Status of neutrino oscillations
and neutrino telescopes

Michele Maltoni
Instituto de Física Teórica UAM/CSIC

4th Uppsala workshop on Particle Physics with Neutrino Telescopes (PPNT19)
Uppsala, Sweden – October 8th, 2019

I. Three-neutrino oscillations

II. Sterile neutrino models

III. Non-standard interactions

General three-neutrino framework

- Equation of motion: **6 parameters** (including Dirac and neglecting Majorana phases):

$$i\frac{d\vec{\nu}}{dt} = H\,\vec{\nu}; \qquad H = U_{\text{vac}} \cdot D_{\text{vac}} \cdot U_{\text{vac}}^{\dagger} \pm V_{\text{mat}};$$

$$U_{\text{vac}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13}\, e^{-i\delta_{\text{CP}}} \\ 0 & 1 & 0 \\ -s_{13}\, e^{i\delta_{\text{CP}}} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \xcancel{\begin{pmatrix} e^{i\eta_1} & 0 & 0 \\ 0 & e^{i\eta_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}}, \qquad \vec{\nu} = \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix};$$

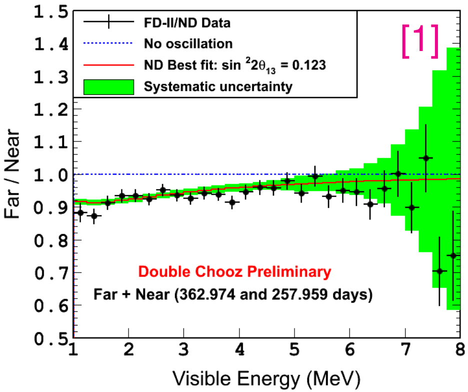
$$D_{\text{vac}} = \frac{1}{2E_\nu}\left[\operatorname{diag}\left(0,\ \Delta m^2_{21},\ \Delta m^2_{31}\right) + \xcancel{m_1^2 I}\right]; \qquad V_{\text{mat}} = \sqrt{2} G_F N_e \operatorname{diag}(1,\ 0,\ 0)\,.$$

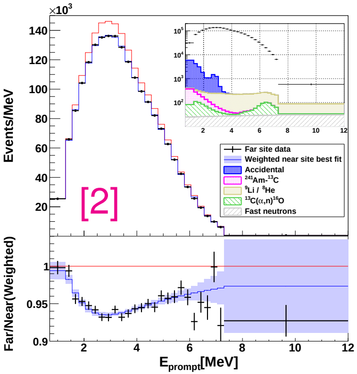
6 parameters $\Longleftrightarrow$ 6 types of experiments

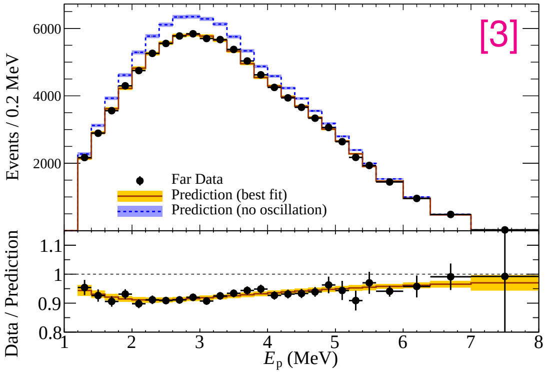
- **SOLAR** sector:
  - – solar experiments (mainly SNO) $\longrightarrow \theta_{12}$
  - – rector LBL (KamLAND) $\longrightarrow \Delta m^2_{21}$
- **REACT** sector:
  - – rector MBL (Double-Chooz, Daya-Bay, Reno) $\longrightarrow \theta_{13}\ [\Delta m^2_{31}]$
- **ATMOS** sector:
  - – atmospheric experiments (SK, DC) $\longrightarrow \theta_{23}$
  - – accelerator LBL-DIS $\nu_\mu \to \nu_\mu$ (T2K, NOvA) $\longrightarrow \Delta m^2_{31}\ [\theta_{23}]$
  - – accelerator LBL-APP $\nu_\mu \to \nu_e$ (T2K, NOvA) $\longrightarrow \delta_{\text{CP}}$

Reactor neutrino disappearance and θ_{13}

- Positive $\bar{\nu}_e$ disappearance signal in DOUBLE-CHOOZ [1], DAYA-BAY [2], RENO [3];
- all these experiments have spectral capabilities and detector units placed at different baselines $\Rightarrow$ uncertainties in the reactor flux predictions do **not** affect the results;
- experimental results are mutually consistent $\Rightarrow$ it is now a firmly established fact that $\underline{\theta_{13} \neq 0}$ $\Rightarrow$ full 3ν oscillation phenomenology.







---

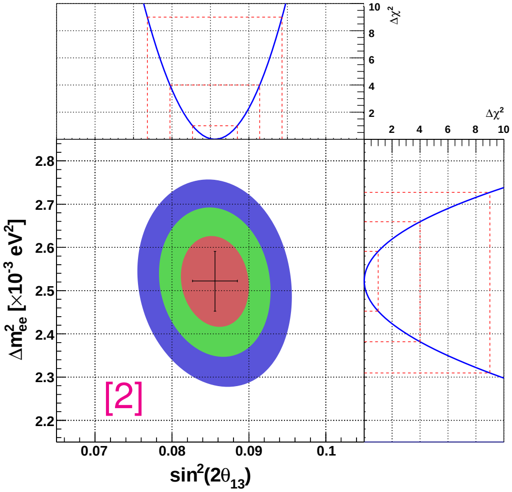
[1] I. Botella [DOUBLE-CHOOZ], talk presented at EPS-HEP 2017, Venice, Italy, July 5–12, 2017.

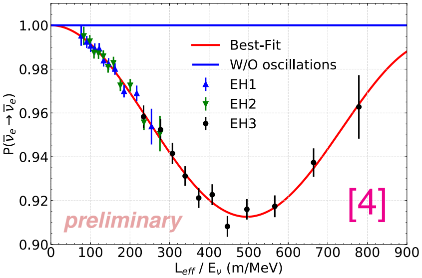
[2] D. Adey *et al.* [DAYA BAY], Phys. Rev. Lett. **121** (2018) 241805 [`arXiv:1809.02261`].

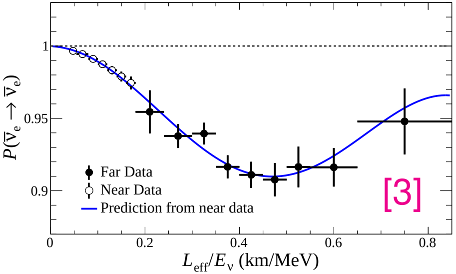
[3] G. Bak *et al.* [RENO], Phys. Rev. Lett. **121** (2018) 201801 [`arXiv:1806.00248`].

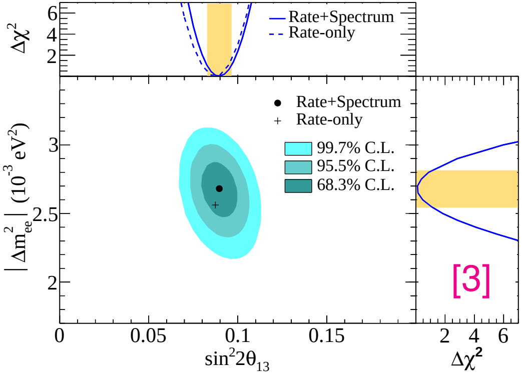
Reconstructing Δm^2_{31} from reactor data

- Spectral information from Double-Chooz, Daya-Bay and Reno ⇒ oscillation pattern clearly visible ⇒ Δm^2_{31} accurately determined by reactor data;
- accuracy from reactor $\nu_e \to \nu_e$ comparable with LBL $\nu_\mu \to \nu_\mu$, but oscillation channel is different ⇒ important **complementary** information available.









---

[2] D. Adey *et al.* [DAYA-BAY], `arXiv:1809.02261`.

[3] G. Bak *et al.* [RENO], `arXiv:1806.00248`.

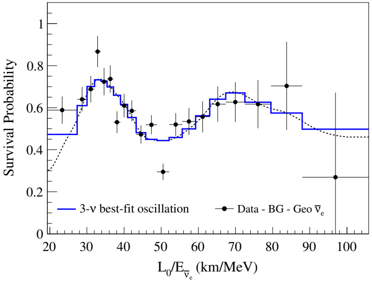
[4] J.P. Ochoa-Ricoux [DAYA-BAY], talk at Neutrino 2018.

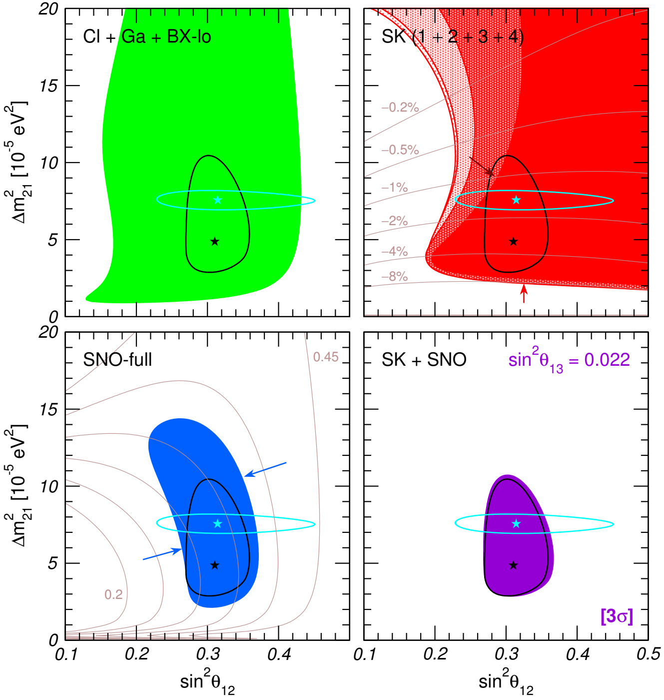
Relevance of solar data in the determination of Δm^2_{21} and θ_{12}

- $P_{ee} = c^4_{13} P_{\text{eff}} + s^4_{13}$, $\quad i\dfrac{d\vec{\nu}}{dt} = \left[\dfrac{\Delta m^2_{21}}{4E_\nu}\begin{pmatrix} -\cos 2\theta_{12} & \sin 2\theta_{12} \\ \sin 2\theta_{12} & \cos 2\theta_{12} \end{pmatrix} \pm \sqrt{2} G_F N_e \begin{pmatrix} c^2_{13} & 0 \\ 0 & 0 \end{pmatrix}\right] \vec{\nu}$, $\quad \vec{\nu} = \begin{pmatrix} \nu_e \\ \nu_a \end{pmatrix}$;
- $\nu_\mu \equiv \nu_\tau \Rightarrow$ no sensitivity to θ_{23} and δ_{CP};
- $\Delta m^2_{31} \approx \infty \Rightarrow$ specific Δm^2_{31} value irrelevant;

$\Rightarrow$ data only depend on Δm^2_{21}, θ_{12} and θ_{13};

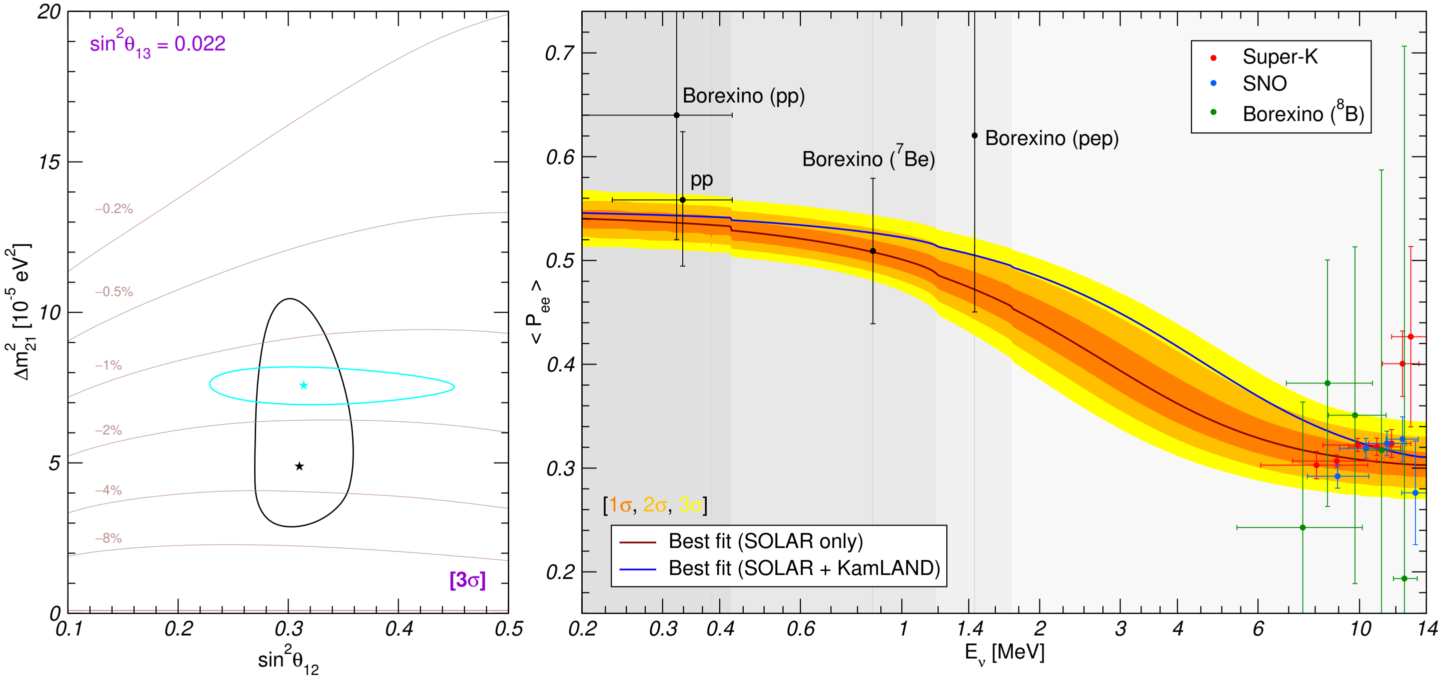
- param's: $\begin{cases} \theta_{12} \text{ dominated by SNO;} \\ \Delta m^2_{21} \text{ dominated by KamLAND;} \end{cases}$
- solar region determined by high-E data, low-E contribution marginal;
- SNO-NC measurement confirms SSM;
- KamLAND precisely determines the oscillation pattern.





Transition between vacuum and MSW regime in solar data

- Tension between solar and KamLAND related to:
  - too much D/N asymmetry in SK;
  - non-observation of low-E turn-up.



KamLAND and reactor ν spectrum

- KamLAND detects neutrinos from various reactors, and has **no** near detector. Hence, spectral distortions may be potentially relevant;
- the effects of such distortions in KamLAND were discussed briefly in [5], and more in detail in [6]. In both cases the impact on Δm^2_{21} was found to be small;
- since 2017 we fix KamLAND reactor spectrum to the measured Daya-Bay ν flux [7];

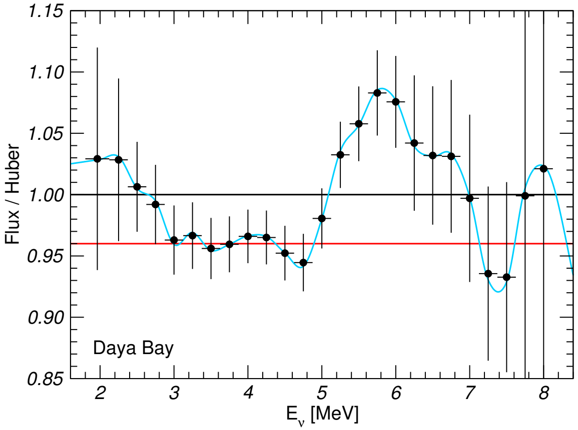
⇒ the determination of Δm^2_{21} is robust against reactor flux uncertainties, and does not help in reconciling solar and KamLAND data.

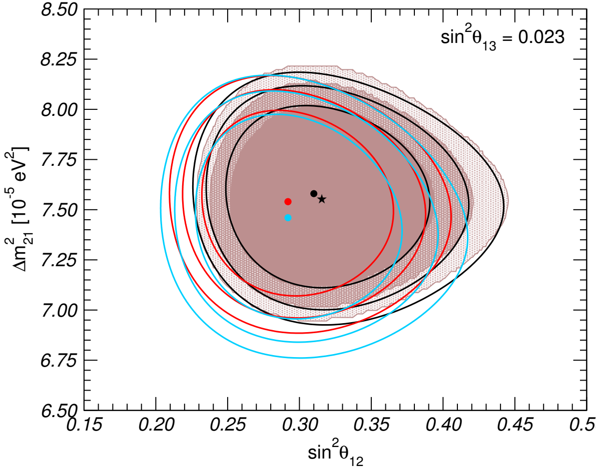
---

[5] M. Maltoni, A.Yu. Smirnov, `arXiv:1507.05287`.

[6] F. Capozzi *et al.*, `arXiv:1601.07777`.

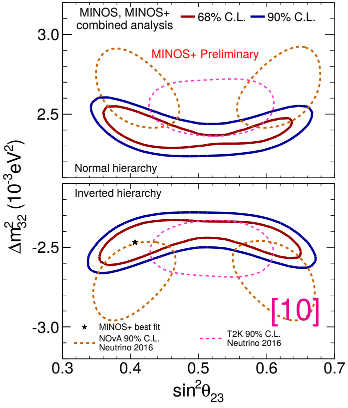
[7] F.P. An *et al.* [DAYA-BAY], `arXiv:1607.05378`.

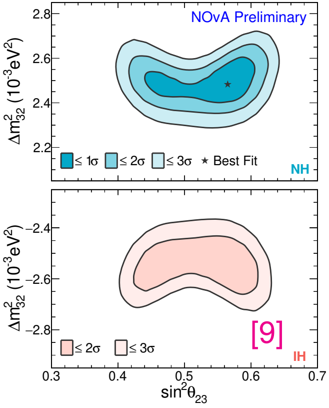


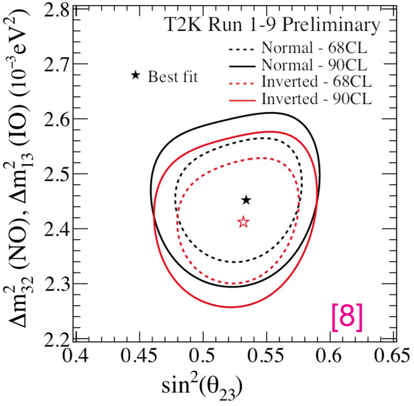


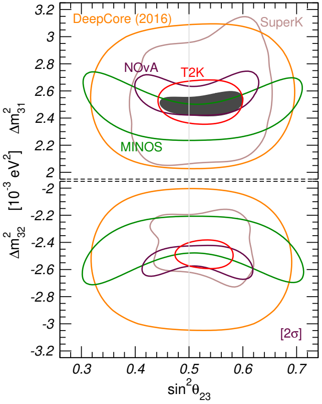
Atmospheric oscillations: Δm^2_{31} and θ_{23}

- Δm^2_{31} & θ_{23} dominated by LBL disappearance ($\nu_\mu \to \nu_\mu$) data;
- Δm^2_{21} effects contribute only at subleading level;
- reasonably good agreement between all experiments in the allowed regions, although some small differences are visible.









---

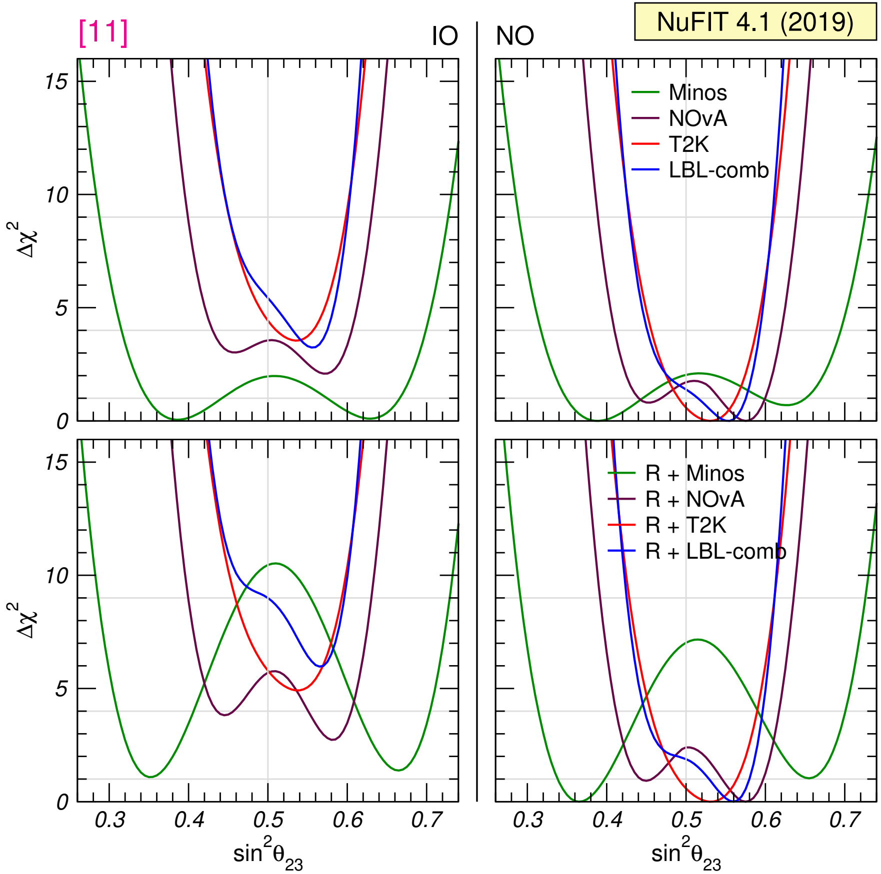
[8] L. Kormos [T2K], talk at EPS-HEP 2019, Ghent, Belgium, 10–17 July 2019.

[9] L. Kolupaeva [NOvA], talk at EPS-HEP 2019, Ghent, Belgium, 10–17 July 2019.

[10] J. Evans [MINOS], talk at Neutrino 2016, London, UK, 4–9 July 2016.

θ_{23} mixing and octant

- Disappearance data:
  - T2K (ν & $\bar{\nu}$) and NOvA (ν) data favor maximal mixing;
  - NOvA ($\bar{\nu}$) still favors non-maximal mixing, but significance is reduced since the previous release (2018);
  - Minos shows strongest deviation but lowest statistics;
- appearance data:
  - all experiments (except Minos) slightly favor $\underline{\theta_{23} > 45^\circ}$;
- similar results for **NO** and **IO**.



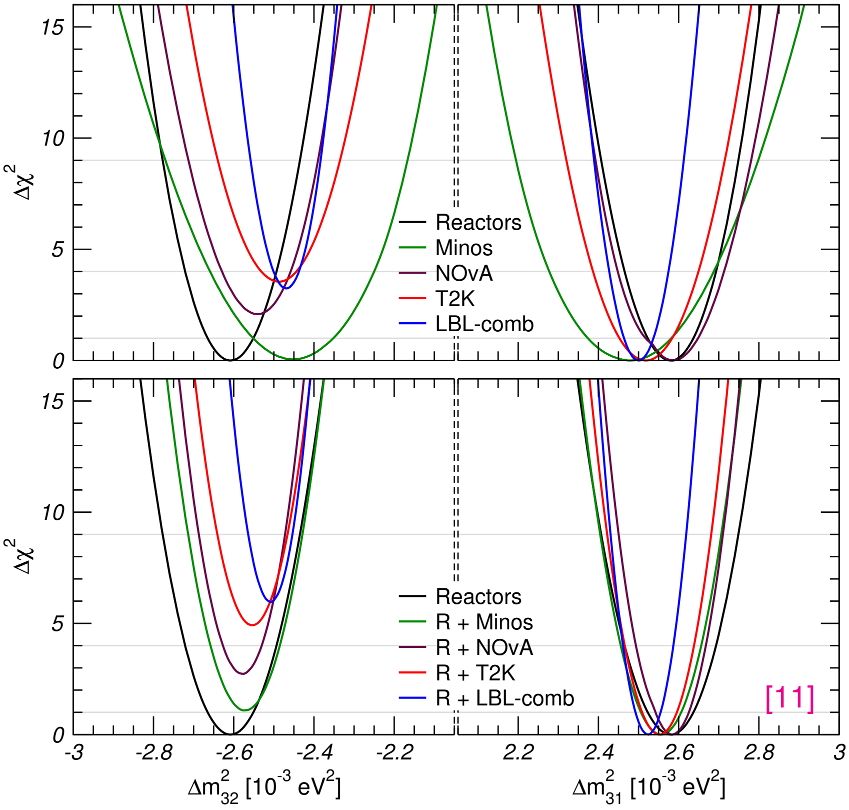
[11] I. Esteban *et al.*, JHEP **01** (2019) 106 [`arXiv:1811.05487`] & NuFIT 4.1 [`http://www.nu-fit.org`].

I. Three-neutrino oscillations

Δm^2_{31} and mass ordering

- All the LBL experiments exhibit a small preference for **NO** over **IO**, even when taken by themselves;
- such preference increases when they are combined with **reactors**, due to better agreement in the preferred Δm^2_{31} range;
- LBL preference for **NO** over **IO**:
  - 1.8σ (only θ_{13} from reactors);
  - 2.4σ (full reactor info);
- inclusion of Super-K atmospheric data raises the significance to 3.2σ ($\Delta\chi^2 = 10.4$).

NuFIT 4.1 (2019)

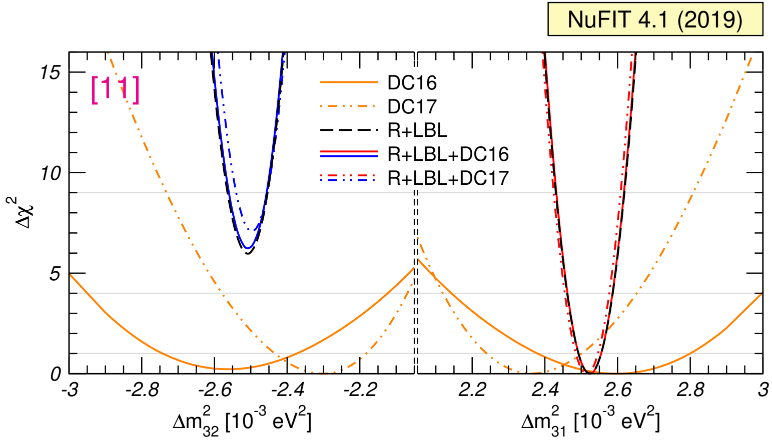


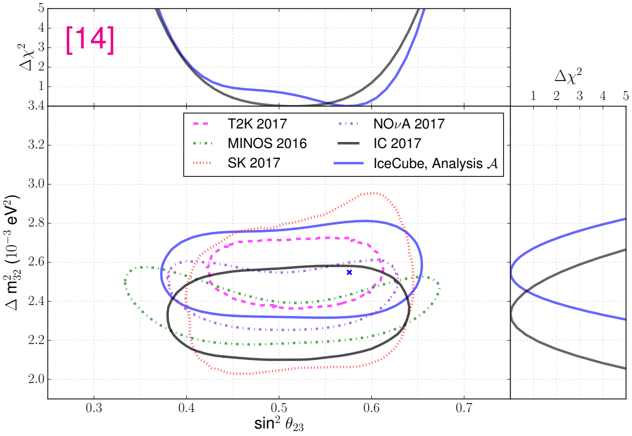
---

[11] I. Esteban *et al.*, JHEP **01** (2019) 106 [`arXiv:1811.05487`] & NuFIT 4.1 [`http://www.nu-fit.org`].

The role of IceCUBE/DeepCore

- Various analysis (DC16 [12], DC17 [13], DC19 [14]) of IceCUBE/DeepCore data have been presented, all based on three-years of data (but **not** the same years);
- despite increasing sensitivity, the contribution to the global fit is still limited.





---

[11] I. Esteban *et al.*, JHEP **01** (2019) 106 [`arXiv:1811.05487`] & NuFIT 4.1 [`http://www.nu-fit.org`].

[12] M.G. Aartsen *et al.* [DEEPCORE], PRD **91** (2015) 072004 [`arXiv:1410.7227`], updated Oct. 2016.

[13] M.G. Aartsen *et al.* [DEEPCORE], PRL **120** (2018) 071801 [`arXiv:1707.07081`].

[14] M.G. Aartsen *et al.* [DEEPCORE], PRD **99** (2019) 032007 [`arXiv:1901.05366`].

Neutrino oscillations: where we are

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

- best-fit point and 1σ (3σ) ranges:

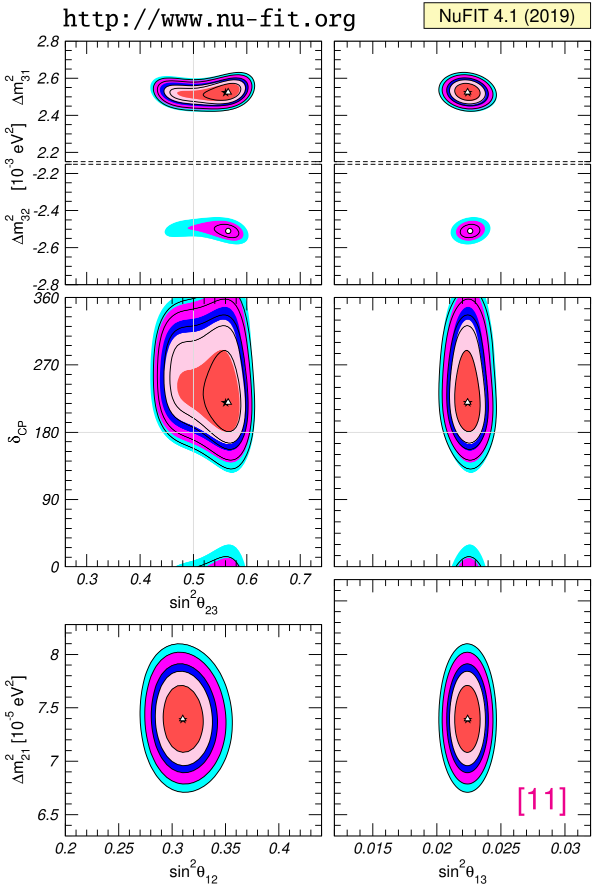
$$\theta_{12} = 33.82\,^{+0.78}_{-0.76}\,\binom{+2.45}{-2.21}, \qquad \Delta m^2_{21} = 7.39\,^{+0.21}_{-0.20}\,\binom{+0.62}{-0.60} \times 10^{-5}\ \text{eV}^2,$$

$$\theta_{23} = \begin{cases} 48.3\,^{+1.1}_{-1.9}\,\binom{+3.0}{-7.5}, \\ 48.6\,^{+1.1}_{-1.5}\,\binom{+2.9}{-7.6}, \end{cases} \qquad \Delta m^2_{31} = \begin{cases} +2.523\,^{+0.032}_{-0.030}\,\binom{+0.095}{-0.091} \times 10^{-3}\ \text{eV}^2, \\ -2.509\,^{+0.032}_{-0.030}\,\binom{+0.093}{-0.094} \times 10^{-3}\ \text{eV}^2, \end{cases}$$

$$\theta_{13} = 8.61\,^{+0.13}_{-0.13}\,\binom{+0.38}{-0.39}, \qquad \delta_{\text{CP}} = 222\,^{+38}_{-28}\,\binom{+148}{-81};$$

- neutrino mixing matrix:

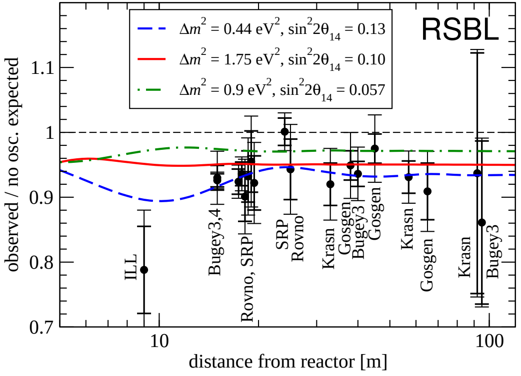
$$|U|_{3\sigma} = \begin{pmatrix} 0.797 \to 0.842 & 0.518 \to 0.585 & 0.143 \to 0.156 \\ 0.244 \to 0.496 & 0.467 \to 0.678 & 0.646 \to 0.772 \\ 0.287 \to 0.525 & 0.488 \to 0.693 & 0.618 \to 0.749 \end{pmatrix}.$$



[11] I. Esteban *et al.*, JHEP **01** (2019) 106 [`arXiv:1811.05487`] & NuFIT 4.1 [`http://www.nu-fit.org`].

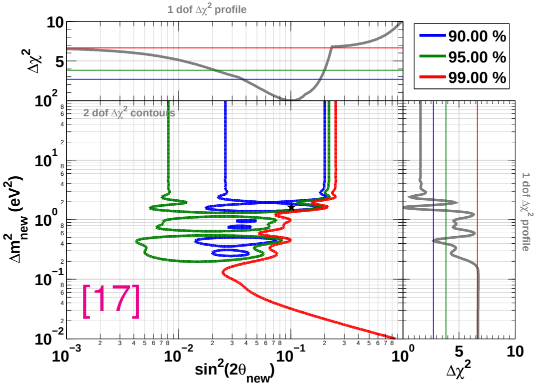
II. Sterile neutrino models

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



- In [15, 16] 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): $\begin{cases} \Delta m^2_{\text{SOL}} \simeq [6.8 \to 8.0] \times 10^{-5}\ \text{eV}^2\,, \\ \left|\Delta m^2_{\text{ATM}}\right| \simeq [2.4 \to 2.6] \times 10^{-3}\ \text{eV}^2\,; \end{cases}$

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



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

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

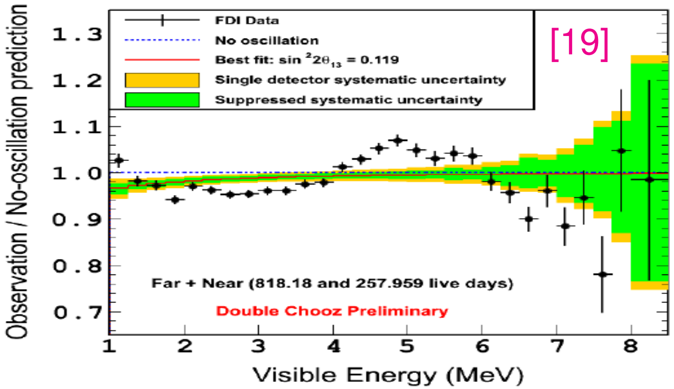
[17] G. Mention *et al.*, Phys. Rev. **D83** (2011) 073006 [`arXiv:1101.2755`].

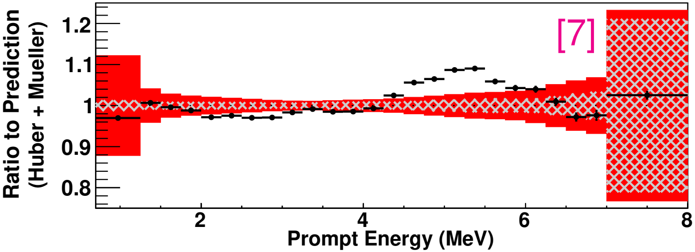
II. Sterile neutrino models

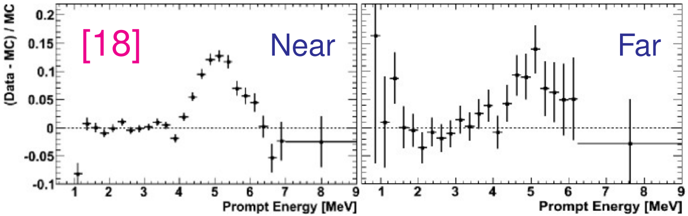
$\bar{\nu}_e$ disapp: 5 MeV excess

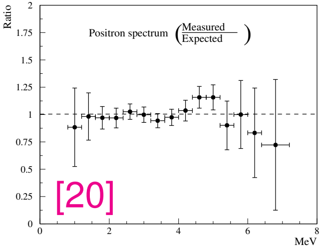
- Neutrino 2014: RENO [18] reported an excess of events around 5 MeV;
- excess (not deficit) & independent of L ⇒ **flux feature**, not ~~**sterile oscillations**~~;
- seen by Daya-Bay [7], Dbl-Chooz [19], and many others (also old Chooz [20]);

⇒ reactor fluxes **not** properly understood.









---

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

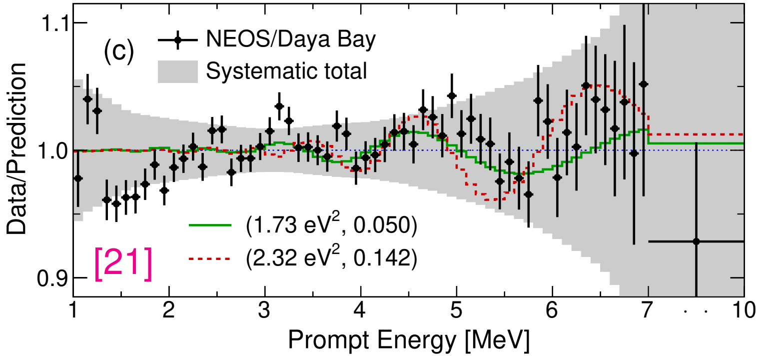
[18] S.H Seo [RENO], talk at Neutrino 2014, Boston, USA, June 2-7, 2014.

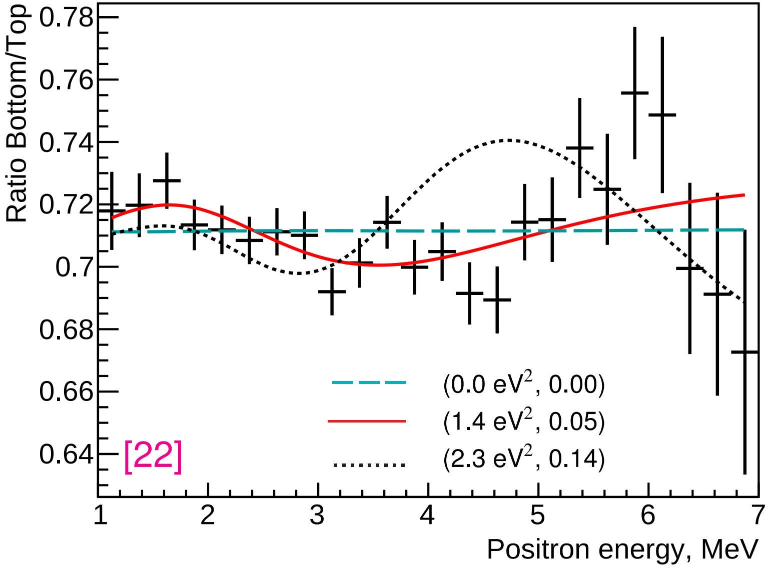
[19] I.G. Botella [Double-Chooz], talk at EPS 2017, Venice, Italy.

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

NEOS and DANSS results

- Both detectors have measured reactor neutrinos at very short baseline:
  - NEOS [21]: 24 m;
  - DANSS [22]: 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.





---

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

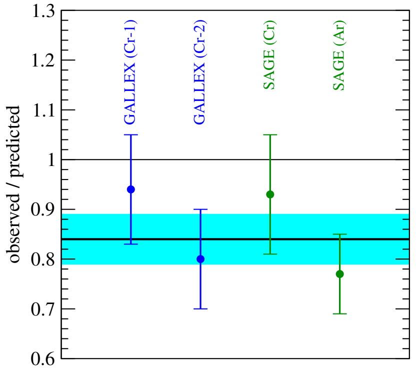
[22] I. Alekseev *et al.* [DANSS], PLB **787** (2018) 56 [`arXiv:1804.04046`].

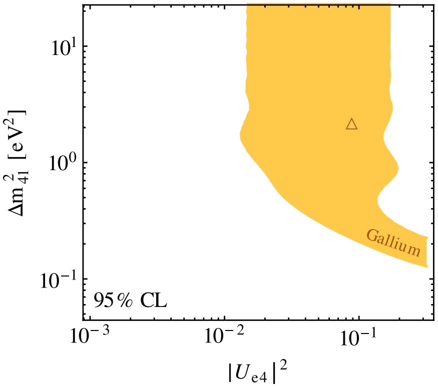
ν_e disappearance: the gallium anomaly

- The $^{71}\text{Ga} \to {}^{71}\text{Ge}$ 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:

$$\left.\begin{array}{r} \text{GALLEX:}\begin{cases} R_1(\text{Cr}) = 0.94 \pm 0.11\ [23] \\ R_2(\text{Cr}) = 0.80 \pm 0.10\ [23] \end{cases} \\ \text{SAGE:}\begin{cases} R_3(\text{Cr}) = 0.93 \pm 0.12\ [24] \\ R_4(\text{Ar}) = 0.77 \pm 0.08\ [25] \end{cases} \end{array}\right\} \Longrightarrow \boxed{0.84 \pm 0.05}$$

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





---

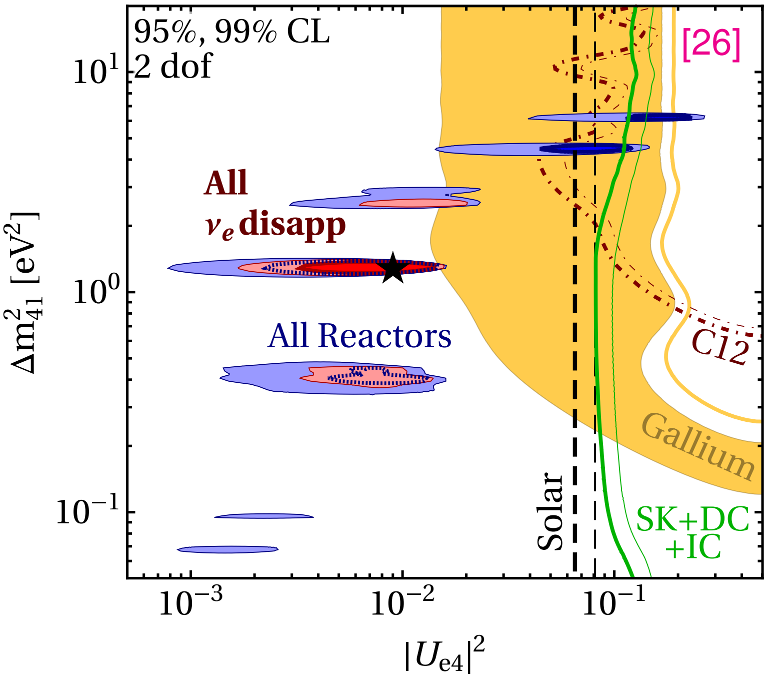
[23] F. Kaether *et al.*, Phys. Lett. **B685** (2010) 47–54 [`arXiv:1001.2731`].

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

[25] J. Abdurashitov *et al.* [SAGE], 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 [27] and LSND [28] 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 [26]:
  - small tension (2.2σ) between gallium and reactor data;
  - 3.2σ hint for sterile neutrino, dominated by DANSS + NEOS;
  - global best-fit at $\Delta m^2_{41} = 1.3$ eV^2.



---

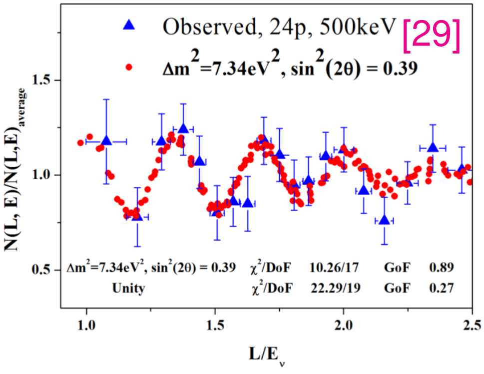
[26] M. Dentler *et al.*, JHEP **08** (2018) 010 [`arXiv:1803.10661`].

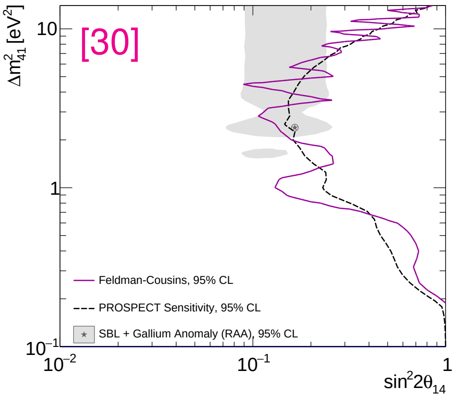
[27] B. Armbruster *et al.* [KARMEN], Phys. Rev. C **57** (1998) 3414 [`hep-ex/9801007`].

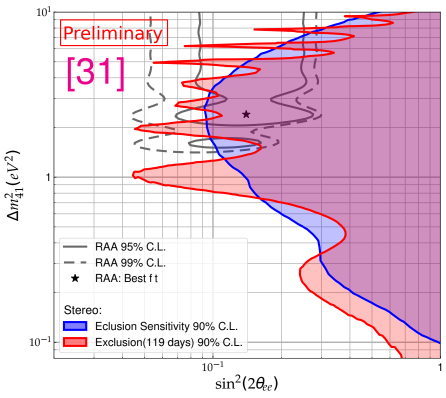
[28] L. B. Auerbach *et al.* [LSND], Phys. Rev. C **64** (2001) 065501 [`hep-ex/0105068`].

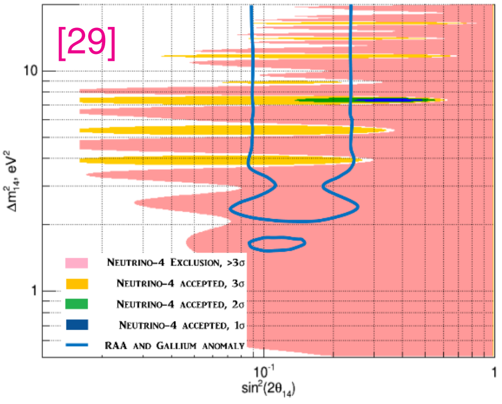
Recent short-baseline reactor data

- Oscillation signal observed by Neutrino-4 [29], pointing to $\Delta m^2_{41} \simeq 7.3\ \text{eV}^2$ and $U_{e4} \simeq 0.11$;
- in contrast, no significant hint of oscillations found in Prospect [30] or Stereo [31] data;
- still no definite solution to the reactor anomaly problem.









---

[29] A. P. Serebrov *et al.* [NEUTRINO-4], JETP Lett. **109** (2019) 213 [`arXiv:1809.10561`].

[30] J. Ashenfelter *et al.* [PROSPECT], Phys. Rev. Lett. **121** (2018) 251802 [`arXiv:1806.02784`].

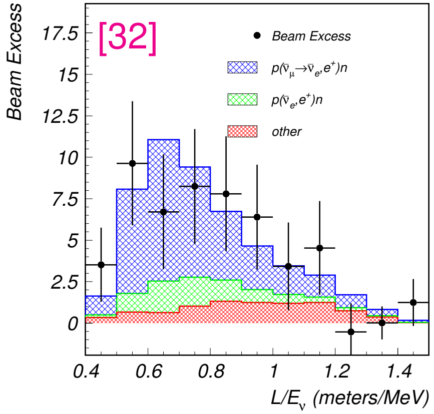
[31] L. Bernard [STEREO], `arXiv:1905.11896`.

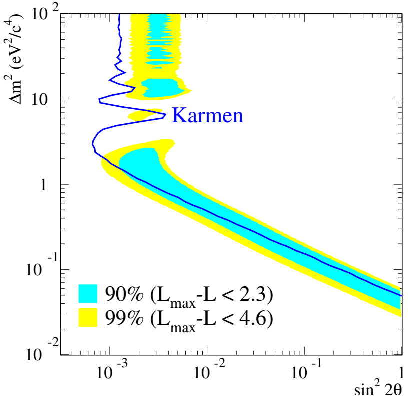
The LSND anomaly

- 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) [32];
- the Karmen collaboration did not confirm the claim, but couldn't fully exclude it either [33];
- 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.





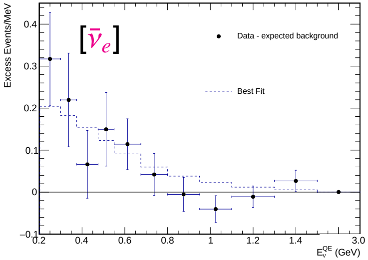
---

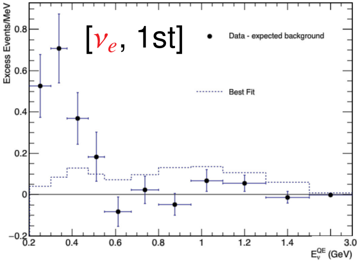
[32] A. Aguilar-Arevalo *et al.* [LSND], Phys. Rev. D **64** (2001) 112007 [`hep-ex/0104049`].

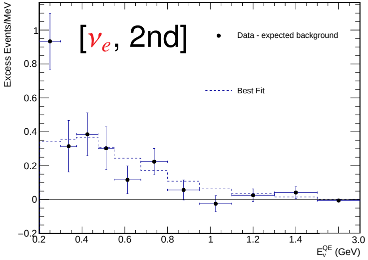
[33] B. Armbruster *et al.* [KARMEN], Phys. Rev. D **65** (2002) 112001 [`hep-ex/0203021`].

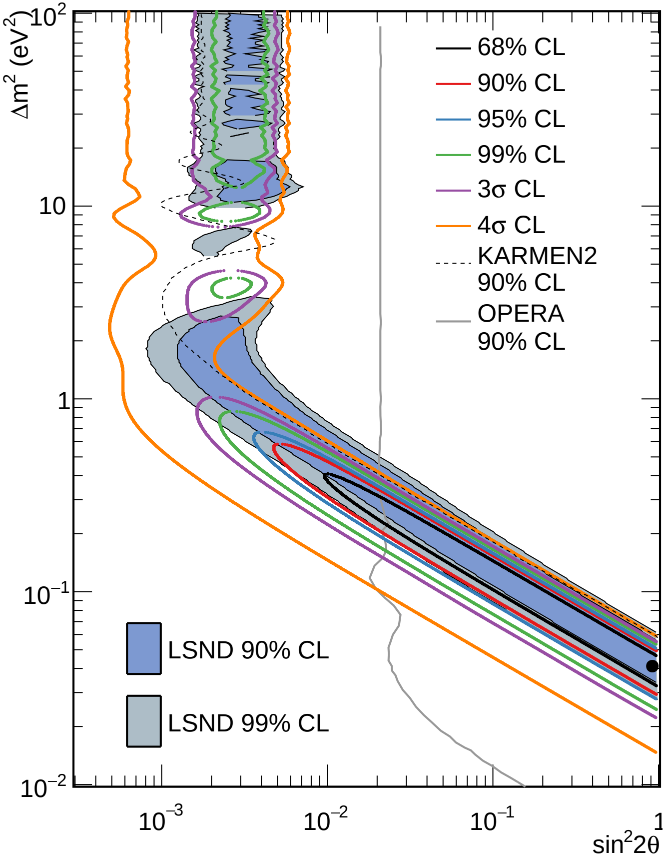
MiniBooNE combined data

- Low-energy excess in 1st half of ν_e data absent from 2nd half (except lowest bin) ⇒ 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.









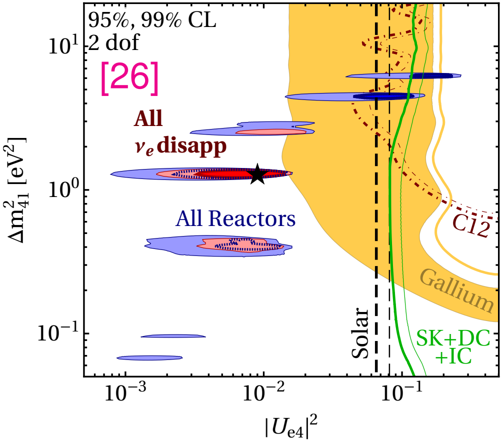
---

[34] A.A. Aguilar-Arevalo *et al.* [MiniBooNE], Phys. Rev. Lett. **121** (2018) 221801 [`arXiv:1805.12028`].

II. Sterile neutrino models

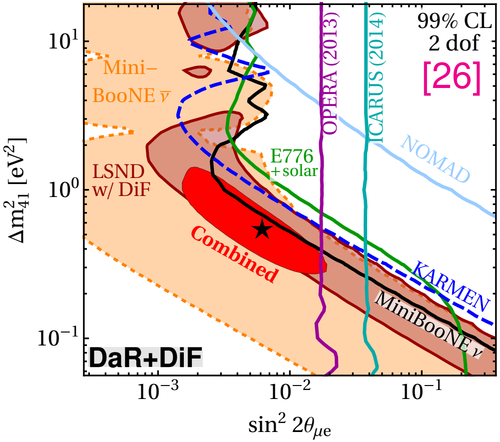
ν_e disappearance

- 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)

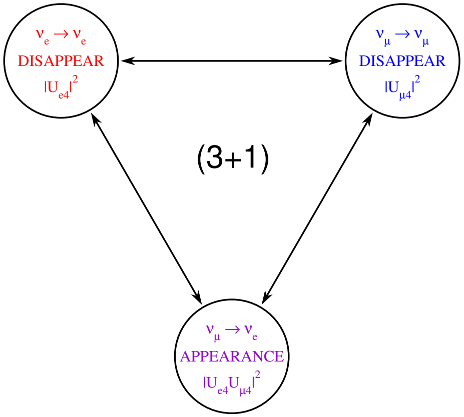


- Note: $\overset{(-)}{\nu}_e \to \overset{(-)}{\nu}_e$ and $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$ probe the same Δm^2 but a different mixing angle $\Rightarrow$ mutual comparison requires embedding them into a **general oscillation model**.

---

[26] M. Dentler *et al.*, JHEP **08** (2018) 010 [`arXiv:1803.10661`].

(3+1): appearance versus disappearance



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

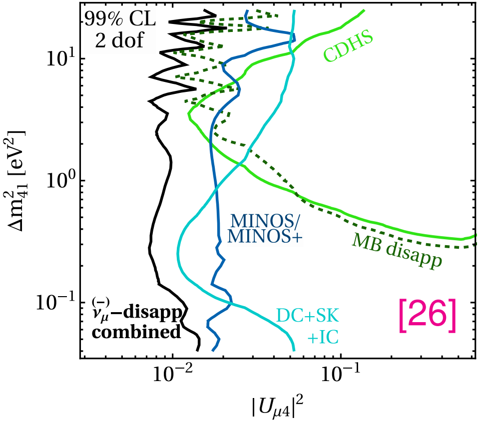
$\nu_\mu \to \nu_\mu$
DISAPPEAR
$|U_{\mu4}|^2$

(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 (ν)
  - – MiniBooNE $(\nu, \bar\nu)$ – NOνA (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...

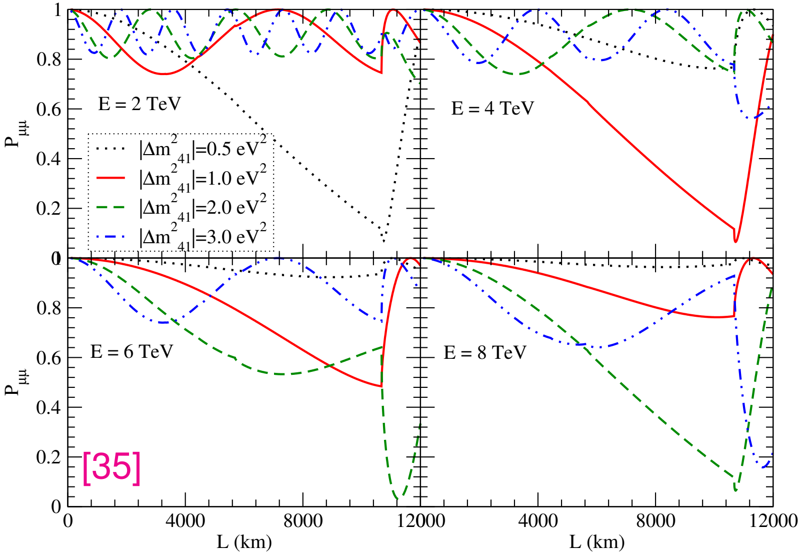
---

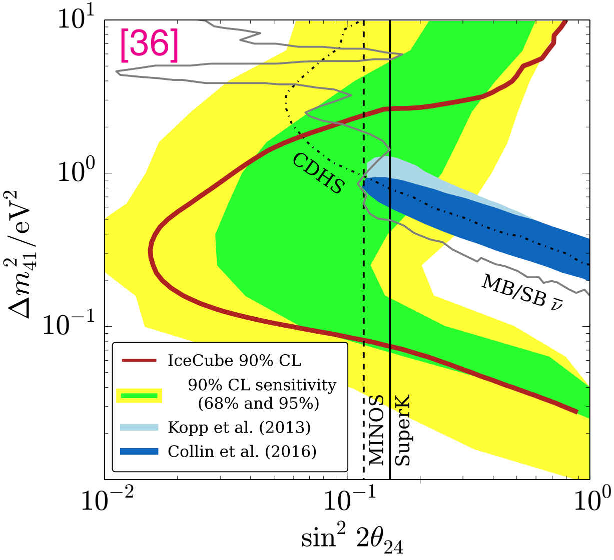
[26] M. Dentler *et al.*, JHEP **08** (2018) 010 [`arXiv:1803.10661`].

II. Sterile neutrino models

Contribution from high-energy ATM data at neutrino telescopes

- As pointed out in [35], for $\Delta m^2 \sim 1$ eV^2 and $L \sim R_\oplus$ there are strong deviations of $P_{\mu\mu}$ from 1 for $E \sim \mathcal{O}(\text{TeV}) \Rightarrow$ precisely the range covered by IceCUBE atm data;
- non-observation of such effect in [36] implies a direct bound on sterile ν.





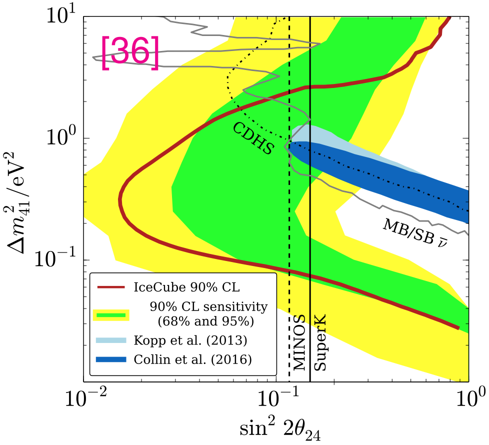
---

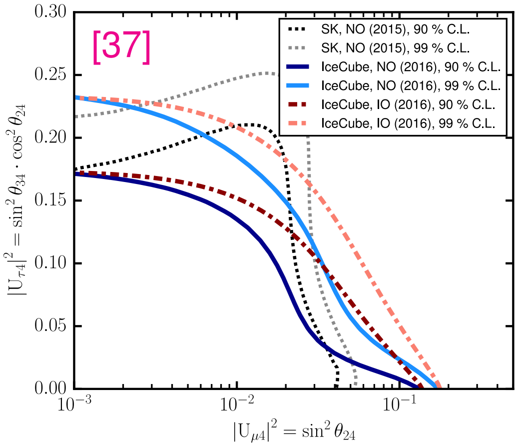
[35] S. Choubey, JHEP **12** (2007) 014 [`arXiv:0709.1937`].

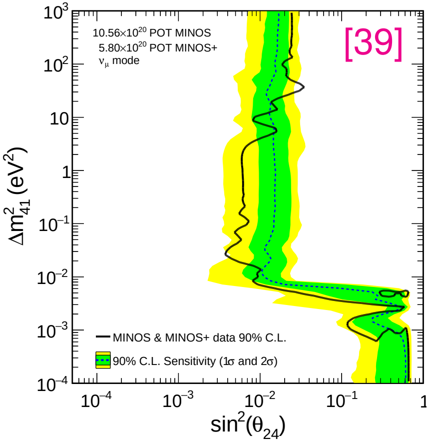
[36] M.G. Aartsen *et al.* [ICECUBE], Phys. Rev. Lett. **117** (2016) 071801 [`arXiv:1605.01990`].

ν_μ disappearance: recent atmospheric and SBL data

- new IceCube [36] and DeepCore [37] atmos. data probe ν_μ mixing with heavy state;
- sterile neutrino oscillations also studied by NOνA using neutral-current data [38];
- recent MINOS/MINOS+ analysis [39] improves bound on ν_μ disappearance.







---

[36] M.G. Aartsen *et al.* [ICECUBE], Phys. Rev. Lett. **117** (2016) 071801 [`arXiv:1605.01990`].

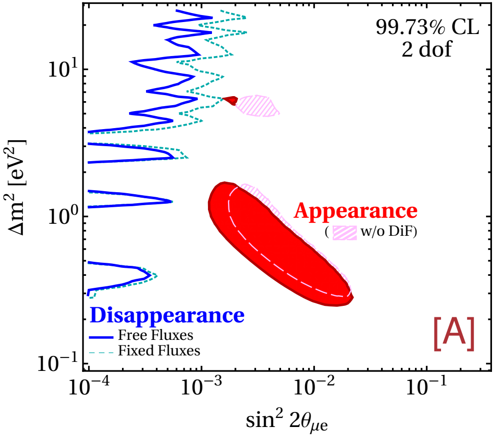
[37] M.G. Aartsen *et al.* [DEEPCORE], Phys. Rev. D **95** (2017) 112002 [`arXiv:1702.05160`].

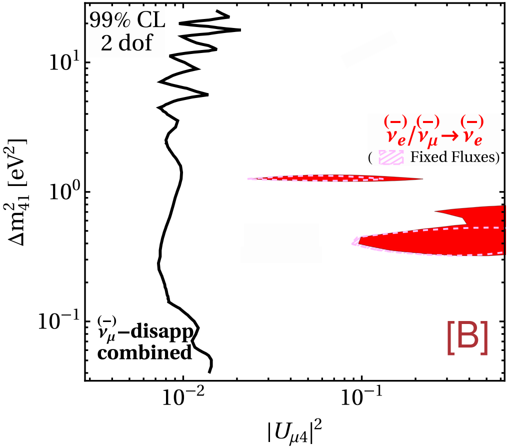
[38] P. Adamson *et al.* [NOvA], Phys. Rev. D **96** (2017) 072006 [`arXiv:1706.04592`].

[39] P. Adamson *et al.* [MINOS], Phys. Rev. Lett. **122** (2019) 091803 [`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: $\chi^2_{\text{PG}}/\text{dof} = 29.6/2 \Rightarrow \text{PG} = 3.7 \times 10^{-7}$ [26];
- 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 [40]. Full global fit in 2001 [41] cornered (3+1) models. No conceptual change since then...





---

[26] M. Dentler *et al.*, JHEP **08** (2018) 010 [`arXiv:1803.10661`].

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

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

Non-standard neutrino interactions: formalism

- Let us extend the SM by a NC-like **non-standard** neutrino-matter term:

$$\mathcal{L}_{\text{NSI}} = -2\sqrt{2}G_F \sum_{f,P,\alpha,\beta} \varepsilon_{\alpha\beta}^{fP} \, [\bar{\nu}_\alpha \gamma_\mu P_L \nu_\beta][\bar{f}\gamma^\mu P f] \, ;$$

where $P \in \{P_L, P_R\}$ and $f \in \{u, d\}$ is a quark present in ordinary matter;

- let's assume that the ν flavor structure is **independent** of the charged fermion type:

$$\varepsilon_{\alpha\beta}^{fP} \equiv \varepsilon_{\alpha\beta}^{\eta} \xi^{fP} \quad \Rightarrow \quad \mathcal{L}_{\text{NSI}} = -2\sqrt{2}G_F \Big[\sum_{\alpha,\beta} \varepsilon_{\alpha\beta}^{\eta} (\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta) \Big] \Big[\sum_{fP} \xi^{fP} (\bar{f}\gamma_\mu P f) \Big] \, ;$$

- since neutrino **propagation** is only sensitive to the vector couplings:

$$\varepsilon_{\alpha\beta}^{f} \equiv \varepsilon_{\alpha\beta}^{fL} + \varepsilon_{\alpha\beta}^{fR} = \varepsilon_{\alpha\beta}^{\eta} \xi^{f} \quad \text{with} \quad \xi^{f} = \xi^{fL} + \xi^{fR} \, ;$$

- only the direction in the (ξ^u, ξ^d) plane is non-trivial for ν oscillations ⇒ define an angle:

$$\xi^u = \frac{\sqrt{5}}{3}(2\cos\eta - \sin\eta) \, , \qquad \xi^d = \frac{\sqrt{5}}{3}(2\sin\eta - \cos\eta) \, ;$$

- special cases: $\eta = \pm 90^\circ$ (n), $\eta = 0$ (p), $\eta \approx 26.6^\circ$ (u), $\eta \approx 63.4^\circ$ (d).

Non-standard interactions and 3ν oscillations

- Equation of motion: **6** (vac) + **8** (NSI-ν) + **1** (NSI-q) = **15** parameters [42]:

$$i\frac{d\vec{\nu}}{dt} = H\,\vec{\nu}; \qquad H = U_\text{vac}\cdot D_\text{vac}\cdot U_\text{vac}^\dagger \pm V_\text{mat}; \qquad D_\text{vac} = \frac{1}{2E_\nu}\,\text{diag}\left(0,\ \Delta m^2_{21},\ \Delta m^2_{31}\right);$$

$$U_\text{vac} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & 1 & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{12} & s_{12}\,e^{i\delta_\text{CP}} & 0 \\ -s_{12}\,e^{-i\delta_\text{CP}} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}, \qquad \vec{\nu} = \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix},$$

$$\mathcal{E}_{\alpha\beta}(x) \equiv \sum_f \frac{N_f(x)}{N_e(x)}\,\varepsilon^f_{\alpha\beta} = \sqrt{5}\,\varepsilon^\eta_{\alpha\beta}\left[\cos\eta + Y_n(x)\sin\eta\right], \qquad Y_n(x) \equiv \frac{N_n(x)}{N_e(x)},$$

$$V_\text{mat} \equiv V_\text{SM} + V_\text{NSI} = \sqrt{2}G_F N_e(x) \begin{pmatrix} 1 + \mathcal{E}_{ee}(x) & \mathcal{E}_{e\mu}(x) & \mathcal{E}_{e\tau}(x) \\ \mathcal{E}^\star_{e\mu}(x) & \mathcal{E}_{\mu\mu}(x) & \mathcal{E}_{\mu\tau}(x) \\ \mathcal{E}^\star_{e\tau}(x) & \mathcal{E}^\star_{\mu\tau}(x) & \mathcal{E}_{\tau\tau}(x) \end{pmatrix};$$

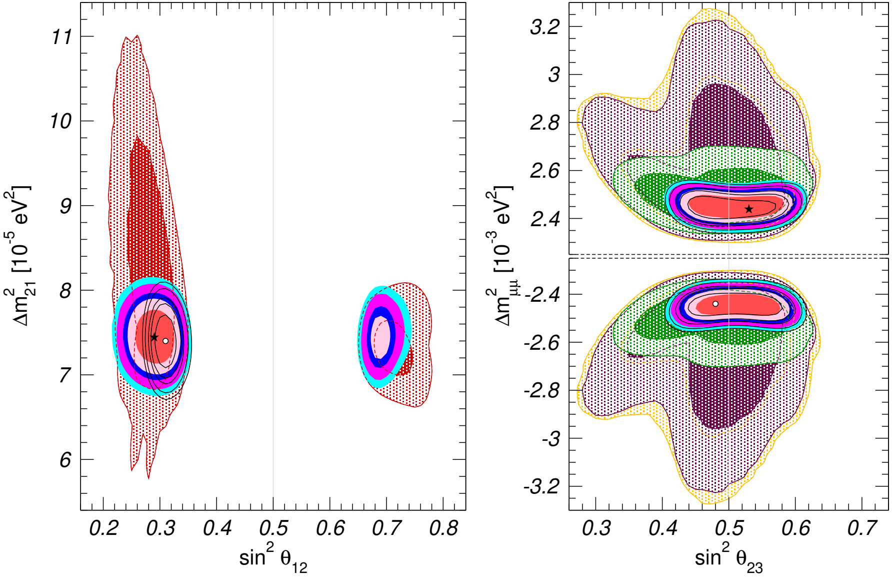
- too much parameters ⇒ assume CP-cons. (always) & set $\Delta m^2_{21} = 0$ (in ATM+LBL);
- in Earth matter, $Y_n(x) \to Y_n^\oplus \approx 1.051$, hence $\mathcal{E}_{\alpha\beta}(x) \to \varepsilon^\oplus_{\alpha\beta}$ becomes an effective param.

---

[42] I. Esteban *et al.*, JHEP **08** (2018) 180 [`arXiv:1805.04530`].

Impact of NSI on the oscillation parameters

- Analysis of solar + KamLAND data shows strong deterioration of the precision on Δm^2_{21} and θ_{12}. In addition, a new region with $\theta_{12} > 45°$ (LMA-D) appear [43];
- a similar worsening appears in ATM + LBL-dis + IceCUBE + MBL-rea + LBL-app analysis;
- synergies between solar and atmospheric sectors allow to recover the SM accuracy on most parameters (except θ_{12});
- notice that the LMA-D solution persists also in the global fit;
- high-energy atmos. IceCUBE data have no sensitivity to oscillations ($P_{\mu\mu} \propto 1/E^2$), hence they contribute little.

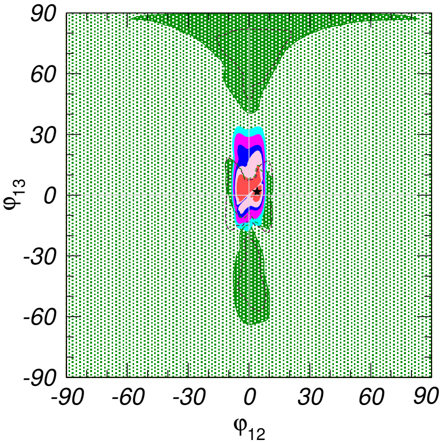


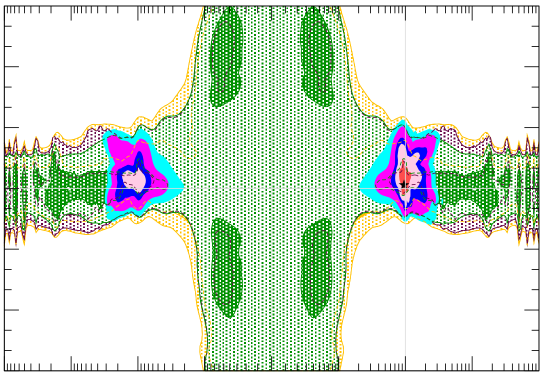
---

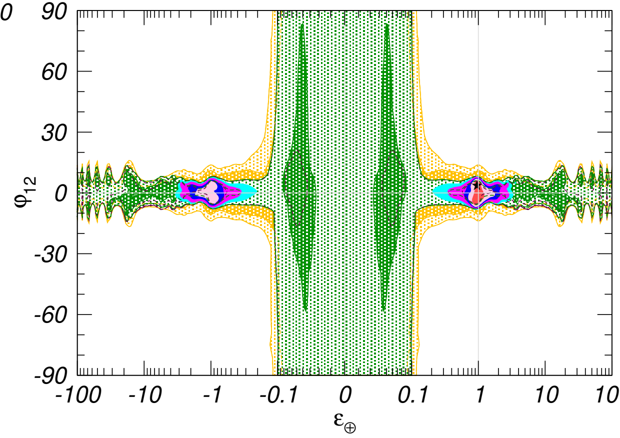
[43] O.G. Miranda, M.A. Tortola, J.W.F. Valle, JHEP **10** (2006) 008 [hep-ph/0406280].

Determination of the NSI parameters

- Further simplification: assume $\varepsilon^{\oplus}_{\alpha\beta}$ has two degenerate eigenvalues $\Rightarrow$ parametrize in terms of $(\varepsilon_{\oplus}, \varphi_{12}, \varphi_{13})$;
- adding IceCUBE data enhance ATM + LBL-dis bounds for $\varepsilon_{\oplus} \lesssim 2$;
- solar + KamLAND required for finite regions.





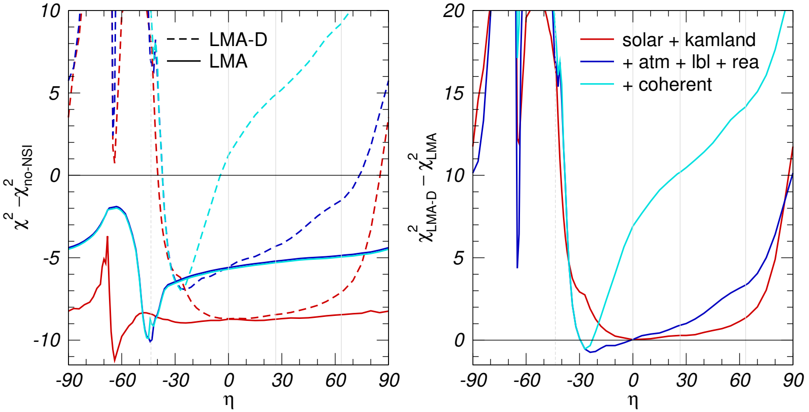


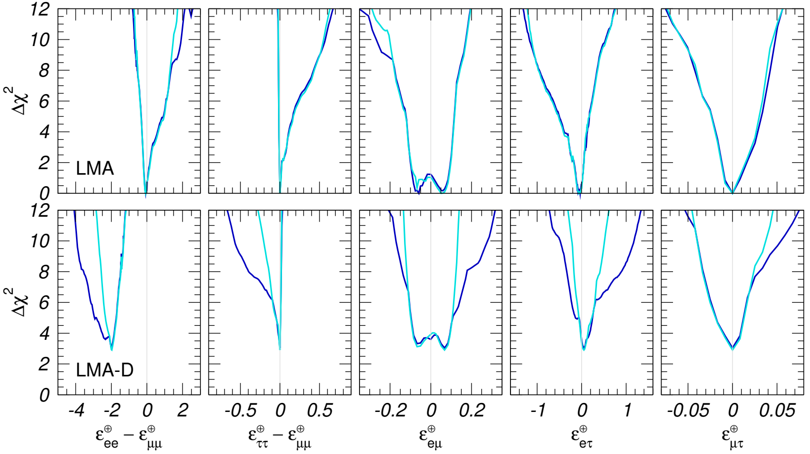
$$
\begin{aligned}
\varepsilon^{\oplus}_{ee} - \varepsilon^{\oplus}_{\mu\mu} &= \varepsilon_{\oplus}\,(\cos^2\varphi_{12} - \sin^2\varphi_{12})\cos^2\varphi_{13} - 1\,, \\
\varepsilon^{\oplus}_{\tau\tau} - \varepsilon^{\oplus}_{\mu\mu} &= \varepsilon_{\oplus}\,(\sin^2\varphi_{13} - \sin^2\varphi_{12}\,\cos^2\varphi_{13})\,, \\
\varepsilon^{\oplus}_{e\mu} &= -\varepsilon_{\oplus}\,\cos\varphi_{12}\,\sin\varphi_{12}\,\cos^2\varphi_{13}\,, \\
\varepsilon^{\oplus}_{e\tau} &= -\varepsilon_{\oplus}\,\cos\varphi_{12}\,\cos\varphi_{13}\,\sin\varphi_{13}\,, \\
\varepsilon^{\oplus}_{\mu\tau} &= \varepsilon_{\oplus}\,\sin\varphi_{12}\,\cos\varphi_{13}\,\sin\varphi_{13}\,.
\end{aligned}
$$

General NSI bounds

- Inclusion of Coherent [44] data rules out LMA-D for NSI with u, d, or p, but **not** in the general case;
- unlike oscillation data, Coherent is sensitive to $\varepsilon_{ee}^{\eta} + \varepsilon_{\mu\mu}^{\eta} + \varepsilon_{\tau\tau}^{\eta}$;
- general 2σ bounds:

OSC			+COHERENT		
	LMA	LMA $\oplus$ LMA-D		LMA	LMA $\oplus$ LMA-D
$\varepsilon_{ee}^{u} - \varepsilon_{\mu\mu}^{u}$	$[-0.020, +0.456]$	$\oplus[-1.192, -0.802]$	ε_{ee}^{u}	$[-0.008, +0.618]$	$[-0.008, +0.618]$
$\varepsilon_{\tau\tau}^{u} - \varepsilon_{\mu\mu}^{u}$	$[-0.005, +0.130]$	$[-0.152, +0.130]$	$\varepsilon_{\mu\mu}^{u}$	$[-0.111, +0.402]$	$[-0.111, +0.402]$
			$\varepsilon_{\tau\tau}^{u}$	$[-0.110, +0.404]$	$[-0.110, +0.404]$
$\varepsilon_{e\mu}^{u}$	$[-0.060, +0.049]$	$[-0.060, +0.067]$	$\varepsilon_{e\mu}^{u}$	$[-0.060, +0.049]$	$[-0.060, +0.049]$
$\varepsilon_{e\tau}^{u}$	$[-0.292, +0.119]$	$[-0.292, +0.336]$	$\varepsilon_{e\tau}^{u}$	$[-0.248, +0.116]$	$[-0.248, +0.116]$
$\varepsilon_{\mu\tau}^{u}$	$[-0.013, +0.010]$	$[-0.013, +0.014]$	$\varepsilon_{\mu\tau}^{u}$	$[-0.012, +0.009]$	$[-0.012, +0.009]$
$\varepsilon_{ee}^{d} - \varepsilon_{\mu\mu}^{d}$	$[-0.027, +0.474]$	$\oplus[-1.232, -1.111]$	ε_{ee}^{d}	$[-0.012, +0.565]$	$[-0.012, +0.565]$
$\varepsilon_{\tau\tau}^{d} - \varepsilon_{\mu\mu}^{d}$	$[-0.005, +0.095]$	$[-0.013, +0.095]$	$\varepsilon_{\mu\mu}^{d}$	$[-0.103, +0.361]$	$[-0.103, +0.361]$
			$\varepsilon_{\tau\tau}^{d}$	$[-0.102, +0.361]$	$[-0.102, +0.361]$
$\varepsilon_{e\mu}^{d}$	$[-0.061, +0.049]$	$[-0.061, +0.073]$	$\varepsilon_{e\mu}^{d}$	$[-0.058, +0.049]$	$[-0.058, +0.049]$
$\varepsilon_{e\tau}^{d}$	$[-0.247, +0.119]$	$[-0.247, +0.119]$	$\varepsilon_{e\tau}^{d}$	$[-0.206, +0.110]$	$[-0.206, +0.110]$
$\varepsilon_{\mu\tau}^{d}$	$[-0.012, +0.009]$	$[-0.012, +0.009]$	$\varepsilon_{\mu\tau}^{d}$	$[-0.011, +0.009]$	$[-0.011, +0.009]$
$\varepsilon_{ee}^{p} - \varepsilon_{\mu\mu}^{p}$	$[-0.041, +1.312]$	$\oplus[-3.327, -1.958]$	ε_{ee}^{p}	$[-0.010, +2.039]$	$[-0.010, +2.039]$
$\varepsilon_{\tau\tau}^{p} - \varepsilon_{\mu\mu}^{p}$	$[-0.015, +0.426]$	$[-0.424, +0.426]$	$\varepsilon_{\mu\mu}^{p}$	$[-0.364, +1.387]$	$[-0.364, +1.387]$
			$\varepsilon_{\tau\tau}^{p}$	$[-0.350, +1.400]$	$[-0.350, +1.400]$
$\varepsilon_{e\mu}^{p}$	$[-0.178, +0.147]$	$[-0.178, +0.178]$	$\varepsilon_{e\mu}^{p}$	$[-0.179, +0.146]$	$[-0.179, +0.146]$
$\varepsilon_{e\tau}^{p}$	$[-0.954, +0.356]$	$[-0.954, +0.949]$	$\varepsilon_{e\tau}^{p}$	$[-0.860, +0.350]$	$[-0.860, +0.350]$
$\varepsilon_{\mu\tau}^{p}$	$[-0.035, +0.027]$	$[-0.035, +0.035]$	$\varepsilon_{\mu\tau}^{p}$	$[-0.035, +0.028]$	$[-0.035, +0.028]$





---

[44] D. Akimov *et al.* [COHERENT], Science **357** (2017) 1123 [`arXiv:1708.01294`].

Summary

- Most of the present data from solar, atmospheric, reactor and accelerator experiments are well explained by the 3ν oscillation hypothesis. The three-neutrino scenario is nowadays well proven and **robust**;
- a few experiments (LSND, MiniBooNe, Gallium, some reactors) exhibit deviations from such "standard" 3ν scenario. Although **individually** each of them can be explained by extra sterile neutrinos, such 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;
- non-standard NC-like neutrino-matter interactions can spoil the precise determination of the oscillation parameters offered by **specific** class of experiments. However, once all the data are combined **together** the precision achieved in the 3ν scenario is recovered, except for θ_{12} where a new region (LMA-D) appears;
- present data collected by neutrino telescopes contribute in all these cases. In particular, the large statistics of high-energy $\mathcal{O}(\text{TeV})$ atmospheric data collected by IceCUBE offers a unique windows over New Physics processes (eV sterile ν, NSI, *etc.*) which is complementary to conventional "low-energy" $\mathcal{O}(\text{GeV})$ experiments.

Acknowledgements

ift Instituto de Física Teórica UAM-CSIC

UAM UNIVERSIDAD AUTONOMA DE MADRID

CSIC CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

- MINECO/FEDER-UE grant FPA2015-65929-P;
- MINECO/FEDER-UE grant FPA2016-78645-P;
- Severo Ochoa program SEV-2016-0597;
- EU grant H2020-MSCA-ITN-2015-674896 “ELUSIVES”;
- EU grant H2020-MSCA-RISE-2015-690575 “INVISIBLES-PLUS”.

FEDER Fondo Europeo de Desarrollo Regional

“Una manera de hacer Europa”

GOBIERNO DE ESPAÑA

MINISTERIO DE ECONOMÍA, INDUSTRIA Y COMPETITIVIDAD

EXCELENCIA SEVERO OCHOA