Results OF THE Search FOR Sterile Neutrinos WITH IceCube

BEN JONES, UNIVERSITY OF TEXAS AT ARLINGTON
Todays Menu:

- Sterile Neutrinos, Anomalies and MSW Resonances
- The IceCube Experiment
- IceCube Sterile Neutrino Search
A Neutrino Oscillation:

\[ P_{osc} = \sin^2 2\theta \sin^2 (1.27\Delta m^2 L/E) \]

- **Source**
- **Oscillation Maximum**

- **Re(\(\psi\))**
- **P(f)**

- **amplitude**
- **wavelength**
Experimentally, $\Delta m_{31}^2 \gg \Delta m_{21}^2$

- Two characteristic oscillation wavelengths.

- Mass ordering unknown (though hints exist)

- Mixing between 3 states dictated by 3 mixing angles and (1 or 3) CP phases.

From PDG:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>best-fit ($\pm 1\sigma$)</th>
<th>$3\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta m_{21}^2 [10^{-5}\text{ eV}^2]$</td>
<td>$7.54 \pm 0.26$</td>
<td>$6.99 - 8.18$</td>
</tr>
<tr>
<td>$</td>
<td>\Delta m^2</td>
<td>[10^{-3}\text{ eV}^2]$</td>
</tr>
</tbody>
</table>
Oscillation Anomalies: LSND

\[ \Delta m^2_{14} \gg \Delta m^2_{13}, \Delta m^2_{23} \]

\[ \pi^+ \rightarrow \mu^+ \nu_\mu \]
\[ \mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu \]

Very small intrinsic \( \bar{\nu}_e \) background

\( \pi^+ \) stop in material, then decay:
Oscillation Anomalies: MiniBooNE

Focussed $\pi^+$ or $\pi^-$ decay in flight to make mostly $\nu_\mu$ or $\bar{\nu}_\mu$

$$\pi^+ \rightarrow \mu^+ \nu_\mu$$

$$\pi^- \rightarrow \mu^- \bar{\nu}_\mu$$
Other Anomalies at Short Baselines

- **Gallium Anomaly**: 2.7σ deficit of $\nu_e$ from intense electron capture calibration sources

- **Reactor Anomaly**: 3σ deficit of $\bar{\nu}_e$ from reactors after applying modern flux calculations to old data
What does world data say?

Kopp et al:
JHEP 1305 (2013) 050
What does world data say?

Compare to Conrad et al

Appearance only

Appearance and disappearance
So far, matter did not matter...

\[ P_{Osc} = A_{mixing} \sin^2 \left( 1.27 \Delta m^2 L / E \right) \]
Neutrinos in matter with refraction

\[ P_{osc} = A_{\text{mixing}} \sin^2 \left( 1.27 \Delta m^2 L / E \right) \]

In this example, phases roll faster in matter \( \rightarrow \) mass states are effectively heavier

Both states have same interaction strength \( \rightarrow \Delta m^2 \) unchanged
Couplings in matter change effective masses of the neutrinos. In the above cartoon (not physical!), one mass state has a matter coupling and the other does not.

Oscillation length changes $\Rightarrow$ **Effective $\Delta m^2$ is modified**
The previous slide showed one mass state coupled more strongly than other

→ Effective $\Delta m^2$ modified

Matter couplings are to flavor states, not directly to mass states

→ Effective mixing is also modified

\[
\Delta m^2_{M} \equiv \Delta m^2 \sqrt{\sin^2 2\theta + (\cos 2\theta - x)^2}
\]

\[
\sin^2 2\theta_M \equiv \frac{\sin^2 2\theta}{\sin^2 2\theta + (\cos 2\theta - x)^2}
\]

X=“how different are the matter couplings between neutrino flavors”
**MSW Effect in the Sun**

* Neutrinos in the sun are all born as $\nu_e$

* Their flavors change as they cross the sun due to oscillations

* Higher energy neutrinos feel stronger matter coupling, emerge with different flavor composition ("MSW effect")
The MSW resonance

\[ \sin^2 2\theta_M \equiv \frac{\sin^2 2\theta}{\sin^2 2\theta + (\cos 2\theta - x)^2} , \]

Maximal flavor change when \( x = \cos 2\theta \) leads to **MSW resonance**

If \( x = \cos 2\theta \), maximal mixing \( \rightarrow \) largest possible amplitude of oscillation

Can happen even when original mixing angle is tiny.

*Full disclosure: I am sweeping important details under the carpet...*
The MSW resonance

\[
\sin^2 2\theta^M \equiv \frac{\sin^2 2\theta}{\sin^2 2\theta + (\cos 2\theta - x)^2},
\]

\[
x \equiv \frac{V_W/2}{\Delta m^2 / 4E} = \frac{2\sqrt{2} G_F N_e E}{\Delta m^2}
\]

- Neutrino energy
- Electron density
MSW resonance in the Sun

$$\sin^2 2\theta_M \equiv \frac{\sin^2 2\theta}{\sin^2 2\theta + (\cos 2\theta - x)^2} ,$$

$$x \equiv \frac{V_W/2}{\Delta m^2/4E} = \frac{2\sqrt{2}G_FN_eE}{\Delta m^2}$$

Neutrinos in the sun move from center to surface, exploring a range of $x$ values.
MSW resonance in the Sun

\[ \sin^2 2\theta_M \equiv \frac{\sin^2 2\theta}{\sin^2 2\theta + (\cos 2\theta - x)^2} , \]

\[ x \equiv \frac{V_W/2}{\Delta m^2/4E} = \frac{2\sqrt{2} G_F N_e E}{\Delta m^2} \]

When crossing the resonance angle (sufficiently slowly) we expect maximal flavor conversion.
MSW resonance in the Sun

When crossing the resonance angle (sufficiently slowly) we expect maximal flavor conversion.
Sterile Neutrinos in Matter

* Sterile neutrinos do not interact with matter AT ALL!
* Thus new MSW-type effects are to be expected.

For full phenomenology: Esmali and Smirnov, JHEP 1312 (2013) 014
MSW Resonant Sterile Neutrinos

- $\Delta m^2$ too large for resonance in the Sun
- Much higher energy neutrinos and antineutrinos are produced in cosmic ray air showers
- They cross the Earth, with active species feeling the matter potential

Effective mixing angle range

Earth Matter Density

Matter density (arb)

Density / gcm$^{-3}$

Radius / km

0

6000

PREM

Inner Core

Outer Core

Core-Mantle-Boundary (CMB)

Mantle

Moho Discontinuity
End of Earth's Crust

Ocean

0.6 TeV

3 TeV

RESONANCE ANGLE

Earth density range
MSW Resonant Sterile Neutrinos

\[ \Delta m_{41}^2 = 1.0 \text{eV}^2 \]
\[ \sin^2(2\theta_{24}) = 0.01 \]

solid : \( \bar{\nu} \)
dashed : \( \nu \)

Oscillation Probability

\[ E_{\nu} \text{[GeV]} \]

\[ \text{P}(\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu) \]
\[ \text{P}(\bar{\nu}_\mu \rightarrow \bar{\nu}_\tau) \]
\[ \text{P}(\bar{\nu}_\mu \rightarrow \bar{\nu}_s) \]
Sterile Neutrinos and MSW Resonances

The IceCube Experiment

IceCube Sterile Neutrino Search
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

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

86 strings of DOMs, set 125 meters apart

IceTop

60 DOMs on each string
DOMs are 17 meters apart

DeepCore

Antarctic bedrock

1450 m

2450 m

50 m
Digital Optical Modules
Astrophysical Neutrinos

IceCube observed the flux of ultra-high-energy astrophysical neutrinos in 2013.

At present there are 54 astrophysical neutrino candidates.

Phys.Rev.Lett. 113 (2014) 101101

These are HESE (High Energy Starting Event) cascades.
- Charged particles in IceCube emit Cerenkov light
- Ice is very transparent at Cerenkov wavelengths
- Dispersed dust particles cause Mie scattering which makes photons "diffuse"
- Photons are detected at DOMs with 125 m spacing
- On-board DAQ digitizes the pulse and sends digital data to ICL at surface
- Space and time information provide event geometry and direction
$\nu_\mu$ detection in IceCube

Kloppo – highest energy neutrino ever detected, 2.6 PeV muon-at-detector

( > 100 times LHC beam energy)

(Muon energy losses are stochastic in this energy regime)
Mostly Muppets (astrophysical)

The Muppet Muons

The Non-Muppet Muons

Where are the standard oscillations?

Sensitive to standard oscillations

Osc. length for standard neutrinos >> Earth diameter except at very lowest energies

Energy is too low for resonance, oscillations are vacuum-like

IceCube Standard Oscillation Result

Todays Menu:

* Sterile Neutrinos and MSW Resonances
* The IceCube Experiment
* IceCube Sterile Neutrino Search
Where might there be sterile neutrino oscillations?

Island allowed by both appearance and disappearance expts is around $\Delta m^2 = 1$ eV$^2$

MSW resonance occurs at:

$$E_{res} = \frac{\Delta m^2 \cos 2\theta}{\sqrt{2} G_F N_e}$$

For $\Delta m^2 = 1$ eV$^2$ and Earth matter density:

$$E_{crit} = 3 \text{ TeV}$$
Resonance energy:

Sensitive to standard oscillations

Right here – big stats in sample!

Resonance energy:
  Right here – big stats in sample!

Example 4 TeV up-going muon event
Predicting the MSW oscillation

At these energies, have refractive (MSW) phenomena, and also significant incoherent scatter cross section.

Have to include both effects to predict survival probability - and they are non-trivially coupled

→ numerically solve flavor evolution master equation through Earth density profile for truth-level oscillation solution.

nuSQuIDS:
https://github.com/arguelles/nuSQuIDS
Expected Stat Uncertainty per Bin
Sources of systematic uncertainty

<table>
<thead>
<tr>
<th>Continuous parameter</th>
<th>Central value</th>
<th>Gaussian prior width</th>
</tr>
</thead>
<tbody>
<tr>
<td>normalization</td>
<td>1</td>
<td>no prior</td>
</tr>
<tr>
<td>DOM Efficiency</td>
<td>0.99</td>
<td>no prior</td>
</tr>
<tr>
<td>cosmic ray spectral shift</td>
<td>0</td>
<td>0.05</td>
</tr>
<tr>
<td>(\pi/K) ratio</td>
<td>1</td>
<td>0.1</td>
</tr>
<tr>
<td>(\nu/\bar{\nu}) ratio</td>
<td>1</td>
<td>0.025</td>
</tr>
<tr>
<td>atmospheric density shift</td>
<td>0</td>
<td>tuned per-model</td>
</tr>
</tbody>
</table>

Table 4.1: Continuous nuisance parameters used in the fit

<table>
<thead>
<tr>
<th>Discrete variant</th>
<th>Variant numbers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central model</td>
<td>0</td>
</tr>
<tr>
<td><em>SPICEMic, PREM, HERAPDF</em></td>
<td></td>
</tr>
<tr>
<td>Ice absorption +10%</td>
<td>1</td>
</tr>
<tr>
<td>Ice scattering +10%</td>
<td>2</td>
</tr>
<tr>
<td>SPICELea</td>
<td>3</td>
</tr>
<tr>
<td>No hole ice effect</td>
<td>4</td>
</tr>
<tr>
<td>Flux variants</td>
<td>5-10</td>
</tr>
<tr>
<td>Cross section variants</td>
<td>11-15</td>
</tr>
<tr>
<td>Earth model variants</td>
<td>16-24</td>
</tr>
</tbody>
</table>

Table 4.2: Discrete simulation sets compared for maximum likelihood
Production of Atmospheric Neutrinos

Lowest energy
Mostly atmospheric π

Highest energy
Mostly atmospheric K

Highest energy
Mostly astro / prompt

cosmic ray primary

Air

K

Decay
π

Decay
μ

ν_μ

K

π

Interaction

ν_μ

μ

46
In our analyses, pi/K production ratio, spectral slope, nu/nubar ratio are all nuisance parameters with priors derived from published models.
Discrete flux models:
- Honda / HKKM (tuned on atmospheric muon flux), plus six cascade calculations from MCEq, sampling 3 primary spectra and 2 hadronic models.

Primary models:
- ZatsepinSokolskaya, Polygonato, Gasser-Honda + Hillas knee correction

Hadronic models:
- SIBYLL 2.3
- QGSJET II-04

Uncertainties in Flux

![Graph showing uncertainties in neutrino and antineutrino fluxes]
Atmospheric density

- Atmospheric density over sample live-time from the Atmospheric Infra-Red Sounder (AIRS) instrument on the NASA AQUA satellite.

Propagated through air shower evolution calculation with stat. and syst. uncertainties.
Earth density profile

* Default Earth model is the Preliminary Reference Earth Model (PREM)

* Constructed by fitting seismic wave data under geodetic constraints

* We polynomially perturb the PREM preserving those constraints to make distorted density models

* We minimize over 10 variants
* In this energy range, scattering is all Deep Inelastic

* Uncertainty enters from parton distribution functions

* We use six PDFs HERAPDF and CT10 at NNLO, each at central and ±1σ

* Final shape effect is very small. Normalization effect is a few %.

**Example structure function comparison**
Optical module uncertainty

- Efficiency of DOM is imprecisely known.
- Lab measurements need correction due to local ice conditions and cable shadow.
- We continuously vary optical efficiency using a reweighting technique.

In practice, tightly constrained by position of energy peak → we fit within 0.1% of dedicated in-ice calibration measurements.
How Transparent is the Ice?

More absorbing

Tap water

Distilled water

Clearest man-made ice (in 1997)

SuperK ultra clean water

More transparent

 VERY TRANSPARENT!

But the detector is big: 1km across!

Absorption on dust is a significant effect and a source of uncertainty
South pole ice is compacted snow: initially has many bubbles.

At high pressures, bubbles dissolve into ice crystal creating clathrate hydrate phase.

No bubbles in IceCube bulk ice.

Clathrate has refractive index within 0.4% of ice → negligible scattering.
“Hole ice” effect

But - refrozen ice in hole does have bubbles, extra scattering behavior occurs in vicinity of DOMs → effective change to angular response function.
Absorption and scattering in bulk ice are both dominated by dust.

Ice optical model built by fit to calibration data from flashers on each DOM.

Due to glacial flow, dust layers display:
- Tilt / buckling
- Anisotropy

Both measured and incorporated into model.
We implement systematic uncertainties on absorption and scattering coefficients, anisotropy strength and hole-ice. These are small compared to flux and DOM efficiency uncertainties, and compared to expected stat error.

Examples-

Left : 90% CL absorption shift

Right: 90% CL scattering shift
Now for the results...

Very important to recognize my two co-analyzers:

CARLOS ARGUELLES DELGADO (UW Madison / MIT)
and
JORDI SALVADO SERRA (UW Madison/ IFIC Valencia)
A first look at the data:

Comparison of data to no-steriles hypothesis, after accounting for systematics
Data in the binned analysis space:

Data (events per bin)

![Heatmap of data points]

- $E_{\mu,\text{proxy}}$ [GeV]
- $\cos\theta_{\mu,z}^{\text{reco}}$
Pulls in the analysis space:

Pulls per bin, no steriles

- \( E_{\mu, \text{proxy}}/\text{GeV} \)
- \( \cos\theta_{\mu, z}^{\text{reco}} \)

IceCube PRELIMINARY
Blind analysis result:

No significant evidence for sterile neutrinos

Exclusion of large parameter space at 99% confidence level
Checking the best-fit

The best fit point is a consistent realization of the no-steriles hypothesis ➔

Its frequentist p-value is 14% ➖

(this part of hypothesis space is a very fast vacuum-like oscillation, nearly indistinguishable from no-effect)
By incorporating other available information (knowledge of flux normalization), exclusion power of result could be reduced.
Comparison to world data:

**Shape-only**

**Rate + Shape**

(blind result – stronger exclusion)

(added information - weakened exclusion)
Realization is fairly typical:

- stronger than sensitivity in some areas, weaker in others
- Always within 95% band from pseudo-data
Based on other mixing angles, how far can MB/LSND slide?

\[ \sin^2 2\theta_{ee} \equiv 4|U_{e4}|^2 (1 - |U_{e4}|^2) \]: 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.
This analysis: 1 year of data, requiring control of systematics at ~6-7% per bin
Data already in hand: 4 more years, requiring control of systematics at ~2-3% per bin

We are only just getting started!
Conclusions

* Sterile neutrinos are a compelling explanation of several anomalies in short-baseline experiments
* Introduction of a $\sim 1\text{eV}^2$ sterile neutrino would lead to dramatic MSW-resonant signatures in the atmospheric neutrino flux
* A search for these features was made using the IceCube neutrino telescope
* No evidence for sterile neutrinos was found
* New limits have been set on the 3+1 model, ruling out appearance region at $>99\%$ CL (IceCube only)
Thank you for your Attention
Conservatism of angle assumptions

Constraint from Minos data, $\text{Th}_{34} < 25$ deg at 90\%CL

*Phys.Rev.Lett.* 107 (2011) 011802
nu/nubar atmospheric flux average in zenith

\[ \frac{\phi_{\nu,\mu}}{\phi_{\bar{\nu},\mu}} \text{[dimensionless]} \]

- CombinedGHandHG-H3a-QGSJET-II-04
- CombinedGHandHG-H3a-SIBYLL2.3_rc1_pl
- PolyGonato-QGSJET-II-04
- PolyGonato-SIBYLL2.3_rc1_pl
- ZatsepinSokolskaya-pamela-QGSJET-II-04
- ZatsepinSokolskaya-pamela-SIBYLL2.3_rc1_pl
- Honda+Gaisser
Anomalous oscillations were at wavelengths shorter than expected given known $\Delta m^2$.

Another neutrino state with larger mass (~1eV$^2$)?

Constraints from LEP show that if such a particle exists, the corresponding extra flavor state must not be weakly interacting.

→ A sterile neutrino?
Neutrinos interact very weakly, so $g$ is very small.

Our experiments are typically more sensitive to refractive index than effects of incoherent scattering.

\[
(n - 1) \propto g \\
\sigma \propto g^2
\]
$\sin(2\theta_{24})^2 = 0.924$, $\Delta m_{41}^2 = 10.0\text{eV}^2$
\[
\begin{align*}
\sin^2 2\theta_{ee} &= \sin^2 2\theta_{14} \\
\sin^2 2\theta_{\mu\mu} &= 4 \cos^2 \theta_{14} \sin^2 \theta_{24} \left( 1 - \cos^2 \theta_{14} \sin^2 \theta_{24} \right) = \sin^2 2\theta_{14} \sin^2 \theta_{24} \\
\sin^2 2\theta_{\mu e} &= \sin^2 2\theta_{14} \cos^2 \theta_{24} \sin^2 \theta_{34} \\
\sin^2 2\theta_{\mu \tau} &= \sin^2 2\theta_{24} \cos^4 \theta_{14} \sin^2 \theta_{34}
\end{align*}
\]
Fedynitch et al

Honda et al