Status of the Reactor Anti-Neutrino Anomaly

Alvaro Hernandez Cabezudo

(arXiv:1709.04294)

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Karlsruher Institut für Technologie

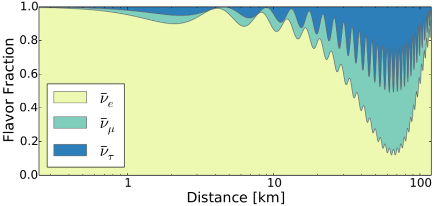
Outline

- Reactor anti-neutrinos
  - Anti-neutrino fluxes
  - what can be measured?
  - SBL experiments
- Reactor anti-neutrino anomaly
- 2 Hypothesis: Fluxes vs Sterile Neutrino
- analysis
  - Reactor data analysis
  - Global $\overline{\nu}_e \to \overline{\nu}_e$ analysis
- Conclusions

Reactor anti-neutrinos

The fuel in nuclear power plants is mainly made of
4 fission isotopes ^{235}U, ^{239}Pu, ^{238}U, ^{241}Pu $\rightarrow \overline{\nu}_e$ ($\sim$MeV)Flux.

(Given an energy)



arXiv:1503.01059

Oscillations in a 3ν framework

$$U_{PMNS} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 21} & U_{\tau 3} \end{pmatrix}$$

$$\Delta m^2_{sol} << \Delta m^2_{atm}$$

$\Rightarrow$ Osc. Prob.: $P_{\overline{\nu}_e \rightarrow \overline{\nu}_e} = 1 - 4 \sum_{i=1}^{2} \sum_{j>i}^{3} |U_{ei}|^2 \, |U_{ej}|^2 \sin^2 \left(\Delta m^2_{ij} \frac{L}{4E} \right)$

$$(L, E)\text{Regimes: } E \sim \text{MeV} \quad \begin{cases} L \sim 100\text{Km} \Rightarrow \text{sensitive to} \Delta m^2_{21} \\ L \sim 1\text{Km} \Rightarrow \text{sensitive to} \Delta m^2_{31} \simeq \Delta m^2_{32} \end{cases} \qquad (1)$$

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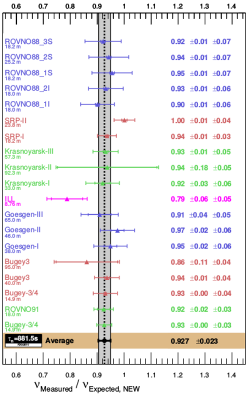

arXiv: 1204.5379

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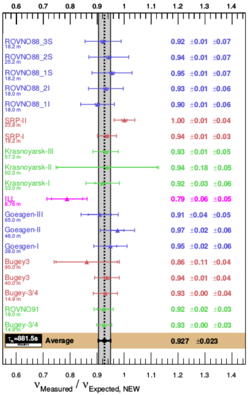

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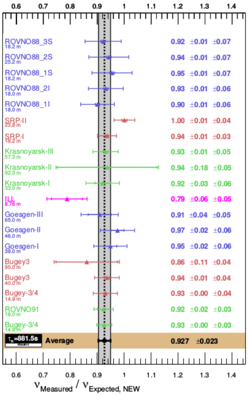
(rely on the theoretical uncertainties)

- Issues with flux predictions.
- $\Delta m^2_{new} \Rightarrow$ eV ν_4 mass eigenstate.



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Reactor anomaly

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Reactor anomaly

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3+1 scenario

New ν_4 mass eigenstate $O(\text{eV}) \Rightarrow$

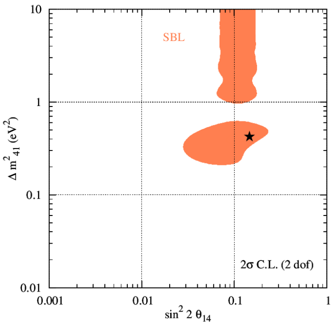
- new mass differences $\Delta m^2_{41} \simeq \Delta m^2_{42} \simeq \Delta m^2_{43}$
-

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

3+1 scenario

$$P_{\overline{\nu}_e \to \overline{\nu}_e} = 1 - 4 \sum_{i=1}^{3} \sum_{j>i}^{4} |U_{ei}|^2 \, |U_{ej}|^2 \sin^2\left(\Delta m^2_{ij} \frac{L}{4E}\right)$$

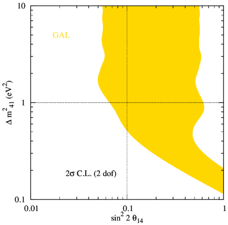
$$\underset{\mathrm{SBL}}{\simeq} 1 - \sin^2 2\theta_{14} \sin^2\left(\Delta m^2_{41} \frac{L}{4E}\right)$$



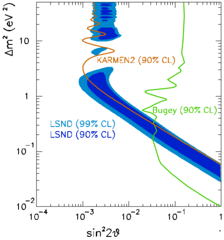
Reactor anomaly

The sterile neutrino hypothesis is supported by other independent results:

- Gallium anomaly:
  - GALLEX and SAGE.
  - measuring in the channel $\nu_e \longrightarrow \nu_e$.
  - sensitive to Δm^2_{new} and $|U_{e4}|^2$.



- LSND anomaly:
  - first one discovered.
  - measuring in the channel $\bar{\nu}_\mu \longrightarrow \bar{\nu}_e$.
  - sensitive to Δm^2_{new} and the product $U_{\mu 4} U_{e4}$.



arXiv: 1607.05378

eV sterile neutrino seems very promising

Fluxes vs Sterile Neutrino

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Are the flux predictions reliable?

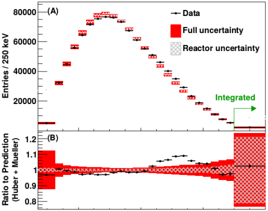
Fluxes vs Sterile Neutrino

In modern reactor experiments

Measurements of the $\overline{\nu}_e$ spectrum show an unexpected bump at $\sim$ 5MeV

NEOS spect.

Daya Bay spect.



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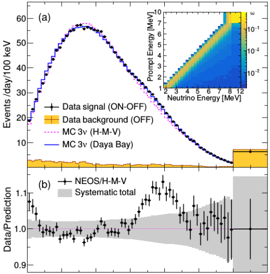
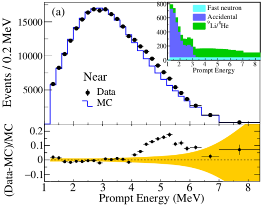


arXiv: 1610.05134

RENO spect.



arXiv: 1610.01326

Something wrong with the flux predictions?

Not very important when doing the ν_s analysis but we can not rely 100% on the predictions.

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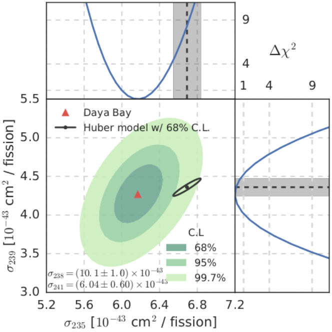

arXiv: 1704.01082

The suppression of the flux is mainly due to ^{235}U

Fluxes vs Sterile Neutrino

In arXiv:1709.04294 we quantify the preference of no oscillation compared to the ν_s oscillation hypothesis with a test statistics T. We reproduce the Daya Bay result.

- H_0: $\boldsymbol{\nu_s}$ **hypothesis** with H-M flux predictions.
- H_1: **flux free hypothesis** without ν_s.

Analysis	$\chi^2_{\text{min}}/\text{dof}$	gof	$\sin^2 2\theta_{14}^{\text{bfp}}$	$\Delta\chi^2$(no osc)
H_0, fixed fluxes $+ \nu_s$	$9.8/(8-1)$	18%	0.11	3.9
H_1, free fluxes (no ν_s)	$3.6/(8-2)$	73%		

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H_0 p-value 18% $\Rightarrow$ H_0 can not be rejected $\Rightarrow$ we proceed with the ν_s analysis.

Update to the reactor data ν_s analysis.

Based on the reactor data analysis in arXiv:1303.3011: SBL experiments, Bugey-3 (energy spectrum), KamLAND (very long baseline): "**Old**" set.

New contributions (+"Old"="**All**" set):

- Spectral information (basically flux independent)
  - NEOS ($L \sim 24$ m)
  - DANSS ($L \sim 11$ m) (preliminary data)
  - Daya Bay ($L \sim 1$ Km)
- Daya Bay flux information

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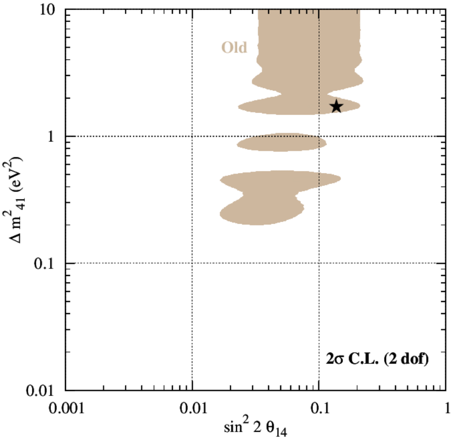
- **Flux fixed**: H-M flux predictions an uncertainties are taken at face value.
- **Flux free**: no assumption for the fluxes. Free parameters on the fit.

Flux fixed analysis



Best fit value $(\sin^2 2\theta_{14},\, \Delta m^2_{41}) = (0.12,\, 1.72)$

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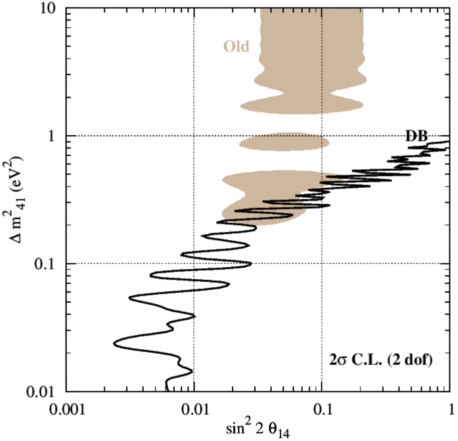

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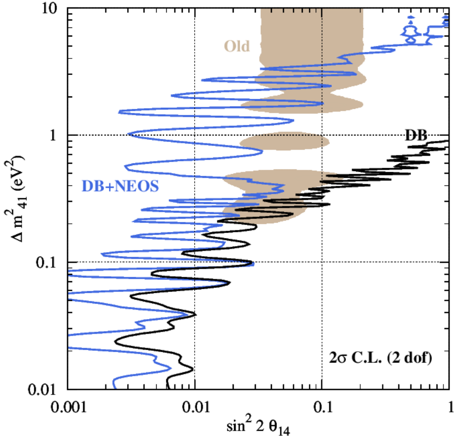

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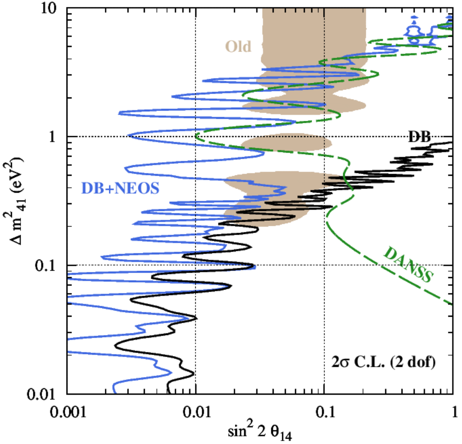

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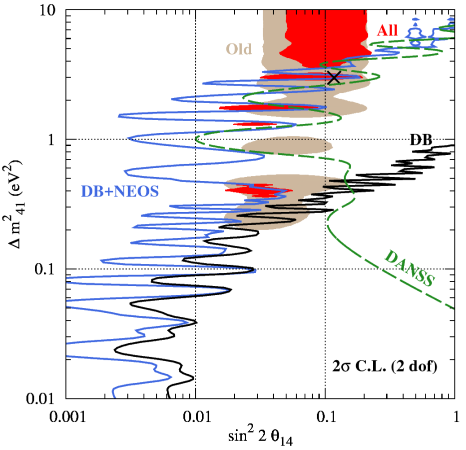

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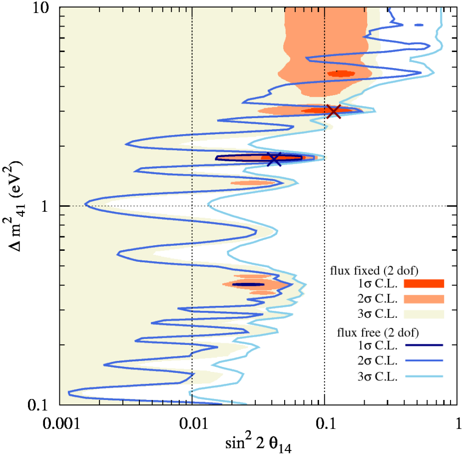
Flux fixed vs free analysis



The oscillation loses statistical significance, but the exclusion region is compatible with the flux-fixed allowed region.

Reactor data analysis

Data	Analysis	Best fit ($\sin^2 2\theta_{14}$, Δm^2_{41})	$\chi^2_{\rm min}$/dof	$\Delta\chi^2$(no osc.)	p-value/$\#\sigma$ (no osc.)
React-old	flux-fixed	(0.12, 1.72)	52.1/68	9.4	$0.0091/2.6\sigma$
React-old	flux-free	(0.06, 0.46)	51.6/66	2.8	$0.25/1.2\sigma$
React-all	flux-fixed	(0.12, 2.99)	196.0/236	11.3	$0.0036/2.9\sigma$
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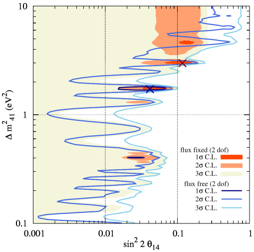

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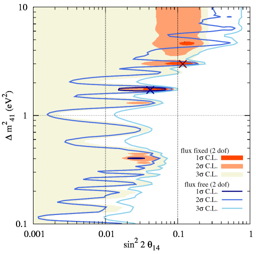
Test statistics $T = \chi^2_{\text{min}}(H_0) - \chi^2_{\text{min}}(H_1)$

$T_{\text{all}} = 2.9$; $(T_{\text{DB}_{\text{flux}}} = 6.3)$



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Flux free, rescales

React-all data	$(\sin^2 2\theta_{14},\ \Delta m^2_{41})$	ξ_{235}	ξ_{239}	ξ_{241}	ξ_{238}
flux-free, osc(bfp)	(0.04, 1.72)	0.95	0.99	1.09	0.88
flux-free, no-osc	–	0.93	0.96	1.09	0.87

^{235}U has a larger suppression than ^{239}Pu

bfp: rescale of the fluxes is not so large

Global $\overline{\nu}_e \to \overline{\nu}_e$ analysis

Non-reactor data measuring in the channel $\overset{(-)}{\nu}_e \to \overset{(-)}{\nu}_e$ can be combined with the reactor ones.

Complementary information from:

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- $\bar{\nu}_e +^{12}\mathrm{C} \rightarrow e^- +^{12}\mathrm{N}$ experiments : LSND, KARMEN.

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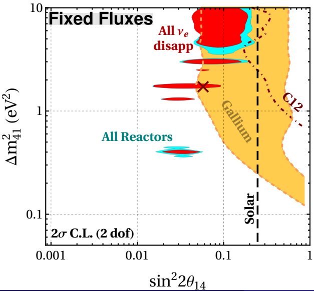

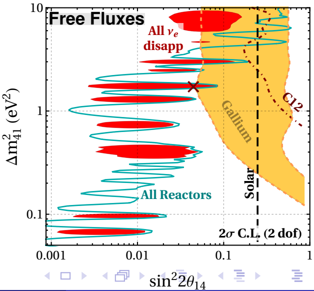

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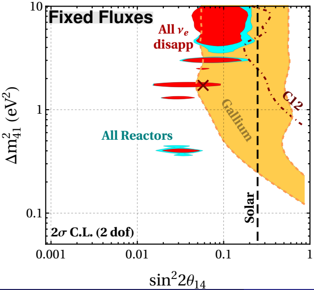
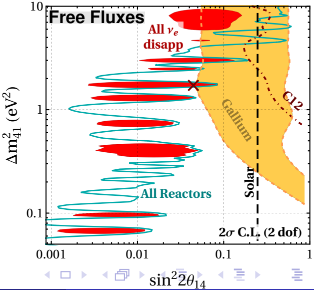
Global	flux-fixed	(0.06, 1.72)	554.3/594	11.9	0.0026/3.0σ
Global	flux-free	(0.04, 1.72)	545.2/592	7.0	0.031/2.2σ





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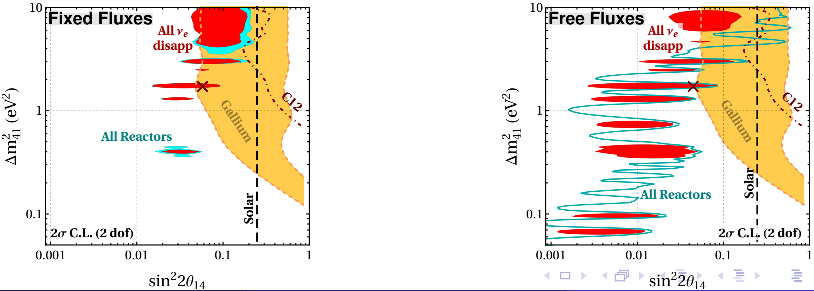
$$\text{Test statistics } T = \chi^2_{\text{min}}(H_0) - \chi^2_{\text{min}}(H_1)$$
$$T_{\text{all}} = 2.9; \; T_{\text{golbal}} = 2.1$$



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- A flux free analysis loose significance to the new oscillation. i.e. The anomaly decreases. Although it is a very conservative assumption, still there is a $\sim 2\sigma$ signal in favour of the oscillations.

Thank you for your attention!