Results from the Search for eV-Sterile Neutrinos with IceCube

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(arXiv:1605.01990)
Today

- Neutrino oscillations and the MSW effect
- IceCube
- The IceCube sterile neutrino search
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Neutrino Oscillations primer

In two generations the oscillation probability at a given distance $L$ and energy $E$ in vacuum

$$P_{\nu_\alpha \rightarrow \nu_\alpha} \left( \frac{L}{E} \right) = 1 - \sin^2 2\theta \sin^2 \left( \frac{\Delta m^2 L}{4E} \right)$$
Neutrino oscillations: mass eigenstates ($\nu_i; i = 1, 2, 3$) and flavor eigenstates ($\nu_\alpha; \alpha = e, \mu, \tau$) are not the same.

\[
\Delta m^2_{\text{sol}} = 7.5 \times 10^{-5}\text{eV}^2 \\
|\Delta m^2_{\text{atm}}| = 2.4 \times 10^{-3}\text{eV}^2
\]

\[
\nu_i = \sum_\beta U_{\beta i} \nu_\beta
\]

\[
U = U(\theta_{12}, \theta_{23}, \theta_{13}, \delta^{CP})
\]

\[
|U| \approx \begin{pmatrix}
0.8 & 0.5 & 0.1 \\
0.3 & 0.7 & 0.6 \\
0.4 & 0.5 & 0.8
\end{pmatrix}
\]
The pieces that do not fit ...

<table>
<thead>
<tr>
<th>Oscillation Channel</th>
<th>Class</th>
<th>Experiments</th>
<th>Oscillation amplitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron Disappearance $P(\nu_e \rightarrow \nu_e)$</td>
<td>Reactor Experiments</td>
<td>GALLEX (ν) SAGE (ν) {Global Reactors}</td>
<td>$4</td>
</tr>
<tr>
<td>Muon Disappearance  $P(\nu_\mu \rightarrow \nu_\mu)$</td>
<td>Long Baseline Experiments</td>
<td>Anomalous-less</td>
<td>$4</td>
</tr>
<tr>
<td>Electron Appearance $P(\nu_\mu \rightarrow \nu_e)$</td>
<td>Short Baseline Experiments</td>
<td>LSND (ν) MiniBooNe (ν, ν)</td>
<td>$4</td>
</tr>
</tbody>
</table>

$\Delta m^2 \sim 1\text{eV}^2$
Introducing a sterile neutrino

One more mass splitting.
Three new angles.
two more CP phases.
What does the World data say?

J. Kopp et al., JHEP 1305 (2013) 050

G. Collins et al., arXiv: 1602.00671

On updated fits solutions remain…

tension between experiments

We need new measurements!
Experiments:

\[ L = 2 \pi E_m^2 |m^2_{LSND}| \]


A global view:
the IceCube-ShortBaseline connection
A closer look at atmospheric neutrinos oscillation

The neutrinos come from different zenith angles \( (\theta_z) \) tranversing different layers of the Earth:

- **core**: 
  \[ \cos \theta_z \sim [-1, -0.8] \]

- **mantle**: 
  \[ \cos \theta_z \sim [-0.8, -0.1] \]

- **crust**: 
  \[ \cos \theta_z > -0.1 \]
Matter effects: Mikheyev-Smirnov-Wolfenstein effect

The $\nu$ oscillation probability in two generations in matter is

$$P_{\nu_\alpha \rightarrow \nu_\alpha} = 1 - \sin^2 2\theta_M \sin^2 \left( \frac{\Delta m^2_M L}{4E_\nu} \right)$$

where $\theta_M$ and $\Delta m^2_M$ satisfy

$$\Delta m^2_M = \sqrt{(\Delta m^2 \cos 2\theta - A)^2 + (\Delta m^2 \sin 2\theta)^2}$$

$$\tan 2\theta_M = \frac{\tan 2\theta}{\frac{A}{\Delta m^2 \cos 2\theta}}$$

and $A = \pm 2\sqrt{2}G_F N$, $N$ number density. Resonant flavor transition can happen if

$$E^\text{res}_\nu = \mp \cos 2\theta \frac{\Delta m^2}{2N} \frac{1}{\sqrt{2}G_F}$$

this resonance (MSW) can enhance the transition between active and sterile antineutrinos.
In the Earth, for sterile neutrino of $\Delta m^2 = O(1eV^2)$ the MSW effect happens when

$$E_{\nu}^{res} = \frac{\Delta m^2 \cos 2\theta}{2\sqrt{2}G_F N} \sim O(TeV)$$

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The IceCube experiment
IceCube Laboratory
Data is collected here and sent by satellite to the data warehouse at UW–Madison

Digital Optical Module (DOM)
5,160 DOMs deployed in the ice

IceCube detector
86 strings of DOMs, set 125 meters apart

DeepCore
DOMs are 17 meters apart

Amundsen–Scott South Pole Station, Antarctica
A National Science Foundation-managed research facility

IceTop
IceCube Lab is 50 m above the Antarctic bedrock
IceCube discovery of high energy astrophysical neutrinos

IceCube Preliminary

Events per 1347 Days

Deposited EM-Equivalent Energy in Detector (TeV)

Bert

Ernie

1PeV

1.1PeV
Through-going muons in IceCube

\[ \Delta \theta \sim 1^\circ \]

(neutrino)

μon Cu

Bethe-Bloch

Anderson-Ziegler

Lindhard-Scharff

Nuclear losses

Minimum ionization

Radiative effects reach 1%

Radiative losses

Without δ

Muon Energy Proxy [arb. units]

\[ \mu^+ \]

\[ 10^{-4} \]

\[ 10^{-3} \]

\[ 10^{-2} \]

\[ 10^{-1} \]

\[ 10^0 \]

Probability

True Neutrino Energy [GeV]

\[ 10^2 \]

\[ 10^3 \]

\[ 10^4 \]

\[ 10^5 \]

\[ 10^6 \]

\[ 10^7 \]

Mu Energy Proxy [arb. units]

[MeVc] [GeVc] [TeVc]
How do they look like?
Through-going nu-mu energy distribution

Events vs. Muon Energy Proxy (arb. units)

- Experimental data
- Sum of predictions
  - Astrophysical
  - Prompt atmospheric
  - Conventional atmospheric

Through-going nu-mu energy distribution

Muon Energy Proxy (arb. units)

Events

Experimental
Sum of predictions
Prompt atmospheric
Conventional atmospheric

Muppet neutrinos (astrophysical)

Through-going nu-mu energy distribution

![Graph showing energy distribution with different energy proxies and predictions.](image)

- **Events**
- **Muon Energy Proxy (arb. units)**
- **Conventional atmospheric**
- **Prompt atmospheric**
- **Astrophysical**
- **Sum of predictions**
- **Experimental data**

**Non-muppet neutrinos (atmospheric)**

Through-going nu-mu energy distribution

Use to measure standard oscillations

Conventional atmospheric
Prompt atmospheric
Astrophysical
Sum of predictions
Experimental data


Today

Neutrino oscillations and the MSW effect

IceCube

The IceCube sterile neutrino search
Through-going nu-mu energy distribution

Events

10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}

10^3
10^4
10^5
10^6

Muon Energy Proxy (arb. units)

Oscillation probability as a function of energy and zenith

\[ E^{\text{res}}_\nu = \frac{\Delta m^2 \cos 2\theta}{2\sqrt{2} G_F N} \sim O(\text{TeV}) \]

\[ \sin^2(2\theta) = 0.1 \]

\[ \Delta m^2 = 1 \text{eV}^2 \]

\[ \text{LSND/MB like} \]
The Signal!

Signal in *reconstructed quantities* for three points in the parameter space.
Data set expected statistical error bars

**Statistical errors on the region of interest ≤10%**

**MSW region**
Systematics!

Systematics are super important; some are more than others. These are the systematics we considered:

- DOM efficiency
- Flux continuous parameters
  - spectral index
  - $\pi/K$ ratio
  - $\nu/\bar{\nu}$ ratio
- Air shower hadronic models
- Primary cosmic ray fluxes
- Hole ice
- Neutrino cross sections
- Bulk ice scattering/absorption
- Earth model

**Continuous systematics**

**Discrete systematics**
Atmospheric flux decomposed

sterile analysis

prompt contribution ~5% at 20 TeV
Atmospheric neutrino flux uncertainties

Cosmic ray models:
- Zatsepin-Sokolskaya
- Polygonato
- Gaisser+Honda

Hadronic models:
- Sibyll 2.3
- QGSJET II

\[ \phi_{\text{atm}} = N_0 \left( \phi_K + \frac{R_\pi}{K} \phi_\pi \right) \times E_{\nu}^{-\Delta\gamma} \]

[Fedynitch et al. arXiv:1504.06639]
[Collins et al. URL: http://dspace.mit.edu/handle/1721.1/98078]
Detector Systematics: DOM efficiency!

Effect of changing the DOM efficiency in the parameter space:

Efficiency of the DOM is imprecisely known. We apply corrections due to ice and cable shadow.
Ice uncertainties
Fit for ice properties as a function of depth.
Hole Ice

Refrozen ice in the hole have **air bubbles** that produce **extra scattering.**
Preunblinding final checks

- We fitted the null hypothesis on the whole sample.
- Blindness is preserved by looking only at the projections.
- Recover good fit and sensible nuisance parameters: all ok.
Pulls per bin on no-sterile hypothesis

Pulls per bin, no steriles

IceCube PRELIMINARY
Almost there...

Before showing the main result I would like to recognize my two co-analyzers:

**Ben Jones** *(MIT → UT Arlington)*

and

**Jordi Salvado Serra** *(UW Madison → IFIC Valencia)*
Opening the box

No significant evidence of a sterile neutrino found.

New bounds placed.
Checks of the best fit point location

Best fit point at

\[ \Delta m^2_{41} = 10 \text{ eV}^2 \]

\[ \sin^2 2\theta_{24} = 0.56 \]

corresponding to a p-value of 19.4% from the no-sterile hypothesis.

Minima location is typical. Fast oscillations indistinguishable from null hypothesis.
A posteriori normalization prior

- Post unblinding a 40% normalization prior was introduced.
- Sensitivities are the same.
- Weakened exclusion.

shape only: no prior
rate+shape: with prior
Rate+Shape Observation and Brazil plot

90% sensitivity and observation

Realization compatible with sensitivity expectation.
The IceCube results versus other disappearance measurements

![Disappearance results, 90% CL](chart)

- IceCube PRELIMINARY
- CDHS
- MB/SB
- rate+shape (IC86) 90% CL
- shape only (IC86) 90% CL

**Axes:**
- $\Delta m^2_{41}$/eV$^2$
- $\sin^2 2\theta_{24}$
Both results versus the world

- **shape-only**: energy-zenith fit and normalization **no prior**.
- **rate+shape**: energy-zenith fit and normalization **Gaussian prior**.

![SHAPE](chart.png)

![SHAPE+RATE](chart.png)
Relationship with other angles

- $\sin^2 2\theta_{ee} \equiv 4|U_{e4}|^2(1 - |U_{e4}|^2)$: reactor experiments.
- $\sin^2 2\theta_{\mu\mu} \equiv 4|U_{\mu4}|^2(1 - |U_{\mu4}|^2)$: MINOS, SK. (this analysis)
- $\sin^2 2\theta_{\mu e} \equiv 4|U_{\mu4}|^2 |U_{e4}|^2$: LSND, MB, KARMEN, NOMAD.

(Kopp et al. arXiv:1303.3011)
A new global fit, but no IceCube yet!


<table>
<thead>
<tr>
<th>$N_{\text{bins}}$</th>
<th>$\chi^2_{\text{min}}$</th>
<th>$\chi^2_{\text{null}}$</th>
<th>$\Delta\chi^2_{\text{null-min}}$ (dof)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>3+1</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>All</td>
<td>315</td>
<td>306.81</td>
<td>359.15</td>
</tr>
<tr>
<td>App</td>
<td>92</td>
<td>88.04</td>
<td>150.84</td>
</tr>
<tr>
<td>Dis</td>
<td>223</td>
<td>195.84</td>
<td>208.32</td>
</tr>
<tr>
<td>$\nu$</td>
<td>155</td>
<td>153.18</td>
<td>164.57</td>
</tr>
<tr>
<td>$\bar{\nu}$</td>
<td>157</td>
<td>138.79</td>
<td>194.59</td>
</tr>
</tbody>
</table>

| $3+1$ | $\Delta m^2_{41}$ | $|U_{e4}|$ | $|U_{\mu 4}|$ |
|-------|------------------|----------|--------------|
| All   | 1.75             | 0.163    | 0.117        |
| App   | $4.75 \times 10^{-2}$ | 0.743 | 0.638        |
| Dis   | 7.79             | 0.217    | 2.94 $\times 10^{-2}$ |
| $\nu$ | 7.71             | 0.248    | 5.67 $\times 10^{-2}$ |
| $\bar{\nu}$ | 5.73             | 0.199    | 0.140        |
Very naïve IceCube + PROSPECT complementarity

\[
\begin{align*}
\sin^2 2\theta_{ee} &= \sin^2 2\theta_{14} \\
\sin^2 2\theta_{\mu\mu} &= 4 \cos^2 \theta_{14} \sin^2 \theta_{24} \left(1 - \cos^2 \theta_{14} \sin^2 \theta_{24}\right) \\
\sin^2 2\theta_{\mu e} &= \sin^2 2\theta_{14} \sin^2 \theta_{24} \\
\sin^2 2\theta_{e\tau} &= \sin^2 2\theta_{14} \cos^2 2\theta_{24} \sin^2 \theta_{34} \\
\sin^2 2\theta_{\mu\tau} &= \sin^2 2\theta_{24} \cos^4 \theta_{14} \sin^2 \theta_{34}
\end{align*}
\]

(IceCube also sensitive to theta-34)

**Warning:**

angles are different!
Future steps: Two ways forward

More statistics
- Repeat the through going analysis with five years of data.
- Smaller systematics now become more relevant, e.g. ice.

Better events
- Select only starting events.
- Better neutrino energy reconstruction: track+shower energies.
- Reduced statistics.
Take home message

- We have performed a search for eV-sterile neutrinos using one year of IceCube. **No significant signal of sterile neutrinos was found.**
- Improved World limits on sterile neutrinos by ~ order of magnitud.
- IceCube has several more years of data ready to analyze: We are just getting started!

THANKS!

See arXiv:1605.01990 for more details
BONUS SLIDES
(Kopp et al. arXiv:1303.3011)
Model Comparison, 90%

\[ \Delta m^2 / \text{eV}^2 \]

\[ \sin^2 2\theta \]

- **Default**
- **2x Tighter Priors**
- **2x Looser Priors**

(Discrete: Polygonato-QGSJET)
Relation with the IC59 result
Neutrino Mass from Cosmology (Hannestad)

- More data
  - +Ly-alpha
    ~ 0.2 eV 0.2–0.3 eV 0.2–0.3 eV
  - + SNI-a +WL
    ~ 0.5 eV 0.5–0.6 eV 0.5–0.6 eV
  - + SDSS
    0.4 eV ~ 1 eV 1–2 eV
  - CMB only
    1.1 eV ~ 2 eV 2.2 eV ??? eV

Minimal $\Lambda$CDM $+N_\nu$ $+w+......$ Larger model space
Neutrino Mass from Cosmology (Hannestad)

- More data
  - +Ly-alpha
  - + SNI-a
  - +WL
- + SDSS
- CMB only
  - 1.1 eV
  - 0.4 eV
  - 0.5 eV
  - 0.2 eV
  - ~ 1 eV
  - ~ 1 eV
  - ~ 2 eV
  - ~ 2 eV

Mineral $\Lambda$CDM

+ $N_\nu$

+ $w$+......

Larger model space
Effect of other mixing angles

\[ P(\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu) \]

\[ E_\nu \text{(TeV)} \]

\[ \cos \theta_z = -1 \]

\[ [\text{Esmaili et al., JHEP12 (2013) 014}] \]
Statistics!

We did a standard binned maximum likelihood fit.

$$\log L(\sin^2 2\theta_{24}, \Delta m^2_{41}) = \min_{\theta, \{d\}} \left( \sum_{i=1}^{N_{\text{bins}}} \left[ x_i \log \lambda_i(\tilde{\theta}, d) - \lambda_i(\tilde{\theta}, d) \right] + \sum_{\eta} \frac{(\theta_\eta - \Theta_\eta)^2}{\sigma_\eta^2} \right),$$

- **continuous nuisance parameters** ($\theta$): DOM efficiency, atmospheric flux normalization, pion/kaon ratio, cosmic ray slope, atmospheric density uncertainties.

- **discrete nuisance parameters** ($d$): ice models, hole ice, atmospheric flux models, Earth variants, cross sections.
Unblinded data

Data (events per bin)

$E_{\mu, \text{proc}} \text{/GeV}$

$\cos \theta_{\mu, z}^{\text{reco}}$

IceCube PRELIMINARY
Rate+Shape in Big Space
Initial neutrino to antineutrino ratio

This Work

HKKM04

Bartol

Fluka

Neutrino Flux Ratios

$\nu_e + \overline{\nu}_e$

$\nu_\mu + \overline{\nu}_\mu$

$\nu_\mu / \overline{\nu}_\mu$ (x1.5)

$\nu_e / \overline{\nu}_e$

$E_V$ (GeV)

SQuiDS/nu-SQuiDS

C.A., J. Salvado, and C. Weaver. [In preparation]

What is it?

Is a software framework written in C++ that evolves quantum mechanical ensembles. nu-SQuiDS calculates neutrino propagation (oscillation+interactions).

What can it do?

- Calculate neutrino oscillation probabilities in 3 generations (can configure mixing angles, CP phases, and mass splittings).
- Ready to use in: short baseline, long baseline, atmospheric, and solar neutrino oscillation experiments.
- Incorporates neutrinos' non-coherent interactions (including tau regeneration).
- Can handle collective neutrino interactions (e.g. supernova), as well as neutrino-antineutrino interactions.
- Easily extendable to BSM physics scenarios. Sterile neutrinos, NSI, and LV already implemented!

Get it here:
https://github.com/jsalvado/SQuiDS
https://github.com/arguelles/nuSQuiDS
Oscillogram $\phi^{3+1}_\mu / \phi^{ini}_\mu$ for $\Delta m^2_{41} = 1\text{eV}^2$, $\sin^2(2\theta_{24}) = 0.251$
Oscillogram $\phi_{3+1}^{\mu}/\phi_{\mu}^{ini}$ for $\Delta m_{41}^2 = 1\text{eV}^2$, $\sin^2(2\theta_{24}) = 0.251$.

\[ \sin^2(2\theta_{24}) = 0.251, \Delta m_{41}^2 = 1\text{eV}^2 \]