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Neutrino lighthouse at Sagittarius A*

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We investigate whether a subset of high-energy events observed by IceCube may be due to neutrinos from Sagittarius A*. We check both spatial and temporal coincidences of IceCube events with other transient activities of Sagittarius A*. Among the seven IceCube shower events nearest to the Galactic center, we have found that event 25 has a time very close to (around three hours after) the brightest x-ray flare of Sagittarius A* observed by the *Chandra X-ray Observatory* with a p-value of 0.9%. Furthermore, two of the seven events occurred within one day of each other (there is a 1.6% probability that this would occur for a random distribution in time). Thus, the determination that some IceCube events occur at similar times as x-ray flares and others occur in a burst could be the smoking gun that Sagittarius A* is a point source of very-high-energy neutrinos. We point out that if IceCube Galactic center neutrino events originate from charged pion decays, then TeV gamma rays should come from neutral pion decays at a similar rate. We show that the CTA, HAWC, H.E.S.S. and VERITAS experiments should be sensitive enough to test this.

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I. INTRODUCTION

The origins of ultra-high-energy and very-high-energy cosmic rays and ultra- and very-high-energy astrophysical neutrinos are major unknowns; see, e.g. [1–4]. These two fundamental open questions may be interconnected, since accelerated protons from a source interact with protons in a surrounding gas and thereby produce charged pions that decay to neutrinos and neutral pions that decay to photons. The questions may be answerable with the advent of detectors of at least area km^2 and volume km^3. The Pierre Auger [5] and Telescope Array (TA) [6] experiments are probing the highest-energy cosmic rays ($> 10^{18}$ eV), but so far a definitive association of ultra-high-energy cosmic rays with astrophysical sources has proved elusive. The proton or iron primaries of cosmic rays get deflected by magnetic fields, and this compromises the identifications of the source locations. The TA data show a possible hot spot region on the sky, but at low significance [7]. Leading astrophysical candidates for cosmic rays are active galactic nuclei (AGNs), starburst galaxies, and galaxy mergers; see, e.g. [8–17] for some recent discussion. The standard model of cosmic rays is shock acceleration by the Fermi mechanism. The energetics of the shock is derived from the central engine, which in galaxies is the supermassive black hole (SMBH) that resides at the compact central region, so either AGNs or starburst galaxies are highly plausible sources for the production of protons and neutrinos of extreme energies.

Although searches for ultra-high-energy neutrinos have so far not resulted in any detections; see e.g. [18], the IceCube experiment [19–21] has observed a game-changing 36 very-high-energy neutrino events with energies in the 30 TeV to 2 PeV range. These IceCube events could well be the key to solving the origins of cosmic rays, though it should be noted that even the highest neutrino energies of the IceCube events, 1–2 PeV, are well below those predicted for cosmic neutrinos associated with ultra-high-energy cosmic rays [22]. The IceCube events provide strong evidence (5.7σ) for a nonterrestrial component of the neutrino flux, since a number of them have directions well beyond the galactic disc. The IceCube data allow a brand new approach for understanding the physics of very-high-energy neutrinos, cosmic rays and possibly even dark matter [22].

A blazar sample has been recently considered in the context of the IceCube events [23]. Assuming that the x-ray to gamma-ray emission originates in the photo production of pions by accelerated protons, it was concluded that the integrated predicted neutrino luminosity of these particular sources is large enough to explain the two detected PeV events. Another suggestion is that BL Lacs and pulsar wind nebulae may be the astrophysical counterparts of IceCube events [24].

Gamma-ray bursts (GRBs) are the most energetic electromagnetic events in the Universe. They are extragalactic, and the bursts are of short duration, from 10 milliseconds to a few minutes. Thus, it is natural to see if there are associated occurrences of neutrino bursts. Tests were made by IceCube to see if very-high-energy neutrino events, both showers and muon tracks, were associated with known GRBs, but no evidence was found for any GRB coincidences [19,20,25,26]. The analysis looked for temporal and spatial correlations with the GRBs reported by the *Fermi* Gamma-ray Burst Monitor and *Swift*.

Other astrophysical sources that are candidates for cosmic rays and very-high-energy neutrinos include TeV gamma-ray sources, hypernovae, and supernovae. The occurrence of hypernovae and supernovae is high in starburst galaxies, which makes them prime possibilities. However, no significant association of IceCube events with starburst galaxies has been established [20]. Magnetars, pulsars, stellar black holes and binary systems are other astrophysical sources that have been considered in the search for a connection with the IceCube events.

Decays of super heavy dark matter with a very long lifetime could alternatively be the source of the IceCube events [27–33]. It may not be easy to differentiate neutrinos from super heavy dark matter decays from those of astrophysical origin, because both should be proportional to the dark matter density to a first approximation.

In this paper, we advance arguments that Sagittarius (Sgr) A* is the source of a subset of IceCube neutrino events. In Sec. II, we summarize salient characteristics of the IceCube new physics signal. In Sec. III, we remark on the positional coincidence of 7 events with the Galactic center (GC). In Sec. IV, we show that there is a suggestive time correlation of IceCube events with large flares at Sgr A*. We find such correlations in *Swift*, *Chandra*, and *NuSTAR* x-ray data but not with *Fermi* low-energy gamma rays. In Sec. V, we examine the time sequence of IceCube events in the Galactic center and compute p-values of random explanations of the timing of the IceCube events using self-clustering analysis and a friends-of-friends clustering analysis, and we do a likelihood analysis for *Chandra* flare coincidence with IceCube events. A prediction of a proton-proton origin of the Galactic center IceCube events is that there will be similar numbers of high-energy gamma-ray events as IceCube neutrino events. In Sec. VI, we present our prediction, which can be confirmed with upcoming gamma-ray detection experiments [34]. In Sec. VII we give our conclusions.

II. ICECUBE HIGH-ENERGY EVENTS

The IceCube experiment has amassed a very large data set of atmospheric neutrino events. At energies > 1 TeV, the atmospheric neutrino energy spectrum, dN/dE_ν, falls approximately as $E_\nu^{-2.7}$. Above 30 TeV, the observed number of neutrino events significantly exceeds an extrapolation of the atmospheric neutrino flux. Above 300 TeV, the neutrino flux has an energy dependence consistent with E_ν^{-2} with a cutoff at a few PeV, or an energy dependence with $E_\nu^{-2.3}$ without a cutoff [20,22]. It has been suggested that the violation of Lorentz invariance could be a cause for the termination of the neutrino energy spectrum at a very high energy [35].

The first IceCube search for high-energy neutrino events above the steeply falling atmospheric background has been based on the selection of events that start inside the detector (so called “contained events”). The atmospheric background is rejected by veto of events in which a muon enters the detector at the same time [36], thus giving 4π coverage of the sky. This approach preferentially selects electron-neutrino or tau-neutrino initiated events, although a few muon-neutrino events are also observed with an angular resolution less than a degree. In these so-called high-energy starting events, the electromagnetic showers from primary electron neutrinos or tau neutrinos have degraded pointing accuracy, of order 15° and larger, but these events provide accurate deposited energy determinations.

For through-going muon-neutrino events, where the neutrino interaction occurs in rock outside the detector, the track of the produced muon will point back to the source with an angular resolution less than a degree. The through-going data are still being analyzed. The through-going muon-neutrino events will provide superior directional information, but they are more dependent on upward acceptance, which is highest for directions near the horizontal. The energy deposited in the detector may only be 1/4 to 1/10 of the incident neutrino energy [21]. A connection of muon-neutrino events with bright astrophysical sources has not been found [20].

The IceCube two-year data set has 28 events with in-detector deposited energies between 30 TeV and 1.1 PeV [19]. The three-year (988 days) data set consists of 36 events [20], well above the estimated backgrounds of $6.6(+5.9, -1.6)$ atmospheric neutrinos and 8.4 ± 4.2 atmospheric muons. The significance of a new physics signal in the three-year data set in comparison to the atmospheric neutrino background is 5.7σ, exceeding the nominal discovery criterion. Most events are downward going, because upward-going neutrinos suffer absorption by the Earth. The three highest-energy events are showers with energies of 1 PeV, 1.1 PeV and 2 PeV, all downward going. Thirty of the events are contained showers, and 6 events have a muon track. The neutrino sky maps of these IceCube events show no significant clustering and are compatible with an isotropic distribution. Moreover, the data are consistent with 1:1:1 neutrino flavor ratios, as would be expected from neutrinos coming from pion decays and their subsequent propagation as mass eigenstates [37,38]. We show a sky map of the three-year data in the galactic coordinate system (longitude, latitude) in Fig. 1.

The fact that the energy spectrum of the new physics neutrino signal shows a E^{-2} dependence, from 60 TeV to 2 PeV, suggests that the Fermi shock mechanism is operative [39,40]. The Fermi mechanism would be

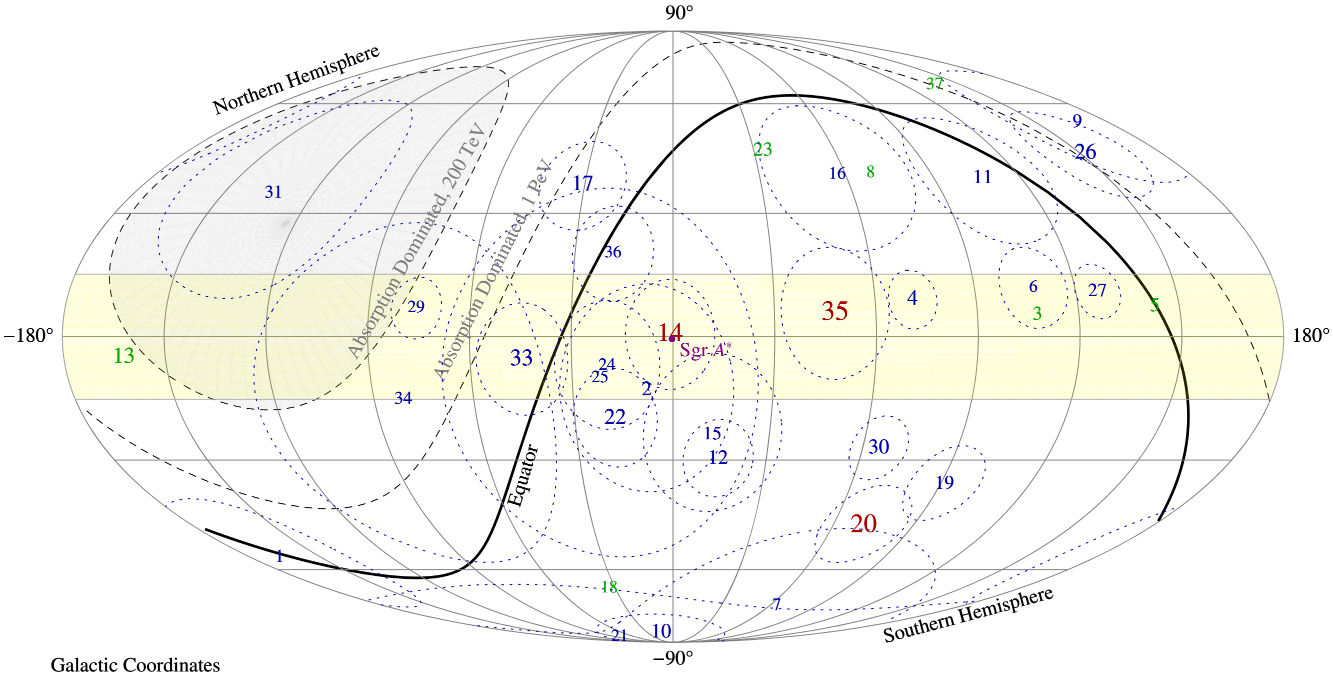

FIG. 1 (color online). Sky map showing the IceCube neutrino events (labeled by event number; blue = shower, green = track, red = PeV shower) in galactic coordinates. The size of each neutrino event number label reflects the event's energy. High-energy neutrinos are absorbed by the Earth; the gray shading and dashed contours denote the regions where the flux attenuation is significant for $E_\nu = 200$ TeV and $E_\nu = 1$ PeV [21]. The black curve separates the northern and southern sky. The horizontal yellow band denotes the galactic plane region. The dotted circles are 1σ angular regions for the IceCube events.

applicable for either an a starburst galaxy or an AGN [41]. The level of the IceCube neutrino flux is about $E_\nu^2 dN_\nu/dE_\nu \approx 1.0 \times 10^{-8}\,\mathrm{GeV\,cm^{-2}\,s^{-1}\,sr^{-1}}$ per flavor [20].

III. GALACTIC CENTER NEUTRINOS

The identification of astrophysical neutrino sources is a primary goal of neutrino telescopes, so evidence for an association of neutrino events with specific sources would be a huge scientific breakthrough. Very-high-energy neutrinos may be galactic or extragalactic in origin and may well consist of a mixed composition of neutrino source types with differing neutrino energy spectra. The high galactic latitudes of some of highest-energy IceCube events suggest at least some extragalactic component [20].

Point-source searches have been made by IceCube, both for cosmic ray events and for very-high-energy neutrino events, to see if there are associations with galaxy clusters and other astrophysical objects (see Introduction). The existence of many possible sources in a small region of the sky makes spatial-only identification difficult. Indeed, IceCube events show no apparent evidence of spatial clustering of neutrino events, but they also do not exclude that possibility, because of the imperfect resolution on the pointing of the more numerous shower events.

Transient outbursts may be the most likely to yield the requisite extreme neutrino energies reported by IceCube. However, IceCube searches for coincidences using three years of data, between April 2008 and May 2011, found no evidence for neutrino event coincidences with *Fermi* gamma-ray data or with a selected catalog of binary systems and micro-quasars with known periodicities in x-ray, gamma-ray and radio data [42]. However, since the search for a time coincidence of neutrinos from the same direction of the sky as photon signals should be a robust way to identify sources, we pursue this approach for events that may be associated with neutrinos from the Galactic center.

A plausible source candidate for neutrino events with extreme energies is the SMBH at the dynamical center of our galaxy, Sgr A*. Analysis of stellar orbits around Sgr A* demonstrate that the mass of this SMBH is about $3 \times 10^6 M_\odot$ [43,44]. Our Galactic center is highly obscured. Sgr A* undergoes bursts of rapid variability in x rays and gamma rays; it is not visible in the optical and UV, and even in x rays it is very dim. The Fermi bubbles above and below the Galactic plane were likely formed by jet activity in the distant past [45]. It has been suggested that the Fermi bubbles may be the origin of some IceCube events [46].

To the best of our knowledge, precise theoretical calculations of the expected neutrino flux from Sgr A* have not been made. High-energy protons from shock acceleration can interact with protons or photons to produce charged pions, kaons and neutrons that decay to neutrinos, along with neutral pions in the pp channel that decay to

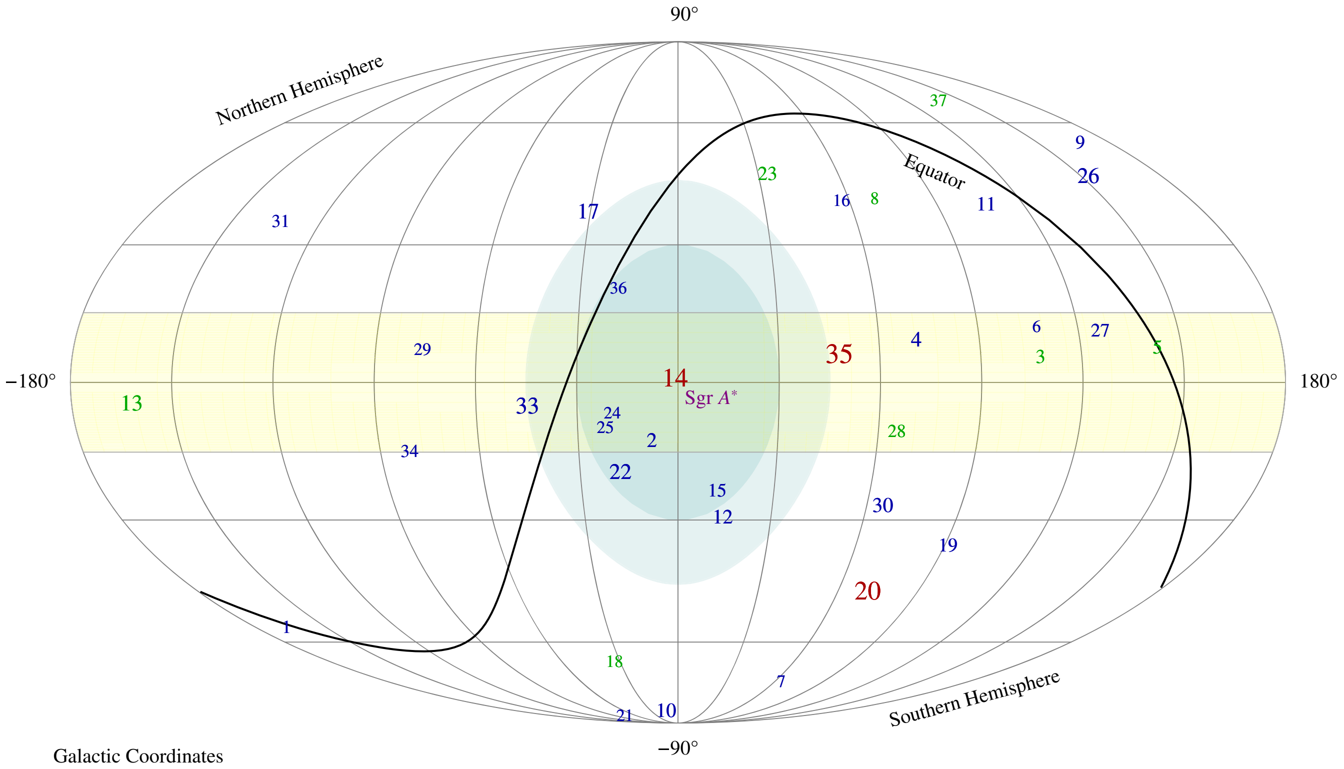

FIG. 2 (color online). Sky map showing the IceCube neutrino events (labeled by event number; blue = shower, green = track, red = PeV shower) in galactic coordinates. The black curve separates the northern and southern sky. The horizontal yellow band denotes the galactic plane region. The IceCube events that are positionally consistent with the Galactic center are approximated by the dark (light) blue shaded ellipses within 30° (45°) angular distance from the Galactic center.

photons. Sgr A* is radiatively inefficient, so the photon density will be low in its environment. In starburst galaxies, proton-proton interactions are expected to be dominant for PeV neutrino production [10].

In Fig. 2, we show that there are 9 IceCube neutrino events that are positionally consistent with the Galactic center. We illustrate this using a dark (light) blue shaded region within 30° (45°) from the Galactic center. In Table I, we summarize the properties of these 9 IceCube events. In our subsequent statistical analyses, we will only consider the 7 IceCube events within a 30° angular region of the Galactic center (this excludes IceCube events #12 and #33).

IV. THE GALACTIC CENTER: SGR A* FLARES

Targeted studies of Sgr A* have been made in gamma rays by the *Fermi* Large Area Telescope (LAT), in hard x rays (2–10 keV) by the *Chandra* [47], *NuSTAR* [48], and *XMM-Newton* observatories and the *Suzaku* satellite, in the NIR by the *Hubble Space Telescope*, at multiple

TABLE I. Properties of the IceCube events consistent with a Galactic center origin. Our subsequent p-value analysis does not include IceCube events #12 and #33.

Event	Date (MJD)	Energy (TeV)	Right ascension (Deg)	Declination (Deg)	Angular error (Deg)	Distance from GC (Deg)	Other observations
2	55351.5 Jun 4, 2010	117	282.6	−28	25.4	14.6	*Swift* largest flare at 55359.5.
12	55739.4 Jun 27, 2011	104	296.1	−52.8	9.8	32.5	*Swift* flare at 55739.5.
14	55782.5 Aug 9, 2011	1040	265.6	−27.9	13.2	1.2	*Swift* flare at 55790.4.
15	55783.2 Aug 10, 2011	57.5	287.3	−49.7	19.7	26.3	*Swift* flare at 55790.4.
22	55942.0 Jan 16, 2012	219.5	293.7	−22.1	12.1	25.9	No x-ray observations.
24	55950.8 Jan 24, 2012	30.5	282.2	−15.1	15.5	20.4	No x-ray observations.
25	55966.7 Feb 9, 2012	33.5	286.0	−14.5	46.3	23.5	*Chandra* largest flare at 55966.3.
33	56221.3 Oct 21, 2012	385	292.5	7.8	13.5	44.8	*Chandra* flare at 56222.7.
36	56308.2 Jan 16, 2013	28.9	257.7	−3.0	11.7	27.2	No x-ray observations.

wavelengths (x-ray, optical, UV) by *Swift*, and in the radio by the Very Large Array. It is found that x rays and NIR emission from Sgr A* have episodic flaring. Most of the time Sgr A* emits at low luminosity, but in its flares the brightness increases are a hundredfold. A quiescent component dominates the emission at radio and submillimeter wavelengths. It is the giant flares of Sgr A* that are of prime interest in seeing if there is an association with IceCube events, since the most energetic flares are the most likely to be associated with high-energy neutrino events, either as precursors or postcursors. We include x-ray flare information in the last column of Table I and discuss the data sets below.

A. *Swift* x-ray flares

In Fig. 3, we show the *Swift* X-Ray Telescope (XRT) observations of Sgr A* versus time. *Swift* detected 6 hard x-ray flares from Sgr A* during six years of intermittent observations, constraining the occurrence rate of bright ($L_X > 10^{35}$ erg s^{-1}) x-ray flares to be ∼0.1–0.2 per day [49]. The flares occurred close to the Sgr A* SMBH event horizon, as inferred from both the total time duration and the short timescale variability. What powers the flares is unknown. Interestingly, the largest flare, #6, occurred near to the time of IceCube event #2 (i.e., the flare happened 8 days after the IceCube event). IceCube event #12 also has a time match to a flare.

B. *Chandra* and *NuSTAR* x-ray flares

In February 2012, *Chandra* began a dedicated 3 Ms observational program of Sgr A* [51] using the High Energy Transmission Grating Spectrometer (HETGS). The goals of this *Chandra* X-ray Visionary Project (XVP) were to study the physics of x-ray flares with the highest spatial and spectral x-ray resolution available and to investigate their relationship to the quiescent x-ray emission. During the XVP, 39 flares were identified. A typical flare was observed to be about 10 times brighter than the background emission. We show these observations in the left panel of Fig. 4.

The brightest Sgr A* x-ray flare ever observed occurred on February 9, 2012 (observation ID 14392). Its peak 2–10 keV luminosity was $L_X \sim 5 \times 10^{35}$ erg s^{-1}. The duration of the flare was 5.9 ks, and its peak flux occurred at 15:10:21 coordinated universal time (UTC) [53]. Intriguingly, IceCube #25 happened on the same date. It was a shower event with an energy of 33.5 TeV and a direction consistent with a Galactic center origin within its 1σ uncertainty (see Fig. 1). The recorded time of this IceCube event was 55966.7422457 MJD = 17:48:50 UTC. Thus, IceCube #25 occurred about 2:38:29 hours after the x-ray flare (see right panel of Fig. 4). Because of the complex dynamics of the processes at the Galactic center with x rays of electromagnetic origin and neutrinos of hadronic origin, the somewhat inexact time coincidence of the x-ray activity and neutrino signal may not be surprising. The association of large x-ray flares with IceCube events is serendipitous, and they may not always occur in conjunction.

The *NuSTAR* high-energy x-ray observatory observed the Galactic center three times in July, August, and October 2012 [48] as part of a coordinated campaign with *Chandra* and the Keck Telescope. Four flares were observed by *NuSTAR*, two of medium amplitude and two weaker ones. One of these flares was observed on October 17, four days preceding IceCube event #33. This flare was simultaneously observed by *Chandra*.

C. *Fermi* activity

The *Fermi* telescope has made gamma-ray observations of the Galactic center. In order to identify flare activities in their data, we used the ObsSim program from the *Fermi* SciTools to obtain the satellite position data and to generate a background distribution. Basically, we specified a point source at the Galactic center with some arbitrary luminosity

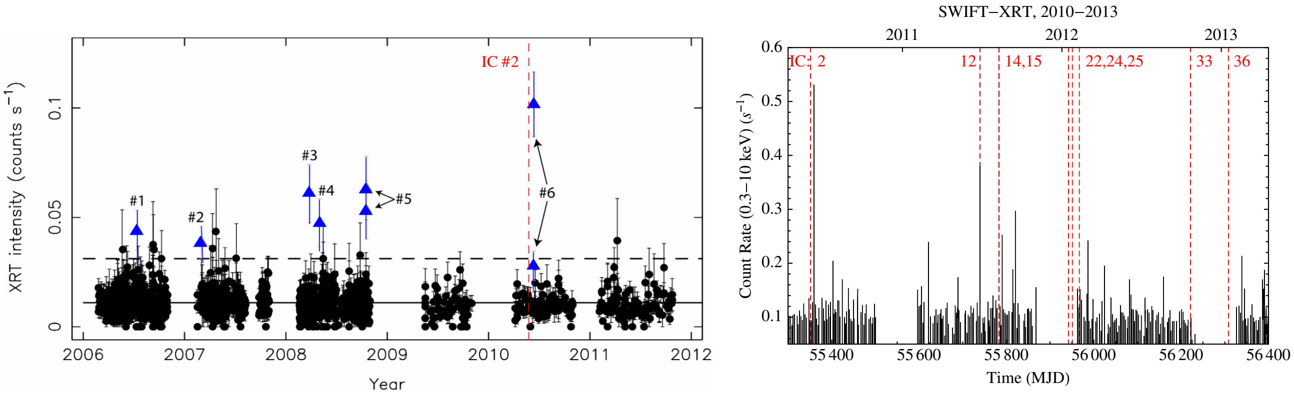

FIG. 3 (color online). Left: *Swift* XRT observations of Sgr A* over six years [49]. The events numbered #1, #2, … #6 in blue are *Swift* flares. The red dashed line shows the timing of IceCube #2. Right: *Swift* XRT observations during the IceCube observation period, with the times of potential Galactic center neutrino events marked with red dashed lines. The x-ray data were generated using *Swift*'s online tools, see [50].

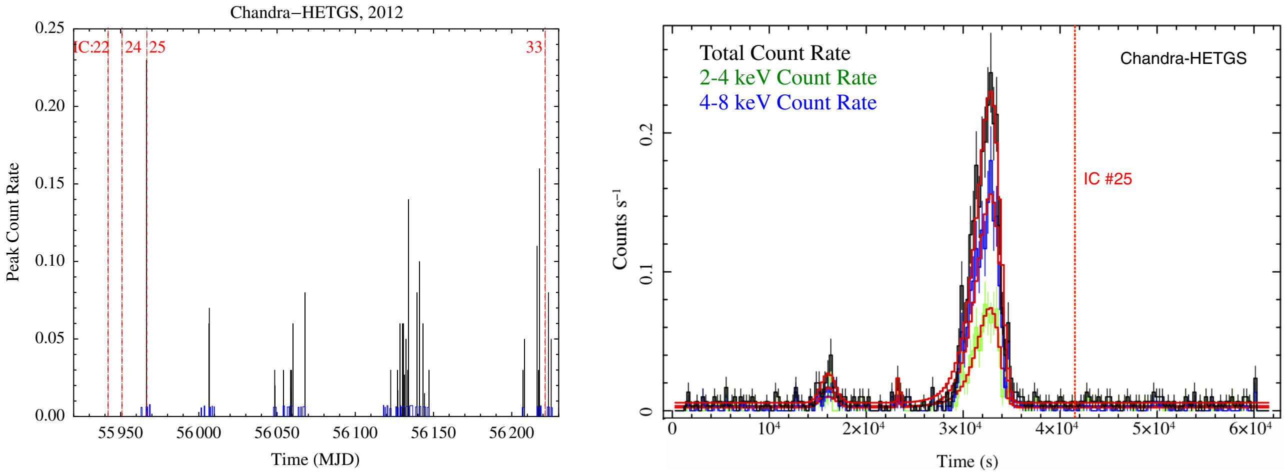

FIG. 4 (color online). Left: *Chandra* HETGS observations of Sgr A* in 2012 [52]. The blue regions along the bottom are the quiescent levels and show when *Chandra* observations were being made. Right: A close-up on the largest flare, observed February 9th [53]. The red dashed line shows the timing of IceCube #25. IceCube #25 occurred 2:38:29 hours after the *Chandra* giant flare.

and power-law spectrum. We then used the simulation program to read the *Fermi* satellite data [54] and to generate photon events from this source when *Fermi* LAT is taking data. The simulated events take into account the orientation of the satellite and assume a 1° cone of observation. We also normalized the simulated events to the total observed number of events. In Fig. 5, we show the difference between the data and a simulated background that assumes a steady source at Sgr A*. The times of the IceCube events in the Galactic center region are indicated by the red dashed lines. No appreciable flaring is observed. This is not so surprising, given that a coincidence between the IceCube neutrino events and GRBs has not been found [19,20,25,26].

V. TIME CLUSTERING OF NEUTRINO EVENTS FROM THE GALACTIC CENTER

Time clustering of the IceCube neutrino events in the Galactic center can indicate a transient nature of the underlying physics. In the left panel of Fig. 6, we plot in time sequence the 9 IceCube events that are positionally consistent within 45° from the Galactic center. A visual comparison of this plot with all the IceCube events (right panel of Fig. 6) suggests the occurrence of neutrino bursts. We hereafter focus on the 7 IceCube events within 30° from the Galactic center. We evaluate the probability (p-value) that the 7 IceCube events are not clustered, i.e., that they are randomly distributed in time. In Fig. 7, we show both time

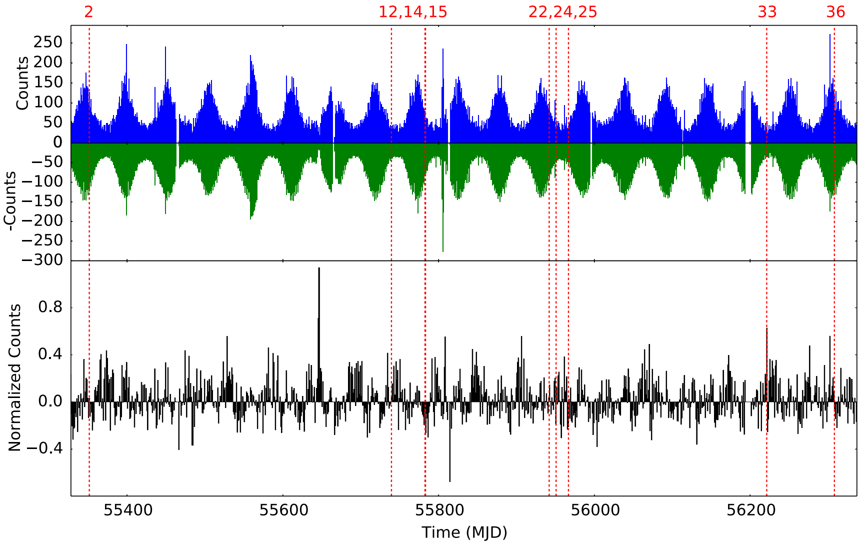

FIG. 5 (color online). *Fermi* observations of Sgr A* within a 1° cone. The red dashed lines show the timing of IceCube neutrino events. To identify activity above quiescent levels, we simulated the expected data (assuming Sgr A* is a steady source) and subtracted the simulated data (middle, green) from the observed data (top, blue). We show the normalized difference in the bottom panel.

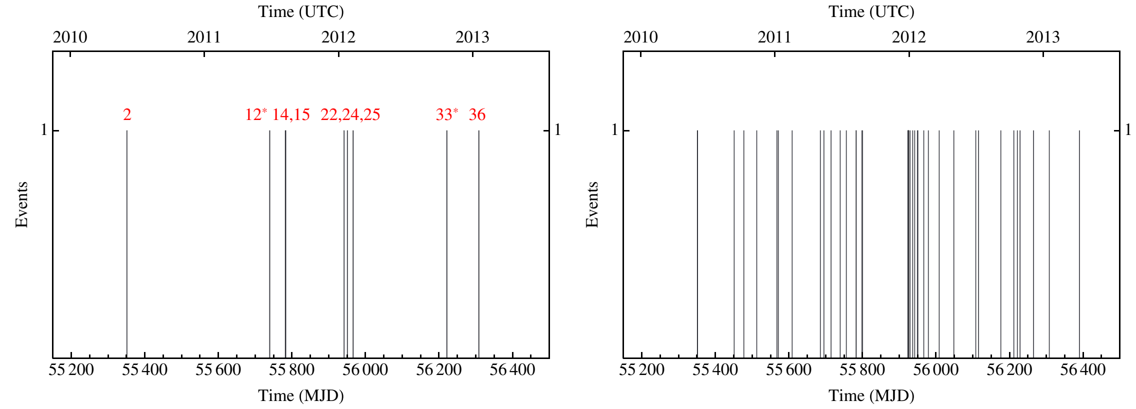

FIG. 6 (color online). Time sequence of IceCube events that are positionally consistent within 45° of the Galactic center. Events #12 and #33 are more than 30° from the Galactic center. For comparison, the time sequence of all IceCube events is also shown.

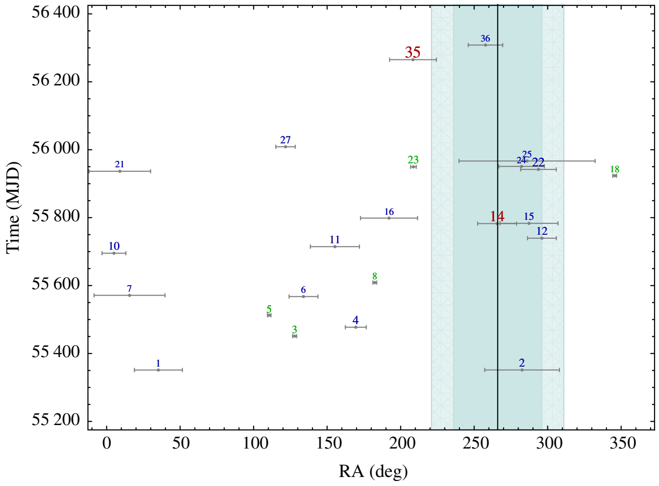

FIG. 7 (color online). The time and RA of all IceCube events within 30° of declination of the Galactic center. The inner [outer] blue band has RA $\in (236°, 296°) = (\mathrm{RA}_{\mathrm{GC}} - 30°, \mathrm{RA}_{\mathrm{GC}} + 30°)$ [RA $\in (221°, 311°) = (\mathrm{RA}_{\mathrm{GC}} - 45°, \mathrm{RA}_{\mathrm{GC}} + 45°)$]. Events positionally consistent within 30° of the Galactic center, which fall within the inner blue band, show more time clustering than events away from the Galactic center.

and space clustering of IceCube events. One can easily see that IceCube events #22, #24, and #25 are clustered both in timing and in location, as are #14 and #15.

A. Self-clustering analysis

IceCube has made studies of the timing correlations of various subsets of the IceCube events [20,55–57]. We adopt the IceCube Collaboration methodology for our analysis of the 7 IceCube events that are less than 30° from the Galactic center: IceCube events #2,#14,#15,#22,#24,#25, and #36. For every pair of events, with times t_{left} and t_{right}, we define a signal function for the IceCube event i as

$$S_i = \frac{H(t_{\mathrm{right}} - t_i)H(t_i - t_{\mathrm{left}})}{t_{\mathrm{right}} - t_{\mathrm{left}}}, \qquad (5.1)$$

and a background function as

$$B = \frac{1}{T}, \qquad (5.2)$$

where H is the Heaviside function and $T = 998$ days is the total observation time. We then define a likelihood function

$$\mathcal{L} = \prod_{i \in \mathrm{events}} \left(\frac{n_s}{N_{\mathrm{events}}} S_i + \frac{N_{\mathrm{events}} - n_s}{N_{\mathrm{events}}} B \right). \qquad (5.3)$$

Here, n_s is the number of signal events in a cluster, and $N_{\mathrm{events}} = 7$ is the total number of events. In order to compute the test statistics (TS), we marginalize n_s and choose the pair of events that gives the best TS. We generate events randomly over the total observation time and marginalize over n_s to compute the p-value. We find a p-value of 1.6% for the pair of IceCube events #14 and #15 ($n_s = 2$; $\Delta t = 0.67$ days).

B. Friends-of-friends clustering analysis

The above test statistic analysis found that the clustering of IceCube events #14 and #15 happens with a probability of $p = 1.6\%$ compared to events that are randomly distributed in time. This result may indicate that the two events come from the same transient phenomenon, but it does not check the clustering of all the Galactic center IceCube events. To test the latter, we use the friends-of-friends algorithm [58].

The algorithm consists of grouping events together if they are friends or connected by friends: two events are friends if they are closer than some threshold distance $\delta t_{\mathrm{friends}}$. We define the TS to be the minimum $\delta t_{\mathrm{friends}}$ that we need to form a given number of clusters. For randomly generated events, we obtain a minimum p-value of 4.2% with the following 4 clusters of IceCube events: (#2), (#14, #15), (#22, #24, #25), (#36).

C. Likelihood analysis for *Chandra* flare coincidence with IceCube neutrino events

To evaluate the probability of a random coincidence of *Chandra* x-ray flares with the 7 IceCube events within 30° from the Galactic center, we perform a likelihood test with the 37 x-ray flares observed at the Galactic center by *Chandra*. We define the signal function as a top-hat distribution around the flare with a time window Δt that is weighted with the counts in the flare. The events are distributed over a total time of $T = 3$ Ms. For the background function, we take a flat distribution over all observation time periods that is normalized to the total number of flare counts. As in the time clustering analysis above, we marginalize n_s to calculate the TS values. We do the same with randomly generated events during the total observation time to compute the p-value. Based on the duration of the observed Sgr A* flares, we choose a time window of $\Delta t = 12$ hours, for which we obtain $p = 0.9\%$ with $n_s = 1$.

VI. ASSOCIATION OF TEV-PEV GALACTIC CENTER GAMMA RAYS WITH PEV GALACTIC CENTER NEUTRINOS

As discussed in the Introduction, the pion production in pp interactions gives both neutrinos (from charged pion decays) and gamma rays (from neutral pion decays). Thus, the existence of the new physics neutrino signal implies the existence of high-energy gamma rays. Our argument that neutrinos are produced at the Galactic center then necessitates a high-energy gamma-ray signal at about the same rate, and this prediction can validate or rule out our hypothesis. In the following, we elaborate on and quantify the gamma-ray prediction.

The acceleration of protons and nuclei by the Fermi mechanism gives cosmic rays with a E^{-2} spectrum, $dN/dE \propto E^{-2}$. The hadronic interactions of these energetic cosmic ray with the diffuse gas surrounding the cosmic accelerator produce mesons (pions, kaons, charm), whose energy spectra are slightly softer, $E^{-2.3}$, than the primary cosmic rays. See, e.g. [12,59]. The inelastic pp collisions populate a democratic pion multiplicity with about equal numbers of π^+, π^-, and π^0. The two-body decays, $\pi^+ \to \mu^+\nu_\mu$, $\pi^- \to \mu^-\bar{\nu}_\mu$, $\pi^0 \to 2\gamma$, have primary neutrinos and photons with similar distributions in neutrino and photon energies. In the propagation of the neutrinos over long baselines the initial flavor converts to a 1∶1∶1 composition of ν_e, ν_μ, ν_τ. Consequently, the ratio of the photon to ν distributions (at $E_\gamma = E_\nu$) is

$$\frac{dN}{dE_\gamma} = \mathcal{O}(1) \times \frac{dN}{dE_\nu}, \tag{6.1}$$

which provides a correlated prediction of high-energy gamma-ray flux from the neutrino flux [60,61].

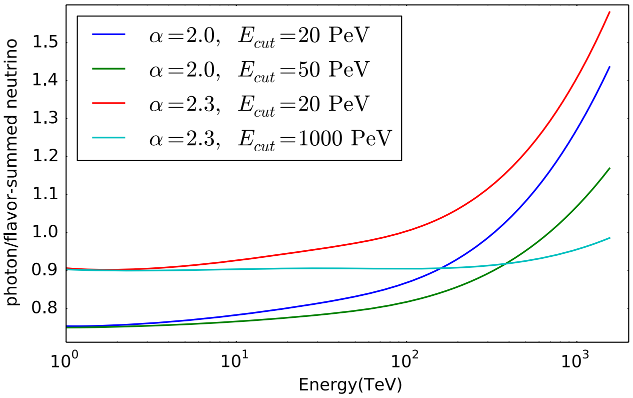

FIG. 8 (color online). The ratio of the gamma-ray flux to the flavor-summed neutrino flux as a function of energy. See Eq. (6.2) for the definition of α and E_{cut}.

We use Pythia8 [62] to simulate the productions of neutrino and photon from the inelastic scattering of a cosmic ray proton with a proton at rest. We use the following spectrum formula for the primary proton flux:

$$\frac{dN(E_p)}{dE_p} = A_p E_p^{-\alpha} e^{-E_p/E_{\mathrm{cut}}}, \tag{6.2}$$

with a power law below the cutoff E_{cut}. Here, A_p is an energy-independent normalization factor. To match the observed neutrino spectrum at IceCube, we choose $\alpha = 2.0$ and $\alpha = 2.3$ as two representative powers. In Fig. 8, we show the ratio of the gamma-ray flux to the neutrino flux as a function of energy. For a very large cutoff $E_{\mathrm{cut}} = 1000$ TeV, the photon over proton flux ratio is a

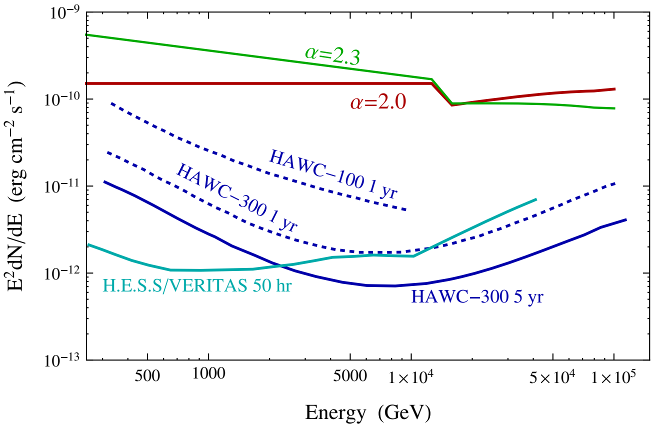

FIG. 9 (color online). The correlated gamma-ray flux from the IceCube neutrino flux based on pp collisions. The predicted values of the gamma flux based on primary proton spectra with a power law, $E^{-\alpha}$, are shown for $\alpha = 2.3$ (green) and $\alpha = 2.0$ (red). The breaks in the predicted gamma-ray flux are due to the attenuation effects. Here, the unit 1 erg = 624.15 GeV. Future experimental sensitivities are taken from Ref. [64].

constant for energies below 100 TeV. However, for a smaller value of cutoff, the photon/neutrino ratio increases as the energy approaches the cutoff. This can be understood from kinematics of charged pion decaying into neutrinos and neutral pion decaying into two photons.

The high-energy gamma rays with $E \gtrsim 10$ TeV in Sgr A* have attenuation effects when gamma rays interact with Galactic interstellar radiation field and cosmic microwave background (CMB) photons by pair production. The CMB photon effects become more important for the gamma-ray energy above around 200 TeV. One can use the optical depth $\tau_{\gamma\gamma}$ to quantify the attenuation effect such that

$$\left.\frac{dN(E_\gamma)}{dE_\gamma}\right|_{\oplus} = \left.\frac{dN(E_\gamma)}{dE_\gamma}\right|_{\mathrm{GC}} \times e^{-\tau_{\gamma\gamma}(E_\gamma)}. \tag{6.3}$$

We use the following numerical function to fit the calculated optical depth in Ref. [63]:

$$\tau_{\gamma\gamma}(E_\gamma) = \sum_{i=0}^{10} a_i (\log_{10} E_\gamma)^i, \tag{6.4}$$

for $14\ \mathrm{TeV} < E_\gamma \le 1000\ \mathrm{TeV}$ and $\tau_{\gamma\gamma}(E_\gamma) = 0$ for $E \le 14$ TeV. The fitted parameter values are

$$(a_0, a_1, a_2, \cdots, a_{10}) = (-553.195, 2368.8, -4399.76, 4664.28, -3125.54, 1384.65, \\ -411.397, 81.1285, -10.1884, 0.737702, -0.0234442). \tag{6.5}$$

After folding the attenuation effects, we show the predicted gamma-ray flux in Fig. 9 for the range of energy from a few hundred GeV to 200 TeV. The optical depth used in the above formula is just an averaged one. If the local environment of the source to generate IceCube neutrinos has a large value of optical depth, an even smaller gamma-ray flux will be expected.

New-generation ground-based gamma-ray observatories are coming into operation that will probe high-energy gamma rays [34]. The High Altitude Water Cherenkov (HAWC) observatory in Mexico is sensitive to gamma rays and cosmic rays of 100 GeV to a few hundred TeV [64,65]. HAWC has a wide field of view and nearly continuous operation. We show the projected sensitivities in Fig. 9. The Cherenkov Telescope Array (CTA) [66,67], with tens of telescopes in several sites, will provide energy coverage from tens of GeV to several tens of TeV. Its sensitivity will be about a factor of 10 better than the current H.E.S.S., MAGIC, MILAGRO and VERITAS gamma-ray detectors. CTA will have a field of view of up to 10 degrees and also have sensitivity to confirm the hadroproduction of neutrinos around Sgr A* [68].

VII. CONCLUSIONS

We proposed that the timings of IceCube neutrino events from Sgr A* are sometimes correlated with the observed photon flaring in x rays at the Galactic center. In particular, we consider the timing and approximate positional coincidences of IceCube #25 and *Chandra* #14392 as an indicator that Sgr A* is the source of IceCube #25. A testable consequence of this interpretation of the data is that major photon flares of other AGNs (or of the cores of starburst galaxies) occur simultaneously with extragalactic IceCube events. This conclusion implies that hadronic processes produce neutrinos from pion production and their subsequent decays, along with the inverse-Compton mediated x-ray flaring. We also investigated the idea that neutrino bursts from Sgr A* occur. We found support for this hypothesis in the low probability of random emissions in time to explain the IceCube observations.

X-ray observations of Sgr A* will continue to provide valuable information about the frequency and brightness of the flares. IceCube continues to map the neutrino sky at the highest neutrino energies. Further coincidences in the timing of x-ray flares with IceCube events that point to the Galactic center would bolster the AGN point-source connection. Our expectation is that high-energy neutrino events would occur in association with giant x-ray and NIR flares [69]. In addition, other variable sources in the Galactic center region near Sgr A*, such as the transient magnetar SGR J1745-29 (e.g. [70,71]), could be another source of neutrinos.

Unusual outbursts could serendipitously arise from disruptions of asteroids, comets, planets or stars that approach the SMBH. A gas cloud of Earth mass, called G2, is approaching Sgr A* [72,73]. The trajectory of G2 is predicted to reach the pericenter of the orbit in 2014. It will be especially interesting if any high-energy neutrino events from Sgr A* occur that can be associated with its passage.

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[1] F. Halzen, Nucl. Phys. B, Proc. Suppl. **246**, 3 (2014).
[2] A. V. Olinto, Nucl. Phys. B, Proc. Suppl. **243–244**, 108 (2013).
[3] P. Blasi, C.R. Phys. **15**, 329 (2014).
[4] G. Sigl, EPJ Web Conf. **53**, 01013 (2013).
[5] P. Abreu *et al.* (Pierre Auger Observatory Collaboration), Astrophys. J. **760**, 148 (2012).
[6] T. Abu-Zayyad, R. Aida, M. Allen, R. Anderson, R. Azuma *et al.* (Telescope Array Experiment Collaboration), Astrophys. J. **777**, 88 (2013).
[7] K. Fang, T. Fujii, T. Linden, and A. V. Olinto, arXiv:1404.6237.
[8] K. Kashiyama and P. Meszaros, Astrophys. J. **790**, L14s (2014).
[9] L. A. Anchordoqui, T. C. Paul, L. H. M. da Silva, D. F. Torres, and B. J. Vlcek, Phys. Rev. D **89**, 127304 (2014).
[10] R. Laha, J. F. Beacom, B. Dasgupta, S. Horiuchi, and K. Murase, Phys. Rev. D **88**, 043009 (2013).
[11] W. Winter, Phys. Rev. D **88**, 083007 (2013).
[12] S. Dado and A. Dar (to be published); private communication.
[13] M. Gonzalez-Garcia, F. Halzen, and V. Niro, Astropart. Phys. **57–58**, 39 (2014).
[14] A. M. Taylor, S. Gabici, and F. Aharonian, Phys. Rev. D **89**, 103003 (2014).
[15] K. Murase, M. Ahlers, and B. C. Lacki, Phys. Rev. D **88**, 121301 (2013).
[16] K. Murase and K. Ioka, Phys. Rev. Lett. **111**, 121102 (2013).
[17] I. Tamborra, S.'i. Ando, and K. Murase, arXiv:1404.1189.
[18] P. Gorham *et al.* (ANITA Collaboration), Phys. Rev. D **85**, 049901(E) (2012).
[19] M. Aartsen *et al.* (IceCube Collaboration), Science **342**, 1242856 (2013).
[20] M. Aartsen *et al.* (IceCube Collaboration), Phys. Rev. Lett. **113**, 101101 (2014).
[21] A. Karle, "High Energy Astrophysical Neutrinos—Observations and Implications," (unpublished).
[22] L. A. Anchordoqui, V. Barger, I. Cholis, H. Goldberg, D. Hooper *et al.*, J. High Energy Astrophys. **1–2** 1 (2014).
[23] F. Krauss, M. Kadler, K. Mannheim, R. Schulz, J. Trstedt *et al.*, Astron. Astrophys. **566**, L7 (2014).
[24] P. Padovani and E. Resconi, Mon. Not. R. Astron. Soc. **443**, 474 (2014).
[25] J. Casey and I. Taboada (IceCube Collaboration), arXiv:1309.6979.
[26] L. Yacobi, D. Guetta, and E. Behar, Astrophys. J. **793**, 48 (2014).
[27] E. W. Kolb, D. J. Chung, and A. Riotto, *Dark Matter in Astrophysics and Particle Physics 1998*, edited by H. V. Klapdor-Kleingrothaus and L. Baudis (Instuite of Physics Publishing, London, 1999).
[28] D. J. Chung, E. W. Kolb, and A. Riotto, Phys. Rev. D **59**, 023501 (1998).
[29] B. Feldstein, A. Kusenko, S. Matsumoto, and T. T. Yanagida, Phys. Rev. D **88**, 015004 (2013).
[30] Y. Bai, R. Lu, and J. Salvado, arXiv:1311.5864.
[31] A. Esmaili and P. D. Serpico, J. Cosmol. Astropart. Phys. 11 (2013) 054.
[32] J. Zavala, Phys. Rev. D **89**, 123516 (2014).
[33] A. Esmaili, A. Ibarra, and O. L. Peres, J. Cosmol. Astropart. Phys. 11 (2012) 034.
[34] J. Holder, arXiv:1407.1080.
[35] L. Anchordoqui, V. Barger, H. Goldberg, J. Learned, D. Marfatia *et al.*, arXiv:1404.0622.
[36] T. K. Gaisser, K. Jero, A. Karle, and J. van Santen, Phys. Rev. D **90**, 023009 (2014).
[37] J. G. Learned and S. Pakvasa, Astropart. Phys. **3**, 267–274 (1995).
[38] J. F. Beacom, N. F. Bell, D. Hooper, S. Pakvasa, and T. J. Weiler, Phys. Rev. D **68**, 093005 (2003).
[39] E. Waxman and J. N. Bahcall, Phys. Rev. D **59**, 023002 (1998).
[40] J. N. Bahcall and E. Waxman, Phys. Rev. D **64**, 023002 (2001).
[41] F. W. Stecker, Phys. Rev. D **88**, 047301 (2013).
[42] J. A. Aguilar, A. Christov, T. Montaruli, and M. Rameez (IceCube Collaboration), arXiv:1309.6979.
[43] A. Ghez, S. Salim, N. Weinberg, J. Lu, T. Do *et al.*, Astrophys. J. **689**, 1044 (2008).
[44] R. Genzel, F. Eisenhauer, and S. Gillessen, Rev. Mod. Phys. **82**, 3121 (2010).
[45] H.-Y. Yang, M. Ruszkowski, P. Ricker, E. Zweibel, and D. Lee, Astrophys. J. **761**, 185 (2012).
[46] C. Lunardini, S. Razzaque, K. T. Theodoseau, and L. Yang, Phys. Rev. D **90**, 023016 (2014).
[47] F. K. Baganoff, Y. Maeda, M. Morris, M. Bautz, W. Brandt *et al.*, Astrophys. J. **591**, 891 (2003).
[48] N. M. Barrière, J. A. Tomsick, F. K. Baganoff, S. E. Boggs, F. E. Christensen *et al.*, Astrophys. J. **786**, 46 (2014).
[49] N. Degenaar, J. Miller, J. Kennea, N. Gehrels, and R. Wijnands, Astrophys. J. **769**, 155 (2013).
[50] P. Evans, A. Beardmore, K. Page, L. Tyler, J. Osborne *et al.*, Astron. Astrophys. **469**, 379 (2007).
[51] J. Neilsen, M. Nowak, C. Gammie, J. Dexter, S. Markoff *et al.*, arXiv:1311.6818.
[52] J. Neilsen, M. Nowak, C. Gammie, J. Dexter, S. Markoff *et al.*, Astrophys. J. **774**, 42 (2013).
[53] M. Nowak, J. Neilsen, S. Markoff, F. Baganoff, D. Porquet *et al.*, Astrophys. J. **759**, 95 (2012).
[54] Fermi-LAT Collaboration, "Fermi Science Support Center, Data Access," http://fermi.gsfc.nasa.gov/cgi-bin/ssc/LAT/LATDataQuery.cgi.
[55] J. Braun, J. Dumm, F. De Palma, C. Finley, A. Karle, and T. Montaruli, Astropart. Phys. **29**, 299 (2008).
[56] J. Braun, M. Baker, J. Dumm, C. Finley, A. Karle, and T. Montaruli, Astropart. Phys. **33**, 175 (2010).
[57] M. Aartsen *et al.* (IceCube Collaboration), arXiv:1406.6757.
[58] Y. Zeldovich, J. Einasto, and S. Shandarin, Nature (London) **300**, 407 (1982).
[59] F. Halzen, Astropart. Phys. **43**, 155 (2013).
[60] M. Ahlers and K. Murase, Phys. Rev. D **90**, 023010 (2014).
[61] A. Supanitsky, Phys. Rev. D **89**, 023501 (2014).
[62] T. Sjostrand, S. Mrenna, and P. Z. Skands, Comput. Phys. Commun. **178**, 852 (2008).
[63] I. V. Moskalenko, T. A. Porter, and A. W. Strong, Astrophys. J. **640**, L155 (2006).

[64] A. Abeysekara, R. Alfaro, C. Alvarez, J. Álvarez, R. Arceo *et al.* (HAWC Collaboration), Astropart. Phys. **50–52**, 26 (2013).
[65] A. Abeysekara *et al.* (HAWC Collaboration), arXiv: 1405.1730.
[66] M. Doro *et al.* (CTA Collaboration), Astropart. Phys. **43**, 189 (2013).
[67] M. Pierre, J. M. Siegal-Gaskins, and P. Scott, J. Cosmol. Astropart. Phys. 06 (2014) 024.
[68] T. Linden and S. Profumo, Astrophys. J. **760**, 23 (2012).
[69] S. Razzaque, Phys. Rev. D **88**, 081302 (2013).
[70] N. Rea, P. Esposito, J. Pons, R. Turolla, D. Torres *et al.*, Astrophys. J. **775**, L34 (2013).
[71] N. Degenaar, R. Wijnands, M. Reynolds, J. Miller, J. Kennea *et al.*, in *Proceedings of IAU symposium 303, The Galactic Center: Feeding and Feedback in a Normal Galactic Nucleus, Santa Fe New Mexico, 2013*.
[72] K. Dodds-Eden, P. Sharma, E. Quataert, R. Genzel, S. Gillessen, F. Eisenhauer, and D. Porquet, Astrophys. J. **725**, 450 (2010).
[73] M. Moscibrodzka, H. Shiokawa, C. F. Gammie, and J. C. Dolence, Astrophys. J. **752**, L1 (2012).