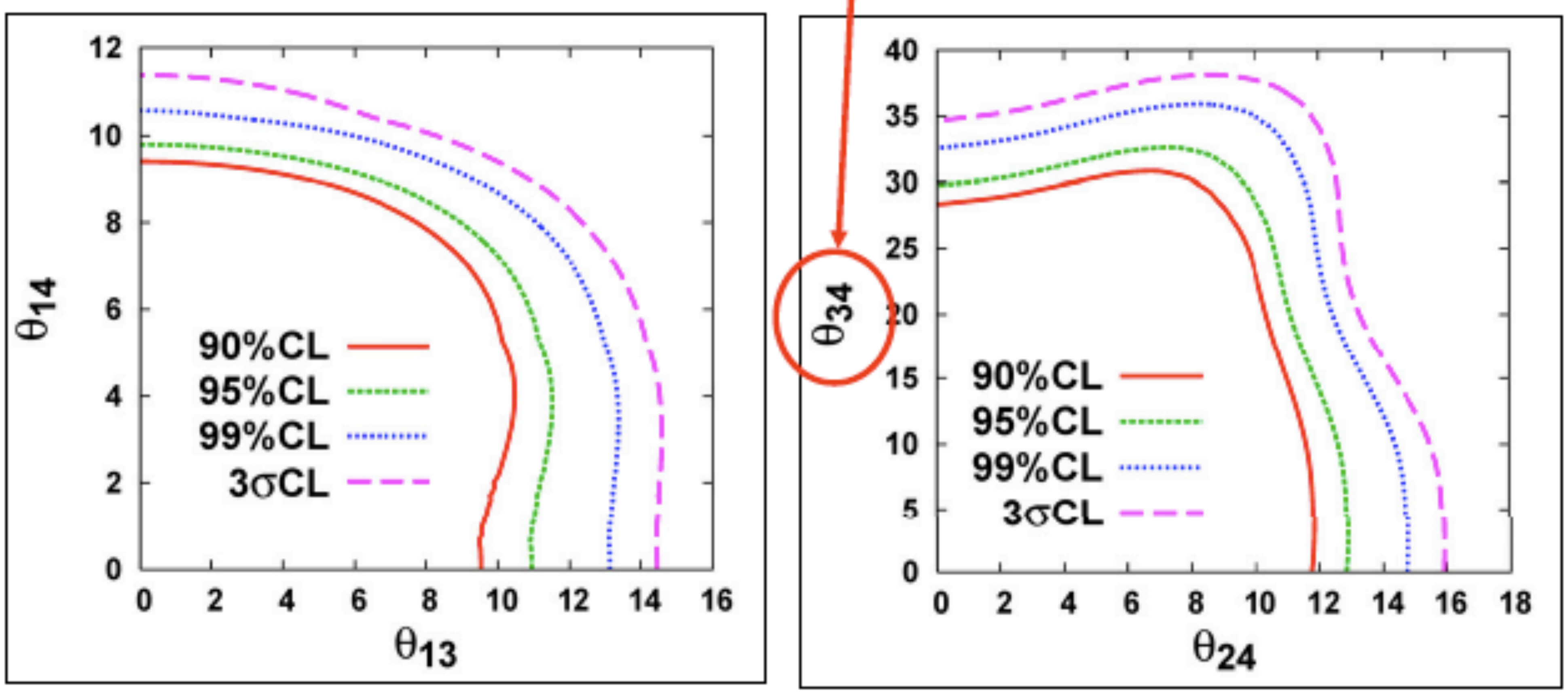
Maltoni and Schwetz, 0705.0107 [hep-ph]

Bounds on 3+1 model

$$U = R_{34}(\theta_{34})\, R_{24}(\theta_{24})\, R_{23}(\theta_{23},\,\delta_3)\, R_{14}(\theta_{14})\, R_{13}(\theta_{13},\,\delta_2)\, R_{12}(\theta_{12},\,\delta_1)$$

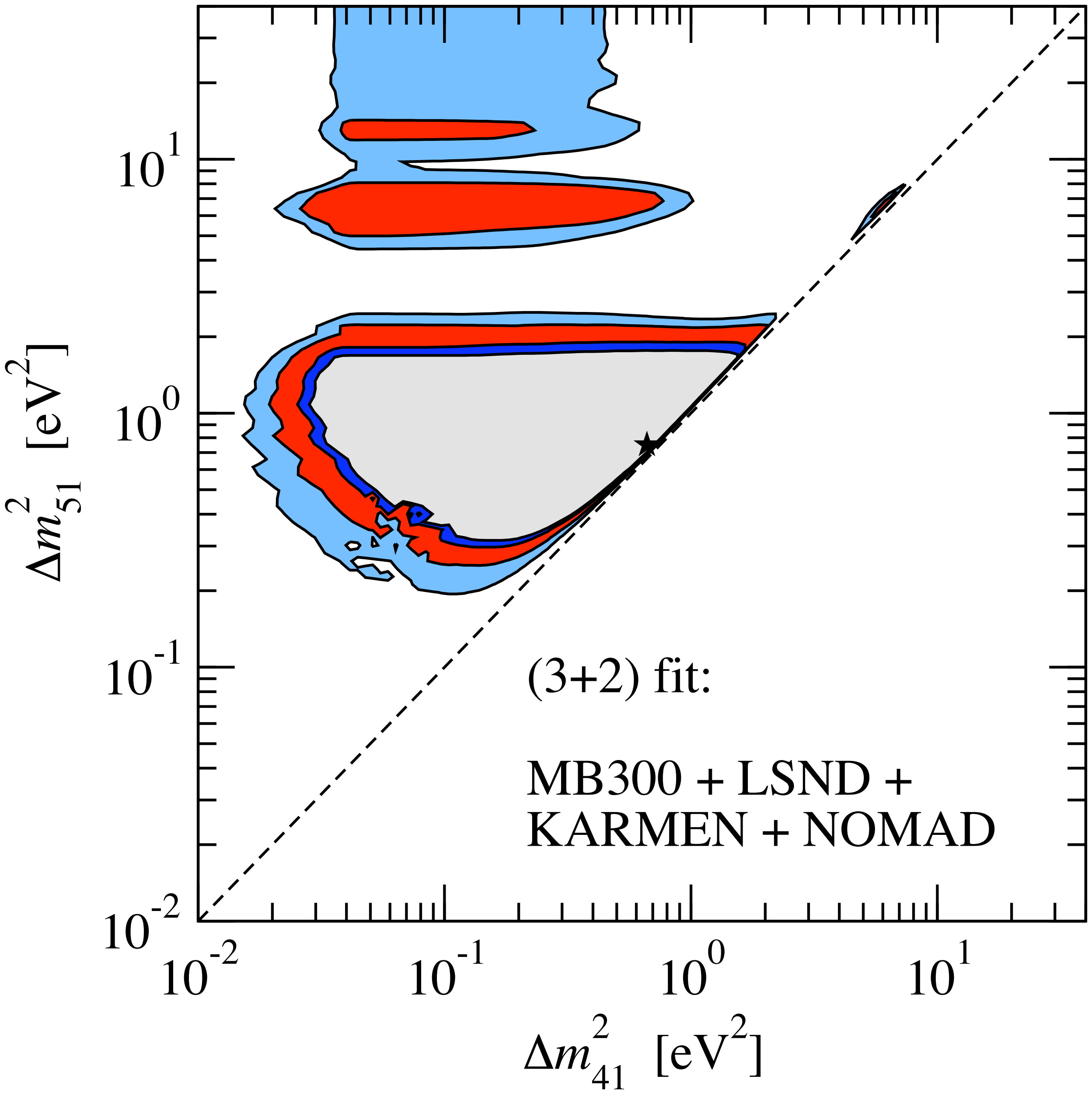
Constraints by all the negative results give the allowed region

θ_{34} : could be relatively large



3+2 after MiniBooNE

Only appearance



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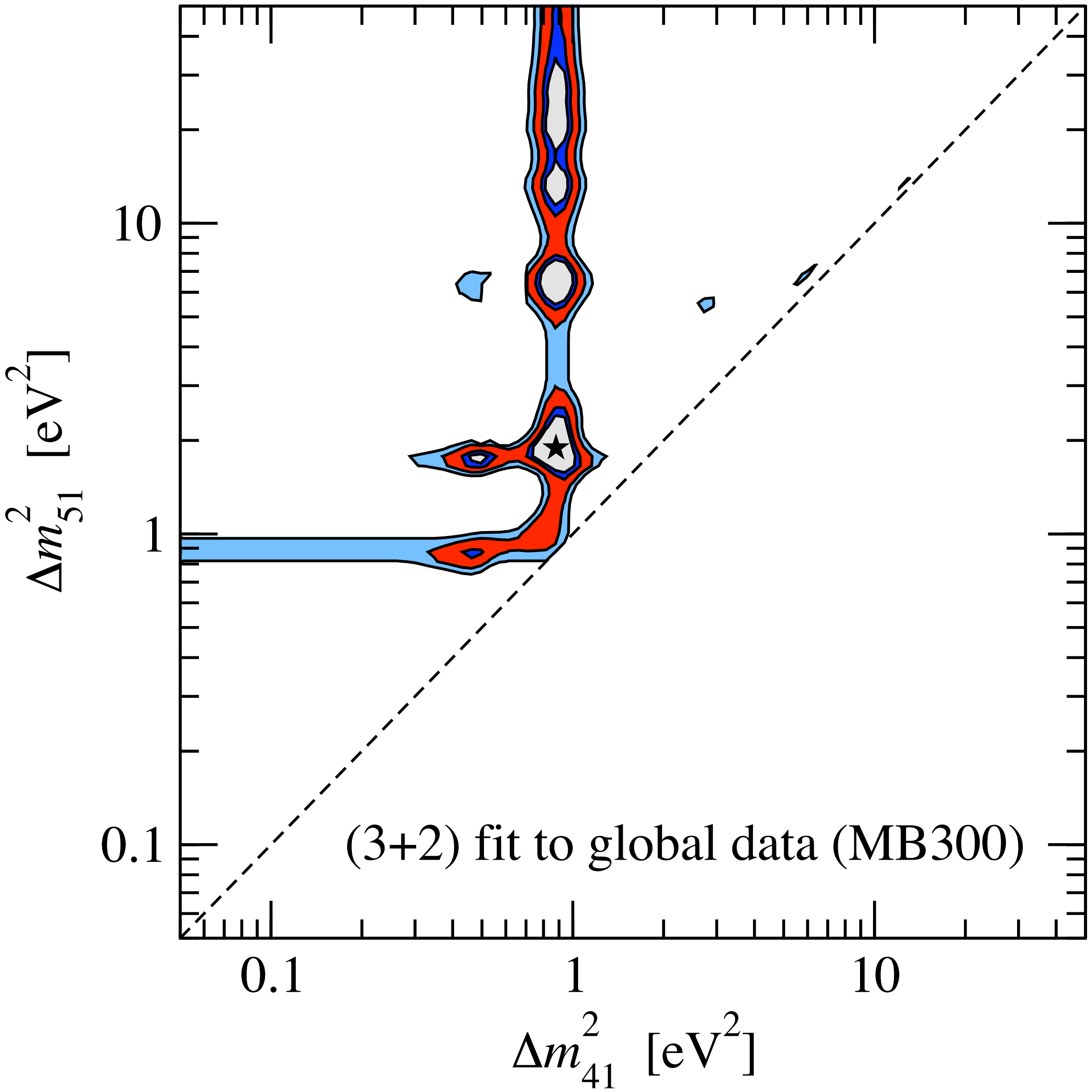

Maltoni and Schwetz, 0705.0107 [hep-ph]

What about cosmology?

Cosmological neutrinos modify the history of the Universe.
The relevant parameters are:

$\sum m_{\nu i}$ and the abundance $\omega_\nu + \omega_s$

Dodelson, Melchiorri and Slosar, astro-ph/0511500

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During the early Universe, active neutrinos can oscillate into sterile neutrinos (if $\Delta m^2 * \sin^4\theta > 3\times10^{-6}$ eV^2)

→ thermal abundance hypothesis, $\omega_\nu = \omega_s$

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For non-thermal sterile neutrinos, the upper bound on m_s depends on the abundance

Dodelson, Melchiorri and Slosar, astro-ph/0511500

NuFact and sterile neutrinos

Two reference detectors have been considered:

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1) 1 TON detector at L = 1 Km;
μ-identification efficiency $\varepsilon_\mu = 0.5$;
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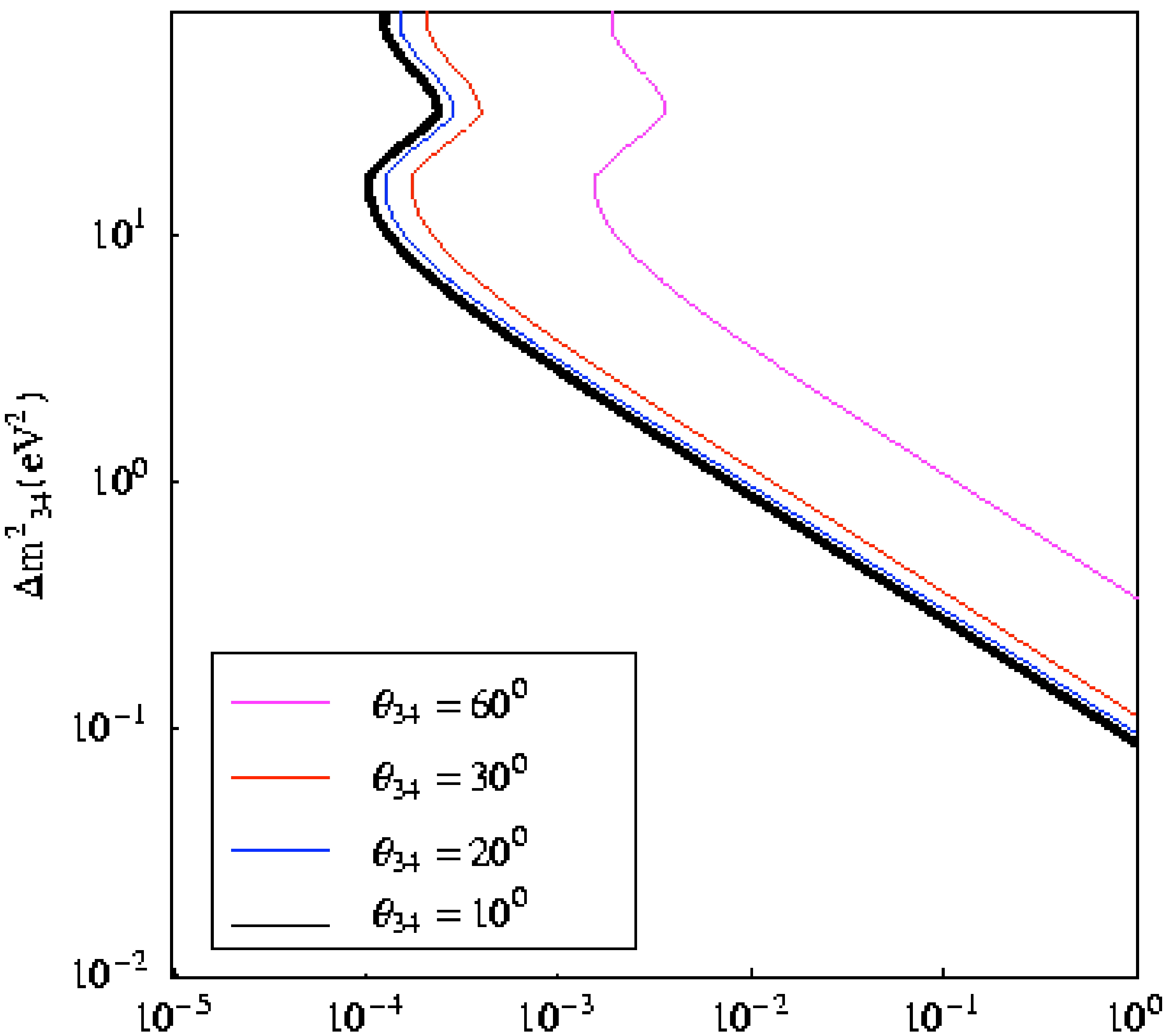
$B = 10^{-5} N_{CC}$

2) 40 Kton magnetized iron detector at $L = 3000$ Km
(the standard detector for the Neutrino Factory
$\nu_e \rightarrow \nu_\mu$ analysis)

Cervera, Dydak and Gómez-Cadenas, NIMA 451 (2000) 123

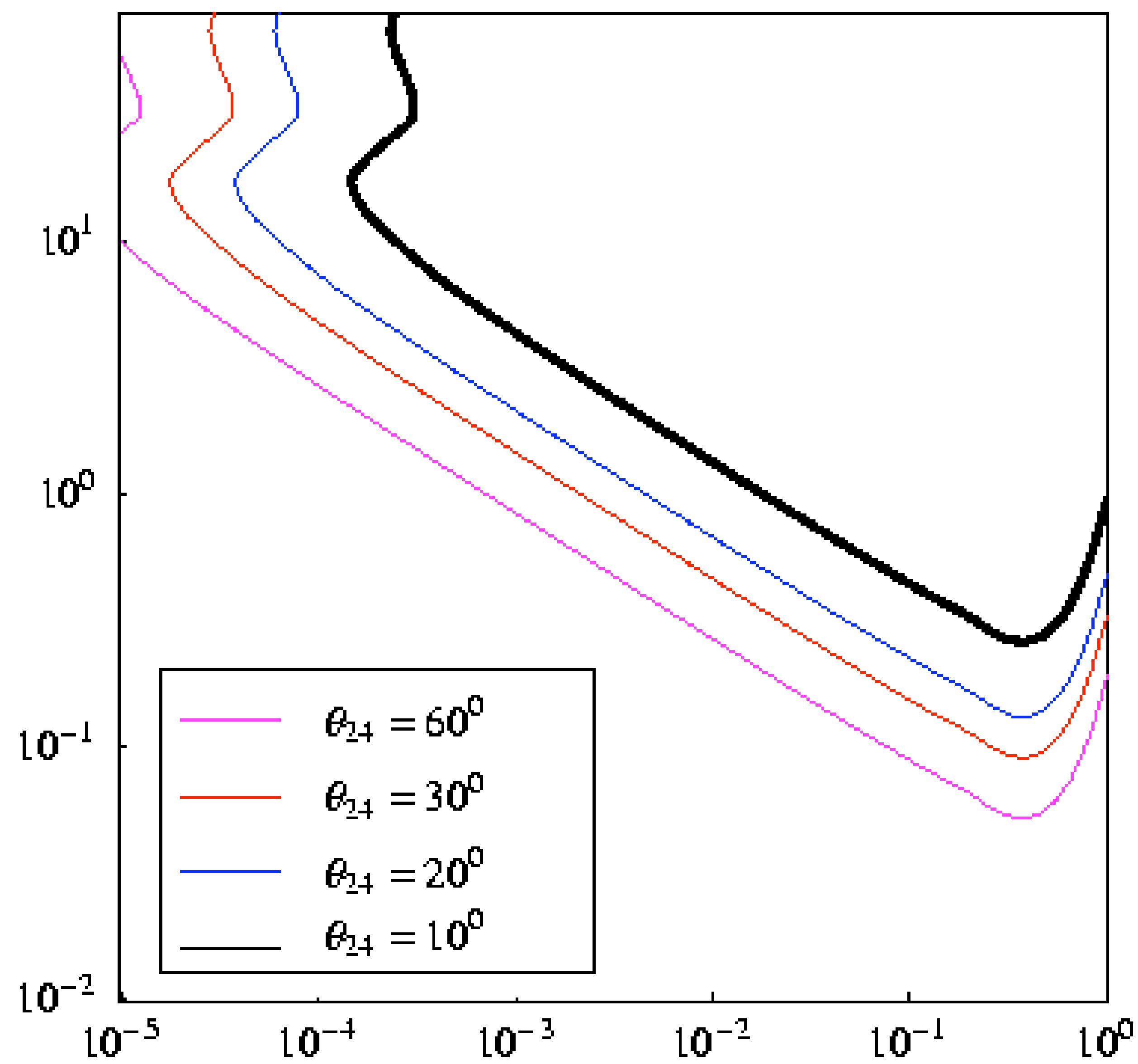
NF results (I)

$\nu_e \rightarrow \nu_\mu$



$\sin^2\theta_{14}$

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



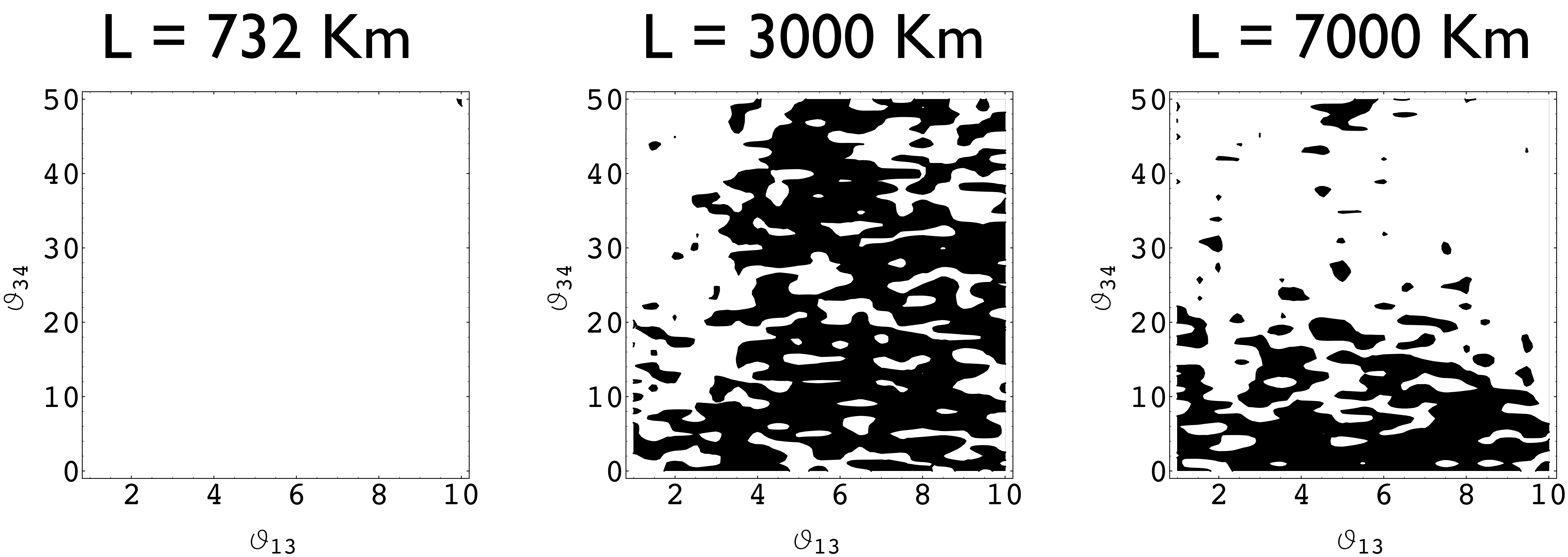
$\sin^2\theta_{34}$

Detector I

Donini and Meloni, hep-ph/0105089

NF results (2)

Dalmatian dog-hair plots



W. Disney et al, "One hundred and one dalmatians", 1961

Regions in which confusion between 3 and 3+1 CP-conserving models is possible

Detector 2

Donini, Lusignoli and Meloni, hep-ph/0107231

CONCLUSIONS

- In order to measure θ_{13} and δ we must study subleading effects in the oscillation probabilities.

- Strategy 1: direct searches (LBL and reactors)
  The present bound for direct searches is $\theta_{13} < 10.8°$

- Strategy 2: global three-family analysis
  The present bound for global fits is:
  $\sin^2\theta_{13} < 0.035$ (Gonzalez-García and Maltoni, 0704.1800)
  $\sin^2\theta_{13} = 0.016 \pm 0.010$ (Fogli et al, 0806.2649)

- Sterile neutrinos: MiniBooNE excludes 4 neutrino models as a solution to the LSND problem; LSND can be explained in 5 neutrino models, though

- Interesting excess at low energy in MiniBooNE data: food for theorists (eg Harvey, Hill and Hill, 0712.1230!)