Status of sterile neutrinos and neutrino anomalies

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I. Neutrino oscillation anomalies

II. Models with one sterile neutrino

III. Models with two sterile neutrinos

Neutrino oscillations: where we are

- Global 6-parameter fit (including δ_{CP}):
  - **Solar**: Cl + Ga + SK(1–4) + SNO-full (I+II+III) + Borexino;
  - **Atmospheric**: SK-1 + SK-2 + SK-3 + SK-4;
  - **Reactor**: KamLAND + Chooz + Palo-Verde + Double-Chooz + Daya-Bay + Reno;
  - **Accelerator**: Minos (DIS+APP) + T2K (DIS+APP);
- best-fit point and 1σ (3σ) ranges:

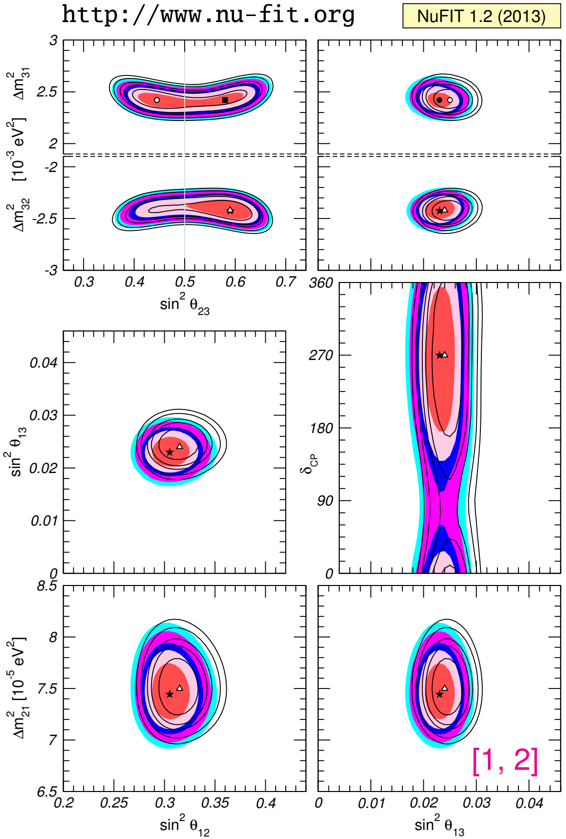
$$\theta_{12} = 33.57\,^{+0.77}_{-0.75}\left(^{+2.44}_{-2.20}\right), \qquad \Delta m^2_{21} = 7.45\,^{+0.19}_{-0.16}\left(^{+0.60}_{-0.47}\right) \times 10^{-5}\ \text{eV}^2,$$

$$\theta_{23} = \begin{cases} 41.9\,^{+0.5}_{-0.4}\left(^{+12.6}_{-4.7}\right), \\ 50.3\,^{+1.6}_{-2.5}\left(^{+4.2}_{-13.1}\right), \end{cases} \qquad \Delta m^2_{31} = \begin{cases} -2.337\,^{+0.062}_{-0.062}\left(^{+0.185}_{-0.191}\right) \times 10^{-3}\ \text{eV}^2, \\ +2.417\,^{+0.014}_{-0.014}\left(^{+0.206}_{-0.171}\right) \times 10^{-3}\ \text{eV}^2, \end{cases}$$

$$\theta_{13} = 8.73\,^{+0.35}_{-0.36}\left(^{+1.03}_{-1.17}\right), \qquad \delta_{\mathrm{CP}} = 341\,^{+58}_{-46}\ (\text{any})\,;$$

- neutrino mixing matrix:

$$|U|_{3\sigma} = \begin{pmatrix} 0.799 \to 0.844 & 0.515 \to 0.581 & 0.132 \to 0.170 \\ 0.214 \to 0.526 & 0.427 \to 0.706 & 0.598 \to 0.805 \\ 0.234 \to 0.537 & 0.451 \to 0.721 & 0.573 \to 0.787 \end{pmatrix}.$$



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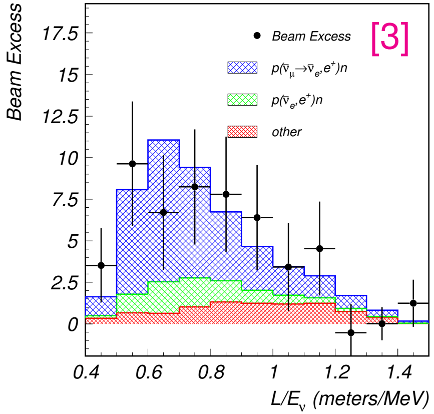
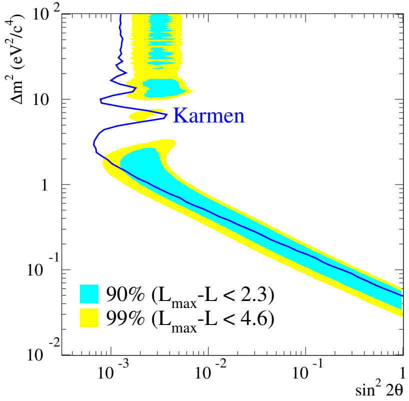
[1] M.C. Gonzalez-Garcia *et al.*, JHEP **12** (2012) 123 [`arXiv:1209.3023`].

[2] M.C. Gonzalez-Garcia *et al.*, NuFIT 1.2 (2013), `http://www.nu-fit.org`.

I. Neutrino oscillation anomalies

$\bar\nu_\mu \to \bar\nu_e$ appearance: the LSND anomaly





- The LSND experiment observed an excess of $\bar\nu_e$ events in a $\bar\nu_\mu$ beam ($E_\nu \sim 30$ MeV, $L \simeq 35$ m) [3];
- the Karmen collaboration did not confirm the claim, but couldn't fully exclude it either [4];
- the signal is compatible with $\bar\nu_\mu \to \bar\nu_e$ oscillations provided that $\Delta m^2 \gtrsim 0.1$ eV^2;
- on the other hand, global neutrino data give (at 3σ):

$$\Delta m^2_{\text{SOL}} \simeq 7.5 \pm 0.6 \times 10^{-5}\ \text{eV}^2\,,$$

$$\left|\Delta m^2_{\text{ATM}}\right| \simeq 2.4 \pm 0.2 \times 10^{-3}\ \text{eV}^2\,;$$

- hence, to explain LSND with mass-induced ν oscillations one needs *at least one more* neutrino mass eigenstate;
- MiniBooNE: much larger E_ν and L but similar L/E_ν ...

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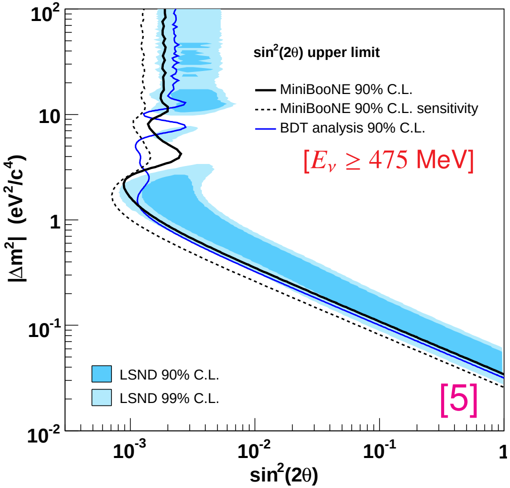
[3] A. Aguilar-Arevalo *et al.* [LSND collab], Phys. Rev. D **64** (2001) 112007 [`hep-ex/0104049`].

[4] B. Armbruster *et al.* [KARMEN collab], Phys. Rev. D **65** (2002) 112001 [`hep-ex/0203021`].

I. Neutrino oscillation anomalies

$\nu_\mu \to \nu_e$ appearance: MiniBooNE neutrino data

- Statistics: 5.58 (2007) → 6.46 (2008) $\times 10^{20}$ POT, then just improved analysis;
- is ν signal compatible with 2ν oscillations? $\begin{cases} \text{2007: } P_\text{osc} \simeq 1\% \Rightarrow \text{no it isn't [5];} \\ \text{2012: } P_\text{osc} \simeq 6\% \Rightarrow \text{maybe it is [6];} \end{cases}$
- do MB ν data rule out the LSND $\bar\nu$ signal? 2007: yes [5]; 2012: not really [6].



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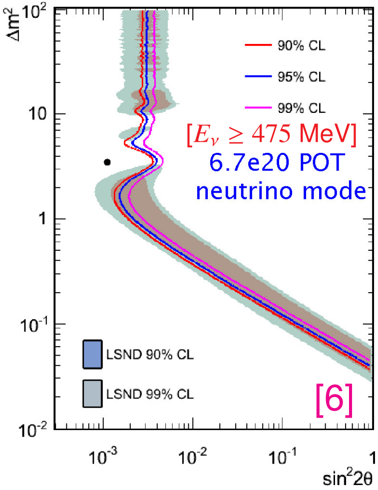

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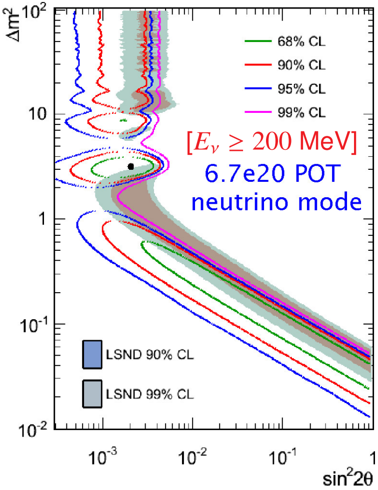

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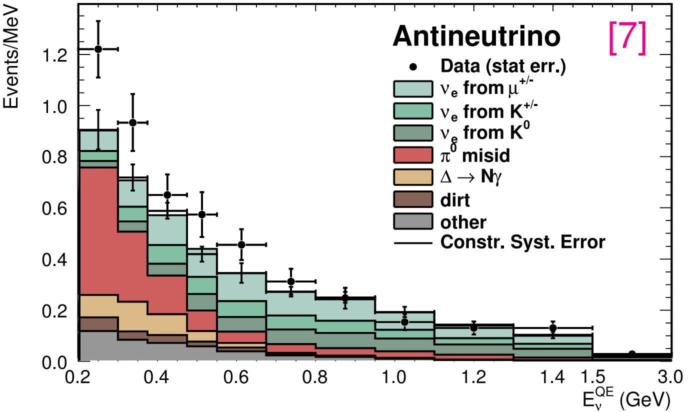
[5] A.A. Aguilar-Arevalo *et al.* [MiniBooNE collab], Phys. Rev. Lett. **98** (2007) 231801 [`arXiv:0704.1500`].

[6] C. Polly, talk at Neutrino 2012, Kyoto, Japan, June 3-9, 2012.

I. Neutrino oscillation anomalies

$\bar{\nu}_\mu \to \bar{\nu}_e$ appearance: MiniBooNE antineutrino data

- New data presented at Neutrino 2012, statistics doubled (→ 11.27×10^{20} POT) [6];
- compatibility with ν data: $\begin{cases} \text{low-energy excess increased} \Rightarrow \text{better agreement;} \\ \text{mid-energy excess reduced} \Rightarrow \text{better agreement;} \end{cases}$
- is $\bar{\nu}$ signal compatible with 2ν oscillations? $P_{\text{osc}} = 67.5\% \Rightarrow$ definitely yes [6, 7];
- is MB-$\bar{\nu}$ signal compatible with LSND? Yes, irrespective of the energy threshold.



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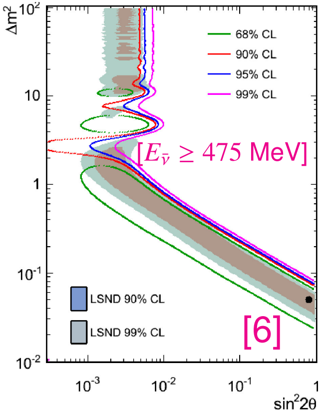

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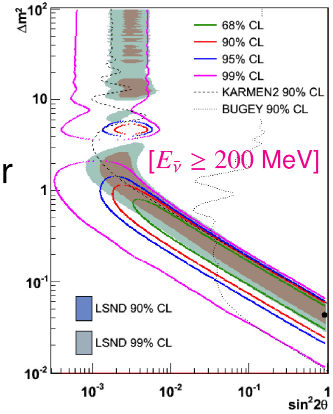

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[6] C. Polly, talk at Neutrino 2012, Kyoto, Japan, June 3-9, 2012.

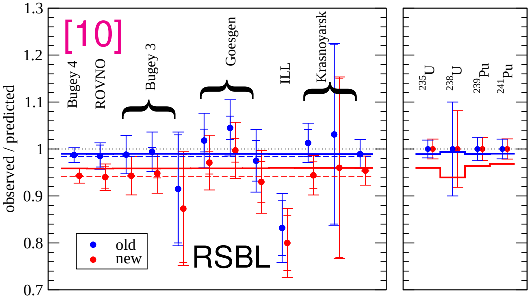
[7] A.A. Aguilar-Arevalo *et al.* [MiniBooNE collab], `arXiv:1207.4809` [hep-ex].

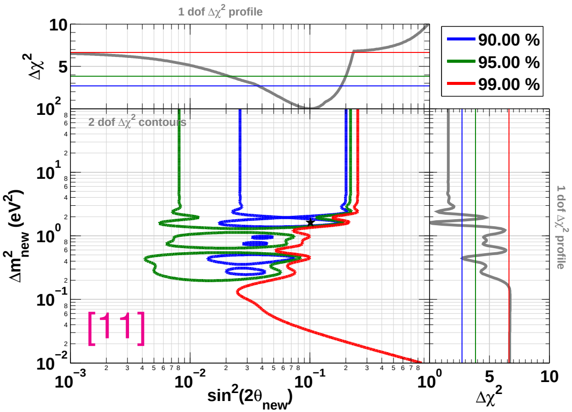
I. Neutrino oscillation anomalies

ν_e disappearance: the reactor anomaly

- In [8, 9] the reactor $\bar{\nu}$ fluxes was reevaluated;
- the new calculations result in a small increase of the flux by about **3.5%**;
- hence, **all** reactor short-baseline (RSBL) finding no evidence are actually observing a deficit;
- this deficit **could** be interpreted as being due to SBL neutrino oscillations;
- no visible dependence on $L \Rightarrow \Delta m^2 \gtrsim 1\ \text{eV}^2$;

⇒ new “hint” in favor of SBL oscillations, **independent** of LSND & MiniBooNE.





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[8] T.A. Mueller *et al.*, Phys. Rev. **C83** (2011) 054615 [`arXiv:1101.2663`].

[9] P. Huber, Phys. Rev. C **84** (2011) 024617 [`arXiv:1106.0687`].

[10] T. Schwetz, M. Tortola, J.W.F. Valle, New J. Phys. **13** (2011) 063004 [`arXiv:1103.0734`].

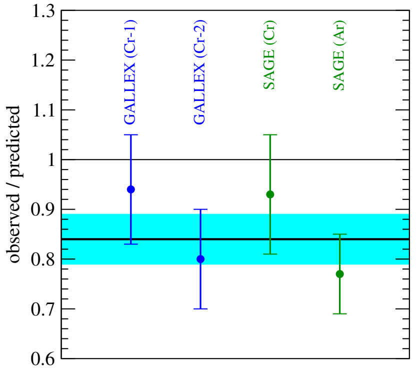
[11] G. Mention *et al.*, Phys. Rev. **D83** (2011) 073006 [`arXiv:1101.2755`].

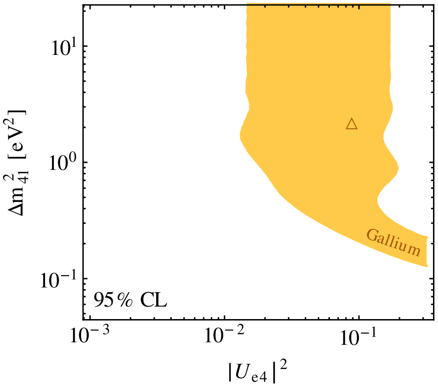
ν_e disappearance: the gallium anomaly

- The $^{71}\mathrm{Ga} \to {}^{71}\mathrm{Ge}$ neutrino capture cross-section, relevant for the GALLEX and SAGE solar neutrino experiments, was calibrated with intense $^{51}\mathrm{Cr}$ and $^{37}\mathrm{Ar}$ neutrino sources;
- these measurements show a significant deficit with respect to the predicted values:

$$\left.\begin{array}{rl} \text{GALLEX:} & \begin{cases} R_1(\mathrm{Cr}) = 0.94 \pm 0.11 \; [12] \\ R_2(\mathrm{Cr}) = 0.80 \pm 0.10 \; [12] \end{cases} \\ \text{SAGE:} & \begin{cases} R_3(\mathrm{Cr}) = 0.93 \pm 0.12 \; [13] \\ R_4(\mathrm{Ar}) = 0.77 \pm 0.08 \; [14] \end{cases} \end{array}\right\} \Longrightarrow \boxed{0.84 \pm 0.05}$$

- such 3σ deficit can be interpreted in terms of ν oscillations;
- once again, data suggests $\Delta m^2 \gtrsim 1$ eV^2.





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[12] F. Kaether *et al.*, Phys. Lett. **B685** (2010) 47–54 [`arXiv:1001.2731`].

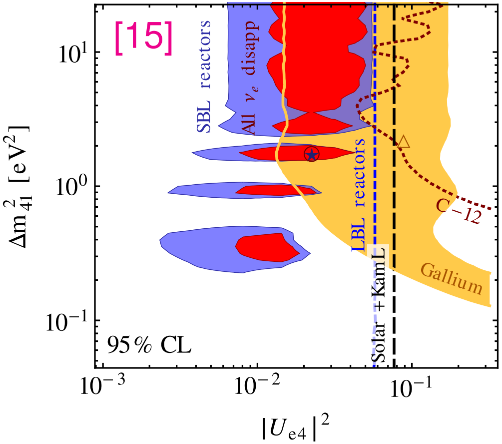
[13] J. Abdurashitov *et al.*, Phys. Rev. **C59** (1999) 2246–2263 [`hep-ph/9803418`].

[14] J. Abdurashitov *et al.*, Phys. Rev. **C73** (2006) 045805 [`nucl-ex/0512041`].

II. Models with one sterile neutrino

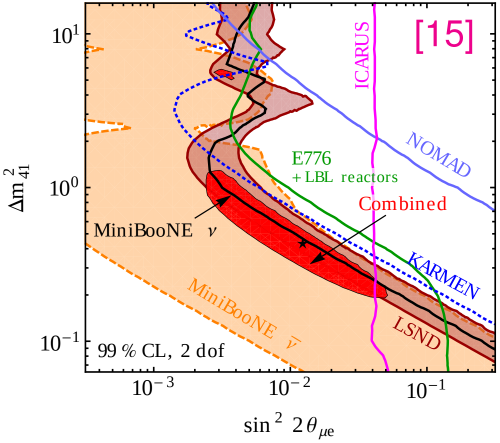
ν_e disappearance

- Relevant experiments:
  - SBL reactors ($\bar{\nu}$)
  - LBL reactors ($\bar{\nu}$)
  - KamLAND ($\bar{\nu}$)
  - Gallium (ν)
  - Solar (ν)
  - ^{12}C (ν)



$\nu_\mu \to \nu_e$ appearance

- Relevant experiments:
  - LSND ($\bar{\nu}$)
  - KARMEN ($\bar{\nu}$)
  - NOMAD (ν)
  - MiniBooNE ($\nu, \bar{\nu}$)
  - E776 ($\nu, \bar{\nu}$)
  - ICARUS (ν)



- Note: $\overset{(-)}{\nu}_e \to \overset{(-)}{\nu}_e$ and $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$ probe the same Δm^2 but a different mixing angle ⇒ mutual comparison requires embedding them into a **general oscillation model**.

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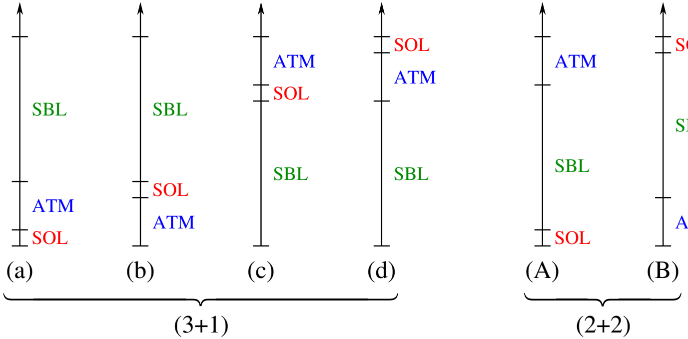
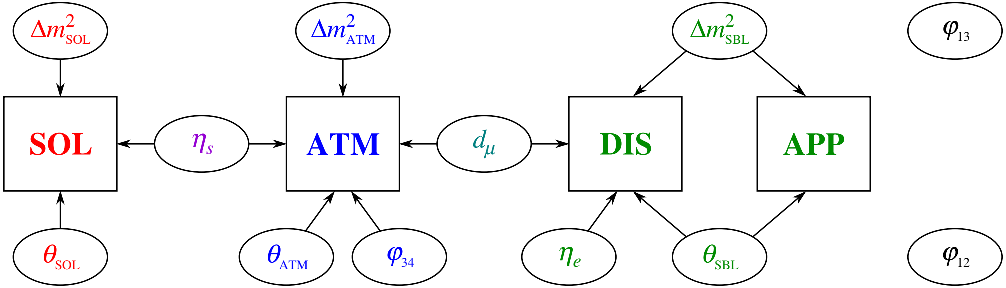
[15] J. Kopp, P.A.N. Machado, M. Maltoni, T. Schwetz, JHEP **05** (2013) 050 [`arXiv:1303.3011`].

Four neutrino mass models

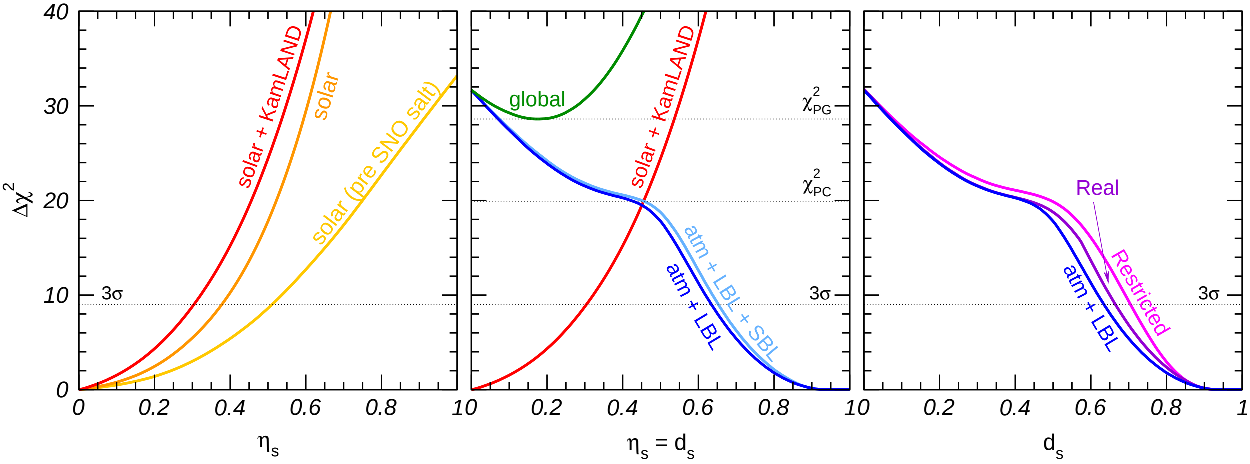
- Approximation: $\Delta m^2_{\text{SOL}} \ll \Delta m^2_{\text{ATM}} \ll \Delta m^2_{\text{SBL}} \Rightarrow$ 6 different mass schemes:



- Total: 3 Δm^2, 6 angles, 3 phases. Different set of experimental data *partially decouple*:



(2+2): ruled out by solar and atmospheric data



- in (2+2) models, fractions of ν_s in solar (η_s) and atmos ($1 - d_s$) add to one $\Rightarrow$ $\boxed{\eta_s = d_s}$;
- 3σ allowed regions $\eta_s \le 0.31$ (solar) and $d_s \ge 0.63$ (atmos) do not overlap; superposition occurs only above 4.5σ ($\chi^2_{\text{PC}} = 19.9$);
- the χ^2 increase from the combination of solar and atmos data is $\chi^2_{\text{PG}} = 28.6$ (1 dof), corresponding to a PG $= 9 \times 10^{-8}$ [16].

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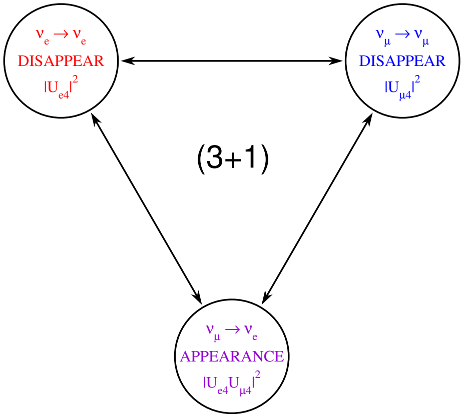
[16] M. Maltoni, T. Schwetz, M.A. Tortola, J.W.F. Valle, Nucl. Phys. **B643** (2002) 321 [`hep-ph/0207157`].

II. Models with one sterile neutrino

(3+1): appearance versus disappearance



$\nu_e \to \nu_e$
DISAPPEAR
$|U_{e4}|^2$

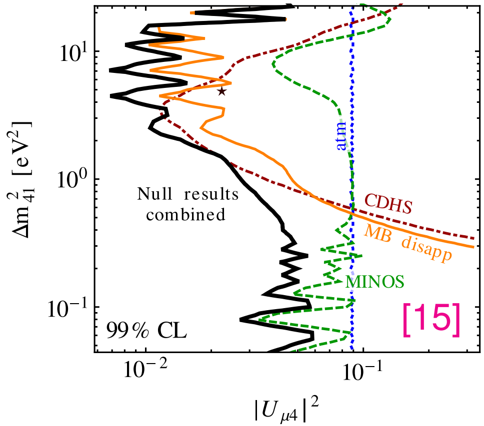
$\nu_\mu \to \nu_\mu$
DISAPPEAR
$|U_{\mu4}|^2$

(3+1)

$\nu_\mu \to \nu_e$
APPEARANCE
$|U_{e4}U_{\mu4}|^2$

- (3+1): $P_{\nu_\mu\to\nu_e} \propto |U_{e4}U_{\mu4}|^2$ with $\begin{cases} |U_{e4}|^2 \propto P_{\nu_e\to\nu_e}\,, \\ |U_{\mu4}|^2 \propto P_{\nu_\mu\to\nu_\mu}\,; \end{cases}$
- hence, $P_{\nu_\mu\to\nu_e} > 0$ requires $\begin{cases} P_{\nu_e\to\nu_e} > 0\,, \\ P_{\nu_\mu\to\nu_\mu} > 0\,; \end{cases}$

¿? are $\nu_\mu \to \nu_\mu$ searches compatible with this?



ν_μ disappearance: present status

- Many experiments have been performed:

– CDHS	(ν)	– MINOS CC	(ν)
– MiniBooNE	$(\nu, \bar\nu)$	– MINOS NC	(ν)
– SciBooNE	$(\nu, \bar\nu)$	– SK atmos	$(\nu, \bar\nu)$

- no hint of ν_μ disappearance has been observed;
- bound on $|U_{\mu4}|^2$ may be in tension with other data. . .

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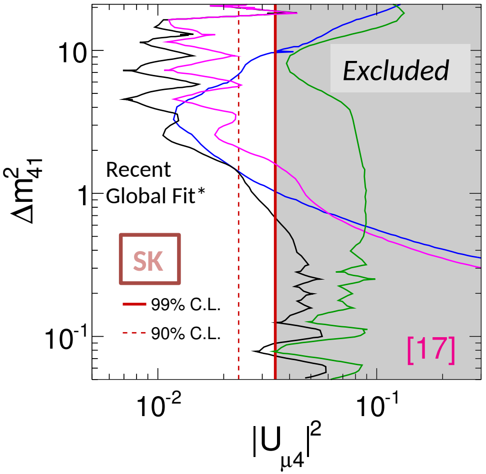
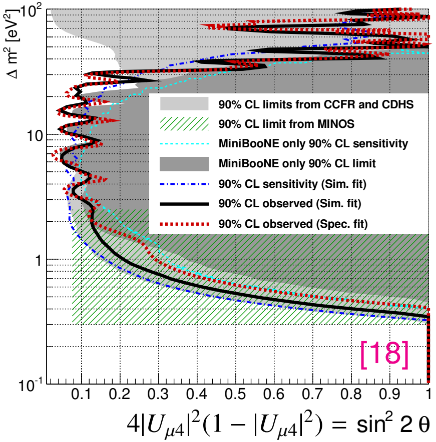
[15] J. Kopp, P.A.N. Machado, M. Maltoni, T. Schwetz, JHEP **05** (2013) 050 [`arXiv:1303.3011`].

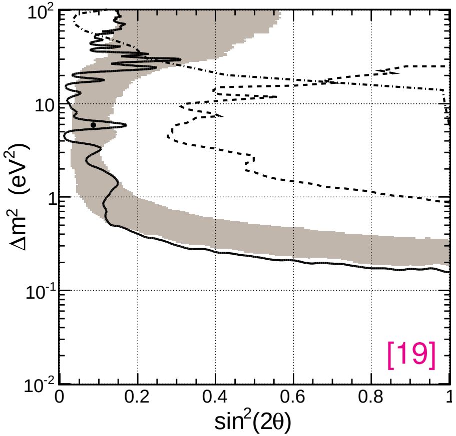
II. Models with one sterile neutrino

ν_μ disappearance: recent atmospheric and SBL data

- New SuperK atmospheric analysis [17] probes ν_μ mixing with heavy sterile state;
- combined analysis of MiniBooNE & SciBooNE, both for ν [18] and $\bar{\nu}$ [19];
- bound on ν_μ disappearance strengthened by absence of conversion signal.







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[17] C. Walter, talk at ISOUPS 2013, Asilomar, California, USA, May 23-27, 2013.

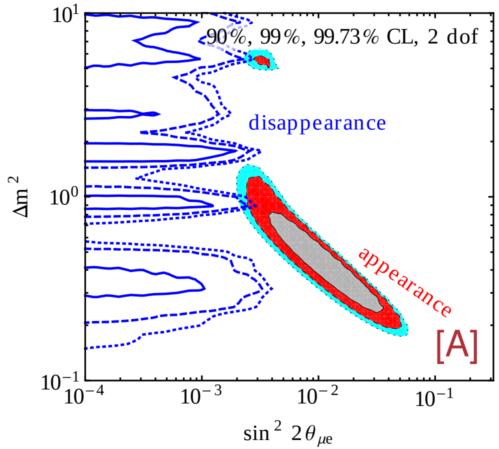
[18] K.B.M. Mahn *et al.* [SciBooNE & MiniBooNE collab], Phys. Rev. D **85** (2012) 032007 [`arXiv:1106.5685`].

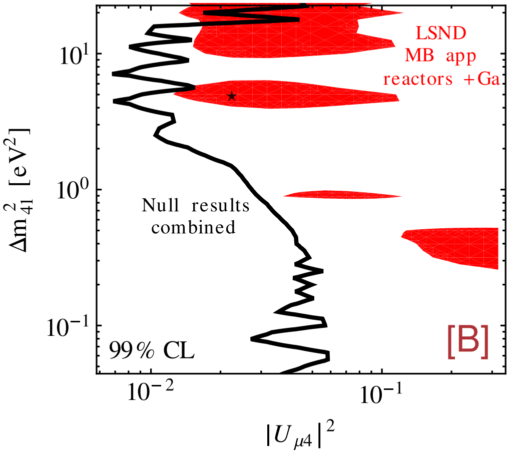
[19] G. Cheng *et al.* [MiniBooNE & SciBooNE collab], Phys. Rev. D **86** (2012) 052009 [`arXiv:1208.0322`].

II. Models with one sterile neutrino

(3+1): tension among data samples

- Limits on $\nu_e \to \nu_e$ and $\nu_\mu \to \nu_\mu$ disappearance imply a bound on the $\nu_\mu \to \nu_e$ appearance probability;
- such bound is stronger than what is required to explain the LSND and MiniBooNe excesses [A];
- hence, severe tension arises between **APP** and **DIS** data: $\chi^2_{\text{PG}}/\text{dof} = 18.0/2 \Rightarrow \text{PG} = 0.012\%$ [15];
- a similar result is obtained when comparing "**positive**" and "**null**" evidence for sterile ν's [B];
- in summary, (3+1) models fail because:
  - the low-energy MiniBooNE excess is poorly fitted;
  - MiniBooNE (ν) and LSND ($\bar{\nu}$) do not really agree;
  - there is tension between **APP** And **DIS** data.





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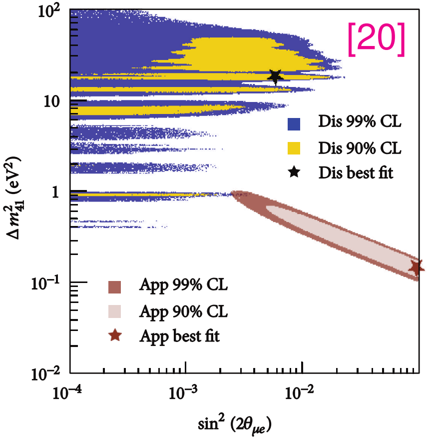
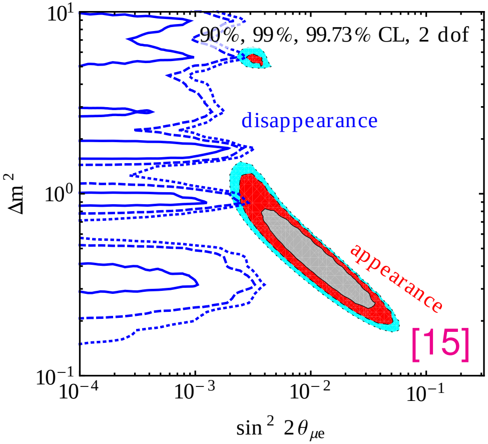
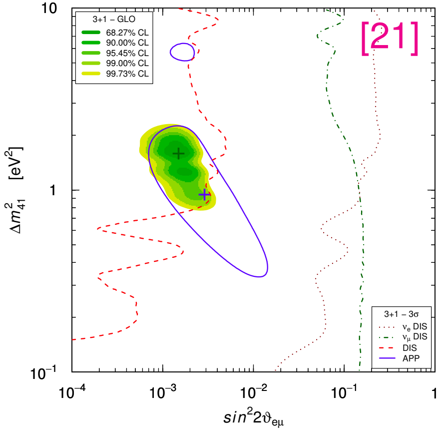
[15] J. Kopp *et al.*, JHEP **05** (2013) 050 [`arXiv:1303.3011`].

(3+1): comparison with other analyses

- A few independent analyses of **APP** versus **DIS** compatibility have been presented;
- results of [20] very similar to ours. (3+1) ruled out: $\chi^2_{\text{PG}}/\text{dof} = 17.8/2 \Rightarrow \text{PG} = 0.013\%$;
- results of [21] differ! $\begin{cases} \text{(3+1) poor: } \chi^2_{\text{PG}}/\text{dof} = 12.7/2 \Rightarrow \text{PG} = 0.2\% \text{ (MB } E_\nu > 200 \text{ MeV),} \\ \text{(3+1) good: } \chi^2_{\text{PG}}/\text{dof} = 4.8/2 \Rightarrow \text{PG} = 9\% \text{ (MB } E_\nu > 475 \text{ MeV).} \end{cases}$







[15] J. Kopp, P.A.N. Machado, M. Maltoni, T. Schwetz, JHEP **05** (2013) 050 [`arXiv:1303.3011`].

[20] J.M. Conrad *et al.*, Adv. High Energy Phys. **2013** (2013) 163897 [`arXiv:1207.4765`].

[21] C. Giunti, M. Laveder, Y.F. Li, H.W. Long, Phys. Rev. D **88** (2013) 073008 [`arXiv:1308.5288`].

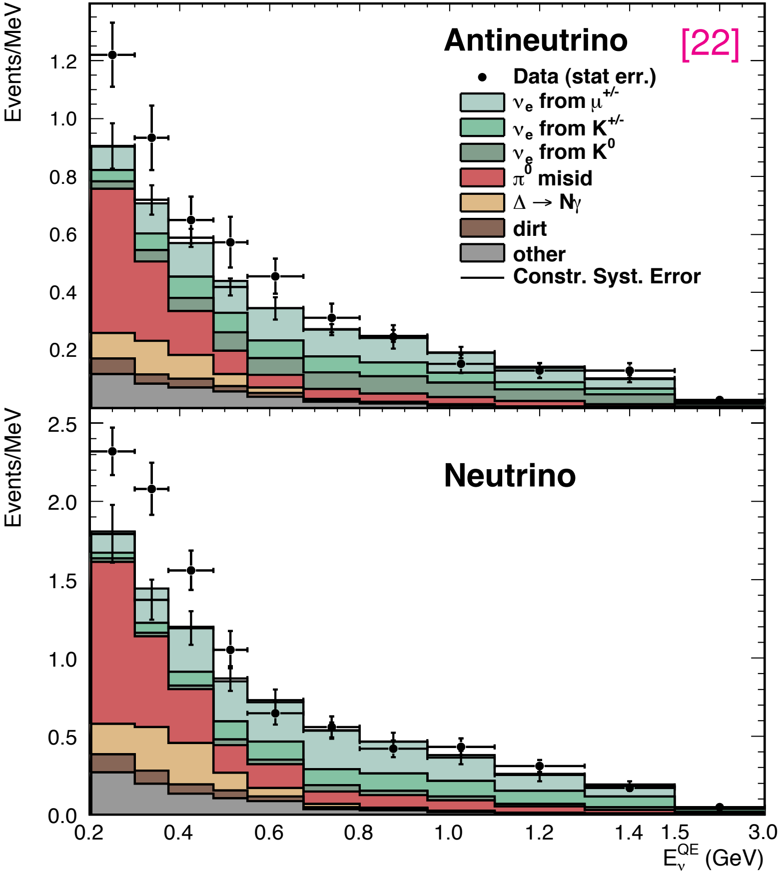
III. Models with two sterile neutrinos

The MiniBooNE excess

- MiniBooNE observed an overall 3.8σ excess, mostly at low energy [22];
- although no longer *“in open disagreement”*, ν and $\bar{\nu}$ signals are not really equivalent either. For example:

$$P_{2\nu} = \begin{cases} 6.1\% & \text{for } \nu; \\ 67.5\% & \text{for } \bar{\nu}; \end{cases}$$

- former omission of low-energy ν bins ($E_\nu^{\text{QE}} < 475$ MeV) based on the hypothesis of **two-flavor oscillations**;
- is it possible to do something better about low-energy data in **more sophisticated** models?



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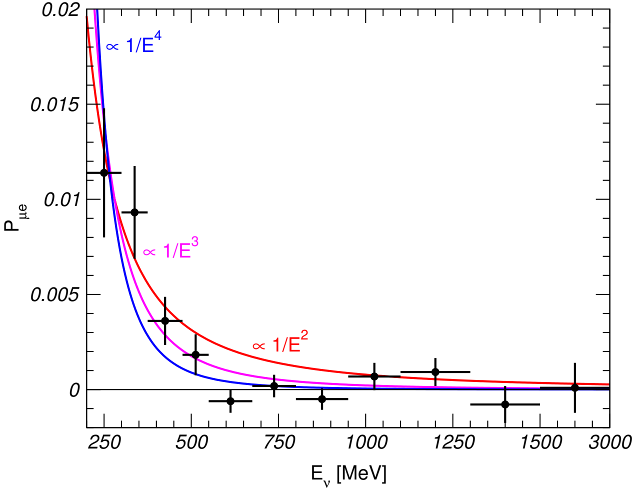
[22] A.A. Aguilar-Arevalo *et al.* [MiniBooNE collab], Phys. Rev. Lett. **110** (2013) 161801 [`arXiv:1303.2588`].

Explaining the MiniBooNE excess with two sterile neutrinos



- With *one* extra sterile neutrino, m_4:

$$P_{\mu e}^{4\nu} = 4|U_{e4}|^2 |U_{\mu 4}|^2 \sin^2 \phi_{41} \quad \text{with} \quad \phi_{ij} \equiv \frac{\Delta m_{ij}^2 L}{4E};$$

- for large energy $P_{\mu e}^{4\nu}$ drops as $1/E^2$;
- however, the low-energy MB excess is much sharper ($\sim 1/E^3$);

⇒ **it is very hard to account for the MB excess with only one extra sterile neutrino.**

- On the other hand, with *two* extra neutrinos, m_4 and m_5:

$$P_{\mu e}^{5\nu} = 4|U_{e4}|^2 |U_{\mu 4}|^2 \sin^2 \phi_{41} + 4|U_{e5}|^2 |U_{\mu 5}|^2 \sin^2 \phi_{51} + 8|U_{e4} U_{e5} U_{\mu 4} U_{\mu 5}| \sin \phi_{41} \sin \phi_{51} \cos(\phi_{54} - \delta);$$

- terms of order $1/E^2$ cancel if $\delta = \pi$ and $|U_{e4}\, U_{\mu 4}| \Delta m_{41}^2 = |U_{e5}\, U_{\mu 5}| \Delta m_{51}^2$;

⇒ **with two extra sterile states it is possible to fit the MB low-energy excess** [23].

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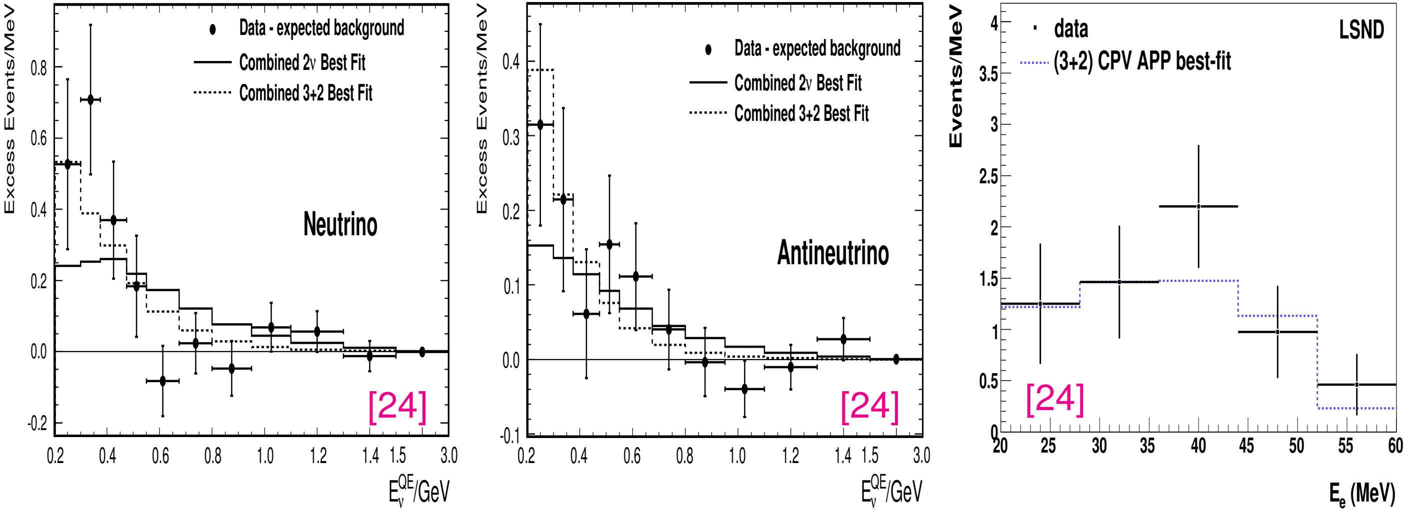
[23] M. Maltoni, T. Schwetz, Phys. Rev. **D76** (2007) 093005 [`arXiv:0705.0107`].

Reconciling MiniBooNE and LSND in (3+2) models



- **Trick**: use the CP phase $\delta = \arg(U_{e4}^* U_{\mu4} U_{e5} U_{\mu5}^*)$ to differentiate ν (MB) from $\bar\nu$ (LSND):

$$P_{\mu e}^{5\nu} = 4|U_{e4}|^2 |U_{\mu4}|^2 \sin^2\phi_{41} + 4|U_{e5}|^2 |U_{\mu5}|^2 \sin^2\phi_{51} + 8|U_{e4} U_{e5} U_{\mu4} U_{\mu5}| \sin\phi_{41} \sin\phi_{51} \cos(\phi_{54} - \delta)\,;$$

- note that $\delta = \pi + \epsilon$ and $|U_{e4}\, U_{\mu4}| \Delta m_{41}^2 \approx |U_{e5}\, U_{\mu5}| \Delta m_{51}^2$ to suppress MB probability [23].

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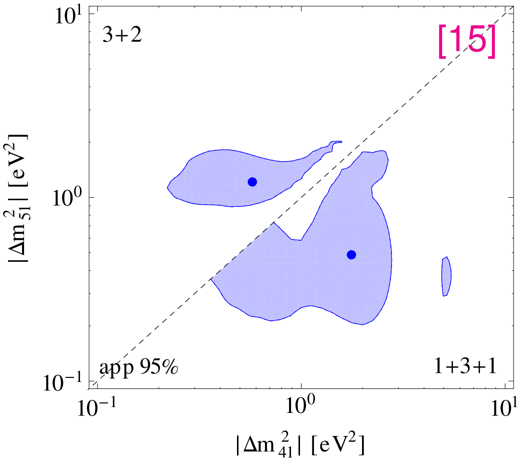
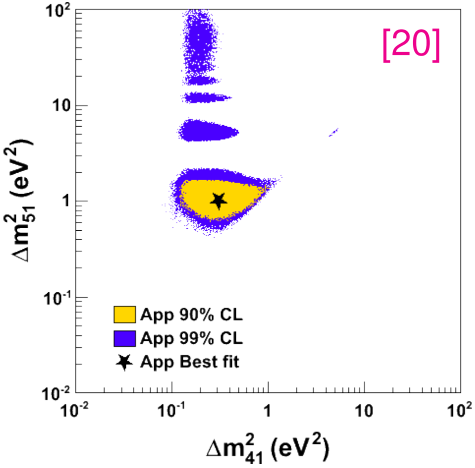
[23] M. Maltoni, T. Schwetz, Phys. Rev. **D76** (2007) 093005 [`arXiv:0705.0107`].

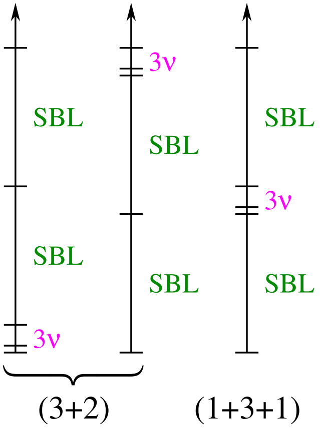
[24] J.M. Conrad, W.C. Louis, M.H. Shaevitz, Ann. Rev. Nucl. Part. Sci. **63** (2013) 45 [`arXiv:1306.6494`].

III. Models with two sterile neutrinos

Fitting all $\nu_\mu \to \nu_e$ appearance data with two sterile ν's







Model	dof	χ^2_min	GOF	$\chi^2_{(3+1)} - \chi^2_\text{min}$	CL
(3+1)	(68 – 2)	87.9	3.7%	—	—
(3+2)	(68 – 5)	72.7	19%	15.2	99.8%
(1+3+1)	(68 – 5)	74.6	15%	13.3	99.6%

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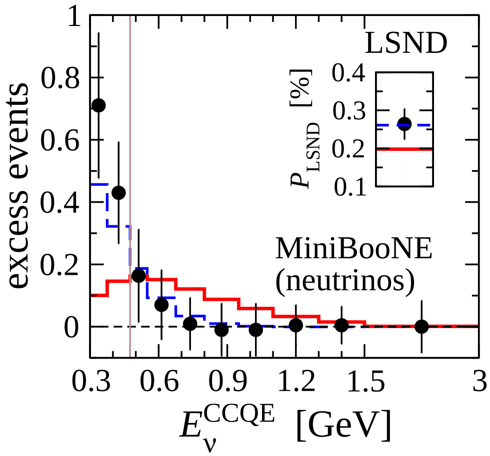
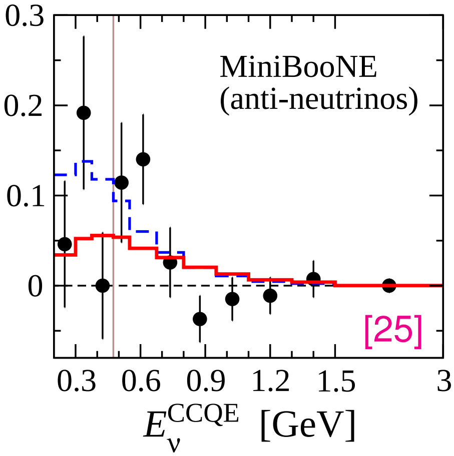
[15] J. Kopp, P.A.N. Machado, M. Maltoni, T. Schwetz, JHEP **05** (2013) 050 [`arXiv:1303.3011`].

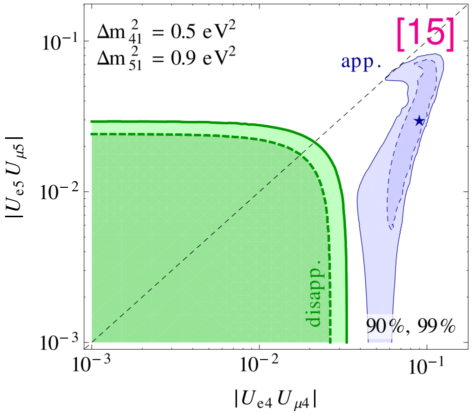
[20] J.M. Conrad *et al.*, Adv. High Energy Phys. **2013** (2013) 163897 [`arXiv:1207.4765`].

Status of (3+2) models from global data

- (3+2) models suffer from severe tension between **APP** and **DIS** data: PG=0.53% [25];
- the situation worsen when MiniBooNE low-E data are included: PG=0.0034% [15];
- (1+3+1) works somewhat better (PG=0.21% [15]), but has stronger problems with cosmology since the sum of neutrino masses ($\sum m_\nu$) is larger.







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[15] J. Kopp, P.A.N. Machado, M. Maltoni, T. Schwetz, JHEP **05** (2013) 050 [`arXiv:1303.3011`].

[25] J. Kopp, M. Maltoni and T. Schwetz, Phys. Rev. Lett. **107** (2011) 091801 [`arXiv:1103.4570`].

Summary

- Most of the present data from solar, atmospheric, reactor and accelerator experiments are well explained by the 3ν oscillation hypothesis;
- however, a few experiments exhibit deviations from the “standard” 3ν scenario:
  - LSND & MiniBooNE observe excesses of $\overset{(-)}{\nu}_e$ events in $\overset{(-)}{\nu}_\mu$ beams;
  - SBL reactors observe a deficit with respect to the expected $\bar{\nu}$ fission flux;
  - gallium experiments exposed to radioactive sources also find a deficit;
- sterile neutrino models fail to explain satisfactorily **all** the experimental data:

Requirement	(3+0)	(2+2)	(3+1)	(3+2)	(1+3+1)
Ordinary neutrino oscillation data	OK	NO	OK	OK	OK
$\overset{(-)}{\nu}_e \to \overset{(-)}{\nu}_e$: SBL reactor & gallium data	NO	OK	OK	OK	OK
$\bar{\nu}_\mu \to \bar{\nu}_e$: LSND & MB $\bar{\nu}$ data	NO	OK	OK	OK	OK
$\nu_\mu \to \nu_e$: MB high-energy ν data	OK	POOR	POOR	OK	OK
$\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$: MB low-energy excess	NO	POOR	POOR	OK	OK
$\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\mu$: disappearance data	OK	OK	NO	NO	NO
Constraints from cosmology	OK	NO	OK	NO	NO

⇒ we are still quite far from the solution of the LSND puzzle!