New Physics Searches With Astrophysical Neutrinos

Carlos Argüelles

Neutrino Platform Week,
CERN, 2019
This year we saw the highest energy neutrino event ever observed!

Deposited energy ~ 5 PeV
This event joins a family of PeV astrophysical neutrino events. How do we find them?

Color indicates time (red earlier, green later)
Sphere sizes indicate charge deposited.
Finding High-Energy Astrophysical Neutrinos
Challenges:

Astrophysical neutrino flux is very small

Large atmospheric neutrino and muon backgrounds
Strategy One: look at the Northern Sky

Strategy:
- Use the Earth to block the large atmospheric muon flux
- Look at the highest energy where the atmospheric neutrino flux is smallest
8 years of northern-sky neutrinos show consistent excess over atmospheric background

Northern-sky astrophysical neutrino flux is well characterized by single power-law with spectral index: $2.19\pm0.10$
Strategy Two: Use the other detector as a veto

Strategy:
- Define a veto region in the detector to suppress the atmospheric background,
- Advantage: All-sky vision
High-Energy Starting Events (HESE)

Large muon background that is well-separated

Astrophysical neutrinos candidates!
Energy distribution

\[ E^2 \Phi = 2.19 \times 10^{-18} (E/100\text{TeV})^{-0.91} \text{ [GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}] \]
HESE-7.5 years distribution

*HESE = high-energy starting events

**IceCube Preliminary**

- **Showers**
- **Tracks**

Deposited EM-Equivalent Energy in Detector (TeV)

sin(Declination)
HESE-7.5 years distribution

*HESE = high-energy starting events
Expected angular distributions

\[ E_\nu = 100 \text{ TeV} \]

\[ E^3 \Phi_\nu \left[ \text{GeV}^2 \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \right] \]

- Astrophysical \( \nu_\mu \)
- Conventional \( \nu_e \)
- Conventional \( \nu_\mu \)
- Prompt \( \nu_e \)
- Prompt \( \nu_\mu \)

\[ \cos \theta_z = - \sin \delta \]
Coincident muons suppress neutrino flux!

$E_\nu = 100 \text{ TeV}$

- Astrophysical $\nu_\mu$
- Conventional $\nu_e$
- Conventional $\nu_\mu$
- Prompt $\nu_e$
- Prompt $\nu_\mu$

An active muon veto removes down-going atmospheric neutrinos.

Primary cosmic ray

$\Pi^-$

$\nu_\mu$

$\mu$

1.5 km of ice

Schönert, Gaisser, Resconi, Schulz
Gaisser, Jero, Karle, van Santen
CA, Palomares-Ruiz, Austin Schneider,
Wille, Yuan
JCAP 1807 (2018) no.07, 047
HESE-7.5 years angular distribution

IceCube Work In Progress
HESE-7.5 years angular distribution

Northern Sky/Up-going

Southern Sky/Down-going

Events per 2635 days (> 60 TeV)

$\cos(\theta_z)$

Data
Astro.
Atmo. Conv.
Atmo. Muons
Atmo. Prompt 90% U.L.

IceCube Work In Progress

astro signal

suppressed background
HESE and Northern-sky muons

IceCube Work In Progress

From northern sky

All-sky HESE

$E_\nu^2 \cdot \Phi_{\nu^+\nu^-}$ [GeVcm$^{-2}$s$^{-1}$sr$^{-1}$]

Neutrino Energy [GeV]

10$^{-10}$

10$^{-9}$

10$^{-8}$

10$^{-7}$

HESE Differential

$\nu_\mu$ Best Fit

HESE Most Likely SPL
What about flavor?

Measuring a flavor composition outside of these regions points to new physics!

Latest astrophysical neutrino flavor measurement

\begin{figure}
\centering
\includegraphics[width=\textwidth]{chart.png}
\end{figure}

Sensitivity

Result

Track

Cascade

\begin{align*}
\nu_e & \quad \nu_\mu & \quad \nu_\tau \\
\text{Fraction of } & \quad \text{Fraction of } & \quad \text{Fraction of }
\end{align*}

\begin{align*}
0.0 & \quad 0.2 & \quad 0.4 \\
0.4 & \quad 0.6 & \quad 0.8 \\
0.8 & \quad 1.0 & \quad 0.0
\end{align*}

HESE with ternary topology ID
\begin{itemize}
\item Best fit: 0.29 : 0.50 : 0.21
\item Sensitivity, $E^{-2.9}$ spectrum
\item 1 : 1 : 1 flavor composition
\end{itemize}

\textbf{WORK IN PROGRESS}
First astrophysical $\nu_\tau$ candidate identified!

Total deposited energy $\sim 90$ TeV.

First “bang” in time (shower)

Second “bang” in time (tau decay)

Separation between bangs $\sim 17$ m,
New Physics Searches with Astrophysical Neutrinos
More: 1907.08690 CA, Bustamante, Kheirandish, Palomares-Ruiz, Salvadó, Vincent

Note: Not an exhaustive list
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Acts at production

- Heavy relics
- DM annihilation
- DM decay
- Sterile $\nu$
- Boosted DM
- NSI

Acts during propagation

- DM-$\nu$ interaction
- Lorentz+CPT violation
- Neutrino decay
- DE-$\nu$ interaction
- Long-range interactions
- Secret $\nu\nu$ interactions
- Supersymmetry
- Effective operators
- Leptoquarks
- Extra dimensions
- Superluminal $\nu$
- Monopoles

More: 1907.08690 CA, Bustamante, Kheirandish, Palomares-Ruiz, Salvadó, Vincent
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Affects energy spectrum

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Affects arrival directions

Affects flavor composition

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- Effective operators

Affects energy spectrum
Affects arrival directions
Affects flavor composition
Affects arrival times
Note: Not an exhaustive list

Affects energy spectrum
- Acts at production
  - Heavy relics
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  - DM decay
  - Sterile ν
  - Boosted DM-NSI

Affects arrival directions
- Acts during propagation
  - DM-ν interaction
  - DE-ν interaction
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Affects flavor composition
- Acts at detection

More: 1907.08690 CA, Bustamante, Kheirandish, Palomares-Ruiz, Salvadó, Vincent
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Acts at production:
- Heavy relics
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Acts during propagation:
- $\nu$ interaction
- Lorentz+CPT violation
- Neutrino decay
- Long-range interactions
- Secret $\nu$ interactions
- Effective operators
- Supersymmetry
- Leptoquarks
- Extra dimensions
- Superluminal $\nu$
- Monopoles

Acts at detection:
- Monopoles
- Leptoquarks
- Extra dimensions
- Superluminal $\nu$
- Effective operators
- Supersymmetry
- Secret $\nu$ interactions
- Long-range interactions
- Neutrino decay
- Lorentz+CPT violation
- $\nu$ interaction

Acts at production:

Acts during propagation:

Acts at detection:

Affects energy spectrum:

Affects arrival directions:

Affects flavor composition:

More: 1907.08690 CA, Bustamante, Kheirandish, Palomares-Ruiz, Salvadó, Vincent
Some examples
Note: Not an exhaustive list

- DM annihilation
- DM decay
- Heavy relics

Acts at production

Acts during propagation
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Acts at detection

Affects energy spectrum

Affects arrival directions

Affects flavor composition

More: 1907.08690 CA, Bustamante, Kheirandish, Palomares-Ruiz, Salvadó, Vincent
Dark matter decay

See talk by Marco Chianese!
CA, H. Dujmovic arXiv 1907.11193
Dark matter annihilation

See talk by Marco Chianese!
CA, H. Dujmovic arXiv 1907.11193
How does this look in the global vision?

Note: Not an exhaustive list
Dark matter neutrino scattering

DM-ν interaction will result in scattering of neutrinos from extragalactic sources, leading to anisotropy of diffuse neutrino flux.
Neutrino skymap
What about the cross section?

\[ \sigma_{DM-\nu} \propto E_{\nu}^2 \rightarrow \left( \frac{\text{PeV}}{T_{\nu,\text{recomb.}}} \right)^2 \sim 10^{30} \]

No!

\[ E \rightarrow \Lambda_{\text{New physics}} \]

The low energy approximation does not work at a PeV!!

Begin to resolve microphysics: need more concrete model
Two Simplified Models

**Fermion DM, vector mediator:**
similar to a leptophillic Z’ model

**Scalar DM, fermionic mediator:**
e.g. sneutrino dark matter, neutralino mediator.
Resonant behavior (s-channel)
Effects in energy and direction

IceCube Work In Progress

Galactic center
New constraints on neutrino-dark matter interactions

Color scale is the maximum allowed coupling.
Cosmological bounds using Large Scale Structure from Escudero et al 2016
We can also neutrinos from individual sources to constraint new interactions!

Kelley JCAP 1810 (2018) no.10, 048
Choi et al. arXiv:1903.03302
Note: Not an exhaustive list
We searched for it with one year of high-energy atmospheric data!

We analyzed one year of IceCube data ~ 20,000 events.
No evidence for a “dip” on the event distribution.

G. Collin, CA, J. Conrad, M. Shaevitz
Phys. Rev. Lett. 117, 221801
See also Dentler et al JHEP 1808 (2018)
8-year search in IceCube
Matter-Enhanced Oscillations With Steriles (MEOWS)

- Optimized event selection
- Improved systematics treatment

15 times more statistics available!
IceCube High-Energy Atmospheric Neutrino Sensitivities With MEOWS-8

\[ \Delta m_{41}^2 \text{ [eV}^2] \]

Brazil Bands 90\% C.L.

- Median Sensitivity
- 68\% (trials)
- 95\% (trials)

\[ \sin^2(2\theta_{24}) \]

IceCube Preliminary

Standard PNMS matrix

\[
U \equiv \begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} & U_{e4} \\
U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\
U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\
U_{s1} & U_{s2} & U_{s3} & U_{s4}
\end{pmatrix}
\]

- \[ |U_{e4}|^2 = 0 \] Assumption (pure $\nu_\mu$ event selection)
- \[ |U_{\mu 4}|^2 = \sin^2 \theta_{24} \] Primary parameter of interest
- \[ |U_{\tau 4}|^2 = \cos^2 \theta_{24} \cdot \sin^2 \theta_{34} \] Secondary parameter of interest

Not necessary since we assume the vPNMS matrix to be unitary.
+ (eV) sterile neutrino

- Sterile neutrinos effect is small on propagation.
- Large change only if the sources are shooting sterile neutrinos

Brdar et al. JCAP 1701 (2017) no.01, 026
 sterile neutrino

Note: Not an exhaustive list
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+Neutrino decay

Normal hierarchy (active only; $\nu_1$ stable)

Neutrino lifetime $\tau_2$, $\tau_3$ [s]

Neutrino mass $m_2$, $m_3$ [eV]

Mixing + decay
$\theta_{ij}, \delta_{CP}$: var. 3$\sigma$

NH

M. Bustamante, J. Beacom, K. Murase (1610.02096)
Invisible Neutrino Decay Resolves IceCube's Track and Cascade Tension

\[ \chi^2 = \sum_{i \in \{t,c\}} \left( \frac{\Phi_i - \Phi_{i,IC}}{\sigma_{\Phi_{\nu,i}}} \right)^2 + \left( \frac{\gamma_i - \gamma_{i,IC}}{\sigma_{\gamma_i}} \right)^2 \]
Note: Not an exhaustive list

- Lorentz+CPT violation
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- Secret νν interactions
- Supersymmetry
- Effective operators
- Leptoquarks
- Extra dimensions
- Superluminal ν
- Monopoles
- Boosted DM
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- DM annihilation
- DM decay
- Heavy relics

More: 1907.08690 CA, Bustamante, Kheirandish, Palomares-Ruiz, Salvadó, Vincent
We have search for Lorentz Violation with high-energy Atmospheric Neutrinos

The analysis sensitivity, especially for high-dimensional operators, is dominated by the highest-energy events.

\[ H \sim \frac{m^2}{2E} + \hat{a}^{(3)} - E \cdot \hat{c}^{(4)} + E^2 \cdot \hat{a}^{(5)} - E^3 \cdot \hat{c}^{(6)} \ldots. \]

Lorentz violation changes the ratio of horizontal to vertical events.

\[ P_{\text{osc}}(c^{(6)}_{\mu\tau} E\nu L) \]

Lorentz violation changes the ratio of horizontal to vertical events.
Leading constraints across several fields of physics

<table>
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<tr>
<th>dim.</th>
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<th>type</th>
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<td>$</td>
<td>\text{Re}(\tilde{a}_{\mu T}^{(8)})</td>
</tr>
</tbody>
</table>

Very strong limits on Lorentz Violation induced by dimension-6 operators! Nature Physics (2018) s41567-018-0172-2
+ New physics: effective operators

\[ H = \frac{1}{2E} U M^2 U^\dagger + \sum_n \left( \frac{E}{\Lambda_n} \right)^n \tilde{U}_n O_n \tilde{U}_n^\dagger \]

(setting operators scales to current SK bounds)

\[ O_0 \sim O(10^{-26}) \text{ GeV} \]

\[ O_0 \sim O(10^{-29}) \text{ GeV} \]
Trajectories in the flavor triangle in the presence of Lorentz Violation (LV)

IceCube Preliminary
Results on high-dimensional LV operators

hashed: atmospheric neutrinos, solid: astrophysical neutrinos

Excluded regions
- $0:1:0$ at source
- $1:0:0$ at source
- Planck Scale Expectation

New Physics Scale $[\log_{10}(\Lambda^{-1}/\text{GeV}^{-d+4})]$
Note: Not an exhaustive list
Results on high-dimensional LV operators
hashed: atmospheric neutrinos, solid: astrophysical neutrinos

Excluded regions
- $0:1:0$ at source
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Energy-independent BSM potential constraints

$(1:2:0)$ source
$(0:1:0)$ source
$(1:0:0)$ source

$V_{e\tau} < 10^{-27}\text{GeV}$
$V_{\mu\tau} < 10^{-28}\text{GeV}$

New Physics Scale $[\log_{10}(\Lambda^{-1} / \text{GeV}^{-d+4})]$
Beyond the Lorentz Violation interpretation

Our analysis is performed by introducing effective terms, which can be due to by other new physics beyond Lorentz Violation.

\[ H = \frac{1}{2E} U M^2 U^\dagger + V_{\text{new physics}} \]

\( V_{e\tau} < 10^{-27}\text{GeV} \)  
\( V_{\mu\tau} < 10^{-28}\text{GeV} \)

New long range forces gauged on \( L_e - L_\alpha \)

Caveat: need to know neutrino source initial flavor composition to get robust bounds with current limits.

Bustamante et al. 1808.02042
Coherent Dark Matter Scattering

\[ H = \frac{1}{2E} U M^2 U^\dagger + V_{\text{new physics}} \]

Standard term \[ V_{e\tau} < 10^{-27}\text{GeV} \]
New physics term \[ V_{\mu\tau} < 10^{-28}\text{GeV} \]

(0:1:0) source
(1:0:0) source

Coherent scattering with dark cosmic background

Our analysis is performed by introducing effective terms, which can be due to by other new physics beyond Lorentz Violation.

\[ V_D \sim G_D N_D \]
\[ G_D \sim \frac{g_d^2}{M_D^2} \]

Caveat: need to know neutrino source initial flavor composition to get robust bounds with current limits.

Capozzi et al. 1804.05117
Summary and outlook

● High-energy astrophysical neutrinos provide a new way to look at the Universe and study neutrinos.
● Multiple observables: energy, flavor, and direction available for new physics searches! Many ideas in the literature!
● Data keeps coming! Many more neutrino observatories soon: Km3Net, GVD, and the IceCube-Upgrade.
● The future is bright in neutrinos!
Thank you!
Gracias!