Phenomenology of sterile neutrinos

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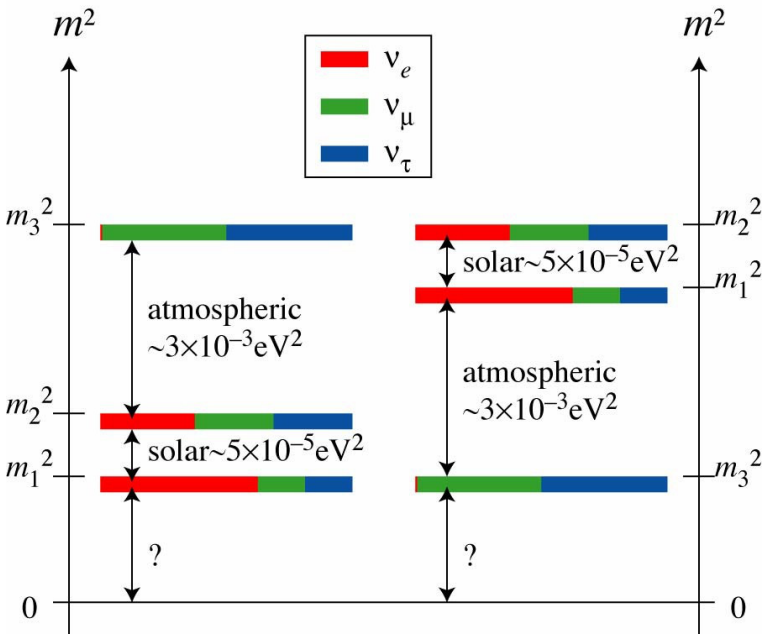
Standard scenario for neutrino oscillations

- Most (all data) can be understand if we assume that Neutrino flavor states are linear combination of mass eigenstates. a Mixing matrix, named Pontecorvo, Maki-Nakagawa-Sakata (PMNS).
  For 3 flavor neutrinos we have a 3 $\times$ 3 matrix,

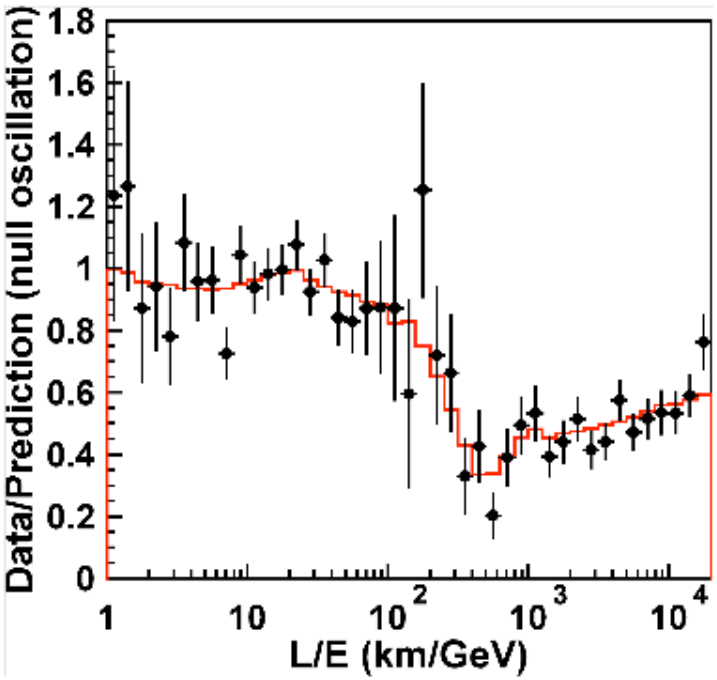
$$|\nu_\alpha\rangle = \sum^{n} U^*_{\alpha i}|\nu_i\rangle \qquad \mathbf{U}_{\mathrm{PMNS}} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$



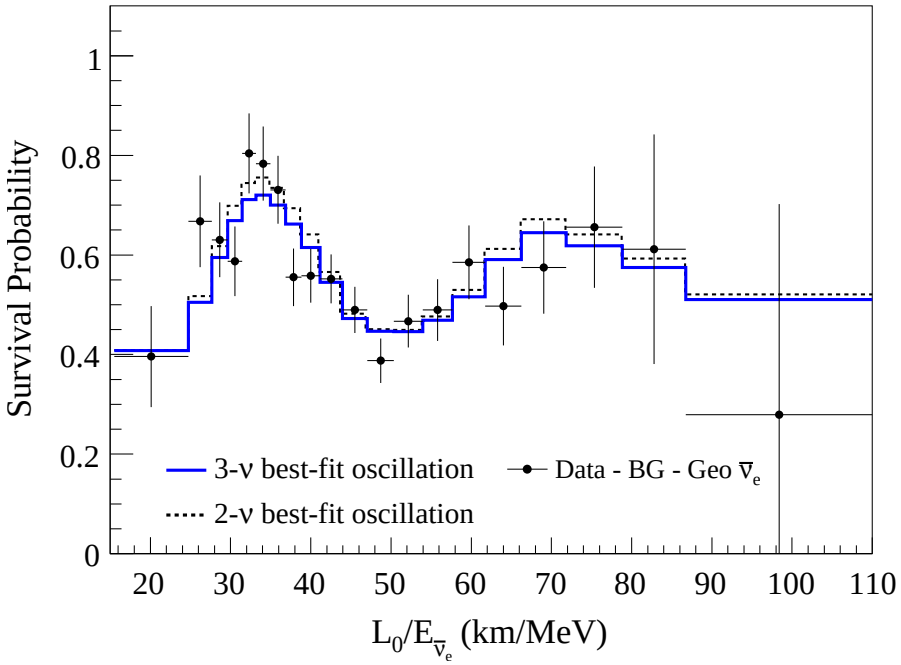
Standard scenario for neutrino oscillations

- In different experiments, it was proved that neutrinos oscillate,

$$P(\nu_\alpha \to \nu_\alpha) = 1 - \sin^2(2\theta)\sin^2\left(1.27\frac{\Delta m^2}{(\mathrm{eV})^2}\frac{\mathrm{L/Km}}{\mathrm{E/GeV}}\right)$$



(a) SK ν_μ data



(b) KamLand $\bar{\nu}_e$ data

$$\Delta M^2 = 2.5\,10^{-3}\mathrm{eV}^2$$

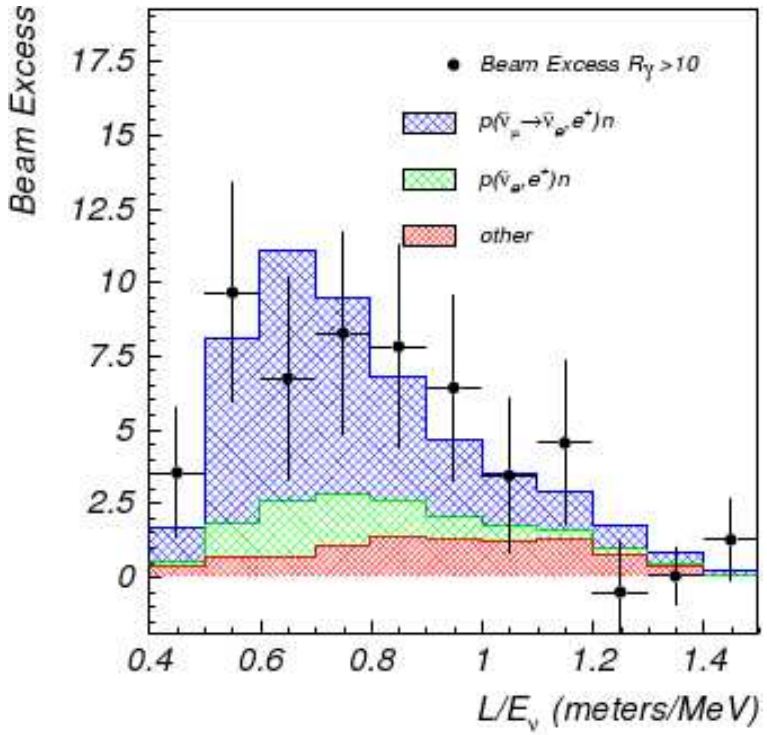
$$\Delta m^2 = 7.5\,10^{-5}\mathrm{eV}^2$$

Sterile neutrino phenomenology

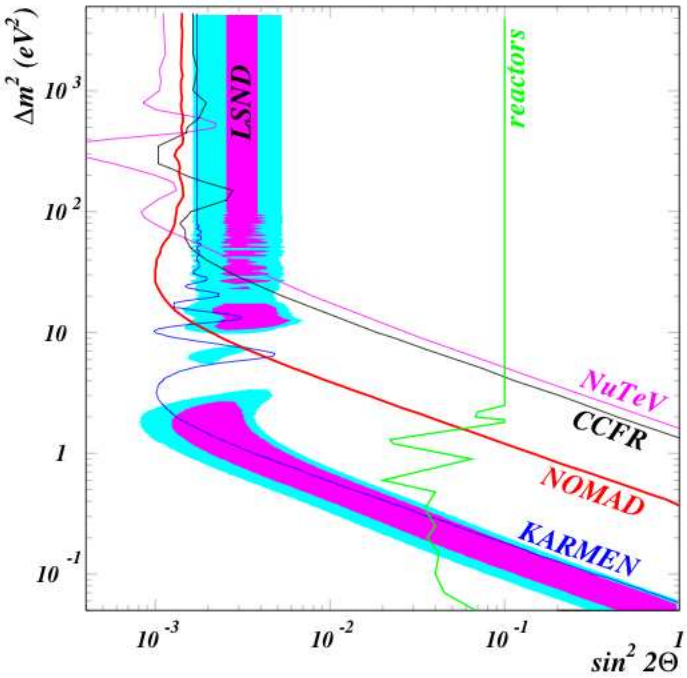
- Why are three generations of neutrinos? Why not, 4,5,...
  Invisible width of boson Z^0 indicate three neutrinos! No room for neutrinos with left-handed couplings!
  But we can think in extra neutrinos with right-handed couplings.:sterile neutrinos: neutrinos with any couplings with gauge bosons and only appear by oscillation.
  Also from the experimental point of view, there a bunch of anomalies that did not fit in the standard view of three light neutrinos:
  LSND anomaly and related
  The reactor neutrino anomaly
  The Gallium anomaly
  The Dark radiation
  The absence of up-turn in solar neutrino data

Sterile neutrino phenomenology

- LSND experiment (2001)[1]: $\bar{\nu}_\mu \to \bar{\nu}_e$ L $\sim$ 30m $E_\nu \sim 20 - 200$ MeV



(c)



(d)

$\Delta m^2_{LSND} \sim 1$ eV $^2 \gtrsim \Delta m^2_{21}, \Delta m^2_{31}$
$\Delta m^2_{21} = 2.5 \times 10^{-3}$ eV^2,$\Delta m^2_{31} = 7 \times 10^{-5}$ eV^2

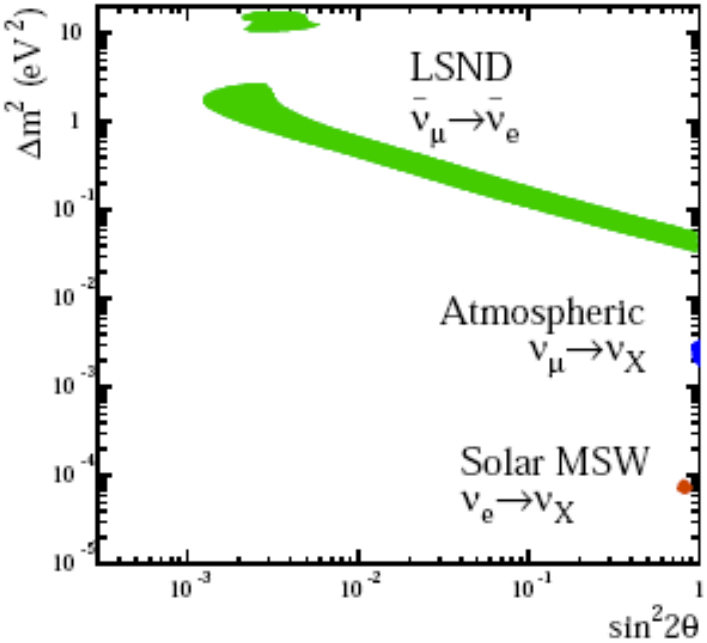
[1] LSND, PRD 64 (2001) 112007, hep-ex/0104049]

Sterile neutrino phenomenology

- to explain LSND experiment require: $\frac{L}{E_\nu} \sim \frac{1m}{MeV} \sim \frac{1Km}{GeV}$ that it is not compatible with the results from other oscillation experiment : $\frac{L}{E_\nu} >\sim \frac{10^3 Km}{GeV}$.

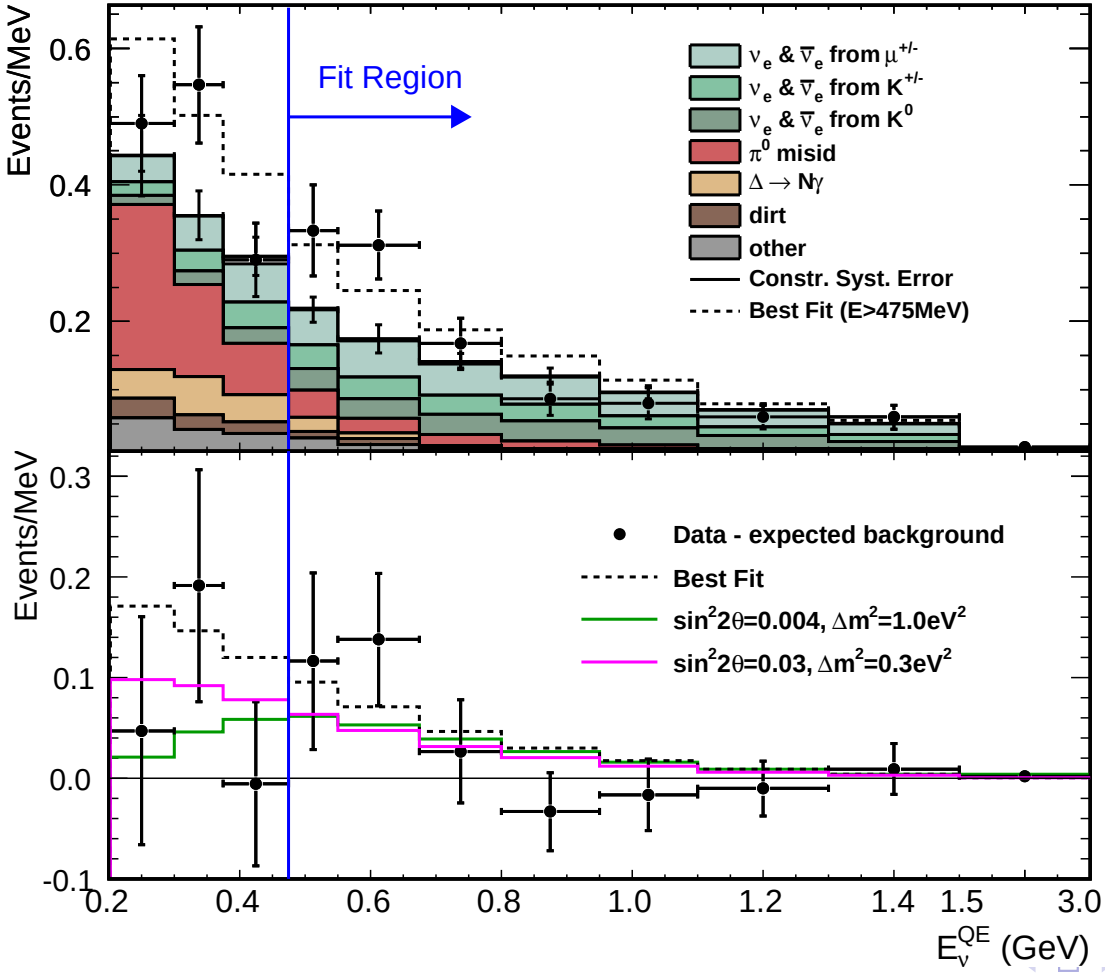
$$P(\nu_\alpha \to \nu_\alpha) = 1 - \sin^2(2\theta)\sin^2\left(1.27\frac{\Delta m^2}{(\mathrm{eV})^2}\frac{\mathrm{L/Km}}{\mathrm{E/GeV}}\right)$$

A possible explanation is to have $\Delta m^2_{LSND} \sim 1\mathrm{eV}^2$



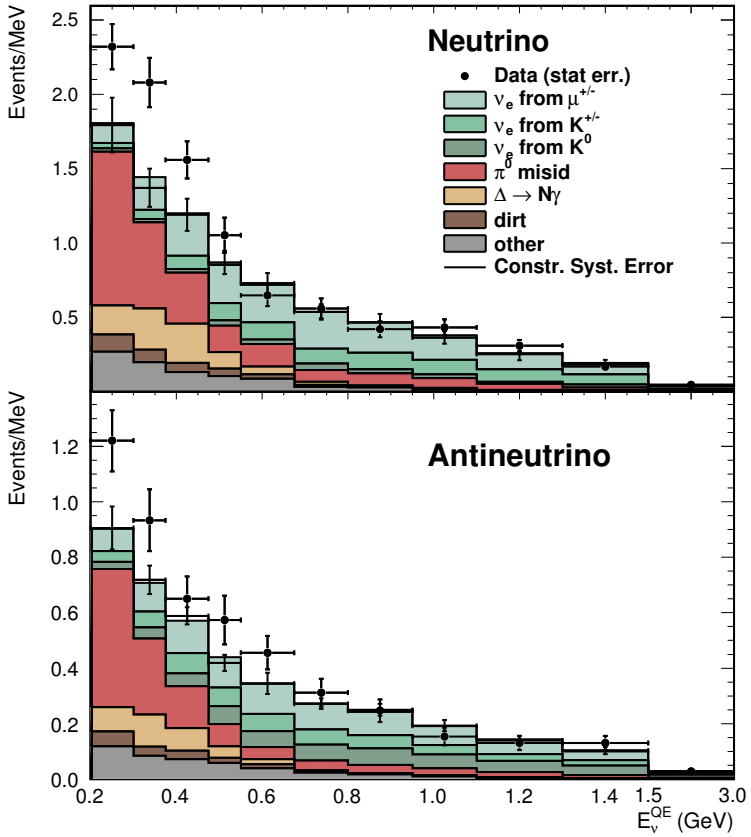
Sterile neutrino phenomenology

- MINI-BOONE experiment (2011) (L $\sim$ 541m $0.475 < E_\nu < 3$ GeV) have a small oscillation signal (2σ) in anti-neutrino $\bar{\nu}_\mu \to \bar{\nu}_e$ and no signal in neutrino oscillation $\nu_\mu \to \nu_e$



Sterile neutrino phenomenology

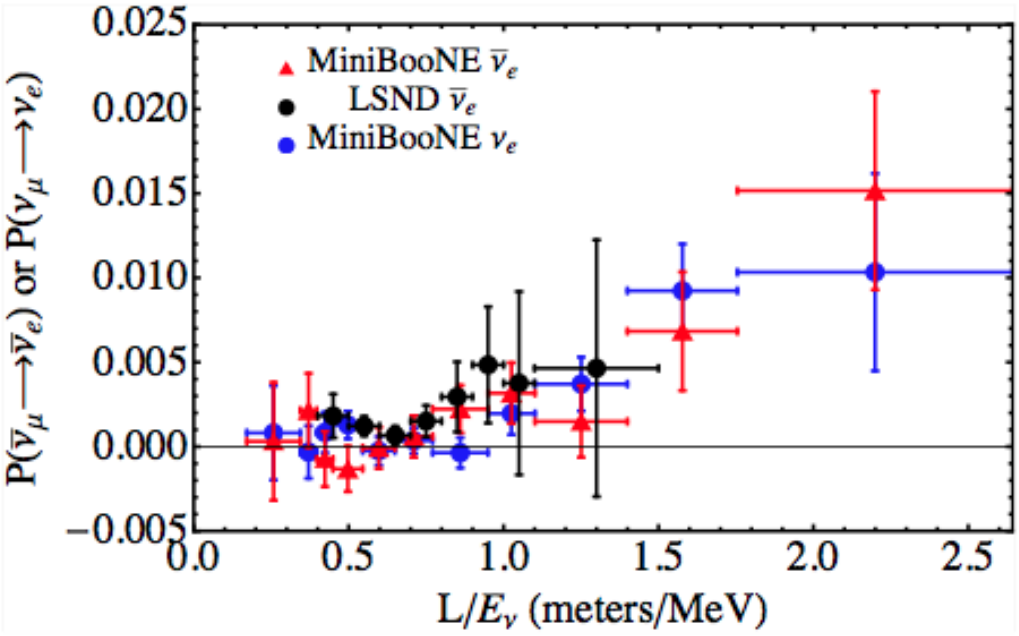
- The Mini-Boone show the neutrino/anti-neutrino (2012)[1] report new results that indicate a 3.8 sigma effect!!



[1] 1207.4809v2: one month ago!!

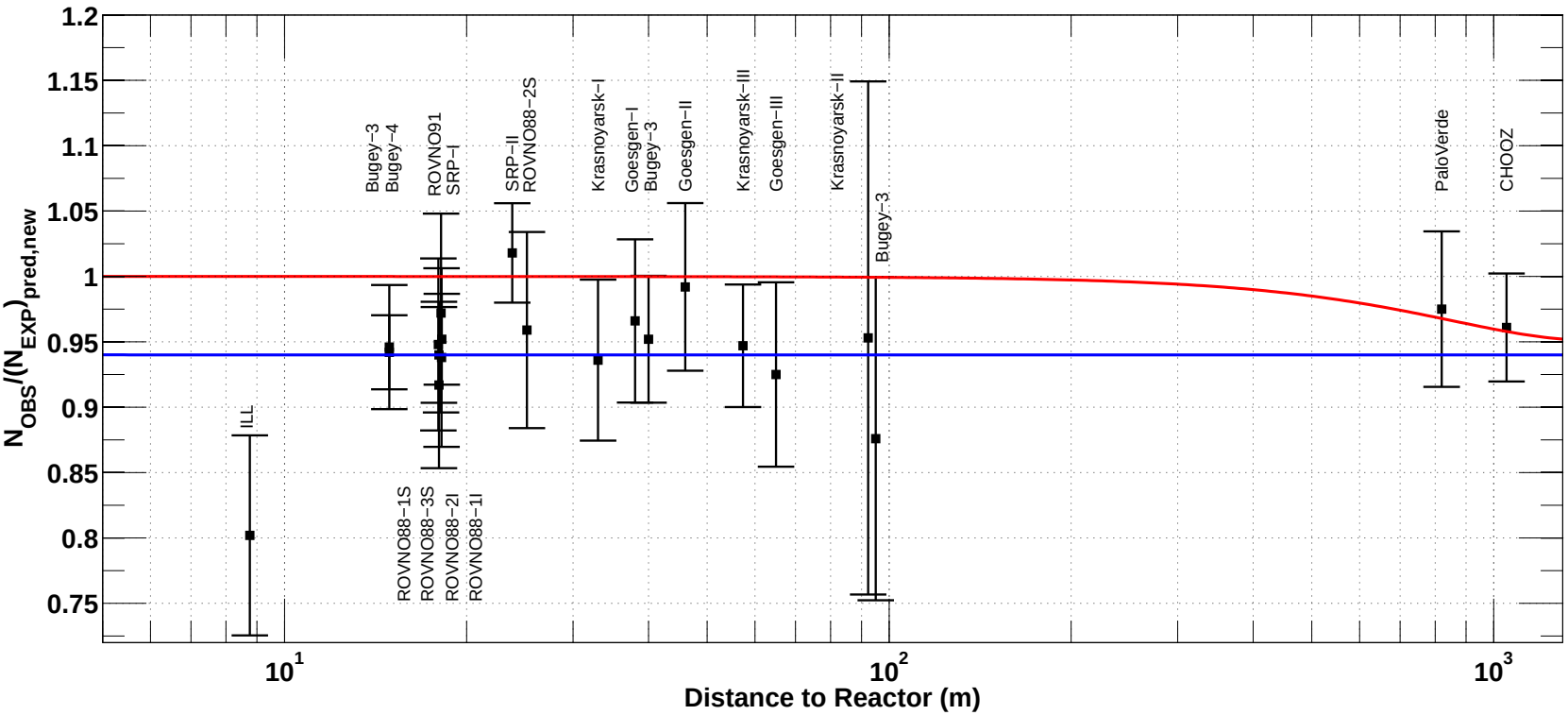
Sterile neutrino phenomenology

- If we compare the probabilities of three experiemts: LSND, Mini-Boone neutrino and Mini-Boone anti-neutrino (the three have the same L/E_ν but different L and different E_ν.)



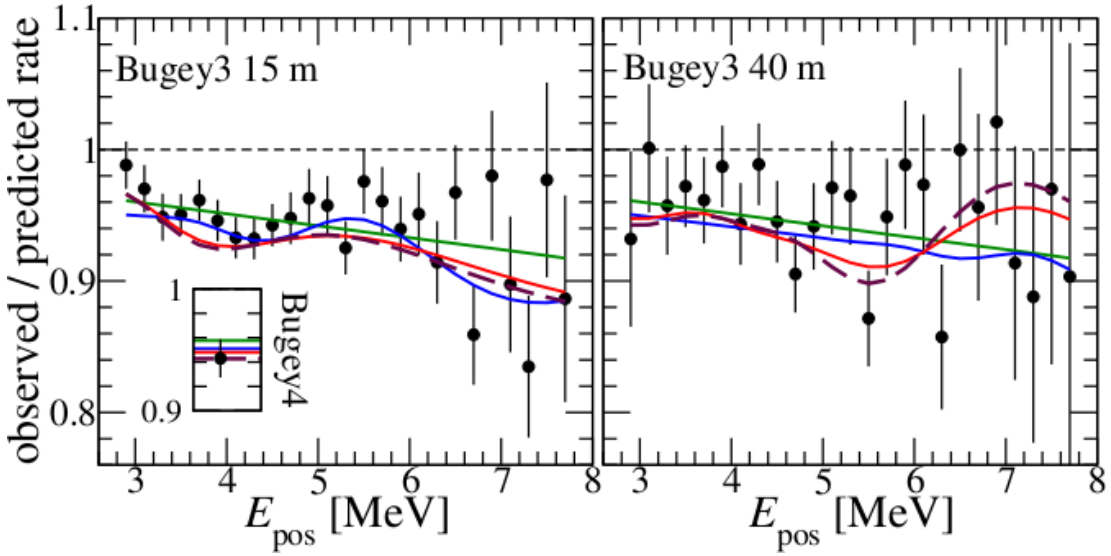
Sterile neutrino phenomenology

- Reactor $\bar{\nu}_e$ anomaly:
  Recent reevaluation of expected reactor $\bar{\nu}_e$ flux is 3.5% higher than previous prediction: Mueller et al. arXiv:1101.2663, confirmed by P. Huber arXiv:1106.0687.
- Reactor anomaly: With new fluxes there is a deficit of $\bar{\nu}_e$



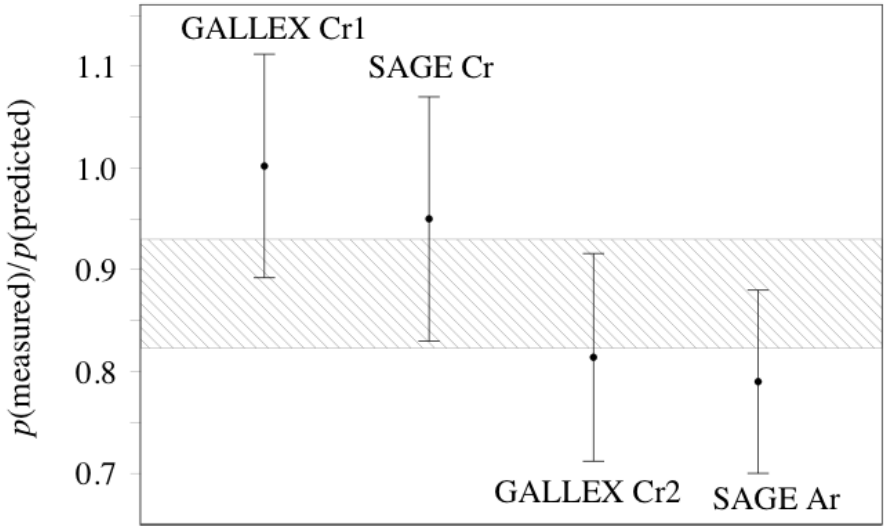
Sterile neutrino phenomenology

- Reactor $\bar{\nu}_e$ anomaly II:

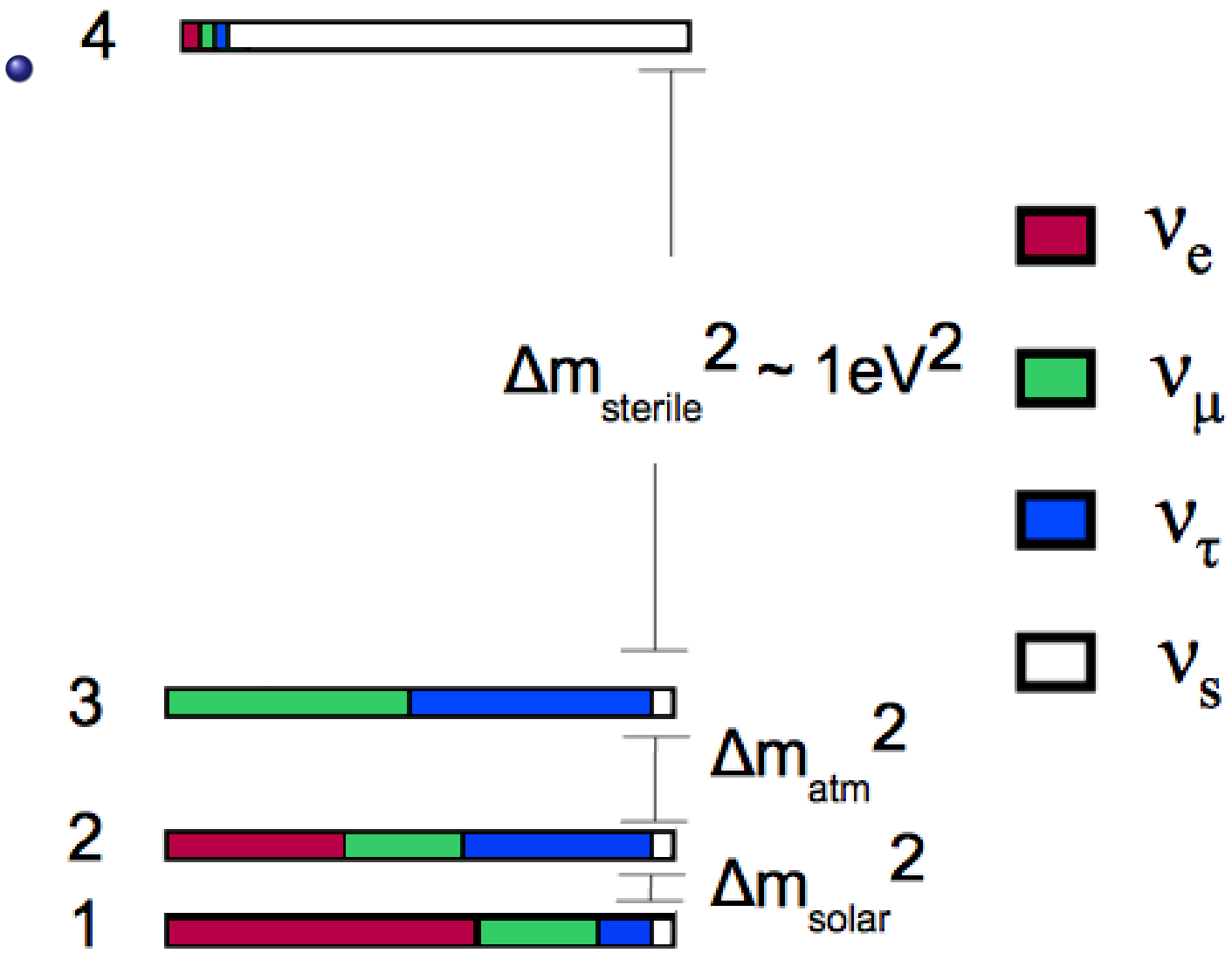


Sterile neutrino phenomenology

- Galium ν_e anomaly: Calibration measurements for the GALLEX and SAGE solar neutrino detectors using intense radioactive sources ($^{5}1$Cr and ^{37}Ar)
  Neutrino detection via $\nu_e +^{71}$ Ga $\rightarrow^{71}$Ge $+e^-$.
  Result: Measurements consistently lower than expectation



Framework: 3+1 model



Framework: 3+1 model

- 90% CL limit on the ν oscillation probabilities from the negative searches at short baseline experiments.

Expt	Beam	Channel	Limit (90%)	Δm^2_{min} (eV^2)
E776	BNL	$\nu_\mu \to \nu_e$	$P_{e\mu} < 1.5 \times 10^{-3}$	0.075
E734	BNL	$\nu_\mu \to \nu_e$	$P_{e\mu} < 1.6 \times 10^{-3}$	0.4
KARMEN	Oxford	$\bar{\nu}_\mu \to \bar{\nu}_e$	$P_{e\mu} < 6.5 \times 10^{-4}$	0.05
E531	FNAL	$\nu_\mu \to \nu_\tau$	$P_{\mu\tau} < 2.5 \times 10^{-3}$	0.9
CCFR/	FNAL	$\nu_\mu \to \nu_e$	$P_{\mu e} < 8 \times 10^{-4}$	1.6
NUTEV		$\bar{\nu}_\mu \to \bar{\nu}_e$	$P_{\mu e} < 5.5 \times 10^{-4}$	2.4
		$\nu_\mu \to \nu_\tau$	$P_{\mu\tau} < 4 \times 10^{-3}$	1.6
		$\nu_e \to \nu_\tau$	$P_{e\tau} < 0.1$	20.0
Chorus	CERN	$\nu_\mu \to \nu_\tau$	$P_{\mu\tau} < 3.4 \times 10^{-4}$	0.6
		$\nu_e \to \nu_\tau$	$P_{e\tau} < 2.6 \times 10^{-2}$	7.5
Nomad	CERN	$\nu_\mu \to \nu_\tau$	$P_{\mu\tau} < 1.7 \times 10^{-4}$	0.7
		$\nu_e \to \nu_\tau$	$P_{e\tau} < 7.5 \times 10^{-3}$	5.9
		$\nu_\mu \to \nu_e$	$P_{\mu e} < 6 \times 10^{-4}$	0.4

Framework: 3+1 model

- The mixing matrix for the 3+1 mass scheme

$$\mathbf{U}_{\mathrm{PMNS}} = \begin{pmatrix} U_{e1} & U_{e2} & \boxed{U_{e3}} & \boxed{U_{e4}} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & \boxed{U_{\mu 4}} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & \boxed{U_{\tau 4}} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

The 3+1 properties

For very short baselines, we can write down the survival probability as

$$P(\nu_\alpha \to \nu_\alpha) = 1 - \sin^2(2\theta_{\alpha\alpha}) sin^2 \left(1.27 \frac{\Delta m^2}{(\mathrm{eV})^2} \frac{\mathrm{L/Km}}{\mathrm{E/GeV}}\right)$$

where $\sin^2(2\theta_{\alpha\alpha}) = 4|U_{\alpha 4}|^2(1 - |U_{\alpha 4}|^2)$
and the conversion probability as

$$P(\nu_\alpha \to \nu_\beta) = \sin^2(2\theta_{\alpha\beta}) sin^2 \left(1.27 \frac{\Delta m^2}{(\mathrm{eV})^2} \frac{\mathrm{L/Km}}{\mathrm{E/GeV}}\right)$$

where $\sin^2(2\theta_{\alpha\beta}) = 4|U_{\alpha 4}|^2|U_{\beta 4}|^2$

The 3+1 properties

From $\sin^2(2\theta_{\alpha\alpha}) = 4|U_{\alpha 4}|^2(1-|U_{\alpha 4}|^2)$ and $\sin^2(2\theta_{\alpha\beta}) = 4|U_{\alpha 4}|^2|U_{\beta 4}|^2$ and because all parameters $|U_{\alpha 4}|^2$ are small, we can write down $\sin^2(2\theta_{\mu\mu}) \sim 4|U_{\mu 4}|^2$, and $\sin^2(2\theta_{\mu e}) = 4|U_{\mu 4}|^2|U_{e4}|^2$.
This allow us to relate the survival amplitude with the conversion amplitude [1]:

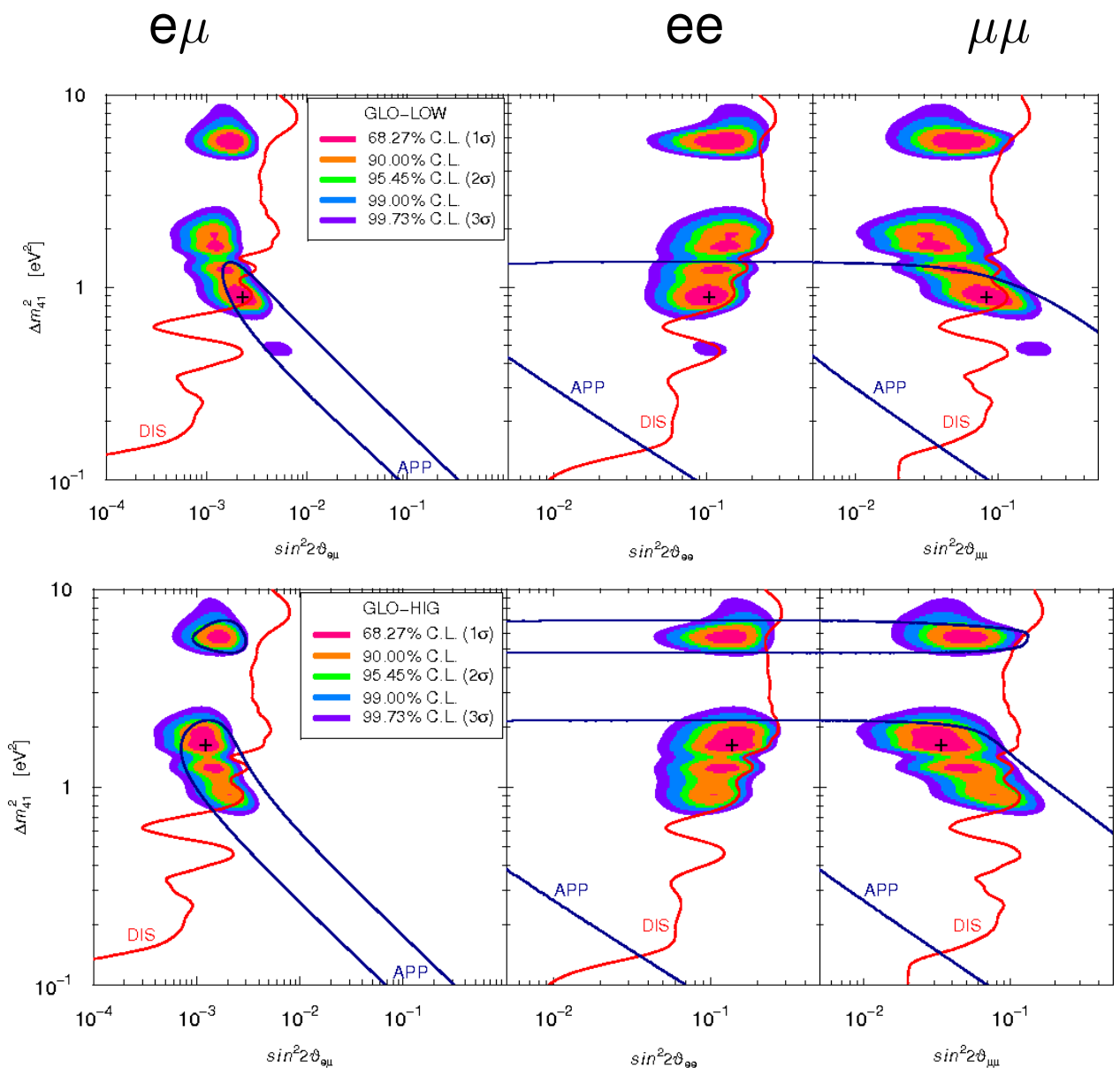
$$\sin^2(2\theta_{\mu e}) = \frac{1}{4}\sin^2(2\theta_{\mu\mu})\sin^2(2\theta_{ee})$$

To have a sizeable $\sin^2(2\theta_{\mu e})$ we should also have sizeable $\sin^2(2\theta_{\mu\mu}), \sin^2(2\theta_{ee})$. if we assume that $\sin^2(2\theta_{\mu\mu}) \sim \sin^2(2\theta_{ee}) \sim \epsilon^2$, where ϵ is a small parameter then

$$\sin^2(2\theta_{\mu e}) \sim \epsilon^4/4 << 1!!$$

[1] O. L. G. P. and A. Y. .Smirnov, Nucl. Phys. B **599**, 3 (2001) [hep-ph/0011054].

Combined analysis of sterile 3+1 scenario



3+1 summary

• A 3+1 scenario in principle can fit now both LSND and MINI-BOONE neutrino e anti-neutrino.
• Still the model have problems coinciling the disappearence constrains and appearence signal: $\sin^2(2\theta_{\mu e}) \sim \epsilon^4/4$ and $\sin^2(2\theta_{\mu\mu}) \sim \sin^2(2\theta_{ee}) \sim \epsilon^2$.
• We need to confirm the reactor neutrino anomaly, new experiments are been planned.
• A positive signal 10% for $\nu_\mu \to \nu_\mu$ and $\nu_e \to \nu_e$ disappearence is expected, new short-baseline experiments?, KATRIN? [2] Can we search for that? [3]

[2] See O.I.G.P. talk at workshop
[3] K. N. Abazajian *et al.*, arXiv:1204.5379 [hep-ph].

Fishing Sterile neutrino in ICE-(CUBE of SUGAR)

The complete evolution equation for sterile neutrinos (3+1 mass scheme) is given by The evolution equations for neutrinos in the flavor basis are

$$\frac{d}{dr}\nu_f = \left[U_4 \frac{M^2}{2E_\nu} U_4^\dagger + A\right]\nu_f,$$

where $\nu_f = (\nu_e \nu_\mu \nu_\tau \nu_s)^T$ and E_ν is the neutrino energy. We get from Reference[4] the mixing matrix for the 3+1 case

$$U_4 = \mathbf{R^{34}}(\theta_{34})\widetilde{\mathbf{R}}^{\mathbf{24}}(\theta_{24},\delta_2)\widetilde{\mathbf{R}}^{\mathbf{14}}(\theta_{14},\delta_1)$$
$$\mathbf{R^{23}}(\theta_{23})\widetilde{\mathbf{R}}^{\mathbf{13}}(\theta_{13},\delta)\mathbf{R^{12}}(\theta_{12})$$

The mixing matrix is parameterized by twelve real parameters: the six mixing angles $\theta_{12}, \theta_{13}, \theta_{23}, \theta_{14}, \theta_{24}, \theta_{34}$, the three Dirac phases $\delta, \delta_1, \delta_2$.

[4] A. de Gouvea and J. Jenkins, Phys. Rev. D **78**, 053003 (2008) arXiv:0804.3627 [hep-ph]].

Fishing Sterile neutrino in ICE-(CUBE of SUGAR)

$$H = \frac{1}{2E_\nu} U_{4\times4} \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 & 0 \\ 0 & 0 & \Delta m^2_{31} & 0 \\ 0 & 0 & 0 & \Delta m^2_{41} \end{pmatrix} U^\dagger_{4\times4}$$

$$+ \begin{pmatrix} A_{CC} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & A_{NC} \end{pmatrix}$$

where $U_{4\times4} = \begin{pmatrix} a & b \\ c & d \end{pmatrix}_{4\times4} \begin{pmatrix} U_{3\times3} & 0 \\ 0 & I \end{pmatrix}$,

and $A_{CC} = \sqrt{2} G_f n_e$ and $A_{NC} = \frac{1}{\sqrt{2}} G_f n_n$

Fishing Sterile neutrino in ICE-(CUBE of SUGAR)

Consequences for sterile neutrino phenomenology:

• Distortion of neutrino probabilities: $|U_{\mu 4}|^2 \leq 0.02$ from DeepCore sensitivity for zenith distortions [4]

$|U_{e4}|^2 \leq 0.05$ from solar neutrino constrains [5]

• η_s parameter: interplay of active-active ($\eta_s = 0$) and active-sterile conversion ($\eta_s = 1$).

Atmospheric (MSW effects due s-neutrino), and solar experiments put constrains on this parameter. $\eta_s < 0.40$

• NC disappearence channel: $\nu_\alpha \to \nu_s$: NC solar neutrino data and from MINOS NC data: $\eta_s < 0.22 \to 0.40$!!

[4] S. Razzaque and A. Y. .Smirnov, Phys. Rev. D **85**, 093010 (2012)

[5] A. Palazzo, Phys. Rev. D **85**, 077301 (2012)

Fishing Sterile neutrino in ICE-(CUBE of SUGAR)

Consequences for sterile neutrino phenomenology:

- New MSW effects, resonant conditions are:[4]

$$\frac{\Delta m^2_{41}}{2E_\nu} = -\cos 2\theta_{eff} V_{nc} \tag{1}$$

for the usual 3×3 neutrinos case, we have

$$\frac{\Delta m^2_{31}}{2E_\nu} = \cos 2\theta_{13} V_{cc} \tag{2}$$

for anti-neutrinos we shift the signal $V_{nc} \to V_{nc}$

[4] O. Yasuda, hep-ph/0102166; H. Nunokawa, O. L. G. P. and R. Z. Funchal, Phys. Lett. B **562**, 279 (2003)
S. Choubey, JHEP **0712**, 014 (2007) ; S. Razzaque and A. Y. .Smirnov, JHEP **1107**, 084 (2011)
V. Barger, Y. Gao and D. Marfatia, Phys. Rev. D **85**, 011302 (2012)
A. Esmaili, F. Halzen and O. L. G. P., arXiv:1206.6903 [hep-ph].

Fishing Sterile neutrino in ICE-(CUBE of SUGAR)

Consequences for sterile neutrino phenomenology:

• New MSW effects, resonant conditions are neutrinos with INVERTED HIERARCHY or anti-neutrinos with NORMAL HIERARCHY

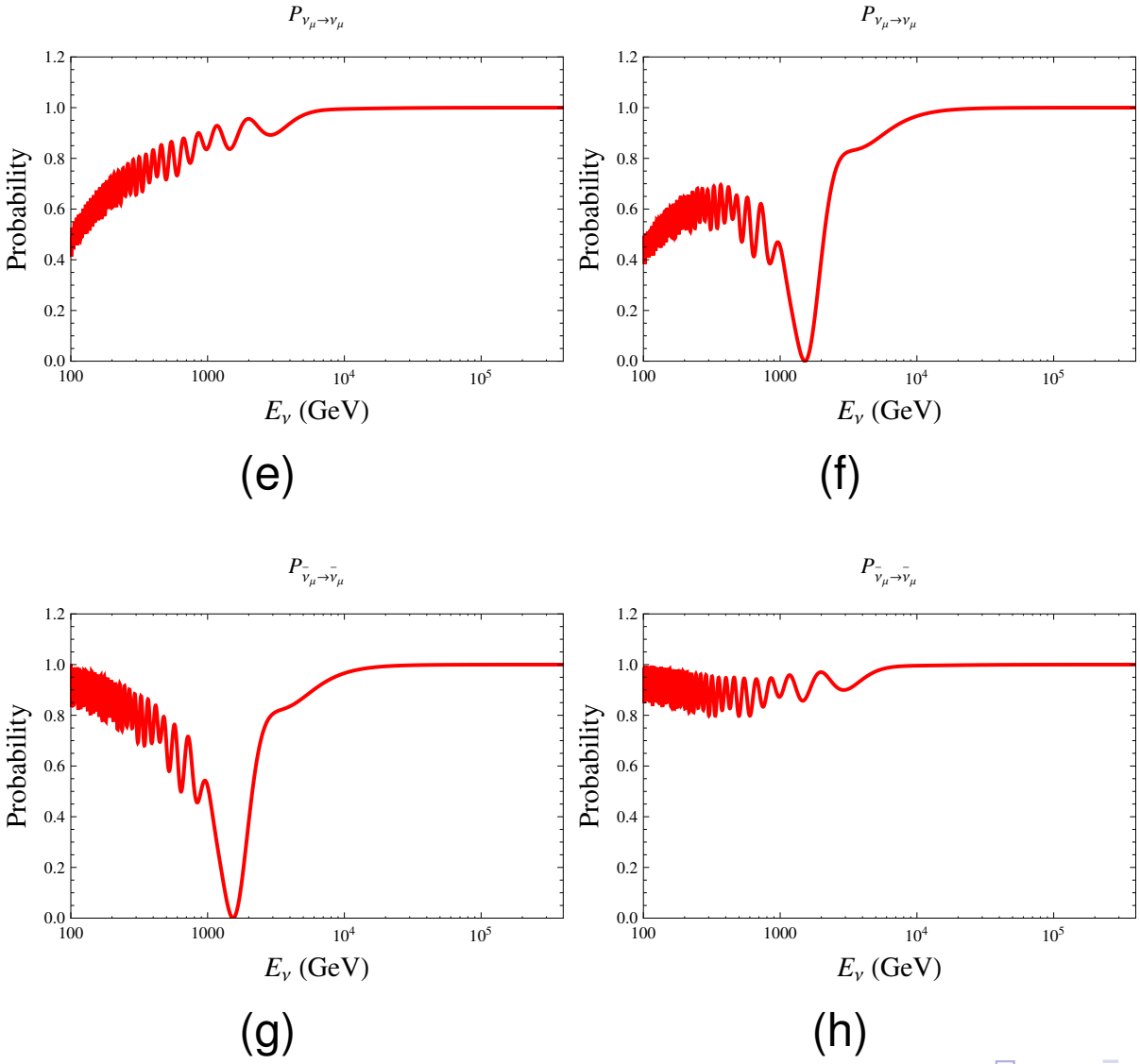
$$E_\nu \sim (2-5)\text{TeV}\left(-\frac{\Delta m^2_{41}}{1eV^2}\right)$$

for the usual 3×3 neutrinos case, we have

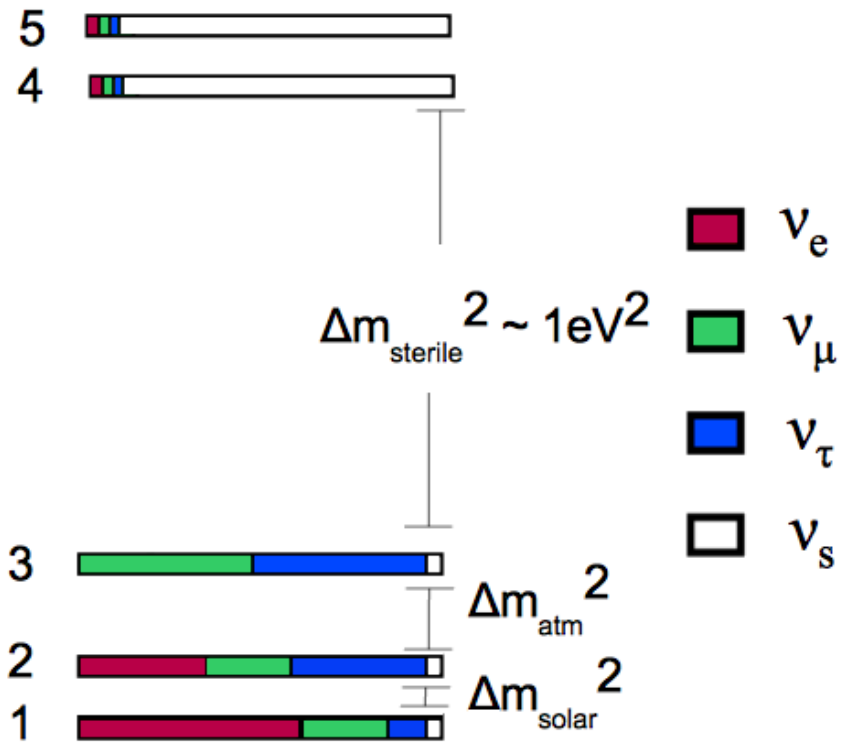
$$E_\nu \sim (2-7)\text{GeV}\left(\frac{\Delta m^2_{31}}{1eV^2}\right)$$

Fishing Sterile neutrino in ICE-(CUBE of SUGAR)

see A. Esmaili talk at Workshop



3+2 model


5
4
3
2
1
$\Delta m_{sterile}^2 \sim 1eV^2$
Δm_{atm}^2
Δm_{solar}^2
ν_e
ν_μ
ν_τ
ν_s

3+2 model

- One additional mass scale:

$$\begin{pmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 & 0 & 0 \\ 0 & 0 & \Delta m^2_{31} & 0 & 0 \\ 0 & 0 & 0 & \Delta m^2_{41} & 0 \\ 0 & 0 & 0 & 0 & \Delta m^2_{51} \end{pmatrix}$$

- This rule did not work $\sin^2(2\theta_{\mu e}) \sim \epsilon^4/4$ and $\sin^2(2\theta_{\mu\mu}) \sim \sin^2(2\theta_{ee}) \sim \epsilon^2$ due the presence of two scales: Δm^2_{41} and Δm^2_{51} .

3+2 model

• Parameter Goodness of fit:[4]
The model should individually each set of data points and not only the global data:
• solar, atmospheric, reactor experiments, short baseline experiments, longbaseline experiments
Define the probability $PG = P(\chi^2_{PG}, ndf_{PG})$ with

$$\chi^2_{PG} = \chi^2_{min,combined} - \sum_d (\chi^2_d)_{min}$$

and $ndf_{PG} = \sum_d N_{p_d} - N_{p_{combined}}$ with N_{p_d} the number of indepedent parameters per data-set and N_p the number of indepedent parameters in the global fit.
Example: for solar analysis, mass differences greater then Δm^2_{41} are averaged out. For short baseline experiments, $\Delta m^2_{21,31} \to 0$.

[4] T. Schwetz and M. Maltoni, hep-ph/0304176v2

3+2 summary

• Using the Parameter Goodness of fit test the 3+2 model is much better then 3+1 model.
• A 3+2 scenario in principle can fit now both LSND and MINI-BOONE neutrino e anti-neutrino.
In the past (over a week ago) the 3+1 model cannot explain the lack of signal of oscillations in neutrino and the signal of oscillations in anti-neutrino) and we need the 3+2 model.
• New CP phases and a new mass scale, $\Delta m^2_{61} \sim 19$eV^2. : conflicts with cosmology?
• Still the model have MINOR problems coinciling the disappearence constrains and appearence signal: but disapearence and appearence point to different sets
• We need to confirm the reactor neutrino anomaly,.
• A positive signal 10% for $\nu_\mu \to \nu_\mu$ and $\nu_e \to \nu_e$ disappearence is expected, new short-baseline experiments?, KATRIN?

Dark radiation

Data from the cosmic microwave background (CMB) and large-scale structure (LSS) show that is necessary to have neutrinos, and including South pole telescope (SPT) and Atacama Cosmology Telescope (ACT) data show the existence of 4 light degree of freedom:
$N_s = 1.12^{+0.86}_{-0.74}$ at 95% c.l. [5]
This have been called dark radiation, because the component of this radiation need to vey light, $\sum m_\nu < 0.6$eV. Then if it is sterile neutrino it should be much lighter then the LSND mass scale.

[5] M. Archidiacono, E. Calabrese and A. Melchiorri, Phys. Rev. D **84**, 123008 (2011)