Geometric Compatibility of IceCube TeV-PeV Neutrino Excess and its Galactic Dark Matter Origin

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We perform a geometric analysis for the sky map of the IceCube TeV-PeV neutrino excess and test its compatibility with the sky map of decaying dark matter signals in our galaxy. Using both Kolmogorov-Smirnov and the likelihood-ratio tests, we have found that the observed event sky map prefers to have a combination of the galactic dark matter and a homogeneous background contribution, compared to a purely galactic dark matter origin. For the assumption that the galactic dark matter is responsible for all neutrino excess, the current data can also exclude a wide range of dark matter profiles except flatter profiles such as the isothermal one. We also consider several representative decaying dark matter spectra, which can provide a good fit to the observed spectrum at IceCube with a dark matter lifetime of around 12 orders of magnitude longer than the age of the universe.

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Introduction

One of the important tasks for physicists is to understand the nature of dark matter (DM). The indirect search of DM from its self-annihilation or decay serves as a promising approach to learn additional interactions of DM with Standard Model (SM) particles. Among many potential products from DM annihilation or decay, neutrino serves a useful candidate because its propagation is less disturbed by the interstellar medium and its observation may point out the DM geometric distribution in the galaxy.

The existing searches of DM from cosmic neutrinos have been concentrated on the galactic center, dwarf galaxies, clusters of galaxies or the center of the Sun 1-4. All previous searches have found good agreements between the neutrino spectrum and the predicted astrophysical background. The story has been changed recently from the observation of 28 high energy neutrino events at IceCube for neutrino energy above 30 TeV 5, which is well above the predicted number of the background events, 10.6+5.0−3.6 6, 7 and has a 4.0σ inconsistency with the standard atmospheric backgrounds.

This IceCube result is based on data taken between May 2010 and May 2012 using detectors with 79 and 86 strings respectively and has a total integrated time of 662 days. The observed 28 events have two events slightly above 1 PeV 8 and the remaining 26 events with an energy between 25 TeV and 0.3 PeV. The observed events can also be divided into “track” and “cascade” events, depending on event shapes. The track events are most likely produced by muon neutrinos via charge-current interactions, while the cascade events could come from electron neutrinos with charge-current interactions or all types of neutrinos with neutral-current interactions. Among the 28 events, the seven track events have a good angular resolution with around 1° uncertainty around the event direction, while the other 21 cascade events have poor angular resolutions ranging from ∼10° to ∼50°.

The angular resolutions of those events play an important role for identifying the geometric origin of the neutrino excess. The IceCube collaboration has performed a point source analysis for the 28 events and found that there is no significant evidence of spatial clustering and the p-value for the hypothesis of a uniform event distribution is 80% 5. Curious about the possible linkage between the TeV-PeV neutrino excess at IceCube and the mysterious DM in our universe, in this paper we analyze the IceCube data with a special attention on its geometric distributions, and study the statistical significance of its potential DM origin, which prefers to have more signal events around the galactic center because of the DM spatial profile.

One could consider DM annihilation as an explanation. However, due to the unitarity bound 9, 10, we found that the annihilation rate for a DM mass around one PeV is about four orders of magnitude lower than the required one for the IceCube data. Therefore, we concentrate on the decaying DM case, which can match to the required rate for a DM lifetime of 10^{28}−10^{29} s. In this paper we do not provide a theoretical understanding of the DM mass scale and the decay lifetime, but we want to point out that a heavy DM with a non-thermal history has been widely predicted in many models 11, 12.

Before entering into our detailed geometric analysis, we point out other recent explanations for the IceCube neutrino excess including cosmogenic productions via photo-meson interactions 13, 15, galactic sources 14, active galactic nuclei 15, 20, 21, gamma-ray bursts 15, 22, and a leptoquark beyond the SM 23.

Geometric analysis for decaying dark matter based on the Kolmogorov-Smirnov test

Our main goal is to study the compatibility of the neutrino sky map from DM and the sky map of the observed events at Ice-
For the integrated time of 662 days and 10 m
2 tails). We define the DM probability distribution using
galactic coordinate in the latitude and longitude angles
translate the DM generated event distribution from the
represented in the equatorial coordinate. We, therefore,
be around 10 events observed at IceCube.

The integrated neutrino flux from DM is
normalized neutrino differential spectrum is
\[
\Phi_\nu = \frac{d\Phi_\nu}{dE_\nu} \cos b \int ds \rho_\text{DM}[r(s)],
\]
where the integral of \( s \) is along the line of sight and the
relation between \( r \) and \( s \) is \( r^2 = s^2 + r_\odot^2 - 2s r_\odot \cos l \cos b \),
where \( -90^\circ < b < 90^\circ \) and \( -180^\circ < l < 180^\circ \) as the
latitude and longitude angles in the galactic coordinate.
\( \tau_\text{DM} \) is the DM lifetime and \( m_\text{DM} \) is the DM mass. The
normalized neutrino differential spectrum is \( dN/(NdE_\nu) \).
The integrated neutrino flux from DM is
\[
\Phi_\nu = 1.7 \times 10^{-12} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \times \frac{10^{28} \text{ s}}{\tau_\text{DM}} \times \frac{1 \text{ PeV}}{m_\text{DM}}.
\]

For the integrated time of 662 days and 10 m\(^2\) \cdot sr acceptance area for the energy around 100 TeV, there could
be around 10 events observed at IceCube.

The geometric distribution of the IceCube events is
represented in the equatorial coordinate. We, therefore,
translate the DM generated event distribution from the
galactic coordinate in the latitude and longitude angles
\((b, l)\) to the equatorial coordinate in the declination angle
and the right ascension angle \((\delta, \alpha)\) (see Ref. \[24\] for de-
tails). We define the DM probability distribution using
the normalized flux
\[
p_{\text{DM}}(\delta, \alpha) = \frac{1}{\Phi_\nu} \frac{d\Phi_\nu}{d\delta d\alpha},
\]
with the DM event sky map shown in the left panel of
Fig. 1. For all or subsets of the observed 28 events from
IceCube, we construct the data probability distribution
using the solid-angular error \( \sigma_i \) for each event by assum-
ing a Gaussian distribution
\[
p_{\text{data}}(\delta, \alpha) = \frac{1}{N} \sum_{i \in N} \frac{1}{2\pi\sigma_i^2} \exp \left[ -\frac{\Delta R(\delta_i, \alpha_i; \delta, \alpha)^2}{2\pi\sigma_i^2} \right],
\]
where \( \Delta R(\delta_i, \alpha_i; \delta, \alpha) \) is the angular distance between
the points \((\delta_i, \alpha_i)\) and \((\delta, \alpha)\) on the sphere. In the right panel
of Fig. 1, we show the sky map of the observed \( N = 28 \)
events at IceCube after implementing the angular resolution
for each event. Comparing these two maps, one can see
that both have a concentration of events around the
galactic center direction. On the other hand, the DM sky
map has very few events in the right and upper corner,
while the IceCube data map has some population in this
region.

To quantify the similarity of the two sky maps in Fig. 1,
we perform a statistical test to calculate the \( p \)-value of the
hypothesis of decaying DM as an explanation of IceCube
neutrino excess. We first use a two-dimensional version
of the Kolmogorov-Smirnov (KS) test statistics (TS) \[24\]
to study the compatibility between the data and the DM
hypothesis. We will use the maximum likelihood-ratio
test as well later. The KS test statistics is defined as the
largest absolute difference between cumulative prob-
ability distributions of the data and the model. It takes
better account of the relation among data points than
the traditional likelihood-ratio test.

To make the definition of the TS less sensitive to the
integration directions, we consider a set of four possible

\[\text{FIG. 1: Left panel: the sky map of the neutrinos from decaying DM with an Einasto profile in Eq. (1). Right panel: the sky}
\text{map of the IceCube 28 events after taking into account the angular resolution. The seven red spots correspond to the seven}
\text{“track” events.}\]
Since the atmospheric backgrounds are dominated in lower energies \([6, 7]\), a bigger fraction of the observed events could be from DM signals if only relatively high energy events are selected. Therefore, we also test the geometric distributions for the 18 events with \(E \gtrsim 50\) TeV. We show the \(p\)-values for all 28 events and the 18 events with \(E \gtrsim 50\) TeV in Table I. One can see that the \(p\)-values are fairly insensitive to the energy cut. In the last row of Table I we also show the \(p\)-values for only the cascade events considering the fact that the track events could have an origin from the atmospheric muon background. From Table I one can already see that there is no dramatrical difference between \(\bar{\alpha} = 0.25\) and \(\bar{\alpha} = 0.17\) cases. This is due to the poor angular resolution of cascade events such that the peaked center of the DM profiles can not be resolved. The increase of the \(p\)-values for the homogeneous distribution from all 28 events to 21 cascade events is due to the extremely good resolution of the 7 track events.

**Geometric analysis using the likelihood ratio test** In this section we check the compatibility of the data with the DM profile using a likelihood ratio test, which was used by the IceCube collaboration in their point source analysis \([27]\). We first treat the homogenous distribution as the null hypothesis with an alternative ho-

\[ S(\delta_0, \alpha_0) = \{(\delta < \delta_0, \alpha < \alpha_0), (\delta > \delta_0, \alpha < \alpha_0), (\delta < \delta_0, \alpha > \alpha_0), (\delta > \delta_0, \alpha > \alpha_0)\} \quad (6) \]

for a given boundary choice \((\delta_0, \alpha_0)\). The TS or the difference of the cumulative probability distributions is defined by

\[ TS(\delta_0, \alpha_0) \equiv \sup_{r \in S(\delta_0, \alpha_0)} \left| \int r \, d\delta \, d\alpha \, p_{\text{model}}(\delta, \alpha) - \int r \, d\delta \, d\alpha \, p_{\text{data}}(\delta, \alpha) \right|. \quad (7) \]

Choosing the largest value for all possible boundary choices, we have the KS test statistics as

\[ TS_{\text{KS}} = \sup \left\{ \bigcup_{(\delta_0, \alpha_0)} TS(\delta_0, \alpha_0) \right\}. \quad (8) \]

To calculate the \(p\)-value for the decaying DM as an explanation for the data, we generate random event maps by choosing a random (according to the model profile) right-ascension angle but keeping the same inclination angle and resolution of the event in the data. In the left panel of Fig. 2 we show the TS distribution of the reference decaying DM model against maps of randomly sampled 28 events. The red vertical line indicates the test statistics \(TS(DM)\) of DM against the observed 28 events at IceCube. The \(p\)-value, or the probability of having \(TS(DM)\) smaller than the TS value from a random event map, is 21.98% for the Einasto model with \(\bar{\alpha} = 0.17\). To test how good the observed 28 events agree with a homogeneously geometrical distribution, we perform the same calculation by assuming a homogeneous model (in the right panel of Fig. 2) and found that the \(p\)-value for a homogeneous distribution is 72.14% for all 28 events.

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We define the likelihood function as
\[ \mathcal{L}(n_s) = \prod_{i} \left[ n_s S_i + \left( 1 - \frac{n_s}{N} \right) B_i \right], \]
where \( B_i \) is the homogeneous background contribution and \( S_i \) is the signal DM contribution. The \( n_s \) is the number of signal events and will be used to maximize the likelihood. We use the observed data locations and errors convoluted by the DM probability distribution to calculate the signal contribution \( S_i \) as
\[ S_i = \int \frac{1}{2\pi\sigma_i^2} e^{-\frac{|\vec{x}_i - \vec{x}_s|}{2\sigma_i^2}} p_{\text{DM}}(\vec{x}_s) d^2\vec{x}_s. \]

Here, \( \vec{x}_i \) is a vector, defined in the \((\delta, \alpha)\) plane, from the location of the observed event and \( \sigma_i \) is the corresponding angular error. We show the log-likelihood function as a function of signal strength \( n_s/N \) in Fig. 3 for three cases: all 28 events, 18 events with \( E > 50 \) TeV and 21 cascade events. We can see from Fig. 3 that the preferred values of \( n_s \) are positive, which suggests that a combination of DM plus homogenous distributions fit the data better than the homogenous-only fit. Comparing the best fitted values of \( n_s \) for \( \bar{\alpha} = 0.17 \) and \( \bar{\alpha} = 0.40 \), one can see that a larger value of \( \bar{\alpha} \) or a flatter DM profile prefers more DM signal events.

To quantify the p-value of the data to reject the homogenous-only hypothesis against the homogenous plus DM hypothesis, we calculate the test statistic as
\[ \text{TS} = \max_{n_s} \left\{ 2 \log \left[ \frac{\mathcal{L}(n_s)}{\mathcal{L}(0)} \right] \right\}. \]

As we did in the last section we compute the p-values by scrambling the events in right ascension angle \( \alpha \) with a distribution consistent with the background. For all the 28 IceCube events, we show the histogram for the TS distribution in Fig. 4 and have the vertical and red line at the real data location. For all three choices of events, we show the p-values and the \( n_s \)'s at the maximum likelihood for two different values of \( \bar{\alpha} \) in Table II, which clearly show that the 21 cascade events have a smaller value for the homogenous-only hypothesis.

|                  | \( \bar{\alpha} = 0.17 \) | \( \bar{\alpha} = 0.25 \) |
|------------------|--------------------------|--------------------------|
| all 28 events    | 33.4% (14.2)             | 36.0% (15.3)             |
| 18 events \( E \gtrsim 50 \) TeV | 25.0% (9.1)             | 27.2% (9.5)             |
| 21 cascade events| 15.8% (16.7)             | 17.9% (18.0)             |

TABLE II: The p-values using the likelihood method using all the events, only the events with \( E \gtrsim 50 \) TeV and only the cascade events. The numbers in the parenthesis are the numbers of signal events after maximize the log-likelihood. Here, we have \( S = \text{DM} \) and \( B = \text{homogeneous} \) in Eq. (10).

Another interesting question one can ask is whether one can exclude the purely galactic DM hypothesis against the galactic DM plus homogeneous distribution (a part of the homogeneous distribution could come from extragalactic DM or other astrophysical objects). We also calculate the p-values for this case. Specifically, one just need to choose \( B = \text{DM} \) and \( S = \text{homogeneous} \) in

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1 We have also calculated the p-value's for the point source signal hypothesis and found a good agreement with the result obtained by the IceCube collaboration [5].
Events

P-value

662 Days

0.01

0.00

0.02

0.04

0.06

0.1

10

0.15

1

20

50

100

200

500

1000

2000

0.00

0.02

0.04

0.06

0.08

0.1

1

10

100

FIG. 5: The $p$-values as a function of $\bar{\alpha}$ of the Einasto DM profiles. A suggestive $p$-value of 0.05 to exclude a certain DM model is shown in the horizontal and black line. Here, we have $S=$homogeneous and $B=$DM, to have the DM distribution as the null hypothesis.

Neutrino spectra from dark matter decays

The energy spectrum of the IceCube neutrino excess has interesting features [5]. First, there are two isolated events at around 1 PeV [8] with one at 1.04 ± 0.16 PeV and the other one at 1.14 ± 0.17 PeV. Secondly, there is an potential energy cutoff at $1.6^{+1.3}_{-0.4}$ PeV. Thirdly, there is an energy gap or no neutrino events observed in the energy range of $\sim (0.3, 1)$ PeV, which is not significant at this moment. Although a wide range of the energy spectrum can be fit by an $E^{-2}$ feature [5], it is still interesting to explore potential DM produced spectra from particle physics.

To fit the observed spectrum at IceCube, one also needs to consider different detector acceptances at different energies. For different flavors of neutrinos, the acceptance areas vary a lot with the largest one for the electron neutrino. In our analysis below, we don’t distinguish different flavors of neutrinos and use the averaged acceptance areas in terms of flavors and declination angles [5], which are only slightly different from Ref. [17]. Because the uncertainties on the acceptance areas and the large statistical errors, the current IceCube data is not sufficient to distinguish spectra among different particle physics models. So, we consider several representative decaying DM models and study their fit to the observed energy spectrum. We consider candidate models according to the operator dimensions of DM coupling to SM particles. At the renormalizable level and for a fermion DM $\chi$, we consider the operator $\lambda H \bar{L}_L \chi$ for DM coupling to the Higgs field in the SM or $\lambda H L \bar{L}_X$ in the lepton-specific two-Higgs doublet models, which has DM decays as $\chi \rightarrow h + \nu$ and $\chi \rightarrow \nu + H_L \rightarrow \nu + \tau^+ + \tau^-$, respectively. Fixing the fermion DM mass to 2.2 PeV, we show the fitted spectra for several DM decay channels. The black and solid line is the atmospheric backgrounds [6, 7]. For the two fermion DM cases, the DM mass is 2.2 PeV and both lifetimes are $\tau_{\chi} = 3.5 \times 10^{29}$ s. For the two scalar DM cases, the DM mass is 5 PeV and the lifetimes are $9.2 \times 10^{28}$ s and $4.6 \times 10^{29}$ s, for 2h and $\tau^- + \tau^+$ channels, respectively.

FIG. 6: The fitted spectra for several DM decay channels. The black and solid line is the atmospheric backgrounds [6, 7]. For the two fermion DM cases, the DM mass is 2.2 PeV and both lifetimes are $\tau_{\chi} = 3.5 \times 10^{29}$ s. For the two scalar DM cases, the DM mass is 5 PeV and the lifetimes are $9.2 \times 10^{28}$ s and $4.6 \times 10^{29}$ s, for 2h and $\tau^- + \tau^+$ channels, respectively.
DM spacial profile like the isothermal one is used. The IceCube has more data to be analyzed and collected, so a more robust conclusion can be drawn in the coming years. Other than IceCube, another neutrino telescope, ANTARES [31], has reached a comparable sensitivity in some declination angle region. A geometric test for the compatibility between the neutrinos (excess) observed in ANTARES and a decaying DM will be demanding.

Beyond the neutrino signal from DM, one could also search for other correlated and for sure model-dependent cosmic ray signatures from the DM decays at other experiments like Fermi LAT [26, 27], PAMELA [31, 32], AMS-02 [33] and HESS [36]. In the few respective models considered in Fig. 6 additional photons, positrons and antiprotons can be produced at the same time when a neutrino signal is generated. Using the model with $\chi \rightarrow h + \nu$ as an example, we show the yields of neutrino, positron, antiproton and photon from a single DM decay in Fig. 7. One can see that the neutrino yield is considerably higher than the photon, positron and antiproton yields in every bin. Furthermore, because of the long DM lifetime of $10^{28} - 10^{29}$ s, the predicted photon, positron and antiproton fluxes have been checked to satisfy the current cosmic ray constraints.

The PeV scale DM considered here is definitely beyond the scope of high energy collider searches. If additional interactions exist between DM and quarks, the direct detection experiments may see a signature [37]. If the IceCube excess is indeed due to decaying DM, a new avenue to understanding the DM properties will be opened.

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[1] F. Halzen and D. Hooper, New J.Phys. 11, 105019 (2009), 0910.4513.
[2] T. Tanaka et al. (Super-Kamiokande Collaboration), Astrophys.J. 742, 78 (2011), 1108.3384.
[3] M. Aartsen et al. (IceCube collaboration), Phys.Rev.Lett. 110, 131302 (2013), 1212.4907.
[4] S. Adrian-Martinez et al. (ANTARES Collaboration) (2013), 1302.6516.
[5] M. Aartsen et al. (IceCube Collaboration), Science 342, 12482856 (2013), 1311.5238.
[6] M. Honda, T. Kajita, K. Kasahara, S. Midorikawa, and T. Sanuki, Phys.Rev. D75, 043006 (2007), astro-ph/0611148.
[7] R. Enberg, M. H. Reno, and I. Sarcevic, Phys.Rev. D78, 043005 (2008), 0806.0418.
[8] M. Aartsen et al. (IceCube Collaboration), Phys.Rev.Lett. 111, 021103 (2013), 1304.5356.
[9] K. Griest and M. Kamionkowski, Phys.Rev.Lett. 64, 615 (1990).
[10] L. Hui, Phys.Rev.Lett. 86, 3467 (2001), astro-ph/0103249.
[11] D. J. Chung, E. W. Kolb, and A. Riotto, Phys.Rev. D59, 023501 (1999), hep-ph/9802238.
[12] D. J. Chung, E. W. Kolb, and A. Riotto, Phys.Rev.Lett. 81, 4048 (1998), hep-ph/9805473.
[13] L. Covi, M. Greve, A. Ibarra, and D. Tran, JCAP 1004, 017 (2010), 0912.3521.
[14] B. Feldstein, A. Kusenko, S. Matsumoto, and T. T. Yanagida (2013), 1303.7320.
[15] I. Cholis and D. Hooper, JCAP 06, 030 (2013), 1211.1974.
[16] R. Laha, J. F. Beacom, B. Dasgupta, S. Horikuchi, and K. Murase (2013), 1306.2309.
[17] L. A. Anchordoqui, H. Goldberg, M. H. Lynch, A. V. Olinto, T. C. Paul, et al. (2013), 1306.5021.
[18] W. Winter (2013), 1307.2793.
[19] M. Gonzalez-Garcia, F. Halzen, and V. Niro (2013), 1310.7194.
[20] O. E. Kalashev, A. Kusenko, and W. Essex, Phys.Rev.Lett. 111, 041103 (2013), 1303.0300.
[21] F. W. Stecker (2013), 1305.7404.
[22] K. Murase and K. Ioka (2013), 1306.2274.
[23] V. Barger and W.-Y. Keung (2013), 1305.7404.
[24] A. W. Graham, D. Merritt, B. Moore, J. Diemand, and B. Terzic, Astron.J. 132, 2701 (2006), astro-ph/0608613.
[25] T. Neunhoffer, Astropart.Phys. 25, 220 (2006), astro-ph/0403367.
[26] J. A. Peacock, Monthly Notices of the Royal Astronomical Society 202, 615 (1983).
[27] J. Braun, J. Dunn, F. De Palma, C. Finley, A. Karle,
et al., Astropart.Phys. 29, 299 (2008), 0801.1604.
[28] A. Burkert, Astrophysical Journal 447, L25 (1995).
[29] T. Sjostrand, S. Mrenna, and P. Z. Skands, Comput.Phys.Commun. 178, 852 (2008), 0710.3820.
[30] A. Esmaili and P. D. Serpico (2013), 1308.1105.
[31] S. Adrian-Martinez et al. (ANTARES Collaboration), Astrophys.J. 760, 53 (2012), 1207.3105.
[32] M. Ackermann et al. (Fermi-LAT collaboration), Astrophys.J. 761, 91 (2012), 1205.6474.
[33] A. Abdo et al. (Fermi-LAT Collaboration), Astrophys.J. 712, 147 (2010), 1001.4531.
[34] O. Adriani et al. (PAMELA Collaboration), Nature 458, 607 (2009), 0810.4995.
[35] O. Adriani et al. (PAMELA Collaboration), Phys.Rev.Lett. 105, 121101 (2010), 1007.0821.
[36] M. Aguilar et al. (AMS Collaboration), Phys.Rev.Lett. 110, 141102 (2013).
[37] I. F. Albuquerque and L. Baudis, Phys.Rev.Lett. 90, 221301 (2003), astro-ph/0301188.