Constraining Dark Matter-Neutrino Interactions with Cosmic Neutrinos

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Outline

• IceCube high energy astrophysical neutrinos
• Dark matter-neutrino interactions
• Scattering of diffuse high energy neutrinos propagating through dark matter
• Analysis method
• Upper limits and cosmology
High energy cosmic neutrinos: Discovery

- IceCube discovered neutrinos with astrophysical origin in 2013.
- Since the discovery IceCube has been observing cosmic neutrinos continuously.
- Source of HE neutrinos still unknown.
High Energy Neutrinos: flux properties

- 54 Events in 4 years.
- Events spatial distribution compatible with isotropic hypothesis.
- No correlation with Galactic plane.
- Event distribution suggests extragalactic origin for the majority of the events.
- Flavor ratio is consistent with 1:1:1 ratio.

\[ E^2 \phi(E) = 2.2 \pm 0.7 \times 10^{-8} (E/100\text{TeV})^{-0.58} \text{GeVcm}^{-2}\text{s}^{-1}\text{sr}^{-1} \]
Dark matter neutrino interactions

DM annihilation near Weak Scale: **WIMP Miracle**

DM-DM → SM-SM

DM-ν interaction motivated by light DM scenarios and appears e.g. in models where dark matter is sneutrino.

SM-DM → DM-SM

basis of direct underground DM experiments searching for DM-q
DM density is largest in center of the galaxy.

DM-\(\nu\) interaction will result in scattering of neutrinos from extragalactic sources, leading to anisotropy of diffuse neutrino flux.
Simplified models of interactions

DM particle

Scalar
Fermion

Mediator

Scalar
Fermion
Fermion
Vector

Couplings

$g_\nu g_\chi$
Scalar/scalar
Fermion/scalar
Fermion/fermion/Vector

$g^2$
Scalar/fermion
Neutrino-dark matter interaction

\[ \frac{d\phi(E)}{d\tau} = -\sigma(E)\phi(E) + \int d\tilde{E} \frac{d\sigma(\tilde{E}, E)}{dE} \phi(\tilde{E}) \]

\[ \tau(b, l) = \int_{l.o.s.} n_{\chi}(x; b, l) dx \]

**DM profile: Einasto**
Analysis method

Full Unbinned likelihood based on IceCube’s event energies and arrival direction

$$\log \mathcal{L}(\{t, E, \vec{x}\} | \vartheta) = \sum_i \log \sum_{f=e,\mu,\tau} P^{astro}(t_i, E, \vec{x})P(t_i | f, E)\phi(E, b, l | \vartheta)$$

We establish a limit based on Markov Chain Monte Carlo search of the parameter space of each interaction model: DM mass, mediator mass, and the coupling strength.

The model dependence of the likelihood thus comes from the directional backscattering with respect to the isotropic hypothesis.
Cosmological constrains

Cosmological limits on the DM-$\nu$ scattering cross section are obtained for two forms of the low-energy cross section:

- **constant with temperature**
  \[ \sigma_{\text{const.}} < 6 \times 10^{-31} \left( \frac{m_\chi}{\text{GeV}} \right) \text{ cm}^2 \]

- **proportional to $T^2$**
  \[ \sigma_{T^2} < 2 \times 10^{-40} \left( \frac{m_\chi}{\text{GeV}} \right) \left( \frac{T}{T_0} \right)^2 \text{ cm}^2 \]
  \[ T_0 = (4/11)^{1/3} T_{\text{CMB}} = 1.95K \]
  \[ \langle E_{\nu}^2 \rangle \propto T^2 \]
  
  - cosmological neutrino temperature today
  - average energy per neutrino in a Fermi-Dirac distribution

*If the cross section is proportional to $E^2$, then we could look at high energy regimes to constrain the parameter space.*

arXiv:1505.06735
Scalar DM, Scalar Mediator

our bound

low energy limit: $\sigma \approx \frac{g_{\nu}^2 g_{\chi}^2 E^2}{16\pi m_{\phi}^4 m_{\chi}^2}$

cosmology+our bound
Scalar DM, Scalar Med.
Fermion DM, Scalar Med.

**low energy limit:**  
\[ \sigma \approx \frac{g_\nu^2 g_\chi^2 E^2}{16\pi m_\phi^4 m_\chi^2} \]

**our bound**  
Fermion DM, Scalar Mediator

**cosmology+our bound**  
Fermion DM, Scalar Mediator
Fermion DM, Vector Mediator.

**our bound**

Fermion DM, Vector Mediator

\[
\begin{align*}
\log m_\phi (\text{GeV}) \\
\log m_\chi (\text{GeV}) \\
\text{low energy limit: } \sigma \approx \frac{g_\chi^2 g_\nu^2 E_\nu^2}{2\pi m_\phi^4}
\end{align*}
\]

**cosmology+our bound**

Fermion DM, Vector Mediator

\[
\begin{align*}
\log g_\chi g_\nu (\text{GeV}) \\
\log m_\phi (\text{GeV}) \\
\log m_\chi (\text{GeV}) \\
\end{align*}
\]
Scalar DM, Fermion Med.

**our bound**

Scalar DM, Fermion Mediator

- **log** $m_\phi$ (GeV)
- **log** $m_\chi$ (GeV)

low energy limit:

$$\sigma \approx \frac{g^4 m_\phi^2 E_\nu^2}{2\pi m_\chi^2 (m_\chi^2 - m_\phi^2)^2}$$

**cosmology+our bound**

Scalar DM, Fermion Mediator

- **log** $m_\phi$ (GeV)
- **log** $m_\chi$ (GeV)
Summary

• Dark Matter-Neutrino interactions are motivated in beyond standard models.
• The discovery of high energy cosmic neutrinos allows us to investigate DM-neutrino interactions.
• The upper limits found on the model parameters are stronger than cosmological constraints in parts of the parameter space.
• Observation of more events would provide stronger constraints, and allow for discovery of this interaction for large part (low DM + med mass) of the parameter space.
Bonus Slides
• update of $\nu_\mu + \bar{\nu}_\mu$ search ("IC tracks")

$\rightarrow$ mild tension with cascade-dominated samples: indication of spectral features?

Credit: Markus Ahlers
IceCube HESE (4yr)

- **High-Energy Starting Event (HESE) sample:** [IceCube Science 342 (2013)]
  - bright events \(E_{\text{th}} \gtrsim 30\text{TeV}\) starting inside IceCube
  - efficient removal of atmospheric backgrounds by veto layer

- 54 events in about four years: [IceCube ICRC'15]
  - 39 **cascades** events
  - 14 **track** events
  - 1 **composite** event (removed)

- expected background events:
  - 9.0\(^{+8.0}_{-2.2}\) **atmospheric neutrinos**
  - 12.6 \(\pm 5.1\) **atmospheric muons**

- best-fit \(E^{-2}\)-flux 60TeV-3PeV (6.5\(\sigma\)):
  \[E^{2}_{\nu} \phi_{\nu_{x}} \simeq (0.84 \pm 0.3) \times 10^{-8} \frac{\text{GeV}}{\text{s cm}^{2} \text{ sr}}\]

Credit: Markus Ahlers
High Energy Neutrinos: Samples

- High Energy Starting Events
  whole sky, 4 years, all flavors, veto
- Through going tracks
  northern sky, 6 years, muons
- Medium Energy Starting Events
  whole sky, 2 years, cascades, veto

Global Fit
DM profiles

\[ \rho_{\text{DM}} \text{ [GeV cm}^{-3}\text{]} \]

\[ \rho_\odot = 0.4 \text{ GeV cm}^{-3} \]

\[ r_\odot = 8.5 \text{ kpc} \]

\[ \text{Isothermal} \]

\[ \text{NFW} \]

\[ \text{Einasto} \]

\[ \text{NFW}_c \]

\[ \text{arXiv:1503.07169} \]