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Magnetic fields are crucial in shaping the non-thermal emission of the TeV–PeV neutrinos of astrophysical origin seen by the IceCube neutrino telescope. The sources of these neutrinos are unknown, but if they harbor a strong magnetic field, then the synchrotron energy losses of the neutrino parent particles—protons, pions, and muons—leave characteristic imprints on the neutrino energy distribution and its flavor composition. We use high-energy neutrinos as “cosmic magnetometers” to constrain the identity of their sources by placing limits on the strength of the magnetic field in them. We look for evidence of synchrotron losses in public IceCube data: 6 years of High Energy Starting Events (HESE) and 2 years of Medium Energy Starting Events (MESE). In the absence of evidence, we place an upper limit of 10 kG–10 MG (95% C.L.) on the average magnetic field strength of the sources.

I. INTRODUCTION

Magnetic fields are pivotal to the dynamics of high-energy astrophysical sources. They help to launch and collimate outflows in relativistic jets, affect matter accretion processes, and aid angular momentum transport. Magnetic fields also play a crucial role in the emission of high-energy astrophysical neutrinos, gamma rays, and cosmic rays. Although the sources of these particles are largely unknown, a fundamental requirement is that they must harbor a magnetic field capable of accelerating protons and charged nuclei to PeV energies or more [1–3]. Some high-energy protons and nuclei escape as cosmic rays; others interact with surrounding matter and radiation to produce neutrinos and gamma rays.

The TeV–PeV neutrinos detected by the IceCube neutrino telescope [5–9] are especially powerful source tracers, due to their low chance of being stopped or deflected on route to Earth. Yet, direct [10–14] and indirect [15–22] searches have not provided conclusive evidence, save for two cases of probable identification [23, 24]. Remarkably, the role of the source magnetic field provides us with a novel indirect search strategy.

We use TeV–PeV astrophysical neutrinos as “cosmic magnetometers” that constrain the average magnetic field of the neutrino sources. Because candidate source classes span a wide range of magnetic field strengths, this constraint narrows down the identity of the sources.

We look for imprints left by the magnetic field of the sources on the diffuse neutrino flux. On the one hand, the average magnetic field must be strong enough to accelerate protons up to PeV energies. On the other hand, it cannot be too strong, or else proton energy losses via synchrotron radiation would lower the maximum proton energy and preclude the production of high-energy neutrinos. Further, intermediate magnetic field strengths may induce synchrotron losses in secondary pions and muons that decay into neutrinos, affecting their energy spectrum and flavor composition. We look for evidence of the interplay of these effects in public IceCube data.

Figure 1 shows that our results limit the average mag-
netic field to be weaker than 10 kG–10 MG. This partial
disfavors low-luminosity GRBs as the main sites of
TeV–PeV neutrino production. Our work builds on and
extends the constraints on magnetic fields of a few MG
found by Ref. [35] using the first 2 years of IceCube data,
by using 4 more years of IceCube data, two different Ice-
Cube event samples, a significantly refined computation
of event spectra, and a Bayesian statistical treatment.

II. ENERGY LOSSES VIA SYNCHROTRON RADIATION

We consider a generic scenario that captures the key
features common to high-energy neutrino source candid-
ates. Neutrinos are produced in an outflow of baryon-loaded
material with a bulk Lorentz factor $\Gamma$ and magnetic
field strength $B'$. To keep our scenario generic, we
consider protons only; see, e.g., Refs. [49] [50] for pro-
tection scenarios including heavier nuclei and nuclear cas-
cades. Here and below, primed quantities are expressed in
the rest frame of the neutrino production region, i.e.,
the shock rest frame; all other quantities are in the com-
oving frame of the production region or, after account-
ing for redshift effects, in the frame of the observer.

Sources accelerate protons via collisionless shocks in
the magnetized outflow, up to a maximum energy $E_p^{\text{max}}$ [51]. To treat all candidate sources on an equal
footing, we assume that $E_p^{\text{max}}$ is limited by proton syn-
chrotron losses. However, alternative energy-loss mechan-
isms may be dominant in some source classes [52–
54] or the flavor content may be affected in an energy-
dependent fashion by oscillations in dense media [55,56];
we comment on source-specific features later. Protons
reach their maximum energy when two time scales be-
come comparable: their acceleration time scale, $\tau_{\text{acc}} = E_p^{\text{max}}/(\eta eB')$, where $e$ is the electron charge and $\eta$ is the
acceleration efficiency, and their synchrotron energy-loss time
scale, $\tau_{\text{sync}} = 9m_p^2/(4\pi^2 B^2 E_p^{\text{max}})$, where $m_p$ is the proton mass. In the comoving frame, this yields $E_p^{\text{max}} \approx 2 \times 10^{11} \Gamma (\eta/eB')^{1/2}$ GeV. Since sources must be rather
efficient accelerators, we fix $\eta = 1$ from here on, and com-
ment later on how the neutrino emission changes with $\eta$.

The interactions of protons with matter and radiation
produce secondary pions and muons that, upon decaying,
generate neutrinos [58]; $\pi^+ \rightarrow \mu^+ + \nu_\mu$, followed by $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$, and the charge-conjugated processes [59,60].
On average, a pion receives 1/3 of the proton energy, each neutrino from muon decay receives 1/3 of the muon
energy, and each final-state neutrino receives 1/4 of the
pion energy. Following theory expectations, each source
emits neutrinos distributed in energy as $E_\nu^2 \, dN_\nu/dE_\nu' \propto E_\nu^{\alpha} E_\nu'^{1-\alpha} E_{\nu'}^{\text{max}}$, where $E_\nu'$ is the neutrino energy. We
assume that the maximum neutrino energy, $E_{\nu'}^{\text{max}}$, and the spectral index, $\alpha_\nu$, are common to neutrinos and anti-
neutrinos of all flavors. Because each neutrino receives
1/20 of the parent proton energy, $E_{\nu'}^{\text{max}} = E_p^{\text{max}}/20$ and

is affected by synchrotron losses of the secondaries affect $\alpha_\nu$.

For the secondary pions, synchrotron losses are sig-
nificant if they occur within a time scale shorter than the
pion decay time, $t_{\text{dec}} = \tau_\pi E_\pi'/m_\pi$, where $E_\pi'$, $\tau_\pi$, and $m_\pi$ are the pion energy, lifetime, and mass. In the
comoving frame, this occurs at neutrino energies above $E_{\nu',\pi}^{\text{sync}} \approx 3 \times 10^{10} (\Gamma/B')$ GeV. By analogous arguments,
for the secondary muons, synchrotron losses are signifi-
cant at energies above $E_{\nu',\mu}^{\text{sync}} \approx 2 \times 10^{10} (\Gamma/B')$ GeV.

Below $E_{\nu',\mu}^{\text{sync}}$, $\alpha_\nu$ is solely determined by the parent proton and photon spectra. In lieu of detailed model-
ing, we parametrize it as $\alpha_\nu(E_\nu < E_{\nu',\mu}^{\text{sync}}) = \gamma$, where $\gamma \in [2,3]$ is a free parameter whose value we vary later. At $E_{\nu',\mu}^{\text{sync}}$, the neutrino spectrum coming from the decay of muons steepens by $\sim E_{\nu'}^{-2}$, so these neutrinos become sub-dominant and the flux is mainly from neutrinos pro-
duced in the direct decay of pions. As a result, the fla-
vor composition of the emitted neutrinos, i.e., the fraction $f_{\nu,\alpha} (\alpha = e, \mu, \tau)$ of neutrinos plus anti-neutrinos of each flavor, changes from that of the full pion decay chain, $(f_{\nu,\alpha}, f_{\bar{\nu},\alpha}, f_{\nu,\bar{\nu}}) = (1/3, 2/3, 0)$, at $E_\nu < E_{\nu',\mu}^{\text{sync}}$, to that coming from the direct pion decay only, $(0, 1/3, 0)$, at $E_\nu \geq E_{\nu',\mu}^{\text{sync}}$. At even higher energies $E_\nu \geq E_{\nu',\mu}^{\text{sync}}$, the neutrino spectrum from pion decays itself steepens by
$\sim E_{\nu'}^{-2}$, so $\alpha_\nu(E_\nu \geq E_{\nu',\mu}^{\text{sync}}) = \gamma + 2$.

III. DIFFUSE FLUX OF HIGH-ENERGY NEUTRINOS

The luminosity of $\nu_\alpha + \bar{\nu}_\alpha$ that reaches Earth from a single source located at redshift $z$, in the frame of the observer, is

$$J_{\nu_\alpha}(E_\nu, z, \gamma, \Gamma, B') \propto f_{\alpha,\oplus} (E_\nu(1+z), \Gamma, B') \times [E_\nu(1+z)]^{2-\alpha_\nu} (E_\nu, \gamma, \Gamma, B') e^{-E_\nu(1+z)/E_{\nu',\mu}^{\text{sync}}(\Gamma, B')}. \quad (1)$$

Because flavors mix, neutrino flavor conversions en route to Earth change the flavor composition into $f_{\alpha,\oplus} = \sum_{\beta=e,\mu,\tau} f_{\beta,\oplus} P_{\beta\alpha}$, where $P_{\beta\alpha}$ is the average $\nu_\beta \rightarrow \nu_\alpha$ conversion probability [61]. To compute it, we fix the mixing parameters to their best-fit values from the recent NuFlit
4.1 global fit to neutrino oscillation data [62,63], assum-
ing normal neutrino mass ordering. The flavor composi-
tion changes from $(f_{\nu,\oplus}, f_{\bar{\nu},\oplus}, f_{\nu,\bar{\nu}}) \approx (1/3, 1/3, 1/3)$ at $E_\nu < E_{\nu',\mu}^{\text{sync}}$ to roughly $(1/5, 2/5, 2/5)$ at $E_\nu \geq E_{\nu',\mu}^{\text{sync}}$.

To compute the diffuse flux of $\nu_\alpha + \bar{\nu}_\alpha$, $\Phi_{\alpha,\oplus}$, we inte-
grate the contribution from all sources up to redshift $z_{\text{max}} = 4$; sources at higher redshifts contribute negligi-
ably. To describe a variety of candidate source classes, we
adopt the following parametrization for the source den-
sity: $\rho \propto (1+z)^m$ up to $z_c \equiv 1.5$, and $\rho \propto (1+z_c)^m$ at $z > z_c$. Later, we let the value of $m$ float. Thus, the
diffuse energy flux is

\[ E_\nu^2 \Phi_{\nu\alpha}(E_\nu, \gamma, m, \Gamma, B') \propto \int_0^{z_{\text{max}}} dz \frac{\rho(z, m)}{h(z)(1+z)^2} J_{\nu\alpha}(E_\nu, z, \gamma, \Gamma, B') , \]

where \( h(z) = [\Omega_\Lambda + (1 + z)^3 \Omega_m]^{1/2} \) is the adimensional Hubble parameter, and \( \Omega_\Lambda = 0.685 \) and \( \Omega_m = 0.315 \) are the energy densities of vacuum and matter \([64, 65]\).

We assume that all of the contributing sources have the same values of \( \gamma, \Gamma, \) and \( B' \). In reality, these parameters likely follow distributions that are presently unknown. By assuming values that are common to all sources, we aim to constrain their population-averaged values.

In summary, if the average \( B' \) is large, the synchrotron losses of protons and secondaries may visibly affect the spectral index \( \alpha_\nu \), flavor composition \( f_{\alpha,\bar{\nu}_\alpha} \), and maximum energy \( E_\nu^{\text{max}} \) of the diffuse neutrino flux \([68, 70]\). These features are softened and spread out in energy by the redshift distribution of the sources.

Figure 2 shows sample fluxes for two choices of \( B' \). The change to the flavor composition due to muon synchrotron cooling is prominent in both fluxes, at \( E_\nu \approx 2 \text{ PeV} \) and \( 200 \text{ TeV} \) for \( B' = 30 \text{ kG} \) and \( 300 \text{ kG} \), respectively. For the flux with \( B' = 300 \text{ kG} \), the spectral softening due to pion synchrotron cooling is also visible around 3 PeV. In Fig. 2 the flux dampening due to proton synchrotron cooling occurs at energies higher than shown. This is true for viable neutrino source candidates, which must be efficient accelerators: as long as \( \eta > 0.01 \), proton cooling becomes important only after muon cooling does, provided \( B' \) is at least a few G.

### A. Neutrino propagation through the Earth

Upon reaching Earth, high-energy neutrinos propagate from its surface, through its interior, and up to the South Pole, where IceCube is located. Neutrino-nucleon interactions along the way modify the neutrino flux. At these energies, neutrinos deep-inelastic scatter off of nucleons. Charged-current (CC) interactions (\( \nu_e + N \rightarrow \alpha + X \), where \( X \) are final-state hadrons) remove neutrinos from the flux. Neutral-current (NC) interactions (\( \nu_\alpha + N \rightarrow \nu_\alpha + X \)) redistribute neutrinos from high to low energies.

To compute the neutrino flux that reaches IceCube, we adopt the Preliminary Reference Earth Model \([71]\) for the matter density inside the Earth and assume that matter is isoscalar, i.e., made up of equal numbers of protons and neutrons. At these energies, there are no matter-driven flavor transitions \([72, 73]\). The flux at IceCube is different for different propagation directions, flavors, and for neutrinos and anti-neutrinos. We use nuSQuIDS \([74, 75]\) to compute the fluxes of \( \nu_\alpha \) and \( \bar{\nu}_\alpha \), astrophysical and atmospheric (see below), that reach IceCube.

### B. Atmospheric backgrounds

The main backgrounds to our analysis are high-energy atmospheric neutrinos and muons produced in the interaction of cosmic rays in the atmosphere of the Earth. They are especially important below 100 TeV \([77]\). In IceCube, the contamination of atmospheric neutrinos is mitigated by using the deep core of the detector as a self-veto \([28, 78-80]\), and the contamination of atmospheric muons, by using a surface array of water-Cherenkov tanks as veto \([6, 81]\). In our analysis, we account for these backgrounds and vetoes.

For atmospheric neutrinos, we use the same state-of-the-art tools used by the IceCube Collaboration: MCEQ \([82, 83]\) to generate neutrino fluxes produced in the decay of pions and kaons, and nuVETO \([80, 84]\) to compute the flux reduction due to the self-veto for HESE events. For MESE events, the self-veto is already included in the effective detector area; see Appendix A2. We do not consider prompt atmospheric neutrinos produced in the decay of charmed mesons, since they have not been observed and are subject to stringent upper limits \([85]\). For atmospheric muons, we approximate the flux that
reaches IceCube, after the surface veto, following the
procedure in Ref. [86] for HESE events, and extending it for
MESE events, as detailed in Appendix A 3.

C. High-energy neutrino detection

In IceCube, neutrinos are detected when they scatter
off of nucleons in the Antarctic ice and trigger particle
showers that emit Cherenkov light that is collected by
photomultipliers buried 1.5–2.5 km underground. From
the amount of light collected and from its spatial and
temporal profiles, IceCube infers the energy deposited,
$E_{\text{dep}}$, and the neutrino arrival direction, $\cos \theta_z$, where $\theta_z$
is the zenith angle measured from the South Pole.

We focus on “starting” events, where the neutrino in-
teraction occurs inside the instrumented volume, so that
$E_{\text{dep}}$ is close to the energy of the interacting neutrino.
In the TeV–PeV range, events are predominantly “show-
ers,” roughly spherical light profiles triggered mainly by
$\nu_e$ and $\nu_{\tau}$, and “tracks,” elongated light profiles made by
final-state muons, triggered mainly by $\nu_\mu$.

For an incoming flux of astrophysical or atmospheric
neutrinos along a given direction, we forecast the spectra
d$N/dE_{\text{dep}}$ of showers and tracks following Ref. [86]; see
Appendix A 1. We account for differences in deposited
energy for different flavors, CC vs. NC, and decay chan-
nels of final-state particles, and for the $\sim$13% detector
energy resolution.

IV. STATISTICAL ANALYSIS

We compare forecasted event spectra computed with
different values of the flux parameters against two public
IceCube event samples: 6 years of High Energy Starting
Events (HESE) [25–27] and 2 years of Medium Energy
Starting Events (MESE) [28, 29]. The HESE sample has
58 showers and 22 tracks with $E_{\text{dep}} = 18$ TeV–2 PeV.
The MESE sample has 278 showers and 105 tracks with
$E_{\text{dep}} = 330$ GeV–1.3 PeV. The samples provide $E_{\text{dep}}$ and
$\cos \theta_z$ for each event. A few events are common to both
samples, but since they cannot be singled out, we treat
the samples separately to avoid double-counting.

In the HESE sample, below a few tens of TeV, roughly
half of the events are of atmospheric origin and half of
the samples separately to avoid double-counting.

We adopt a Bayesian approach to search for evidence
of synchrotron cooling and constrain $B'$. For a sample of

Table I. Allowed marginalized ranges of the average
Lorentz factor, $\Gamma$, and magnetic field strength, $B'$, of
the sources of high-energy astrophysical neutrinos, obtained using
the public IceCube 6-year HESE [25]–[27] and 2-year MESE
[28, 29] event samples. The preference for synchrotron-loss
features in the data is insignificant; see the main text.

| Parameter | HESE | MESE ($E_{\text{dep}} > 20$ TeV) |
|-----------|------|---------------------------------|
| $\log_{10} \Gamma$ | $1.78 \pm 0.86$ | $0.22 \pm 0.86$ |
| $\log_{10}(B'/G)$ | $2.96 \pm 1.78$ | $0.23 \pm 5.97$ |

$N_{\text{obs}}$ IceCube events, our likelihood function is

$$L(\gamma, m, \Gamma, B', N_{\text{ast}}, N_{\text{atm}}, N_{\mu}) = e^{-N_{\text{ast}}-N_{\text{atm}}-N_{\mu}} \prod_{i=1}^{N_{\text{obs}}} L_i(\gamma, m, \Gamma, B', N_{\text{ast}}, N_{\text{atm}}, N_{\mu}),$$

where $N_{\text{ast}}$, $N_{\text{atm}}$, and $N_{\mu}$ are, respectively, the
number of events due to astrophysical neutrinos, atmos-
pheric neutrinos, and atmospheric muons. For astrophysical
neutrinos, $\mathcal{P}_{i,\text{ast}} = (dN_i/dE_{\text{dep}})/\int dE_{\text{dep}} (dN_i/dE_{\text{dep}})$, the
event spectrum is computed using the flux along the di-
rection of the $i$-th event, and similarly for atmospheric
neutrinos. The procedure differs slightly for HESE and
MESE, and for muons; see Appendix A.

We maximize the likelihood separately for the HESE
and MESE samples. For $N_{\text{ast}}$, $N_{\text{atm}}$, $N_{\mu}$, and $\gamma$ (only for
HESE), we adopt informed priors based on the HESE
[27] and MESE [28] analyses by IceCube. For $m$, $\log_{10} \Gamma$, and
$\log_{10}(B'/G)$, we adopt wide uniform priors to avoid
introducing bias. See Appendix B for details about the
priors. To maximize the likelihood, we use the efficient
Bayesian sampler MultiNest [87, 90]. We quantify the
preference for synchrotron-loss features via the Bayes fac-
tor, $K \equiv Z_{\text{signal}}/Z_{\text{null}}$, that compares the evidence, or
marginalized likelihood, in favor of their presence, $Z_{\text{signal}}$,
over their absence, $Z_{\text{null}}$. Appendix B contains details of the
statistical analysis.

V. RESULTS

Table I shows the allowed ranges of $\Gamma$ and $B'$ that re-
sult from our analysis. Both event samples prefer values
of $B'$ that push the synchrotron-loss features to energies
beyond a few PeV, past the energies covered by the sam-
pies. For both samples, $\log_{10} K \approx 0.3$, i.e., the evidence
for synchrotron-loss features in the data is insignificant.
Figure 1 shows our limits on $B'$ as a function of $\Gamma$, after marginalizing over all other likelihood parameters. The limits are isocontours of $E_{\nu,\mu}^{\text{synch}}$ and $E_{\nu,\pi}^{\text{synch}}$, and, in agreement with Ref. [48], we find that they are predominantly driven by the absence of a spectral break, rather than by the absence of a change in flavor composition, to which there is currently little sensitivity. The limits are similar for both samples because, after selecting MESE events with $E_{\text{dep}} \geq 20$ TeV, both samples cover roughly the same $E_{\text{dep}}$ range. The MESE limit is worse because there are 26 fewer MESE than HESE events.

Our results disfavor a predominant origin of the TeV–PeV neutrinos in astrophysical sources with average magnetic field stronger than $\sim 10(1 + \Gamma)$ kG, i.e., 10 kG–10 MG approximately. This partially includes low-luminosity GRBs [52–53, 92, 96]. Fast radio bursts (FRBs) have been considered as potential neutrino sources, but their feasibility as such depends on their origin, which is currently subject of intense investigation. So far, direct searches have found no evidence for FRBs as high-energy neutrino sources [27, 101]. If FRBs are connected to magnetars [102, 107], then our limits would disfavor relativistic outflows in FRBs as regions of copious production of high-energy neutrinos. Our results also disfavor the non-thermal emission of high-energy neutrinos from the crusts of magnetars and neutron stars [108], with $B' \approx 10^{14}–10^{15}$ G, but these sites are not expected to be efficient hadronic accelerators.

Sources with an intermediate field of 10 kG–1 MG—high-luminosity GRBs [50–53, 109–115], blazars [116–129], pulsar and magnetar winds [30, 33, 54, 130, 131]—remain viable candidates according to our analysis. These are electromagnetically luminous and relatively abundant sources; at face value, they are ideal neutrino emitters. However, they are strongly constrained by dedicated searches: the contribution of high-luminosity GRBs and blazars is restricted to be less than 2% [12] and 15% [11, 132] of the diffuse flux, respectively.

Sources with a weak field—non-blazar AGN [47, 132–137], TDEs [138–142], starburst galaxies [137, 143–149], supernovae [42, 150, 155], supernova remnants [43, 150, 156], and galaxy clusters [159–164]—remain viable candidates in a broader sense and may account for a large fraction of the diffuse neutrino flux. The neutrino emission from these sources is largely unconstrained by direct searches due to their high abundance and low luminosity per source [13, 158, 160].

While we have derived our results assuming that the sources emit neutrinos with a power-law energy distribution, they are valid within a more general framework. We have repeated our analysis using a broken power-law energy distribution where the spectral index $\alpha_\nu$ steepens by $\Delta \alpha_\nu$ after a break energy $E_{\nu,br}$. This steepening mimics a production scenario where neutrinos inherit the peaked shape of a parent photon spectrum or the pile-up of low-energy neutrinos produced by the decay of synchrotron-cooled muons; see, e.g., Refs. [60, 167, 170]. Also in this case, we find no evidence of synchrotron-loss features in the HESE and MESE samples. The resulting upper limits on $B'$ are very similar to those shown in Fig. 1.

VI. SUMMARY AND OUTLOOK

The magnetic field of the sources that populate the high-energy Universe remain enigmatic. At the same time, one of the main goals of neutrino astronomy is to identify the sources of the TeV–PeV neutrinos seen by IceCube. We have introduced a new way to address these two long-standing questions, by using high-energy neutrinos as cosmic magnetometers.

We look in the diffuse flux of TeV–PeV astrophysical neutrinos for imprints left by the magnetic field of their sources on the energy spectrum and flavor composition. These imprints originate in the energy losses via synchrotron radiation of the protons, pions, and muons that produce the neutrinos. We find no evidence in 6 years of IceCube high-energy events (HESE) and 2 years of medium-energy events (MESE). Thus, we constrain the average magnetic field strength of the neutrino sources to be smaller than 10 kG–10 MG. Consequently, we partially disfavor low-luminosity GRBs as the predominant sources of TeV–PeV neutrinos, but sources with a weak magnetic field—AGN, TDEs, SNe, SNRs, starburst galaxies, magnetar and neutron star winds, and galaxy clusters—remain viable candidates.

Because we use a generic model of neutrino production, our results apply to a wide range of candidate source classes. Future work may explore source- and population-dependent modeling in order to boost the sensitivity to specific source classes. Further refinements include a detailed treatment of the source physics and cosmic-ray acceleration, the interaction not only of protons, but also of nuclei, additional neutrino-production channels, and non-synchrotron losses; see, e.g., Refs. [49, 53, 170, 173]. Further, the acceleration of secondary muons, pions, and kaons, which we have neglected, could play an important role in mitigating synchrotron cooling in astrophysical environments with efficient particle diffusion [174, 175].

In the future, larger detectors, like the planned IceCube-Gen2 [176], will be able to detect neutrinos at a higher rate, at energies beyond the PeV scale, and will have improved sensitivity to changes in flavor composition with energy [177]. This will allow to place tighter bounds on the source magnetic field and probe the existence of synchrotron-loss features at higher energies, i.e., of magnetic fields weaker than the ones that we are currently sensitive to.
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Appendix A: Overview of the calculation of event spectra at IceCube

1. HESE events

To compute the differential spectrum \( dN/dE_{\text{dep}} \) of HESE events at IceCube, we follow the detailed procedure from Ref. [85]. The spectra of showers and tracks are computed separately, accounting in each case for the contributing interactions of all flavors of neutrinos and anti-neutrinos. The event rates are computed from first principles, i.e., from the effective IceCube mass and the deep-inelastic-scattering neutrino-nucleon differential cross section for \( \nu_e \) and \( \bar{\nu}_e \), based on the CTEQ14 parton distribution functions [178]. The procedure accounts for differences in deposited energy for different flavors, CC vs. NC, and decay channels of final-state particles, and for the \( \sim 13\% \) detector energy resolution. We defer to Ref. [86] for the explanation of the full procedure and to Appendix A in Ref. [179] and Appendix C in Ref. [180] for an overview.

2. MESE events

To compute the spectrum of MESE events, we use the IceCube effective area, \( A_{\text{eff}}^{s,t}(E_\nu, E_{\text{rec}}, \cos \theta_z, \cos \theta_{z,\text{rec}}) \), provided by the IceCube Collaboration for its 2-year MESE analysis [28, 29], as a function of true neutrino energy \( E_\nu \), reconstructed (i.e., deposited) energy \( E_{\text{rec}} \), true neutrino direction \( \cos \theta_z \), and reconstructed direction \( \cos \theta_{z,\text{rec}} \). The effective area is provided separately for each neutrino species \( s = \nu_e, \bar{\nu}_e, \nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau \), and topology \( t = \text{sh} \) (shower), \( \text{tr} \) (track). It includes the effects of the MESE self-veto and of the mapping between true and reconstructed quantities.

In general, given diffuse neutrino fluxes \( \Phi_s \), the number of detected events at IceCube after a time \( T \), at a given reconstructed energy and direction is

\[
N_t(E_{\text{rec}}, \cos \theta_{z,\text{rec}}) = 2\pi T \sum_s \int_{E_{\text{min}}}^{E_{\text{max}}} \cos \theta_z A_{\text{eff}}^{s,t}(E_\nu, E_{\text{rec}}, \cos \theta_z, \cos \theta_{z,\text{rec}}) \Phi_s(E_\nu, \cos \theta_z) . \tag{A1}
\]

The sum over \( s \) adds the contribution of all flavors of neutrinos and anti-neutrinos that make showers or tracks.

For our analysis, we make two modifications to this expression. First, because the effective area is binned in all of its input parameters, we change the integrals in Eq. \( \text{(A1)} \) for sums over bins. To do this, we write the effective area in the \( j \)-th bin of \( E_\nu \), the \( k \)-th bin of \( \cos \theta_{z,\text{rec}} \), the \( l \)-th bin of \( E_{\text{rec}} \), and the \( m \)-th bin of \( \cos \theta_z \)

\[
N_t(E_{\text{rec}}, \cos \theta_{z,\text{rec}}) = 2\pi T \sum_s \sum_{l=1}^{N_{E_\nu}} \sum_{k=1}^{N_{E_{\text{rec}}}} \sum_{m=1}^{N_{E_{\text{rec}}}} A_{\text{eff},jklm}^{s,t}(E_\nu, E_{\text{rec}}, \cos \theta_z, \cos \theta_{z,\text{rec}}) \int_{E_{\text{min}}}^{E_{\text{max}}} dE_\nu \Phi_s(E_\nu, \cos \theta_z) , \tag{A2}
\]

where \( N_{E_\nu} \) is the number of bins of \( E_\nu \), and \( E_{\text{min}} \) and \( E_{\text{max}} \) are the minimum and maximum energies in the \( l \)-th bin of \( E_{\text{rec}} \).

After this, the statistical procedure described in the main text proceeds similarly for MESE and HESE events.

There are only two differences. The first one is in the computation of the spectra of atmospheric muons, which we describe in Appendix \( \text{[A3]} \). The second one is in the computation of the astrophysical and atmospheric probability distribution functions, \( P_{t,\text{ast}} \) and \( P_{t,\text{atm}} \), for the
$i$-th MESE event. The probability distribution functions are computed similarly as for HESE events, but using the total event rate, Eq. (A2), instead of the differential event rate (see the main text). For astrophysical neutrinos, this is

$$P_{i,\text{ast}} = \frac{N_i(E_{\text{rec},i}, \cos \theta_{z,\text{rec},i})}{\sum_{j=1}^{N_{\text{rec}}} N_i(E_{\text{rec},j}, \cos \theta_{z,\text{rec},i})}, \quad (A3)$$

where $t$ depends on whether this event is a shower or track, $N_i$ is computed using the astrophysical neutrino fluxes, $E_{\text{rec},i}$ and $\cos \theta_{z,\text{rec},i}$ are the deposited energy and direction of the $i$-th event, and $N_{E_{\text{rec}}}$ is the number of bins of $E_{\text{rec}}$. The calculation is analogous for $P_{i,\text{atm}}$, changing only the astrophysical fluxes for the atmospheric neutrinos, this is

$$N_{\mu}(< E^*_{\text{dep}}) = \frac{1}{1 - \gamma_{\mu}} (E^*_{\text{dep}})^{1-\gamma_{\mu}} - (E^*_{\text{dep}})^{1-\gamma_{\mu}}, \quad (A4)$$

$$N_{\mu}(\geq E^*_{\text{dep}}) = -\frac{1}{1 - \gamma_{\mu}} (E^*_{\text{dep}})^{1-\gamma_{\mu}} \quad (A5)$$

where $E^*_{\text{dep}}$ is the minimum deposited energy in the event sample. With this, the spectral index $\gamma_{\mu}$ varies for HESE versus MESE events.

$$\gamma_{\mu} = 1 - \ln \left( 1 + \frac{N_{\mu}(< E^*_{\text{dep}})}{N_{\mu}(\geq E^*_{\text{dep}}/E^*_{\text{dep}})} \right) \quad (A6)$$

For HESE events, we compute $\gamma_{\mu}$ using the muon rates reported in the 3-year IceCube HESE analysis [1]. Table IV in Ref. [1] reports 8 passing muons below $E^*_{\text{dep}} = 60$ TeV and 0.4 passing muons above it. In that sample, $E^*_{\text{min}} = 28$ TeV. Therefore, for HESE events, $\gamma_{\mu} \approx 5$, as reported by Ref. [80].

For MESE events, we compute $\gamma_{\mu}$ using the muon rates reported in the 2-year IceCube MESE analysis [28]. Figure 8 in Ref. [28] reports 64.78 passing muons below $E^*_{\text{dep}} = 50$ TeV and 0.44 passing muons above it. In that sample, $E^*_{\text{min}} = 0.33$ TeV. Therefore, for MESE events, $\gamma \approx 2$.

The probability distribution function for the $i$-th event in a sample to have been generated by atmospheric muons is then $P_{i,\mu} = E^*_{\text{dep},i}/\int dE_{\text{dep}} E^*_{\text{dep}}^{-\gamma_{\mu}}$, where $E_{\text{dep},i}$ is the deposited energy of the event.

**Appendix B: Details of the statistical analysis**

1. **Prior distributions of the likelihood parameters**

Table B1 shows the prior probability distributions of the likelihood parameters that we have used in our Bayesian statistical analysis. For the definition of each parameter, see the main text. Priors are different for the two public IceCube event samples that we use: the 6-year HESE sample [25–27] and the 2-year MESE sample [28, 29] restricted to $E_{\text{dep}} \geq 20$ TeV.

For $m$ and $\log_{10} \Gamma$, we use wide uniform priors to avoid introducing unnecessary bias. For $\log_{10} (B'/G)$, we choose ranges based on criteria that we explain below. For $N_{\text{ast}}, N_{\text{atm}}, N_{\mu},$ and $\gamma$ (in the case of HESE) we use priors informed by the IceCube analyses of the HESE and MESE samples; see the footnotes in Table B1 for details.

The “signal hypothesis” in Table B1 refers to the hypothesis where synchrotron-loss features in the diffuse neutrino flux may exist within the energy range of the sample—where they could be detectable—or above its energy range—where they would not affect the sample—but not below its energy range. By doing this, we prevent the Bayesian parameter scan from finding high values of $B'$ that would induce synchrotron-loss features at artificially low neutrino energies, below the energy range of the sample. We ensure this by choosing, for each sample, a prior for $\log_{10} (B'/G)$ such that the energy where muon synchrotron cooling starts to become important, $E_{\text{synch}}$, is larger than the minimum neutrino energy of the sample, for any value of $\Gamma$, and for neutrinos that come from even the highest redshift of $z_{\text{max}} = 4$. See the main text for the definition of $E_{\text{synch}}$ and Table B1 for details.

The “null hypothesis” in Table B1 refers to the hypothesis where synchrotron-loss features do not affect the event sample, i.e., they may exist only at energies higher than the maximum energy of the sample. We ensure this by choosing, for each sample, a prior for $\log_{10} (B'/G)$ such that $E_{\text{synch}}$ is larger than the maximum energy of the sample, for any value of $\Gamma$, and for neutrinos that come from even the highest redshift of $z_{\text{max}} = 4$. Only the prior for $\log_{10} (B'/G)$ is different between the signal and null hypotheses. See Table B1 for details.

2. **Posterior distributions of the likelihood parameters**

Figures A1 and A2 show the resulting one-dimensional and two-dimensional marginalized posterior probability
TABLE B1. Likelihood parameters varied in our statistical analysis and their prior probability distributions; see Eq. (3) in the main text. See Appendix E for details.

| Parameter | Signal hypothesis | Null hypothesis | Ref. Signal hypothesis | Null hypothesis | Ref. |
|-----------|-------------------|-----------------|------------------------|-----------------|------|
| $\gamma$  | Normal 2.92 ± 0.33| Normal 2.92 ± 0.33| [27] Uniform [2, 3] | Uniform [2, 3] | –   |
| $m$       | Uniform [−1, 4]  | Uniform [−1, 4]  | –                      | Uniform [−1, 4] | –   |
| log$_{10}(\Gamma)$ | Uniform [0, 3] | Uniform [0, 3] | –                      | Uniform [0, 3] | –   |
| log$_{10}(B'/G)$ | Uniform [0, 4.34 + log$_{10} \Gamma$] | Uniform [0, 2.29 + log$_{10} \Gamma$] | Uniform [0, 2.29 + log$_{10} \Gamma$] | Uniform [0, 2.29 + log$_{10} \Gamma$] | –   |
| $N_{\text{ast}}$ | Uniform [0, $N_{\text{obs}} = 80$] | Uniform [0, $N_{\text{obs}} = 80$] | Normal 35.29 ± 5.95 | Normal 35.29 ± 5.95 | [27] |
| $N_{\text{atm}}$ | Skew-normal 15.6$\pm_{-3.9}^{+11.4}$ | Skew-normal 15.6$\pm_{-3.9}^{+11.4}$ | Normal 13.92 ± 3.75 | Normal 13.92 ± 3.75 | [27] |
| $N_{\mu}$  | Normal 25.2 ± 7.3 | Normal 25.2 ± 7.3 | Normal 2.83 ± 1.66 | Normal 2.83 ± 1.66 | [27] |

a This ensures that synchrotron-loss features, if any, appear in the diffuse flux only at energies $E^\mu_{\nu, \text{HESE}} > (1 + z_{\text{max}})E^\mu_{\nu, \text{MESE}}$, i.e., not below the energy window of the HESE sample. We approximate the minimum neutrino energy that could be affected by synchrotron losses by equating it to the smallest HESE deposited energy, i.e., $E^\mu_{\nu, \text{HESE}} = 18$ TeV.
b This restricts synchrotron-loss features in the diffuse flux to appear only at energies $E^\mu_{\nu, \text{HESE}} > (1 + z_{\text{max}})E^\mu_{\nu, \text{MESE}} = 10$ PeV, beyond the energy windows of the HESE and MESE sample. We approximate the maximum neutrino energy that could be affected by synchrotron losses by equating it to the largest HESE deposited energy, i.e., $E^\mu_{\nu, \text{HESE}} = 2$ PeV. (The maximum MESE deposited is 1.3 PeV, but we use the same prior for MESE and for HESE, since the difference is small.)
c This ensures that synchrotron-loss features in the diffuse flux to appear only at energies $E^\mu_{\nu, \text{HESE}} > (1 + z_{\text{max}})E^\mu_{\nu, \text{MESE}}$, i.e., not below the energy window of the MESE sample selected for $E_{\text{dep}} \geq 20$ TeV. We approximate the minimum neutrino energy that could be affected by synchrotron losses by equating it to the smallest MESE deposited energy, i.e., $E^\mu_{\nu, \text{MESE}} = 20$ TeV.
d For $N_{\text{ast}}$, $N_{\text{atm}}$, and $N_{\mu}$, the central value of each is inferred from interpolating their best-fit contribution to the measured MESE event rates in Fig. 8 of Ref. [25]. We count only MESE events with $E_{\text{dep}} \geq 20$ TeV. For each parameter, the standard deviation is assumed to be that for a normal distribution, i.e., the square root of the central value. For $N_{\mu}$, we make sure that its sampled values are always non-negative.

of the parameters—under the signal and null hypotheses, $Z_{\text{signal}}$ and $Z_{\text{null}}$, respectively. With them, we compute the Bayes factor $K \equiv Z_{\text{signal}}/Z_{\text{null}}$ for each sample, to estimate the strength of the evidence in favor of the existence of synchrotron-loss effects in the sample. We qualify the strength of the evidence using Jeffreys’ empirical scale [91]. For both samples, log$_{10} K \approx 0.3$, so the strength of the evidence is insignificant, or “not worth more than a bare mention,” according to the scale.

3. Computing limits

To compute the Bayes factor above, we allow all of the likelihood parameters in Table B1 to vary simultaneously. In contrast, to compute the upper limit on log$_{10}(B'/G)$ as a function of log$_{10} \Gamma$, we fix log$_{10} \Gamma$ to a given value, vary all of the remaining likelihood parameters, and finally marginalize over all of them except for log$_{10}(B'/G)$. Figure 1 shows the resulting one-dimensional 95% C.L. upper limit on log$_{10}(B'/G)$ as a function of log$_{10} \Gamma$. 


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FIG. A1. Posterior probability distributions, central values, and standard deviations of the likelihood parameters for the 6-year IceCube HESE sample, obtained under the signal hypothesis; see Table B1. The shaded regions show the 68%, 90%, and 95% C.L. regions, from darkest to lightest shading.
FIG. A2. Same as Fig. A1 but for the 2-year IceCube MESE sample.
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