The Reactor Anomaly at 1 Kilometer

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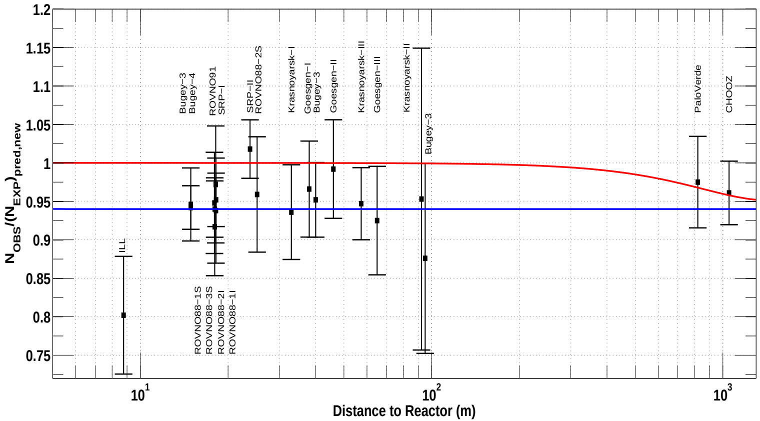
Reactor Anomaly

In 2011 two independent calculations (Mueller et al., 2011; Huber, 2011) reevaluated the expected reactor antineutrino flux upwards by about 3.5% leading to a 2.5σ inconsistency with fluxes observed at very short baselines (Mention et al., 2011):



Other evidence for a disappearance anomaly

This disappearance is consistent with the gallium anomaly, which is a deficit of neutrinos measured when ^{51}Cr and ^{37}Ar radioactive sources are placed near a detector:

According to a recent analysis (Giunti and Leveder, 2011) the GALLEX (Anselmann et al., 1995; Hampel et al., 1998) and SAGE (Abdurashitov et al., 1996; 1998; 2005; 2009) experiments using an updated calibration (Kaether et al., 2010) report an event deficit of

$$14\% \pm 5\%.$$

Electron neutrino appearance at LSND and MiniBooNE also suggest such an anomaly if it results from sterile neutrino oscillations.

The reactor anomaly and θ_{13}

At distances above a few hundred meters 1-3 neutrino oscillation is large enough to be measured.

Below 5 km 1-2 oscillation has never been measured and so, for now, can be ignored and 1-3 and 2-3 oscillation are sufficiently in phase to be combined.

With these approximations, the electron (anti)neutrino survival probability at a distance L is

$$P = (1-a)\left[1 - \sin^2(2\theta_{13}) \int sin^2\left(\frac{\Delta m^2_{13} L}{4E}\right)\rho(E)dE\right]$$

$\rho(E)$ is the normalized energy spectrum.

At a fixed L there is a degeneracy between disappearance due to 1-3 oscillations θ_{13} and the anomalous disappearance a.

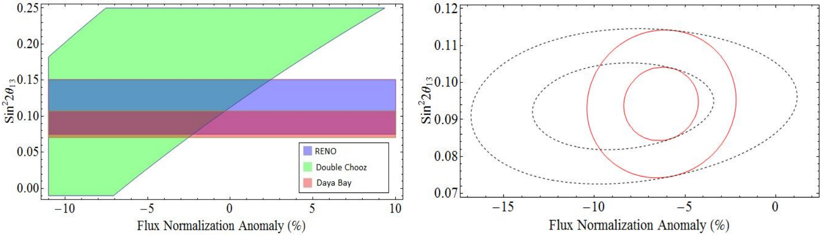
Breaking the degeneracy

The degeneracy of θ_{13} and the anomalous disappearance a prevents Palo Verde, Chooz and Double Chooz from determining either.

The degeneracy has been broken by Daya Bay's (An et al., 2012;Dwyer, 2012) and RENO's (Ahn et al., 2012) measurements of θ_{13}, which are independent of the overall flux normalization as only differences between fluxes at various detectors are used (Mikaelyan and Sinev, 2000).

Assuming that the anomaly saturates to a constant disappearance a at short distances, a 2-dimensional fit of 1 km baseline reactor experiments may simultaneously determine a and θ_{13}.

2 Parameter fit

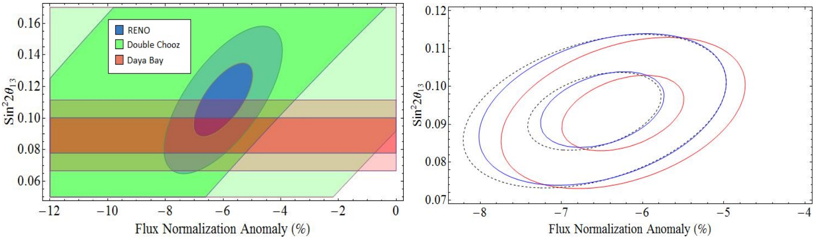


In the left panel Double Chooz corresponds to a stripe reflecting the degeneracy between θ_{13} and the anomaly.

The Double Chooz collaboration resolved this degeneracy by asserting that the anomaly is equal to that measured by Bugey4.

In the right panel, the blue dotted curves are the 1 and 2 σ allowed regions for the 3 experiments and the purple curve includes the very short baseline experiments.

2 Parameter fit with RENO's preliminary flux normalization



In the right panel, the dotted curves are the 1 and 2 σ confidence regions for the 3 experiments including the preliminary flux normalization announced by RENO at νTURN. The red curve includes the very short baseline experiments and the blue curve includes Chooz, Palo Verde and the gallium experiments.

As one can see, the reactor anomaly measured at RENO, if confirmed, would be the strongest evidence yet for an anomaly. Normalization results from Daya Bay may be even more significant.

Possible causes of the anomaly

Very short baseline and 1 km baseline reactor experiments seem consistent with a baseline-independent anomalous neutrino deficit.

There are two popular explanations for such a deficit:

I) The 2011 theoretical flux calculations overestimate the flux normalization by 2-3 times their reported error.

II) The electron neutrinos oscillate to a different flavor

We will turn our attention to the second possibility.

3+1 Models

The anomaly at very short baselines implies that the neutrino mass squared difference is larger than the atmospheric or solar mass difference, therefore this must be a fourth generation.

LEP's Z width measurement then implies that the fourth generation must either be heavier than 45 GeV (heavier than reactor neutrino energies) or else sterile.

MiniBooNE suggested that sterile neutrino mixing violates CP (Aguilar-Arevalo et al., 2007; 2009; 2010) which, in the absence of unconventional matter effects, implies at least 2 sterile neutrinos.

With 52% more flux (Zimmerman, 2012) this evidence for CP violation has essentially disappeared.

As a result (3+1) models may simultaneously explain the gallium and reactor deficits and the LSND/MiniBooNE appearance.

Sterile neutrinos and big bang nucleosynthesis

Are sterile neutrinos compatible with standard cosmologies?

Every species of sterile neutrino with mass well below 1 MeV adds energy $\propto T^4$ to the universe during big bang nucleosynthesis (BBN).

This increases the total density ρ and so, due to the Friedmann equation $H^2 \sim \rho$, increases the Hubble parameter, decreasing the time before BBN.

This means that less neutrons will have decayed before BBN and so they are trapped in helium nucleii, increasing the primordial helium abundance.

BBN bounds on the number of extra neutrino flavors

Recent studies of helium in metal poor H II regions have revised this abundance upwards and better addressed systematic errors:

For example Izotov and Thuan, 2010 have found that between 0 and 1.6 additional neutrino flavors are compatible at 2σ.

Therefore the (3+2) models favored by MiniBooNE until last year are excluded at 2.5σ while the (3+1) models favored by MiniBooNE this year are also favored by BBN.

The primordial energy contribution of light flavors also makes matter-radiation equality occur later, changing the relative heights of the 1st and 3rd acoustic peaks of the CMB which are well measured by WMAP7 (Larson et al., 2011). This is compatible with (3+2) models at about 1 σ but also prefers (3+1).

Massive sterile neutrinos

A flavor of sterile neutrinos easily satisfies cosmological bounds, it is even *preferred*.

Massive neutrinos are more difficult to reconcile with cosmology.

How massive do the sterile neutrinos need to be?

The reactor anomaly is dominated by neutrinos at energies below 5 MeV and baselines above 15 meters.

For such an effect it suffices to have sterile neutrino masses of order 0.5 eV, which is more or less compatible with cosmological bounds.

However such a light neutrino cannot explain the gallium anomaly (Giunti and Laveder, 2011) and provides a poor fit to the LSND/MiniBooNE anomaly.

These prefer a sterile neutrino mass of at least 0.8-1 eV.

Massive neutrinos and large scale structure formation

If sterile neutrinos explain any of these anomalies then the corresponding mixing angles must be at least of order 5 degrees.

This implies that the sterile neutrinos will have been in equilibrium with the cosmological plasma when its temperature was a few MeV (Hannestad, Tamborra and Tram, 2012).

This allows a determination of the temperature and so velocity of sterile neutrinos at any time.

Sterile neutrinos hardly interact and so they cannot be concentrated into a region smaller than about the integral of their velocity over history, the free streaming length.

Together with the backreaction of the neutrinos on dark matter, this effect can halve large scale structure formation at scales beneath the free streaming length.

The dark matter fraction

By increasing the dark matter fraction one can increase large scale structure (LSS) formation on the smallest scales, countering the effects of free streaming caused by massive neutrinos.

A higher dark matter fraction also moves back matter-radiation equality, countering the effect of the extra radiation from a sterile neutrino:

$$z_{eq} = -1 + \frac{\Omega_m}{\Omega_\gamma (1 + 0.227 N_{eff})}$$

Therefore a massive, sterile neutrino can be consistent with CMB and LSS bounds if the dark matter density is increased.

But this increase in the dark matter density must satisfy other bounds ...

Type Ia supernova and the dark matter density

The low redshift Hubble parameter is

$$H = \sqrt{\frac{8\pi G_N \rho}{3}} = H_0 \sqrt{\Omega_m (1+z)^3 + \Omega_\Lambda (1+z)^{3+3w}}$$

Keeping H_0 fixed, a higher value of Ω_m can be compensated by a lower value of w.

The luminosity distance to a supernova at fixed redshift z_0 is entirely determined by $H(z)$ at $0 < z < z_0$.

Summary: Higher neutrino mass implies a higher Ω_m and so the best fit to redshifts and brightnesses of any standard candle leads to a *more negative* w.

Baryon acoustic oscillations vs Supernova

An increase in Ω_m also increases the Hubble parameter between matter-radiation equality and recombination.

As a result the sound horizon at recombination will be smaller, leading to a smaller BAO length scale.

This can be compensated if the galaxies at fixed redshift z_0 observed in LSS surveys are moved closer, corresponding to a larger Hubble parameter at $0 < z < z_0$, which can be achieved for example with a higher value of w.

Supernova data required the Hubble parameter at small z to remain unchanged, thus changing Ω_m leads to tension between supernova and BAO constraints.

While supernova pull down w, BAO prefers a higher value of w.

MCMC Analysis

We used a modified CosmoMC to confront a varying EOS

$$w(a) = w_0 + w_a(1 - a)$$

with 7-year WMAP temperature and polarization power spectra (Komatsu et al., 2011), Union2.1 supernova data (Suzuki et al., 2012), LSS from the SDSS data release 7 and 2dFGRS (Percival et al, 2007;2010) and H_0 measured by the Hubble space telescope (Riess et al., 2011).

Neutrino mass compatibility with time-dependent w

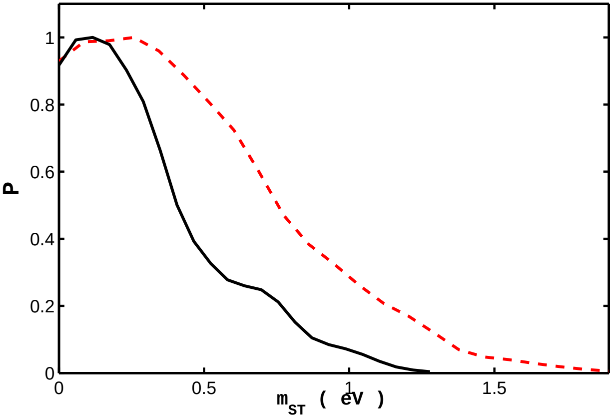


Figure: Frequentist probability distribution of the sterile neutrino mass. The black solid line is given by fitting with the ΛCDM model, while the red dashed line is obtained using a time evolving dark energy model.

Best fit EOS parameters

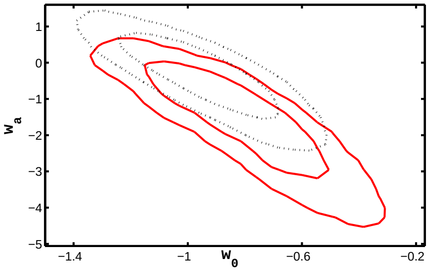


Figure: 2-dimensional cross correlation constraints on w_0 and w_a. The red solid lines and black dotted lines are the 1 and 2σ compatibility regions with and without a single 1 eV sterile neutrino flavor respectively.

The equation of state at $z = 0$ is $w_0 > -1$, satisfying BAO constraints, but at $z > 1$, $w < -1$, satisfying SN Ia constraints.
This is because, unlike Giusarma et al., 2012 we have used the Union2.1 supernova data set, which extends to much higher redshift than current LSS surveys. - can be ruled out by EUCLID

Environmentally-dependent neutrino mass model

Time dependent dark energy of state models may well be eliminated by the friction between high w BAO fits and low w supernova fits, once large scale structure surveys extend out to the same high redshifts as supernova surveys.

A very different explanation of the anomalies, *which is even easier to rule out*, is a model in which the sterile neutrino mass is proportional to the background density.

These anomalies can be satisfied if the mass per unit density is at least 1 $eV/(gm/cm^3)$.

Cosmological constraints would be avoided as the background density after BBN is much lower than that of the Earth.

It reduces friction between appearance at LSND and no anomaly at KARMEN as the KARMEN baseline is more air-dominated.

Summary

I) Now that RENO and Daya Bay have determined θ_{13}, the degeneracy between 1-3 oscillation and anomalous disappearance is broken, allowing 1 km baseline reactor experiments to test the anomaly.

II) These experiments are consistent with the disappearance anomaly and lend it mild support. A confirmation of RENO's preliminary normalization would strengthen this support considerably.

III) A 1 eV sterile neutrino could explain the reactor anomaly, gallium anomaly and LSND/MiniBooNE anomalies. For now it is consistent with cosmological constraints with a time-dependent dark energy equation of state, but this solution may well be ruled out by higher redshift LSS surveys.

IV) If sterile neutrino masses are density dependent then the cosmological constraints are easily satisfied, as are precision gravity and equivalence principle bounds (Kaplan, Nelson and Weiner, 2004)