The Reactor Neutrino Anomaly
Status and Recent Developments

Joachim Kopp  (University of Mainz &  CERN)
53rd Rencontres de Moriond  |  Electroweak Session  |  March 10—16, 2018
In this Talk

- The Reactor Anomaly
- Sterile Neutrinos or Problem with Flux Prediction?
- Sterile Neutrinos: Global Status
- Cosmological Constraints (and how to evade them)
The Reactor Anomaly
A Hint for Sterile Neutrinos?
$\overline{\nu}_e$ flux from nuclear reactors is $\sim 3.5\%$ ($\sim 3\sigma$) below prediction ➟ oscillations of $\overline{\nu}_e$ into sterile neutrinos $\overline{\nu}_s$?

Mueller et al. 1101.2663, Huber 1106.0687
\( \bar{\nu}_e \) flux from nuclear reactors is \( \sim 3.5\% \) (\( \sim 3\sigma \)) below prediction

\[ \rightarrow \text{oscillations of } \bar{\nu}_e \text{ into sterile neutrinos } \bar{\nu}_s? \]
The Reactor Anomaly

\( \bar{\nu}_e \) flux from nuclear reactors is \( \sim 3.5\% \) (\( \sim 3\sigma \)) below prediction

\( \Rightarrow \) oscillations of \( \bar{\nu}_e \) into sterile neutrinos \( \bar{\nu}_s \)?


Predicting reactor $\bar{\nu}_e$ fluxes:

- Use measured $\beta$ spectra from $^{235}\text{U}$, $^{238}\text{U}$, $^{239}\text{Pu}$, $^{241}\text{Pu}$ fission
- Convert to $\bar{\nu}_e$ spectrum
- For single $\beta$ decay: $E_\nu = Q - E_e$
- Reality: thousands of decay branches, many not known precisely
- Use (incomplete) information from nuclear data tables …
- … complemented by a fit to “effective decay branches”

$\bar{\nu}_e$ flux from nuclear reactors is $\sim 3.5\% \ (\sim 3\sigma)$ below prediction → oscillations of $\bar{\nu}_e$ into sterile neutrinos $\bar{\nu}_s$?

Mueller et al. [1101.2663], Huber [1106.0687]
\bar{\nu}_e \text{ flux from nuclear reactors is } \sim 3.5\% \ (\sim 3\sigma) \text{ below prediction } \\
\rightarrow \text{ oscillations of } \bar{\nu}_e \text{ into sterile neutrinos } \bar{\nu}_s \text{?}
Sterile Neutrinos or Problem with Flux Prediction?
Isotope-Dependent Fluxes
Reactor fuel composition evolves with time ("burnup")
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\[
F_{239}(t) = \sum_{r=1}^{6} \frac{W_{th,r} \bar{P}_{ee,r} f_{i,r}(t)}{L_r^2 E_r(t)} \frac{W_{th,r} \bar{P}_{ee,r}}{L_r^2 E_r(t)}
\]

Effective fraction of $^{239}$Pu fissions

4.01082
Reactors fuel composition evolves with time ("burnup")

Measure inverse $\beta$ decay rate as function of $F_{239}$
Isotope-Dependent Fluxes

- Reactor fuel composition evolves with time (“burnup”)
- Measure inverse $\beta$ decay rate as function of $F_{239}$
- Sterile Neutrino: same deficit for all isotopes
- Flux Misprediction: isotope-dependent deficits
Sterile Neutrinos or Flux Uncertainty?

Daya Bay 1704.01082
Sterile Neutrinos or Flux Uncertainty?

$^{235}\text{U}$ prediction off

$^{239}\text{Pu}$ prediction OK

Daya Bay 1704.01082
Sterile Neutrinos or Flux Uncertainty?

$^{235}$U prediction off

$^{239}$Pu prediction OK

Daya Bay 1704.01082
Sterile Neutrinos or Flux Uncertainty?
Full analysis:

- Compare fit with free $^{235}\text{U}$, $^{238}\text{U}$, $^{239}\text{Pu}$, $^{241}\text{Pu}$ fluxes to fit with fixed fluxes + $\nu_s$

$\Delta\chi^2 = 7.9$
Sterile Neutrinos or Flux Uncertainty?

☑ Full analysis:

☐ Compare fit with free $^{235}\text{U}$, $^{238}\text{U}$, $^{239}\text{Pu}$, $^{241}\text{Pu}$ fluxes to fit with fixed fluxes + $\nu_s$

$\Delta \chi^2 = 6.3$ (with theoretical uncertainties)

Dentler Hernández JK Maltoni Schwetz 1709.04294
Full analysis:

- Compare fit with free $^{235}\text{U}$, $^{238}\text{U}$, $^{239}\text{Pu}$, $^{241}\text{Pu}$ fluxes to fit with fixed fluxes + $\nu_s$

$$\Delta \chi^2 = 6.3 \text{ (with theoretical uncertainties)}$$

But both hypothesis yield excellent goodness of fit

- Fluxes within errors + $\nu_s$: $p = 0.18$
- Fluxes free: $p = 0.73$
- $\Delta \chi^2$ (sterile neutrino vs. free fluxes): $p = 0.007$

Dentler Hernández JK Maltoni Schwetz 1709.04294
Daya Bay method assumes flux from each isotope is time and burnup-independent.
Non-Equilibrium Effects

- Some relevant decays are out of equilibrium
  - $^{90}$Sr $\rightarrow$ $^{90}$Y $\rightarrow$ $^{90}$Zr
    - $t_{1/2}=29$ yrs
    - $Q=0.55$ MeV
    - $t_{1/2}=2.7$ days
    - $Q=2.2$ MeV

- Extra $t$-dependence in $\nu$ flux

Non-Linear Isotopes

- Neutron capture on fission products

- Extra neutron flux/burnup dependence in $\nu$ flux

Jaffke Huber 1510.08948, Huber Sharma, in preparation
Huber Sharma, in preparation
Improved Analysis

χ^2 \ (\Delta \chi^2)^{1/2}

<table>
<thead>
<tr>
<th>Model</th>
<th>\chi^2</th>
<th>(\Delta \chi^2)^{1/2}</th>
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<tbody>
<tr>
<td>Best Fit</td>
<td>5.8</td>
<td></td>
</tr>
<tr>
<td>Uncorrected Model</td>
<td>15.0</td>
<td>3\sigma</td>
</tr>
<tr>
<td>Corrected Model</td>
<td>8.5</td>
<td>1.6\sigma</td>
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Huber Sharma, in preparation
NEOS and DANSS

NEOS

Ko et al. 1610.05134
Daya Bay 1607.05378

DANSS

Danilov, Moriond 2017
Danilov, Solvay Workshop Dec 2017
NEOS and DANSS

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Dentler Hernández JK Machado Maltoni Martinez Schwetz, in preparation
Sterile Neutrinos
Global Status
Fit to All Reactor Data

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Dentler Hernández JK Machado Maltoni Martinez Schwetz, in preparation
Global Fit to $\nu_e$ and $\bar{\nu}_e$ Disappearance

Dentler Hernández JK Maltoni Schwetz 1709.04294

Dentler Hernández JK Machado Maltoni Martinez Schwetz, in preparation
Global Fit to $\nu_e$ and $\bar{\nu}_e$ Disappearance

flux deficit in experiments with intense radioactive sources ("Gallium Anomaly")

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Dentler Hernández JK Machado Maltoni Martinez Schwetz, in preparation
Global Fit to $\nu_e$ and $\bar{\nu}_e$ Disappearance

Dentler Hernández JK Maltoni Schwetz 1709.04294
Dentler Hernández JK Machado Maltoni Martinez Schwetz, *in preparation*
$\nu_\mu \rightarrow \nu_e$ appearance

Dentler Hernández JK Machado Maltoni Martinez Schwetz, in preparation
$\nu_\mu \rightarrow \nu_e$ appearance

Global fit to $\nu_e$ appearance data consistent.

Dentler Hernández JK Machado Maltoni Martinez Schwetz, in preparation
Oscillation channels are related:

\[ P_{\nu_e \rightarrow \nu_e} \approx 1 - 2|U_{e4}|^2 (1 - |U_{e4}|^2) \]

\[ P_{\nu_\mu \rightarrow \nu_\mu} \approx 1 - 2|U_{\mu4}|^2 (1 - |U_{\mu4}|^2) \]

\[ P_{\nu_\mu \rightarrow \nu_e} \approx 2|U_{e4}|^2 |U_{\mu4}|^2 \]

(for \( 4\pi E/\Delta m_{41}^2 \ll L \ll 4\pi E/\Delta m_{31}^2 \))

Models can be over-constrained.
Global Fit in 3+1 Model

Dentler Hernández JK Machado Maltoni Martinez Schwetz, in preparation
see also works by Collin Argüelles Conrad Shaevitz, e.g. 1607.00011,
Gariazzo Giunti Laveder Li, e.g. 1703.00860
Global Fit in 3+1 Model

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Reactor + Gallium Anomalies,
LSND, MiniBooNE

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Global Fit in 3+1 Model

Dentler et al. in preparation

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Global Fit in 3+1 Model

Parameter Goodness-of-Fit Test:
Quantifies penalty for combining data sets

Maltoni Schwetz hep-ph/0304176

Dentler et al.
in preparation

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Can Sterile Neutrinos Explain All Anomalies?
Can Sterile Neutrinos Explain All Anomalies?

severe tension \( (p < 10^{-5}) \)

- Scrutinize anomalies for unknown systematics (need 4 independent effects!)
- Scrutinize also null results!
Cosmological Constraints
and how to evade them
Reconciling Sterile Neutrinos with Cosmology

Standard picture: $\nu_s$ production via oscillation at $T \gtrsim \text{MeV}$

$$\Sigma m_\nu \lesssim 0.23$$  
$$N_{\text{eff}} \lesssim 3.38$$
Reconciling Sterile Neutrinos with Cosmology

Standard picture: $\nu_s$ production via oscillation at $T \gtrsim \text{MeV}$

- $\sum m_\nu \lesssim 0.23$
- $N_{\text{eff}} \lesssim 3.38$

- Entropy production at $T < \text{MeV}$
  - $\nu_s$ diluted

- New interactions in the $\nu_s$ sector
  - production suppressed by thermal potential
  - minimal scenario now disfavored

- $\nu_s$ properties change in late phase transition

- …

Fuller Kishimoto Kusenko, 1110.6479
Ho Scherrer, 1212.1689

Hannestad et al. 1310.5926
Dasgupta JK, 1310.6337

Cherry Friedland Shoemaker 1605.06506
Chu Dasgupta Dentler JK Saviano, in preparation

Bezrukov Chudaykin Gorbunov, 1705.02184
Chu Dasgupta Dentler JK Saviano, in preparation
Summary
Summary

- **Reactor anomaly**: significant $\bar{\nu}_e$ deficit
- **Daya Bay**: flux as function of isotope composition
  - mild preference ($< 2\sigma$) for flux misprediction over sterile neutrino
  - non-equilibrium effects and non-linear isotopes previously neglected
- **Global Fit**: severe tension with $\nu_\mu$ disappearance
- **Cosmology**: constraints evaded in non-minimal models

Mona Dentler  Álvaro Hernández  Ivan Martinez
Thank You!
Bonus Slides
Corrections to Reactor Neutrino Fluxes

\[ \bar{\nu}_e \text{ flux from nuclear reactors is } \sim 3.5\% \text{ below prediction} \]

- **Important corrections**
  - Finite size of nucleus
  - Weak magnetism: \[ \mathcal{L} \supset (\bar{e}_L \sigma^{\mu\nu} \nu_L) W_{\mu\nu} \]
  - Screening of nuclear charge: \[ Z \rightarrow Z_{\text{eff}} \]
  - Radiative corrections (\( \gamma \) emission)
  - Non-equilibrium effects in measured \( \beta \) spectra
  - Neutron lifetime uncertainty

Mueller et al. 1101.2663, Huber 1106.0687
Isotope-Dependent Fluxes
Reactors fuel composition evolves with time ("burnup") as shown in the graph with data from Daya Bay 1704.01082.
Reactor fuel composition evolves with time ("burnup")

\[
F_{239}(t) = \frac{\sum_{r=1}^{6} W_{th,r} \bar{P}_{ee,r} f_{i,r}(t)}{L^2_r E_r(t)} \frac{\sum_{r=1}^{6} W_{th,r} \bar{P}_{ee,r}}{L^2_r E_r(t)}
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Effective fraction of $^{239}$Pu fissions

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Reactor fuel composition evolves with time ("burnup")
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- Reactor fuel composition evolves with time ("burnup")
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Daya Bay 1704.01082
Isotope-Dependent Fluxes

- Reactor fuel composition evolves with time ("burnup")
- Measure inverse $\beta$ decay rate as function of $F_{239}$

**SM or $\nu_s$ model predict agreement in slope!**

Daya Bay 1704.01082
Experiments with intense radioactive sources

Neutrino detection via

\[ ^{71}\text{Ga} + \nu_e \rightarrow ^{71}\text{Ge} + e^- \]

3σ deficit!

\[ \nu_e \text{ disappearance into sterile state?} \]

Giunti Laveder 1006.3244
Appearance vs. Disappearance

Dentler Hernández JK Machado Maltoni Martinez Schwetz, *in preparation*
see also works by Collin Argüelles Conrad Shaevitz, e.g. 1607.00011,
Gariazzo Giunti Laveder Li, e.g. 1703.00860
### Appearance vs. Disappearance

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<td><strong>Appearance</strong></td>
<td>79.1/69</td>
<td>11.9</td>
<td></td>
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<tr>
<td><strong>Disappearance</strong></td>
<td>1012.2/1040</td>
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Dentler et al. \textit{in preparation}

\[\sin^2 2\theta_{\mu e}\]

\[\text{Free Fluxes} \quad \text{Fixed Fluxes} \]

99.73% CL 2 dof
Sterile Neutrinos in Cosmology

Standard picture: $\nu_s$ production via oscillation at $T \gtrsim \text{MeV}$

- $\nu_{e,\mu,\tau}$ evolve into superposition with $\nu_s$
- Hard interaction collapses $\nu$ wave function
  - $\frac{1}{2} \sin^2 2\theta$ of $\nu$ converted to $\nu_s$
- Remaining $\nu_{e,\mu,\tau}$ start to oscillate again
- Constrained by CMB, LSS, BBN:
  - $\Sigma m_\nu \approx 0.23$
  - $N_{\text{eff}} \approx 3.38$
Assume $\nu_s$ charged under a new $U(1)'$ gauge group

Neutrino self-energy contributes to effective potential $V_{\text{eff}}$

MSW potential $V \sim n_f - \bar{n}_f$

Effective mixing angle

$$\sin^2 2\theta_{\text{eff}} = \frac{\sin^2 2\theta}{\sin^2 2\theta + \left(\cos 2\theta - \frac{2EV_{\text{eff}}}{\Delta m^2}\right)^2}$$
Assume $\nu_s$ charged under a new $U(1)'$ gauge group

Neutrino self-energy contributes to effective potential $V^{\text{eff}}$

$\nu_s$ production strongly suppressed at high $T$  

Effective mixing angle

$$\sin^2 2\theta_{\text{eff}} = \frac{\sin^2 2\theta}{\sin^2 2\theta + \left(\cos 2\theta - \frac{2E V^{\text{eff}}}{\Delta m^2}\right)^2}$$
Suppressed vs Production
Suppressed $\nu_s$ Production

If $V_{\text{eff}} \gg \Delta m^2 / (2T)$: $\nu_s$ production suppressed

Hannestad et al. 1310.5926
Dasgupta JK 1310.6337
If $V_{\text{eff}} \gg \Delta m^2 / (2T)$: $\nu_s$ production suppressed

Hannestad et al. 1310.5926
Dasgupta JK 1310.6337

Problem: late equilibration between $\nu_e, \nu_\mu, \nu_\tau$ and $\nu_s$

Chu Dasgupta JK 1505.02795, Cherry Friedland Shoemaker 1605.06506
Chu Dasgupta Dentler JK Saviano, in preparation
Basic idea

- large $\nu_s$ mass at early times $\Longrightarrow$ production kinematically suppressed
- late phase transition reduces mass to $\sim$ eV

Toy model

$$V(\phi_1, \phi_2) = \frac{\lambda_1}{4} \phi_1^4 + \frac{\lambda_2}{4} \phi_2^4 + \frac{\lambda_p}{2} \phi_1^2 \phi_2^2 + \frac{\mu_1^2}{2} \phi_1^2 + \frac{\mu_2^2}{2} \phi_2^2$$

$$\mathcal{L}_{\text{Yukawa}} = -y_1 \bar{\nu}_{sL} \nu_s \nu_{sR} - \frac{1}{2} m_{sL} \bar{\nu}_{sL}^c \nu_{sL} - \frac{1}{2} m_{sR} \bar{\nu}_{sR}^c \nu_{sR} + \text{h.c.}$$

Possible behavior: inverse symmetry breaking

- large $T$: $\langle \phi_1 \rangle \neq 0, \langle \phi_2 \rangle = 0$ ($V_{\text{eff}}$ dominated by thermal corrections)
- small $T$: $\langle \phi_1 \rangle = 0, \langle \phi_2 \rangle = 0$ $\Longrightarrow \nu_s$ mass given by $m_{sL}, m_{sR}$