(eV) sterile neutrinos: the global picture

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I. **Oscillation anomalies: ν_e disappearance**

II. **Oscillation anomalies: $\nu_\mu \to \nu_e$ appearance**

III. **Sterile neutrino models and ν_μ disappearance**

3ν oscillations (until last week)

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

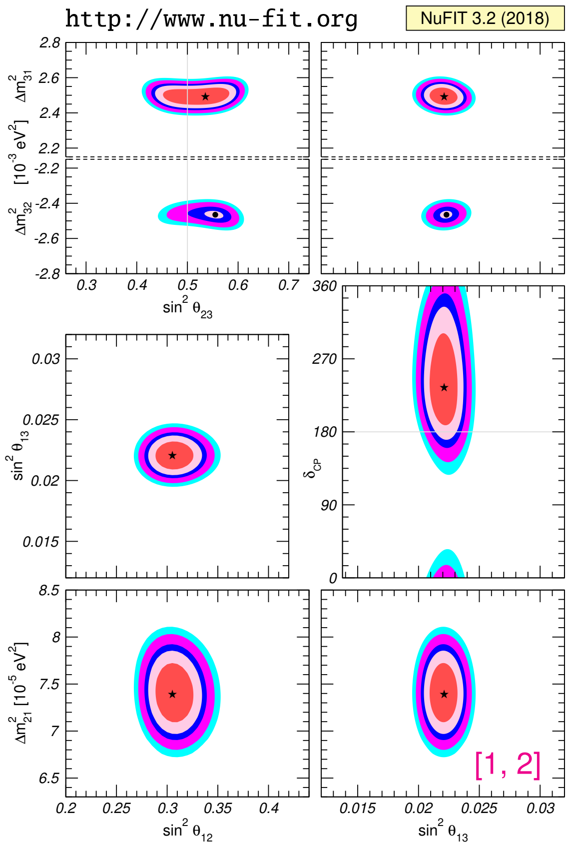
$$\theta_{12} = 33.62\,^{+0.78}_{-0.76}\,\left(^{+2.44}_{-2.20}\right), \qquad \Delta m^2_{21} = 7.40\,^{+0.21}_{-0.20}\,\left(^{+0.62}_{-0.60}\right) \times 10^{-5}\ \text{eV}^2,$$

$$\theta_{23} = \begin{cases} 47.2\,^{+1.9}_{-3.9}\,\left(^{+4.4}_{-6.9}\right), \\ 48.1\,^{+1.4}_{-1.9}\,\left(^{+3.6}_{-6.8}\right), \end{cases} \qquad \Delta m^2_{31} = \begin{cases} +2.494\,^{+0.033}_{-0.031}\,\left(^{+0.099}_{-0.095}\right) \times 10^{-3}\ \text{eV}^2, \\ -2.465\,^{+0.032}_{-0.031}\,\left(^{+0.096}_{-0.097}\right) \times 10^{-3}\ \text{eV}^2, \end{cases}$$

$$\theta_{13} = 8.54\,^{+0.15}_{-0.15}\,\left(^{+0.44}_{-0.45}\right), \qquad \delta_{\text{CP}} = 234\,^{+43}_{-31}\,\left(^{+141}_{-90}\right);$$

- neutrino mixing matrix:

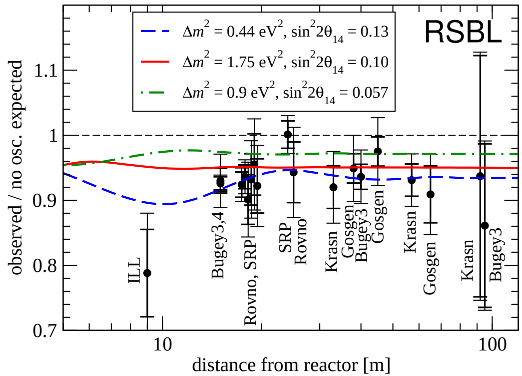
$$|U|_{3\sigma} = \begin{pmatrix} 0.799 \to 0.844 & 0.516 \to 0.582 & 0.141 \to 0.156 \\ 0.242 \to 0.494 & 0.467 \to 0.678 & 0.639 \to 0.774 \\ 0.284 \to 0.521 & 0.490 \to 0.695 & 0.615 \to 0.754 \end{pmatrix}.$$



[1] I. Esteban *et al.*, JHEP **01** (2017) 087 [arXiv:1611.01514].

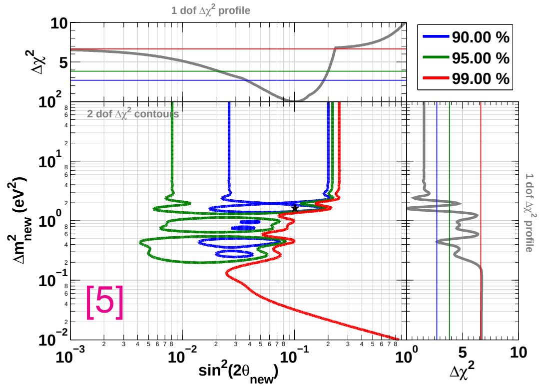
[2] I. Esteban *et al.*, NuFIT 3.2 (2018), http://www.nu-fit.org.

$\bar{\nu}_e$ disappearance: the reactor anomaly



- In [3, 4] 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 $L \Rightarrow \Delta m^2 \gtrsim 1$ eV^2;
- global data (3σ): $\begin{cases} \Delta m^2_{\text{SOL}} \simeq [6.8 \to 8.0] \times 10^{-5} \text{ eV}^2 , \\ |\Delta m^2_{\text{ATM}}| \simeq [2.4 \to 2.6] \times 10^{-3} \text{ eV}^2 ; \end{cases}$

$\Rightarrow$ solutions: **add new neutrinos** or **revise fluxes**.

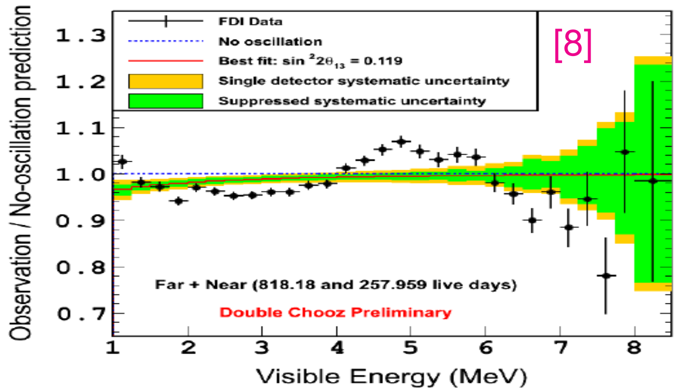


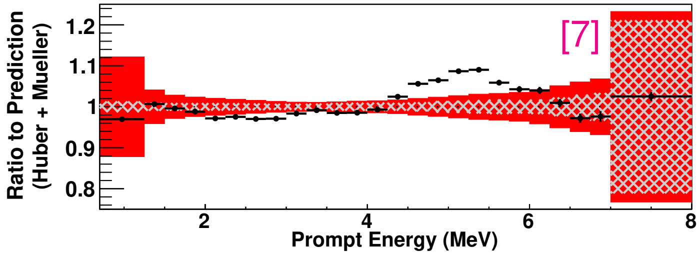
[3] T.A. Mueller *et al.*, Phys. Rev. **C83** (2011) 054615 [arXiv:1101.2663].
[4] P. Huber, Phys. Rev. C **84** (2011) 024617 [arXiv:1106.0687].
[5] G. Mention *et al.*, Phys. Rev. **D83** (2011) 073006 [arXiv:1101.2755].

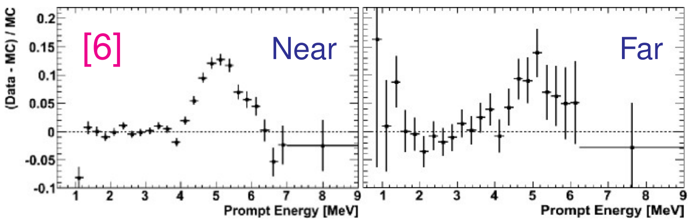
$\Rightarrow$ Talk: Hayes
$\Rightarrow$ Talk: Suhonen

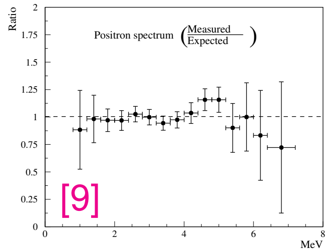
$\bar{\nu}_e$ disapp: 5 MeV excess

- Neutrino 2014: RENO [6] reported an excess of events around 5 MeV;
- excess (not deficit) & independent of $L \Rightarrow$ **flux feature**, not ~~**sterile oscillations**~~;
- seen by Daya-Bay [7], Double-Chooz [8], and many others (also old Chooz [9]);
- more info: ⇒ Talks: Hayes









[6] S.H Seo [RENO collab], talk at Neutrino 2014, Boston, USA, June 2-7, 2014.

[7] F. P. An *et al.* [Daya-Bay collab], CPC **41** (2017) [arXiv:1607.05378].

[8] I.G. Botella [Double-Chooz collab], talk at EPS 2017, Venice, Italy.

[9] M. Apollonio *et al.* [Chooz collab], PLB **466** (1999) 415 [hep-ex/9907037].

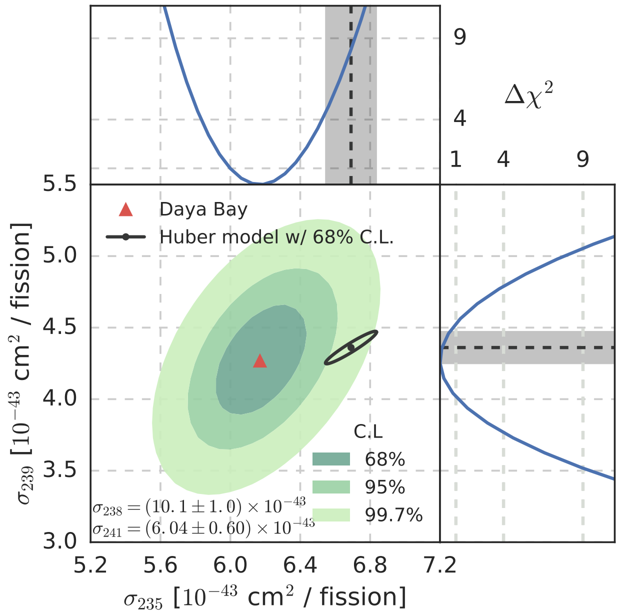
Reactor $\bar{\nu}_e$ flux at the Daya-Bay

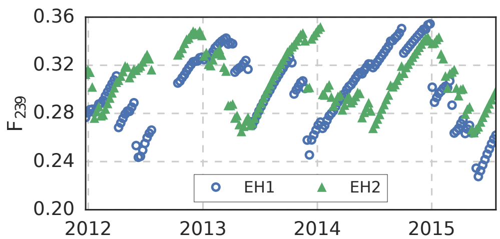
- $\bar{\nu}_e$ from [^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu] fission chains;
- Daya-Bay: varying fuel composition ⇒ reconstruct contribution of individual isotopes;
- Results on the overall IBD yield σ_f:

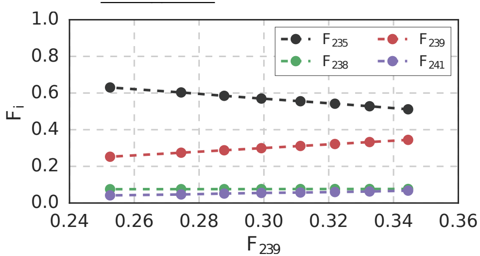
(A) 1.7σ below expectation (known);

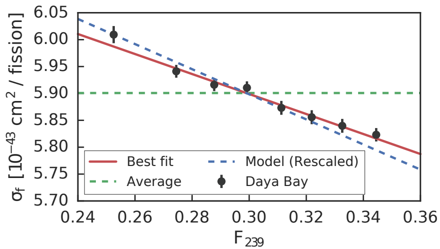
(B) dependence on fuel composition (described by ^{239}Pu) is 3.1σ away from model;

- sterile neutrinos can explain **(A)** but not **(B)**;
- isotopes: measured ^{239}Pu OK, ^{235}U not OK.





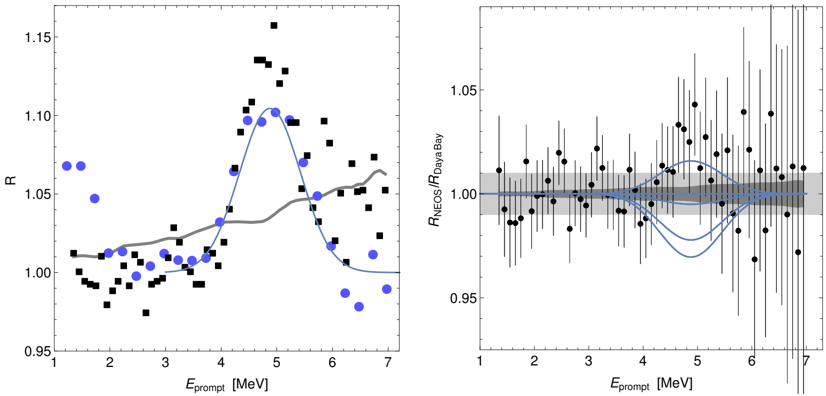




[10] F.P. An *et al.* [Daya-Bay collab], Phys. Rev. Lett. **118** (2017) 251801 [arXiv:1704.01082].

The 5 MeV excess at Daya-Bay and NEOS

- In Ref. [11], the Daya-Bay spectrum from Ref. [7] was combined with the NEOS spectrum presented at ICHEP 2016 (later published in Ref. [12]) to infer which isotope is most likely to contribute to the 5 MeV excess;
- idea: fission fractions in Daya-Bay ($^{235}\mathrm{U} = 56.1\%$, $^{239}\mathrm{Pu} = 30.7\%$) sizably different from NEOS ($^{235}\mathrm{U} = 65.5\%$, $^{239}\mathrm{Pu} = 23.5\%$) $\Rightarrow$ data are complementary;
- method:
  - construct a double ratio to cancel systematics;
  - add a “bump” to a given isotope and fit its amplitude;
- result: fit is best when the bump is ascribed to $^{235}\mathrm{U}$.



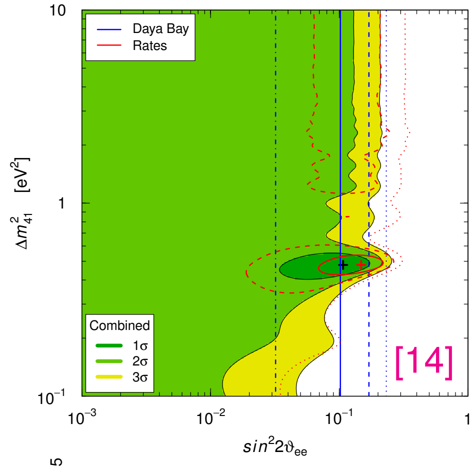
[7] F. P. An *et al.* [Daya-Bay collab], Chin. Phys. C **41** (2017) [arXiv:1607.05378].
[11] P. Huber, Phys. Rev. Lett. **118** (2017) 042502 [arXiv:1609.03910].
[12] Y. J. Ko *et al.* [NEOS collab], Phys. Rev. Lett. **118** (2017) 121802 [arXiv:1610.05134].

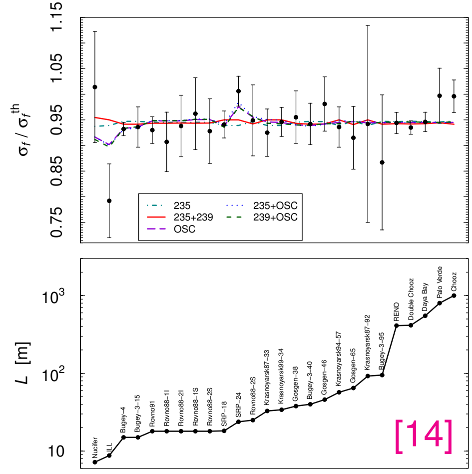
$\bar{\nu}_e$ disapp: new fluxes or new neutrinos?

- ^{235}U flux prediction is in tension with reactor rates [13], with Daya-Bay time evolution [10], and with DB/NEOS spectral data [11];
- however, reactor rates favor sterile solution [14];
- combined fit [14]: flux-only and sterile-only solutions give similar fits, but flux+sterile best;

Sample	235	235+239	OSC	235+OSC	239+OSC
Rates	20.7	17.7	12.8	12.6	12.7
Daya-Bay	3.8	3.6	9.5	3.6	3.8
Combined	25.3	24.8	23.0	20.2	17.5

- anyway, free fluxes reduce significance of sterile hint.





[10] F.P. An *et al.* [DB], PRL **118** (2017) 251801 [arXiv:1704.01082].

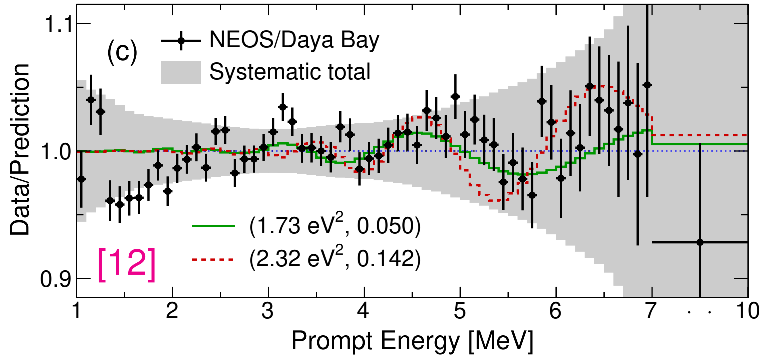
[11] P. Huber, PRL **118** (2017) 042502 [arXiv:1609.03910].

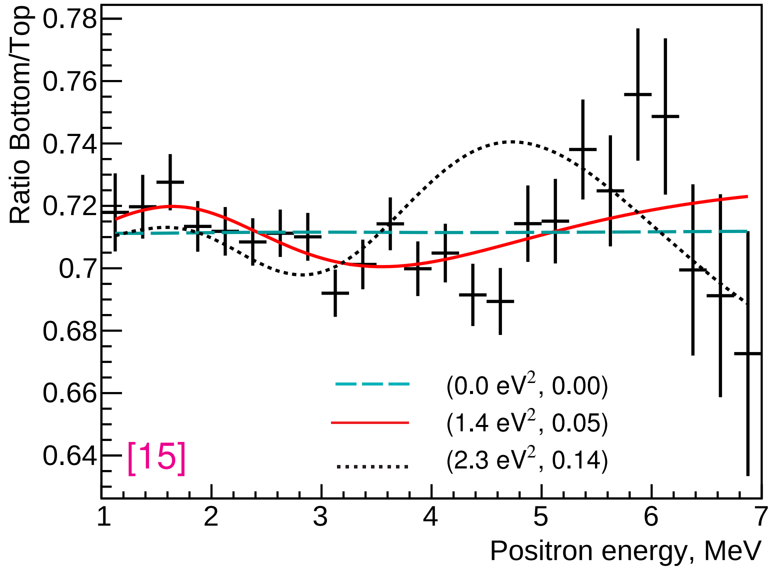
[13] C. Giunti, PLB **764** (2017) 145 [arXiv:1608.04096].

[14] C. Giunti *et al.*, JHEP **10** (2017) 143 [arXiv:1708.01133].

NEOS and DANSS results

- Both detectors have measured reactor neutrinos at very short baseline:
  - NEOS [12]: 24 m;
  - DANSS [15]: 10.7 m $\to$ 12.7 m;
- data: near/far spectral ratios $\Rightarrow$ insensitive to flux shape & normalization:
  - NEOS: normalized to Daya-Bay;
  - DANSS: movable detector;
- both detectors observe small energy modulations $\Rightarrow$ hints of sterile ν.



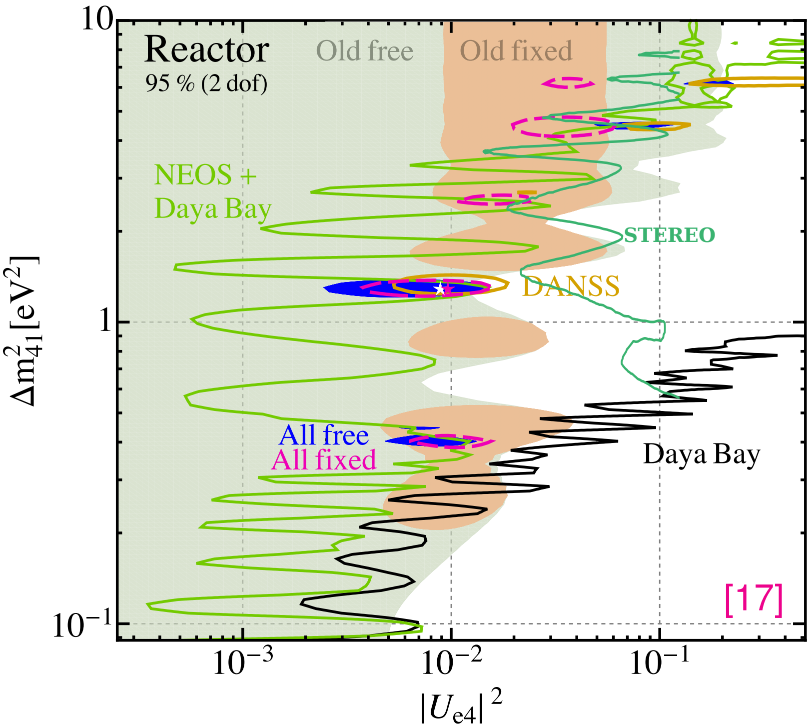


[12] Y. J. Ko *et al.* [NEOS collab], PRL **118** (2017) 121802 [arXiv:1610.05134].

[15] I. Alekseev *et al.* [DANSS collabortion], arXiv:1804.04046.

Global analysis of all reactor $\bar{\nu}_e$ disappearance data

- Total rates only $\Rightarrow$ two models [16]:
  - "free": unconstrained normalizations for $[{}^{235}\mathrm{U}, {}^{238}\mathrm{U}, {}^{239}\mathrm{Pu}, {}^{241}\mathrm{Pu}]$;
  - "fixed": assumes Huber fluxes;
- spectral data as near/far ratios $\Rightarrow$ independent of flux assumptions;
- results [17]:
  - 2.9σ (3.5σ) hint for sterile ν from analysis with free (fixed) fluxes;
  - fit dominated by DANSS + NEOS;
  - DANSS osc. agree with NEOS;
  - DANSS osc. in tension with fixed.



[16] M. Dentler *et al.*, JHEP **11** (2017) 099 [arXiv:1709.04294].

[17] M. Dentler *et al.*, arXiv:1803.10661.

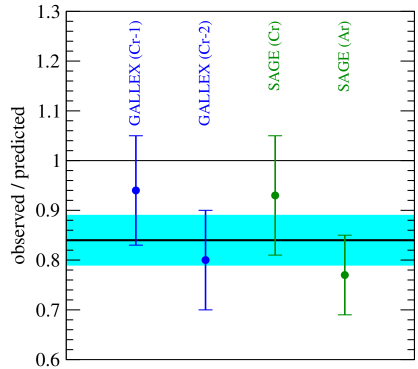
$\Rightarrow$ Poster #M/147: Á. Hernández-Cabezudo

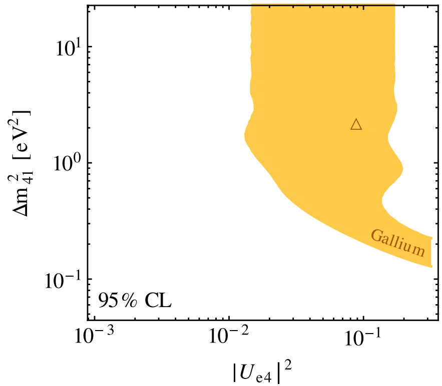
ν_e disappearance: the gallium anomaly

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

$$\left.\begin{array}{l}\text{GALLEX:}\begin{cases}R_1(\text{Cr}) = 0.94 \pm 0.11 \text{ [18]}\\ R_2(\text{Cr}) = 0.80 \pm 0.10 \text{ [18]}\end{cases}\\ \text{SAGE:}\begin{cases}R_3(\text{Cr}) = 0.93 \pm 0.12 \text{ [19]}\\ R_4(\text{Ar}) = 0.77 \pm 0.08 \text{ [20]}\end{cases}\end{array}\right\} \Longrightarrow \boxed{0.84 \pm 0.05}$$

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

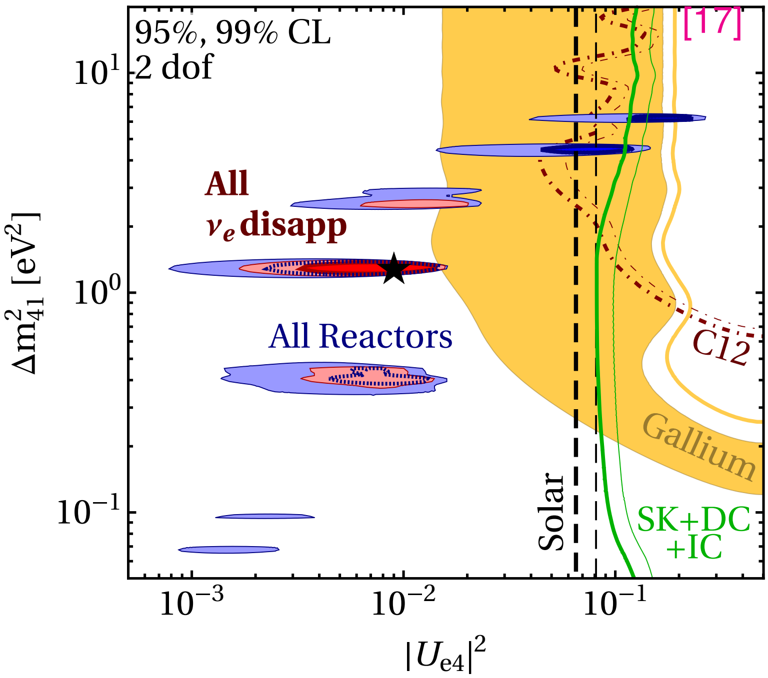




[18] F. Kaether *et al.*, Phys. Lett. **B685** (2010) 47–54 [arXiv:1001.2731].
[19] J. Abdurashitov *et al.* [SAGE collab], Phys. Rev. **C59** (1999) 2246–2263 [hep-ph/9803418].
[20] J. Abdurashitov *et al.* [SAGE collab], Phys. Rev. **C73** (2006) 045805 [nucl-ex/0512041].

Global analysis of ν_e and $\bar{\nu}_e$ disappearance

- In addition to reactor ($\bar{\nu}_e$) and gallium (ν_e) data, we include:
  - Karmen [21] and LSND [22] data on $\nu_e + {}^{12}\mathrm{C} \to e^- + {}^{12}\mathrm{N}$ reaction;
  - atmospheric neutrino data ($\nu_e + \bar{\nu}_e$);
  - **solar** neutrino data (ν_e);
- results [17]:
  - small tension (2.2σ) between gallium and reactor (free fluxes) data;
  - hint for sterile slightly increases to 3.2σ (3.8σ) for free (fixed) fluxes;
  - global best-fit at $\Delta m^2_{41} = 1.3$ eV^2.



[17] M. Dentler *et al.*, arXiv:1803.10661.

[21] B. Armbruster *et al.* [Karmen collab], Phys. Rev. C **57** (1998) 3414 [hep-ex/9801007].

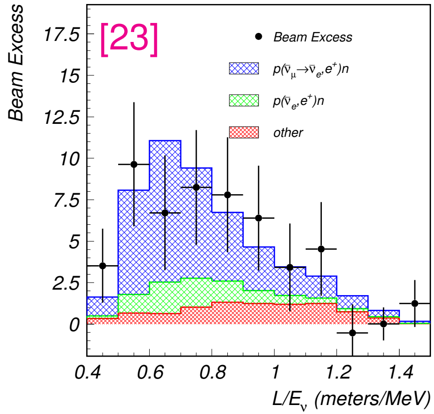
[22] L. B. Auerbach *et al.* [LSND collab], Phys. Rev. C **64** (2001) 065501 [hep-ex/0105068].

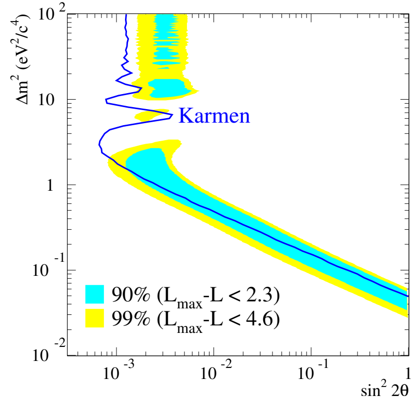
The LSND anomaly

- 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) [23];
- the Karmen collaboration did not confirm the claim, but couldn't fully exclude it either [24];
- 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):

$$\Delta m^2_{\text{SOL}} \simeq [6.8 \to 8.0] \times 10^{-5}\ \text{eV}^2\,,$$
$$\left|\Delta m^2_{\text{ATM}}\right| \simeq [2.4 \to 2.6] \times 10^{-3}\ \text{eV}^2\,;$$

- again, to explain LSND with mass-induced ν oscillations one needs **new** neutrino mass eigenstates;
- MiniBooNE: much larger E_ν and L but similar L/E_ν.

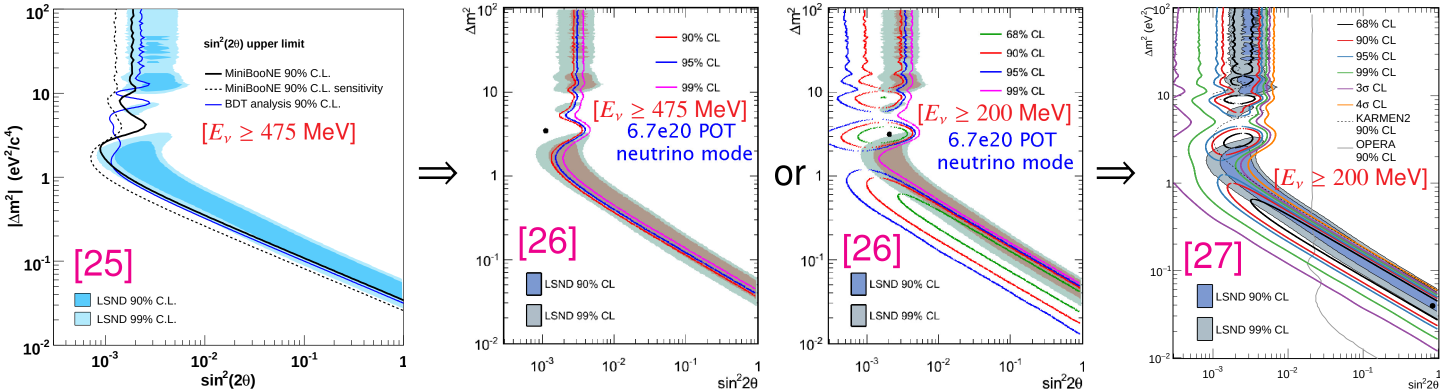




[23] A. Aguilar-Arevalo *et al.* [LSND collab], Phys. Rev. D **64** (2001) 112007 [hep-ex/0104049].
[24] B. Armbruster *et al.* [KARMEN collab], Phys. Rev. D **65** (2002) 112001 [hep-ex/0203021].

MiniBooNE neutrino data

- Statistics: 5.58 (2007) $\to$ 6.46 (2008) $\to$ 12.84 (2018) $\times 10^{20}$ POT;
- is ν signal compatible with 2ν oscillations?
  - 2007: $P_{\text{osc}} \simeq 1\%$ $\Rightarrow$ no it isn't [25];
  - 2012: $P_{\text{osc}} \simeq 6\%$ $\Rightarrow$ maybe it is [26];
  - 2018: $P_{\text{osc}} \simeq 15\%$ $\Rightarrow$ yes it is [27];
- do MB-ν rule out LSND-$\bar\nu$ signal? 2007: yes [25]; 2012: not really [26]; 2018: no [27].



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

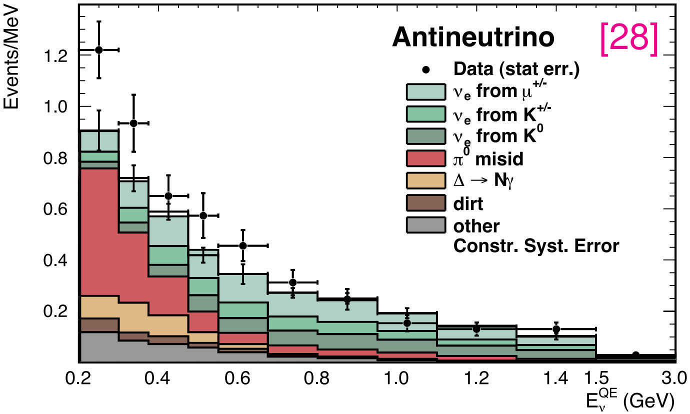
[26] C. Polly, talk at Neutrino 2012, Kyoto, Japan, June 3-9, 2012.

[27] A.A. Aguilar-Arevalo *et al.* [MiniBooNE collab], arXiv:1805.12028.

⇒ Talk: Huang

MiniBooNE antineutrino data

- New data presented at Neutrino 2012, statistics doubled ($\to 11.27 \times 10^{20}$ POT) [26];
- 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? $P_{\text{osc}} = 66\% \Rightarrow$ definitely yes [28];
- is MB-$\bar\nu$ signal compatible with LSND? Yes, irrespective of the energy threshold.



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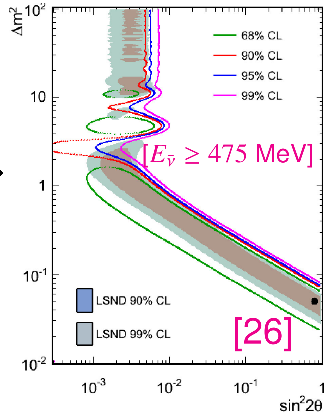

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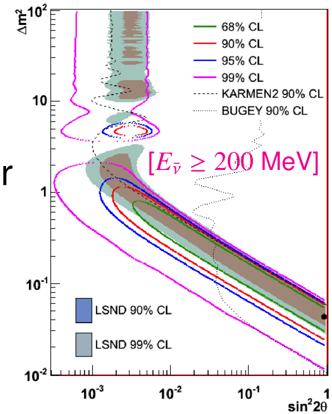


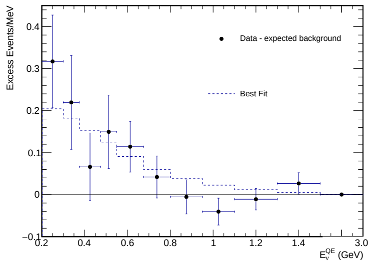
[26] C. Polly, talk at Neutrino 2012, Kyoto, Japan, June 3-9, 2012.

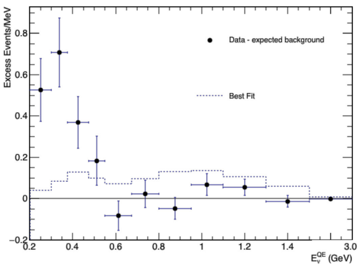
[28] A.A. Aguilar-Arevalo *et al.* [MiniBooNE collab], PRL **110** (2013) 161801 [`arXiv:1303.2588`].

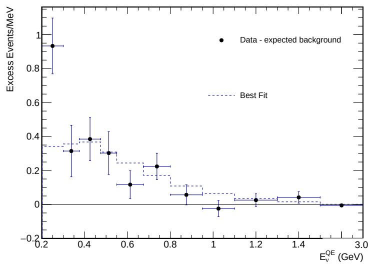
II. Oscillation anomalies: $\nu_\mu \to \nu_e$ appearance

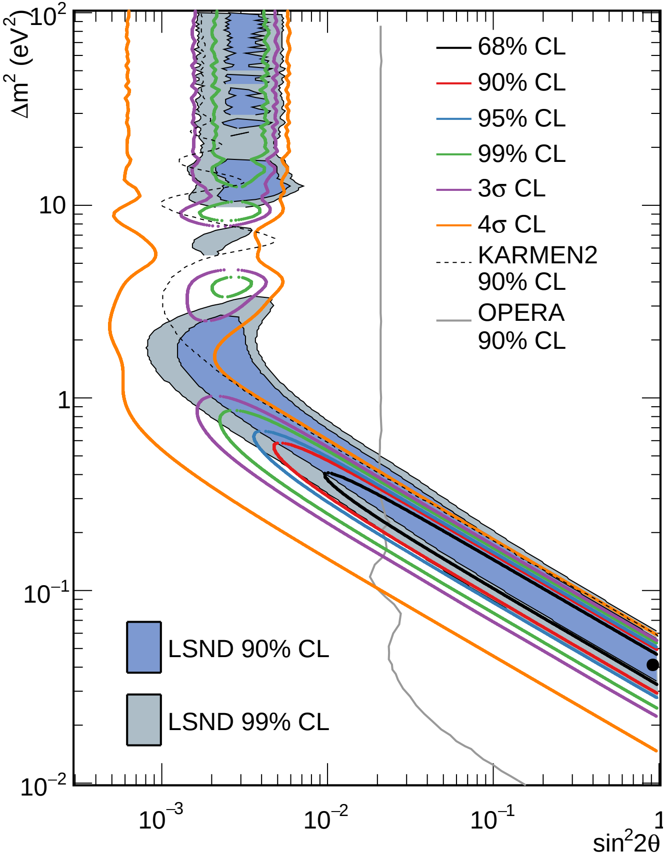
MiniBooNE combined data

- Low-energy excess in 1st half of ν data absent from 2nd half (except lowest bin) $\Rightarrow$ overall excess is only mild;
- combined $\nu_e + \bar{\nu}_e$ fit: 4.8σ evidence for sterile;
- LSND signal: 3.8σ;
- global LSND + MB preference for sterile neutrinos: 6.1σ.





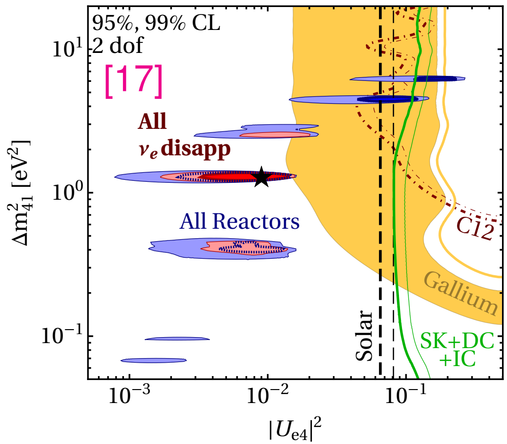




[27] A.A. Aguilar-Arevalo *et al.* [MiniBooNE collab], arXiv:1805.12028.

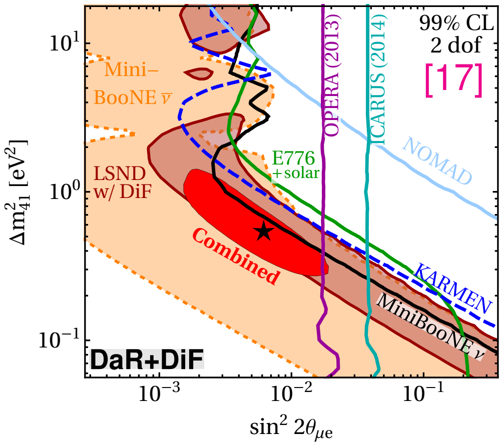
ν_e disappearance

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



$\nu_\mu \to \nu_e$ appearance

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

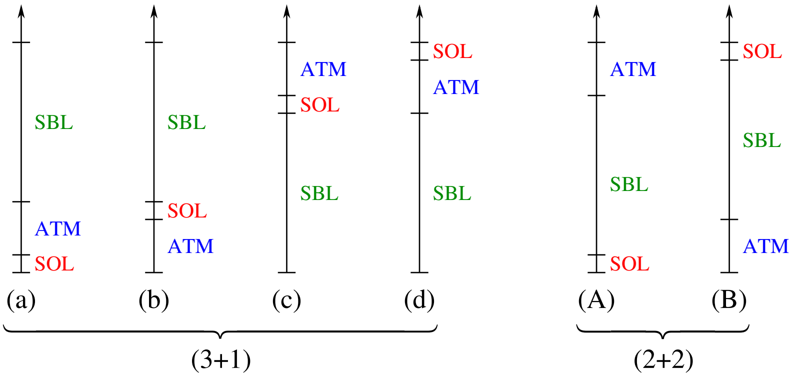


- Note: $\bar\nu_e \to \bar\nu_e$ and $\bar\nu_\mu \to \bar\nu_e$ probe the same Δm^2 but a different mixing angle $\Rightarrow$ mutual comparison requires embedding them into a **general oscillation model**.

[17] Dentler, Hernández-Cabezudo, Kopp, Machado, MM, Martinez-Soler, Schwetz, arXiv:1803.10661.

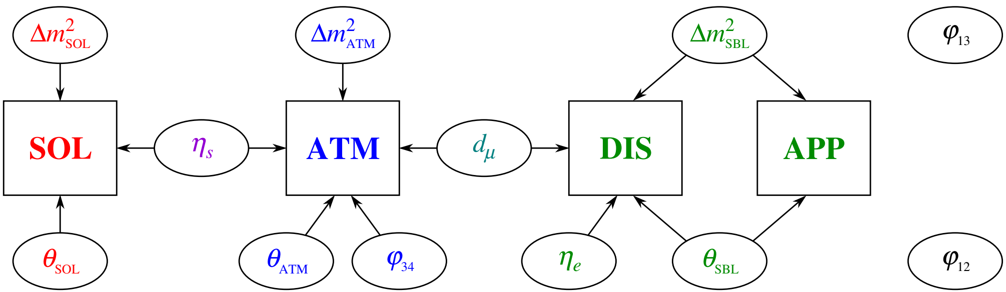
Four neutrino mass models

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

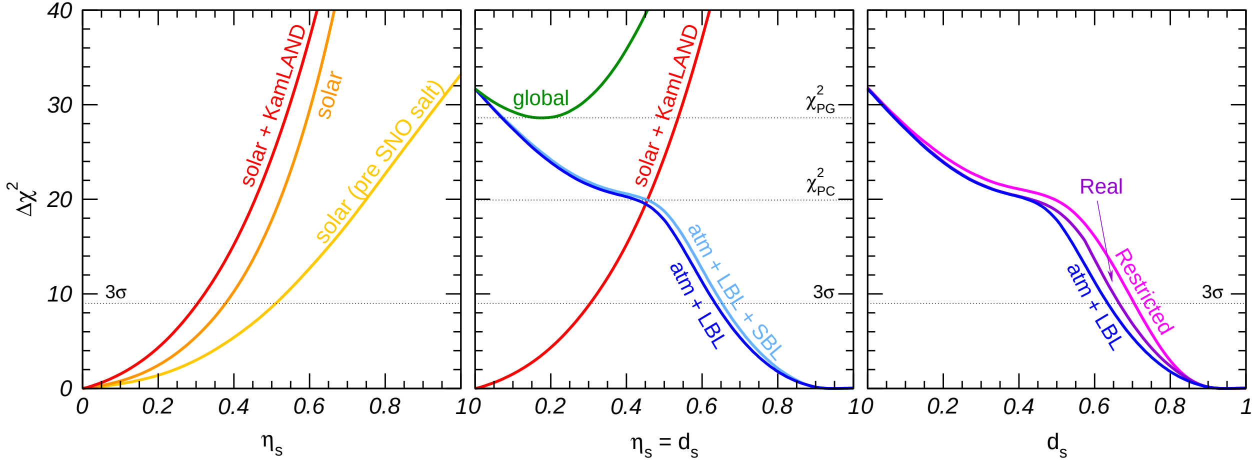


$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

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



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



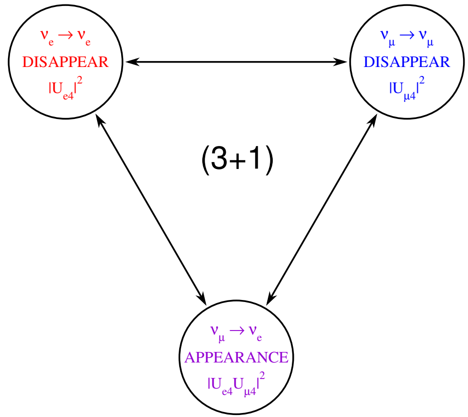
- in (2+2) models, fractions of ν_s in solar (η_s) and atmos ($1 - d_s$) add to one $\Rightarrow$ $\boxed{\eta_s = d_s}$;
- 3σ allowed regions $\eta_s \leq 0.31$ (solar) and $d_s \geq 0.63$ (atmos) do not overlap; superposition occurs only above 4.5σ ($\chi^2_{\text{PC}} = 19.9$);
- the χ^2 increase from the combination of solar and atmos data is $\chi^2_{\text{PG}} = 28.6$ (1 dof), corresponding to a PG $= 9 \times 10^{-8}$ [29].

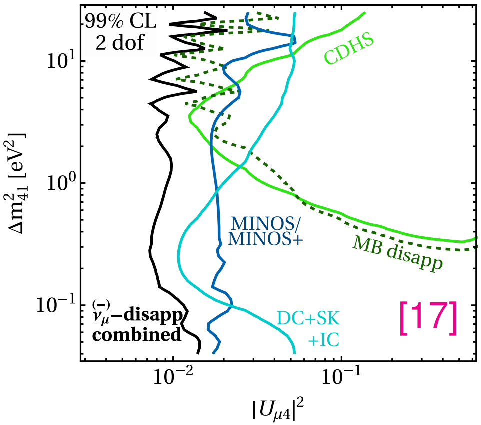
[29] M. Maltoni, T. Schwetz, M.A. Tortola, J.W.F. Valle, Nucl. Phys. **B643** (2002) 321 [hep-ph/0207157].

(3+1): appearance versus disappearance

- (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?





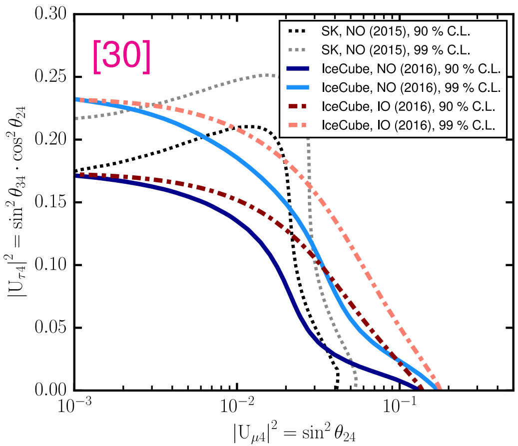
ν_μ disappearance: present status

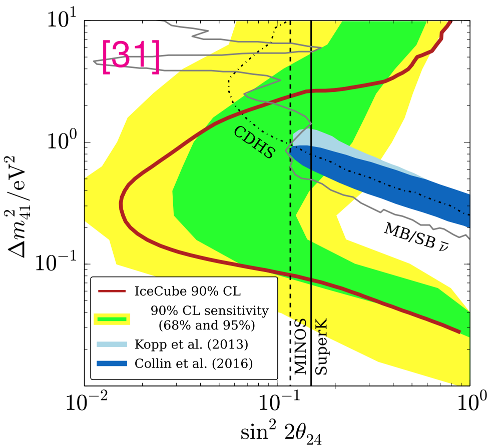
- Many experiments have been performed:
  - CDHS (ν)
  - MiniBooNE ($\nu, \bar\nu$)
  - SciBooNE ($\nu, \bar\nu$)
  - MINOS (ν)
  - NOνA (ν)
  - SK atmos ($\nu, \bar\nu$)
- no hint of ν_μ disappearance has been observed;
- bound on $|U_{\mu4}|^2$ may be in tension with other data. . .

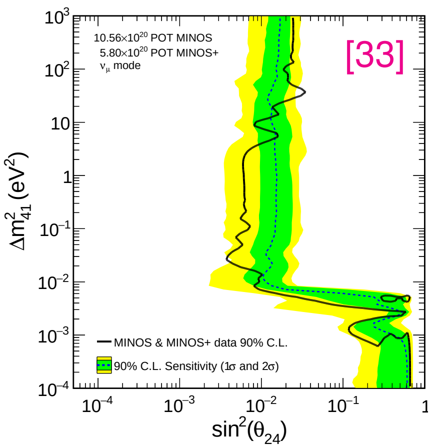
[17] Dentler, Hernández-Cabezudo, Kopp, Machado, MM, Martinez-Soler, Schwetz, arXiv:1803.10661.

ν_μ disappearance: recent atmospheric and SBL data

- new DeepCore [30] and IceCube [31] atmos. data probe ν_μ mixing with heavy state;
- sterile neutrino oscillations also studied by NOνA using neutral-current data [32];
- recent MINOS/MINOS+ analysis [33] improves bound on ν_μ disapp. ⇒ Talk: Aurisano







[30] M.G. Aartsen *et al.* [IceCube collab], Phys. Rev. D **95** (2017) 112002 [arXiv:1702.05160].

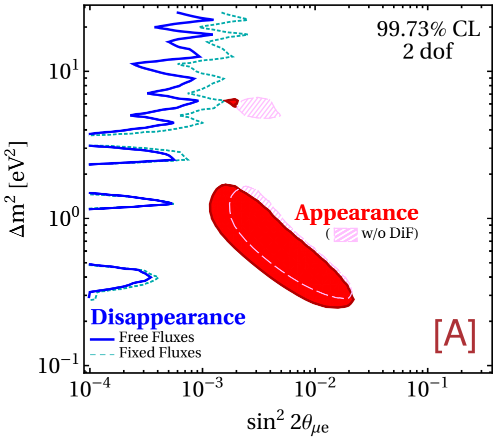
[31] M.G. Aartsen *et al.* [IceCube collab], Phys. Rev. Lett. **117** (2016) 071801 [arXiv:1605.01990].

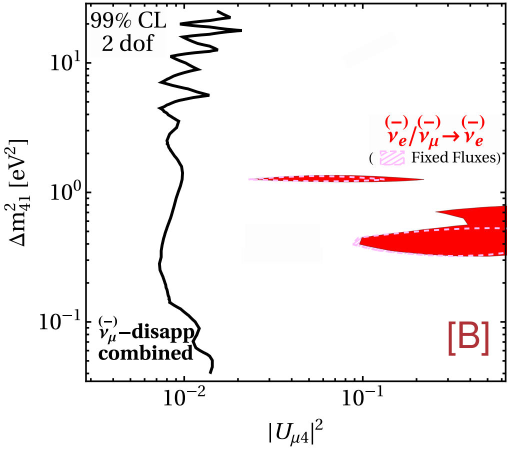
[32] P. Adamson *et al.* [NOvA collab], Phys. Rev. D **96** (2017) 072006 [arXiv:1706.04592].

[33] P. Adamson *et al.* [MINOS collab], [arXiv:1710.06488].

(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: $\chi^2_{\text{PG}}/\text{dof} = 29.6/2 \Rightarrow \text{PG} = 3.7 \times 10^{-7}$ [17];
- a similar result is visible when comparing "ν_e-data" ($\nu_e \to \nu_e$ and $\nu_\mu \to \nu_e$) and "ν_μ-data" ($\nu_\mu \to \nu_\mu$) [B];
- note: tension between **APP** and **DIS** data first pointed out in 1999 [34]. Full global fit in 2001 [35] cornered (3+1) models. No conceptual change since then...





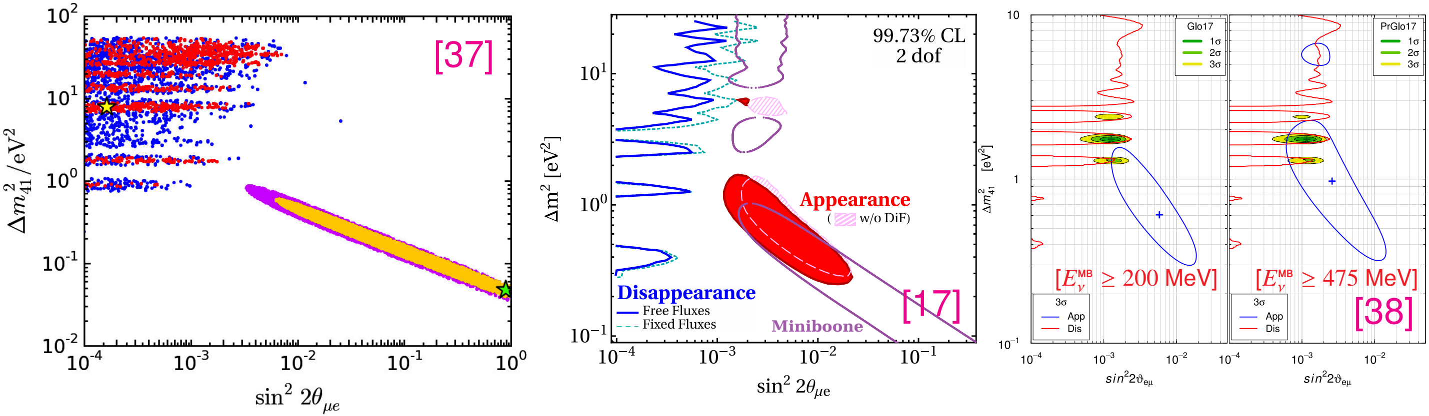
[17] M. Dentler *et al.*, arXiv:1803.10661.

[34] S.M. Bilenky *et al.*, PRD **60** (1999) 073007 [hep-ph/9903454].

[35] MM, Schwetz, Valle, PLB **518** (2001) 252 [hep-ph/0107150].

(3+1): comparison with other analyses

- A few independent analyses of **APP** versus **DIS** compatibility have been presented;
- results of [36, 37] similar to ours ⇒ (3+1) ruled out: $\chi^2_{PG}/\text{dof} = 22.9/2 \Rightarrow \text{PG} = 10^{-5}$;
- results of [38]: (3+1) ruled out: $\chi^2_{PG}/\text{dof} = 17.2/2 \Rightarrow \text{PG} = 0.019\%$ (MB $E_\nu > 200$ MeV), (3+1) very poor: $\chi^2_{PG}/\text{dof} = 7.2/2 \Rightarrow \text{PG} = 2.7\%$ (MB $E_\nu > 475$ MeV).



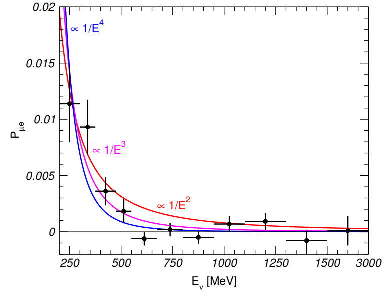
[17] Dentler, Hernández-Cabezudo, Kopp, Machado, MM, Martinez-Soler, Schwetz, arXiv:1803.10661.
[36] J.M. Conrad *et al.*, Adv. High Energy Phys. **2013** (2013) 163897 [arXiv:1207.4765].
[37] G.H. Collin *et al.*, Nucl. Phys. B **908** (2016) 354 [arXiv:1602.00671].
[38] S. Gariazzo, C. Giunti, M. Laveder and Y. F. Li, JHEP **06** (2017) 135 [arXiv:1703.00860].

(3+1): robustness of the result

- The tension cannot be eliminated by discarding any *individual* experiment.

Analysis	$\chi^2_{\text{min,global}}$	$\chi^2_{\text{min,app}}$	$\Delta\chi^2_{\text{app}}$	$\chi^2_{\text{min,disapp}}$	$\Delta\chi^2_{\text{disapp}}$	χ^2_{PG}/dof	PG
Global	1120.9	79.1	11.9	1012.2	17.7	29.6/2	3.7×10^{-7}
Removing anomalous data sets							
w/o LSND	1099.2	86.8	12.8	1012.2	0.1	12.9/2	1.6×10^{-3}
w/o MiniBooNE	1012.2	40.7	8.3	947.2	16.1	24.4/2	5.2×10^{-6}
w/o reactors	925.1	79.1	12.2	833.8	8.1	20.3/2	3.8×10^{-5}
w/o gallium	1116.0	79.1	13.8	1003.1	20.1	33.9/2	4.4×10^{-8}
Removing constraints							
w/o IceCube	920.8	79.1	11.9	812.4	17.5	29.4/2	4.2×10^{-7}
w/o MINOS(+)	1052.1	79.1	15.6	948.6	8.94	24.5/2	4.7×10^{-6}
w/o MB disapp	1054.9	79.1	14.7	947.2	13.9	28.7/2	6.0×10^{-7}
w/o CDHS	1104.8	79.1	11.9	997.5	16.3	28.2/2	7.5×10^{-7}
Removing classes of data							
$\overset{(-)}{\nu}_e$-dis vs app	628.6	79.1	0.8	542.9	5.8	6.6/2	3.6×10^{-2}
$\overset{(-)}{\nu}_\mu$-dis vs app	564.7	79.1	12.0	468.9	4.7	16.7/2	2.3×10^{-4}
$\overset{(-)}{\nu}_\mu$-dis+solar vs app	884.4	79.1	13.9	781.7	9.7	23.6/2	7.4×10^{-6}

More sterile neutrinos? The case of (3+2) models



- 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 ($\sim 1/E^3$);
- 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 $1/E^2$ suppressed if $\delta \approx \pi$ and $|U_{e4}U_{\mu 4}|\Delta m_{41}^2 \approx |U_{e5}U_{\mu 5}|\Delta m_{51}^2$;

⇒ two extra sterile states provide a better desciption of the MB low-energy ν data [39].

- also, $\delta = \arg(U_{e4}^* U_{\mu 4} U_{e5} U_{\mu 5}^*)$ differentiates between ν (MB) from $\bar\nu$ (MB/LSND);
- however, (3+2) models suffer from **the same APP/DIS tension** as (3+1) models;
- also, (3+2) models have stronger problems with cosmology since $\sum m_\nu$ is larger;

⇒ (3+N) models **do not present substantial advantages** over the simpler (3+1) model.

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

- Anomalies in $\nu_e \to \nu_e$ disappearance and $\nu_\mu \to \nu_e$ appearance experiments point towards conversion mechanisms beyond the well-established 3ν oscillation paradigm;
- each of these anomalies can be **individually** explained by sterile neutrinos;
- sterile neutrinos still succeed in simultaneously explaining groups of anomalies **sharing the same oscillation channel**. However some problem arises:
  - $\nu_e \to \nu_e$ disappearance data face issues with flux normalization and the 5 MeV bump, as well as small tensions in reactor vs gallium and "rates" vs DANSS/NEOS;
  - $\nu_\mu \to \nu_e$ appearance data show an excess in low-E neutrino data, which is not so manifest in antineutrino data.
- in contrast, no anomaly is found in any $\nu_\mu \to \nu_\mu$ disappearance data set;

$\Rightarrow$ sterile neutrino models **fail to simultaneously account** for **all** the $\nu_e \to \nu_e$ data, the $\nu_\mu \to \nu_e$ data and the $\nu_\mu \to \nu_\mu$ data. This conclusion is robust;

- if the $\nu_e \to \nu_e$ and $\nu_\mu \to \nu_e$ anomalies are confirmed, and the $\nu_\mu \to \nu_\mu$ bounds are not refuted, new physics will be needed. Such new physics may well involve extra sterile neutrinos, but together with something else (or some "unusual" neutrino property).