Super heavy dark matter may show its presence in high energy neutrino signals detected on earth. From the latest results of IceCube, we could set the strongest lower bound on the lifetime of dark matter beyond 100 TeV around $10^{28}$ sec. The excess around a PeV is noticed and may be interpreted as the first signal of DM even though further confirmation and dedicated searches are invited.

I. INTRODUCTION

One of the most pressing problems in nature is to understand the origin of dark matter (DM) and measure its properties. Several DM candidates have been suggested but weakly interacting massive particles (WIMPs) have attracted the largest attention since WIMPs can naturally explain the observed density of DM thanks to the effective ‘WIMP miracle’ following the Lee-Weinberg calculation in big bang theory. A relatively low mass window below 100 TeV is open for WIMPs because of the model independent theoretical upper bound coming from perturbative unitarity thus main experimental efforts for DM searches have been given to this low mass window. No confirmed experimental evidence, however, has been found after many years of endeavour. On the other hand, the heavier mass regime beyond the unitarity bound has attracted less attention even though superheavy DM, or WIMPZILLA, could be produced by nonthermal processes and explains the observed DM density in universe. For strongly interacting superheavy DM, DM could be also produced in high energy inelastic scattering processes. The stability of superheavy DM was discussed earlier.

Differently from DM at TeV scales, superheavy DM candidates are hard to test because

- the high mass surpasses the currently available collider energies so that DM production is kinematically forbidden,
- the longevity of DM implies that interaction strengths with the standard model particles are largely suppressed. Even worse, the number density in the galaxy is low ($\sim 1/M_{DM}$) so that the direct detection rate by a detector on earth becomes doubly suppressed.

However, if DM decays, the decay products carry distinctively high energies $E \sim M_{DM}/N$ when the DM turns into a small number ($N$) of particles unless they are highly red shifted. This opens a unique new window for superheavy DM. In particular, neutrinos among other potential decay products have advantages as messenger particles as they can be directly observable on Earth preserving initial properties of DM.

Indeed, IceCube recently reported their observation of high energy neutrinos in 30–2000 TeV. Very interestingly, the observed neutrinos are isotropic in arrival directions and show no particular pattern identified in arrival times, which suggest that the source is not local and violent but broadly distributed and stable, which is consistent with the properties of DM as stable (lifetime $\gg 4.3 \times 10^{17}$ sec) and broadly distributed DM in the Galactic halo.

The main goal of this letter is to examine the IceCube results and what they can tell us about superheavy DM with masses $M_{DM} > 100$ TeV. In Sec. II we show that decaying DM provides better fit to the IceCube data compared to annihilating DM then provide a benchmark model for concrete analysis. We set the most stringent new bound on the lifetime of DM above 100 TeV in Sec. III. We note that some excess events in PeV-energy could be interpreted as an indication of decaying DM, which needs further studies. We conclude in Sec. IV.

II. A BENCHMARK MODEL OF DECAYING DM

Two key observables that could distinguish decaying DM from self-annihilating are directional information and energy of neutrino signals. The neutrino flux

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1 For WIMP DM below 1 TeV, the most stringent bounds on the spin independent DM-nucleon cross-section have been obtained $\sigma_{N} \leq 2.0(7.6) \times 10^{-45(40)}$ cm$^2$ by XENON100 (LUX) experiment at the WIMP mass $m_{\chi} = 55(33)$ GeV. It needs to be further improved to the level of $\sigma_{N} \sim 10^{-49}$ cm$^2$ in the future to cover all the relevant parameters for WIMP in minimal supersymmetric standard model.
is proportional to the density ($\rho$) or the square of the density ($\rho^2$) for decaying and annihilating DM, respectively. As a consequence, the signals are more localized toward the Galactic center (GC) for annihilating DM but more isotropic for decaying DM. Assuming the NFW profile \cite{20} we expect more than 50% of events are within 65° from GC for decaying DM but within 25° for annihilating DM. Isotropy of the observed neutrinos would prefer the decaying DM interpretation. As the observed neutrino energies surpass 100 TeV, annihilating WIMP DM is excluded as a source because the energy domain lies beyond the perturbative unitarity bound.

A model of decaying DM producing neutrinos by $\chi \rightarrow \nu h$ is suggested in accordance with the seesaw mechanism. We introduce a Majorana DM component in addition to the original seesaw Lagrangian and extend the mass matrix by a small non-diagonal part, which eventually leads to a small coupling of DM to the neutrino and the Higgs boson. The model Lagrangian is given as

$$\mathcal{L} \supset -\lambda \overline{\psi} L (h + v) n - (\overline{\nu}, \overline{\nu}) \begin{pmatrix} M_n & \sigma \\ \sigma & M_\psi \end{pmatrix} \begin{pmatrix} n \\ \psi \end{pmatrix},$$

where $v \approx 246$ GeV is the vacuum expectation value of the Higgs field. Here we assume $M_n > M_n - M_\psi > M_\psi \gg \sigma$ and a negligibly small Yukawa coupling with $\psi$. Flavour indices are suppressed. The mass matrix is first diagonalized with the eigenmasses $M_\pm = \frac{1}{2} (M_n + M_\psi \pm \sqrt{(M_n - M_\psi)^2 + 4 \sigma^2})$ and the mass eigenstates

$$\begin{align*}
\chi_+ &= \cos \theta n + \sin \theta \psi, \\
\chi_- &= -\sin \theta n + \cos \theta \psi.
\end{align*}$$

The mixing angle is $\theta = \tan^{-1}(\sigma/2\delta) \ll 1$ where $\delta = \frac{1}{2} (M_n - M_\psi) \gg \sigma$ as we assumed. In terms of $\chi_+$ and $\chi_-$, the interaction Lagrangian is rewritten as

$$L_{\text{int}} = -\lambda_h \overrightarrow{\nu} \chi_+ + \frac{\sigma}{2\delta} \chi_-,$$

For DM, $\chi_-$, the suppressed effective coupling constant $\lambda_{\text{eff}} = \lambda \cdot \frac{\sigma}{2\delta}$ provides the largely suppressed decay width

$$\Gamma_{\chi_- \rightarrow \nu h} \approx \frac{\lambda_{\text{eff}}^2}{32\pi} M_-. $$

that provides the required lifetime to account the excess at PeV, $\tau \approx 1.9N_\nu \times 10^{28}$ s \cite{18}, with $\lambda_{\text{eff}} \approx 5.3 \times 10^{-29}$. A large suppression factor is provided by a small mixing mass $\sigma \sim 10^{-5}$ eV when the seesaw relation $m_\nu \approx (\lambda_n)^2 \frac{M_n}{M_+}$ is assumed with $M_+ \sim M_{\text{GUT}} \sim 10^{14}$ GeV and $m_\nu = 0.1$ eV.

### III. BOUNDS ON DECAYING DM

In this section we review existing bounds on heavy decaying DM and derive the most stringent limit for DM masses above 100 TeV based on recent public IceCube data.

Neutrinos are often described as the least detectable channel, however for heavy decaying DM signals this picture changes and neutrinos turn into the most competitive detection channel. This can be understood by the fact that neutrino backgrounds are steeply falling as function of energy and that the neutrino cross-section increases with energy compensating for reduced number densities of DM particles. IceCube has produce a very stringent bound on DM decays in the Galactic halo using one year of data collected with the partially instrumented detector. The limit on the lifetime for a heavy particle decaying into two neutrinos is strongest at the largest mass considered of 100 TeV and given with $10^{27}$ s \cite{21}. Searches with anti-protons and gamma-rays have also produced limits on decaying dark matter with masses up to 5 TeV and 10 TeV, respectively. Depending on the decay channel lifetime limits are typically between $10^{25}$ s to $10^{29}$ s. Cosmological constraints have been set \cite{22} and limits derived from neutrino data \cite{23, 24}. For a recent review on these bounds we refer the reader to the CF2 Snowmass working group summary \cite{25}.

IceCube recently reported the observation of a high-energy extra-terrestrial neutrino flux \cite{17}. The data from this result can be used to also set a limit on the lifetime of heavy dark matter. We present a straightforward analysis that produces a conservative bound based on the data and invite the collaboration to perform a dedicated analysis to improve on our derived limit.

We assume that the dark matter distribution in our Galaxy follows an NFW profile and that decays from this Milky Way halo dominate compared to extra-galactic contributions, that are neglected. We note that for dark matter decays the choice of halo profile has a rather small impact on the expected flux. Previous works found that the extra-galactic contribution is about one order of magnitude smaller compared to the Galactic flux \cite{26, 28}.

For the Galactic signal from $\chi \rightarrow \nu h$ we expect two components, a continuum (from the cascade decay of $h$) and a nearly mono-energetic line at $E_{\nu} \approx M_\chi/2$. To constrain the dark matter lifetime we use the most observable feature of the DM particle decaying with some branching fraction to a neutrino and other particles, which is the neutrino line signal. Using only the Galactic origin we obtain the most model independent bound for any scenario in which neutrinos are produced directly through DM decay. The spectral component from cosmological decays is redshifted to lower neutrino energies and hence can be neglected for our analysis \cite{28}, however the extra-galactic contribution could be valuable to verify a signal. The expected neutrino flux will further be affected by neutrino absorption in the Earth at high-energies, to include this effect we calculate a survival rate that is shown in Fig. \ref{fig:neutrino_flux}. At a PeV, this effect removes about 20% of the signal. Also shown is the survival rate for an isotropic flux, which has been assumed when creating IceCube’s effective areas used here \cite{19}. For our calculation we remove the absorption effect already included in the effective area and apply the survival rate
for the neutrino flux expected from the dark matter distribution. Note, that a full correction is not possible as the effective areas released by IceCube are averaged for neutrino and anti-neutrino fluxes. However the impact on our final result is small and can hence be neglected.

The most detectable neutrino signal will be at the highest energy, at this point atmospheric backgrounds are smallest and the signal will be most present. Since IceCube has reported results as function of the deposited energy, which corresponds approximately to the neutrino energy for an electromagnetic shower of an electron neutrino, we here concentrate only on cascade events as our signal. By including other flavours and neutral current interactions, which will produce signals at lower electromagnetic energy, one can further improve the sensitivity, but for our analysis that is focused on the neutrino line they are not relevant. Muon event contributions to the background estimate given by IceCube that we use to derive our limit only become relevant for energies below 100 TeV and hence we constrain ourselves to the region where the contribution from muon events are negligible.

We compute the expect event rates from charged current neutrino interactions of electron and tau flavours and compare them to the reported observed events and expected atmospheric backgrounds of the equivalent electromagnetic energy. Neutral current have a much smaller cross section and events are not considered as their electromagnetic energy. Neutral current are negligible.

FIG. 1. Neutrino survival probability due to Earth absorption at the South Pole near surface location as function of the neutrino energy for an isotropic flux compared to the flux expected from dark matter decay originating from a NFW halo distribution and parameterized as [27].

and hence our analysis is more conservative as we underestimate the background.

The expected number of neutrino events summed over all flavours is given by

\[ N = \frac{1}{\tau} J_{4\pi} \frac{R_{sc} \rho_{sc}}{4\pi m_\chi} 4\pi A_{\text{eff}} (E = m_\chi/2) T_{\text{life}} N_\nu, \]

where \( R_{sc} \) and \( \rho_{sc} \) are scale factors [27], \( m_\chi \) dark matter particle mass, \( A_{\text{eff}} \) the neutrino affective area for the corresponding flavour, \( T_{\text{life}} \) the lifetime of the experiment. \( J_{4\pi} \) is the angle average line-of-sight integral over the dark matter density distribution per solid angle. We use the neutrino flux from the Milky Way halo assuming an NFW profile \( J_{4\pi} \approx 2.0 \) [23].

We compute a 90% C.L. limit on the number of signal events, \( N_{90} \), using the observed events and expected background in each bin and compare it to the expected neutrino event numbers for a specific decay time. The limit is then obtained by \( \tau_{90} = \tau \cdot \frac{N_{90}}{N} \). Figure 2 shows our derived limit, following IceCube event binning in neutrino energy [17] in comparison to previous limits from the partially instrumented IceCube detector [21] which investigated the decay of DM into two neutrinos, Fermi LAT analysis of gamma-ray emission from the Milky Way halo [12] and from PAMELA observations of the anti-proton flux [13] based on the assumed DM decay into \( bb \), which is the dominant Higgs decay channel. The existing other channels with larger photon yields make our derived bound conservative. The observed three PeV neutrinos are seen as ‘dip’ in the two bins covering masses 2-5 PeV in the limit plot as the flux shows ‘excess’ over the expectation. The excess needs further investigation but
an extremely interesting interpretation would be the signal from DM. We would invite more detailed study for further clarification. A complete analysis could further benefit from the less dominant extra-galactic redshifted line spectrum smeared to lower neutrino energies and a potential continuum neutrino spectrum from secondary particle decays. A dedicated IceCube collaboration analysis will be able to improve significantly on our derived limit or lead to the identification of a signal with higher statistics.

IV. CONCLUSION

Heavy decaying dark matter might be most detectable with high-energy neutrinos. We use the recently reported observation of high energy extraterrestrial neutrinos, which includes three PeV-energy neutrinos, to set the most stringent bound on 100 TeV to PeV regime. This limit can be achieved by exploiting the line feature present in models with a non zero branching fraction into $\chi \rightarrow \nu + X$. We use the IceCube released data, effective areas and compute neutrino absorption effects in the Earth to derive the constraint.

Our bound is very conservative in its derivation and suggests that dedicated searches by the experiments can surpass the limit of $10^{28}$ s and have significant discovery potential.

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